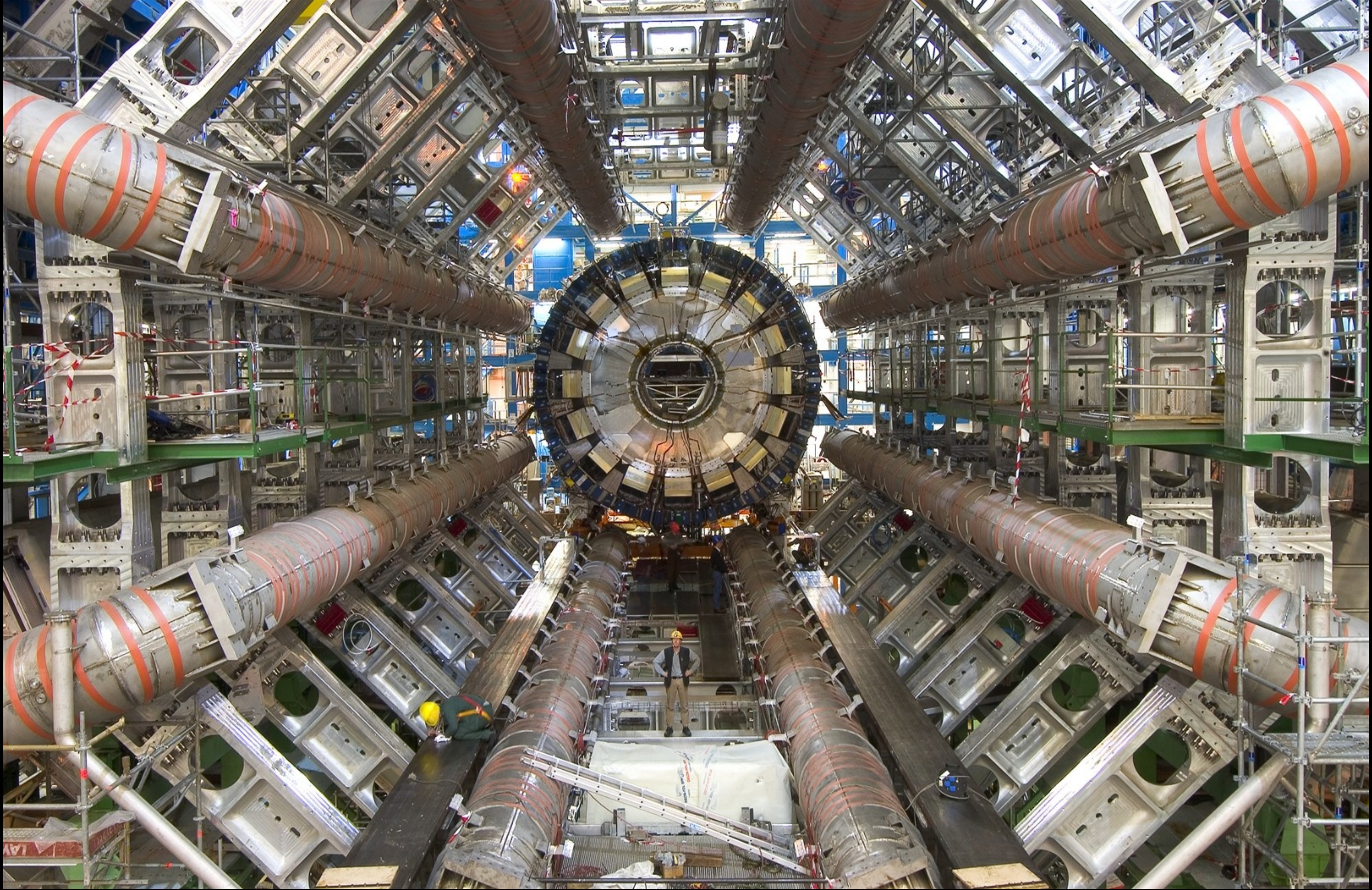
Particle physics and astrophysics with high-energy cosmic neutrinos

Mauricio Bustamante
Niels Bohr Institute, University of Copenhagen

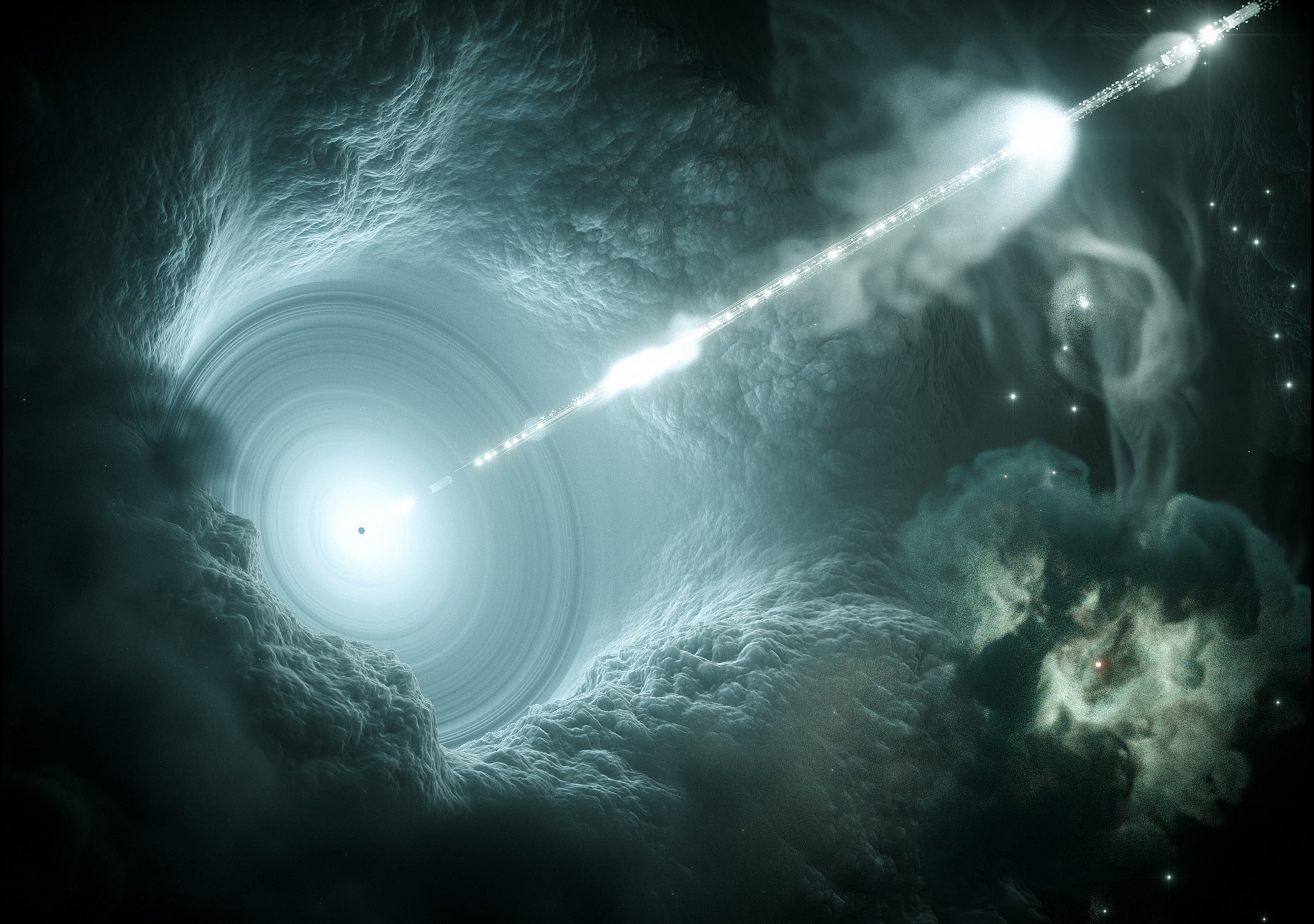
Master's Program in Physics of the Universe
University of Zaragoza, May 14, 2026

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

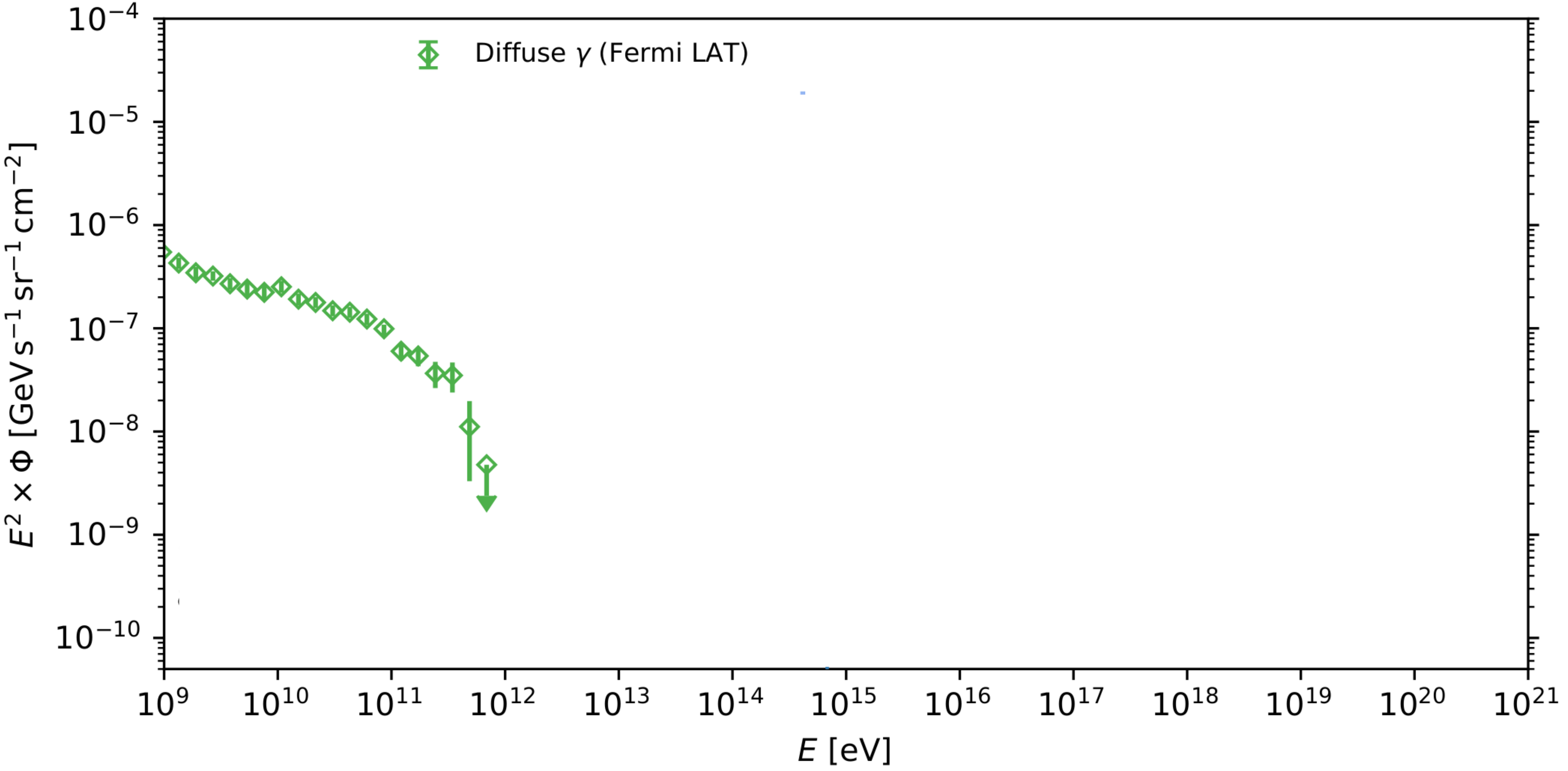


ATLAS



DESY

Gamma rays Neutrinos Cosmic rays



M. Ackermann, **MB**, *et al.*, *JHEAp* 35, 55 (2022) [2203.08096]

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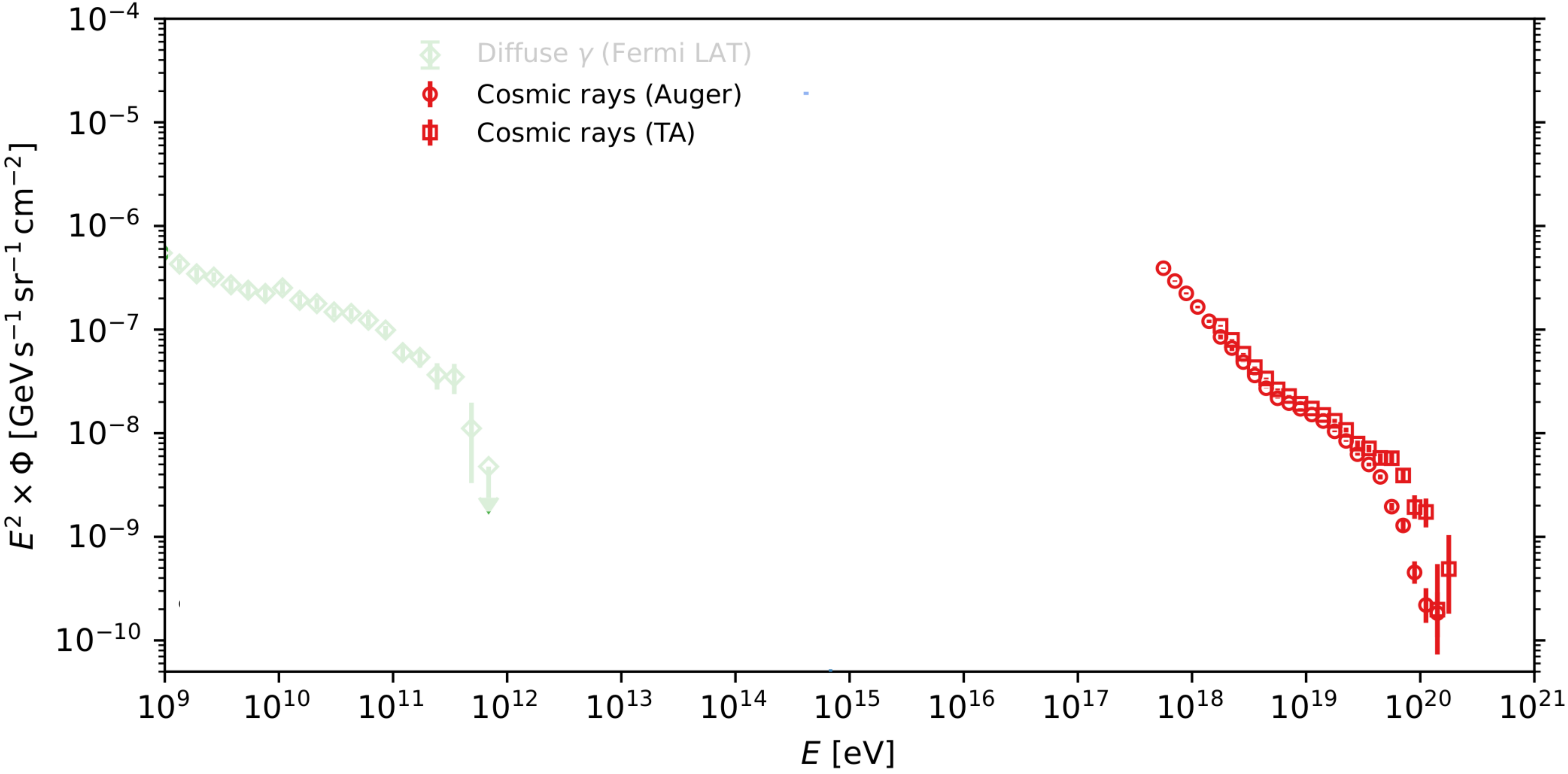

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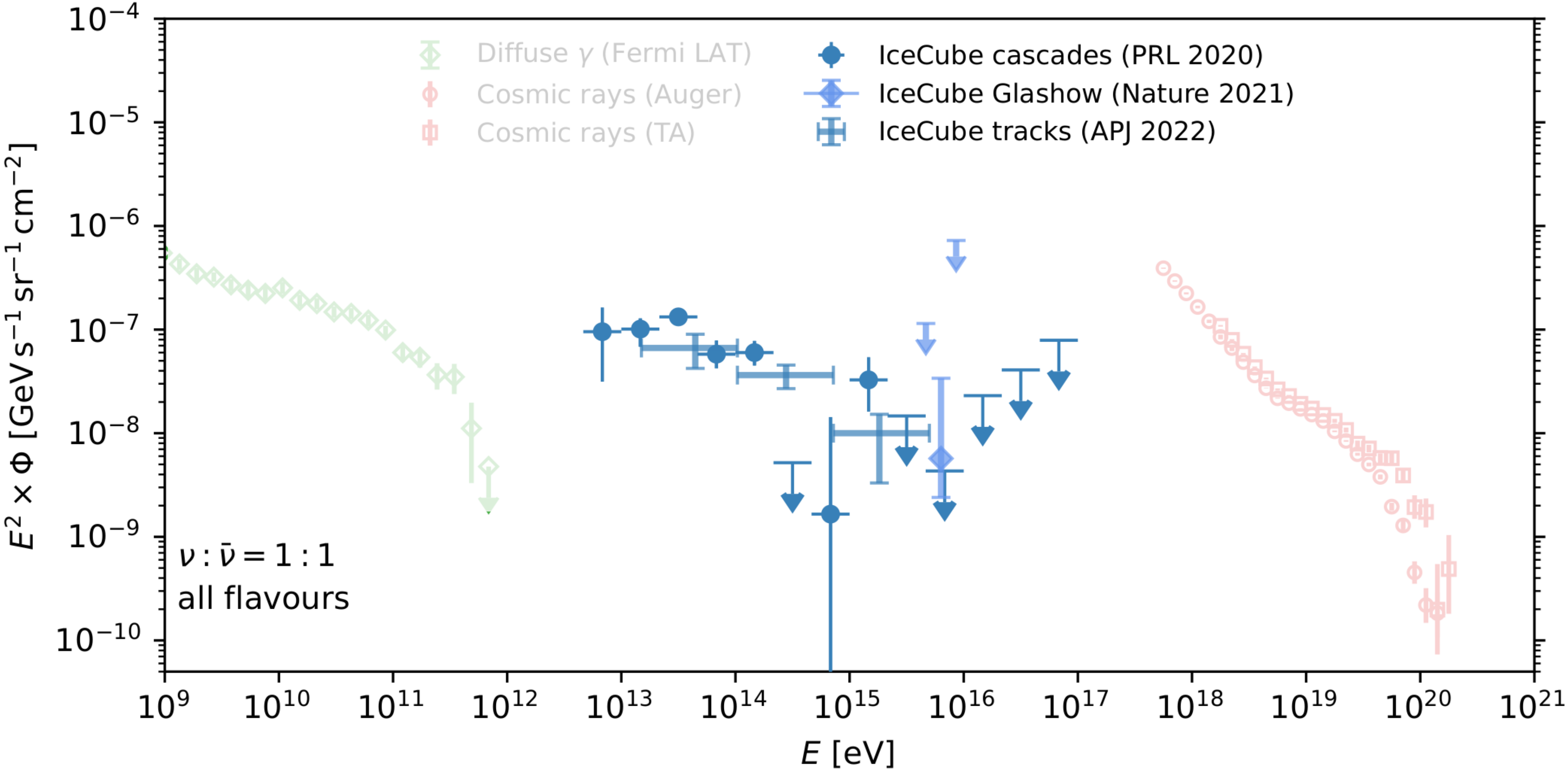

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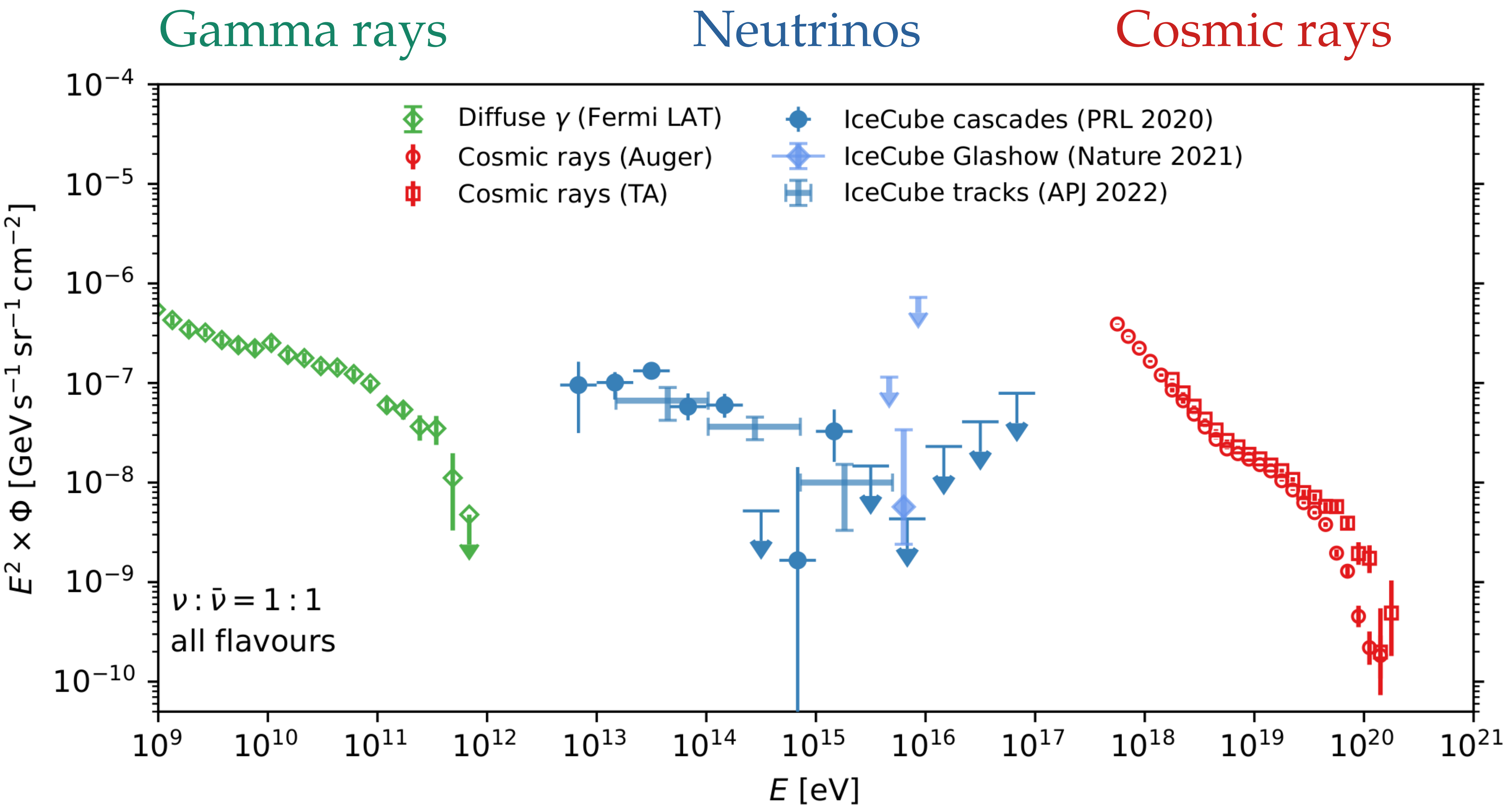

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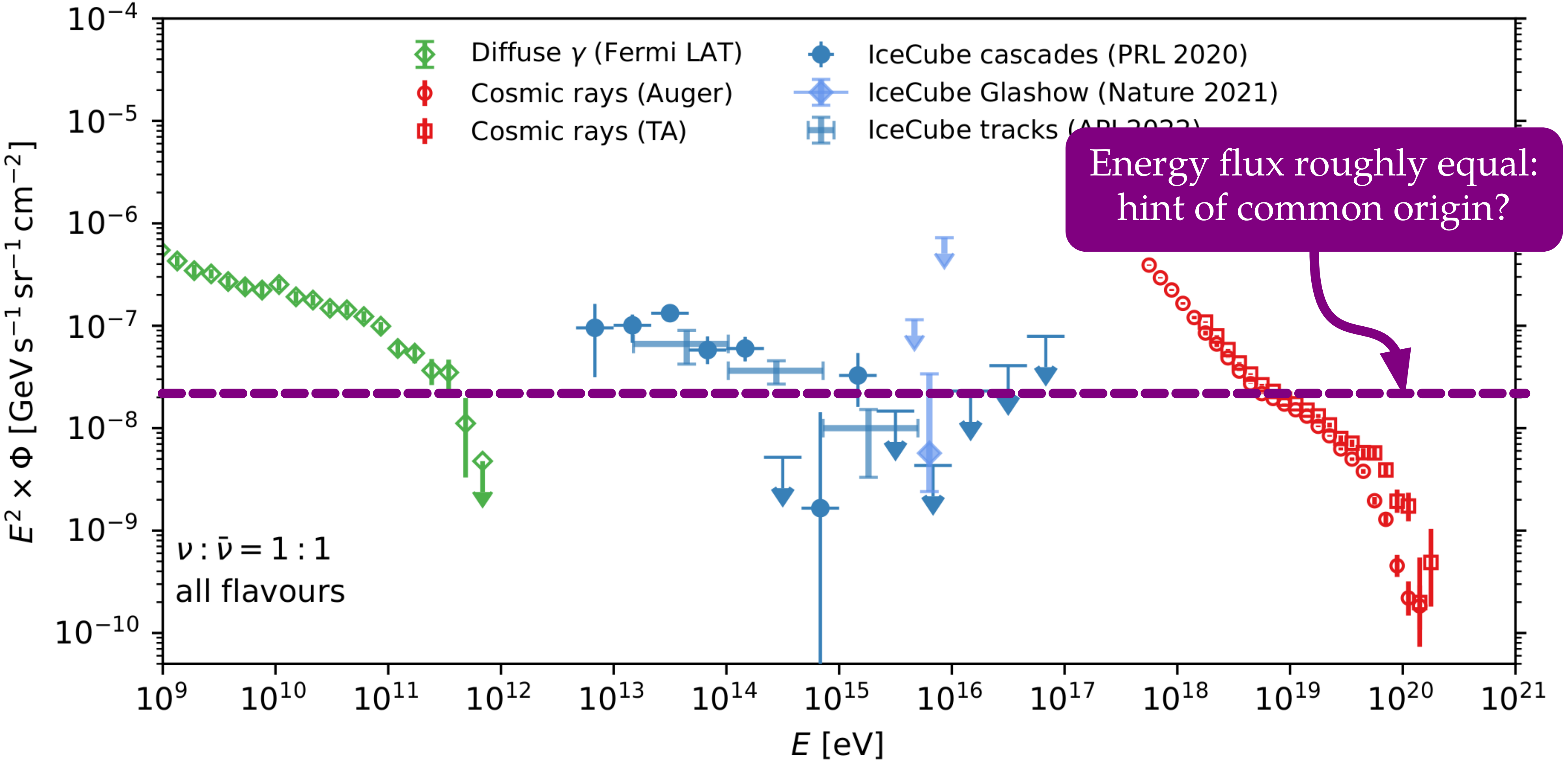

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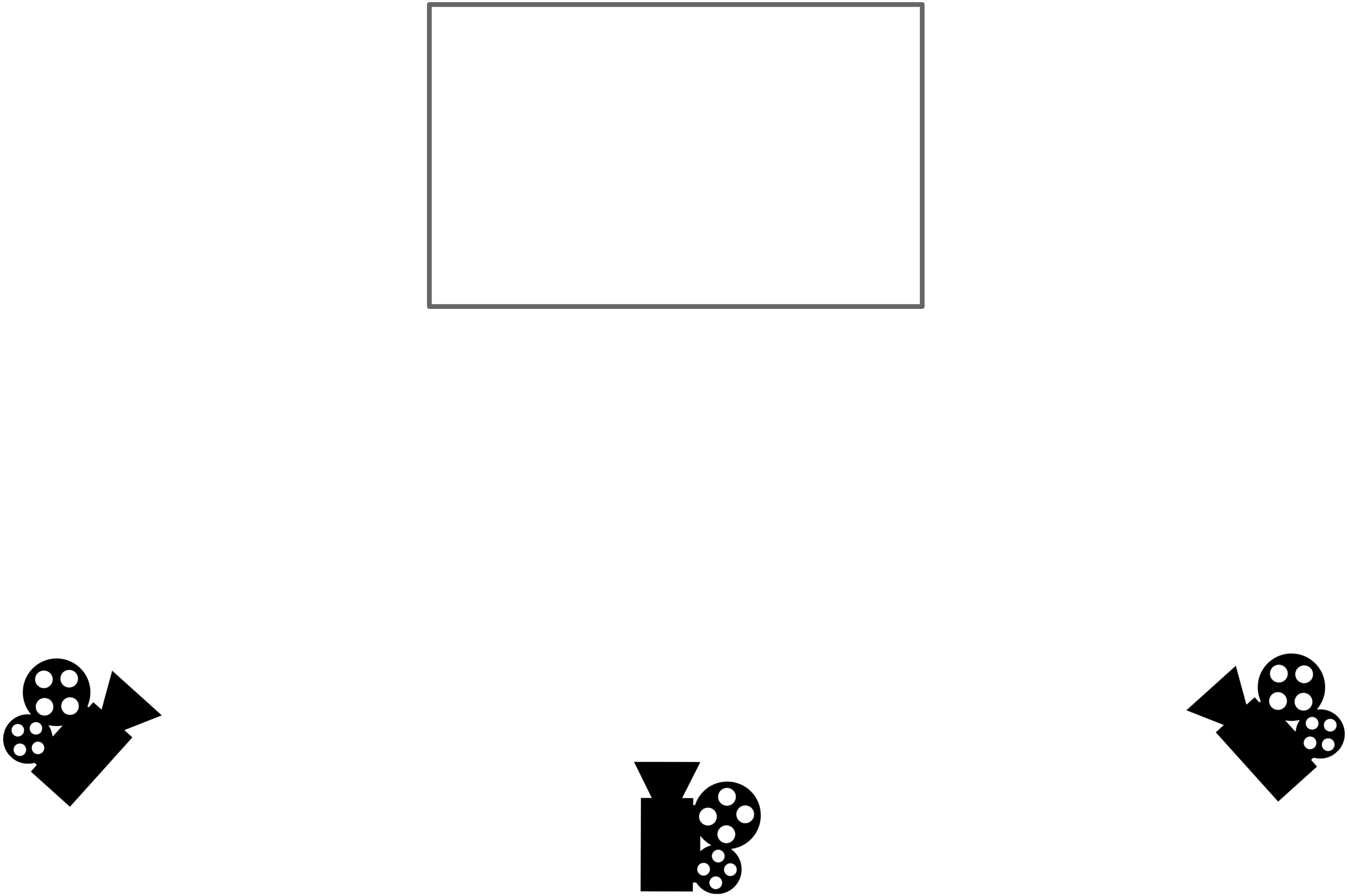
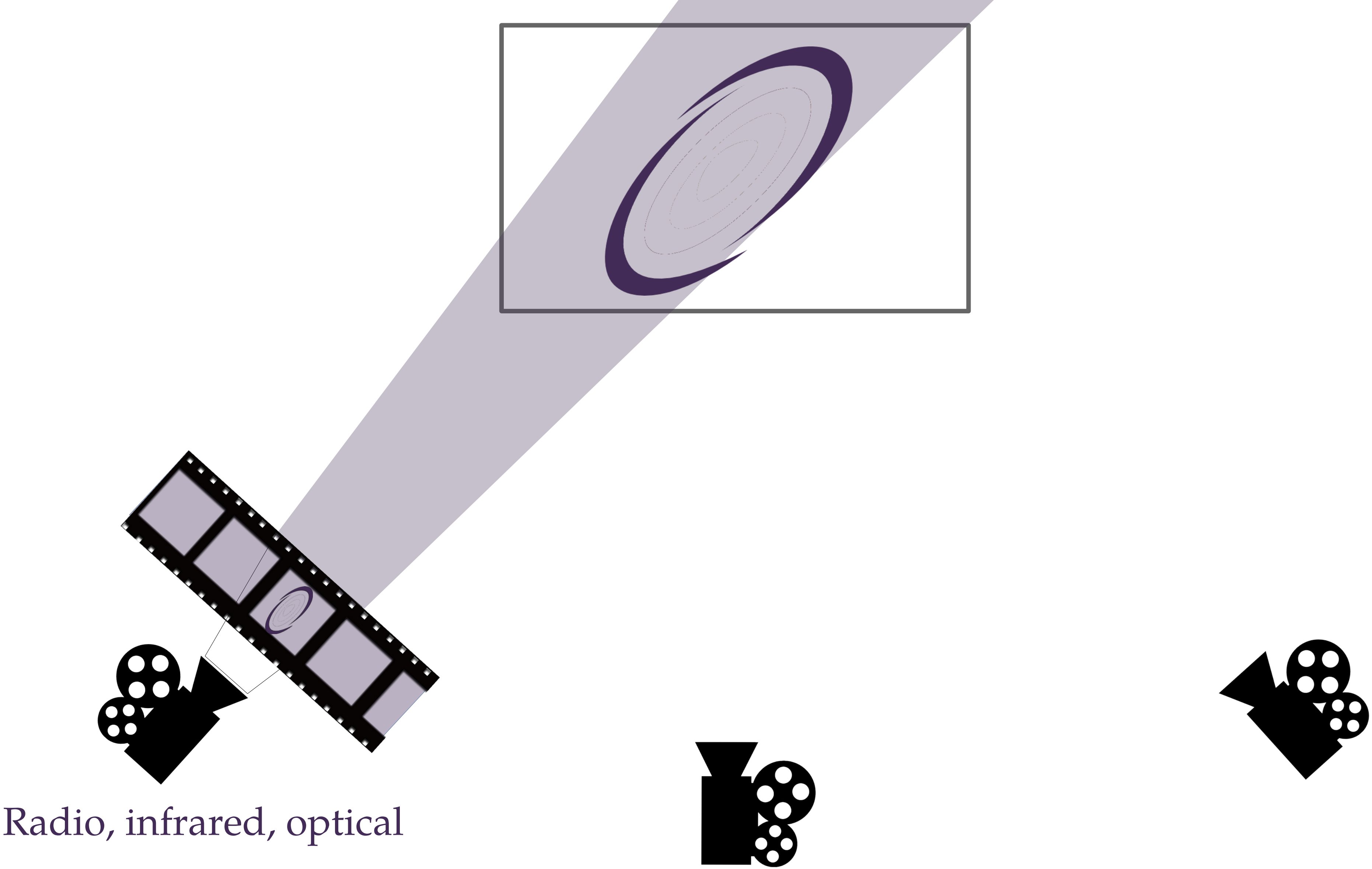
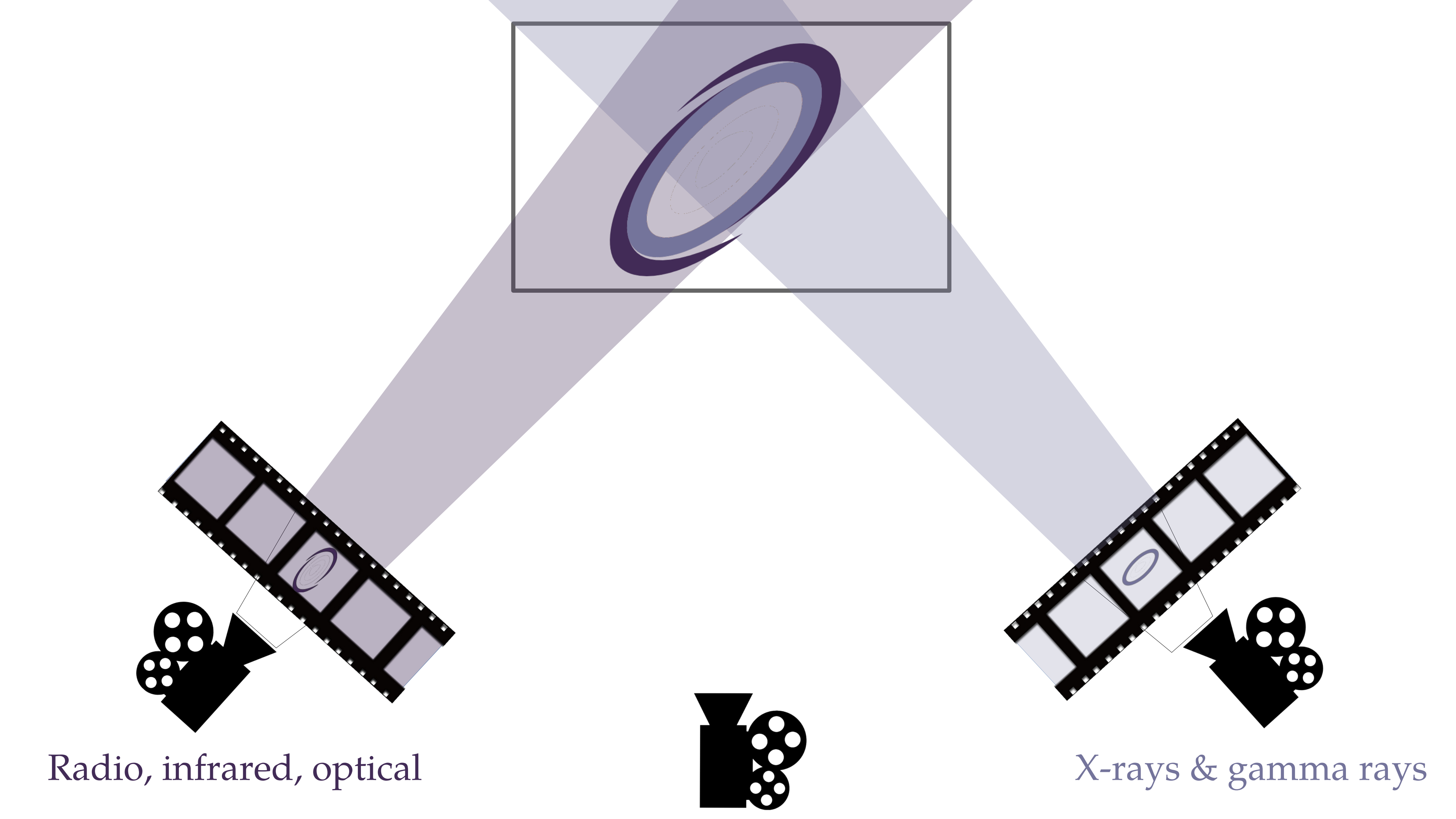
YouTube

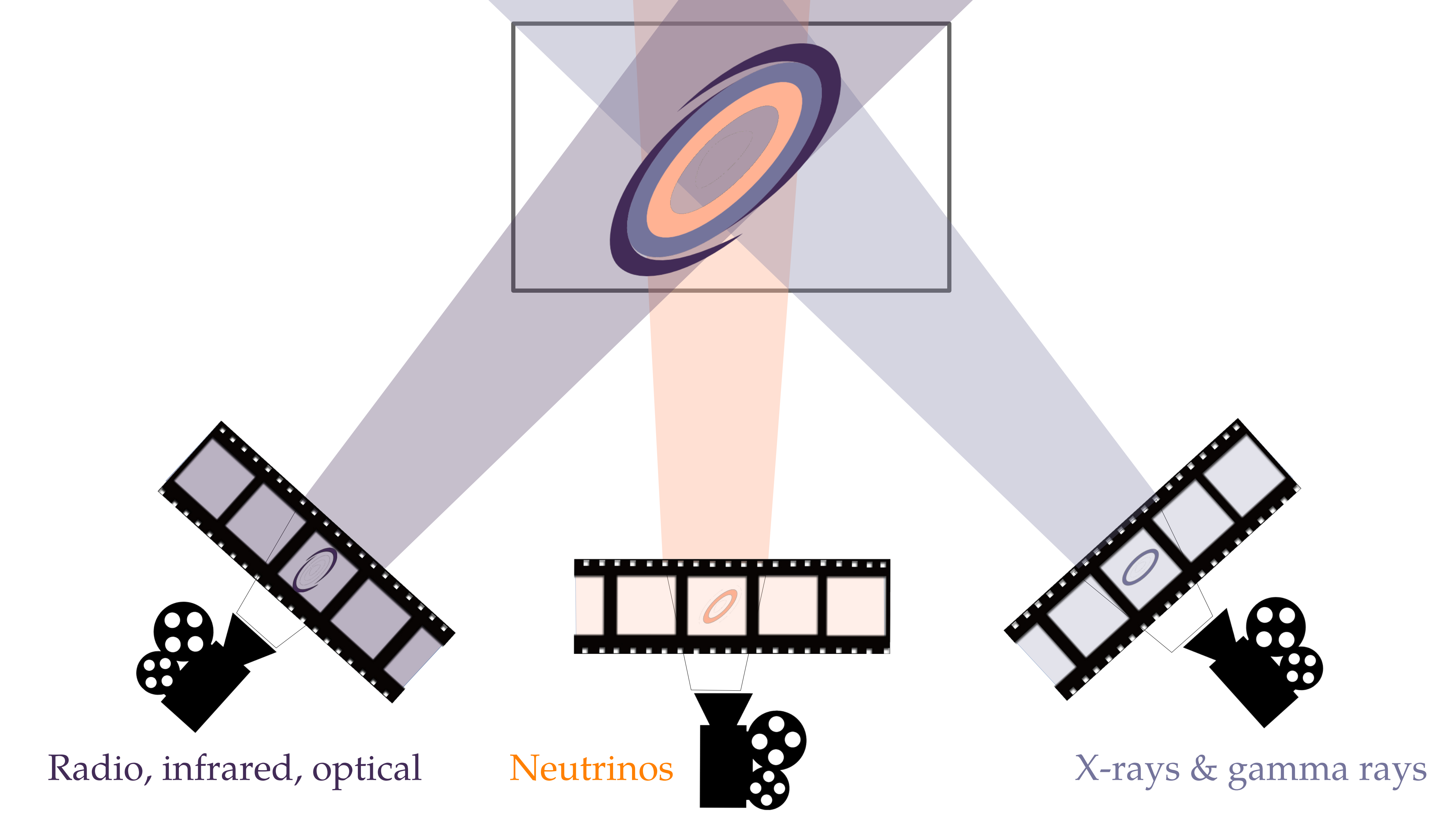



YouTube

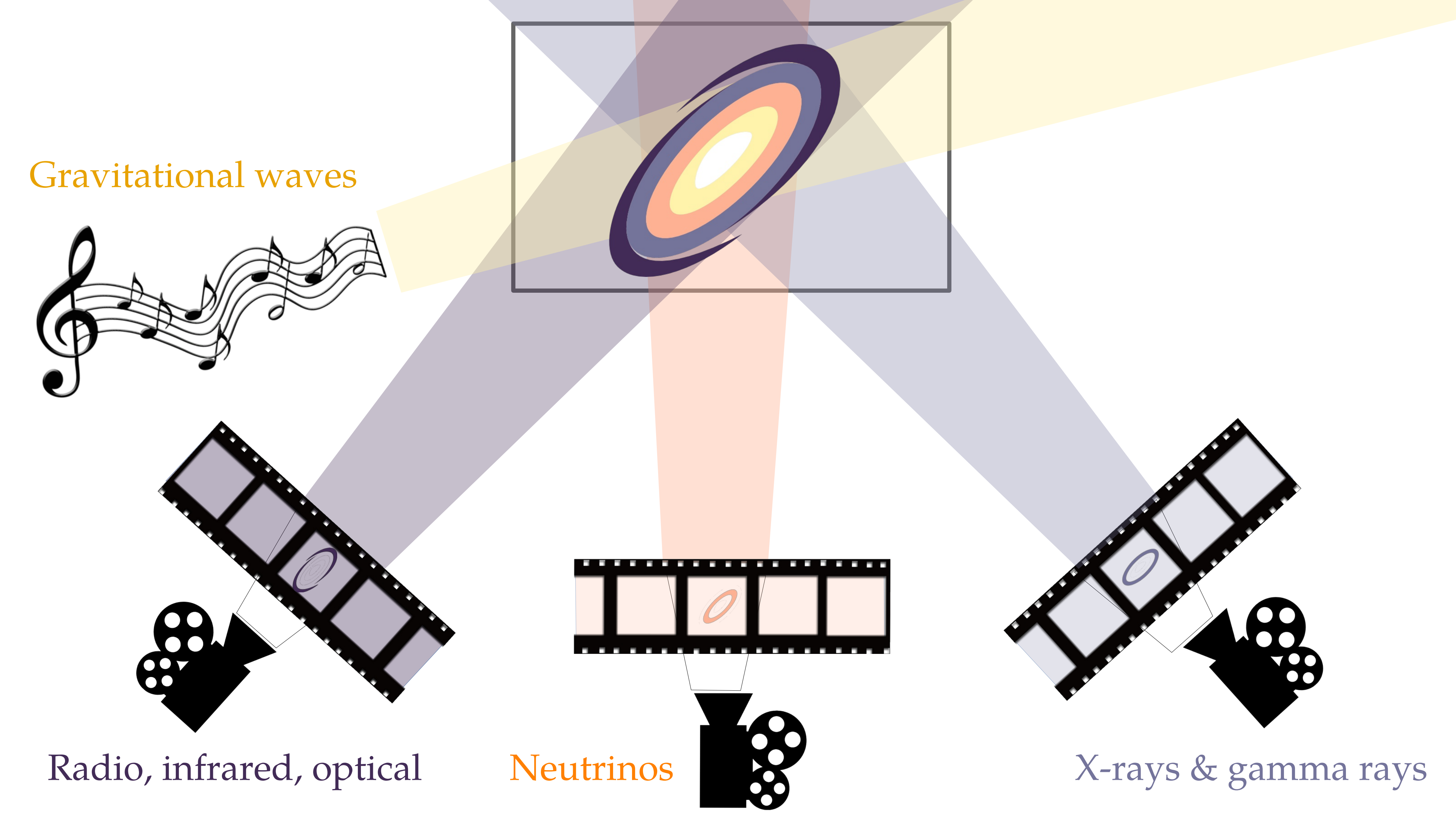


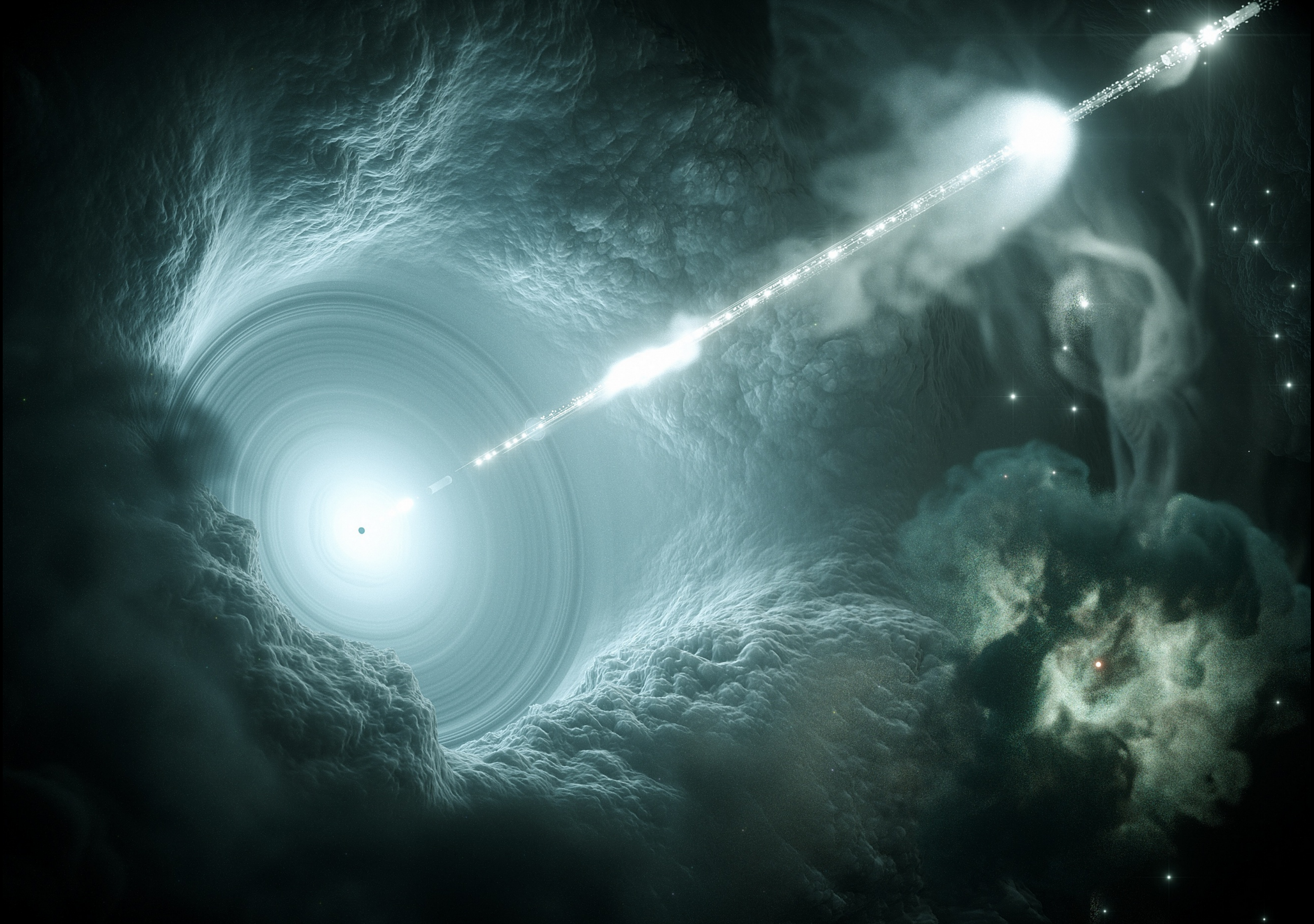

Radio, infrared, optical


Radio, infrared, optical
X-rays & gamma rays

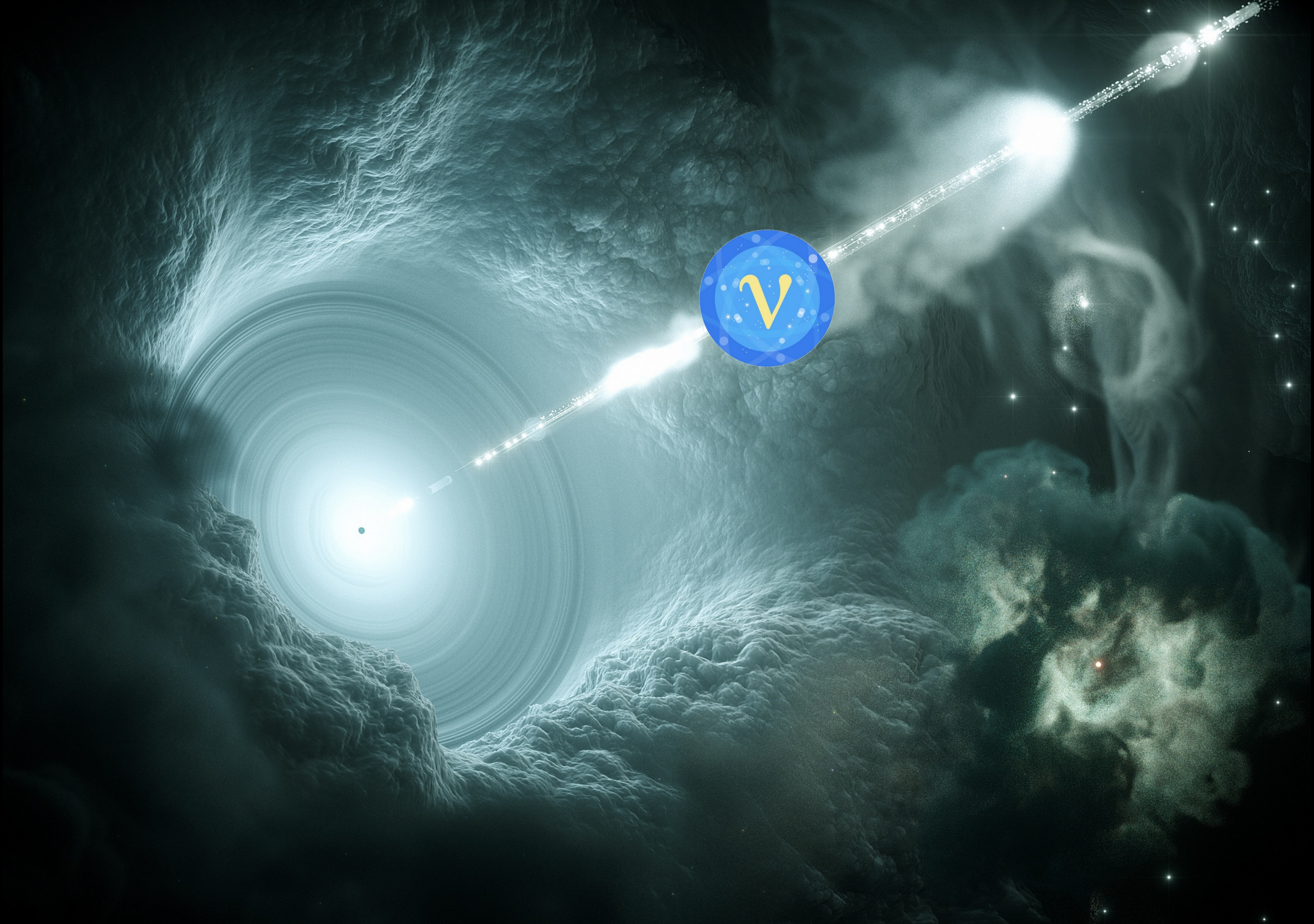


Radio, infrared, optical
Neutrinos
X-rays & gamma rays


Gravitational waves
Radio, infrared, optical
Neutrinos
X-rays & gamma rays



DESY



DESY

Neutrinos are elementary particles,

electrically neutral,

very light,

and superbly antisocial

ν

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Neutrinos are $\underbrace{\text{elementary particles}}_{= \textit{indivisible}}$,

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Neutrinos are $\underbrace{\text{elementary particles}}_{=\ \textit{indivisible}}$,

$\underbrace{\text{electrically neutral}}_{=\ \textit{no electric charge}}$,

$\underbrace{\text{very light}}_{=\ \textit{so light that we don't know their mass!}}$,

and superbly antisocial

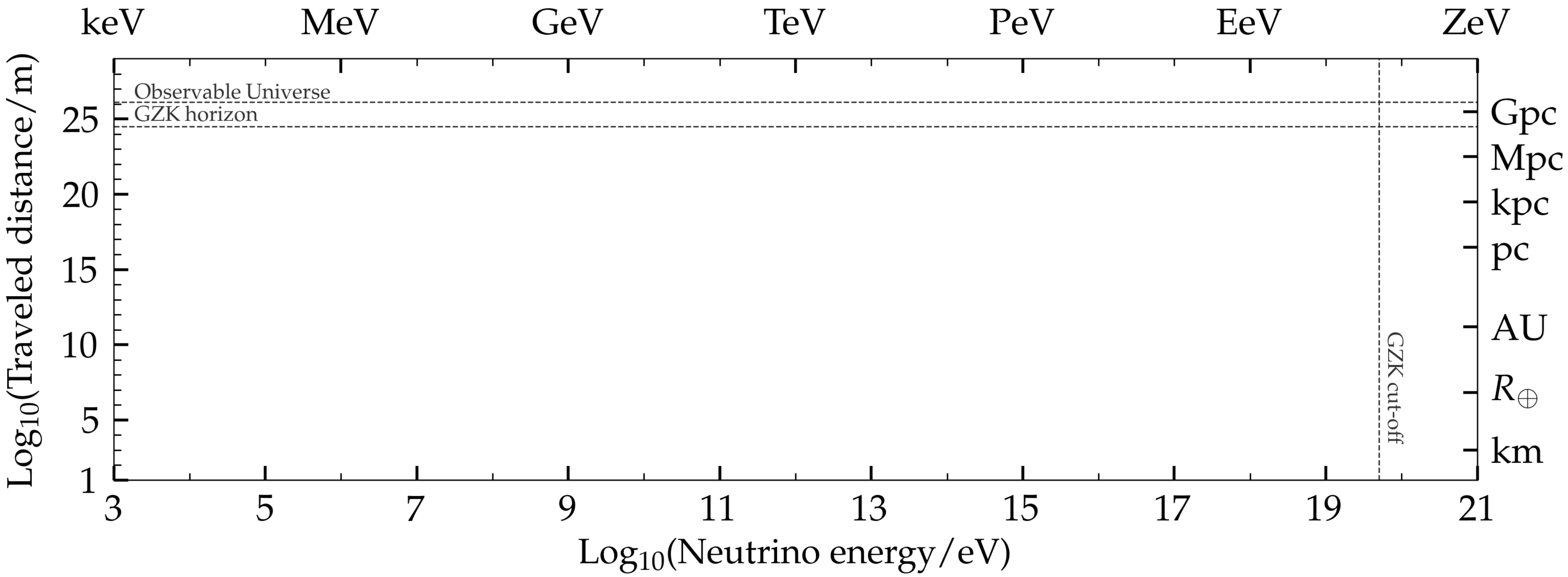
ν

Neutrinos are $\underbrace{\text{elementary particles}}_{=\textit{ indivisible}}$,

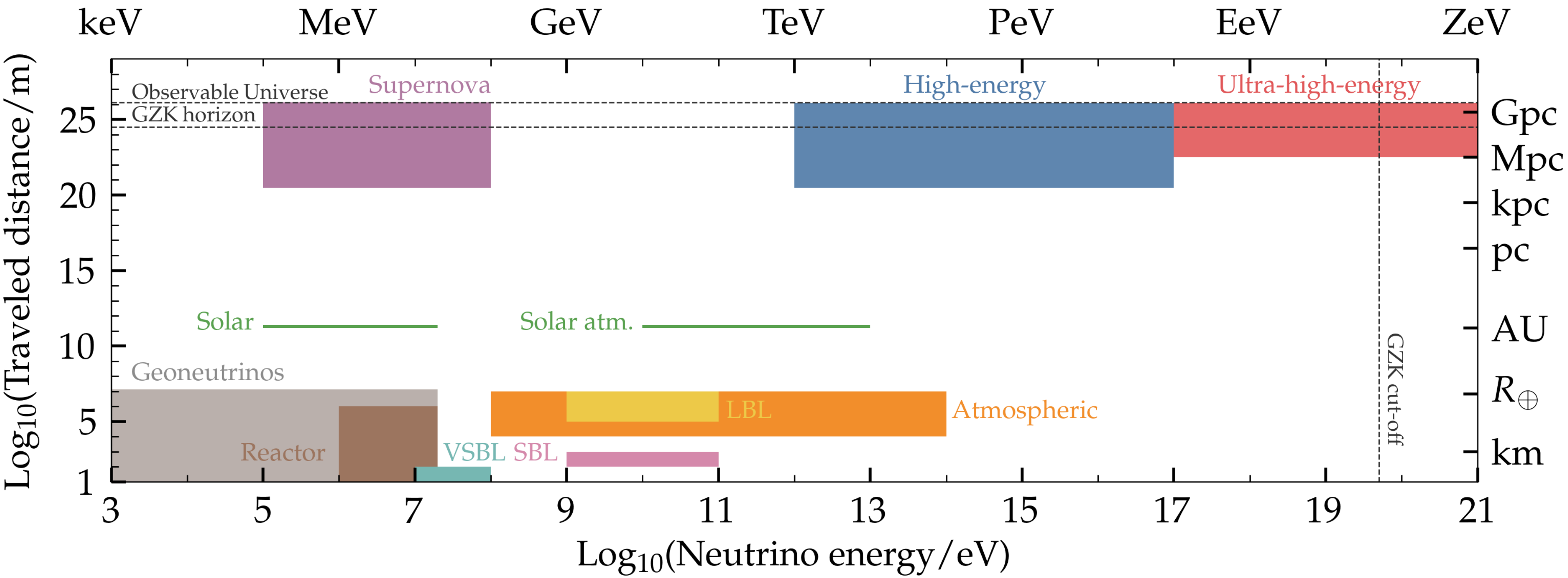
$\underbrace{\text{electrically neutral}}_{=\textit{ no electric charge}}$,

$\underbrace{\text{very light}}_{=\textit{ so light that we don't know their mass!}}$,

and $\underbrace{\text{superbly antisocial}}_{=\textit{ barely interact with matter}}$

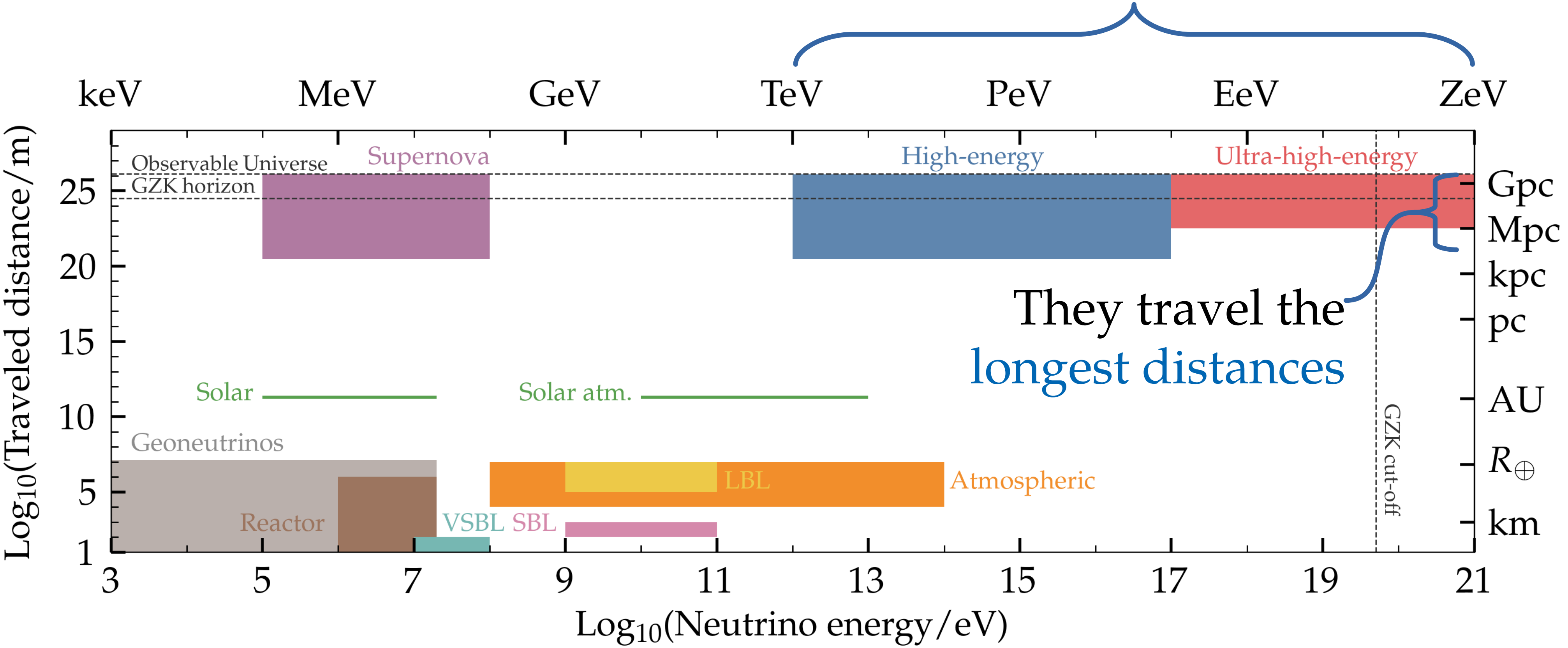


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

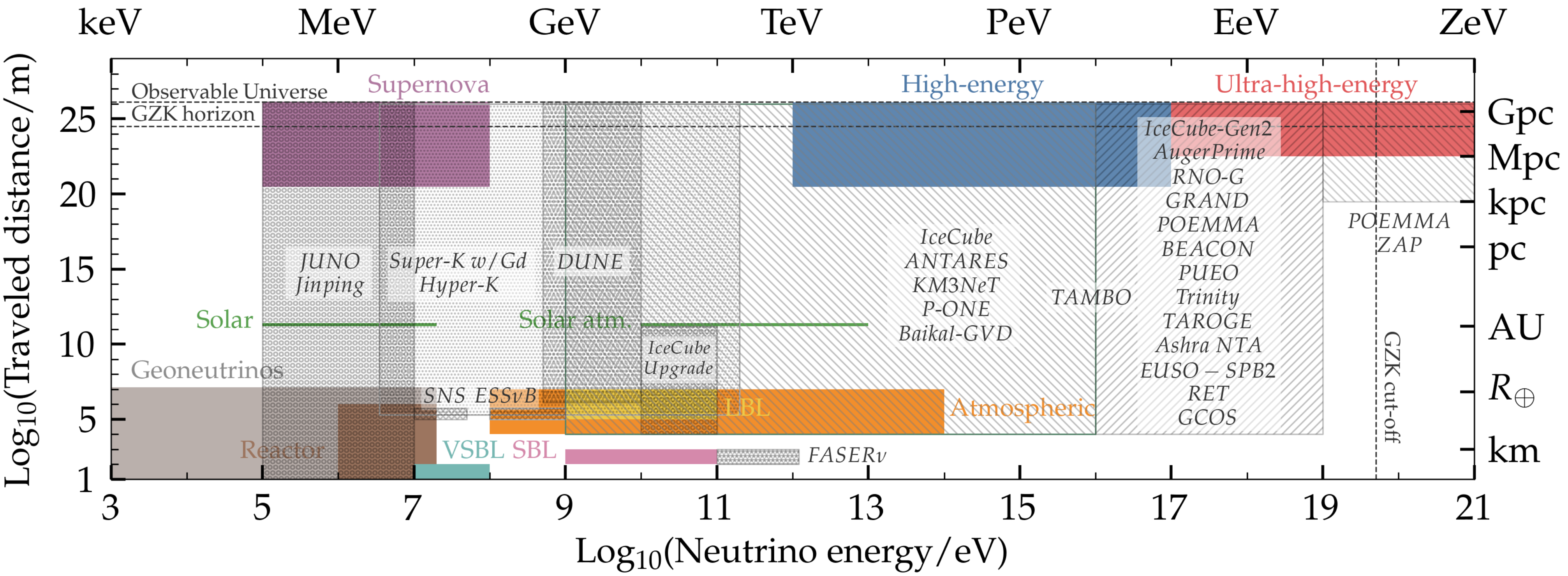


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

They have the highest energies



Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



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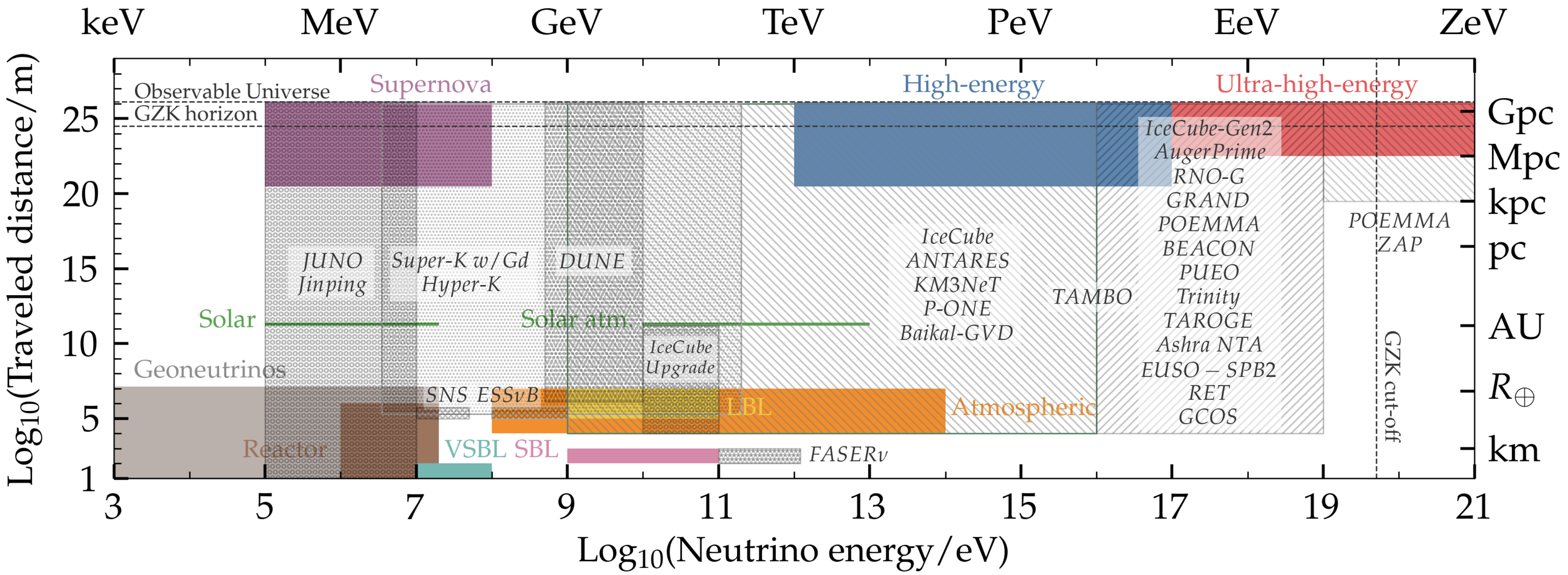
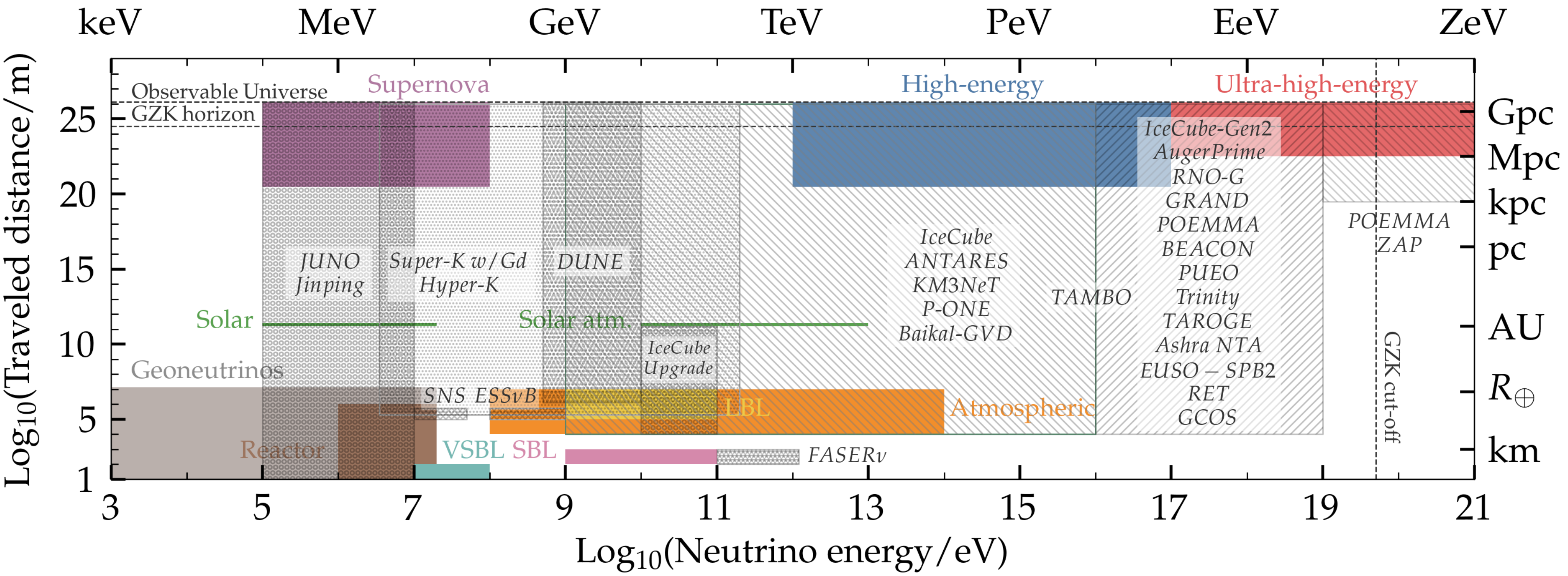


Synergies with lower energies

Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

Discovered in 2013
by IceCube



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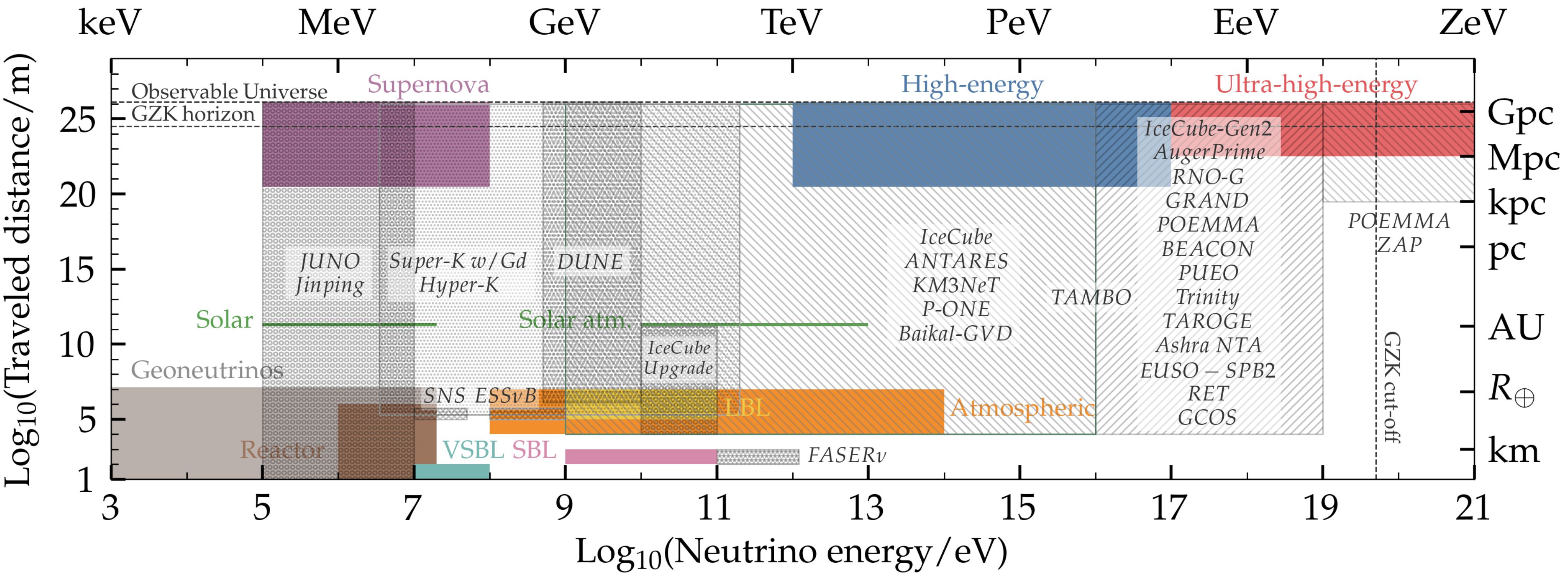


Discovered in 2013
by IceCube

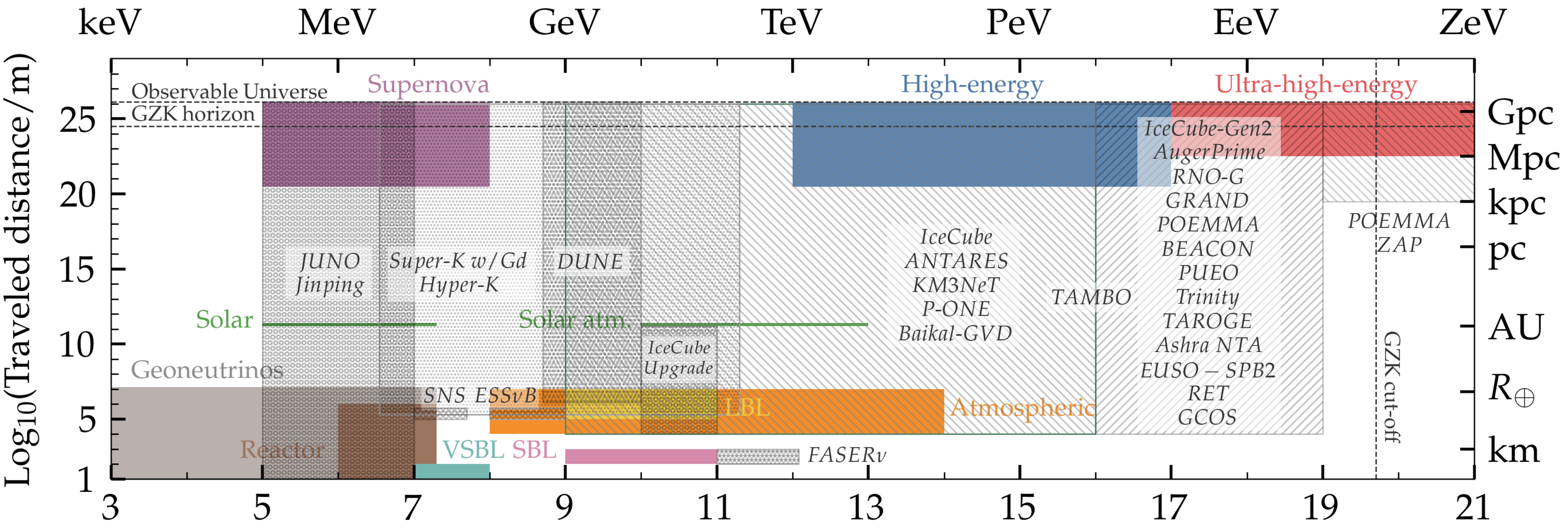
Synergies with lower energies

Increase TeV–PeV
ν statistics

Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

Discovered in 2013 by IceCube

Predicted in 1969 by Berezinksy



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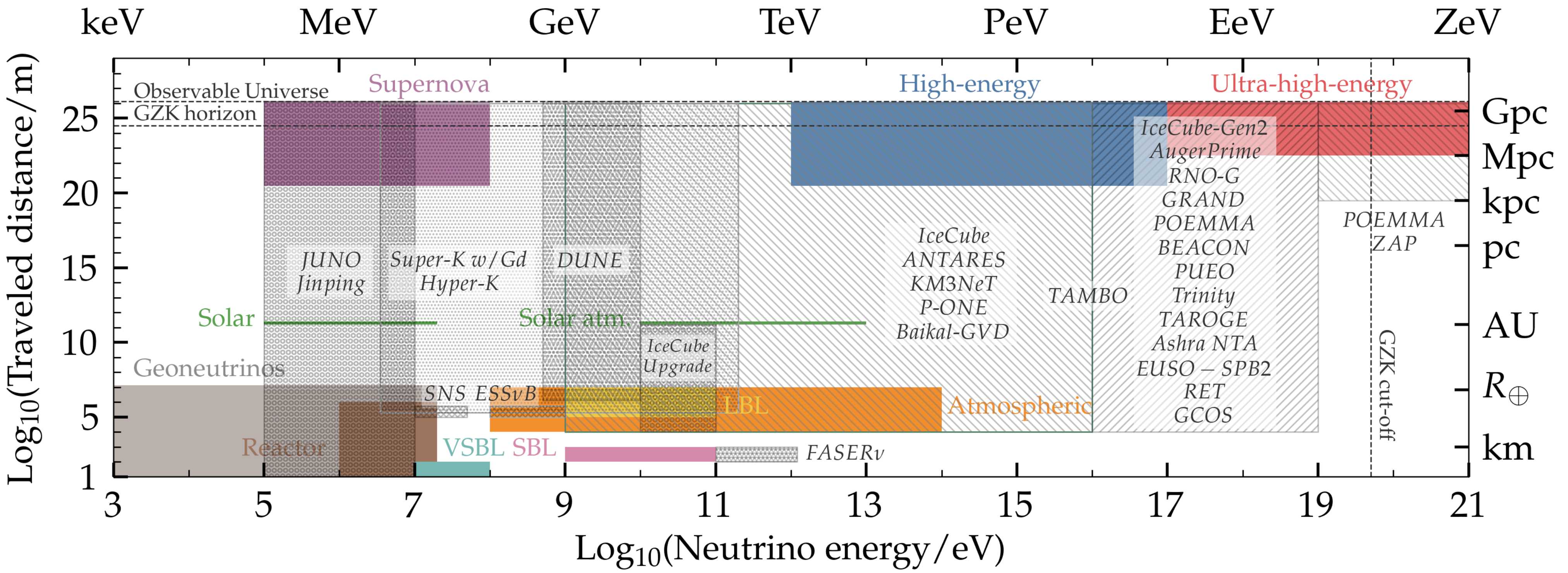

Synergies with lower energies

Increase TeV–PeV ν statistics

Discover > EeV ν

Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

The fundamentals

The multi-messenger connection: a simple picture

(or $p + p$)

$$p + \gamma_{\text{target}} \longrightarrow \Delta^+ \longrightarrow \begin{cases} p + \pi^0, & \text{Br} = 2/3 \\ n + \pi^+, & \text{Br} = 1/3 \end{cases}$$

The multi-messenger connection: a simple picture

(or $p + p$)

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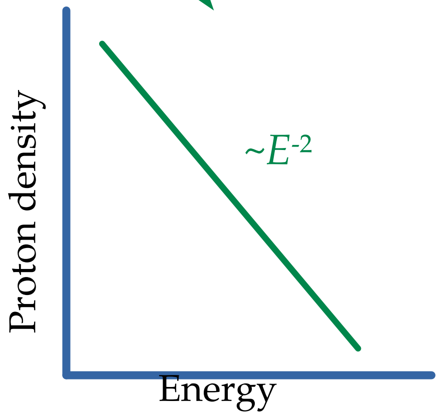

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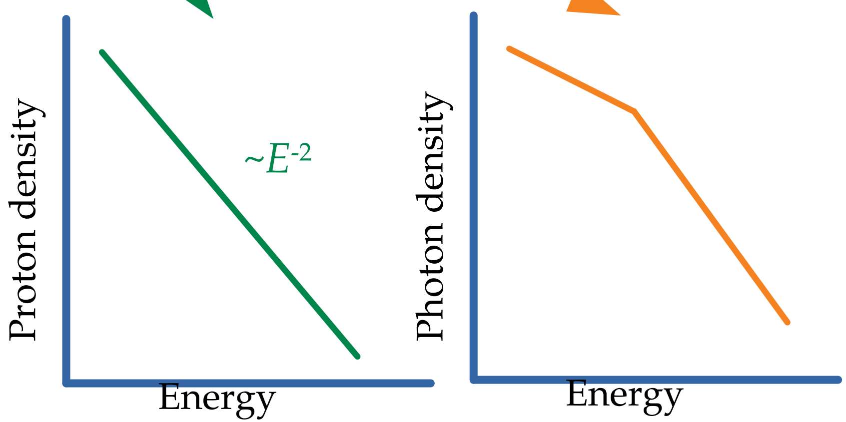

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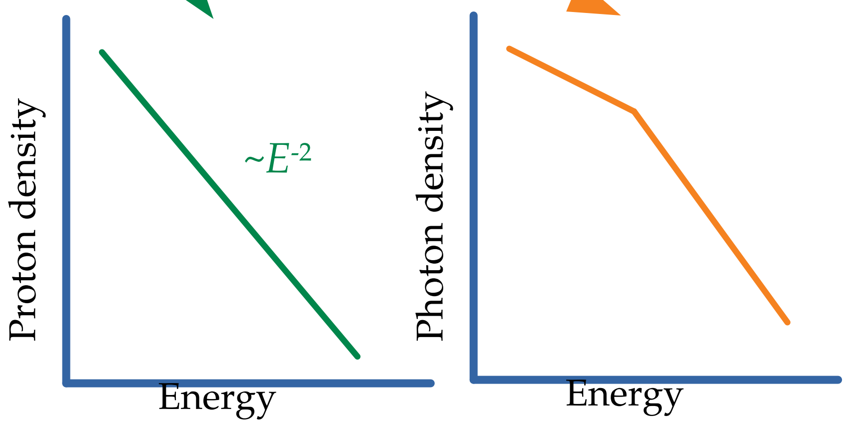
$$\pi^0 \longrightarrow \gamma + \gamma$$

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \longrightarrow \bar{\nu}_\mu + e^+ + \nu_e + \nu_\mu$$

$$n \text{ (escapes)} \longrightarrow p + e^- + \bar{\nu}_e$$



The multi-messenger connection: a simple picture

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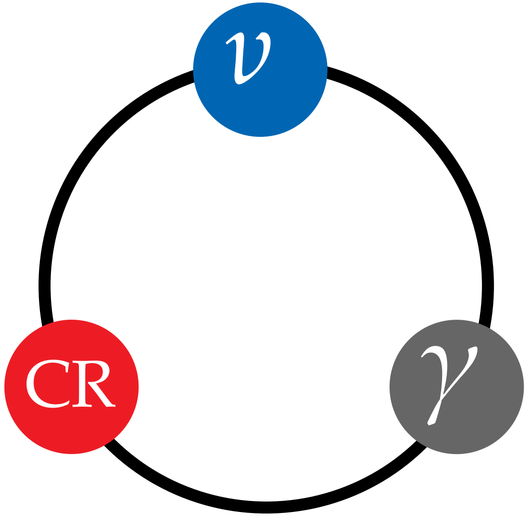
$$p + \gamma_{\text{target}} \longrightarrow \Delta^{+} \longrightarrow \begin{cases} p + \pi^{0}, & \text{Br} = 2/3 \\ n + \pi^{+}, & \text{Br} = 1/3 \end{cases}$$

$$\pi^{0} \longrightarrow \gamma + \gamma$$

$$\pi^{+} \longrightarrow \mu^{+} + \nu_{\mu} \longrightarrow \bar{\nu}_{\mu} + e^{+} + \nu_{e} + \nu_{\mu}$$

$$n \text{ (escapes)} \longrightarrow p + e^{-} + \bar{\nu}_{e}$$



Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

The multi-messenger connection: a simple picture

(or $p + p$)

$$p + \gamma_{\text{target}} \longrightarrow \Delta^+ \longrightarrow \begin{cases} p + \pi^0, & \text{Br} = 2/3 \\ n + \pi^+, & \text{Br} = 1/3 \end{cases}$$

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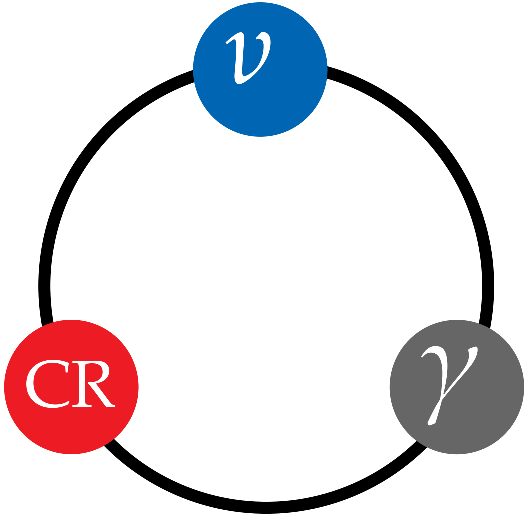

1 PeV 20 PeV

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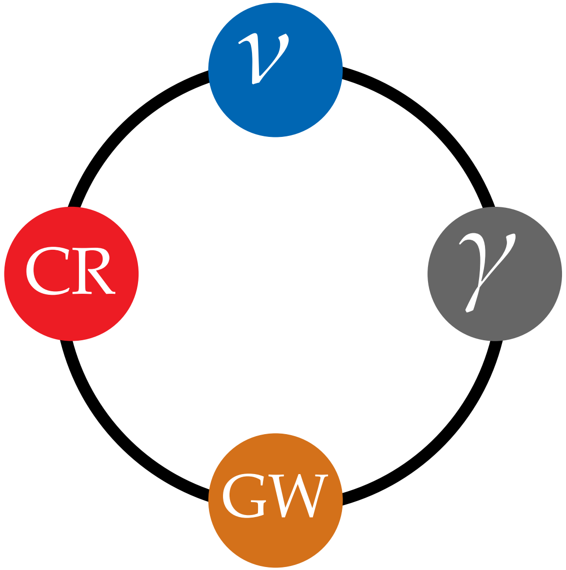

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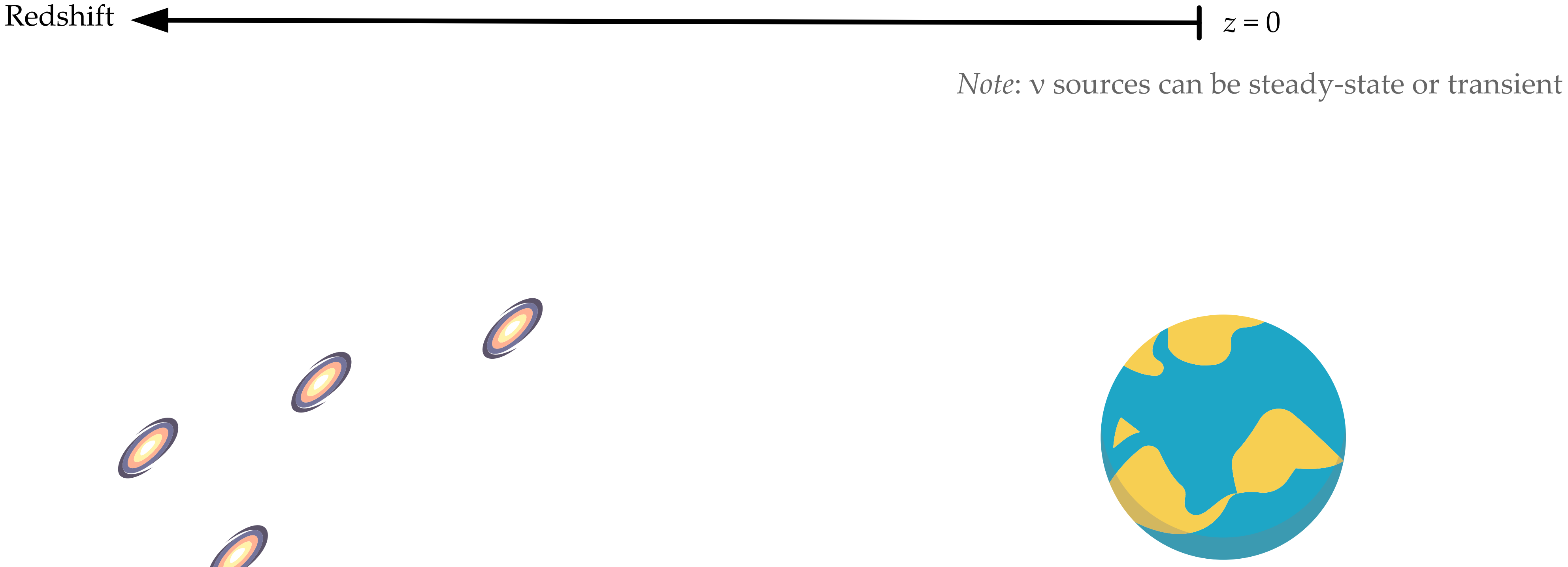
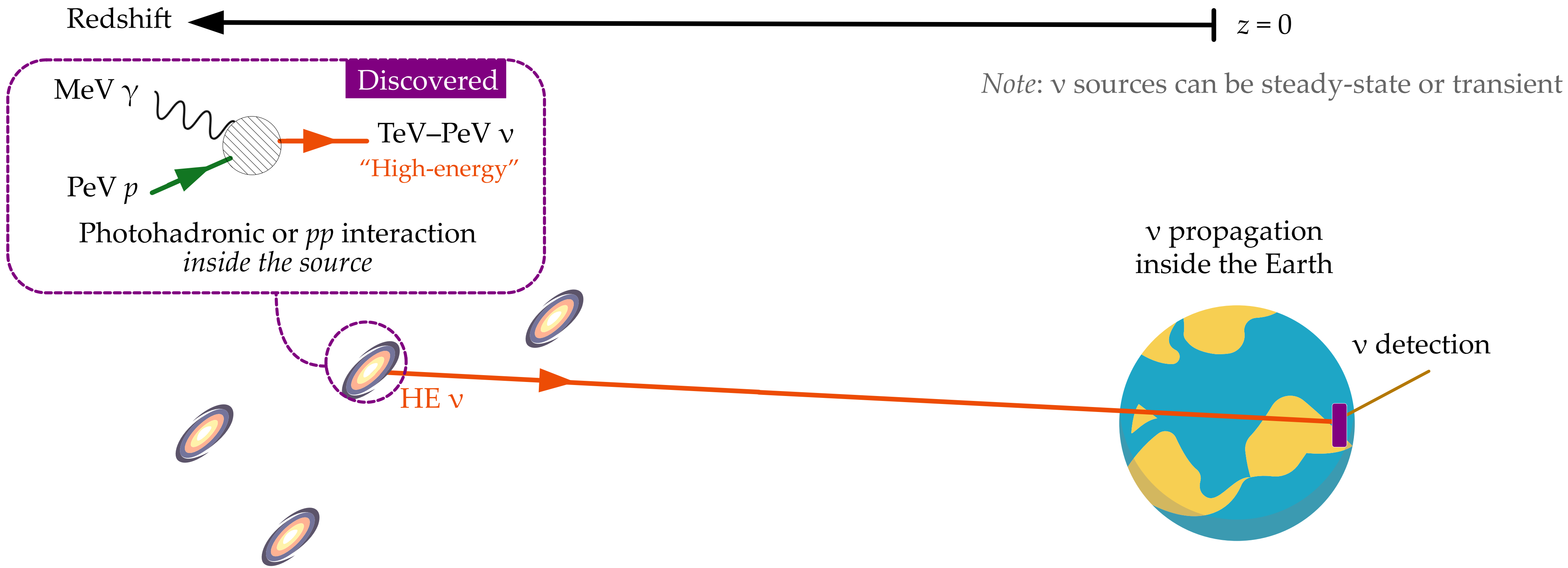
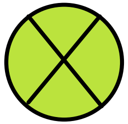

Redshift
$z = 0$
Note: ν sources can be steady-state or transient

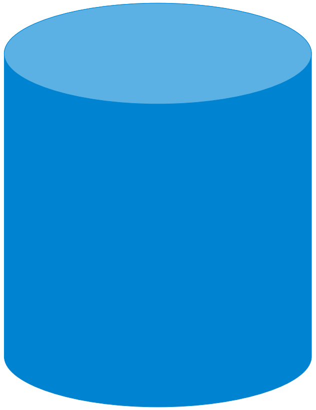

Redshift
$z = 0$
Discovered
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or pp interaction
inside the source
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν

Detecting the undetectable

Neutrino source

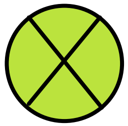


Water tank

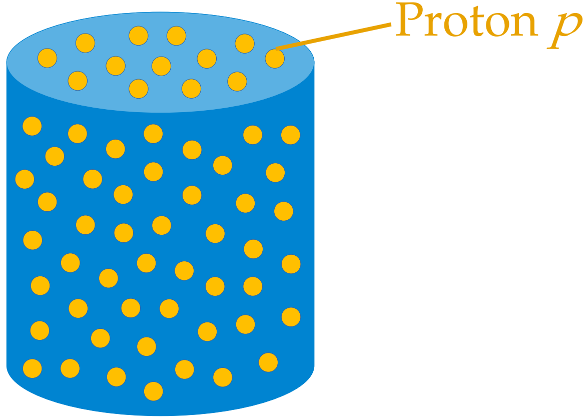


Detecting the undetectable

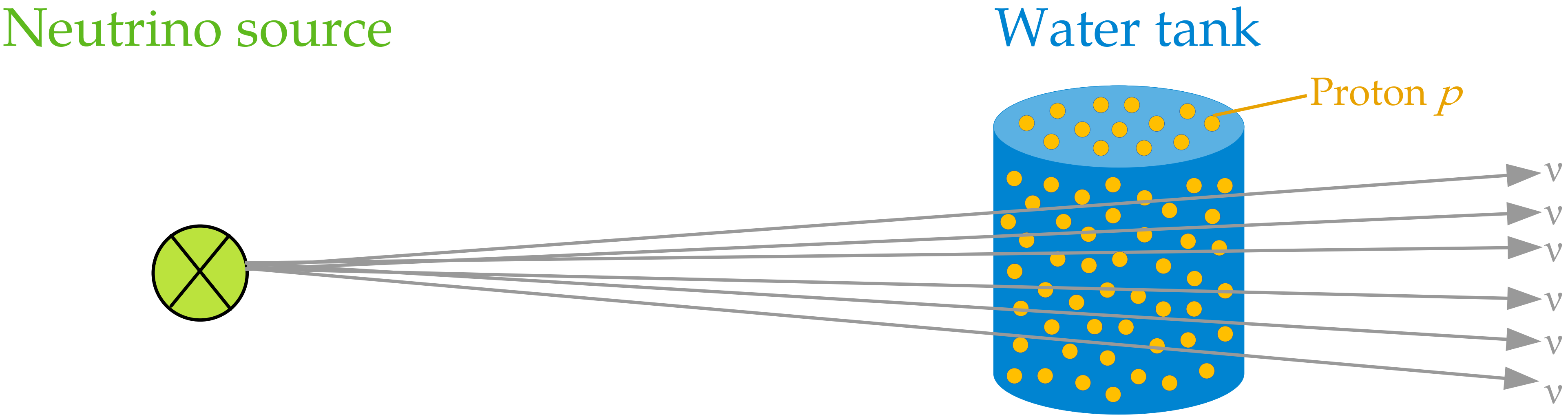
Neutrino source



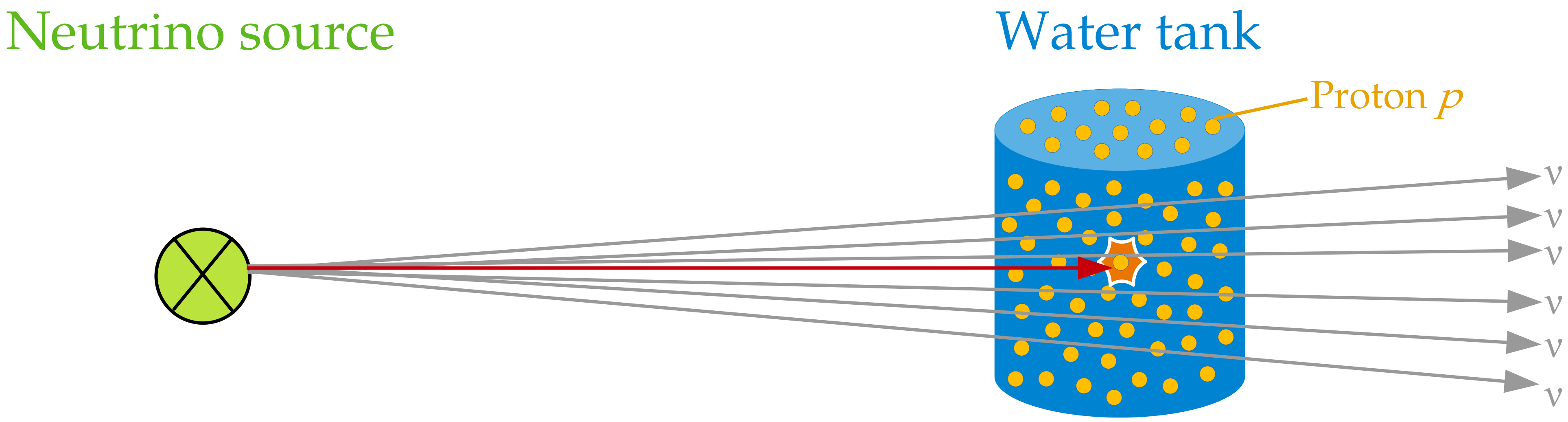
Water tank



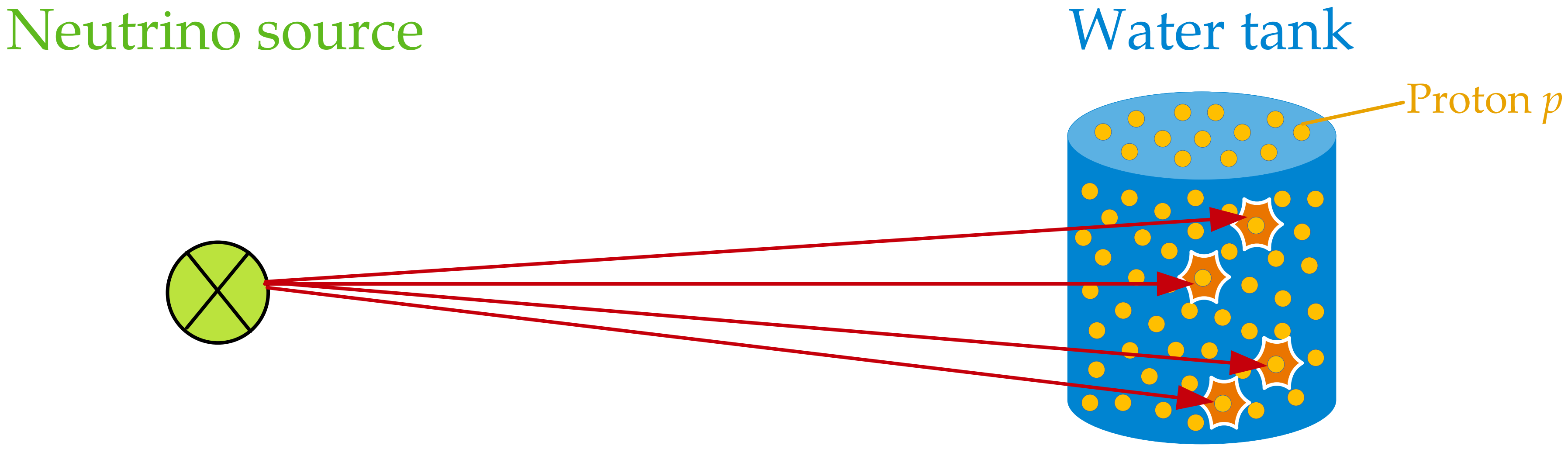
Detecting the undetectable



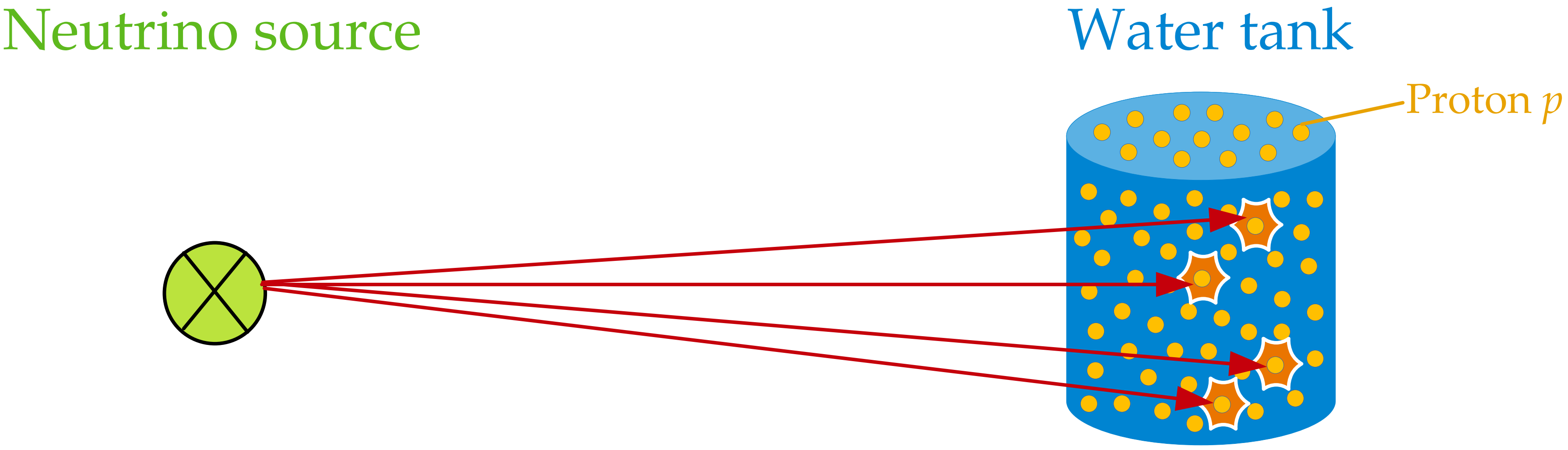
Detecting the undetectable



Detecting the undetectable

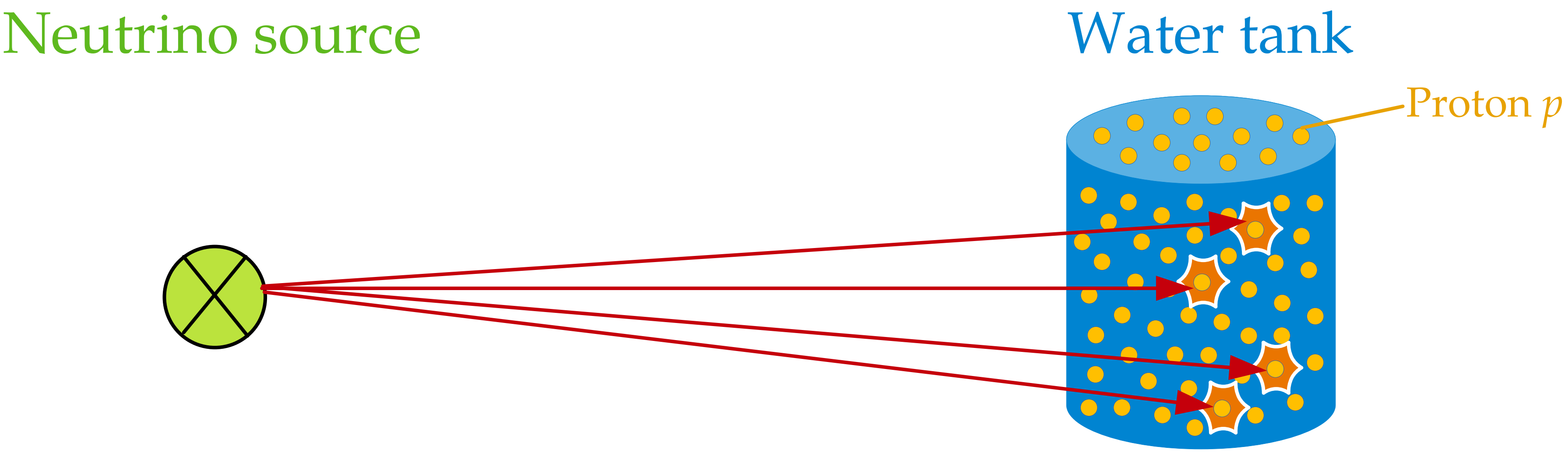


Detecting the undetectable



Number of interacting ν =

Detecting the undetectable

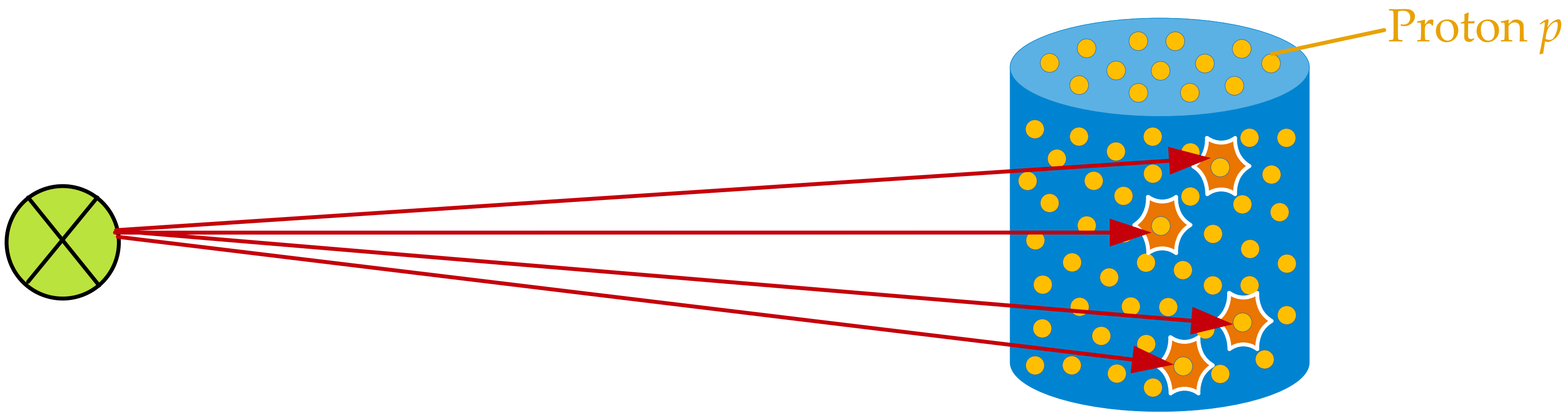


Number of interacting ν = Chance that one ν interacts with one p

Detecting the undetectable

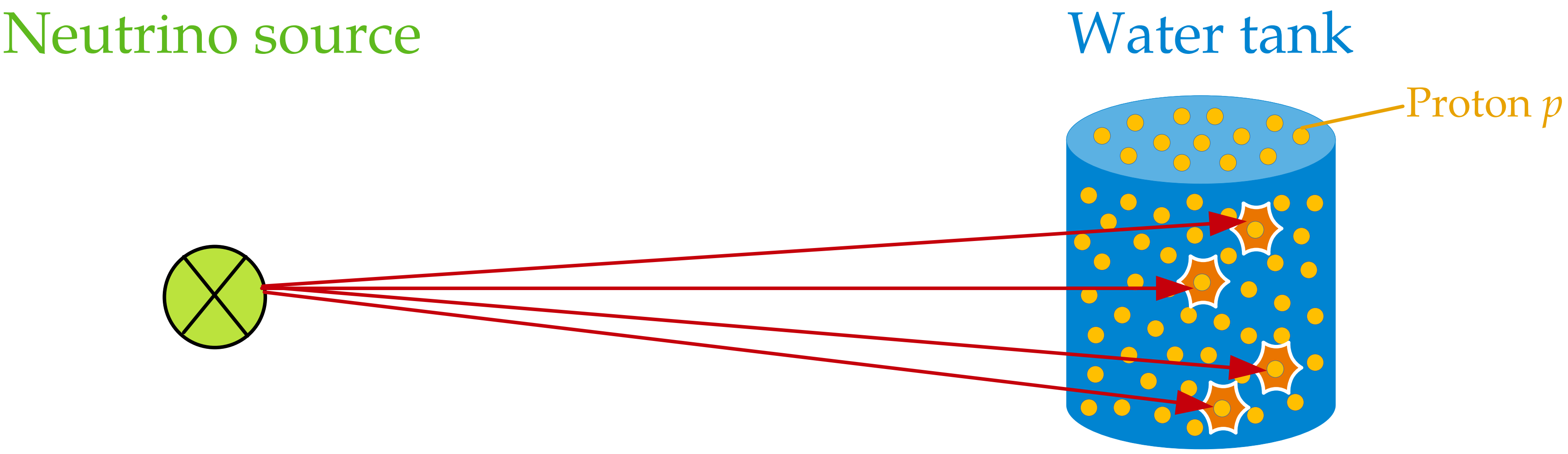
Neutrino source

Water tank



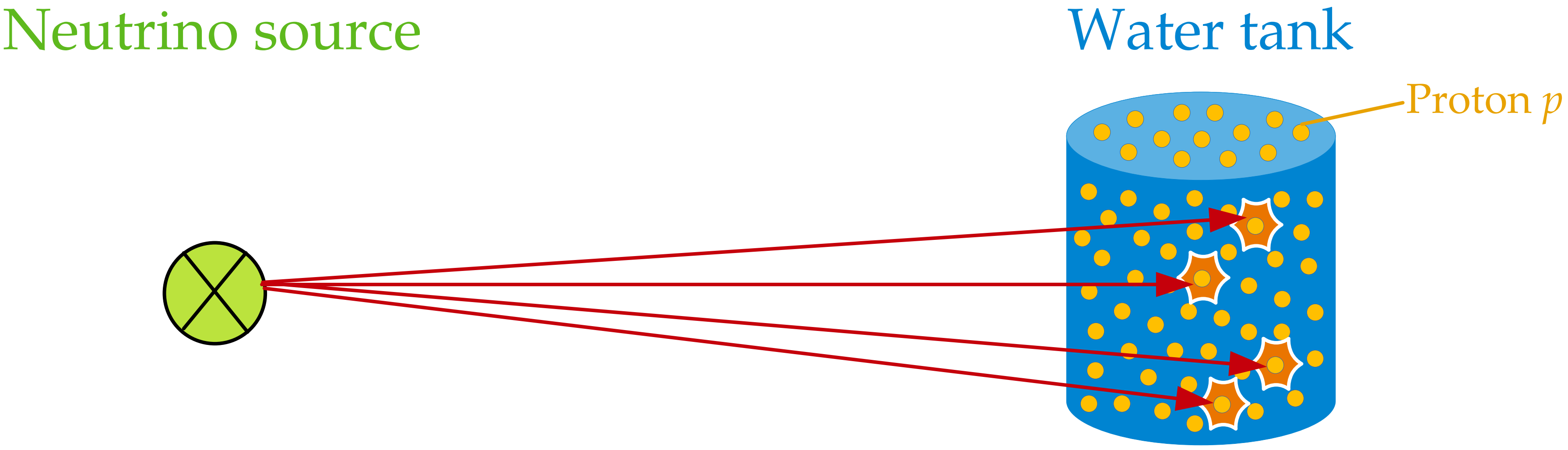
$$\text{Number of interacting } \nu = \underbrace{\text{Chance that one } \nu \text{ interacts with one } p}_{\substack{\text{Fixed by Nature} \\ \text{(weak interactions):} \\ \textit{neutrino-proton cross section}}}$$

Detecting the undetectable



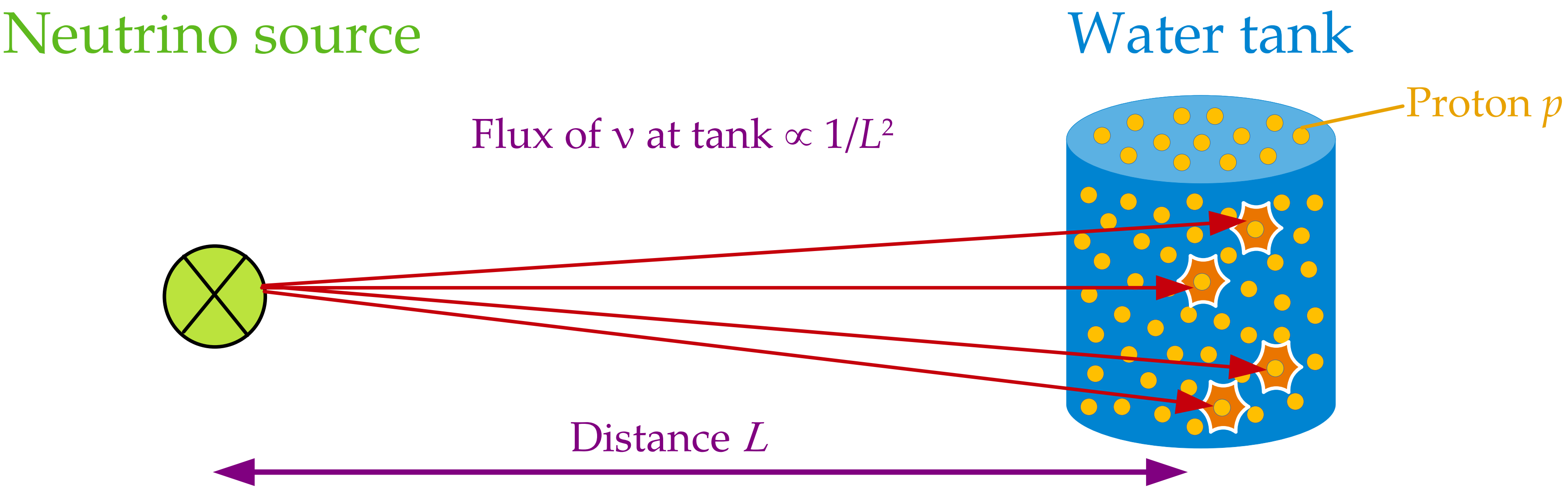
$$\text{Number of interacting } \nu = \underbrace{\text{Chance that one } \nu \text{ interacts with one } p}_{\substack{\text{Fixed by Nature} \\ \text{(weak interactions):} \\ \textit{neutrino-proton cross section}}} \times \text{Number of } \nu \text{ that reach the tank}$$

Detecting the undetectable



$$\text{Number of interacting } \nu = \underbrace{\text{Chance that one } \nu \text{ interacts with one } p}_{\text{Fixed by Nature (weak interactions): \textit{neutrino-proton cross section}}} \times \underbrace{\text{Number of } \nu \text{ that reach the tank}}_{\text{Use an intense source, place the tank close to it, and be patient}}$$

Detecting the undetectable



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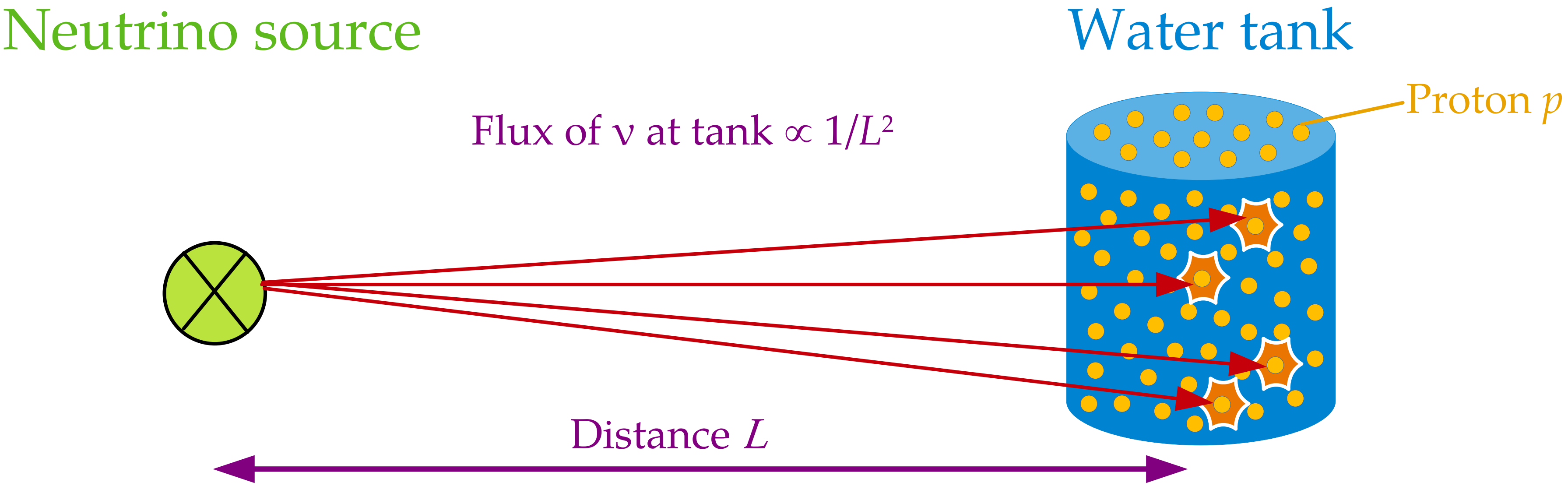
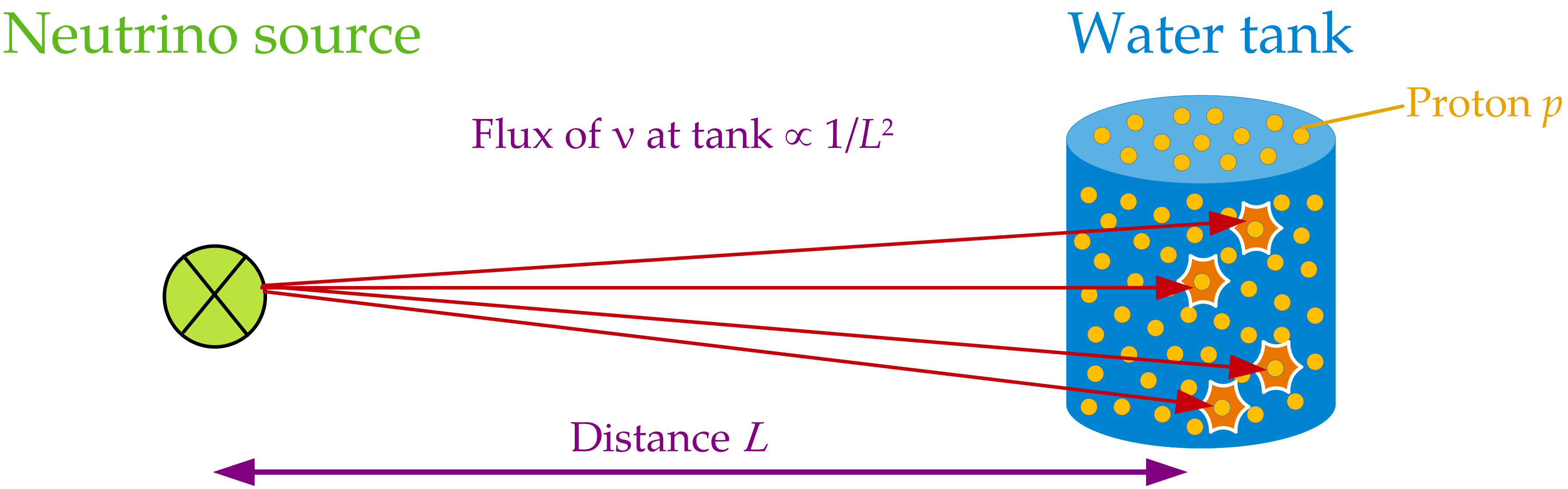
Detecting the undetectable



$$\text{Number of interacting } \nu = \underbrace{\text{Chance that one } \nu \text{ interacts with one } p}_{\substack{\text{Fixed by Nature} \\ \text{(weak interactions):} \\ \textit{neutrino-proton cross section}}} \times \underbrace{\text{Number of } \nu \text{ that reach the tank}}_{\substack{\text{Use an intense source,} \\ \text{place the tank close to it,} \\ \text{and be patient}}} \times \text{Number of } p \text{ in the tank}$$

Detecting the undetectable



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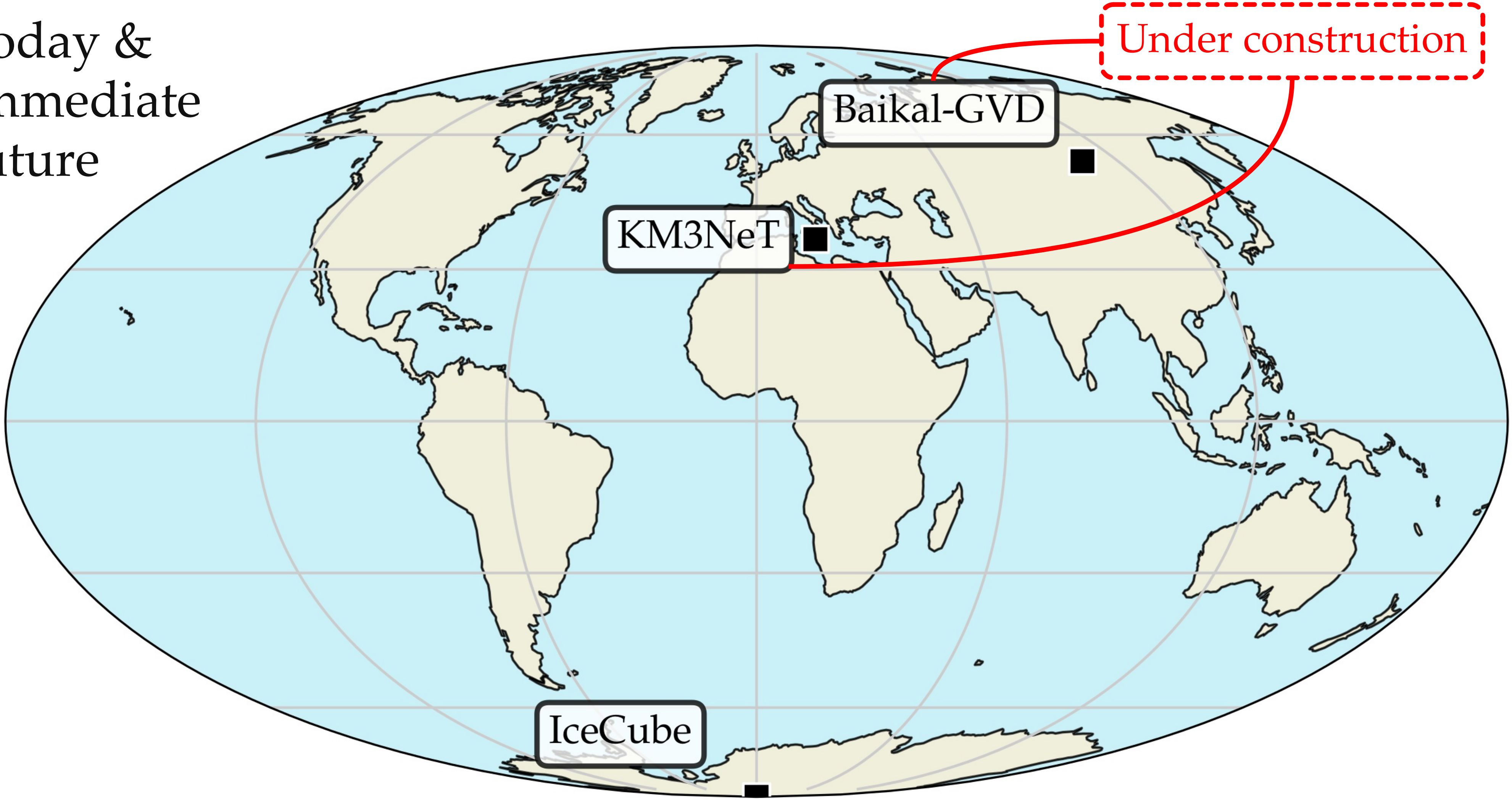
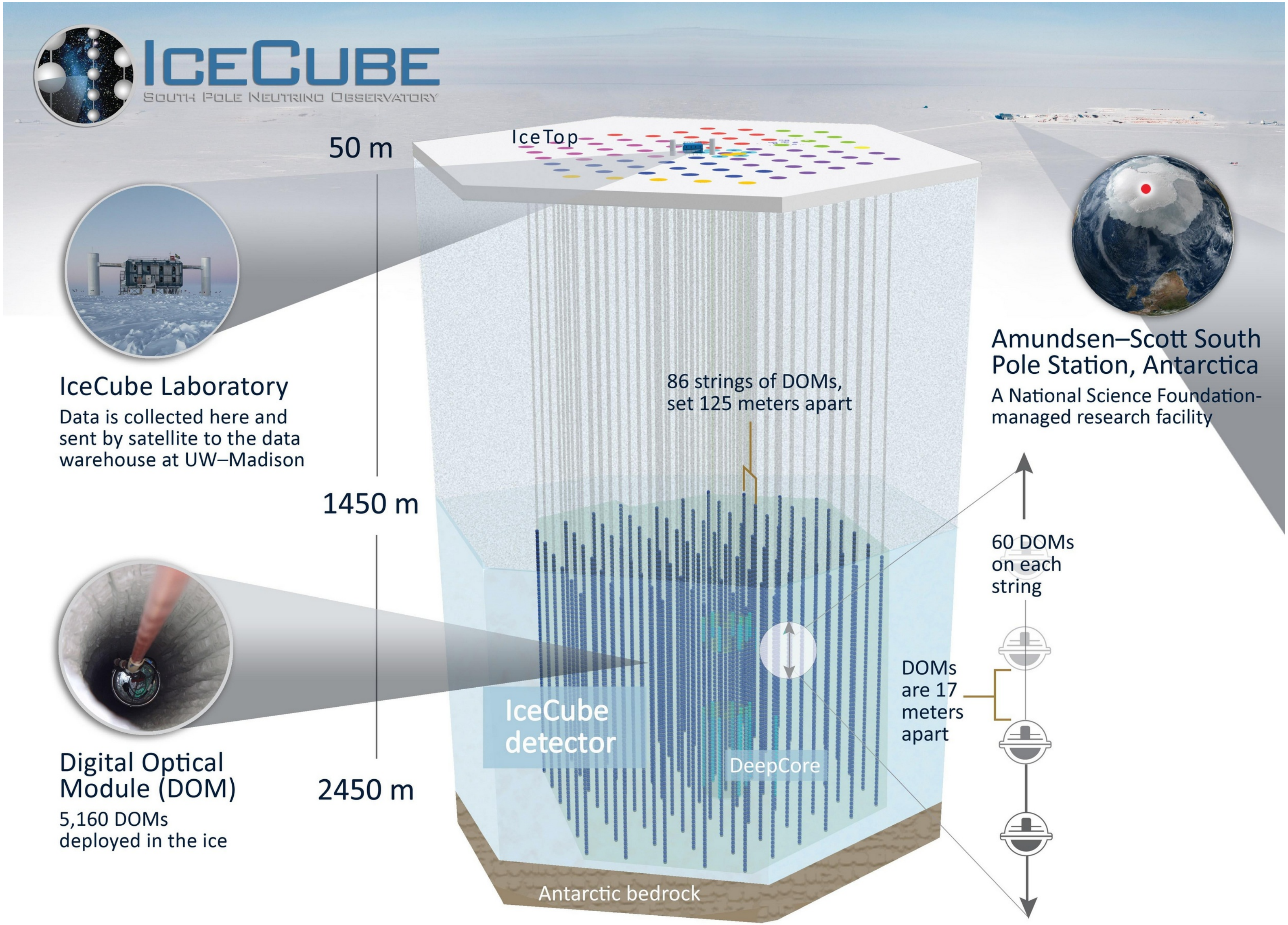
Today & immediate future



Schumacher, **MB**, Agostini, Oikonomou, Resconi, 2503.07549

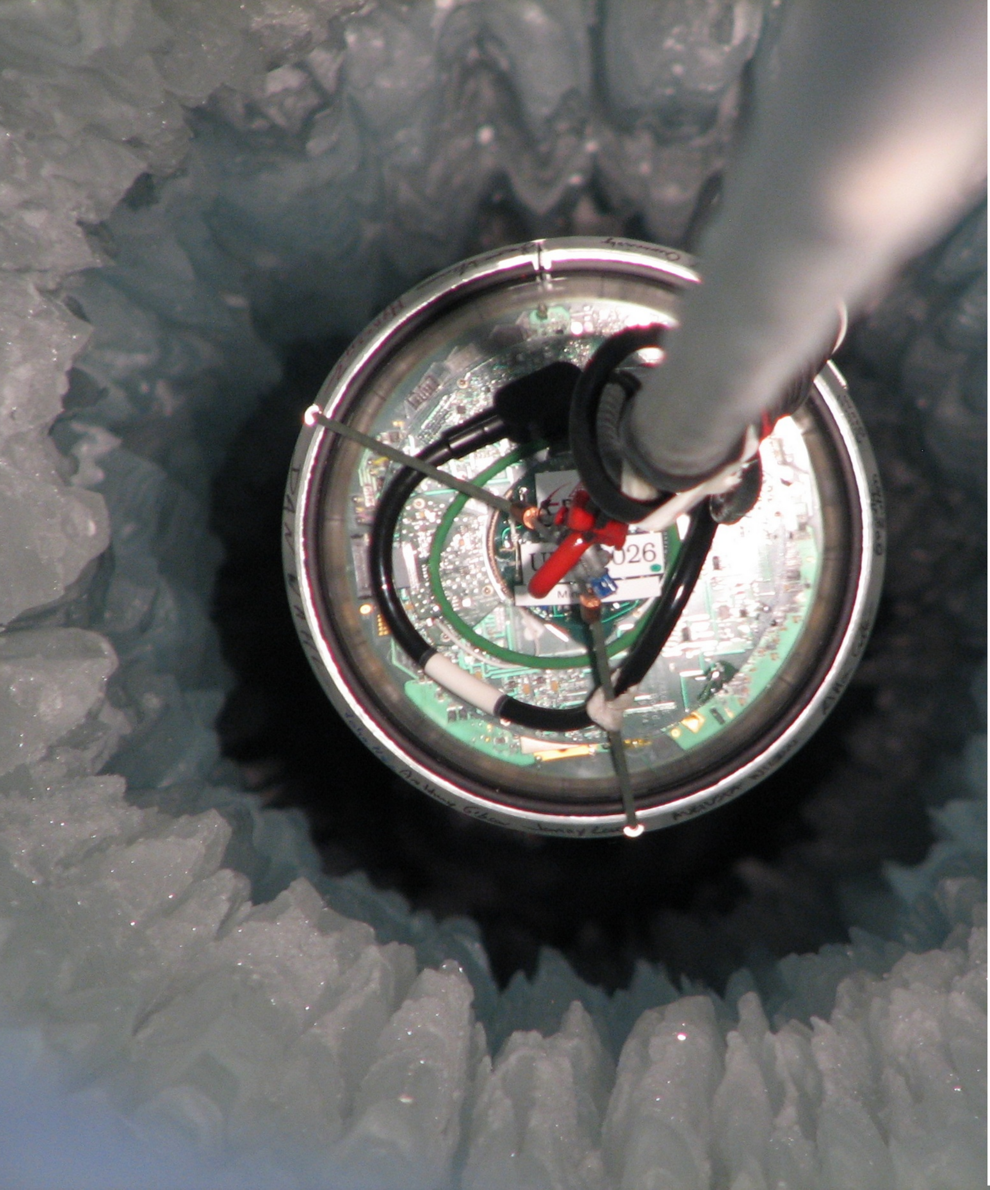
IceCube

Yuya Makino, IceCube/NSF



ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
IceCube detector
DeepCore
Antarctic bedrock

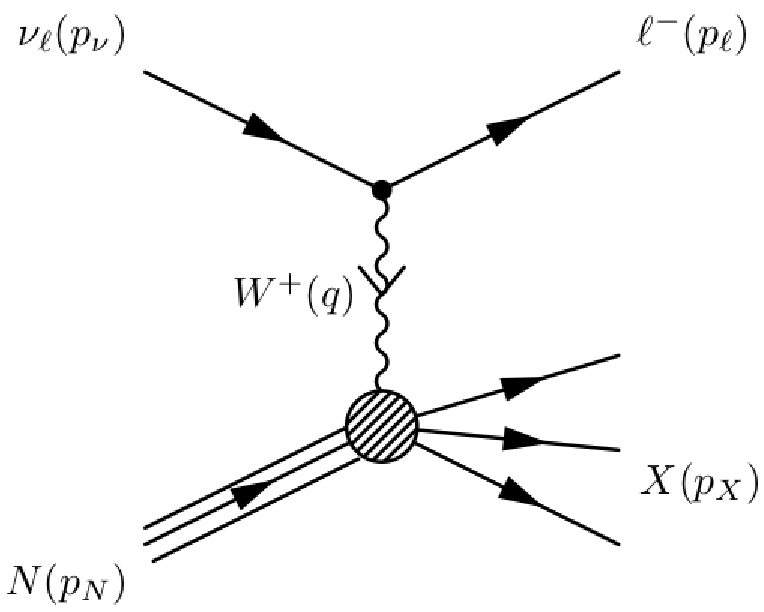
WIPAC



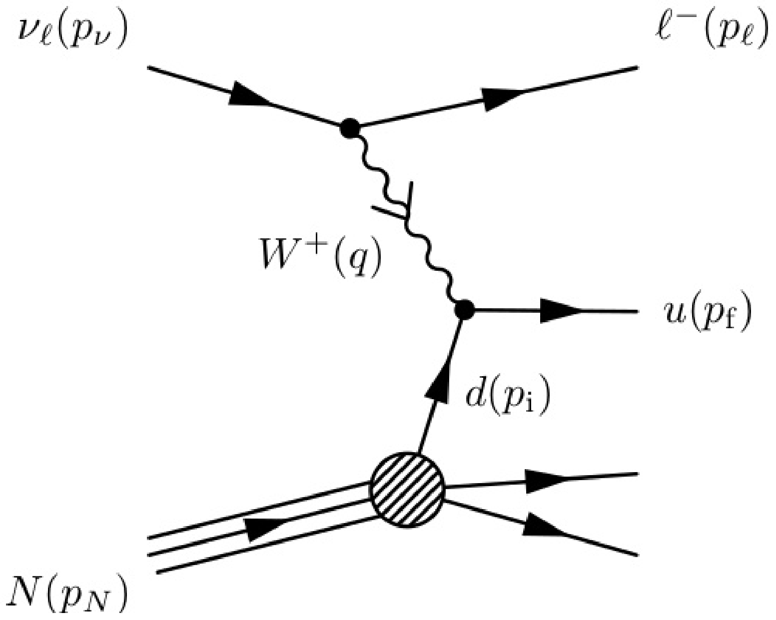

TRUDY Lyn
Ken Iserson

Neutrino-nucleon deep inelastic scattering

What you see



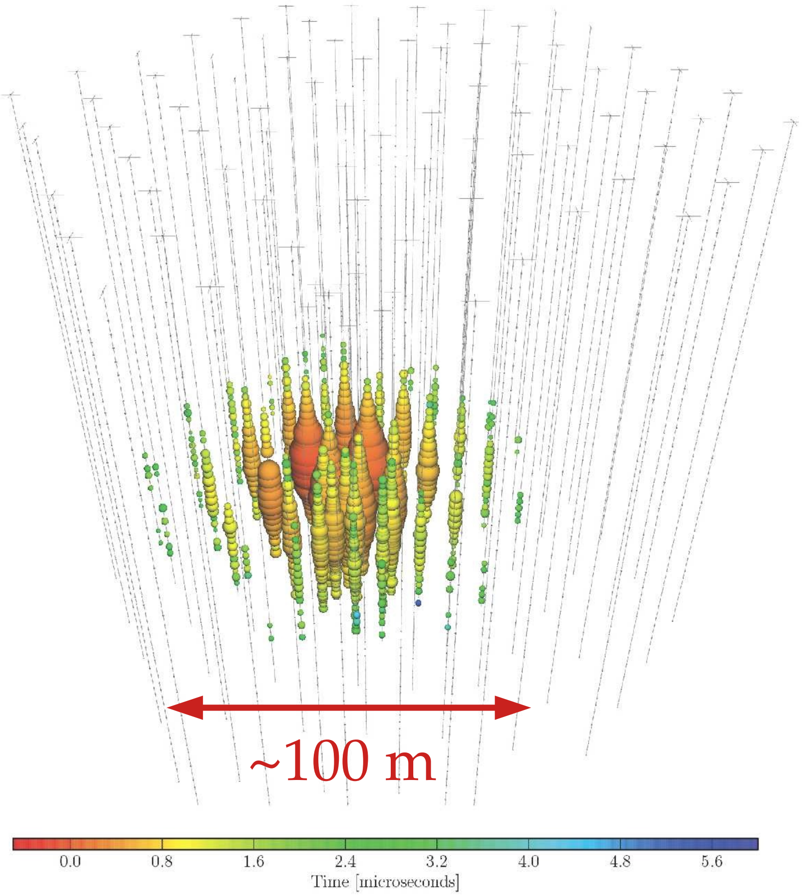
Beneath the hood



(Plus the equivalent neutral-current process (Z-exchange))

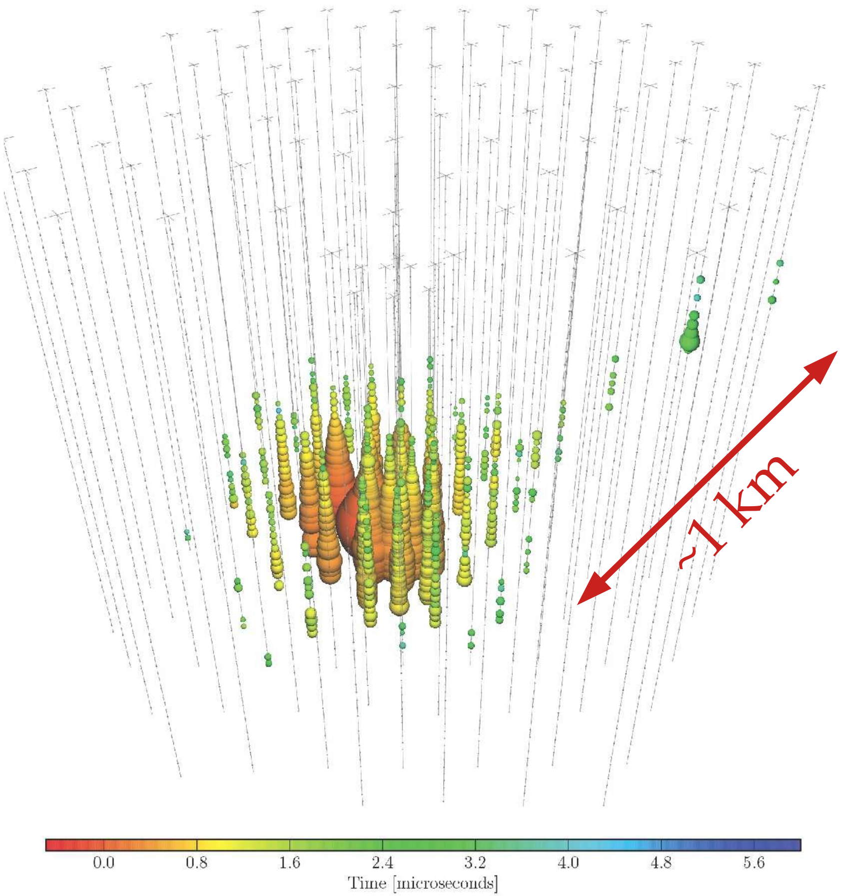
Giunti & Kim, *Fundamentals of Neutrino Physics & Astrophysics*

Shower
(mainly from ν_e and ν_τ)

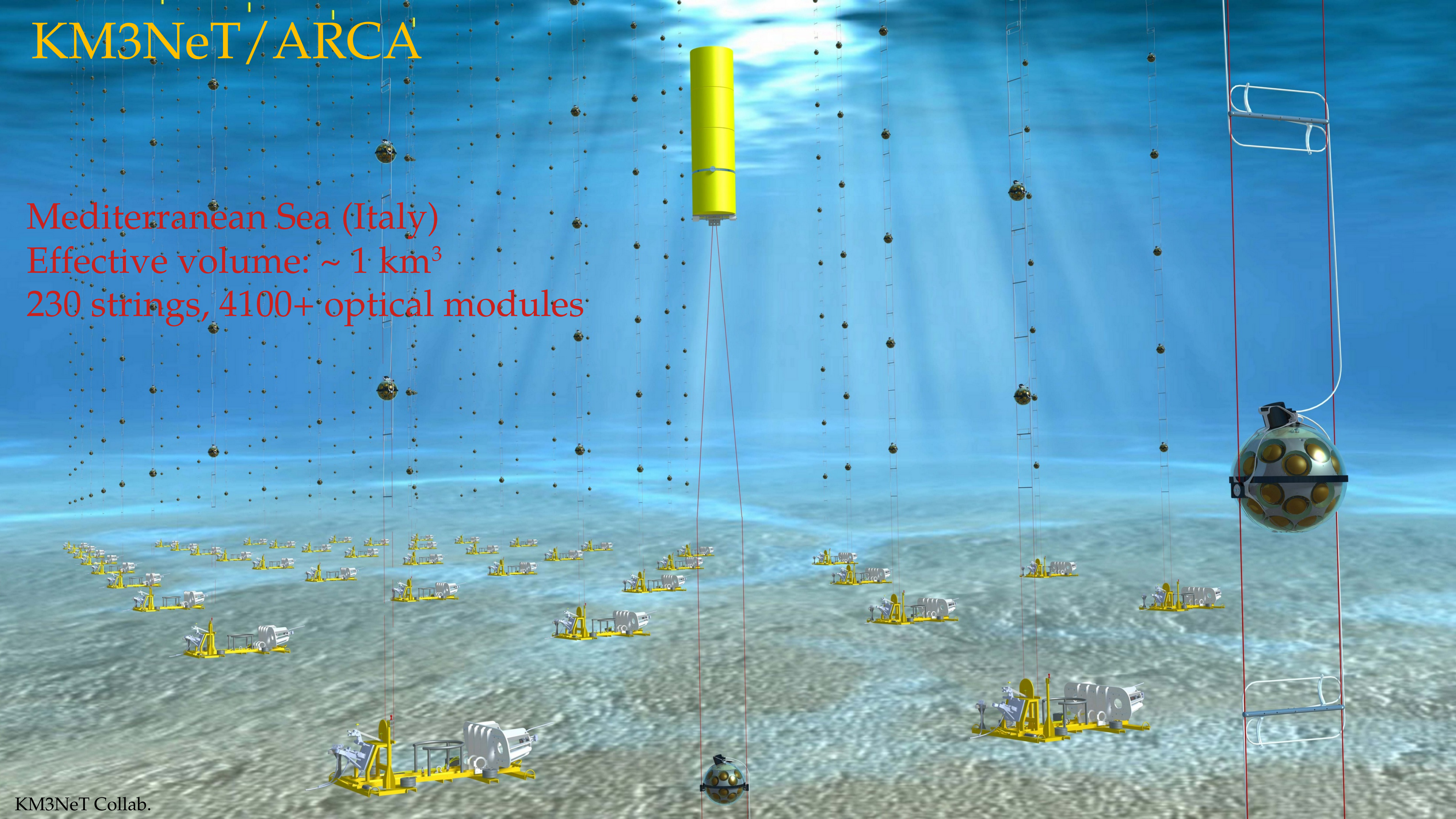


Poor angular resolution: < 5°

Track
(mainly from ν_μ)



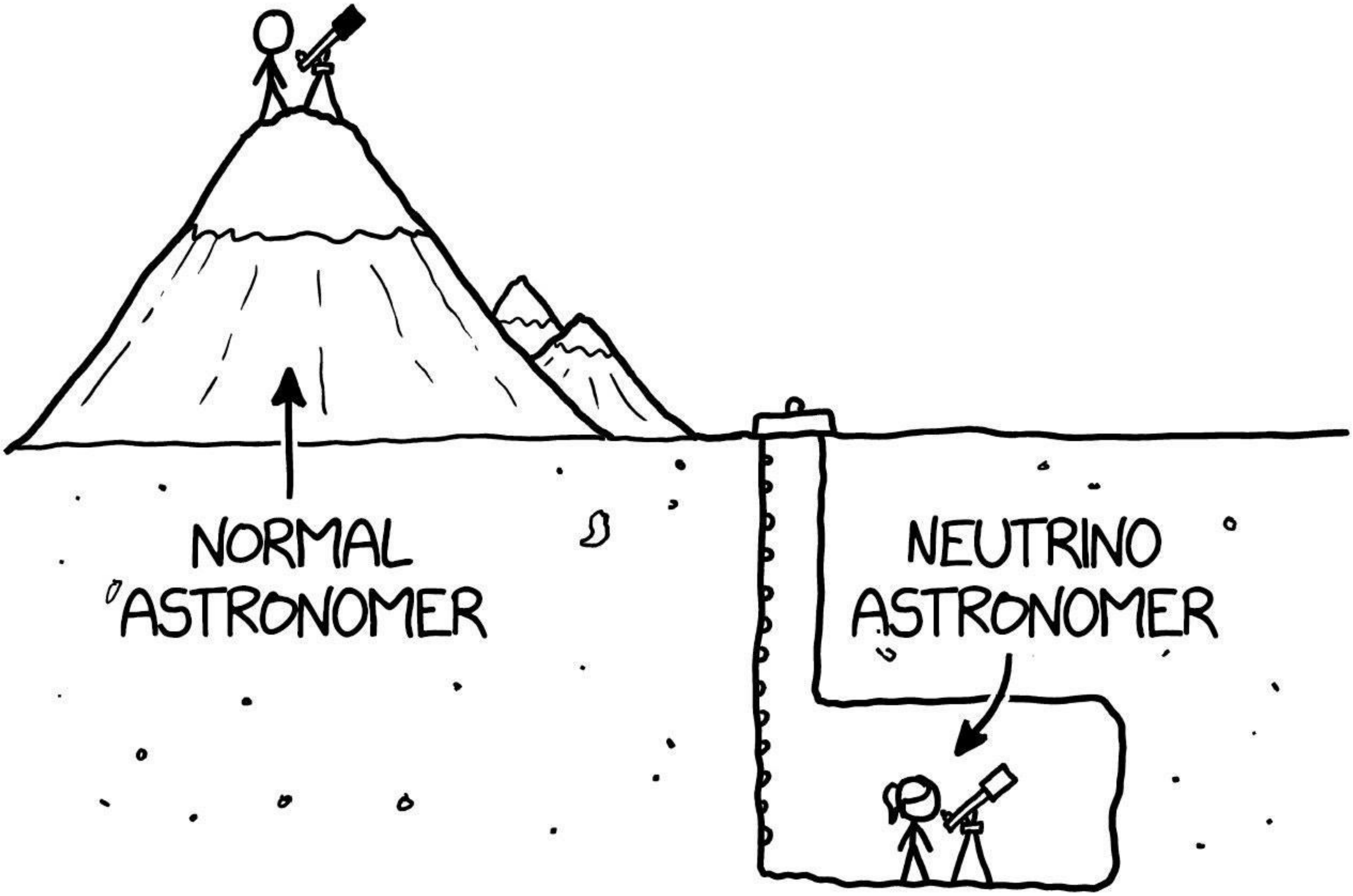
Angular resolution: < 1°


KM3NeT/ARCA
Mediterranean Sea (Italy)
Effective volume: ~ 1 km^3
230 strings, 4100+ optical modules
KM3NeT Collab.

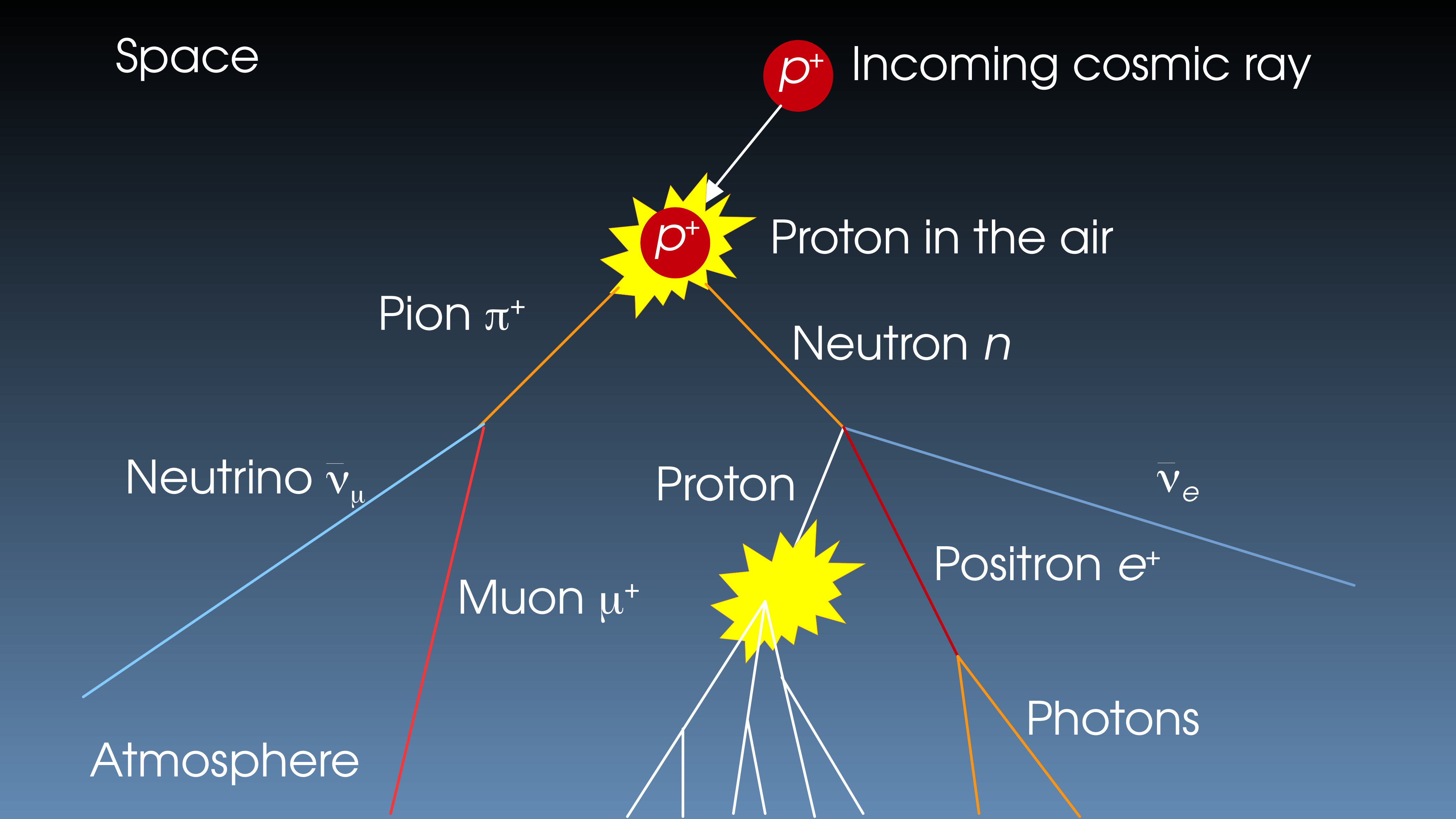
Baikal-GVD

Lake Baikal, Russia
Effective volume: ~ 1.5 km3
90 strings, 1000+ optical modules

JINR

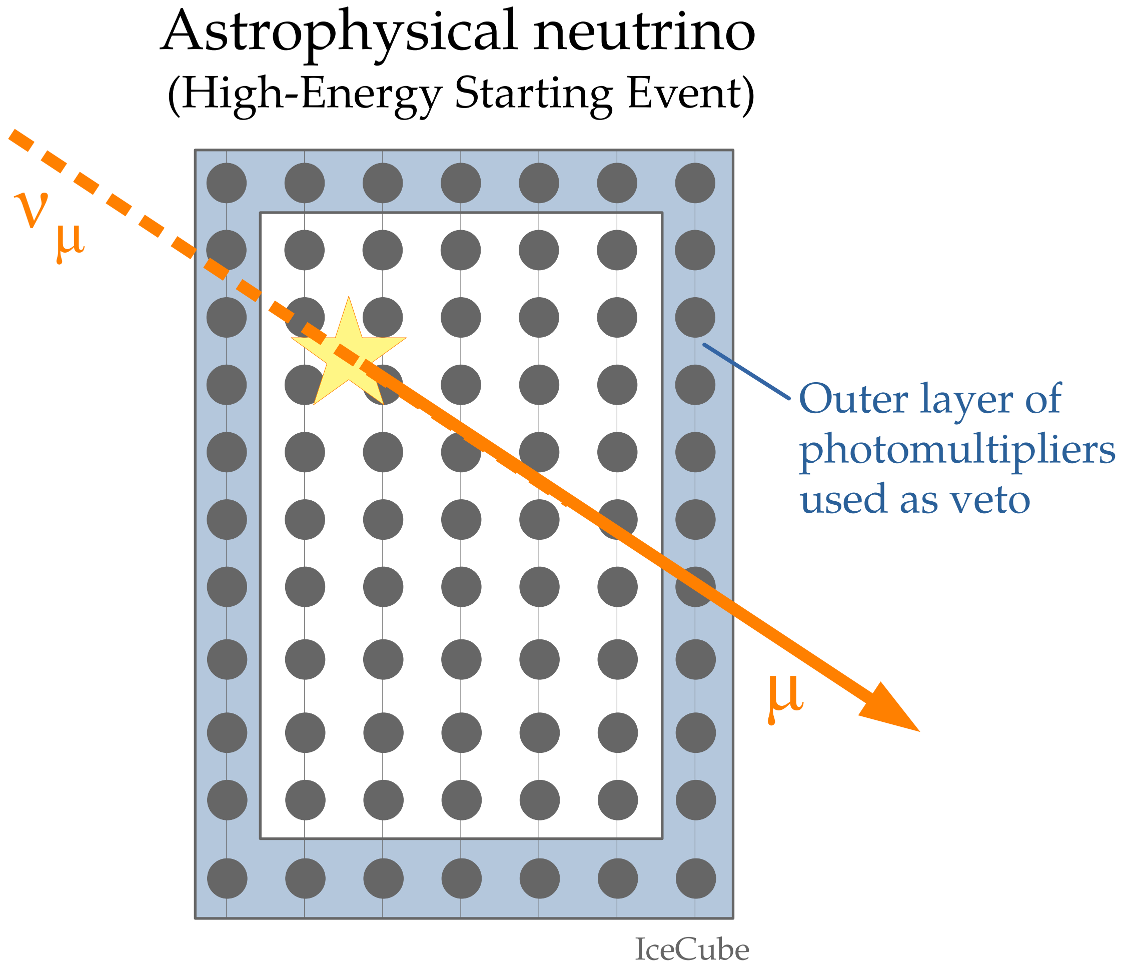


xkcd



Space
p^+
Incoming cosmic ray
p^+
Proton in the air
Pion π^+
Neutron n
Neutrino $\bar{\nu}_\mu$
Proton
$\bar{\nu}_e$
Positron e^+
Muon μ^+
Photons
Atmosphere

IceCube self-veto: High-Energy Starting Events (HESE)



Schönert, Gaisser, Resconi, Schulz, *PRD* 2008
Gaisser, Jero, Karle, van Santen, *PRD* 2014

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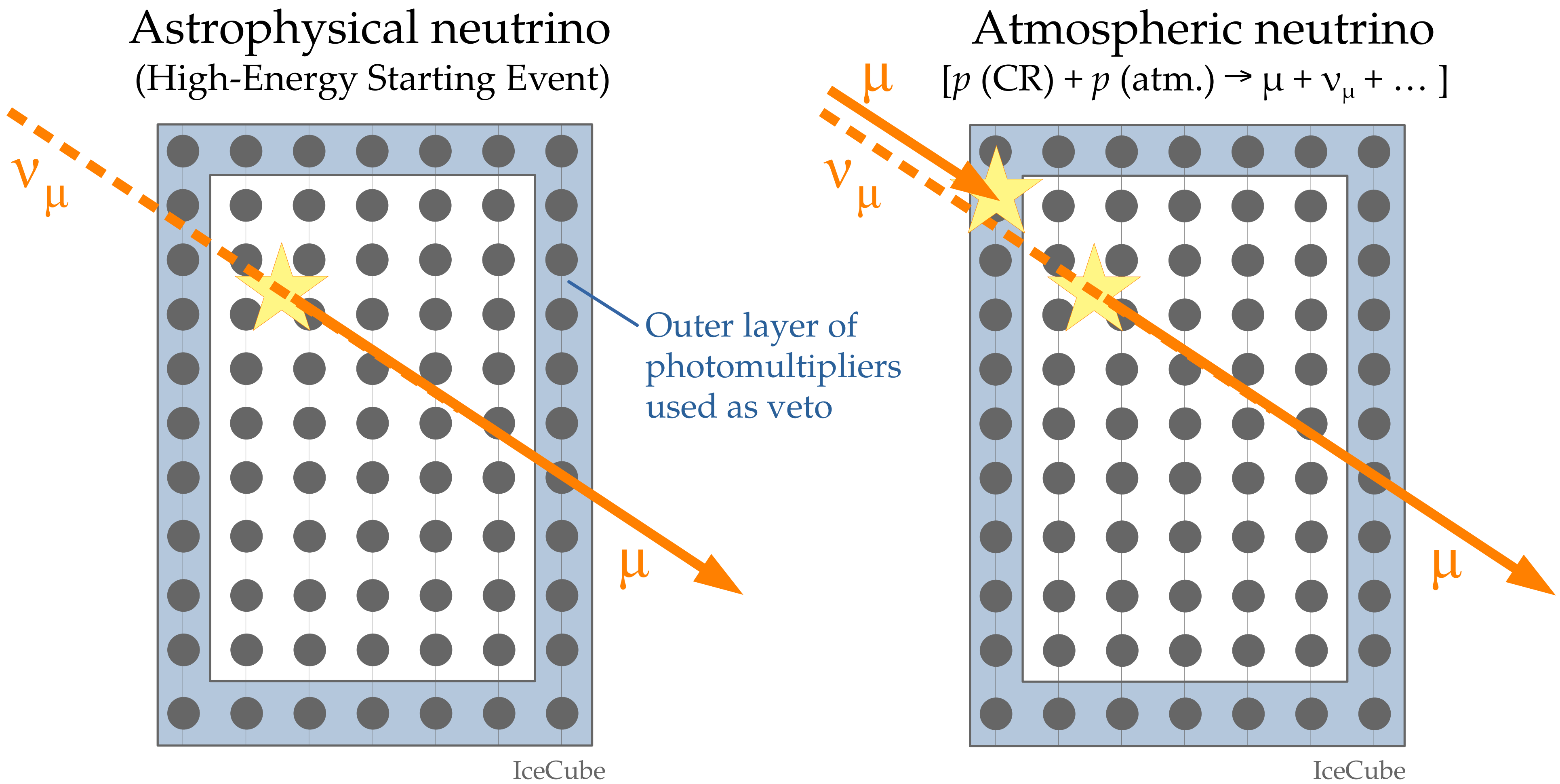
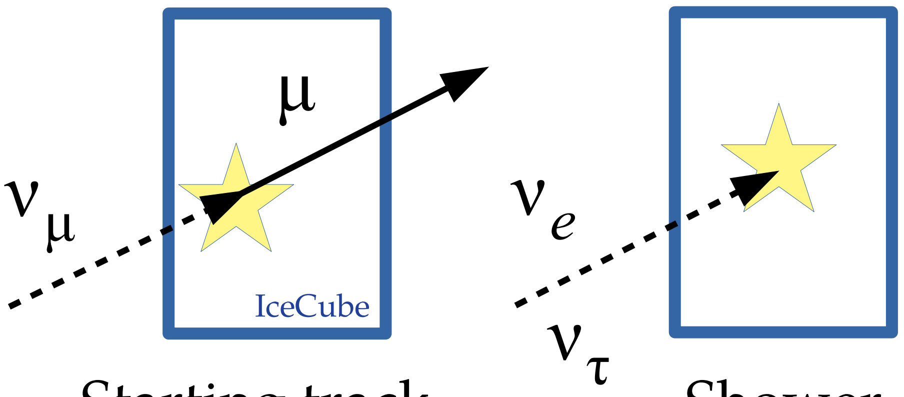


Schönert, Gaisser, Resconi, Schulz, *PRD* 2008
Gaisser, Jero, Karle, van Santen, *PRD* 2014

Contained *vs.* uncontained events

Contained events



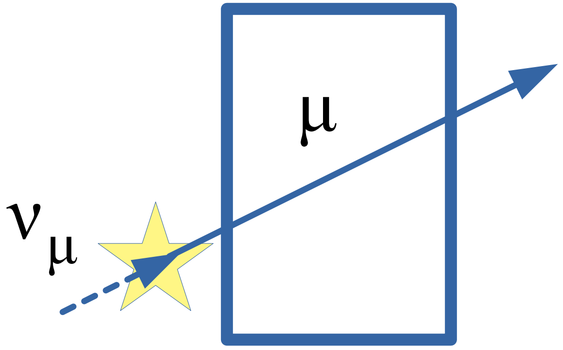
Starting track

Shower

Pro: Clean determination of E_ν

Con: Few events (~100 in 10 yr)

Through-going muons



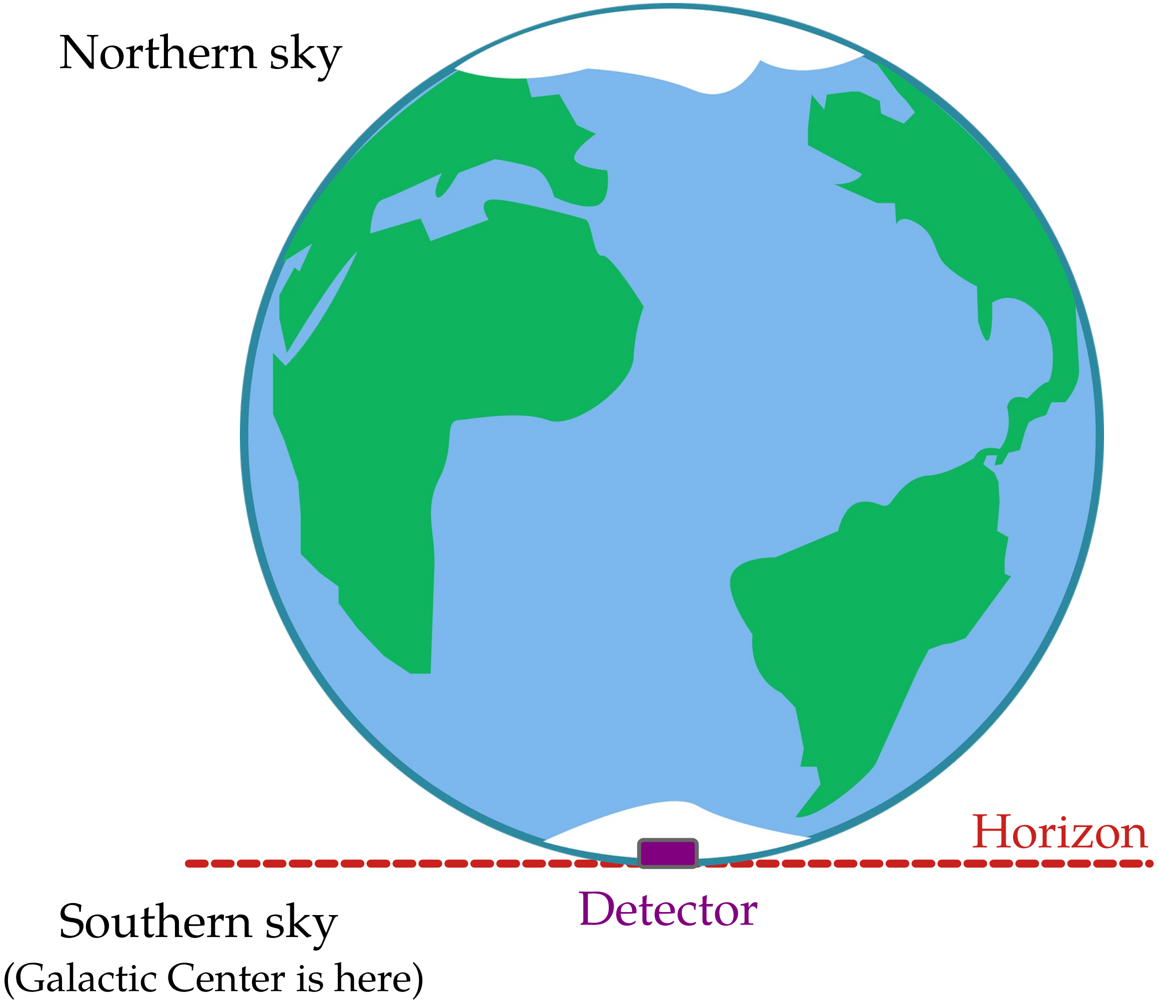
Through-going muon

Pro: Lots of events (few 100k)

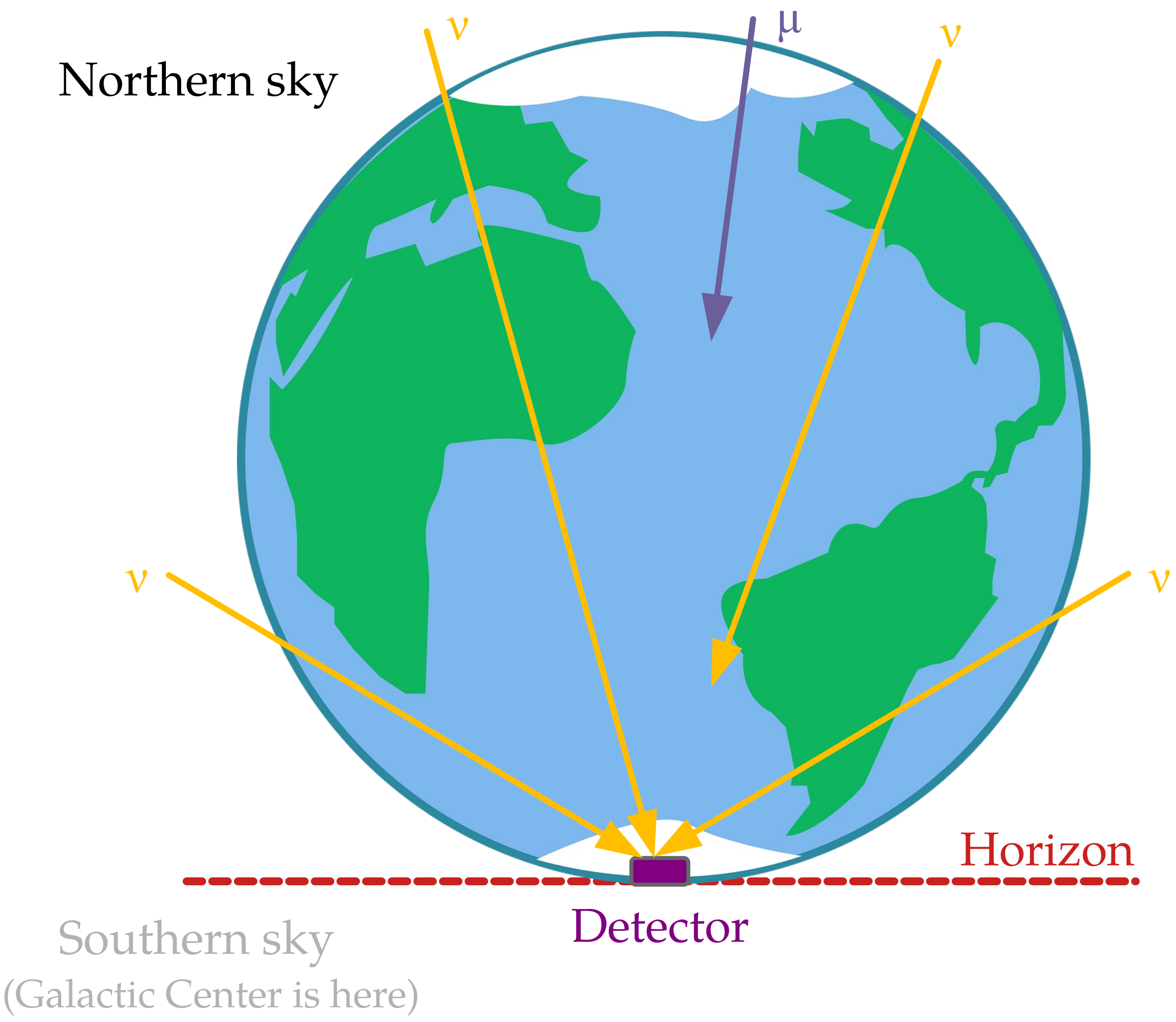
Con: Uncertain estimates of E_ν

What happens inside the Earth

Upgoing *vs.* downgoing neutrinos



Upgoing *vs.* downgoing neutrinos



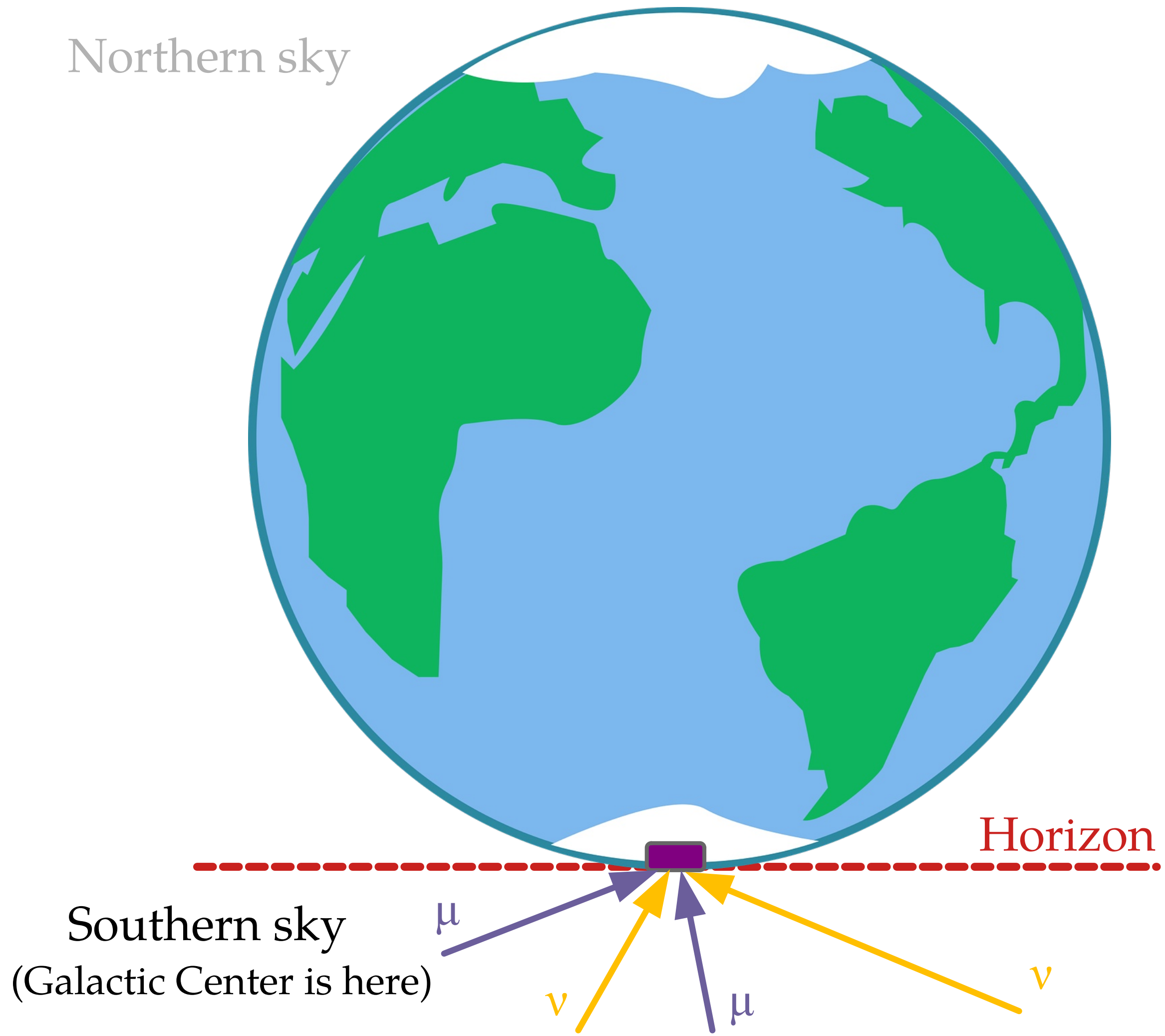
Neutrinos from the Northern sky

≡

Upgoing neutrinos

- Atmospheric muons stopped
- Dominated by atmospheric ν
- High-energy ν flux attenuated
- High statistics
- Good for finding sources with through-going muon tracks

Upgoing *vs.* downgoing neutrinos



Neutrinos from the Southern sky

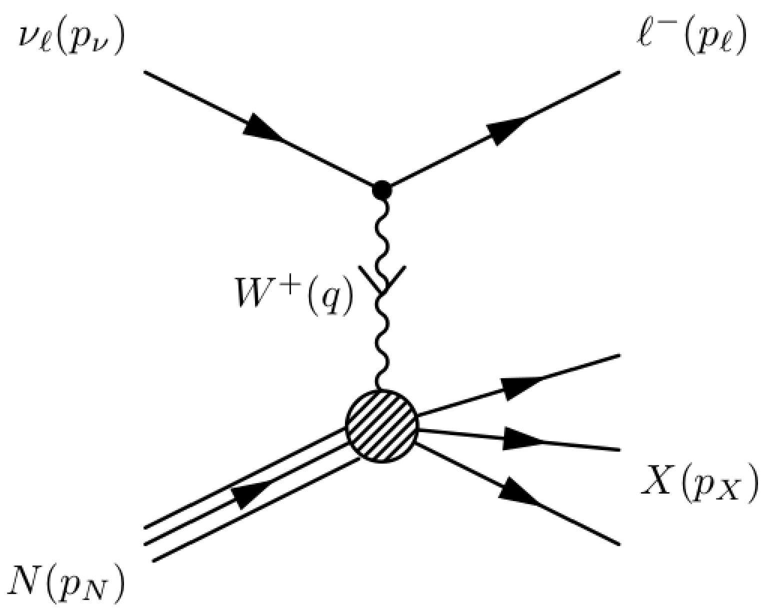
≡

Downgoing neutrinos

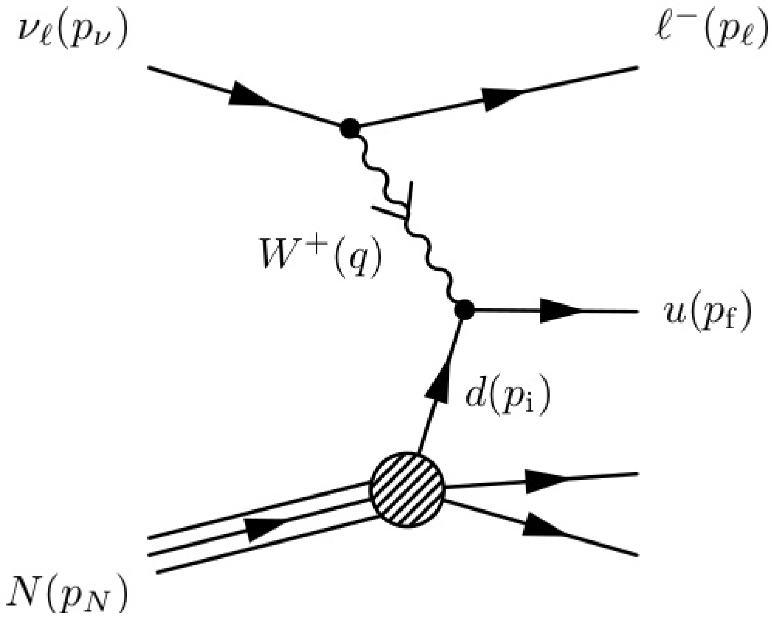
- Need to mitigate atmospheric muons and ν:
  - Use higher-energy events
  - Use starting a self-veto
- Dominated by astrophysical ν (*after* event selection)
- Low statistics
- Good for measuring the diffuse flux of astrophysical ν

Neutrino-nucleon deep inelastic scattering

What you see



Beneath the hood



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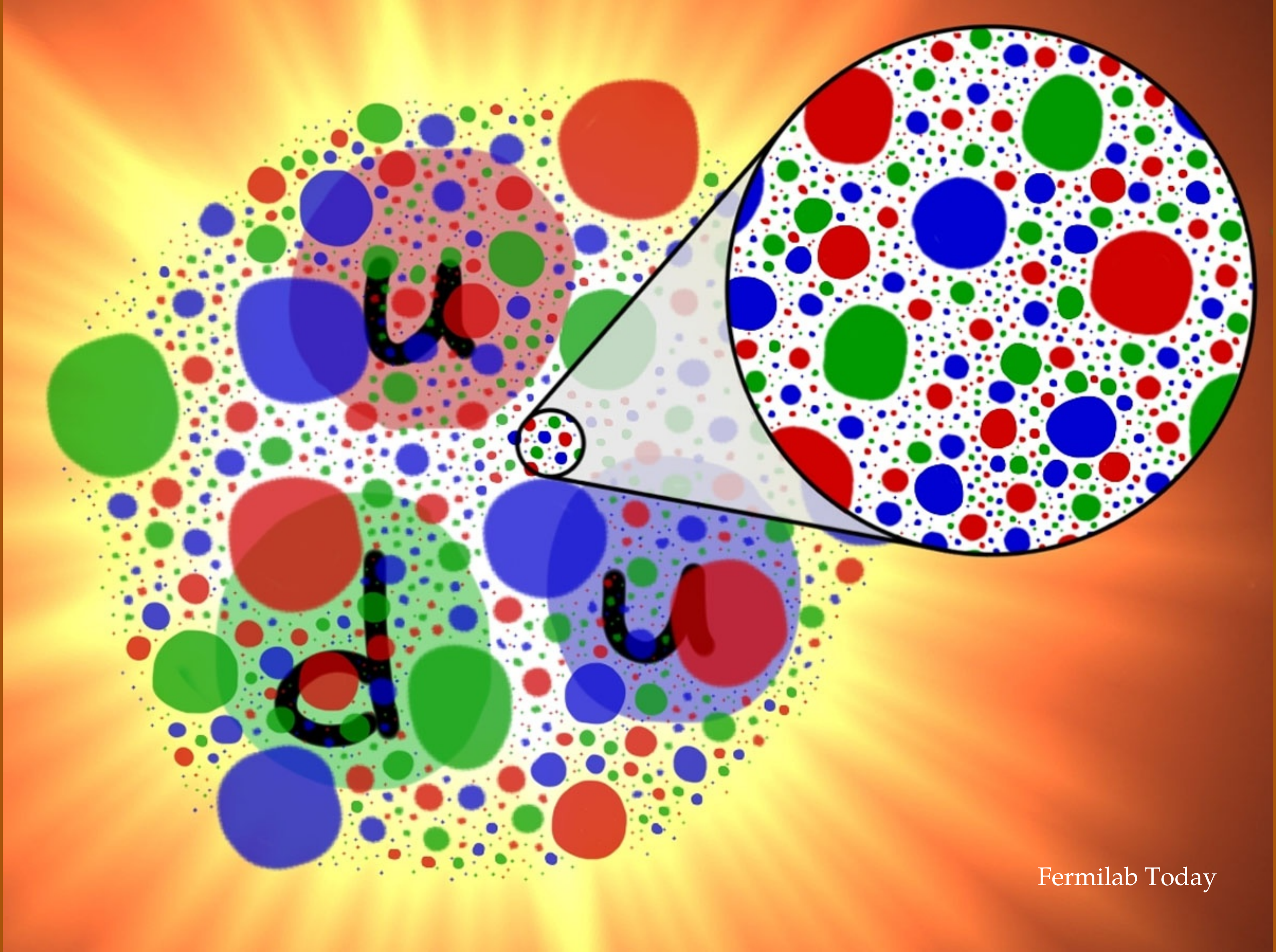
Giunti & Kim, *Fundamentals of Neutrino Physics & Astrophysics*


u
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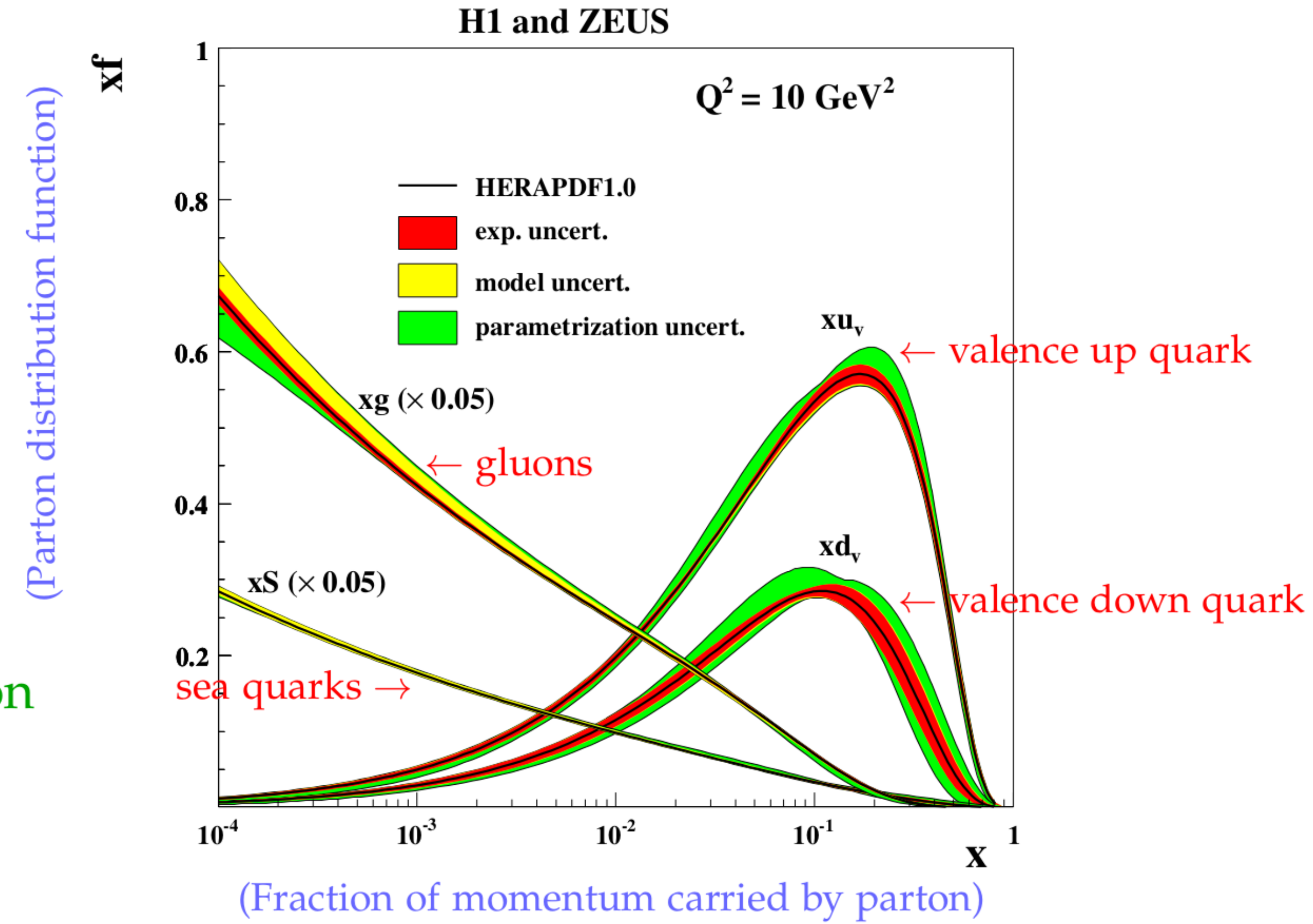
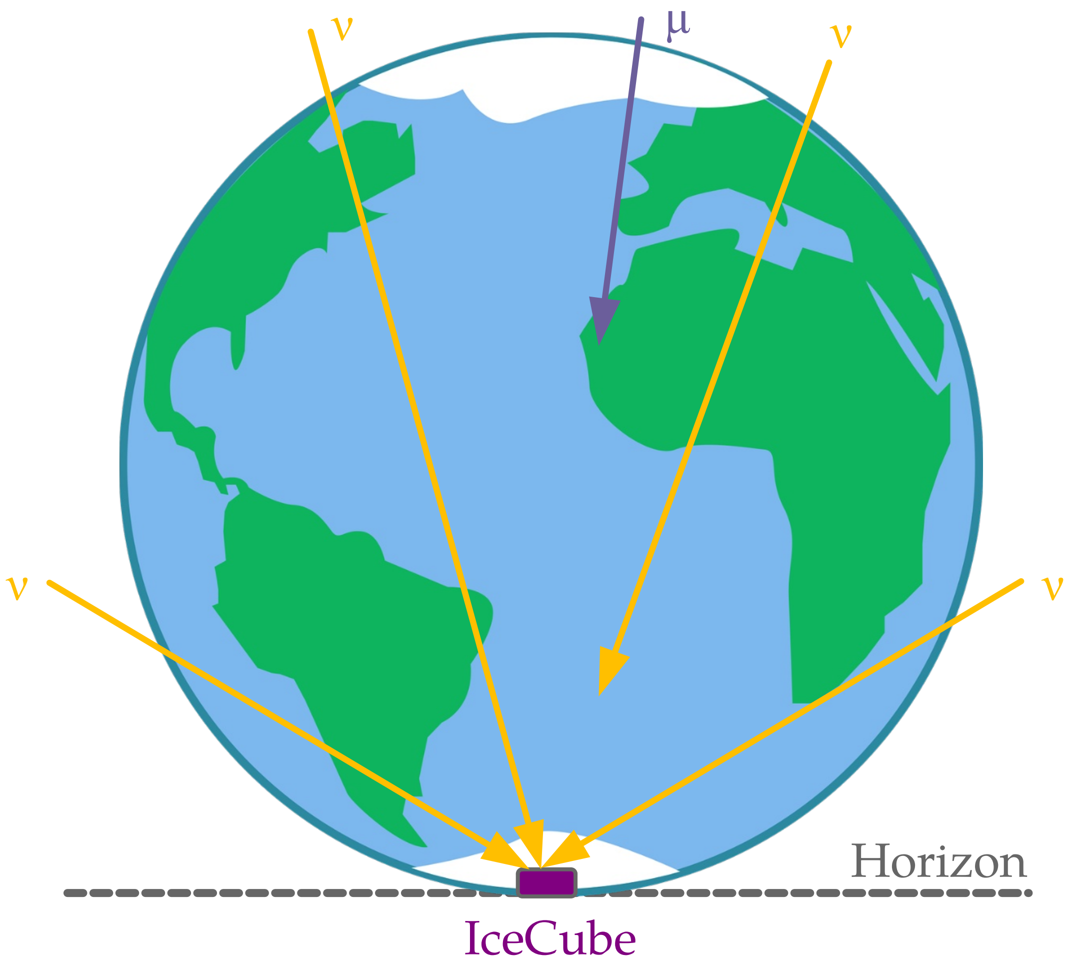
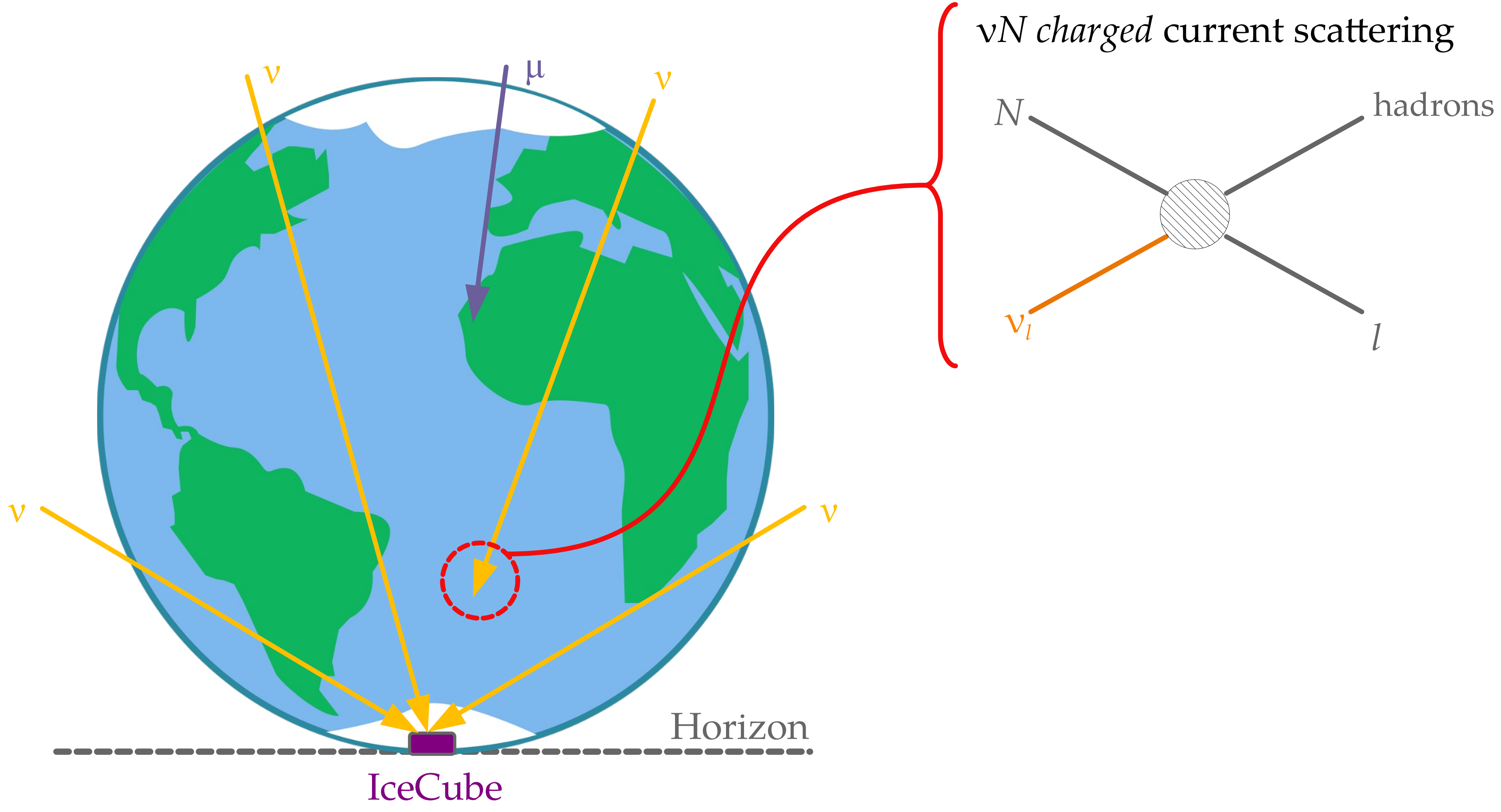
u
Fermilab Today

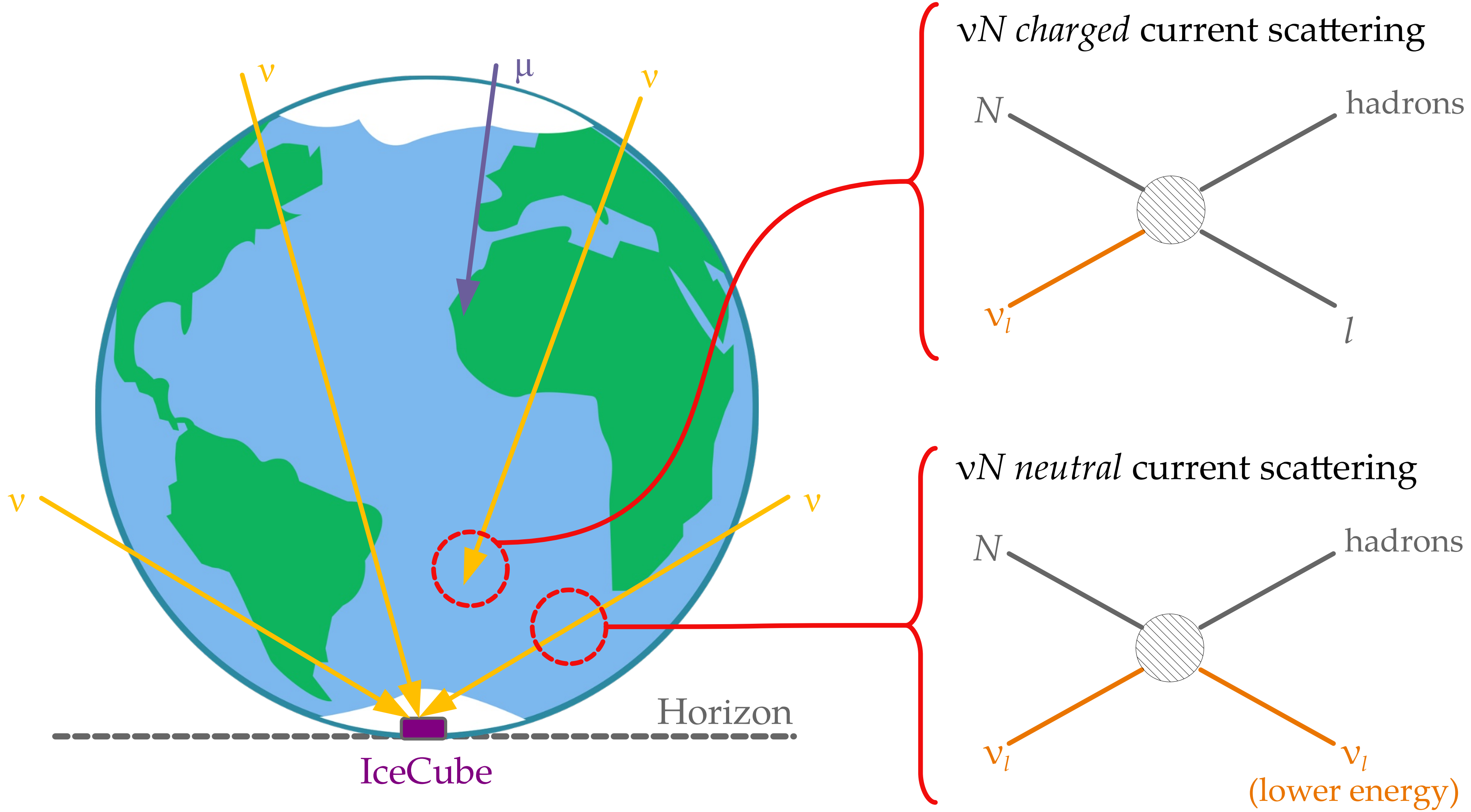
Peeking inside a proton



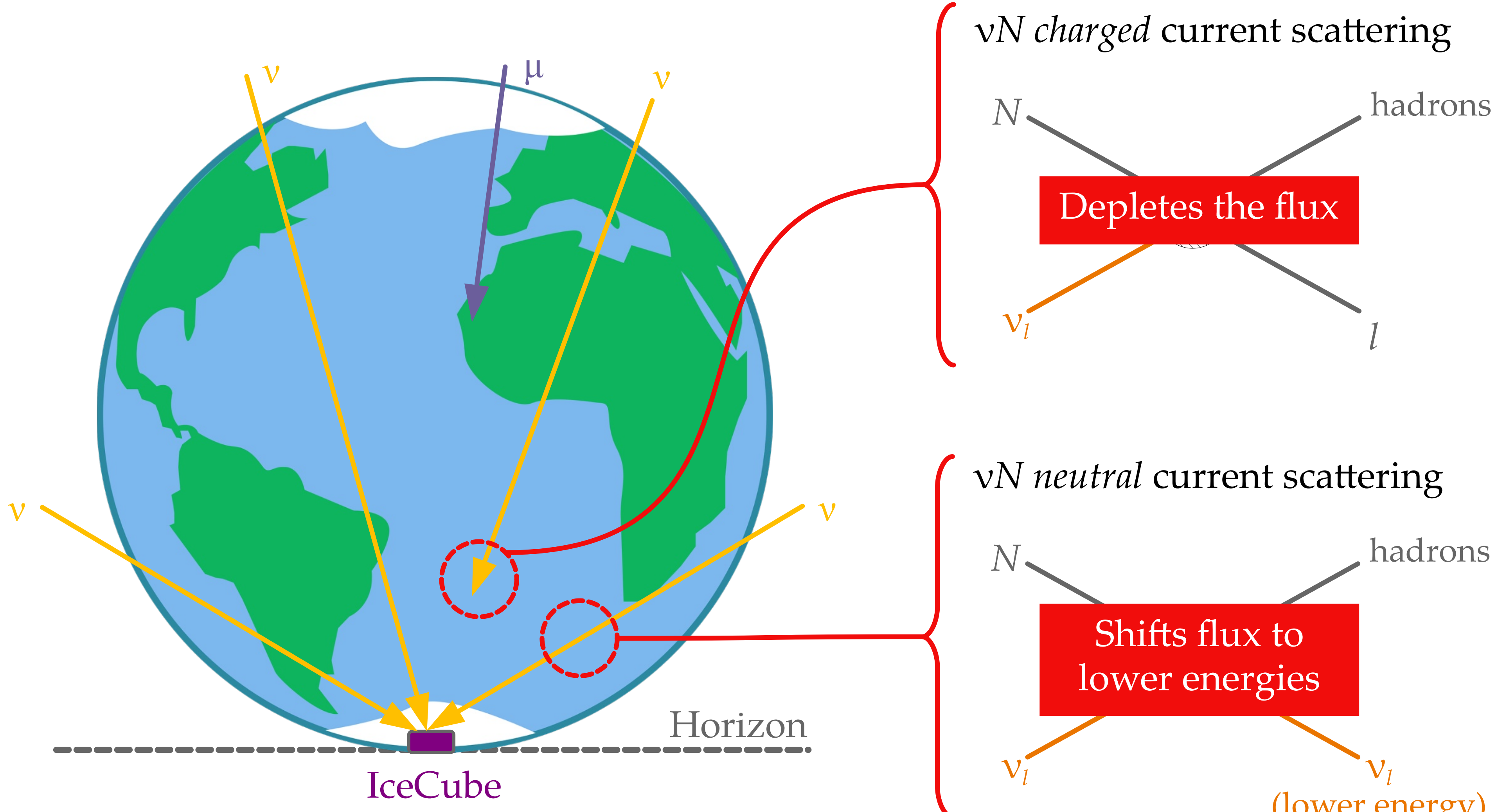
← Extrapolation


ν
μ
ν
ν
ν
Horizon
IceCube


νN *charged* current scattering
N
hadrons
ν_l
l
ν
μ
ν
ν
ν
Horizon
IceCube



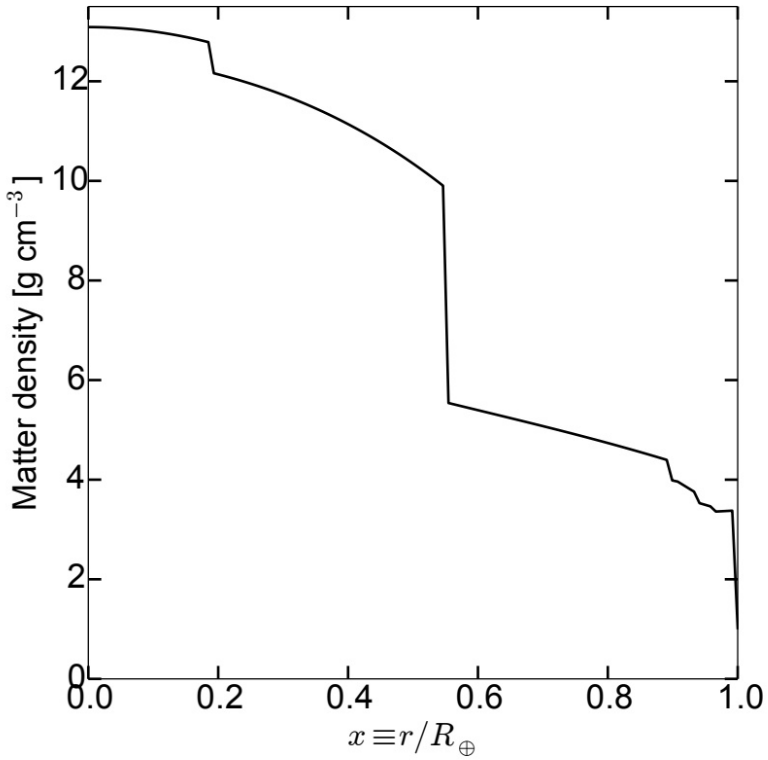
ν
μ
ν
ν
ν
Horizon
IceCube
νN *charged* current scattering
N
hadrons
ν_l
l
νN *neutral* current scattering
N
hadrons
ν_l
ν_l
(lower energy)


ν
μ
ν
ν
ν
Horizon
IceCube
νN *charged* current scattering
N
hadrons
Depletes the flux
ν_l
l
νN *neutral* current scattering
N
hadrons
Shifts flux to lower energies
ν_l
ν_l
(lower energy)

A feel for the in-Earth attenuation

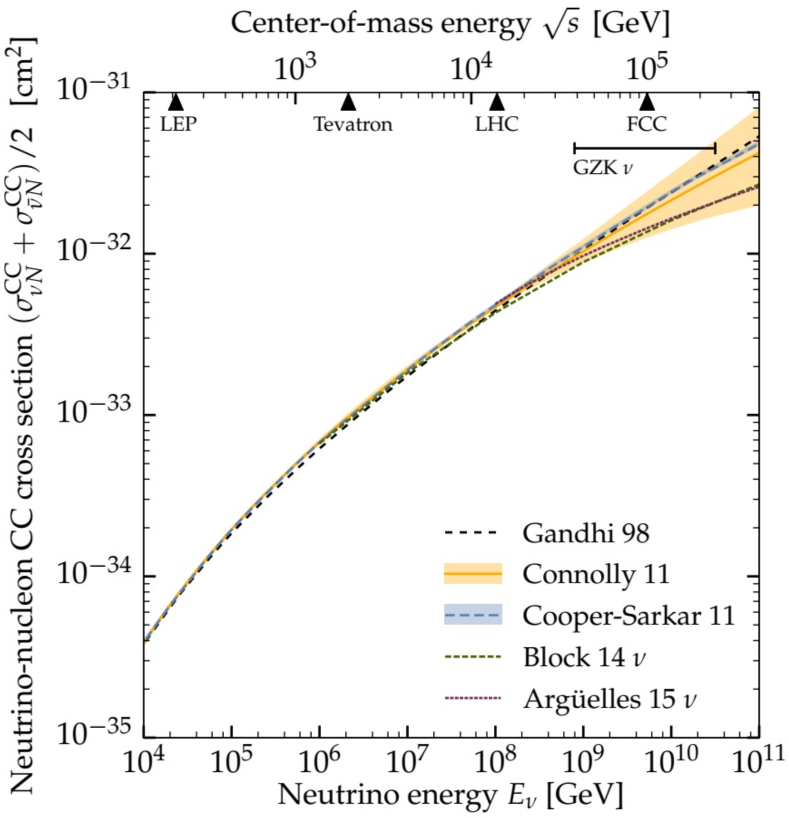
Earth matter density

(Preliminary Reference Earth Model)



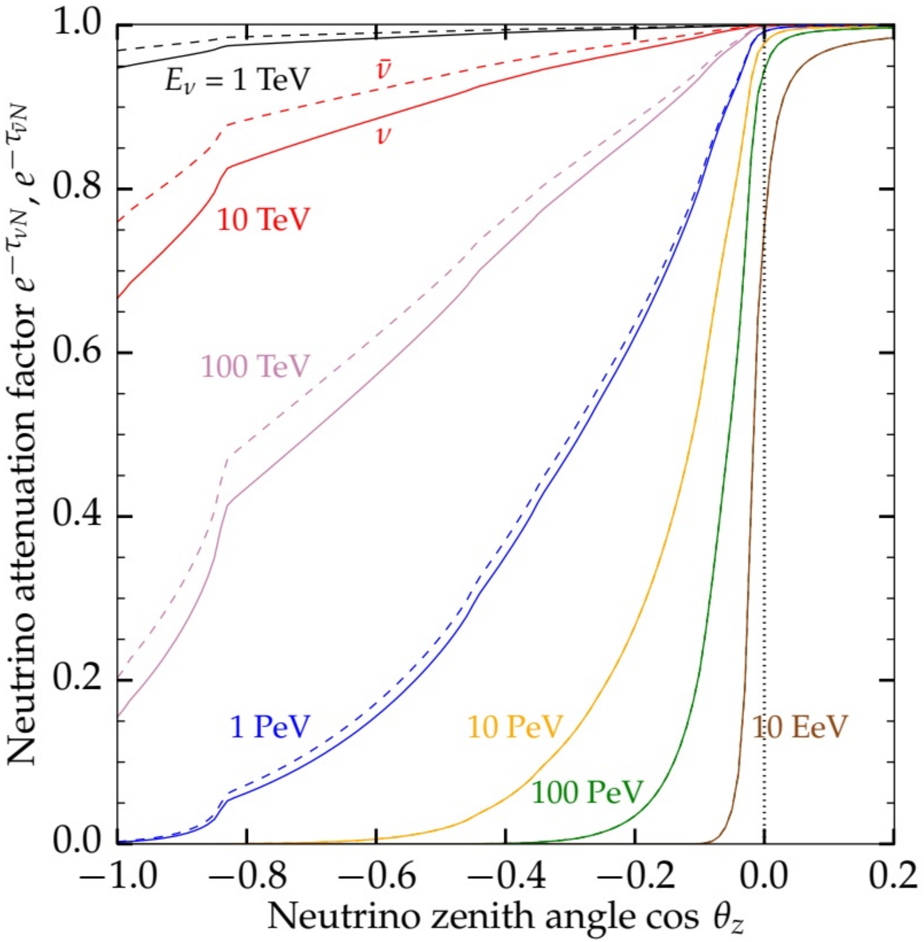
+

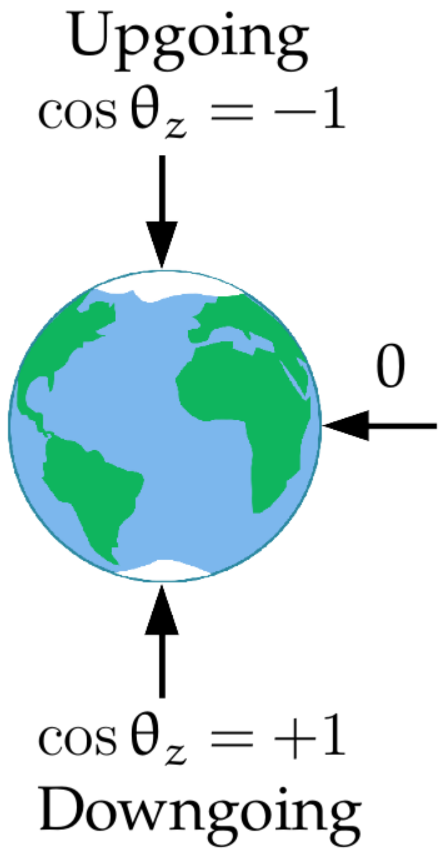
Neutrino-nucleon cross section

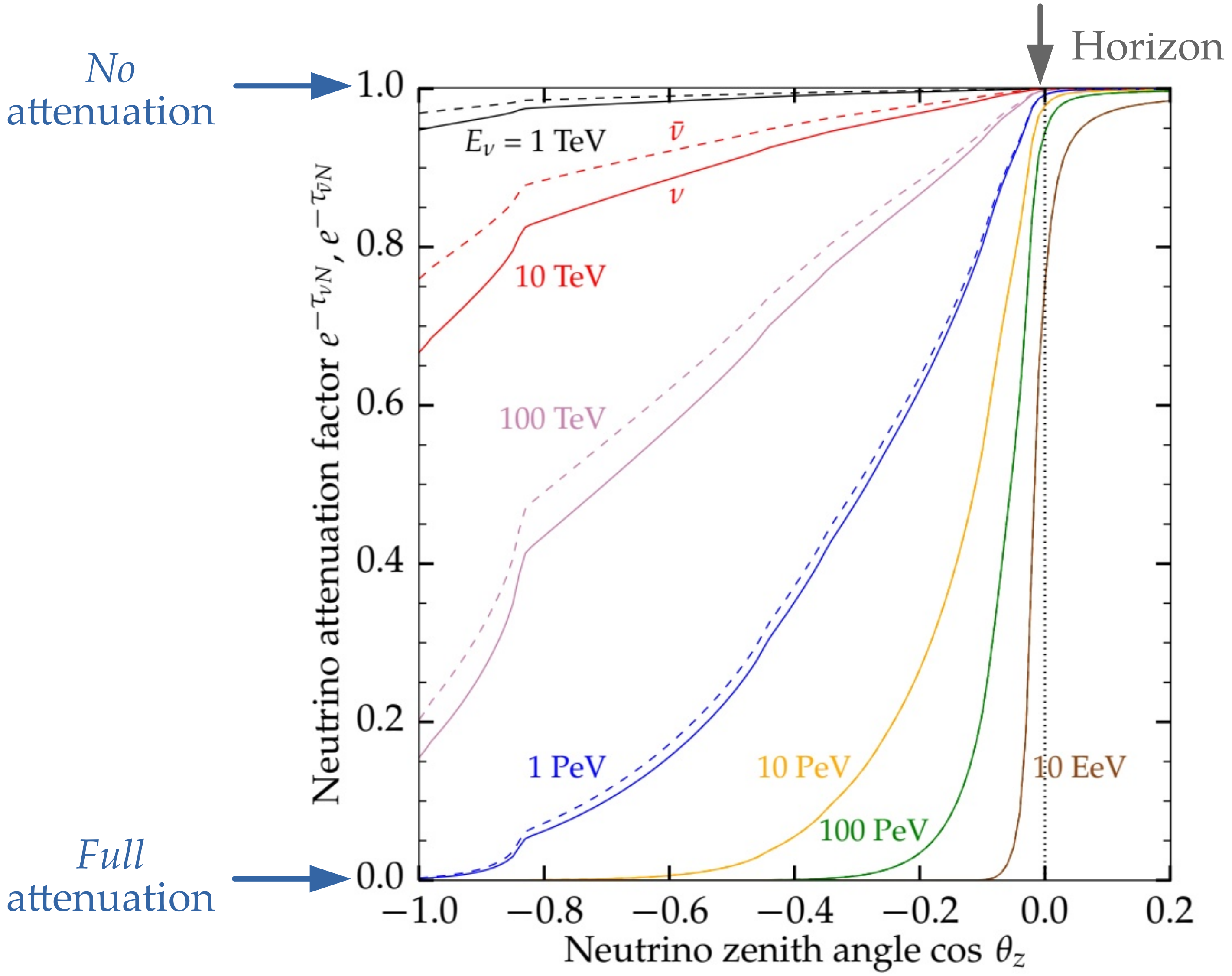


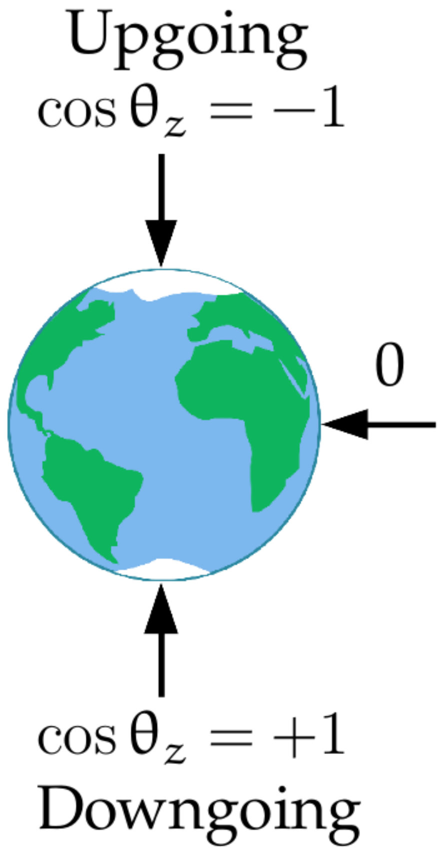
A feel for the in-Earth attenuation

=

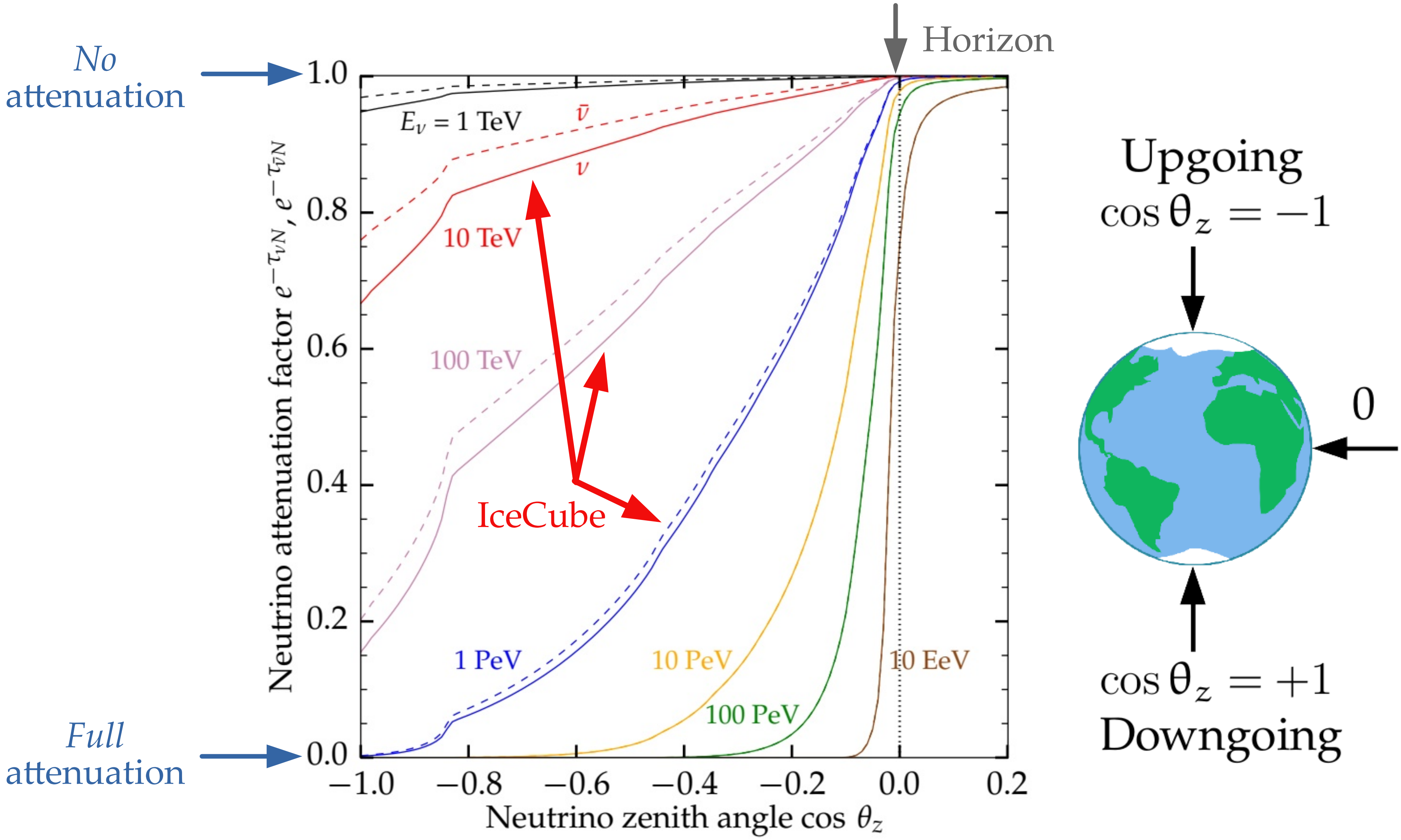






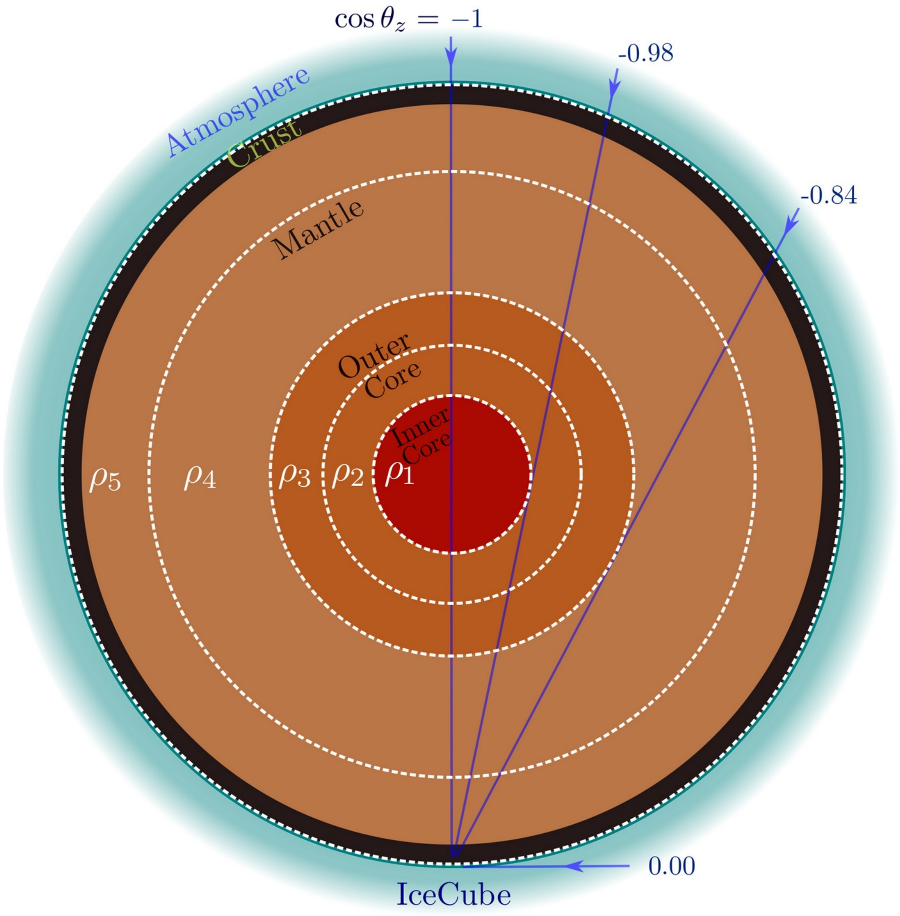


MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019

Tomography of the Earth



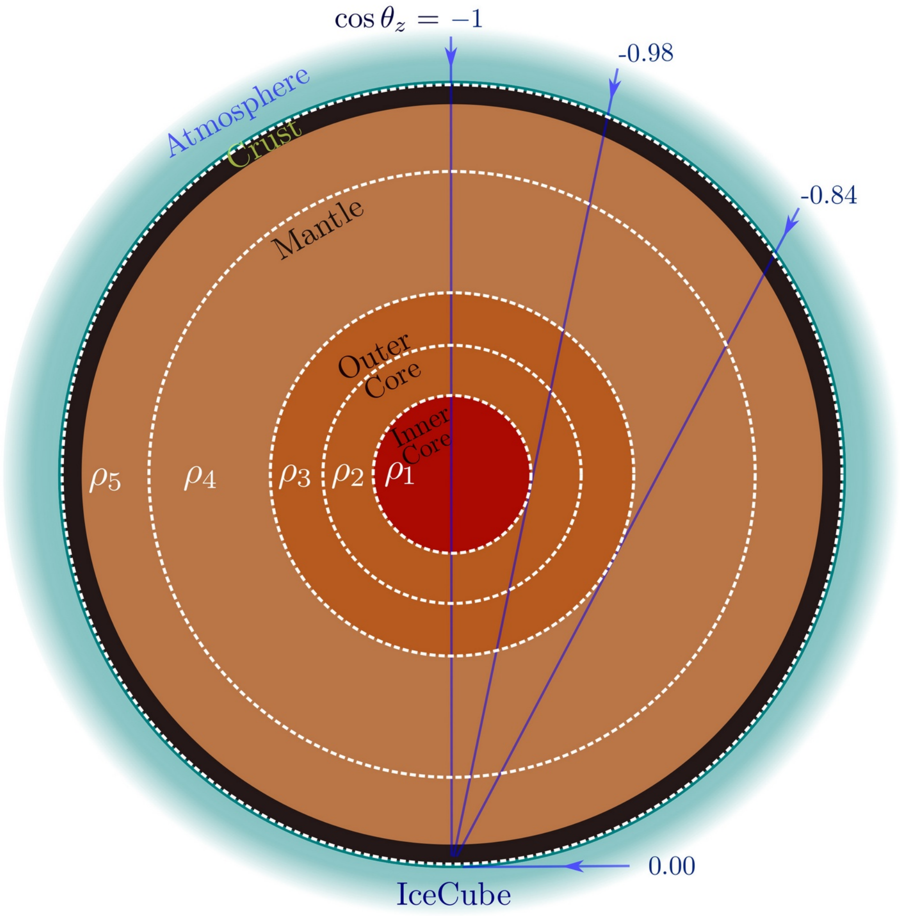
Neutrinos are more likely to interact while traveling inside the Earth …

… the higher their energy, and

… the longer the distance they travel.

Donini, Palomares-Ruiz, Salvadó, *Nature Phys.* 1, 37 (2019)

Tomography of the Earth



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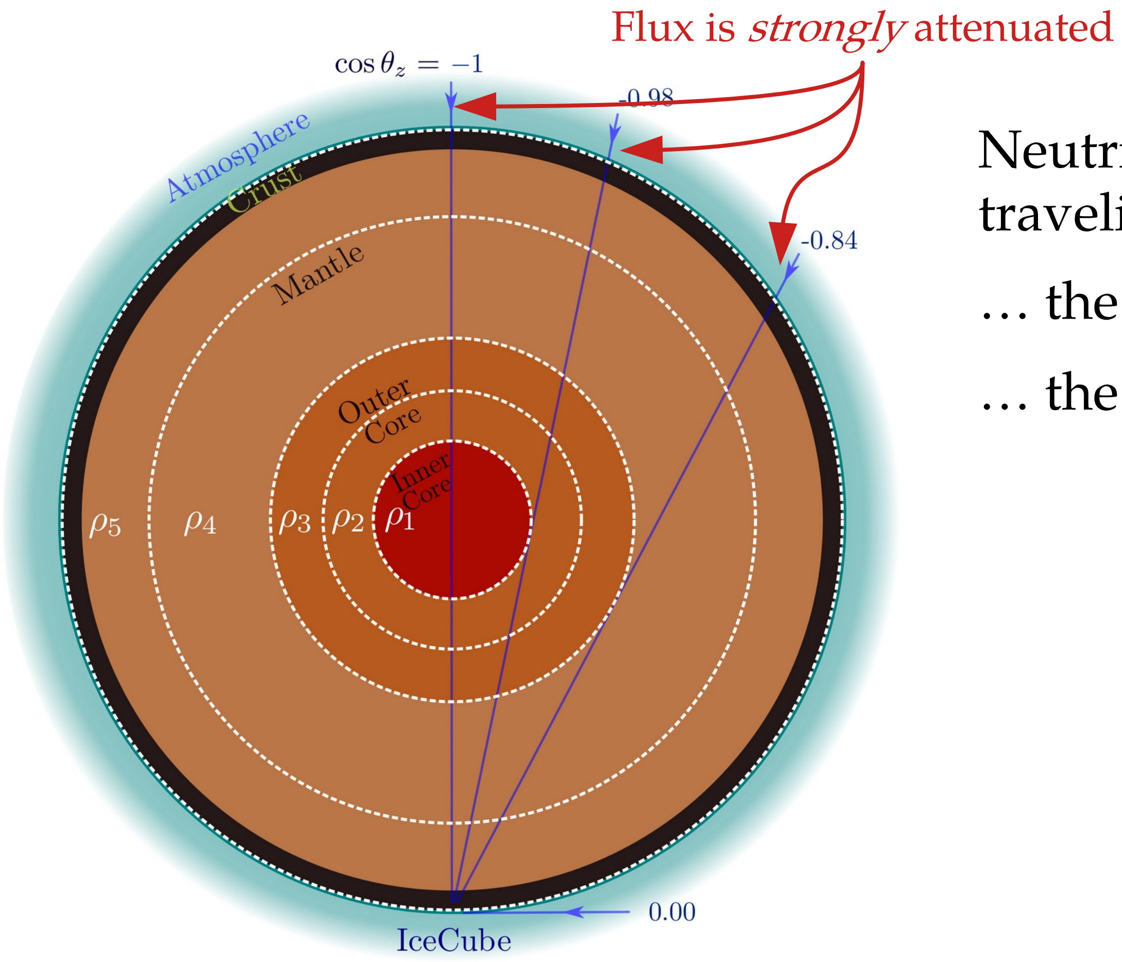

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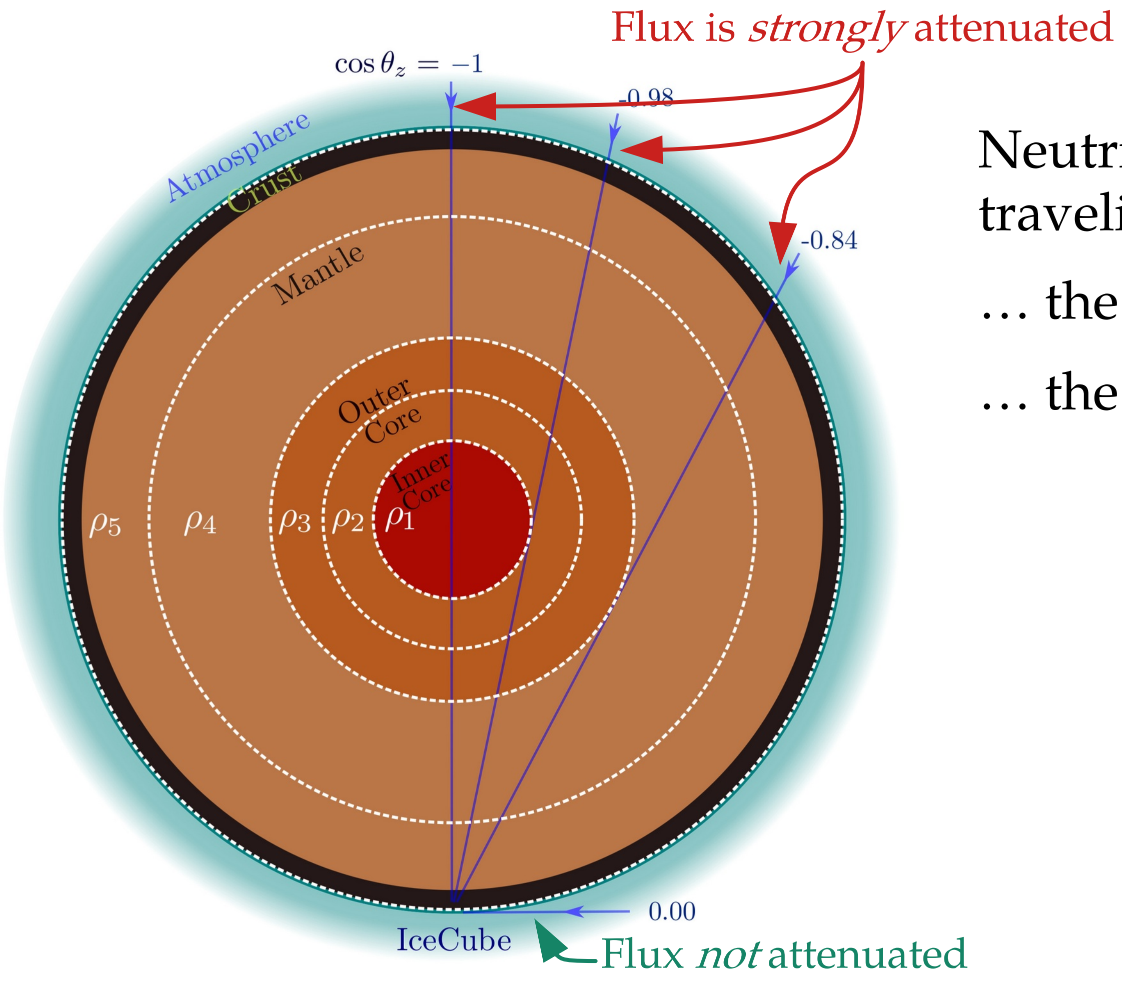

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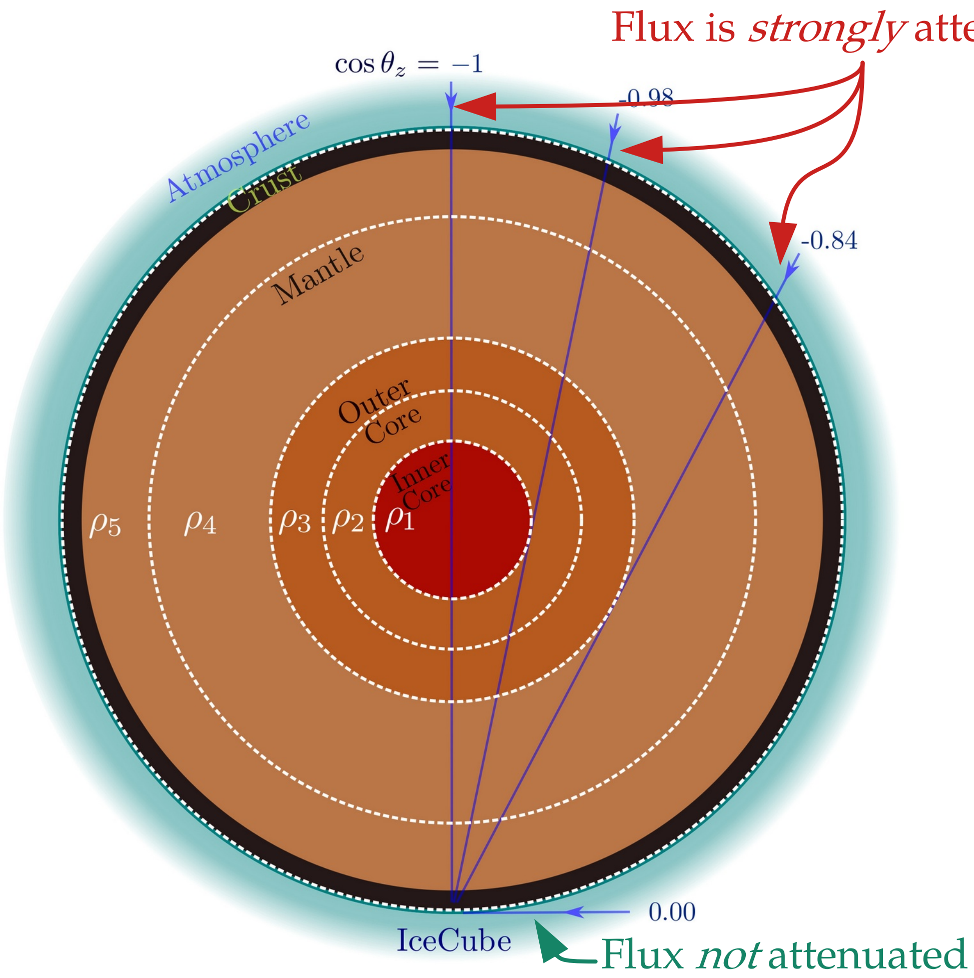

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Comparing atmospheric neutrino fluxes reaching IceCube from different directions:

$$\text{Earth's mass} = 6.0^{+1.6}_{-1.3} \times 10^{24}\ \text{kg}$$

Donini, Palomares-Ruiz, Salvadó, *Nature Phys.* 1, 37 (2019)

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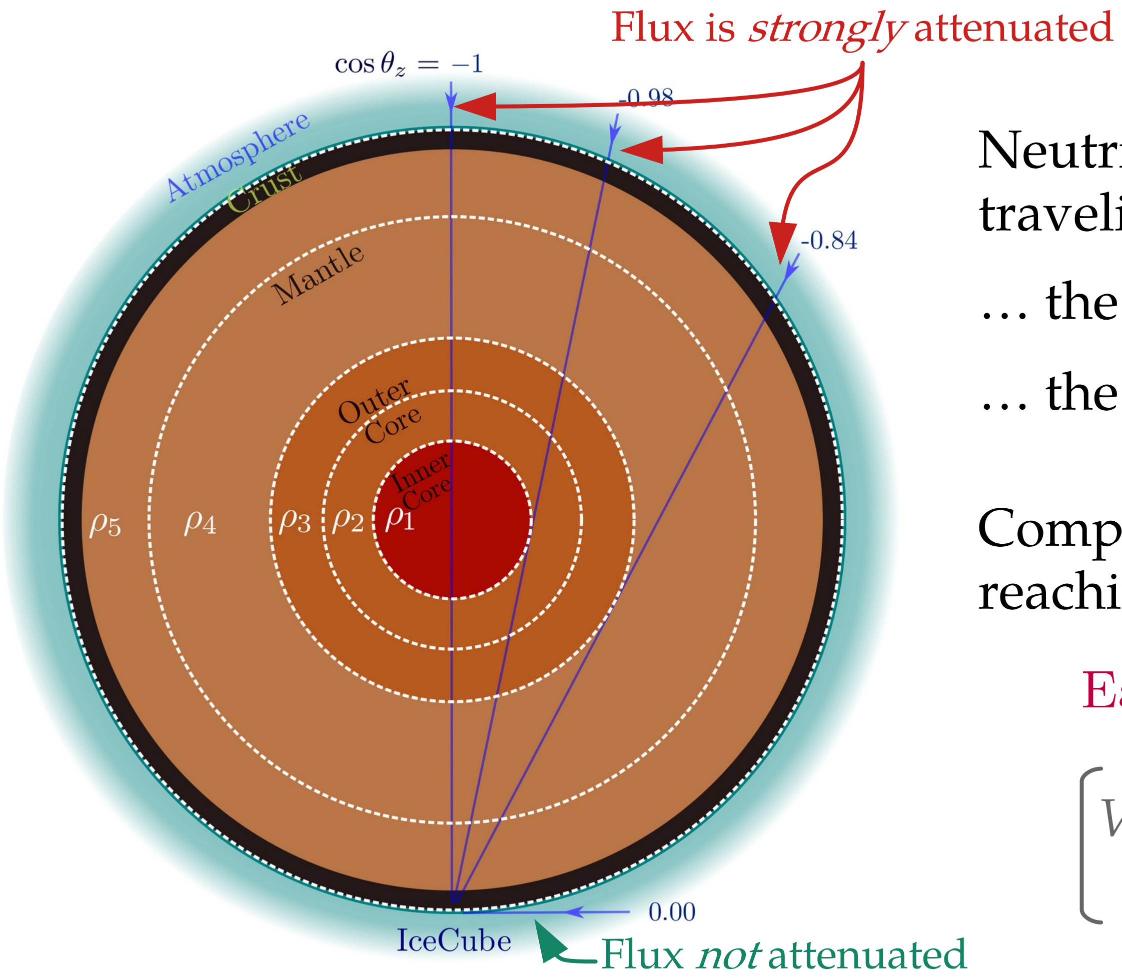

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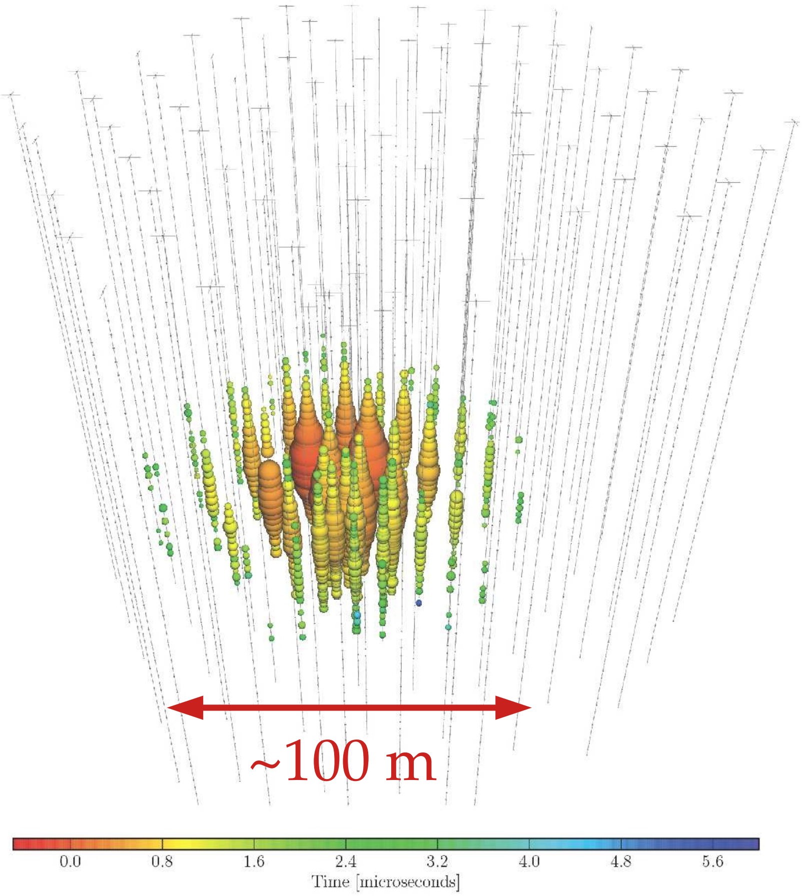
Vs. gravitational measurements: $(5.9722 \pm 0.0006) \times 10^{24}$ kg

Donini, Palomares-Ruiz, Salvadó, *Nature Phys.* 1, 37 (2019)

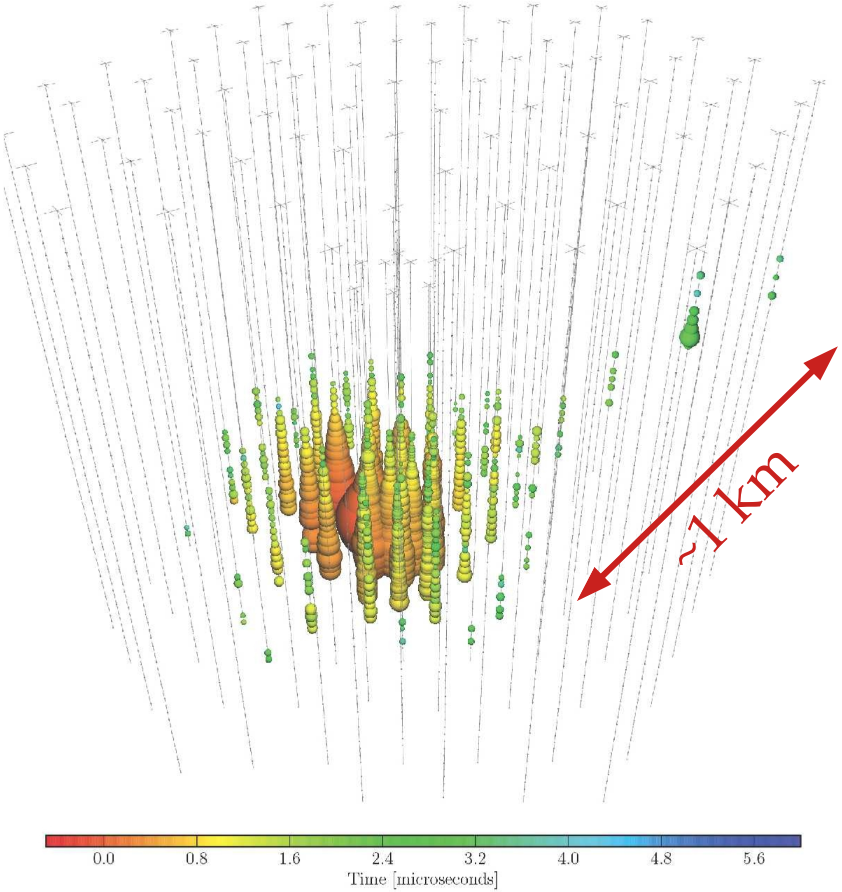
What have we observed?

Shower (mainly from ν_e and ν_τ)



Poor angular resolution: < 5°

Track (mainly from ν_μ)



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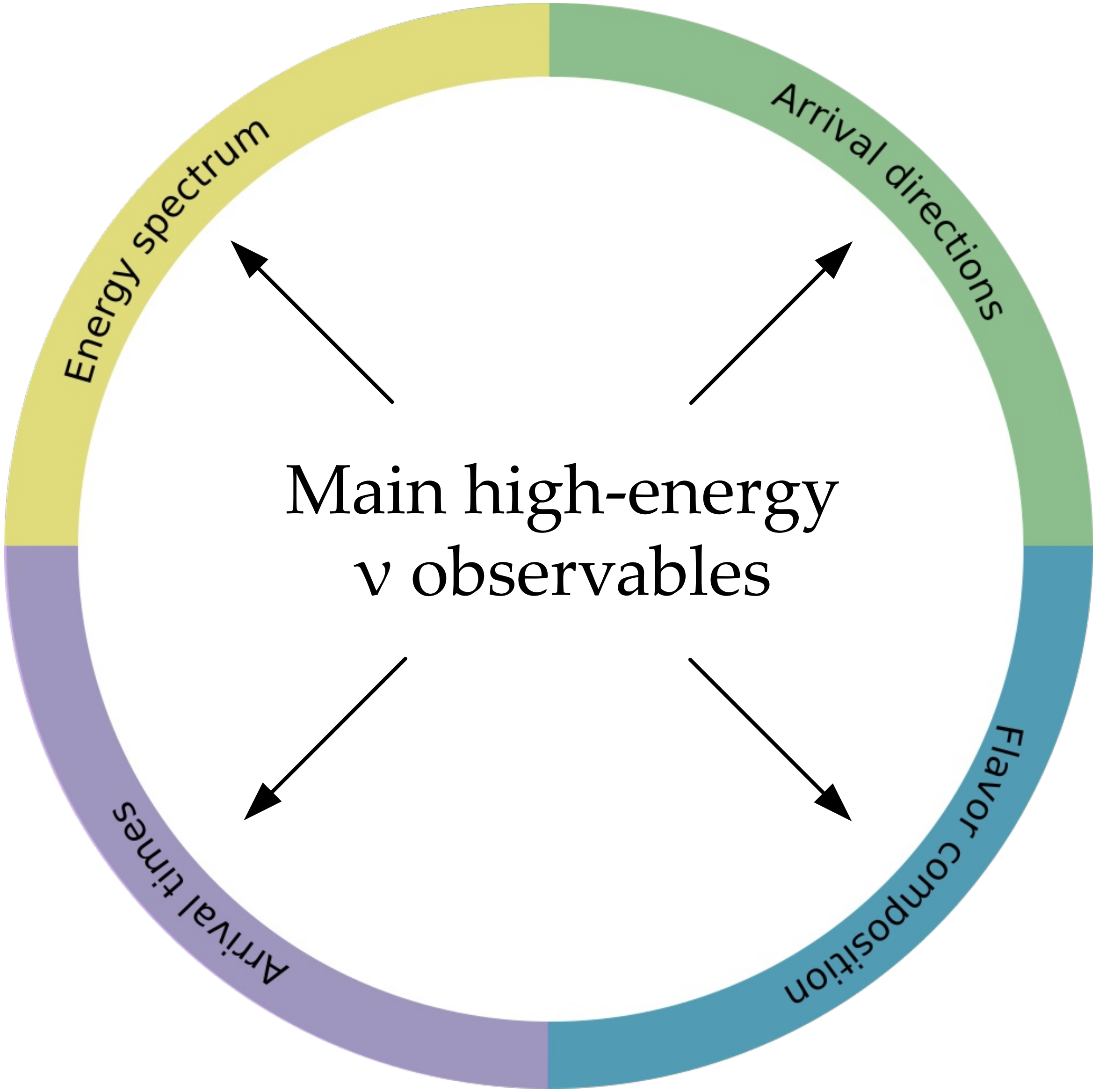
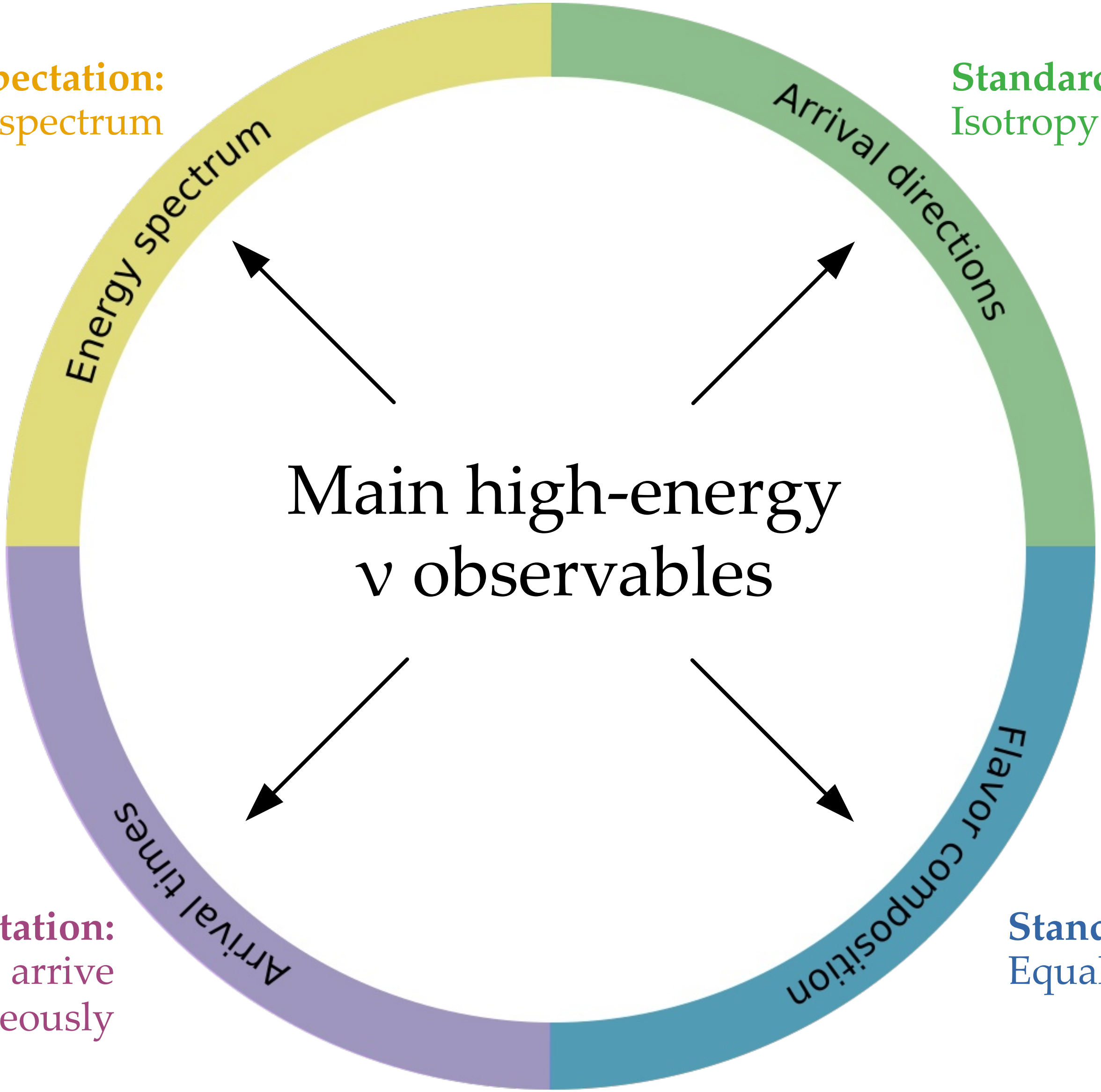

Main high-energy ν observables
Energy spectrum
Arrival directions
Flavor composition
Arrival times

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Standard expectation:
Power-law energy spectrum

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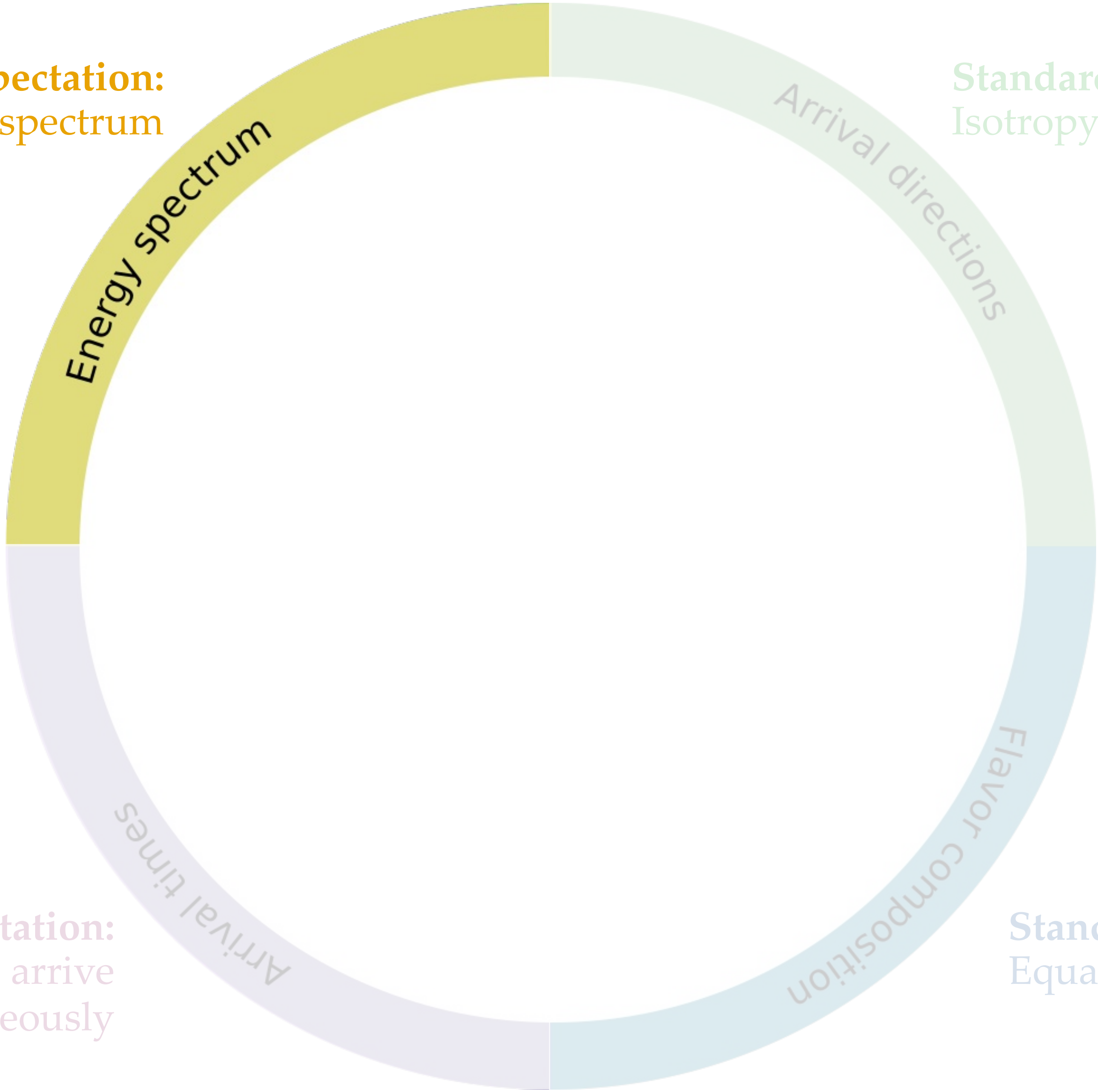
Isotropy (for diffuse flux)



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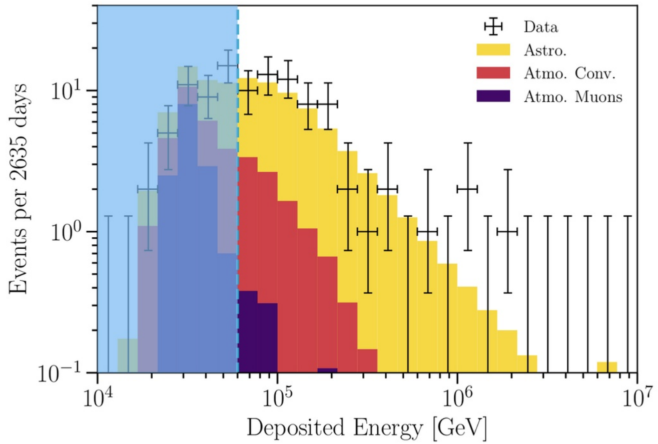
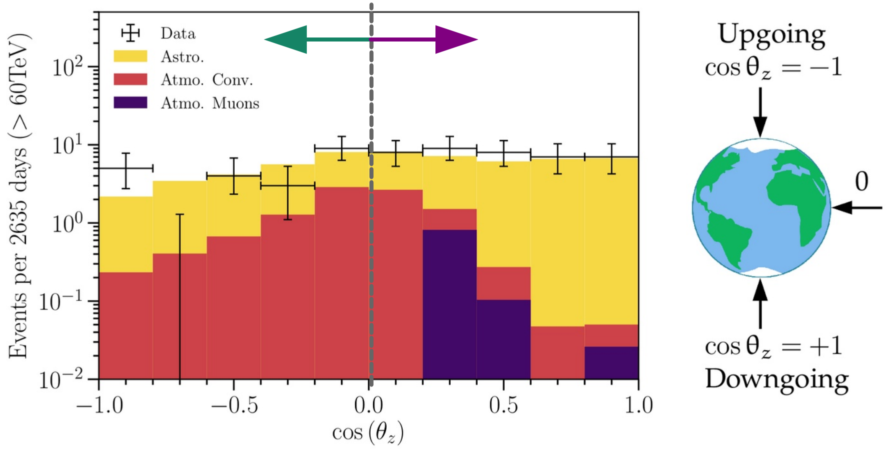
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Energy spectrum (7.5 yr)

100+ contained events above 60 TeV:

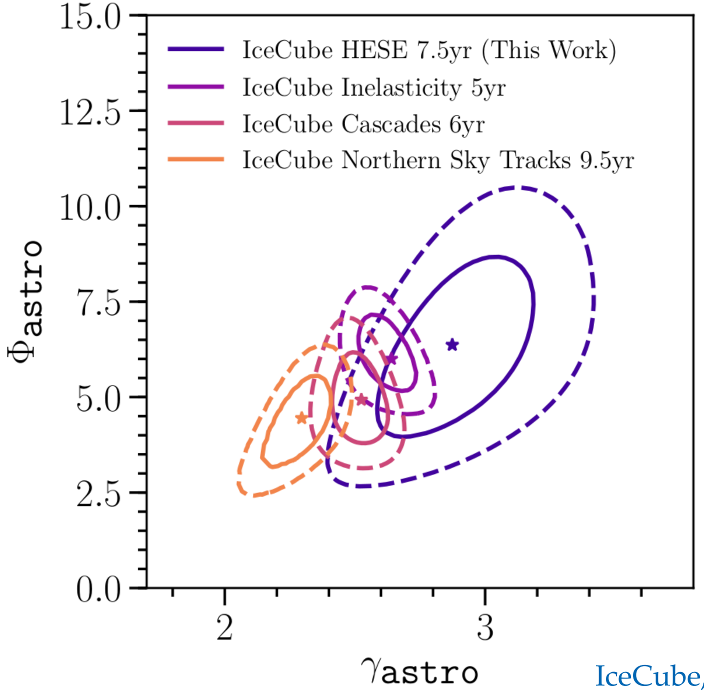


ν attenuated by Earth   Atm. ν and μ vetoed



Data is fit well by a single power law:

$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\text{astro}} \left(\frac{E_\nu}{100\ \text{TeV}} \right)^{-\gamma_{\text{astro}}} \cdot 10^{-18}\ \text{GeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$



IceCube, *PRD* 2021

Energy spectrum (7.5 yr)

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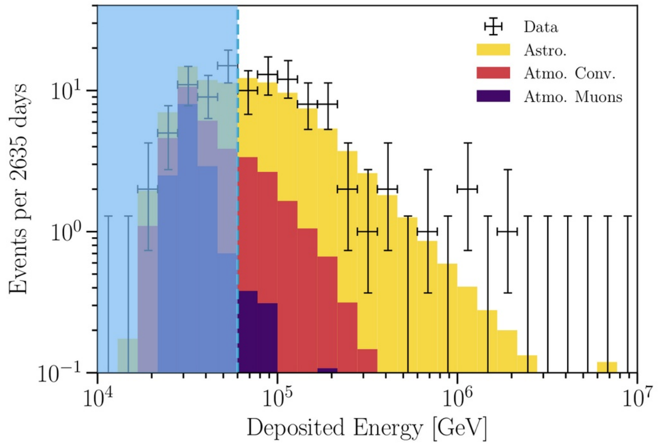

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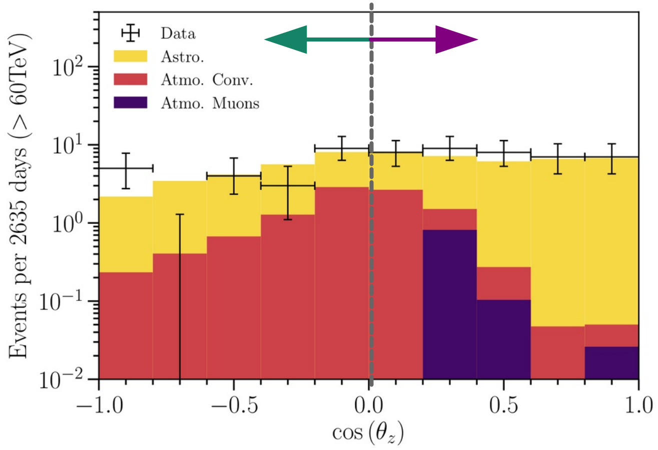

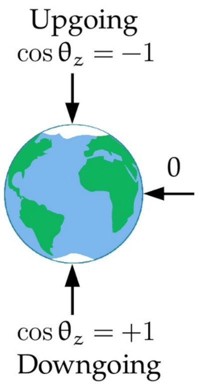

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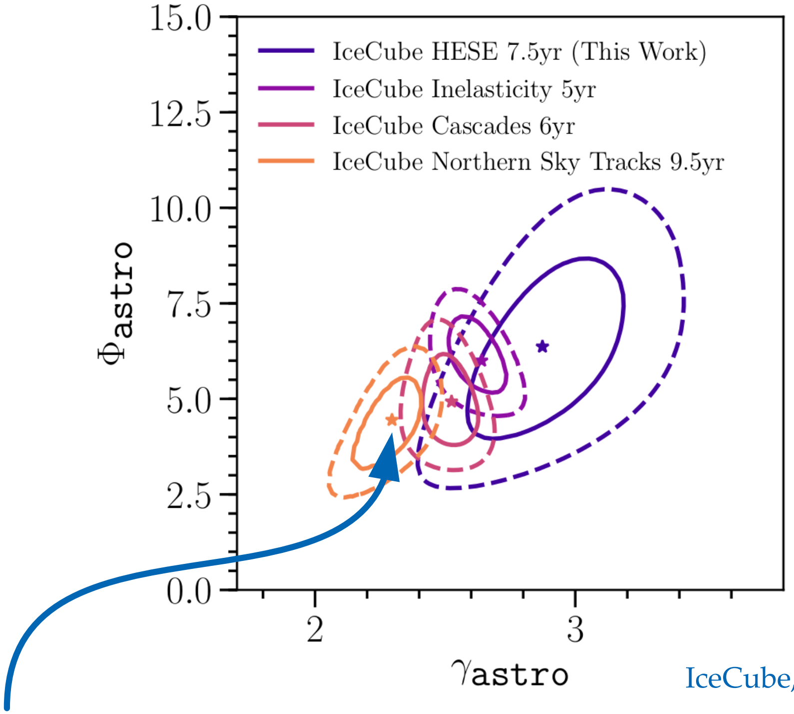
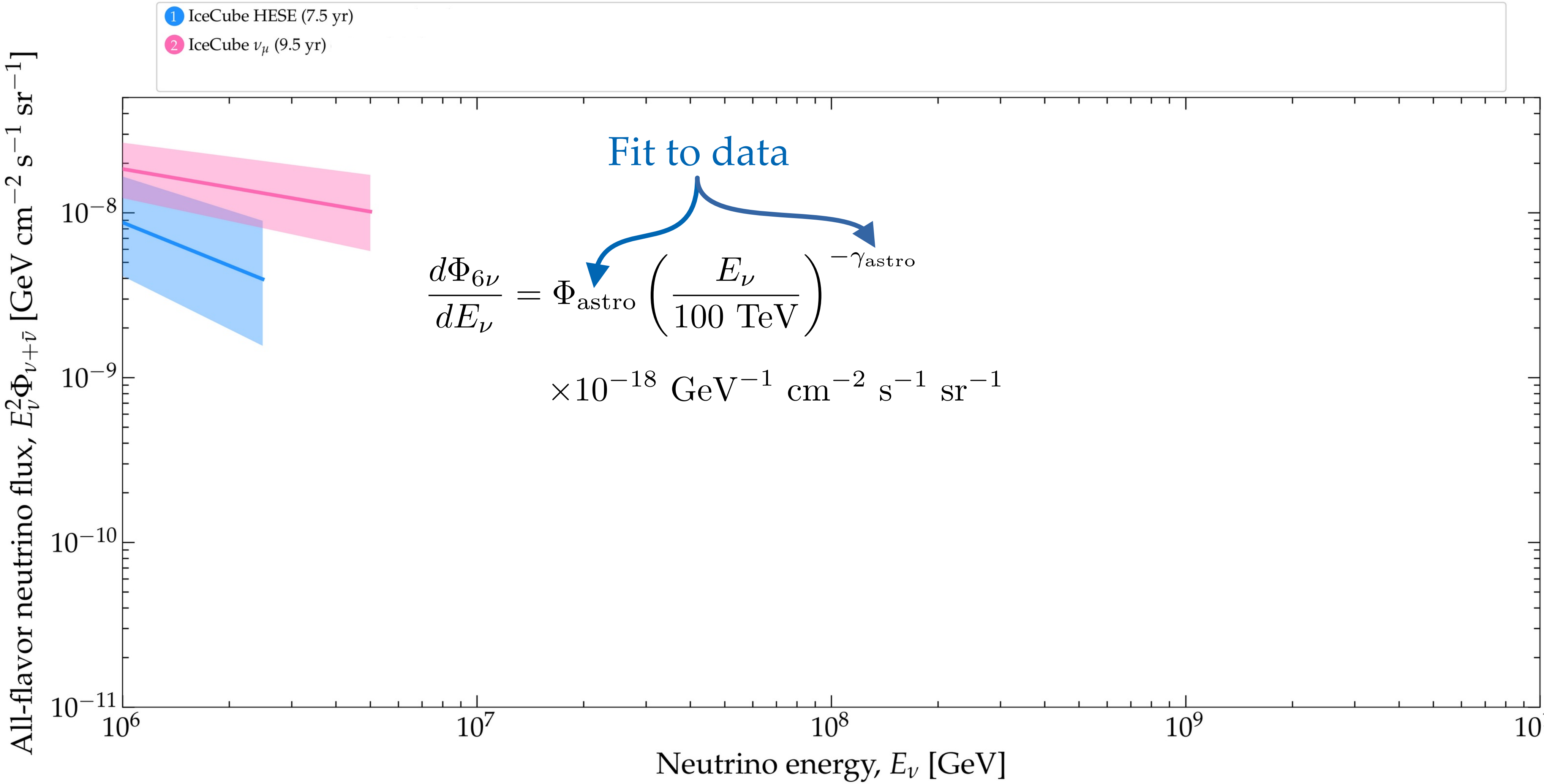


IceCube, *PRD* 2021

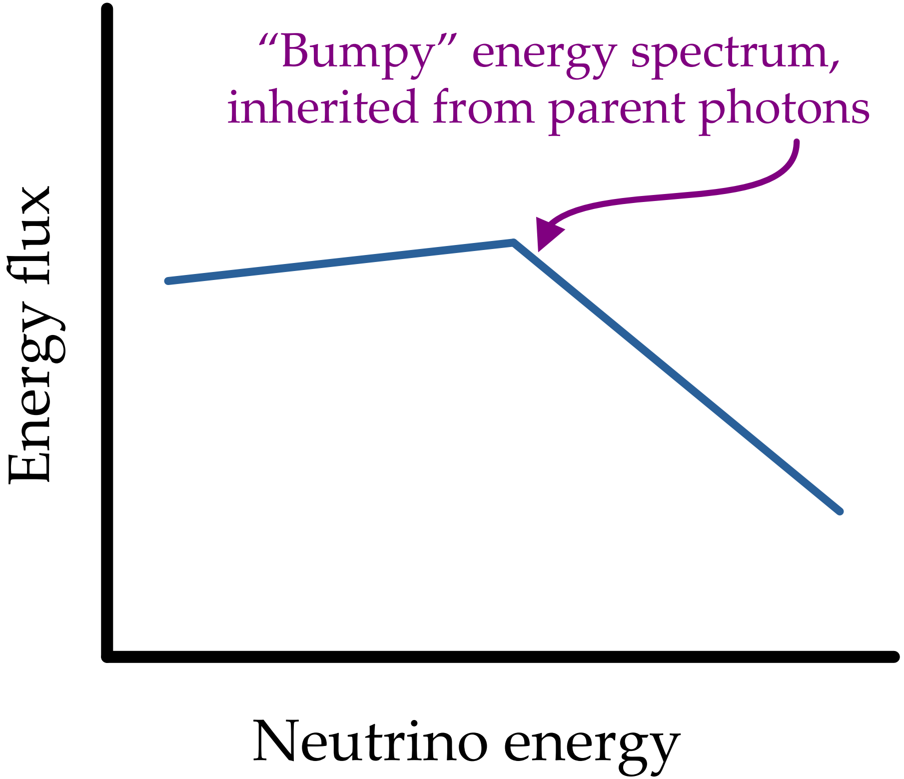
Spectrum looks harder for through-going ν_μ



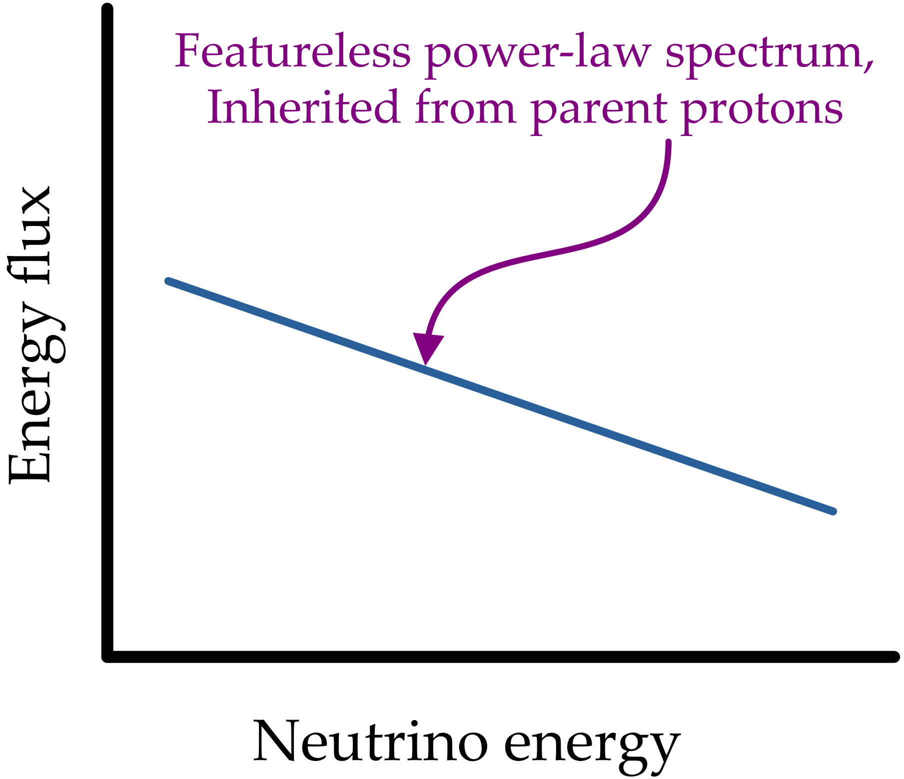
$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\rm astro} \left(\frac{E_\nu}{100~{\rm TeV}} \right)^{-\gamma_{\rm astro}}$$

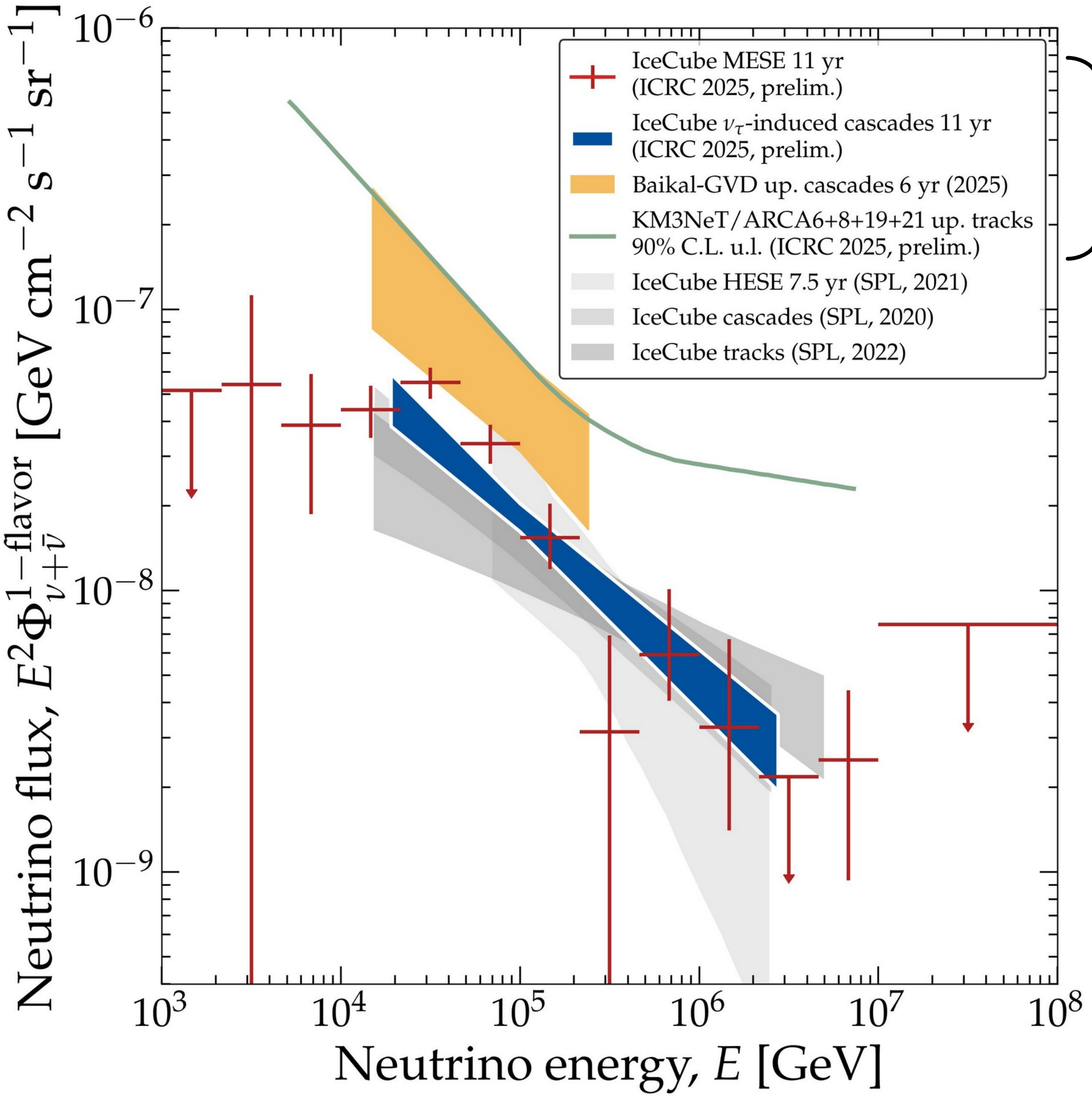
$$\times 10^{-18}~{\rm GeV}^{-1}~{\rm cm}^{-2}~{\rm s}^{-1}~{\rm sr}^{-1}$$

Neutrinos from *pγ* interactions

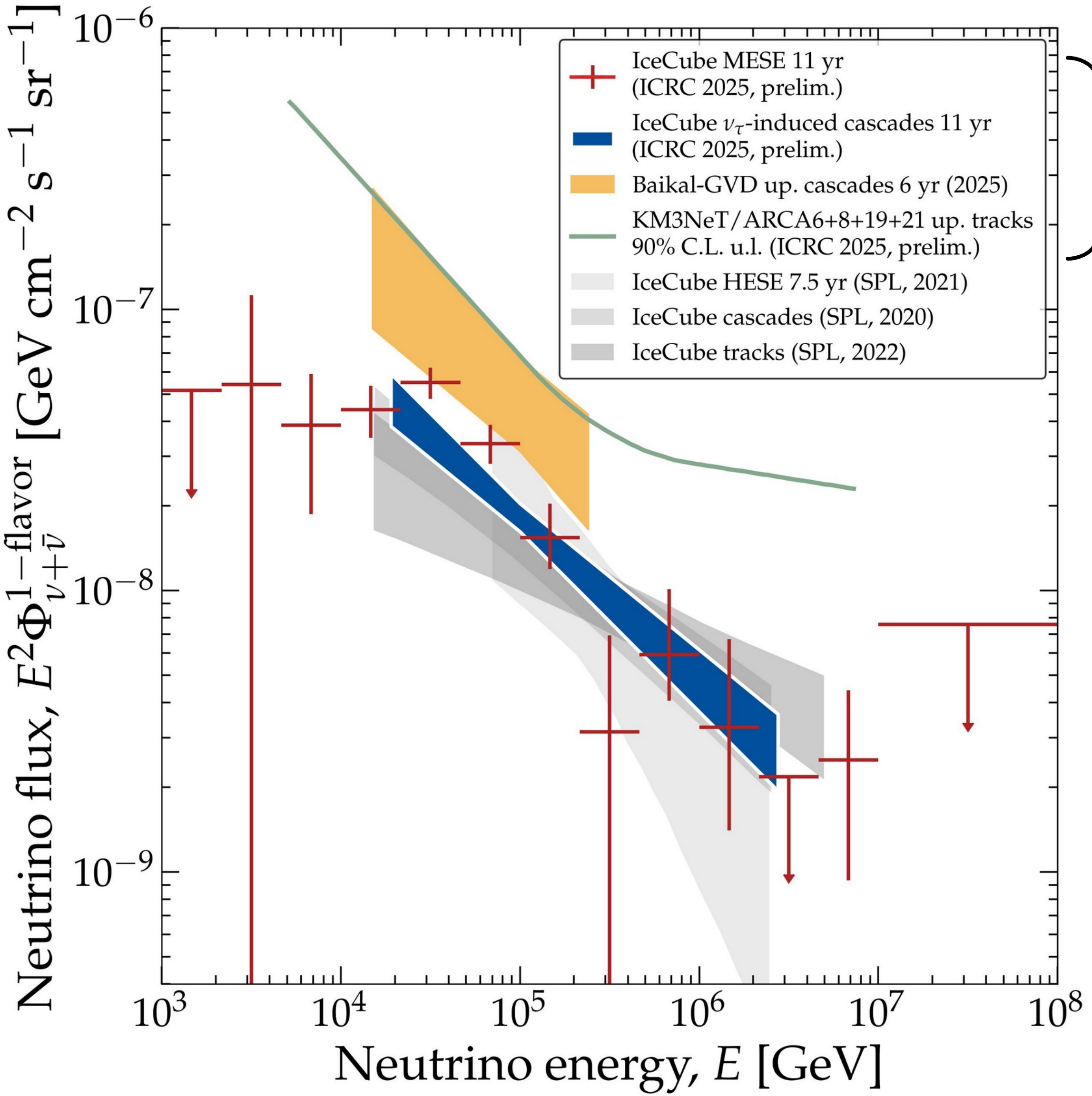


Neutrinos from *pp* interactions



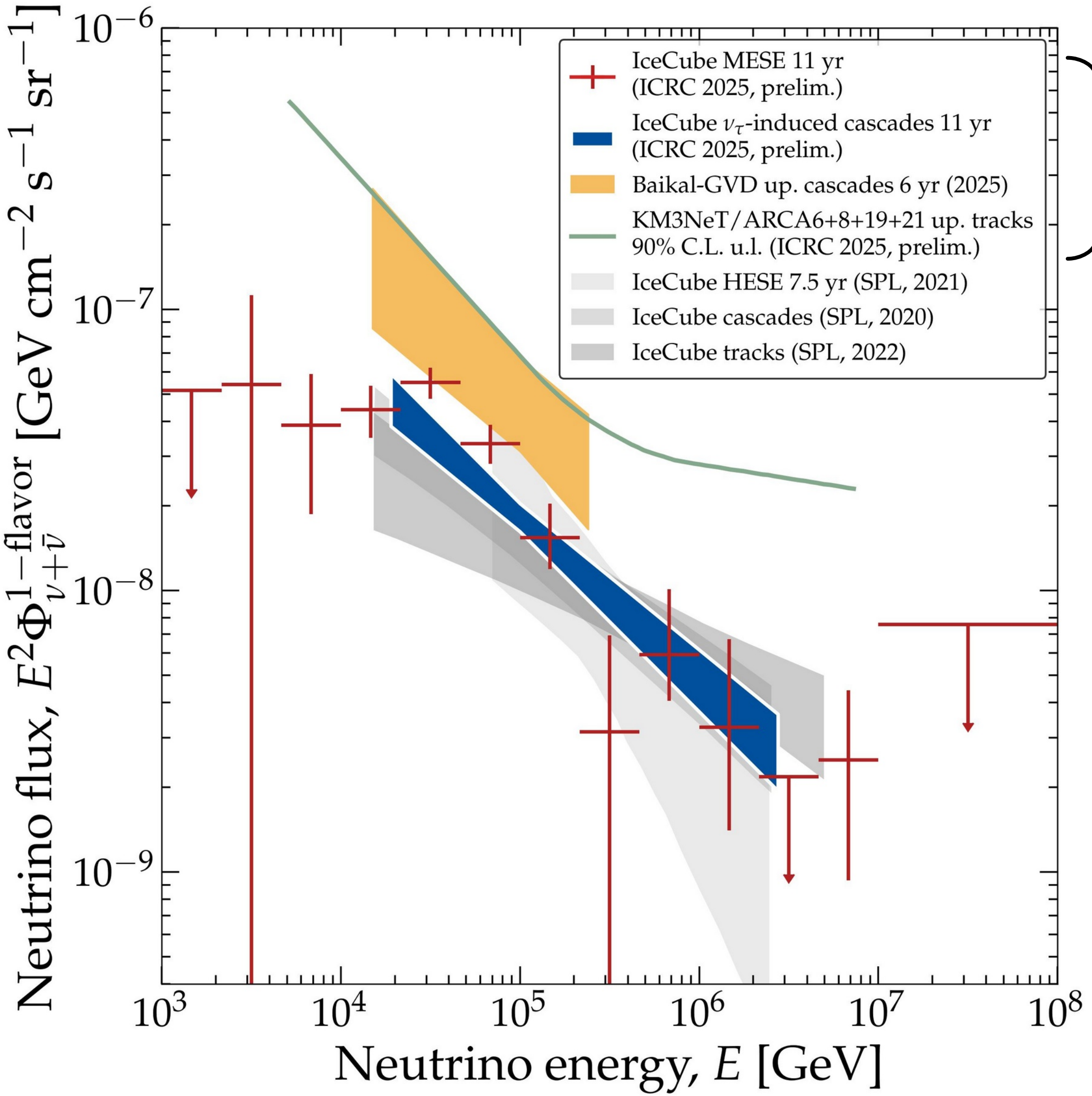

IceCube MESE 11 yr
(ICRC 2025, prelim.)
IceCube ν_τ-induced cascades 11 yr
(ICRC 2025, prelim.)
Baikal-GVD up. cascades 6 yr (2025)
KM3NeT/ARCA6+8+19+21 up. tracks
90% C.L. u.l. (ICRC 2025, prelim.)
IceCube HESE 7.5 yr (SPL, 2021)
IceCube cascades (SPL, 2020)
IceCube tracks (SPL, 2022)
Neutrino flux, $E^2\Phi_{\nu+\bar{\nu}}^{1-\text{flavor}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^3
10^4
10^5
10^6
10^7
10^8
Neutrino energy, E [GeV]

New in 2025



New in 2025

The three existing large neutrino telescopes are independently probing the diffuse flux of TeV–PeV cosmic ν!



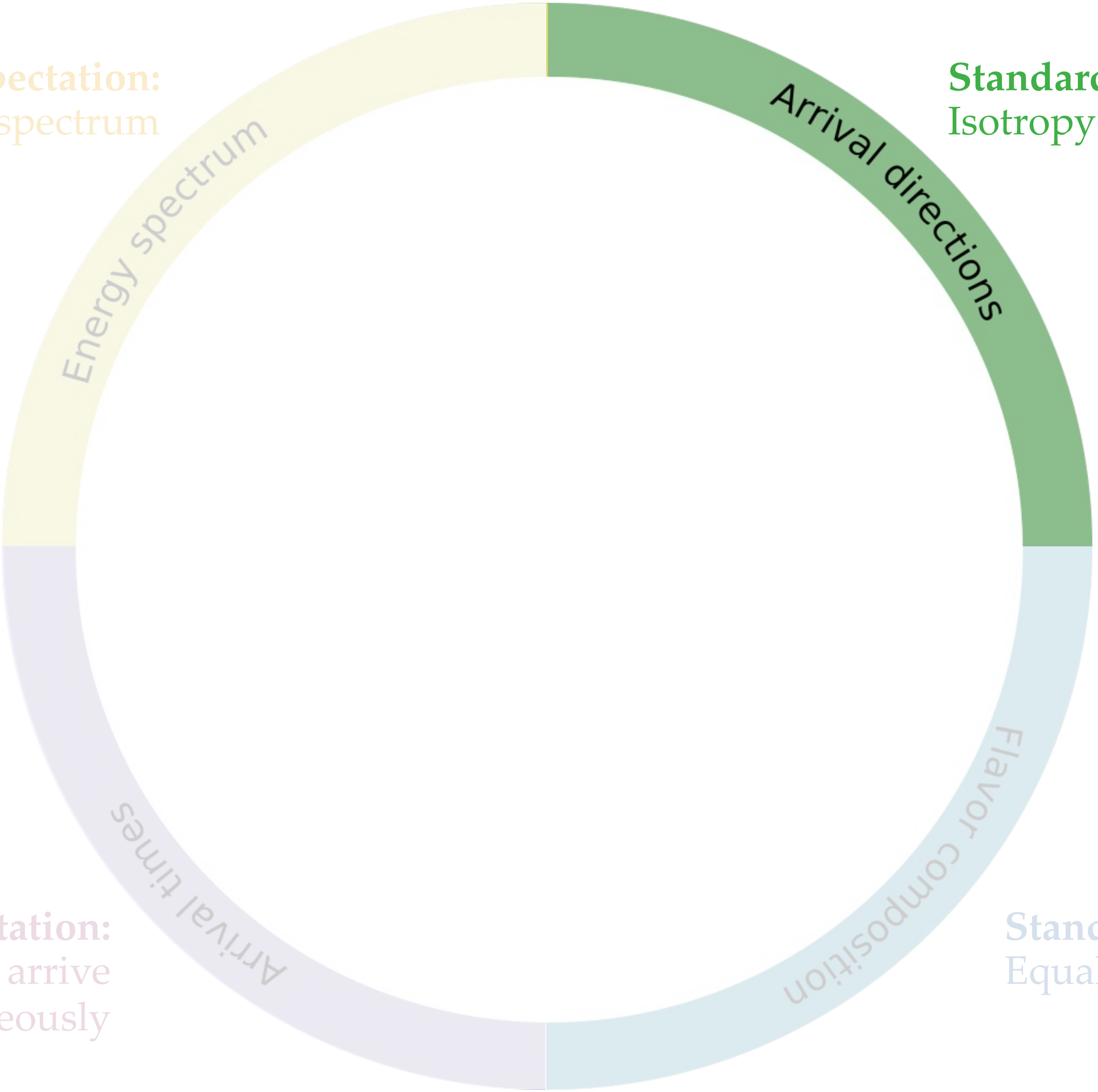
New in 2025

And IceCube is finding structure in the energy spectrum

The three existing large neutrino telescopes are independently probing the diffuse flux of TeV–PeV cosmic υ!

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

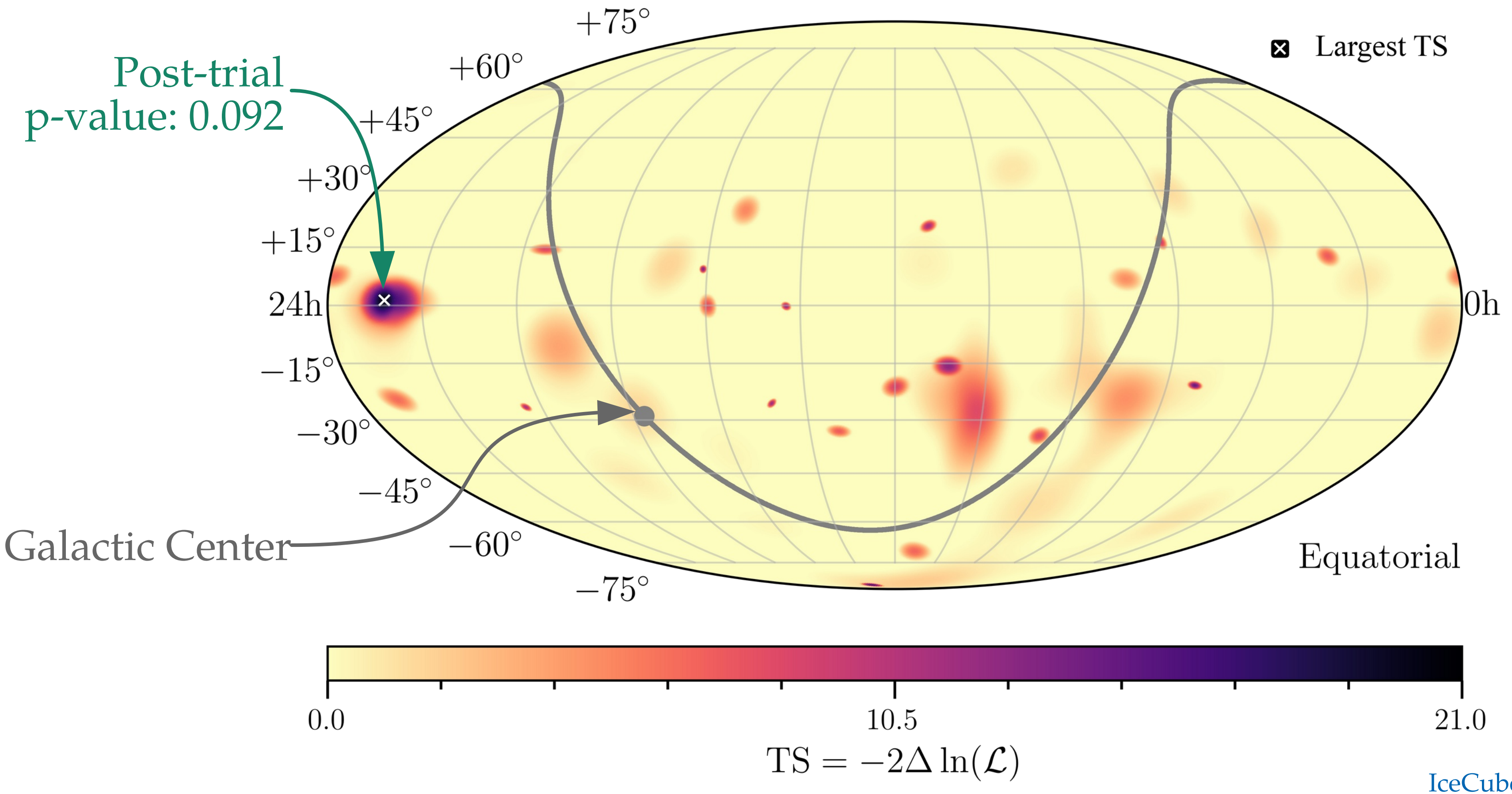


Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

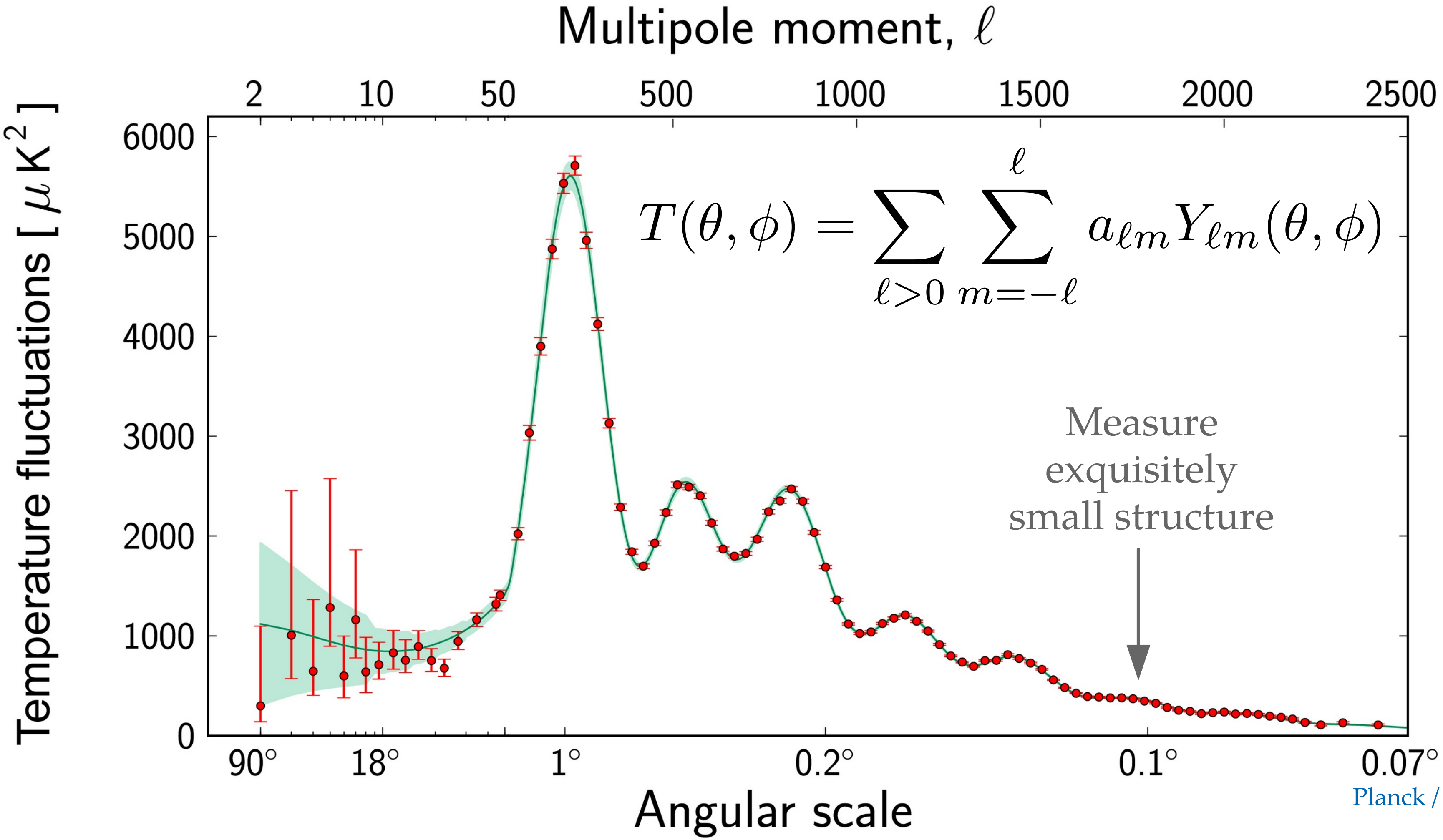
Arrival directions (7.5 yr)

No significant excess in the neutrino sky map:



IceCube, *PRD* 2021

CMB power spectrum (of temperature fluctuations)



Planck / ESA

Flavor dipoles and quadrupoles in the sky?

Flavor-dependent multipole expansion

Isotropic flux

$$\Phi_{\nu_\alpha}(E_\nu, \theta_z, \phi) = \Phi_0 \left(\frac{E_\nu}{100~\mathrm{TeV}} \right)^{-\gamma} \times \frac{1}{6} \left[1 + \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} q_{\ell,m}^{\alpha} Y_\ell^m(\theta_z, \phi) \right]$$

Telalovic, **MB**, *JCAP* 2025

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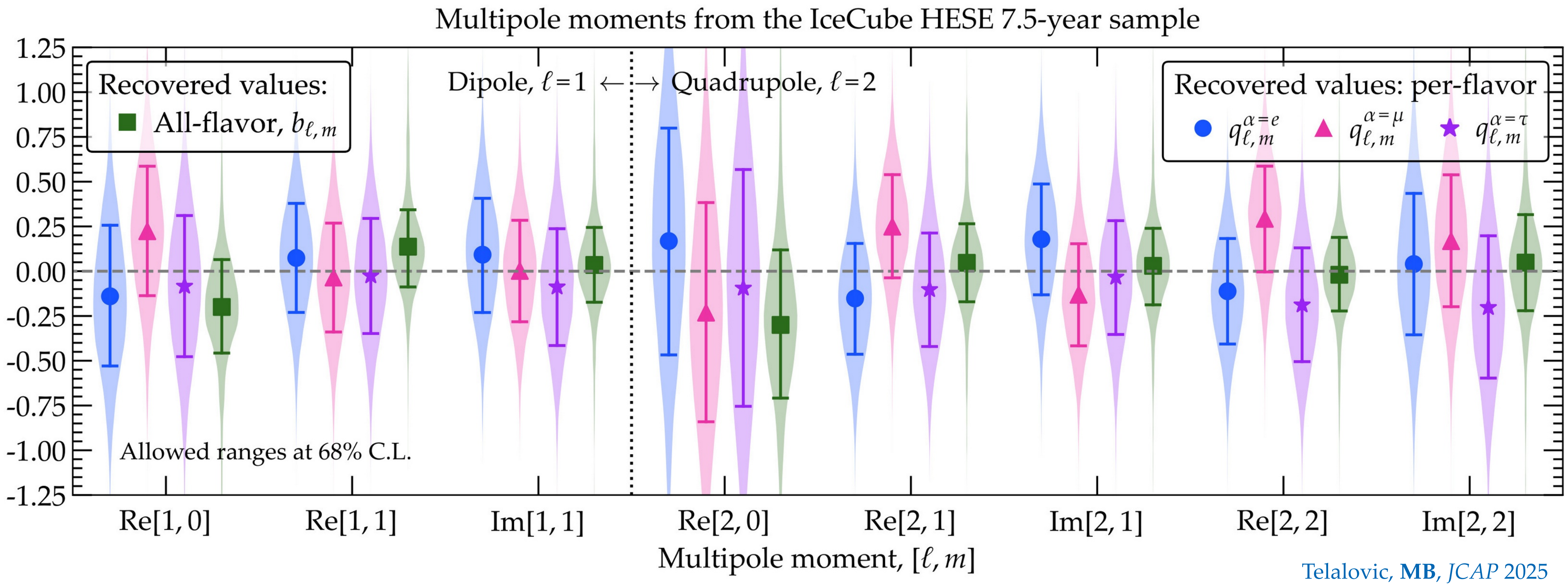

Telalovic, **MB**, *JCAP* 2025

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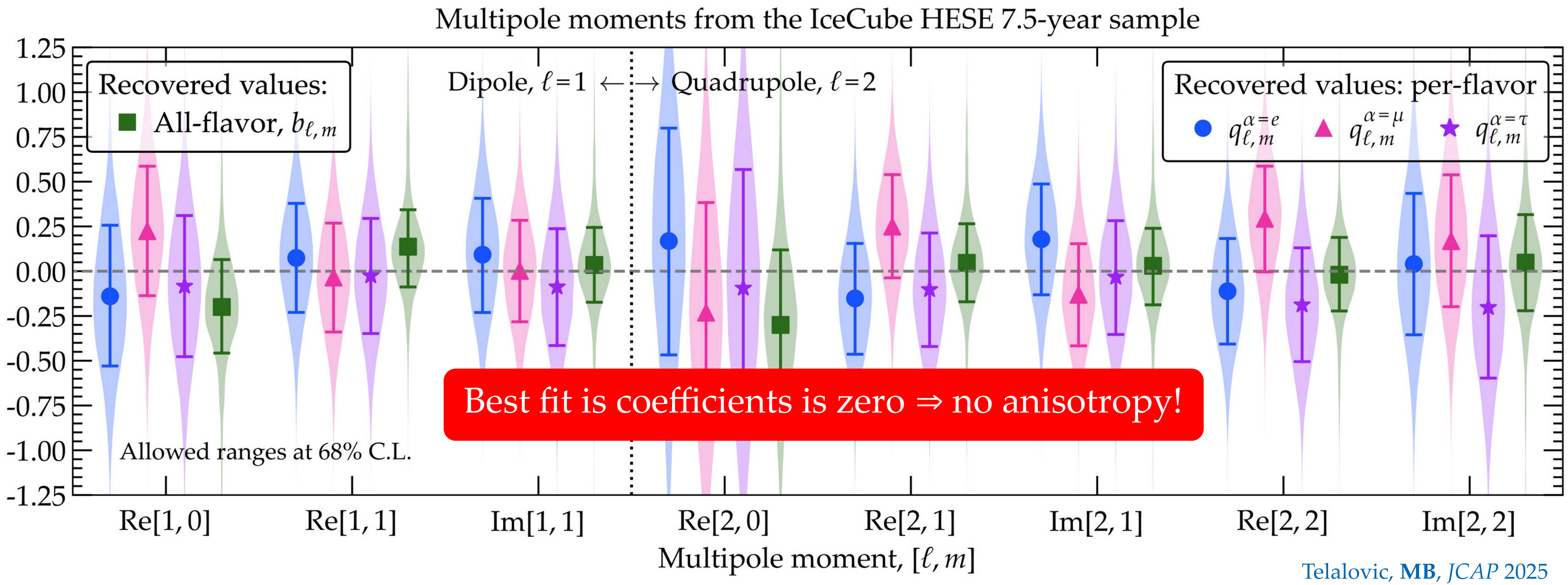
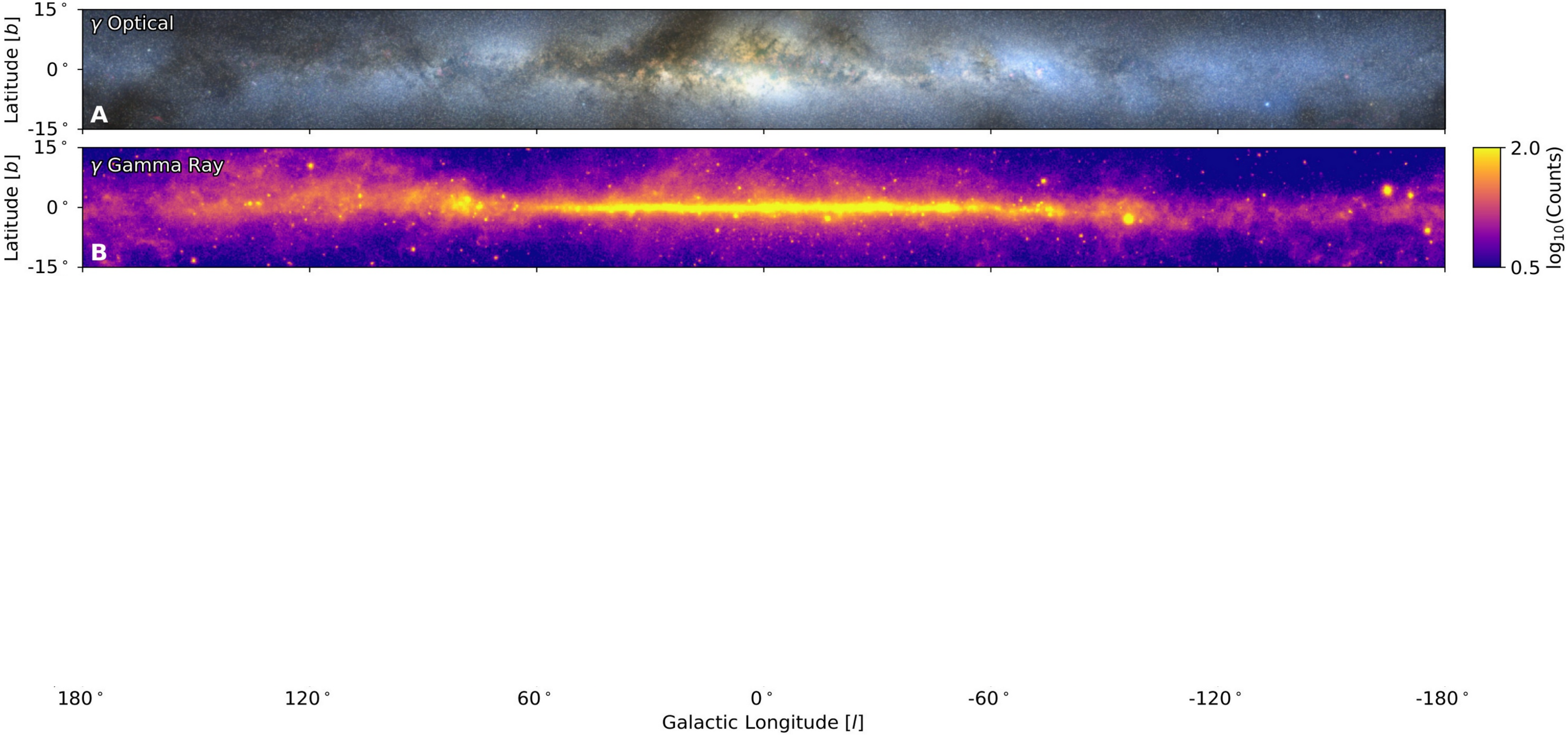


Telalovic, **MB**, *JCAP* 2025

Neutrinos from the Galaxy



IceCube Collab., *Science* 2023

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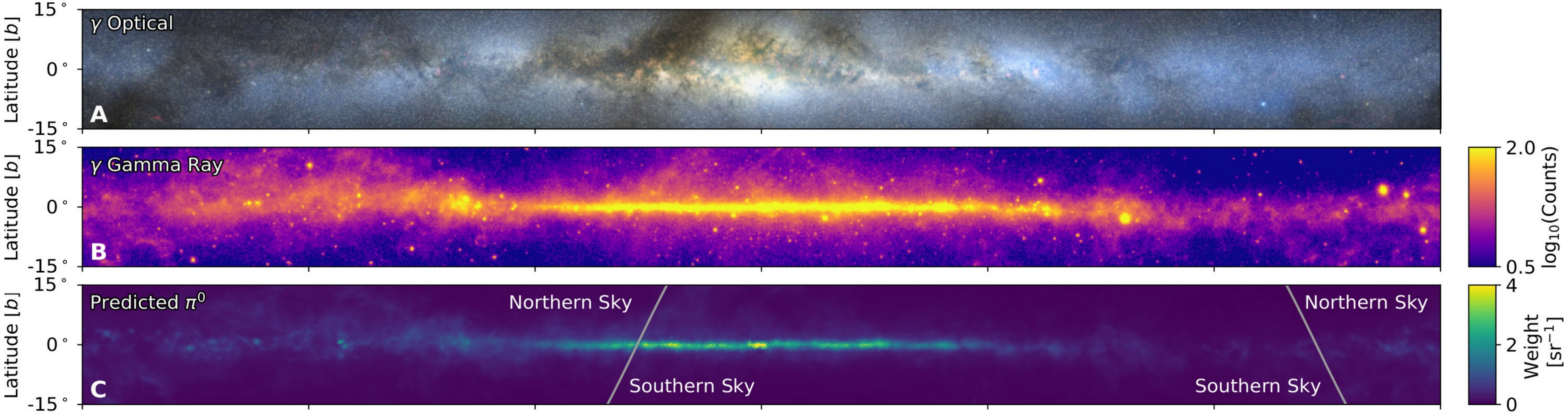


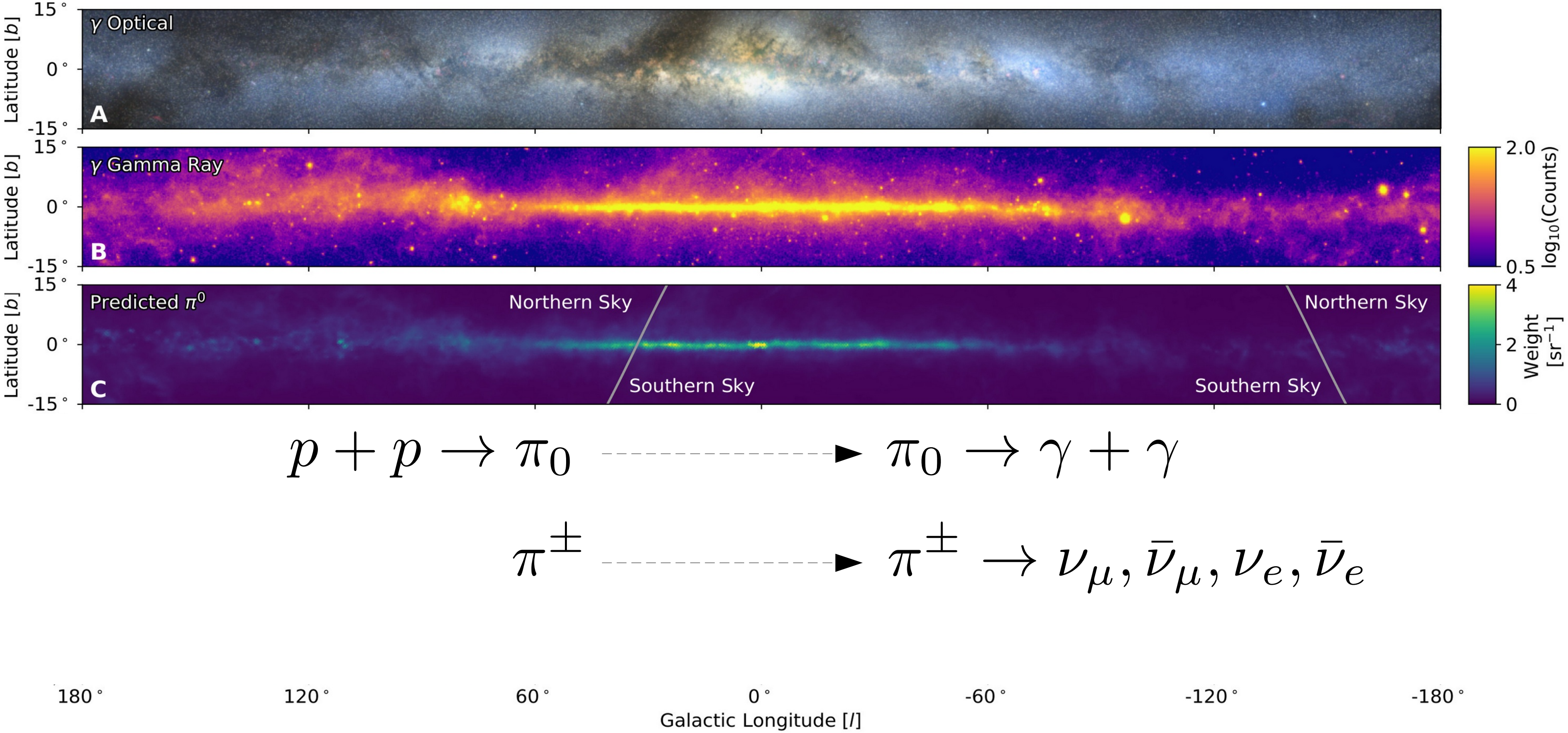
$$p + p \rightarrow \pi_0 \dashrightarrow \pi_0 \rightarrow \underbrace{\gamma + \gamma}$$

Cosmic rays

Interstellar medium (aligned with GP)

Gamma rays from the GP

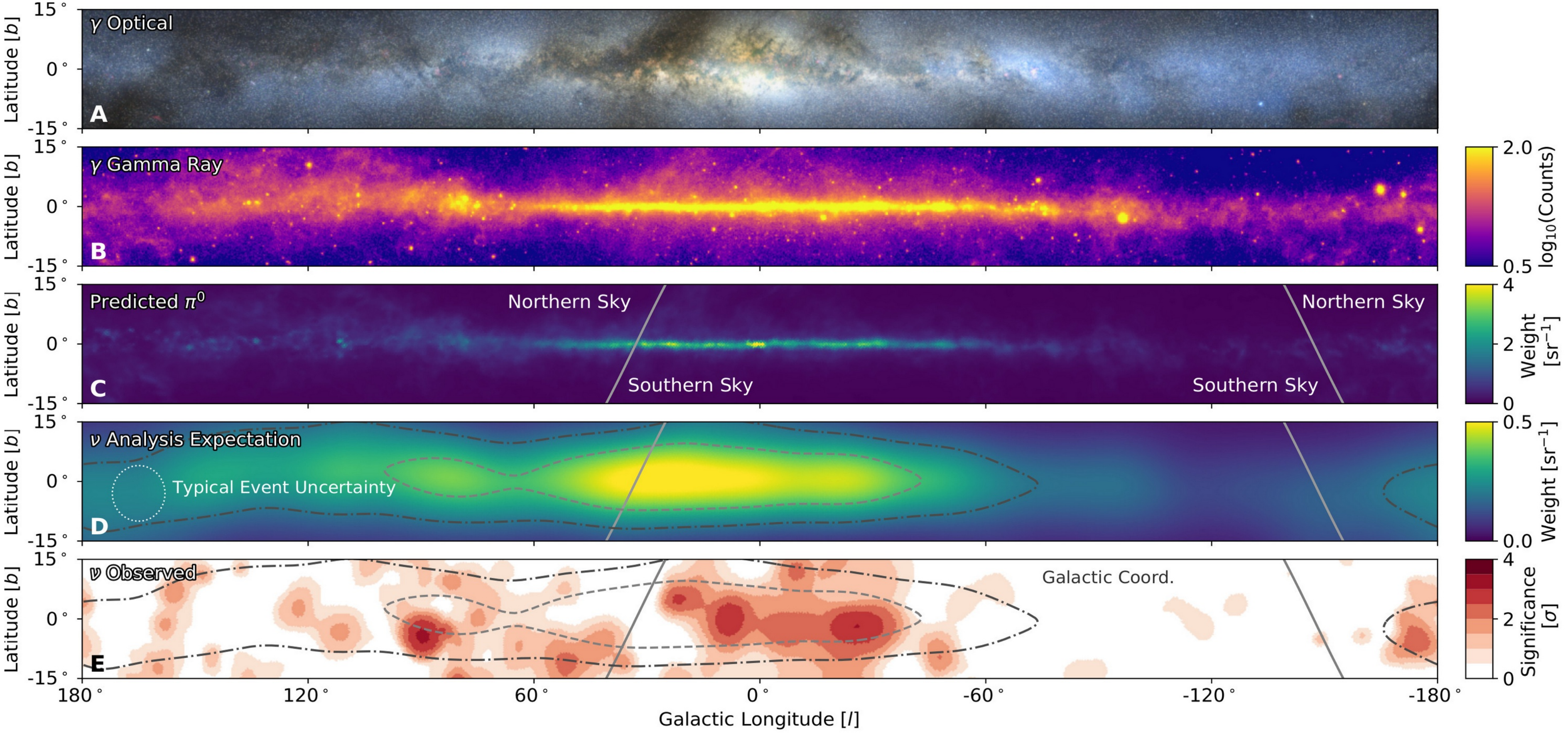
Neutrinos from the Galaxy



$$p + p \rightarrow \pi_0 \dashrightarrow \pi_0 \rightarrow \gamma + \gamma$$

$$\pi^{\pm} \dashrightarrow \pi^{\pm} \rightarrow \nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$$

Neutrinos from the Galaxy



IceCube Collab., *Science* 2023

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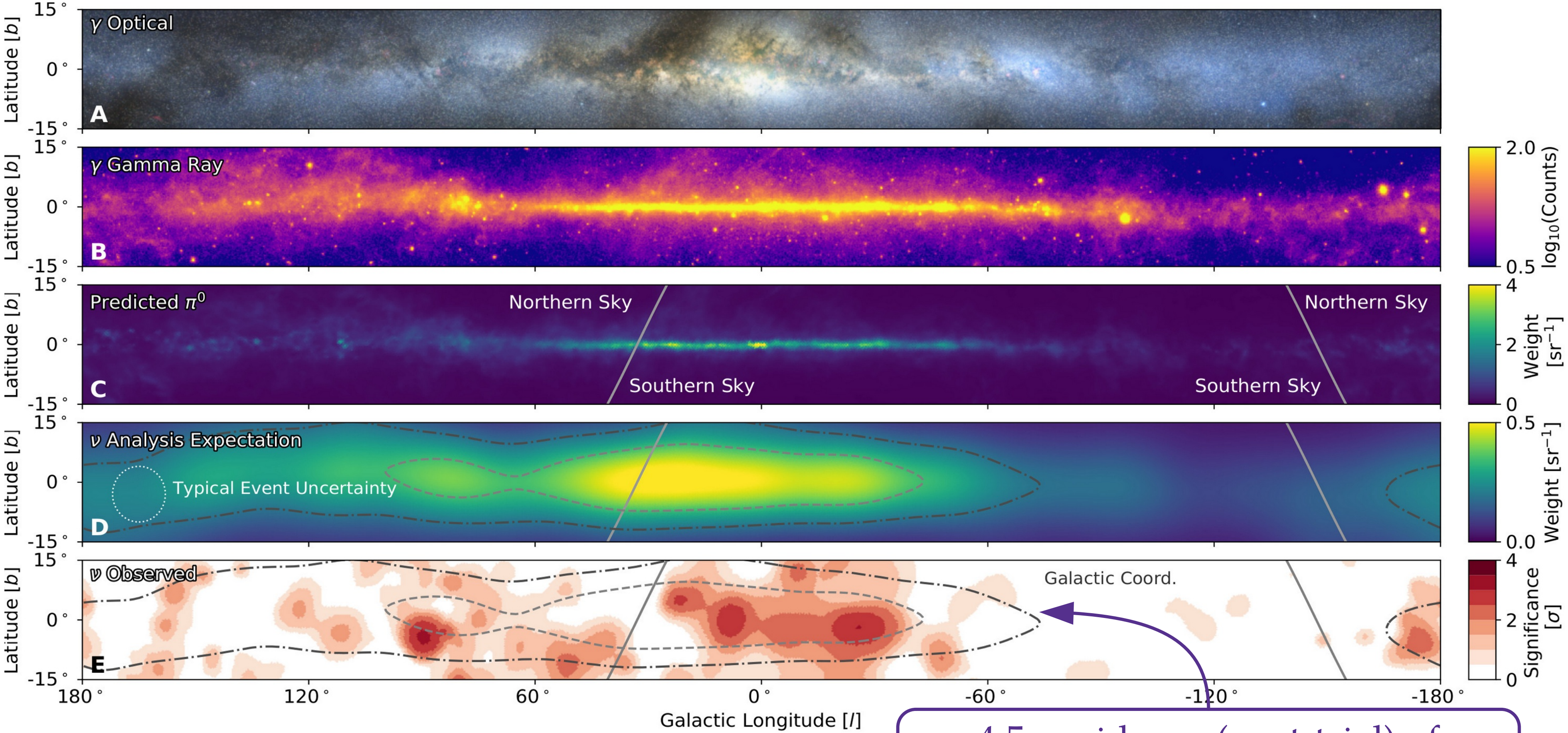
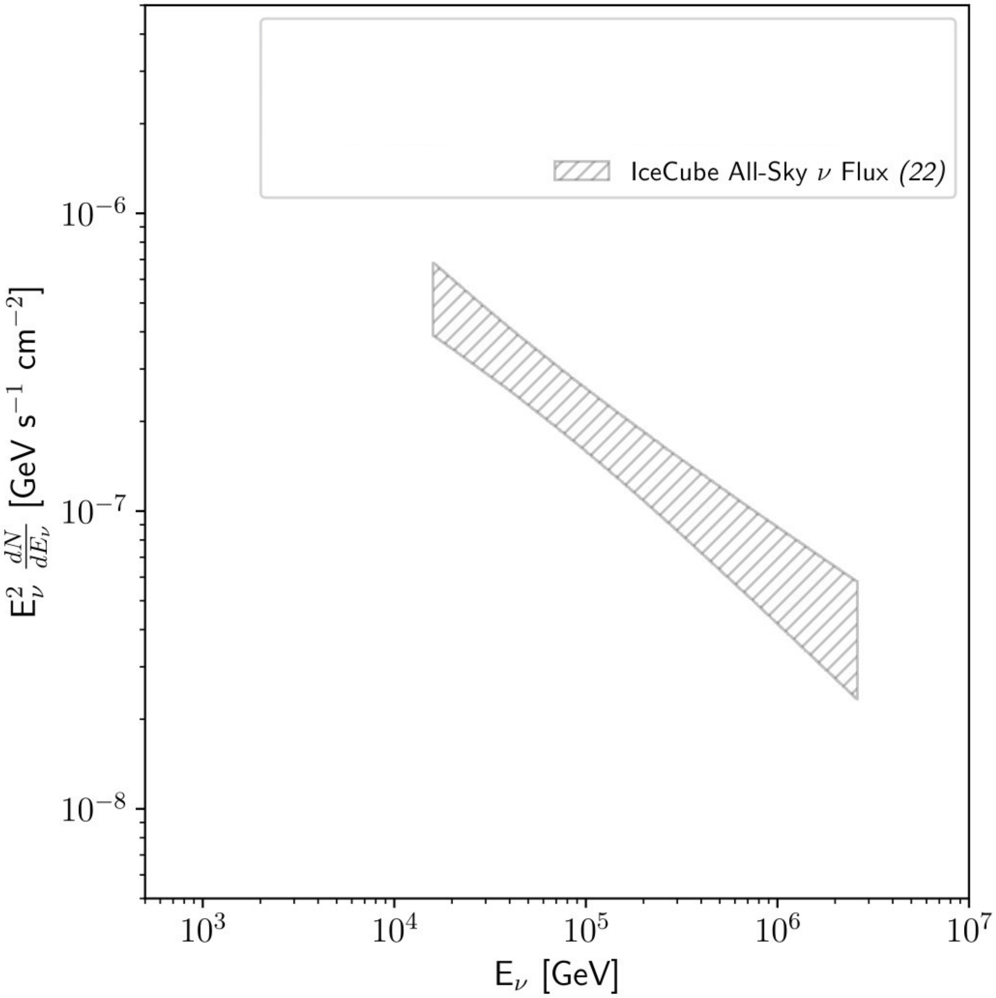


4.5σ evidence (post-trial) of diffuse flux of > TeV ν from the GP

IceCube Collab., *Science* 2023

Neutrinos from the Galaxy



IceCube Collab., *Science* 2023

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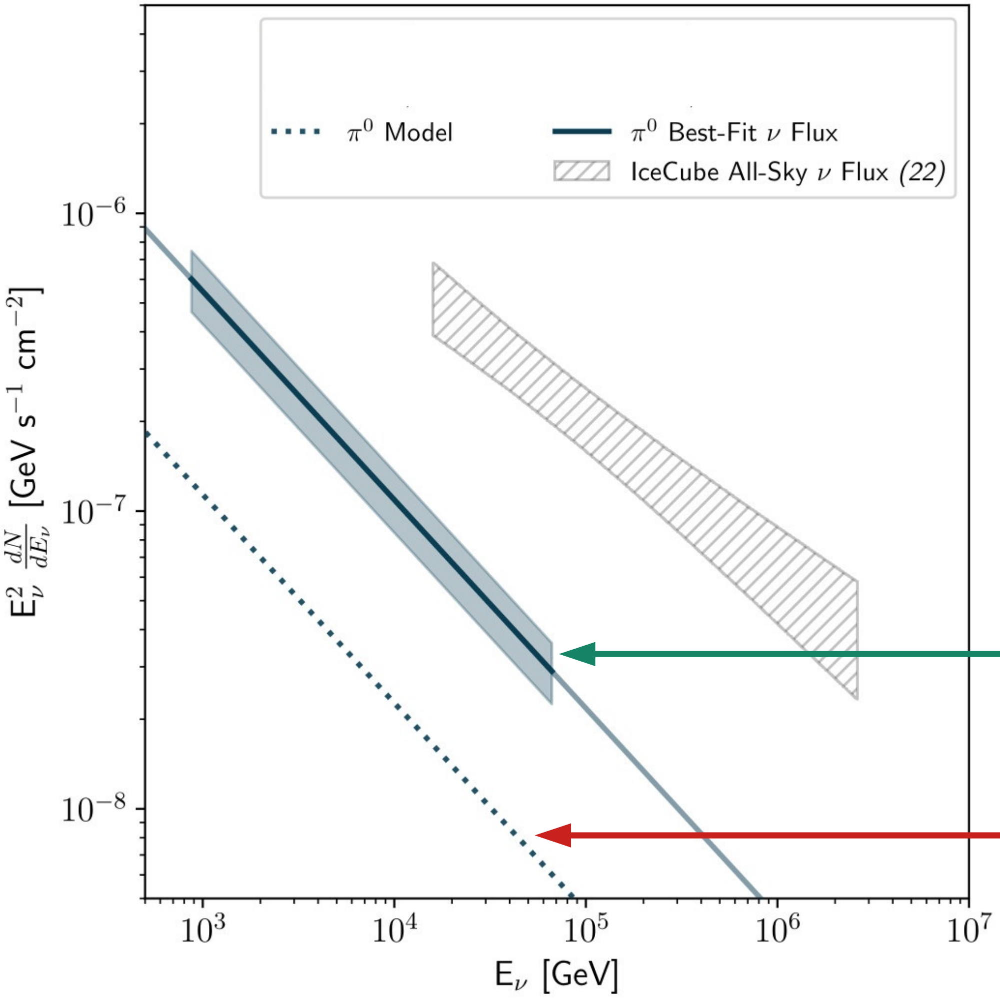


Three models of Galactic diffuse ν:

π^0: MeV–GeV π^0 template inferred from gamma rays extrapolated to TeV

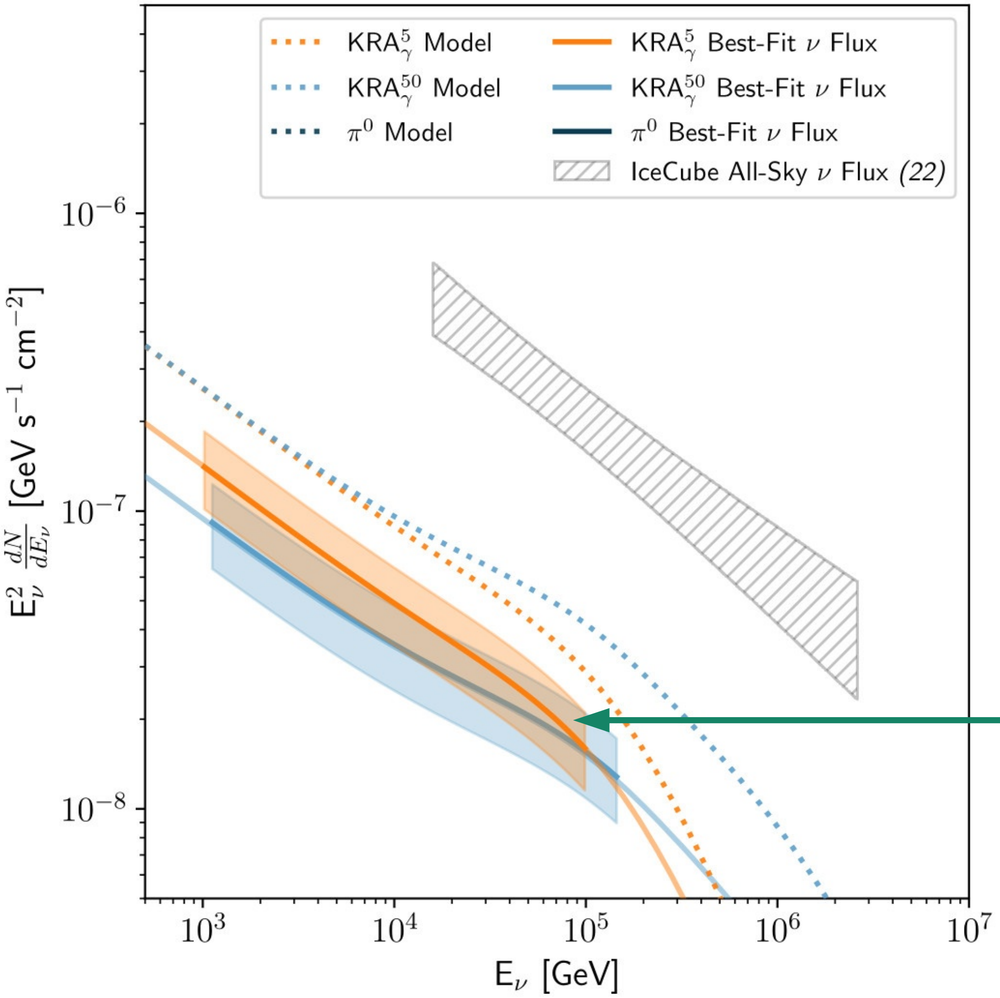
Observed (×5 model)

Consistent with 100-TeV observations by Tibet Air Shower Array

Model

IceCube Collab., *Science* 2023

Neutrinos from the Galaxy



Three models of Galactic diffuse ν:

π^0: MeV–GeV π^0 template inferred from gamma rays extrapolated to TeV

KRA$_\gamma^5$: Spectrum varies spatially, harder ν spectrum, cut-off at 5 PeV in CR energy

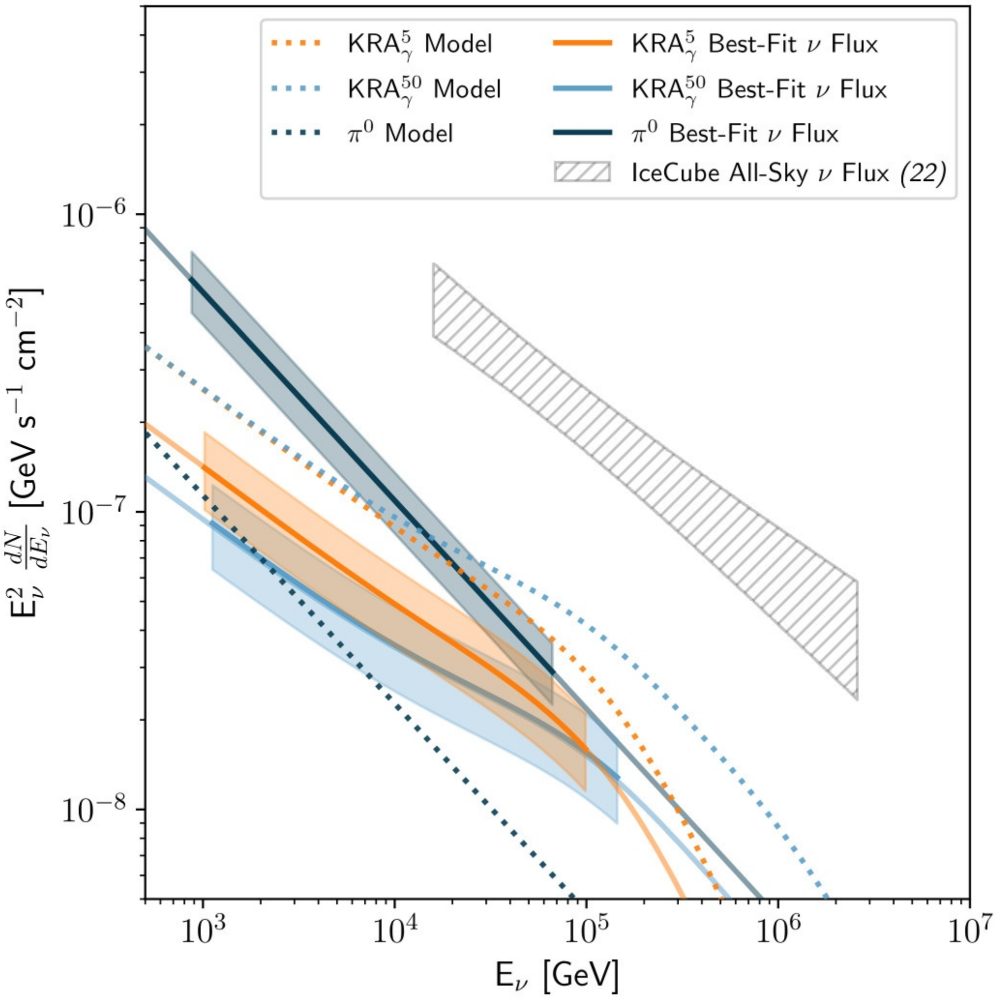
KRA$_\gamma^{50}$: Cut-off at 50 PeV in CR energy

Observed (×0.5 model)

Cut-off energy could be different from the 5 and 50 PeV tested

IceCube Collab., *Science* 2023

Neutrinos from the Galaxy



Three models of Galactic diffuse ν:

π^0: MeV–GeV π^0 template inferred from gamma rays extrapolated to TeV

KRA^5_γ: Spectrum varies spatially, harder ν spectrum, cut-off at 5 PeV in CR energy

KRA^{50}_γ: Cut-off at 50 PeV in CR energy

None of the models matched data

(caveat: there are relatively simple models)

No Galactic ν source identified

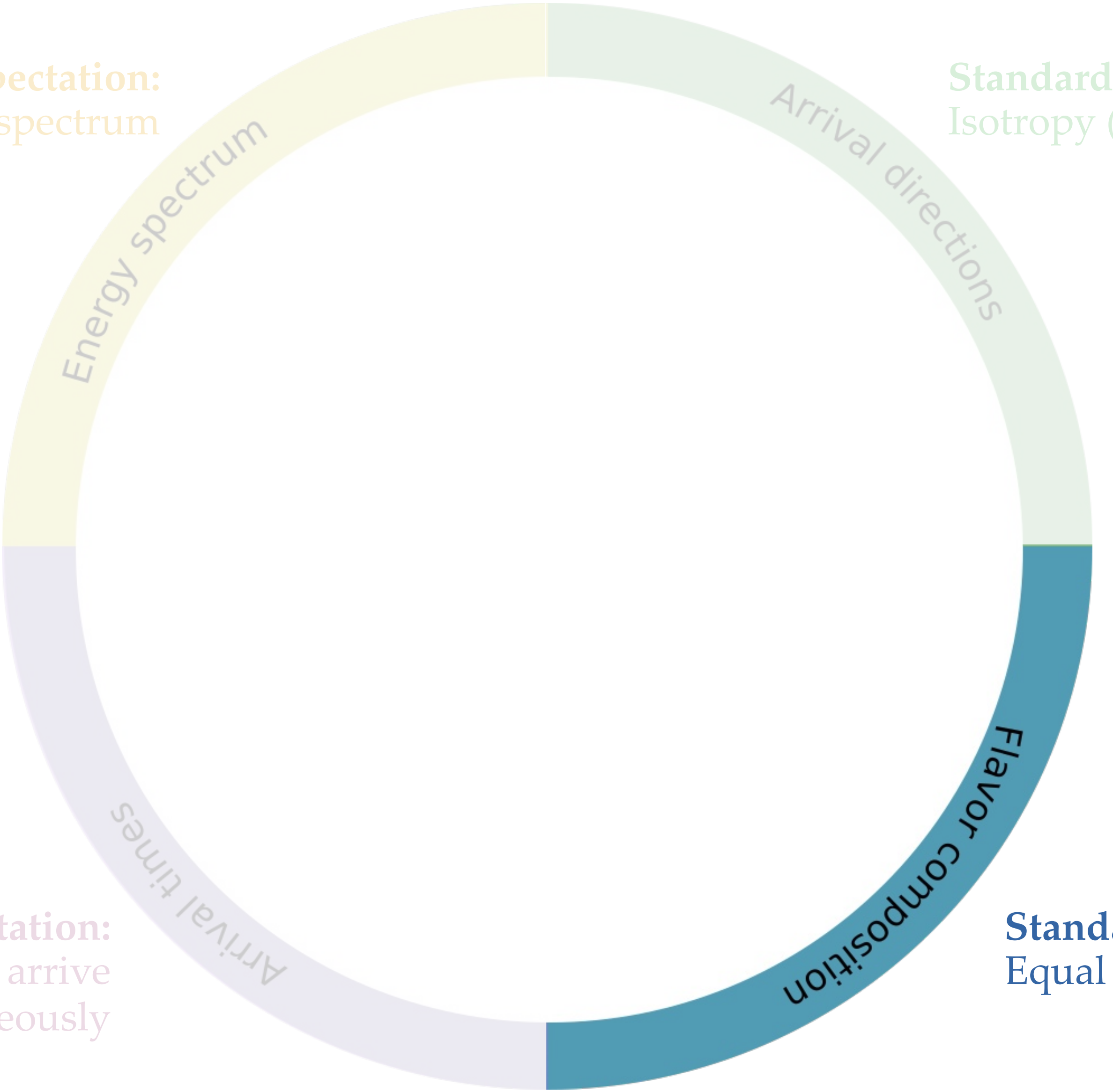
(likely diffuse + source: Fang & Murase, 2307.02905)

GP flux is 6–13% of all-sky at 30 TeV

IceCube Collab., *Science* 2023

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



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Equal number of ν_e, ν_μ, ν_τ

Neutrinos are quintessential quantum particles

There are three types, or *flavors*, of neutrinos:

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ν_e

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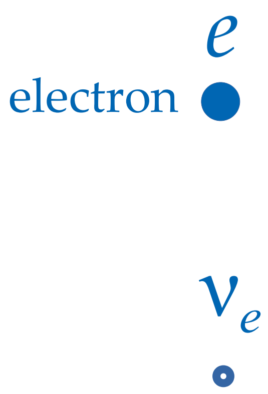

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e

electron

ν_e

electron neutrino

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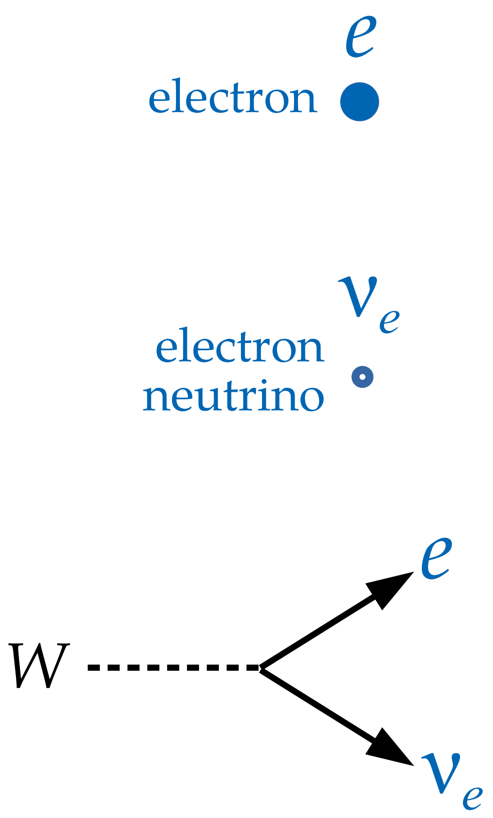

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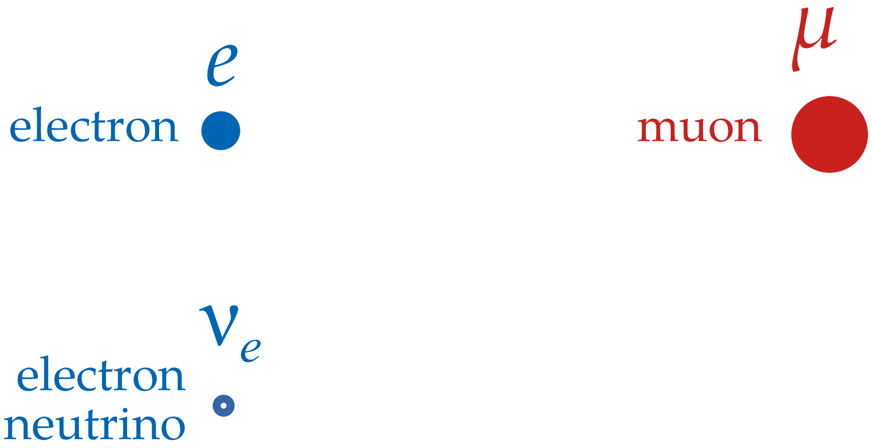

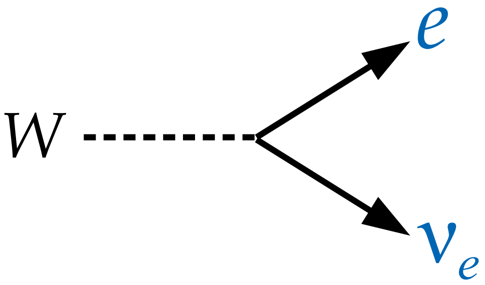

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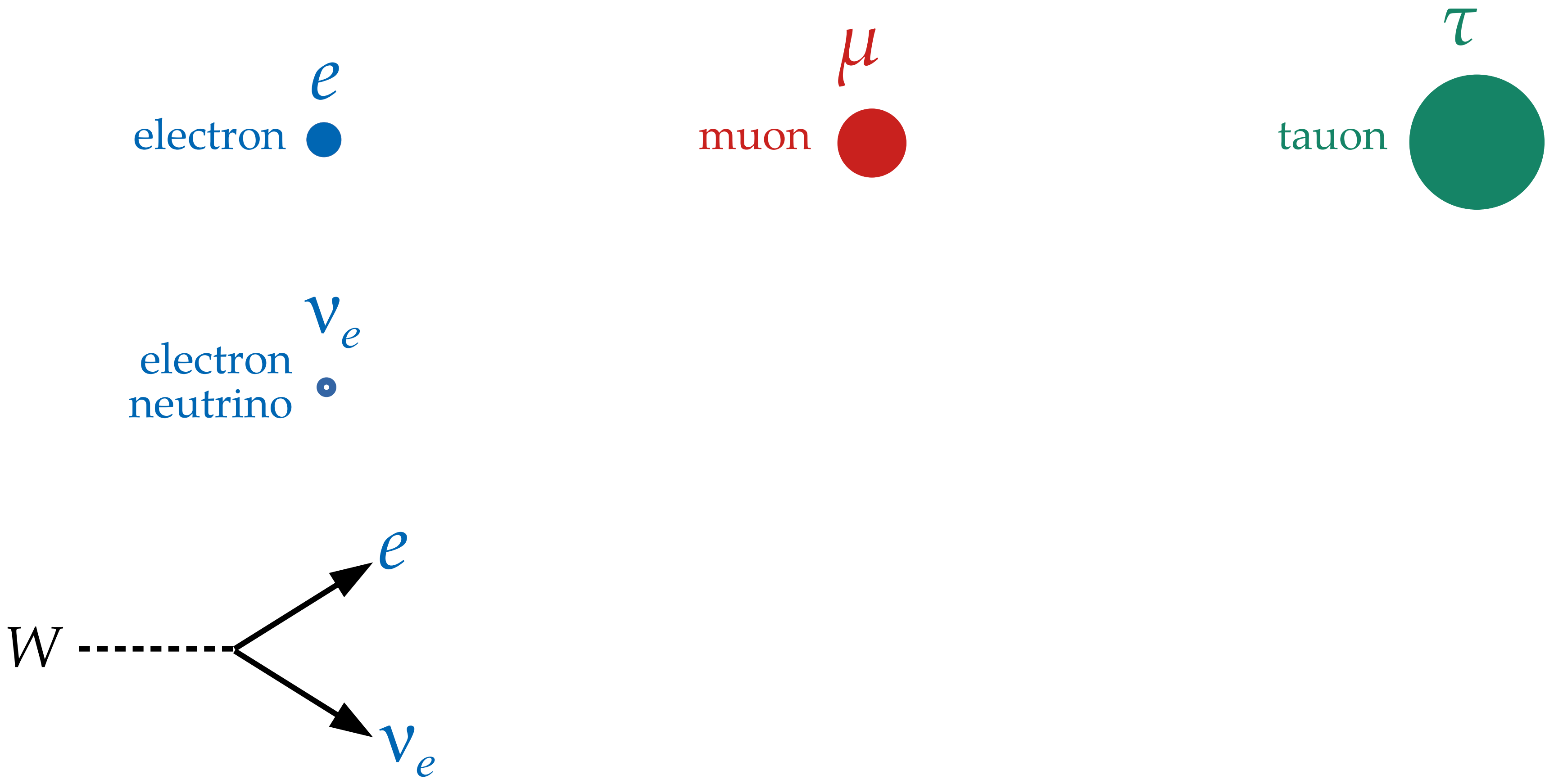

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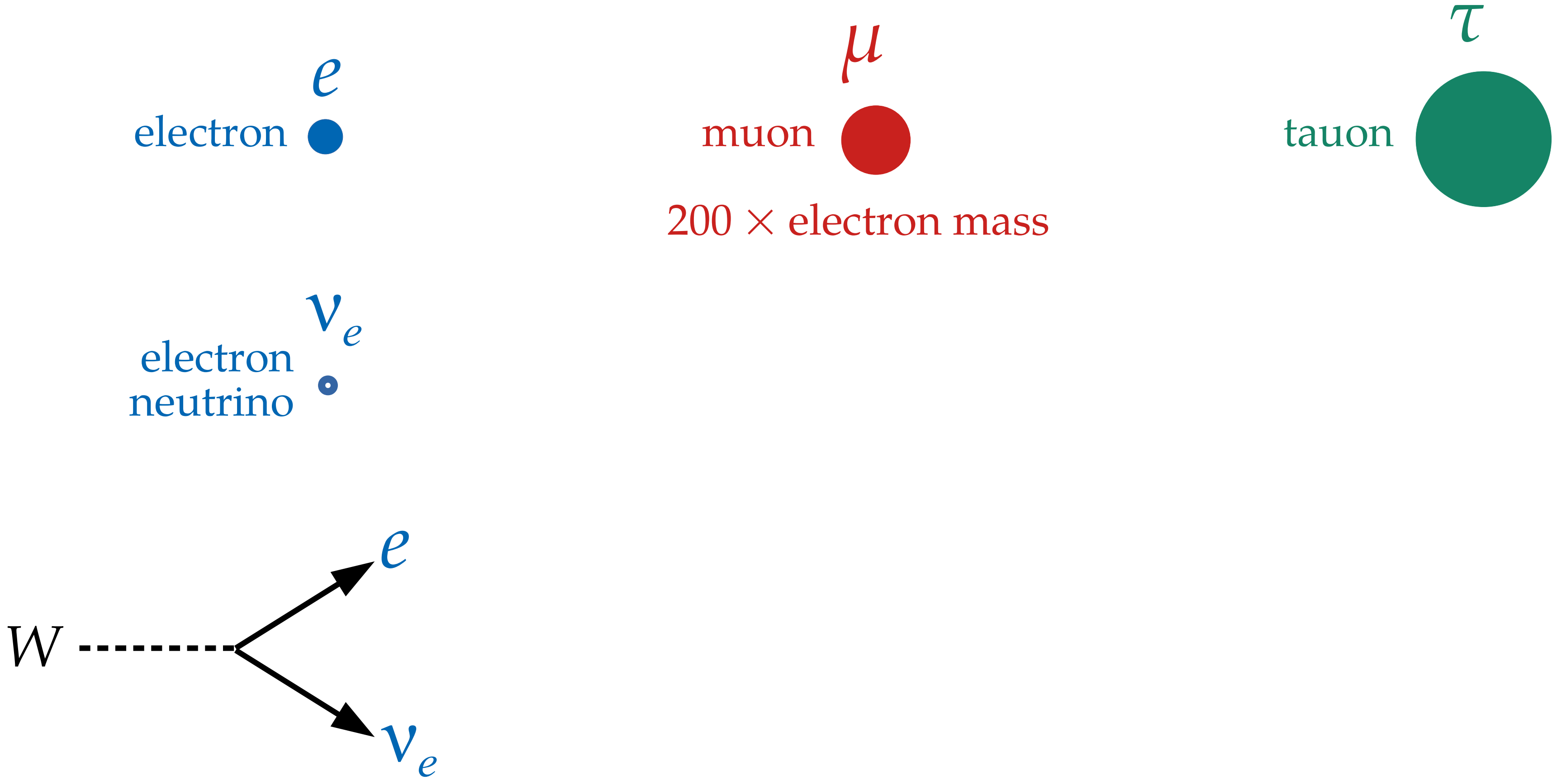

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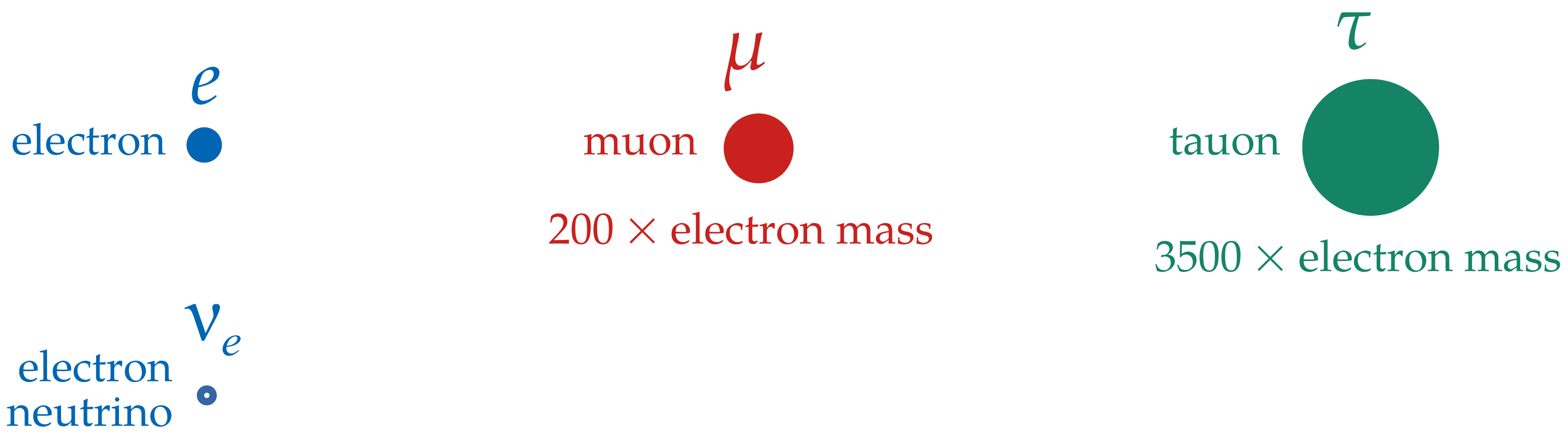

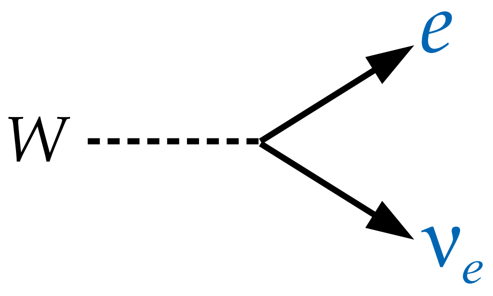

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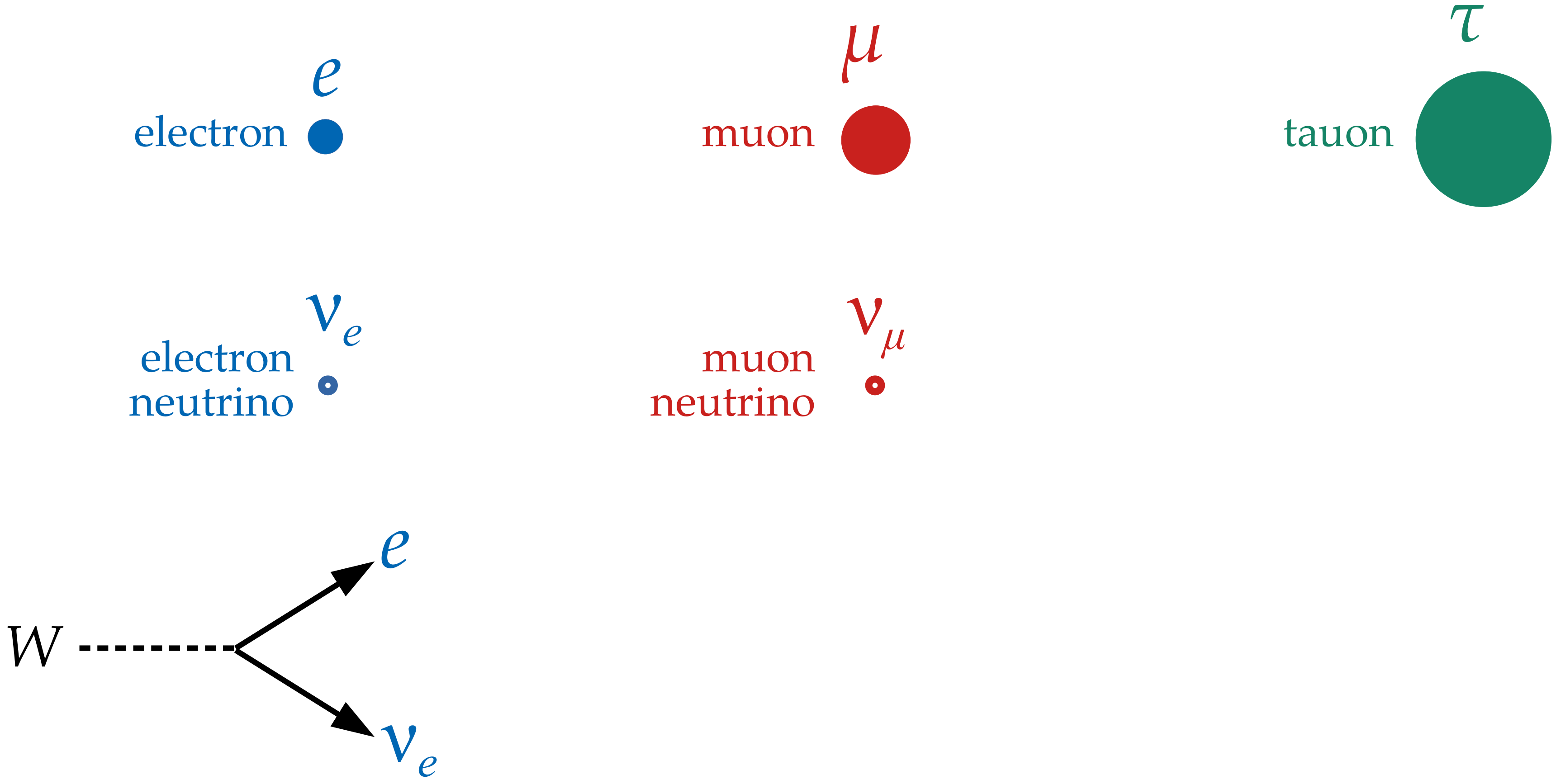

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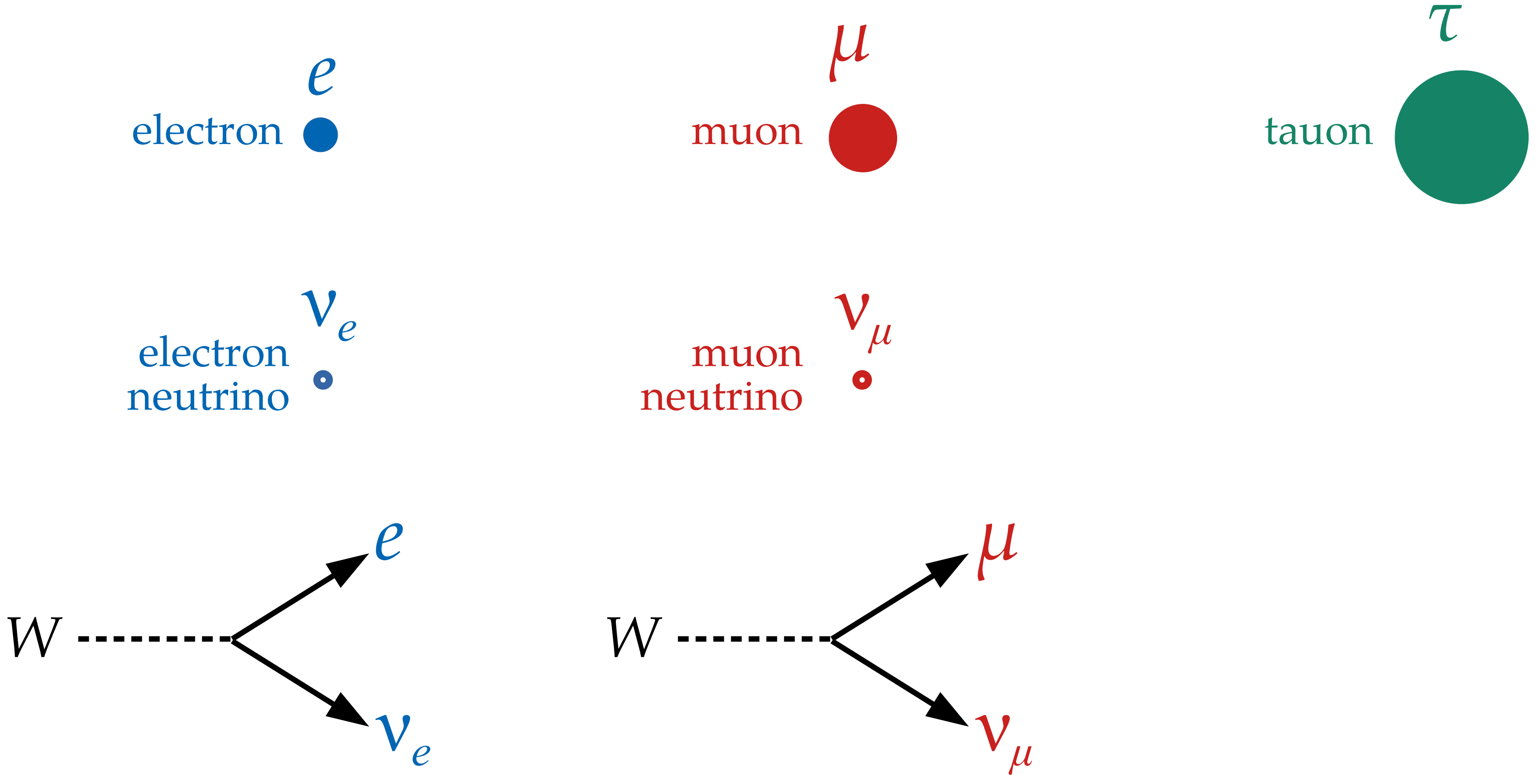

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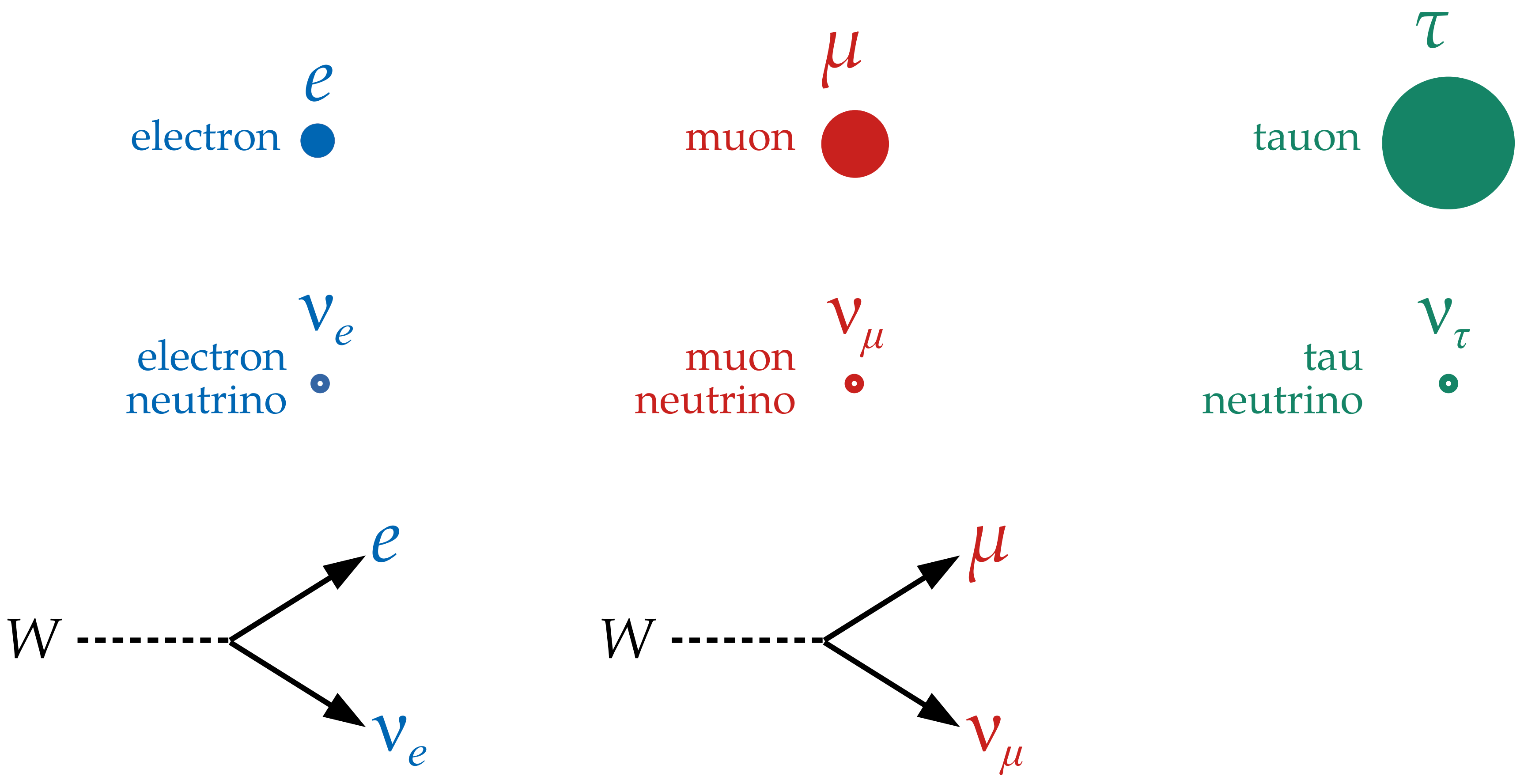

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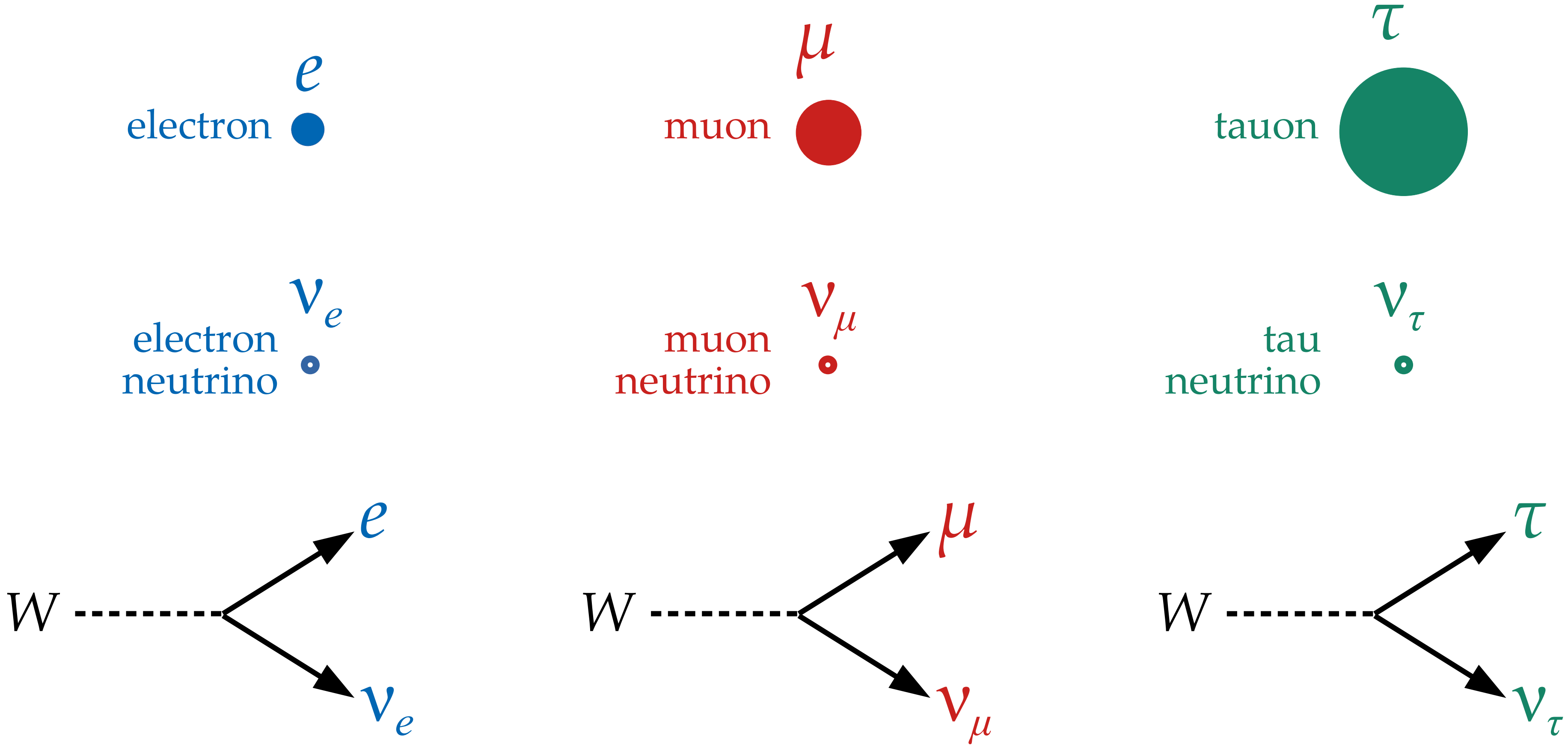

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A neutrino is created
with *one* definite flavor, *e.g.*,

ν_e

Neutrino source

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ν_e

It travels a long
distance to the detector

Neutrino source

Neutrinos are quintessential quantum particles

A neutrino is created
with *one* definite flavor, *e.g.*,

But may be detected with a
different flavor, with some probability

ν_e

It travels a long
distance to the detector

ν_e or ν_μ or ν_τ

Neutrino source

Neutrino detector

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"flavor oscillations"

Neutrino source

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(Nobel Prize 2002, 2015)

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Neutrino source

"flavor oscillations"
(Nobel Prize 2002, 2015)

Neutrino detector

We use quantum mechanics to compute probabilities over *macroscopic* distances!

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

$\odot$

ν_e

"flavor state"

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

$$\nu_e = (\quad \nu_1 + \nu_2 + \nu_3 \quad)$$

"flavor state"

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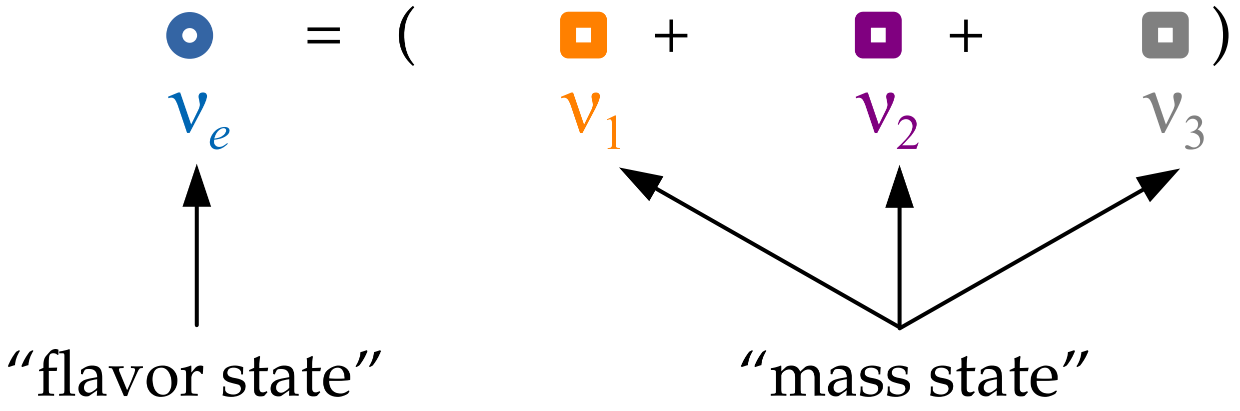

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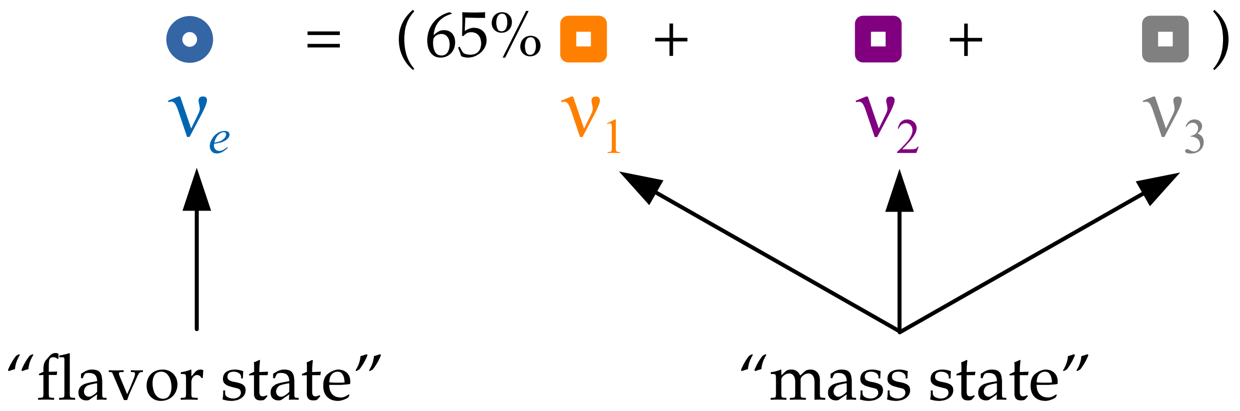

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

$$\underbrace{\nu_e}_{\text{“flavor state”}} = (65\%\ \nu_1 + 18\%\ \nu_2 + \ \ \nu_3)$$

“flavor state” “mass state”

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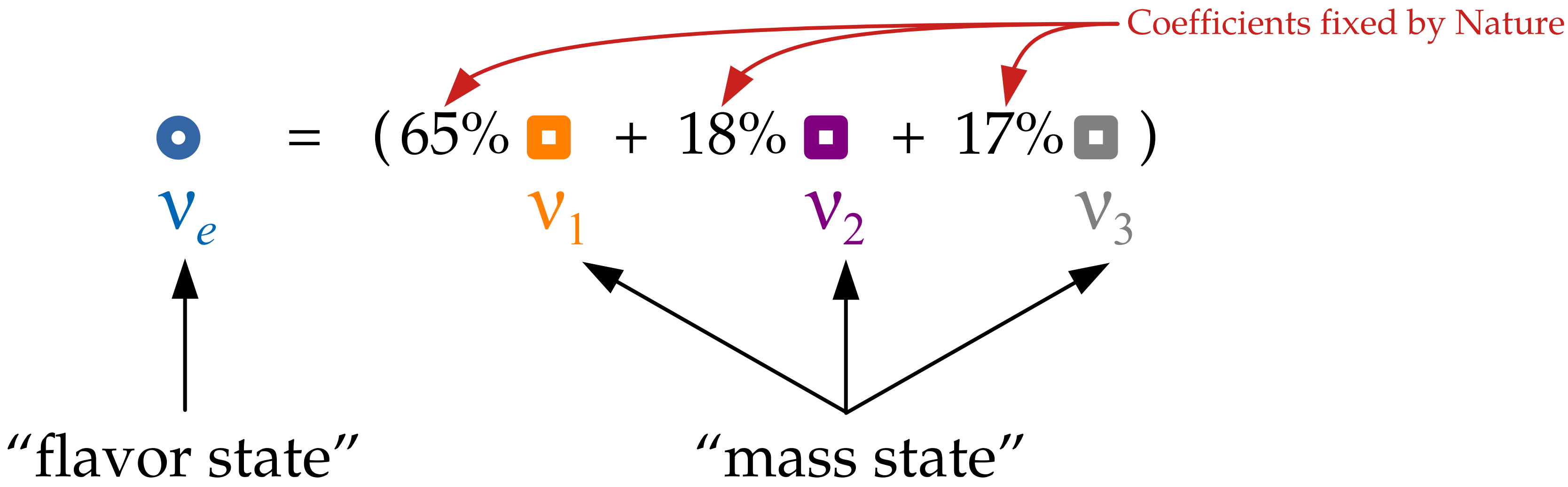

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A neutrino of a given flavor is a quantum superposition:

Coefficients fixed by Nature

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"flavor state"

"mass state"

Defined flavor (e)

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Undefined mass

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Defined flavor (e)
Undefined mass

Defined mass (m_1, m_2, m_3)

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"flavor state"

Defined flavor (e)
Undefined mass

"mass state"

Defined mass (m_1, m_2, m_3)
Undefined flavor

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A neutrino of a given flavor is a quantum superposition:

$$\begin{array}{ccccccc} & & & \nu_1 & & \nu_2 & & \nu_3 \\ \nu_e & = & (& 65\% & + & 18\% & + & 17\% &) \end{array}$$

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

$$\nu_e = (U_{e1}\, \nu_1 + U_{e2}\, \nu_2 + U_{e3}\, \nu_3)$$

Neutrinos are quintessential quantum particles

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$$\begin{array}{cccccc} & & \nu_1 & & \nu_2 & \nu_3 \\ \nu_e & = & (U_{e1} & + & U_{e2} & + \; U_{e3}) \\ \nu_\mu & = & (U_{\mu 1} & + & U_{\mu 2} & + \; U_{\mu 3}) \end{array}$$

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

$$\begin{array}{rcl} & & \qquad\quad \nu_1 \qquad\qquad\quad \nu_2 \qquad\qquad\quad \nu_3 \\ \nu_e \odot & = & (U_{e1} \boxdot + U_{e2} \boxdot + U_{e3} \boxdot) \\ \nu_\mu \odot & = & (U_{\mu 1} \boxdot + U_{\mu 2} \boxdot + U_{\mu 3} \boxdot) \\ \nu_\tau \odot & = & (U_{\tau 1} \boxdot + U_{\tau 2} \boxdot + U_{\tau 3} \boxdot) \end{array}$$

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A neutrino of a given flavor is a quantum superposition:

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[Or, you can write: $\nu_\alpha = \sum_{j=1}^{3} U^*_{\alpha i} \nu_j$ for $\alpha = e, \mu, \tau$]

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

$$
\begin{array}{ccccccccc}
 & & & \nu_1 & & \nu_2 & & \nu_3 & \\
\nu_e \odot & = & (& U_{e1} \boxdot & + & U_{e2} \boxdot & + & U_{e3} \boxdot &) \\
\nu_\mu \odot & = & (& U_{\mu 1} \boxdot & + & U_{\mu 2} \boxdot & + & U_{\mu 3} \boxdot &) \\
\nu_\tau \odot & = & (& U_{\tau 1} \boxdot & + & U_{\tau 2} \boxdot & + & U_{\tau 3} \boxdot &)
\end{array}
$$

ν_1, ν_2, ν_3 have different masses, so they travel at different speeds

So the coefficients of the superposition change with time!

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

$$\nu_1 \qquad \nu_2 \qquad \nu_3$$

Produced as: $\nu_e \odot \quad = \left(U_{e1} \boxdot + U_{e2} \boxdot + U_{e3} \boxdot \right)$

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

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Produced as: $\nu_e = (U_{e1} + U_{e2} + U_{e3})$

Travel a distance
L to the detector

Neutrinos are quintessential quantum particles

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Travel a distance
L to the detector

Detected as:

Neutrinos are quintessential quantum particles

A neutrino of a given flavor is a quantum superposition:

ν_1 ν_2 ν_3

Produced as: $\nu_e = (U_{e1}\,\nu_1 + U_{e2}\,\nu_2 + U_{e3}\,\nu_3)$

Travel a distance L to the detector

Detected as: $U_{e1}\, e^{-i m_1 L/E}\, \nu_1$

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A neutrino of a given flavor is a quantum superposition:

Produced as: $$\nu_e \odot \;=\; \left(U_{e1}\,\overset{\nu_1}{\boxdot} + U_{e2}\,\overset{\nu_2}{\boxdot} + U_{e3}\,\overset{\nu_3}{\boxdot} \right)$$

Travel a distance
L to the detector

Detected as: $$U_{e1}\,\overbrace{e^{-im_1 L/E}\,\boxdot} + U_{e2}\,\overbrace{e^{-im_2 L/E}\,\boxdot}$$

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Produced as: $\nu_e \odot \;=\; \left(U_{e1}\,\boxdot + U_{e2}\,\boxdot + U_{e3}\,\boxdot \right)$

Travel a distance L to the detector

Detected as: $U_{e1}\,\overbrace{e^{-im_1 L/E}\,\boxdot} + U_{e2}\,\overbrace{e^{-im_2 L/E}\,\boxdot} + U_{e3}\,\overbrace{e^{-im_3 L/E}\,\boxdot}$

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A neutrino of a given flavor is a quantum superposition:

Produced as: $\nu_e \odot \;=\; \left(U_{e1}\,\overset{\nu_1}{\square} + U_{e2}\,\overset{\nu_2}{\square} + U_{e3}\,\overset{\nu_3}{\square} \right)$

Travel a distance L to the detector

The mass states evolve with time

Detected as: $U_{e1}\,\overbrace{e^{-im_1 L/E}\,\square} + U_{e2}\,\overbrace{e^{-im_2 L/E}\,\square} + U_{e3}\,\overbrace{e^{-im_3 L/E}\,\square}$

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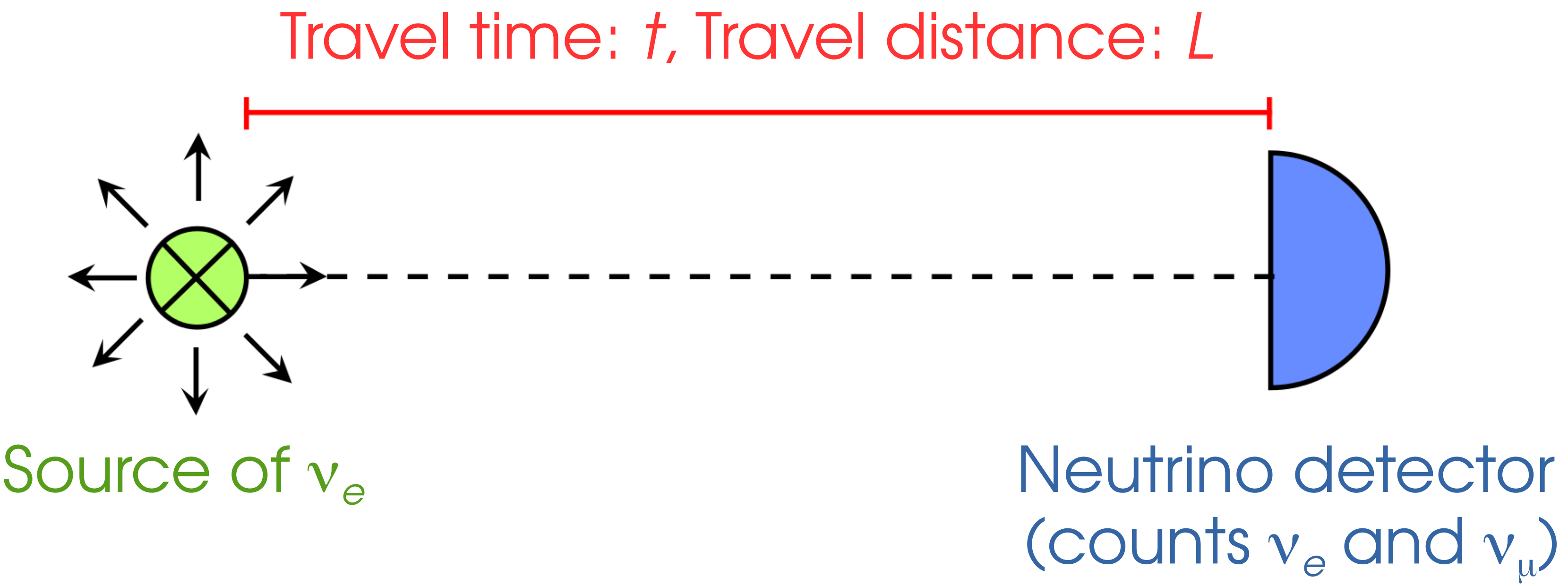
A neutrino of a given flavor is a quantum superposition:

Produced as: $$\nu_e = \left(U_{e1}\,\nu_1 + U_{e2}\,\nu_2 + U_{e3}\,\nu_3 \right)$$

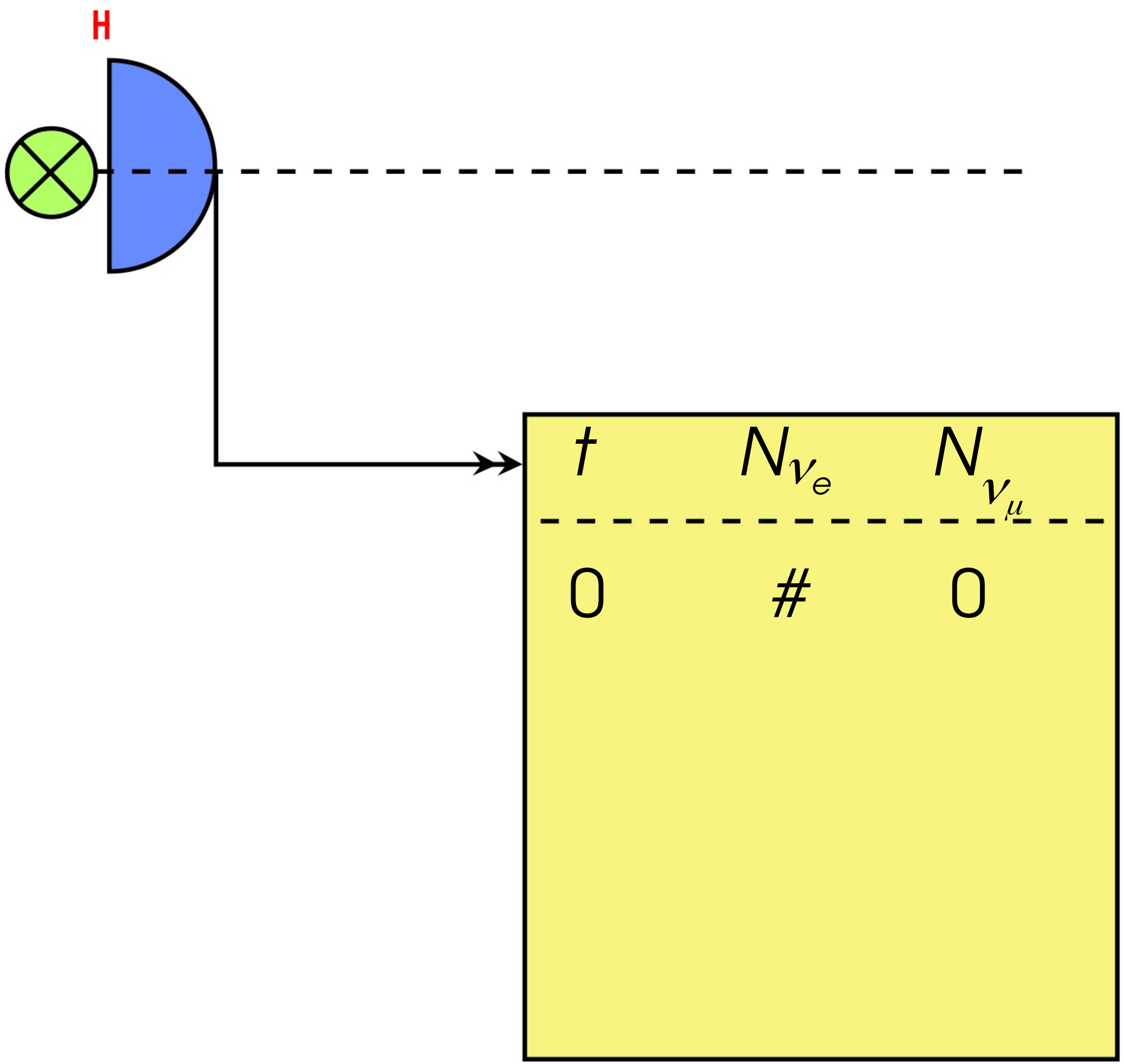
Travel a distance L to the detector

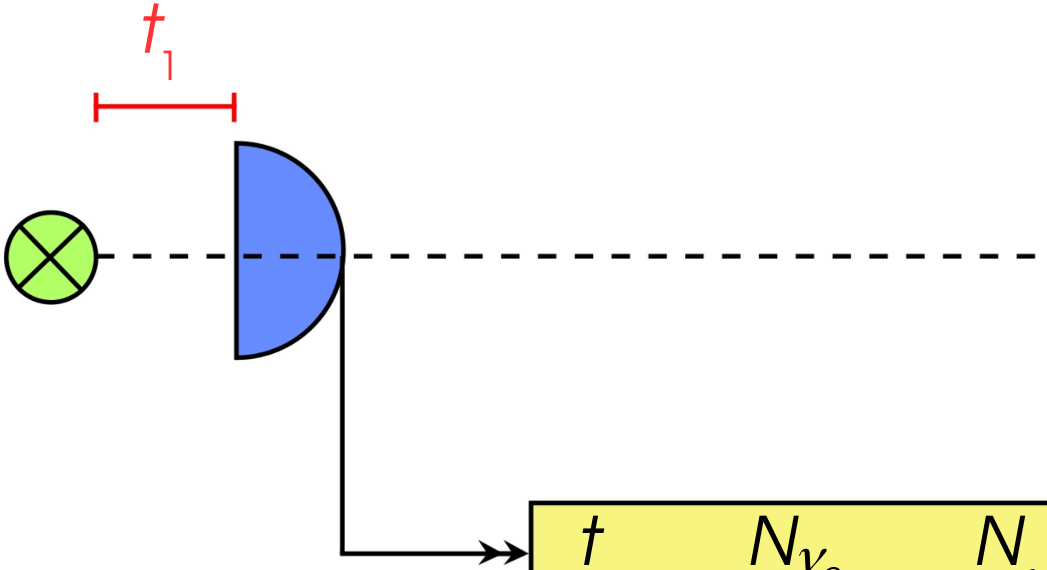
The mass states evolve with time

Detected as: $$\underbrace{U_{e1}\, e^{-im_1 L/E}\,\nu_1 + U_{e2}\, e^{-im_2 L/E}\,\nu_2 + U_{e3}\, e^{-im_3 L/E}\,\nu_3}_{\text{This is no longer a } \nu_e}$$

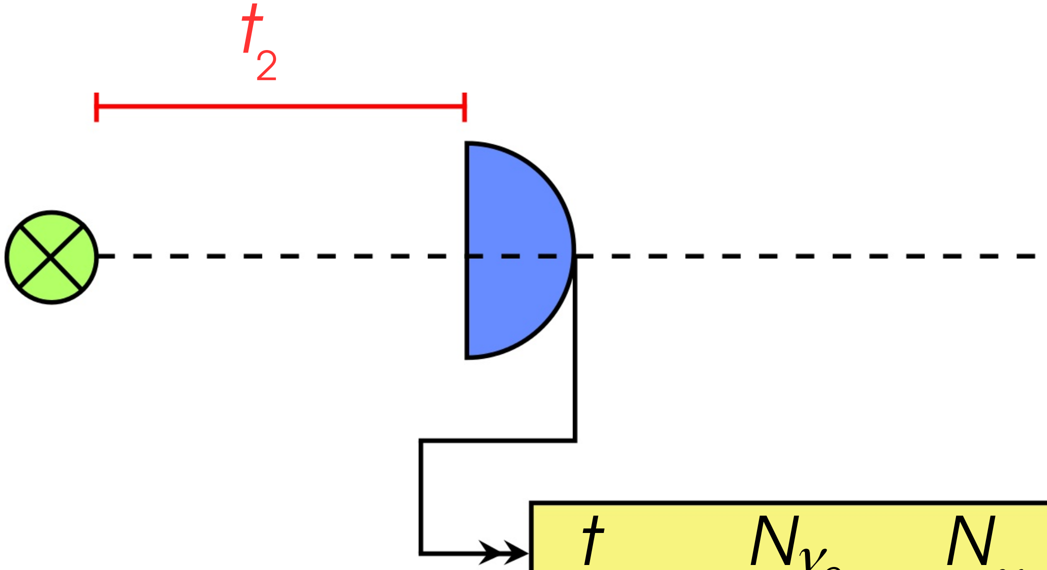

Travel time: t, Travel distance: L
Source of ν_e
Neutrino detector
(counts ν_e and ν_μ)

$t = 0$

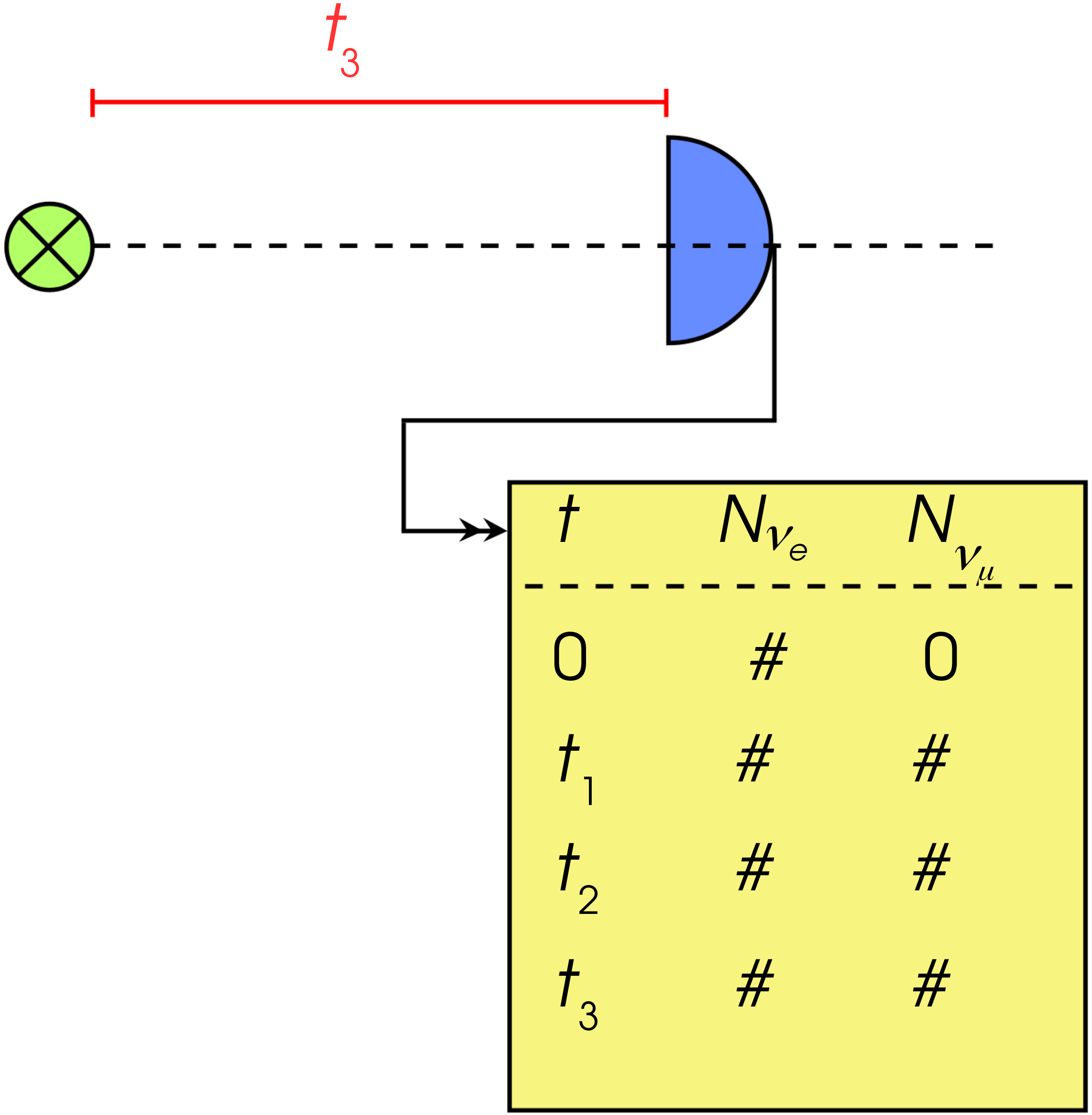




t	N_{ν_e}	N_{ν_μ}
0	#	0
t_1	#	#

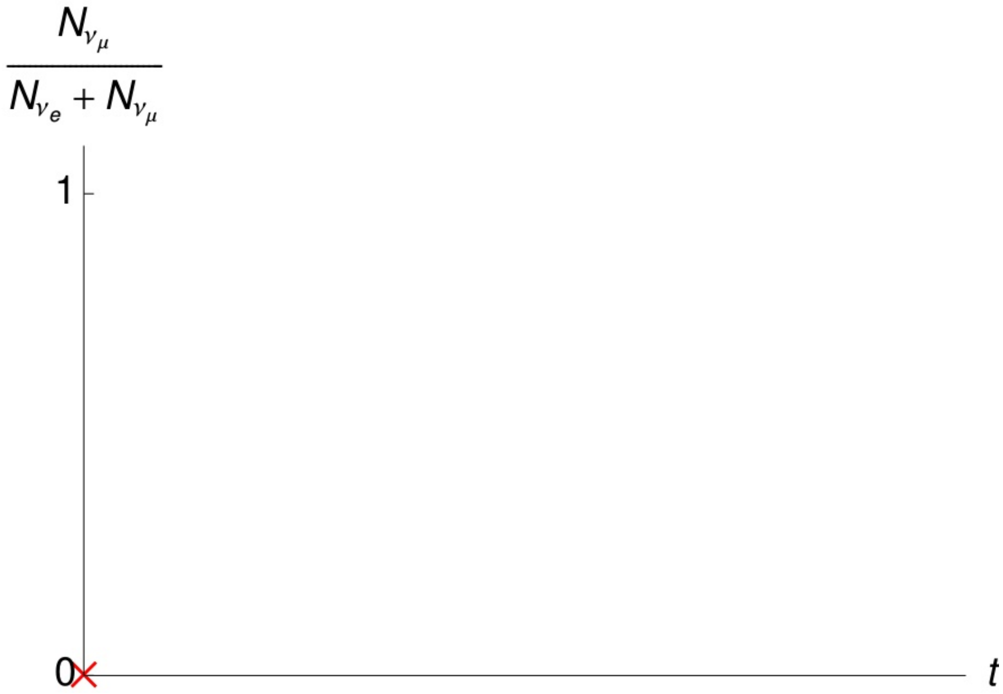


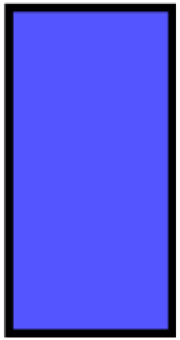
t	N_{ν_e}	N_{ν_μ}
0	#	0
t_1	#	#
t_2	#	#



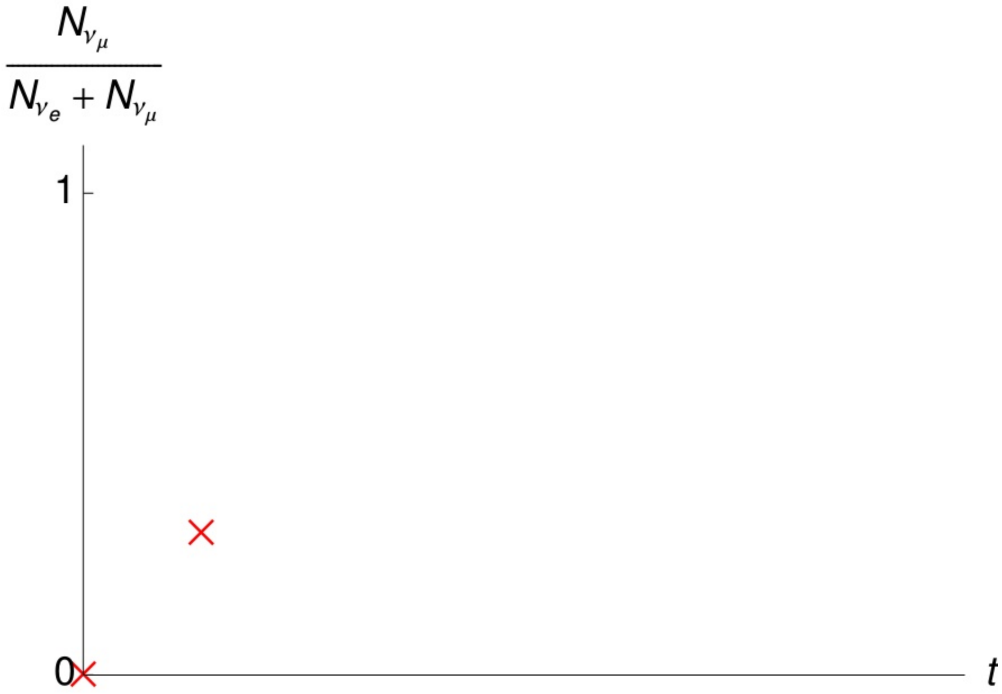
t	N_{ν_e}	N_{ν_μ}
0	#	0
t_1	#	#
t_2	#	#
t_3	#	#


t

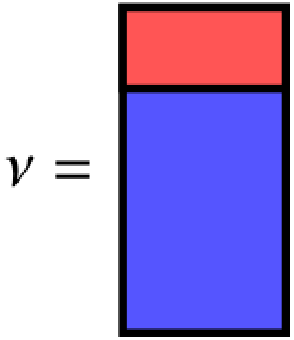


$\nu =$ 

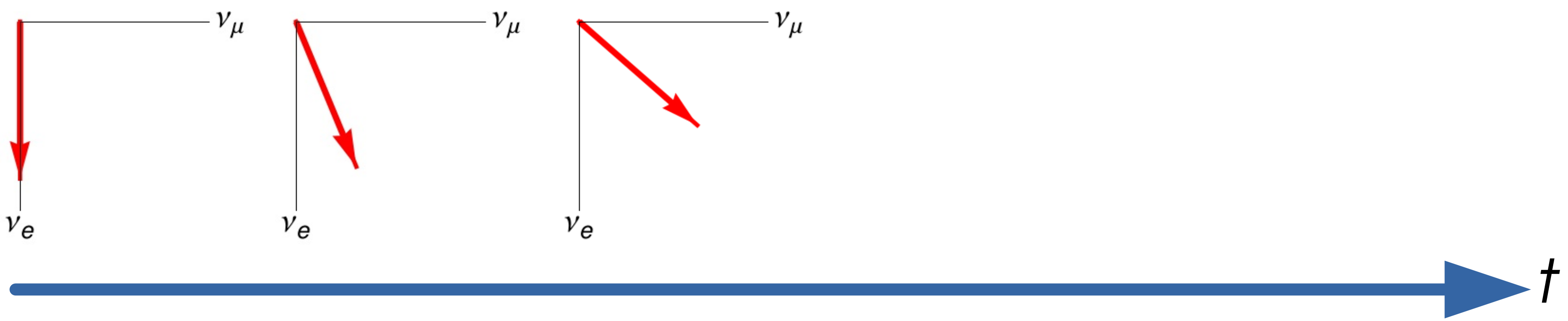
ν_μ
ν_e
ν_μ
ν_e
t

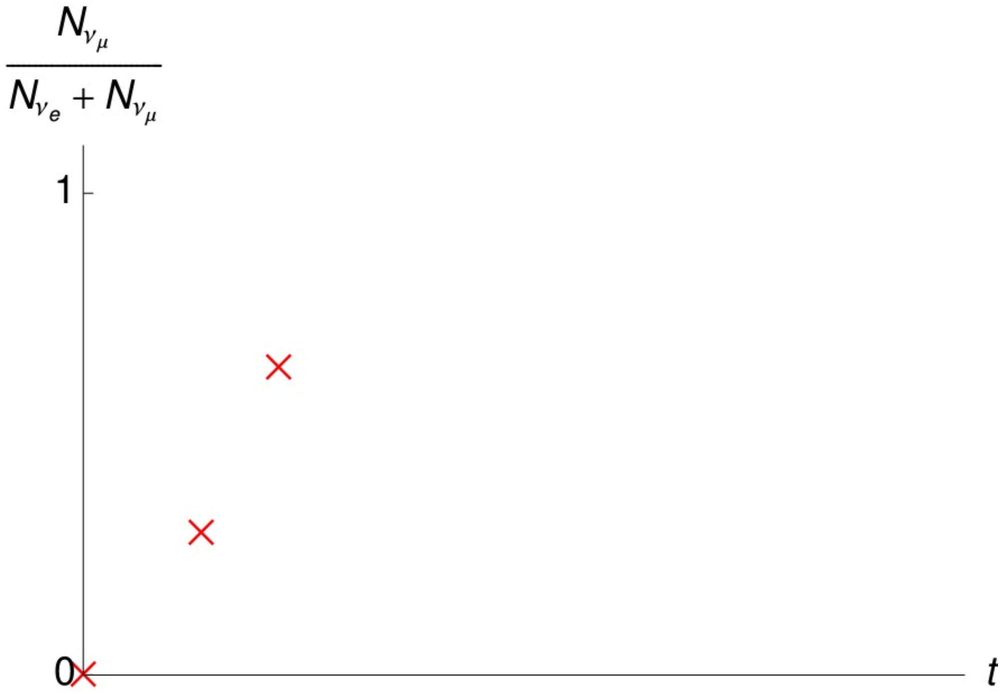


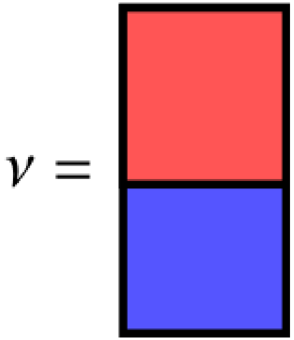
$\frac{N_{\nu_\mu}}{N_{\nu_e} + N_{\nu_\mu}}$
1
0
t

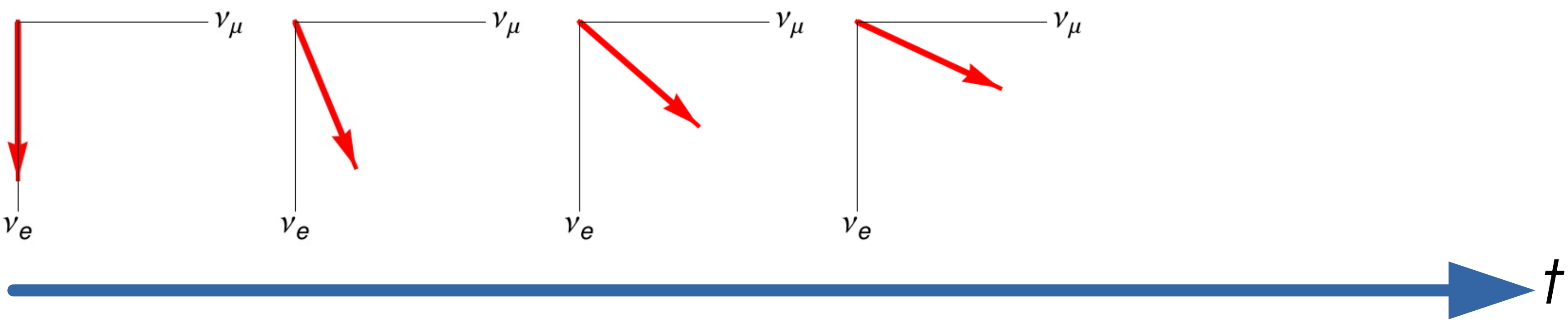


$\nu =$

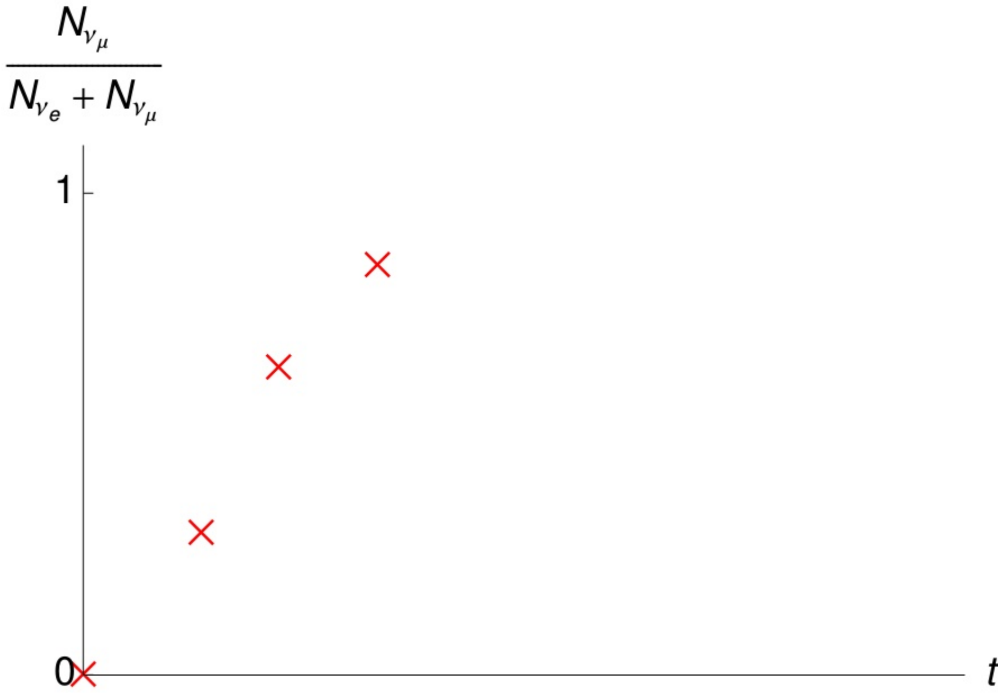

ν_μ
ν_e
ν_μ
ν_e
ν_μ
ν_e
t


$\frac{N_{\nu_\mu}}{N_{\nu_e} + N_{\nu_\mu}}$
1
0
t

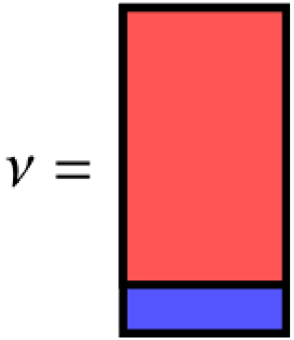

$\nu =$



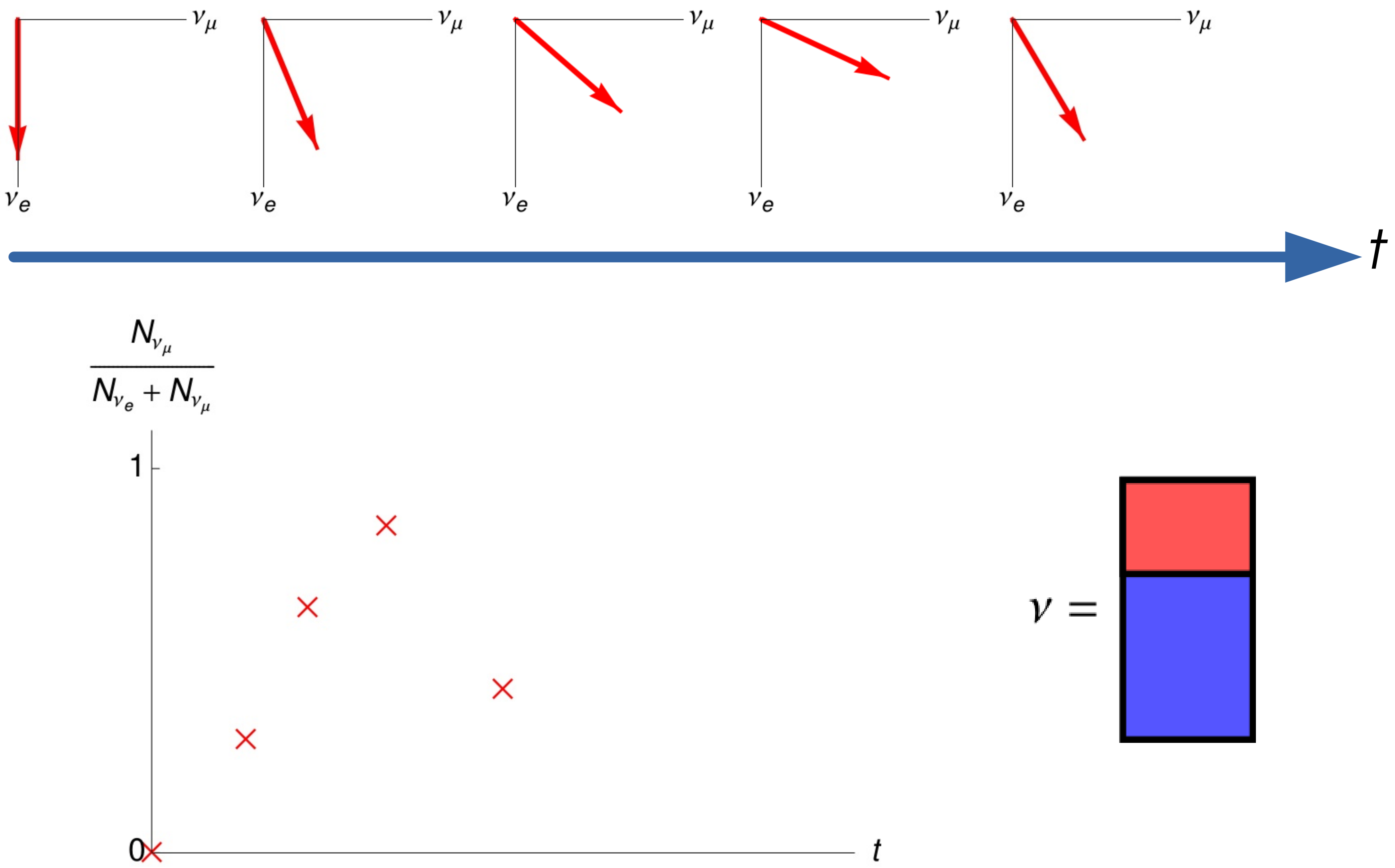
ν_μ
ν_e
t



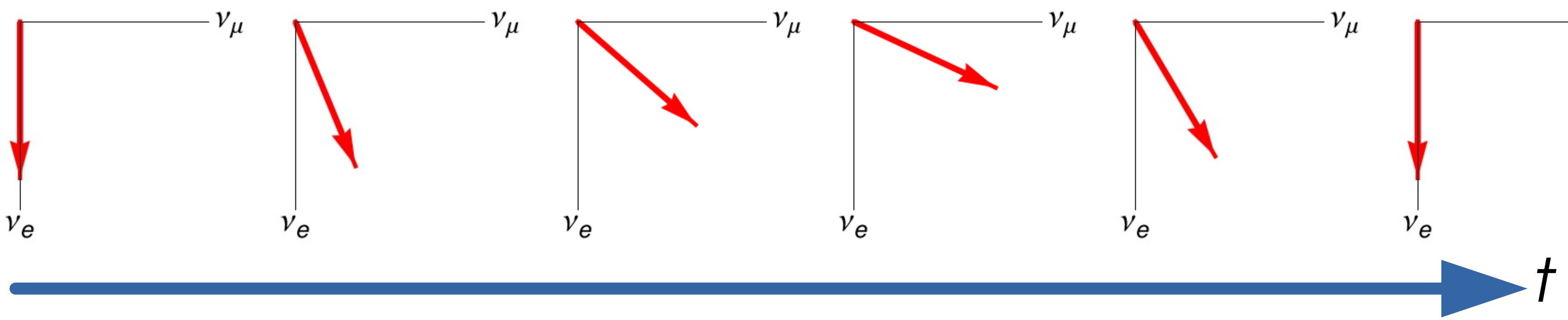
$\frac{N_{\nu_\mu}}{N_{\nu_e} + N_{\nu_\mu}}$
1
0
t

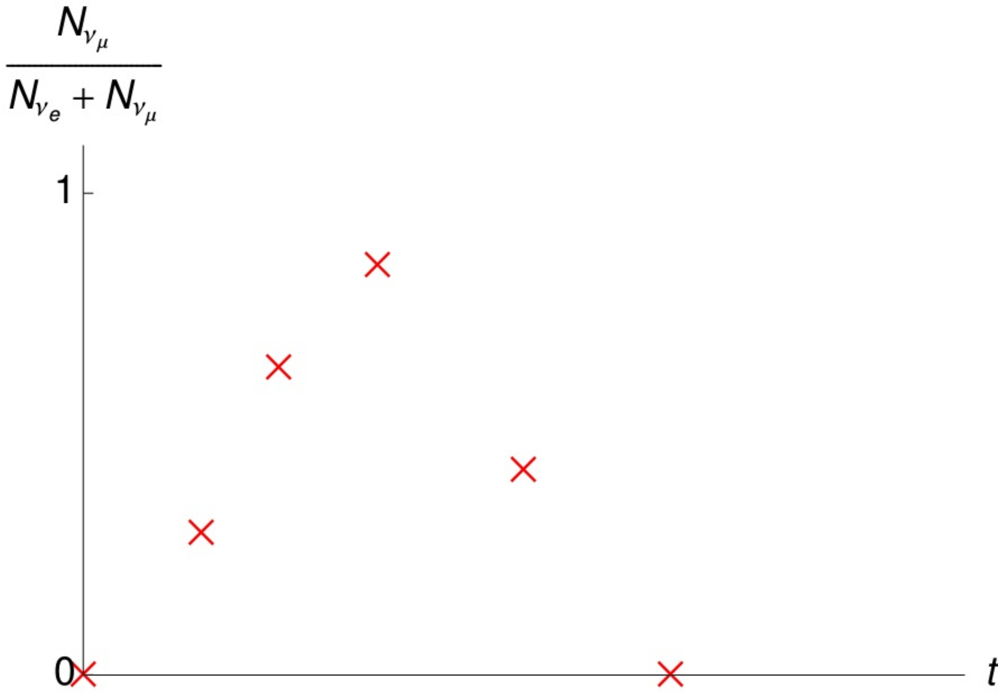


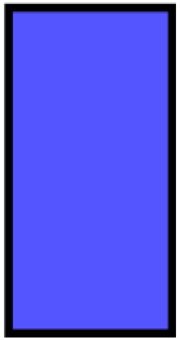
$\nu =$

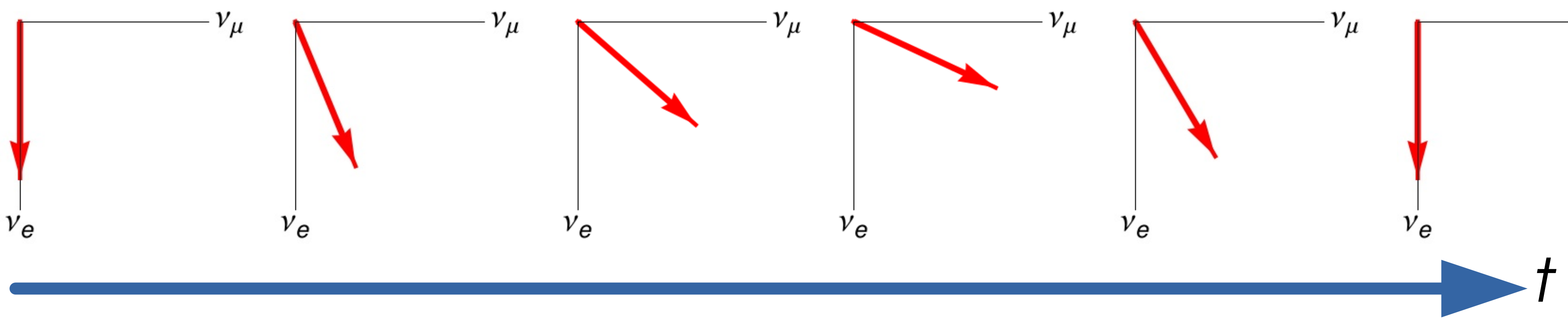


ν_μ
ν_e
t
$\frac{N_{\nu_\mu}}{N_{\nu_e} + N_{\nu_\mu}}$
1
0
t
$\nu =$

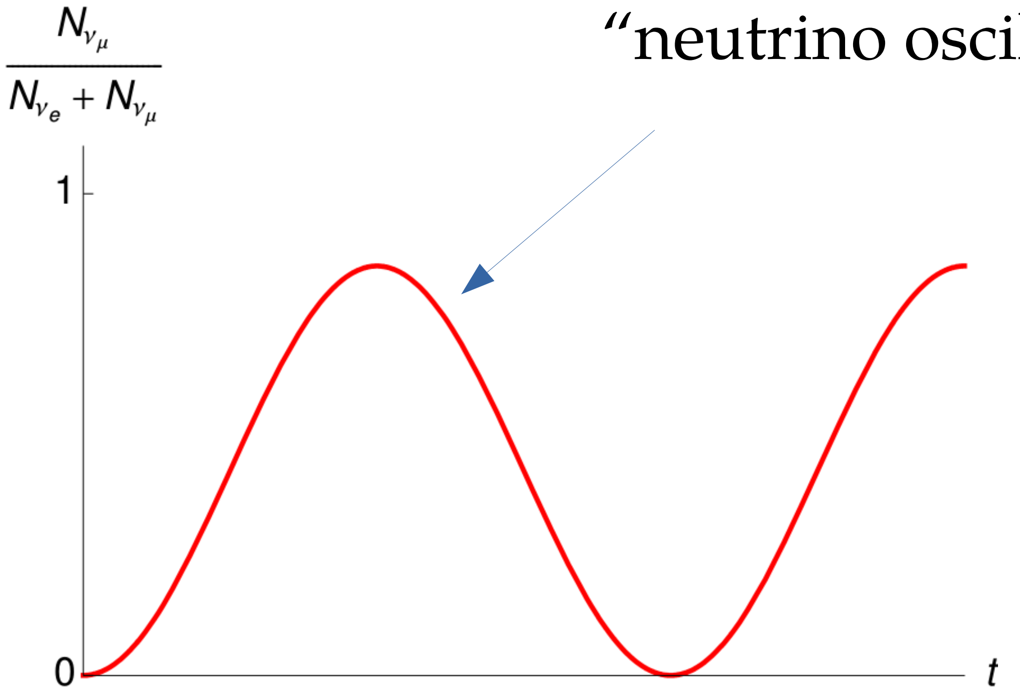


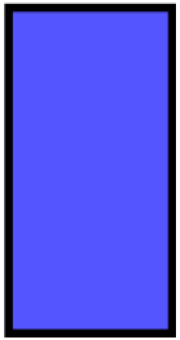


$\nu =$ 

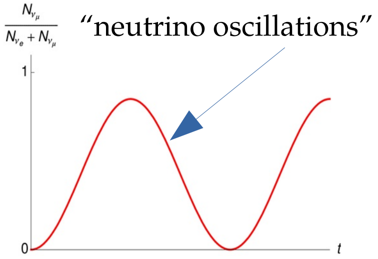


"neutrino oscillations"



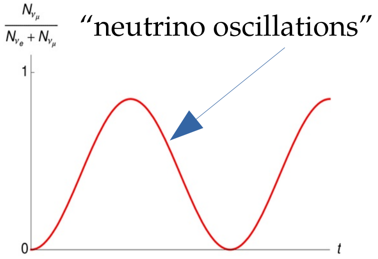
$\nu =$ 

Neutrinos oscillate, therefore they have mass!



Probability that a neutrino born ν_e is detected as ν_μ:

Neutrinos oscillate, therefore they have mass!



Probability that a neutrino born ν_e is detected as ν_μ:

$$P_{\nu_e \to \nu_\mu} \propto \sin^2\left(1.27\Delta m^2[\mathrm{eV}^2] \cdot \frac{L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$

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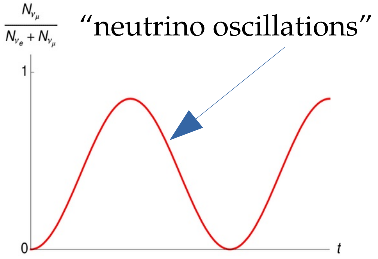

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It is oscillatory

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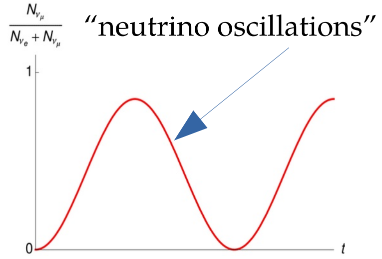

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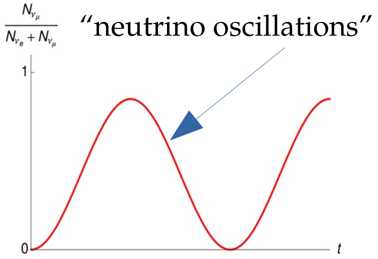

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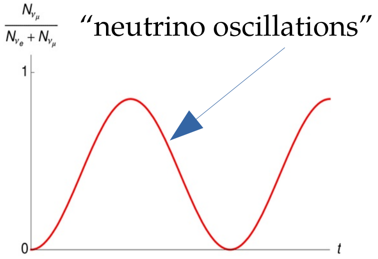
It is oscillatory

$$P_{\nu_e \to \nu_e} = 1 - P_{\nu_e \to \nu_\mu}$$

Neutrinos oscillate, therefore they have mass!



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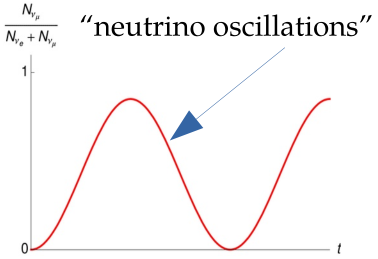
It is oscillatory

$$P_{\nu_e \to \nu_e} = 1 - P_{\nu_e \to \nu_\mu} \qquad \leftarrow \text{Survival}$$

Neutrinos oscillate, therefore they have mass!



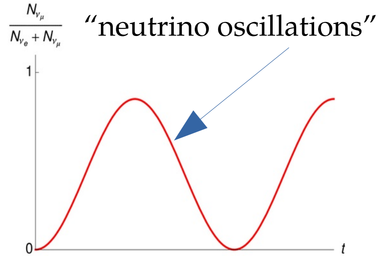
Probability that a neutrino born ν_e is detected as ν_μ:

$$P_{\nu_e \to \nu_\mu} \propto \sin^2 \left(\underbrace{1.27 \Delta m^2 [\mathrm{eV}^2]}_{\Delta m^2 \equiv m_2^2 - m_1^2} \cdot \frac{L[\mathrm{km}]}{E[\mathrm{GeV}]} \right) \quad \leftarrow \text{Transition}$$

It is oscillatory

$$P_{\nu_e \to \nu_e} = 1 - P_{\nu_e \to \nu_\mu} \quad \leftarrow \text{Survival}$$

Neutrinos oscillate, therefore they have mass!



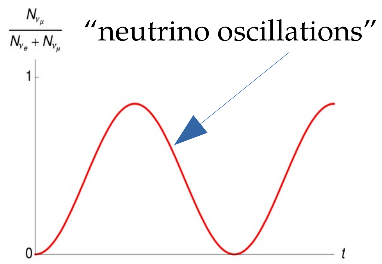
Probability that a neutrino born ν_e is detected as ν_μ:

(Derived using the rules of quantum mechanics)

$$P_{\nu_e \to \nu_\mu} \propto \sin^2 \left(1.27 \underbrace{\Delta m^2 [\mathrm{eV}^2]}_{} \cdot \frac{L[\mathrm{km}]}{E[\mathrm{GeV}]} \right)$$

$$\Delta m^2 \equiv m_2^2 - m_1^2$$

Neutrinos oscillate, therefore they have mass!



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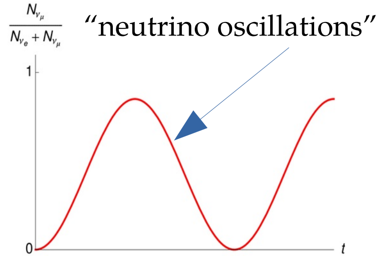
If the masses were zero ($m_1 = 0$ and $m_2 = 0$) or equal ($m_1 = m_2$)
then $\Delta m^2 = 0$ and oscillations would ***not*** occur

Neutrinos oscillate, therefore they have mass!



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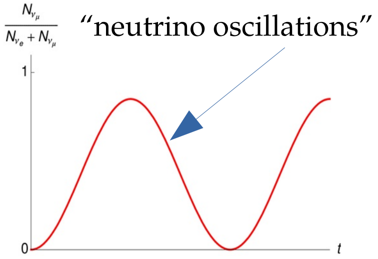
But we observe oscillations — so neutrinos have masses!

Neutrinos oscillate, therefore they have mass!



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$$P_{\nu_e \to \nu_\mu} \propto \sin^2\left(1.27\underbrace{\Delta m^2[\mathrm{eV}^2]}_{\Delta m^2 \equiv m_2^2 - m_1^2 \approx 10^{-4}\ \mathrm{eV}^2} \cdot \frac{L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$

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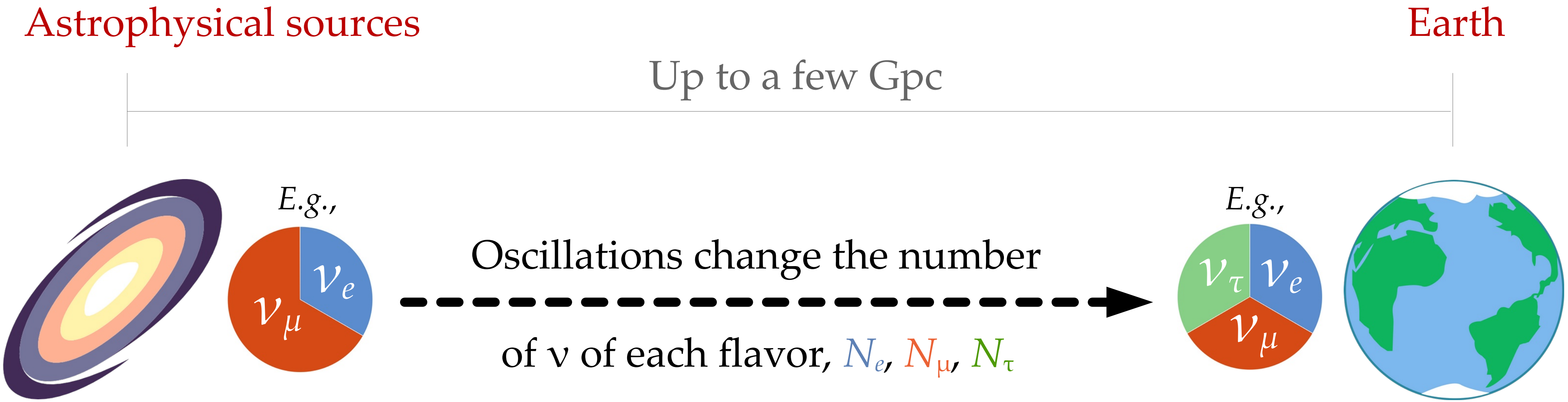
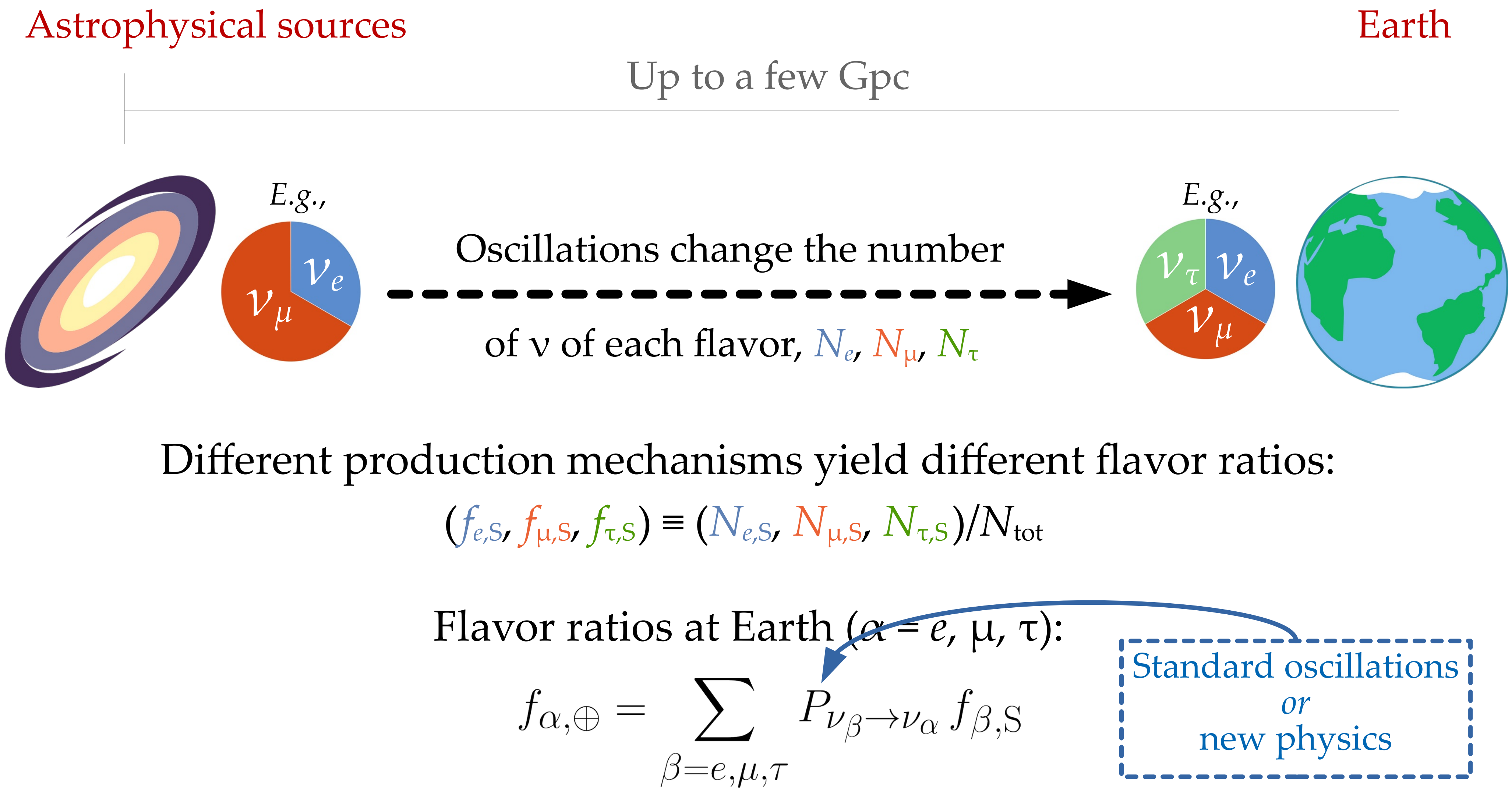


Different production mechanisms yield different flavor ratios:

$$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}}) \equiv (N_{e,\mathrm{S}}, N_{\mu,\mathrm{S}}, N_{\tau,\mathrm{S}})/N_{\mathrm{tot}}$$

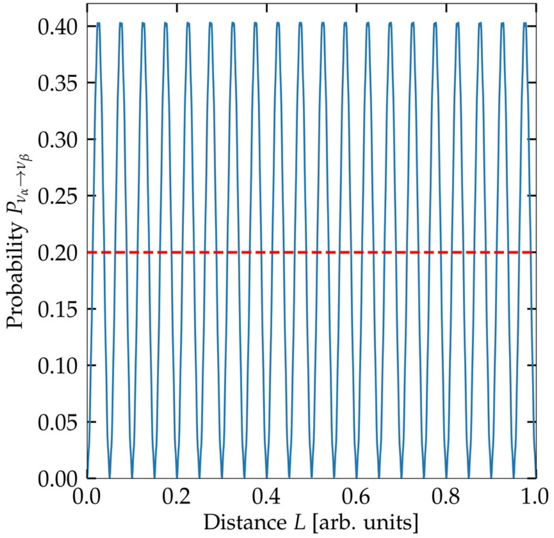
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,\mathrm{S}}$$


Astrophysical sources
Earth
Up to a few Gpc
E.g.,
ν_e
ν_μ
Oscillations change the number
of ν of each flavor, N_e, N_μ, N_τ
E.g.,
ν_τ
ν_e
ν_μ
Different production mechanisms yield different flavor ratios:
$(f_{e,\rm S}, f_{\mu,\rm S}, f_{\tau,\rm S}) \equiv (N_{e,\rm S}, N_{\mu,\rm S}, N_{\tau,\rm S})/N_{\rm tot}$
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):
$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta\to\nu_\alpha} f_{\beta,\rm S}$$
Standard oscillations
or
new physics

Full 3ν oscillation probability:

$$P_{\alpha\beta}(E,L) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$
$$+2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$



Oscillation length for 1-TeV ν: $2\pi \times 2E/\Delta m^2 \sim 0.1$ pc

~ 8% of the way to Proxima Centauri
≪ Distance to Galactic Center (8 kpc)
≪ Distance to Andromeda (1 Mpc)
≪ Cosmological distances (few Gpc)

We cannot resolve oscillations, so we use instead the average probability:

$$P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 \, |U_{\beta i}|^2$$

Full 3ν oscillation probability:

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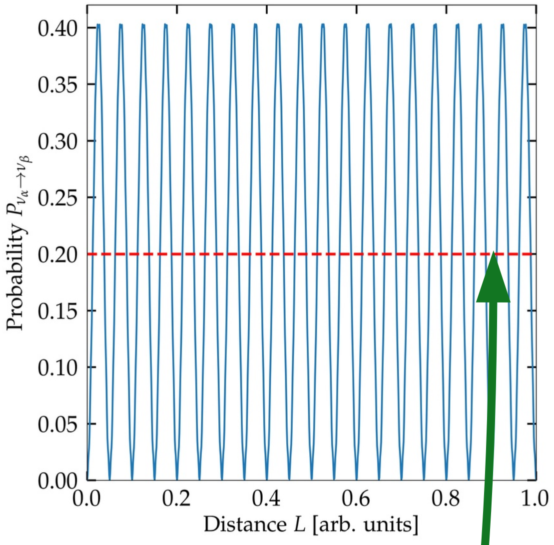

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Flavor composition at the Earth:

$$\begin{pmatrix} f_{e,\oplus} \\ f_{\mu,\oplus} \\ f_{\tau,\oplus} \end{pmatrix} = \underbrace{\begin{pmatrix} P_{ee} & P_{e\mu} & P_{e\tau} \\ P_{e\mu} & P_{\mu\mu} & P_{\mu\tau} \\ P_{e\tau} & P_{\mu\tau} & P_{\tau\tau} \end{pmatrix}}\begin{pmatrix} f_{e,\mathrm{S}} \\ f_{\mu,\mathrm{S}} \\ f_{\tau,\mathrm{S}} \end{pmatrix}$$

Informed by
particle physics

Informed by astrophysics

Flavor composition at the Earth:

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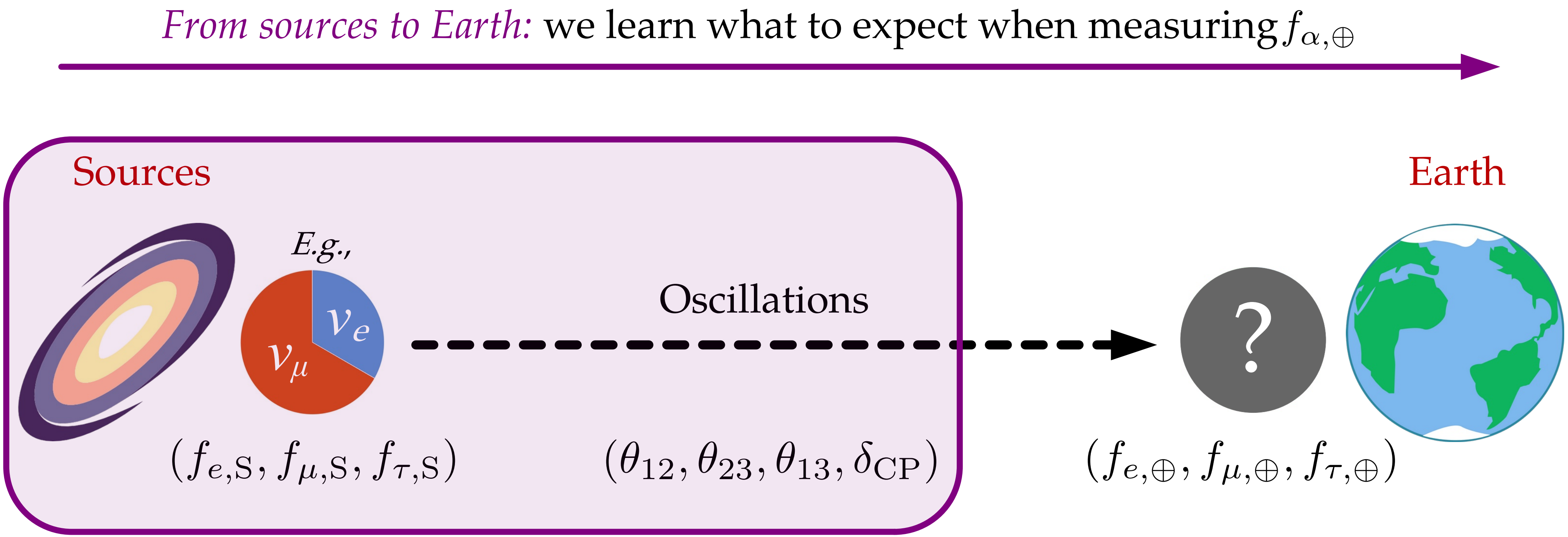
Assume no ν_τ production,
so we only need vary the ν_e fraction

Farzan, *JHEP* 2021


From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$
Sources
Earth
E.g.,
ν_e
ν_μ
Oscillations
?
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

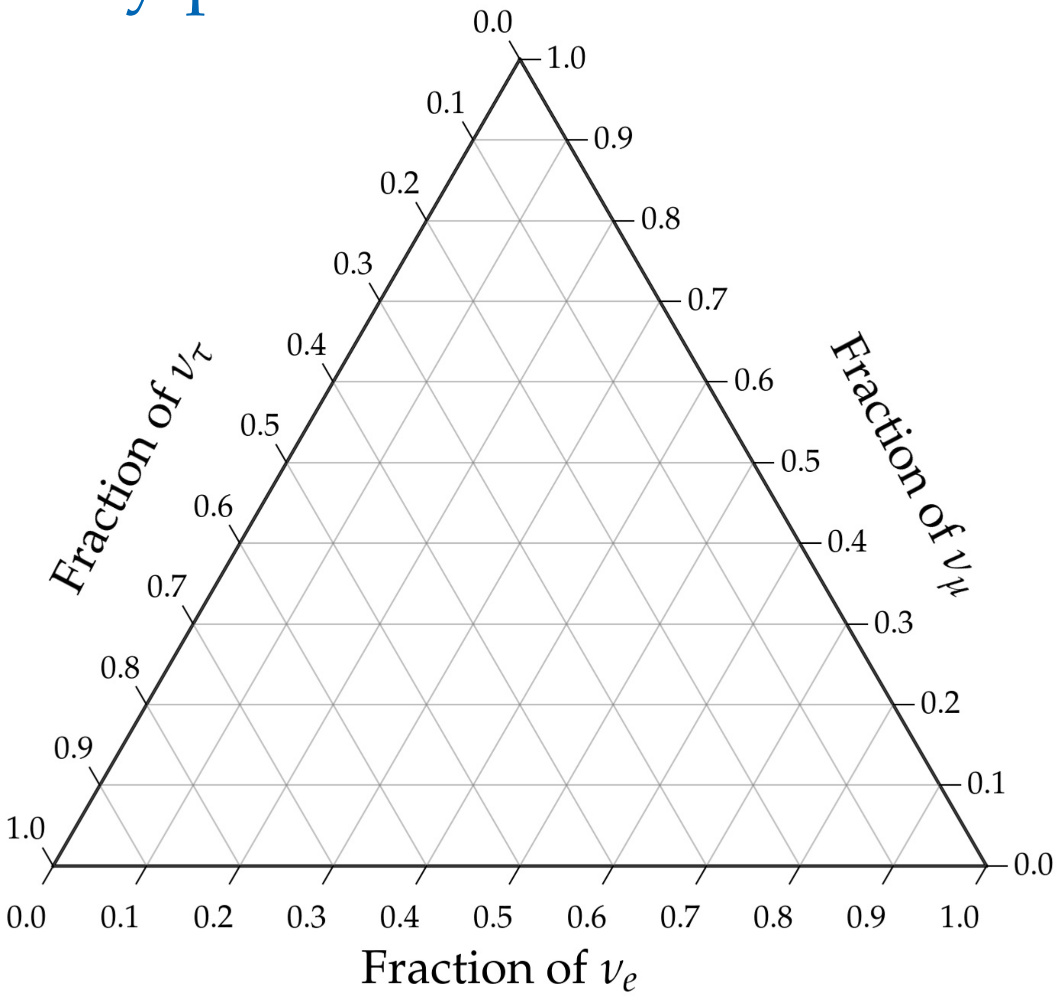
Quick aside: how to read a ternary plot

Assumes underlying unitarity –
sum of projections on each axis is 1

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



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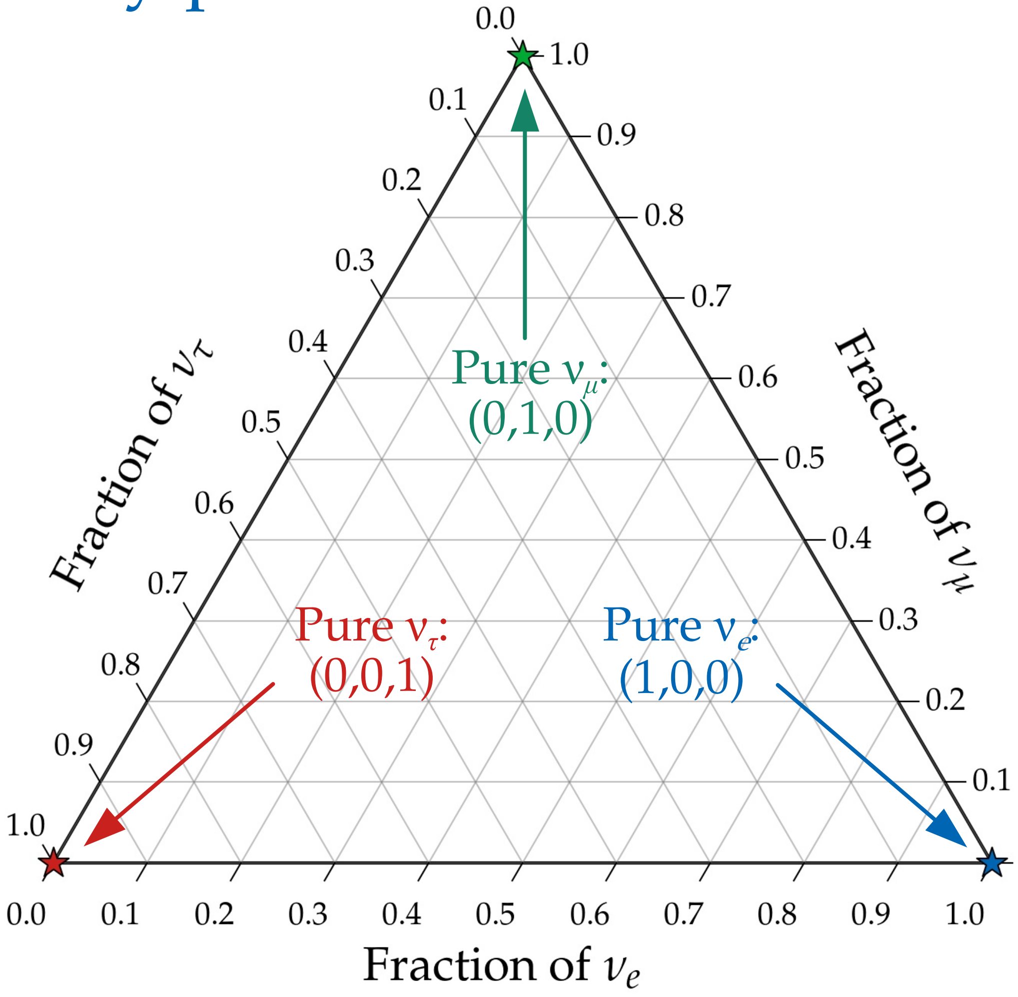

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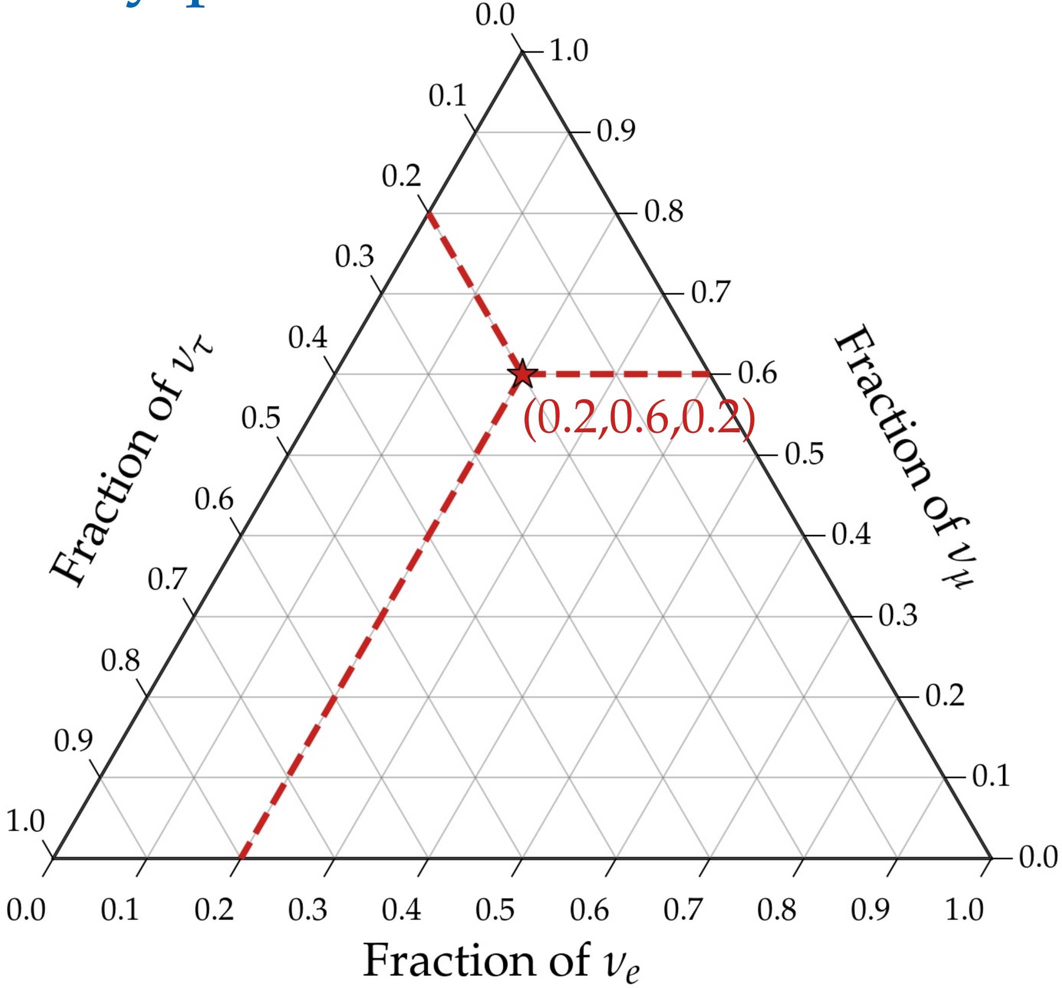

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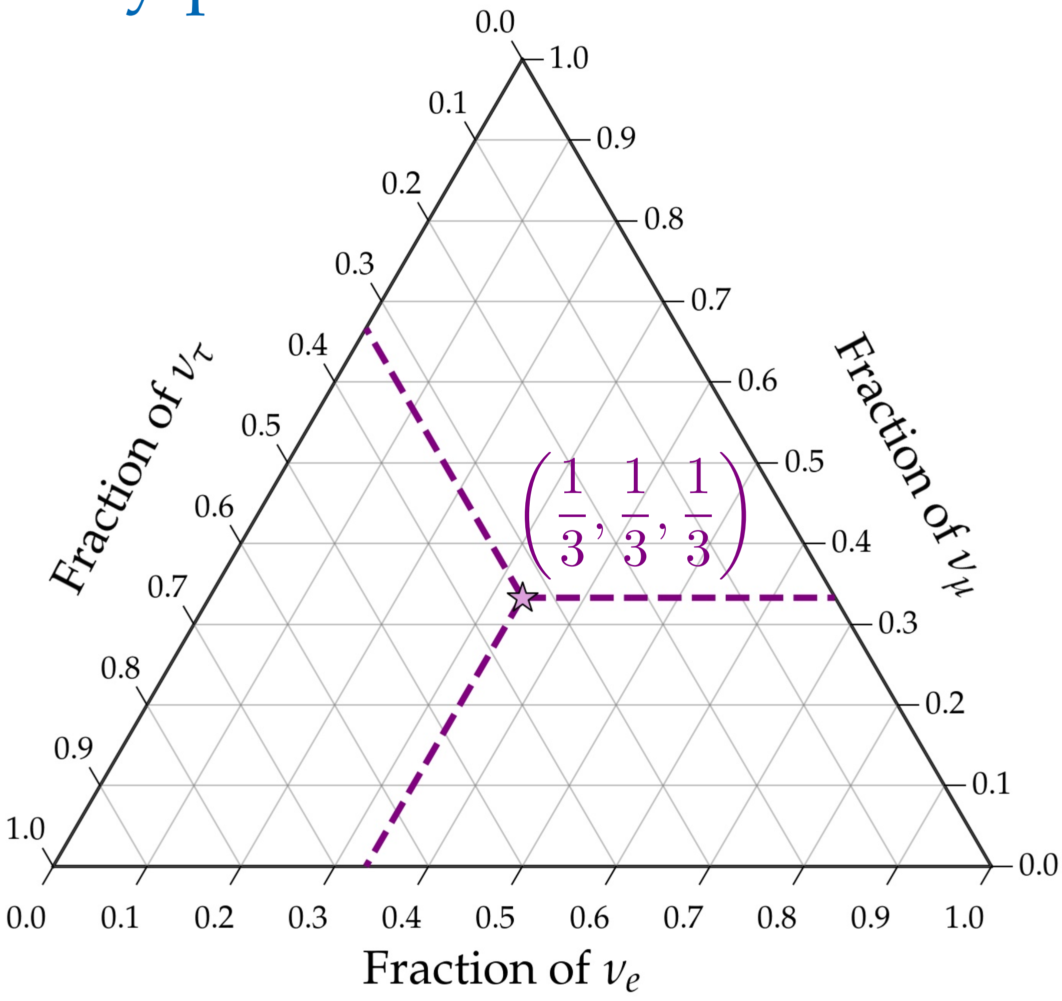

One likely TeV–PeV ν production scenario:

$p + \gamma \to \pi^+ \to \mu^+ + \nu_\mu$ followed by $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$

Full π decay chain

$(1/3:2/3:0)_S$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

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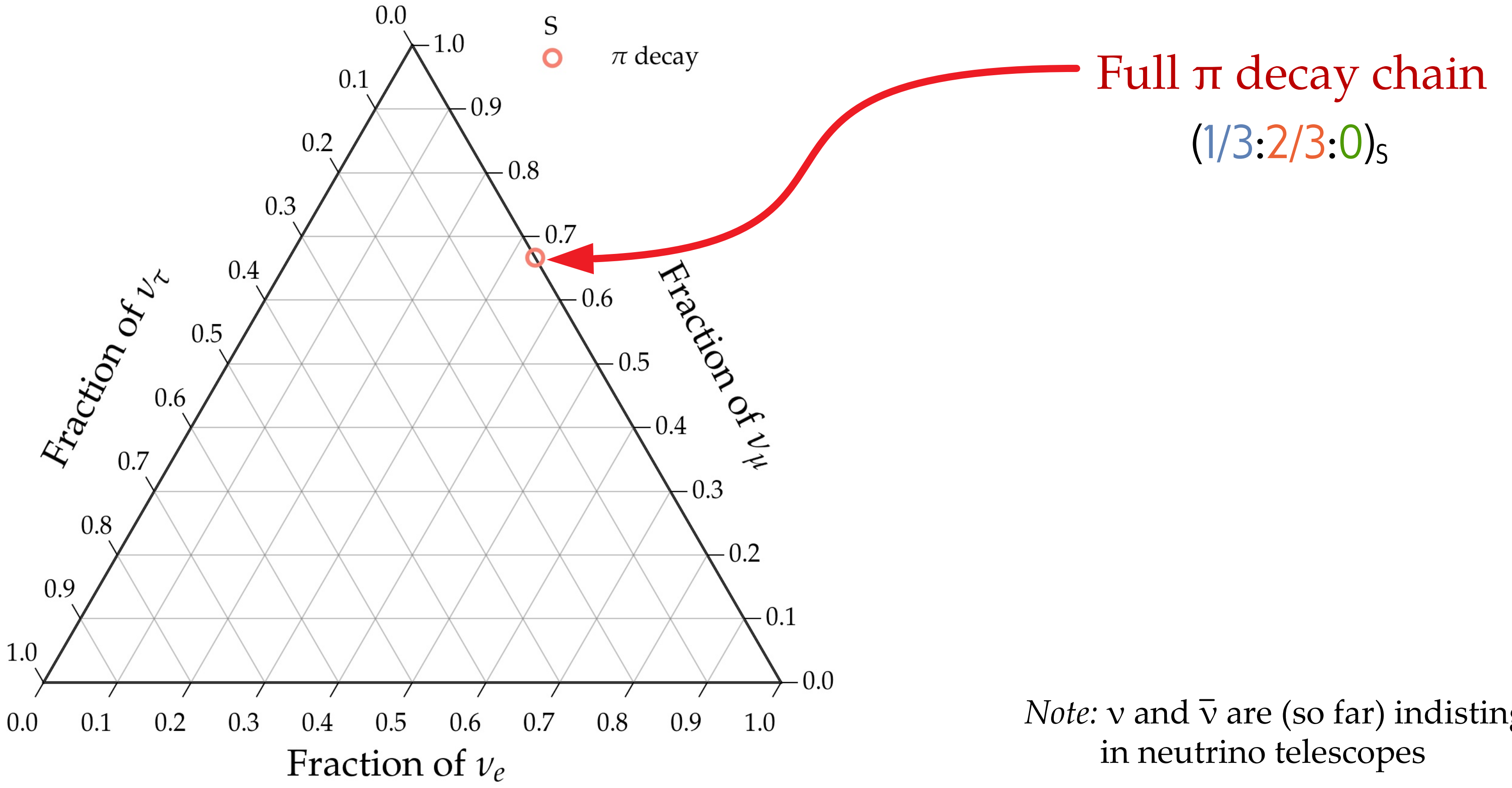

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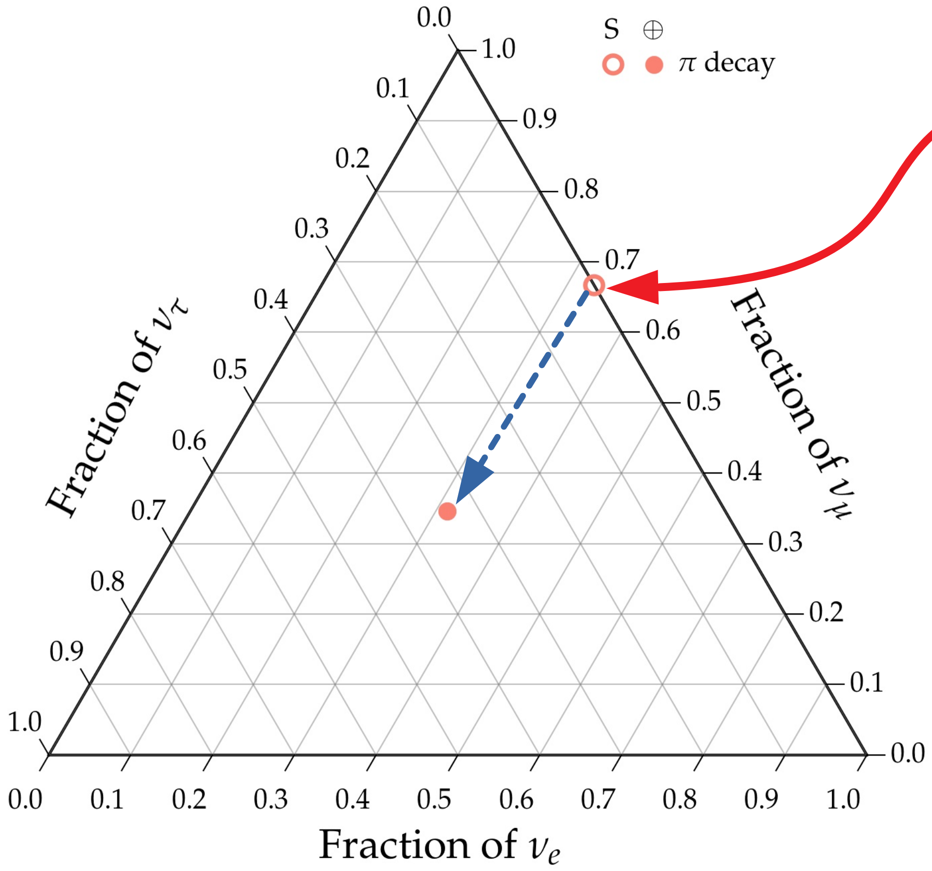

Full π decay chain

$(1/3:2/3:0)_S$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

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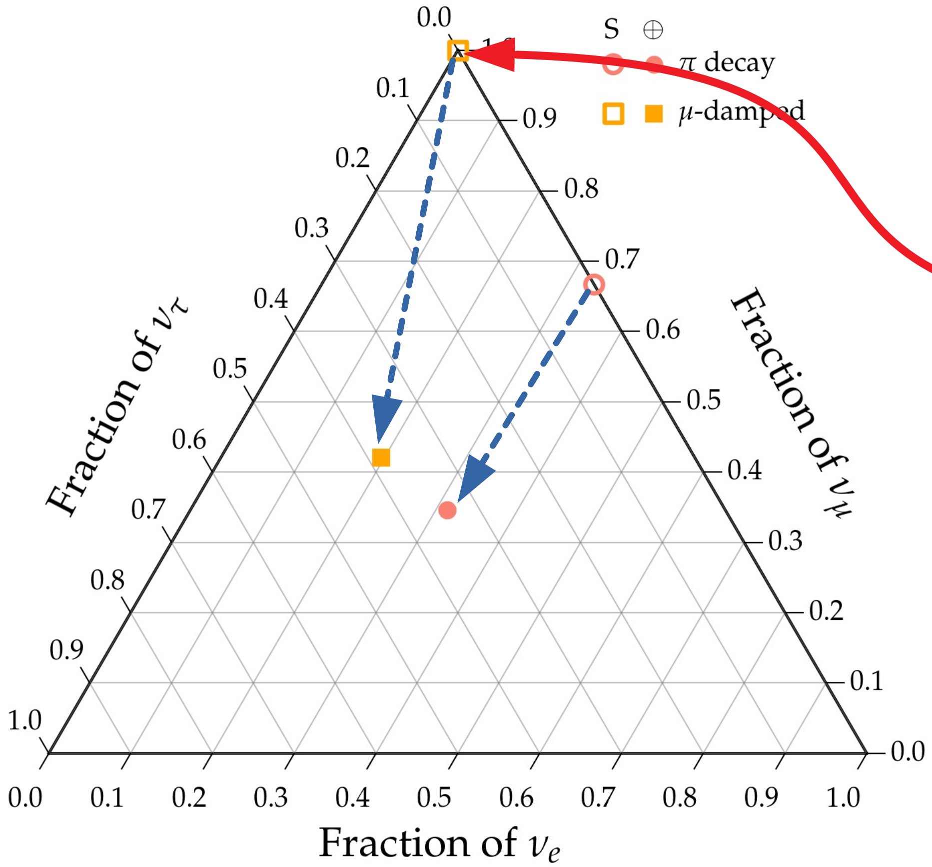

Full π decay chain

$(1/3 : 2/3 : 0)_S$

Muon damped

$(0:1:0)_S$

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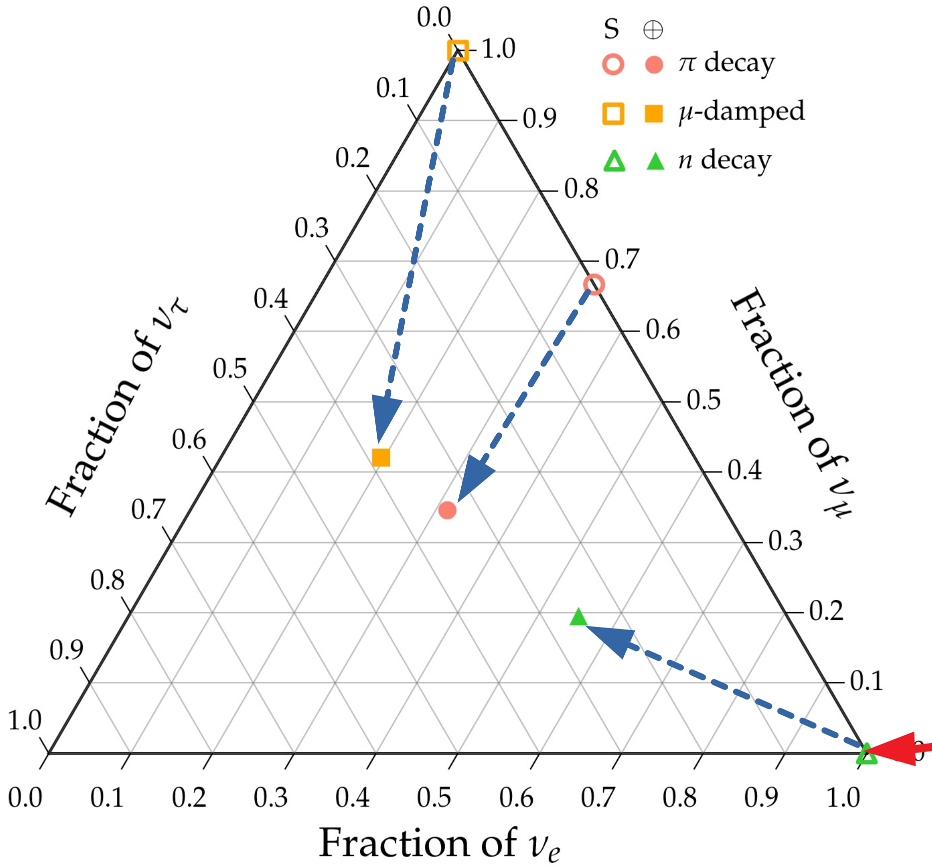


Full π decay chain

$(1/3:2/3:0)_S$

Muon damped

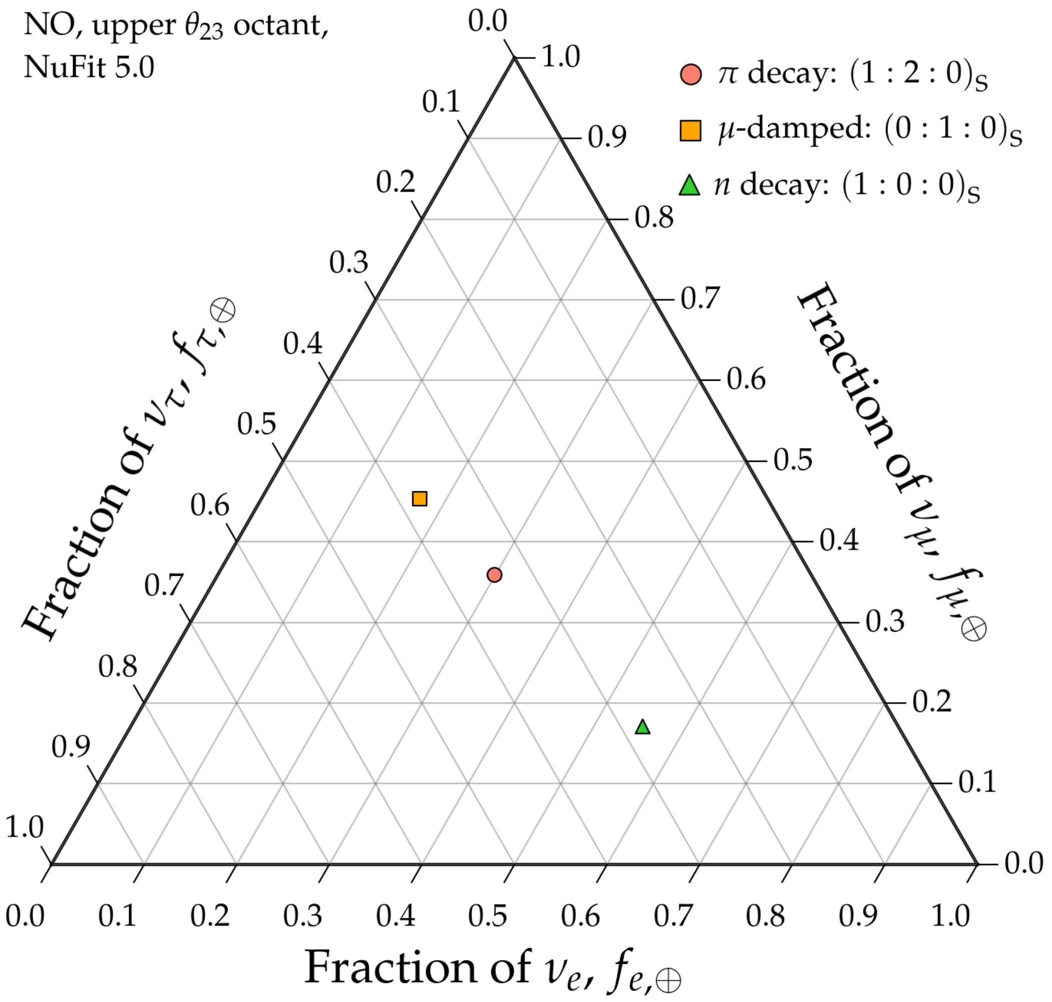
$(0:1:0)_S$

Neutron decay

$(1:0:0)_S$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

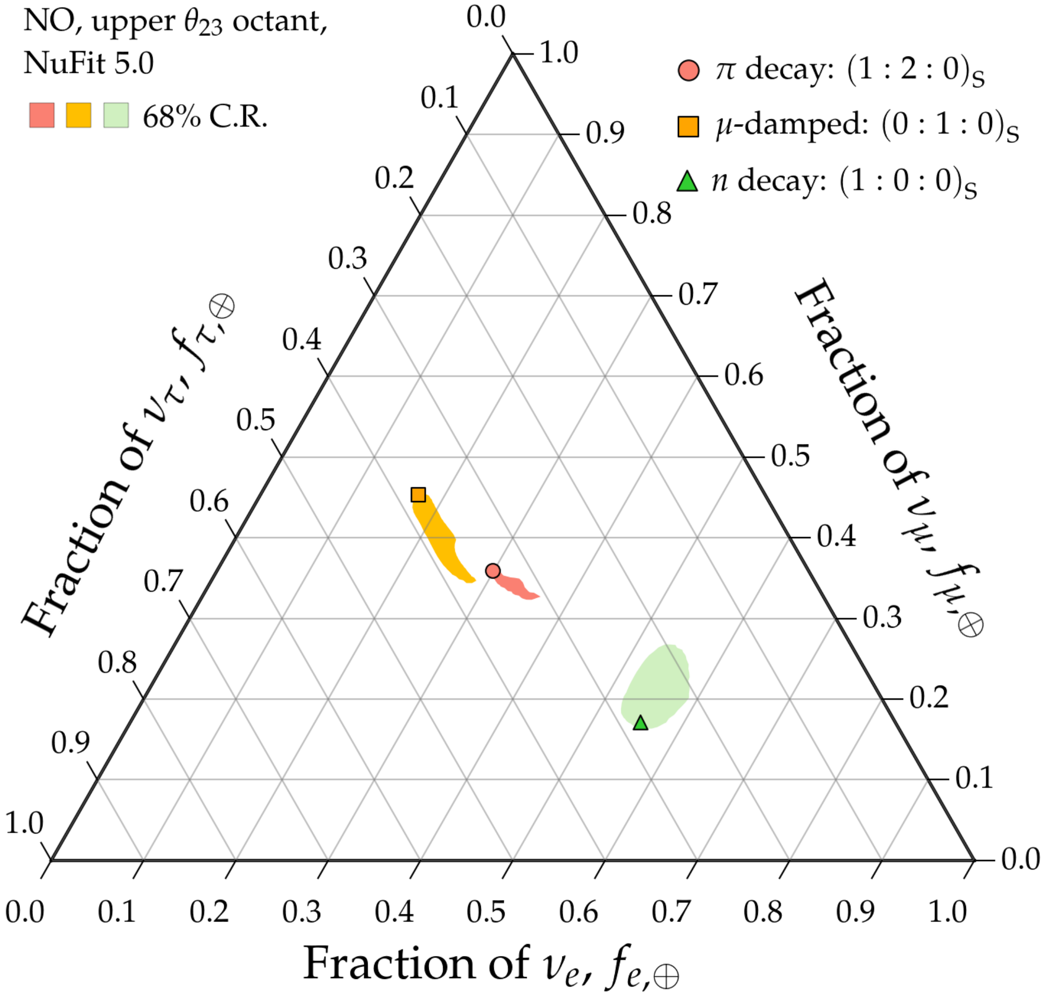
Theoretically palatable regions: today



Note:
All plots shown are for normal neutrino mass ordering (NO); inverted ordering looks similar

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
See also: **MB**, Beacom, Winter, *PRL* 2015

Theoretically palatable regions: today



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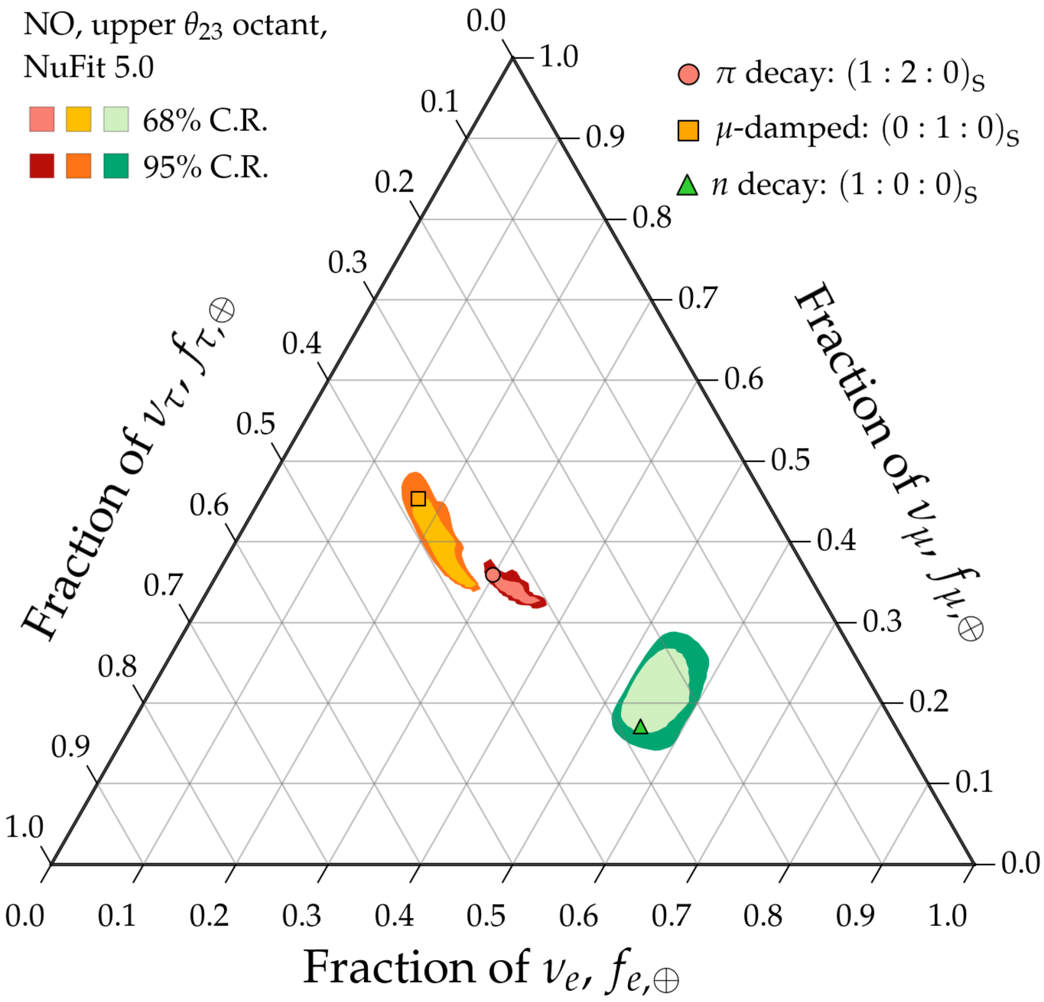

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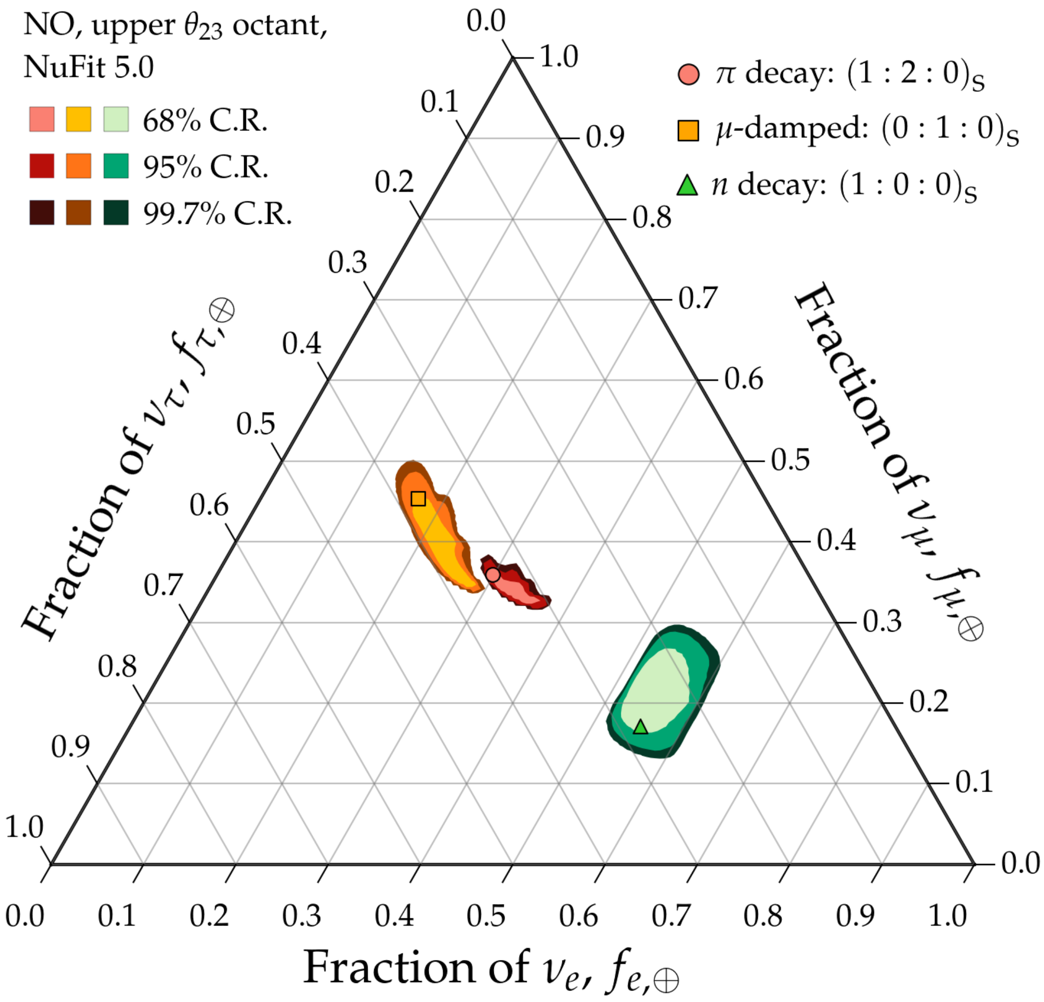

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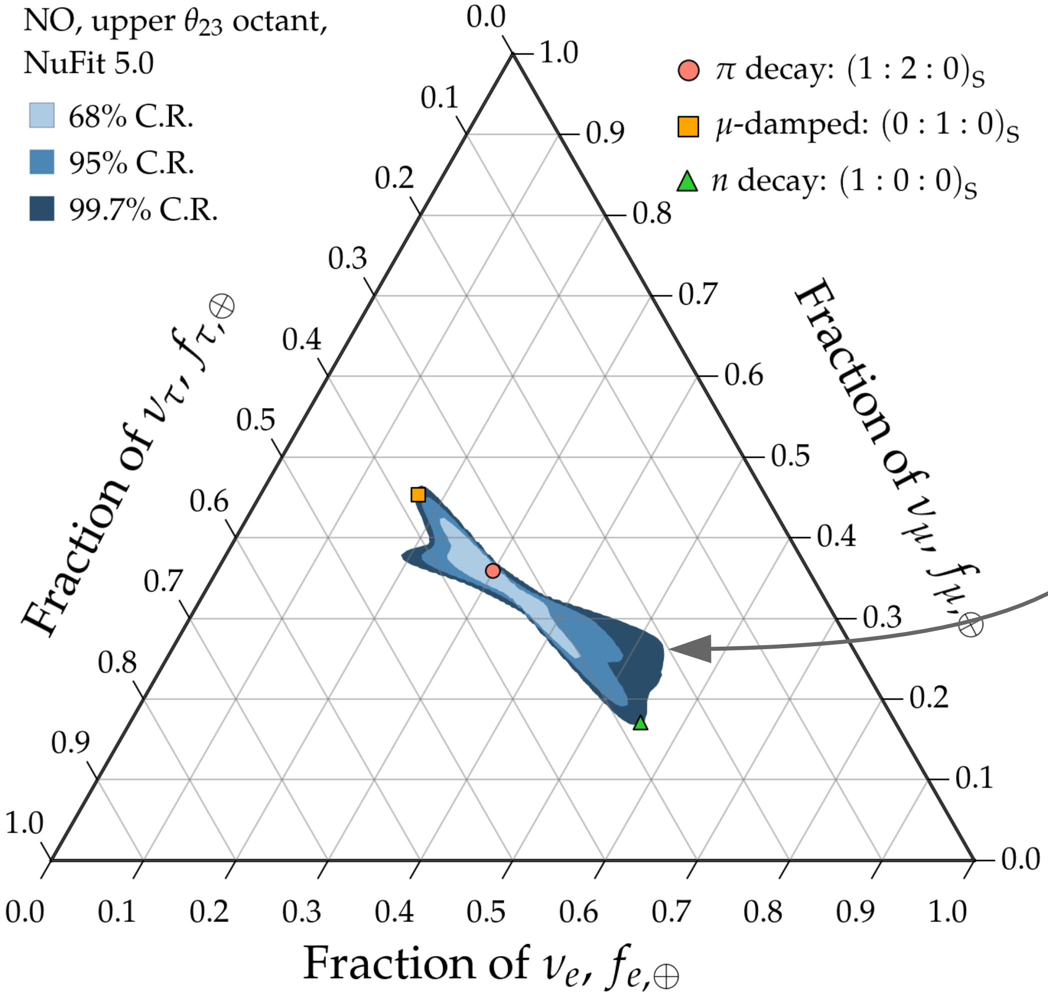
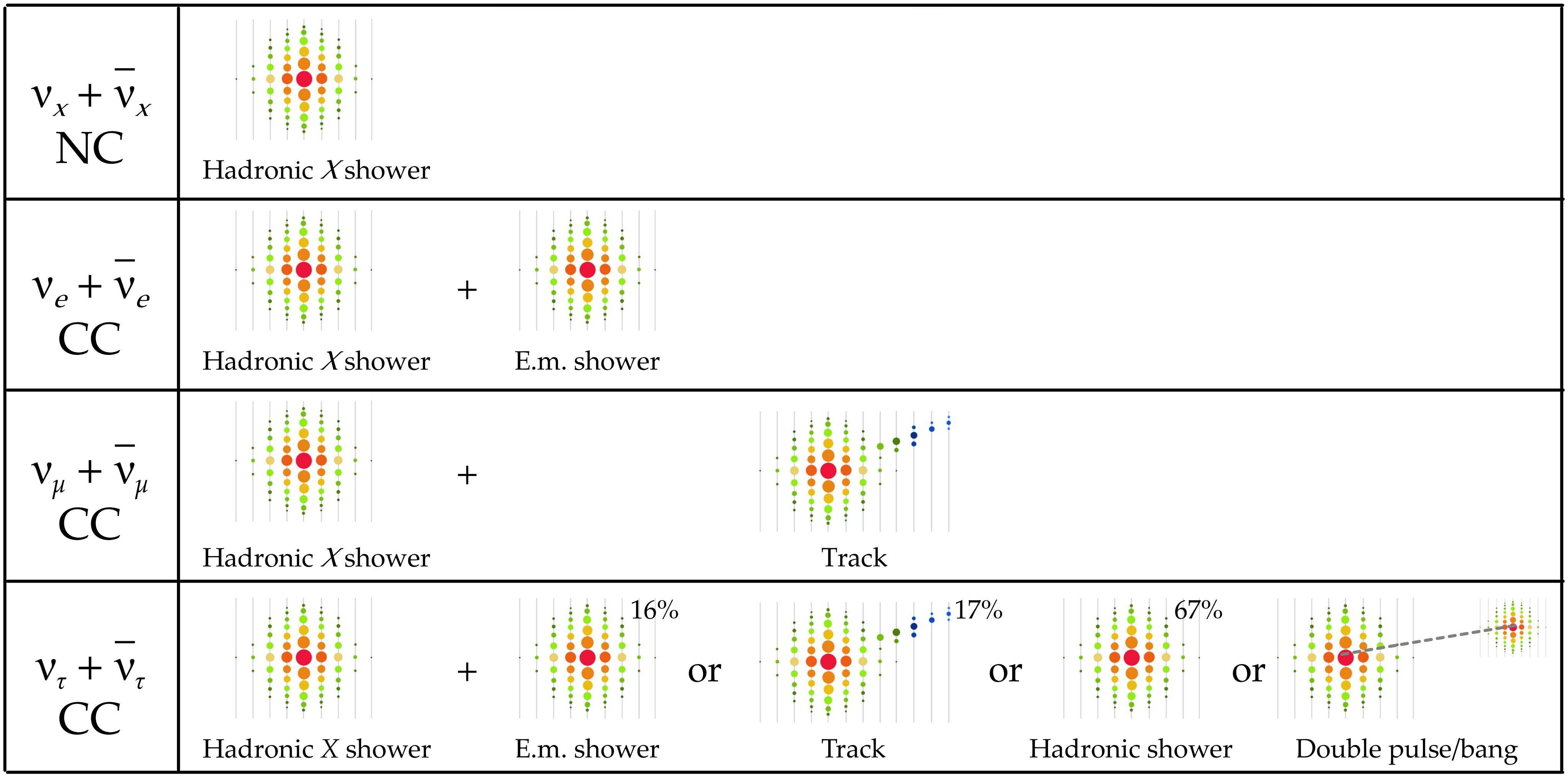


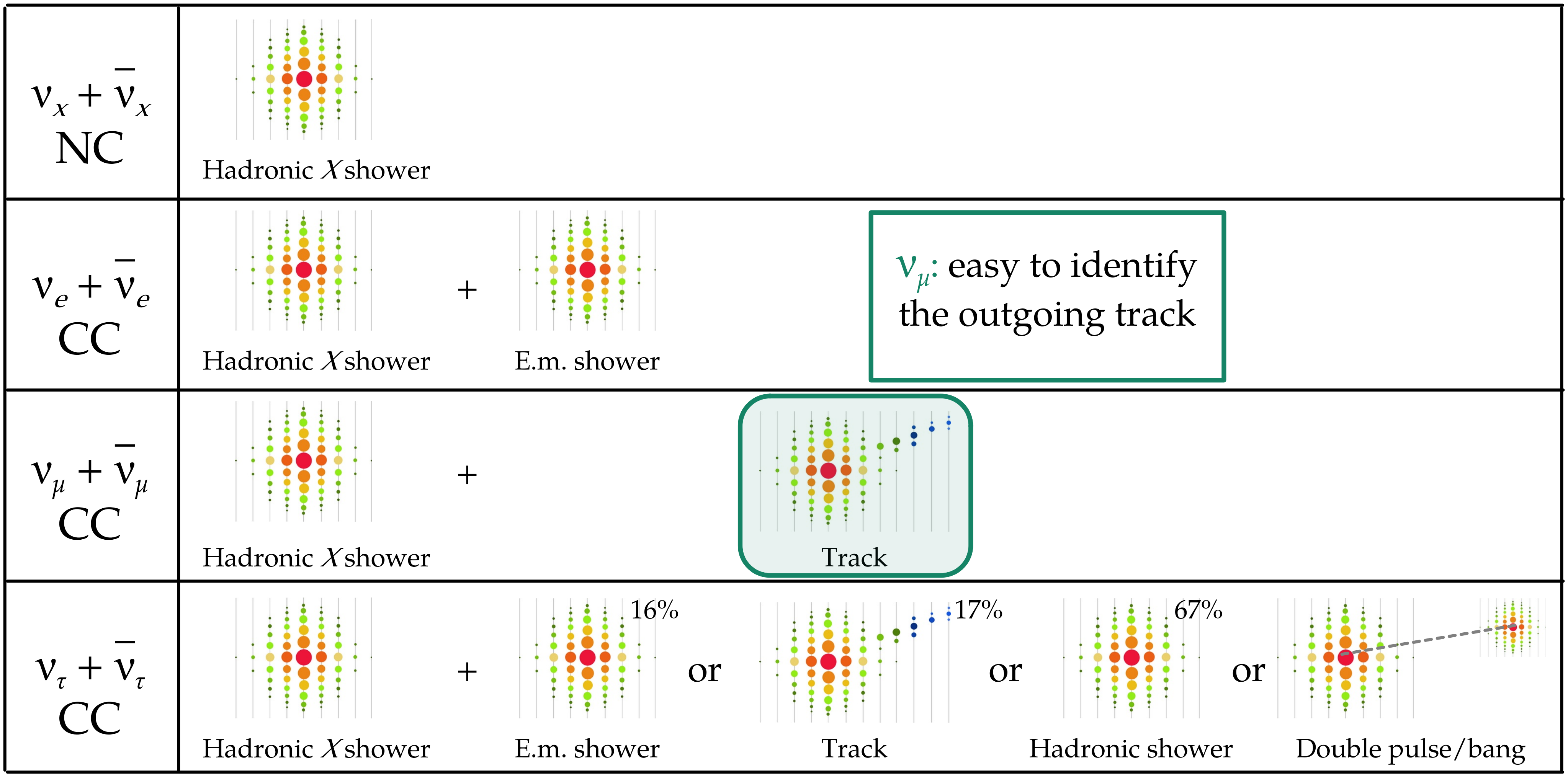
Varying over all possible flavor ratios at the source

Note:
All plots shown are for normal neutrino mass ordering (NO); inverted ordering looks similar

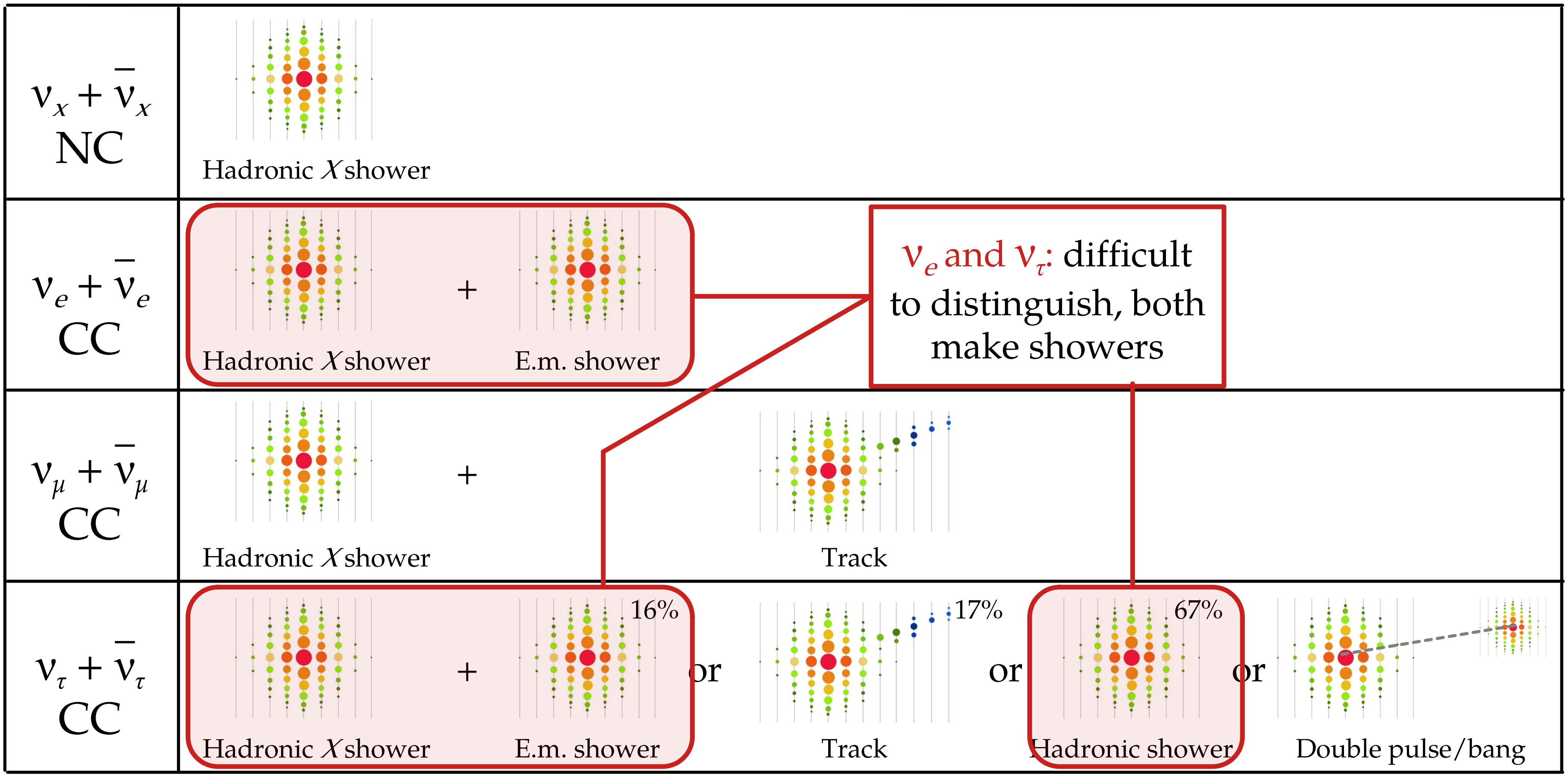
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
See also: **MB**, Beacom, Winter, *PRL* 2015

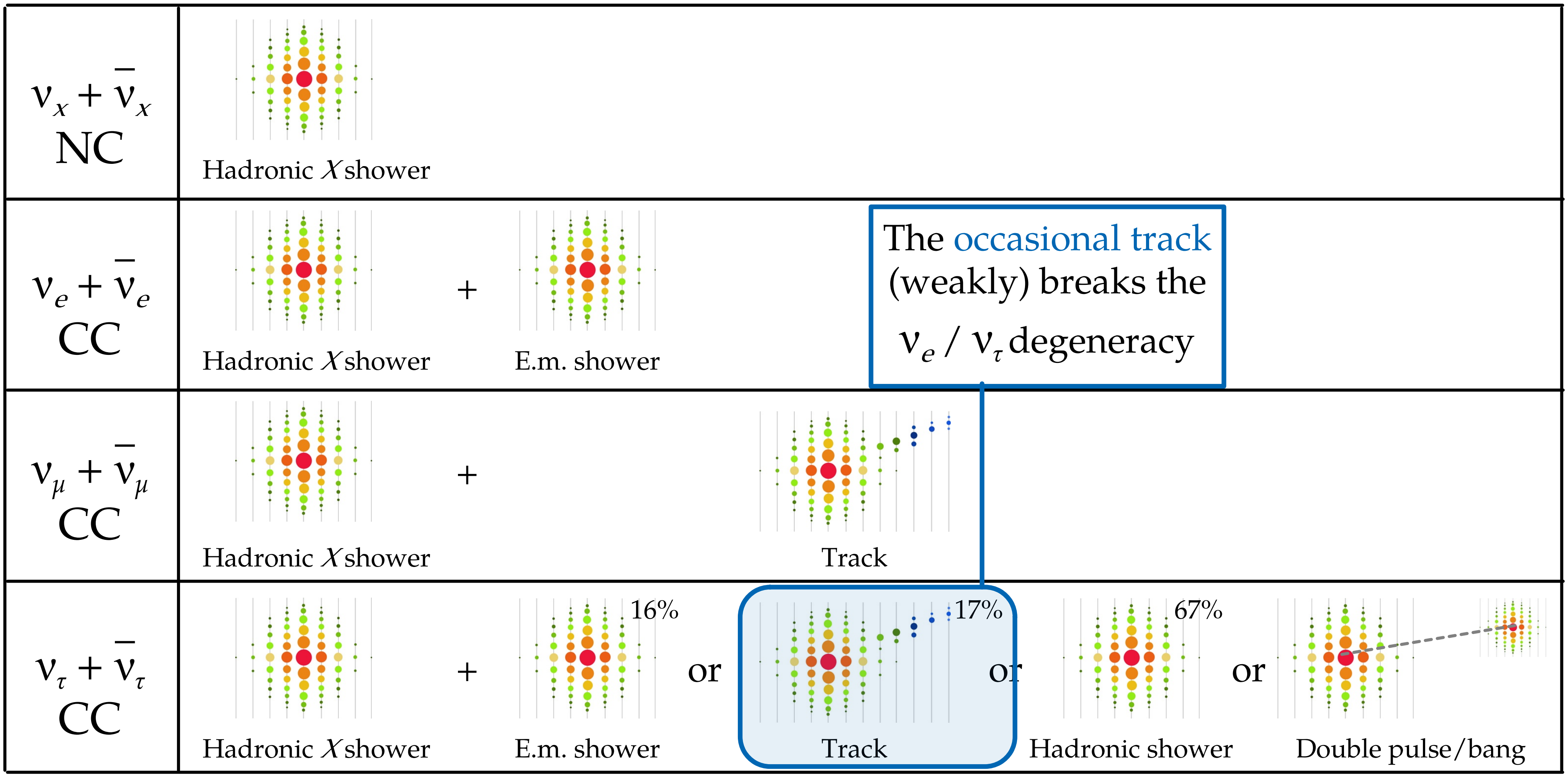


$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
or
Double pulse/bang



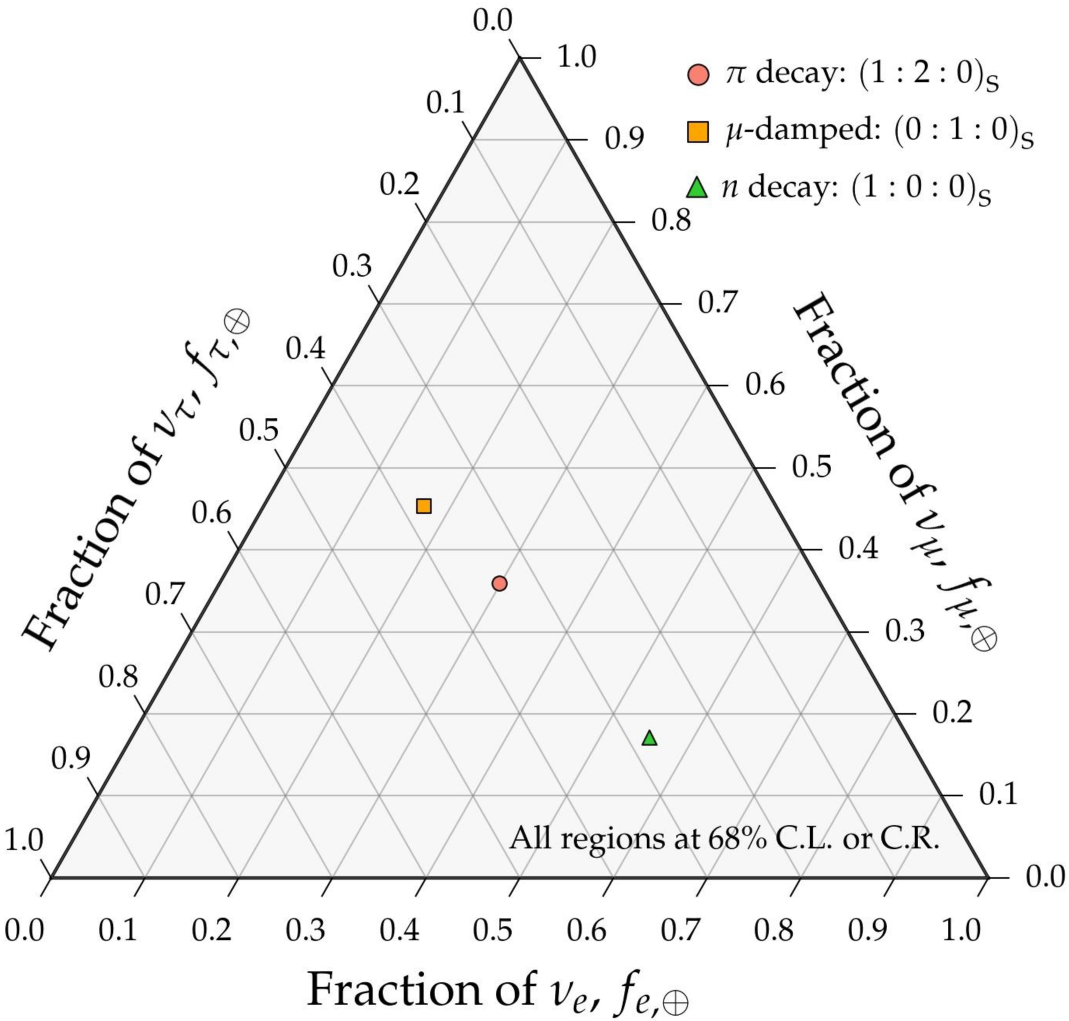
$\nu_x + \bar{\nu}_x$
NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$
CC
Hadronic X shower
+
E.m. shower
ν_μ: easy to identify the outgoing track
$\nu_\mu + \bar{\nu}_\mu$
CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$
CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
or
Double pulse/bang


$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
ν_e and ν_τ: difficult to distinguish, both make showers
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
E.m. shower
16%
or
Track
17%
or
Hadronic shower
67%
or
Double pulse/bang



$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
The occasional track (weakly) breaks the ν_e / ν_τ degeneracy
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
or
Double pulse/bang

Measuring flavor composition 2015–2025



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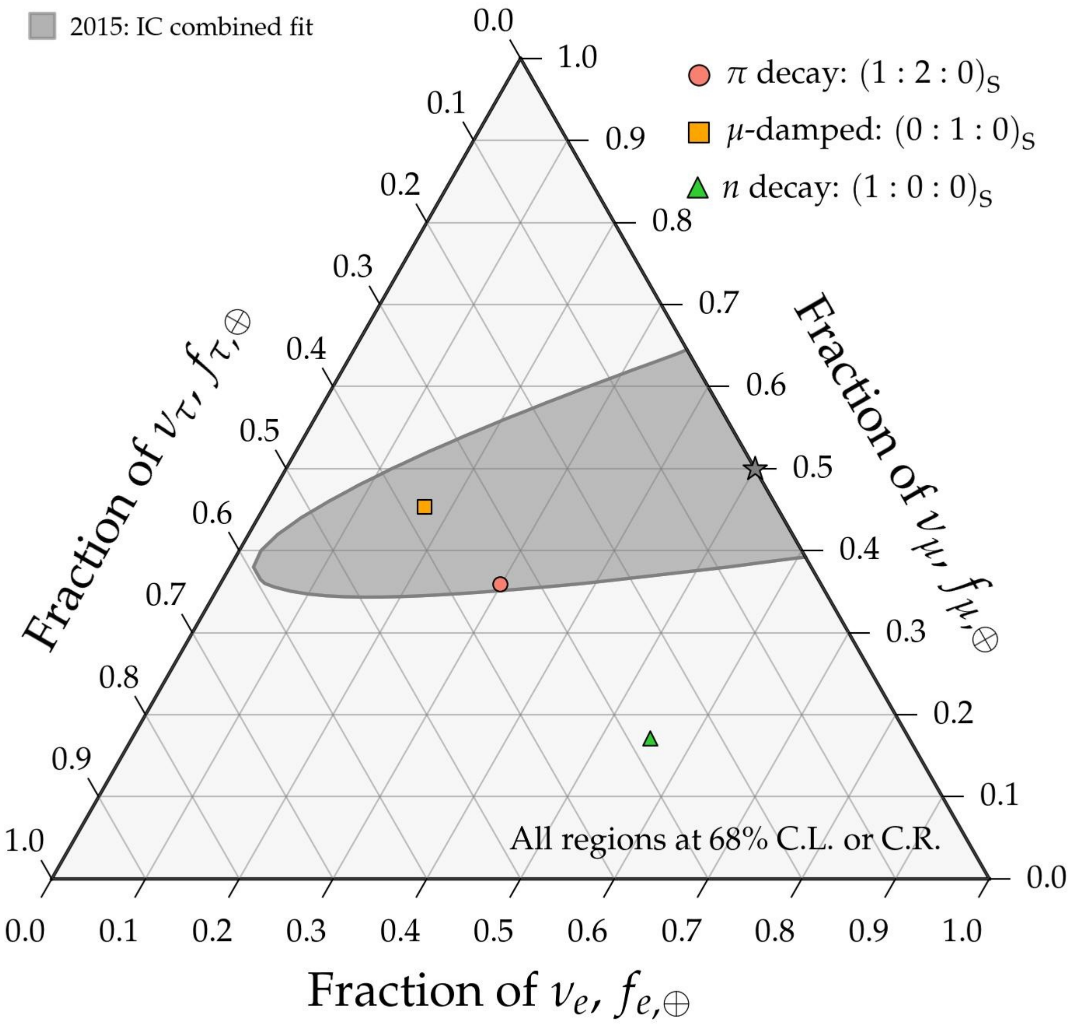

IceCube Collab., 2510.24957, 2507.06835,
EPJC 2022, PRD 2019, *ApJ* 2015, *PRL* 2015

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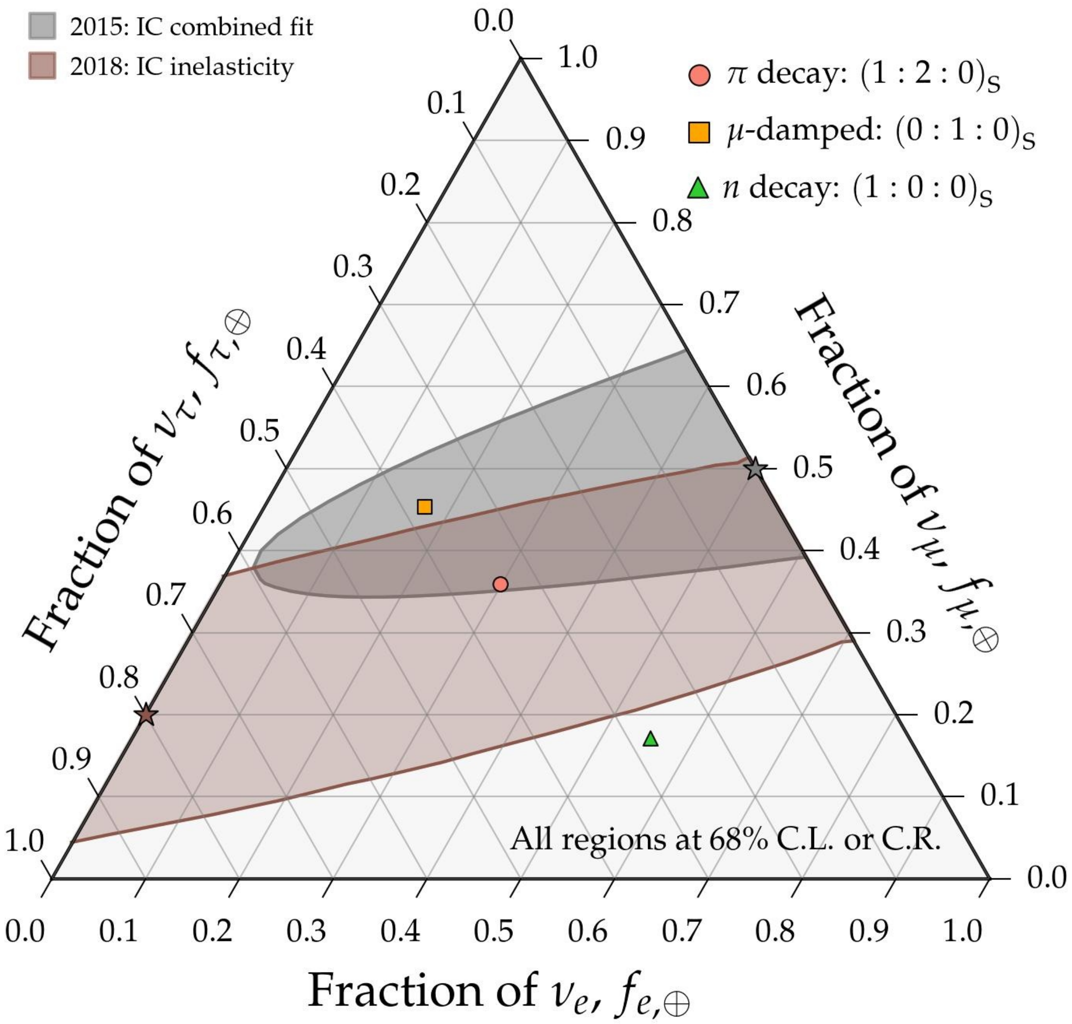

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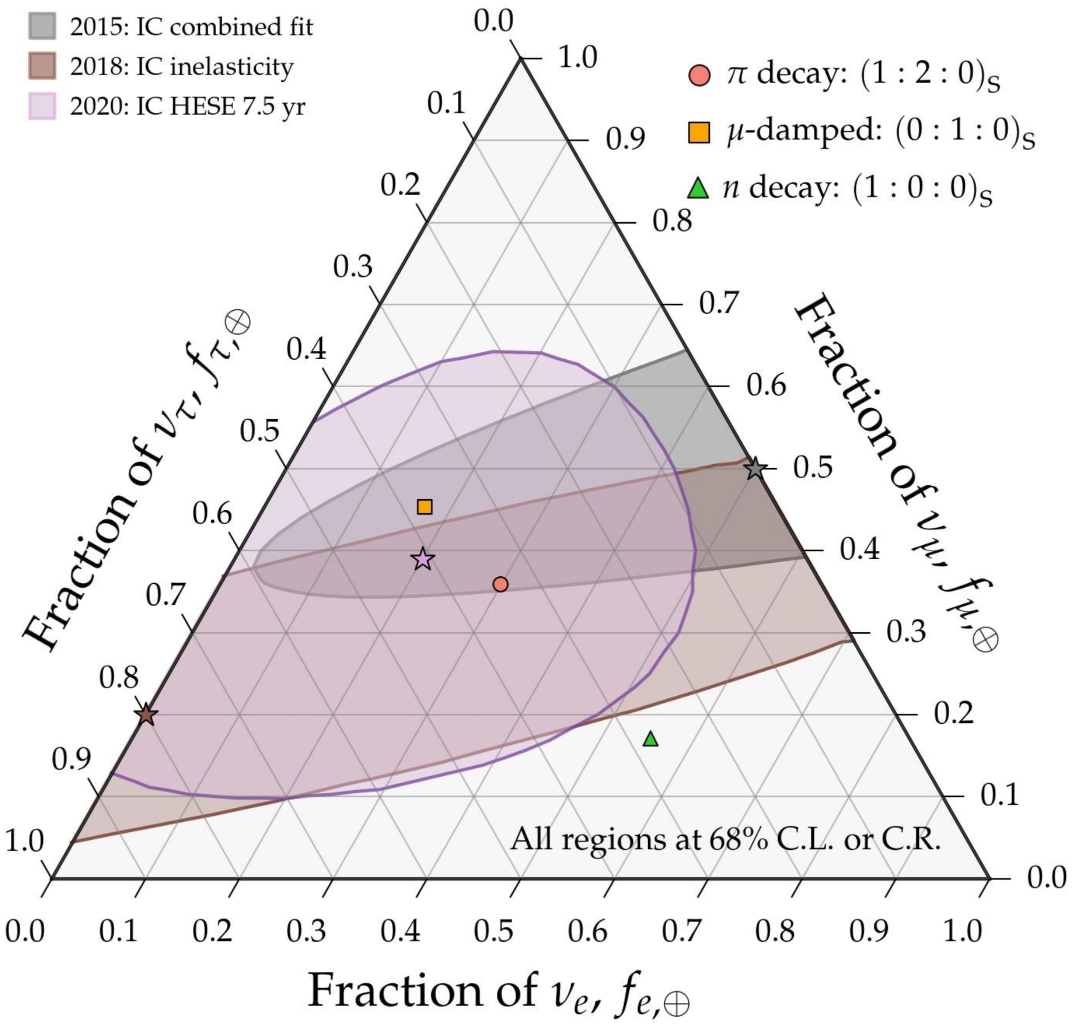

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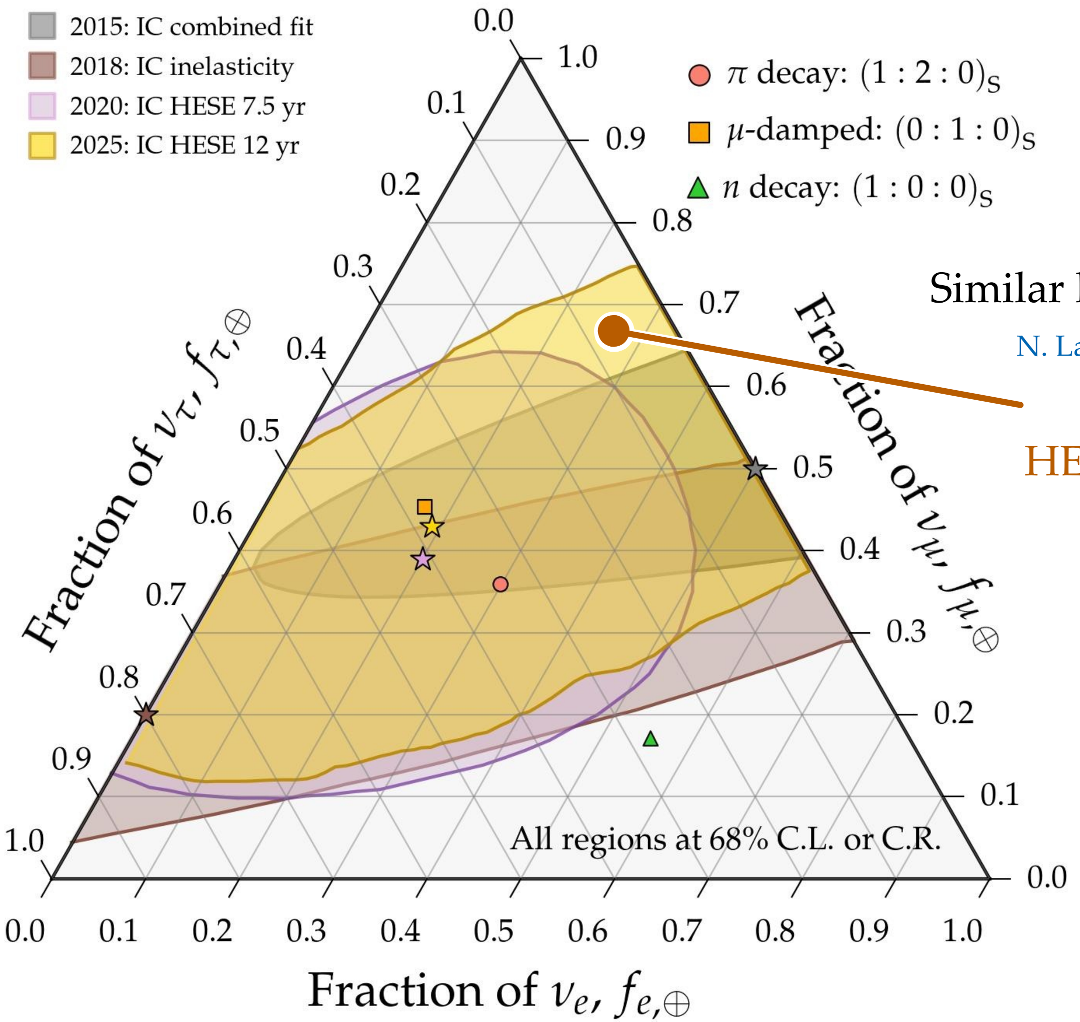

Similar likelihood as with 7.5 yr

N. Lad, T. J. van Eeden, M. Ackermann
PoS(ICRC2025)1198

HESE (> 60 TeV) are scarce
(~100 events in 12 yr)

IceCube Collab., 2510.24957, 2507.06835,
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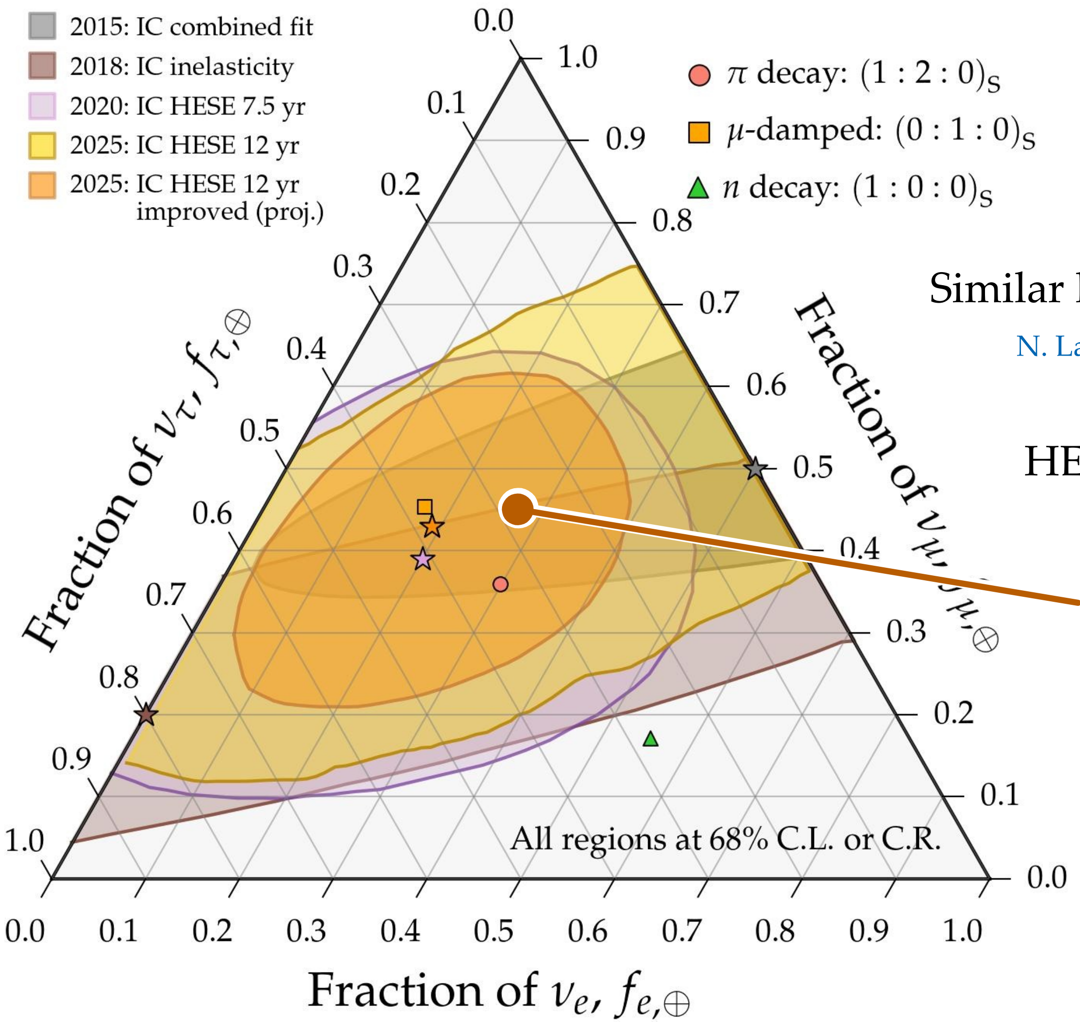

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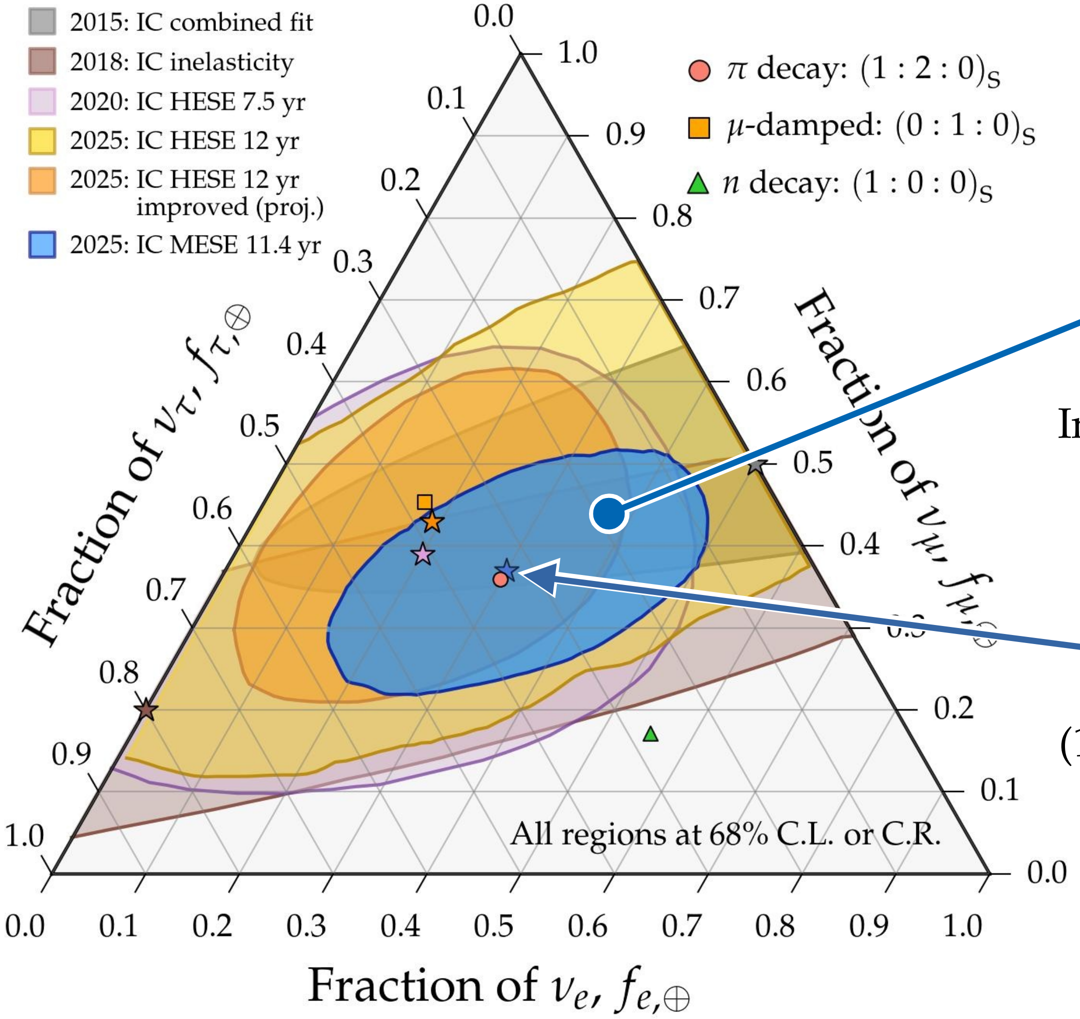
PoS(ICRC2025)1198

HESE (> 60 TeV) are scarce (~100 events in 12 yr)

Improve via a neural network that uses the energy asymmetry of the two bangs and the direction

IceCube Collab., 2510.24957, 2507.06835, *EPJC* 2022, PRD 2019, *ApJ* 2015, *PRL* 2015

Measuring flavor composition 2015–2025



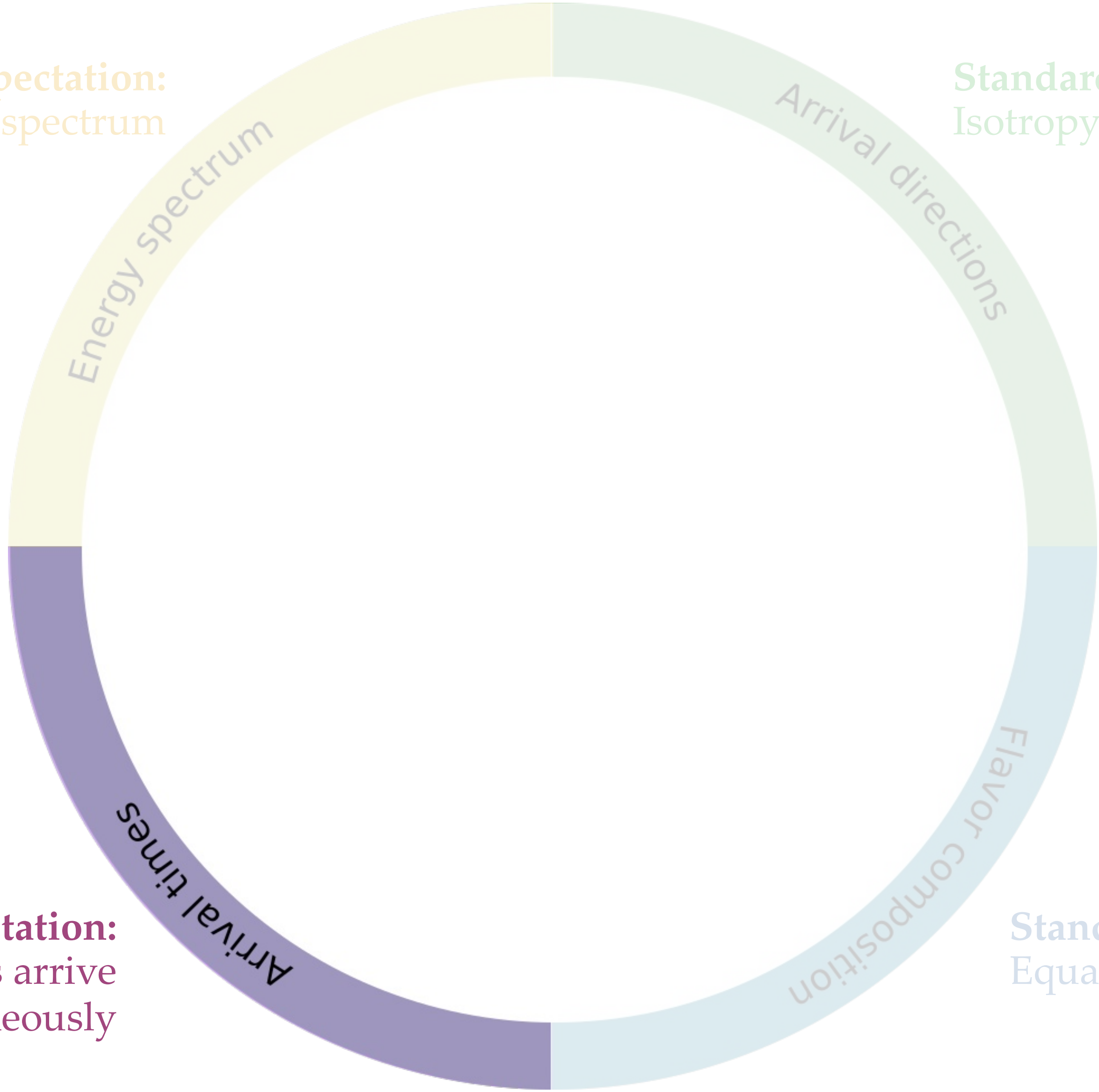
MESE events (> 1 TeV) are more abundant

Includes classification of υ_τ

First time all flavors are nonzero at 68% C.L.

Best fit very close to nominal expectation of (1:1:1) from production via pion decay

IceCube Collab., 2510.24957, 2507.06835, *EPJC* 2022, PRD 2019, *ApJ* 2015, *PRL* 2015



Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Bright in gamma rays, bright in high-energy neutrinos

Energy in neutrinos $\propto$ energy in gamma rays

$$\int_0^\infty \mathrm{d}E_\nu E_\nu F_\nu(E_\nu) = \frac{1}{8}\left[1 - \left(1 - \langle x_{p\to\pi}\rangle\right)^{\tau_{p\gamma}}\right] \frac{f_p}{f_e} \int_{1\ \mathrm{keV}}^{10\ \mathrm{MeV}} \mathrm{d}E_\gamma E_\gamma F_\gamma(E_\gamma)$$

E. Waxman & J. Bahcall, *PRL* 1997
D. Guetta *et al.*, *Astropart. Phys.* 2004

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Baryonic loading

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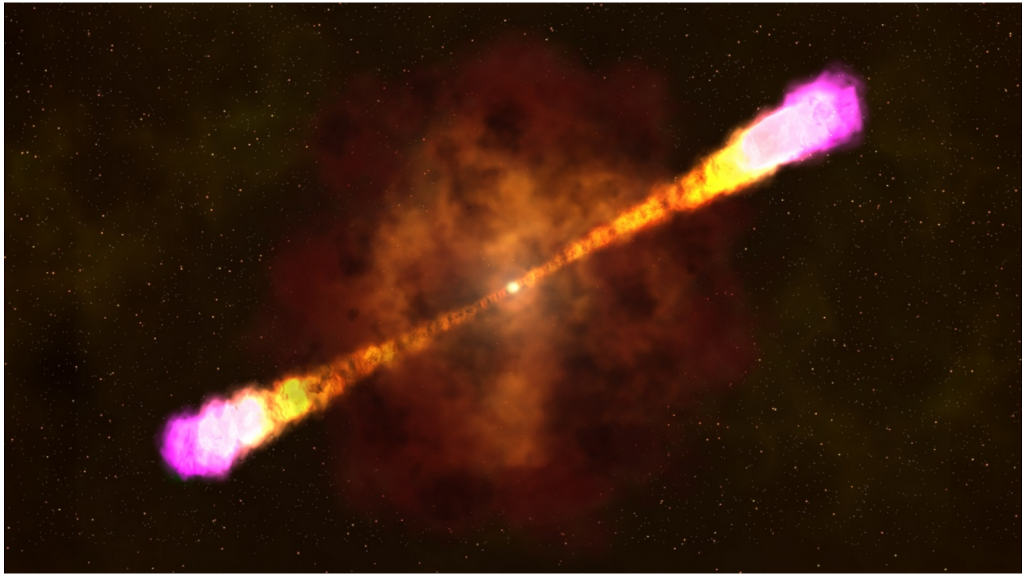
Baryonic loading

Optical depth to $p\gamma$: $$\tau_{p\gamma} = \left(\frac{L_\gamma^{\mathrm{iso}}}{10^{52}\mathrm{erg s}^{-1}}\right) \left(\frac{0.01}{t_{\mathrm{v}}}\right) \left(\frac{300}{\Gamma}\right)^4 \left(\frac{\mathrm{MeV}}{\epsilon_{\gamma,\mathrm{break}}}\right)$$

E. Waxman & J. Bahcall, *PRL* 1997
D. Guetta *et al.*, *Astropart. Phys.* 2004

Gamma-ray bursts and blazars – *not* dominant

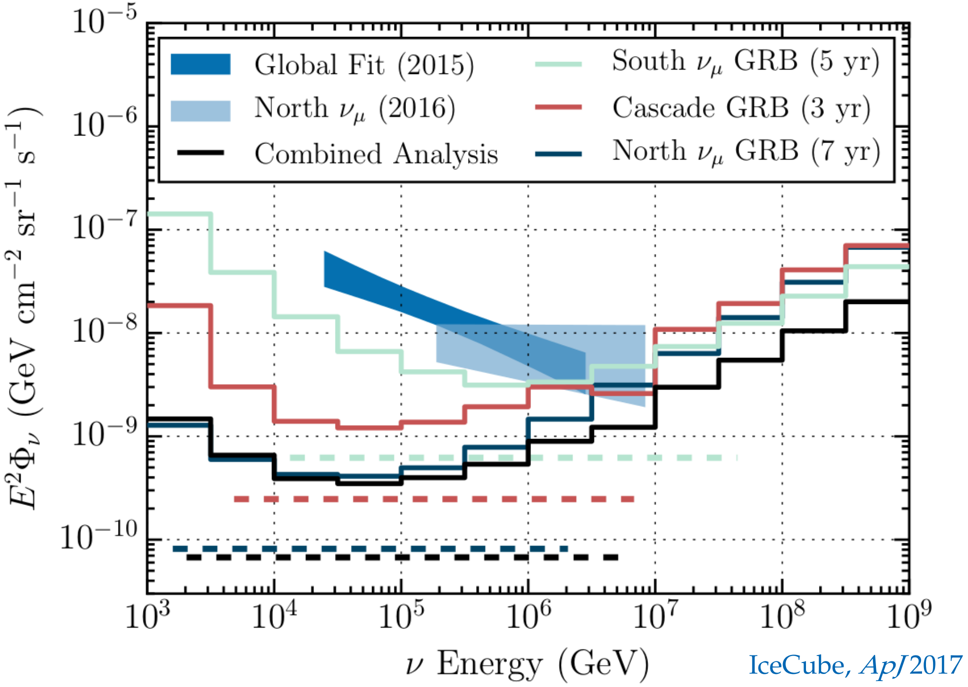
Gamma-ray bursts



Blazars

Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts

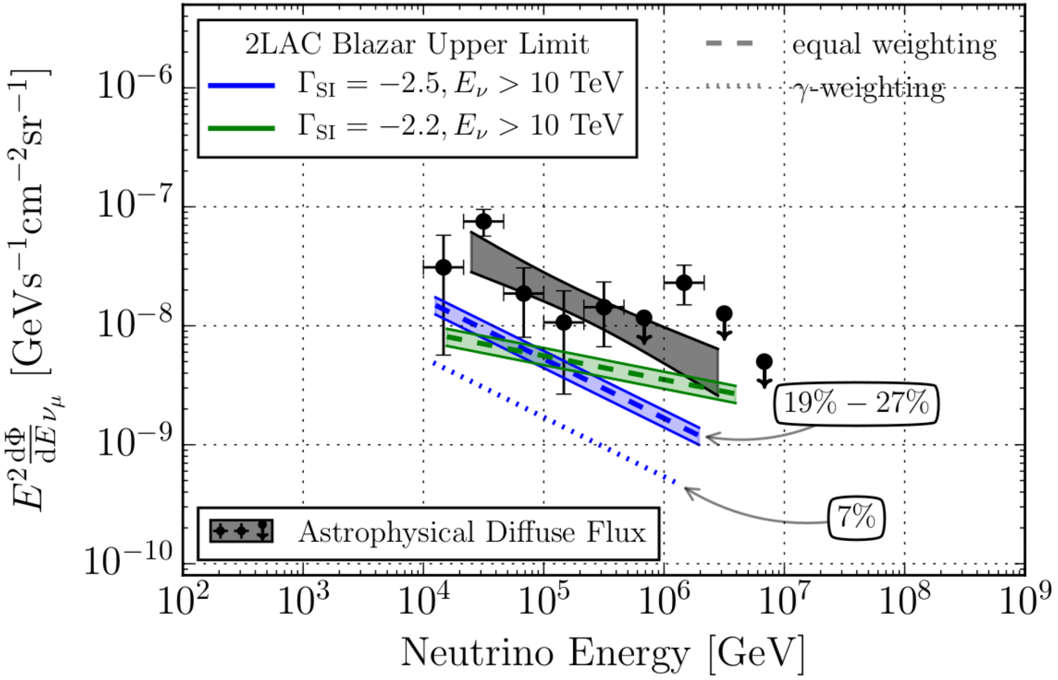


IceCube, *ApJ* 2017

1172 GRBs inspected, no correlation found

< 1% contribution to diffuse flux

Blazars



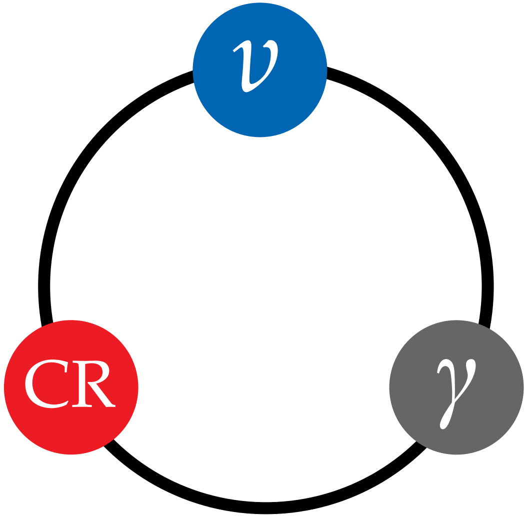
862 blazars inspected, no correlation found

< 27% contribution to diffuse flux

Bright in gamma rays, bright in high-energy neutrinos (?)

Energy in neutrinos ∝ energy in gamma rays

Waxman & Bahcall, *PRL* 1997



Bright in gamma rays, bright in high-energy neutrinos (?)

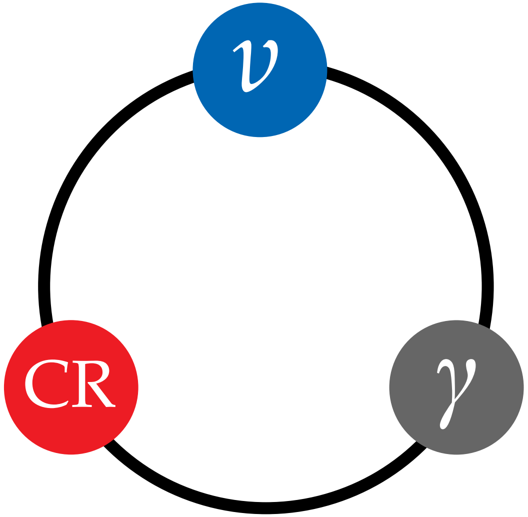
Energy in neutrinos $\propto$ energy in gamma rays

Waxman & Bahcall, *PRL* 1997

Fudge factors:

Source properties (*e.g.*, baryonic loading)

Particle effects (*e.g.*, ν-producing channels)



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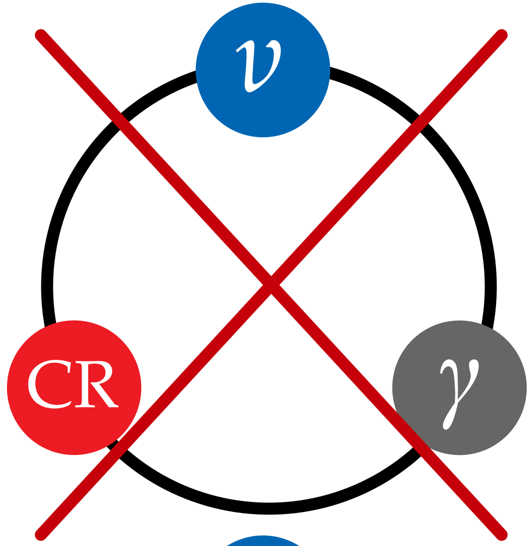
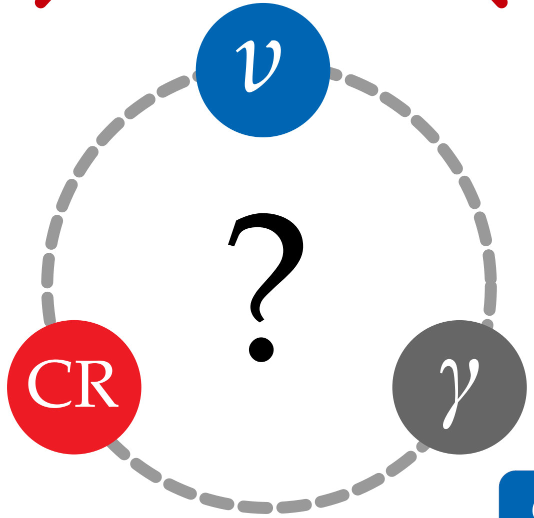


But the correlation between ν and γ may be more nuanced:

Gao, Pohl, Winter, *ApJ* 2017



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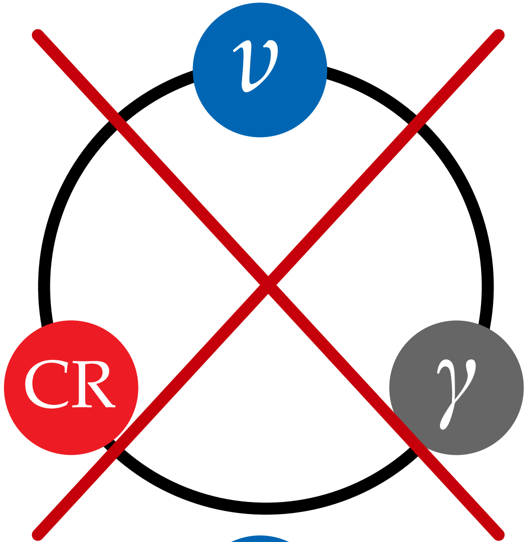


But the correlation between ν and γ may be more nuanced:

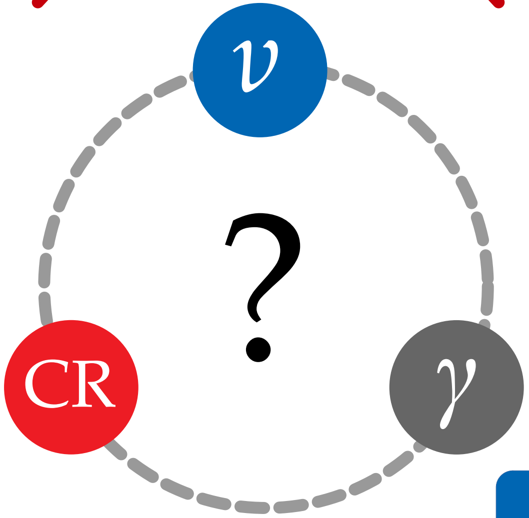
Gao, Pohl, Winter, *ApJ* 2017

Sources that make neutrinos via *p*γ
may be opaque to 1–100 MeV gamma rays

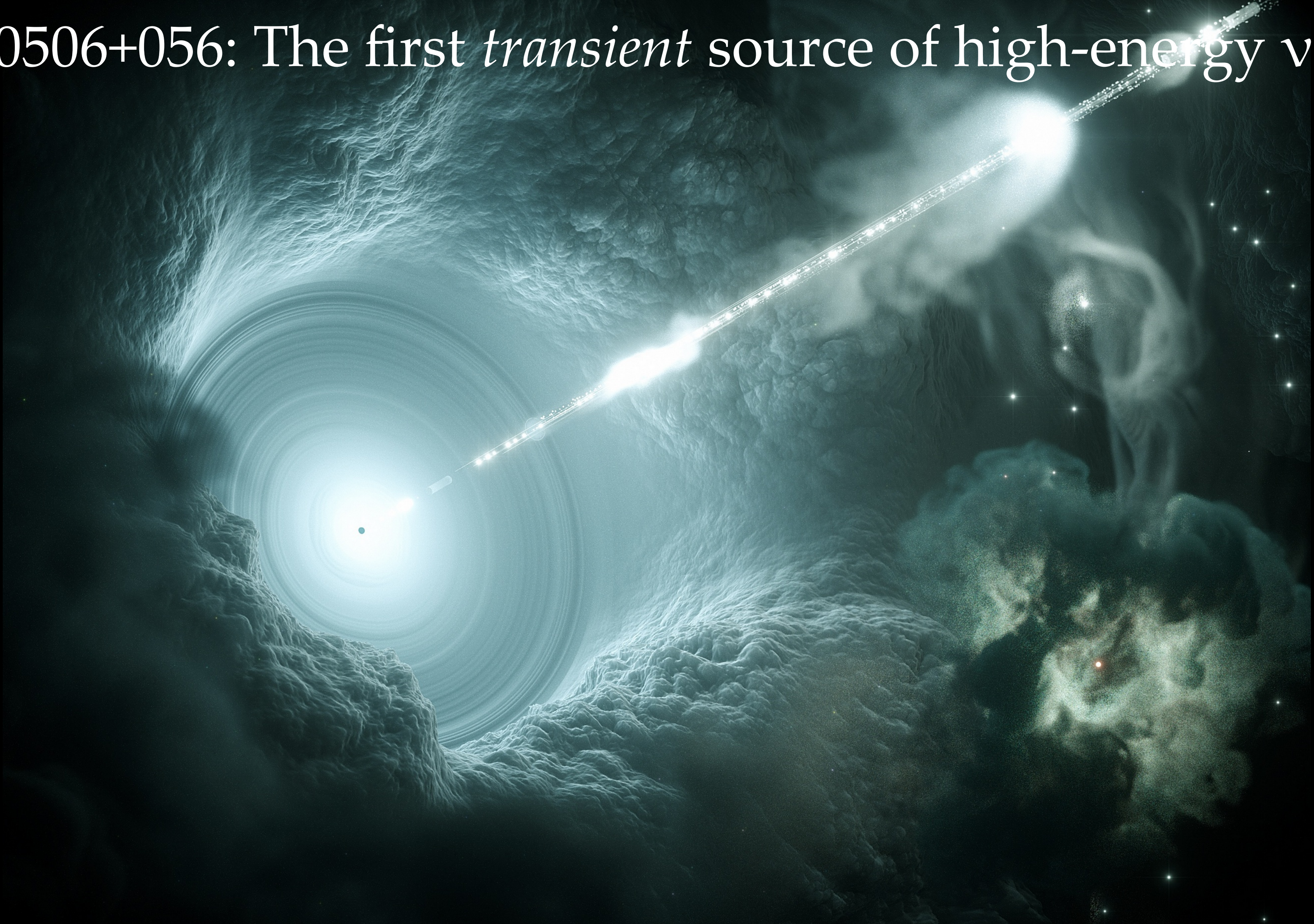
Murase, Guetta, Ahlers, *PRL* 2016

Modeling of *p*γ interactions & nuclear cascading
in the sources is complex and uncertain

Morejon, Fedynitch, Boncioli, Winter, *JCAP* 2019
Boncioli, Fedynitch, Winter, *Sci. Rep.* 2017



TXS 0506+056: The first *transient* source of high-energy ν

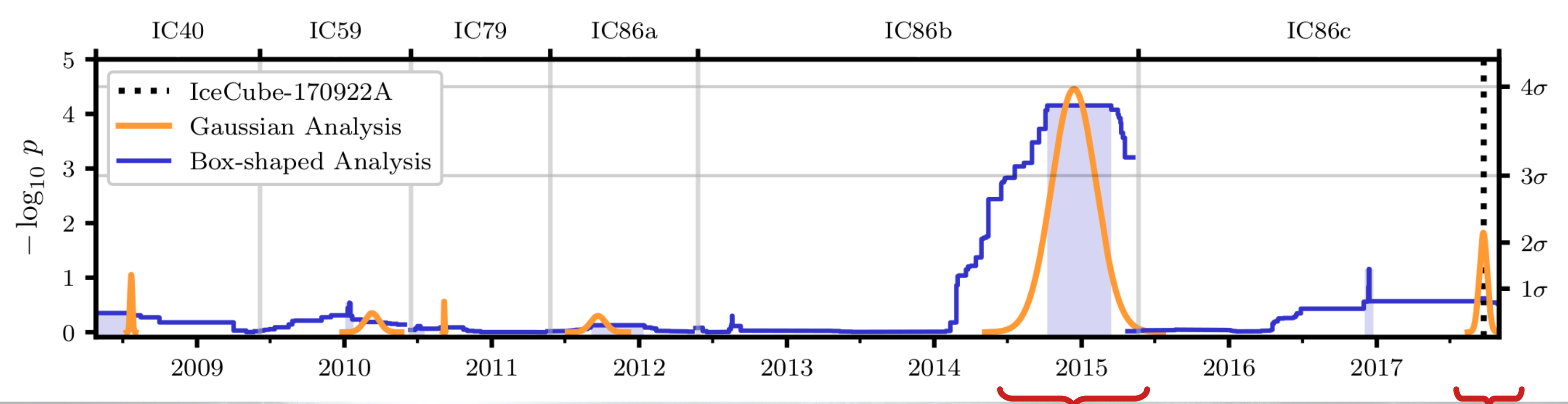


DESY

TXS 0506+056: The first *transient* source of high-energy ν

Blazar TXS 0506+056:

IceCube, *Science* 2018



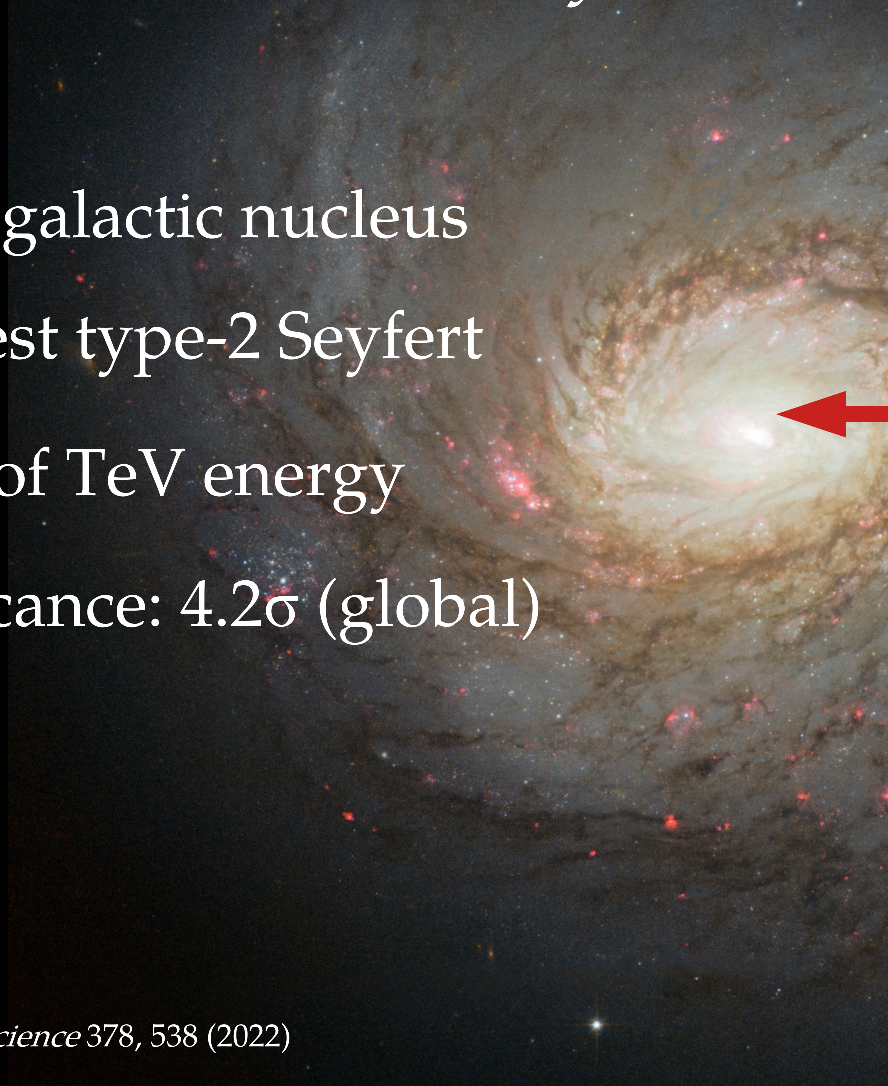
After re-analysis (2101.09836), significance dropped from $p=7\times10^{-5}$ to $p=8\times10^{-3}$

2014–2015: 13±5 ν flare, no X-ray flare
3.5σ significance of correlation (post-trial)

2017: one 290-TeV ν + X-ray flare
1.4σ significance of correlation

Combined (pre-trial): 4.1σ

NGC1068: The first *steady-state* source of high-energy ν

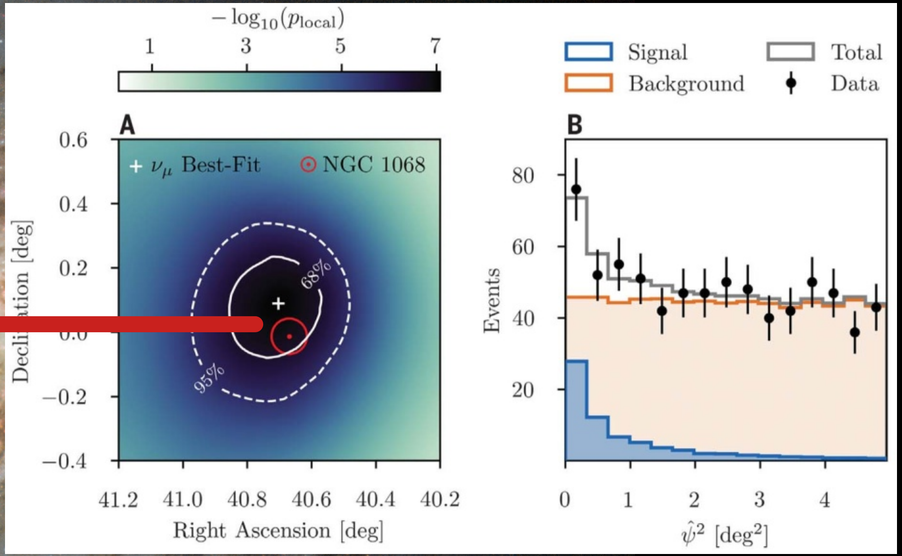


Active galactic nucleus

Brightest type-2 Seyfert

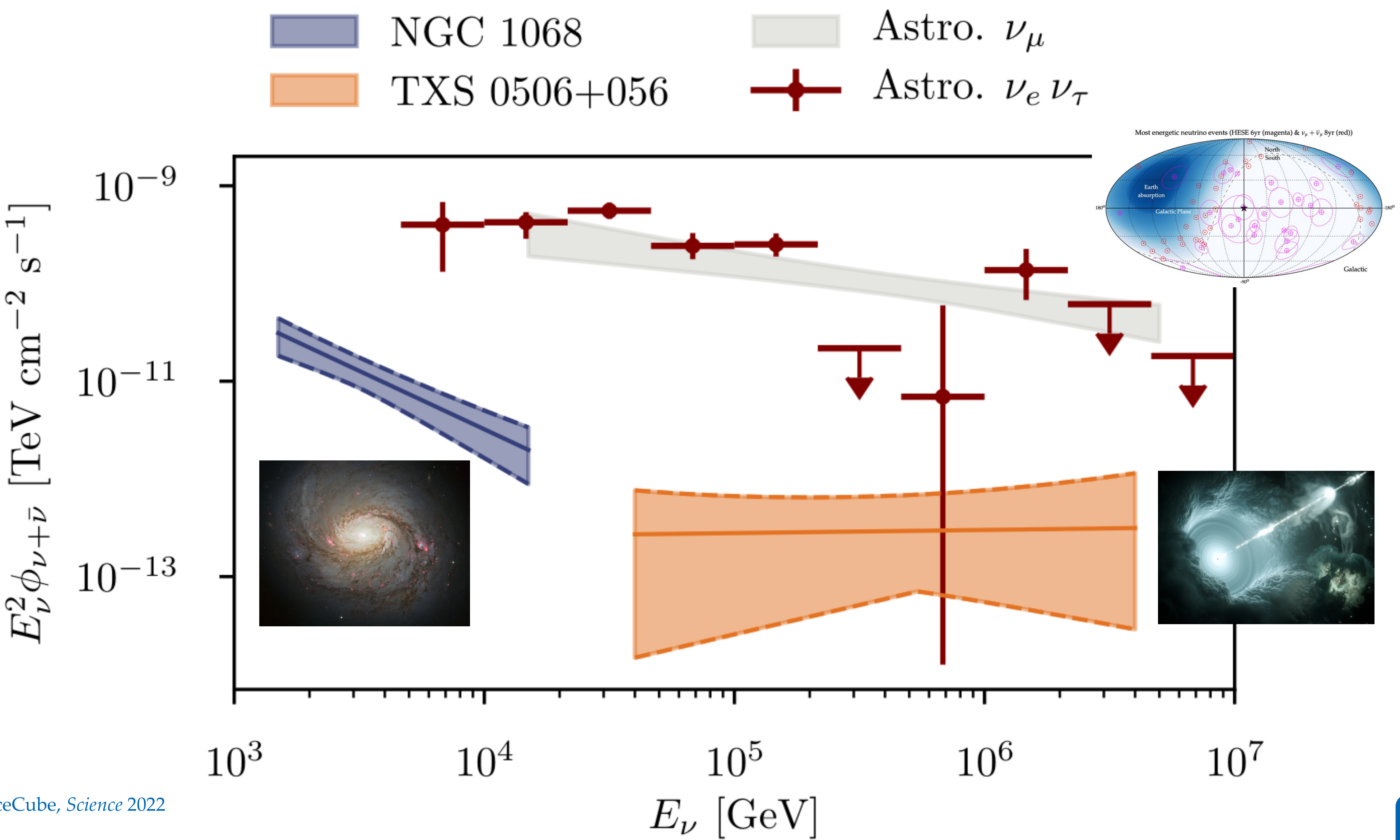
79^{+22}_{-20} ν of TeV energy

Significance: 4.2σ (global)



IceCube Collab., *Science* 378, 538 (2022)

Hubble Space Telescope,
NASA, ESA & A. van der Hoeven



IceCube, *Science* 2022

Pushing ν physics to the cosmic frontier

Fundamental physics with high-energy cosmic neutrinos

Numerous new ν physics effects grow as ~ $\kappa_n \cdot E^n \cdot L$

If BSM effects are comparable in size to SM effects, then we can probe

$$\kappa_n \sim 10^{-47} \left(\frac{E}{\mathrm{PeV}}\right)^{-n} \left(\frac{L}{\mathrm{Gpc}}\right)^{-1} \mathrm{PeV}^{1-n}$$

With 1-PeV ν: $\kappa_2 \sim 10^{-47}$ PeV^{-1} With 100-PeV ν: $\kappa_2 \sim 10^{-51}$ PeV^{-1}

Orders-of-magnitude improvement

Fundamental physics with high-energy cosmic neutrinos

Numerous new ν physics effects grow as ~ $\kappa_n \cdot E^n \cdot L$

E.g.,
n = -1: neutrino decay
n = 0: CPT-odd Lorentz violation
n = +1: CPT-even Lorentz violation

If BSM effects are comparable in size to SM effects, then we can probe

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Orders-of-magnitude improvement

Note: Not an exhaustive list

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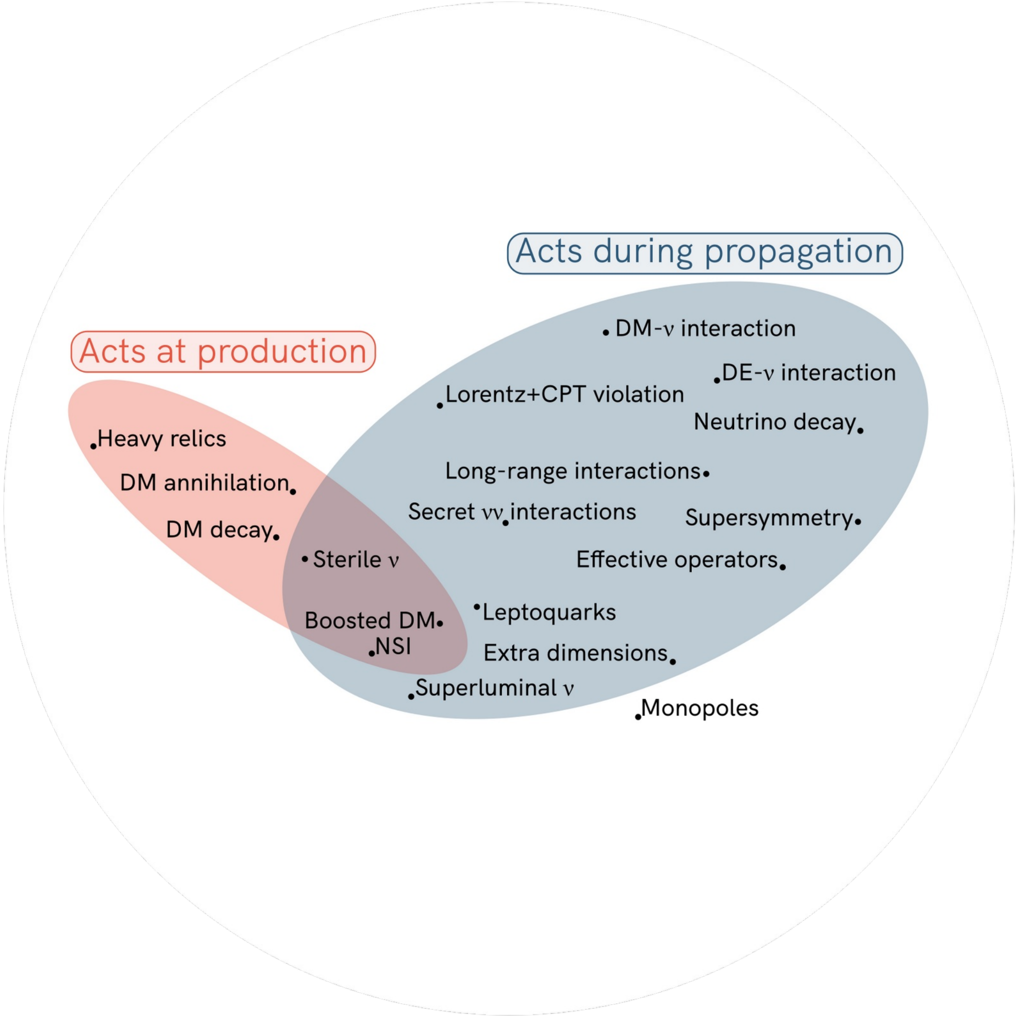
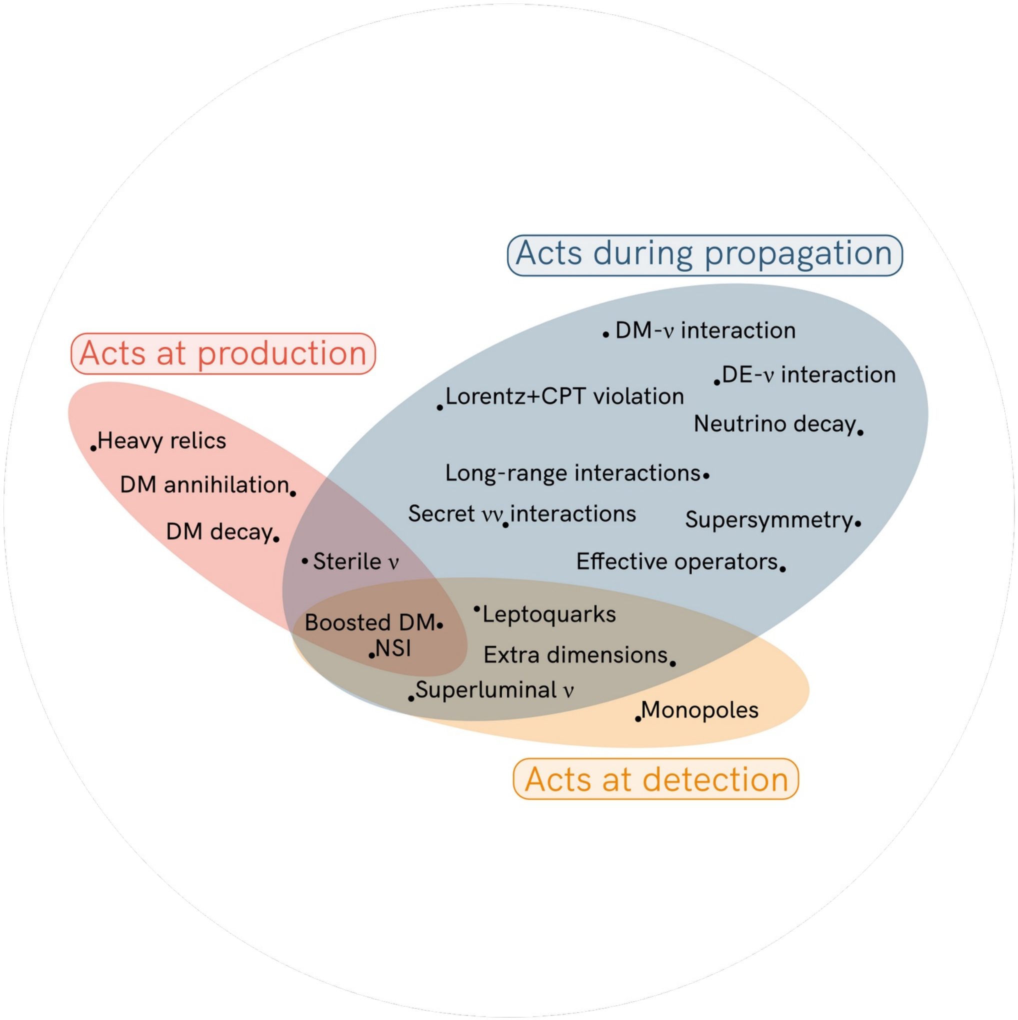
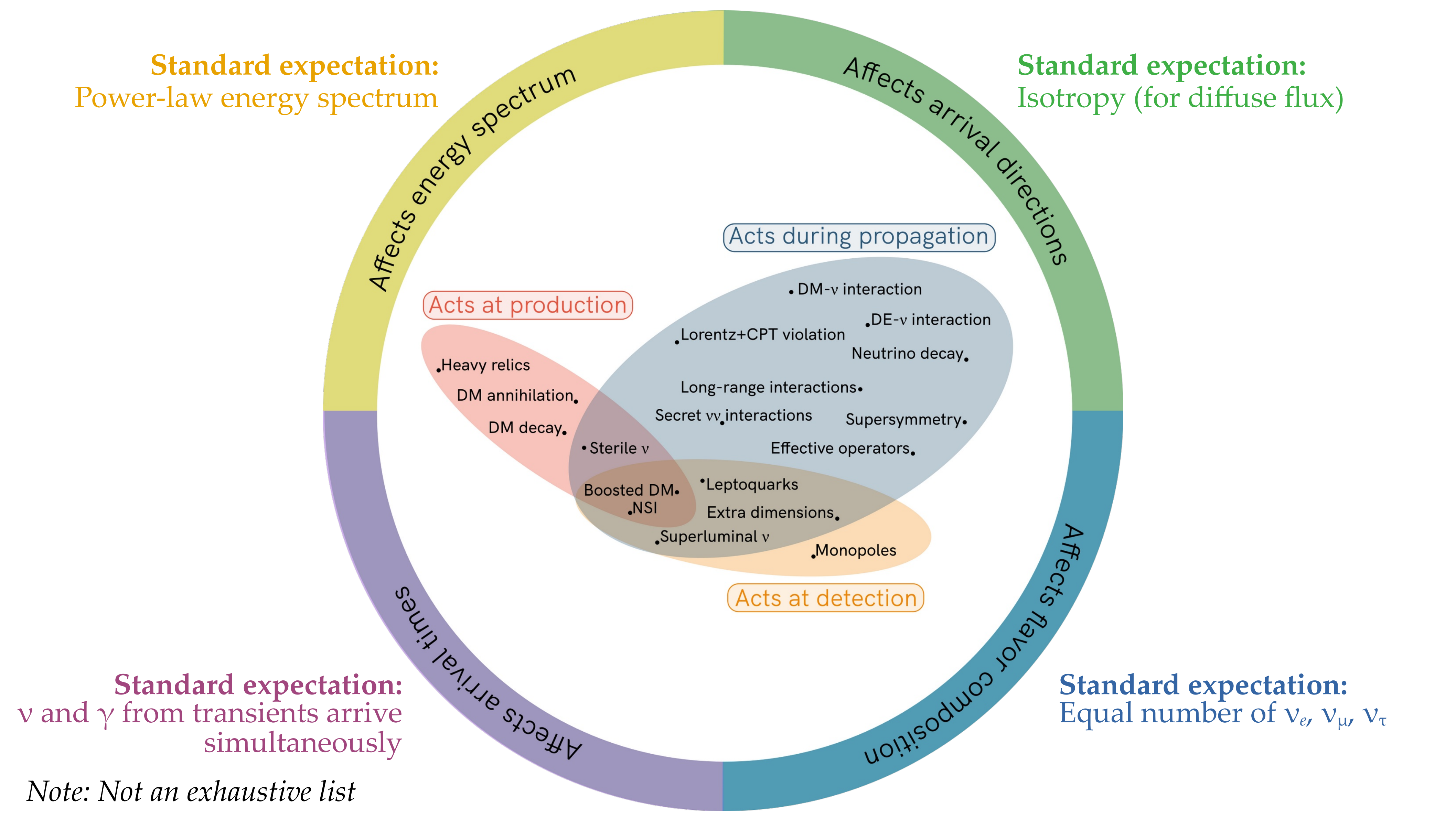
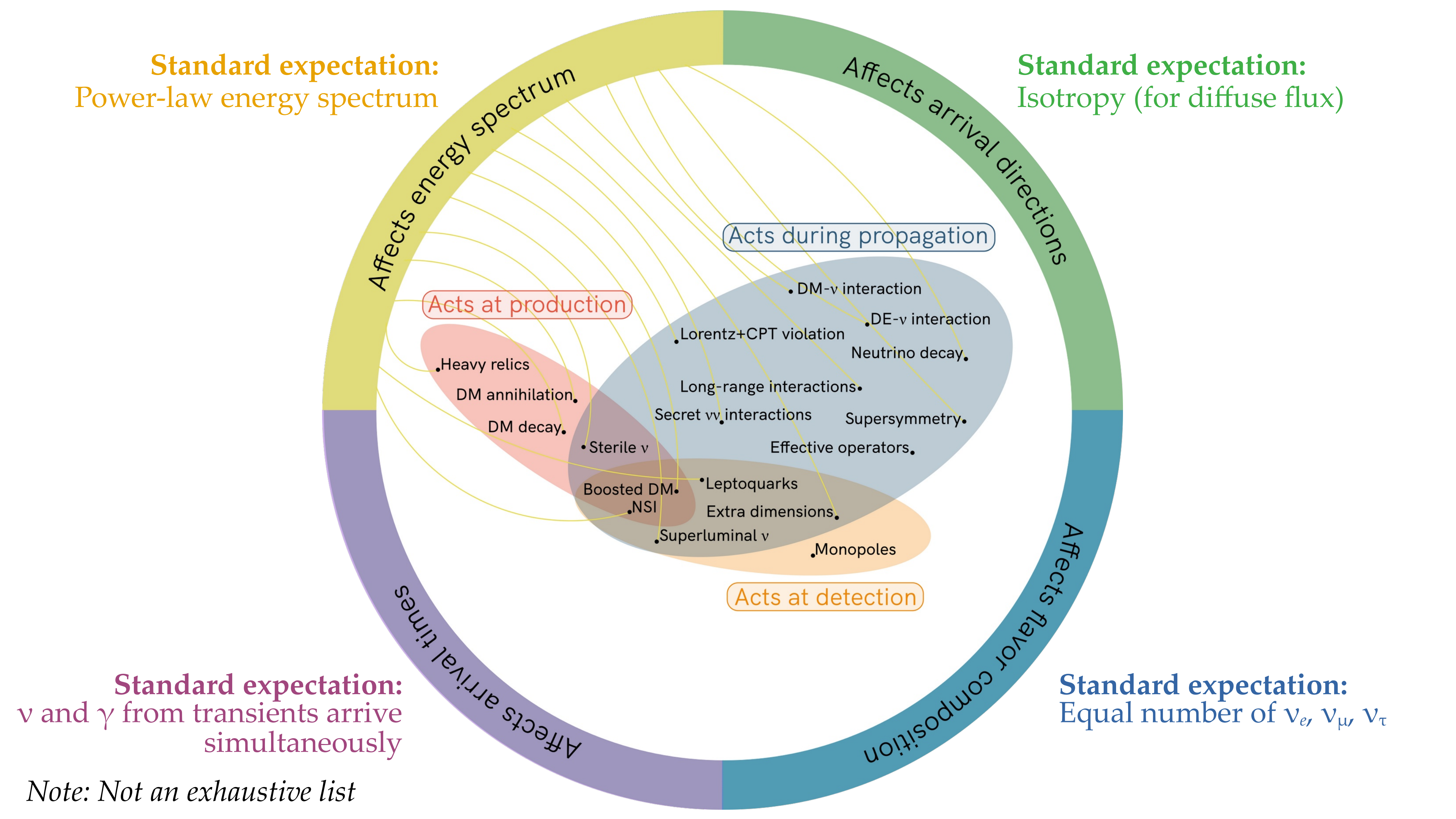


Note: Not an exhaustive list



Note: Not an exhaustive list


Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Acts during propagation
Acts at production
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Heavy relics
DM annihilation
DM decay
Long-range interactions
Secret νν interactions
Supersymmetry
Sterile ν
Effective operators
Leptoquarks
Boosted DM
NSI
Extra dimensions
Superluminal ν
Monopoles
Acts at detection
Affects arrival times
Affects flavor composition
Standard expectation:
ν and γ from transients arrive simultaneously
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ
Note: Not an exhaustive list



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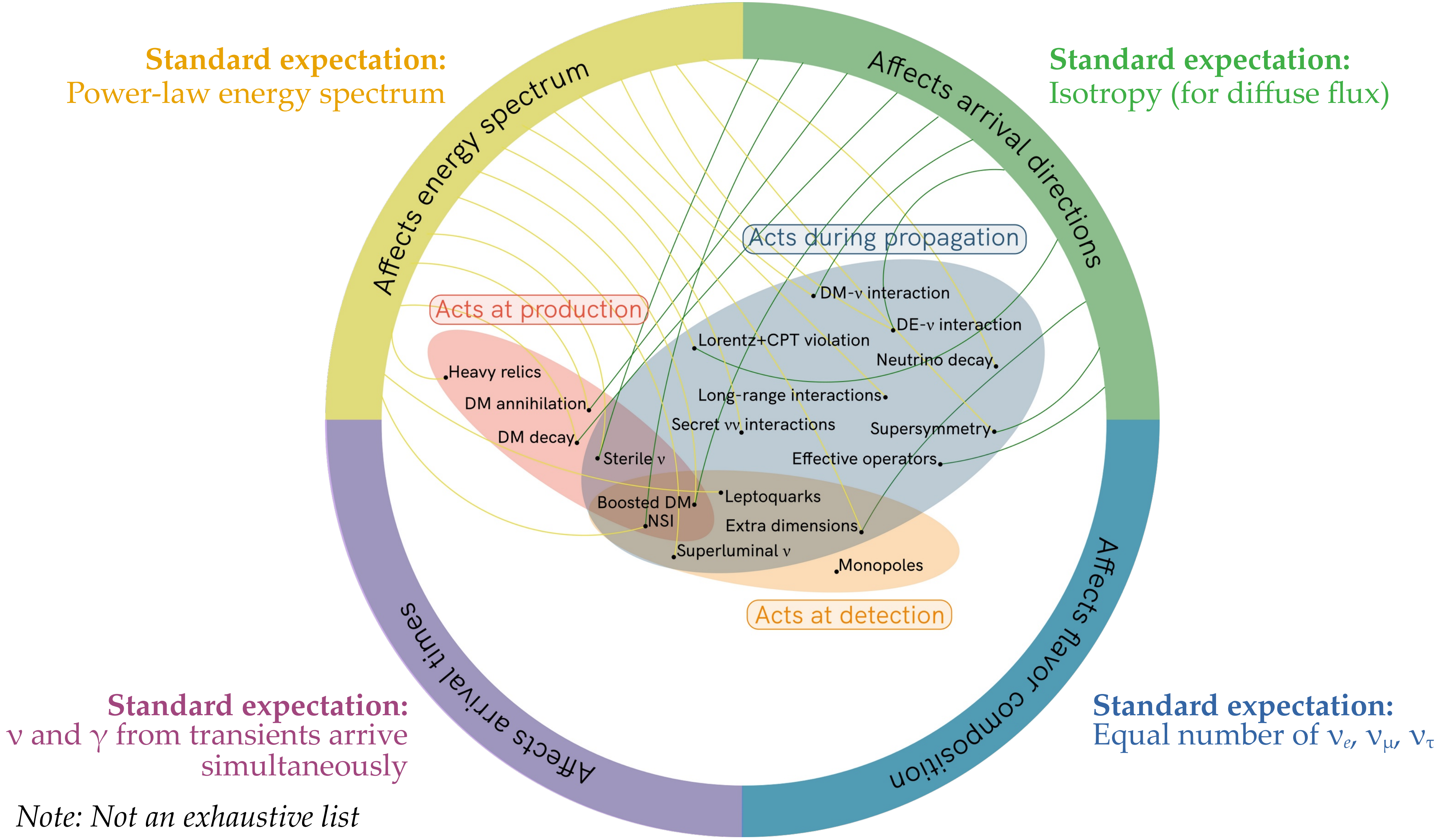
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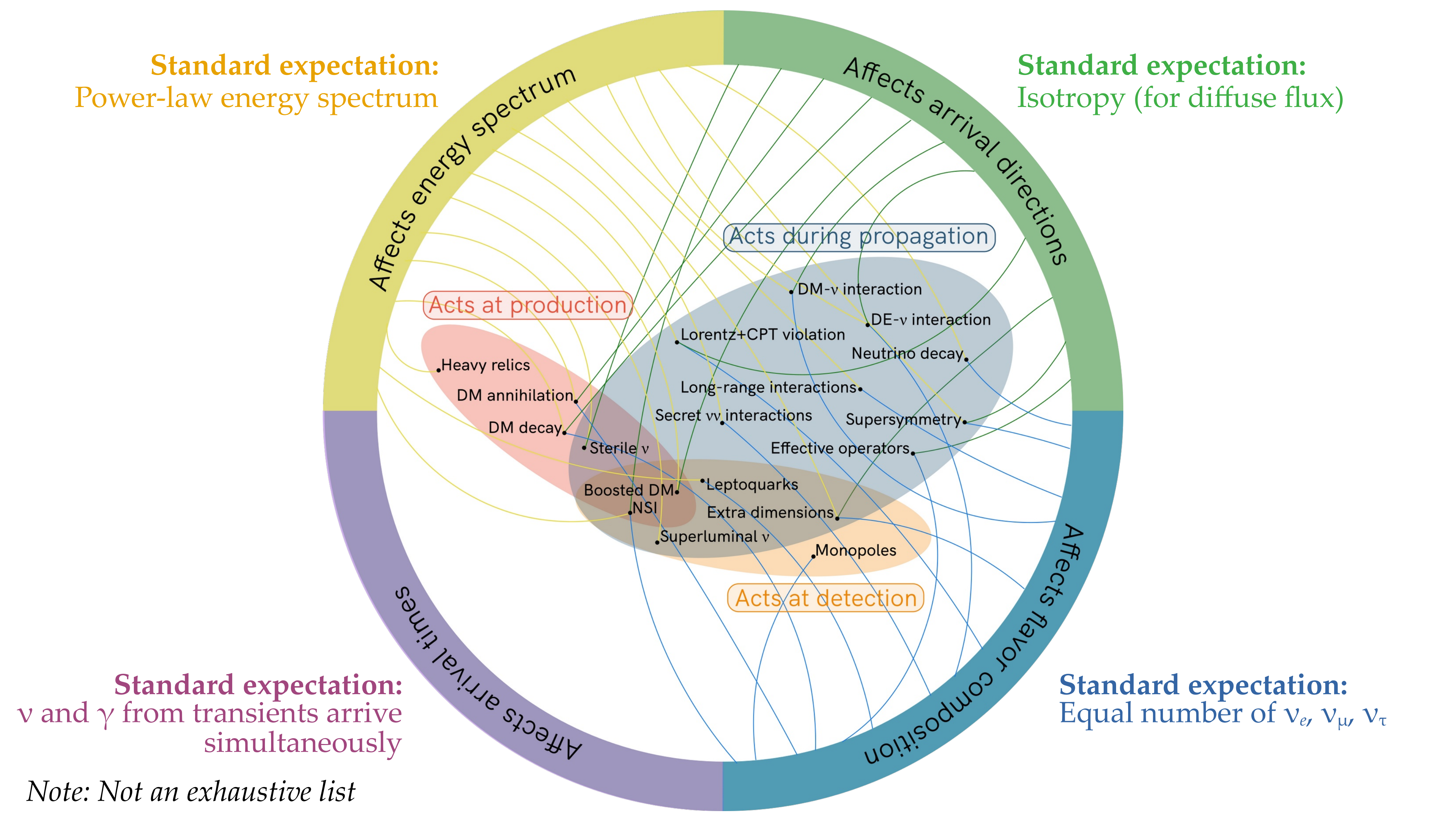
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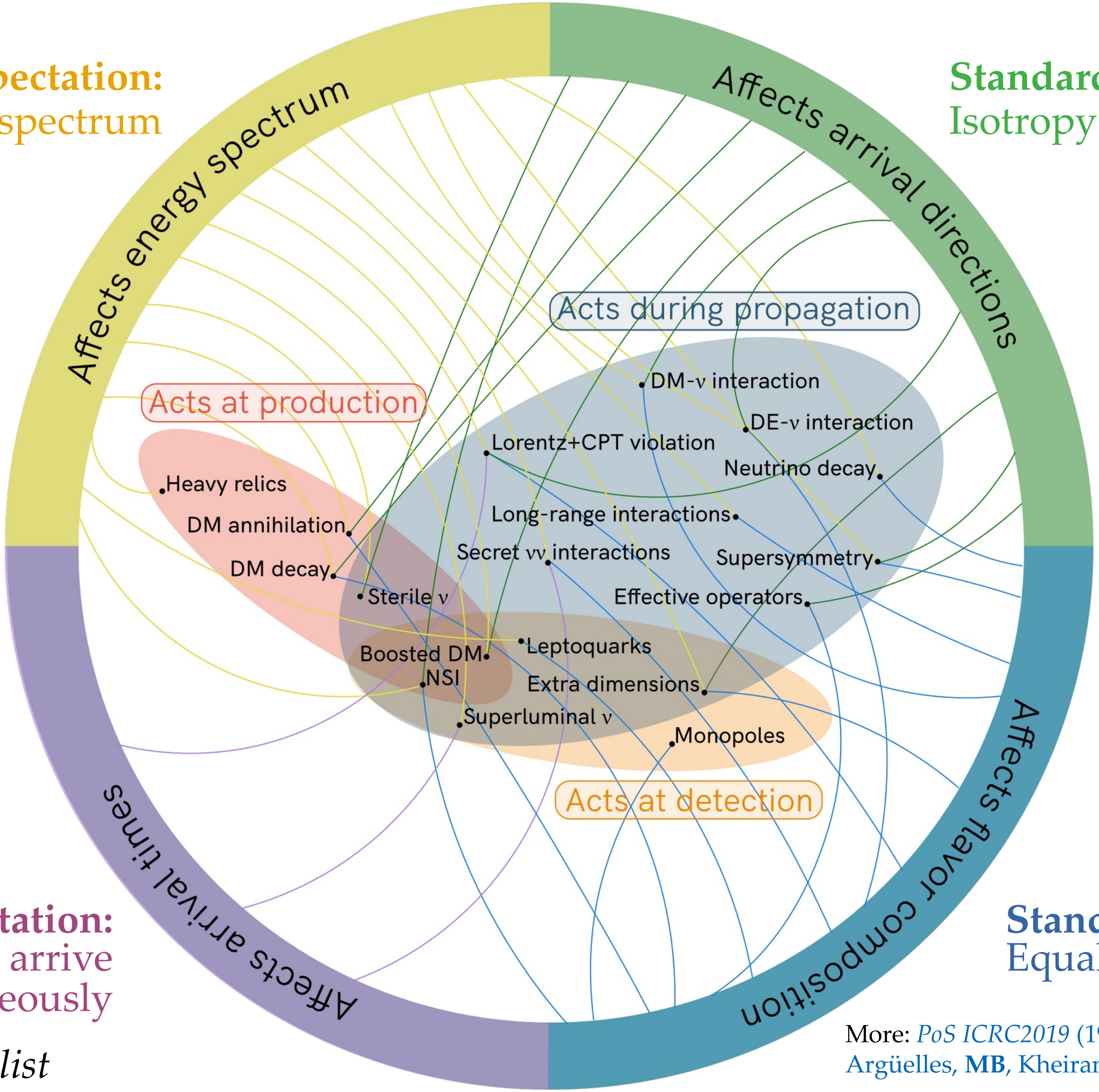

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Note: Not an exhaustive list

More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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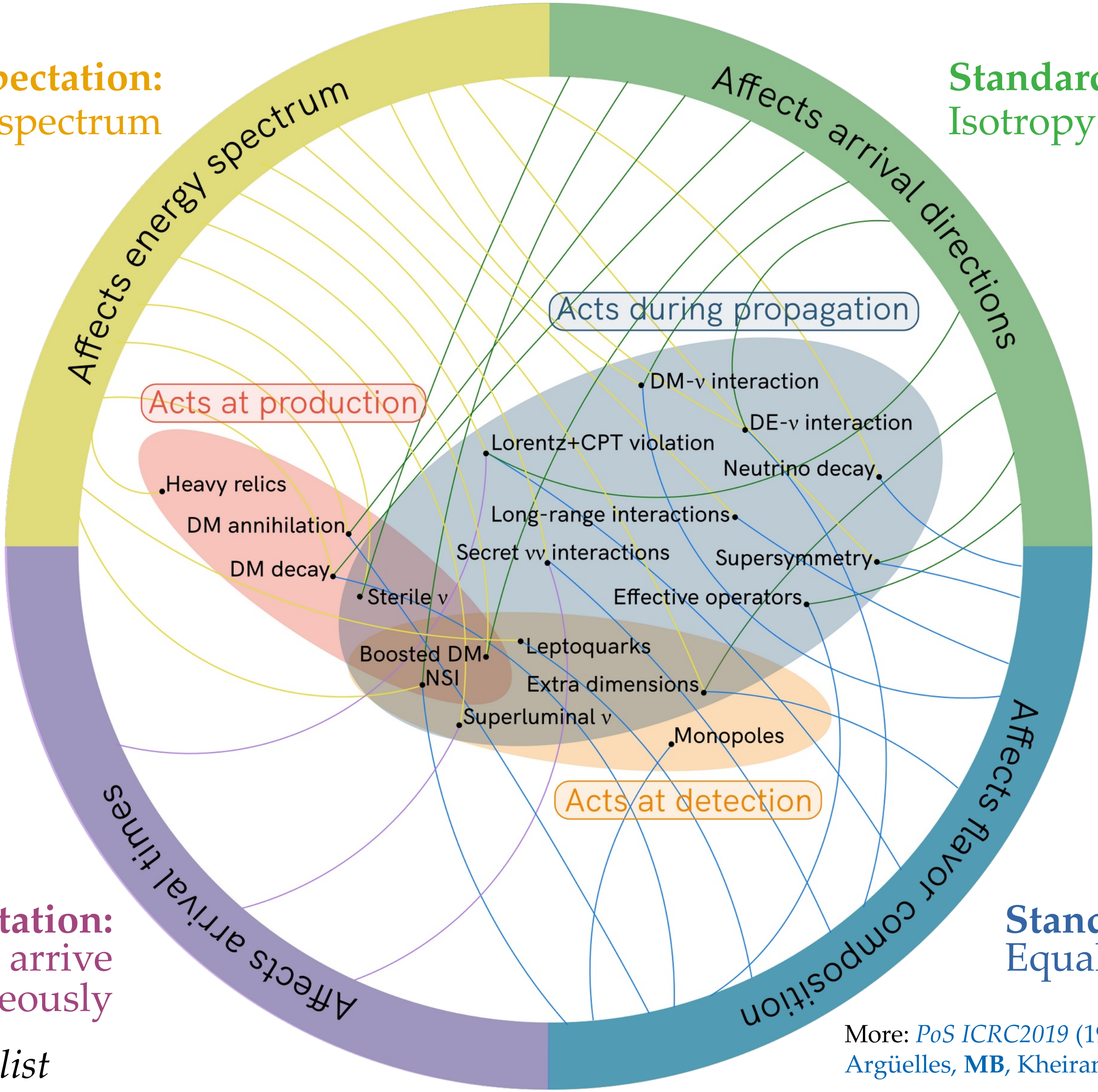
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



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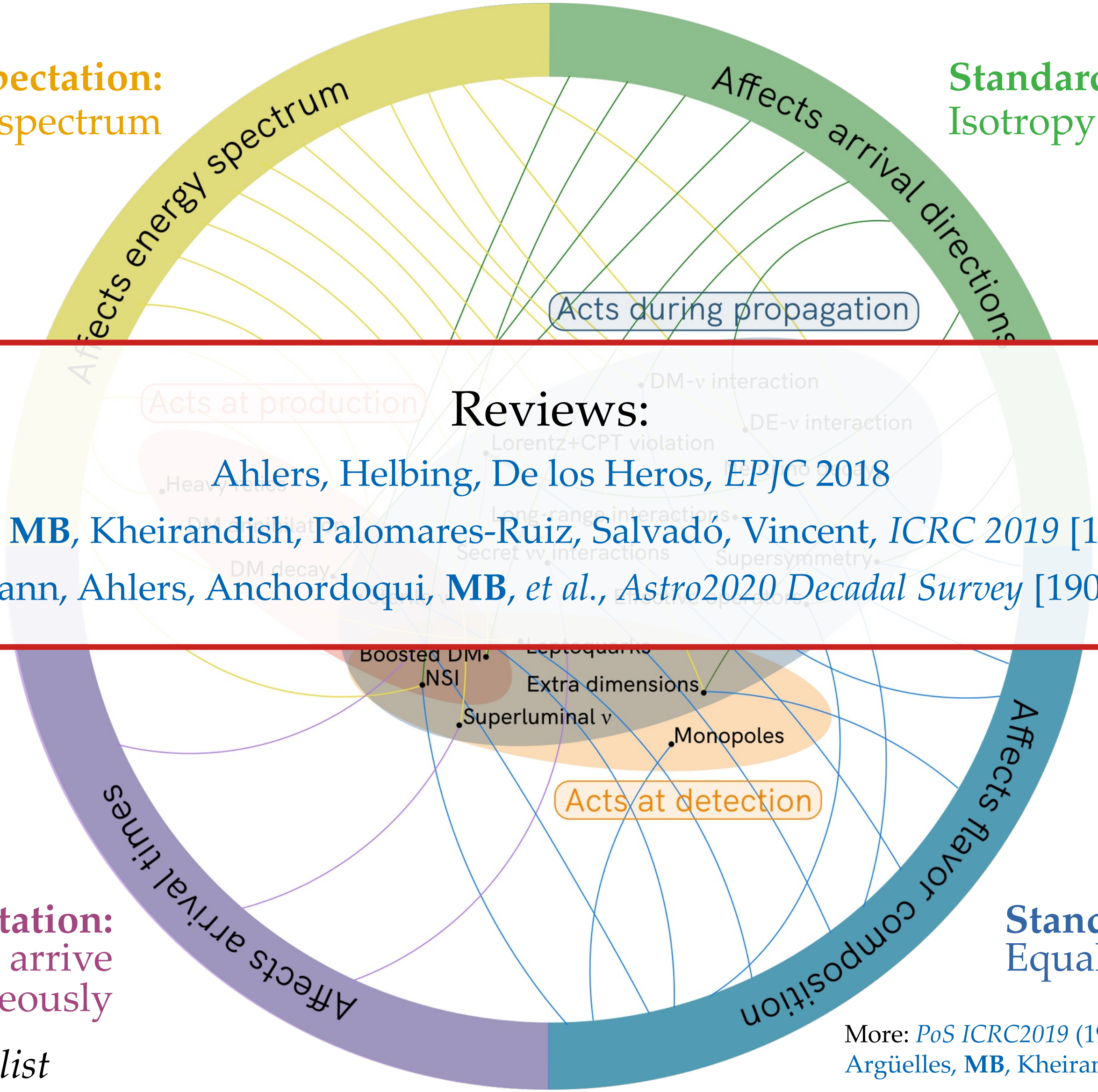

Reviews:

Ahlers, Helbing, De los Heros, *EPJC* 2018

Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, *ICRC 2019* [1907.08690]

Ackermann, Ahlers, Anchordoqui, **MB**, *et al.*, *Astro2020 Decadal Survey* [1903.04333]

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Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

A warning

"When you have eliminated all which is impossible, then whatever remains, however improbable, must be the truth."

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Arthur Conan-Doyle,
The Case-Book of Sherlock Holmes (1927)

Evidence for BSM

Evidence for BSM
Evidence for SM

$$\text{Bayes factor} = \frac{\text{Evidence for BSM}}{\text{Evidence for SM}}$$

$$\text{Bayes factor} = \frac{\text{Evidence for BSM}}{\text{Evidence for SM}}$$

If $B \ll 1$: SM is favored

If $B \gg 1$: BSM is favored

If $B \sim 1$: No preference

$$\text{Bayes factor} = \frac{\text{Evidence for BSM}}{\text{Evidence for SM}}$$

$$\text{Bayes factor} = \frac{\text{Evidence for BSM}}{\text{Evidence for SM}}$$

$$\mathcal{Z}_{\mathrm{SM}} = \int \mathcal{L}(\theta_{\mathrm{SM}}, \theta_{\mathrm{astro}}, \theta_{\mathrm{det}})\pi(\theta_{\mathrm{SM}}, \theta_{\mathrm{astro}}, \theta_{\mathrm{det}})\mathrm{d}\theta_{\mathrm{SM}}\mathrm{d}\theta_{\mathrm{astro}}\mathrm{d}\theta_{\mathrm{det}}$$

Account for particle-physics + astrophysical + detector uncertainties

$$\text{Bayes factor} = \frac{\text{Evidence for BSM}}{\text{Evidence for SM}}$$

$$\mathcal{Z}_{\mathrm{SM}} = \int \overbrace{\mathcal{L}(\theta_{\mathrm{SM}}, \theta_{\mathrm{astro}}, \theta_{\mathrm{det}})}^{\text{Likelihood}} \overbrace{\pi(\theta_{\mathrm{SM}}, \theta_{\mathrm{astro}}, \theta_{\mathrm{det}})}^{\text{Prior}} \mathrm{d}\theta_{\mathrm{SM}} \mathrm{d}\theta_{\mathrm{astro}} \mathrm{d}\theta_{\mathrm{det}}$$

Account for particle-physics + astrophysical + detector uncertainties

$$\mathcal{Z}_{\mathrm{BSM}} = \int \mathcal{L}(\theta_{\mathrm{SM}}, \theta_{\mathrm{astro}}, \theta_{\mathrm{det}}, \theta_{\mathrm{BSM}}) \pi(\theta_{\mathrm{SM}}, \theta_{\mathrm{astro}}, \theta_{\mathrm{det}}, \theta_{\mathrm{BSM}}) \times \mathrm{d}\theta_{\mathrm{SM}} \mathrm{d}\theta_{\mathrm{astro}} \mathrm{d}\theta_{\mathrm{det}} \mathrm{d}\theta_{\mathrm{BSM}}$$

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Account for particle-physics + astrophysical + detector uncertainties

A selection of neutrino physics

1. Discovering the Glashow resonance

2. Neutrino-matter cross section

3. Secret neutrino interactions

4. New physics via flavor

More in backup slides (ν decay, flavor anisotropy, *etc.*)

Discovering the Glashow resonance

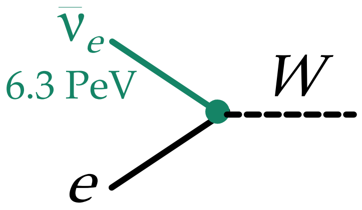
First observation of a Glashow resonance

Predicted in 1960:

IceCube, *Nature* 2021
Glashow, *PR* 1960

First observation of a Glashow resonance

Predicted in 1960:



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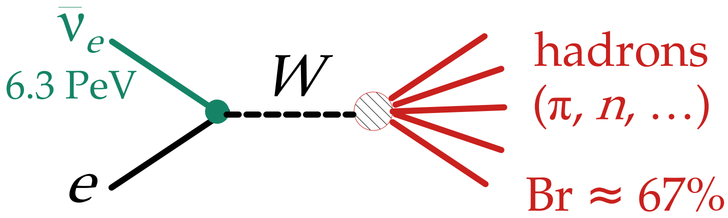

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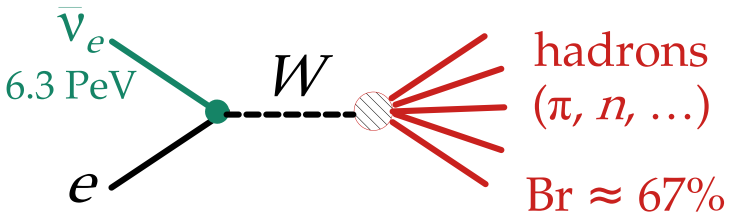

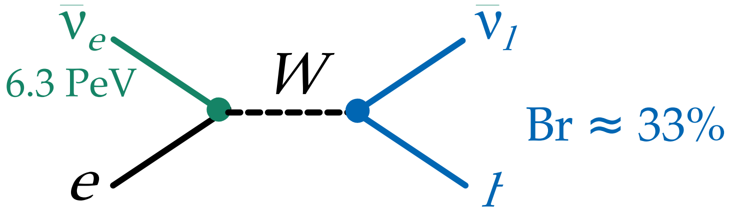

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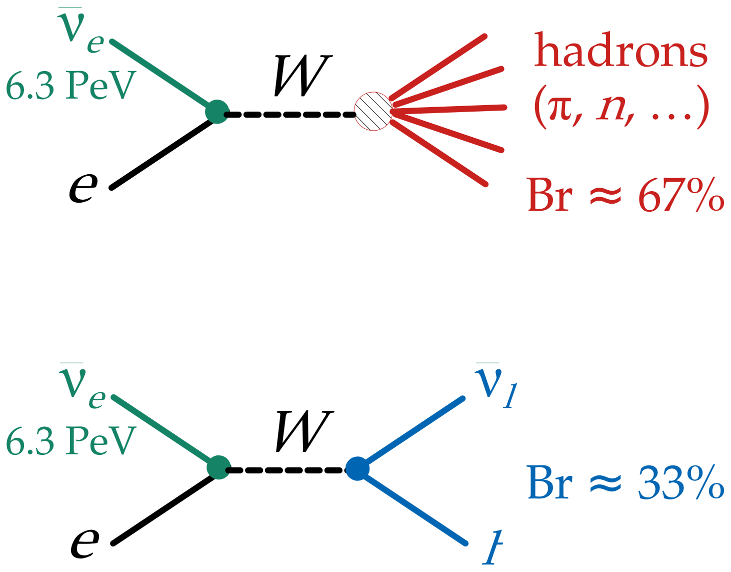
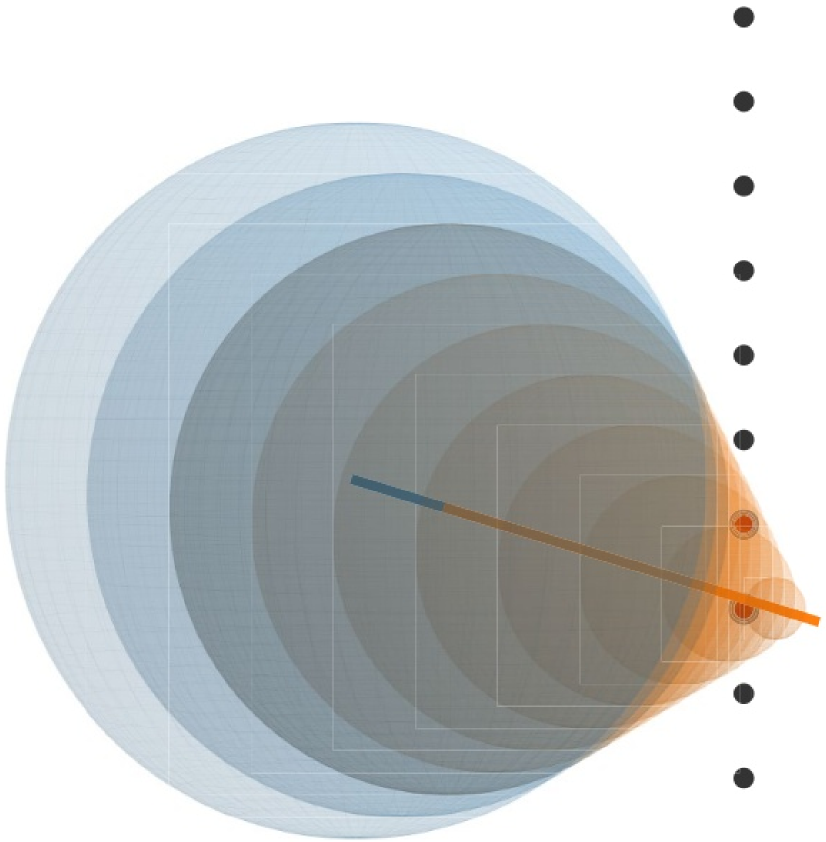


First reported by IceCube in 2021:



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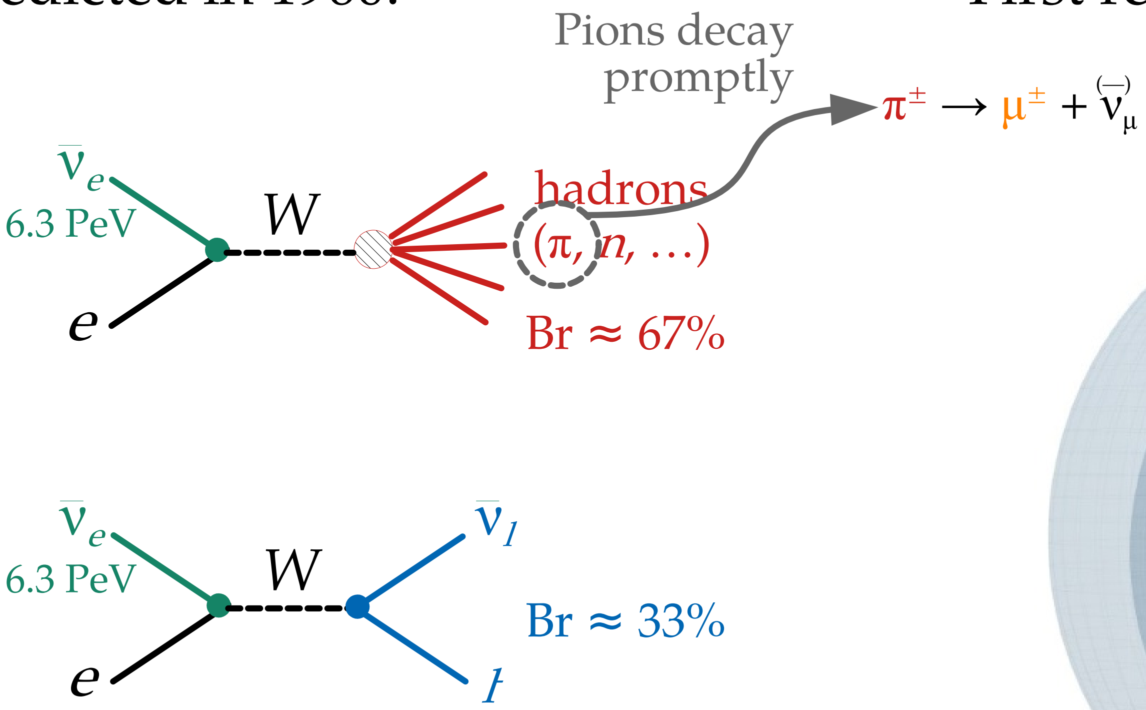

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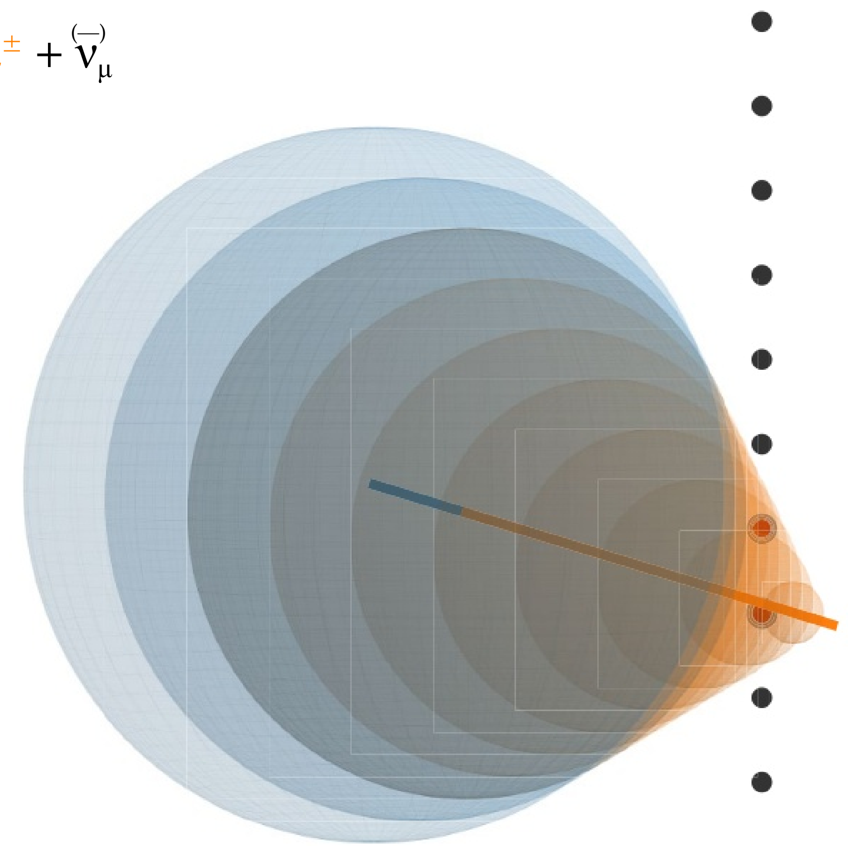

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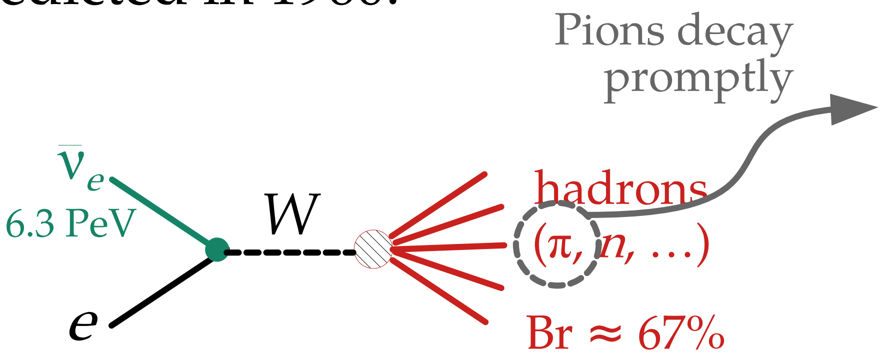
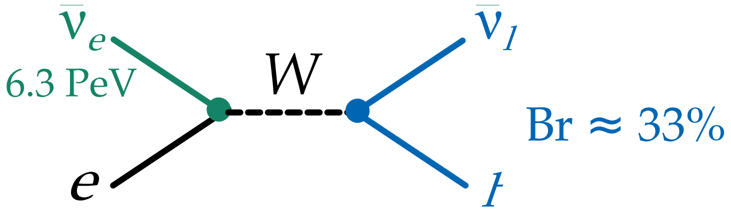
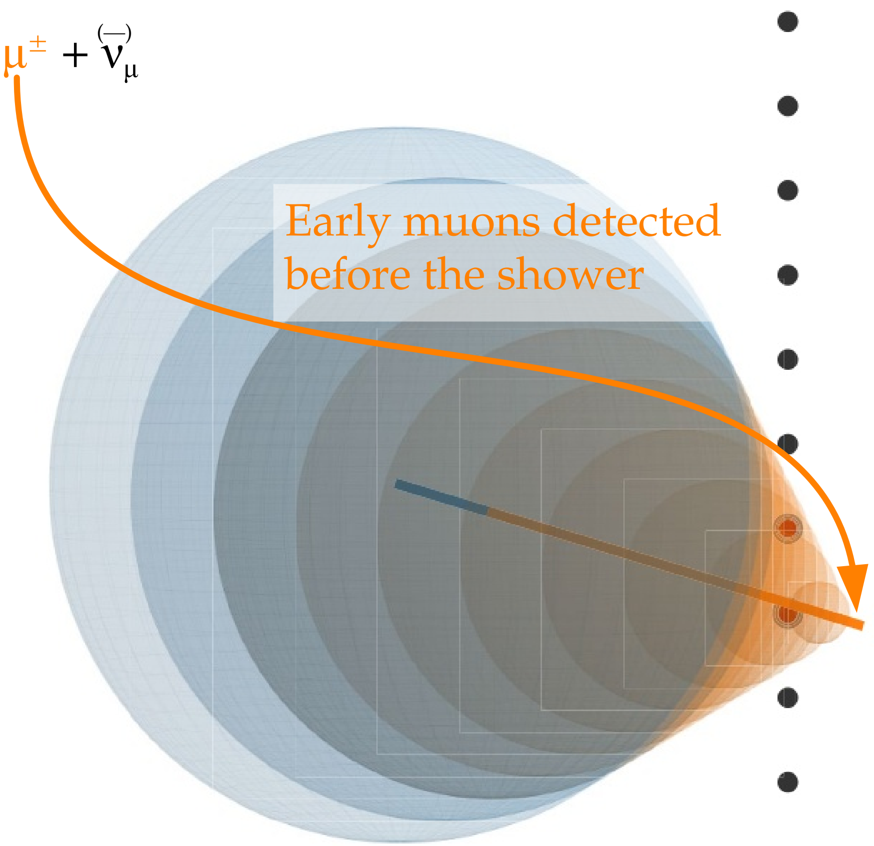




First reported by IceCube in 2021:

$\pi^\pm \longrightarrow \mu^\pm + \overset{(-)}{\nu}_\mu$



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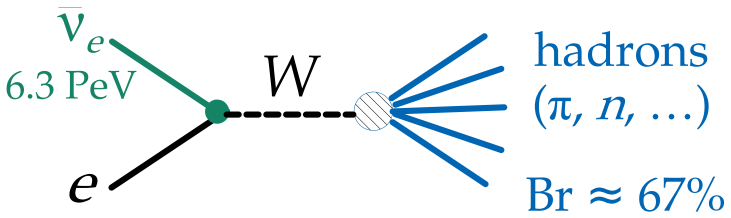

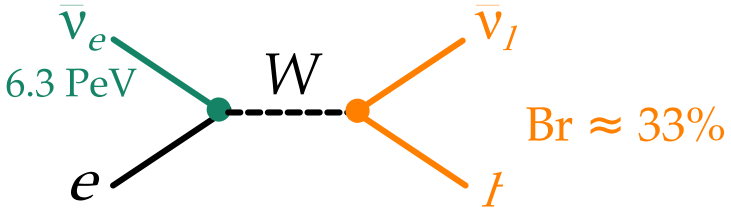

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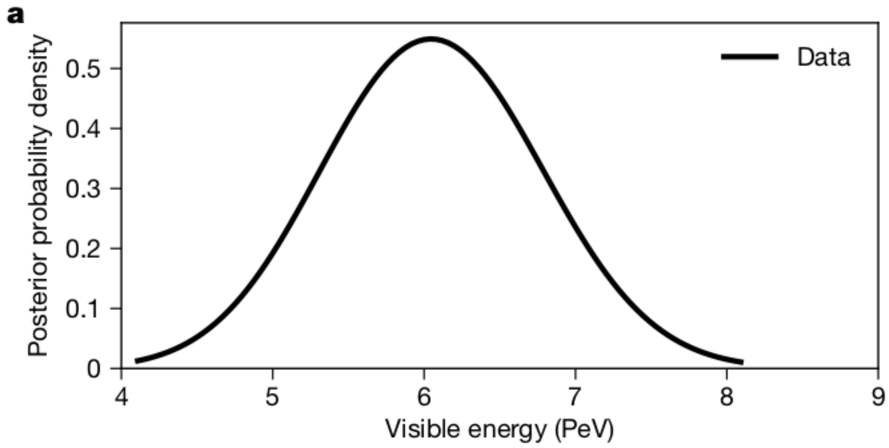

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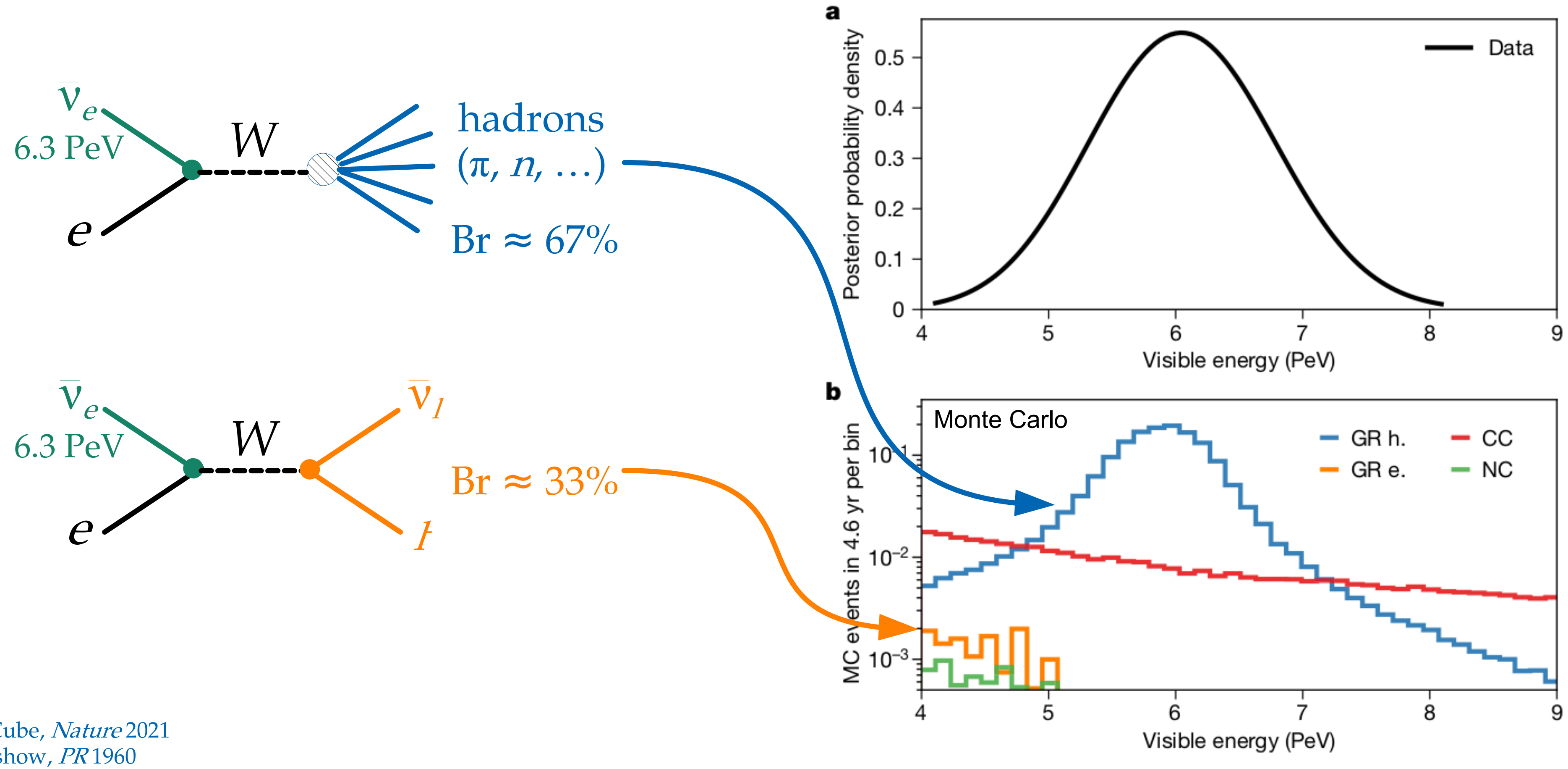
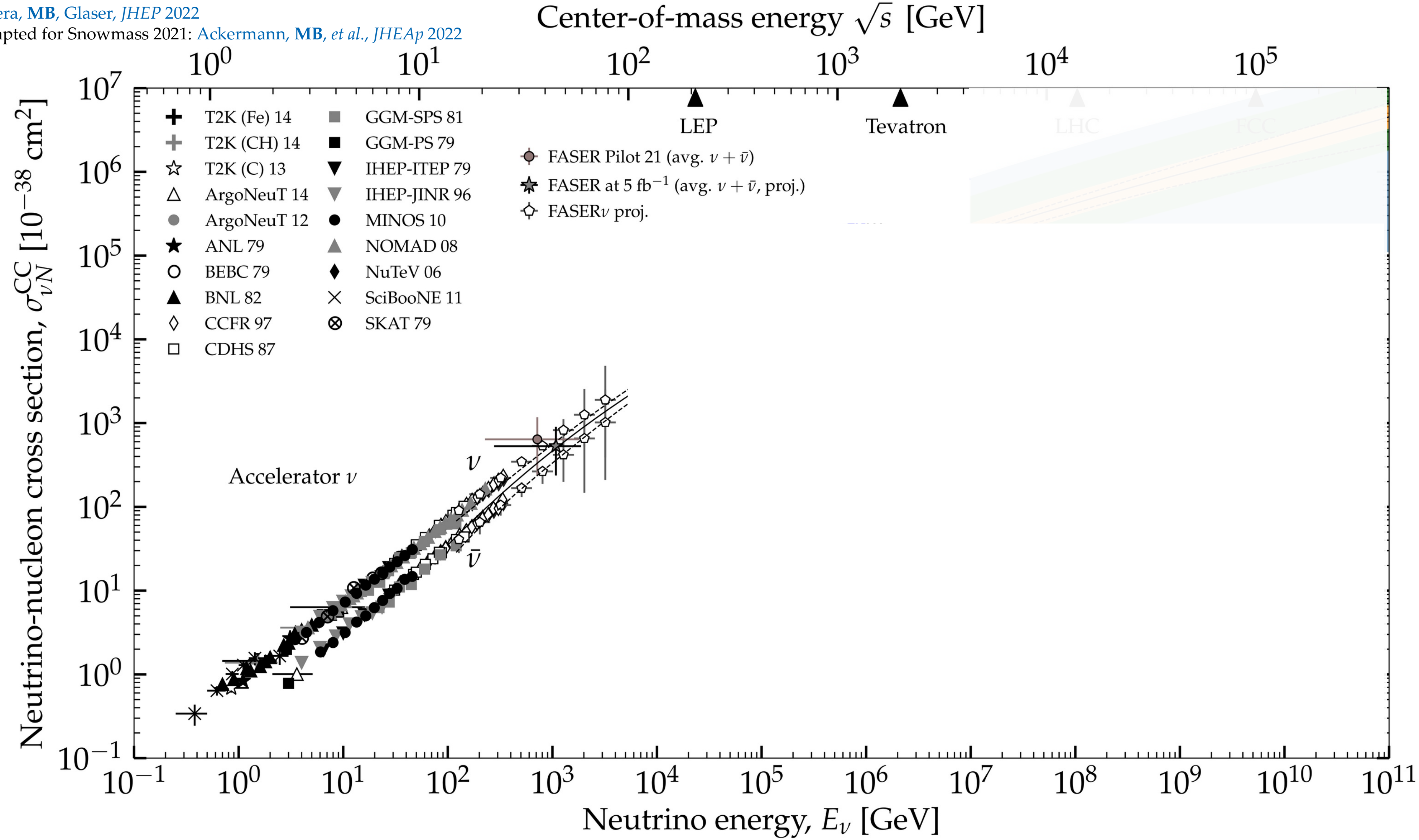
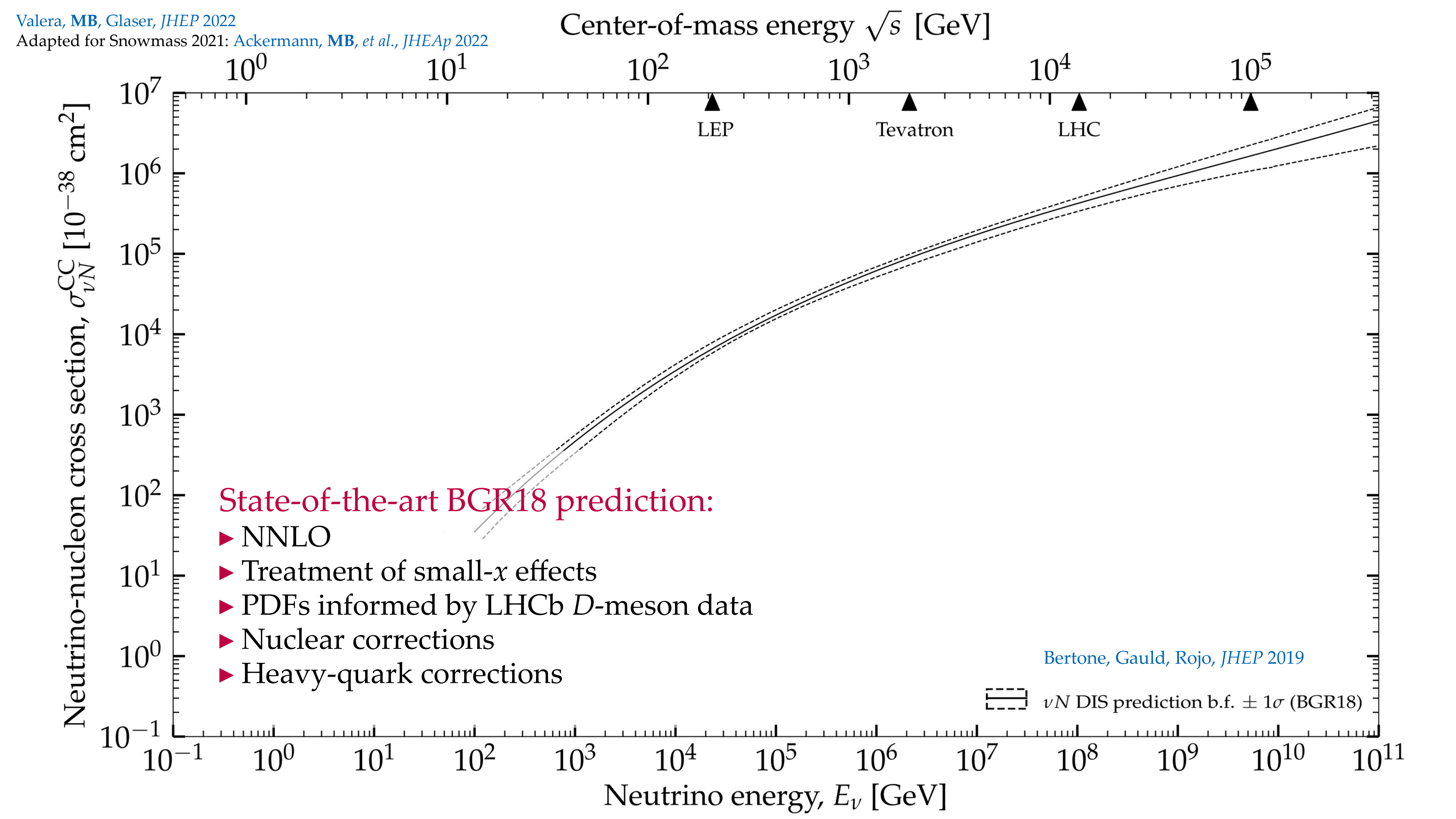


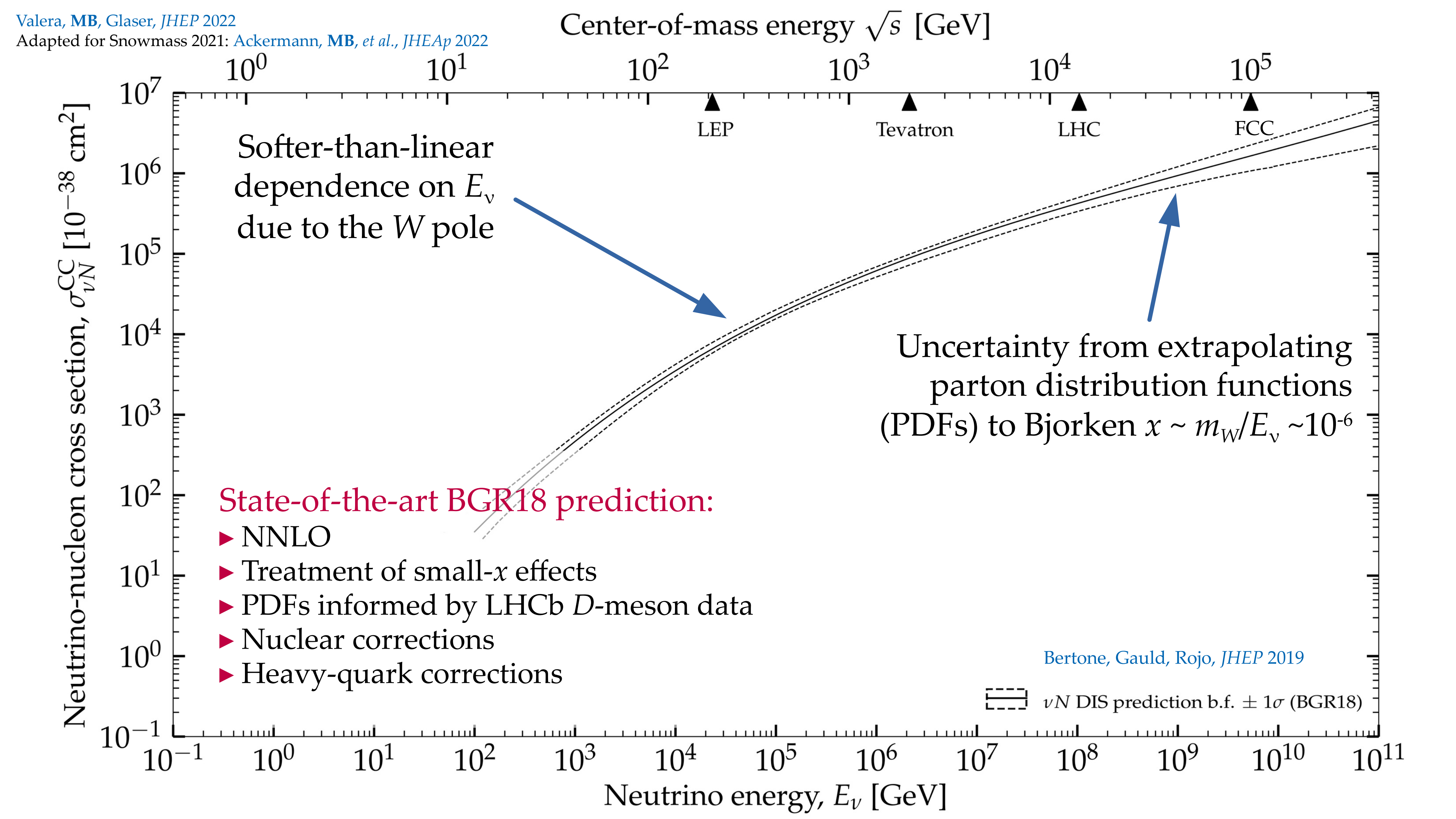
IceCube, *Nature* 2021
Glashow, *PR* 1960

Neutrino-nucleon cross sections

Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022




Valera, MB, Glaser, JHEP 2022
Adapted for Snowmass 2021: Ackermann, MB, et al., JHEAp 2022
Center-of-mass energy $\sqrt{s}$ [GeV]
LEP
Tevatron
LHC
Neutrino-nucleon cross section, $\sigma_{\nu N}^{\mathrm{CC}}$ [10^{-38} cm^2]
State-of-the-art BGR18 prediction:
▸ NNLO
▸ Treatment of small-x effects
▸ PDFs informed by LHCb D-meson data
▸ Nuclear corrections
▸ Heavy-quark corrections
Bertone, Gauld, Rojo, JHEP 2019
νN DIS prediction b.f. $\pm$ 1σ (BGR18)
Neutrino energy, E_ν [GeV]



Valera, MB, Glaser, JHEP 2022
Adapted for Snowmass 2021: Ackermann, MB, et al., JHEAp 2022
Center-of-mass energy $\sqrt{s}$ [GeV]
LEP
Tevatron
LHC
FCC
Softer-than-linear dependence on E_ν due to the W pole
Uncertainty from extrapolating parton distribution functions (PDFs) to Bjorken $x \sim m_W/E_\nu \sim 10^{-6}$
State-of-the-art BGR18 prediction:
▸ NNLO
▸ Treatment of small-x effects
▸ PDFs informed by LHCb D-meson data
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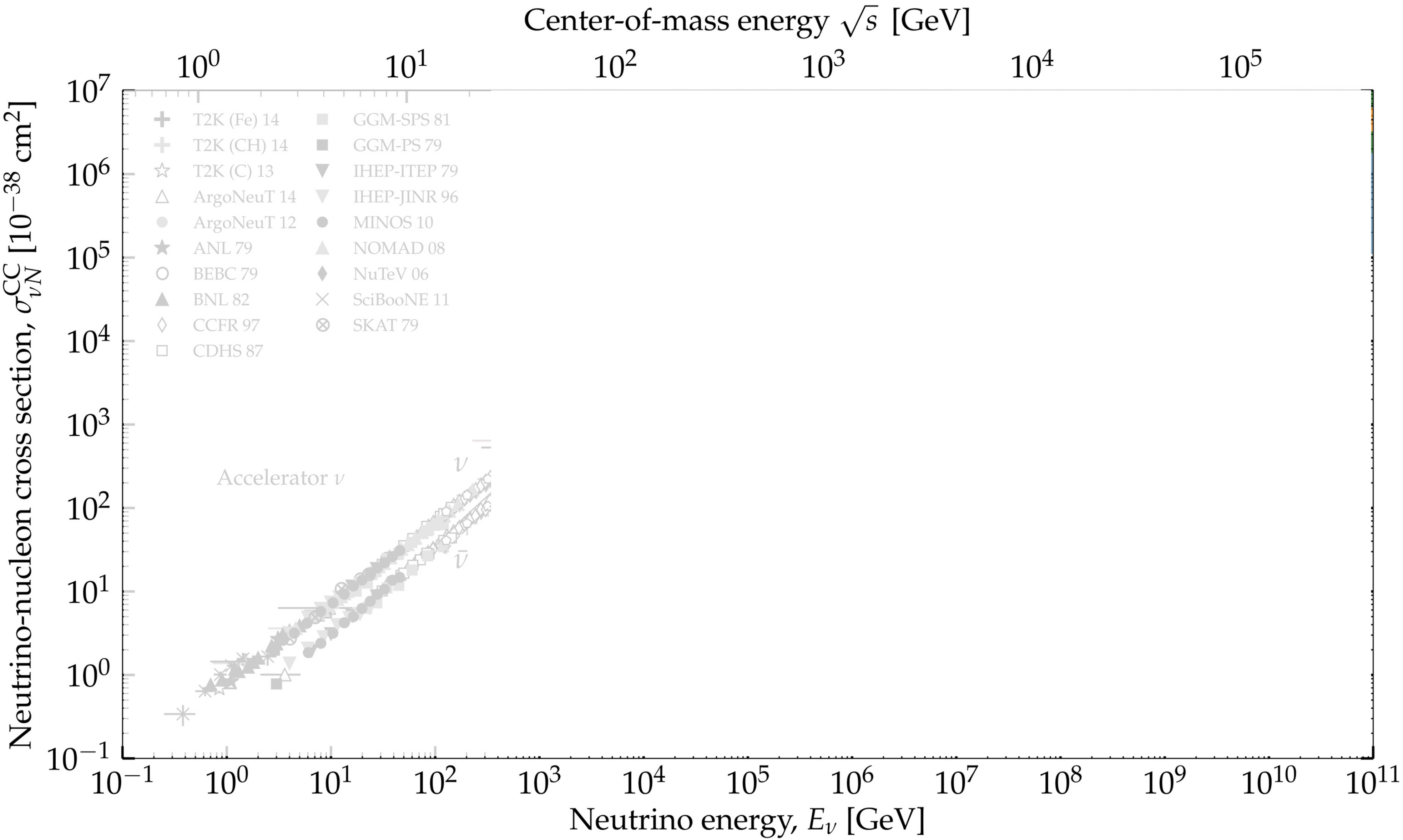
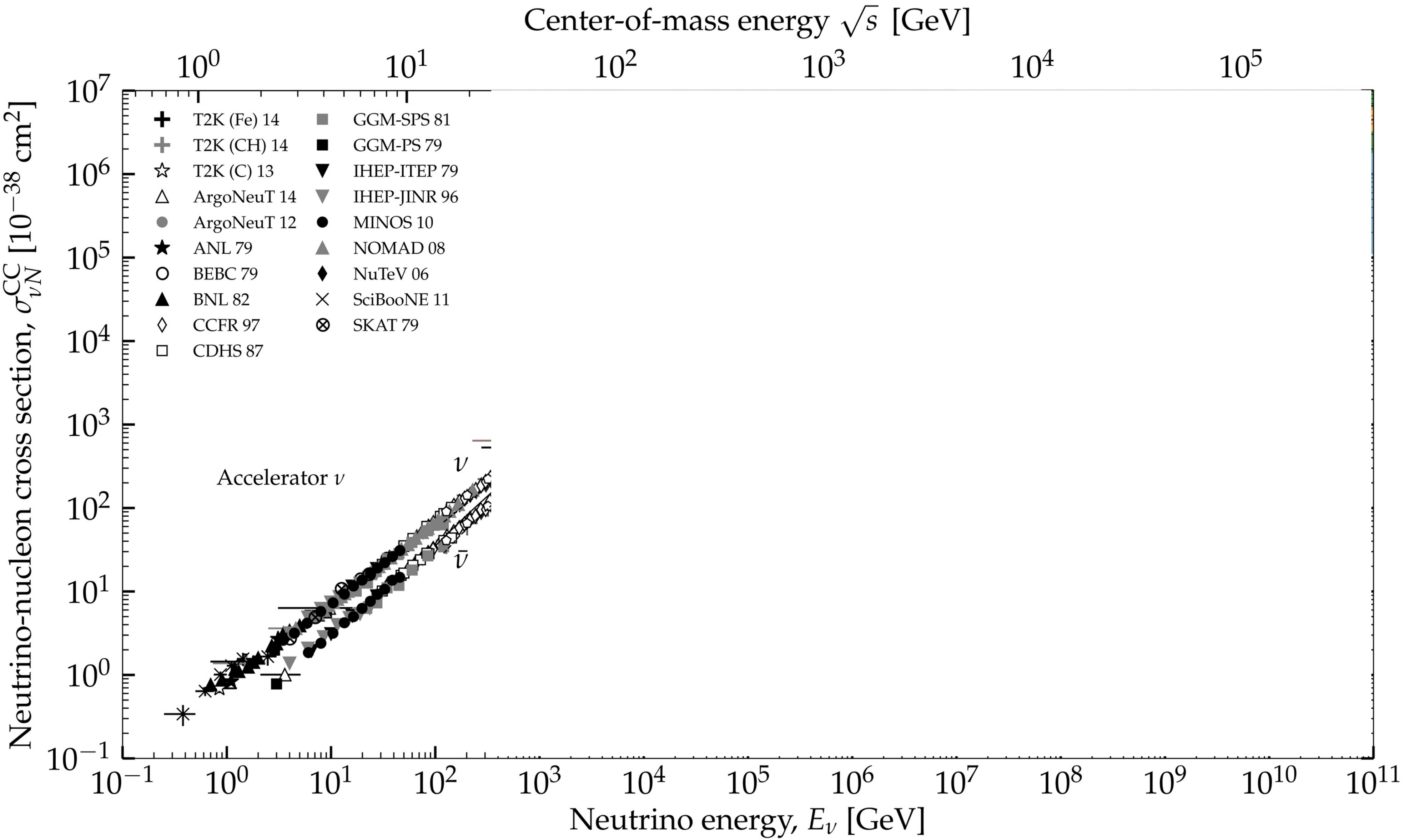


Center-of-mass energy $\sqrt{s}$ [GeV]
Neutrino-nucleon cross section, $\sigma_{\nu N}^{\mathrm{CC}}$ [10^{-38} cm^2]
Neutrino energy, E_ν [GeV]
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
GGM-PS 79
IHEP-ITEP 79
IHEP-JINR 96
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
Accelerator ν
ν
$\bar{\nu}$



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Neutrino energy, E_ν [GeV]
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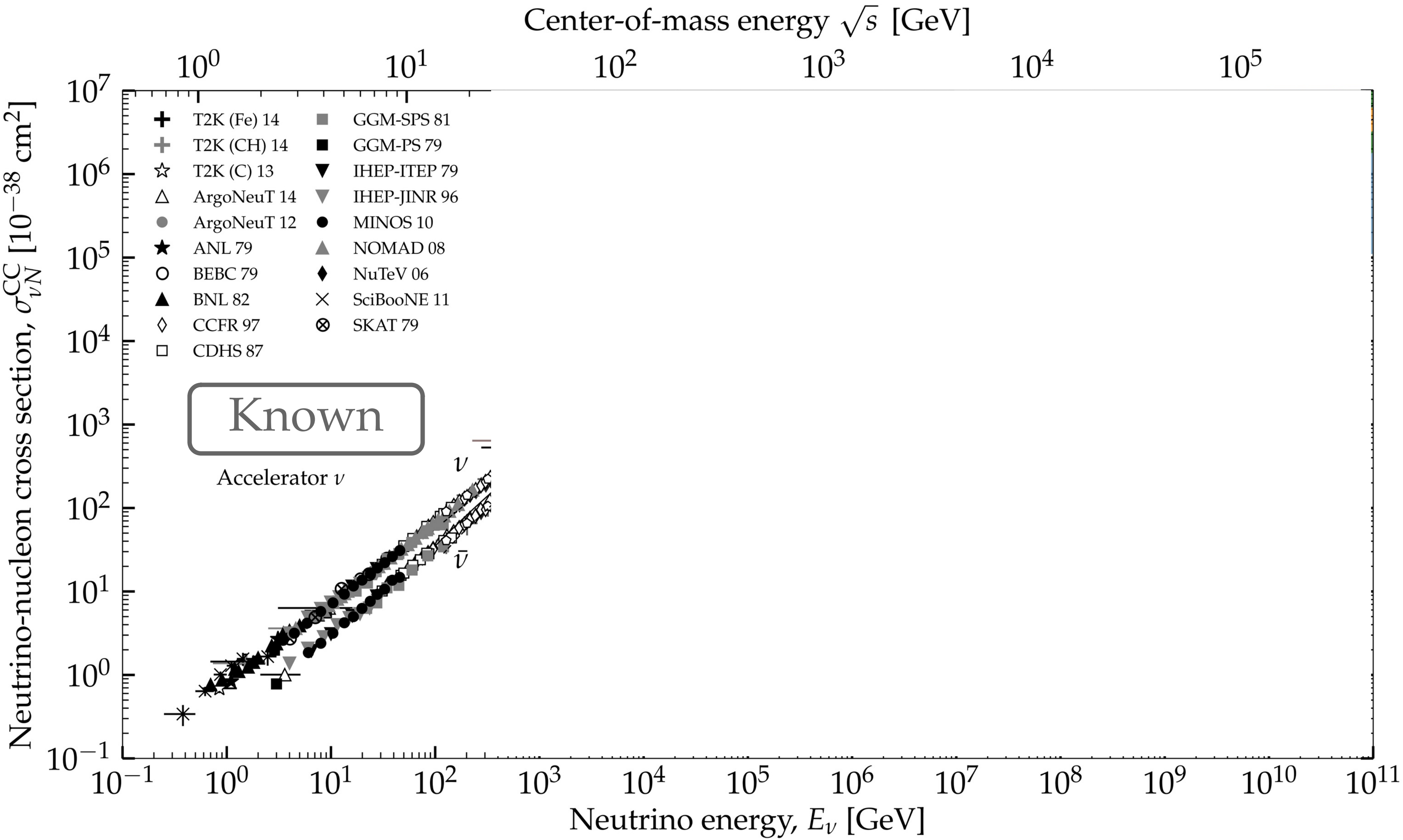
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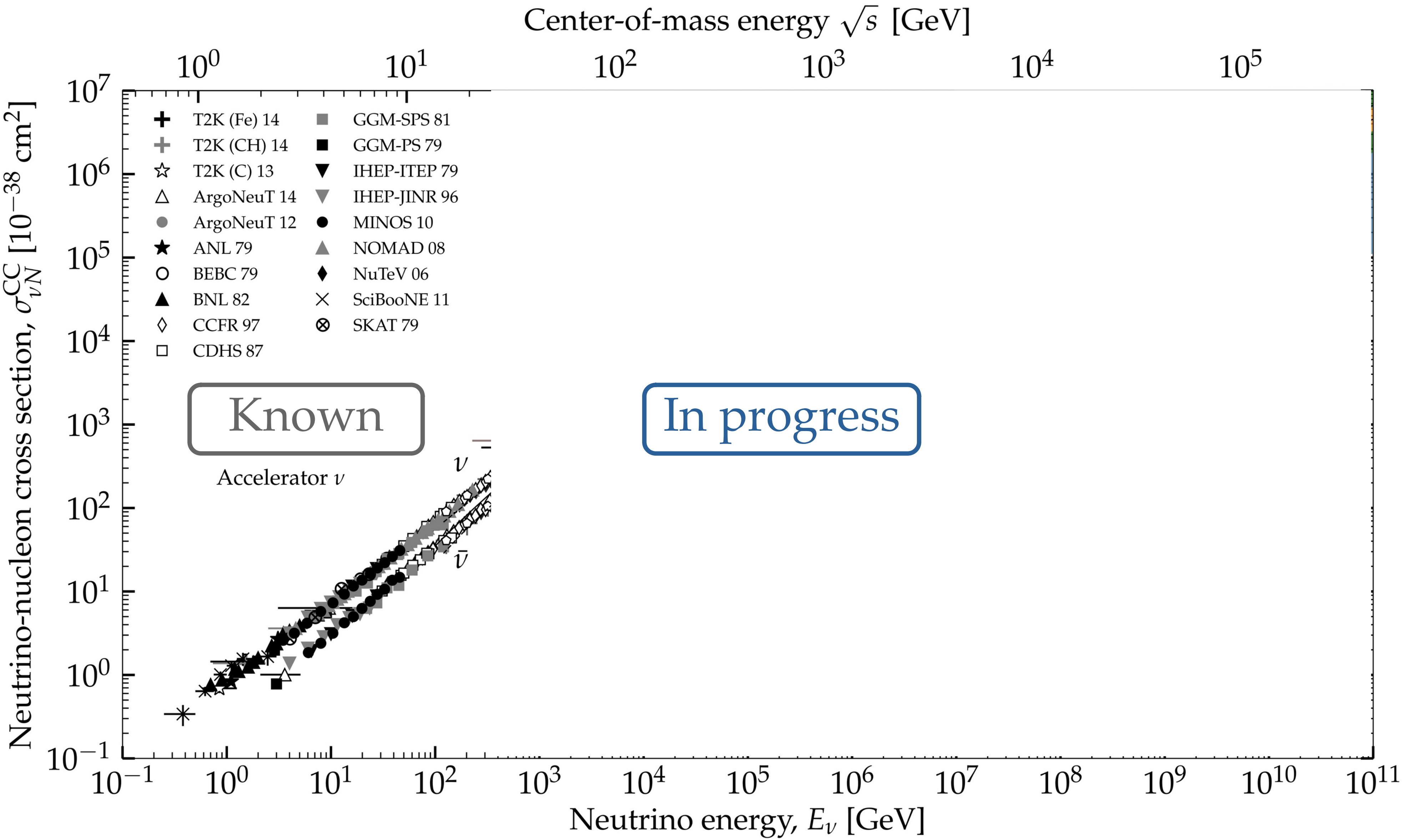
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
Known
Accelerator ν
ν
$\bar{\nu}$



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ArgoNeuT 14
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ANL 79
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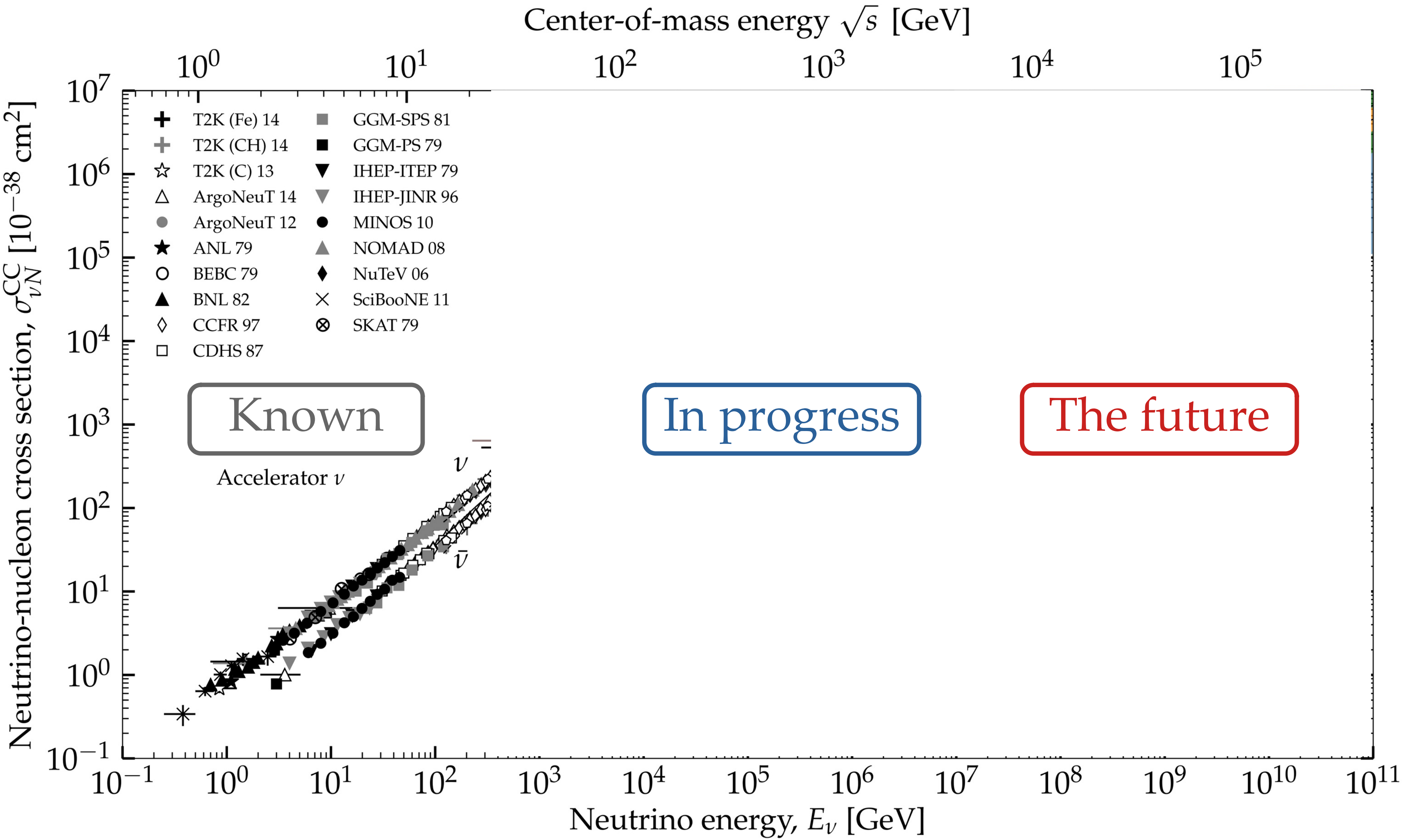
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
Known
In progress
Accelerator ν
ν
$\bar{\nu}$



Center-of-mass energy $\sqrt{s}$ [GeV]
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Neutrino energy, E_ν [GeV]
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ArgoNeuT 14
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IHEP-ITEP 79
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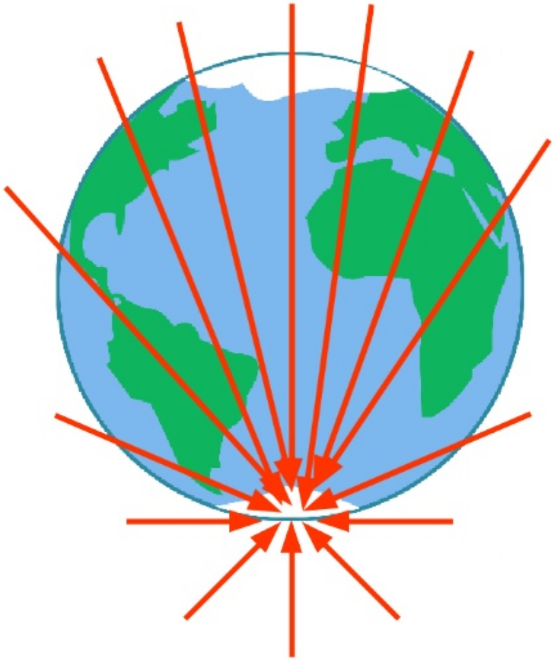
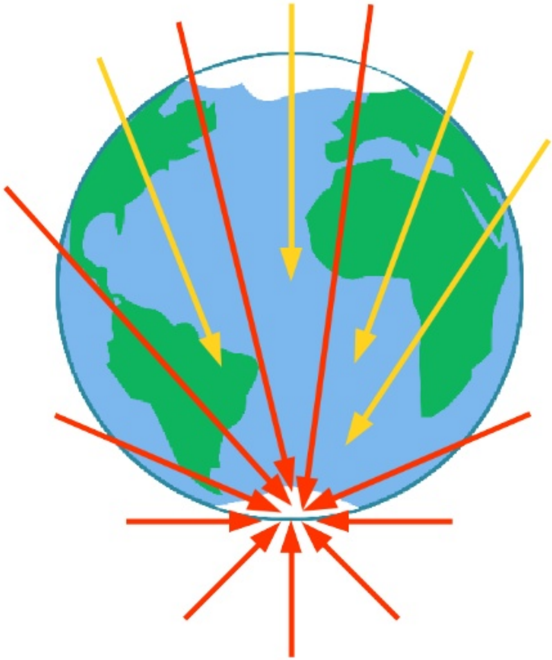
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
Known
Accelerator ν
ν
$\bar{\nu}$
In progress
The future

Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent



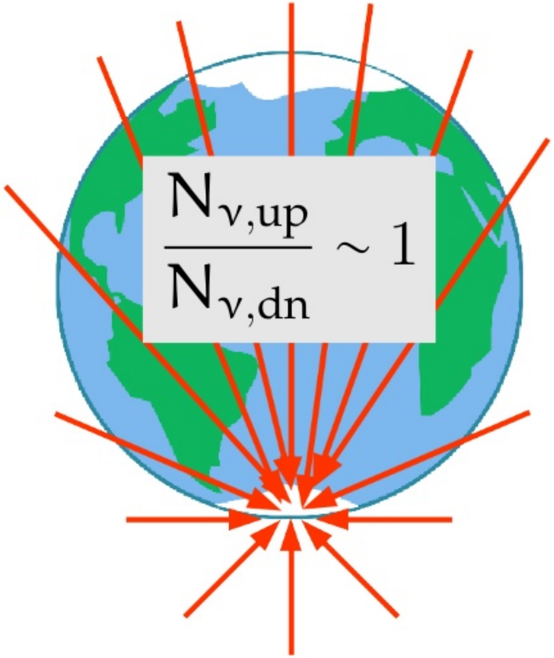
Above ~ 10 TeV: Earth is opaque



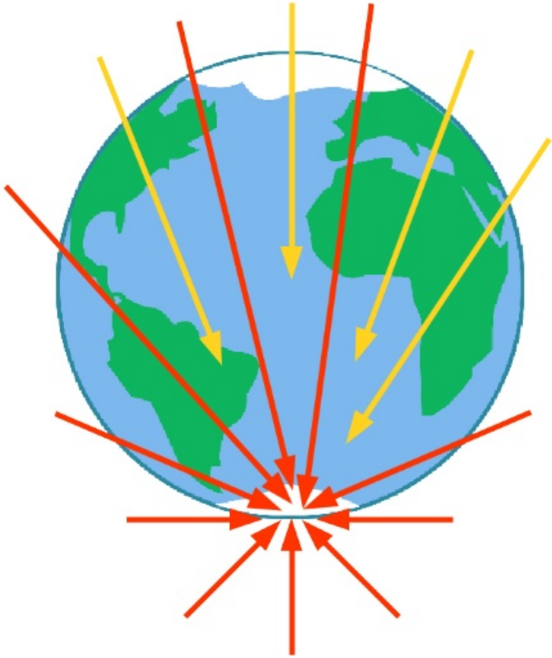
Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008; Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent



Above ~ 10 TeV: Earth is opaque



Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
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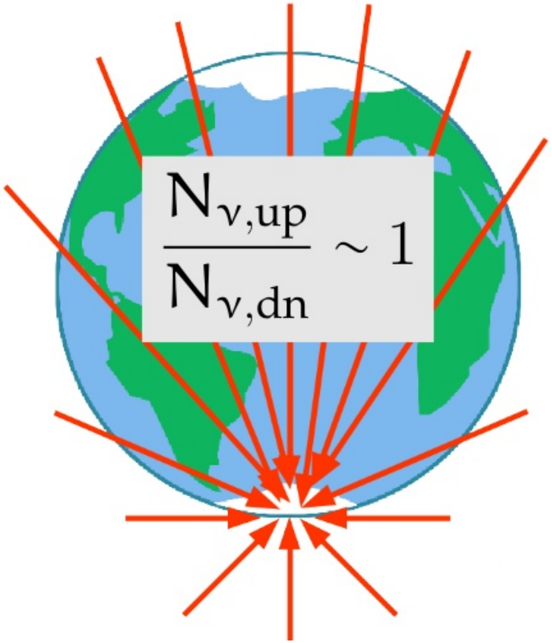
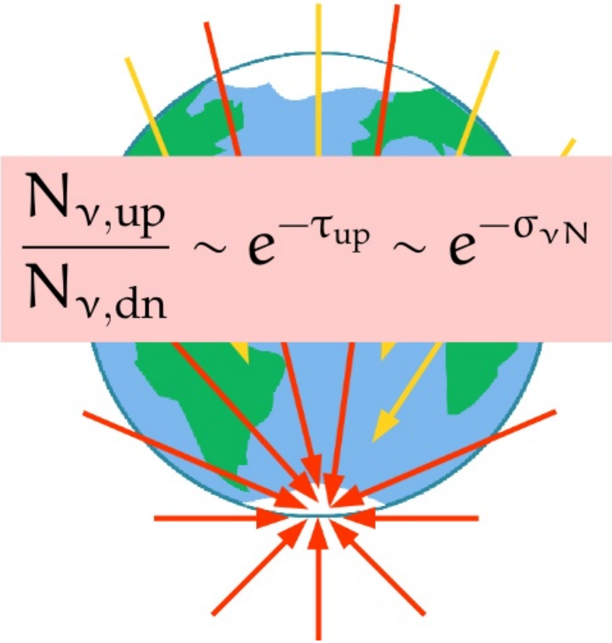


$$\frac{N_{\nu,\mathrm{up}}}{N_{\nu,\mathrm{dn}}} \sim 1$$

Above ~ 10 TeV: Earth is opaque



$$\frac{N_{\nu,\mathrm{up}}}{N_{\nu,\mathrm{dn}}} \sim e^{-\tau_{\mathrm{up}}} \sim e^{-\sigma_{\nu N}}$$

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Measuring the high-energy νN cross section

Number of detected neutrinos (simplified for presentation):

$$N \propto \underbrace{\Phi_\nu}_{\text{Neutrino flux}} \underbrace{\sigma_{\nu N}}_{\text{Cross section}} e^{-\tau_{\nu N}} = \Phi_\nu \sigma_{\nu N} e^{-L \sigma_{\nu N} n_N}$$

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(L short $\rightarrow$ no matter)

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Downgoing neutrinos
(L short $\rightarrow$ no matter)

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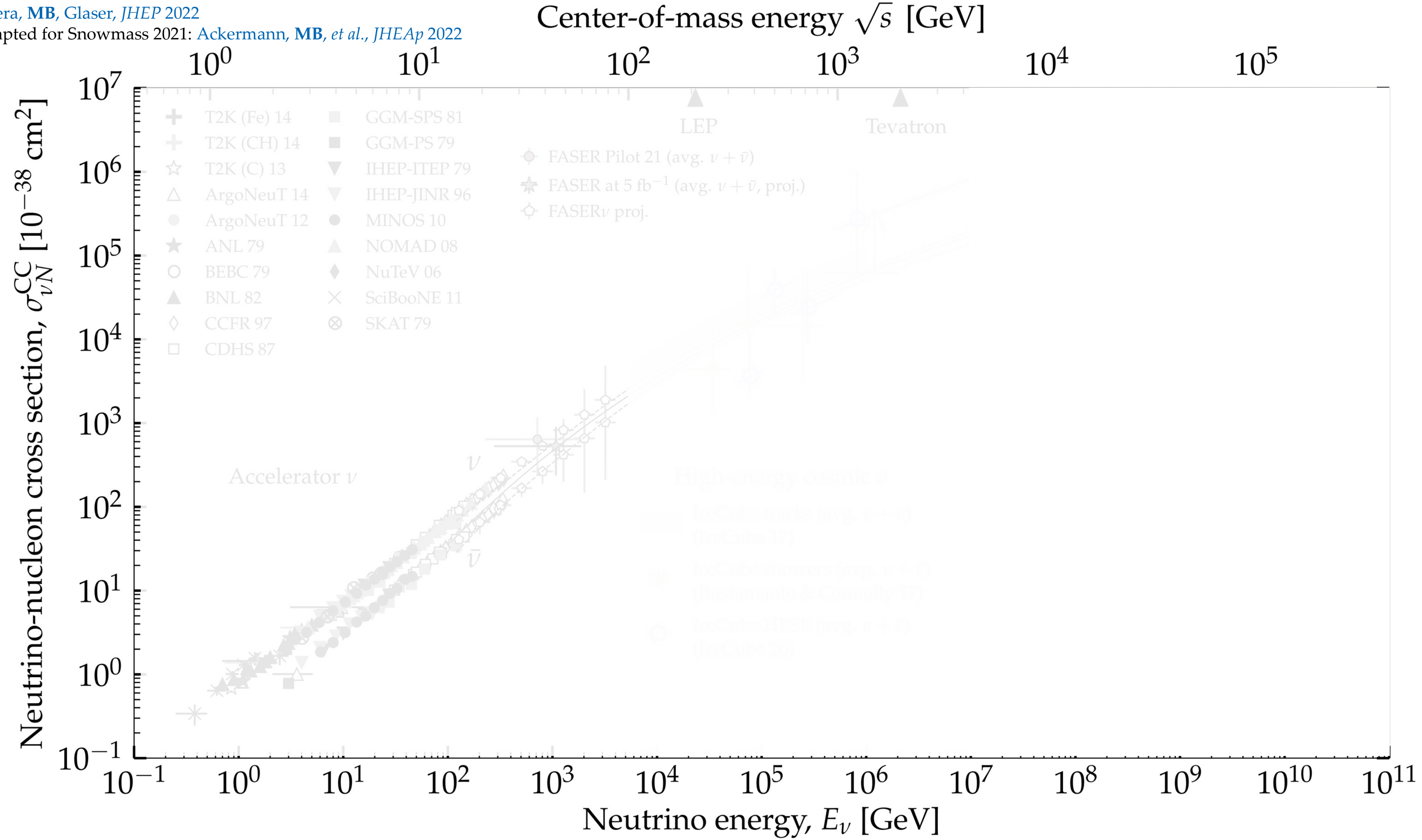
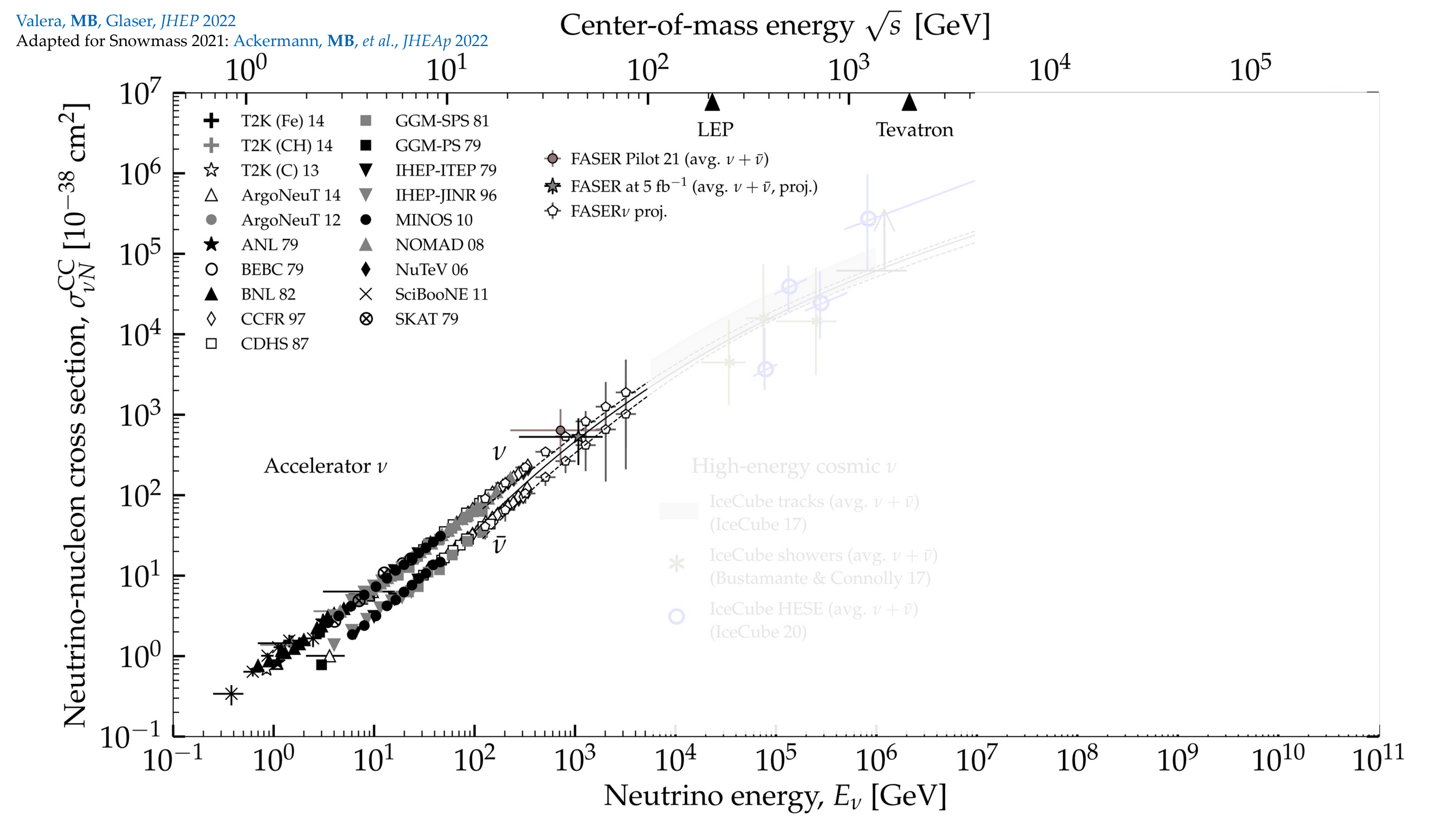
Upgoing neutrinos
(L long $\rightarrow$ lots of matter)

$$N \propto \Phi_\nu \sigma_{\nu N} \underbrace{e^{-L \sigma_{\nu N} n_N}}_{\text{Breaks the degeneracy}}$$

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008 Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

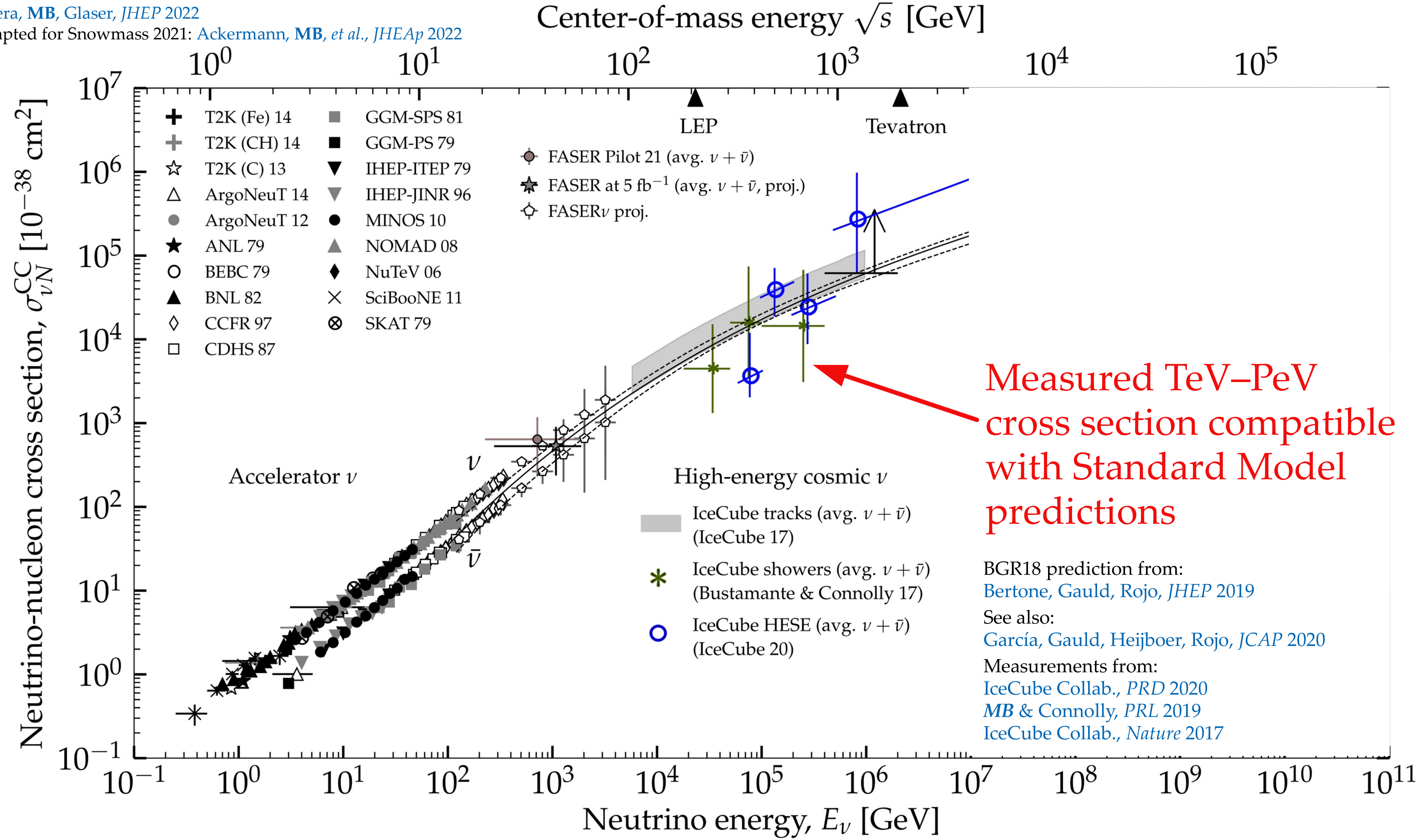
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



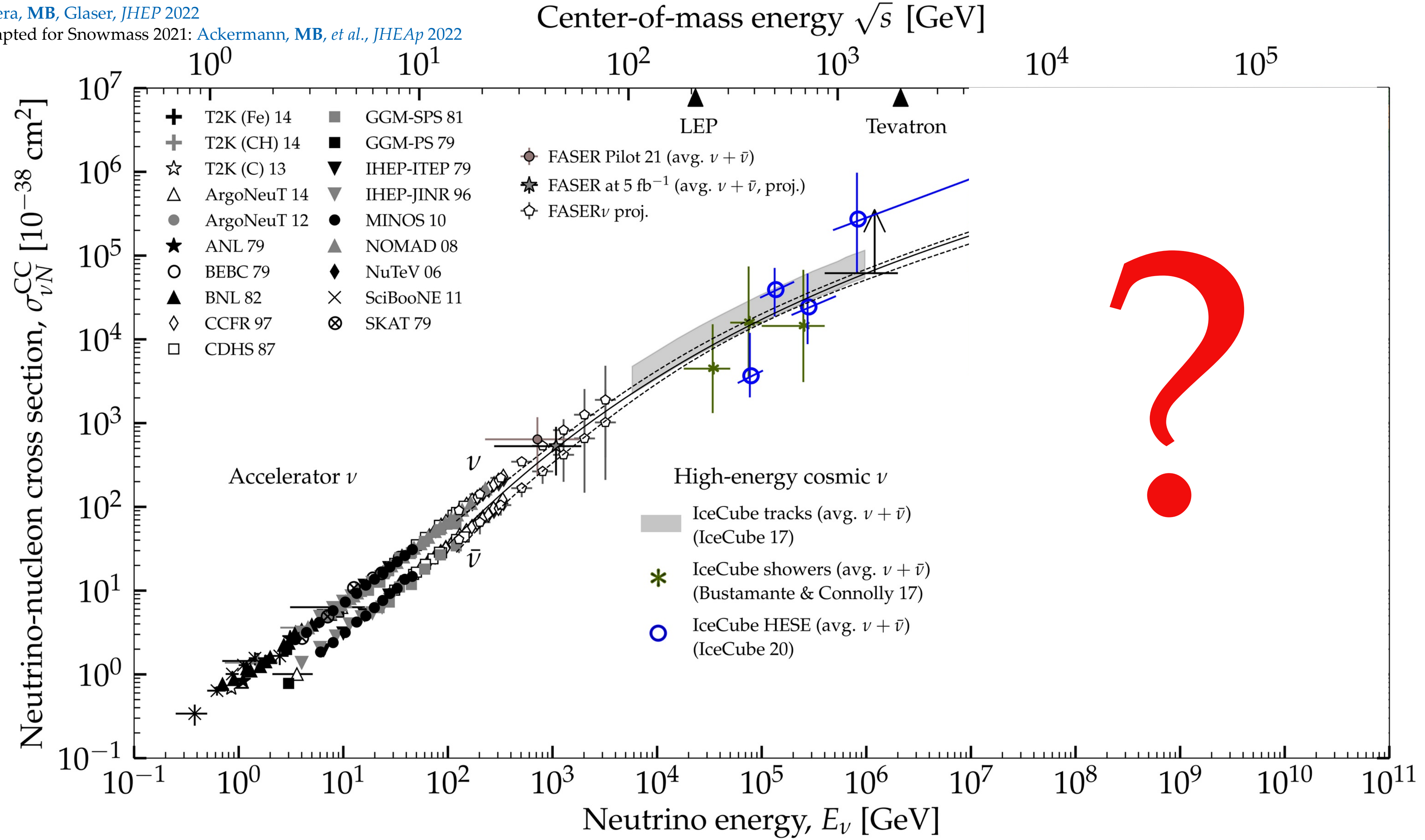


Valera, MB, Glaser, JHEP 2022
Adapted for Snowmass 2021: Ackermann, MB, et al., JHEAp 2022
Center-of-mass energy $\sqrt{s}$ [GeV]
LEP
Tevatron
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
GGM-PS 79
IHEP-ITEP 79
IHEP-JINR 96
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
FASER Pilot 21 (avg. $\nu + \bar{\nu}$)
FASER at 5 fb^{-1} (avg. $\nu + \bar{\nu}$, proj.)
FASERν proj.
Accelerator ν
ν
$\bar{\nu}$
High-energy cosmic ν
IceCube tracks (avg. $\nu + \bar{\nu}$)
(IceCube 17)
IceCube showers (avg. $\nu + \bar{\nu}$)
(Bustamante & Connolly 17)
IceCube HESE (avg. $\nu + \bar{\nu}$)
(IceCube 20)
Neutrino-nucleon cross section, $\sigma_{\nu N}^{CC}$ [10^{-38} cm^2]
Neutrino energy, E_ν [GeV]

Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



Secret neutrino interactions

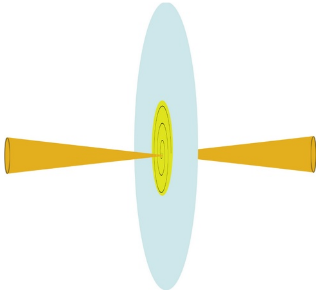
Astrophysical neutrino sources Earth

Galactic (kpc) or extragalactic (Mpc – Gpc) distance

Astrophysical neutrino sources

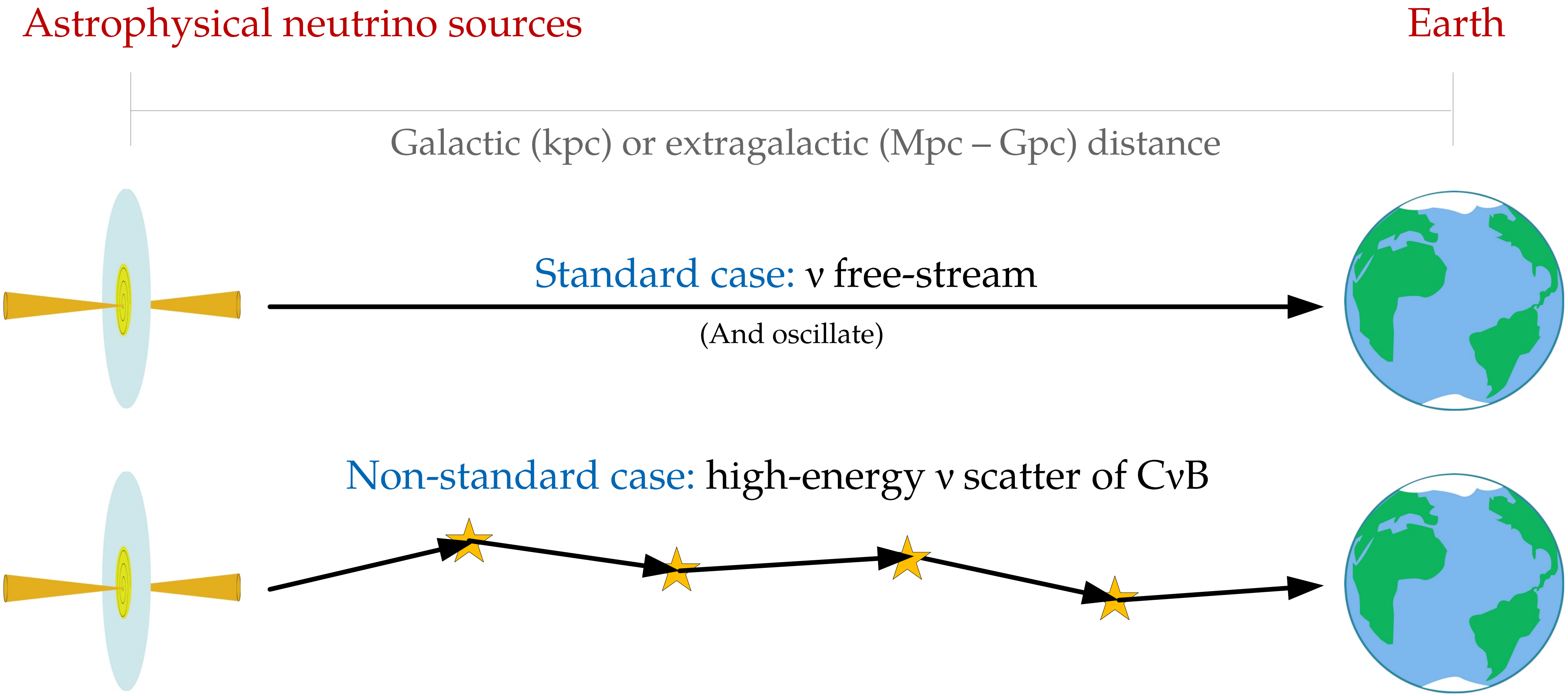
Earth

Galactic (kpc) or extragalactic (Mpc – Gpc) distance



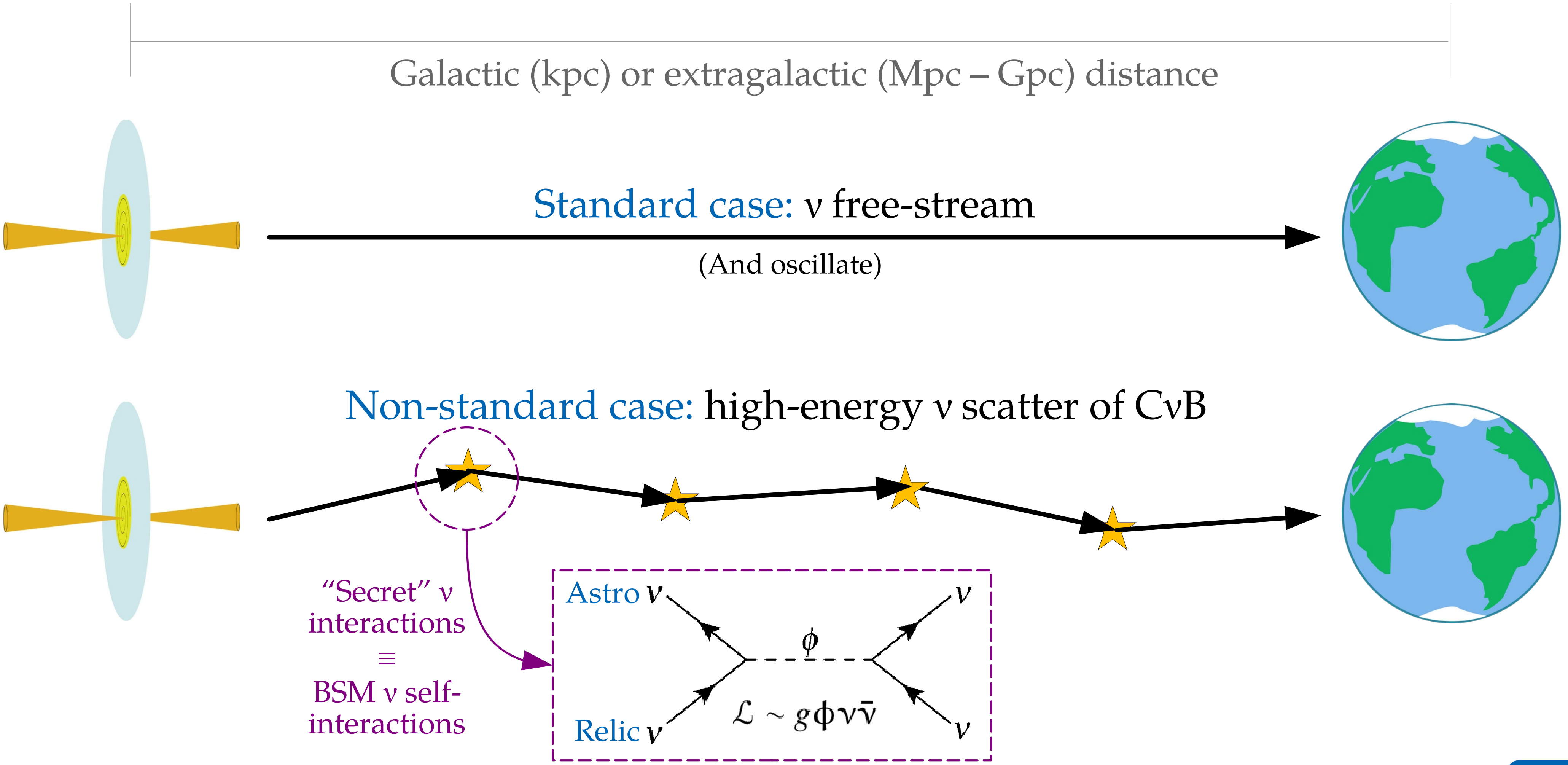
Standard case: ν free-stream

(And oscillate)


Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
(And oscillate)
Non-standard case: high-energy ν scatter of CνB

Astrophysical neutrino sources

Earth



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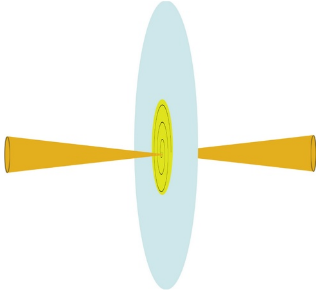

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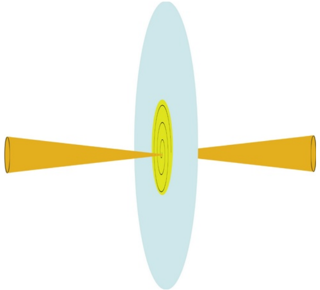
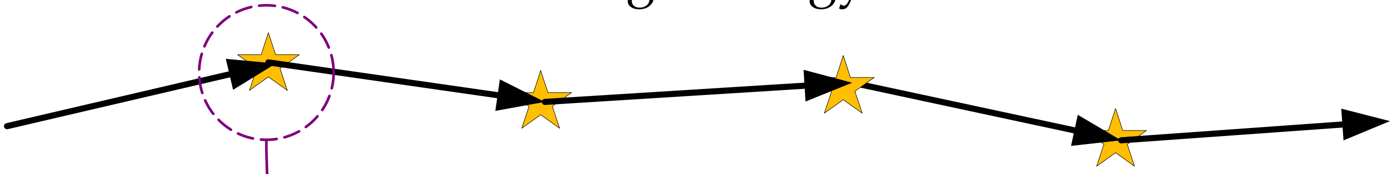
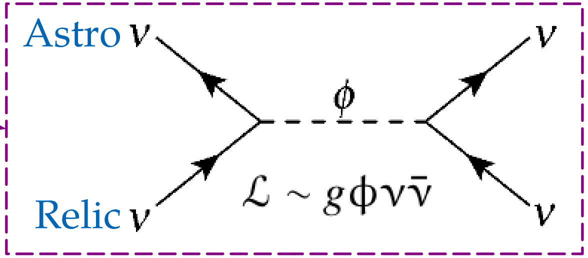




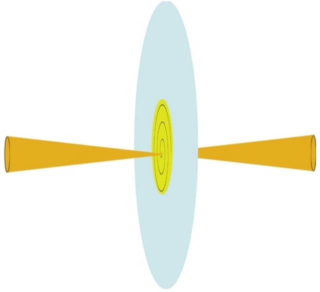
"Secret" ν interactions
≡
BSM ν self-interactions



Can change:

Astrophysical neutrino sources | Earth

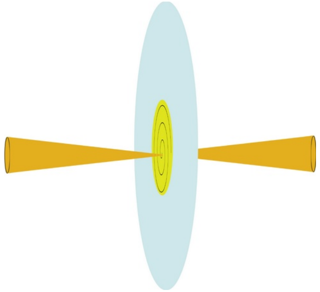
Galactic (kpc) or extragalactic (Mpc – Gpc) distance

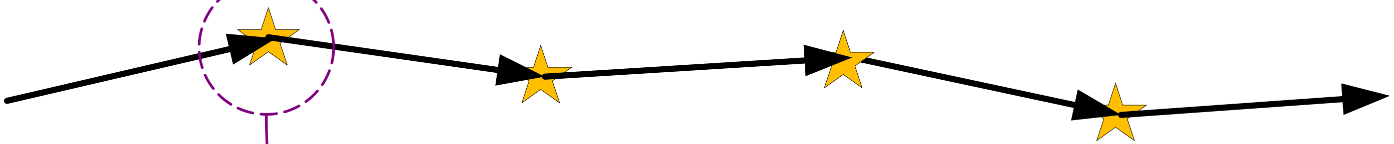


Standard case: ν free-stream

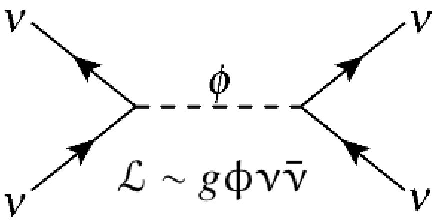
(And oscillate)

Non-standard case: high-energy ν scatter of CνB





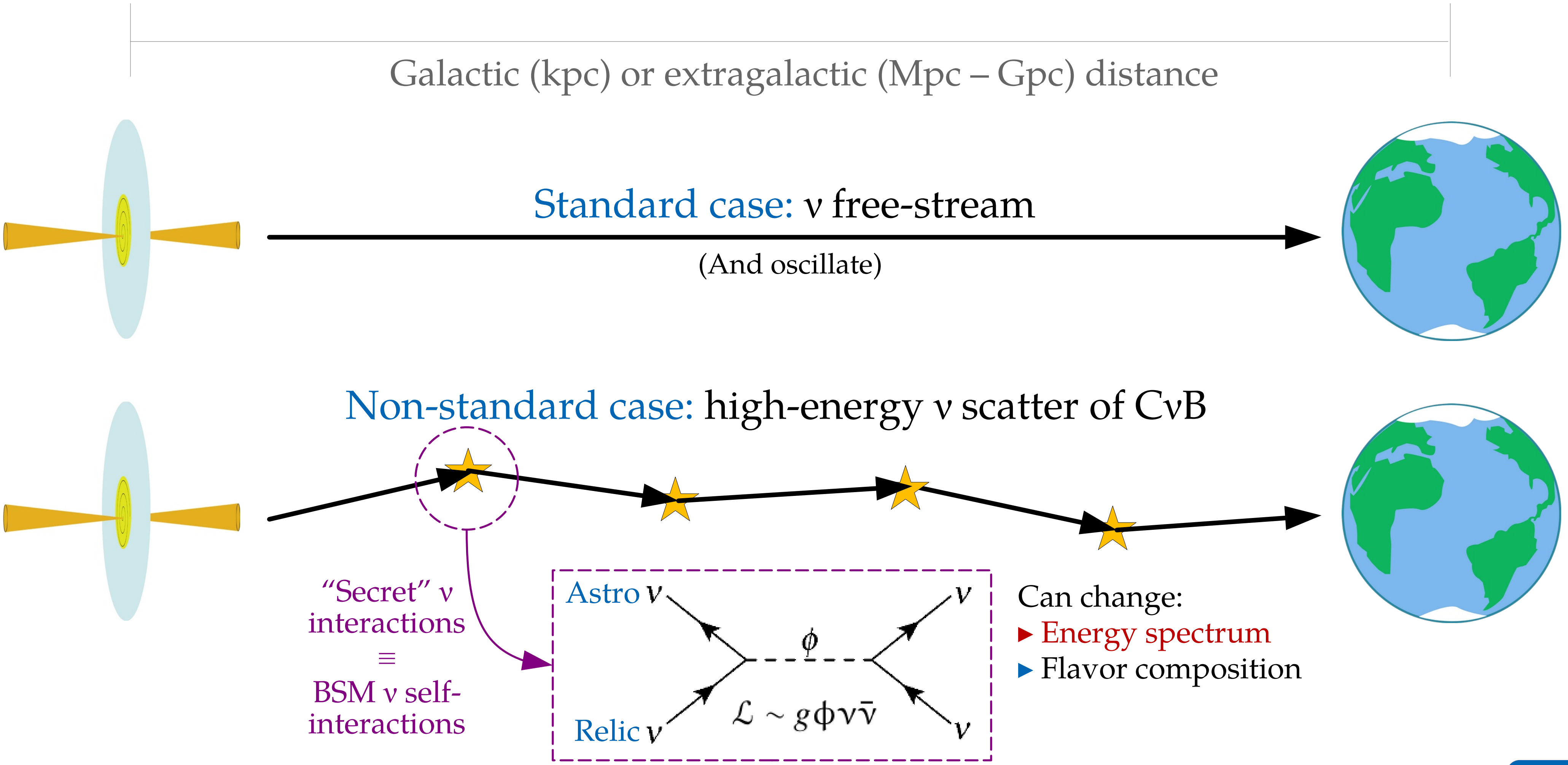
"Secret" ν interactions ≡ BSM ν self-interactions

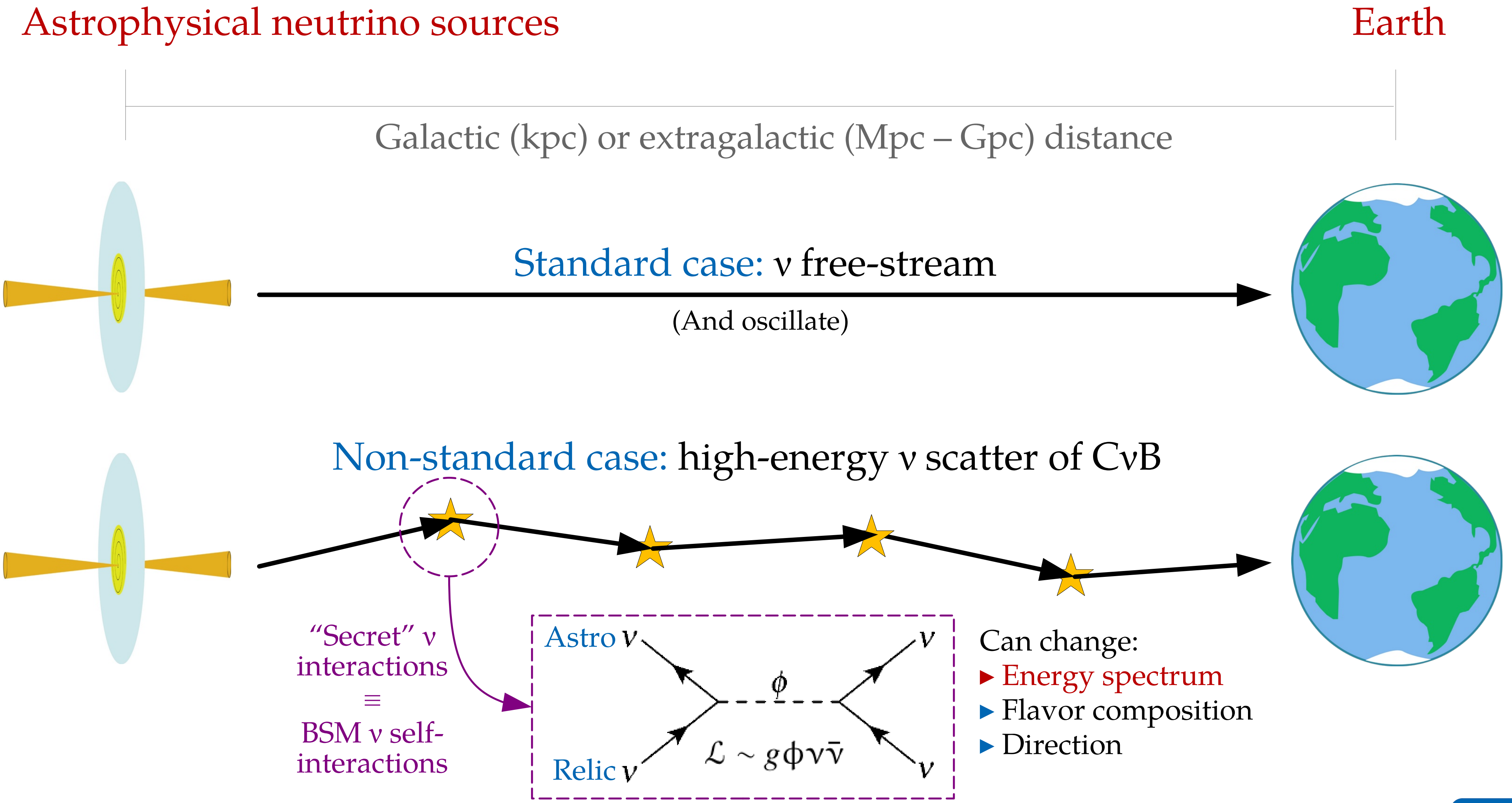


Can change:

- Energy spectrum

Astrophysical neutrino sources — Earth





Astrophysical neutrino sources
Earth
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Standard case: ν free-stream
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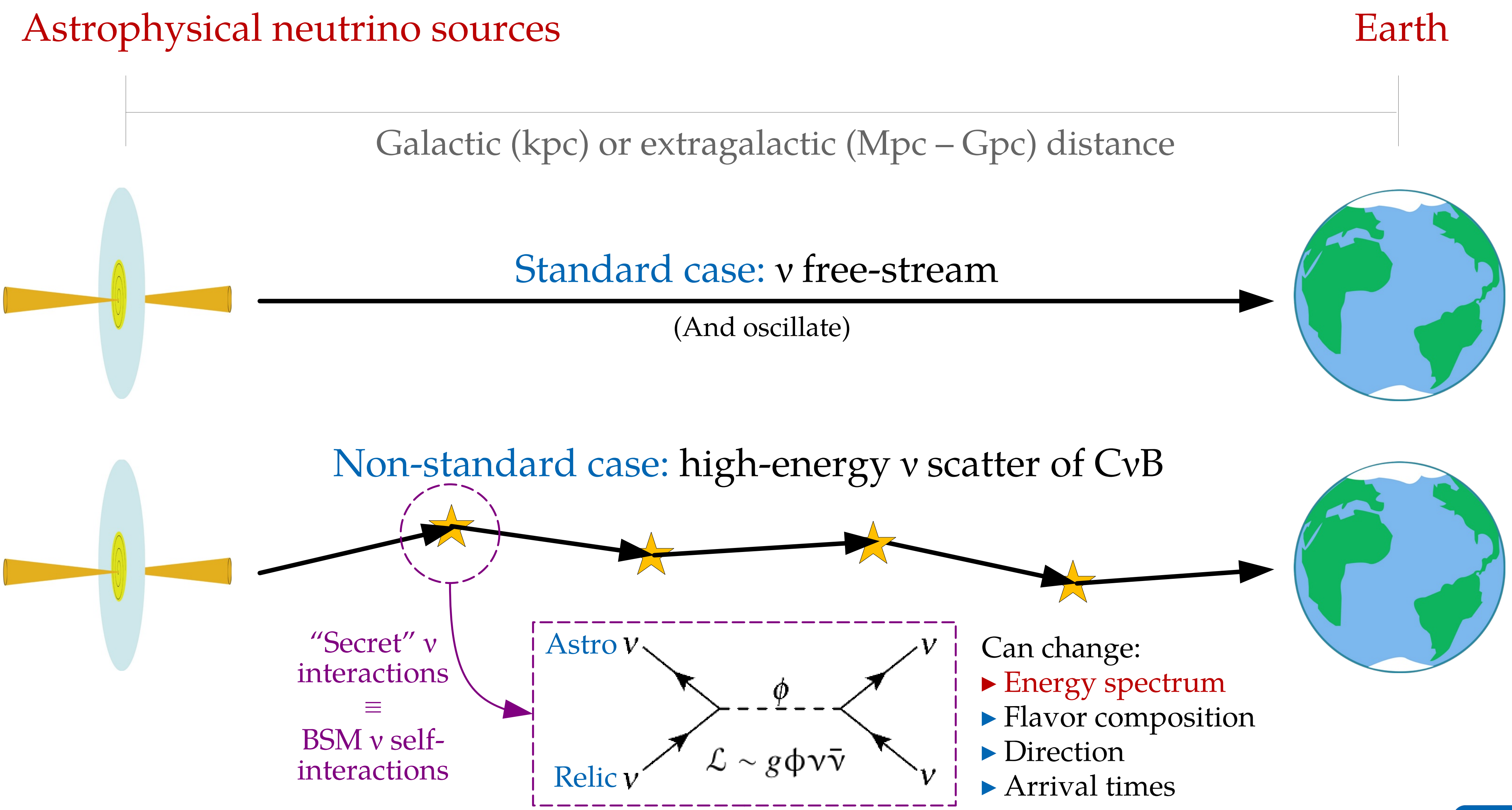
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change:
▸ Energy spectrum
▸ Flavor composition
▸ Direction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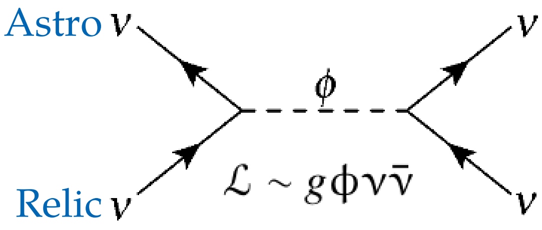
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change:
▸ Energy spectrum
▸ Flavor composition
▸ Direction
▸ Arrival times

Secret interactions of high-energy astrophysical neutrinos

“Secret” neutrino interactions between astrophysical ν (PeV) and relic ν (0.1 meV):



Cross section: $$\sigma = \frac{g^4}{4\pi}\frac{s}{(s-M^2)^2+M^2\Gamma^2}$$

Resonance energy: $$E_{\rm res} = \frac{M^2}{2m_\nu}$$

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021
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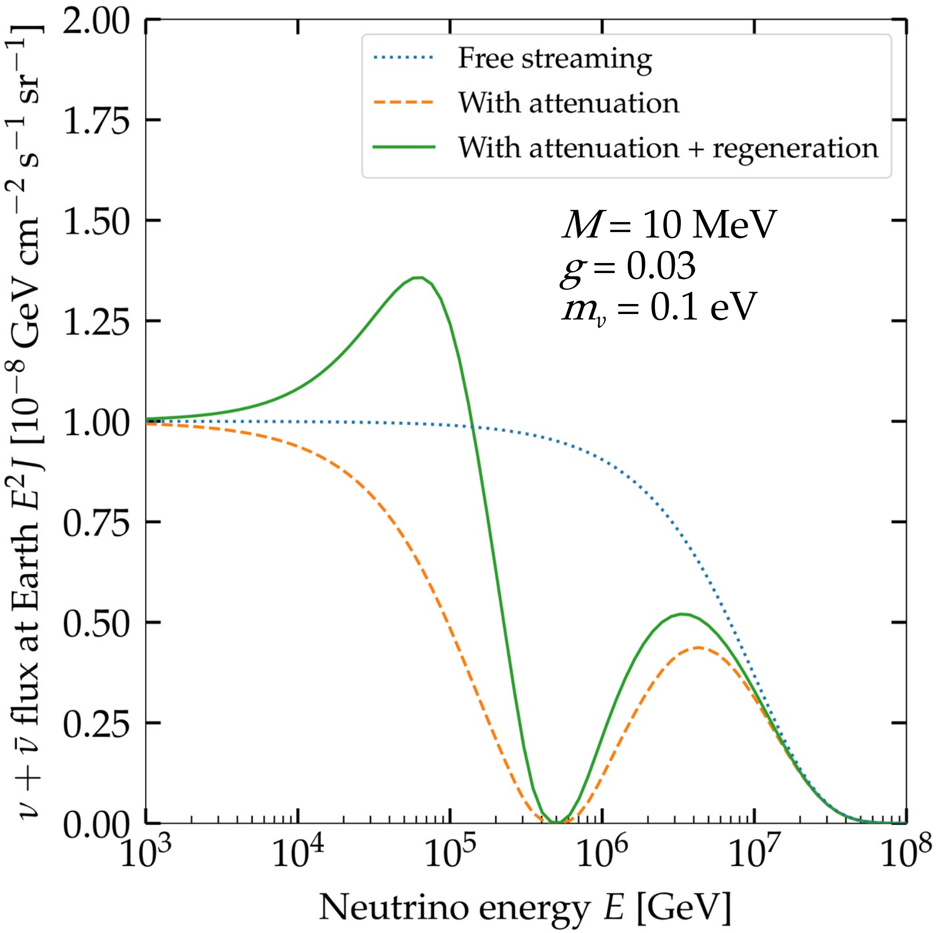
Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799



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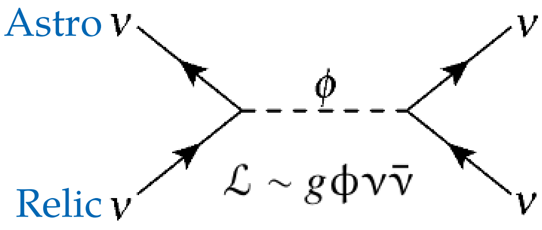

New coupling

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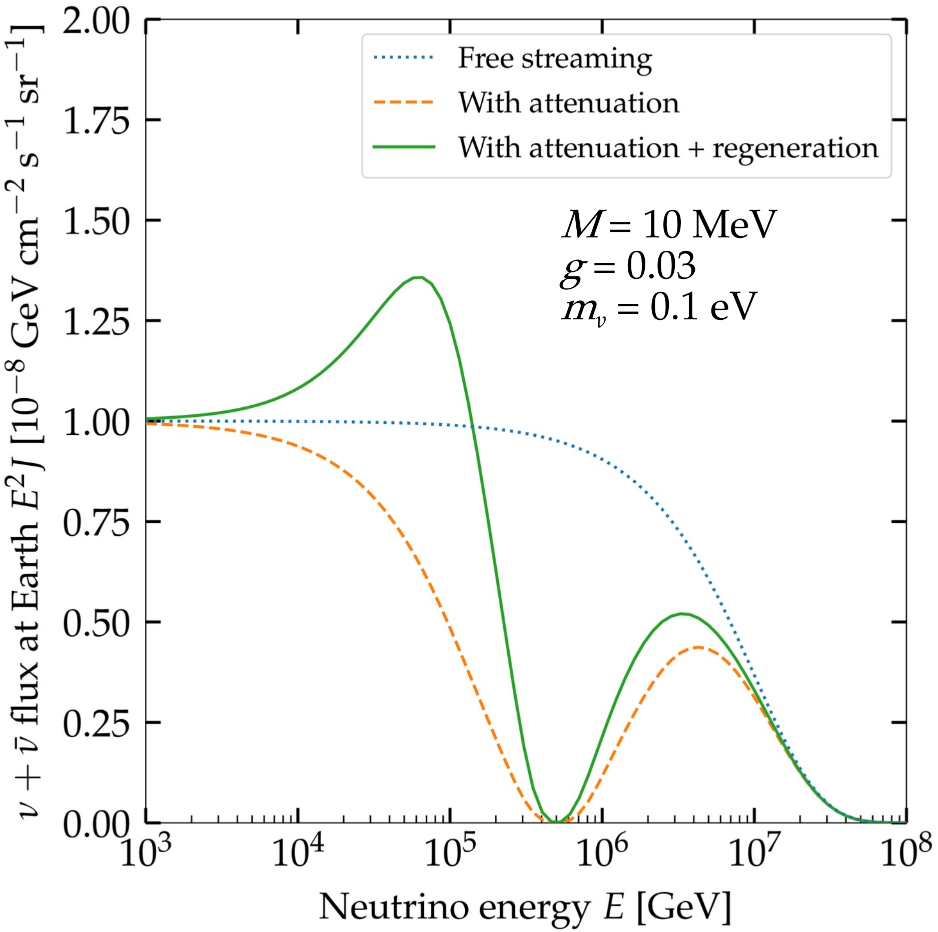

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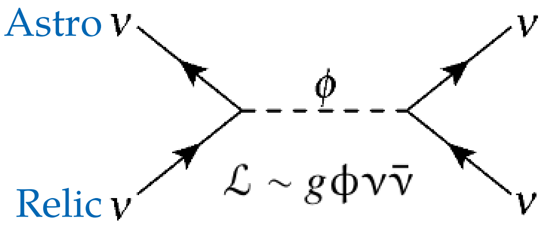

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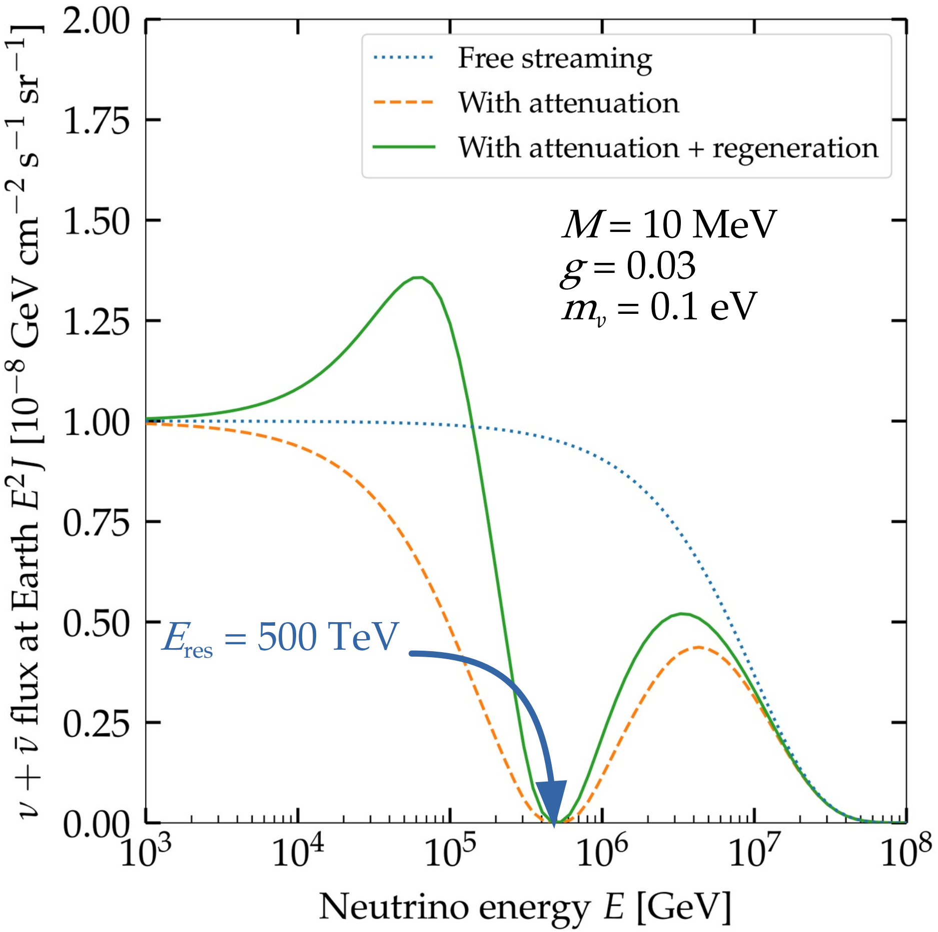

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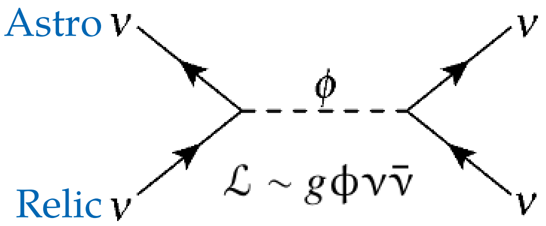

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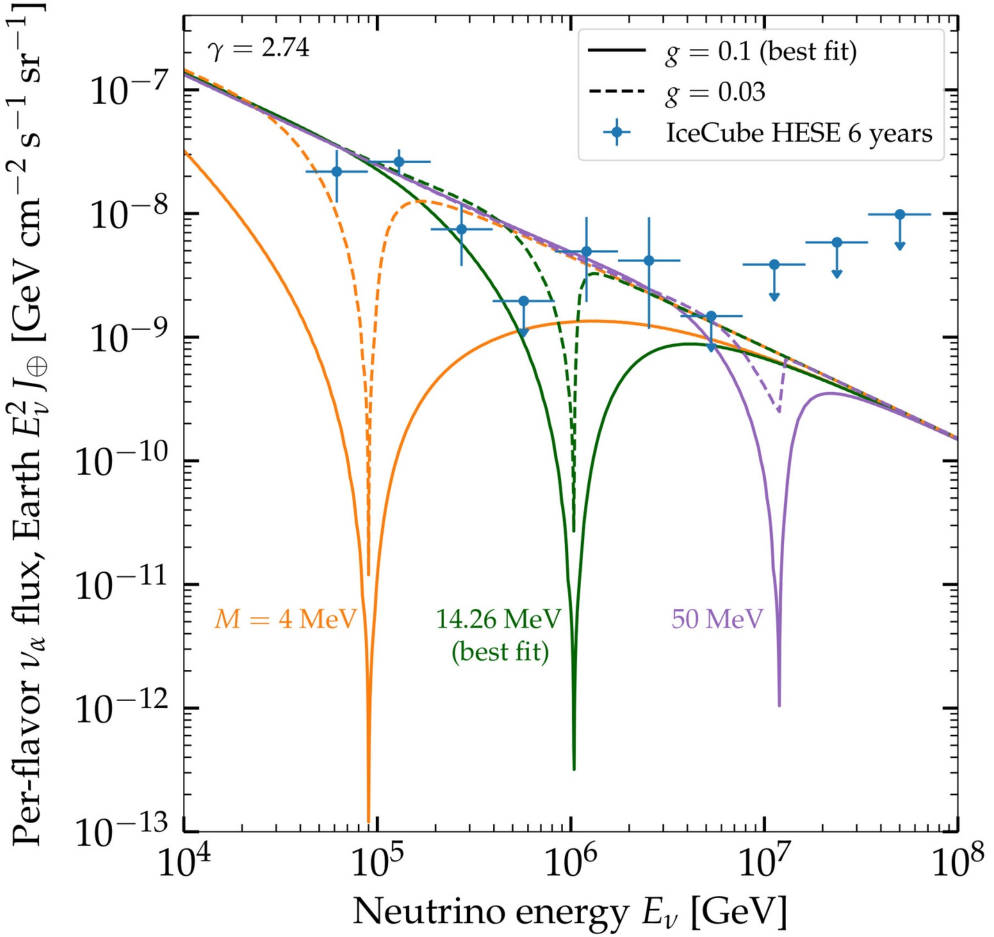

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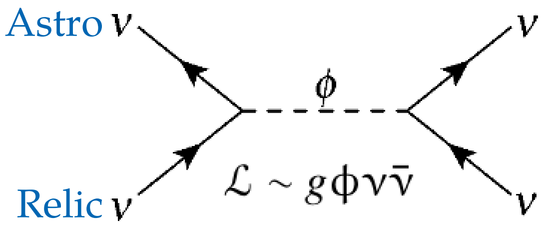

New coupling

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Mediator mass

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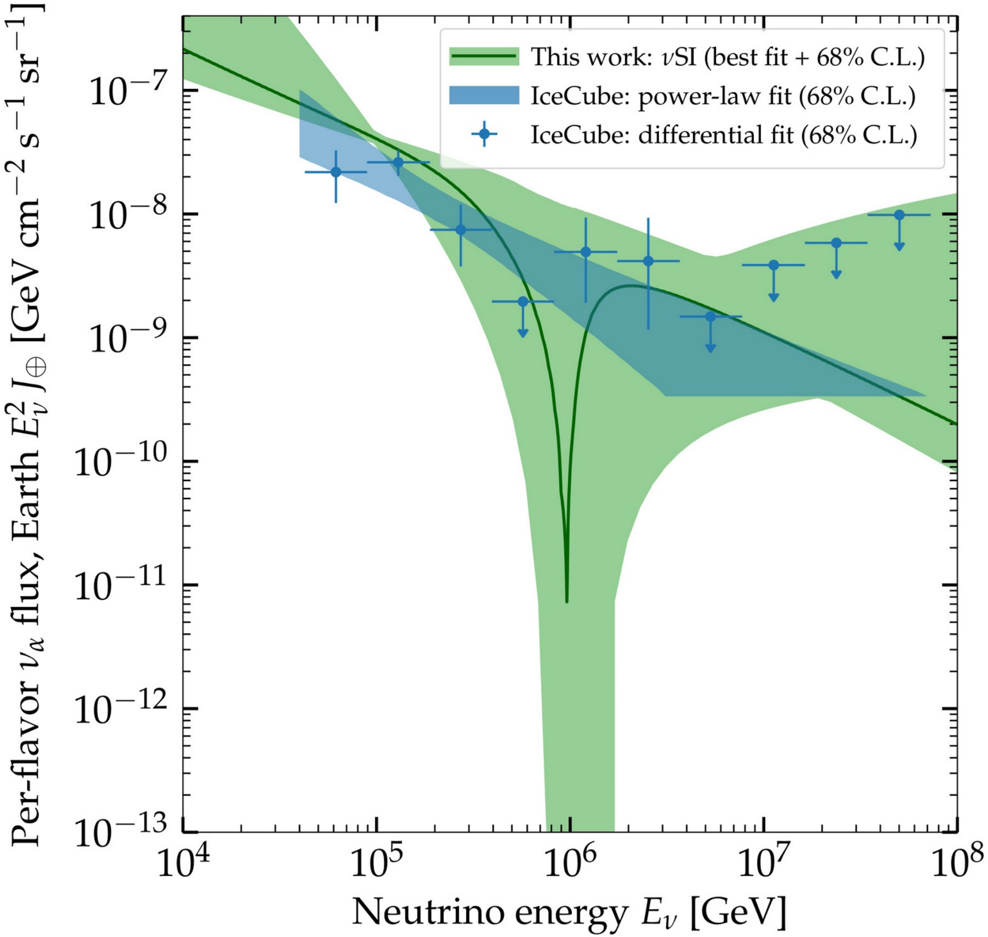
Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

Looking for evidence of νSI

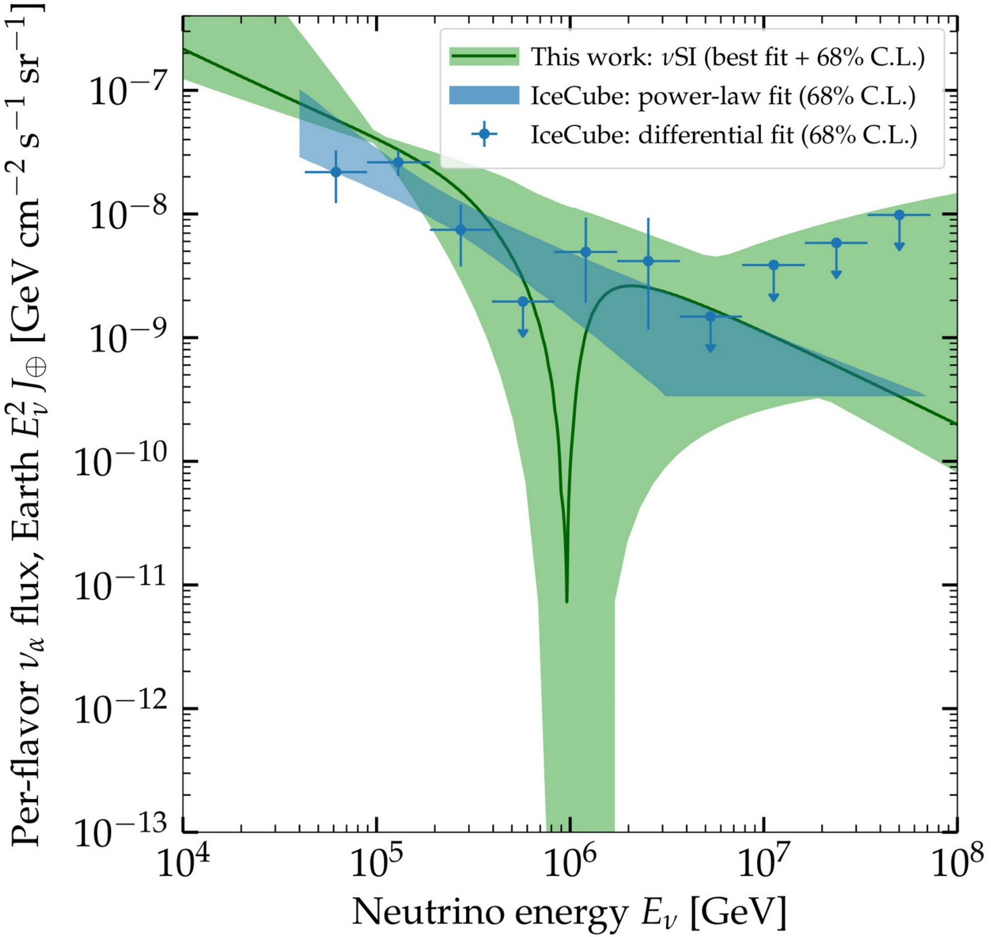
- Look for dips in 6 years of public IceCube data (HESE)
- 80 events, 18 TeV–2 PeV
- Assume flavor-diagonal and universal: $g_{\alpha\alpha} = g\,\delta_{\alpha\alpha}$
- Bayesian analysis varying M, g, shape of emitted flux (γ)
- Account for atmospheric ν, in-Earth propagation, detector uncertainties

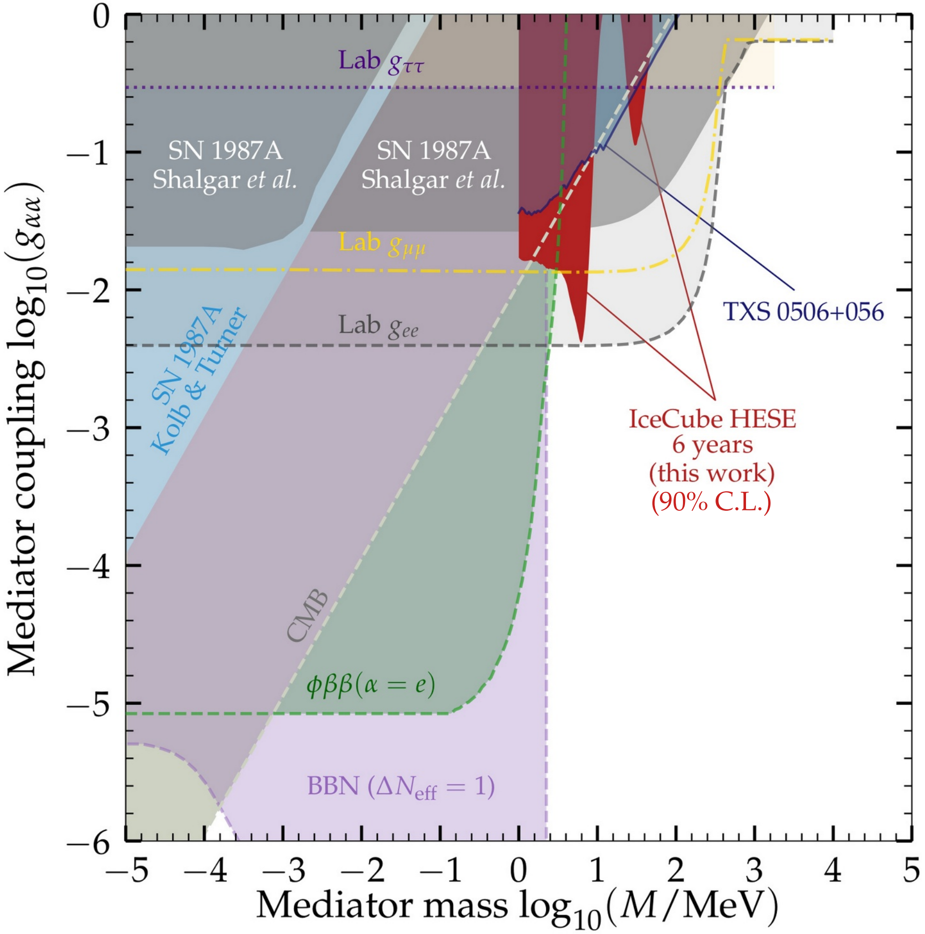
No significant (> 3σ) evidence for a spectral dip …



MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Shalgar, **MB**, Tamborra, *PRD* 2020
Esteban, Pandey, Brdar, Beacom, *PRD* 2021

No significant (> 3σ) evidence for a spectral dip … … so we set upper limits on the coupling g





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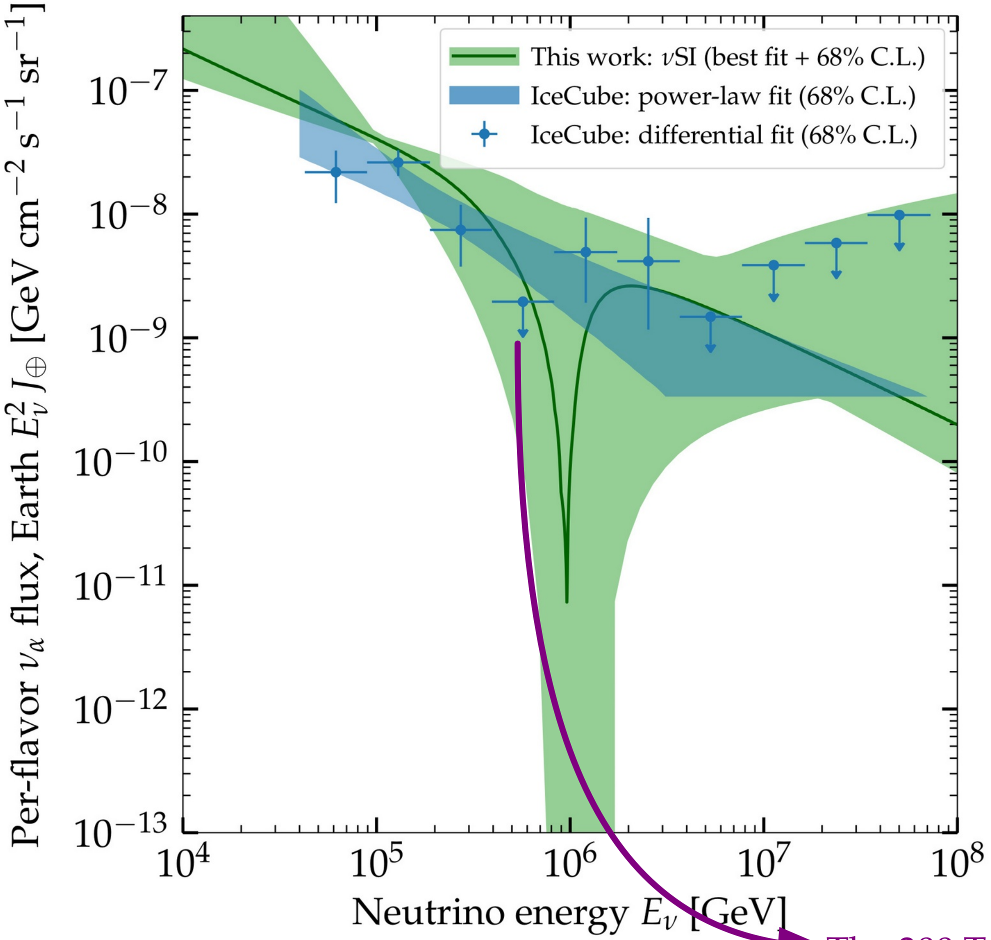
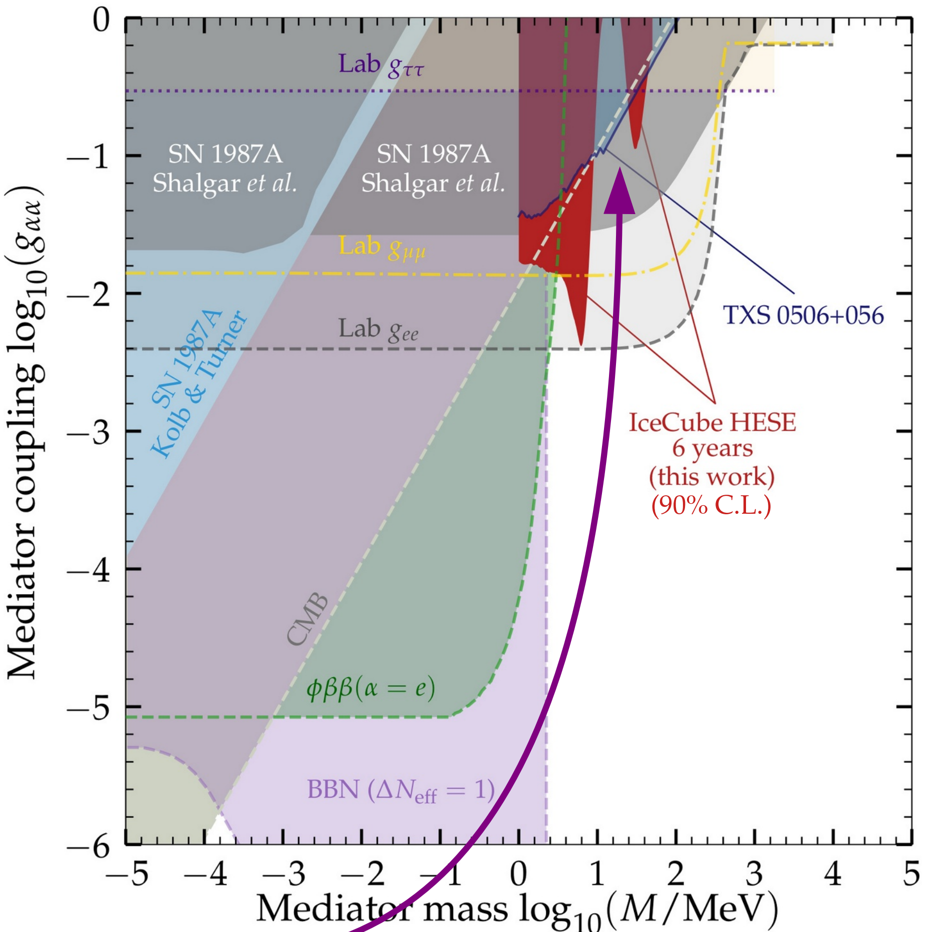
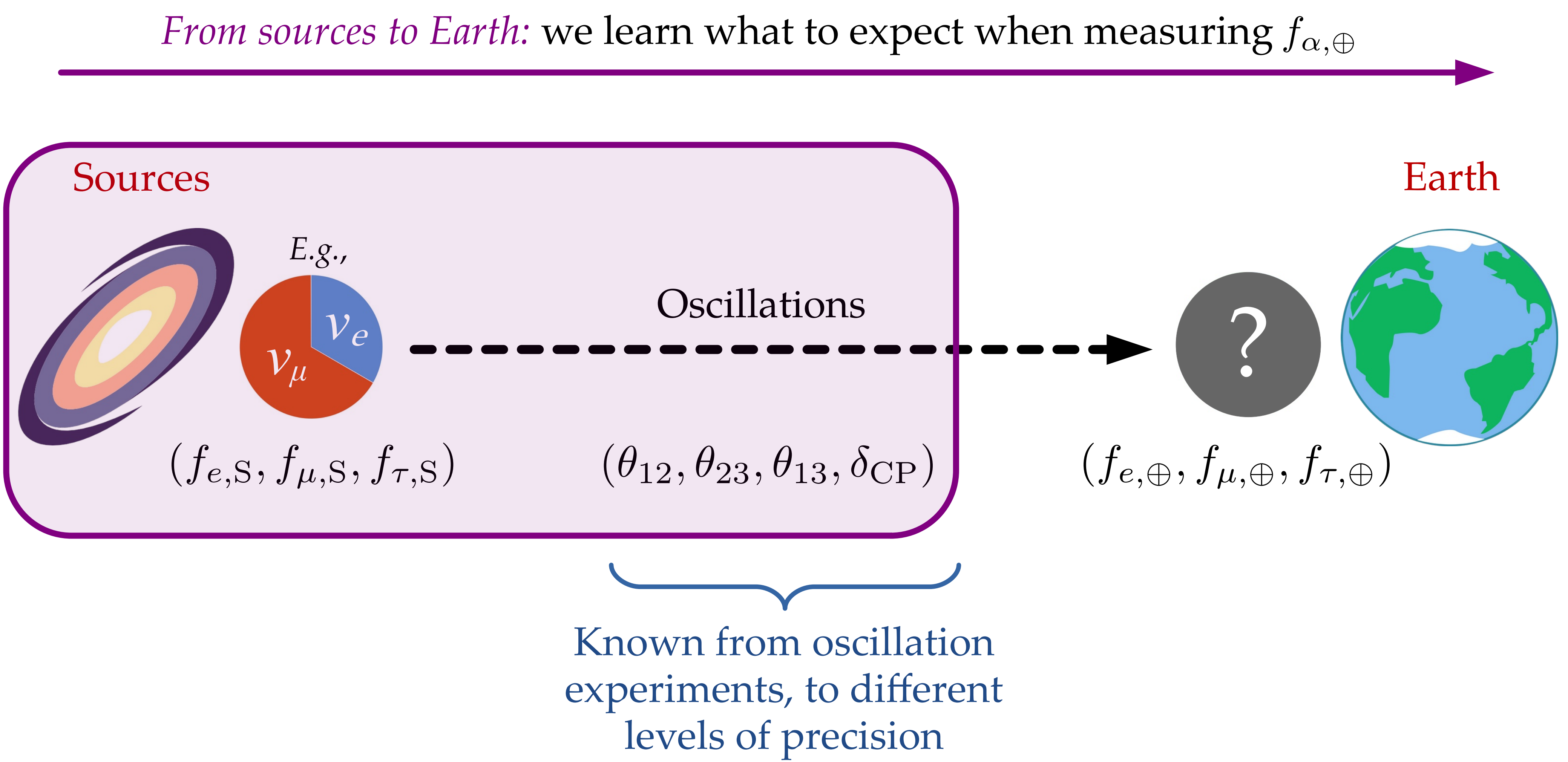




The 300 TeV–1 PeV "gap" degrades the limit at ~10 MeV

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Shalgar, **MB**, Tamborra, *PRD* 2020
Esteban, Pandey, Brdar, Beacom, *PRD* 2021

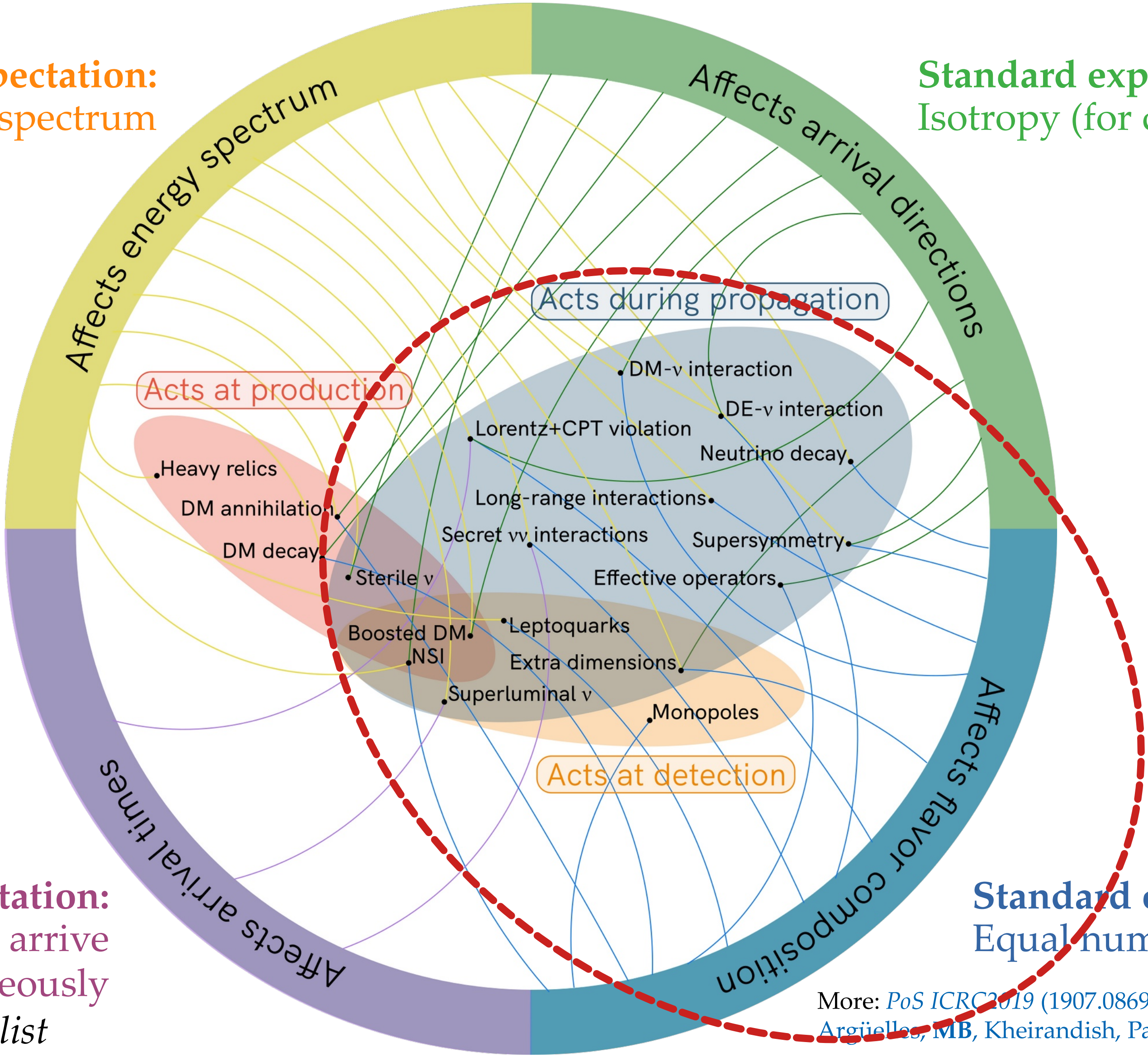
Testing new physics via flavor



From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$
Sources
E.g.,
ν_e
ν_μ
Oscillations
?
Earth
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$
Known from oscillation experiments, to different levels of precision

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

New physics in flavor composition

Use the flavor sensitivity to test new physics:

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Reviews:
Argüelles *et al.* (inc. ***MB***), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

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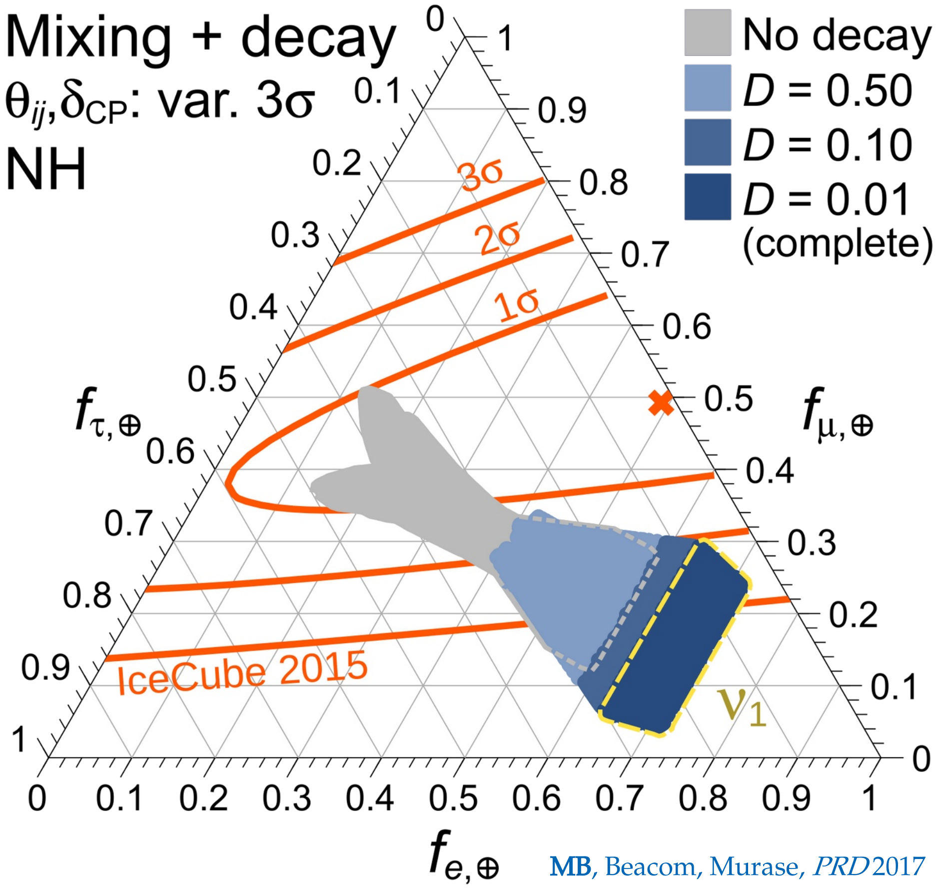

MB, Beacom, Murase, *PRD* 2017

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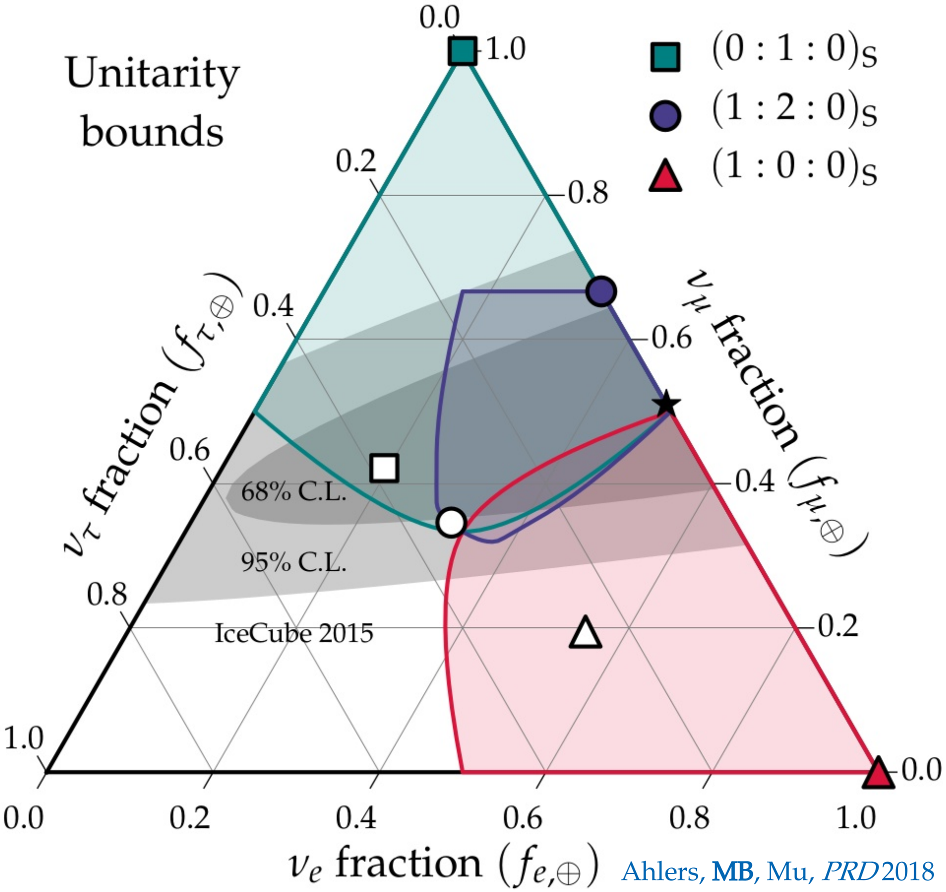

Ahlers, **MB**, Mu, *PRD* 2018

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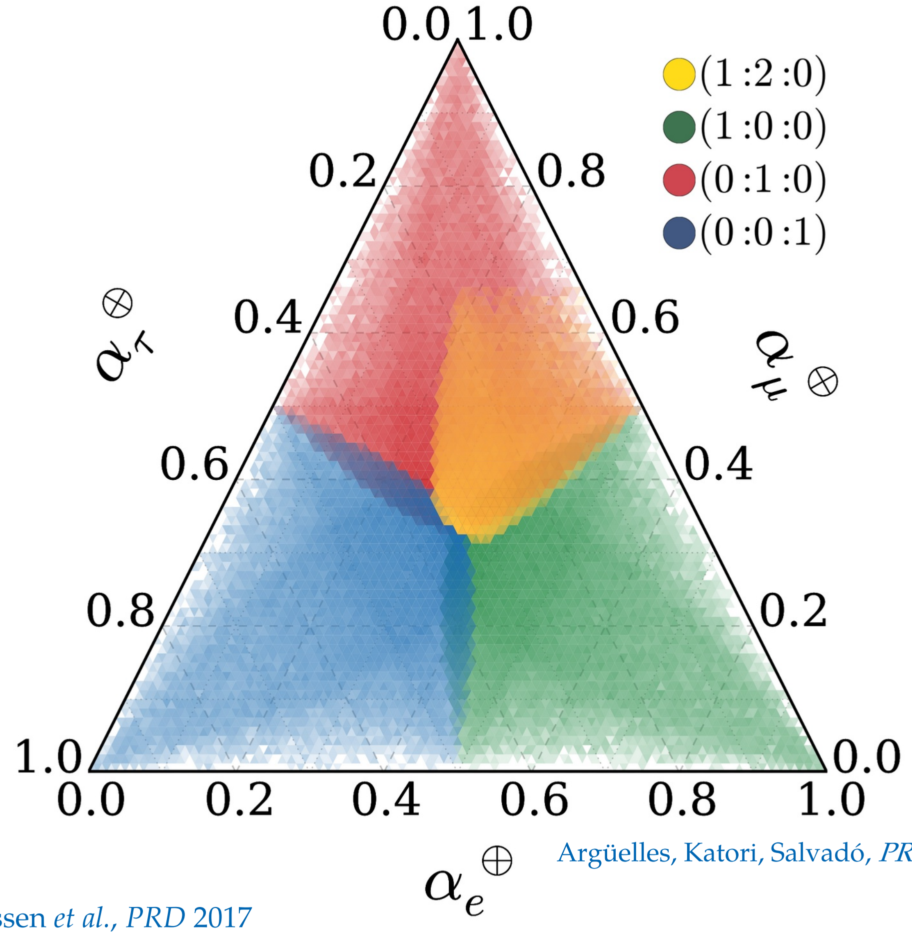

Argüelles, Katori, Salvadó, *PRL* 2015

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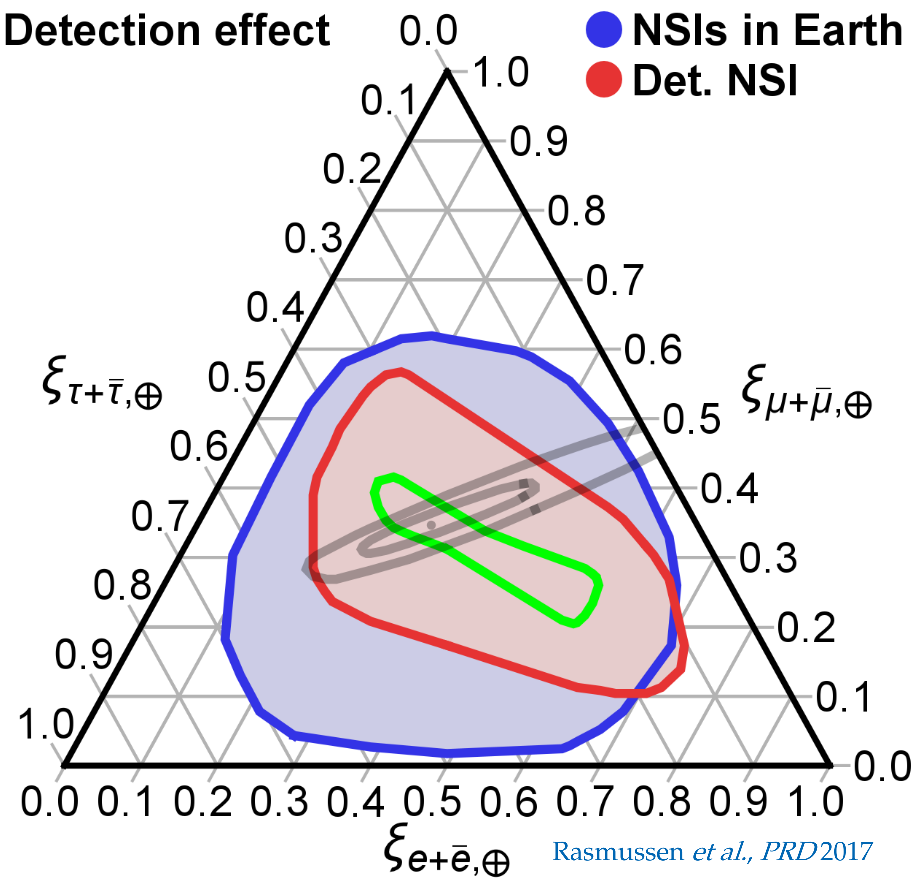

Rasmussen *et al.*, *PRD* 2017

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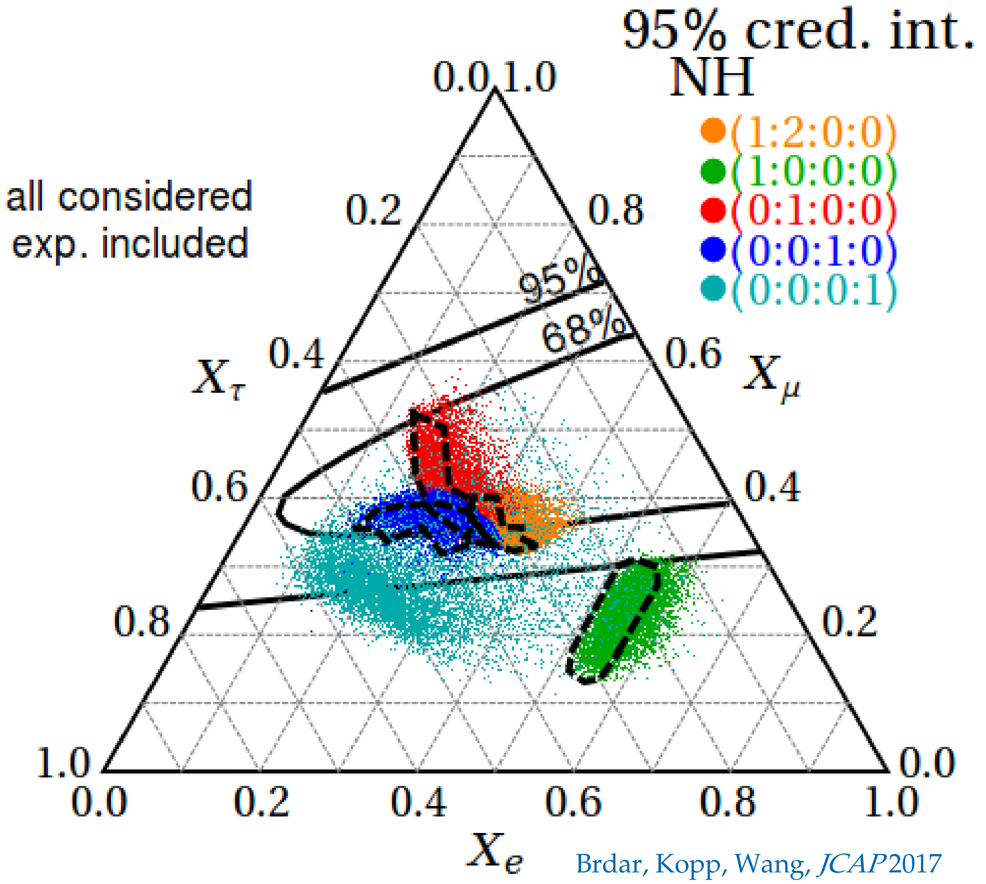

Brdar, Kopp, Wang, *JCAP* 2017

Reviews:
Argüelles *et al.* (inc. ***MB***), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

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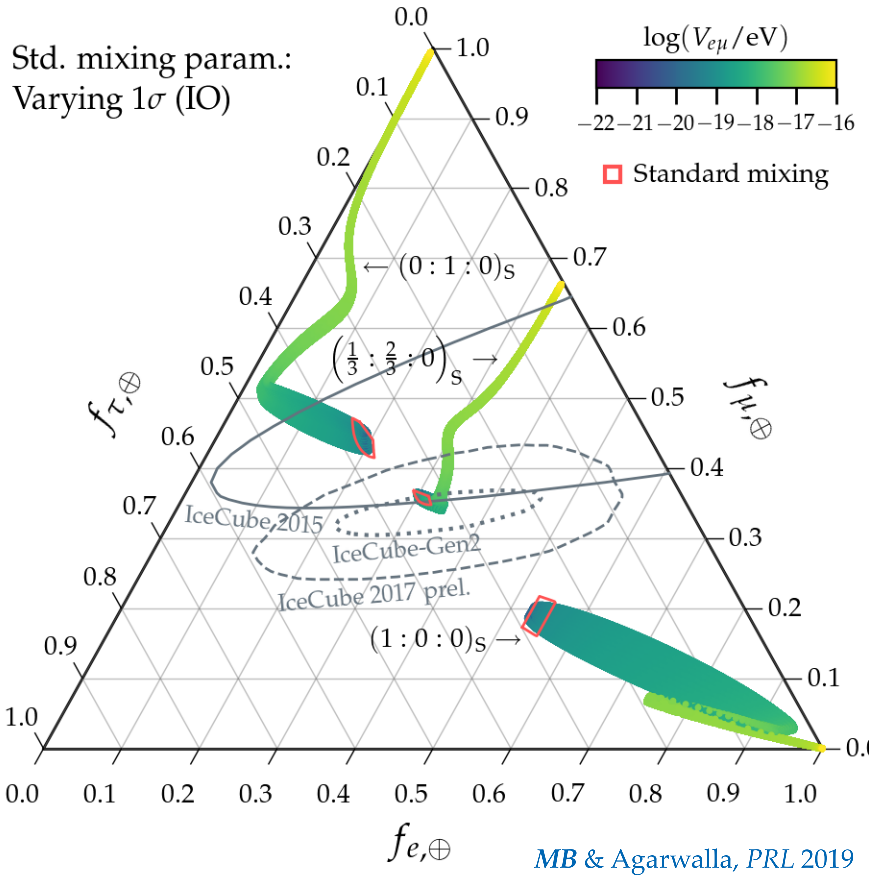
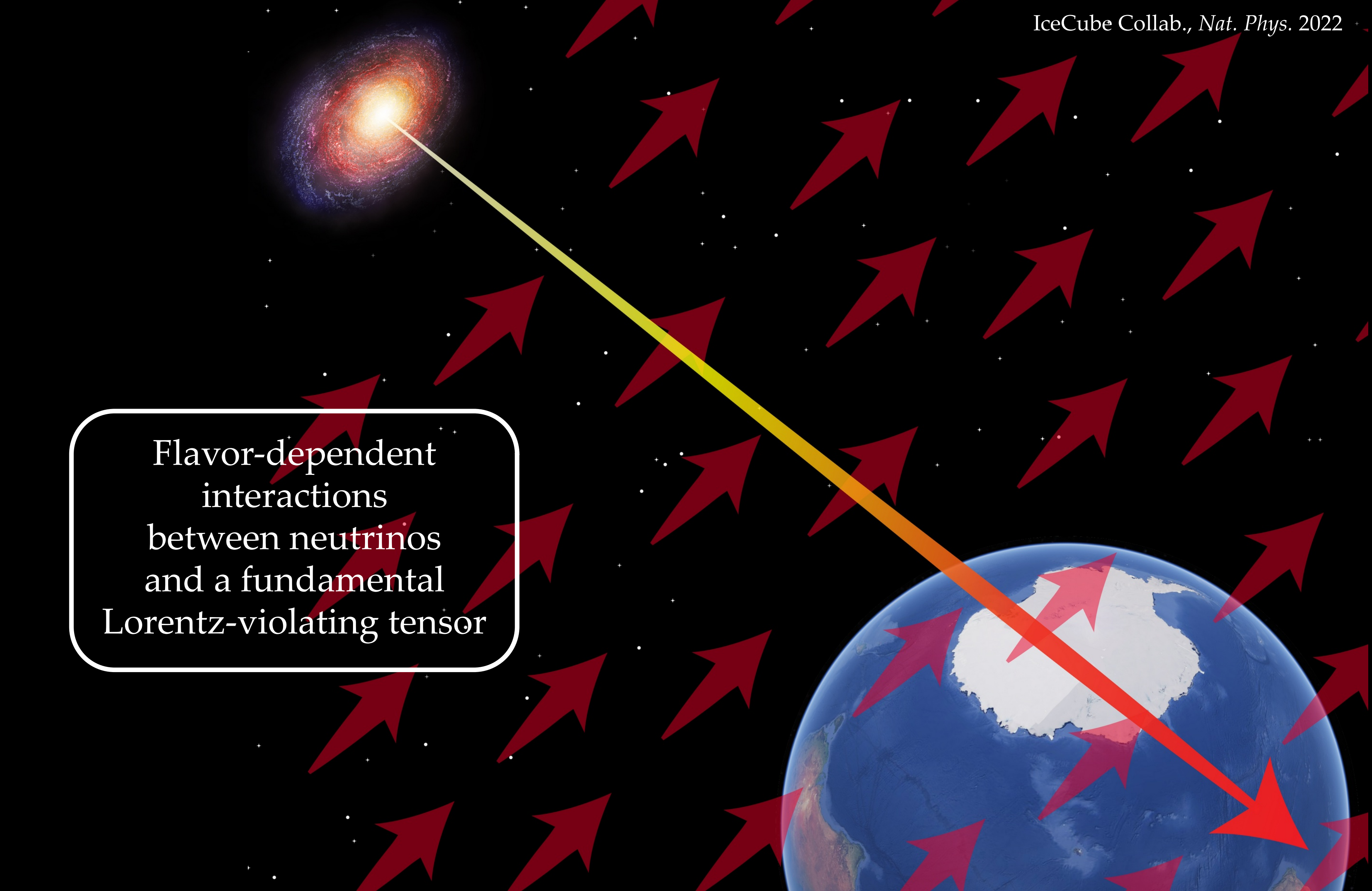
- ▸ Long-range $e\nu$ interactions
  [***MB*** & Agarwalla, *PRL* 2019]



MB & Agarwalla, *PRL* 2019

Reviews:
Argüelles *et al.* (inc. ***MB***), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017


IceCube Collab., *Nat. Phys.* 2022
Flavor-dependent interactions between neutrinos and a fundamental Lorentz-violating tensor

Standard oscillations:

$$H_{\mathrm{std}} = \frac{1}{2E} U^\dagger_{\mathrm{PMNS}} \mathrm{diag}(0, \Delta m^2_{21}, \Delta m^2_{31}) U_{\mathrm{PMNS}}$$

Lorentz-violating interactions (Standard Model Extension):

Kostelecky, Mewes, *PRD* 2004

$$H_{\mathrm{new}} = \sum_{n \geq 0} \left(\frac{E}{\Lambda_n} \right)^n U^\dagger_n (\mathcal{O}_{n,1}, \mathcal{O}_{n,2}, \mathcal{O}_{n,3}) U_n$$

U_n has the same shape as U_{PMNS},
but its entries are a priori undetermined

Total Hamiltonian:

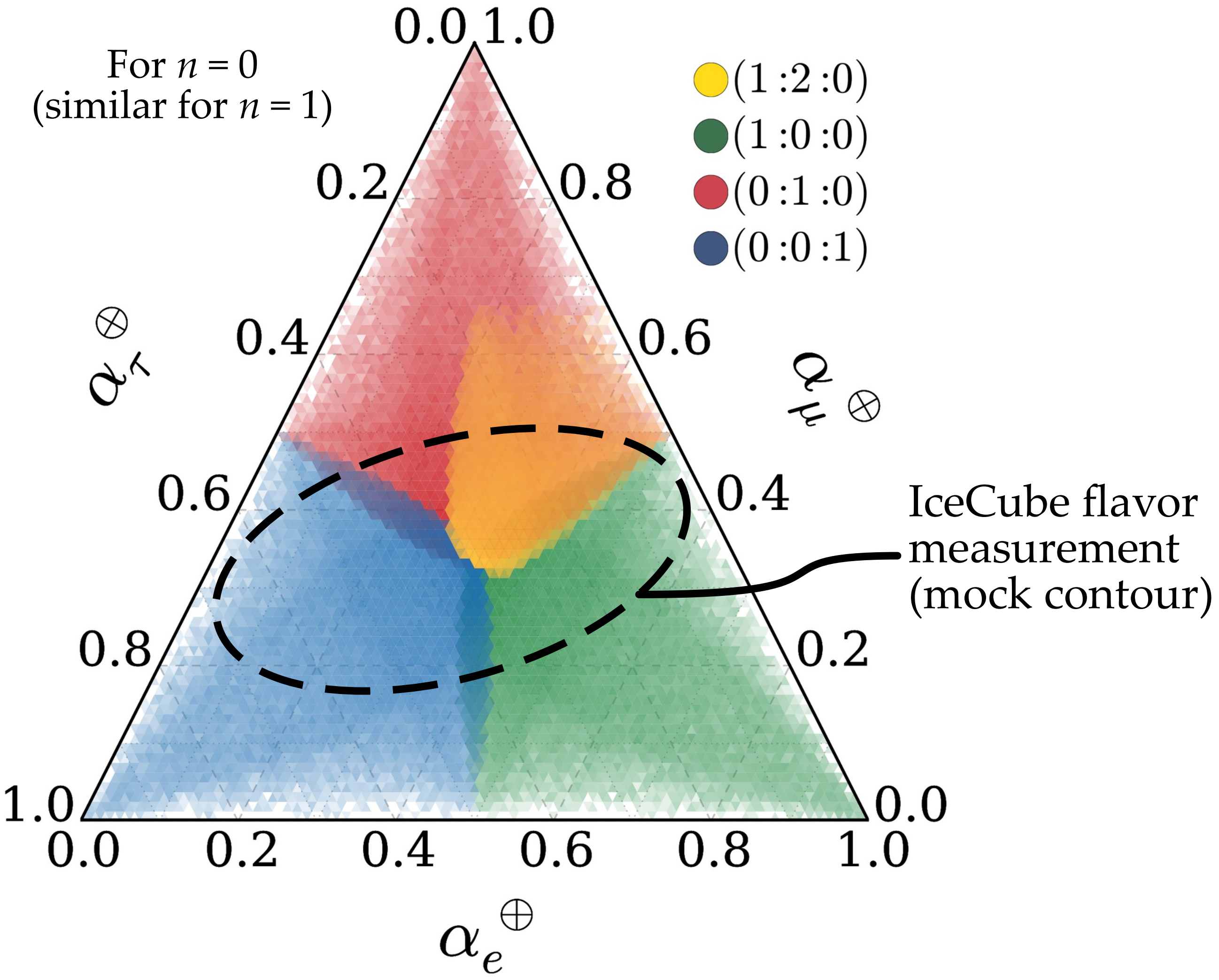
$$H_{\mathrm{tot}} = H_{\mathrm{std}} + H_{\mathrm{new}}$$

The flavor-transition probabilities are calculated as before,

$$P_{\alpha\beta} = \sum_{i=1}^{3} |(U_{\rm tot})_{\alpha i}|^2 |(U_{\rm tot})_{\beta i}|^2 \ ,$$

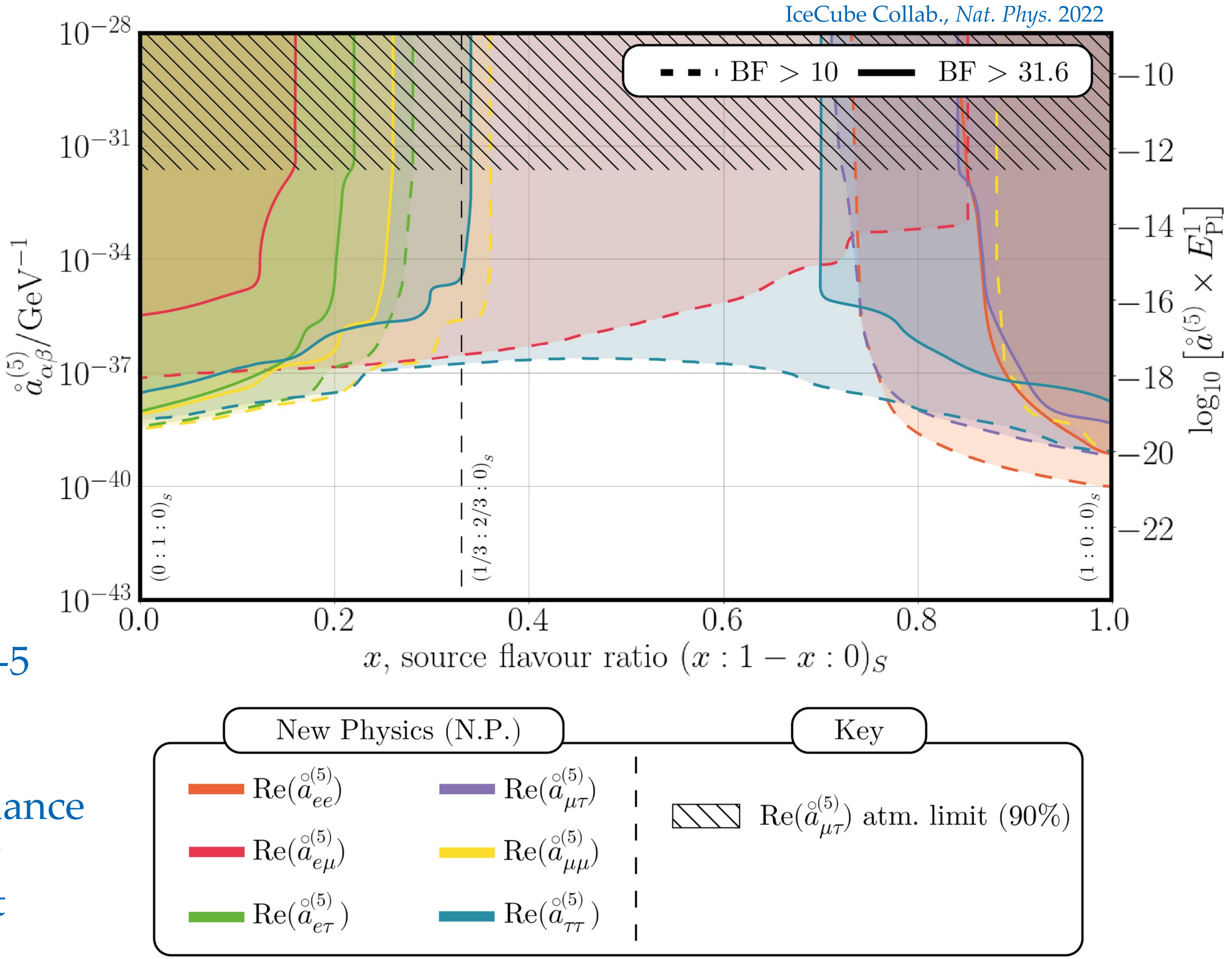
Depends on standard & new parameters

but now the lepton mixing matrix, $U_{\rm tot}$, is the one that diagonalizes $H_{\rm tot}$



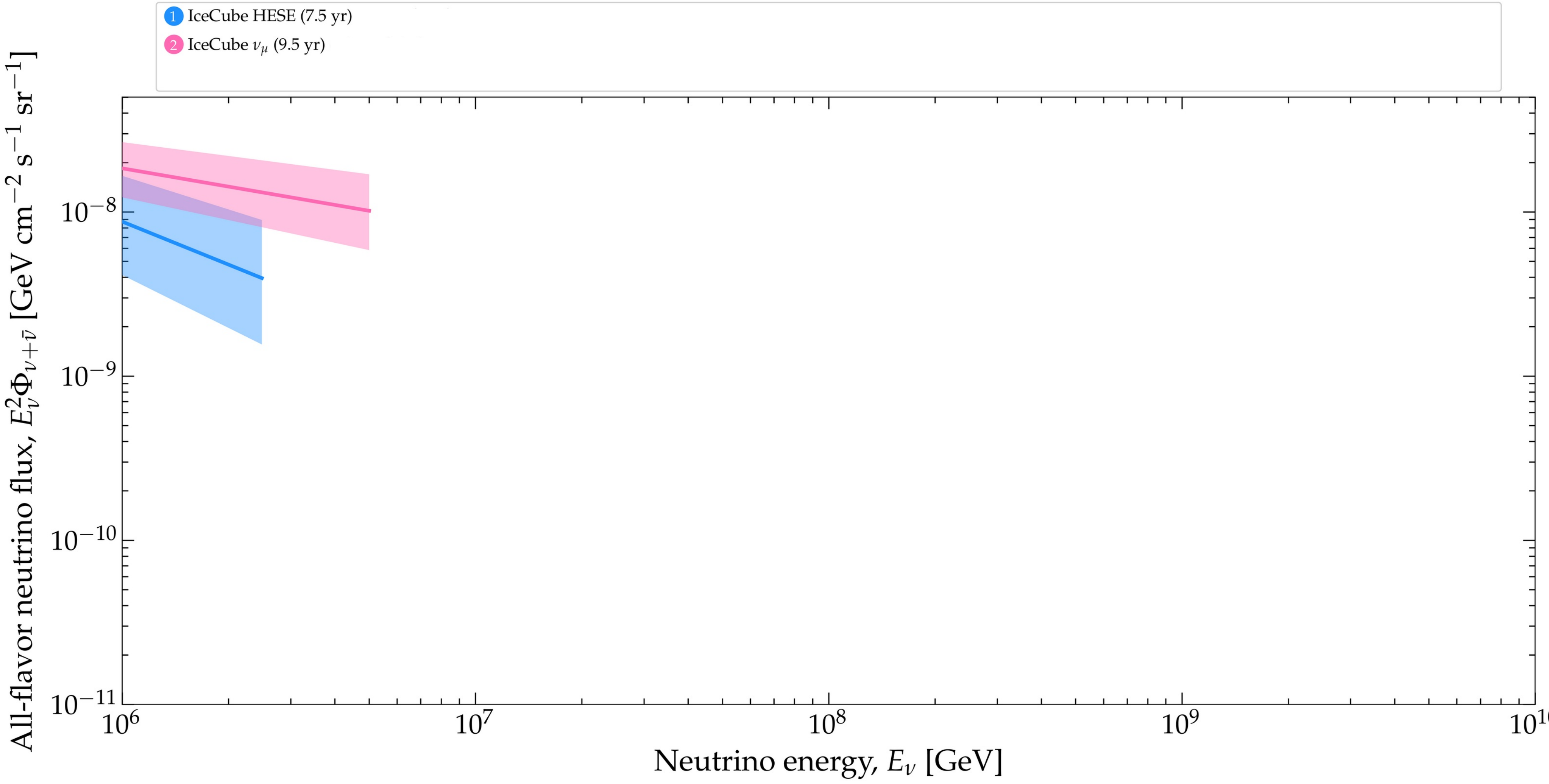
Argüelles, Katori, Salvadó, *PRL* 2015

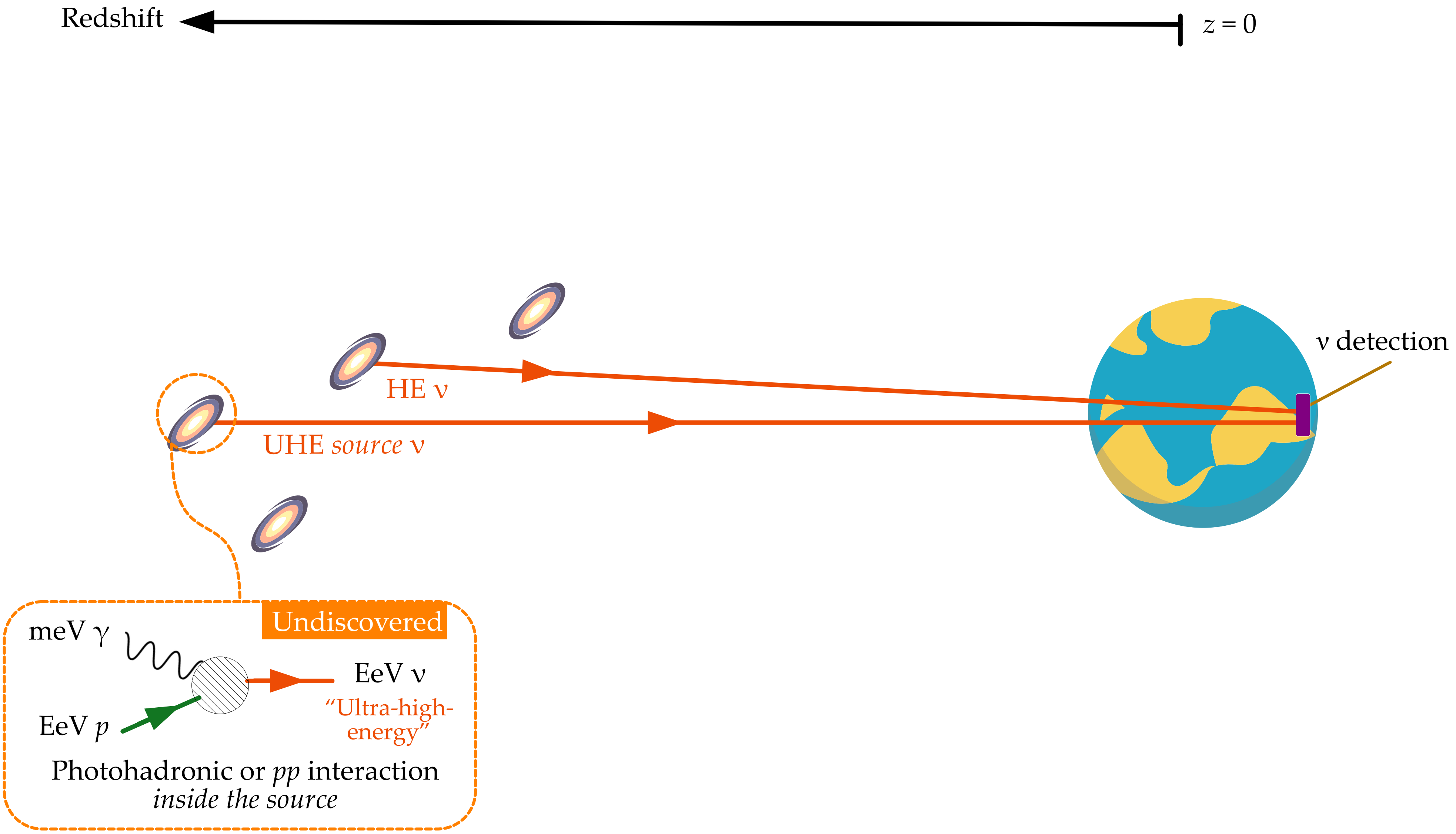
See also Ahlers, **MB**, Mu, *PRD* 2018; Rasmusen *et al.*, *PRD* 2017; **MB**, Beacom, Winter *PRL* 2015; **MB**, Gago, Peña-Garay *JCAP* 2010; Bazo, **MB**, Gago, Miranda *IJMPA* 2009; + many others

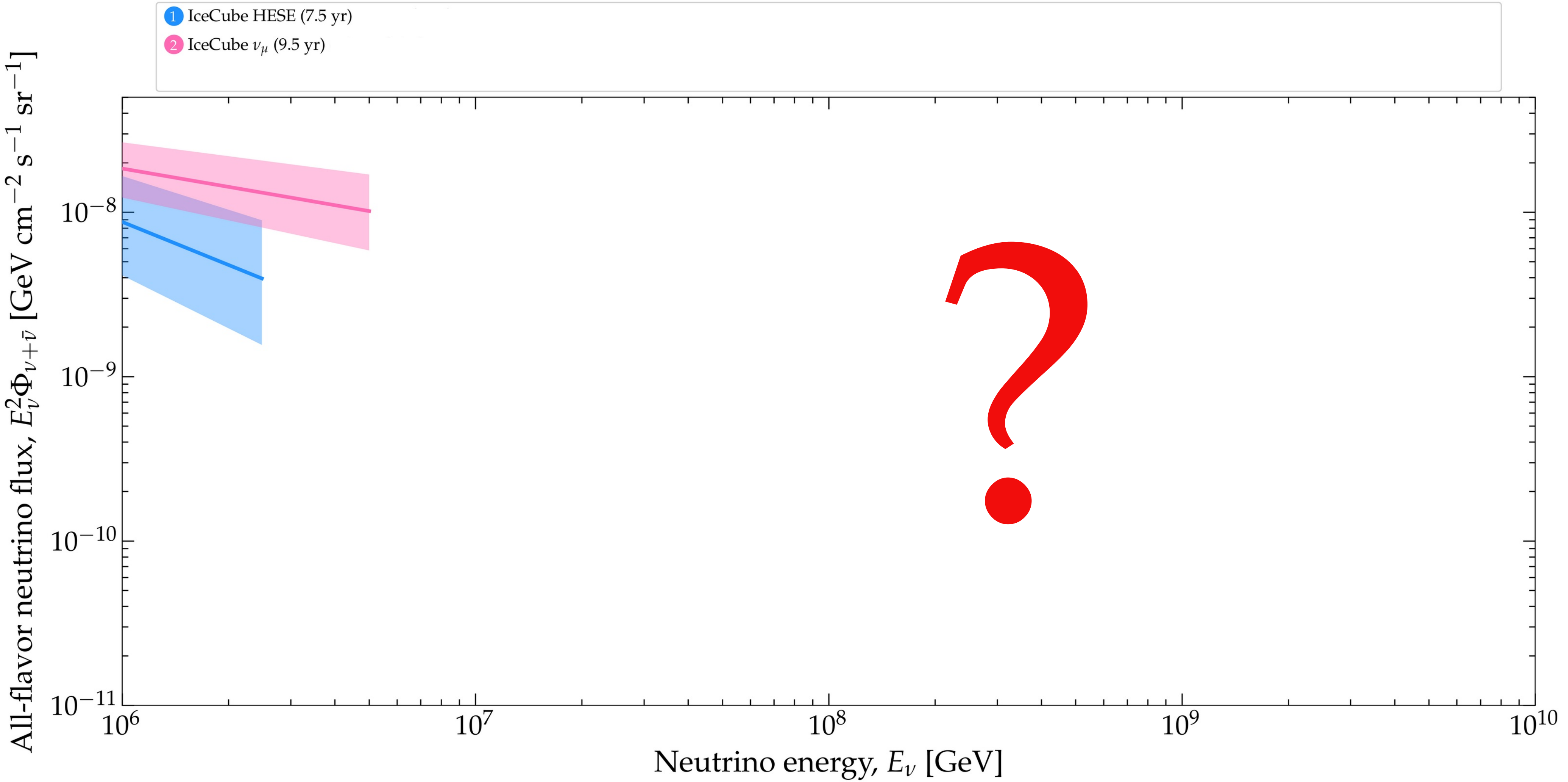


Dimension-5
CPT-odd
isotropic
Lorentz-invariance
-violating
coefficient

Ultra-high energies (> 100 PeV)


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]


Redshift
$z = 0$
HE ν
UHE *source* ν
ν detection
Undiscovered
meV γ
EeV ν
"Ultra-high-energy"
EeV p
Photohadronic or pp interaction
inside the source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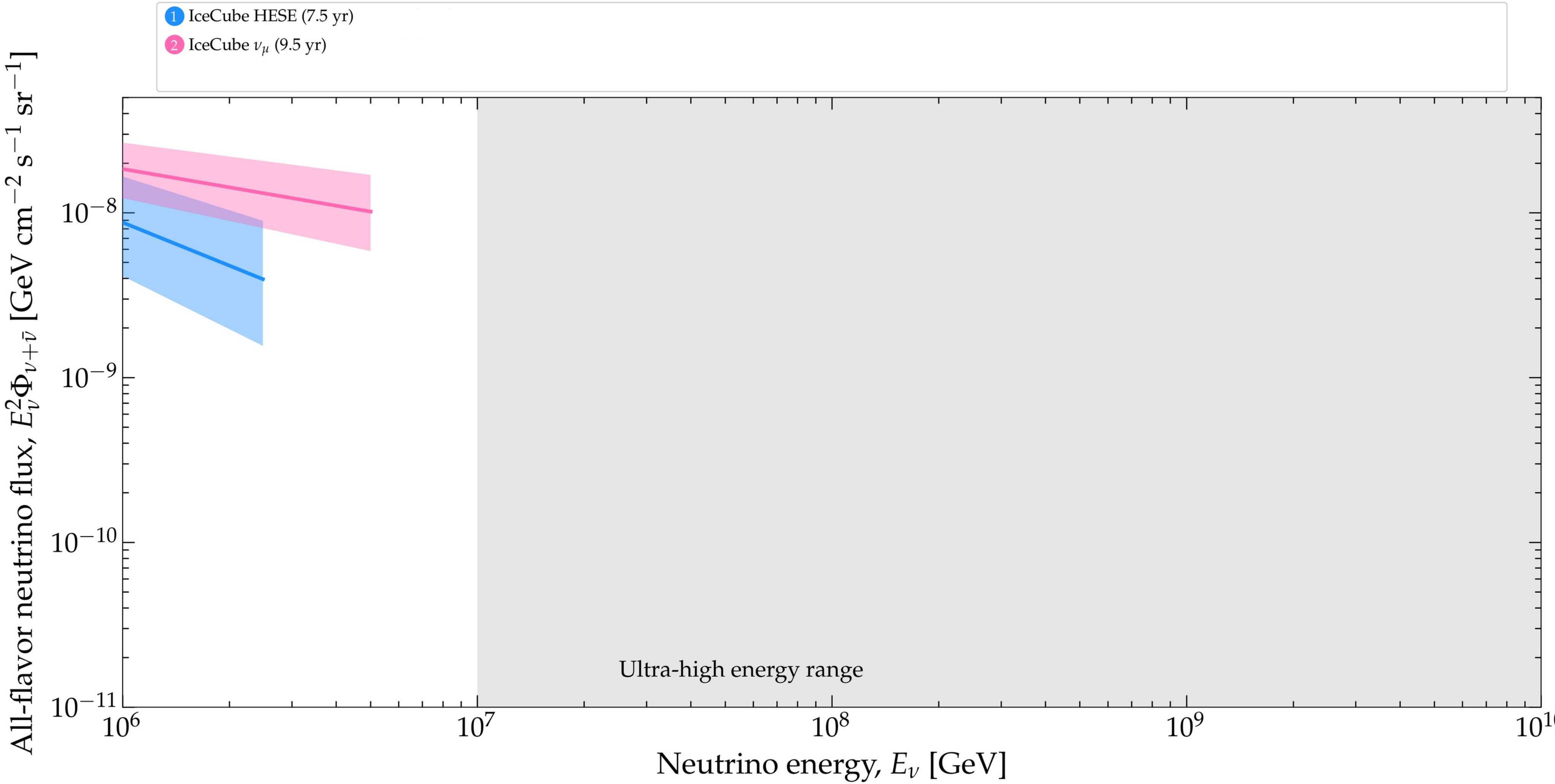
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]
?


1 IceCube HESE (7.5 yr)
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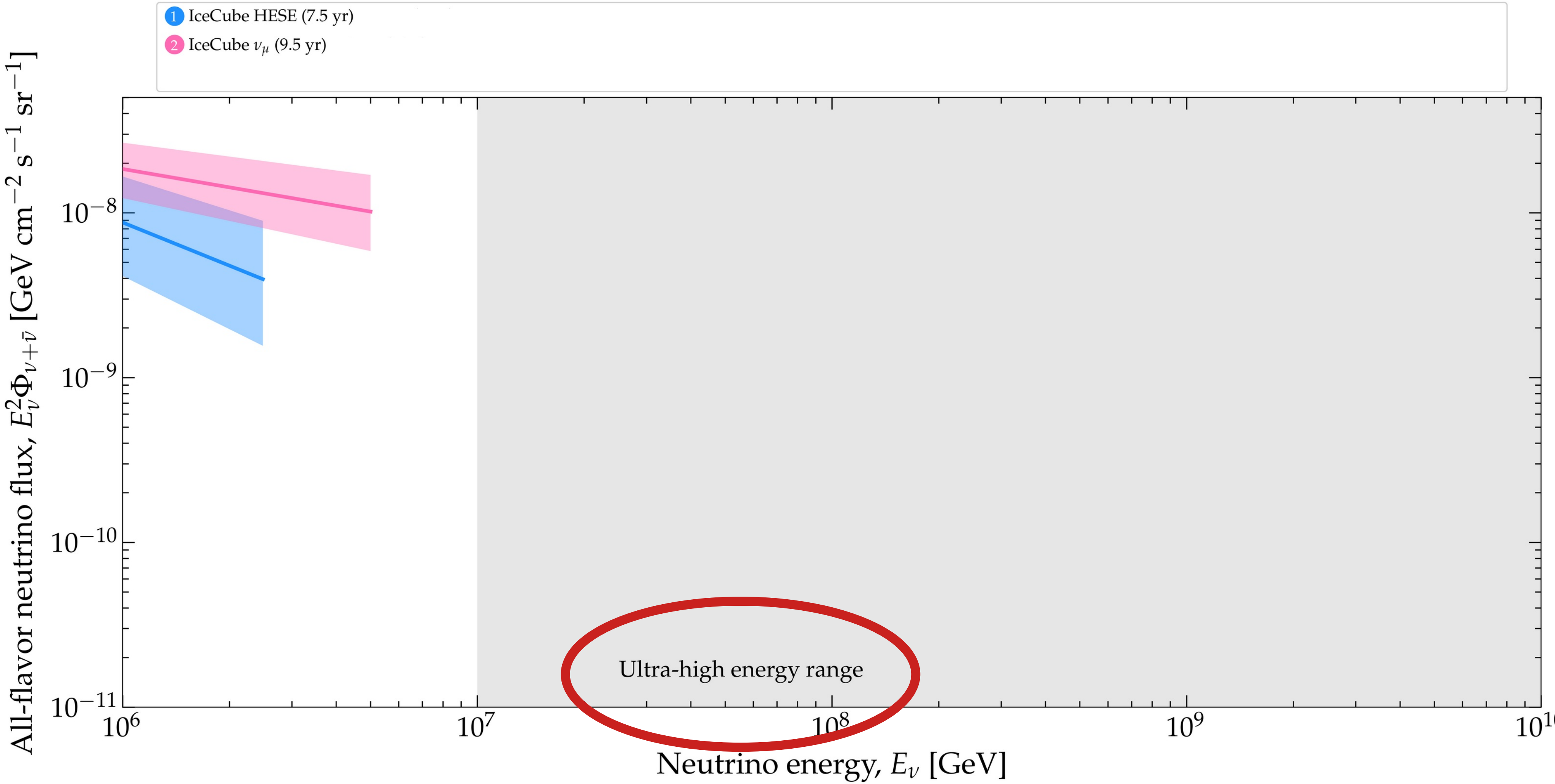
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]



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Article

Observation of an ultra-high-energy cosmic neutrino with KM3NeT

KM3NeT Collab. *Nature* 638, 376 (2025)

One muon detected with 120^{+110}_{-60} PeV

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But is it due to a neutrino?

Yes! Direction points underground, after traveling 150 km through Earth

Inferred neutrino energy: 220^{+570}_{-110} PeV

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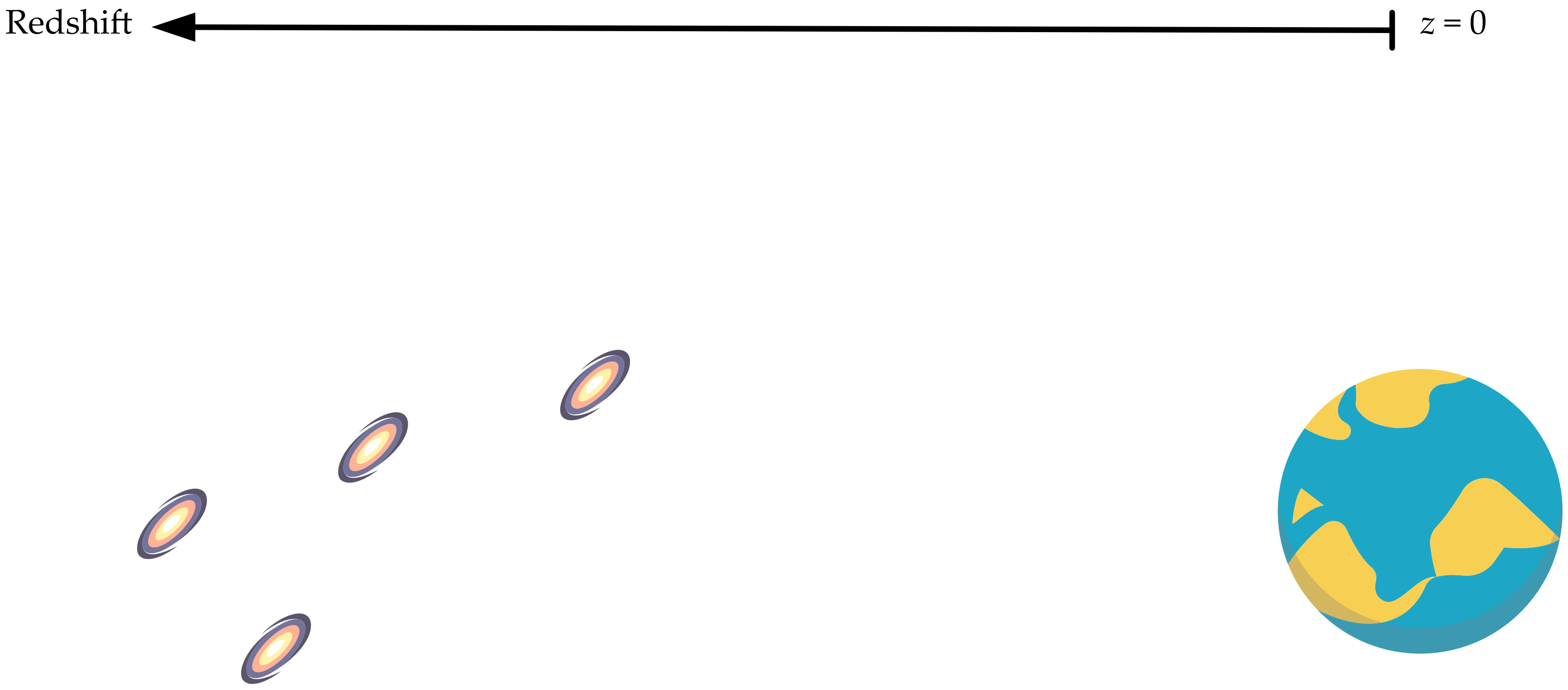
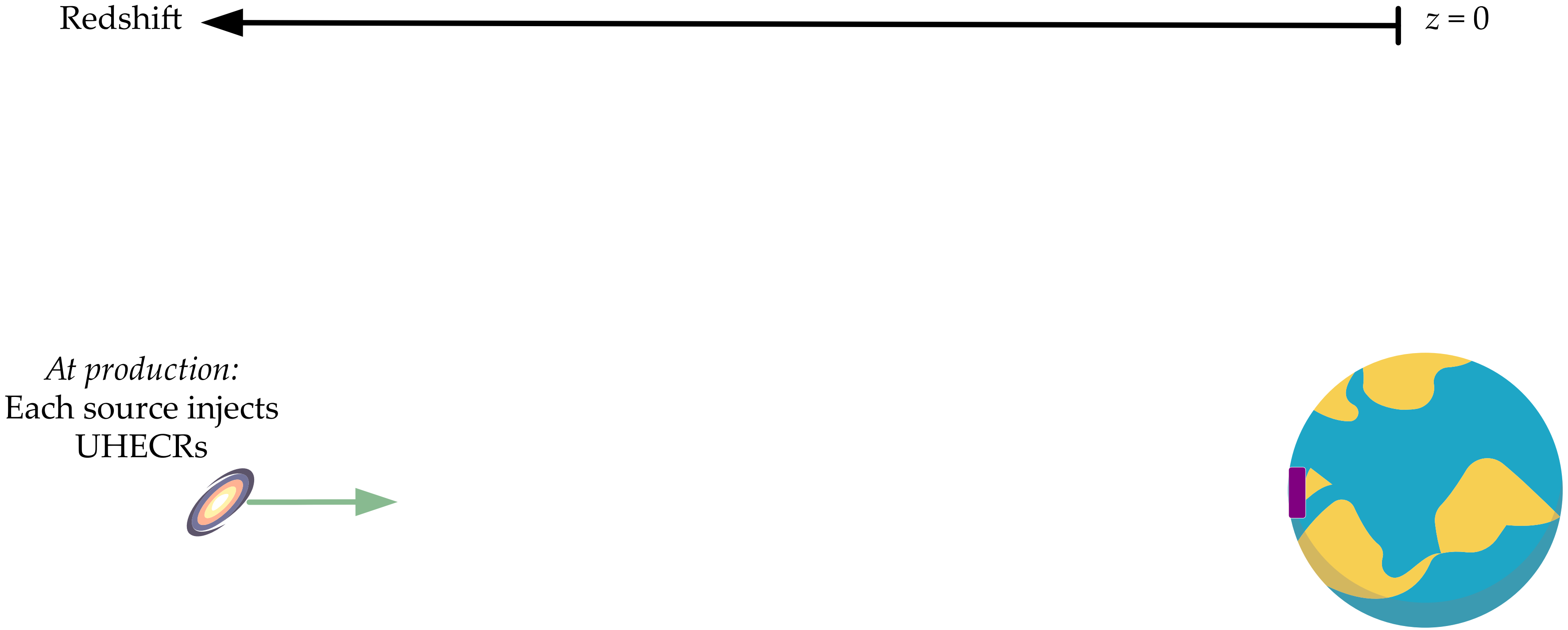
RECORD BREAKER


Redshift
$z = 0$


Redshift
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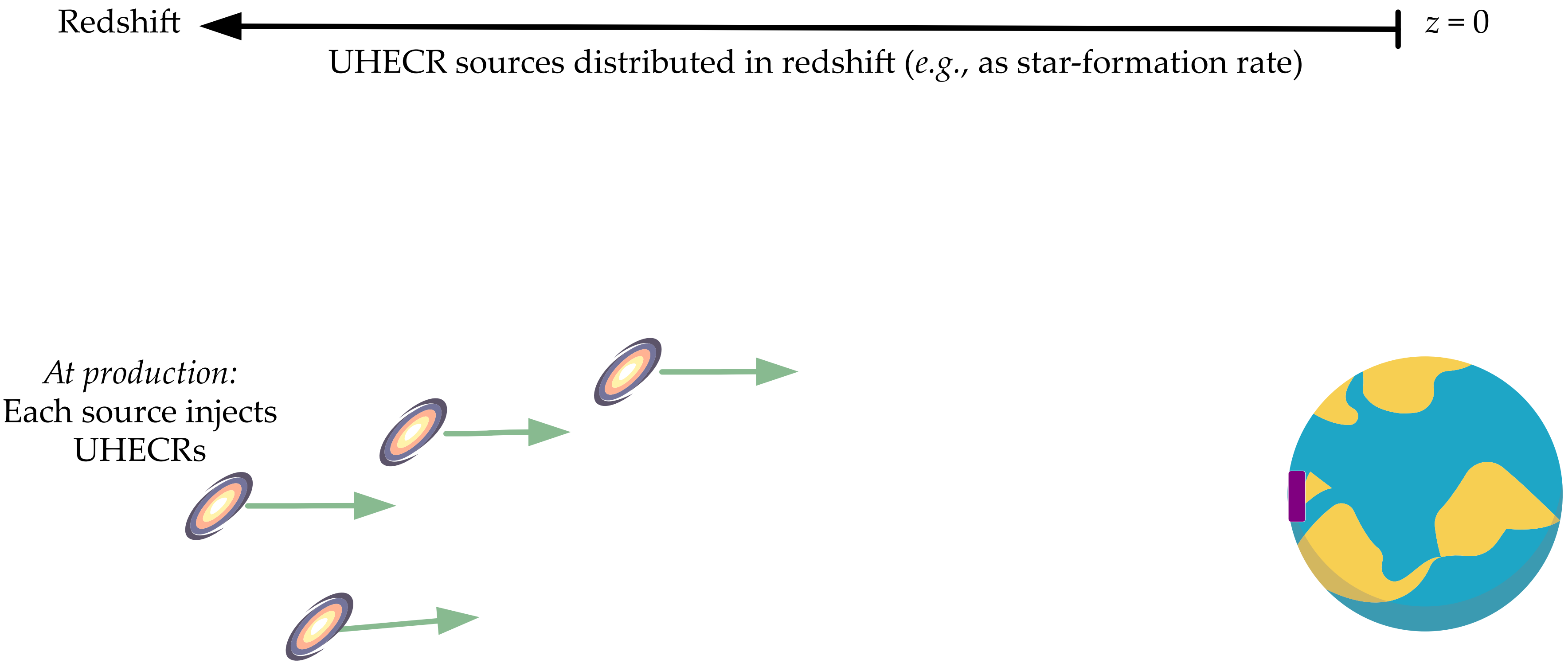
At production:
Each source injects
UHECRs


Redshift
$z = 0$
UHECR sources distributed in redshift (*e.g.*, as star-formation rate)
At production:
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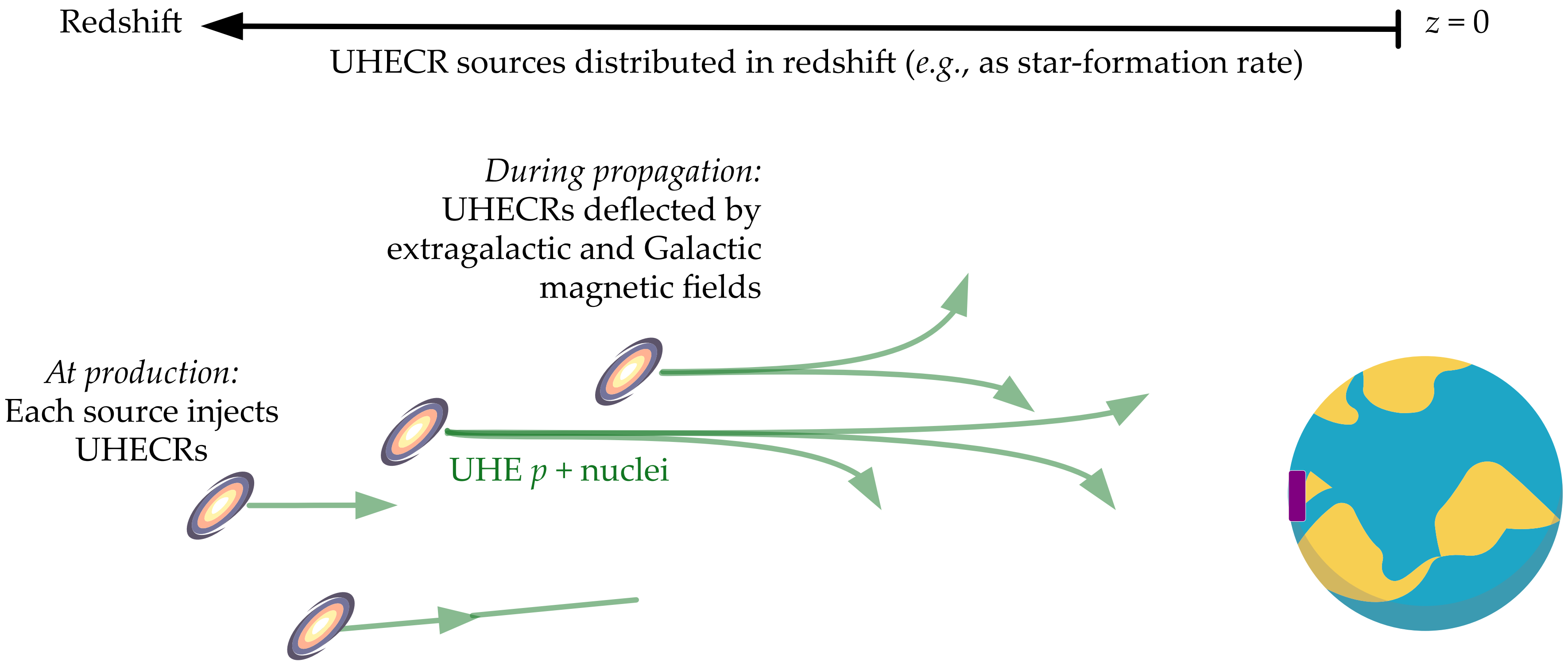
Redshift
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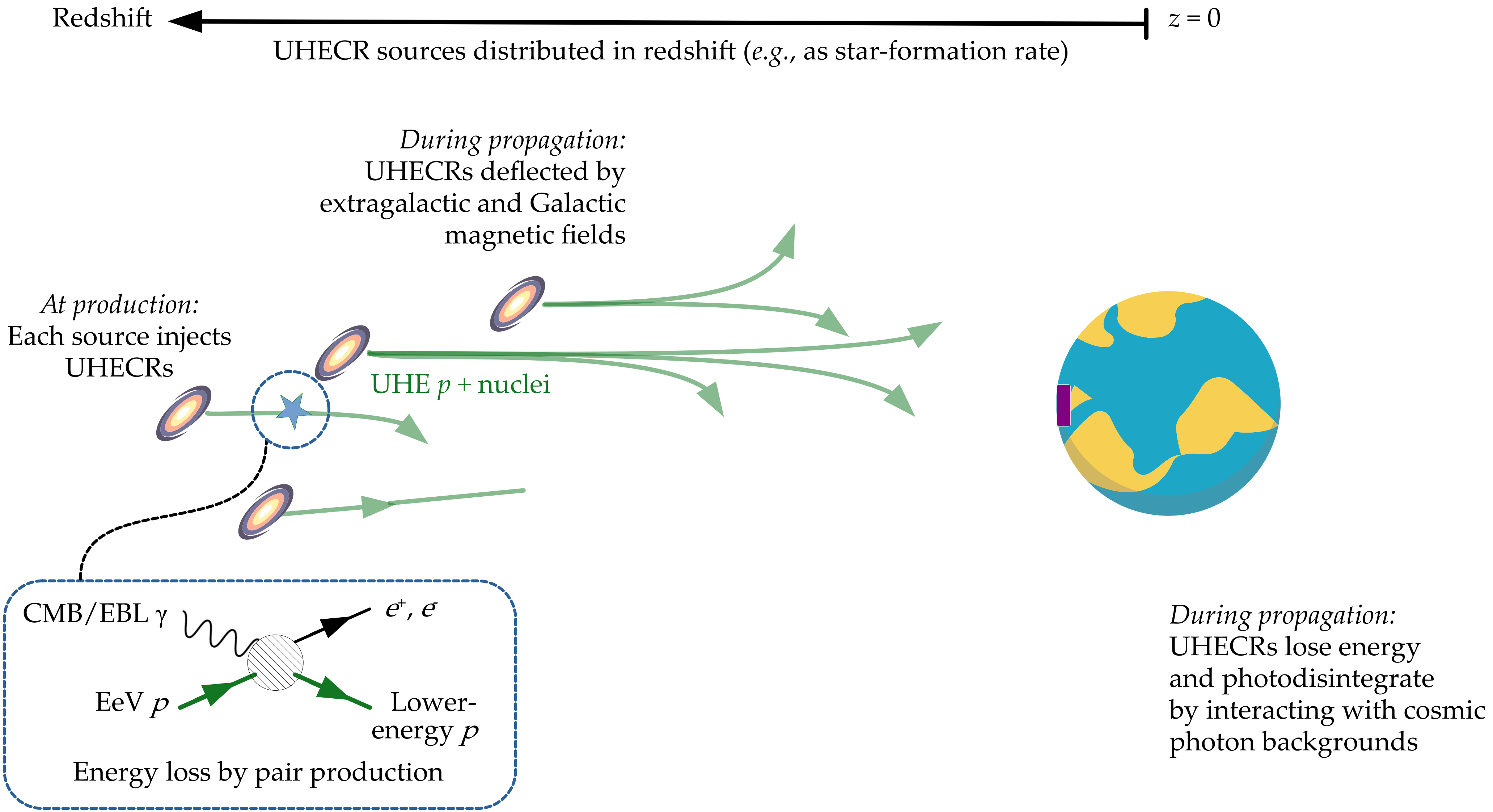
UHECR sources distributed in redshift (*e.g.*, as star-formation rate)
During propagation:
UHECRs deflected by
extragalactic and Galactic
magnetic fields
At production:
Each source injects
UHECRs
UHE p + nuclei



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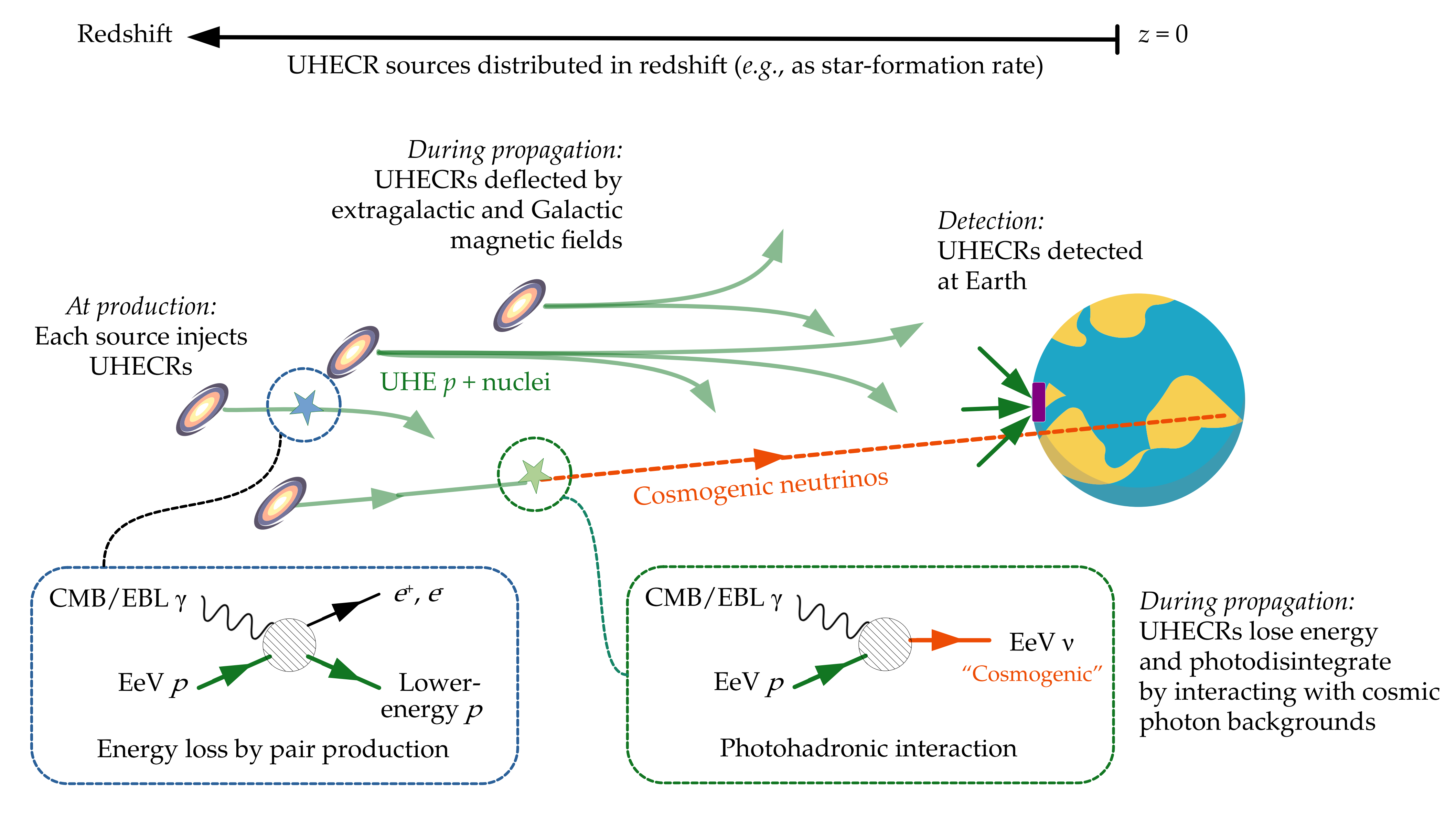
UHECR sources distributed in redshift (*e.g.*, as star-formation rate)
During propagation:
UHECRs deflected by
extragalactic and Galactic
magnetic fields
At production:
Each source injects
UHECRs
UHE p + nuclei
CMB/EBL γ
e^+, e^-
EeV p
Lower-
energy p
Energy loss by pair production
During propagation:
UHECRs lose energy
and photodisintegrate
by interacting with cosmic
photon backgrounds



Redshift
z = 0
UHECR sources distributed in redshift (e.g., as star-formation rate)
During propagation:
UHECRs deflected by
extragalactic and Galactic
magnetic fields
Detection:
UHECRs detected
at Earth
At production:
Each source injects
UHECRs
UHE p + nuclei
Cosmogenic neutrinos
CMB/EBL γ
e+, e-
EeV p
Lower-
energy p
Energy loss by pair production
CMB/EBL γ
EeV ν
"Cosmogenic"
EeV p
Photohadronic interaction
During propagation:
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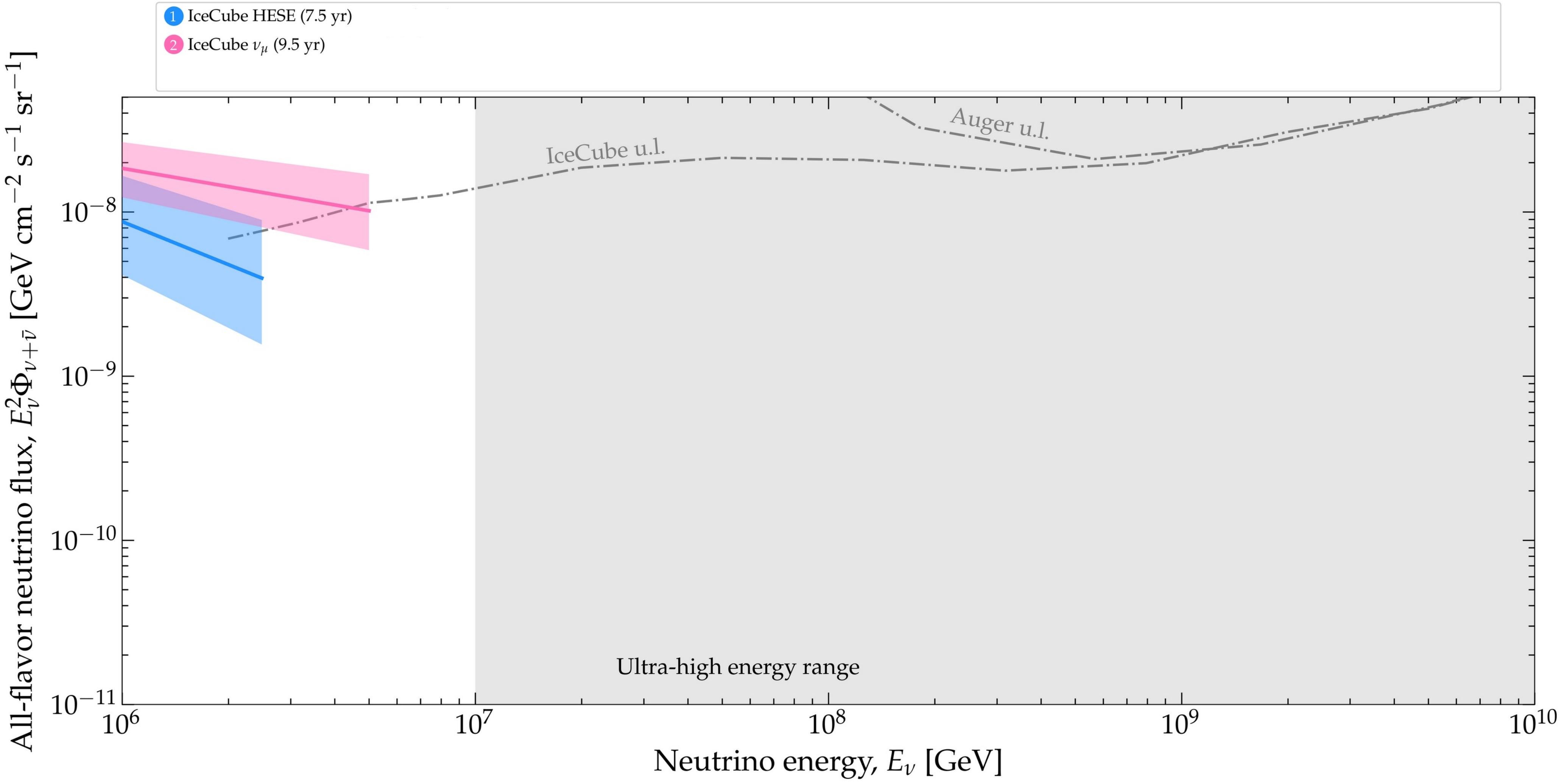

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IceCube u.l.
Auger u.l.
Ultra-high energy range
10^{-8}
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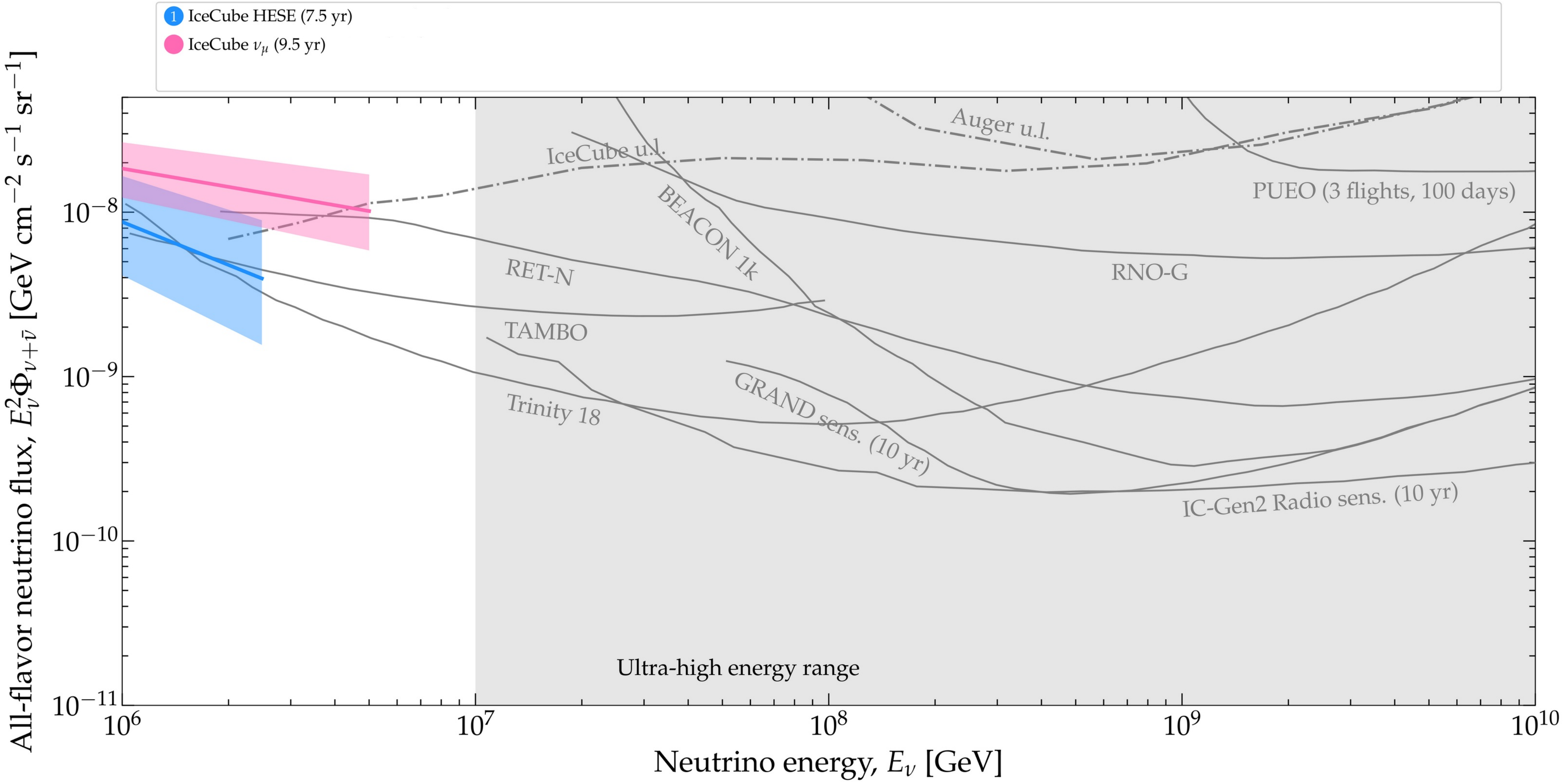

1 IceCube HESE (7.5 yr)
IceCube ν_μ (9.5 yr)
Auger u.l.
IceCube u.l.
PUEO (3 flights, 100 days)
BEACON 1k
RET-N
RNO-G
TAMBO
GRAND sens. (10 yr)
Trinity 18
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
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Neutrino energy, E_ν [GeV]
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10^{-11}
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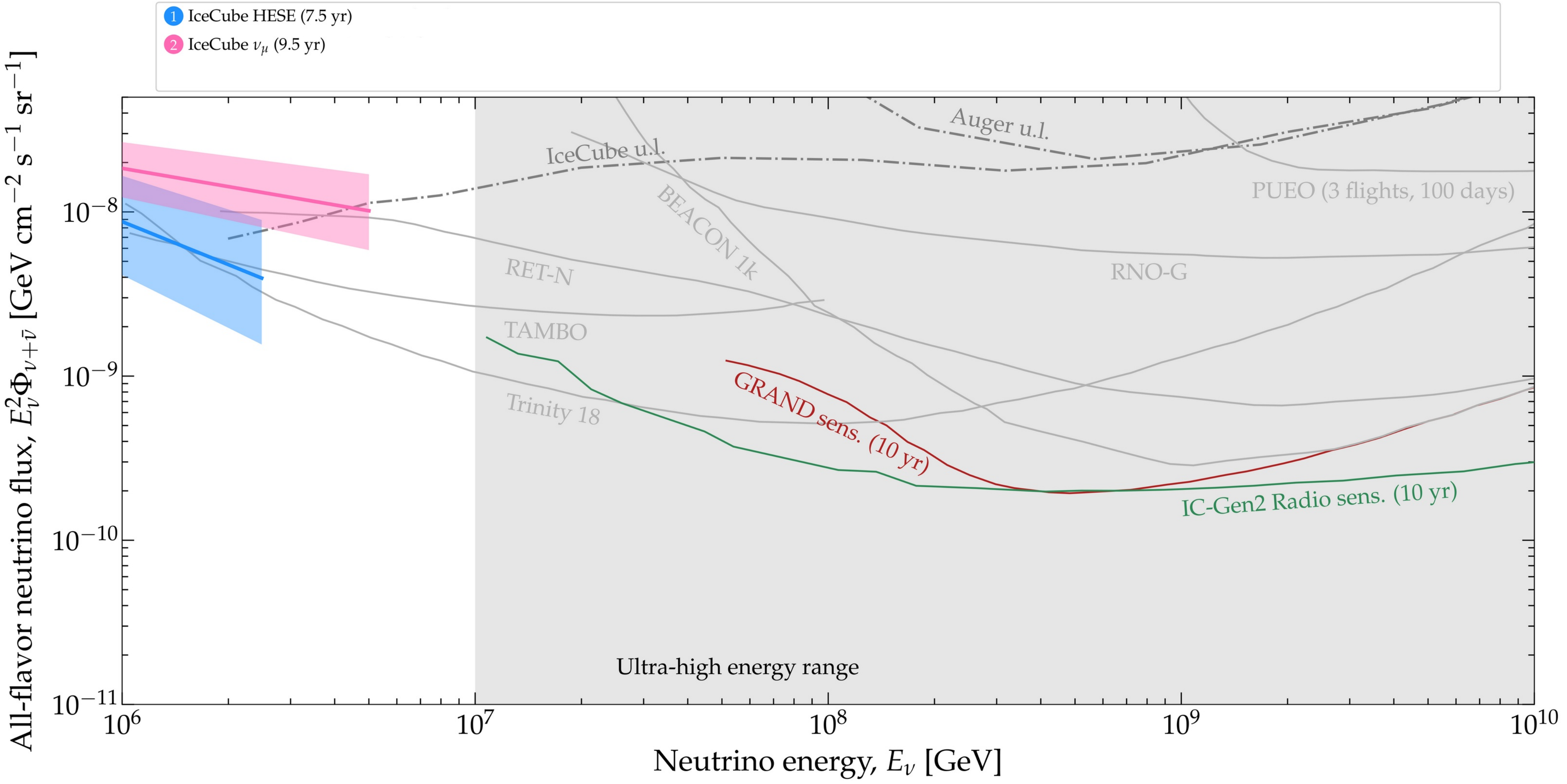
10^7
10^8
10^9
10^{10}



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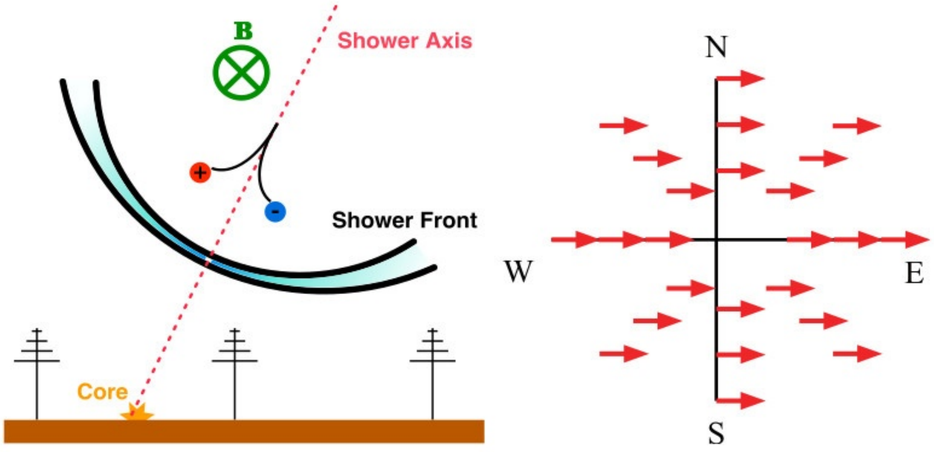
Neutrino energy, E_ν [GeV]

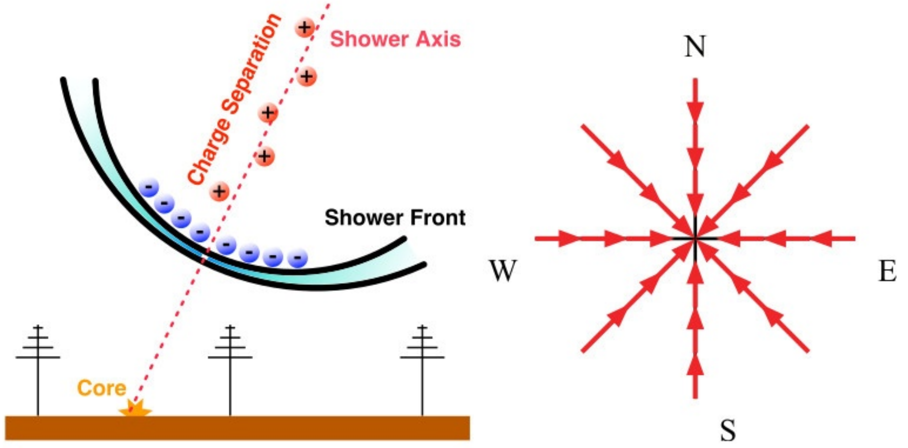
Radio emission: geomagnetic and Askaryan

Geomagnetic



- Time-varying transverse current
- Linearly polarized parallel to Lorentz force
- Dominant in air showers

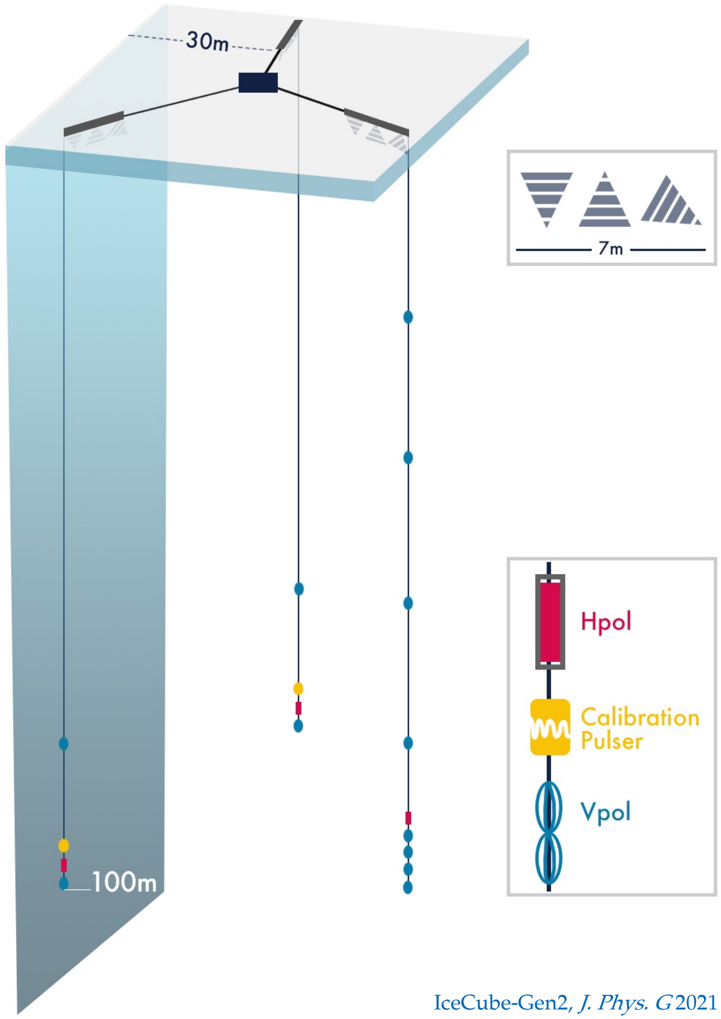
Askaryan



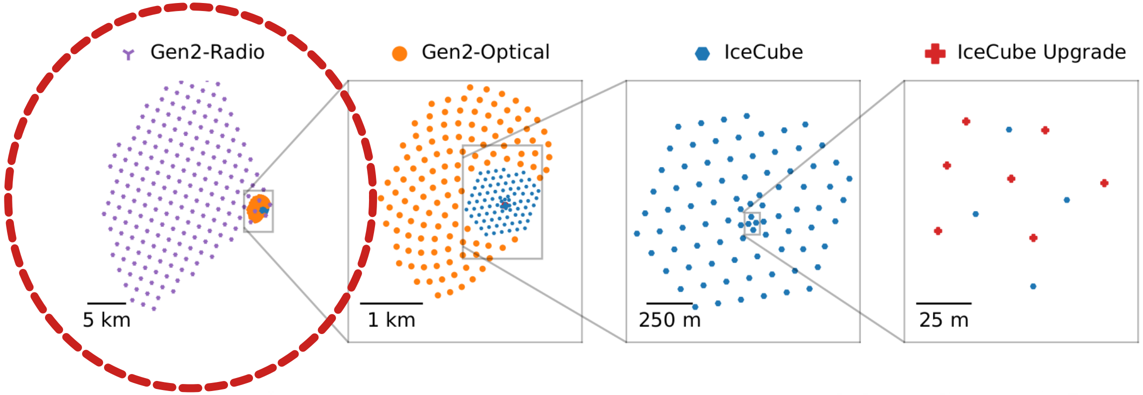
- Time-varying negative-charge ~20% excess
- Linearly polarized towards axis
- Sub-dominant in air showers

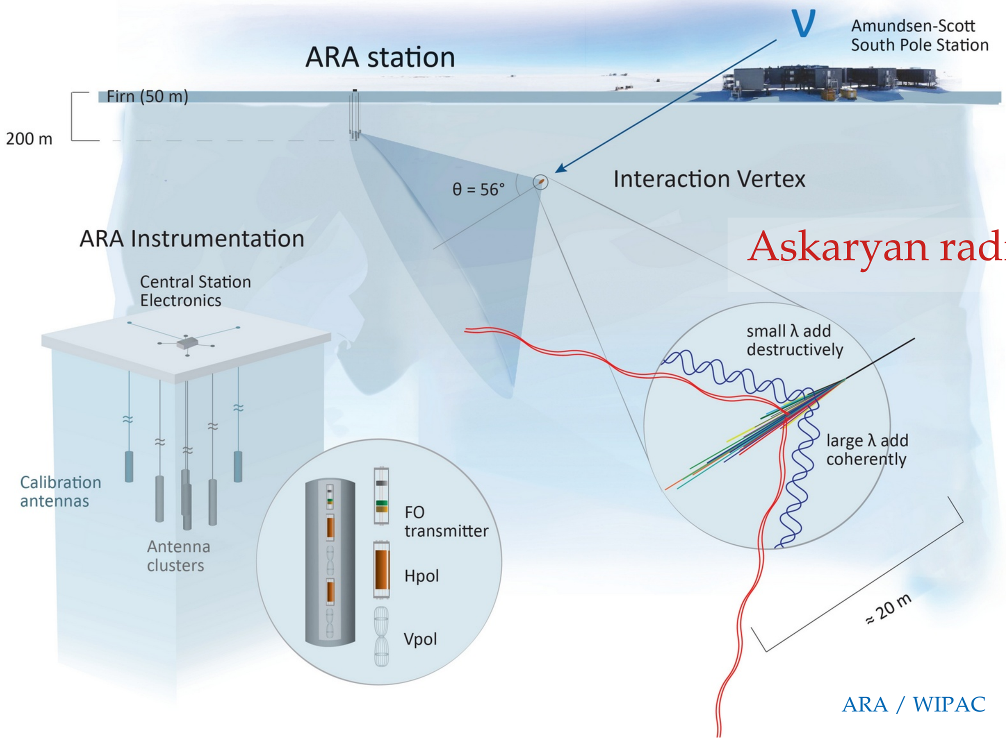
Figures by H. Schoorlemmer and K. D. de Vries

IceCube-Gen2 Radio



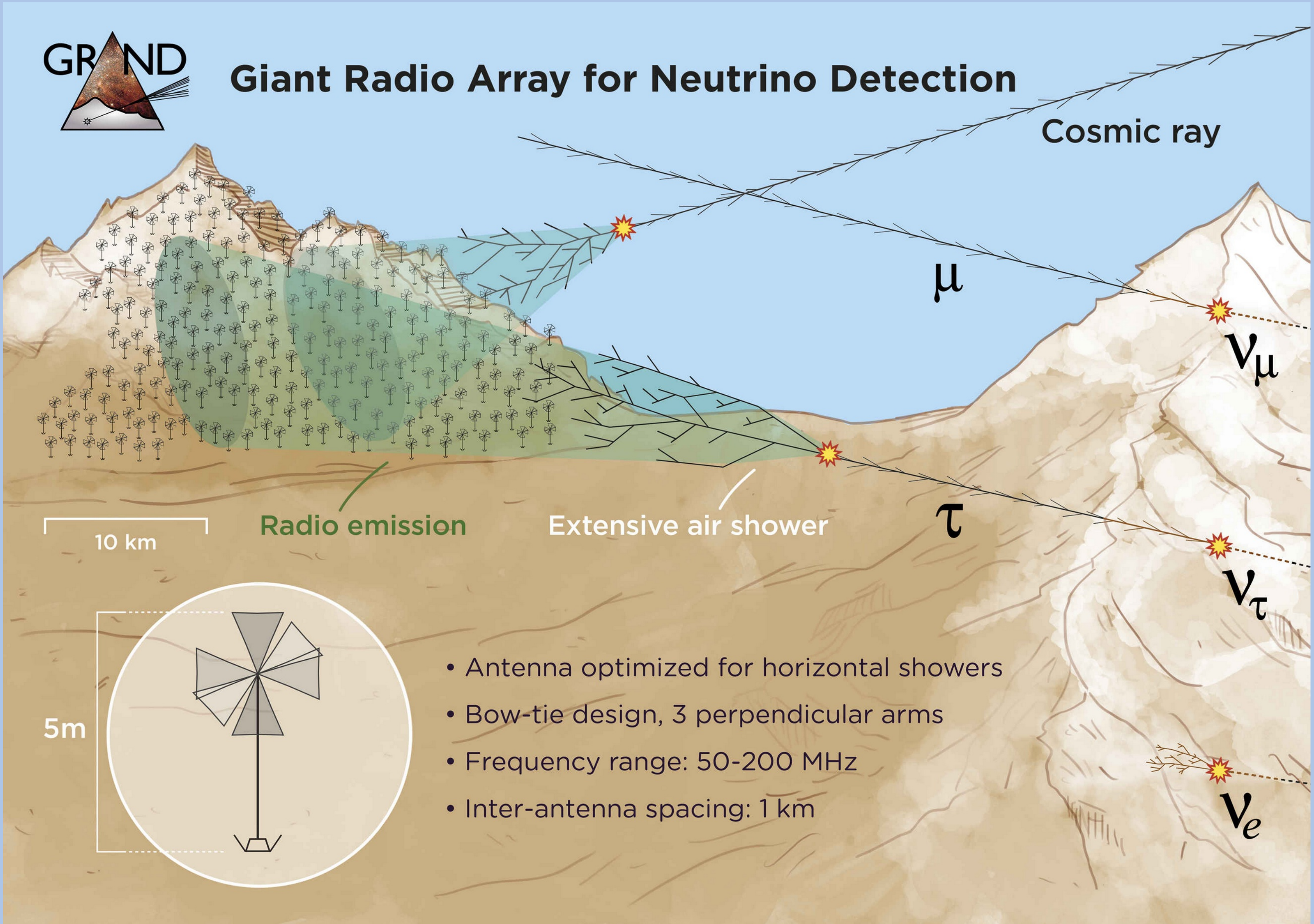
IceCube-Gen2, *J. Phys. G* 2021

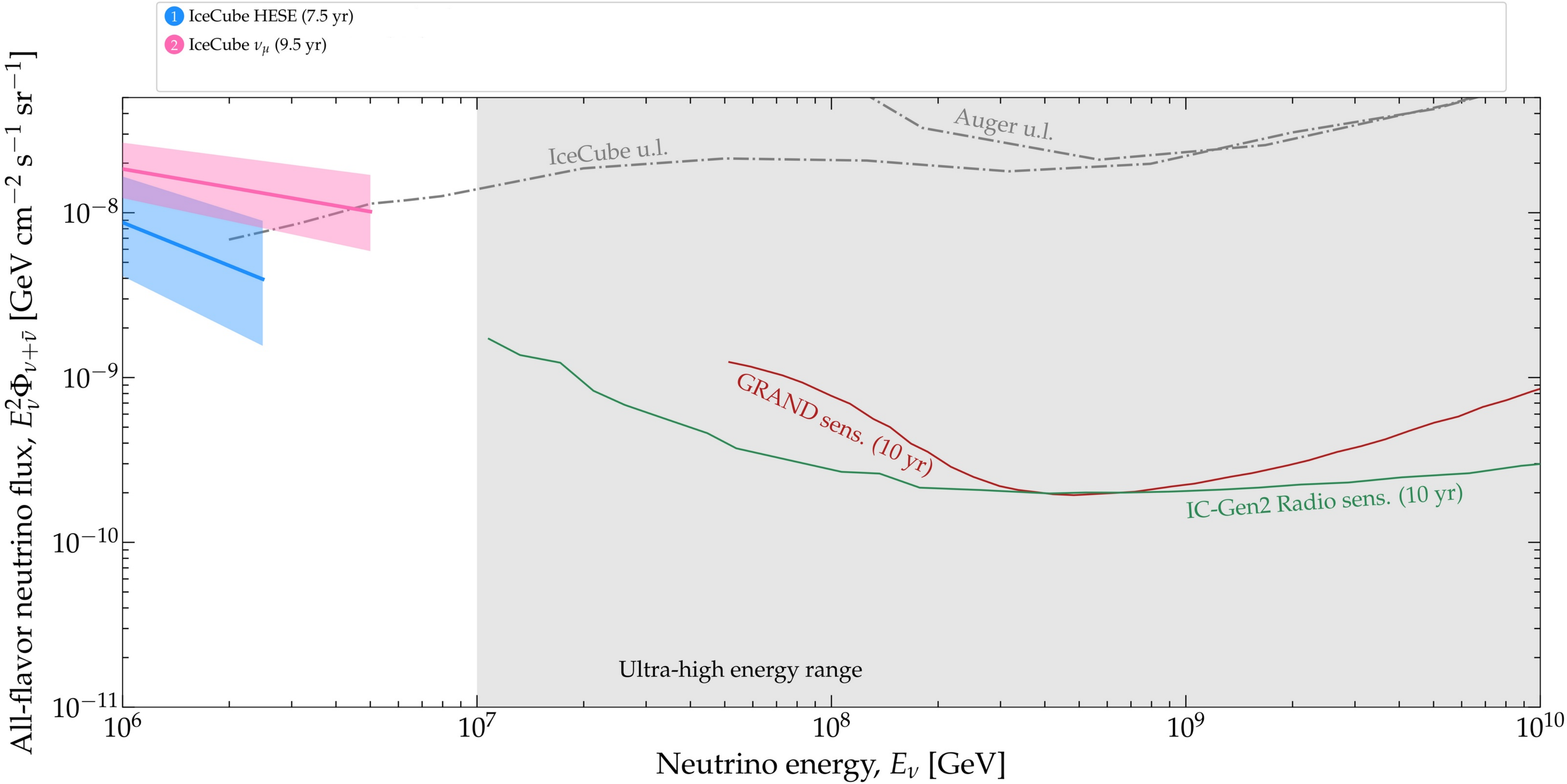




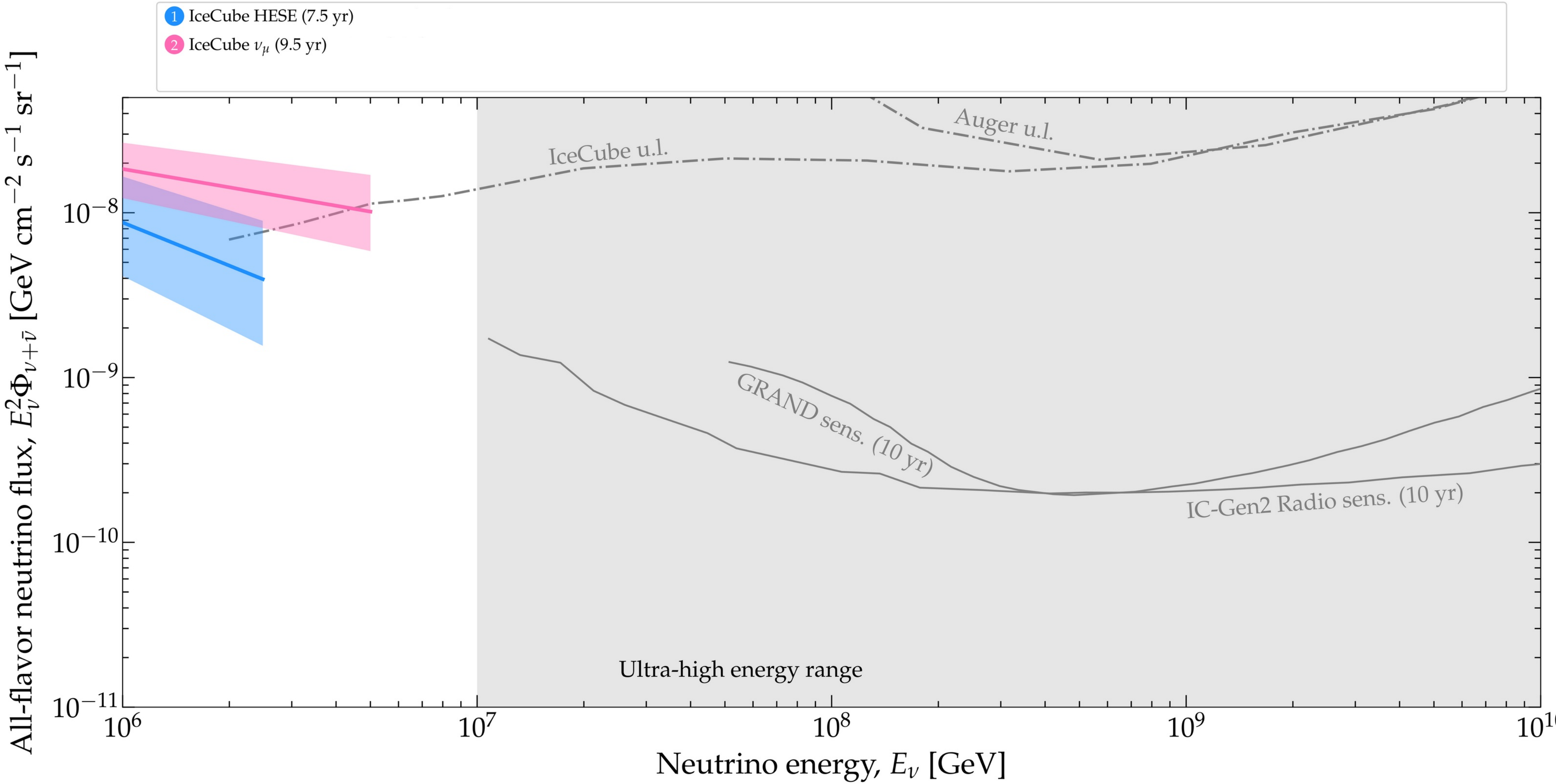
Askaryan radiation

ARA / WIPAC

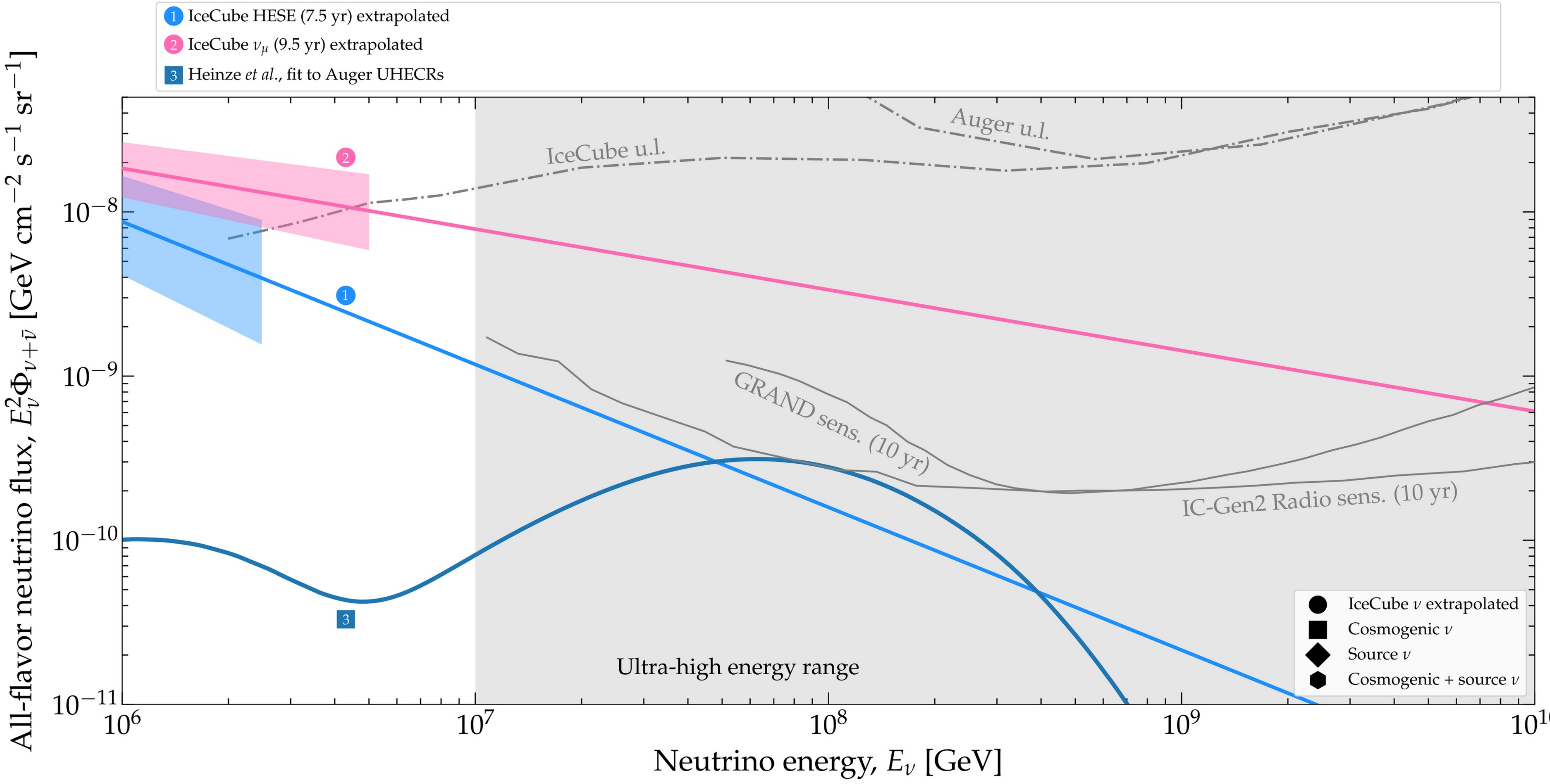

GRAND
Giant Radio Array for Neutrino Detection
Cosmic ray
μ
ν_μ
τ
ν_τ
ν_e
10 km
Radio emission
Extensive air shower
5m
• Antenna optimized for horizontal showers
• Bow-tie design, 3 perpendicular arms
• Frequency range: 50-200 MHz
• Inter-antenna spacing: 1 km



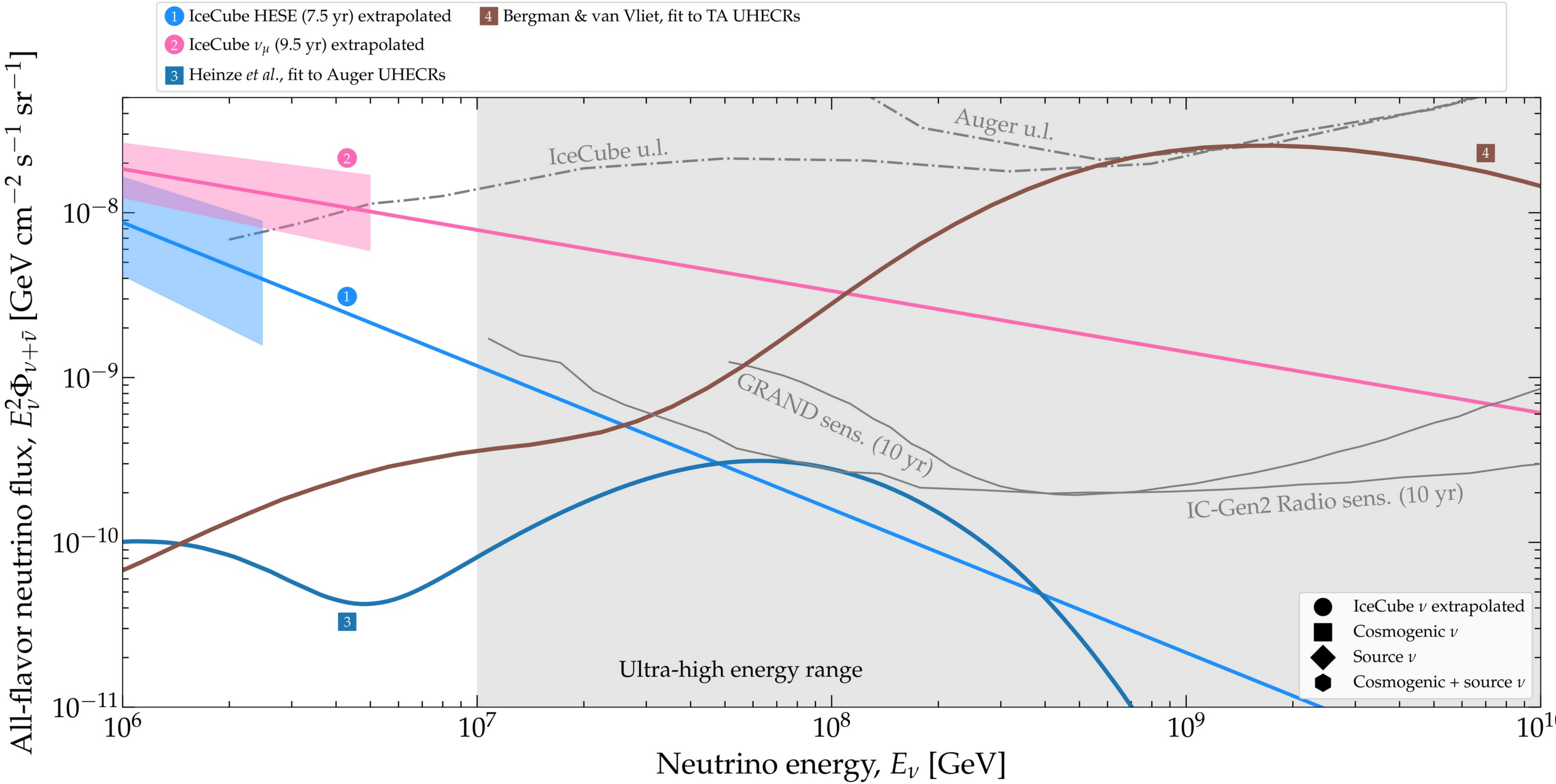
Valera, **MB**, Glaser, *PRD* 2023



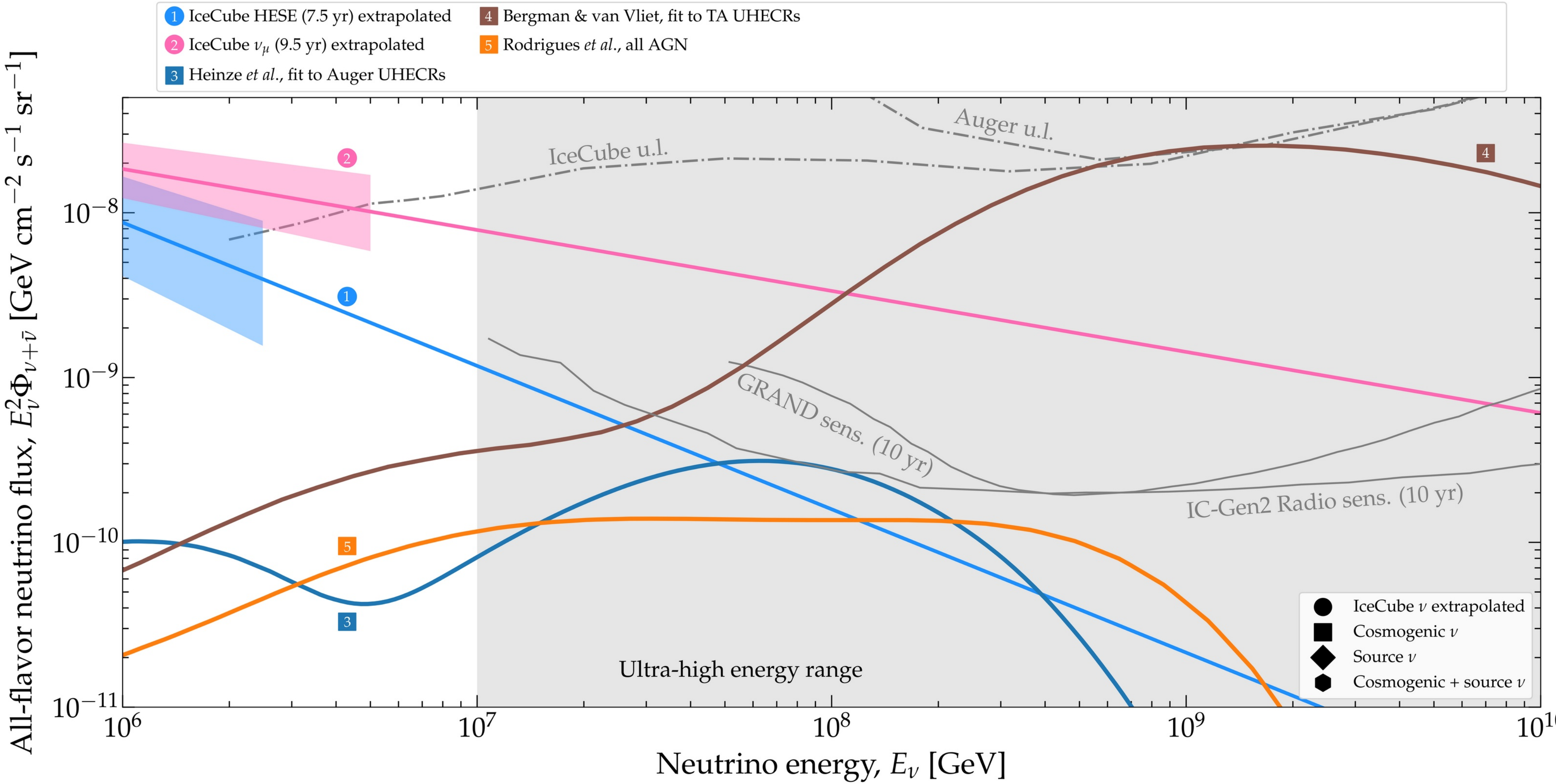
Valera, **MB**, Glaser, *PRD* 2023



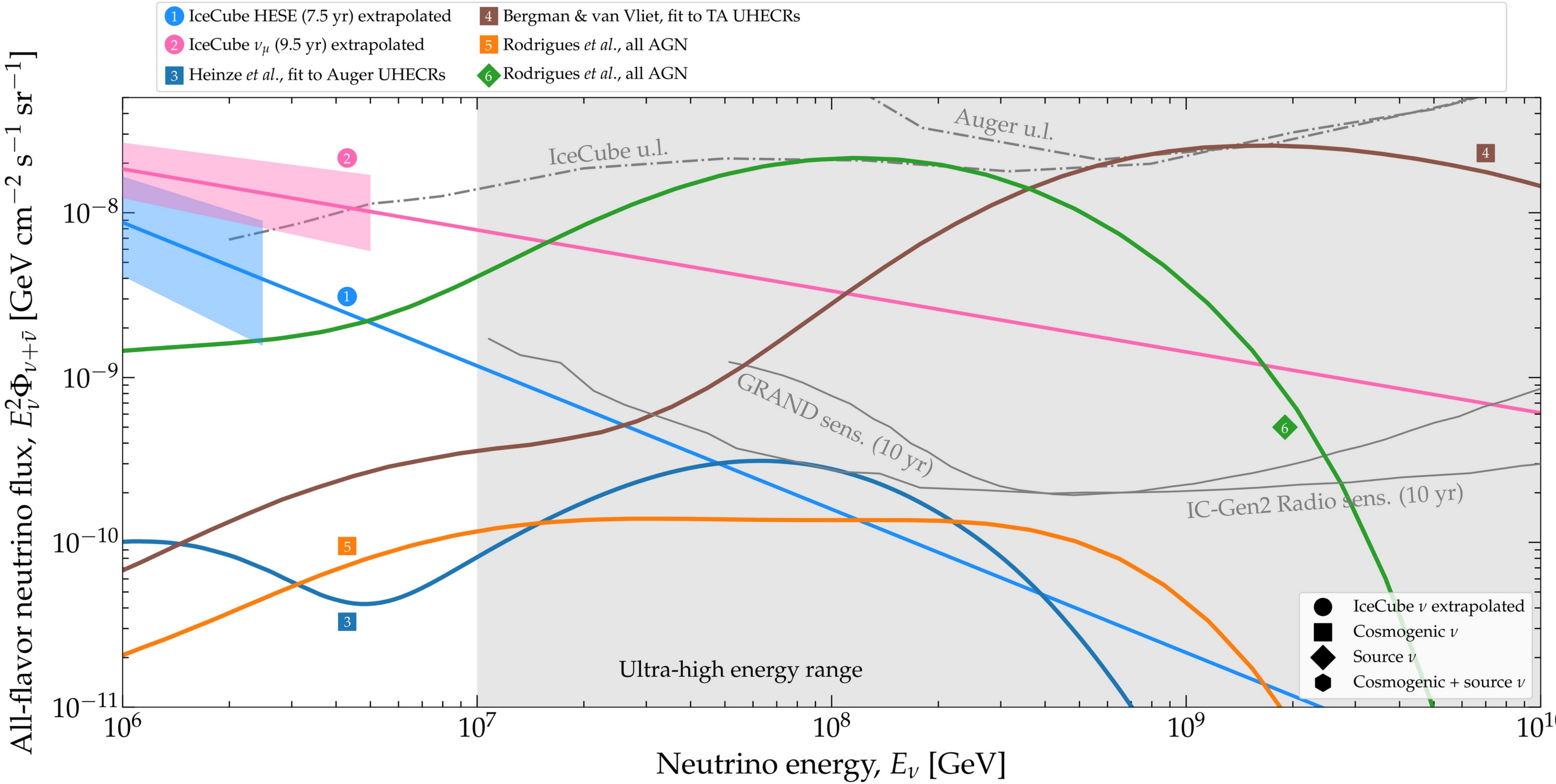
Valera, **MB**, Glaser, *PRD* 2023



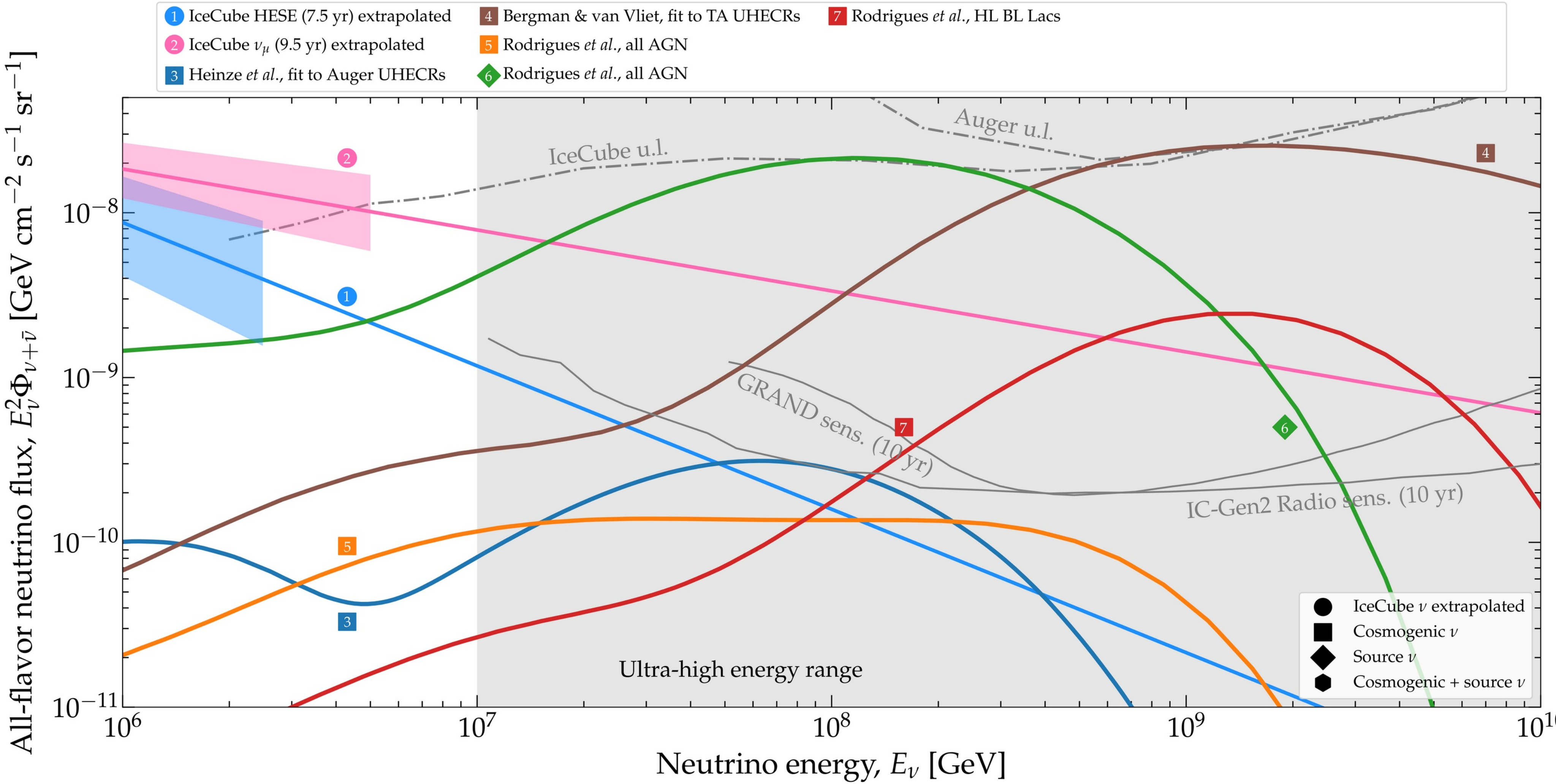
Valera, **MB**, Glaser, *PRD* 2023



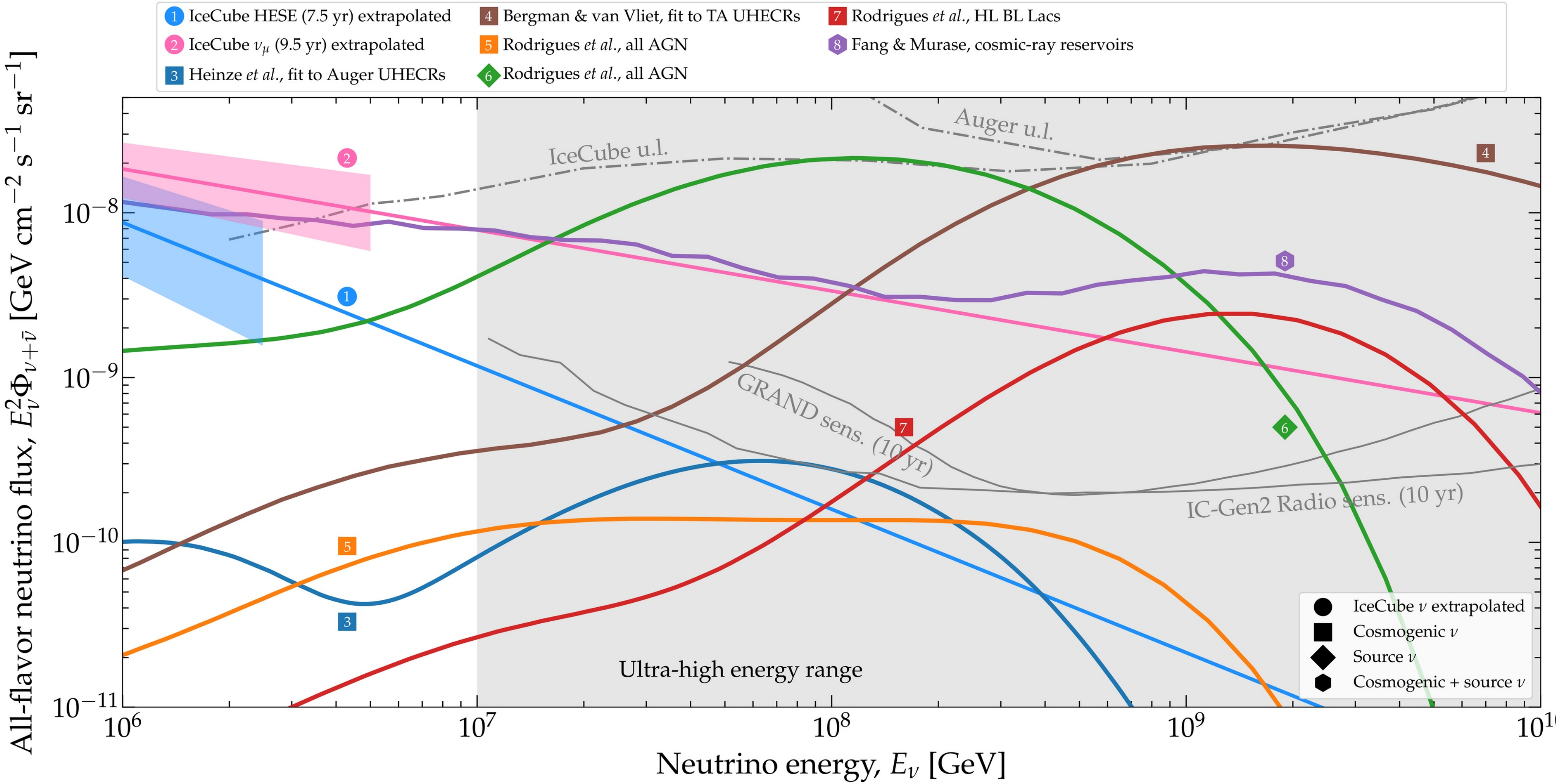
Valera, **MB**, Glaser, *PRD* 2023



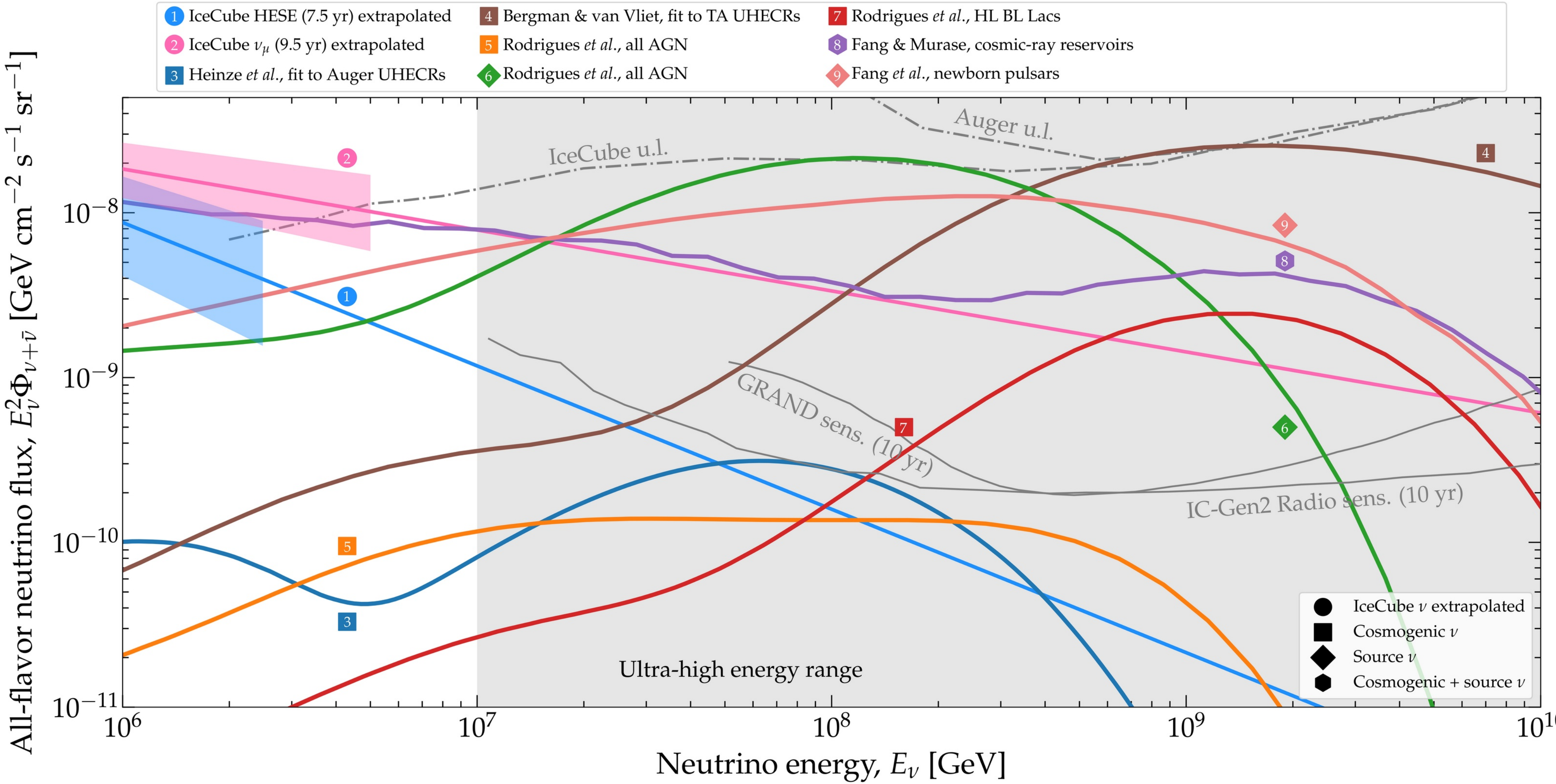
Valera, **MB**, Glaser, *PRD* 2023



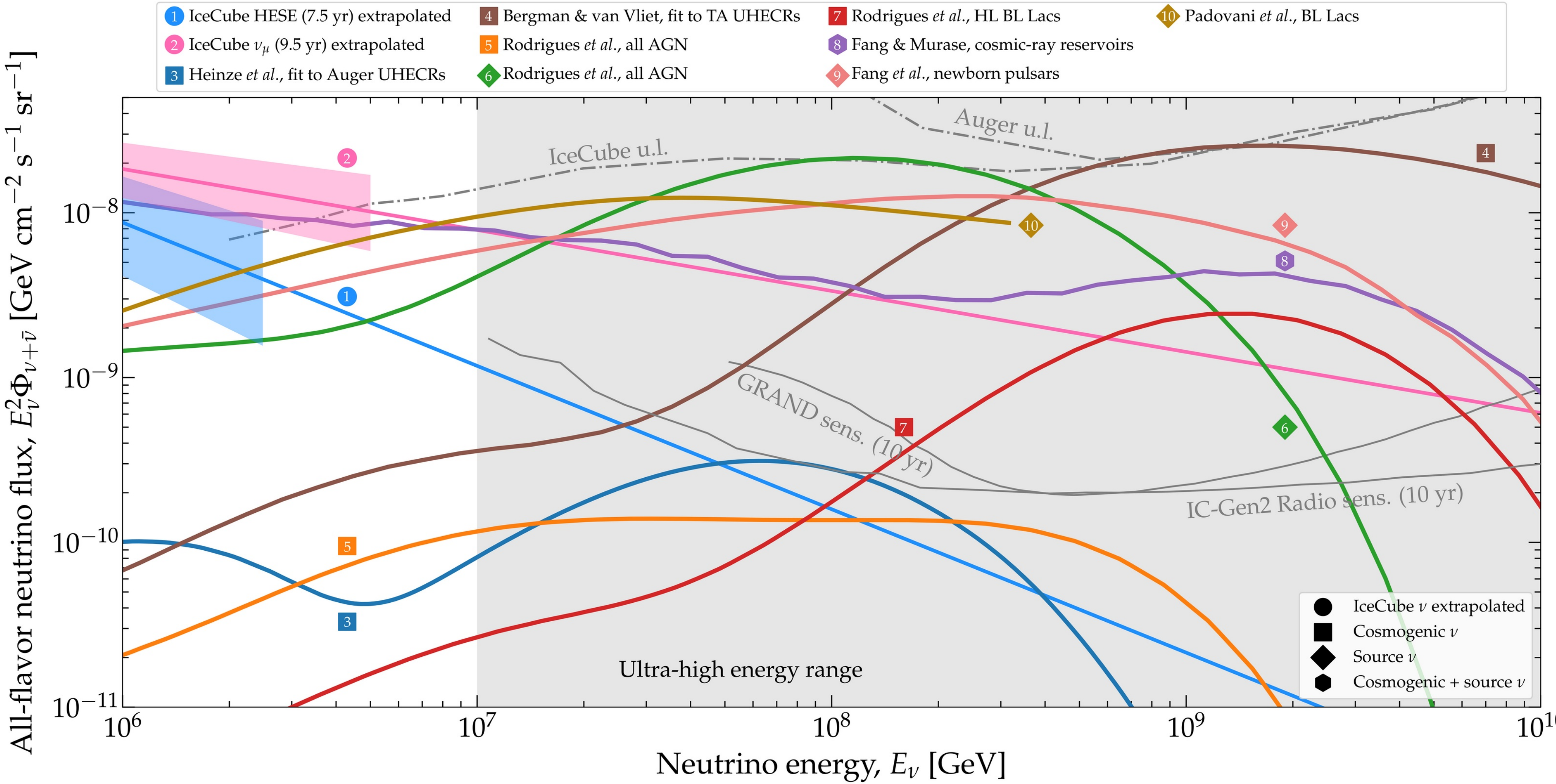
Valera, **MB**, Glaser, *PRD* 2023



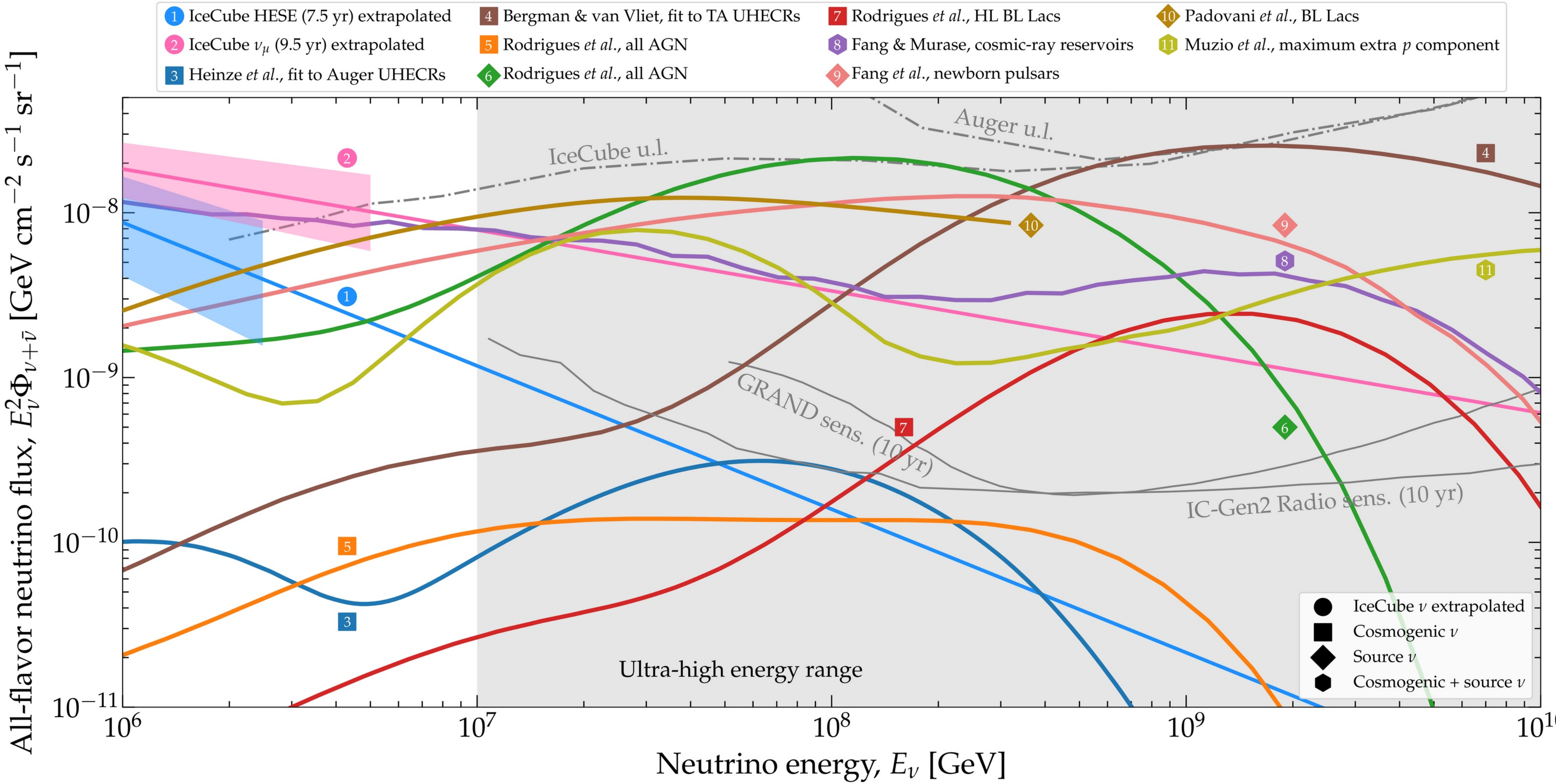
Valera, **MB**, Glaser, *PRD* 2023

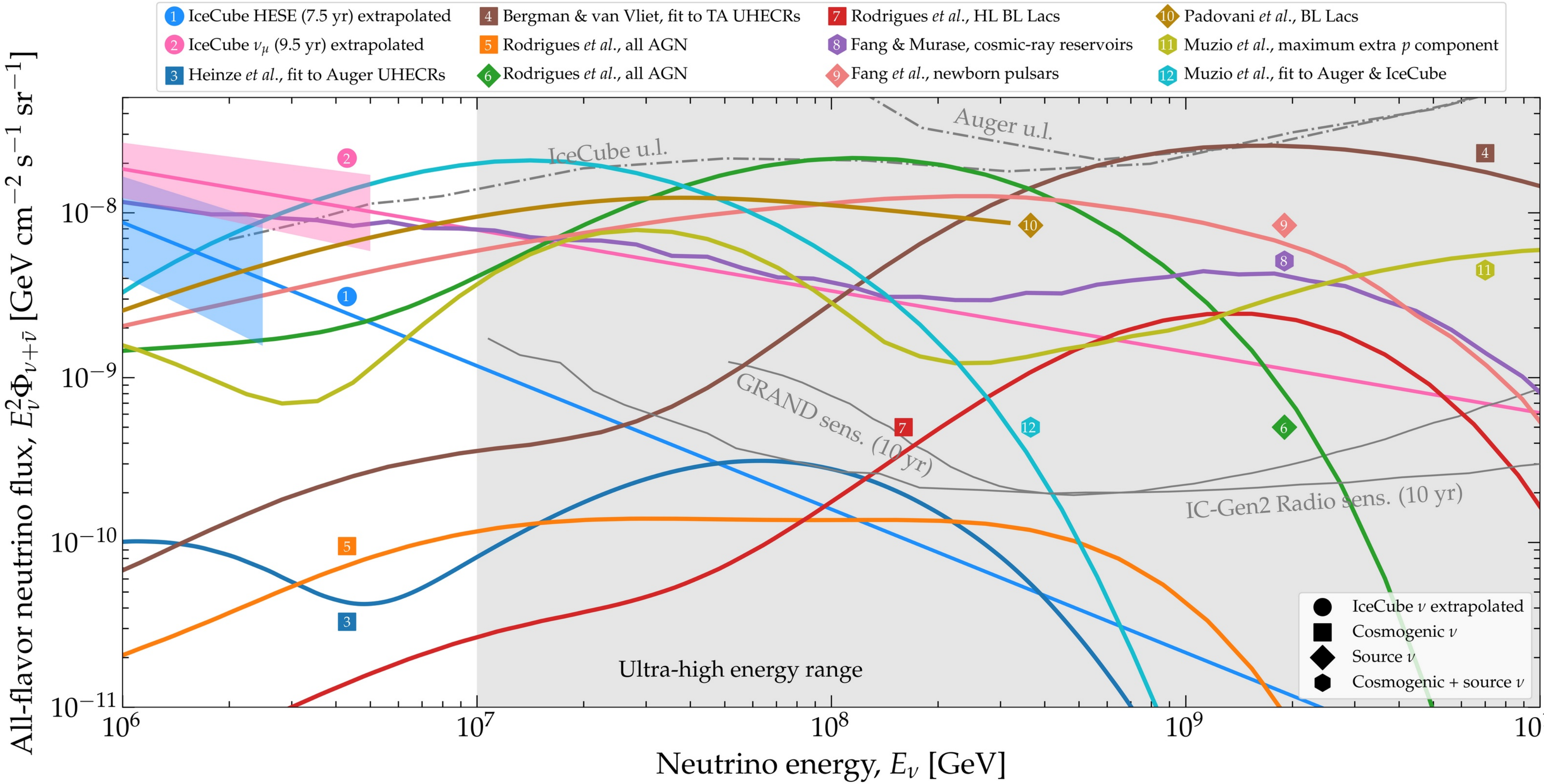


Valera, **MB**, Glaser, *PRD* 2023

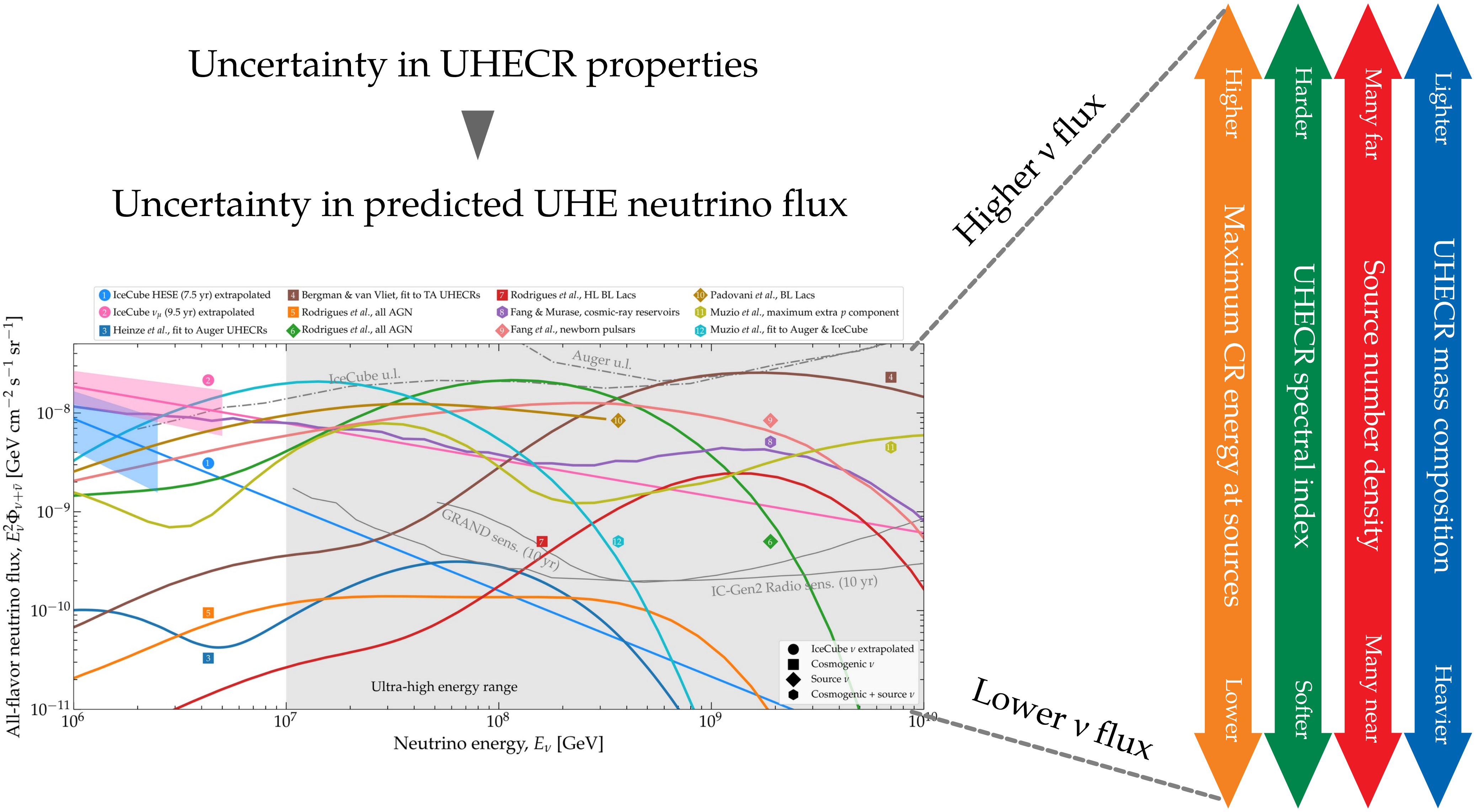


Valera, **MB**, Glaser, *PRD* 2023


1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze et al., fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
5 Rodrigues et al., all AGN
6 Rodrigues et al., all AGN
7 Rodrigues et al., HL BL Lacs
8 Fang & Murase, cosmic-ray reservoirs
9 Fang et al., newborn pulsars
10 Padovani et al., BL Lacs
11 Muzio et al., maximum extra p component
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2\Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]



Valera, **MB**, Glaser, *PRD* 2023



Uncertainty in UHECR properties
Uncertainty in predicted UHE neutrino flux
1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze et al., fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
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IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
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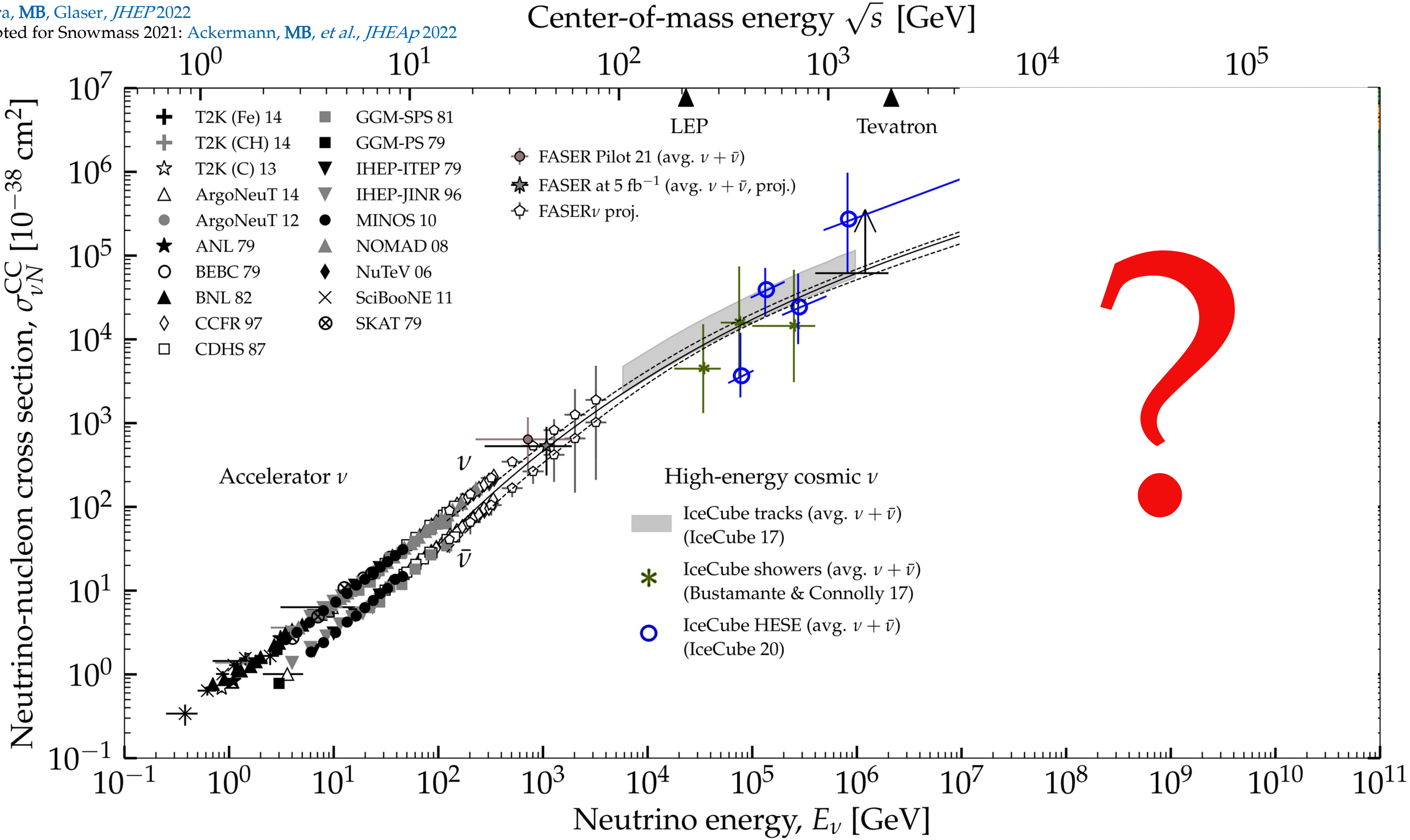
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
Higher ν flux
Lower ν flux
Higher
Maximum CR energy at sources
Lower
Harder
UHECR spectral index
Softer
Many far
Source number density
Many near
Lighter
UHECR mass composition
Heavier

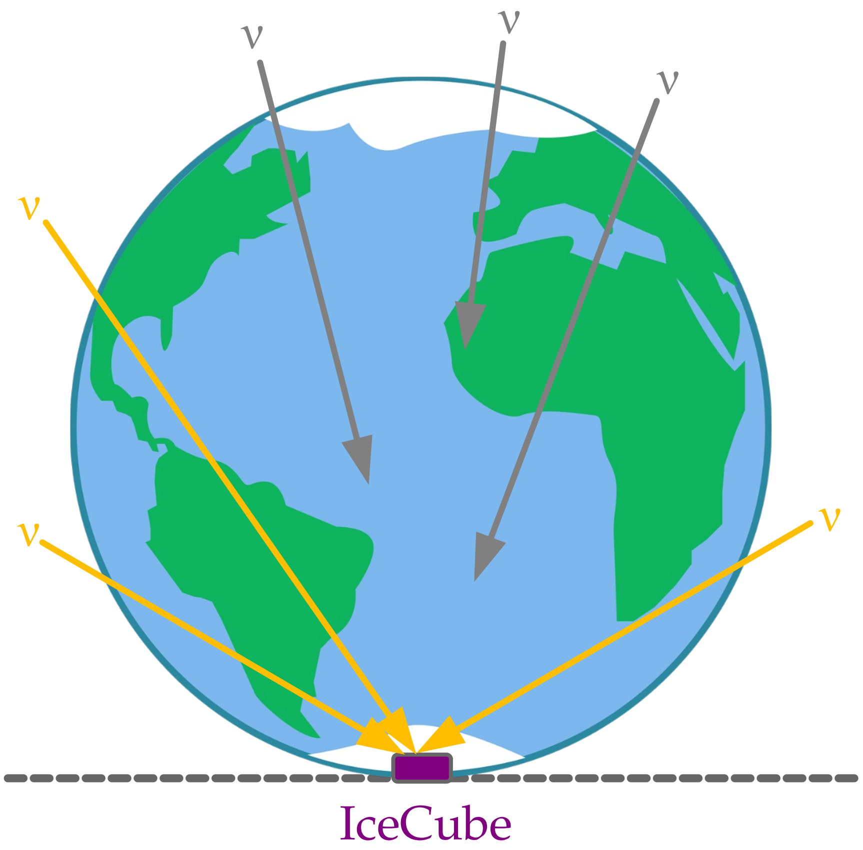
Tests at ultra-high energies (> 100 PeV)

Cross sections at UHE

Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022

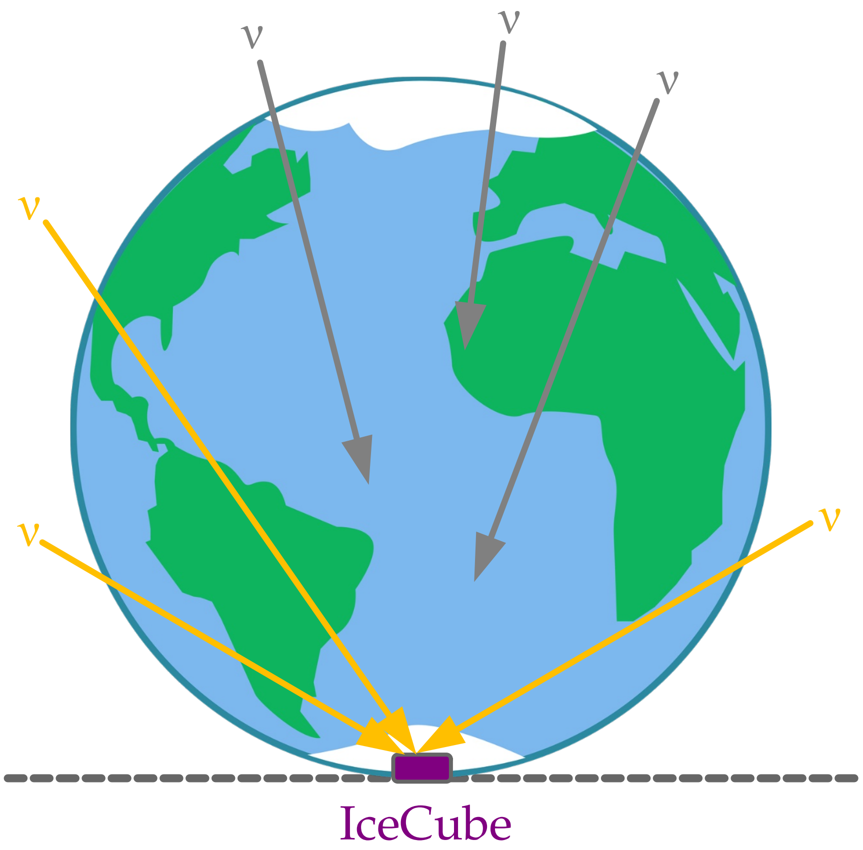


TeV–PeV:



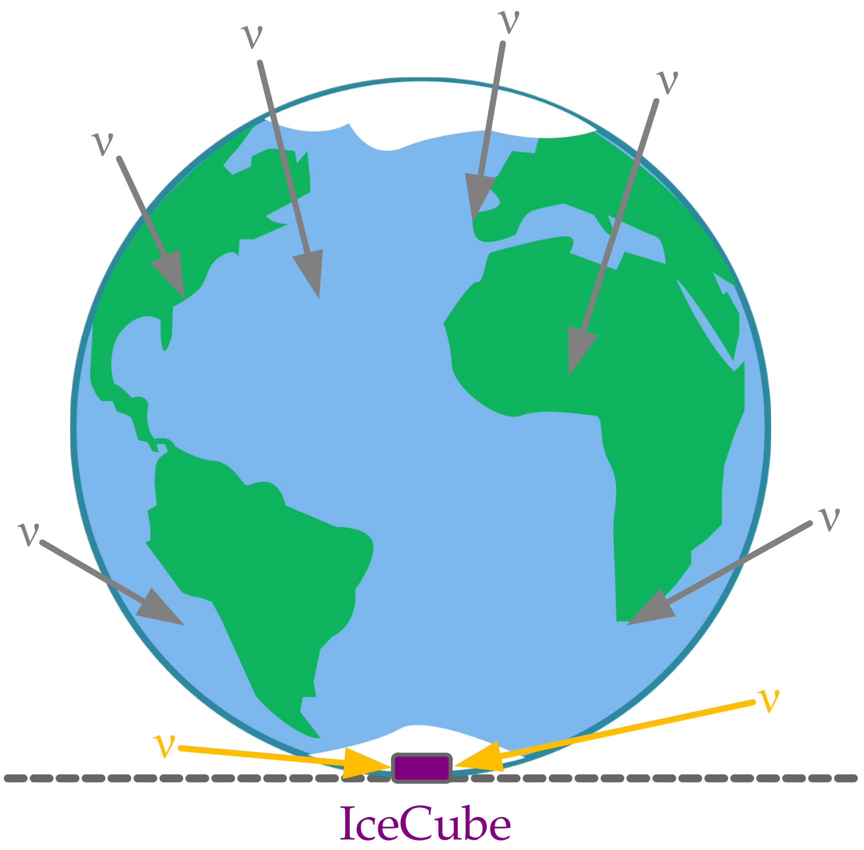
Earth is *almost fully* opaque,
some upgoing ν still make it through

TeV–PeV:



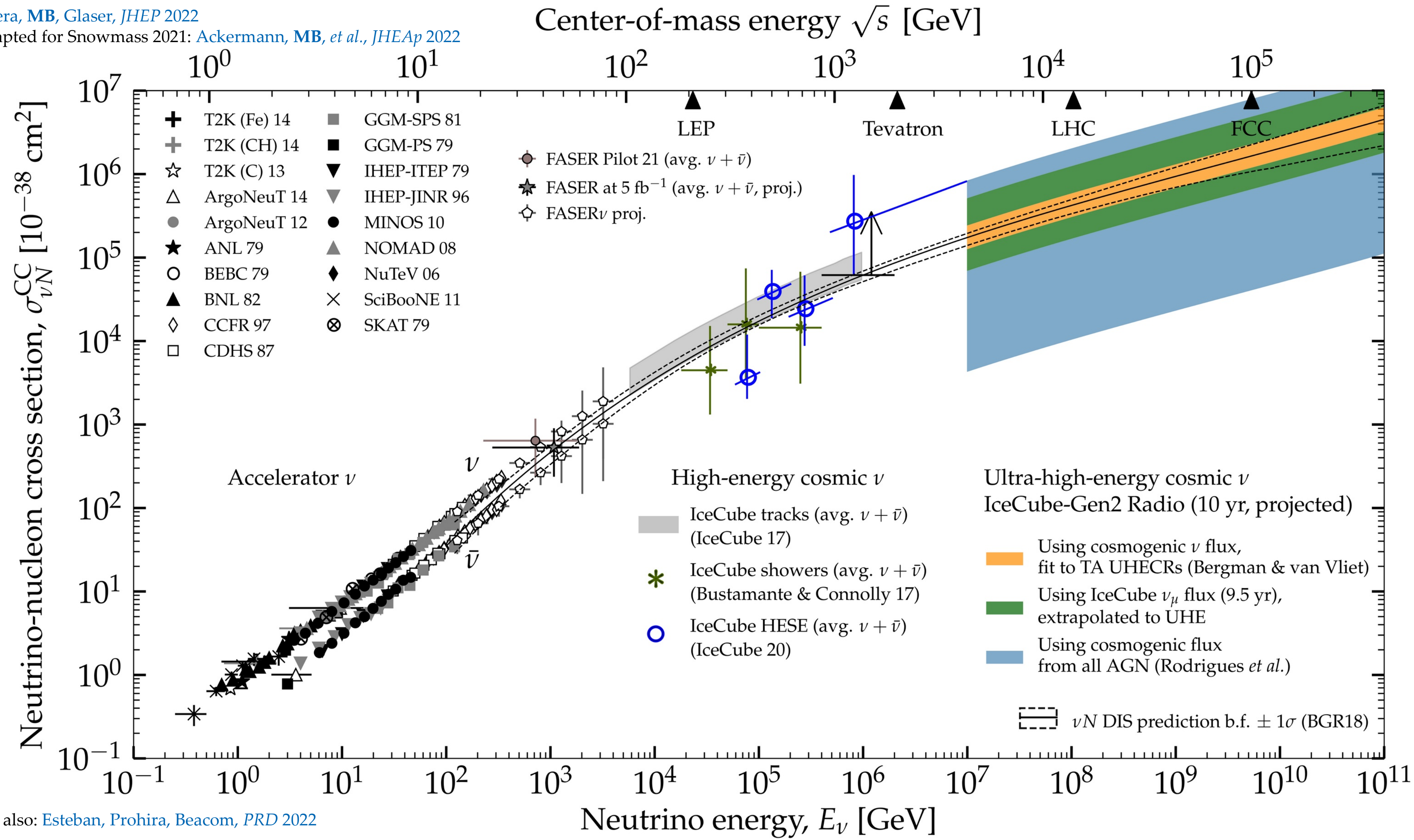
Earth is *almost fully* opaque,
some upgoing ν still make it through

$>$ 100 PeV:



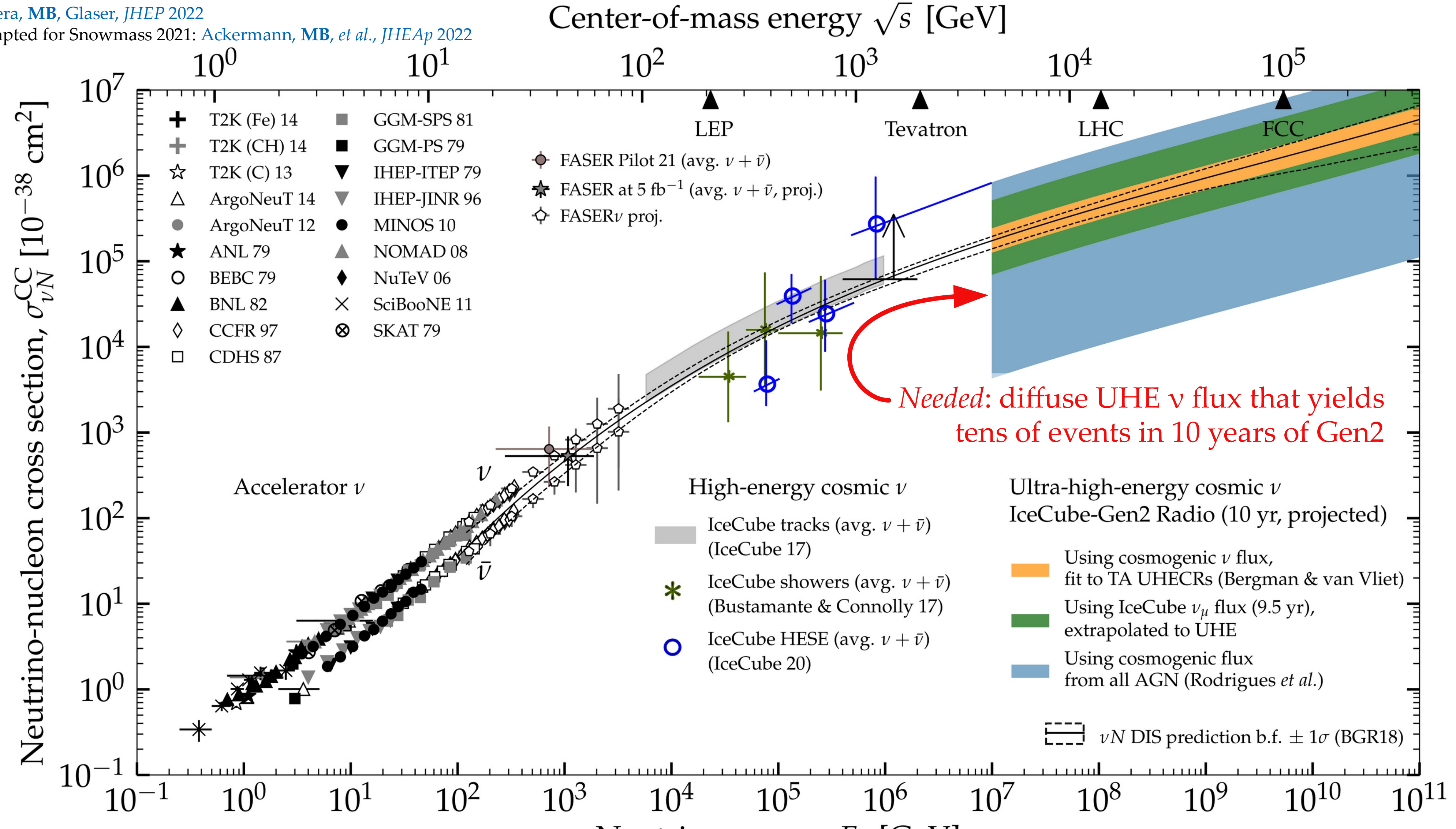
Earth is *completely* opaque,
but horizontal ν still make it through

Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



See also: Esteban, Prohira, Beacom, *PRD* 2022

Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



See also: Esteban, Prohira, Beacom, *PRD* 2022

Lorentz-invariance violation at UHE

Lorentz-invariance violation — from superluminal speeds

A superluminal ν loses energy via pair production, *i.e.*,

$$\nu \rightarrow \nu + e^{+} + e^{-}$$

Cohen & Glashow, *PRL* 2011

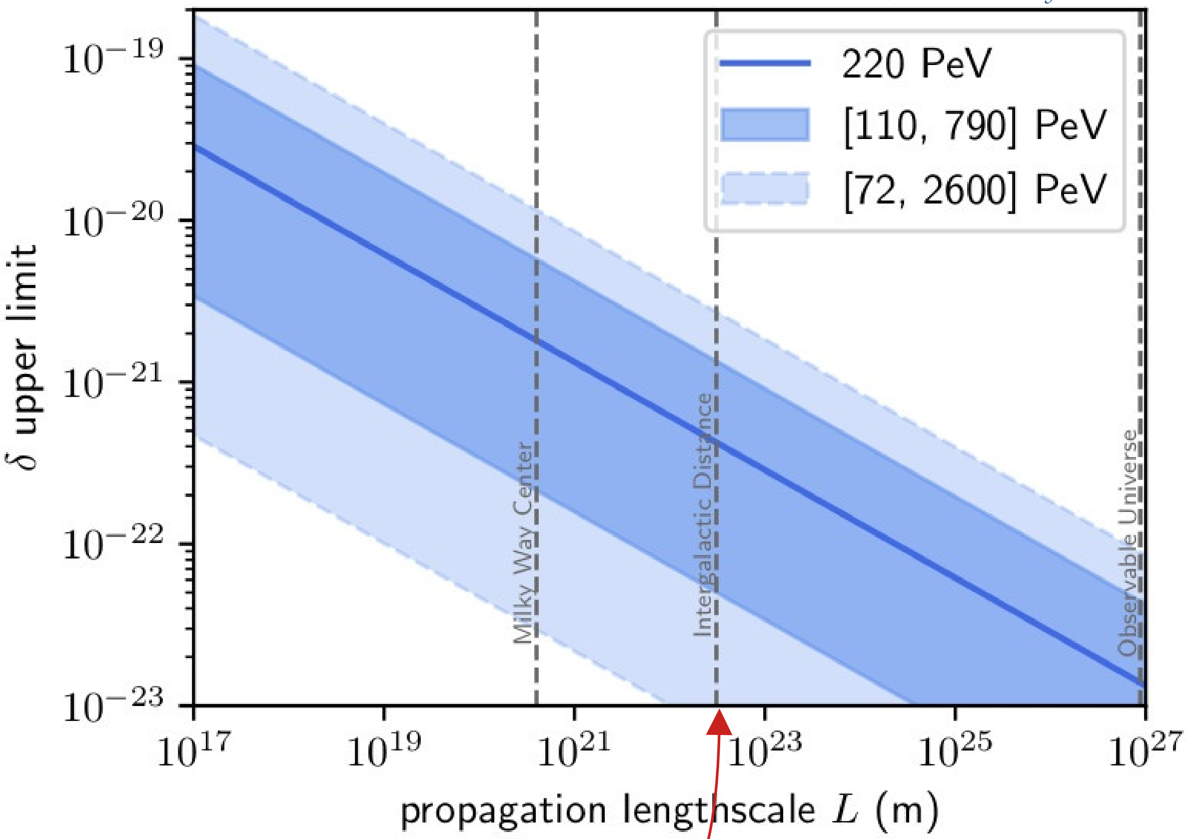
Excess over light speed: $\delta = c_\nu - 1$

Decay length: $L_{dec} = c_\nu \,/\, \Gamma \;\propto\; E^{-5}\,\delta^{-3}$

Decay width

Demanding that the travel distance $L < 10\, L_{dec}$ sets upper limits on δ

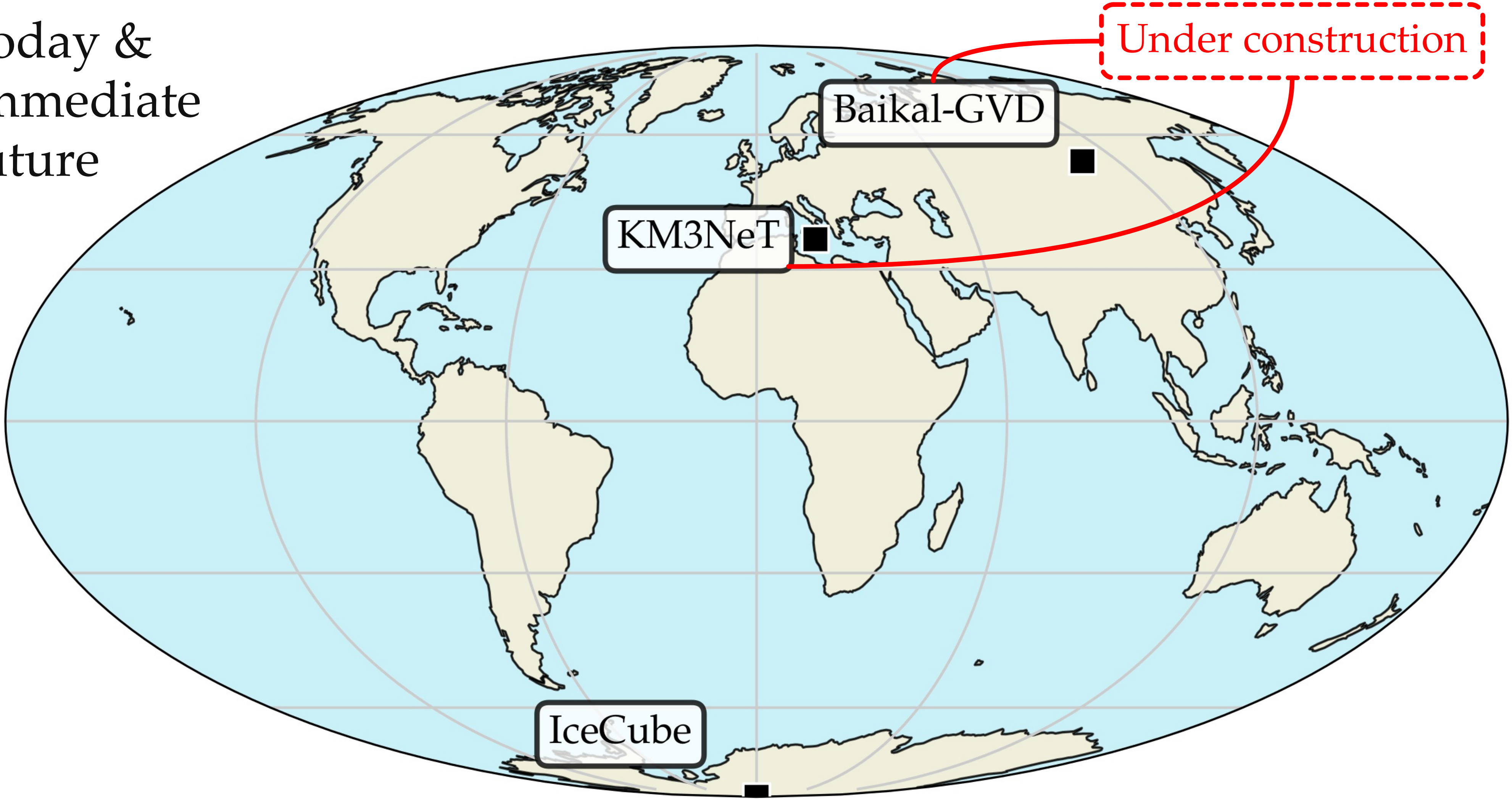
KM3NeT Collab., *Commun. Phys.* 2025



New limit is ~1000 times stronger than previous one from TXS 0506+056

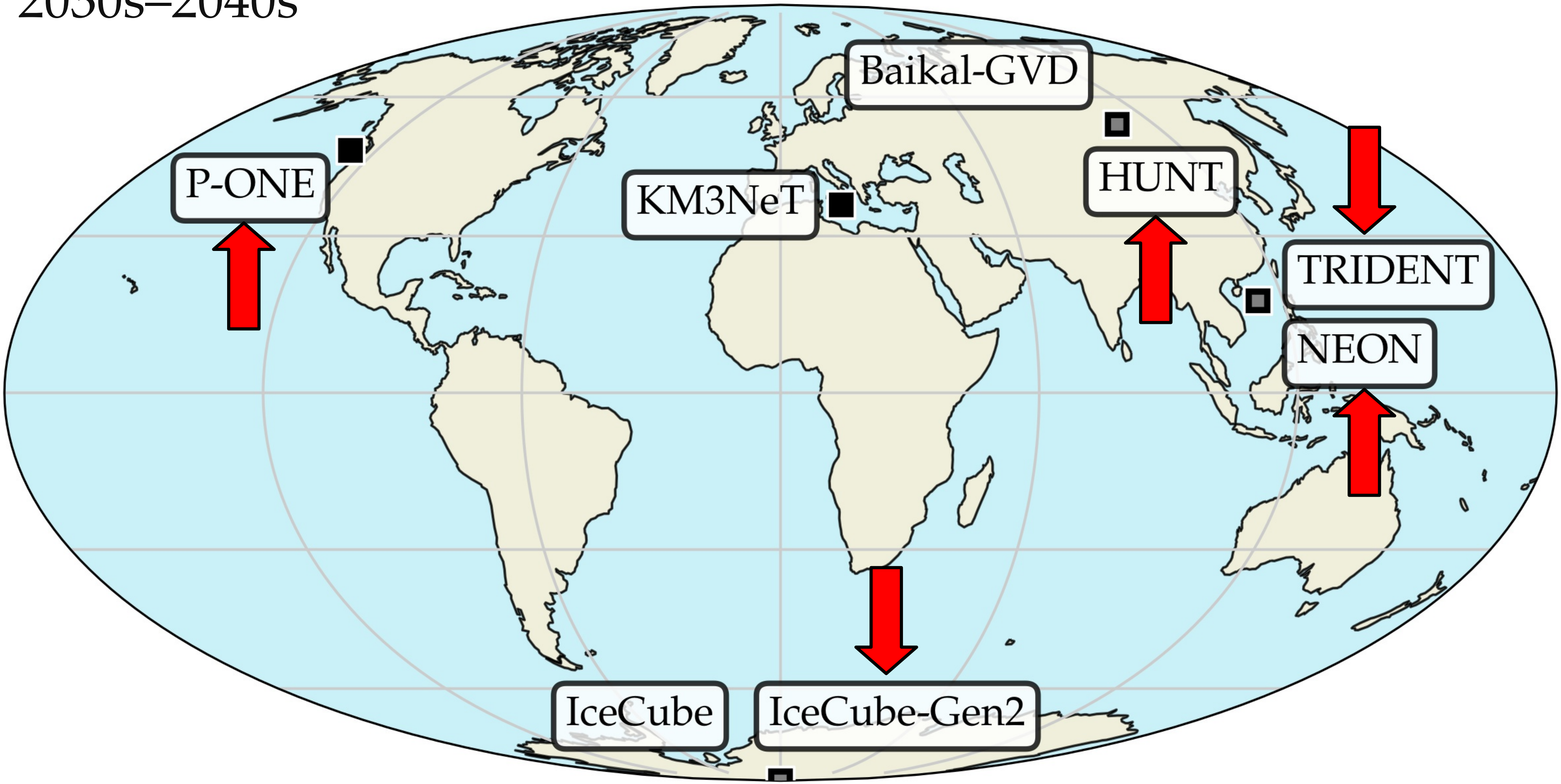
A global network of neutrino telescopes

Today & immediate future

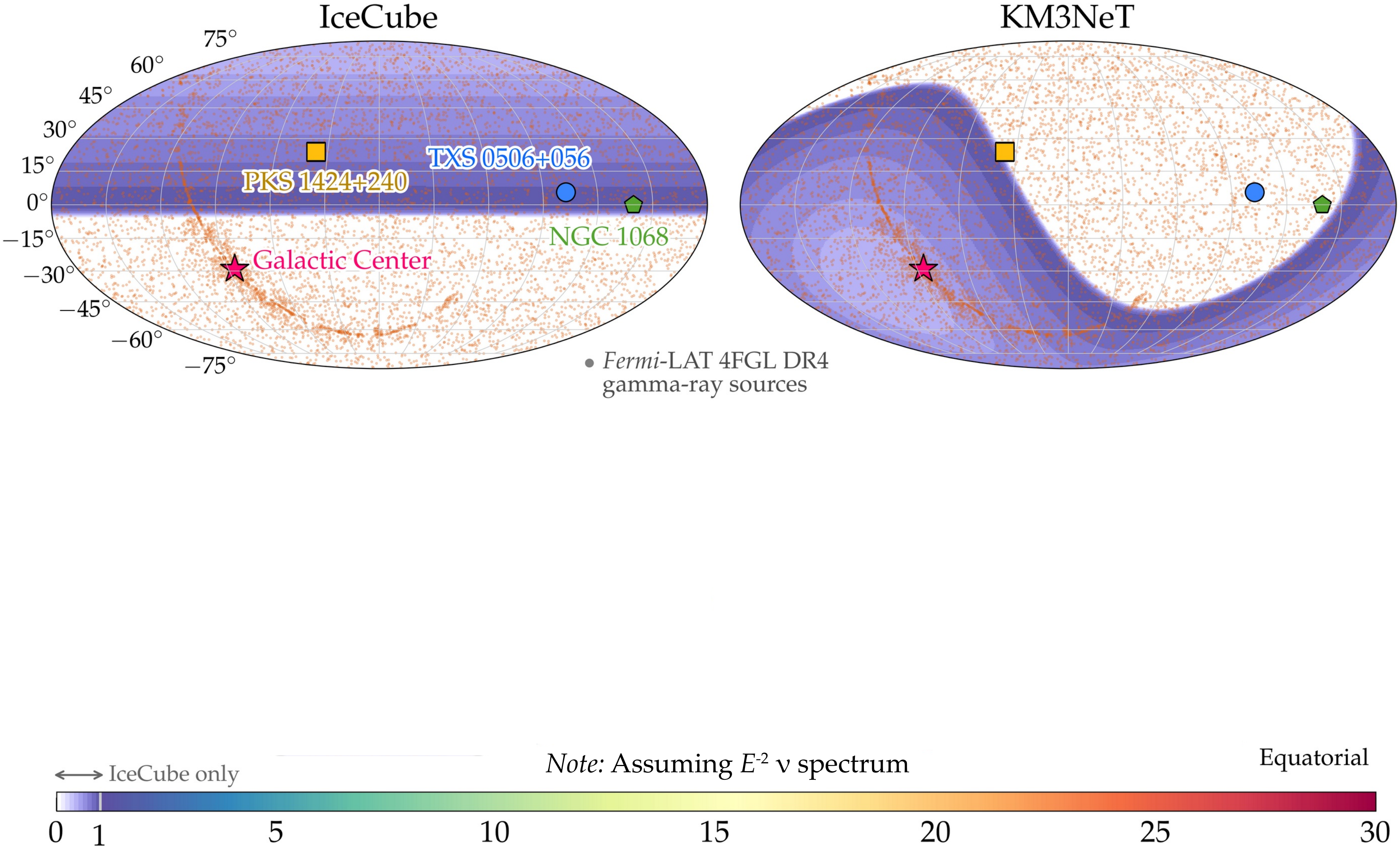


Schumacher, **MB**, Agostini, Oikonomou, Resconi, 2503.07549

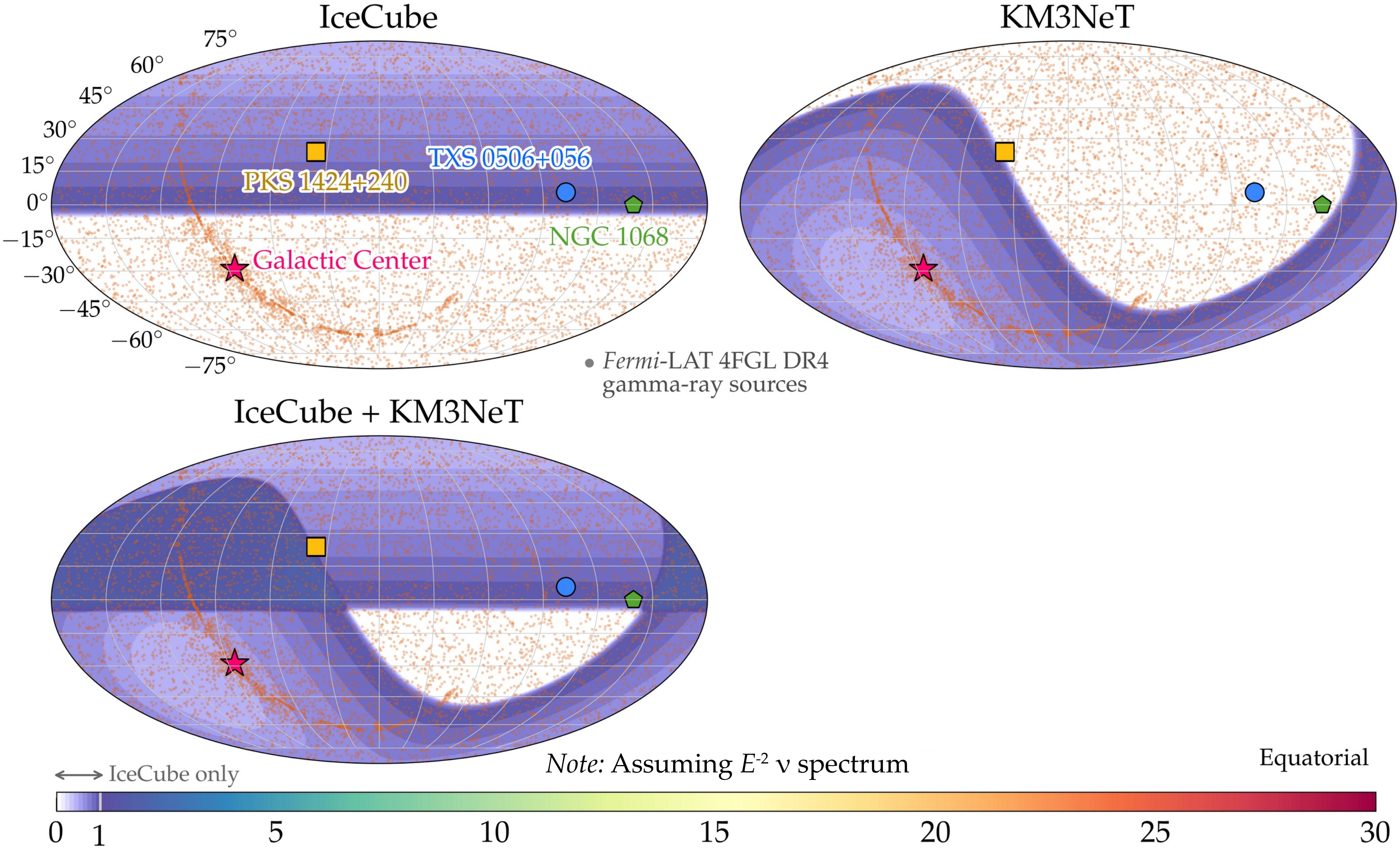
2030s–2040s



P-ONE
KM3NeT
Baikal-GVD
HUNT
TRIDENT
NEON
IceCube
IceCube-Gen2

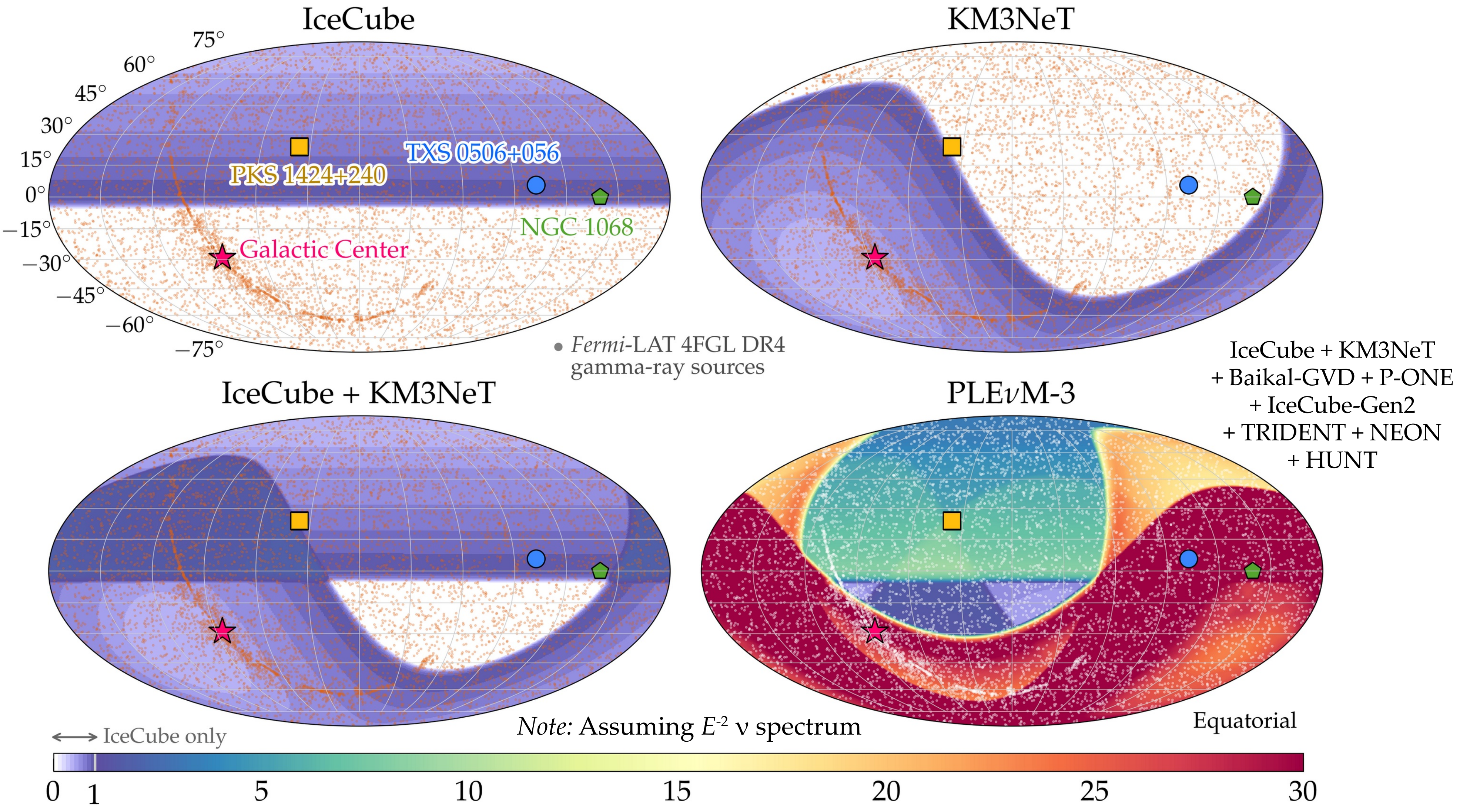


Schumacher, **MB**, Agostini, Oikonomou, Resconi, 2503.07549



Rate of detected muon tracks relative to IceCube maximum

Schumacher, **MB**, Agostini, Oikonomou, Resconi, 2503.07549



Schumacher, **MB**, Agostini, Oikonomou, Resconi, 2503.07549

So…

Today

TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:

Bigger detectors → larger statistics

Better reconstruction

Smaller astrophysical uncertainties

Today
TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:
Bigger detectors → larger statistics
Better reconstruction
Smaller astrophysical uncertainties

Next decade
$>$ 100-PeV ν

Today

TeV–PeV ν

Turn predictions
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Key developments:

Bigger detectors → larger statistics

Better reconstruction

Smaller astrophysical uncertainties

Next decade

> 100-PeV ν

Make predictions for
a new energy regime

Today
TeV–PeV ν

Turn predictions
into data-driven tests

<u>Key developments</u>:
Bigger detectors → larger statistics
Better reconstruction
Smaller astrophysical uncertainties

Next decade
> 100-PeV ν

Make predictions for
a new energy regime

<u>Key developments</u>:
Discovery
New detection techniques
Better UHE ν flux predictions

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TeV–PeV ν

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Key developments:
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Smaller astrophysical uncertainties

Next decade
> 100-PeV ν

Make predictions for
a new energy regime

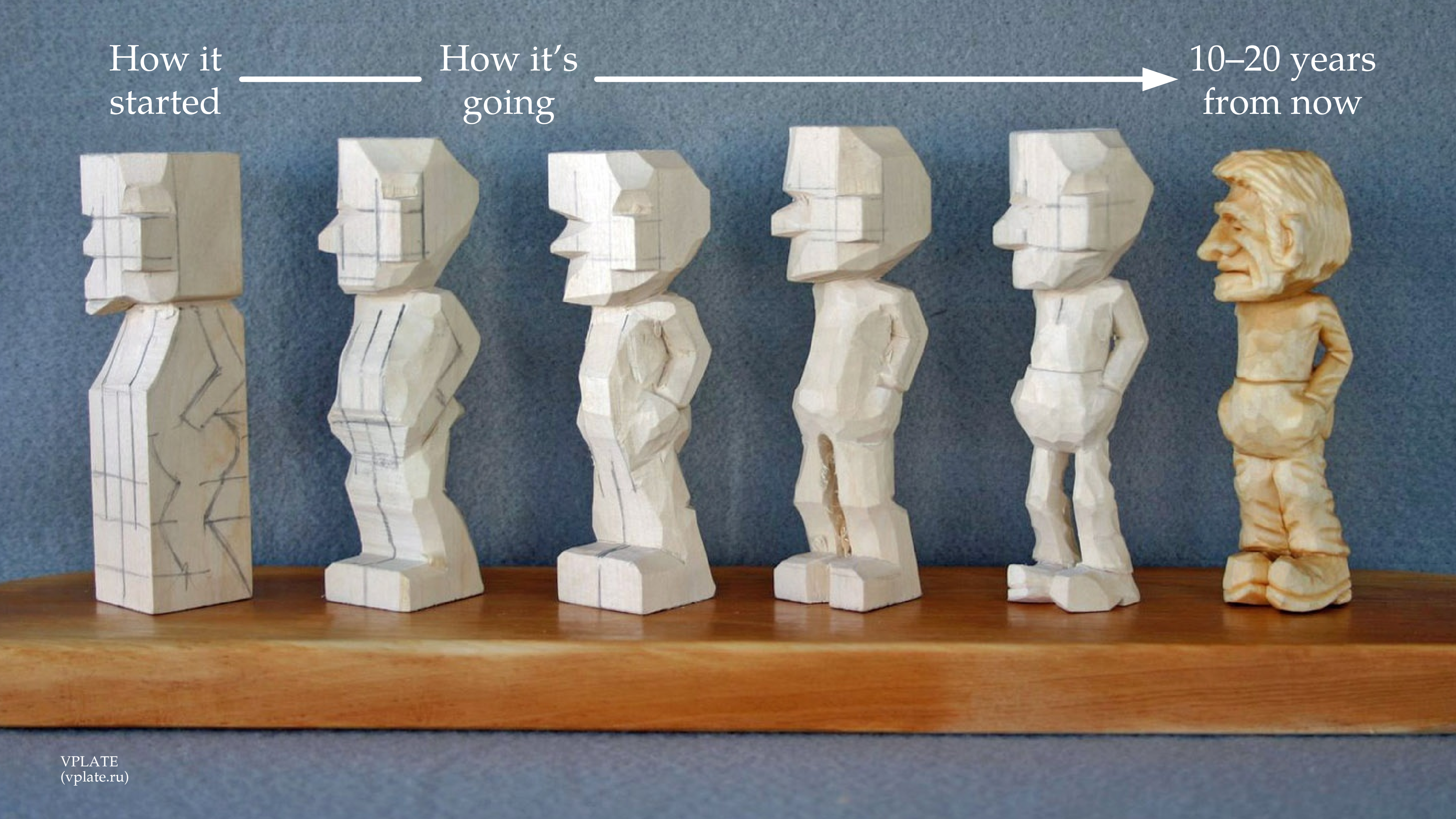
Key developments:
Discovery
New detection techniques
Better UHE ν flux predictions

Made robust and meaningful by accounting
for all relevant particle and astrophysics uncertainties

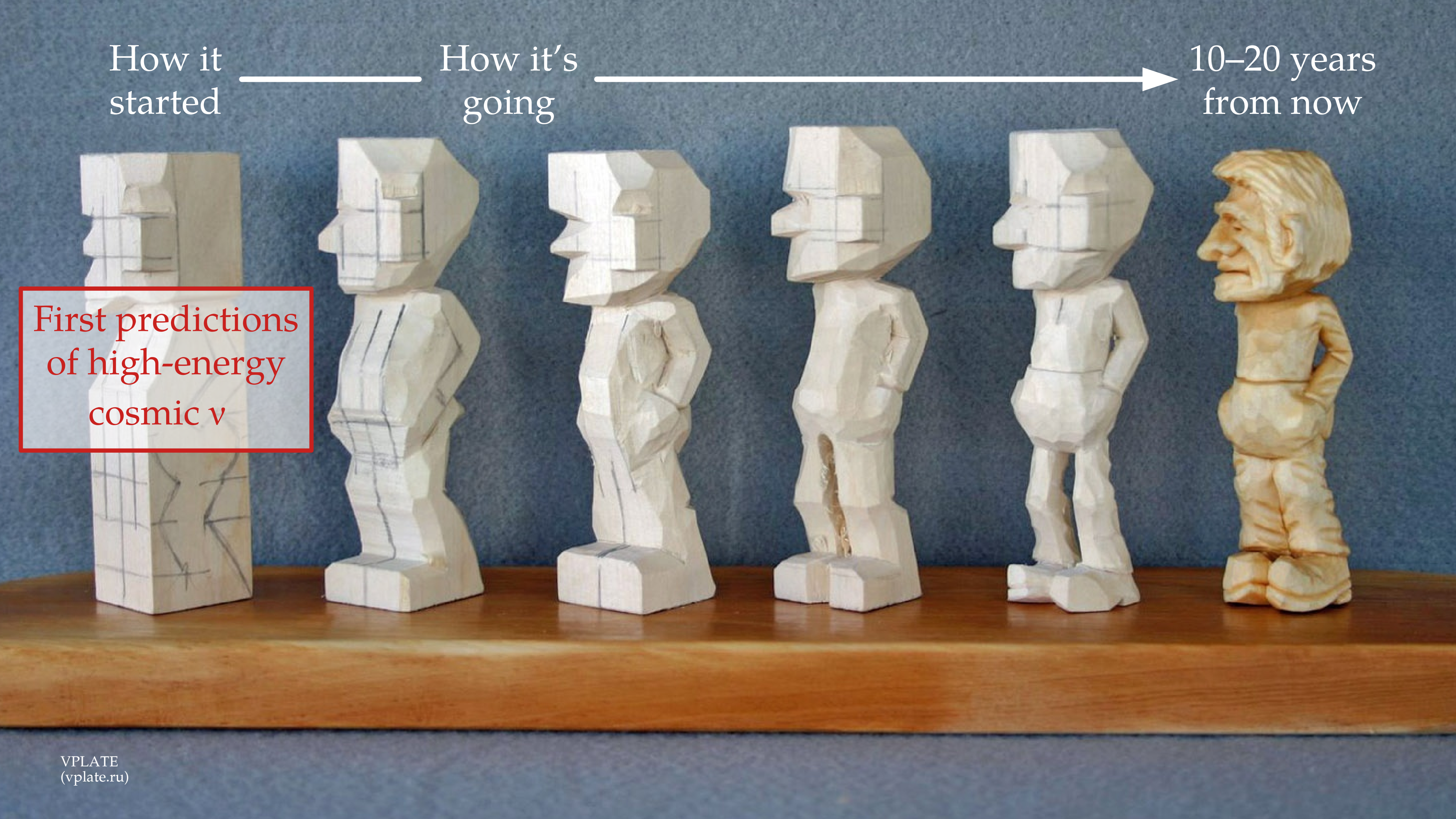
Today	*Next decade*
TeV–PeV ν	> 100-PeV ν
Turn predictions into data-driven tests	Make predictions for a new energy regime
Key developments:	Key developments:
Bigger detectors → larger statistics	Discovery
Better reconstruction	New detection techniques
Smaller astrophysical uncertainties	Better UHE ν flux predictions

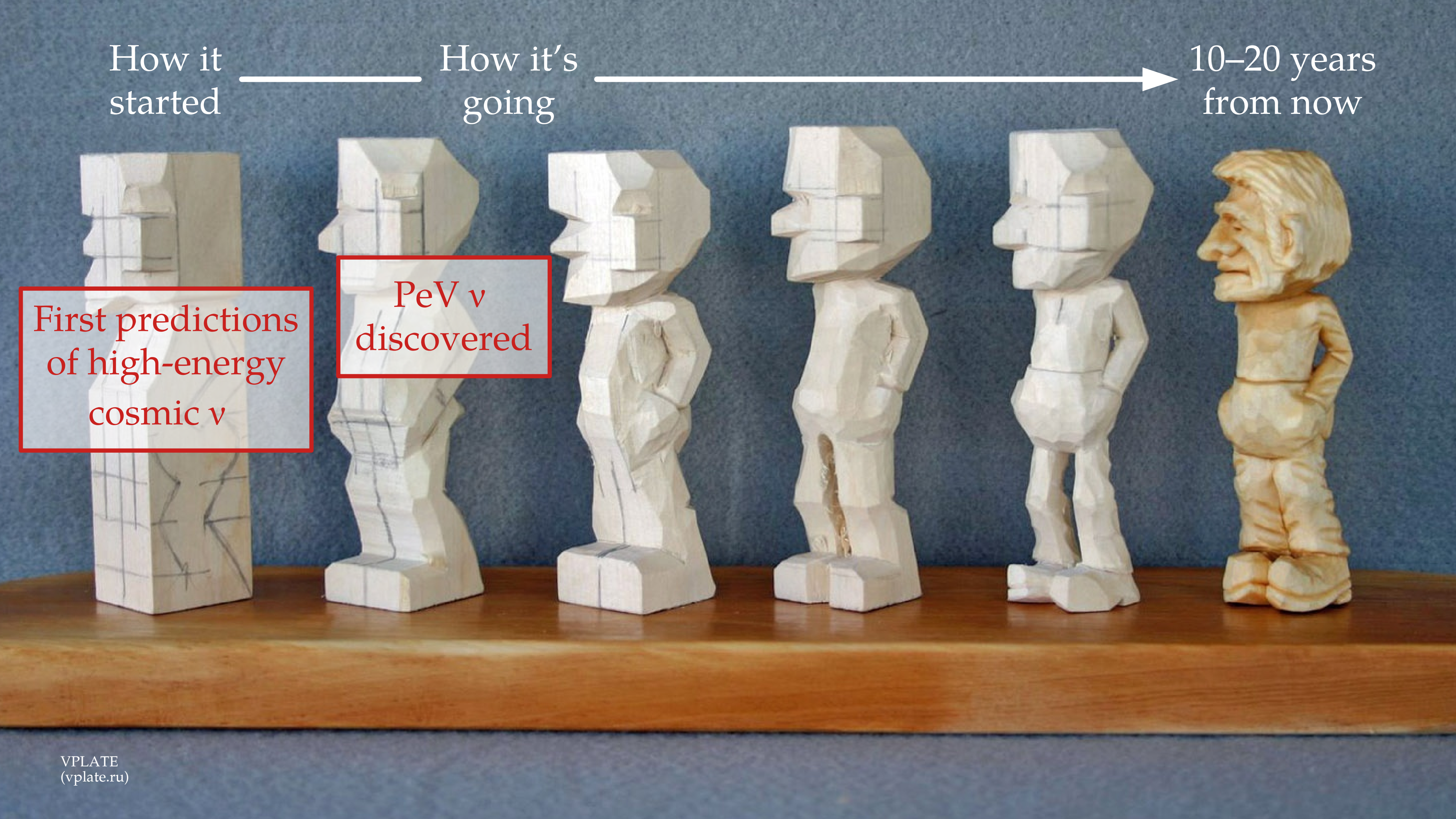
Similar to the evolution of cosmology to a high-precision field in the 1990s

Made robust and meaningful by accounting for all relevant particle and astrophysics uncertainties



VPLATE
(vplate.ru)


How it started
How it's going
10–20 years from now
First predictions of high-energy cosmic ν
VPLATE
(vplate.ru)


How it started
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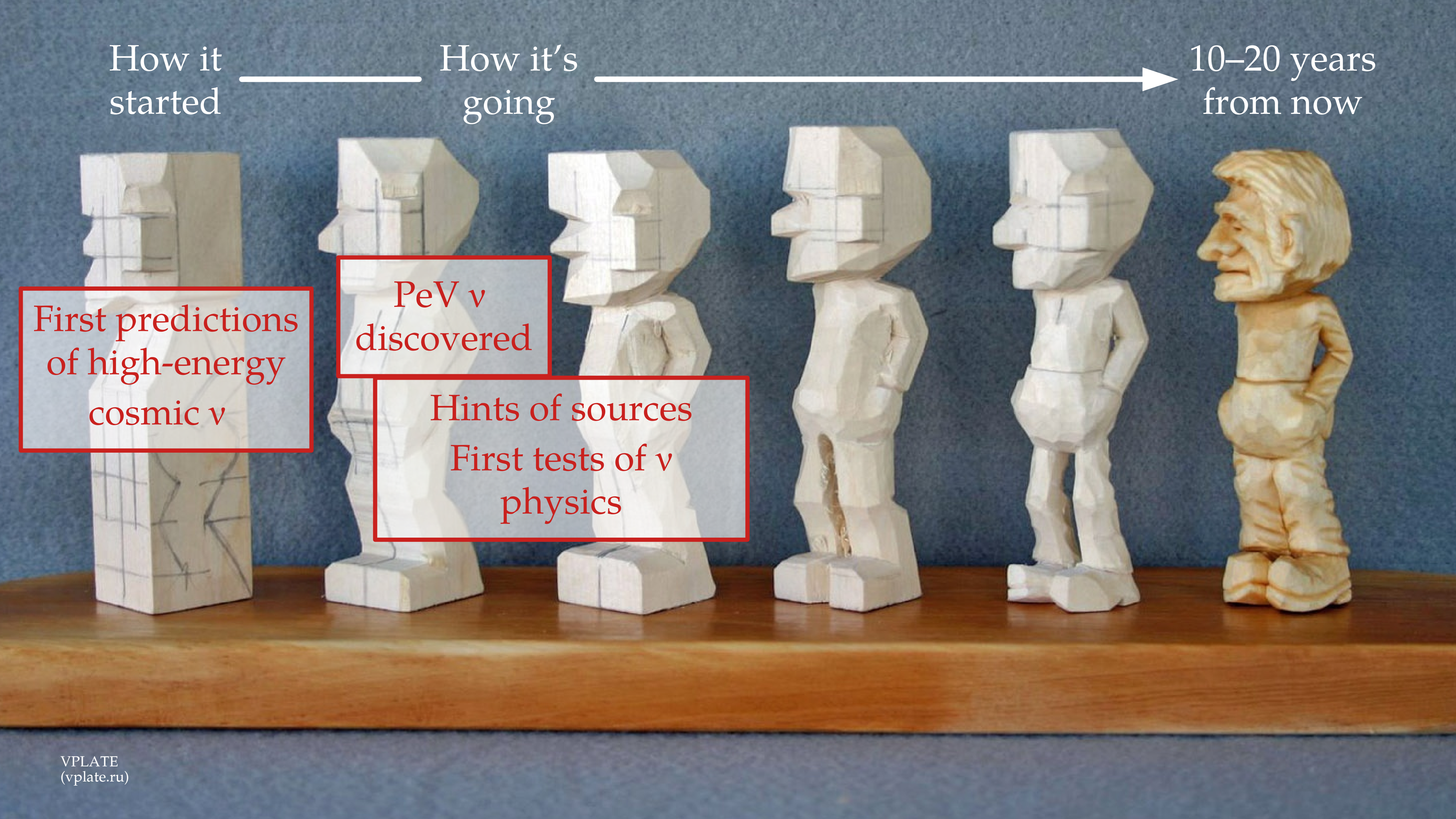
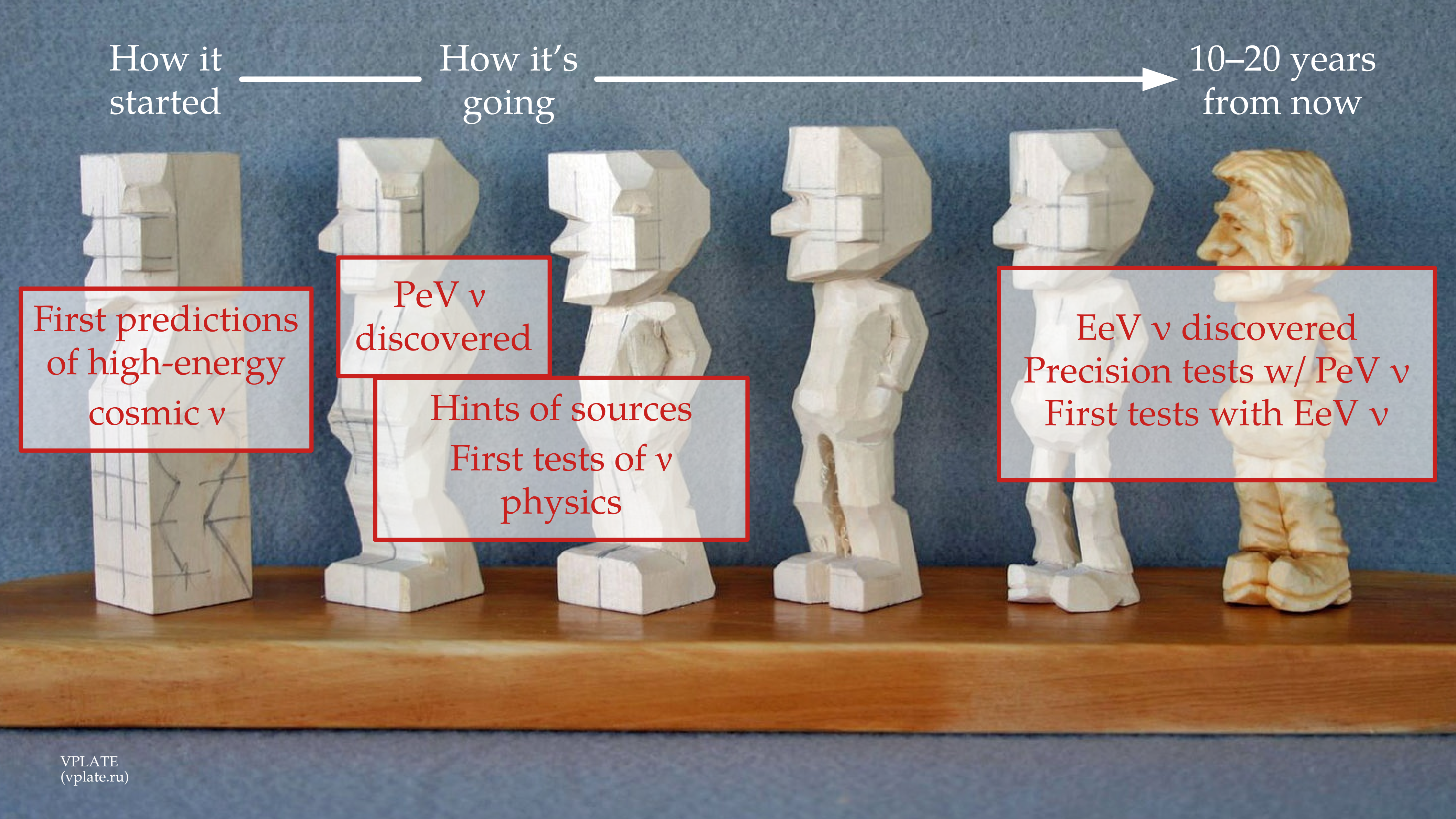
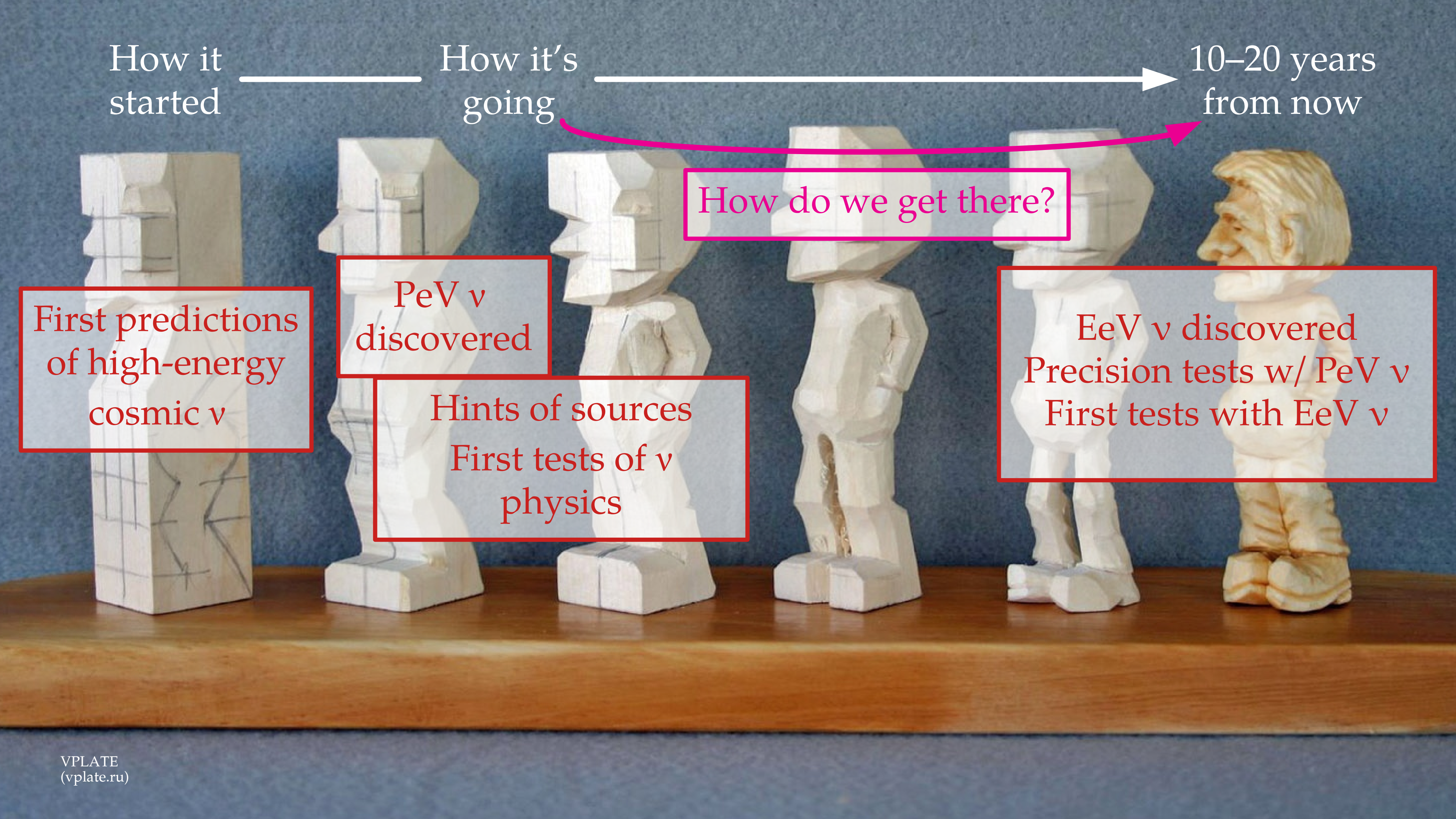
PeV ν discovered
VPLATE (vplate.ru)


How it started
How it's going
10–20 years from now
First predictions of high-energy cosmic ν
PeV ν discovered
Hints of sources
First tests of ν physics
VPLATE (vplate.ru)



VPLATE
(vplate.ru)


How it started
How it's going
10–20 years from now
How do we get there?
First predictions of high-energy cosmic ν
PeV ν discovered
Hints of sources
First tests of ν physics
EeV ν discovered
Precision tests w/ PeV ν
First tests with EeV ν
VPLATE (vplate.ru)

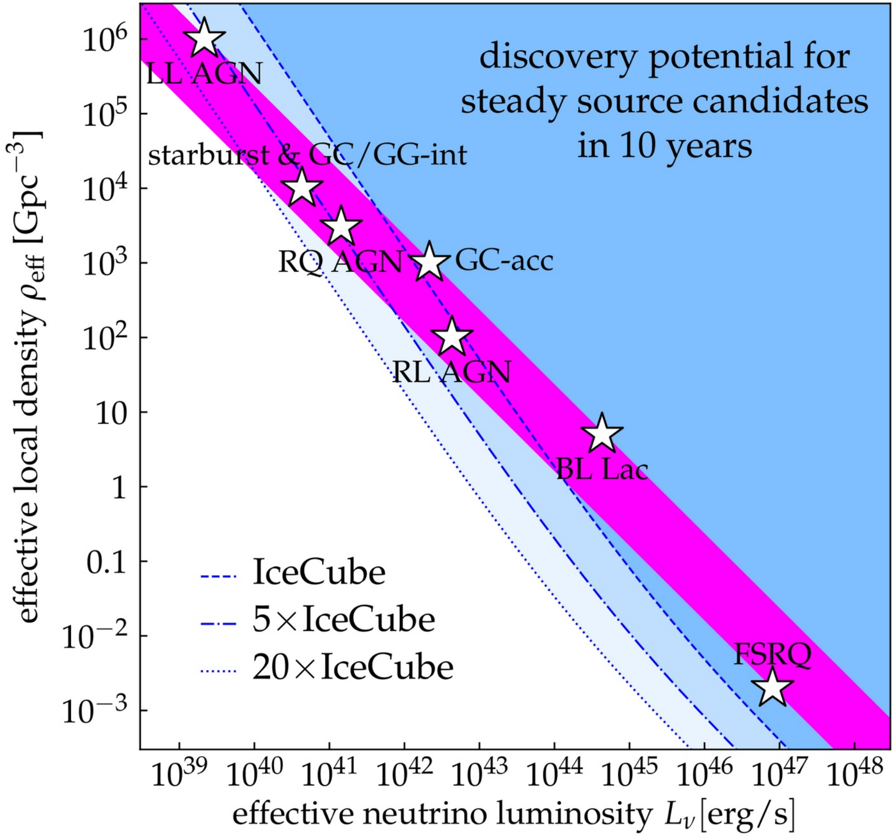
Thank you!

Backup slides

Source discovery potential: today and in the future

Accounts for the observed diffuse ν flux (lower/upper edge: rapid/no redshift evolution)

Closest source with $E^2\phi_{\nu_\mu+\bar{\nu}_\mu} = 10^{-9}\ \mathrm{GeV cm^{-2} s^{-1}}$



Ackermann, **MB** *et al.*, Astro2020 Survey (1903.04333) – See also: Silvestri & Barwick, *PRD* 2010; Murase & Waxman, *PRD* 2016

Neutrinos as cosmic magnetometers

Using high-energy neutrinos as magnetometers

If sources have strong magnetic fields, charged particles cool via synchrotron:

$$p + \gamma_{\text{target}} \longrightarrow \Delta^+ \longrightarrow \begin{cases} p + \pi^0, & \text{Br} = 2/3 \\ n + \pi^+, & \text{Br} = 1/3 \end{cases}$$

$$\pi^0 \longrightarrow \gamma + \gamma$$

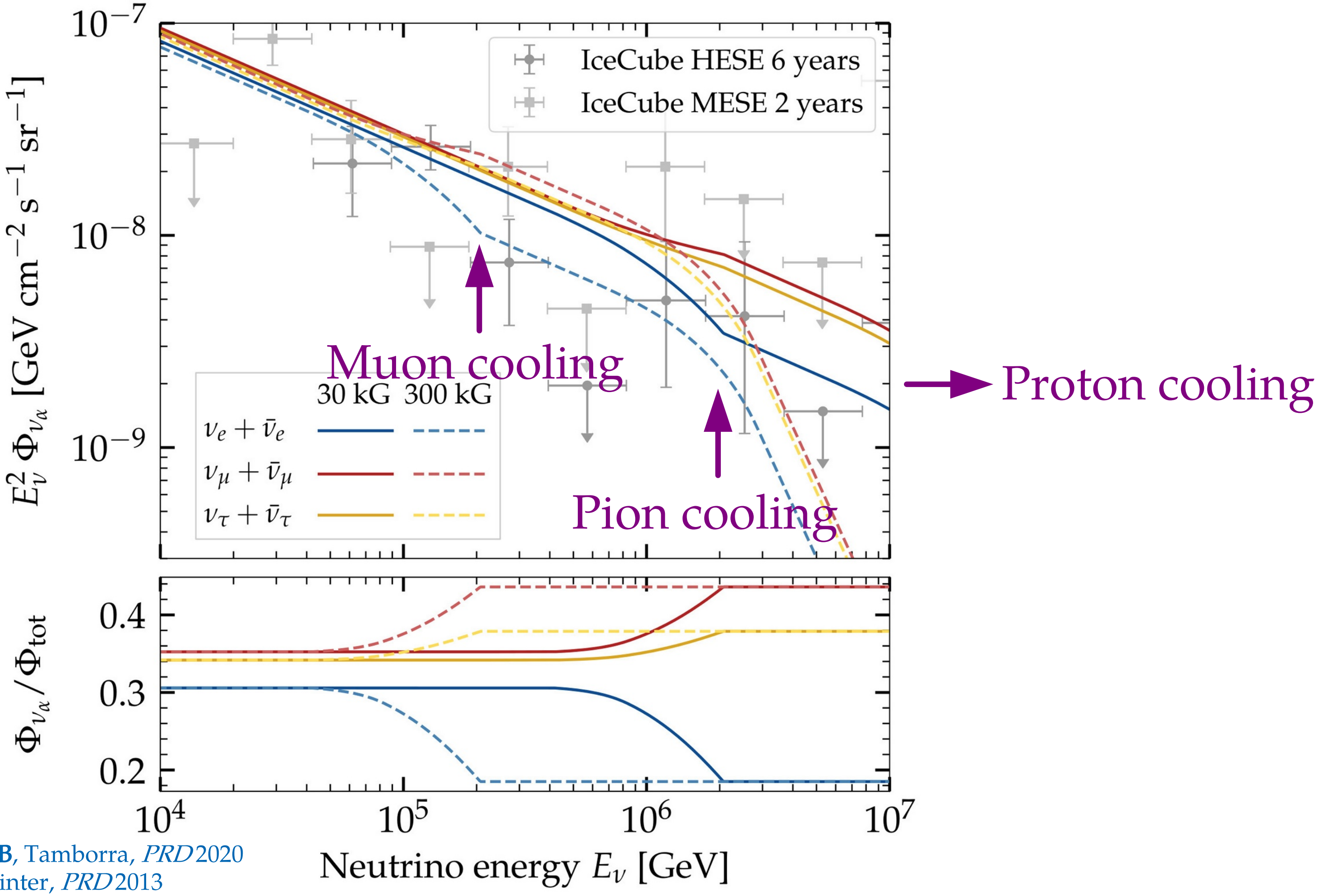
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \longrightarrow \bar{\nu}_\mu + e^+ + \nu_e + \nu_\mu$$

$$n\,(\text{escapes}) \longrightarrow p + e^- + \bar{\nu}_e$$

MB, Tamborra, *PRD* 2020
Winter, *PRD* 2013

Using high-energy neutrinos as magnetometers

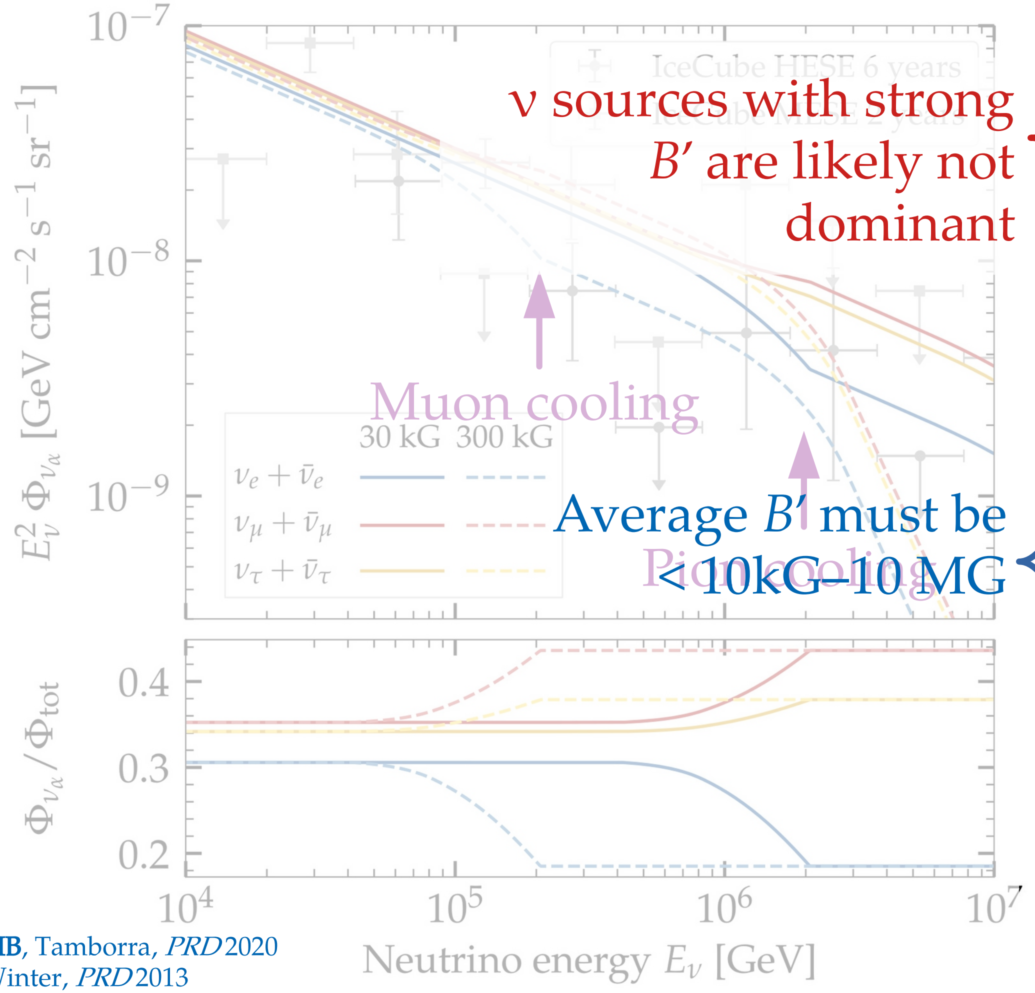
If sources have strong magnetic fields, charged particles cool via synchrotron:



MB, Tamborra, *PRD* 2020
Winter, *PRD* 2013

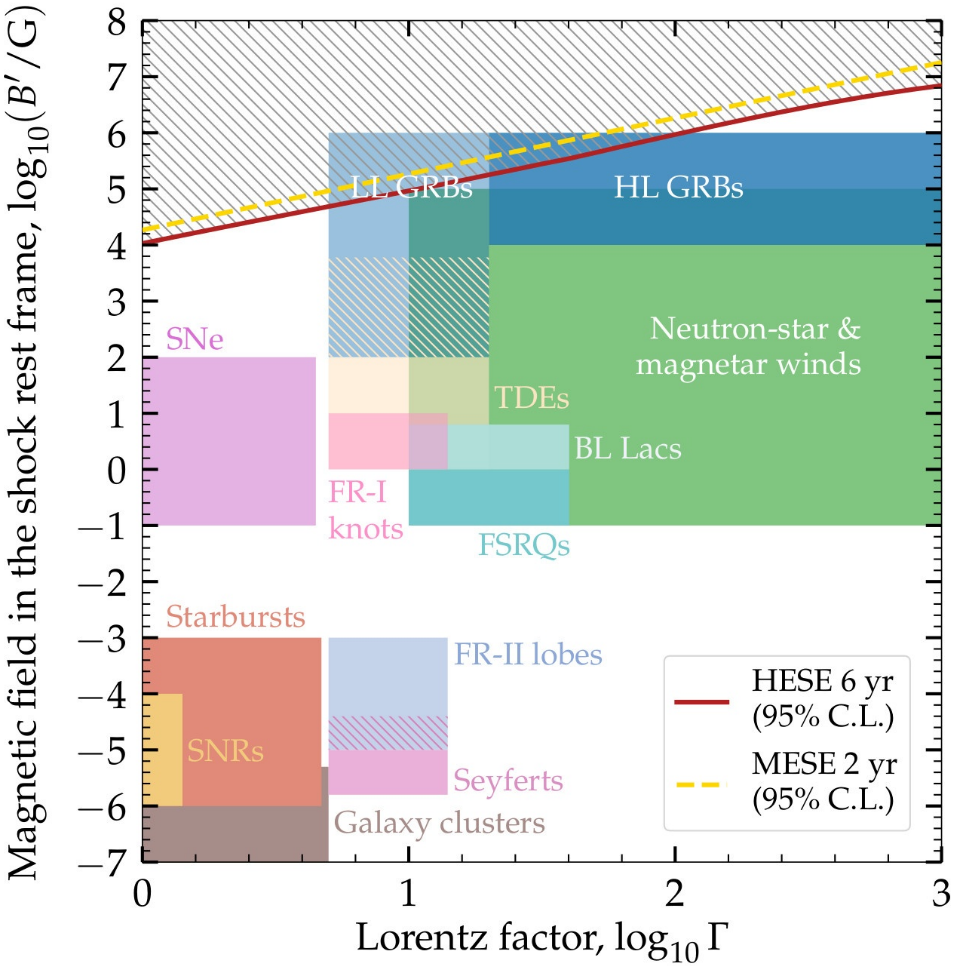
Using high-energy neutrinos as magnetometers

If sources have strong magnetic fields, charged particles cool via synchrotron:



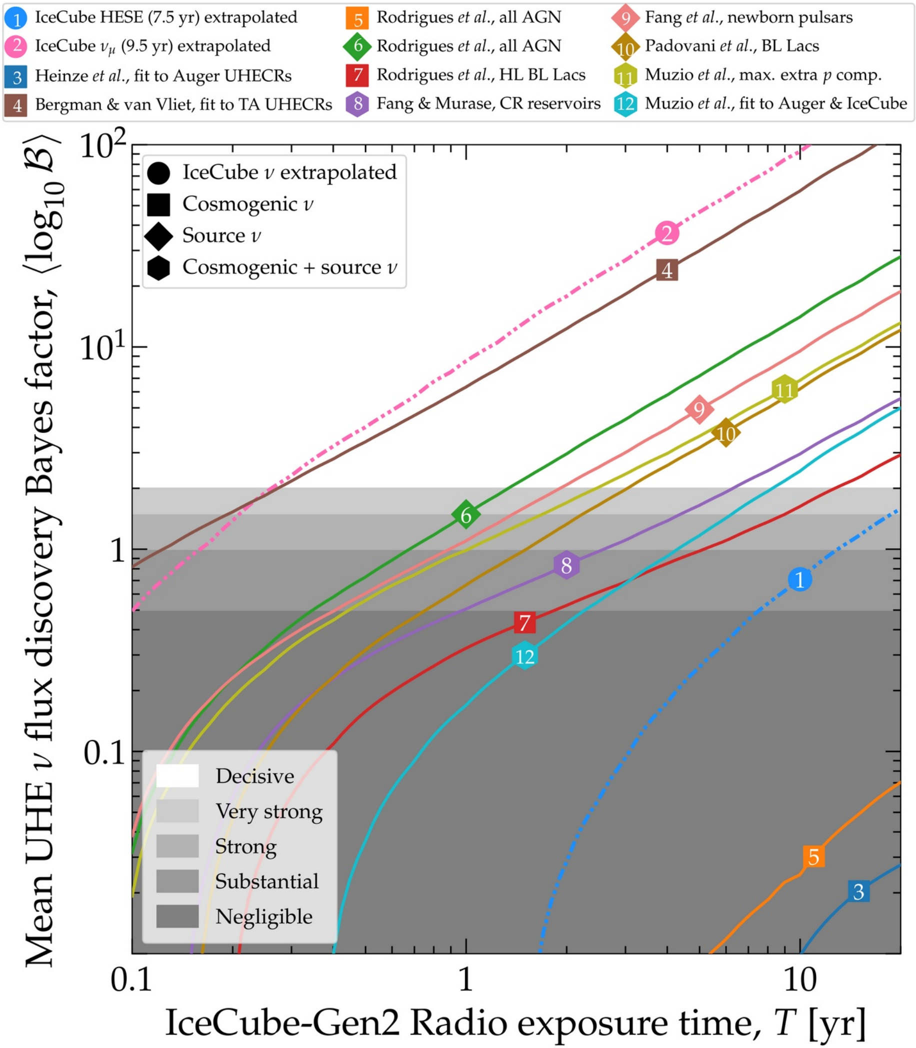
ν sources with strong B' are likely not dominant

Average B' must be < 10kG–10 MG



MB, Tamborra, *PRD* 2020
Winter, *PRD* 2013

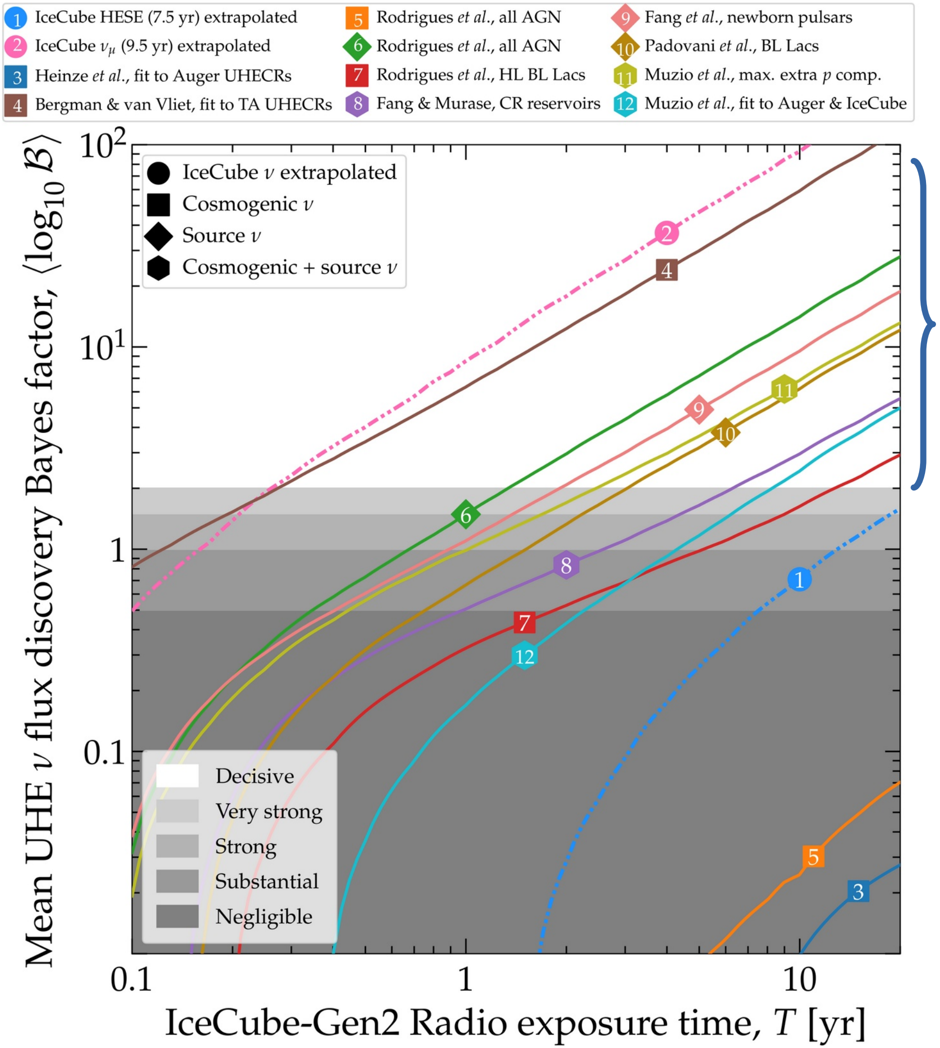
Discovering the diffuse flux of UHE neutrinos



Valera, **MB**, Glaser, *PRD* 2023

Discovering the diffuse flux of UHE neutrinos

Bayes factor compares signal+bkg. *vs.* bkg.-only

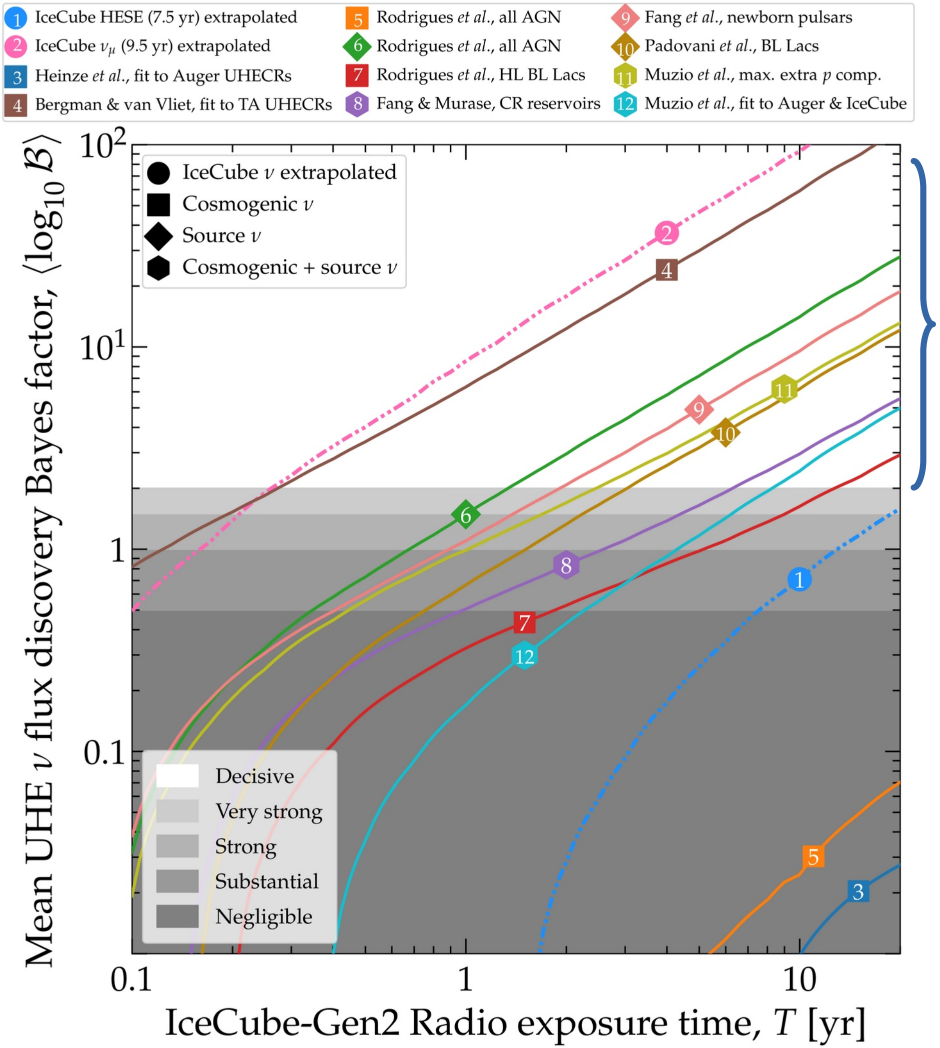


Large Bayes factor
=
decisive flux discover

Valera, **MB**, Glaser, *PRD* 2023

Discovering the diffuse flux of UHE neutrinos

Bayes factor compares signal+bkg. *vs.* bkg.-only



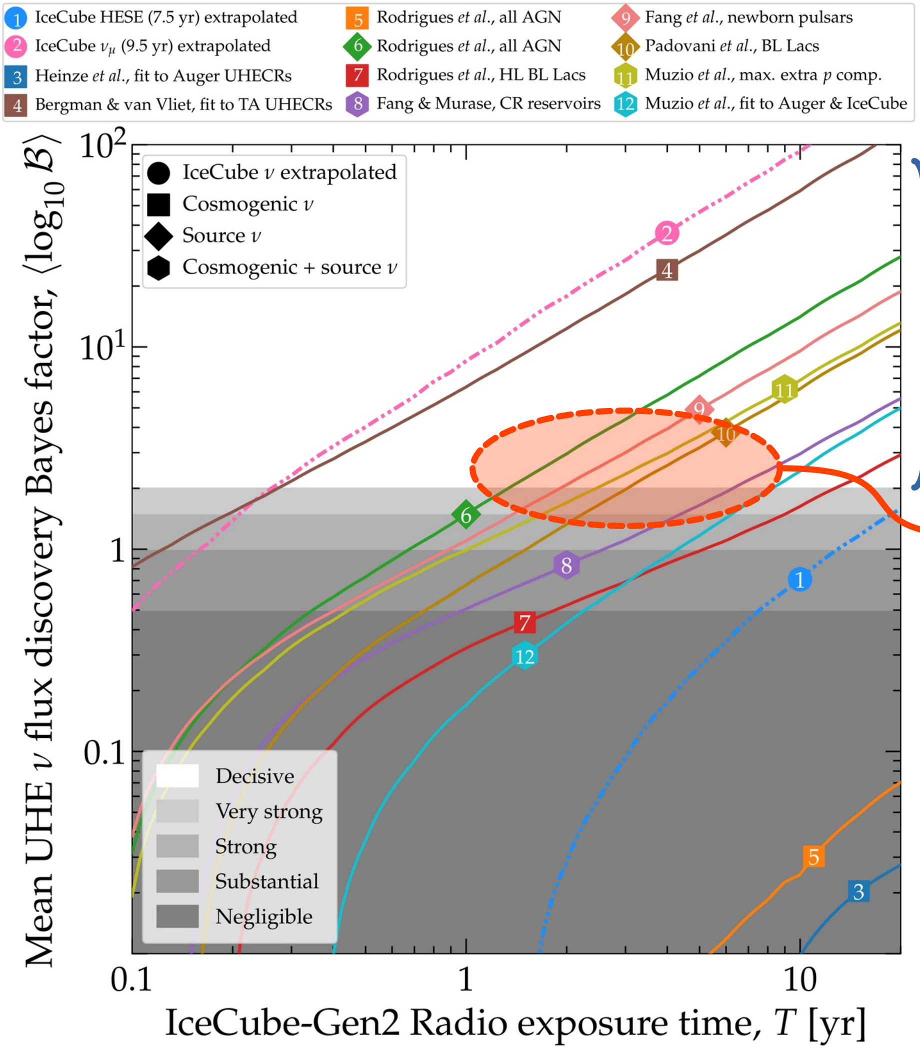
Large Bayes factor
=
decisive flux discover

Forecasts are state-of-the-art:
- Neutrino propagation inside Earth
- Detailed simulation of radio in ice
- Detailed antenna response
- Detector energy & angular resolution
- Statistical fluctuations

Valera, **MB**, Glaser, *PRD* 2023

Discovering the diffuse flux of UHE neutrinos

Bayes factor compares signal+bkg. *vs.* bkg.-only

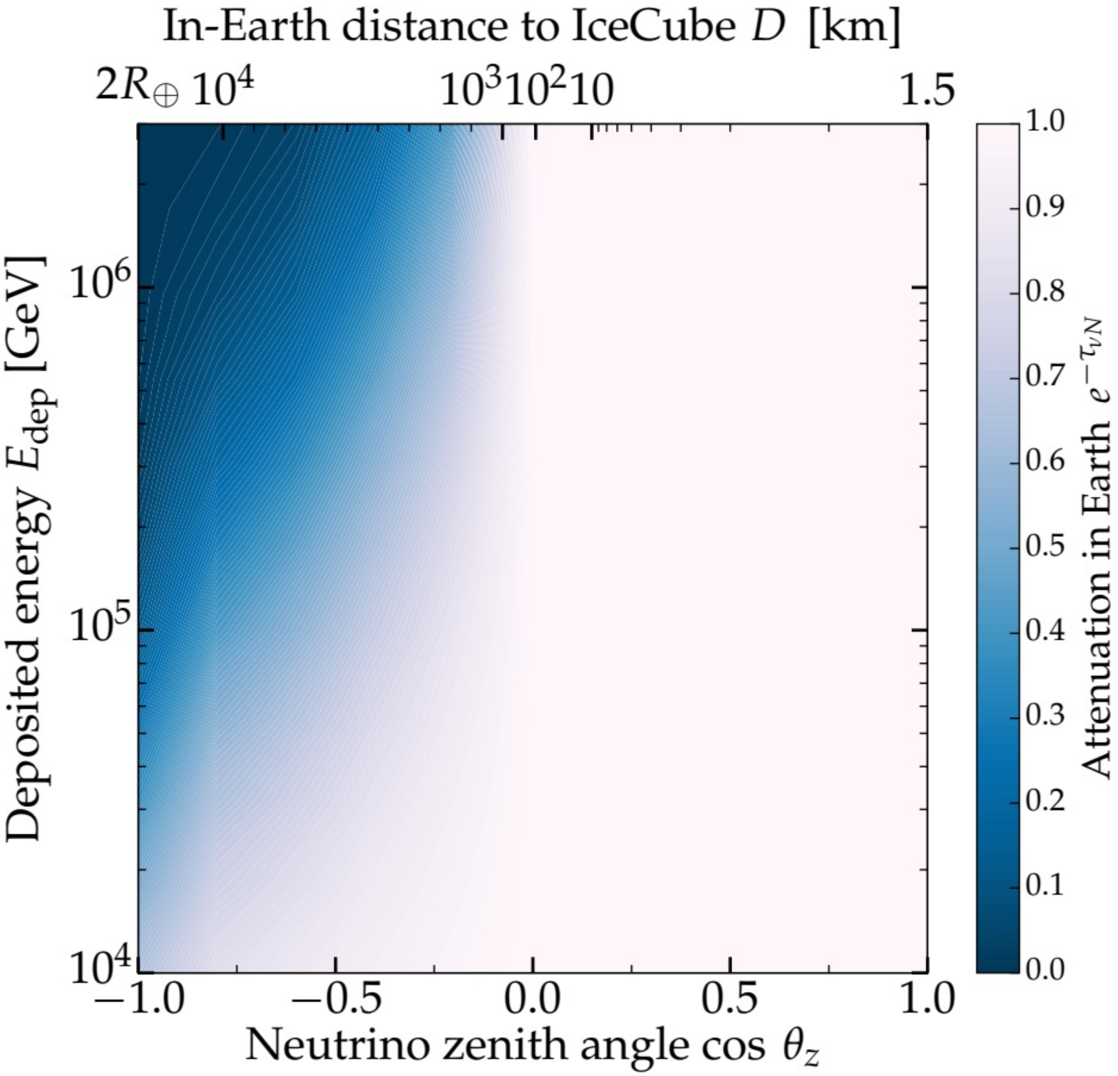


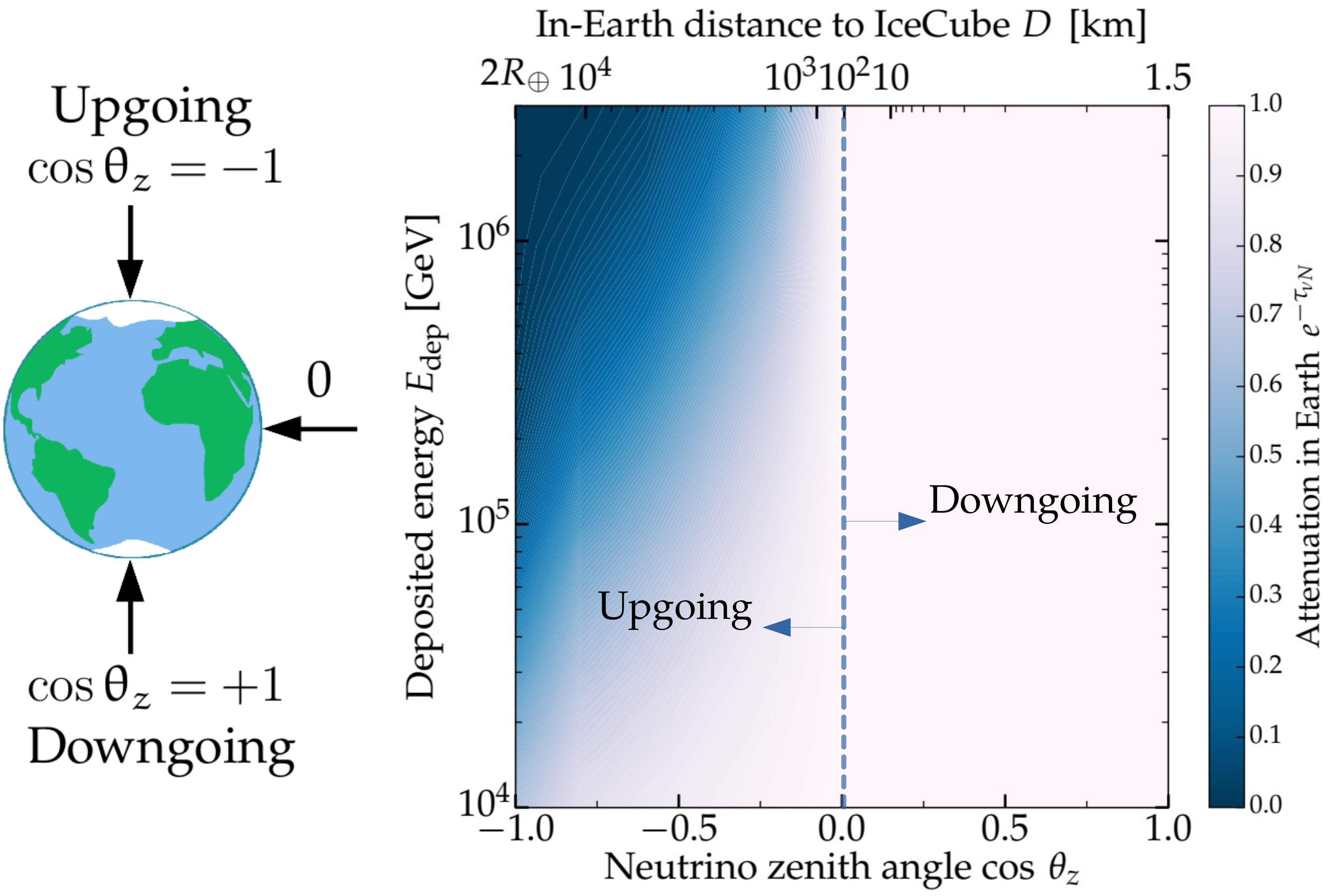
Large Bayes factor = decisive flux discover

Most flux models are discoverable with a few years

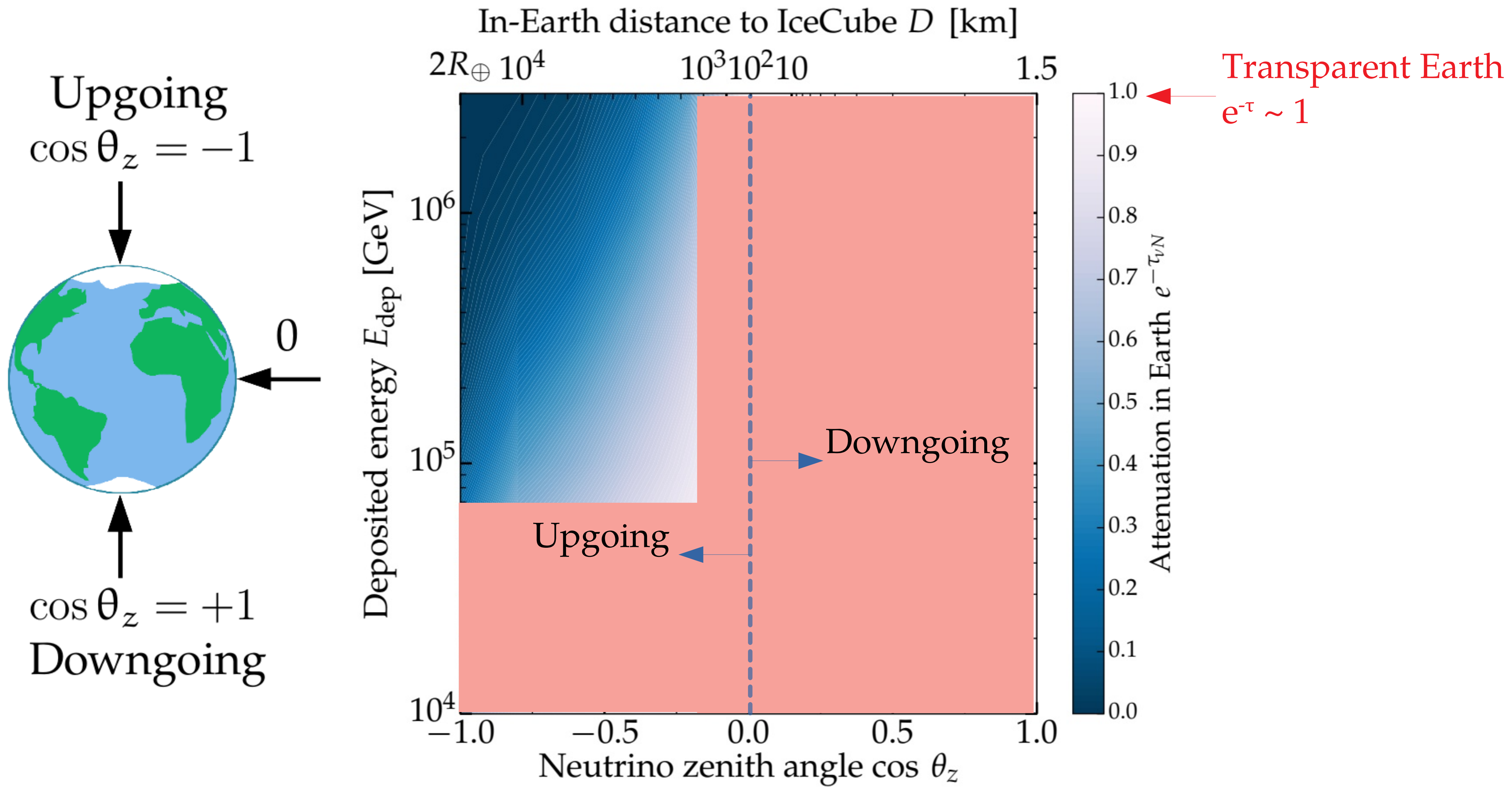
Forecasts are state-of-the-art:
- Neutrino propagation inside Earth
- Detailed simulation of radio in ice
- Detailed antenna response
- Detector energy & angular resolution
- Statistical fluctuations

Valera, **MB**, Glaser, *PRD* 2023

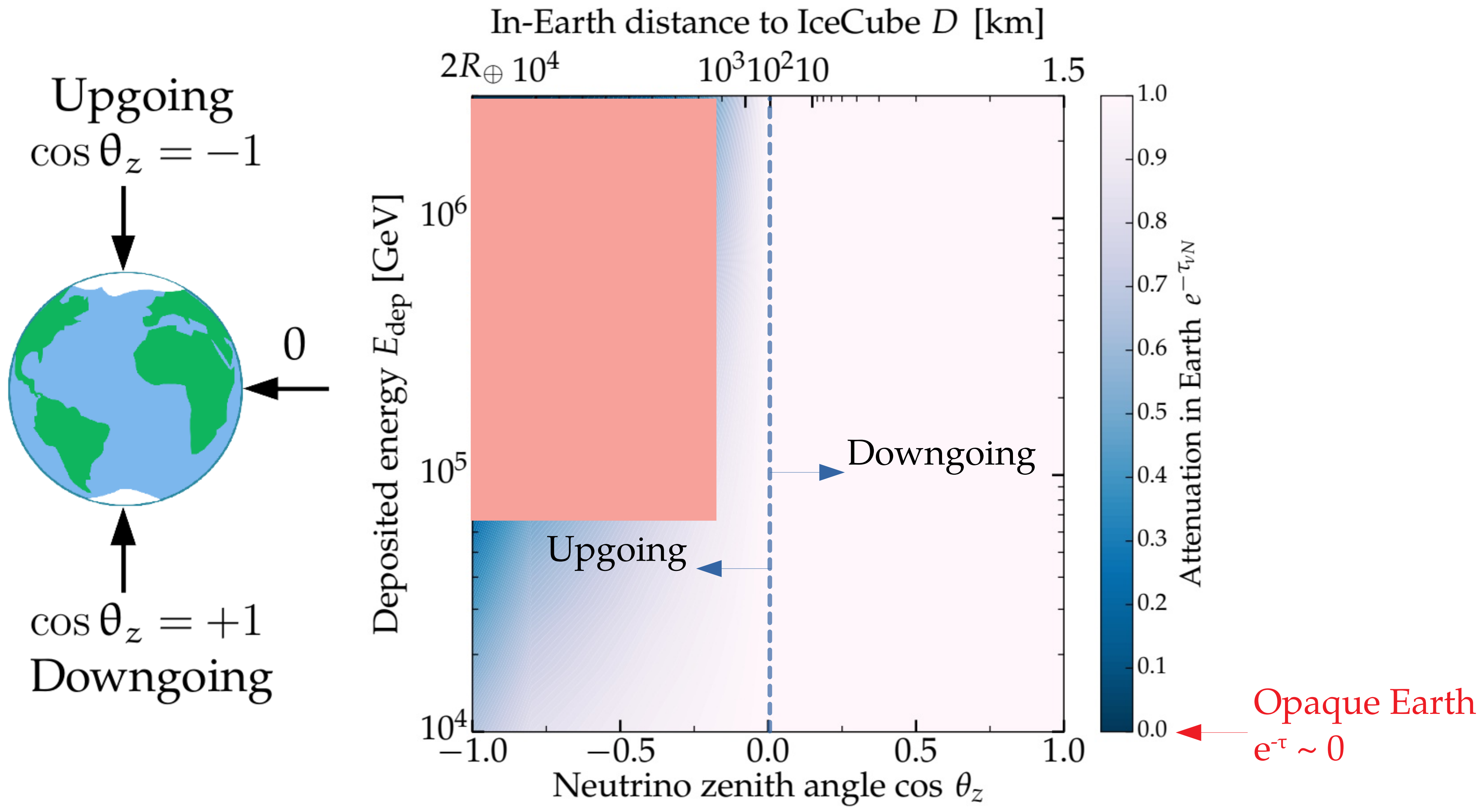

In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0



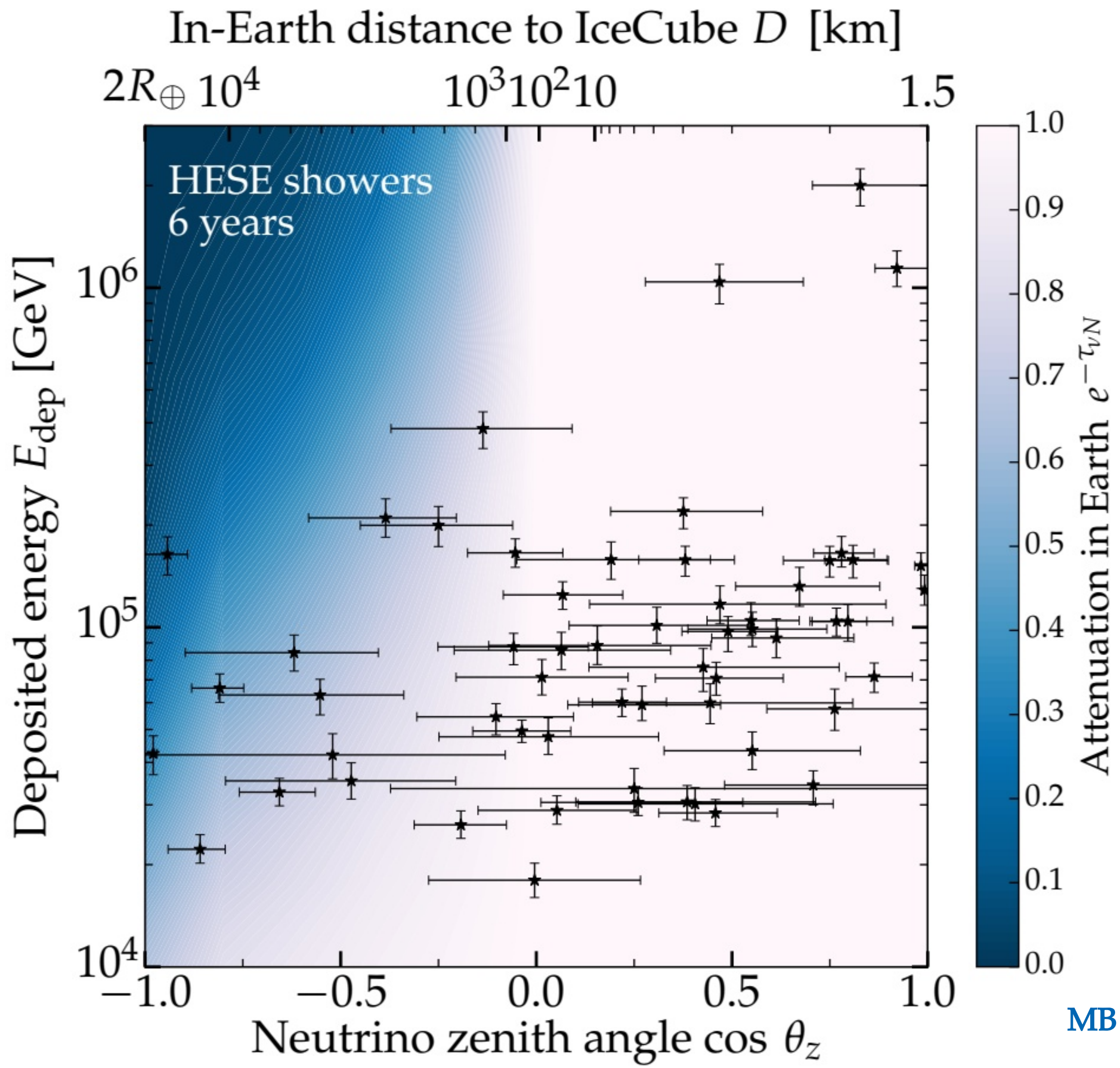
Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle $\cos\,\theta_z$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Attenuation in Earth $e^{-\tau_{\nu N}}$



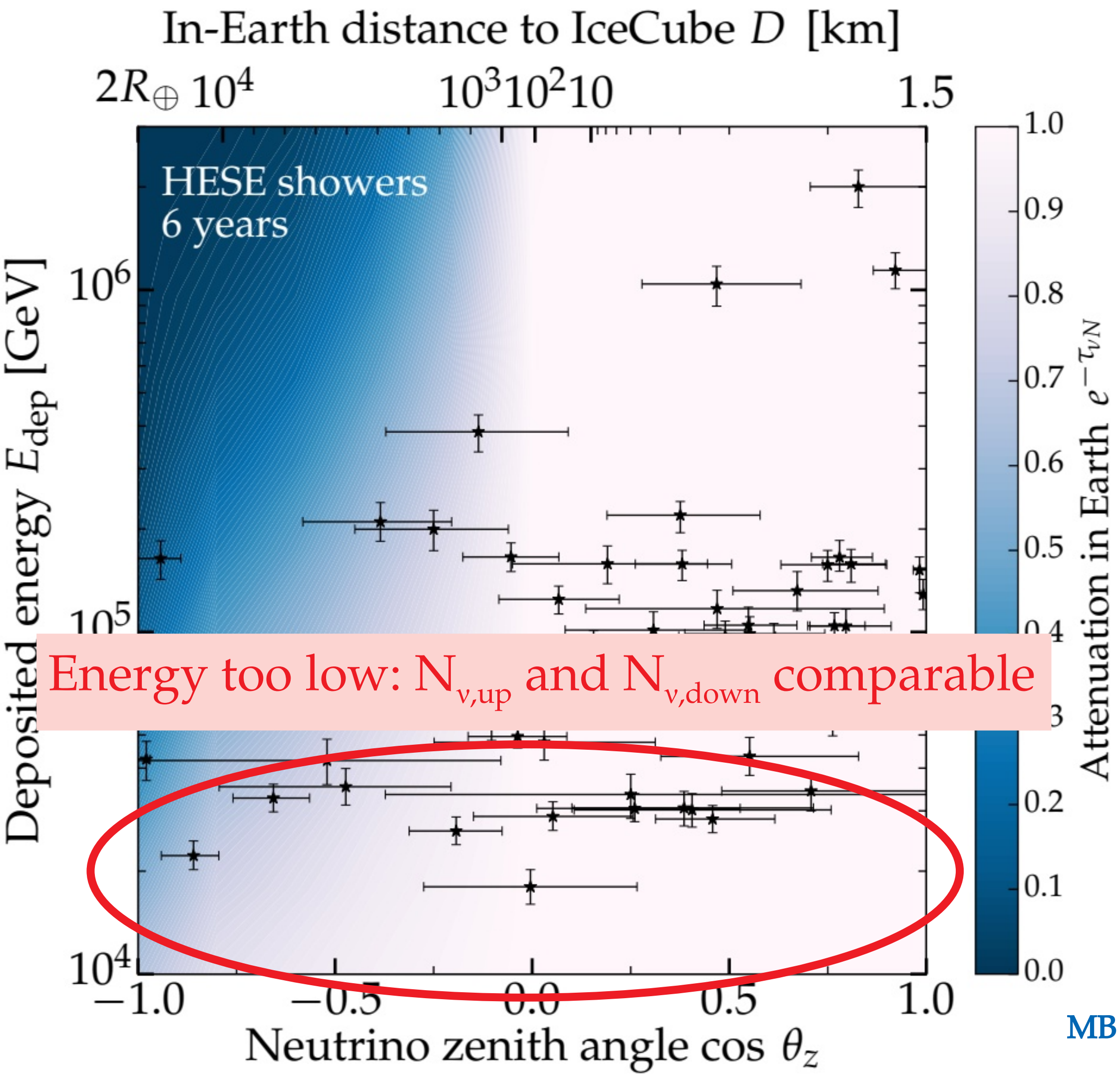
Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^4 10^5 10^6
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Transparent Earth
$e^{-\tau} \sim 1$



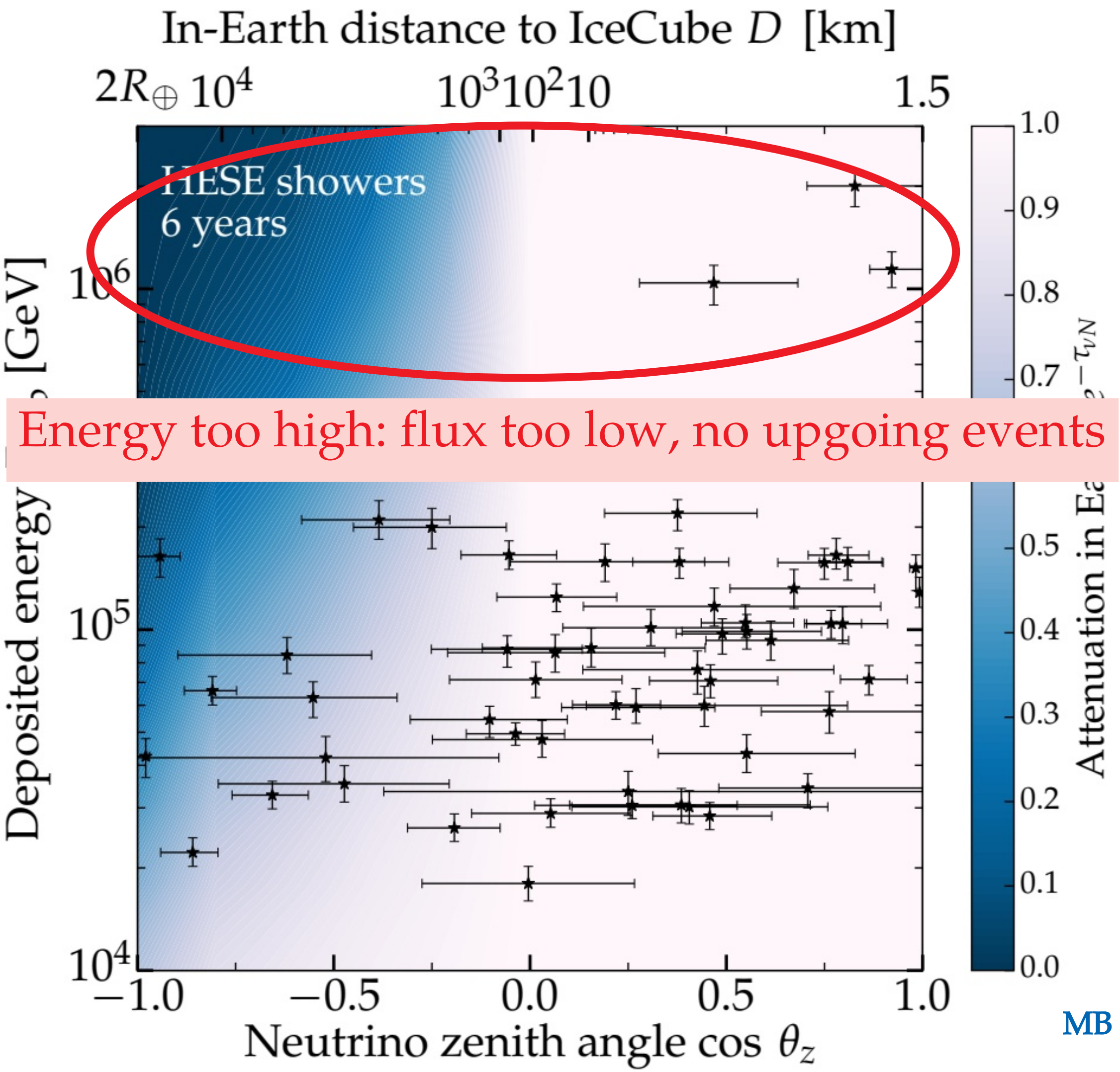
Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
-1.0 -0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\theta_z$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Attenuation in Earth $e^{-\tau_{\nu N}}$
Opaque Earth
$e^{-\tau} \sim 0$



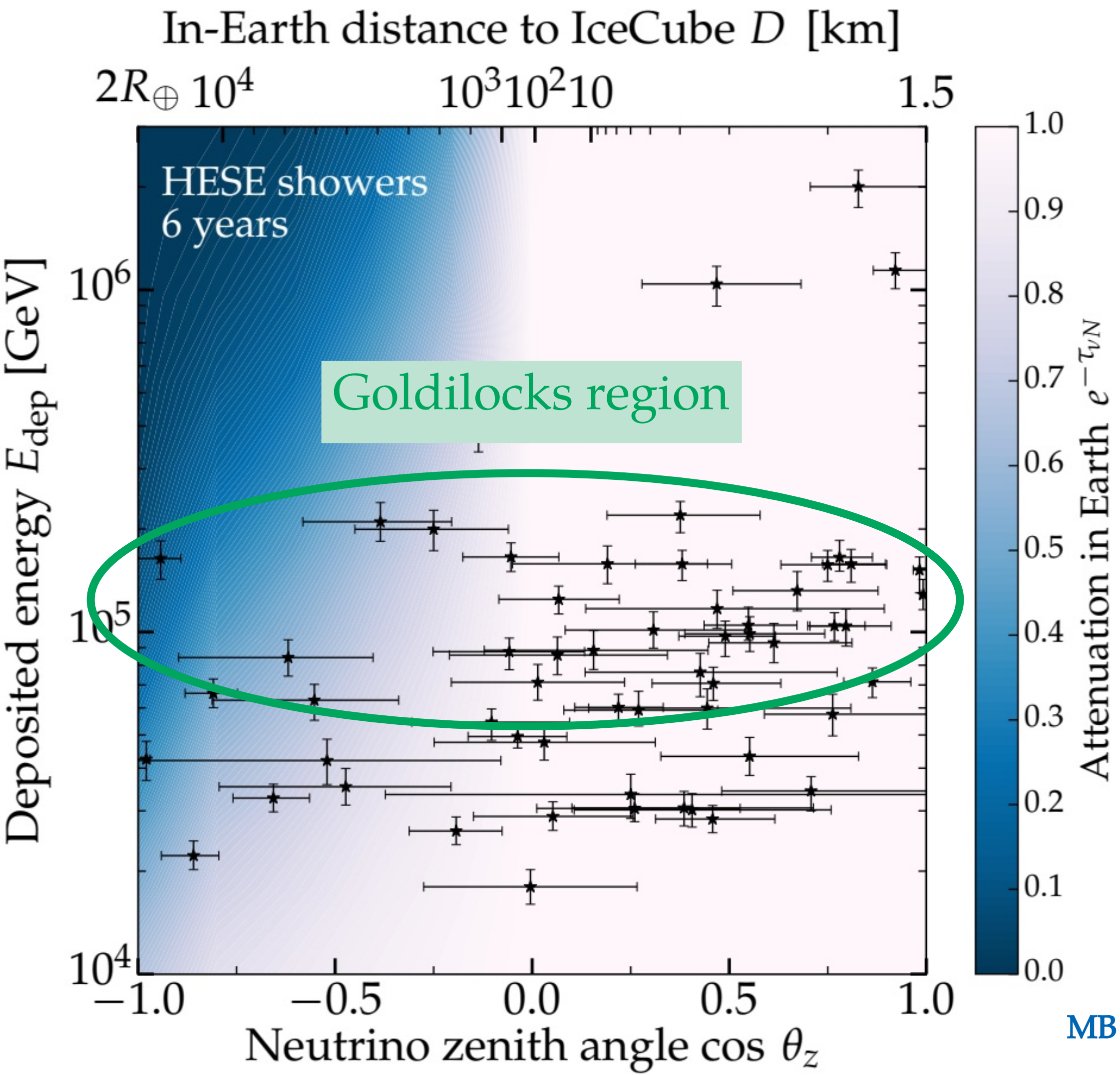
MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019

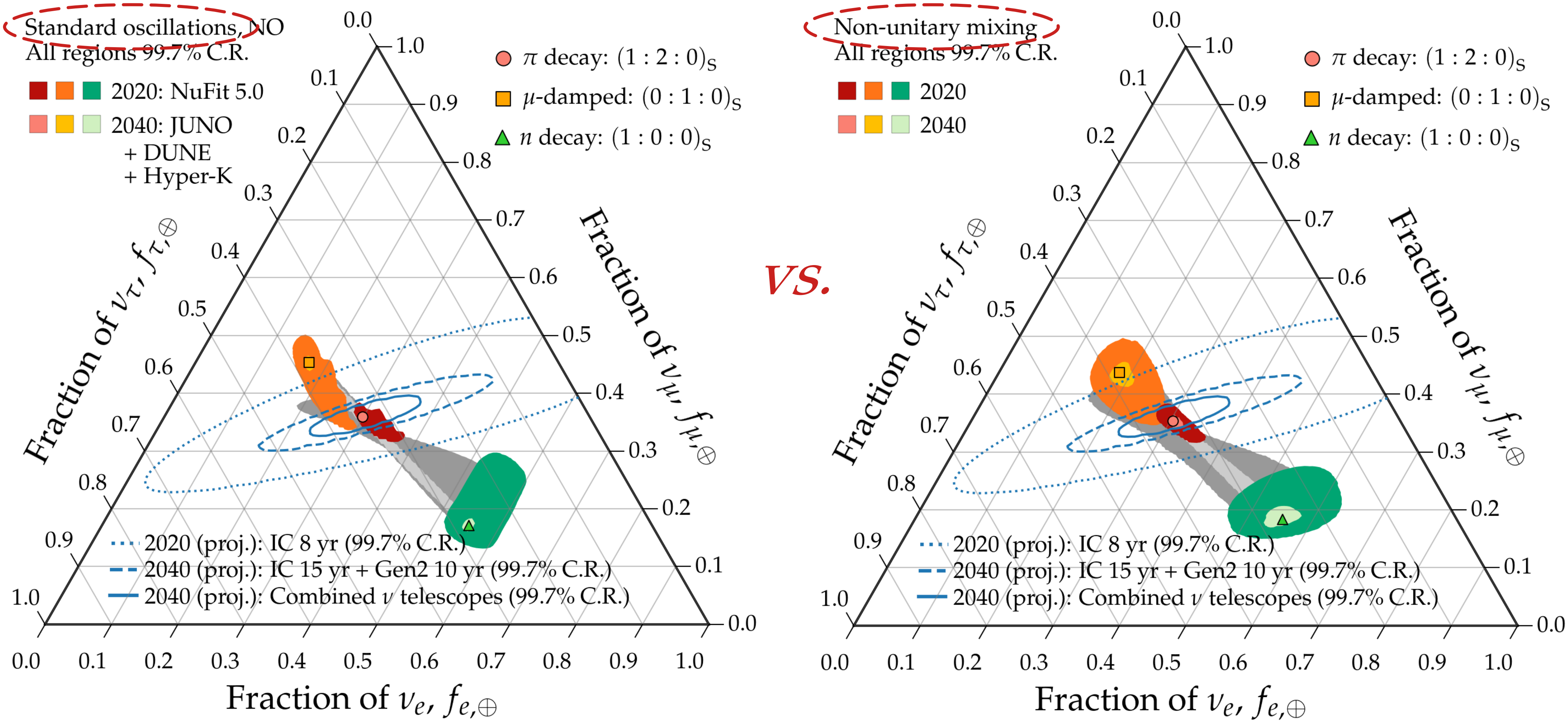


MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019

No unitarity? *No problem*



Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

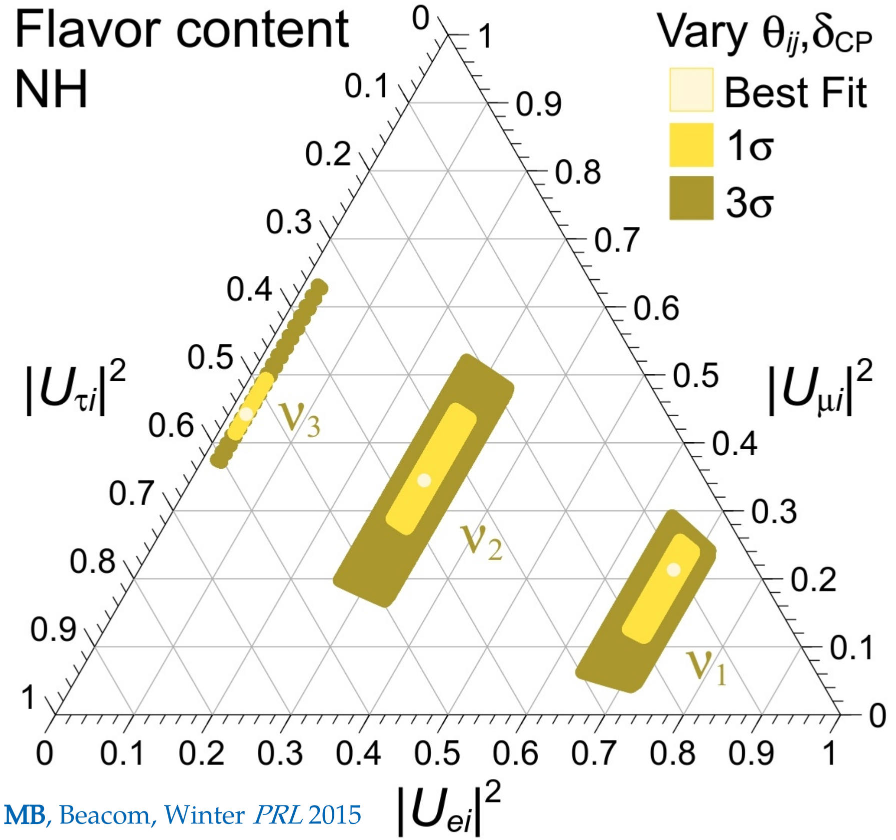
Flavor content of mass eigenstates:

Known to within 2%

$$|U_{\alpha i}|^2 = |U_{\alpha i}(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})|^2$$

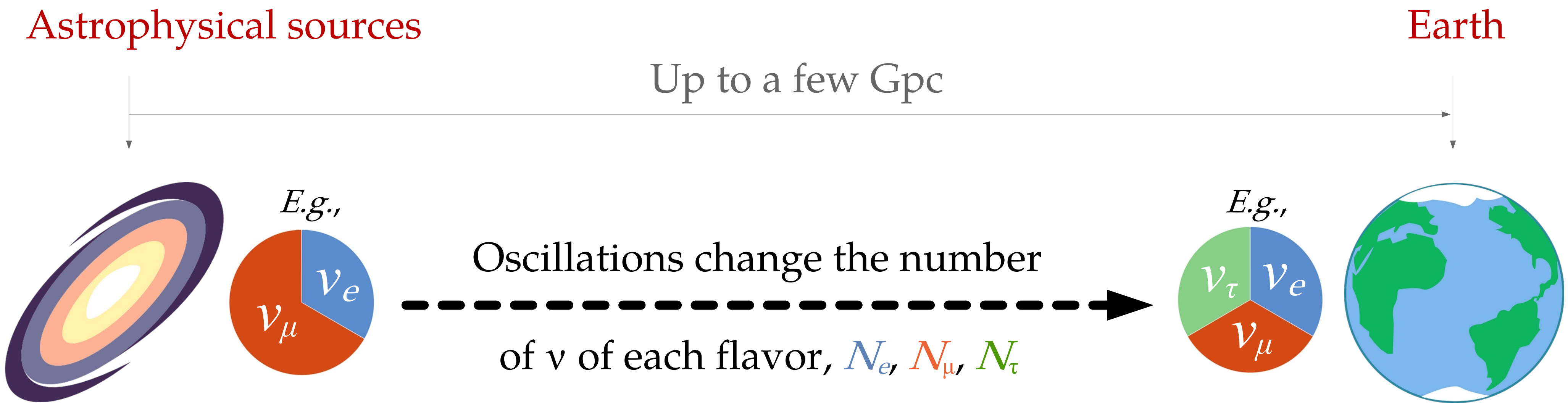
Known to within 8%

Known to within 20% (or worse)



MB, Beacom, Winter *PRL* 2015

Precision in flavor

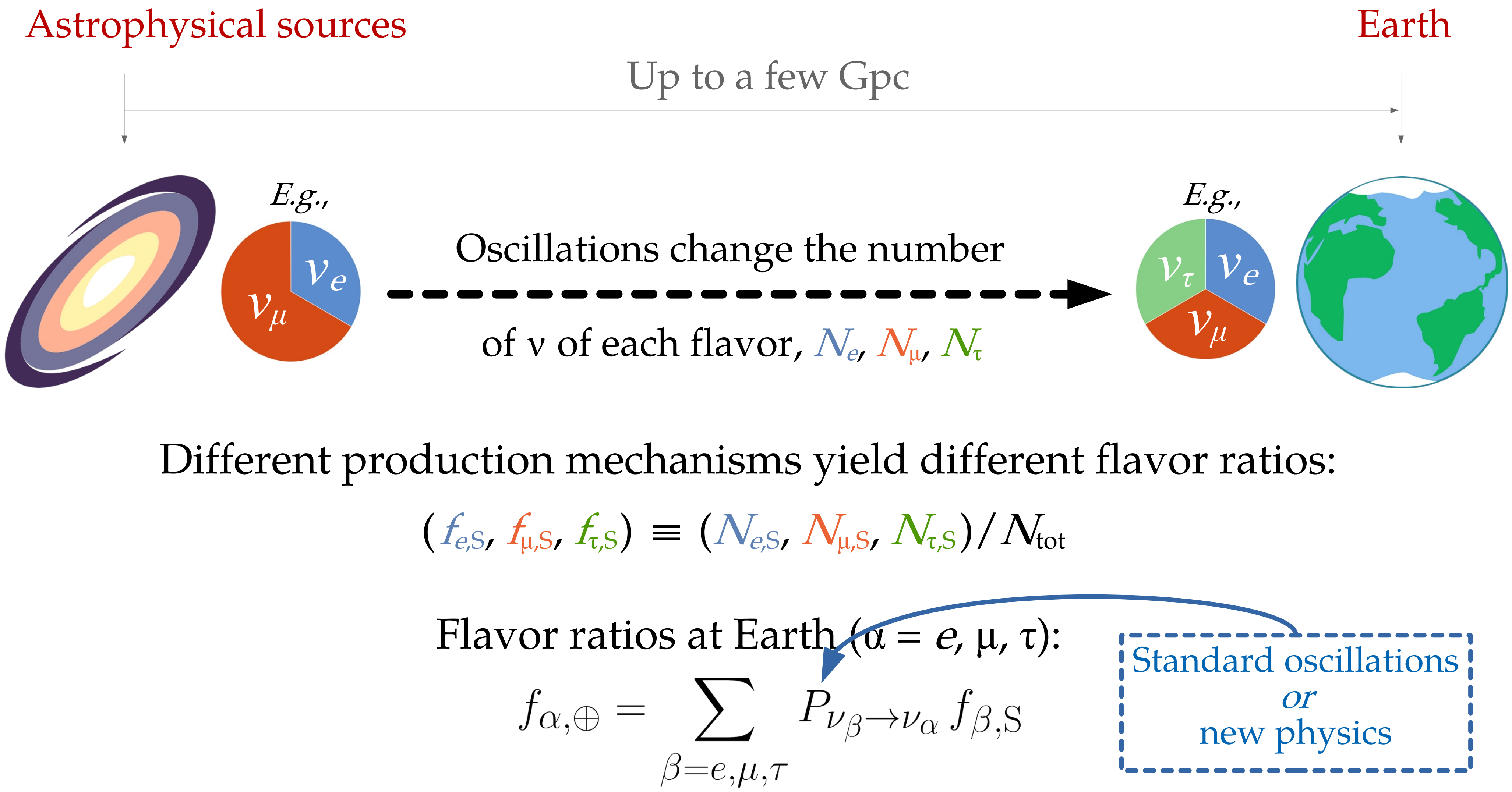


Different production mechanisms yield different flavor ratios:

$$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}}) \equiv (N_{e,\mathrm{S}}, N_{\mu,\mathrm{S}}, N_{\tau,\mathrm{S}})/N_{\mathrm{tot}}$$

Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

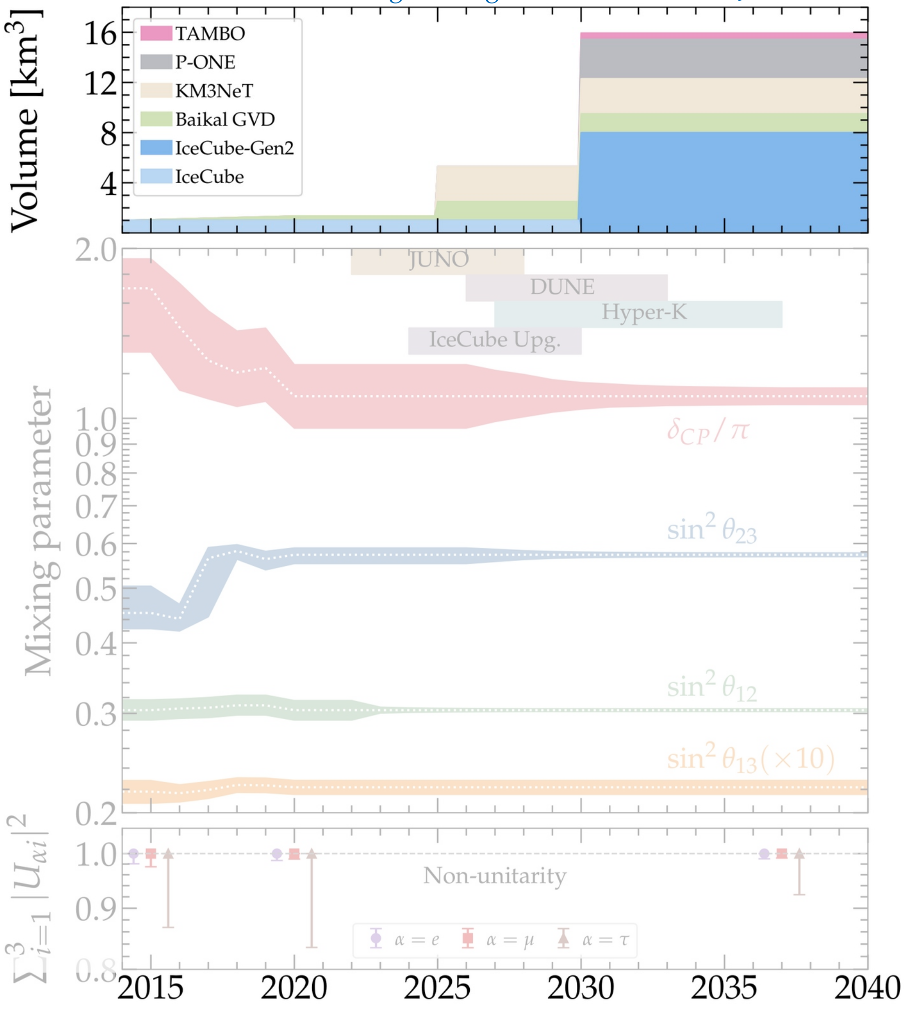
$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,\mathrm{S}}$$



Astrophysical sources
Earth
Up to a few Gpc
E.g.,
ν_e
ν_μ
Oscillations change the number
of ν of each flavor, N_e, N_μ, N_τ
E.g.,
ν_τ
ν_e
ν_μ
Different production mechanisms yield different flavor ratios:
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}}) \equiv (N_{e,\mathrm{S}}, N_{\mu,\mathrm{S}}, N_{\tau,\mathrm{S}})/N_{\mathrm{tot}}$
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):
$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,\mathrm{S}}$
Standard oscillations
or
new physics

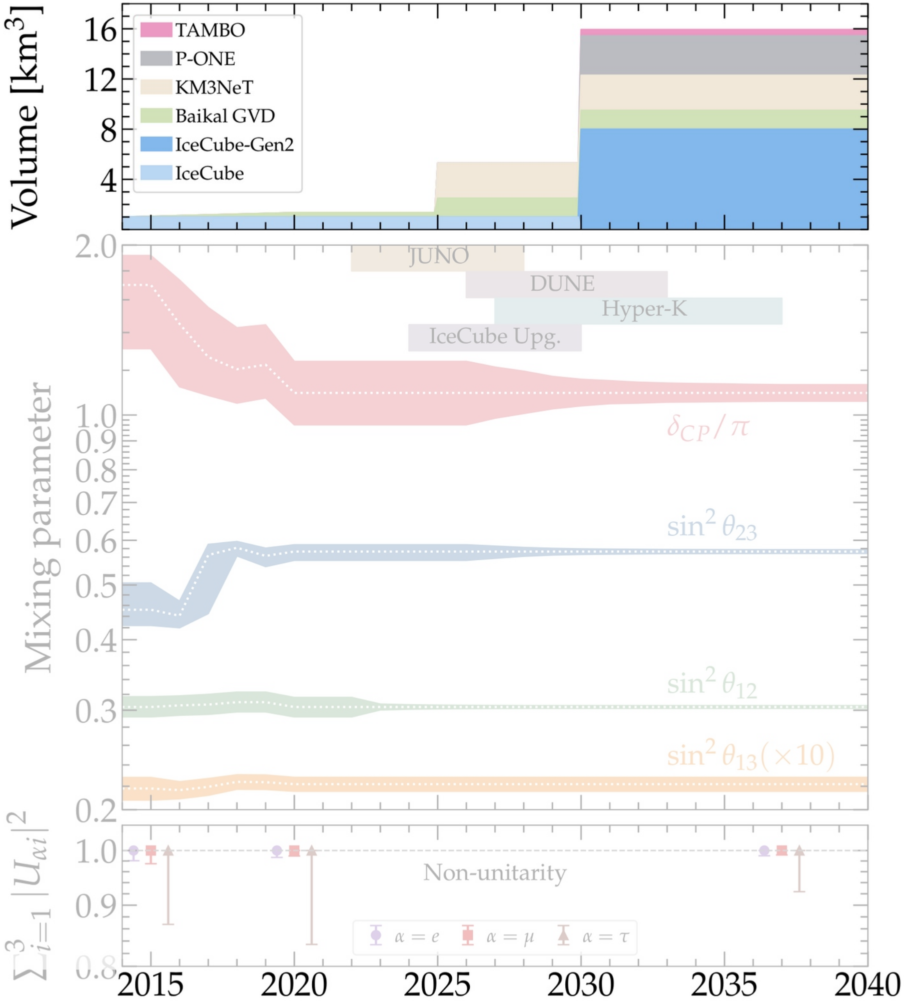
Measuring flavor composition: 2015–2040

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



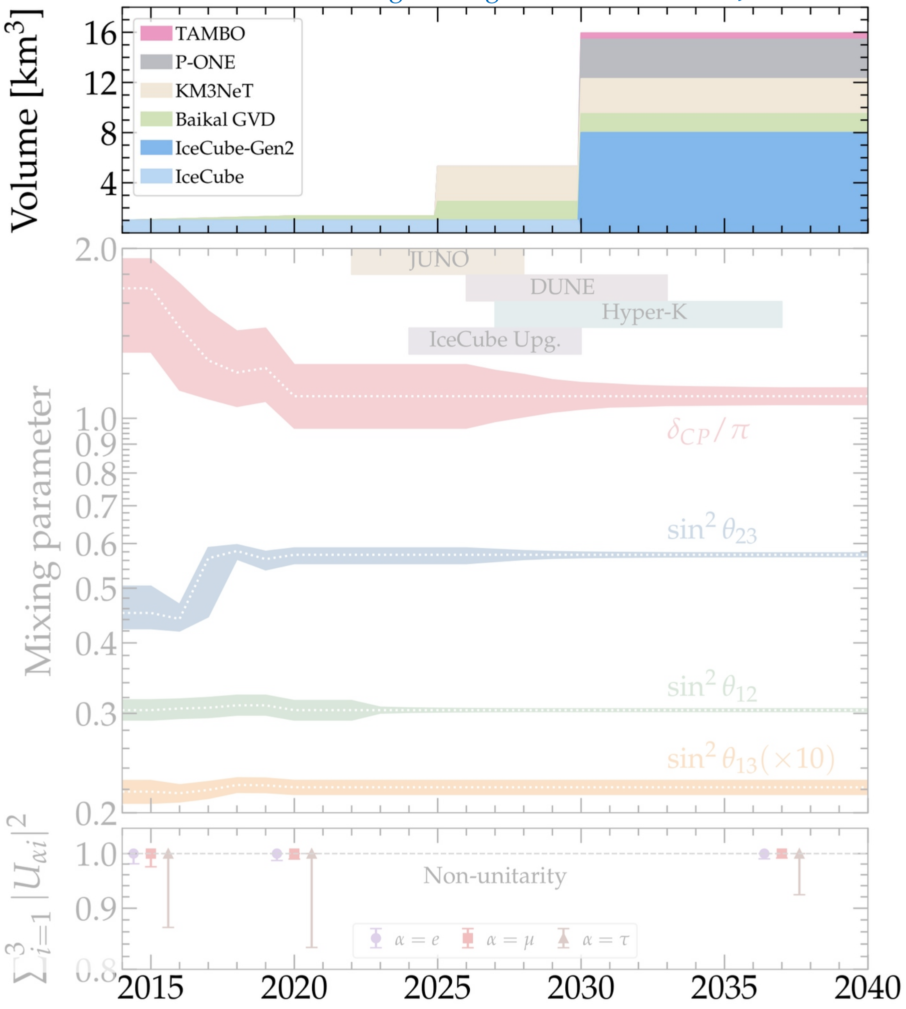
Measuring flavor composition: 2015–2040

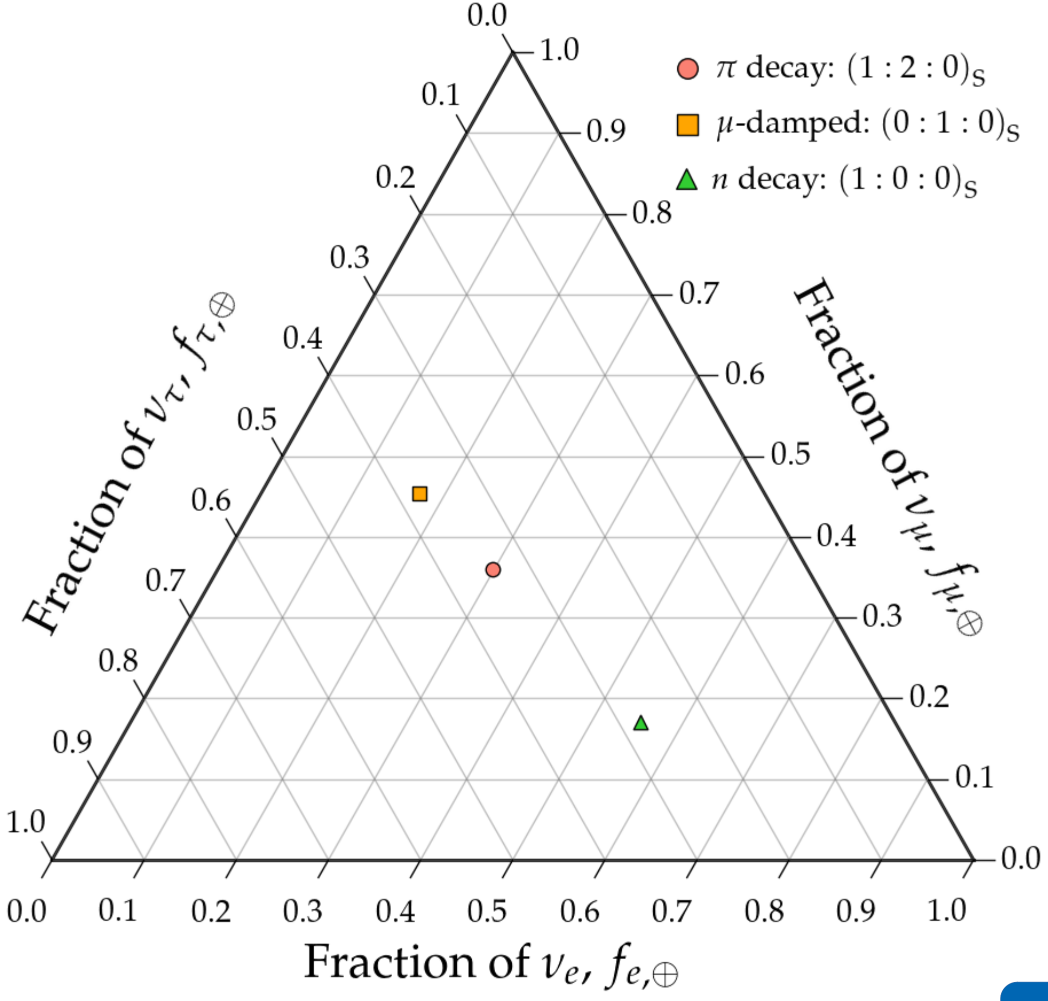
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



Measuring flavor composition: 2015–2040

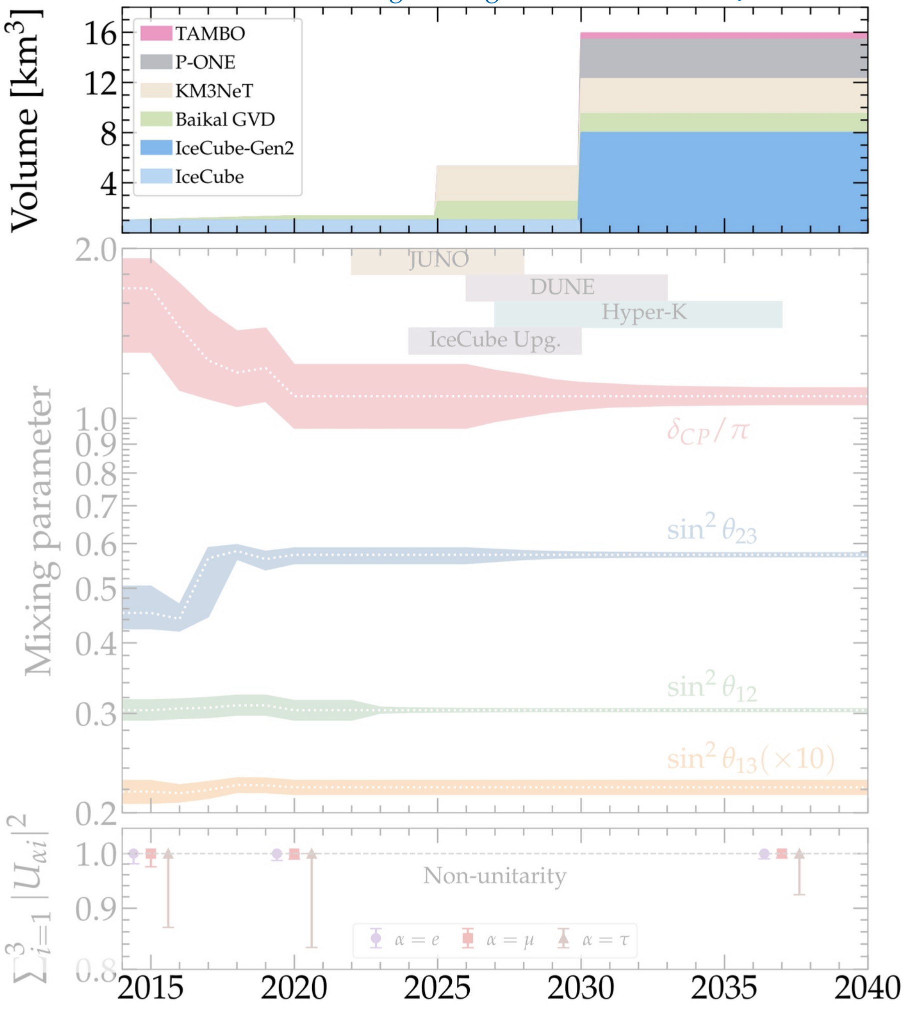
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

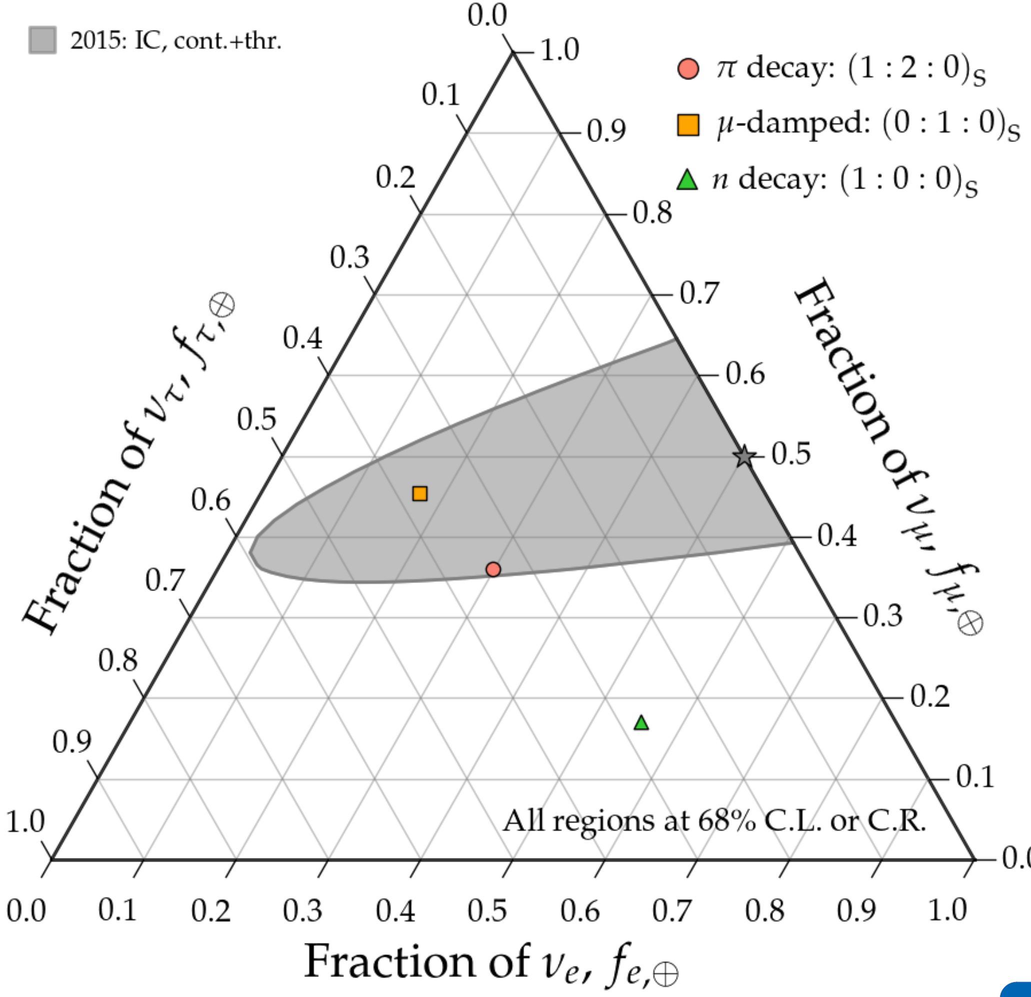




Measuring flavor composition: 2015–2040

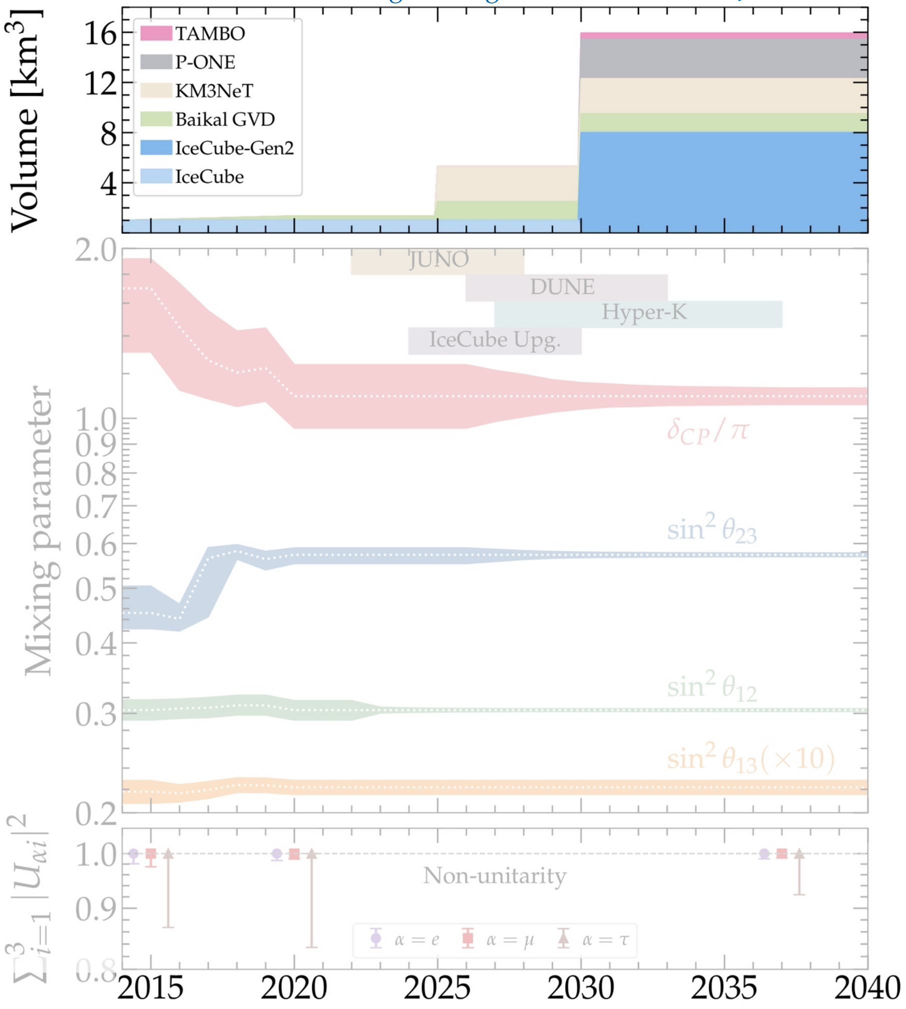
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

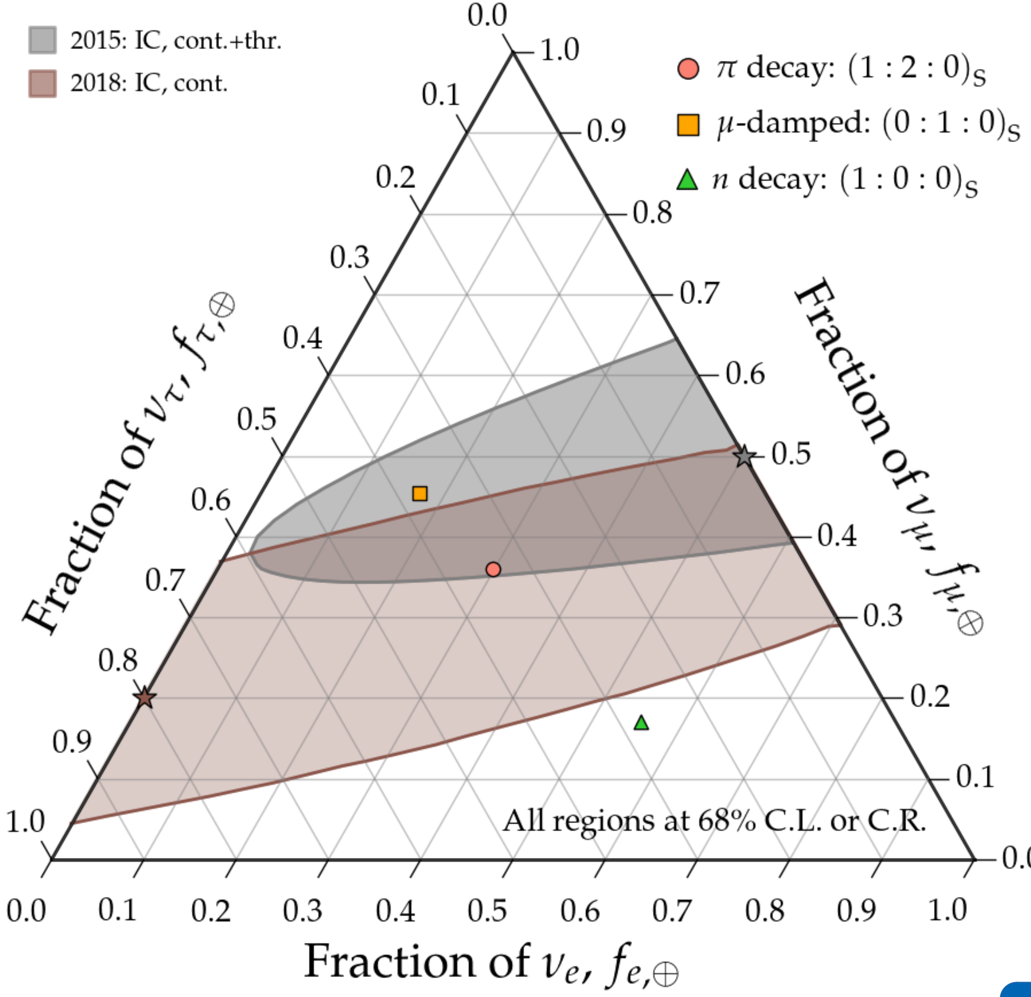




Measuring flavor composition: 2015–2040

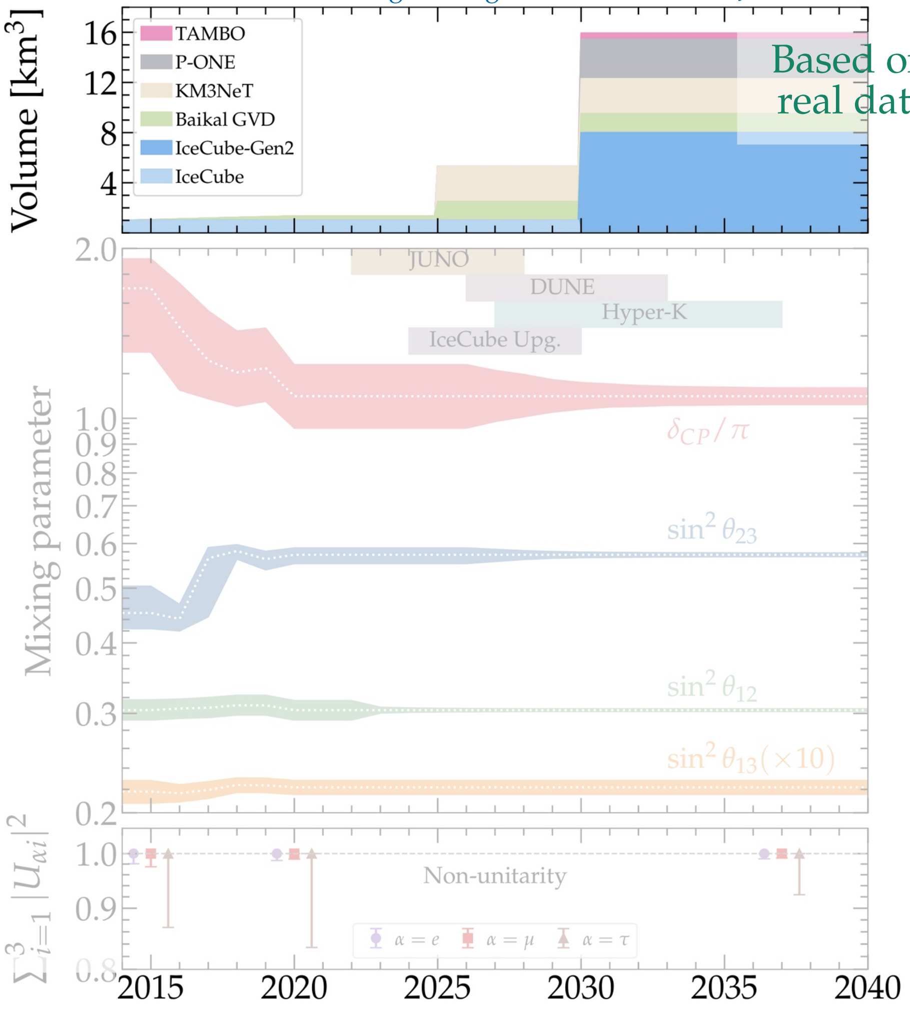
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



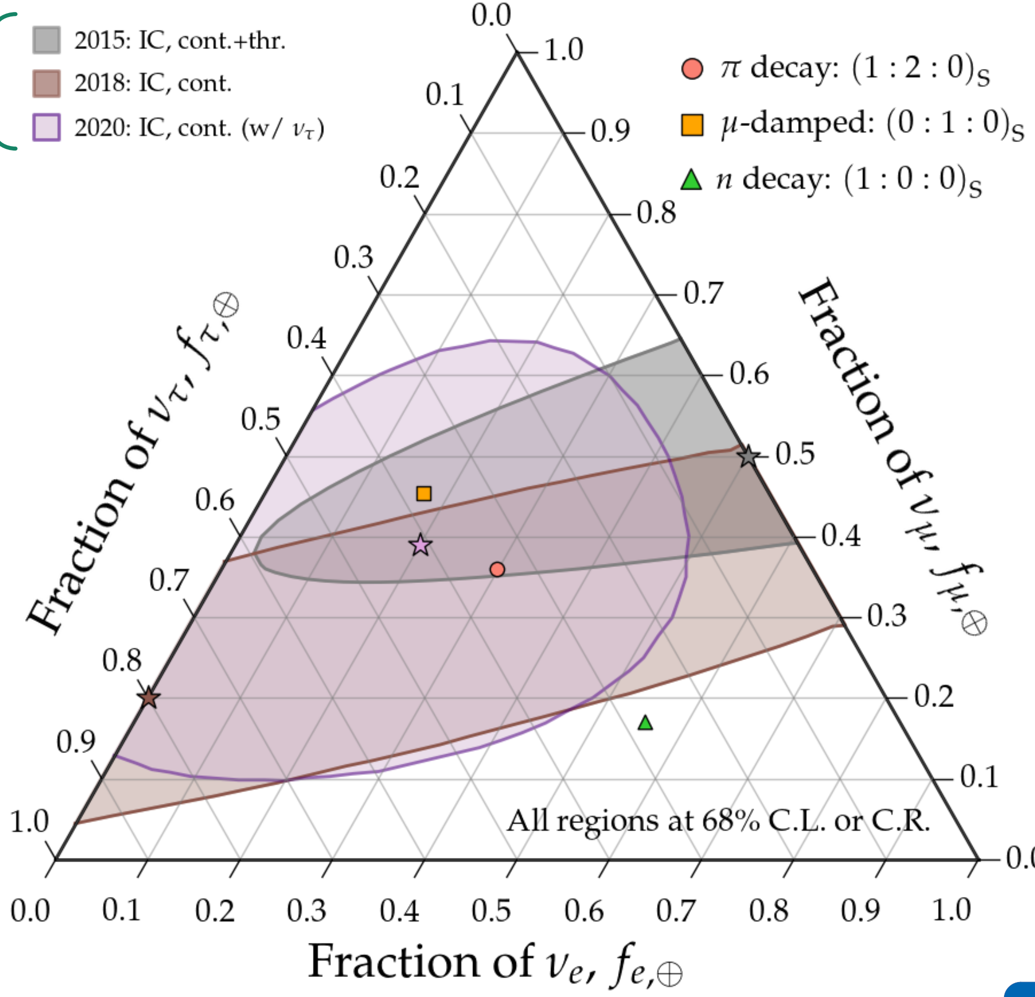


Measuring flavor composition: 2015–2040

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

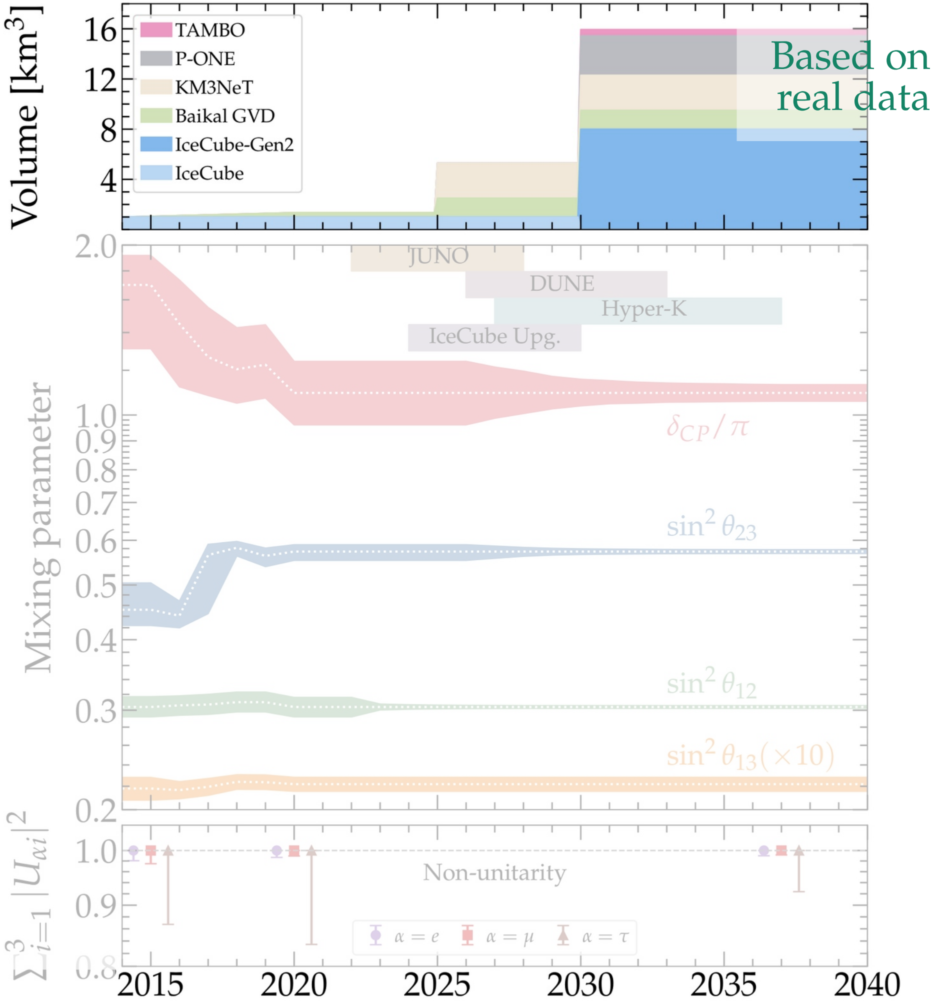


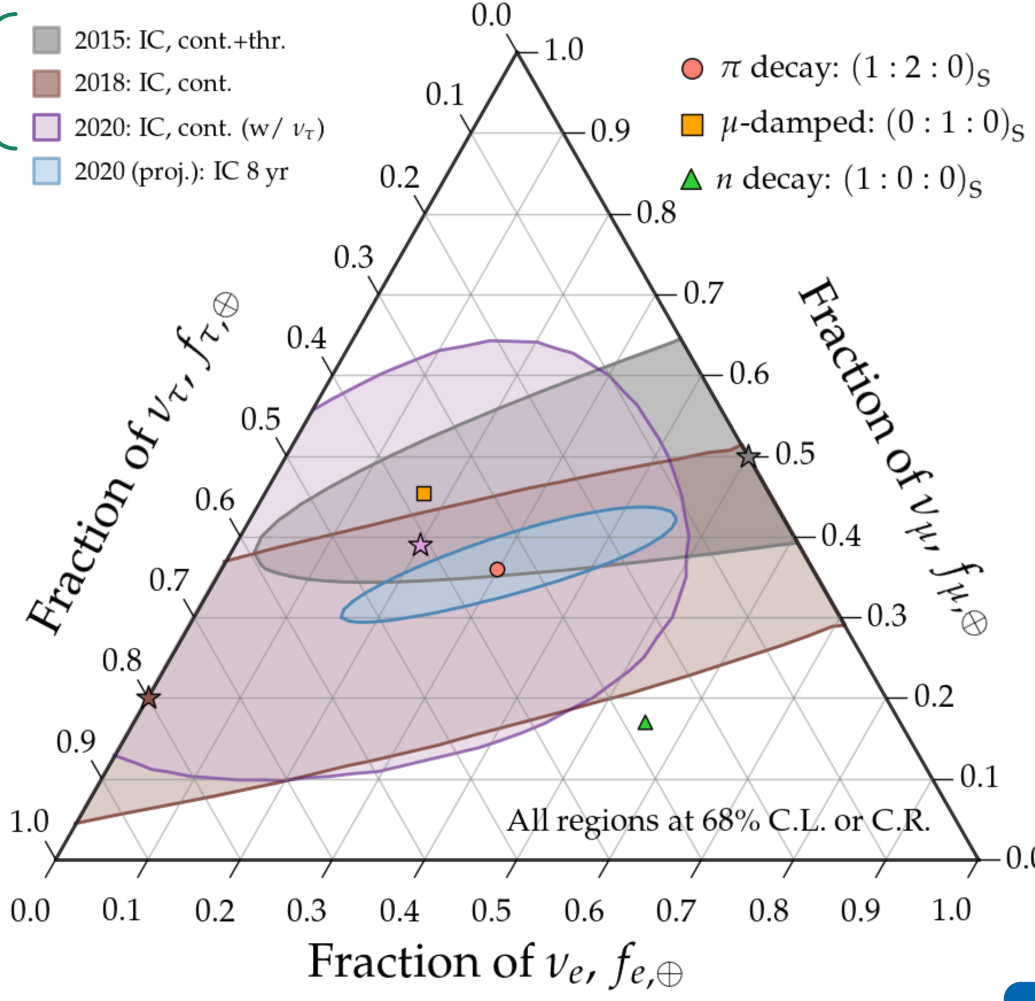
Based on real data



Measuring flavor composition: 2015–2040

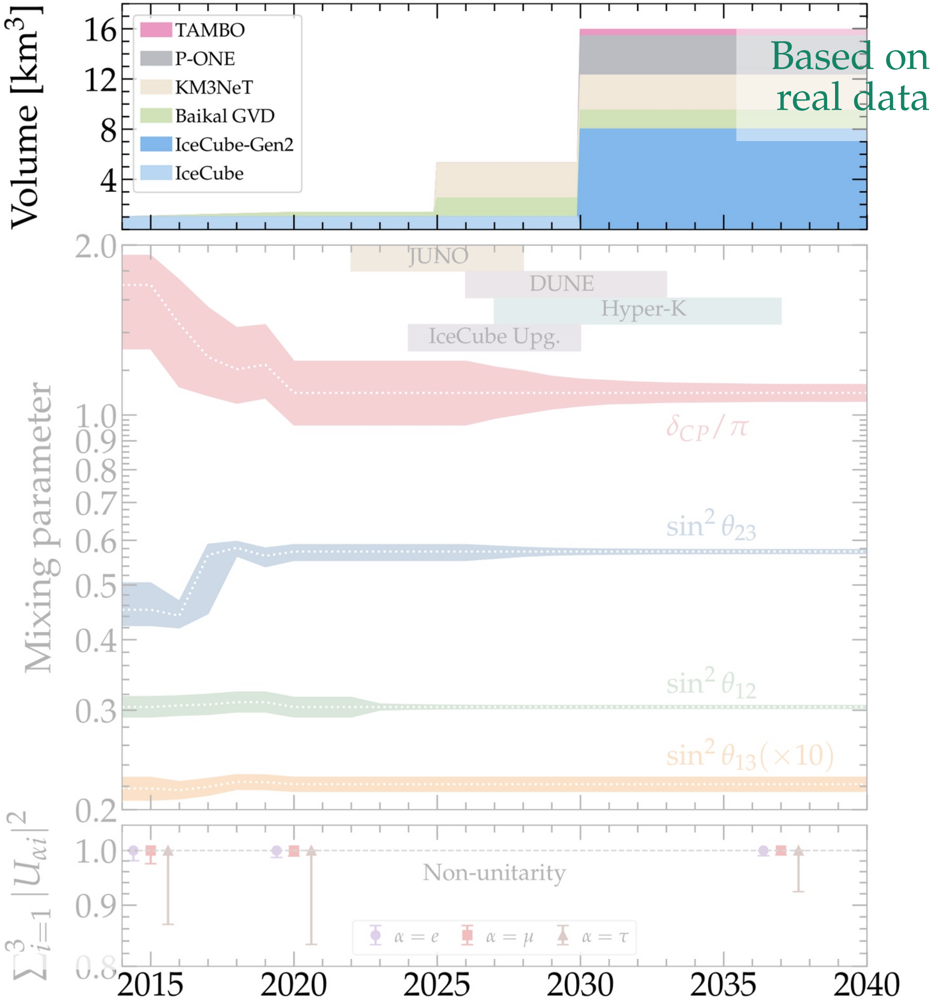
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

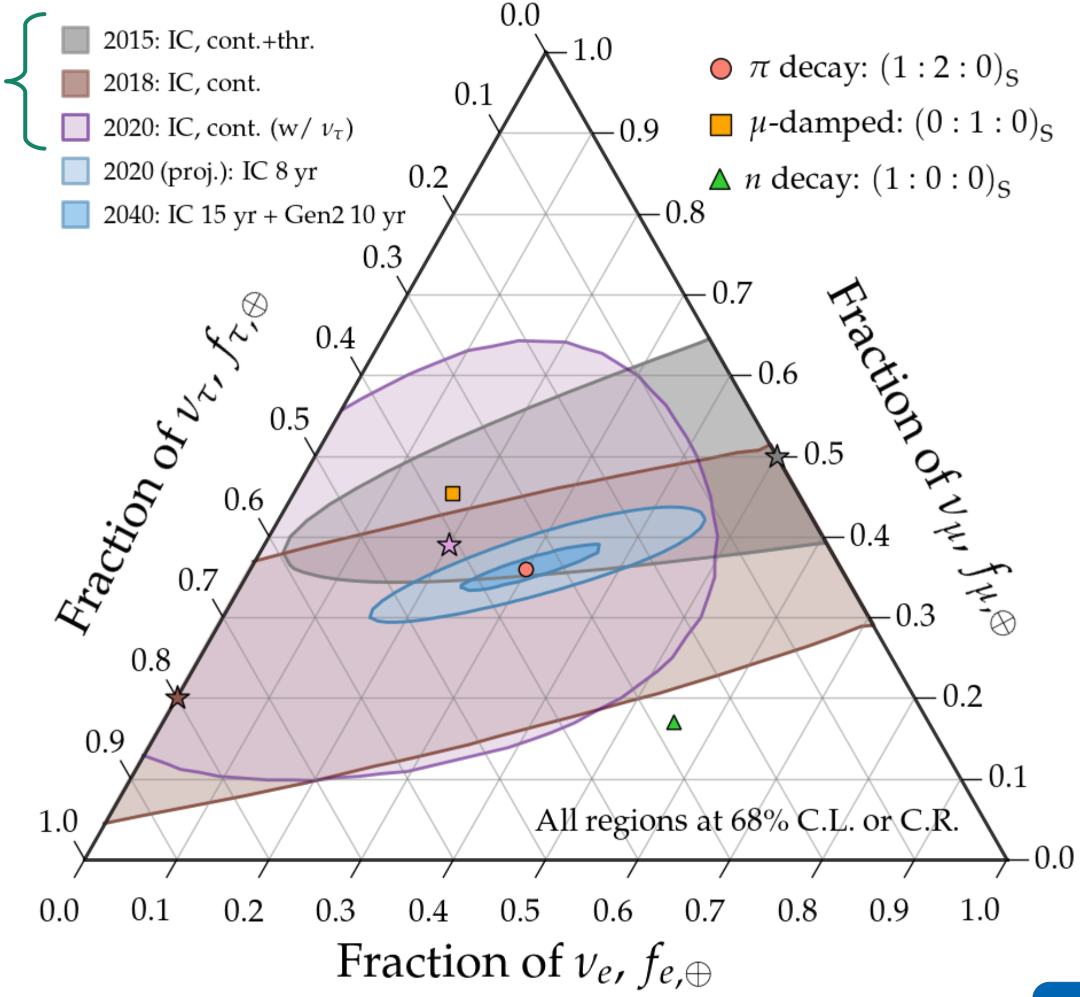




Measuring flavor composition: 2015–2040

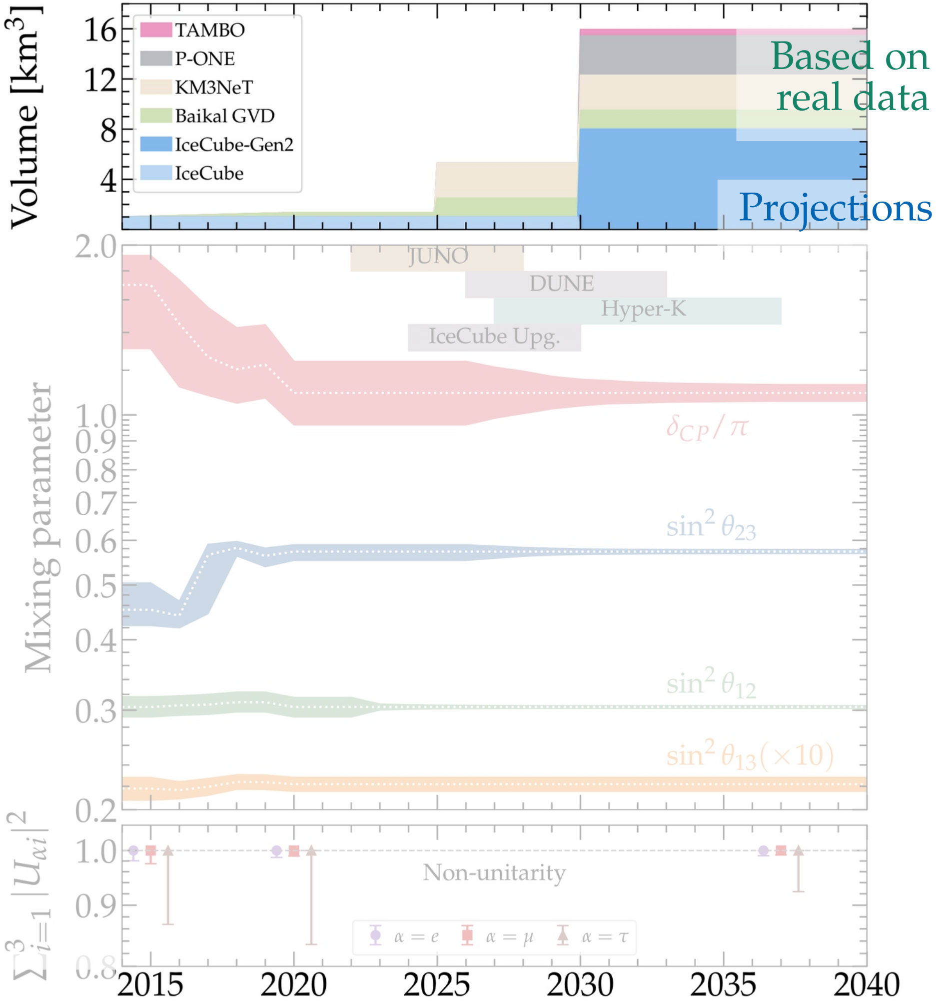
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

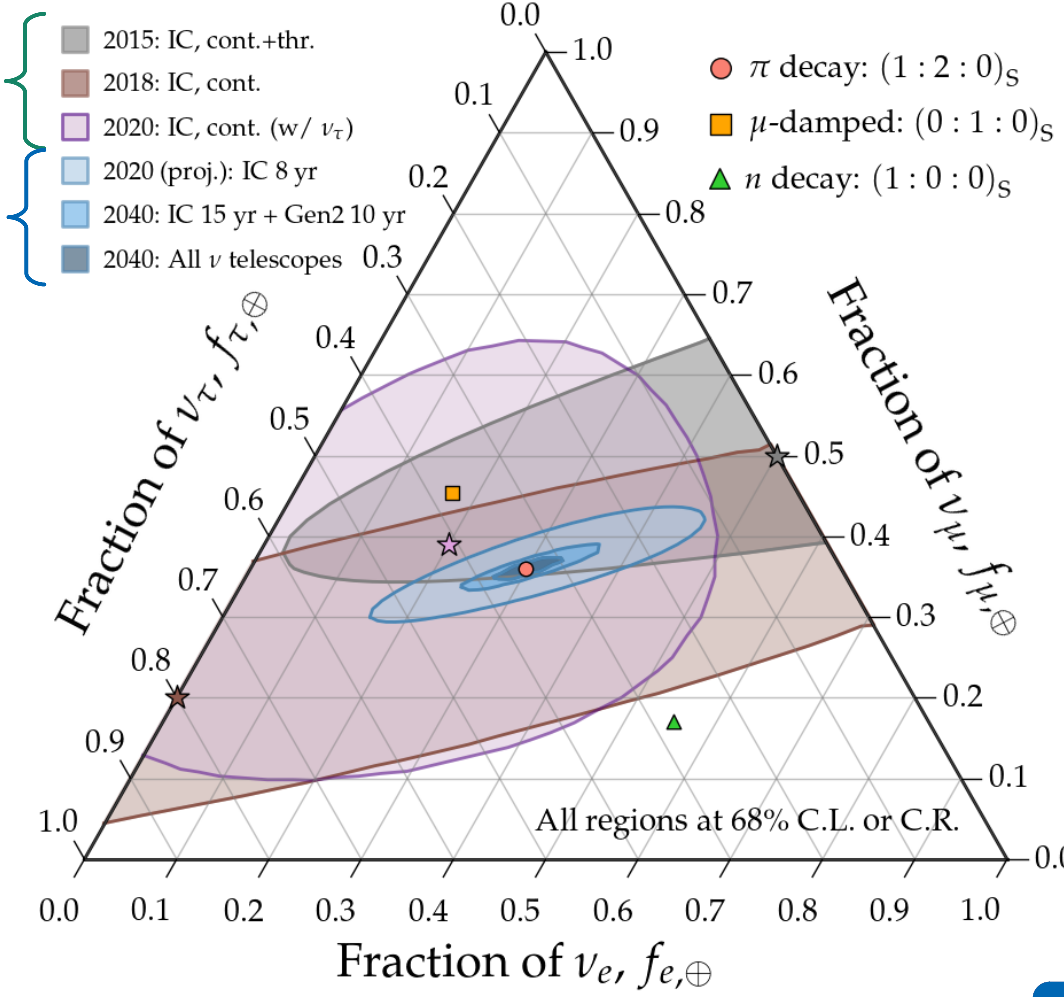




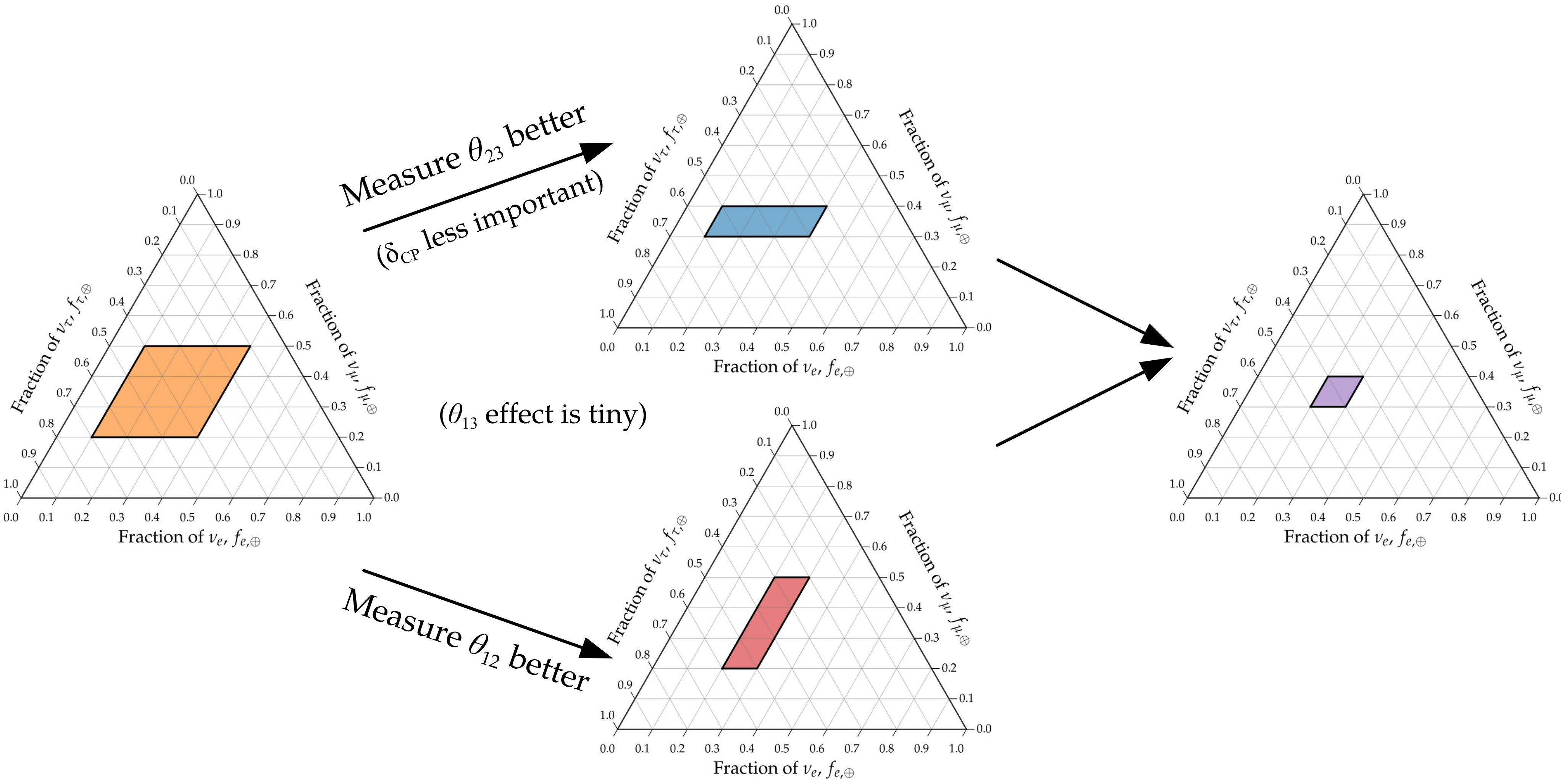
Measuring flavor composition: 2015–2040

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021





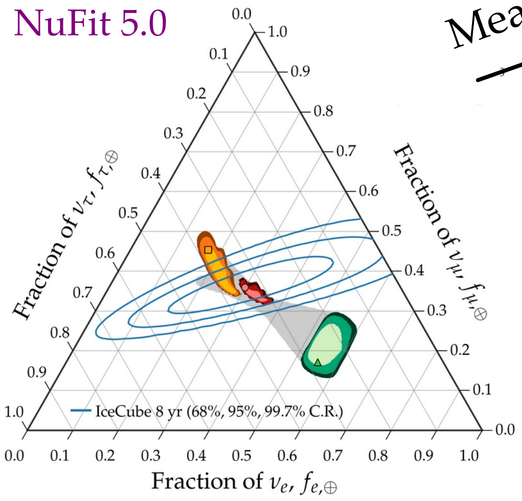
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

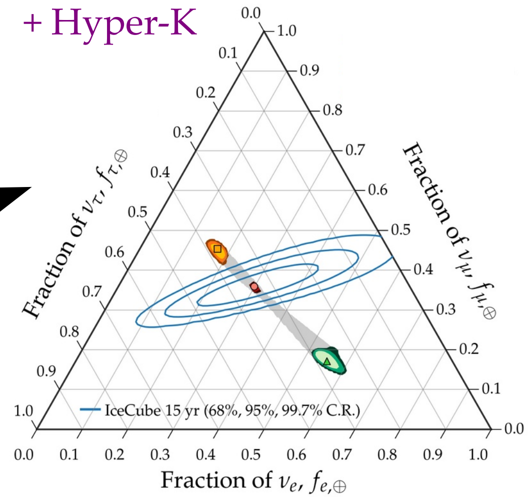
2020

NuFit 5.0



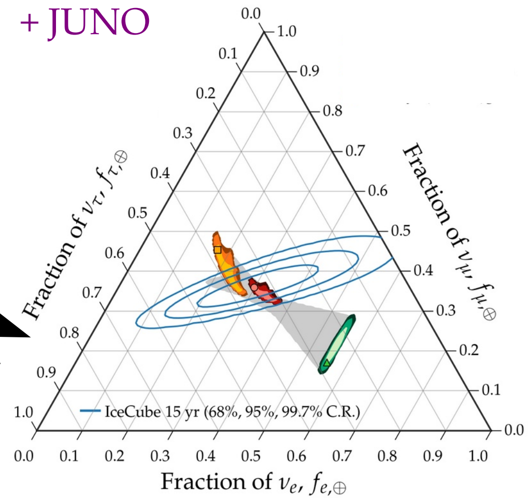
Measure θ_{23} better

+ Hyper-K



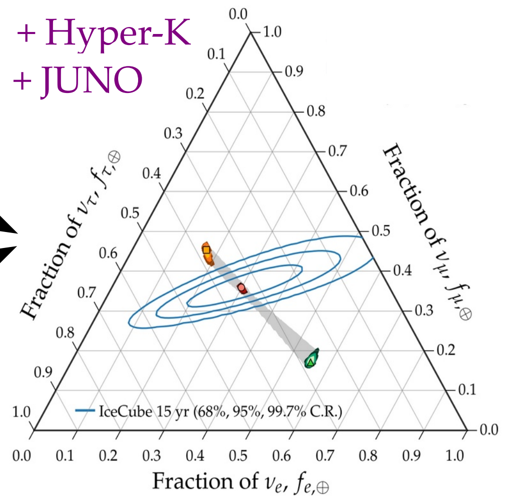
Measure θ_{12} better

+ JUNO



~2030

+ Hyper-K
+ JUNO

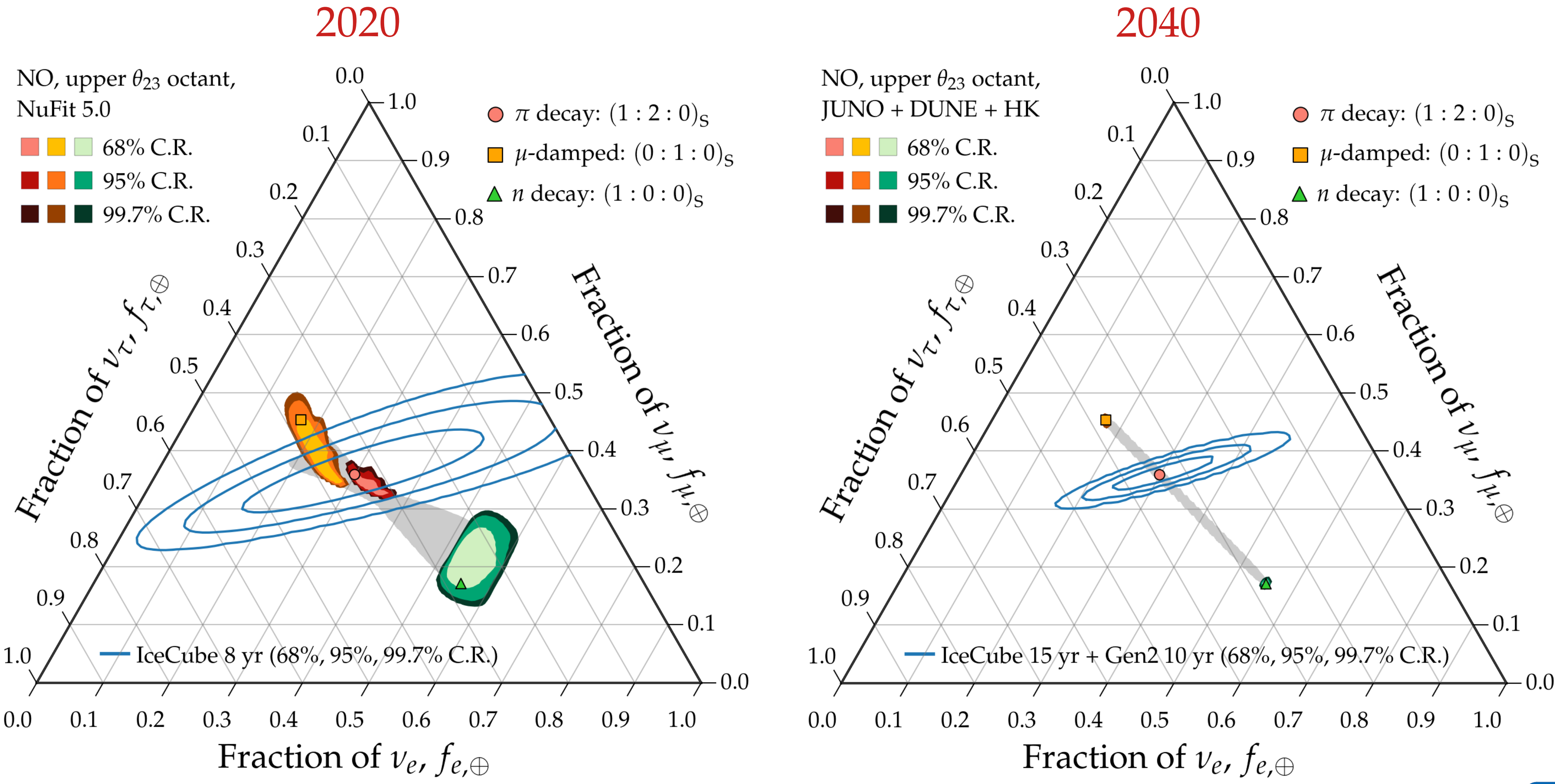


In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: 2020 → 2040

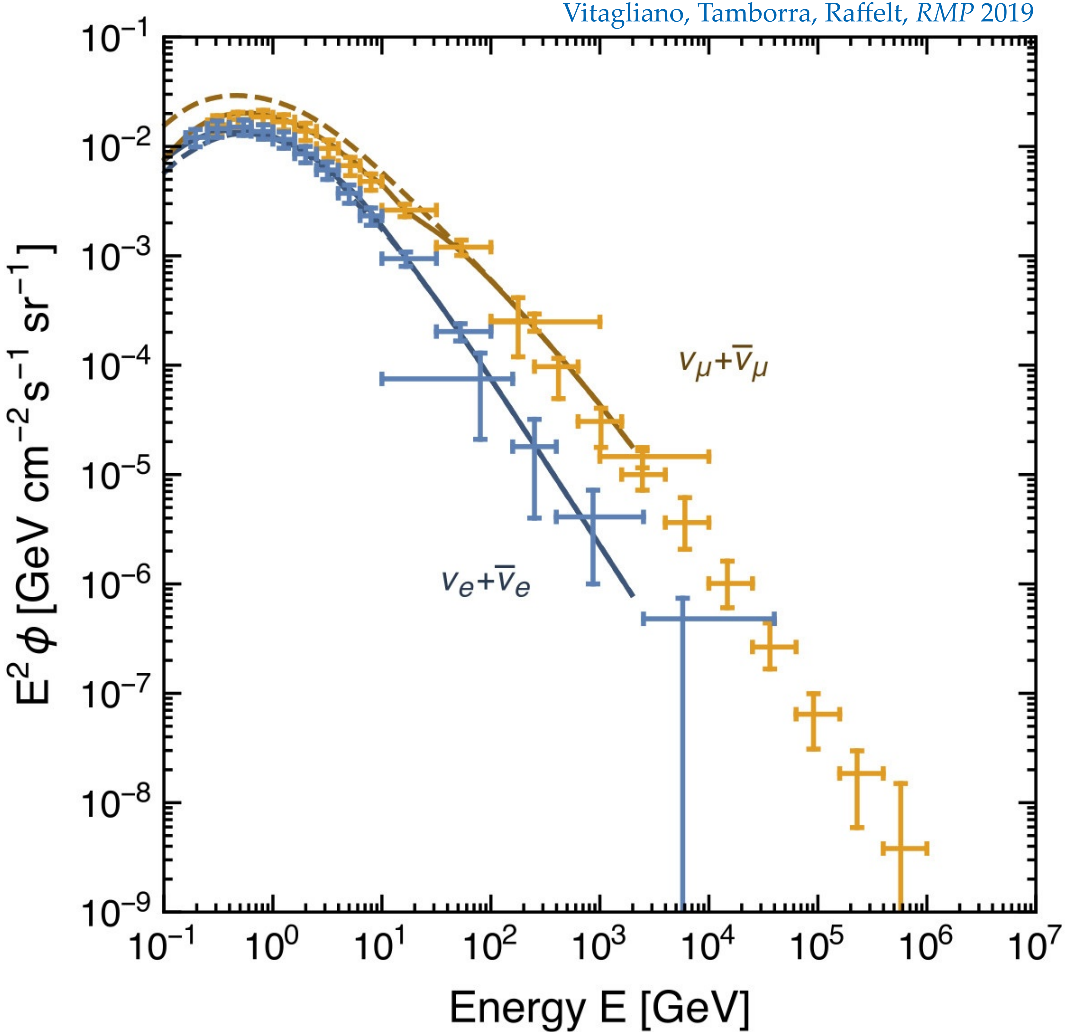


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Neutrinos from the Milky Way

Neutrinos from the Galaxy

Vitagliano, Tamborra, Raffelt, *RMP* 2019



See also: Beacom & Candia, *JCAP* 2004

Neutrinos from the Galaxy

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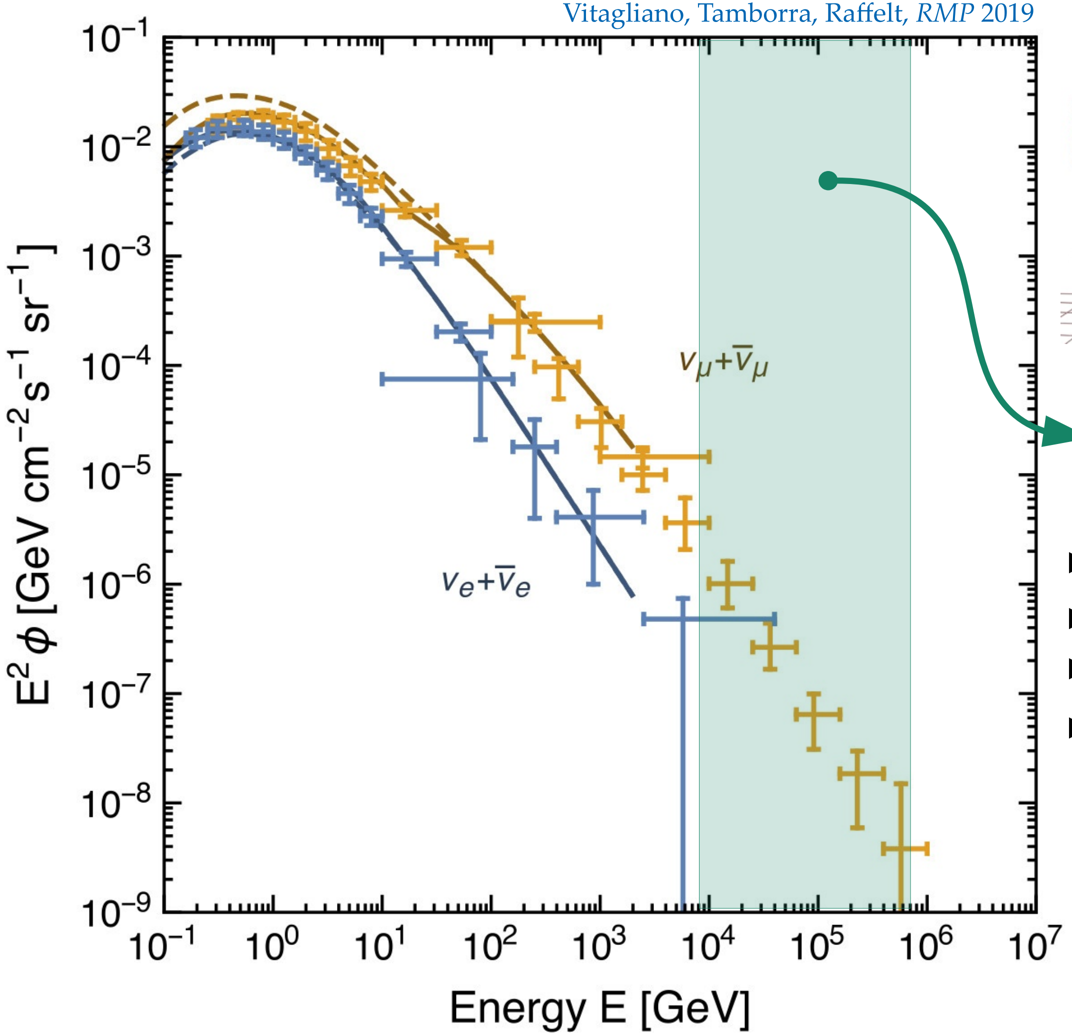
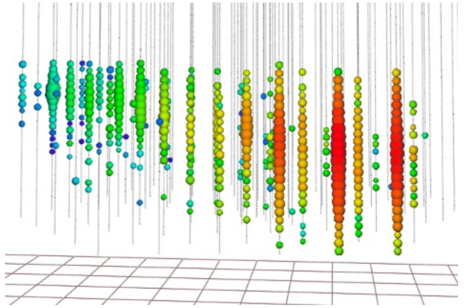


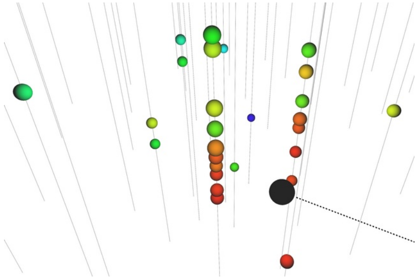


Search for **>10-TeV** astrophysical ν

- Use ***muon tracks***
- Pointing accuracy: ~1°
- Atm. bg. is mostly ν_μ
- Self-veto screens for atm. muons to cut ν bg.

See also: Beacom & Candia, *JCAP* 2004

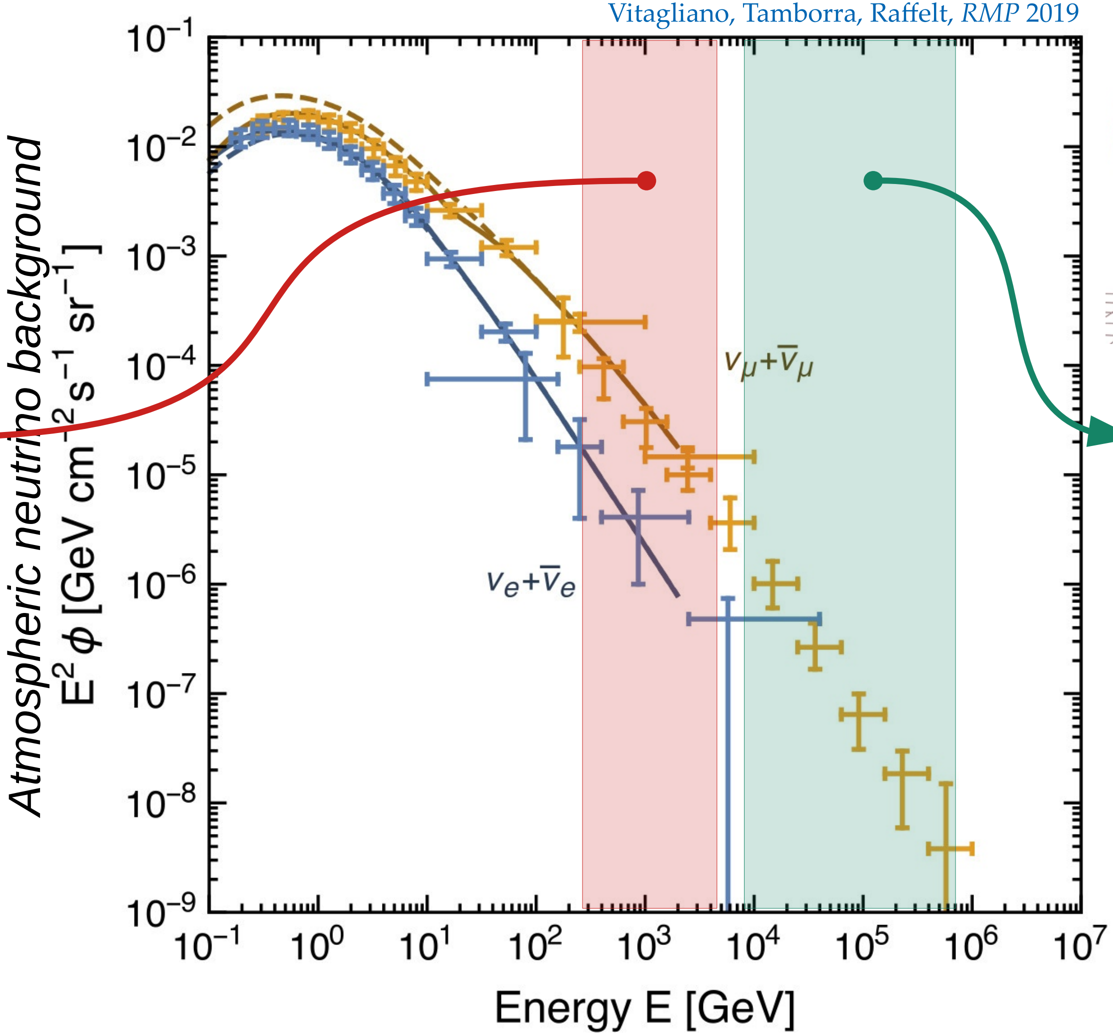
Neutrinos from the Galaxy

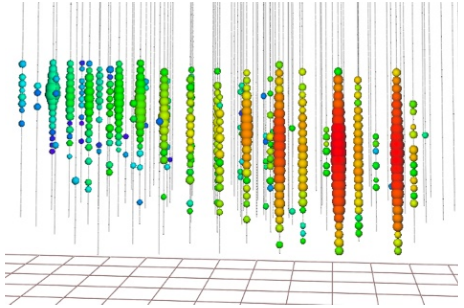


Search for **TeV** astrophysical ν

- But GP ν are TeV
- Use cascades
- Atm. ν_e bg. 10× lower
- Bg.-to-signal: 10^8:1
- *Deep learning retains 20 times more events, 2× better angular res.*

Vitagliano, Tamborra, Raffelt, *RMP* 2019





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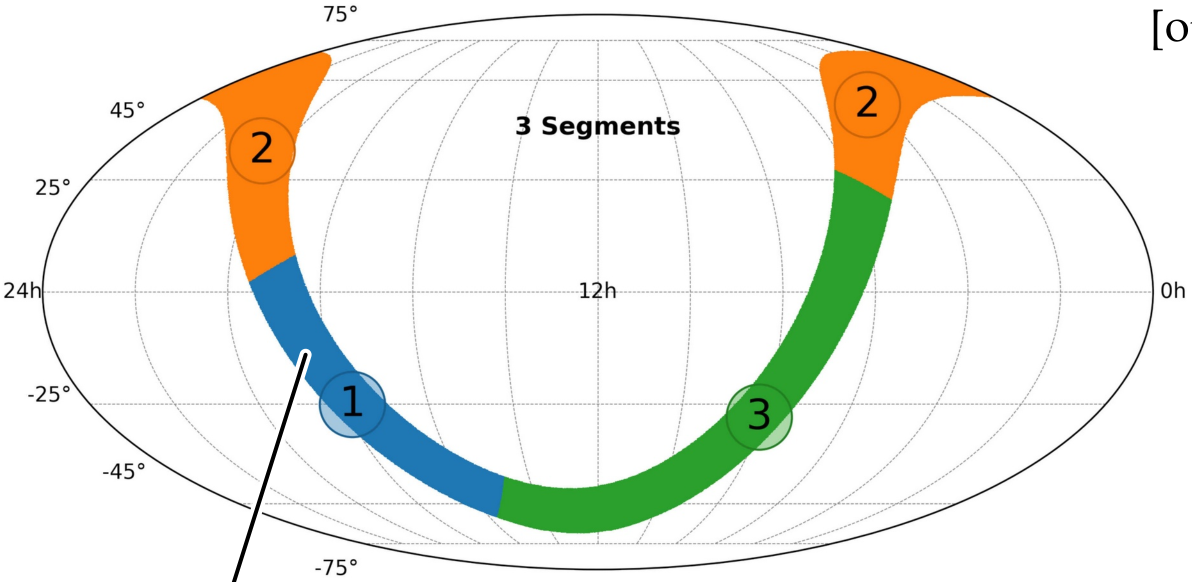
See also: Beacom & Candia, *JCAP* 2004

Neutrinos from the Galaxy: **IceCube**

Improvements **without** template fitting



±8° width in Galactic latitude
-40° < Galactic longitude < 40°

Divide the Galactic Plane into 3 generic segments
[other segmentation schemes, too (*e.g.*, 2, 6)]

Same cascade sample as 2023 discovery

Same unbinned maximum likelihood
… but now segmented

In each segment: single power law

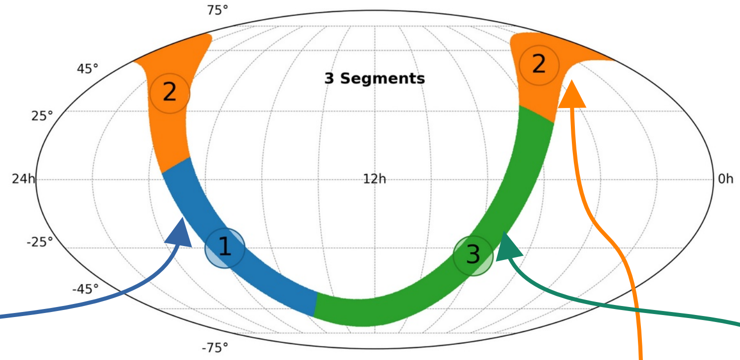
Fit flux normalization and spectral index

Note: No systematics yet

Neutrinos from the Galaxy: **IceCube**

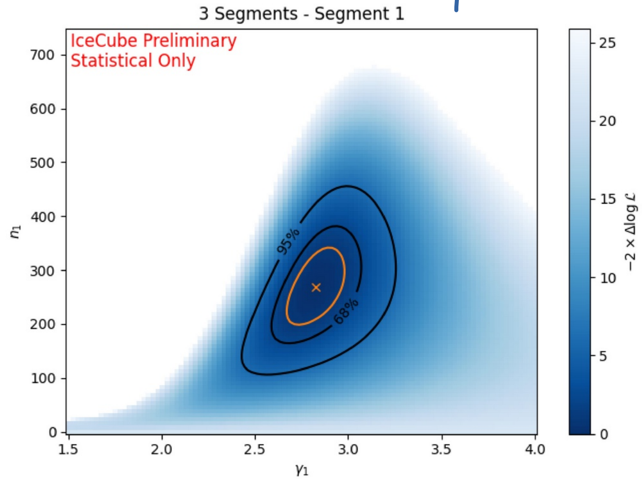
L. Neste, M. Hünnefeld, C. Finley
PoS(ICRC2025)1130 • Talk July 21

Improvements **without** template fitting

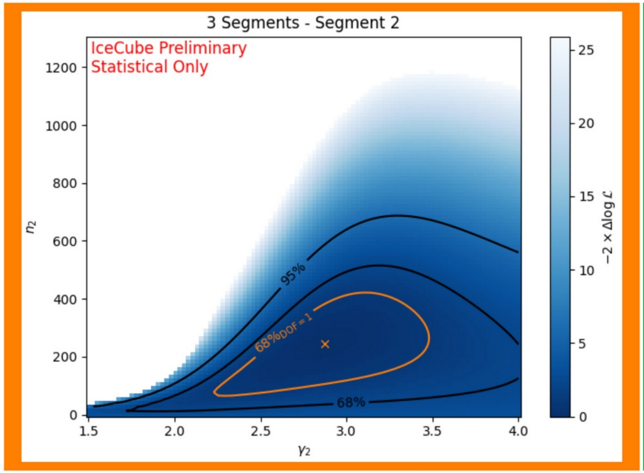


Inner galaxy

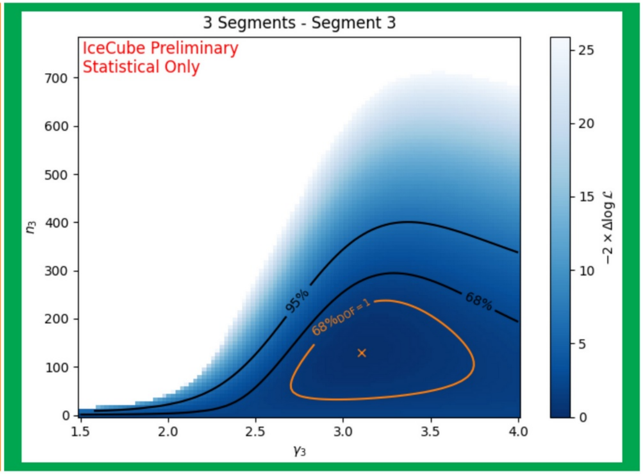
Outer galaxy



$-40^\circ < l < 40^\circ$



$40^\circ < l < 180^\circ$



$-180^\circ < l < -40^\circ$

Neutrinos from the Galaxy: **IceCube**

L. Neste, M. Hünnefeld, C. Finley
PoS(ICRC2025)1130 • Talk July 21

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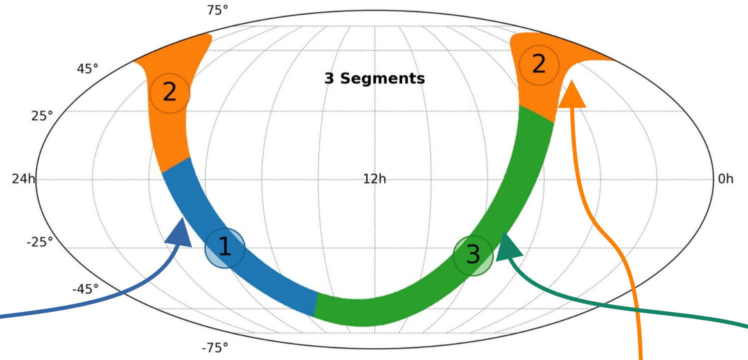

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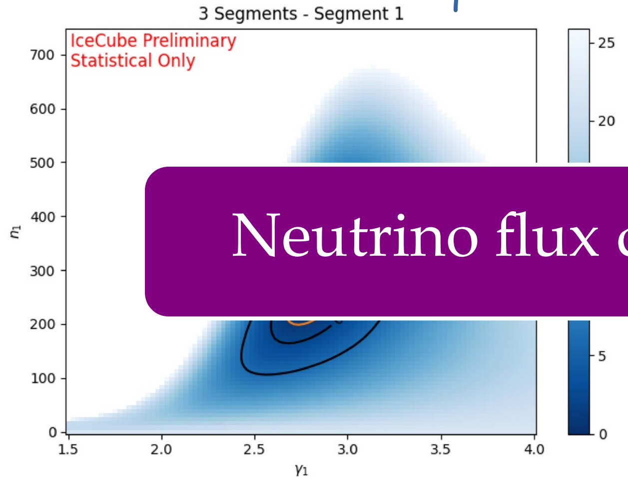

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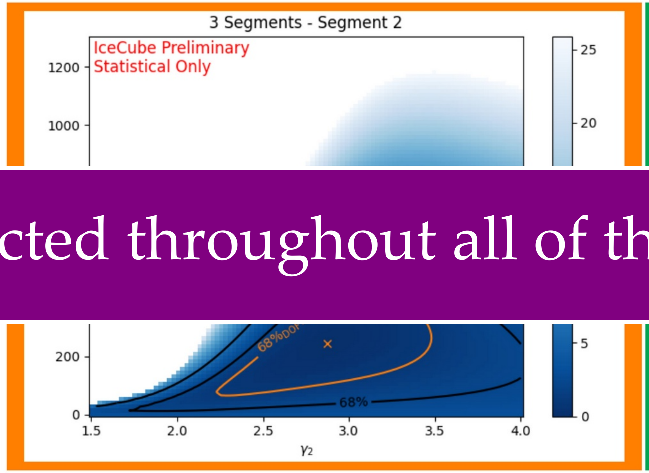

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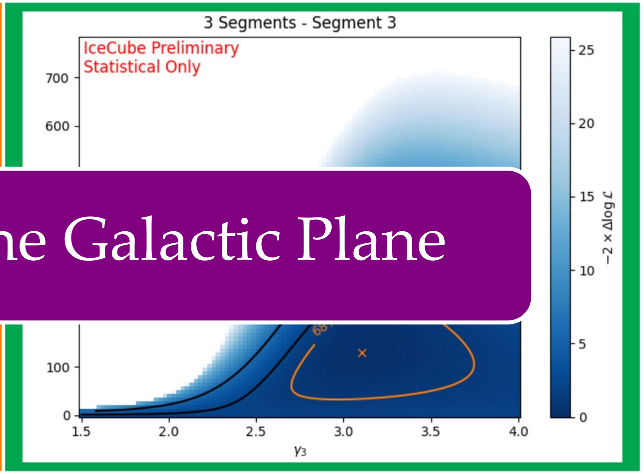
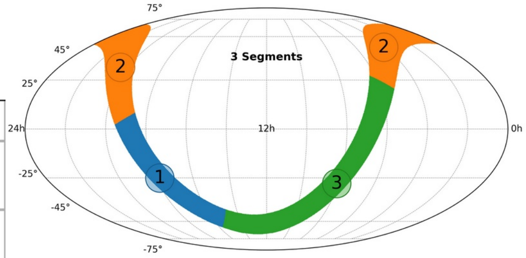


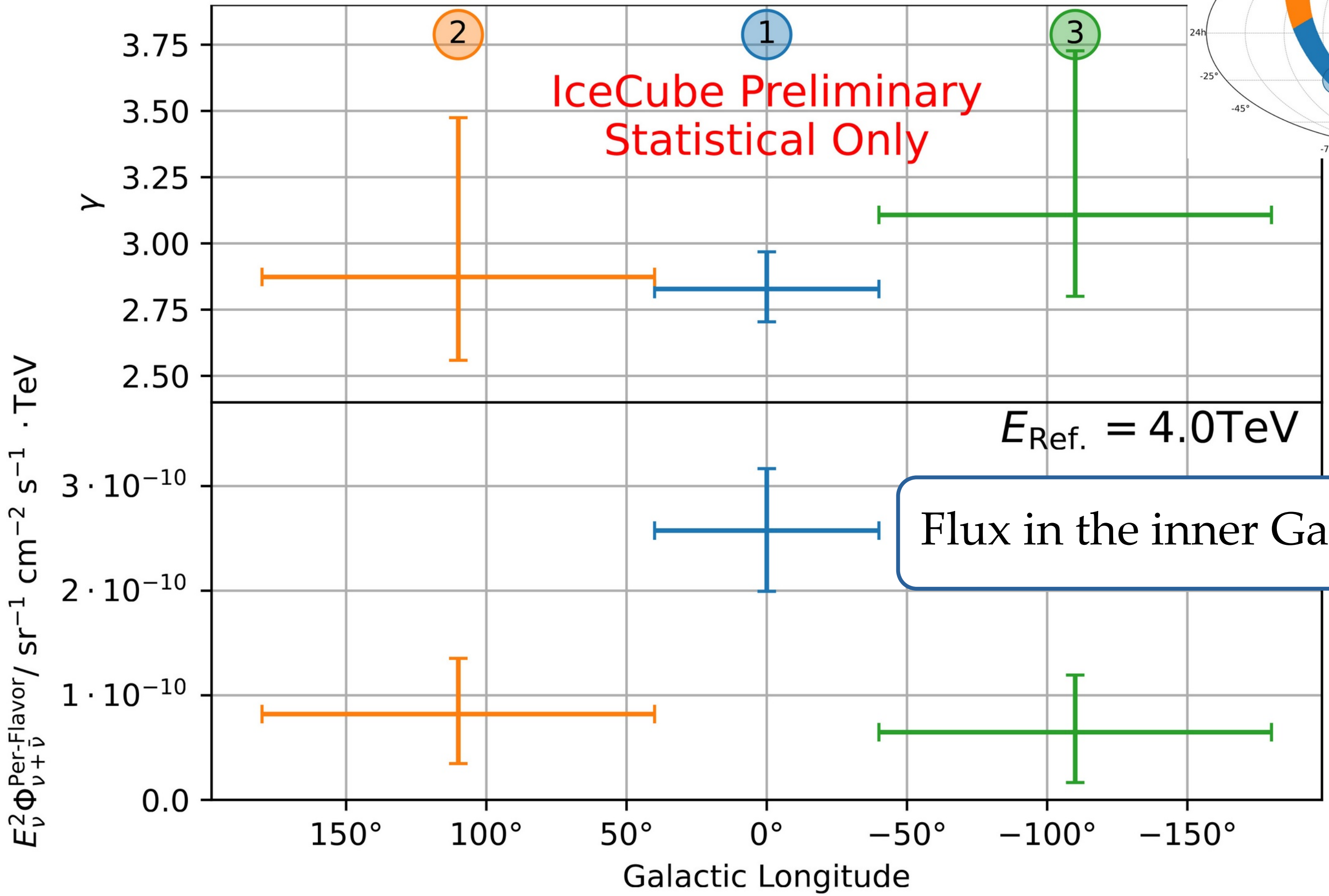
$-180^\circ < l < -40^\circ$

Neutrino flux detected throughout all of the Galactic Plane

Neutrinos from the Galaxy: **IceCube**

Improvements **without** template fitting



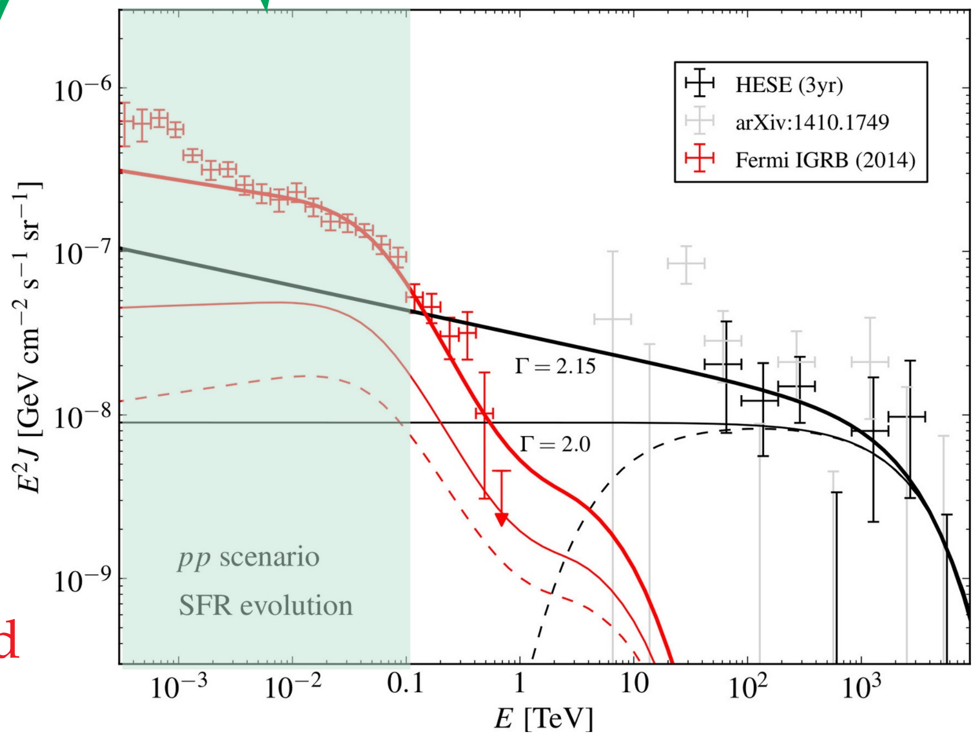


Flux in the inner Galaxy is 2× higher

Constraints from the gamma-ray background

- Production via *pp*: ν and gamma-ray spectra follow the CR spectrum E^{Γ}
- Gamma-ray interactions on the CMB make them pile up at GeV
- *Fermi* gamma-ray background is not exceeded only if $\Gamma < 2.2$
- But IceCube found $\Gamma = 2.5$–2.7
- Therefore, production via *pp* is disfavored between 10–100 TeV

Murase, Ahlers, Lacki, *PRD* 2013

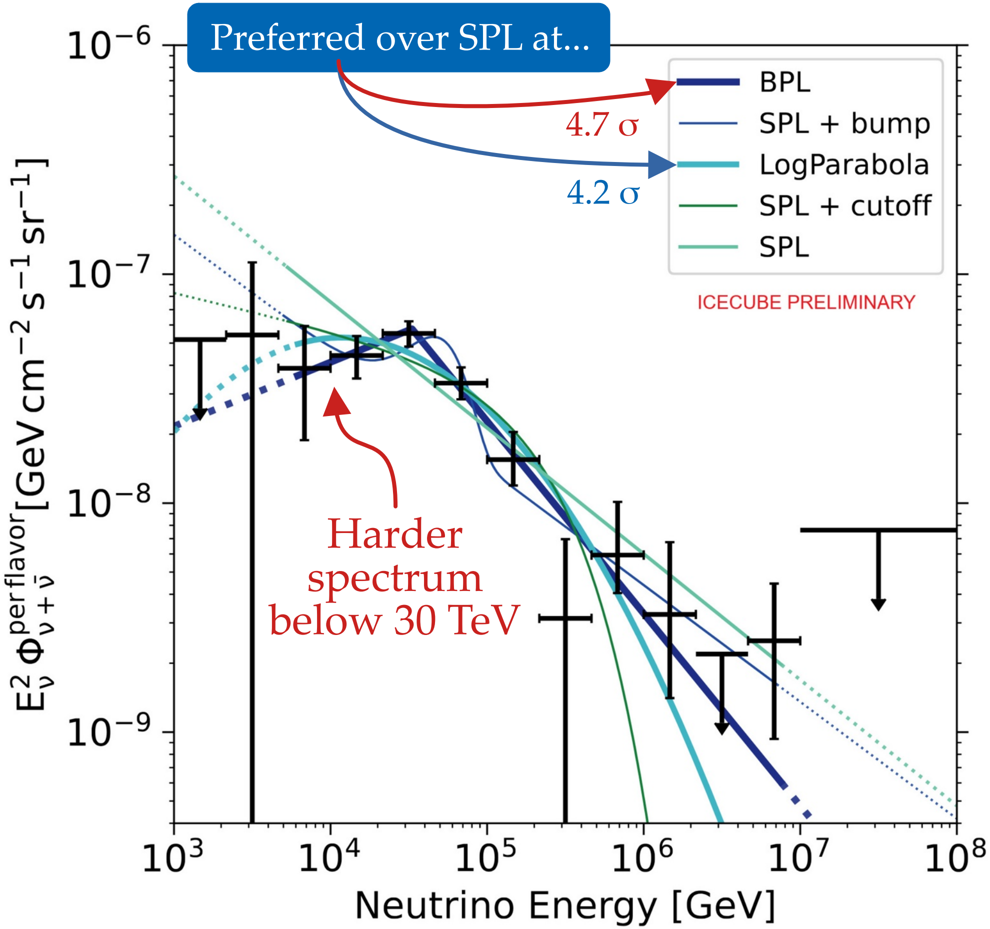


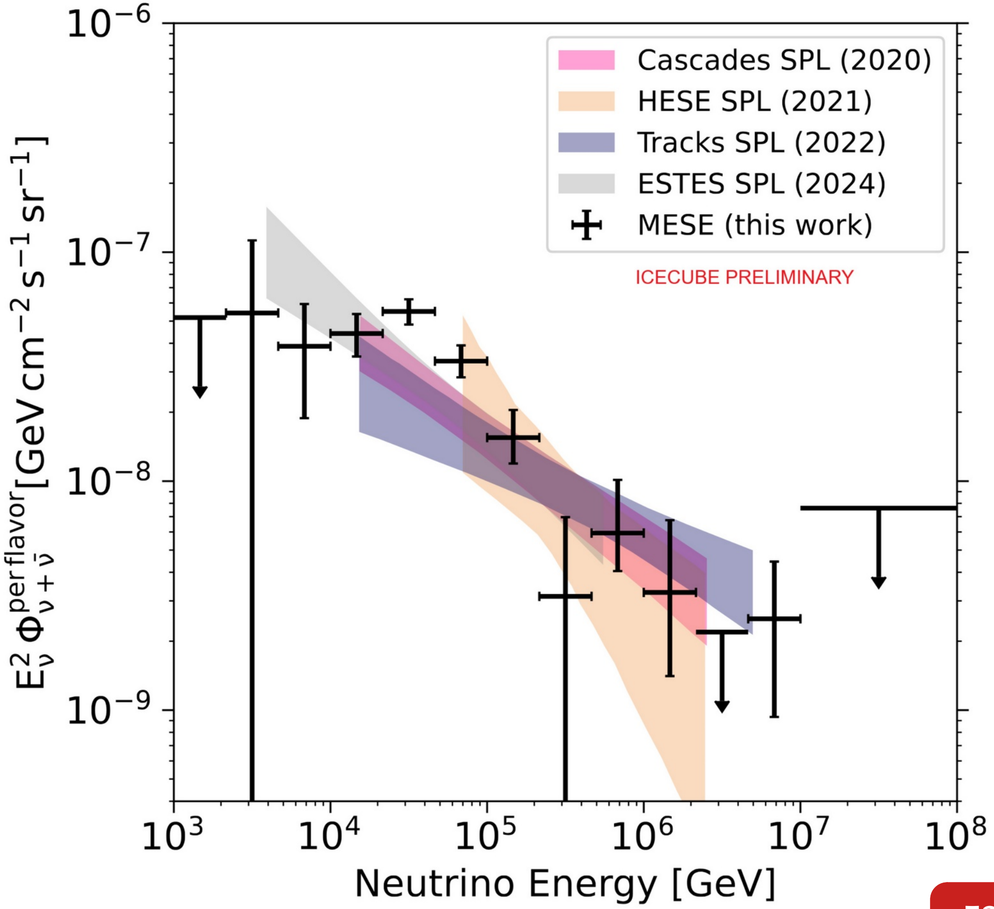
Diffuse v flux: beyond the power law

Diffuse TeV–PeV υ flux: **IceCube**

V. Basu, A. Balagopal, A. Karle,
PoS(ICRC2025)985

1 – New all-flavor flux measurement at 1 TeV–10 PeV

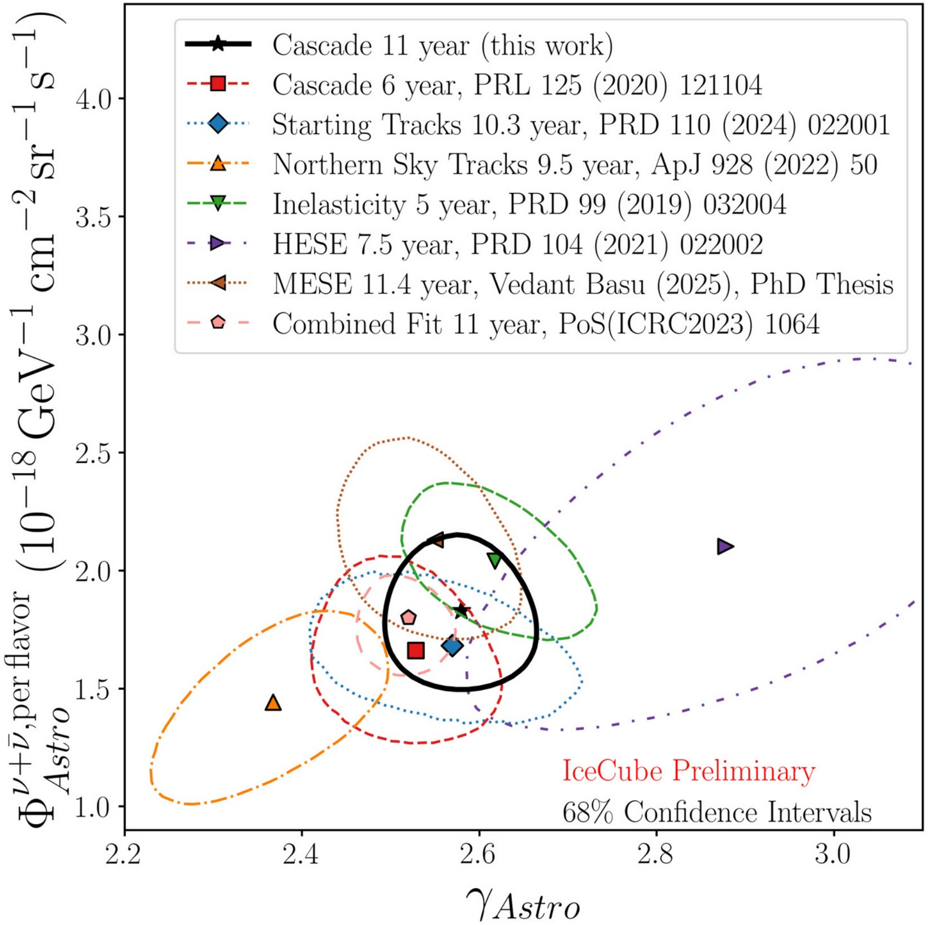


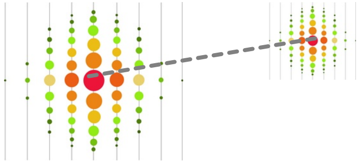


Diffuse TeV–PeV υ flux: **IceCube**

Z. Chen, Z. Zhang, J. Kiryluk (for IceCube)
PoS(ICRC2025)1011

2 – New measurement using cascades at > 10 TeV





11 yr of cascade data

Cascades (υ_e, υ_μ, υ_τ) and double cascades (υ_τ)

Background to double-cascade search:
- υ_e charged-current cascades
- υ_e, υ_μ, υ_τ neutral-current cascades
- υ_μ starting tracks

Extra cuts to find double cascades (+ self-veto):
- total energy > $10^{4.5}$ GeV
- inter-cascade length > 10 m
- energy asymmetry

Produce υ_τ-enriched sample with 90% υ_τ purity

(Great for flavor measurements, see later)

Diffuse TeV–PeV υ flux: **IceCube**

Z. Chen, Z. Zhang, J. Kiryluk (for IceCube)
PoS(ICRC2025)1011

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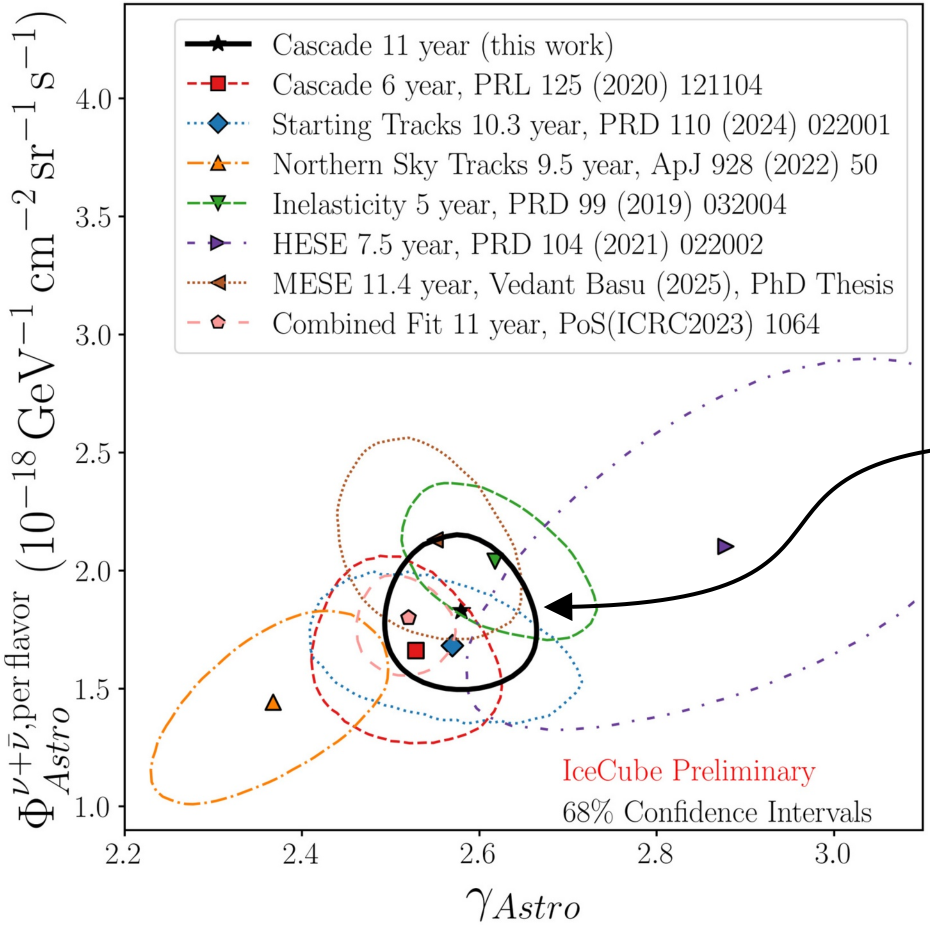
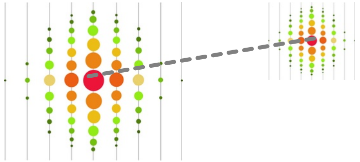




11 yr of cascade data

Cascades (υ_e, υ_μ, υ_τ) and double cascades (υ_τ)

Single-power-law (SPL) fit to data,

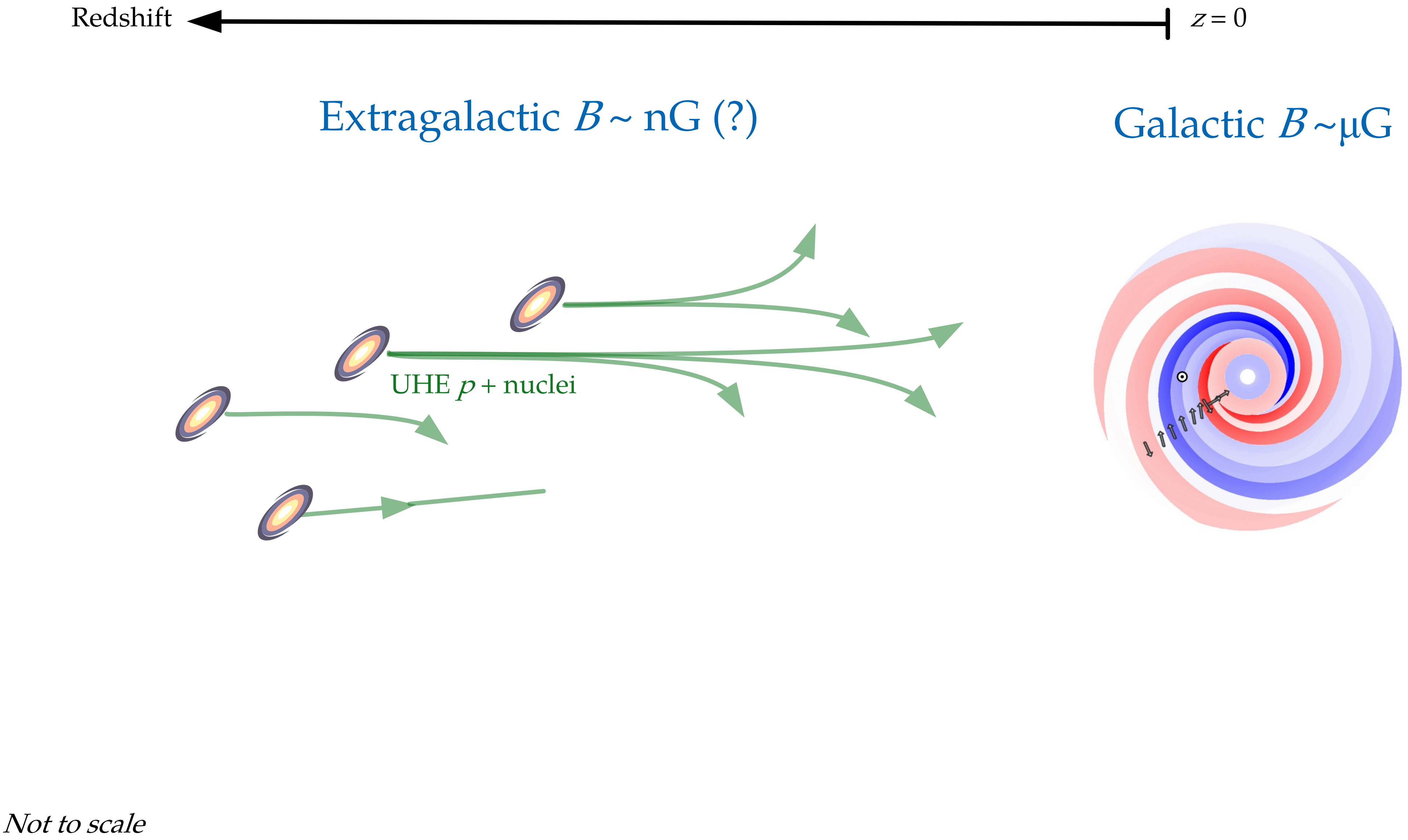
$$\Phi = \Phi_0 \times \left(\frac{E}{100\ \text{TeV}}\right)^{-\gamma},$$

agrees with previous results

Best-fit values:

$$\Phi_0 = 1.83 \pm 0.21$$
$$\gamma = 2.68 \pm 0.06$$

UHECR anisotropy

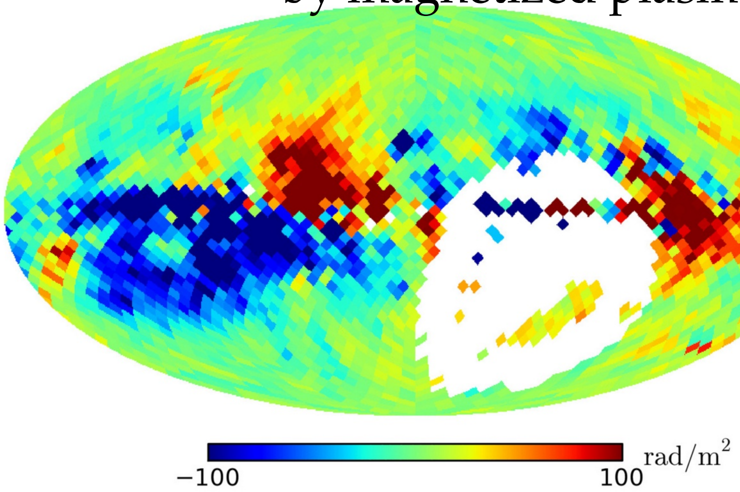


Redshift
$z = 0$
Extragalactic $B \sim$ nG (?)
Galactic $B \sim \mu$G
UHE p + nuclei
Not to scale

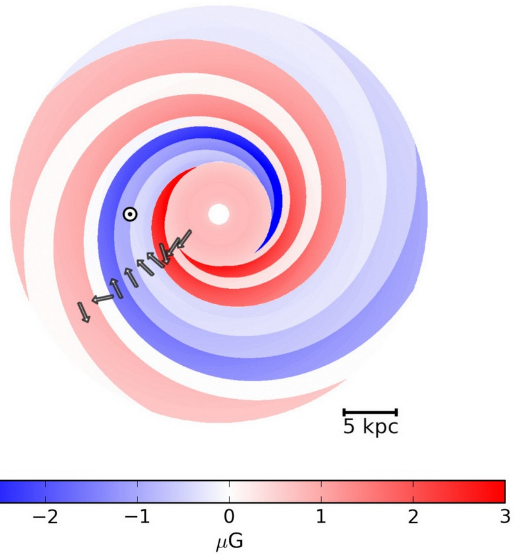
Scattering on magnetic fields

Faraday rotation: Polarization of e.m. waves

by magnetized plasma $\Delta\Psi = \mathrm{RM}\cdot\lambda^2$



Galactic B~μG



Milky Way electron density

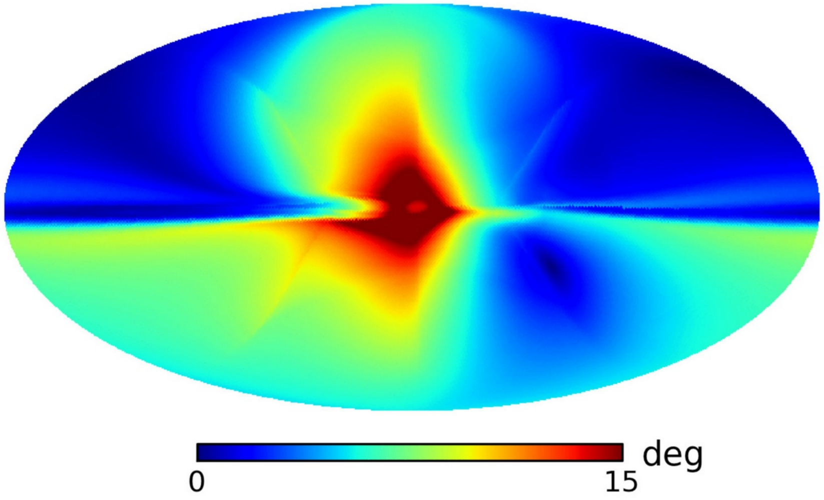
$$\mathrm{RM} \simeq 0.81 \int_0^L \left(\frac{n_e(l)}{\mathrm{cm}^{-3}}\right)\left(\frac{B(l)}{\mu\mathrm{G}}\right)\left(\frac{dl}{\mathrm{pc}}\right)$$

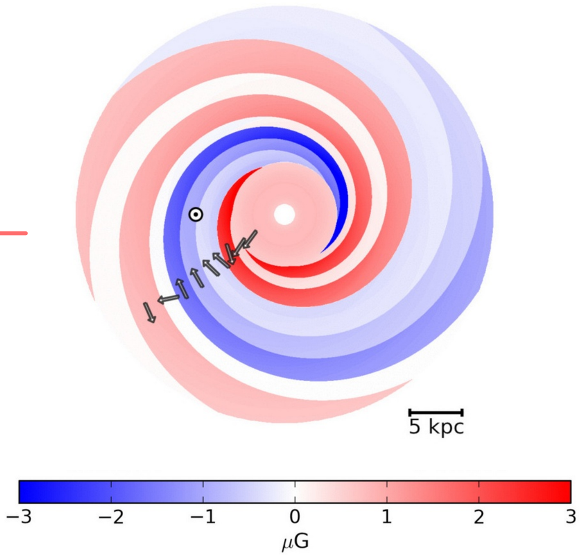
Jansson & Farrar, *ApJ* 2012

Scattering on magnetic fields

Galactic $B \sim \mu$G

Galactic deflections of 60-EeV protons





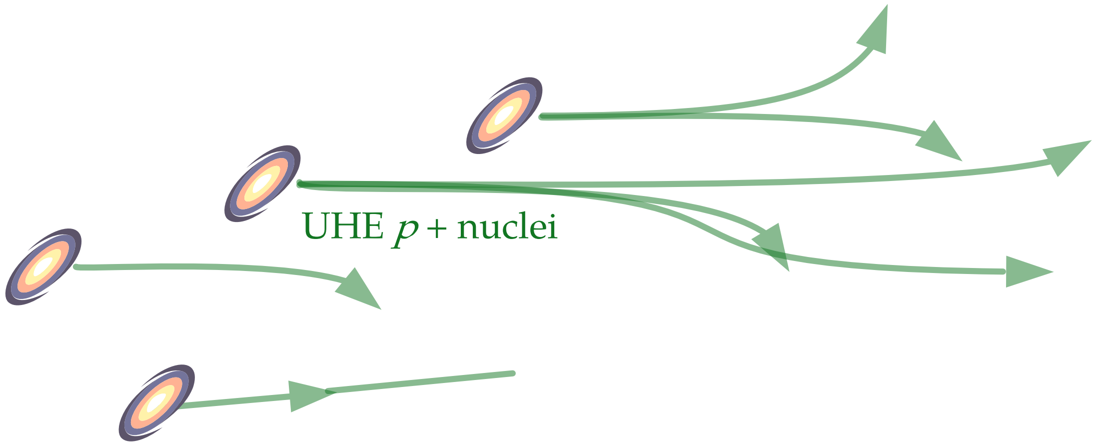
$$\delta \approx 16^\circ Z \left(\frac{20\ \mathrm{EeV}}{E}\right) \int_0^L \frac{dL}{3\ \mathrm{kpc}} \left(\frac{B}{2\ \mu\mathrm{G}}\right)$$

Auger Collab., *Astropart. Phys.* 2007

Jansson & Farrar, *ApJ* 2012

Redshift ← $z = 0$

Extragalactic $B \sim$ nG (?)



Larger charge bends more   Longer trajectories bend more   Magnetic field intensity

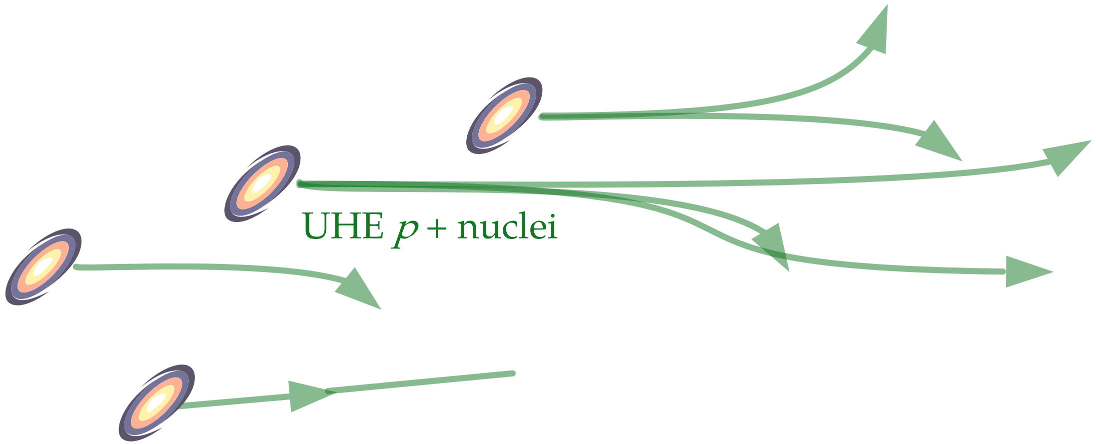
$$\delta_{\mathrm{rms}} \approx 0.8^\circ Z \left(\frac{10\ \mathrm{EeV}}{E}\right)\left(\frac{L}{10\ \mathrm{Mpc}}\right)^{1/2}\left(\frac{L_c}{\mathrm{Mpc}}\right)^{1/2}\left(\frac{B_{\mathrm{rms}}}{n\mathrm{G}}\right)$$

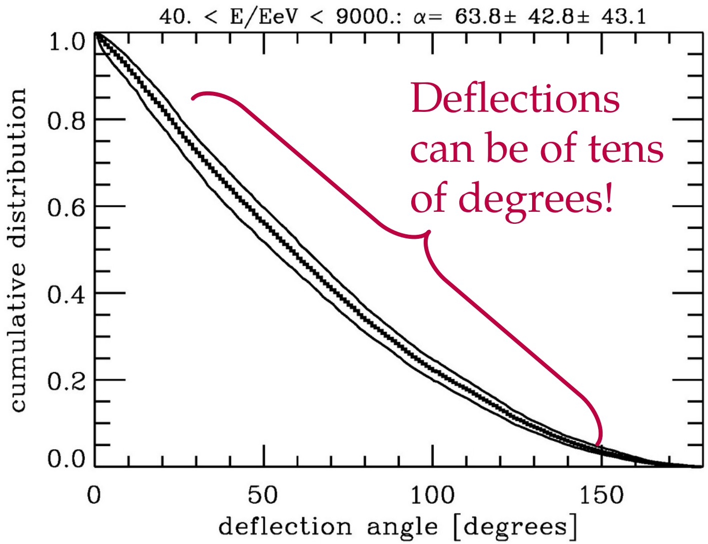
Larger charge bends more L_c: field coherence length

Sigl, Miniati, Ensslin, *PRD* 2004

Redshift $\longleftarrow$ $z = 0$

Extragalactic $B \sim$ nG (?)





Larger charge bends more

Longer trajectories bend more

Magnetic field intensity

$$\delta_{\rm rms} \approx 0.8^\circ\, Z \left(\frac{10\ \mathrm{EeV}}{E}\right) \left(\frac{L}{10\ \mathrm{Mpc}}\right)^{1/2} \left(\frac{L_c}{\mathrm{Mpc}}\right)^{1/2} \left(\frac{B_{\rm rms}}{n\mathrm{G}}\right)$$

Larger charge bends more

L_c: field coherence length

Sigl, Miniati, Ensslin, *PRD* 2004

UHECR anisotropy

How do we know that UHECRs have an extragalactic origin?

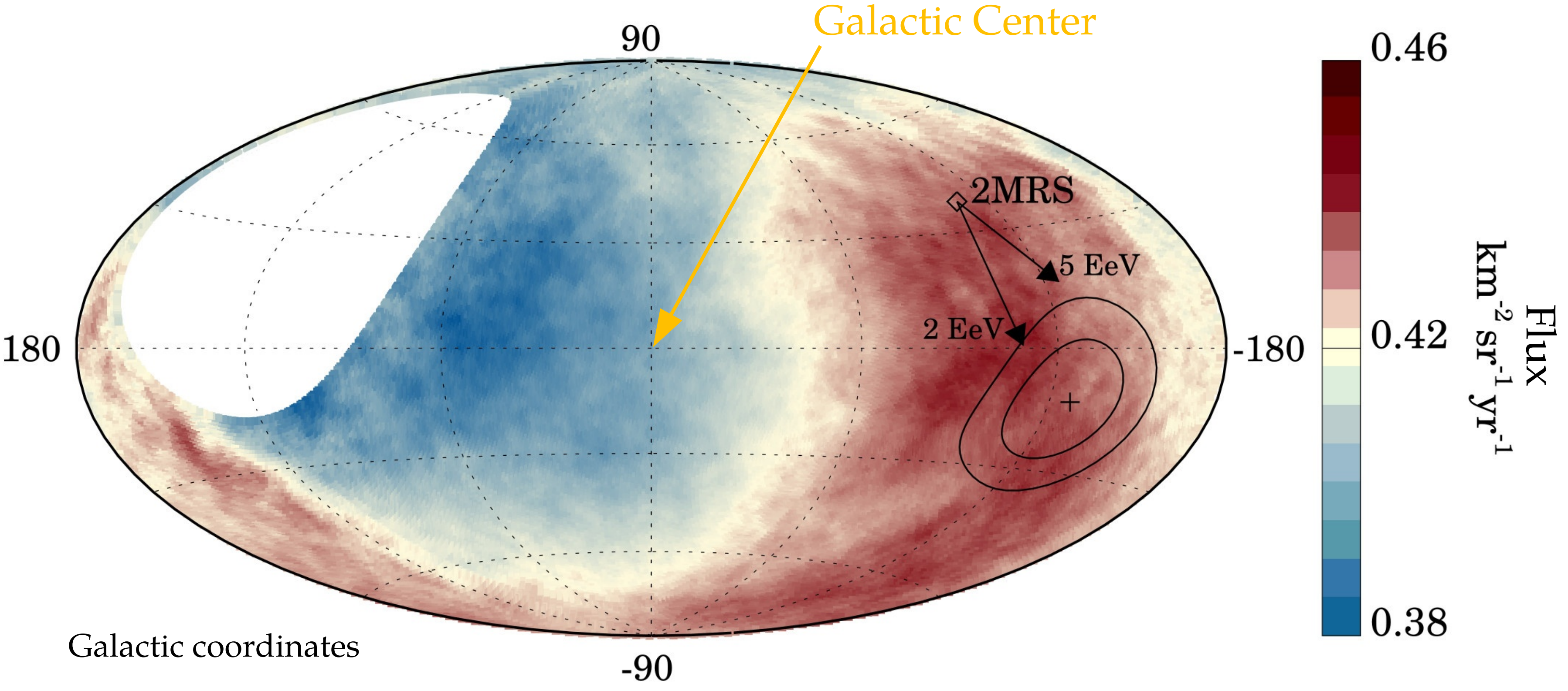
1 Their energies are so large that their Larmor radius cannot be contained by the Milky Way

$$R_L = \frac{E_p}{eB} \approx \frac{10^{18}\ \mathrm{eV}}{e \times 1\ \mu\mathrm{G}} \gg 100\ \mathrm{kpc}$$

2 We can look at the distribution of arrival directions of UHECRs

UHECR anisotropy

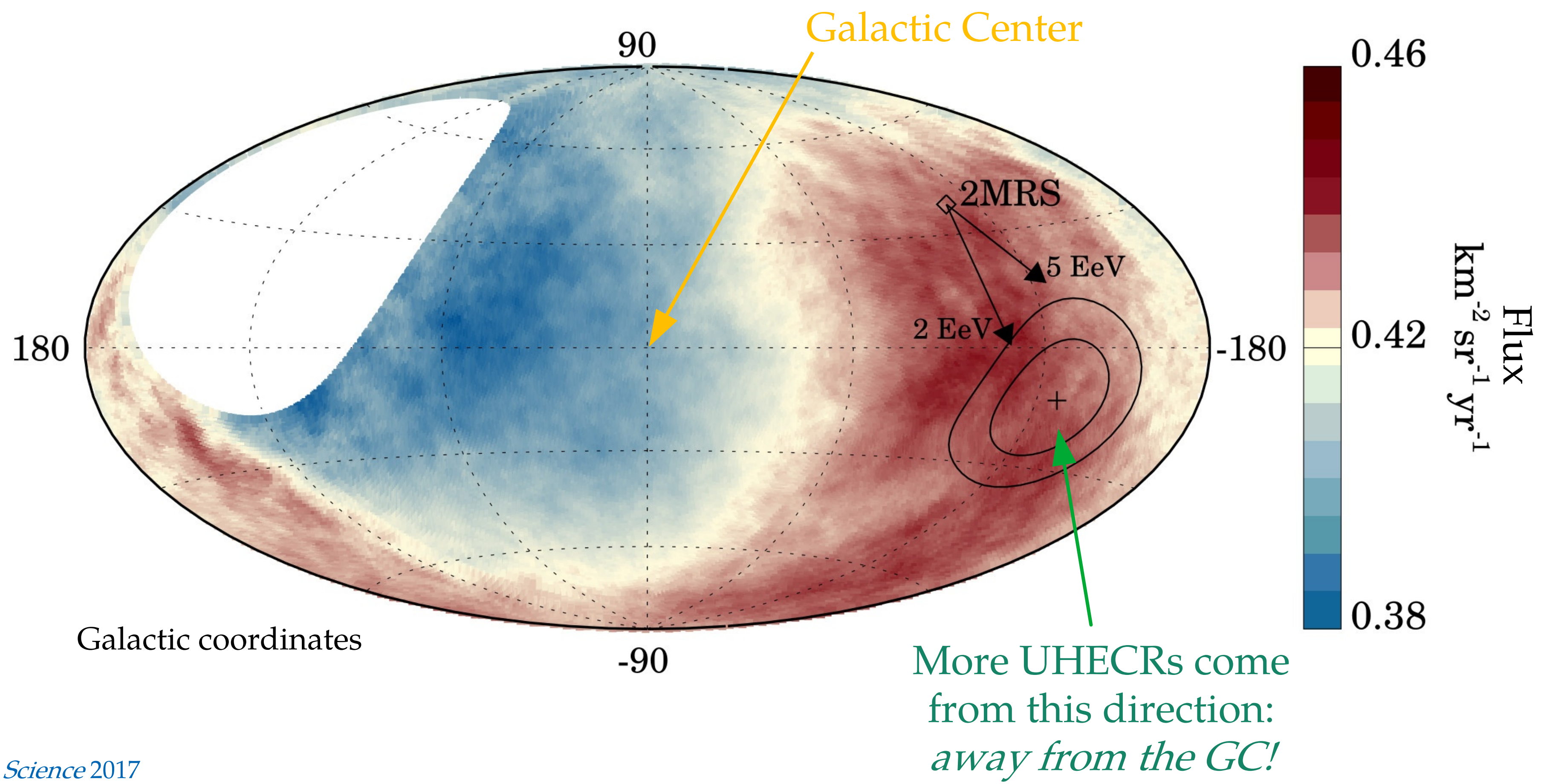
Flux of UHECRs > 8 EeV (Auger, 12 years of data!):



Auger Collab., *Science* 2017

UHECR anisotropy

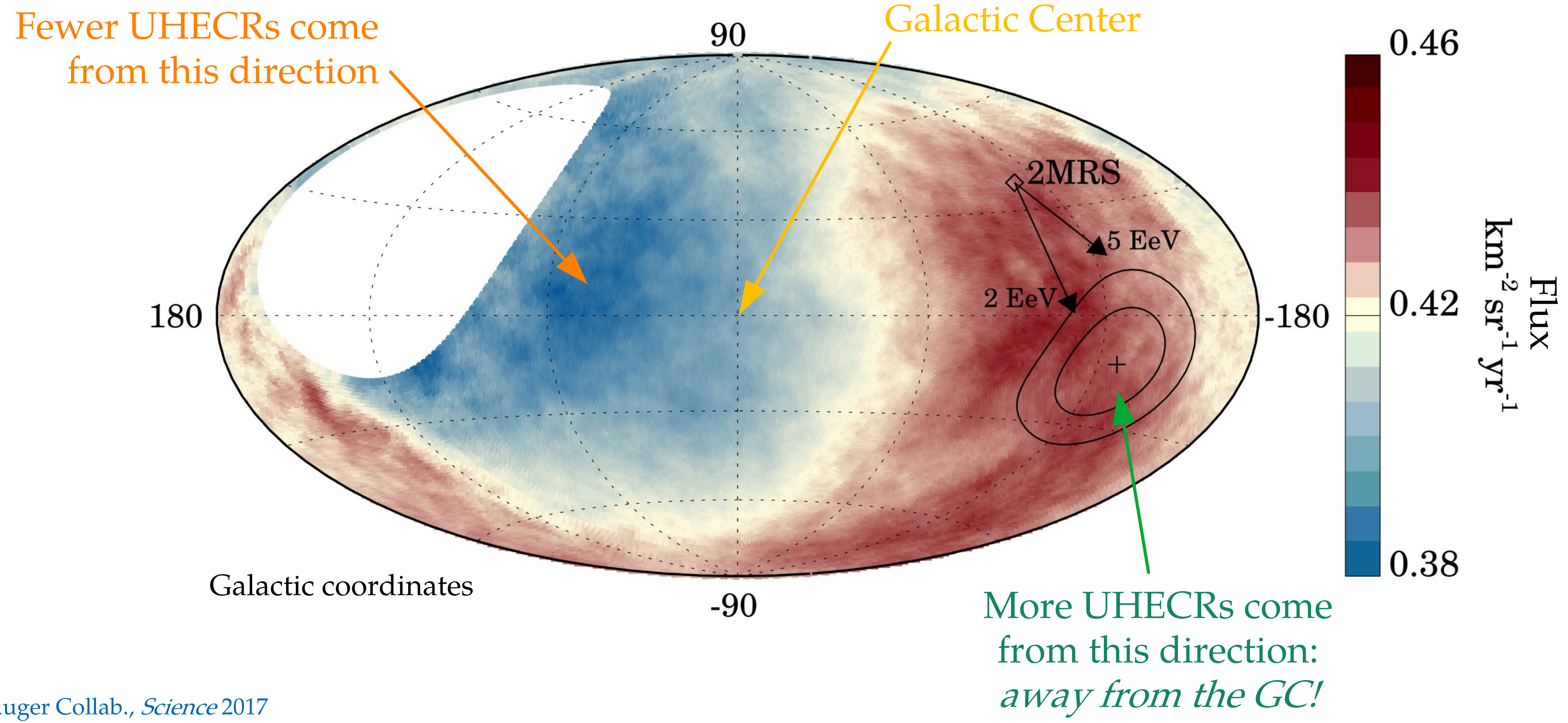
Flux of UHECRs > 8 EeV (Auger, 12 years of data!):



Auger Collab., *Science* 2017

UHECR anisotropy

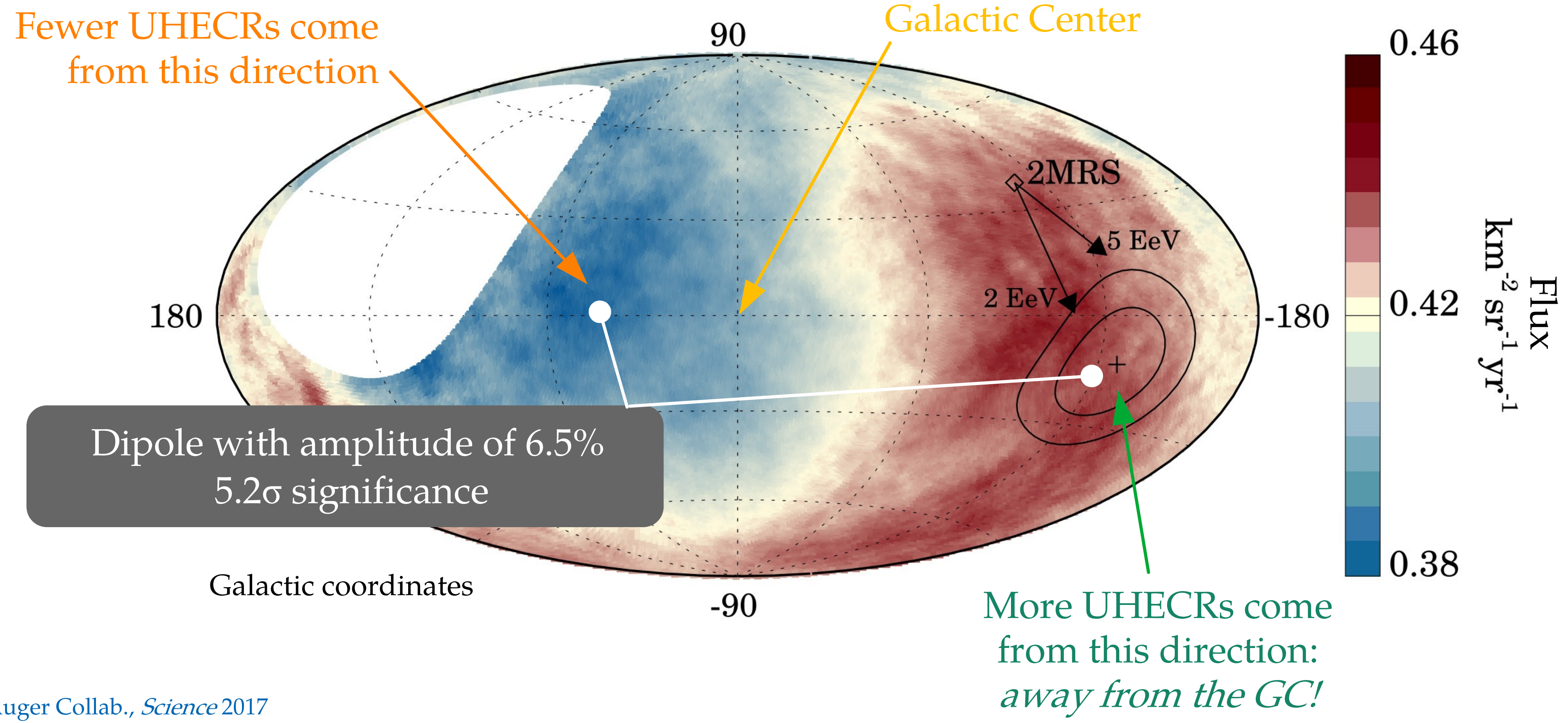
Flux of UHECRs > 8 EeV (Auger, 12 years of data!):



Auger Collab., *Science* 2017

UHECR anisotropy

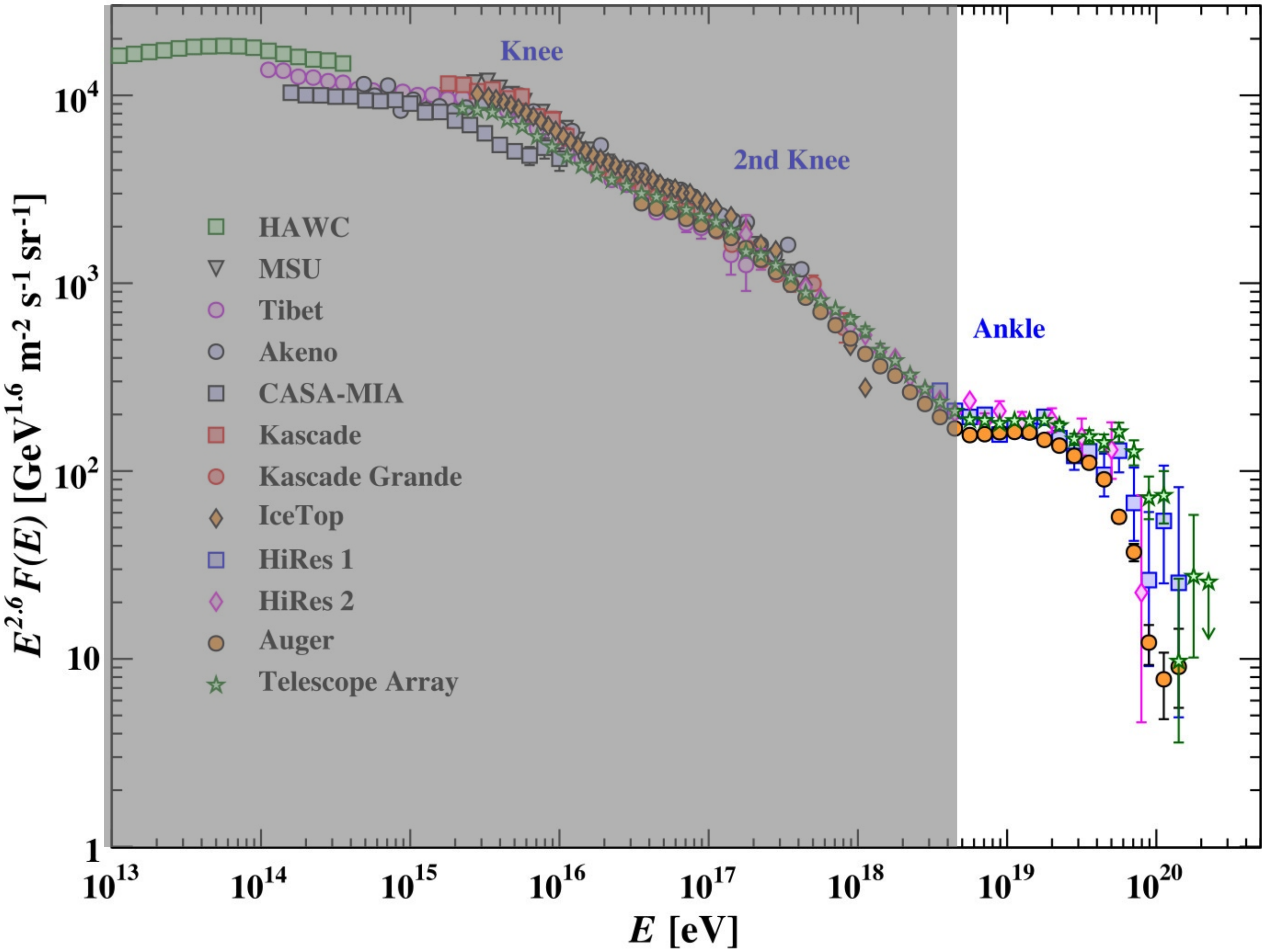
Flux of UHECRs > 8 EeV (Auger, 12 years of data!):



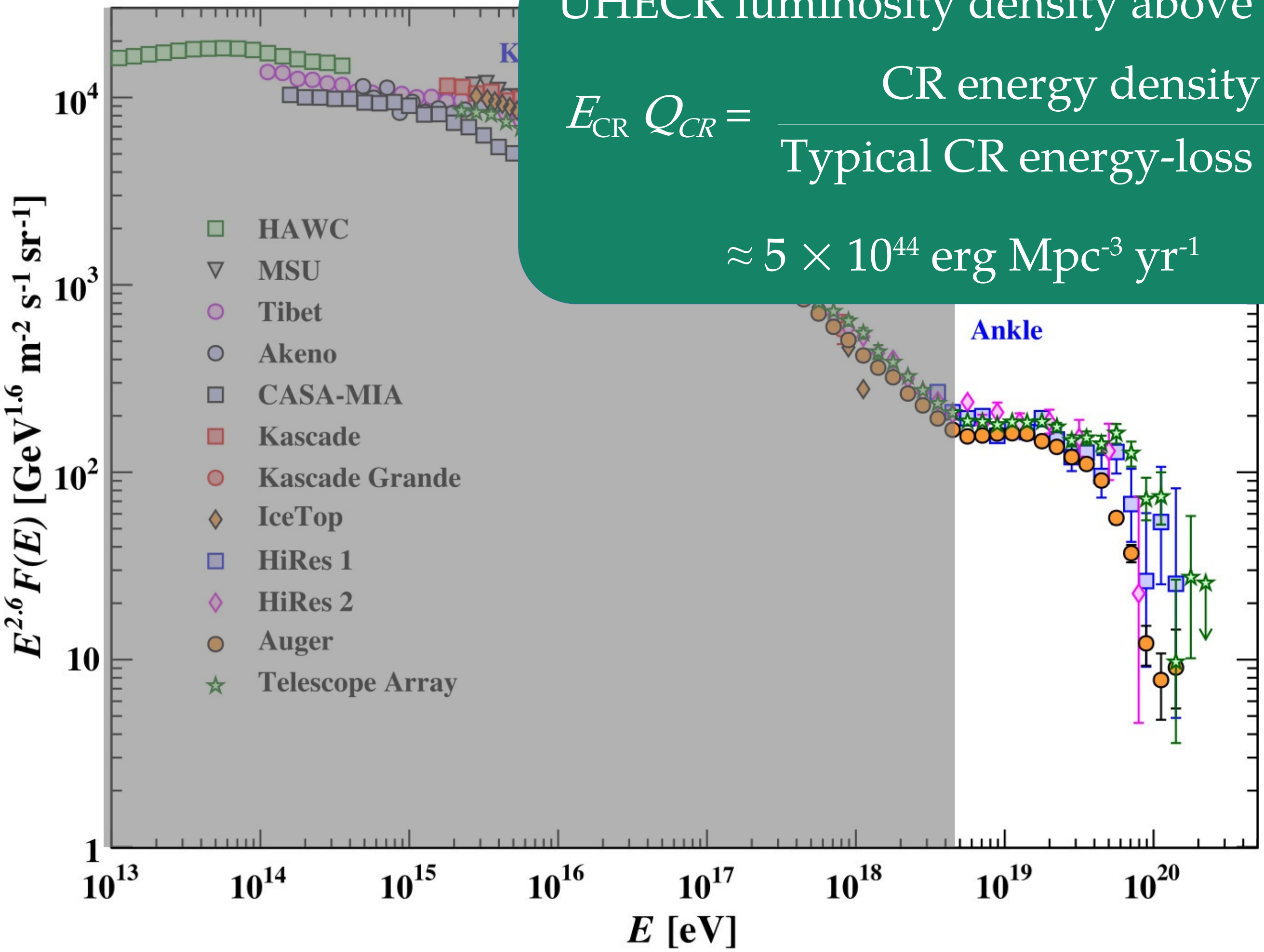
Auger Collab., *Science* 2017

UHECR source population

Luminosity density of UHECR sources



Luminosity density of UHECR sources

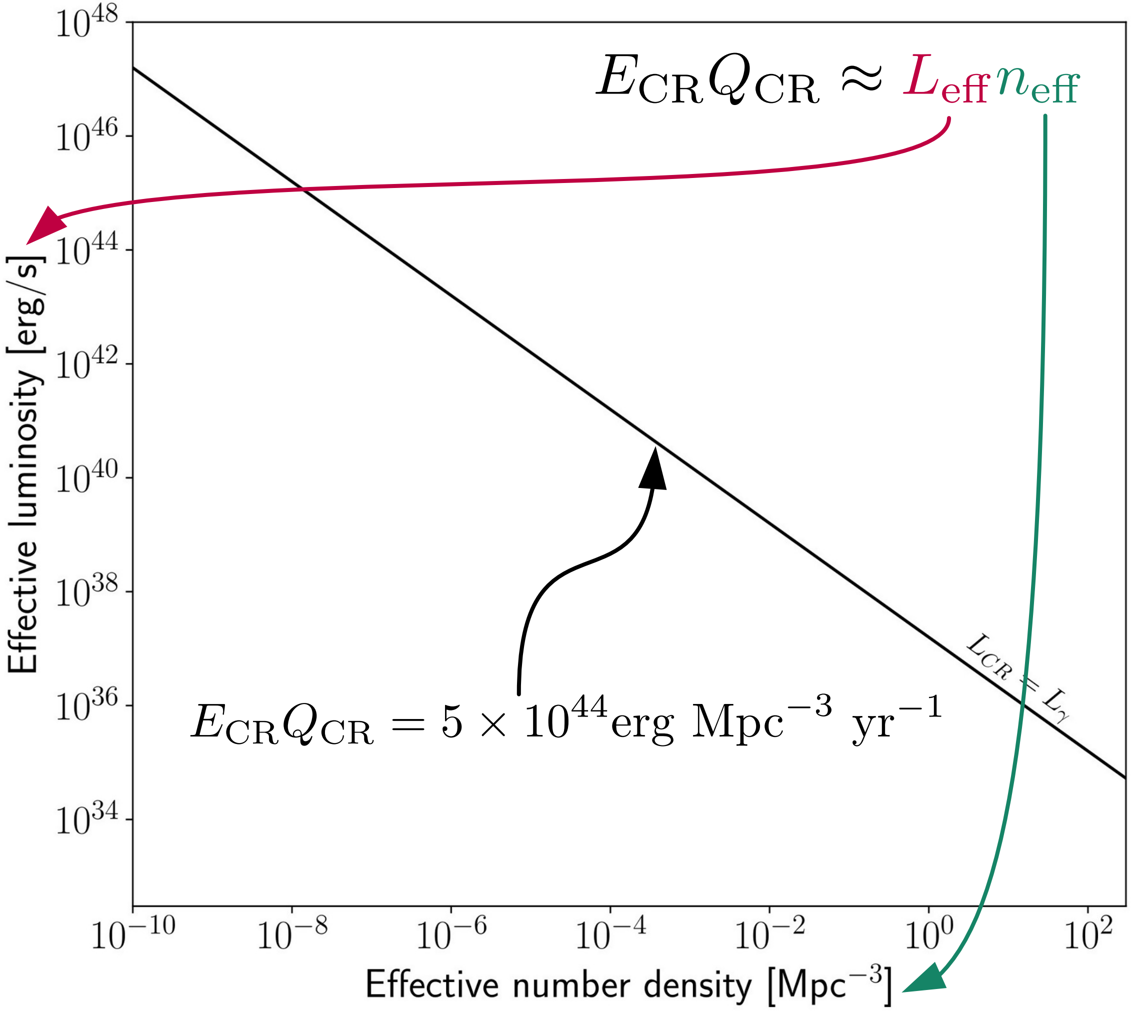


UHECR luminosity density above 5×10^{18} eV:

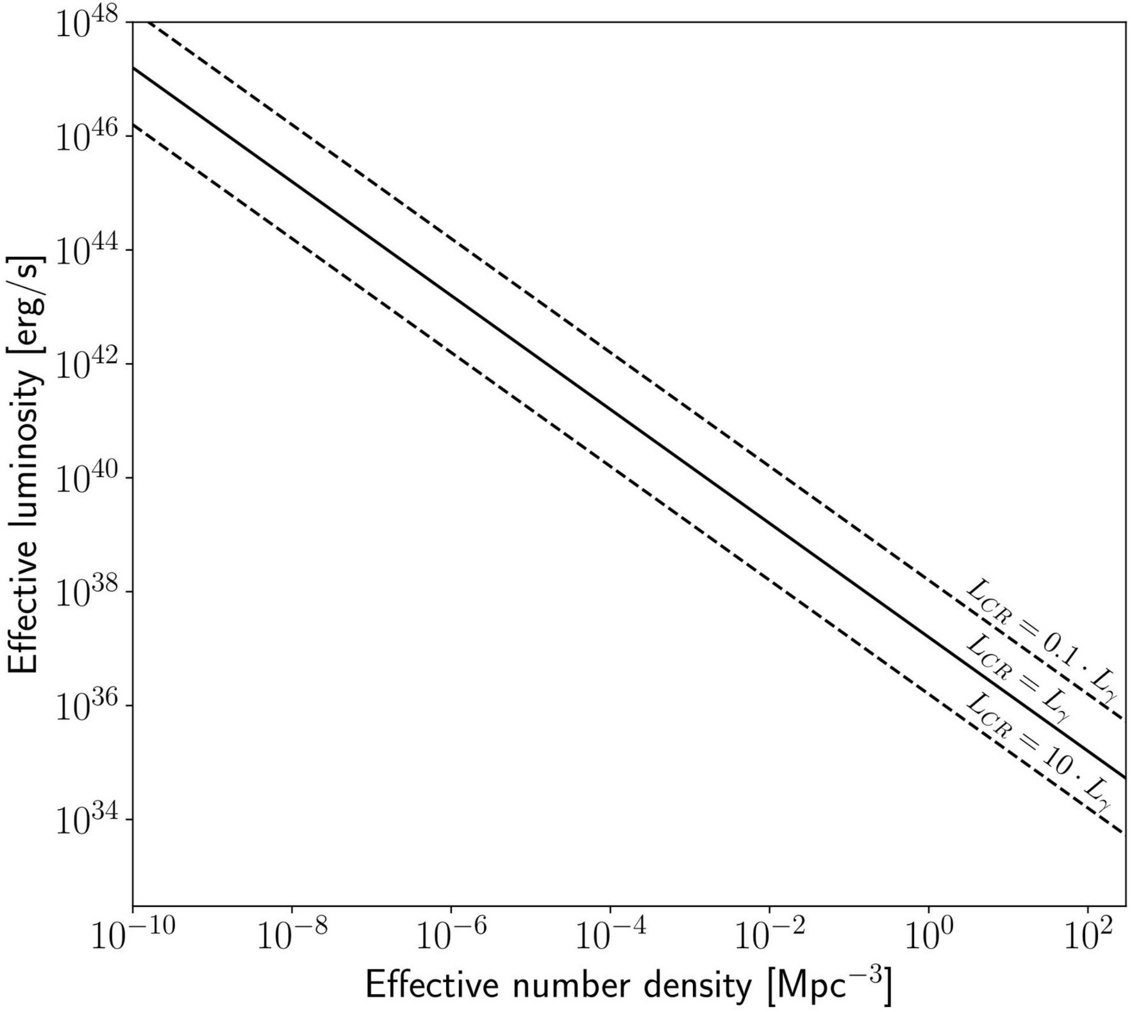
$$E_{\mathrm{CR}}\, Q_{CR} = \frac{\text{CR energy density (measured)}}{\text{Typical CR energy-loss time (estimated)}}$$

$$\approx 5 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$$

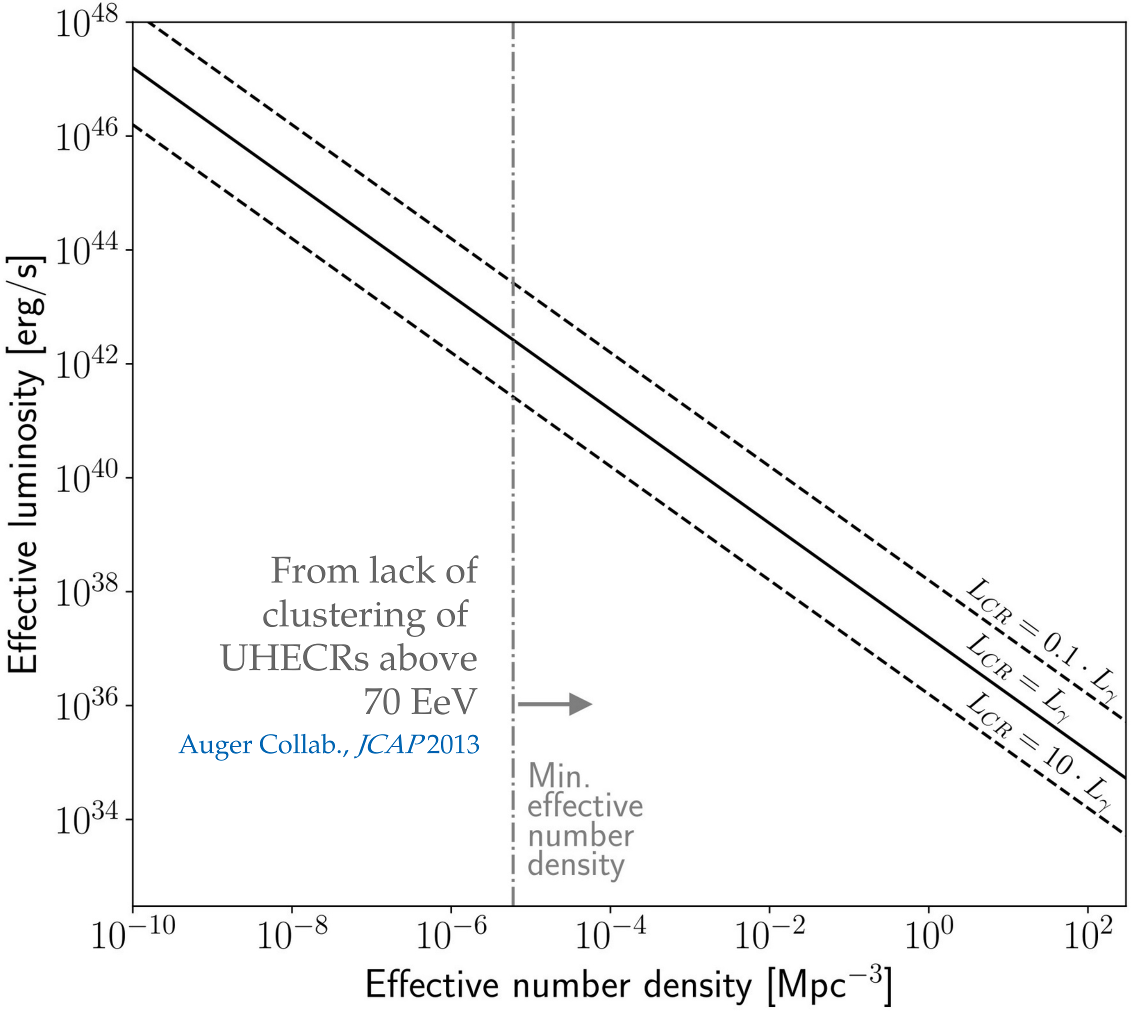
Luminosity density of UHECR sources



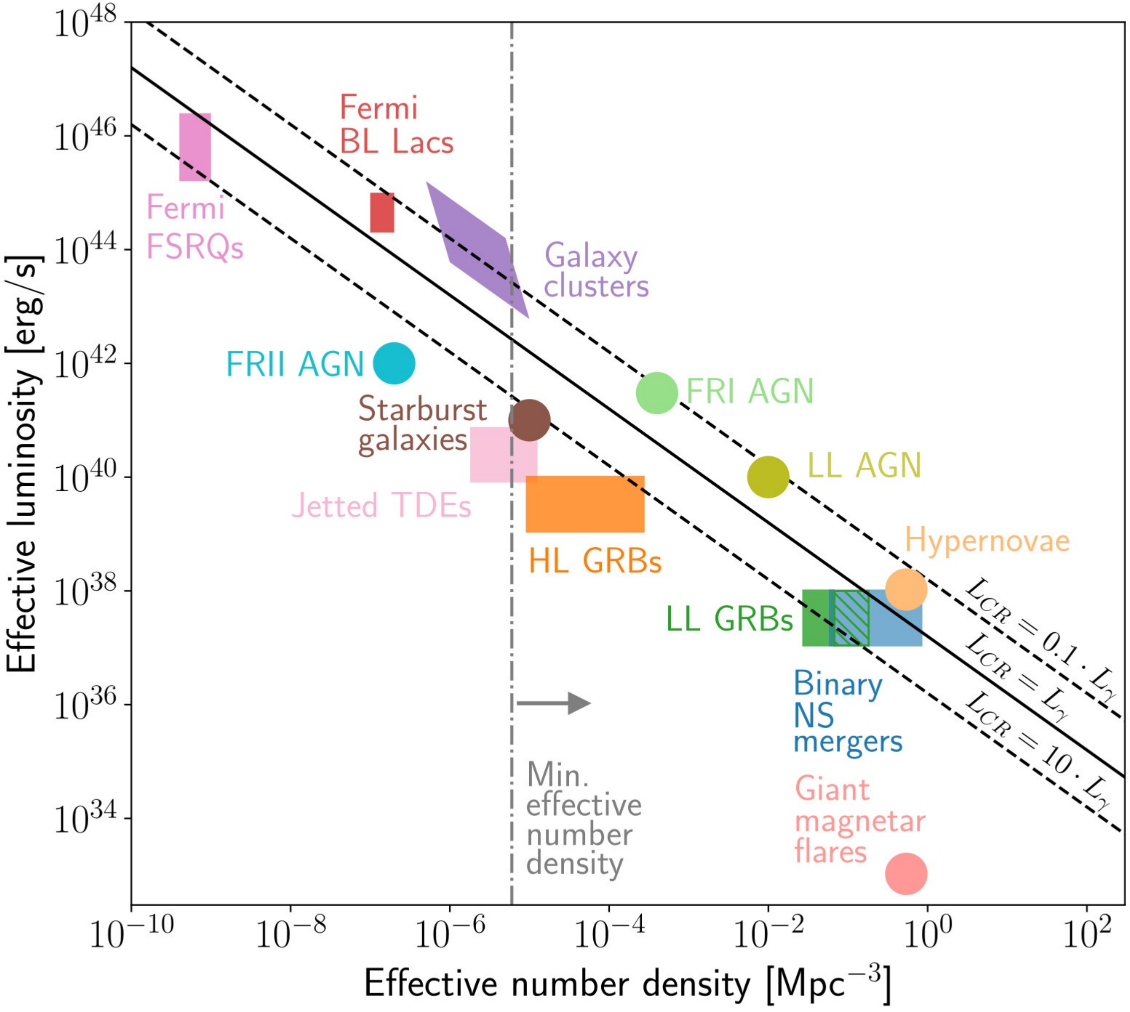
Luminosity density of UHECR sources



Luminosity density of UHECR sources



Luminosity density of UHECR sources



Relation between UHECR and e.m. emission is uncertain and model-dependent

UHECR propagation

Calculating the UHECR flux at Earth

a: Scale factor n_p: Real number density

Comoving number density of protons (GeV^{-1} cm^{-3}): $Y_p(E,z) = a^3(z)\,n_p(E,z) = \frac{1}{(1+z)^3}n_p(E,z)$

Calculating the UHECR flux at Earth

a: Scale factor n_p: Real number density

Comoving number density of protons (GeV^{-1} cm^{-3}): $Y_p(E,z) = a^3(z) n_p(E,z) = \frac{1}{(1+z)^3} n_p(E,z)$

Solve a propagation equation:

$$\dot{Y}_p = \partial_E(HEY_p) + \partial_E(b_{e^+e^-}Y_p) + \partial_E(b_{p\gamma}Y_p) + \mathcal{L}_{\mathrm{CR}}$$

Calculating the UHECR flux at Earth

a: Scale factor n_p: Real number density

Comoving number density of protons (GeV^{-1} cm^{-3}): $Y_p(E,z) = a^3(z)n_p(E,z) = \frac{1}{(1+z)^3}n_p(E,z)$

Solve a propagation equation:

$$\dot{Y}_p = \underbrace{\partial_E(HEY_p)}_{\text{Energy loss due to adiabatic cosmological expansion}} + \partial_E(b_{e^+e^-}Y_p) + \partial_E(b_{p\gamma}Y_p) + \mathcal{L}_{\mathrm{CR}}$$

Energy loss due to adiabatic cosmological expansion

Calculating the UHECR flux at Earth

a: Scale factor n_p: Real number density

Comoving number density of protons ($\mathrm{GeV^{-1}\,cm^{-3}}$): $Y_p(E,z) = a^3(z)\,n_p(E,z) = \frac{1}{(1+z)^3}\,n_p(E,z)$

Solve a propagation equation:

Energy loss rates: $b \equiv -\frac{dE}{dt}$

$$\dot{Y}_p = \underbrace{\partial_E(HEY_p)}_{} + \partial_E(b_{e^+e^-}Y_p) + \partial_E(b_{p\gamma}Y_p) + \mathcal{L}_{\mathrm{CR}}$$

Energy loss due to adiabatic cosmological expansion

Calculating the UHECR flux at Earth

a: Scale factor n_p: Real number density

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Energy loss due to adiabatic cosmological expansion

Energy loss due to pair production:

$p + \gamma \rightarrow p + e^+ + e^-$

Calculating the UHECR flux at Earth

a: Scale factor $\quad n_p$: Real number density

Comoving number density of protons (GeV^{-1} cm^{-3}): $Y_p(E,z) = a^3(z)\,n_p(E,z) = \dfrac{1}{(1+z)^3}\,n_p(E,z)$

Solve a propagation equation:

Energy loss rates: $b \equiv -\dfrac{dE}{dt}$

$$\dot{Y}_p = \underbrace{\partial_E(HEY_p)}_{\text{Energy loss due to adiabatic cosmological expansion}} + \underbrace{\partial_E(b_{e^+e^-}Y_p)}_{\text{Energy loss due to pair production}} + \underbrace{\partial_E(b_{p\gamma}Y_p)}_{\text{Energy loss due to photohadronic int.}} + \mathcal{L}_{\mathrm{CR}}$$

Energy loss due to adiabatic cosmological expansion

Energy loss due to pair production:

$p + \gamma \rightarrow p + e^+ + e^-$

Energy loss due to photohadronic int.:

$p + \gamma \rightarrow p + \pi^0$

$p + \gamma \rightarrow n + \pi^+$

+ other process

+ n beta-decay into p

Calculating the UHECR flux at Earth

a: Scale factor n_p: Real number density

Comoving number density of protons (GeV⁻¹ cm⁻³): $Y_p(E,z) = a^3(z)n_p(E,z) = \frac{1}{(1+z)^3}n_p(E,z)$

Solve a propagation equation:

Energy loss rates: $b \equiv -\frac{dE}{dt}$

$$\dot{Y}_p = \underbrace{\partial_E(HEY_p)}_{} + \underbrace{\partial_E(b_{e^+e^-}Y_p)}_{} + \underbrace{\partial_E(b_{p\gamma}Y_p)}_{} + \underbrace{\mathcal{L}_{\rm CR}}_{}$$

Energy loss due to adiabatic cosmological expansion

Energy loss due to pair production: $p + \gamma \rightarrow p + e^+ + e^-$

Energy loss due to photohadronic int.: $p + \gamma \rightarrow p + \pi^0$, $p + \gamma \rightarrow n + \pi^+$, + other process, + n beta-decay into p

Cosmic-ray injection by UHECR sources

Calculating the UHECR flux at Earth

a: Scale factor n_p: Real number density

Comoving number density of protons (GeV^{-1} cm^{-3}): $Y_p(E,z) = a^3(z) n_p(E,z) = \frac{1}{(1+z)^3} n_p(E,z)$

Solve a propagation equation:

$$\dot{Y}_p = \partial_E(HEY_p) + \partial_E(b_{e^+e^-}Y_p) + \partial_E(b_{p\gamma}Y_p) + \mathcal{L}_{\mathrm{CR}}$$

Recast in terms of redshift using

$$\frac{dz}{dt} = -(1+z)H(z)$$

with Hubble parameter

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$

Calculating the UHECR flux at Earth

a: Scale factor n_p: Real number density

Comoving number density of protons ($\mathrm{GeV}^{-1}\,\mathrm{cm}^{-3}$): $Y_p(E,z) = a^3(z)\,n_p(E,z) = \frac{1}{(1+z)^3}\,n_p(E,z)$

Solve a propagation equation:

$$\dot{Y}_p = \partial_E(HEY_p) + \partial_E(b_{e^+e^-}Y_p) + \partial_E(b_{p\gamma}Y_p) + \mathcal{L}_{\mathrm{CR}}$$

Recast in terms of redshift using

$$\frac{dz}{dt} = -(1+z)H(z)$$

with Hubble parameter

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$$

$$\partial_z Y_p(E,z) = \frac{-1}{(1+z)H(z)}\left\{\partial_E(H(z)EY_p(E,z)) + \partial_E(b_{e^+e^-}(E,z)Y_p(E,z)) + \partial_E(b_{p\gamma}(E,z)Y_p(E,z)) + \mathcal{L}_{\mathrm{CR}}(E,z)\right\}$$

Calculating the UHECR flux at Earth

a: Scale factor n_p: Real number density

Comoving number density of protons (GeV^{-1} cm^{-3}): $Y_p(E,z) = a^3(z) n_p(E,z) = \frac{1}{(1+z)^3} n_p(E,z)$

Solve a propagation equation:

$$\dot{Y}_p = \partial_E(HEY_p) + \partial_E(b_{e^+e^-} Y_p) + \partial_E(b_{p\gamma} Y_p) + \mathcal{L}_{\mathrm{CR}}$$

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$$\partial_z Y_p(E,z) = \frac{-1}{(1+z)H(z)}\{\partial_E(H(z)EY_p(E,z)) + \partial_E(b_{e^+e^-}(E,z)Y_p(E,z)) + \partial_E(b_{p\gamma}(E,z)Y_p(E,z)) + \mathcal{L}_{\mathrm{CR}}(E,z)\}$$

Evolve this equation from $z_{\max} \sim 4$ to Earth ($z = 0$)

Calculating the UHECR flux at Earth

$$\partial_z Y_p(E,z) = \frac{-1}{(1+z)H(z)} \{\partial_E(H(z)EY_p(E,z)) + \partial_E(b_{e^+e^-}(E,z)Y_p(E,z)) + \partial_E(b_{p\gamma}(E,z)Y_p(E,z)) + \mathcal{L}_{\rm CR}(E,z)\}$$

Cosmic-ray injection by UHECR sources

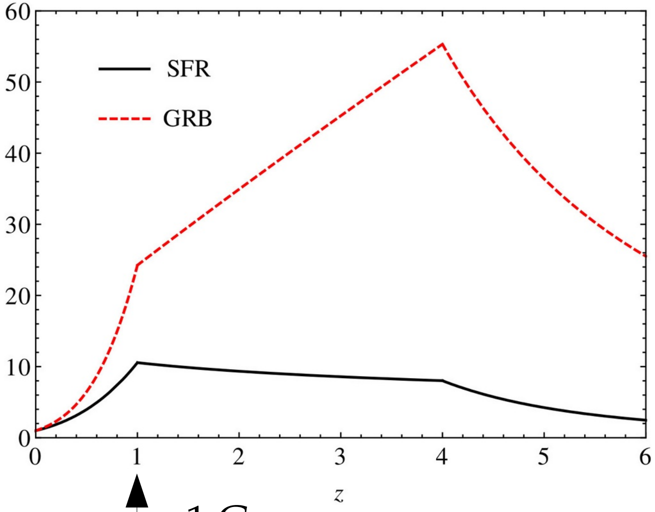
Each source injects UHECRs with a spectrum (GeV^{-1} s^{-1})

$$Q_{\rm CR}(E) \propto E^{-\gamma} e^{-E/E_{\max}}$$

$$\mathcal{L}_{\rm CR} = Q_{\rm CR}(E(1+z))\mathcal{H}_{\rm CR}(z)$$

The number density of sources evolves with redshift (Mpc^{-3})

$\mathcal{H}_{\rm CR}(z)$



~1 Gpc

Calculating the UHECR flux at Earth

$$\partial_z Y_p(E,z) = \frac{-1}{(1+z)H(z)} \{\partial_E(H(z)EY_p(E,z)) + \partial_E(b_{e^+e^-}(E,z)Y_p(E,z)) + \partial_E(b_{p\gamma}(E,z)Y_p(E,z)) + \mathcal{L}_{\mathrm{CR}}(E,z)\}$$

Adiabatic cosmological expansion

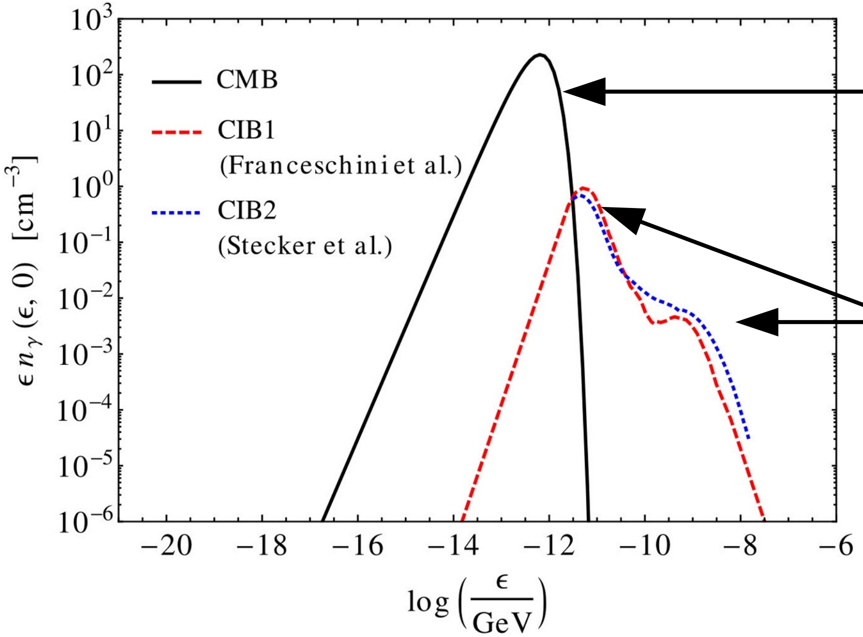
$$\text{Energy at Earth} = \frac{\text{Energy at production}}{1+z}$$

Calculating the UHECR flux at Earth

$$\partial_z Y_p(E,z) = \frac{-1}{(1+z)H(z)} \{\partial_E(H(z)EY_p(E,z)) + \partial_E(b_{e^+e^-}(E,z)Y_p(E,z)) + \partial_E(b_{p\gamma}(E,z)Y_p(E,z)) + \mathcal{L}_{\mathrm{CR}}(E,z)\}$$

Interaction with cosmological backgrounds
(pair production + photohadronic)

$p + \gamma \to \Delta$



Blackbody spectrum

Optical/UV emission from stars, reprocessed into infrared by dust

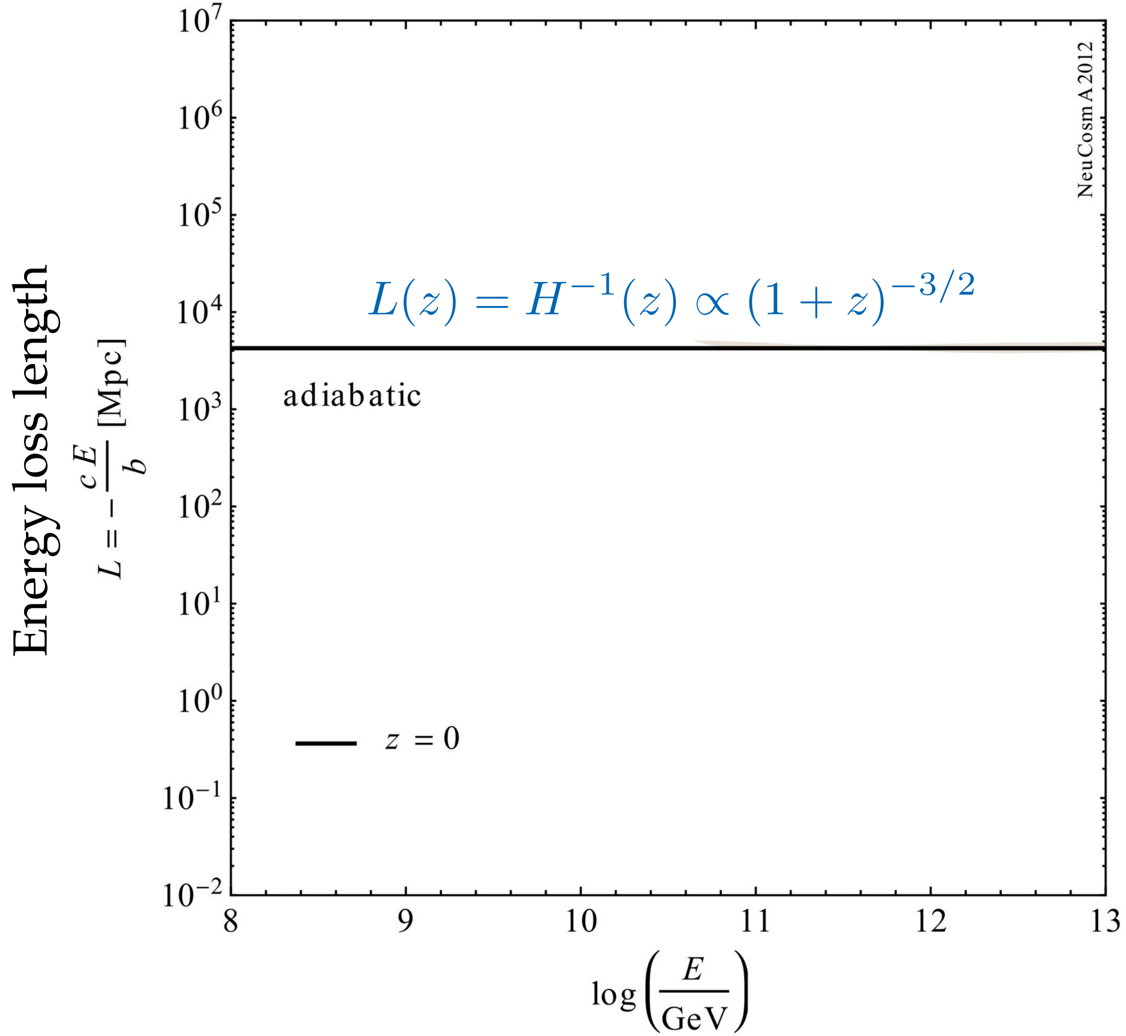
Energy threshold to produce a $\Delta(1232)$ resonance:

$$p_p + p_\gamma = p_\Delta$$

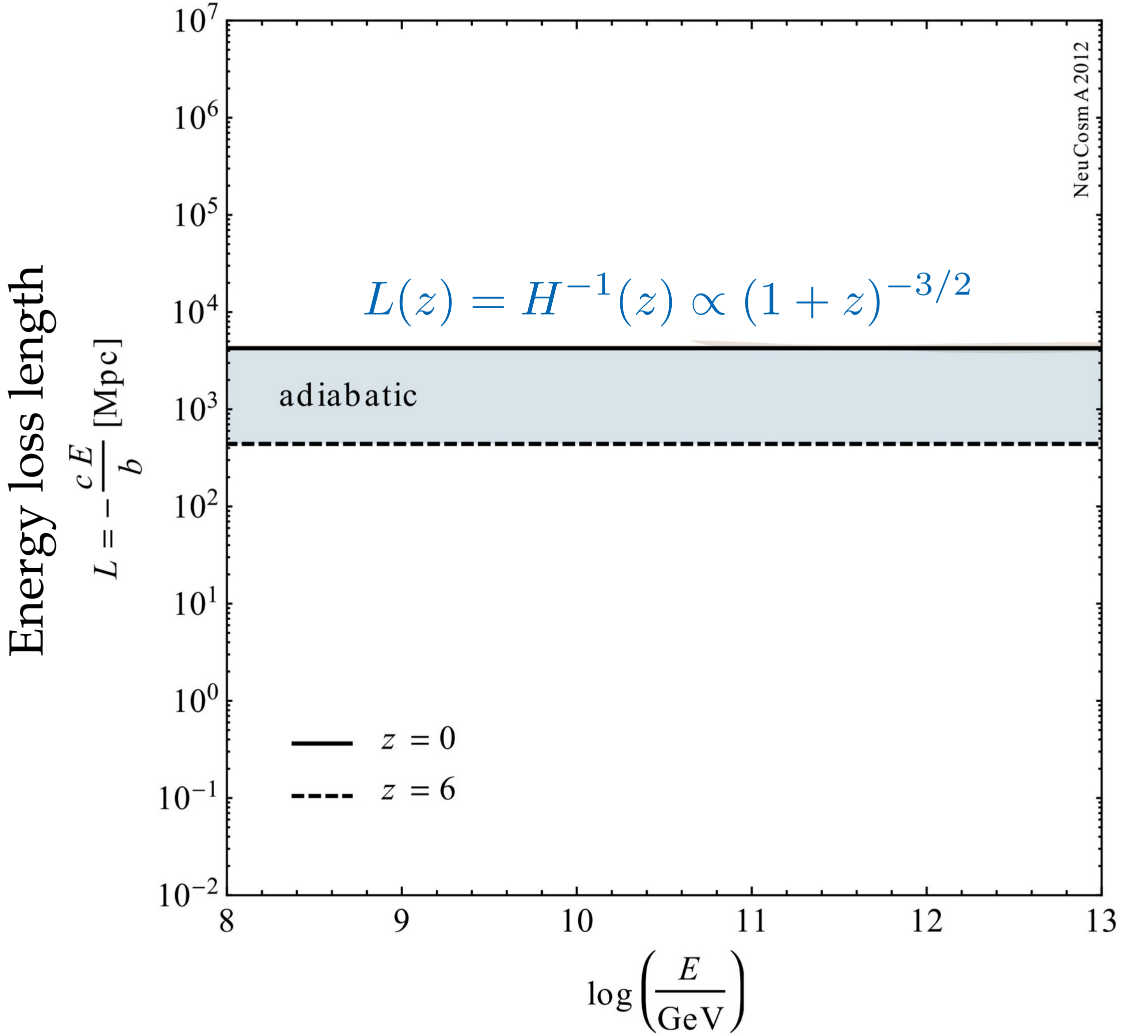
$$E_p E_\gamma \approx 0.16\ \mathrm{GeV}^2$$

(We will use this later, too)

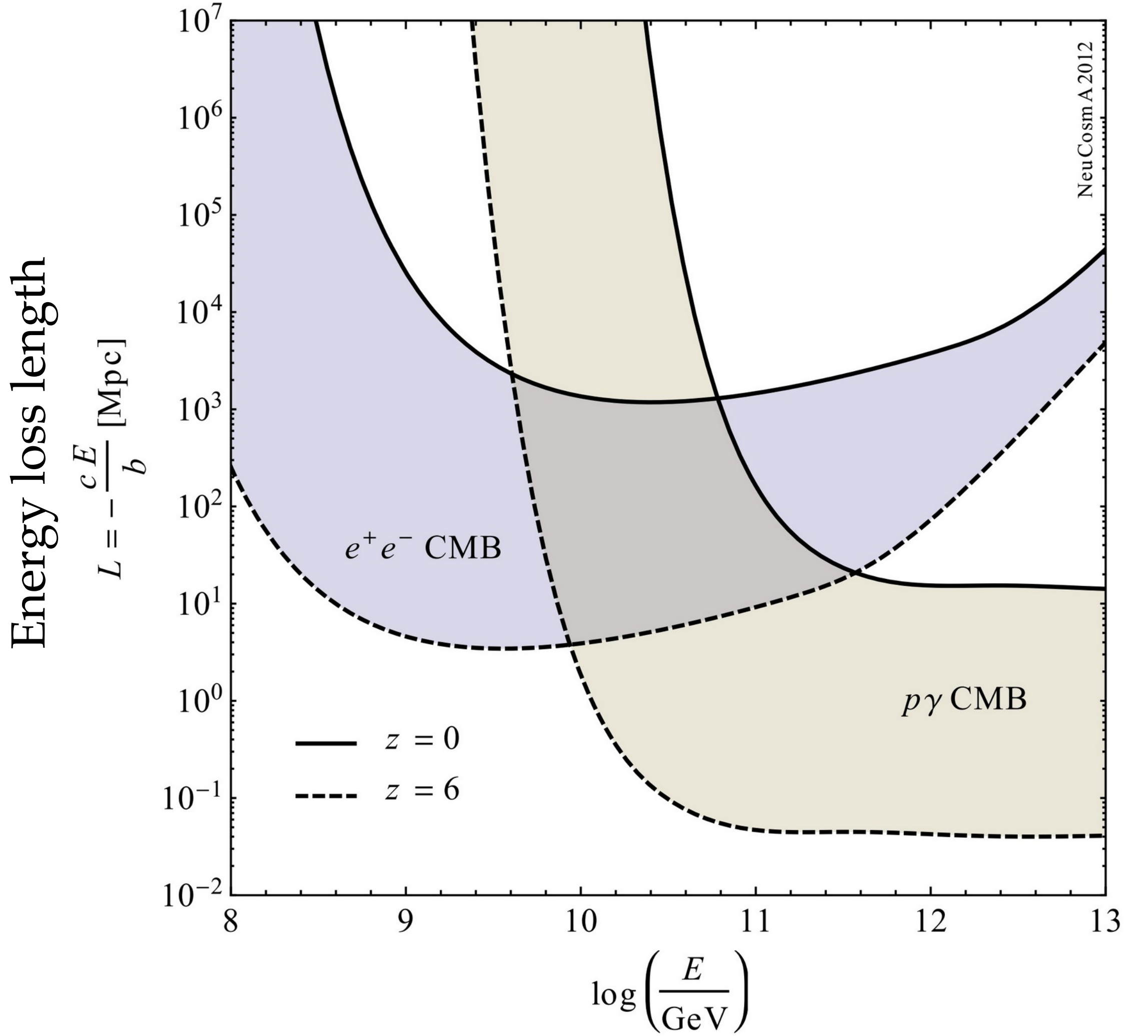
Calculating the UHECR flux at Earth



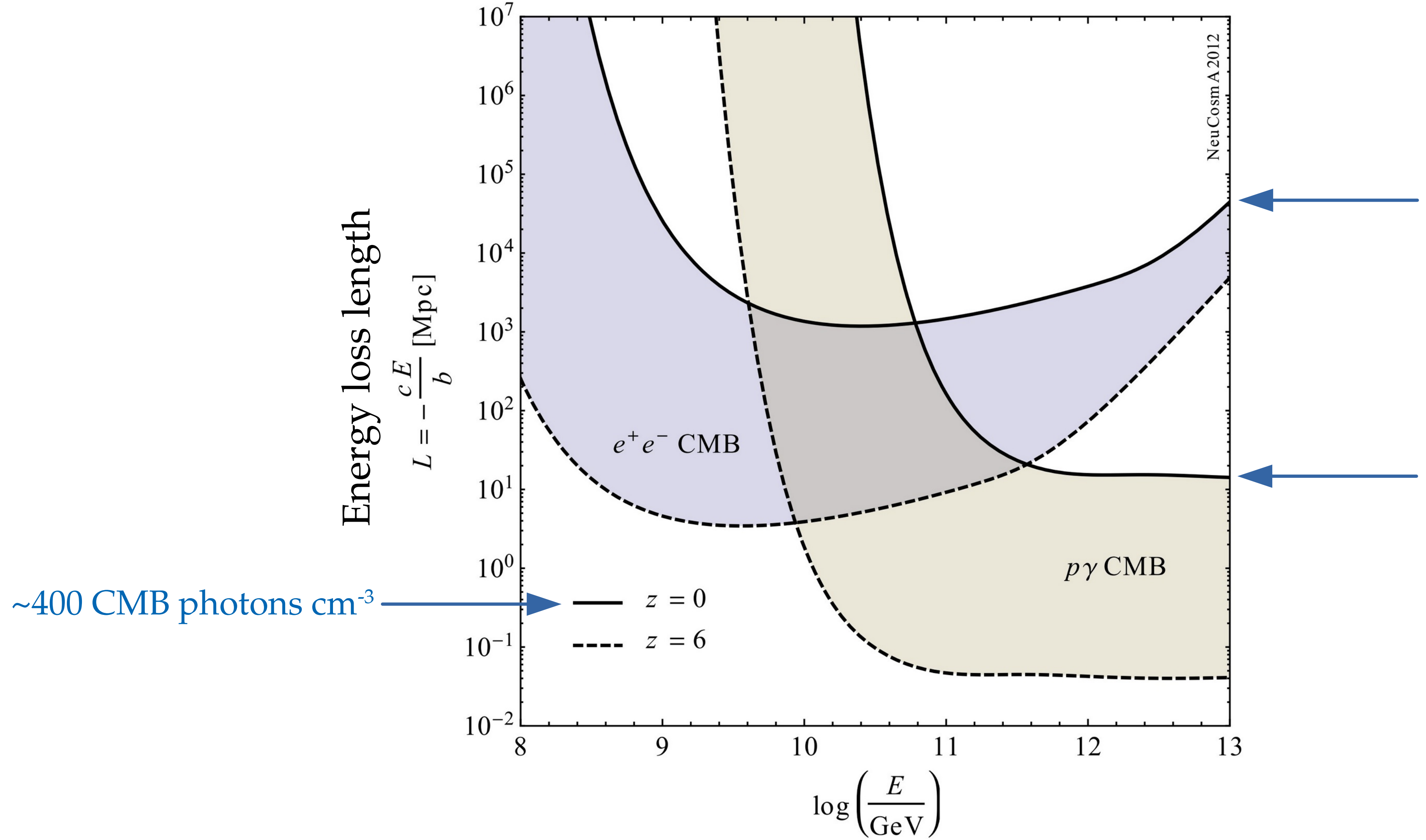
Calculating the UHECR flux at Earth



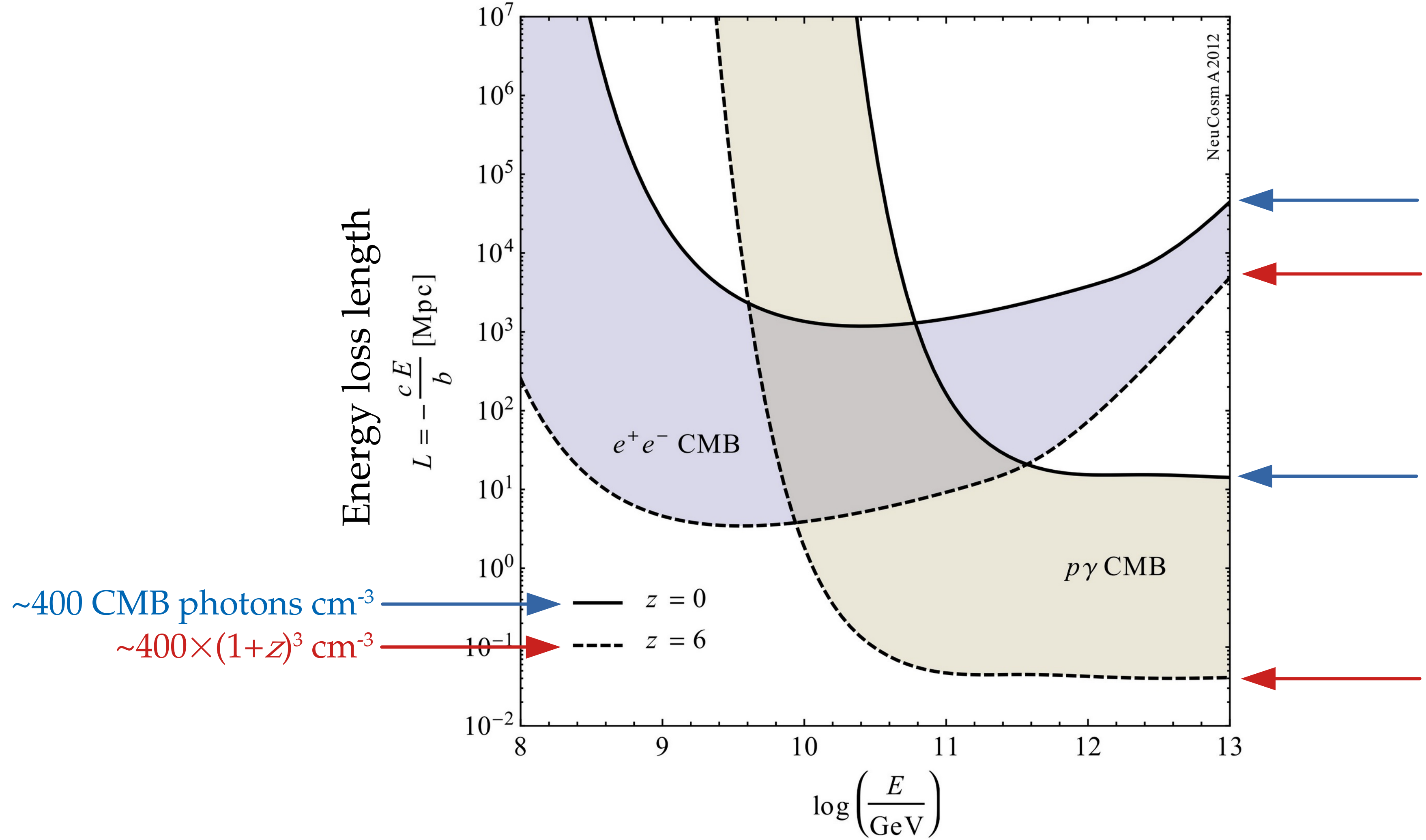
Calculating the UHECR flux at Earth



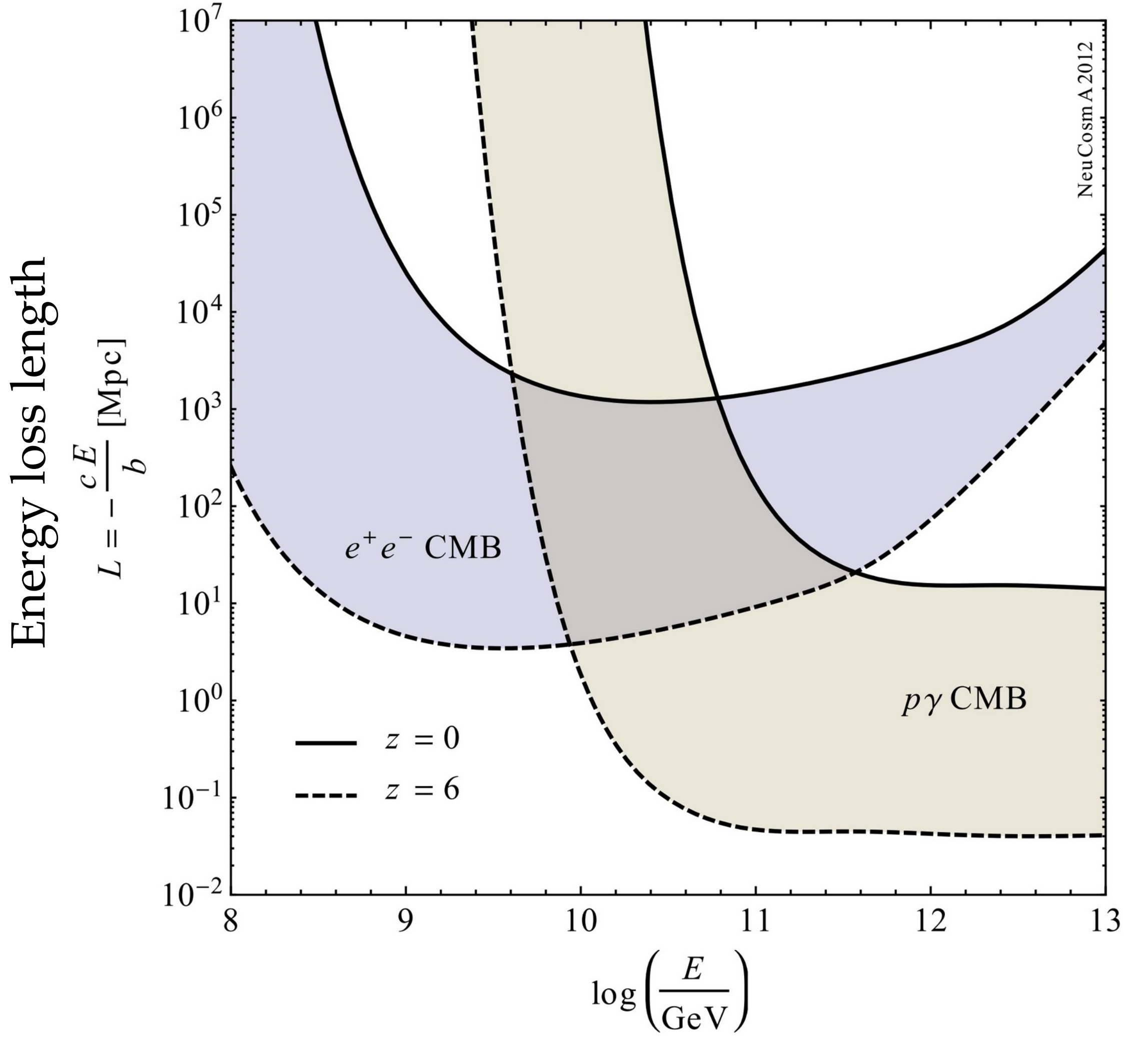
Calculating the UHECR flux at Earth



Calculating the UHECR flux at Earth



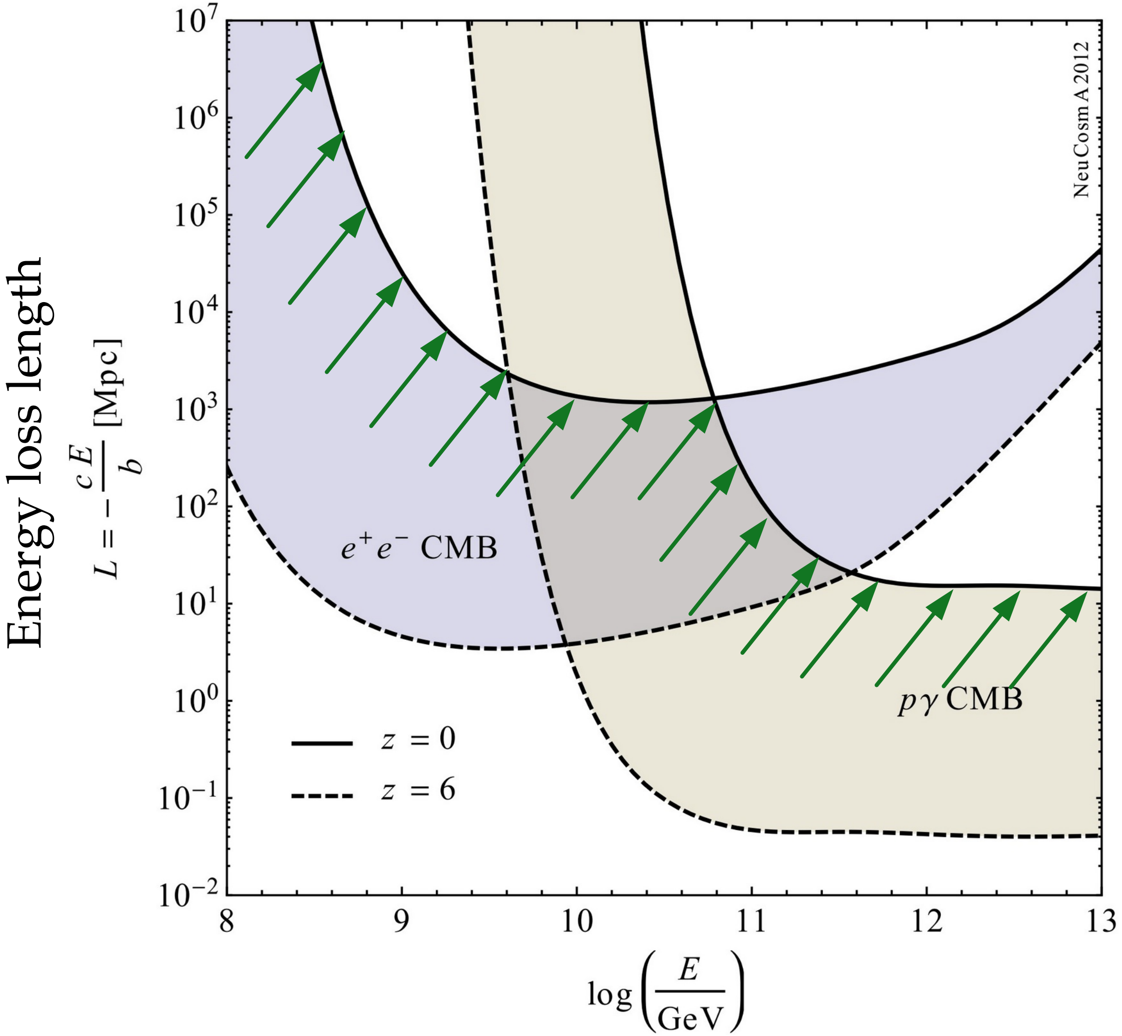
Calculating the UHECR flux at Earth



1

The shorter the energy loss length, the faster the UHECR proton loses energy during propagation

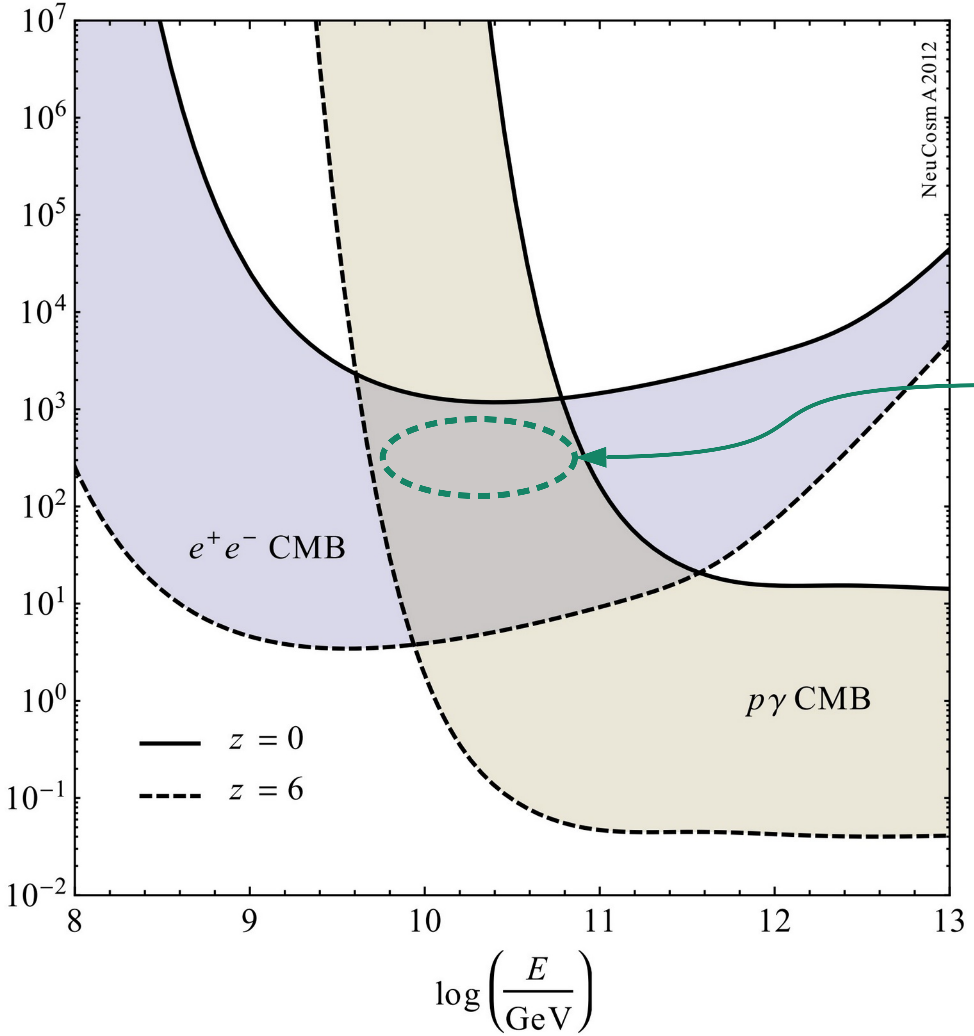
Calculating the UHECR flux at Earth



2

At each energy, the energy loss length is dominated by the fastest energy-loss process

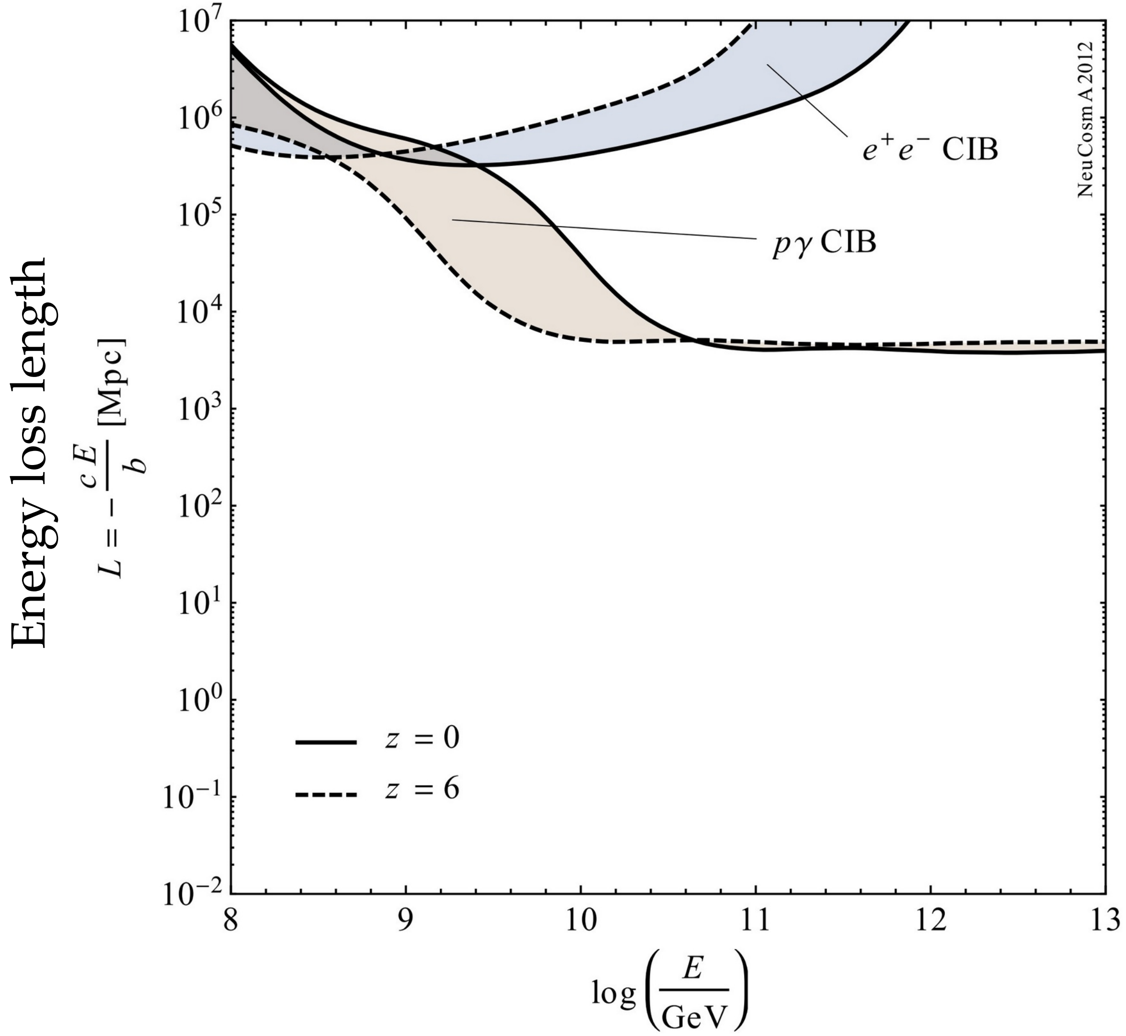
Calculating the UHECR flux at Earth



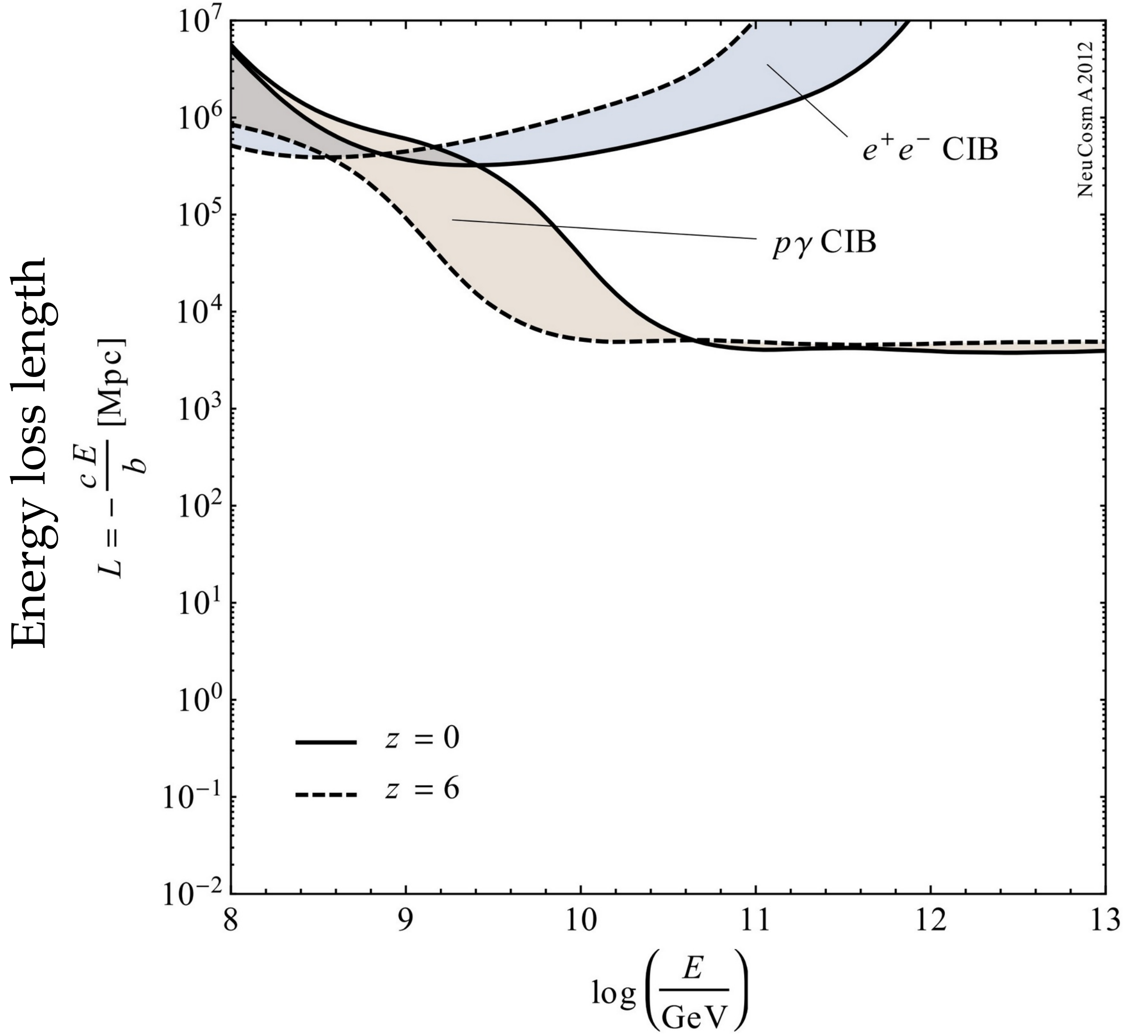
3

Greisen-Zatsepin-Kuzmin (GZK) cut-off is ~100 Mpc

Calculating the UHECR flux at Earth



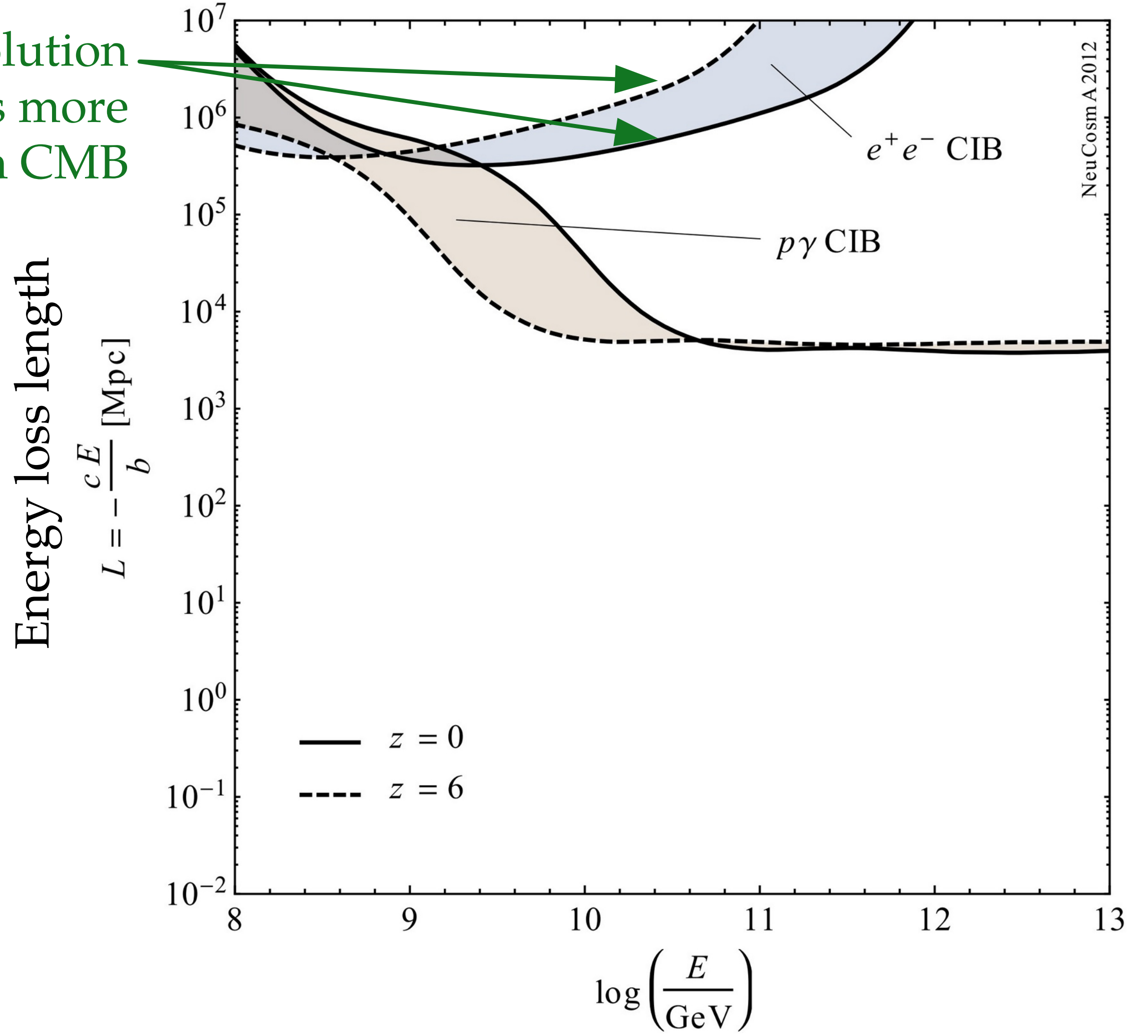
Calculating the UHECR flux at Earth



CIB number density is $\ll$ CMB number density, so there are fewer UHECR interactions on CIB photons ($b_{\mathrm{CIB}} \ll b_{\mathrm{CMB}}$)

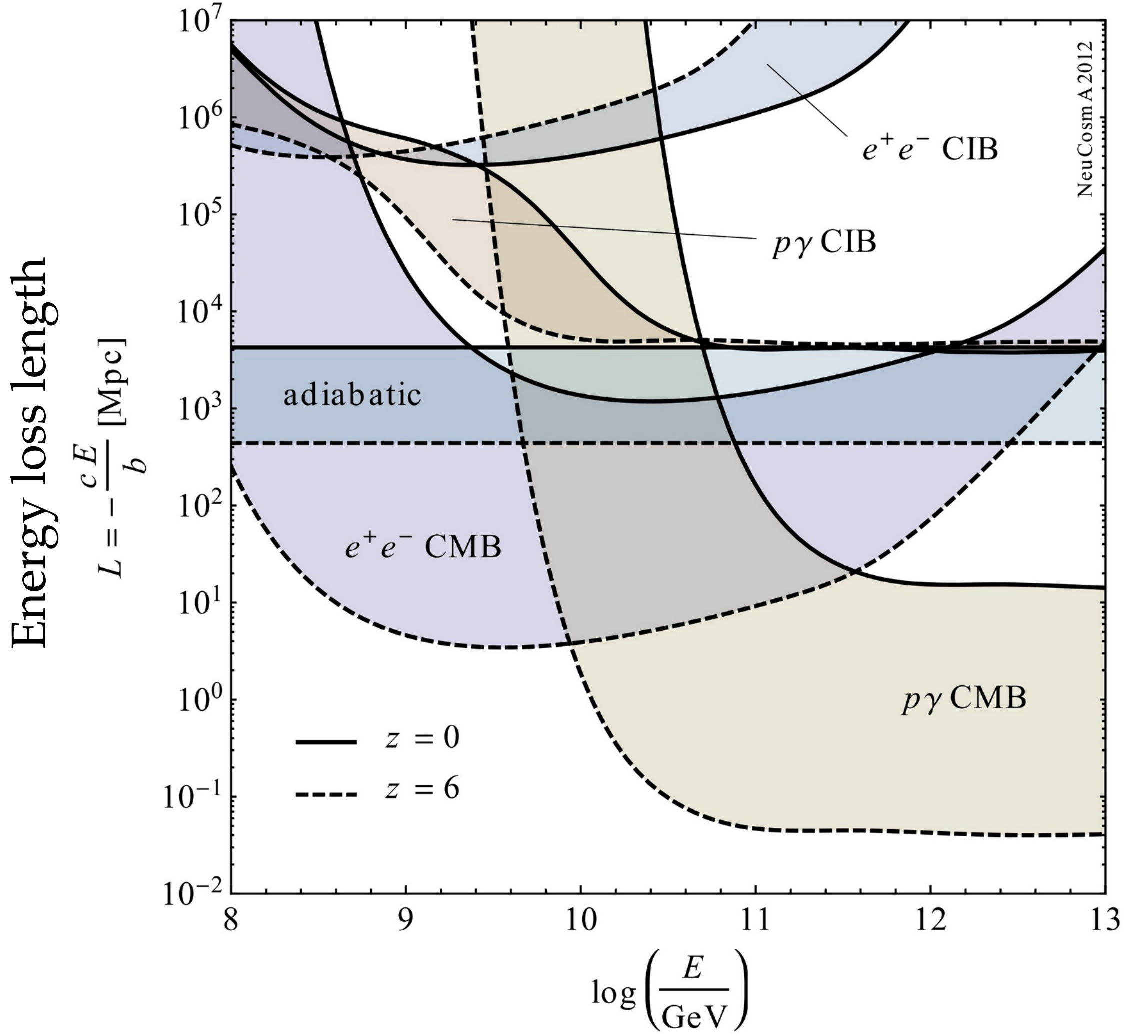
Calculating the UHECR flux at Earth

The redshift evolution of CIB is more complex than CMB

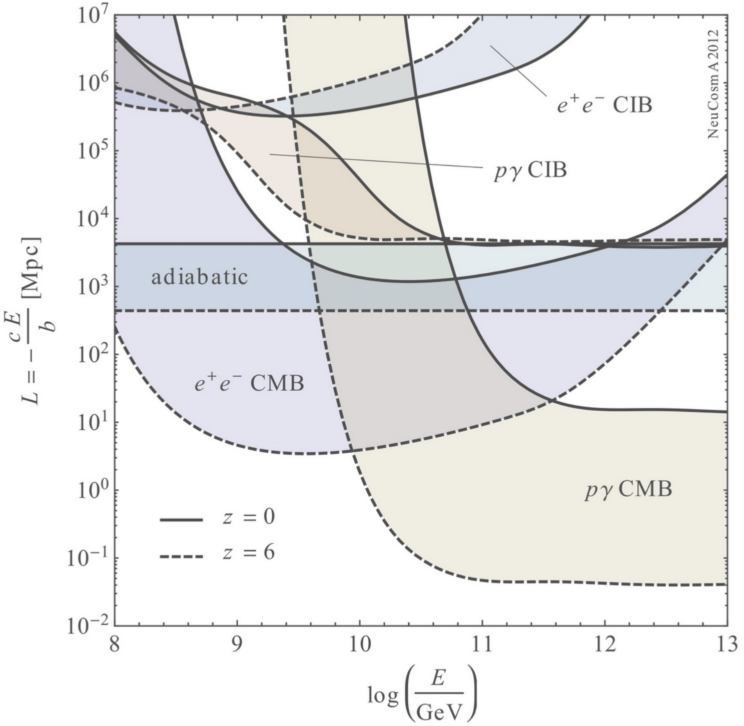


CIB number density is $\ll$ CMB number density, so there are fewer UHECR interactions on CIB photons ($b_{\text{CIB}} \ll b_{\text{CMB}}$)

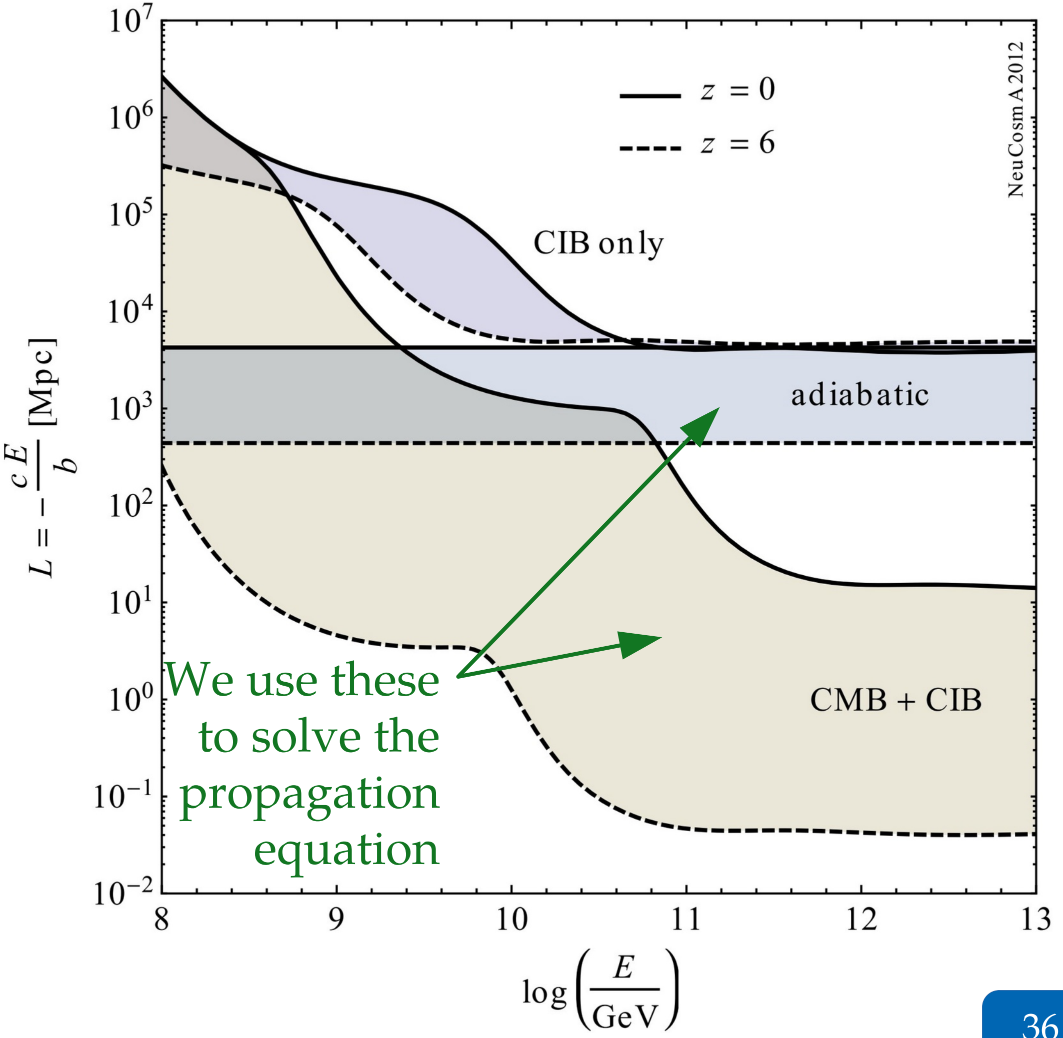
Calculating the UHECR flux at Earth



Calculating the UHECR flux at Earth



Faster energy-loss process dominates



We use these to solve the propagation equation

The Universe is opaque to UHECRs

Photohadronic processes:

$$p + \gamma \rightarrow \Delta \rightarrow \begin{cases} p + \pi^0 \quad \hookrightarrow \gamma + \gamma \\ n + \pi^+ \quad \hookrightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e + e^+ \end{cases}$$

Pair production:

$$p + \gamma \rightarrow p + e^- + e^+$$

Greisen-Zatsepin-Kuzmin (GZK) cut-off:

$$E_p \approx \frac{0.16\ \mathrm{GeV}^2}{0.66\ \mathrm{meV}} \approx 2 \cdot 10^{11}\ \mathrm{GeV}$$

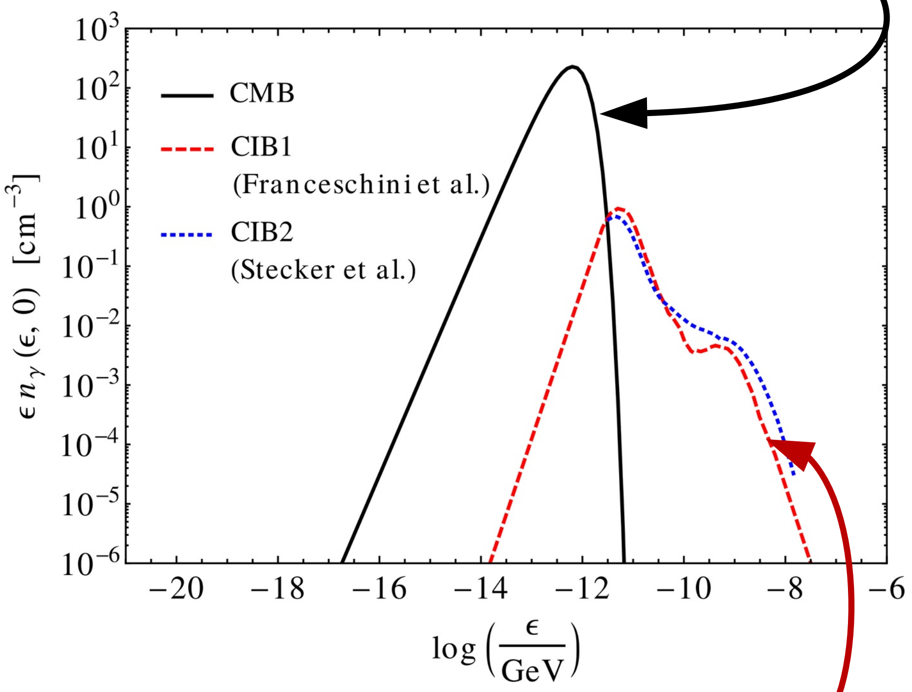
(Assuming only photohadronic interaction)

Accounting also for pair production and CMB width:

$$E_p \approx 5 \cdot 10^{10}\ \mathrm{GeV}$$

Target photon spectra (at $z = 0$):

CMB: Microwave (black body, <ϵ> ~ 0.66 meV)



CIB: optical (stars) + infrared (dust remission)

$n_\gamma(z) = (1+z)^3\, n_\gamma(z=0)$ (exact only for CMB)

Greisen *PRL* 1966; Zatsepin & Kuzmin, *JETP* 1966

The Universe is opaque to UHECRs

Photohadronic processes:

$$p + \gamma \rightarrow \Delta \rightarrow \begin{cases} p + \pi^0 \quad \Rsh\ \gamma + \gamma \\ n + \pi^+ \quad \Rsh\ \nu_\mu + \bar{\nu}_\mu + \nu_e + e^+ \end{cases}$$

Pair production:

$$p + \gamma \rightarrow p + e^- + e^+$$

Greisen-Zatsepin-Kuzmin (GZK) cut-off:

$$E_p \approx \frac{0.16 \text{ GeV}^2}{0.66 \text{ meV}} \approx 2 \cdot 10^{11} \text{ GeV}$$

(Assuming only photohadronic interaction)

Accounting also for pair production and CMB width:

$$E_p \approx 5 \cdot 10^{10} \text{ GeV}$$

Mean free path:

$$(n_\gamma \langle\sigma\rangle_{p\gamma})^{-1} = (413 \text{ cm}^{-3} \times 200\ \mu\text{barn})^{-1}$$
$$\approx 10^{25} \text{ cm}$$
$$\approx 4 \text{ Mpc}$$

Energy-loss scale:

$$L = (E/\Delta E)(n_\gamma \langle\sigma\rangle_{p\gamma})^{-1}$$
$$\approx (1/0.2) \times 4 \text{ Mpc}$$
$$\approx 20 \text{ Mpc}$$

A more detailed calculation yields

$$L_{\text{GZK}} \approx 100 \text{ Mpc}$$

Greisen *PRL* 1966; Zatsepin & Kuzmin, *JETP* 1966

The Universe is opaque to UHECRs

Photohadronic processes:

$$p + \gamma \rightarrow \Delta \rightarrow \begin{cases} p + \pi^0 \quad \Rightarrow \gamma + \gamma \\ n + \pi^+ \quad \Rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e + e^+ \end{cases}$$

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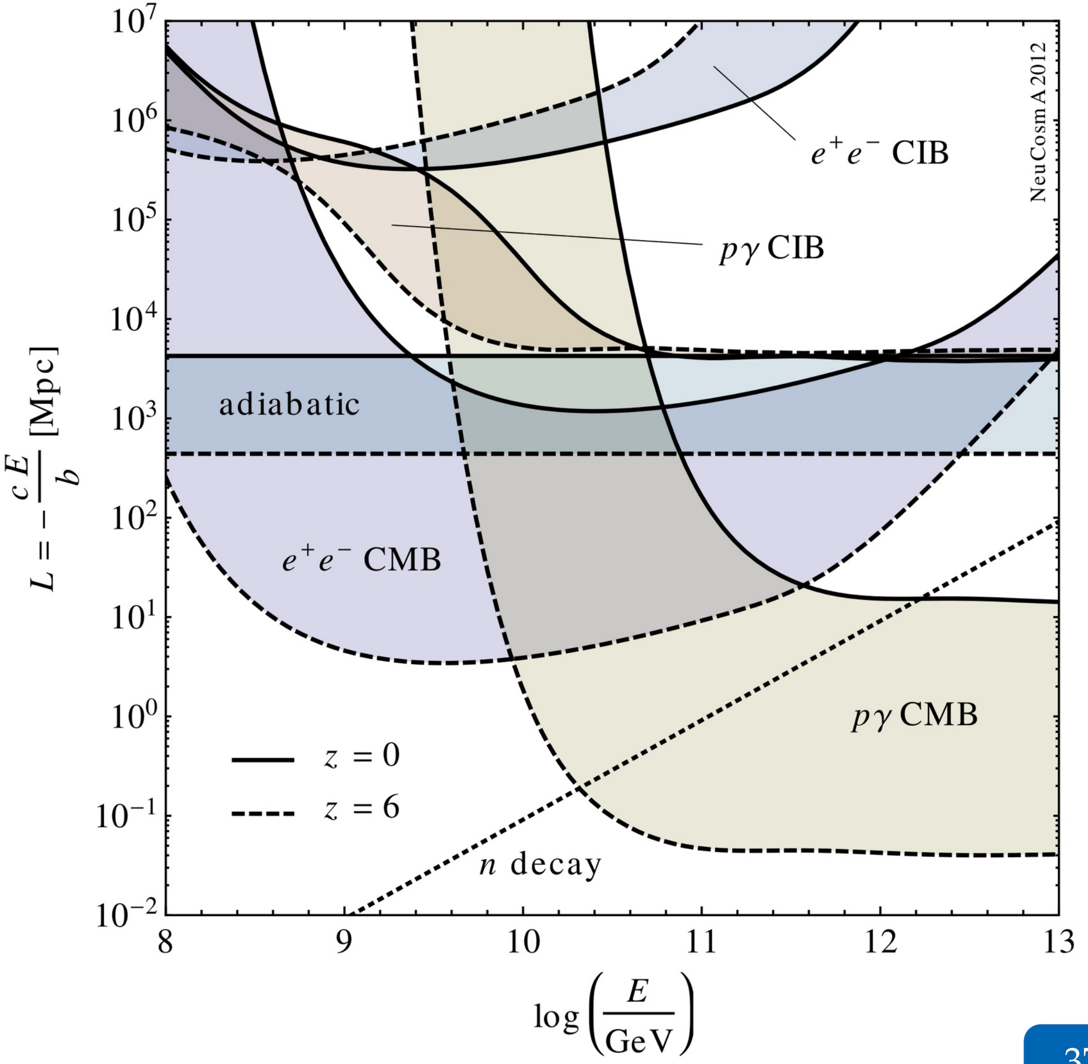


Greisen *PRL* 1966; Zatsepin & Kuzmin, *JETP* 1966

The Universe is *also* opaque to PeV gamma rays

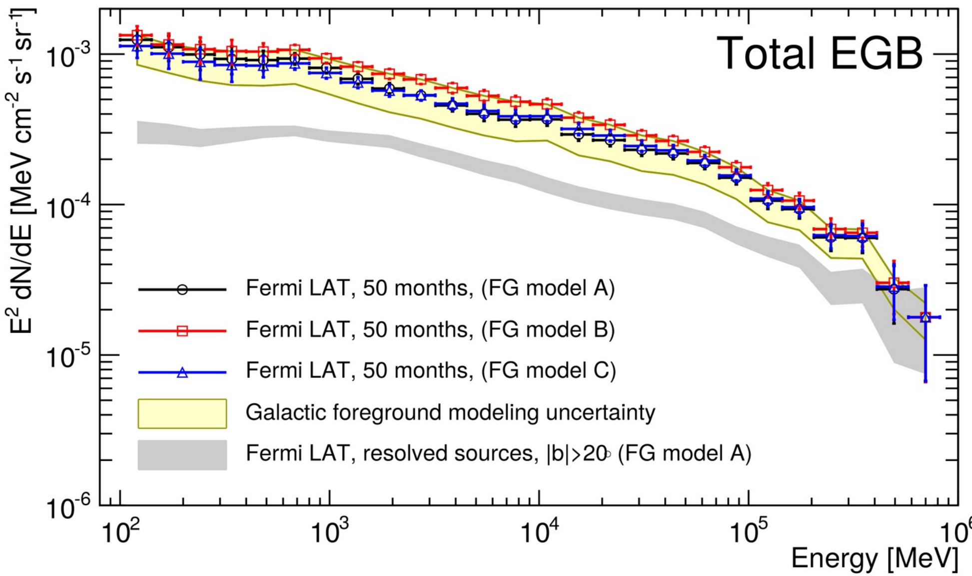
Pair production:

$$\gamma_{\text{astro}} + \gamma_{\text{cosmo}} \rightarrow e^- + e^+$$

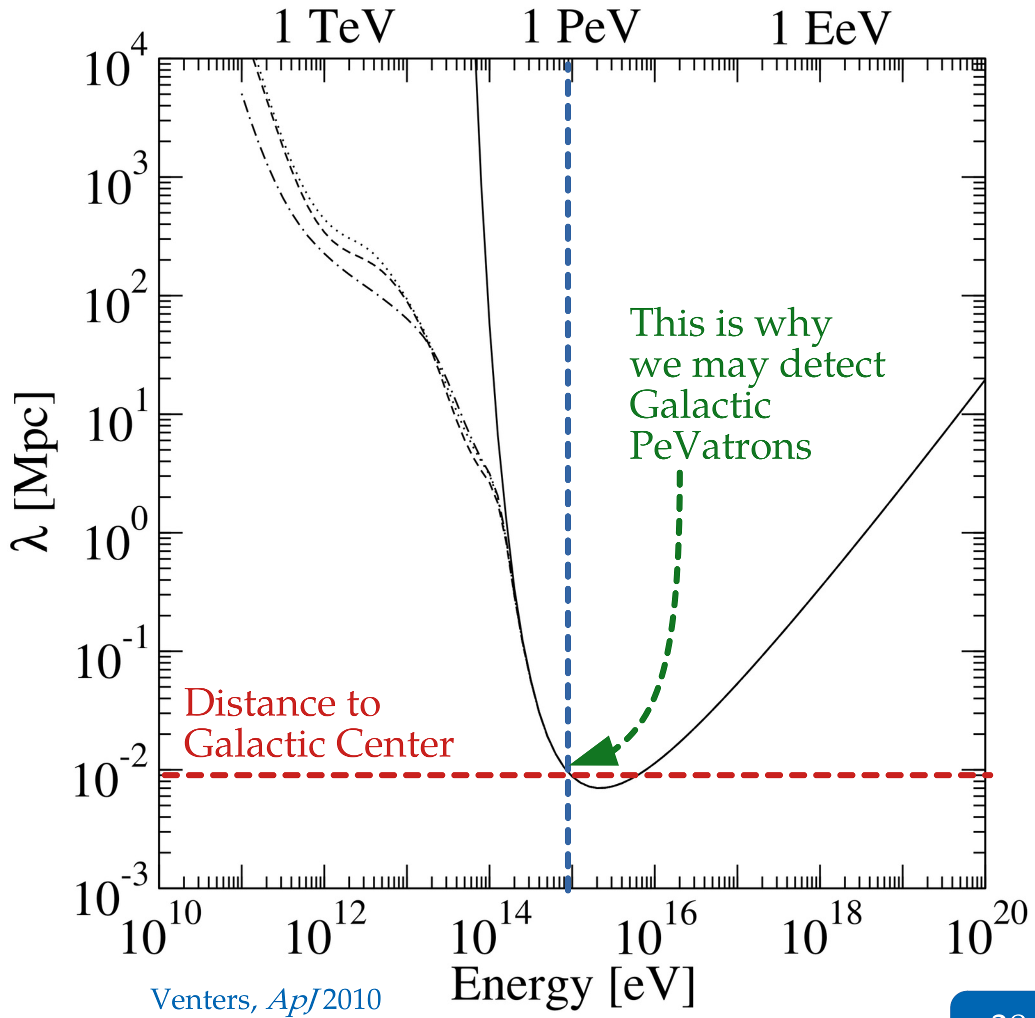
Inverse Compton scattering:

$$e^{\pm} + \gamma_{\text{cosmo}} \rightarrow e^{\pm} + \gamma$$

PeV gamma rays cascade down to MeV–GeV:



Fermi-LAT, *ApJ* 2015



Venters, *ApJ* 2010

Calculating the UHECR flux at Earth

Putting it all together…

$$\partial_z Y_p(E,z) = \frac{-1}{(1+z)H(z)} \{\partial_E(H(z)EY_p(E,z)) + \partial_E(b_{e^+e^-}(E,z)Y_p(E,z)) + \partial_E(b_{p\gamma}(E,z)Y_p(E,z)) + \mathcal{L}_{\rm CR}(E,z)\}$$

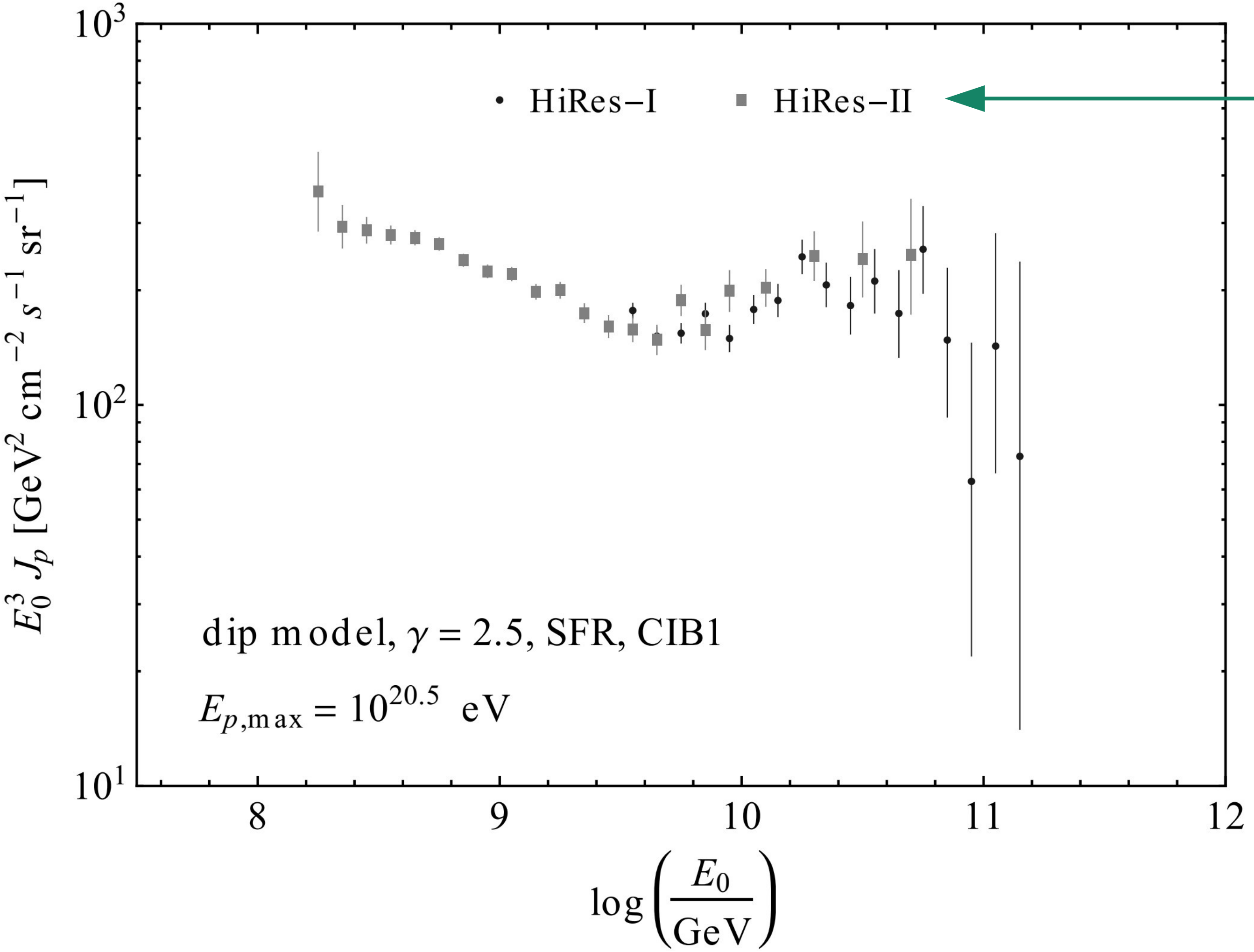
Evolve
numerically
from $z_{\rm max} \sim 4$
to Earth ($z = 0$)

Diffuse UHECR proton flux at Earth (GeV^{-1} cm^{-2} s^{-1} sr^{-1}):

$$J_p(E) = \underbrace{\frac{c}{4\pi}} n_p(E, z=0)$$

This factor converts density to flux

Calculating the UHECR flux at Earth



Old UHECR data (just as example)

Calculating the UHECR flux at Earth

Compare our predicted flux to the measured flux:

$$\underbrace{\chi^2(\overbrace{J_{p,0}}^{\text{Flux normalization}}, \delta_E)}_{\text{Energy shift (nuisance)}} = \sum_i^{\text{data}} \left(\frac{E^3 J_p(J_{p,0}) - \overbrace{\left(E^3 J_p\right)_i^{\text{HiRes}}}^{\text{Flux data points}}}{\underbrace{\sigma_i}_{\text{Uncertainty of } i\text{-th data point}}} \right)^2 + \underbrace{\left(\frac{\delta_E}{\sigma_E} \right)^2}_{\text{Systematic energy uncertainty}}$$

Minimize the function with respect to $J_{p,0}$ and δ_E

Note: This is a simplified setup; in reality, many flux parameters are jointly varied

Calculating the UHECR flux at Earth

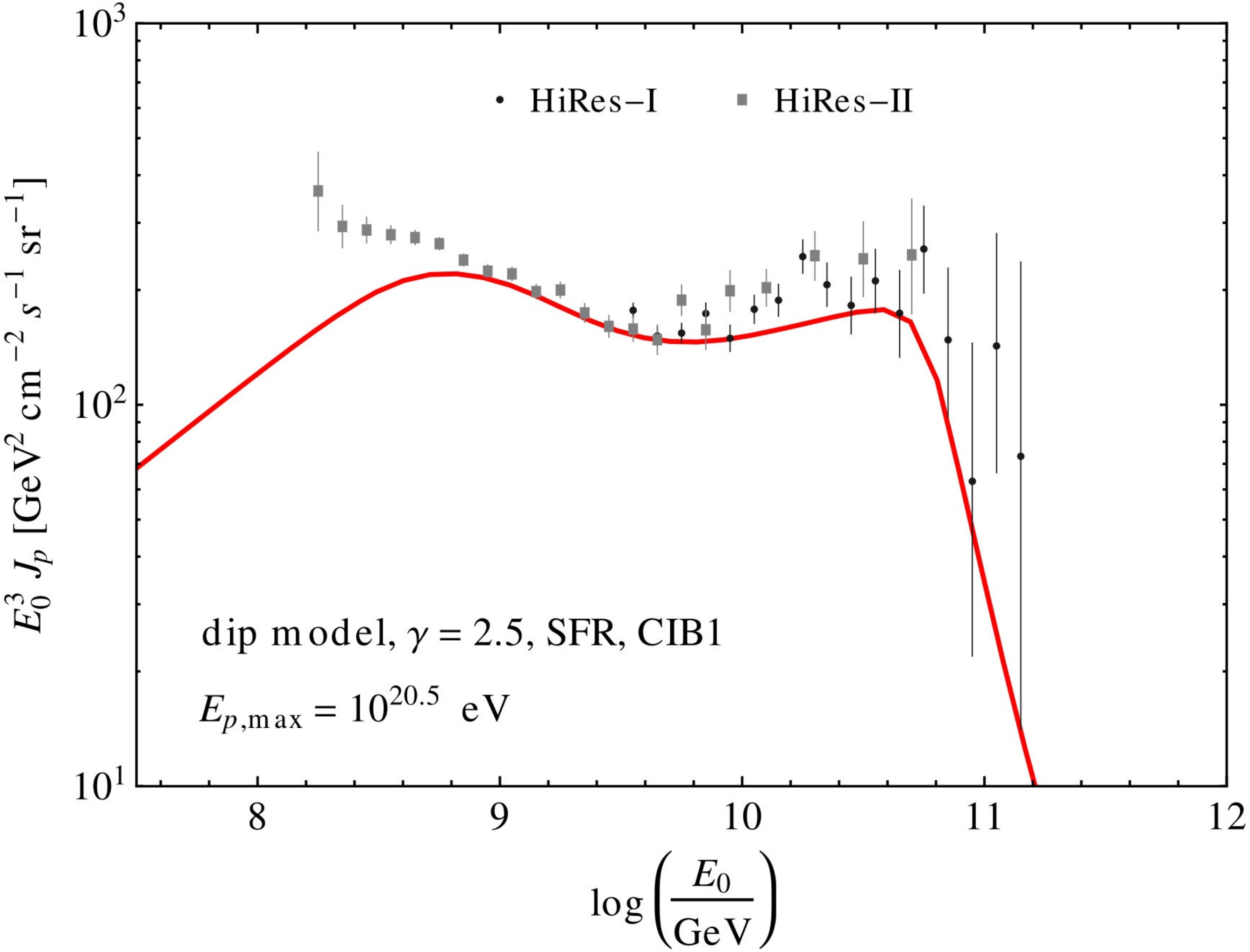
Compare our predicted flux to the measured flux:

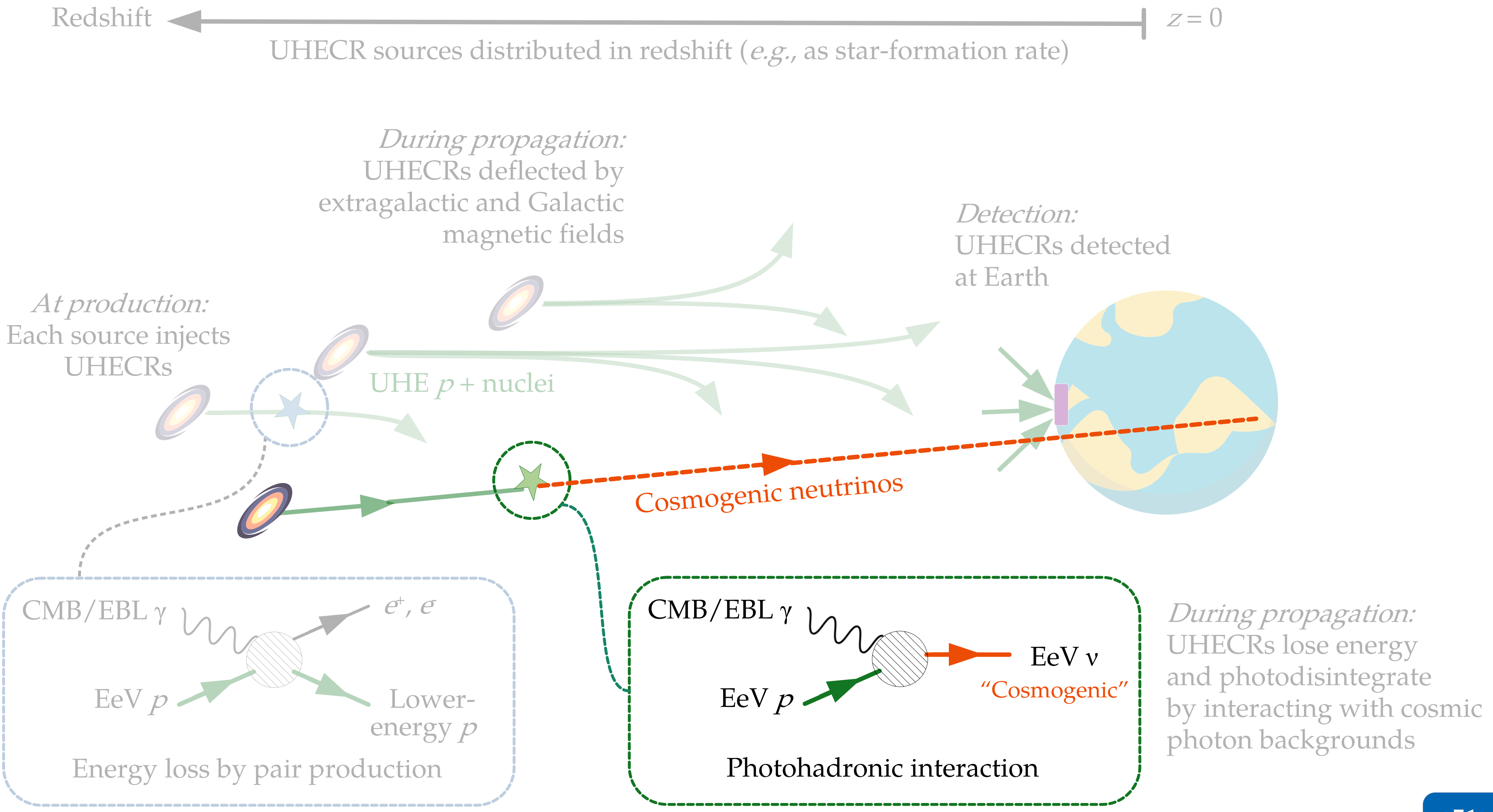
$$\chi^2(\overbrace{J_{p,0}}^{\text{Flux normalization}}, \underbrace{\delta_E}_{\text{Energy shift (nuisance)}}) = \sum_i^{\text{data}} \left(\frac{E^3 J_p(J_{p,0}) - \overbrace{(E^3 J_p)_i^{\text{HiRes}}}^{\text{Flux data points}}}{\underbrace{\sigma_i}_{\text{Uncertainty of } i\text{-th data point}}} \right)^2 + \underbrace{\left(\frac{\delta_E}{\underbrace{\sigma_E}_{\text{Systematic energy uncertainty}}} \right)^2}_{\text{"Pull term"}}$$

Minimize the function with respect to $J_{p,0}$ and δ_E

Note: This is a simplified setup; in reality, many flux parameters are jointly varied

Calculating the UHECR flux at Earth





Redshift
$z = 0$
UHECR sources distributed in redshift (*e.g.*, as star-formation rate)
During propagation:
UHECRs deflected by
extragalactic and Galactic
magnetic fields
Detection:
UHECRs detected
at Earth
At production:
Each source injects
UHECRs
UHE p + nuclei
Cosmogenic neutrinos
CMB/EBL γ
e^+, e^-
EeV p
Lower-energy p
Energy loss by pair production
CMB/EBL γ
EeV ν
"Cosmogenic"
EeV p
Photohadronic interaction
During propagation:
UHECRs lose energy
and photodisintegrate
by interacting with cosmic
photon backgrounds

What about the cosmogenic neutrinos?

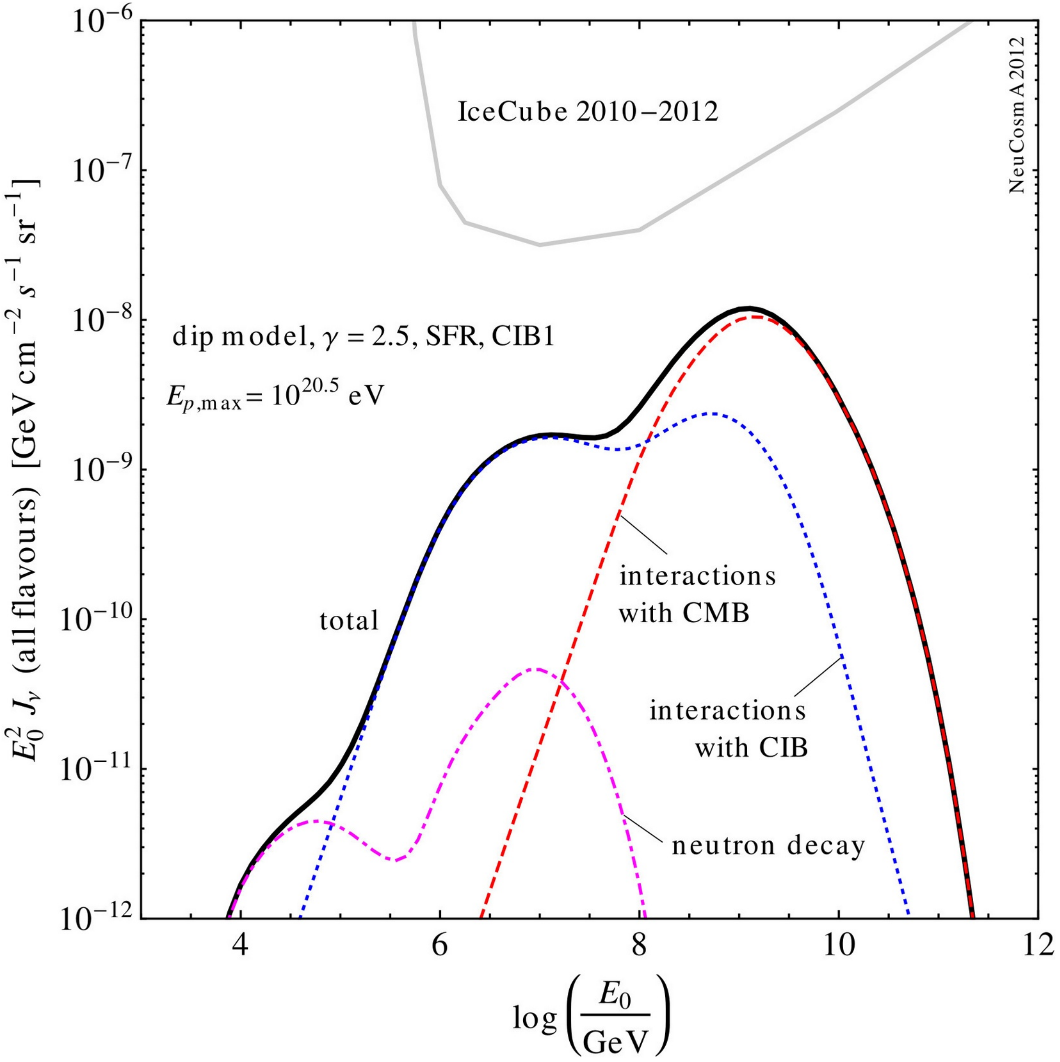
Co-evolve UHECRs and cosmogenic neutrinos:

UHECRs: $$\partial_z Y_p(E,z) = \frac{-1}{(1+z)H(z)} \{\partial_E(H(z)EY_p(E,z)) + \partial_E(b_{e^+e^-}(E,z)Y_p(E,z)) + \partial_E(b_{p\gamma}(E,z)Y_p(E,z)) + \mathcal{L}_{\mathrm{CR}}(E,z)\}$$

Neutrinos: $$\partial_z Y_\nu(E,z) = \frac{-1}{(1+z)H(z)} \{\partial_E(H(z)EY_\nu(E,z)) + \mathcal{L}_\nu(E,z)\}$$

Note: We can propagate gamma rays by adding an additional equation for them

Cosmogenic neutrinos



The position of the ν bump is determined by the Δ-resonance production threshold,

$$E_p E_\gamma \approx 0.2\ \text{GeV}^2 \quad ,$$

and the relation between neutrino energy and proton energy,

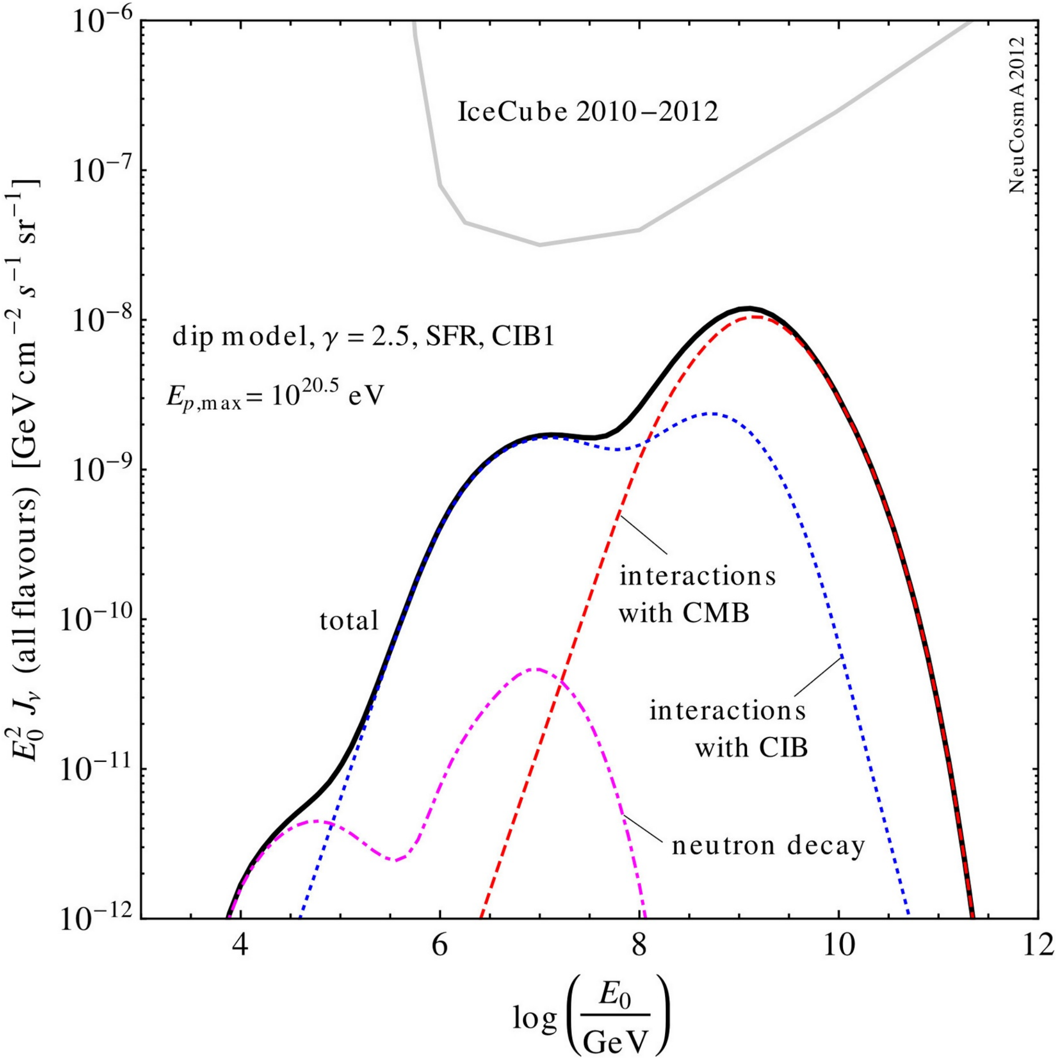
$$E_\nu \approx E_p/20 \, .$$

So the neutrino spectrum peaks at

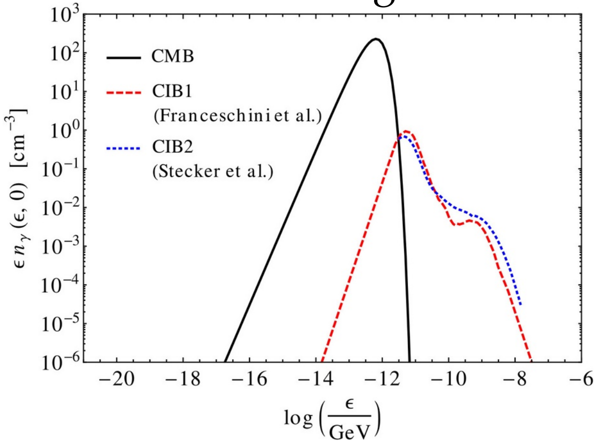
$$E_\nu \approx \frac{0.01\ \text{GeV}}{E_\gamma/\text{GeV}}$$

Let's put this to test ▸

Cosmogenic neutrinos



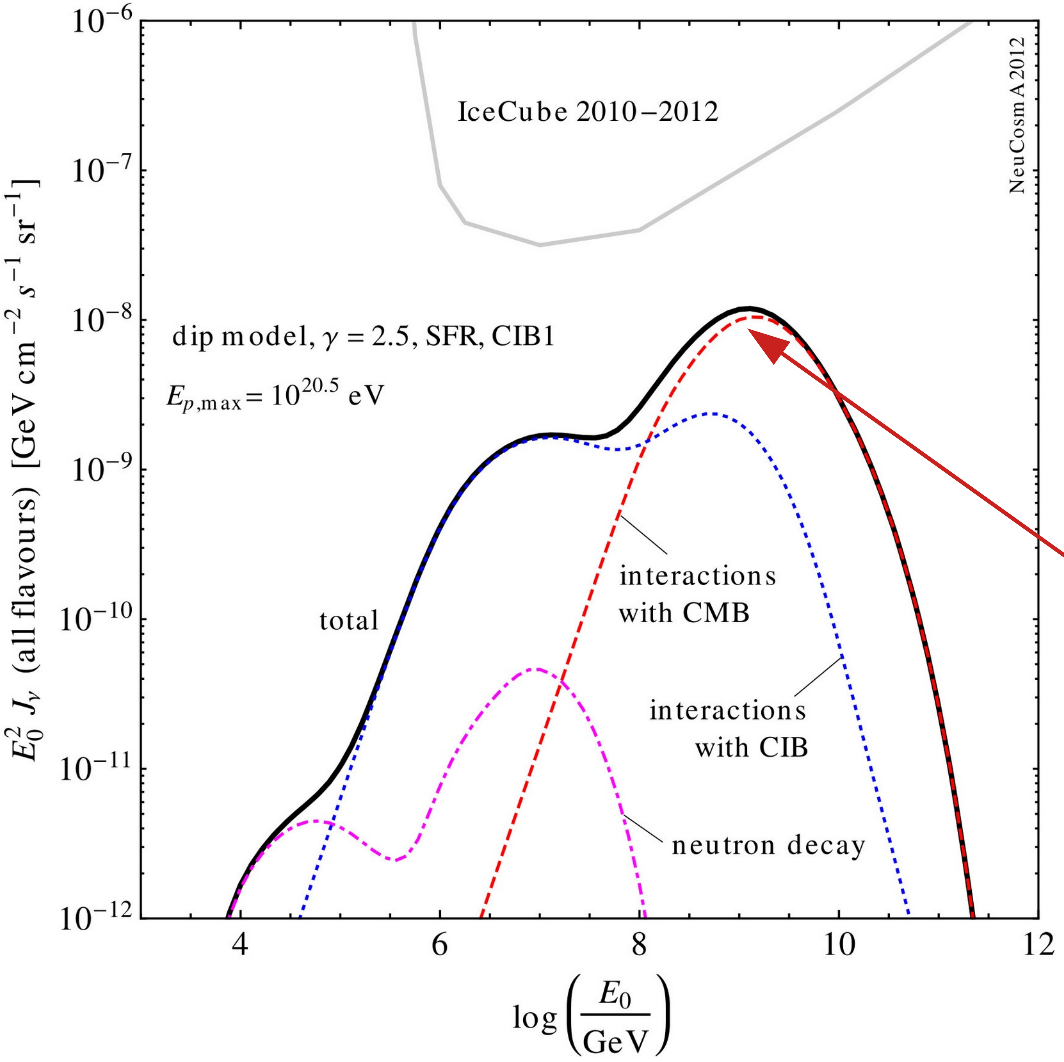
Photon backgrounds

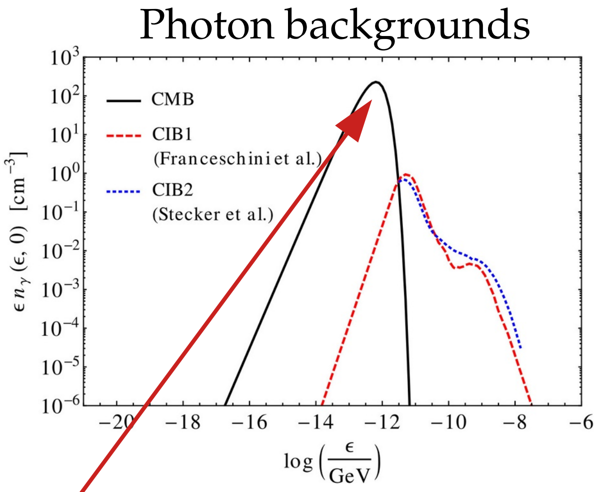


Position of the ν bump from $p\gamma$:

$$E_\nu \approx \frac{0.01\ \mathrm{GeV}}{E_\gamma/\mathrm{GeV}}$$

Cosmogenic neutrinos



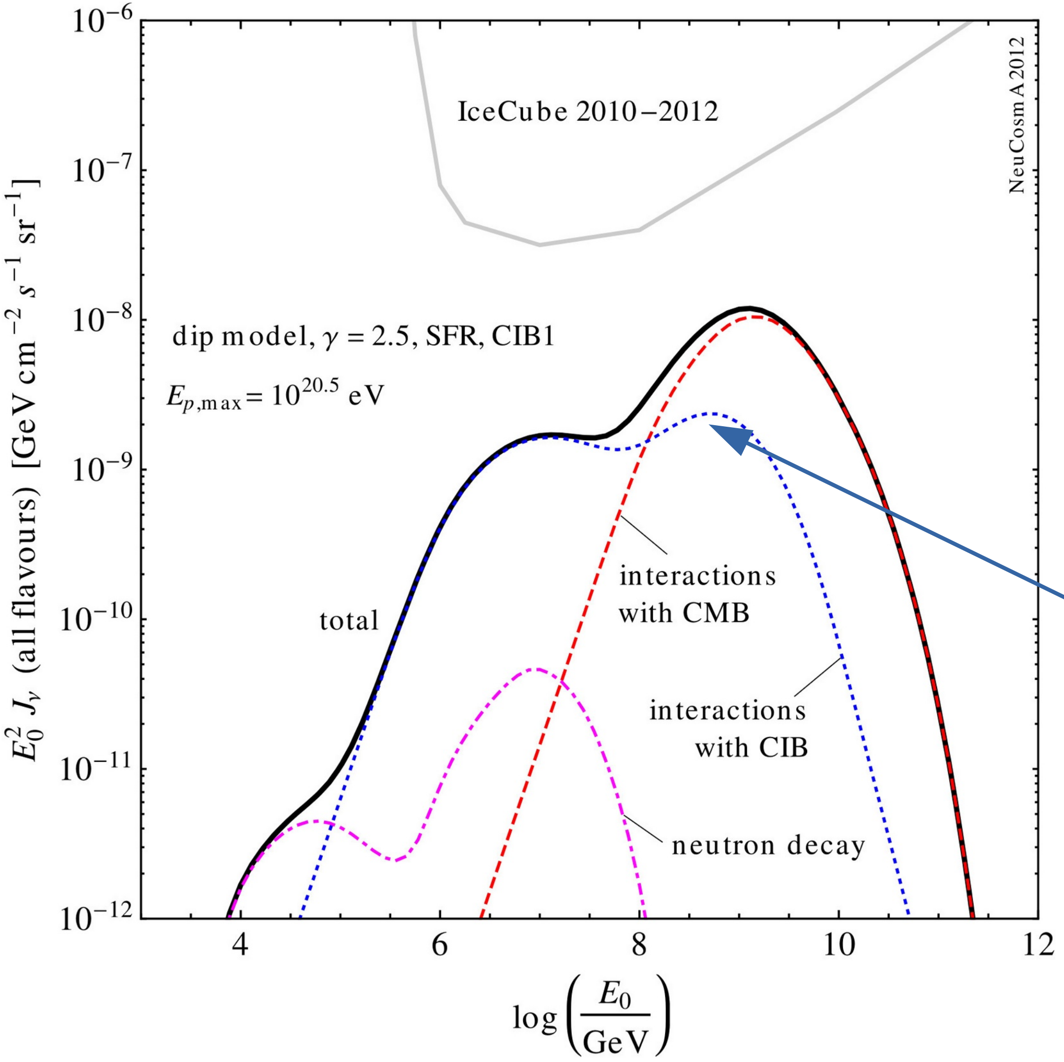


Position of the ν bump from $p\gamma$:

$$E_\nu \approx \frac{0.01\ \text{GeV}}{E_\gamma/\text{GeV}}$$

ν from CMB: $E_\nu \approx \dfrac{0.01\ \text{GeV}}{10^{-12}} = 10^{10}\ \text{GeV}$

Cosmogenic neutrinos



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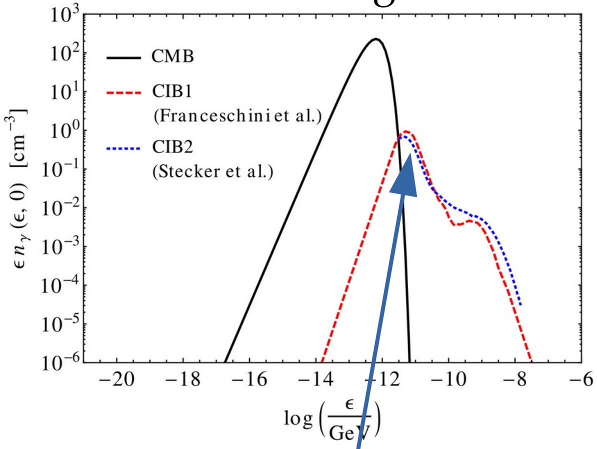

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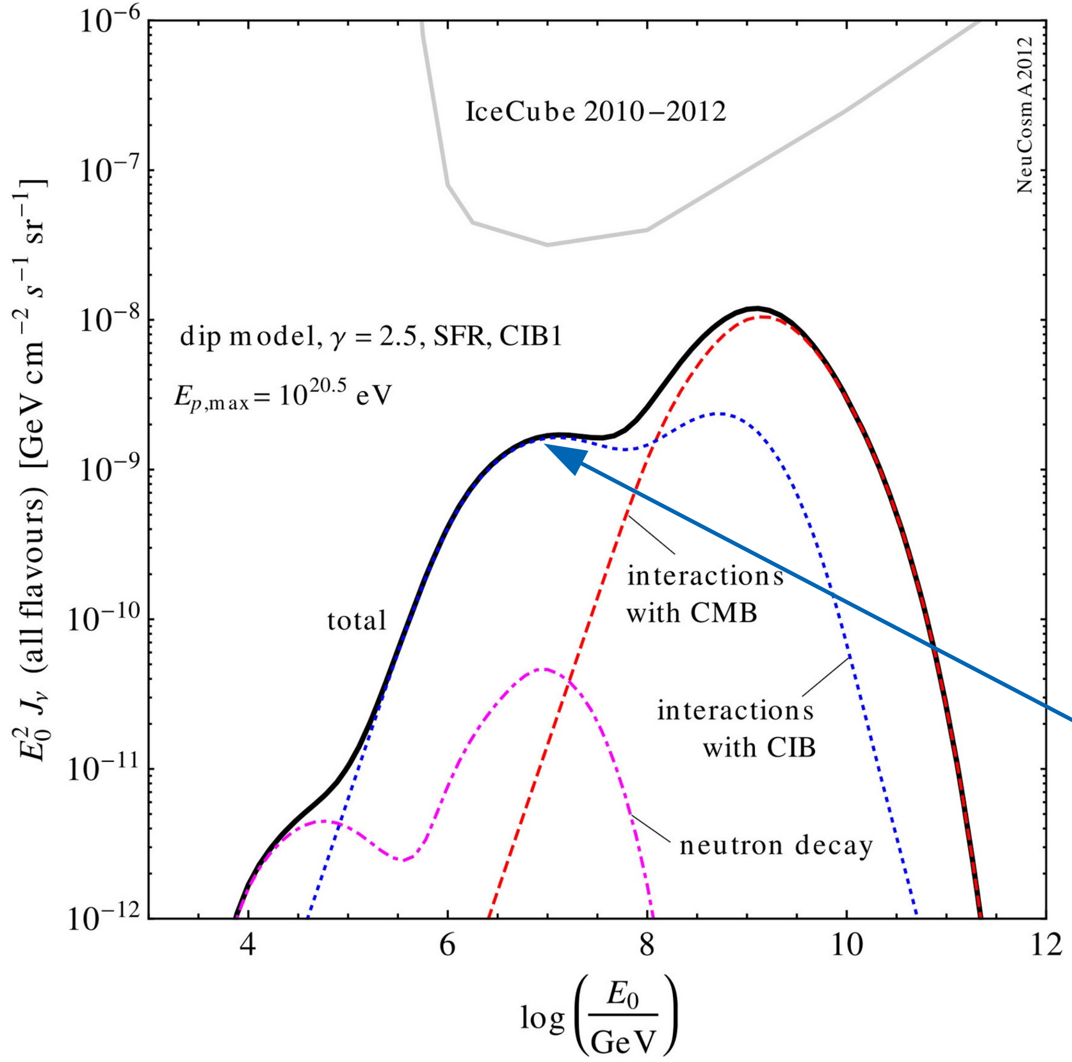
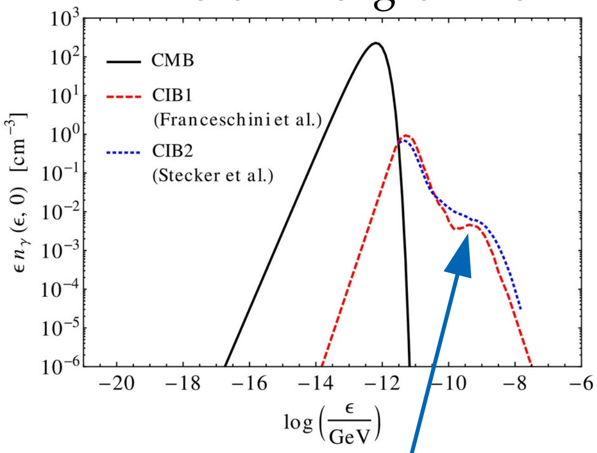
ν from CIB: $E_\nu \approx \frac{0.01\ \mathrm{GeV}}{10^{-11}} = 10^{9}\ \mathrm{GeV}$

Cosmogenic neutrinos



Photon backgrounds



Position of the ν bump from *pγ*:

$$E_\nu \approx \frac{0.01\ \text{GeV}}{E_\gamma/\text{GeV}}$$

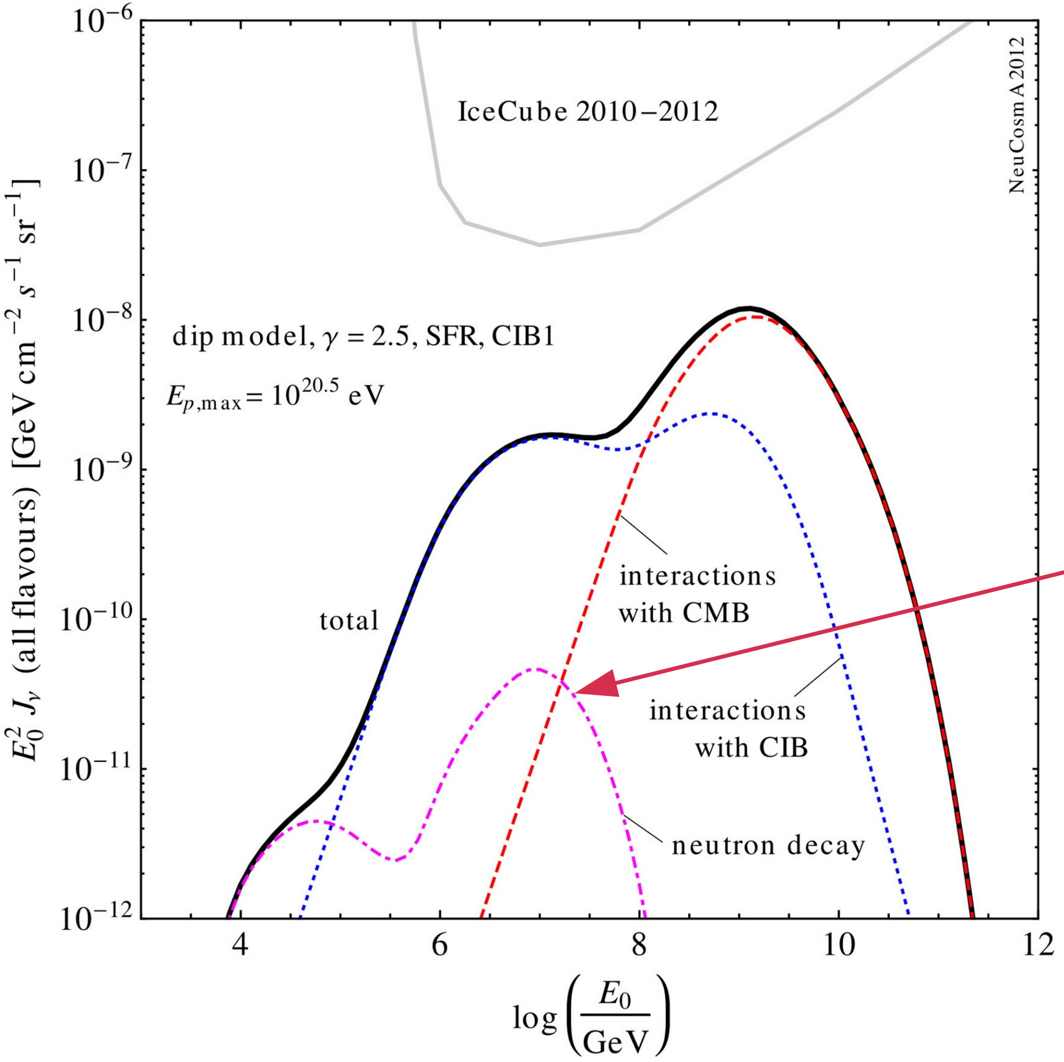
ν from CMB: $E_\nu \approx \dfrac{0.01\ \text{GeV}}{10^{-12}} = 10^{10}\ \text{GeV}$

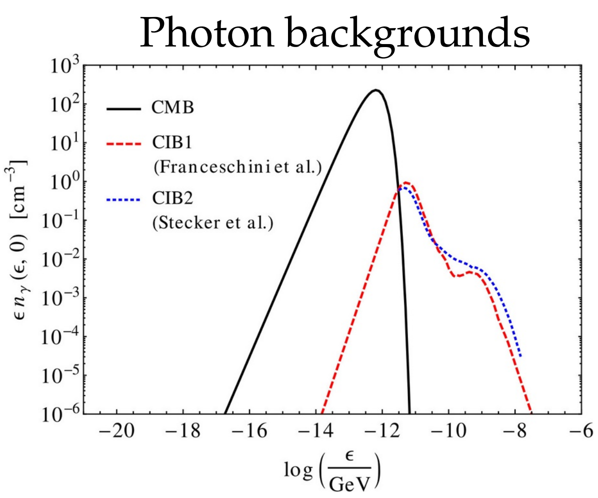
ν from CIB:

$$E_\nu \approx \frac{0.01\ \text{GeV}}{10^{-11}} = 10^{9}\ \text{GeV}$$

$$E_\nu \approx \frac{0.01\ \text{GeV}}{10^{-9}} = 10^{7}\ \text{GeV}$$

Cosmogenic neutrinos





Position of the ν bump from *p*γ:

$$E_\nu \approx \frac{0.01\ \mathrm{GeV}}{E_\gamma/\mathrm{GeV}}$$

Why are ν from *n* decay lower-energy?

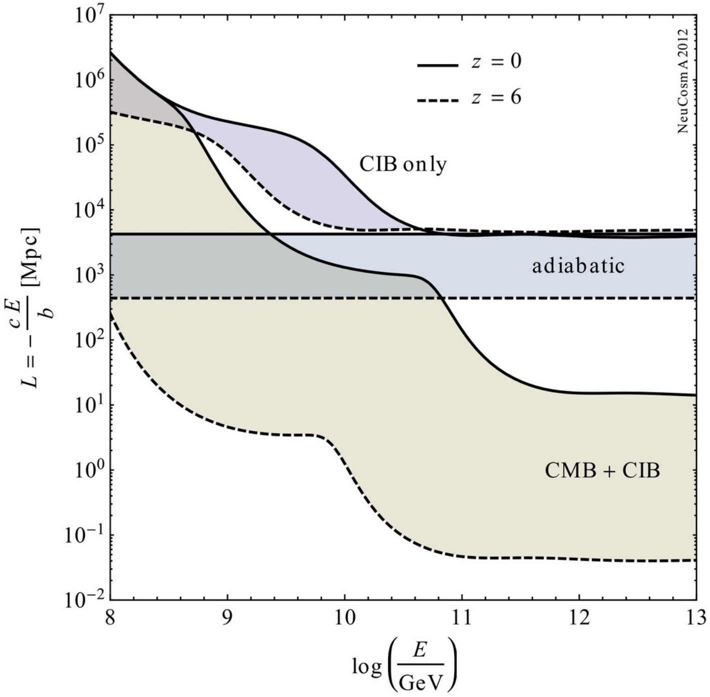
$$n \to p + e^- + \bar{\nu}_e$$

The *n* and *p* mass are very similar …

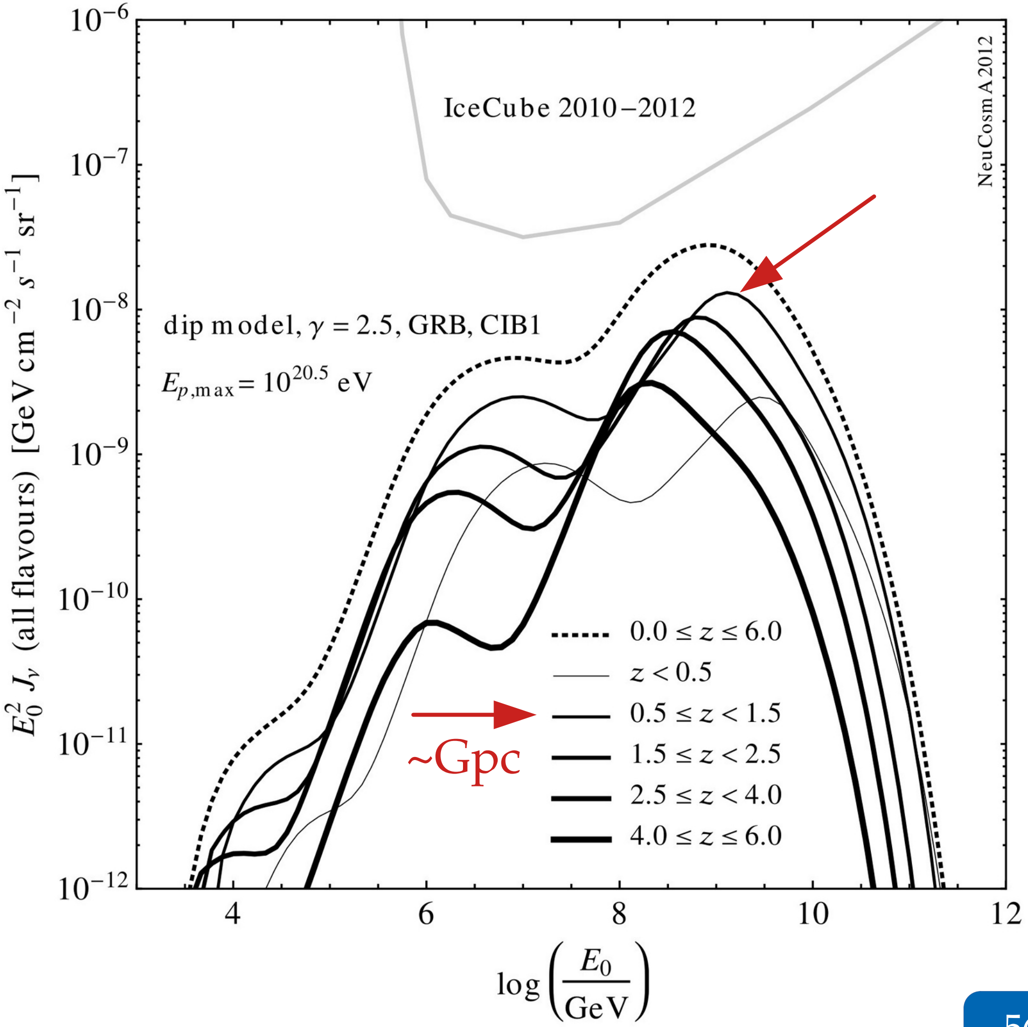
… so there is little energy left for *e*, ν

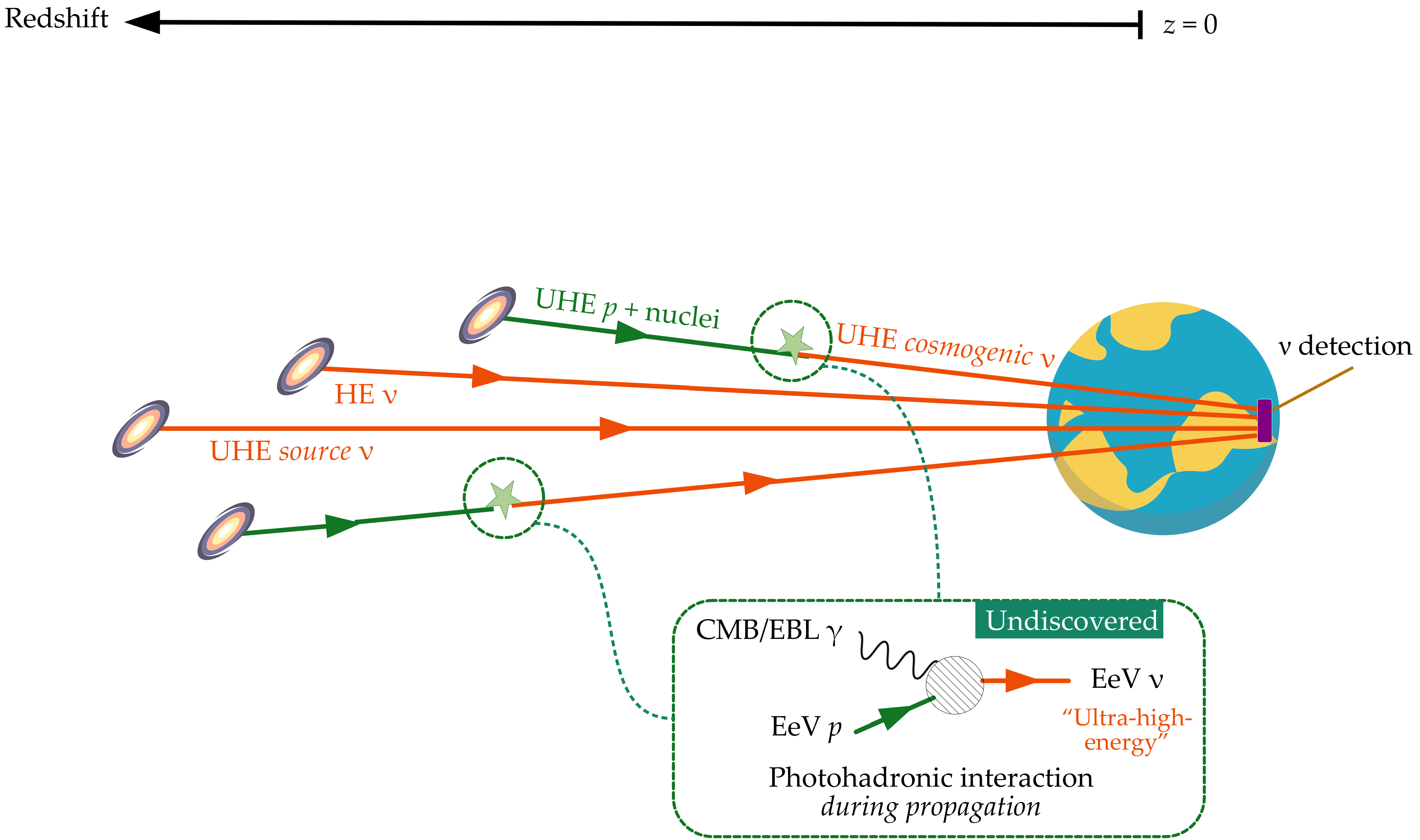
Cosmogenic neutrinos—they come from afar

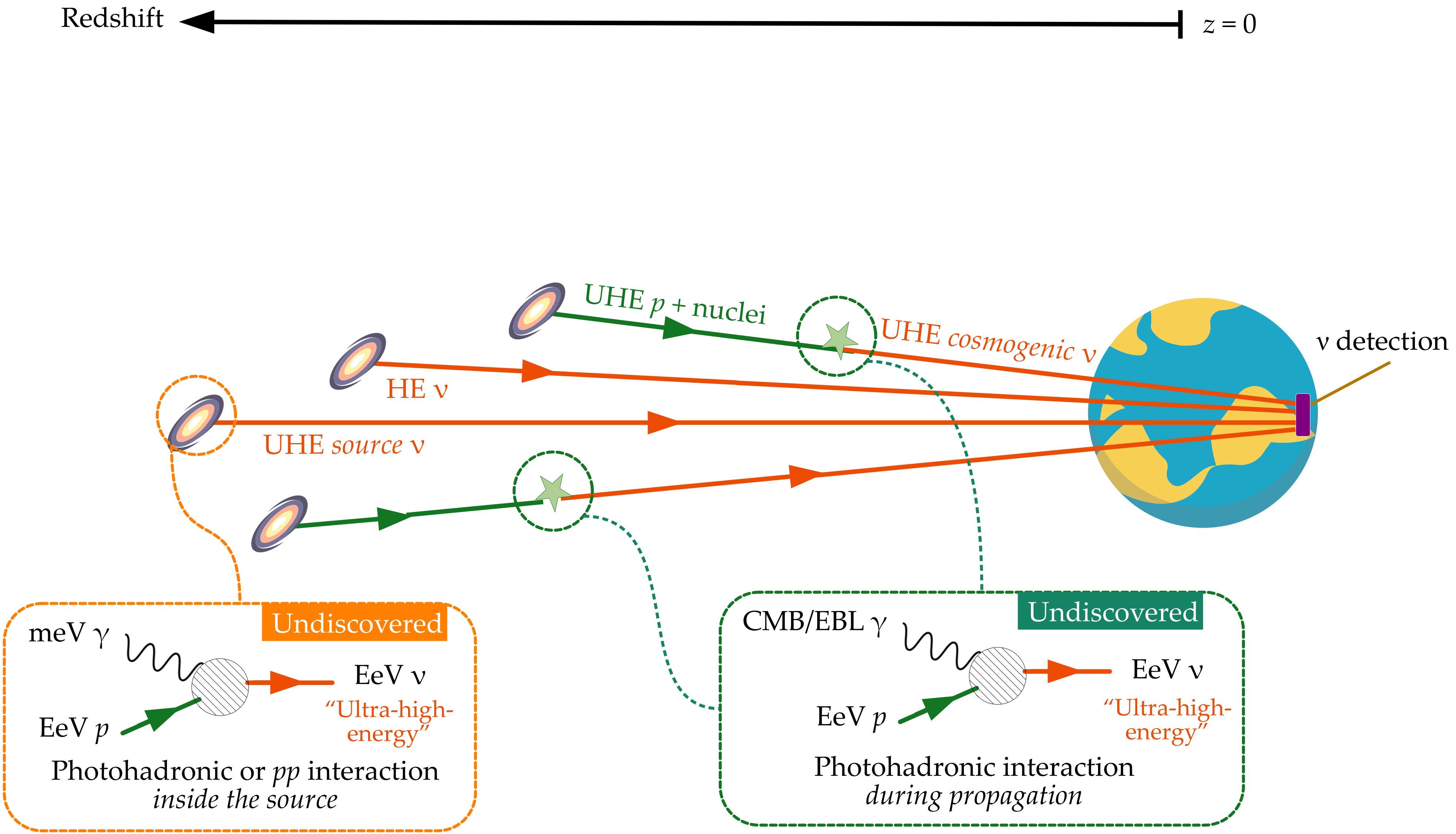
UHECRs cannot travel farther than the GZK horizon (~100 Mpc)



But neutrinos can!



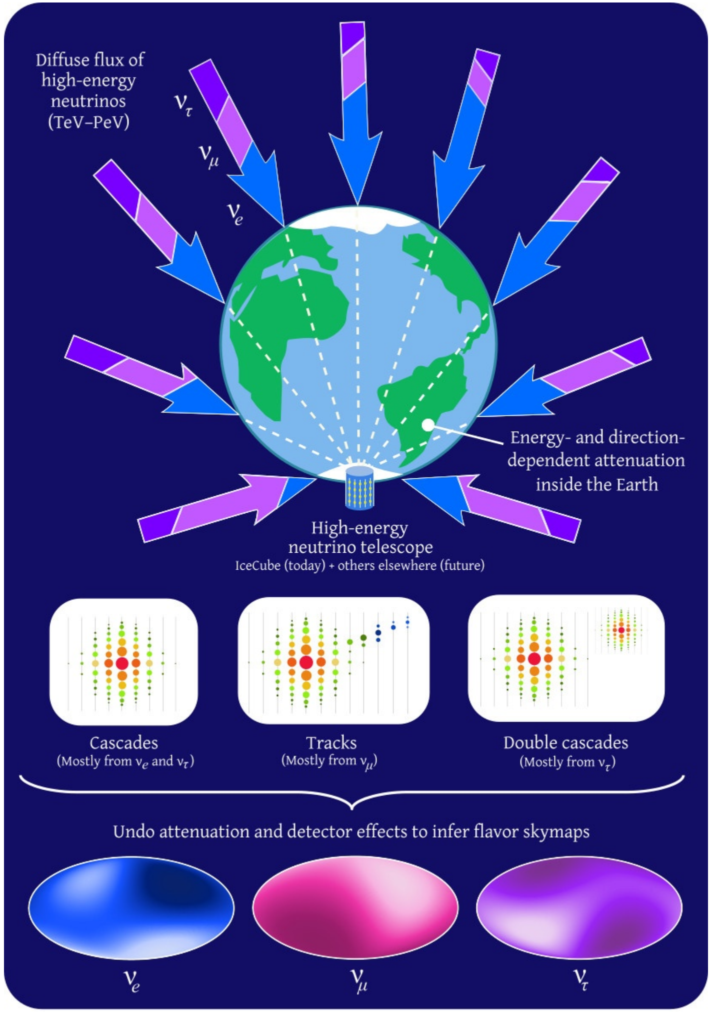

Redshift
$z = 0$
UHE p + nuclei
UHE cosmogenic ν
ν detection
HE ν
UHE source ν
CMB/EBL γ
Undiscovered
EeV ν
EeV p
"Ultra-high-energy"
Photohadronic interaction
during propagation



Redshift
z = 0
UHE p + nuclei
UHE cosmogenic ν
HE ν
UHE source ν
ν detection
Undiscovered
meV γ
EeV ν
EeV p
"Ultra-high-energy"
Photohadronic or pp interaction
inside the source
Undiscovered
CMB/EBL γ
EeV ν
EeV p
"Ultra-high-energy"
Photohadronic interaction
during propagation

Direction-dependent LIV in flavor

Flavor anisotropy in the high-energy neutrino sky



Does the high-energy sky shine equally brightly In neutrinos of all flavors?

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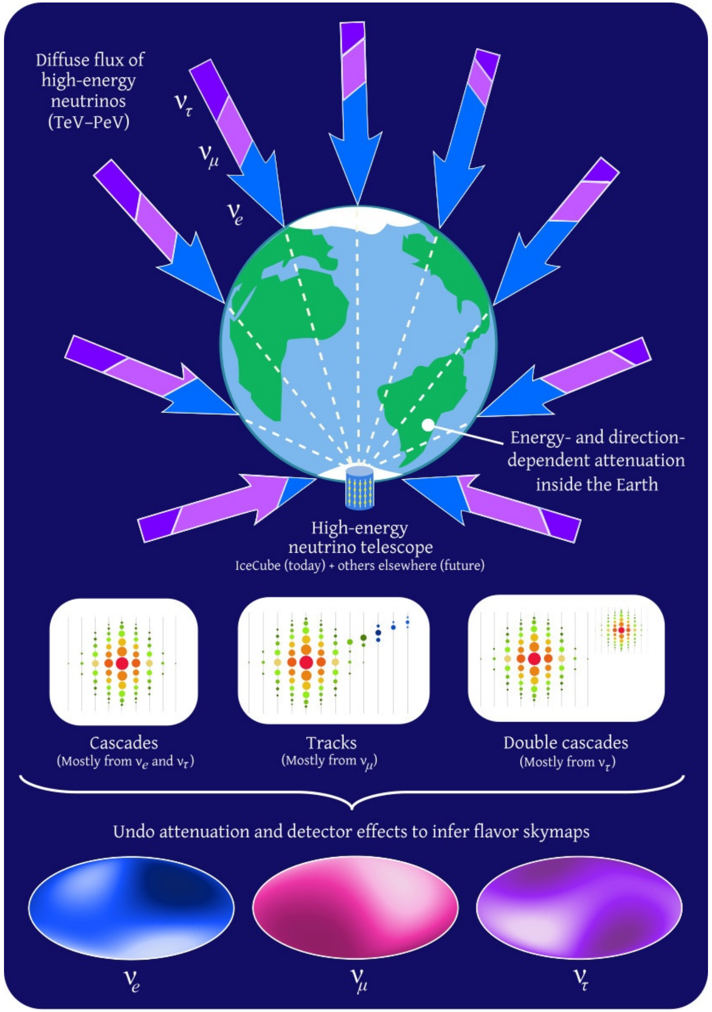
Flavor anisotropy in the high-energy neutrino sky



Does the high-energy sky shine equally brightly
In neutrinos of all flavors?

From the angular distribution of detected events in neutrino telescopes (HESE cascades, tracks, double cascades) …

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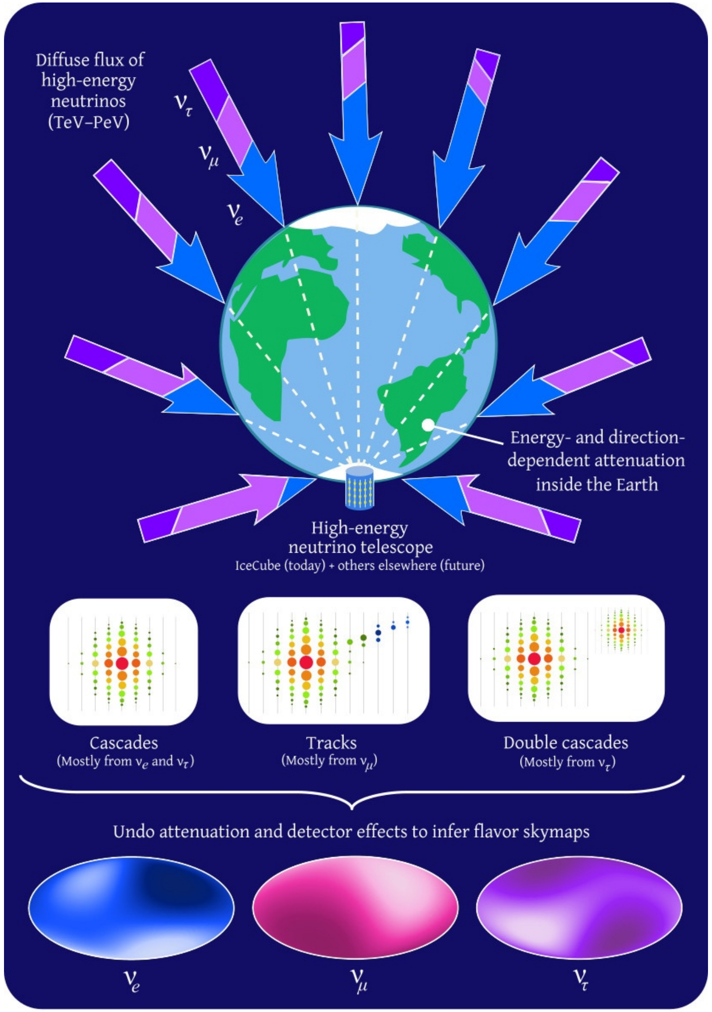
Flavor anisotropy in the high-energy neutrino sky



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… we infer the directional dependence of the diffuse fluxes of ν_e, ν_μ, ν_τ

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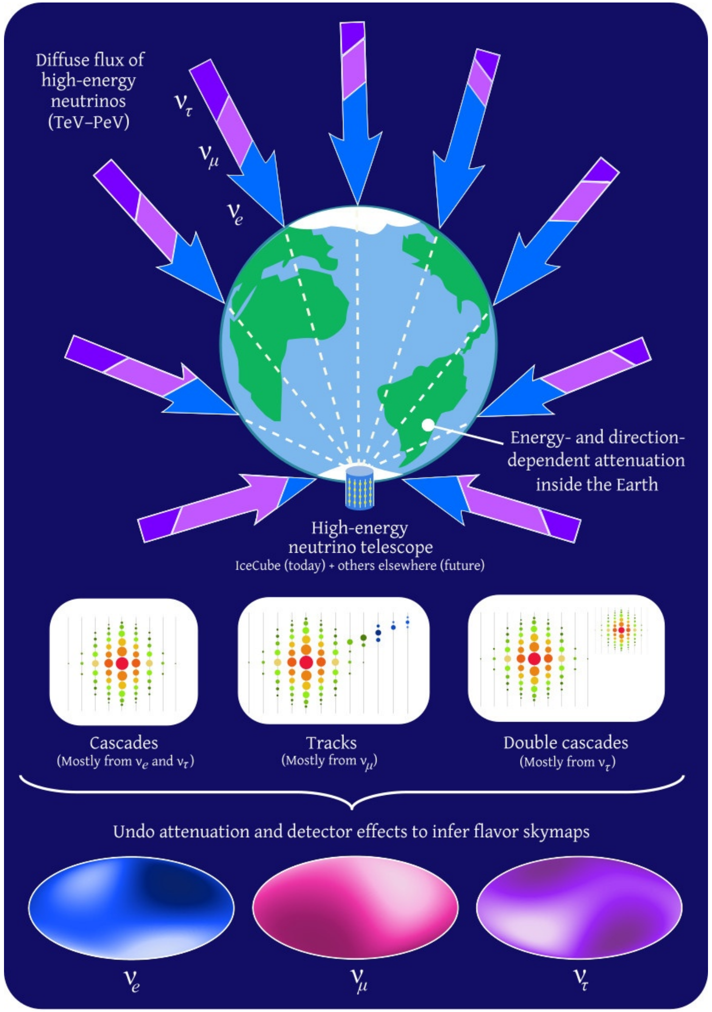
Flavor anisotropy in the high-energy neutrino sky



Does the high-energy sky shine equally brightly In neutrinos of all flavors?

From the angular distribution of detected events in neutrino telescopes (HESE cascades, tracks, double cascades) …

How? Undo detection effects (use public IceCube HESE Monte Carlo)

… we infer the directional dependence of the diffuse fluxes of ν_e, ν_μ, ν_τ

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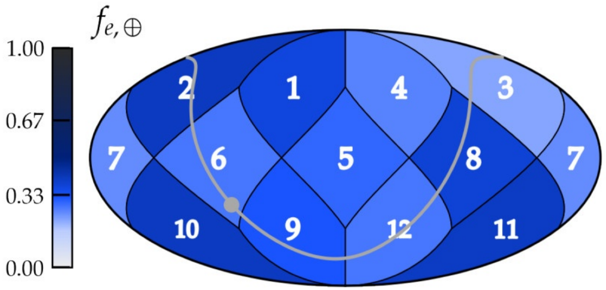
Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)

Real, public data

Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)

Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)



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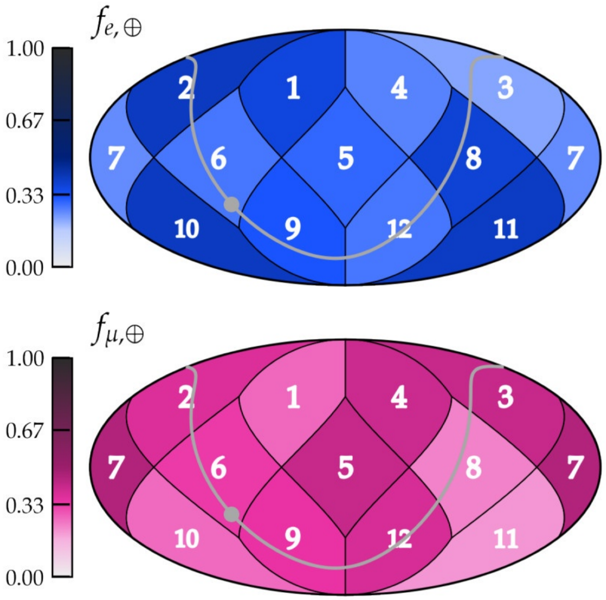

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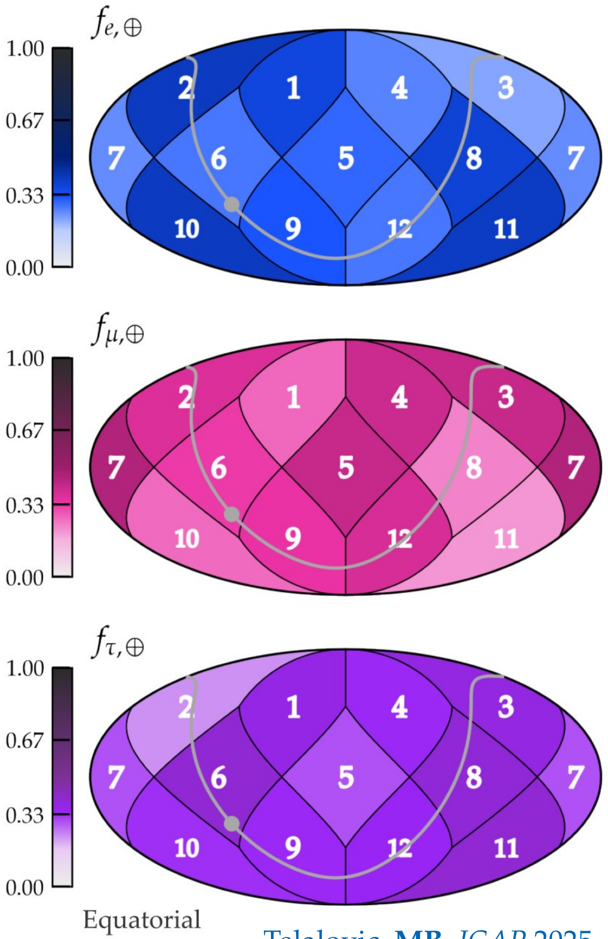

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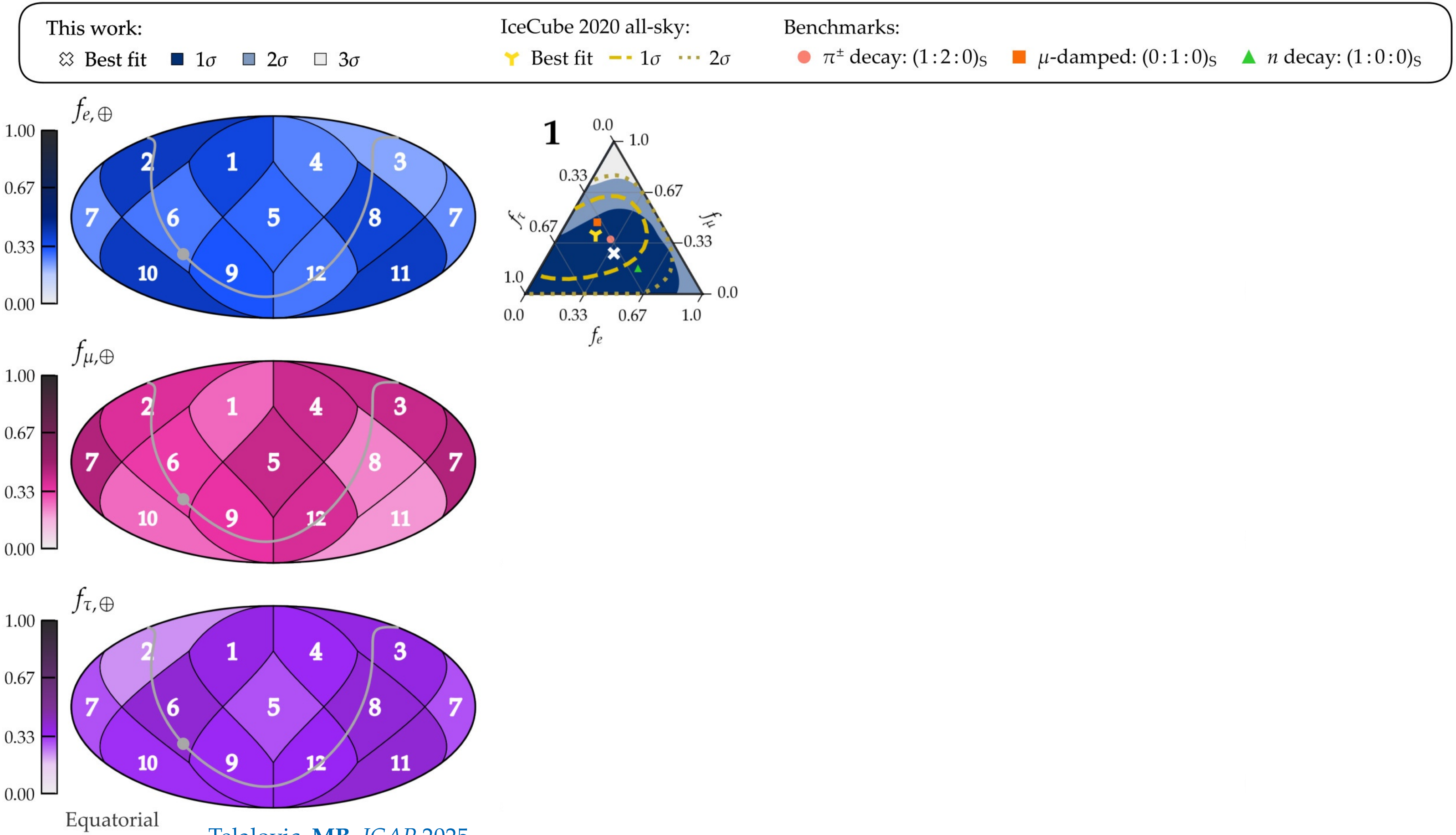

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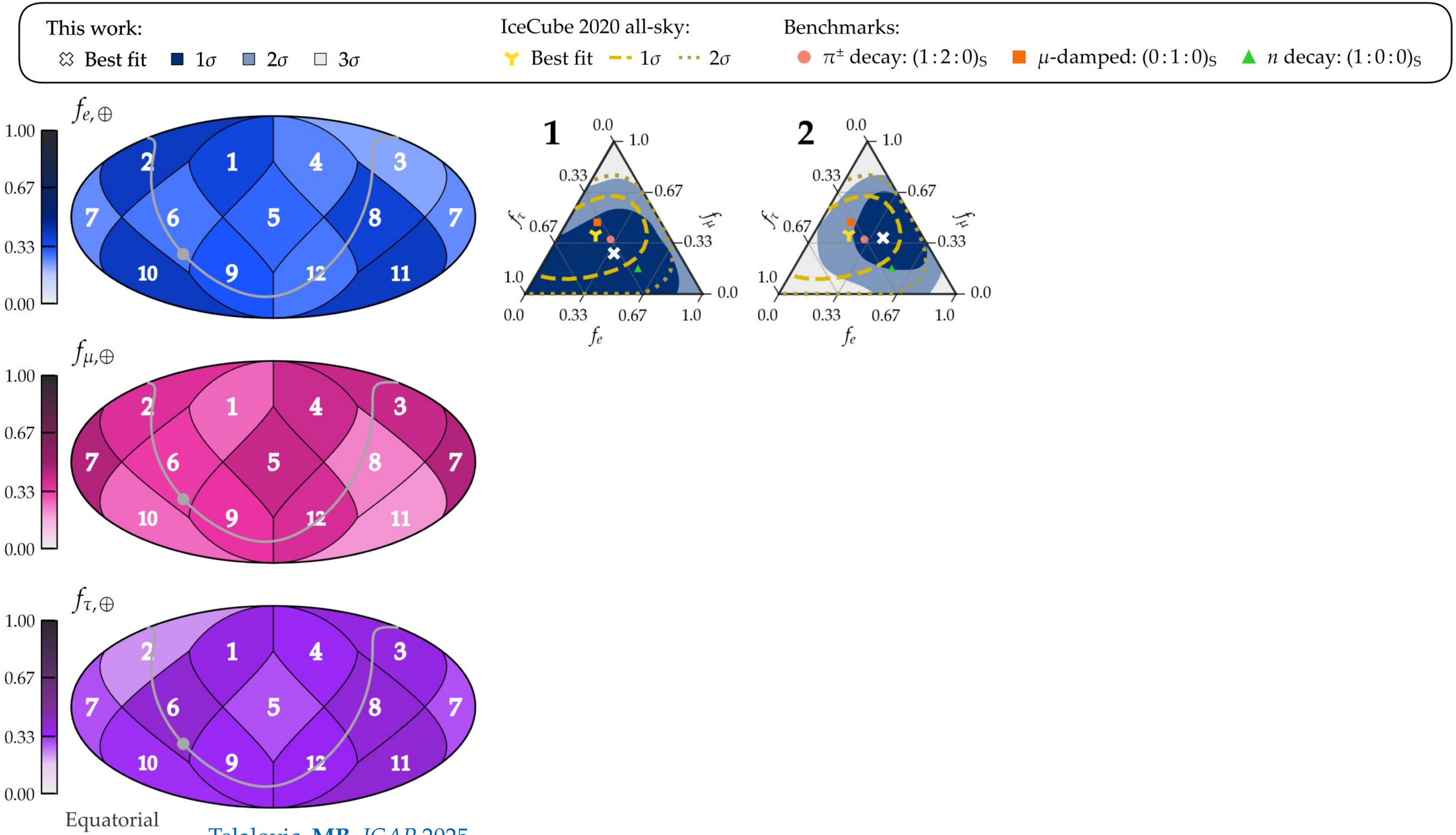

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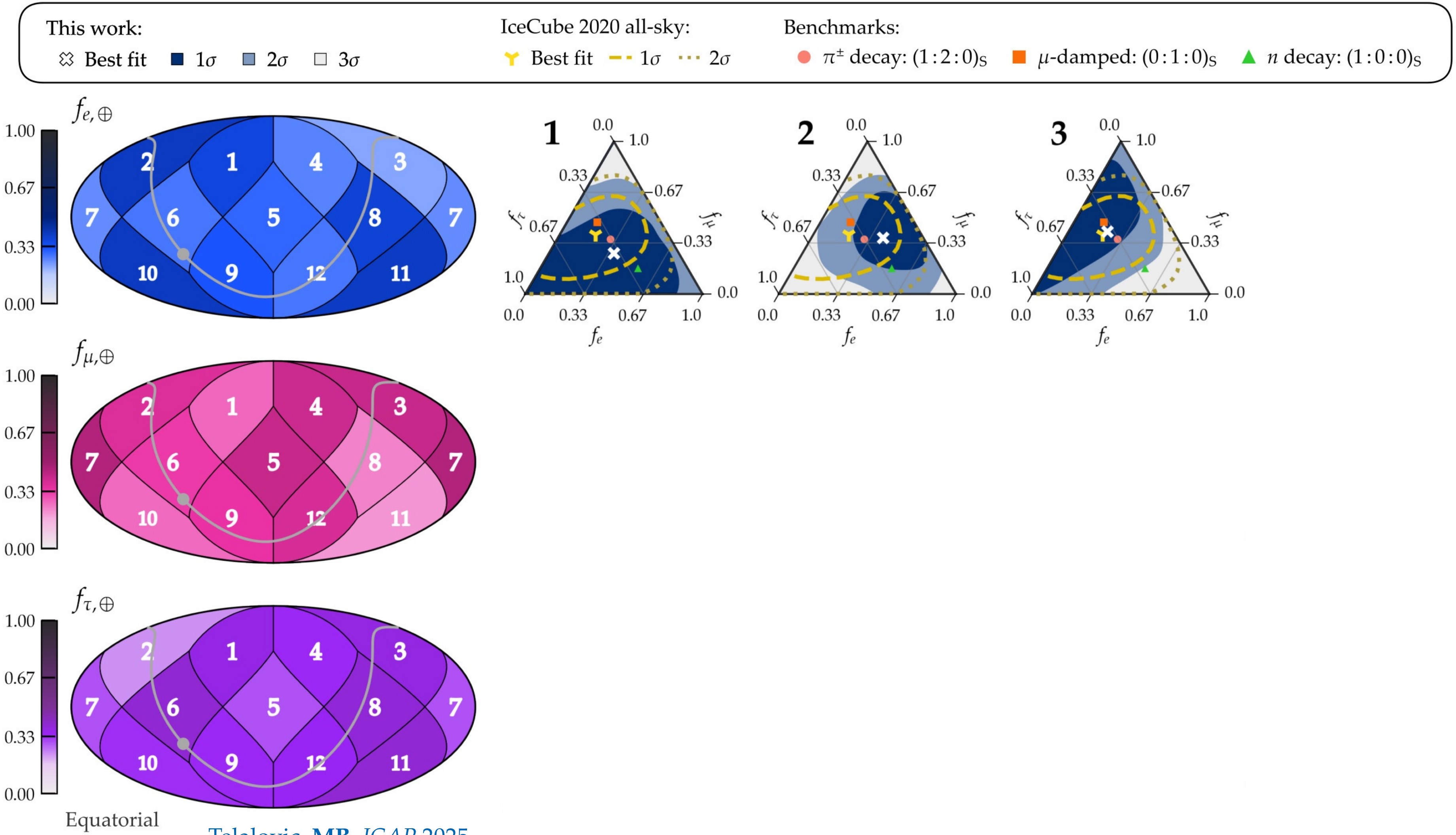

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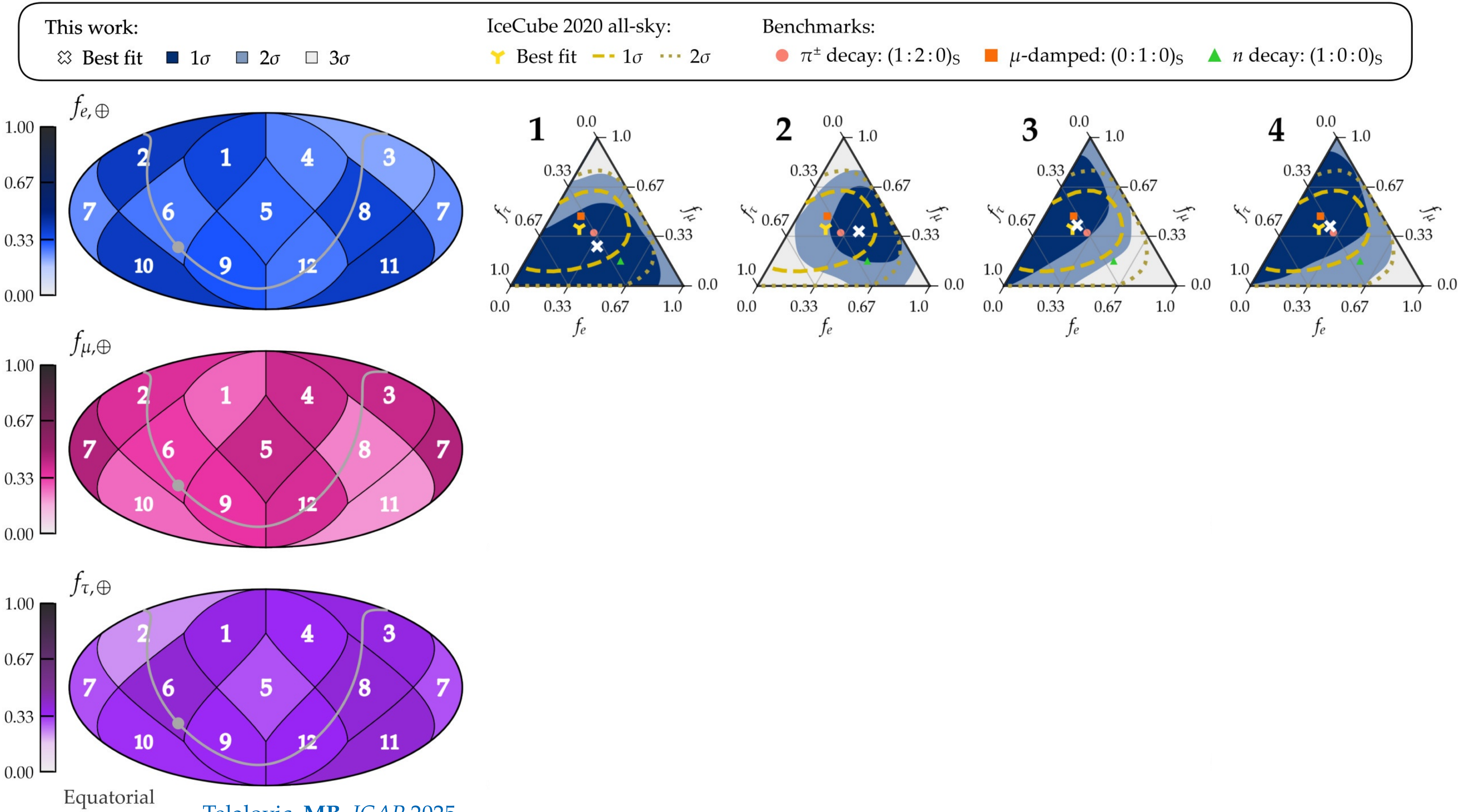

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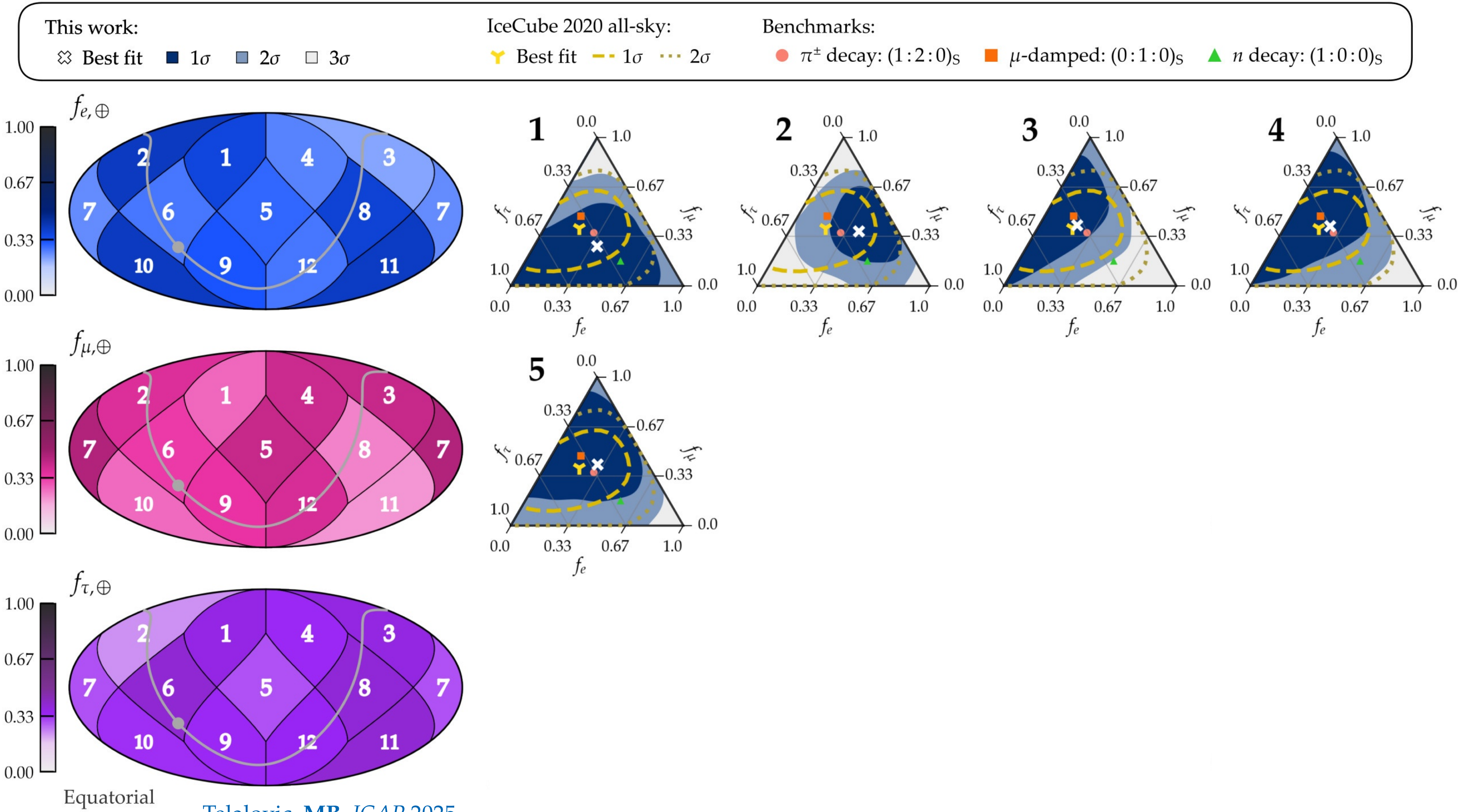

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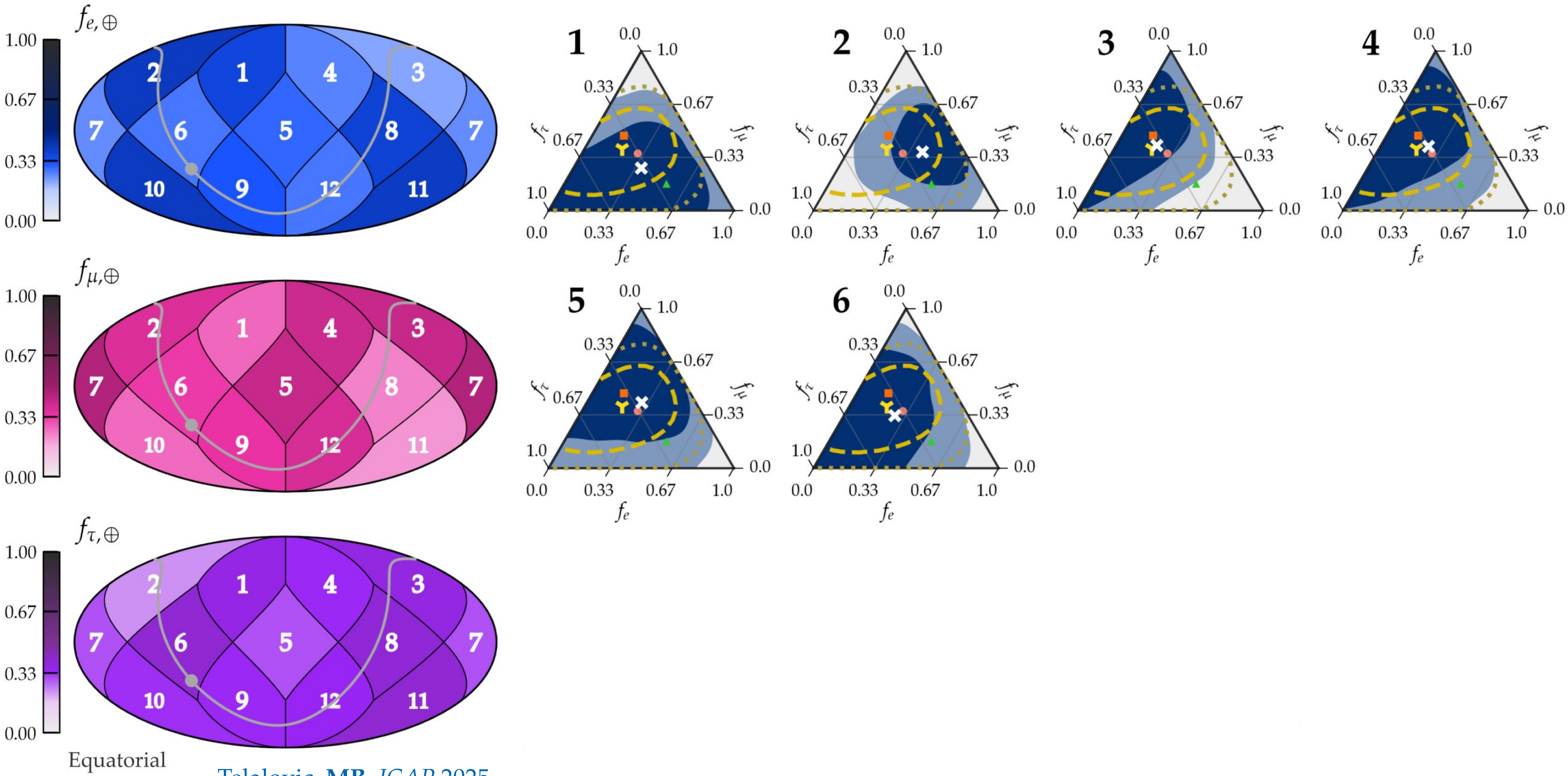
Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)

This work: Best fit · 1σ · 2σ · 3σ | IceCube 2020 all-sky: Best fit · 1σ · 2σ | Benchmarks: $\pi^{\pm}$ decay: $(1:2:0)_S$ · μ-damped: $(0:1:0)_S$ · n decay: $(1:0:0)_S$



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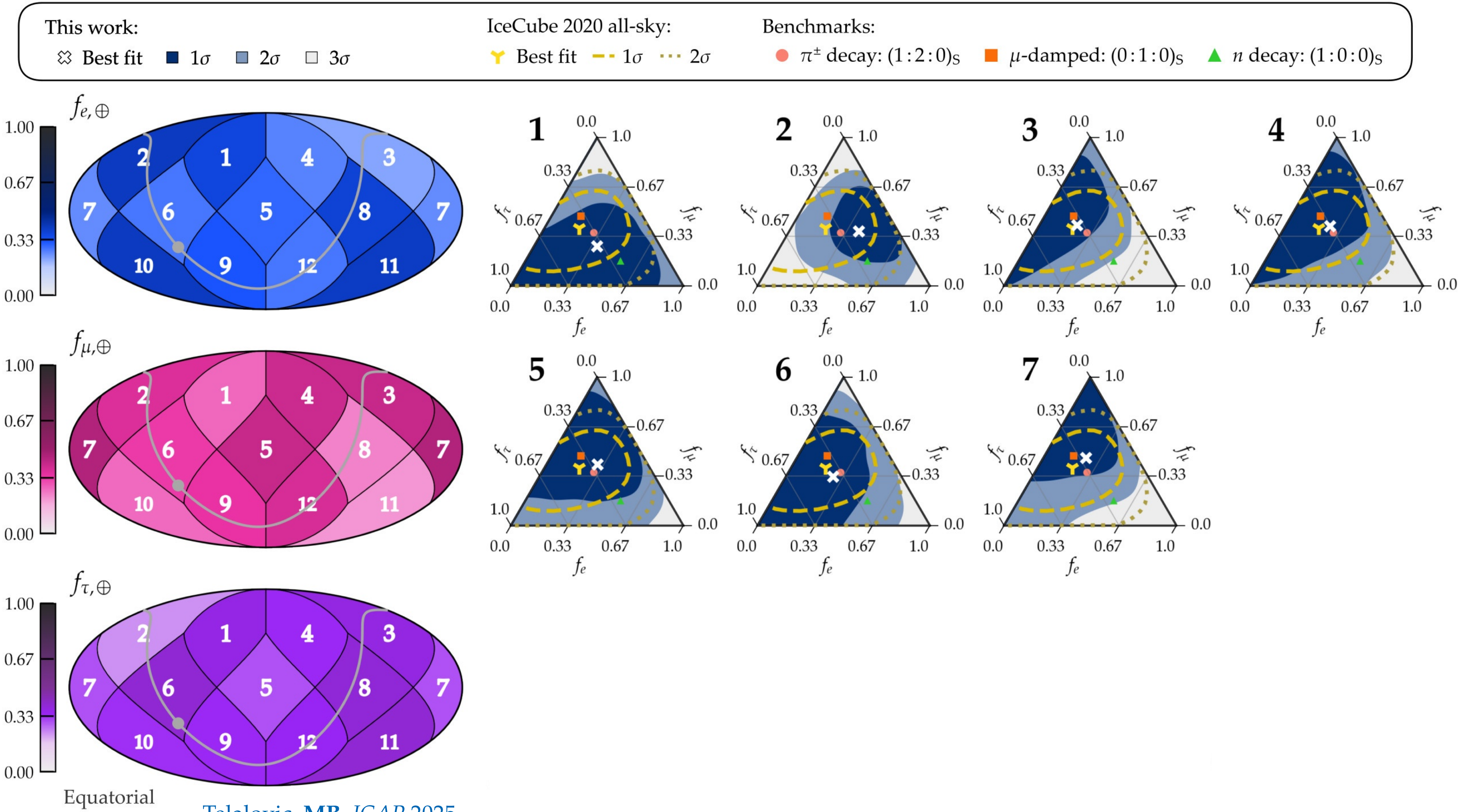

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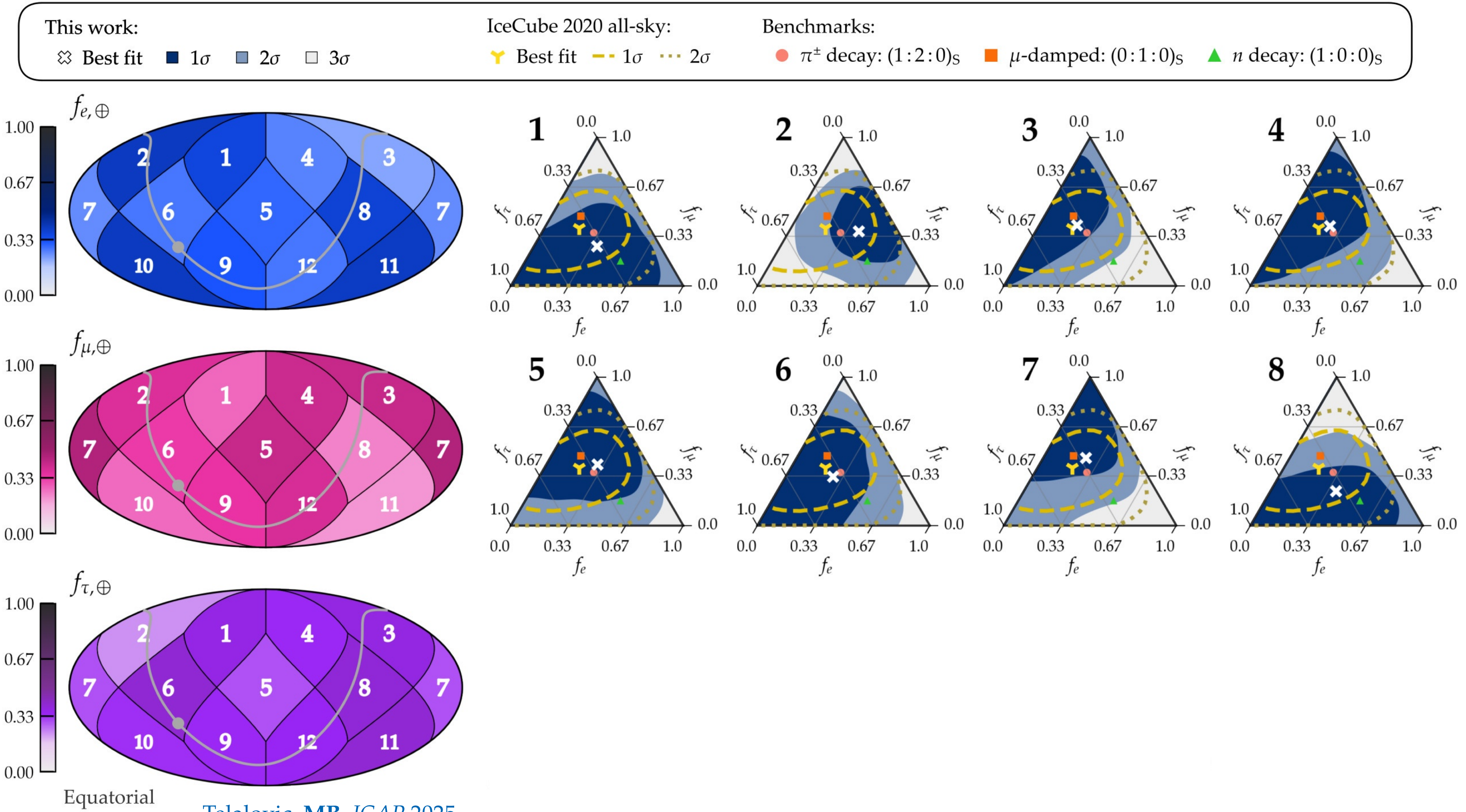

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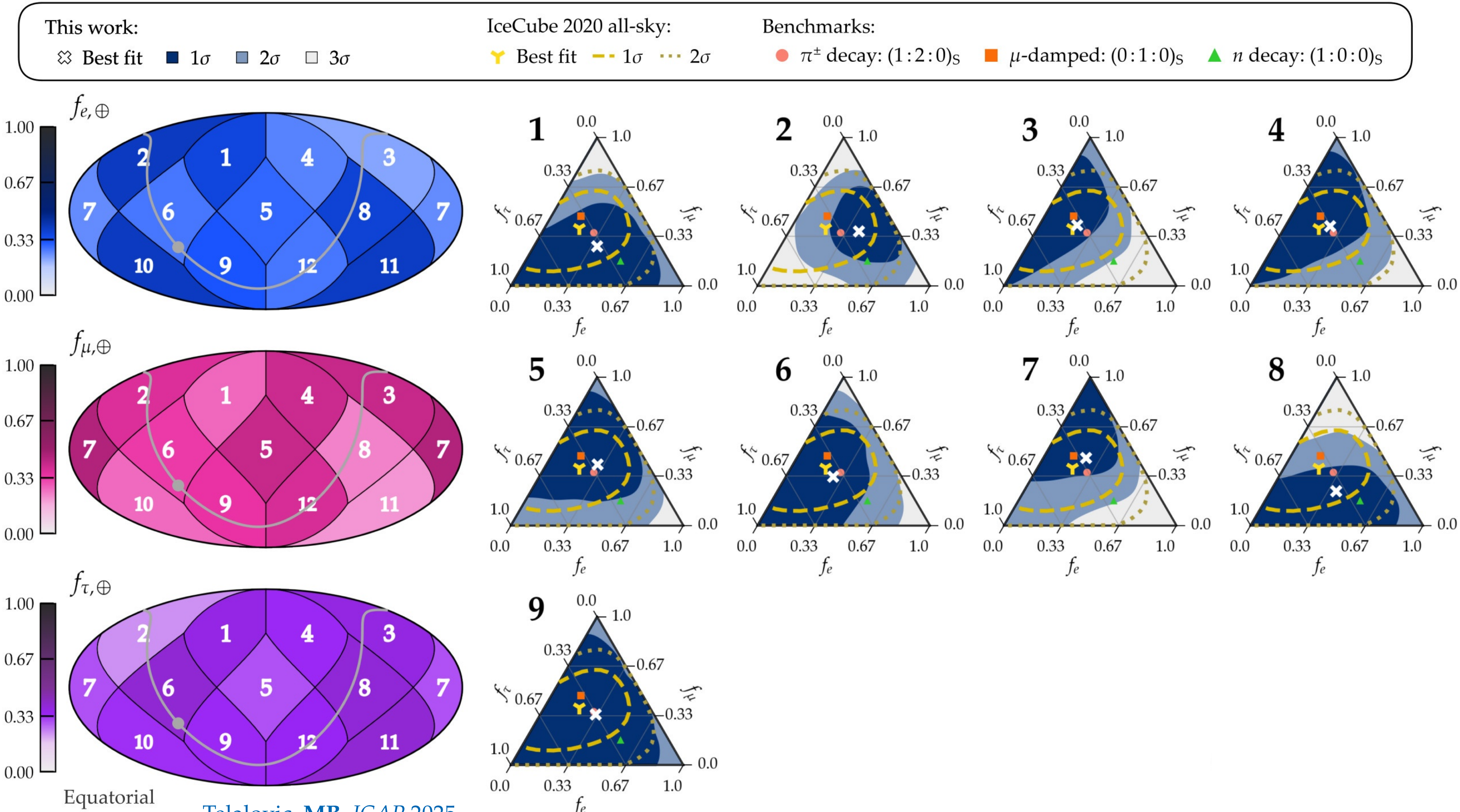

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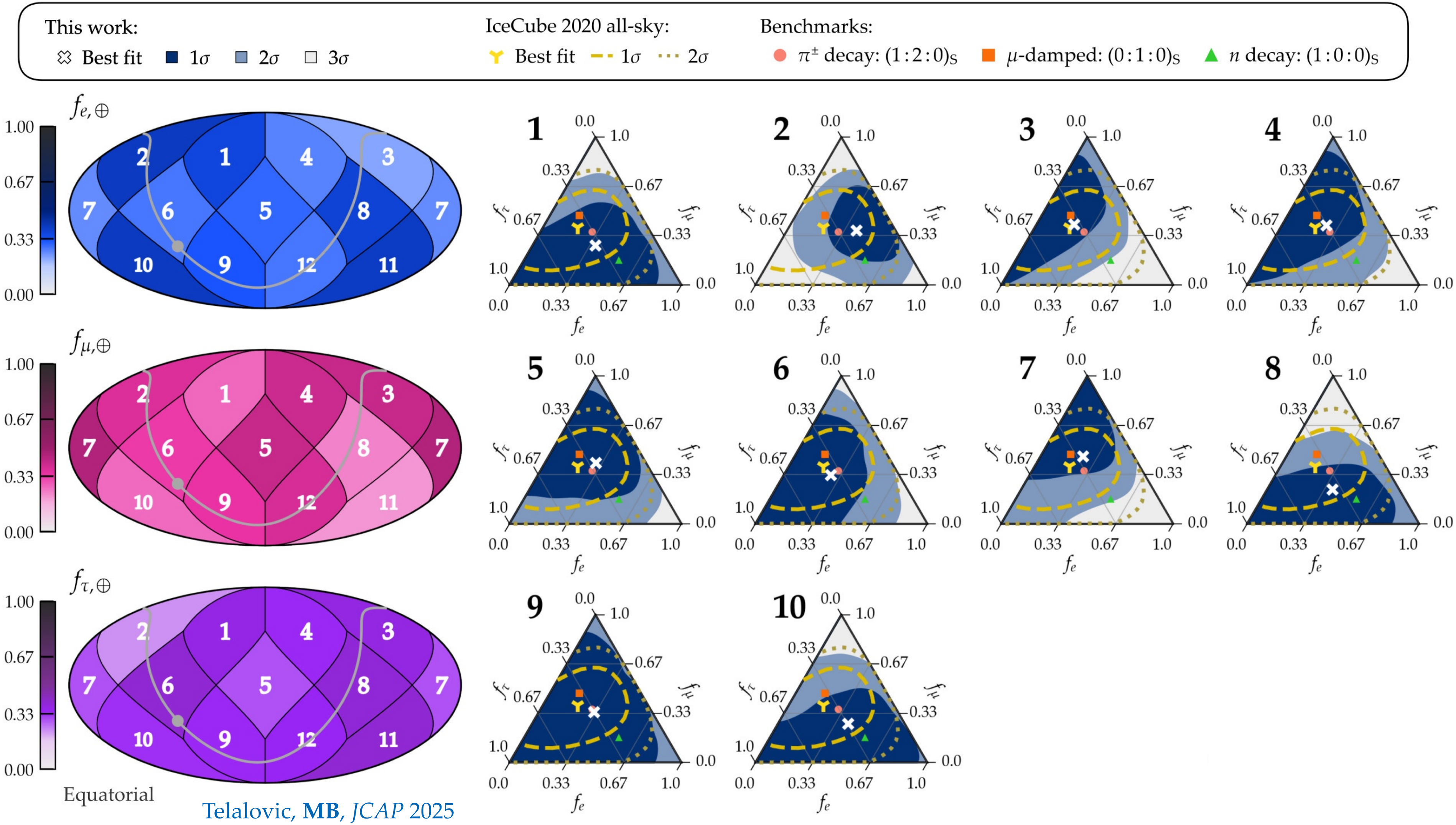

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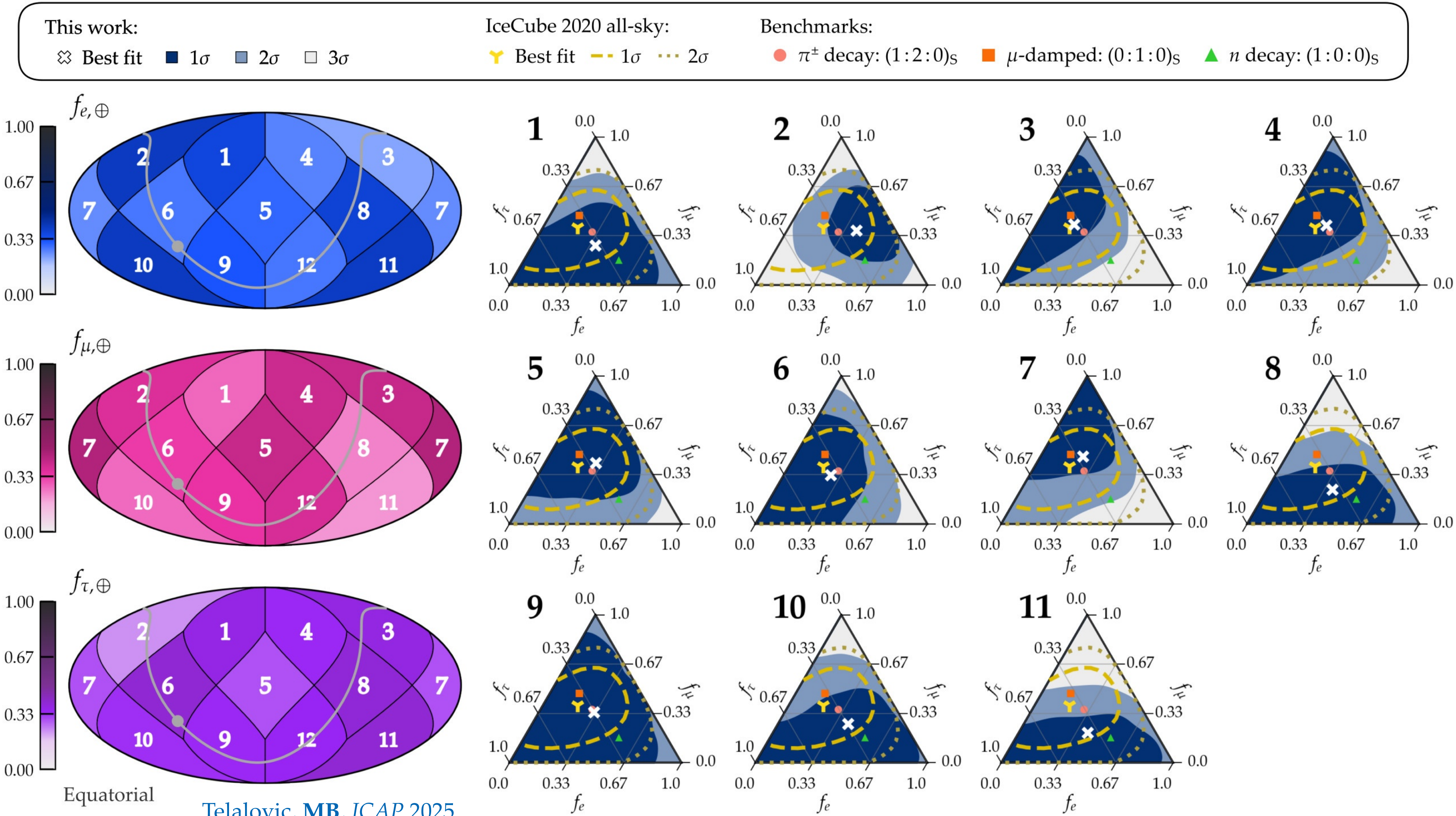

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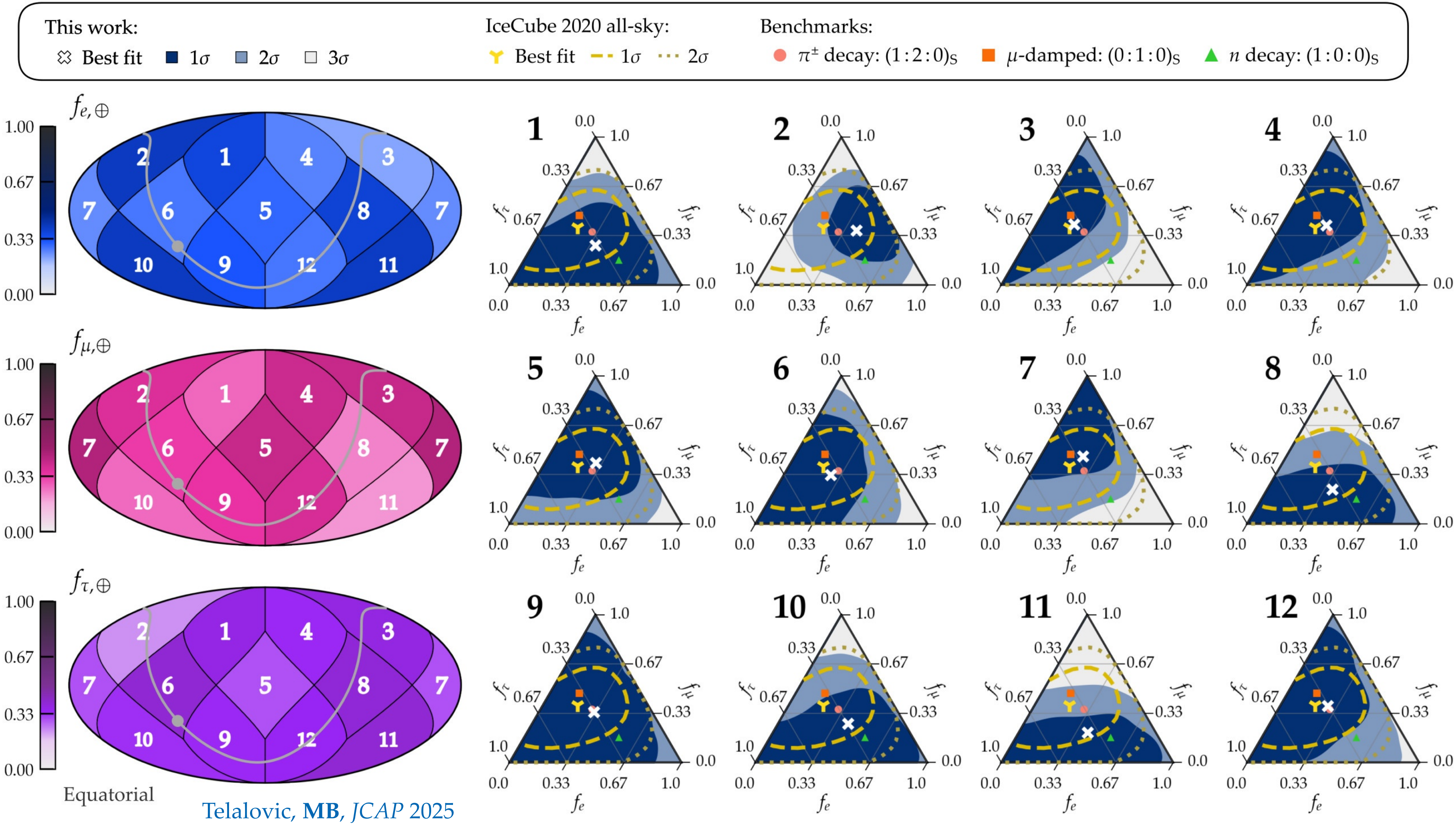

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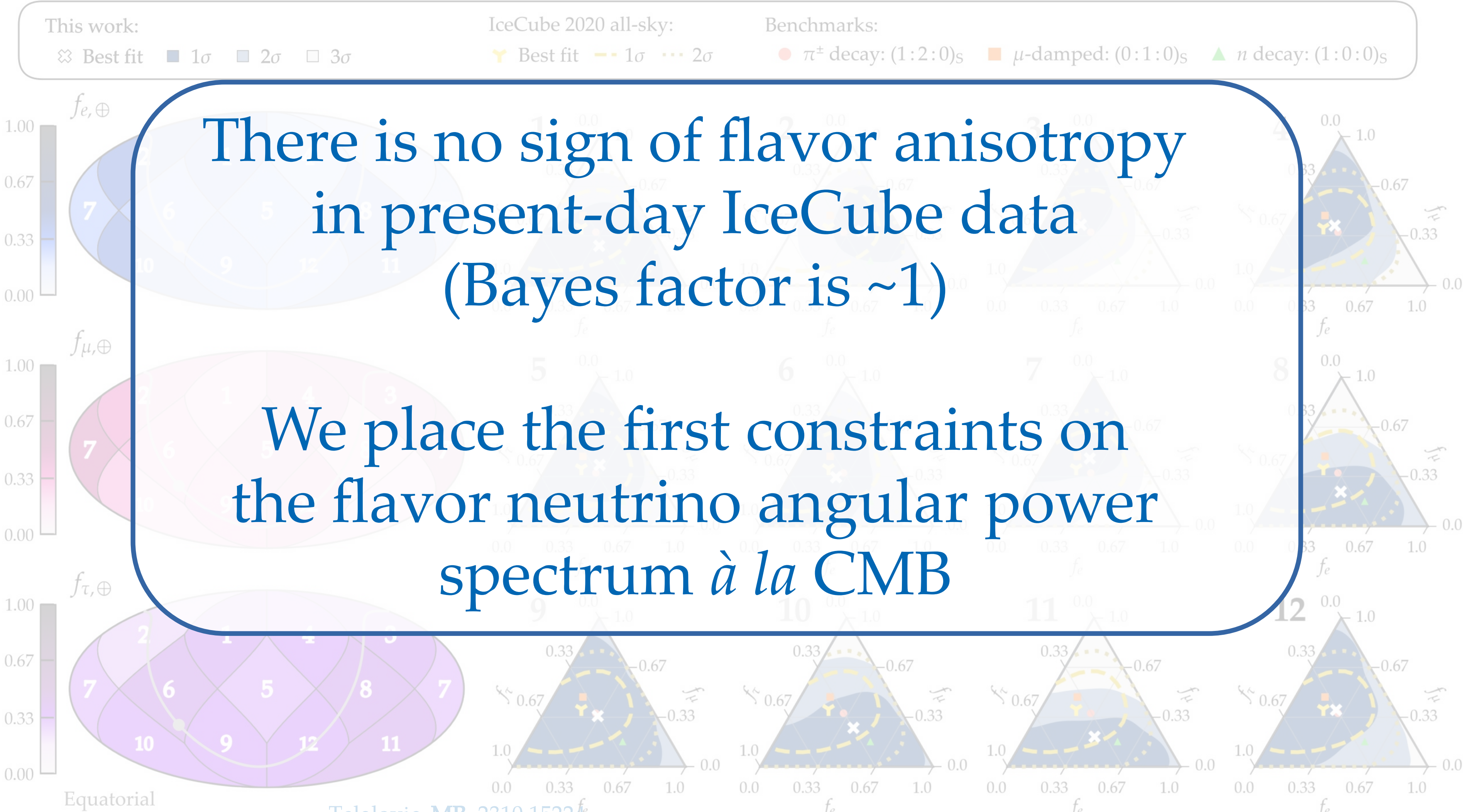
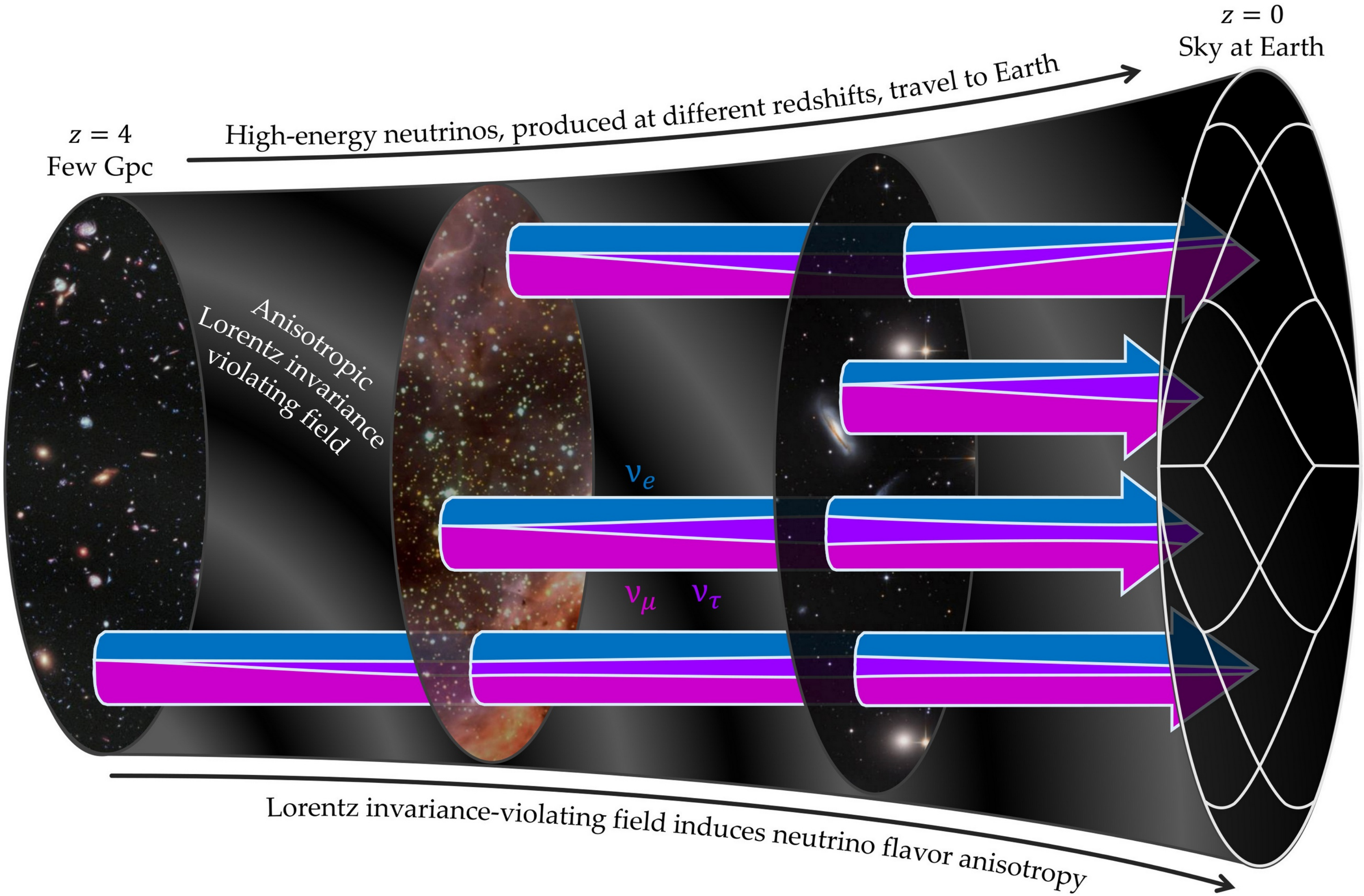


There is no sign of flavor anisotropy in present-day IceCube data (Bayes factor is ~1)

We place the first constraints on the flavor neutrino angular power spectrum *à la* CMB

Telalovic, MB, 2310.15224



Telalovic, **MB**, 2503.15468 (*JHEP*, to appear)

Anisotropic Lorentz-invariance violation makes the flavor sky anisotropic:

$$H_{\rm tot} = H_{\rm vac} + \sum_{d=2}^{\infty} H_{\rm LIV}^{(d)} = H_{\rm vac} + E^{d-3} \sum_{\ell=0}^{d-1} \sum_{m=-\ell}^{\ell} Y_{\ell}^{m}(\hat{\boldsymbol{p}}) (a_{\rm eff}^{(d)})_{\ell m}^{\alpha\beta}$$

Neutrino oscillation probability becomes direction-dependent

Telalovic, **MB**, *JCAP* 2025

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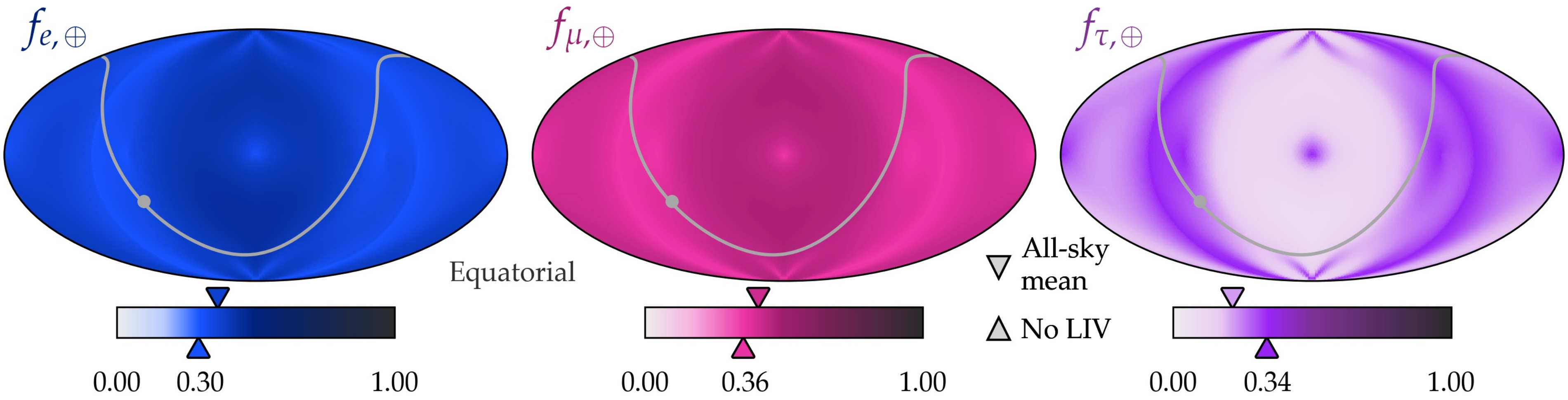

Telalovic, **MB**, *JCAP* 2025

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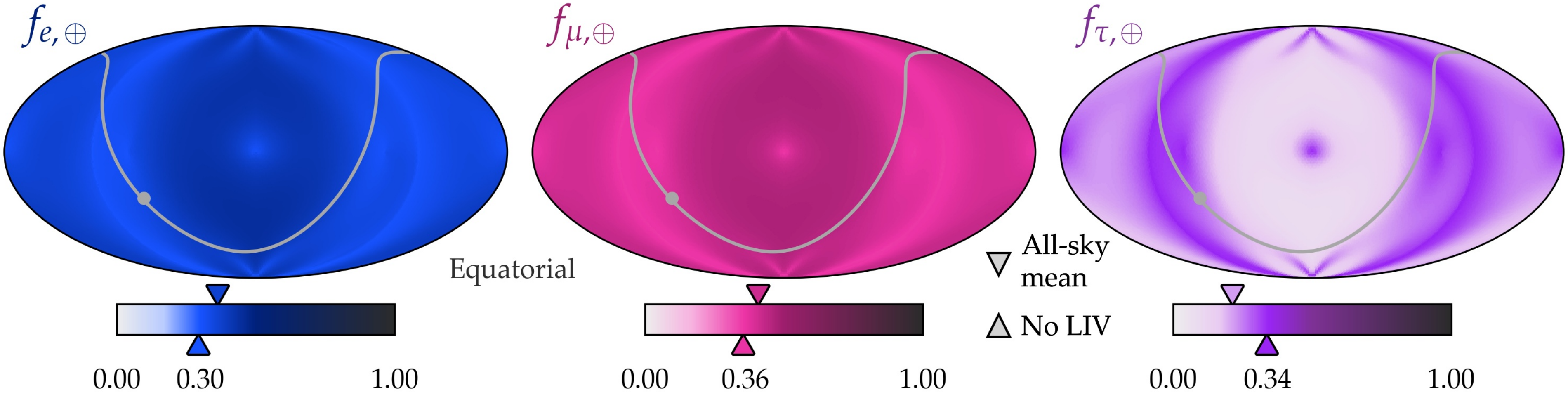

For dimension-5 CPT-odd LIV coefficient

Upper limits from accelerator ν (MINOS): $< 10^{-20}$–10^{-15} GeV^{-1}

Telalovic, **MB**, *JCAP* 2025

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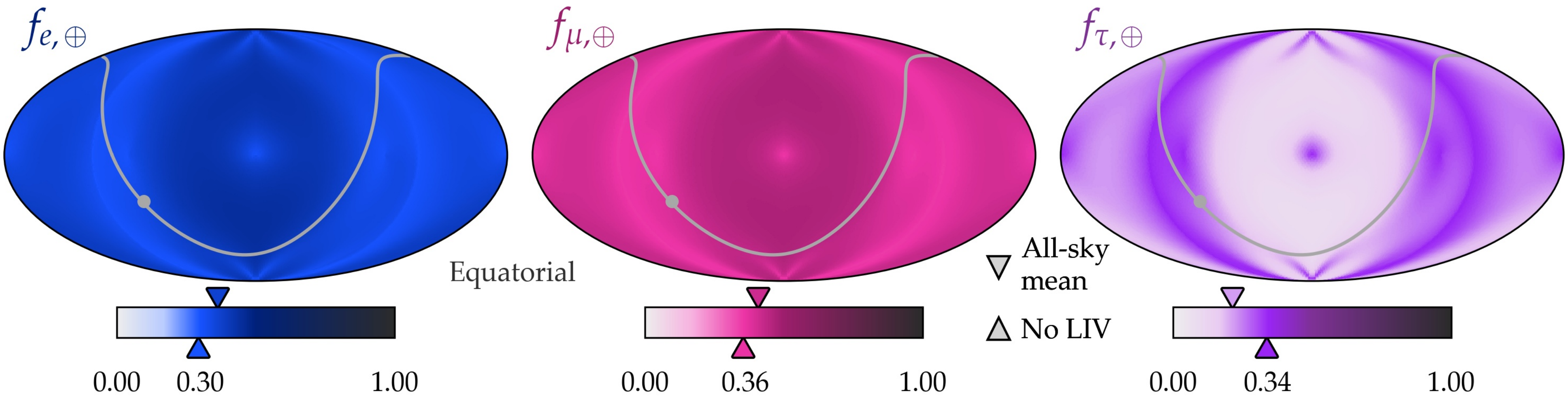


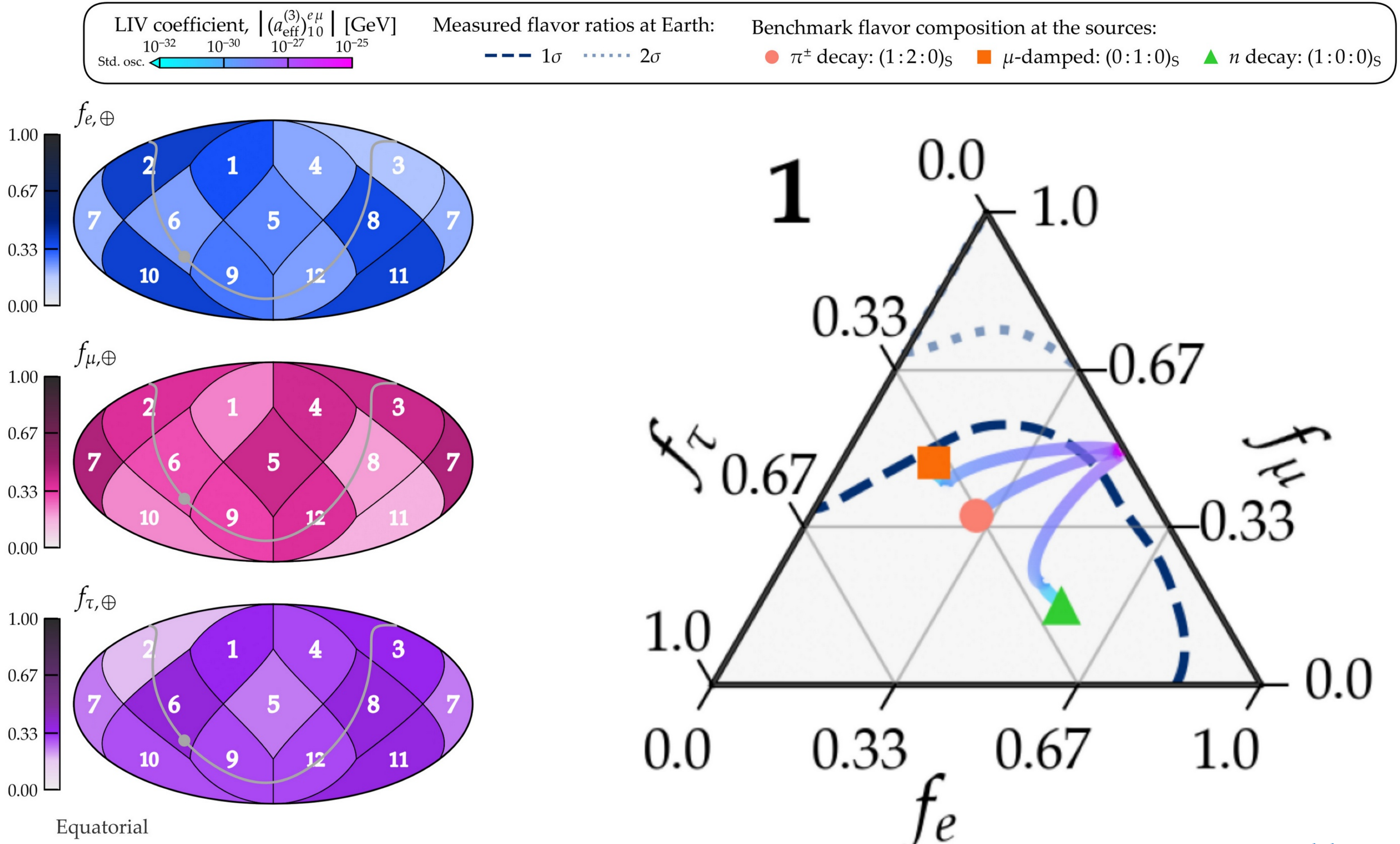
For dimension-5 CPT-odd LIV coefficient

Upper limits from accelerator ν (MINOS): $< 10^{-20}$–10^{-15} GeV^{-1}

Upper limits from 7.5-year HESE: $< 10^{-34}$ GeV^{-1}

Telalovic, **MB**, *JCAP* 2025

Lorentz-violating high-energy neutrino flavor anisotropy (IceCube HESE 7.5 years)



Telalovic, **MB**, *JHEP* 2025

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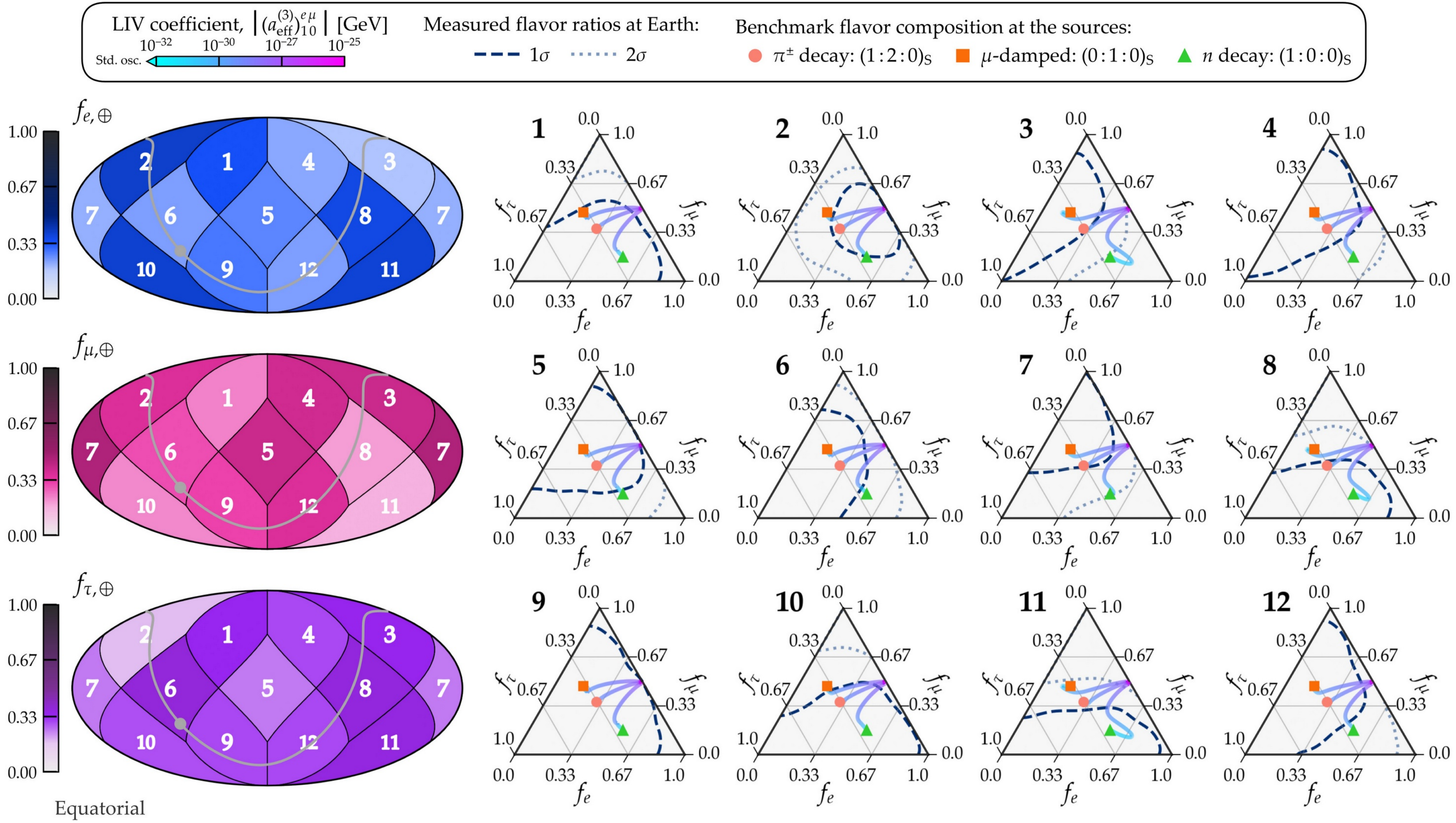
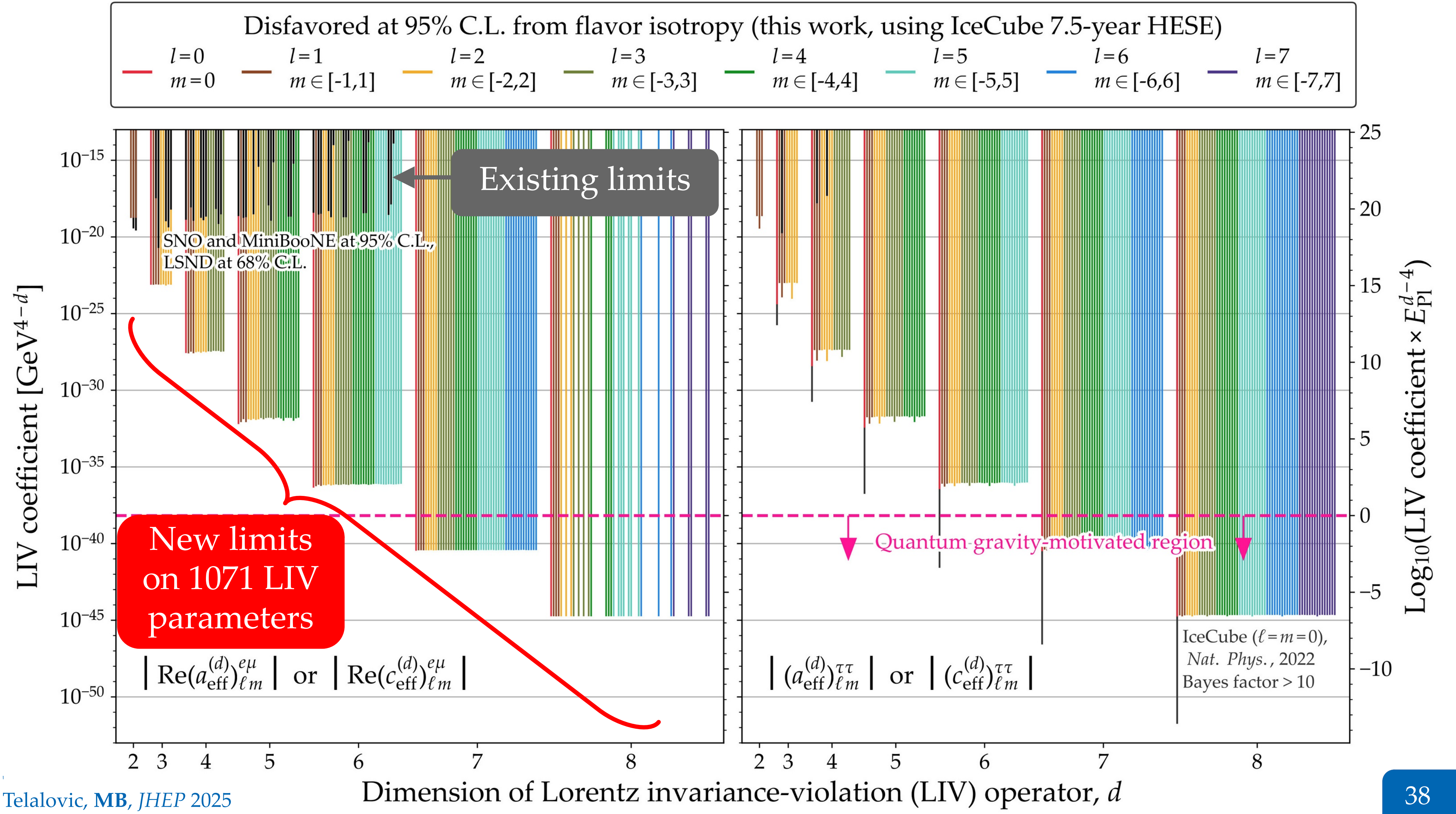


Telalovic, **MB**, *JHEP* 2025



Telalovic, **MB**, *JHEP* 2025

Do neutrinos decay?

Are neutrinos forever?

- In the Standard Model (νSM), neutrinos are essentially stable ($\tau > 10^{36}$ yr):
  - One-photon decay ($\nu_i \rightarrow \nu_j + \gamma$): $\tau > 10^{36} (m_i/\mathrm{eV})^{-5}$ yr
  - Two-photon decay ($\nu_i \rightarrow \nu_j + \gamma + \gamma$): $\tau > 10^{57} (m_i/\mathrm{eV})^{-9}$ yr
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  » Age of Universe (~ 14.5 Gyr)

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Nambu-Goldstone boson of a broken symmetry

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Astrophysical sources

Earth

L ~ up to a few Gpc

E.g.,

Decay changes the number

of each ν mass eigenstate, N_1, N_2, N_3

?

The flux of ν_i is attenuated by $\exp[-(L/E)\cdot(\underbrace{m_i}_{\text{Mass of } \nu_i}/\underbrace{\tau_i}_{\text{Lifetime of } \nu_i})]$

Astrophysical sources — Earth

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E.g.,

Decay changes the number

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?

Lower-E ν are longer-lived…

The flux of ν_i is attenuated by $\exp[-\,(L/E)\cdot(m_i/\tau_i)]$

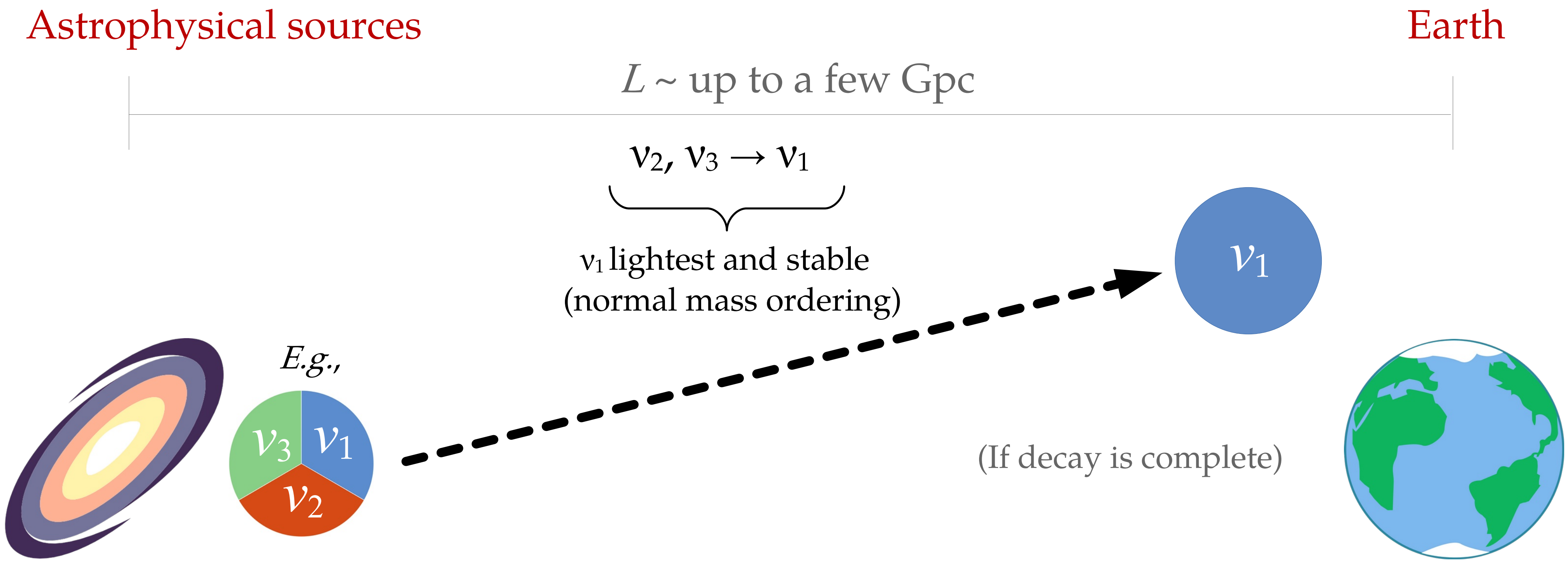
… but ν that travel longer L are more attenuated!

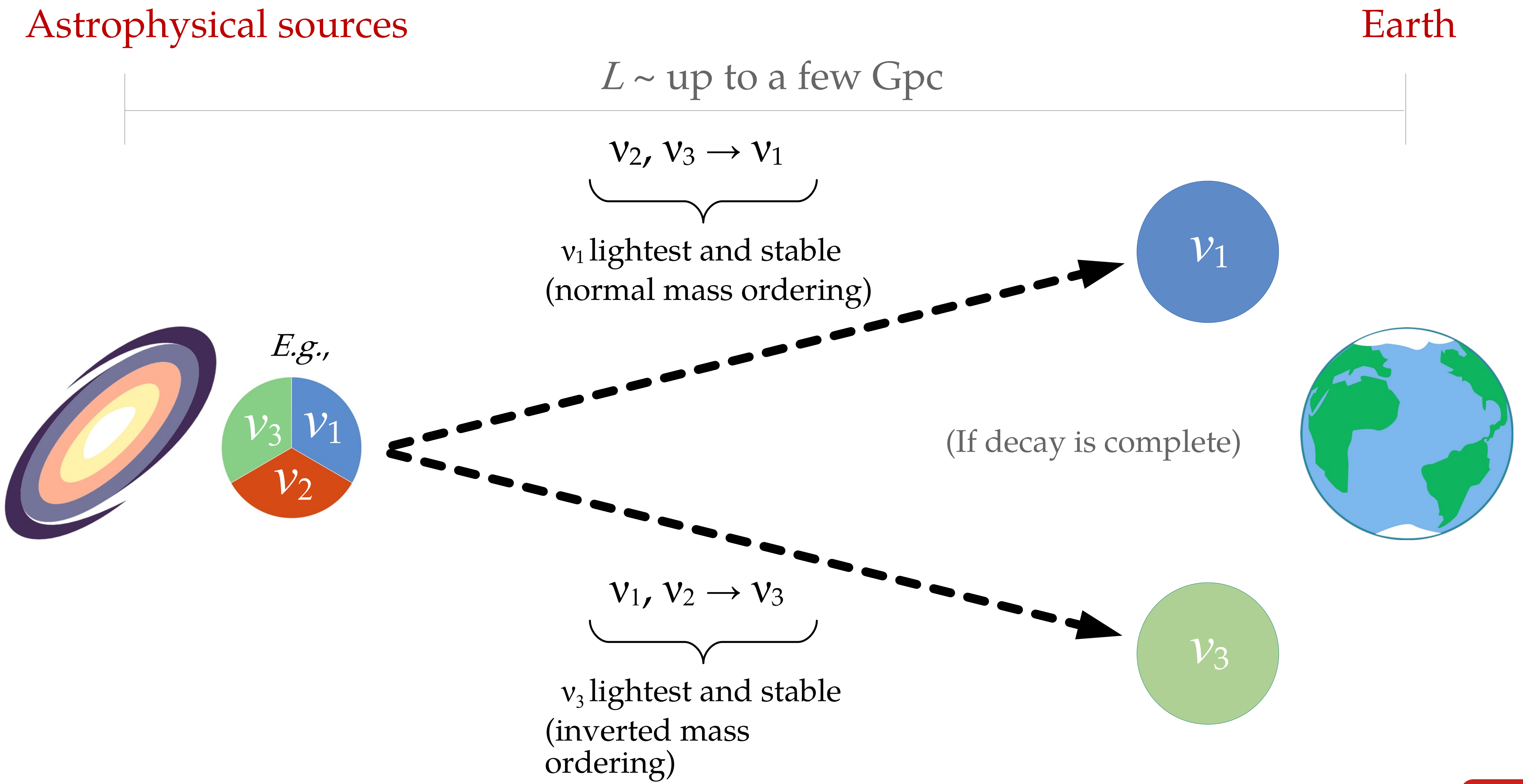
Astrophysical sources

Earth

$L \sim$ up to a few Gpc

E.g.,


Astrophysical sources
Earth
L ~ up to a few Gpc
ν2, ν3 → ν1
ν1 lightest and stable
(normal mass ordering)
E.g.,
ν3
ν1
ν2
ν1
(If decay is complete)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E.g.,
ν3 ν1
ν2
ν1
(If decay is complete)
ν1, ν2 → ν3
ν3 lightest and stable
(inverted mass
ordering)
ν3

Astrophysical sources — Earth

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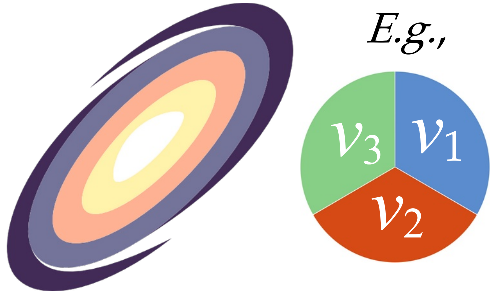
E.g.,



$$\underbrace{\nu_2,\ \nu_3 \rightarrow \nu_1}_{}$$

ν_1 lightest and stable
(normal mass ordering)

(If decay is complete)

$$\underbrace{\nu_1,\ \nu_2 \rightarrow \nu_3}_{}$$

ν_3 lightest and stable
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Fine print:

- Decay can be incomplete
- Final-state ν might be detectable or not
- Many more possible decay channels (see Winter & Mehta, *JCAP* 2011)

Astrophysical sources Earth

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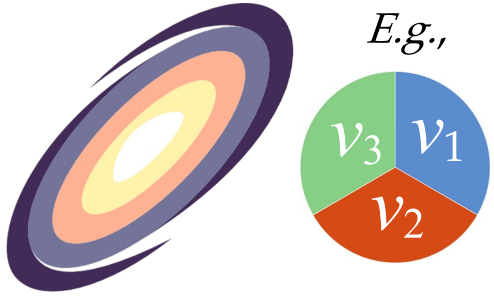

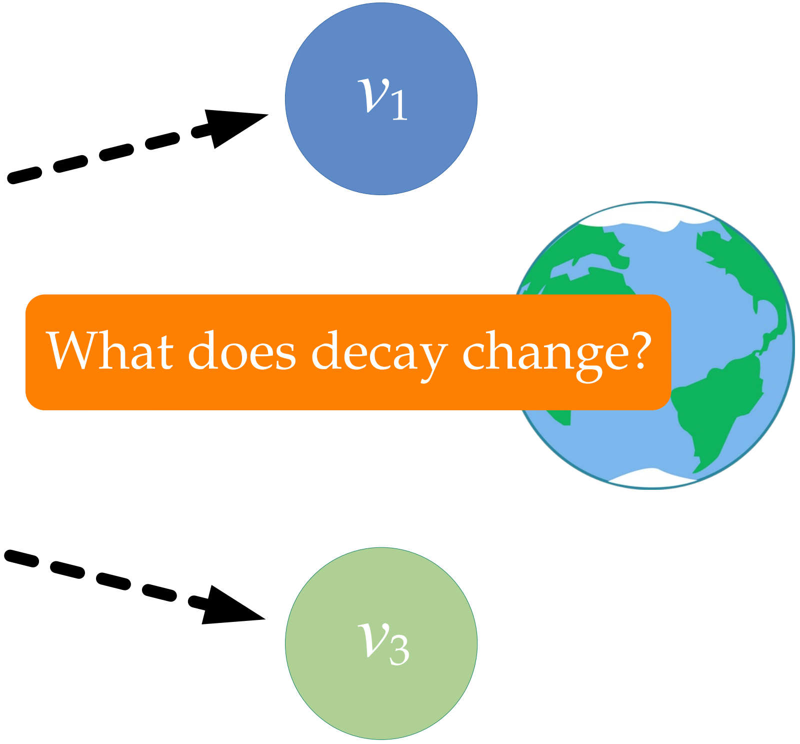

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What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

What does neutrino decay change?

Flavor composition Spectrum shape Event rate

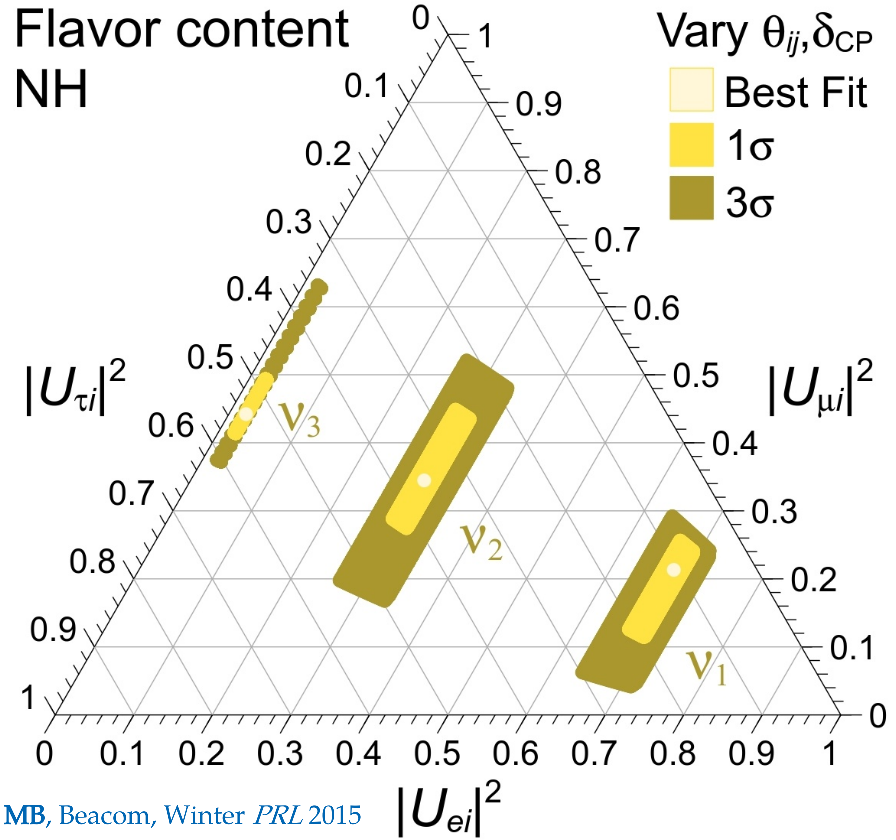
Flavor content of mass eigenstates:

Known to within 2%

$$|U_{\alpha i}|^2 = |U_{\alpha i}(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})|^2$$

Known to within 8%

Known to within 20% (or worse)



MB, Beacom, Winter *PRL* 2015

What does neutrino decay change?

Flavor composition | Spectrum shape | Event rate

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$$\underbrace{\nu_2,\ \nu_3 \to \nu_1}$$

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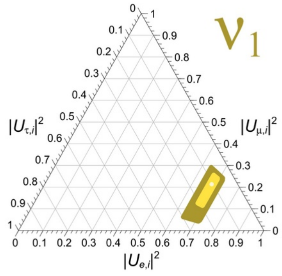

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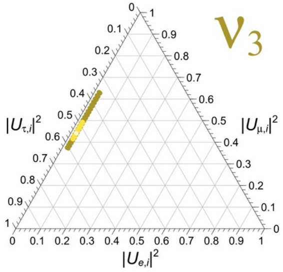

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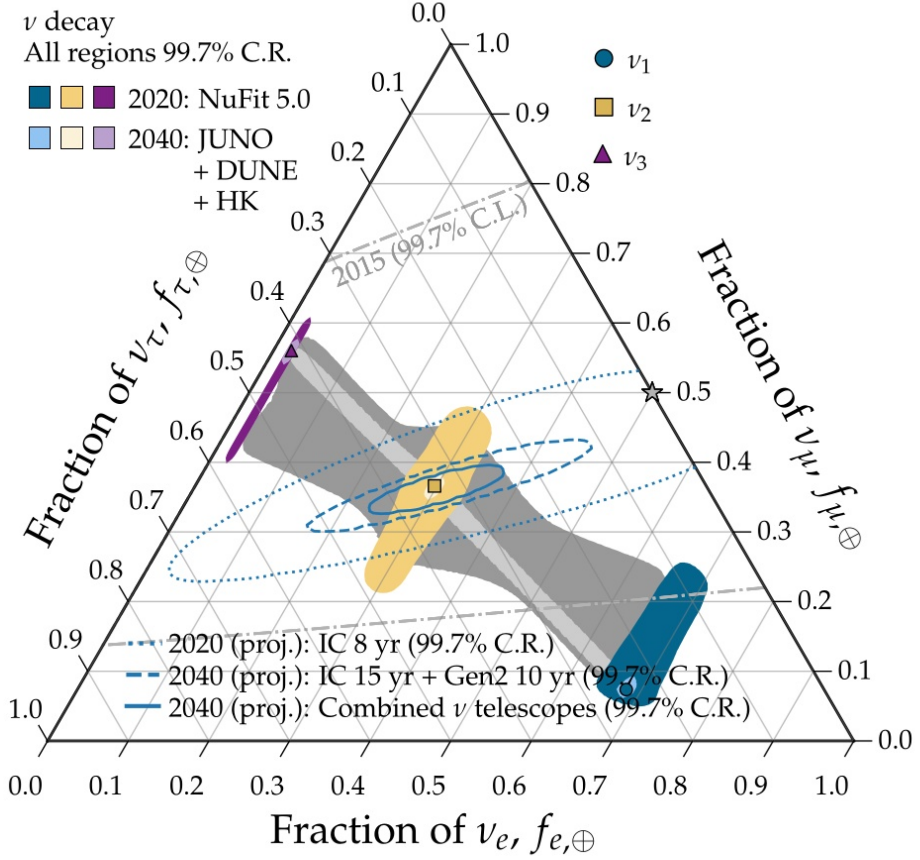
Flavor composition ⟺ Spectrum shape ⟺ Event rate



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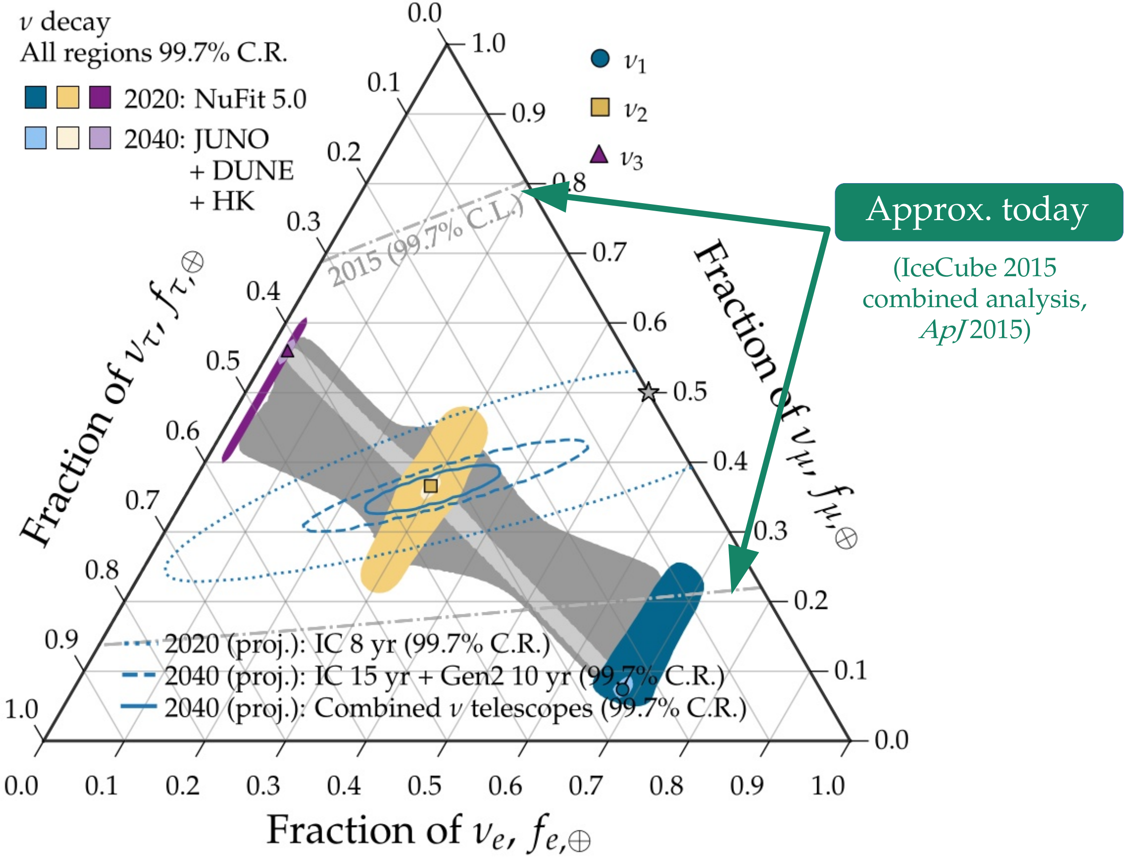

(IceCube 2015 combined analysis, *ApJ* 2015)

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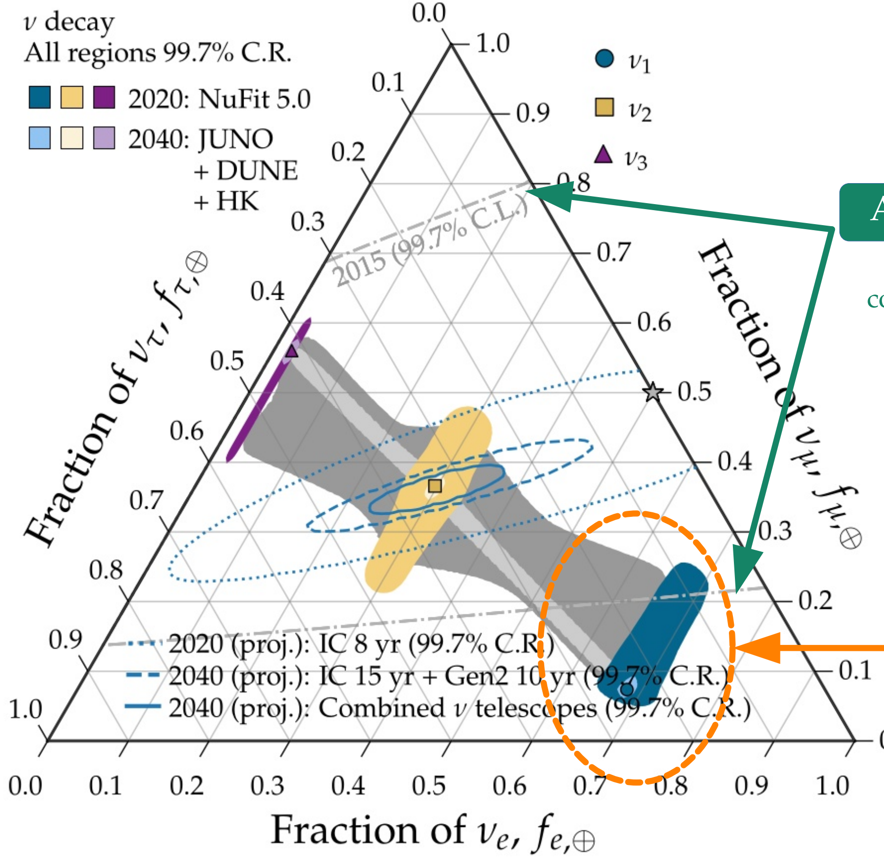

Approx. today

(IceCube 2015 combined analysis, *ApJ* 2015)

Complete decay into ν_1 disfavored by 2015 IceCube flavor measurement

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

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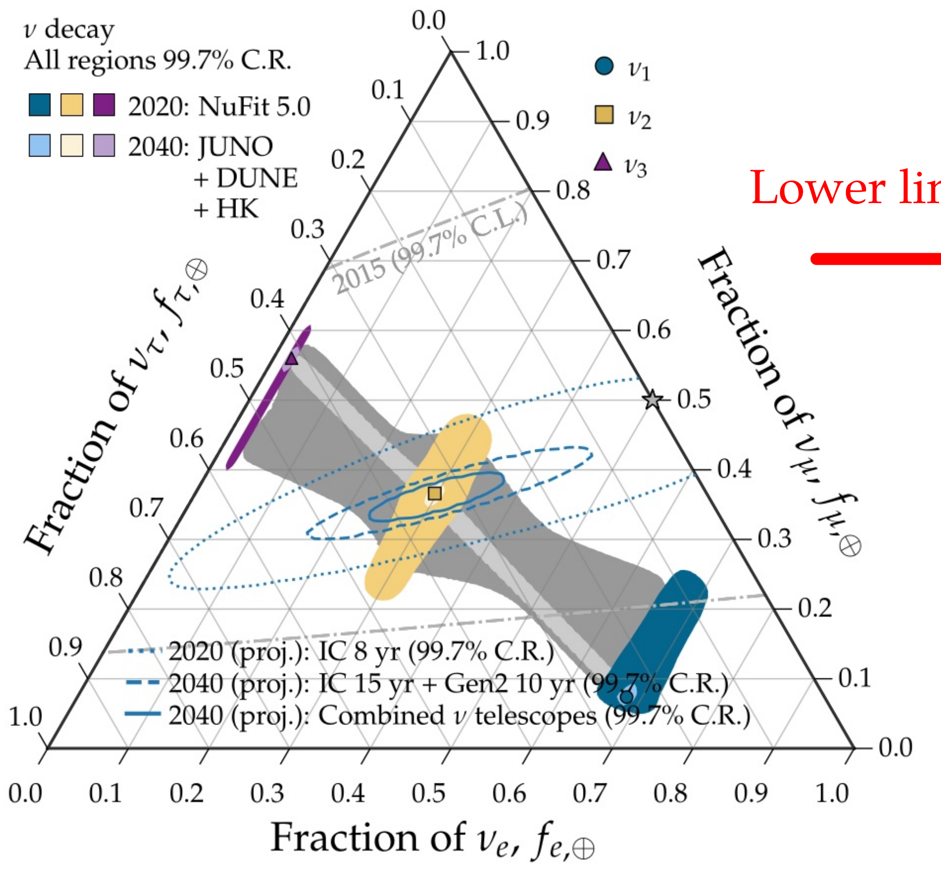

Lower limit on τ/m →

What does neutrino decay change?

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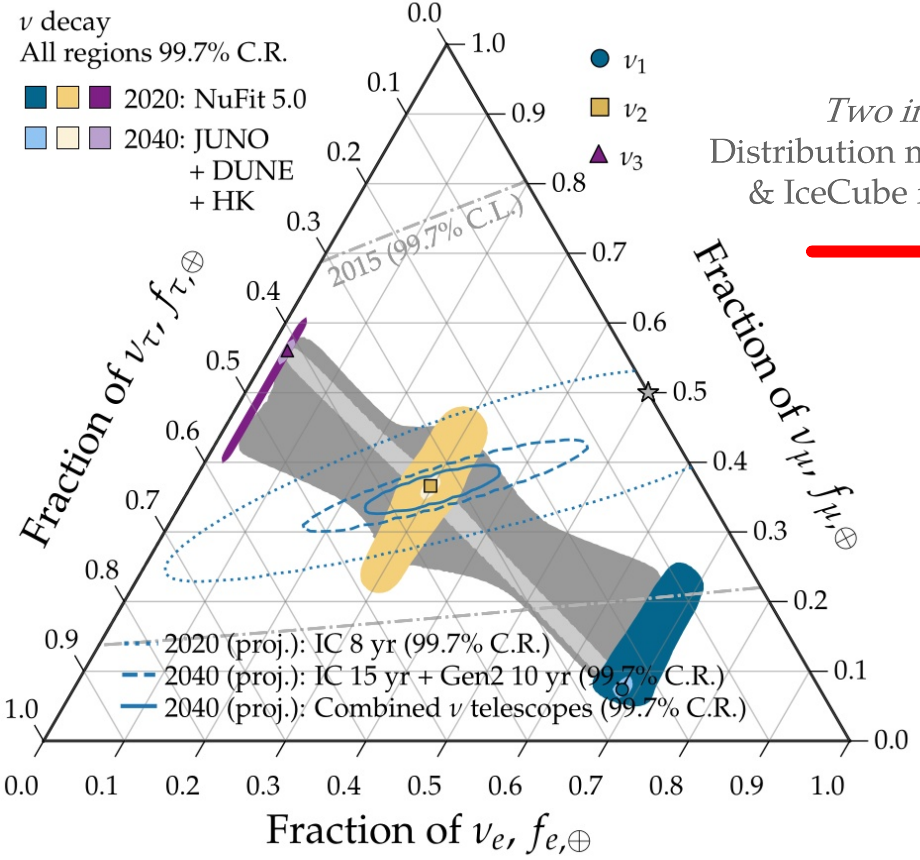
Flavor composition ⟺ Spectrum shape ⟺ Event rate



Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

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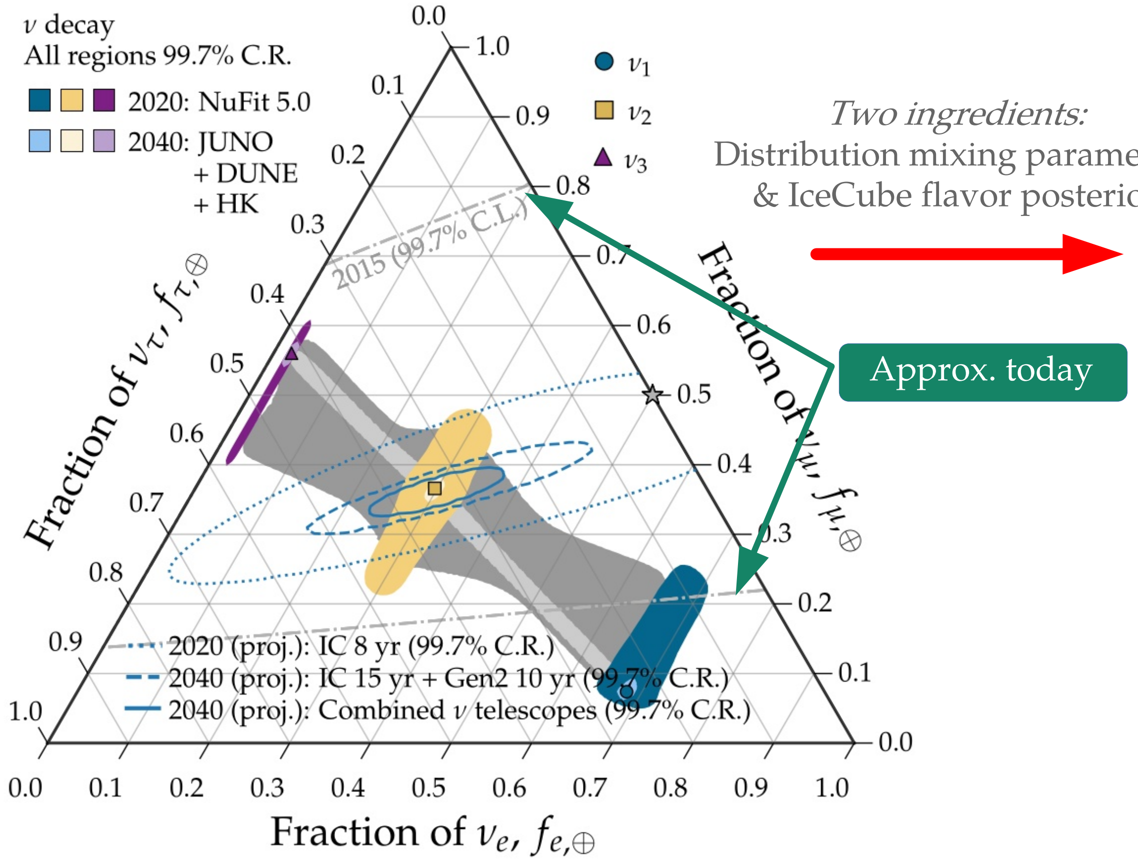

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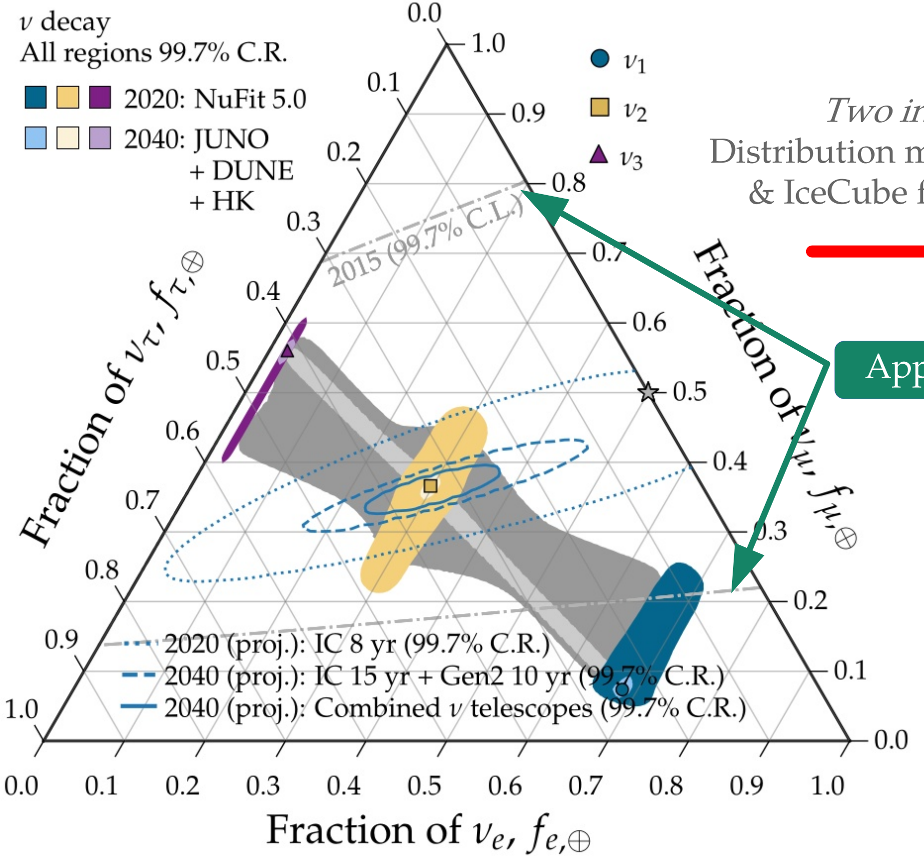

Approx. today

Two ingredients:
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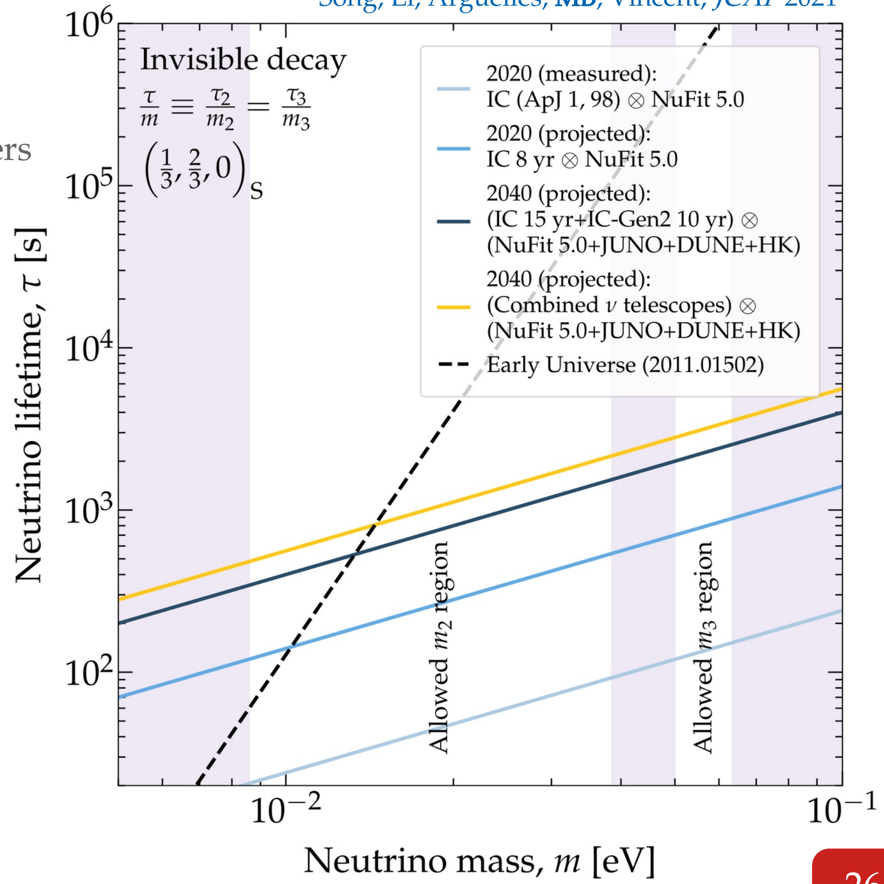
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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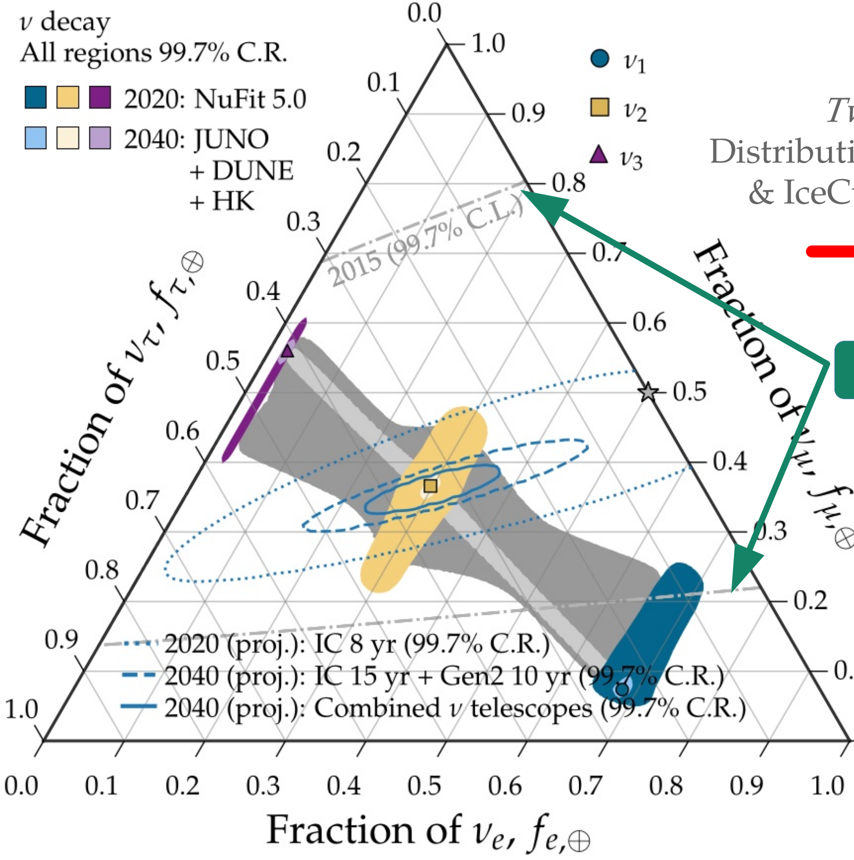

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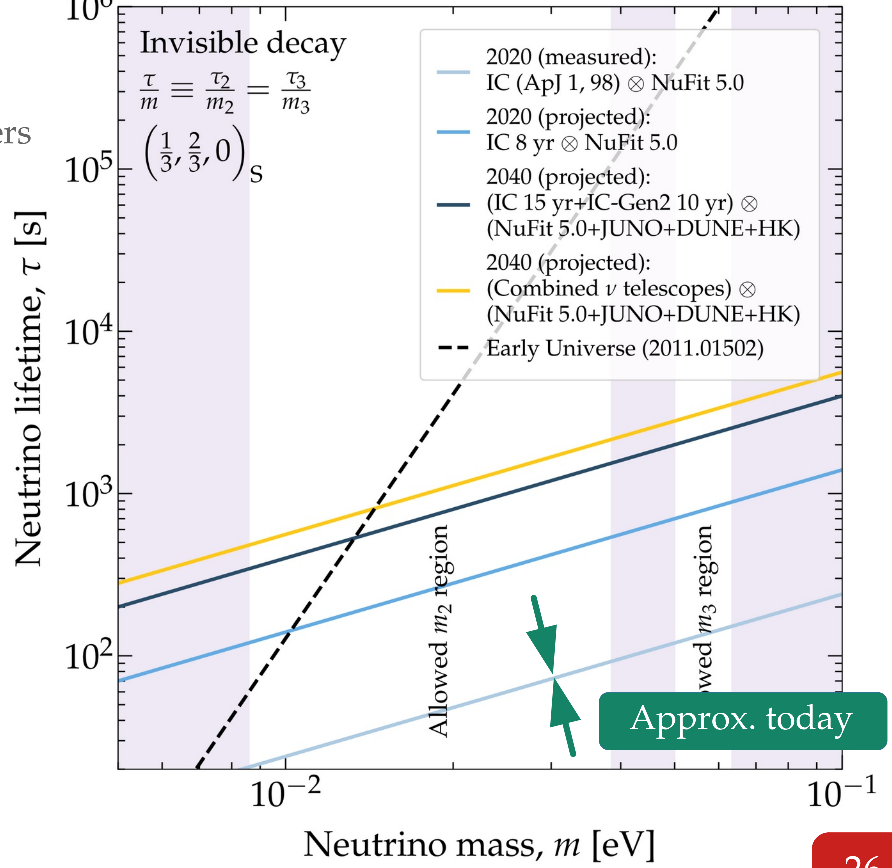
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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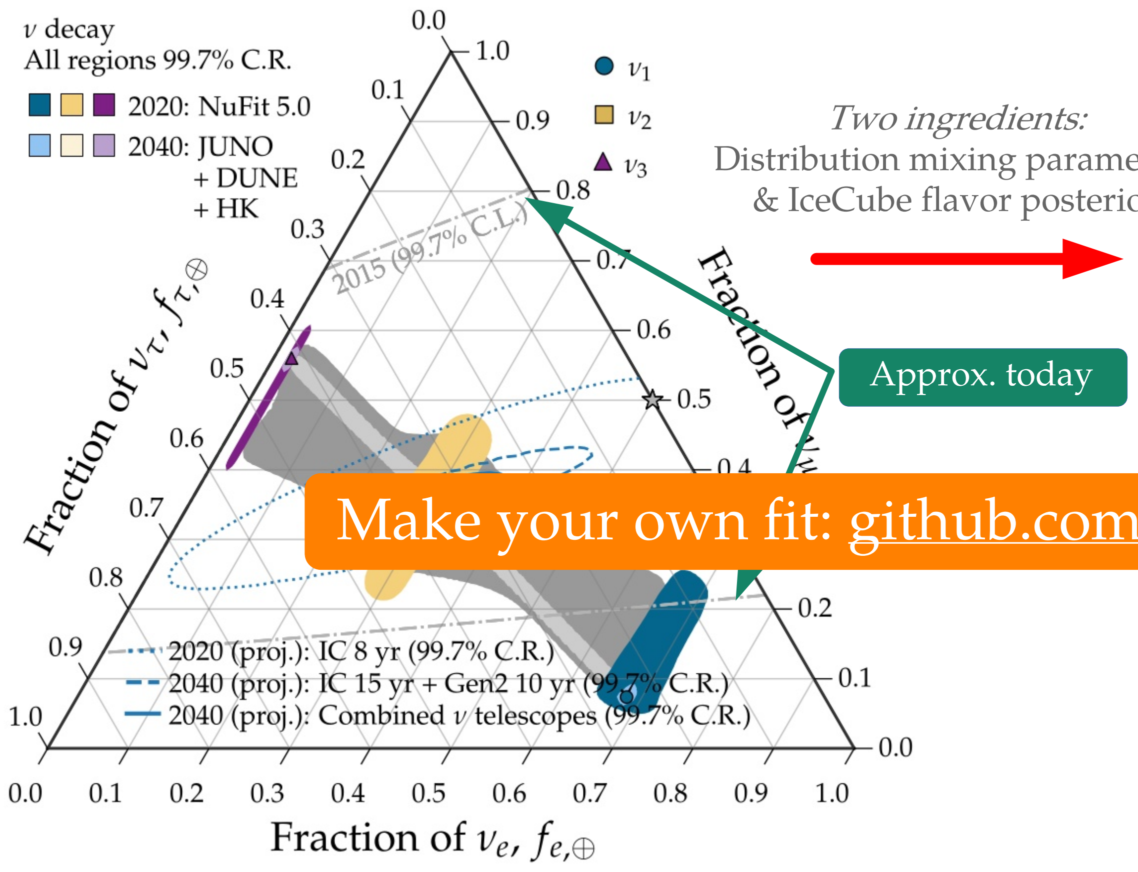
Flavor composition ⟺ Spectrum shape ⟺ Event rate



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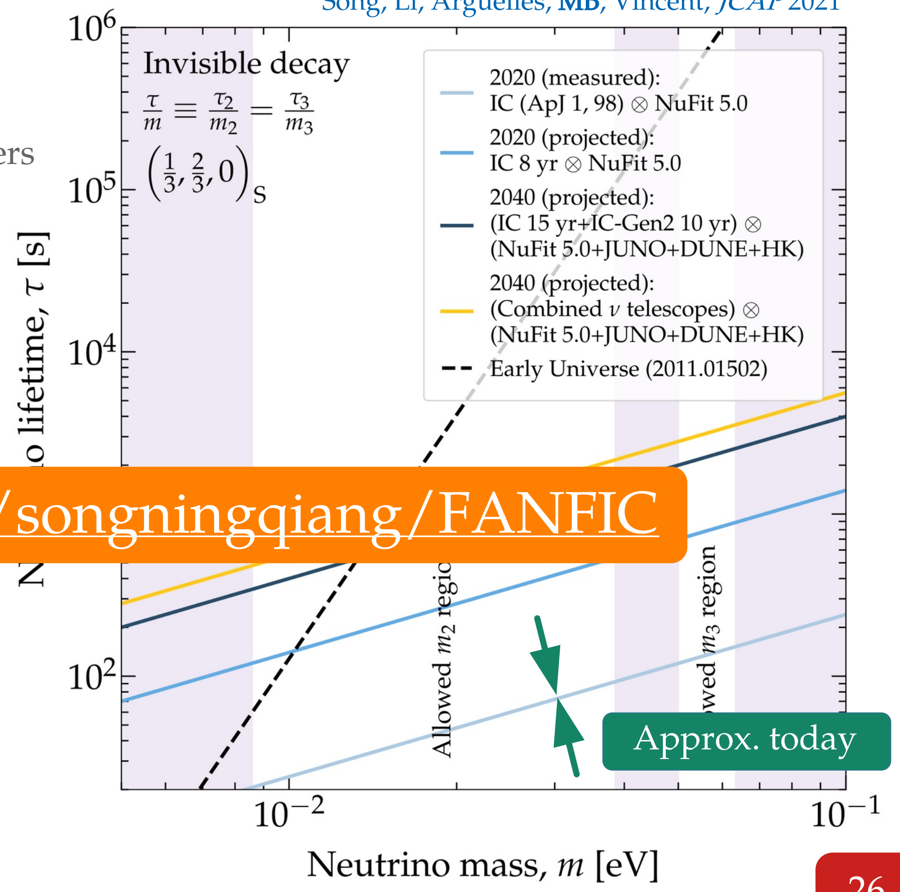

Make your own fit: github.com/songningqiang/FANFIC

What does neutrino decay change?

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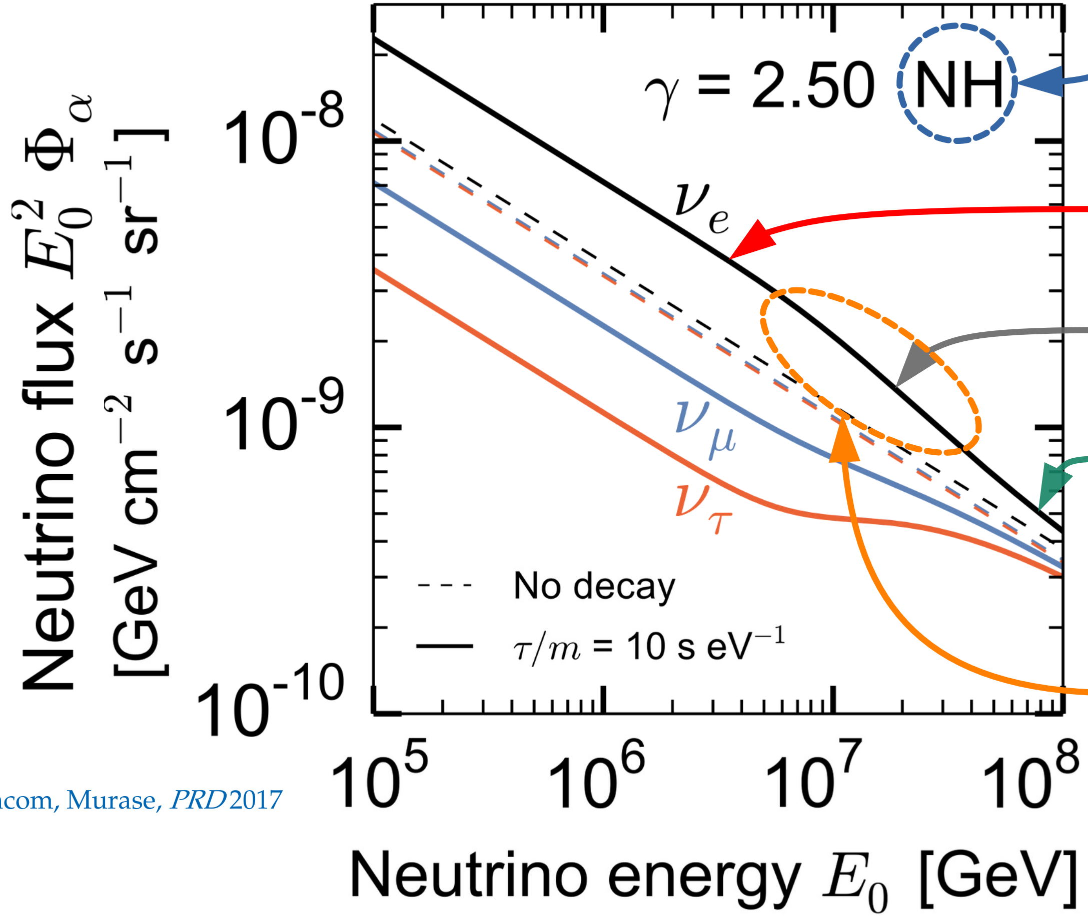
Flavor composition ⟺ **Spectrum shape** ⟺ Event rate



$\nu_2, \nu_3 \to \nu_1$

Low energy: decay evident

Transition region

High energy: no decay

Look for sigmoid-like transition in spectrum: *challenging, but possible with more statistics*

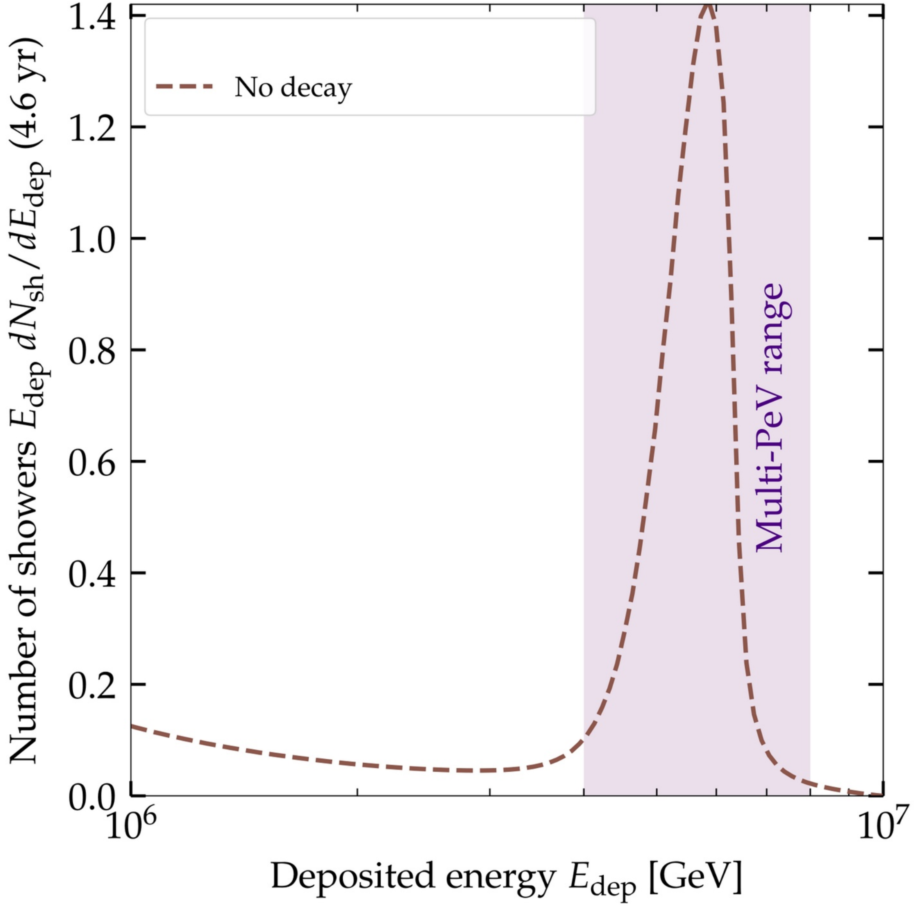
MB, Beacom, Murase, *PRD* 2017

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



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Flavor composition ⟺ Spectrum shape ⟺ Event rate

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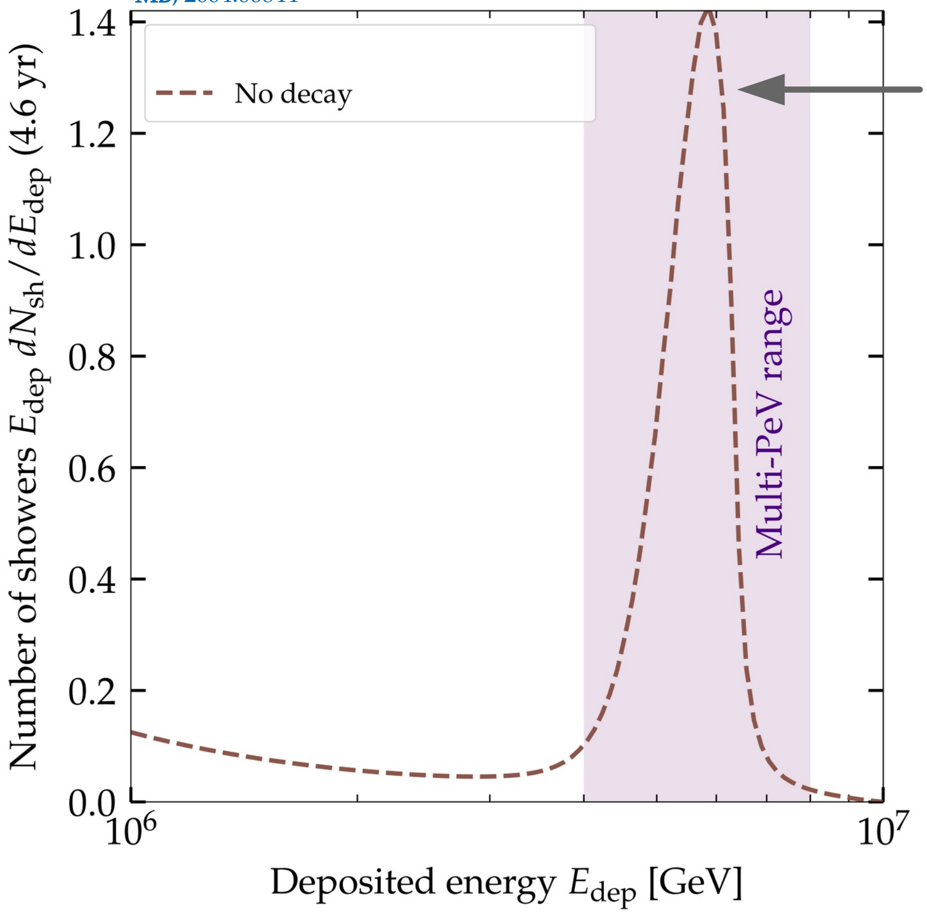

Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

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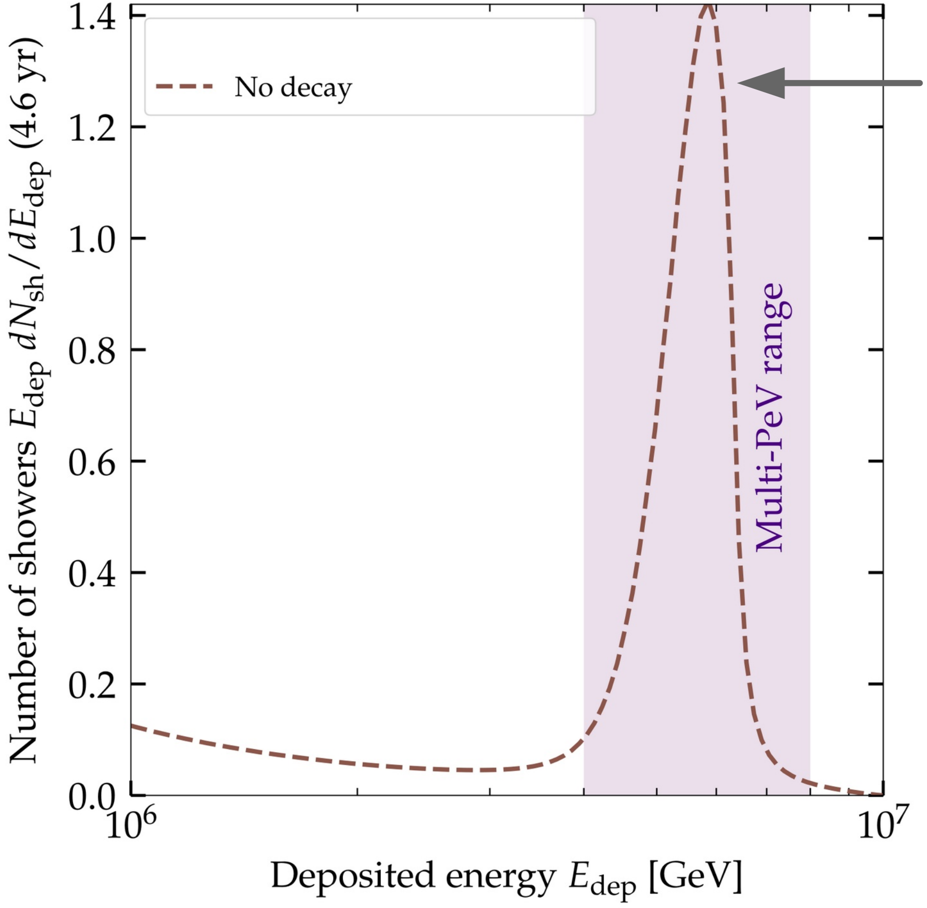
See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

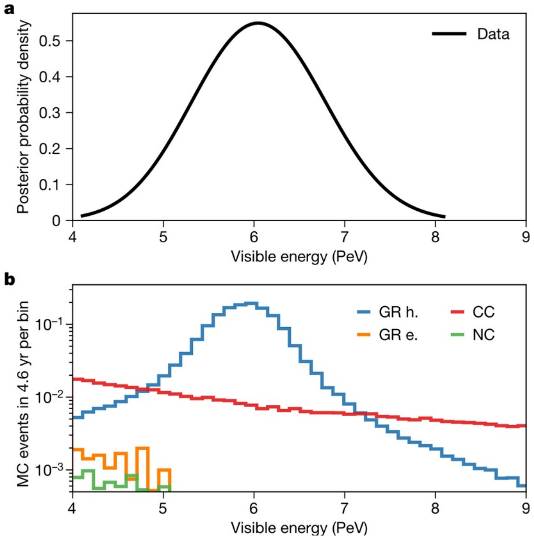
Flavor composition ⟺ Spectrum shape ⟺ **Event rate**

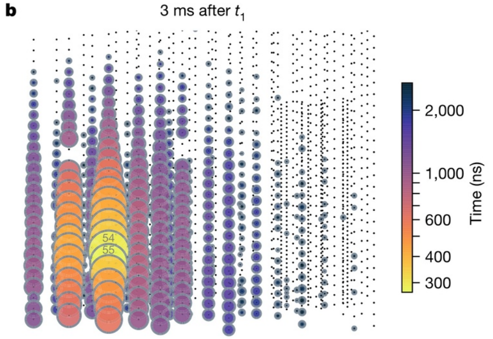
MB, 2004.06844



Glashow resonance (GR):
$\bar{\nu}_e + e \to W \to$ hadrons $\to$ shower

IceCube has seen one GR candidate in 4.6 years:





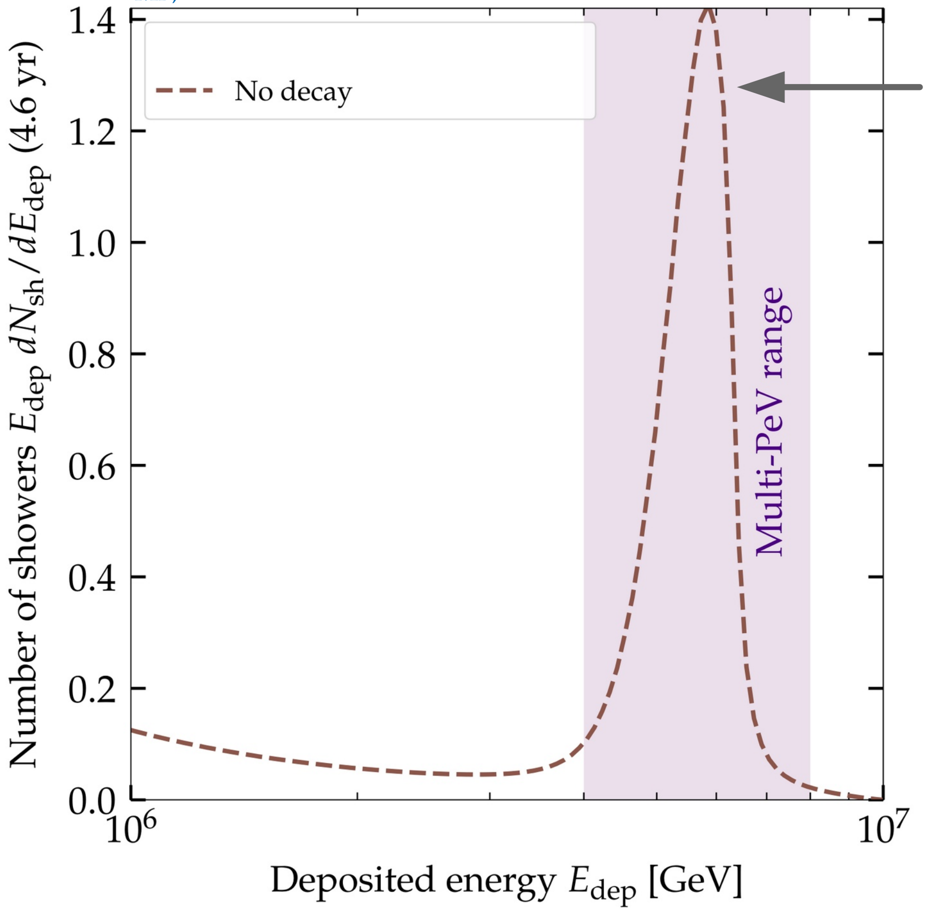
IceCube Collab., *Nature* 2021

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



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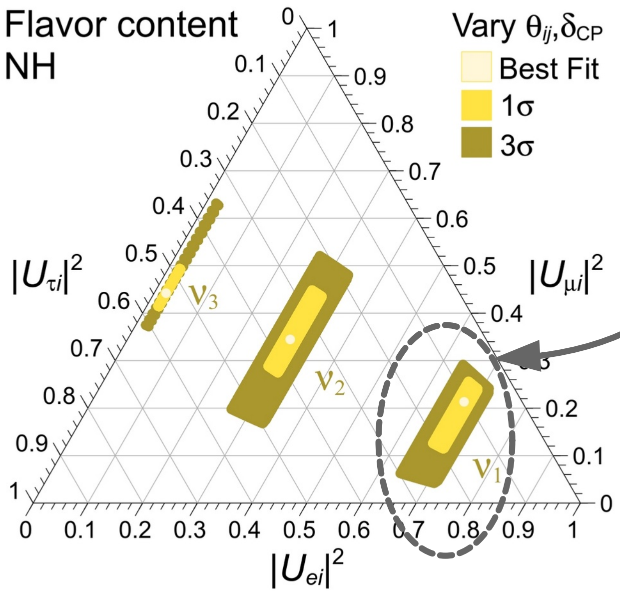
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

ν_1 is the mass eigenstate with the most e flavor

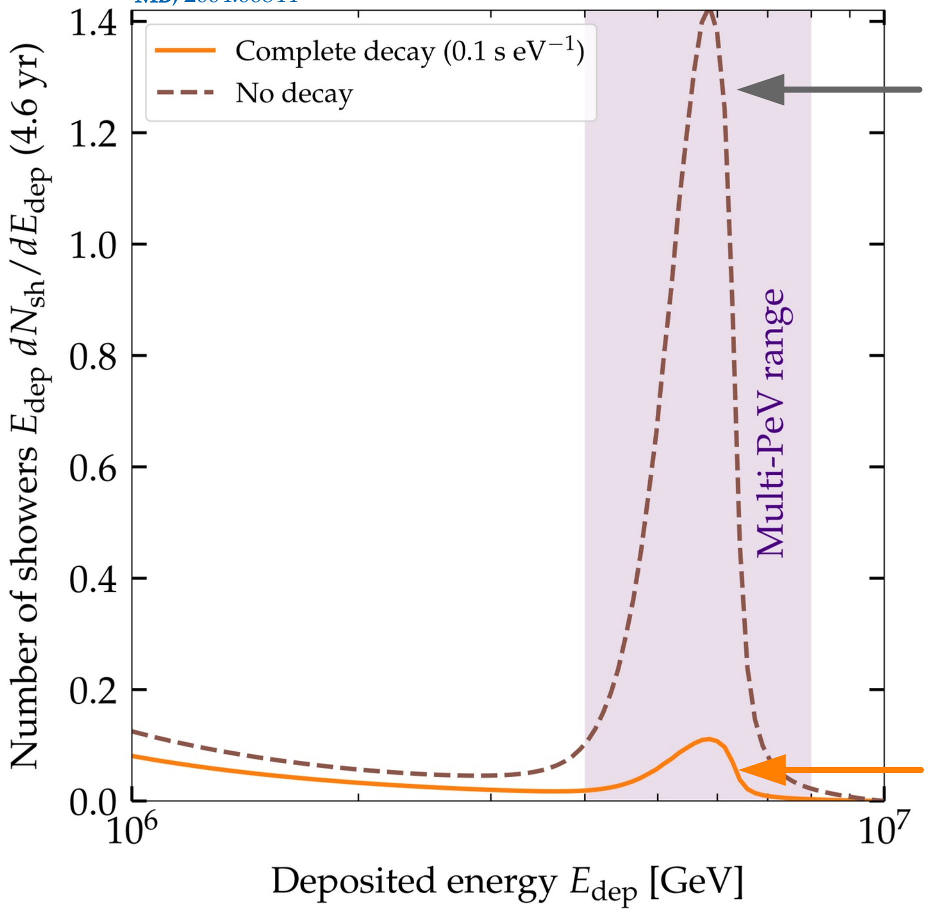


What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



Glashow resonance (GR):
$\bar{\nu}_e + e \to W \to$ hadrons $\to$ shower

If $\bar{\nu}_1$ had decayed en route to Earth,
there would not have been $\bar{\nu}_e$ left to trigger a GR

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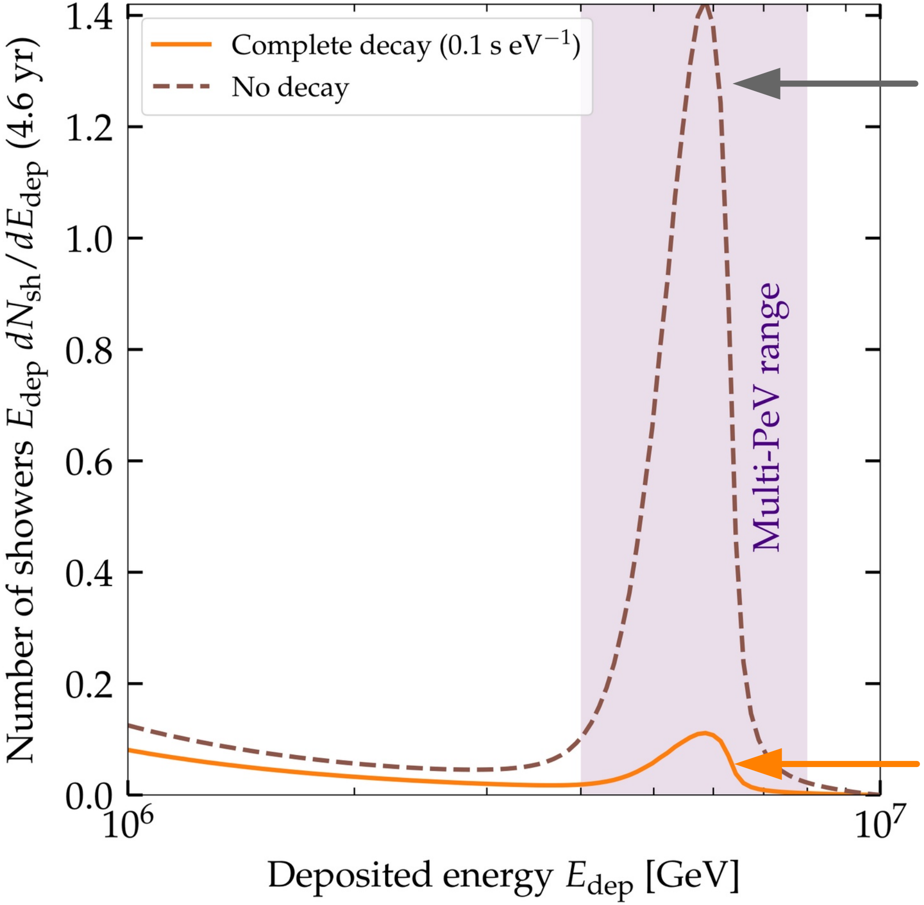

Glashow resonance (GR):
$\bar{\nu}_e + e \to W \to$ hadrons $\to$ shower

So by having observed 1 GR event we can place a *lower* limit on the lifetime of $\bar{\nu}_1$ ($= \nu_1$)

If $\bar{\nu}_1$ had decayed en route to Earth, there would not have been $\bar{\nu}_e$ left to trigger a GR

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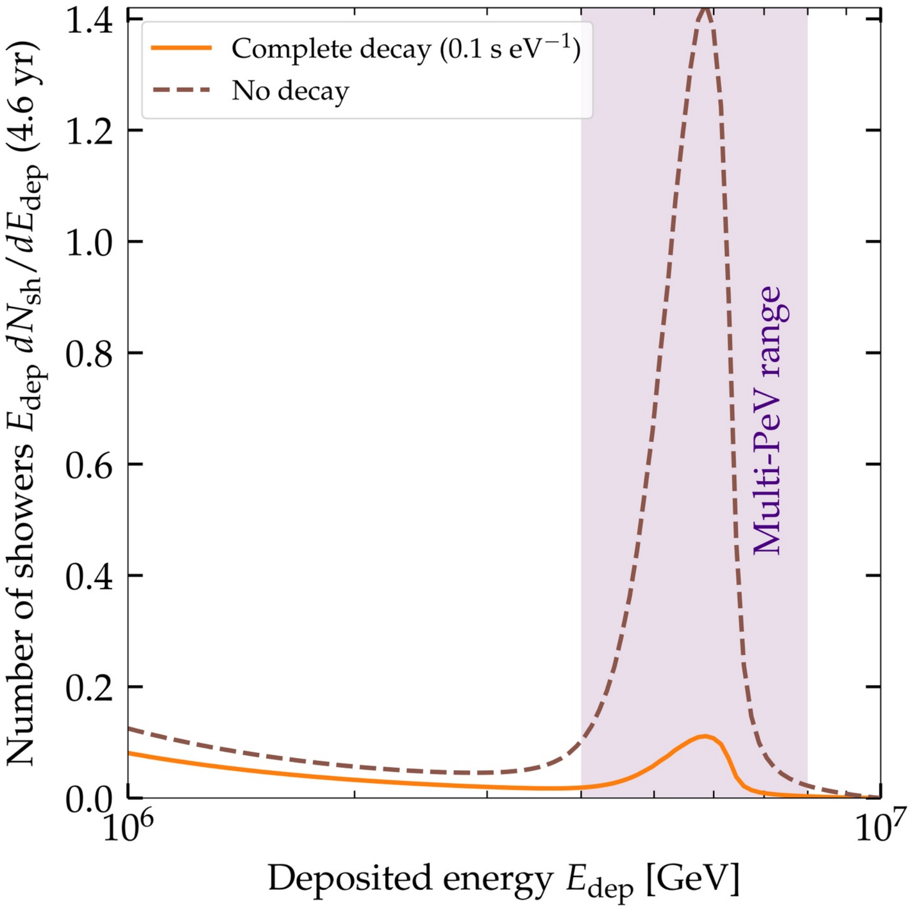

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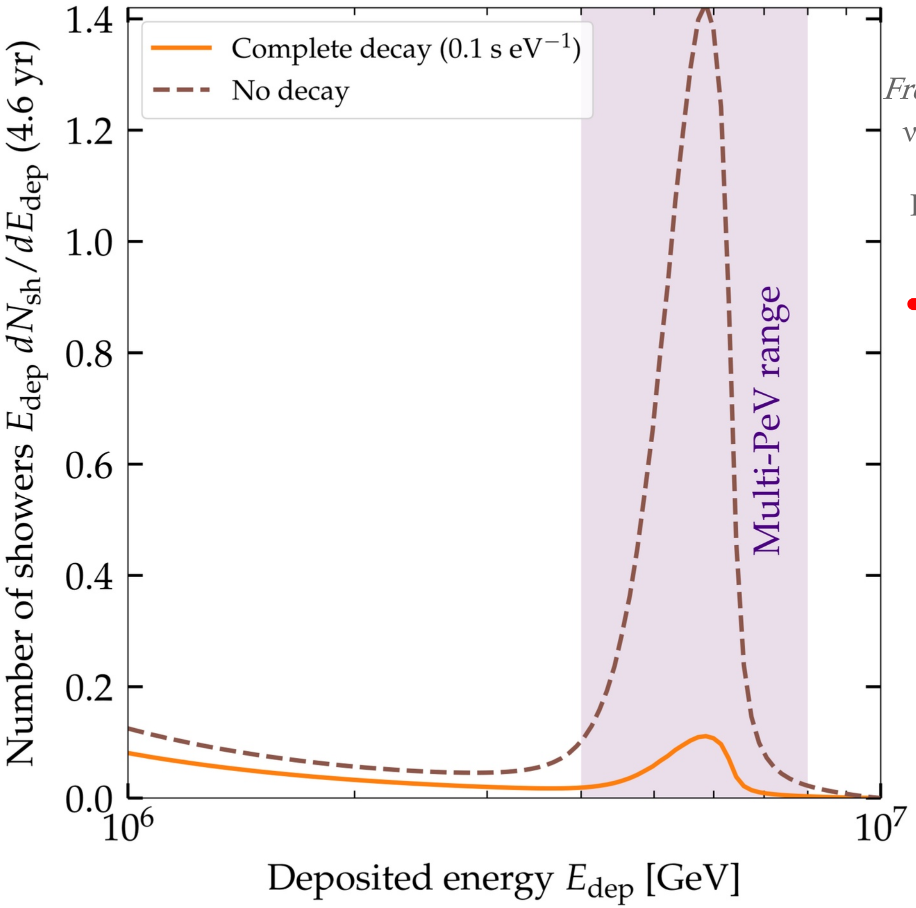

Free parameters:
ν_1, ν_2 lifetimes
Mix. par.
Flavor ratios
$\bar{\nu}/\nu$ ratio

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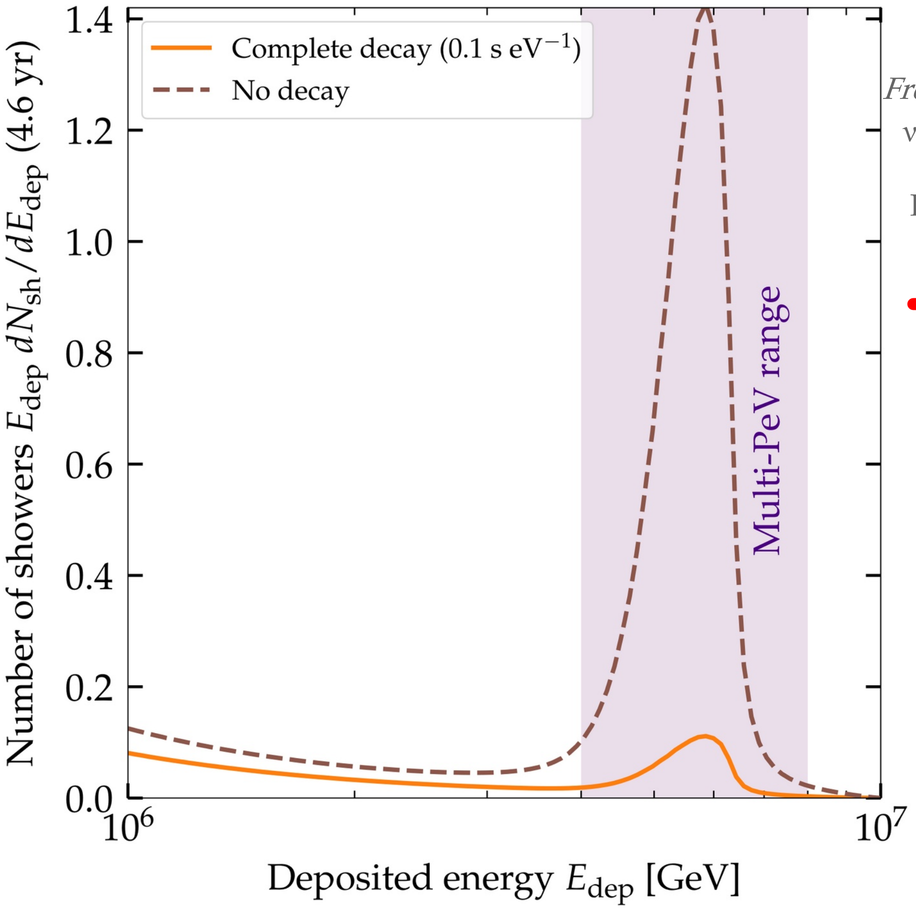
Flavor composition ⟺ Spectrum shape ⟺ **Event rate**



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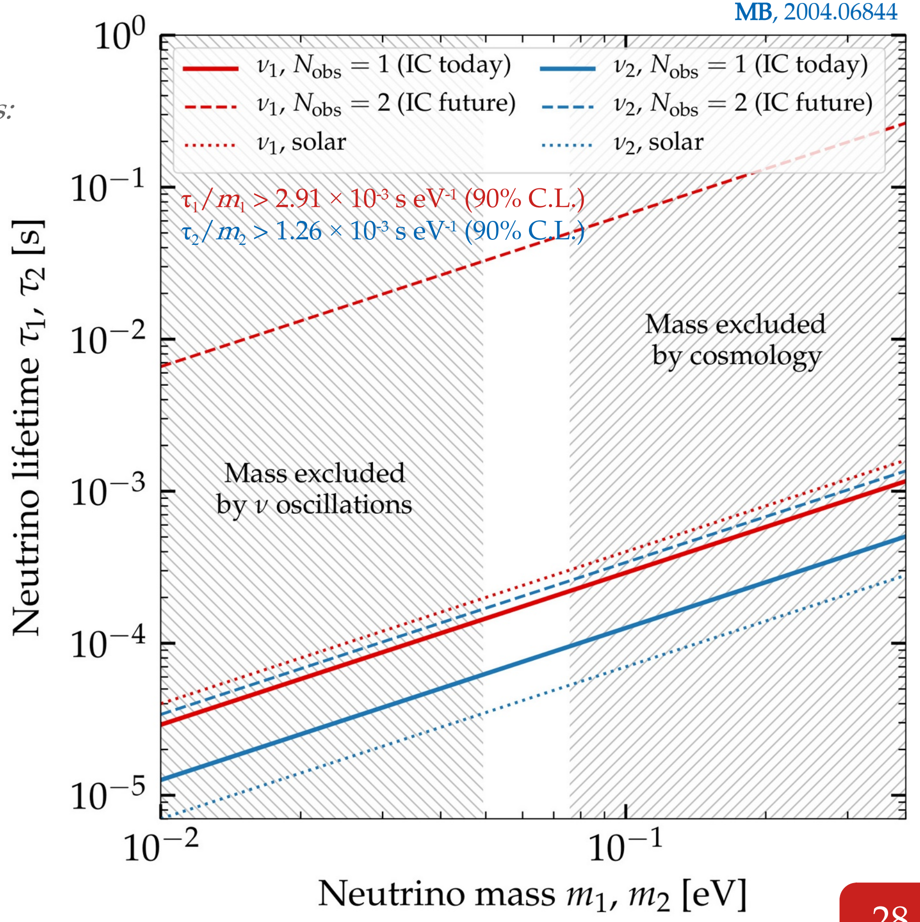

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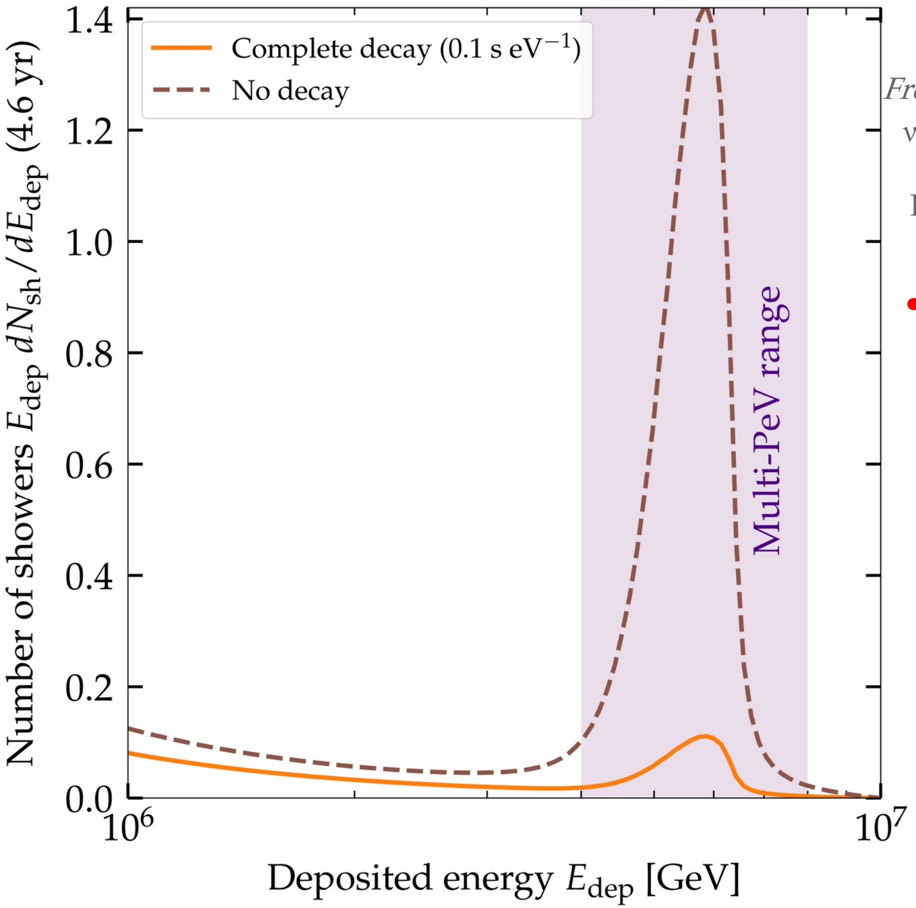

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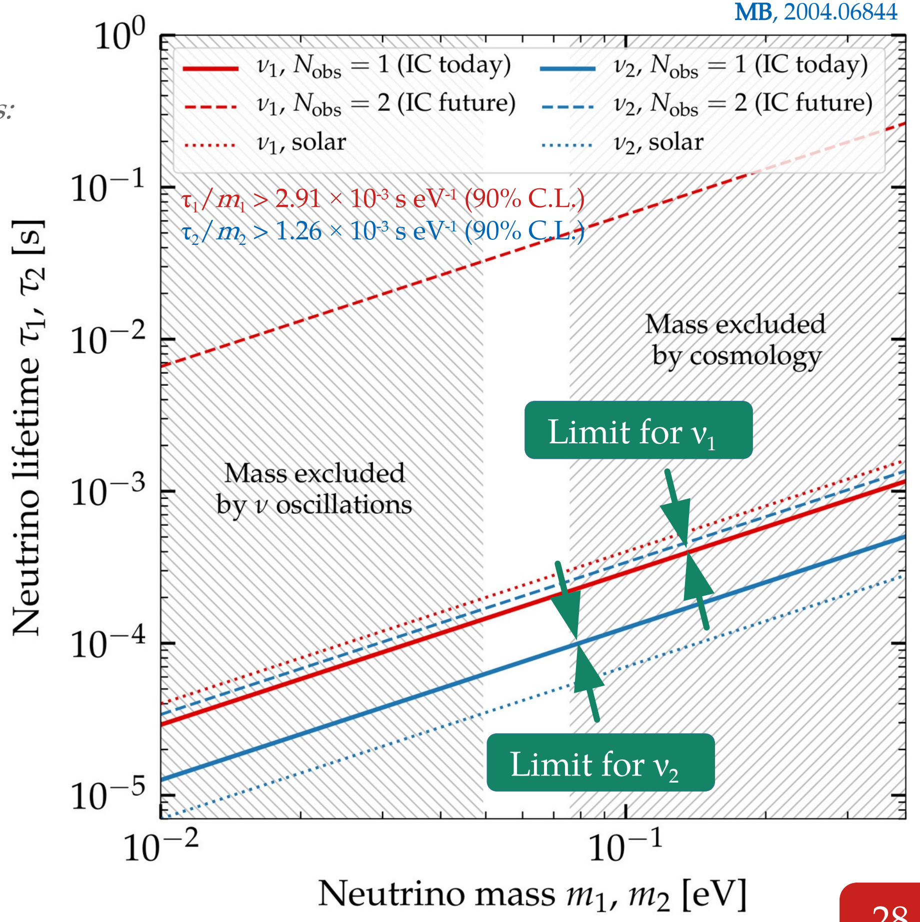
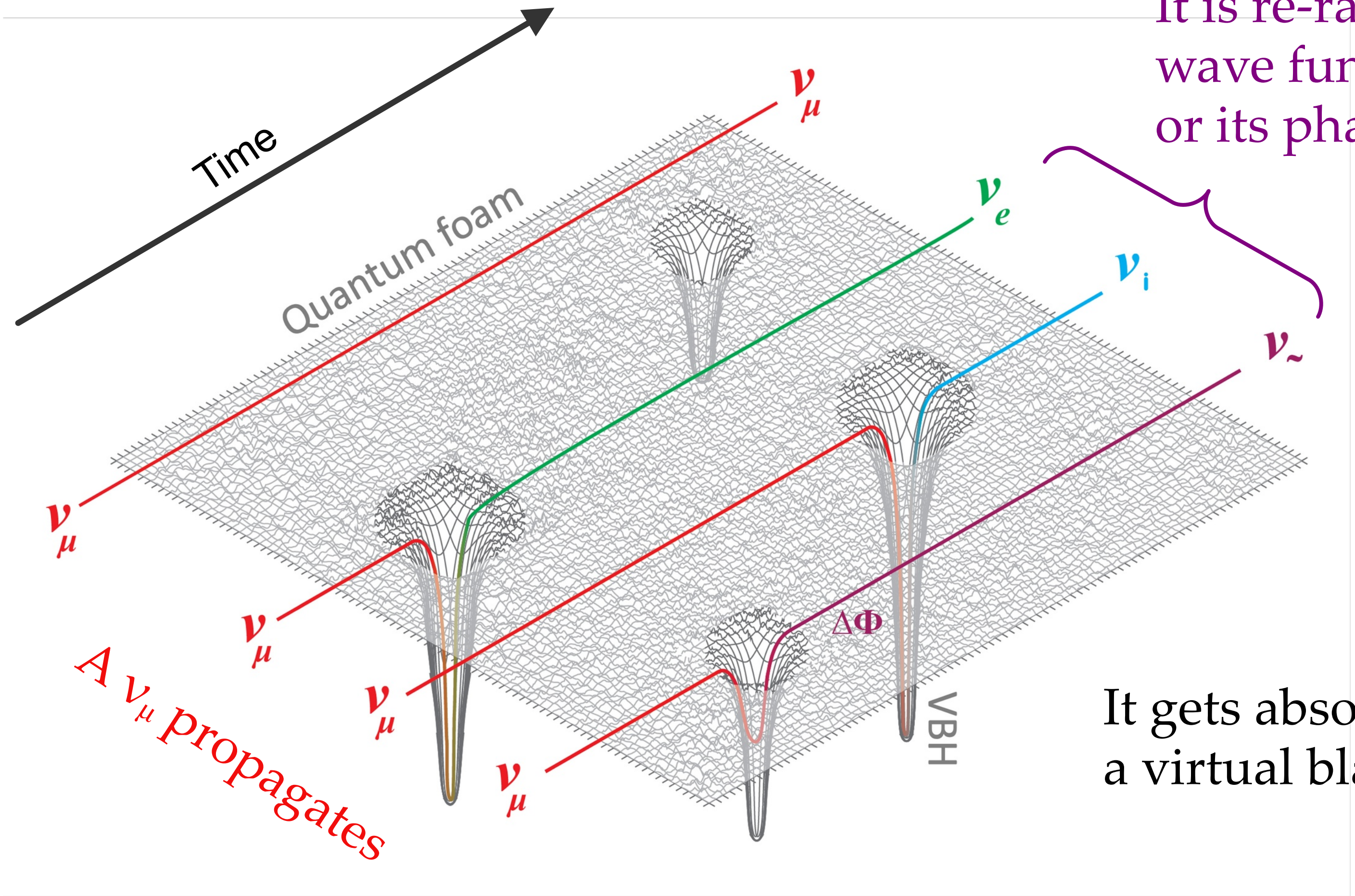


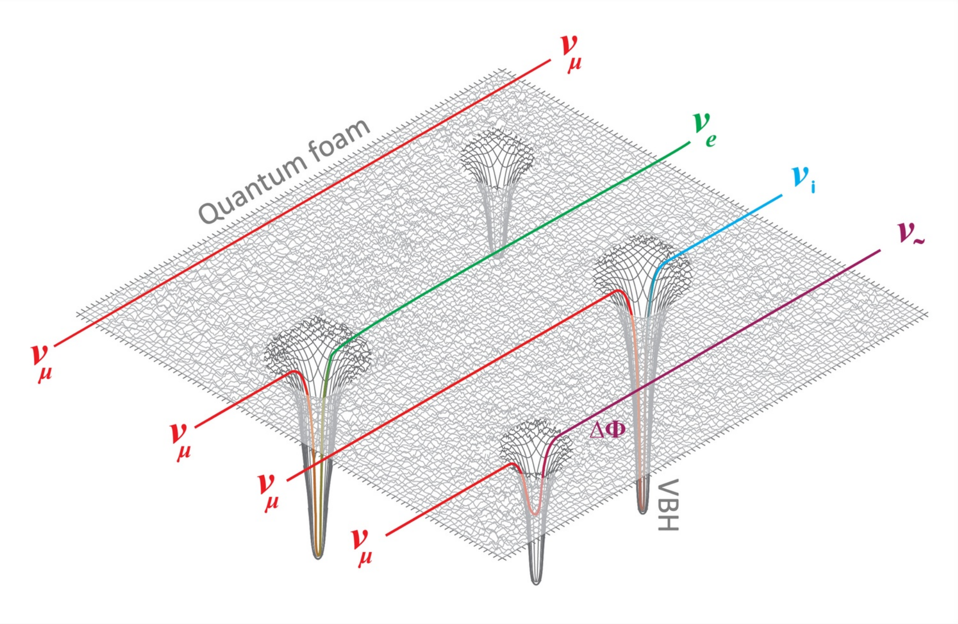
Quantum-gravity decoherence

It is re-radiated with its wave function collapse or its phase perturbed

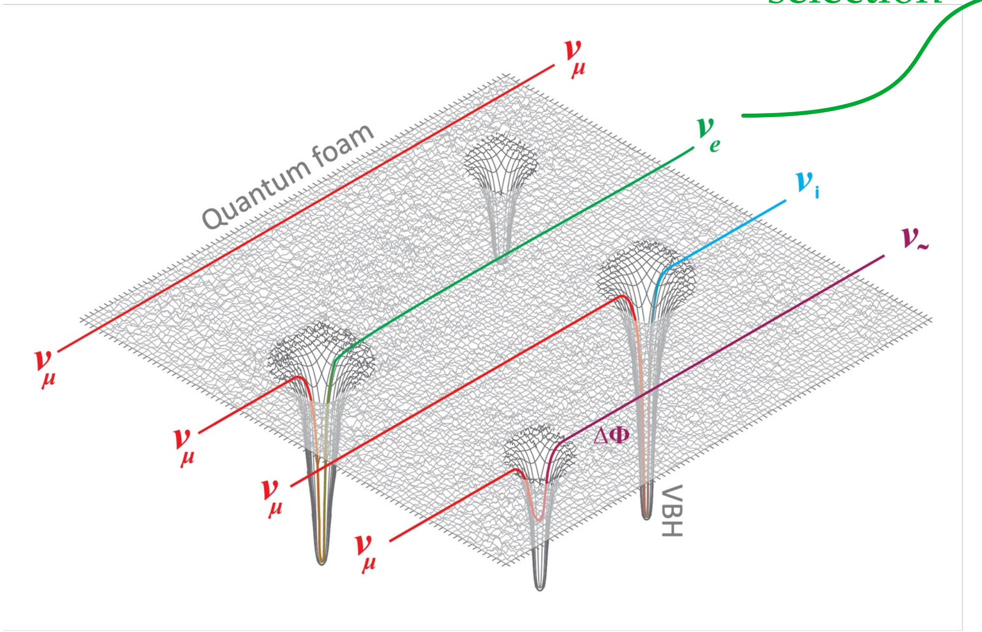


It gets absorbed by a virtual black hole

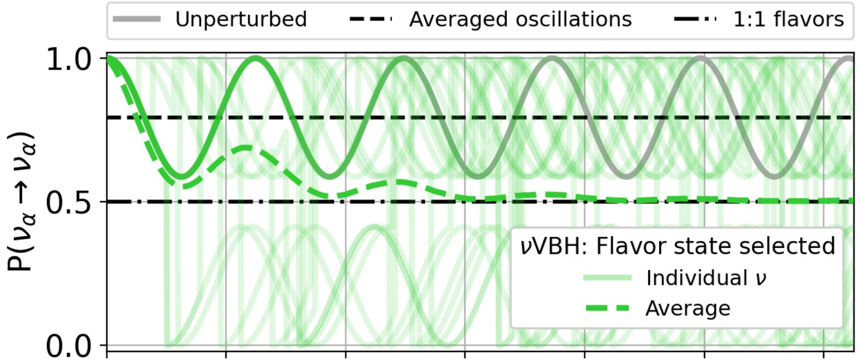
IceCube Collab., *Nature Phys.* 2024



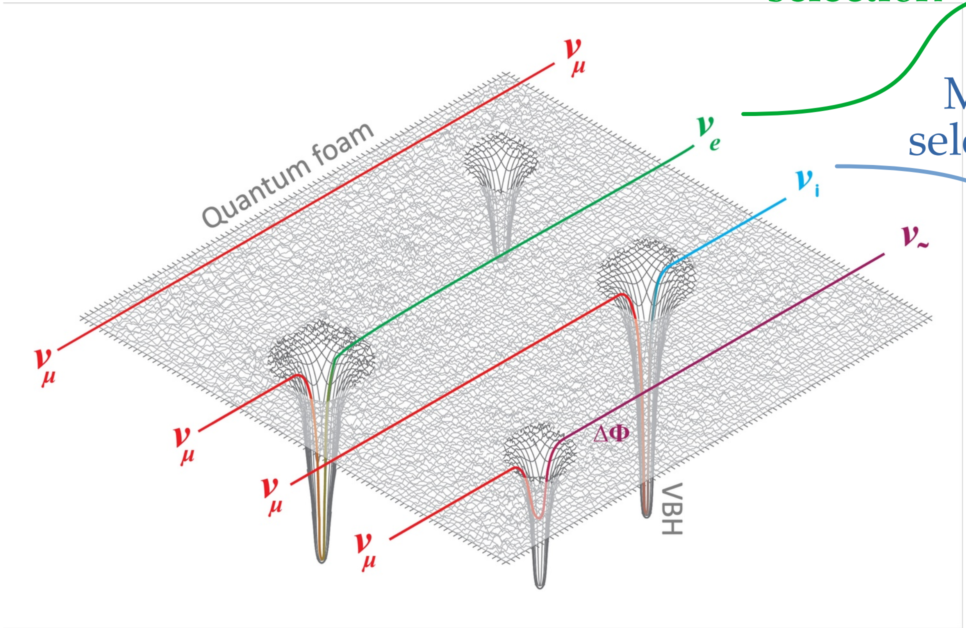
IceCube Collab., *Nature Phys.* 2024

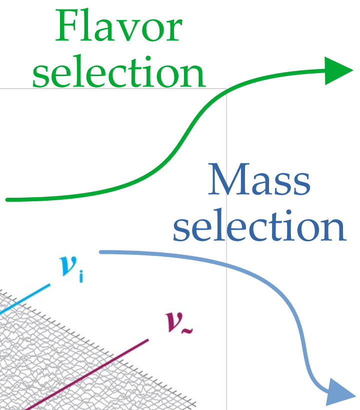


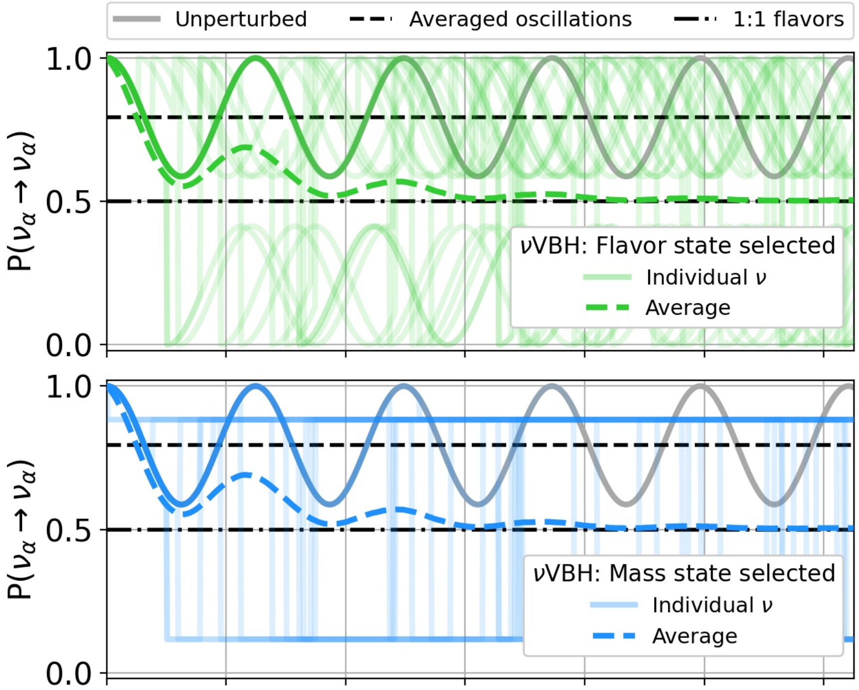
Flavor
selection



IceCube Collab., *Nature Phys.* 2024







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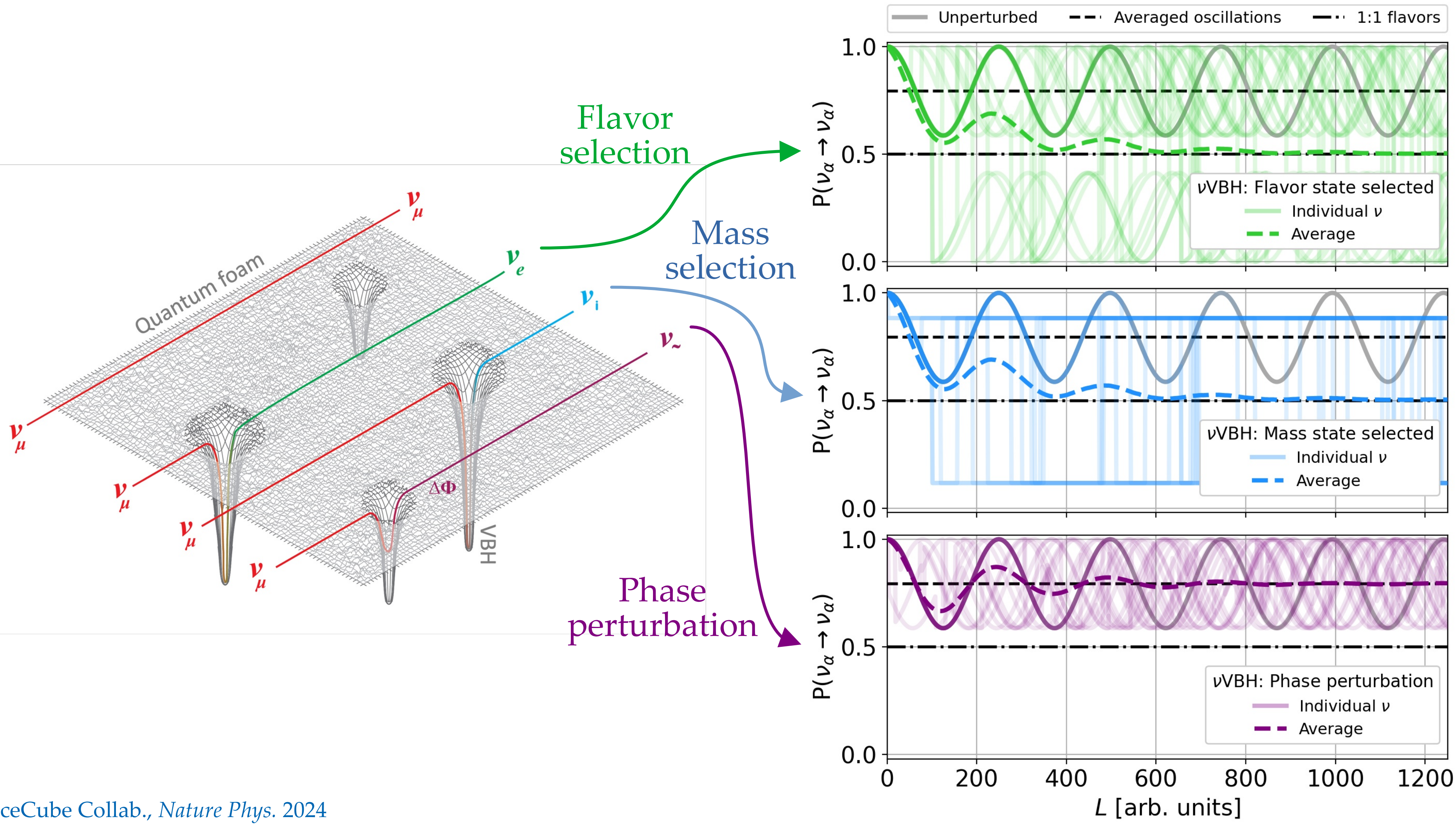

IceCube Collab., *Nature Phys.* 2024

The density matrix ρ of the neutrino system evolves as

Standard unitary time evolution

Non-unitary unitary time evolution

$$\mathcal{D}[\rho] = (D_{\mu\nu}\rho^{\nu})\, b^{\mu}$$

$$\dot{\rho} = -i[H, \rho] - \mathcal{D}[\rho]$$

Gell-Mann matrices

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9×9 matrix

Gell-Mann matrices

Phase perturbation:

$$\mathcal{D}_{\text{phase}} = \text{diag}(0, \Gamma, \Gamma, 0, \Gamma, \Gamma, \Gamma, \Gamma, 0)$$

($L \gg 1/\Gamma$: incoherent sum of mass eigenstates)

State selection:

$$\mathcal{D}_{\text{state}} = \text{diag}(0, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma)$$

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9×9 matrix

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Use ~300k IceCube atmospheric ν_μ with 0.5–10 TeV

Strongest constraints to date

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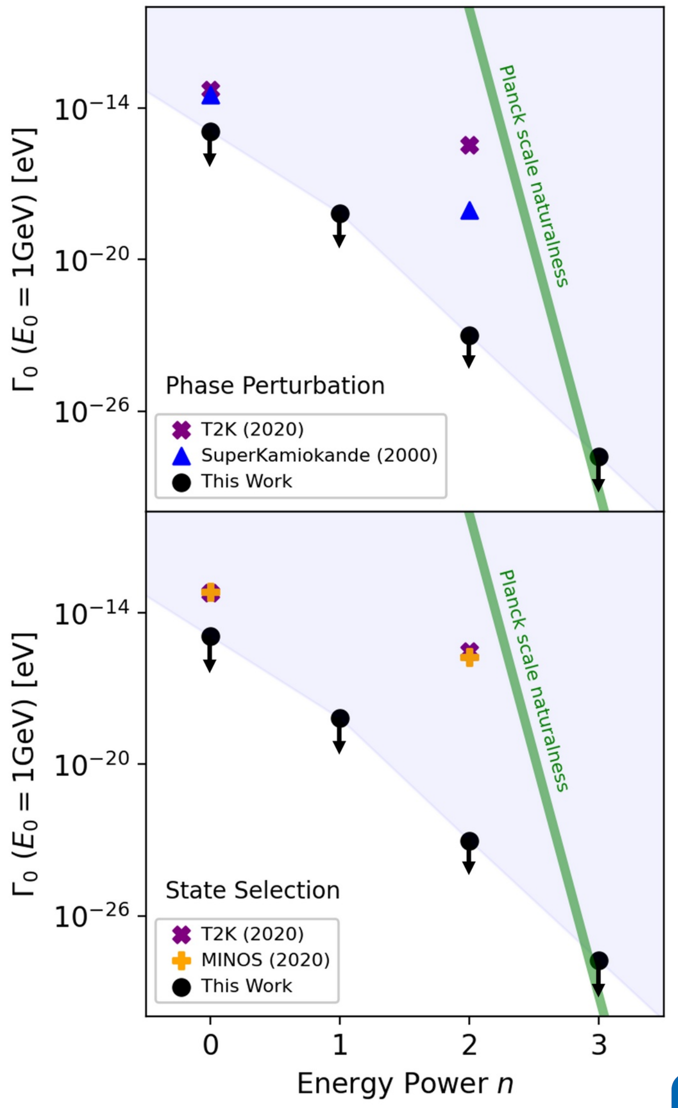


IceCube Collab., *Nature Phys.* 2024

Use ~300k IceCube atmospheric ν_μ with 0.5–10 TeV

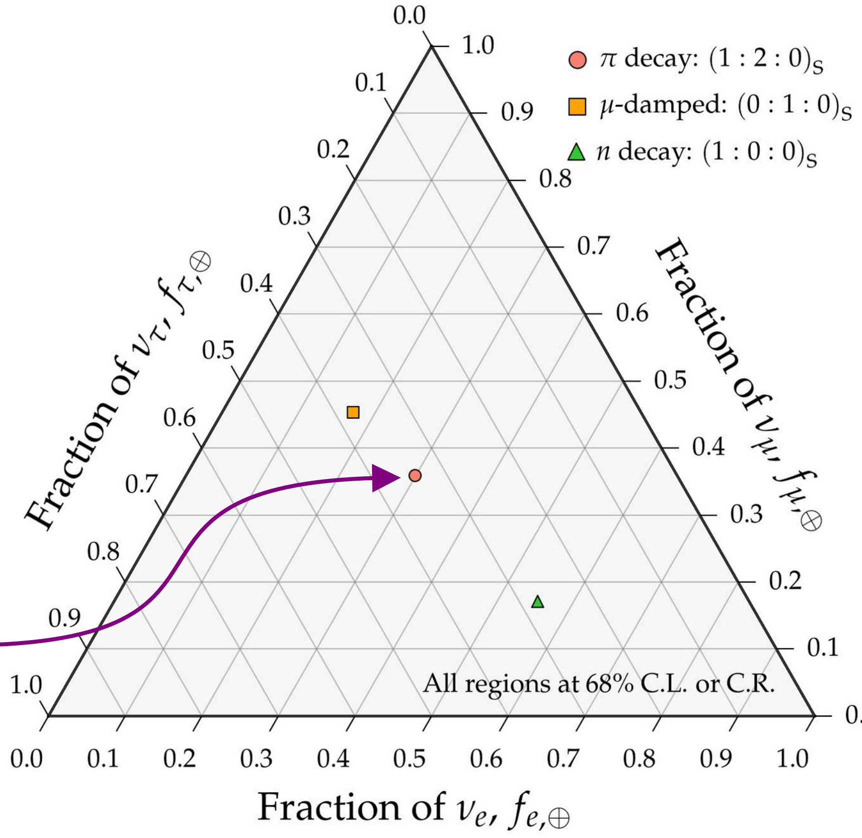
Strongest constraints to date

$$\Gamma(E_\nu) = \Gamma_0 \left(\frac{E_\nu}{E_0} \right)$$

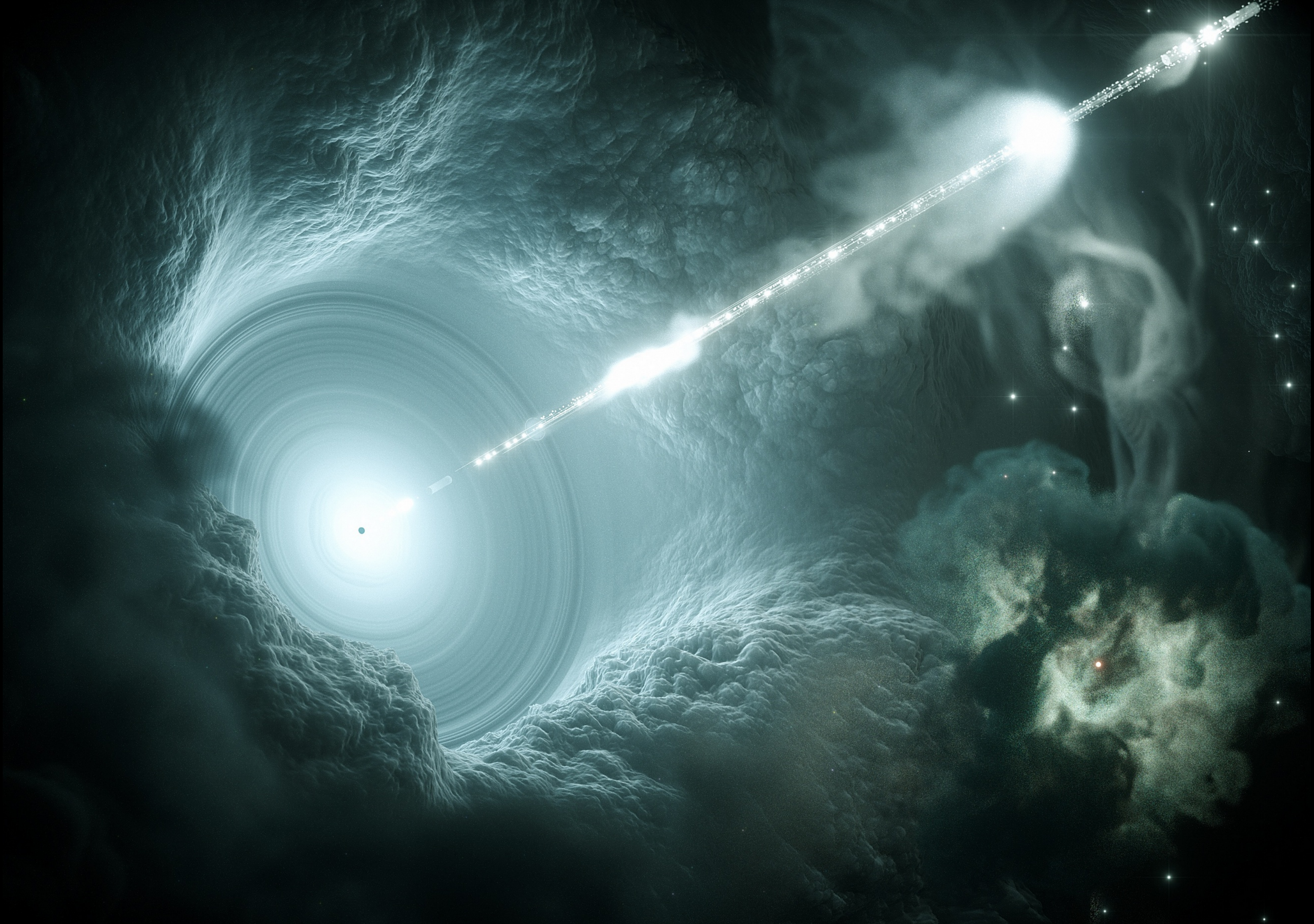
How about using astrophysical TeV—PeV ν?

State selection yields $\nu_e:\nu_\mu:\nu_\tau \approx 1:1:1$
Problem: this matches the standard expectation

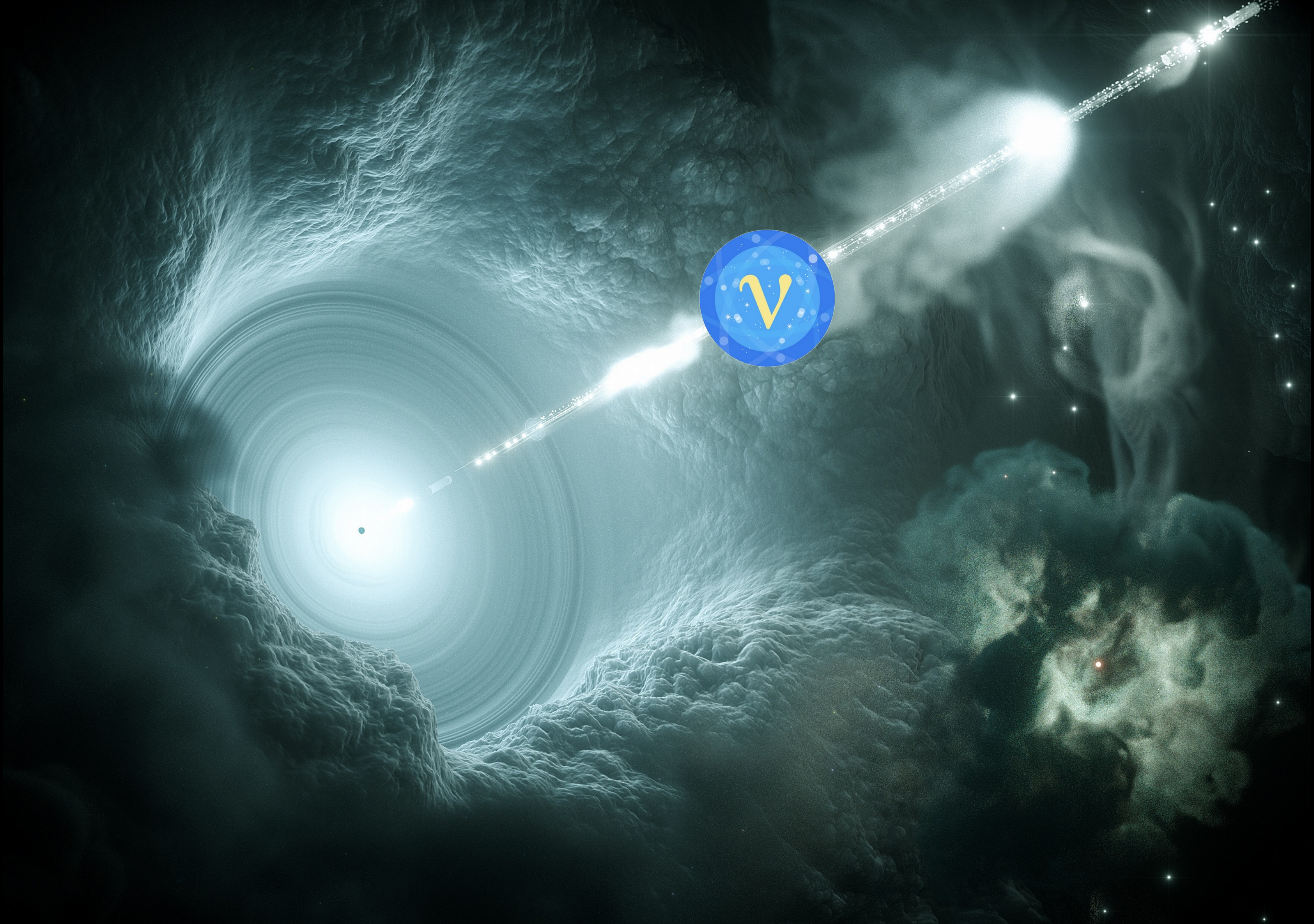
Phase perturbation yields something different
Could be worth exploring



LIV from a high-energy ν flare

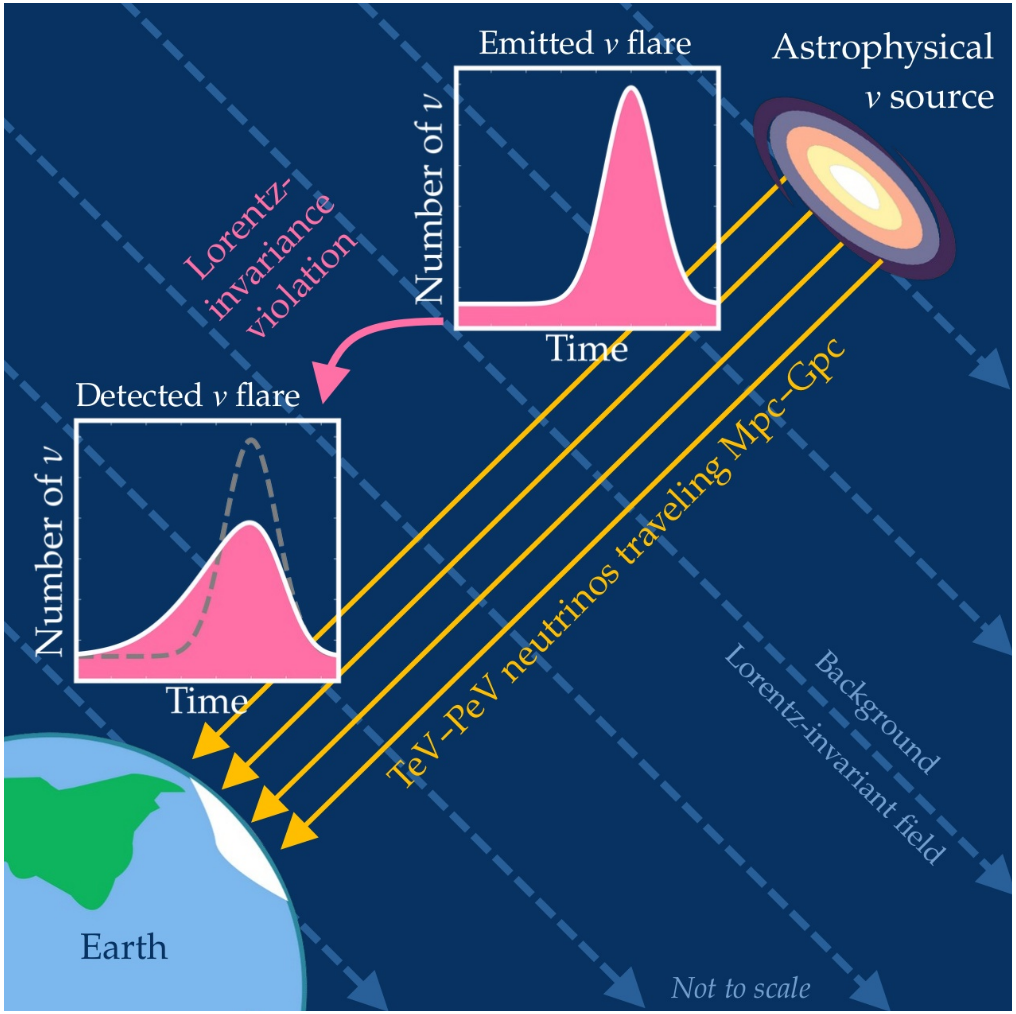


DESY



DESY

New physics from high-energy neutrino flares



Lorentz-invariance violation may change the neutrino speed relative to light speed:

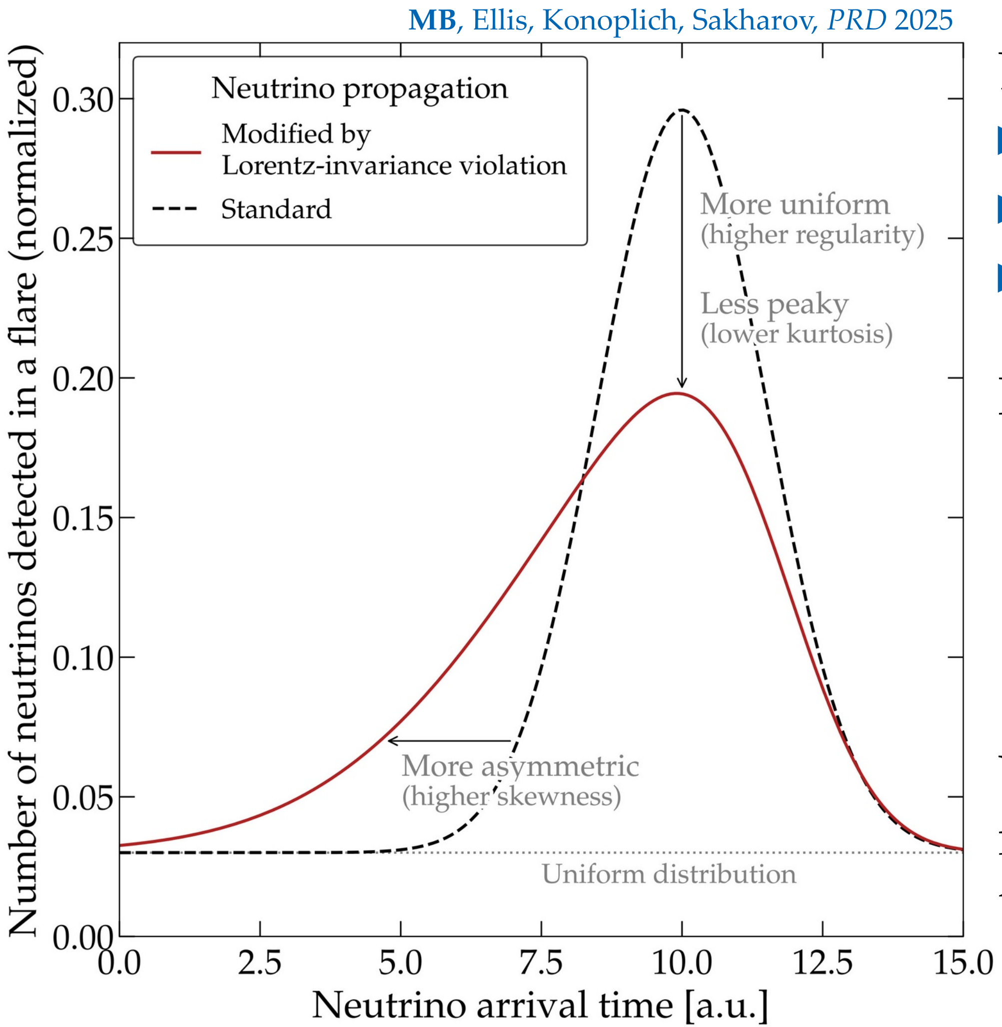
$$v(E_\nu) = \left[1 - \frac{n+1}{2}\left(\frac{E_\nu}{M_n}\right)^n\right] \equiv 1 - \Delta v(E_\nu)$$

M_n: LIV energy scale (unknown)

From the time profile of a neutrino flare we can bound the value of M_n *without an electromagnetic counterpart* and *without knowing the original time profile*

MB, Ellis, Konoplich, Sakharov, *PRD* 2025

New physics from high-energy neutrino flares



LIV makes the υ flare time-distribution...

- More uniform
- Less peaky (lower kurtosis)
- More asymmetric (negative skewness)

For a detected neutrino with E_υ in a flare:

$$t_{\mathrm{obs}}(E_\nu) = b_{\mathrm{s}}(E_\nu)(1 + z_{\mathrm{src}}) + \tau_n(z_{\mathrm{src}})E_\nu^n$$

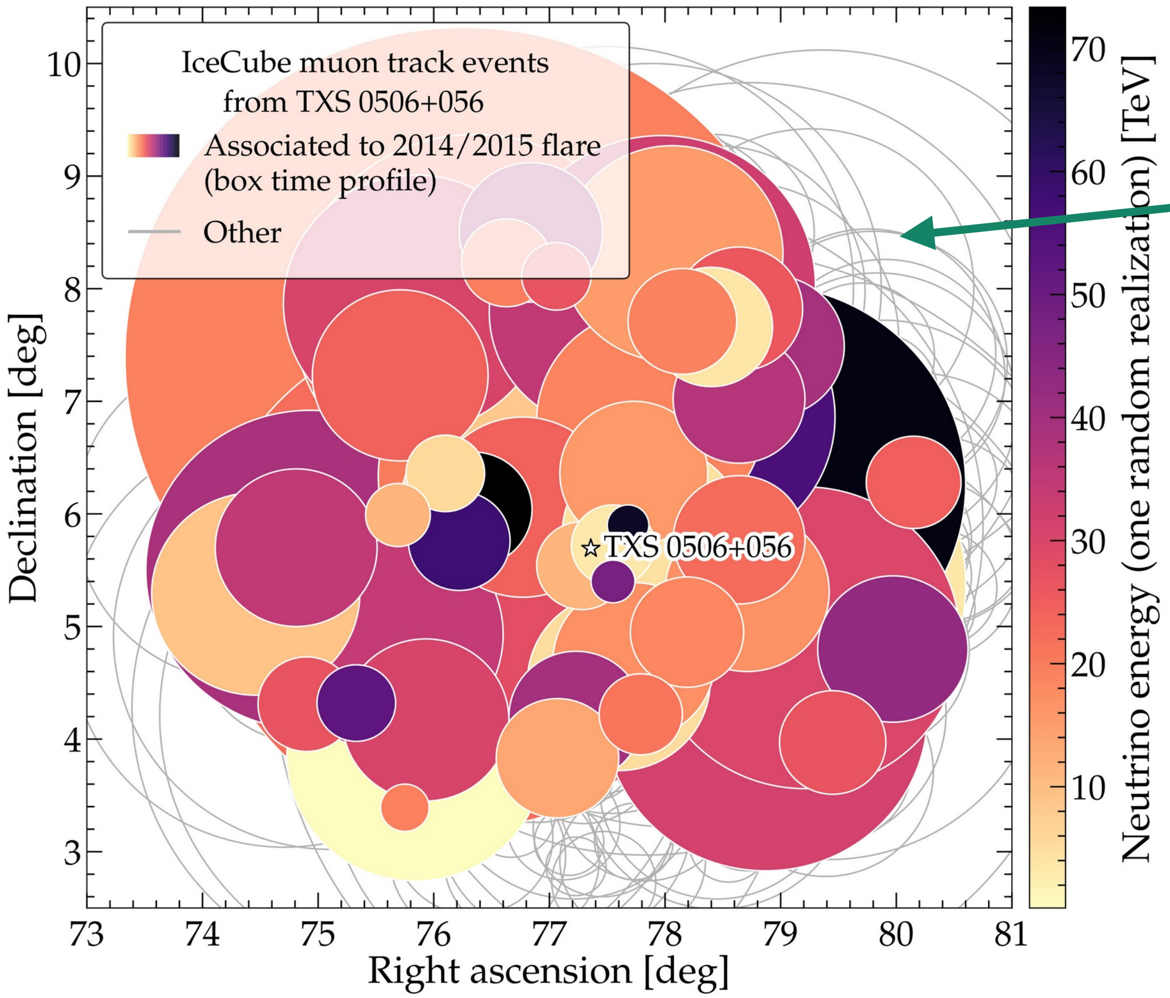
Detection time of a at Earth

Intrinsic lag in the source

Effect of LIV

We find the value of τ_n that restores irregularity, peakiness, and asymmetry to time-distribution of the flare

New physics from high-energy neutrino flares

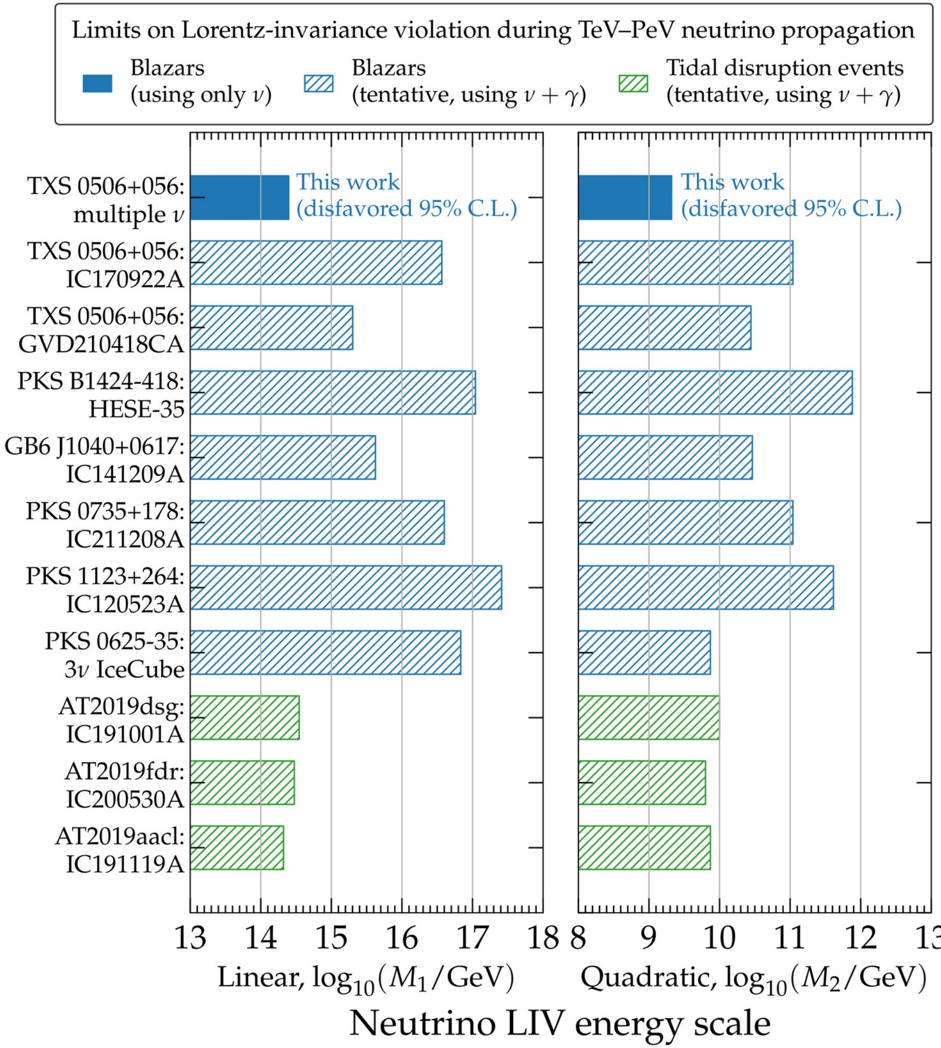


Use IceCube through-going muons associated to the 2015/2015 flare of TXS 0506+056

- Higher weight if closer to the source
- Account for uncertainty in linking muon energy (measured) to neutrino energy (inferred)

MB, Ellis, Konoplich, Sakharov, *PRD* 2025

New physics from high-energy neutrino flares



New limits from the TXS 0506+056 2014/2015 flare *using only neutrinos*

Limits from the coincident emission of neutrinos and electromagnetic emission (generally low or unspecified credibility)

MB, Ellis, Konoplich, Sakharov, *PRD* 2025

Lorentz-invariance violation at UHE

Lorentz-invariance violation — from a GRB association

GRB emitted neutrinos & photons simultaneously

Time delay induced by dispersion of neutrinos on spacetime foam:

Neutrino energy

$$\Delta t = D(z)\frac{E}{\Lambda} \approx 14 \text{ years}$$

Cosmological expansion

Energy scale of LIV (10^{14}–10^{15} GeV)

GRB-ν association: 2.4σ

(p-value of 0.015)

Amelino-Camelia *et al.*, *PLB* 2025