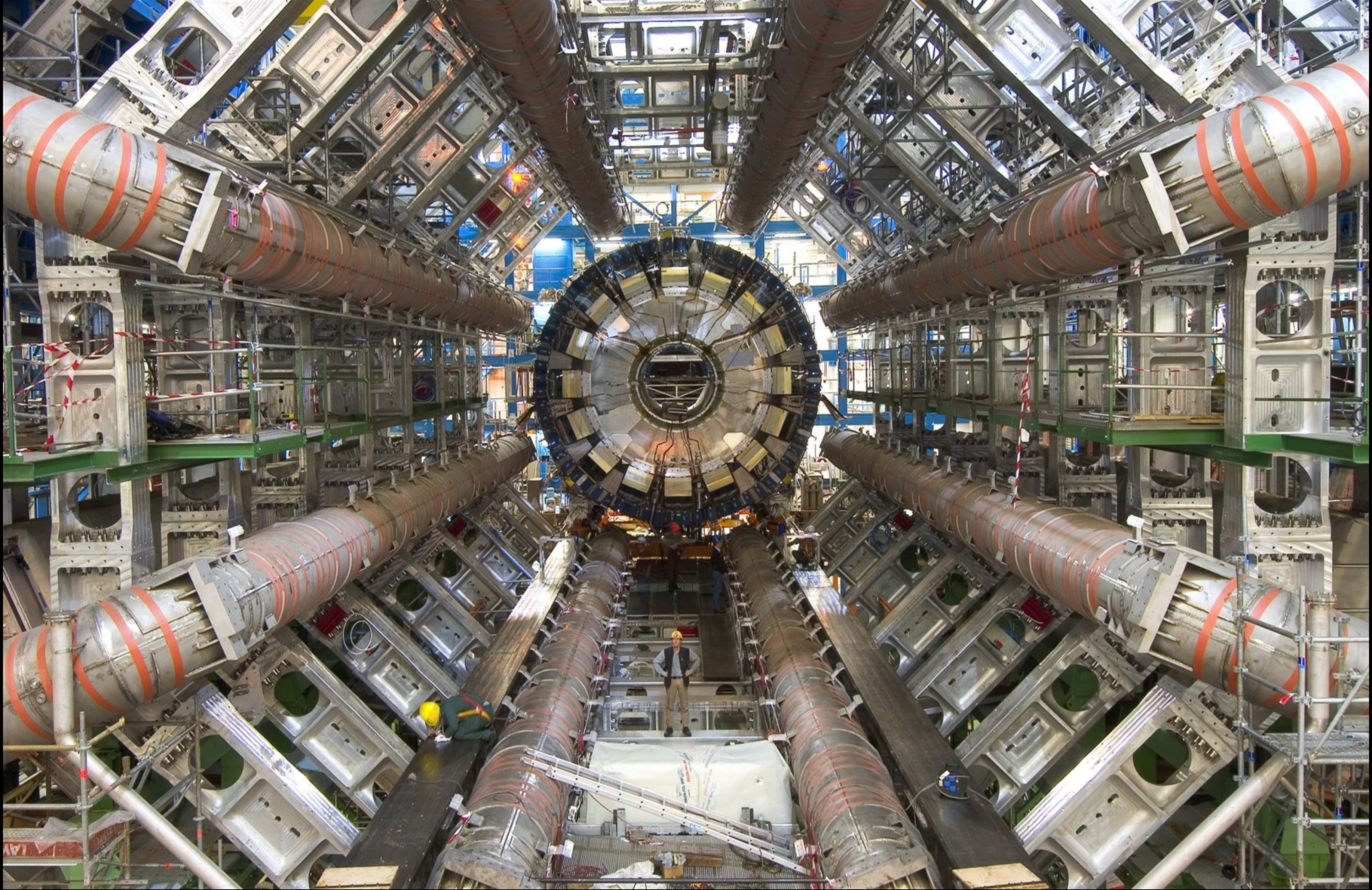
Higher, further, faster: neutrino physics at the cosmic and energy frontiers

Mauricio Bustamante
Niels Bohr Institute, University of Copenhagen

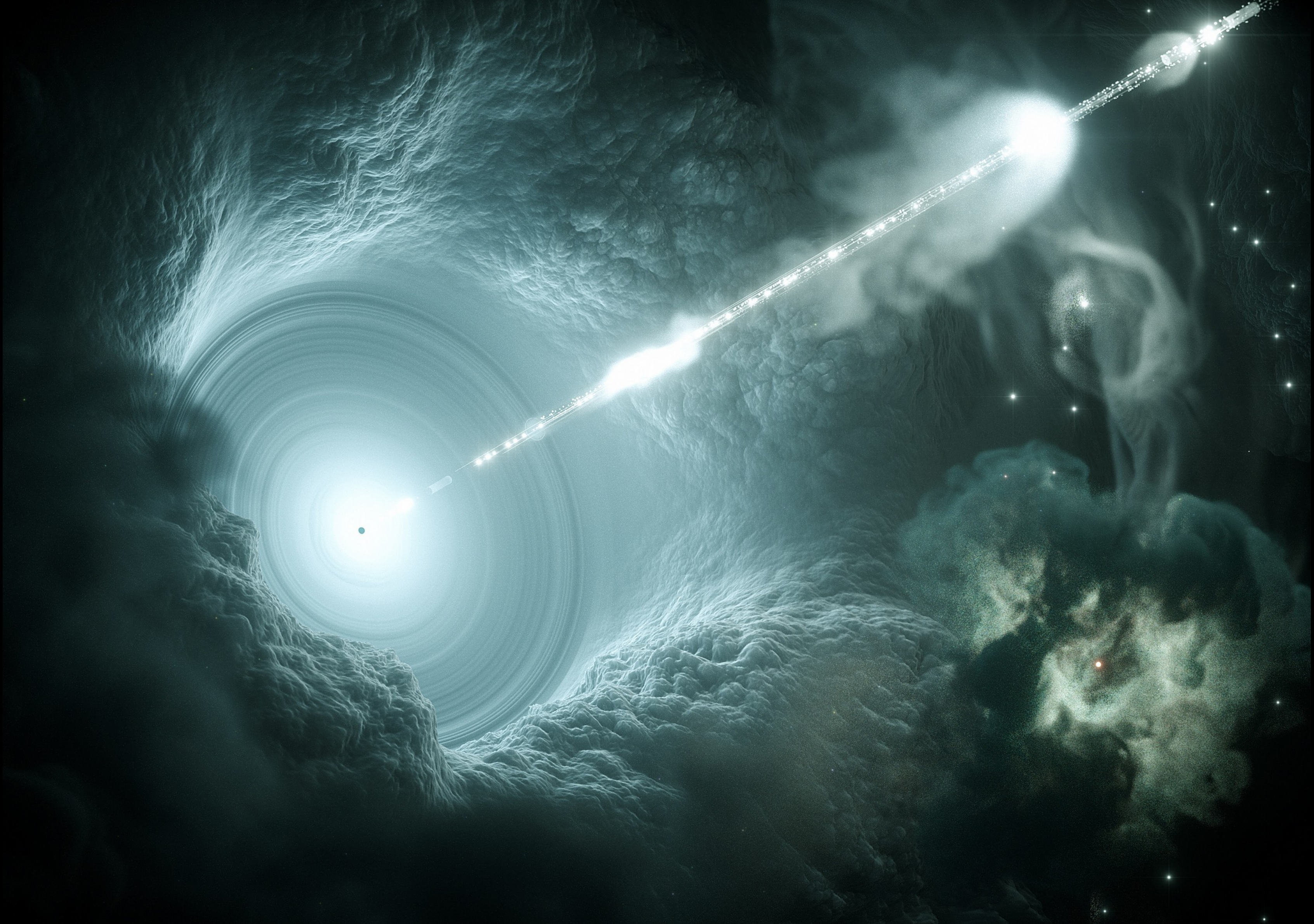
Oskar Klein Center Colloquium
February 07, 2023

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN



ATLAS



DESY

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Neutrinos are elementary particles,

electrically neutral,

very light,

and superbly antisocial

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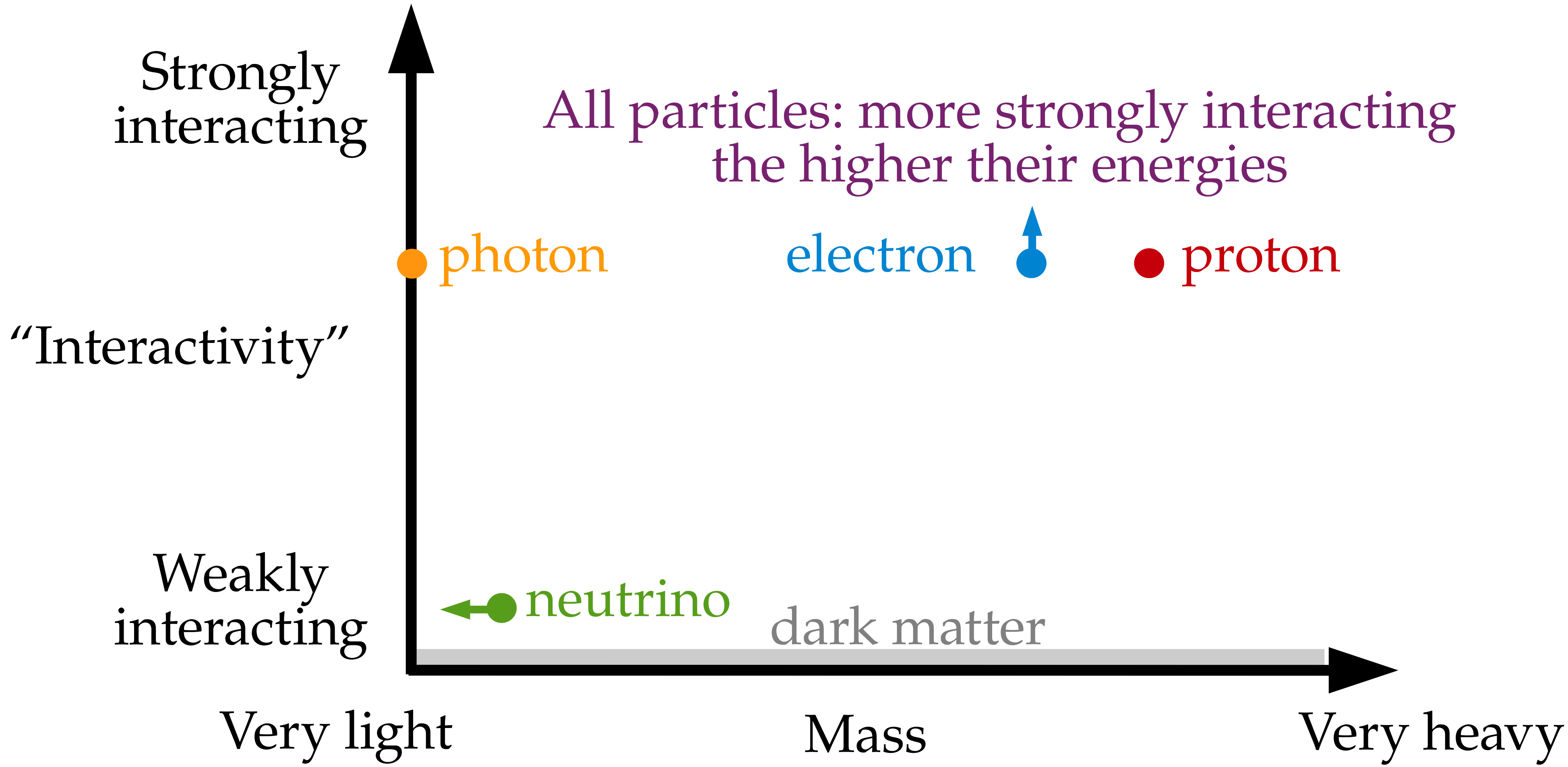
Neutrinos are $\underbrace{\text{elementary particles}}_{=\ \textit{indivisible}}$,

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

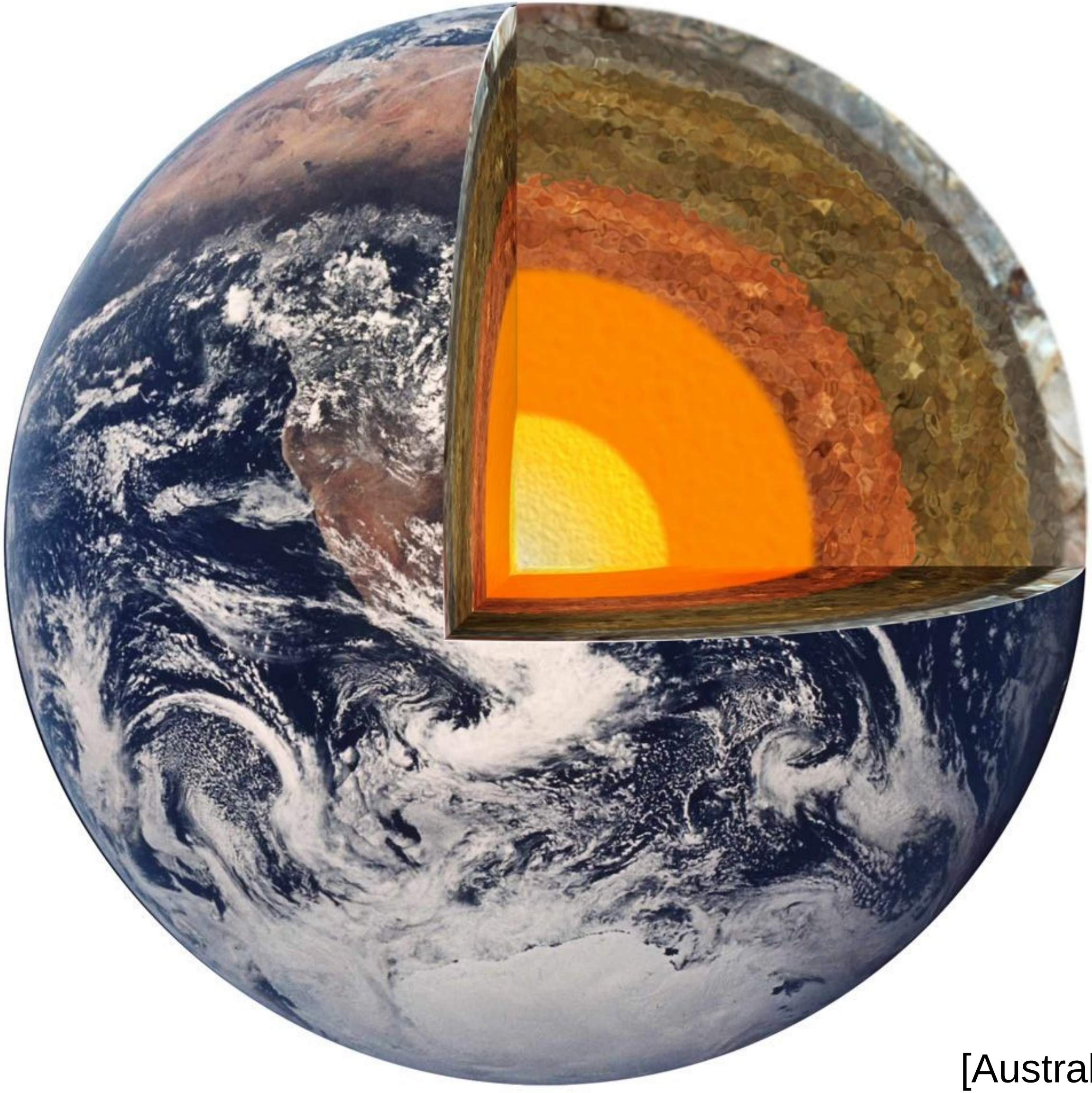
$\underbrace{\text{very light}}_{=\ \textit{so light that we don't know their mass!}}$,

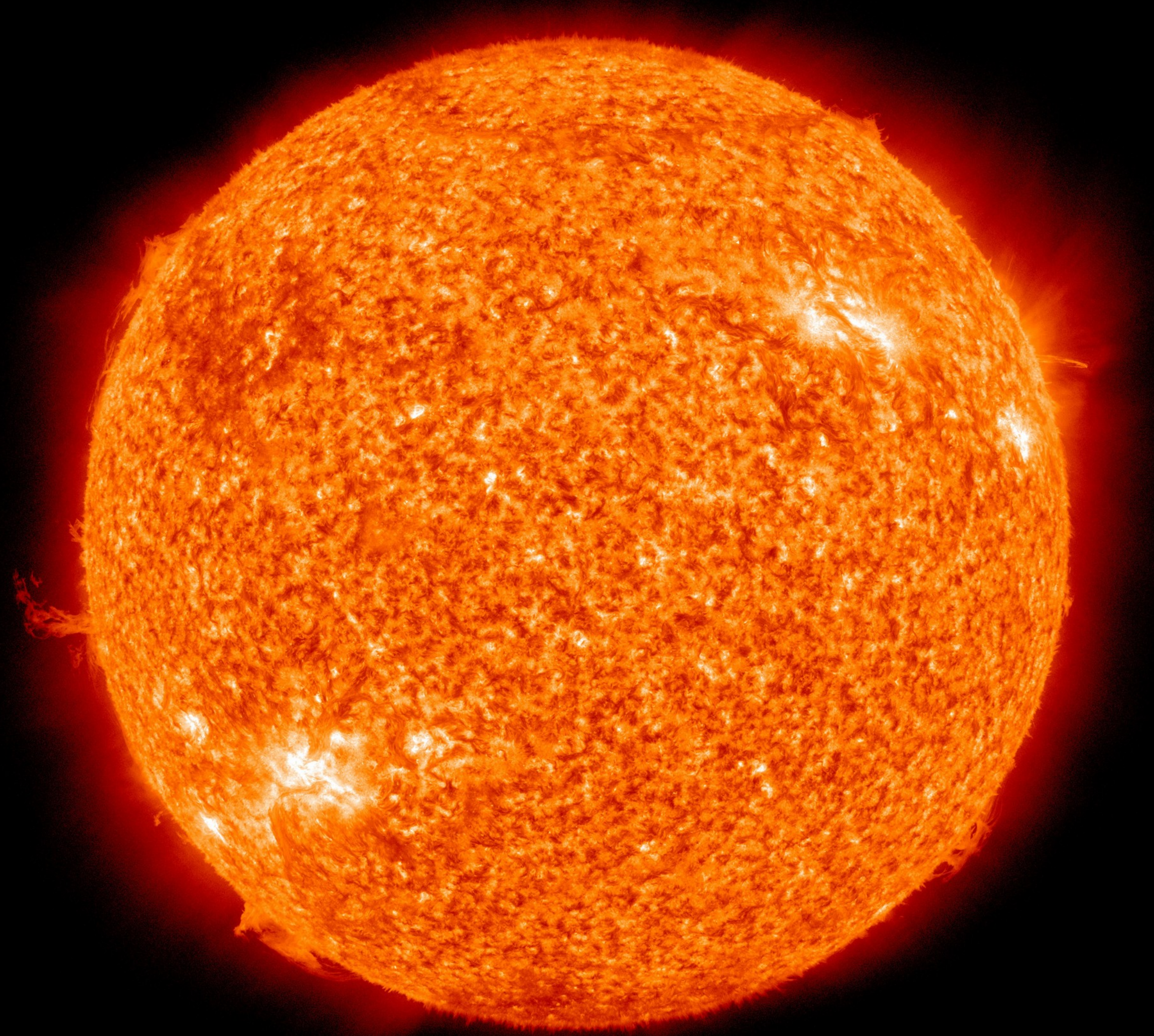
and $\underbrace{\text{superbly antisocial}}_{=\ \textit{barely interact with matter}}$

Neutrinos are *very* light and *very* anti-social

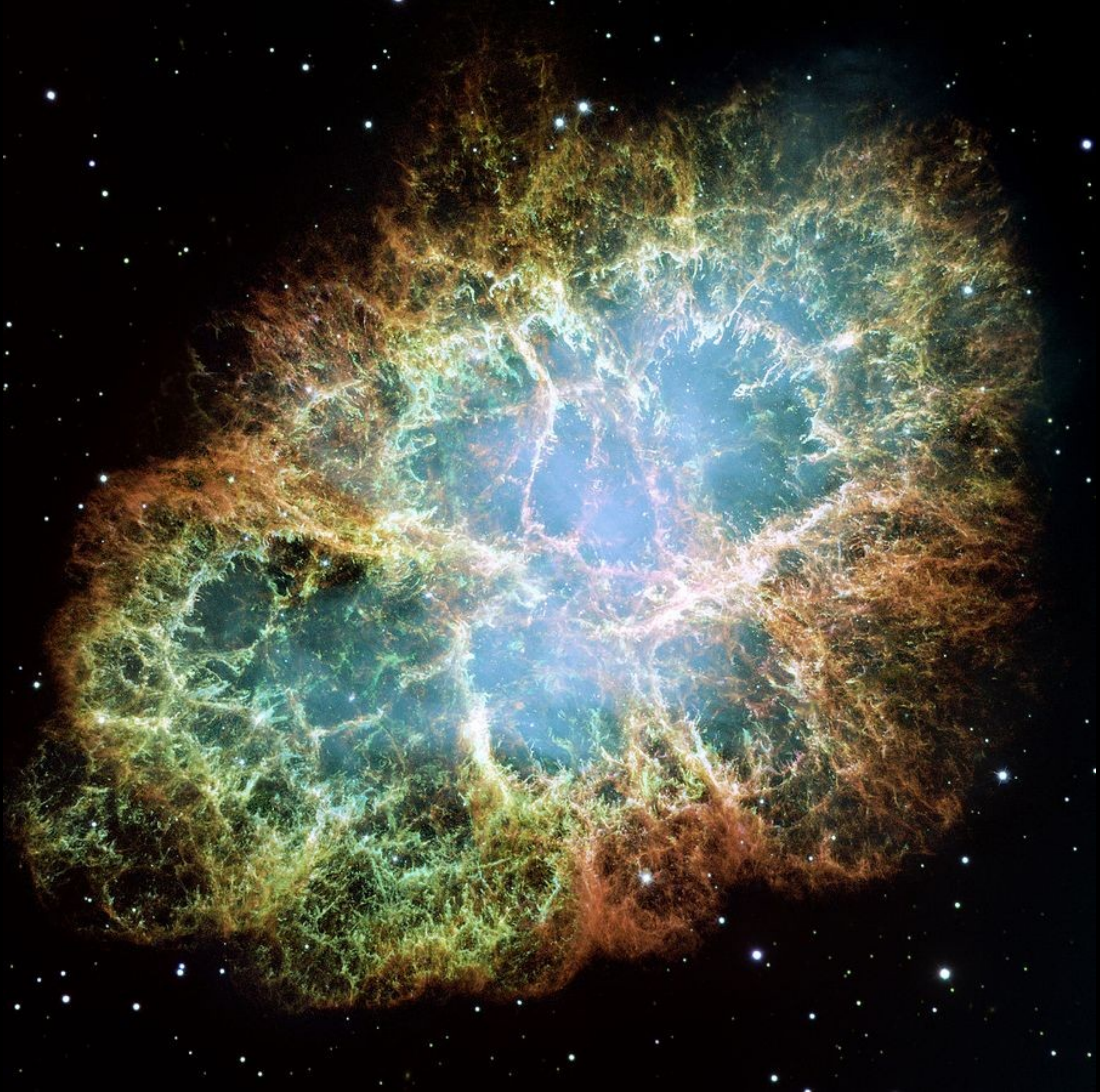


[Avda]

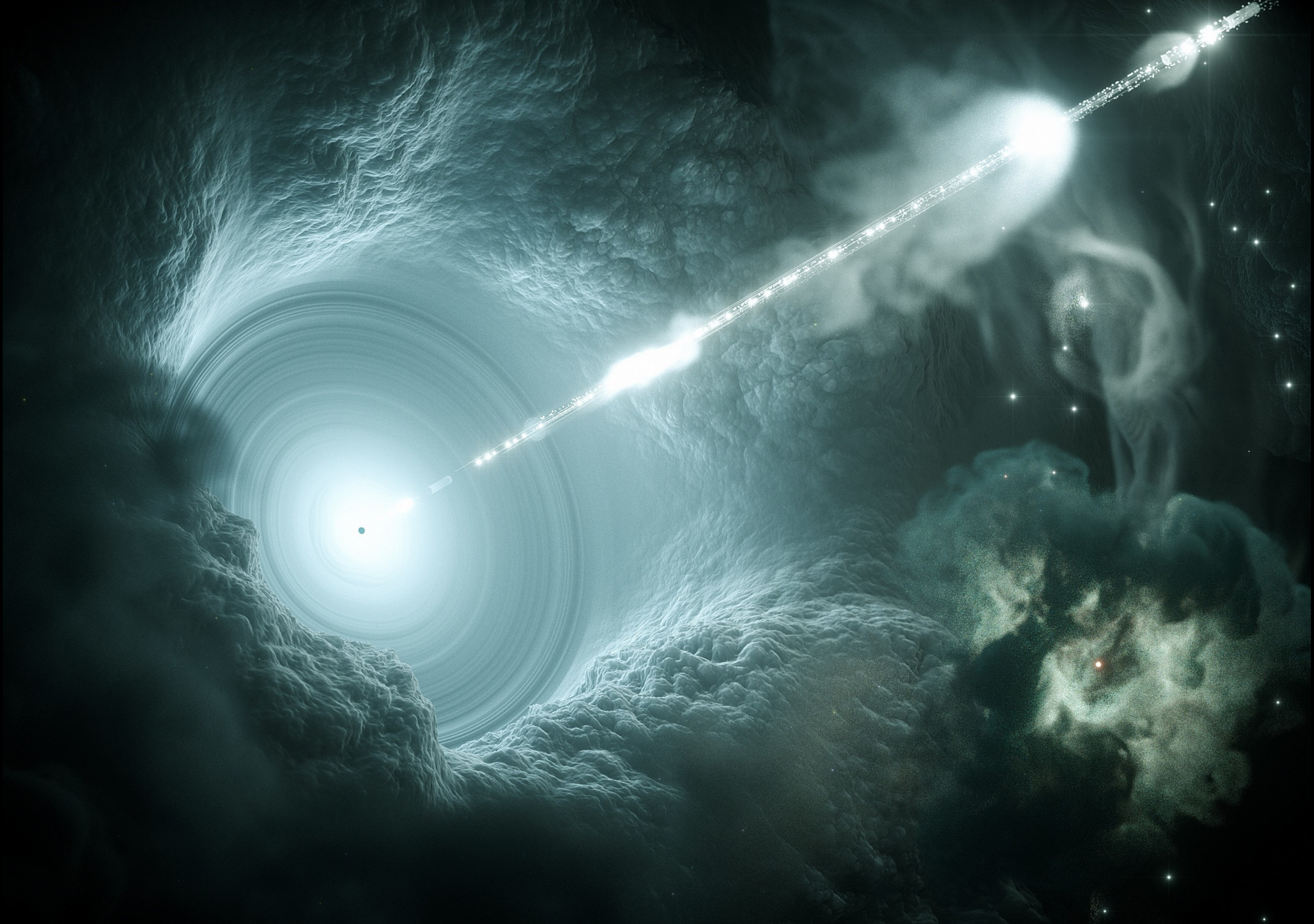

[Australian National University]



[NASA]



[NASA, ESA]



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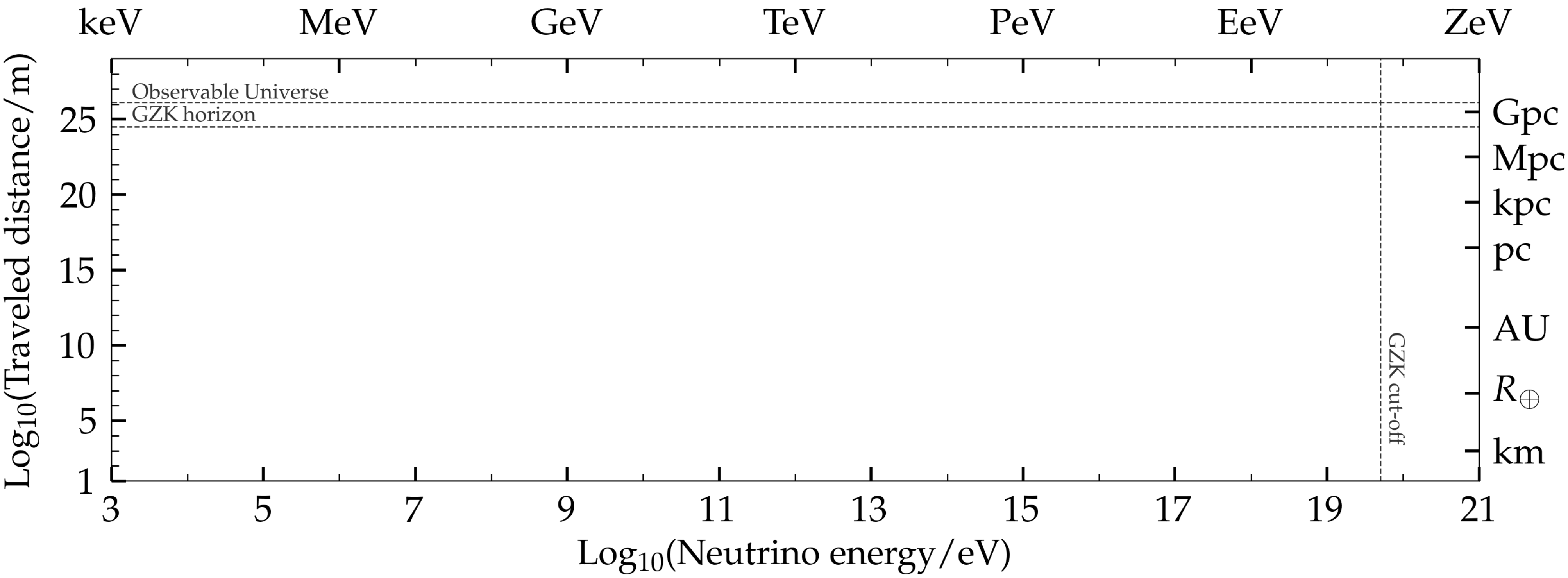
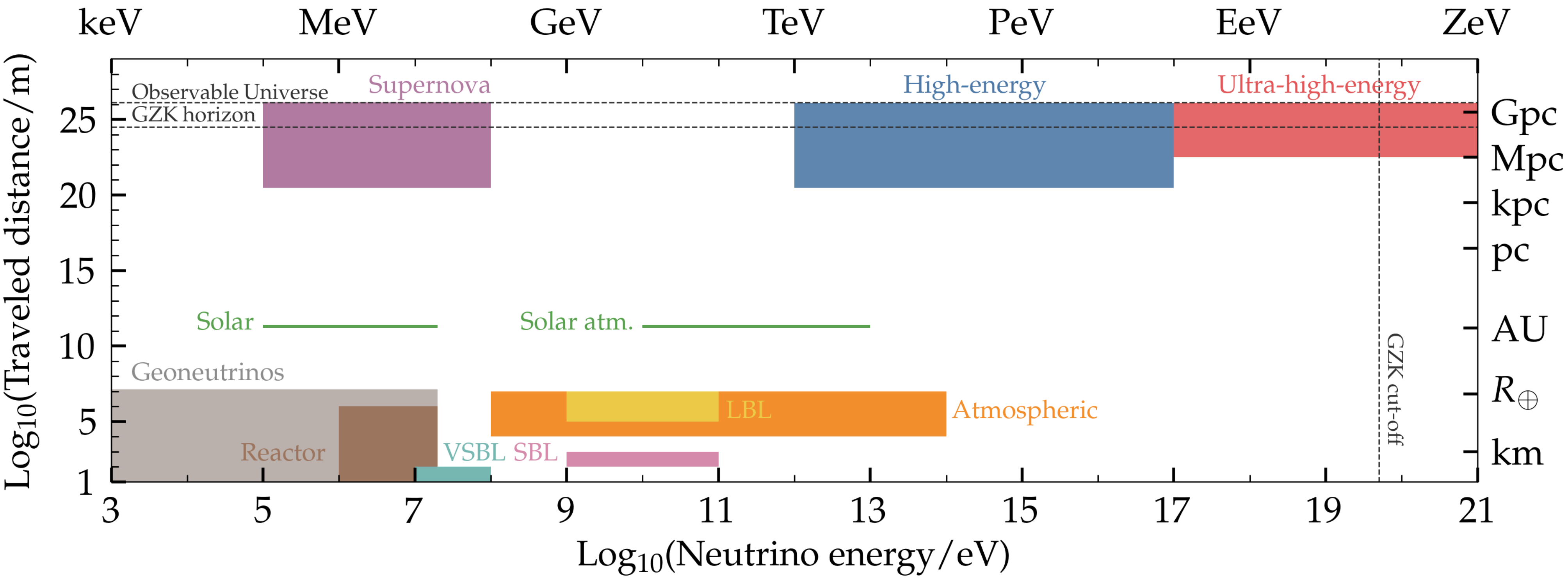


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



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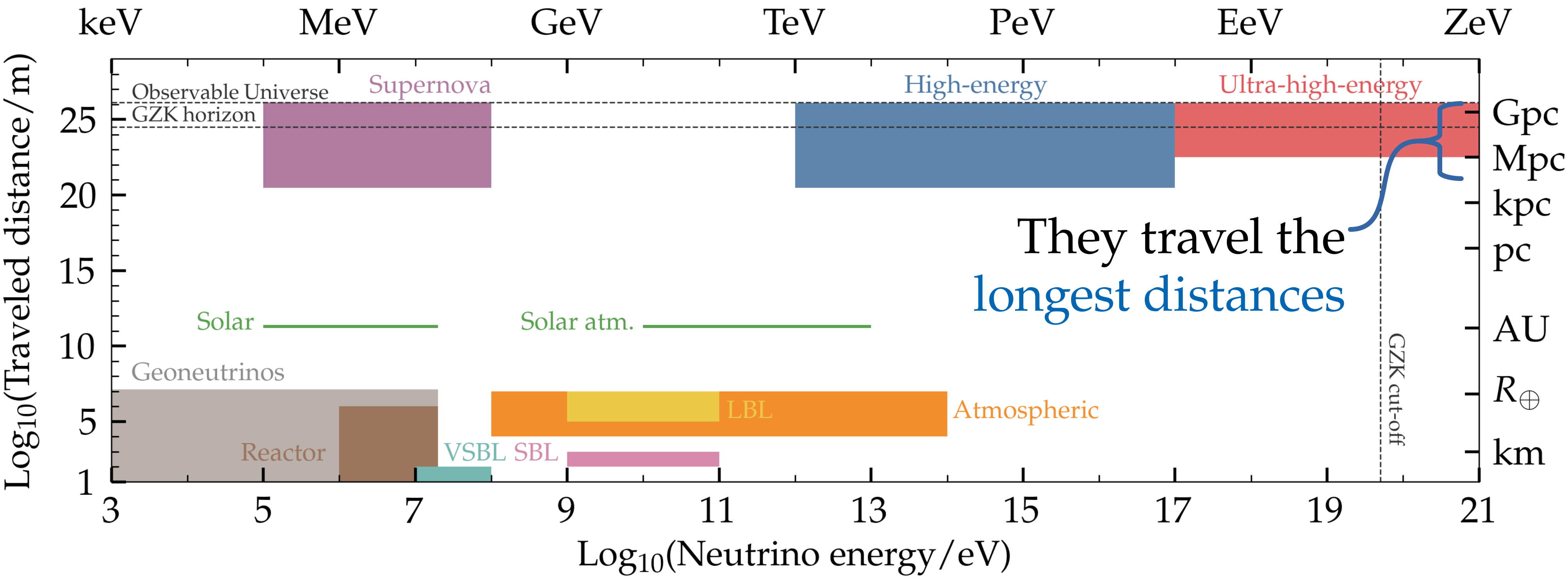
They have the highest energies



They travel the longest distances

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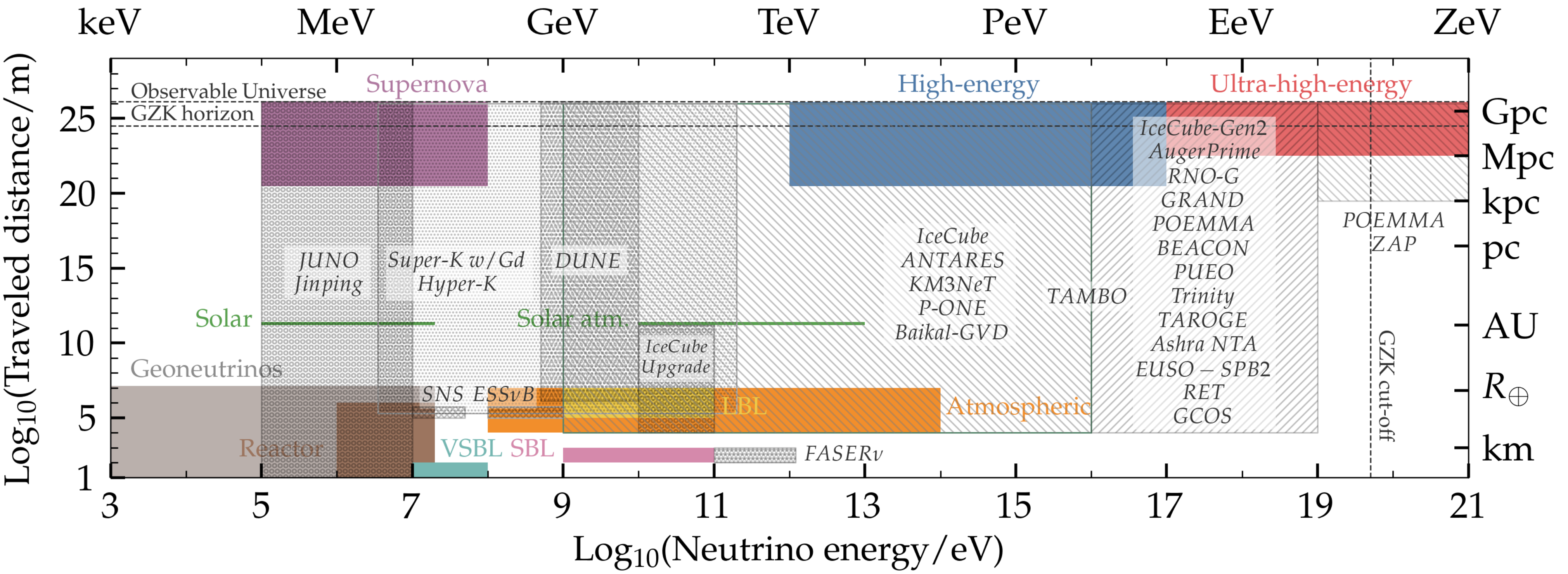

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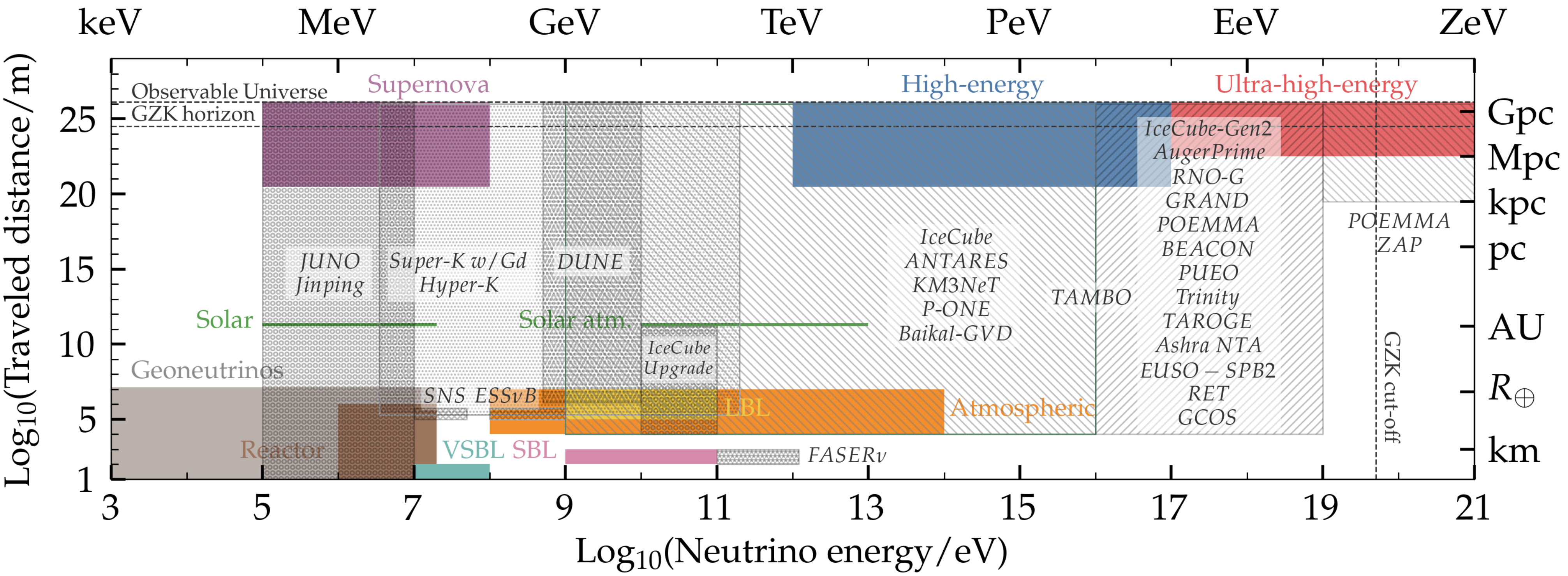
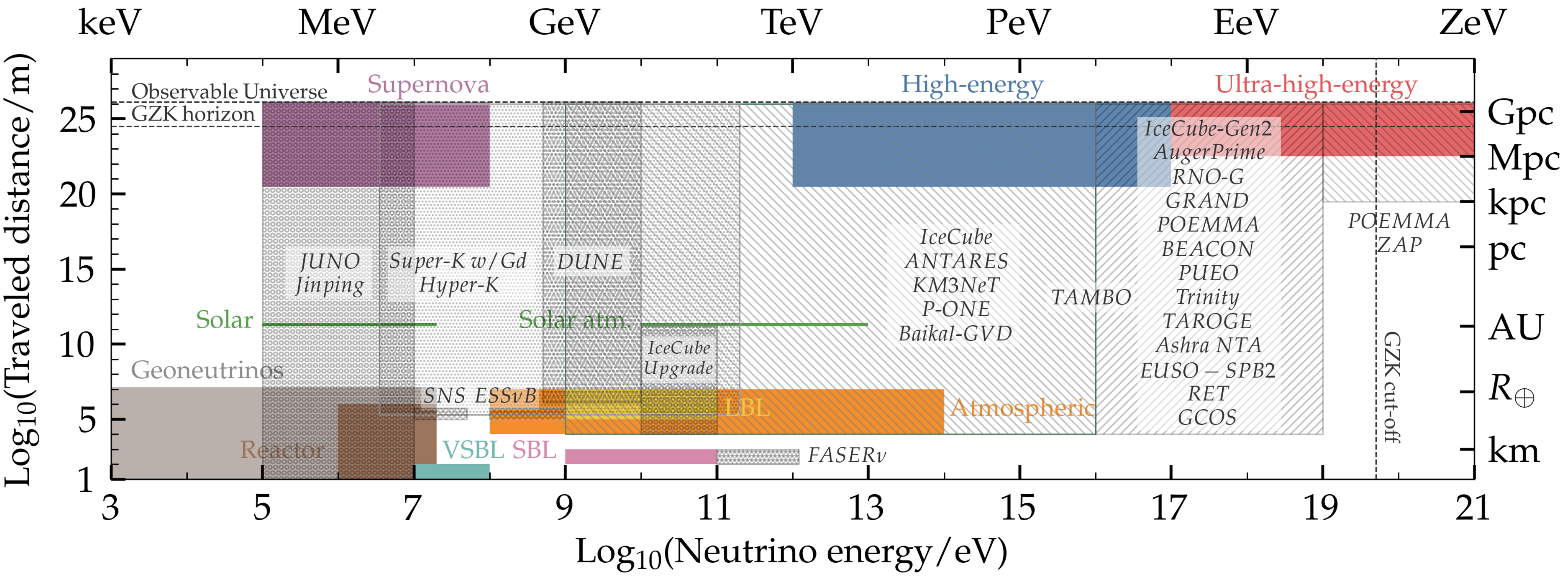


Synergies with lower energies

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

Discovered in 2013
by IceCube



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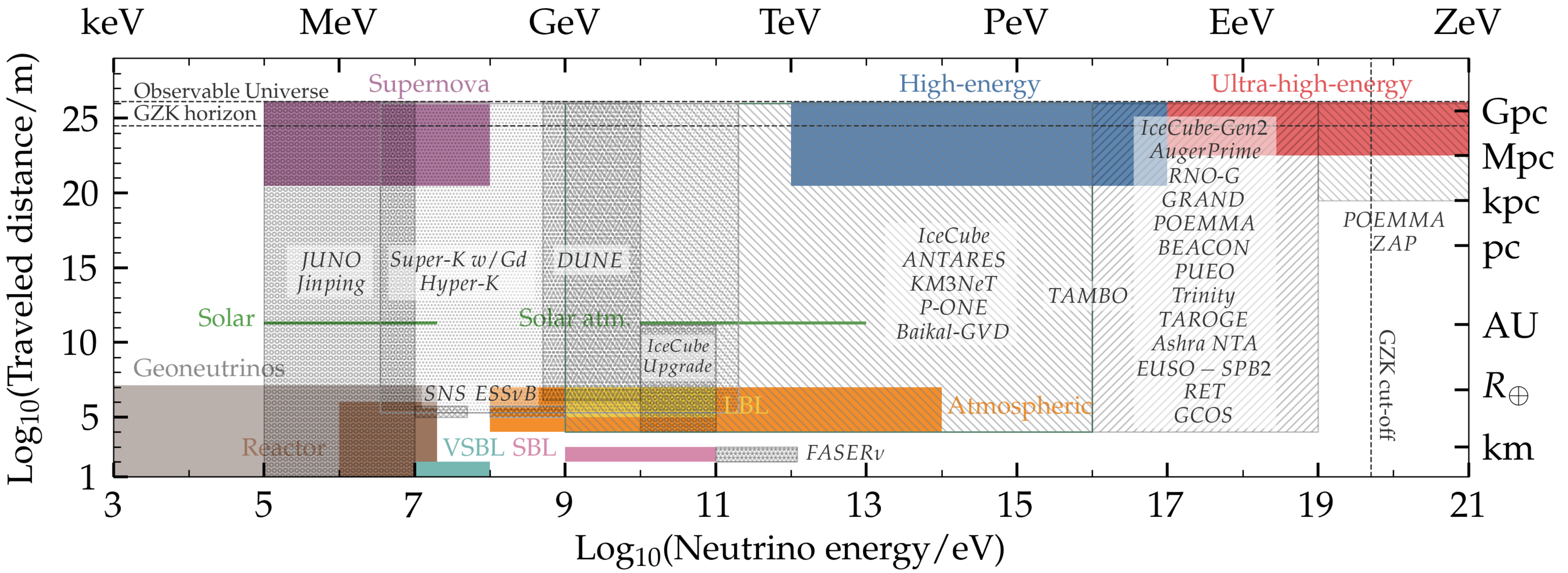

Synergies with lower energies

Increase TeV–PeV
ν statistics

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Predicted in 1969
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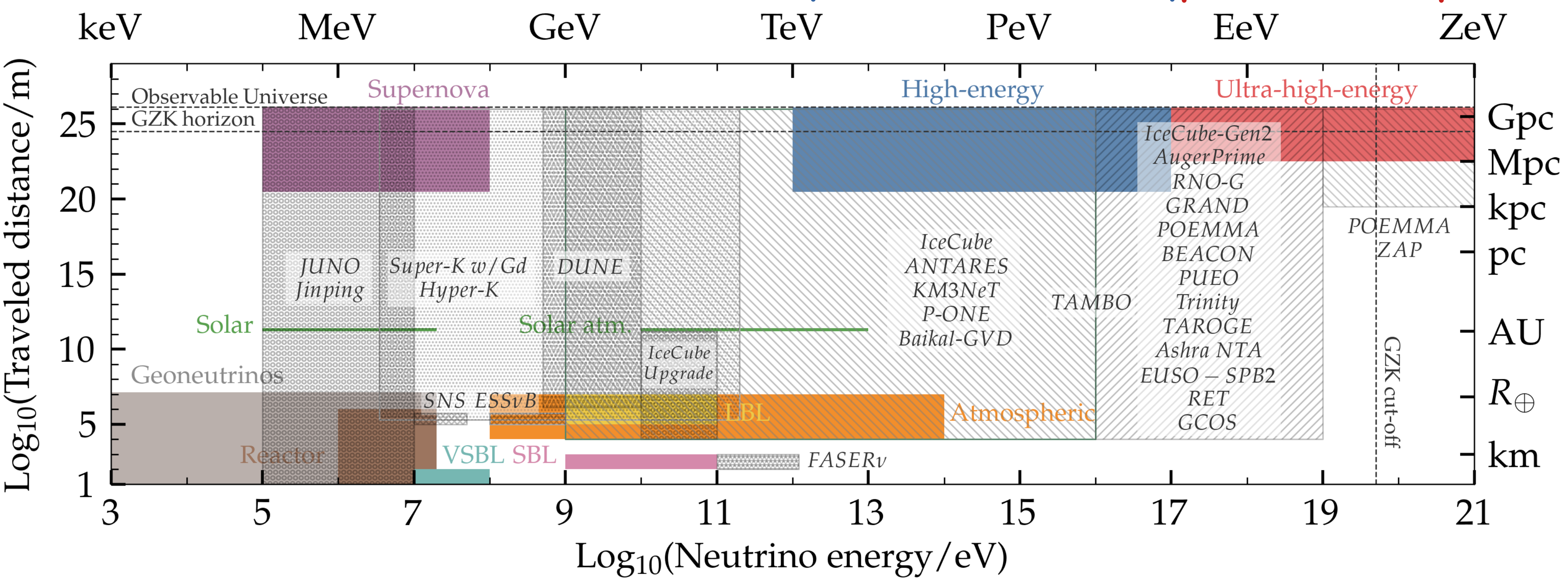

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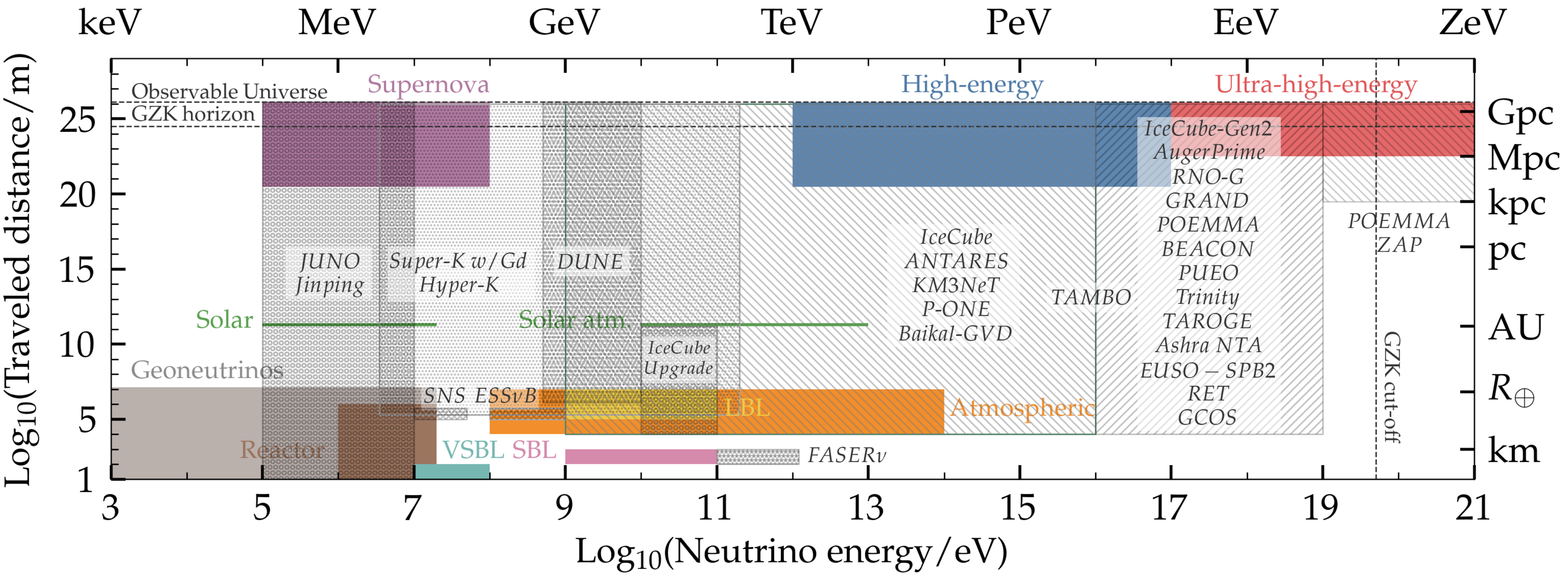

Synergies with lower energies

Increase TeV–PeV ν statistics

Discover > EeV ν

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

Today

TeV–PeV ν

Next decade

$>$ 100-PeV ν

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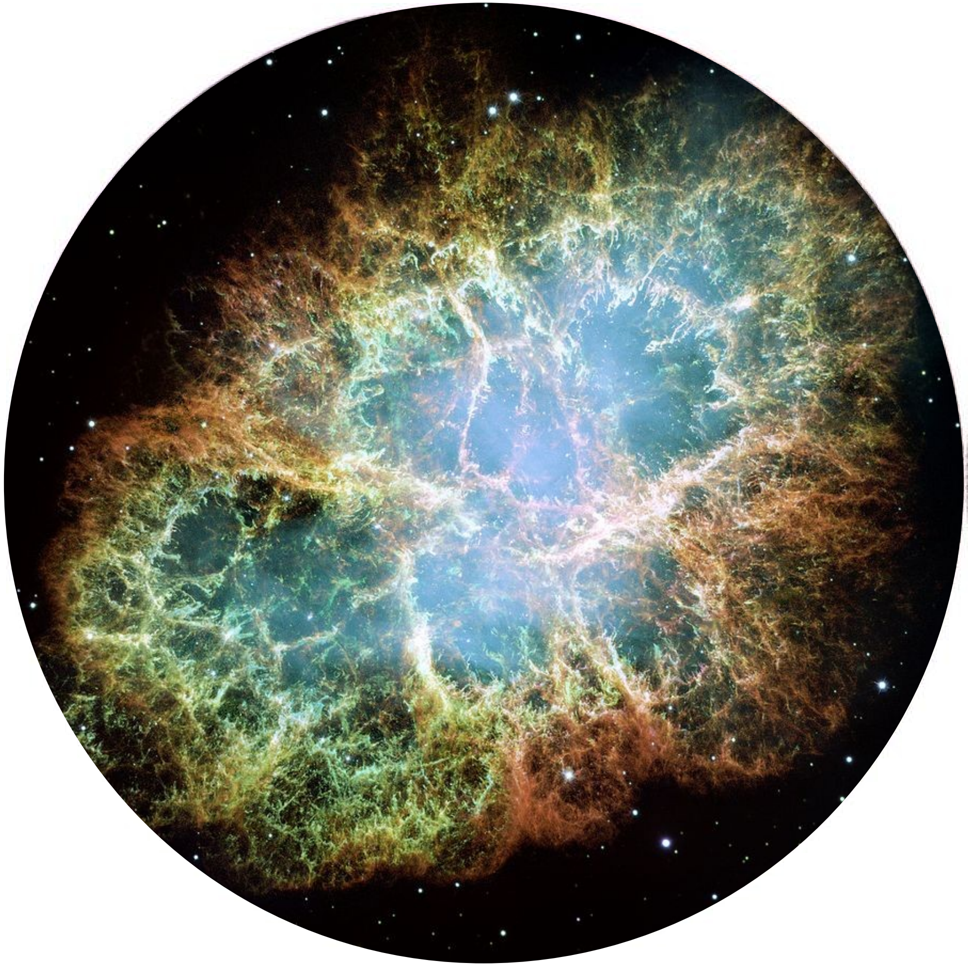

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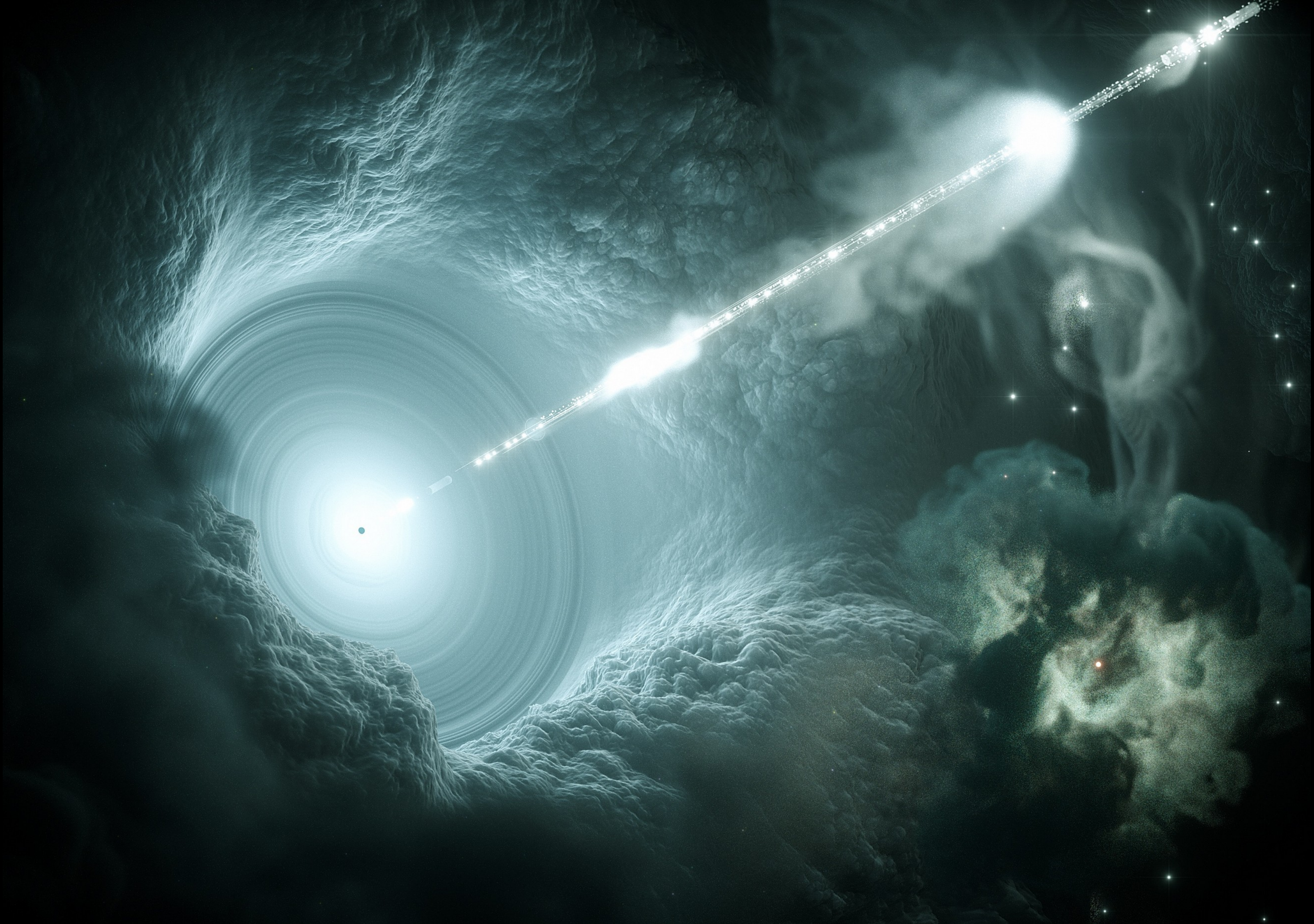
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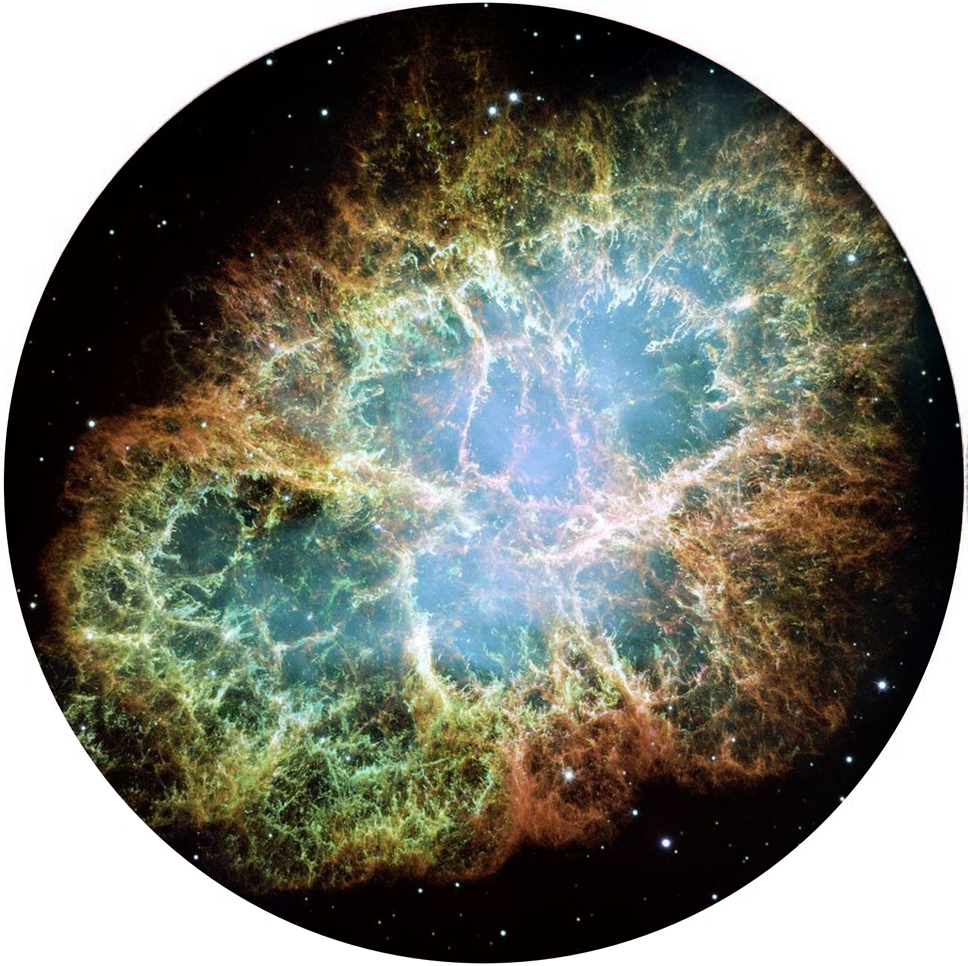

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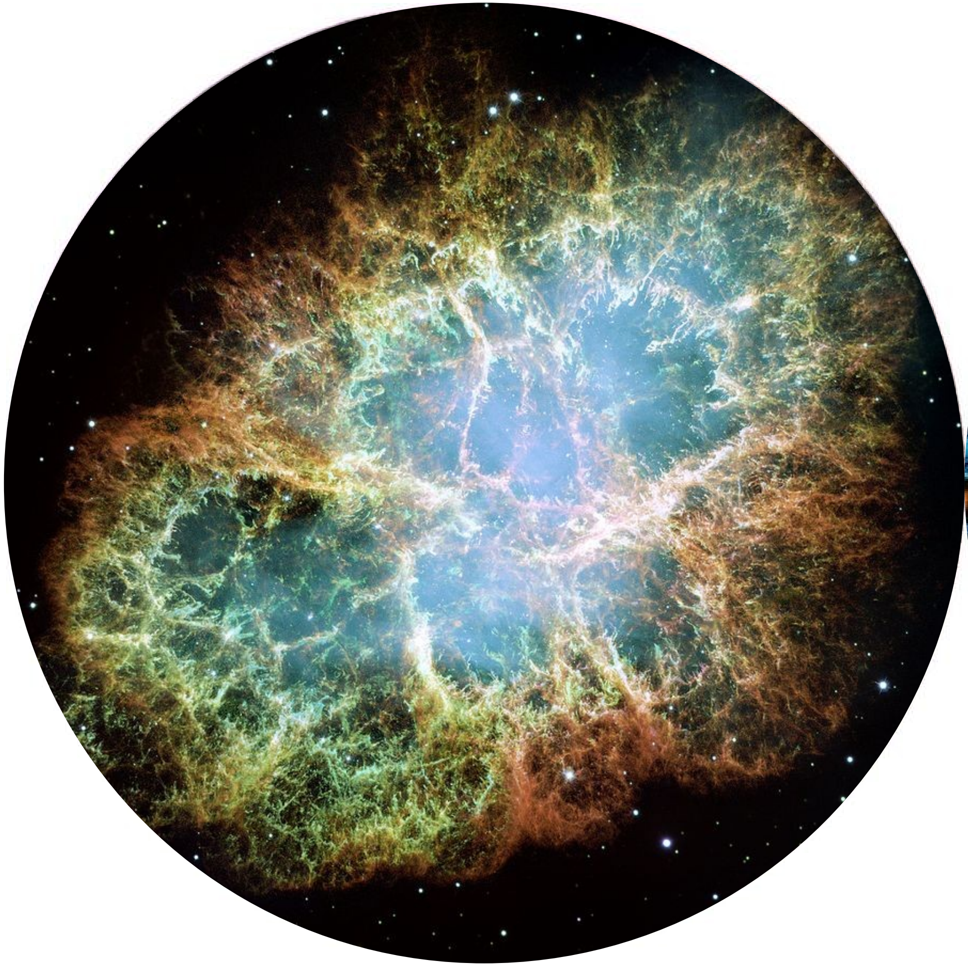

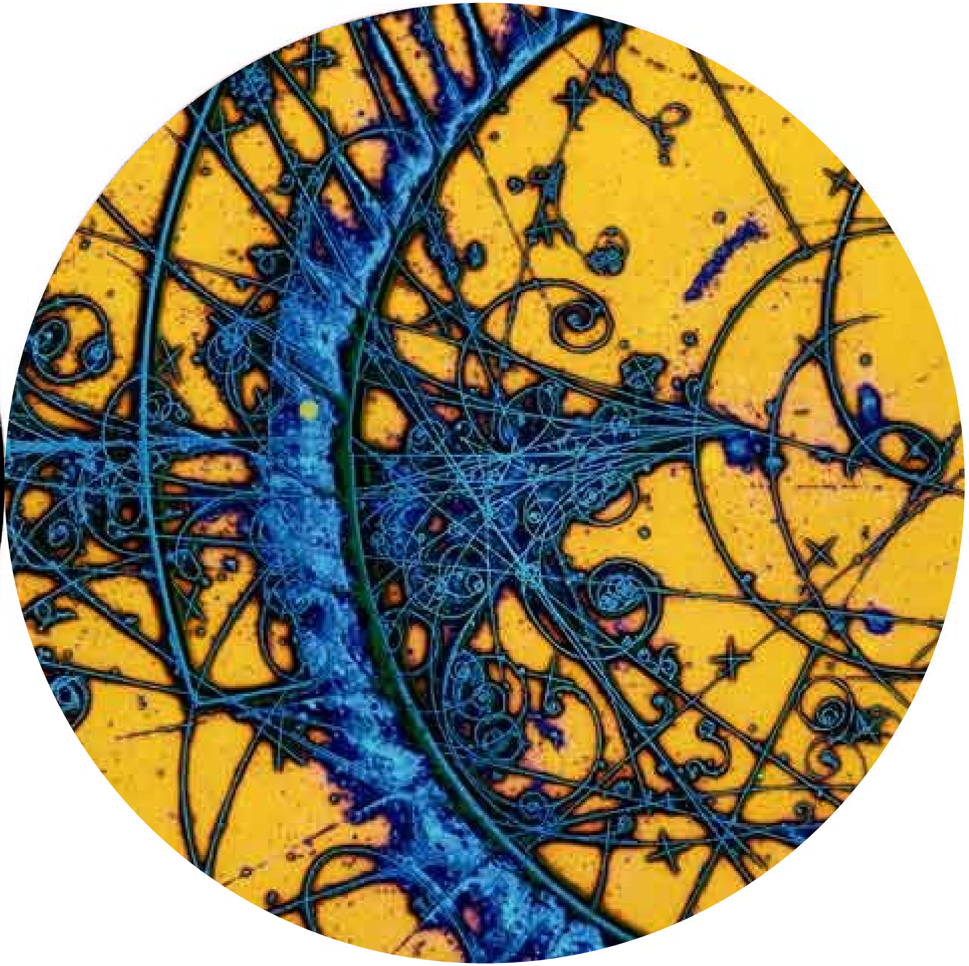

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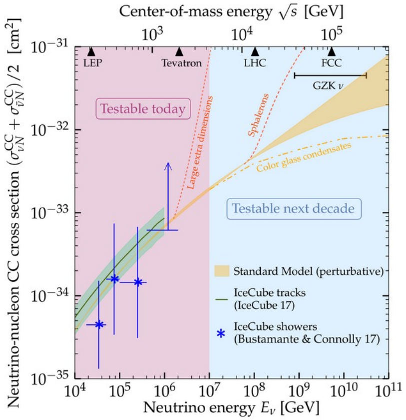
TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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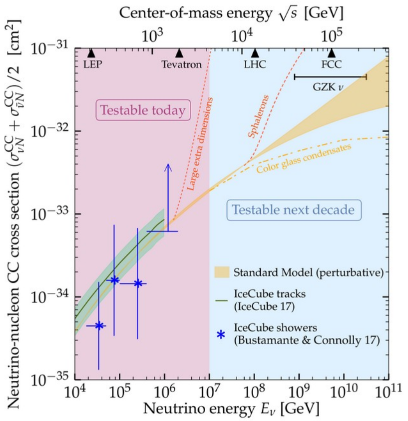
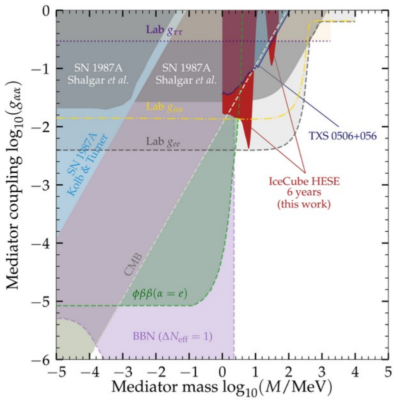


MB & Connolly, *PRL* 2019

ν self-interactions



MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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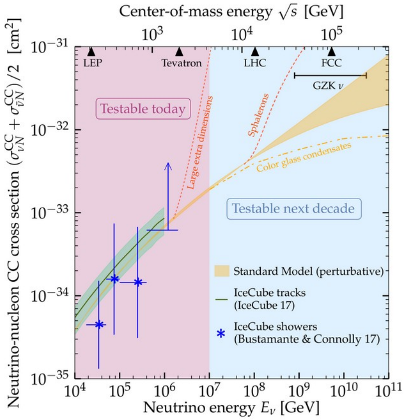

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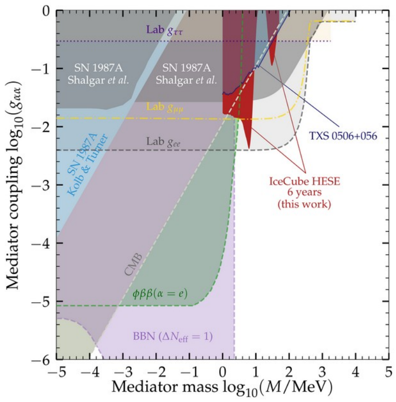
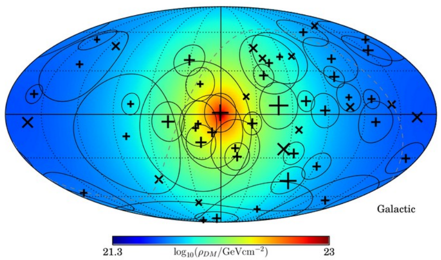


MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



Argüelles, Kheirandish, Vincent, *PRL* 2017

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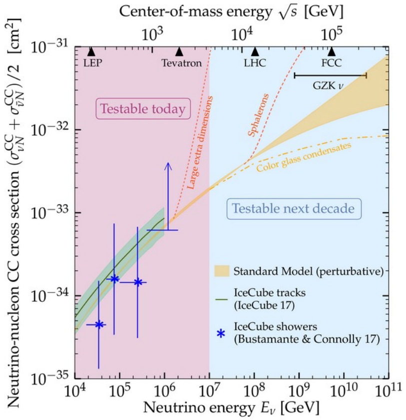

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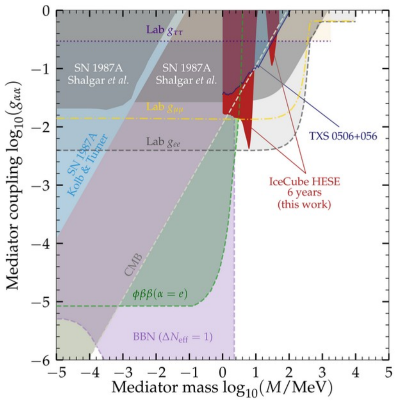

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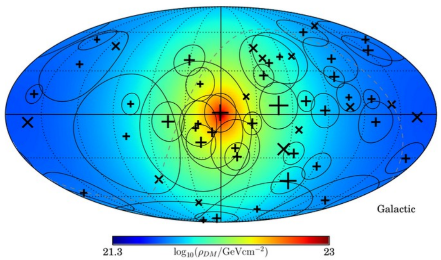

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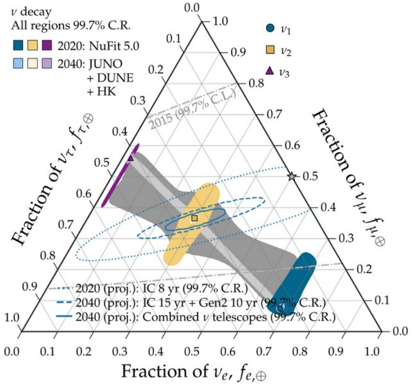
ν decay



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

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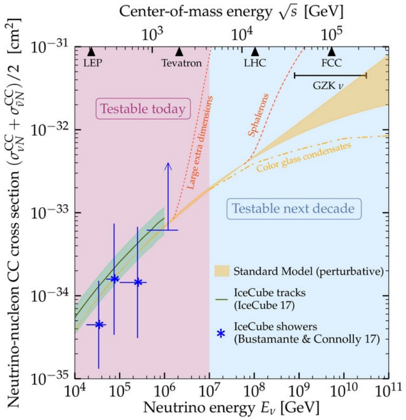

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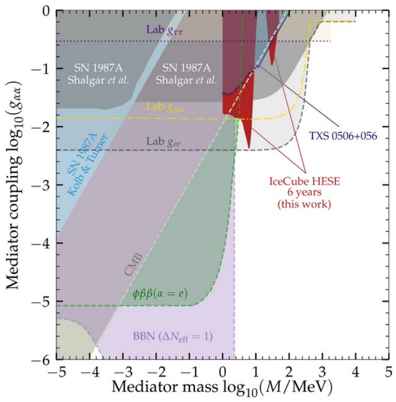

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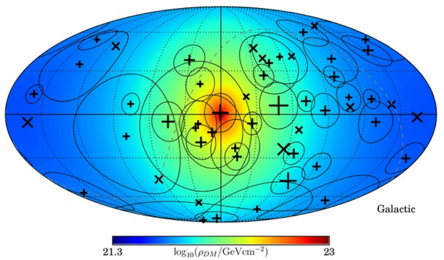

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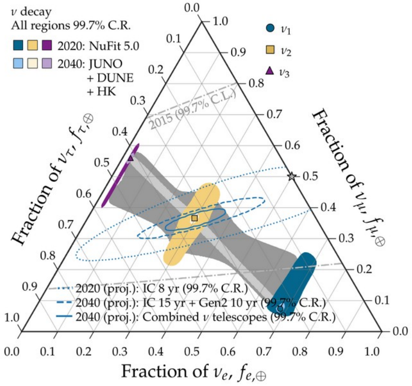

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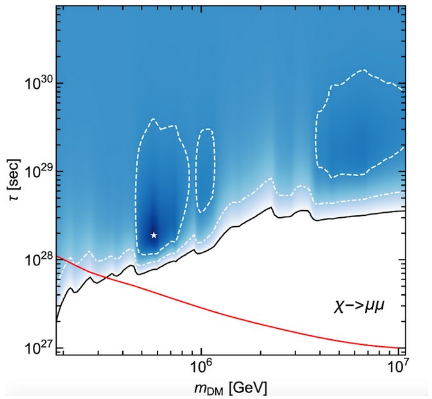
Dark matter decay



Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

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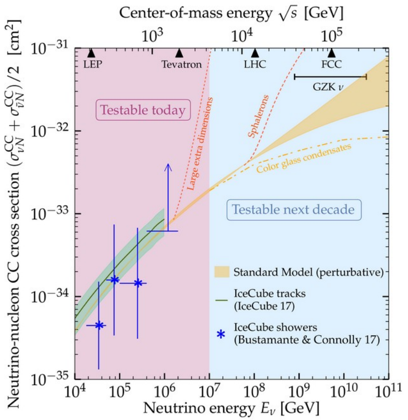

MB & Connolly, *PRL* 2019

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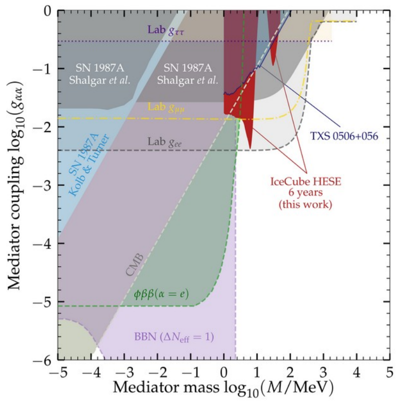

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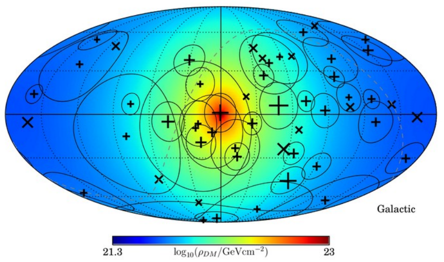

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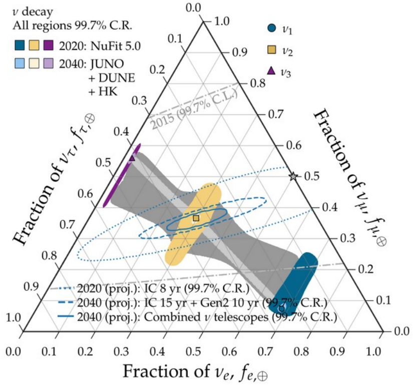

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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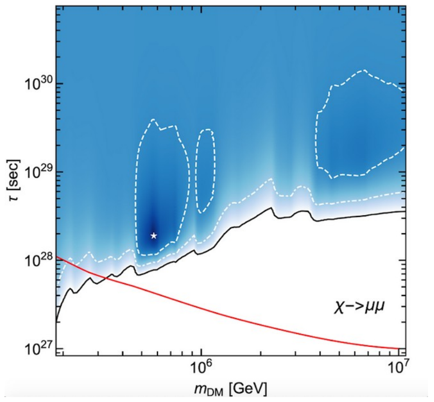
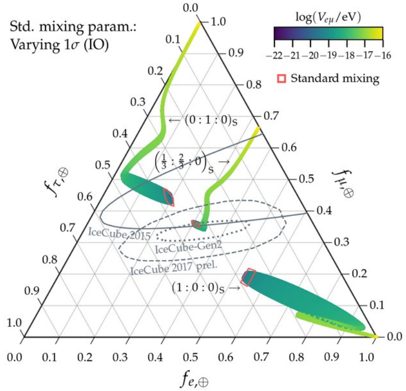


Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



MB & Agarwalla, *PRL* 2019

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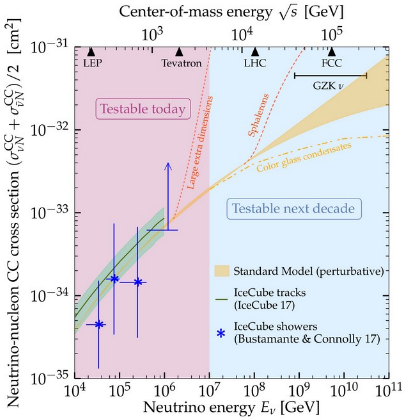

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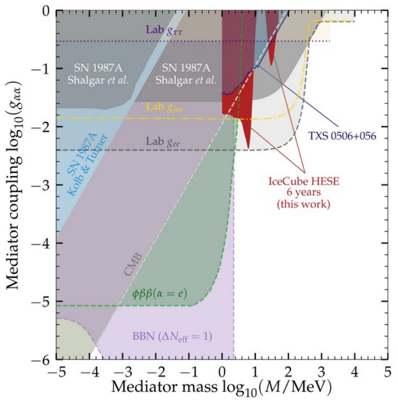

MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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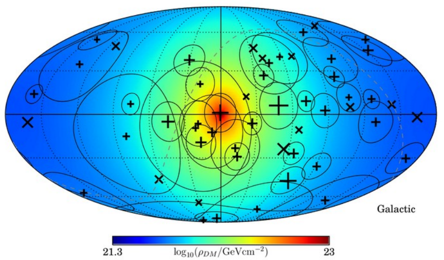

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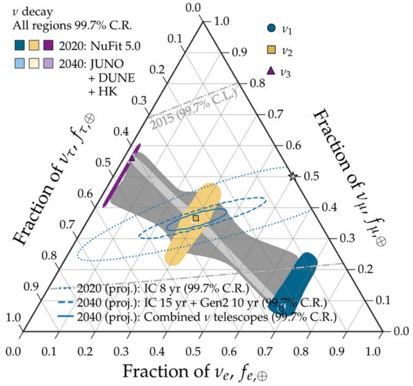

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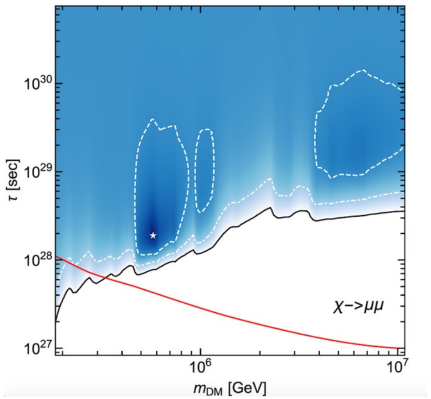

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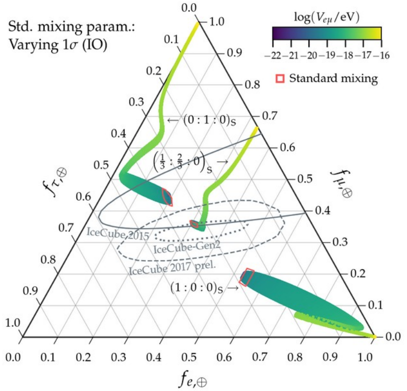
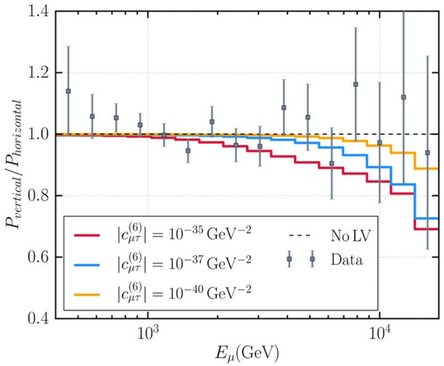


MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



IceCube, *Nature Phys.* 2018

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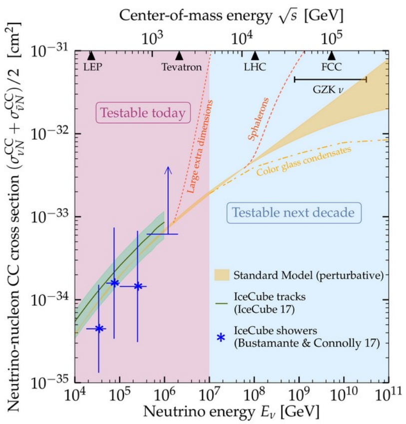

MB & Connolly, *PRL* 2019

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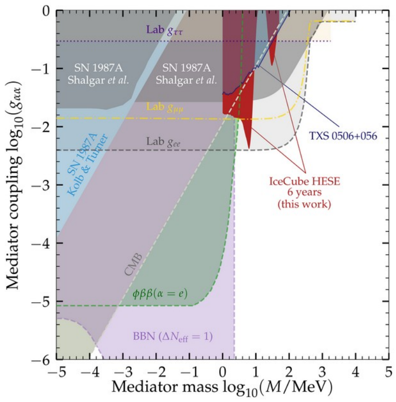

MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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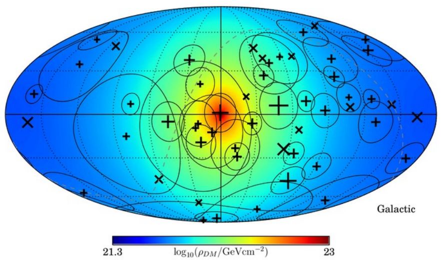

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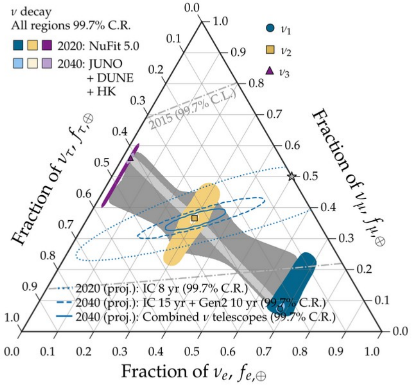

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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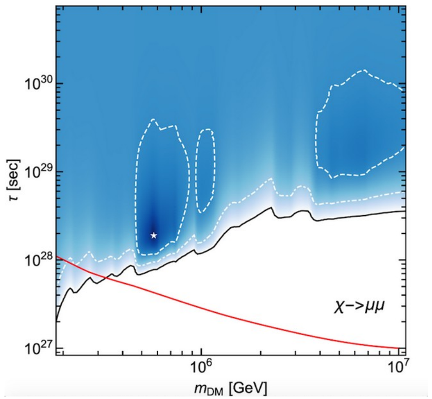

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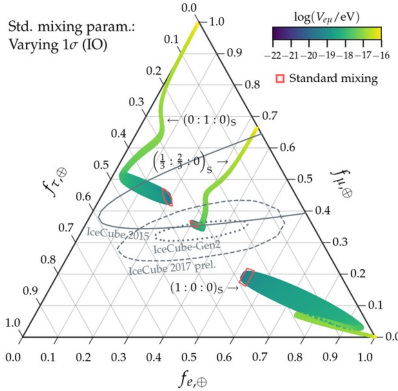

MB & Agarwalla, *PRL* 2019

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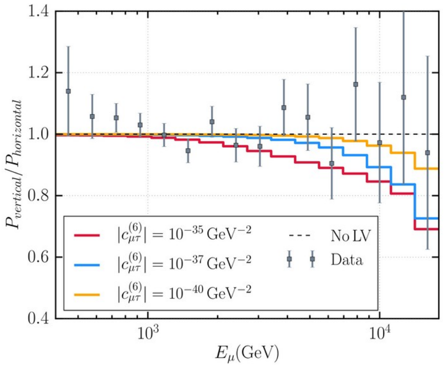
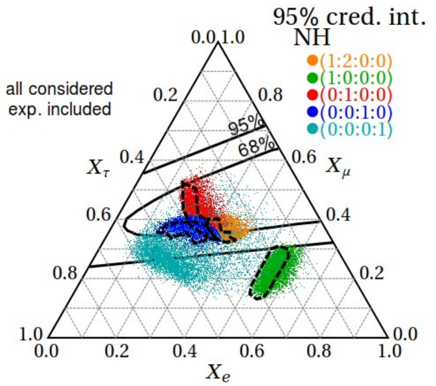


IceCube, *Nature Phys.* 2018

Sterile neutrinos



Brdar, Kopp, Wang, *JCAP* 2017

Fundamental physics with high-energy cosmic neutrinos

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

- So we can probe $\kappa_n \sim 4 \cdot 10^{-47}\,(E/\mathrm{PeV})^{-n}\,(L/\mathrm{Gpc})^{-1}\,\mathrm{PeV}^{1-n}$

- Improvement over limits using atmospheric ν: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$

Fundamental physics with high-energy cosmic neutrinos

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

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

- So we can probe $\kappa_n \sim 4 \cdot 10^{-47}\,(E/\mathrm{PeV})^{-n}\,(L/\mathrm{Gpc})^{-1}\,\mathrm{PeV}^{1-n}$

- Improvement over limits using atmospheric ν: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$

High-energy cosmic neutrinos:
Basics and current status

Making high-energy astrophysical neutrinos: a toy model

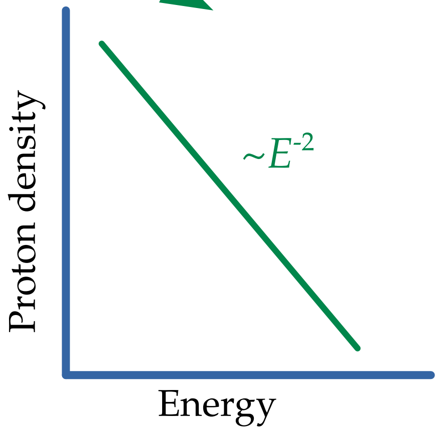
(or $p + p$)

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

Making high-energy astrophysical neutrinos: a toy model

(or $p + p$)

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



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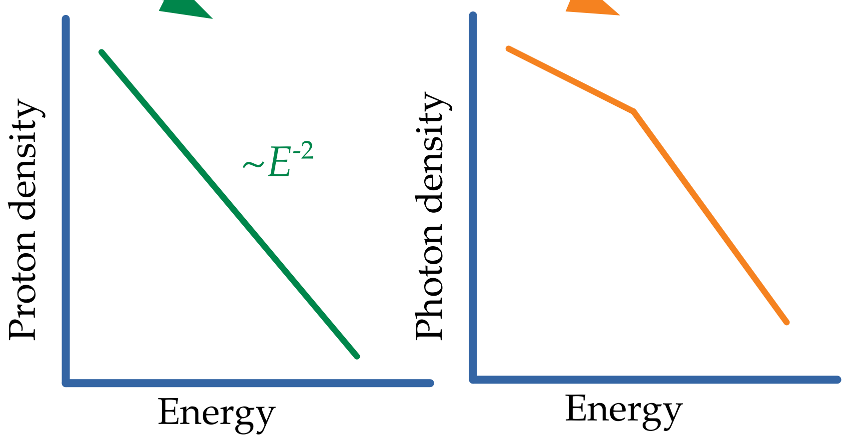

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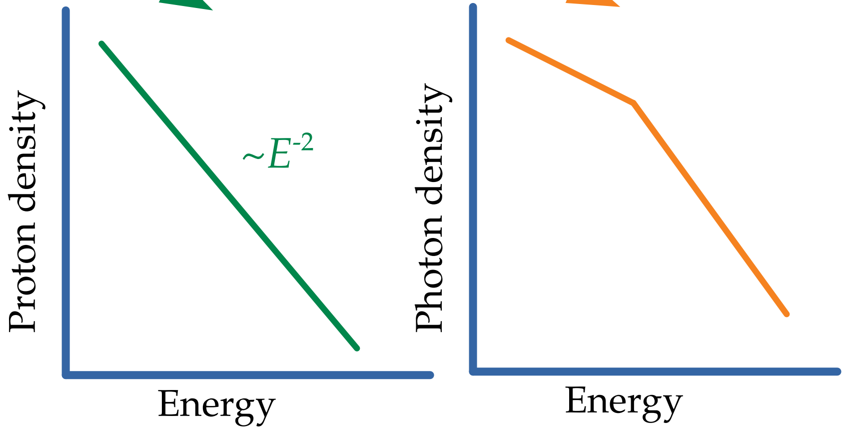
$$\pi^0 \longrightarrow \gamma + \gamma$$

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

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



Making high-energy astrophysical neutrinos: a toy model

(or $p + p$)

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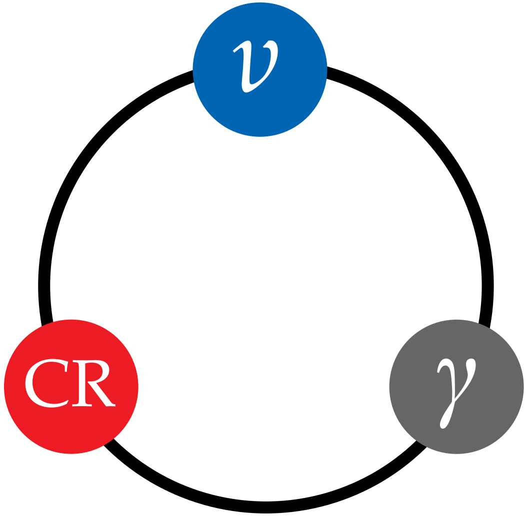
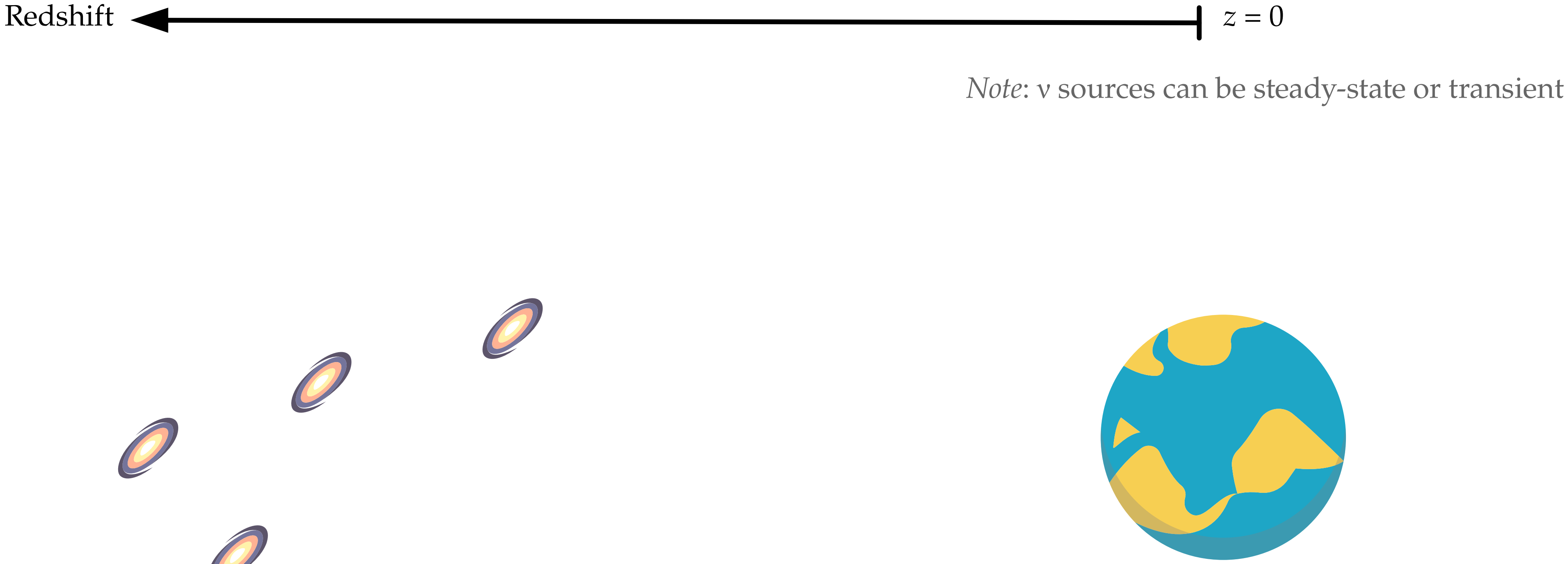
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \longrightarrow \bar{\nu}_\mu + e^+ + \nu_e + \nu_\mu$$

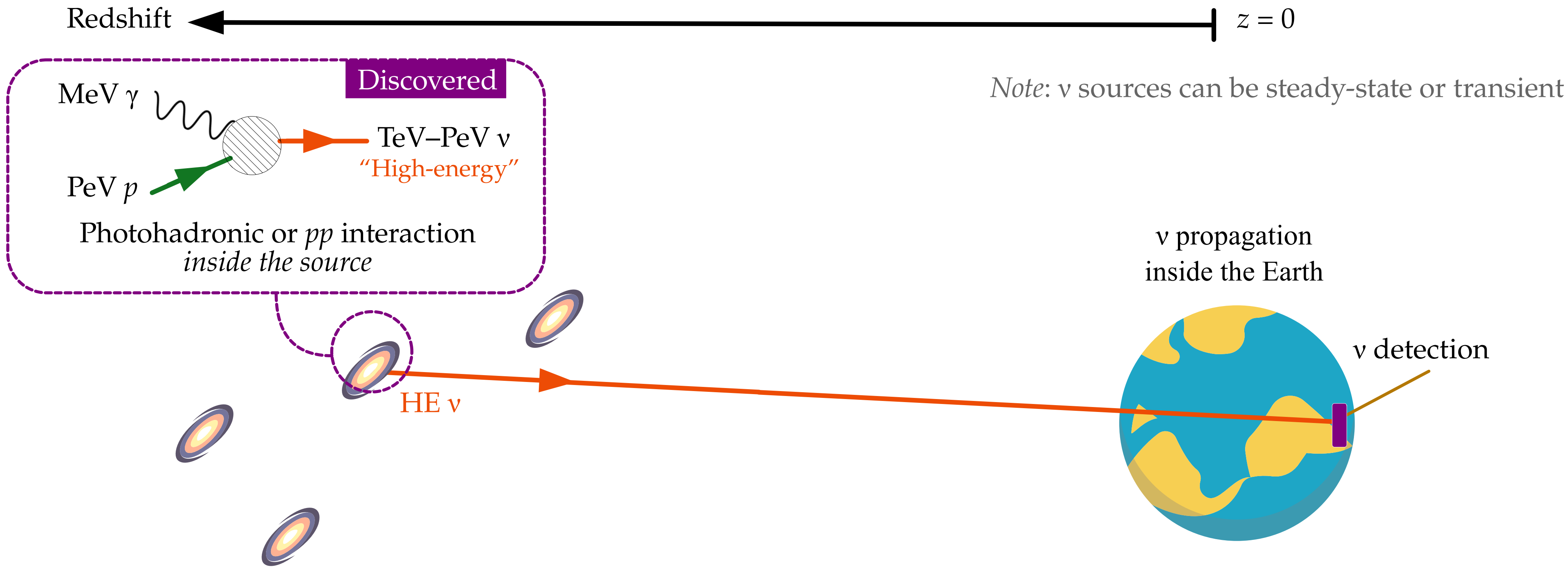
$$n \text{ (escapes)} \longrightarrow p + e^- + \bar{\nu}_e$$

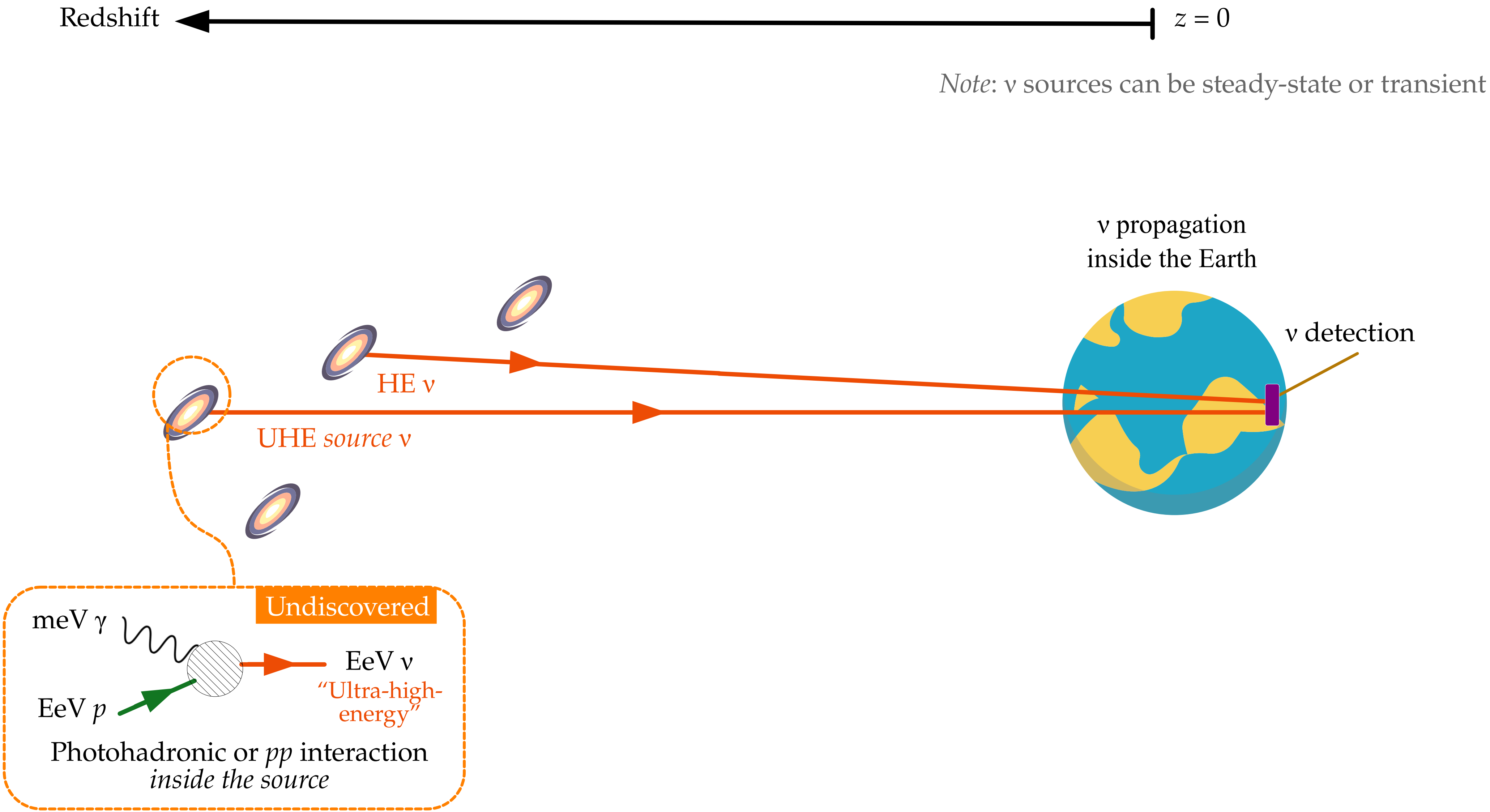


Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10


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



Redshift
$z = 0$
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν
UHE *source* ν
Undiscovered
meV γ
EeV ν
"Ultra-high-energy"
EeV *p*
Photohadronic or *pp* interaction
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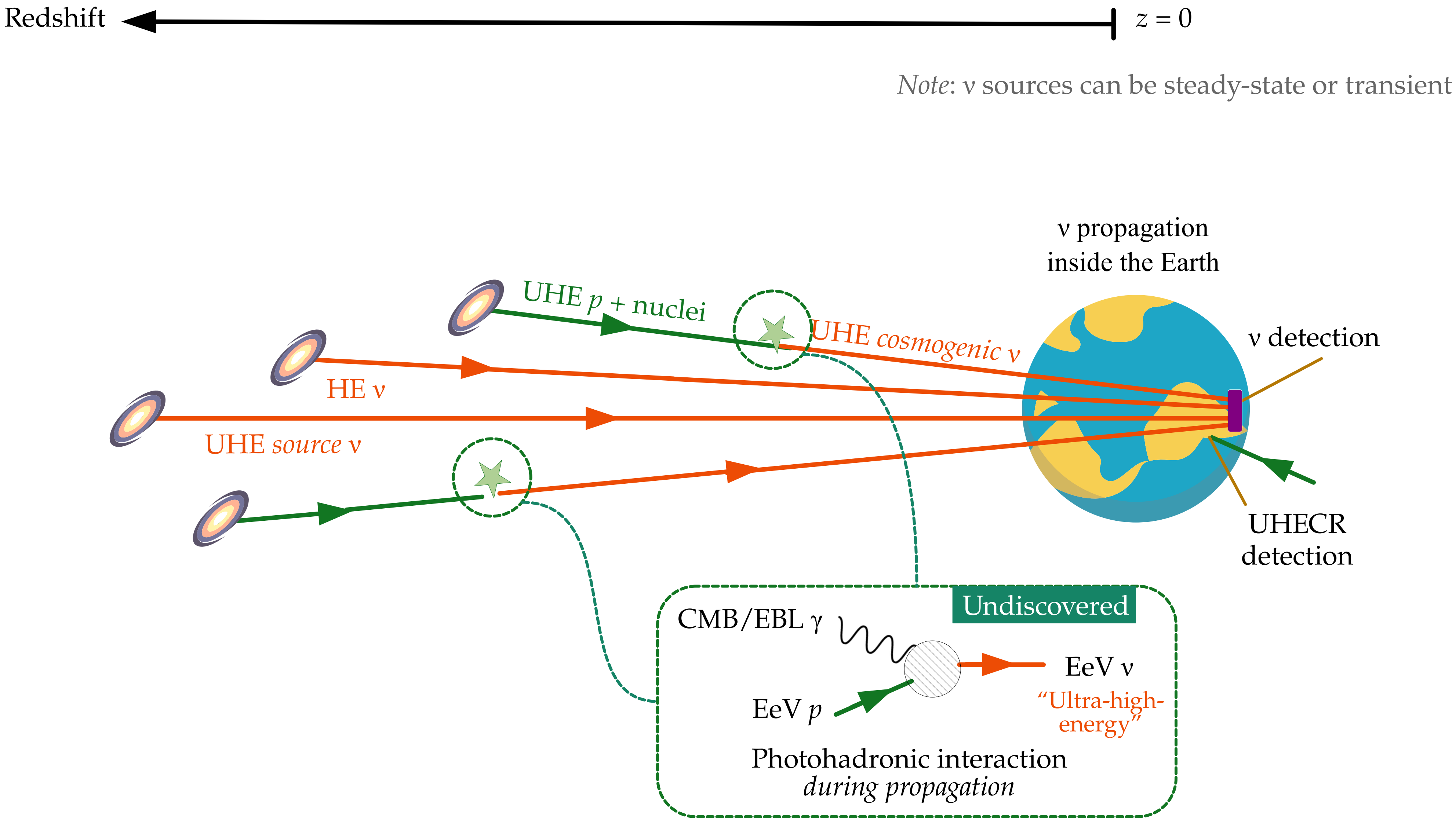
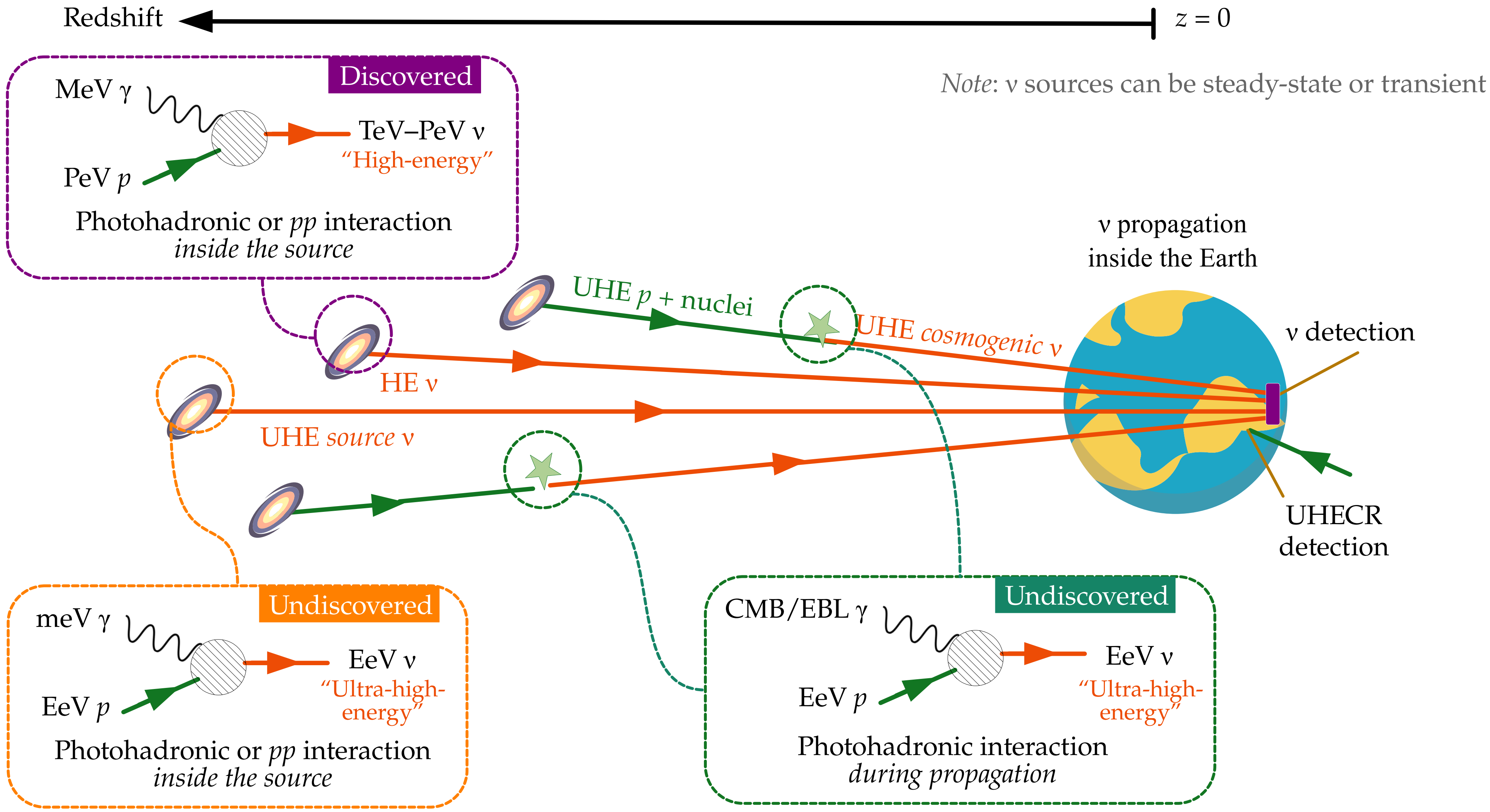


Redshift
$z = 0$
Note: ν sources can be steady-state or transient
ν propagation inside the Earth
UHE p + nuclei
UHE *cosmogenic* ν
ν detection
HE ν
UHE *source* ν
UHECR detection
Undiscovered
CMB/EBL γ
EeV ν
"Ultra-high-energy"
EeV p
Photohadronic interaction
during propagation



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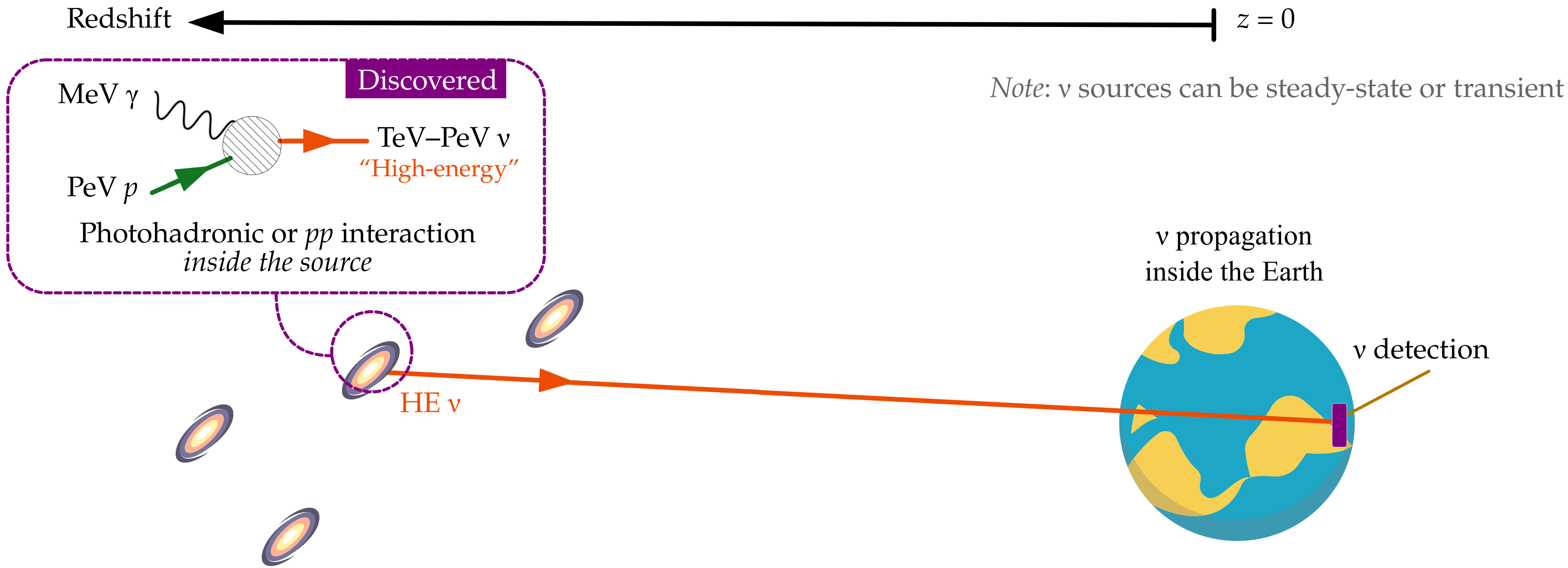
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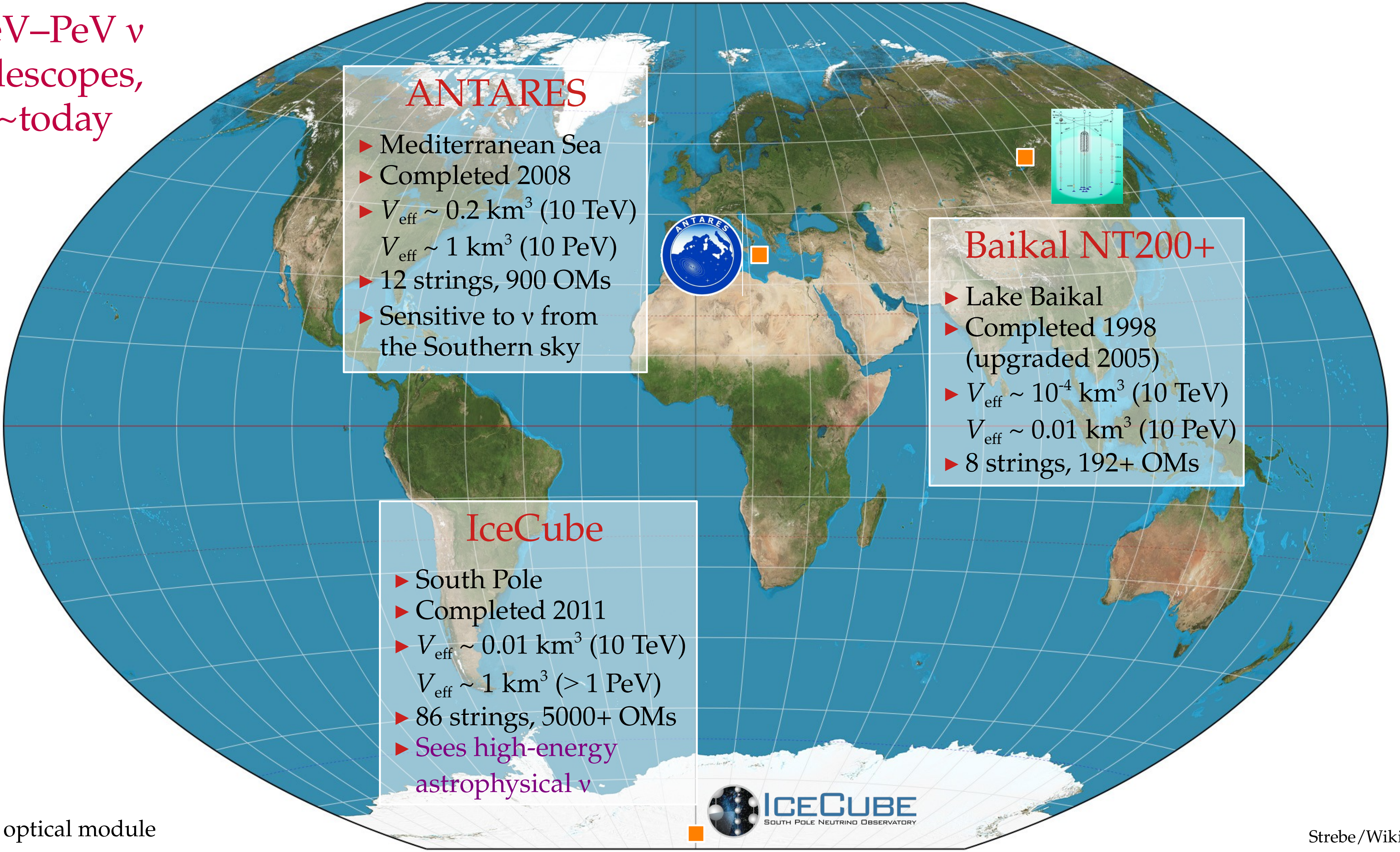
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν

TeV–PeV ν telescopes, ~today



ANTARES

- Mediterranean Sea
- Completed 2008
- $V_{\text{eff}} \sim 0.2\ \text{km}^3$ (10 TeV)
  $V_{\text{eff}} \sim 1\ \text{km}^3$ (10 PeV)
- 12 strings, 900 OMs
- Sensitive to ν from the Southern sky

Baikal NT200+

- Lake Baikal
- Completed 1998 (upgraded 2005)
- $V_{\text{eff}} \sim 10^{-4}\ \text{km}^3$ (10 TeV)
  $V_{\text{eff}} \sim 0.01\ \text{km}^3$ (10 PeV)
- 8 strings, 192+ OMs

IceCube

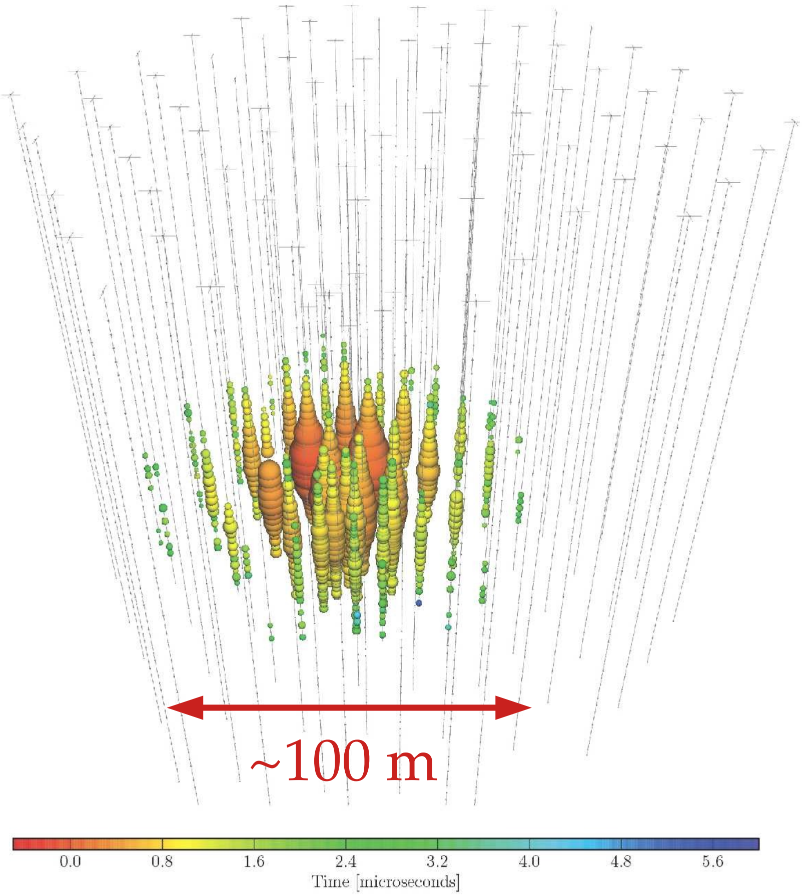
- South Pole
- Completed 2011
- $V_{\text{eff}} \sim 0.01\ \text{km}^3$ (10 TeV)
  $V_{\text{eff}} \sim 1\ \text{km}^3$ (> 1 PeV)
- 86 strings, 5000+ OMs
- Sees high-energy astrophysical ν

OM: optical module

Strebe/Wikipedia

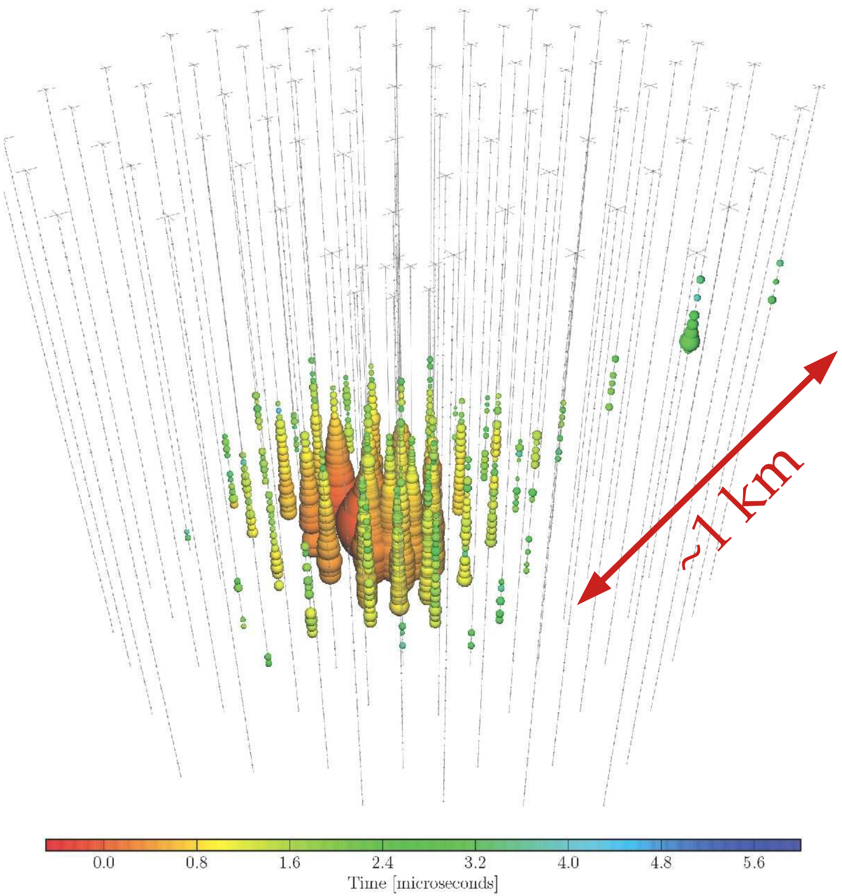

Yuya Makino, IceCube/NSF

Shower (mainly from ν_e and ν_τ)

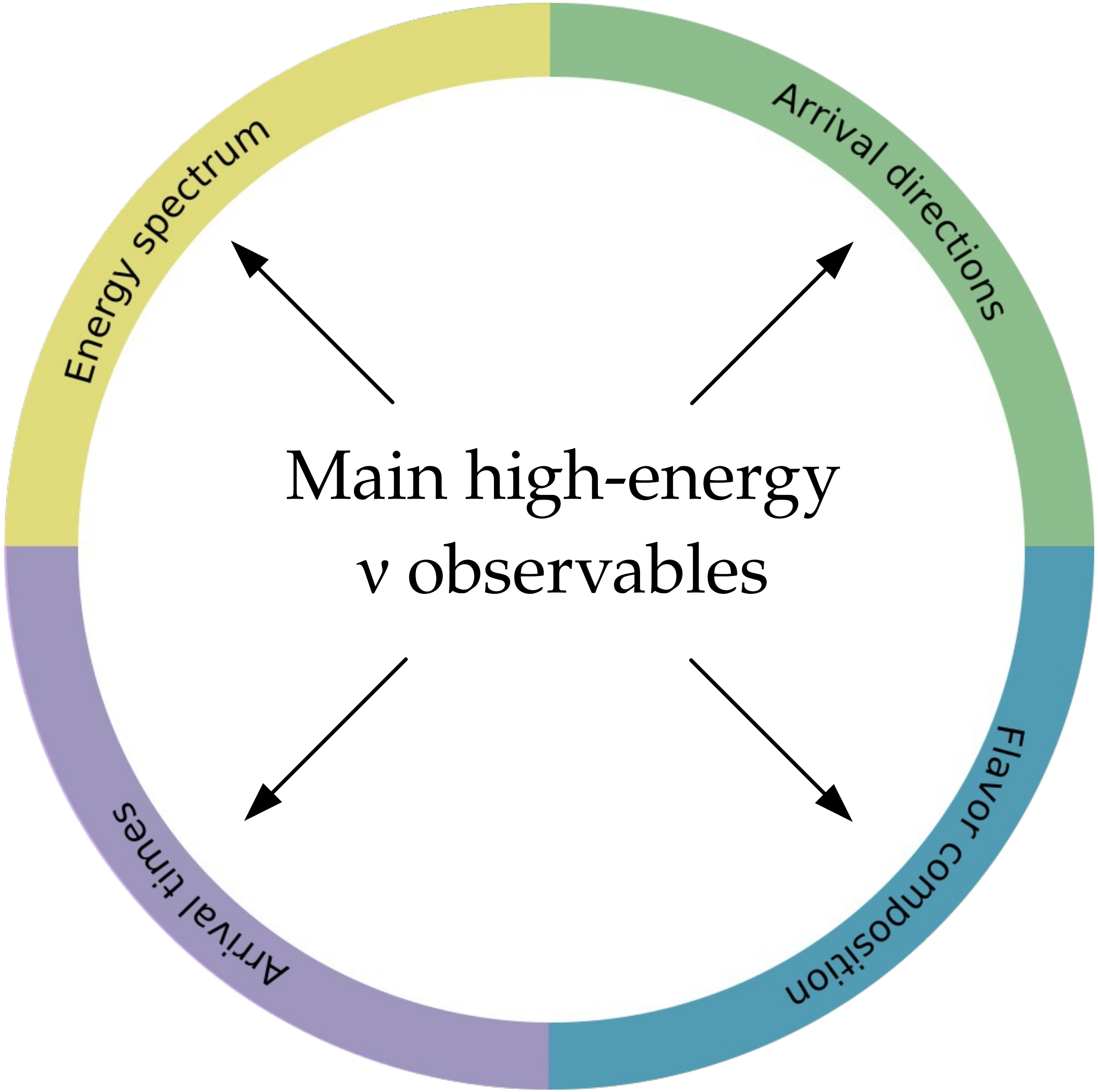


Poor angular resolution: ~10°

Track (mainly from ν_μ)

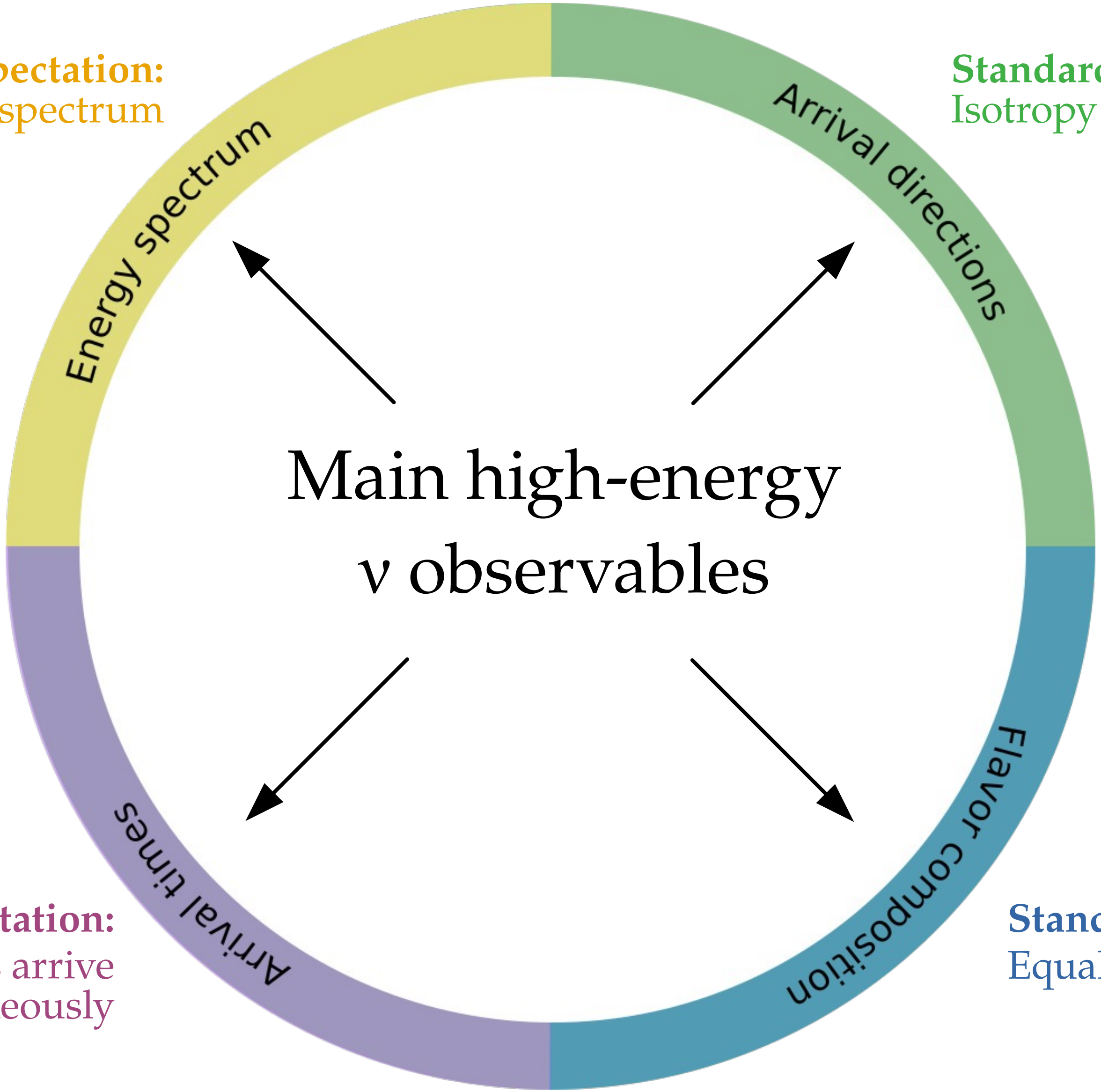


Angular resolution: < 1°


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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

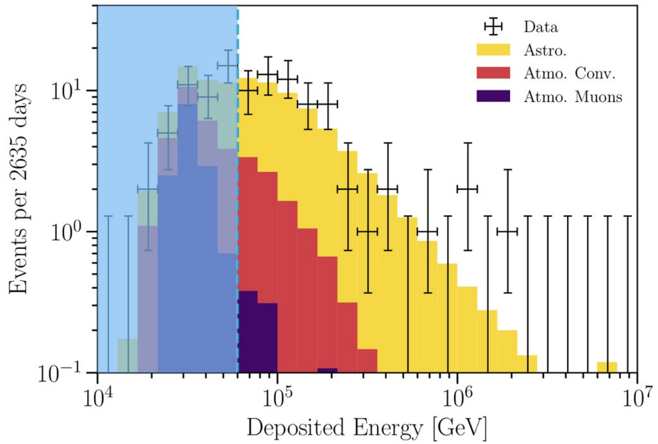


Standard expectation:
ν and γ from transients arrive simultaneously

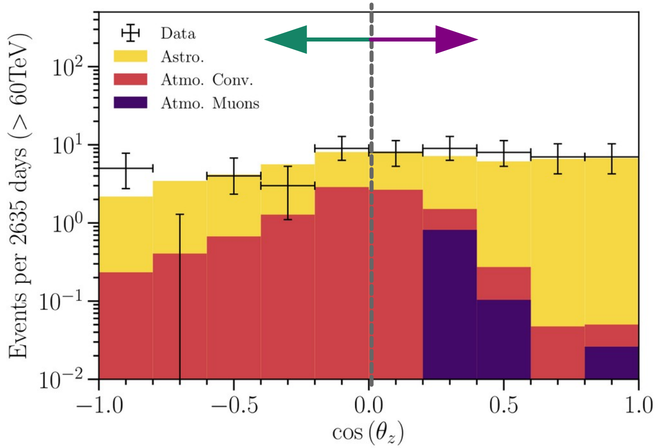
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

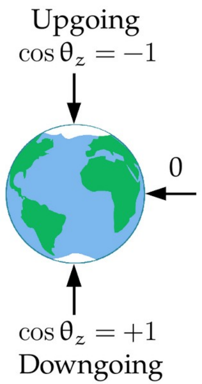
Energy spectrum (7.5 yr)

100+ contained events above 60 TeV:



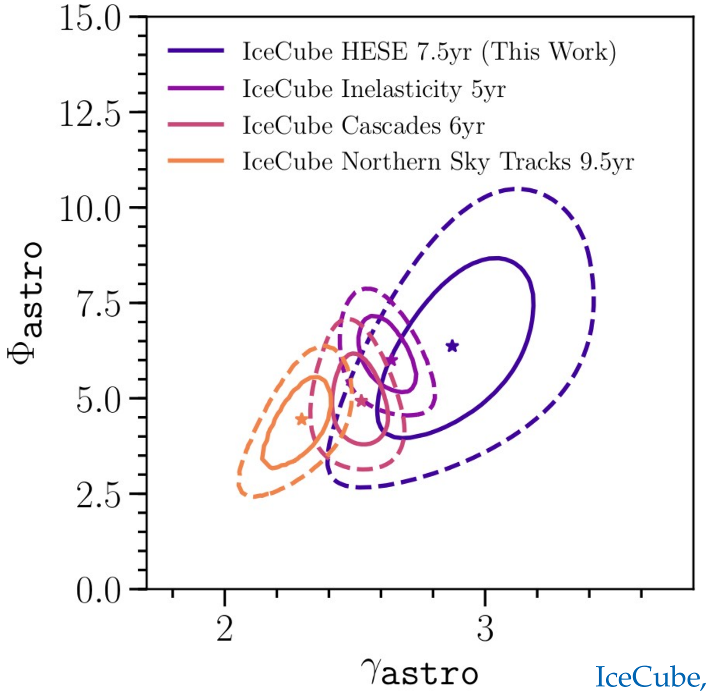
ν attenuated by Earth   Atm. ν and μ vetoed





Data is fit well by a single power law:

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



IceCube, 2011.03545

Energy spectrum (7.5 yr)

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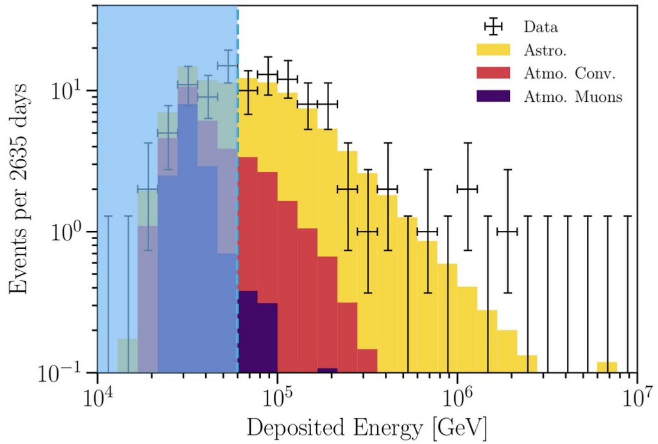

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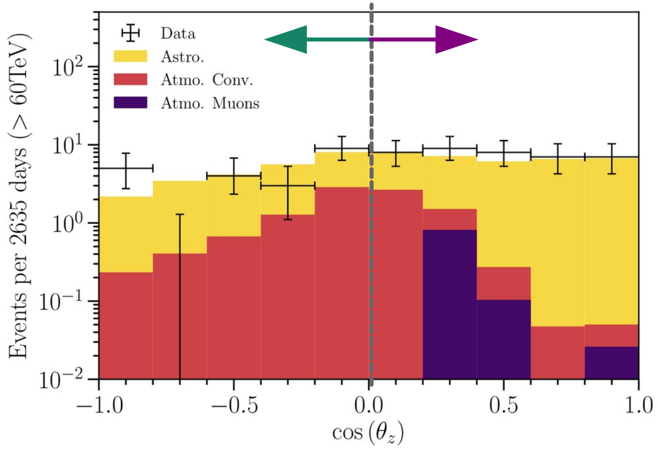

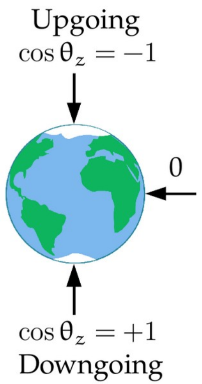

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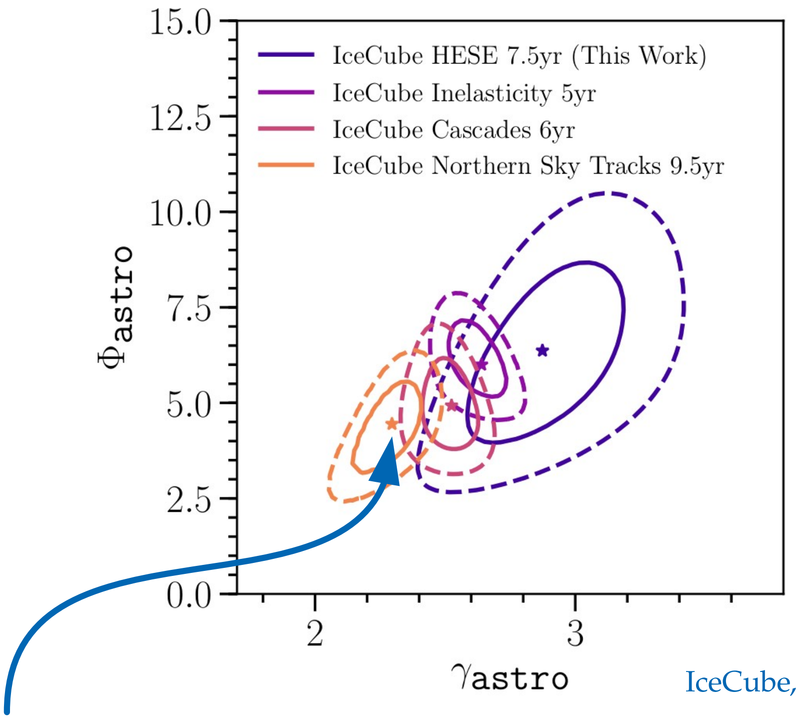
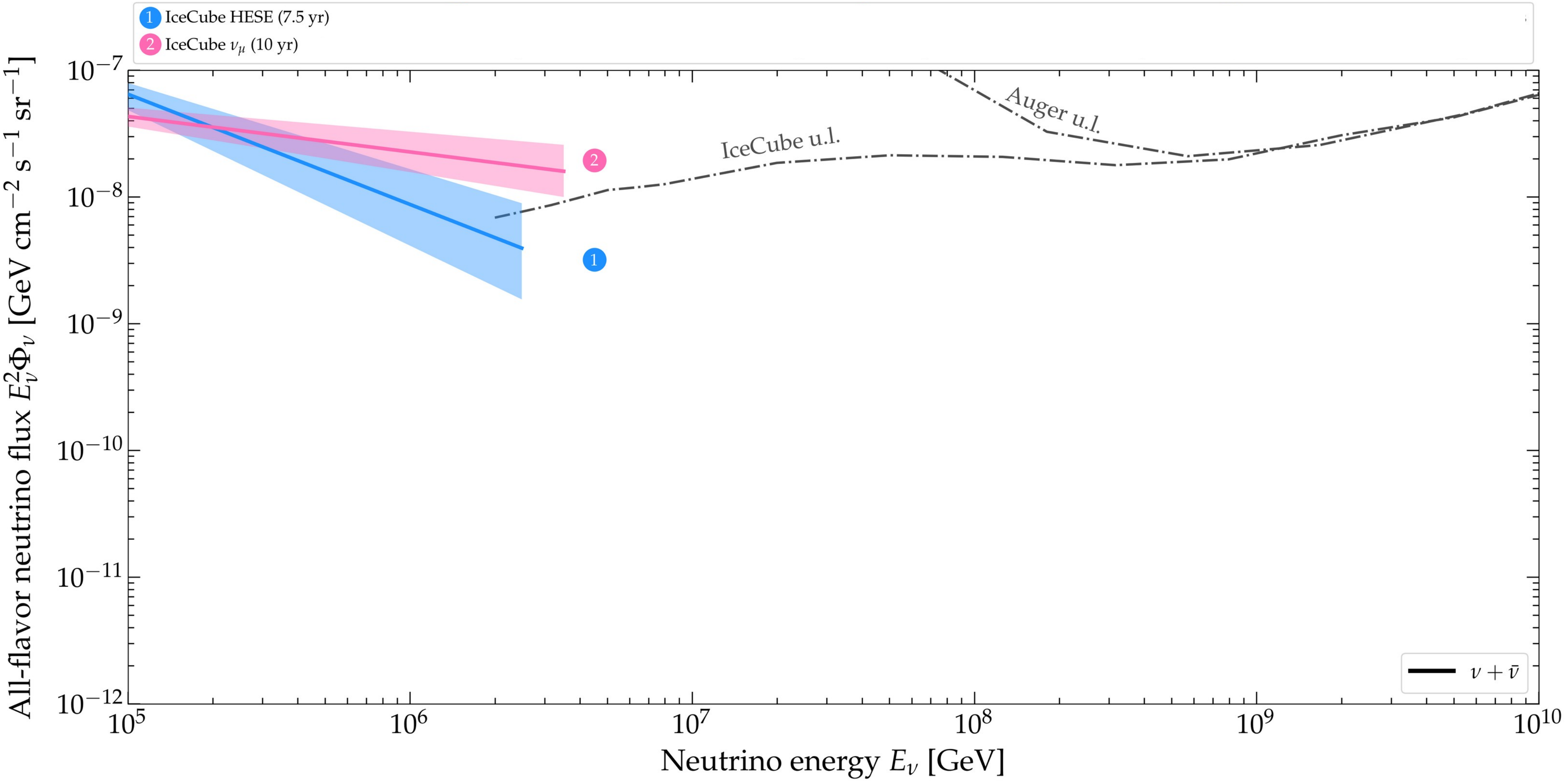


IceCube, 2011.03545

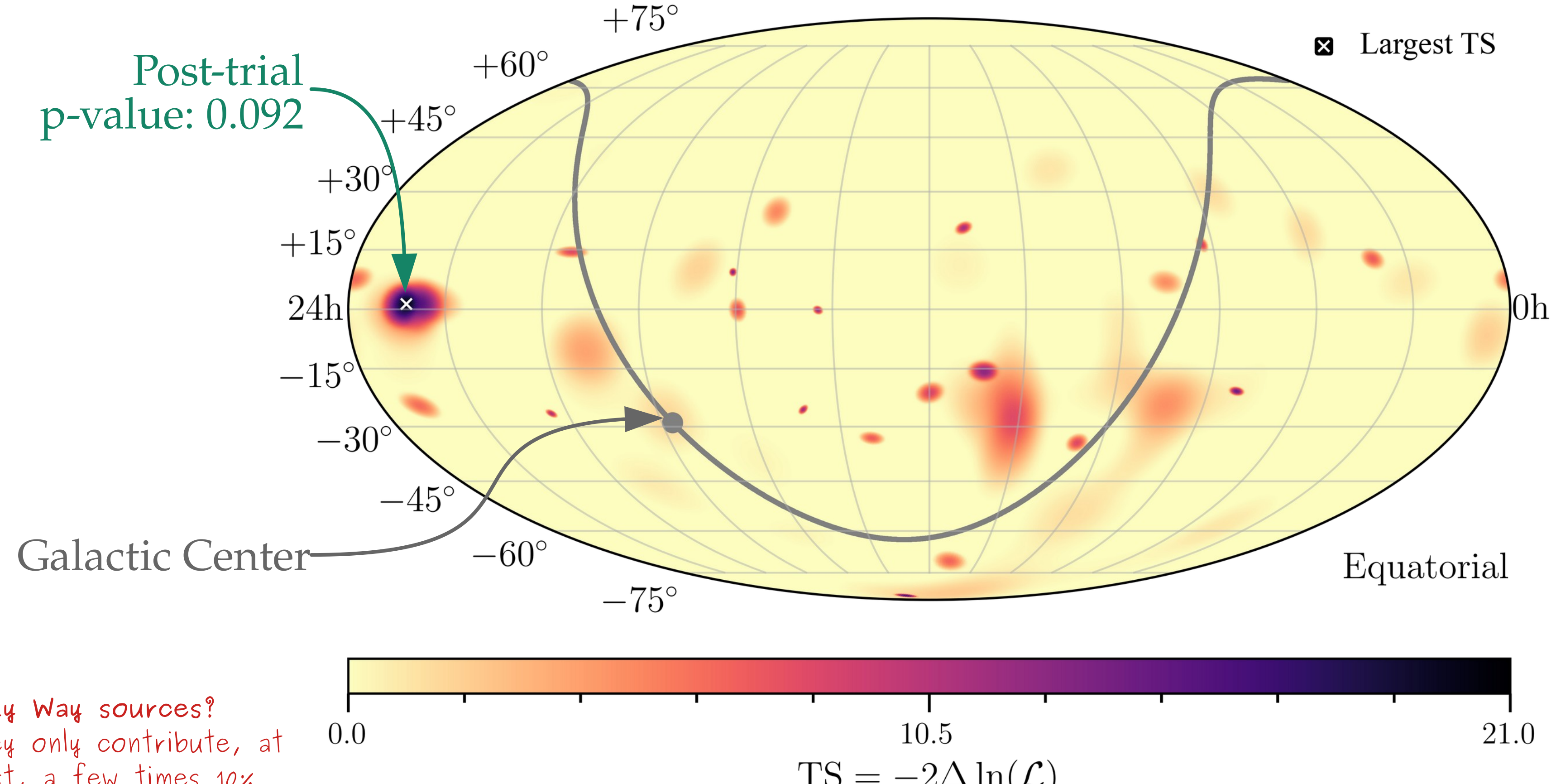
Spectrum looks harder for through-going ν_μ



1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
Auger u.l.
IceCube u.l.
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy E_ν [GeV]

Arrival directions (7.5 yr)

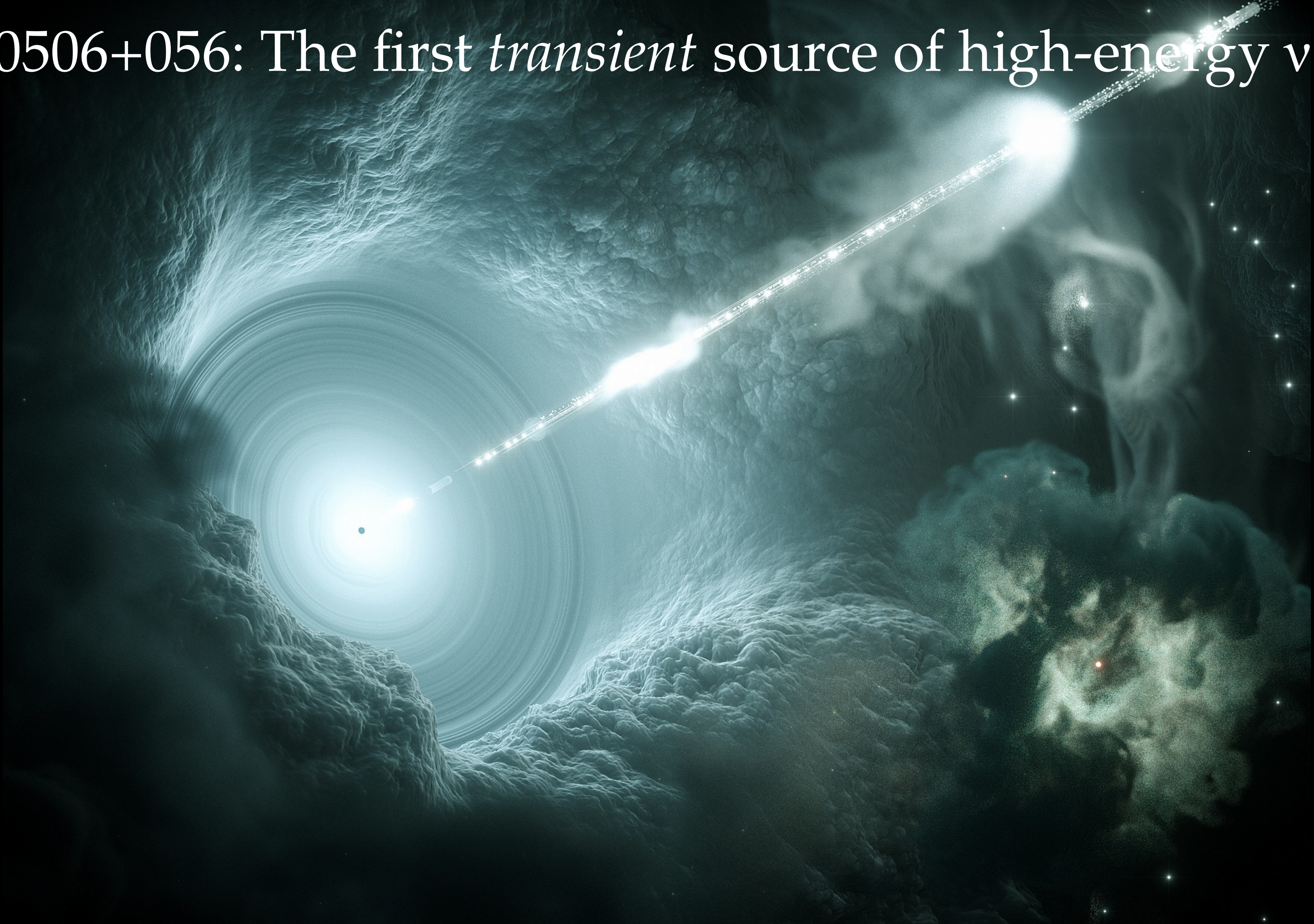
No significant excess in the neutrino sky map:



Milky Way sources?
They only contribute, at most, a few times 10% of the total diffuse flux

IceCube, 2011.03545

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



DESY

Tidal disruption events

Solar-mass star disrupted by SMBH ($>10^5\ M_\odot$)

~50% of the debris bound to the SMBH, creates a flare (occasionally a jet)

NASA

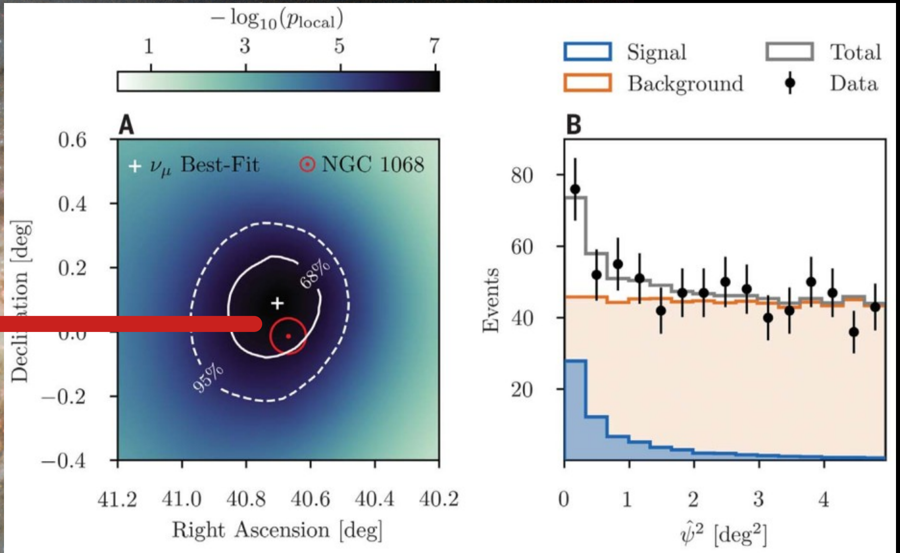
NGC1068: The first *steady-state* source of high-energy ν

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

Today

TeV–PeV ν

Today

TeV–PeV ν

Turn predictions
into data-driven tests

Today

TeV–PeV ν

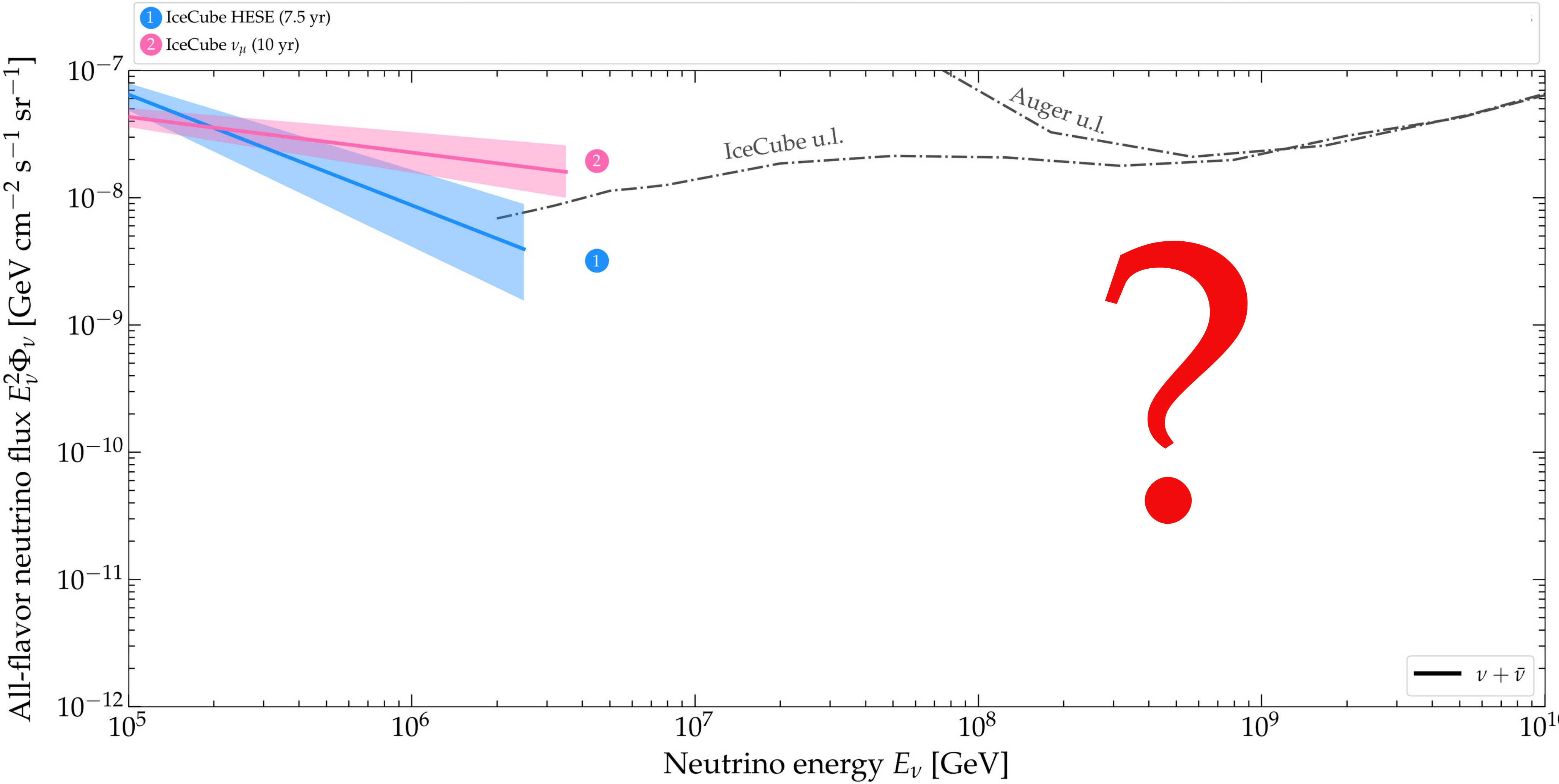
Turn predictions
into data-driven tests

Key developments:

Bigger detectors → larger statistics

Better reconstruction

Smaller astrophysical uncertainties



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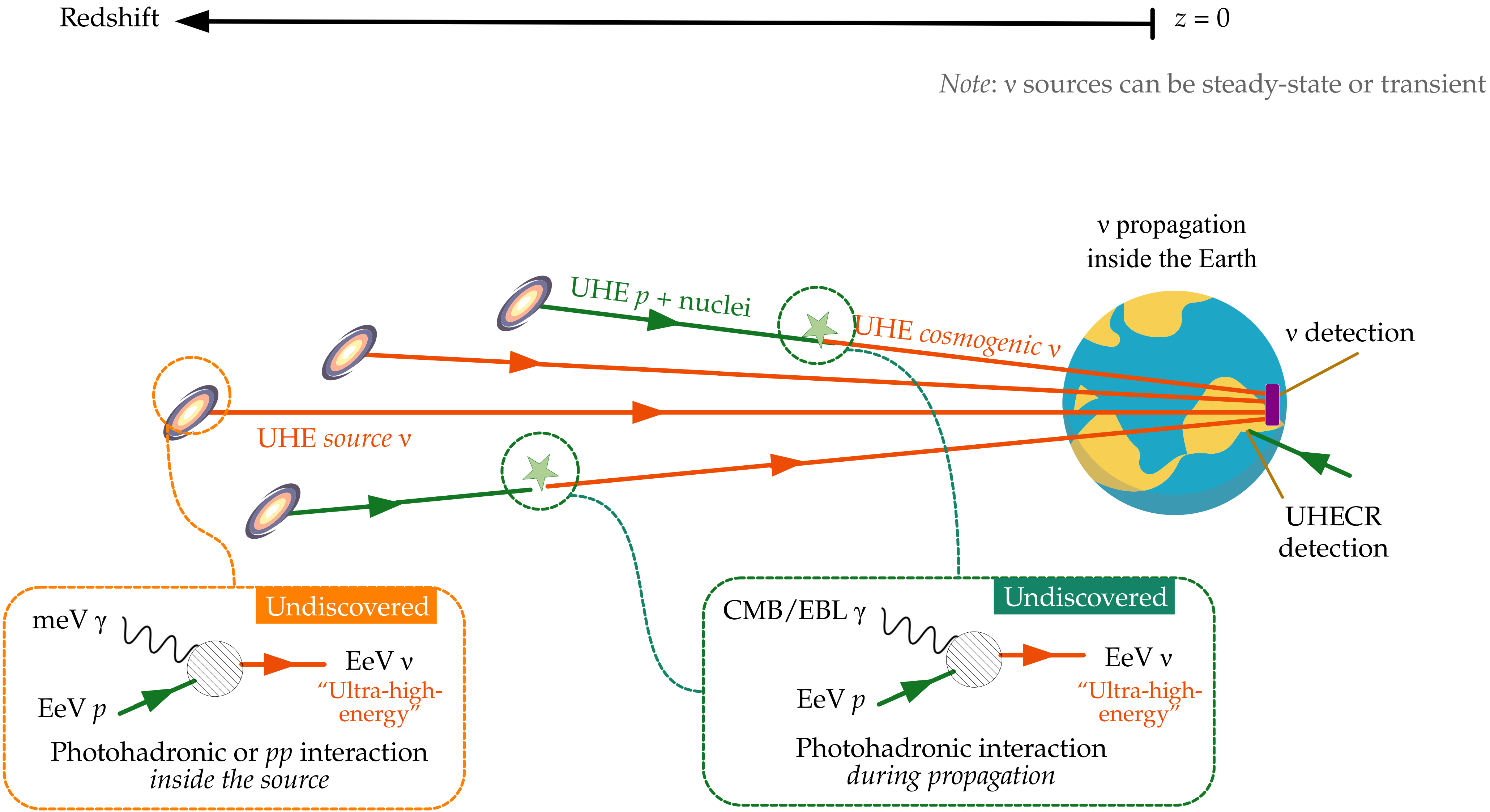
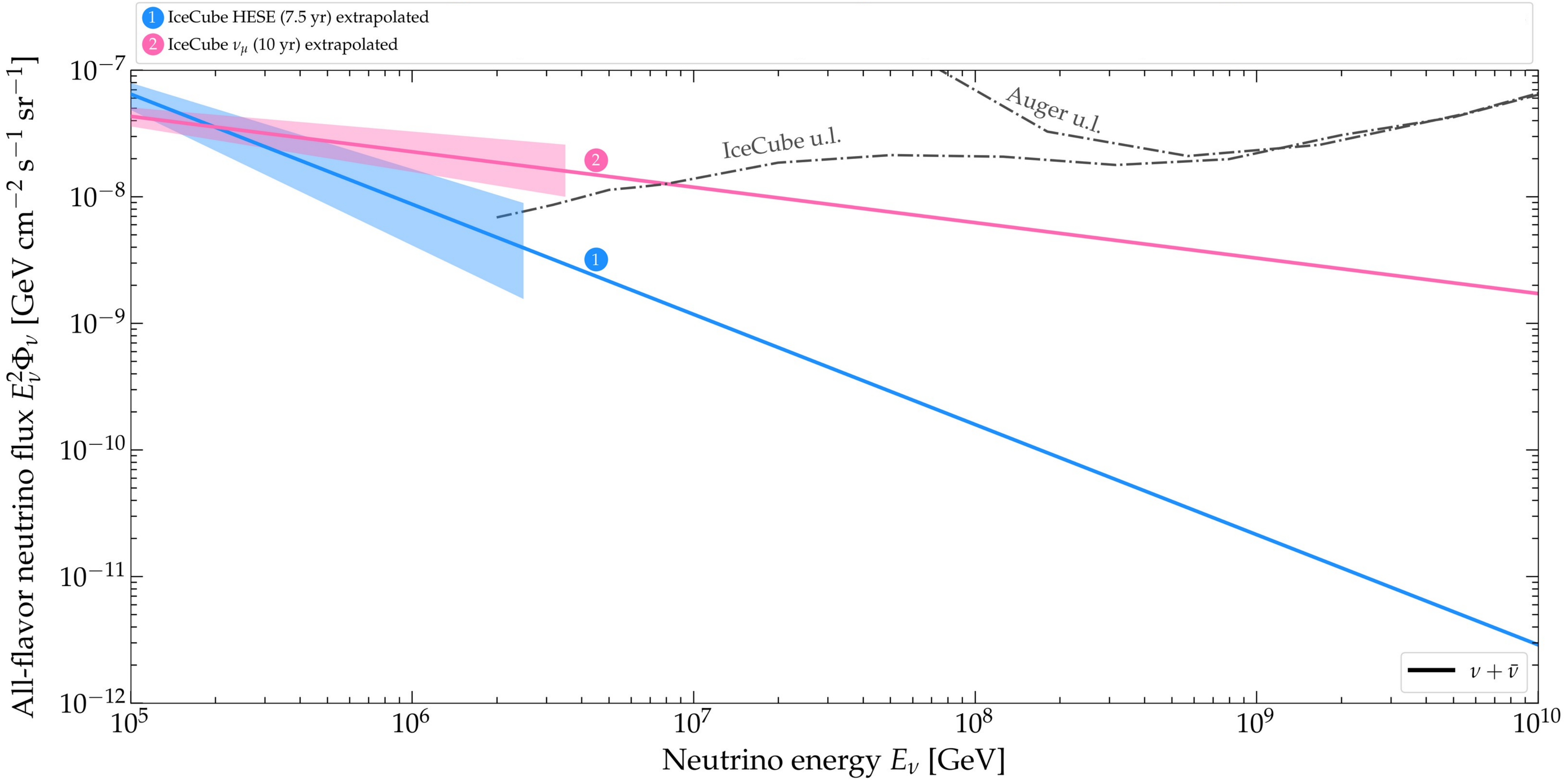
2 IceCube ν_μ (10 yr)
Auger u.l.
IceCube u.l.
1
2
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy E_ν [GeV]
?


Redshift
$z = 0$
Note: ν sources can be steady-state or transient
ν propagation inside the Earth
UHE p + nuclei
UHE *cosmogenic* ν
ν detection
UHE *source* ν
UHECR 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*



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All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-7}
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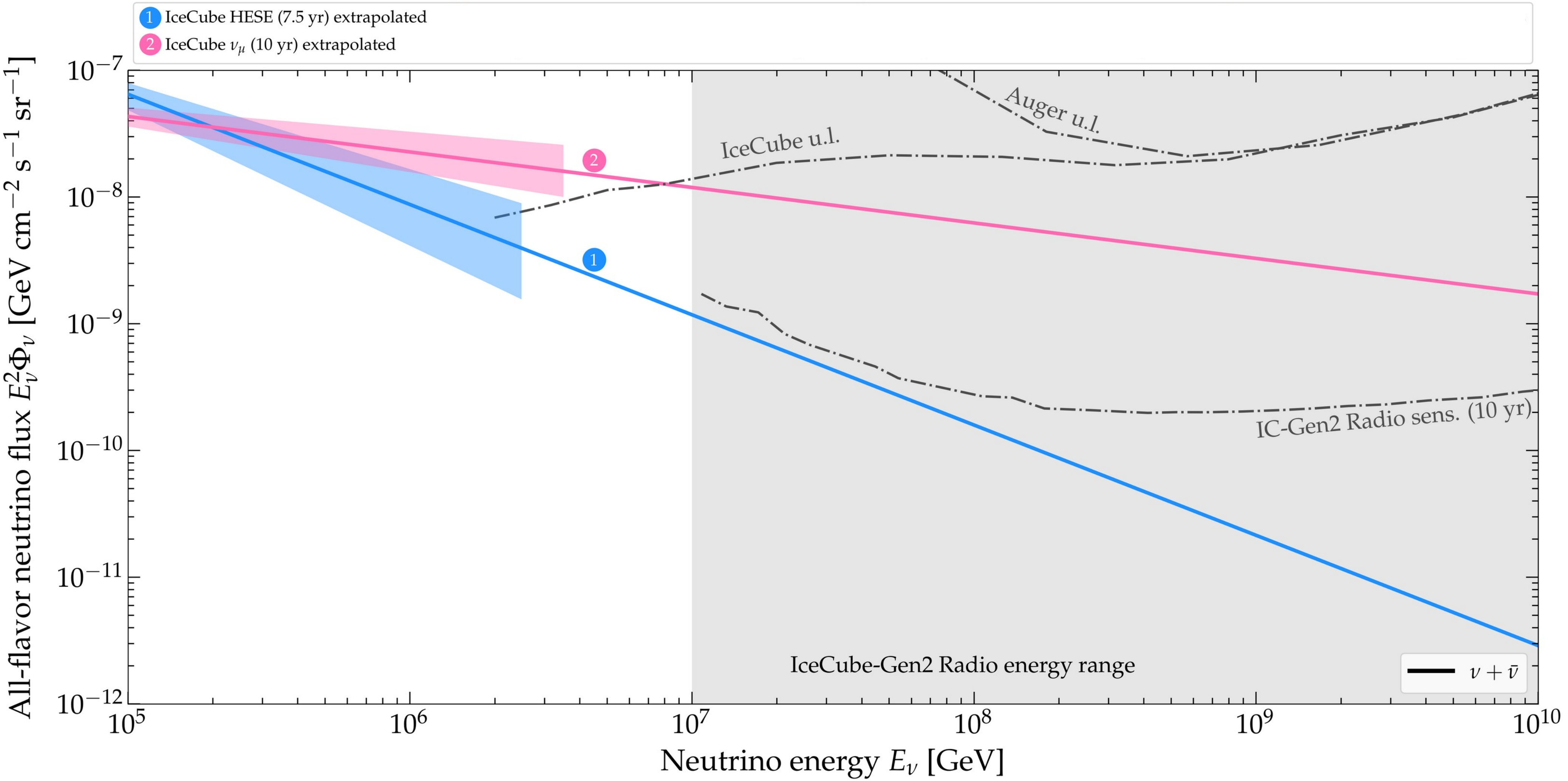
10^{-9}
10^{-10}
10^{-11}
10^{-12}
Auger u.l.
IceCube u.l.
2
1
$\nu + \bar{\nu}$
10^5
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy E_ν [GeV]



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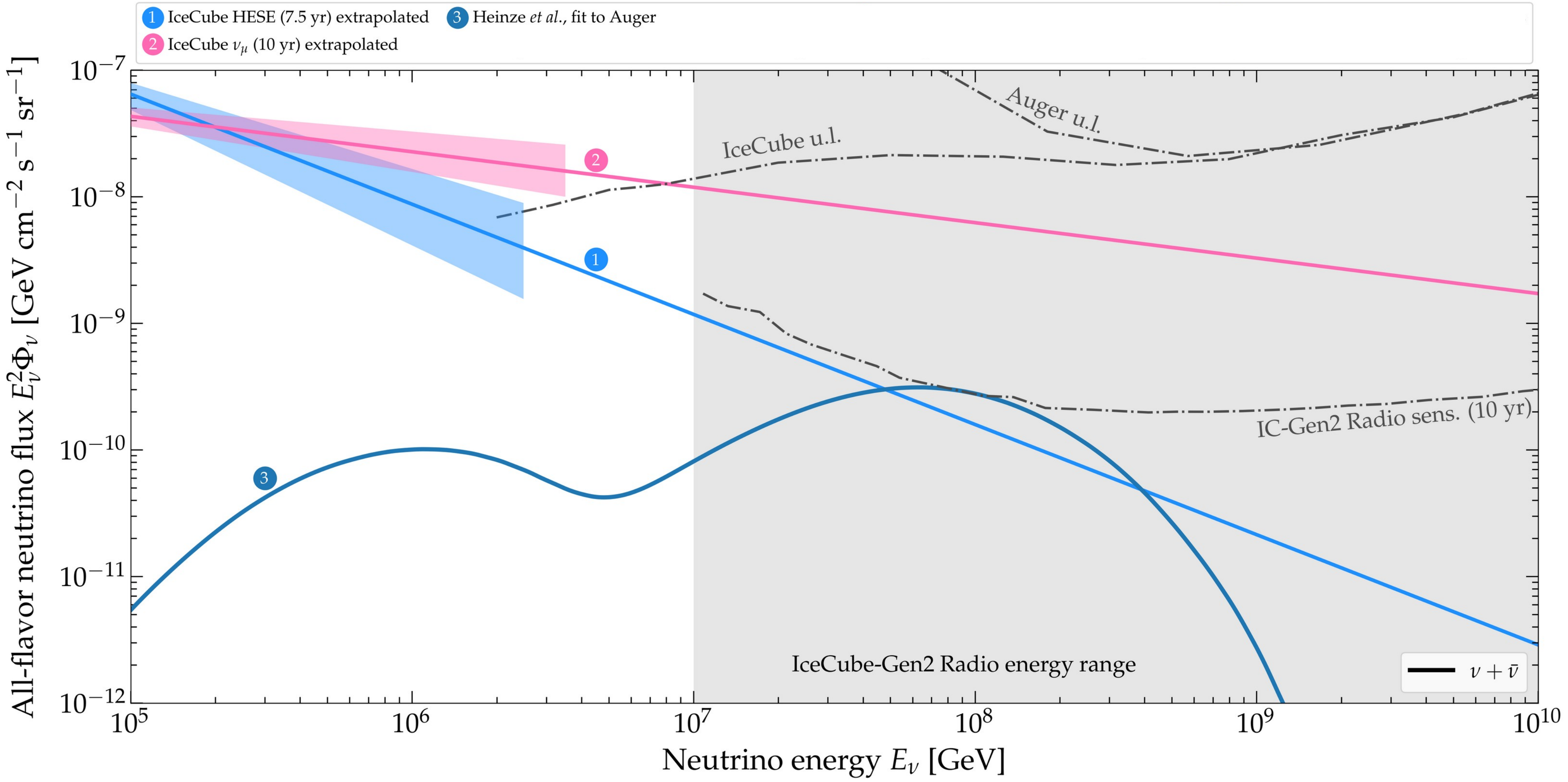
2 IceCube ν_μ (10 yr) extrapolated
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]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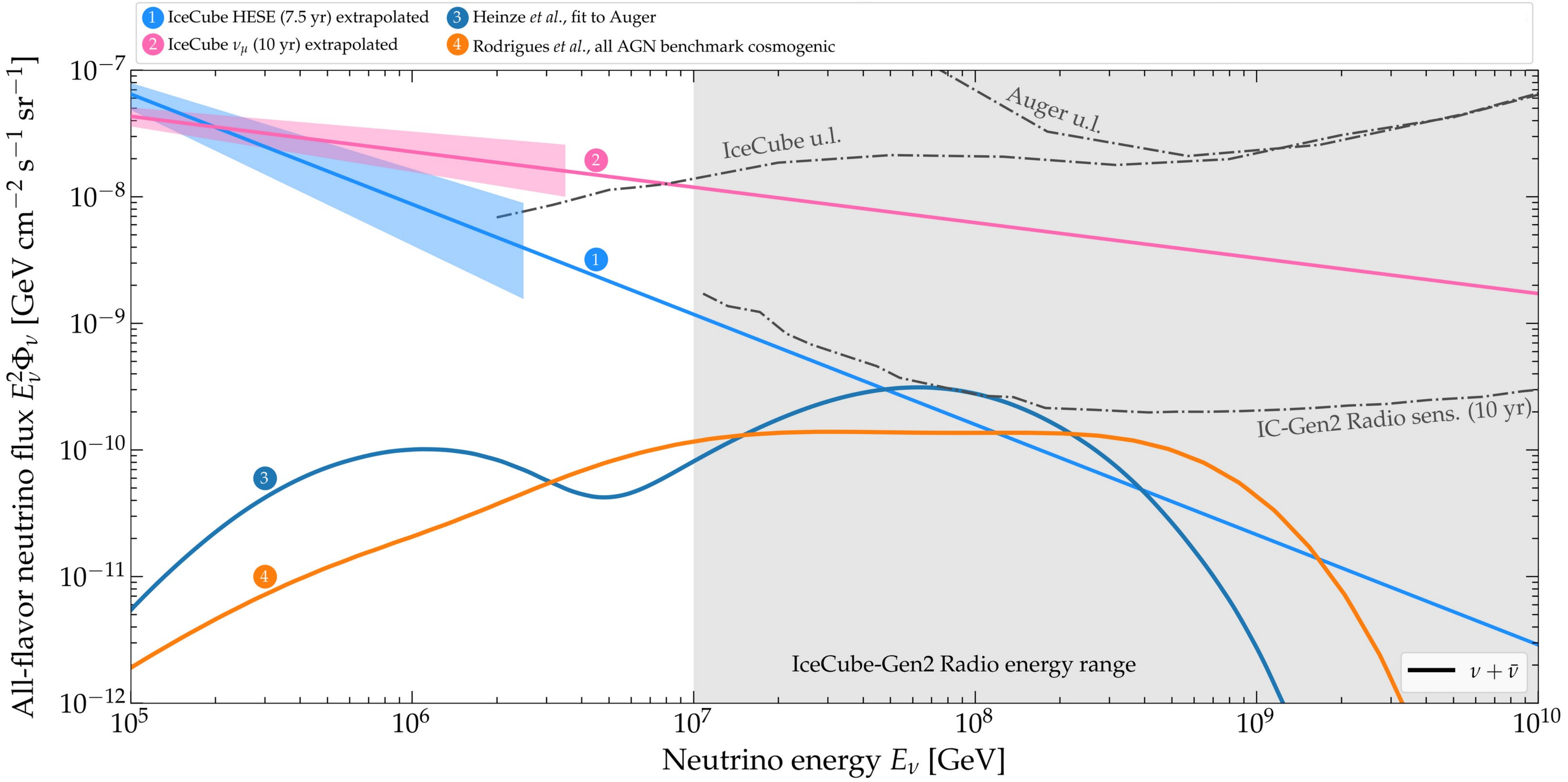
10^8
10^9
10^{10}



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IceCube-Gen2 Radio energy range
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All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
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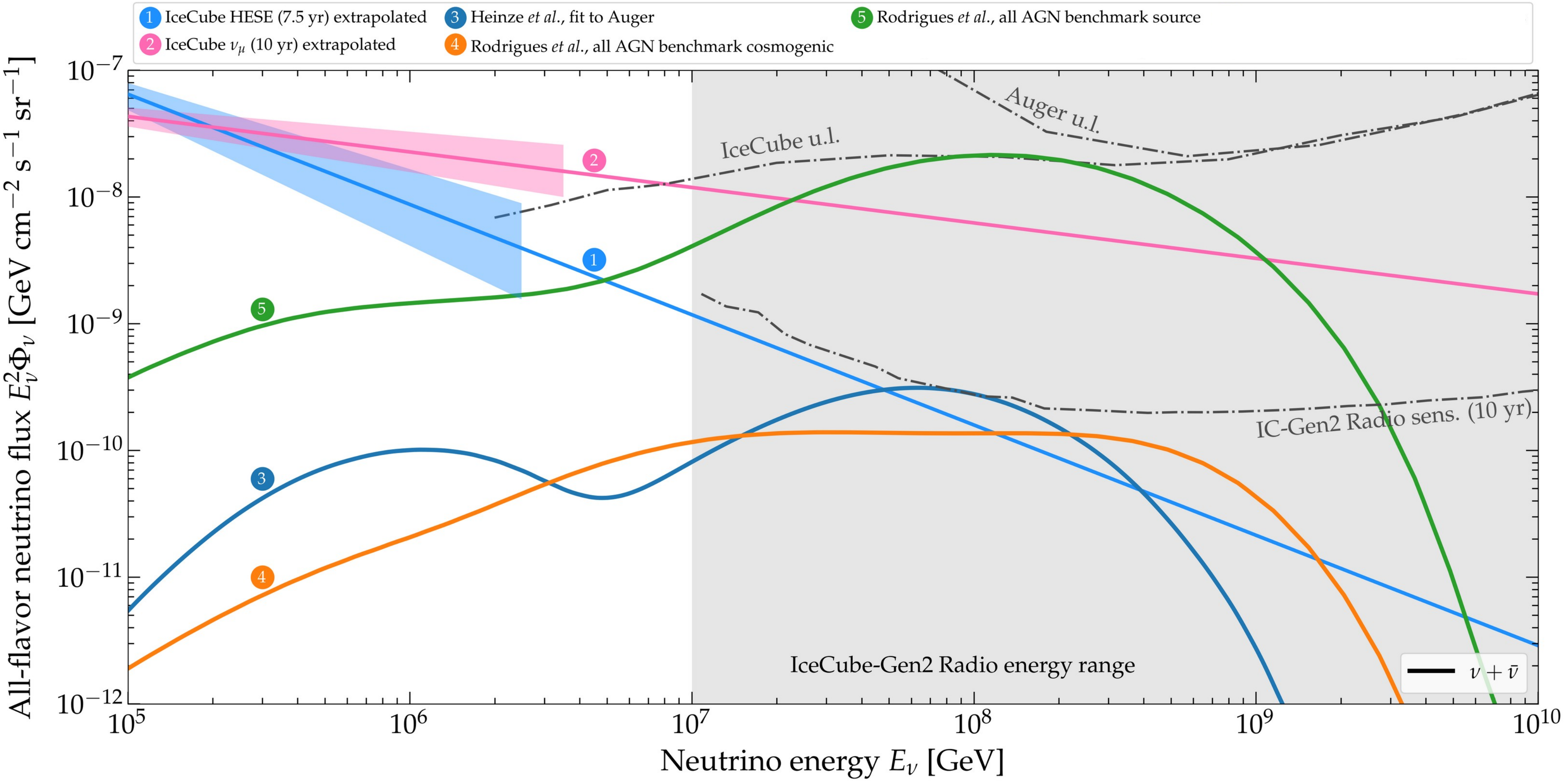
10^{10}



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5 Rodrigues *et al.*, all AGN benchmark source
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
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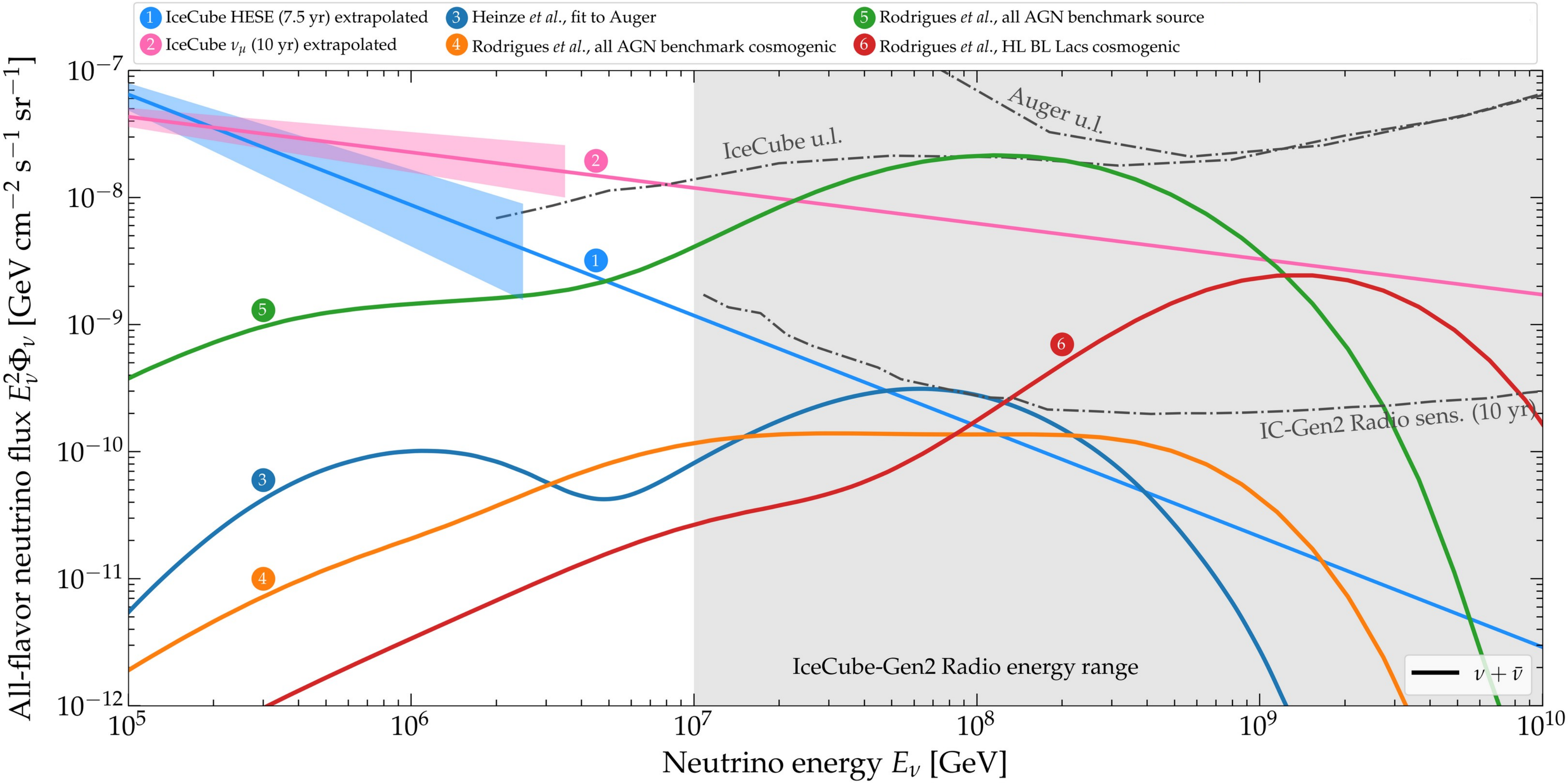

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6 Rodrigues *et al.*, HL BL Lacs cosmogenic
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
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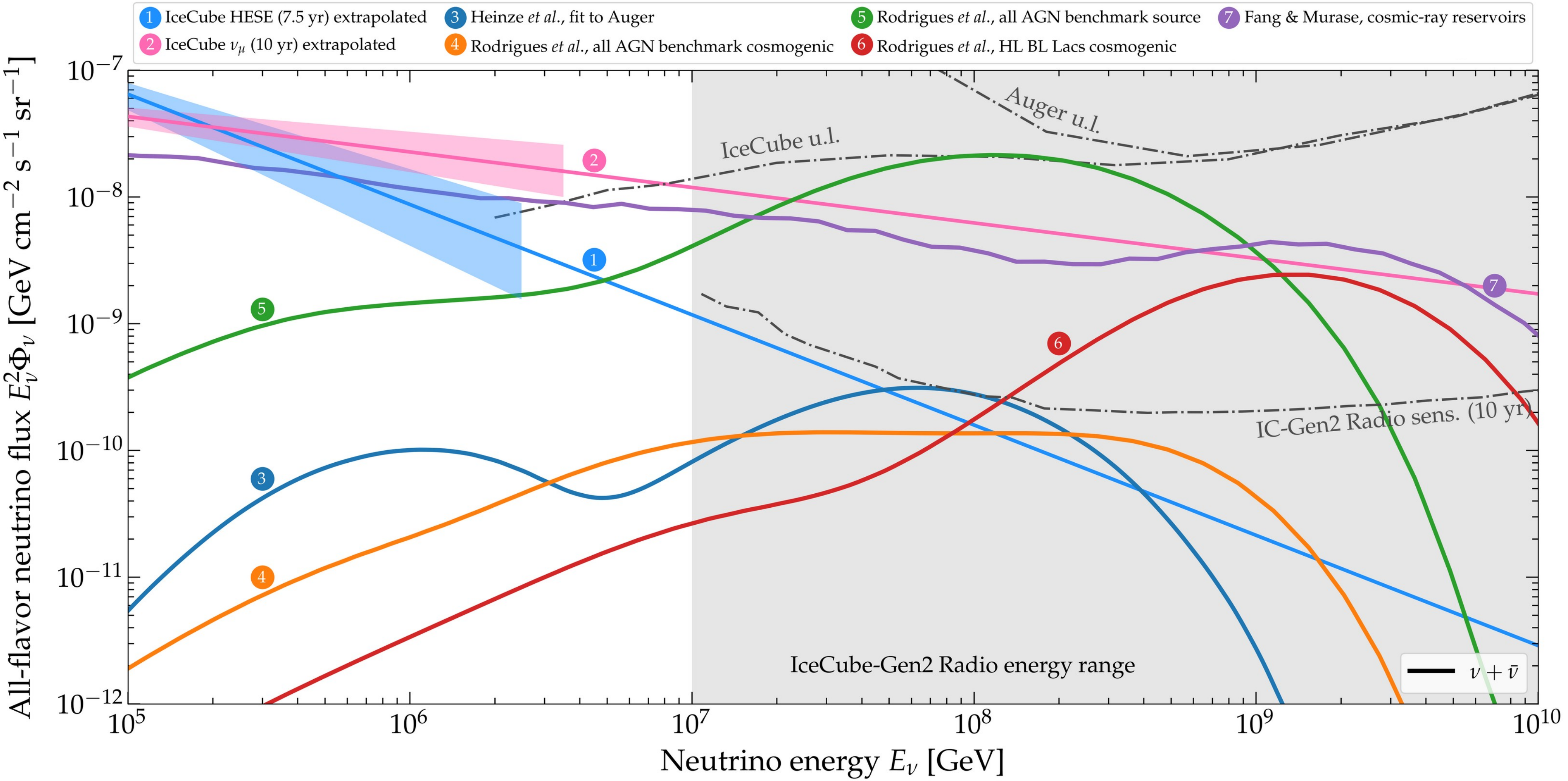

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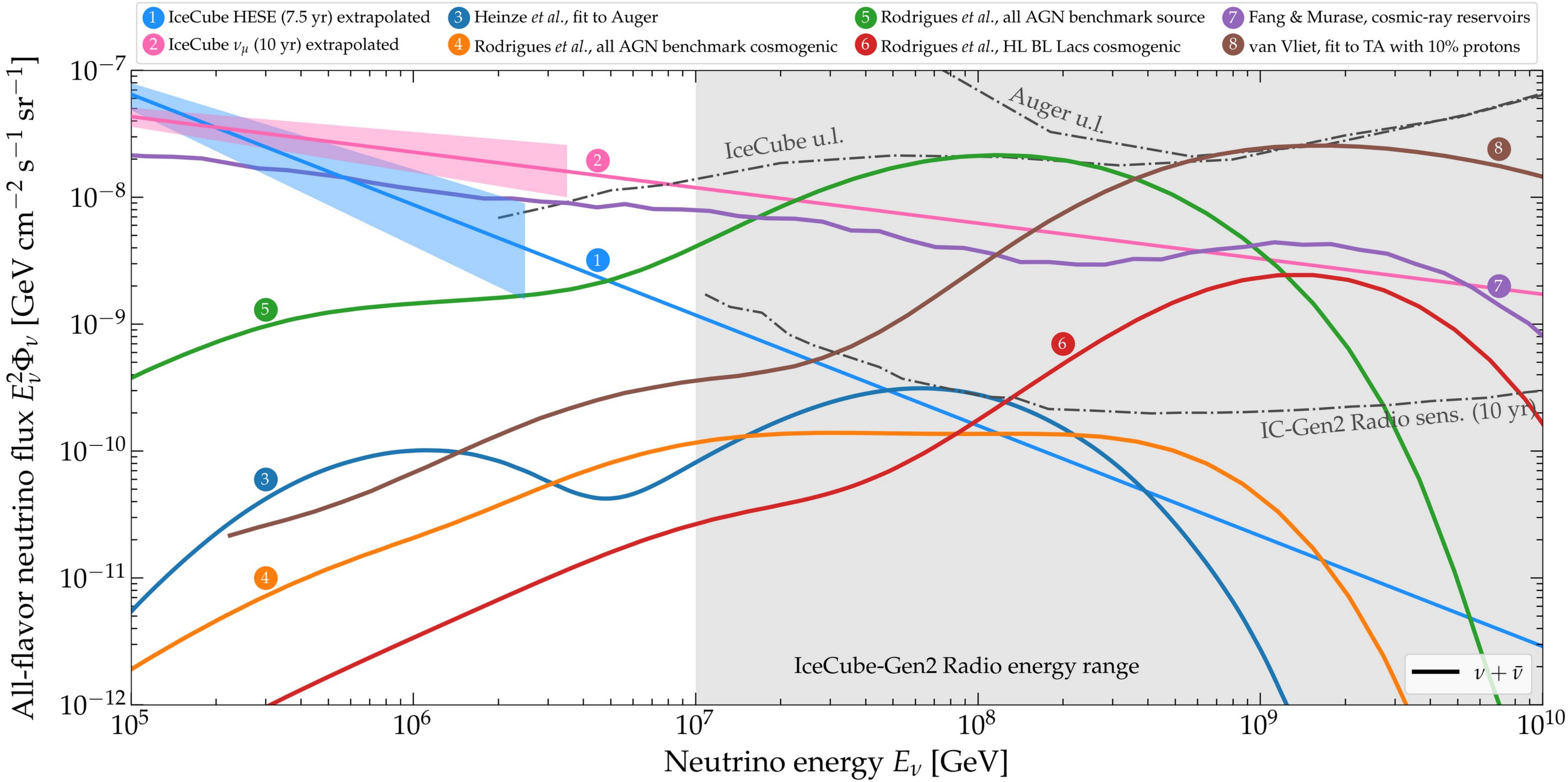
7 Fang & Murase, cosmic-ray reservoirs
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$



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5 Rodrigues *et al.*, all AGN benchmark source
6 Rodrigues *et al.*, HL BL Lacs cosmogenic
7 Fang & Murase, cosmic-ray reservoirs
8 van Vliet, fit to TA with 10% protons
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
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10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}

Today

TeV–PeV ν

Turn predictions
into data-driven tests

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

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Next decade

$>$ 100-PeV ν

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

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Bigger detectors → larger statistics
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Make predictions for
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<u>Key developments</u>:
Discovery
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Made robust and meaningful by accounting
for all relevant particle and astrophysics uncertainties

Today

TeV–PeV ν

Turn predictions
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Key developments:
Bigger detectors $\rightarrow$ larger statistics
Better reconstruction
Smaller astrophysical uncertainties

Next decade

> 100-PeV ν

Make predictions for
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Key developments:
Discovery
New detection techniques
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

Note: Not an exhaustive list

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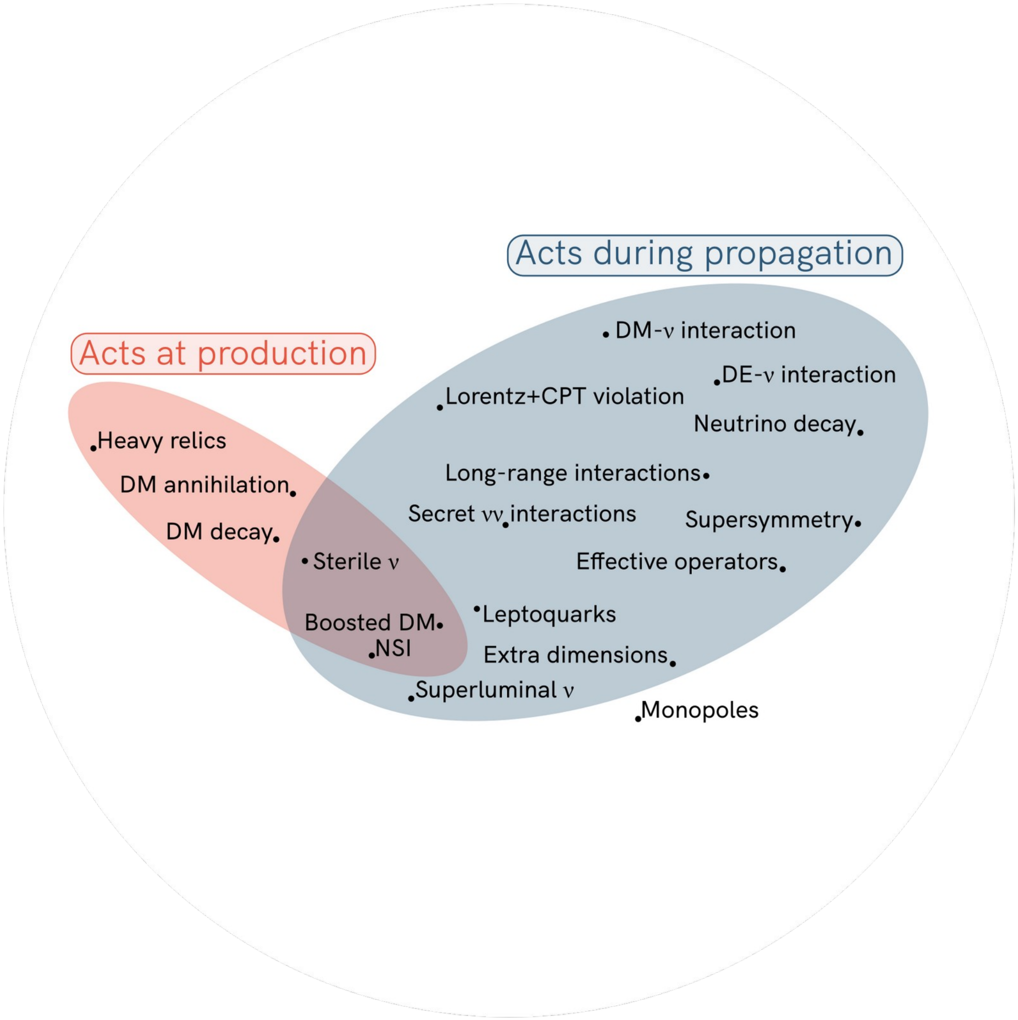

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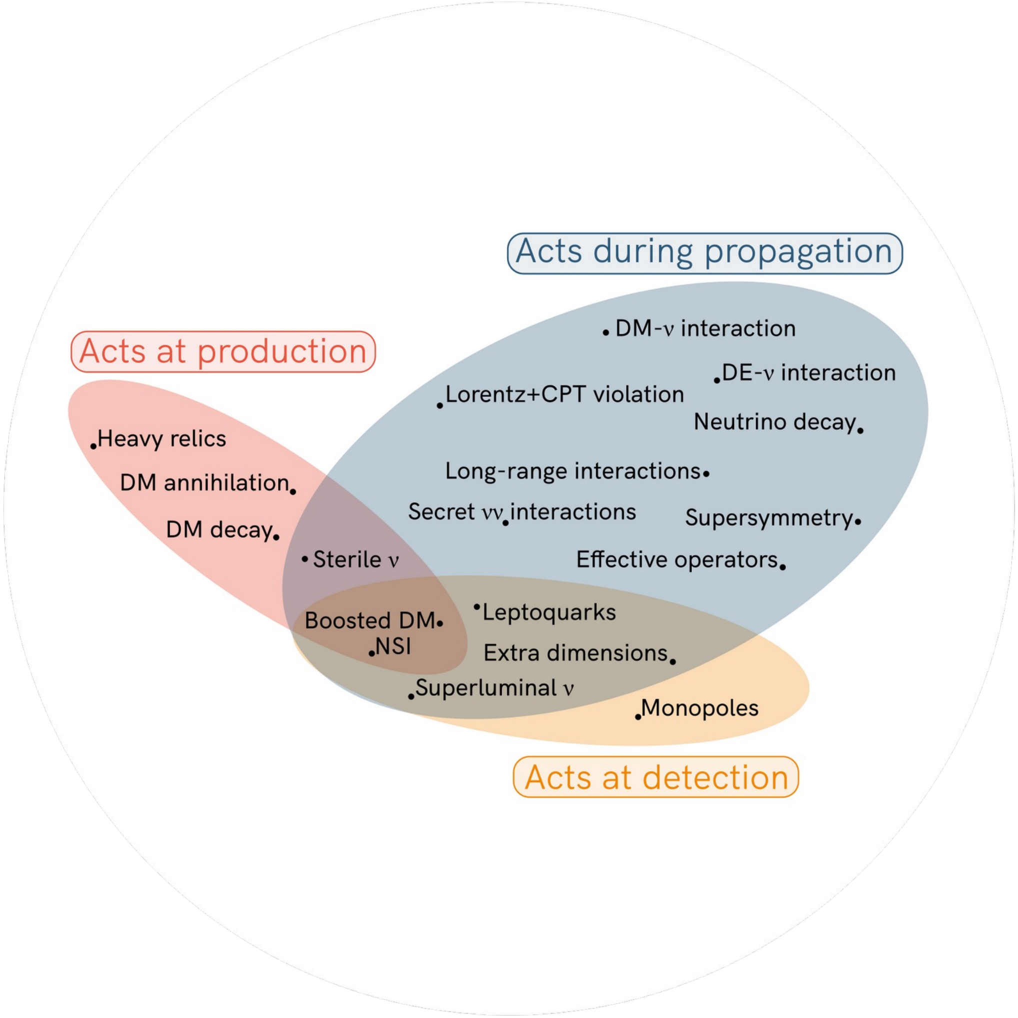

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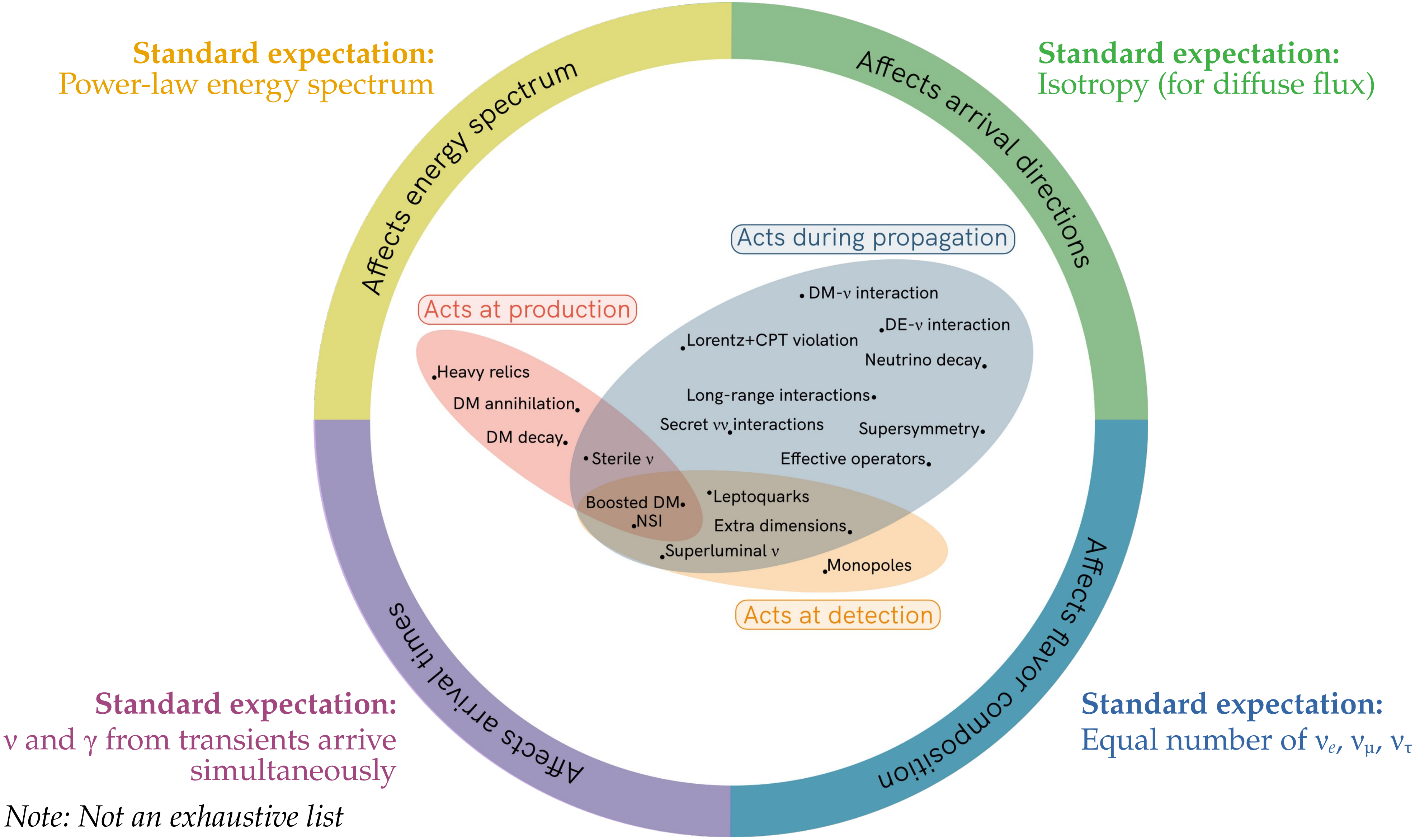

Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Acts during propagation
Acts at production
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Heavy relics
DM annihilation
Long-range interactions
Secret νν interactions
Supersymmetry
DM decay
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
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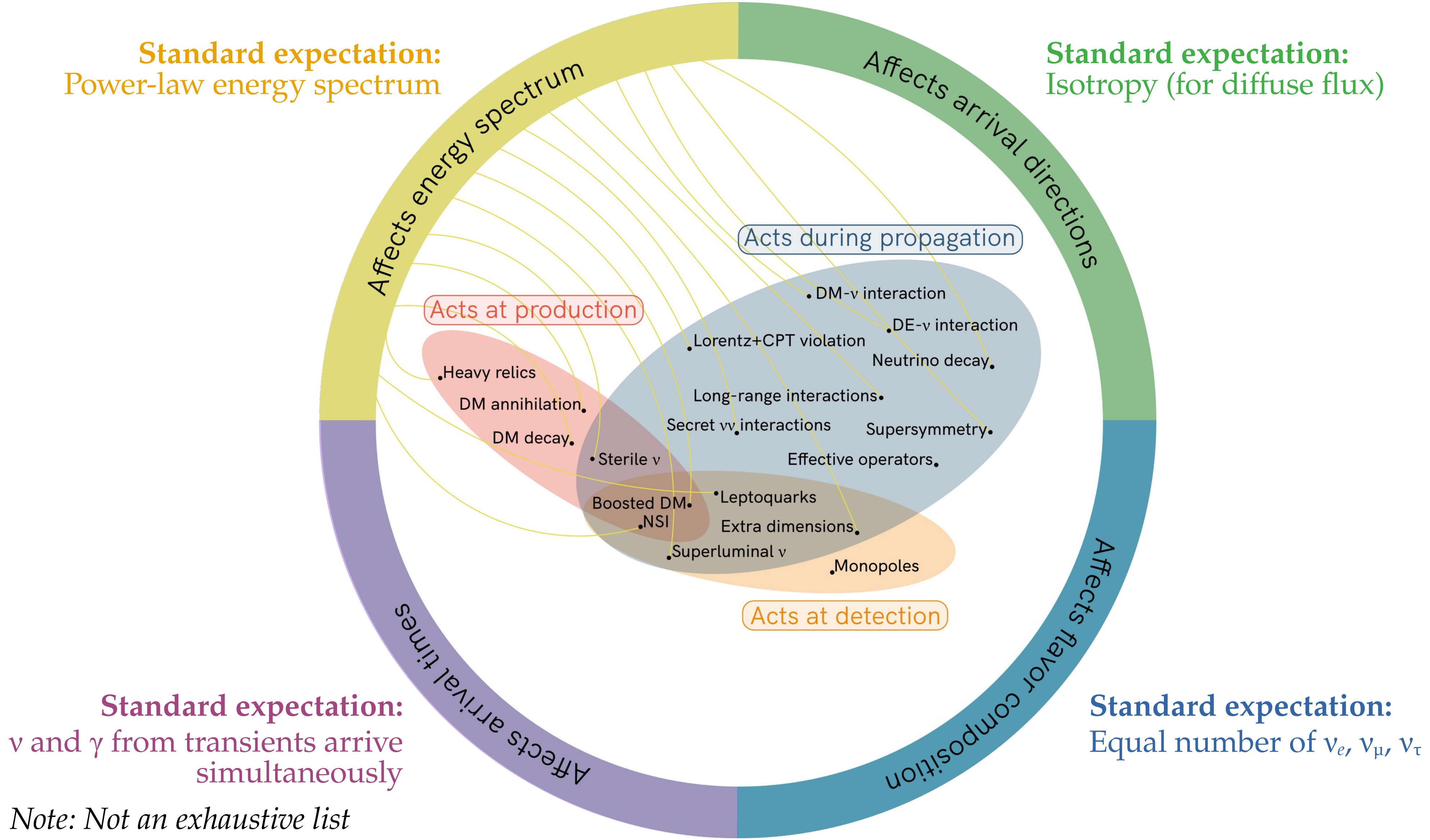

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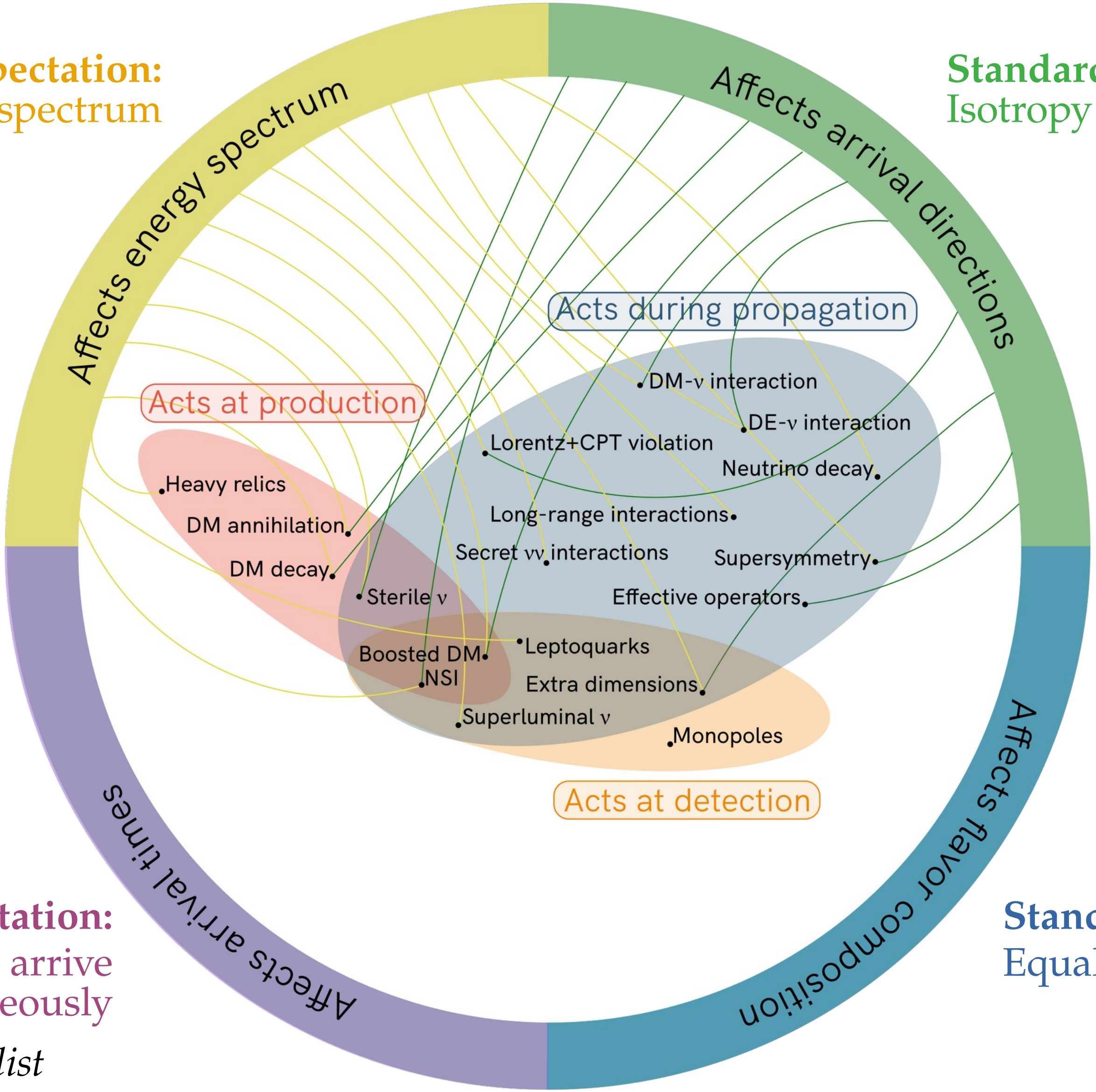

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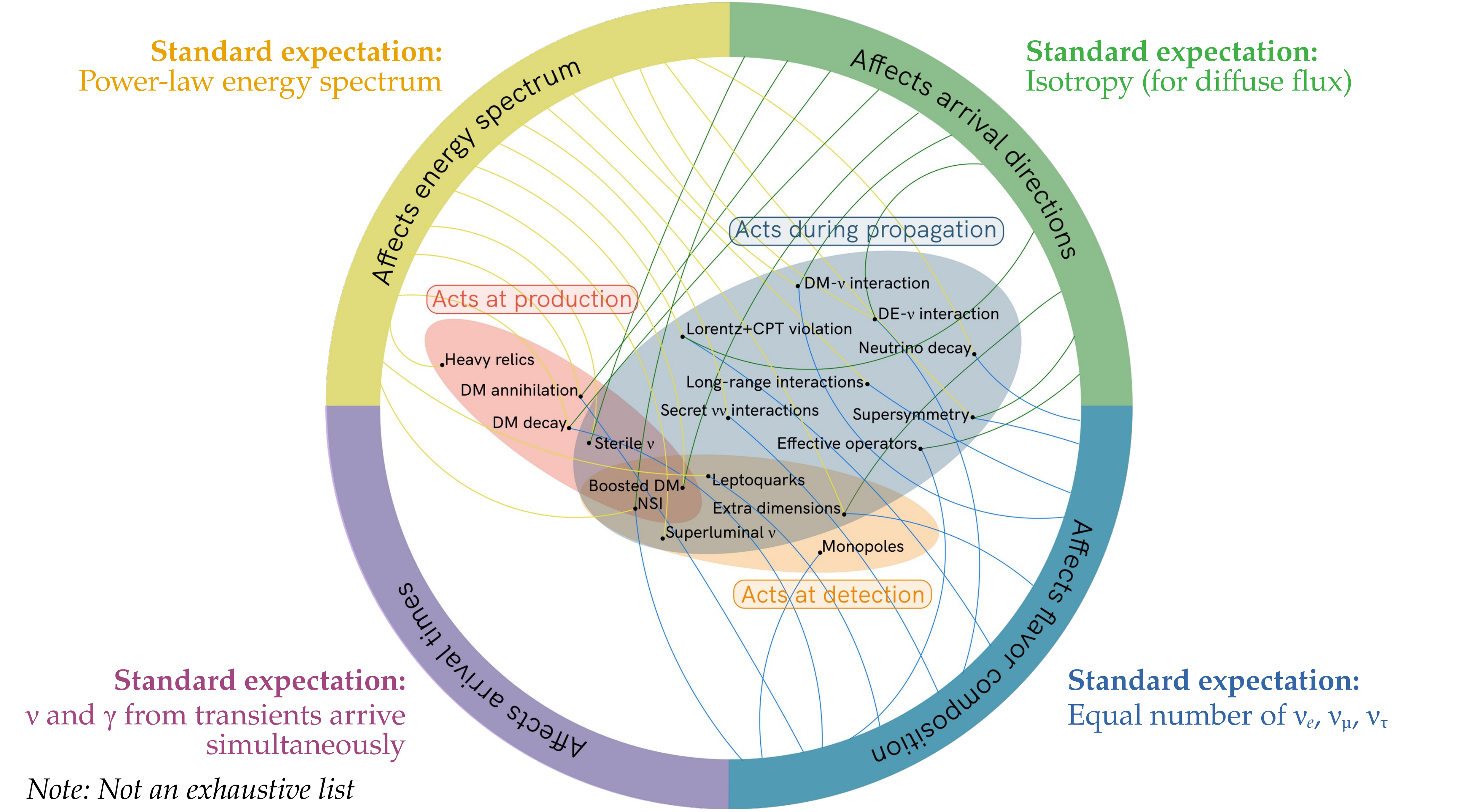

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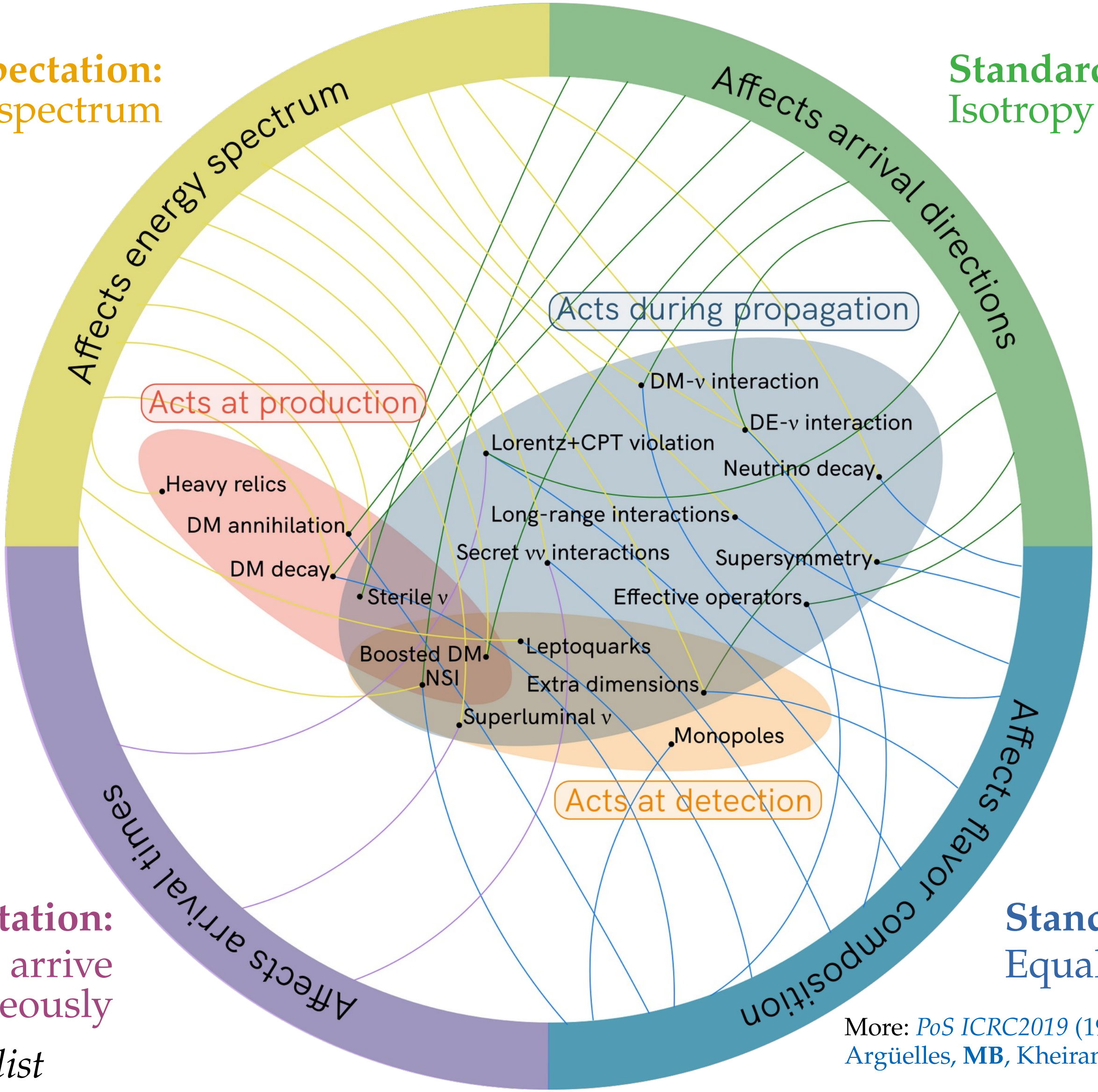

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More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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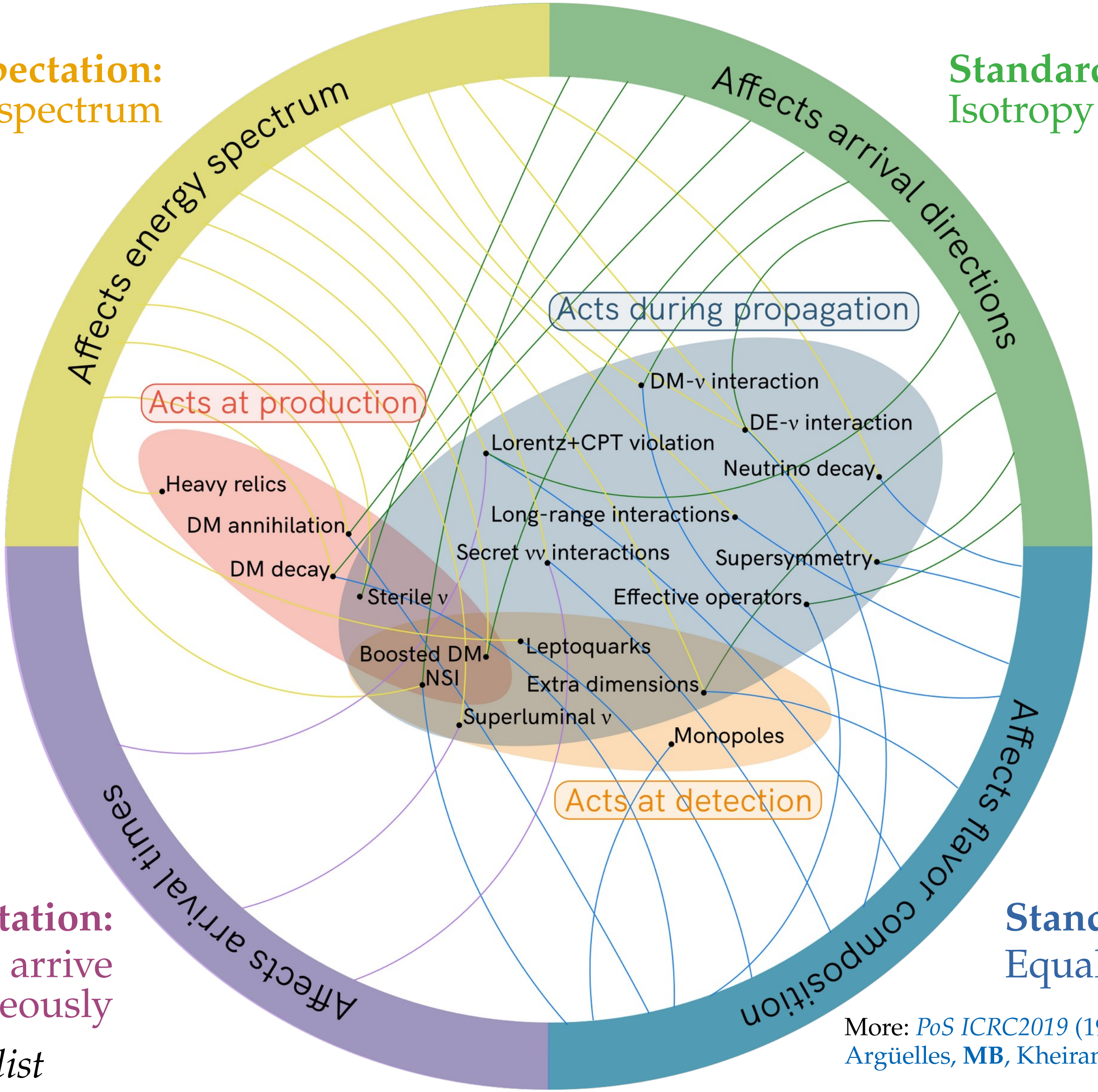

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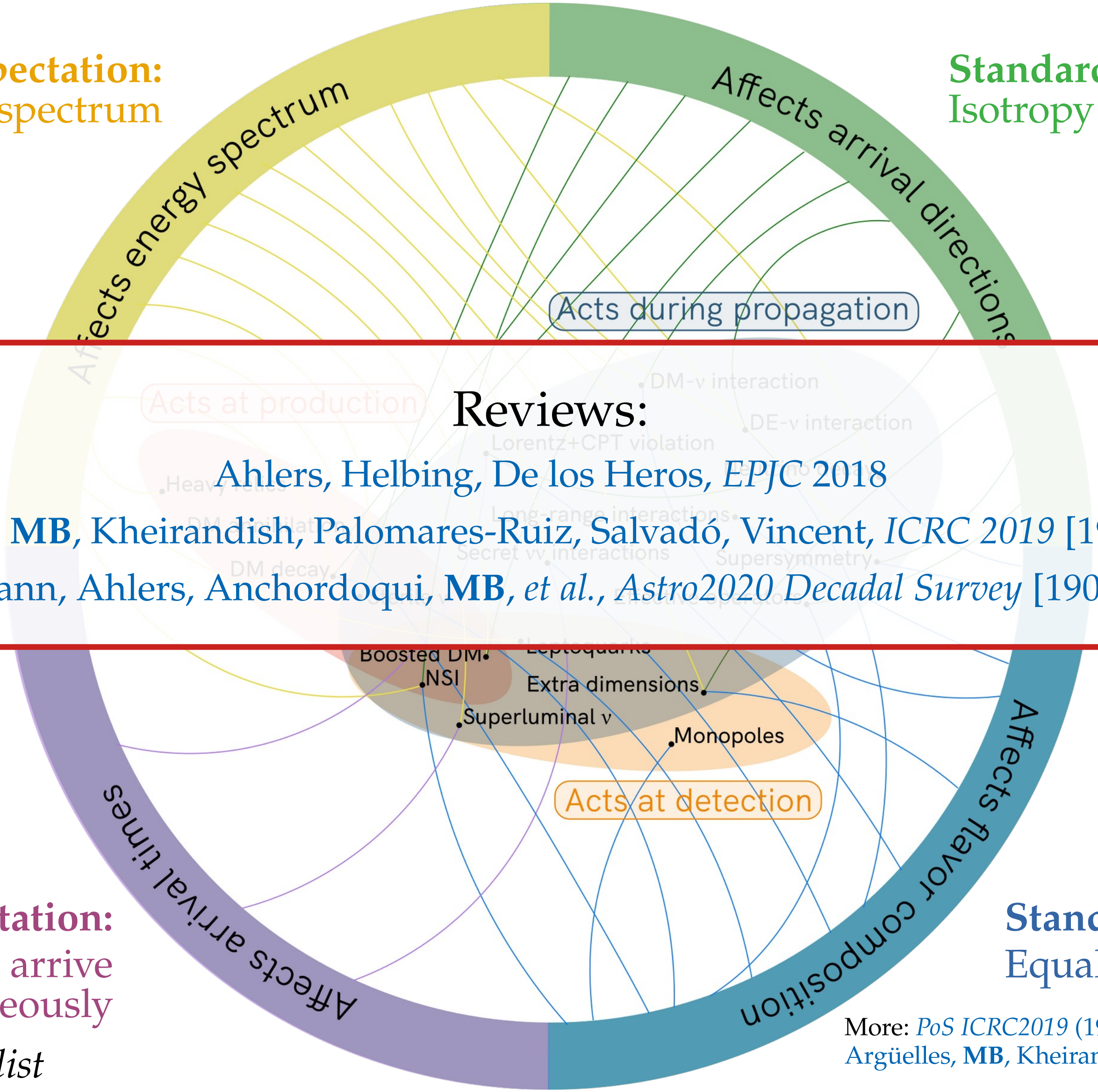

Reviews:

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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A selection of neutrino physics

1. Discovering the Glashow resonance
2. Neutrino-matter cross section
3. New physics via flavor

1. Glashow resonance:
Long-sought, finally seen

First observation of a Glashow resonance

Predicted in 1960:

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

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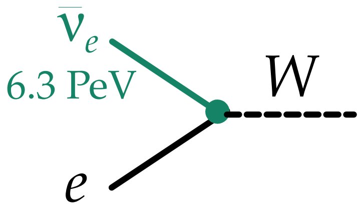

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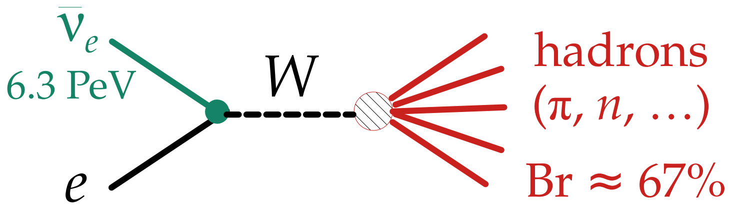

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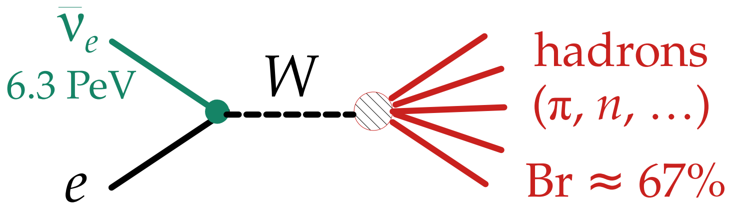

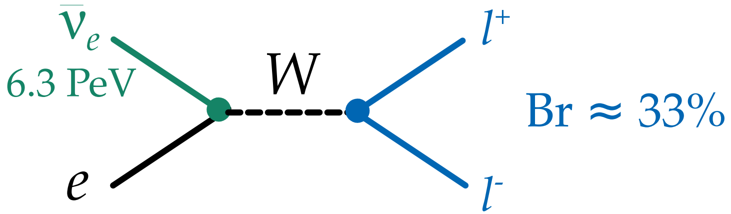

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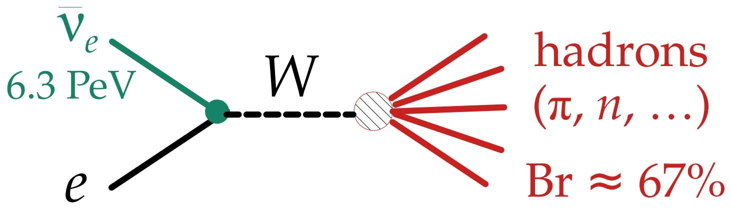

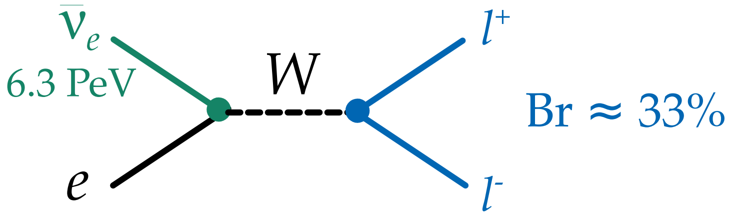

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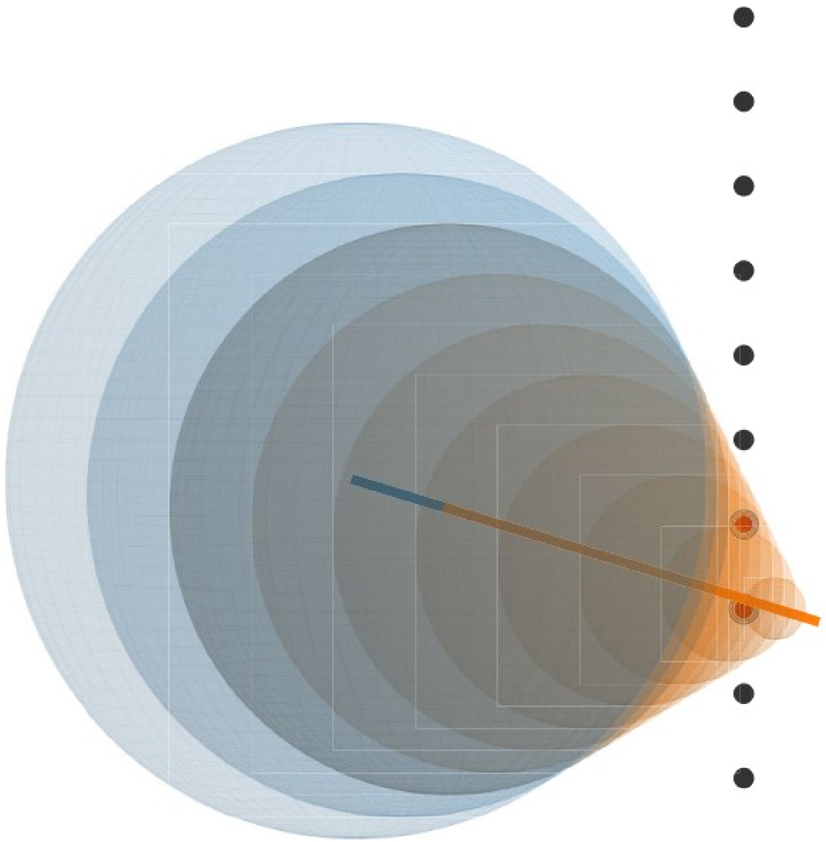

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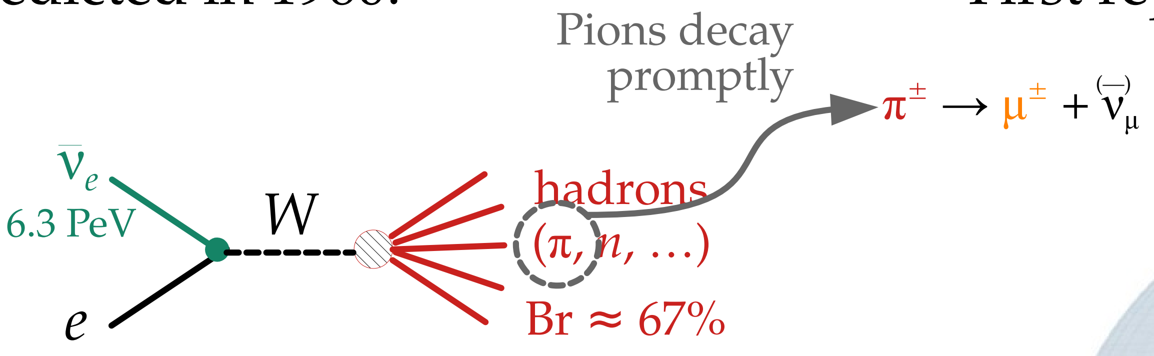

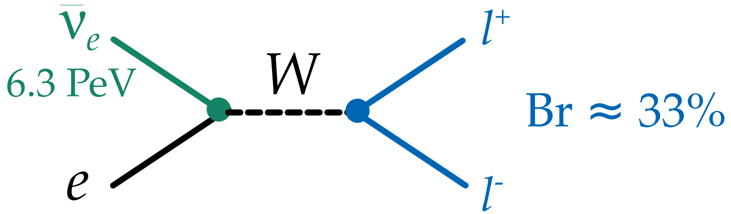

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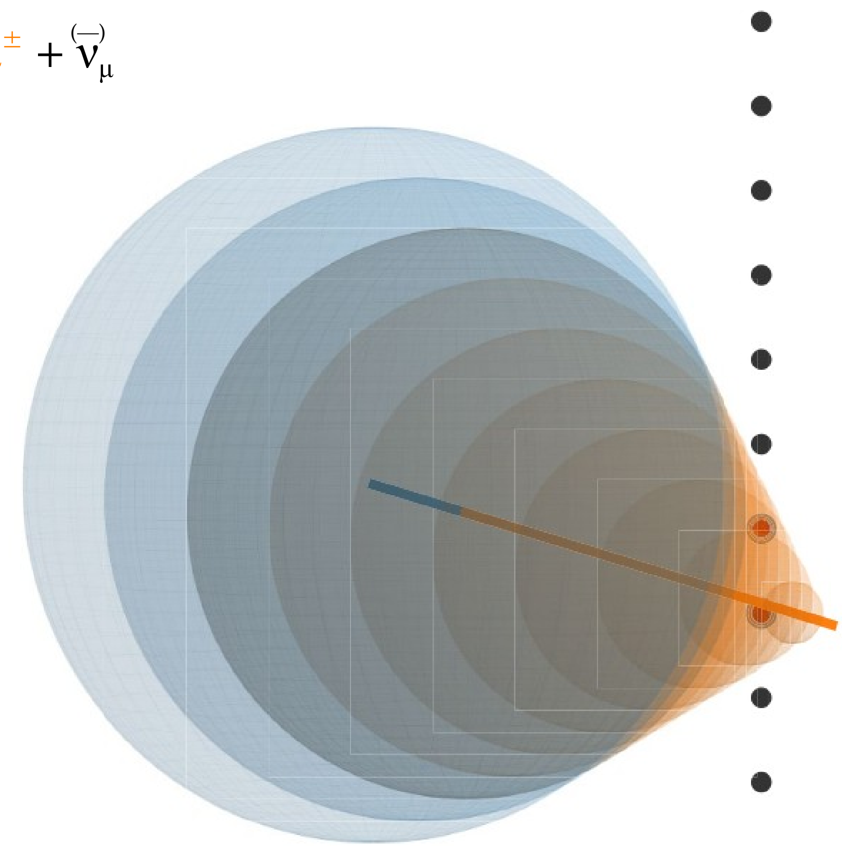

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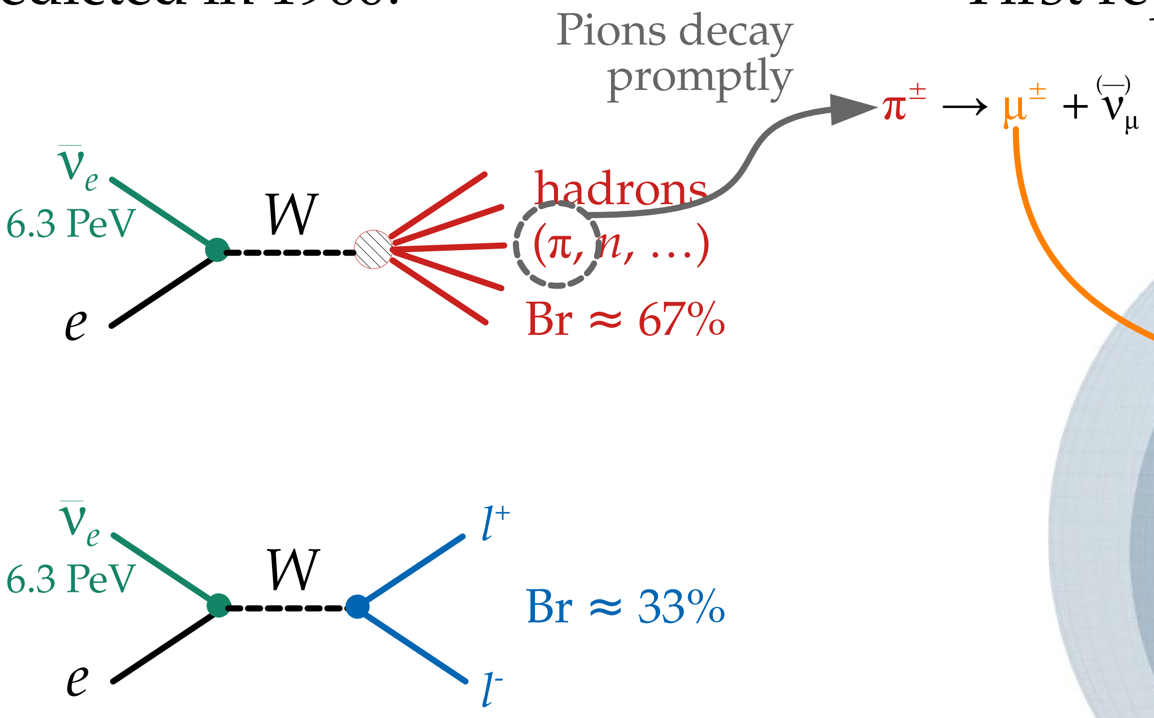

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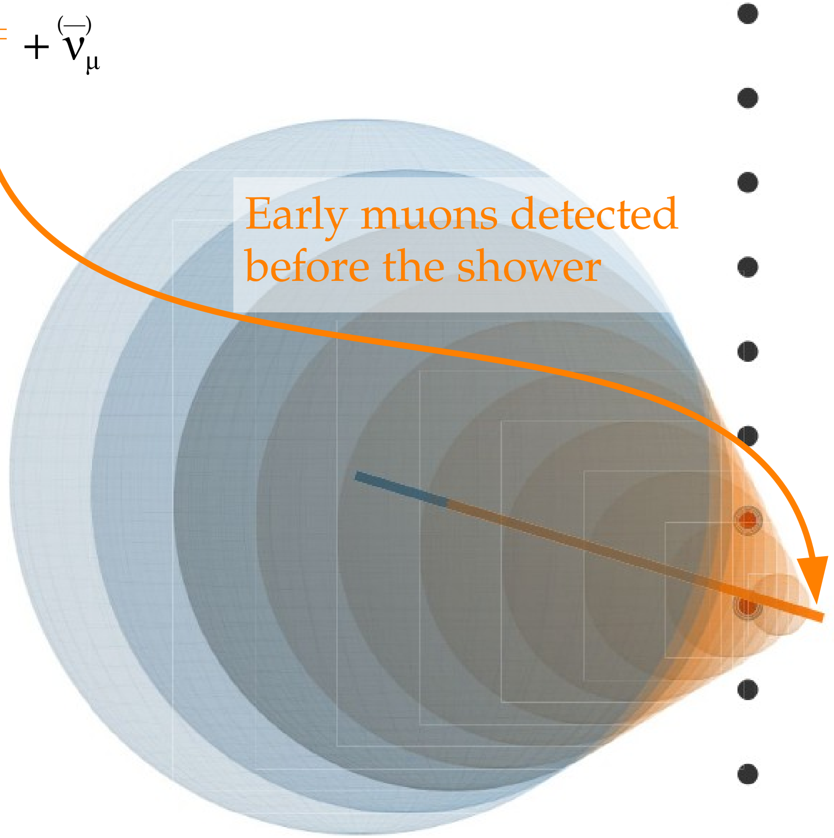

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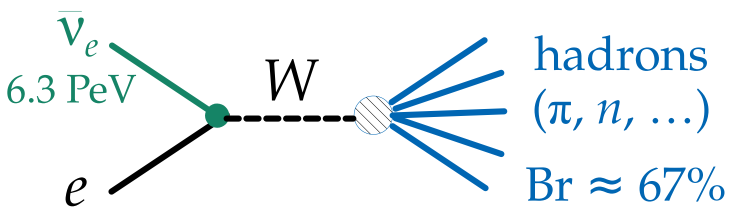

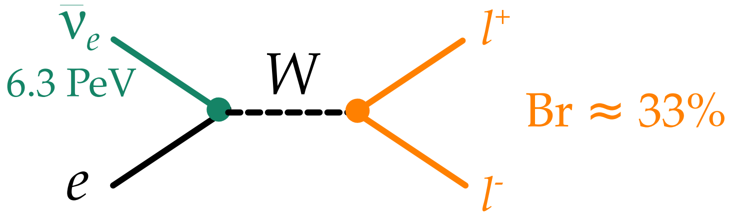

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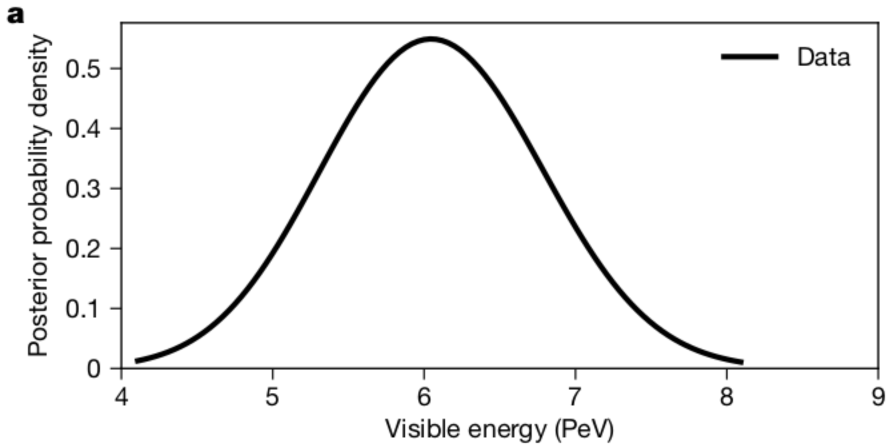

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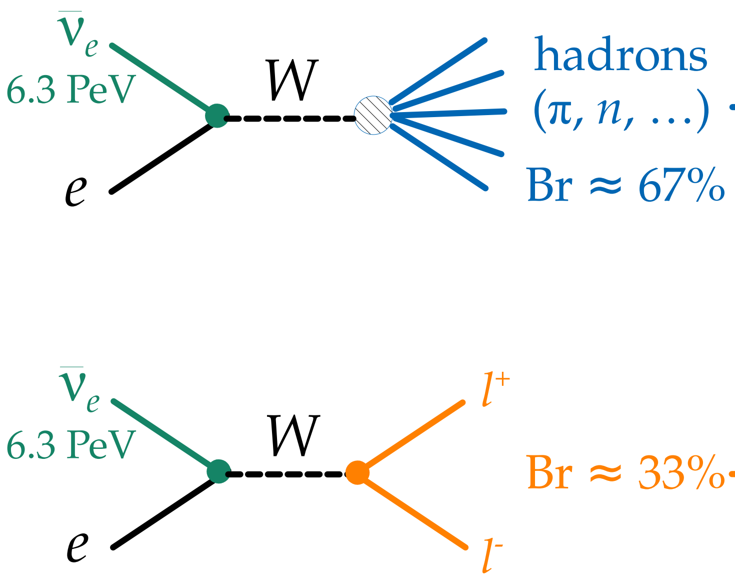

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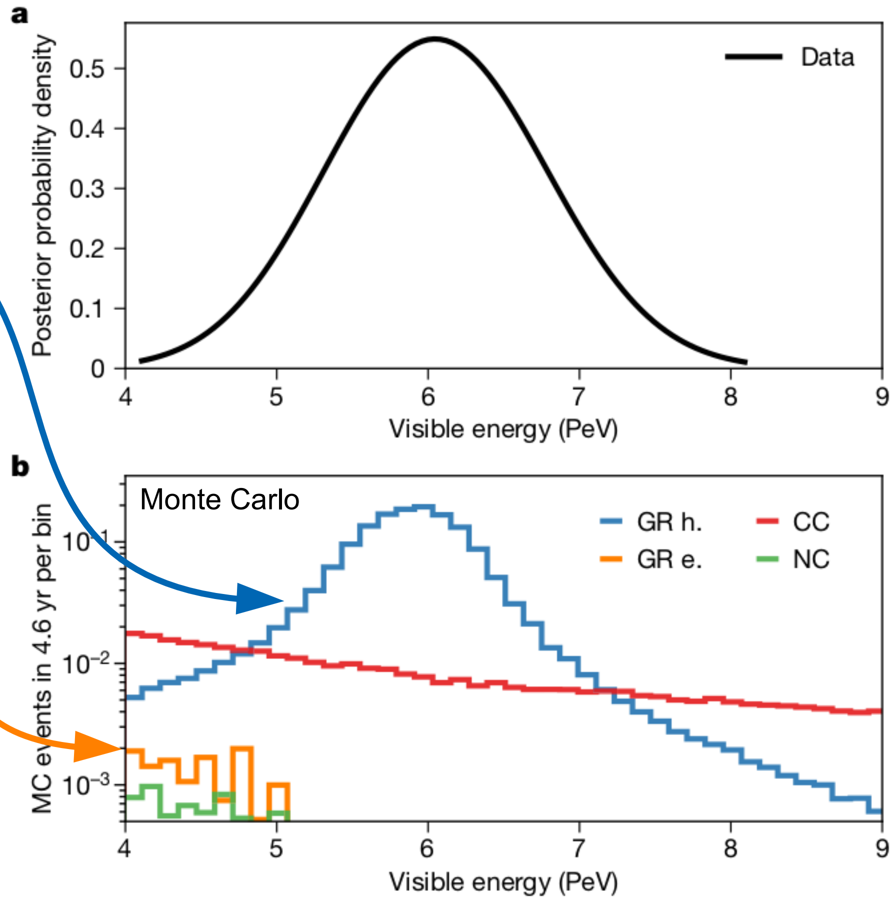

IceCube, *Nature* 2021
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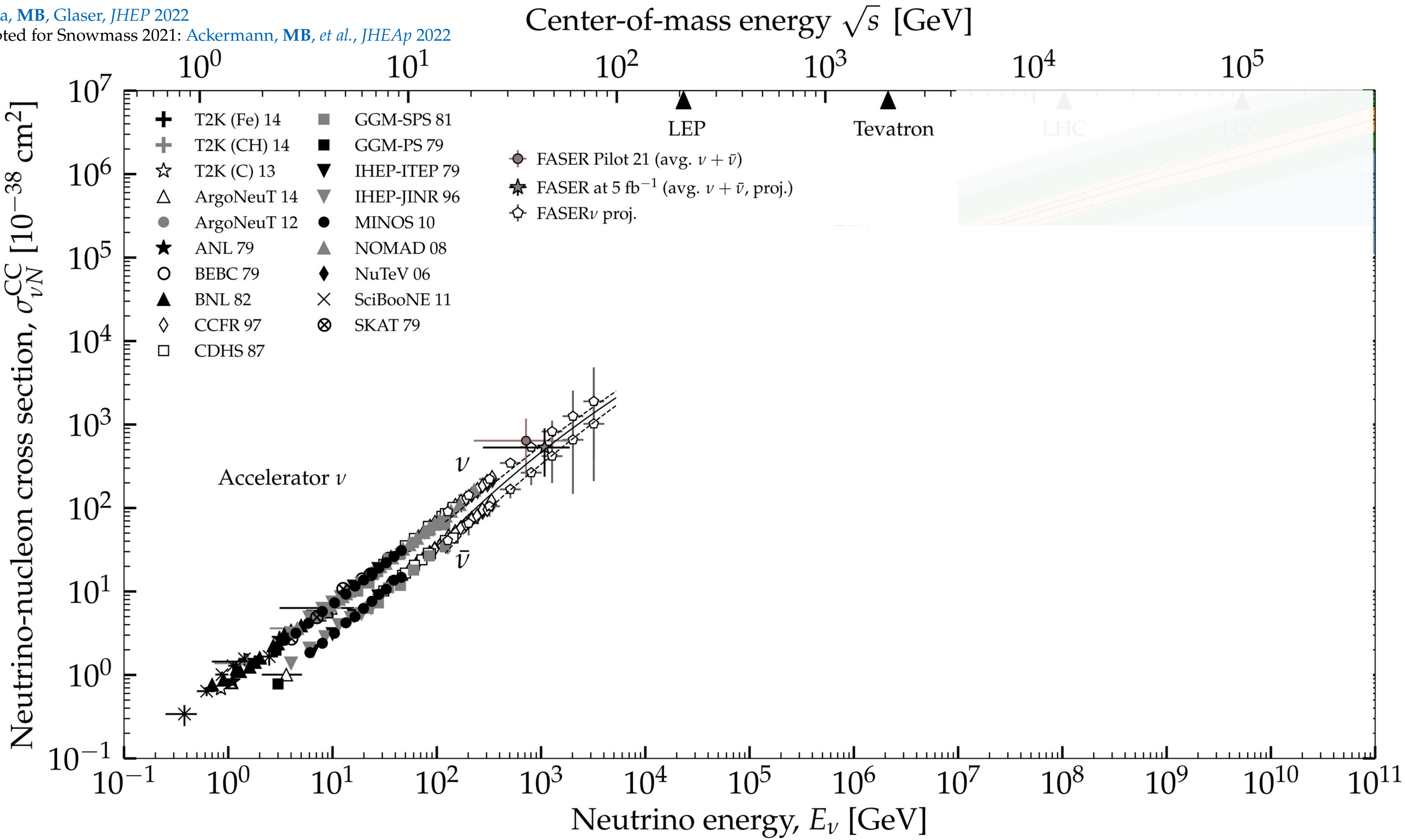
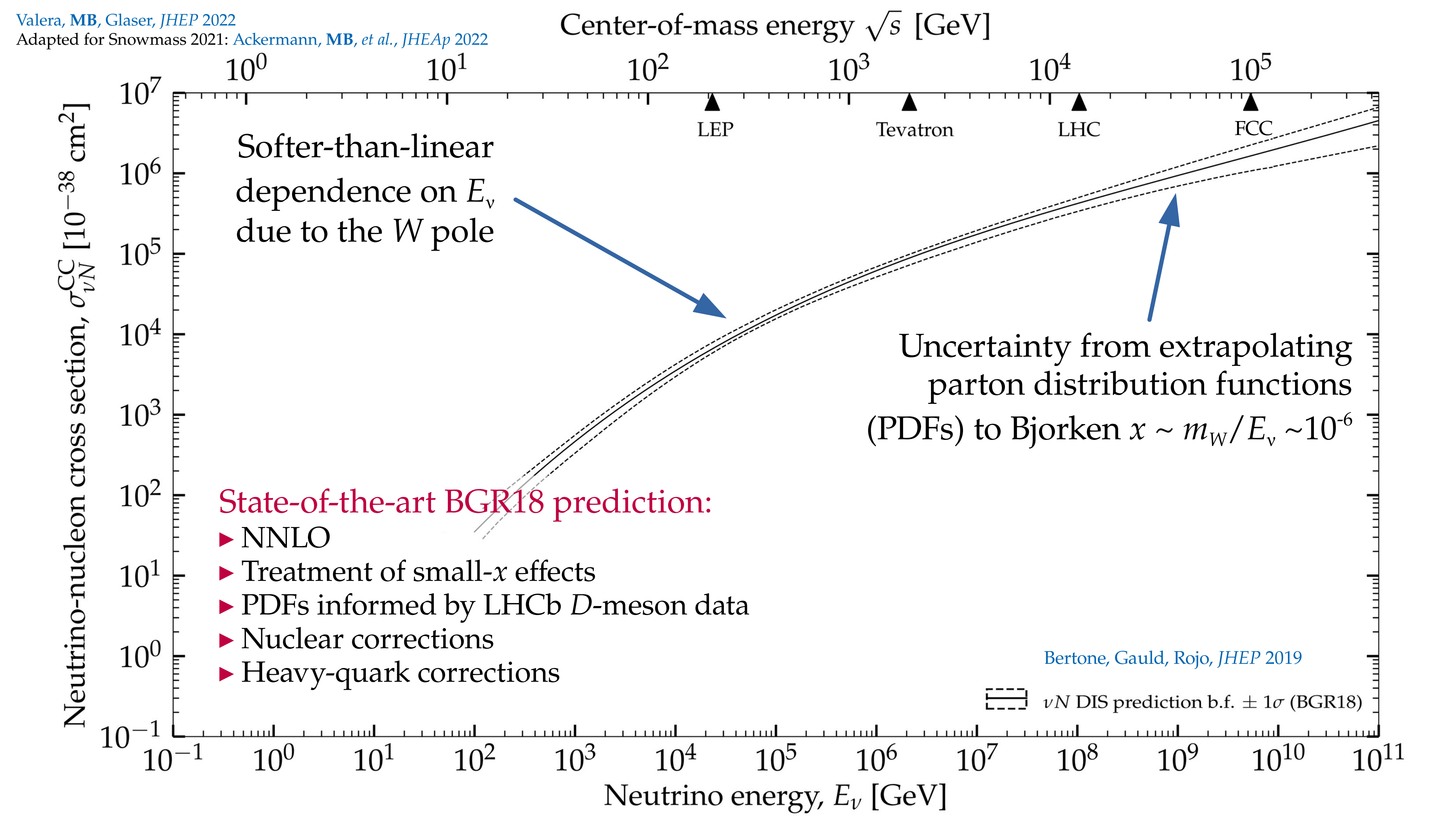
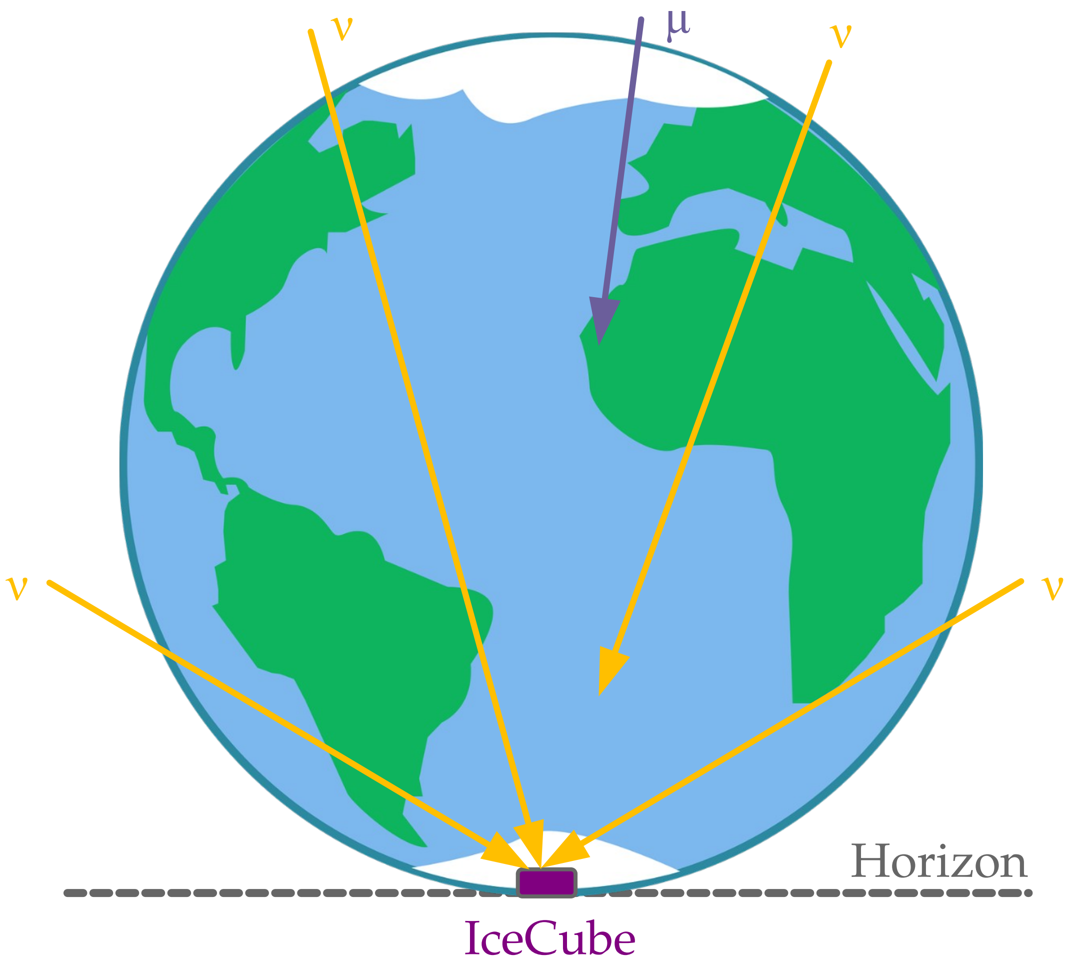
2. Neutrino-matter cross section:
From TeV to EeV

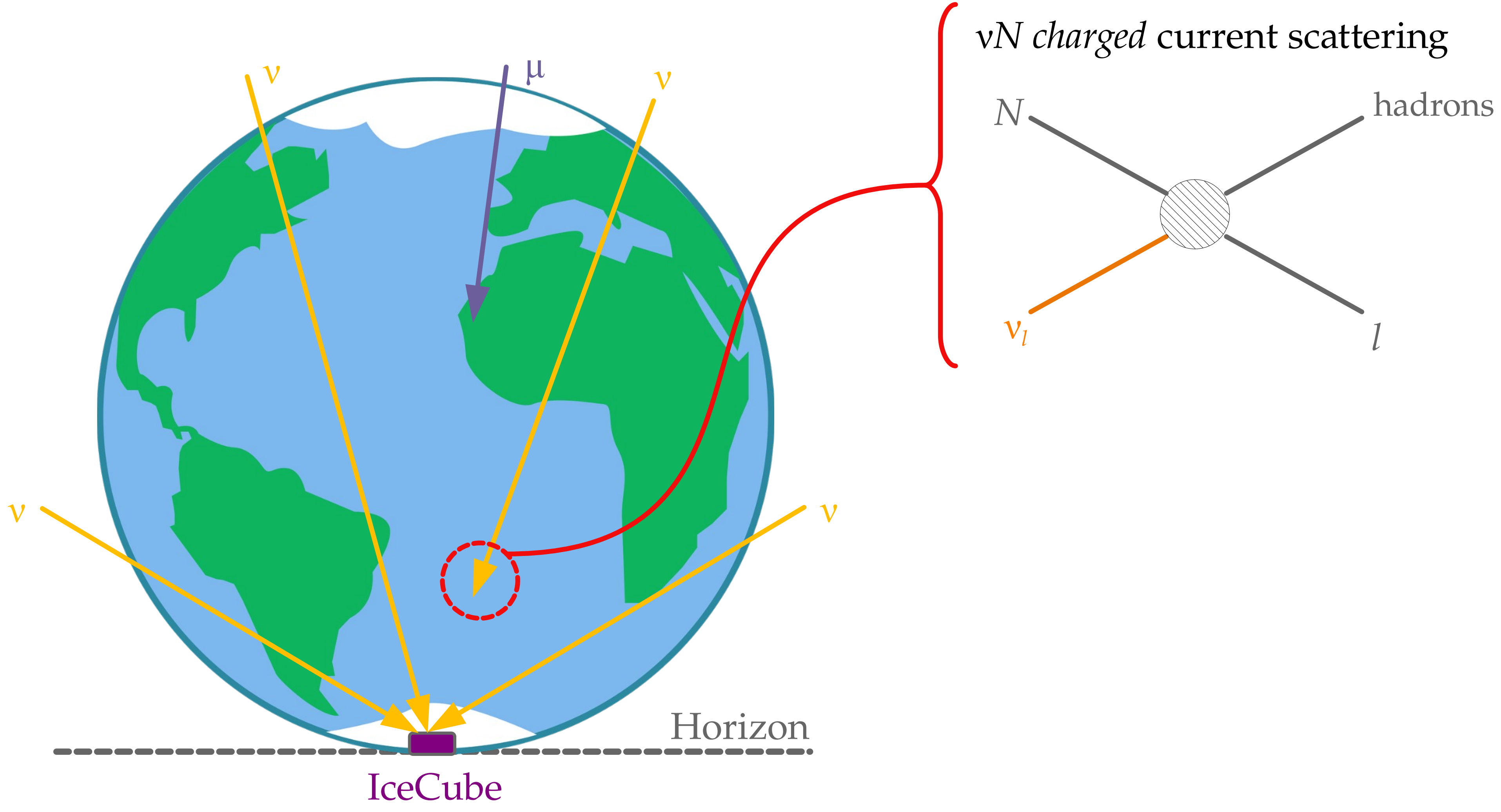
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



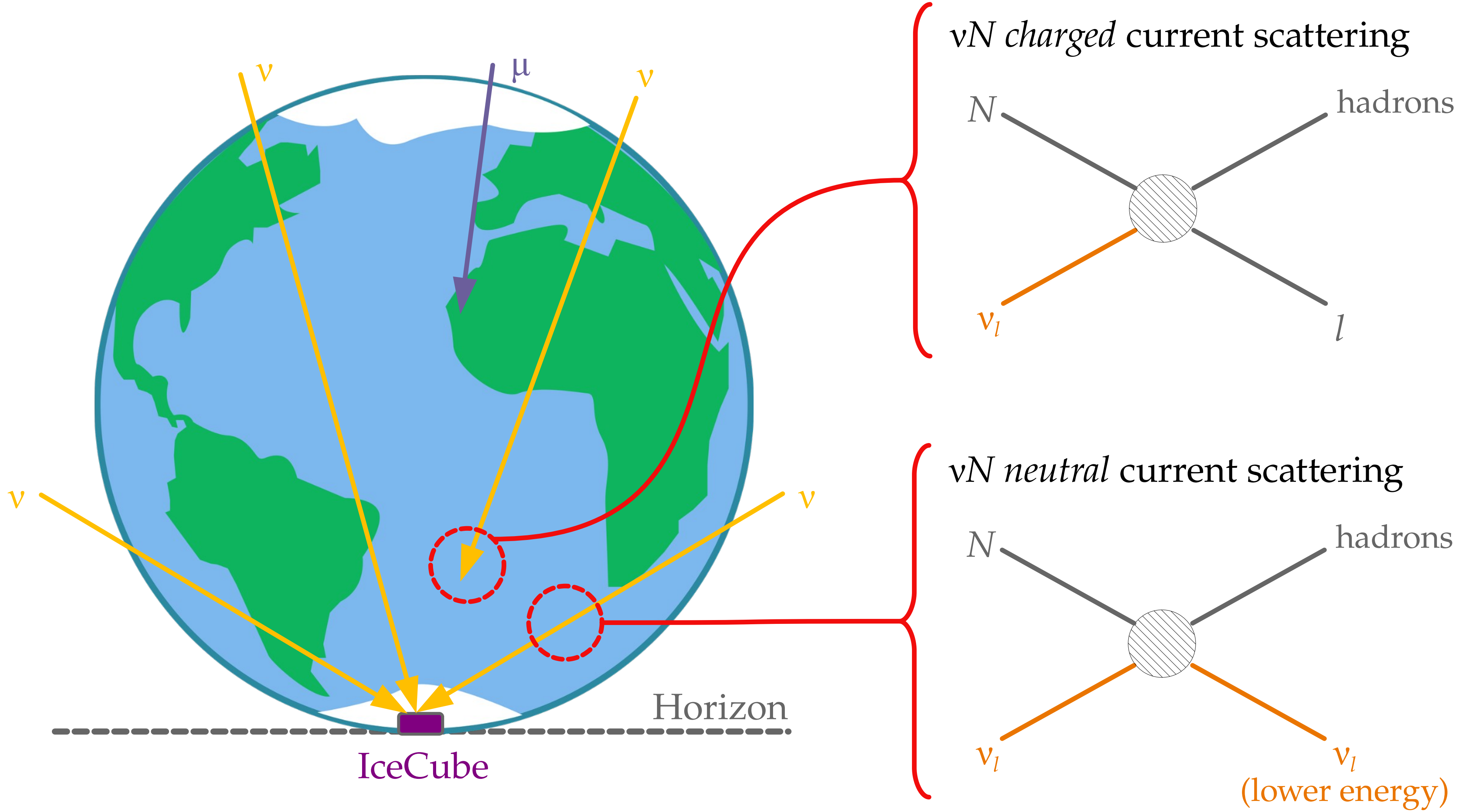


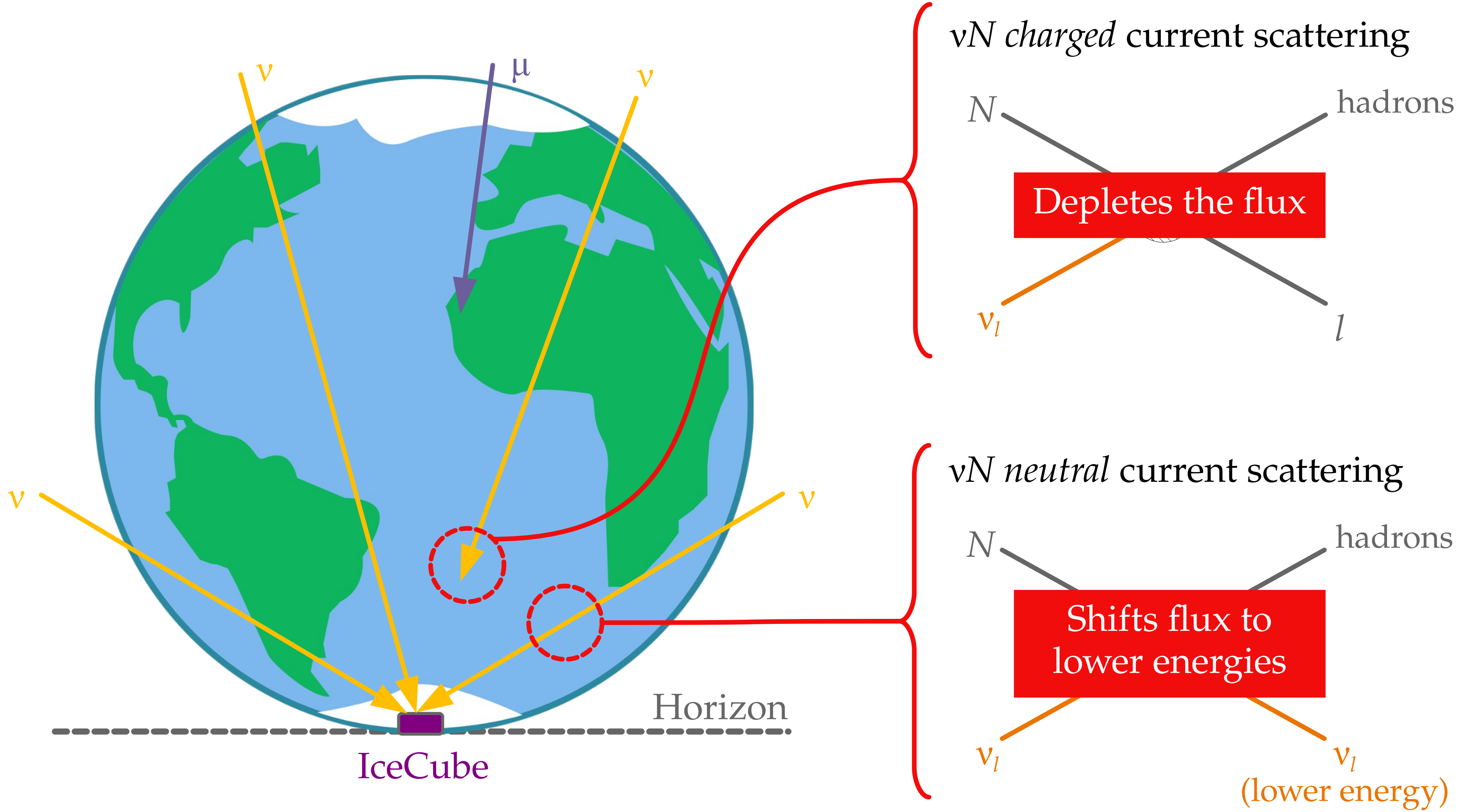
Valera, MB, Glaser, JHEP 2022
Adapted for Snowmass 2021: Ackermann, MB, et al., JHEAp 2022
Center-of-mass energy $\sqrt{s}$ [GeV]
LEP
Tevatron
LHC
FCC
Softer-than-linear dependence on E_ν due to the W pole
Uncertainty from extrapolating parton distribution functions (PDFs) to Bjorken $x \sim m_W/E_\nu \sim 10^{-6}$
State-of-the-art BGR18 prediction:
▸ NNLO
▸ Treatment of small-x effects
▸ PDFs informed by LHCb D-meson data
▸ Nuclear corrections
▸ Heavy-quark corrections
Bertone, Gauld, Rojo, JHEP 2019
νN DIS prediction b.f. $\pm\, 1\sigma$ (BGR18)
Neutrino-nucleon cross section, $\sigma^{CC}_{\nu N}$ [10^{-38} cm^2]
Neutrino energy, E_ν [GeV]


ν
μ
ν
ν
ν
Horizon
IceCube



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


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)



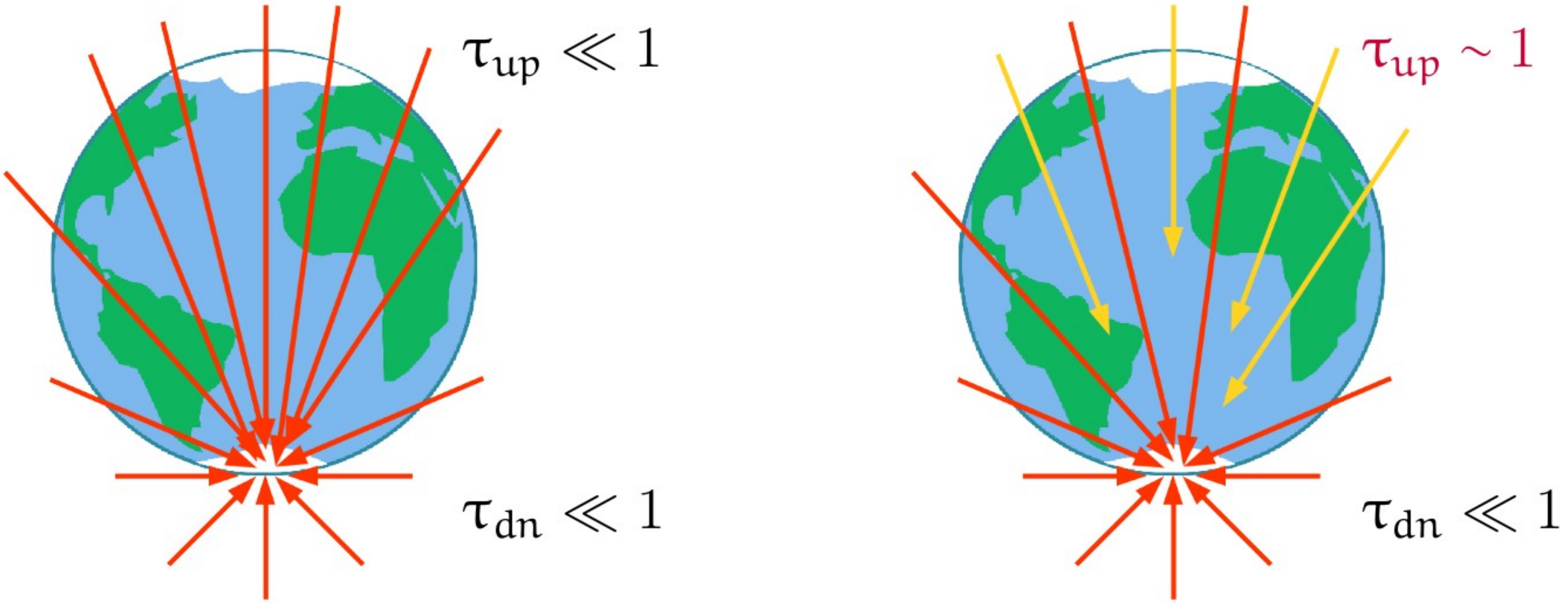
ν
μ
ν
ν
ν
Horizon
IceCube
νN *charged* current scattering
N
hadrons
Depletes the flux
ν_l
l
νN *neutral* current scattering
N
hadrons
Shifts flux to lower energies
ν_l
ν_l
(lower energy)

Measuring the high-energy νN cross section

$$\text{Optical depth to } \nu N \text{ int's} = \frac{\text{Distance from Earth's surface to IceCube}}{\text{Mean free path inside Earth}} \equiv \tau(E_\nu, \theta_z) \propto \sigma_{\nu N}$$

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

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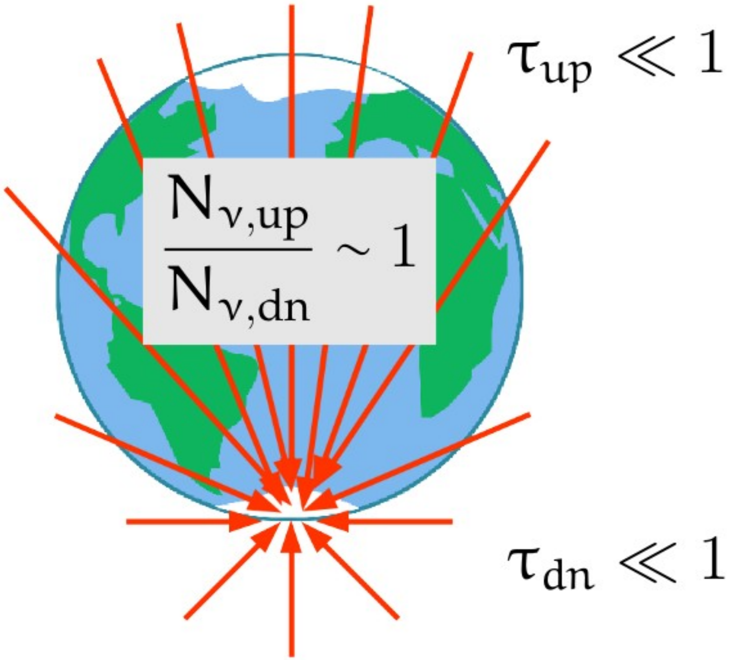
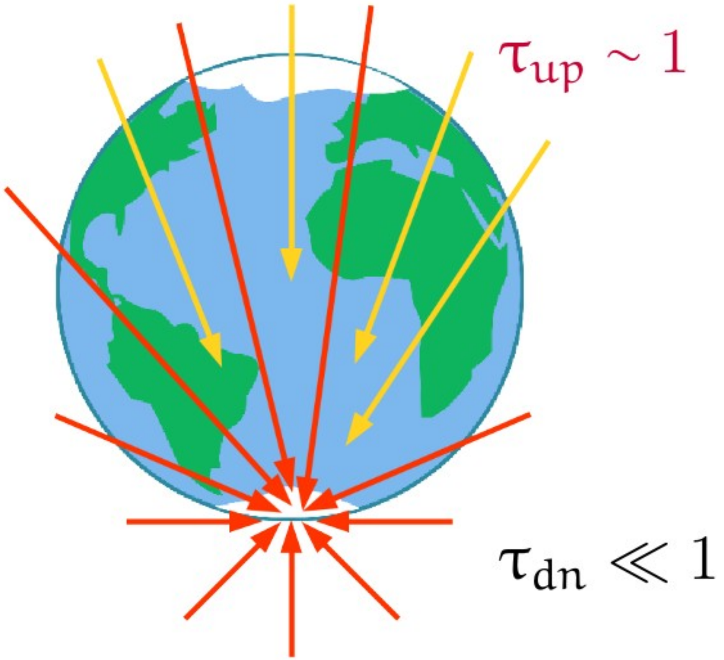


Above ~ 10 TeV: Earth is opaque



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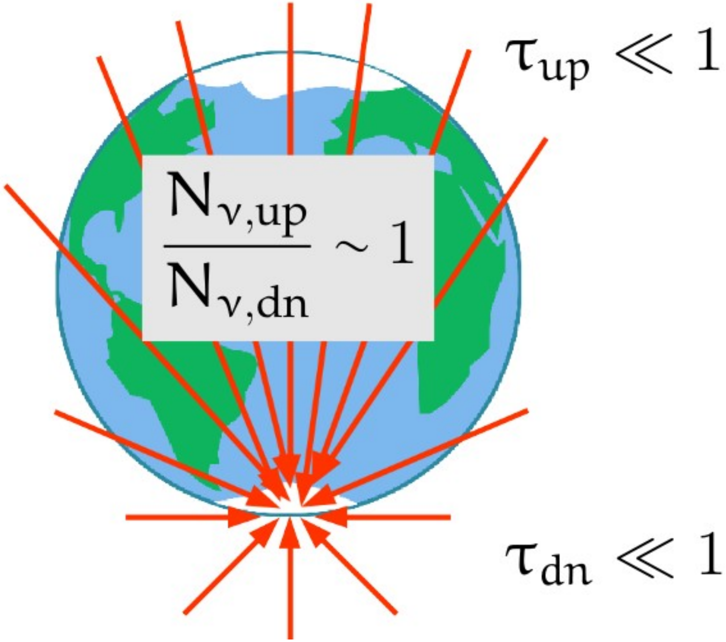

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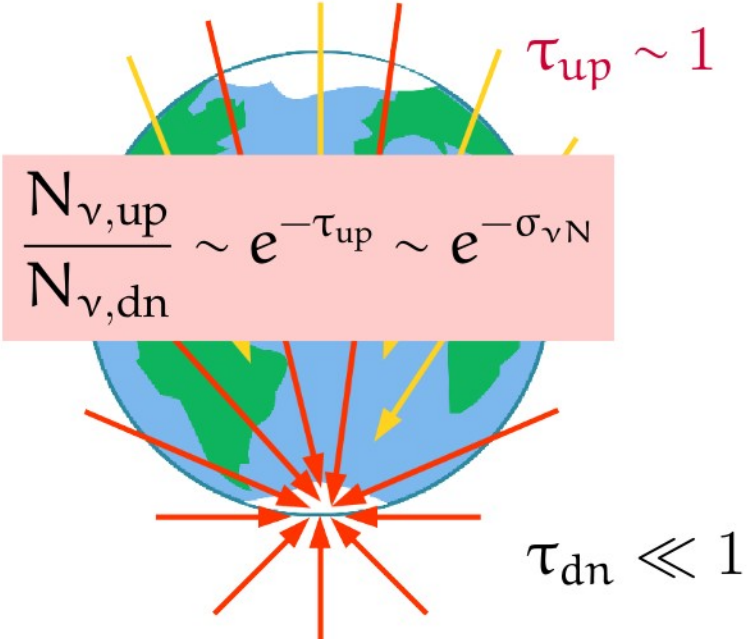

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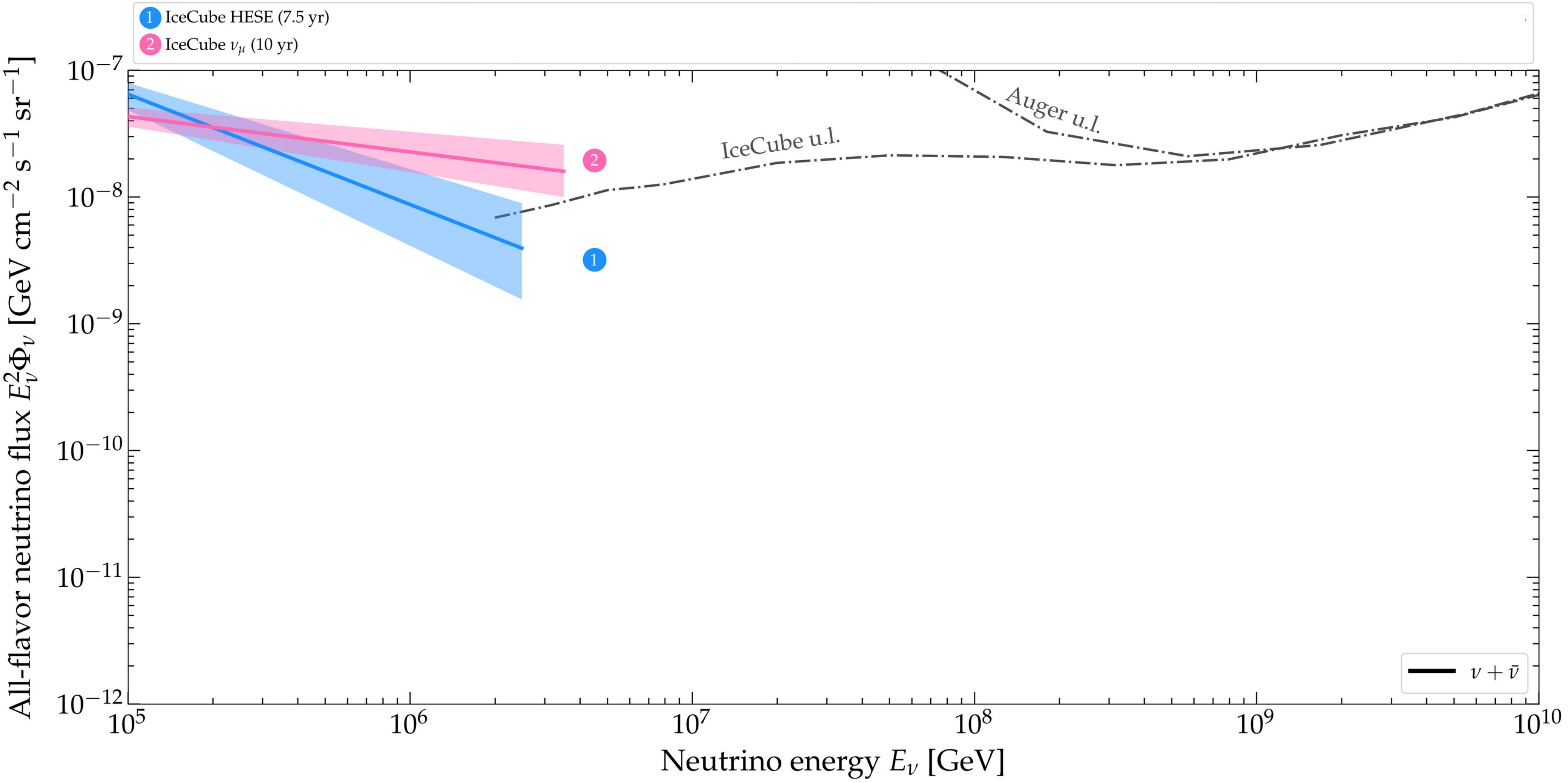
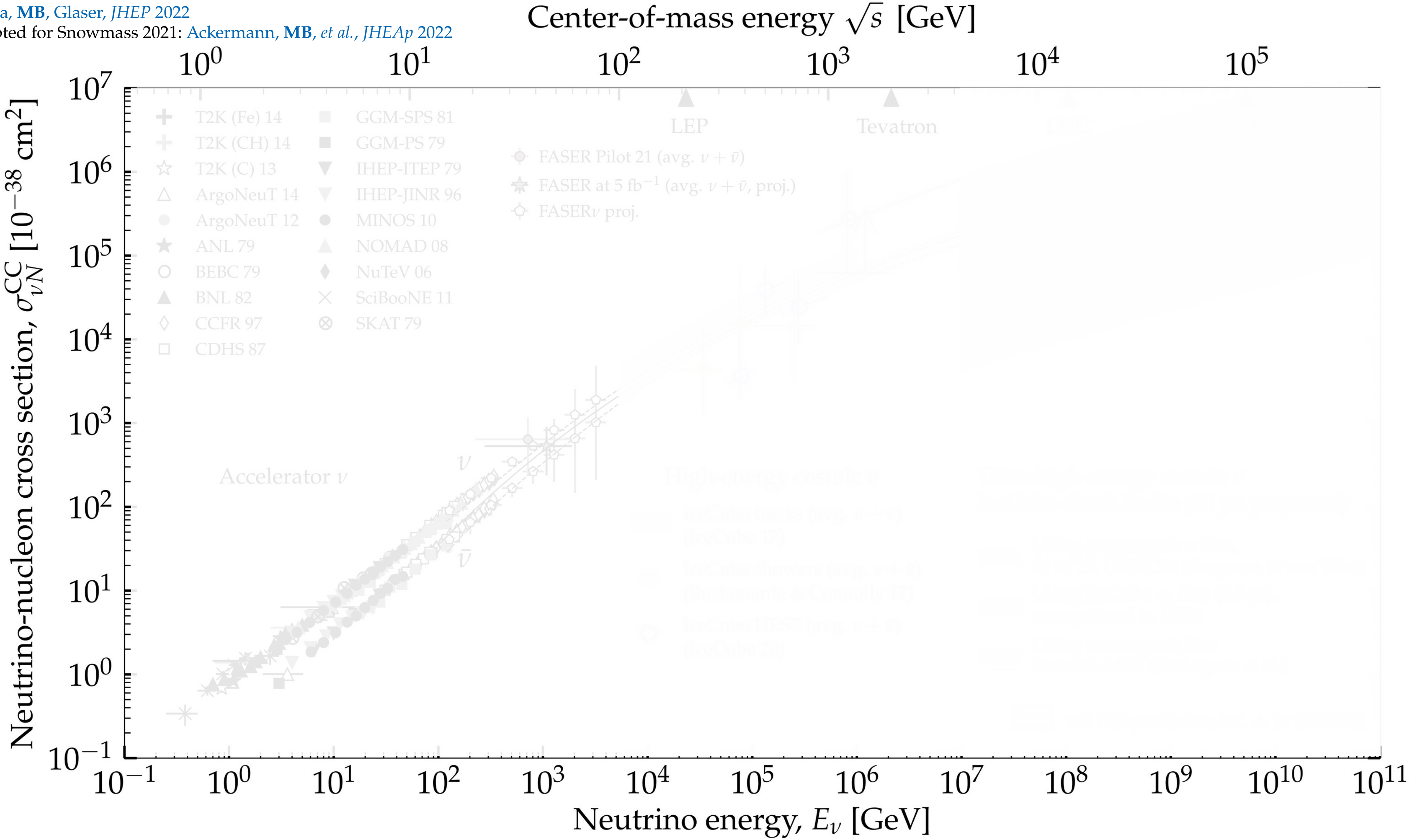


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
Auger u.l.
IceCube u.l.
1
2
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy E_ν [GeV]

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



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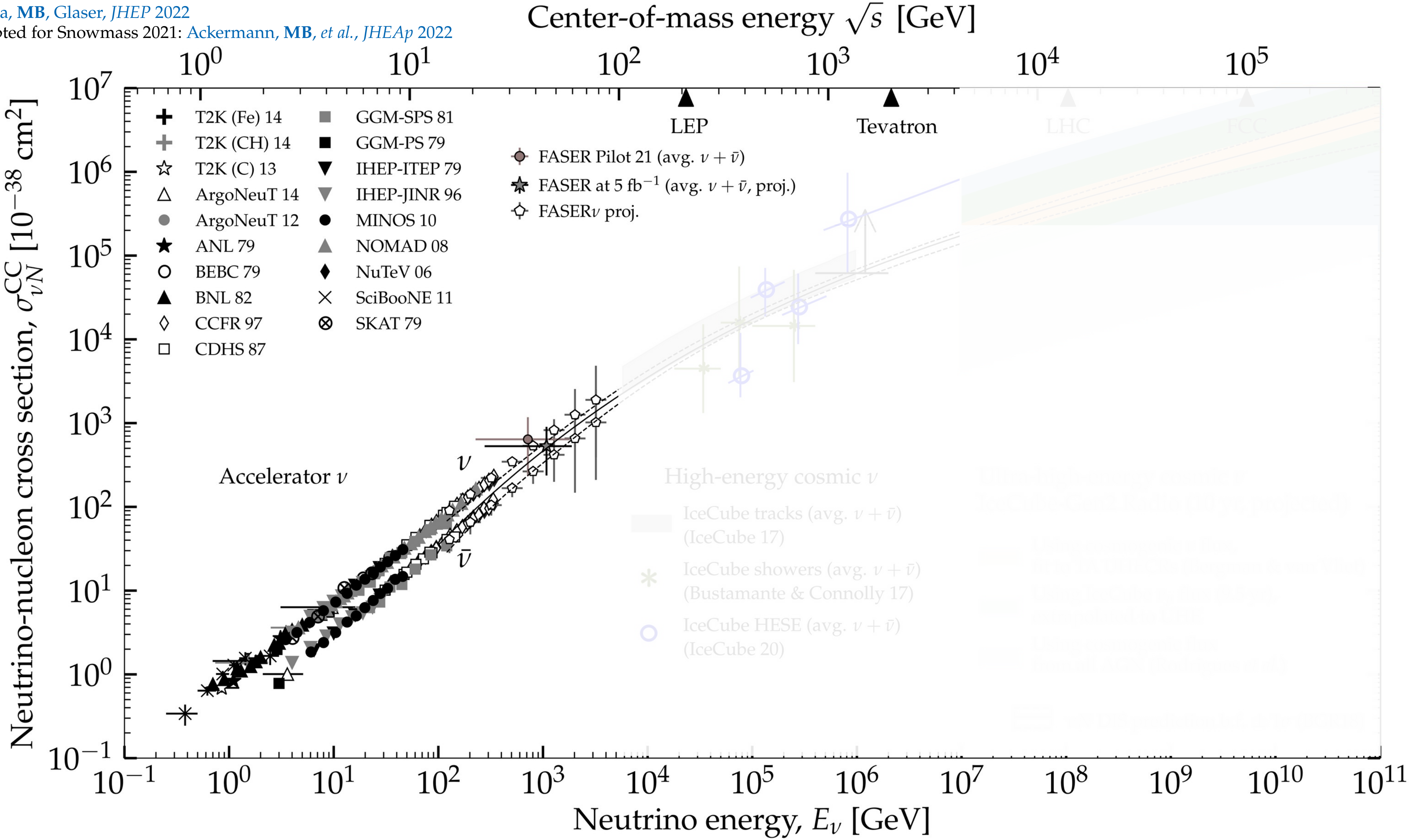

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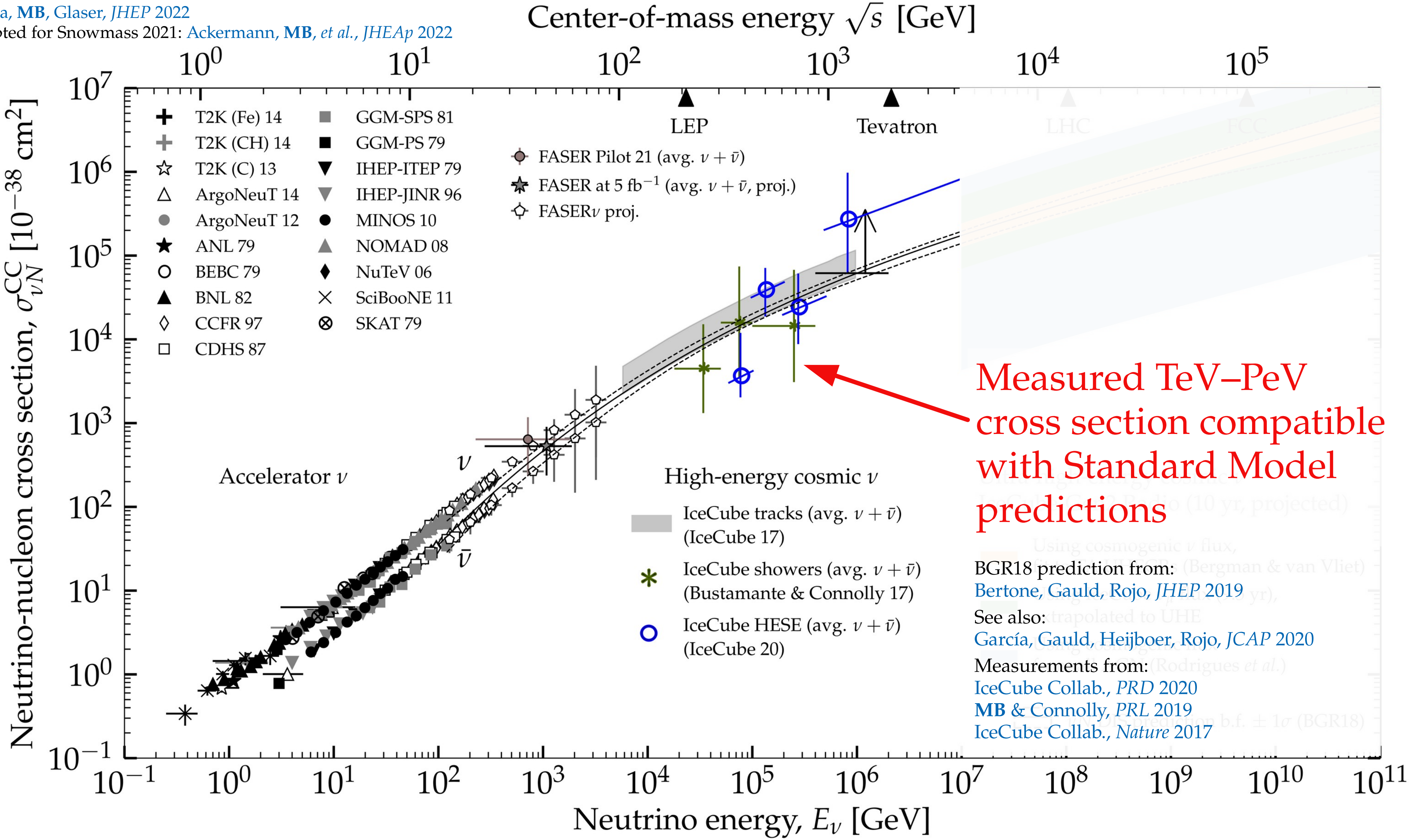

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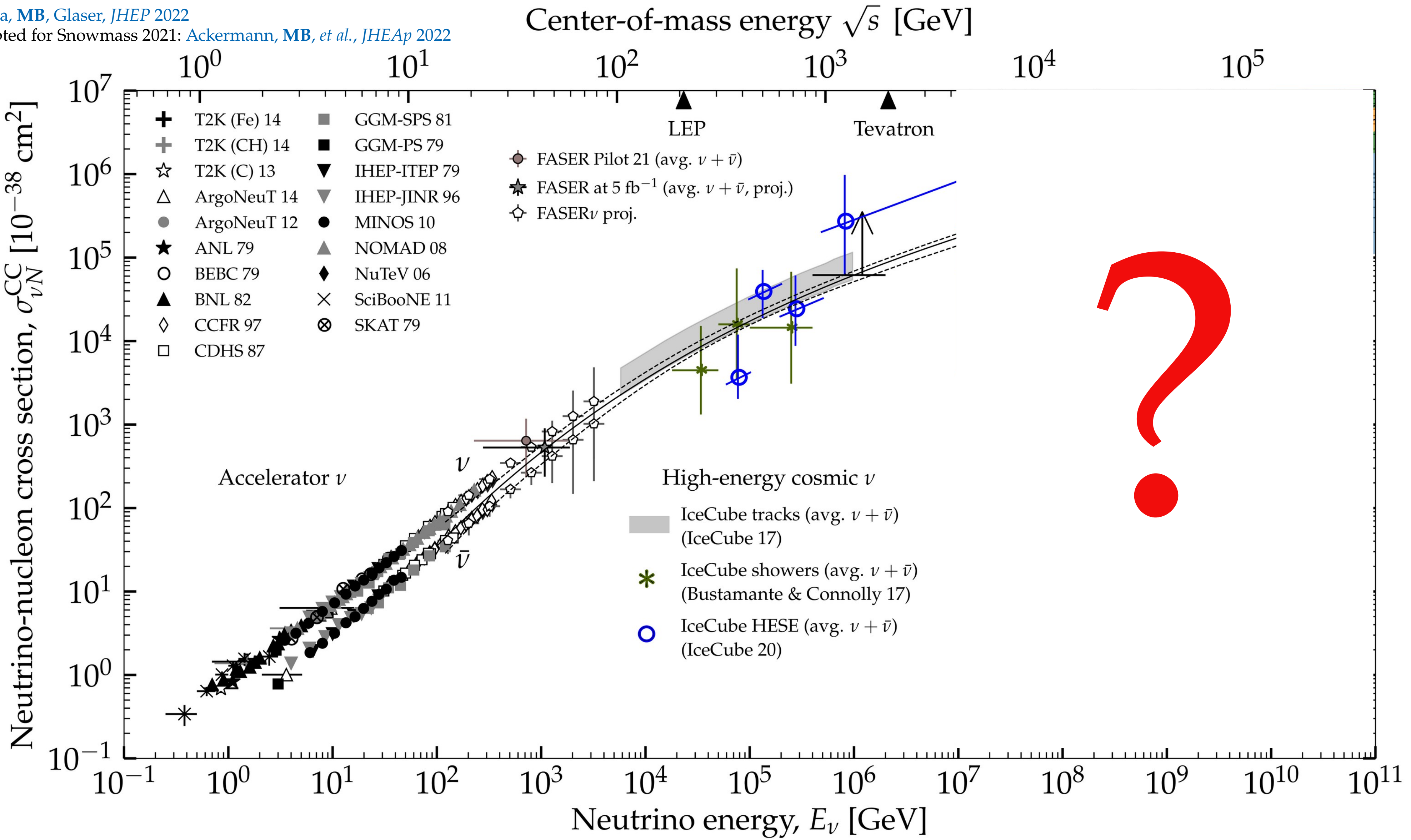
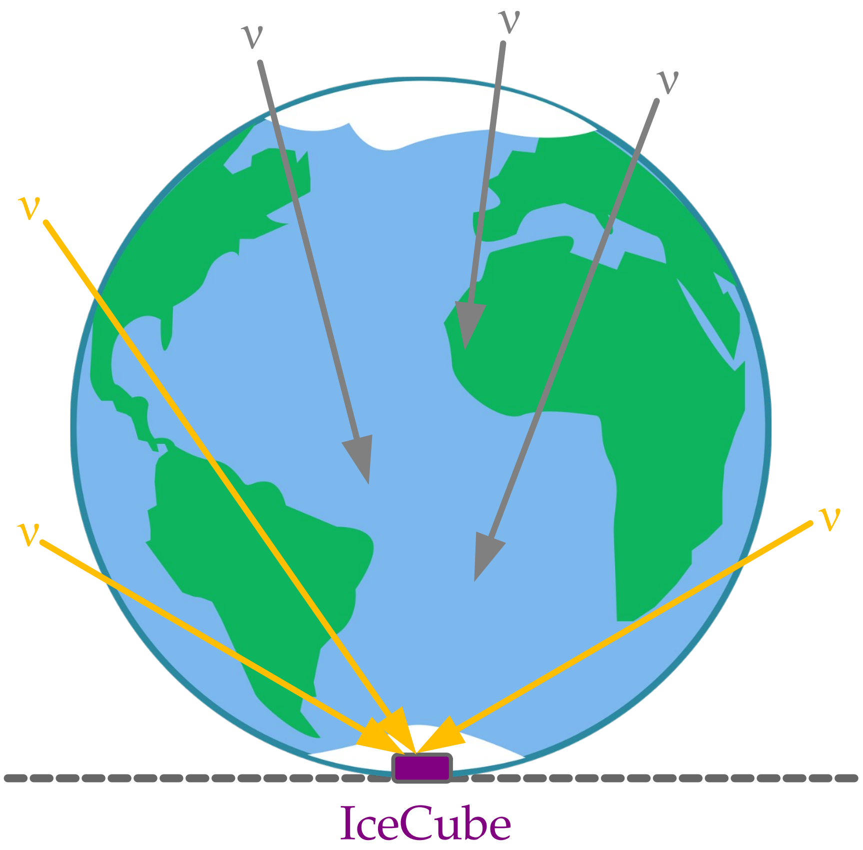
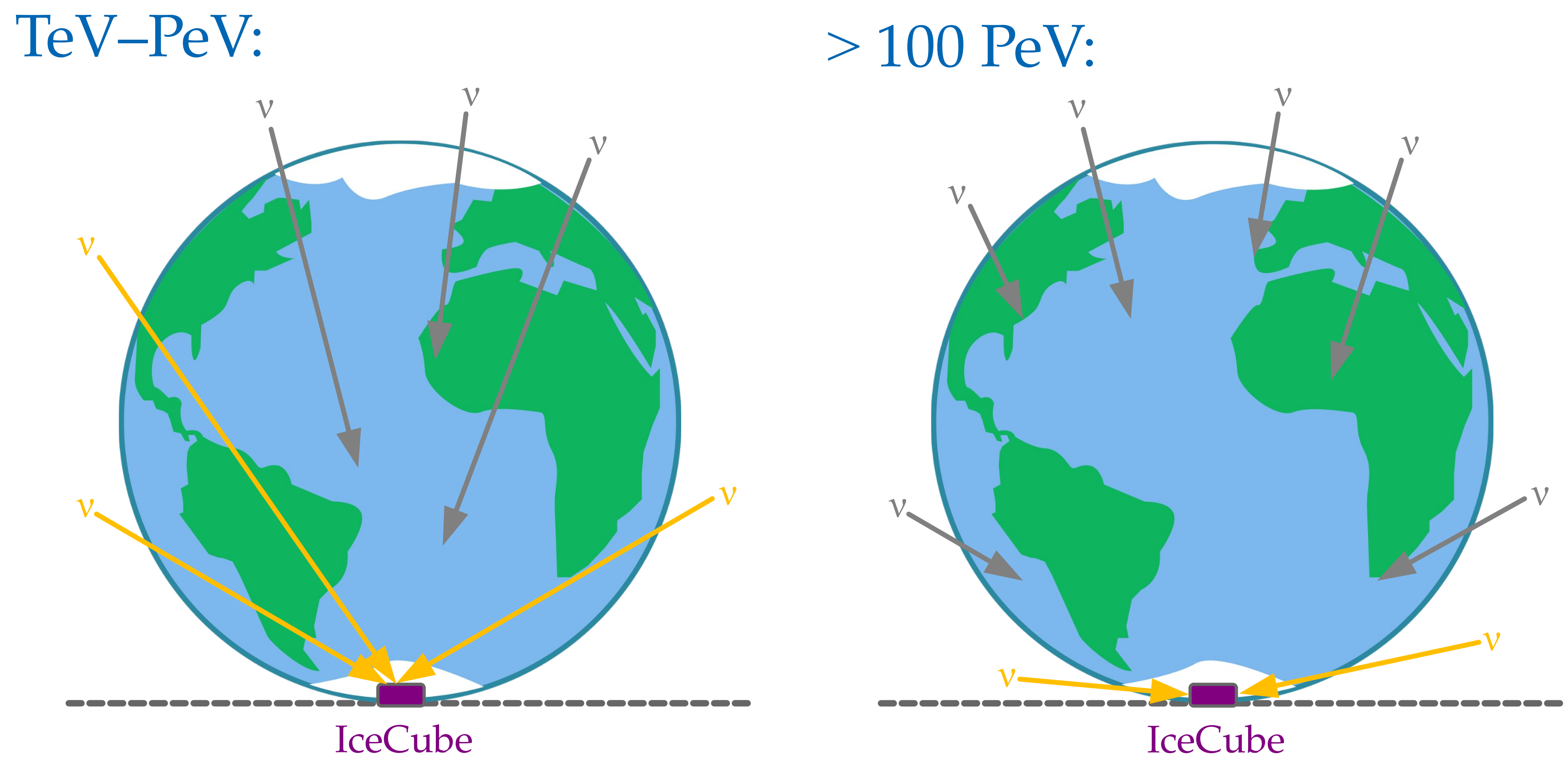


TeV–PeV:

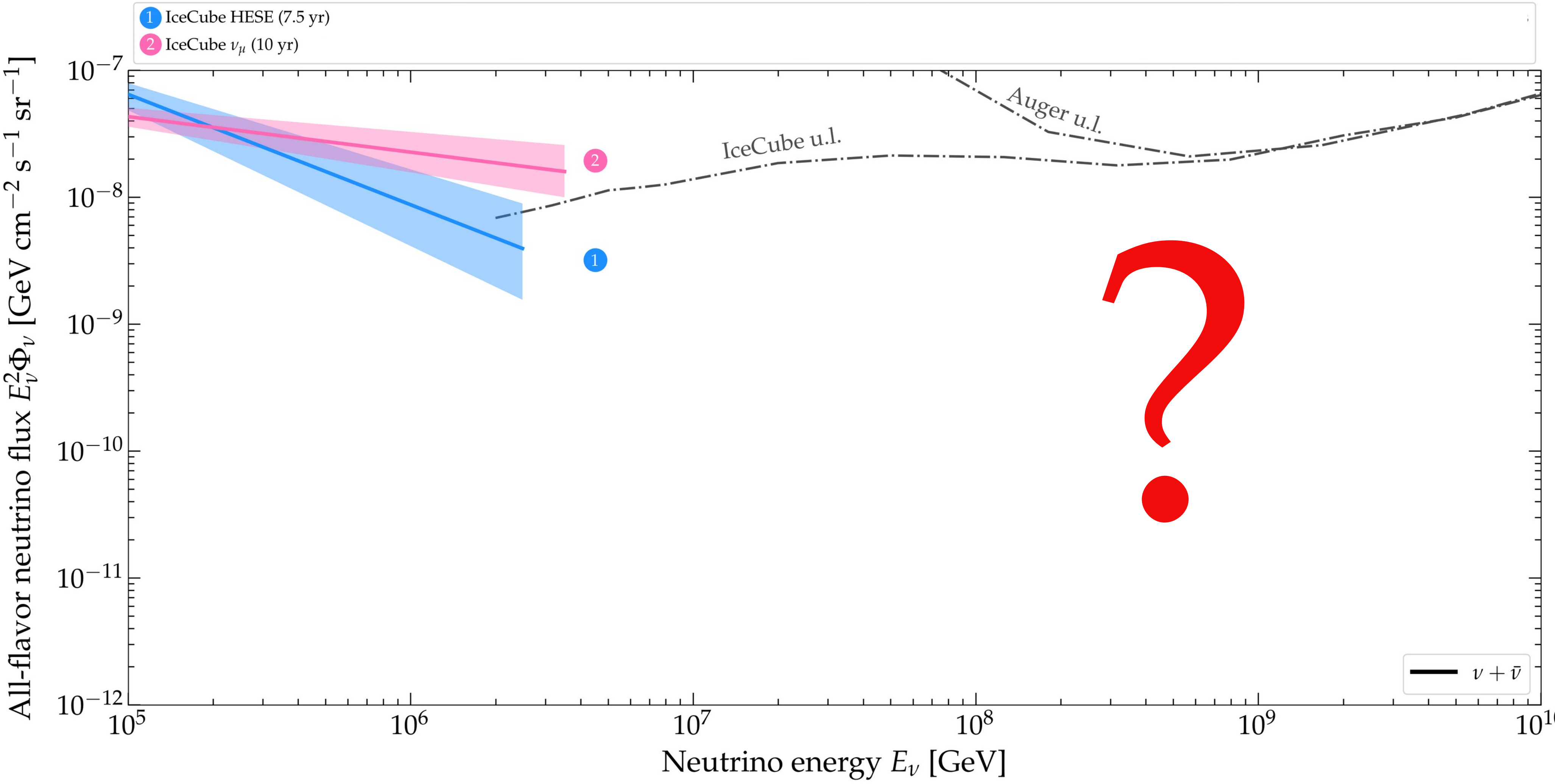


Earth is *almost fully* opaque,
some upgoing ν still make it through

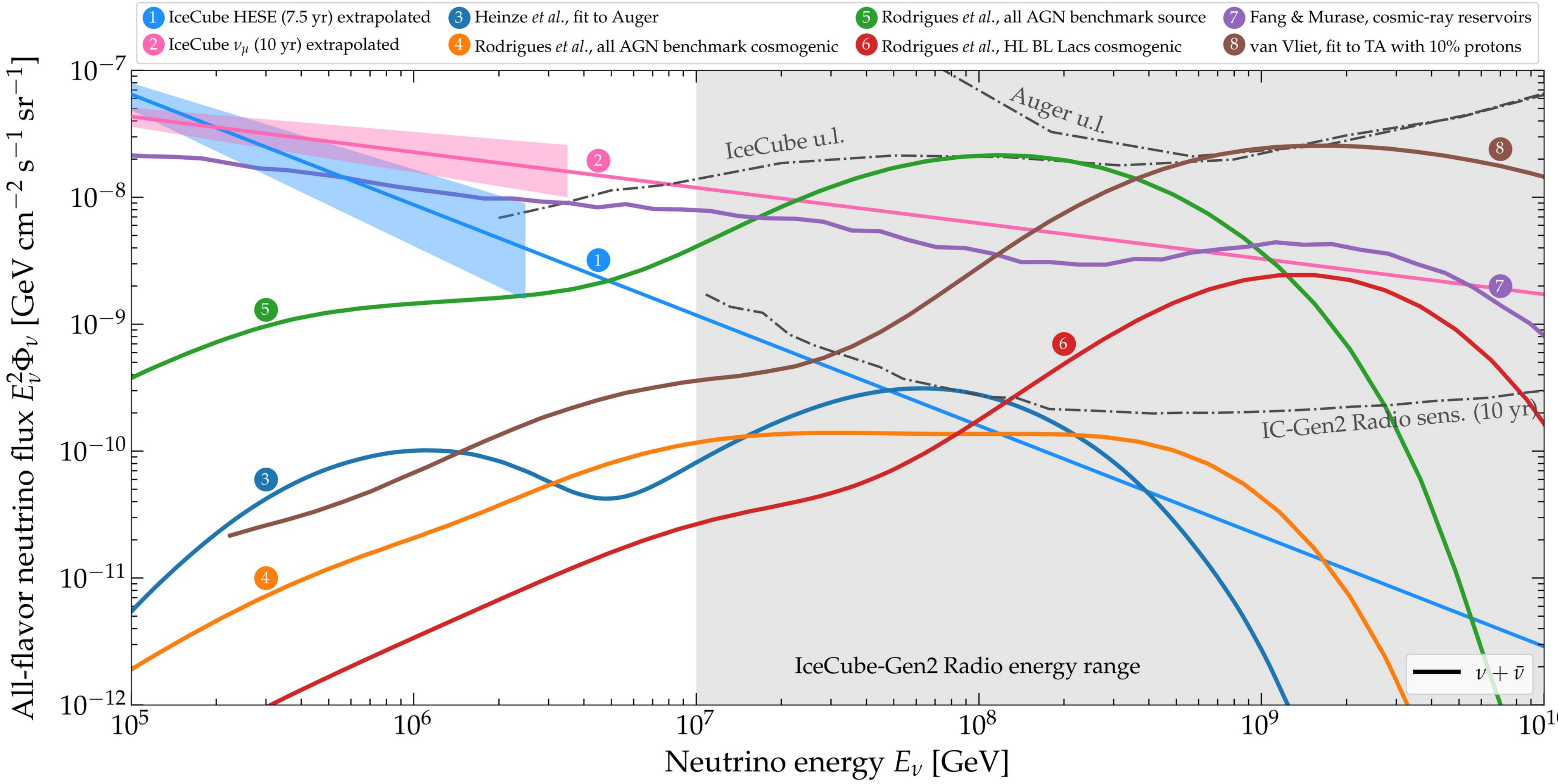


Earth is *almost fully* opaque,
some upgoing ν still make it through

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

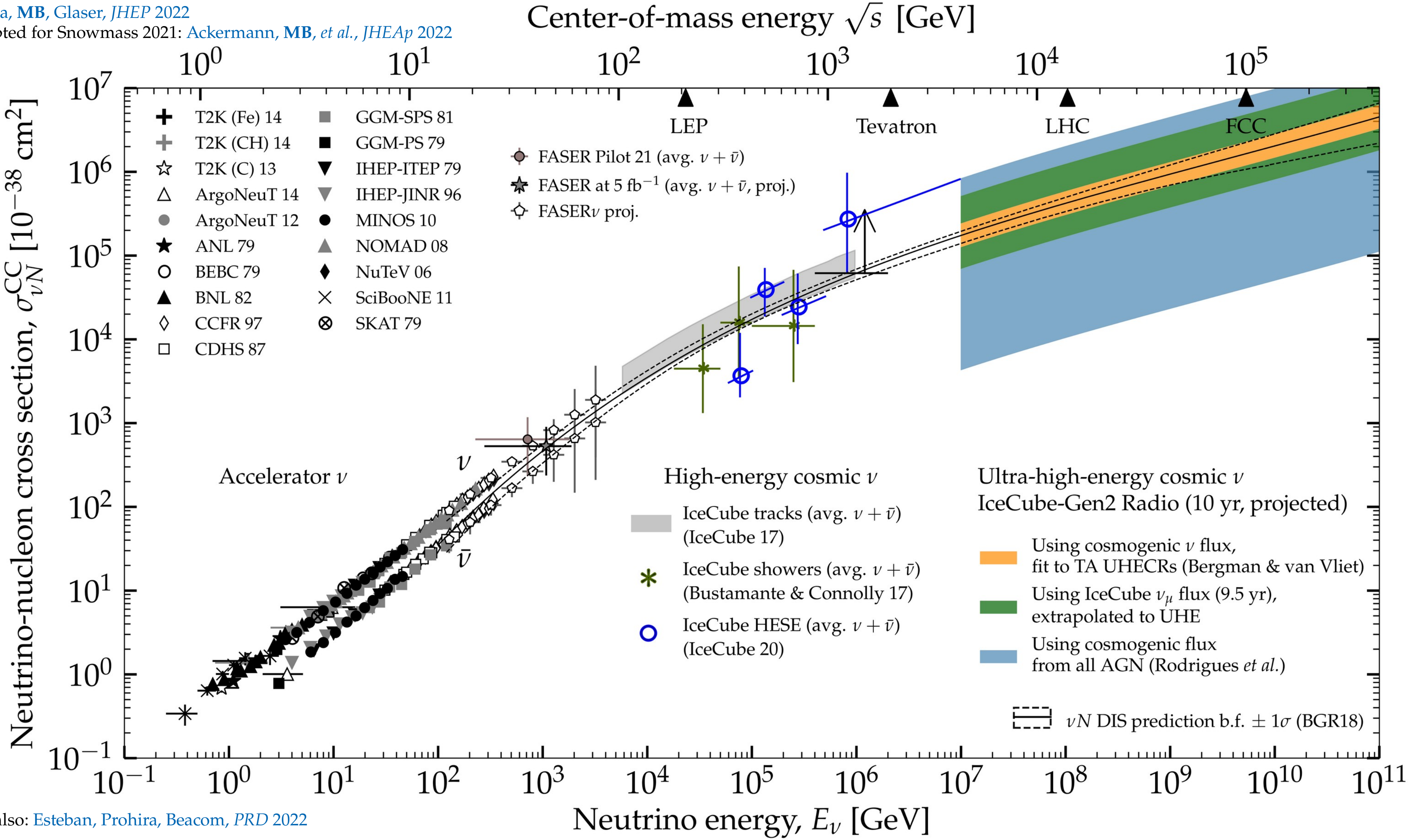


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
All-flavor neutrino flux $E_\nu^2\Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
IceCube u.l.
Auger u.l.
?
$\nu + \bar{\nu}$
10^5
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy E_ν [GeV]



1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
3 Heinze et al., fit to Auger
4 Rodrigues et al., all AGN benchmark cosmogenic
5 Rodrigues et al., all AGN benchmark source
6 Rodrigues et al., HL BL Lacs cosmogenic
7 Fang & Murase, cosmic-ray reservoirs
8 van Vliet, fit to TA with 10% protons
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}

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
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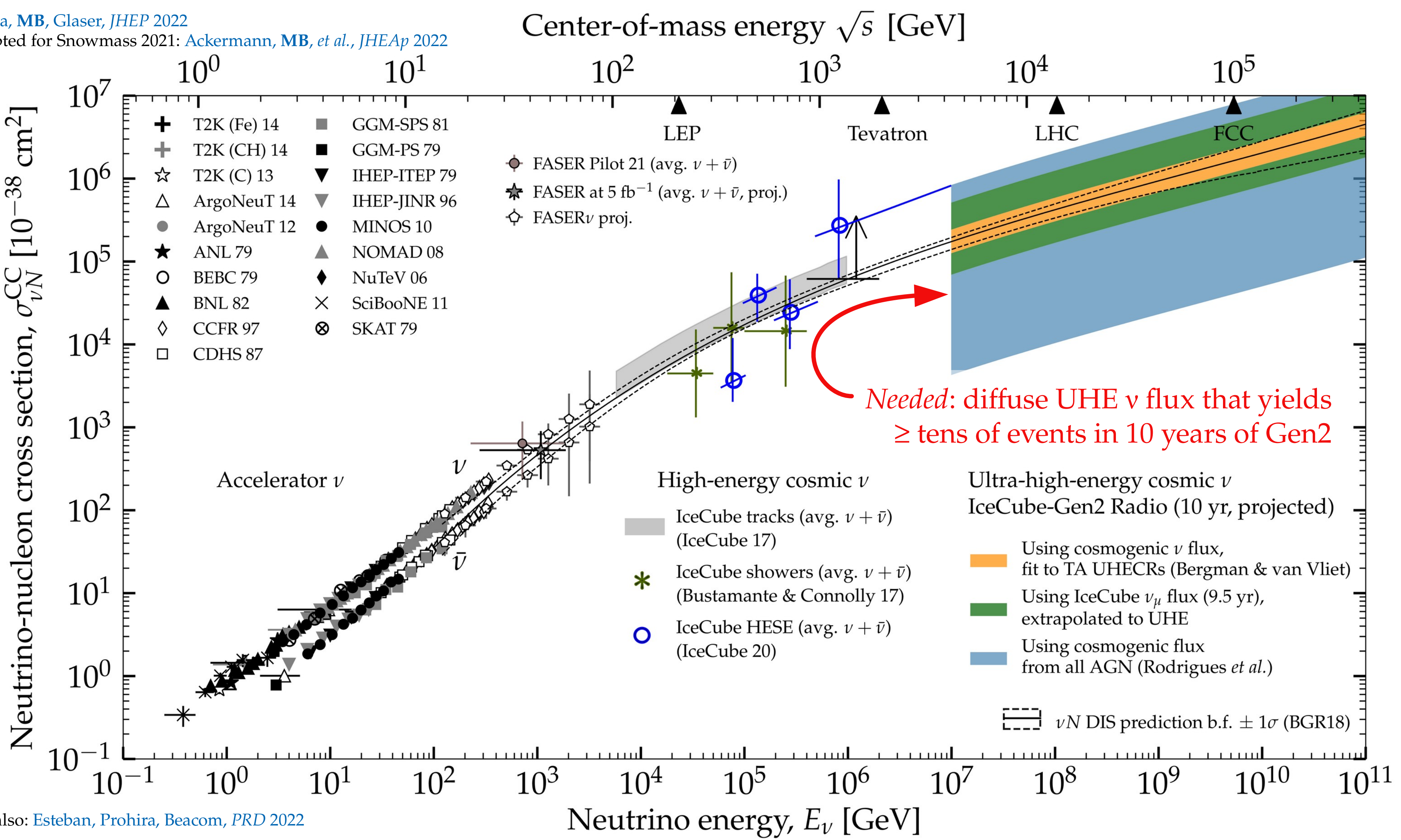

See also: Esteban, Prohira, Beacom, *PRD* 2022

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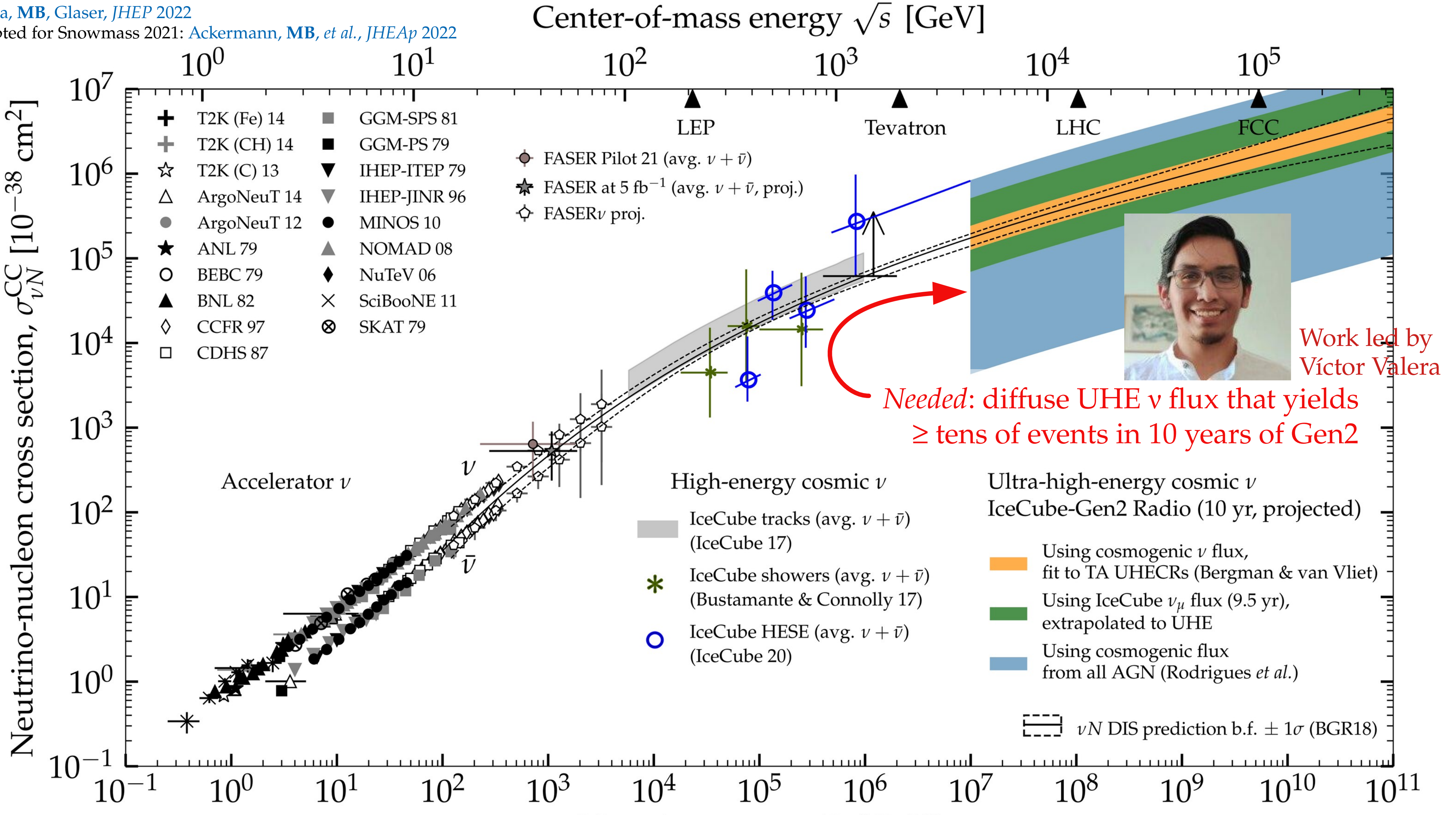
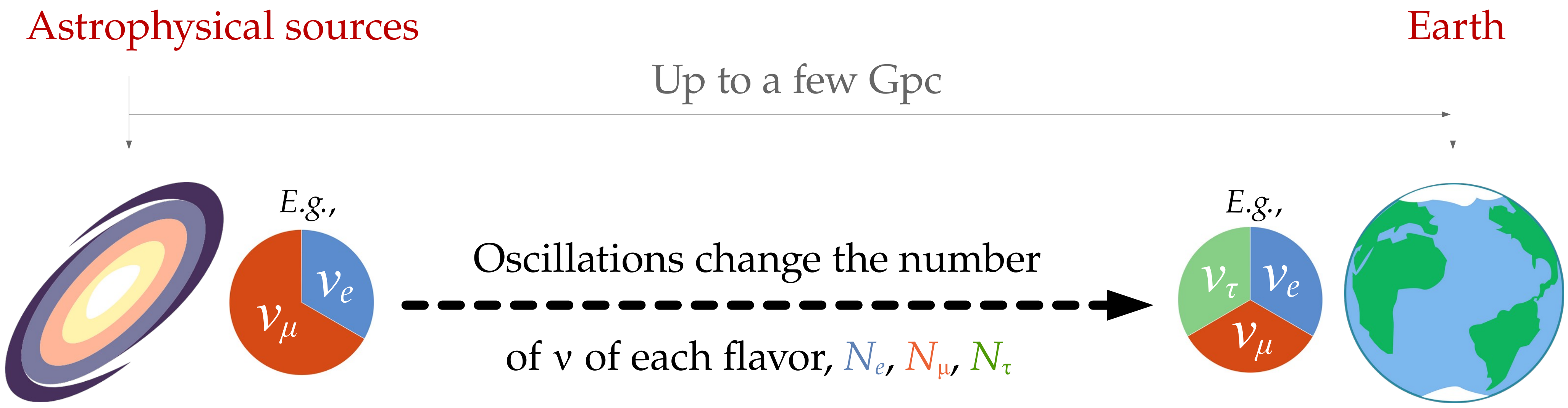


See also: Esteban, Prohira, Beacom, *PRD* 2022

3. Flavor:
Towards precision, finally

(with the help of lower-energy experiments)

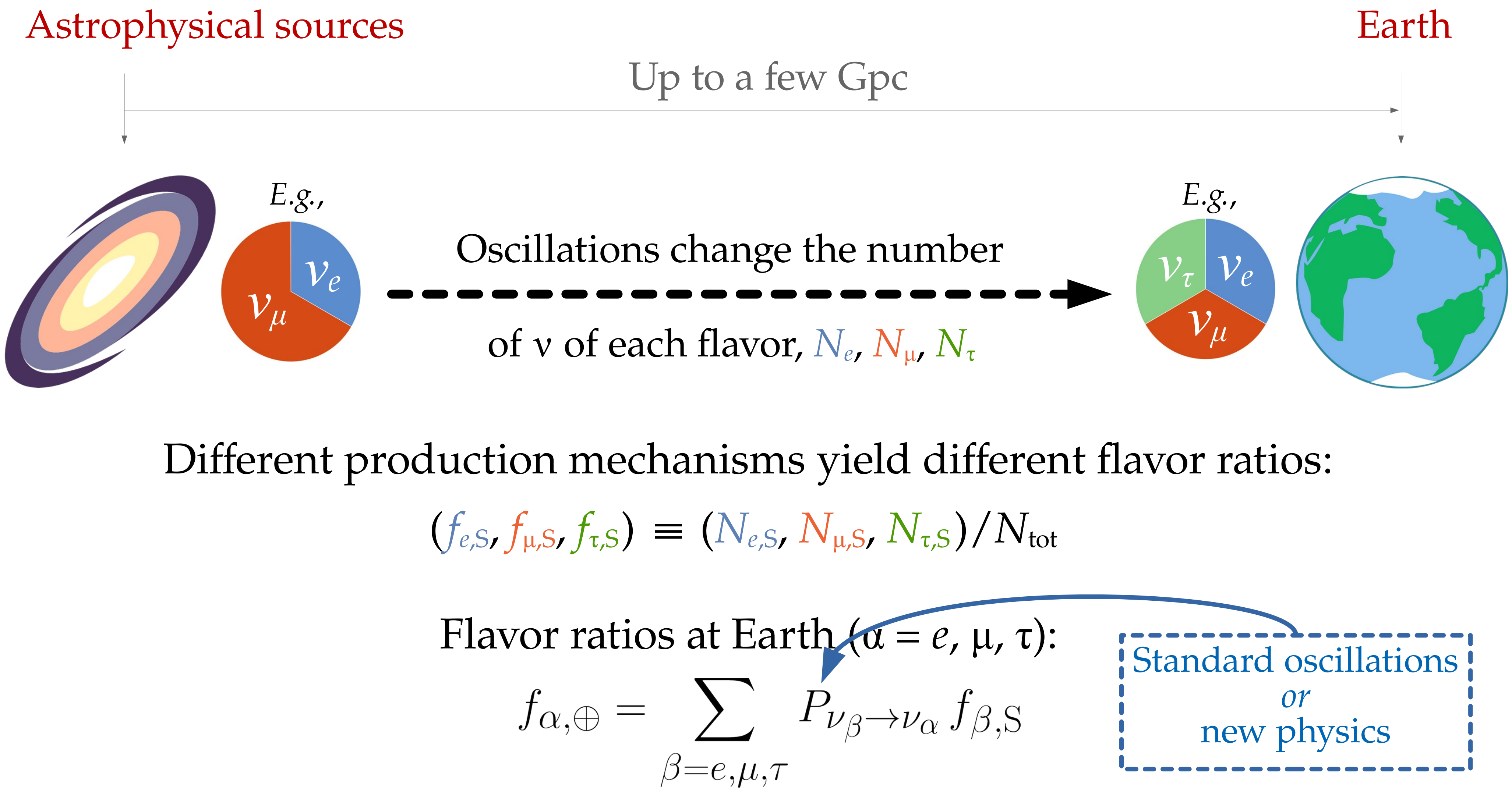


Different production mechanisms yield different flavor ratios:

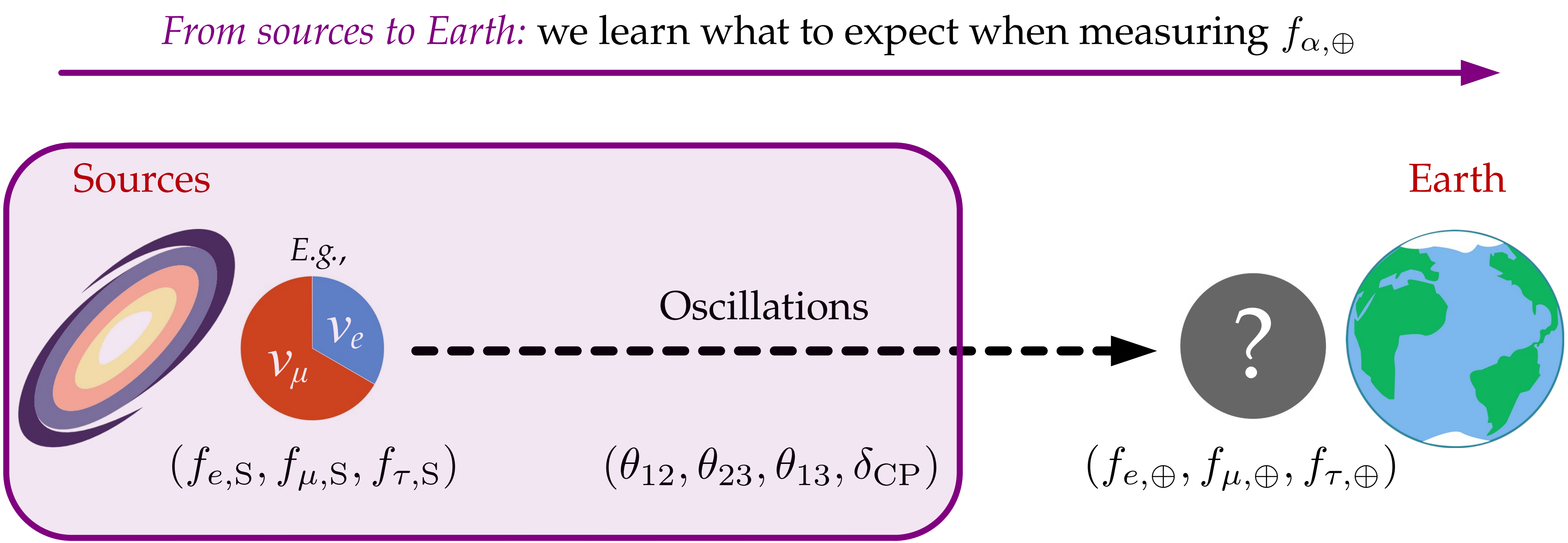
$$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}}) \equiv (N_{e,\mathrm{S}}, N_{\mu,\mathrm{S}}, N_{\tau,\mathrm{S}})/N_{\mathrm{tot}}$$

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



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

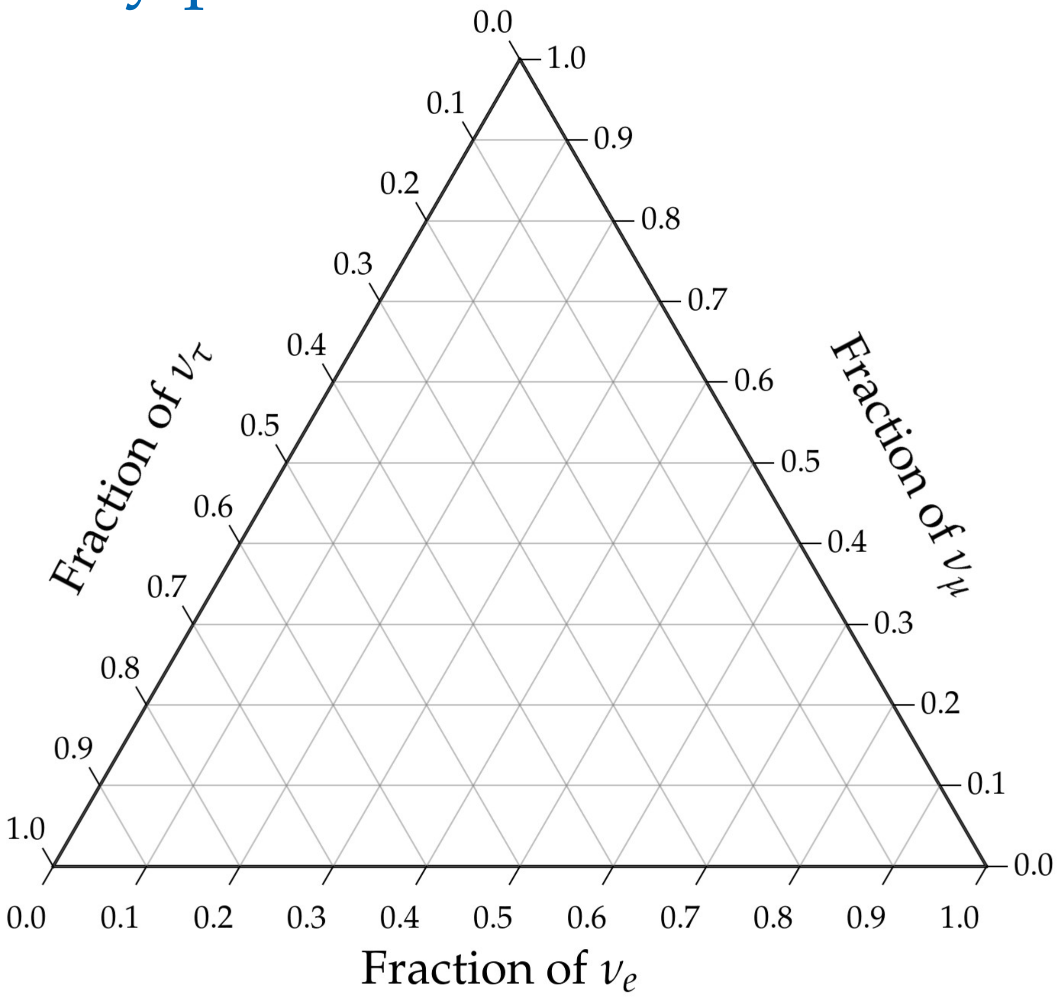
Quick aside: how to read a ternary plot

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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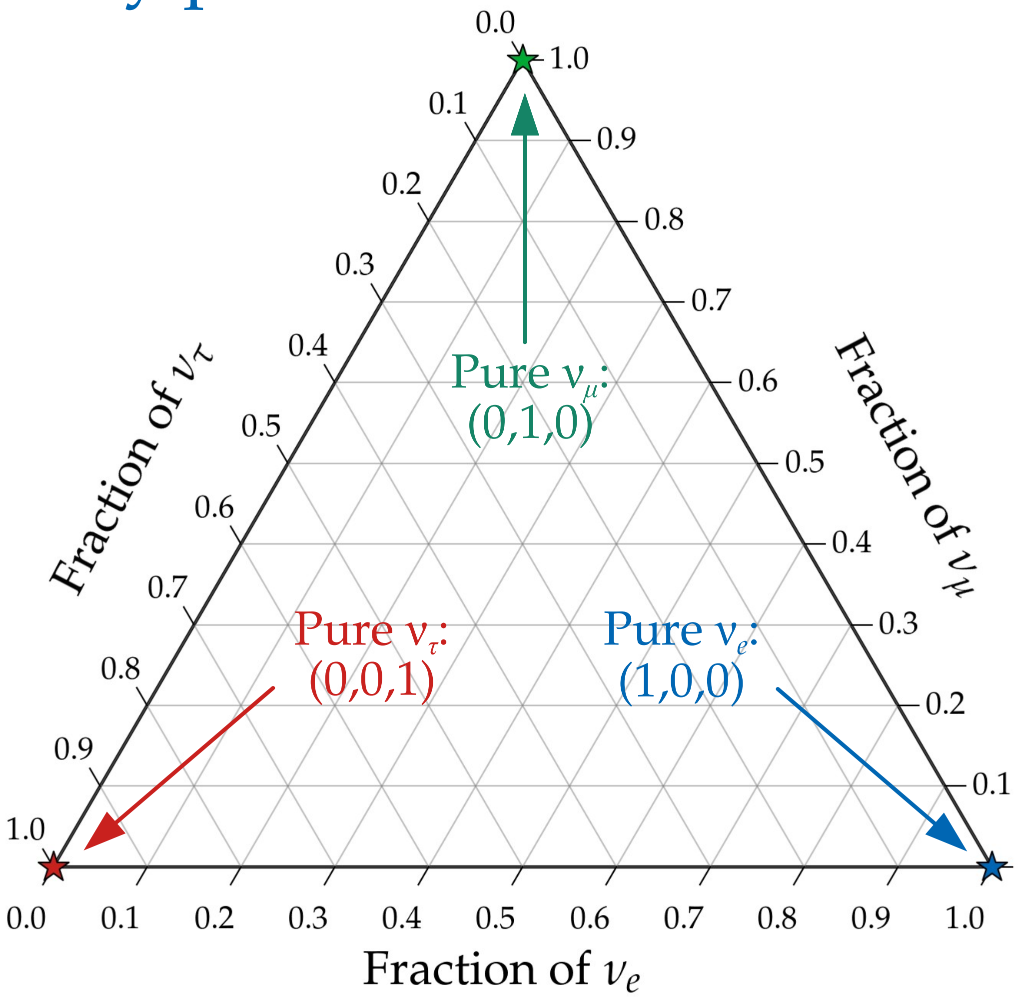

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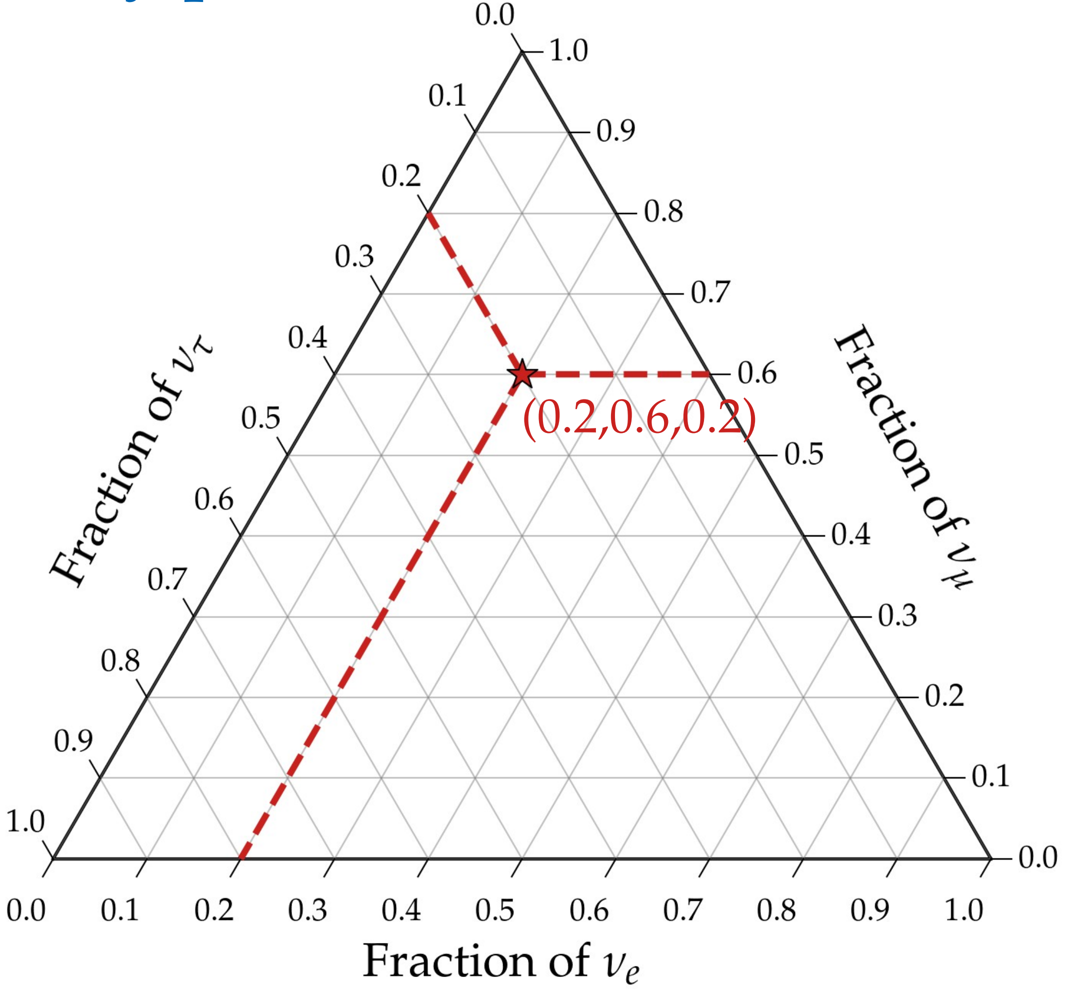

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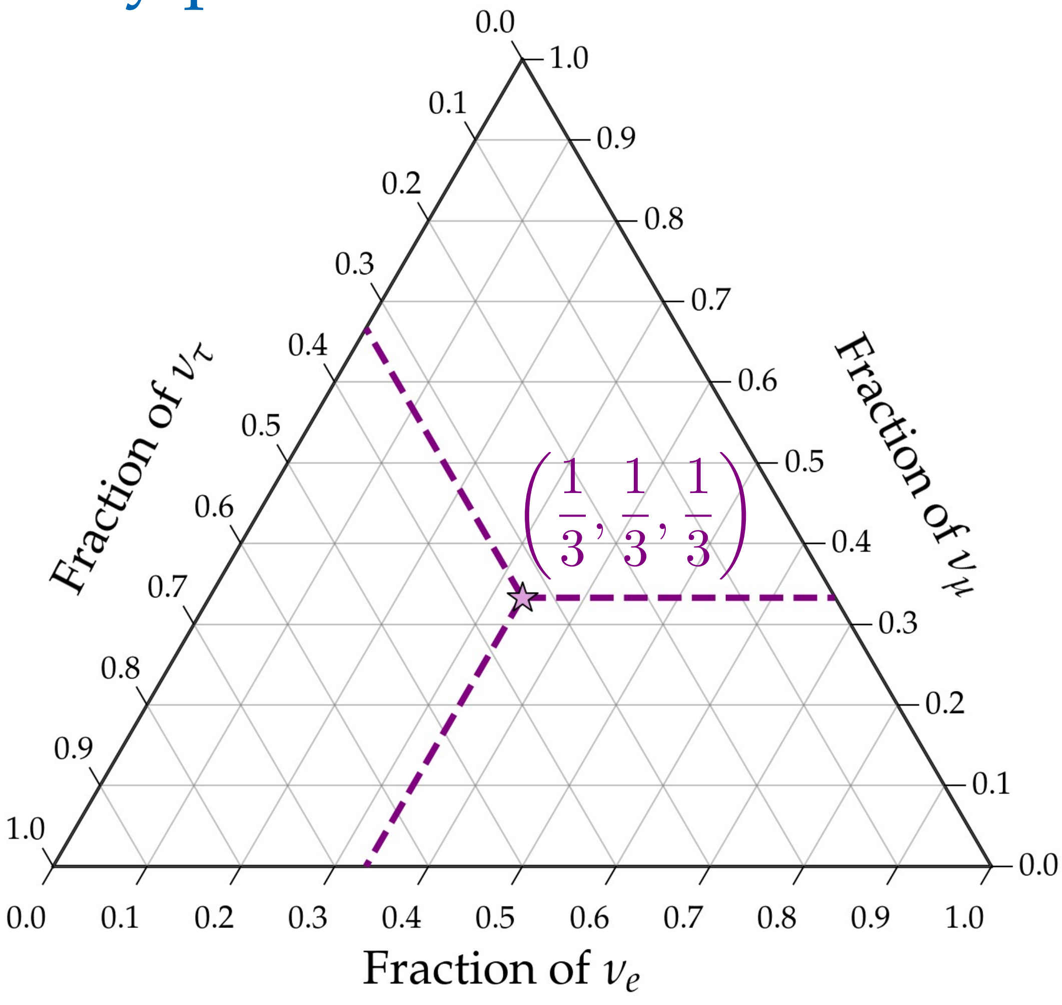

One likely TeV–PeV ν production scenario:

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

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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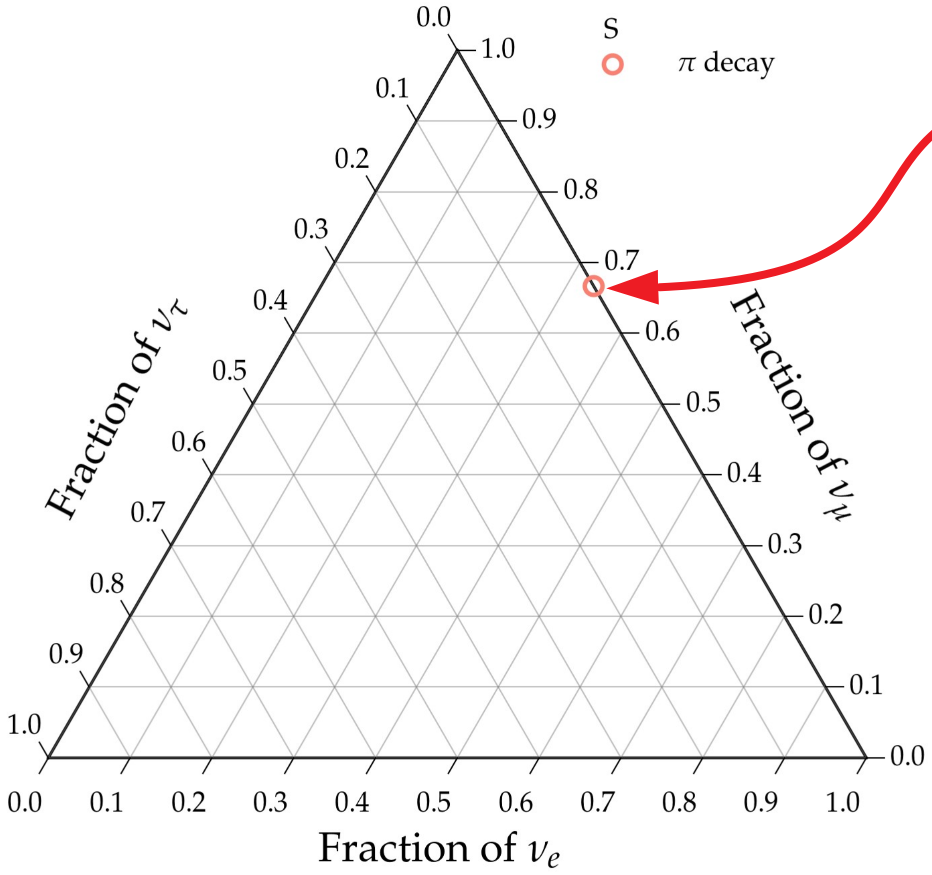

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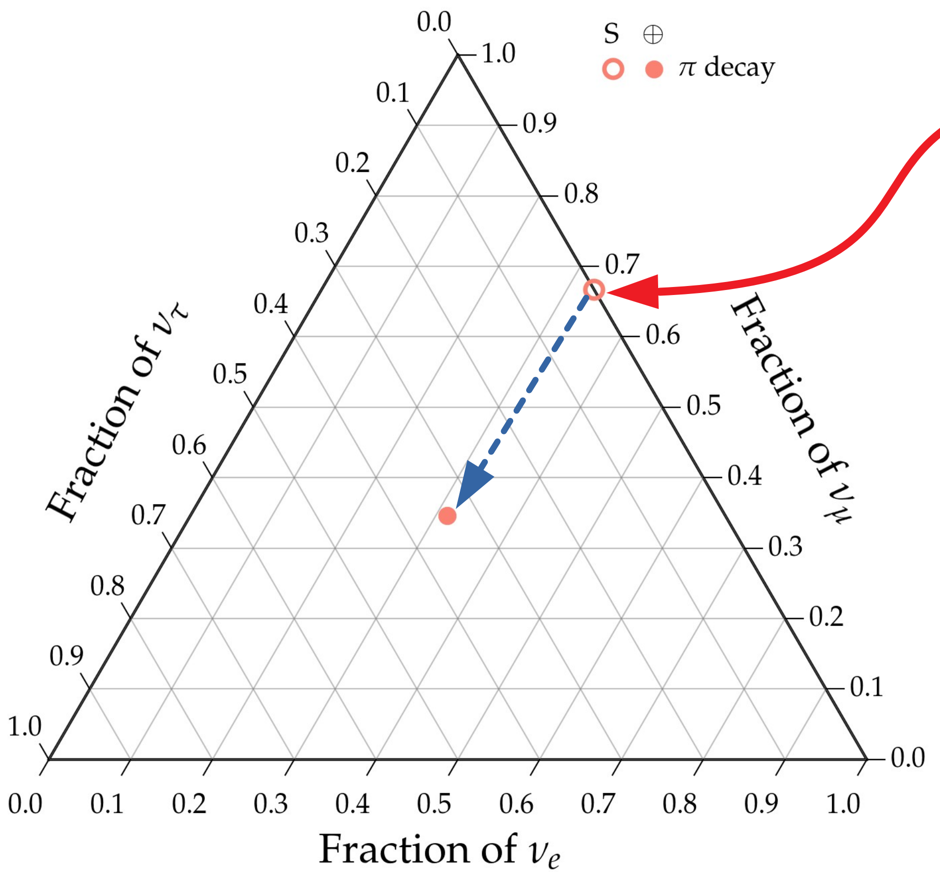

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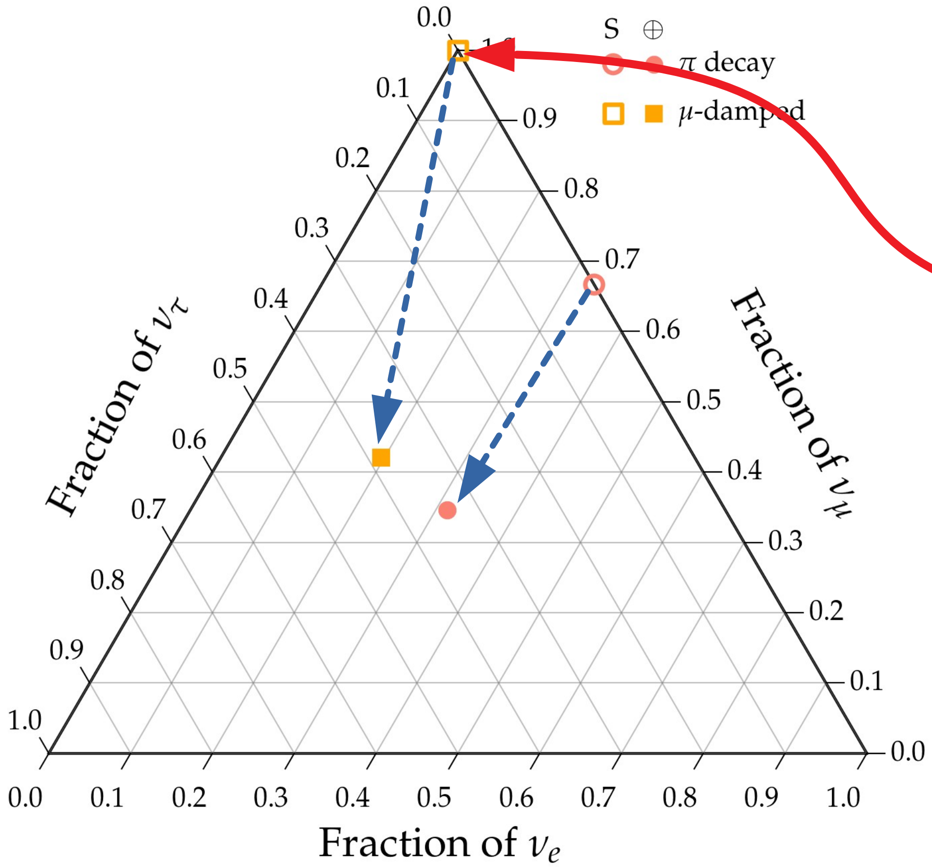

Full π decay chain

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

Muon damped

$(0:1:0)_S$

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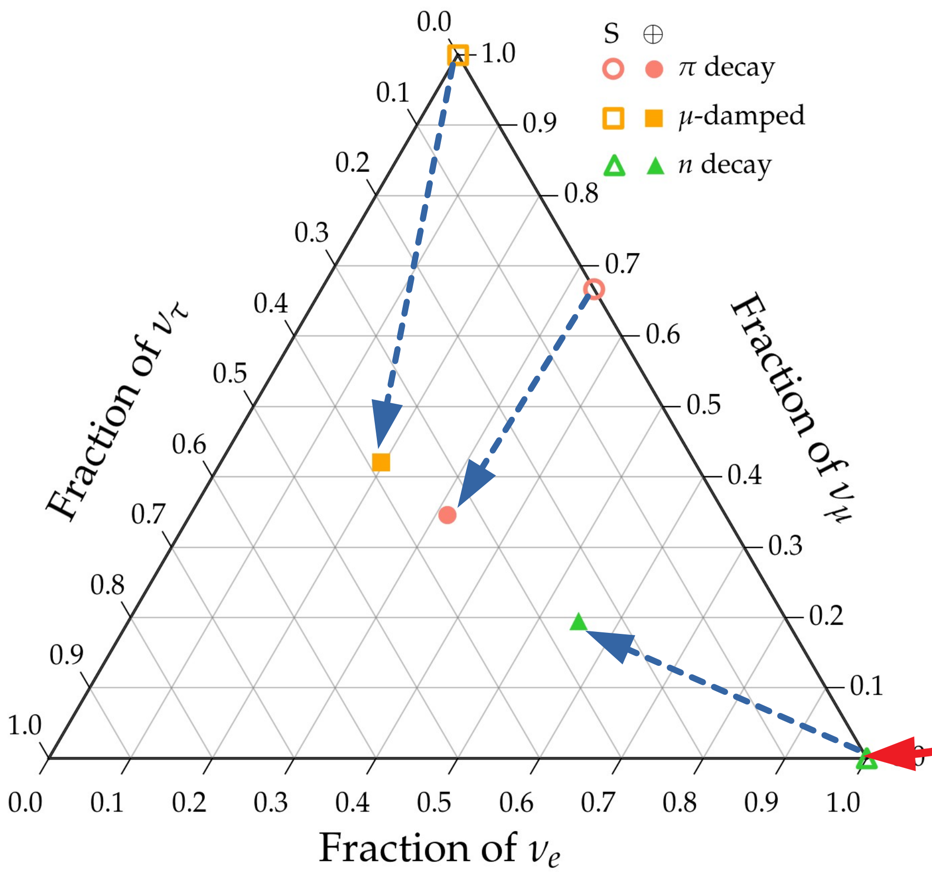


Full π decay chain

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

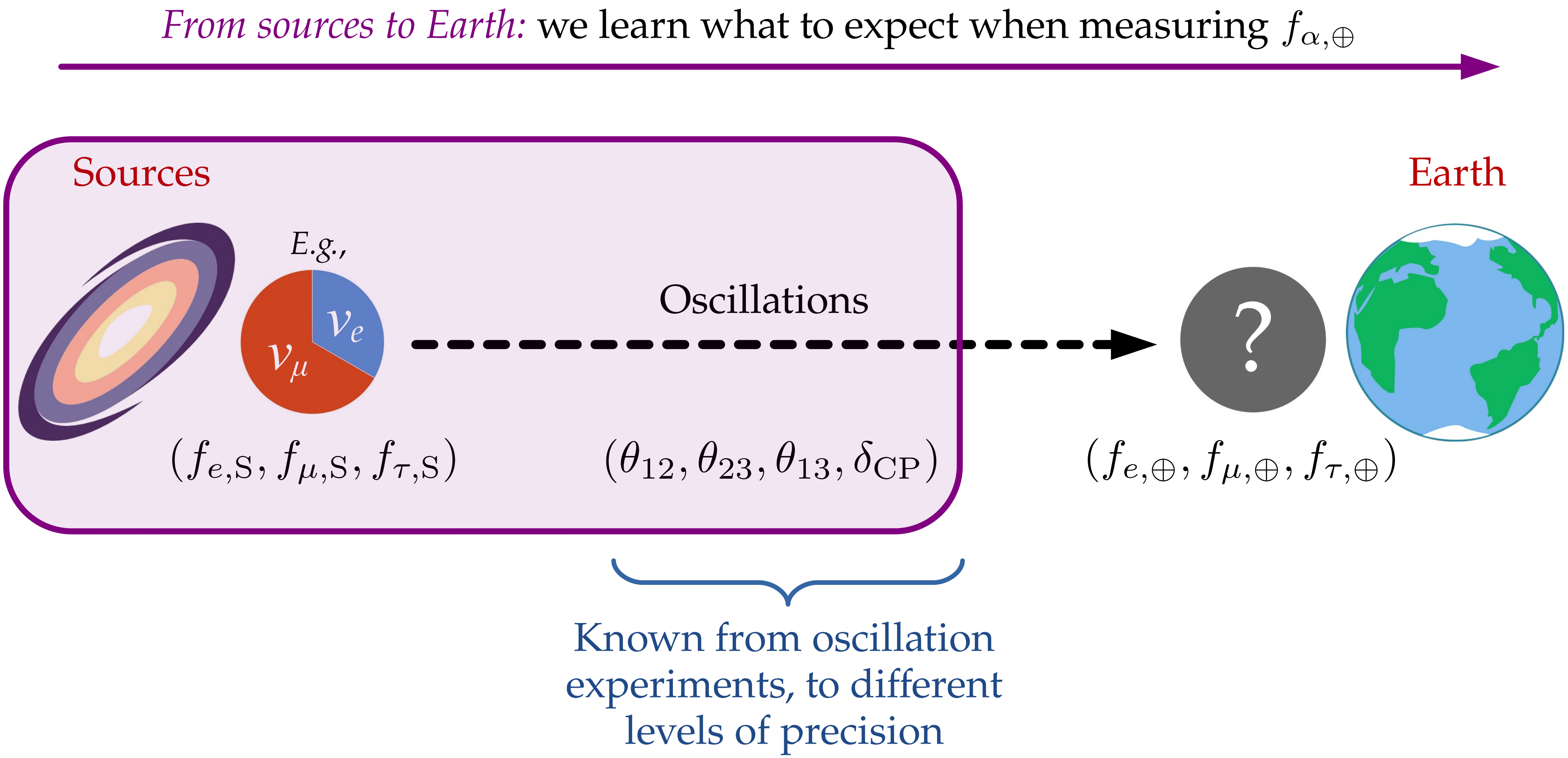
Muon damped

$(0:1:0)_S$

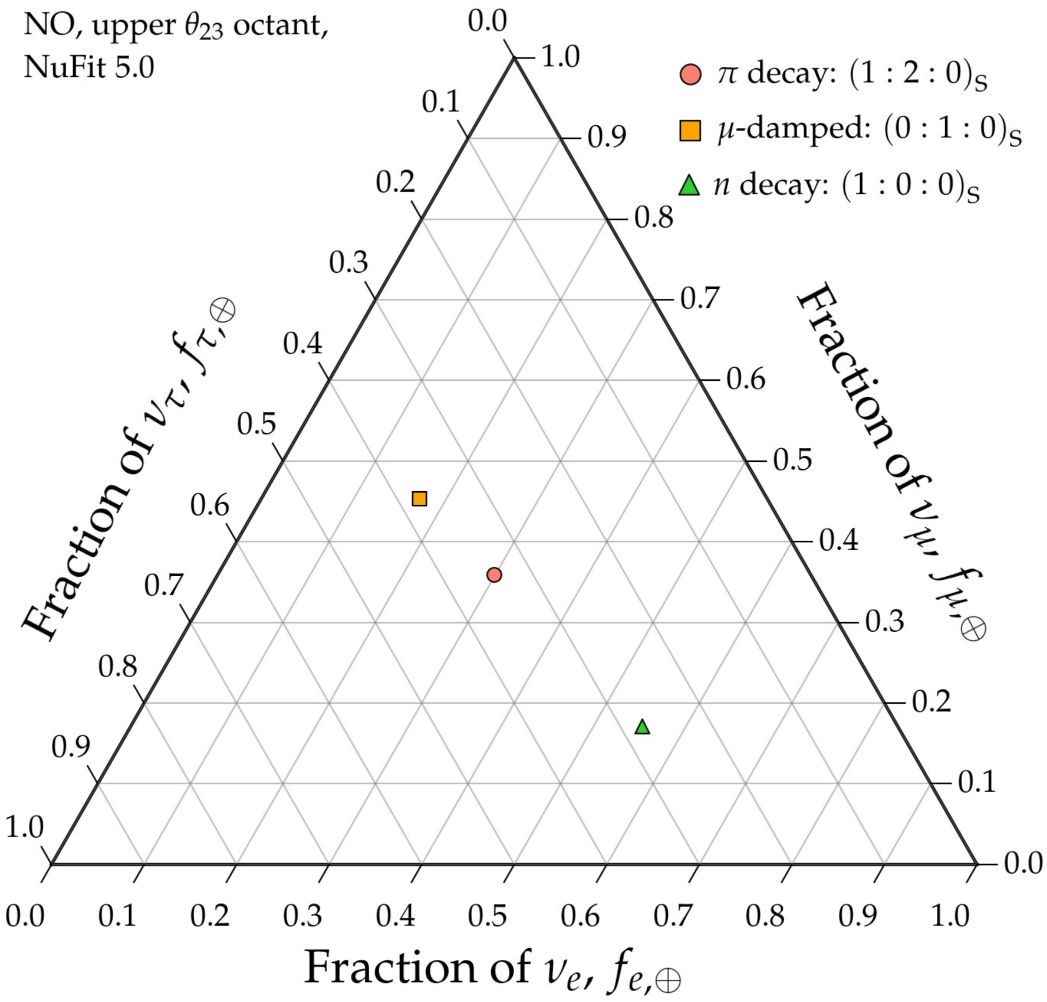
Neutron decay

$(1:0:0)_S$

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


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

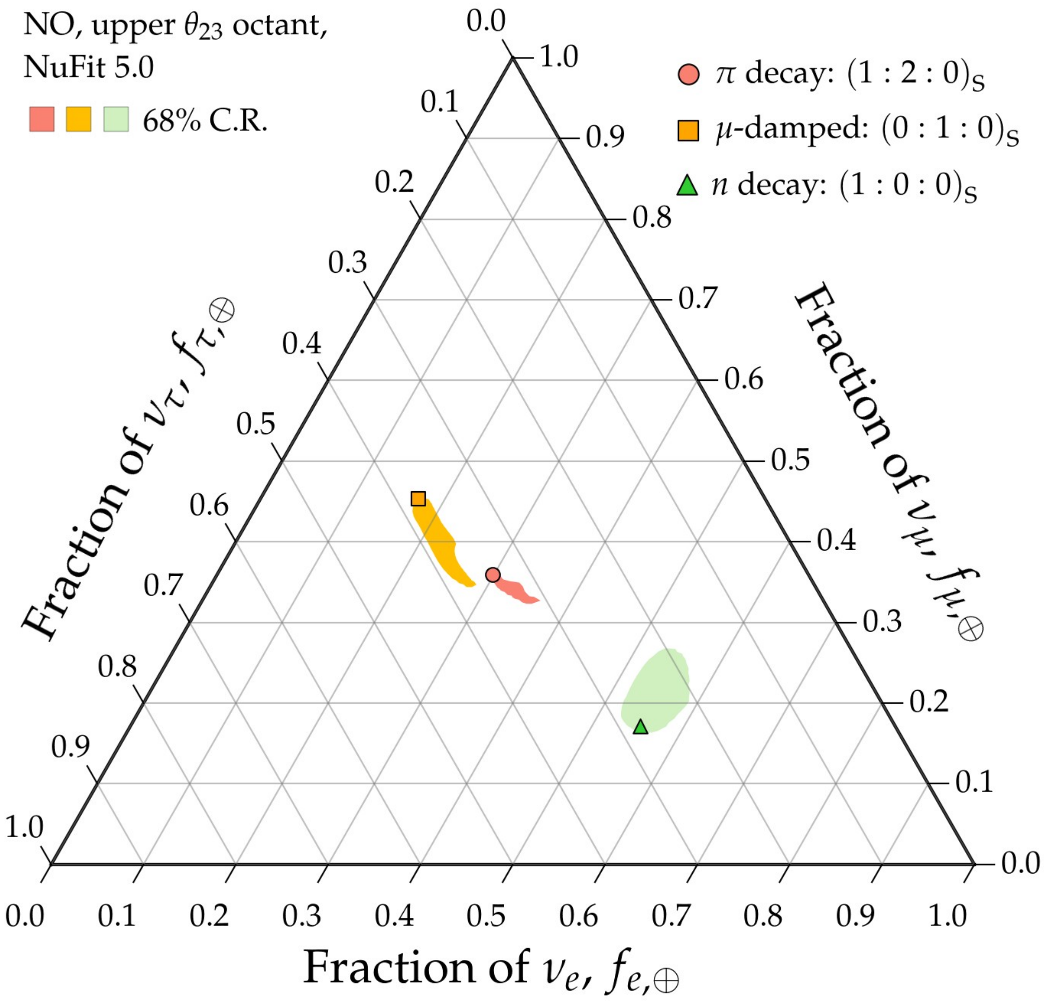
Theoretically palatable regions: today



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

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

Theoretically palatable regions: today



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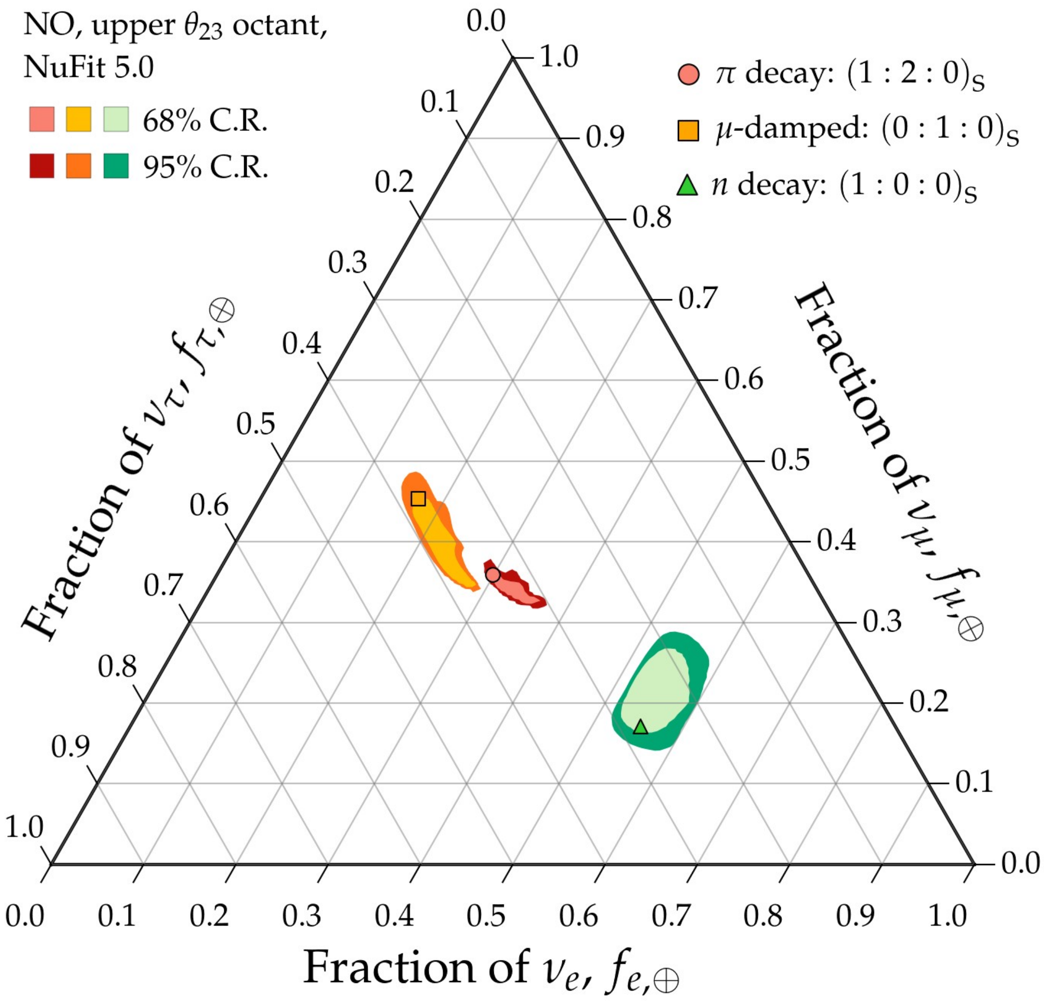

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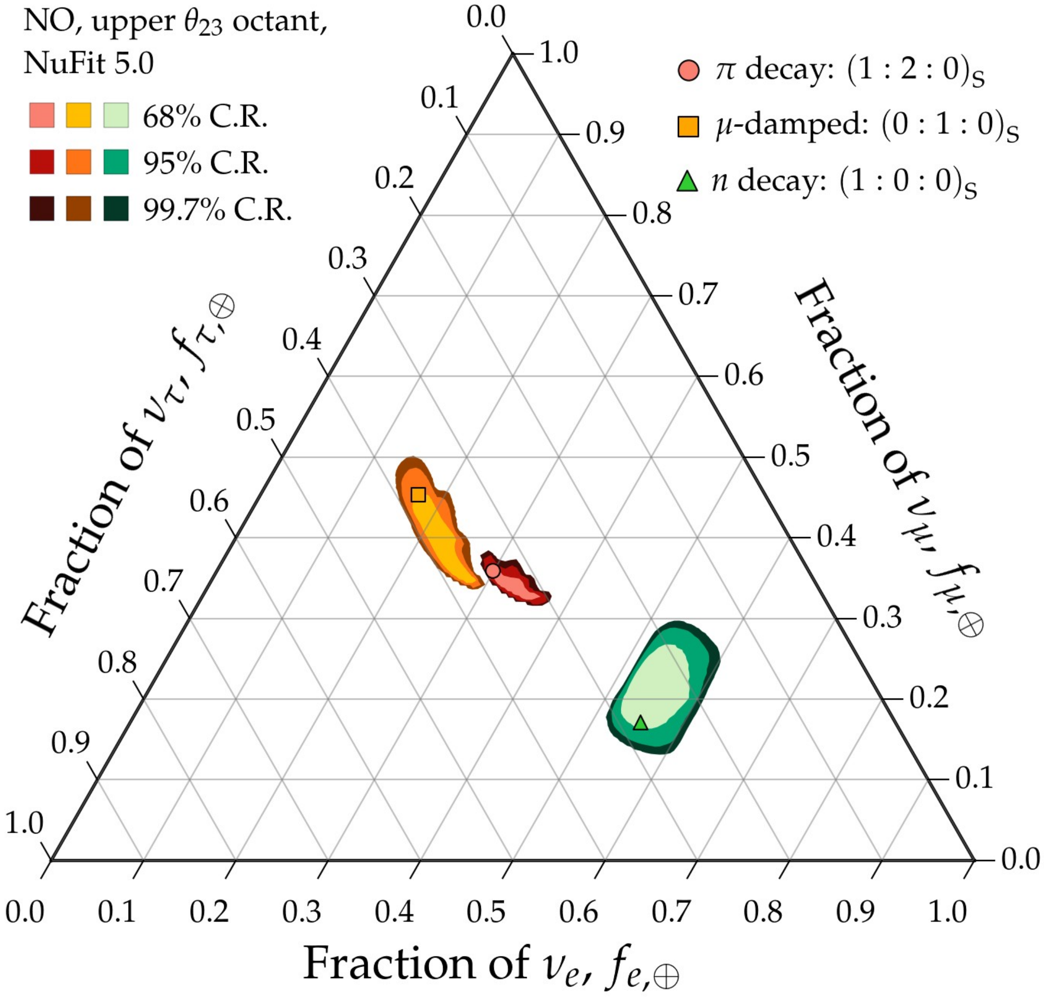

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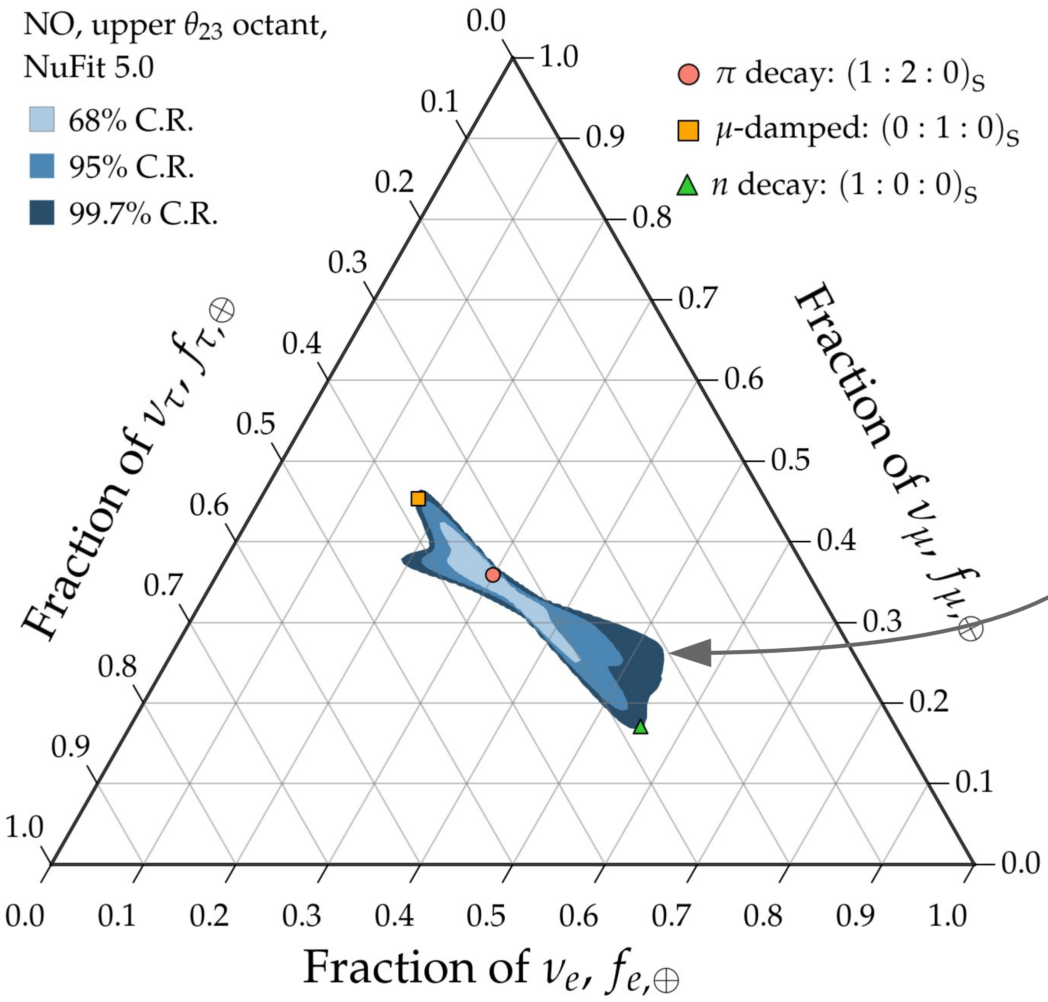
Theoretically palatable regions: today

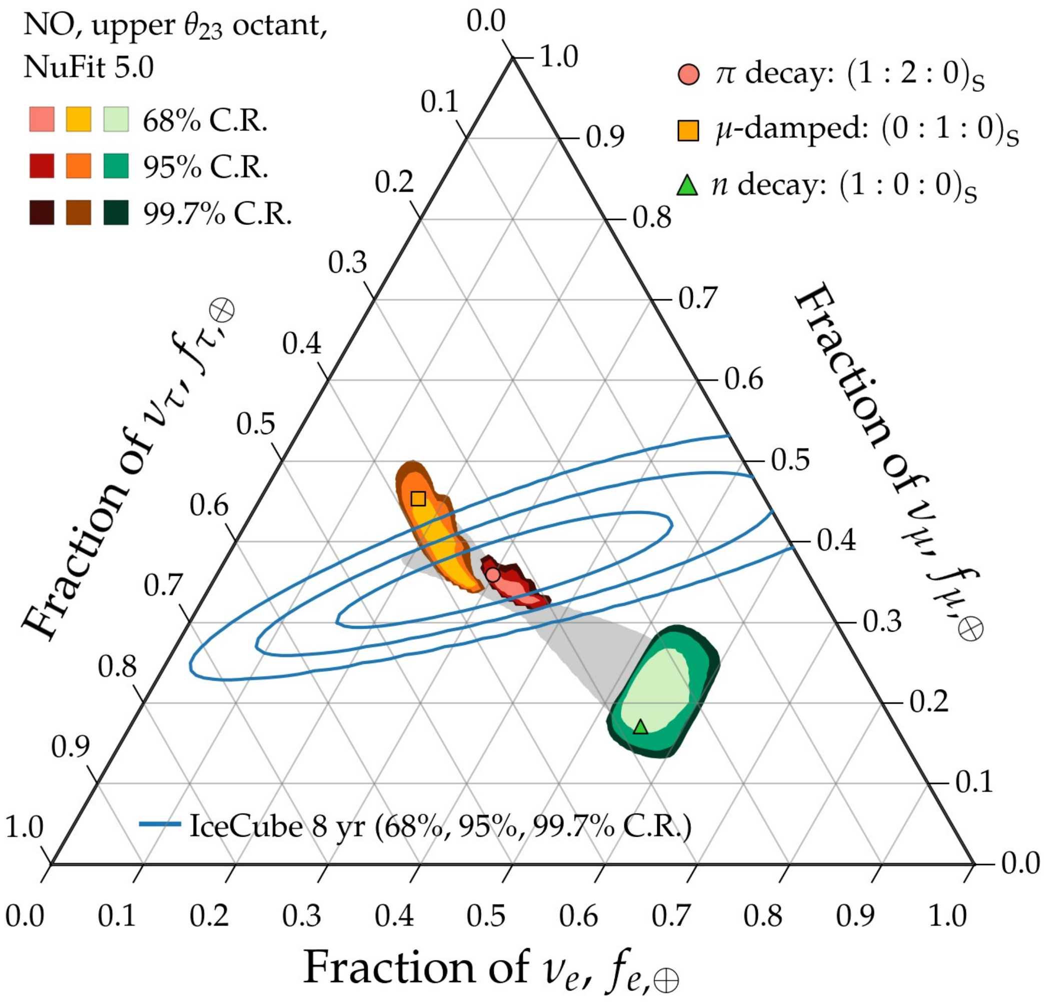


Varying over all possible flavor ratios at the source

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

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

Theoretically palatable regions: today



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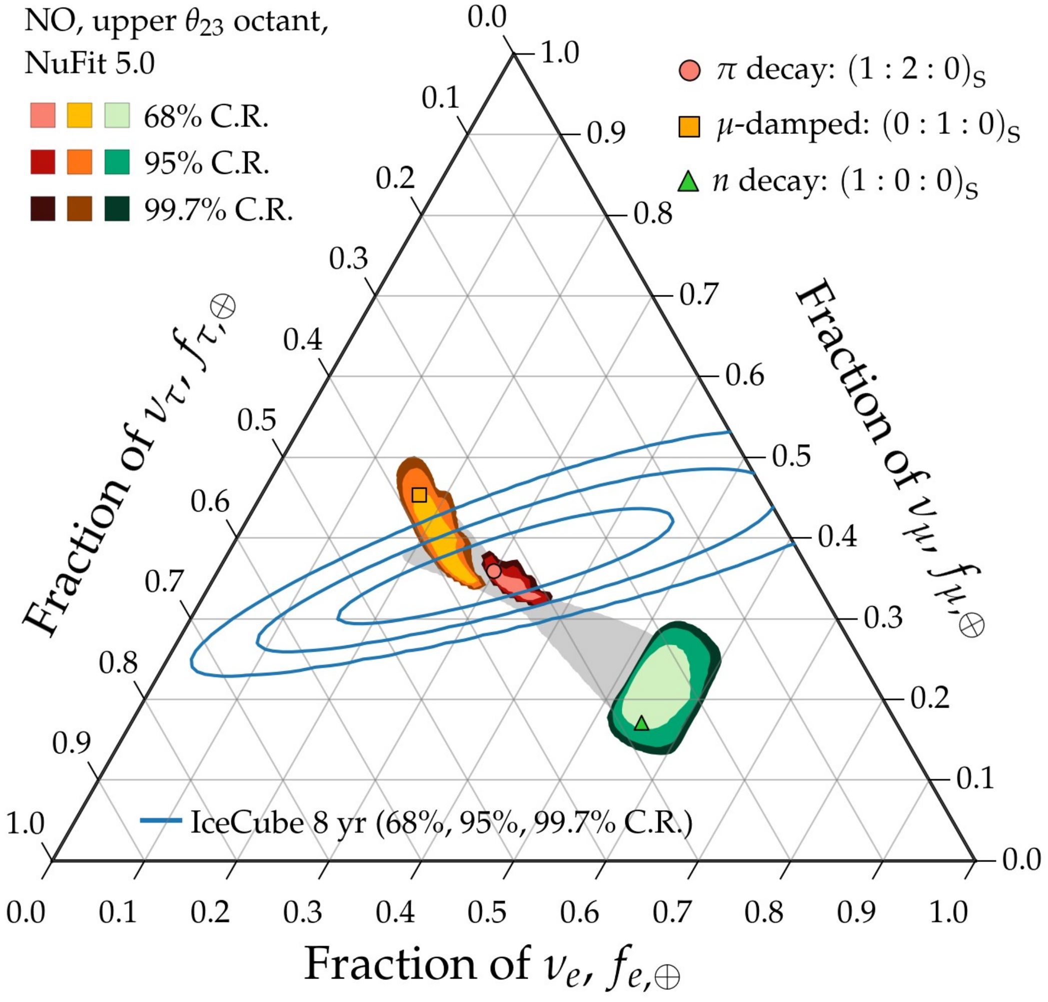


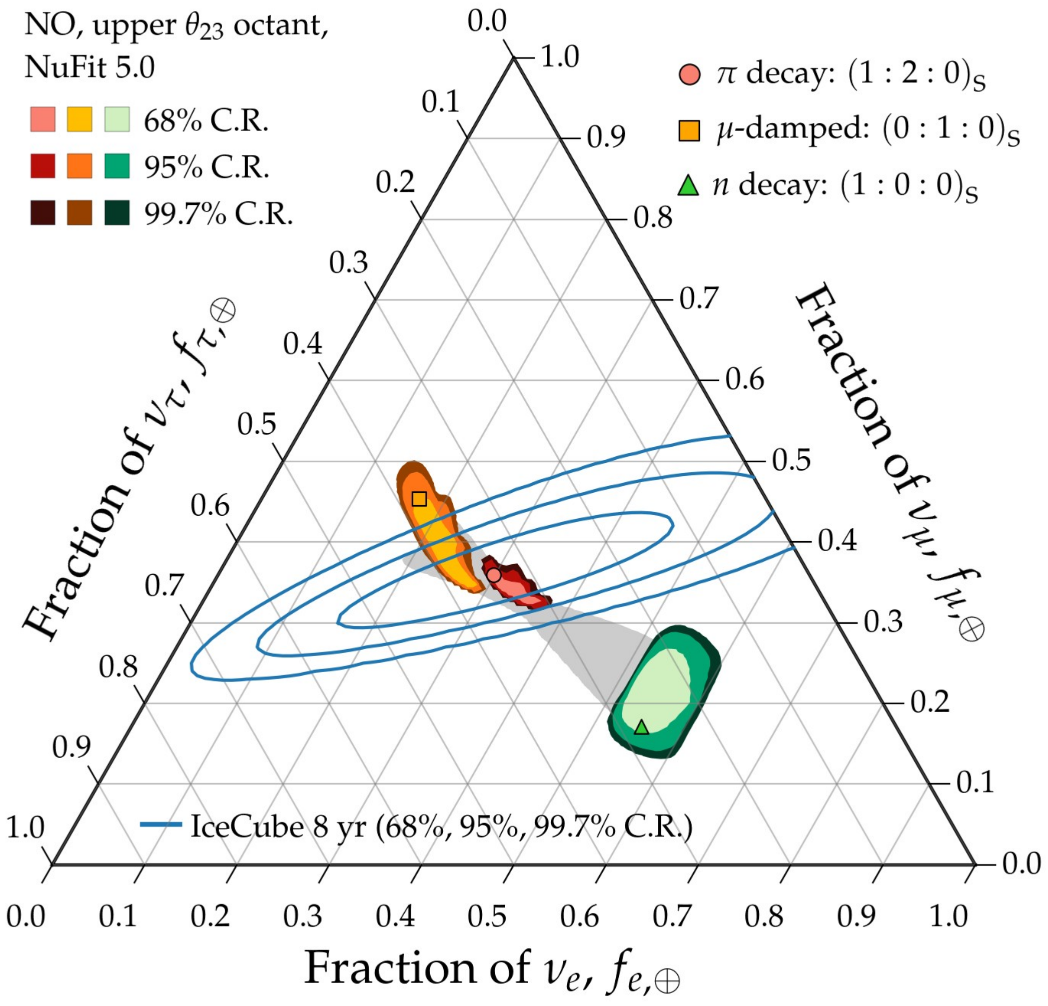
Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

Measurement of flavor ratios –
Cannot distinguish between pion-decay and muon-damped benchmarks even at 68% C.R. (1σ)

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

Theoretically palatable regions: today



Two limitations:

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Will be overcome by 2030

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Cannot distinguish between pion-decay and muon-damped benchmarks even at 68% C.R. (1σ)

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

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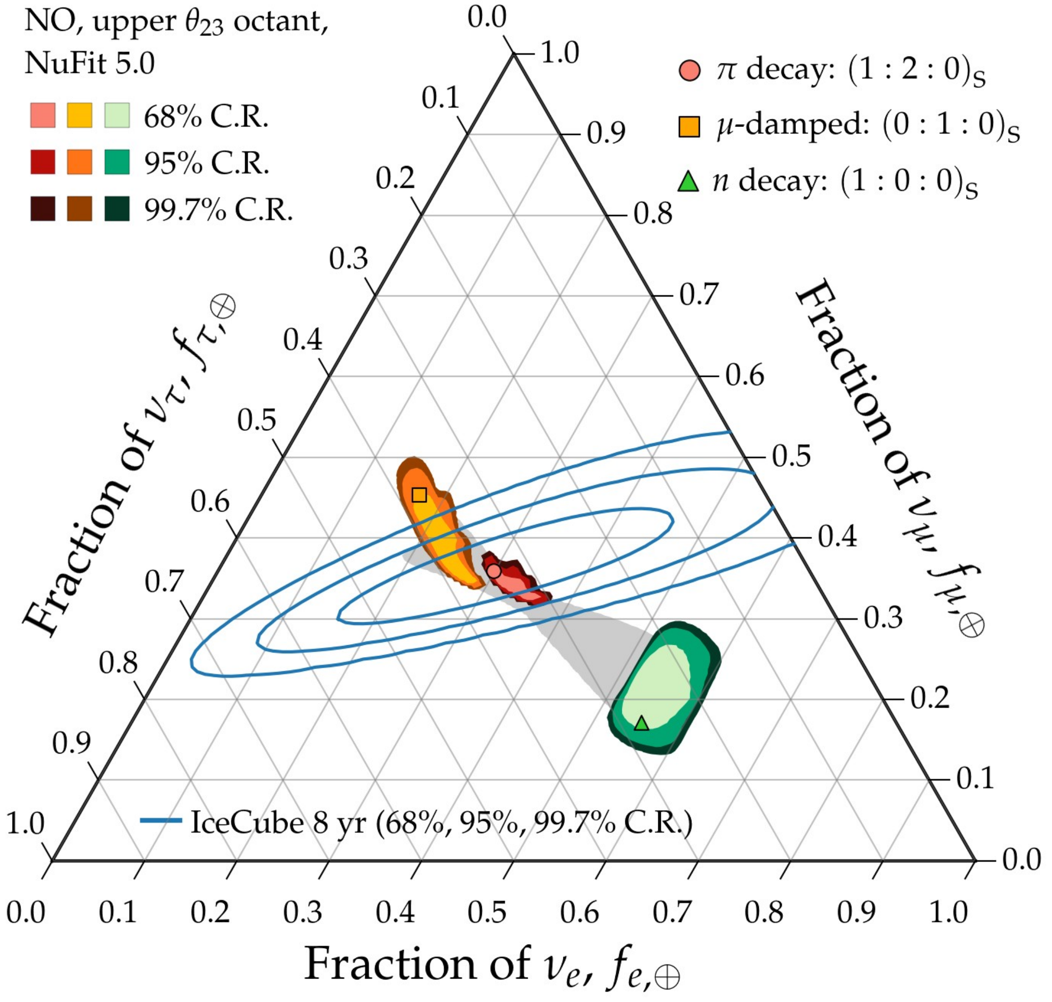

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Allowed flavor regions overlap –
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Will be overcome by 2030

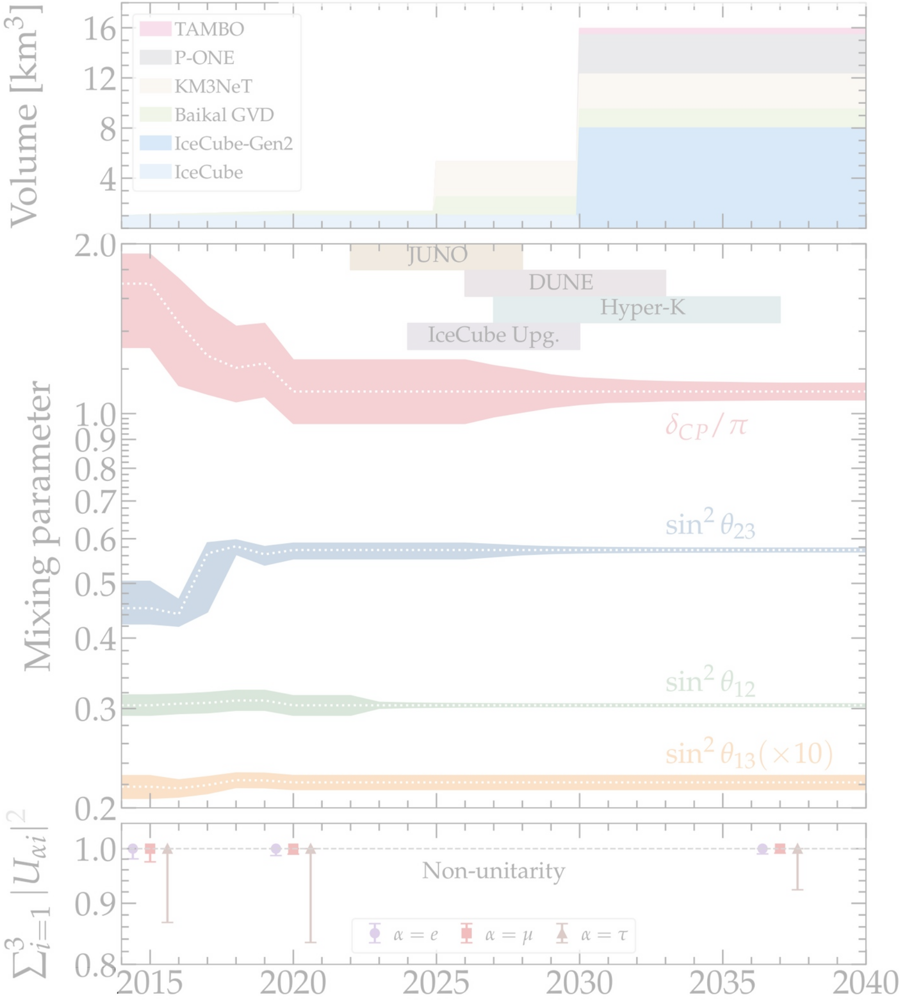
Measurement of flavor ratios –
Cannot distinguish between pion-decay and muon-damped benchmarks even at 68% C.R. (1σ)

Will be overcome by 2040

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

Three reasons to be excited

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



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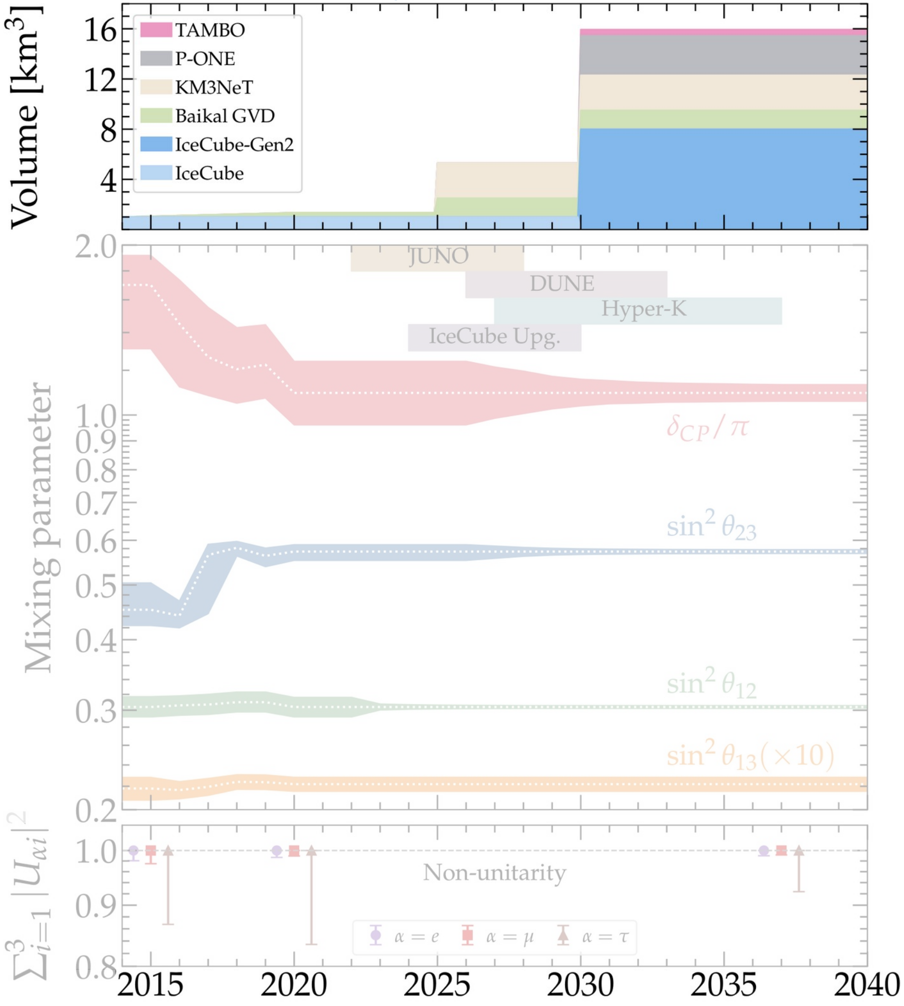

Flavor measurements:

New neutrino telescopes = more events, better flavor measurement

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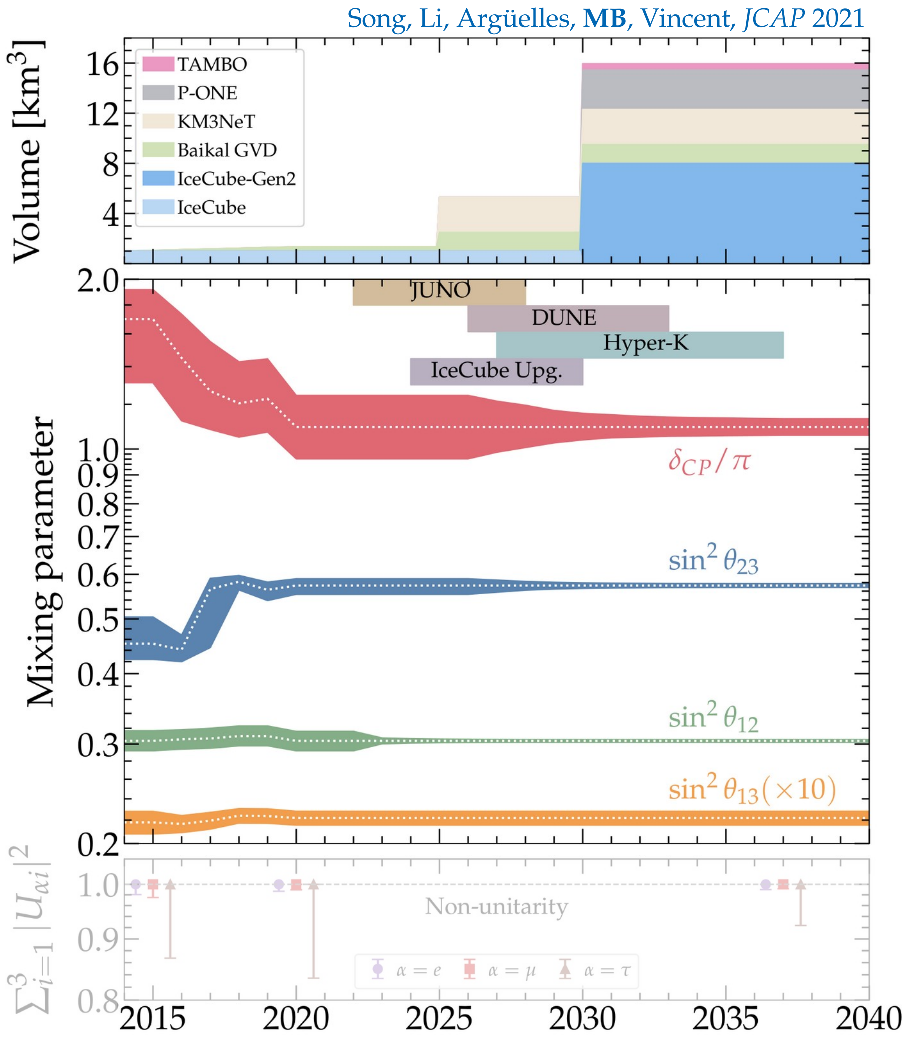

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Oscillation physics:

We will know the mixing parameters better (JUNO, DUNE, Hyper-K, IceCube Upgrade)

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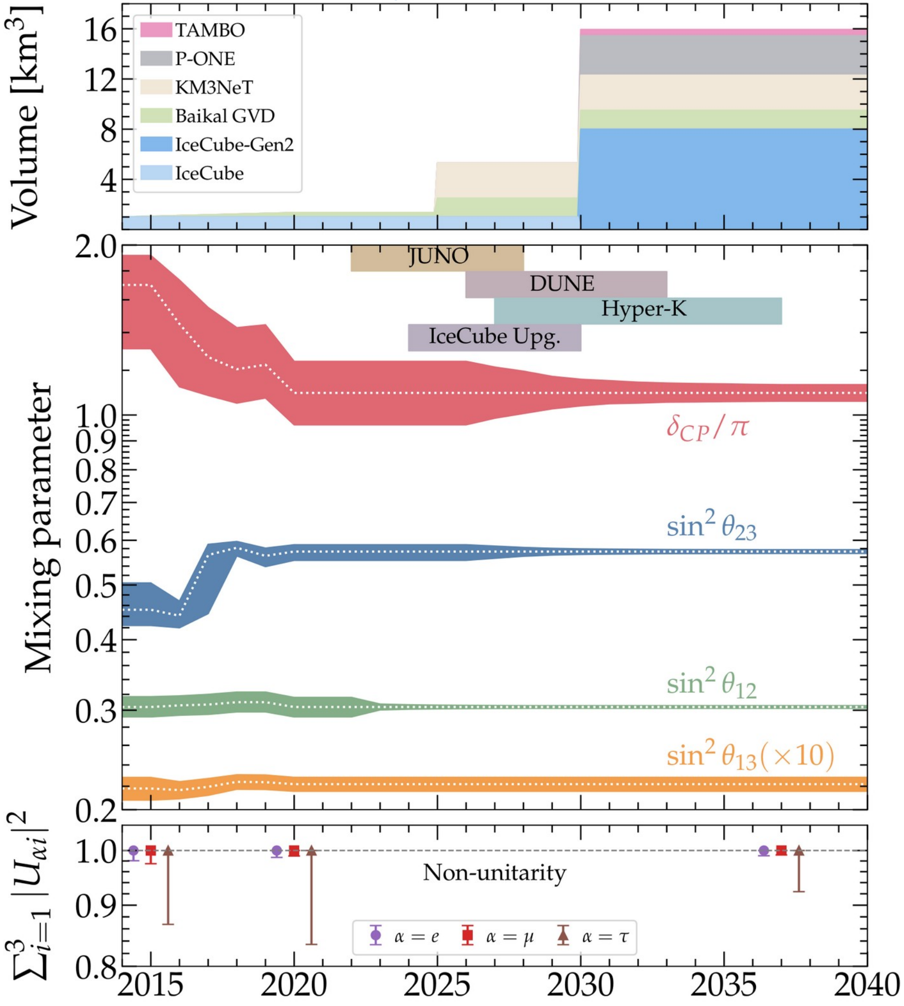
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



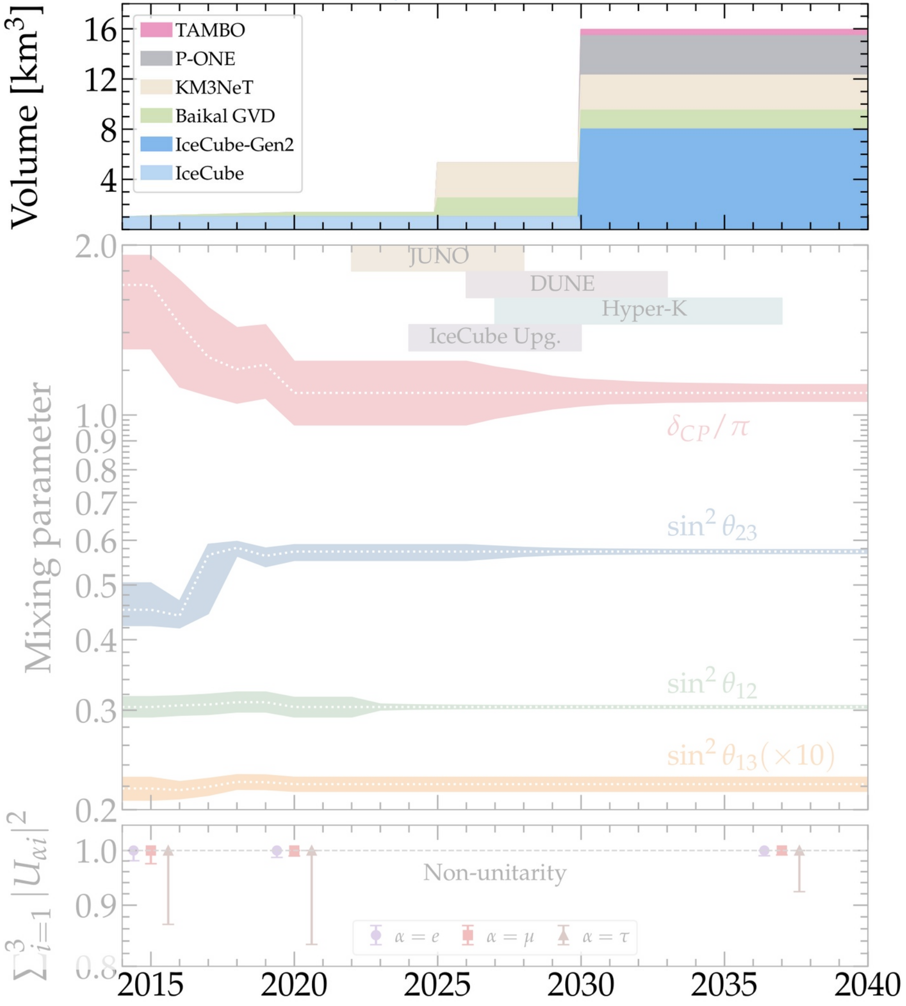
Flavor measurements:
New neutrino telescopes = more events, better flavor measurement

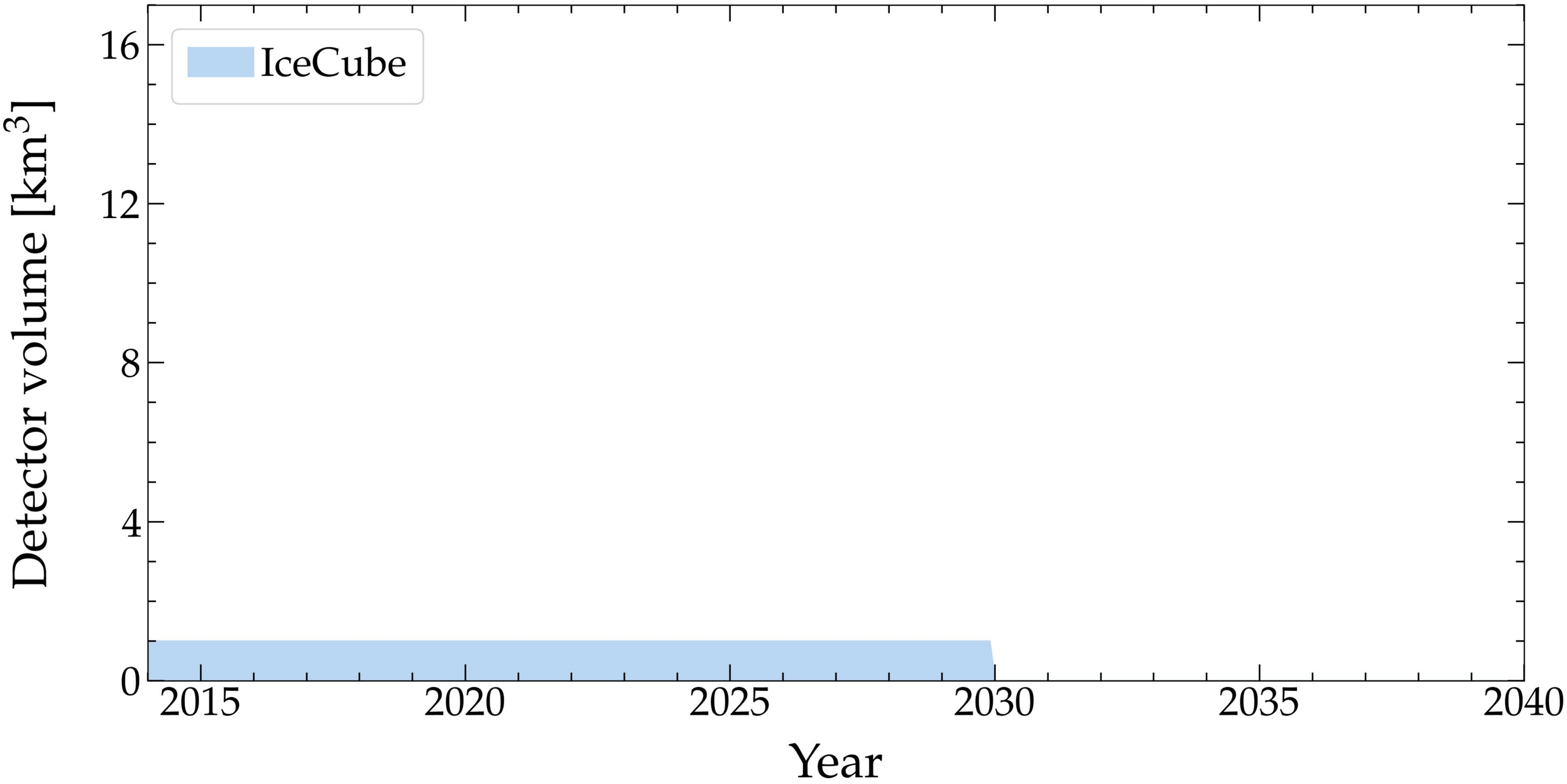
Oscillation physics:
We will know the mixing parameters better (JUNO, DUNE, Hyper-K, IceCube Upgrade)

Test of the oscillation framework:
We will be able to do what we want even if oscillations are non-unitary

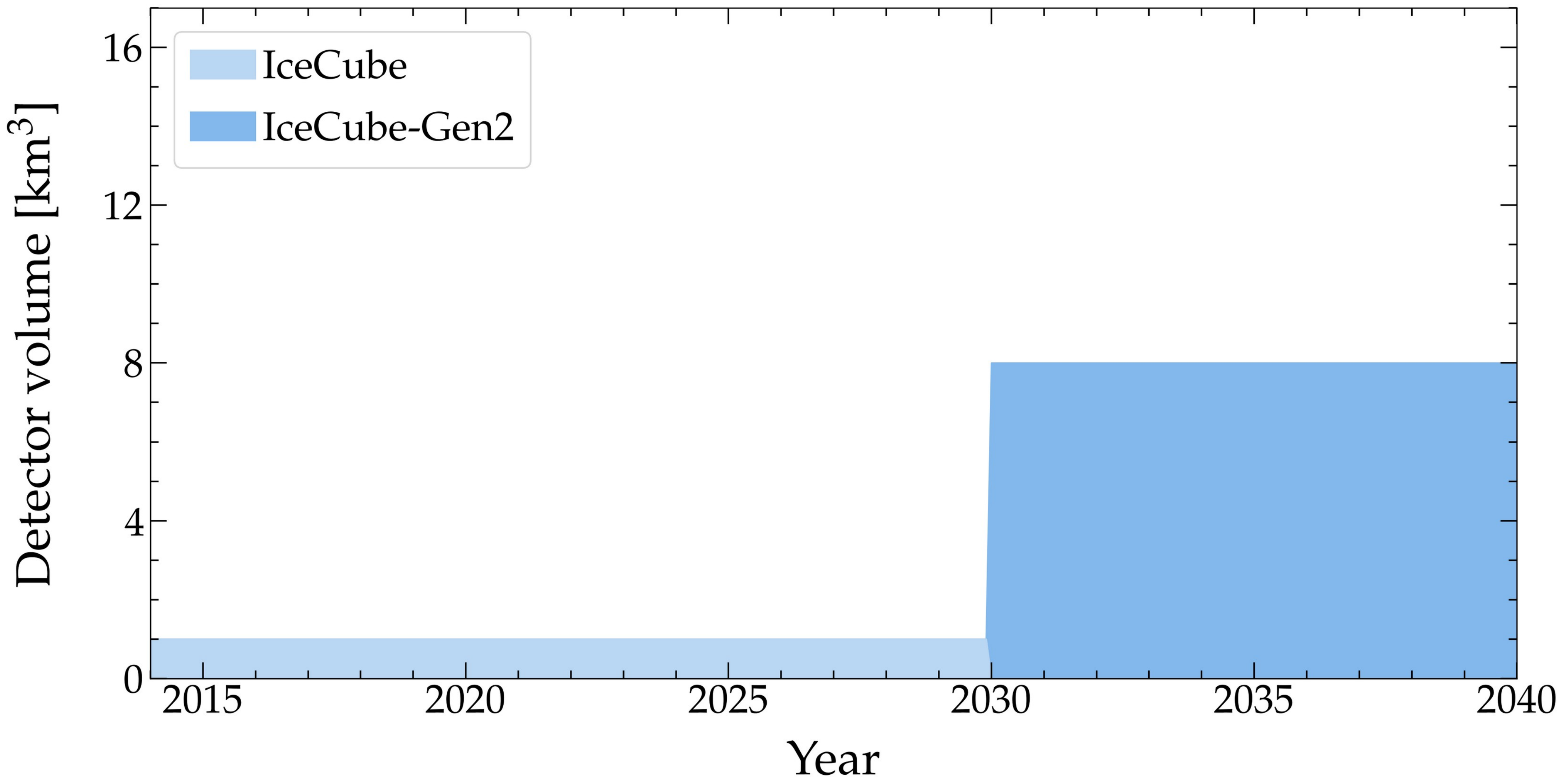
Measuring flavor composition: 2015–2040

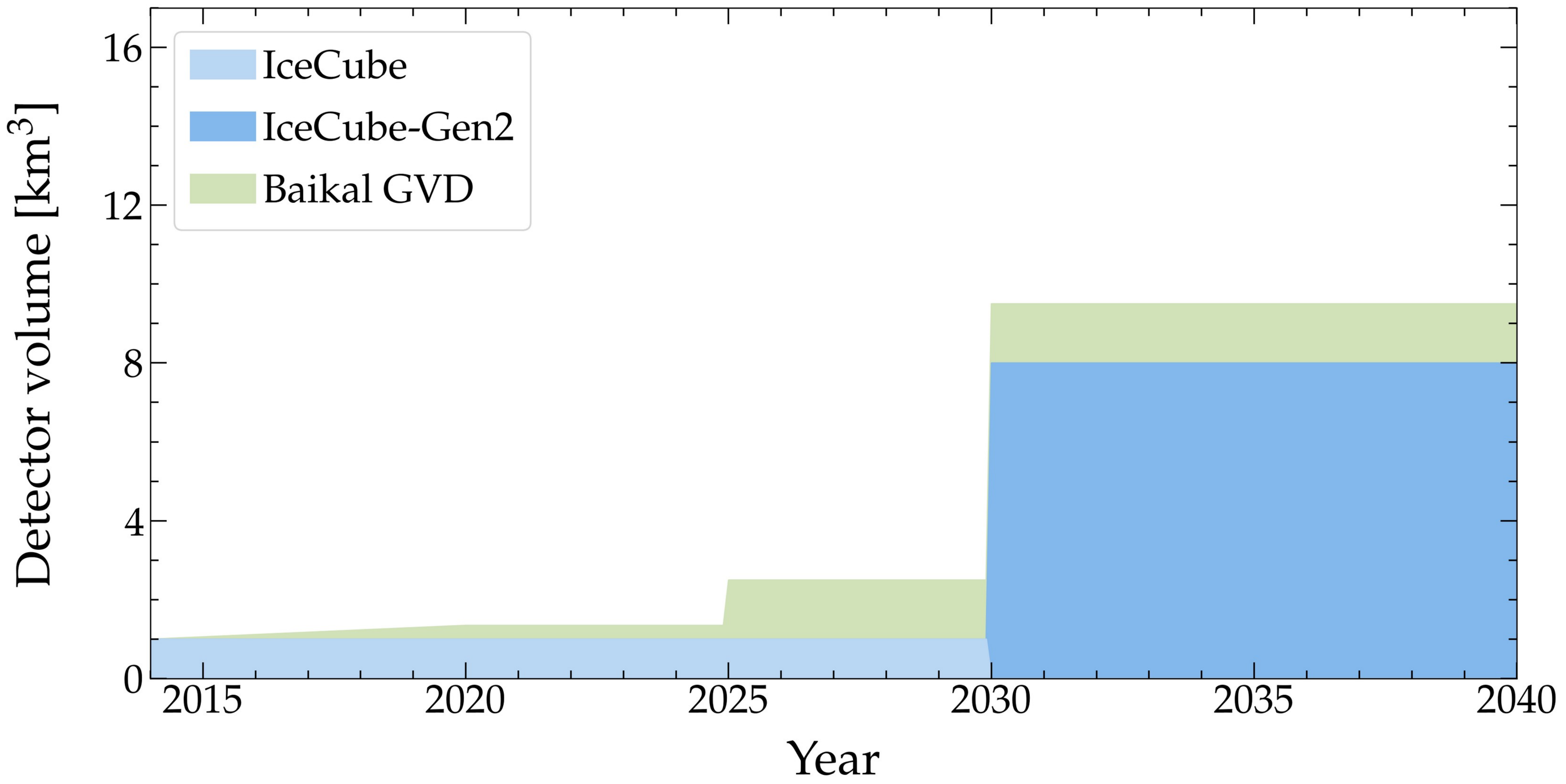
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021





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


IceCube
IceCube-Gen2
Detector volume [km^3]
0
4
8
12
16
2015
2020
2025
2030
2035
2040
Year



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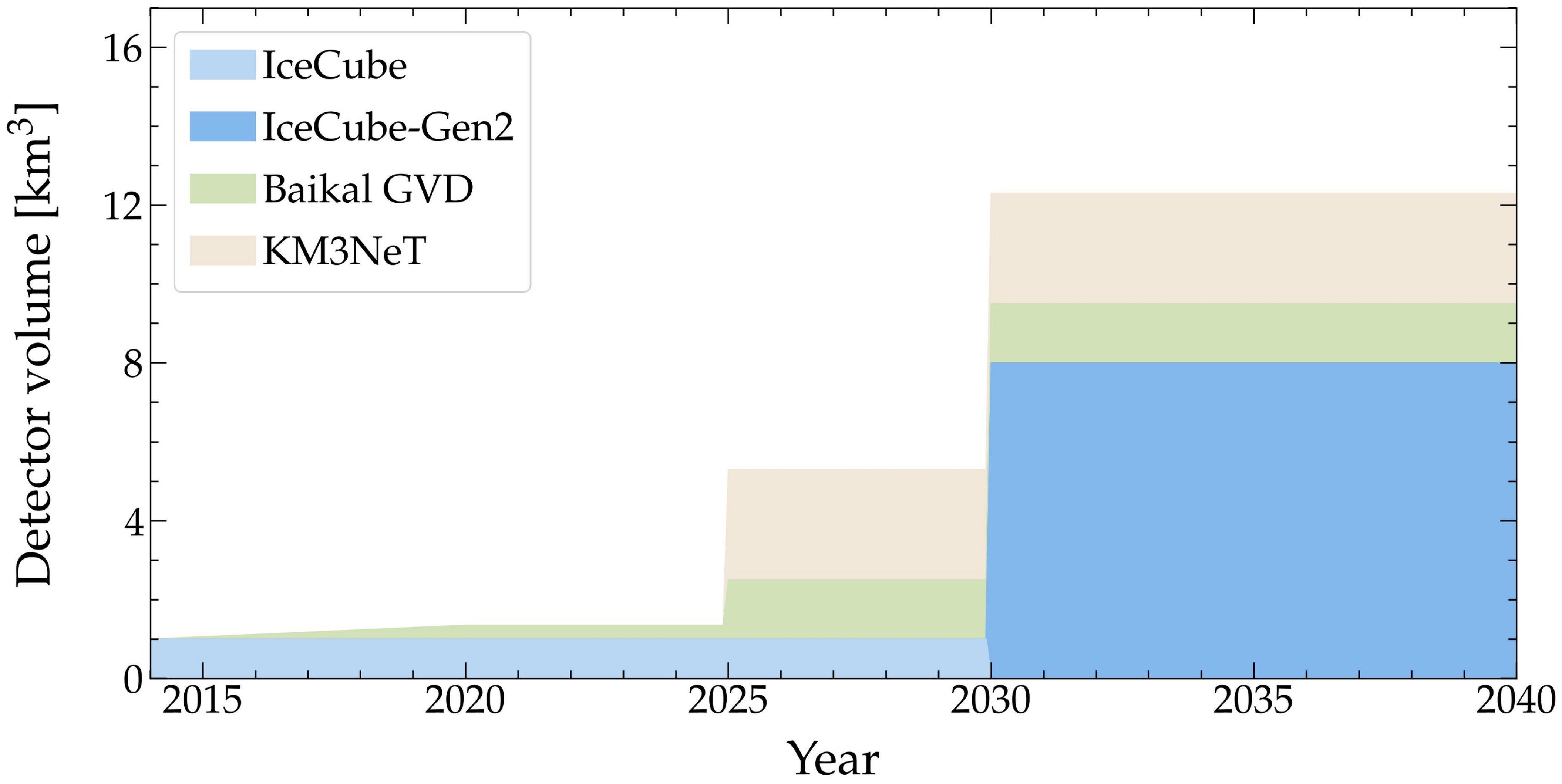

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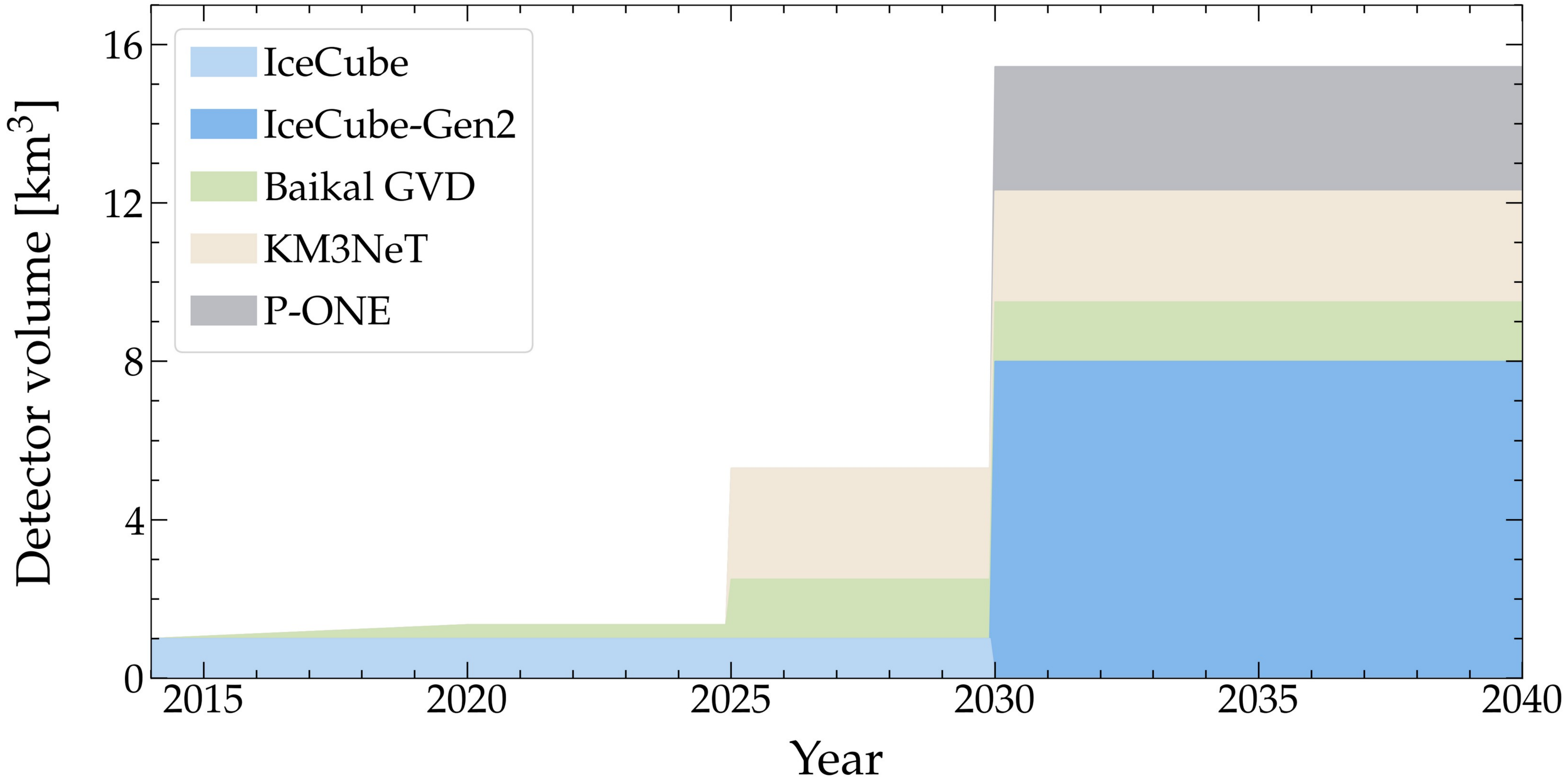

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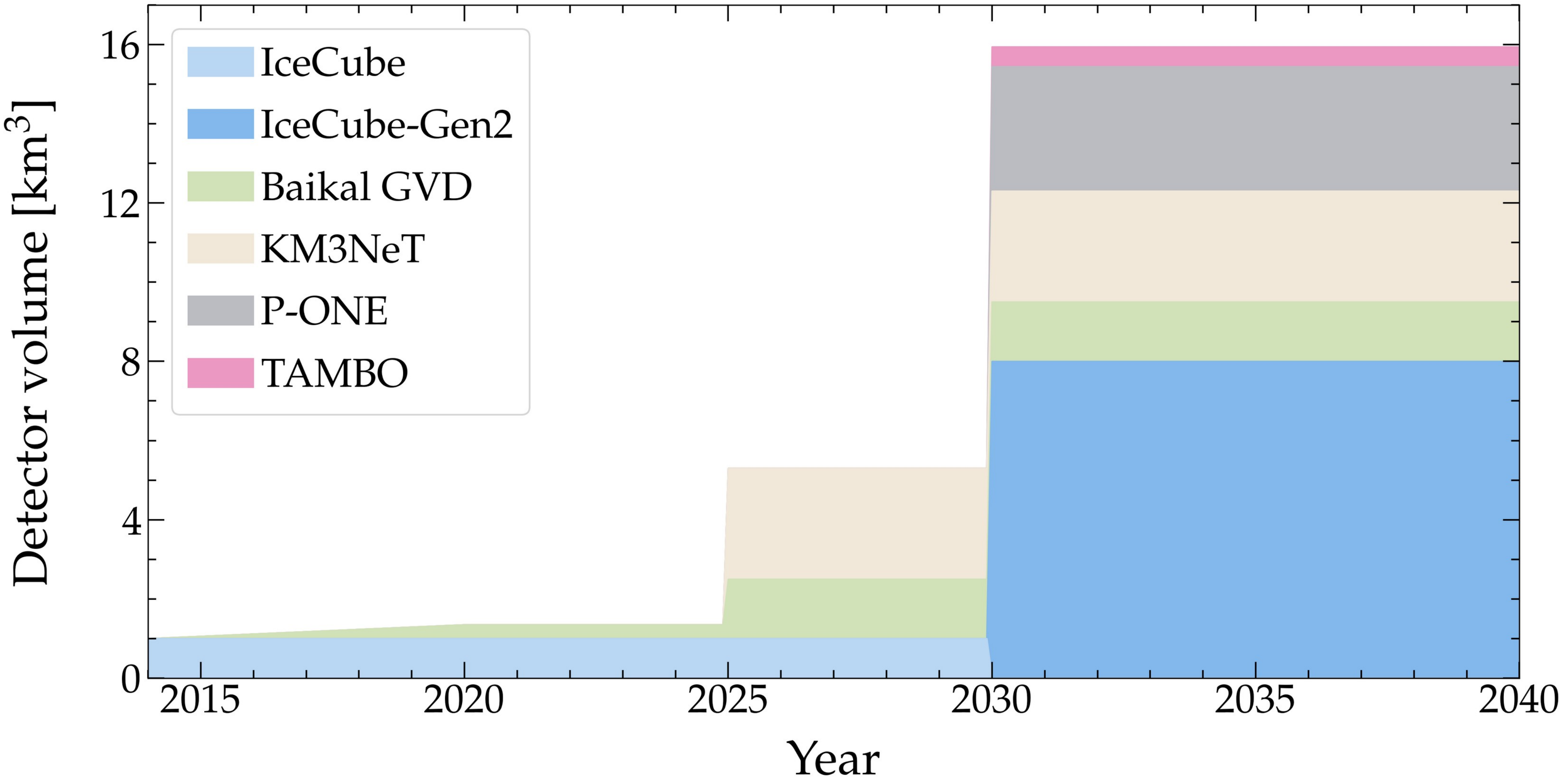
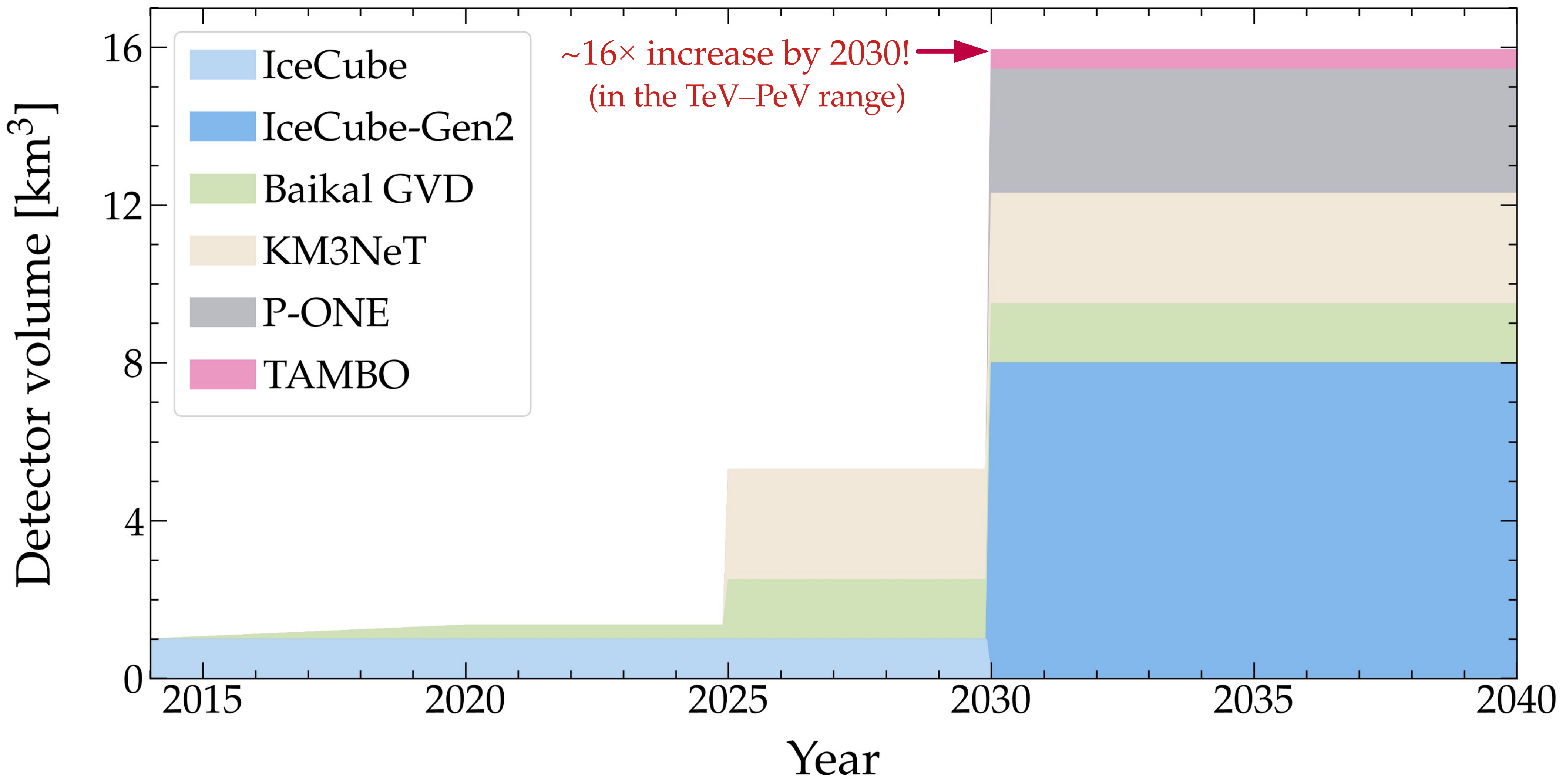


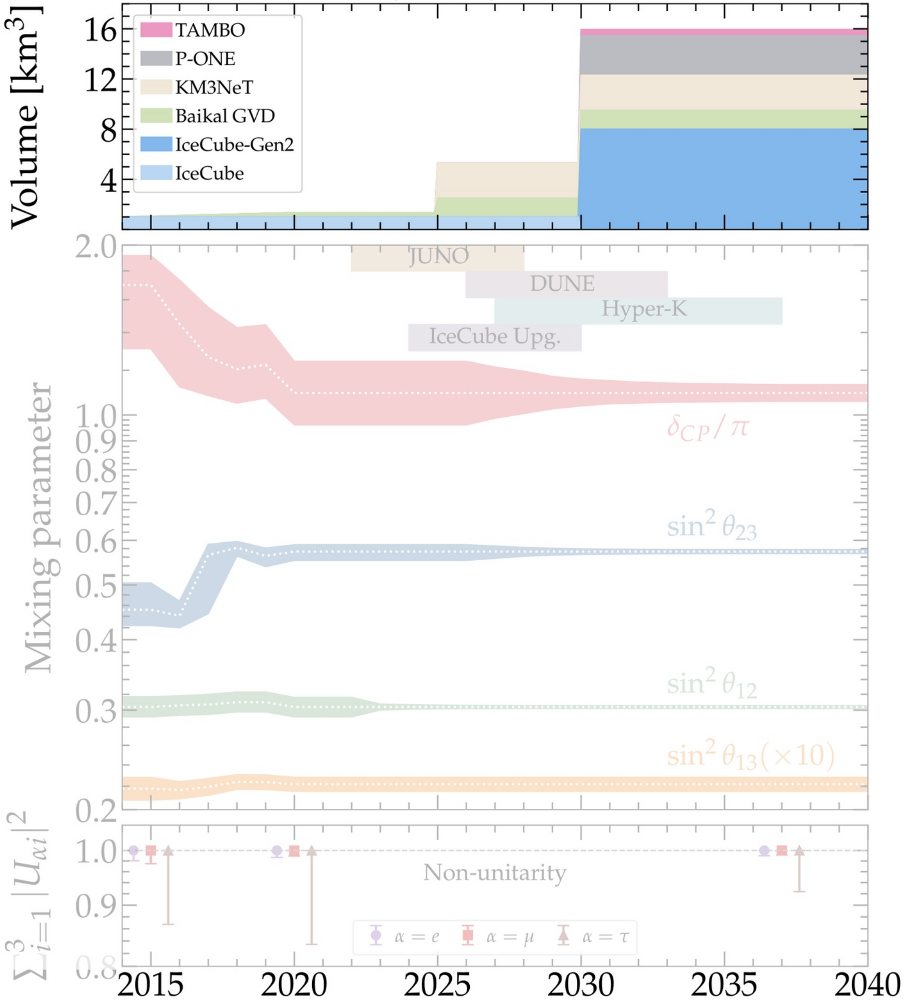
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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

Measuring flavor composition: 2015–2040

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



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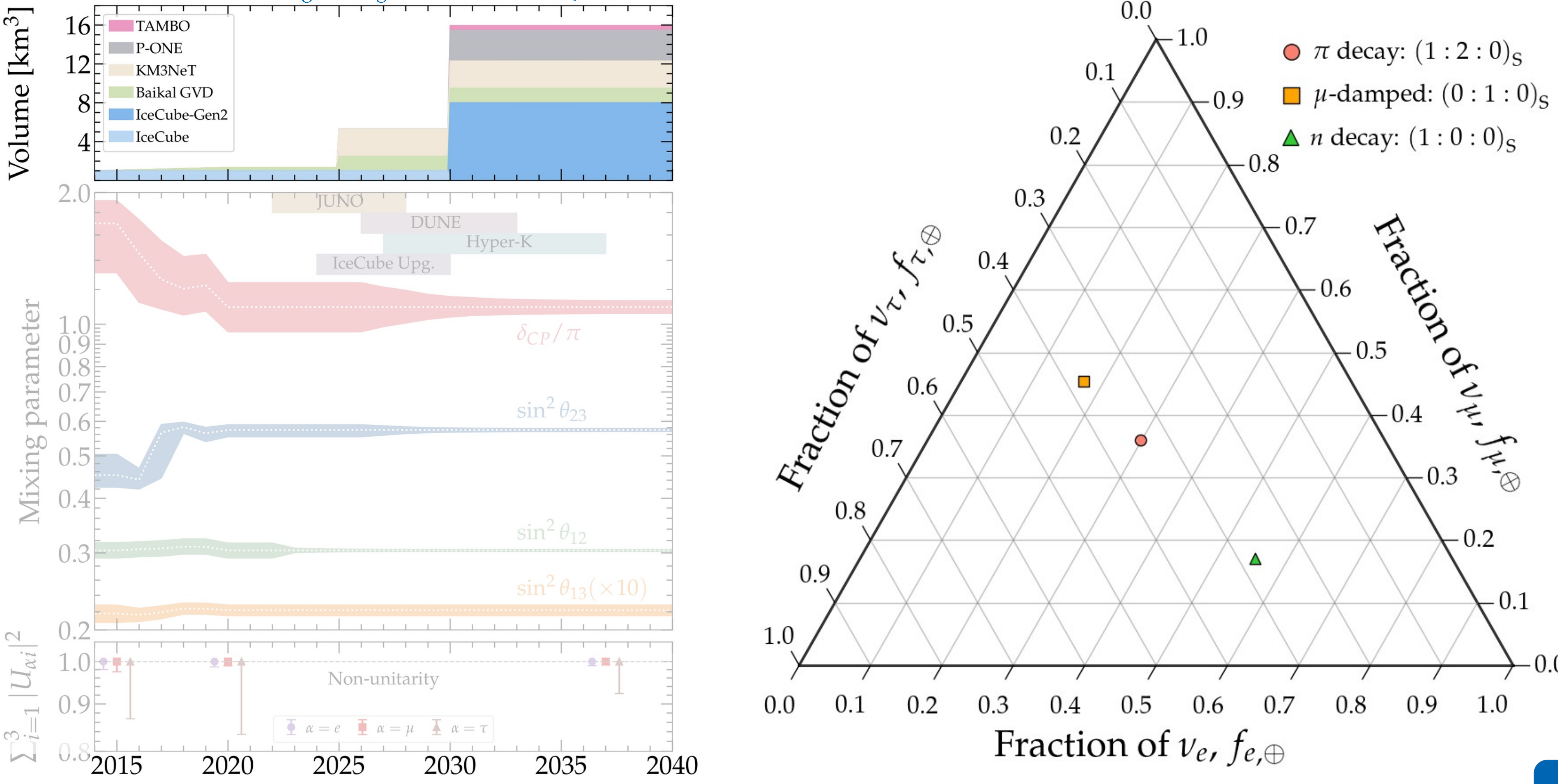

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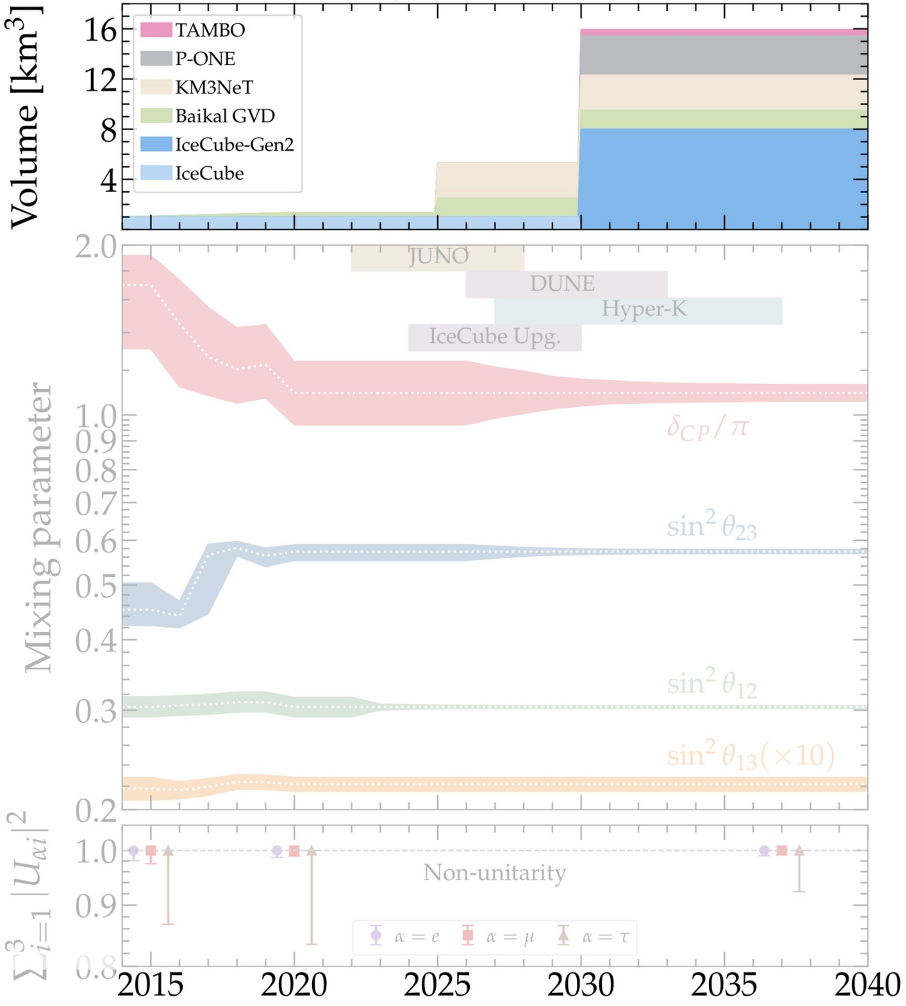

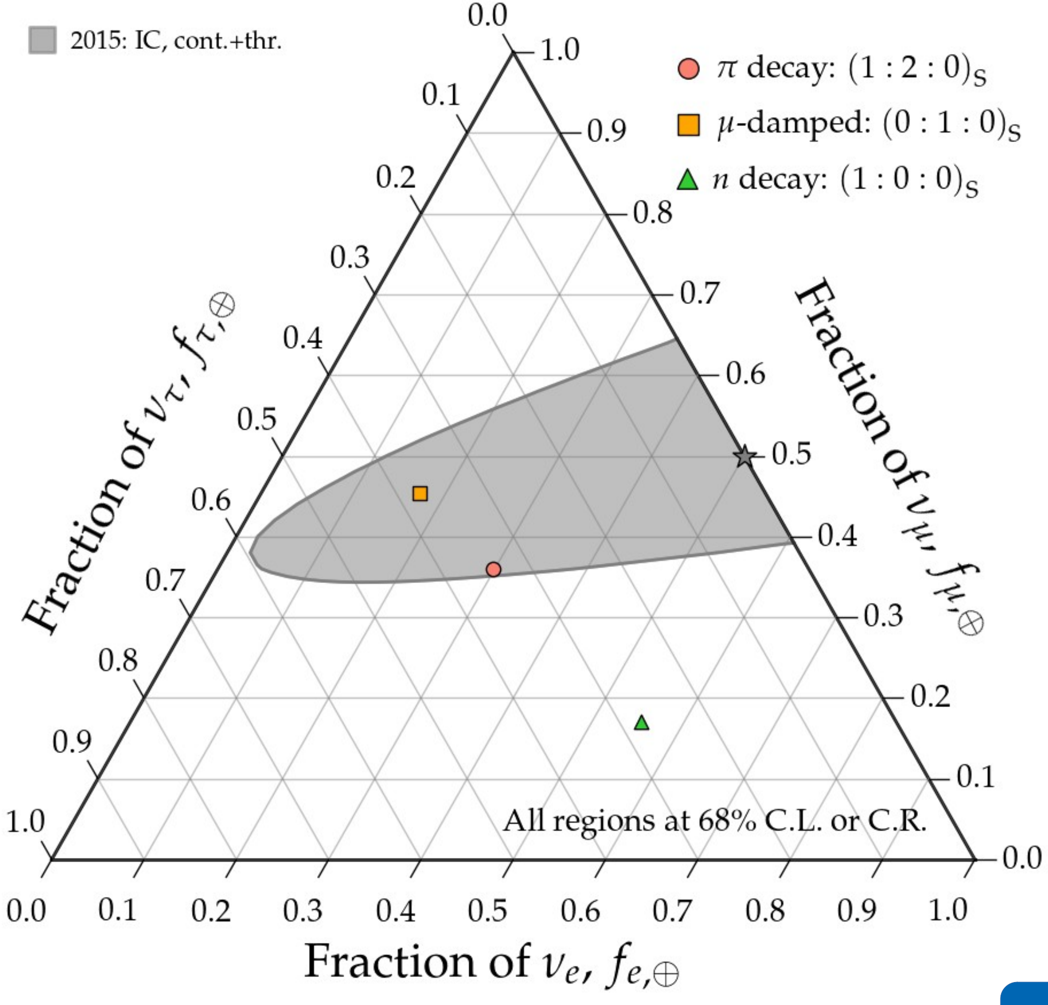

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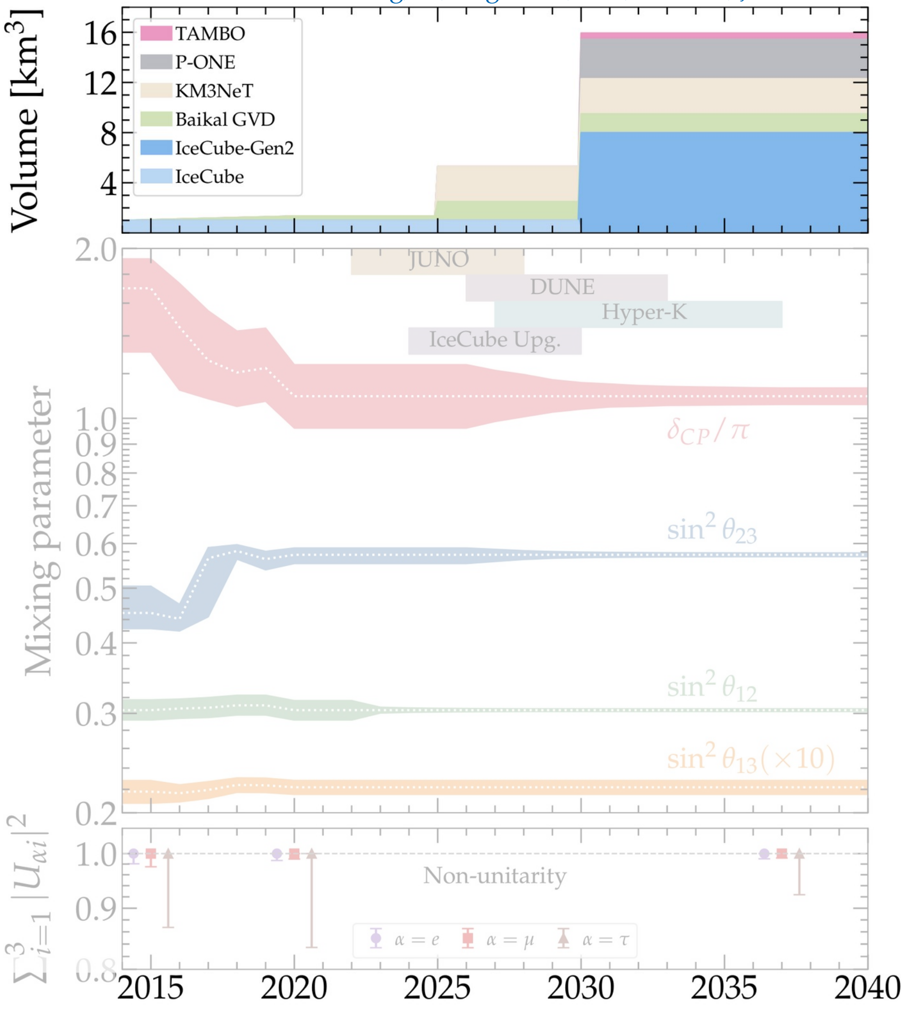

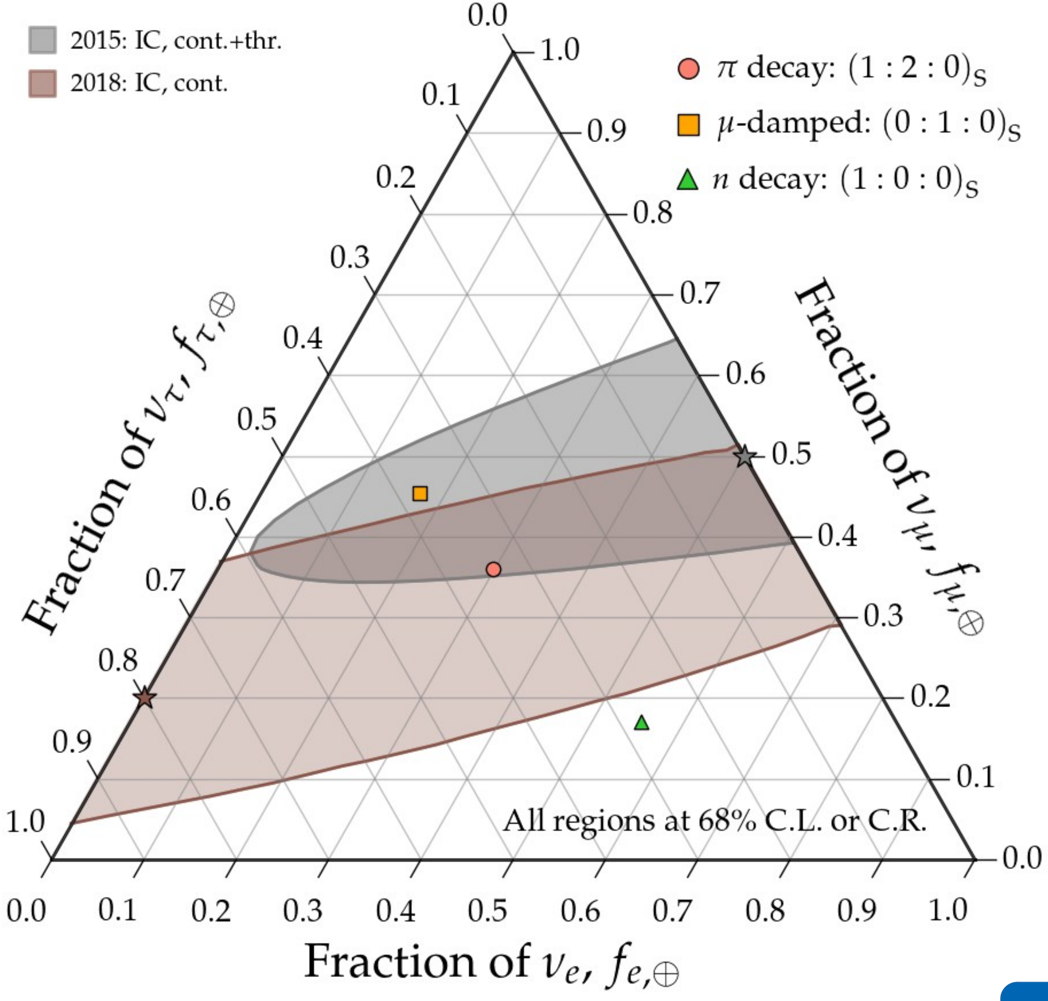

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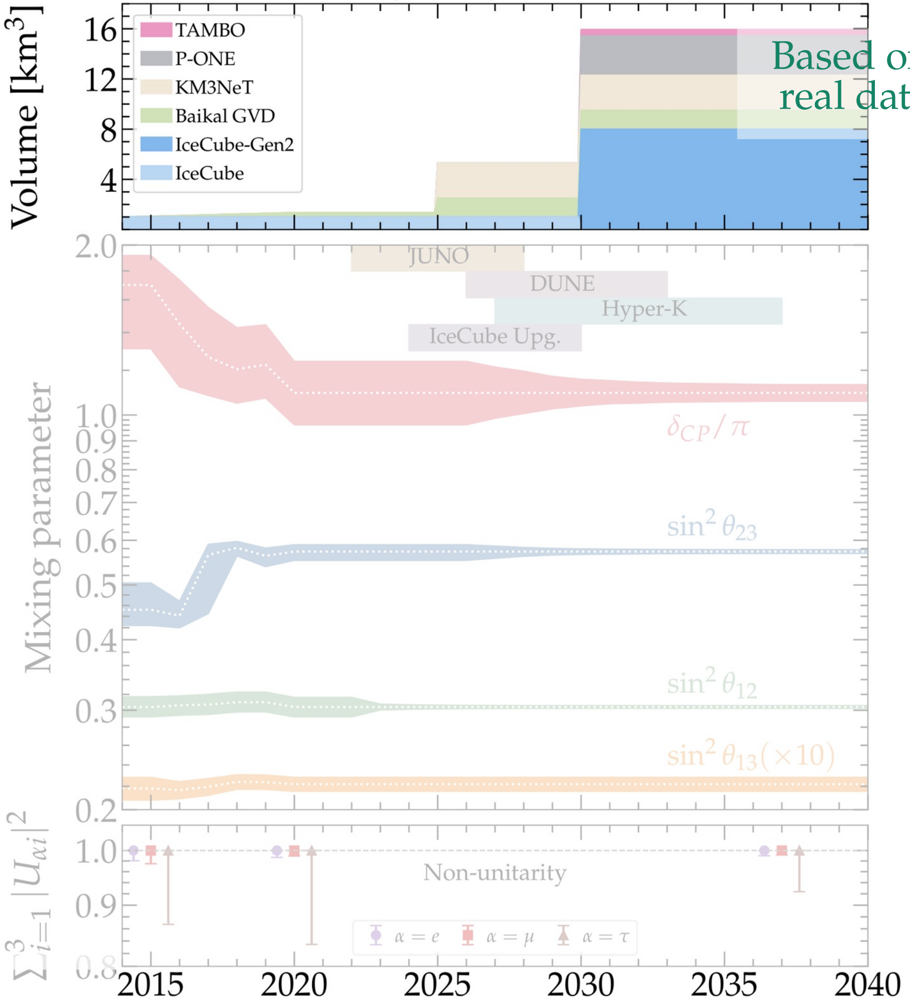
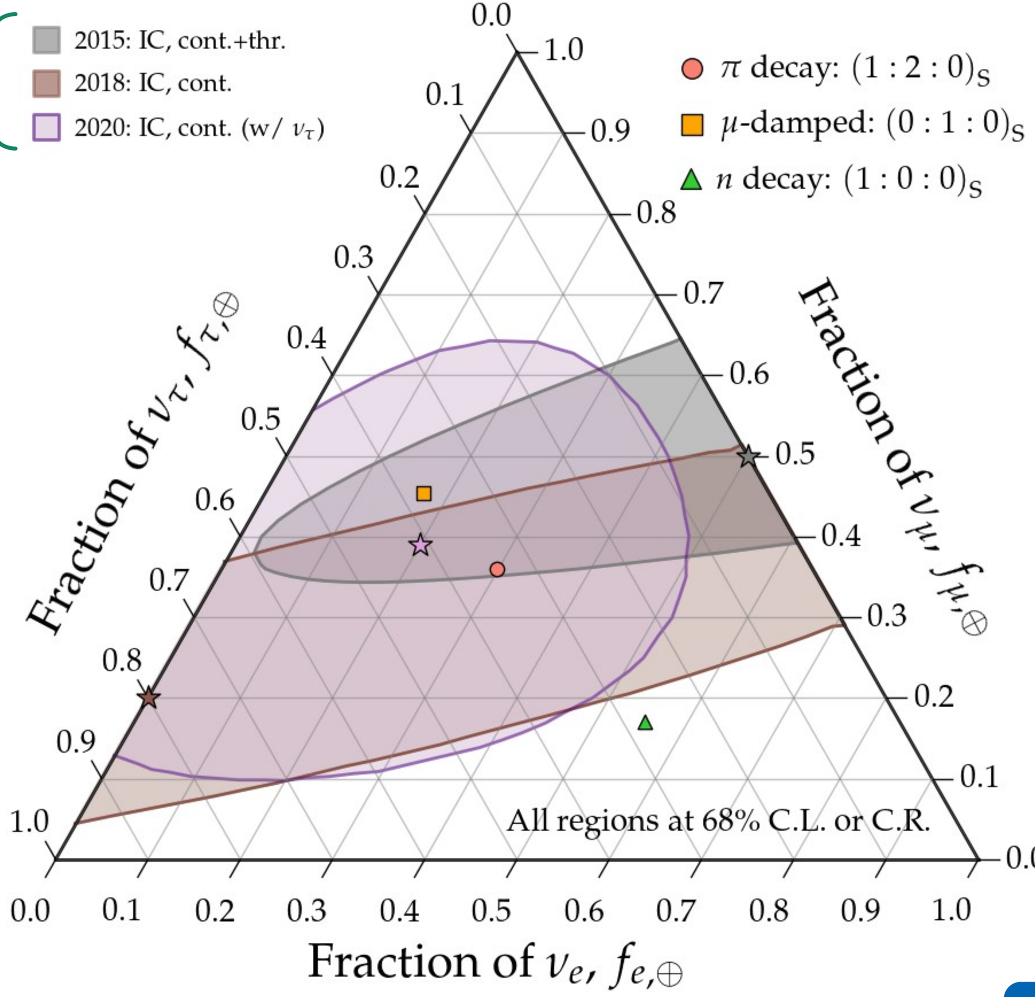
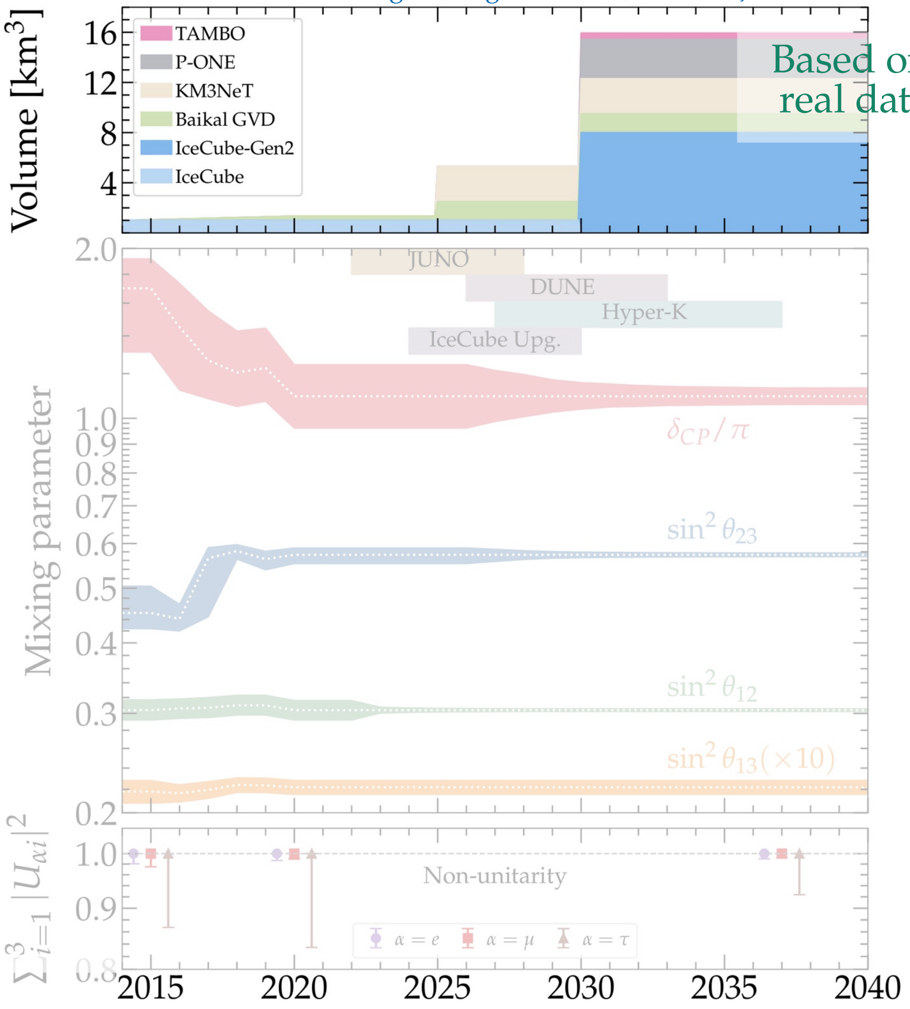


Based on real data

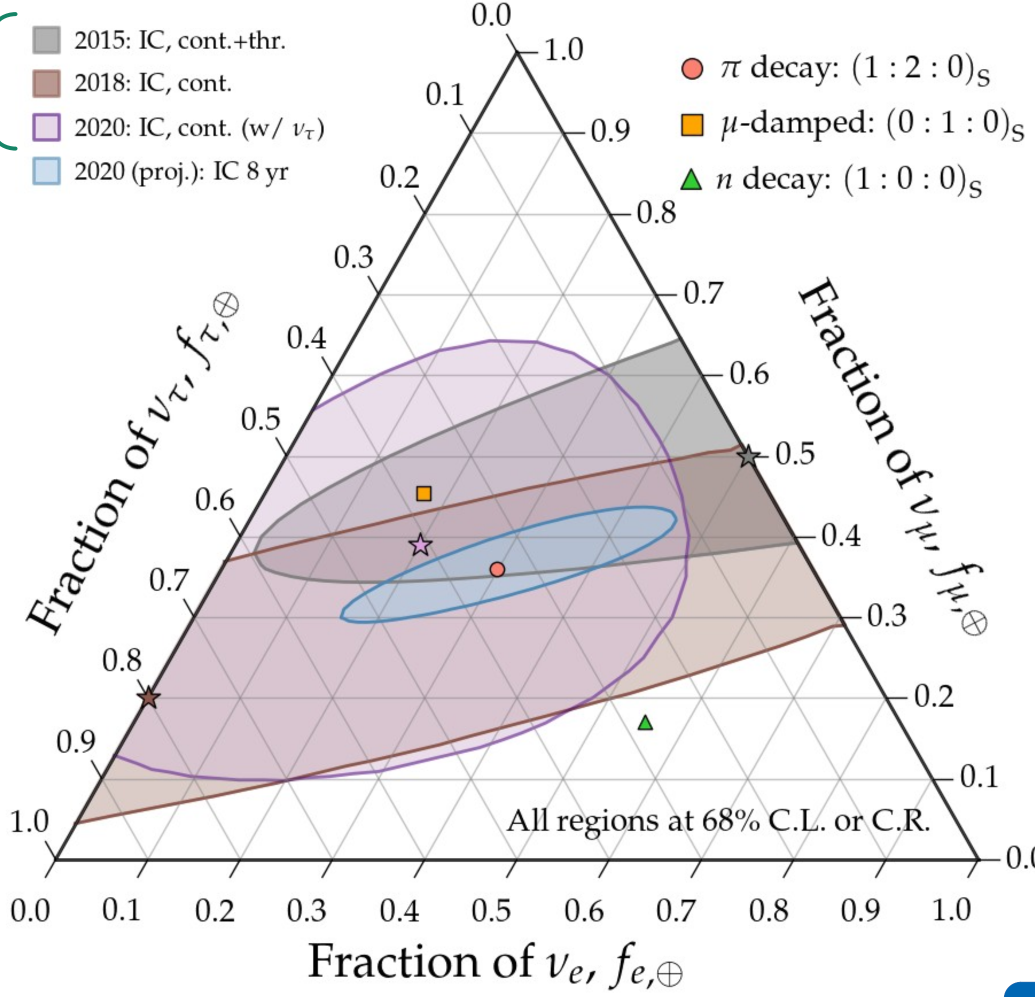


Measuring flavor composition: 2015–2040

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

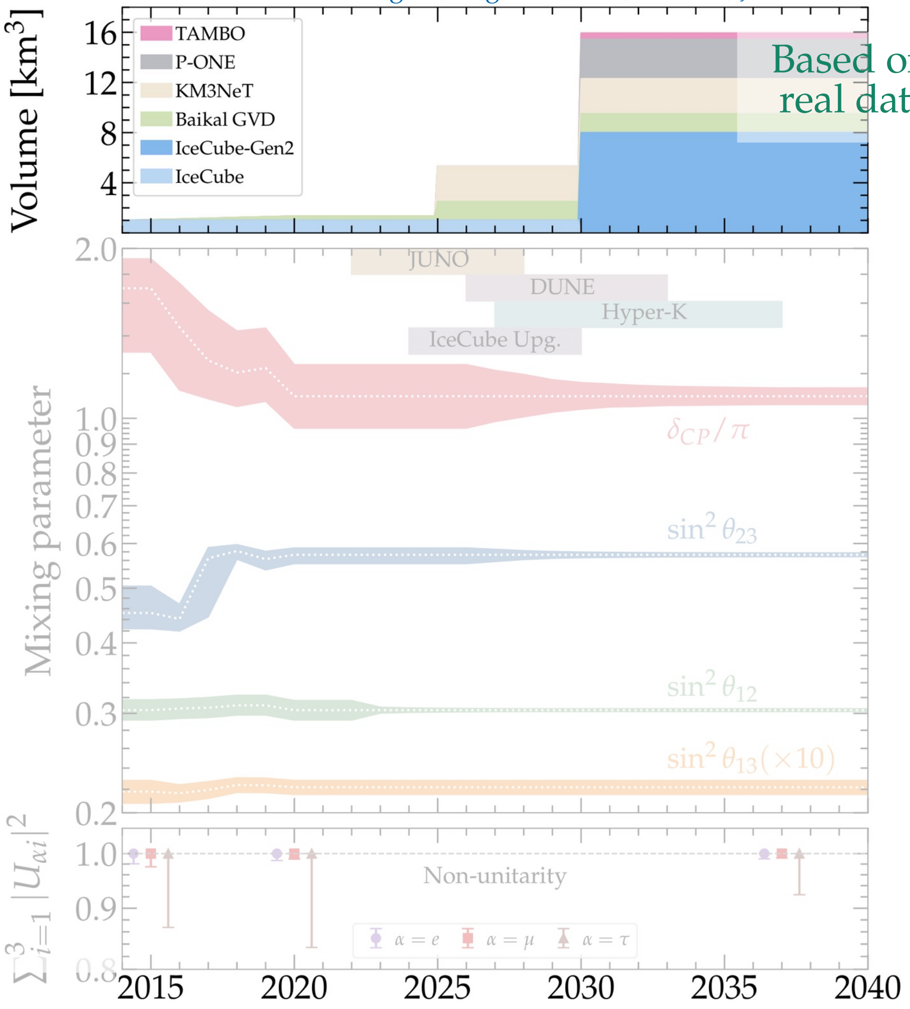


Based on real data



Measuring flavor composition: 2015–2040

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



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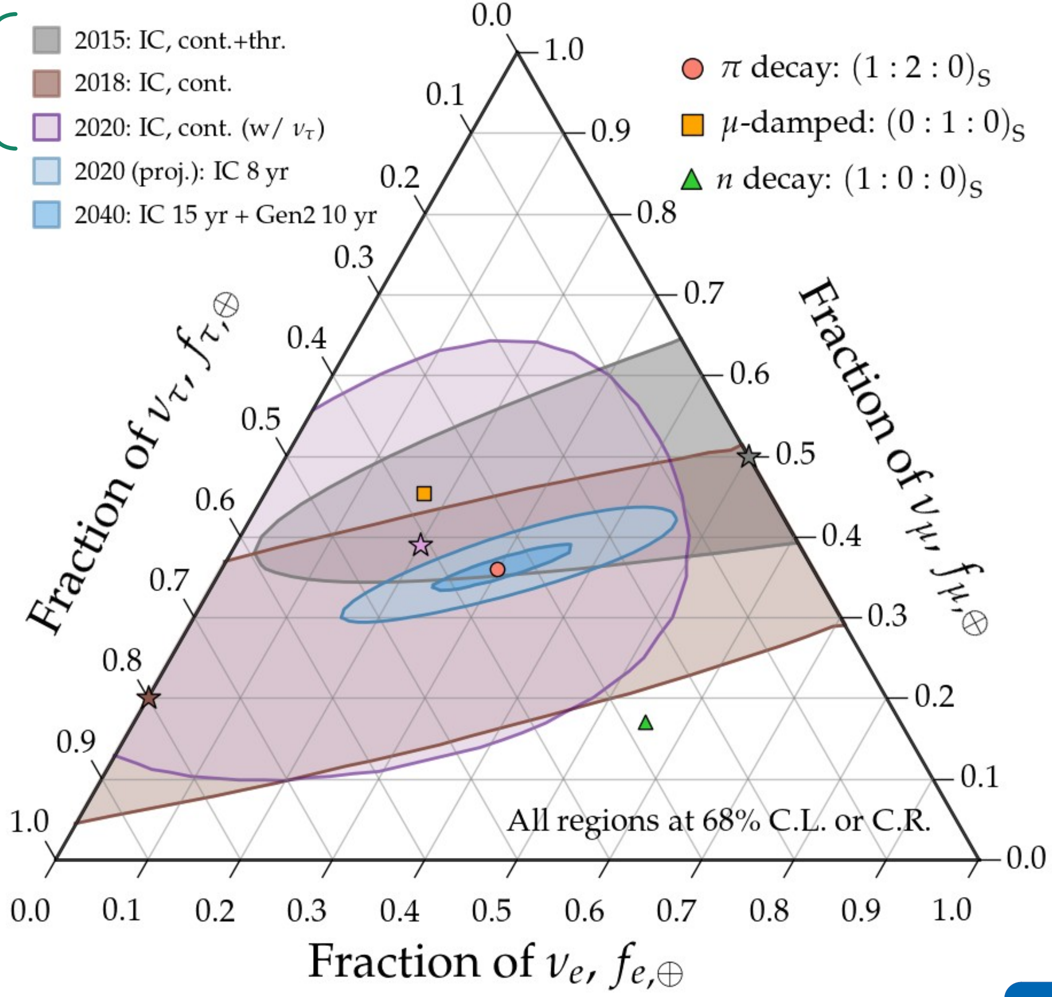
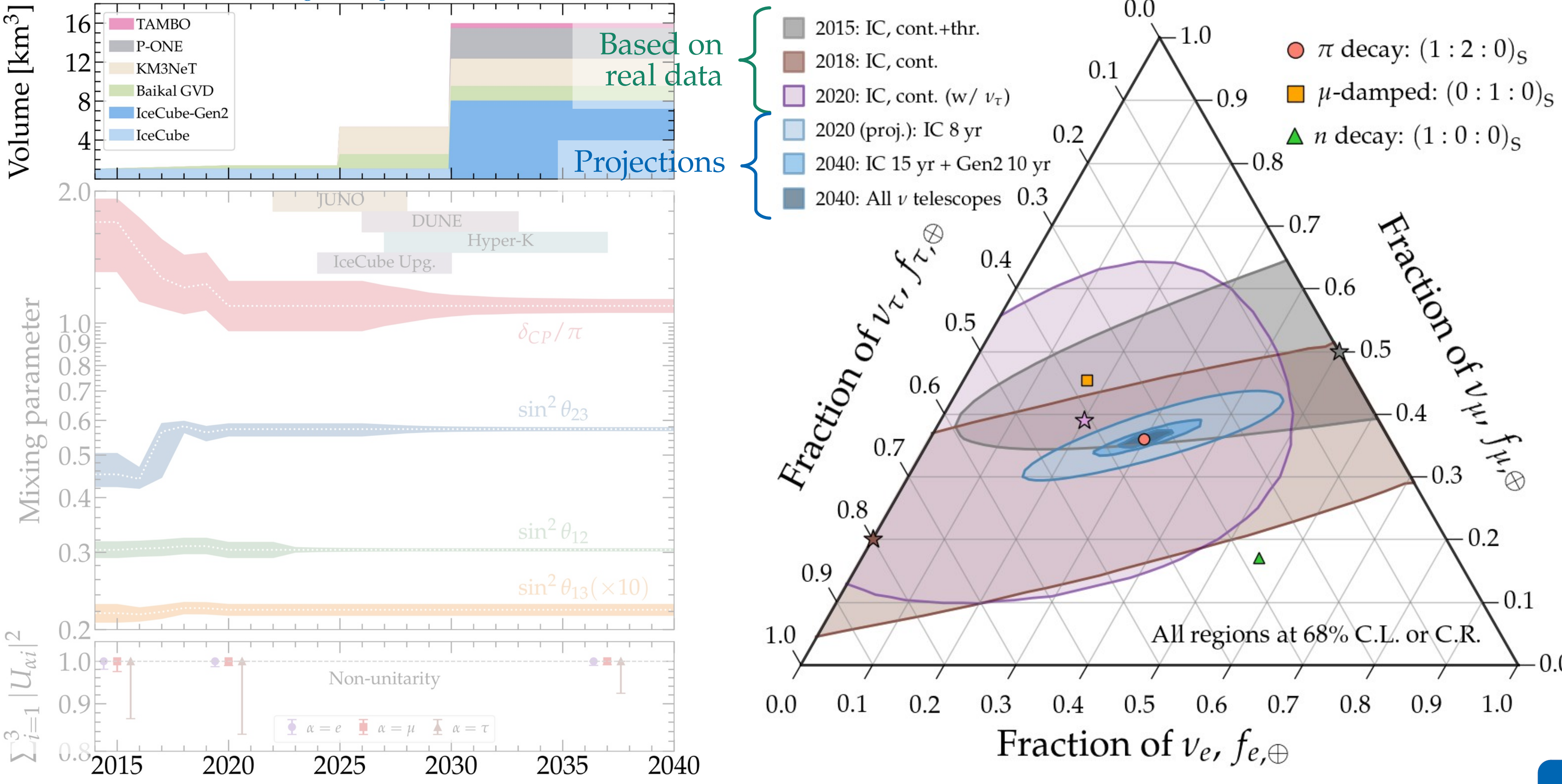
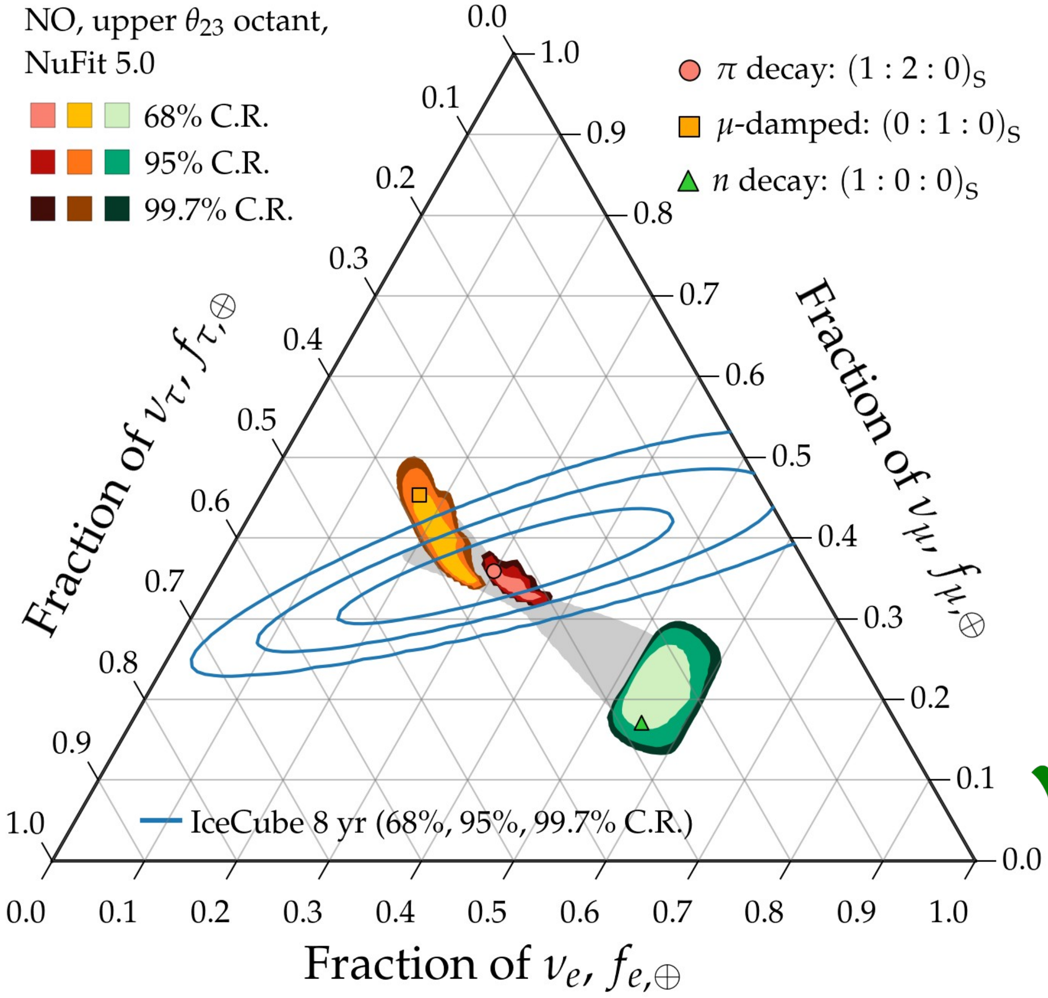


Measuring flavor composition: 2015–2040

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



Theoretically palatable regions: today



Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

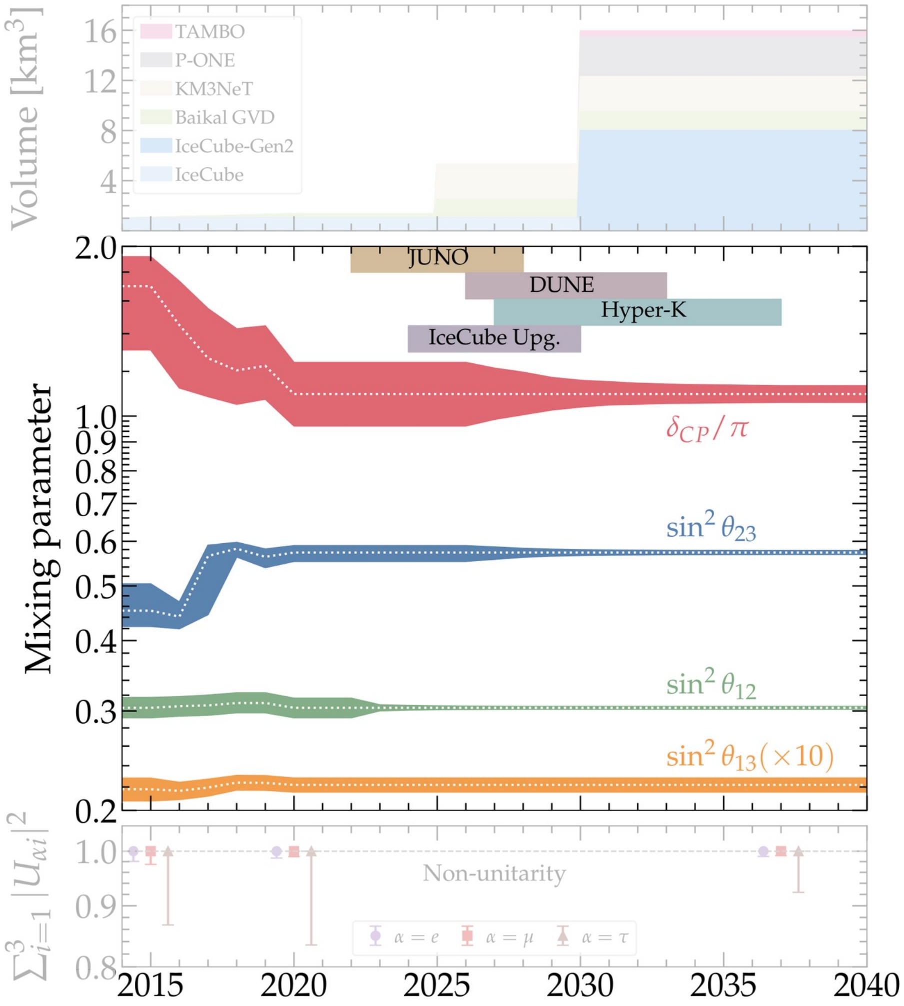
Will be overcome by 2030

Measurement of flavor ratios –
~~Cannot distinguish between pion-decay and muon-damped benchmarks even at 68% C.R. (1σ)~~

✓ *Will be overcome by 2040*

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

How knowing the mixing parameters better helps



We can compute the oscillation probability more precisely:

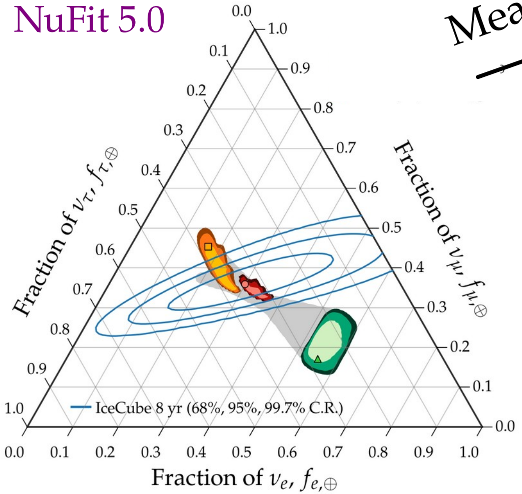
$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\beta\alpha} f_{\beta,\mathrm{S}}$$

So we can convert back and forth between source and Earth more precisely

How knowing the mixing parameters better helps

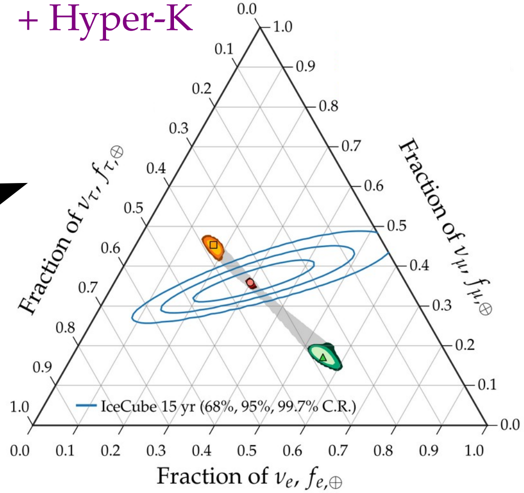
2020

NuFit 5.0



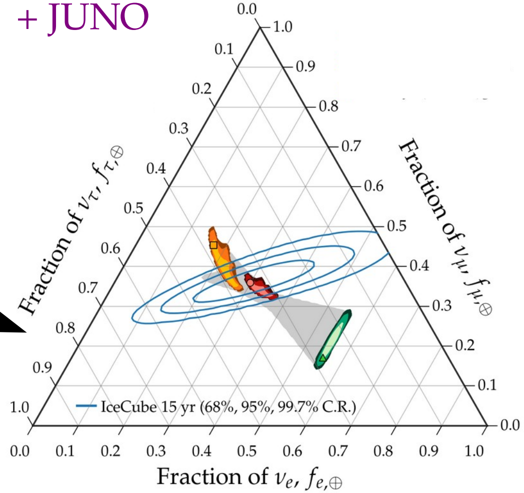
Measure θ_{23} better

+ Hyper-K



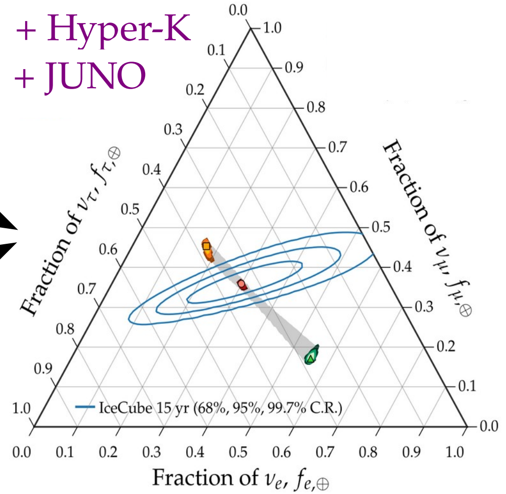
Measure θ_{12} better

+ JUNO



~2030

+ Hyper-K
+ JUNO



In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

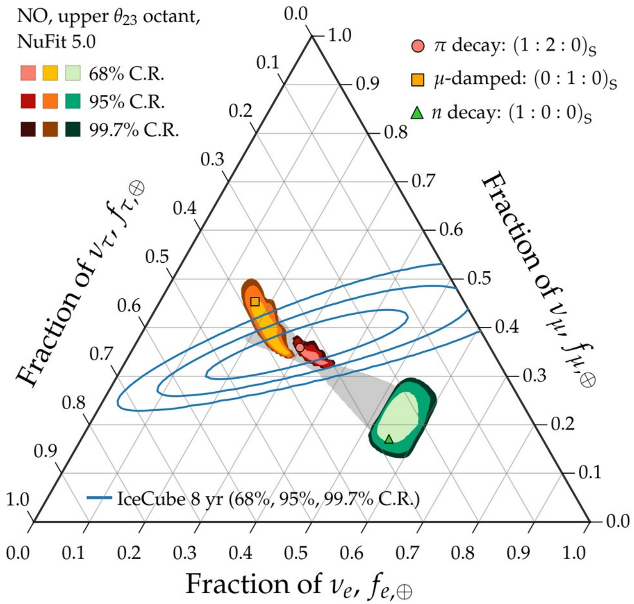
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: 2020 $\rightarrow$ 2030 $\rightarrow$ 2040

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



Allowed regions: overlapping

Measurement: imprecise

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

Theoretically palatable regions: 2020 → 2030 → 2040

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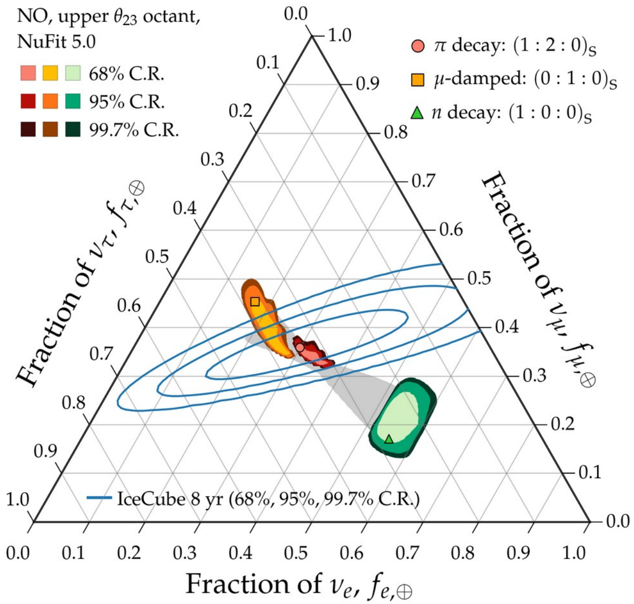

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Not ideal

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

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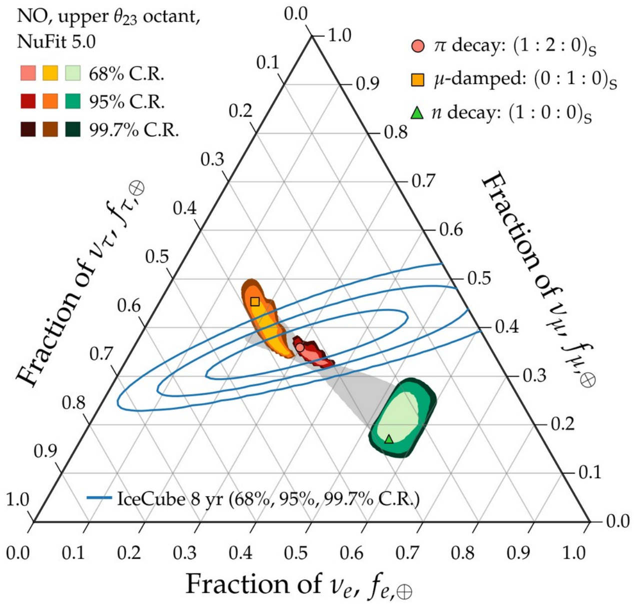

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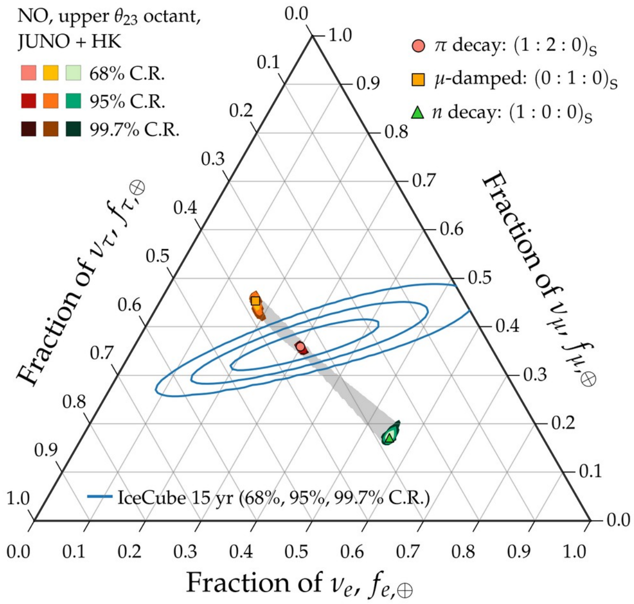
2030



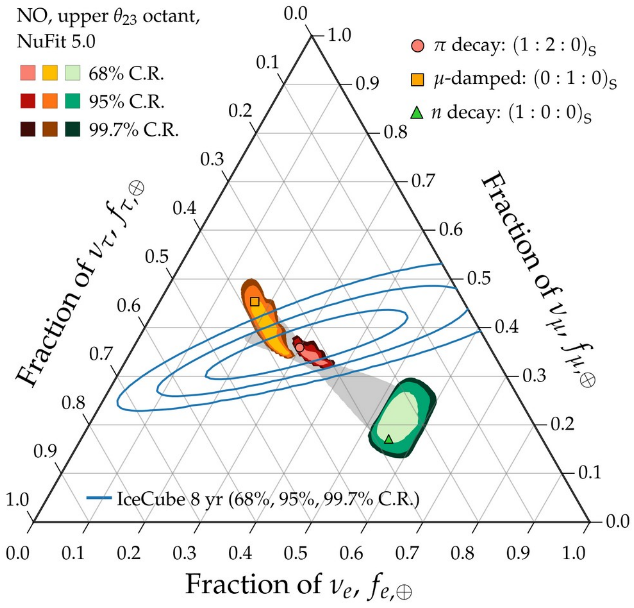
Allowed regions: well separated

Measurement: improving

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



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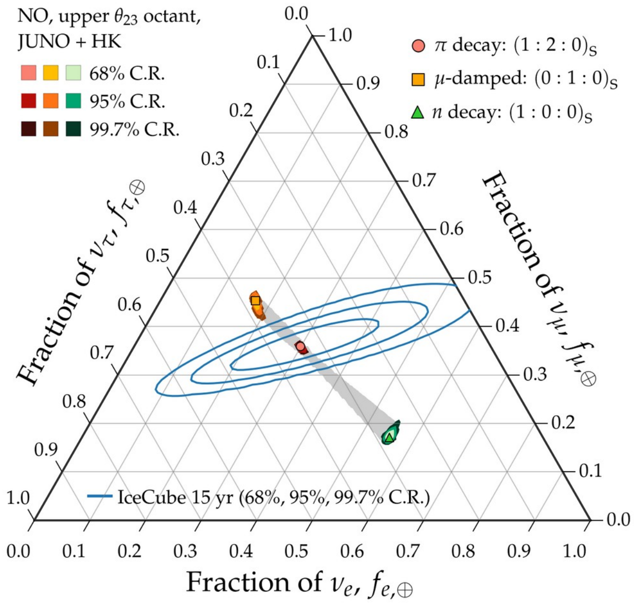


Allowed regions: well separated

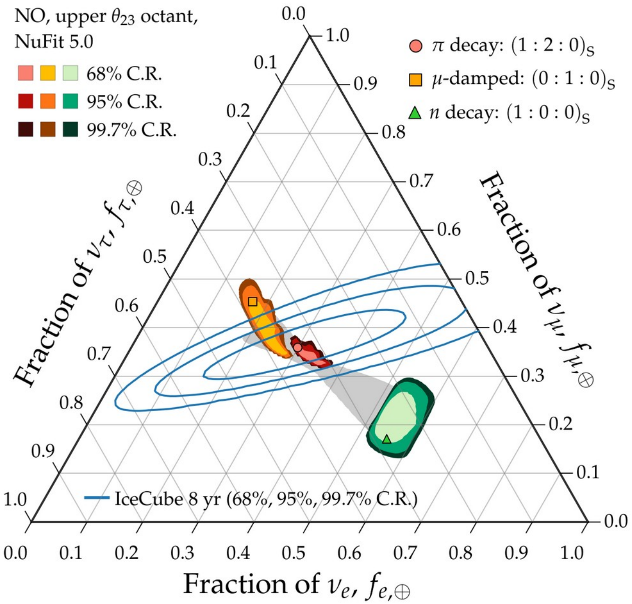
Measurement: improving

Nice

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



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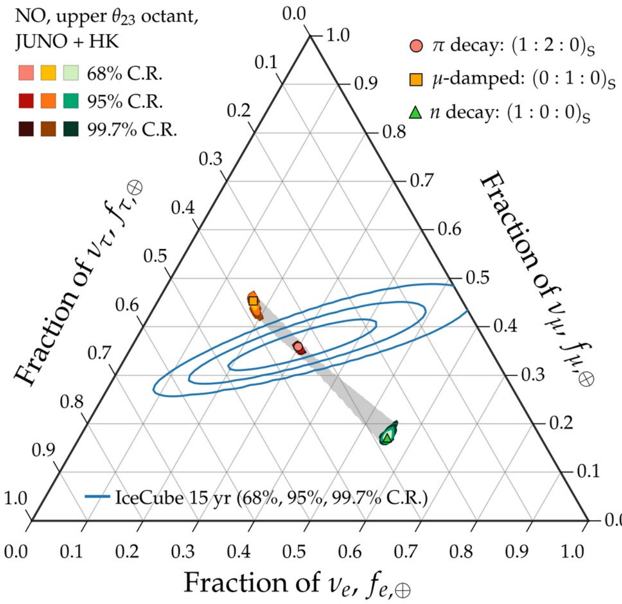

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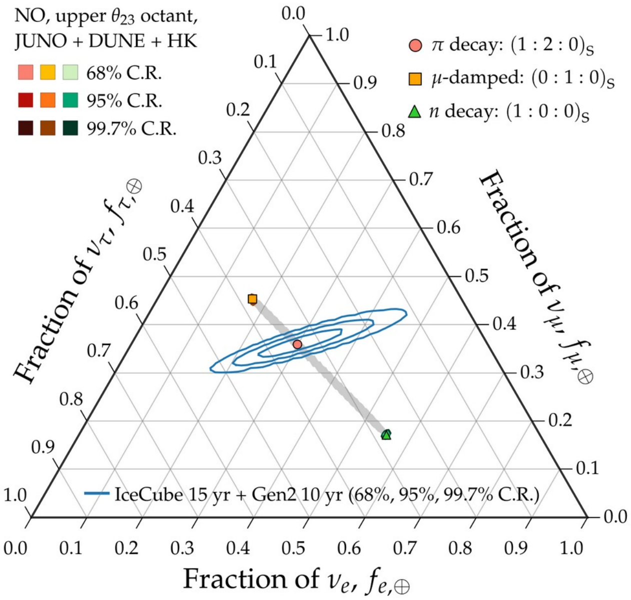
2040

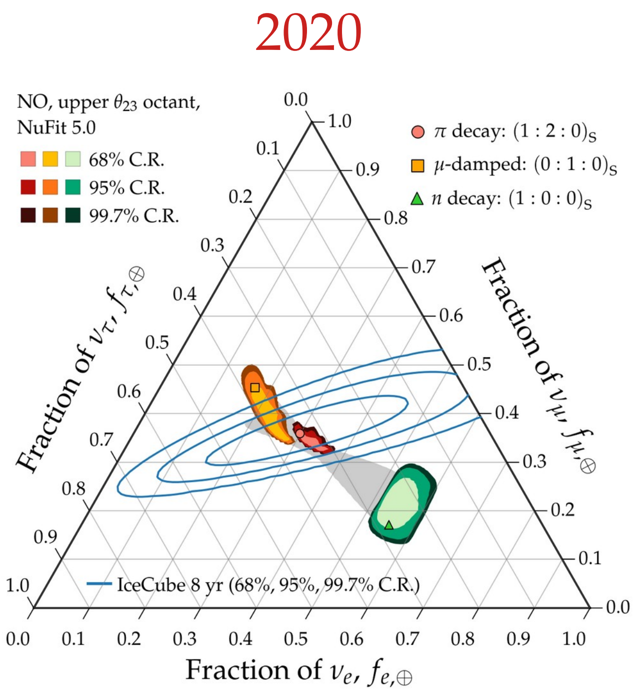


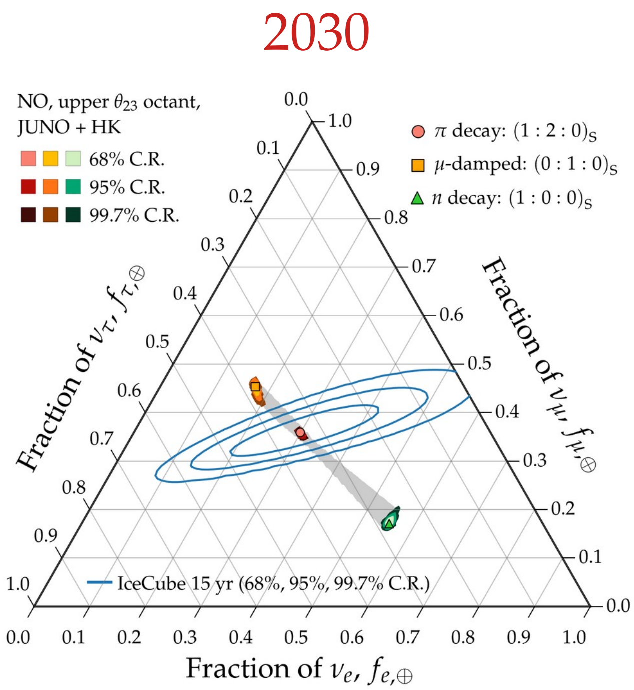
Allowed regions: well separated

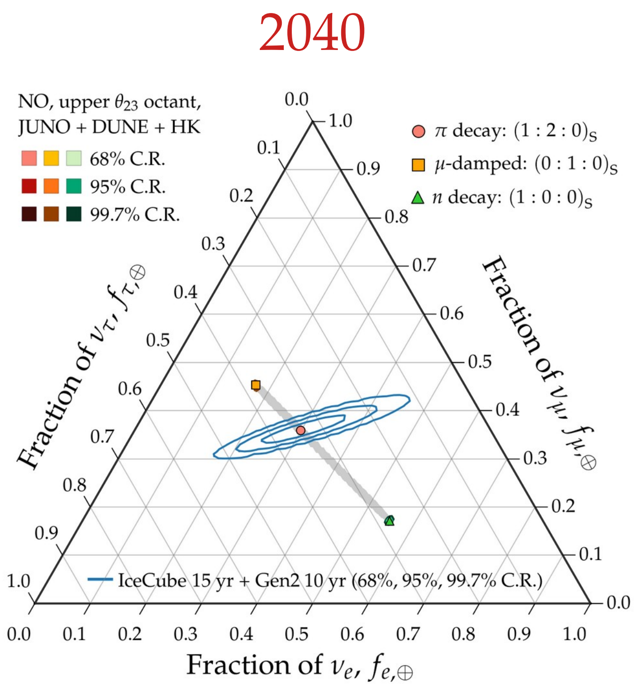
Measurement: precise

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

Theoretically palatable regions: 2020 → 2030 → 2040







Allowed regions: overlapping
Measurement: imprecise

Not ideal

Allowed regions: well separated
Measurement: improving

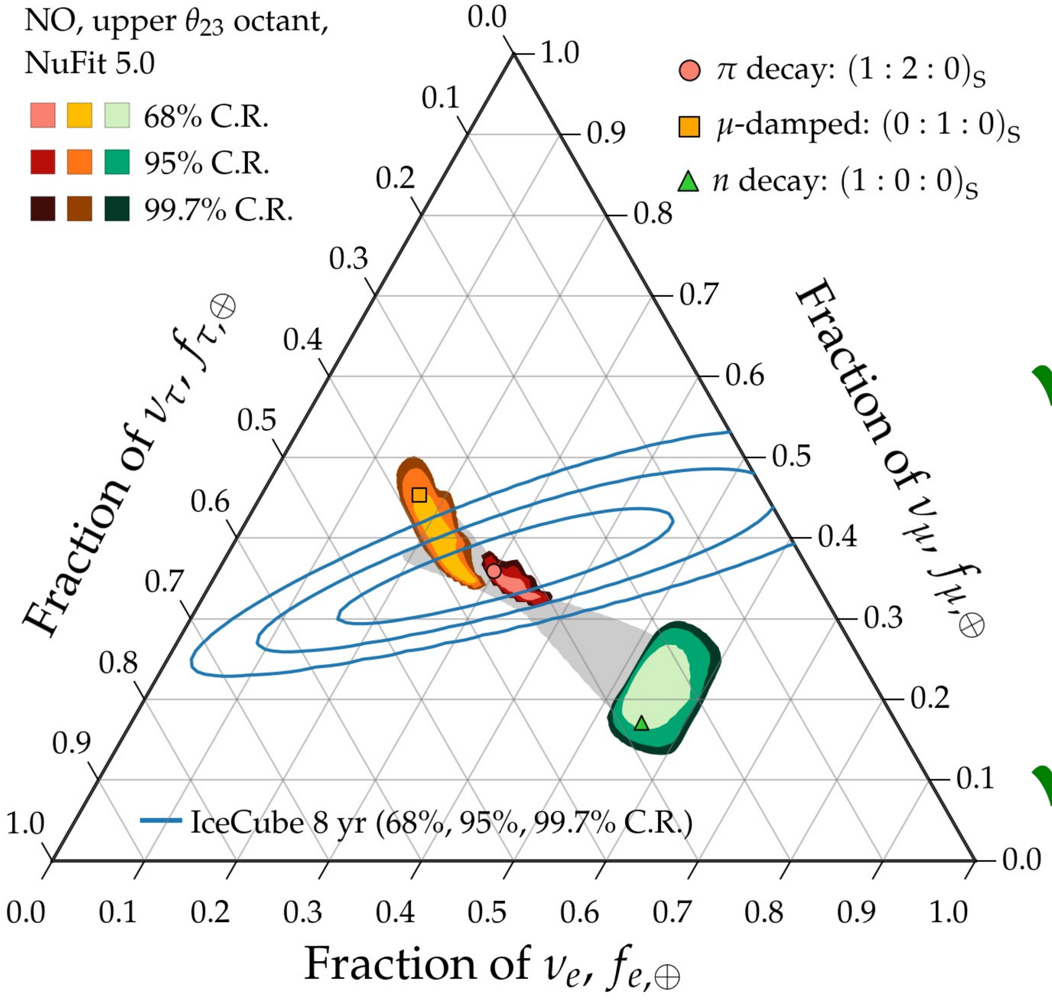
Nice

Allowed regions: well separated
Measurement: precise

Success

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

Theoretically palatable regions: today



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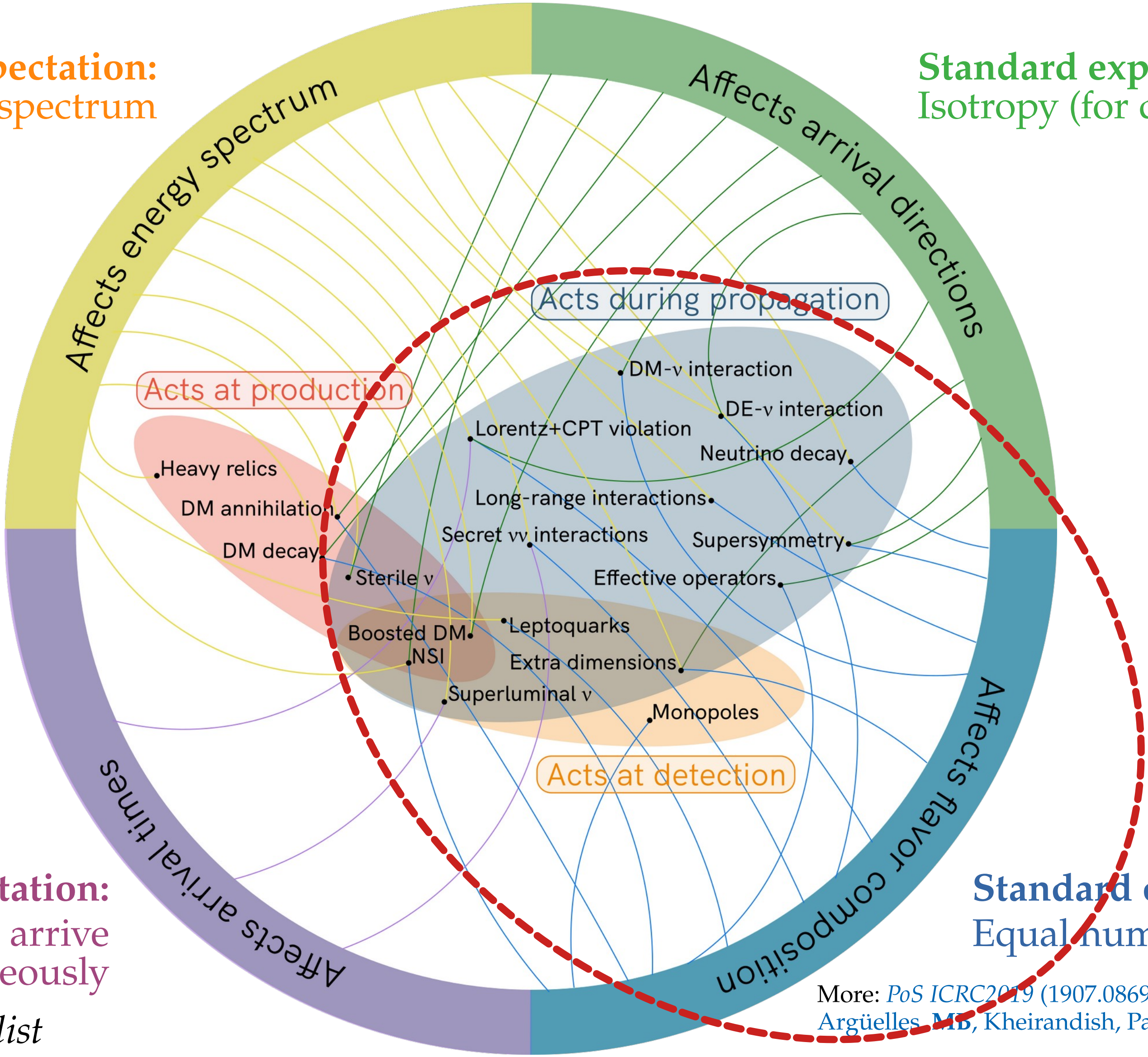
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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

Repurpose the flavor sensitivity to test new physics:

New physics in flavor composition

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Reviews:
Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

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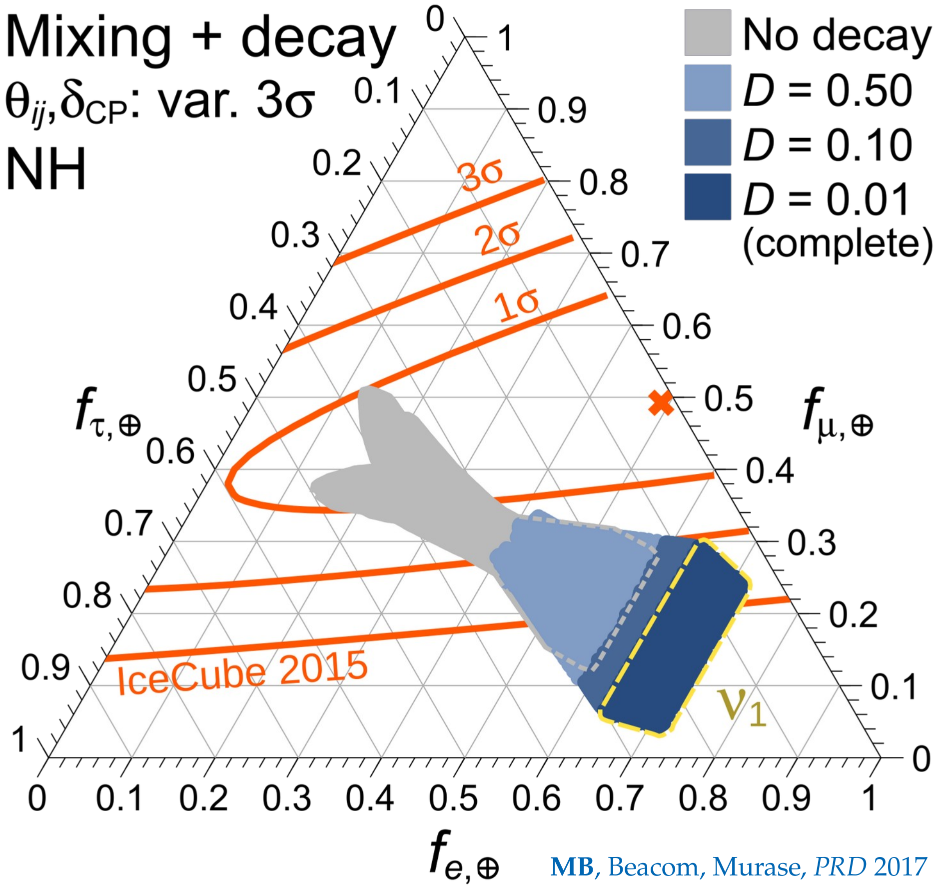
Repurpose the flavor sensitivity to test new physics:

- Neutrino decay
  [Beacom *et al.*, *PRL* 2003; Baerwald, **MB**, Winter, JCAP 2010; **MB**, Beacom, Winter, *PRL* 2015; **MB**, Beacom, Murase, *PRD* 2017]



MB, Beacom, Murase, *PRD* 2017

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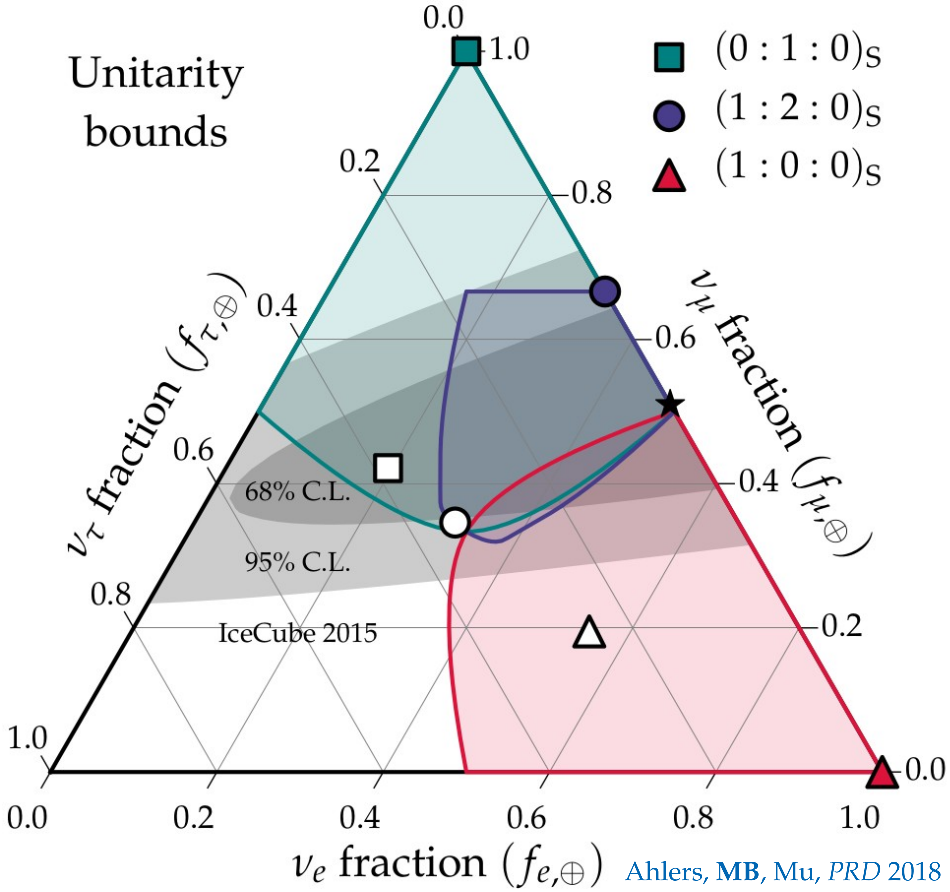

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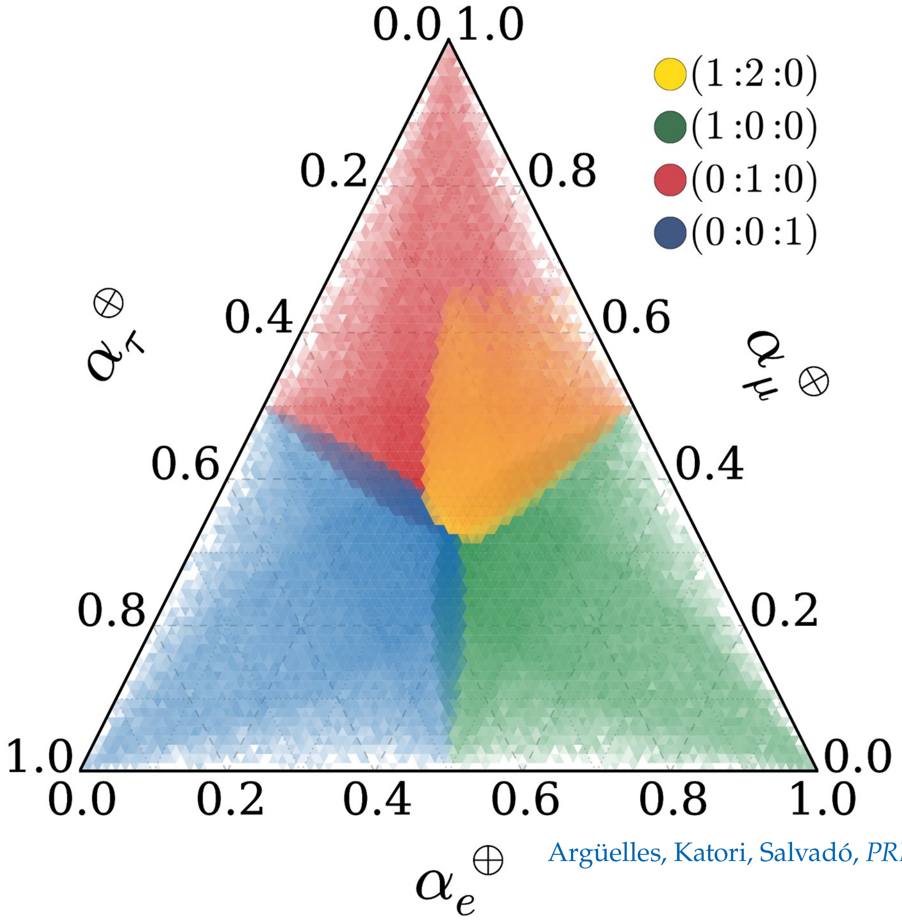

Argüelles, Katori, Salvadó, *PRL* 2015

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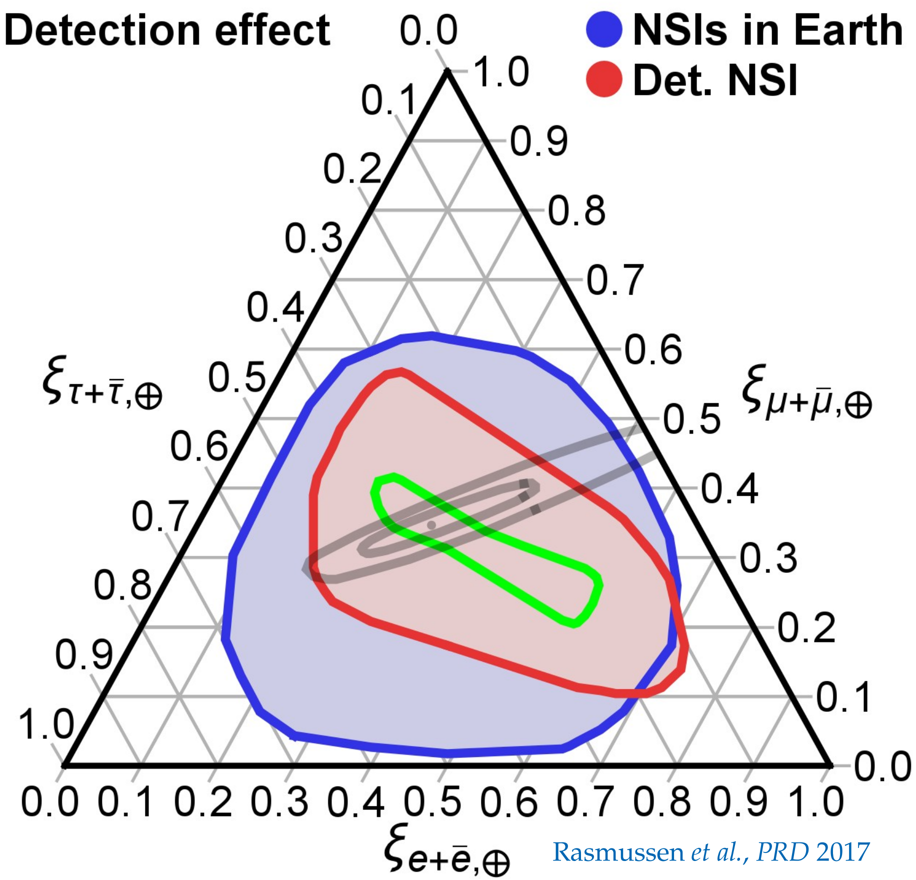

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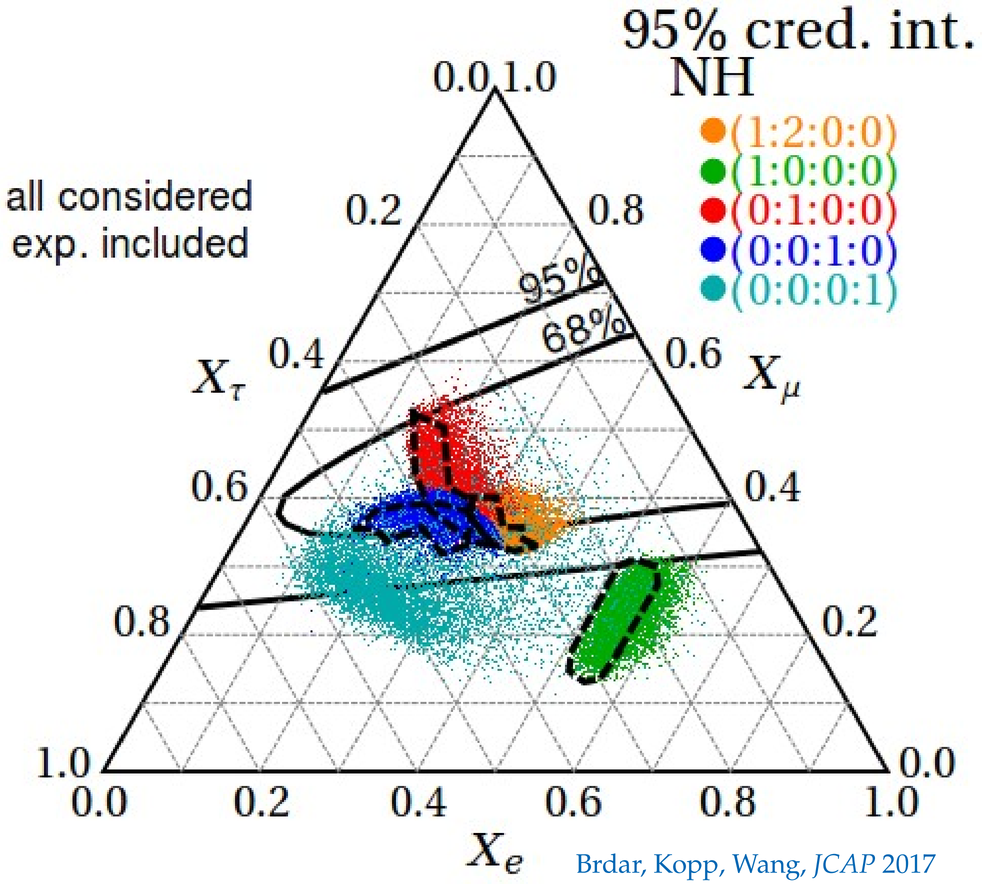

Brdar, Kopp, Wang, *JCAP* 2017

Reviews:
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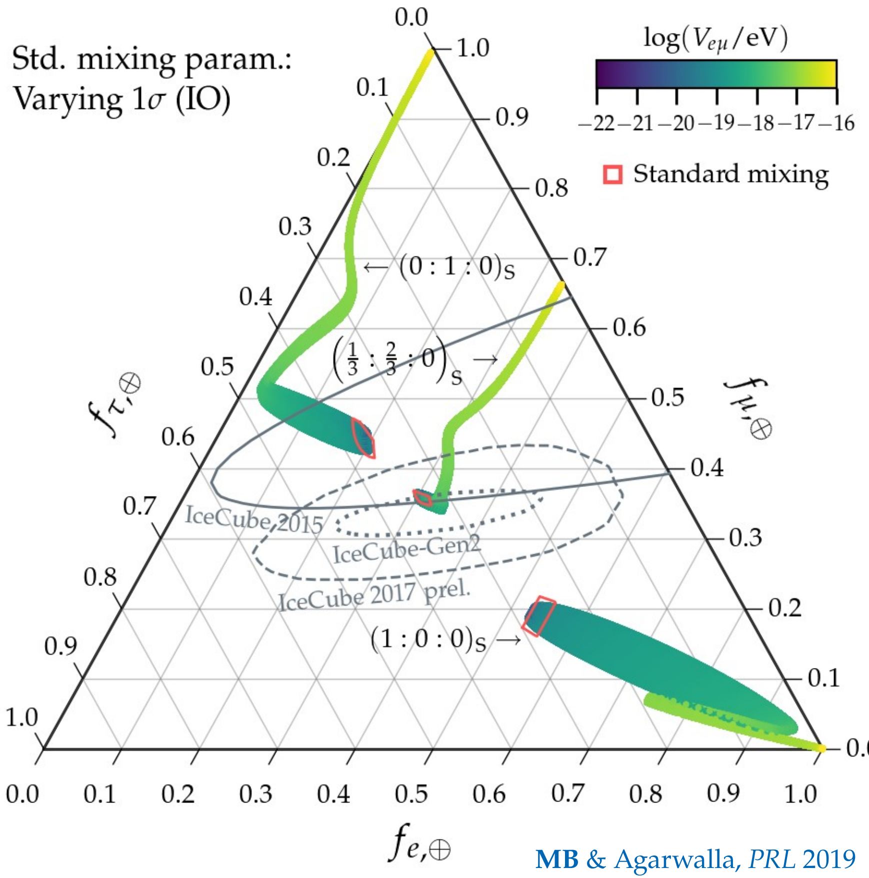
- **Long-range *e*ν interactions**
  [**MB** & Agarwalla, *PRL* 2019]

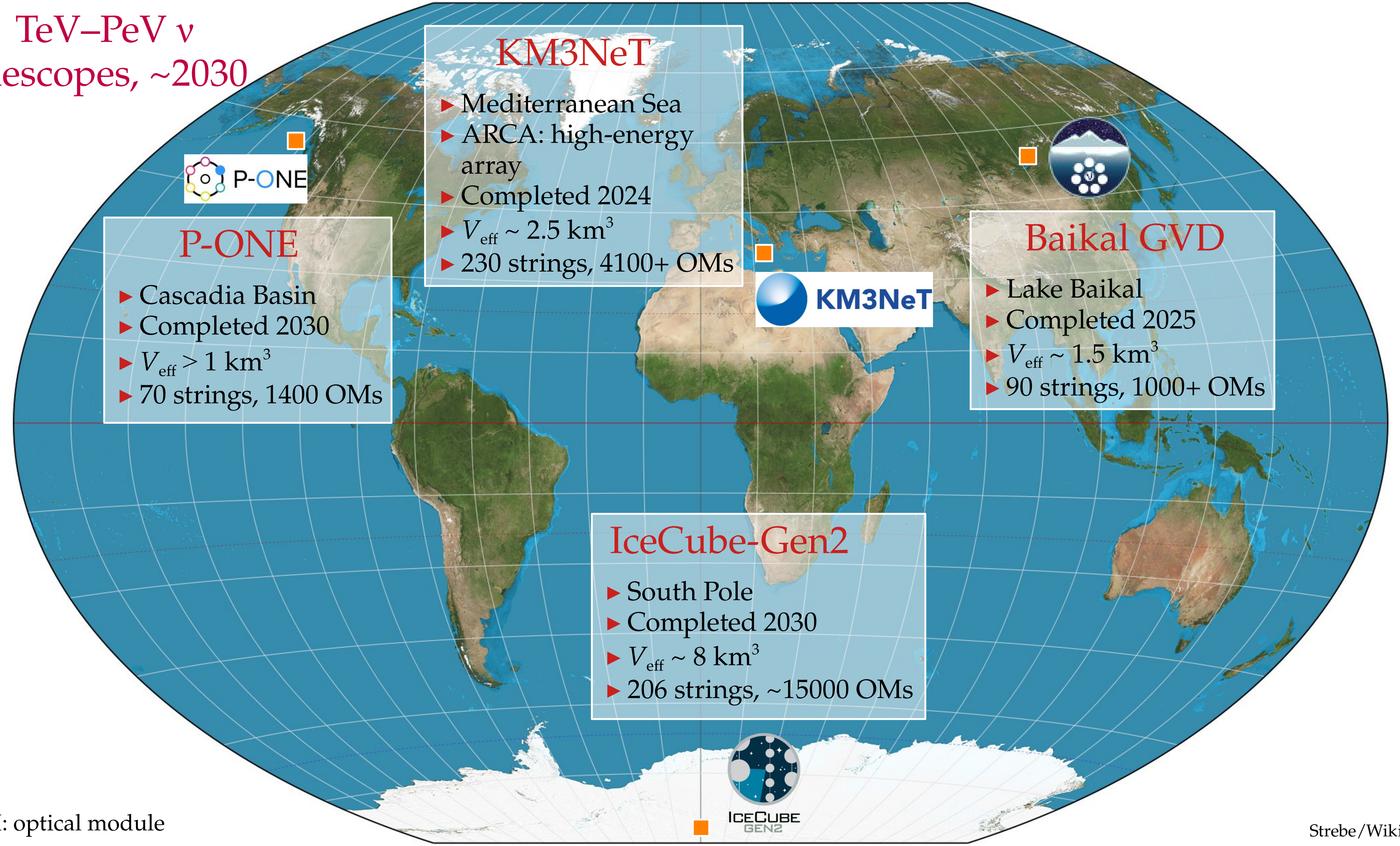
Reviews:
Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017



MB & Agarwalla, *PRL* 2019

What's next?

TeV–PeV ν telescopes, ~2030



OM: optical module

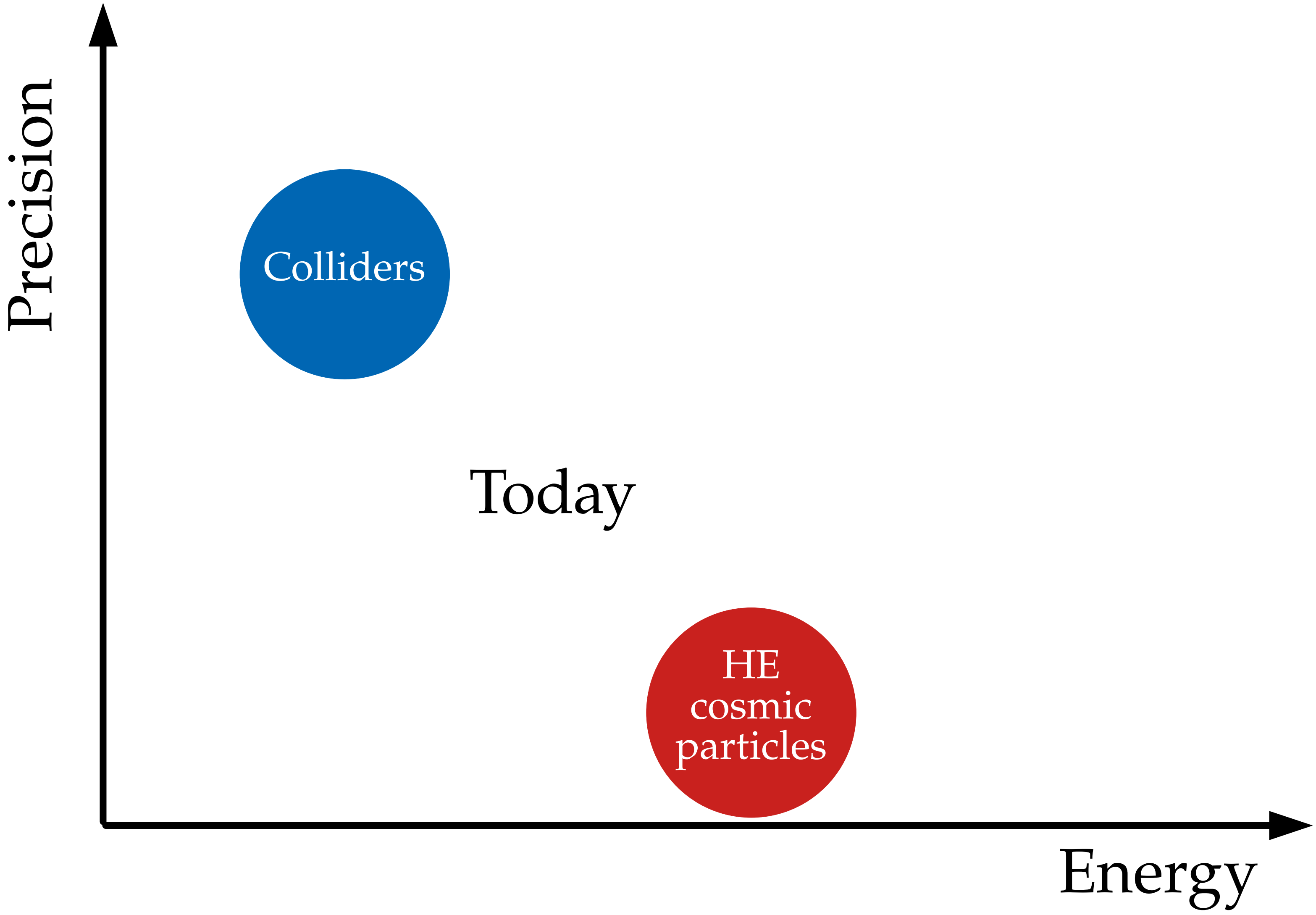
Strebe/Wikipedia

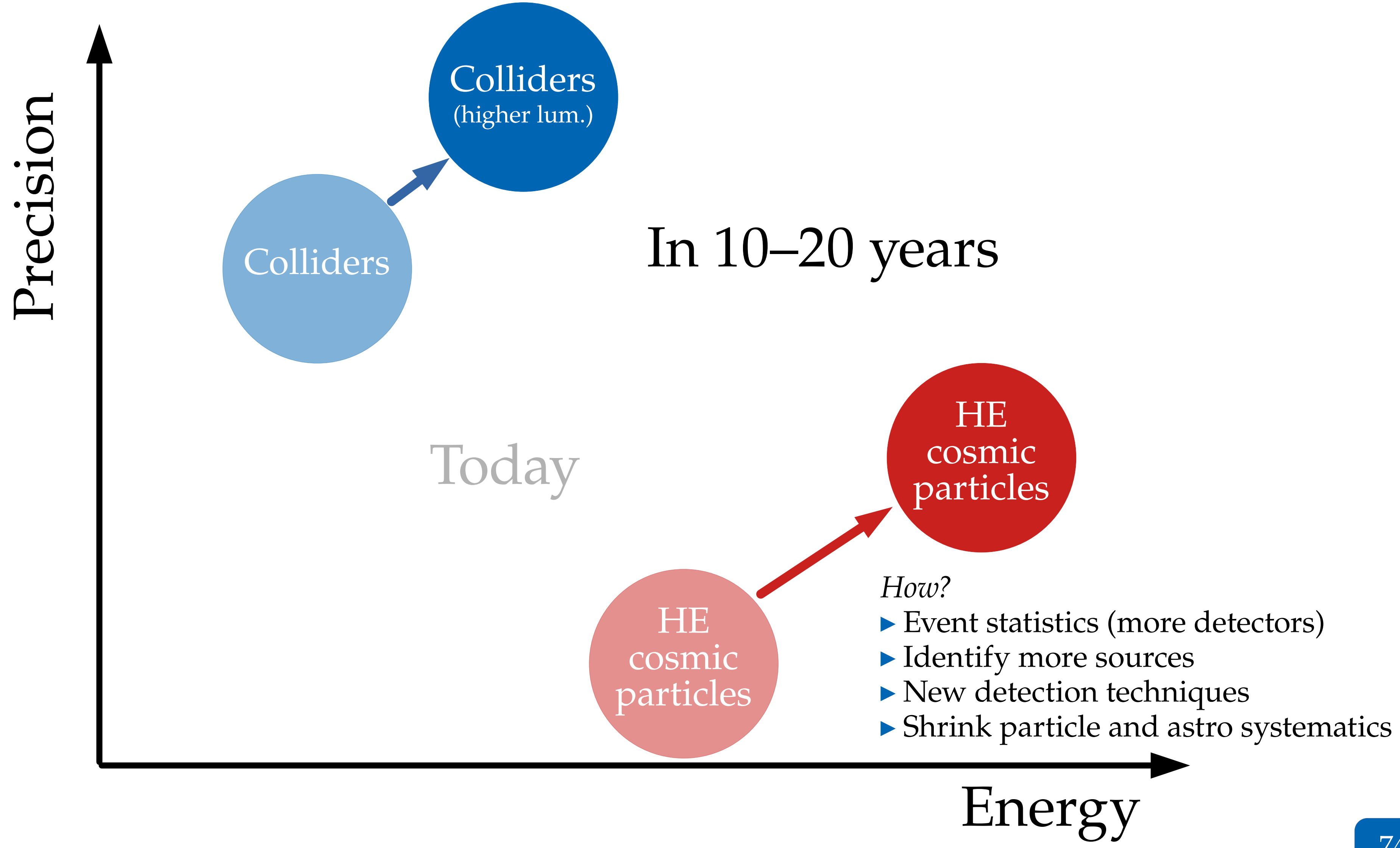
Many TeV–EeV
ν telescopes
in planning for
2020–2040

Experiments	Phase & Online Date	Energy Range	Site	Tau	All Flavor	Optical / UV	Radio	Showers	H_2O	Atmosphere	Earth's limb	Topography	Lunar Regolith	Embedded	Planar Arrays	Valley	Mountains	Balloon	Satellite
				Flavor		**Technique**			**Neutrino Target**					**Geometry**					
IceCube	2010	TeV-EeV	South Pole		✓	✓			✓					✓					
KM3NeT	2021	TeV-PeV	Mediteranean		✓	✓			✓					✓					
Baikal-GVD	2021	TeV-PeV	Lake Baikal		✓	✓			✓					✓					
P-ONE	2020	TeV-PeV	Pacific Ocean		✓	✓			✓					✓					
IceCube-Gen2	2030+	TeV-EeV	South Pole		✓	✓	✓		✓					✓					
ARIANNA	2014	>30 PeV	Moore's Bay		✓		✓		✓					✓					
ARA	2011	>30 PeV	South Pole		✓		✓		✓					✓					
RNO-G	2021	>30 PeV	Greenland		✓		✓		✓					✓					
RET-N	2024	PeV-EeV	Antarctica		✓		✓		✓					✓					
ANITA	2008,2014,2016	EeV	Antarctica	✓	✓		✓		✓		✓							✓	
PUEO	2024	EeV	Antarctica	✓	✓		✓		✓		✓							✓	
GRAND	2020	EeV	China / Worldwide	✓			✓			✓	✓	✓			✓		✓		
BEACON	2018	EeV	CA, USA/ Worldwide	✓			✓				✓	✓					✓		
TAROGE-M	2018	EeV	Antarctica	✓			✓				✓	✓					✓		
SKA	2029	>100 EeV	Australia		✓		✓						✓		✓				
Trinity	2022	PeV-EeV	Utah, USA	✓		✓					✓						✓		
POEMMA		>20 PeV	Satellite	✓	✓	✓				✓	✓								✓
EUSO-SPB	2022	EeV	New Zealand	✓		✓					✓							✓	
Pierre Auger	2008	EeV	Argentina	✓	✓			✓		✓	✓	✓			✓				
AugerPrime	2022	EeV	Argentina	✓	✓		✓	✓		✓	✓	✓			✓				
Telescope Array	2008	EeV	Utah, USA	✓	✓			✓		✓					✓				
TAx4		EeV	Utah, USA	✓	✓			✓											
TAMBO	2025-2026	PeV-EeV	Peru	✓				✓				✓				✓			

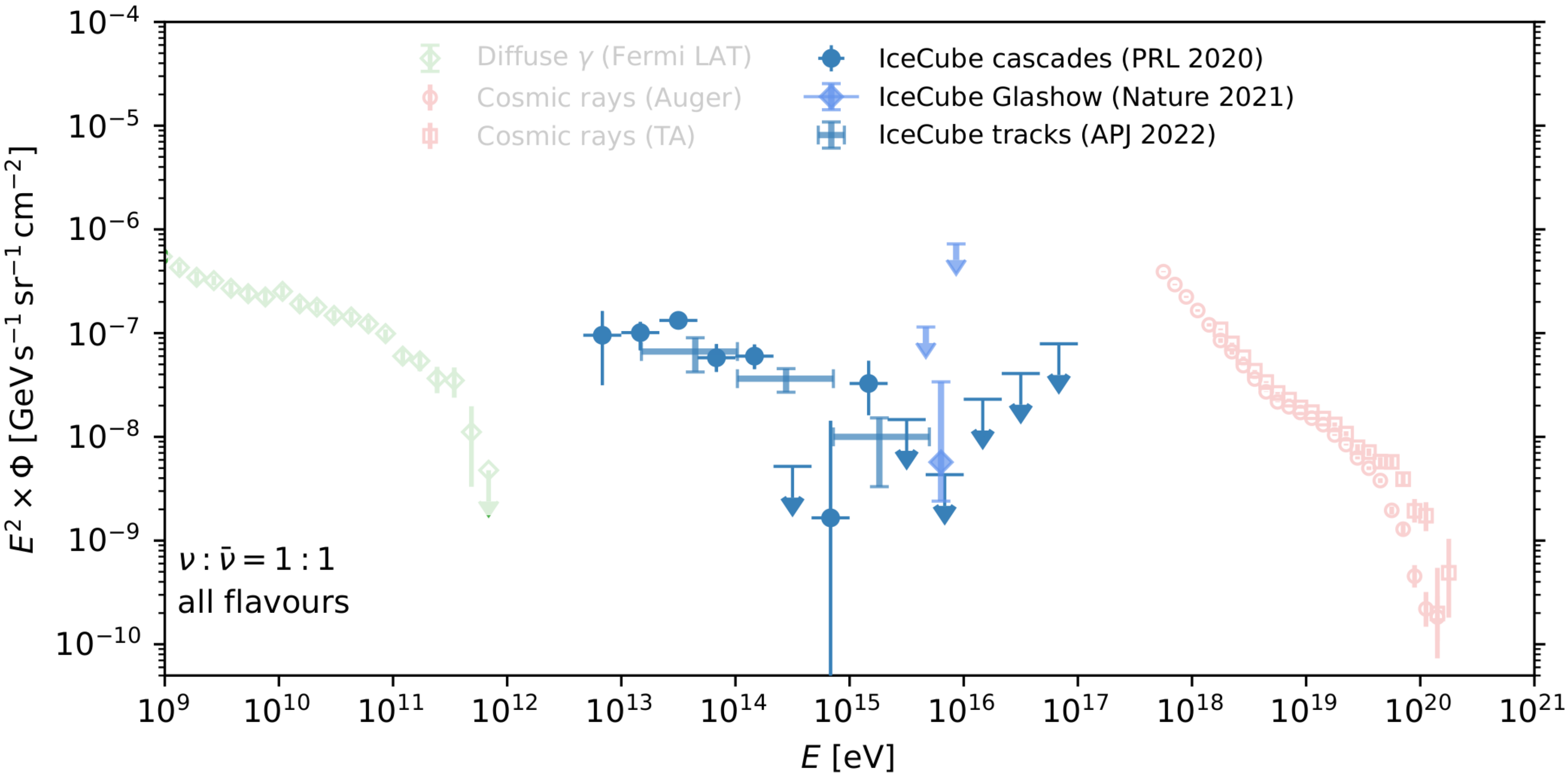
Operational		Date full operations began
Prototype		Date protoype operations began or begin
Planning		Projected full operations

Abraham *et al.* (inc. **MB**),
J. Phys. G: Nucl. Part. Phys. 59, 11 (2022) [2203.05591]


Precision
Colliders
Today
HE
cosmic
particles
Energy


Precision
Colliders
(higher lum.)
Colliders
In 10–20 years
Today
HE cosmic particles
HE cosmic particles
How?
▸ Event statistics (more detectors)
▸ Identify more sources
▸ New detection techniques
▸ Shrink particle and astro systematics
Energy

Gamma rays Neutrinos Cosmic rays



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

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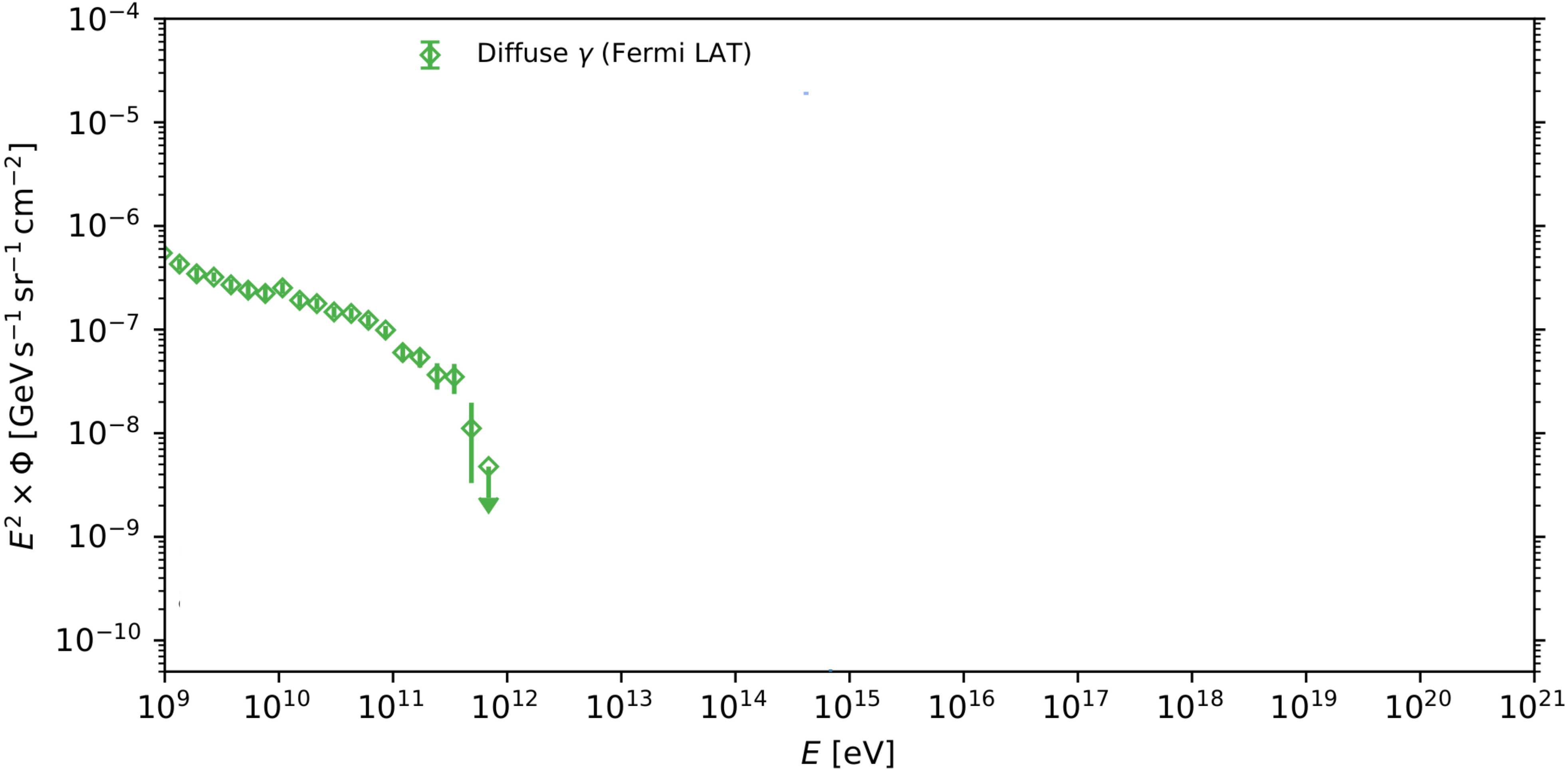

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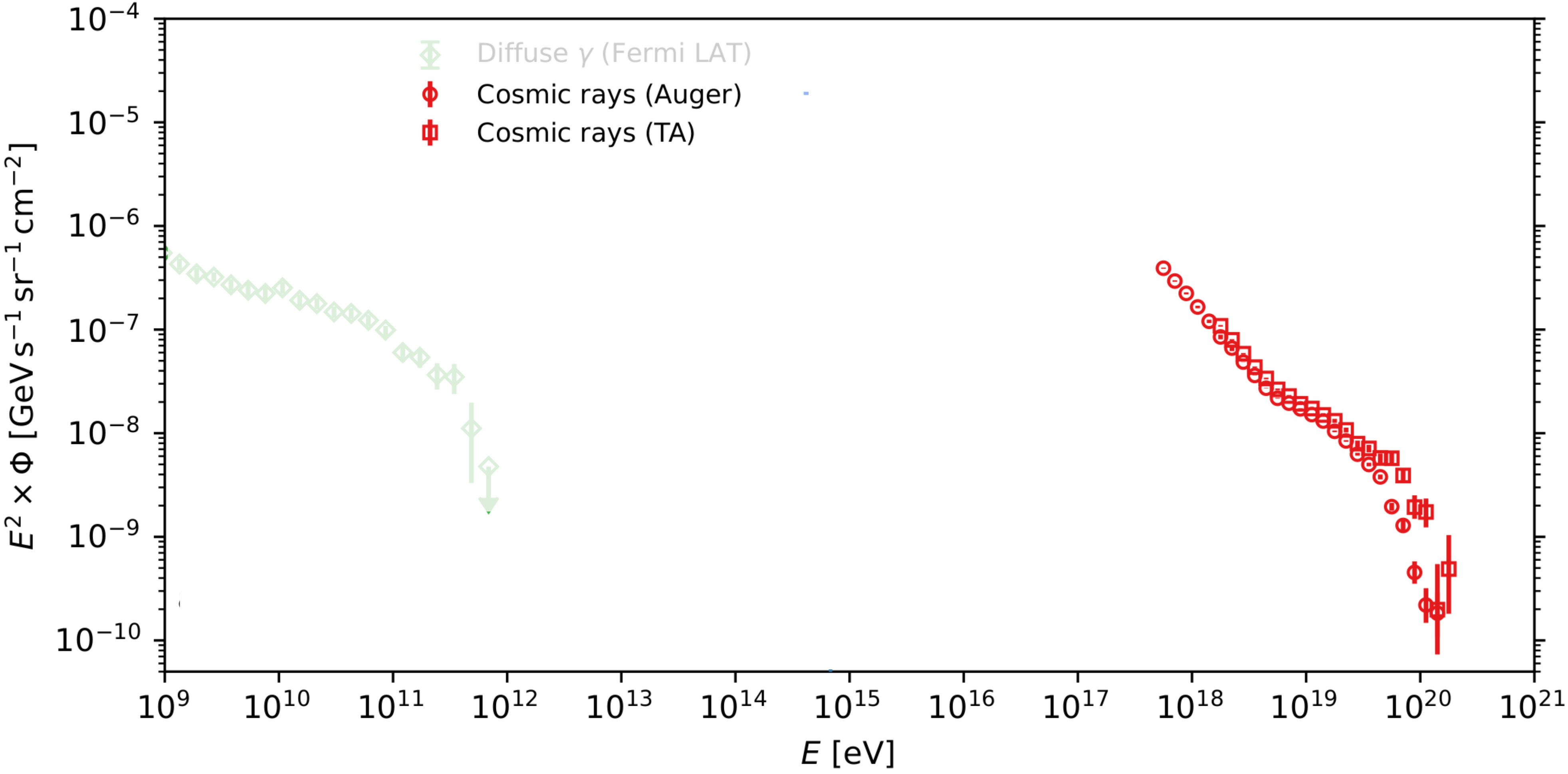

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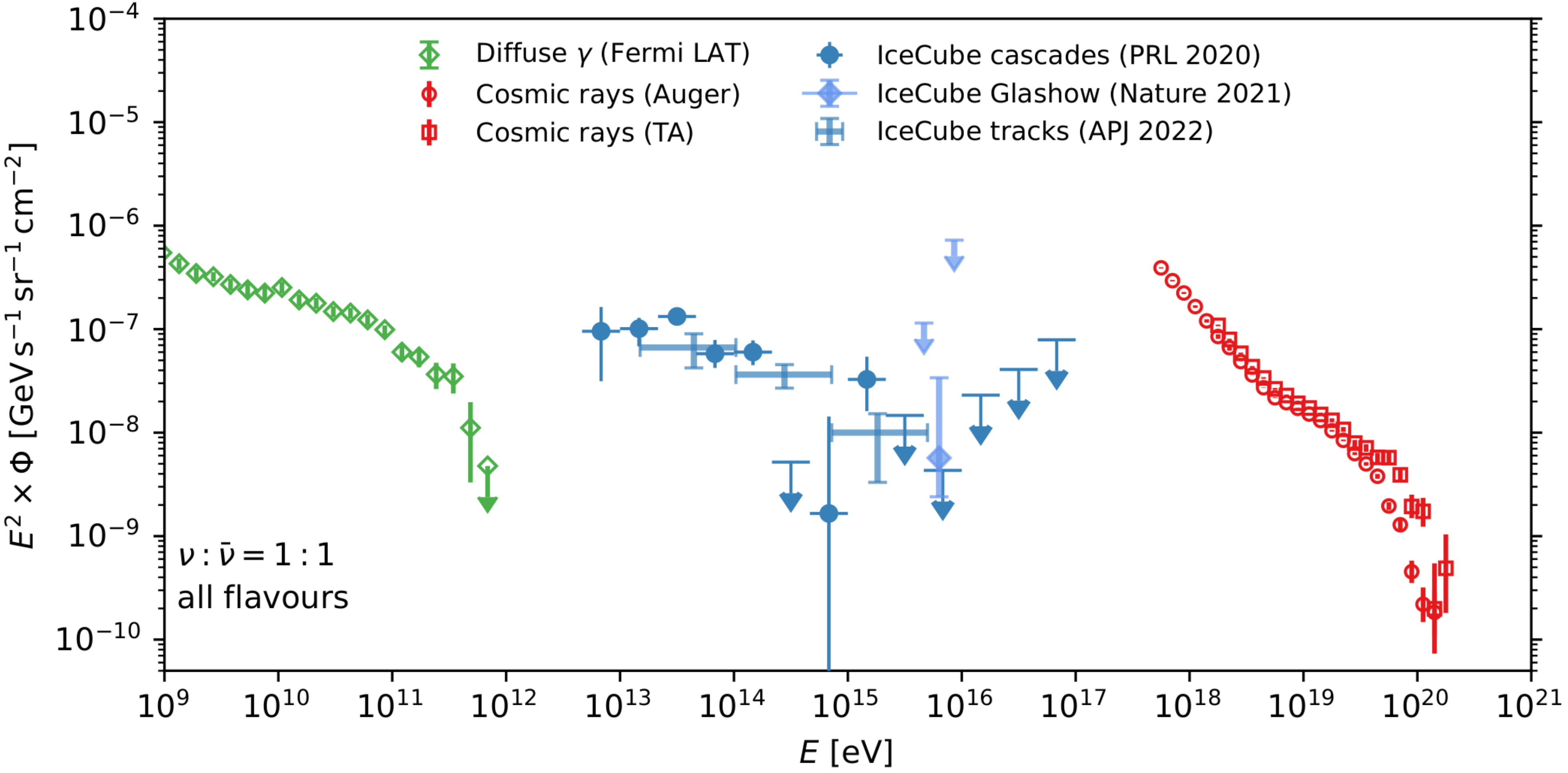
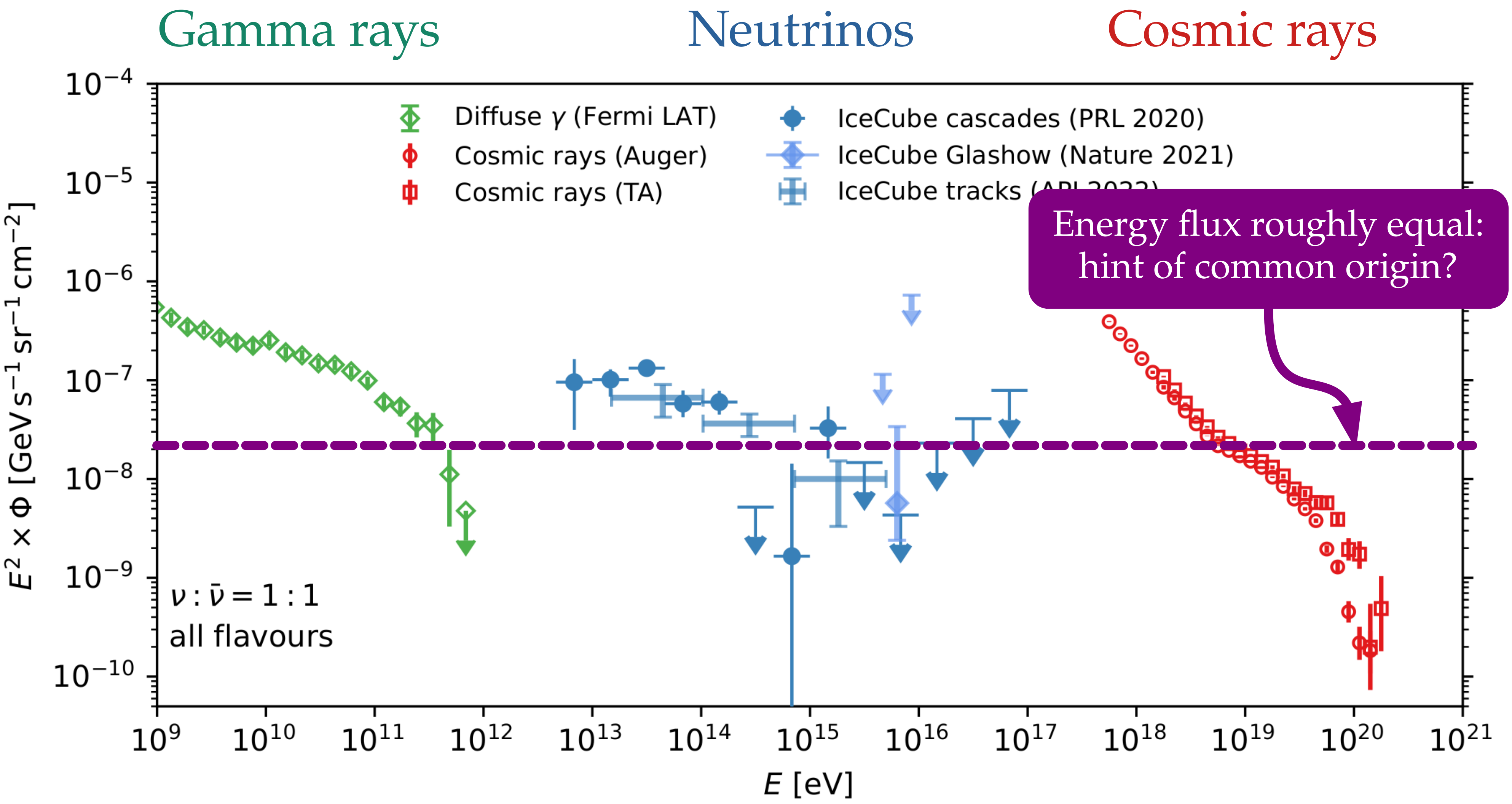
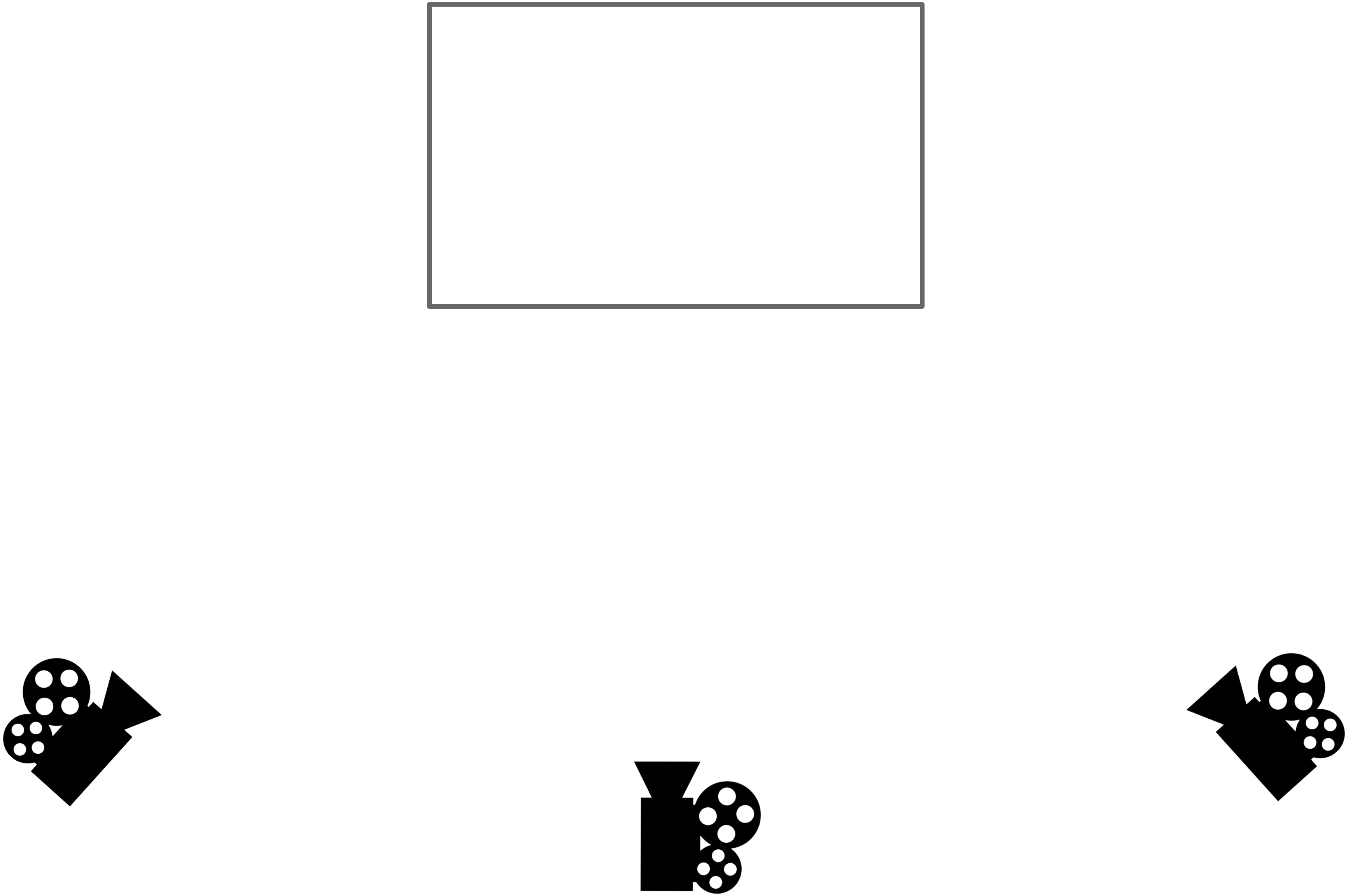
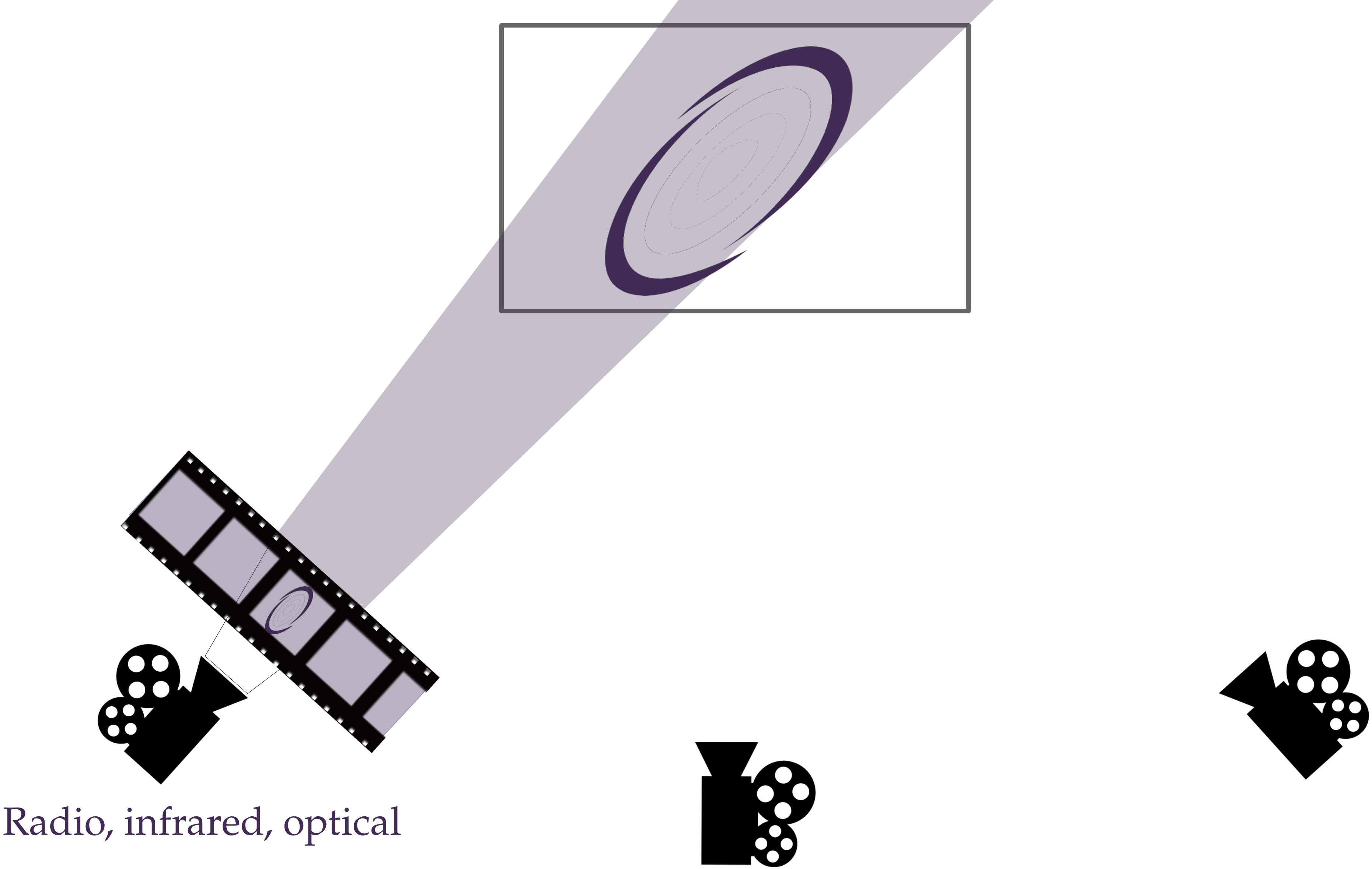


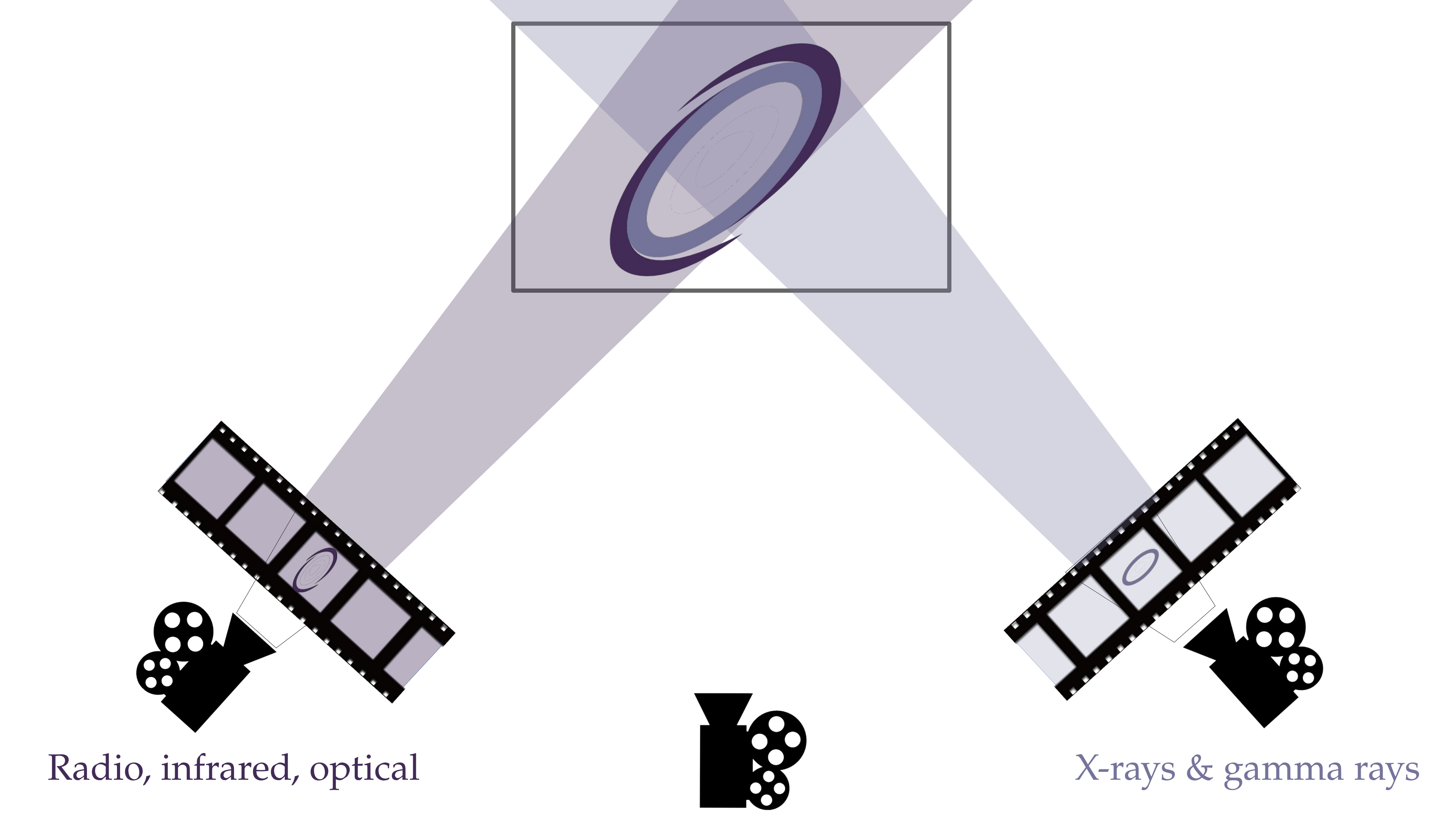
M. Ackermann, **MB**, *et al.*, *JHEAp* 35, 55 (2022) [2203.08096]



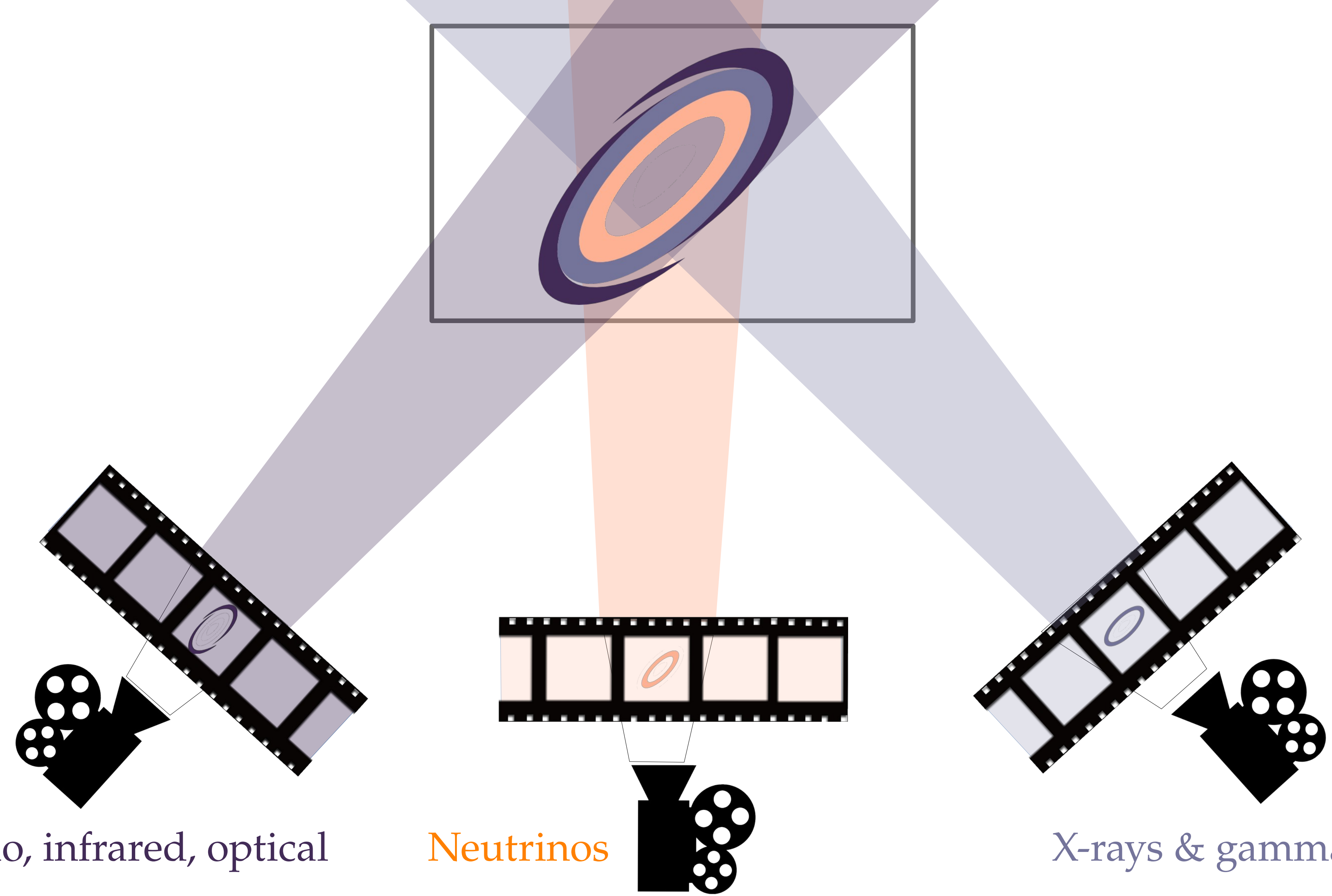
M. Ackermann, **MB**, *et al.*, *JHEAp* 35, 55 (2022) [2203.08096]



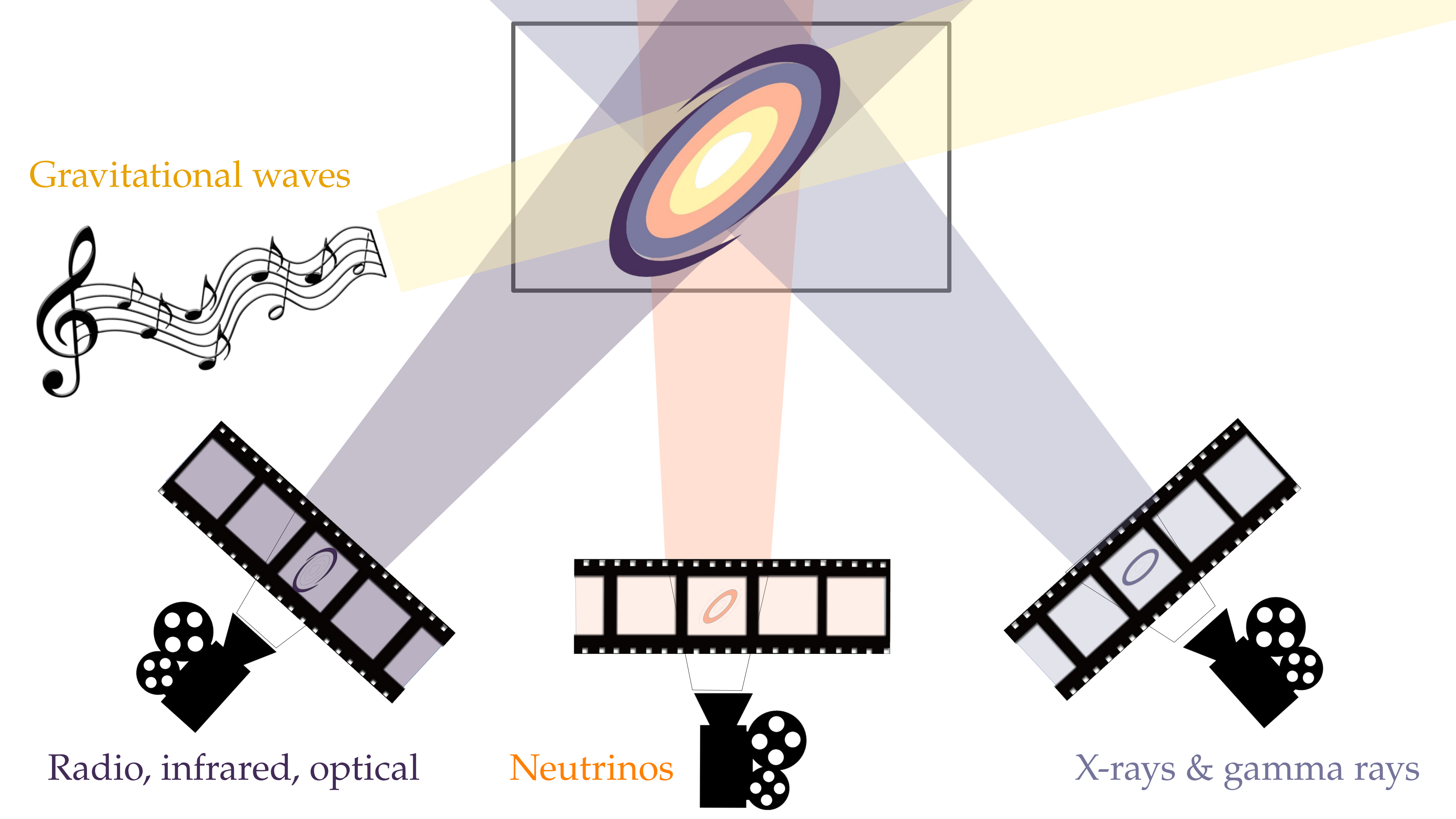

Radio, infrared, optical

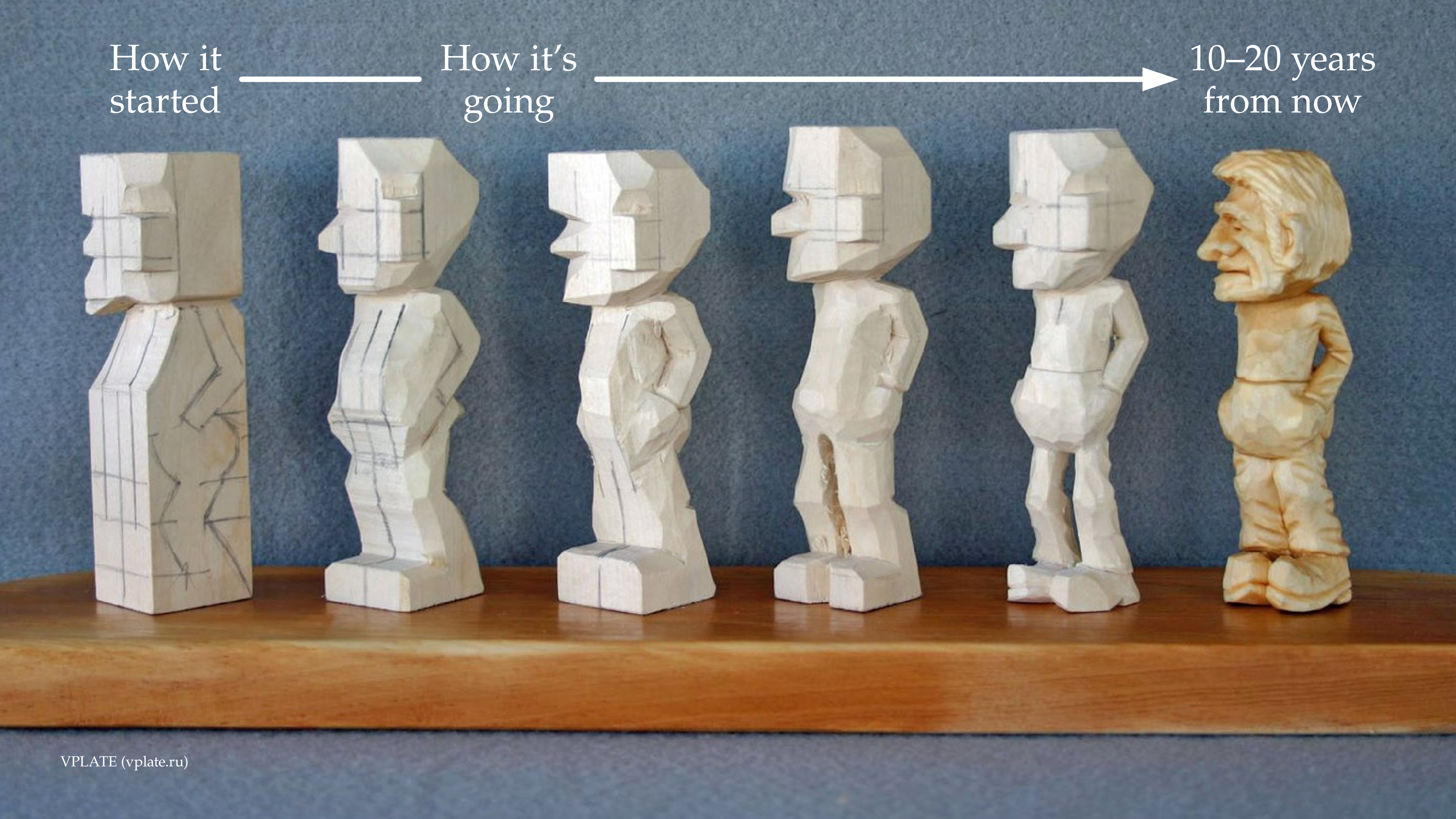


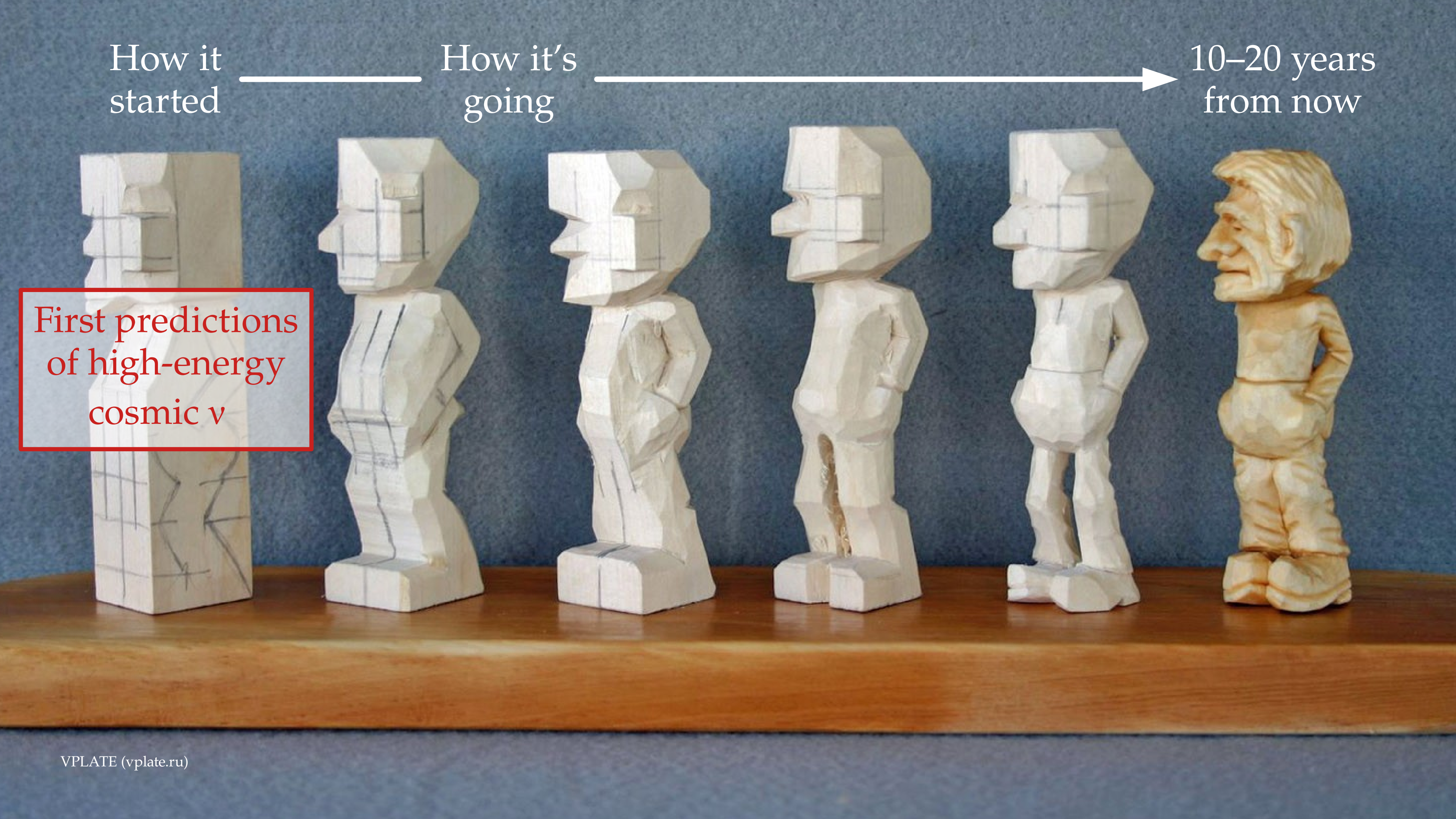
Radio, infrared, optical
X-rays & gamma rays

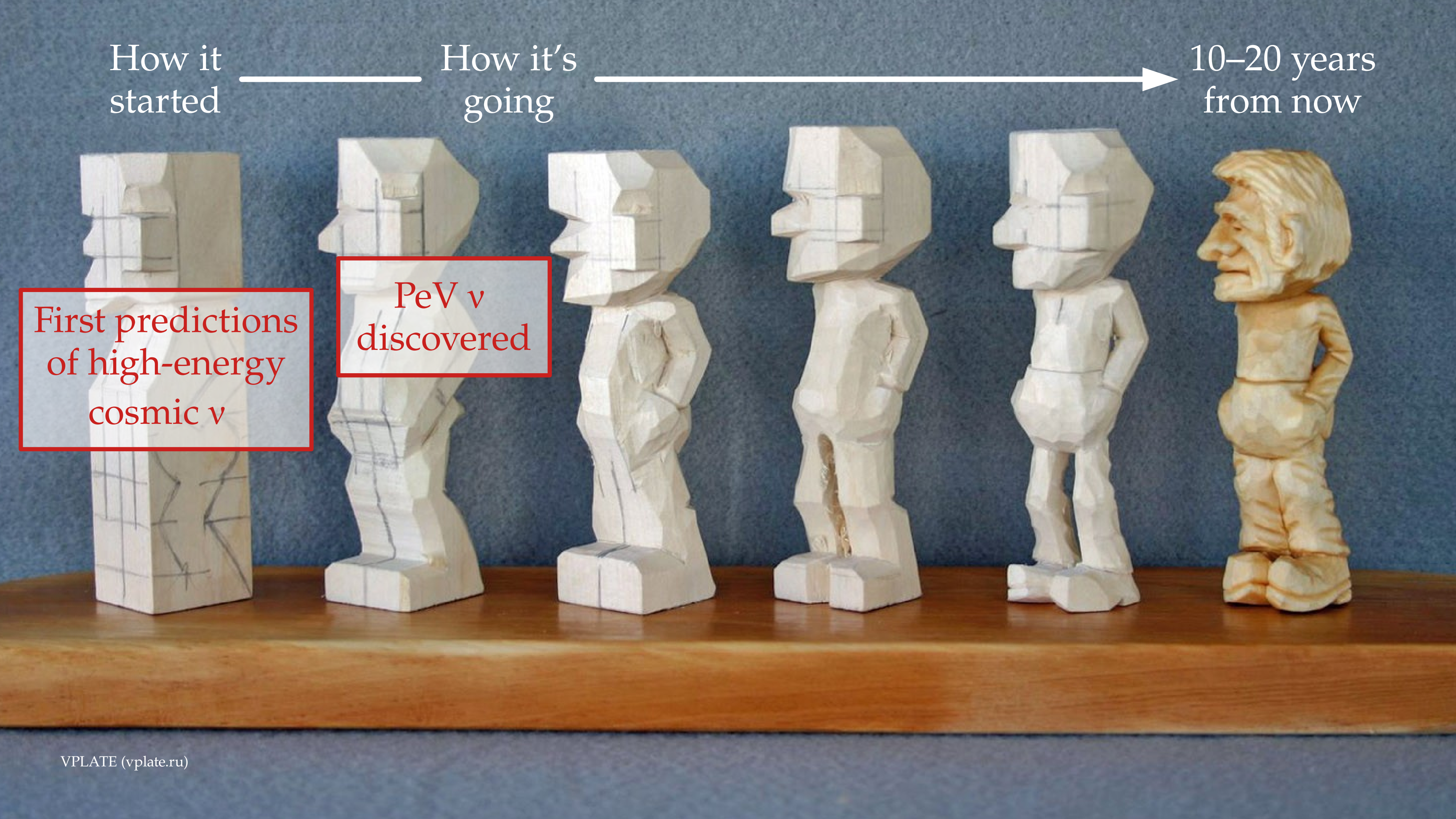


Radio, infrared, optical
Neutrinos
X-rays & gamma rays


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


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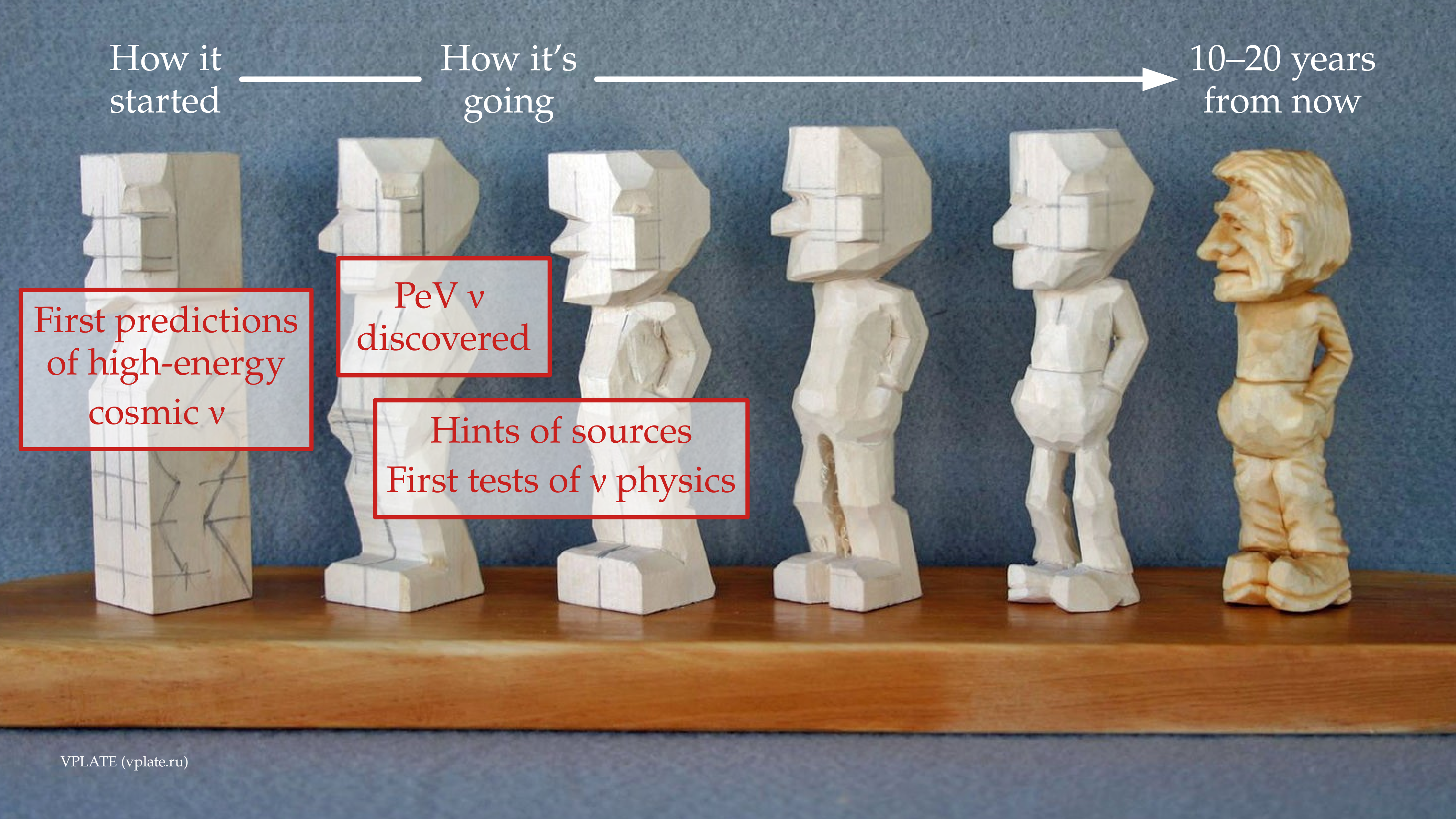
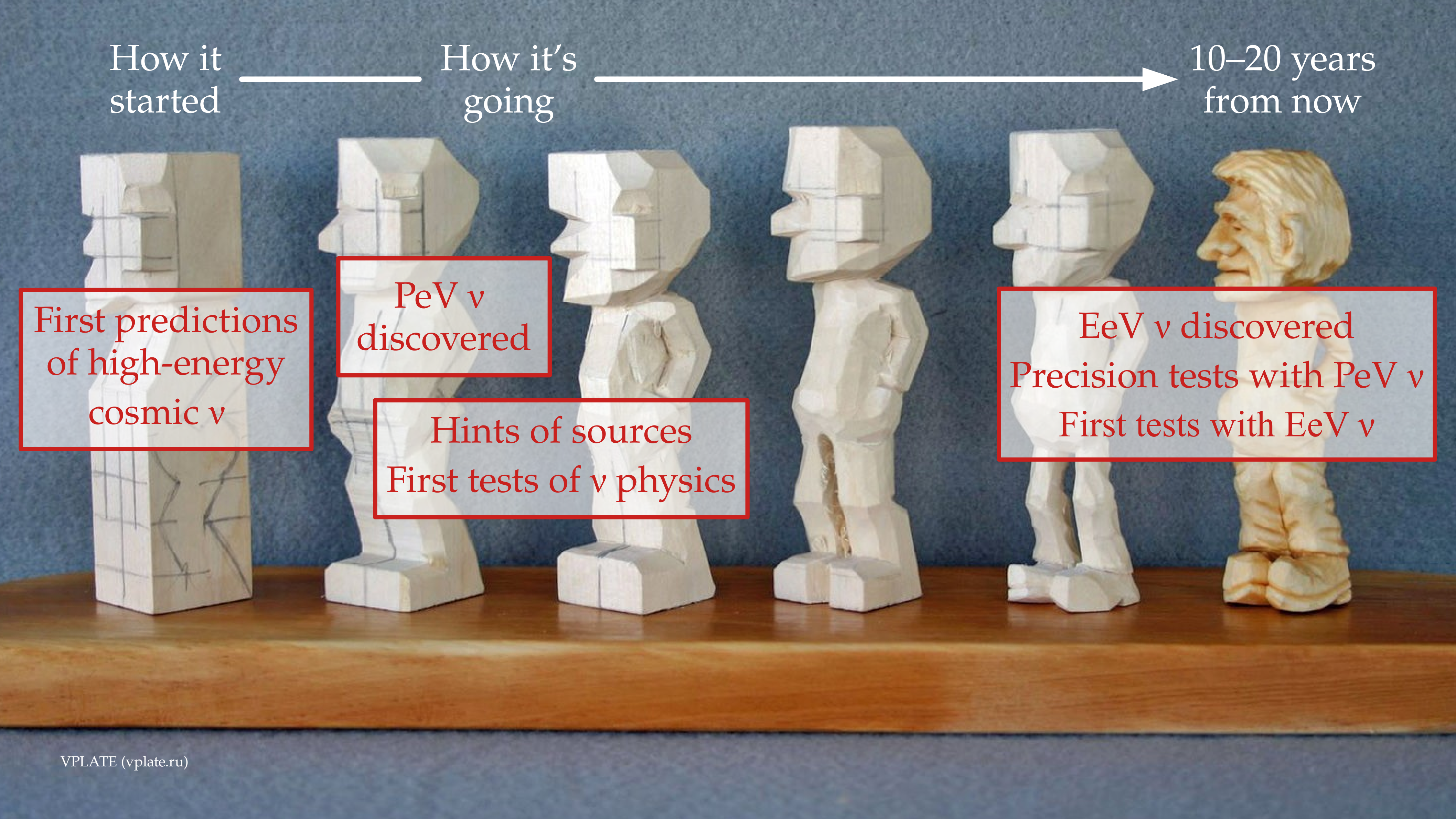
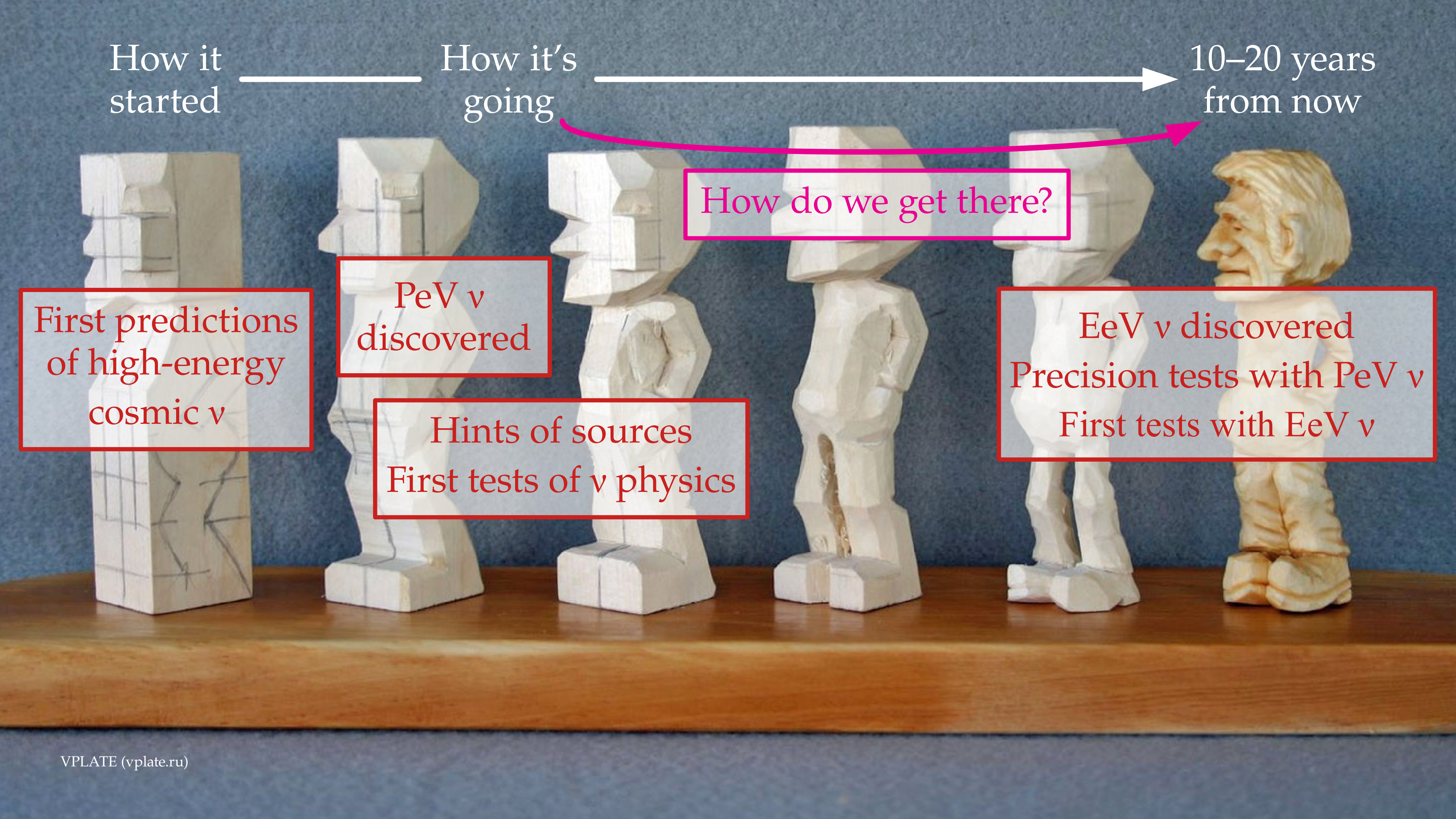
First predictions of high-energy cosmic ν
PeV ν discovered
VPLATE (vplate.ru)


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)


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
EeV ν discovered
Precision tests with PeV ν
First tests with EeV ν
VPLATE (vplate.ru)



VPLATE (vplate.ru)

Thanks!

Backup slides

Just how weak is *weak*

Just how weak is *weak*

Just how weak is *weak*

Strong	Electromagnetism	Weak	Gravity

Just how weak is *weak*

	Strong	Electromagnetism	Weak	Gravity
Relative strength (force between two protons)				

Just how weak is *weak*

	Strong	Electromagnetism	Weak	Gravity
Relative strength (force between two protons)	1			

Just how weak is *weak*

	Strong	Electromagnetism	Weak	Gravity
Relative strength (force between two protons)	1			10^{-38}

Just how weak is *weak*

	Strong	Electromagnetism	Weak	Gravity
Relative strength (force between two protons)	1	10^{-2}		10^{-38}

Just how weak is *weak*

	Strong	Electromagnetism	Weak	Gravity
Relative strength (force between two protons)	1	10^{-2}	10^{-13}	10^{-38}

Just how weak is *weak*

	Strong	Electromagnetism	Weak	Gravity
Relative strength (force between two protons)	1	10^{-2}	10^{-13}	10^{-38}
Range of action	10^{-15} m	∞	10^{-18} m	∞

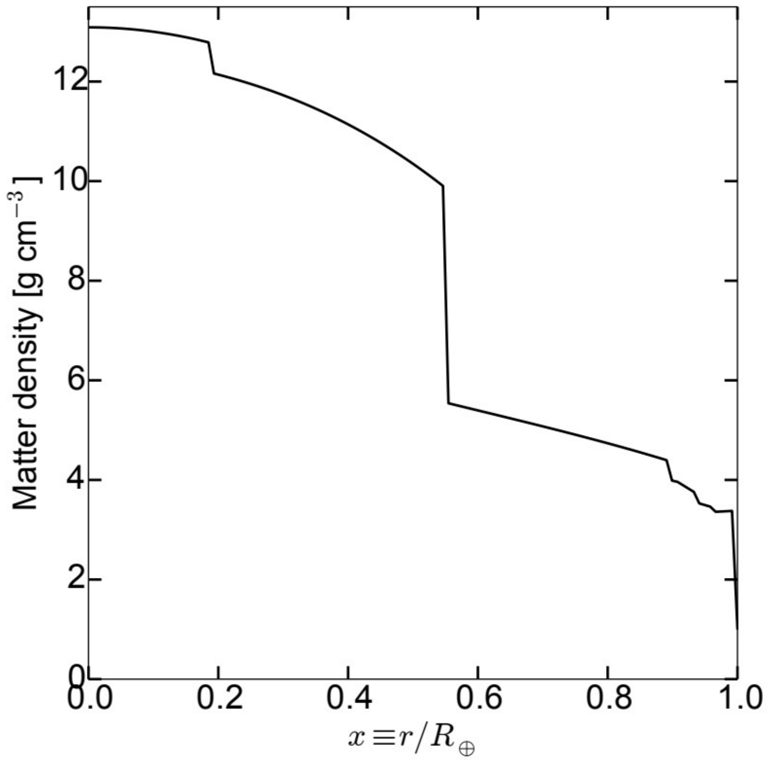
Just how weak is *weak*

	Strong	Electromagnetism	Weak	Gravity
Relative strength (force between two protons)	1	10^{-2}	10^{-13}	10^{-38}
Range of action	10^{-15} m	∞	10^{-18} m	∞

A feel for the in-Earth attenuation

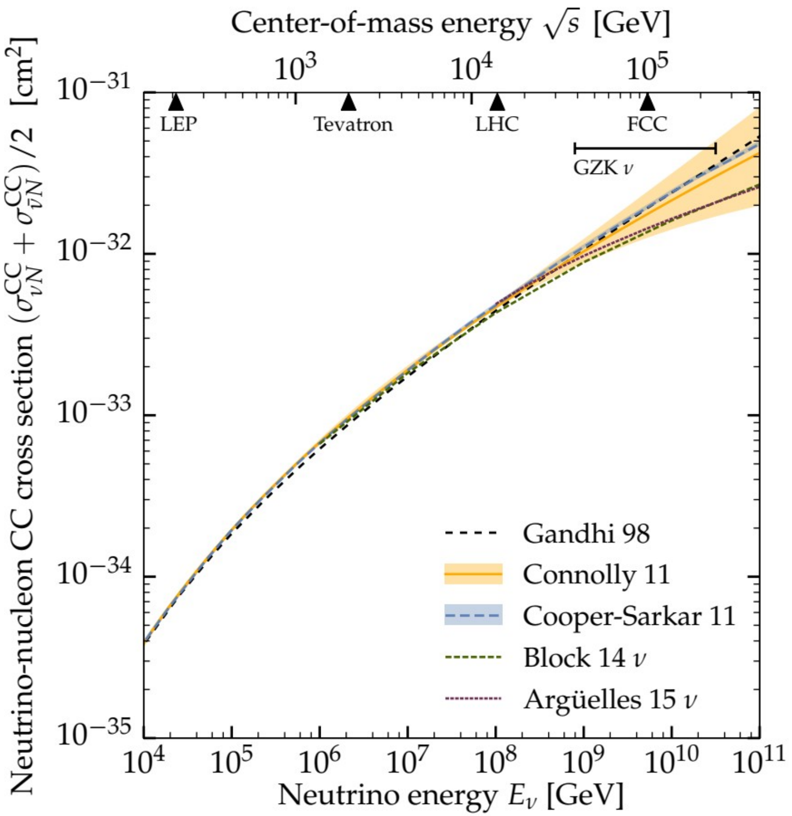
Earth matter density

(Preliminary Reference Earth Model)



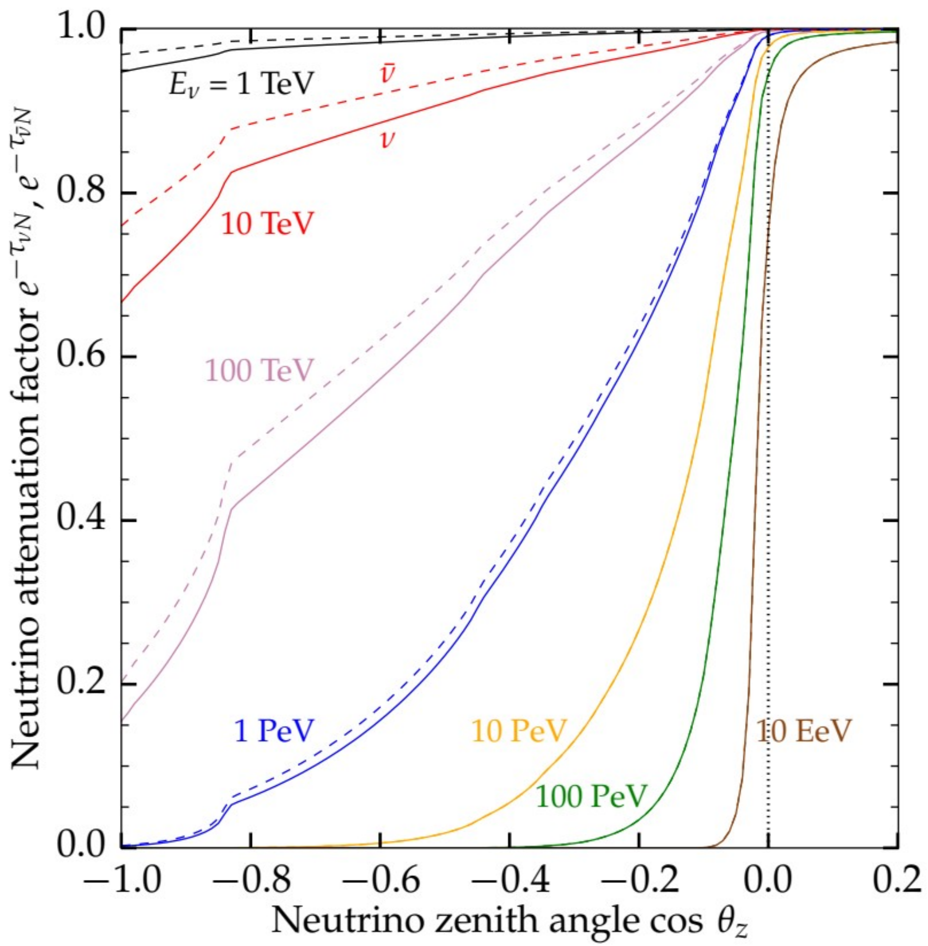
+

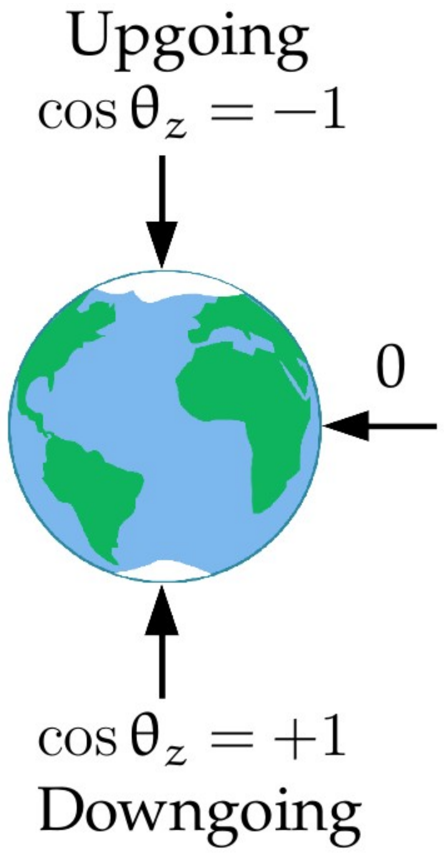
Neutrino-nucleon cross section

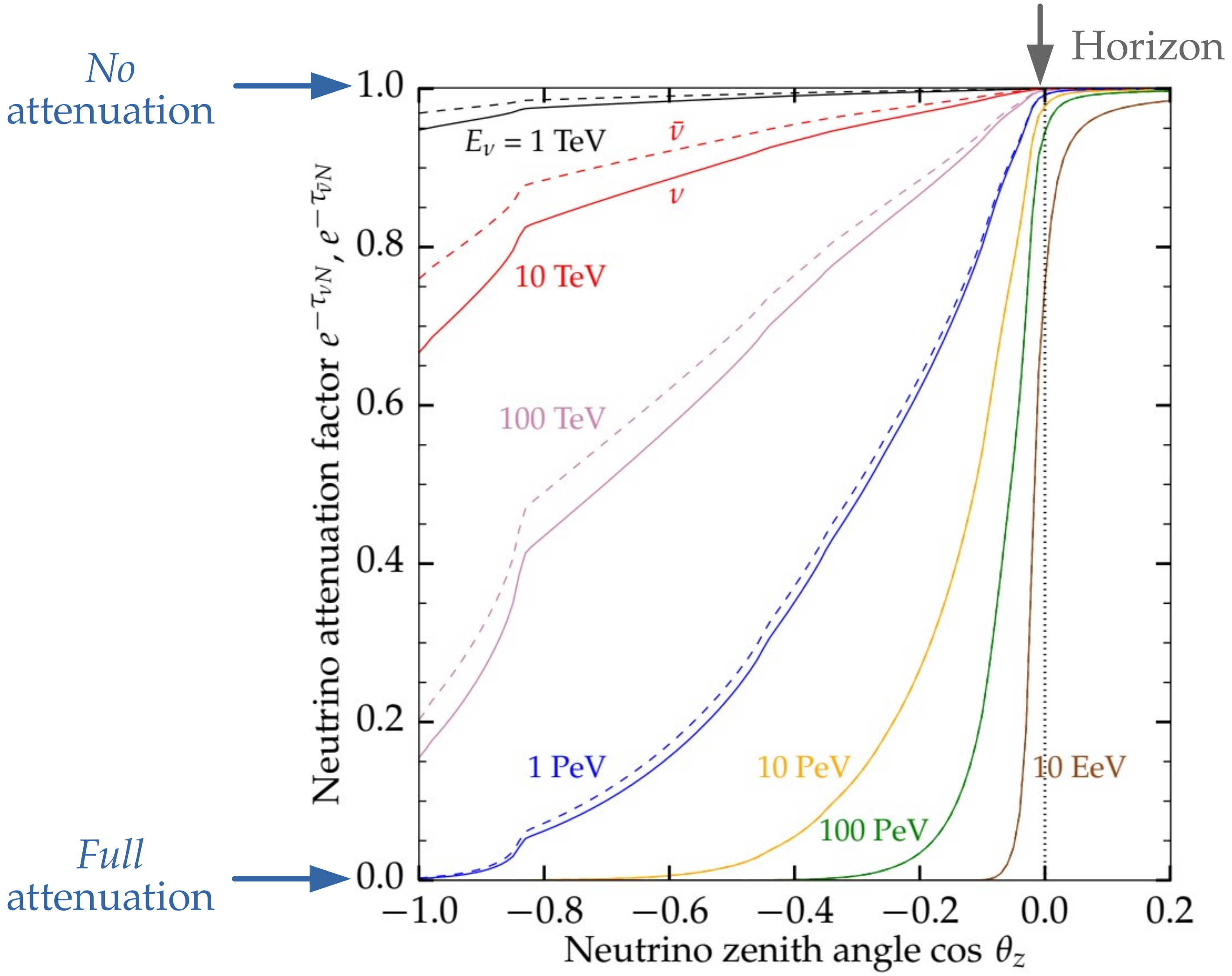


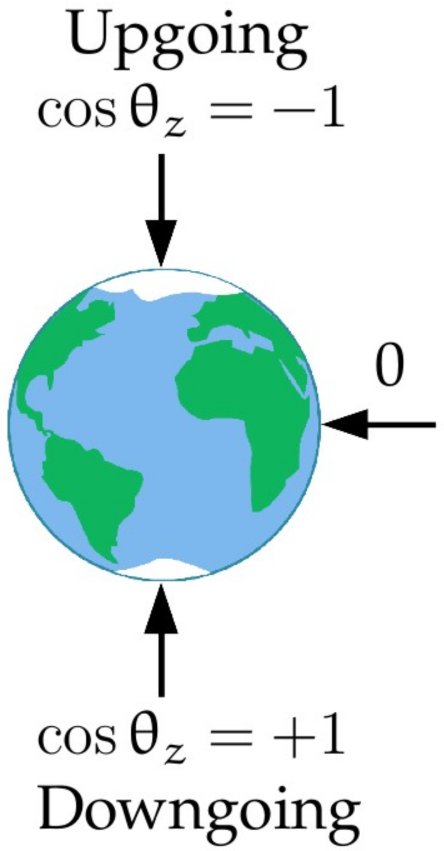
A feel for the in-Earth attenuation

=

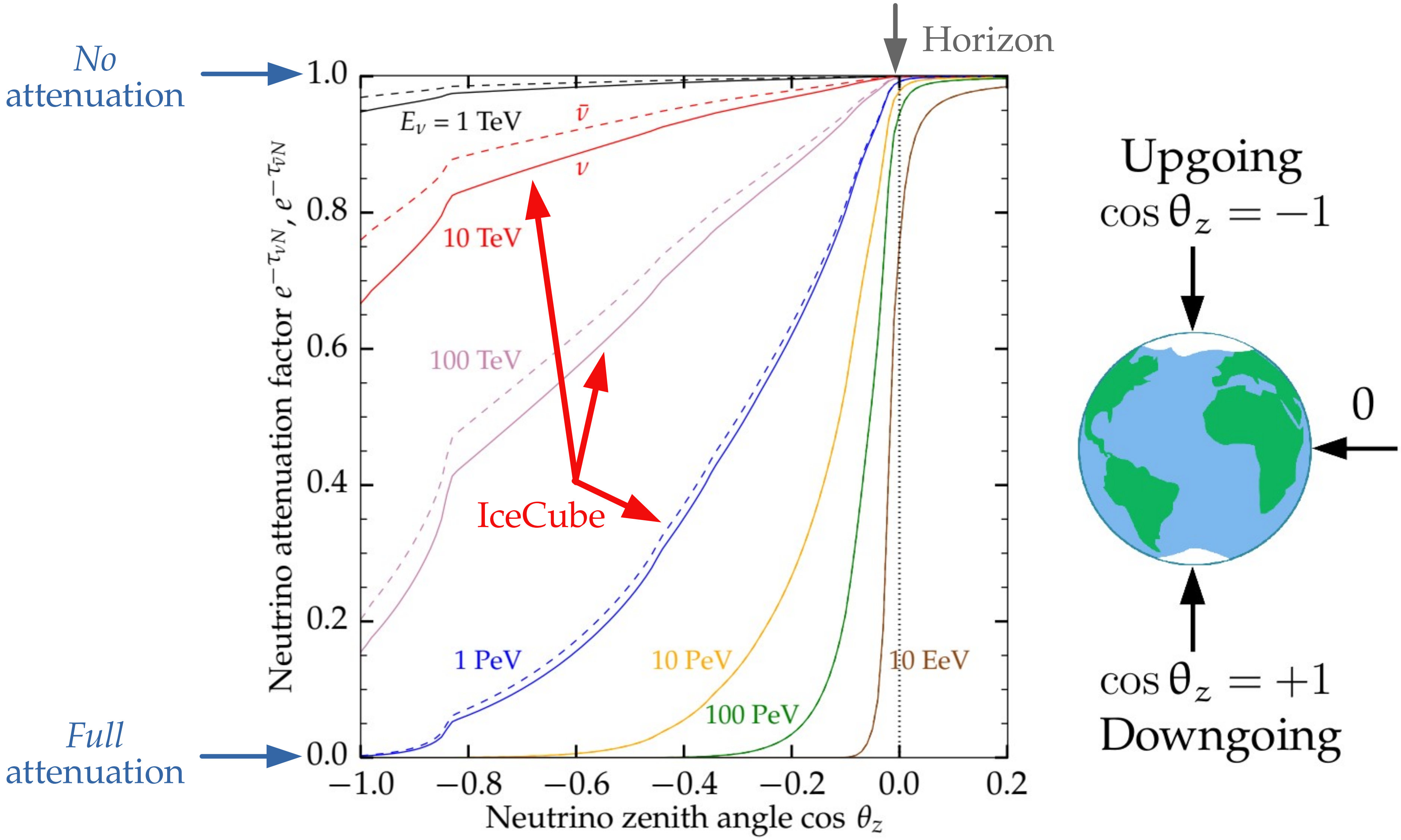




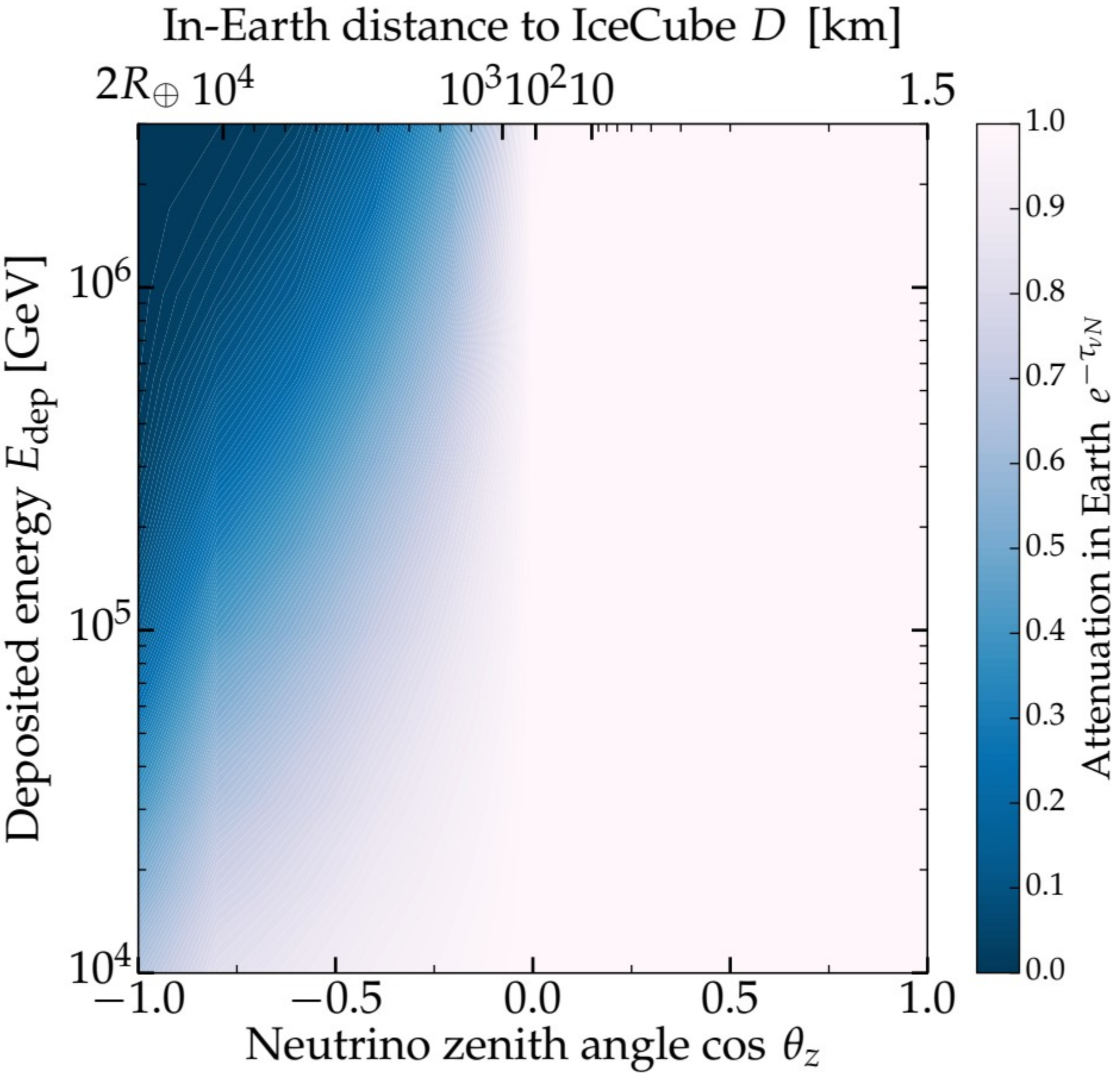




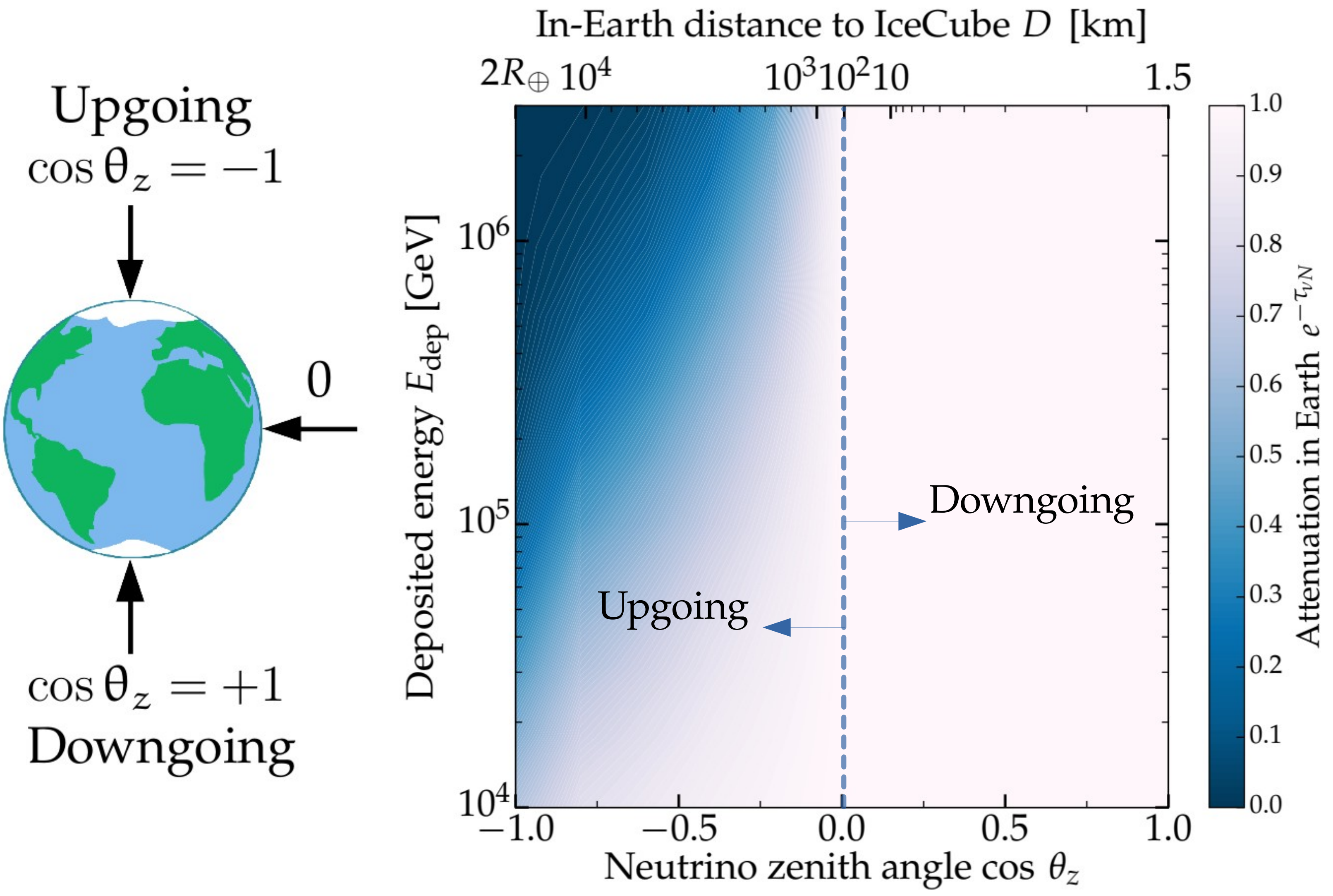
MB & Connolly, *PRL* 2019



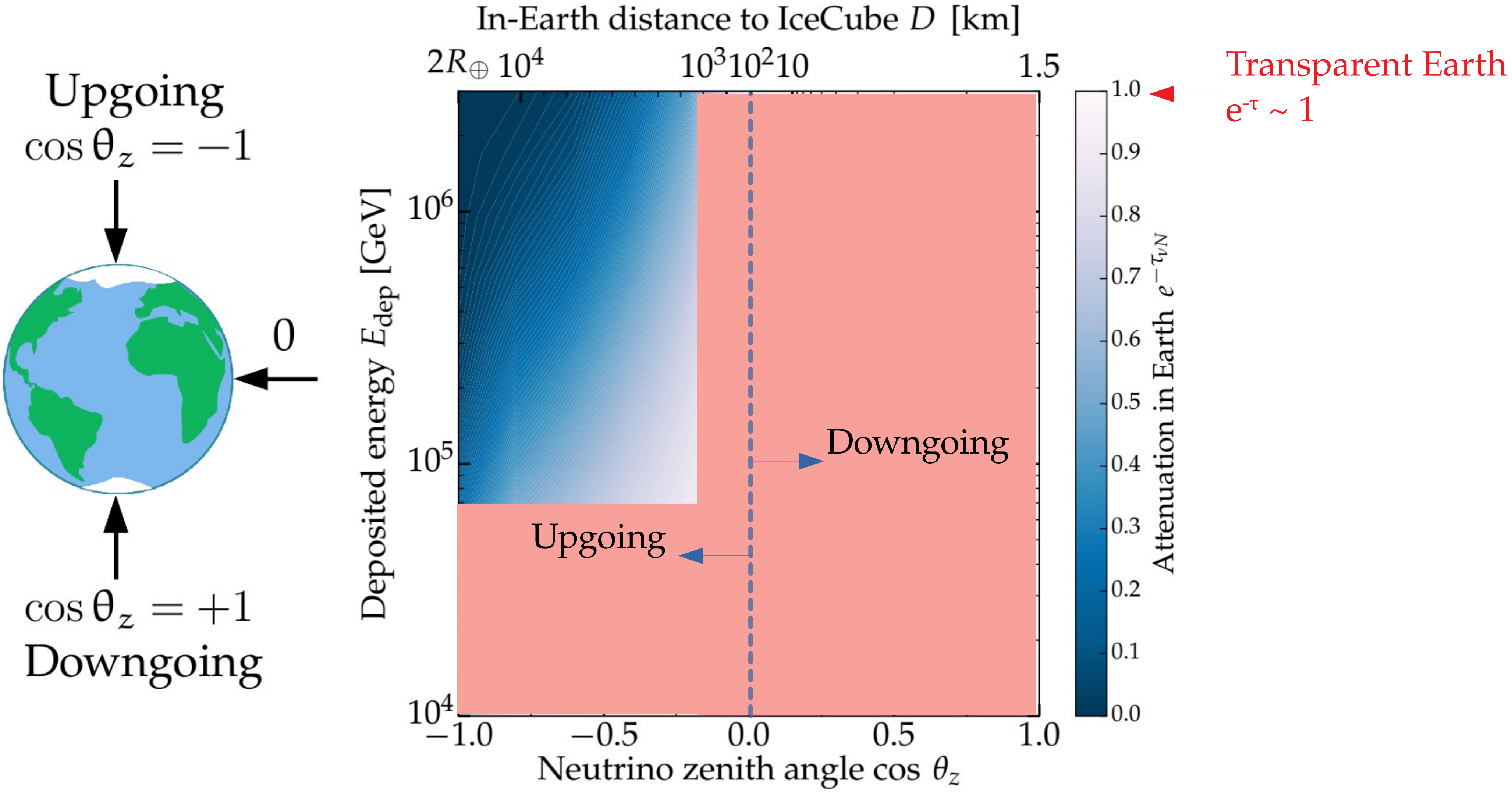
MB & Connolly, *PRL* 2019



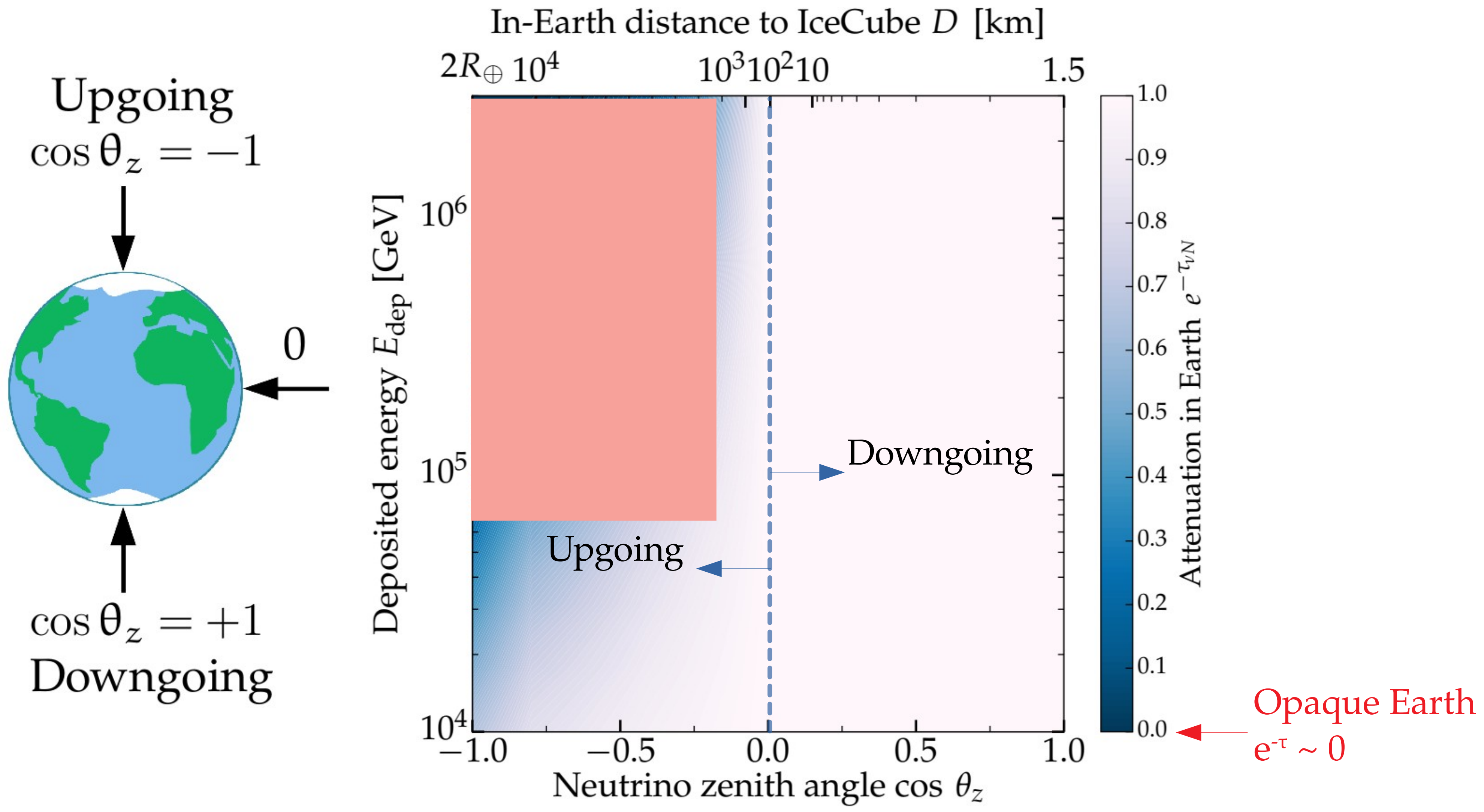
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
10^6
10^5
10^4
Deposited energy $E_{\rm dep}$ [GeV]
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle $\cos\theta_z$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Attenuation in Earth $e^{-\tau_{\nu N}}$



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
Neutrino zenith angle $\cos\theta_z$
−1.0 −0.5 0.0 0.5 1.0
Downgoing
Upgoing
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

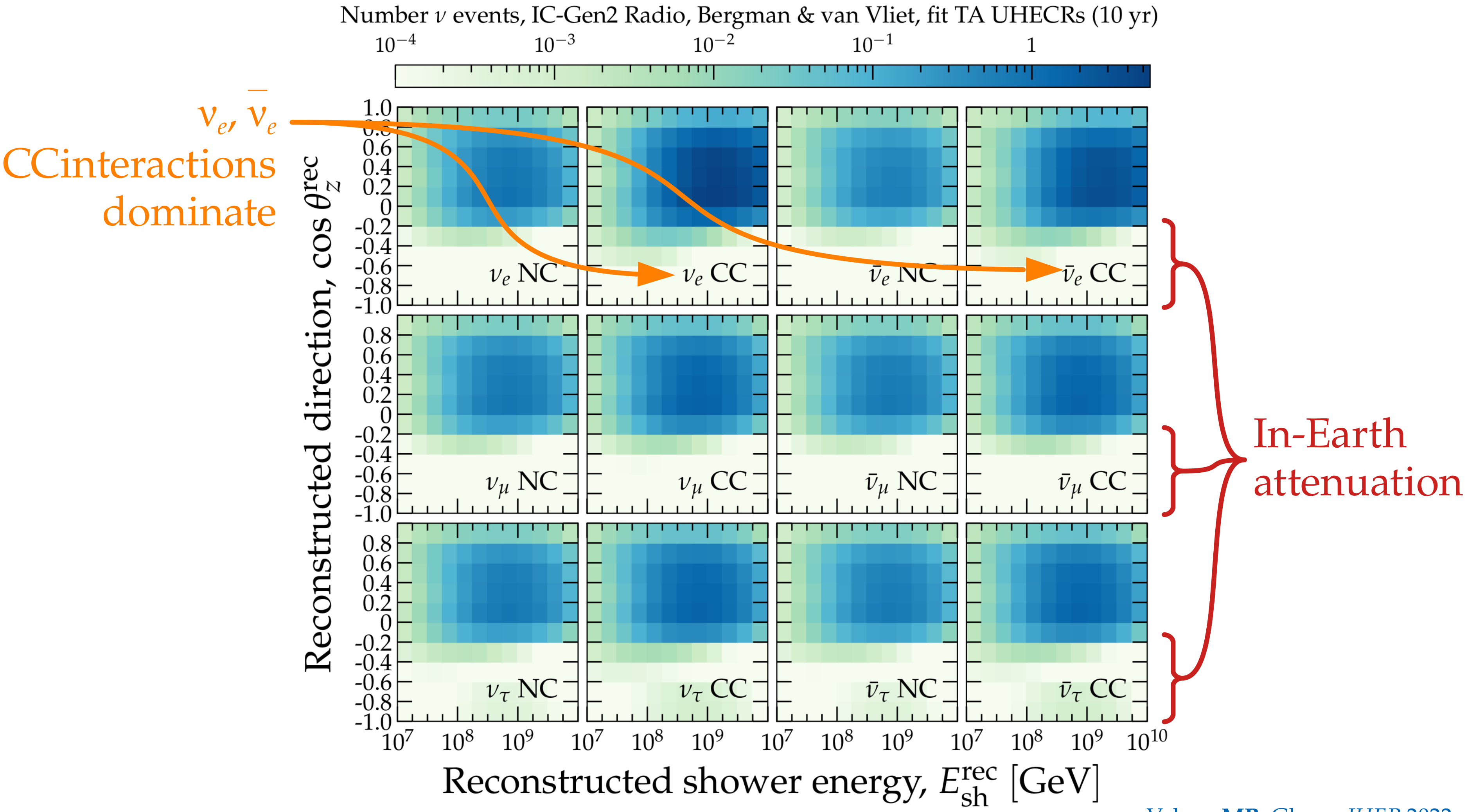


Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^4 10^5 10^6
Neutrino zenith angle $\cos\theta_z$
−1.0 −0.5 0.0 0.5 1.0
Downgoing
Upgoing
Attenuation in Earth $e^{-\tau_{\nu N}}$
0.0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

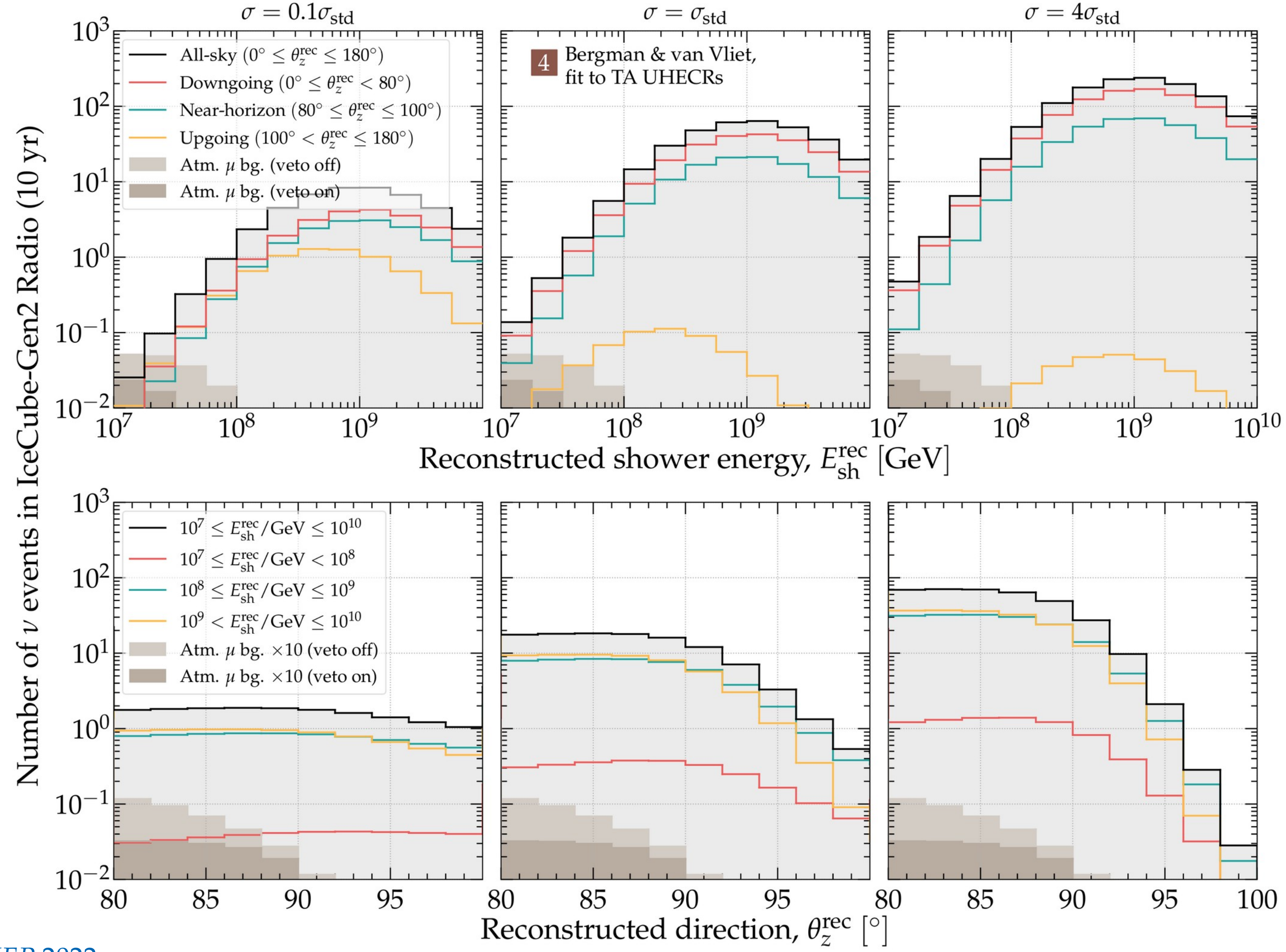


Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9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

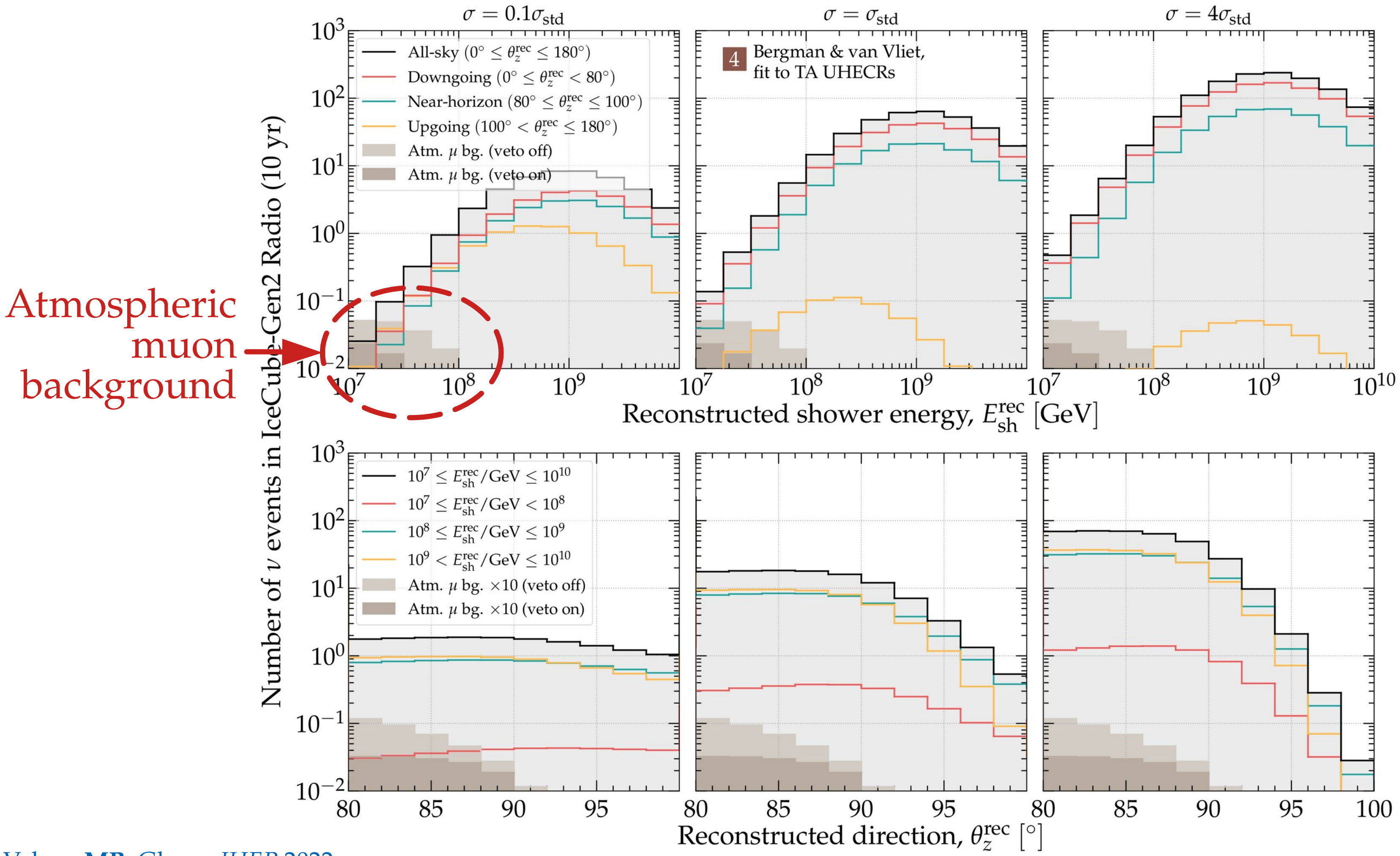
Event rates per channel



Valera, **MB**, Glaser, *JHEP* 2022

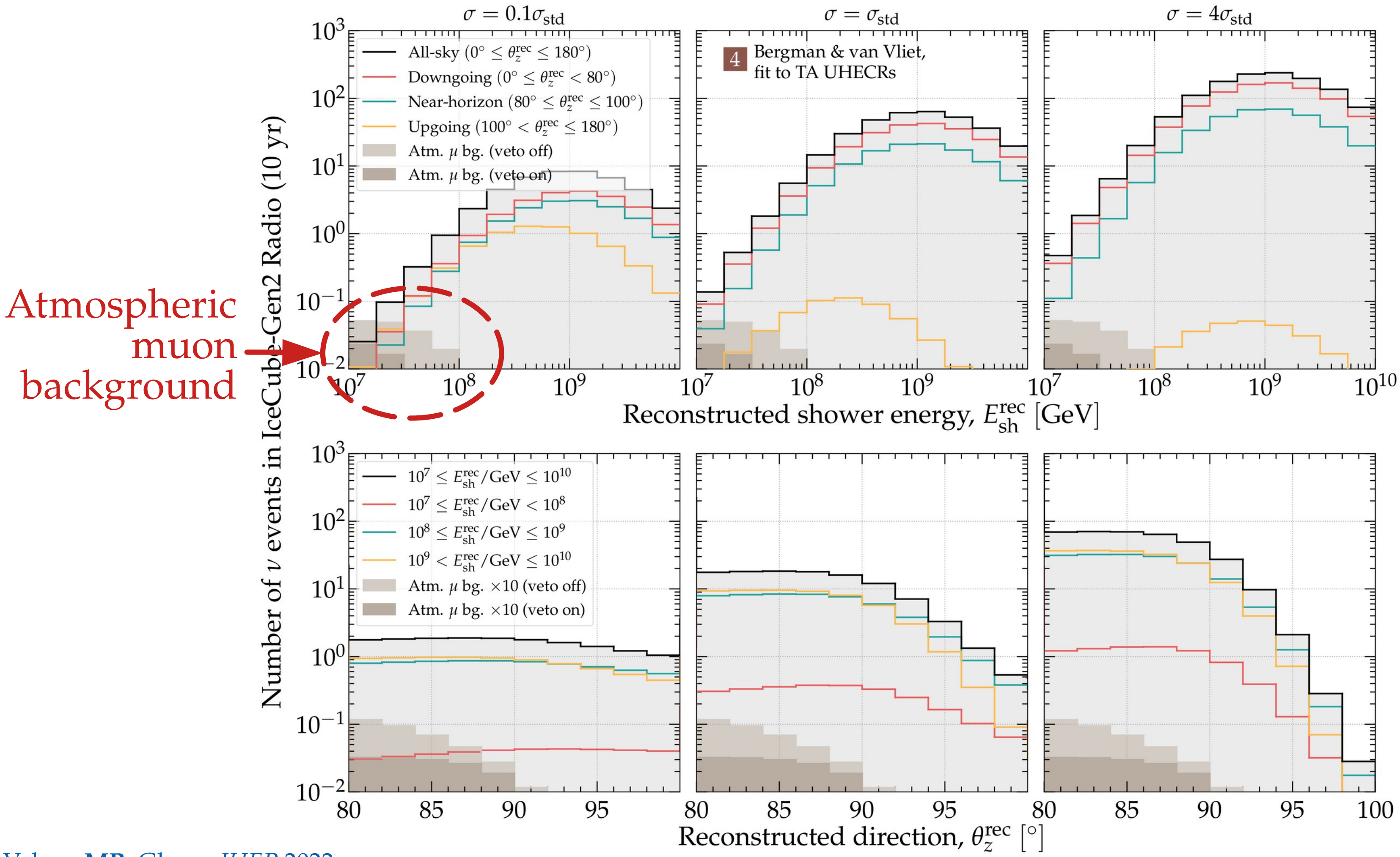


Valera, **MB**, Glaser, *JHEP* 2022

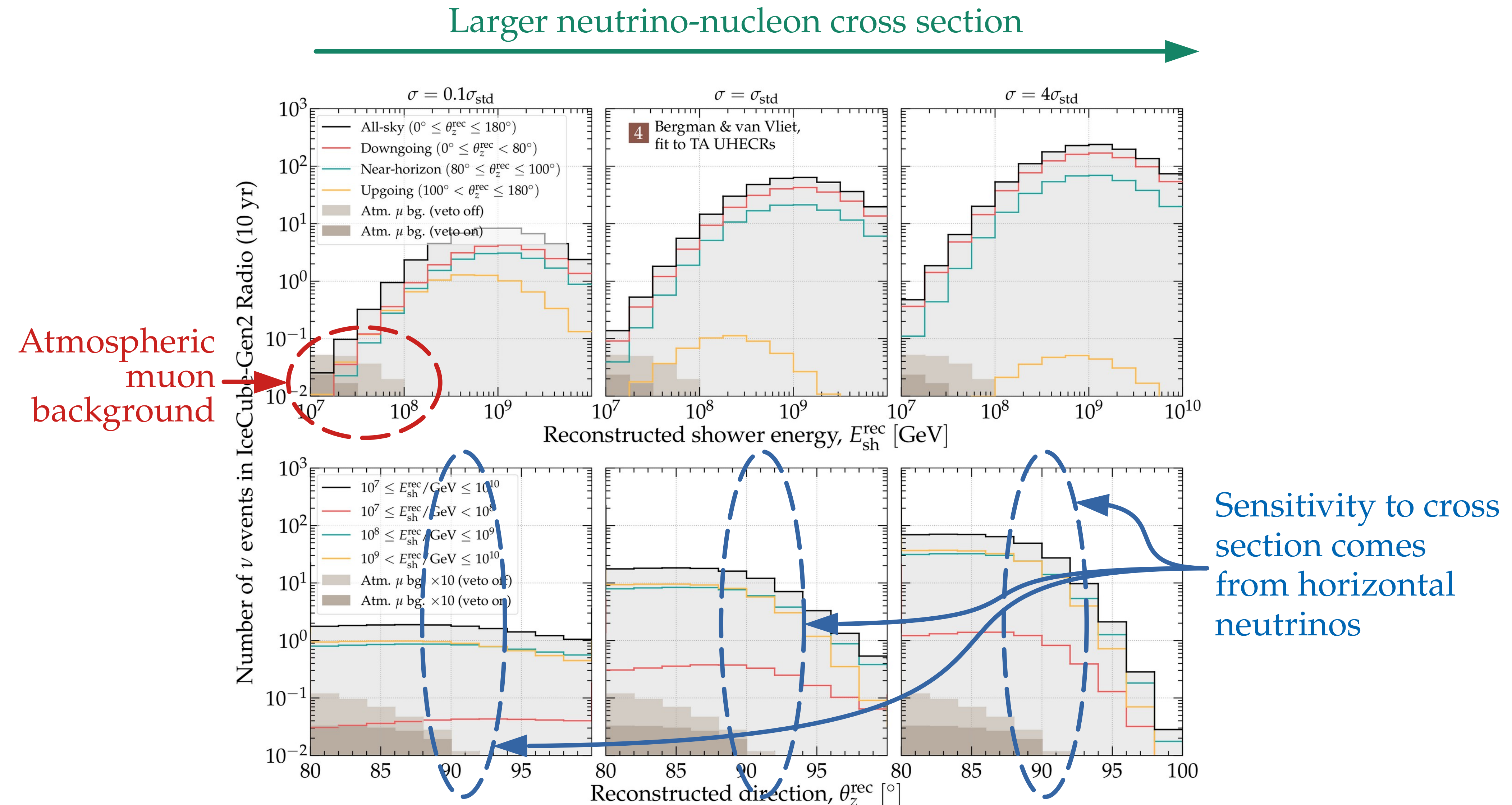


Valera, **MB**, Glaser, *JHEP* 2022

Larger neutrino-nucleon cross section



Valera, **MB**, Glaser, *JHEP* 2022



Valera, **MB**, Glaser, *JHEP* 2022

Measuring cross section *and* flux normalization

Two physical parameters:

Neutrino-nucleon cross section: $$f_\sigma = \frac{\sigma}{\sigma_{\rm std}}$$

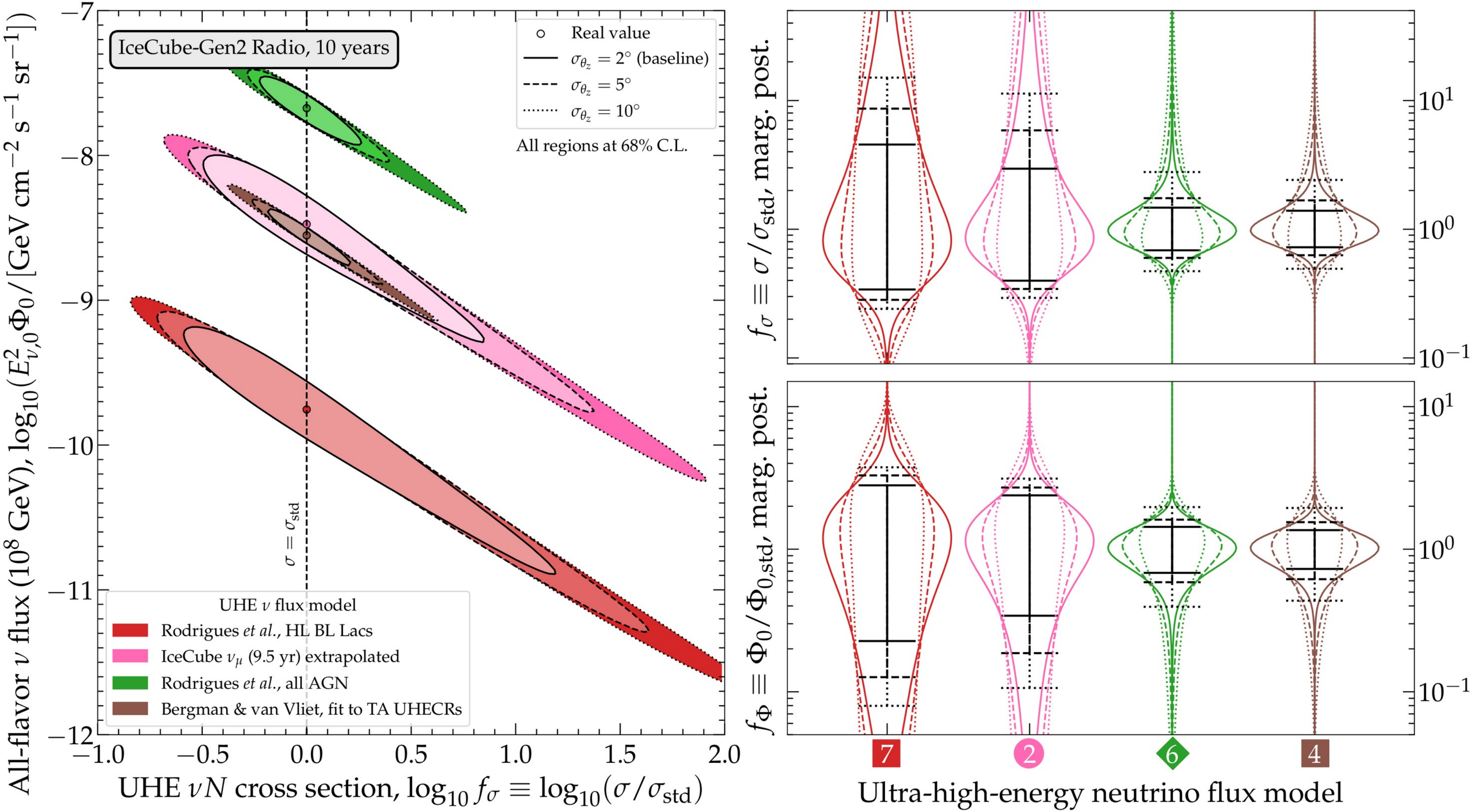
Neutrino flux normalization:
(Keep the spectral shape fixed for now)

$$f = \frac{\Phi_\nu(10^8\ \mathrm{GeV})}{\Phi_{\nu,\rm std}(10^8\ \mathrm{GeV})}$$

We vary and extract both simultaneously *always*,
and marginalize over each at a time

Effect of angular resolution

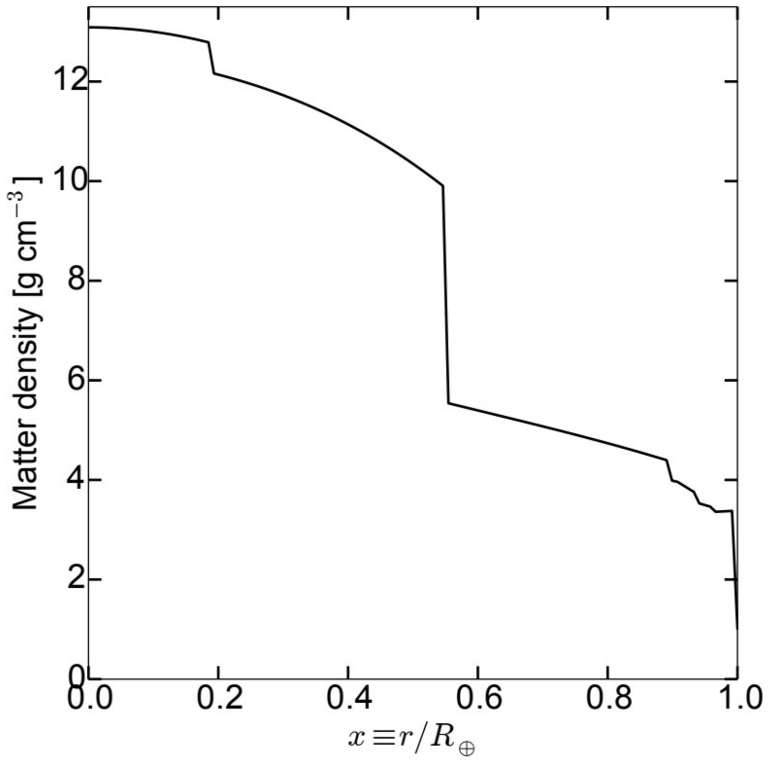
Valera, **MB**, Glaser, 2204.04237



A feel for the in-Earth attenuation

Earth matter density

(Preliminary Reference Earth Model)



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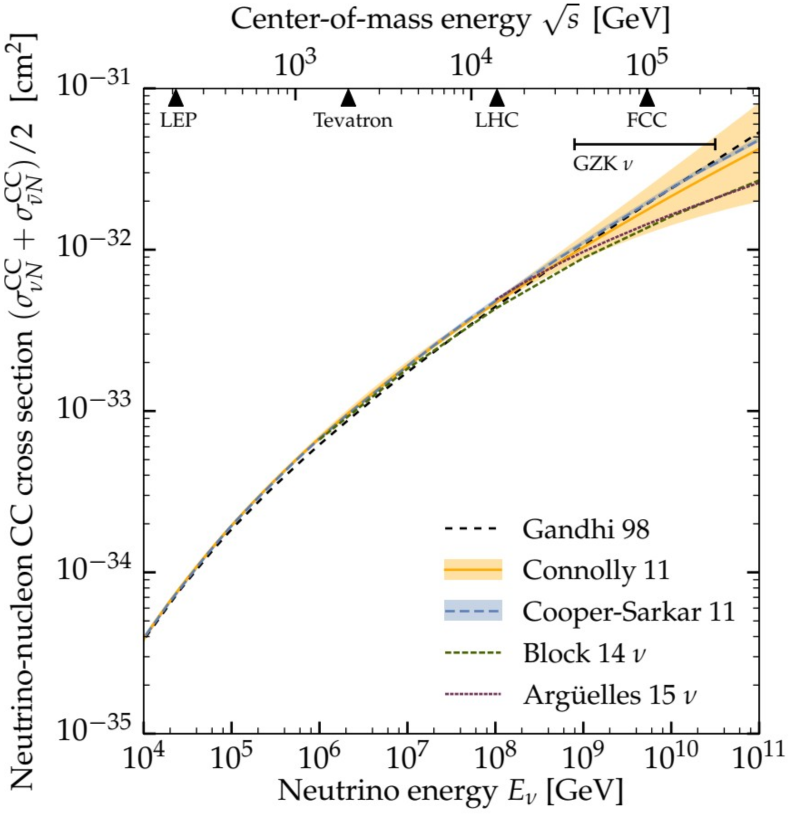
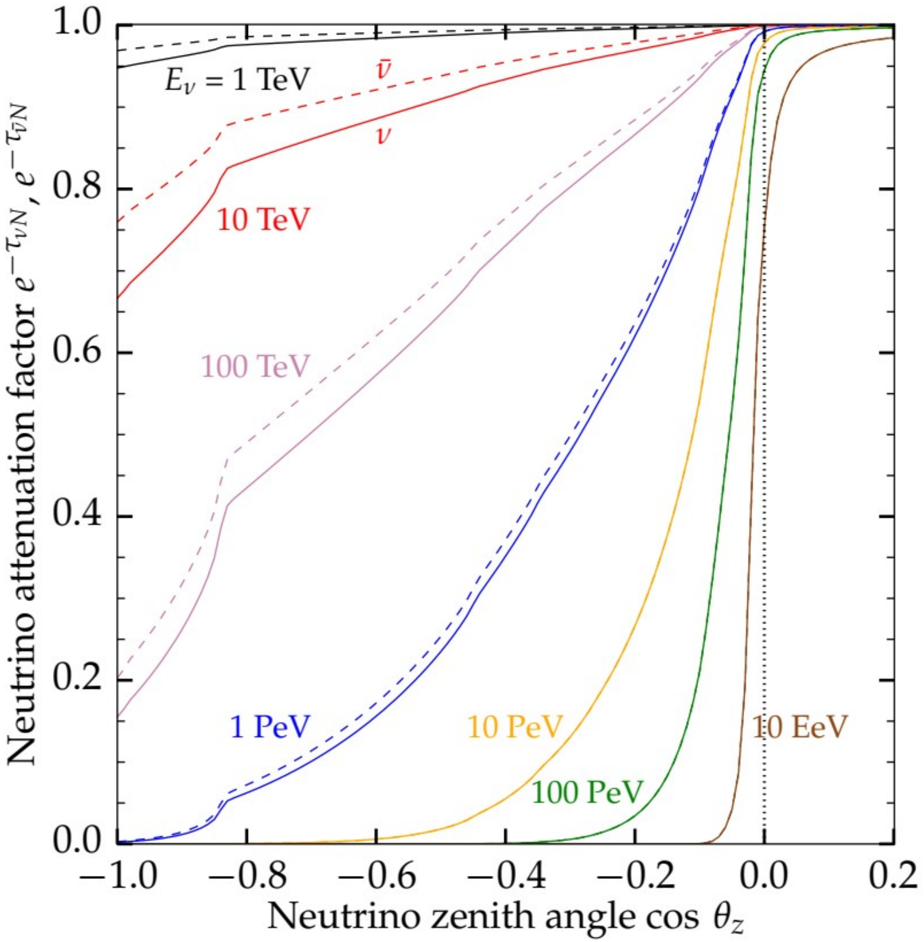
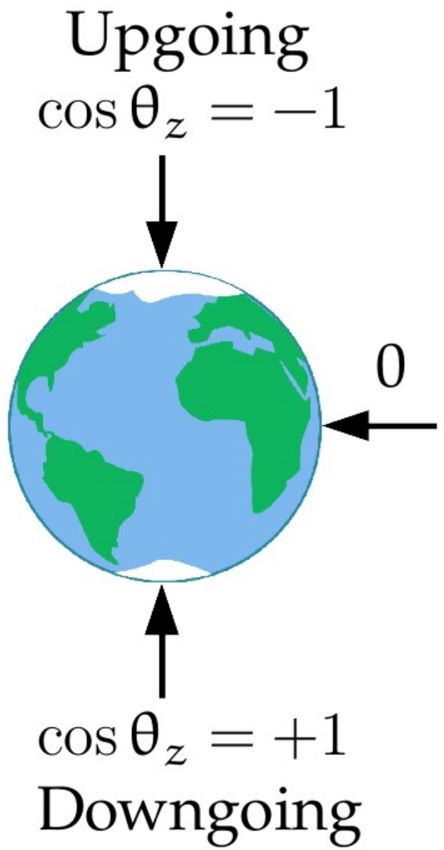
Neutrino-nucleon cross section



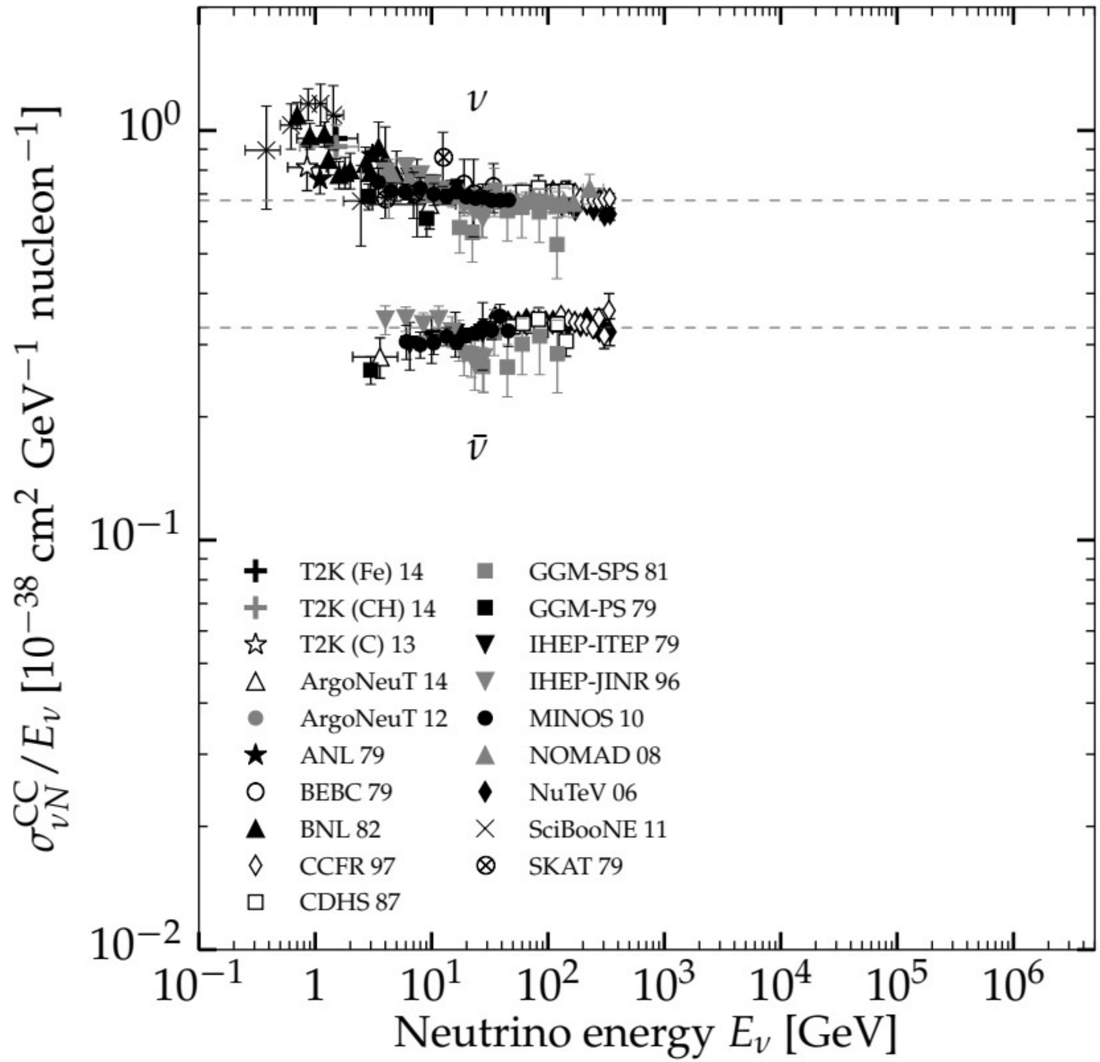
A feel for the in-Earth attenuation

=





MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017



MB & Connolly *PRL* 2019
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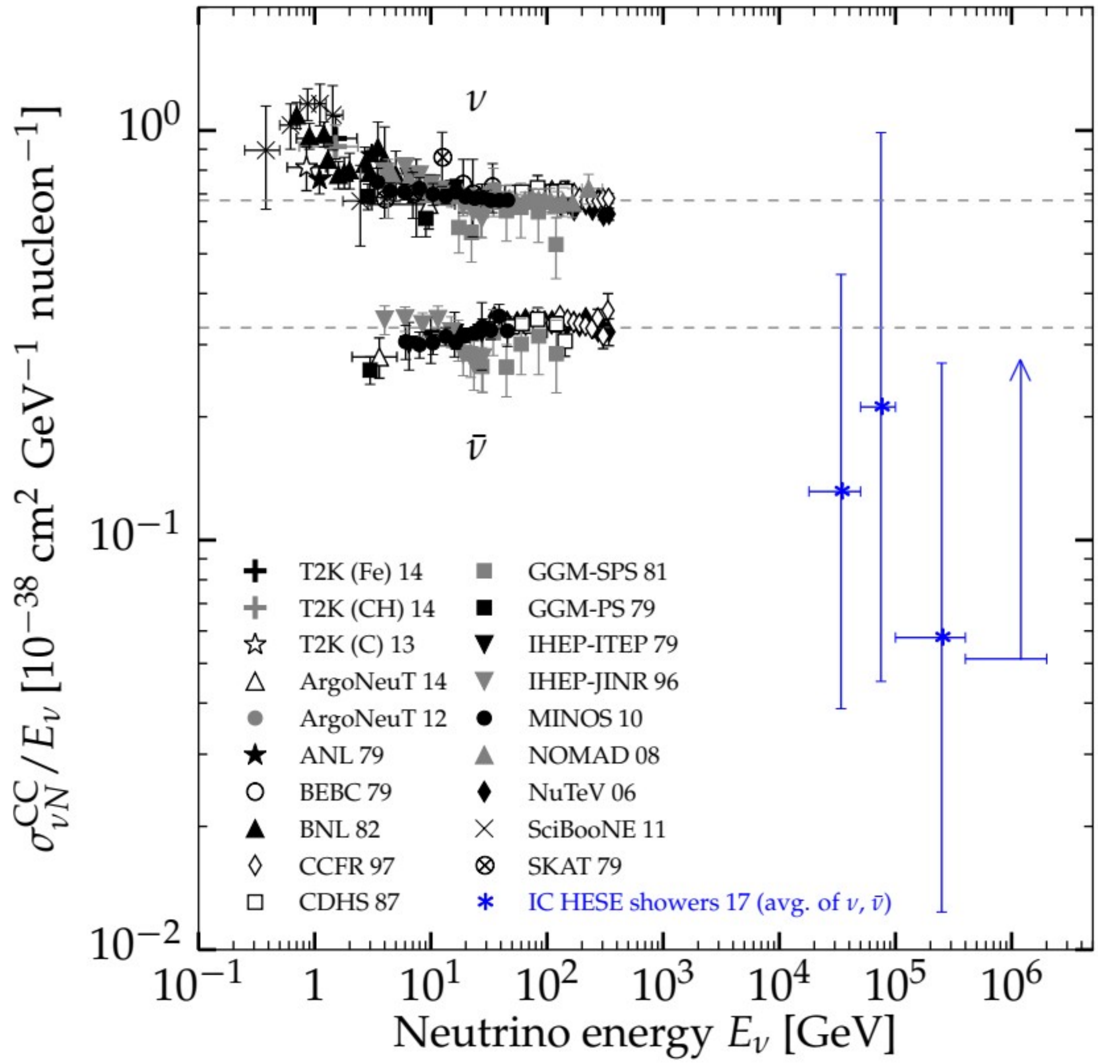
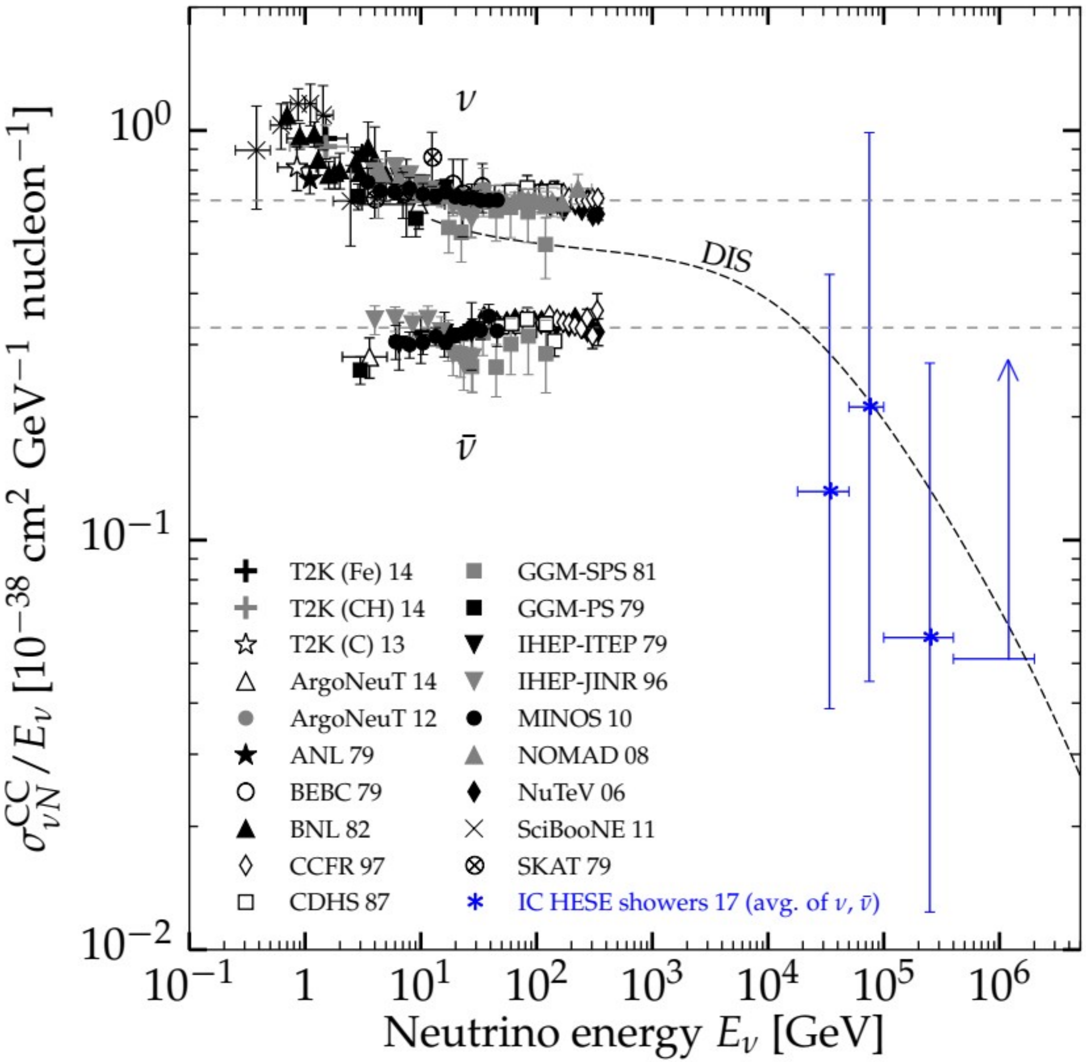
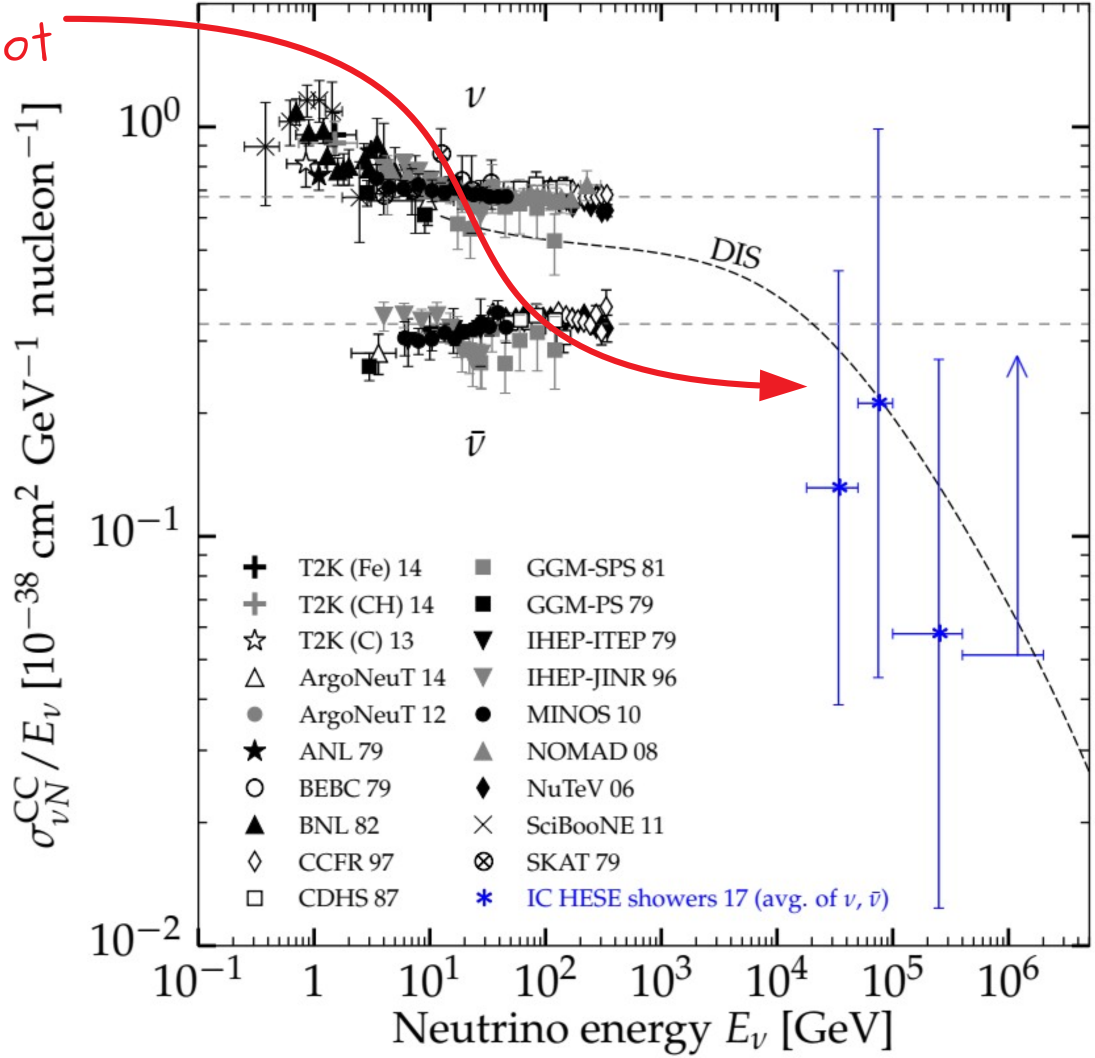




MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017

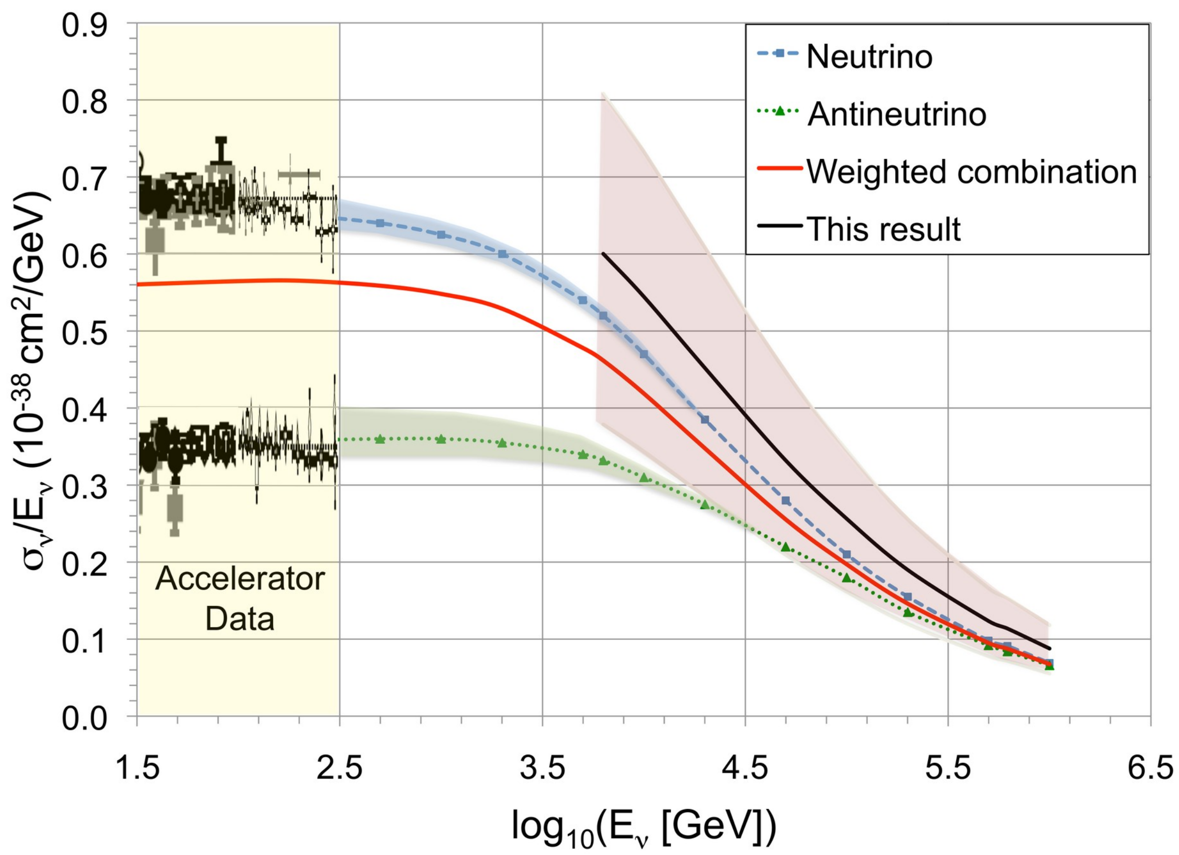
Extending the PDG cross-section plot

MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017



Using through-going muons instead

- Use ~10^4 through-going muons
- Measured: $\mathrm{d}E_\mu/\mathrm{d}x$
- Inferred: $E_\mu \approx \mathrm{d}E_\mu/\mathrm{d}x$
- From simulations (uncertain): most likely E_ν given E_μ
- Fit the ratio σ_{obs}/σ_{SM}
  $1.30\,^{+0.21}_{-0.19}(\text{stat.})\,^{+0.39}_{-0.43}(\text{syst.})$
- All events grouped in a single energy bin 6–980 TeV

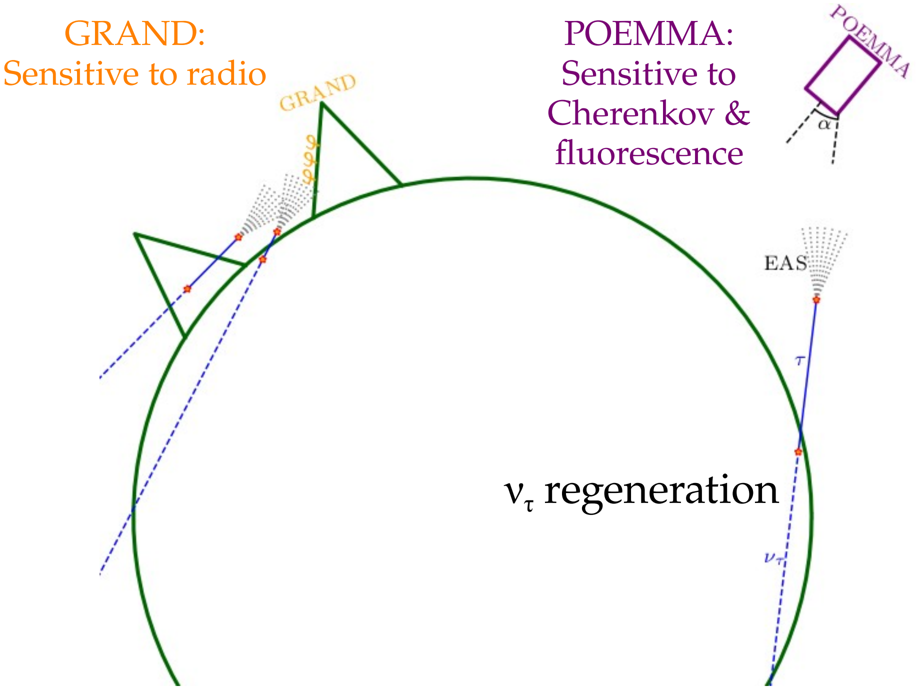


IceCube, *Nature* 2017

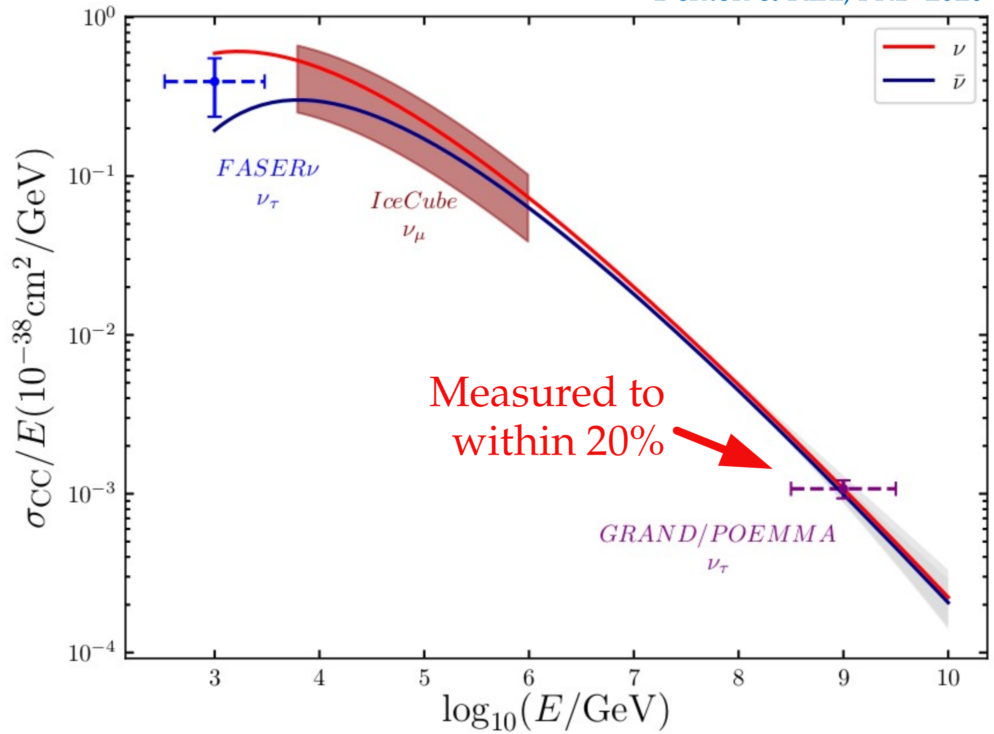
GRAND & POEMMA

Both sensitive to extensive air showers induced by Earth-skimming UHE ν_τ

If they see 100 events from ν_τ with initial energy of 10^9 GeV (pre-attenuation):



Denton & Kini, *PRD* 2020



Bonus: Measuring the inelasticity $\langle y \rangle$

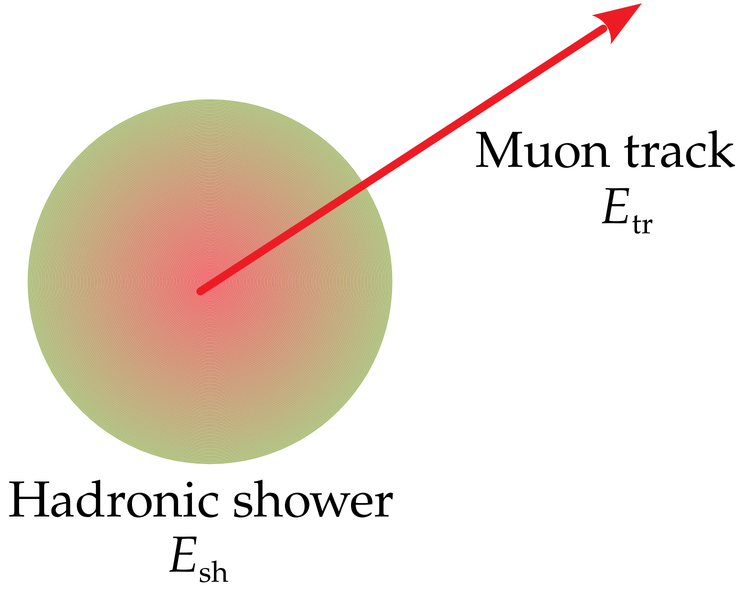
- Inelasticity in CC ν_μ interaction $\nu_\mu + N \to \mu + X$:

  $E_X = y\, E_\nu$ and $E_\mu = (1\text{-}y)\, E_\nu \;\Rightarrow\; y = (1 + E_\mu/E_X)^{-1}$

- The value of y follows a distribution $\mathrm{d}\sigma/\mathrm{d}y$

- In a HESE starting track:

$$\left.\begin{array}{l} E_X = E_{sh} \text{ (energy of shower)} \\ E_\mu = E_{tr} \text{ (energy of track)} \end{array}\right\}\; y = (1 + E_{tr}/E_{sh})^{-1}$$



IceCube Collab., *PRD* 2019

- New IceCube analysis:
  - 5 years of starting-track data (2650 tracks)
  - Machine learning separates shower from track
  - Different y distributions for ν and $\bar{\nu}$

Bonus: Measuring the inelasticity $\langle y \rangle$

- Inelasticity in CC ν_μ interaction $\nu_\mu + N \rightarrow \mu + X$:

  $E_X = y\, E_\nu$ and $E_\mu = (1-y)\, E_\nu \;\Rightarrow\; y = (1 + E_\mu / E_X)^{-1}$

- The value of y follows a distribution $d\sigma/dy$

- In a HESE starting track:

  $$\left.\begin{aligned} E_X &= E_{sh} \text{ (energy of shower)} \\ E_\mu &= E_{tr} \text{ (energy of track)} \end{aligned}\right\} \; y = (1 + E_{tr}/E_{sh})^{-1}$$

- New IceCube analysis:
  - 5 years of starting-track data (2650 tracks)
  - Machine learning separates shower from track
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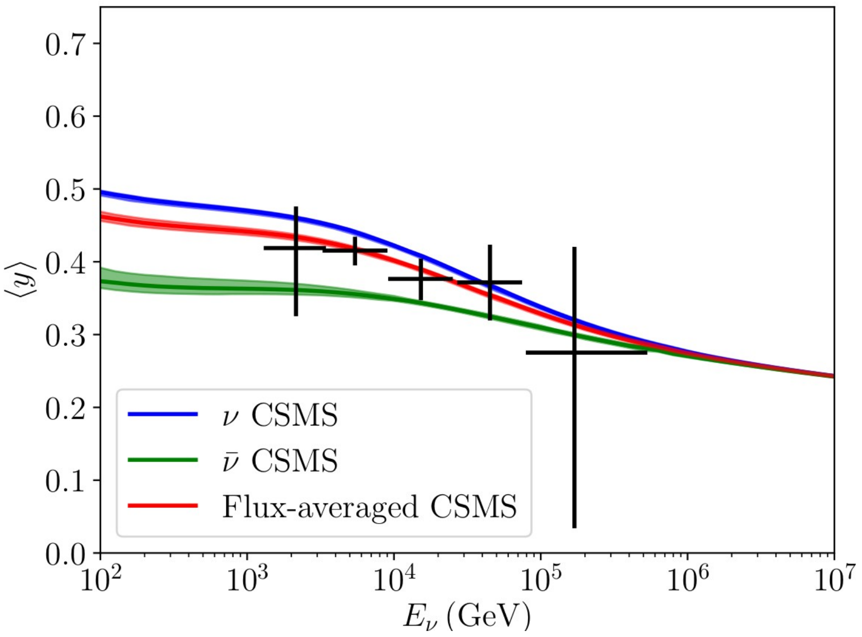
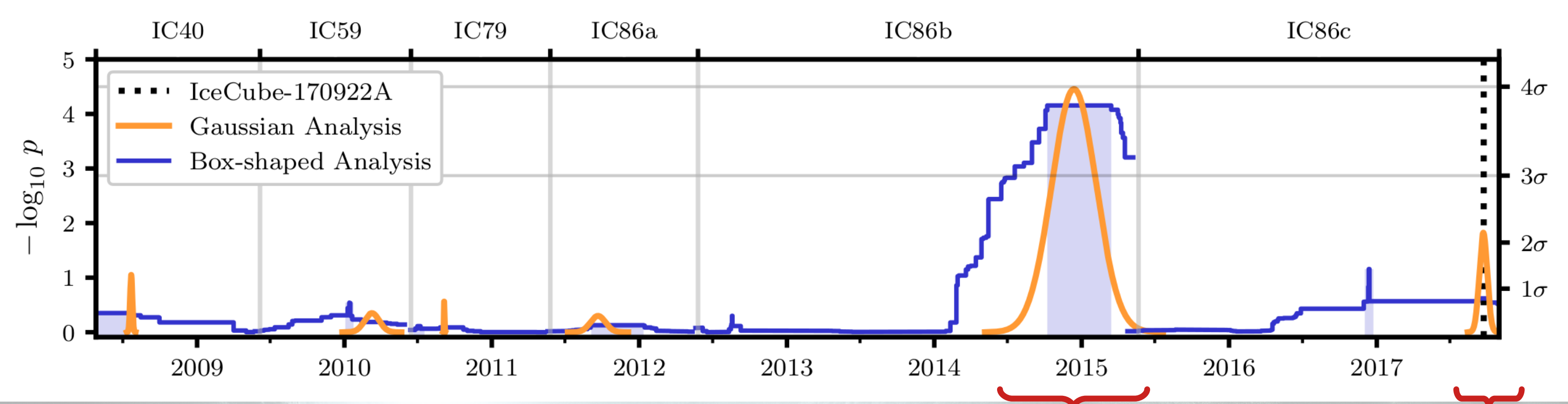


IceCube Collab., *PRD* 2019

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 $p=8\times10^{-3}$

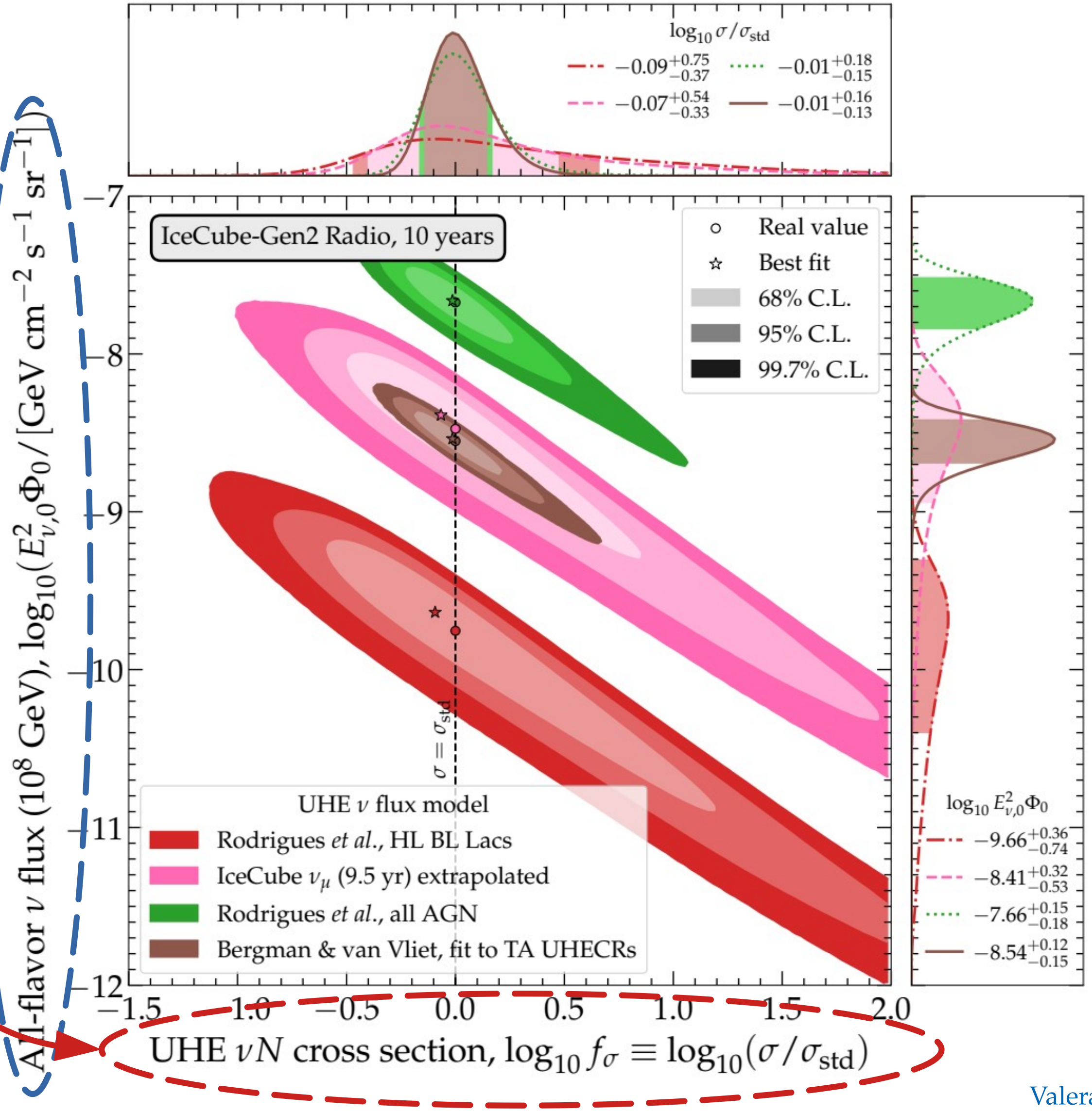
2014–2015: 13±5 ν flare, no X-ray flare
3.5σ significance of correlation (post-trial)

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

$\underbrace{\qquad\qquad}_{\text{Combined (pre-trial): 4.1σ}}$

Flux normalization

Cross section



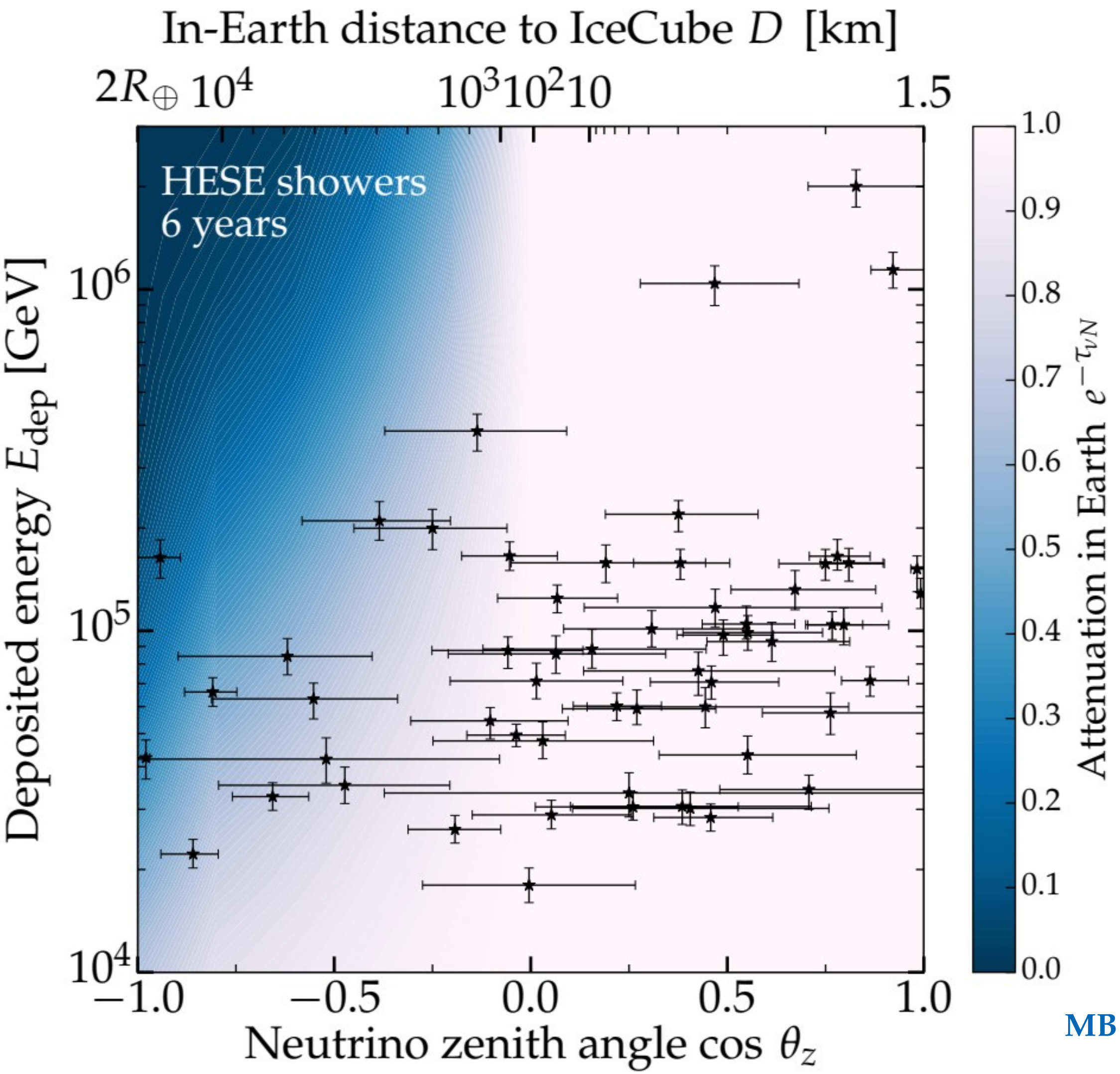
Needed to measure the cross section?

~30–300 events

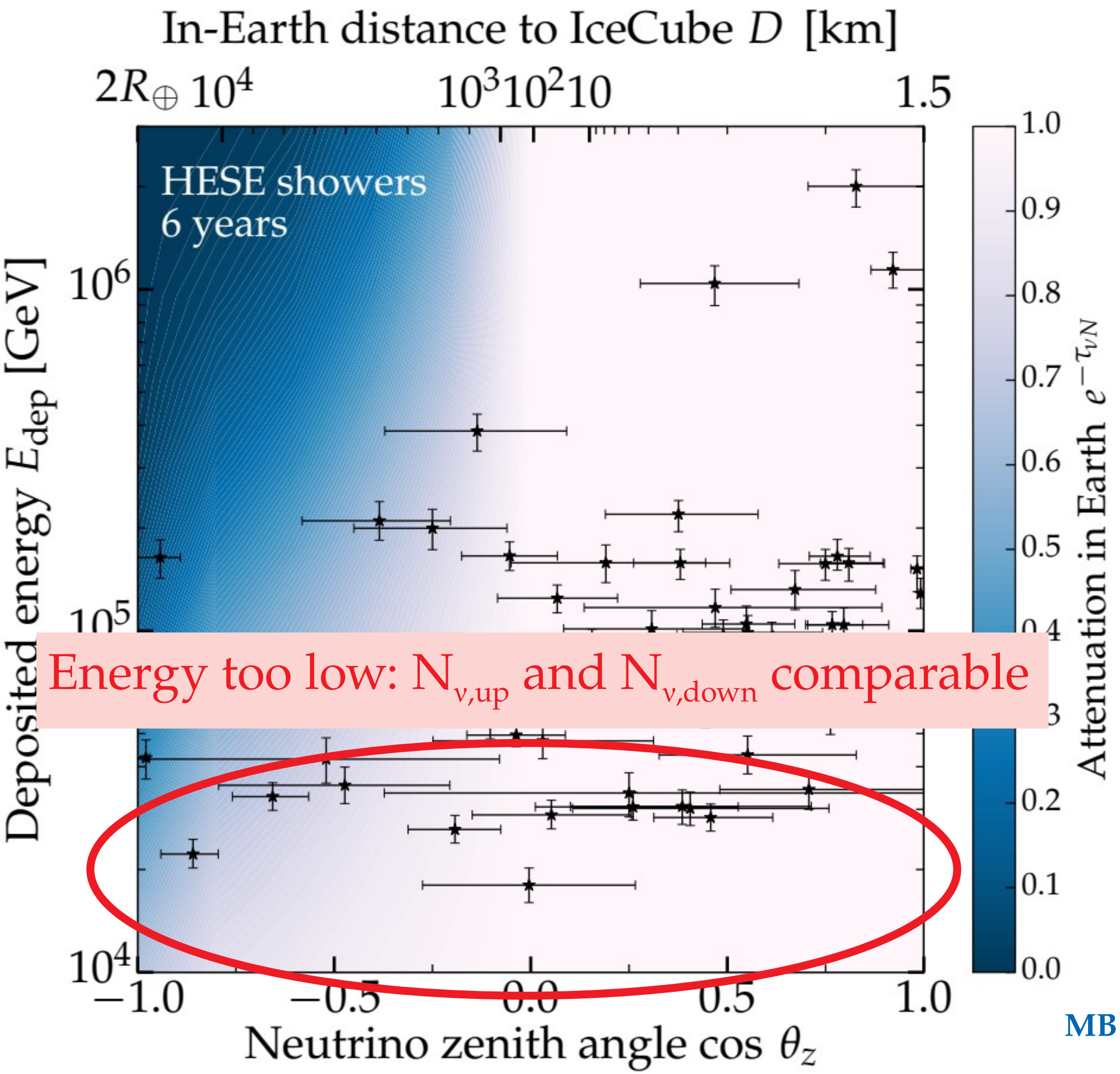
In this work:
We fix the energy dependence of flux and cross section (but explore many alternatives)

Soon to come:
Measure the energy dependence of the flux and cross section

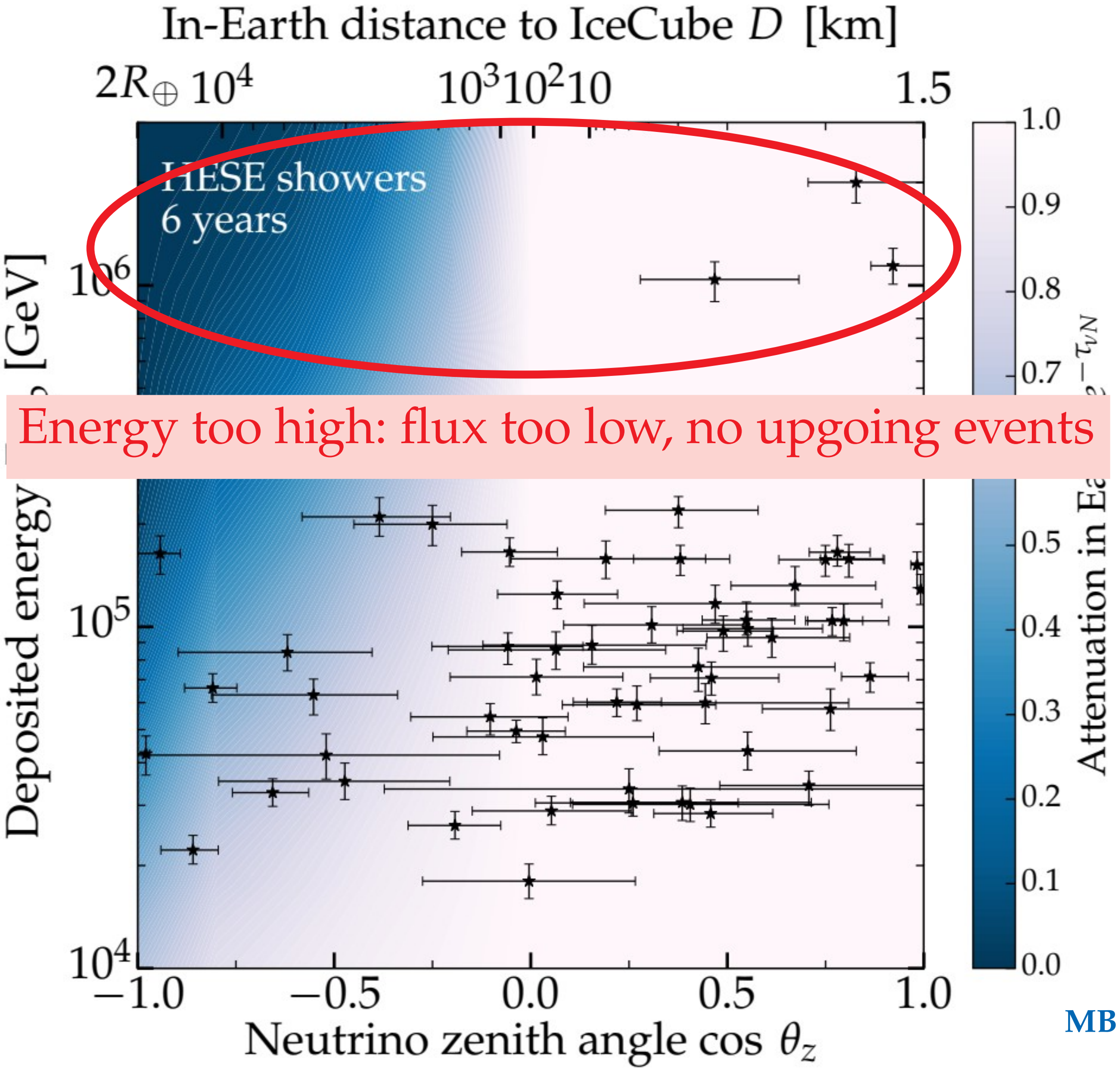
Valera, **MB**, Glaser, *JHEP* 2022



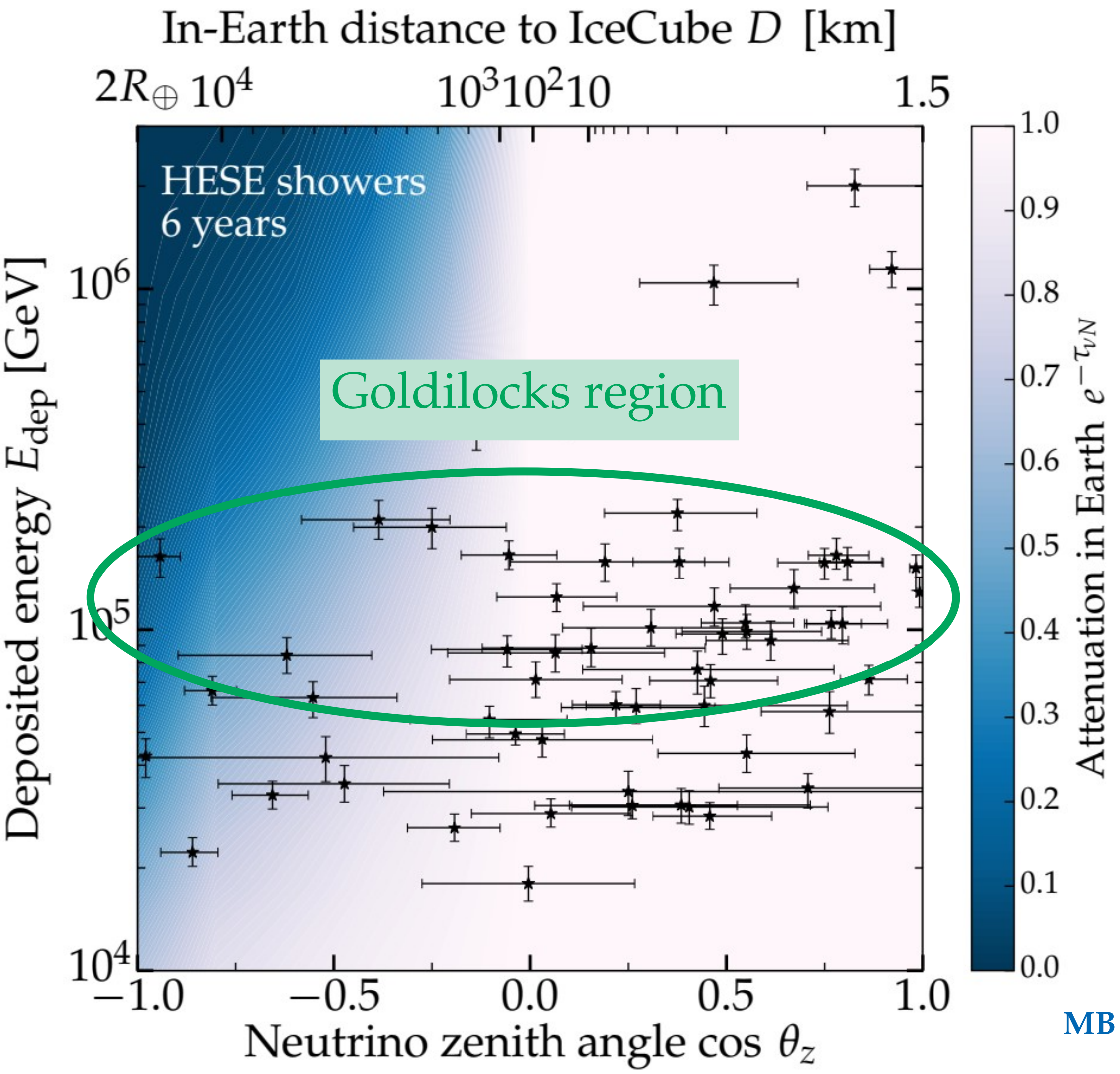
MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

$\equiv$

Allowed regions of flavor ratios at Earth derived from oscillations

MB, Beacom, Winter, *PRL* 2015

Note:
The original palatable regions were frequentist [**MB**, Beacom, Winter, *PRL* 2015]; the new ones are Bayesian

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Explore all possible combinations

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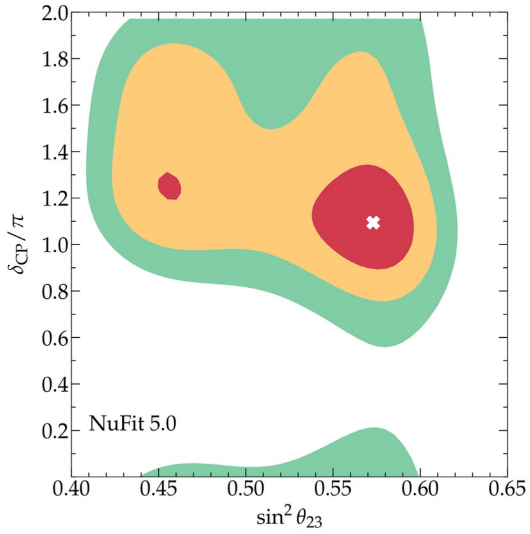
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

Esteban *et al.*, *JHEP* 2020
www.nu-fit.org



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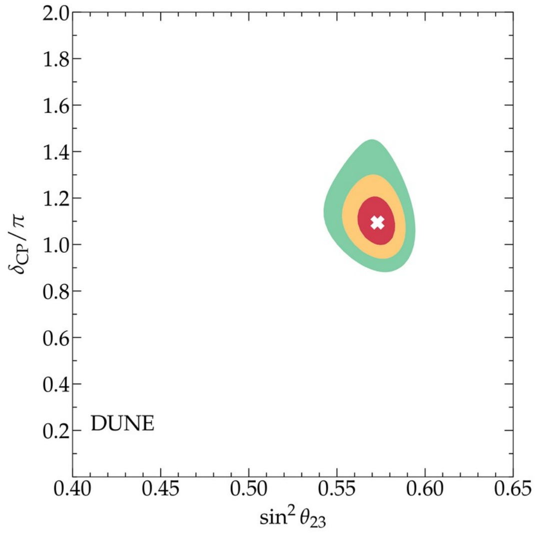
Esteban *et al.*, *JHEP* 2020
www.nu-fit.org

Post-2020: Build our own profiles using simulations of JUNO, DUNE, Hyper-K

An *et al.*, *J. Phys. G* 2016
DUNE, 2002.03005
Huber, Lindner, Winter, *Nucl. Phys. B* 2002



Measuring the high-energy *νN* cross section

Number of detected neutrinos (simplified for presentation):

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

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
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(L short → no matter)

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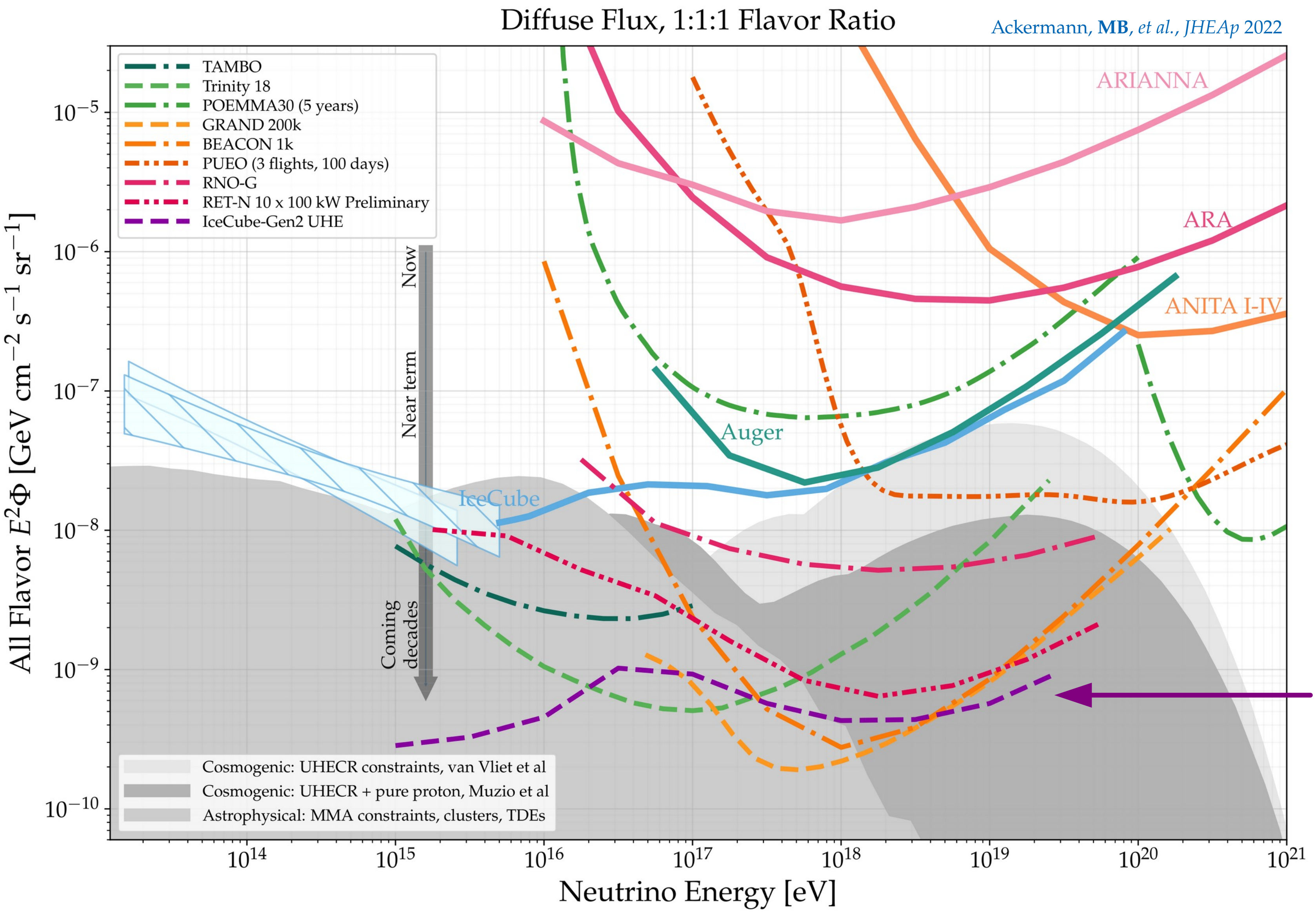
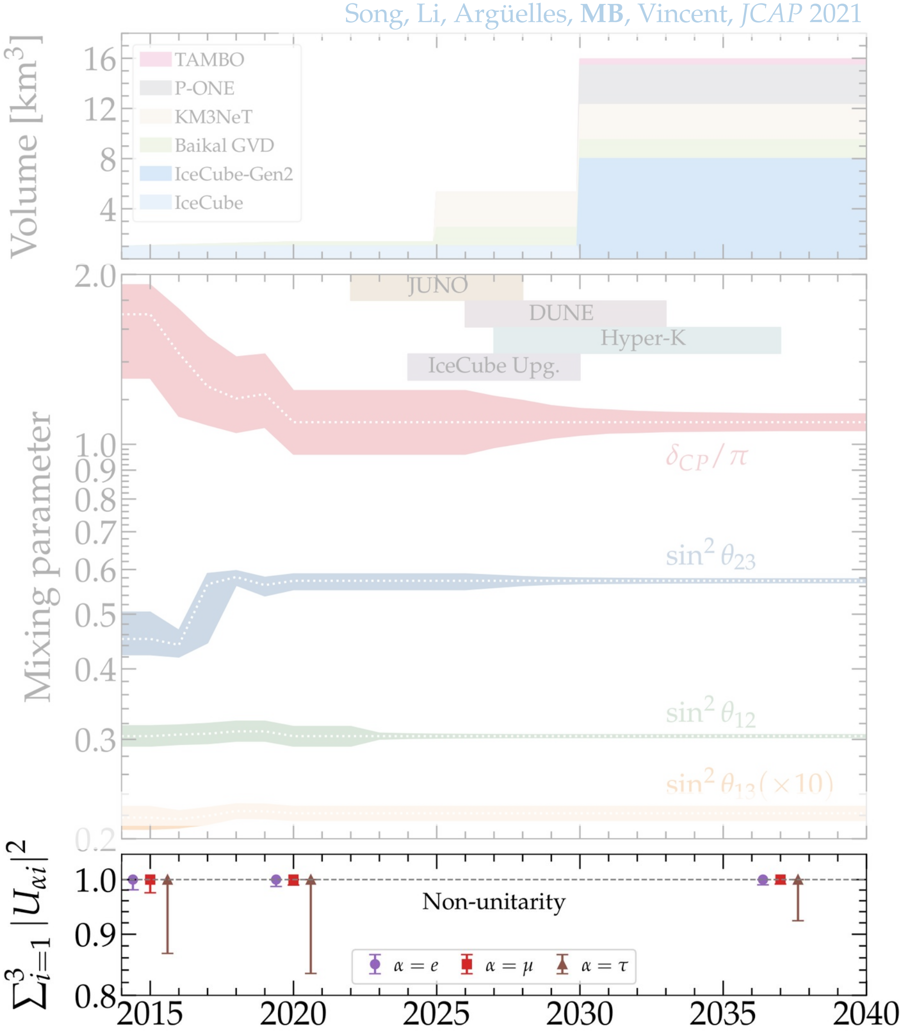


UHE radio-detection at Gen2 in our forecasts

Three reasons to be excited

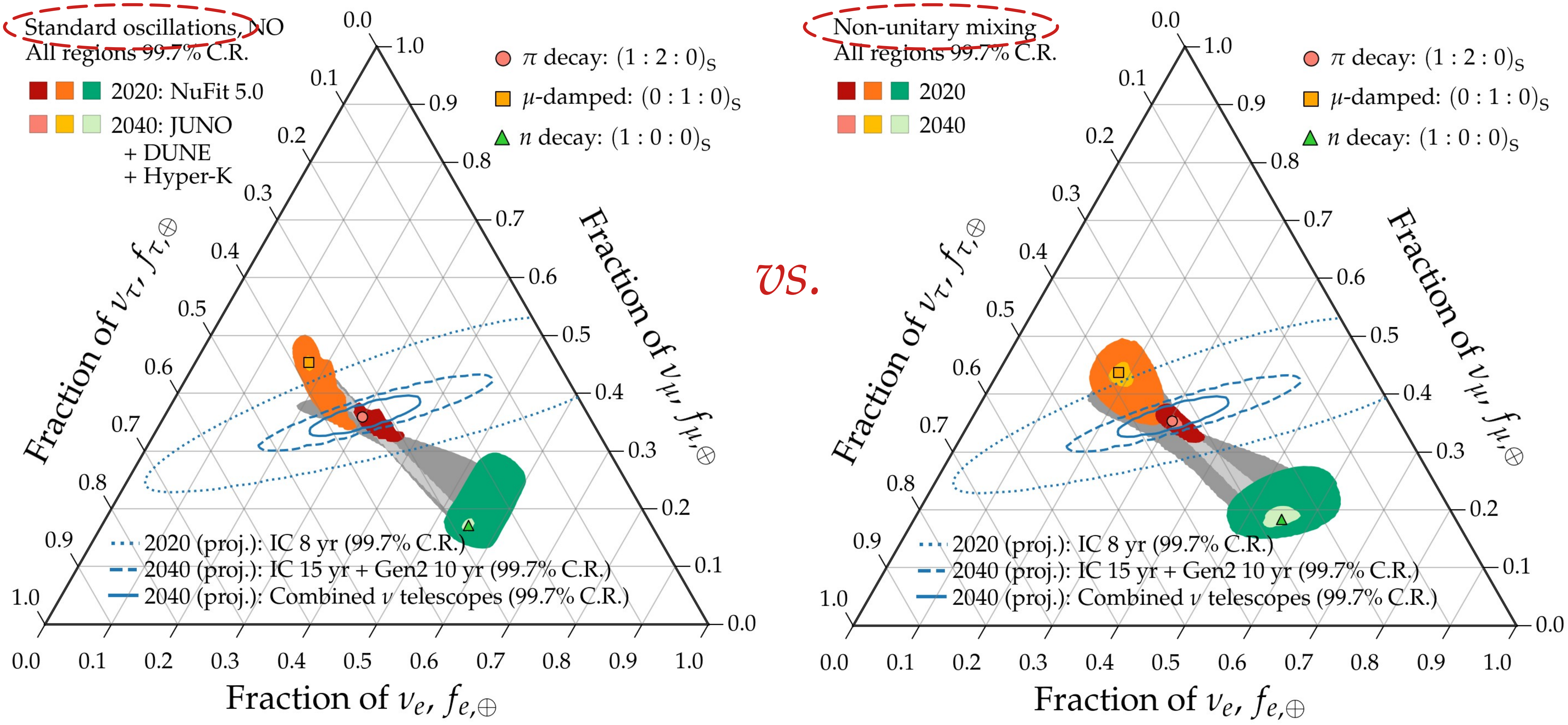


Flavor measurements:
New neutrino telescopes = more events, better flavor measurement

Oscillation physics:
We will know the mixing parameters better (JUNO, DUNE, Hyper-K, IceCube Upgrade)

Test of the oscillation framework:
We will be able to do what we want even if oscillations are non-unitary

No unitarity? *No problem*



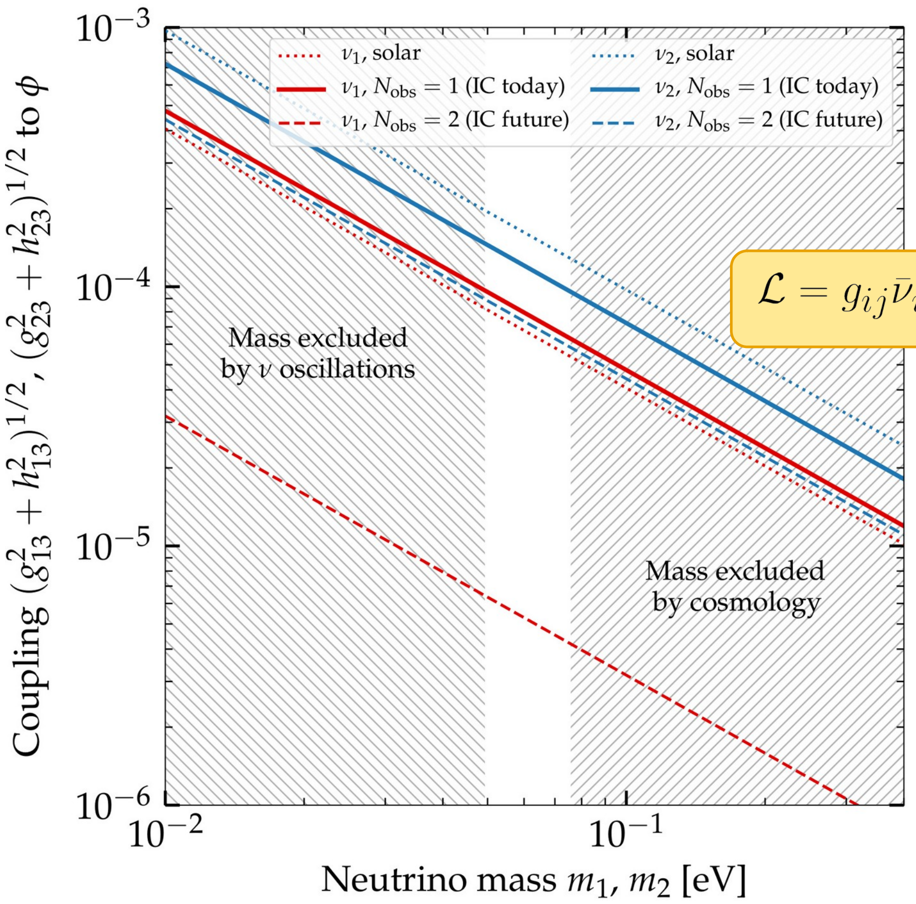
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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



$$\mathcal{L} = g_{ij}\bar{\nu}_i\nu_j\phi + h_{ij}\bar{\nu}_i\gamma_5\nu_j\phi + \text{h.c.}$$

Lower limits on couplings

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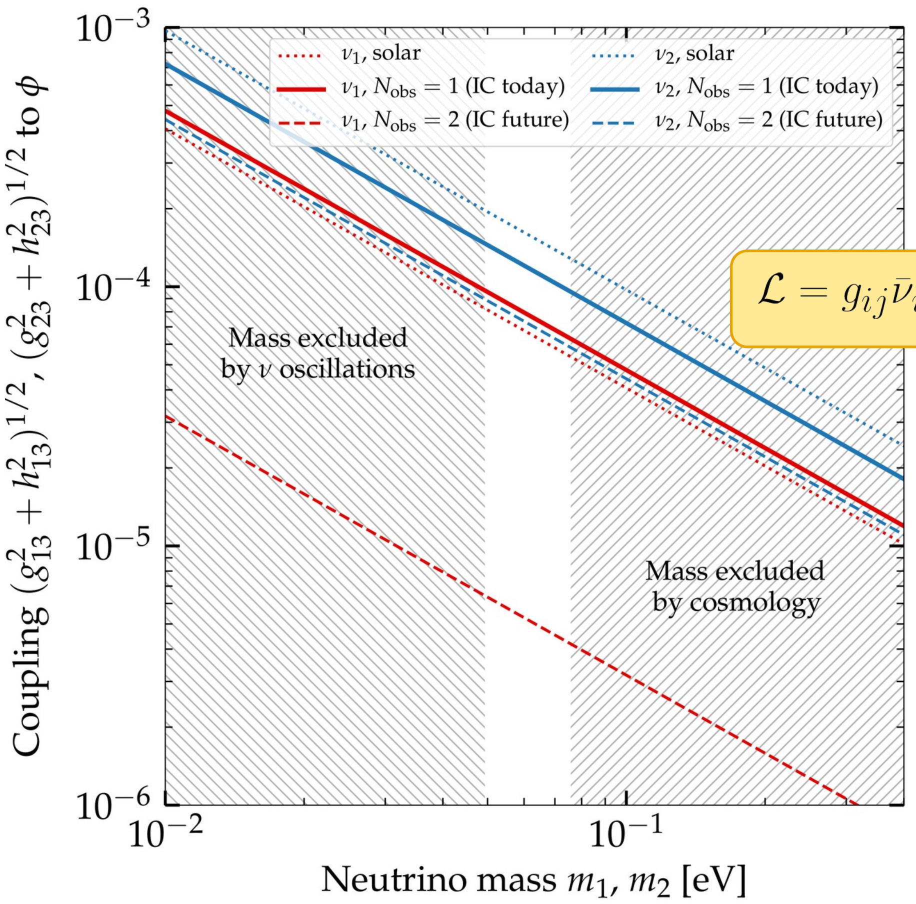

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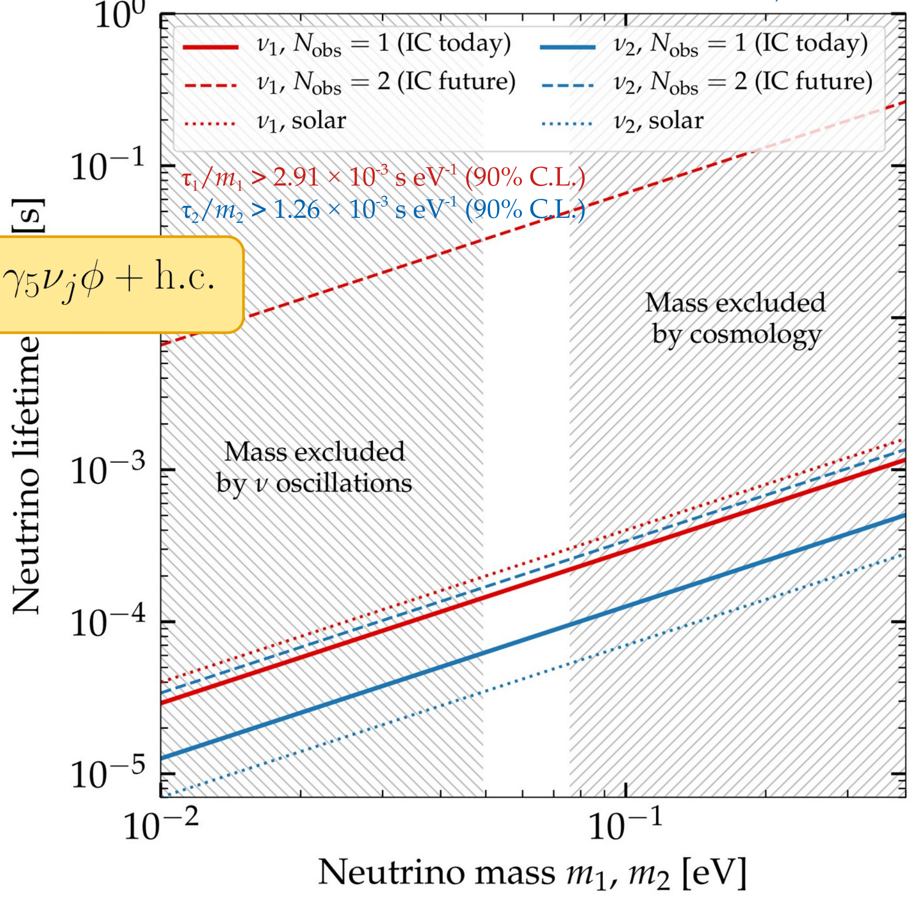

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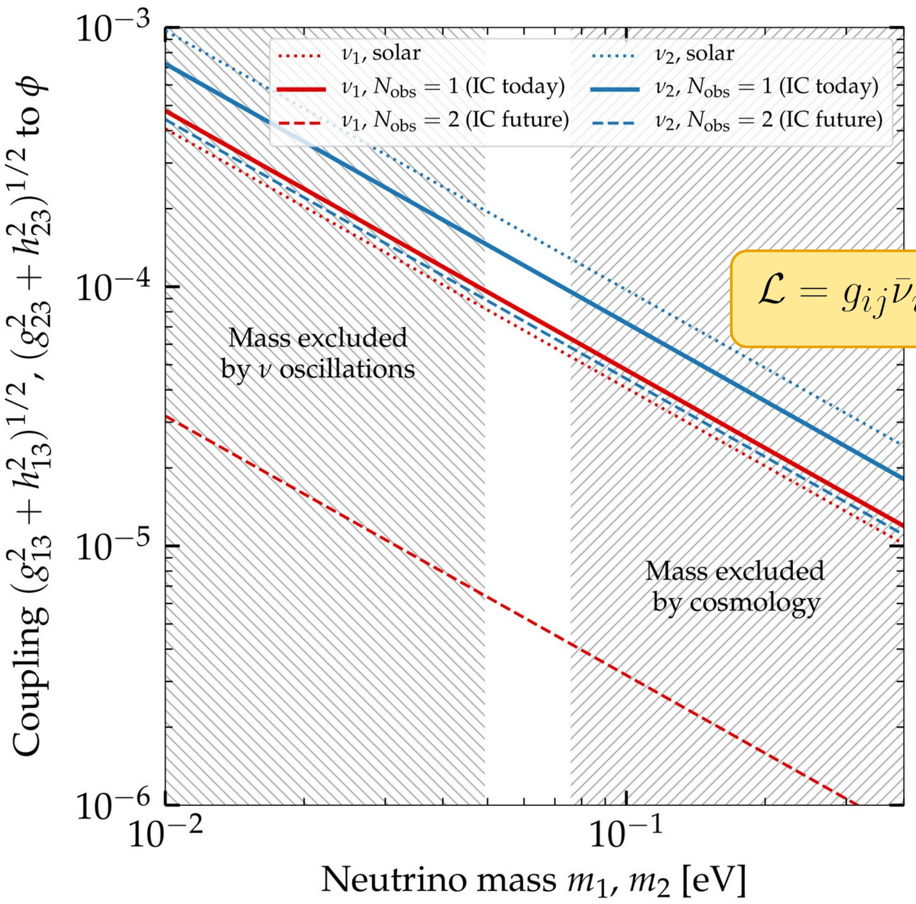

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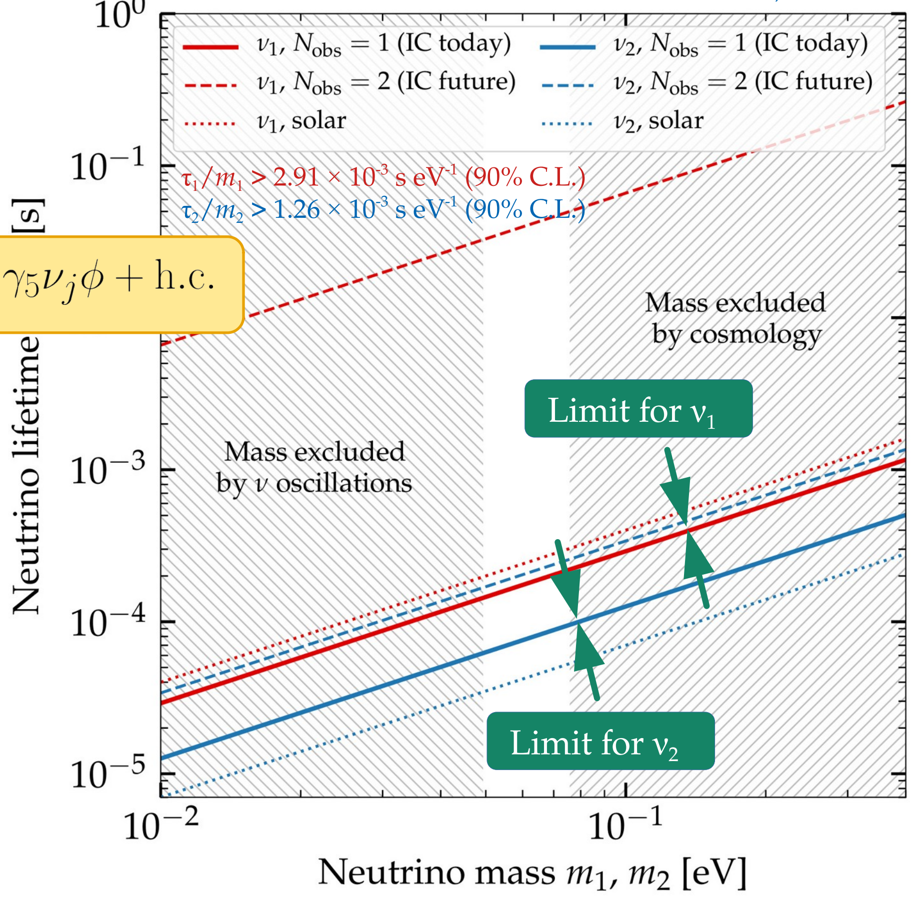
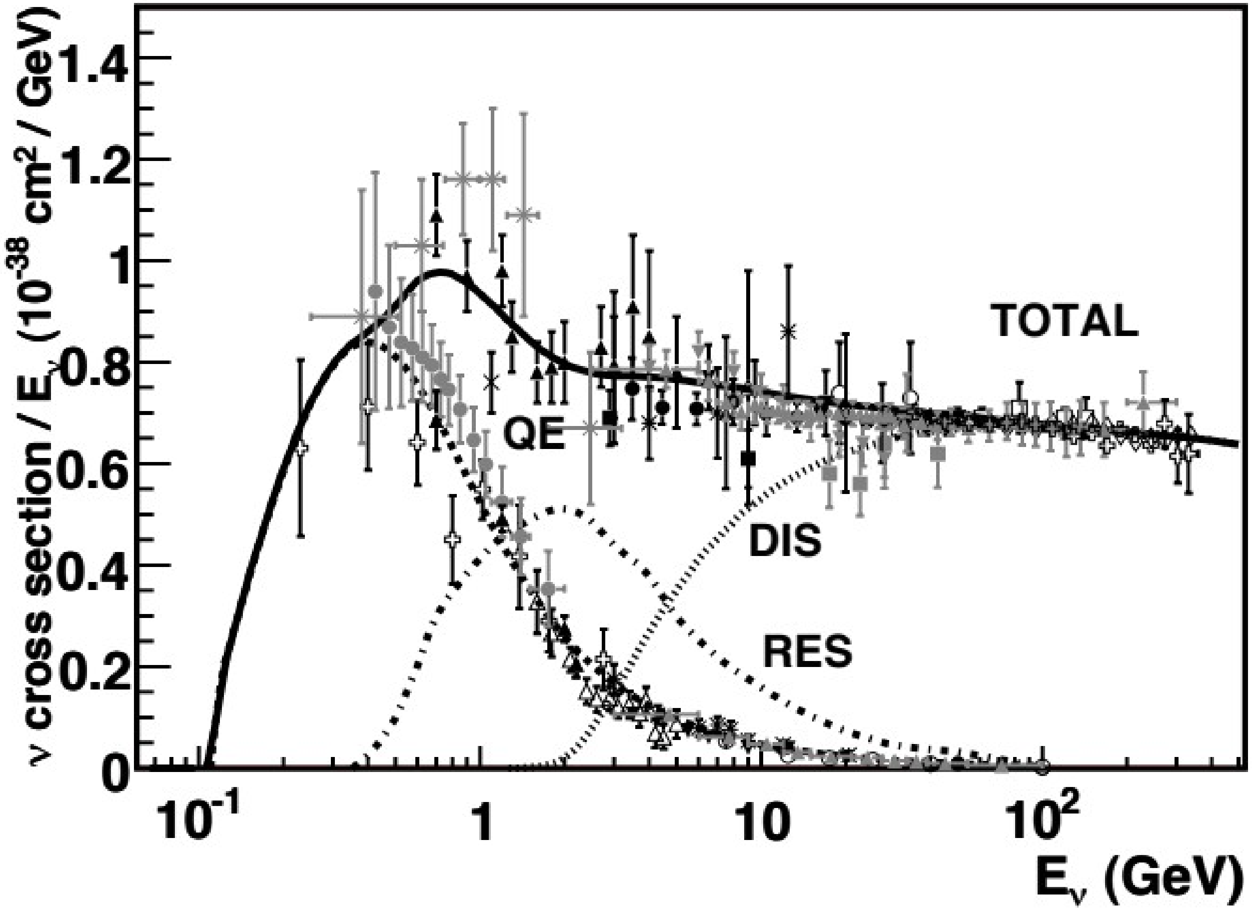
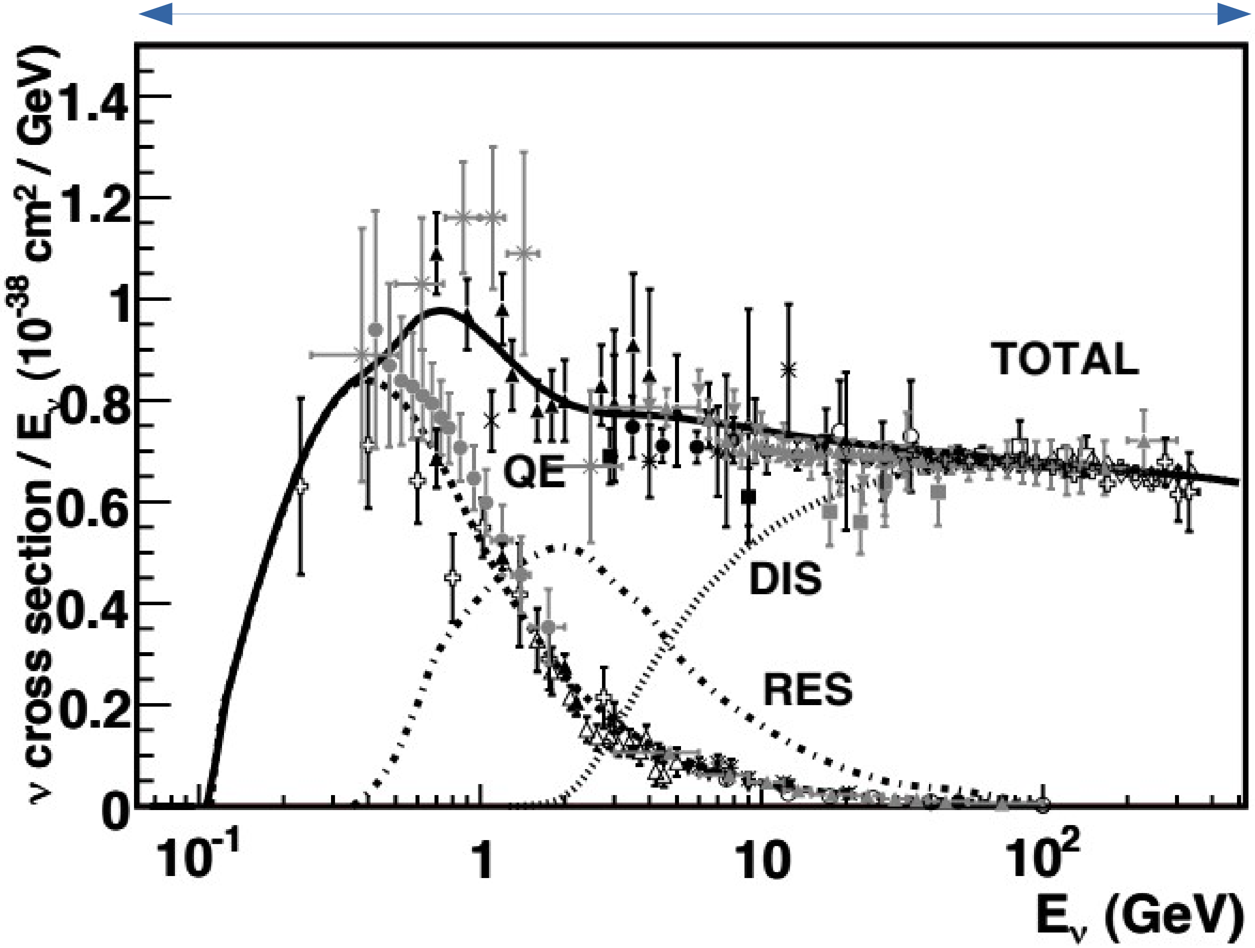




Particle Data Group

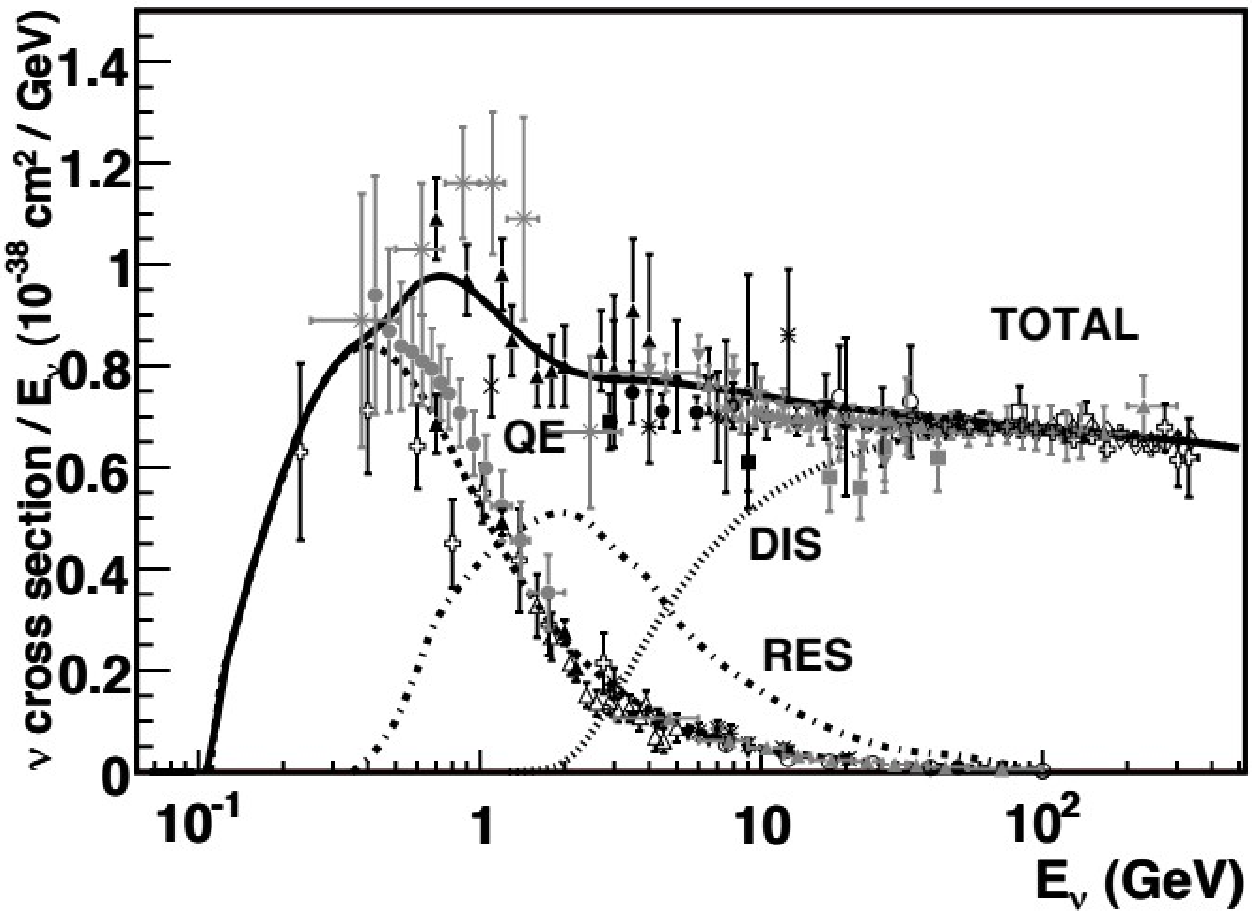
Accelerator experiments



Particle Data Group

Accelerator experiments

Coherent neutrino scattering



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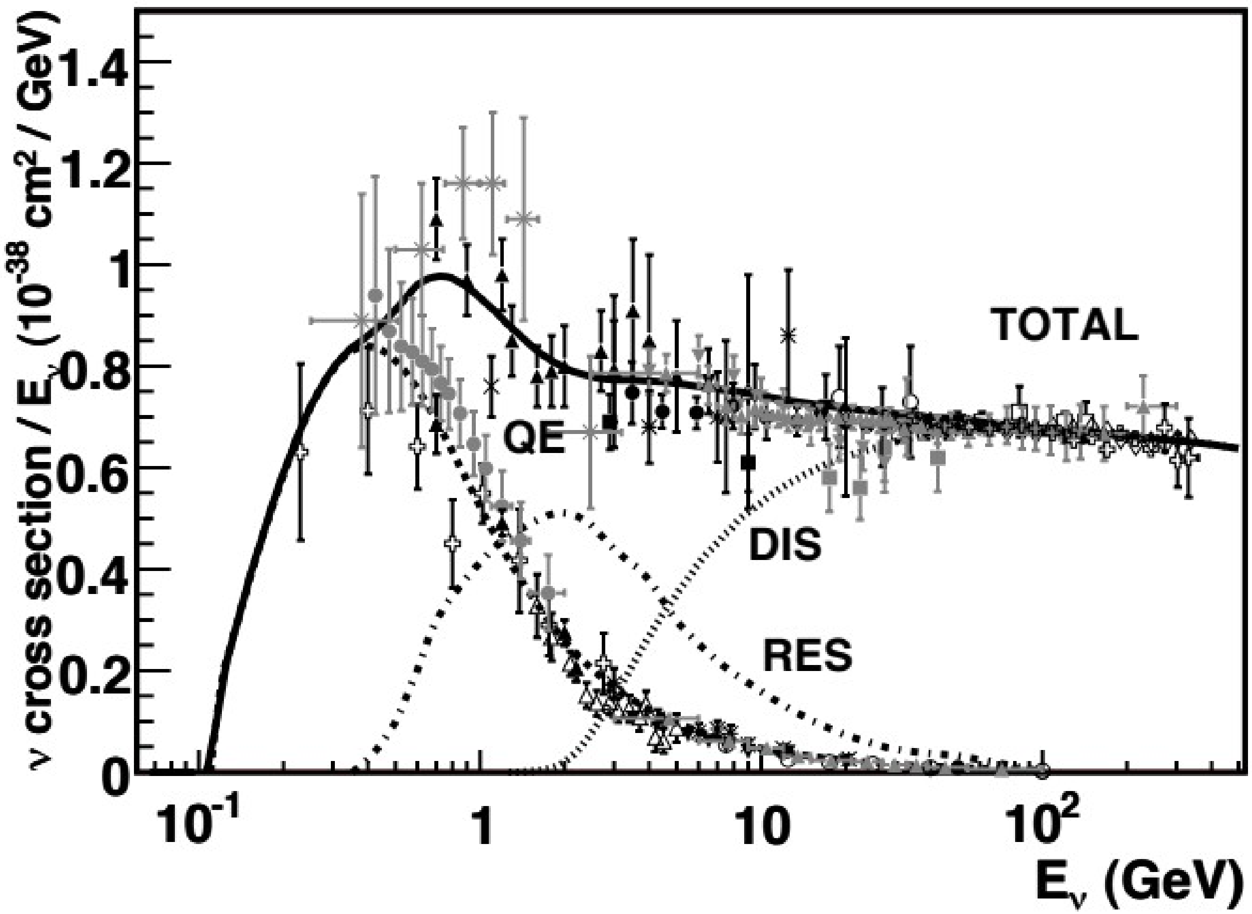

No measurements
… until recently!

Particle Data Group

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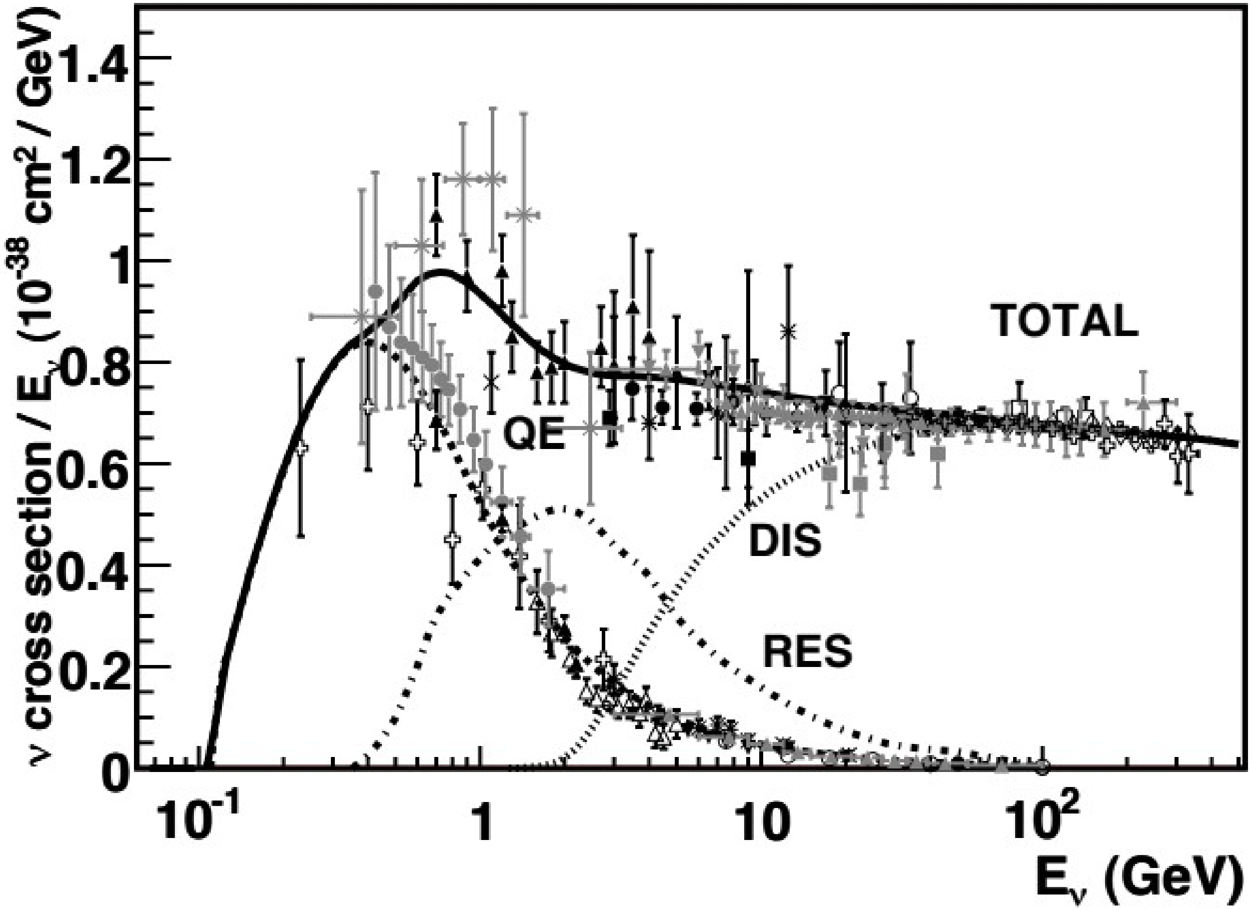

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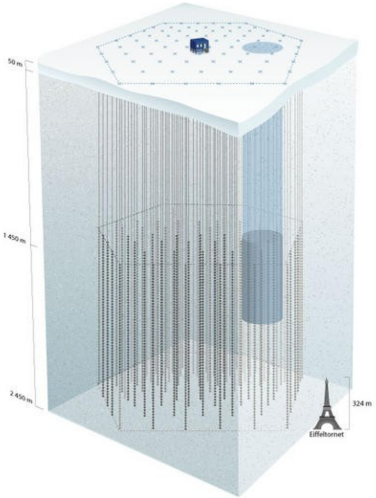
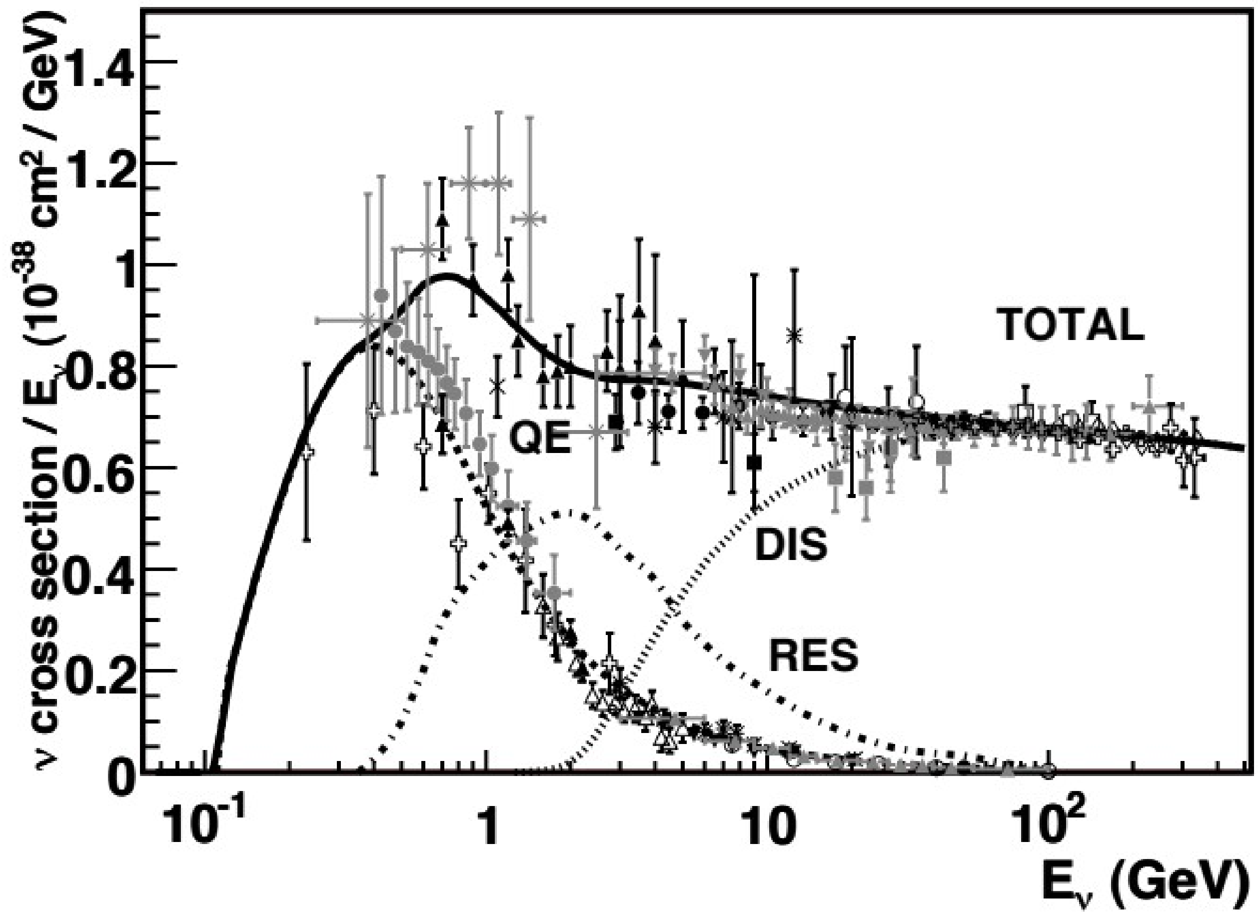


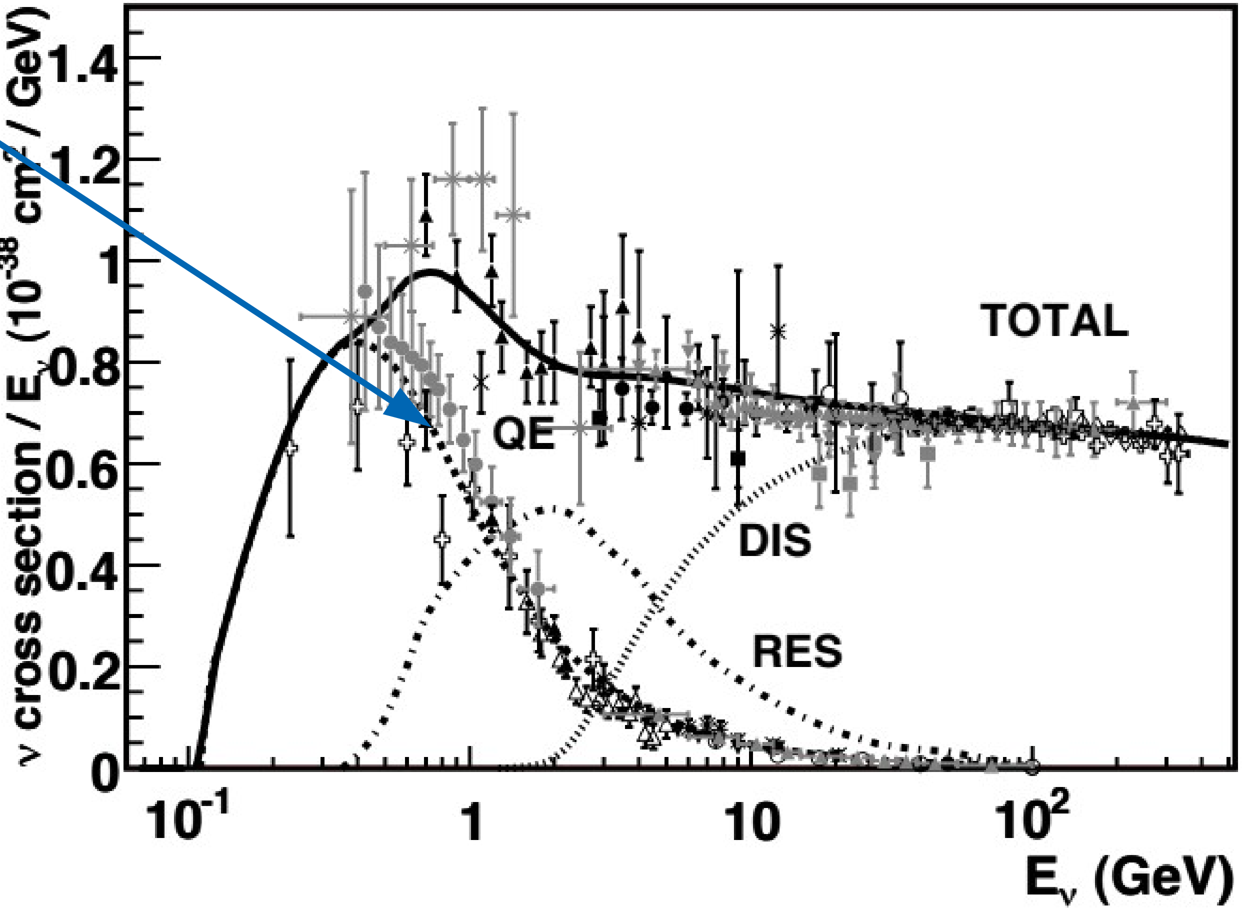


Particle Data Group

Quasi-elastic scattering:

$\nu_l + n \rightarrow l^- + p$

$\bar{\nu}_l + p \rightarrow l^+ + n$



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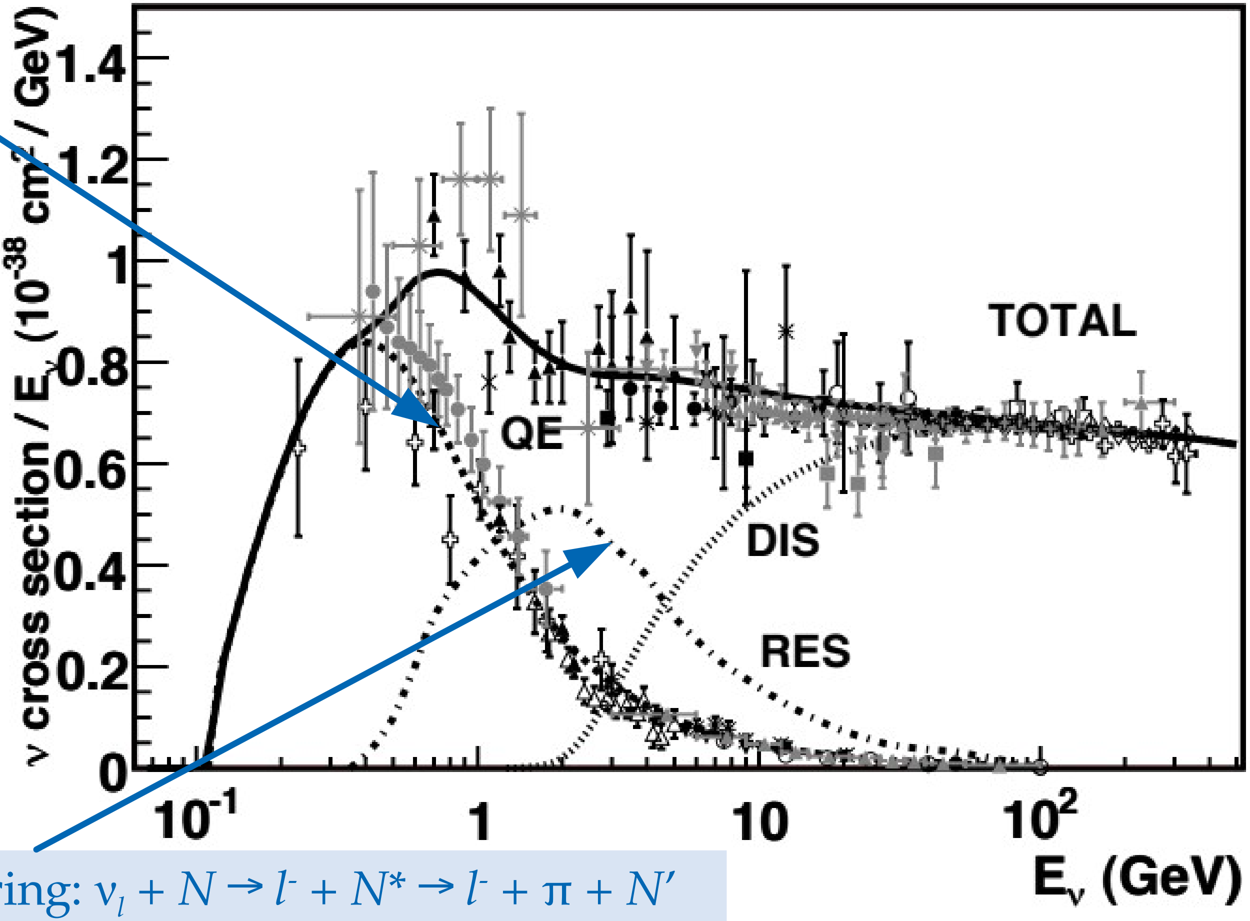

Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

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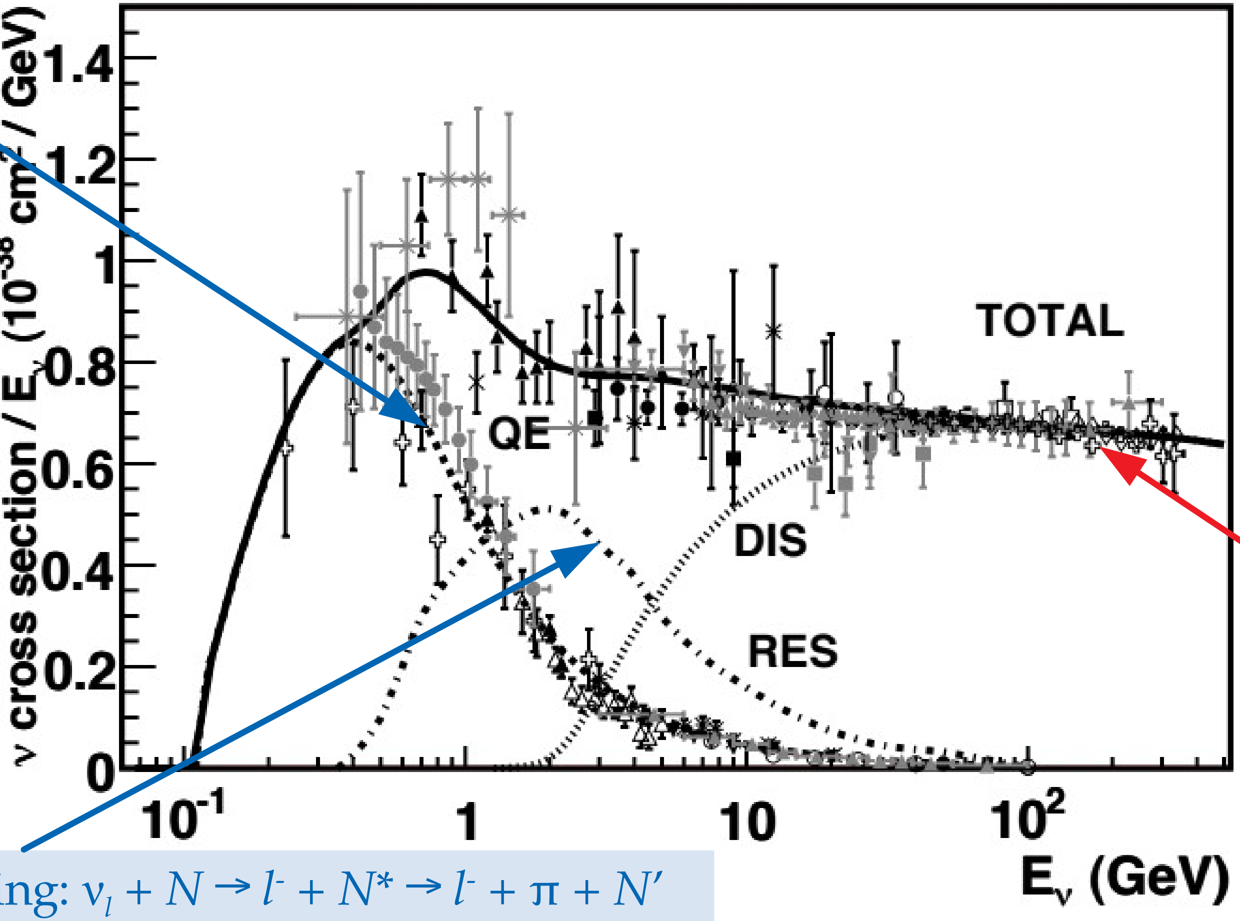


Deep inelastic scattering:

$\nu_l + N \rightarrow l^- + X$

$\bar{\nu}_l + N \rightarrow l^+ + X$

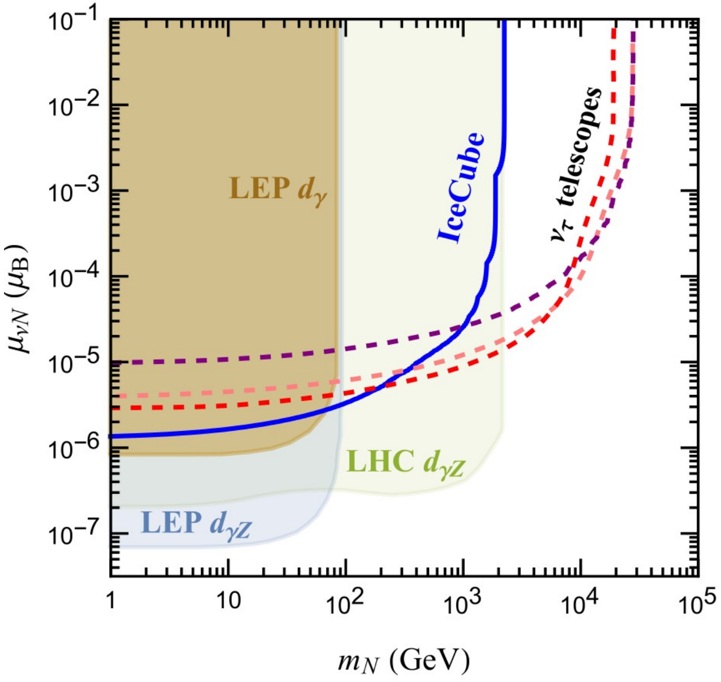
Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

New physics in the UHE νN cross section

New physics in the UHE νN cross section

Heavy sterile neutrinos
via the dipole portal



Huang, Jana, Lindner, Rodejohann, 2204.10347

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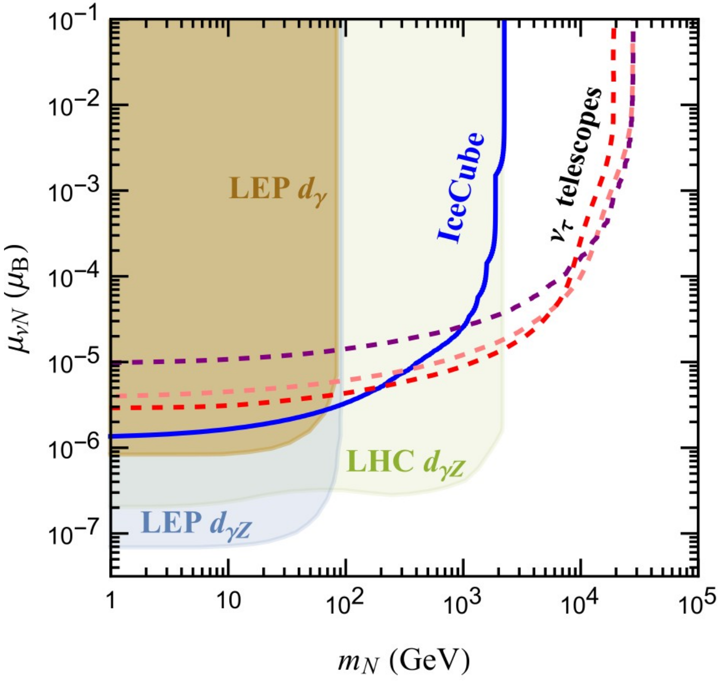
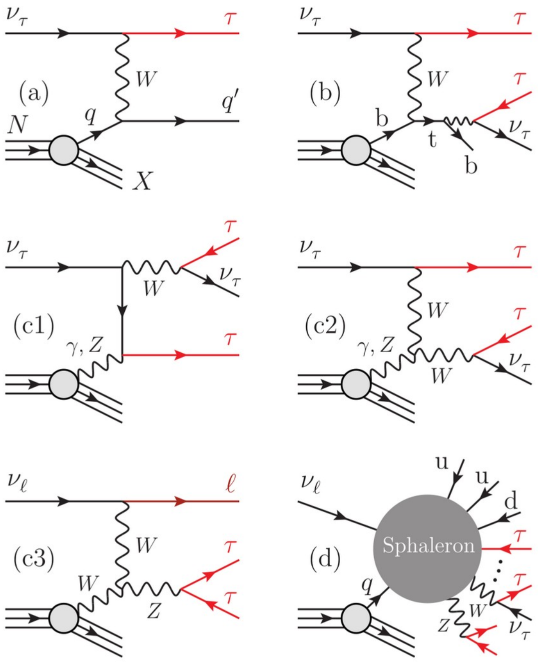


Huang, Jana, Lindner, Rodejohann, 2204.10347

Multiple ν_τ-induced
bangs



Huang, *EPJC* 2022 [2207.02222]

New physics in the UHE νN cross section

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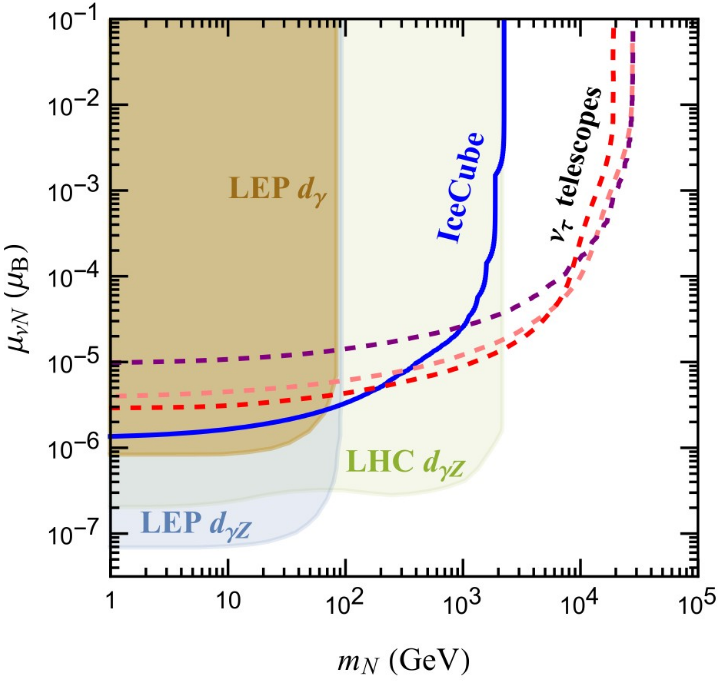

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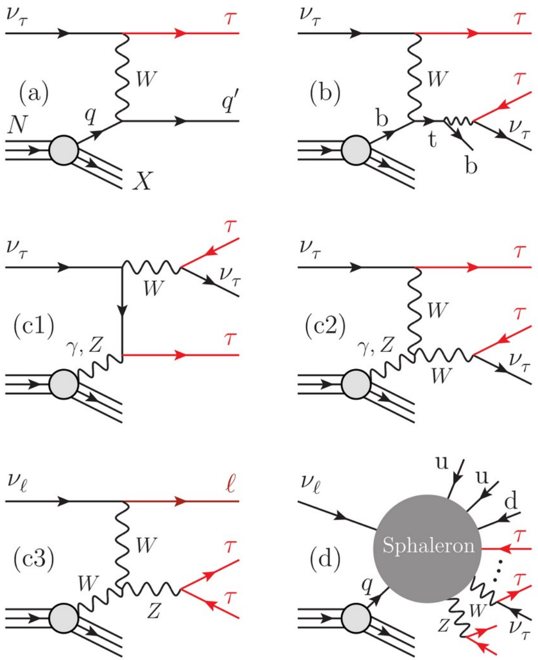
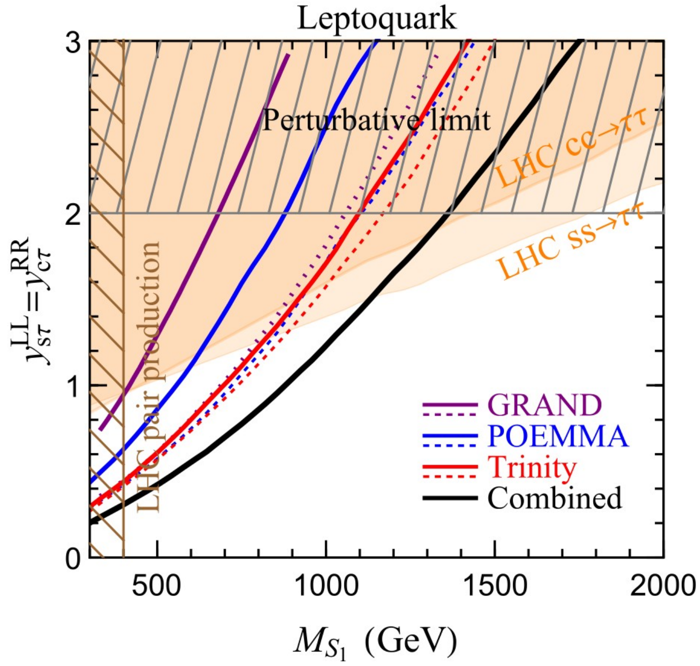


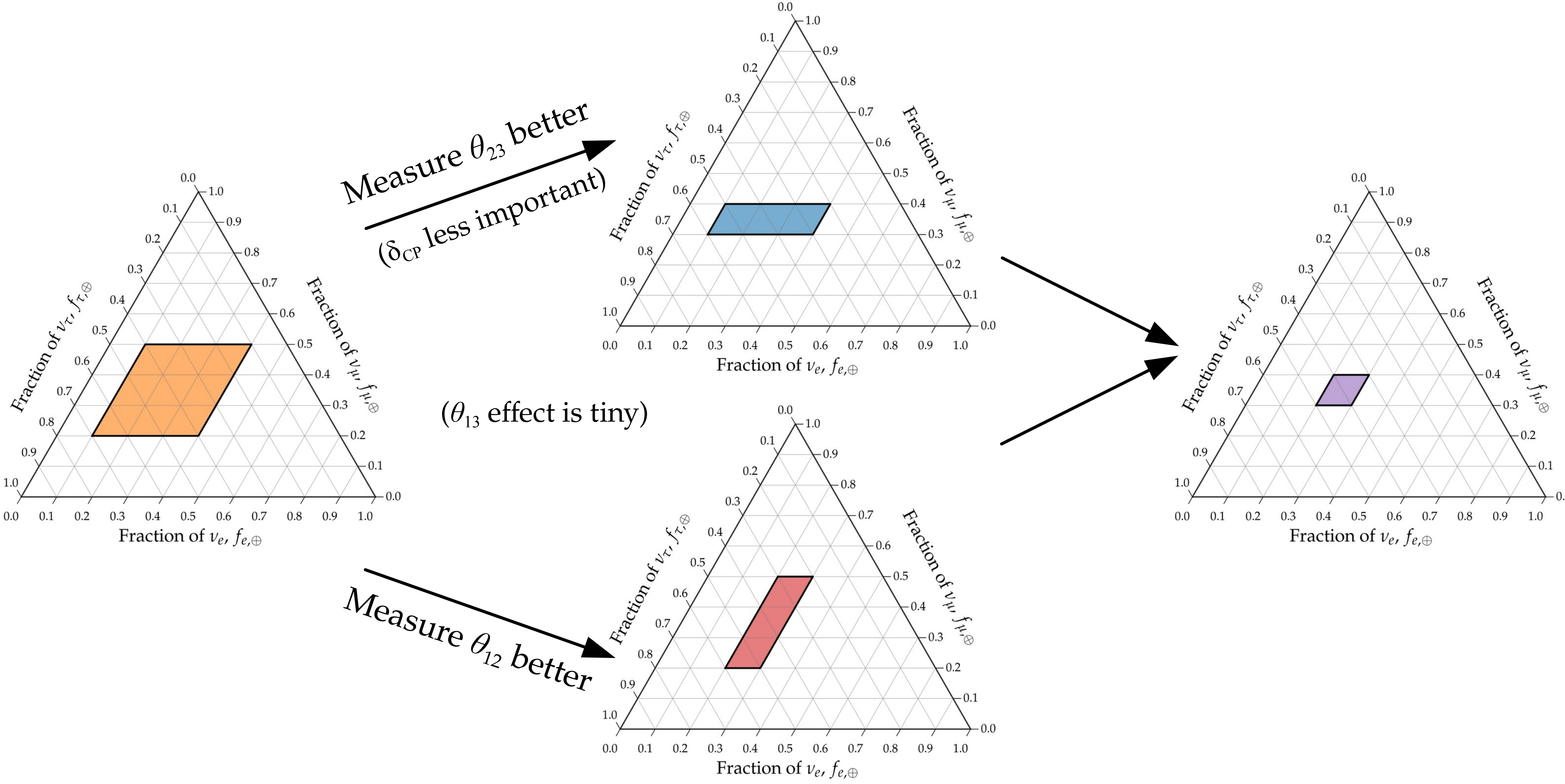
Huang, *EPJC* 2022 [2207.02222]

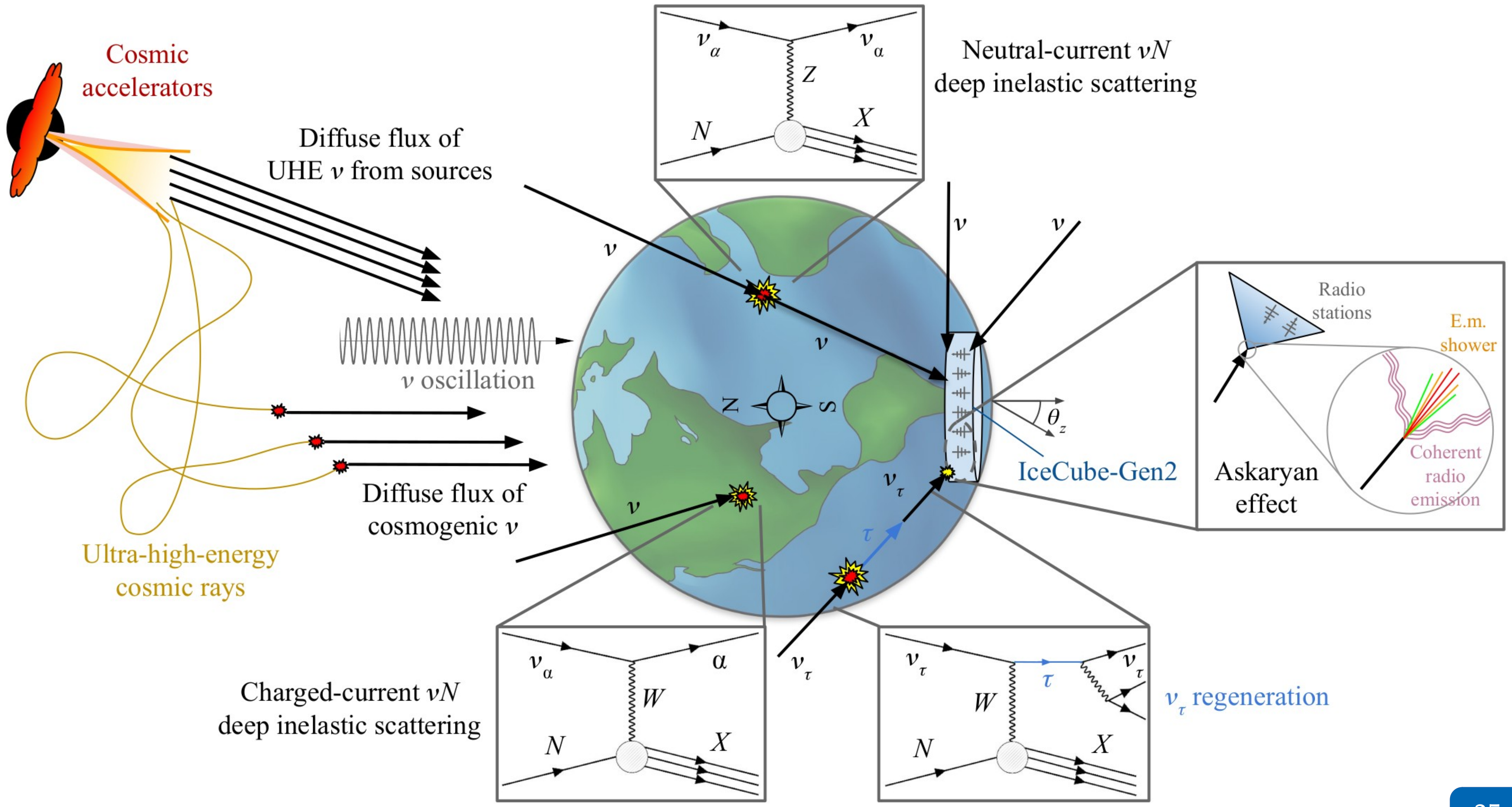
Leptoquarks, charged Higgs, *etc*.



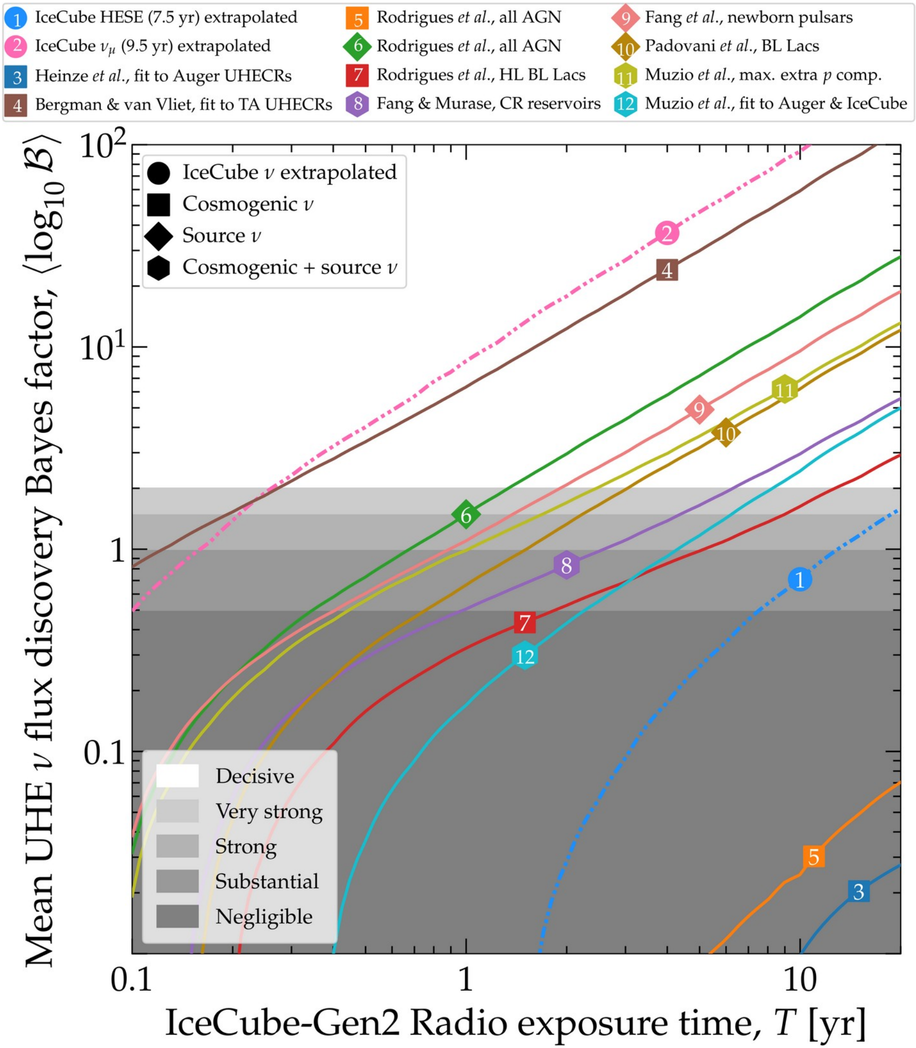
Huang, Jana, Lindner, Rodejohann, *JCAP* 2022 [2112.09476]

How knowing the mixing parameters better helps




Cosmic accelerators
Diffuse flux of UHE ν from sources
ν oscillation
Diffuse flux of cosmogenic ν
Ultra-high-energy cosmic rays
Neutral-current νN deep inelastic scattering
Charged-current νN deep inelastic scattering
ν_τ regeneration
IceCube-Gen2
Askaryan effect
Radio stations
E.m. shower
Coherent radio emission
ν_α
Z
W
N
X
α
τ
ν_τ
θ_z
N
S

Side note: Discovering the diffuse flux of UHE neutrinos

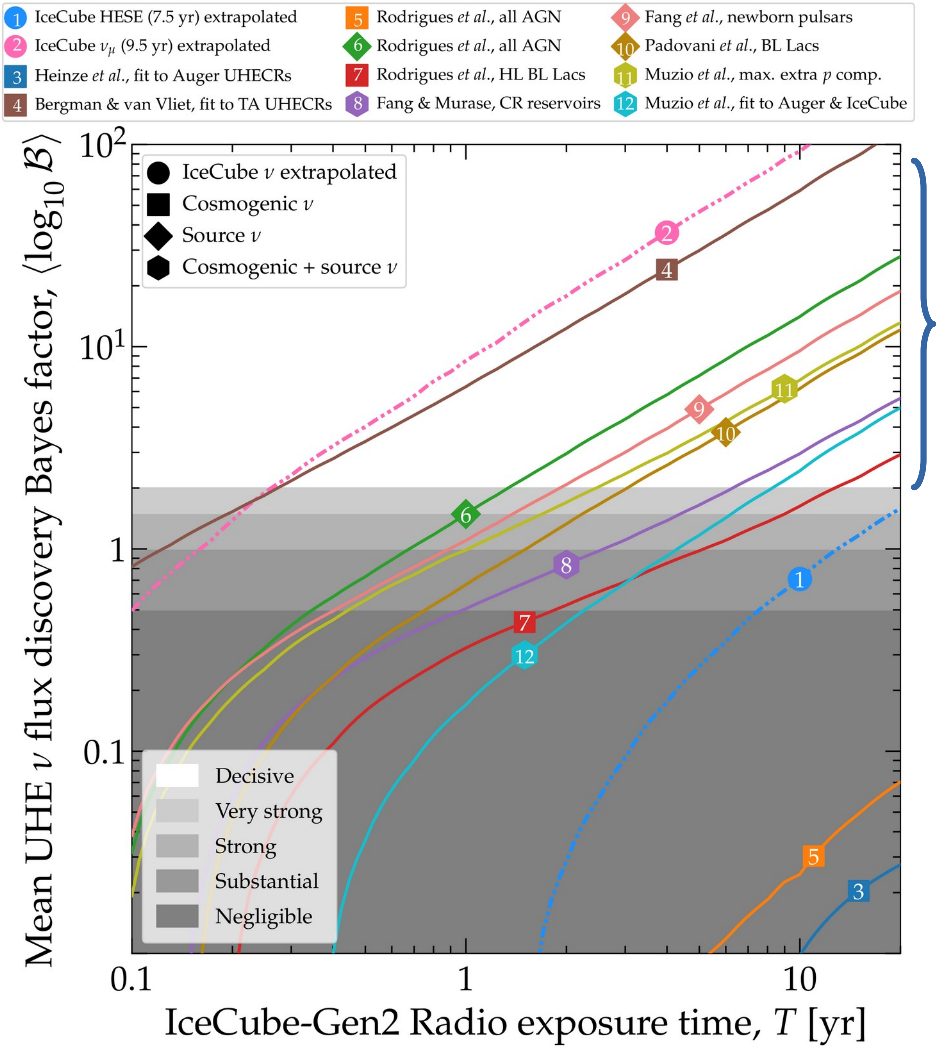


Work led by Víctor Valera

Valera, **MB**, Glaser, *PRD* (to appear) [2210.03756]

Side note: Discovering the diffuse flux of UHE neutrinos

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



Large Bayes factor = decisive flux discover

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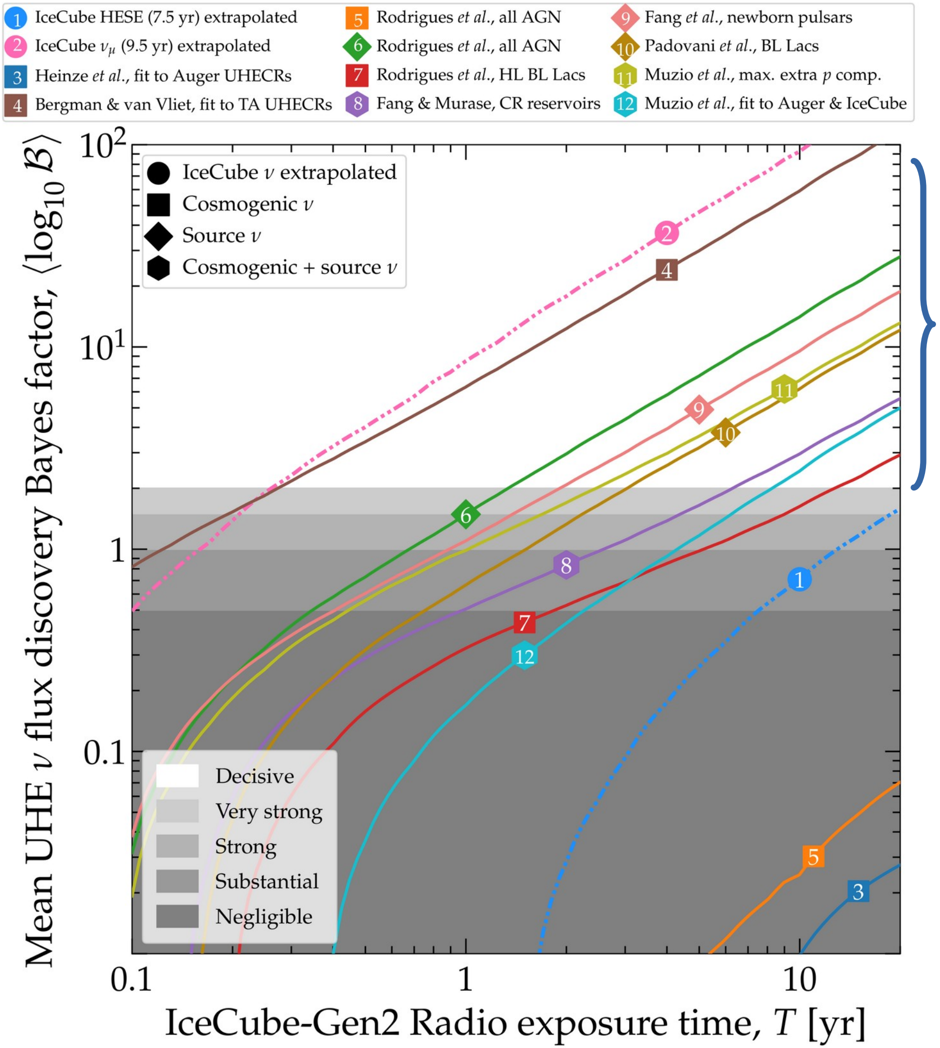

Large Bayes factor
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Forecasts are state-of-the-art:
- Neutrino propagation inside Earth
- Detailed simulation of radio in ice
- Detailed antenna response
- Detector energy & angular resolution
- Statistical fluctuations

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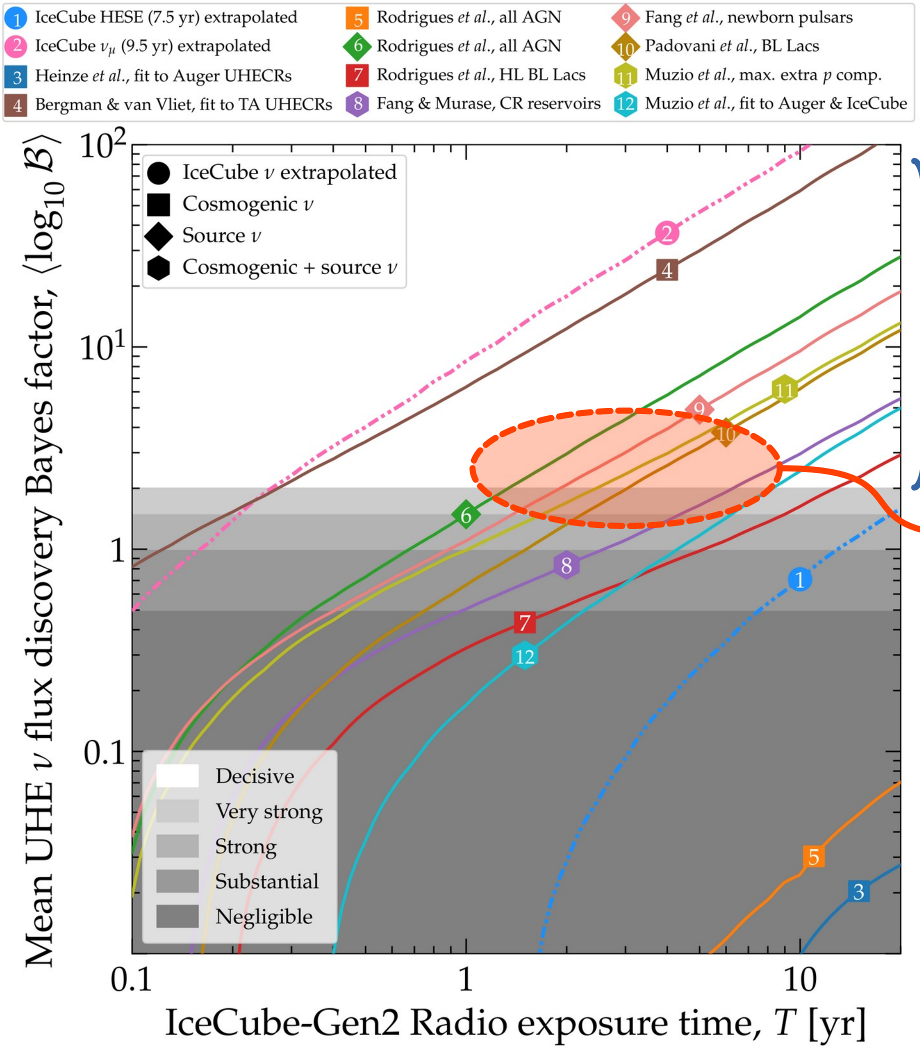

Work led by Víctor Valera

Large Bayes factor = decisive flux discover

Most flux models are discoverable with a few years

Forecasts are state-of-the-art:
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- Detailed antenna response
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Valera, **MB**, Glaser, *PRD* (to appear) [2210.03756]

4. Unstable neutrinos:
Are neutrinos for ever?

Are neutrinos forever?

- In the Standard Model (νSM), neutrinos are essentially stable ($\tau > 10^{36}$ yr):
  - One-photon decay ($\nu_i \to \nu_j + \gamma$): $\tau > 10^{36}\,(m_i/\text{eV})^{-5}$ yr
  - Two-photon decay ($\nu_i \to \nu_j + \gamma + \gamma$): $\tau > 10^{57}\,(m_i/\text{eV})^{-9}$ yr
  - Three-neutrino decay ($\nu_i \to \nu_j + \nu_k + \bar{\nu}_k$): $\tau > 10^{55}\,(m_i/\text{eV})^{-5}$ yr

  » Age of Universe (~ 14.5 Gyr)

- BSM decays may have significantly higher rates: $\nu_i \to \nu_j + \varphi$

- We work in a model-independent way:
  the nature of φ is unimportant if it is invisible to neutrino detectors

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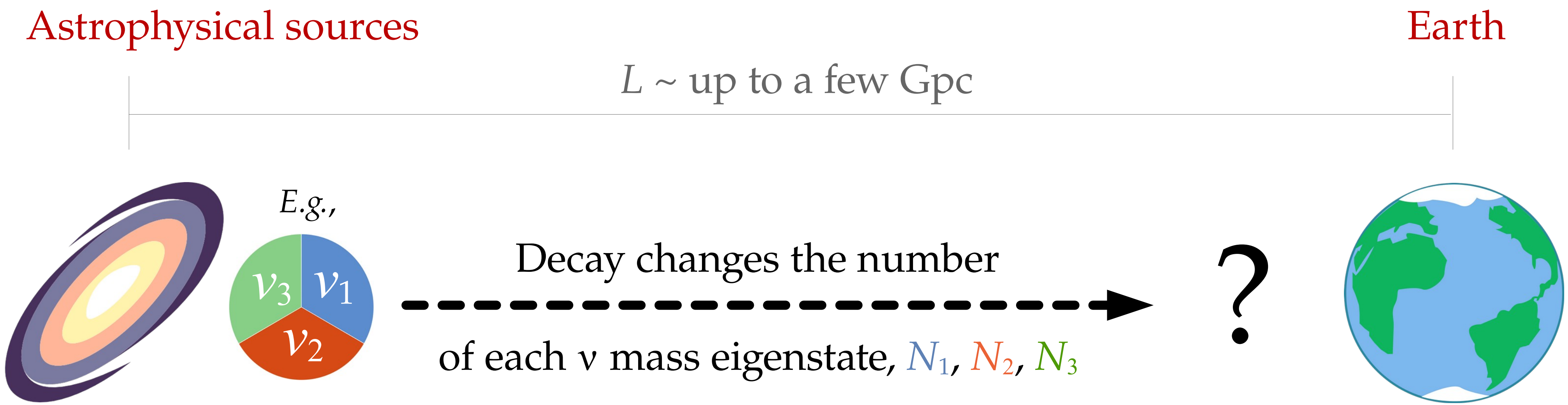
  Nambu-Goldstone boson of a broken symmetry

- We work in a model-independent way:
  the nature of φ is unimportant if it is invisible to neutrino detectors



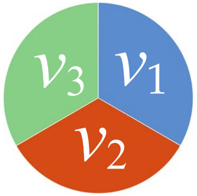
The flux of ν_i is attenuated by $\exp[-\,(L/E)\cdot(\underbrace{m_i}_{\text{Mass of }\nu_i}/\underbrace{\tau_i}_{\text{Lifetime of }\nu_i})]$

Astrophysical sources

Earth

L ~ up to a few Gpc

E.g.,



Decay changes the number

of each ν mass eigenstate, N_1, N_2, N_3

?

$$\text{The flux of } \nu_i \text{ is attenuated by } \exp\Big[-\,(L/E)\cdot \overbrace{(\underbrace{m_i}_{\text{Mass of } \nu_i}/\underbrace{\tau_i}_{\text{Lifetime of } \nu_i})}^{\text{Only sensitive to their ratio}}\Big]$$

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

?

Lower-E ν are longer-lived…

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

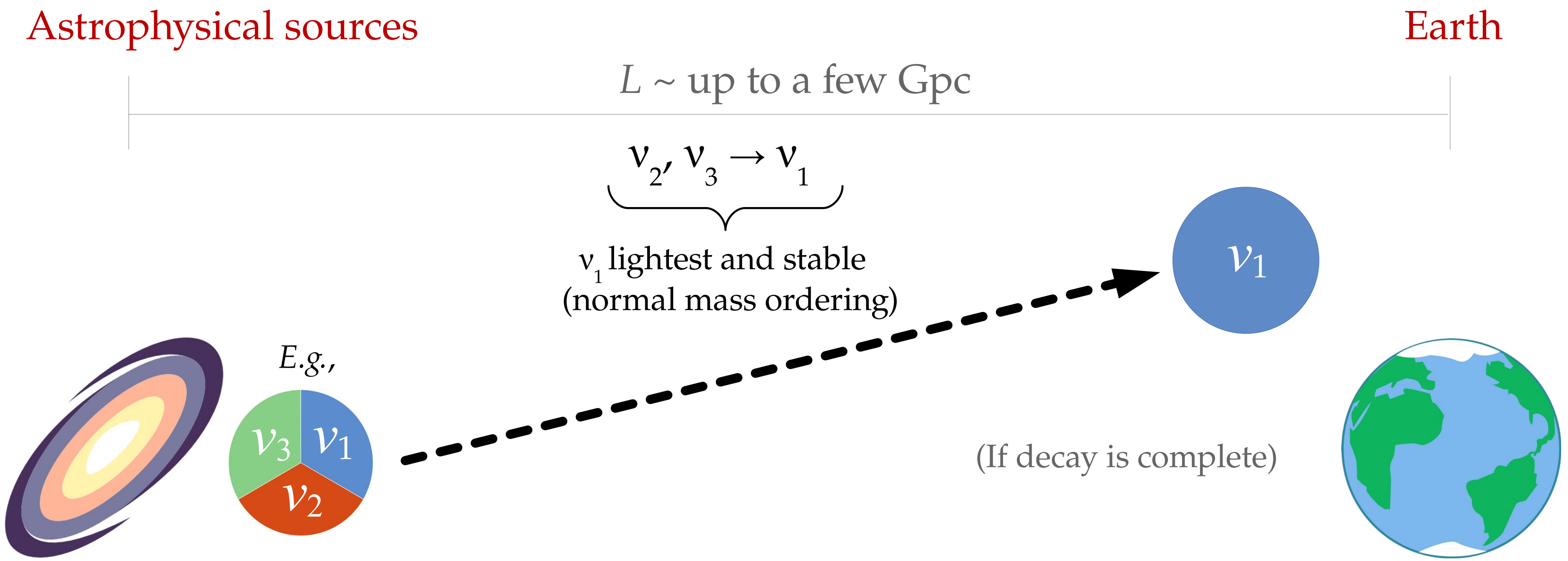
… but ν that travel longer L are more attenuated!

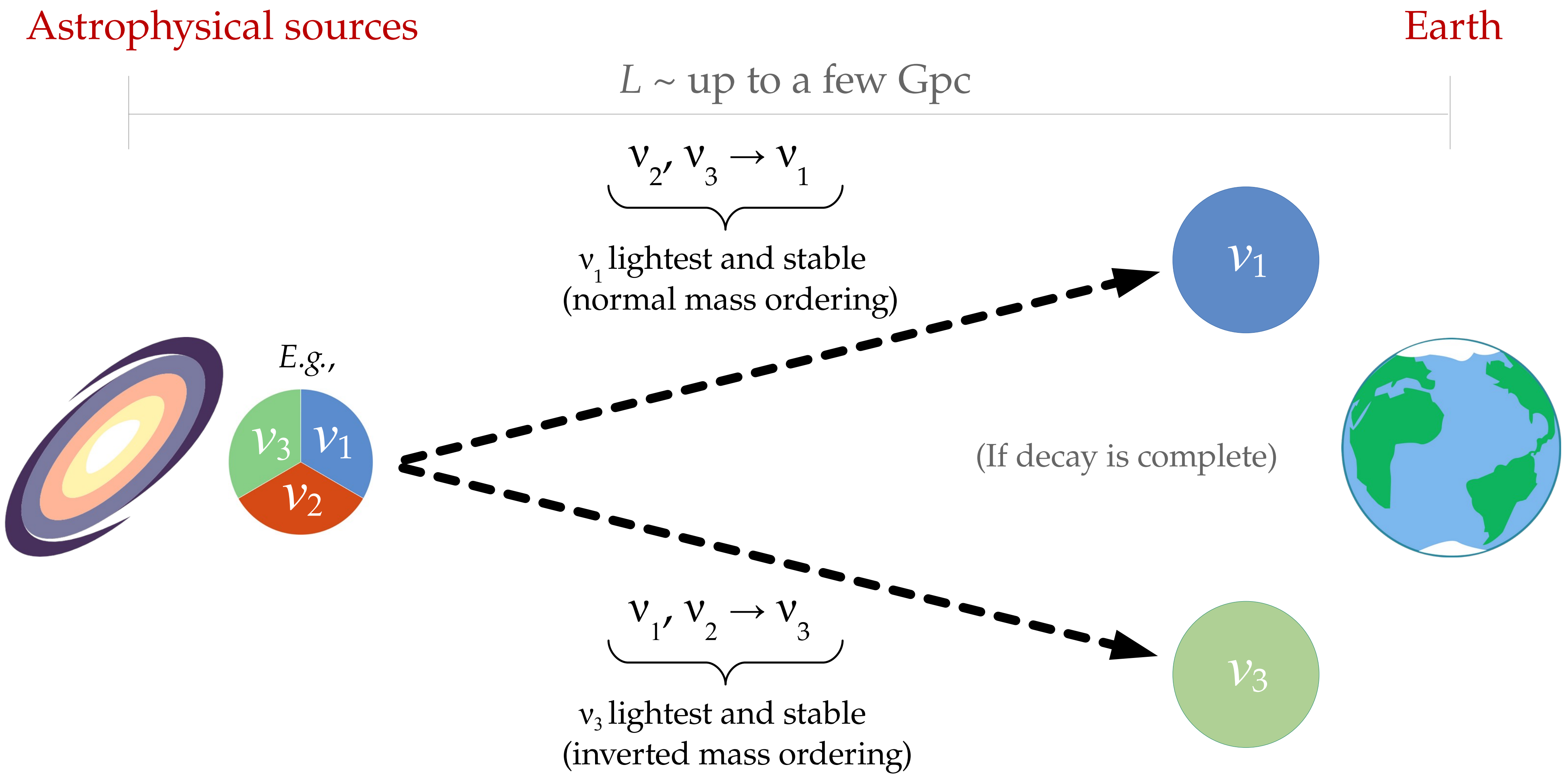
Astrophysical sources

Earth

$L \sim$ up to a few Gpc

E.g.,


Astrophysical sources
Earth
L ~ up to a few Gpc
$\nu_2, \nu_3 \rightarrow \nu_1$
ν_1 lightest and stable
(normal mass ordering)
E.g.,
ν_3
ν_1
ν_2
ν_1
(If decay is complete)


Astrophysical sources
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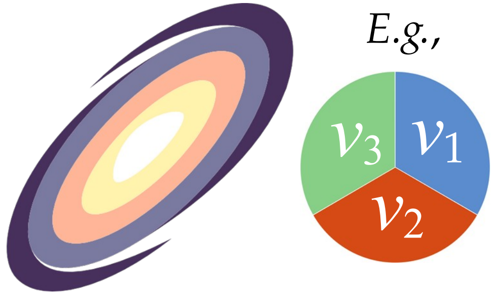
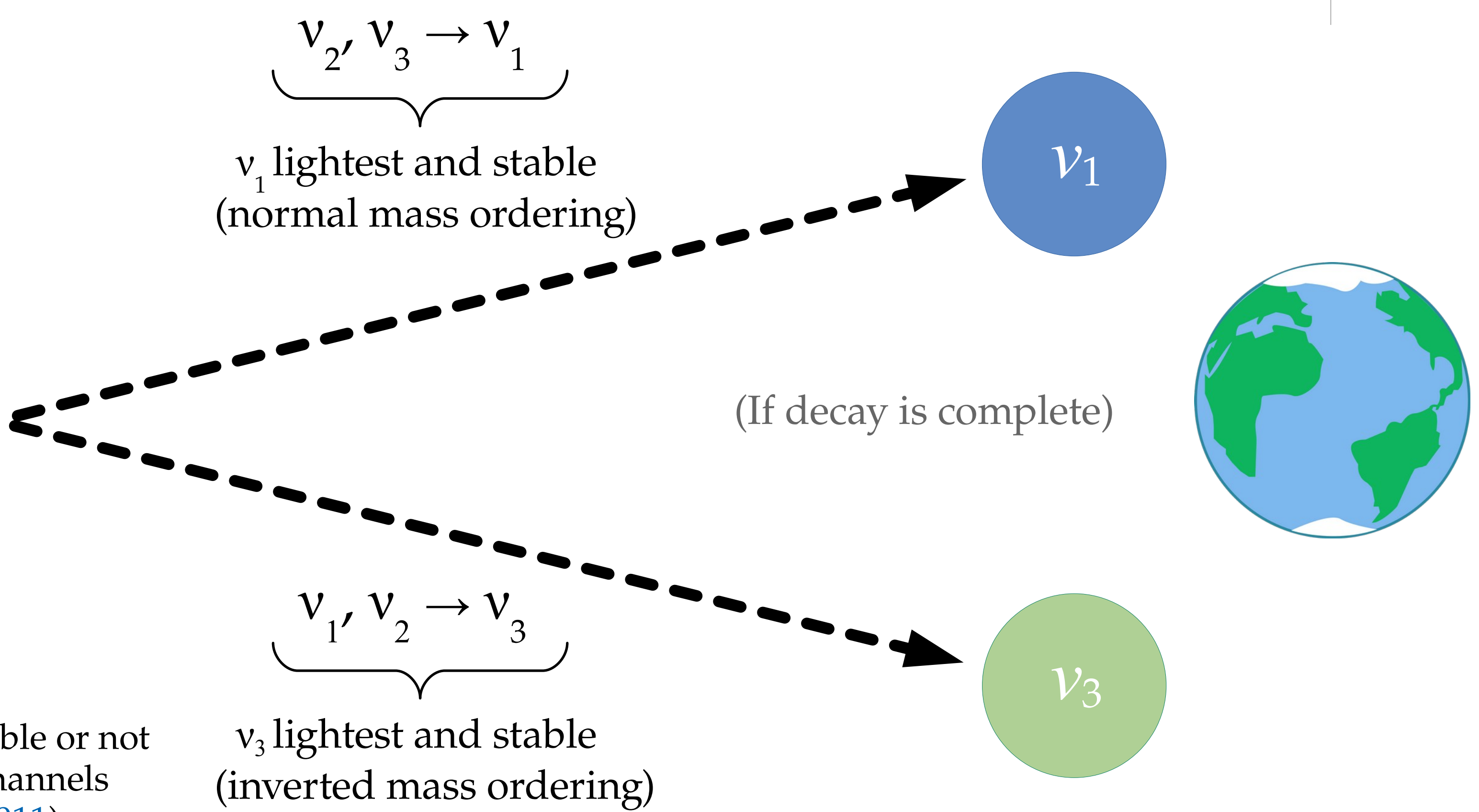
$\nu_2, \nu_3 \rightarrow \nu_1$
ν_1 lightest and stable
(normal mass ordering)
E.g.,
ν_3 ν_1 ν_2
ν_1
(If decay is complete)
$\nu_1, \nu_2 \rightarrow \nu_3$
ν_3 lightest and stable
(inverted mass ordering)
ν_3

Astrophysical sources | Earth

L ~ up to a few Gpc





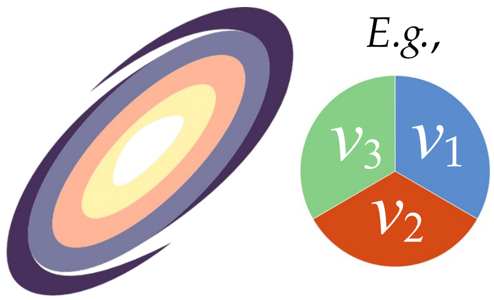
Fine print:

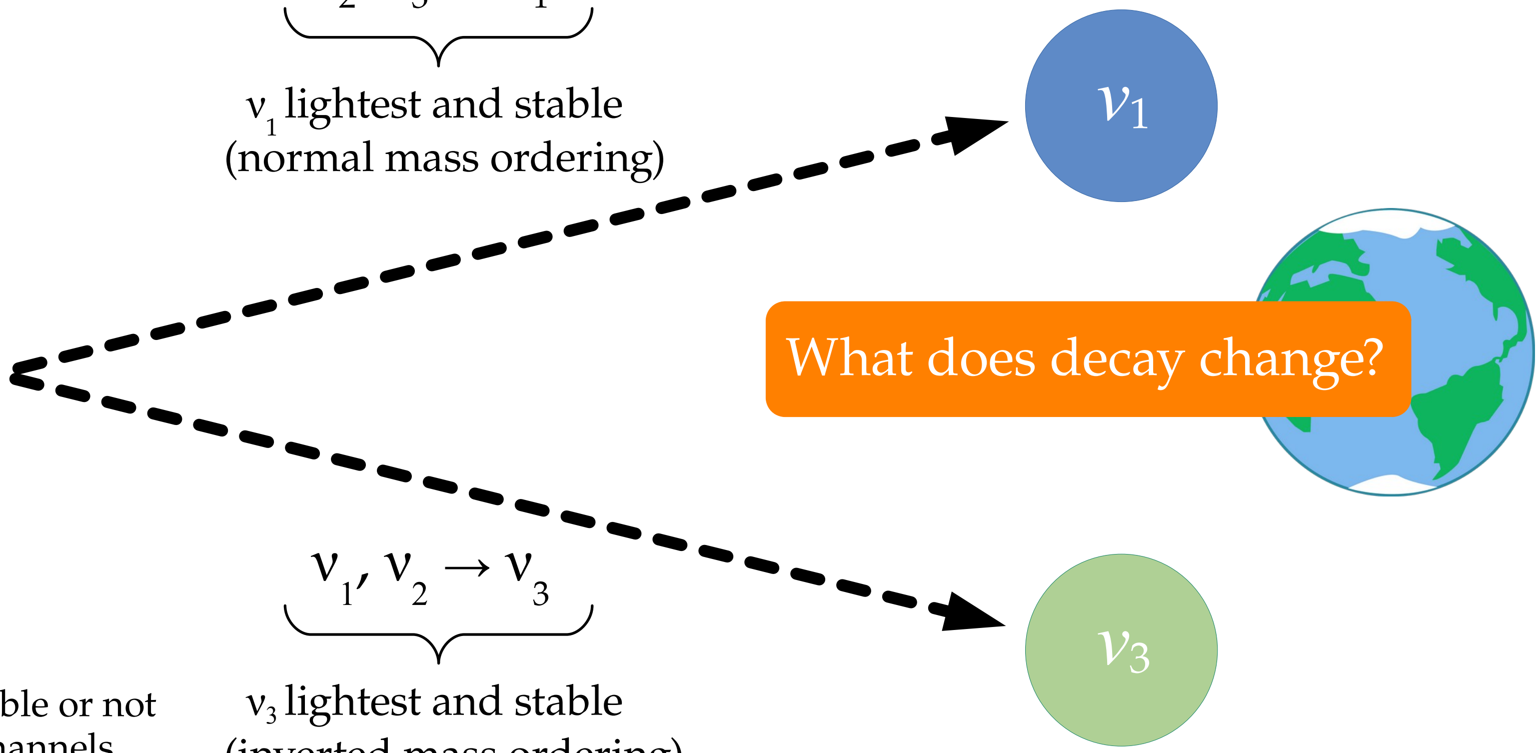
- Decay can be incomplete
- Final-state ν might be detectable or not
- Many more possible decay channels (see Winter & Mehta, *JCAP* 2011)

Astrophysical sources Earth

L ~ up to a few Gpc

E.g.,





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

What does neutrino decay change?

Flavor composition $\Longleftrightarrow$ Spectrum shape $\Longleftrightarrow$ Event rate

What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

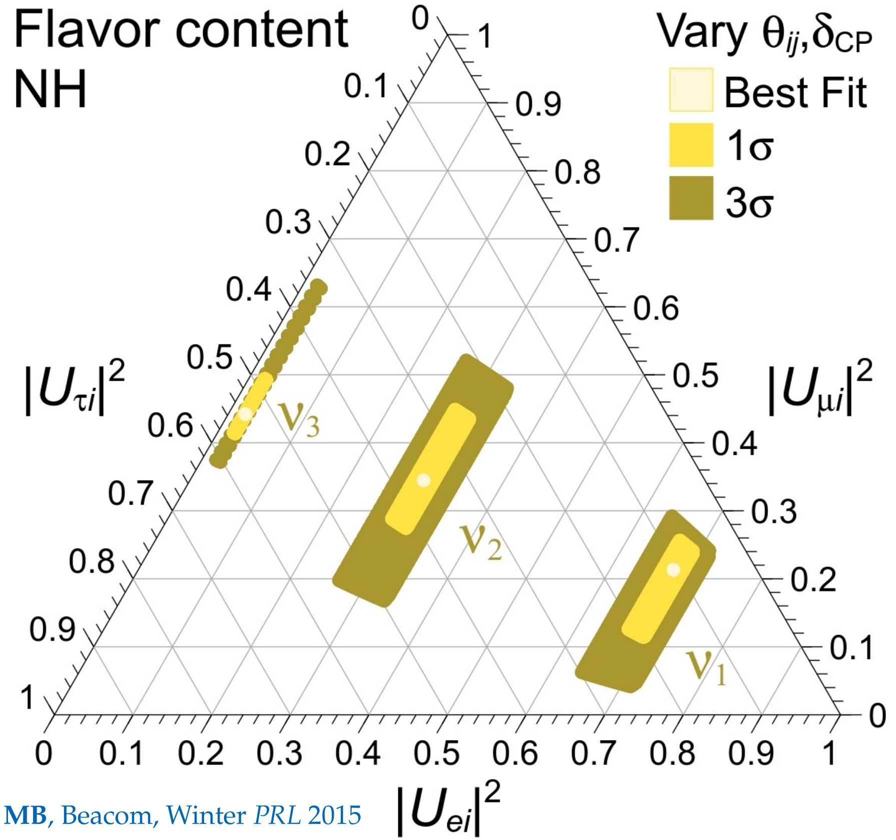
Flavor content of mass eigenstates:

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

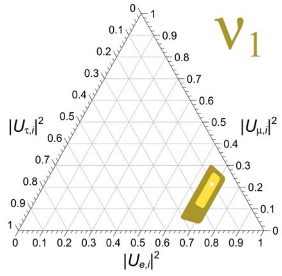
What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

E.g.,

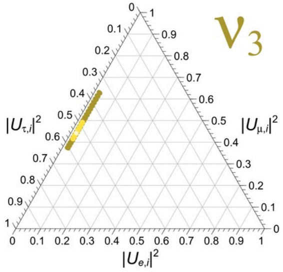
$$\underbrace{\nu_2, \nu_3 \to \nu_1}$$

ν_1 lightest and stable
(normal mass ordering)



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

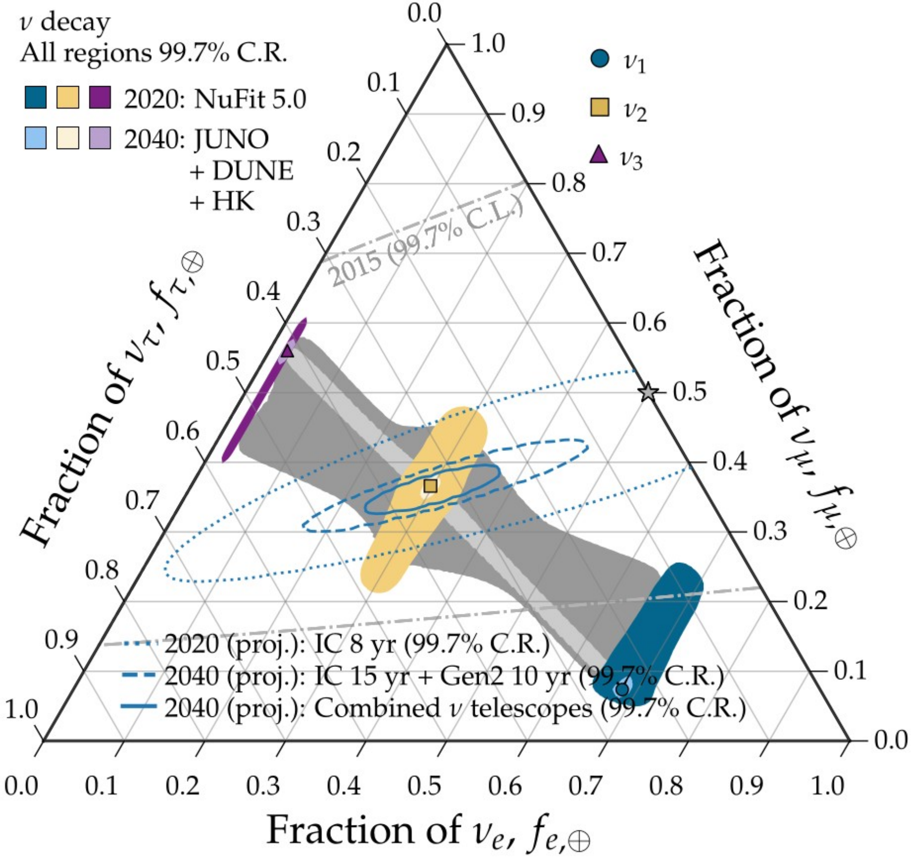
ν_3 lightest and stable
(inverted mass ordering)



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

Flavor composition ⟺ Spectrum shape ⟺ Event rate



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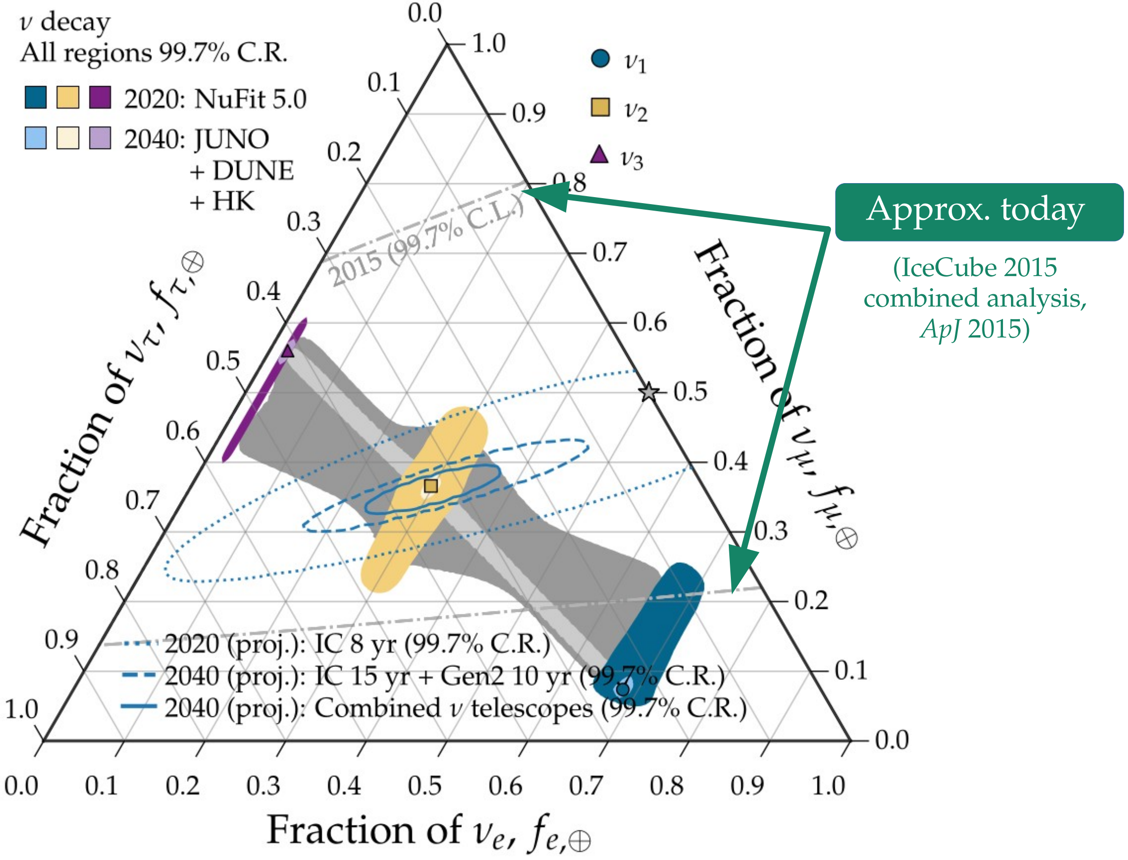
Flavor composition ⟺ Spectrum shape ⟺ Event rate



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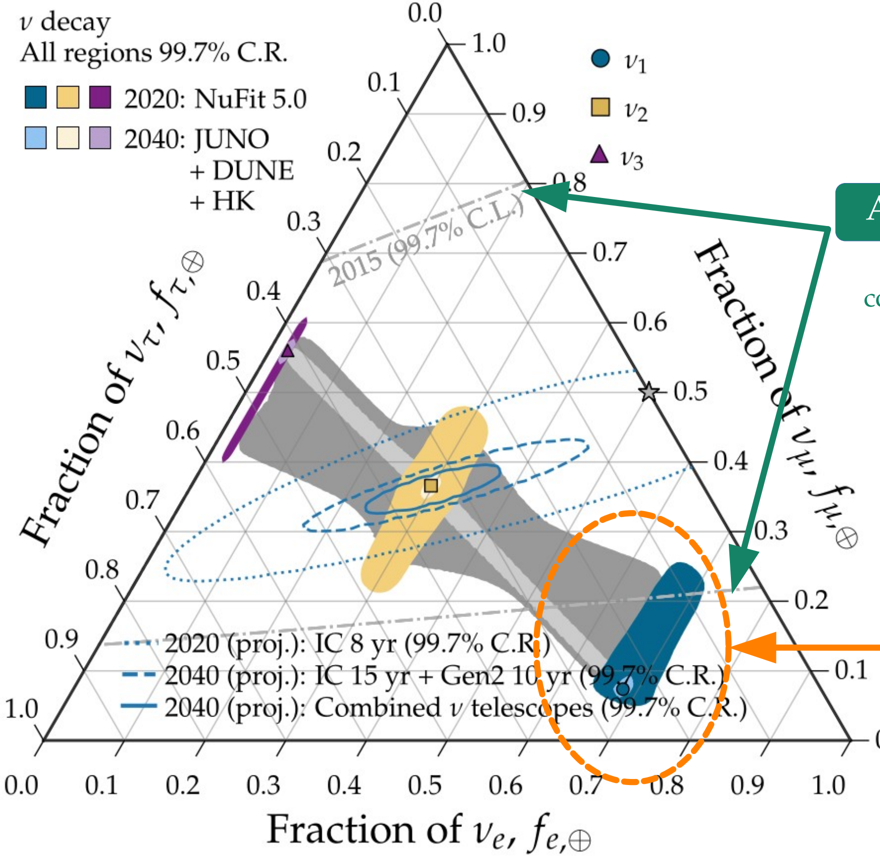
Flavor composition ⟺ Spectrum shape ⟺ Event rate



Approx. today

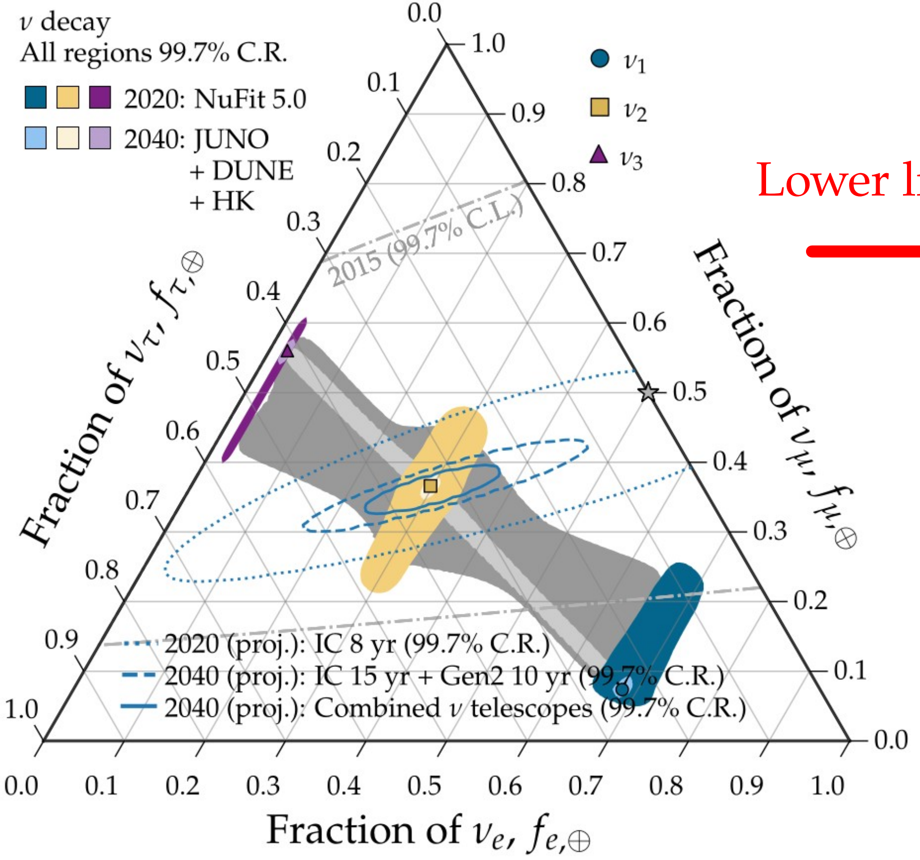
(IceCube 2015 combined analysis, *ApJ* 2015)

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

Flavor composition ⇔ Spectrum shape ⇔ Event rate

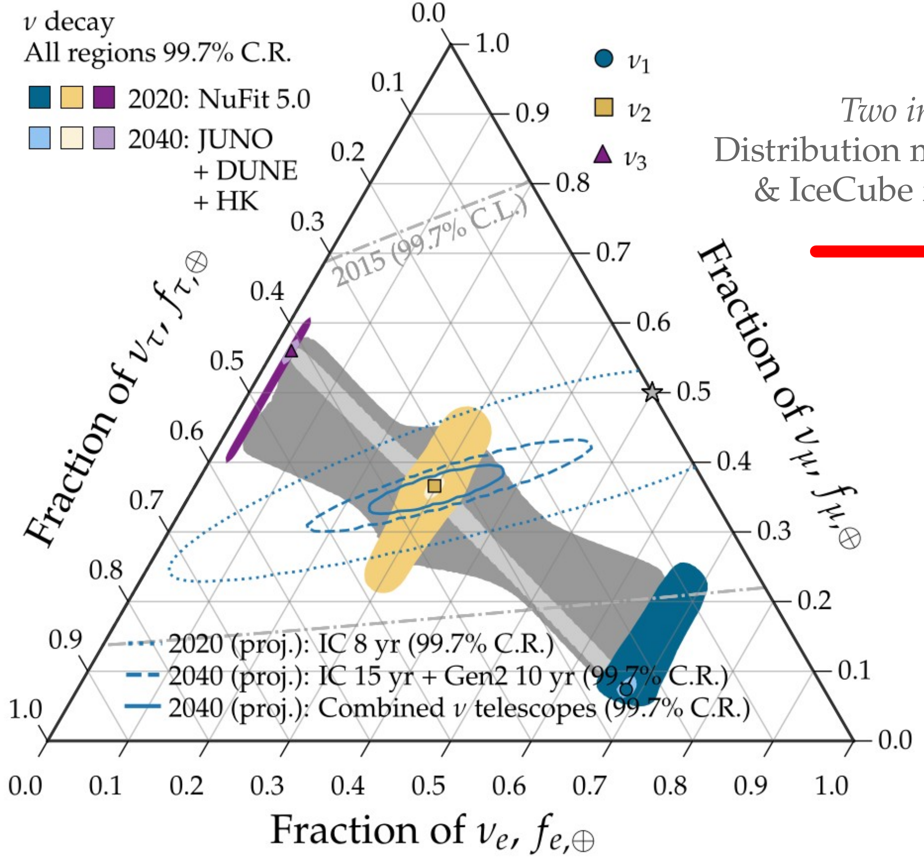


Lower limit on τ/m →

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate



Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

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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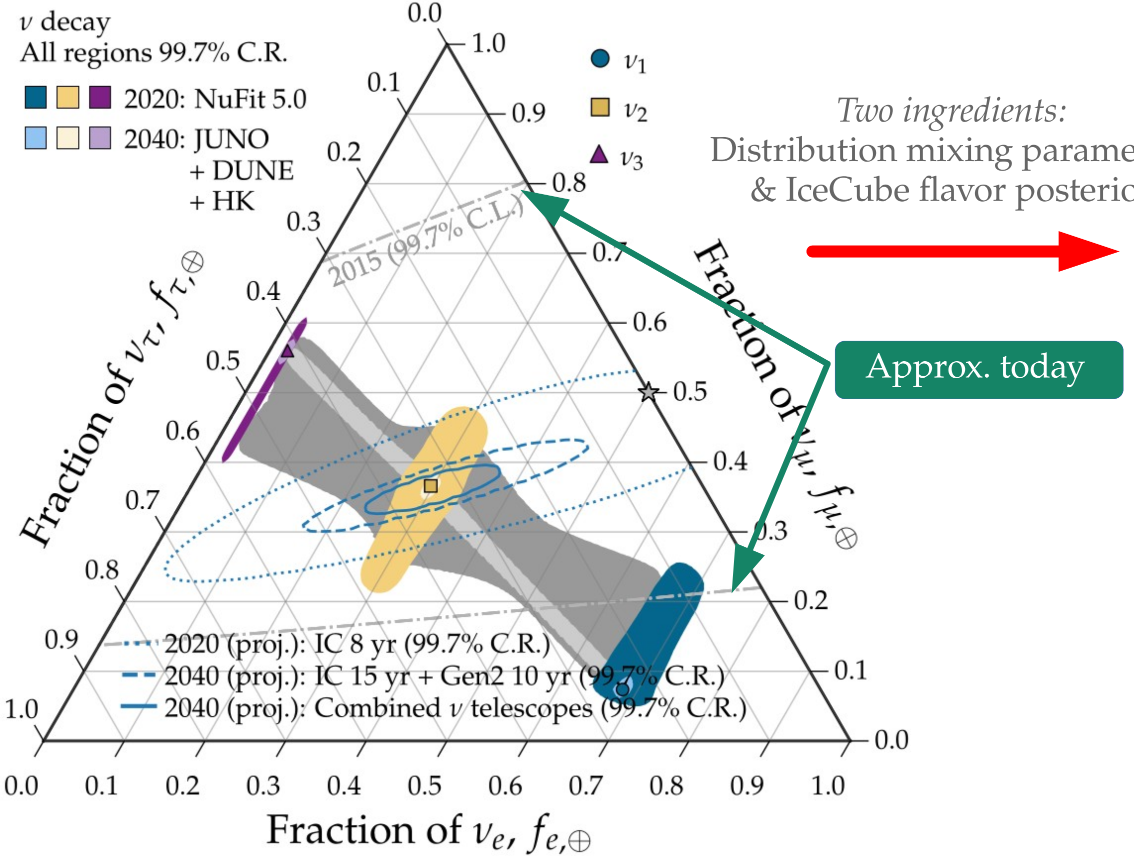

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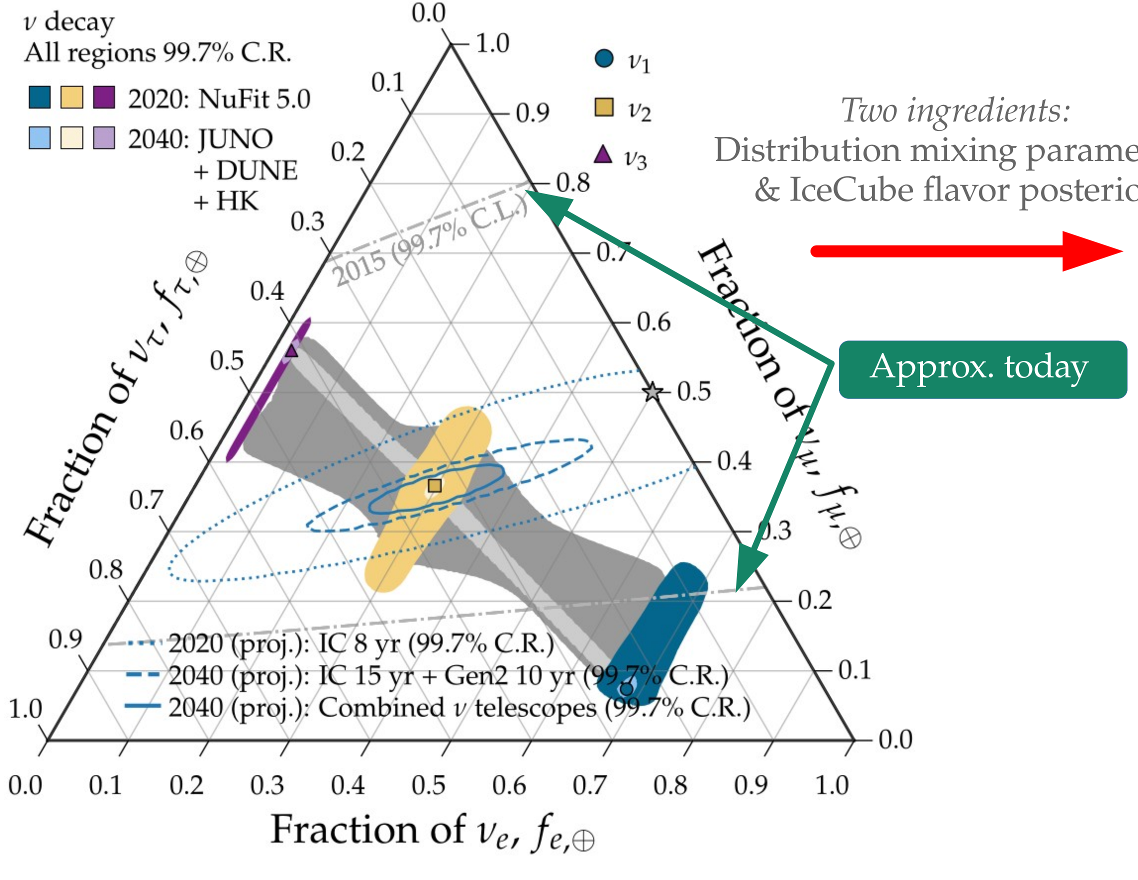
Flavor composition ⇔ Spectrum shape ⇔ Event rate



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Distribution mixing parameters
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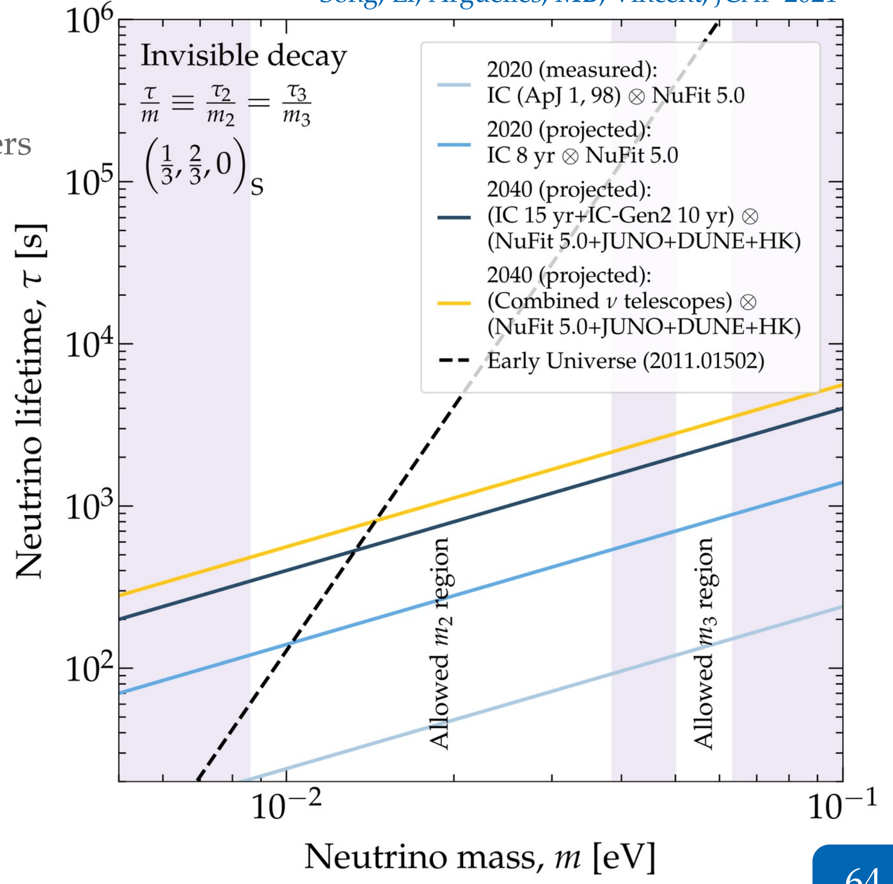
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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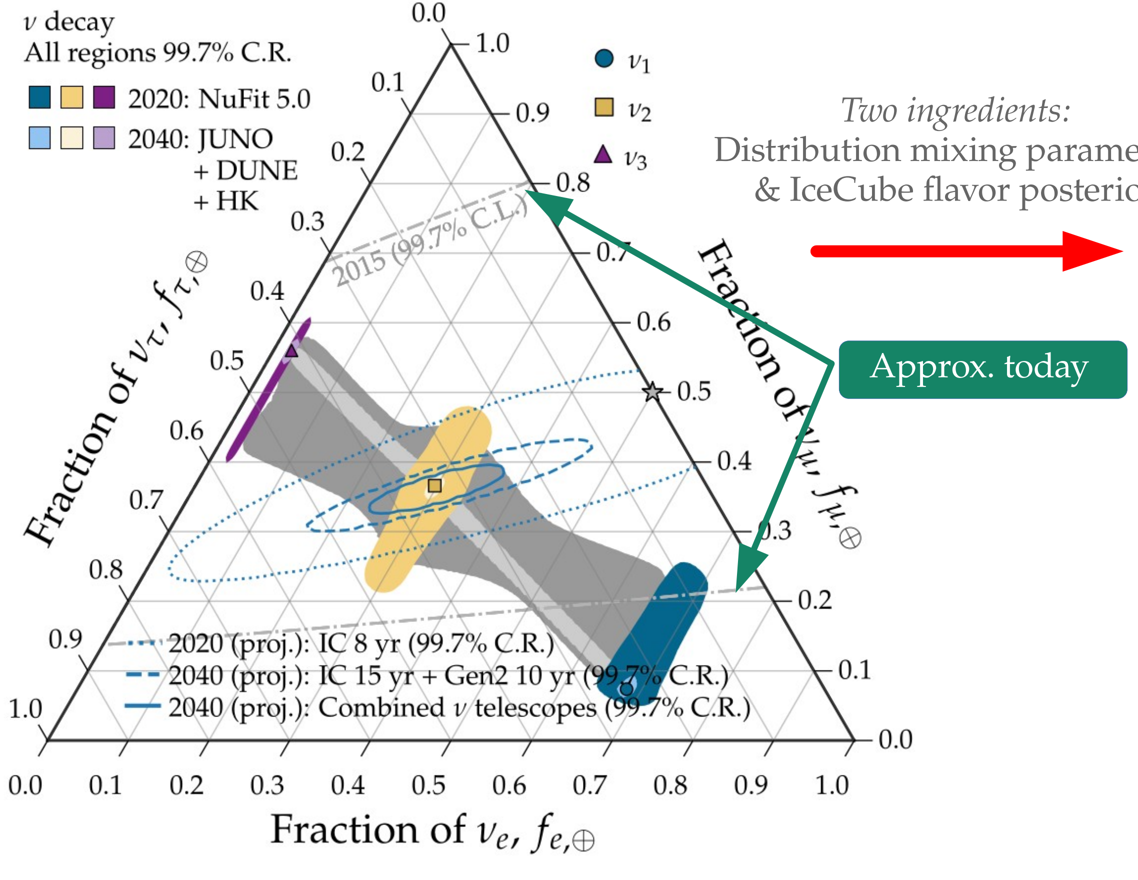
Flavor composition ⟺ Spectrum shape ⟺ Event rate



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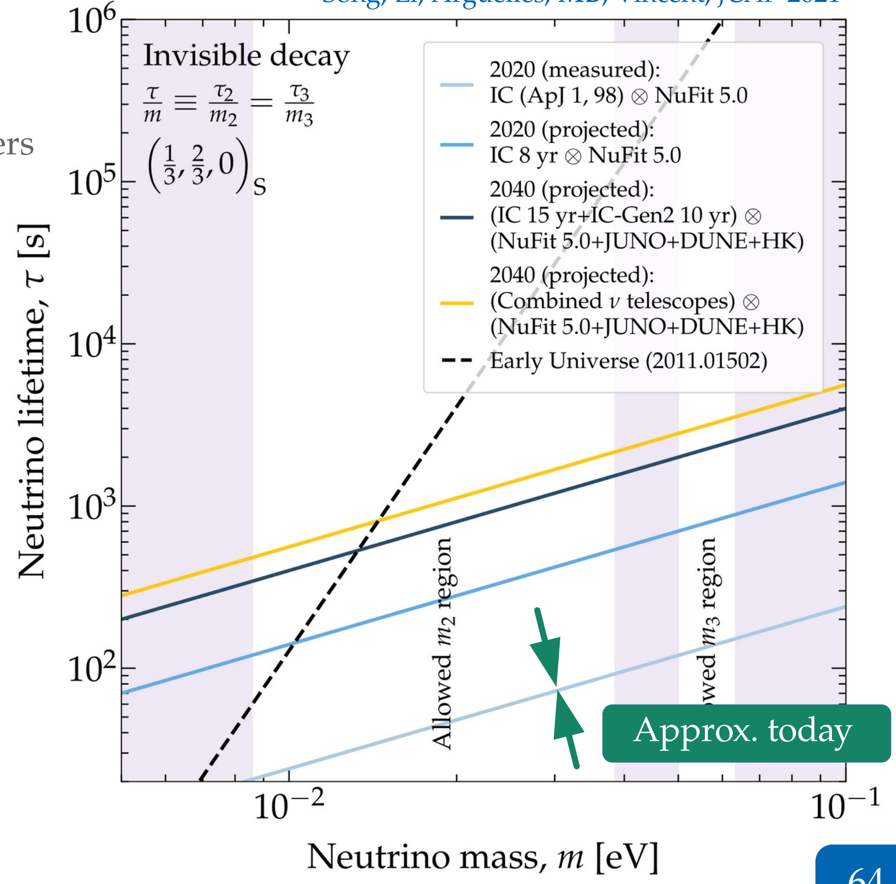
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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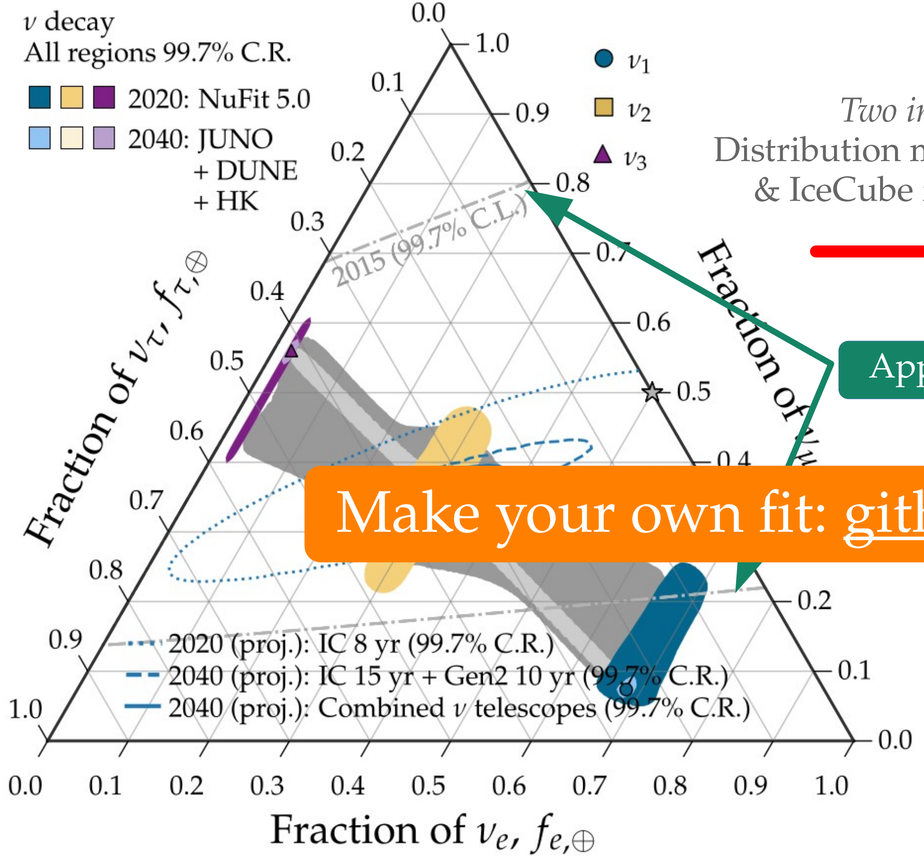
Flavor composition ⟺ Spectrum shape ⟺ Event rate



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Distribution mixing parameters
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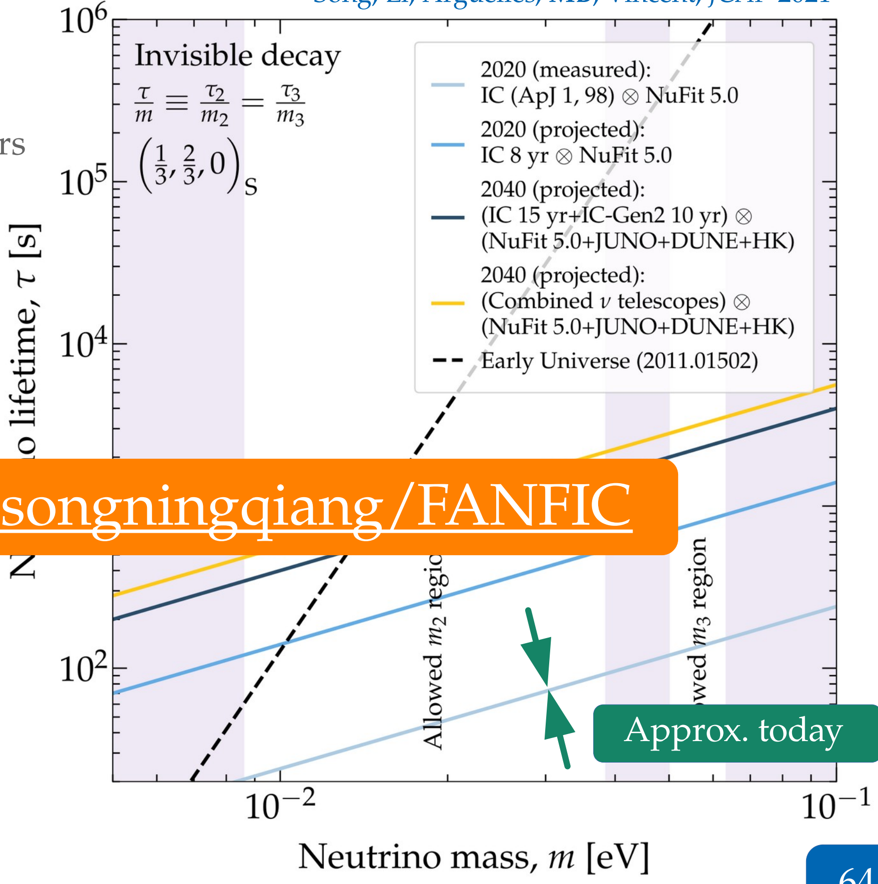
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

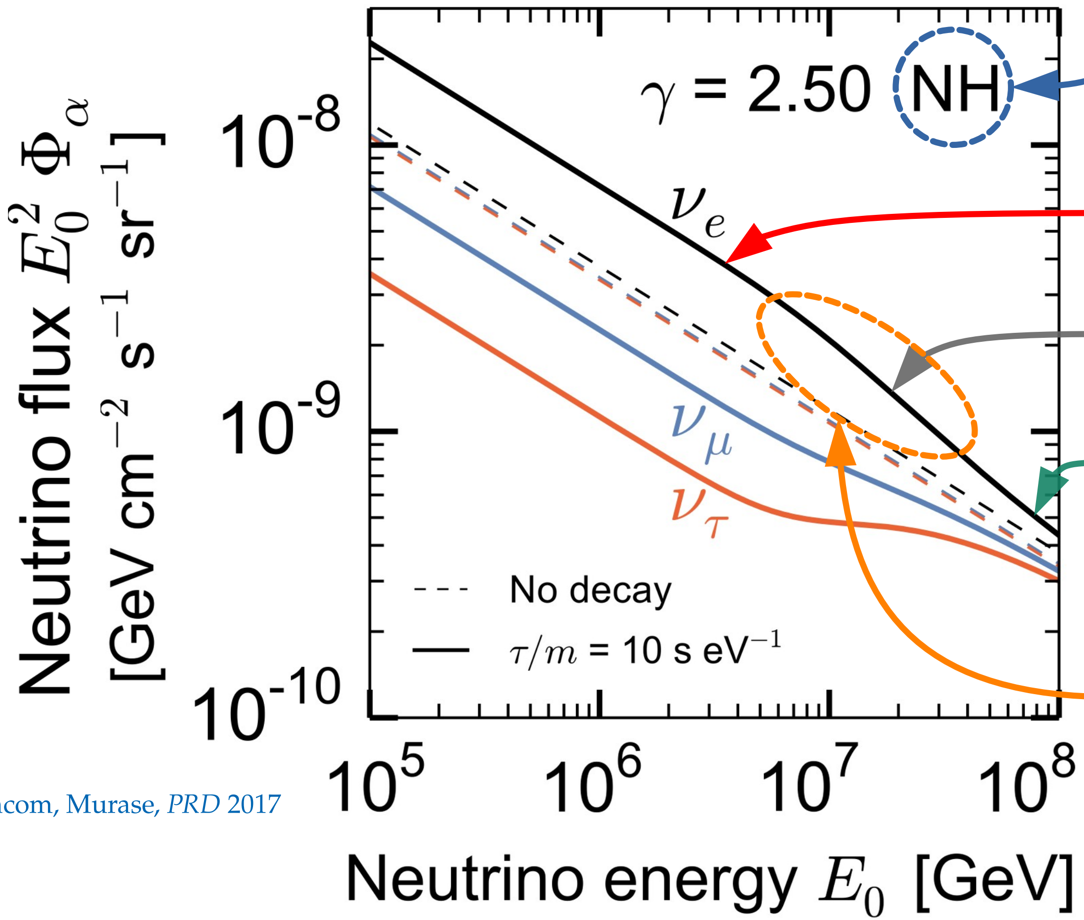


Make your own fit: github.com/songningqiang/FANFIC

What does neutrino decay change?

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

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*!

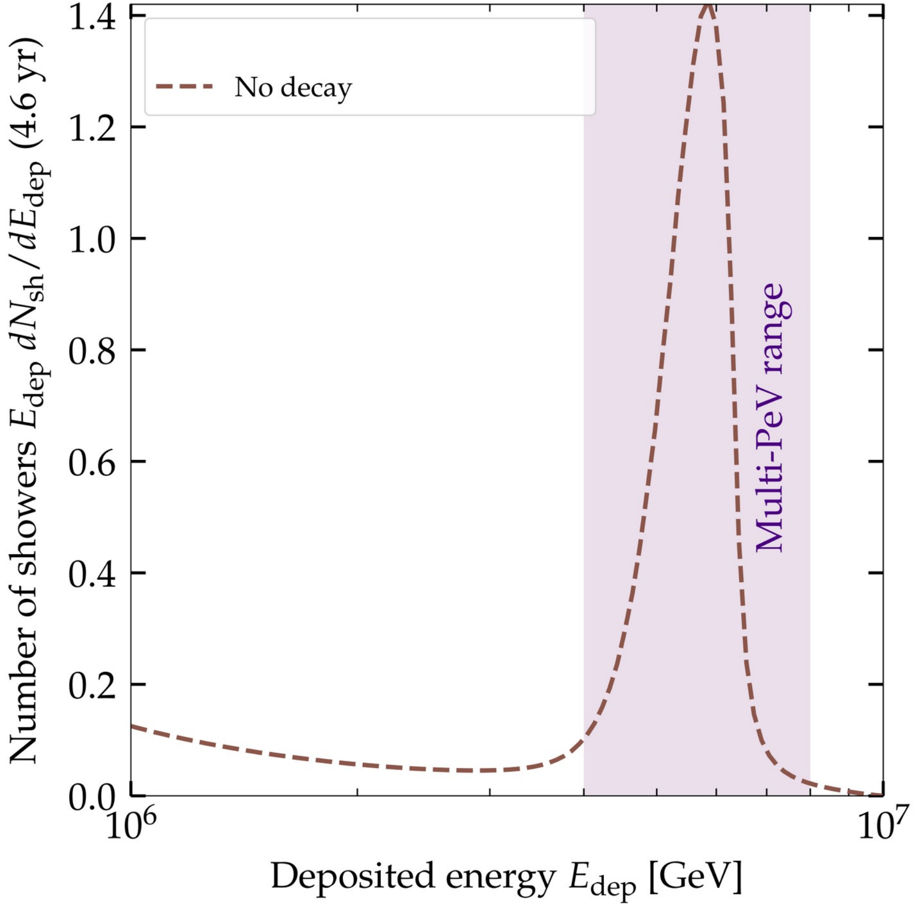
MB, Beacom, Murase, *PRD* 2017

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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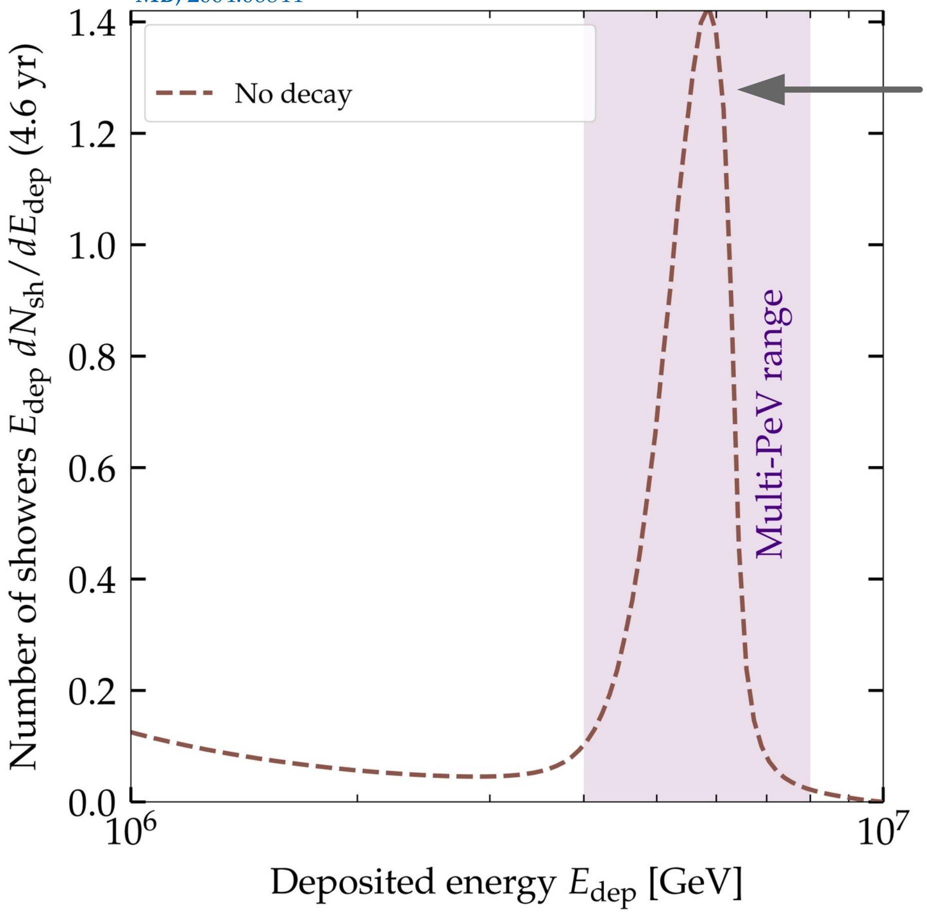
Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



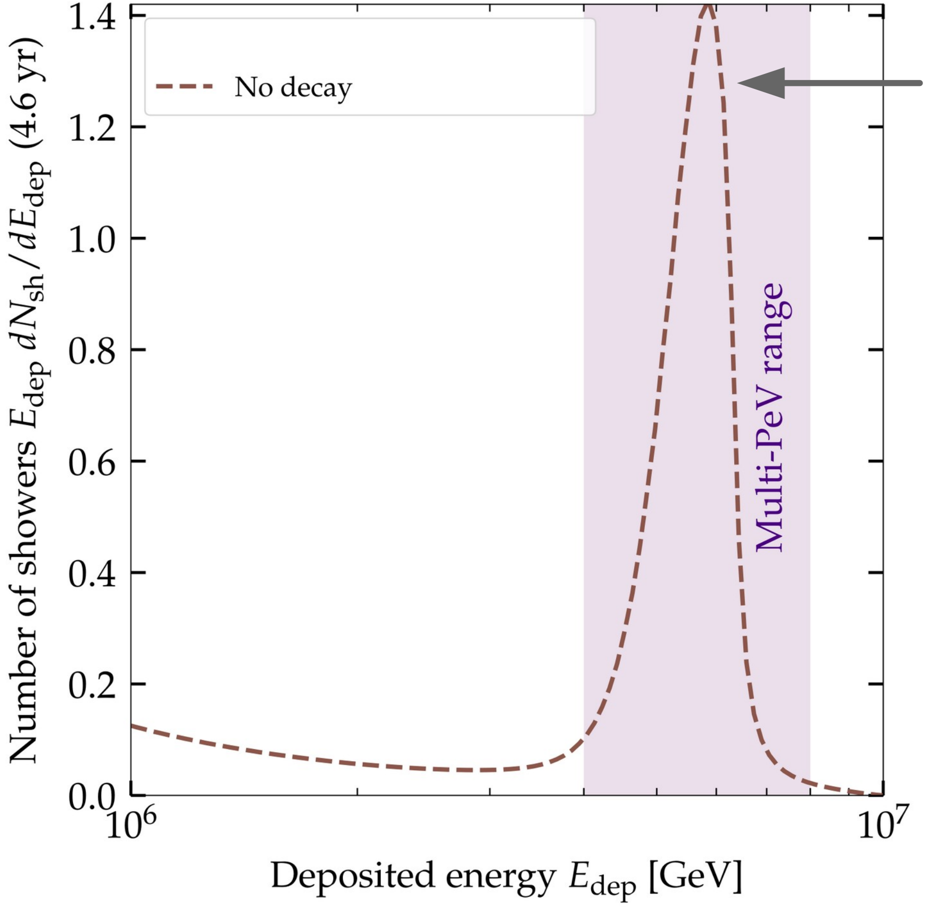
Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

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

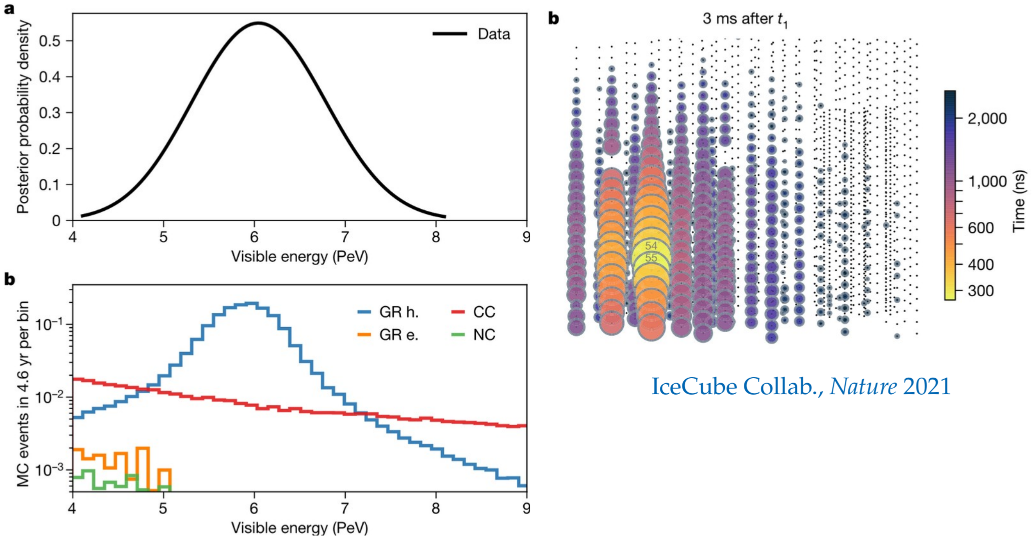
Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



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

IceCube has seen one GR candidate in 4.6 years:

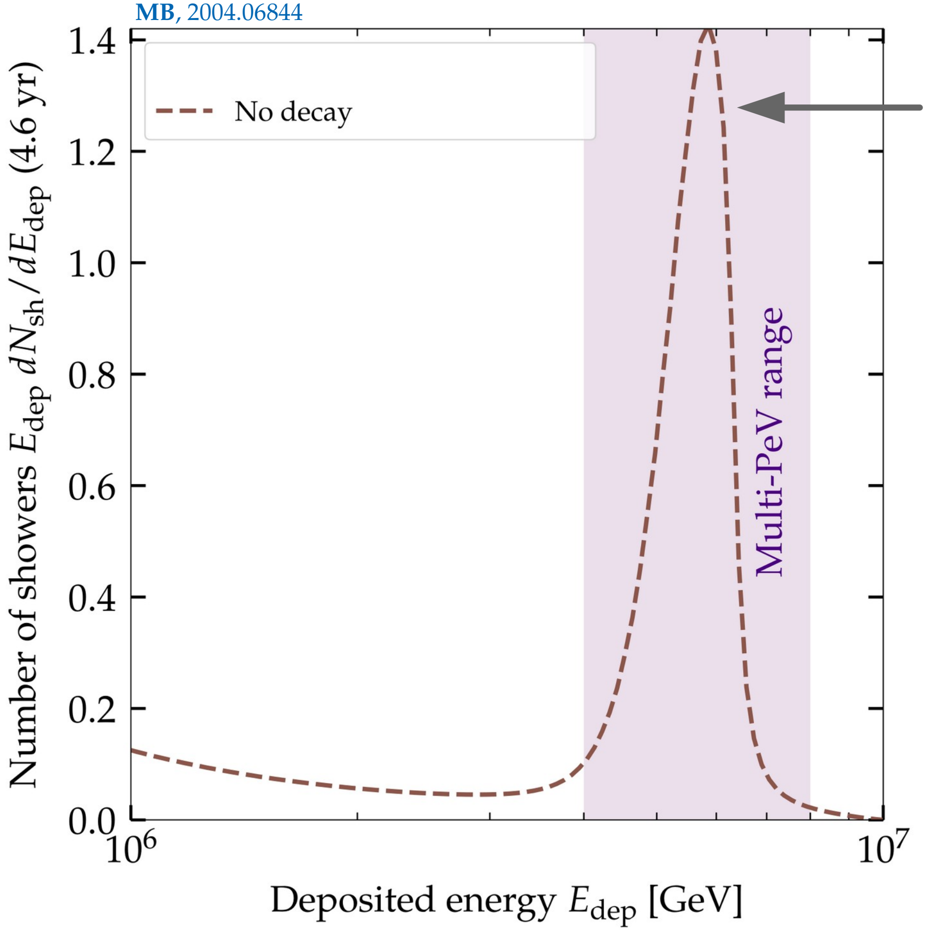


IceCube Collab., *Nature* 2021

What does neutrino decay change?

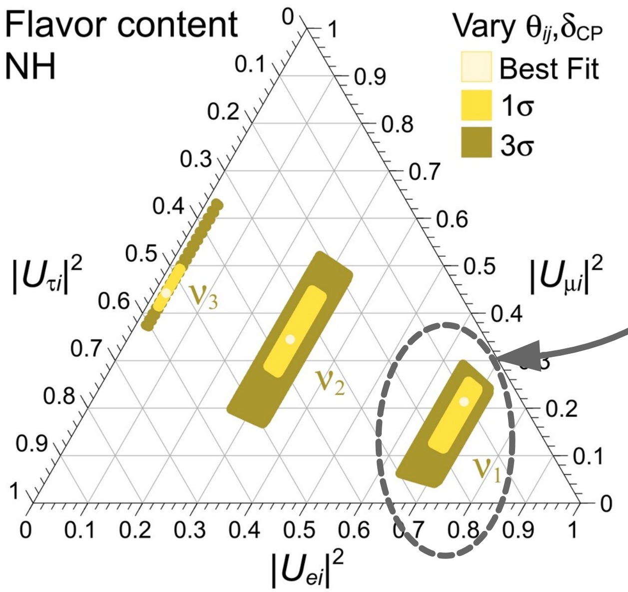
See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

Flavor composition ⟺ Spectrum shape ⟺ Event rate



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

ν_1 is the mass eigenstate with the most e flavor



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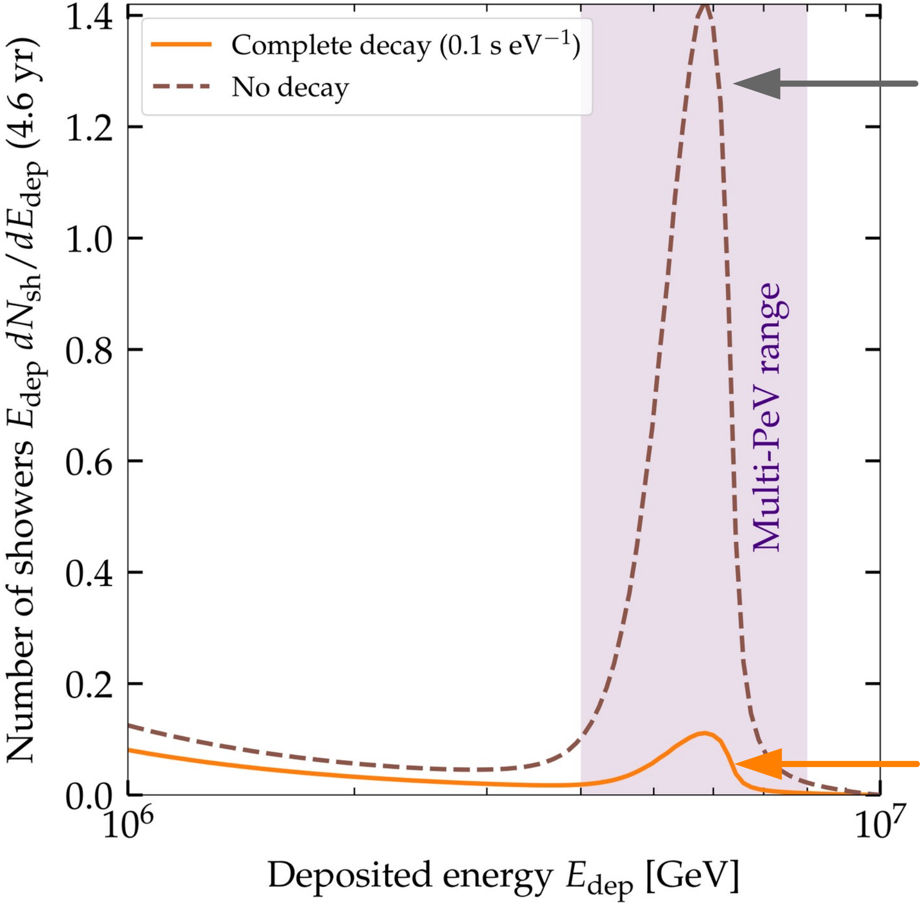
Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



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

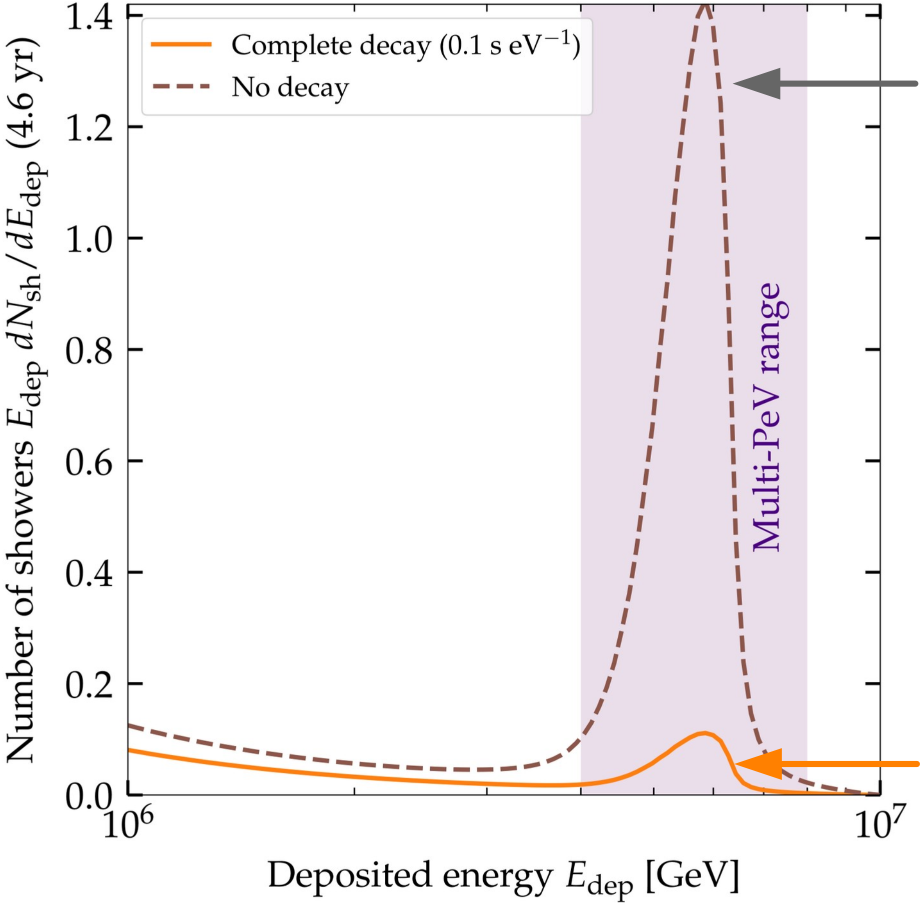
If $\bar{\nu}_1$ had decayed en route to Earth,
there would not have been $\bar{\nu}_e$ left to trigger a GR

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

So by having observed 1 GR event we can place a *lower* limit on the lifetime of $\bar{\nu}_1$ (= ν_1)

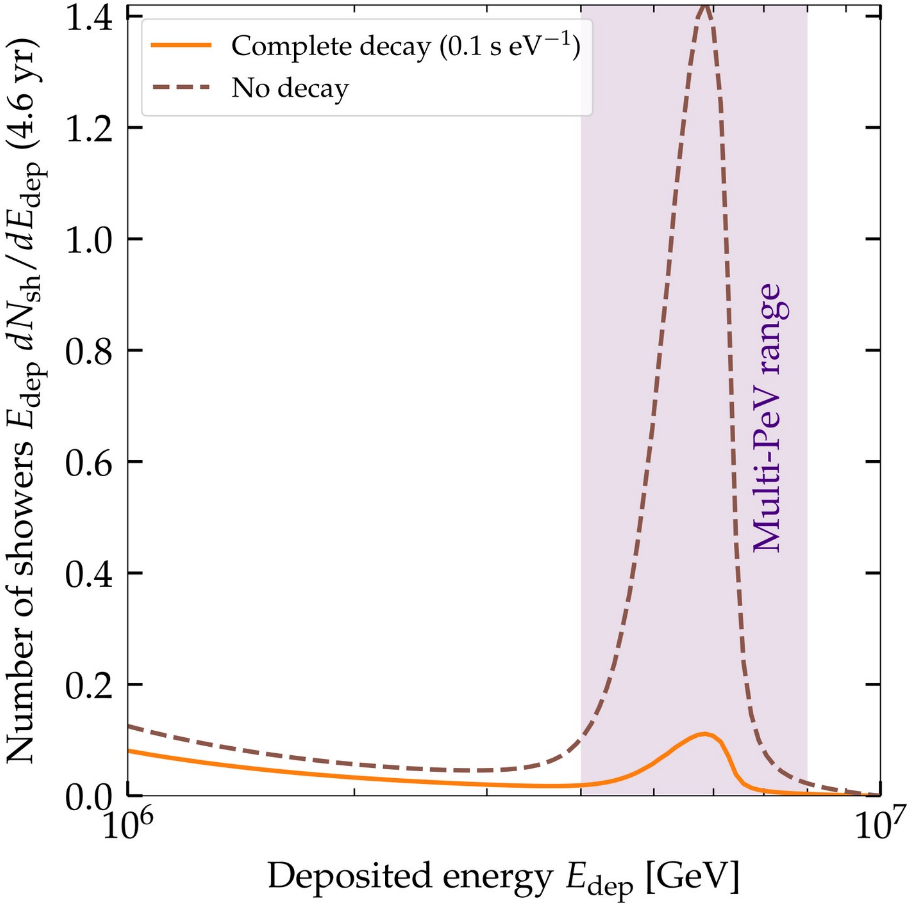
If $\bar{\nu}_1$ had decayed en route to Earth, there would not have been $\bar{\nu}_e$ left to trigger a GR

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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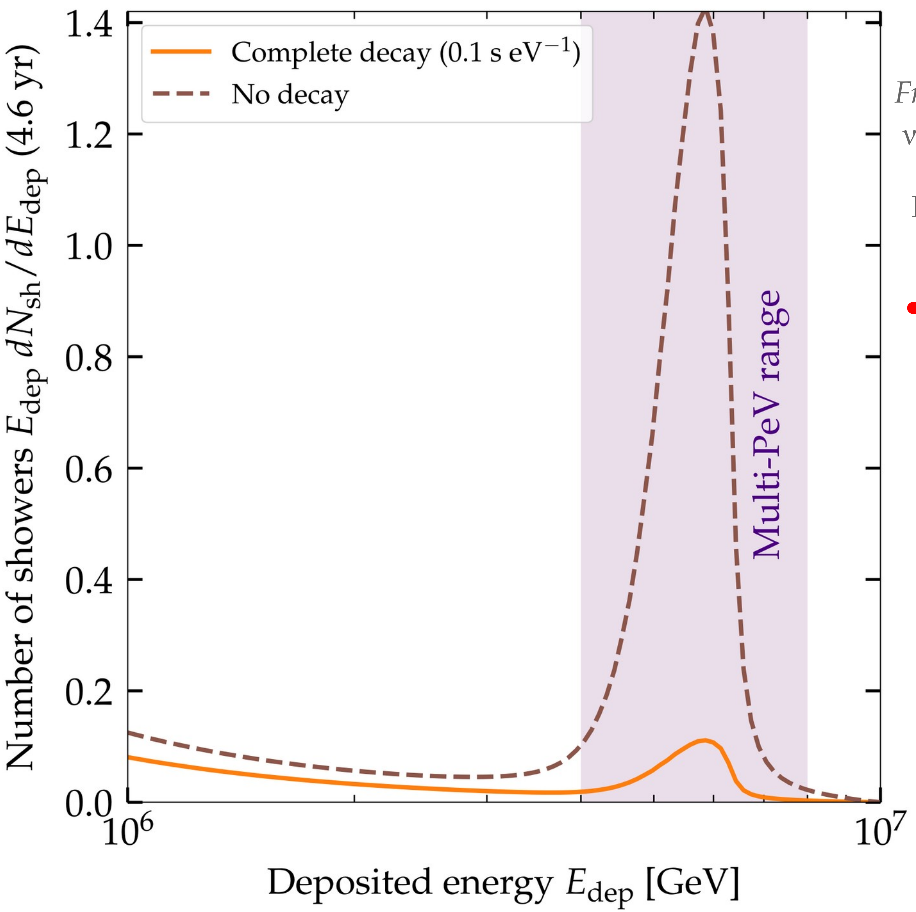
Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844

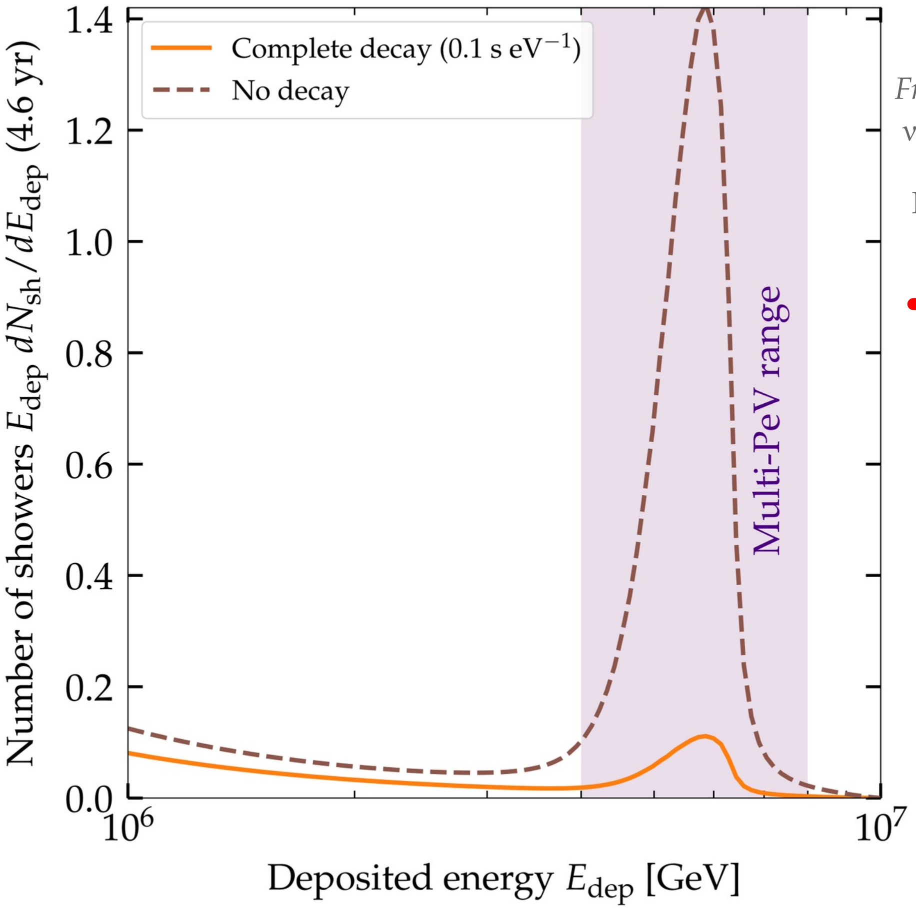


Free parameters:
ν_1, ν_2 lifetimes
Mix. par.
Flavor ratios
$\bar{\nu}/\nu$ ratio

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**



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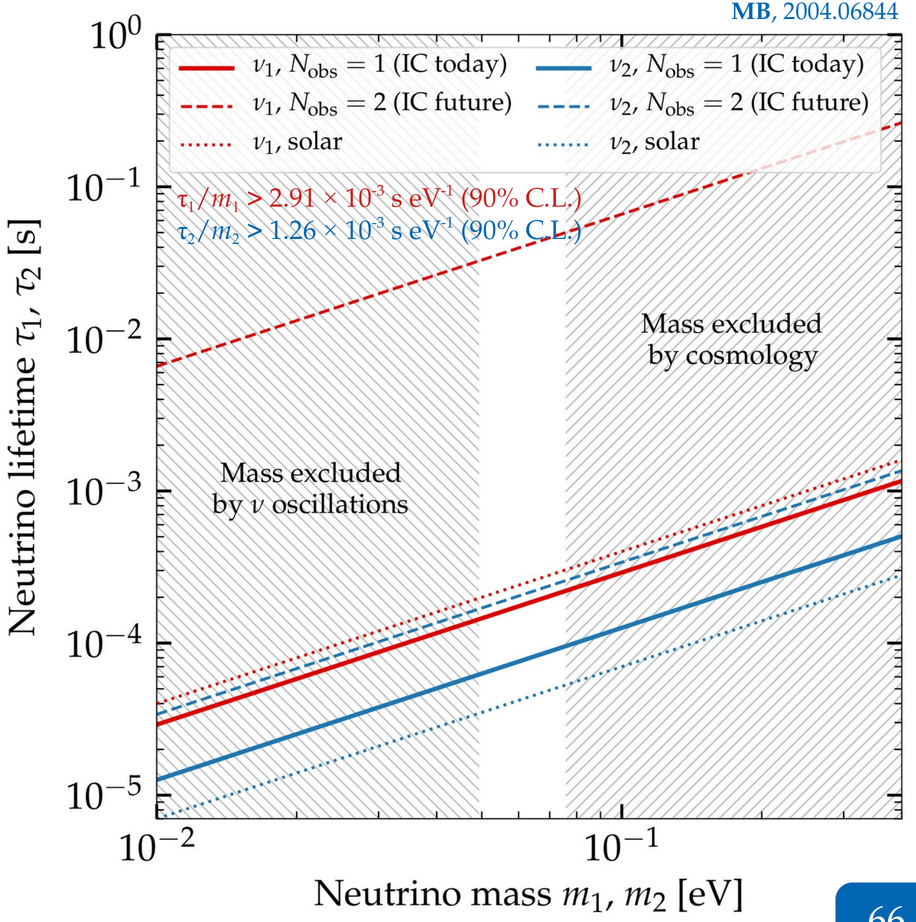
MB, 2004.06844



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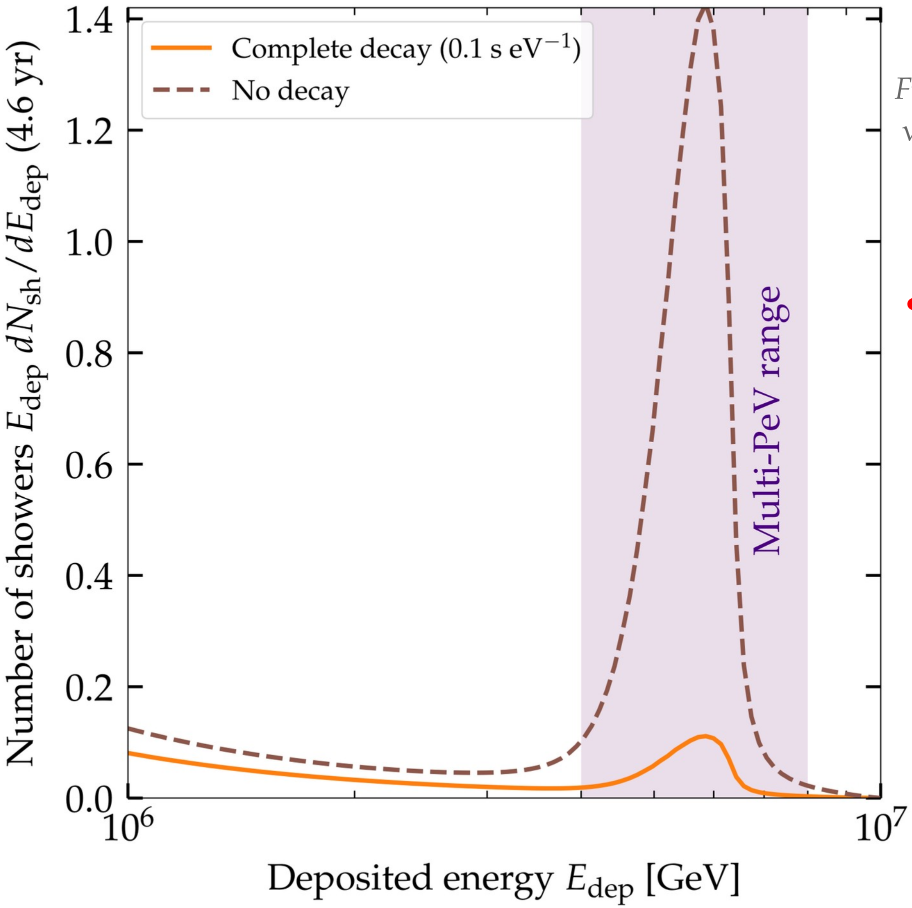
Flavor composition ⟺ Spectrum shape ⟺ **Event rate**



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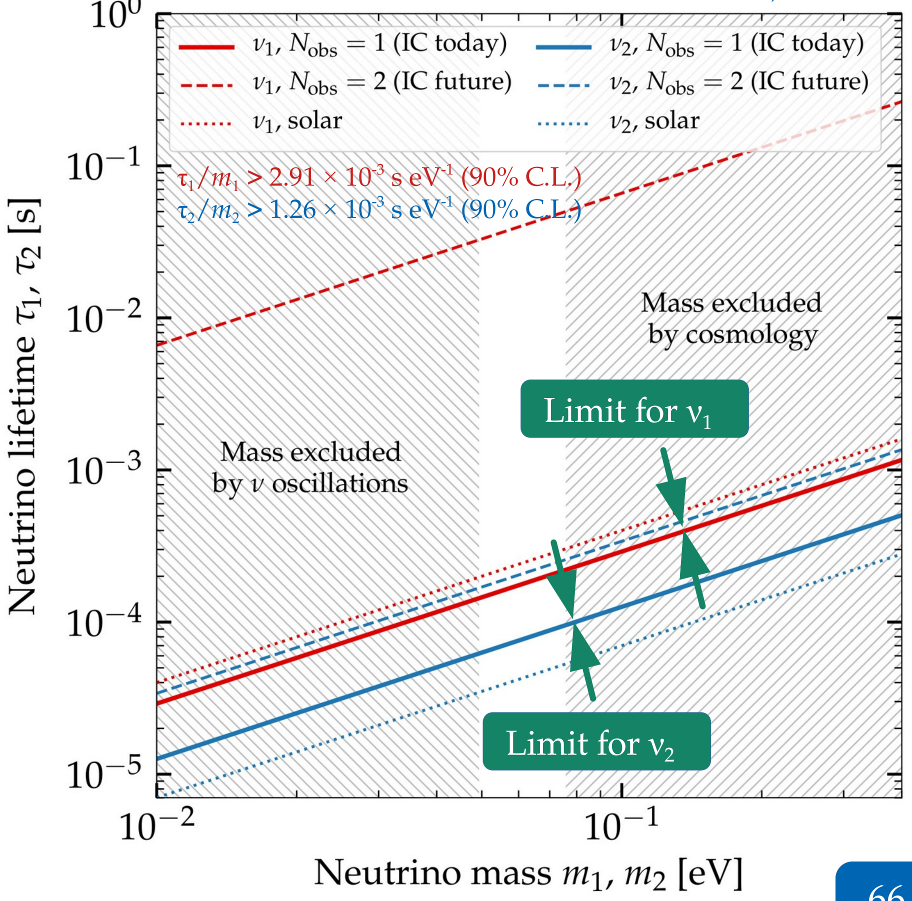


5. New neutrino interactions:

Are there secret νν interactions?

Astrophysical neutrino sources

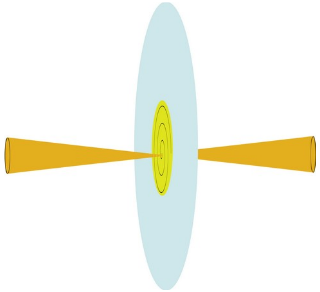
Earth

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

Astrophysical neutrino sources

Earth

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

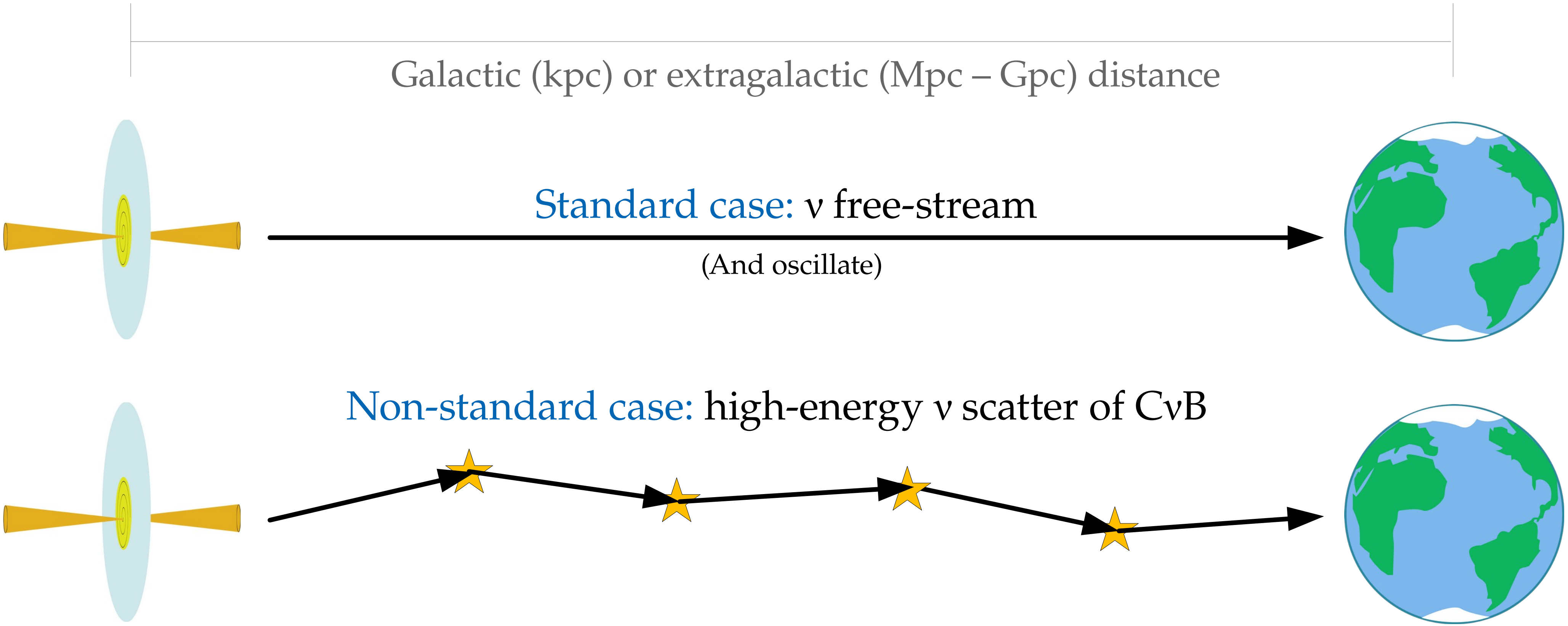


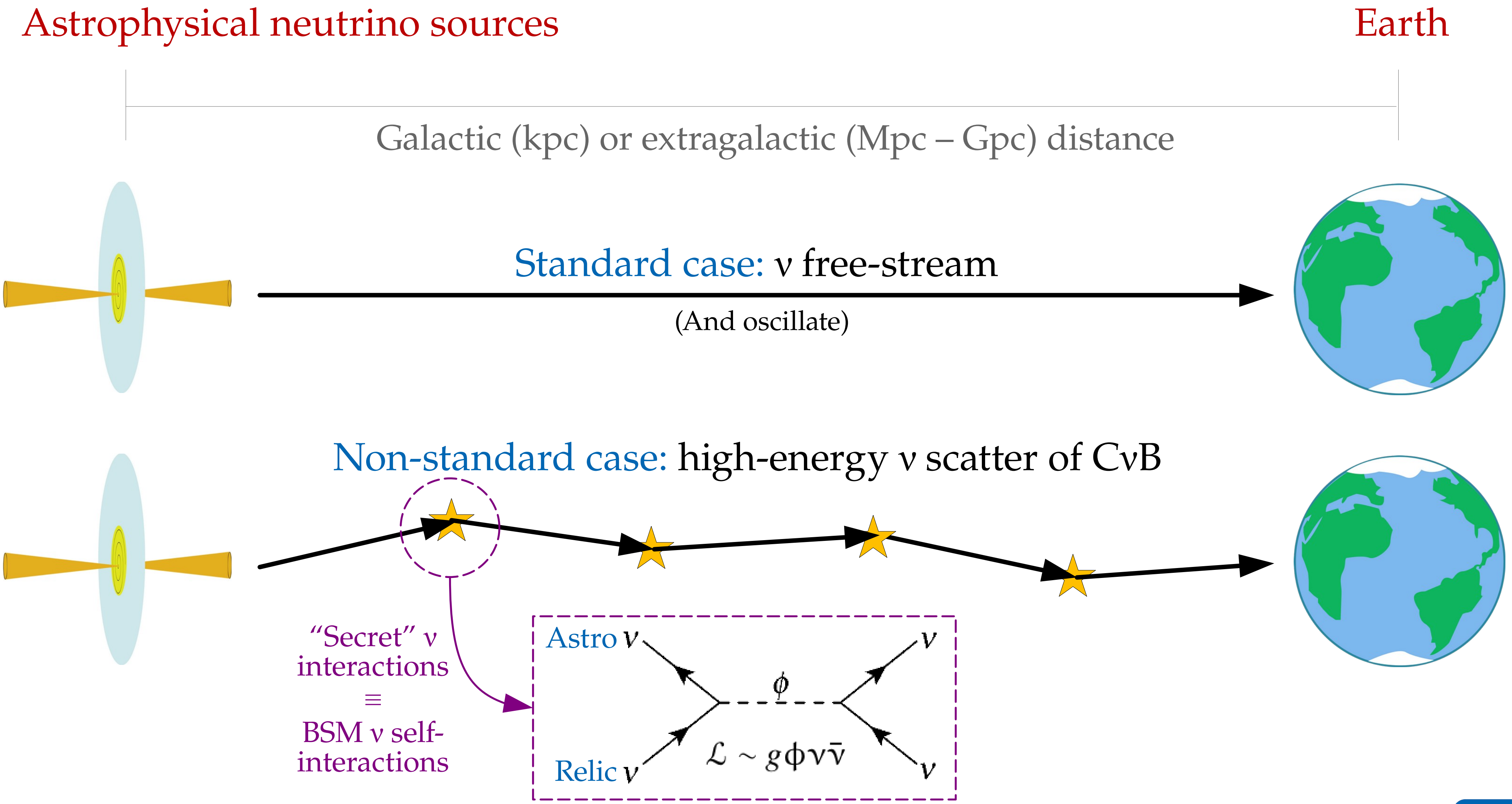
Standard case: ν free-stream

(And oscillate)

Astrophysical neutrino sources

Earth




Astrophysical neutrino sources
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Standard case: ν free-stream
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Non-standard case: high-energy ν scatter of CνB
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$

Astrophysical neutrino sources | Earth

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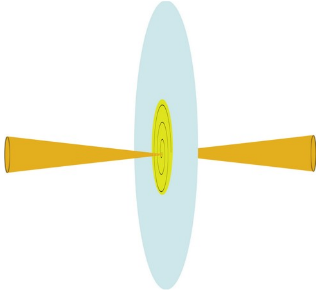

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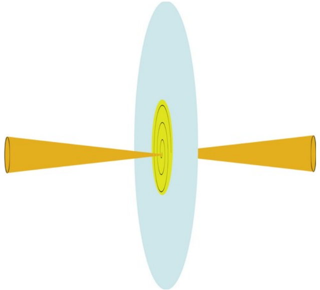

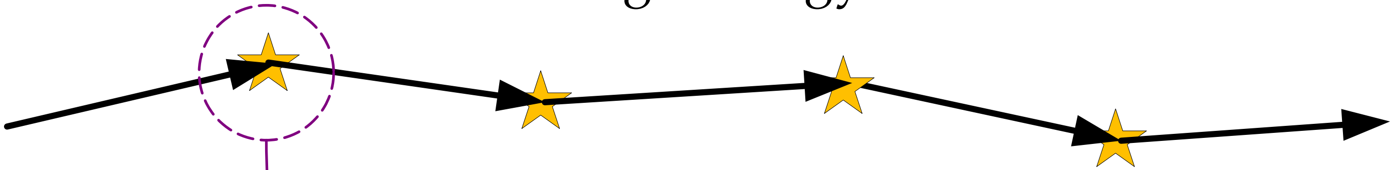

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$\equiv$
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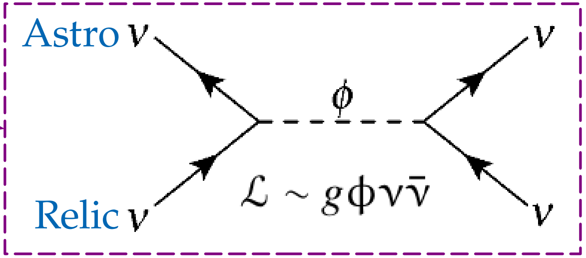
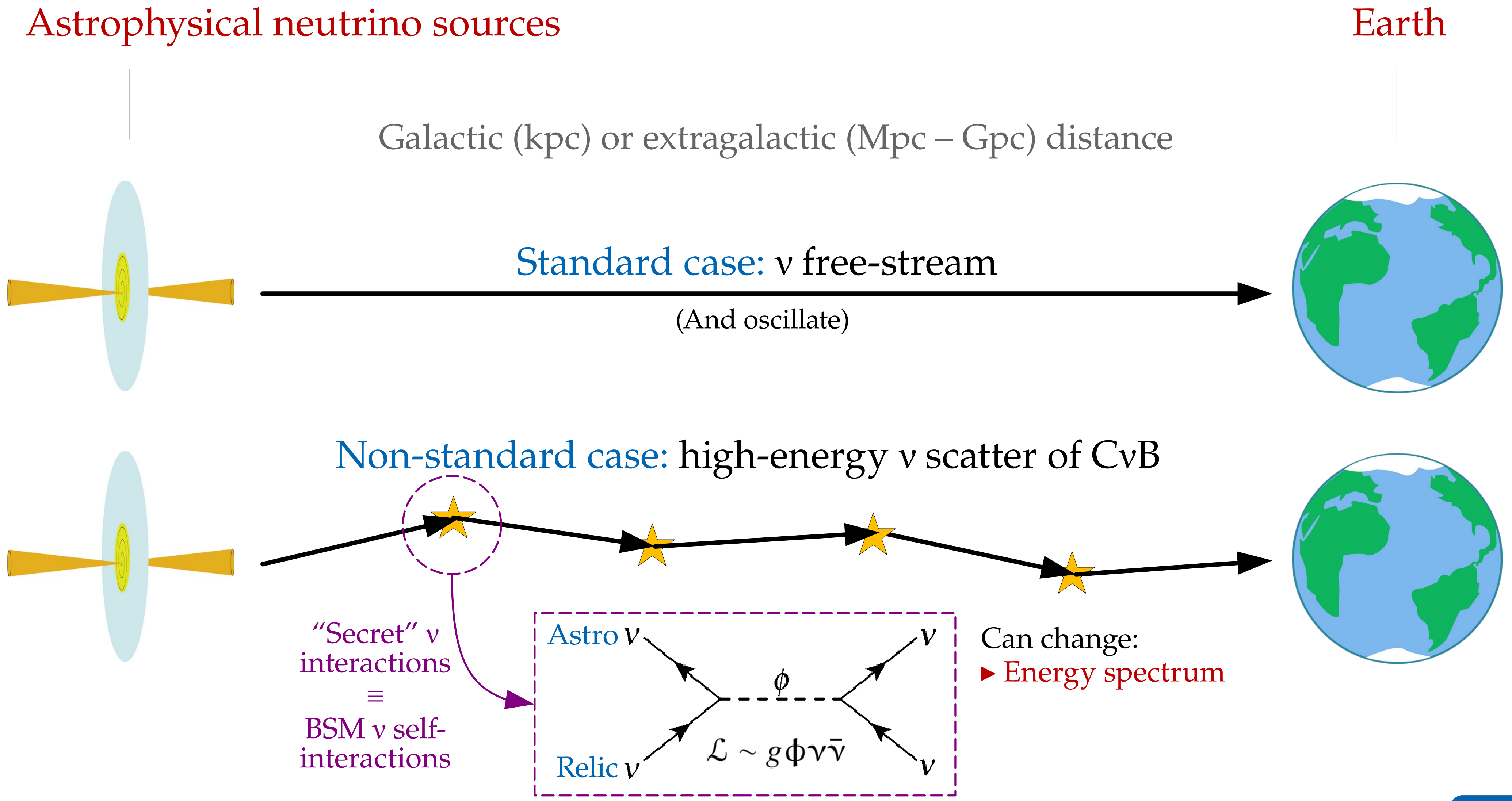


Can change:



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Can change:
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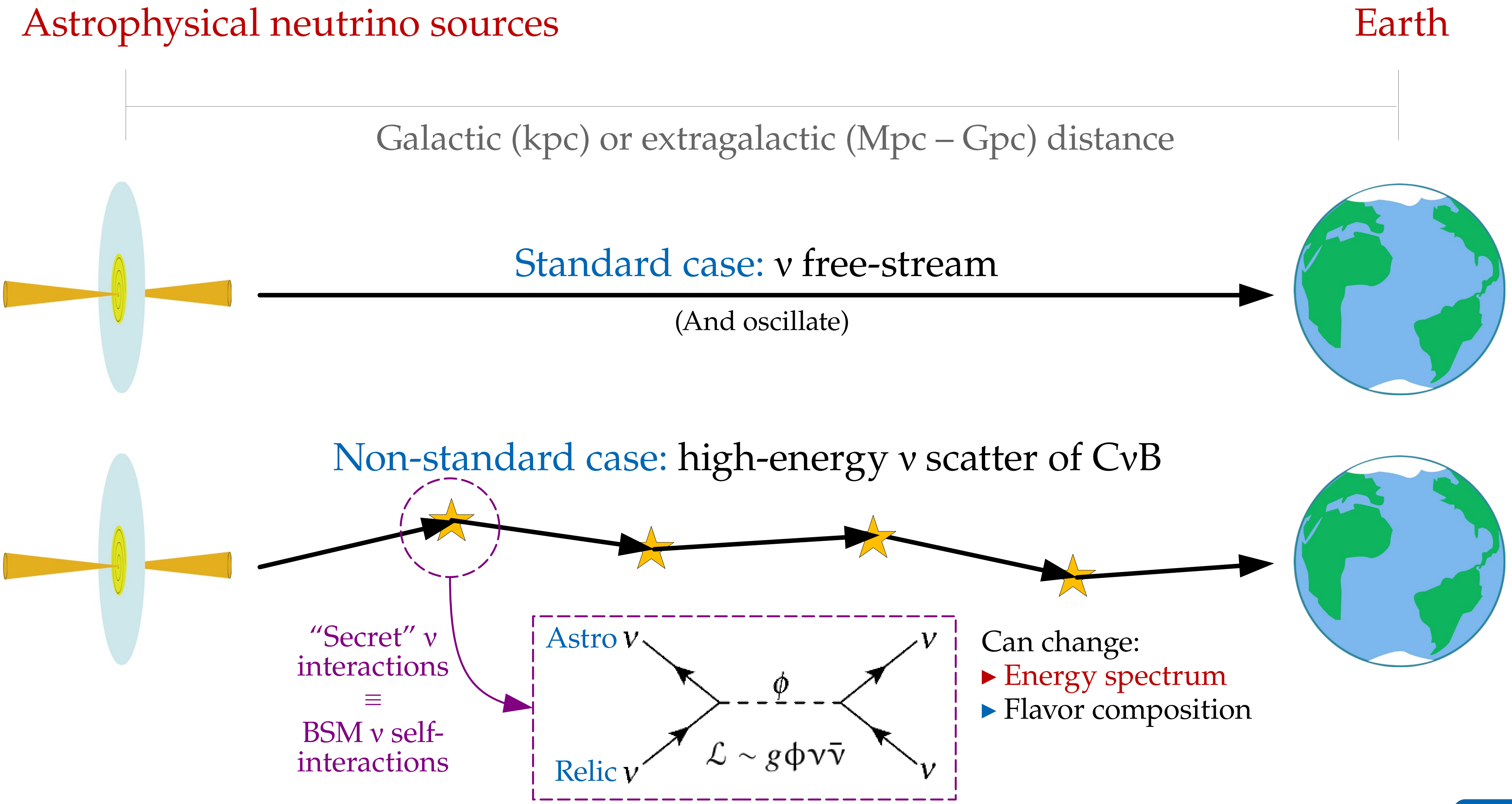
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Can change:
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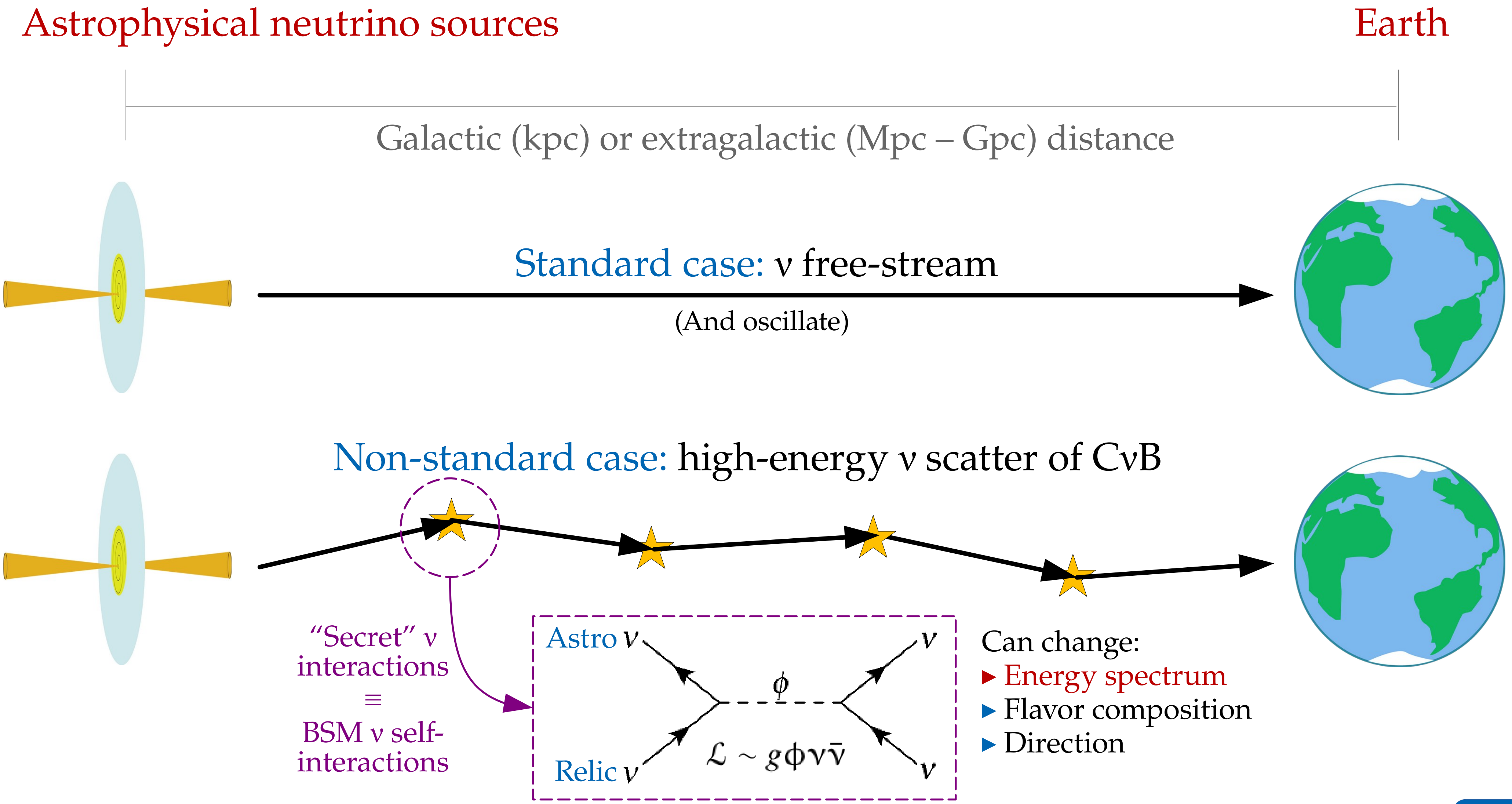
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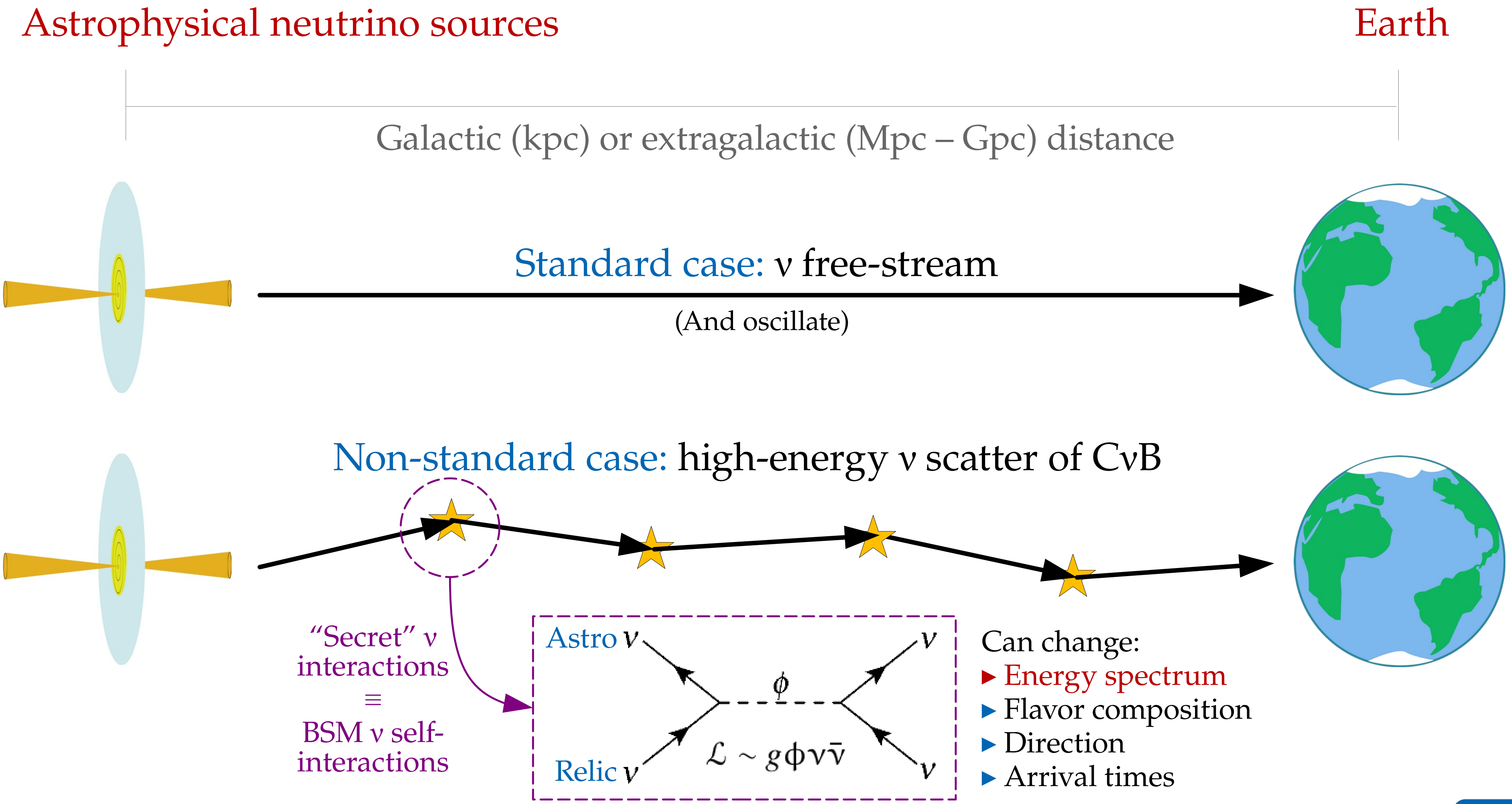
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Can change:
▸ Energy spectrum
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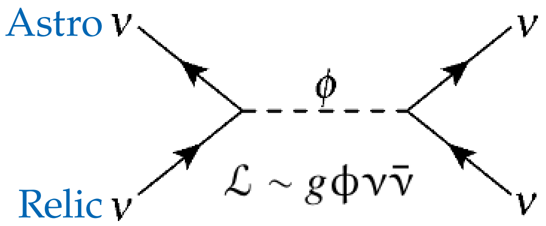
▸ Direction
▸ Arrival times

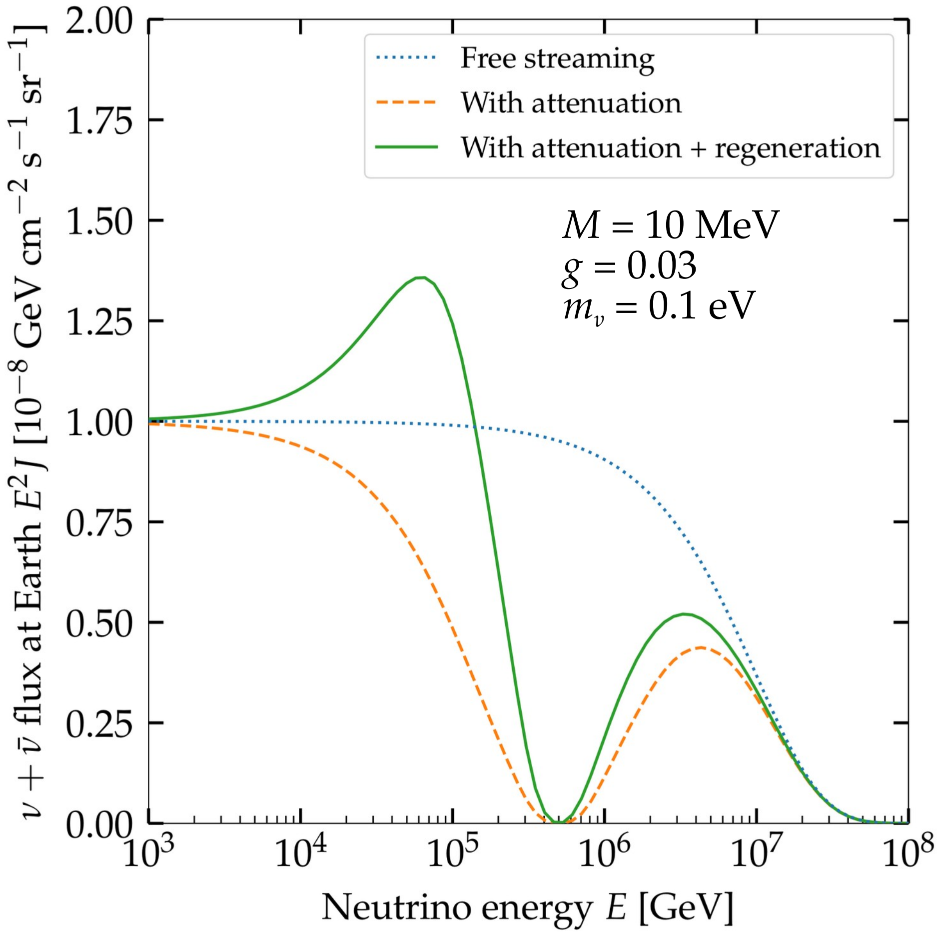
Secret interactions of high-energy astrophysical neutrinos

"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
Creque-Sarbinowski, Hyde, Kamionkowski, *PRD* 2021
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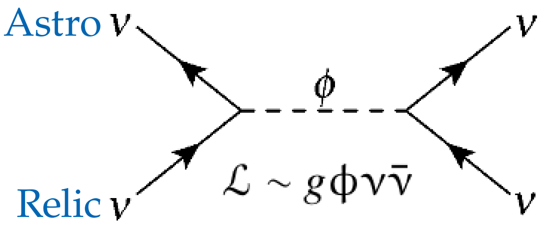

New coupling

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Mediator mass

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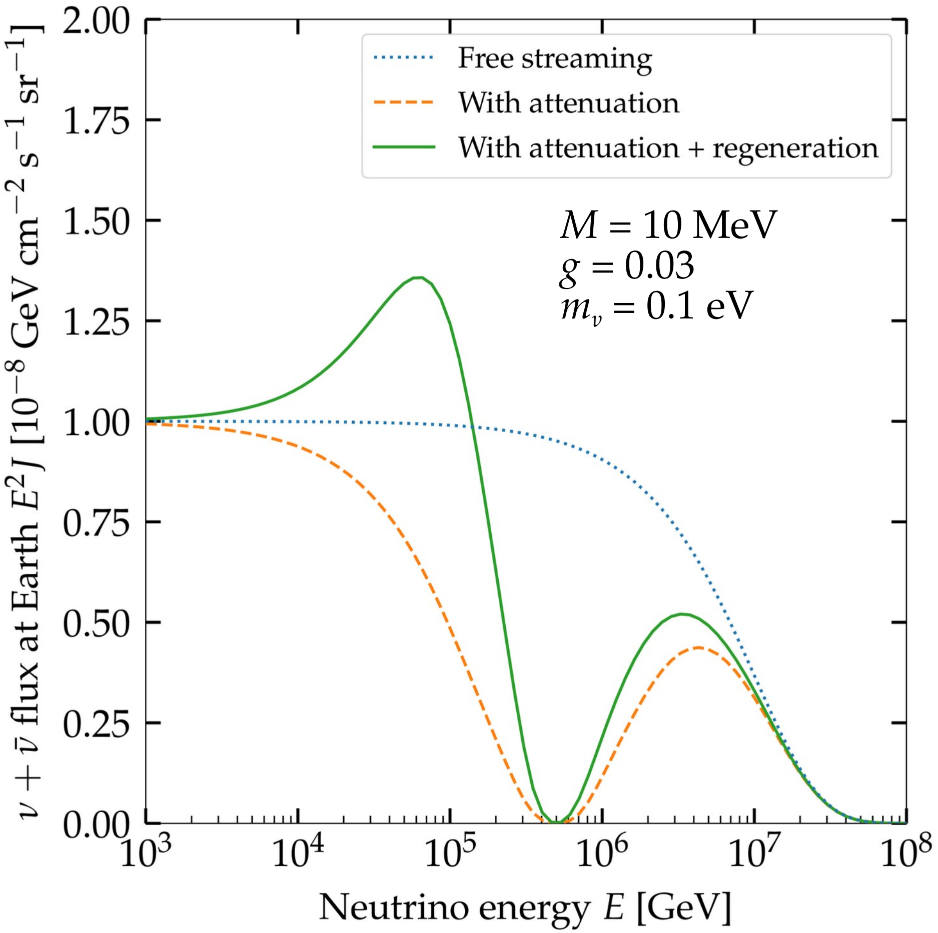

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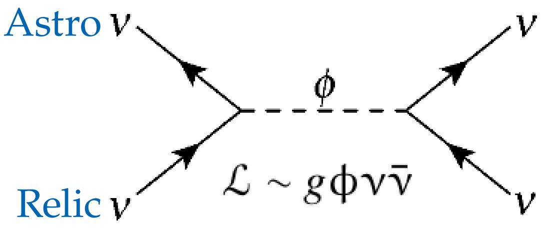

New coupling

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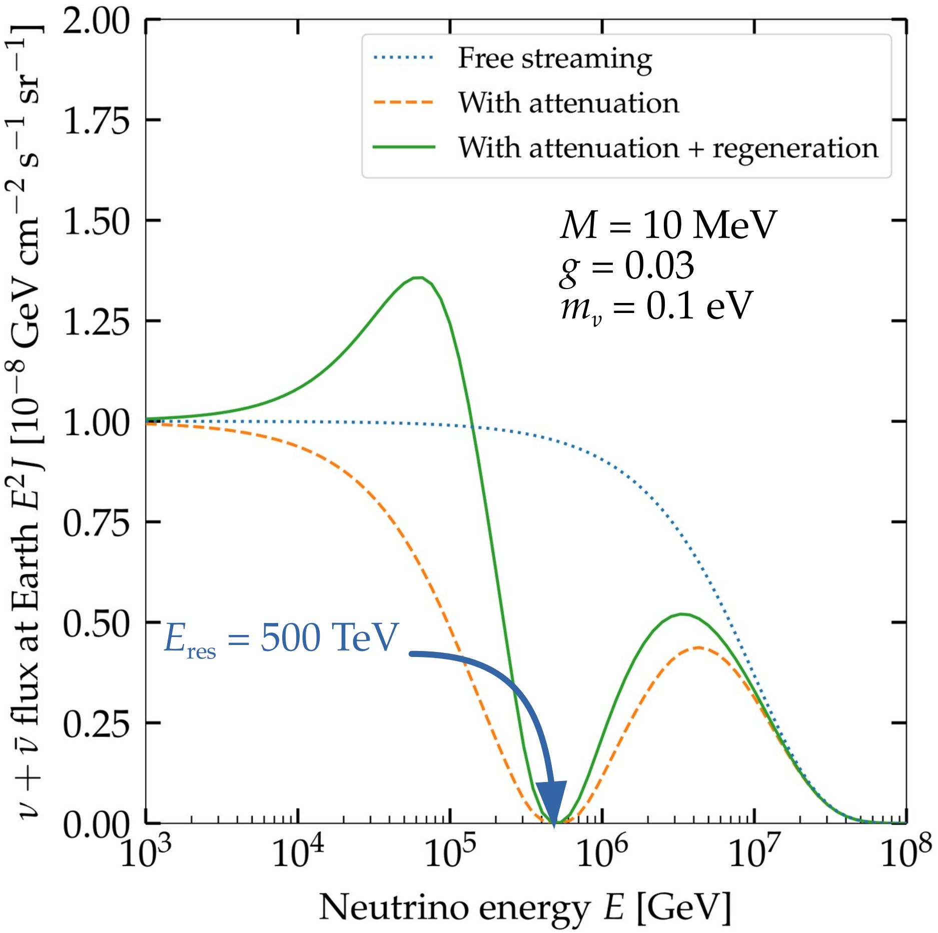
Mediator mass

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



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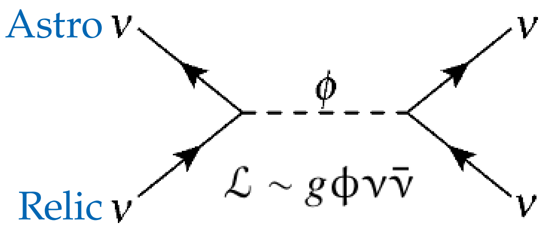

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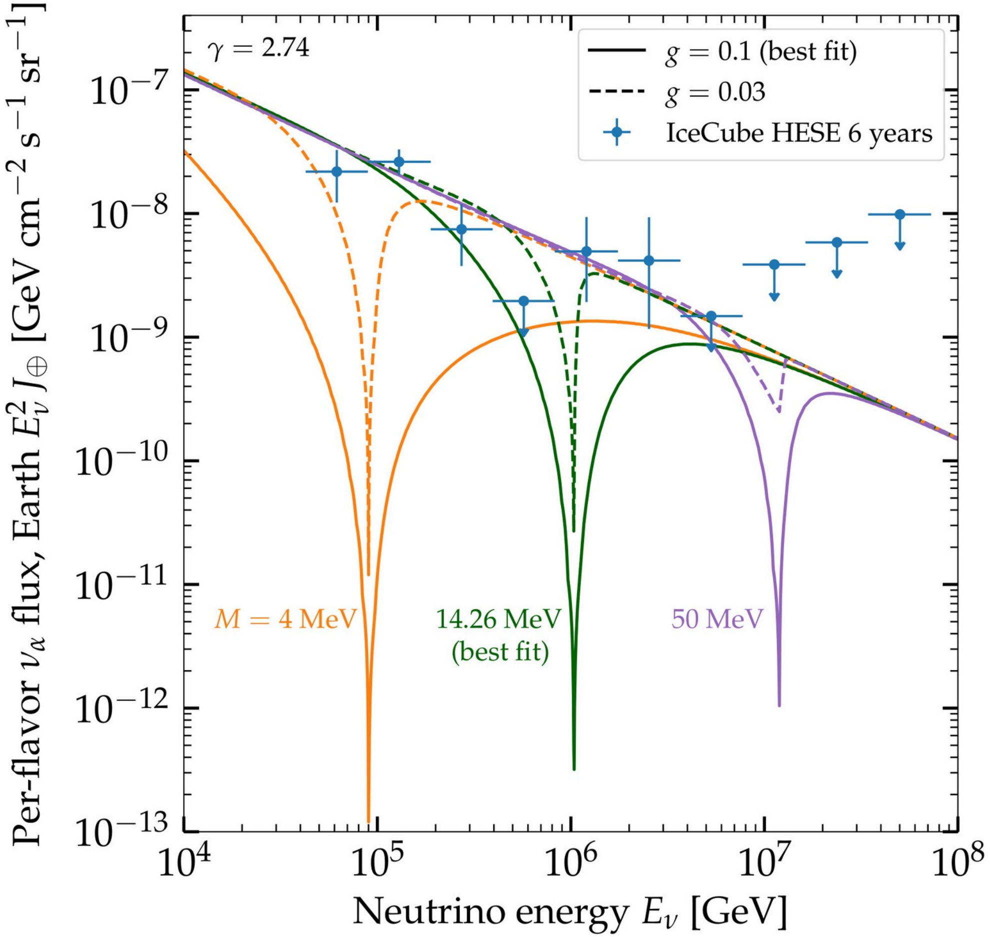

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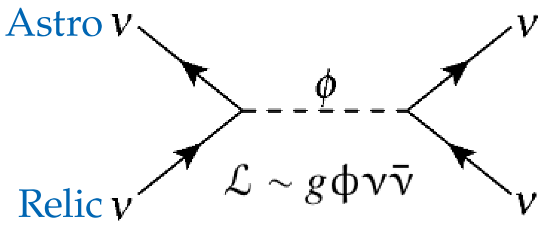

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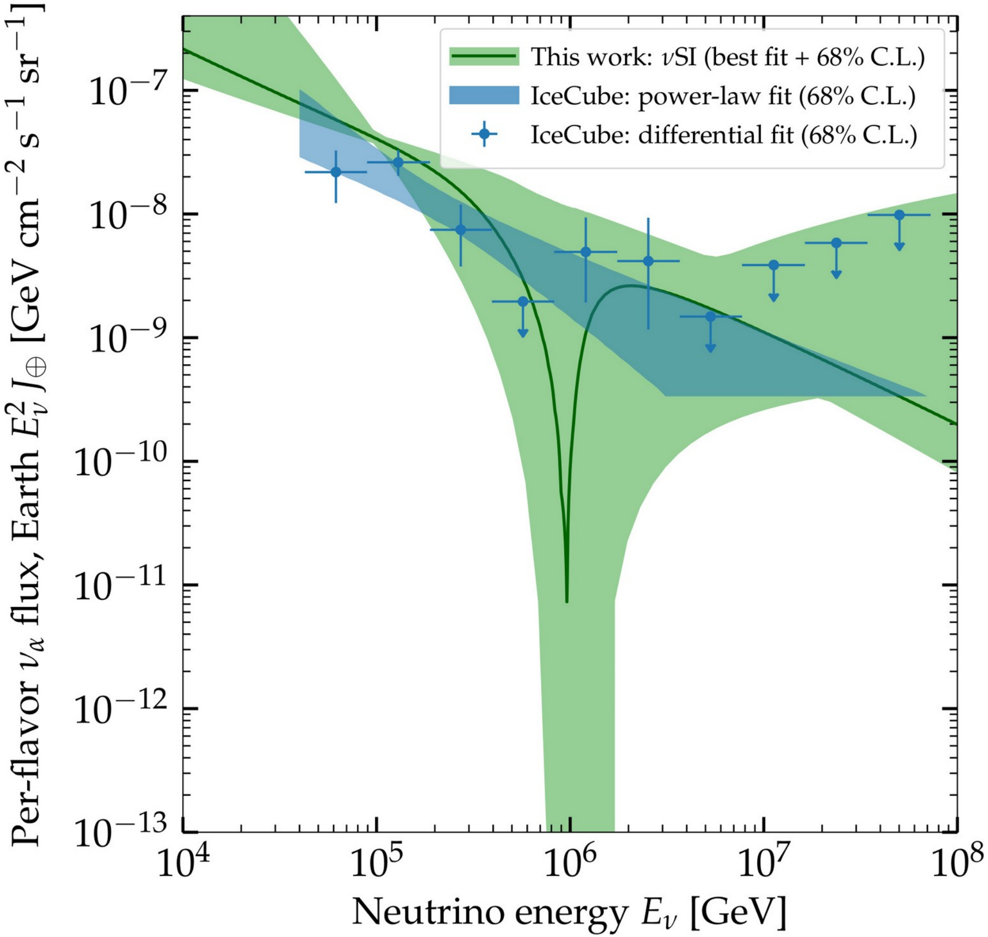
Looking for evidence of νSI

- 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 …



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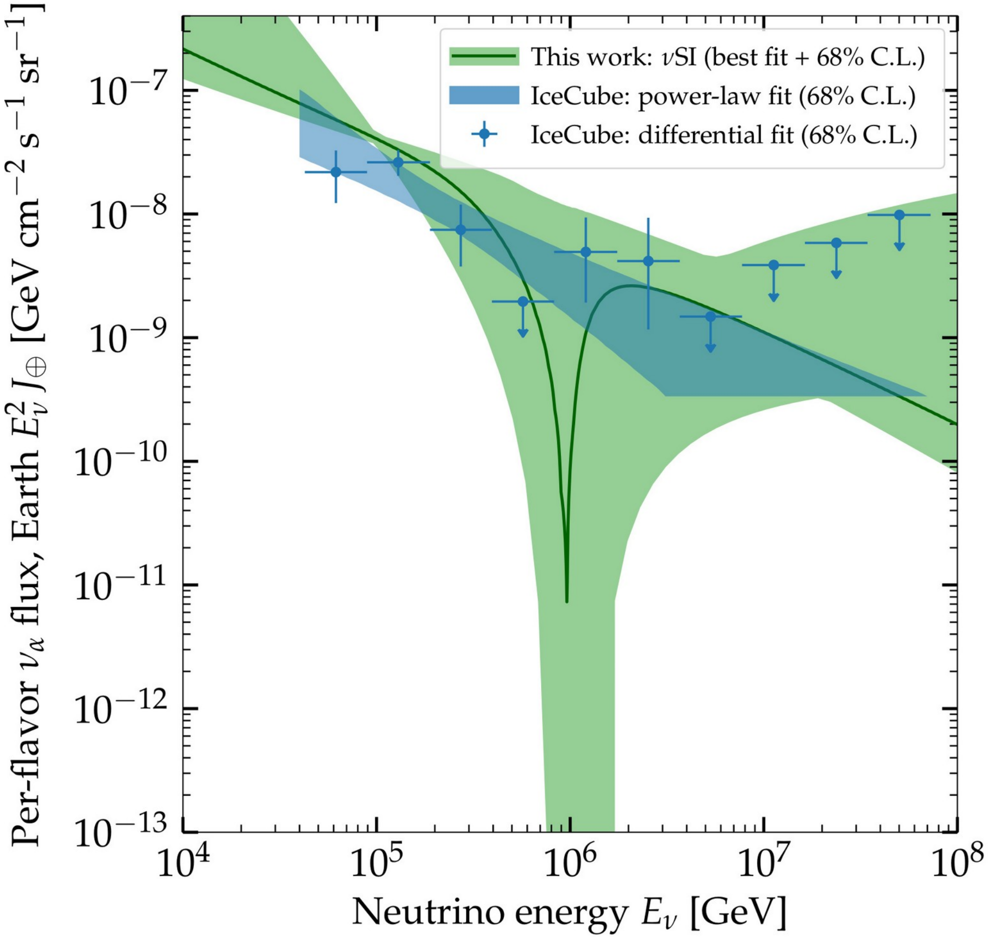

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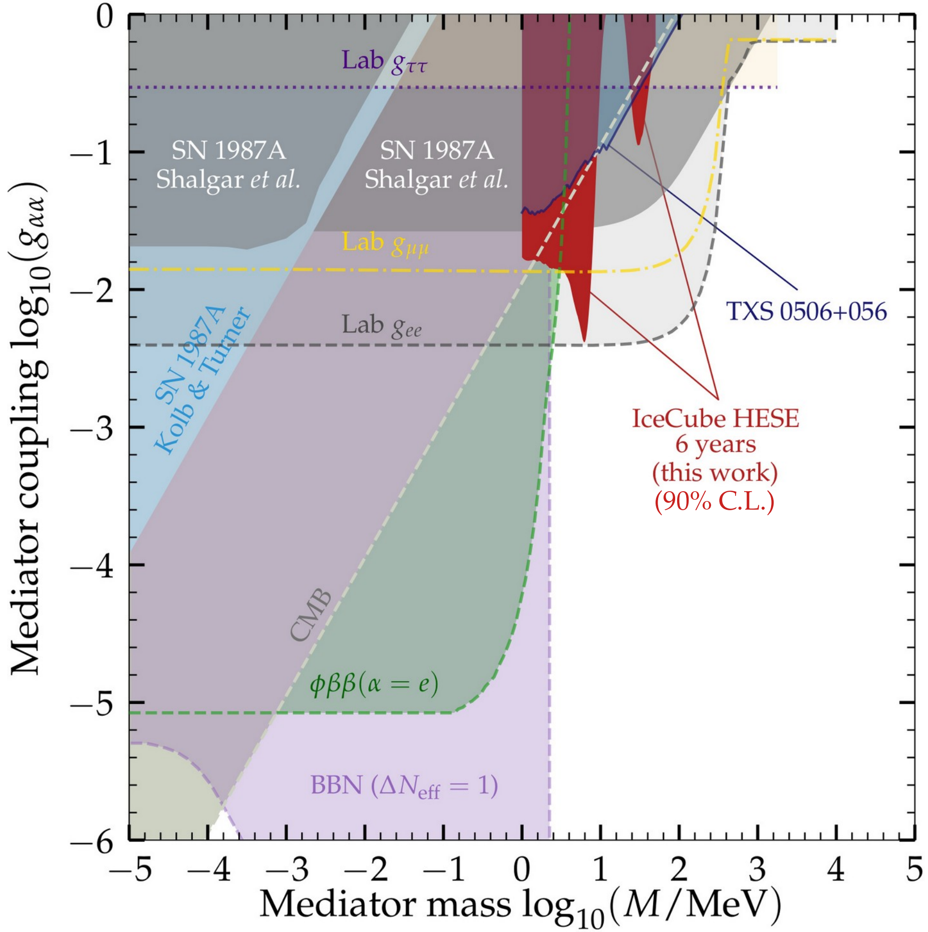

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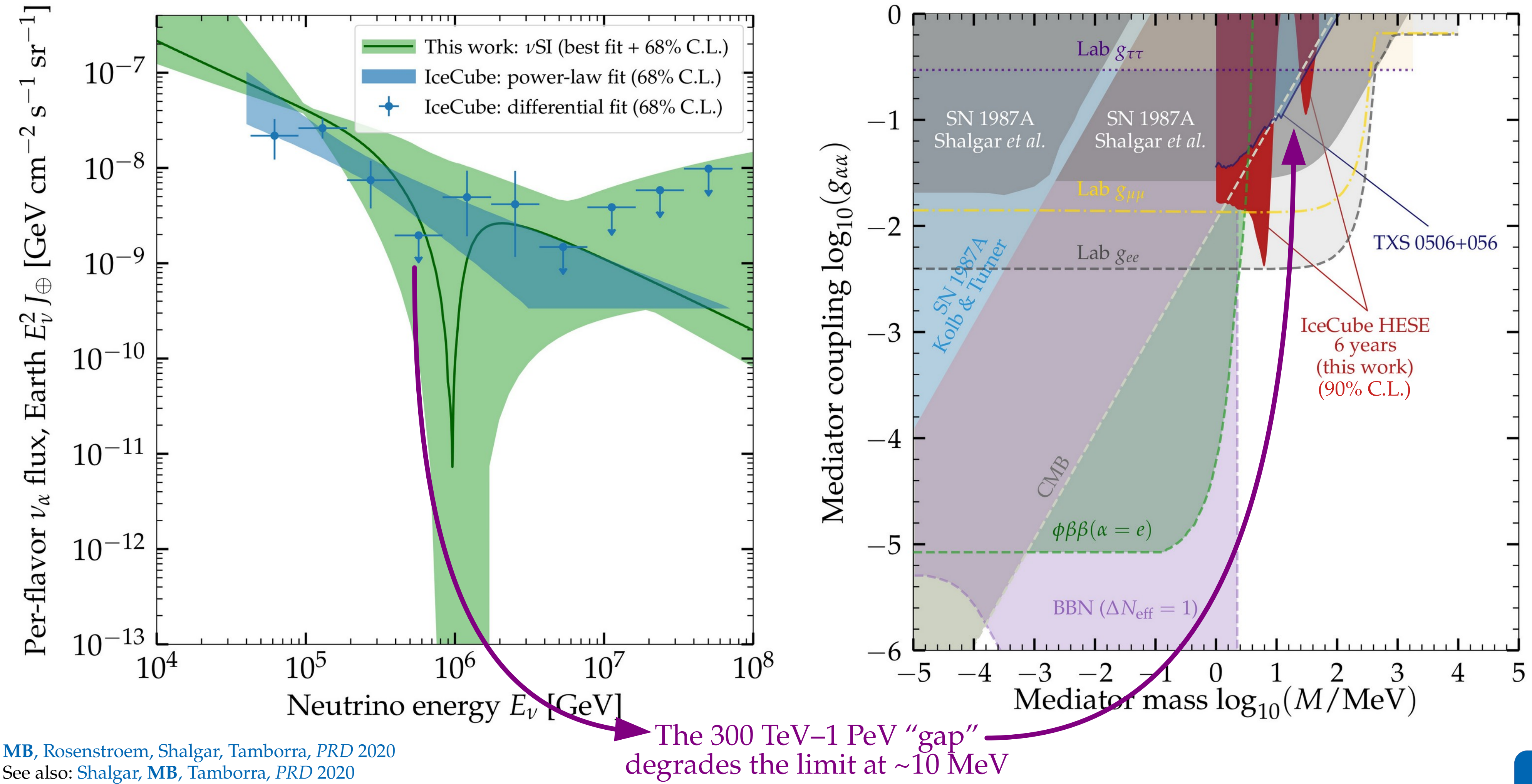

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