Neutrino physics and astrophysics at the highest energies

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PUCP
November 22, 2022

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

Optical light

Mycelia muralis by Bjørn Rørsletr / NN, naturfotograf.com

Optical light

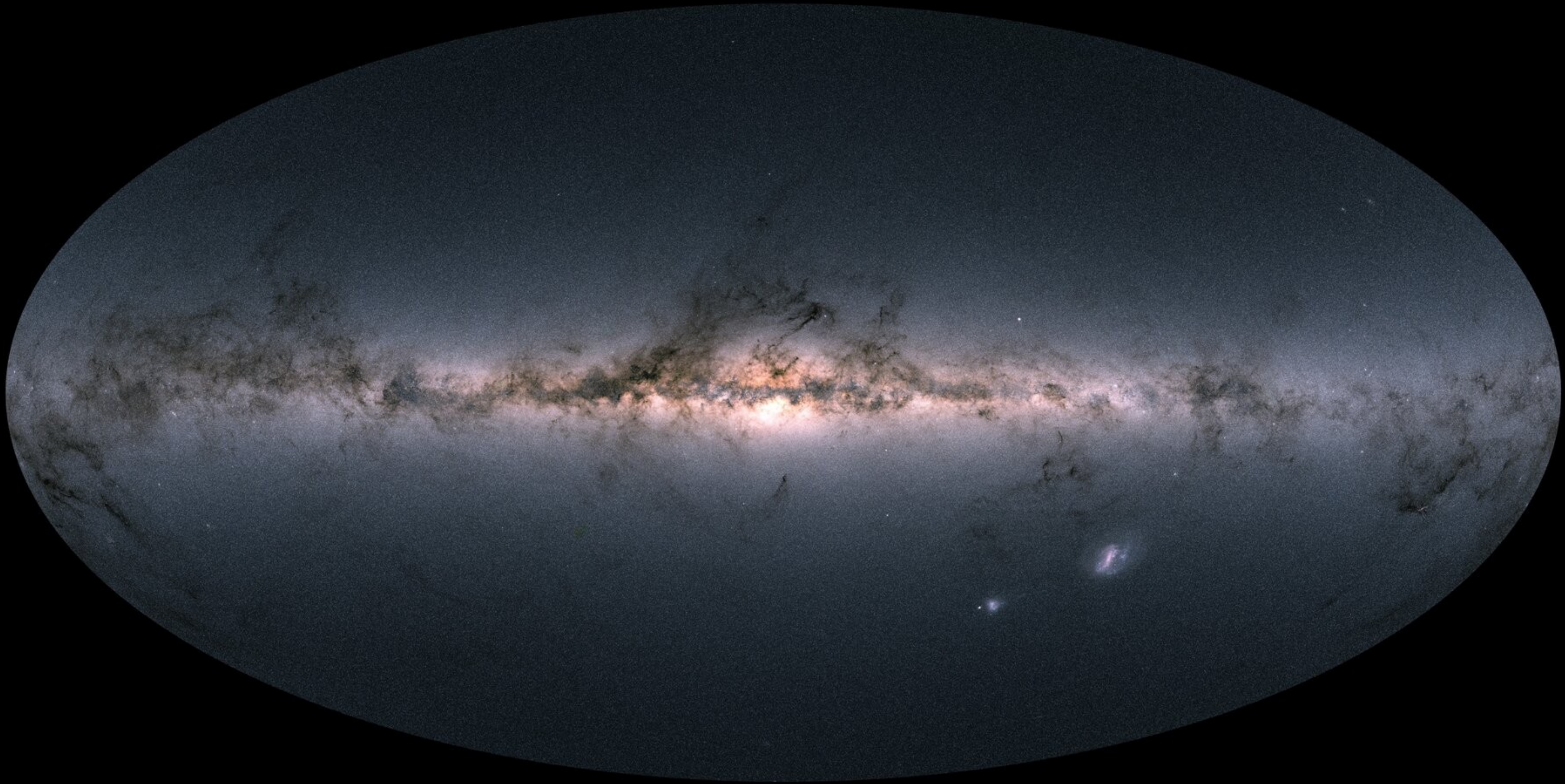
Mycelia muralis by Bjørn Rørsletr / NN, naturfotograf.com

Optical light

Ultraviolet light

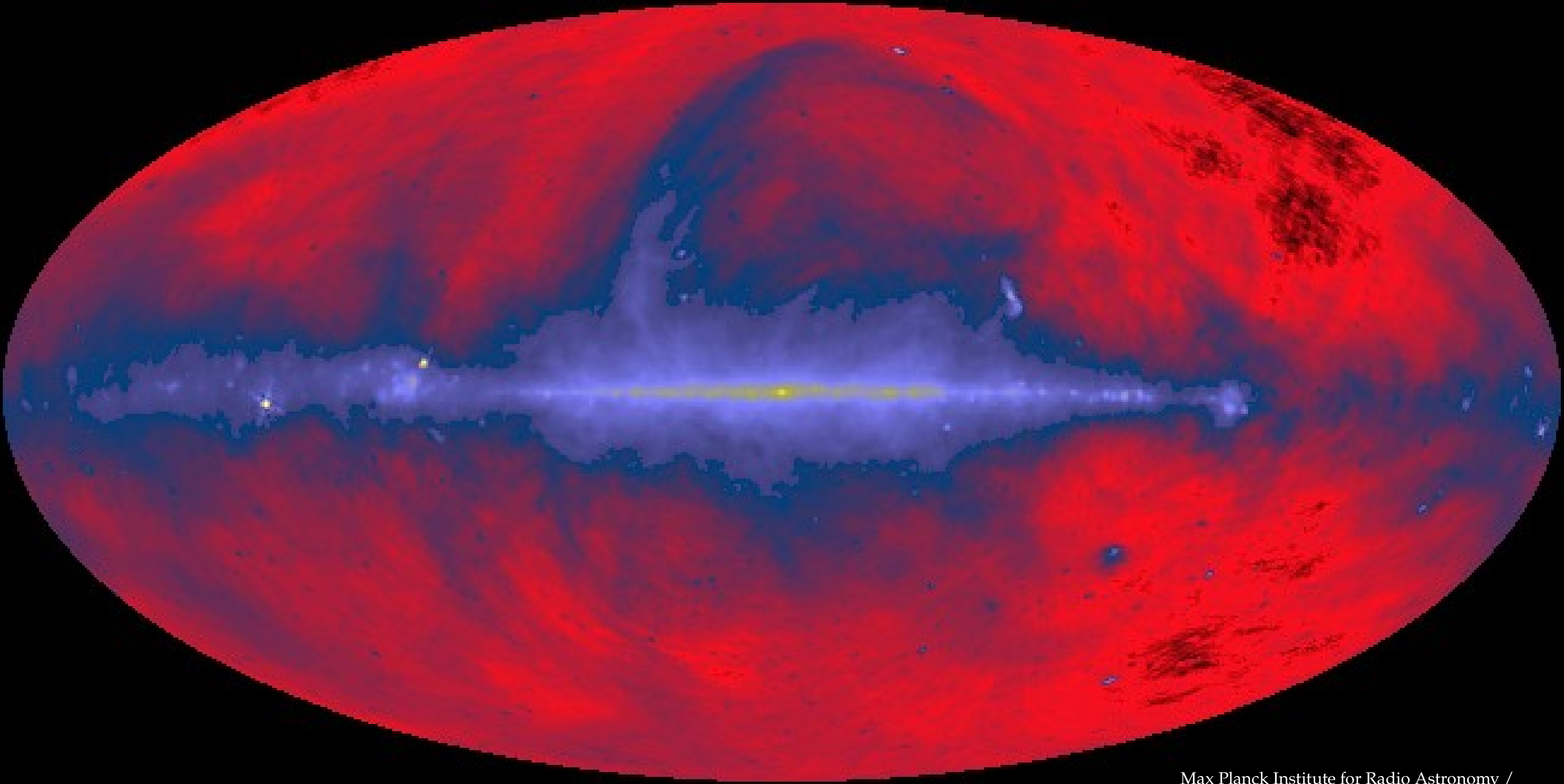
Mycelia muralis by Bjørn Rørsletr / NN, naturfotograf.com

Optical light



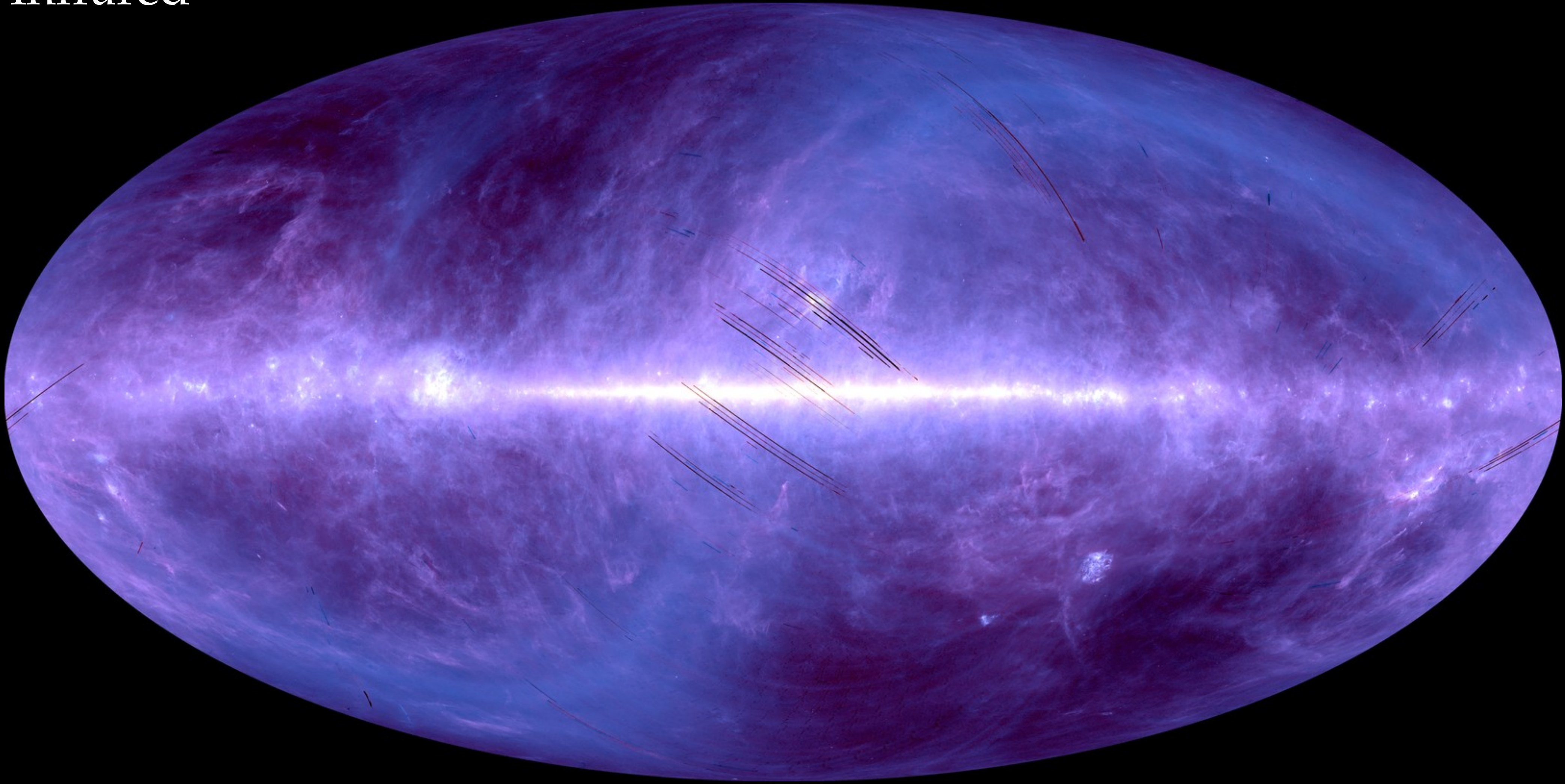
Gaia

Radio waves



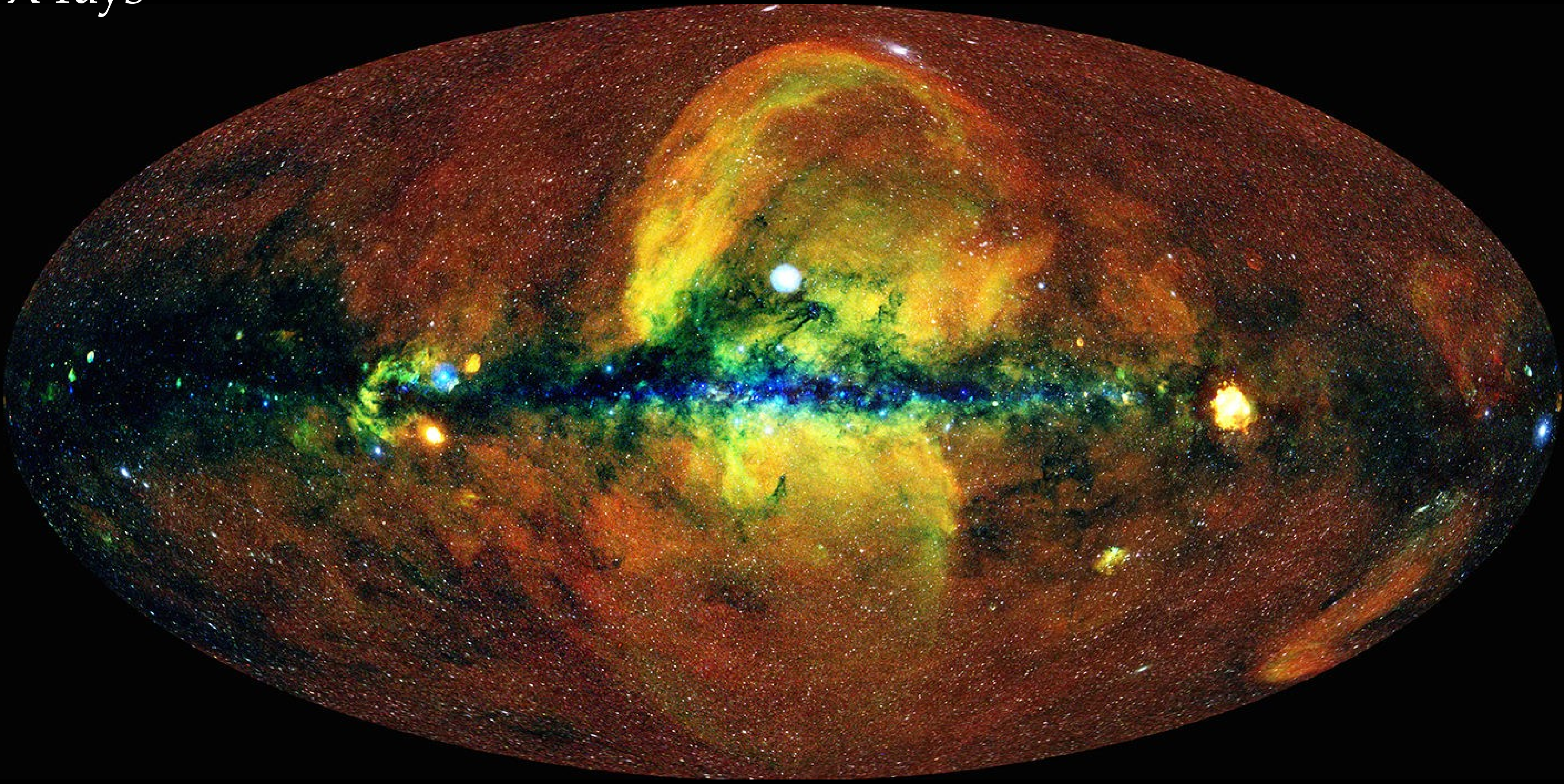
Max Planck Institute for Radio Astronomy /
Glyn Haslam / Jodrell Bank / Effelsberg / Parkes

Infrared



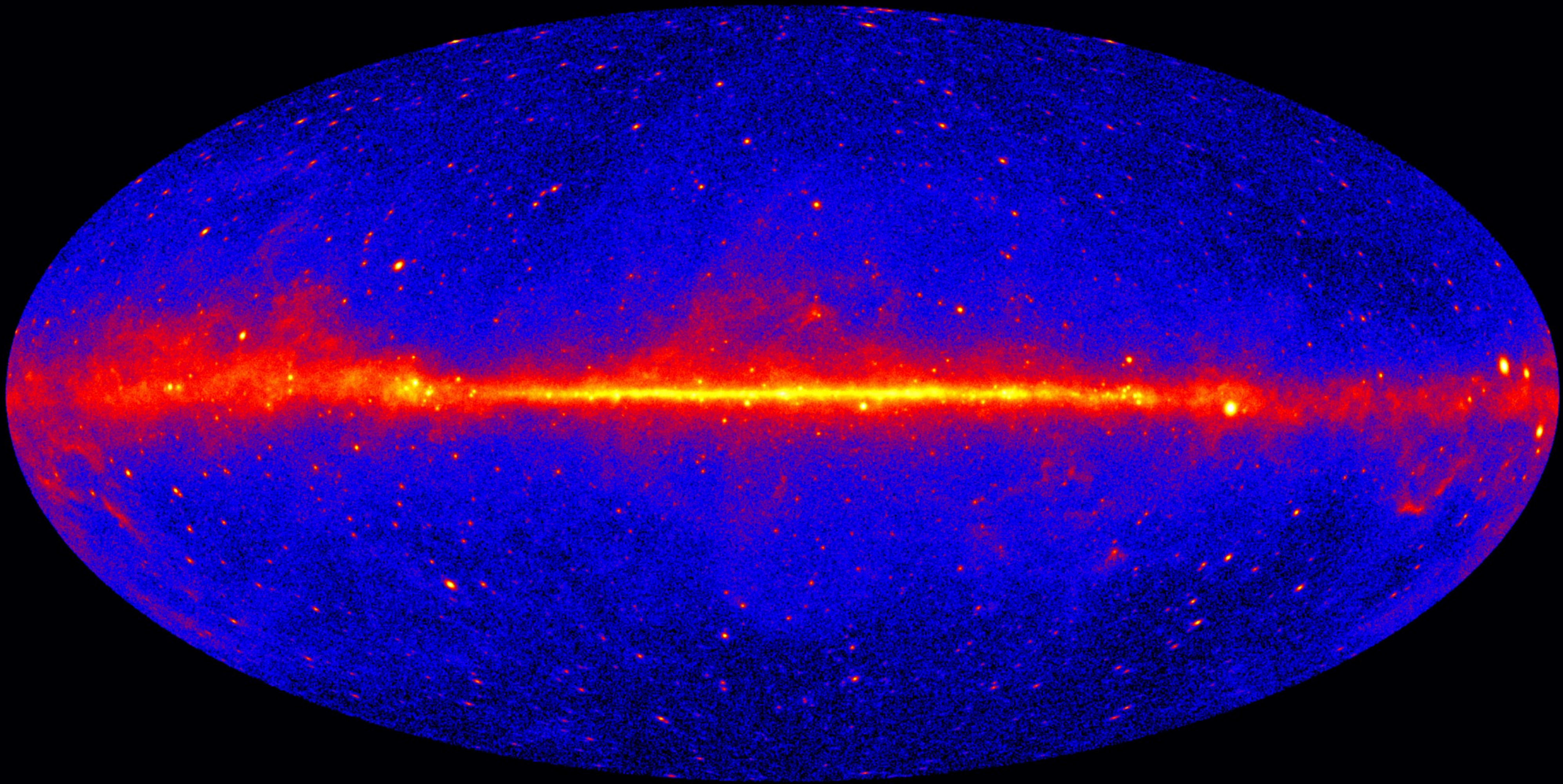
AKARI

X-rays



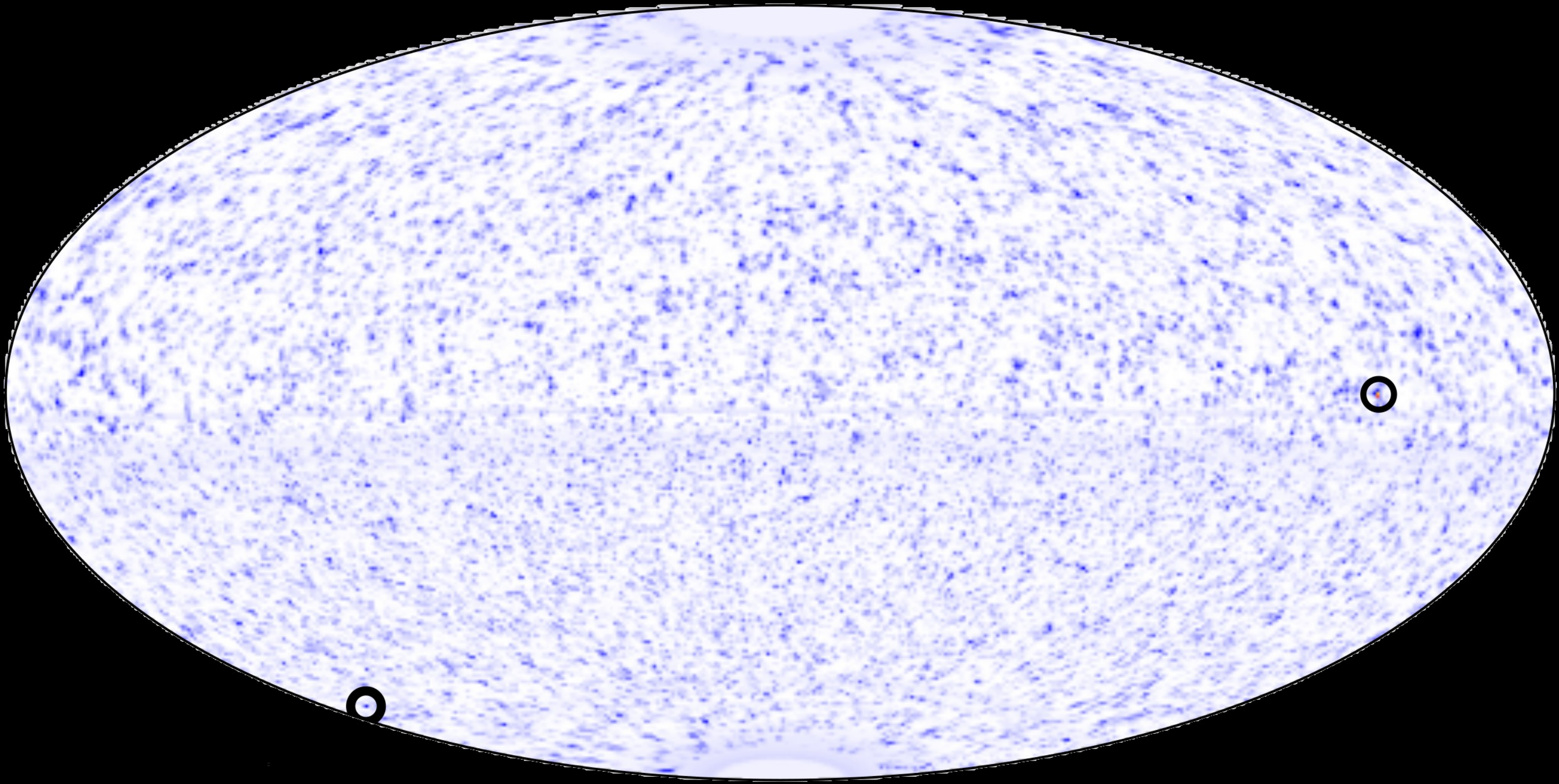
eRosita

Gamma rays

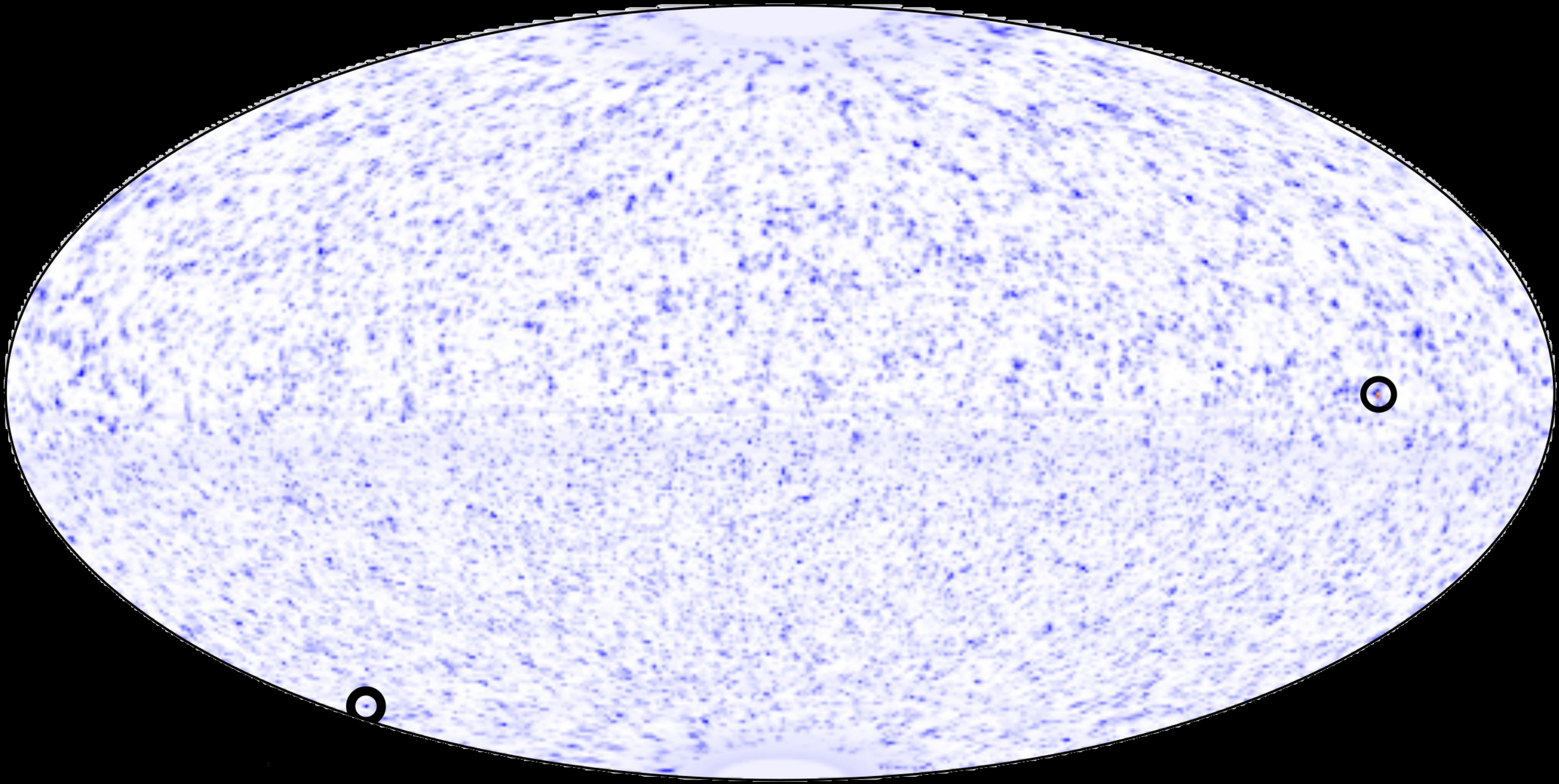


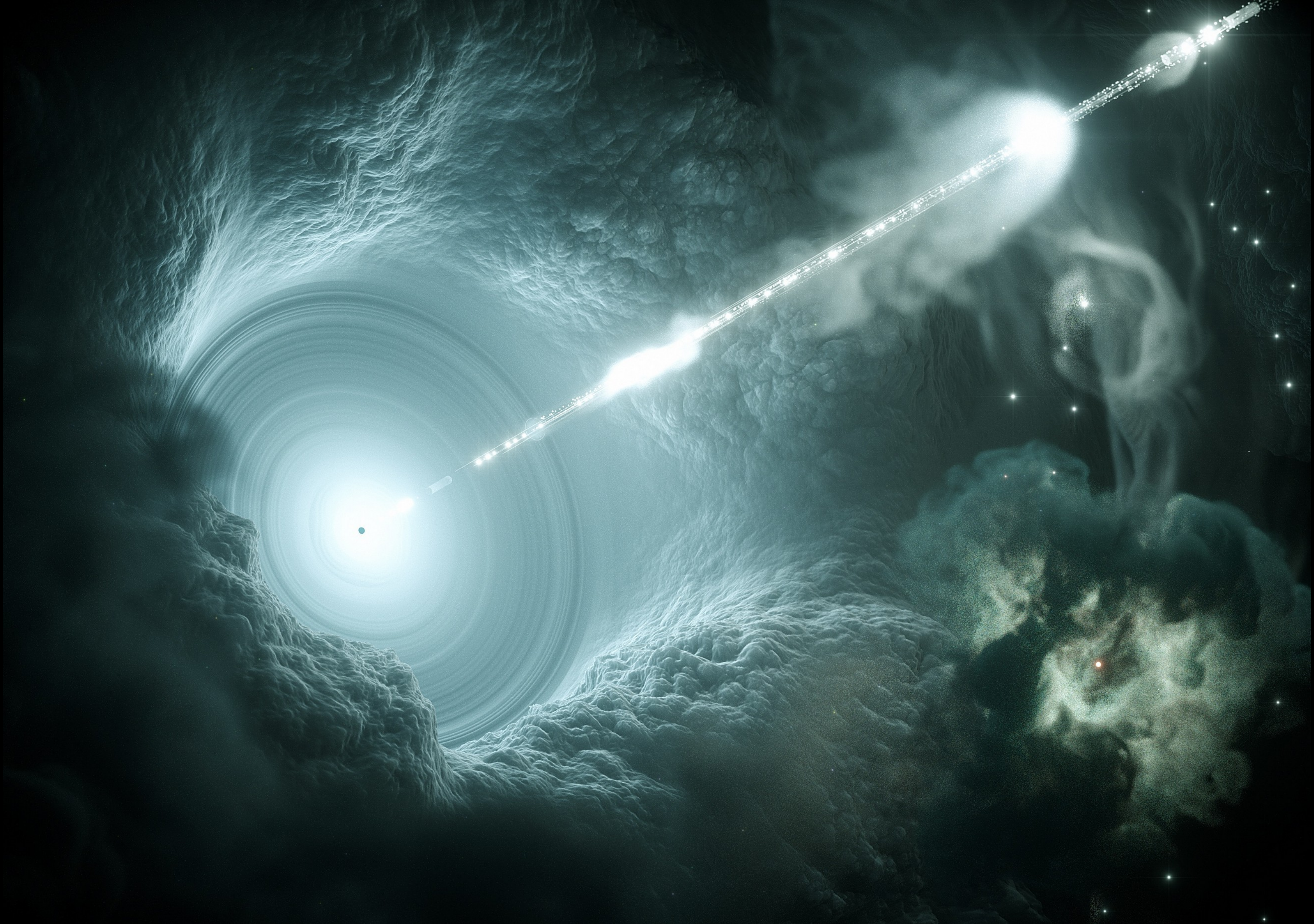
Fermi

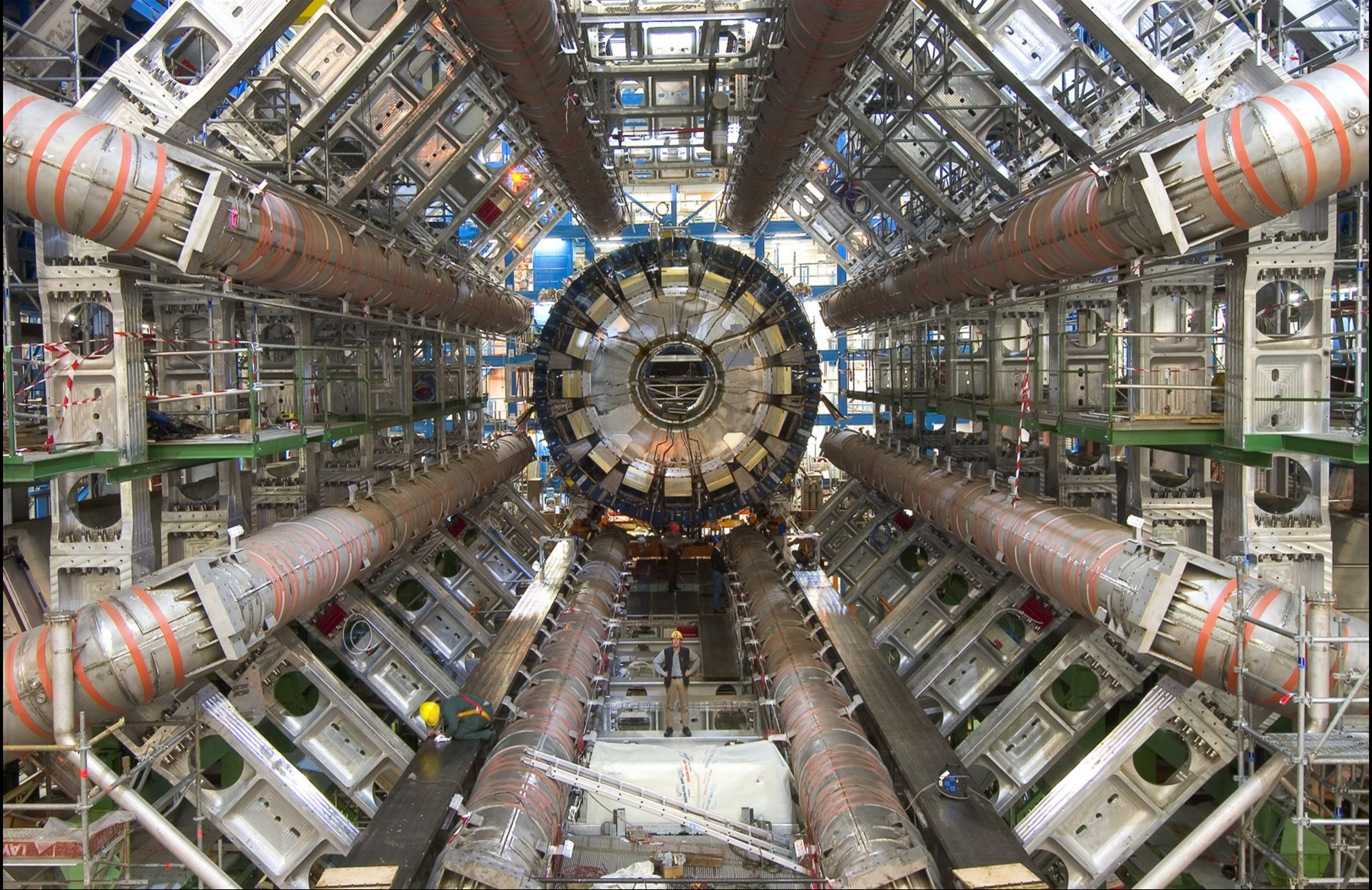
?????????????



Neutrinos




DESY



ATLAS

Neutrinos are elementary particles,

electrically neutral,

very light,

and superbly antisocial

Neutrinos are elementary particles,

= *indivisible*

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Neutrinos are elementary particles,

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= *so light that we don't know their mass!*

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Neutrinos are elementary particles,

= *indivisible*

electrically neutral,

= *no electric charge*

very light,

= *so light that we don't know their mass!*

and superbly antisocial

= *barely interact with matter*

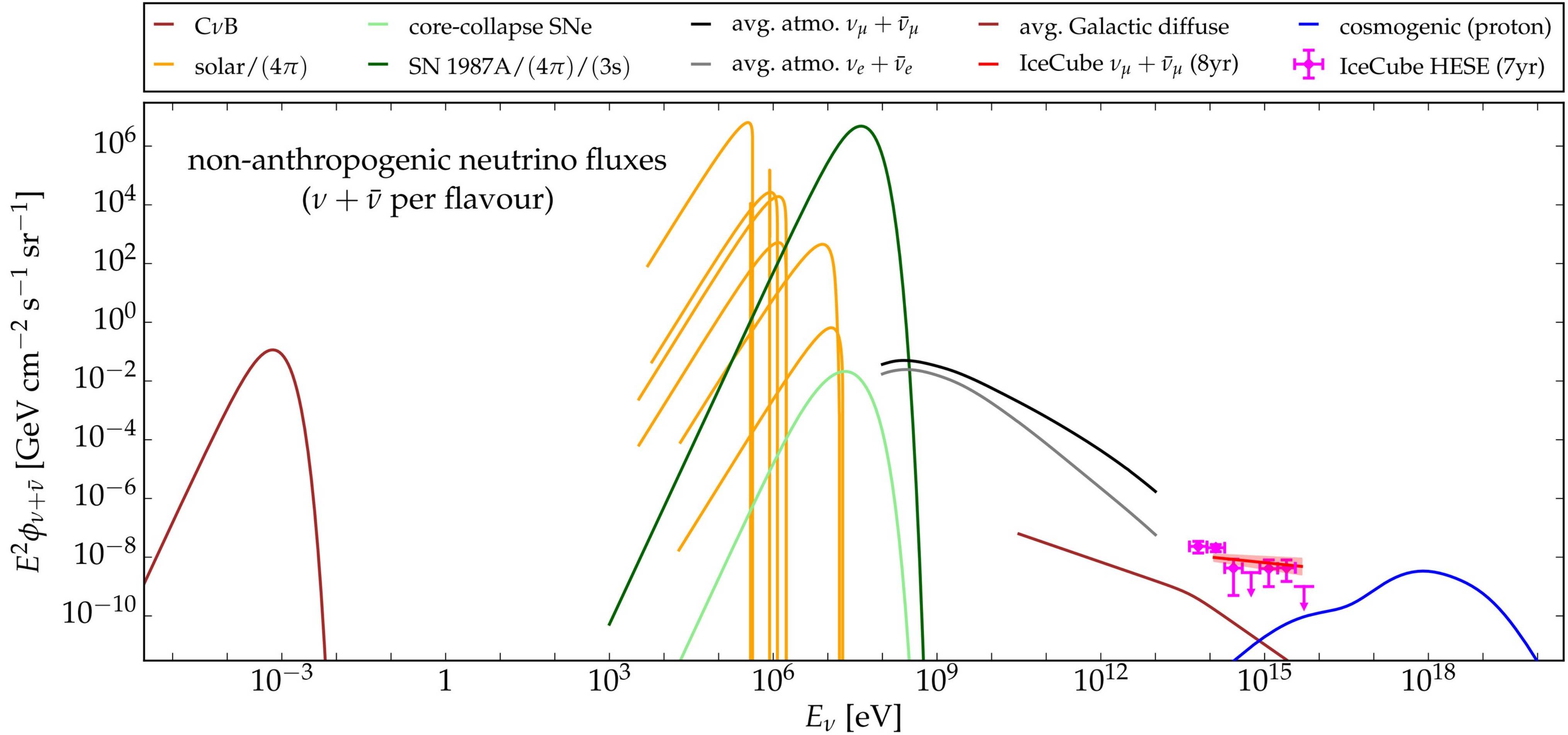
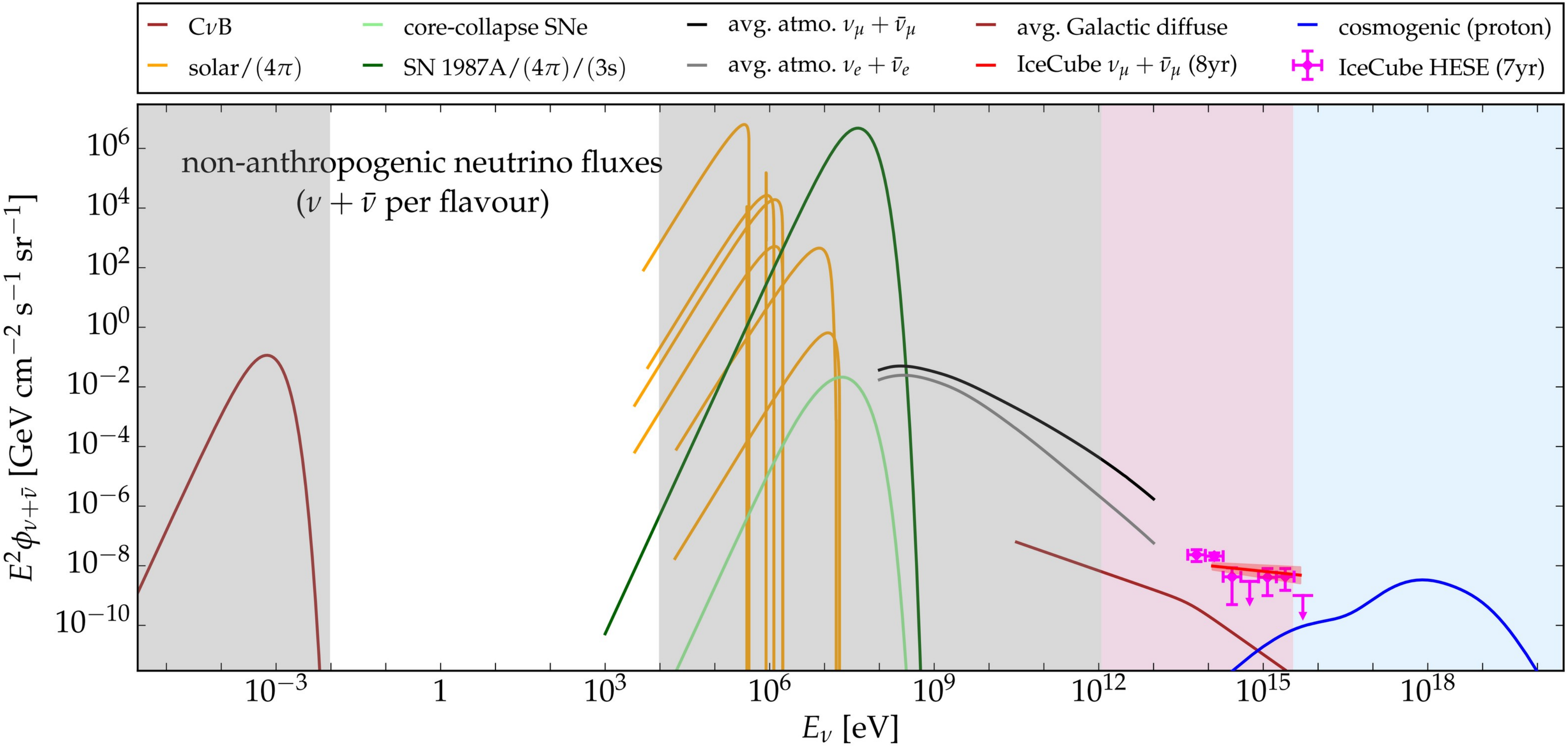


Figure courtesy of Markus Ahlers
Maoloud, De Wasseige, Ahlers, **MB**, Van Elewyck, PoS(ICRC2019), 1023



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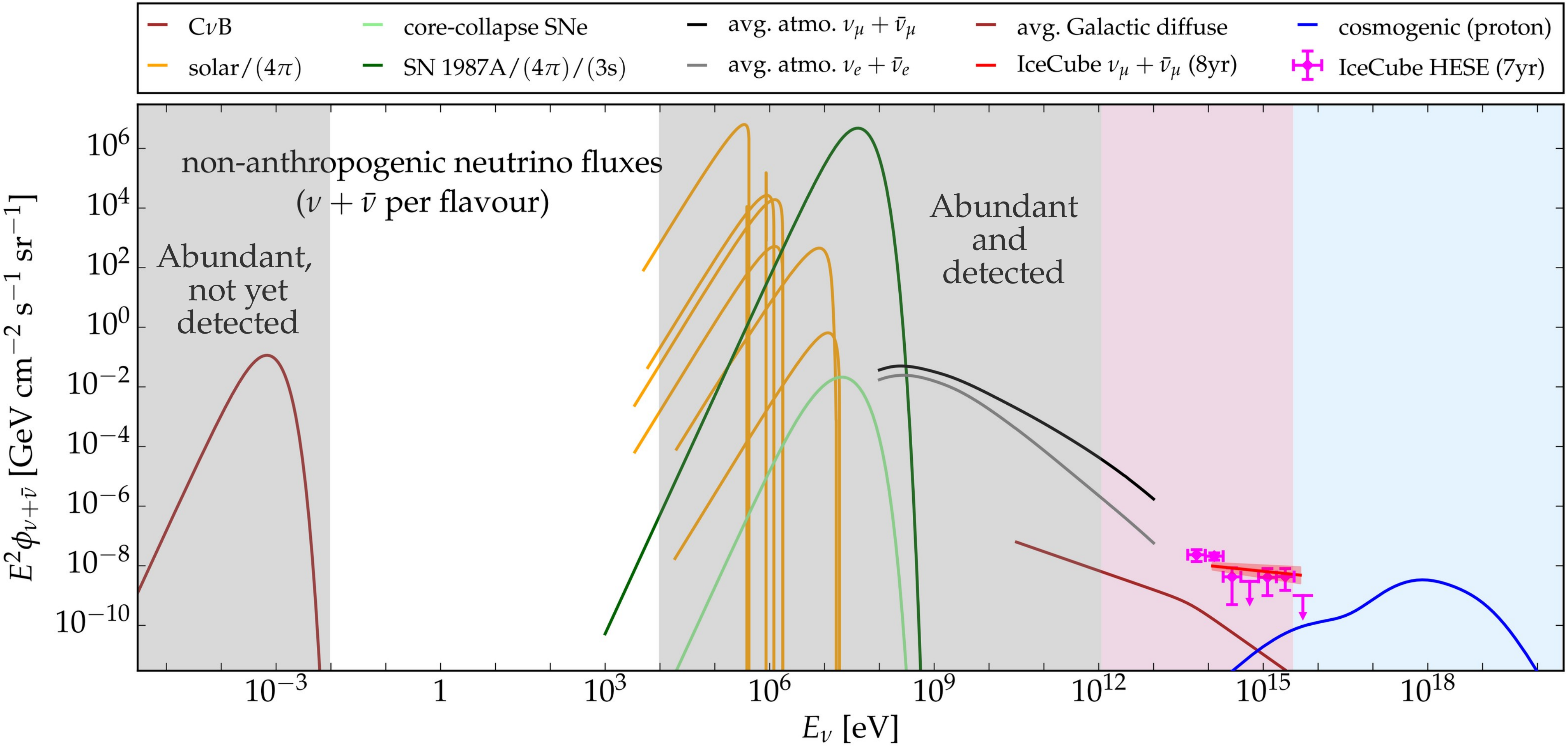
Maloud, De Wasseige, Ahlers, **MB**, Van Elewyck, PoS(ICRC2019), 1023



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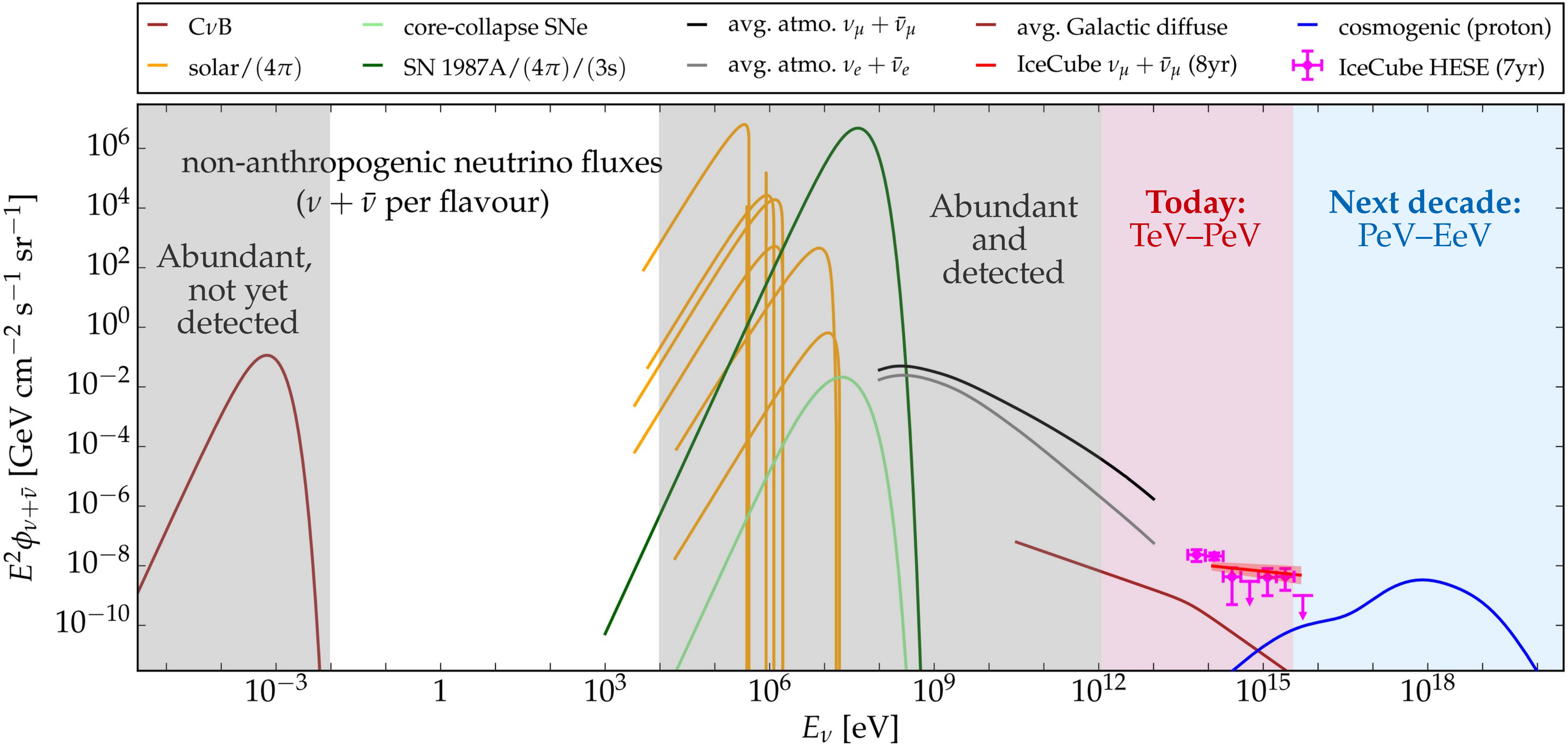

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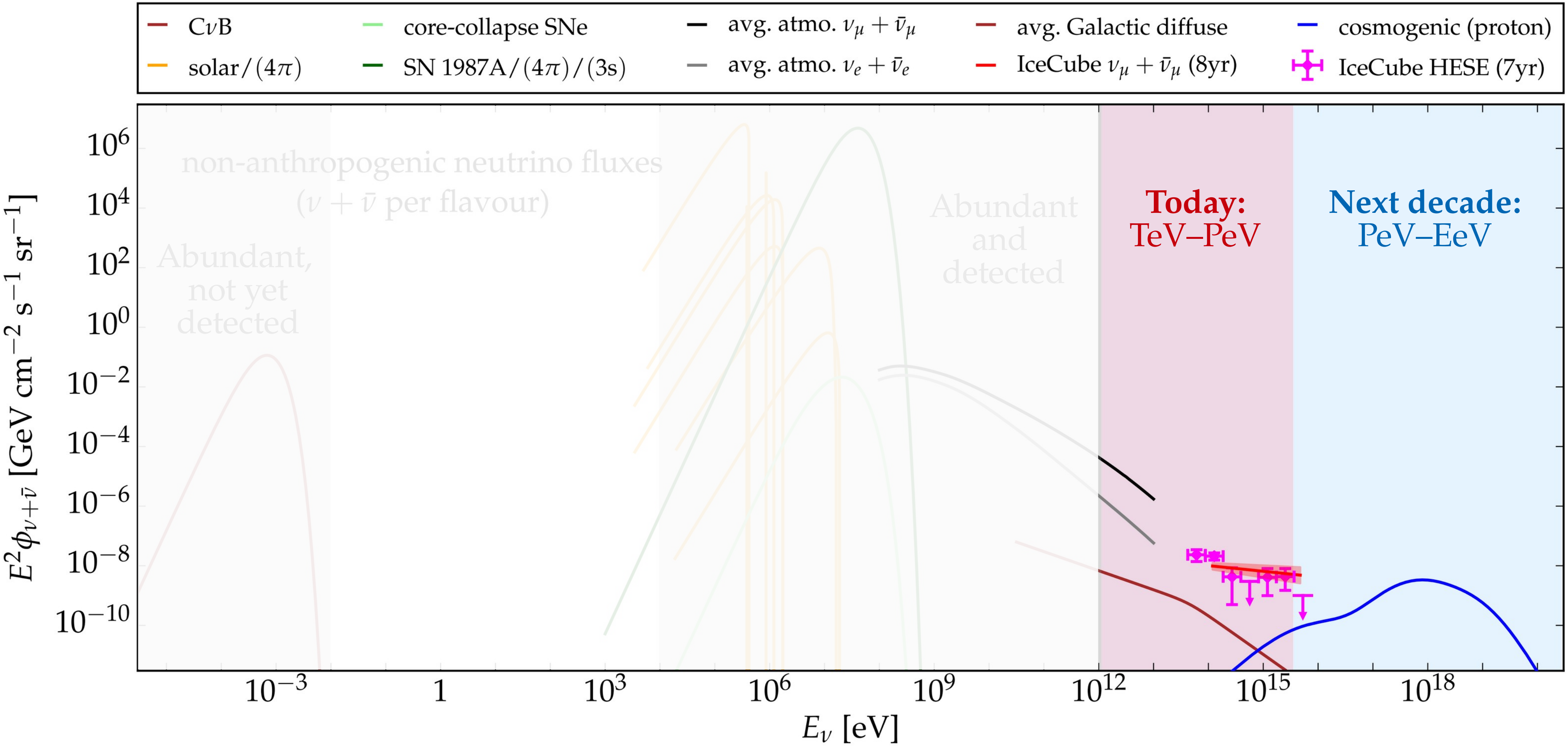

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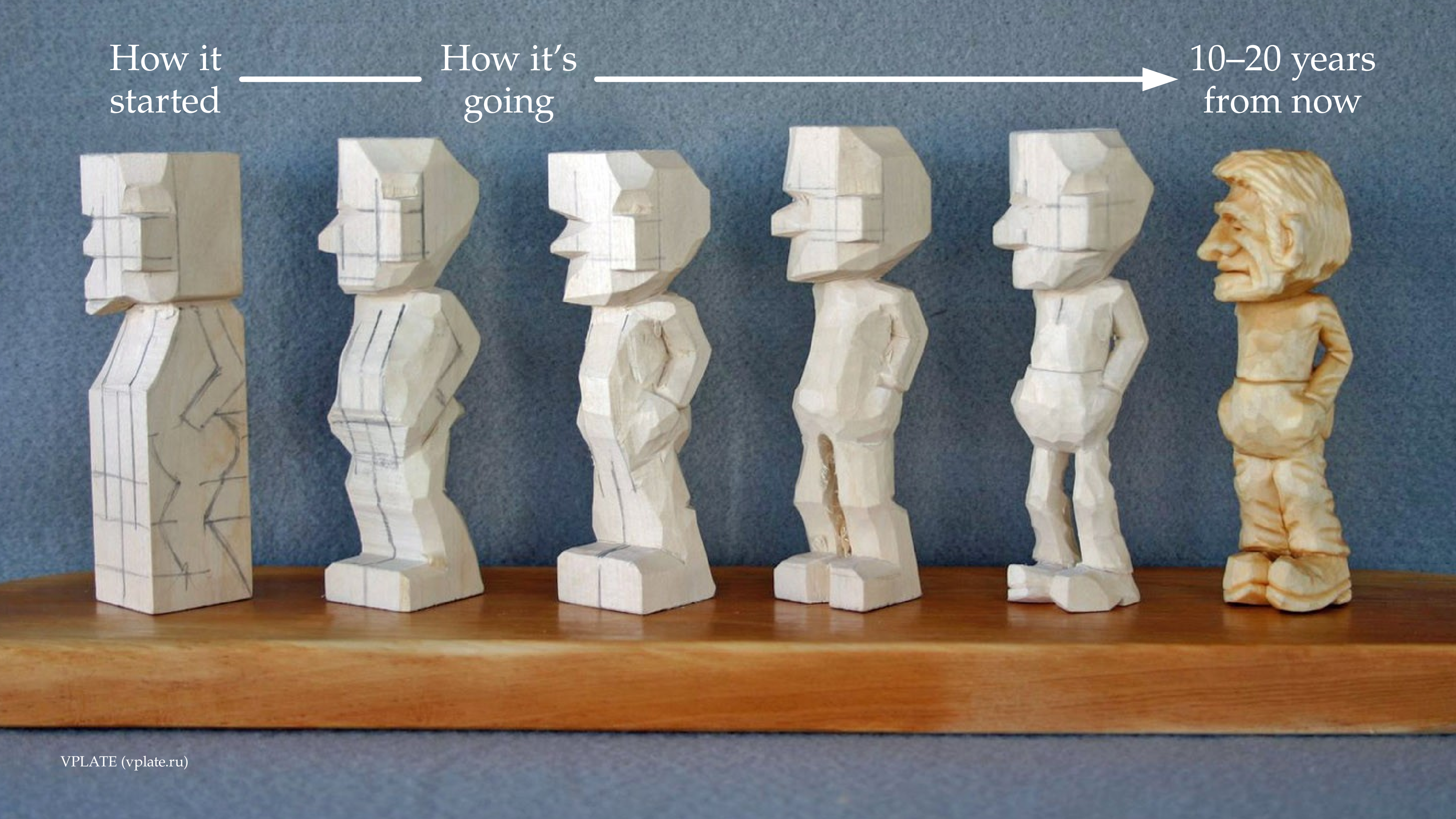
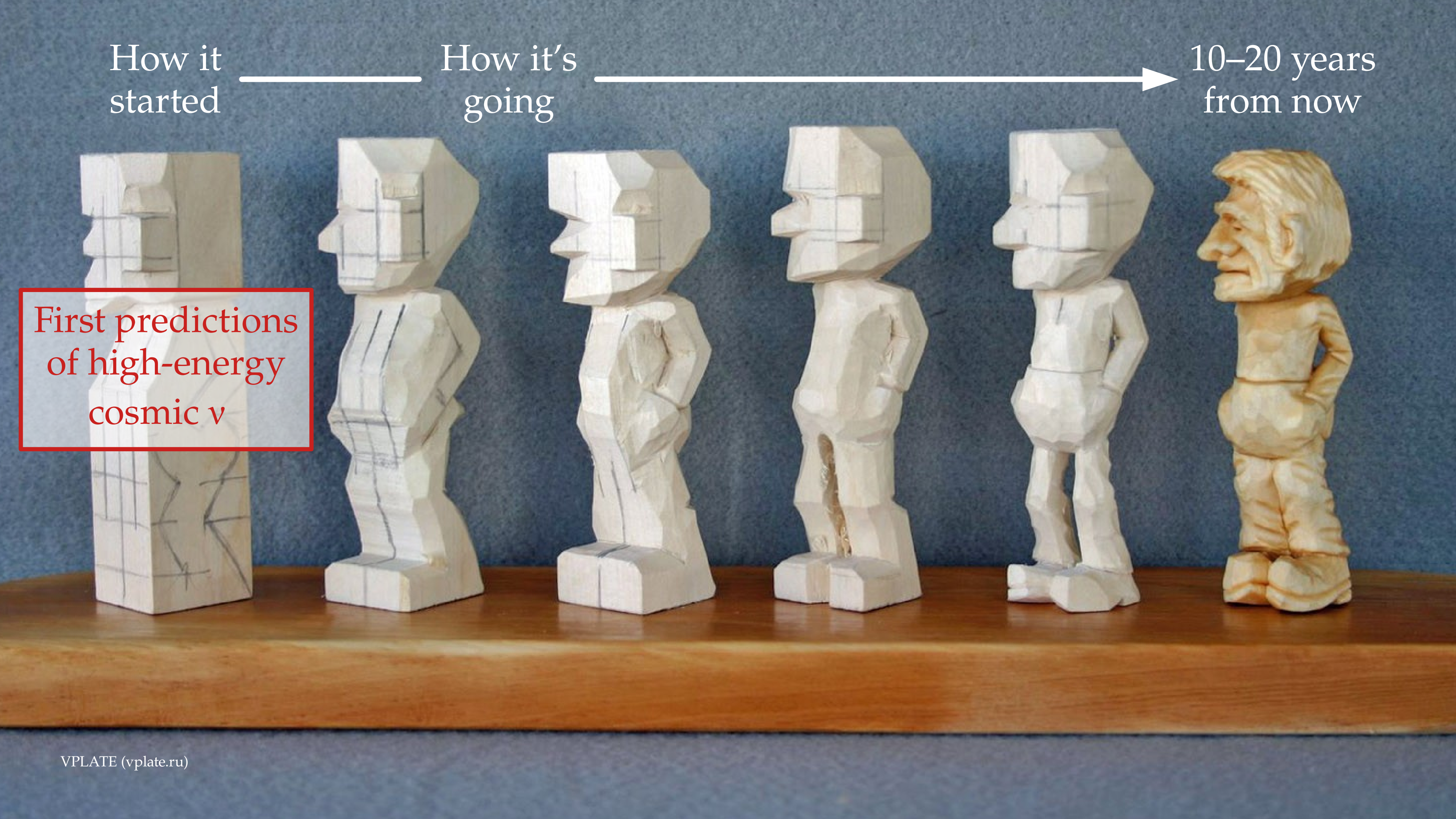
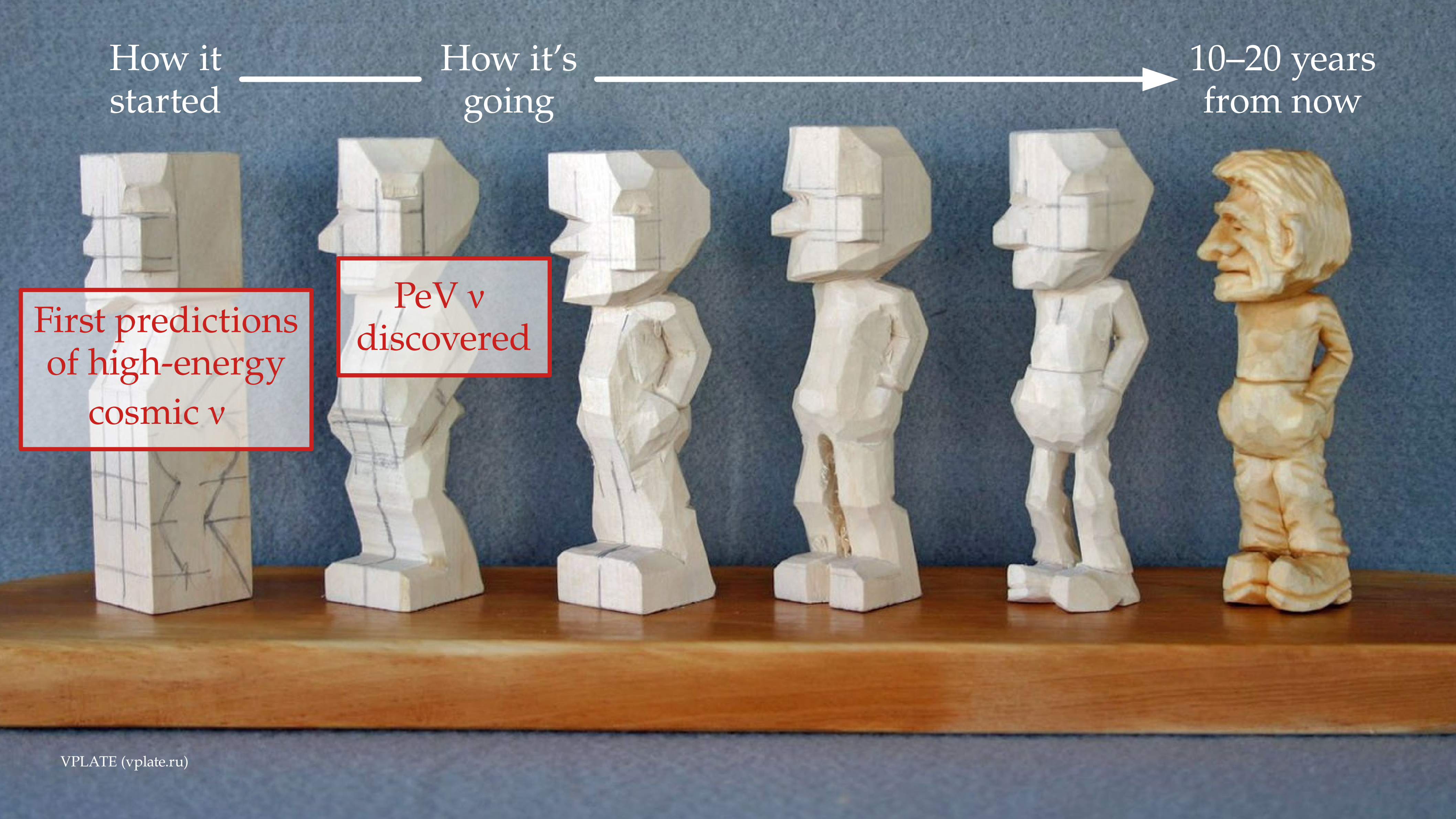


VPLATE (vplate.ru)



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



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PeV ν discovered
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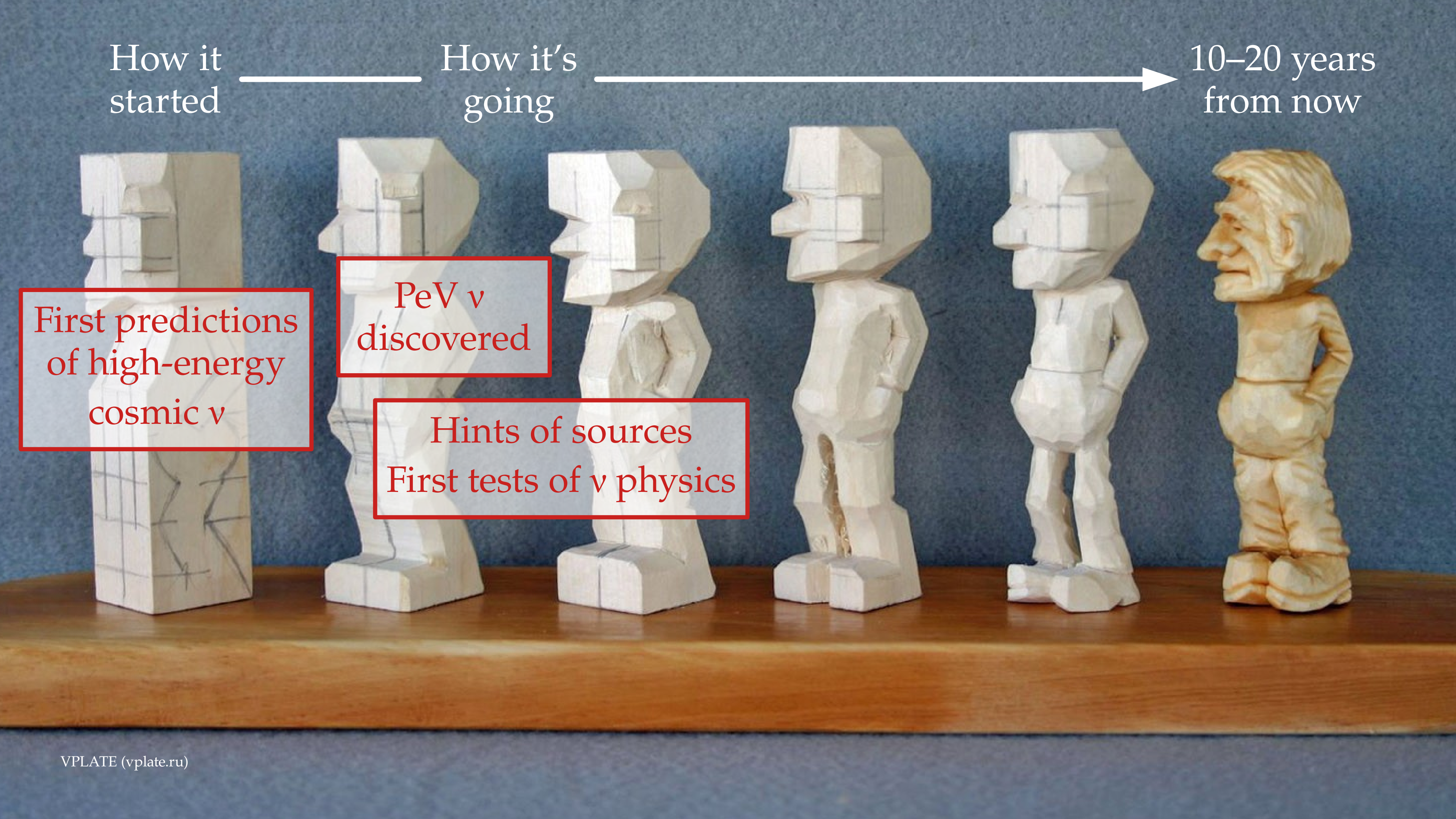
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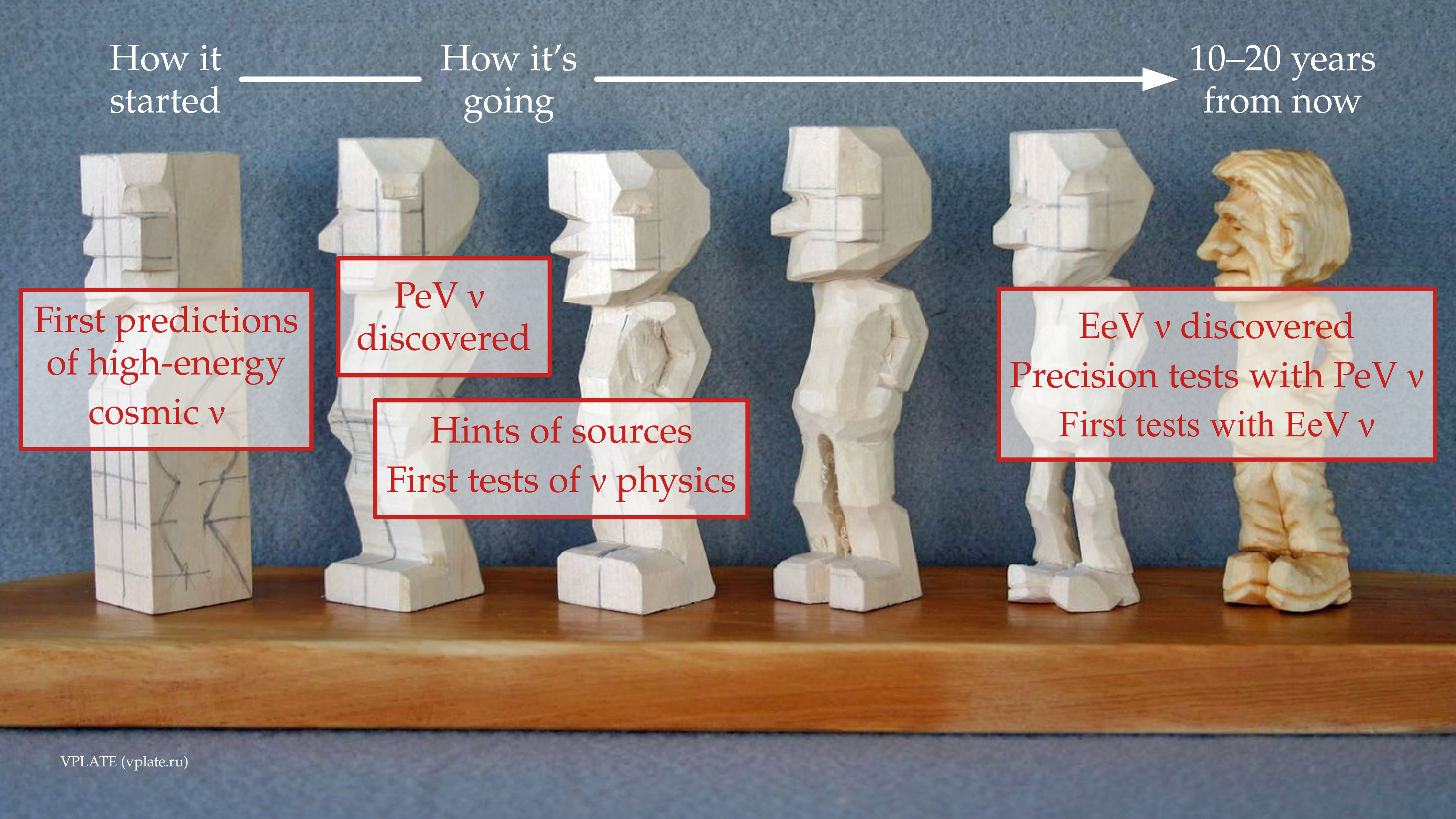
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Precision tests with PeV ν
First tests with EeV ν
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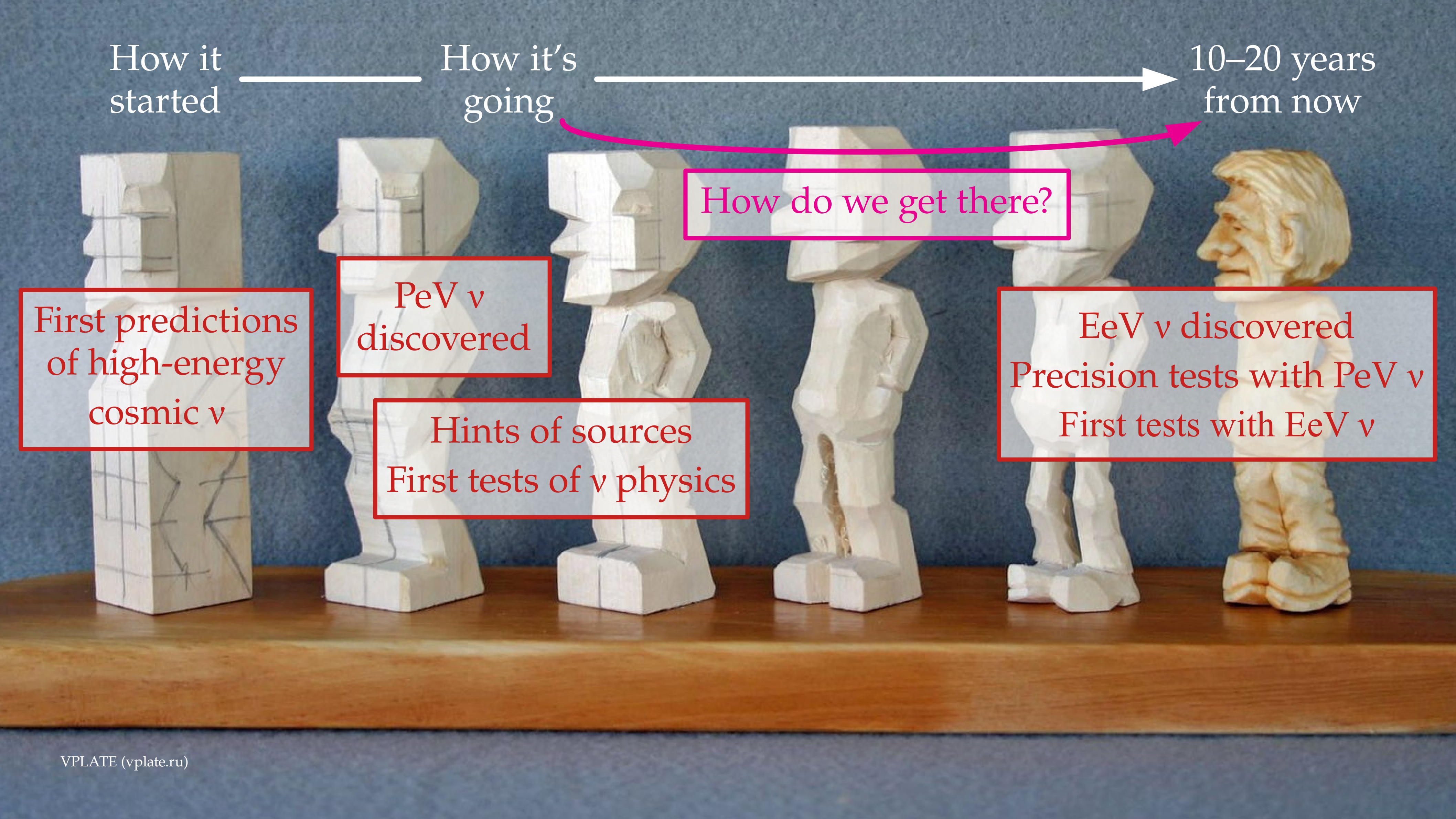
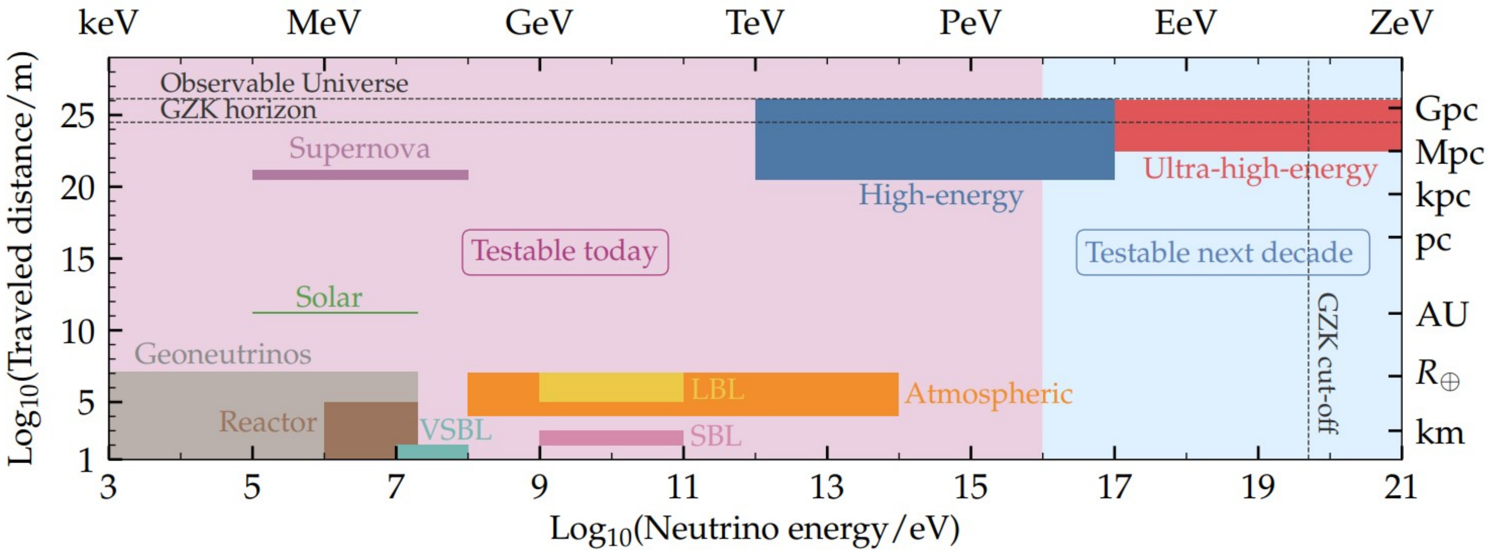

How it started
How it's going
10–20 years from now
How do we get there?
First predictions of high-energy cosmic ν
PeV ν discovered
Hints of sources
First tests of ν physics
EeV ν discovered
Precision tests with PeV ν
First tests with EeV ν
VPLATE (vplate.ru)

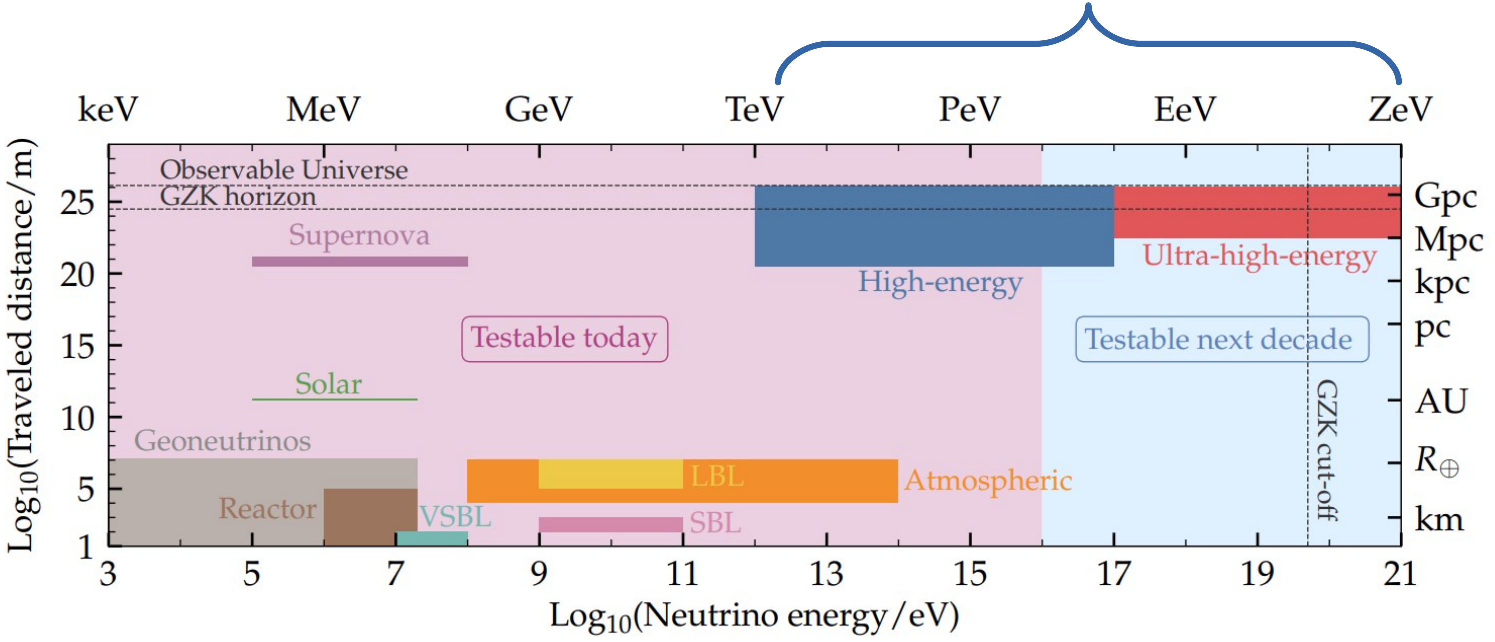
What makes high-energy cosmic ν exciting?



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

What makes high-energy cosmic ν exciting?

They have the highest energies



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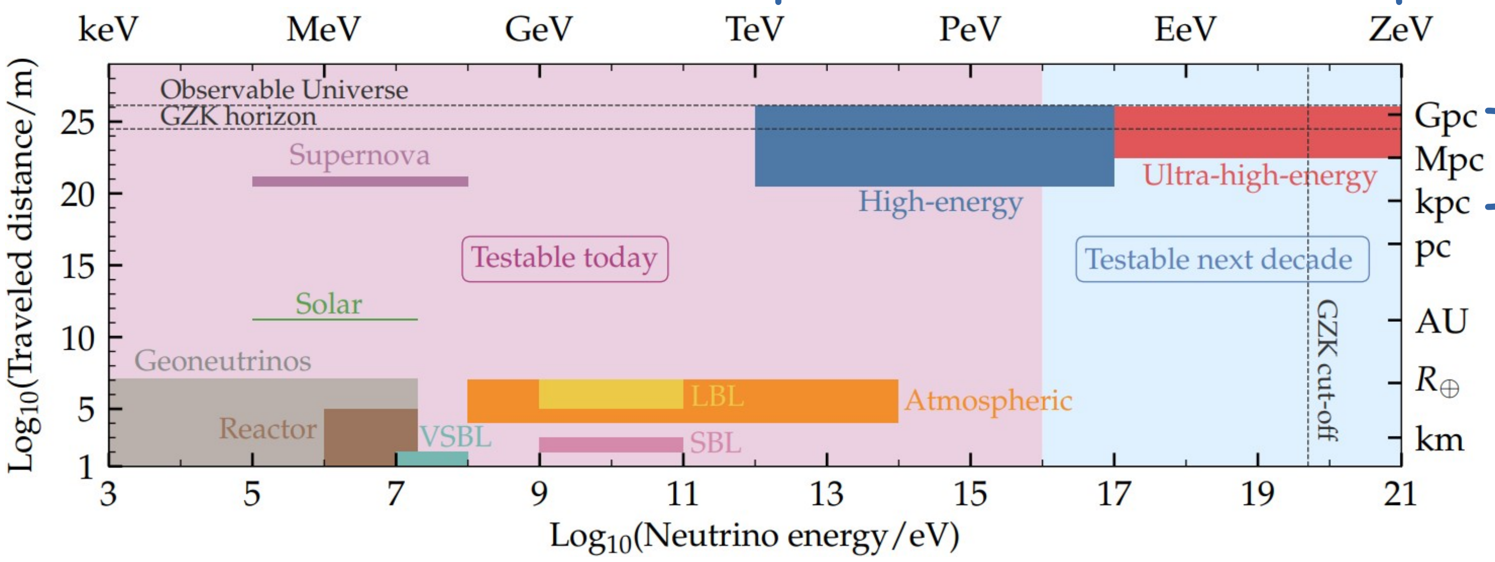
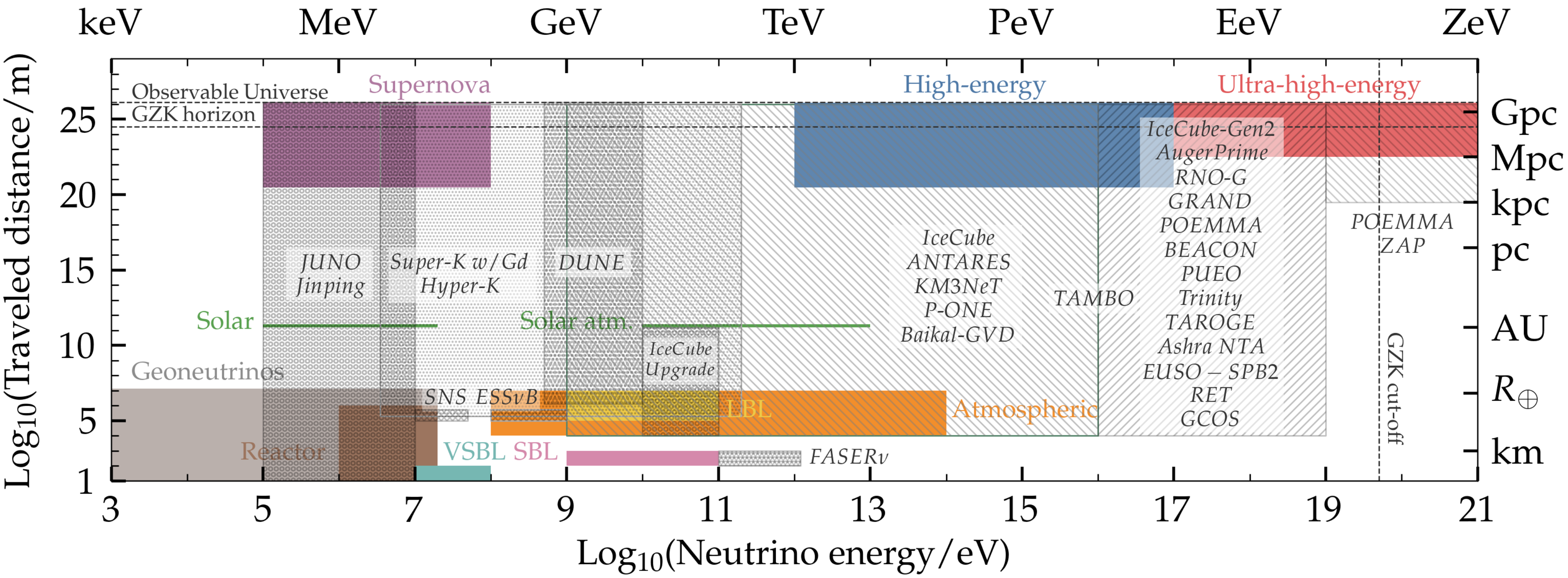
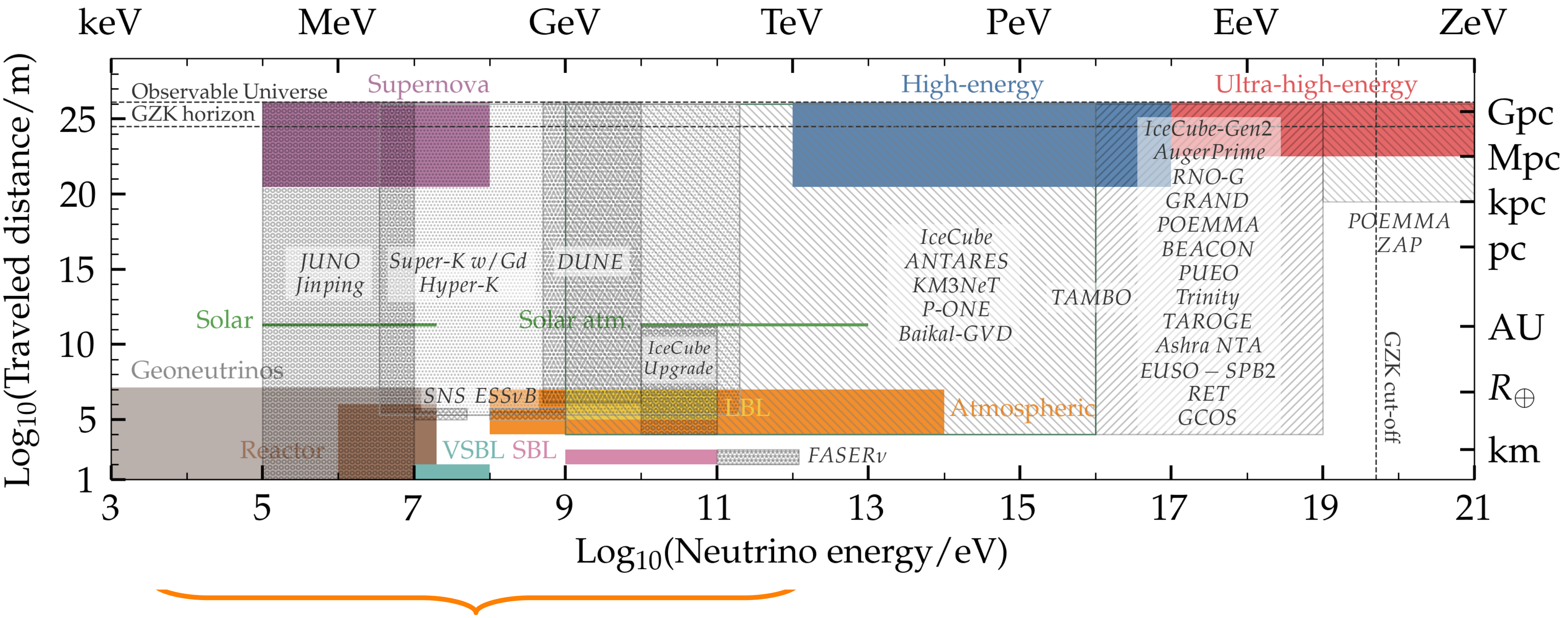


They travel the longest distances

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



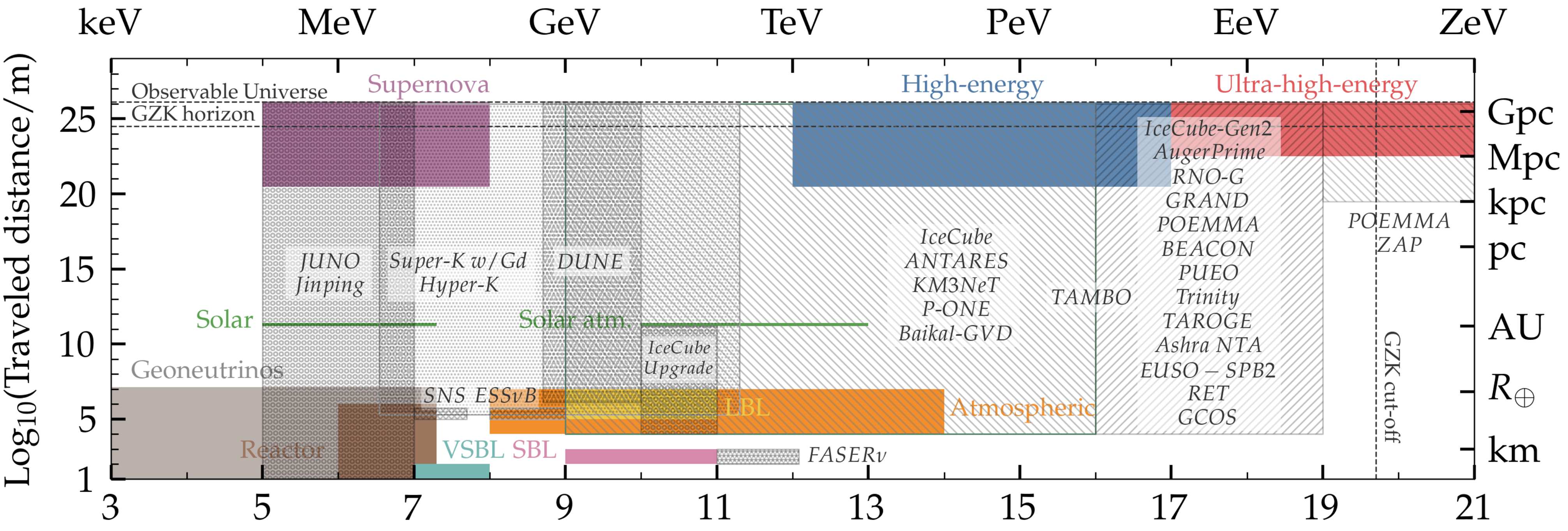
Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



Synergies with lower energies

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

Discovered in 2013
by IceCube



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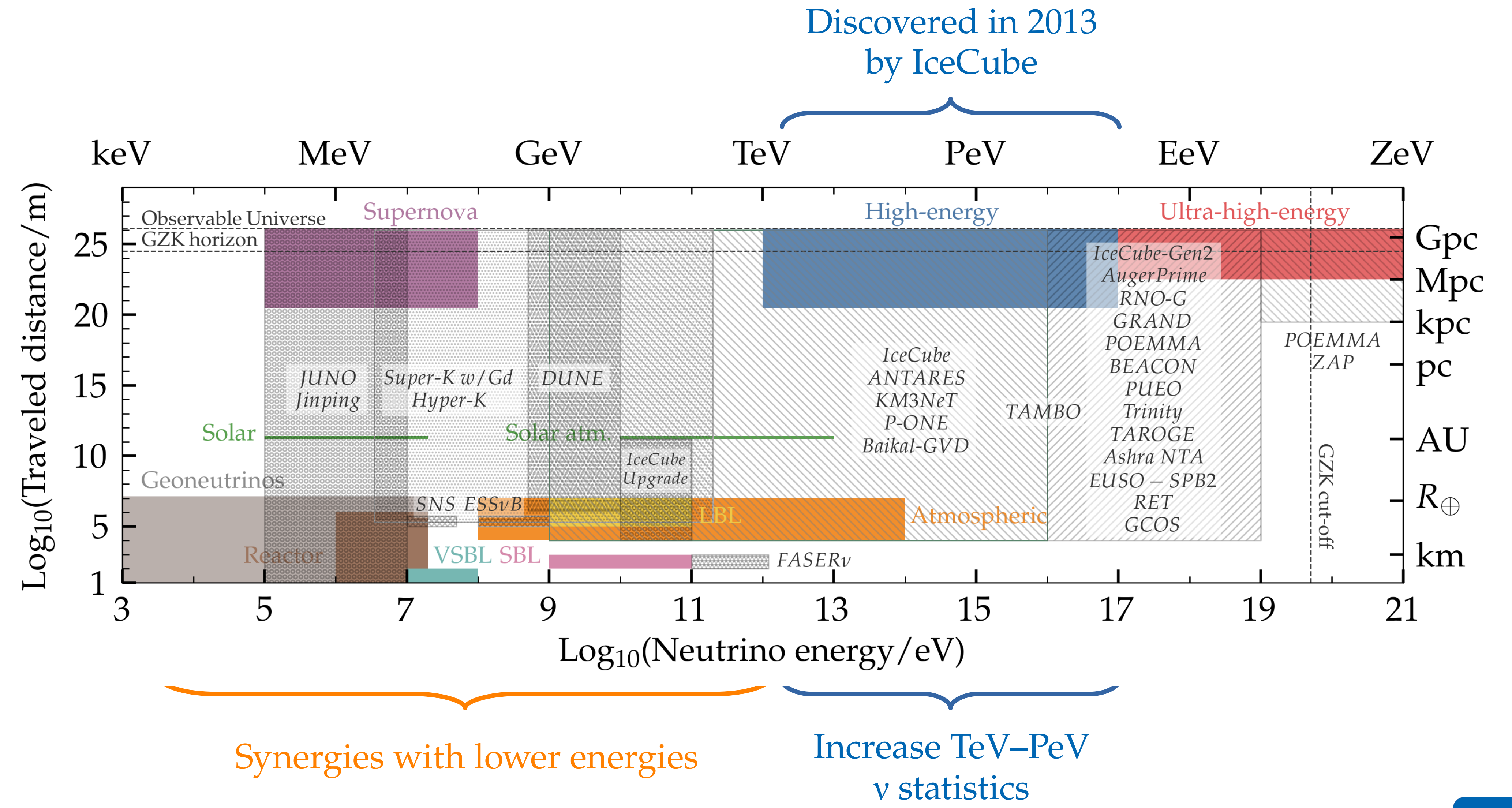
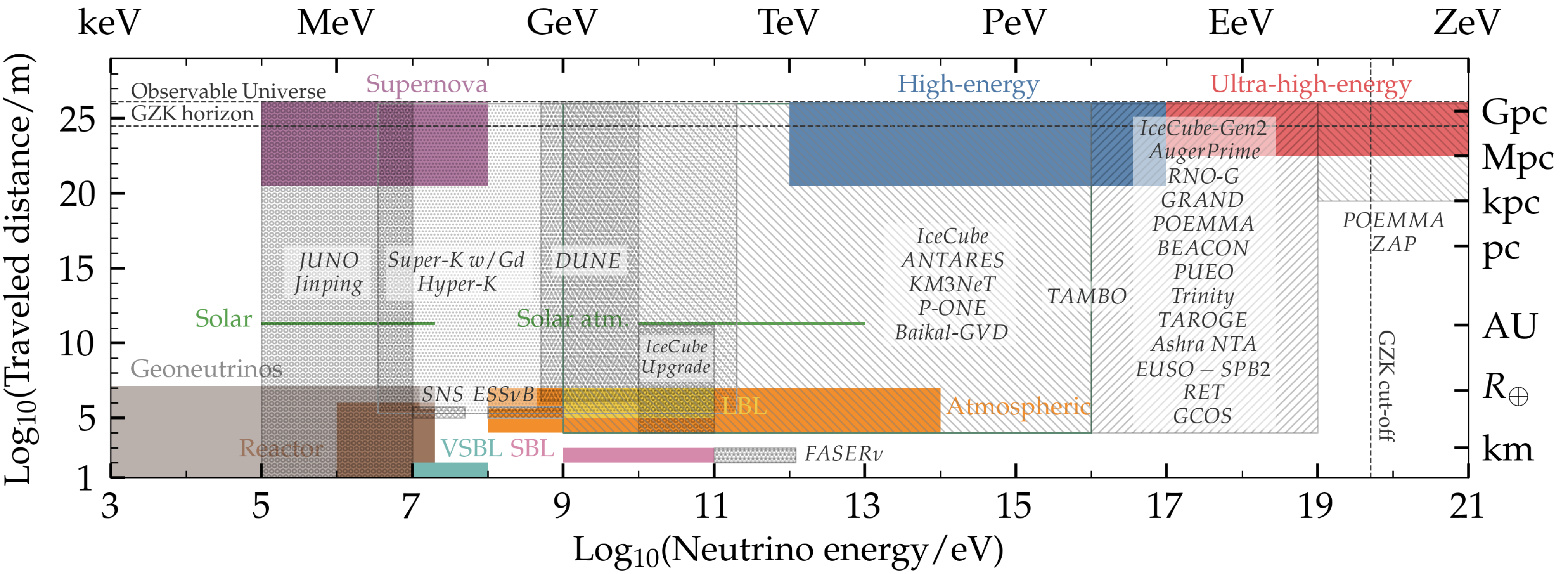


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

Discovered in 2013 by IceCube

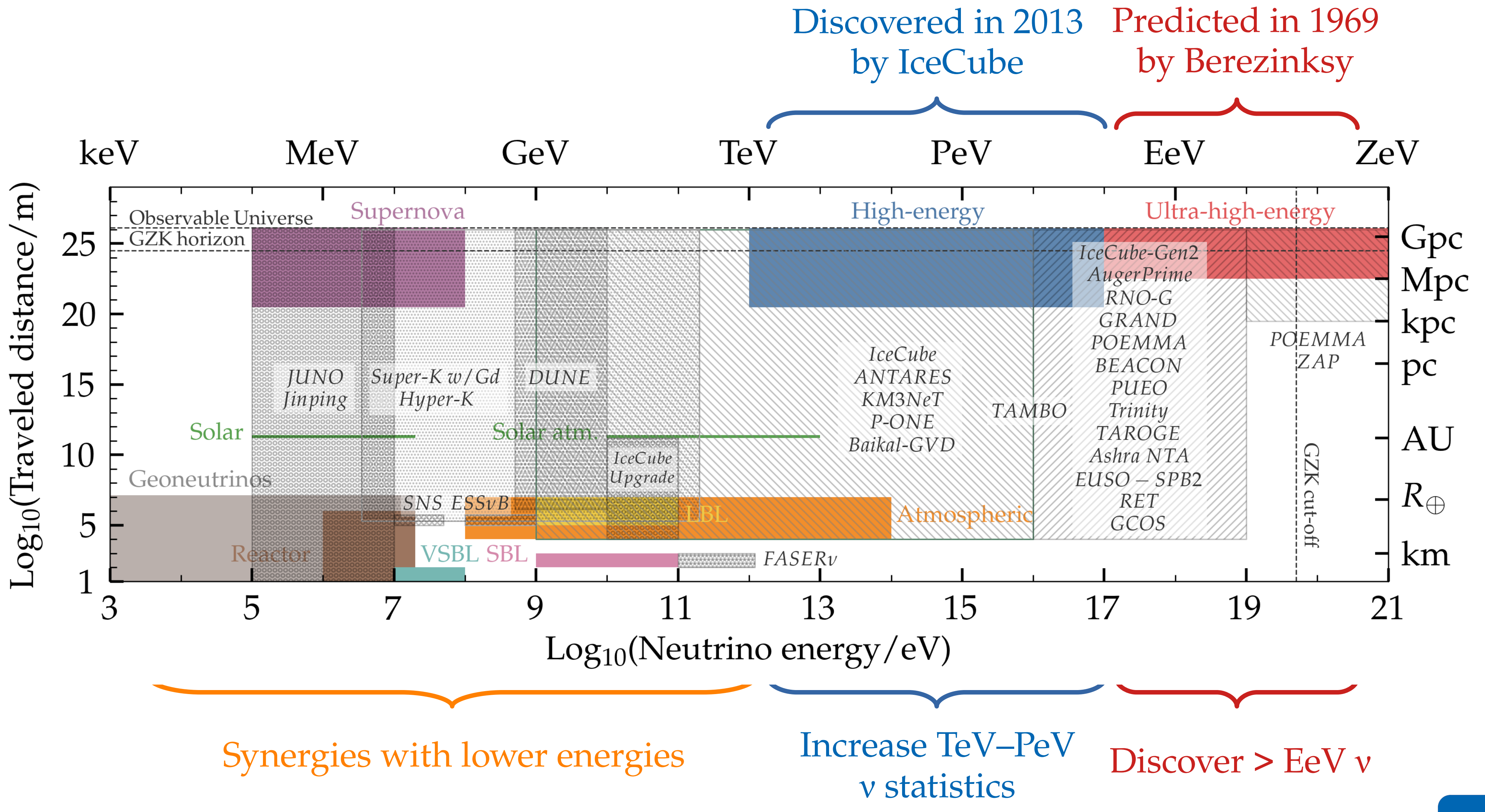
Predicted in 1969 by Berezinksy



Synergies with lower energies

Increase TeV–PeV ν statistics

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



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

High-energy neutrinos: TeV–PeV

(*Discovered*)

Ultra-high-energy neutrinos: $>$ 100 PeV

(*Predicted but undiscovered*)

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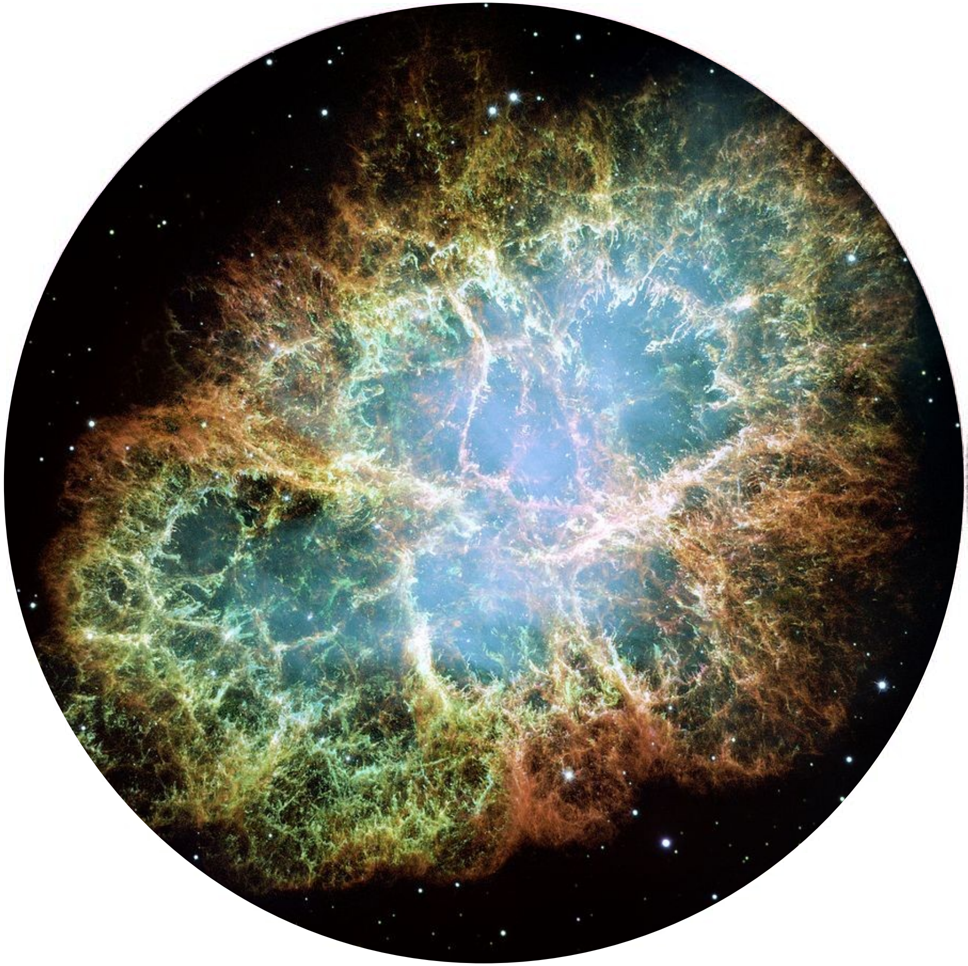

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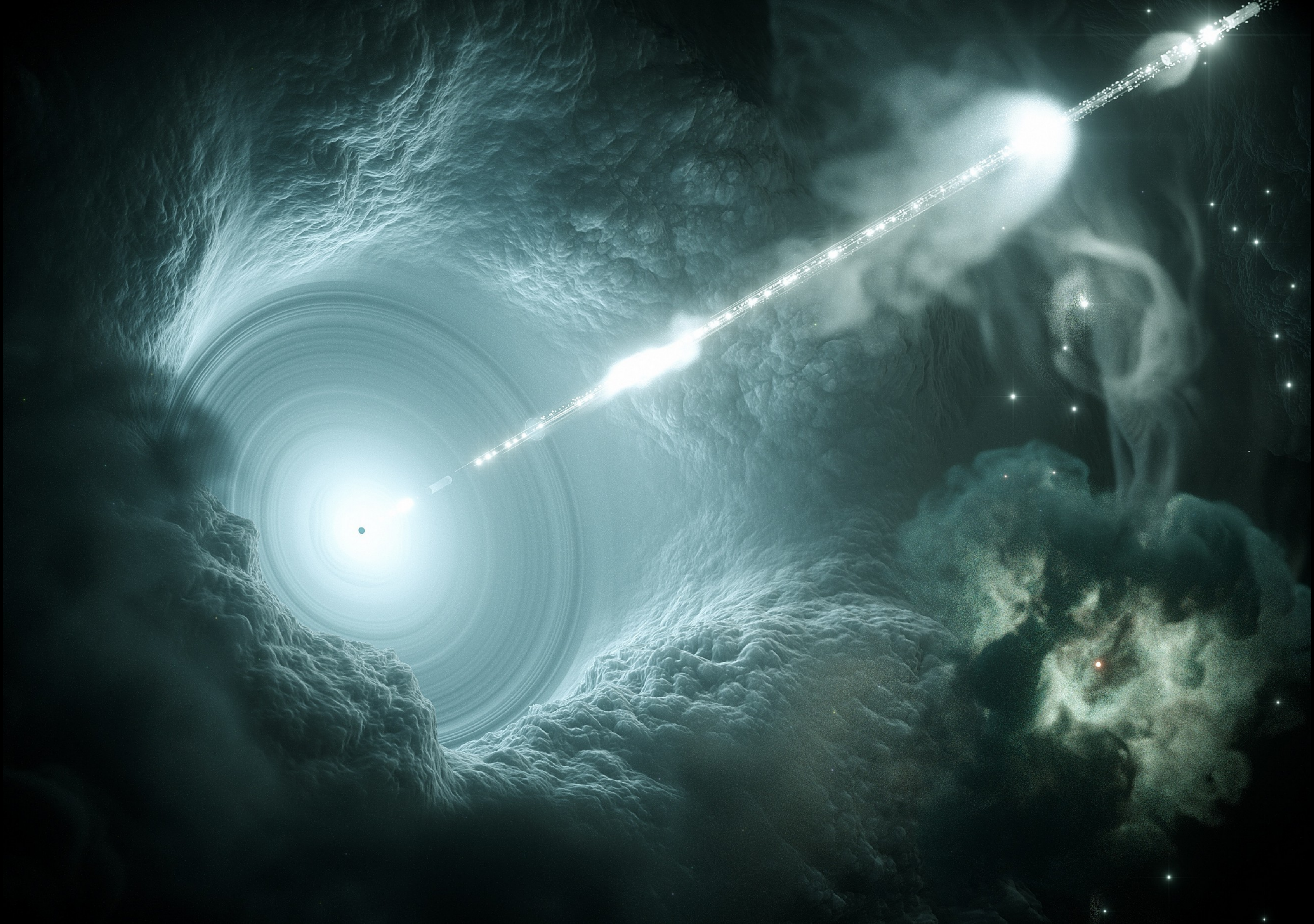
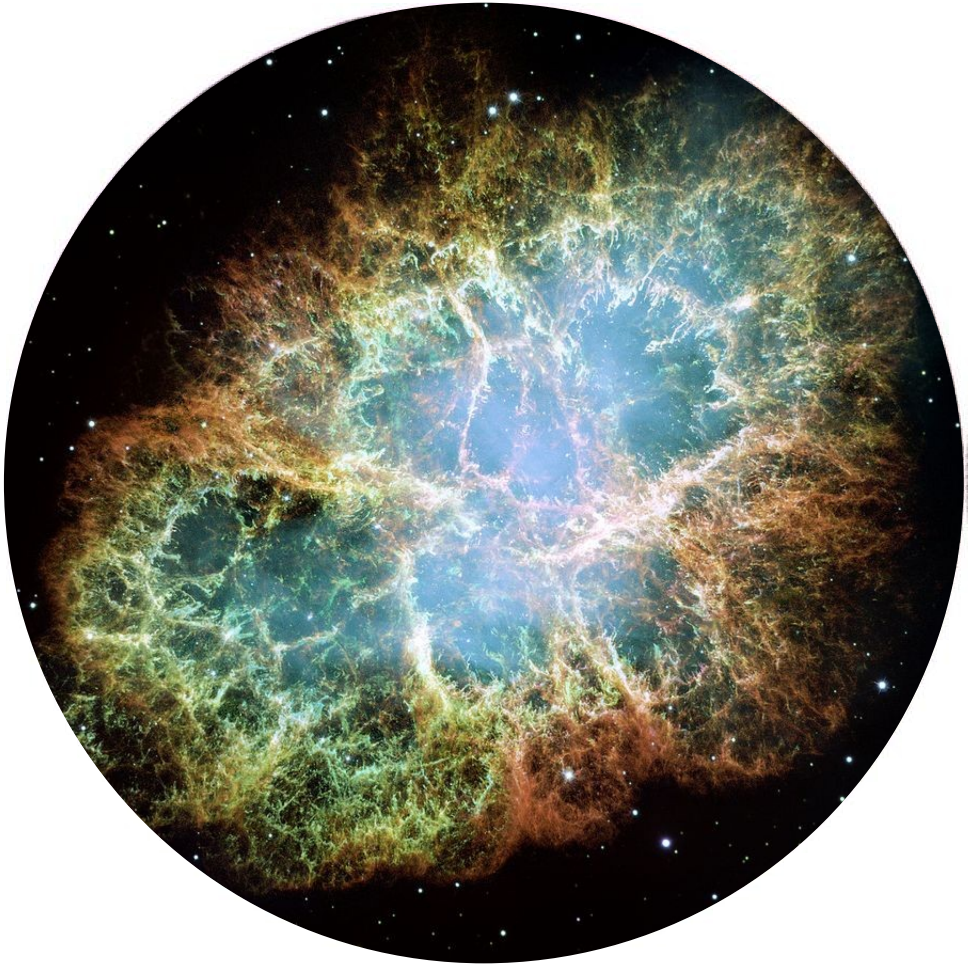


DESY


ν
DESY



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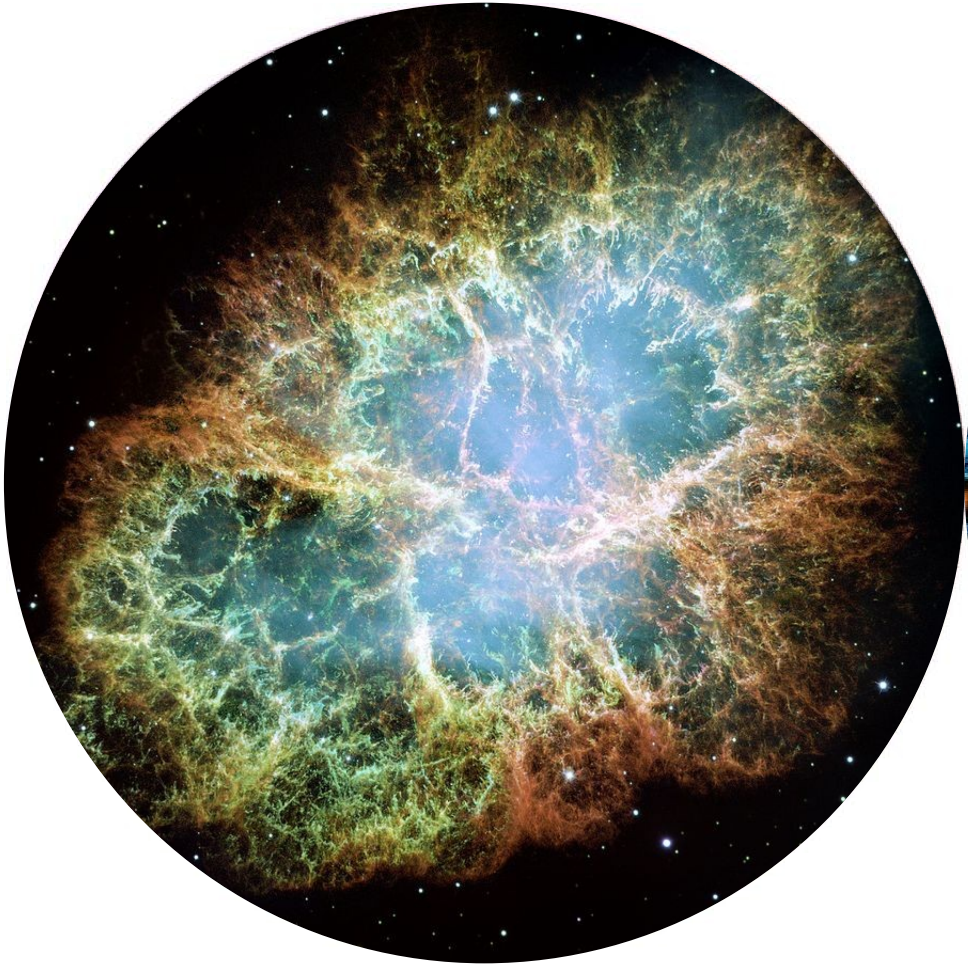
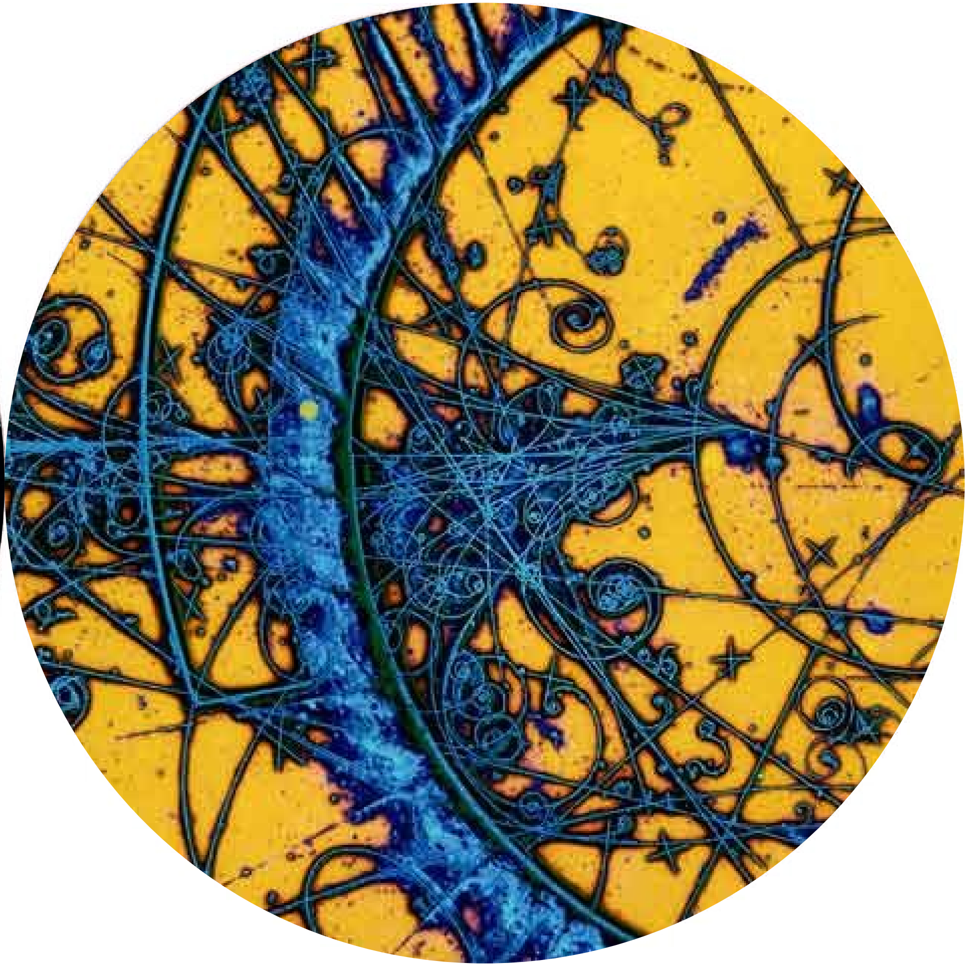
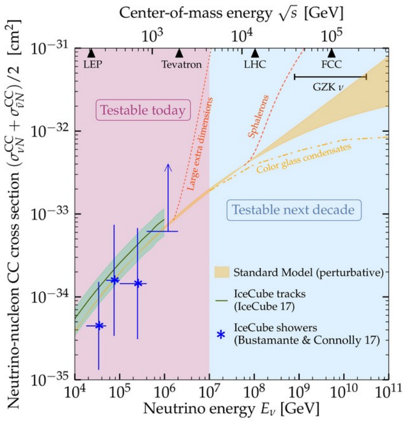




Banco Central de Reserva del Perú / NASA / ESA / CERN / Symmetry Magazine

TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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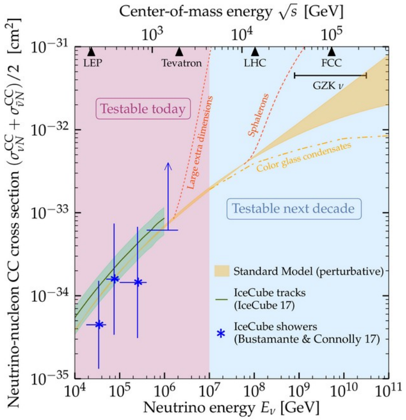
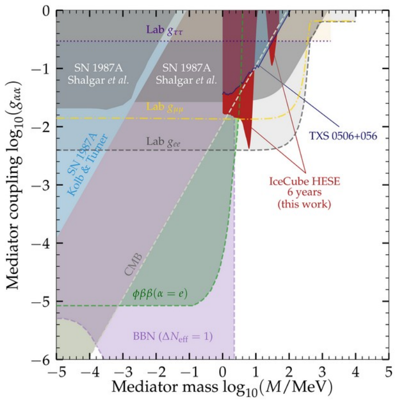


MB & Connolly, *PRL* 2019

ν self-interactions



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

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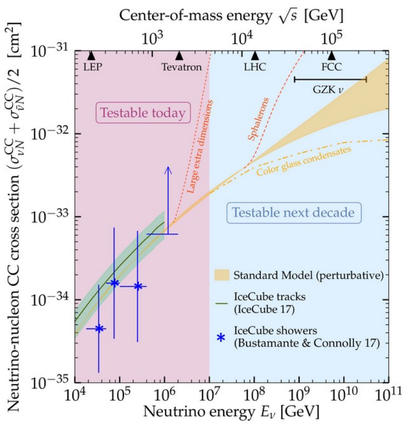

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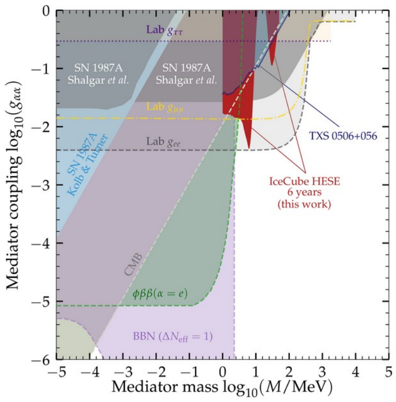
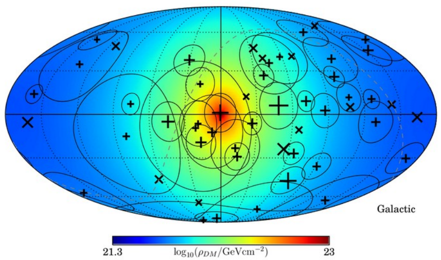


MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



Argüelles, Kheirandish, Vincent, *PRL* 2017

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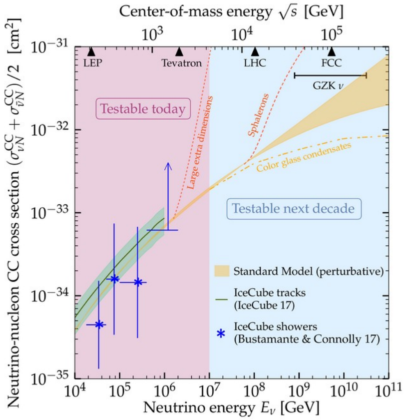

MB & Connolly, *PRL* 2019

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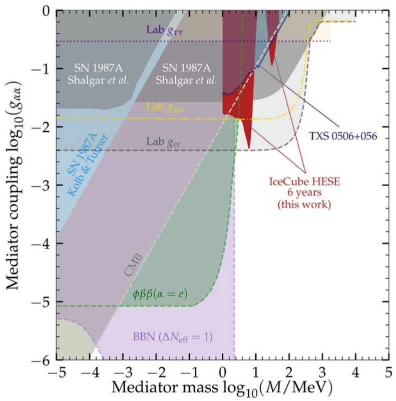

MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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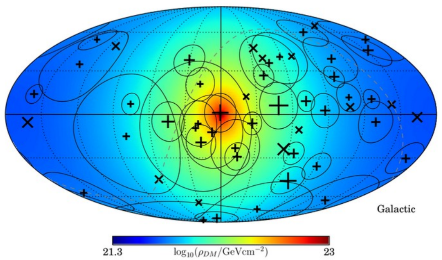
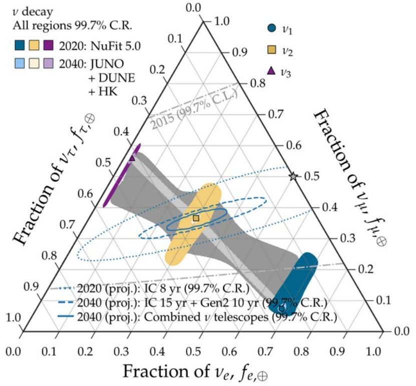


Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



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

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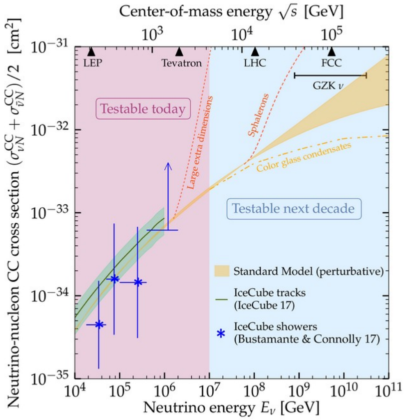

MB & Connolly, *PRL* 2019

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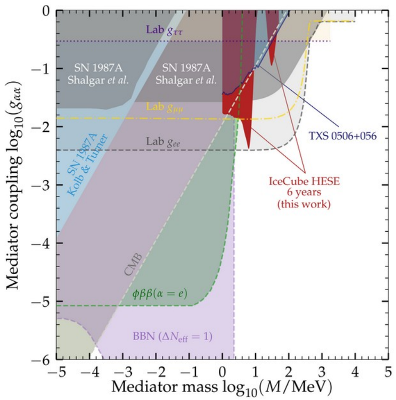

MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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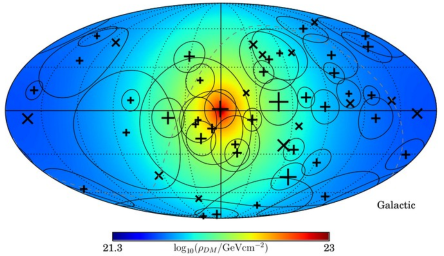

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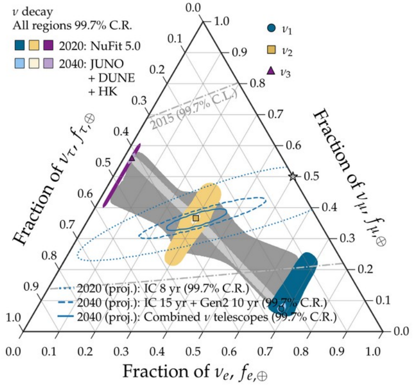
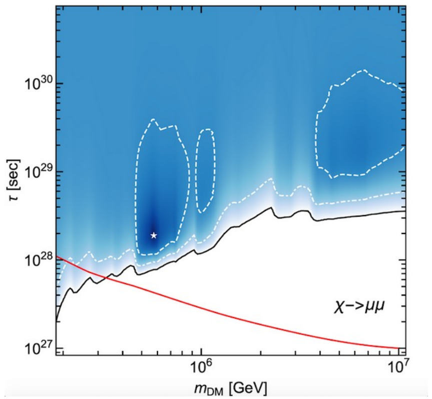


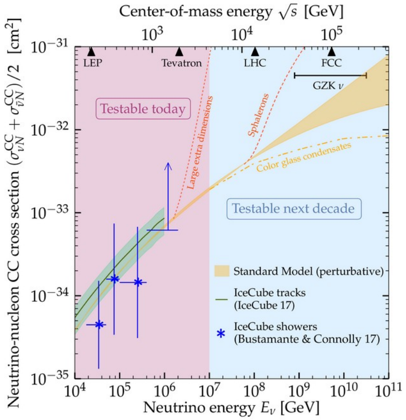
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



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

TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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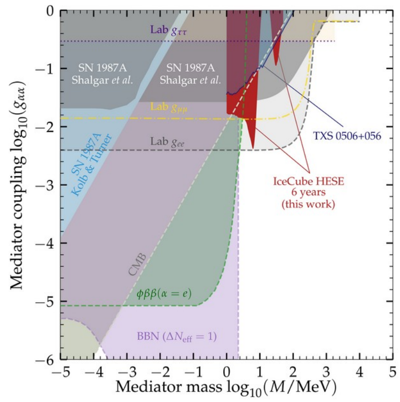
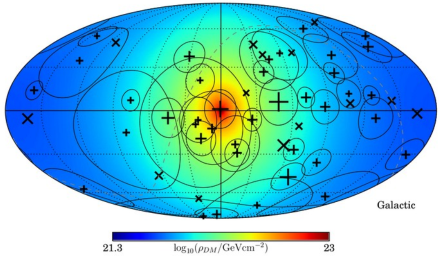


MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



Argüelles, Kheirandish, Vincent, *PRL* 2017

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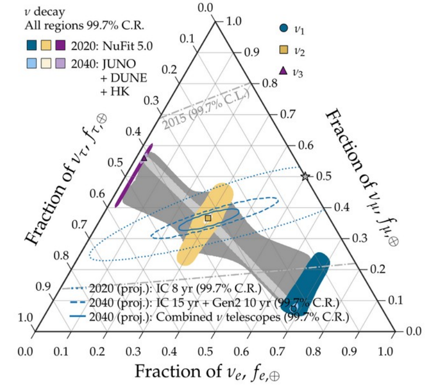

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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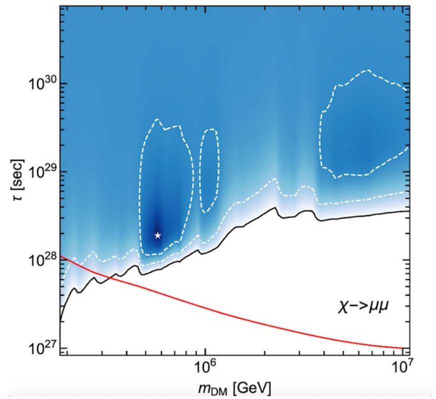
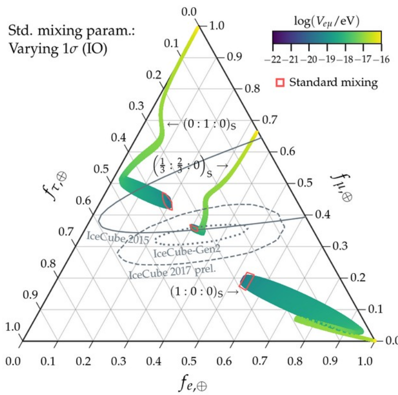


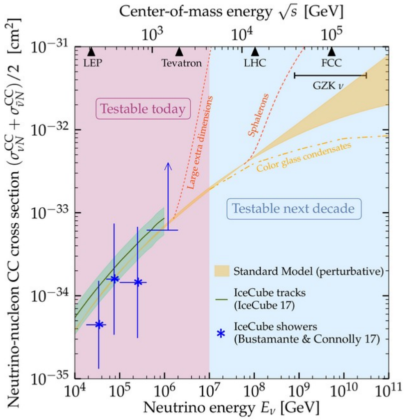
Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



MB & Agarwalla, *PRL* 2019

TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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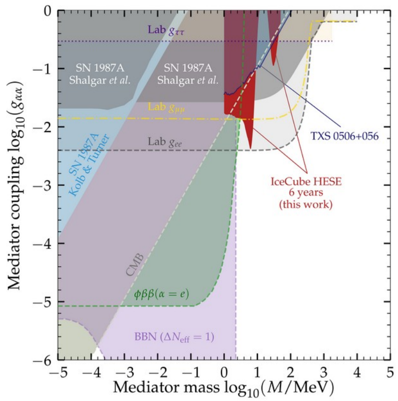

MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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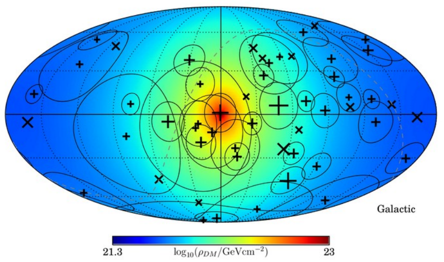
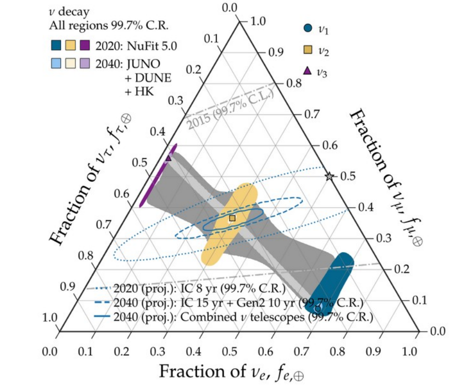


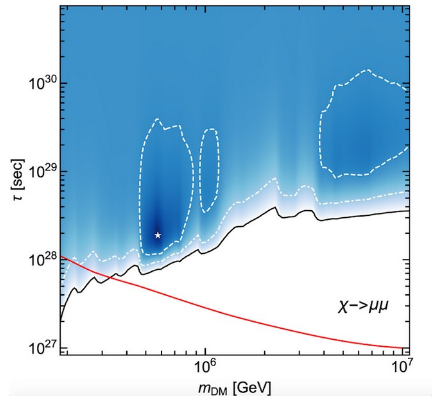
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



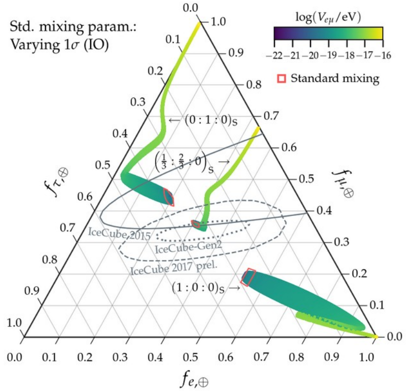
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



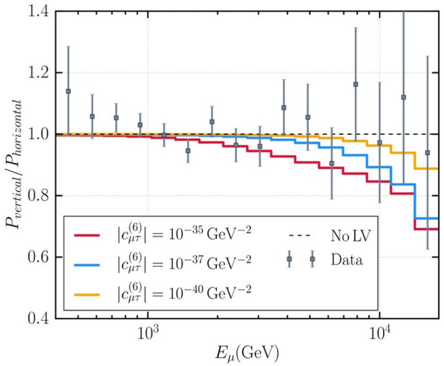
Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



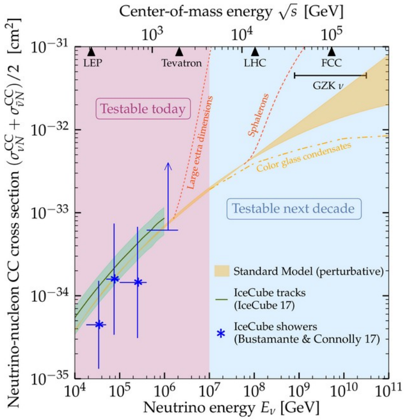
MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



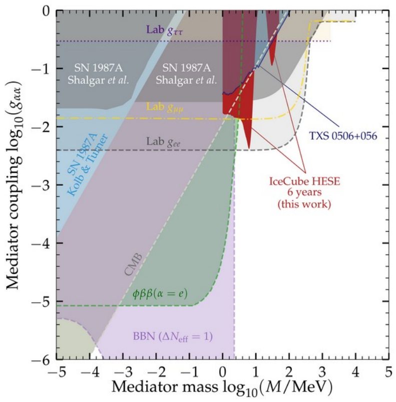
IceCube, *Nature Phys.* 2018

TeV–EeV ν cross sections



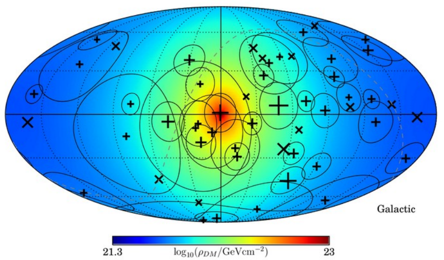
MB & Connolly, *PRL* 2019

ν self-interactions



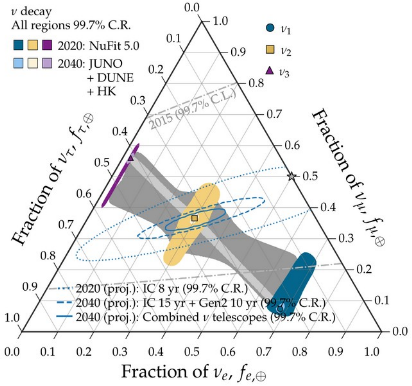
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



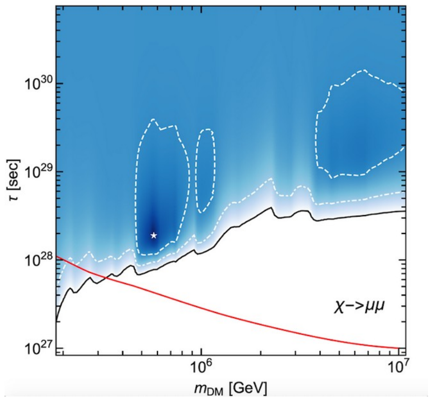
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



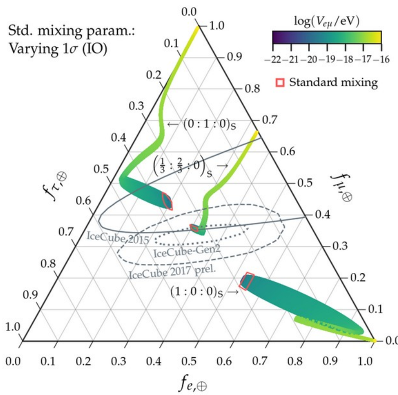
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



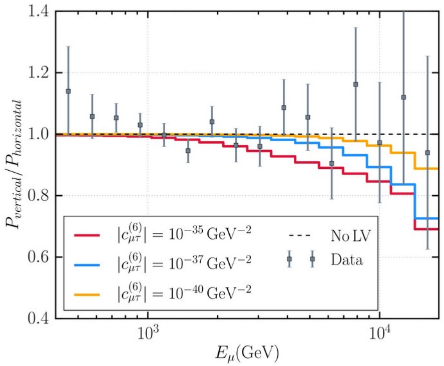
Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



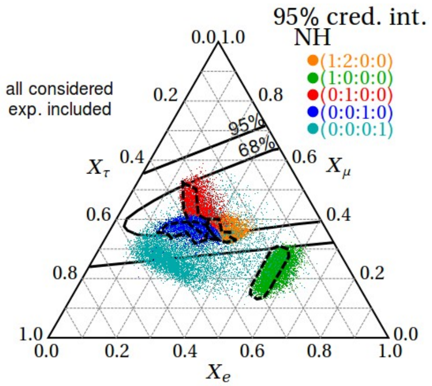
MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



IceCube, *Nature Phys.* 2018

Sterile neutrinos



Brdar, Kopp, Wang, *JCAP* 2017

I.
The story so far

Making high-energy astrophysical neutrinos

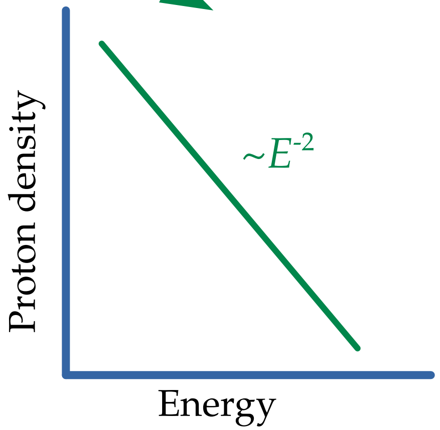
(or $p + p$)

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

Making high-energy astrophysical neutrinos

(or $p + p$)

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



Making high-energy astrophysical neutrinos

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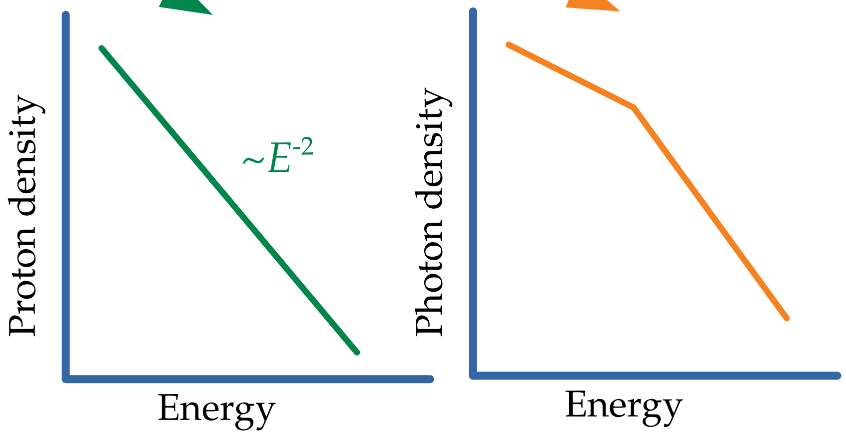

Making high-energy astrophysical neutrinos

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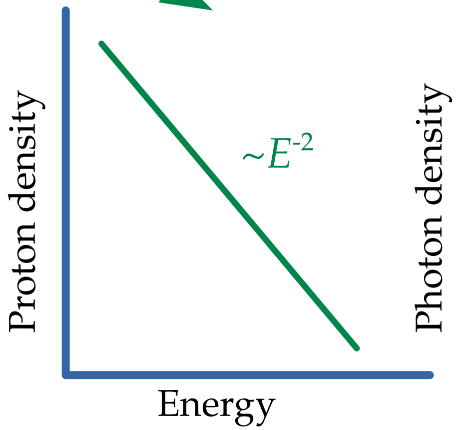
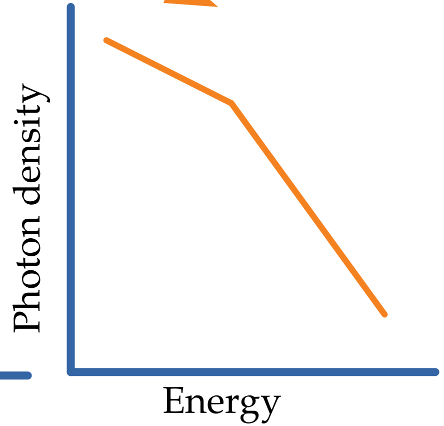
$$p + \gamma_{\text{target}} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0, & \text{Br} = 2/3 \\ n + \pi^+, & \text{Br} = 1/3 \end{cases}$$

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

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

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





Making high-energy astrophysical neutrinos

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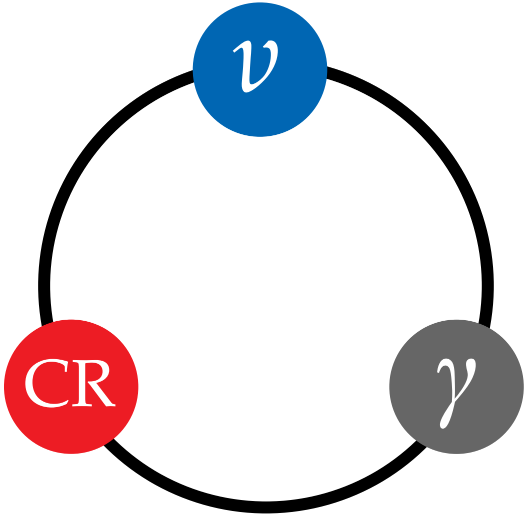
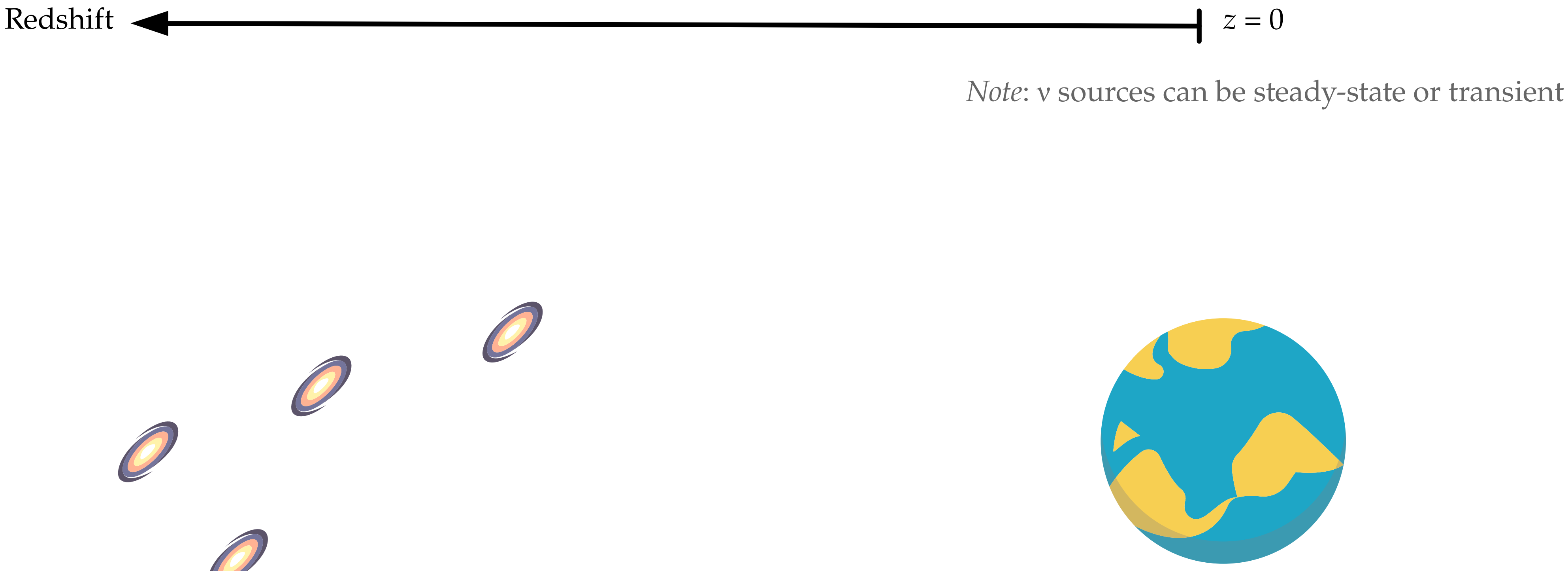
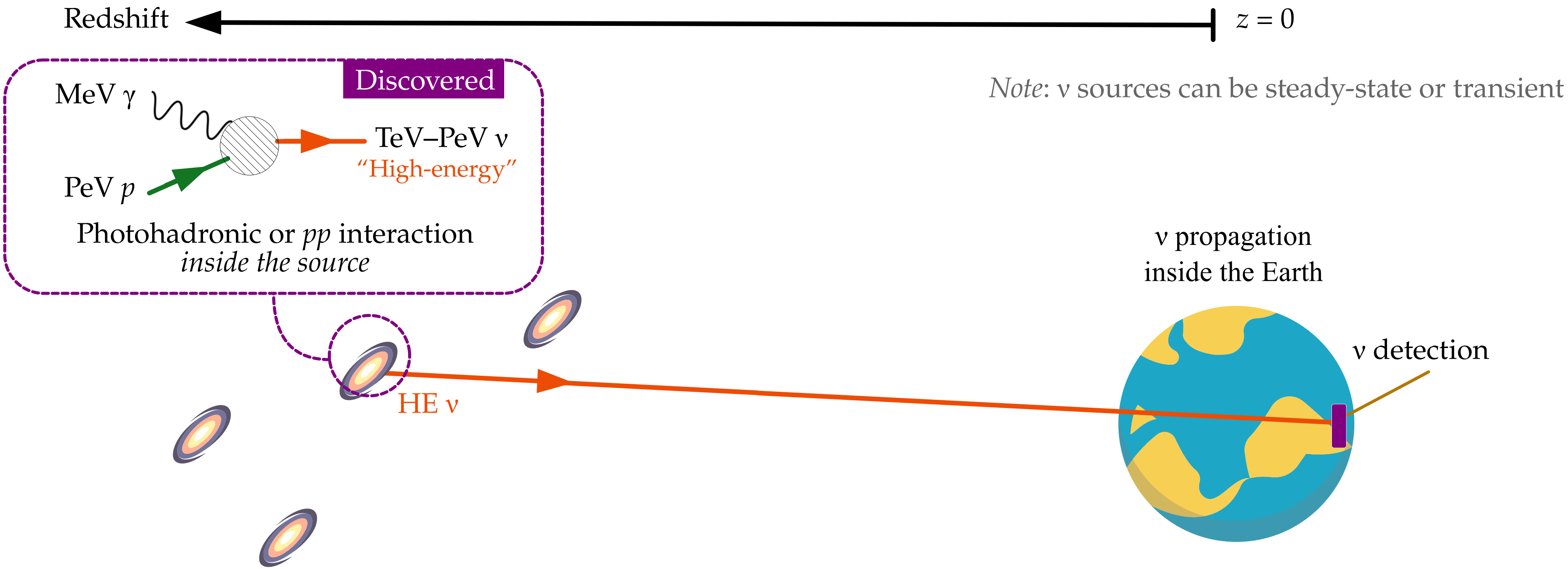
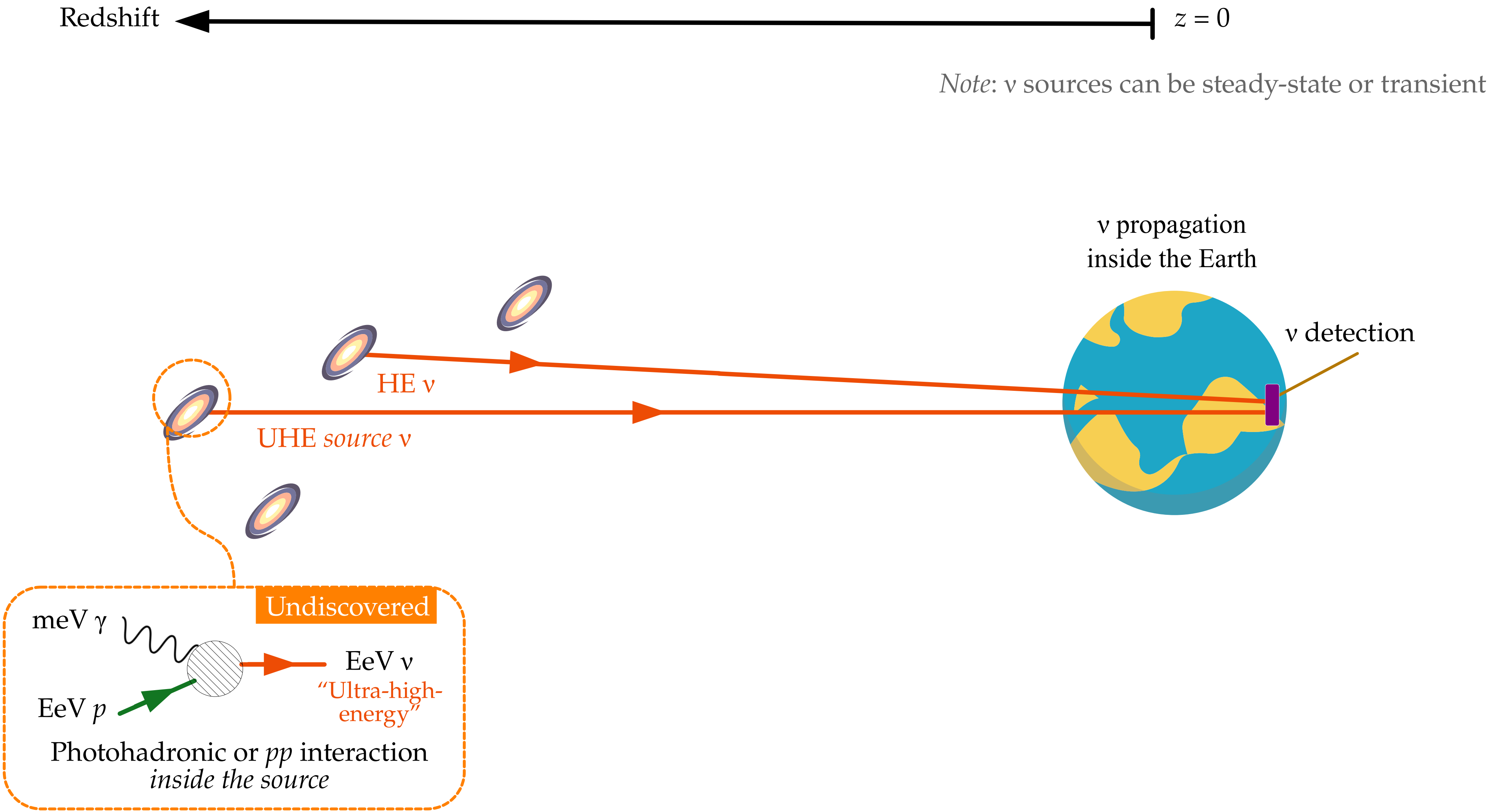


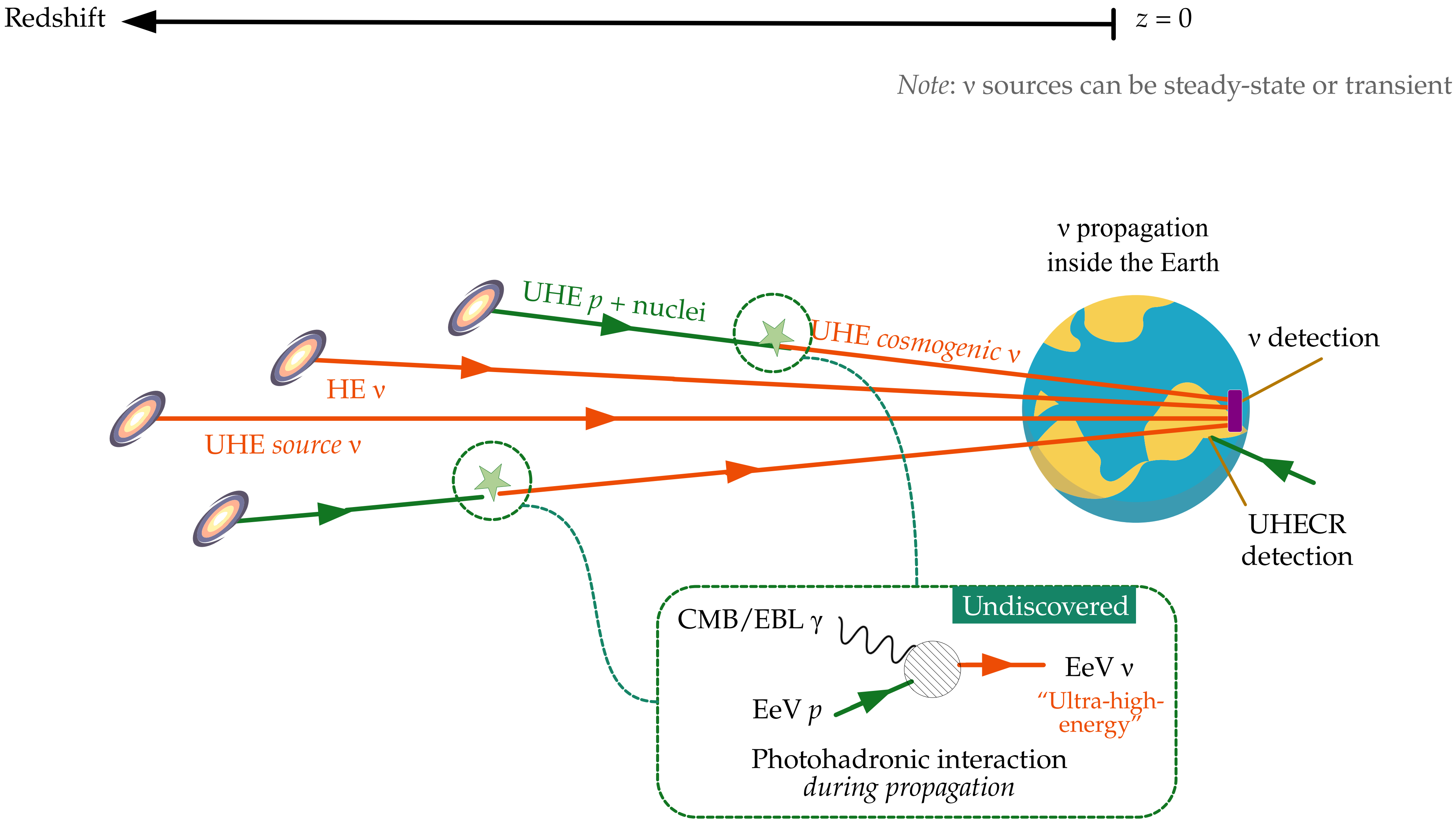
Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

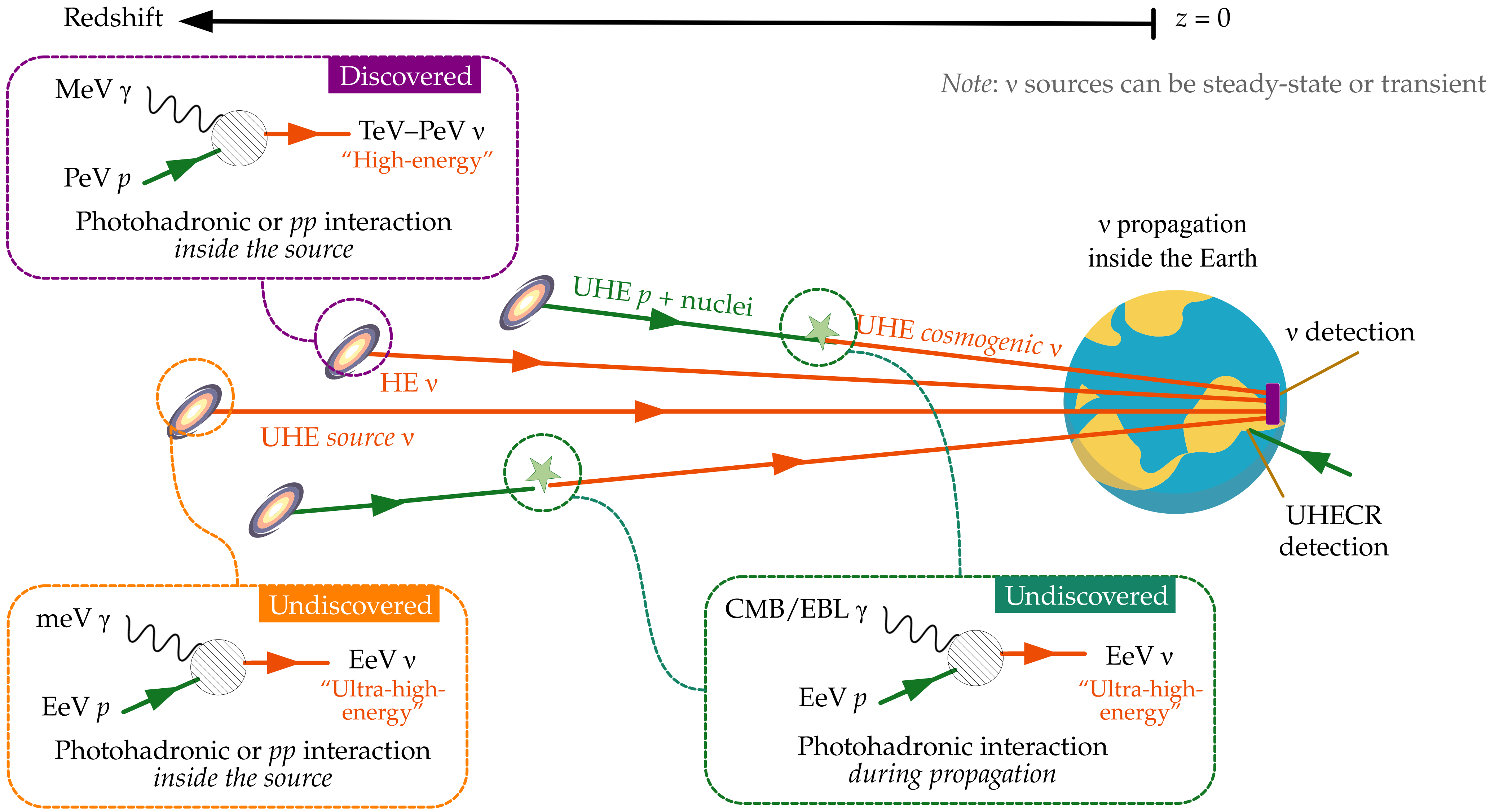

Redshift
$z = 0$
Note: ν sources can be steady-state or transient


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
inside the source



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



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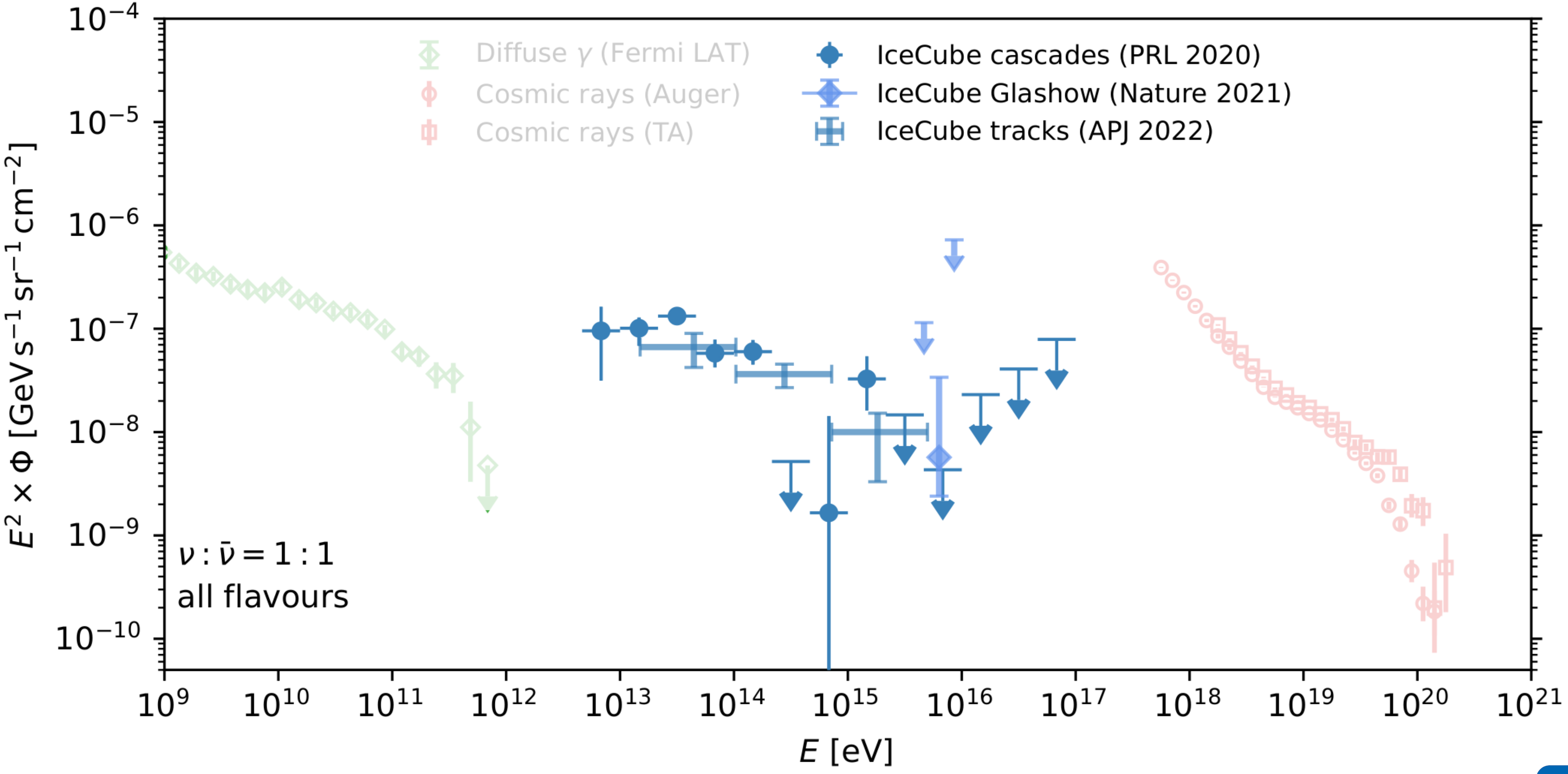
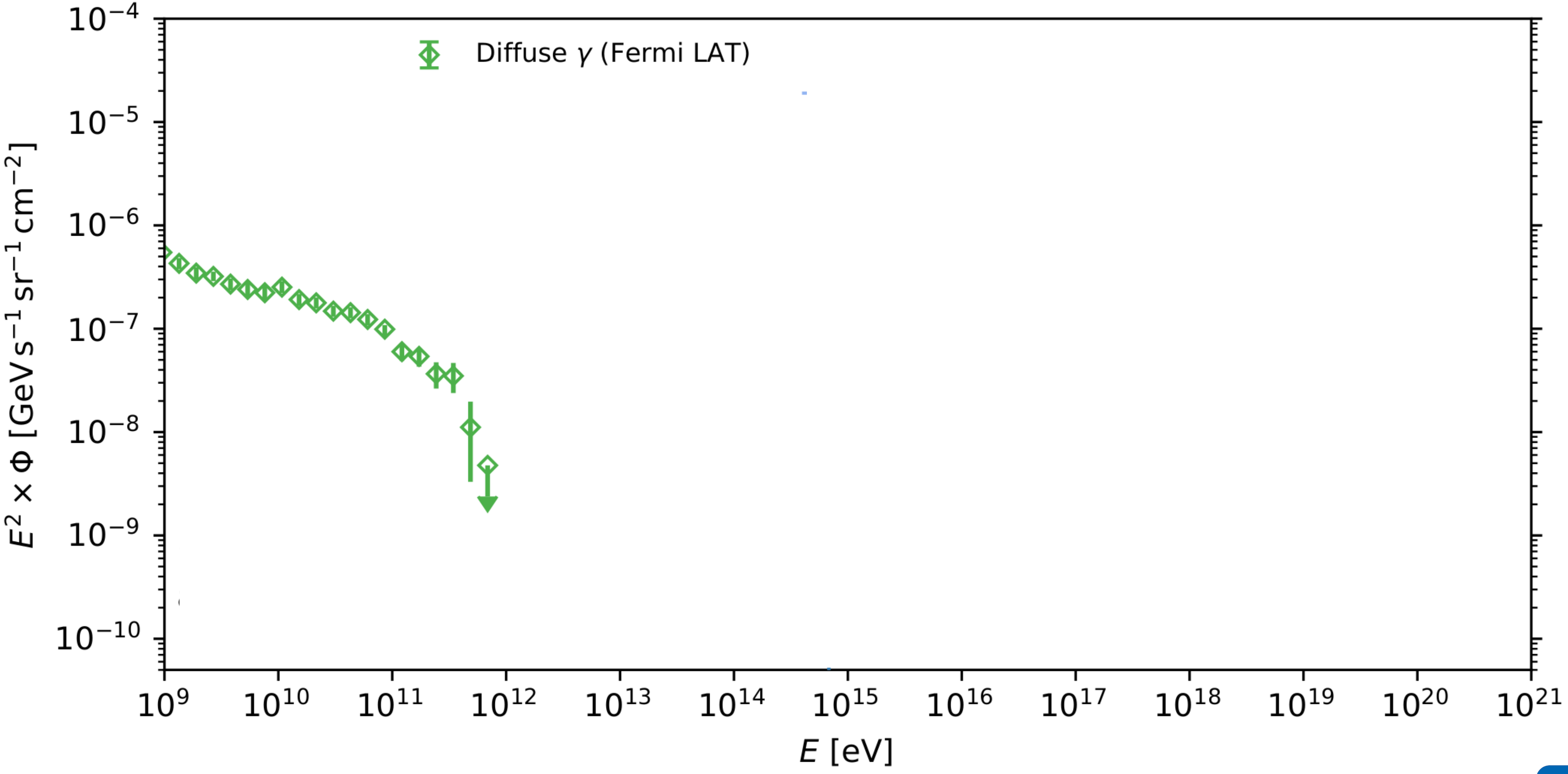
ν detection
HE ν
UHE *source* ν
UHECR
detection
Undiscovered
meV γ
EeV ν
EeV p
"Ultra-high-energy"
Photohadronic or pp interaction
inside the source
Undiscovered
CMB/EBL γ
EeV ν
EeV p
"Ultra-high-energy"
Photohadronic interaction
during propagation

Gamma rays   **Neutrinos**   Cosmic rays



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

Gamma rays Neutrinos Cosmic rays



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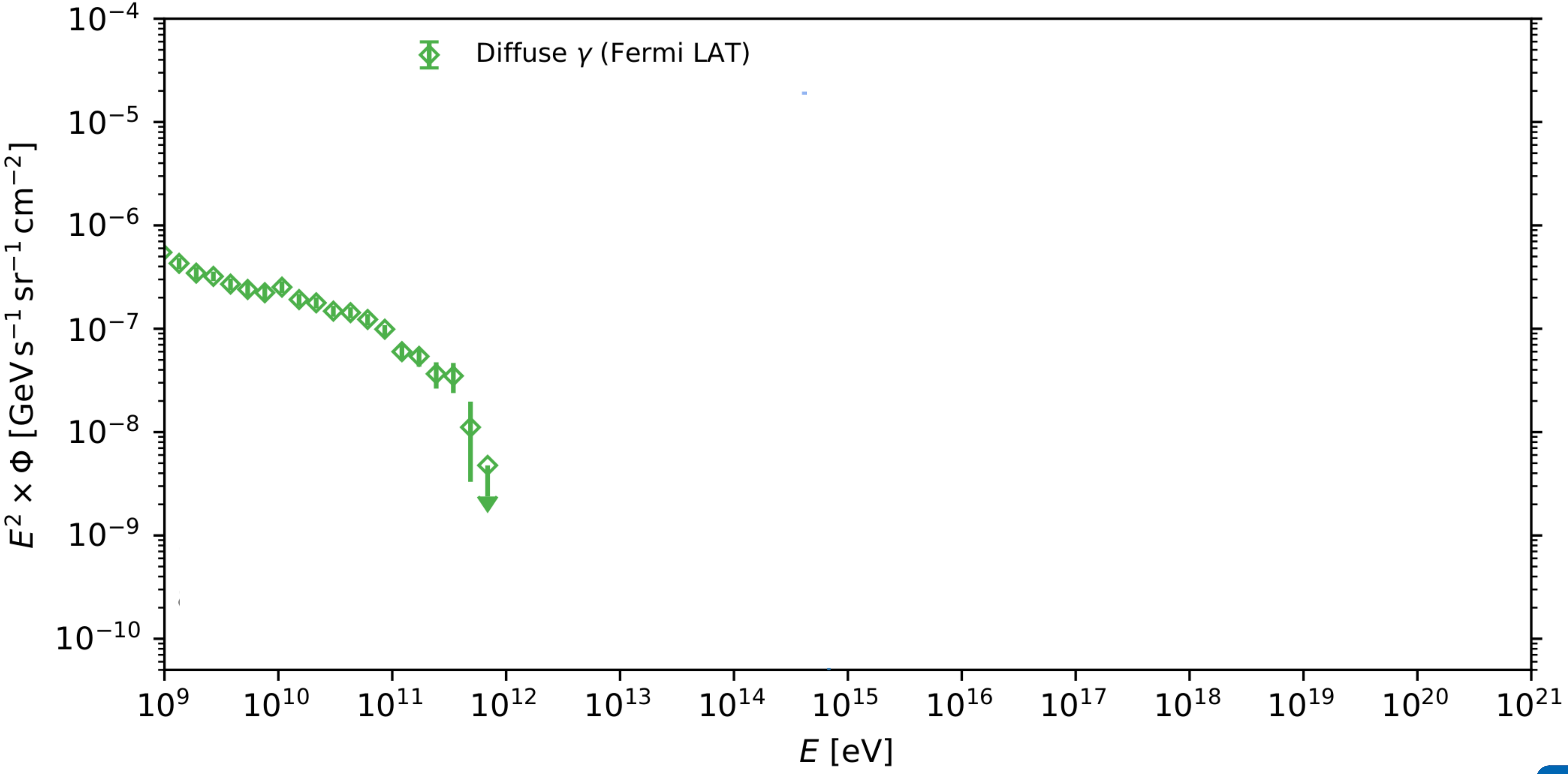
Gamma rays Neutrinos Cosmic rays



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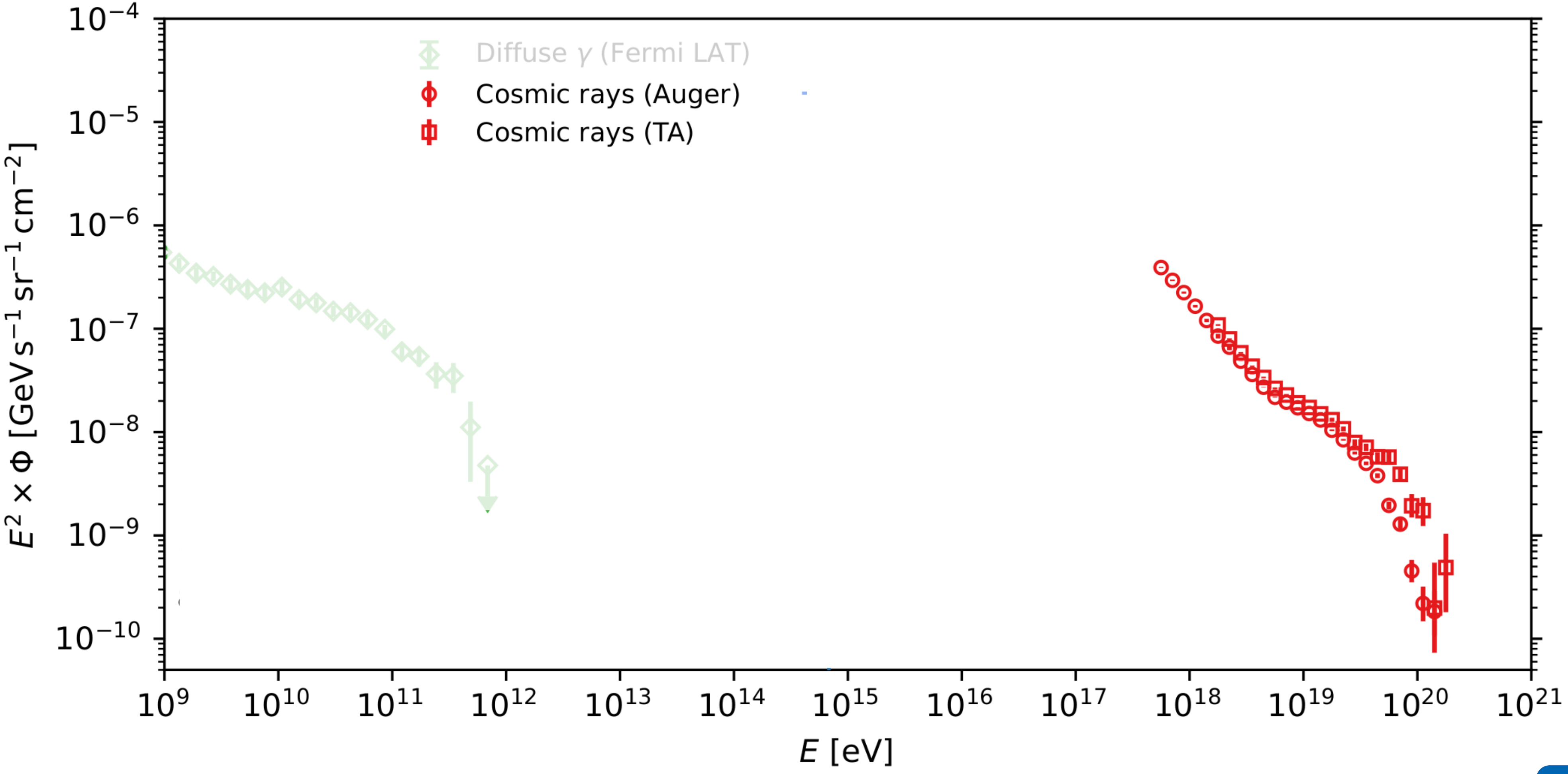

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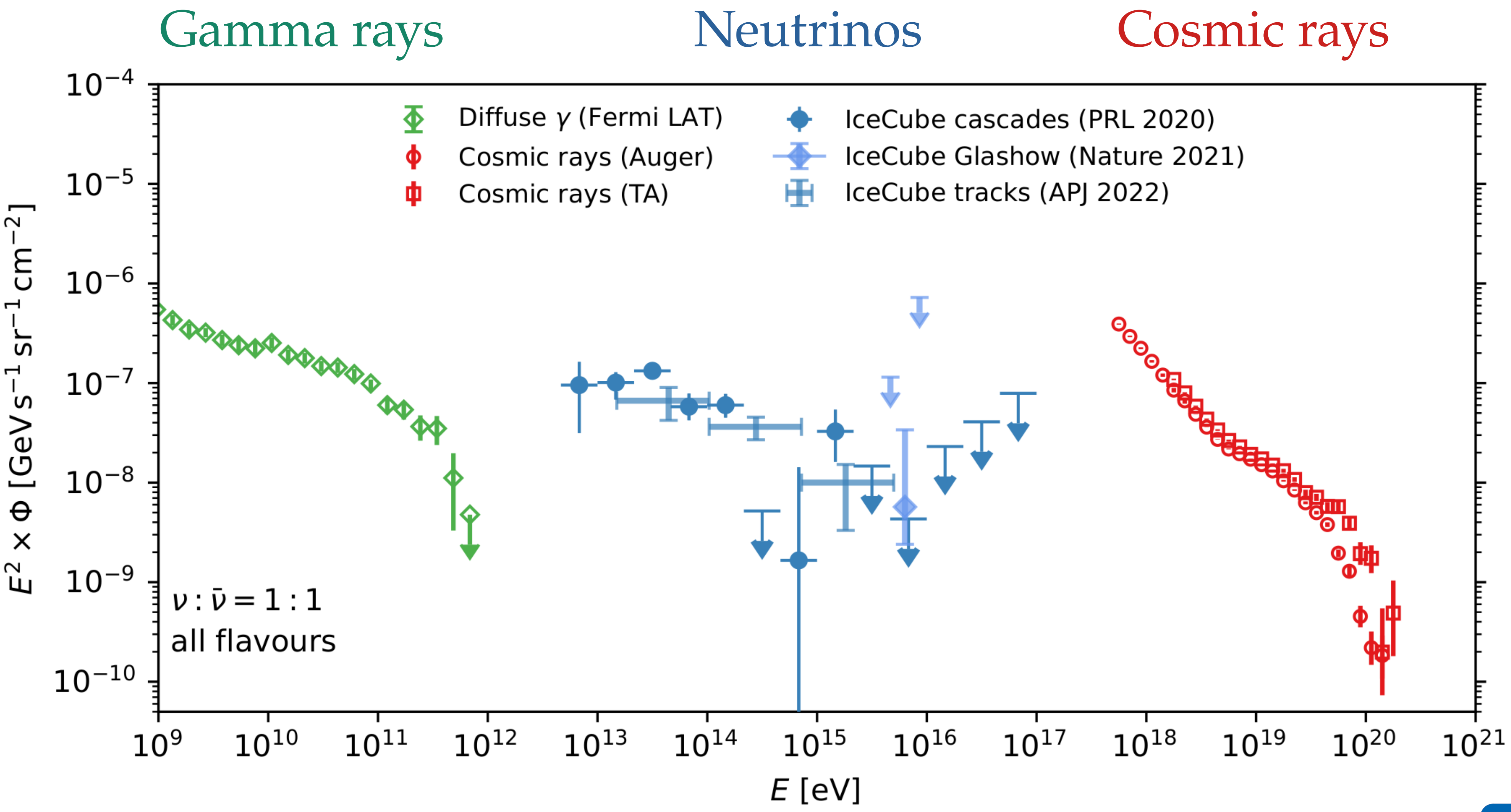

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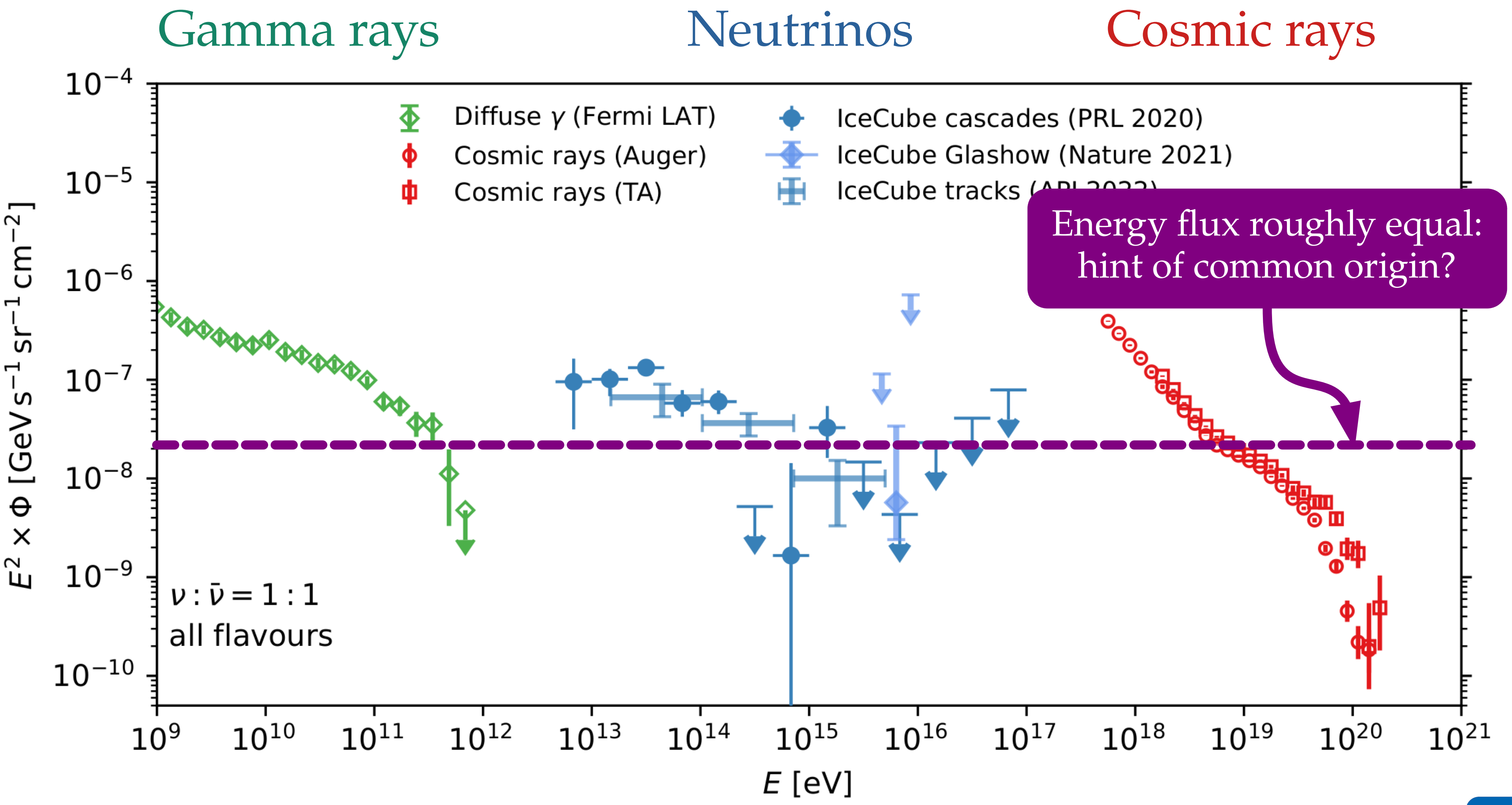
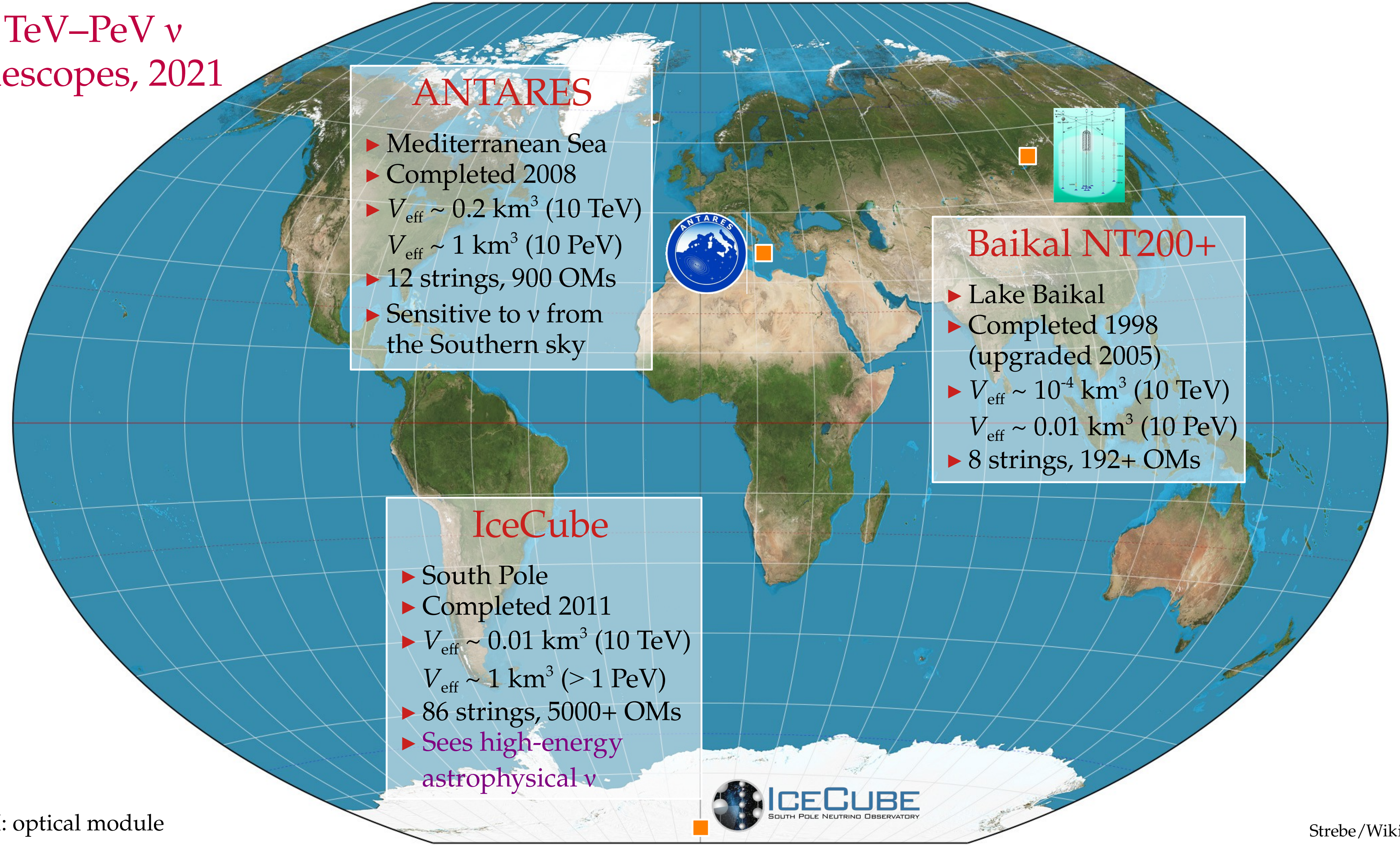


M. Ackermann, **MB**, *et al.*, *JHEAp* 35, 55 (2022) [2203.08096]

TeV–PeV ν telescopes, 2021



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

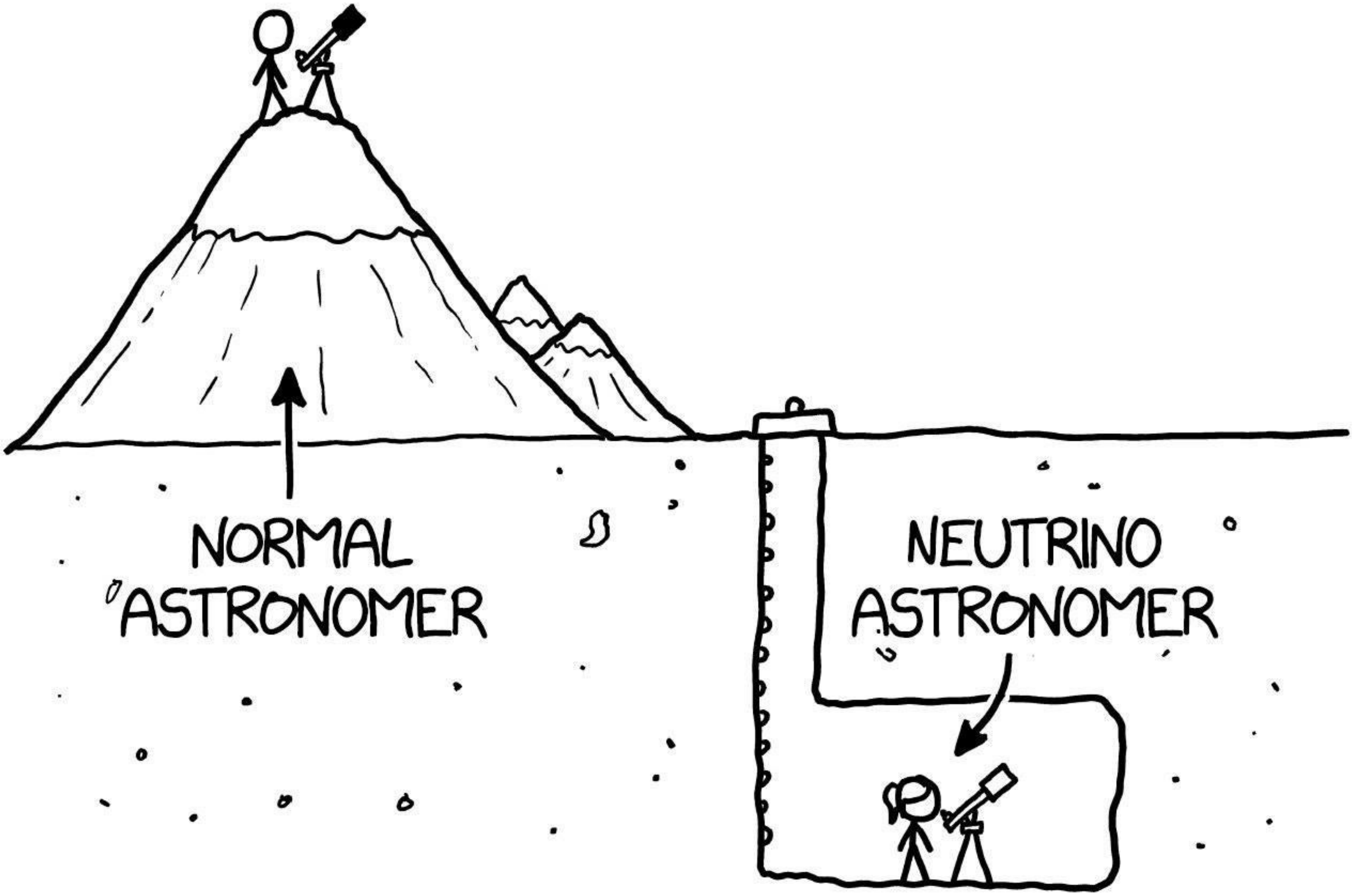
IceCube

- 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

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

OM: optical module

Strebe/Wikipedia



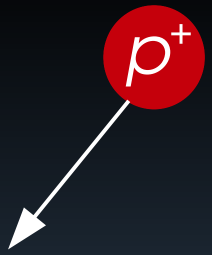
xkcd

Space

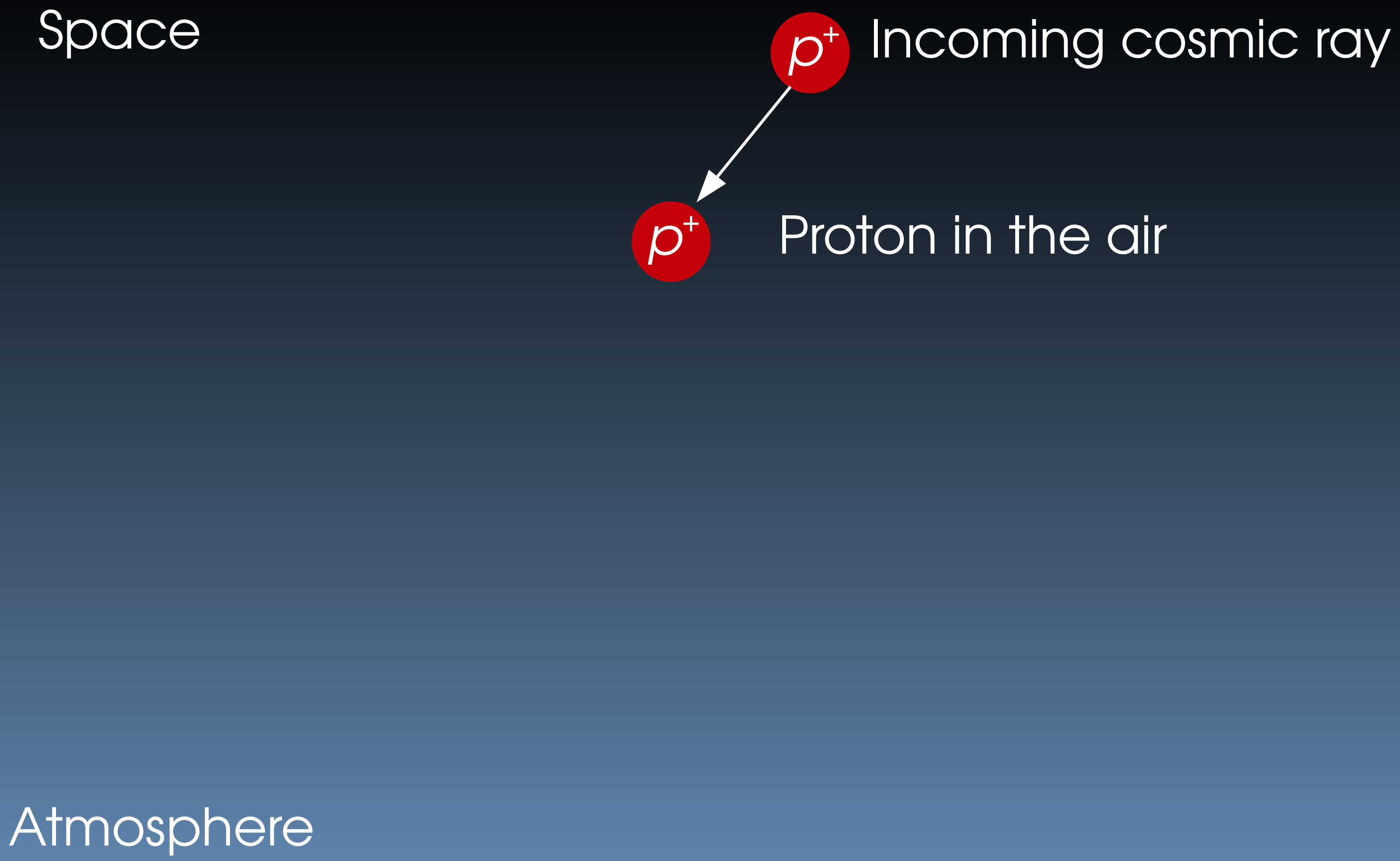
Atmosphere

Space

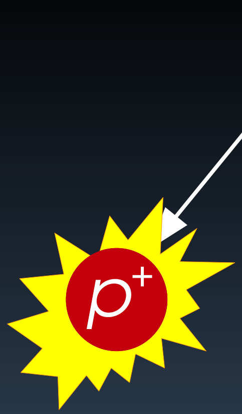
Incoming cosmic ray



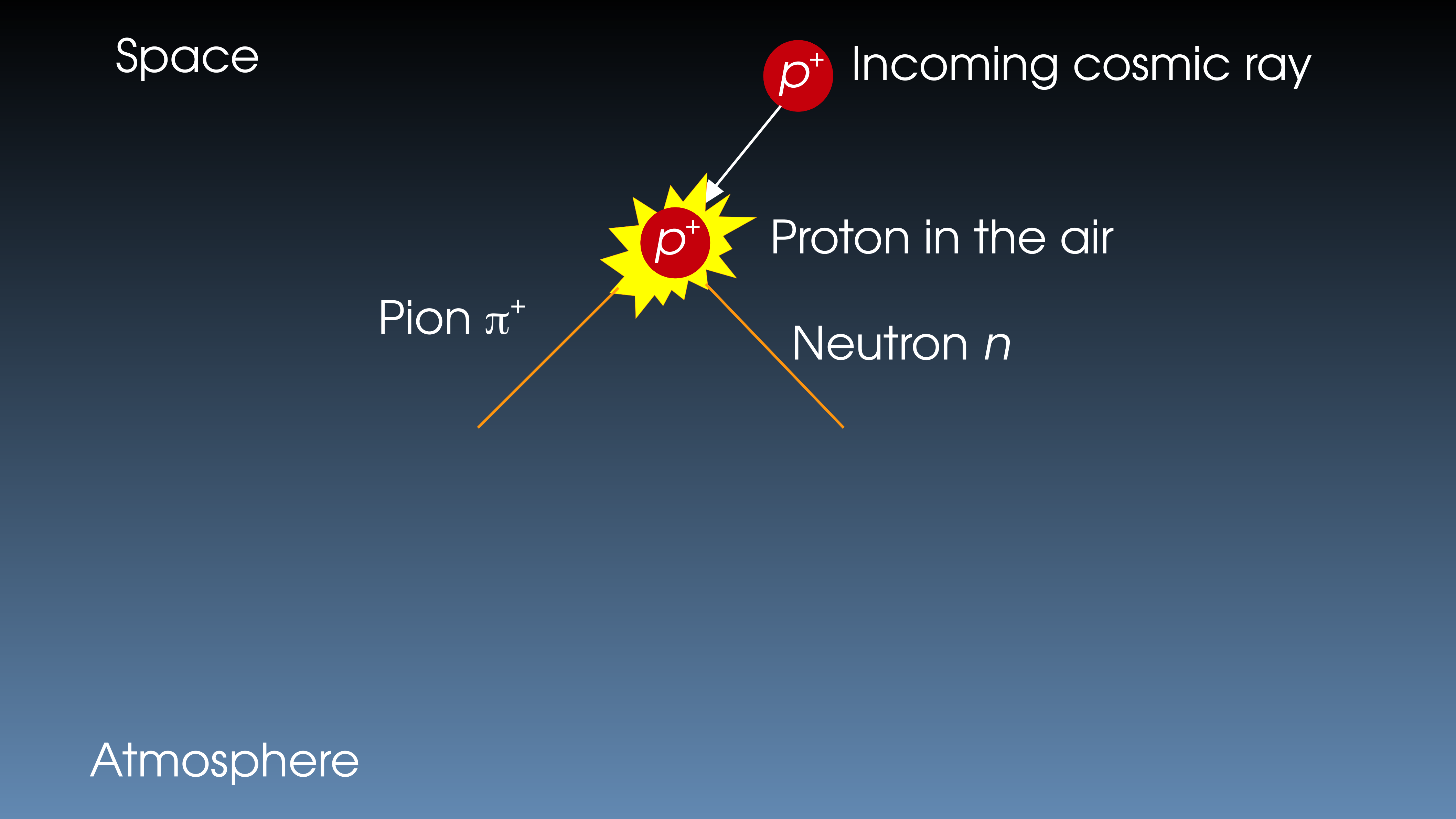
Atmosphere


Space
p^+
Incoming cosmic ray
p^+
Proton in the air
Atmosphere

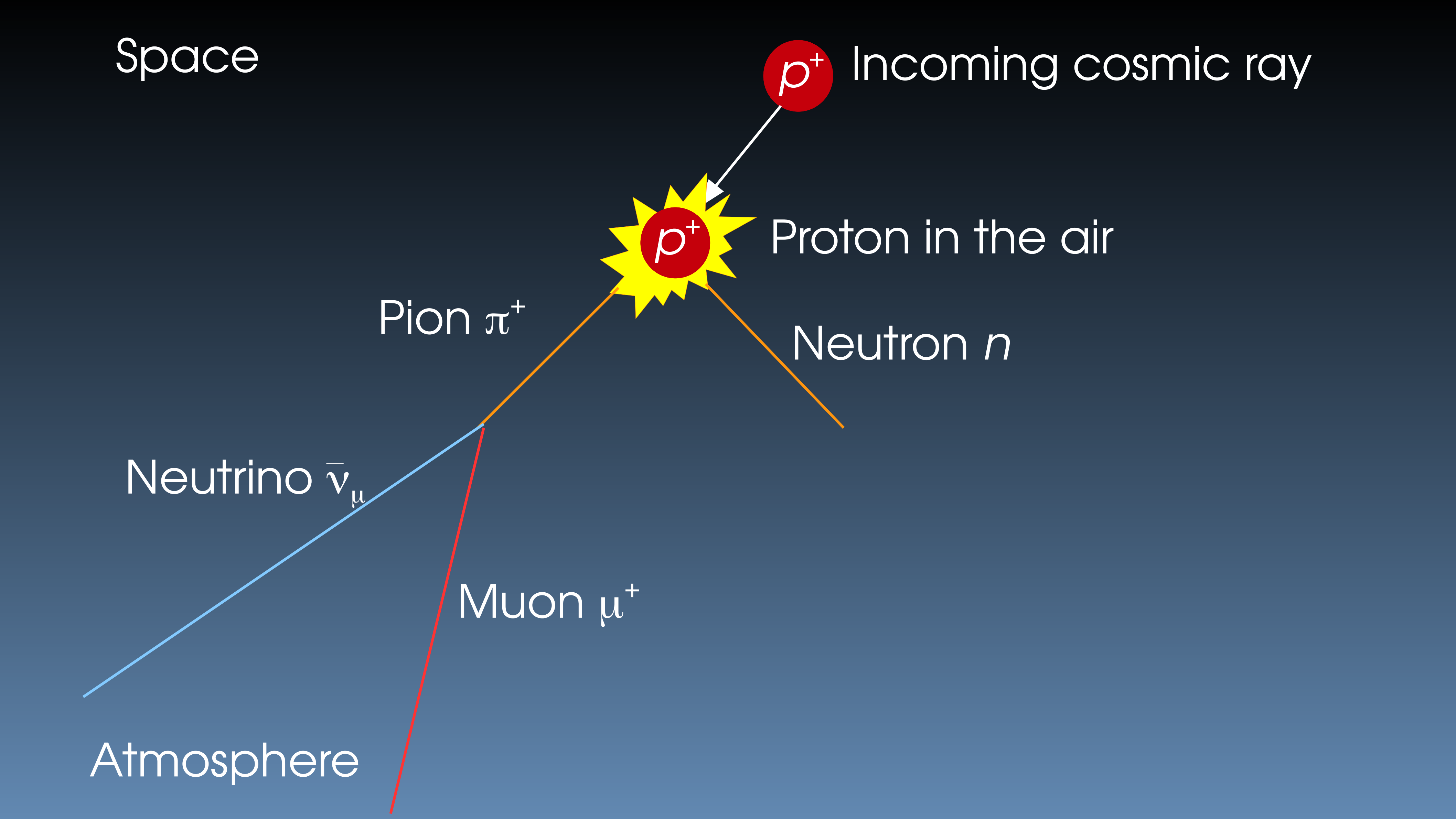
Space

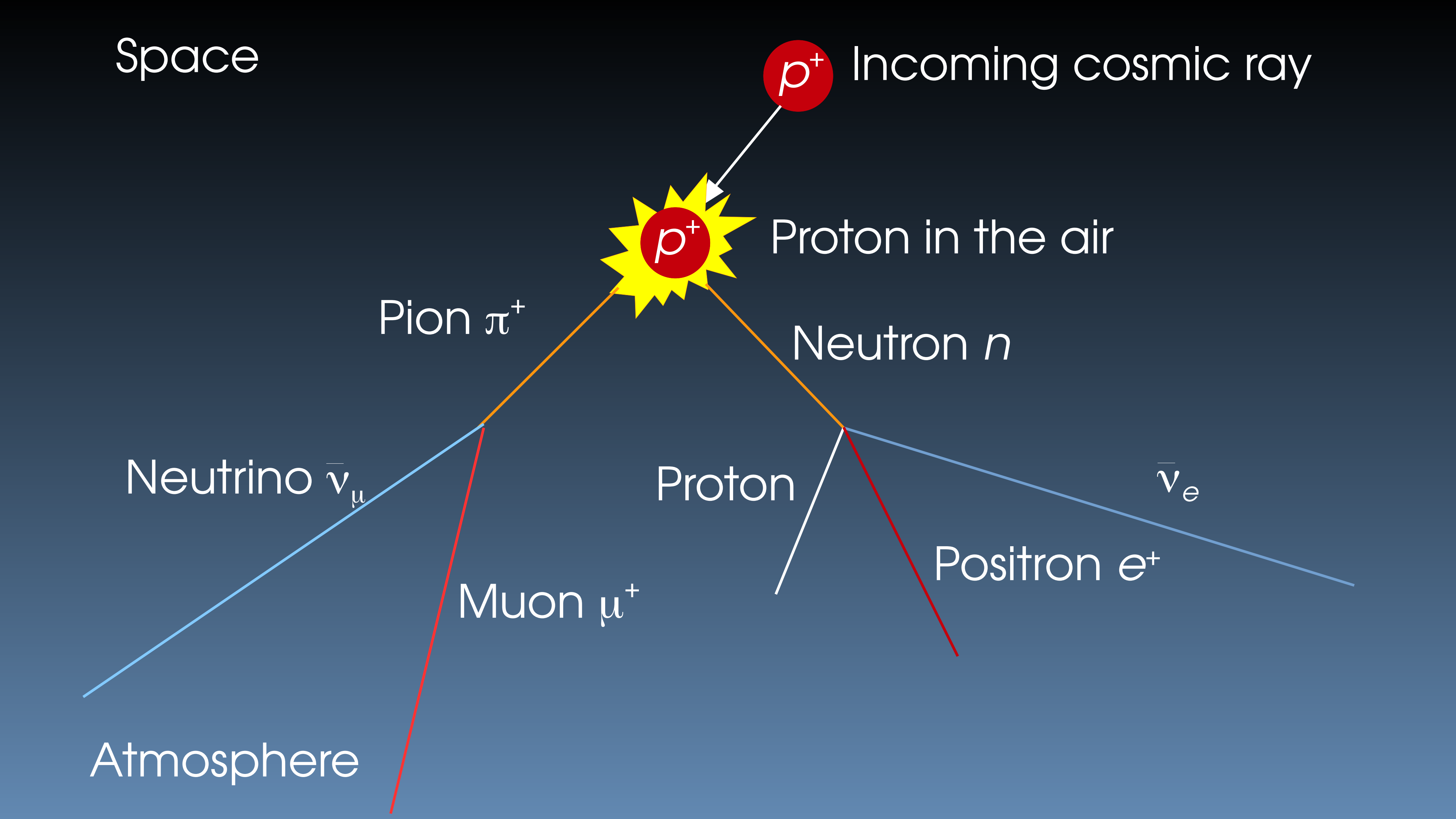


Atmosphere



Space
p^+
Incoming cosmic ray
p^+
Proton in the air
Pion π^+
Neutron n
Atmosphere


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


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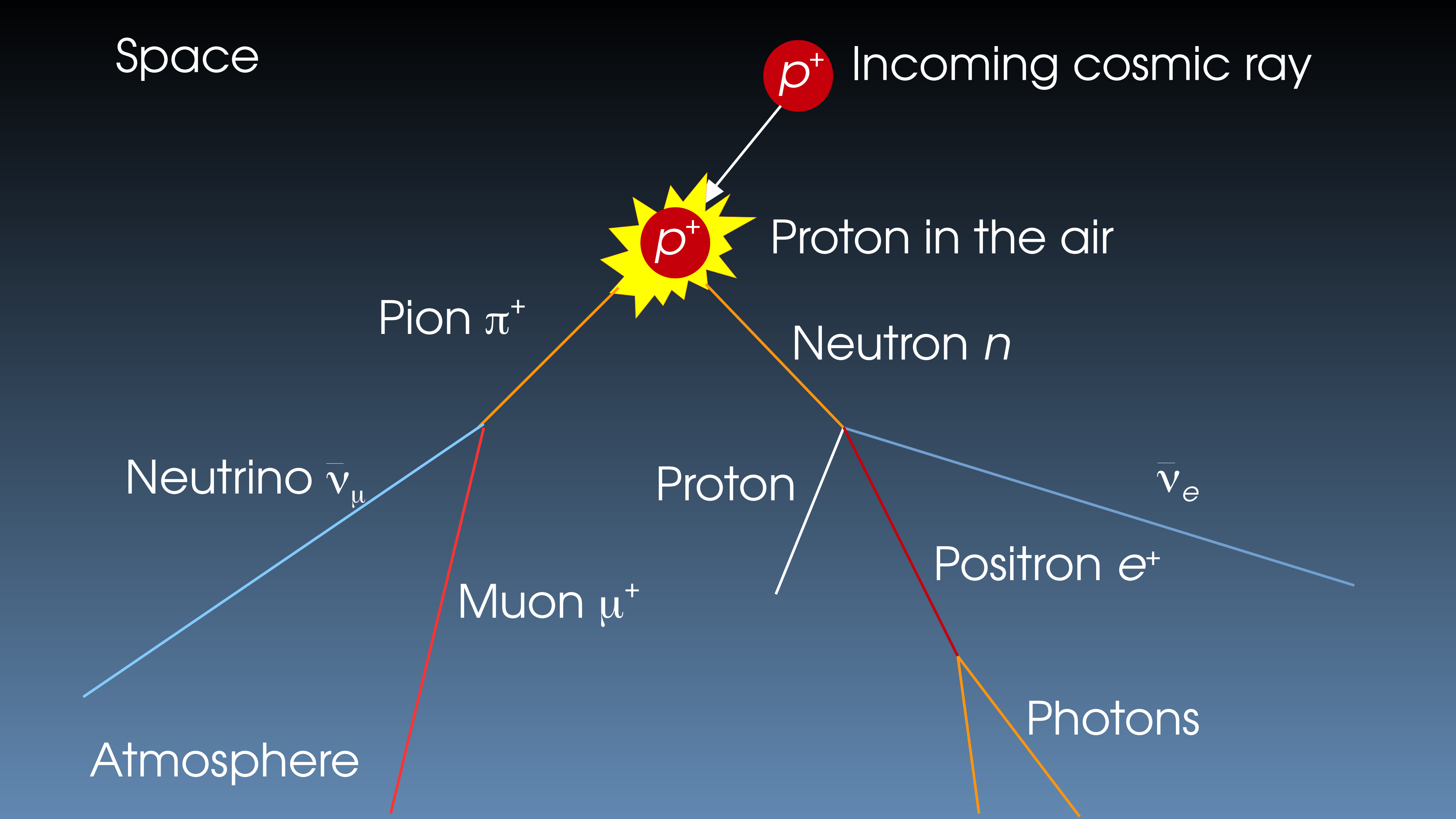
Pion π^+
Neutron n
Neutrino $\bar{\nu}_\mu$
Proton
$\bar{\nu}_e$
Positron e^+
Muon μ^+
Atmosphere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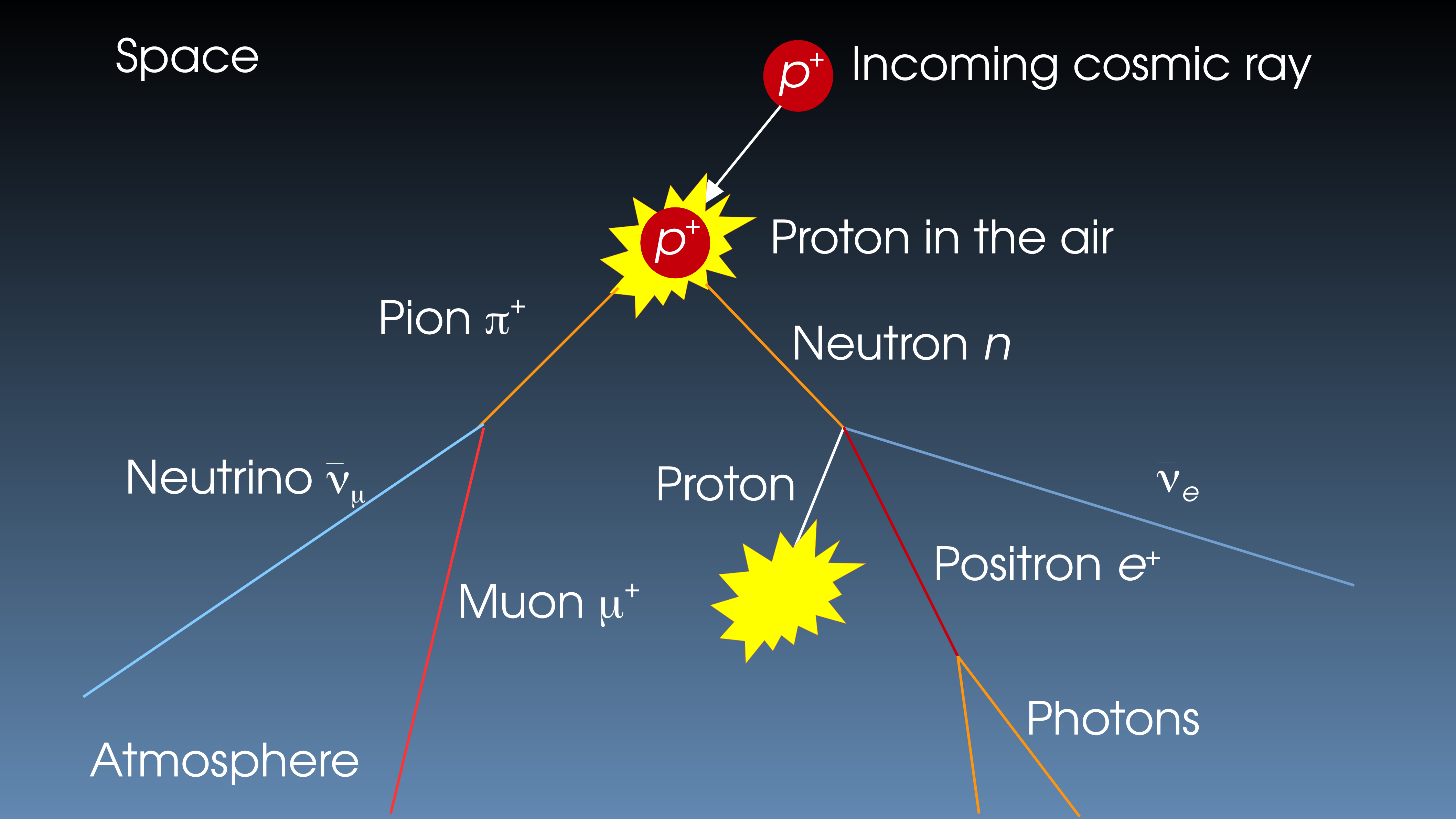
Incoming cosmic ray
p^+
Proton in the air
Pion π^+
Neutron n
Neutrino $\bar{\nu}_\mu$
Proton
$\bar{\nu}_e$
Positron e^+
Muon μ^+
Photons
Atmosphere



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p^+
Incoming cosmic ray
p^+
Proton in the air
Pion π^+
Neutron n
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$\bar{\nu}_e$
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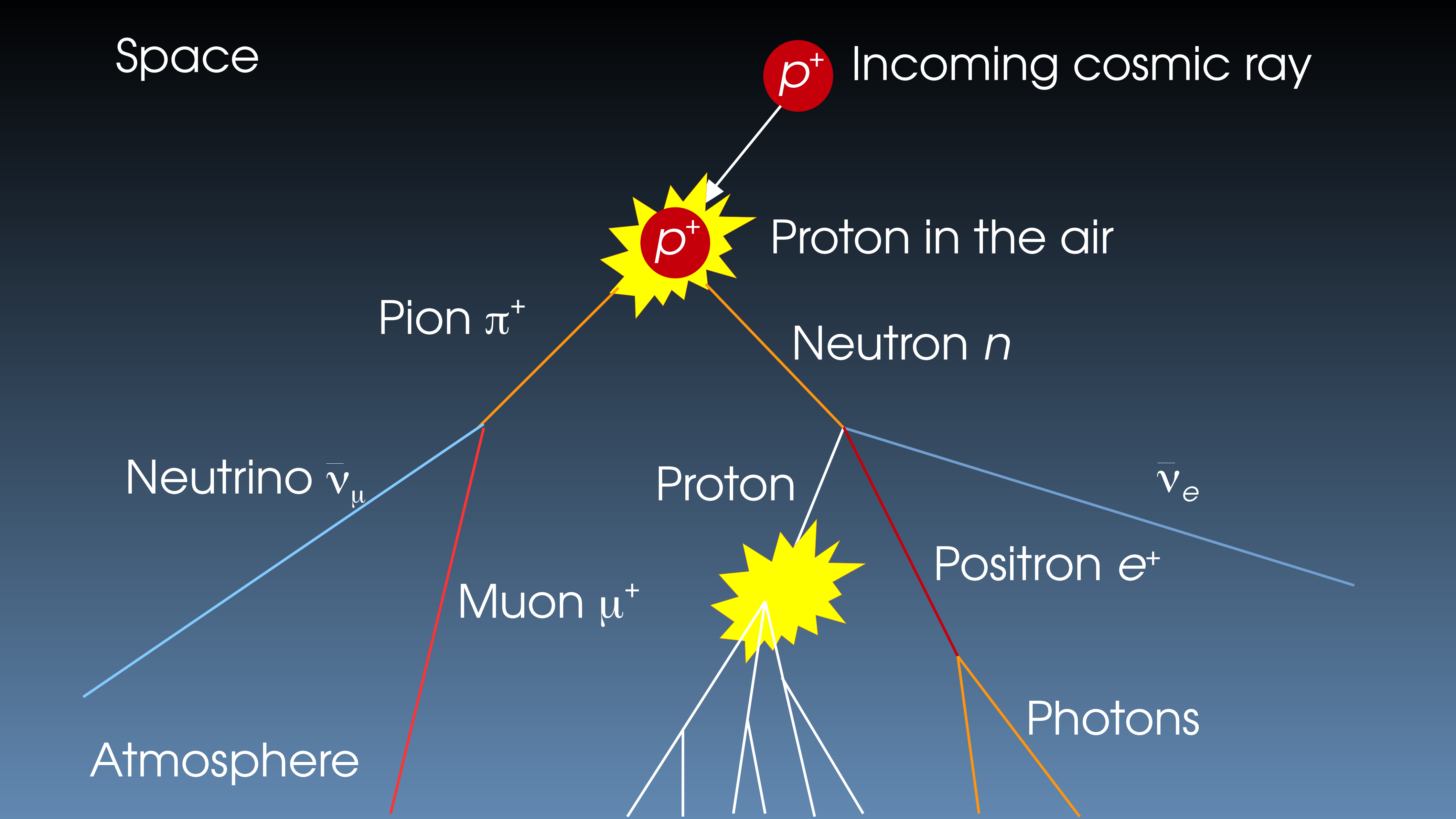
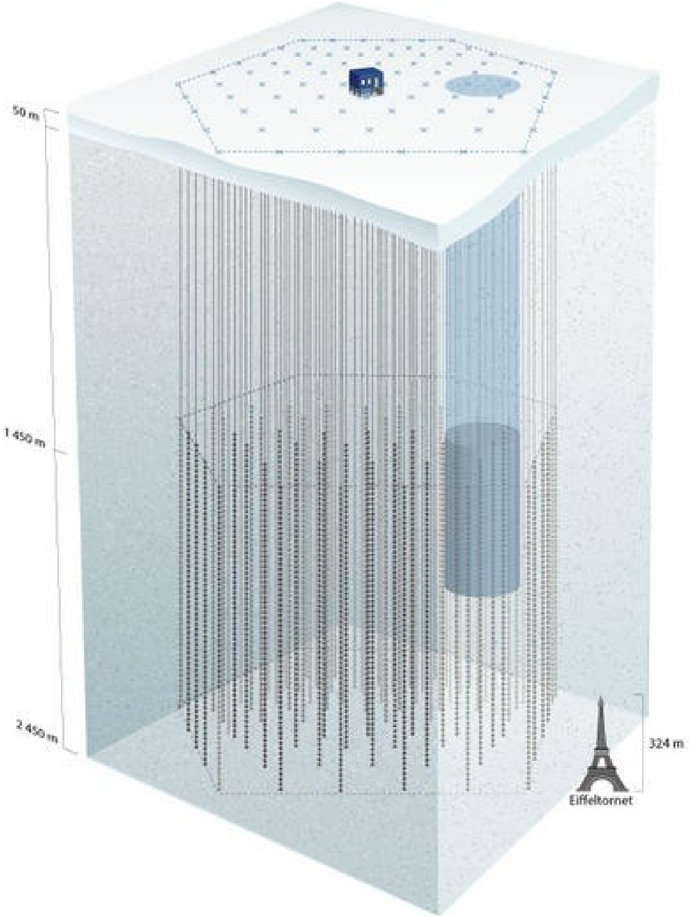
Photons
Atmosphere



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

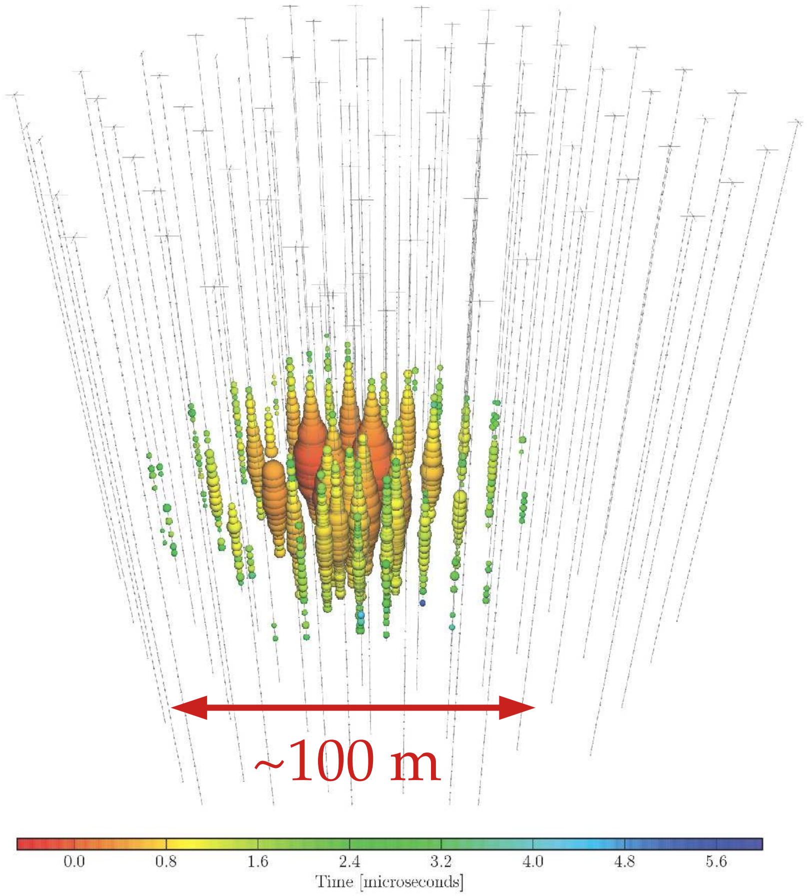
Yuya Makino, IceCube/NSF

IceCube – What is it?



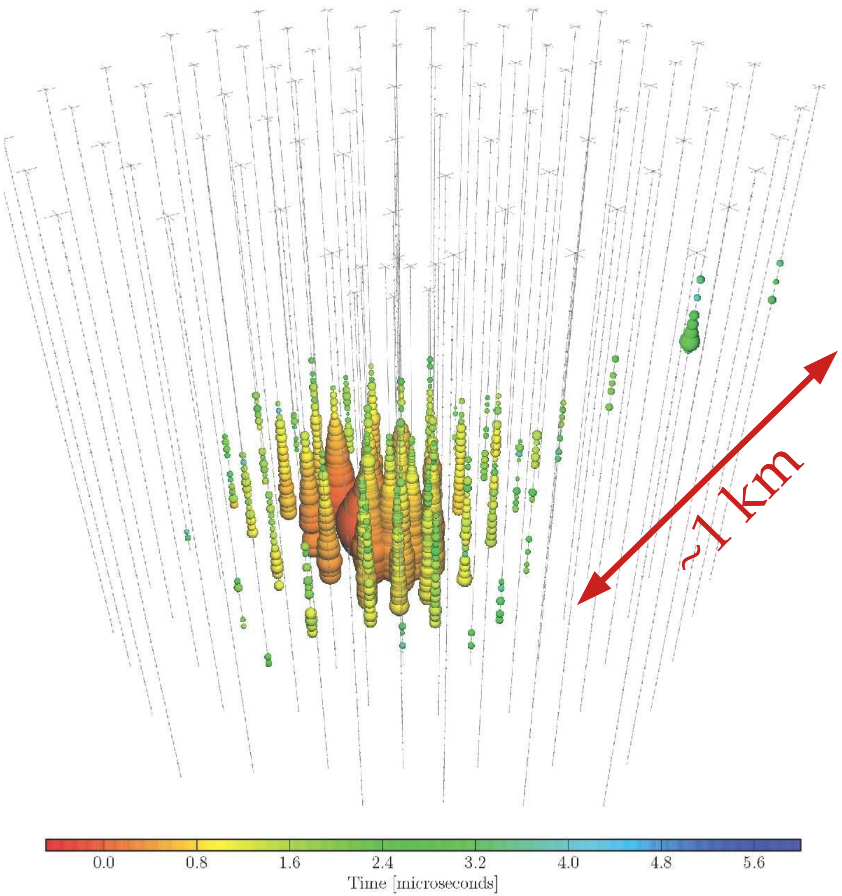
- Km^3 in-ice Cherenkov detector in Antarctica
- > 5000 PMTs at 1.5–2.5 km of depth
- Sensitive to neutrino energies > 10 GeV

Shower (mainly from ν_e and ν_τ)



Poor angular resolution: ~10°

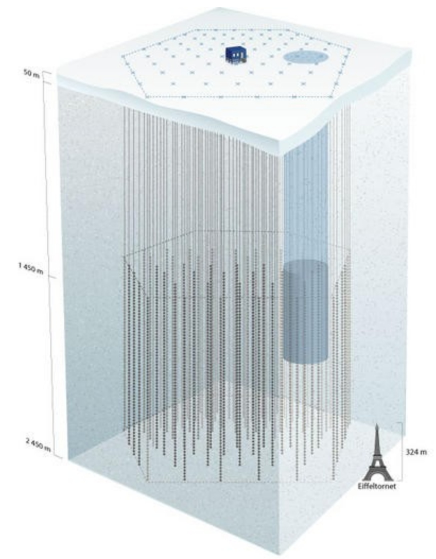
Track (mainly from ν_μ)



Angular resolution: < 1°

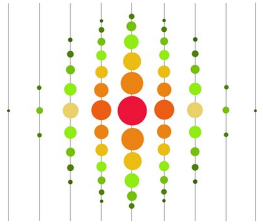
IceCube (~10 years)

km³ in-ice
Cherenkov detector



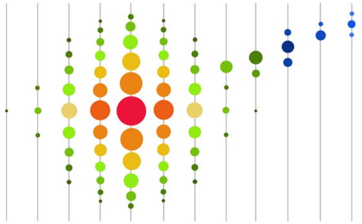
Showers

(mostly from ν_e, ν_τ)



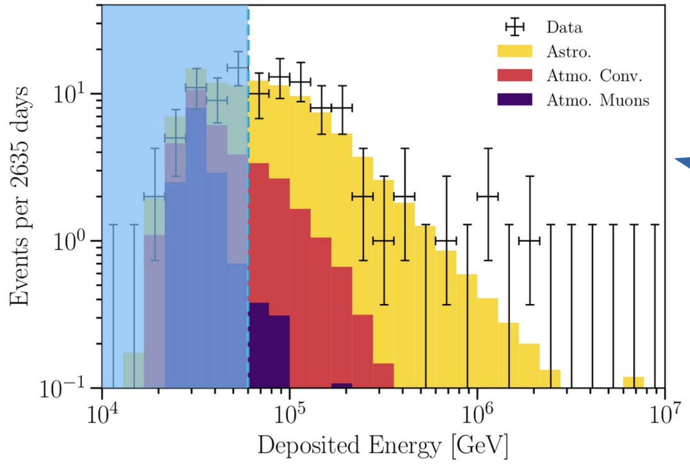
Tracks

(from ν_μ)



~100 contained events, 15 TeV–2 PeV

Astrophysical ν flux detected at > 8σ



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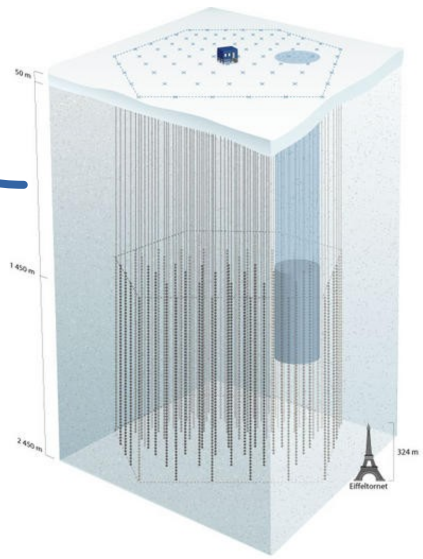
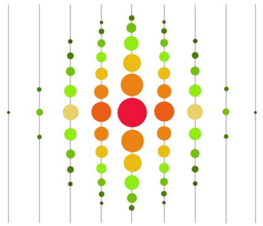


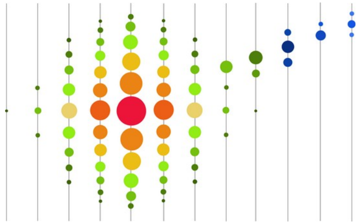
Showers

(mostly from ν_e, ν_τ)



Tracks

(from ν_μ)



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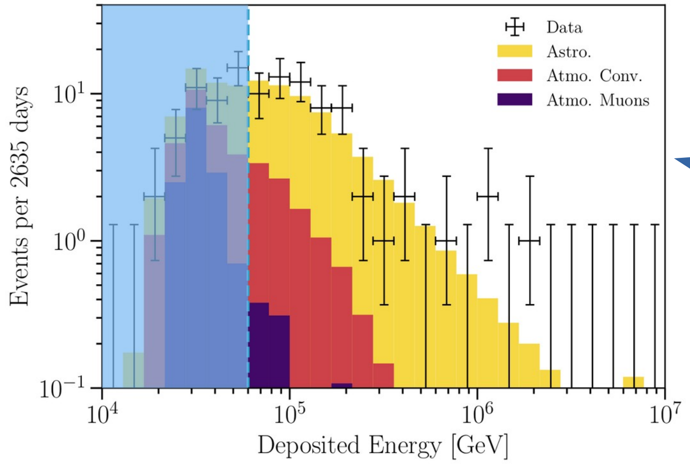

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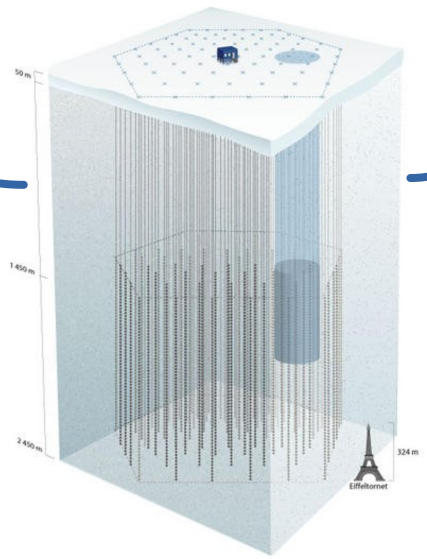
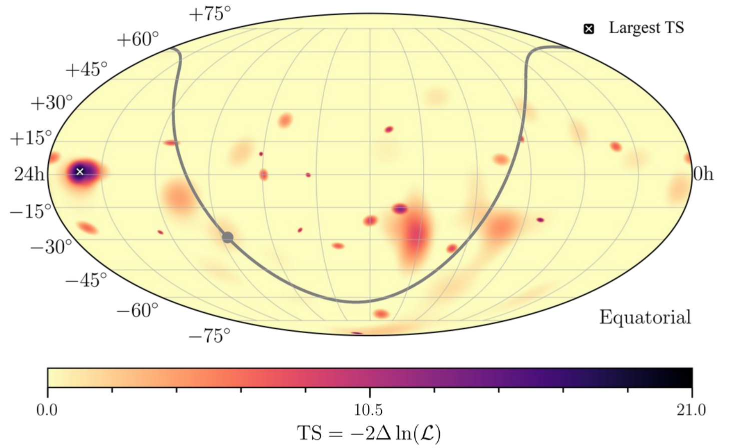
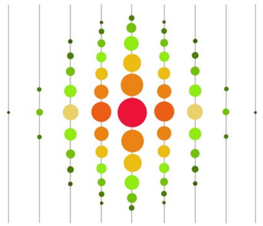


Arrival directions compatible with isotropy



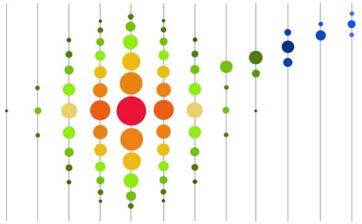
Showers

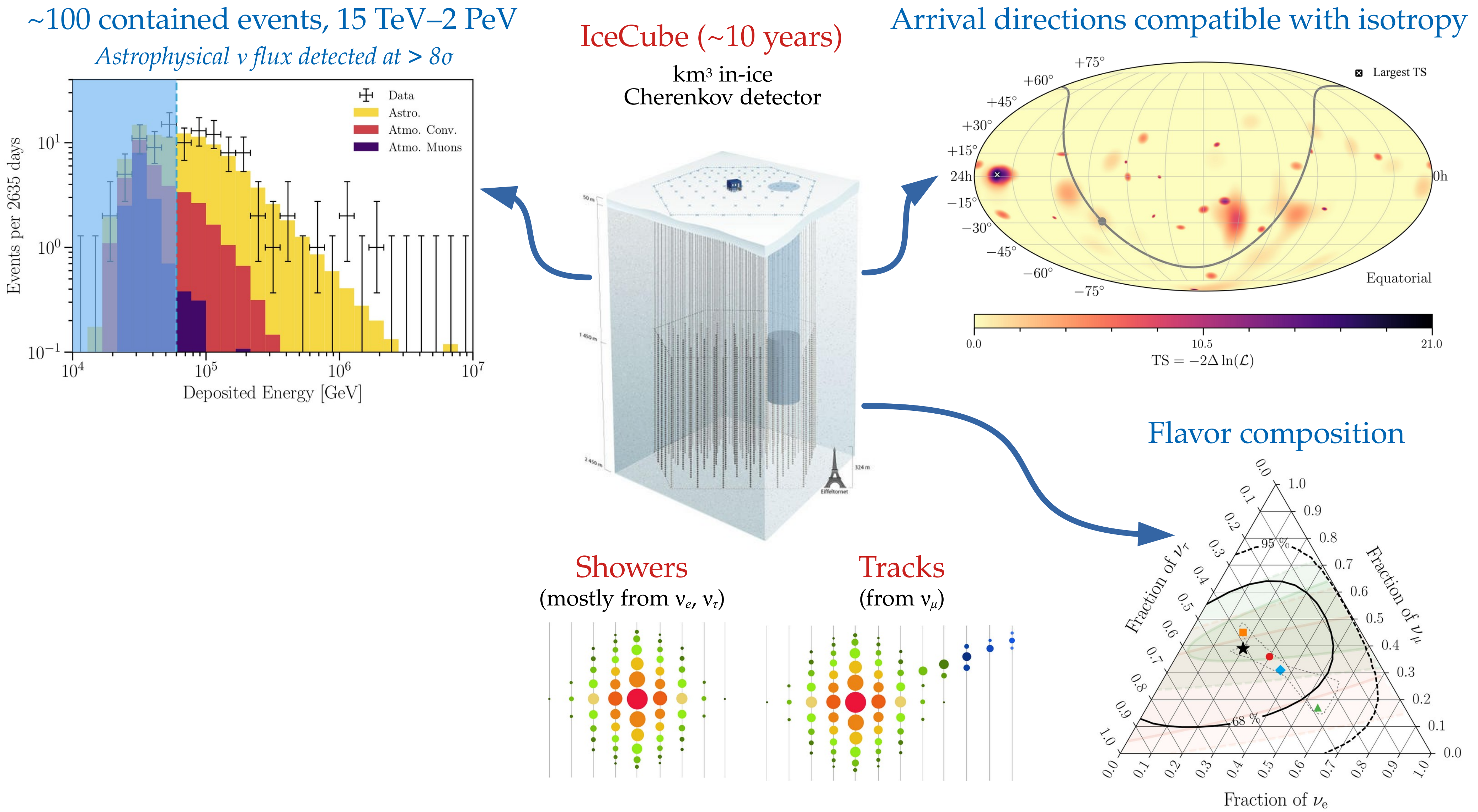
(mostly from ν_e, ν_τ)

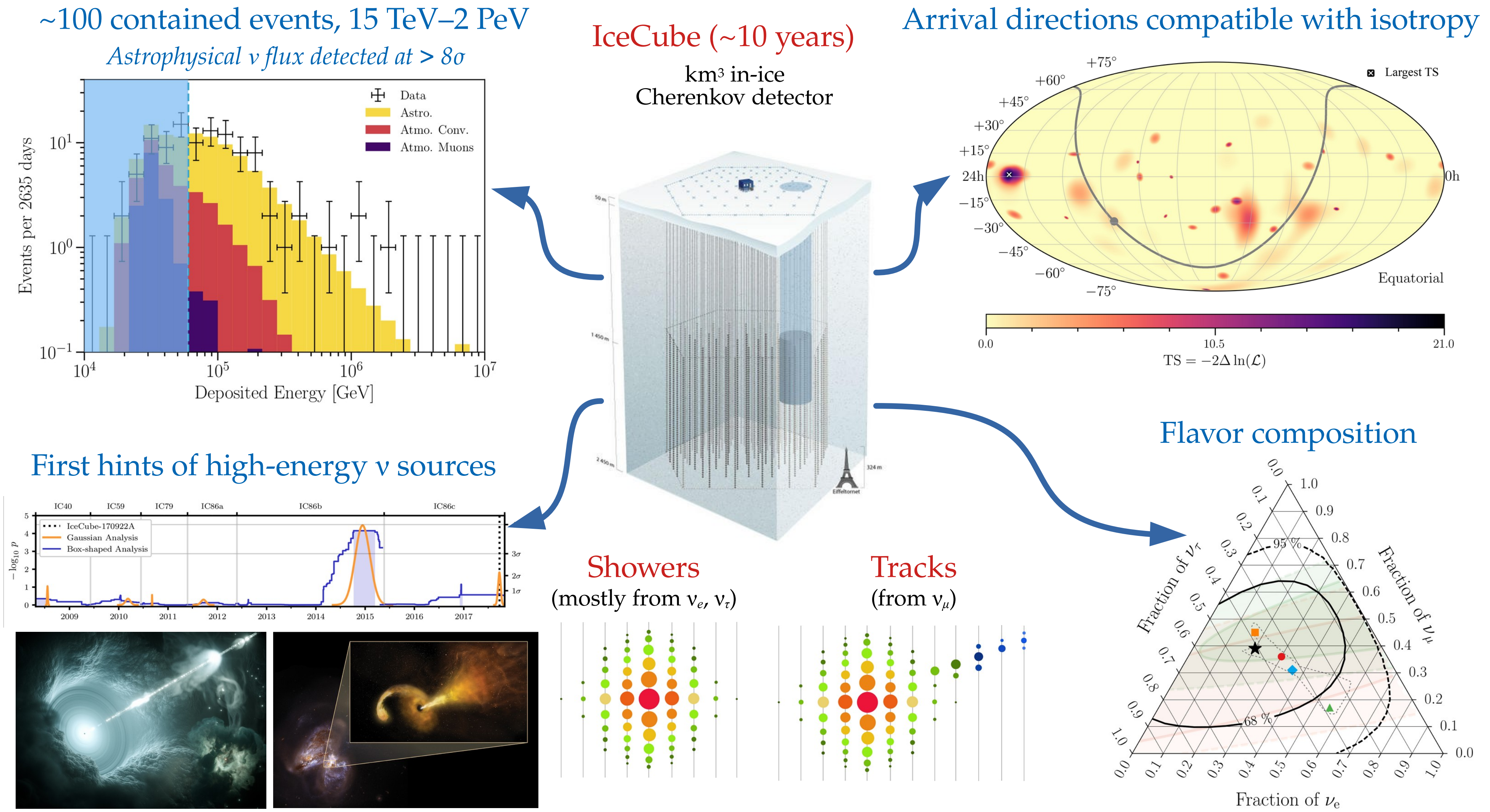


Tracks

(from ν_μ)




~100 contained events, 15 TeV–2 PeV
Astrophysical ν flux detected at > 8σ
Data
Astro.
Atmo. Conv.
Atmo. Muons
Events per 2635 days
Deposited Energy [GeV]
IceCube (~10 years)
km³ in-ice
Cherenkov detector
Arrival directions compatible with isotropy
Largest TS
Equatorial
TS = −2Δ ln(ℒ)
Flavor composition
Fraction of ν_τ
Fraction of ν_μ
Fraction of ν_e
95 %
68 %
Showers
(mostly from ν_e, ν_τ)
Tracks
(from ν_μ)


~100 contained events, 15 TeV–2 PeV
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Astro.
Atmo. Conv.
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Events per 2635 days
Deposited Energy [GeV]
IceCube (~10 years)
km³ in-ice
Cherenkov detector
Arrival directions compatible with isotropy
Largest TS
Equatorial
24h
0h
TS = −2Δ ln(ℒ)
First hints of high-energy ν sources
IC40
IC59
IC79
IC86a
IC86b
IC86c
IceCube-170922A
Gaussian Analysis
Box-shaped Analysis
Showers
(mostly from ν_e, ν_τ)
Tracks
(from ν_μ)
Flavor composition
Fraction of ν_τ
Fraction of ν_μ
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95 %
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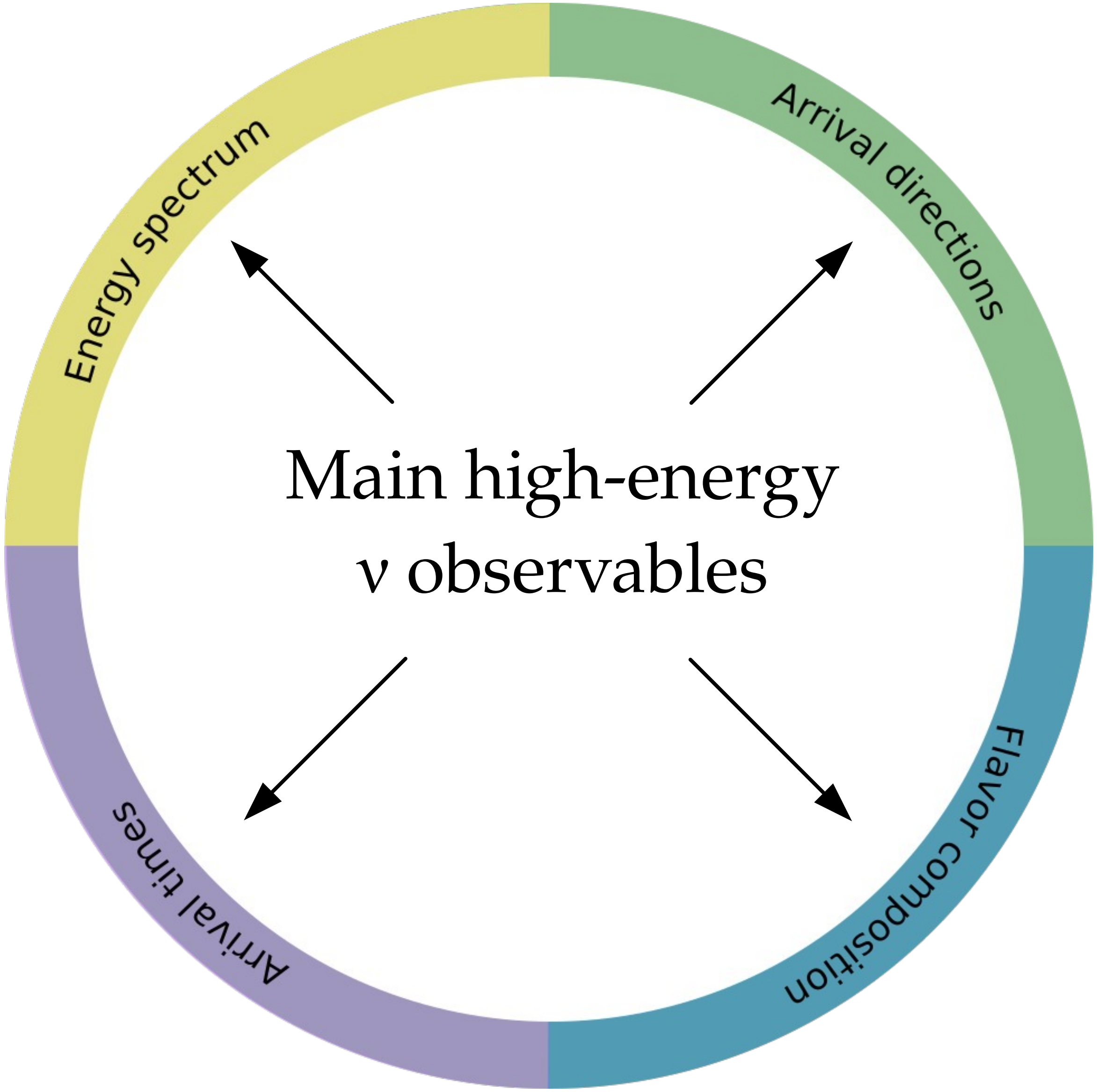
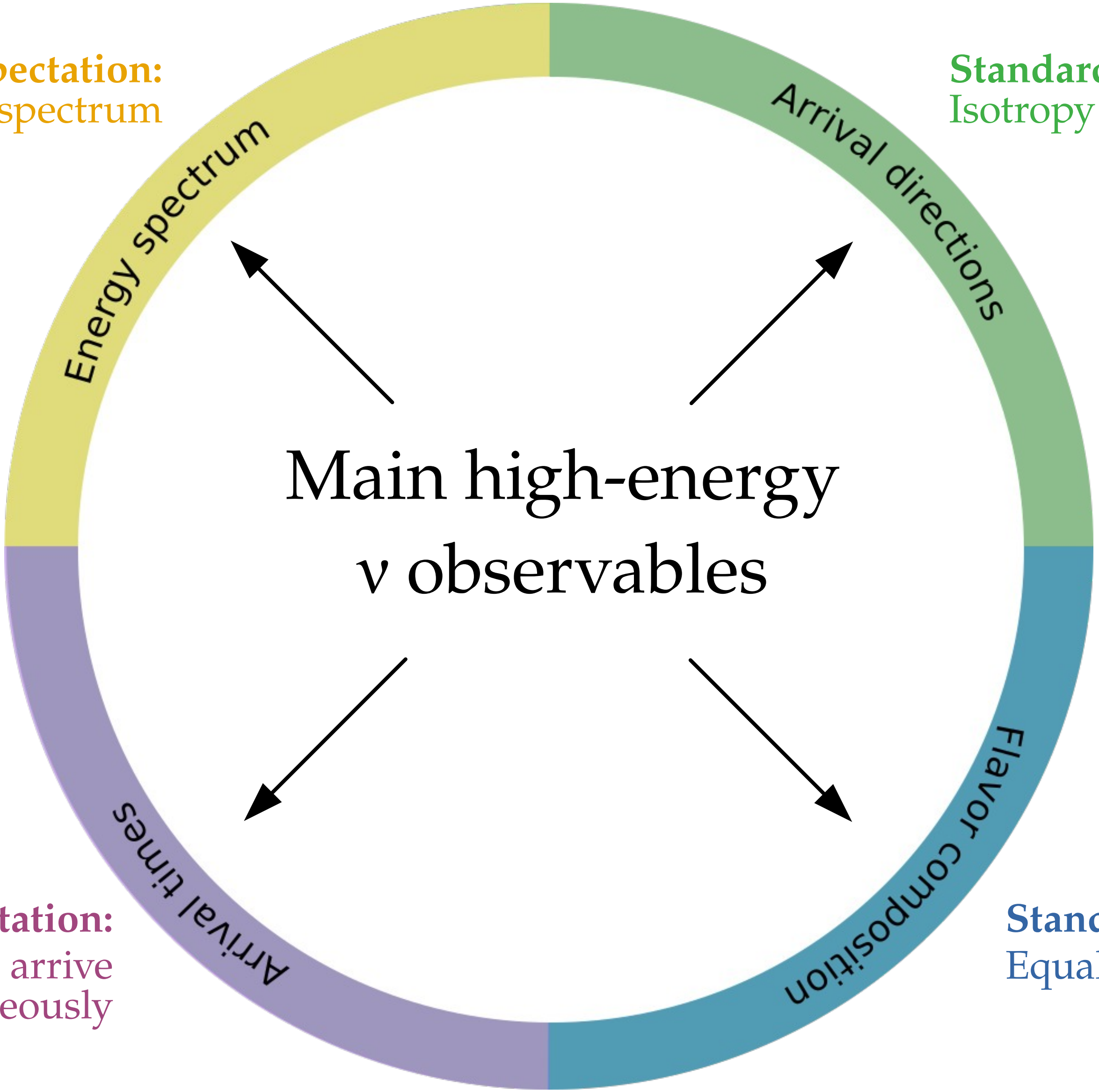

Main high-energy
ν observables
Energy spectrum
Arrival directions
Flavor composition
Arrival times

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

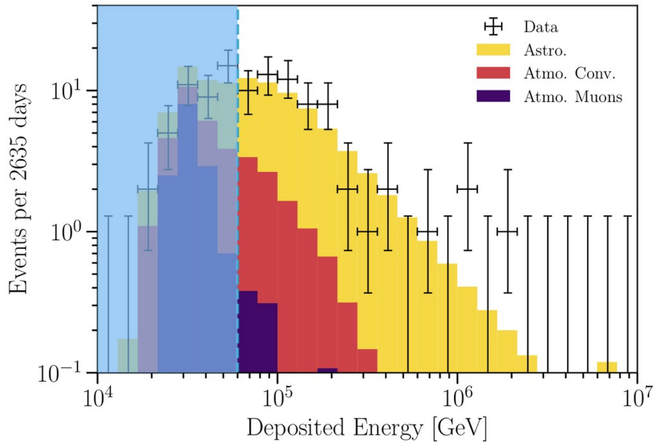


Standard expectation:
ν and γ from transients arrive simultaneously

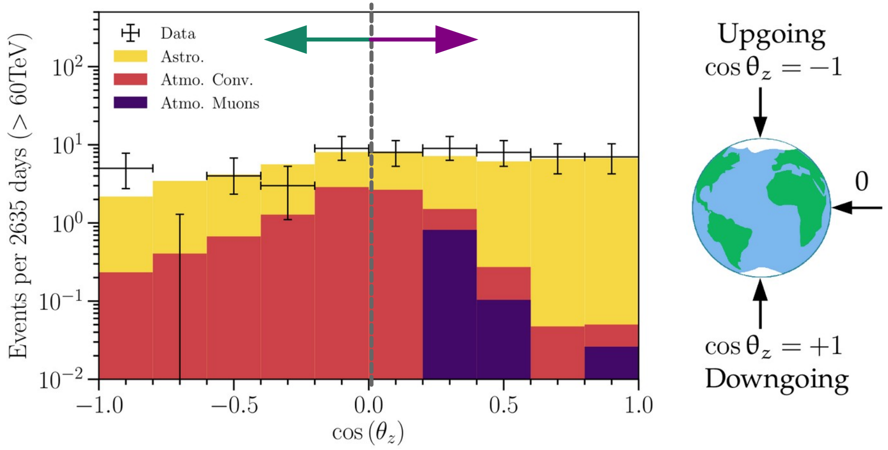
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Neutrino energy spectrum (7.5 yr)

100+ contained events above 60 TeV:

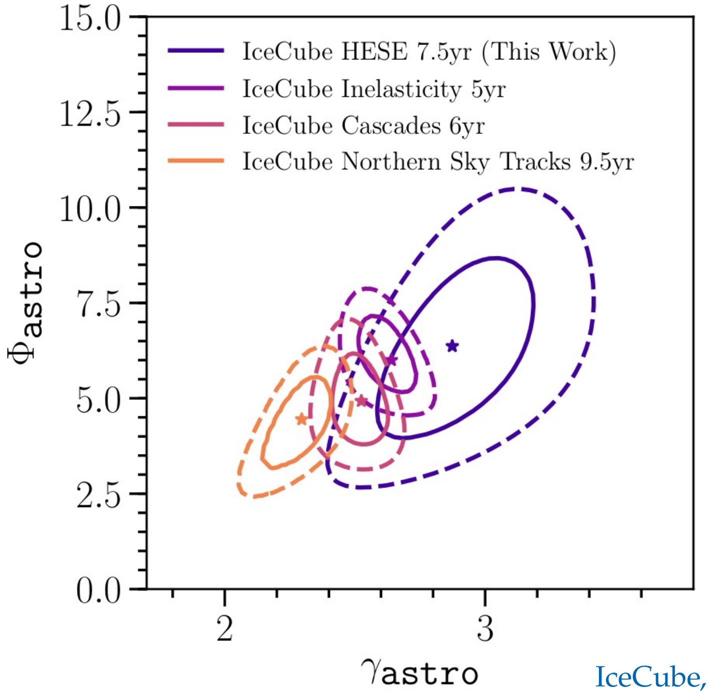


ν attenuated by Earth Atm. ν and μ vetoed



Data is fit well by a single power law:

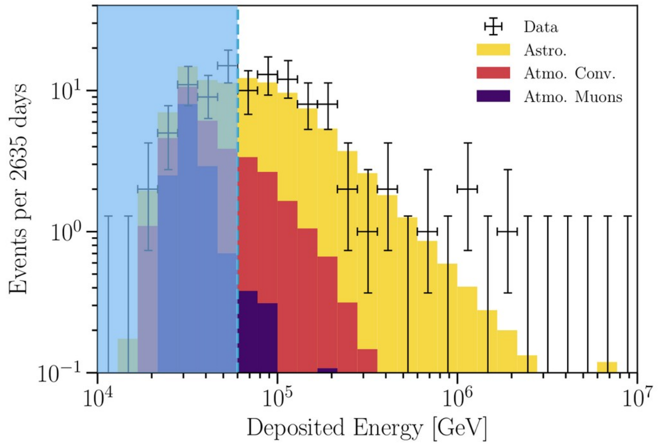
$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\text{astro}} \left(\frac{E_\nu}{100\ \text{TeV}} \right)^{-\gamma_{\text{astro}}} \cdot 10^{-18}\ \text{GeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$



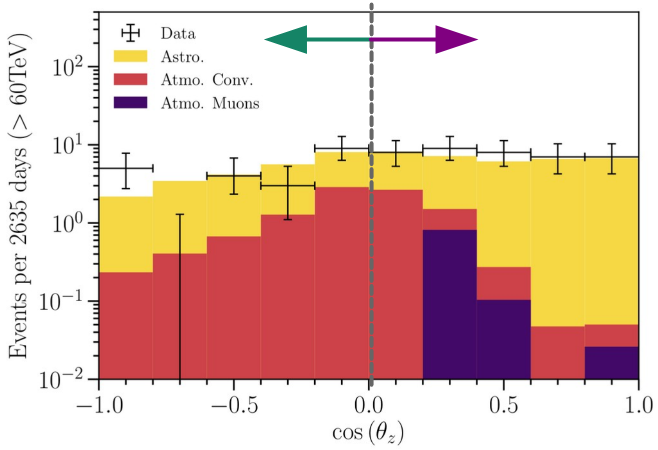
IceCube, 2011.03545

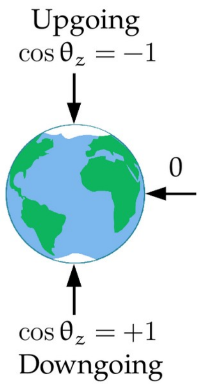
Neutrino energy spectrum (7.5 yr)

100+ contained events above 60 TeV:



ν attenuated by Earth   Atm. ν and μ vetoed





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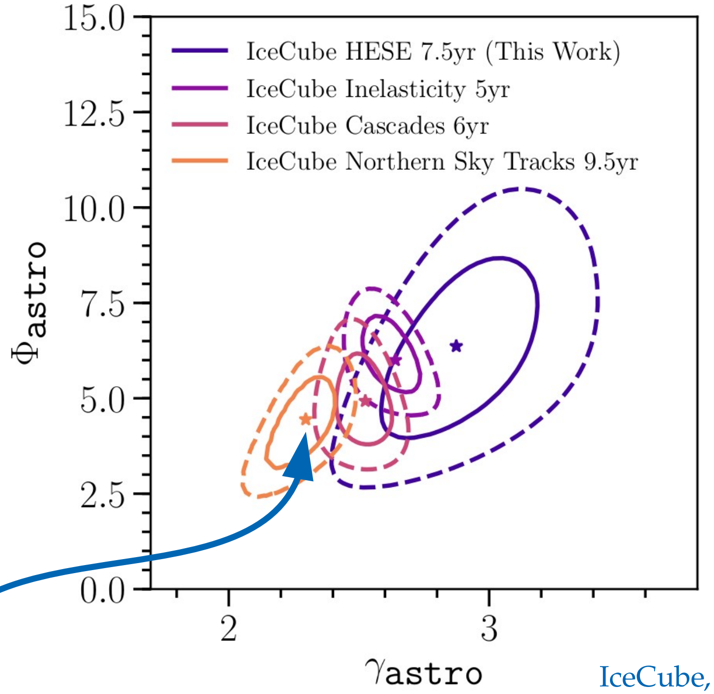
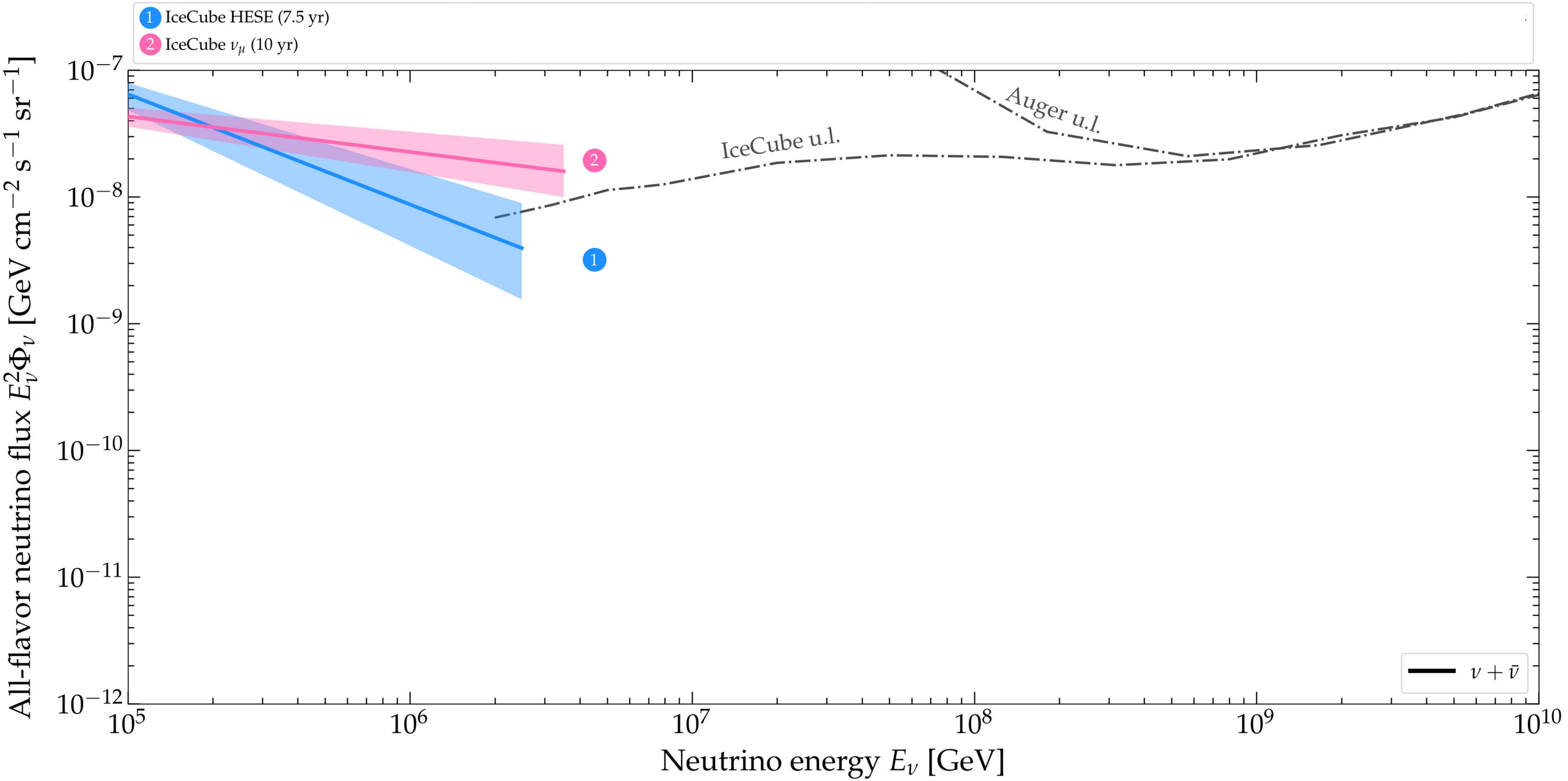


IceCube, 2011.03545

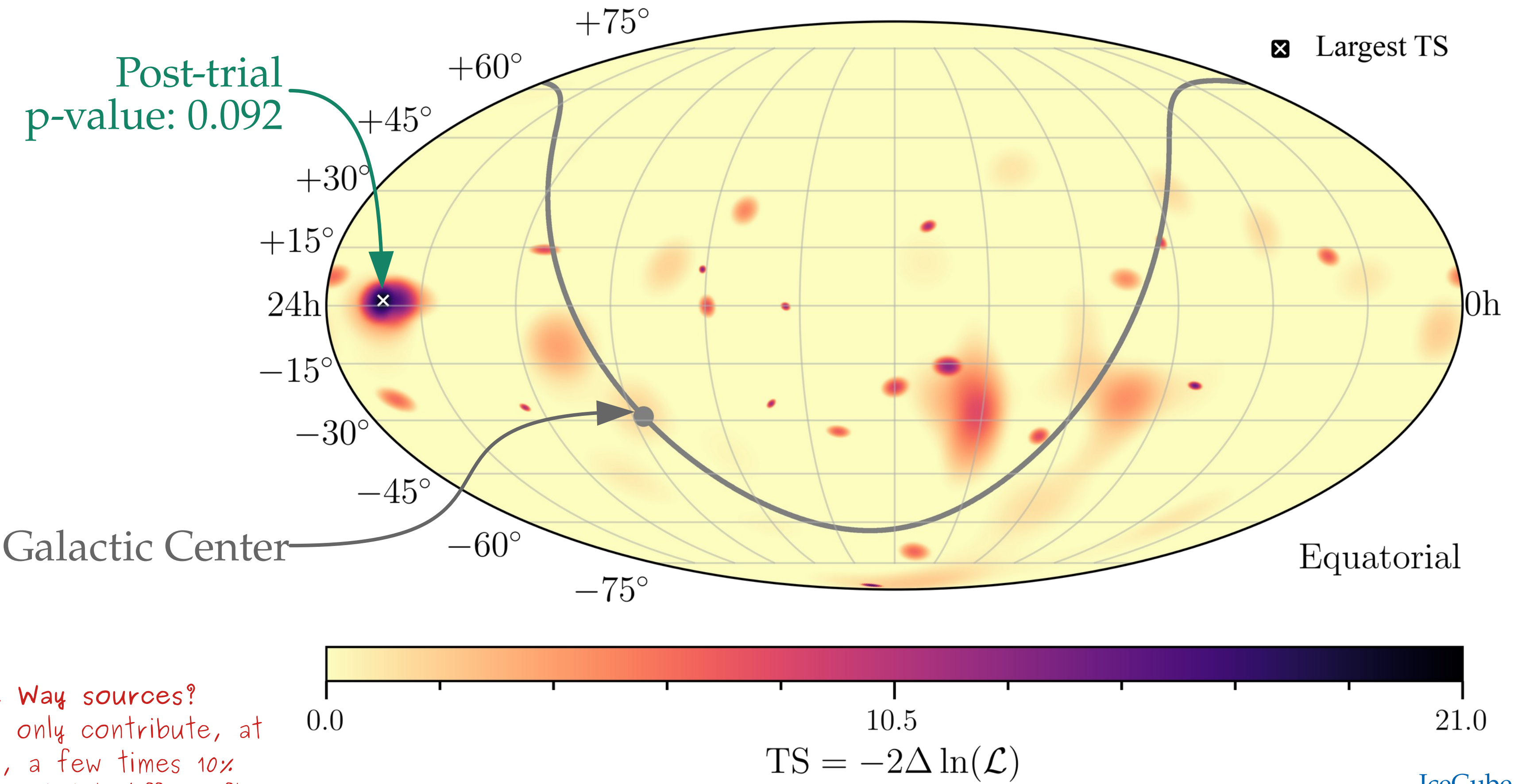
Spectrum looks harder for through-going ν_μ



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]

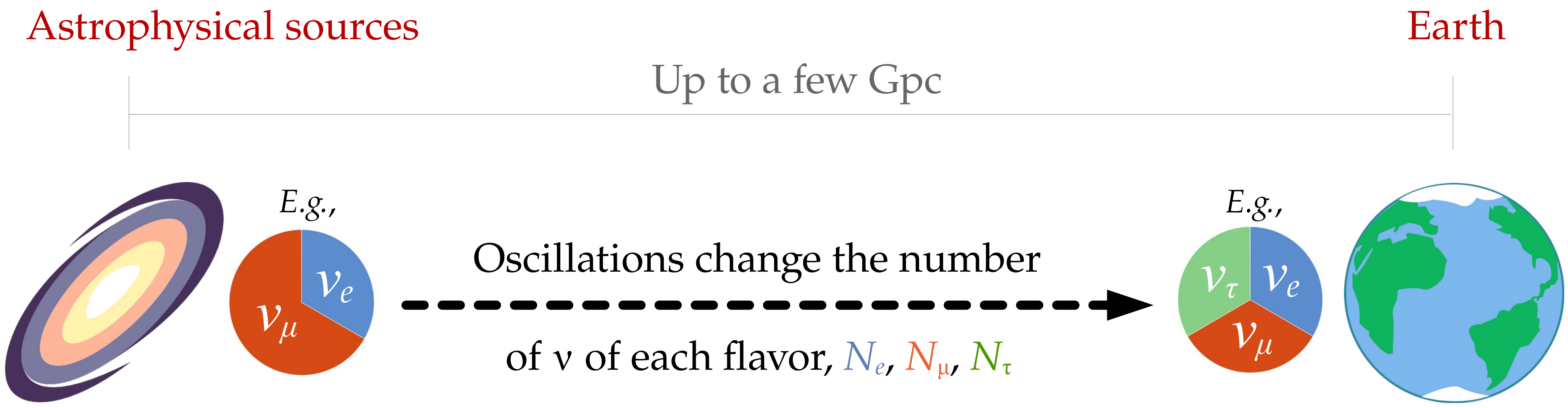
Distribution of arrival directions (7.5 yr)

No significant excess in the neutrino skymap:



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

IceCube, 2011.03545

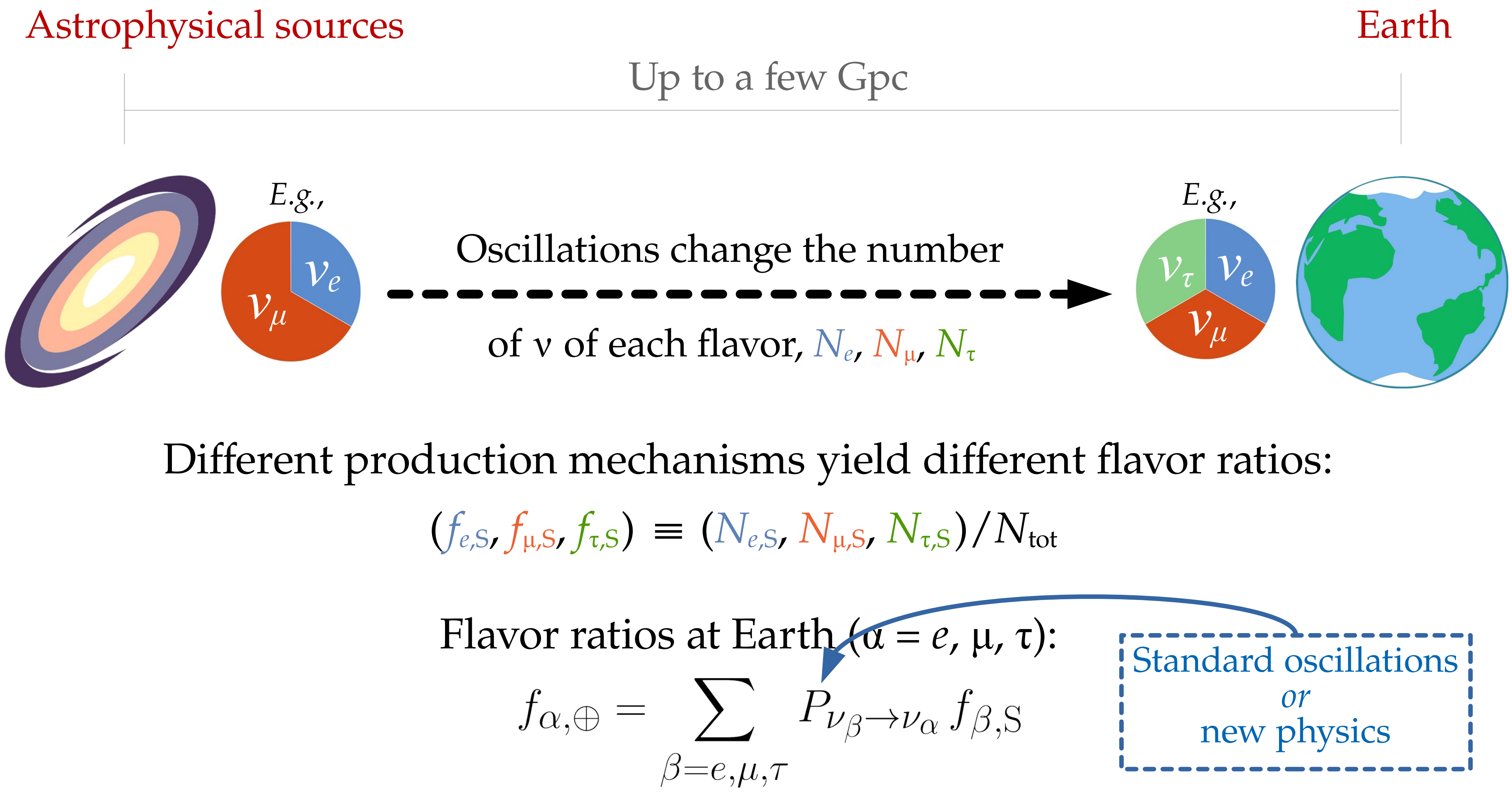


Different production mechanisms yield different flavor ratios:

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

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:
$(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S})/N_{tot}$
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):
$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,S}$
Standard oscillations
or
new physics

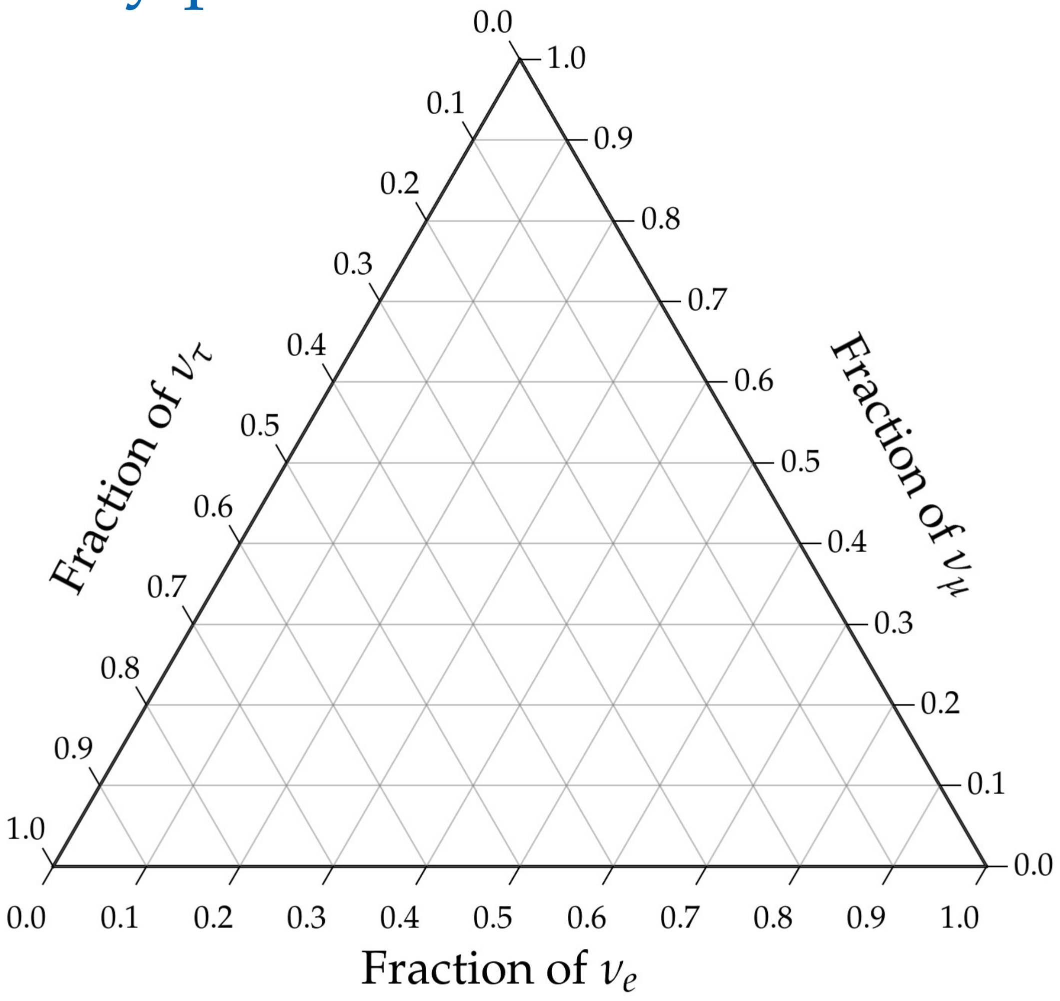
Quick aside: how to read a ternary plot

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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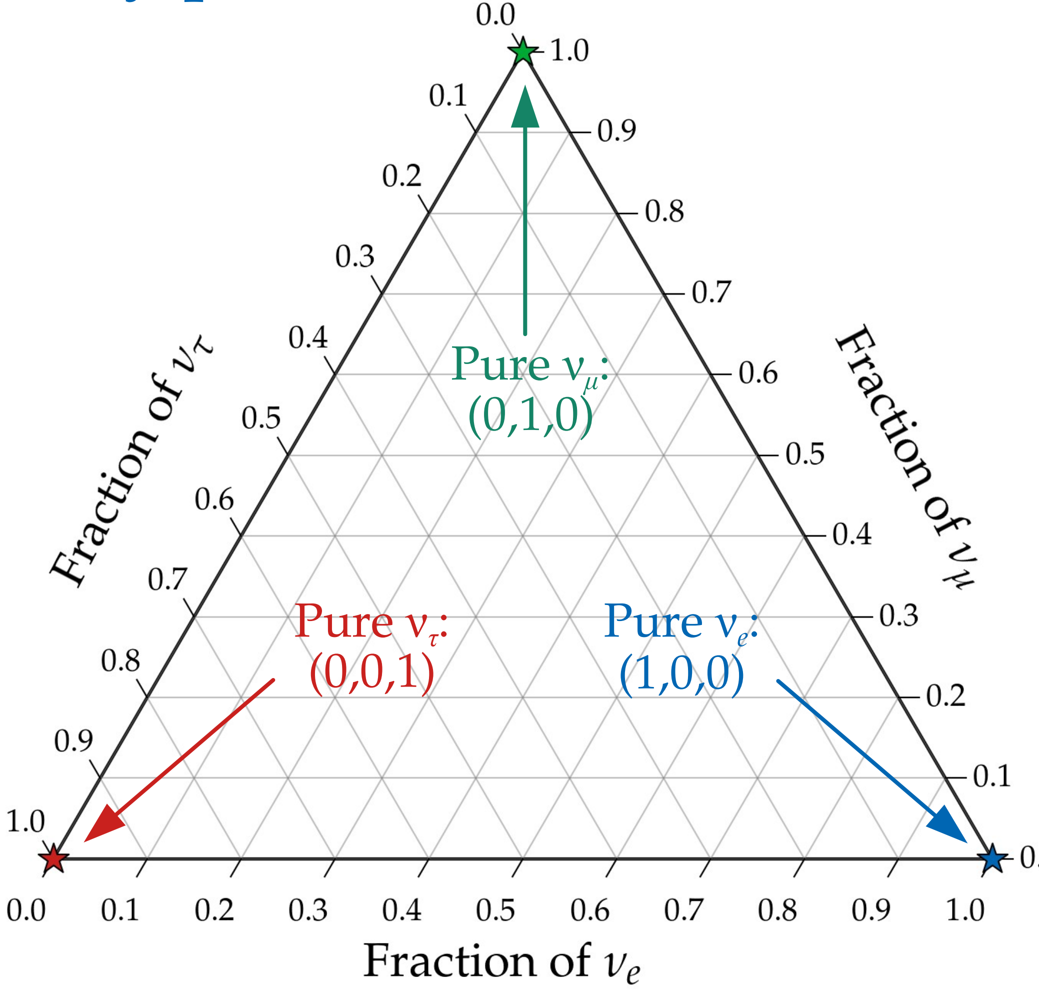

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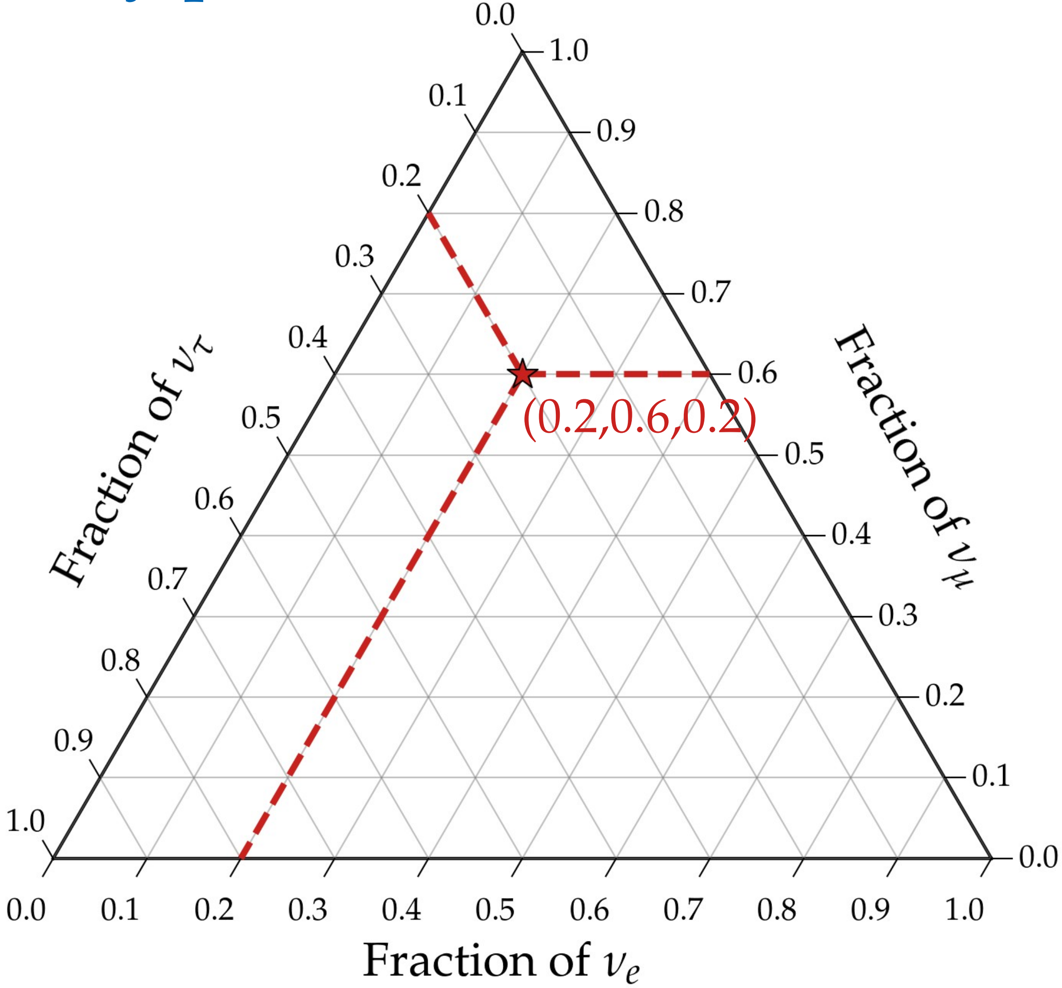

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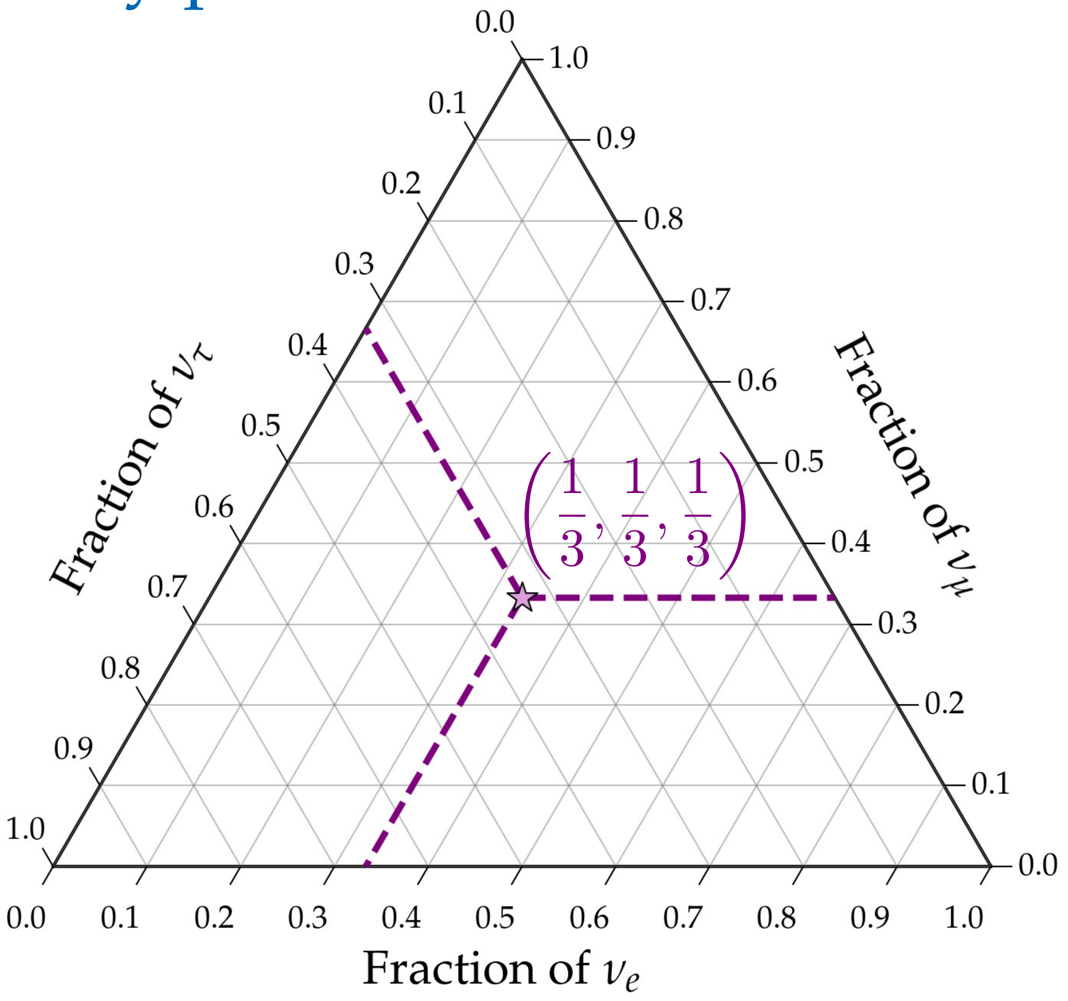
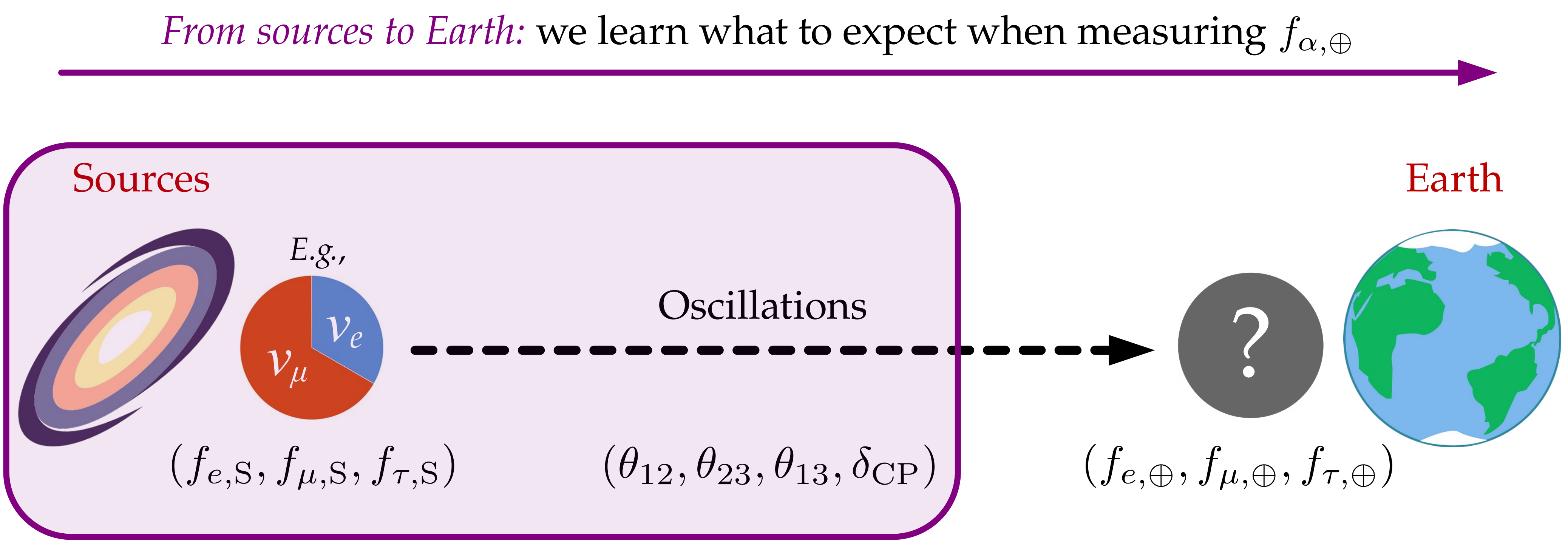
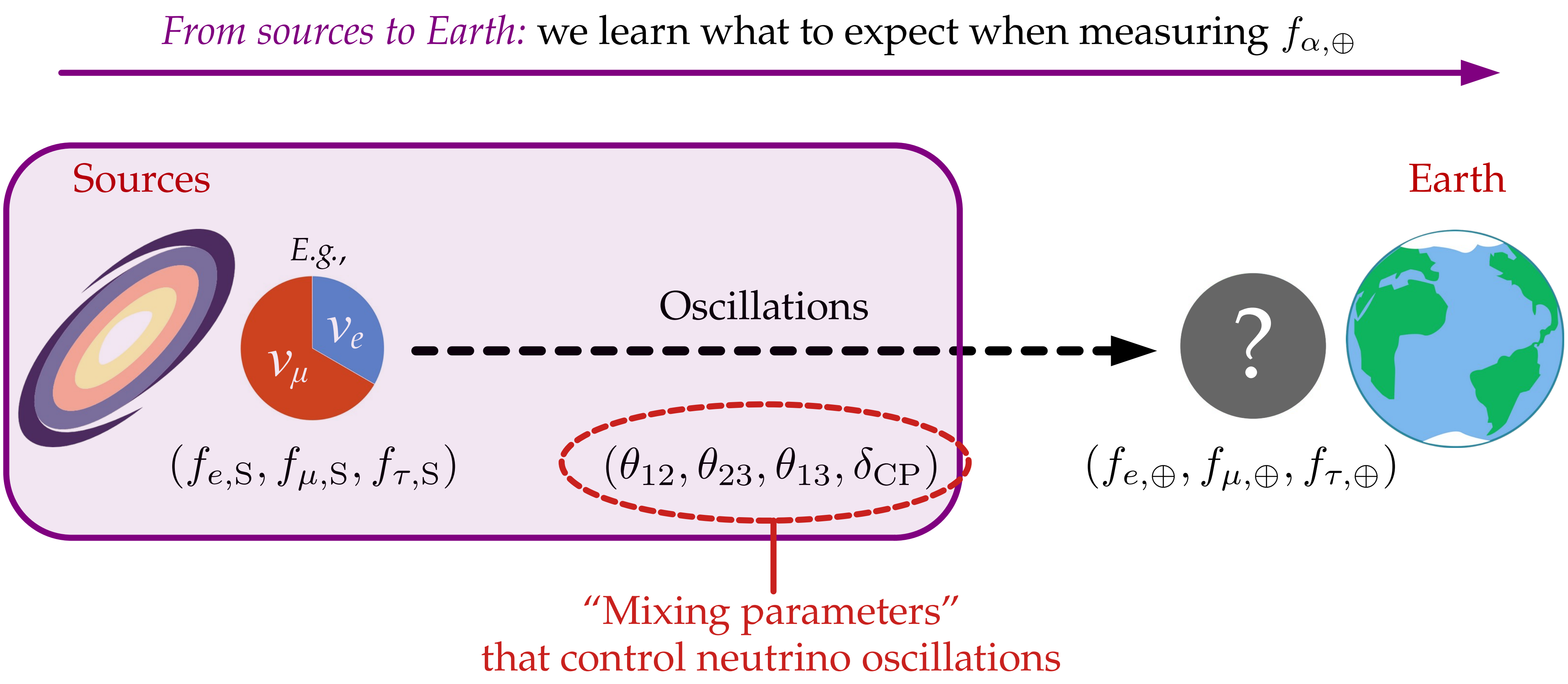



From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$
Sources
Earth
E.g.,
ν_e
ν_μ
Oscillations
?
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$



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

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

One likely TeV–PeV ν production scenario:

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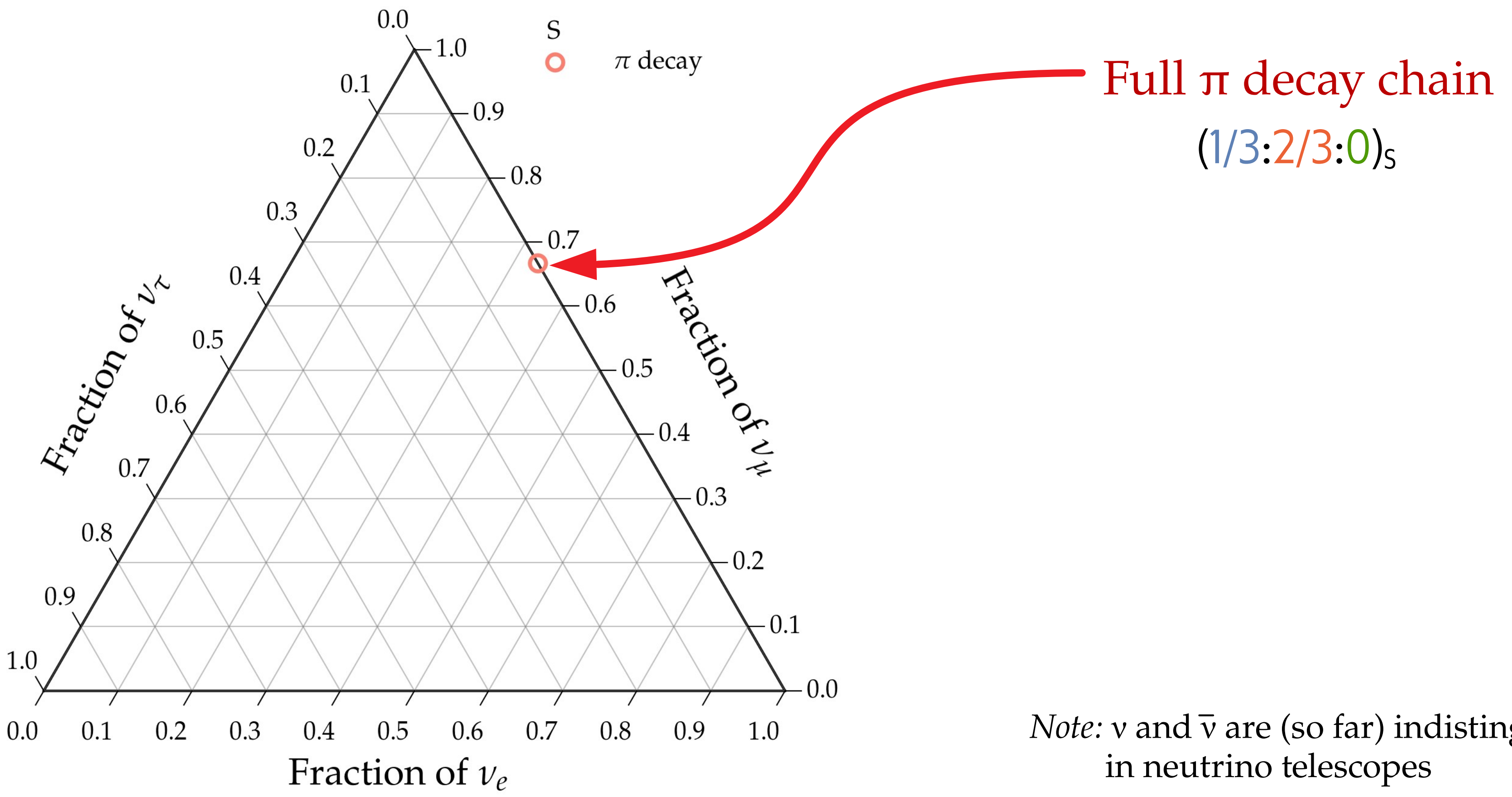

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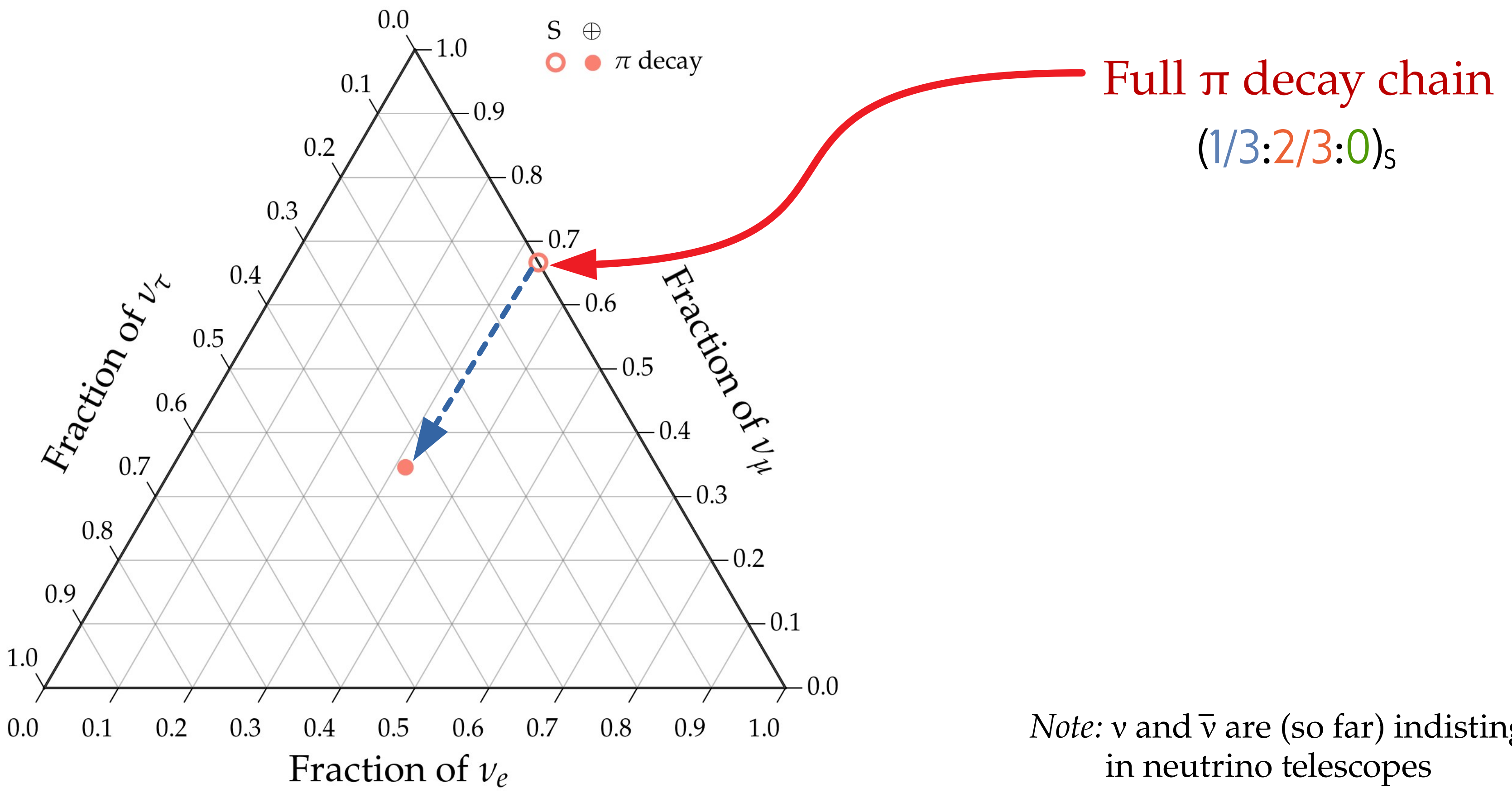

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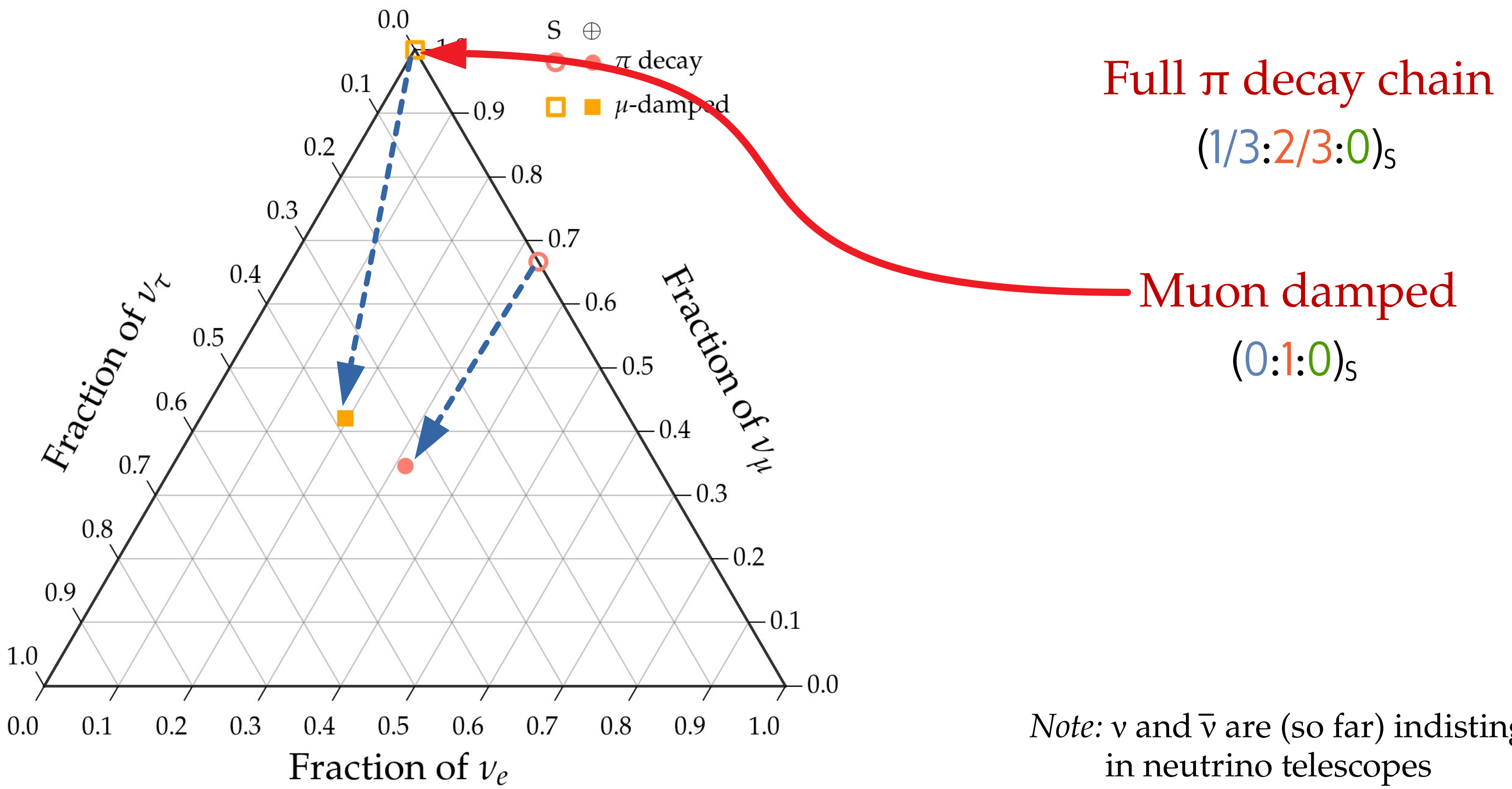

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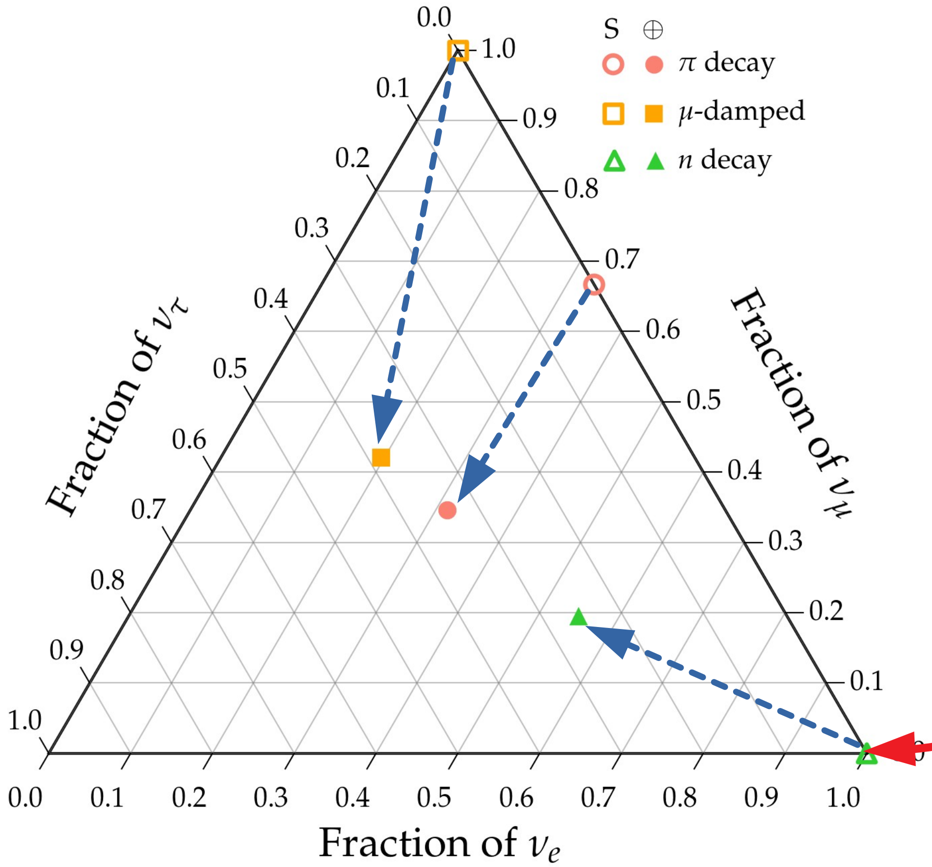


Full π decay chain

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

Muon damped

(0:1:0)$_S$

Neutron decay

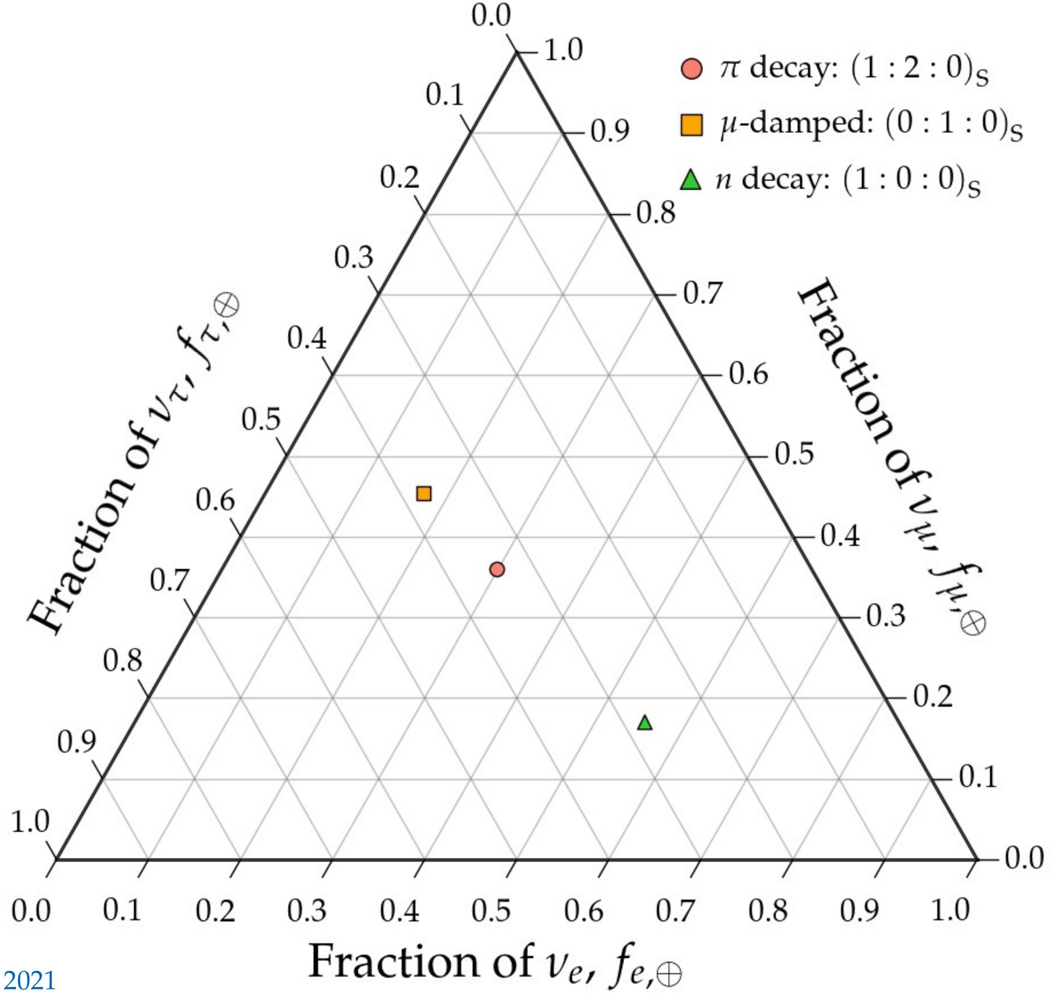
(1:0:0)$_S$

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

Measuring flavor composition: 2015–2040

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
IceCube, *PRL* 2015, *ApJ* 2015, *PRD* 2019, *J. Phys. G* 2021, 2011.03561

Measuring flavor composition: 2015–2040



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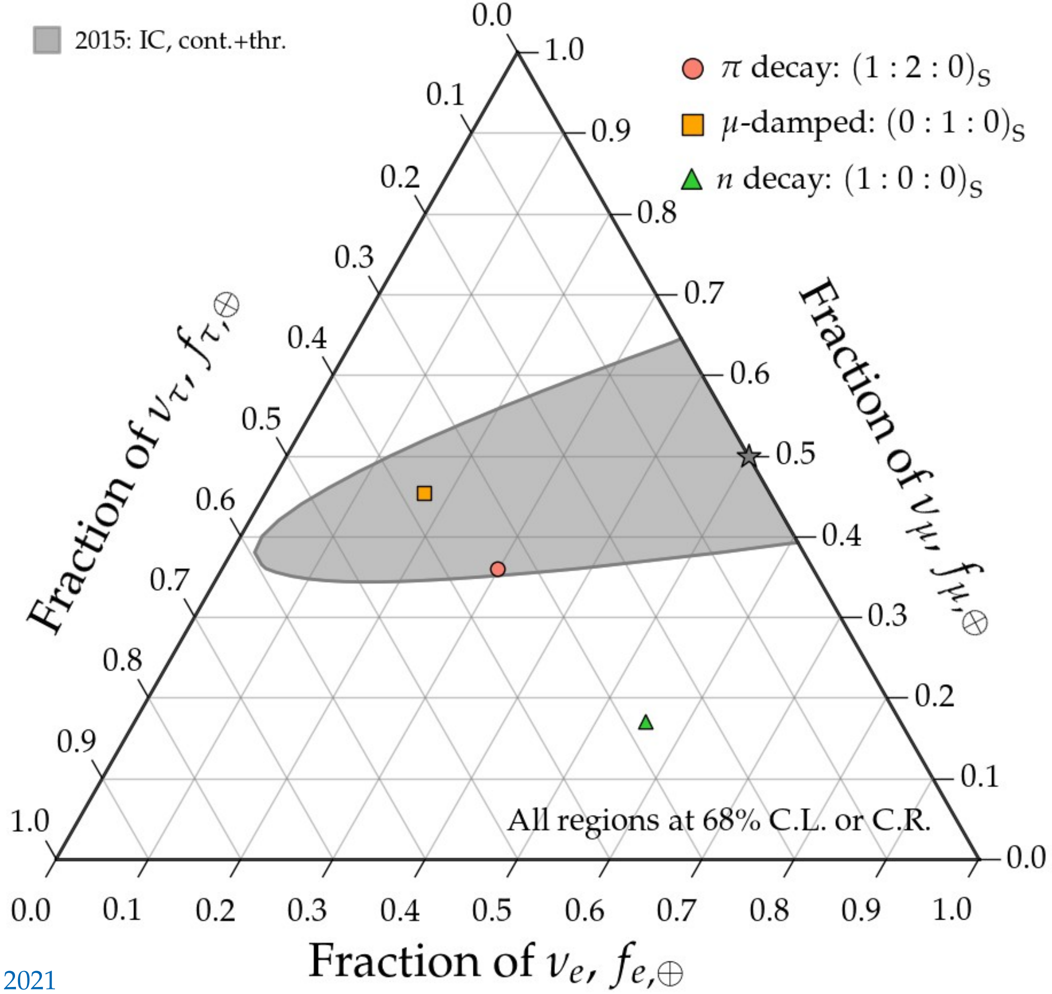

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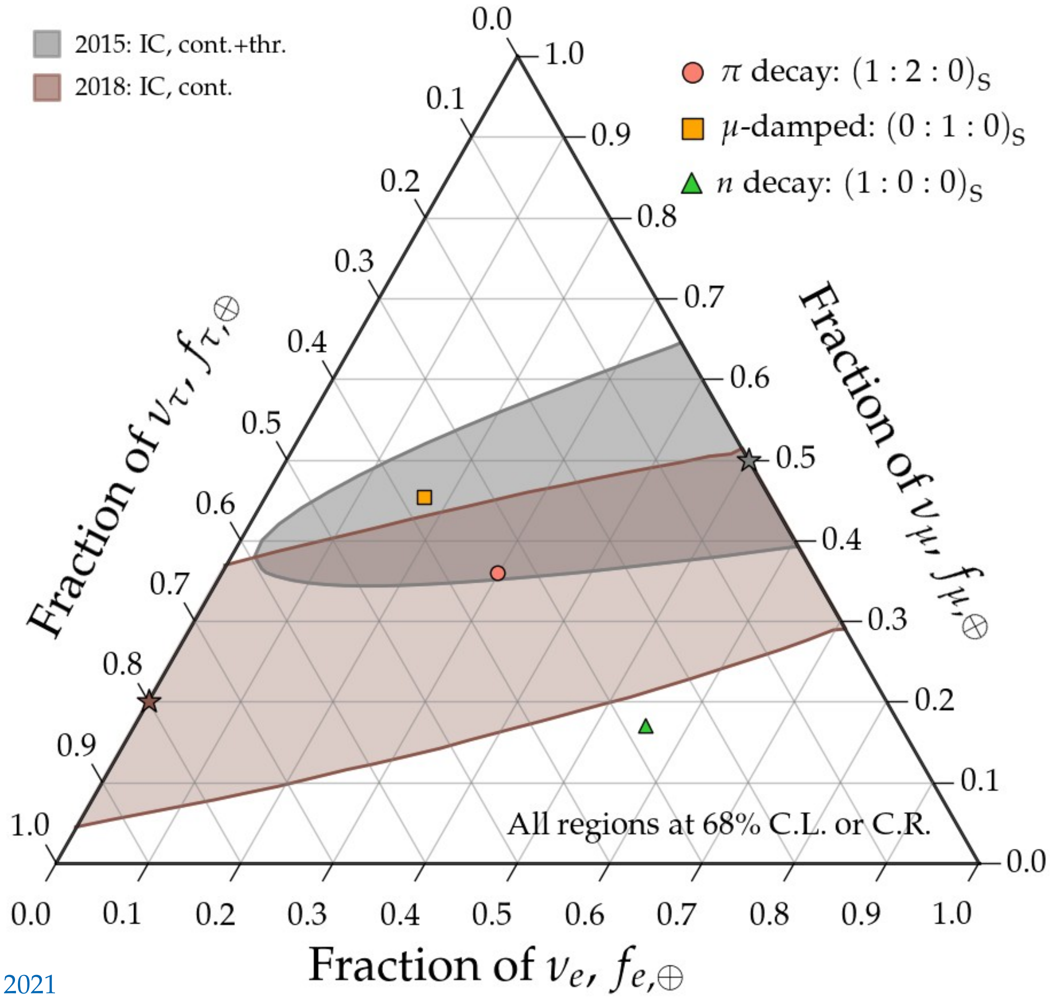

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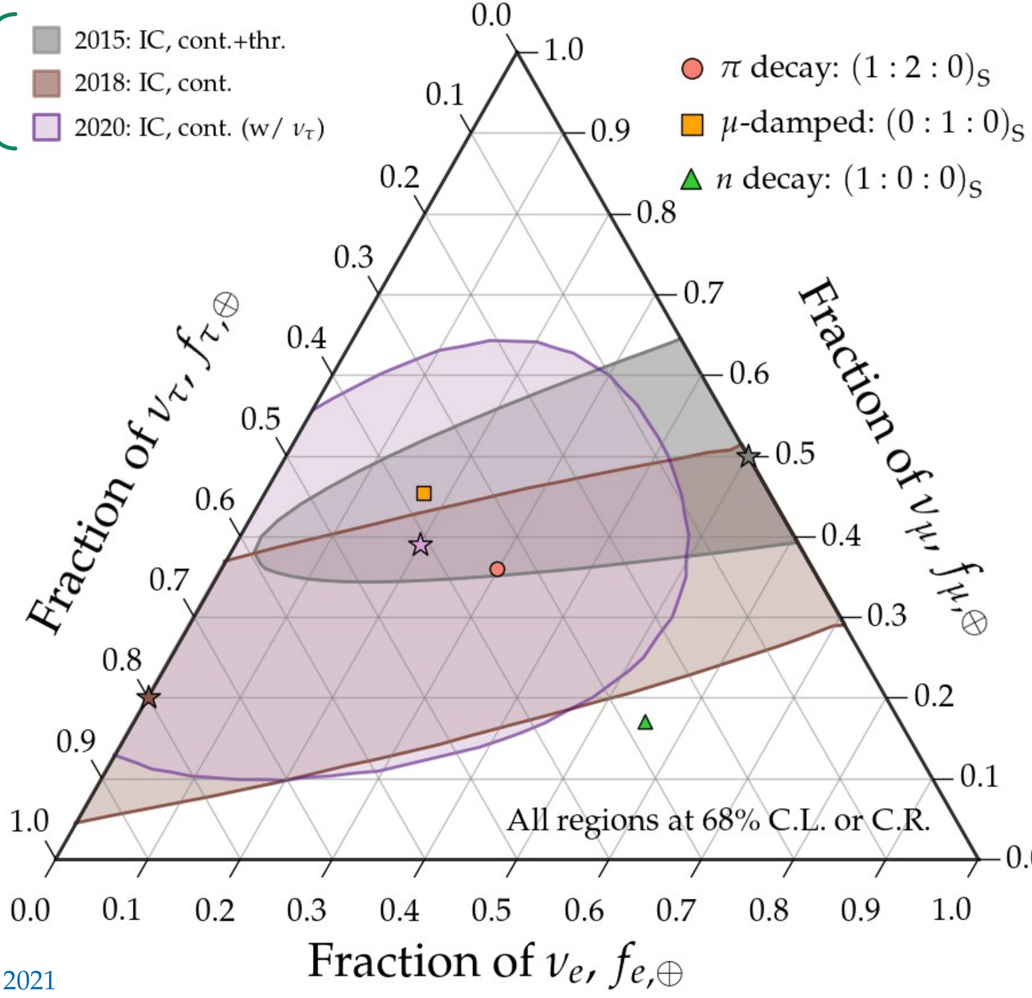
IceCube, *PRL* 2015, *ApJ* 2015, *PRD* 2019, *J. Phys. G* 2021, 2011.03561

Measuring flavor composition: 2015–2040

Based on real data



Status today:
Measurements are compatible with standard expectations (but errors are large!)

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
IceCube, *PRL* 2015, *ApJ* 2015, *PRD* 2019, *J. Phys. G* 2021, 2011.03561

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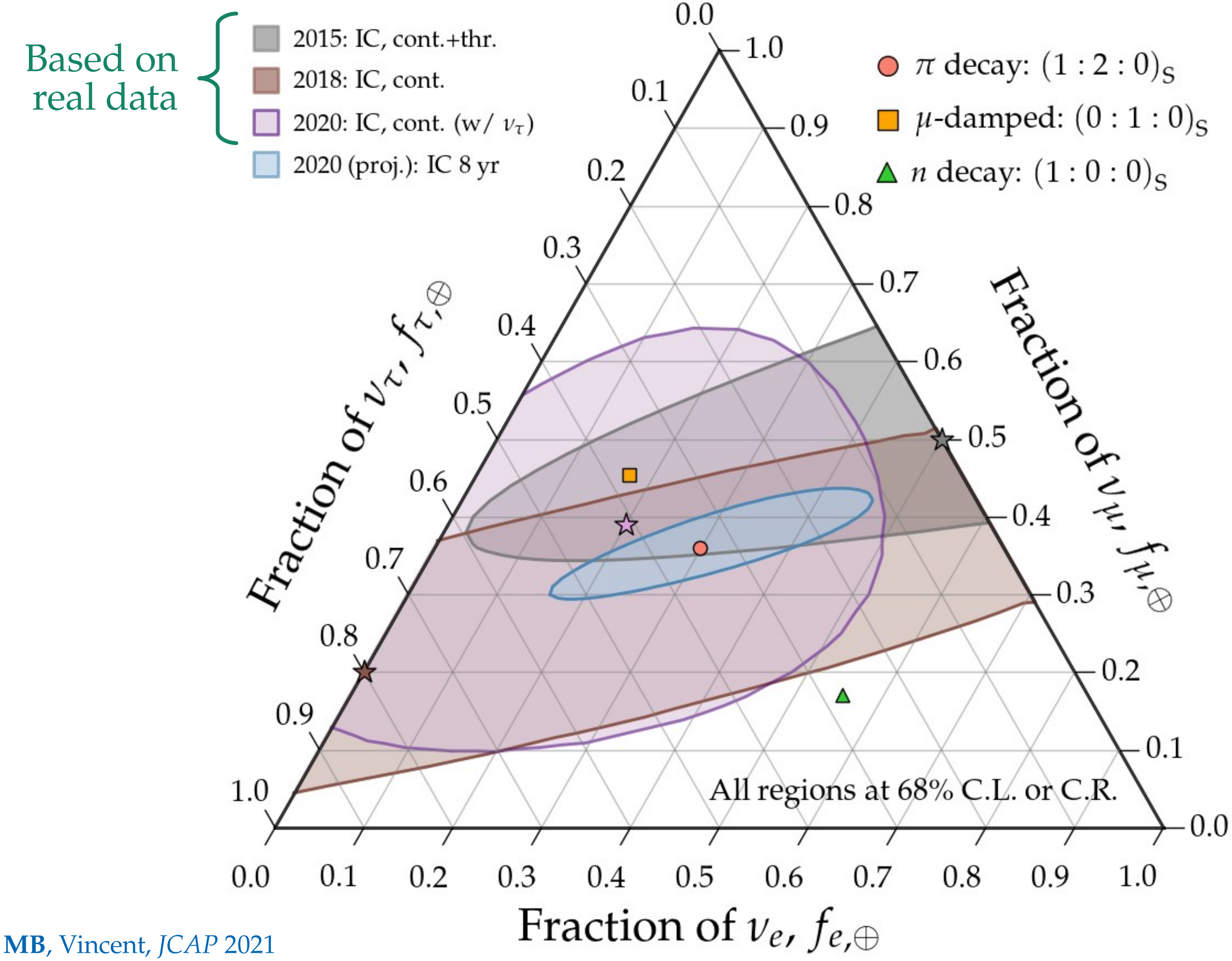

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Near future (~2020):
× 5 reduction using 8 yr of IC contained + thru.

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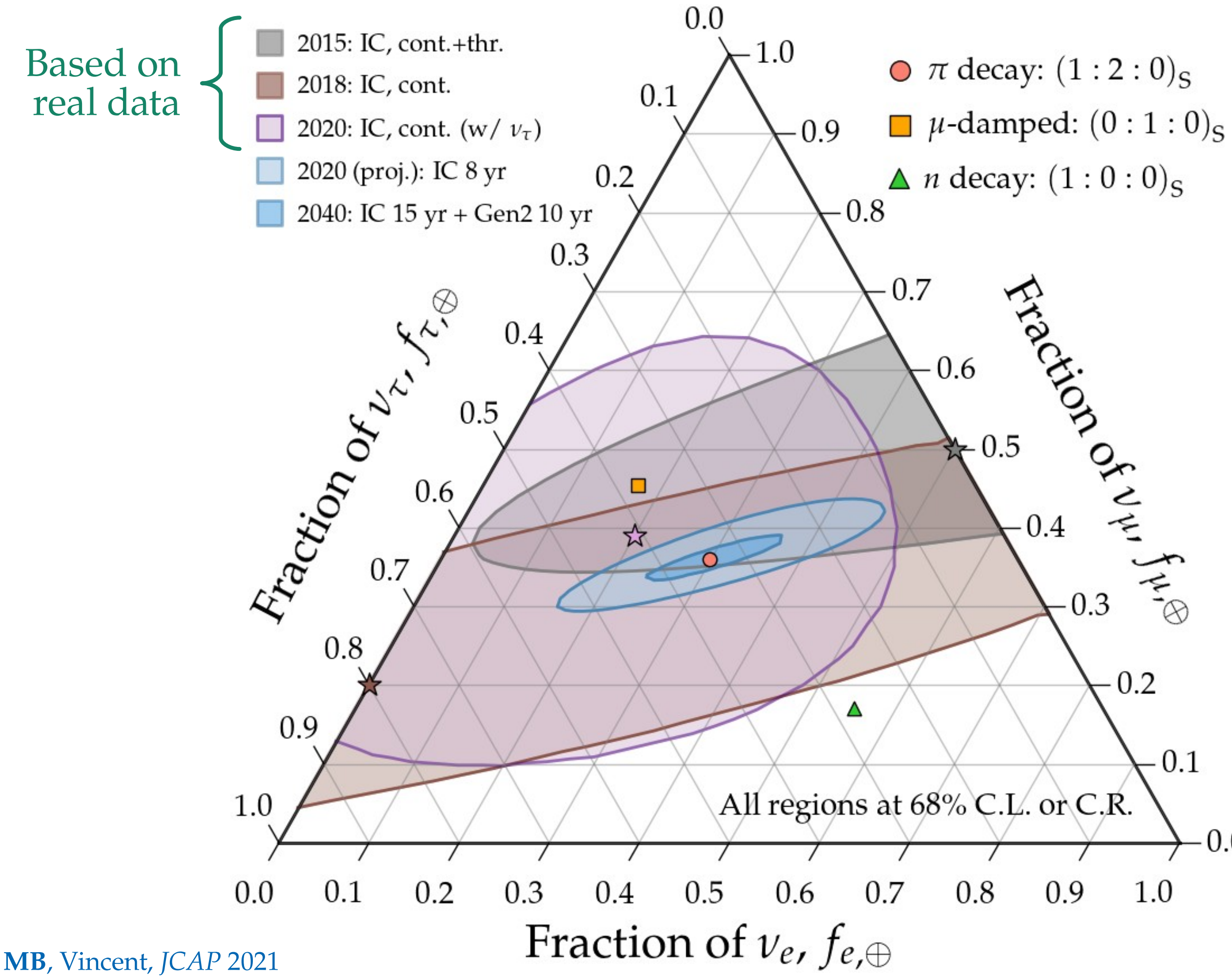

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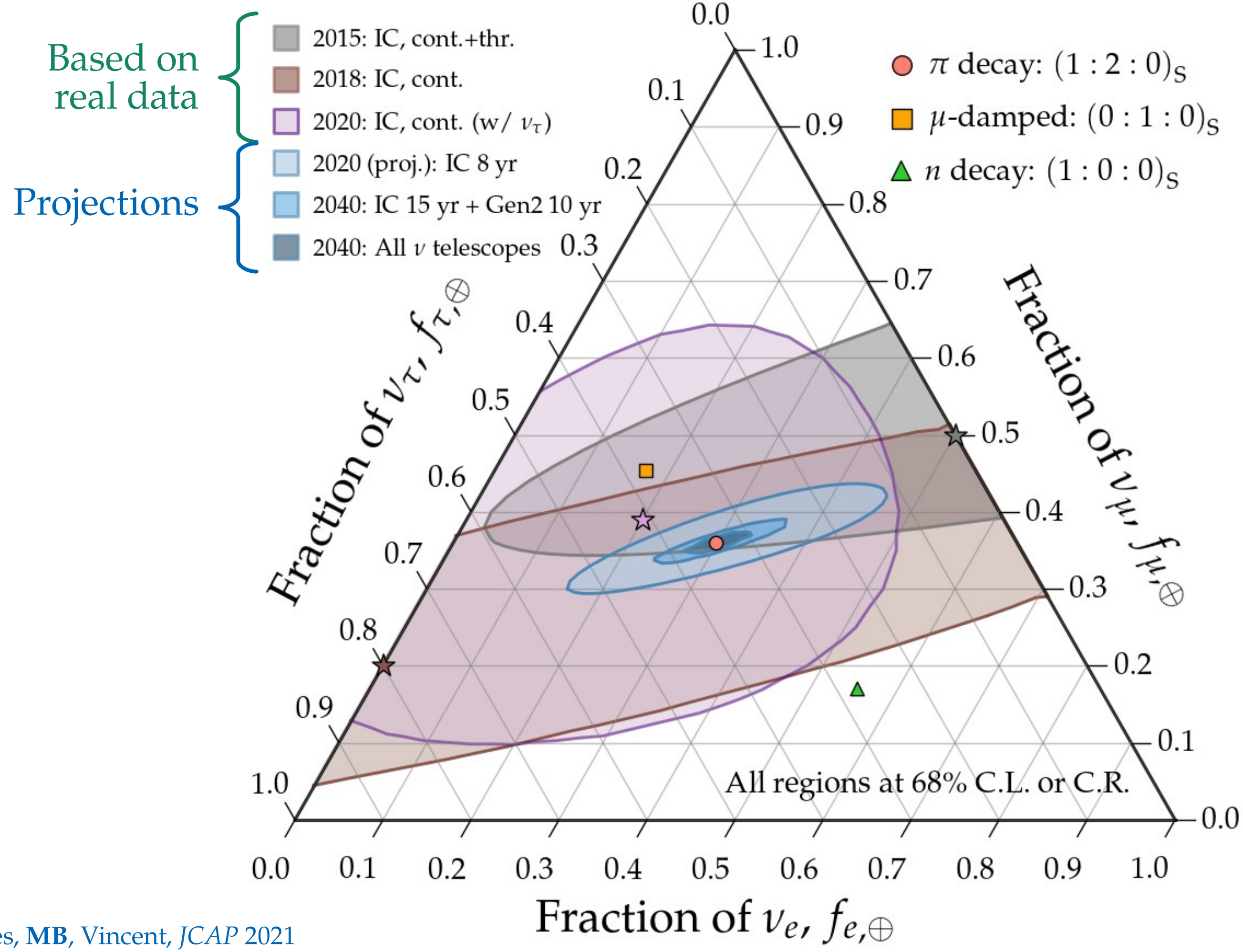
Measuring flavor composition: 2015–2040



Status today:
Measurements are compatible with standard expectations (but errors are large!)

Projections:

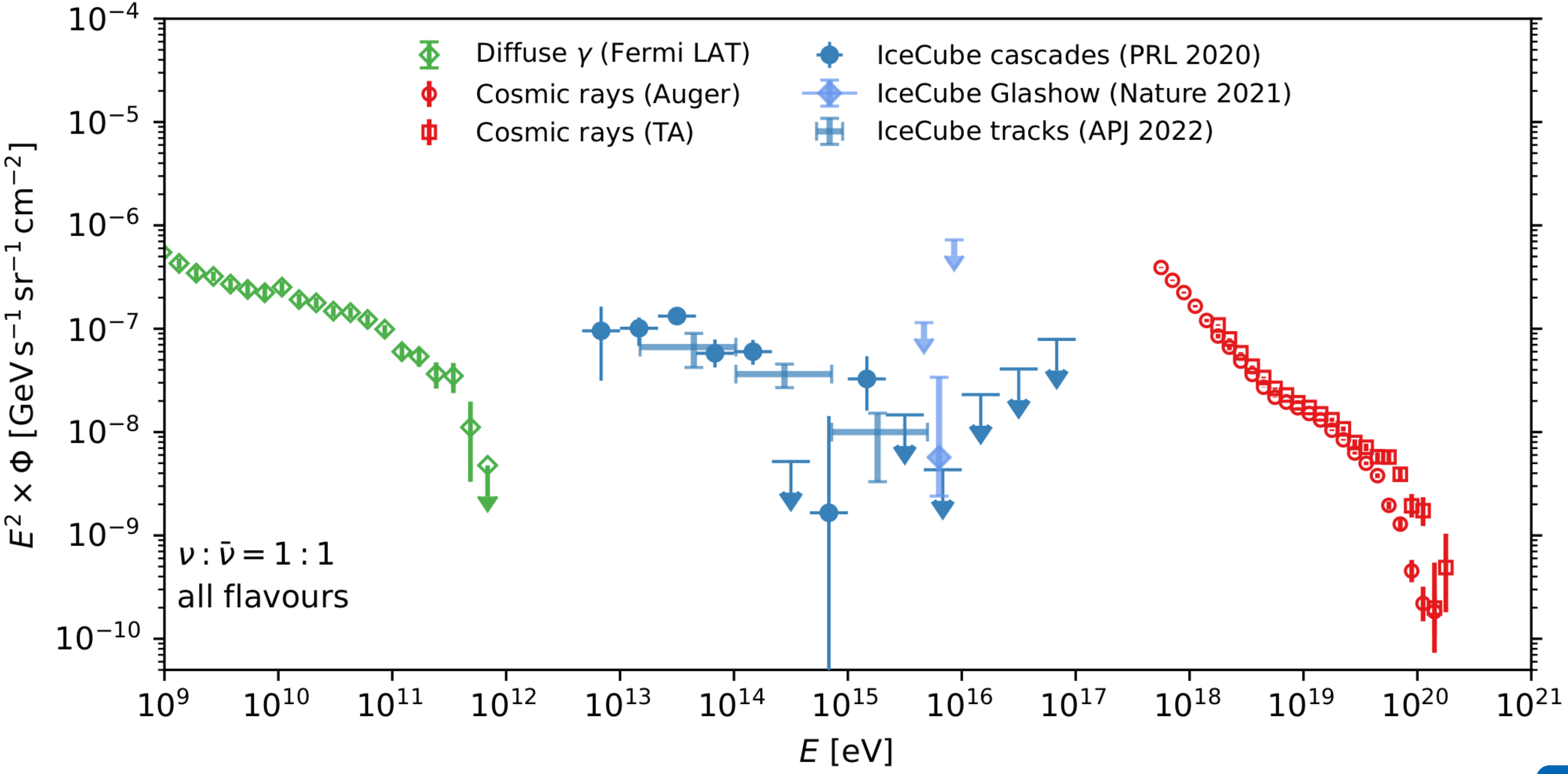
Near future (~2020):
× 5 reduction using 8 yr of IC contained + thru.

Coming up (~2040):
× 10 reduction using Gen2 and all ν telescopes

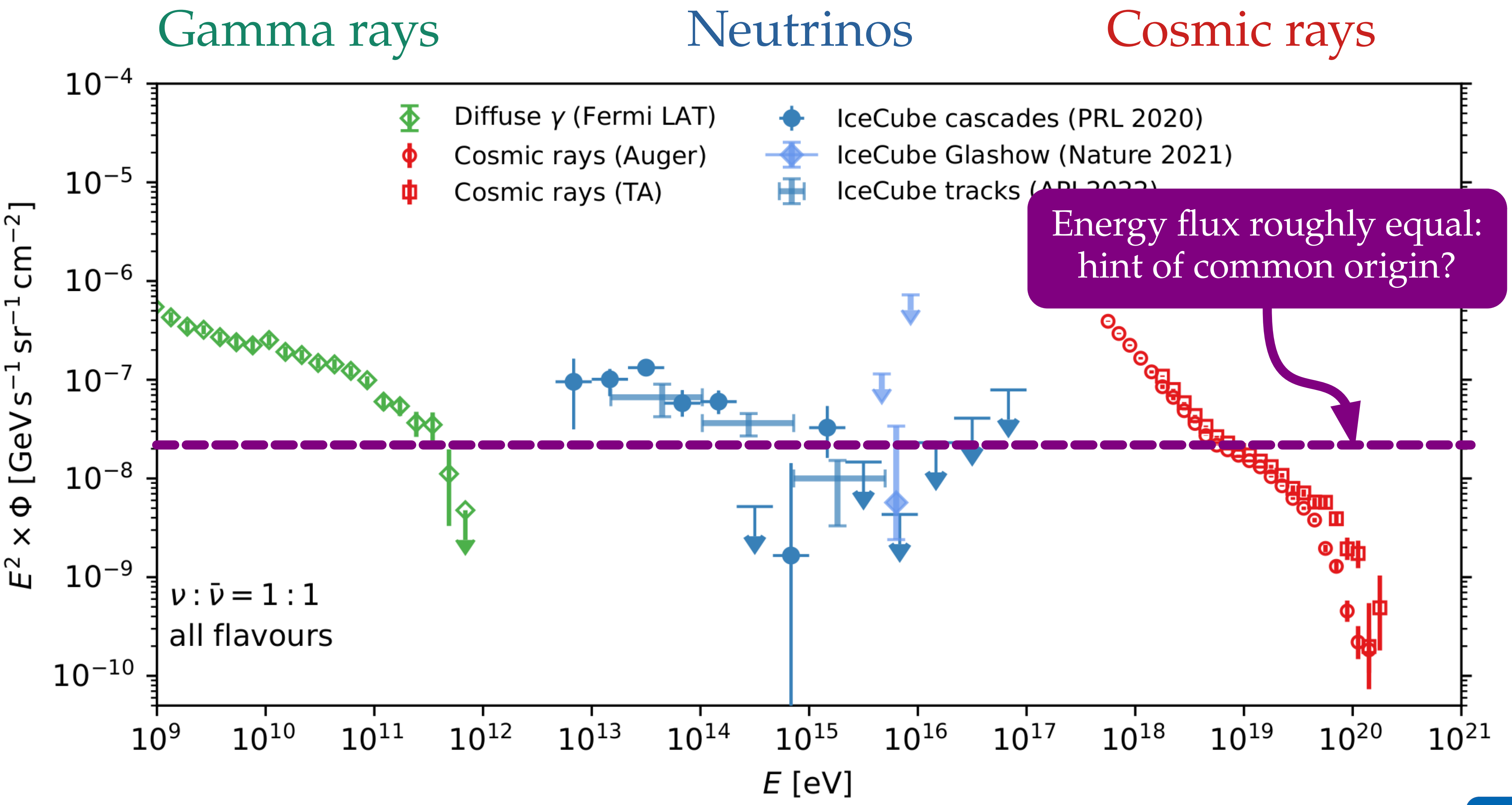
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
IceCube, *PRL* 2015, *ApJ* 2015, *PRD* 2019, *J. Phys. G* 2021, 2011.03561

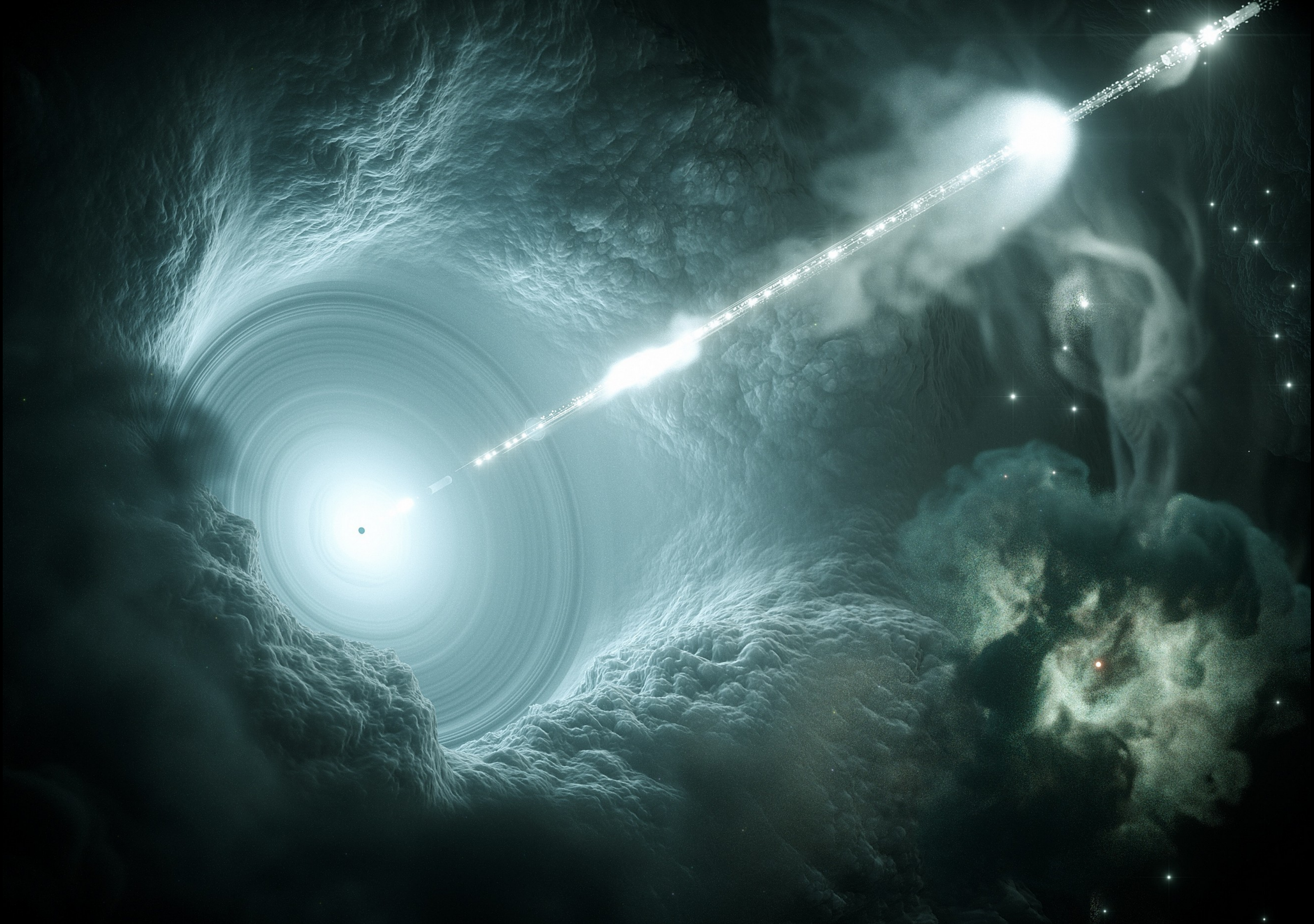
II.
What have we learned about *astrophysics*

Gamma rays Neutrinos Cosmic rays



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

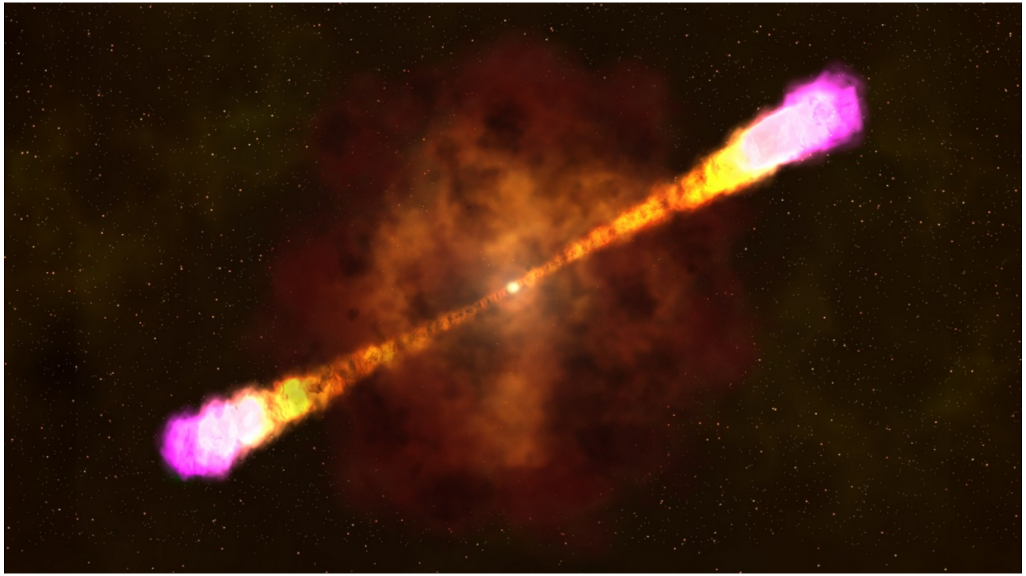

Gamma rays
Neutrinos
Cosmic rays
Diffuse γ (Fermi LAT)
Cosmic rays (Auger)
Cosmic rays (TA)
IceCube cascades (PRL 2020)
IceCube Glashow (Nature 2021)
IceCube tracks
Energy flux roughly equal:
hint of common origin?
$\nu : \bar{\nu} = 1:1$
all flavours
$E^2 \times \Phi$ [GeV s^{-1} sr^{-1} cm^{-2}]
E [eV]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} 10^{21}



DESY

Gamma-ray bursts and blazars – *not* dominant

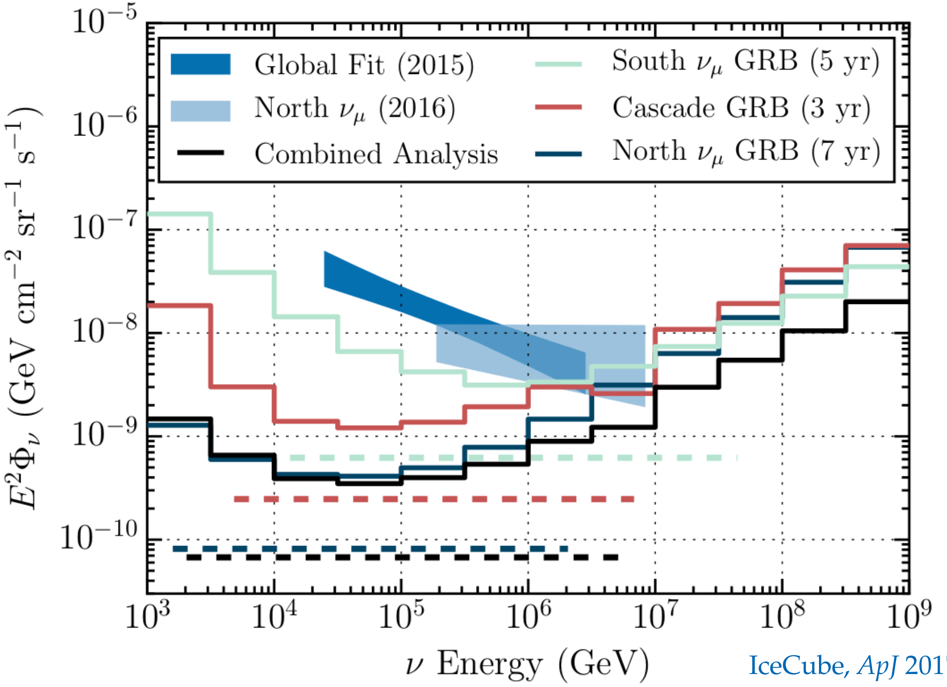
Gamma-ray bursts



Blazars

Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts

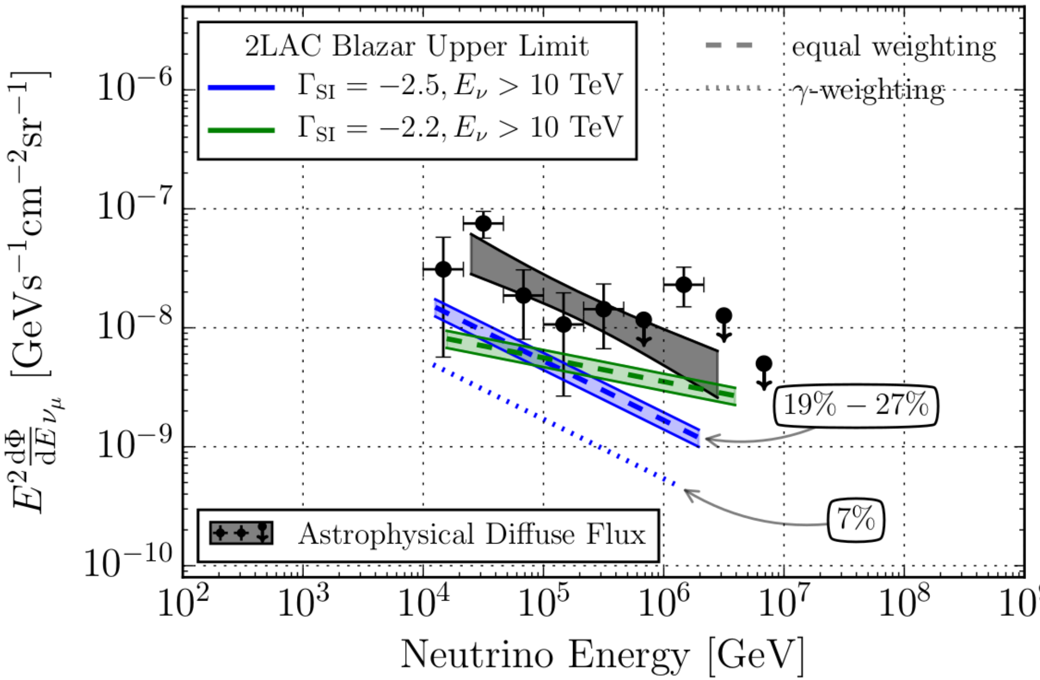


IceCube, *ApJ* 2017

1172 GRBs inspected, no correlation found

$<1\%$ contribution to diffuse flux

Blazars

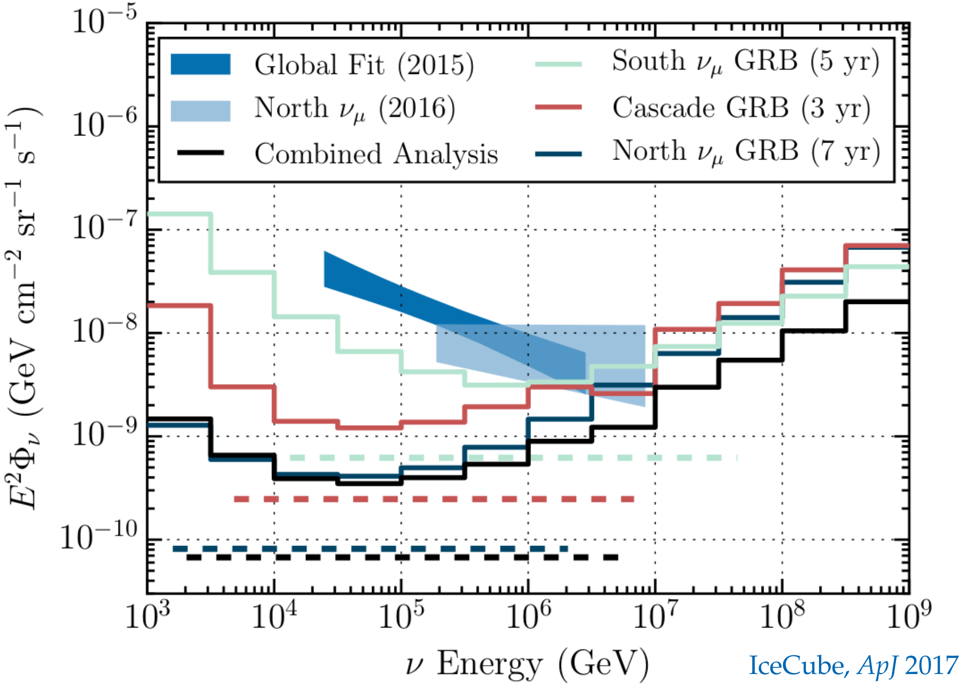


862 blazars inspected, no correlation found

$<27\%$ contribution to diffuse flux

Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts

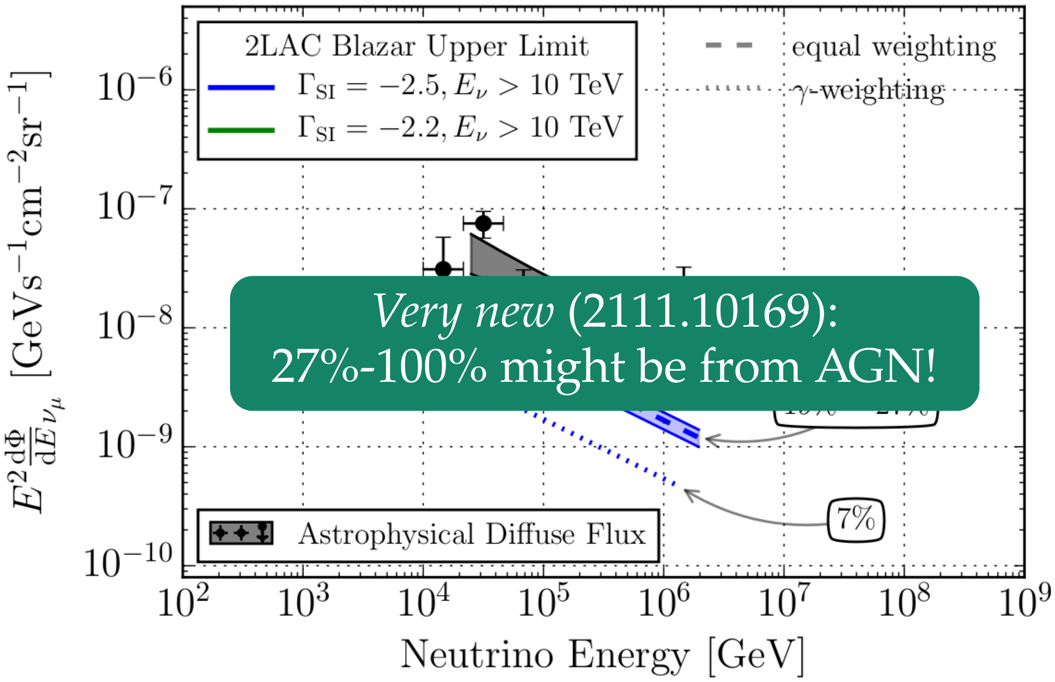


IceCube, *ApJ* 2017

1172 GRBs inspected, no correlation found

< 1% contribution to diffuse flux

Blazars

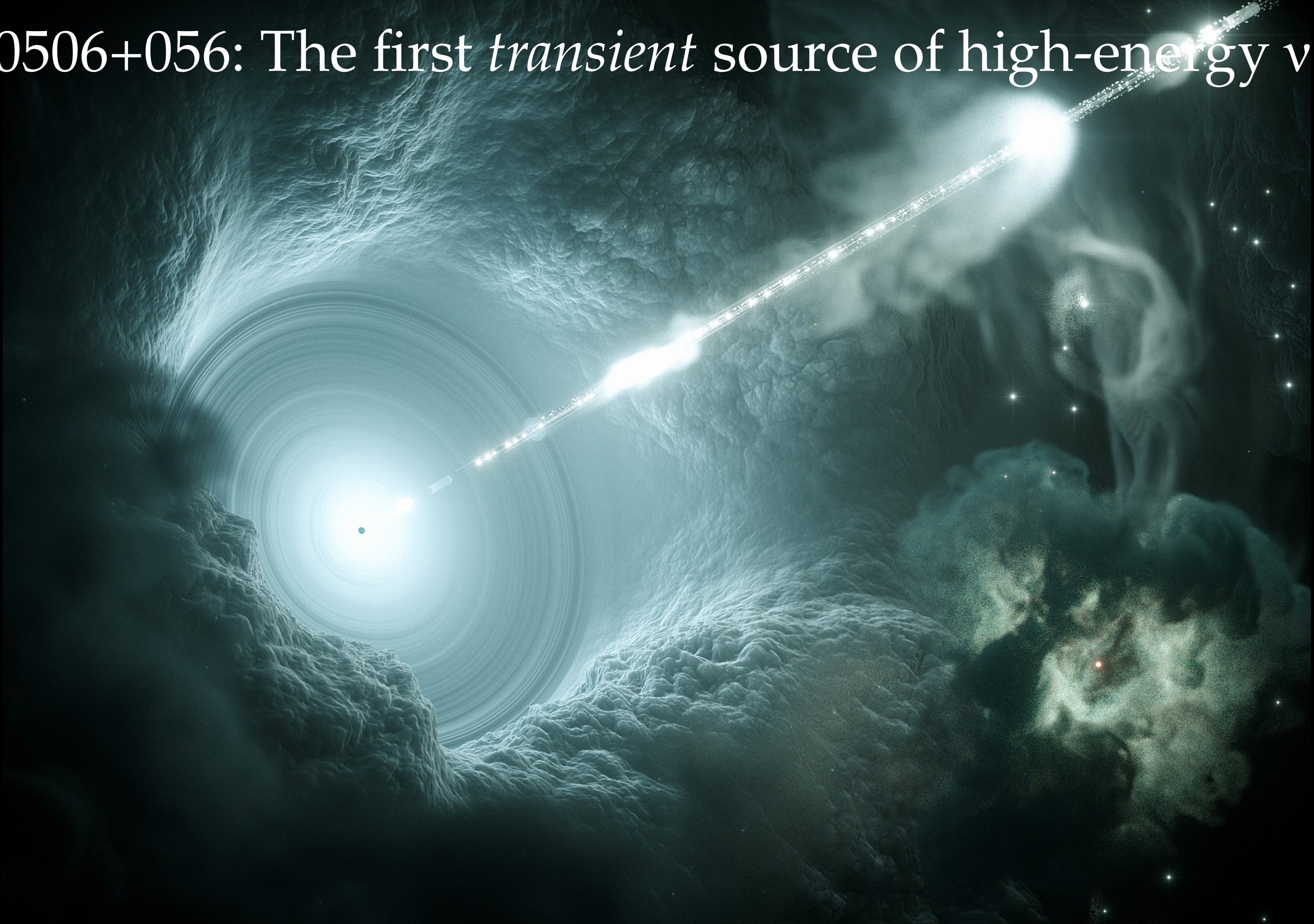


Very new (2111.10169):
27%-100% might be from AGN!

862 blazars inspected, no correlation found

< 27% contribution to diffuse flux

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

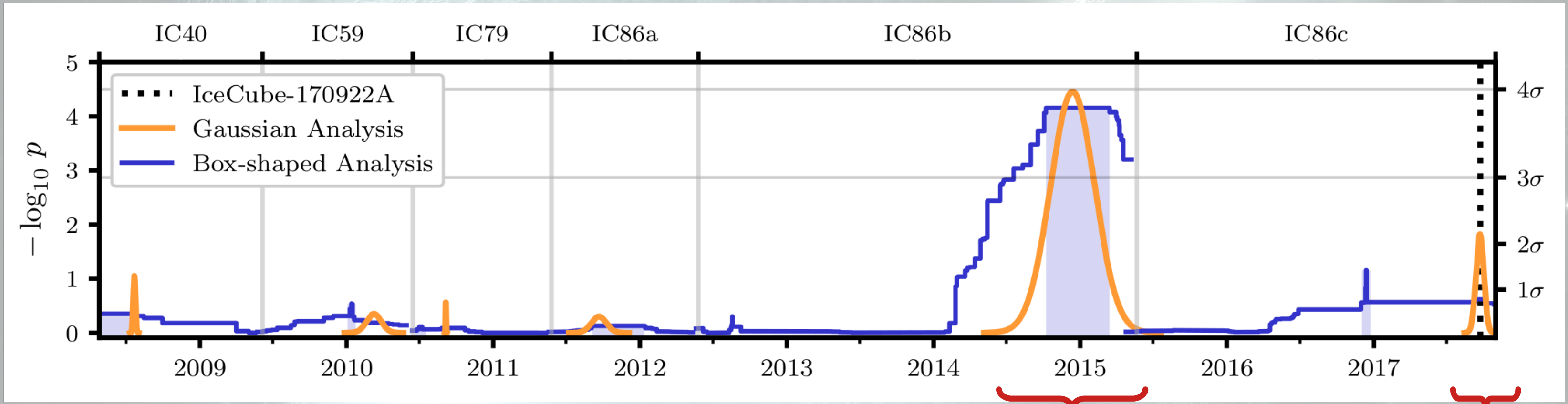


DESY

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

Blazar TXS 0506+056:

IceCube, *Science* 2018



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

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

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

Combined (pre-trial): 4.1σ

Tidal disruption events

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

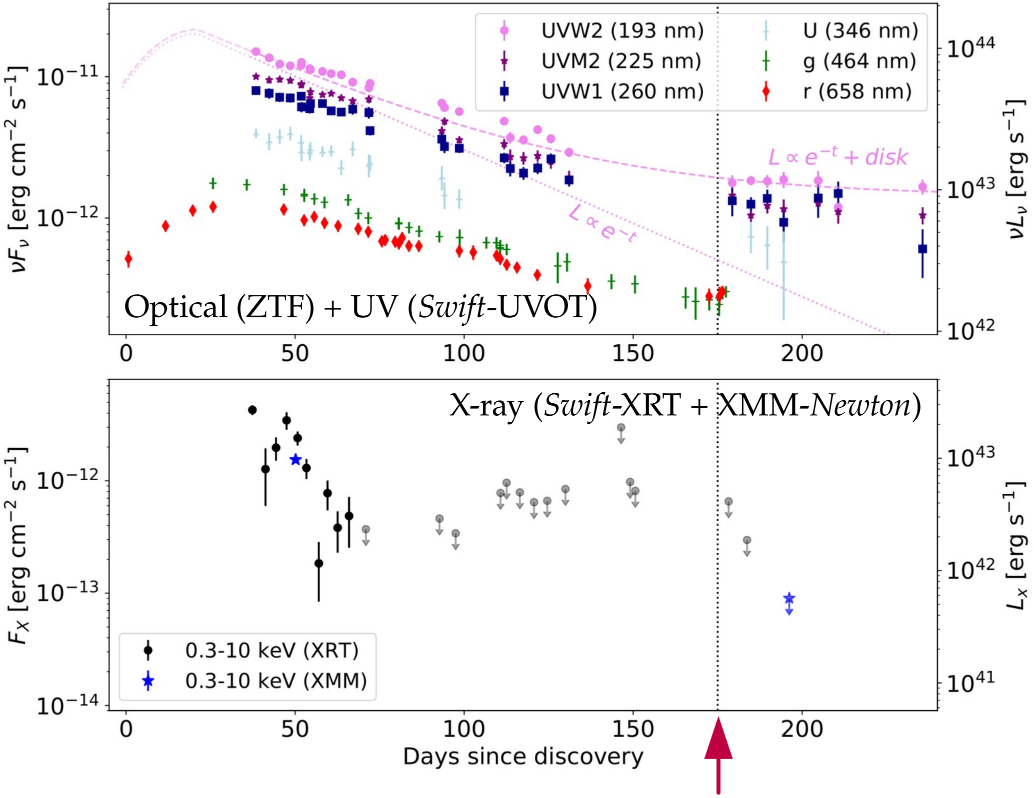
~50% of the debris bound to the SMBH, creates a flare (occasionally a jet)

NASA

An apparent TDE neutrino source

Radio-emitting TDE AT2019dsg coincident with neutrino event IC191001A:

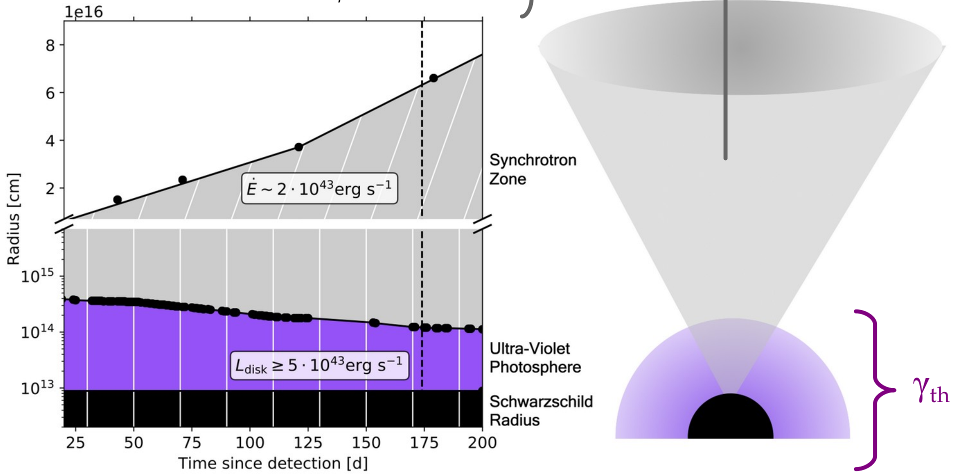
AT2019dsg: Apr 9, 2019 / $z = 0.051$ (230 Mpc) / $M_{BH} = 3 \times 10^7 M_\odot$



Multi-zone model:

From radio:
mildly relativistic expansion
($v/c \sim 0.2$) + acceleration

p and e accelerated here
($B = 0.07$ G, $E_p < 160$ PeV)



$$p + \gamma_{th} \text{ (or } p) \rightarrow \nu$$

Stein *et al.*, *Nature Astron.* 2021 – See also: Winter & Lunardini, *Nature Astron.* 2021; Murase, Kimura, Zhang, Oikonomou, Petropoulou, *ApJ* 2020

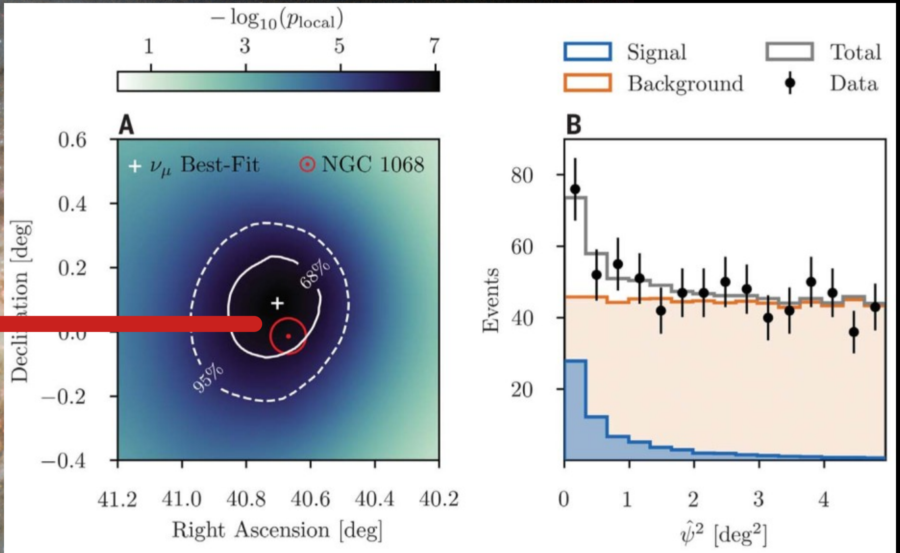
NGC1068: The first *steady-state* source of high-energy ν

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

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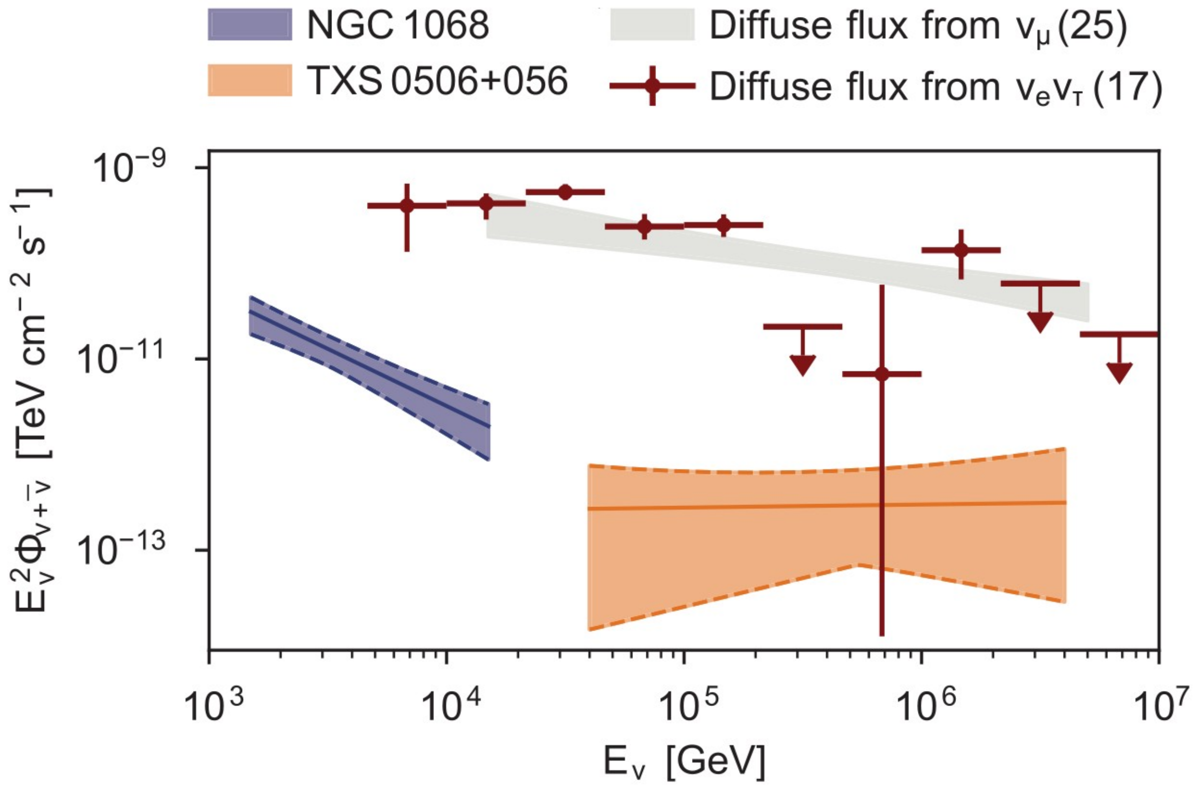

IceCube Collab., *Science* 378, 538 (2022)

Hubble Space Telescope,
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III.
What have we learned about *particle physics*

Note: Not an exhaustive list

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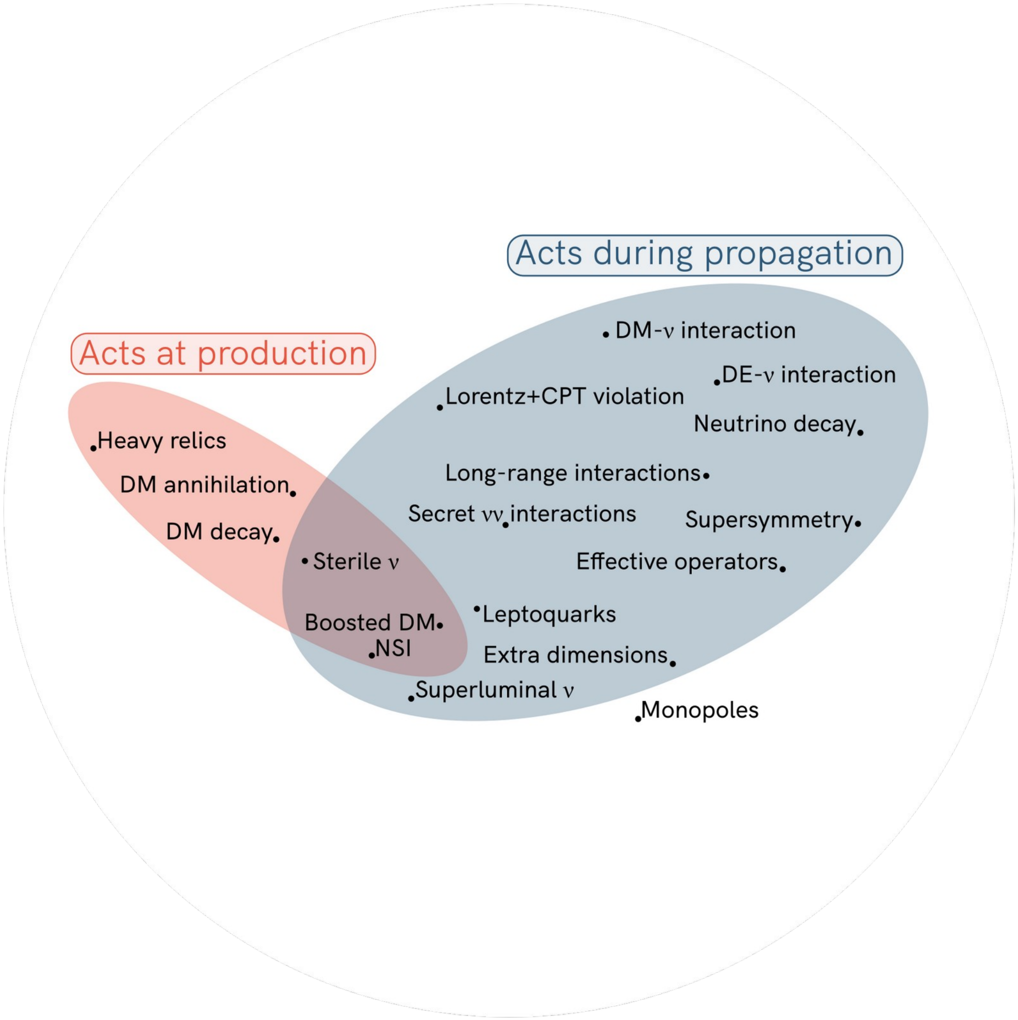

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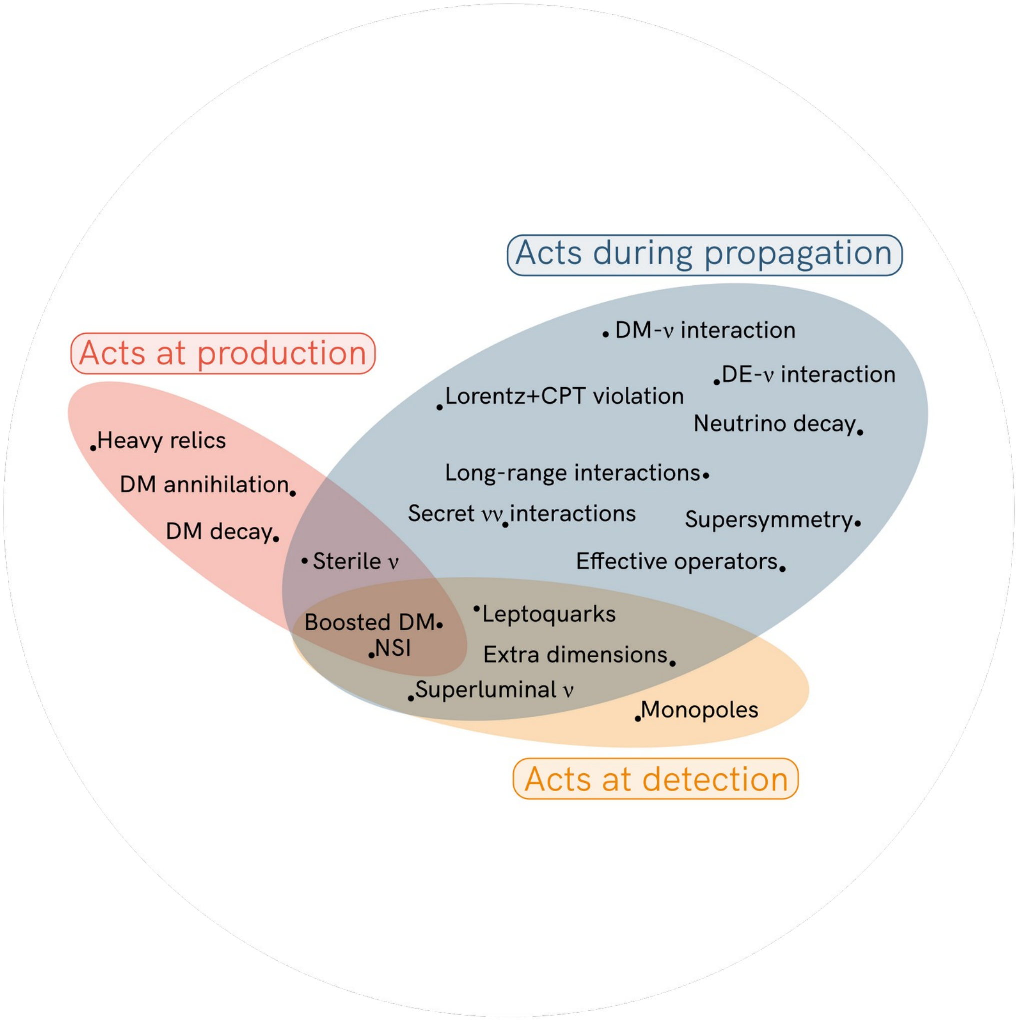

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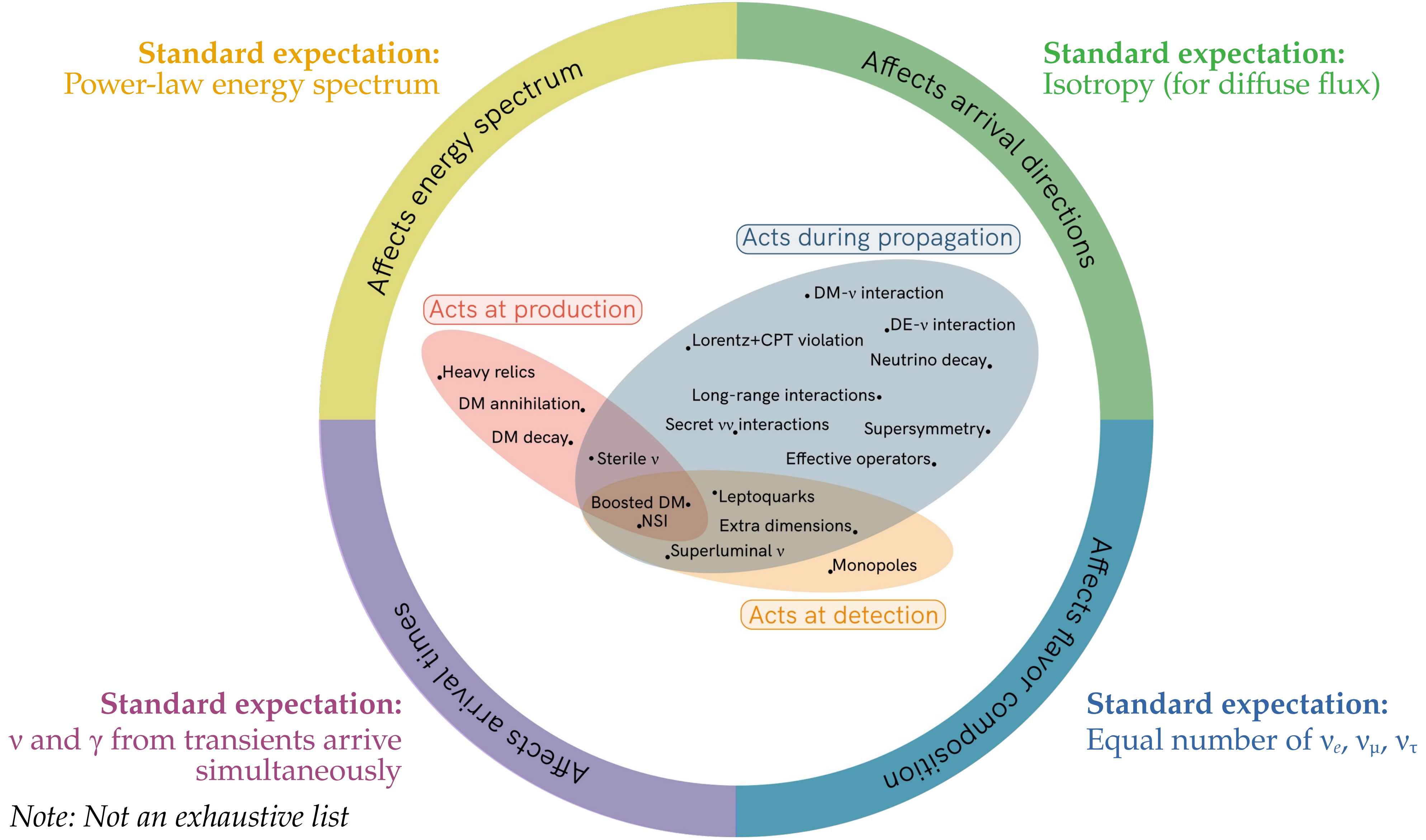

Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Acts during propagation
Acts at production
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Heavy relics
DM annihilation
Long-range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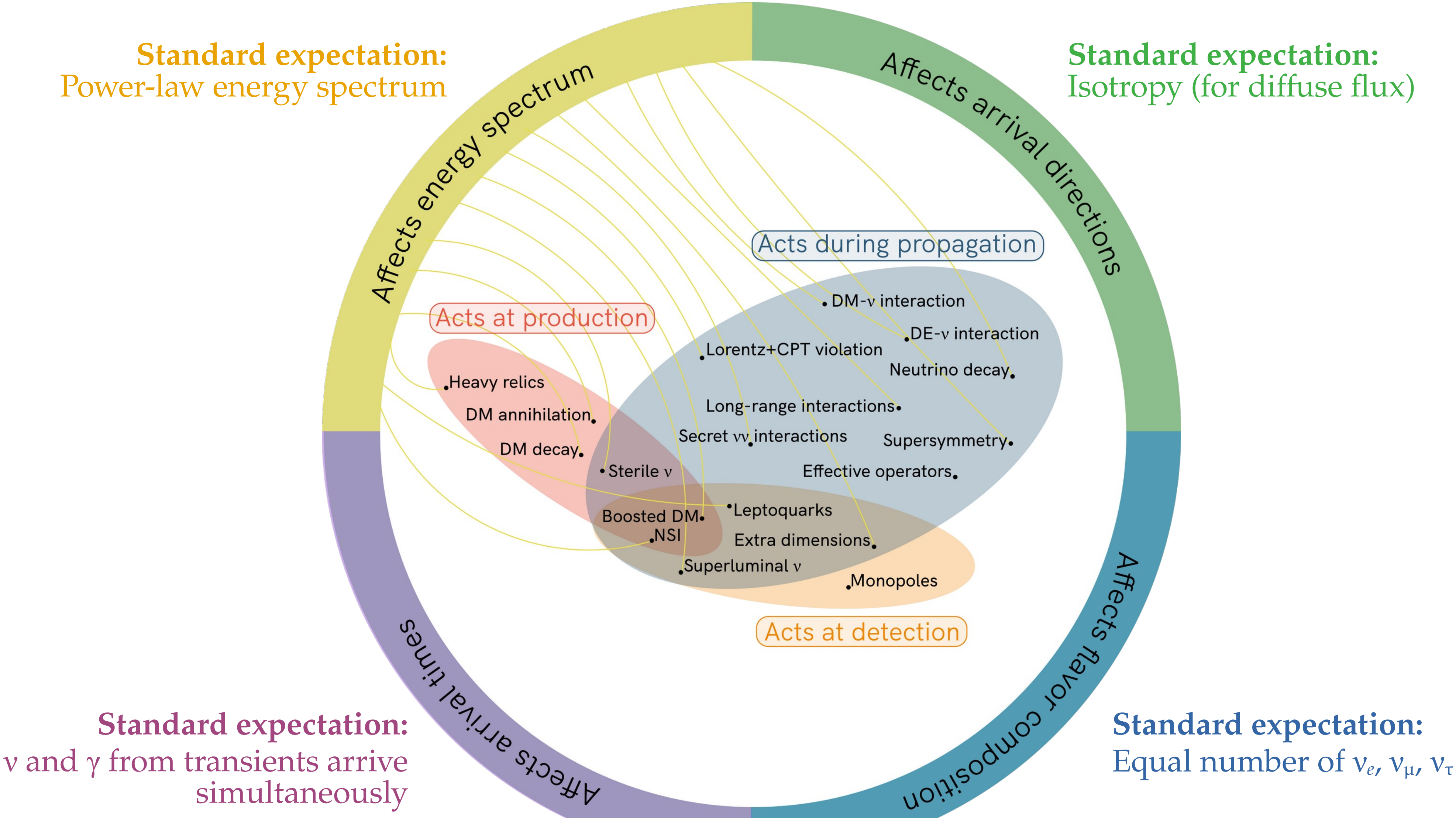

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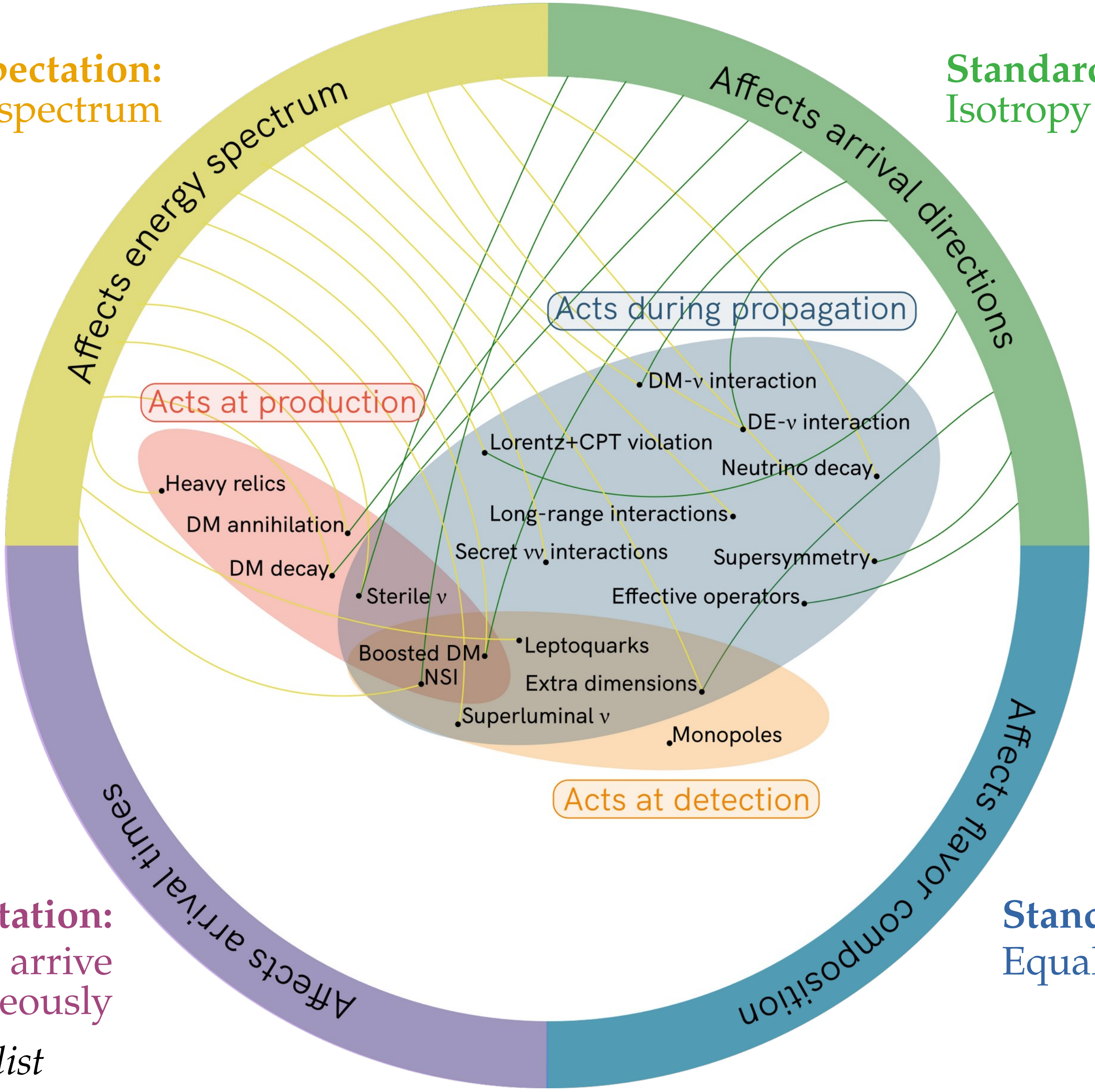

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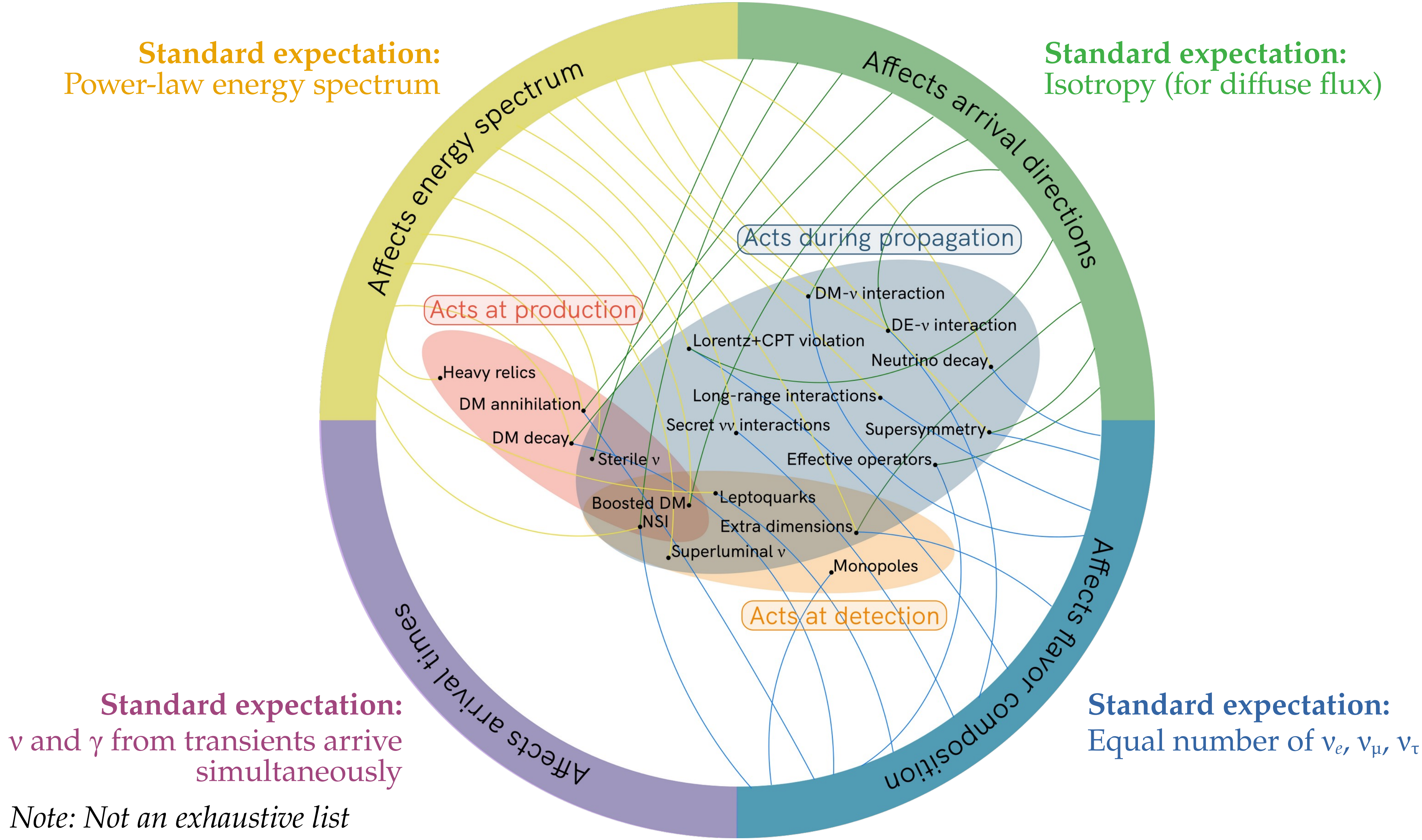

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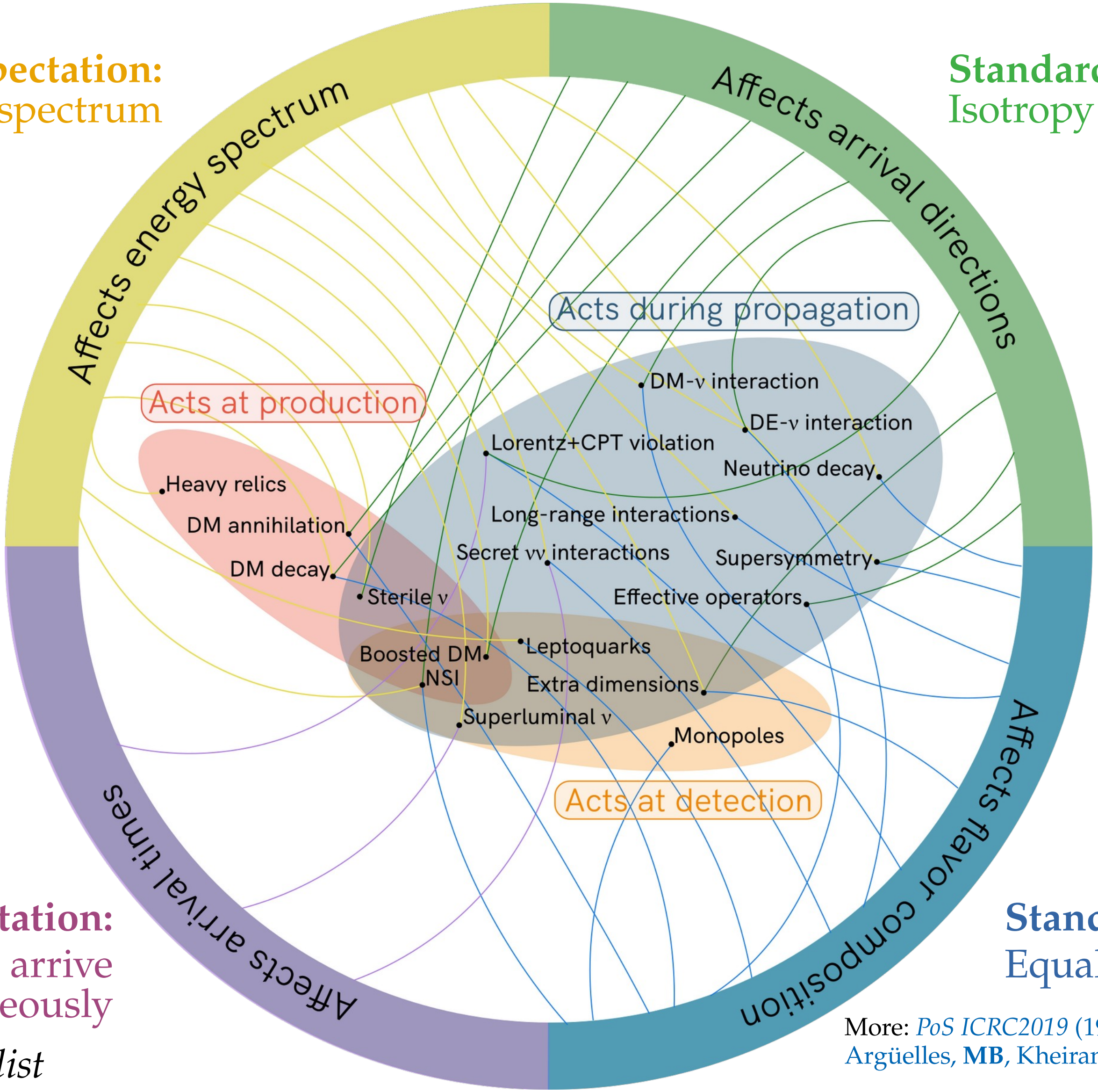

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More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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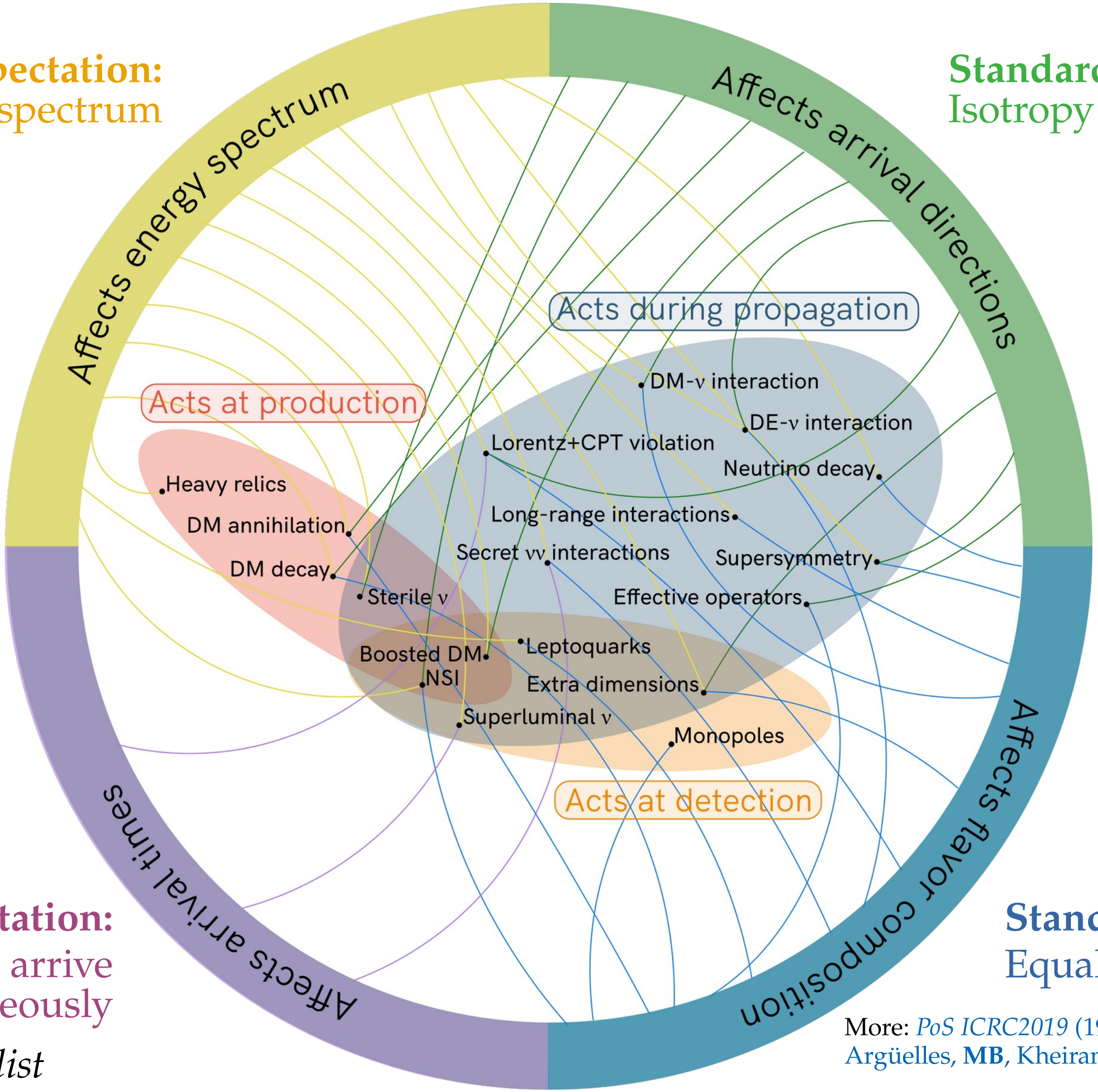

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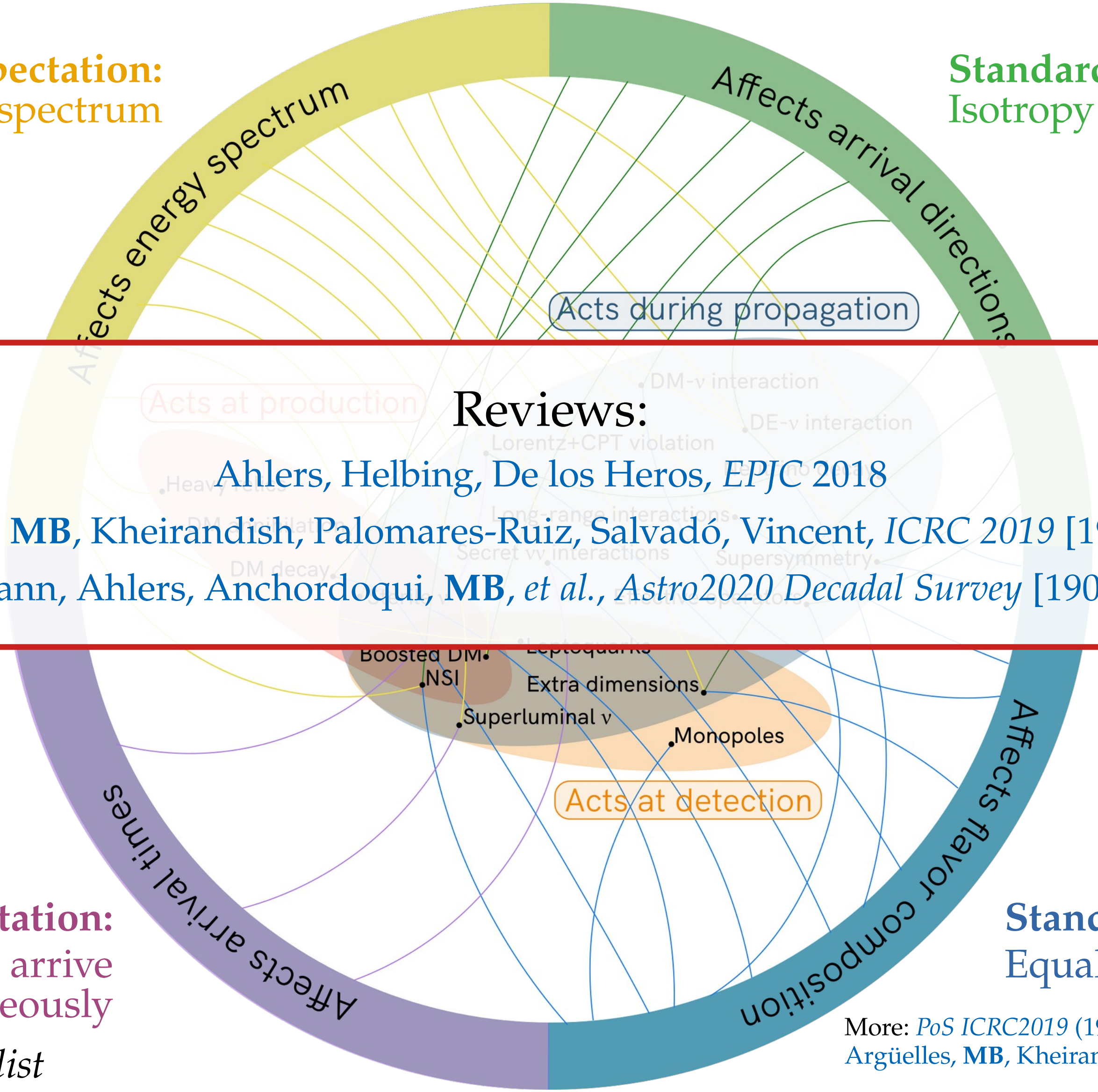

Reviews:

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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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 can be extracted from four neutrino observables:
  - Spectral shape
  - Angular distribution
  - Flavor composition
  - Timing

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- Fundamental physics can be extracted from four neutrino observables:
  - Spectral shape
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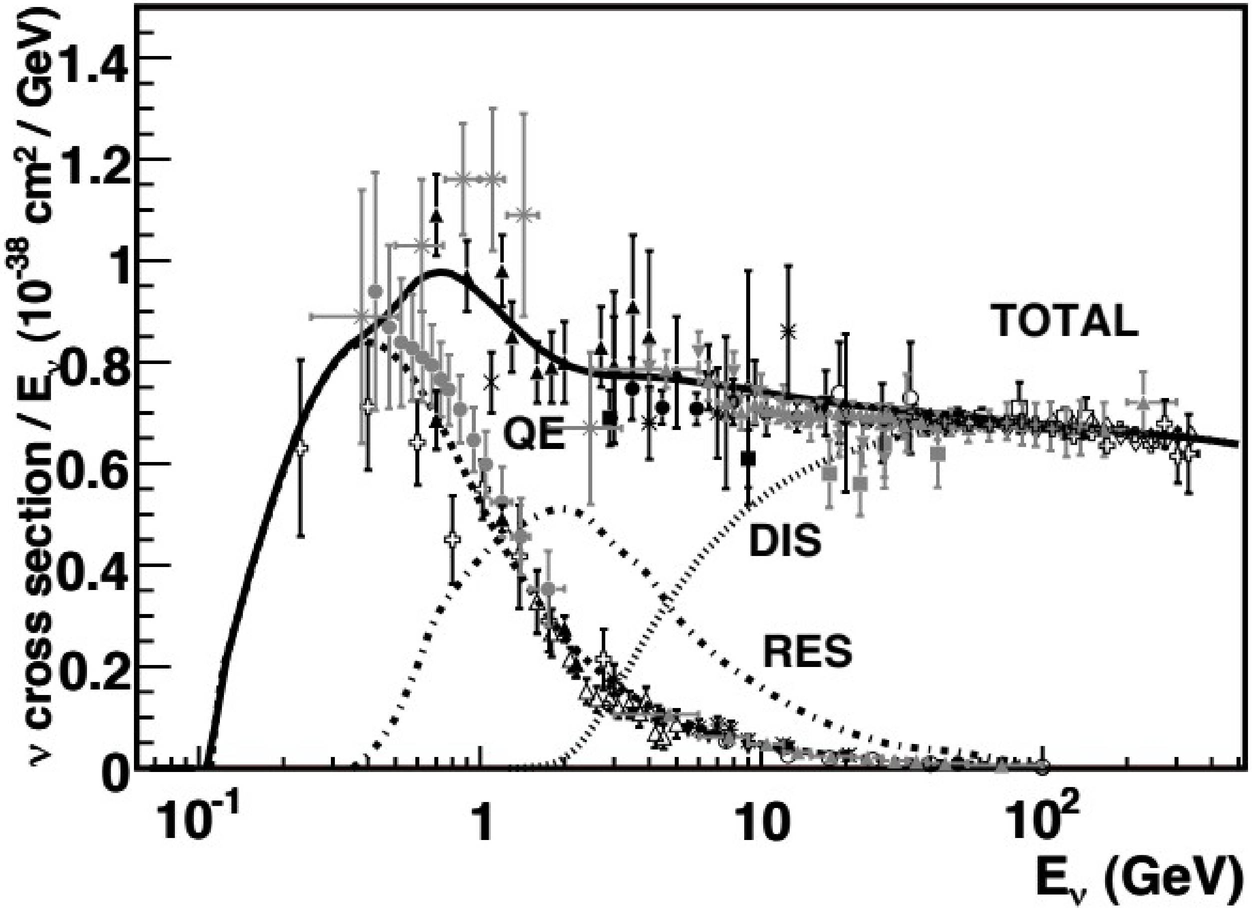
  - Timing

  In spite of
  poor energy, angular, flavor reconstruction
  & astrophysical unknowns

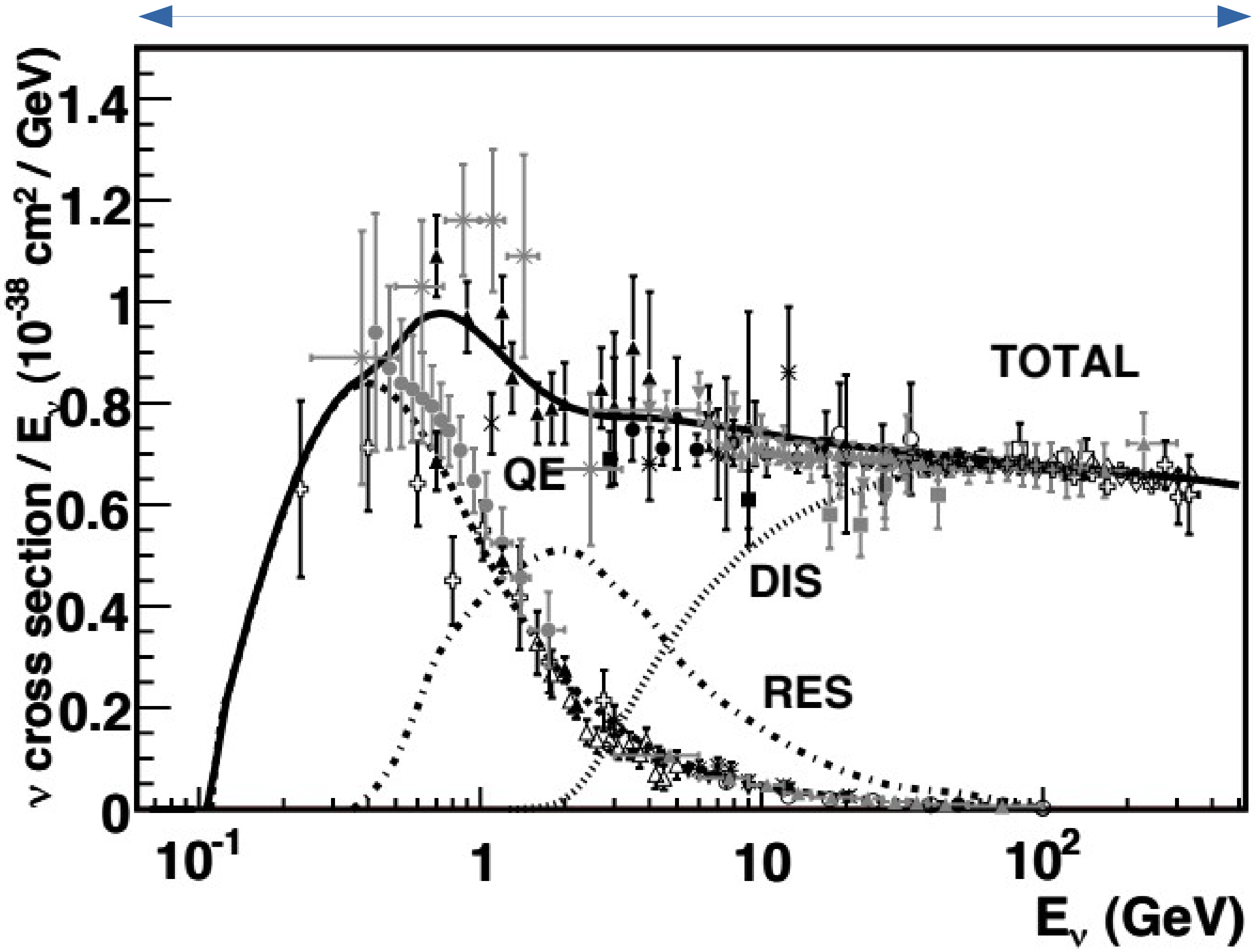
Neutrino-nucleon cross section:

From high to ultra-high energies



Particle Data Group

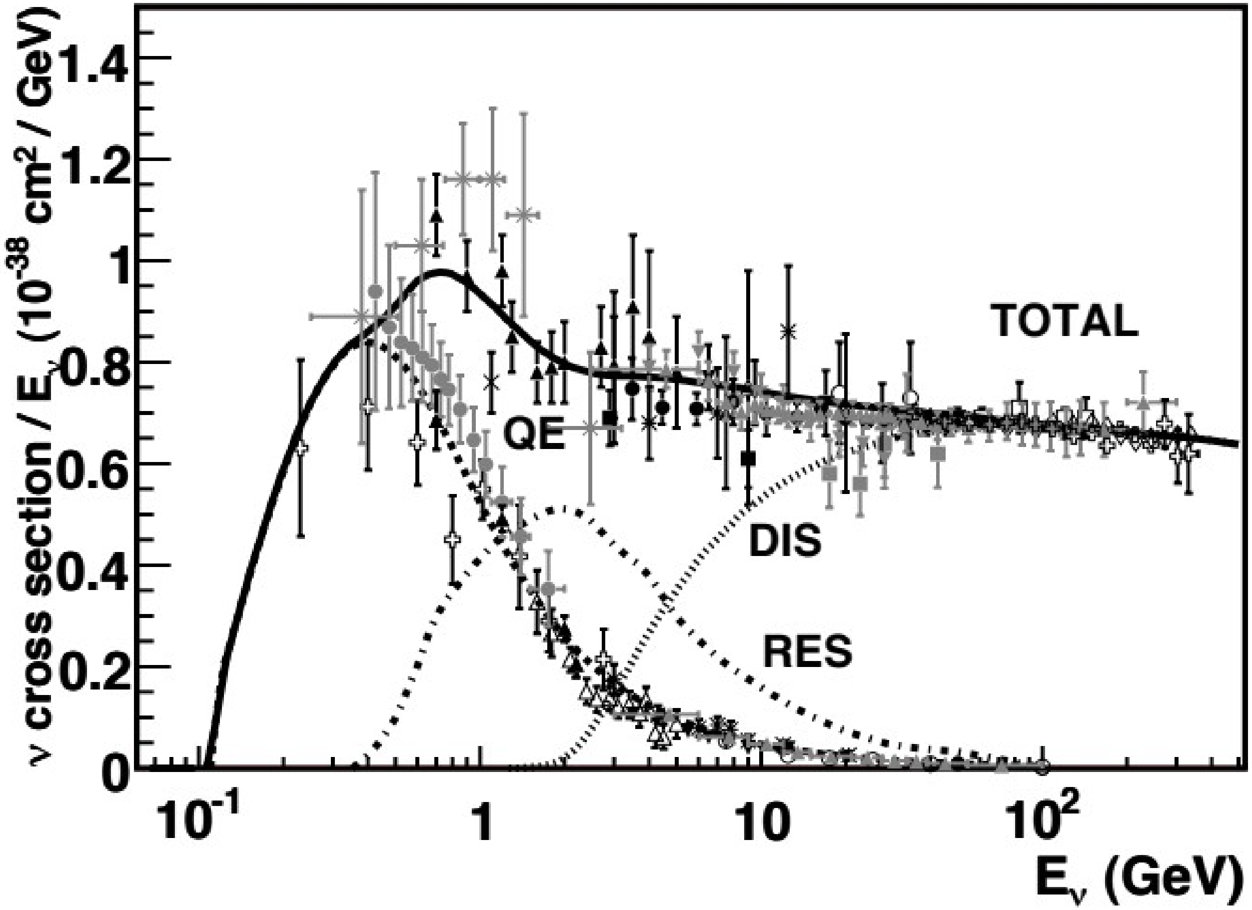
Accelerator experiments



Particle Data Group

Accelerator experiments

One recent measurement (COHERENT)



Particle Data Group

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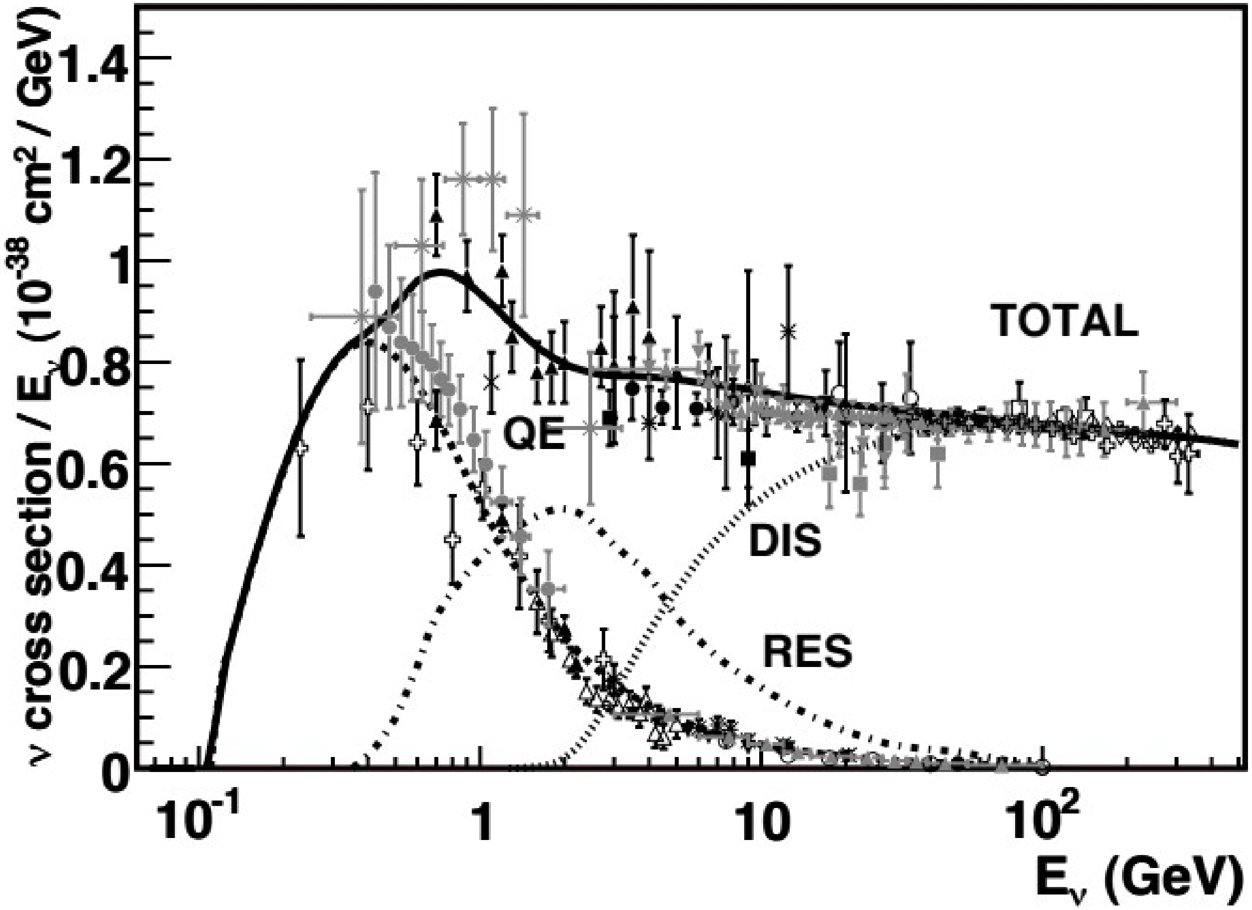

One recent measurement (COHERENT)

No measurements … until recently!

Particle Data Group

Accelerator experiments

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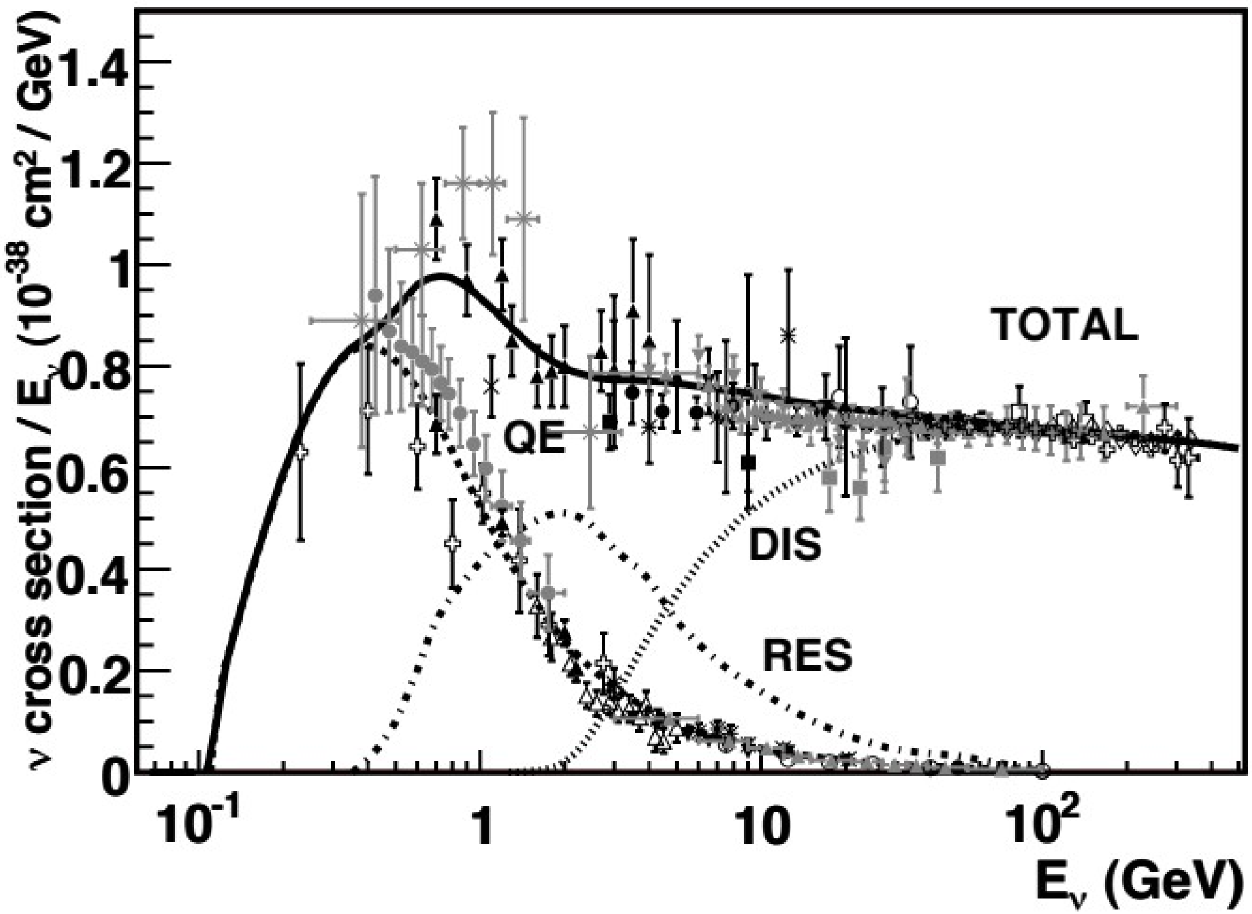
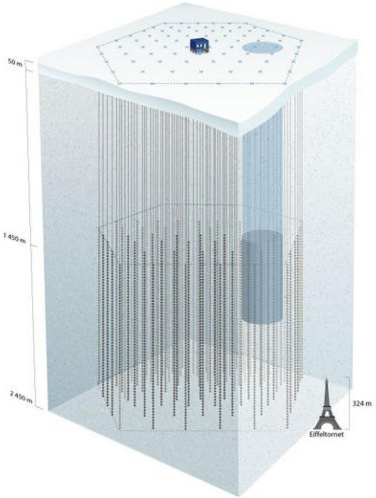
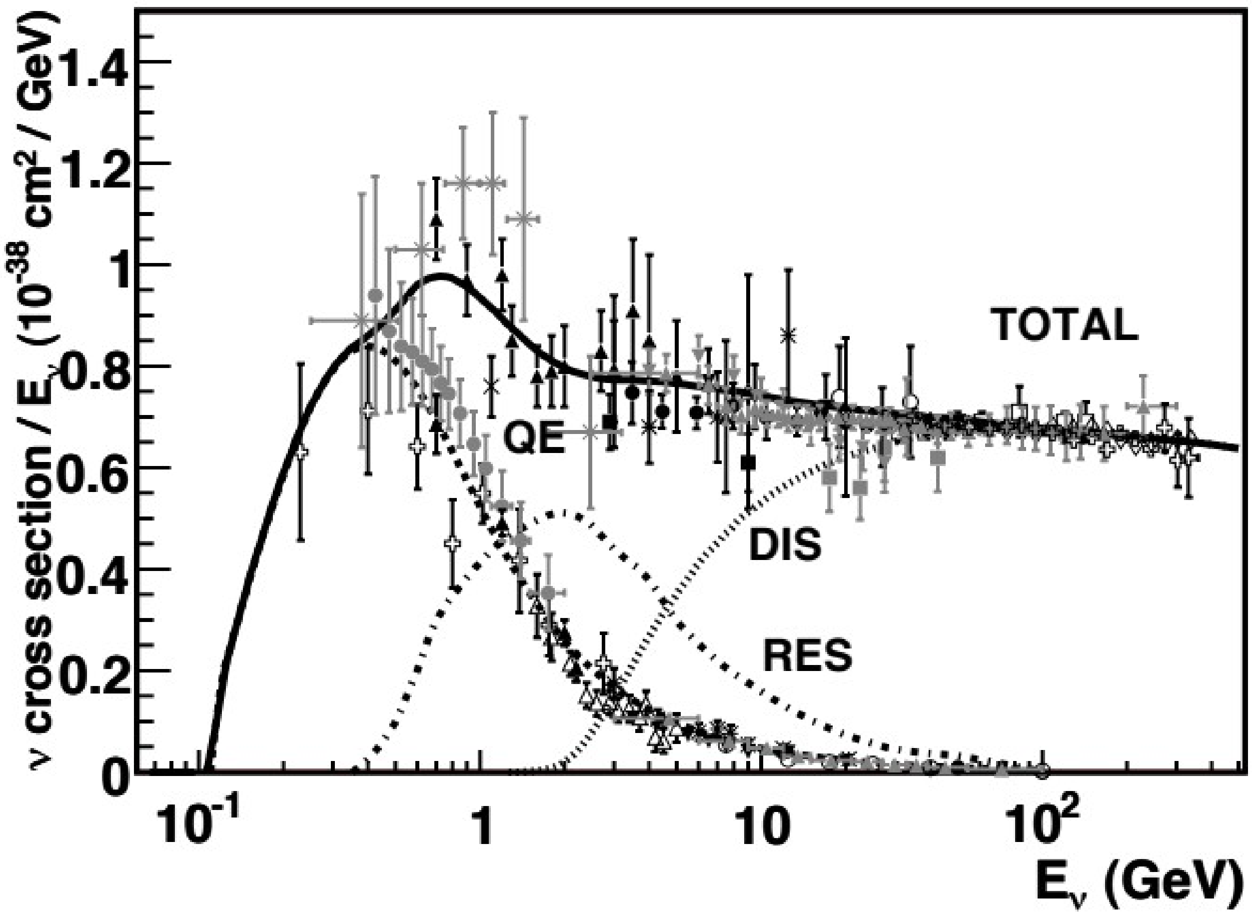


Particle Data Group



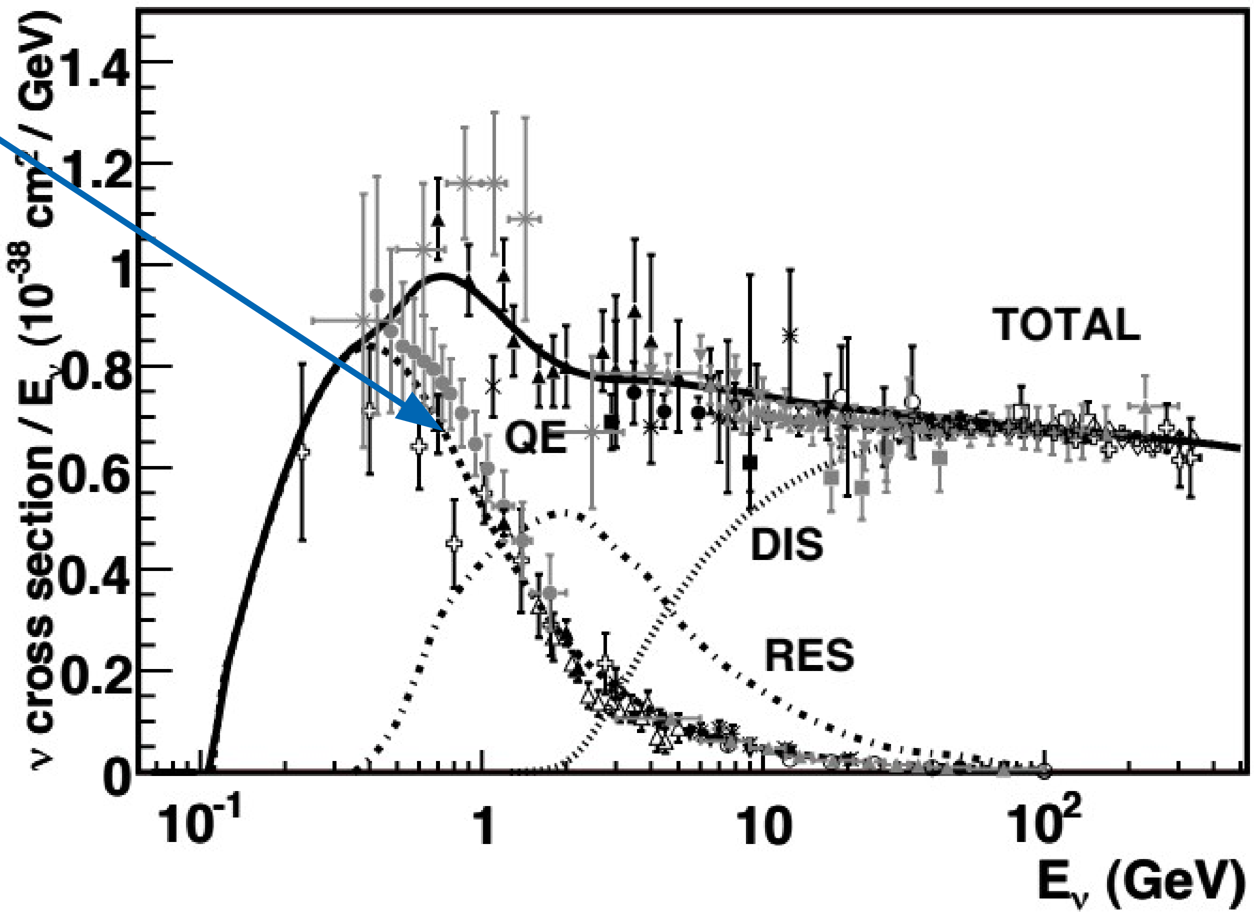


Particle Data Group

Quasi-elastic scattering:

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

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



Particle Data Group

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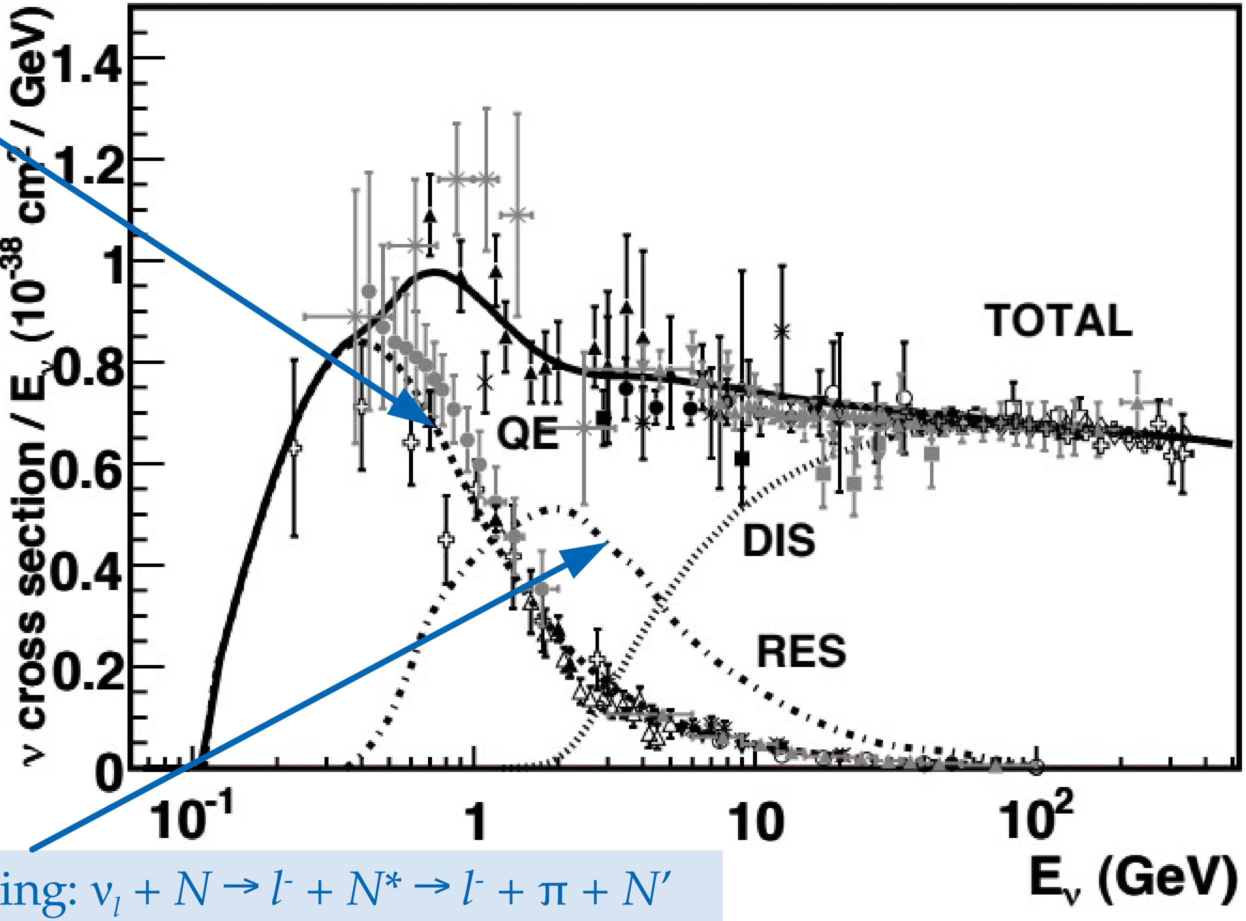

Particle Data Group

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

Quasi-elastic scattering:

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

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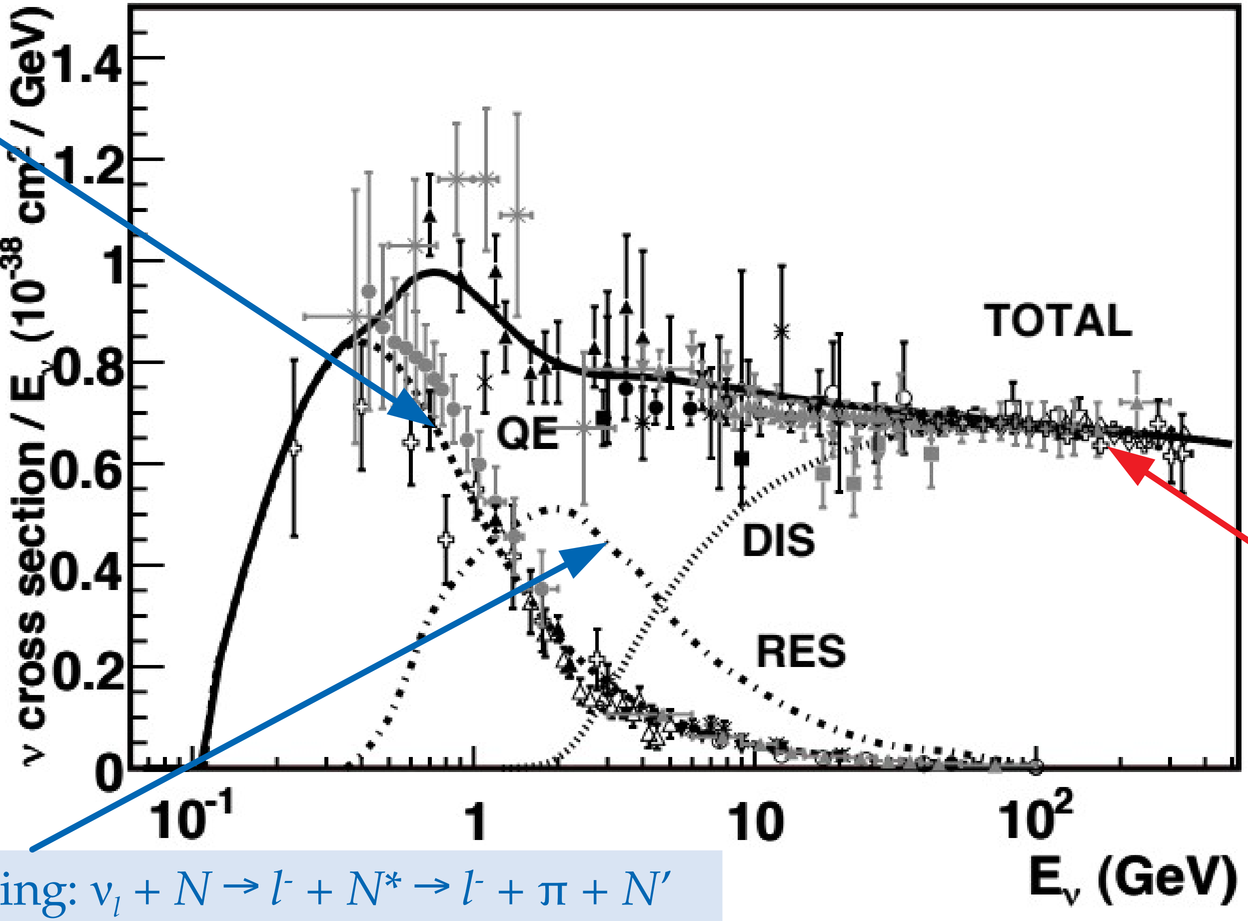


Deep inelastic scattering:

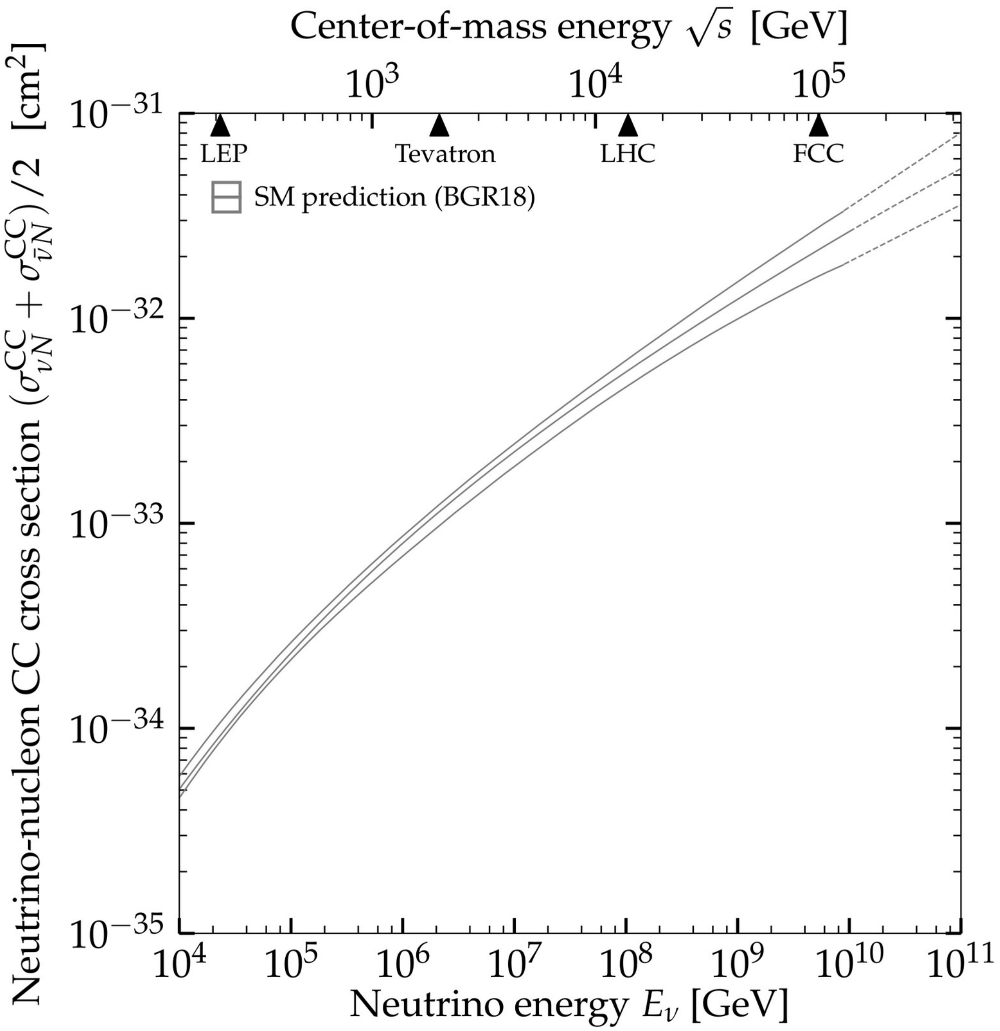
$\nu_l + N \rightarrow l^- + X$

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

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

Particle Data Group

High-energy νN cross section: *prediction*

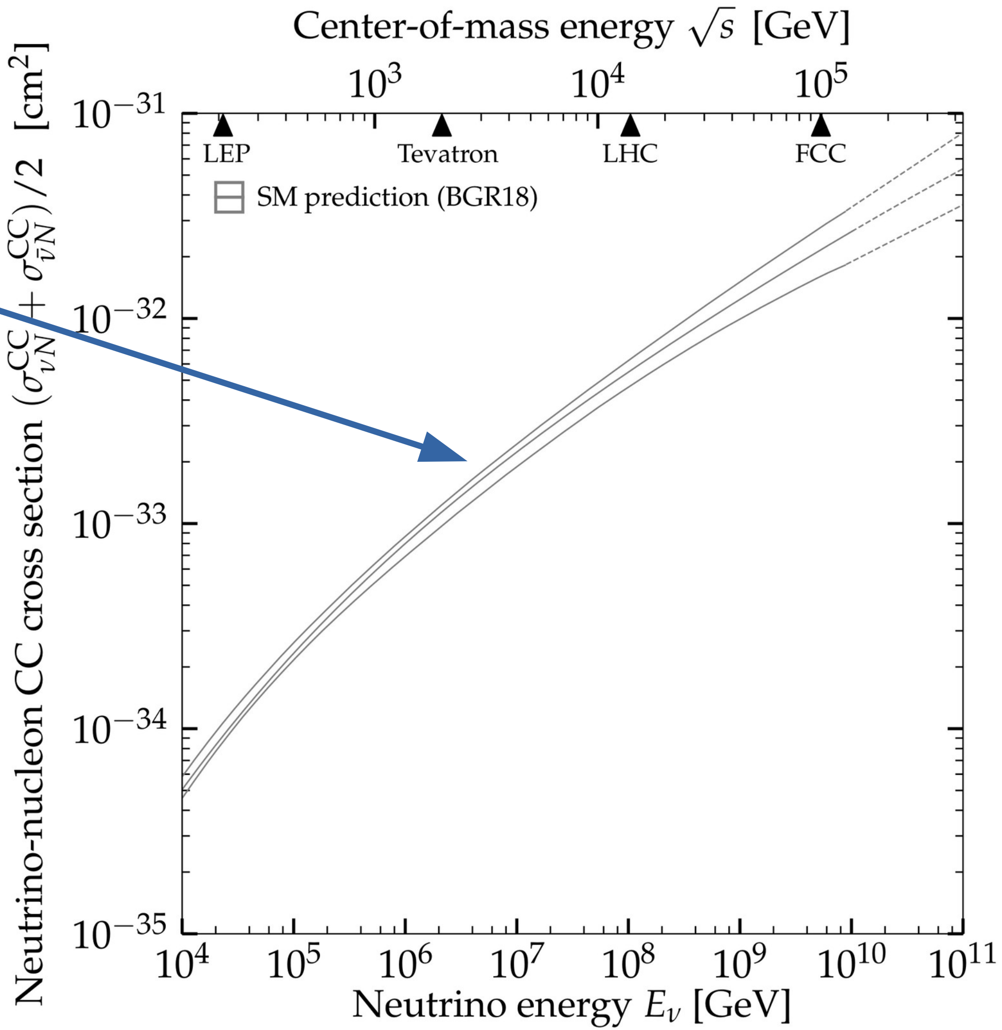


Bertone, Gauld, Rojo, *JHEP* 2019

High-energy νN cross section: *prediction*

Softer-than-linear dependence on E_ν due to the W pole

Uncertainty from extrapolating parton distribution functions (PDFs) to Bjorken $x \sim m_W/E_\nu \sim 10^{-6}$



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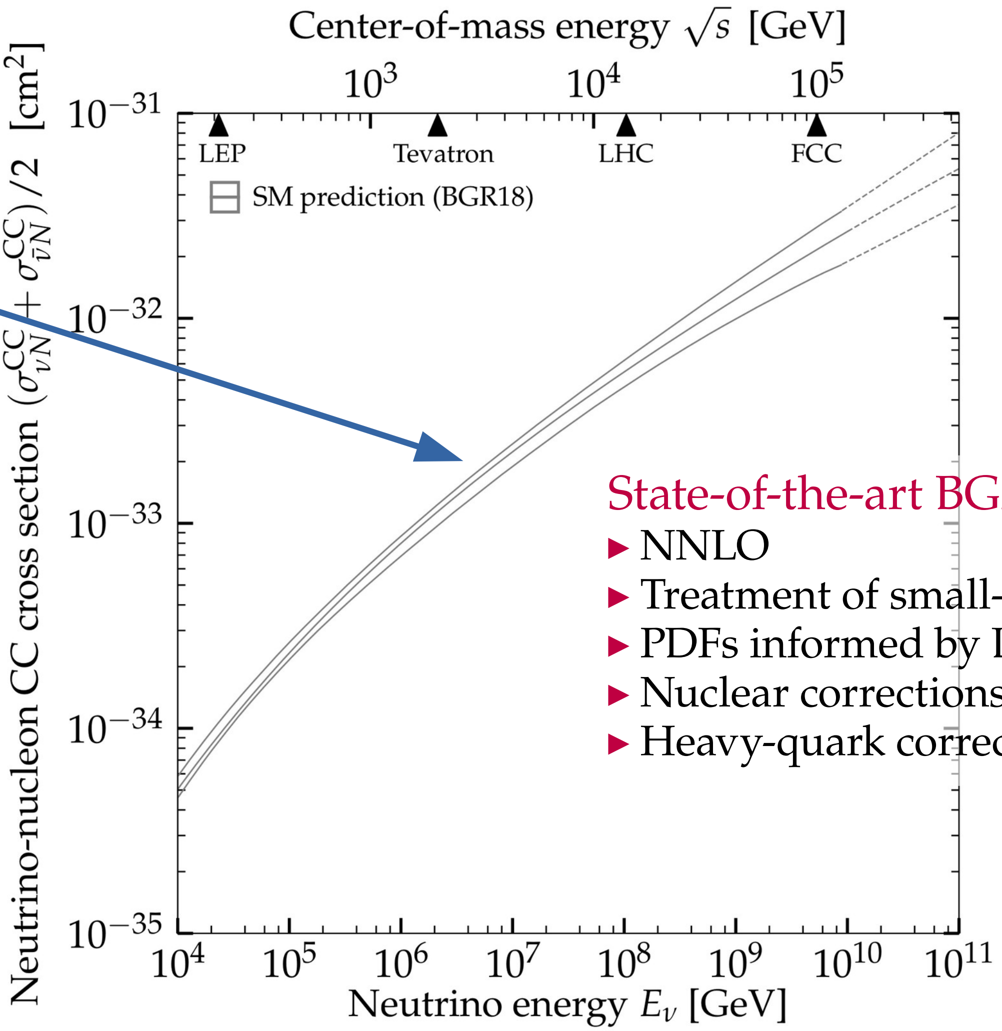
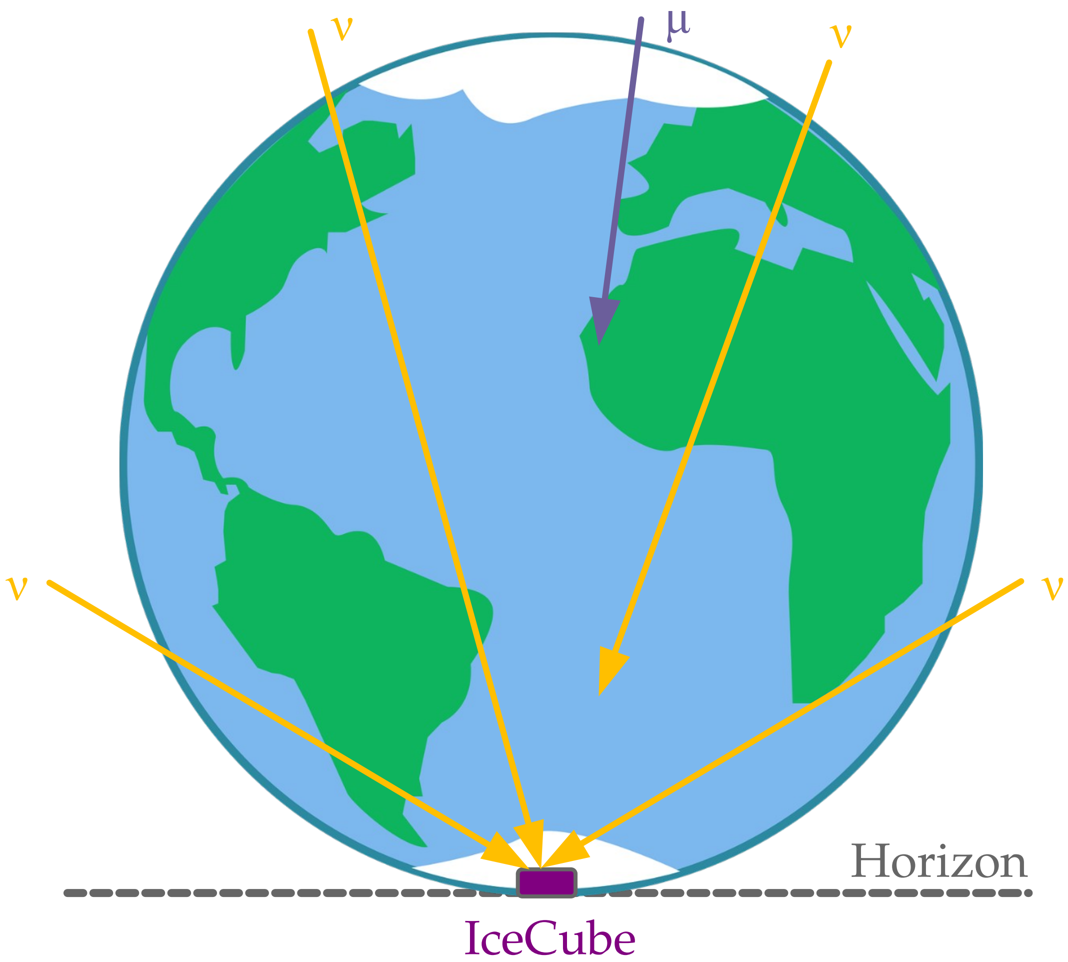
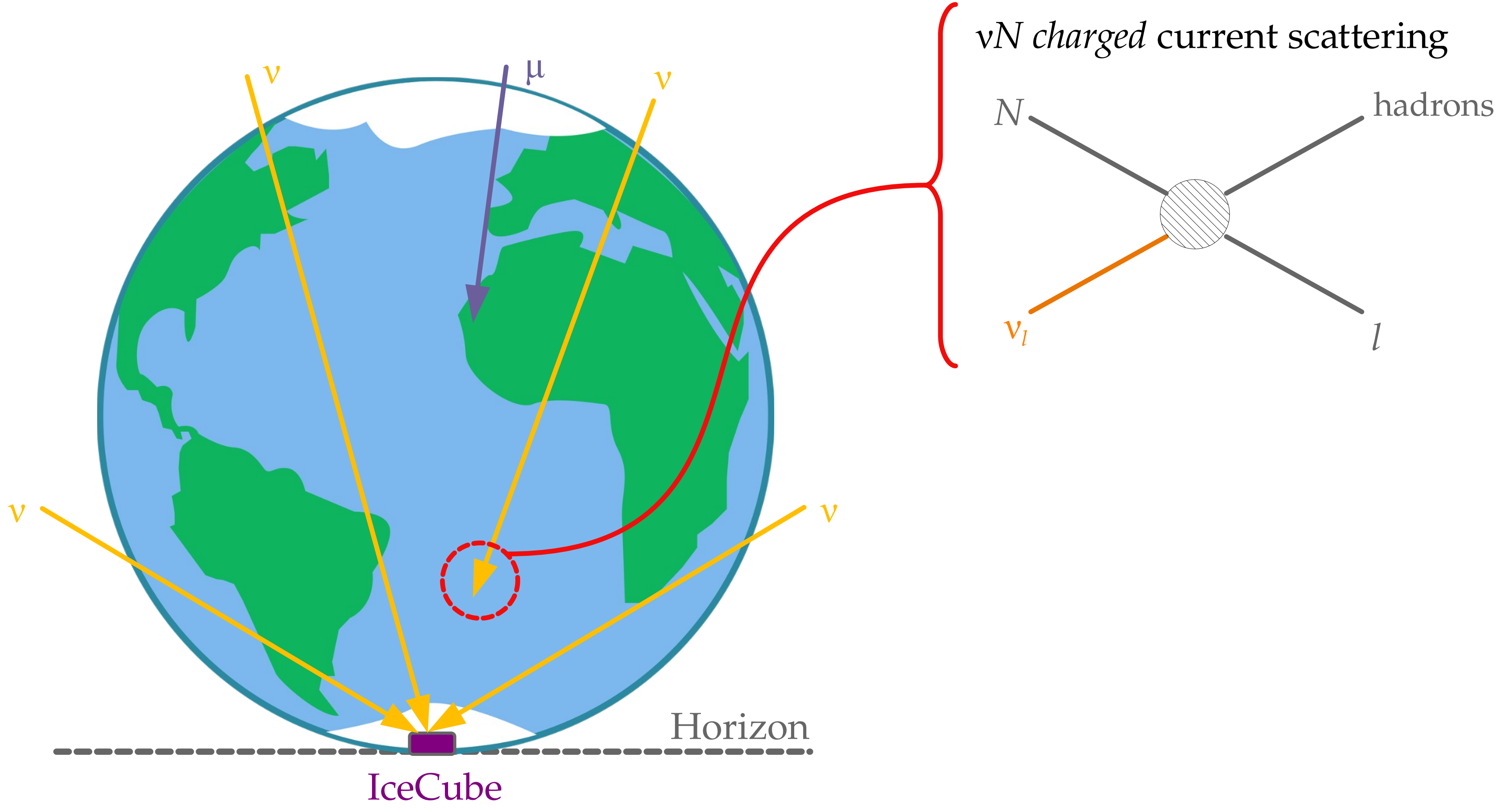


State-of-the-art BGR18 prediction:

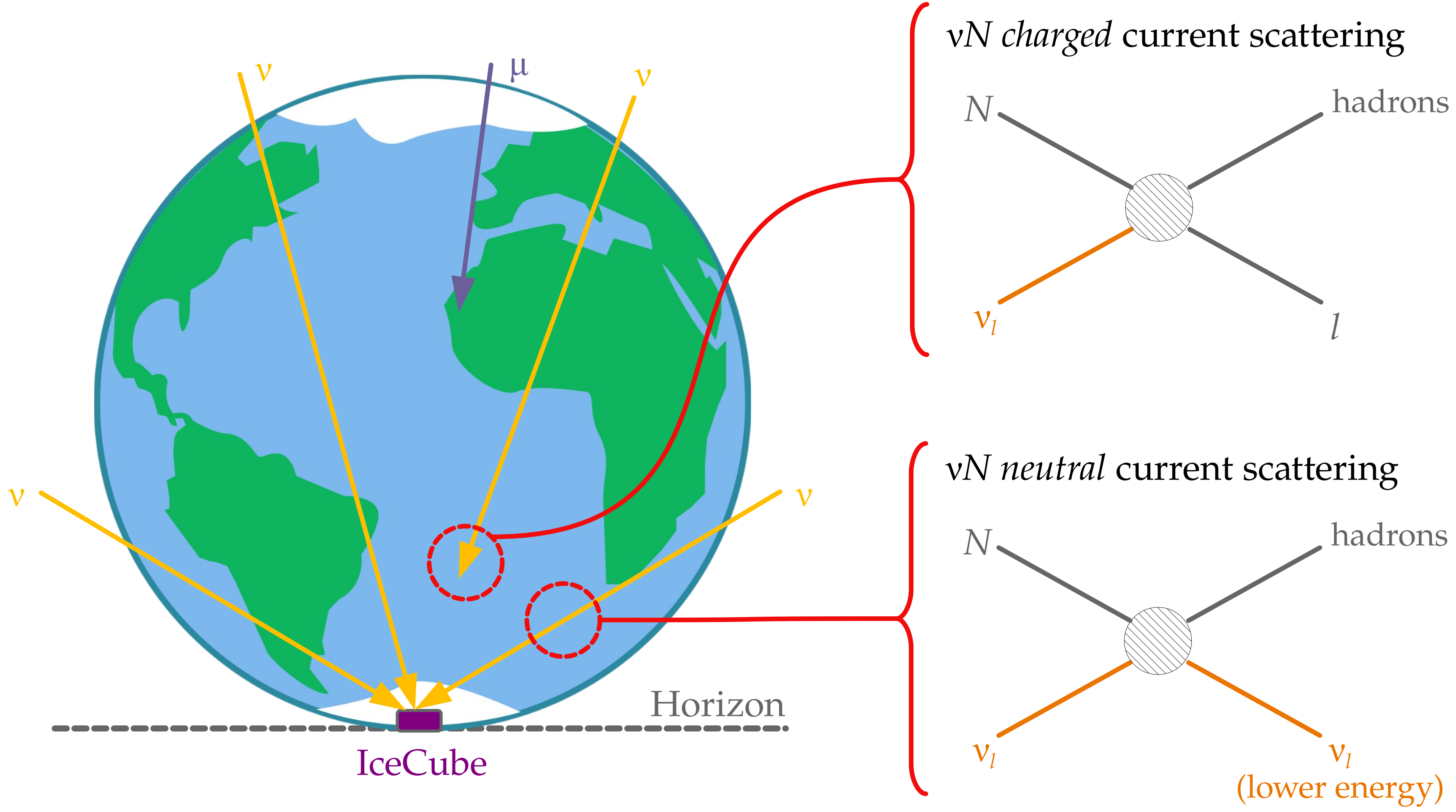
- NNLO
- Treatment of small-x effects
- PDFs informed by LHCb D-meson data
- Nuclear corrections
- Heavy-quark corrections

Bertone, Gauld, Rojo, *JHEP* 2019

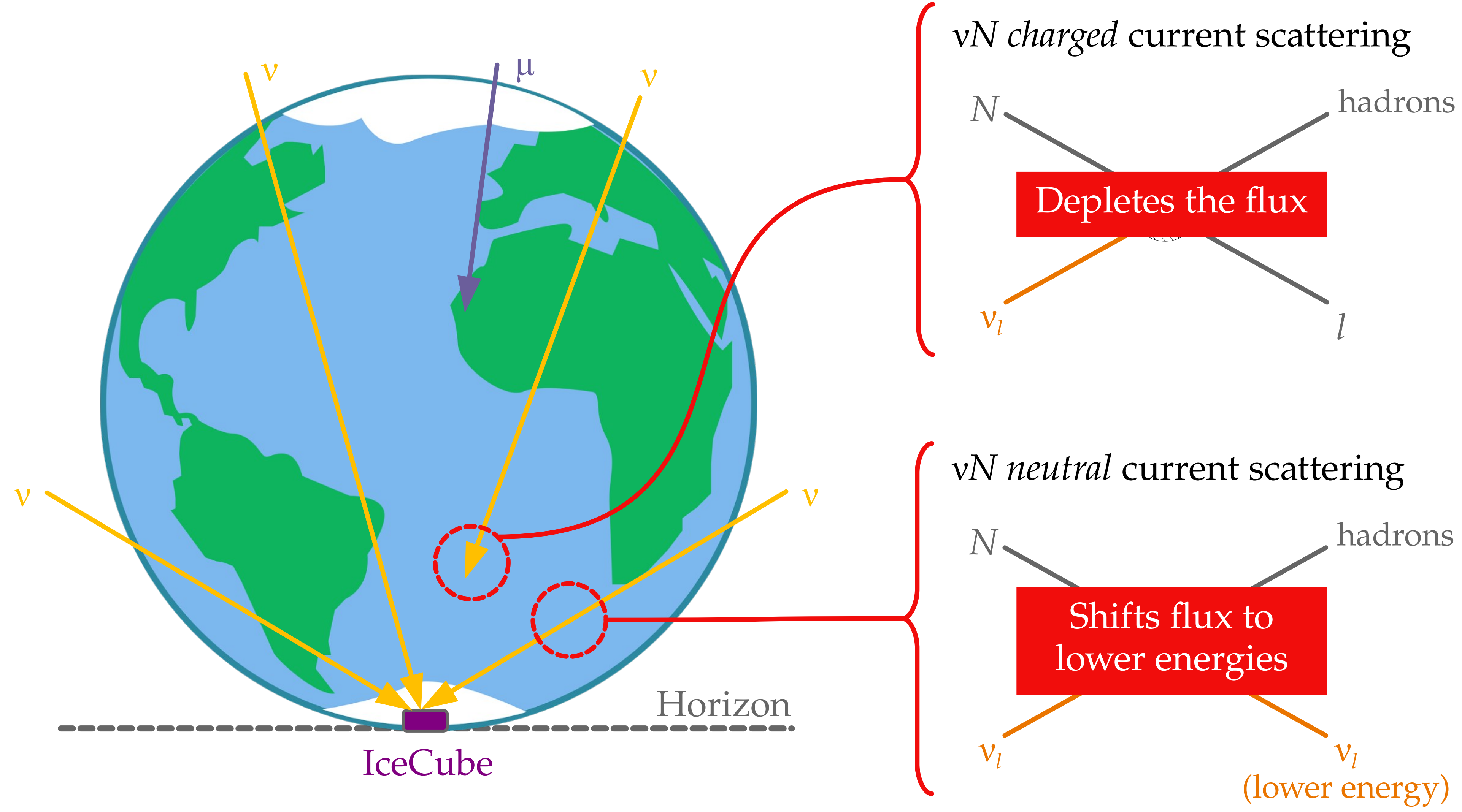

ν
μ
ν
ν
ν
Horizon
IceCube



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

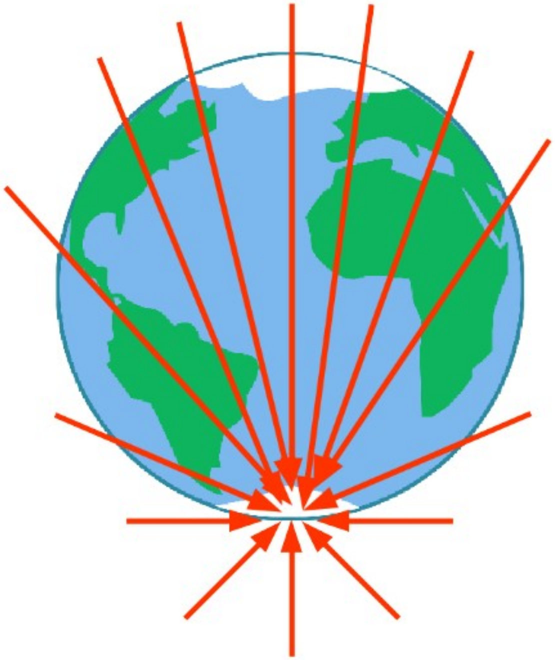


ν
μ
ν
ν
ν
Horizon
IceCube
νN *charged* current scattering
N
hadrons
ν_l
l
νN *neutral* current scattering
N
hadrons
ν_l
ν_l
(lower energy)


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

Below ~ 10 TeV: Earth is transparent



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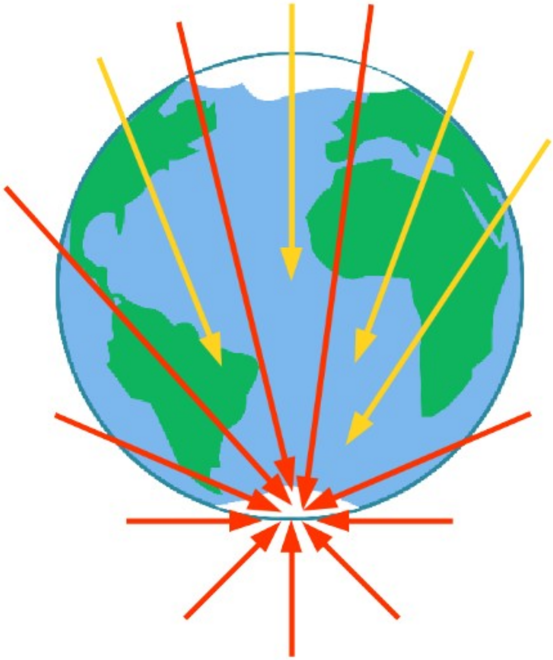

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008 Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

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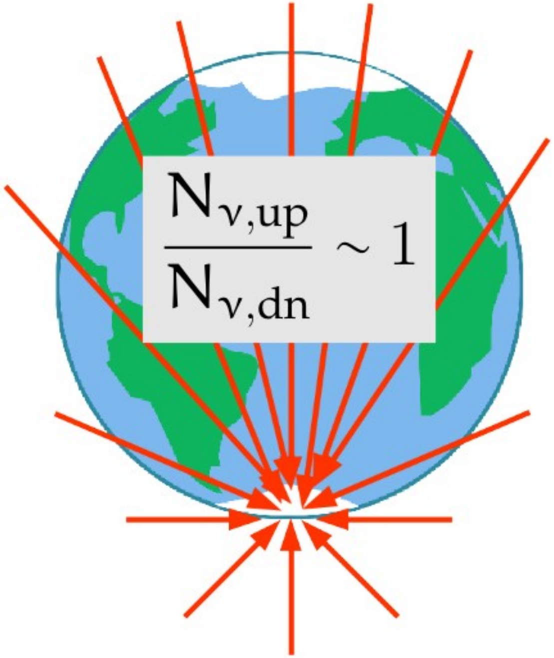

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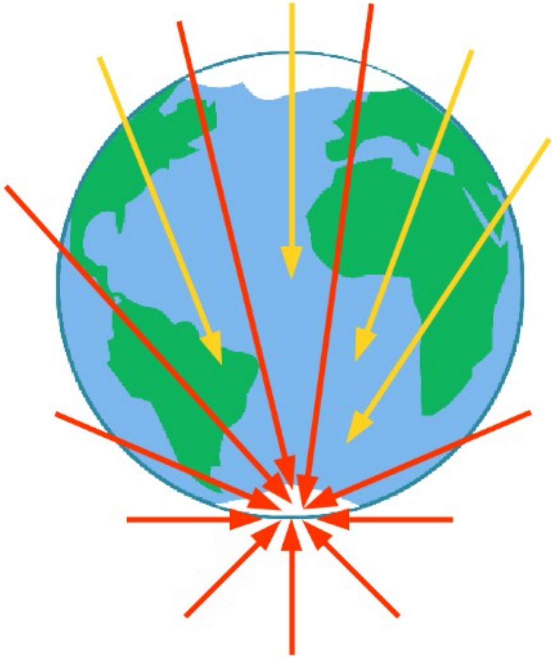

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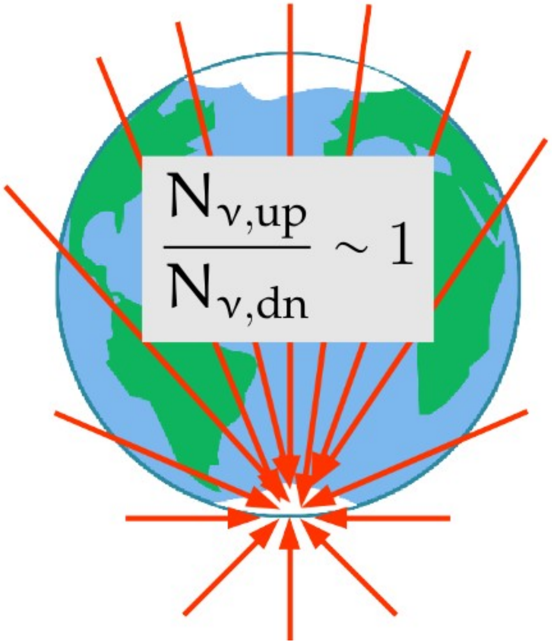

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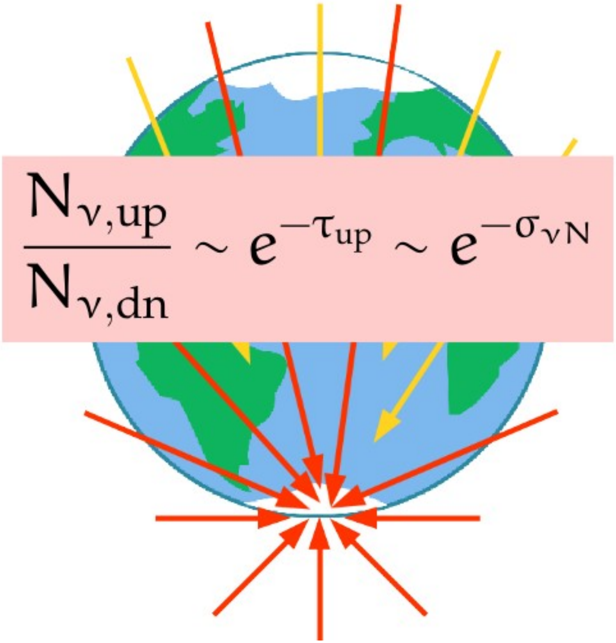

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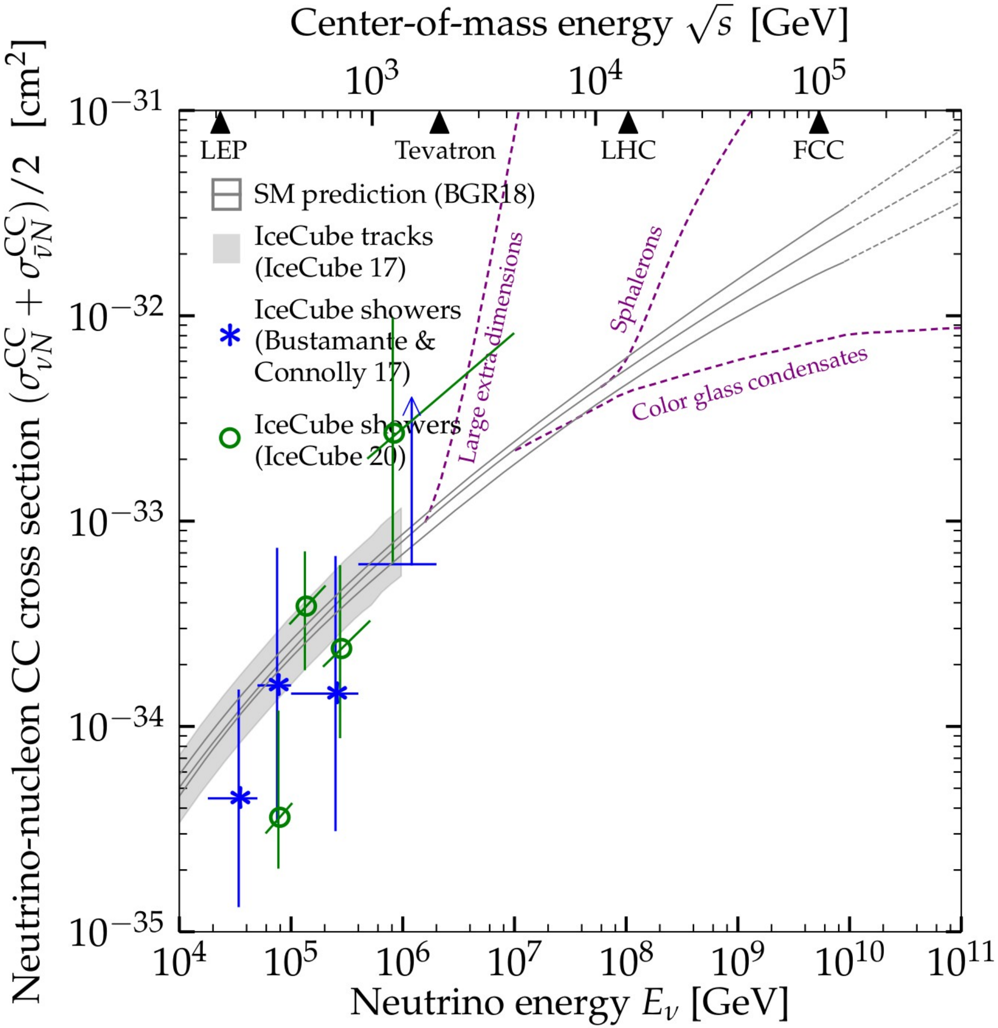
High-energy νN cross section: *today*

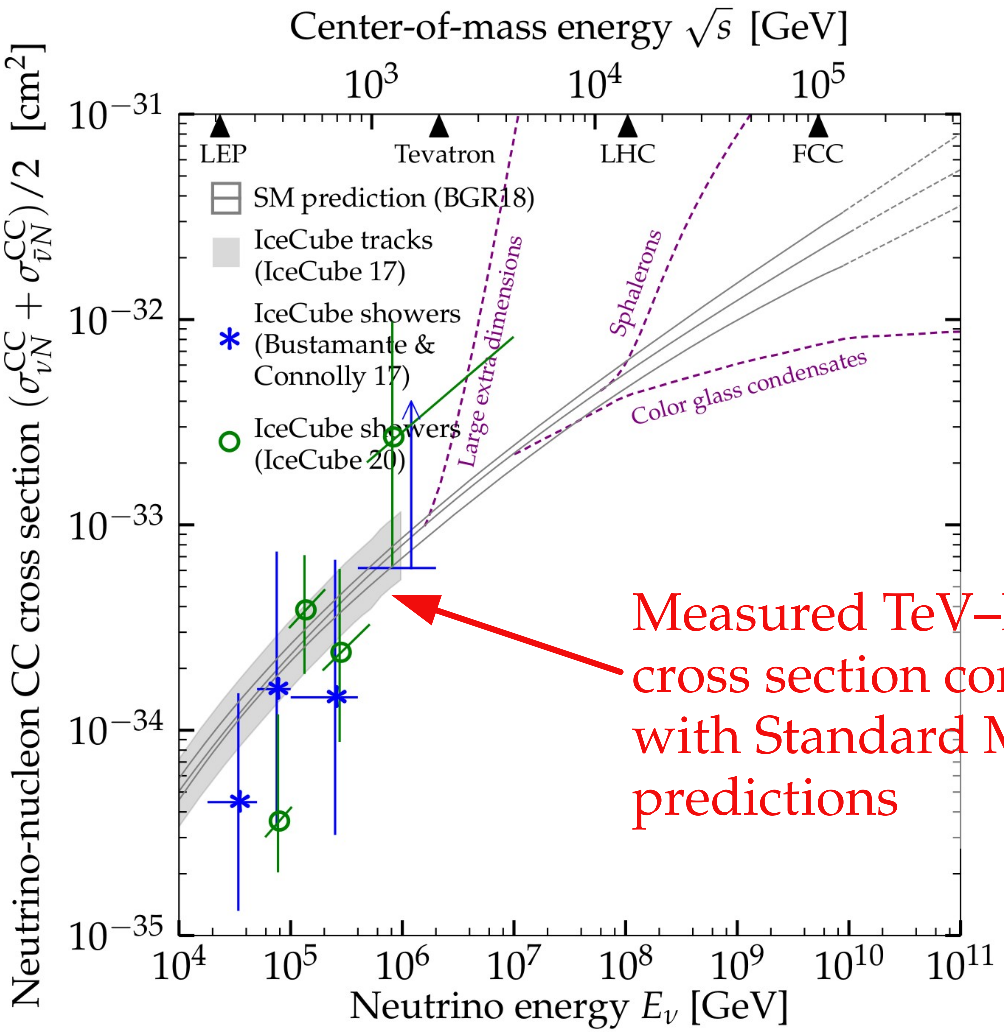


BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019

See also:
García, Gauld, Heijboer, Rojo, *JCAP* 2020

Measurements from:
IceCube, 2011.03560
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

High-energy νN cross section: *today*



Measured TeV–PeV cross section compatible with Standard Model predictions

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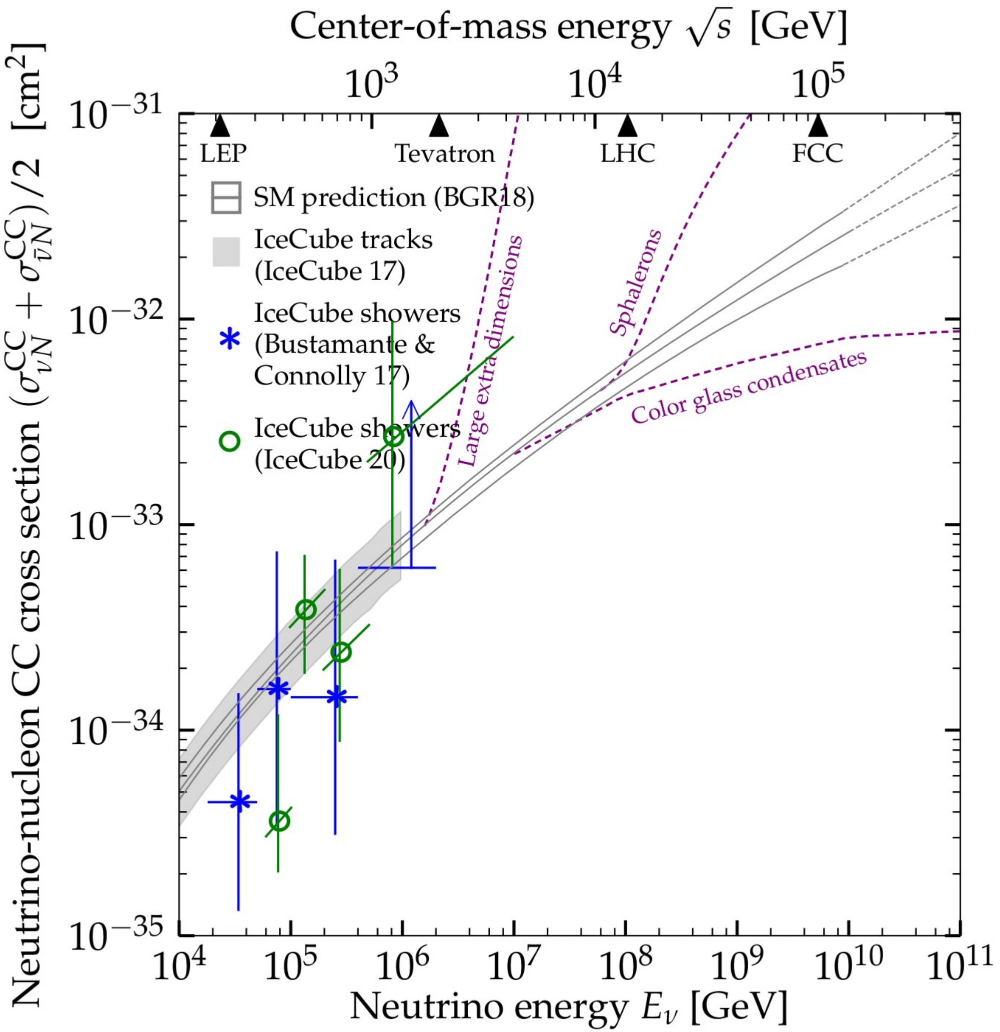

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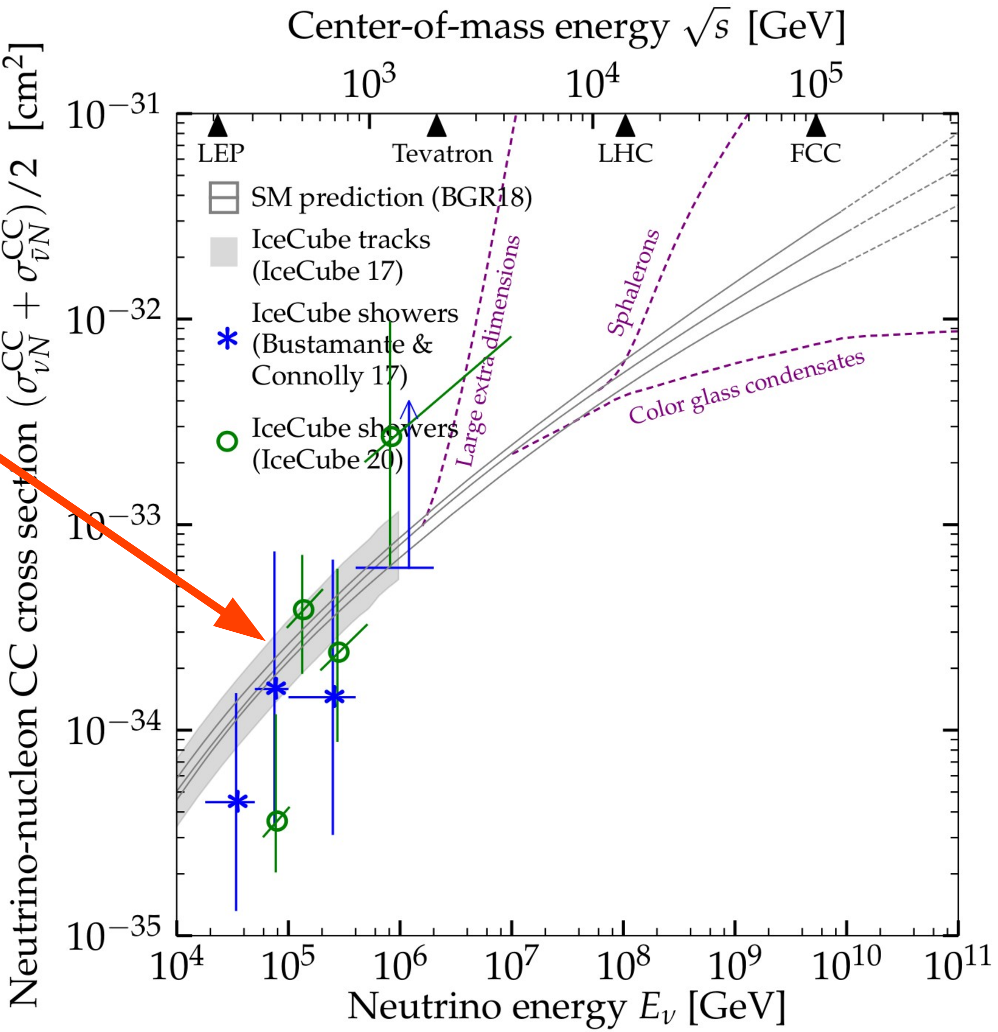
High-energy *νN* cross section: *today*

Measured:
TeV – PeV
cross section



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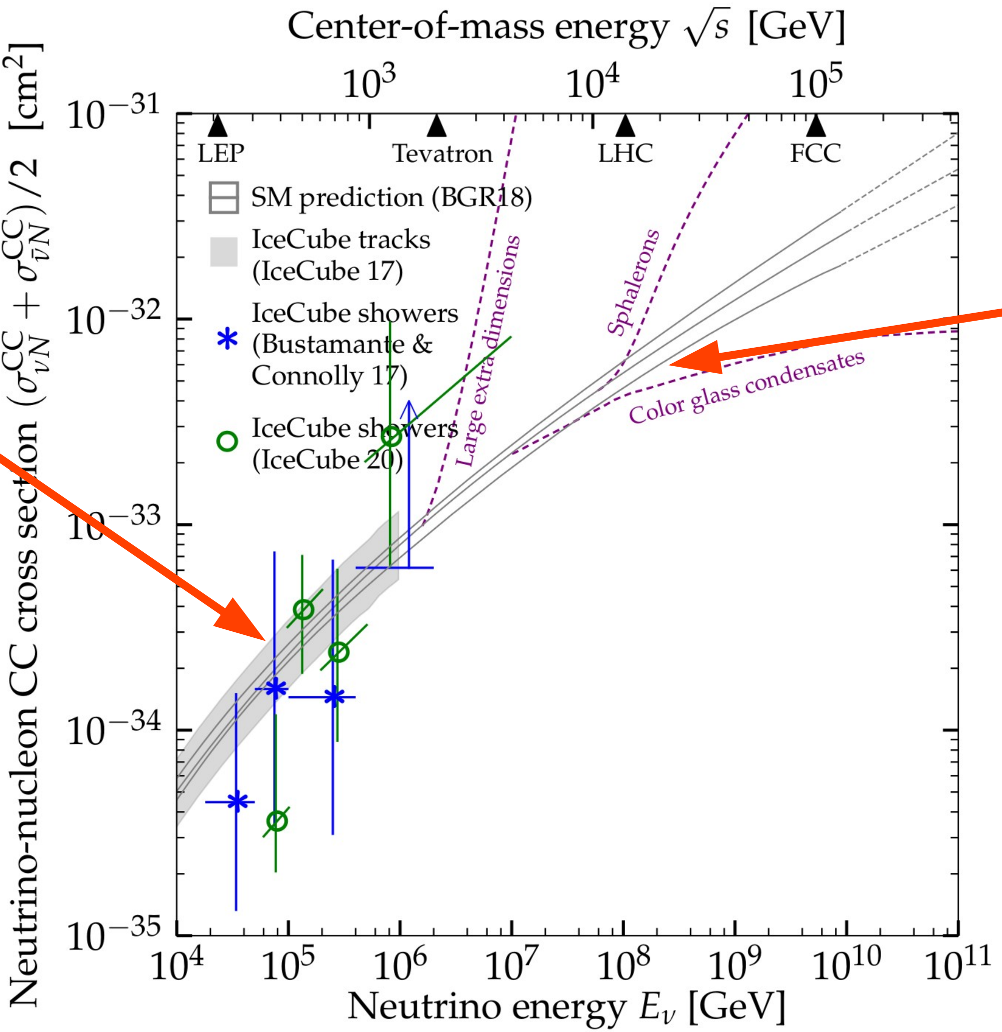
García, Gauld, Heijboer, Rojo, *JCAP* 2020

Measurements from:
IceCube, 2011.03560
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

High-energy νN cross section: *today*

Measured:
TeV – PeV
cross section



Not measured:
> 10-PeV
cross section

BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019

See also:
García, Gauld, Heijboer, Rojo, *JCAP* 2020

Measurements from:
IceCube, 2011.03560
MB & Connolly, *PRL* 2019
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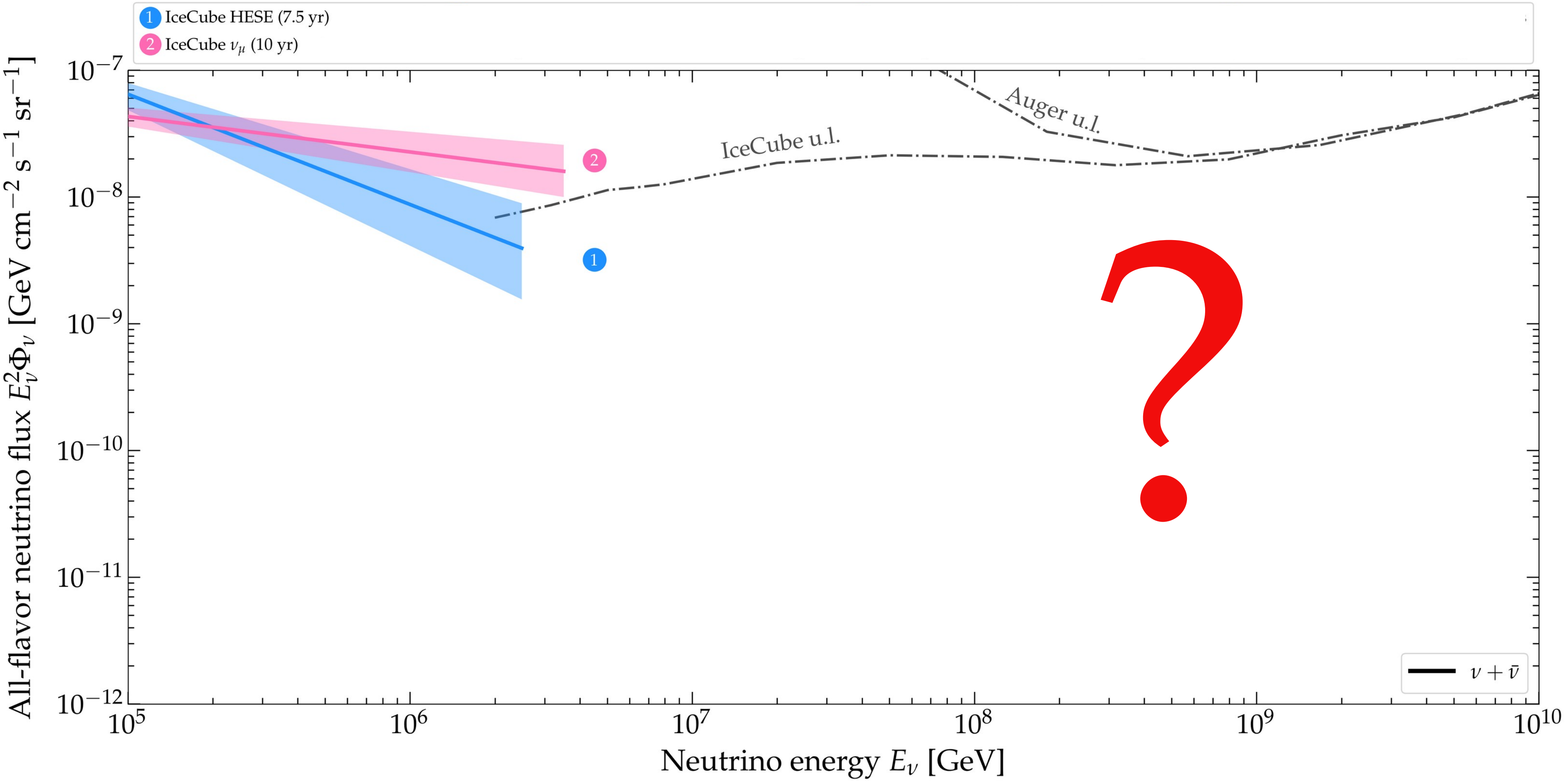
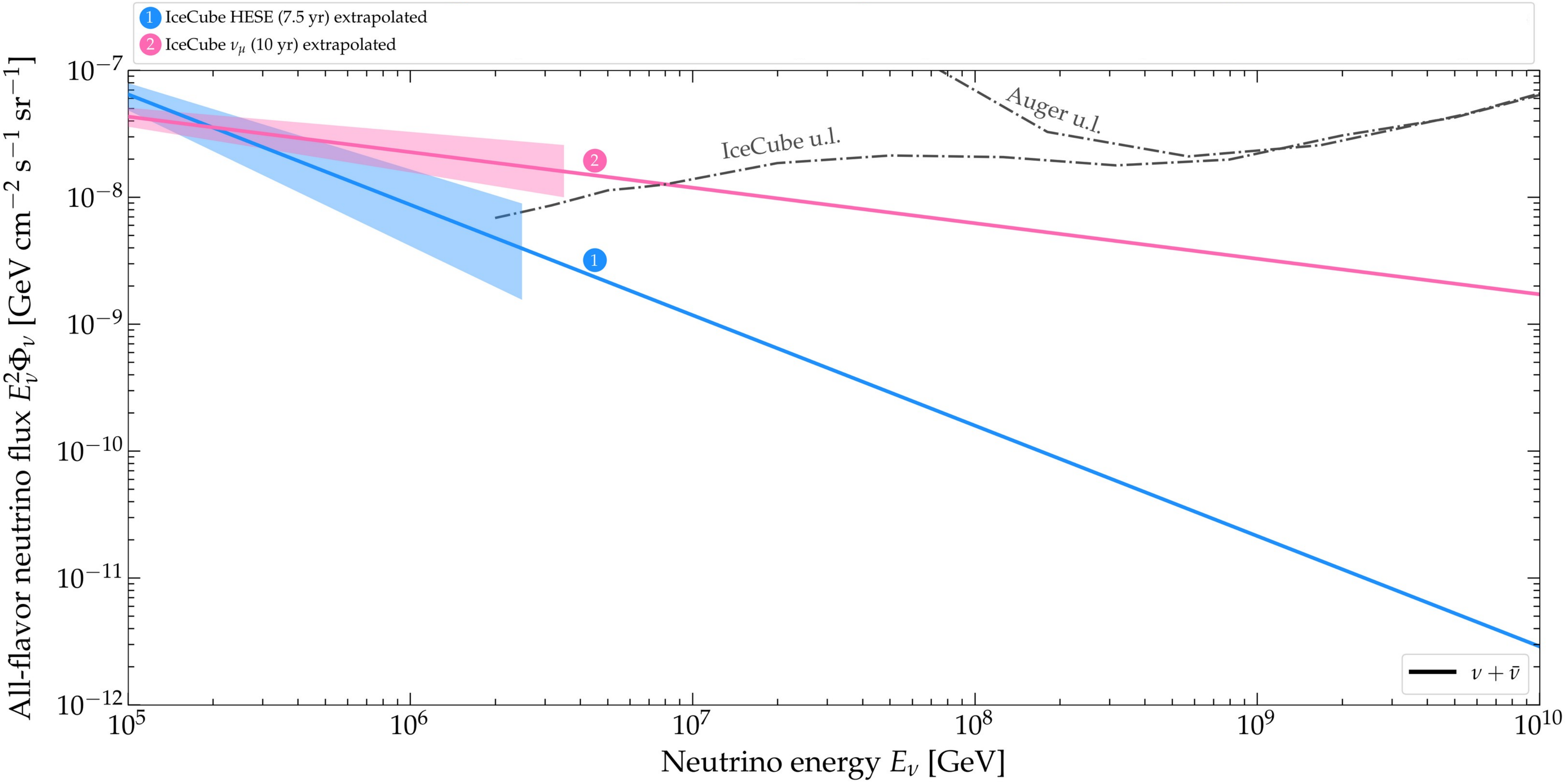
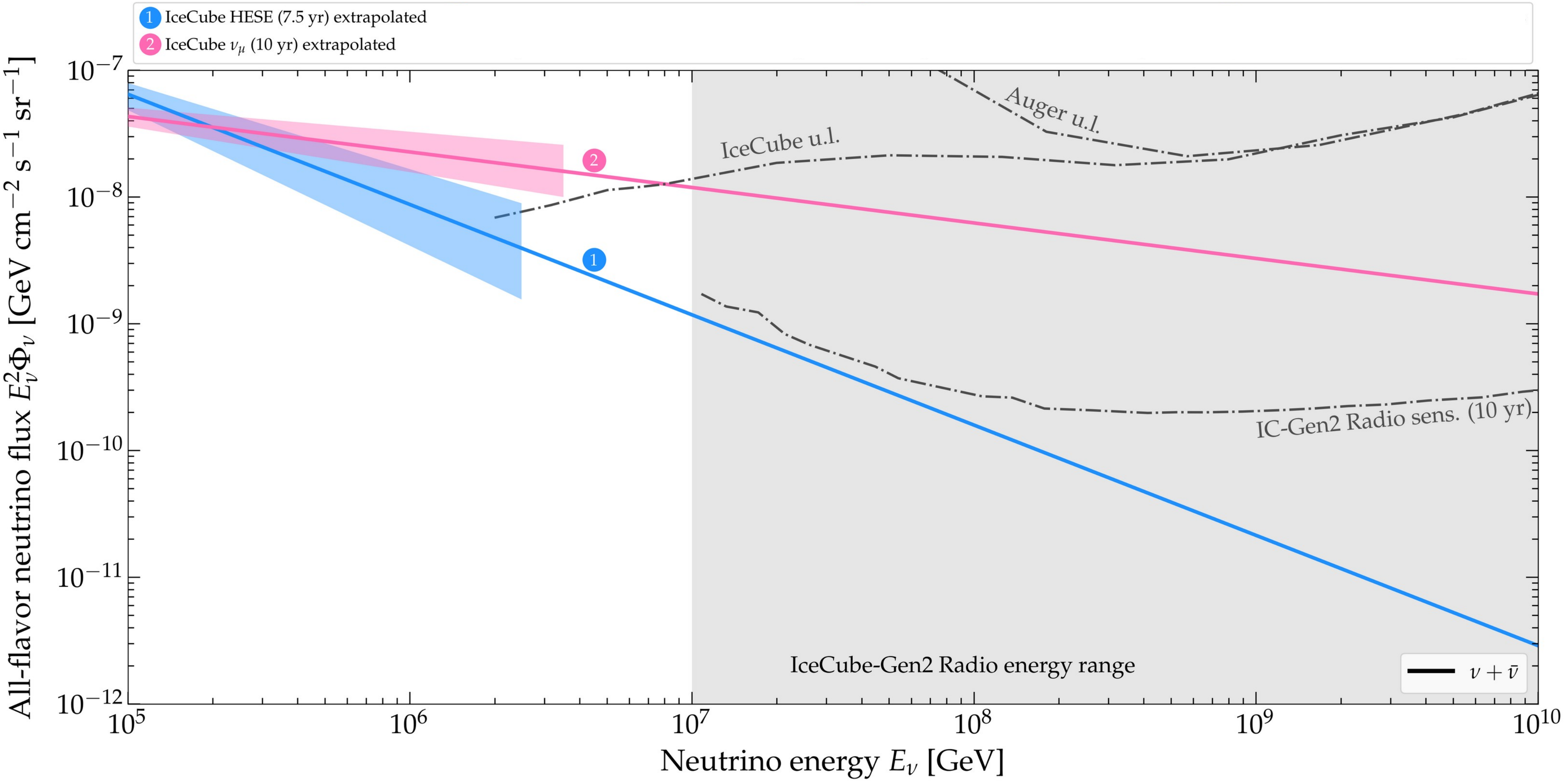


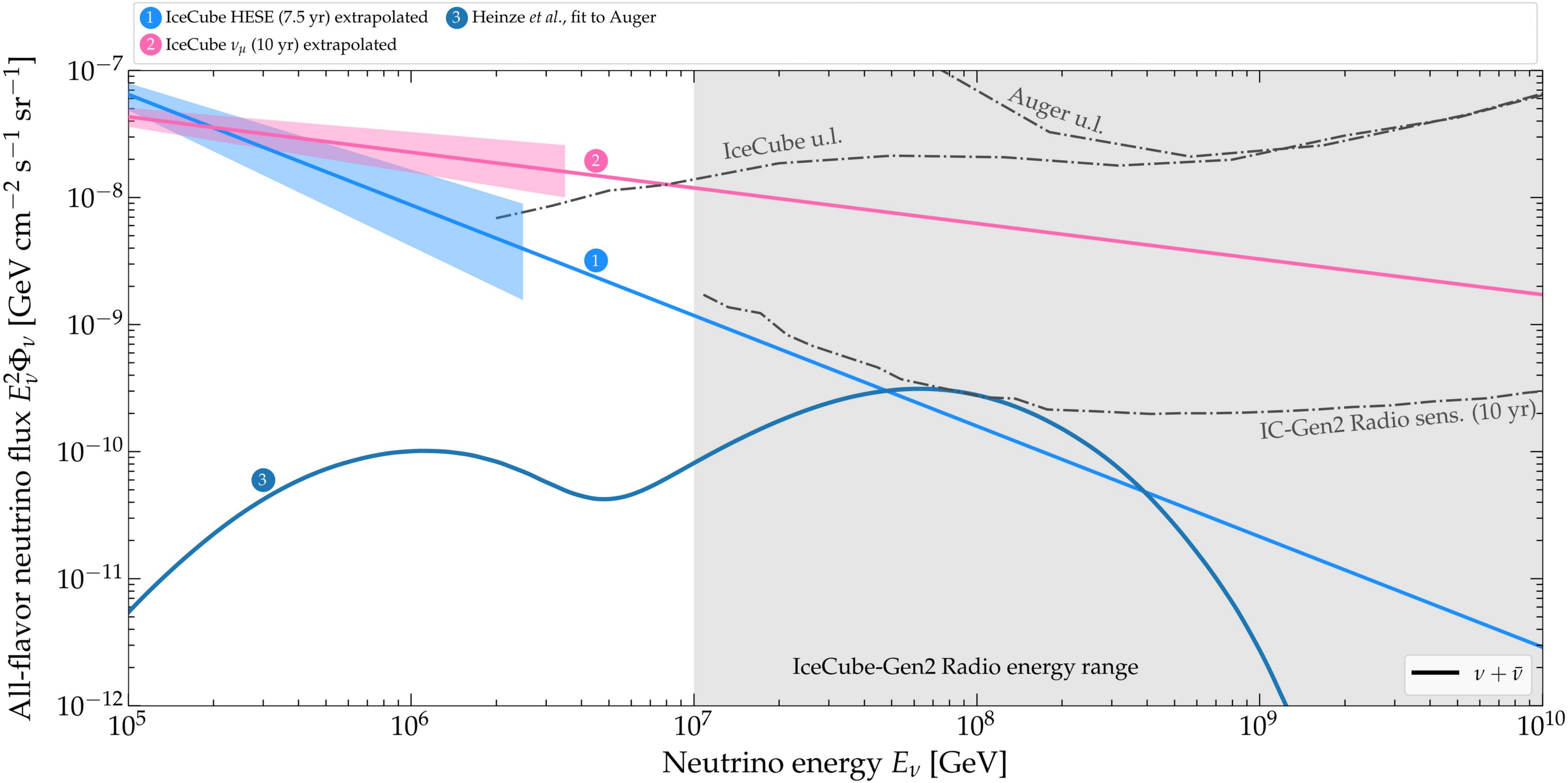
1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Auger u.l.
IceCube u.l.
?
$\nu + \bar{\nu}$
10^5
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy E_ν [GeV]



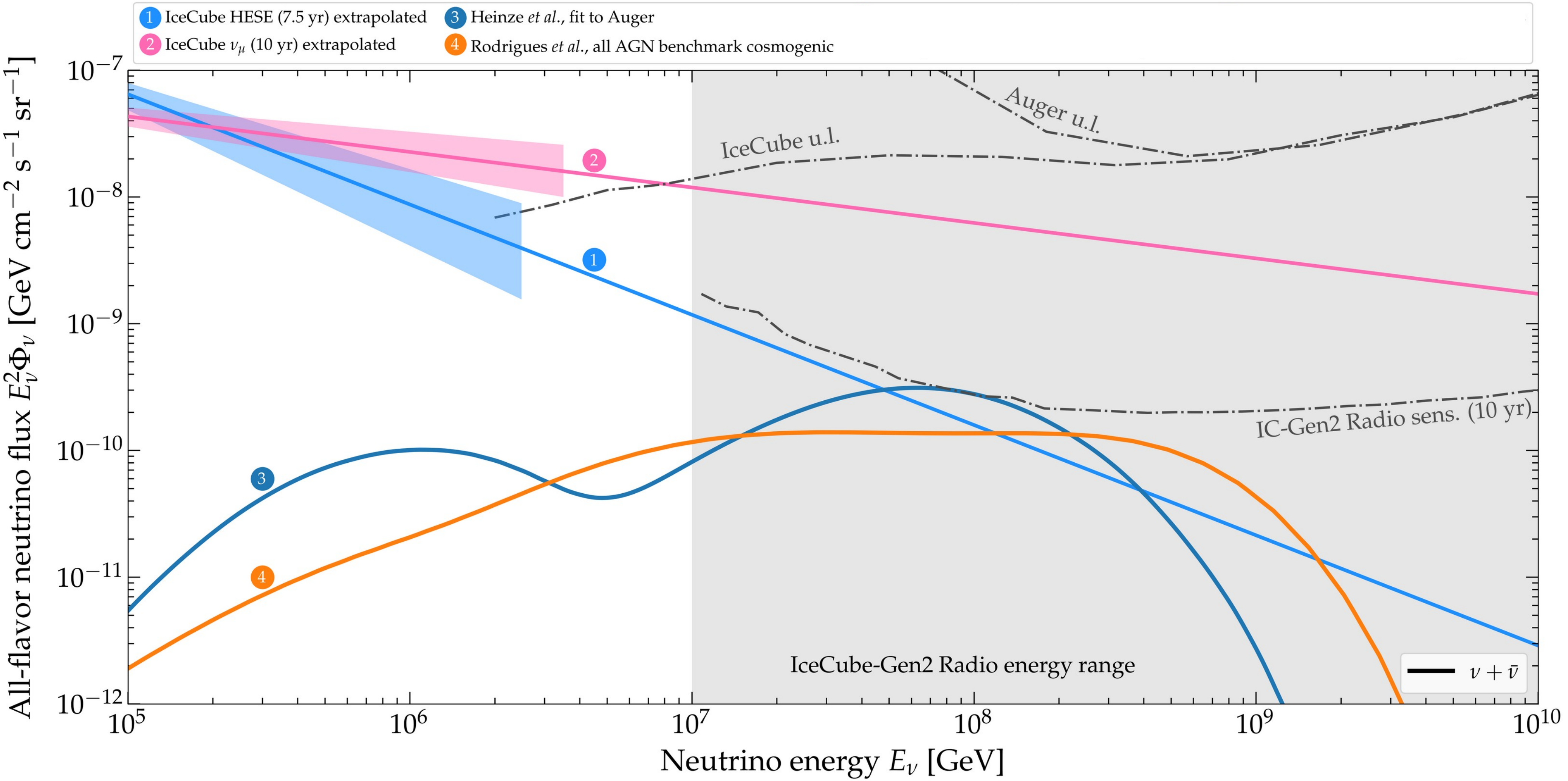
1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
Auger u.l.
IceCube u.l.
1
2
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy E_ν [GeV]



1 IceCube HESE (7.5 yr) extrapolated
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]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}



1 IceCube HESE (7.5 yr) extrapolated
3 Heinze et al., fit to Auger
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]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}



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3 Heinze *et al.*, fit to Auger
4 Rodrigues *et al.*, all AGN benchmark cosmogenic
Auger u.l.
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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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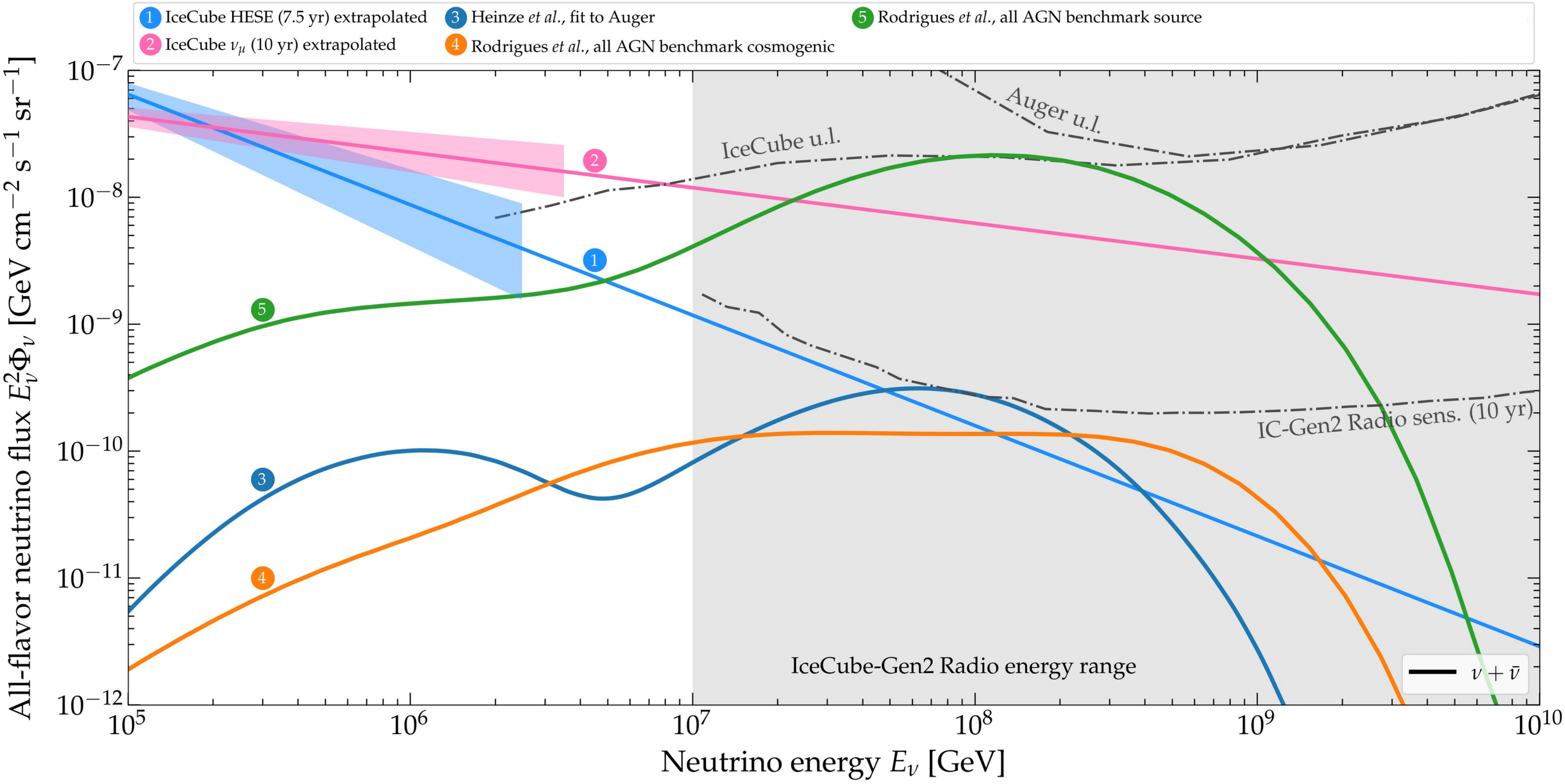
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}



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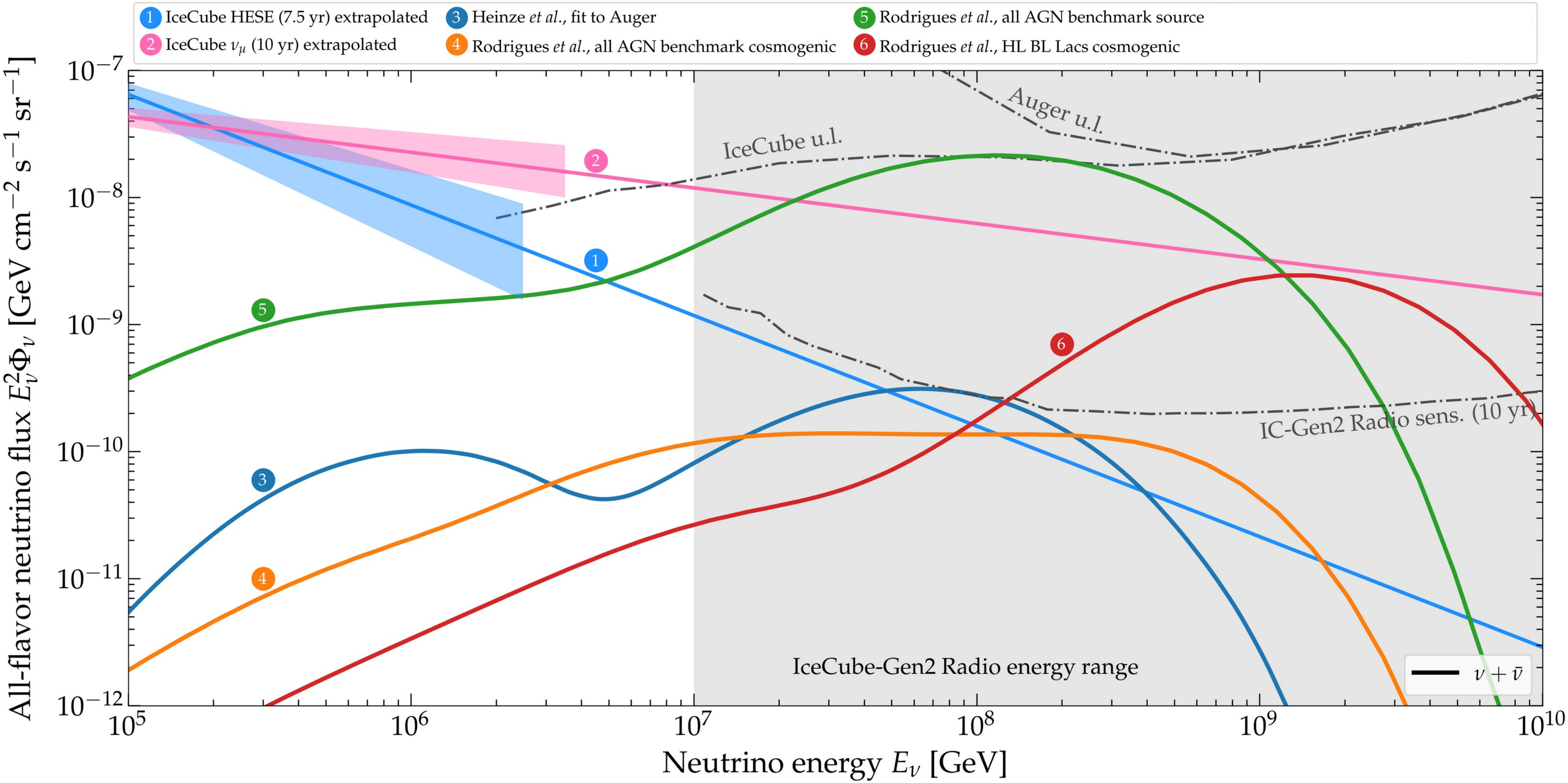
4 Rodrigues *et al.*, all AGN benchmark cosmogenic
5 Rodrigues *et al.*, all AGN benchmark source
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2\Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}



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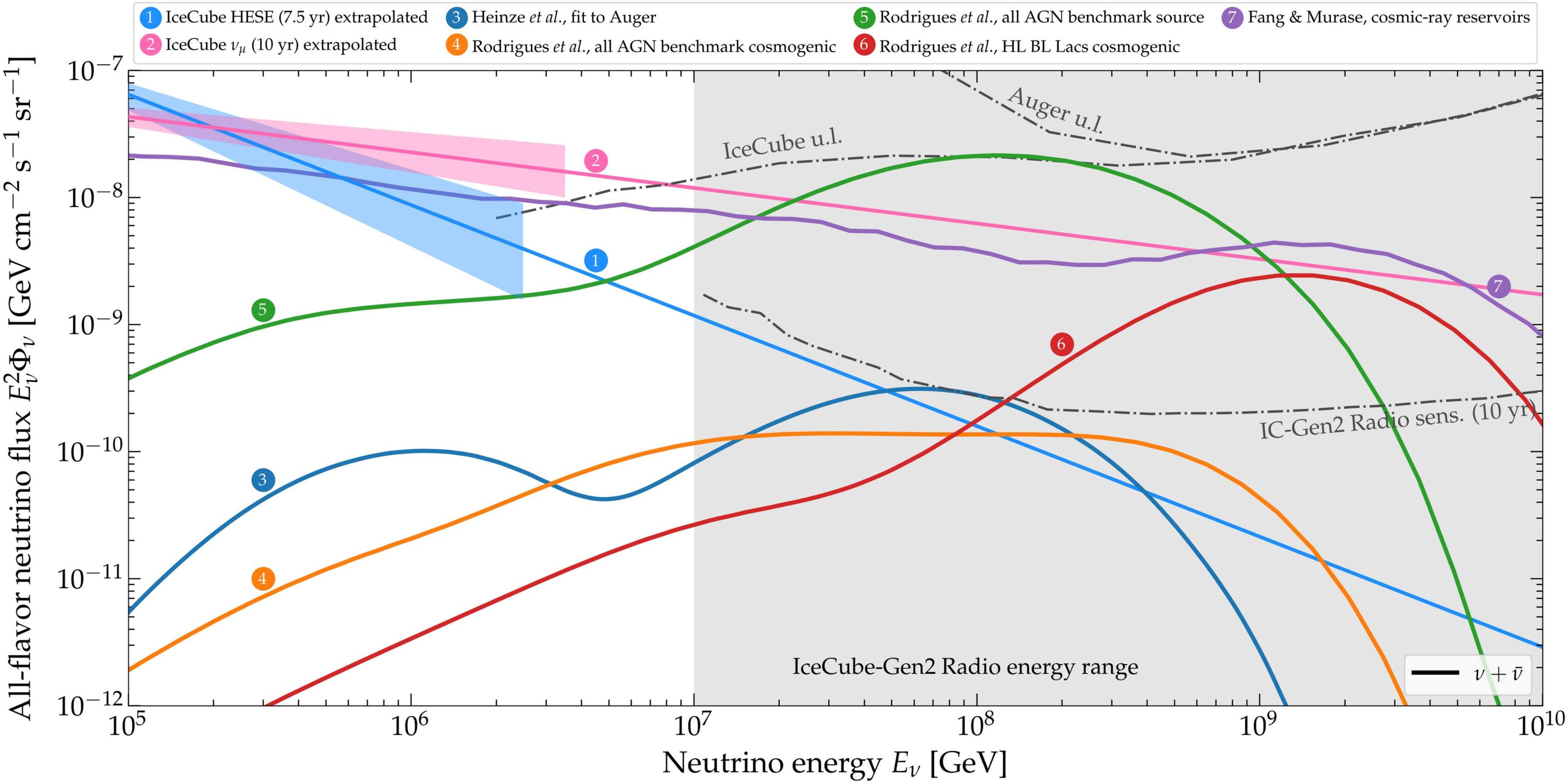
6 Rodrigues et al., HL BL Lacs cosmogenic
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}



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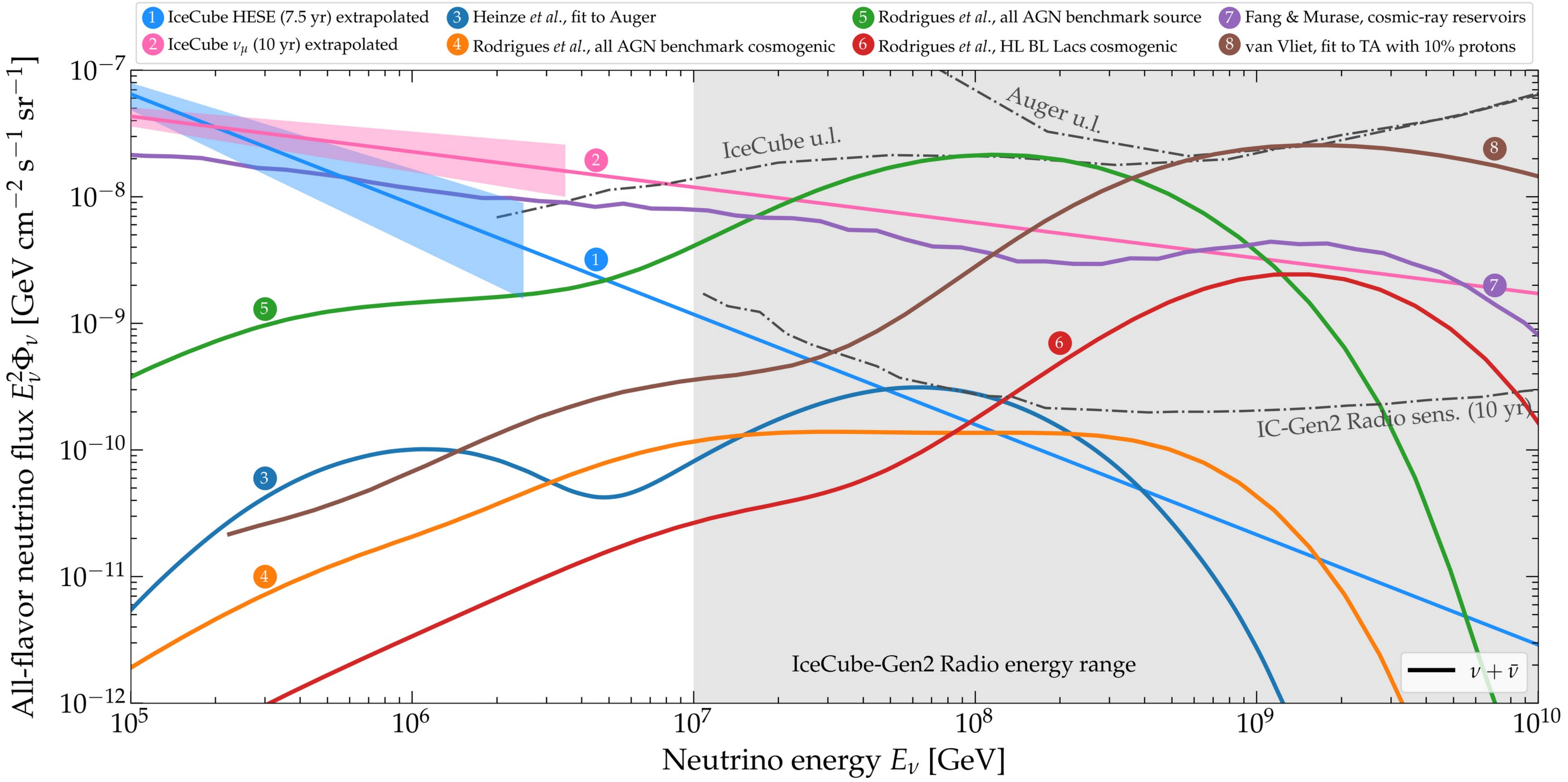
6 Rodrigues *et al.*, HL BL Lacs cosmogenic
7 Fang & Murase, cosmic-ray reservoirs
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2\Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}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



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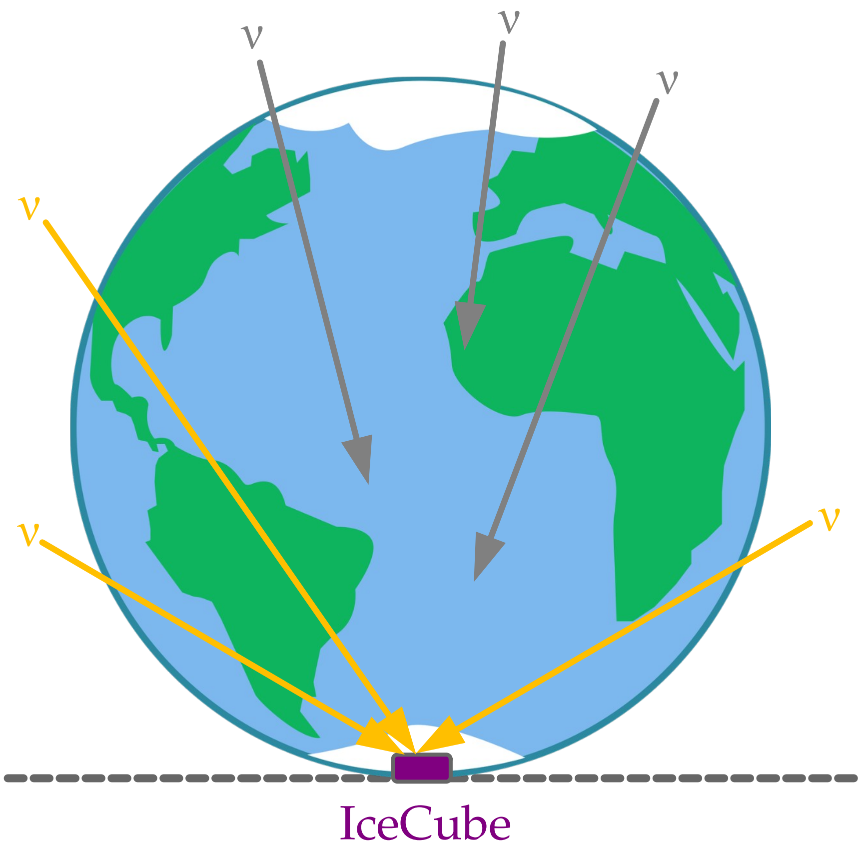
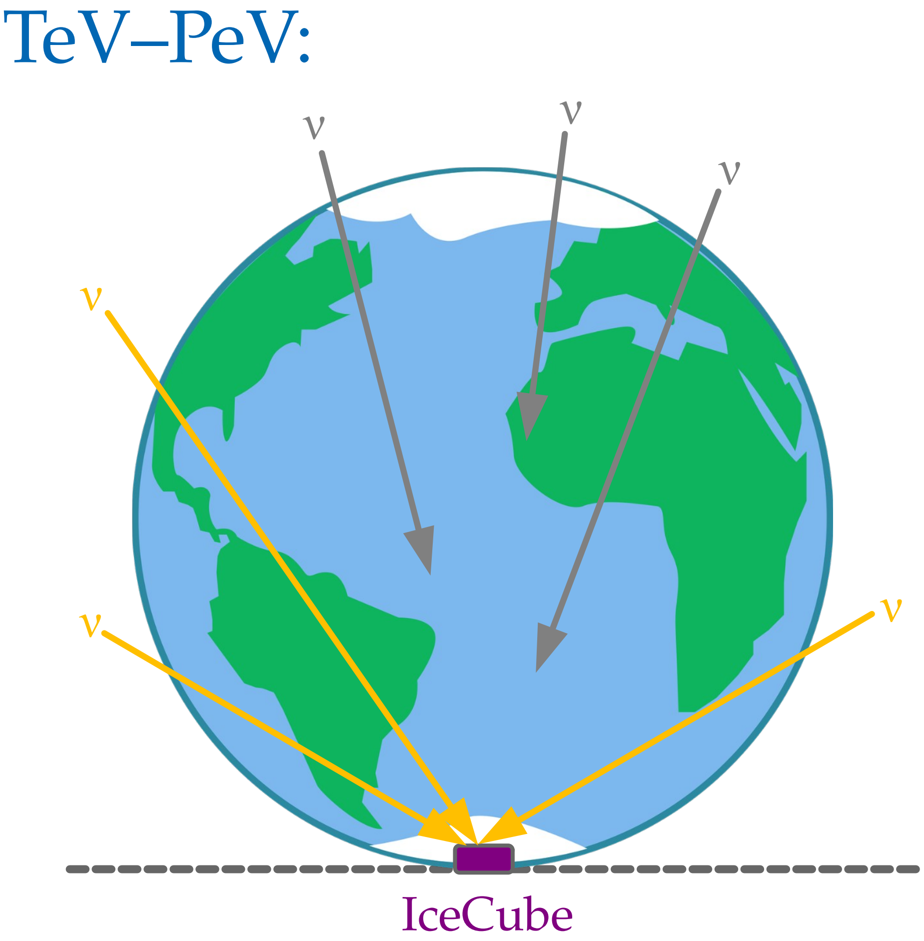
3 Heinze et al., fit to Auger
4 Rodrigues et al., all AGN benchmark cosmogenic
5 Rodrigues et al., all AGN benchmark source
6 Rodrigues et al., HL BL Lacs cosmogenic
7 Fang & Murase, cosmic-ray reservoirs
8 van Vliet, fit to TA with 10% protons
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 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}

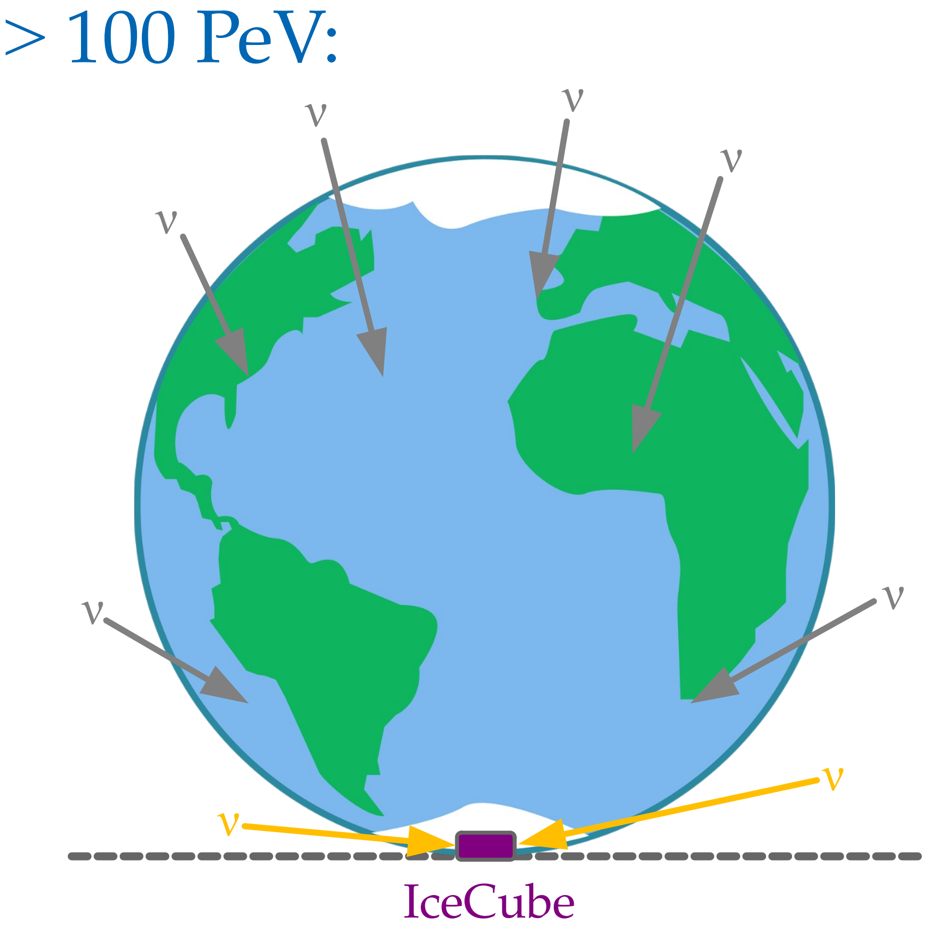
TeV–PeV:



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

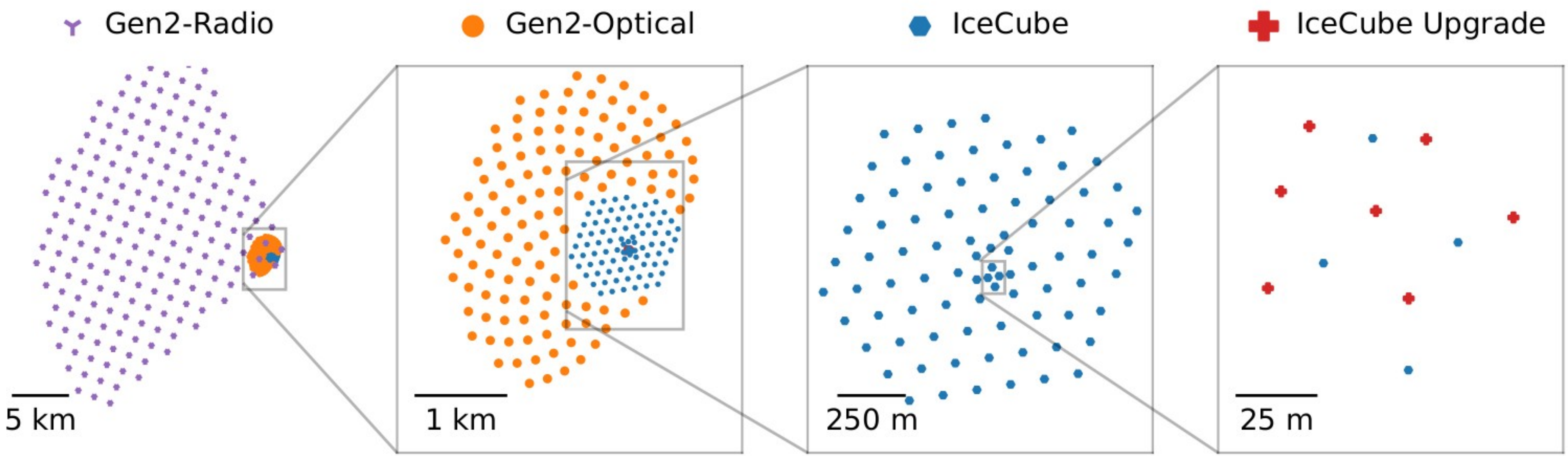


Earth is *almost fully* opaque,
some upgoing ν still make it through



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

IceCube-Gen2



~2040

10s km^3

> 100 PeV ν

~8 km^3

TeV–10 PeV ν

Today

1 km^3

TeV–few PeV ν

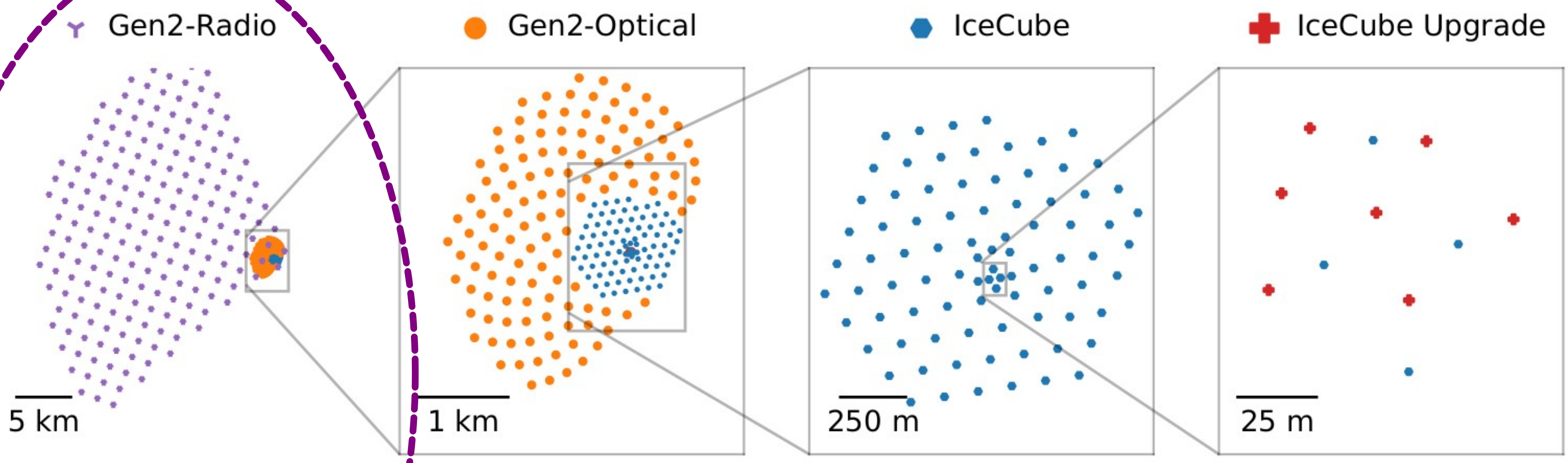
2023

7 new strings

GeV–TeV ν

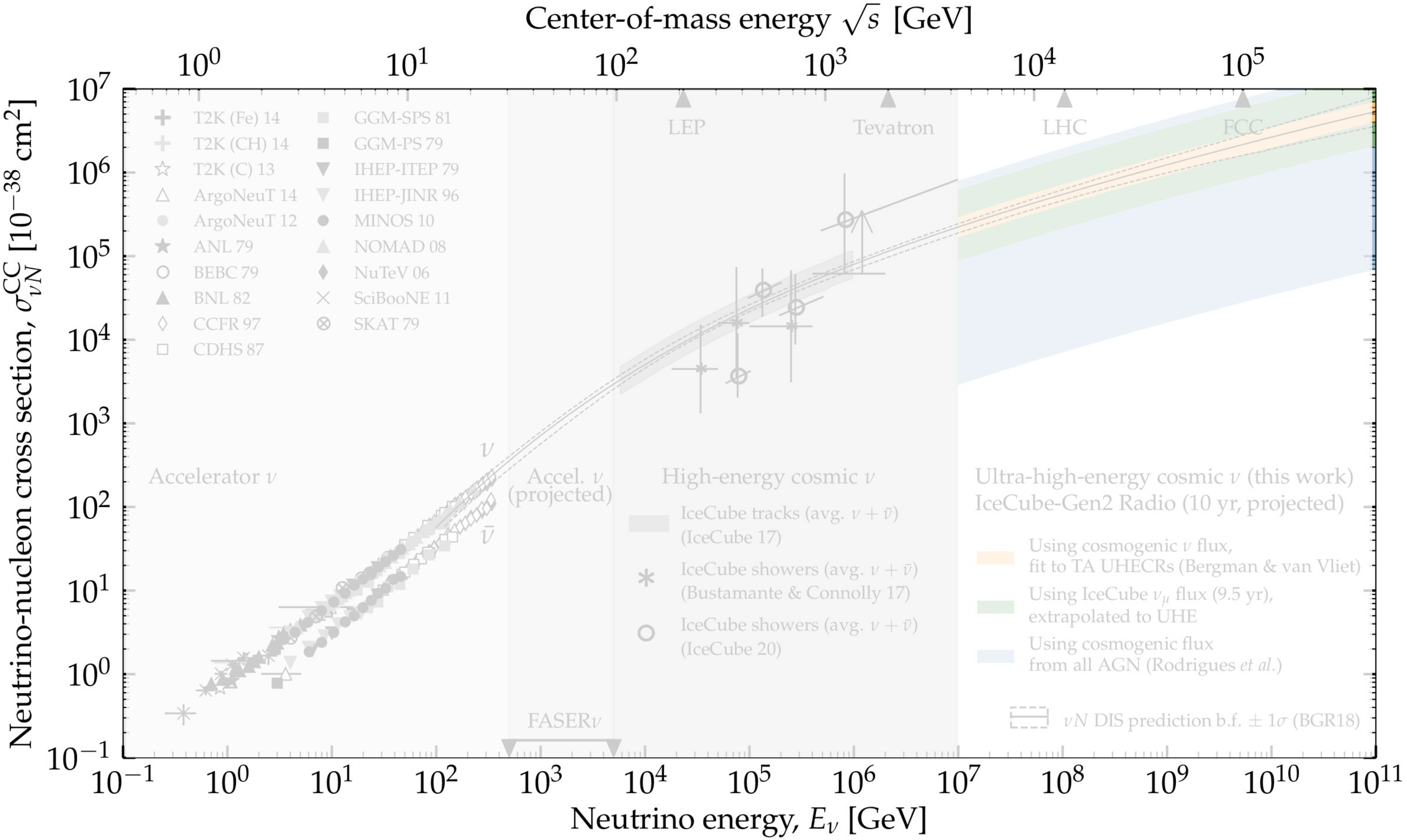
IceCube-Gen2, 2008.04323

IceCube-Gen2



~2040		Today	2023
10s km^3	~8 km^3	1 km^3	7 new strings
> 100 PeV ν	TeV–10 PeV ν	TeV–few PeV ν	GeV–TeV ν

IceCube-Gen2, 2008.04323



Center-of-mass energy $\sqrt{s}$ [GeV]
10^0
10^1
10^2
10^3
10^4
10^5
Neutrino-nucleon cross section, $\sigma_{\nu N}^{CC}$ [10^{-38} cm^2]
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
GGM-PS 79
IHEP-ITEP 79
IHEP-JINR 96
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
LEP
Tevatron
LHC
FCC
ν
$\bar{\nu}$
Accelerator ν
Accel. ν (projected)
High-energy cosmic ν
Ultra-high-energy cosmic ν (this work)
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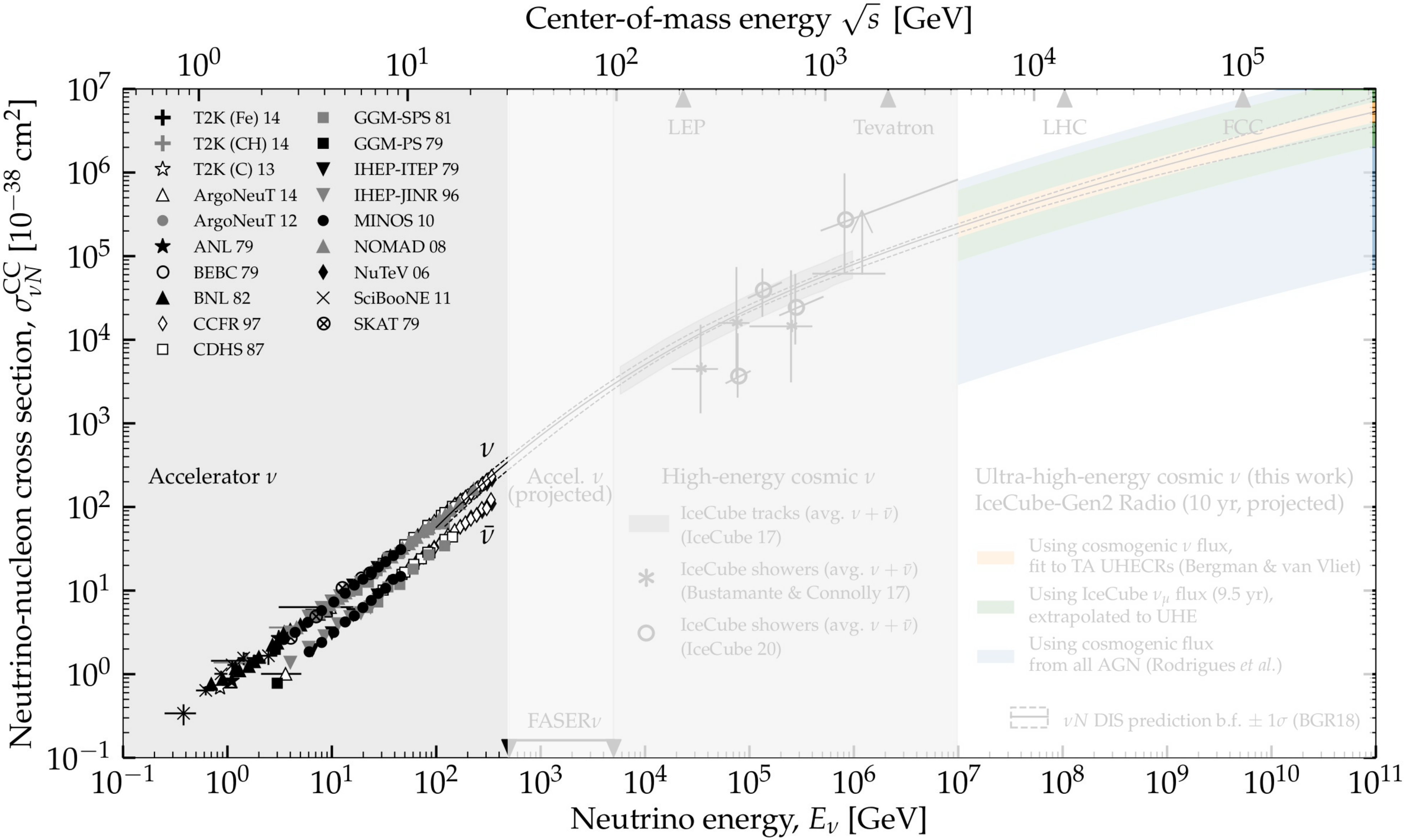
νN DIS prediction b.f. $\pm 1\sigma$ (BGR18)
FASERν
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
Neutrino energy, E_ν [GeV]



Center-of-mass energy $\sqrt{s}$ [GeV]
Neutrino-nucleon cross section, $\sigma_{\nu N}^{CC}$ [10^{-38} cm^2]
Neutrino energy, E_ν [GeV]
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
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CCFR 97
CDHS 87
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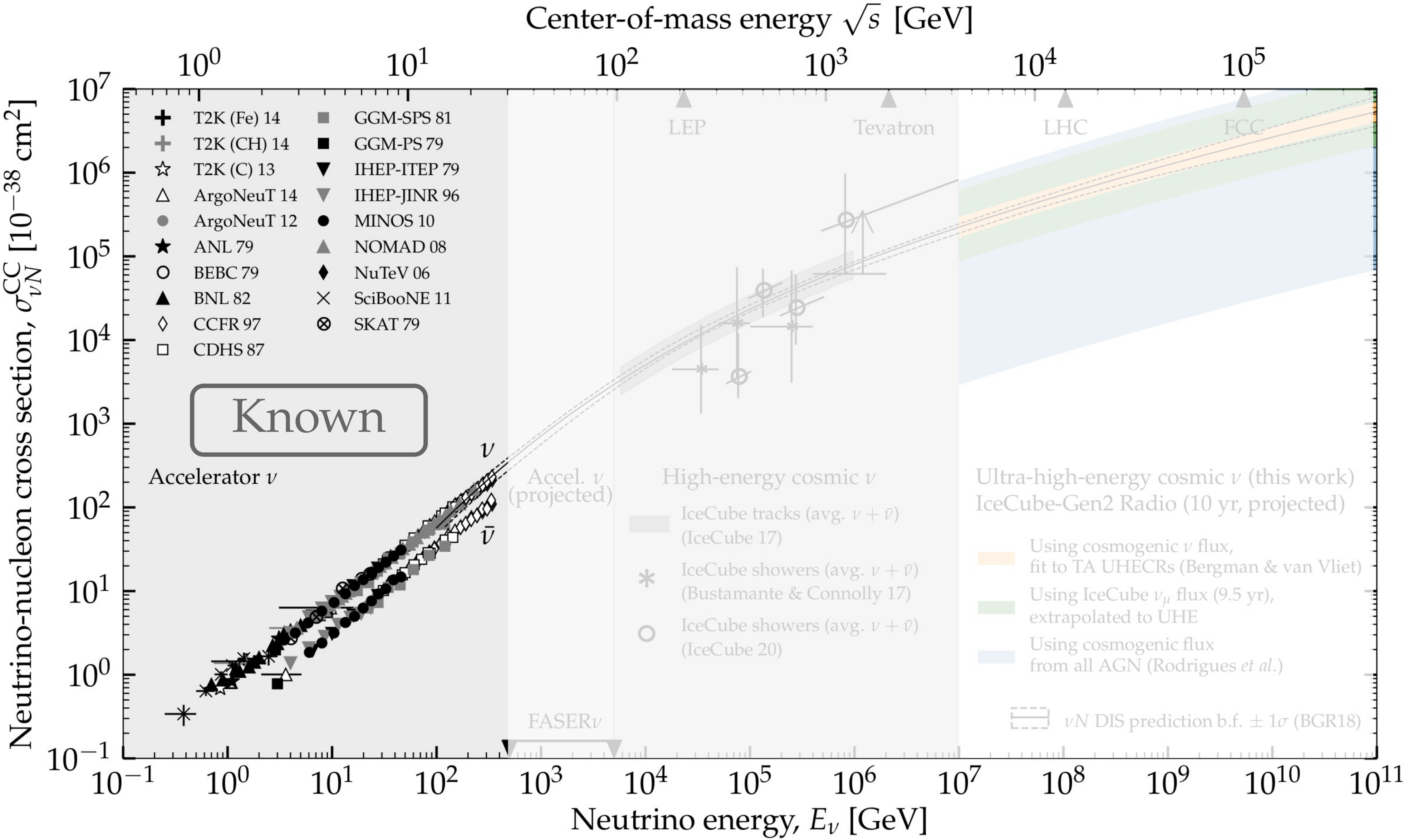

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FASERν
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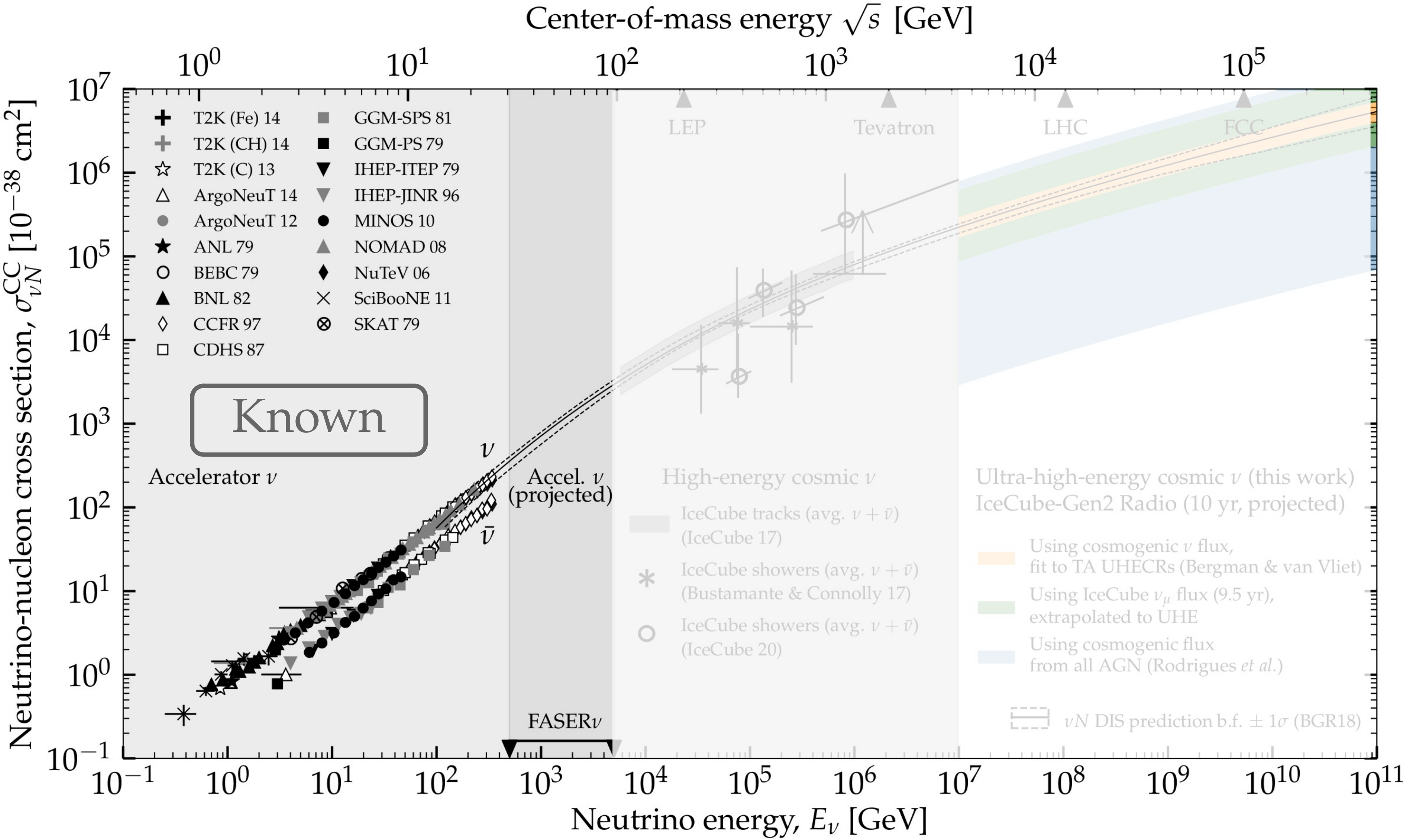

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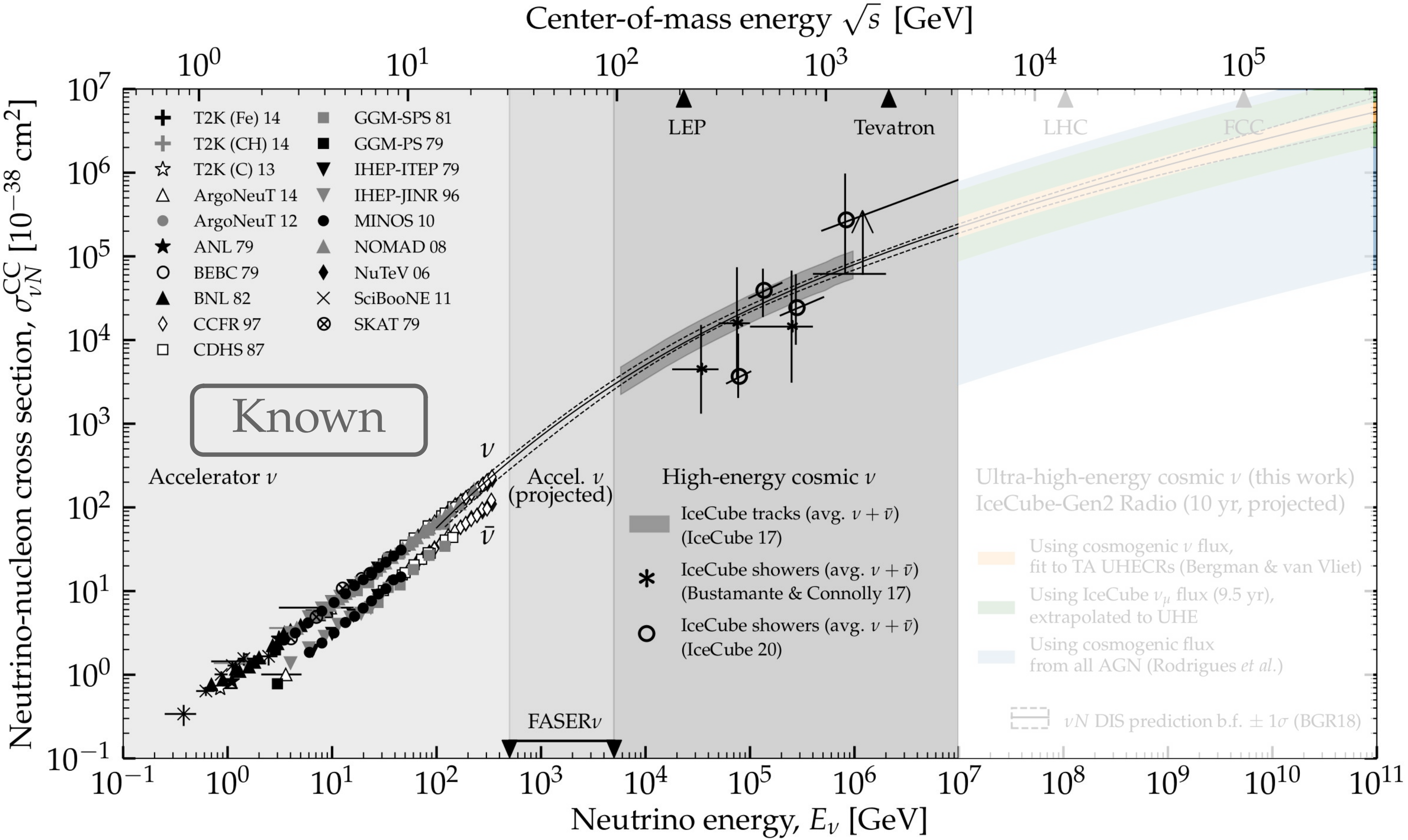

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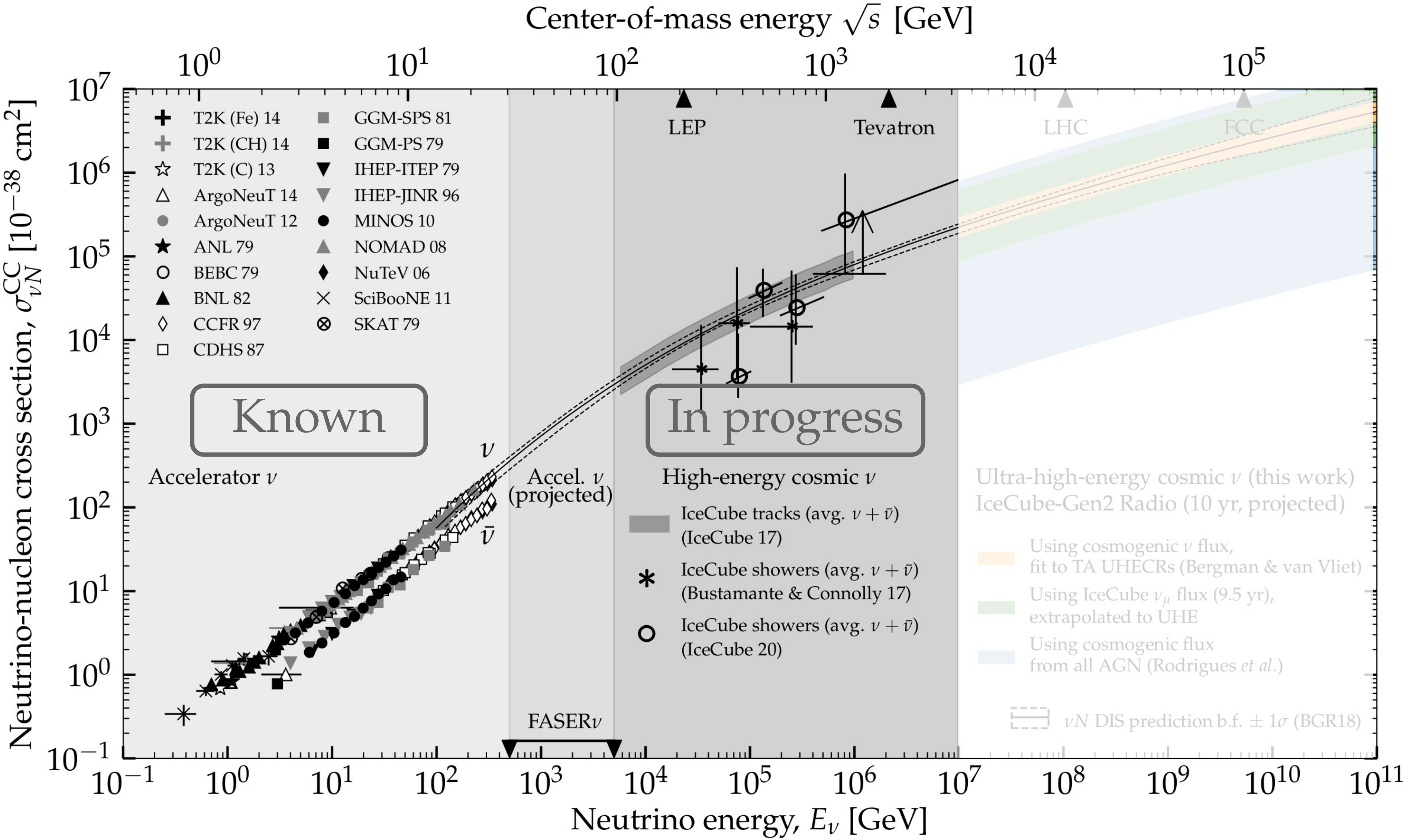
FASERν
ν
$\bar{\nu}$



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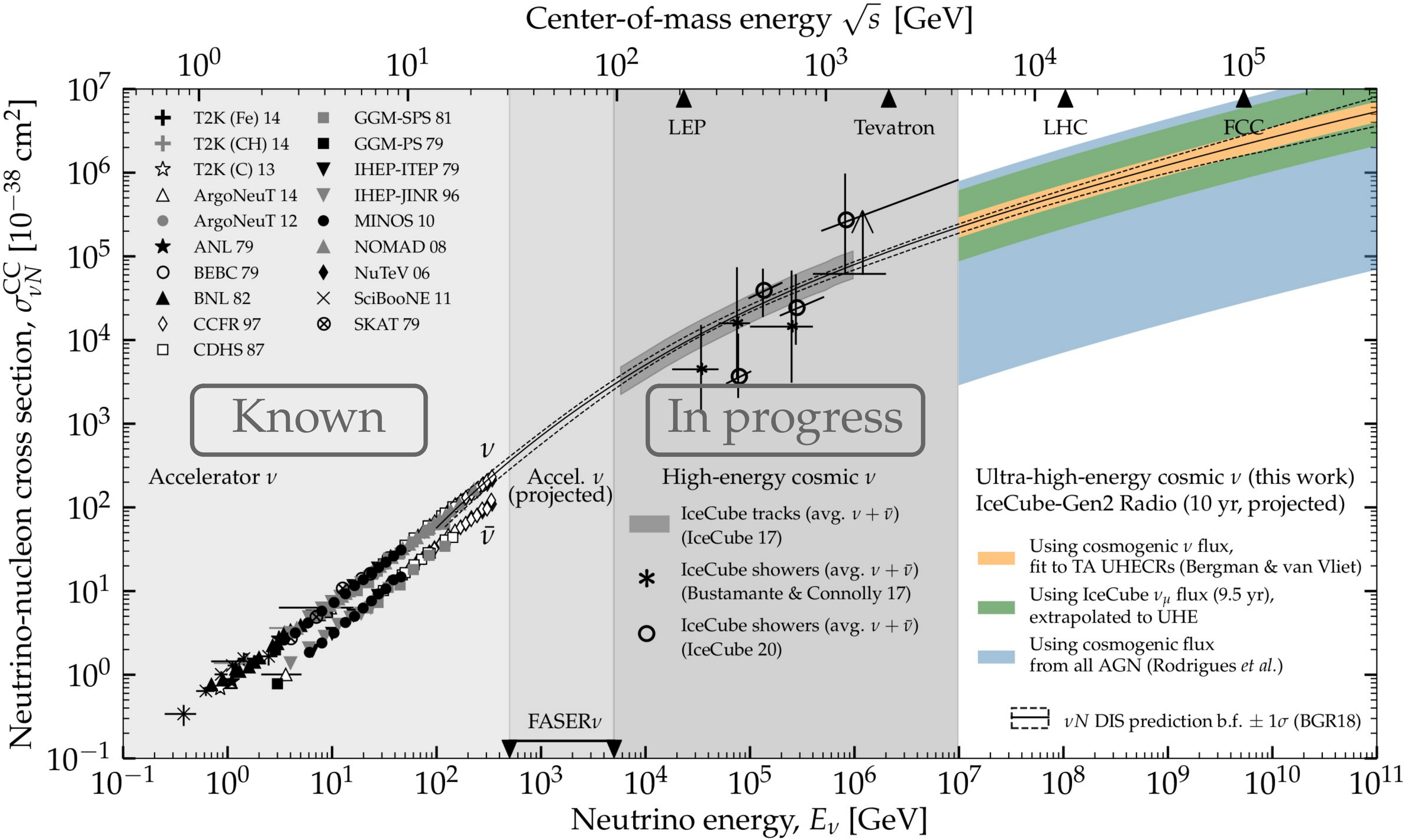
$\bar{\nu}$



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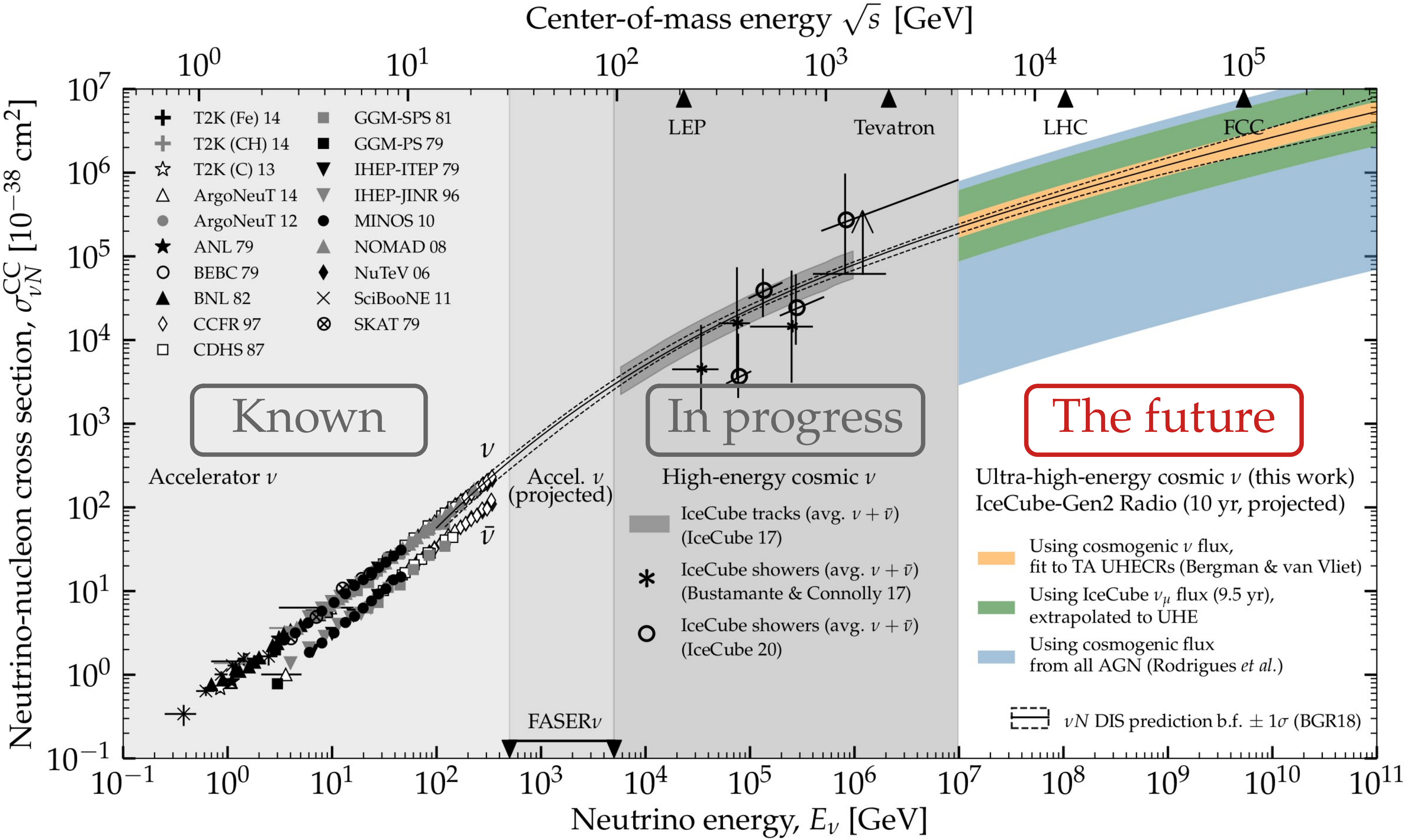
ν
$\bar{\nu}$



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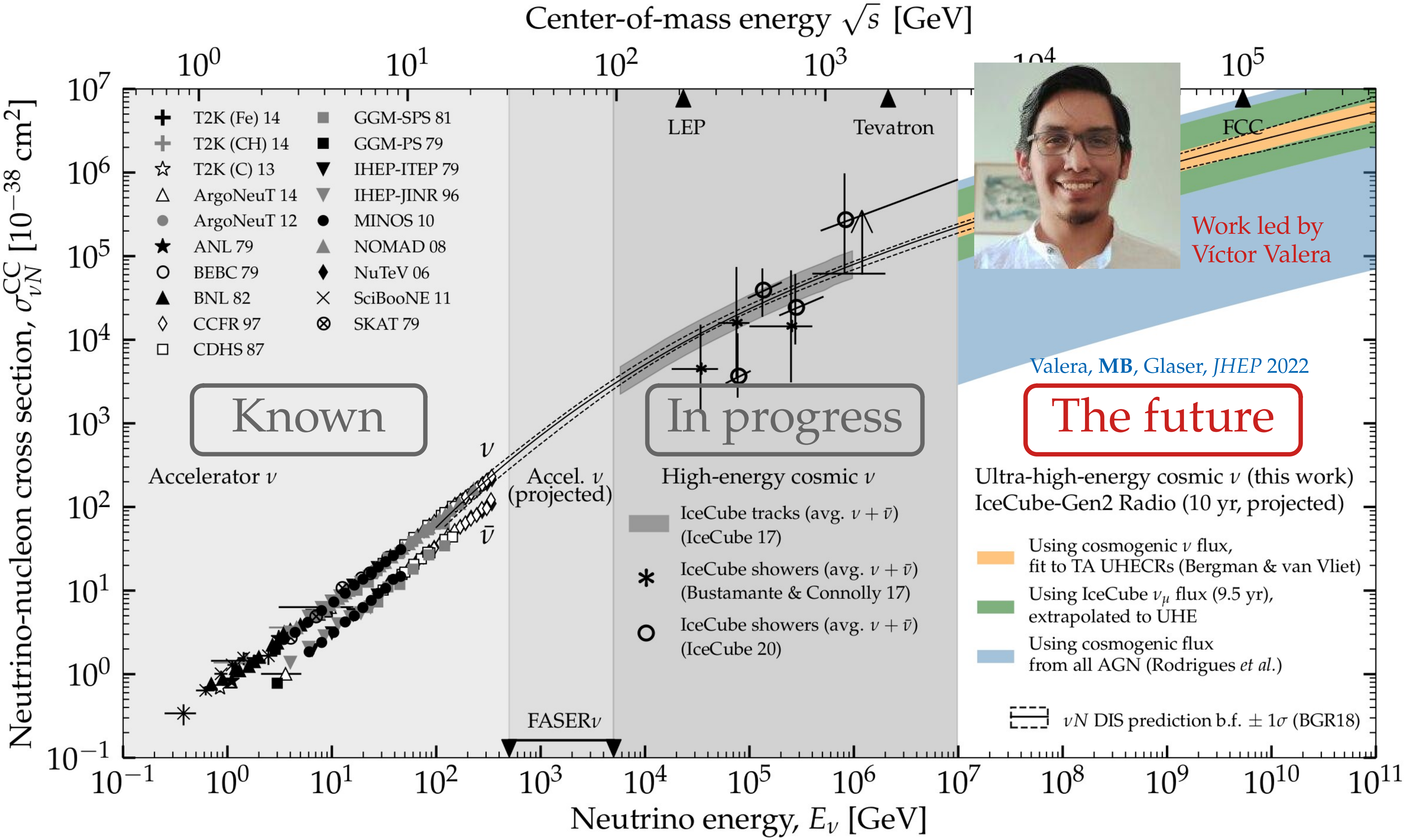
SKAT 79
LEP
Tevatron
LHC
FCC
Known
In progress
The future
Accelerator ν
Accel. ν (projected)
High-energy cosmic ν
Ultra-high-energy cosmic ν (this work)
IceCube-Gen2 Radio (10 yr, projected)
IceCube tracks (avg. $\nu + \bar{\nu}$) (IceCube 17)
IceCube showers (avg. $\nu + \bar{\nu}$) (Bustamante & Connolly 17)
IceCube showers (avg. $\nu + \bar{\nu}$) (IceCube 20)
Using cosmogenic ν flux, fit to TA UHECRs (Bergman & van Vliet)
Using IceCube ν_μ flux (9.5 yr), extrapolated to UHE
Using cosmogenic flux from all AGN (Rodrigues *et al.*)
νN DIS prediction b.f. $\pm 1\sigma$ (BGR18)
FASERν
ν
$\bar{\nu}$



Center-of-mass energy $\sqrt{s}$ [GeV]
Neutrino-nucleon cross section, $\sigma_{\nu N}^{CC}$ [10^{-38} cm^2]
Neutrino energy, E_ν [GeV]
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
GGM-PS 79
IHEP-ITEP 79
IHEP-JINR 96
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
LEP
Tevatron
FCC
Work led by Víctor Valera
Valera, **MB**, Glaser, *JHEP* 2022
Known
In progress
The future
Accelerator ν
Accel. ν (projected)
FASERν
High-energy cosmic ν
IceCube tracks (avg. $\nu + \bar{\nu}$) (IceCube 17)
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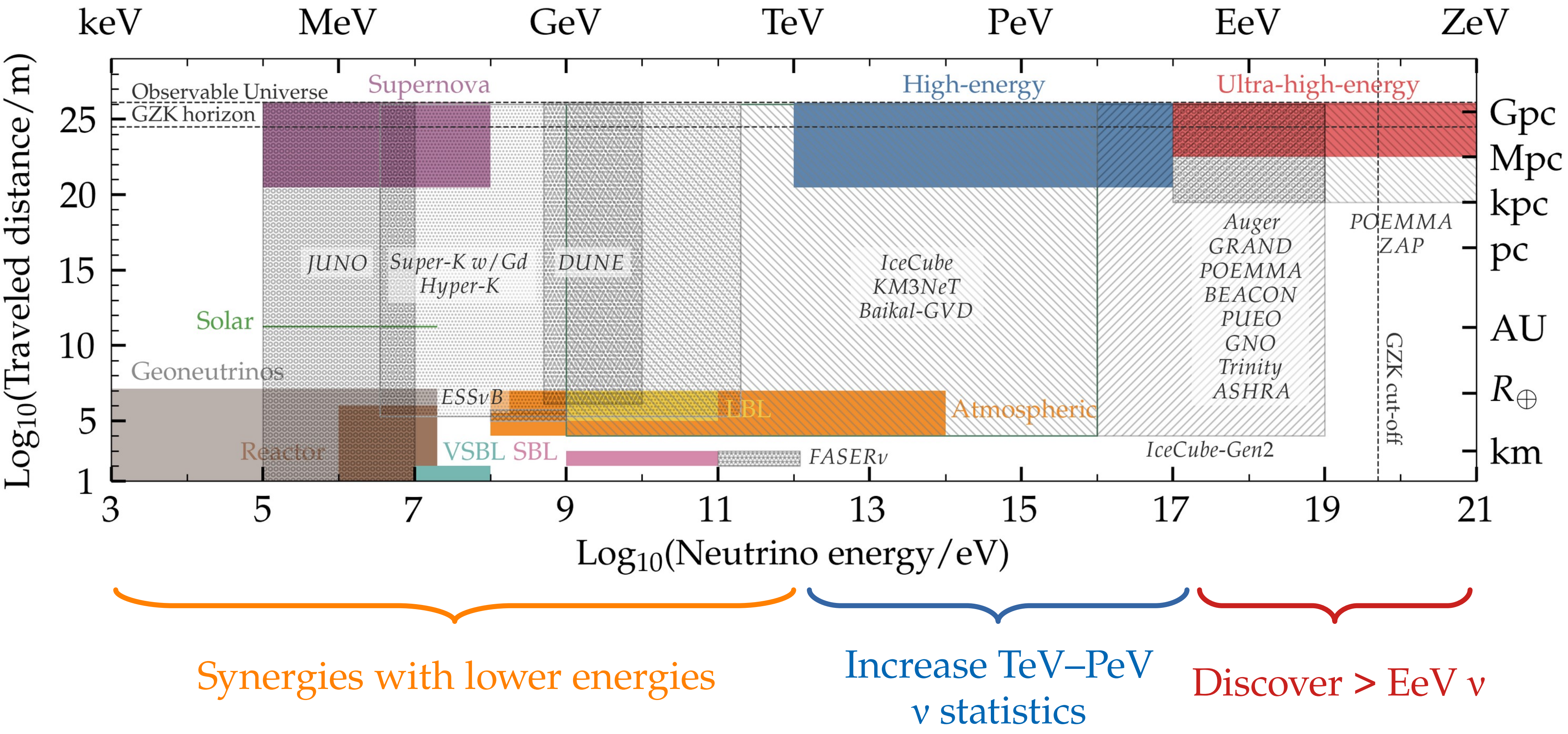
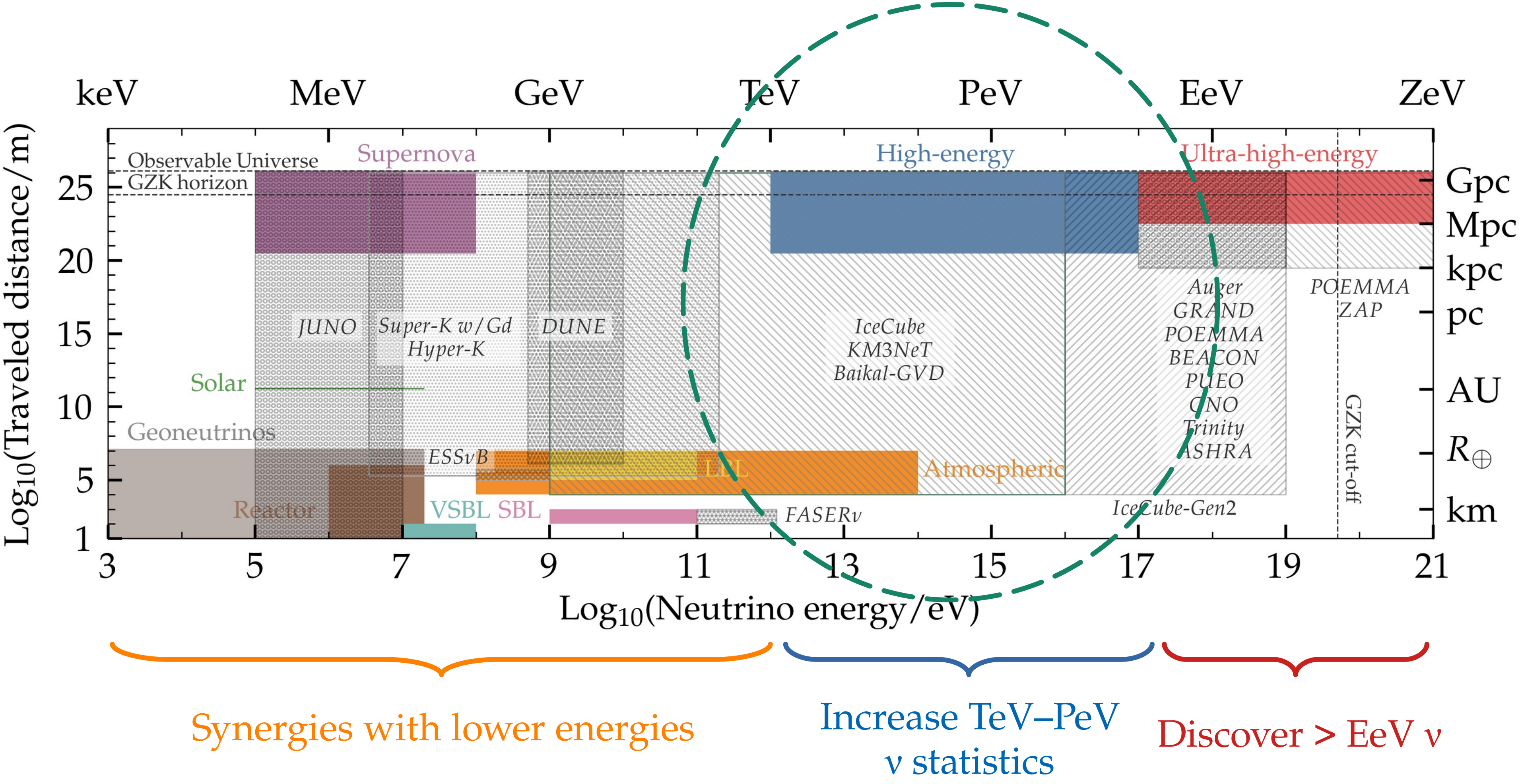
Using cosmogenic flux from all AGN (Rodrigues *et al.*)
νN DIS prediction b.f. ± 1σ (BGR18)

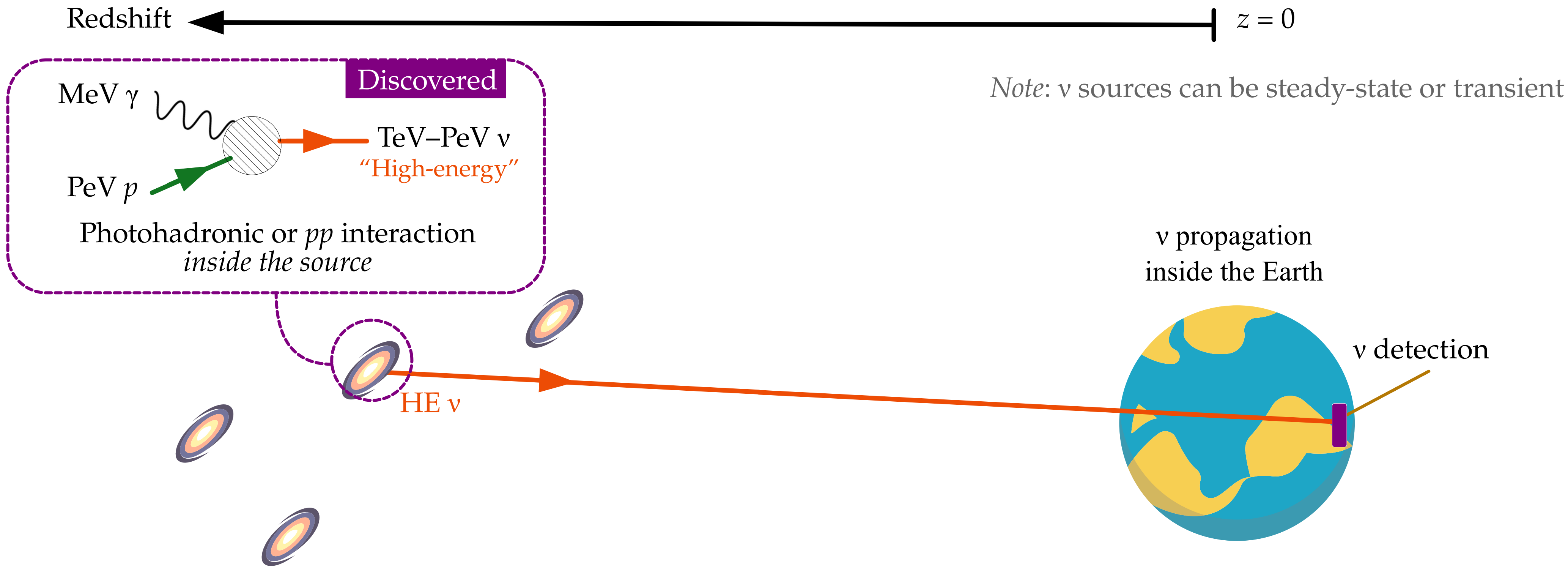
IV.
The future



MB *et al.*, Snowmass 2020 Letter of interest

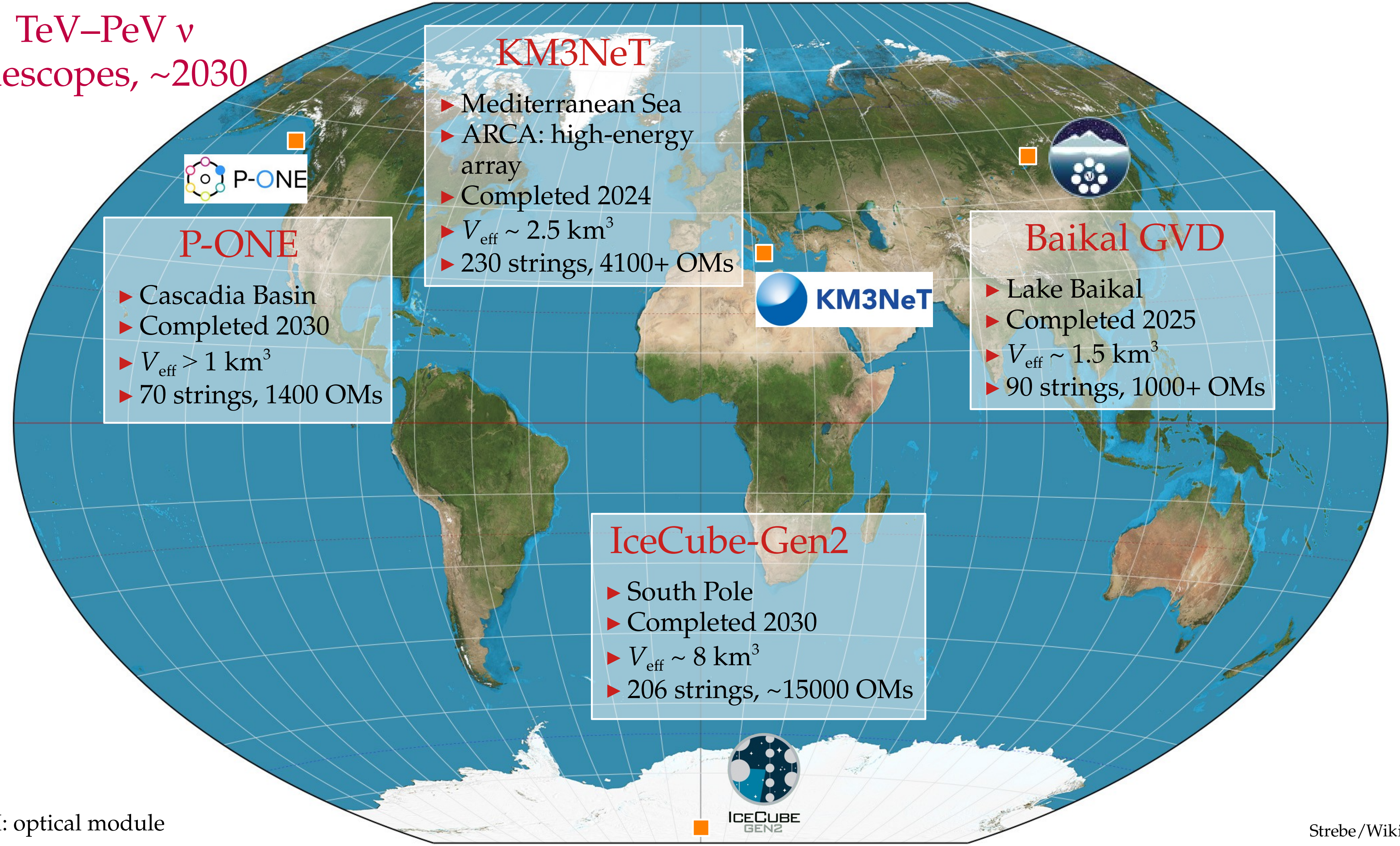


MB *et al.*, Snowmass 2020 Letter of interest



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

TeV–PeV ν telescopes, ~2030



KM3NeT

- Mediterranean Sea
- ARCA: high-energy array
- Completed 2024
- $V_{\text{eff}} \sim 2.5$ km^3
- 230 strings, 4100+ OMs

P-ONE

- Cascadia Basin
- Completed 2030
- $V_{\text{eff}} > 1$ km^3
- 70 strings, 1400 OMs

Baikal GVD

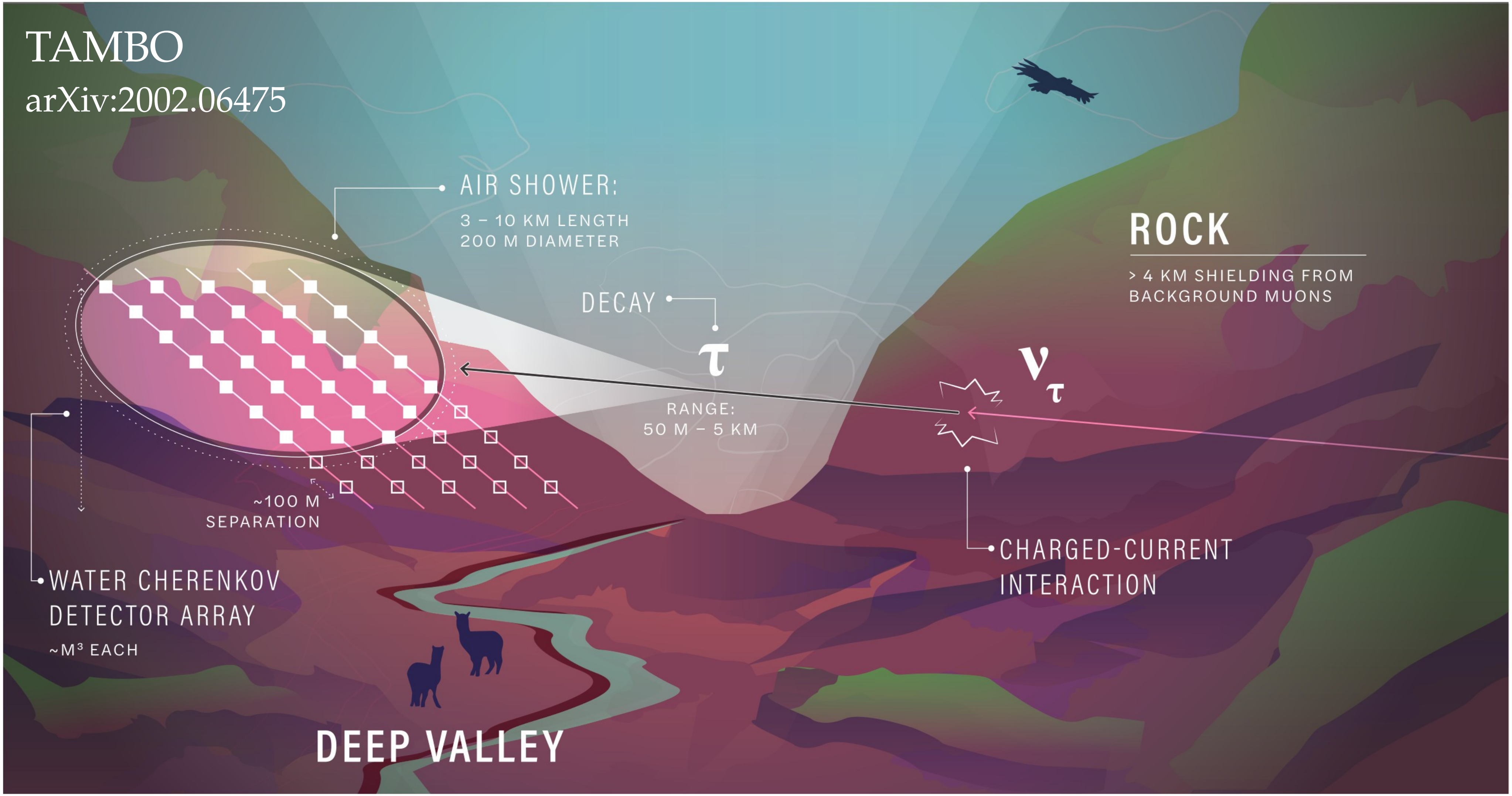
- Lake Baikal
- Completed 2025
- $V_{\text{eff}} \sim 1.5$ km^3
- 90 strings, 1000+ OMs

IceCube-Gen2

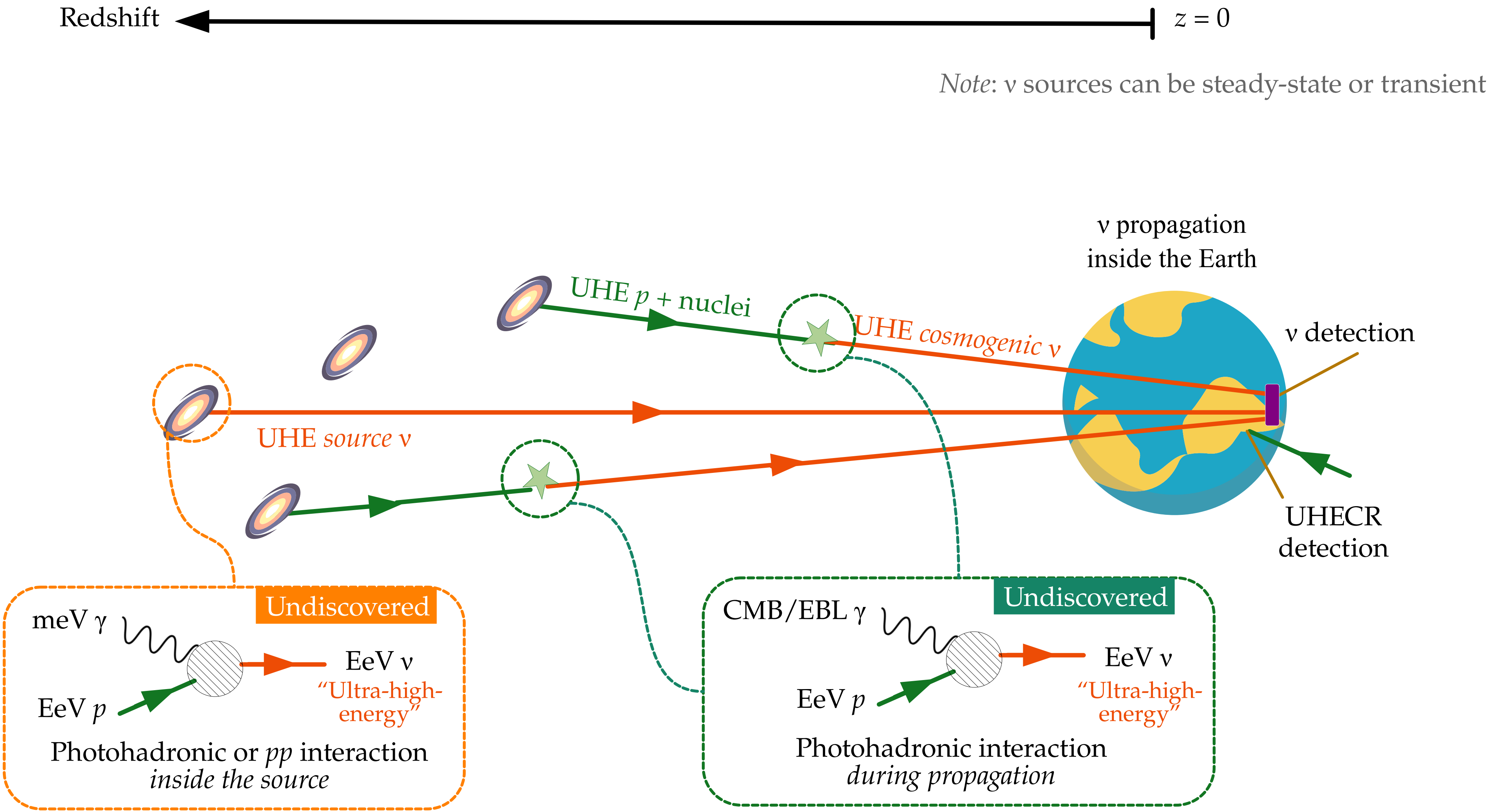
- South Pole
- Completed 2030
- $V_{\text{eff}} \sim 8$ km^3
- 206 strings, ~15000 OMs

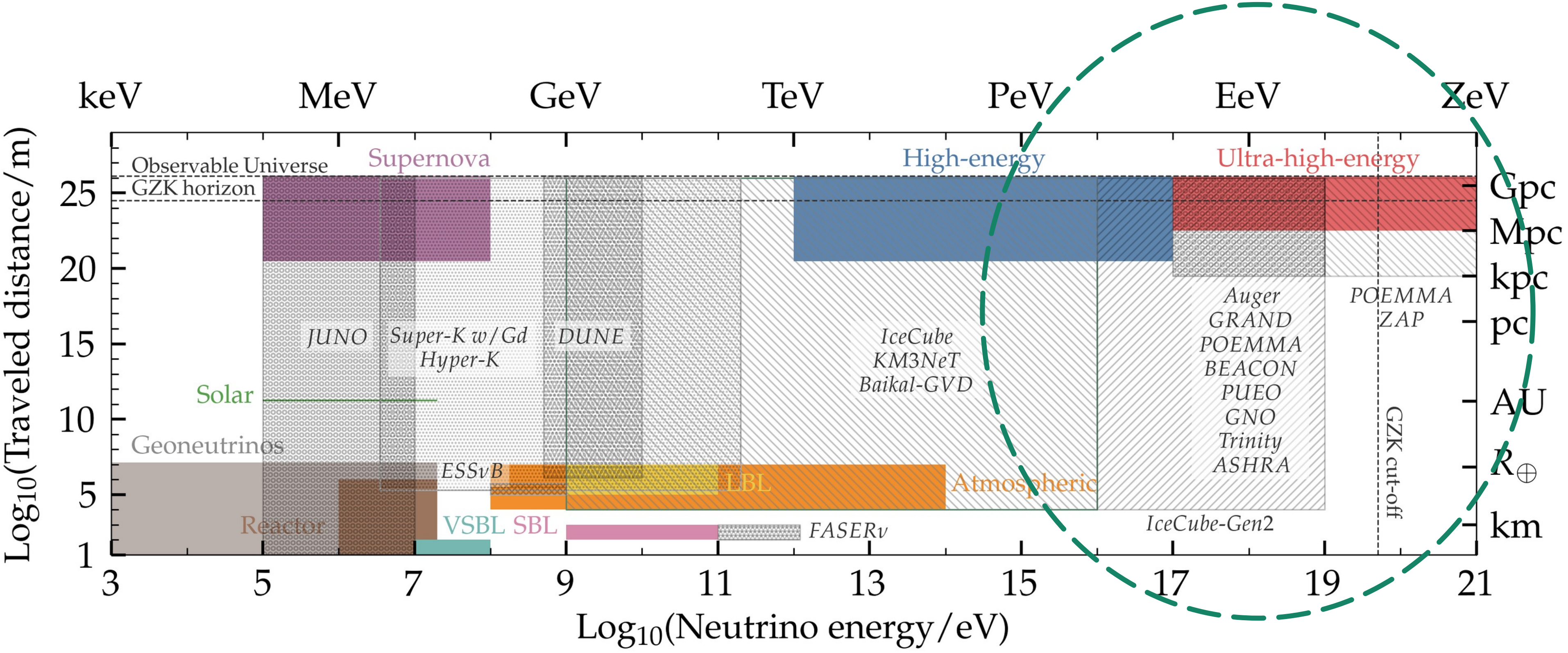
OM: optical module

Strebe/Wikipedia



TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) · COLCA VALLEY, PERU


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
"Ultra-high-energy"
EeV p
Photohadronic or pp interaction *inside the source*
Undiscovered
CMB/EBL γ
EeV ν
"Ultra-high-energy"
EeV p
Photohadronic interaction *during propagation*

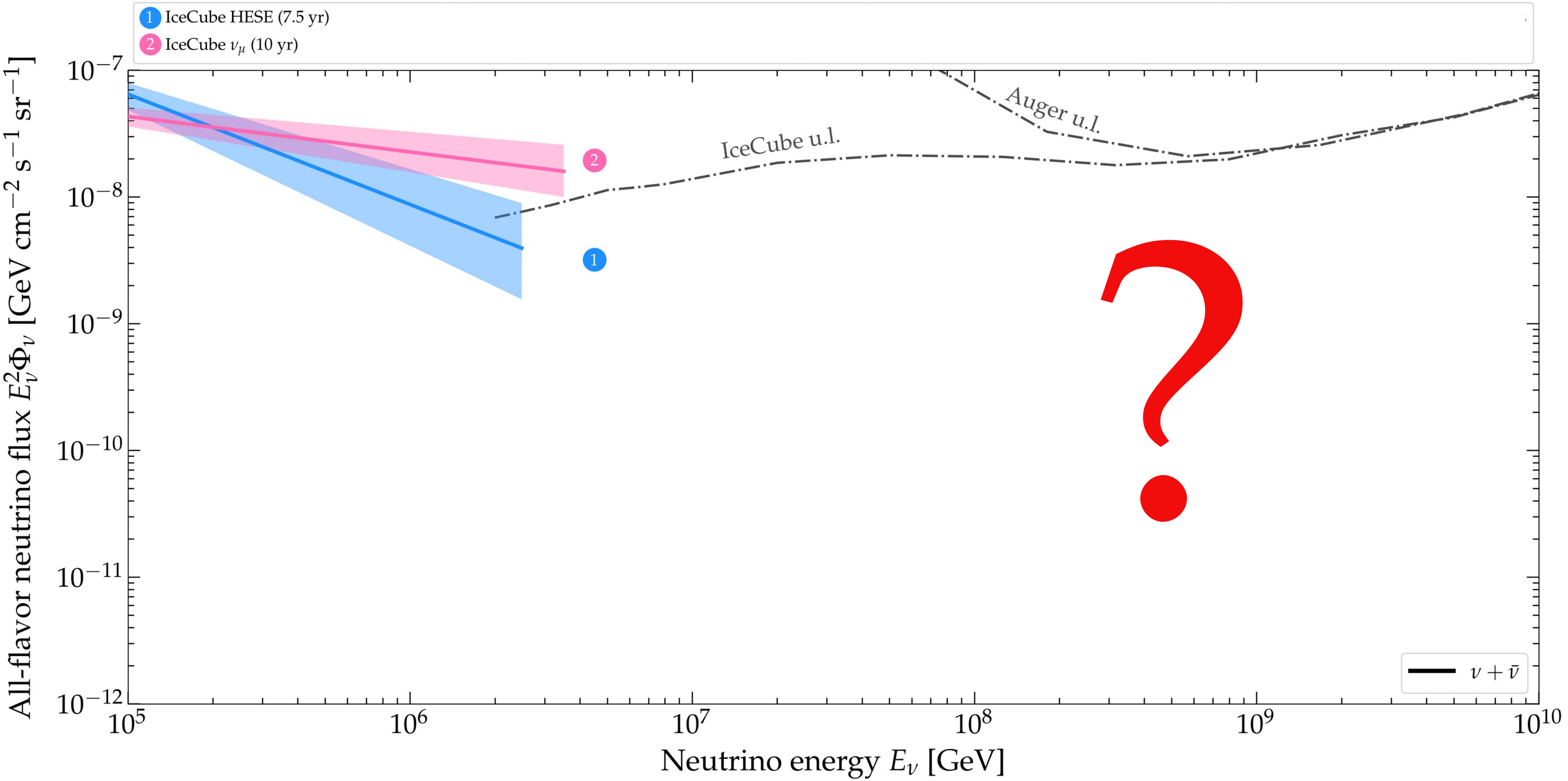


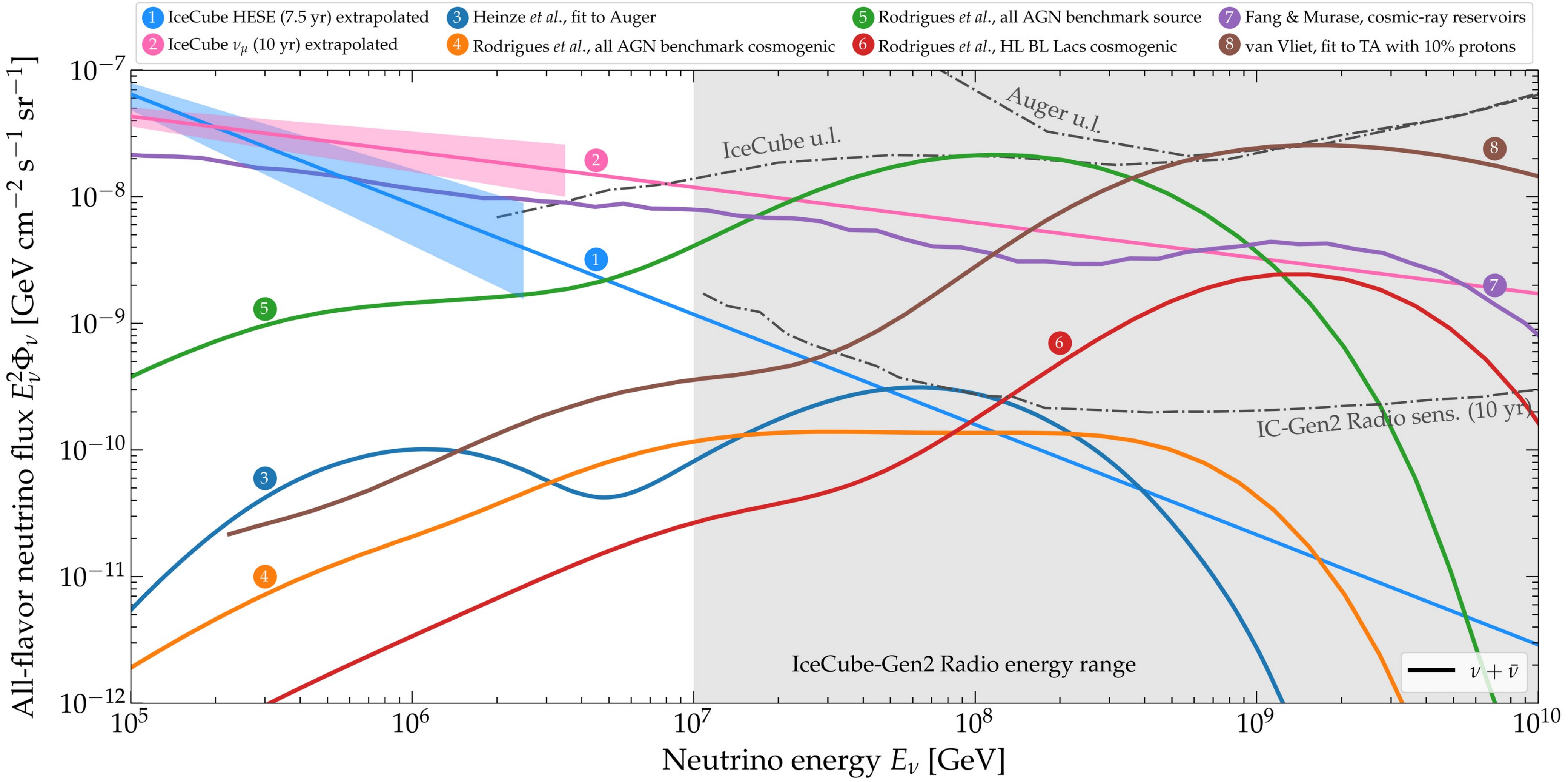
Synergies with lower energies

Increase TeV–PeV ν statistics

Discover > EeV ν

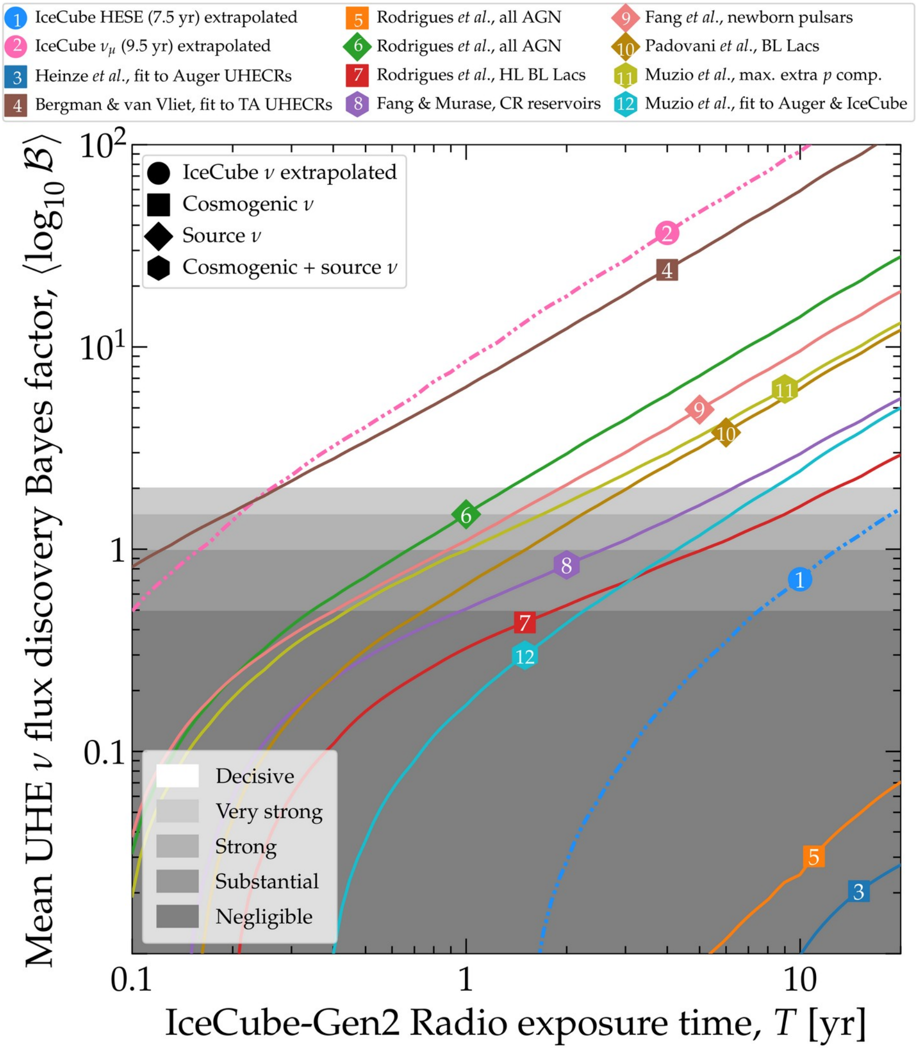
MB *et al.*, Snowmass 20201 Letter of interest


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}]
Neutrino energy E_ν [GeV]
Auger u.l.
IceCube u.l.
?
$\nu + \bar{\nu}$
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}



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}

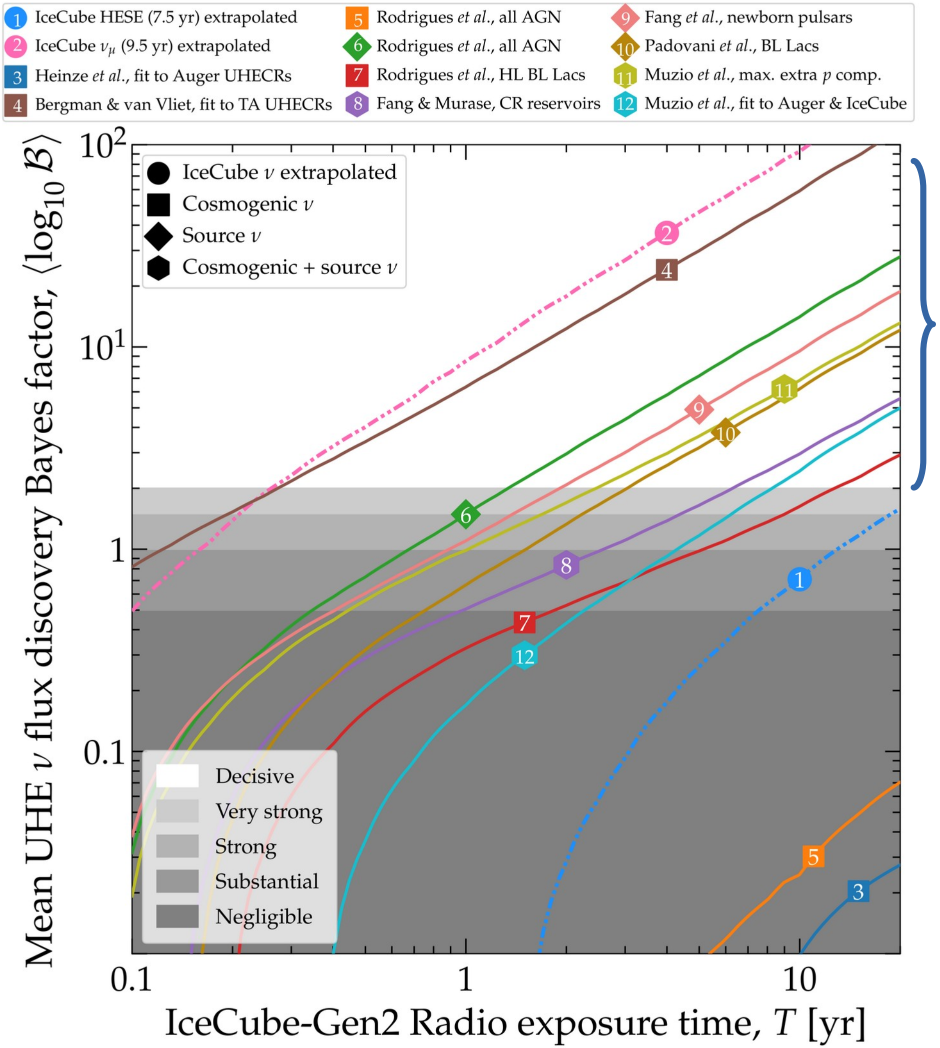
Discovering the diffuse flux of UHE neutrinos



V. B. Valera, **MB**, C. Glaser, 2210.03756

Discovering the diffuse flux of UHE neutrinos

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

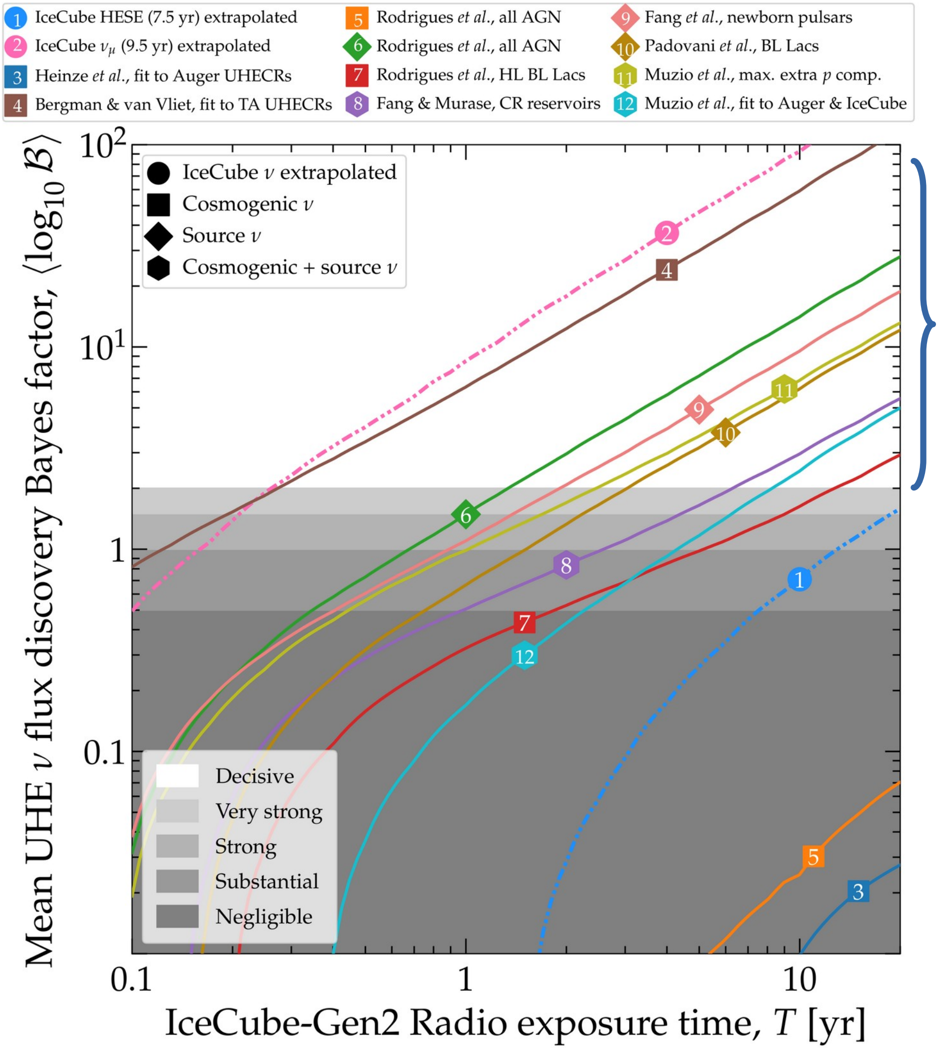


Large Bayes factor = decisive flux discover

V. B. Valera, **MB**, C. Glaser, 2210.03756

Discovering the diffuse flux of UHE neutrinos

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



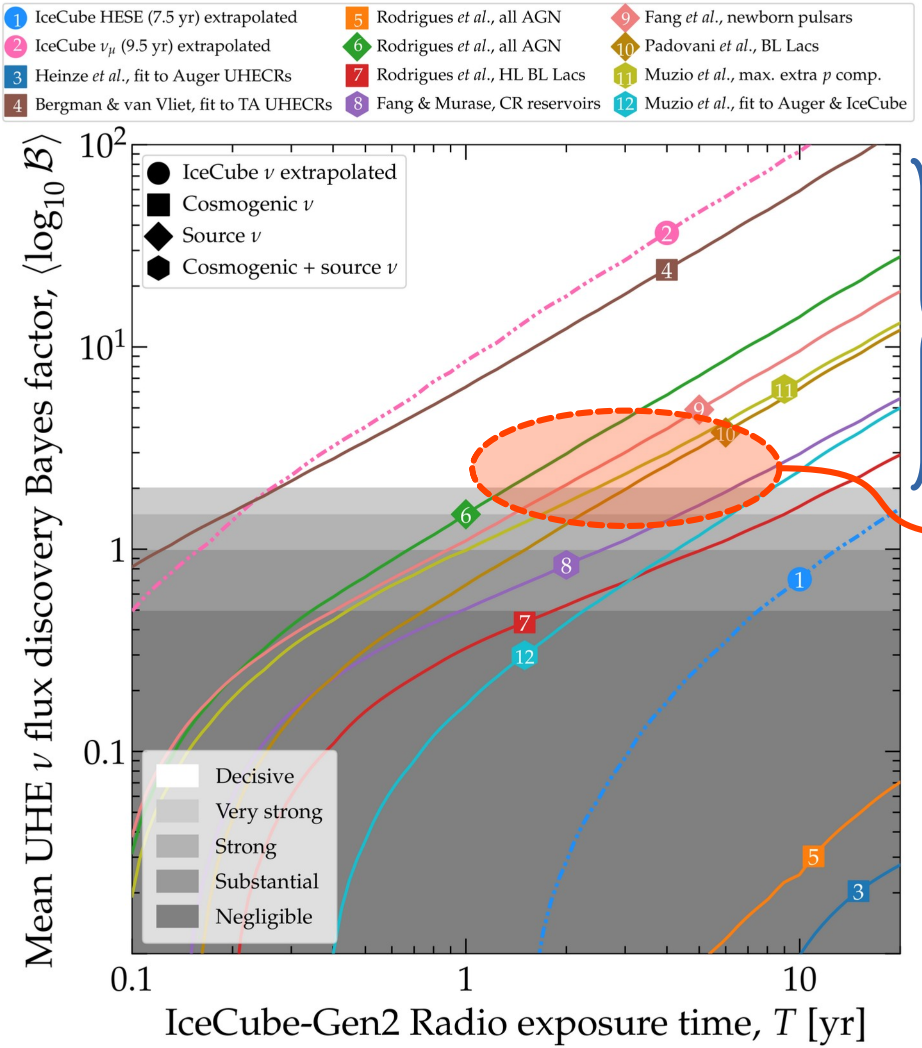
Large Bayes factor
=
decisive flux discover

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

V. B. Valera, **MB**, C. Glaser, 2210.03756

Discovering the diffuse flux of UHE neutrinos

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



Large Bayes factor = decisive flux discover

Most flux models are discoverable with a few years

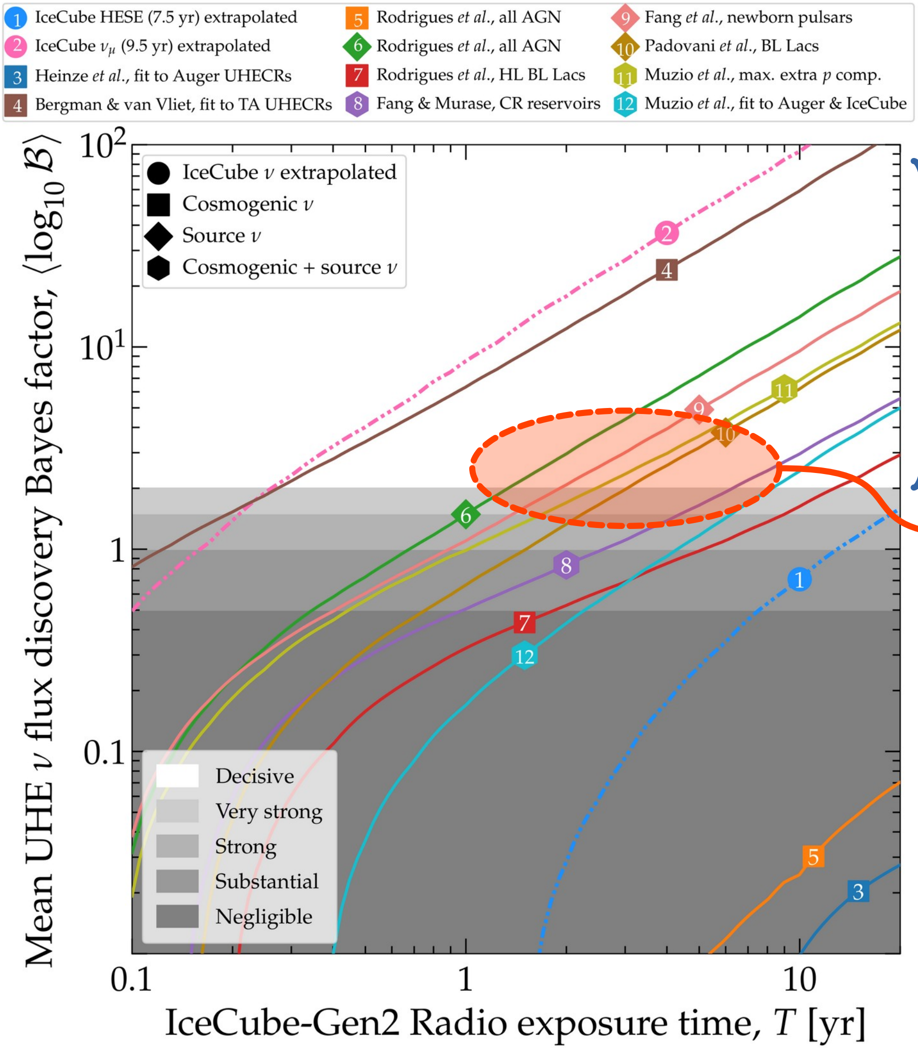
Forecasts are state-of-the-art:
- Neutrino propagation inside Earth
- Detailed simulation of radio in ice
- Detailed antenna response
- Detector energy & angular resolution
- Statistical fluctuations

V. B. Valera, **MB**, C. Glaser, 2210.03756

Discovering the diffuse flux of UHE neutrinos

Work led by Víctor Valera

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



Large Bayes factor = decisive flux discover

Most flux models are discoverable with a few years

Forecasts are state-of-the-art:
- Neutrino propagation inside Earth
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- Detailed antenna response
- Detector energy & angular resolution
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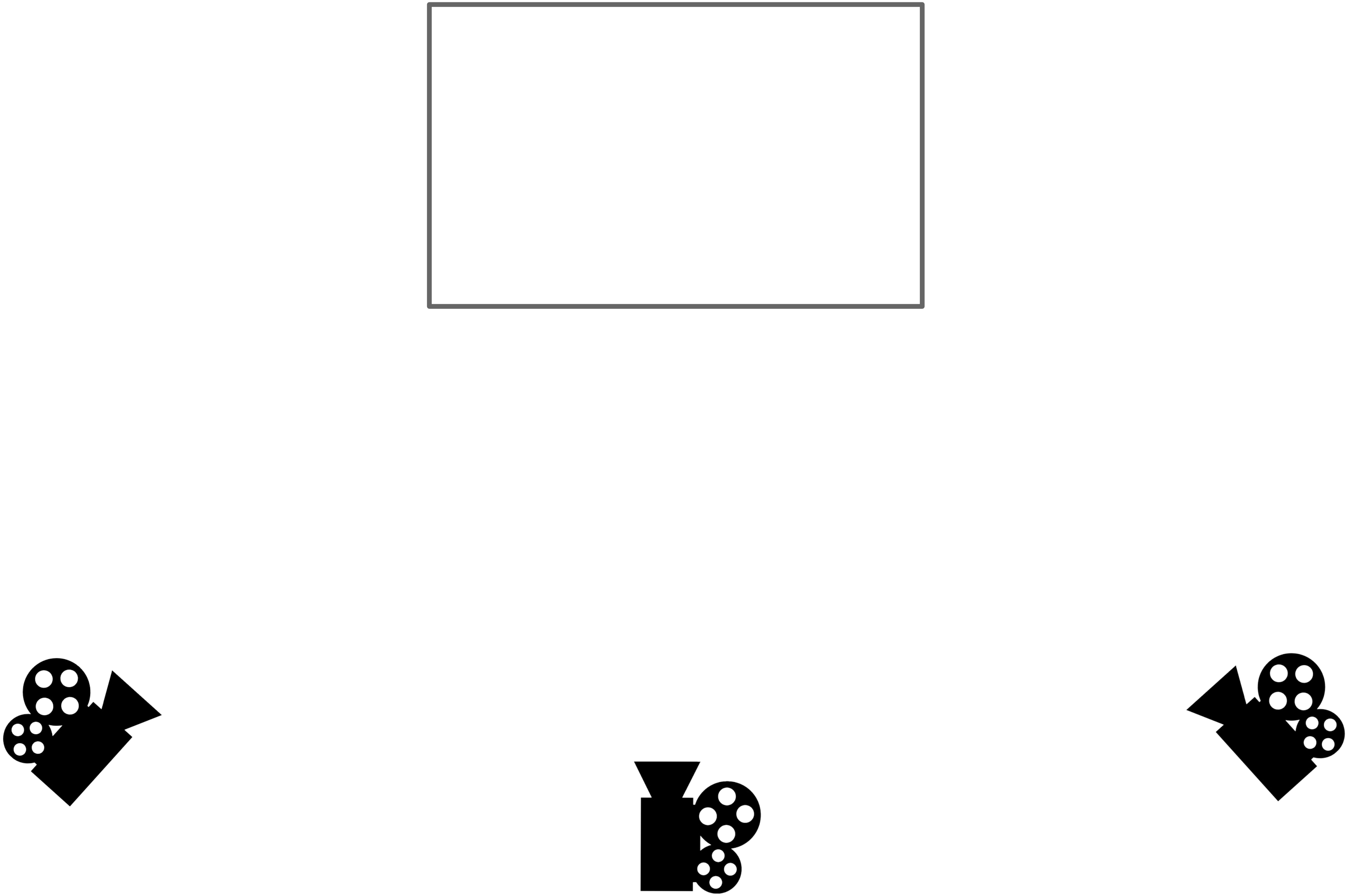
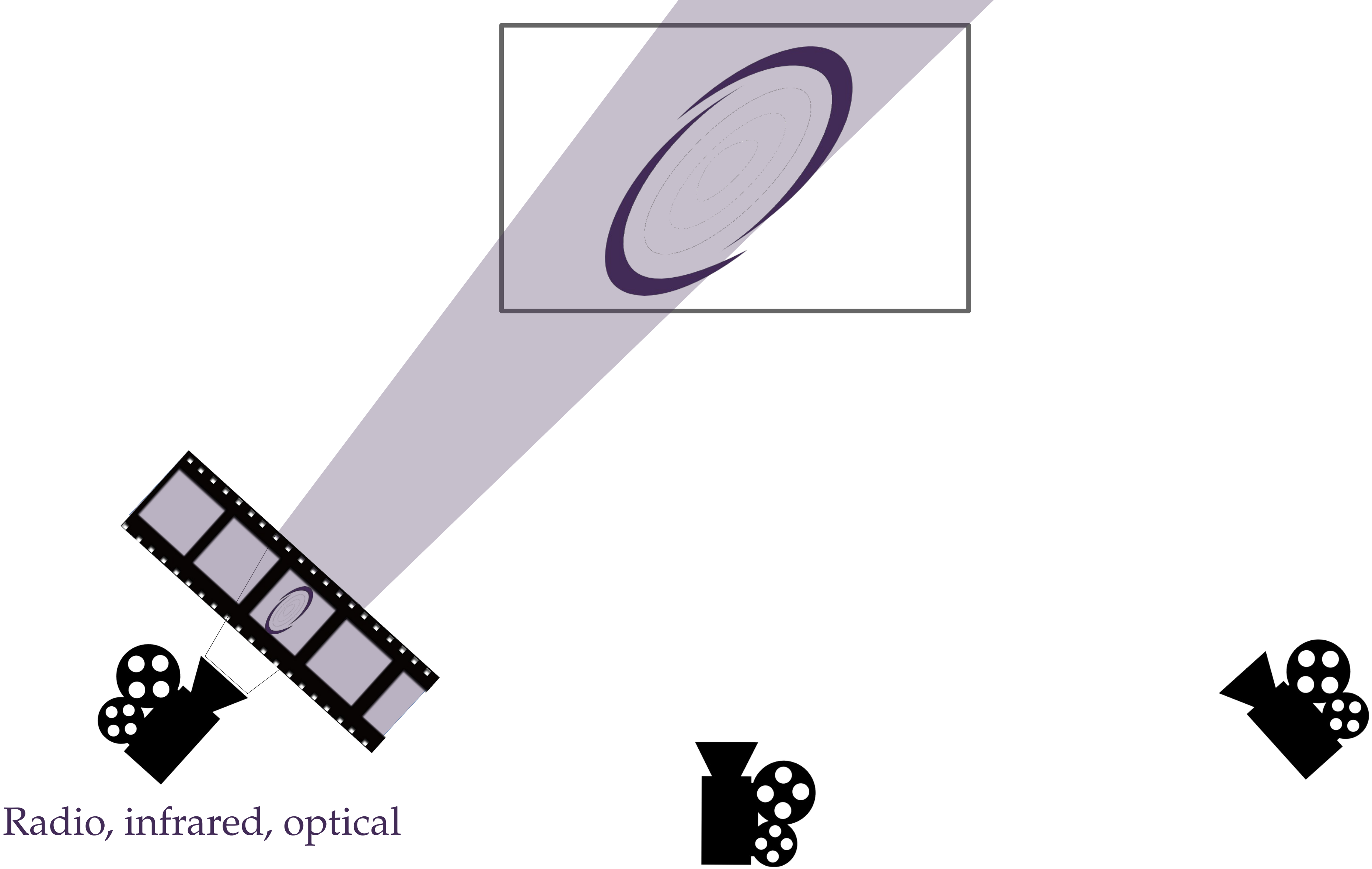
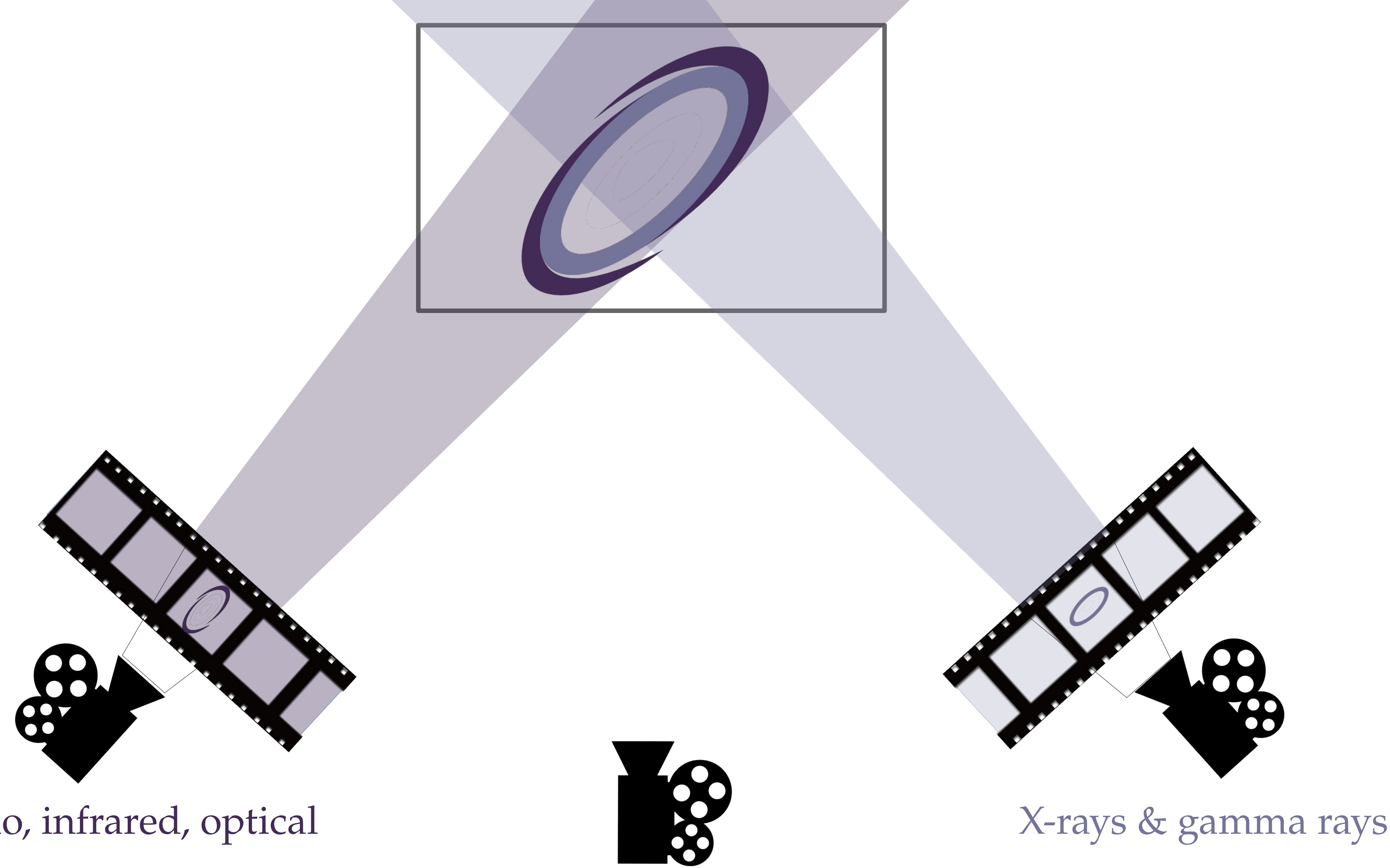
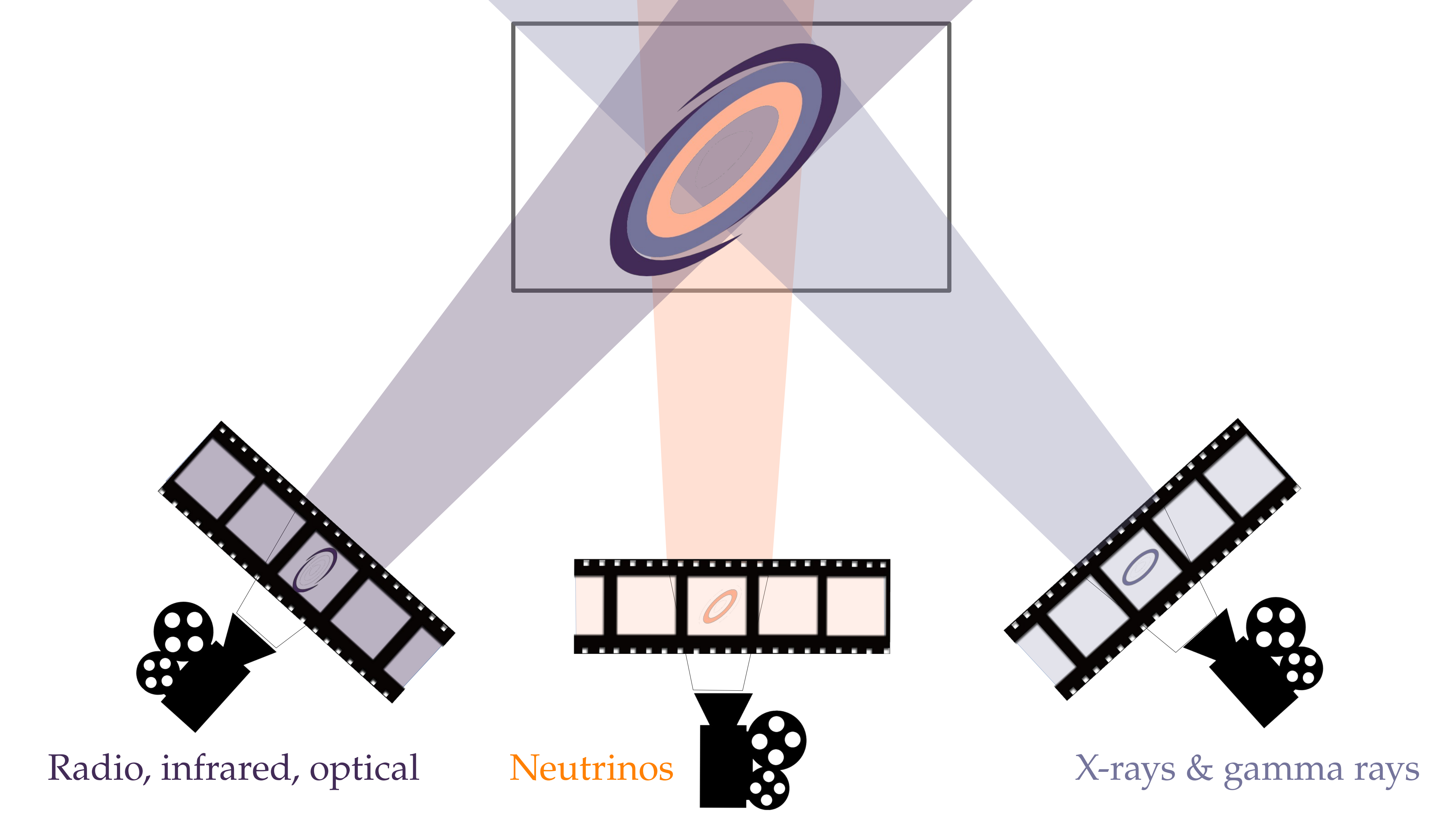
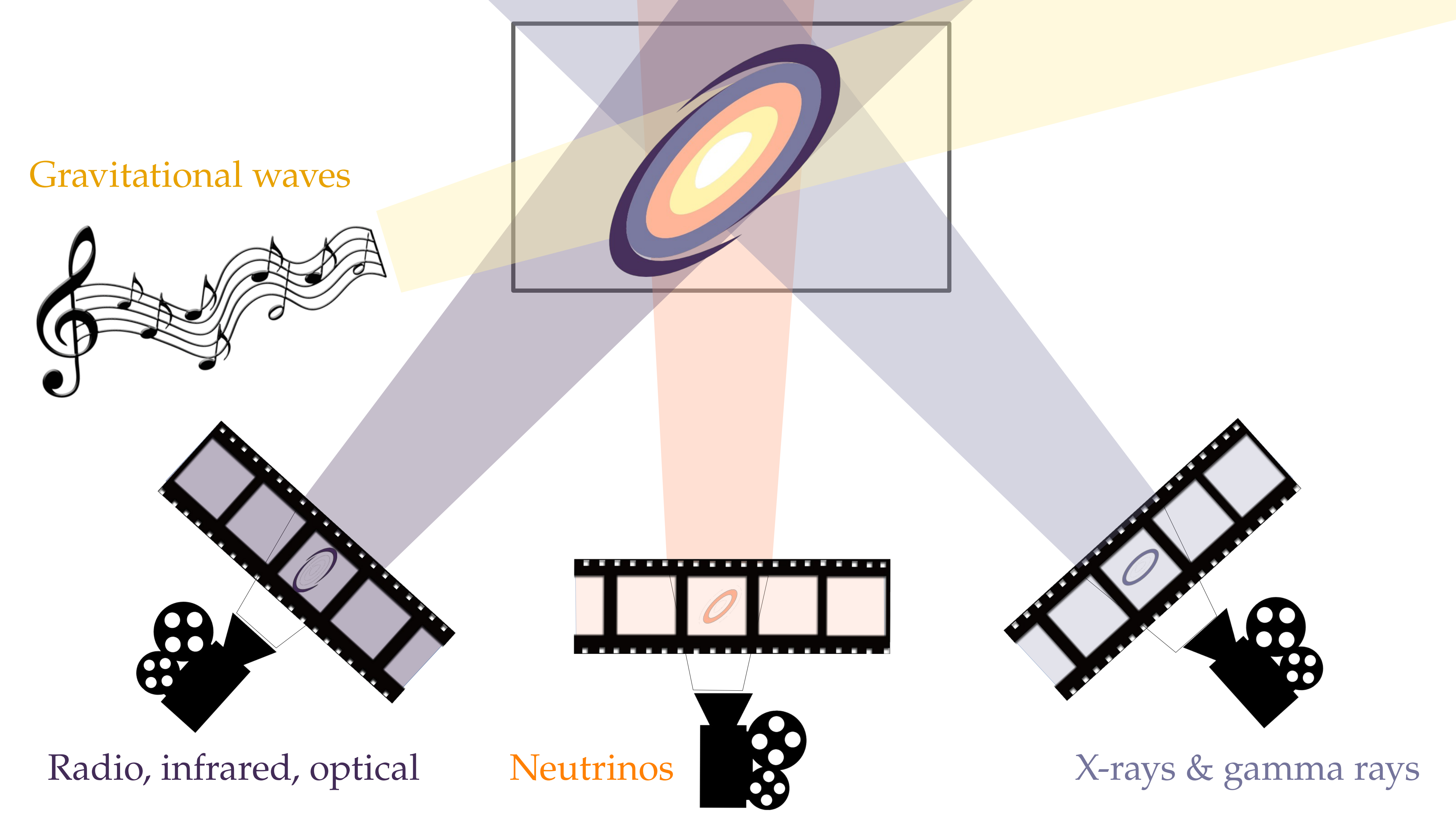
V. B. Valera, **MB**, C. Glaser, 2210.03756

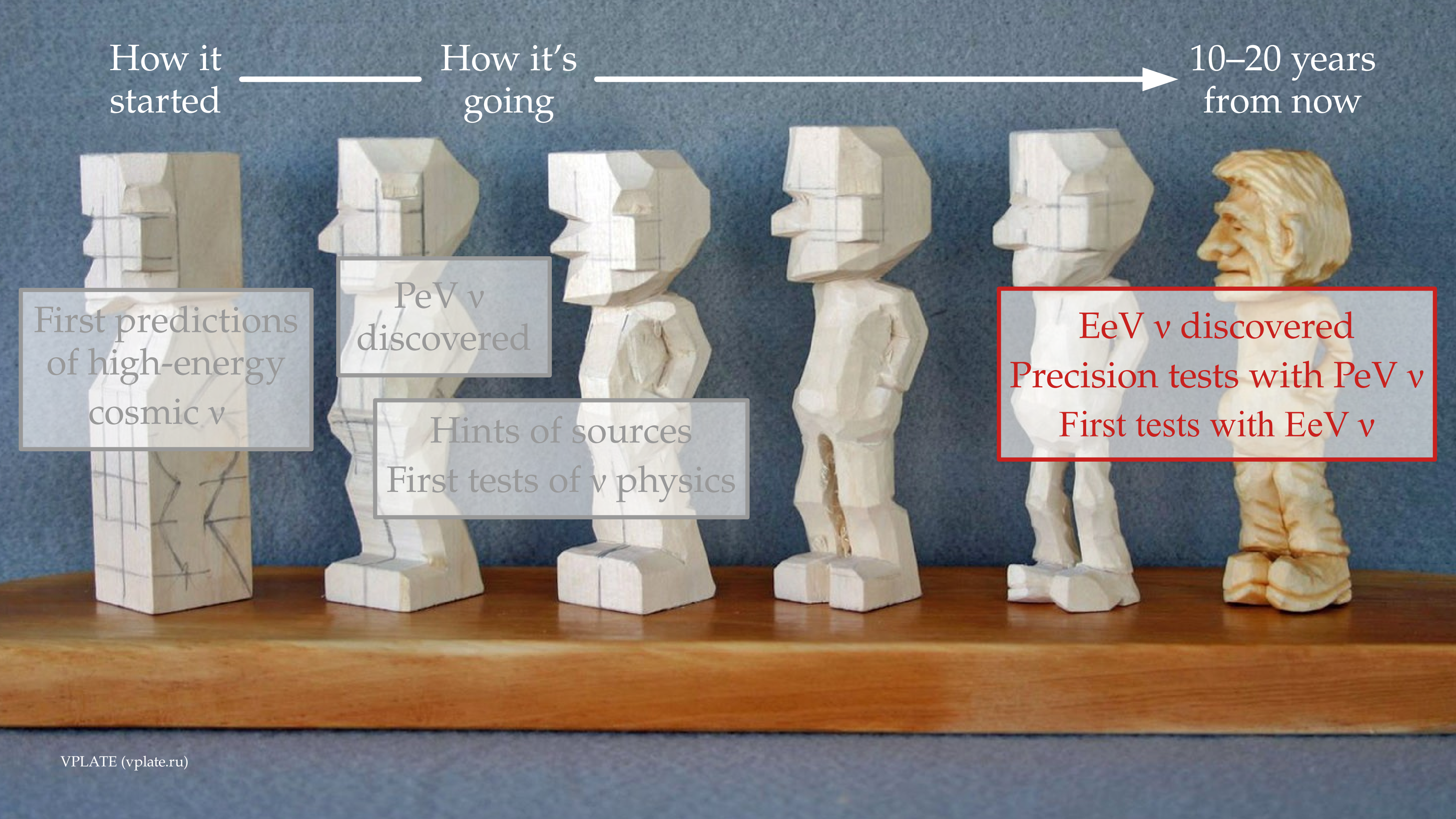



Radio, infrared, optical


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

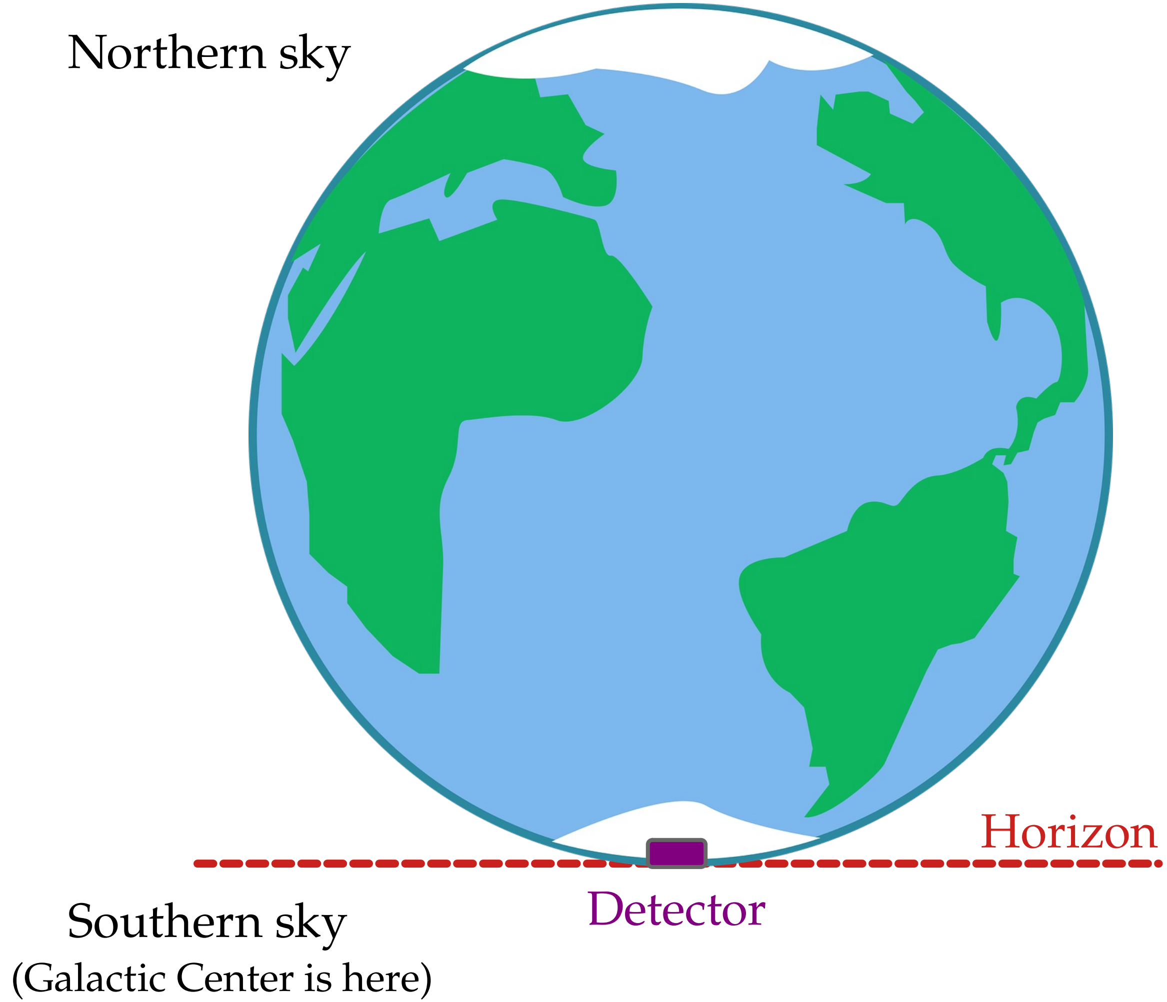

How it started
How it's going
10–20 years from now
First predictions of high-energy cosmic ν
PeV ν discovered
Hints of sources
First tests of ν physics
EeV ν discovered
Precision tests with PeV ν
First tests with EeV ν
VPLATE (vplate.ru)

Thank you!

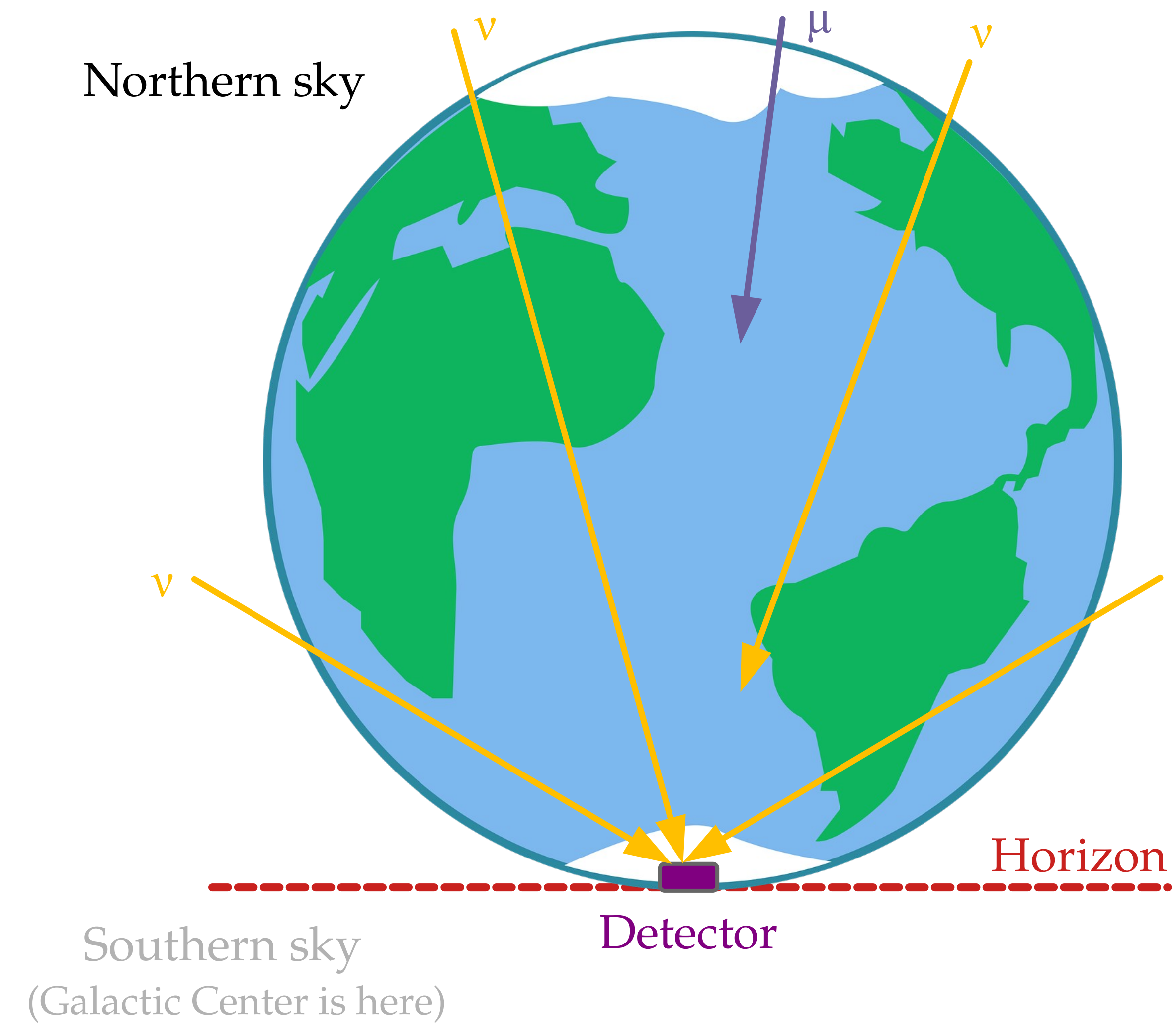
Backup slides

Basics

Upgoing *vs.* downgoing neutrinos



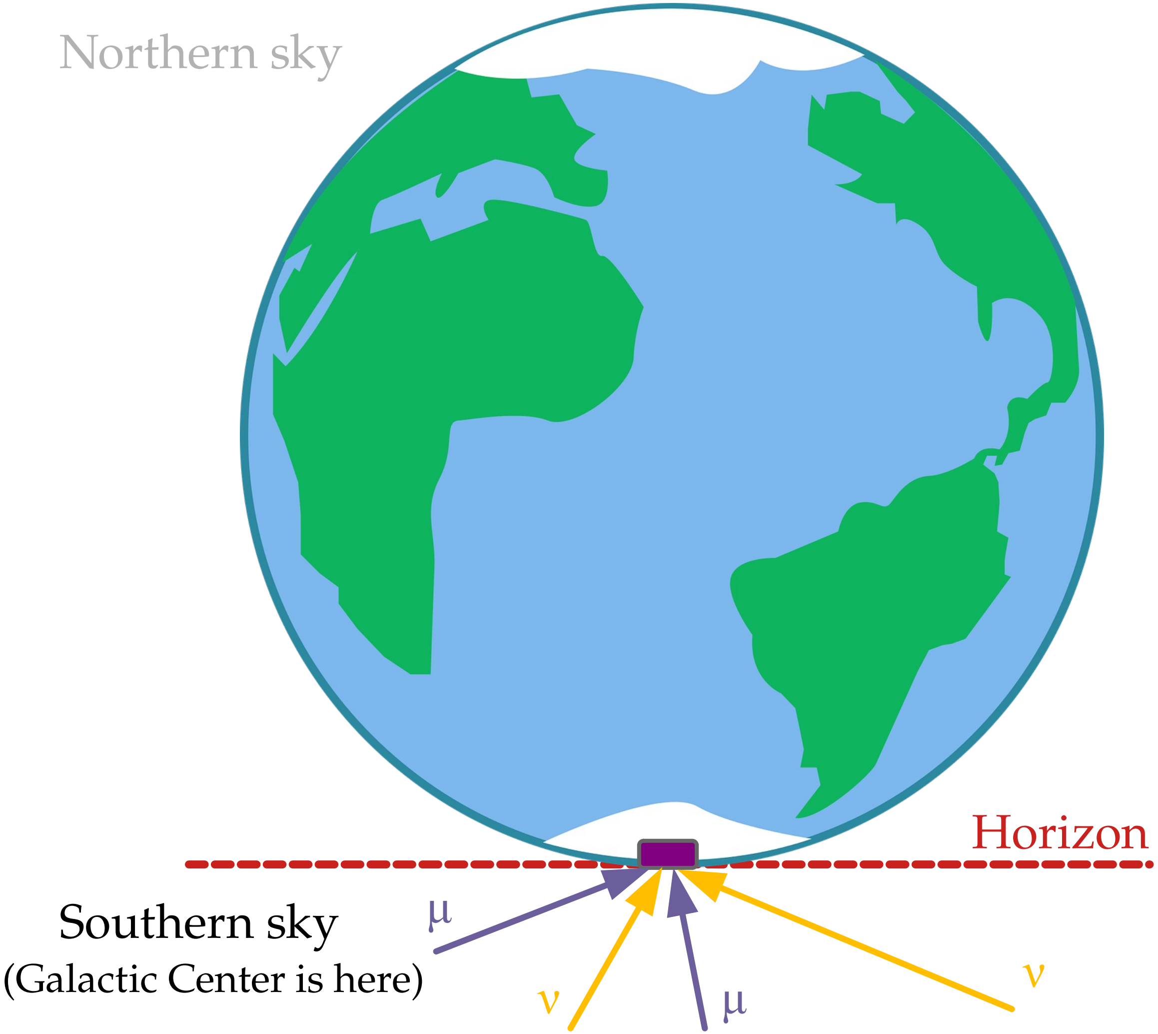
Upgoing *vs.* downgoing neutrinos



Neutrinos from the Northern sky
≡
Upgoing neutrinos

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

Downgoing *vs.* upgoing neutrinos



Neutrinos from the Southern sky
≡
Downgoing neutrinos

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

How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering

Neutral current (NC)

$$\nu_x + N \rightarrow \nu_x + X$$

Charged current (CC)

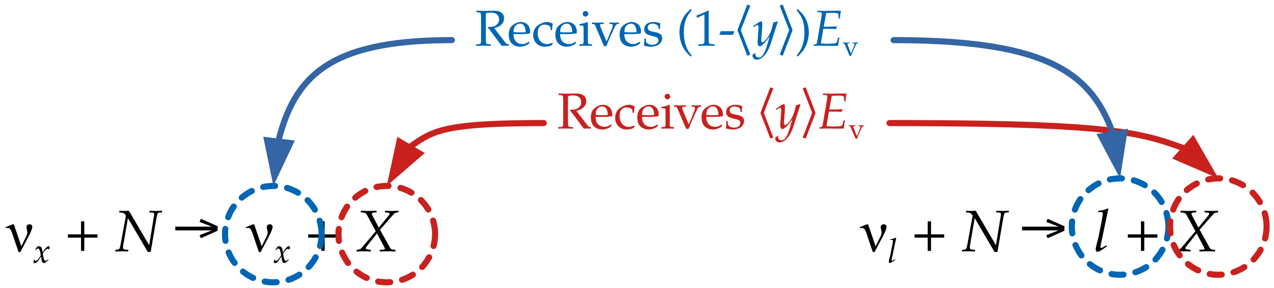
$$\nu_l + N \rightarrow l + X$$

How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering

Neutral current (NC)

Charged current (CC)

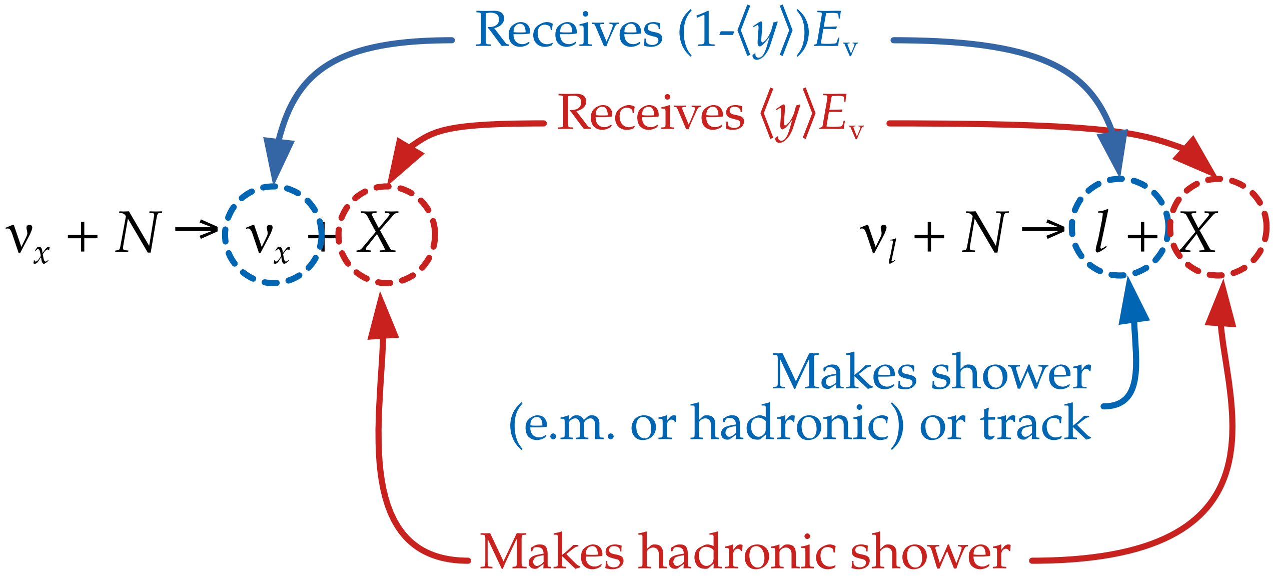


At TeV–PeV, the average inelasticity $\langle y \rangle$ = 0.25–0.30

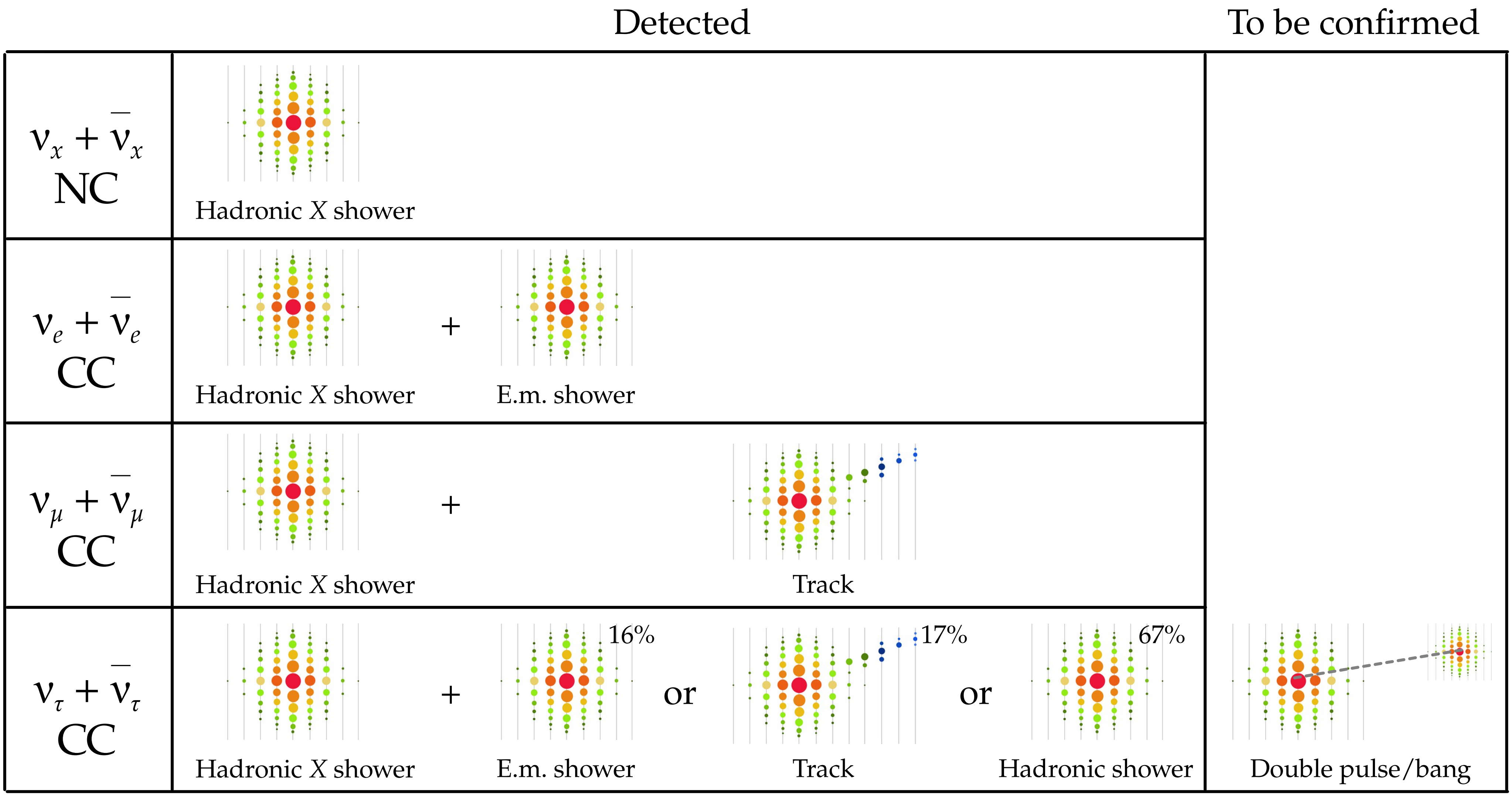
How does IceCube see TeV–PeV neutrinos?

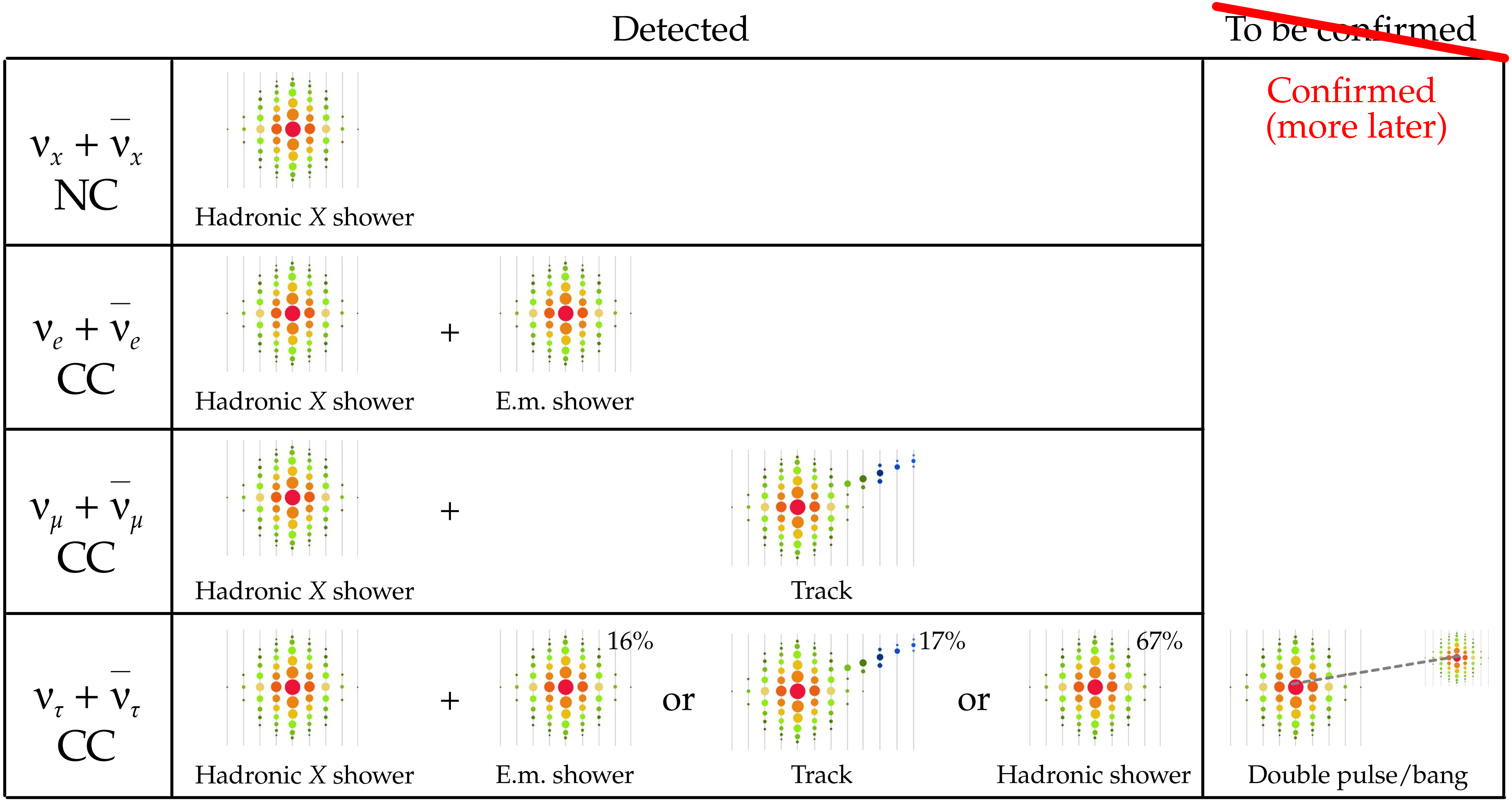
Deep inelastic neutrino-nucleon scattering

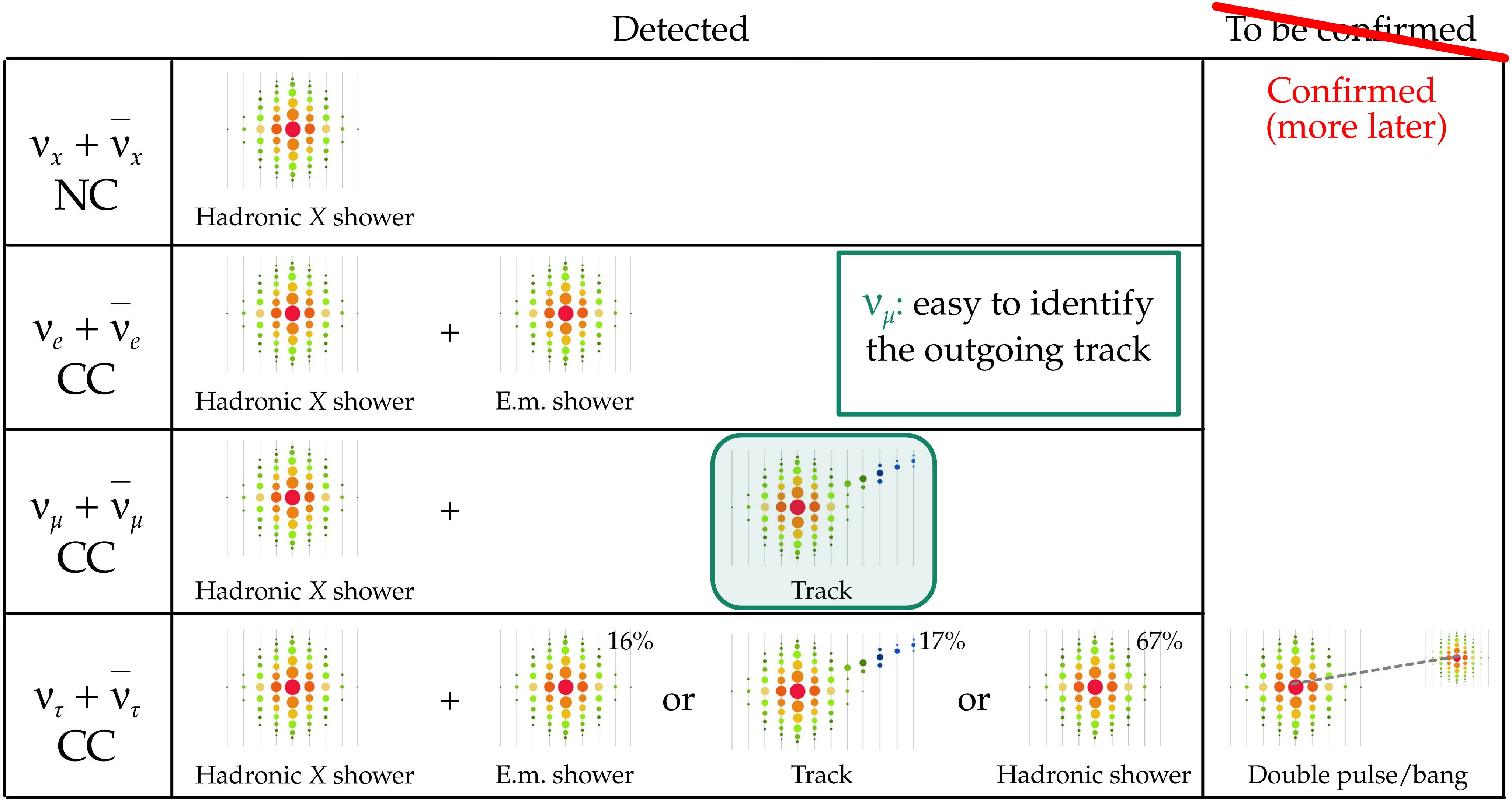
Neutral current (NC) | Charged current (CC)



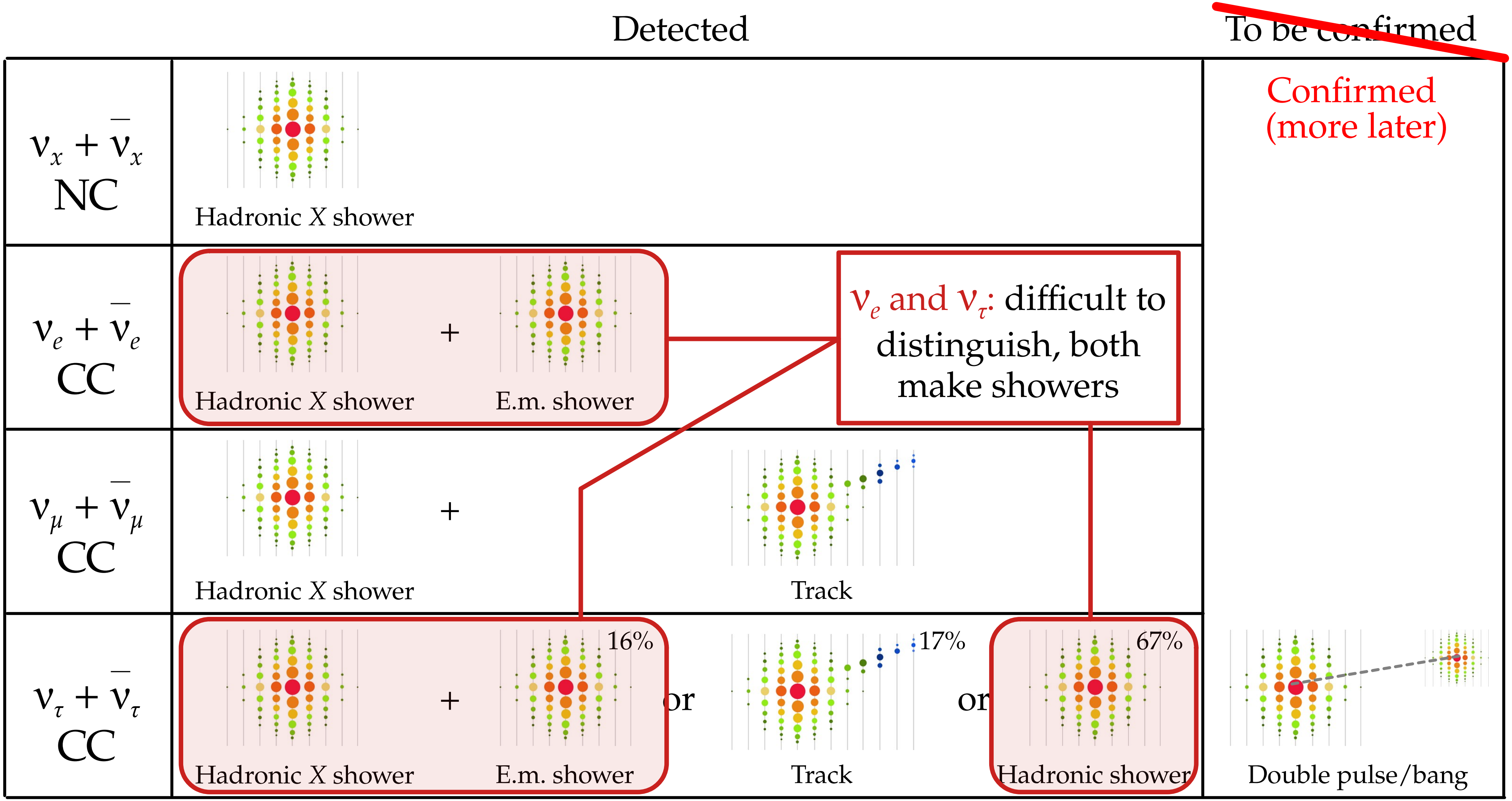
At TeV–PeV, the average inelasticity $\langle y \rangle$ = 0.25–0.30


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

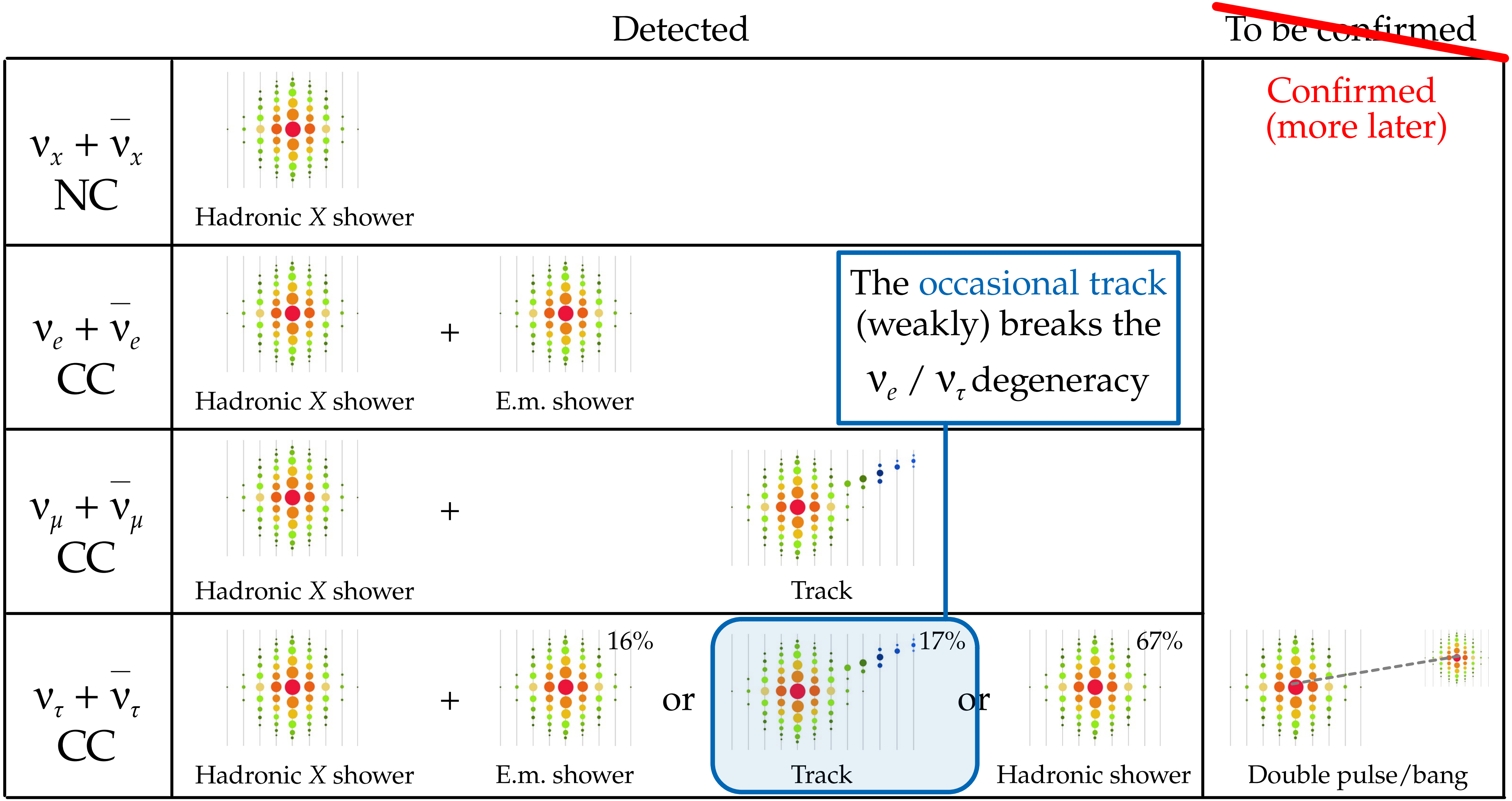

Detected
To be confirmed
Confirmed
(more later)
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
E.m. shower
16%
or
Track
17%
or
Hadronic shower
67%
Double pulse/bang



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

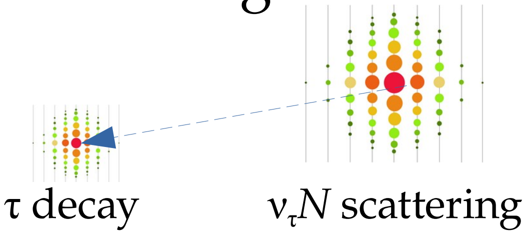


Detected
To be confirmed
Confirmed
(more later)
$\nu_x + \bar{\nu}_x$
NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$
CC
Hadronic X shower
+
E.m. shower
ν_e and ν_τ: difficult to distinguish, both make showers
$\nu_\mu + \bar{\nu}_\mu$
CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$
CC
Hadronic X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


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

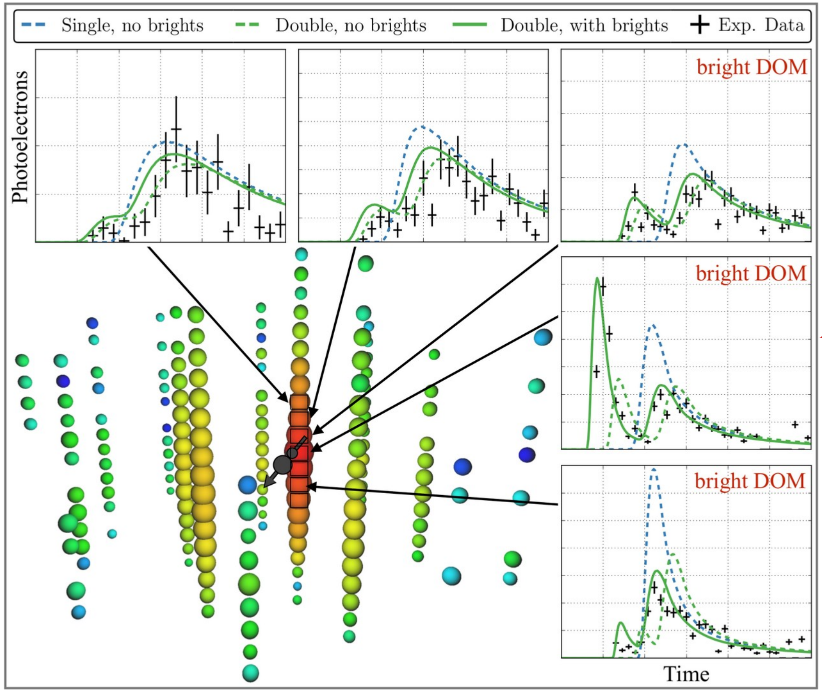
First identified high-energy astrophysical ν_τ

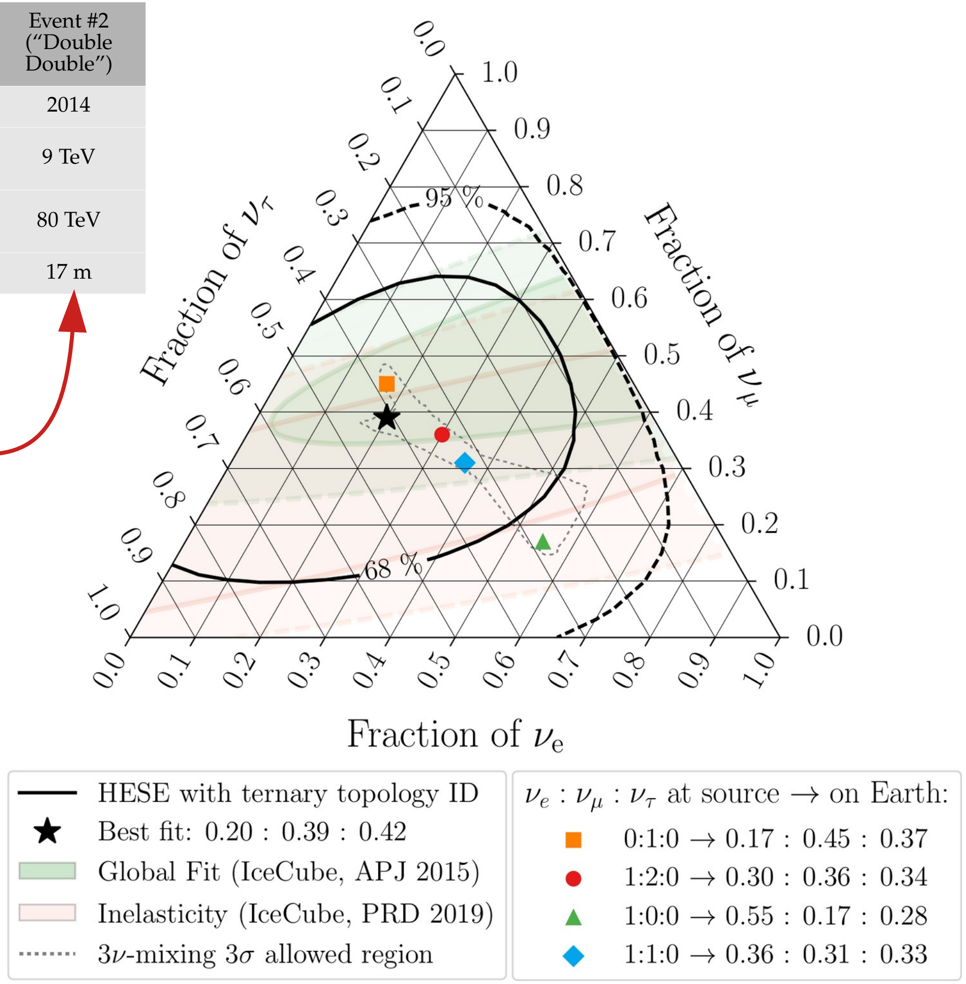
Double bang:



	Event #1 ("Big Bird")	Event #2 ("Double Double")
Year	2012	2014
Energy 1st cascade	1.2 PeV	9 TeV
Energy 2nd cascade	0.6 PeV	80 TeV
Length	16 m	17 m

Most likely to be a ν_τ

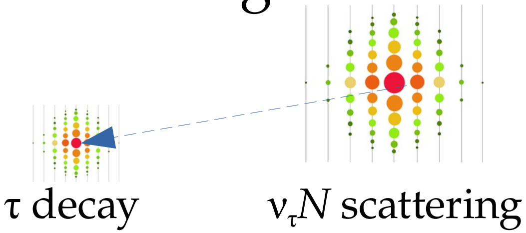




IceCube, 2011.03561

First identified high-energy astrophysical ν_τ

Double bang:



	Event #1 ("Big Bird")	Event #2 ("Double Double")
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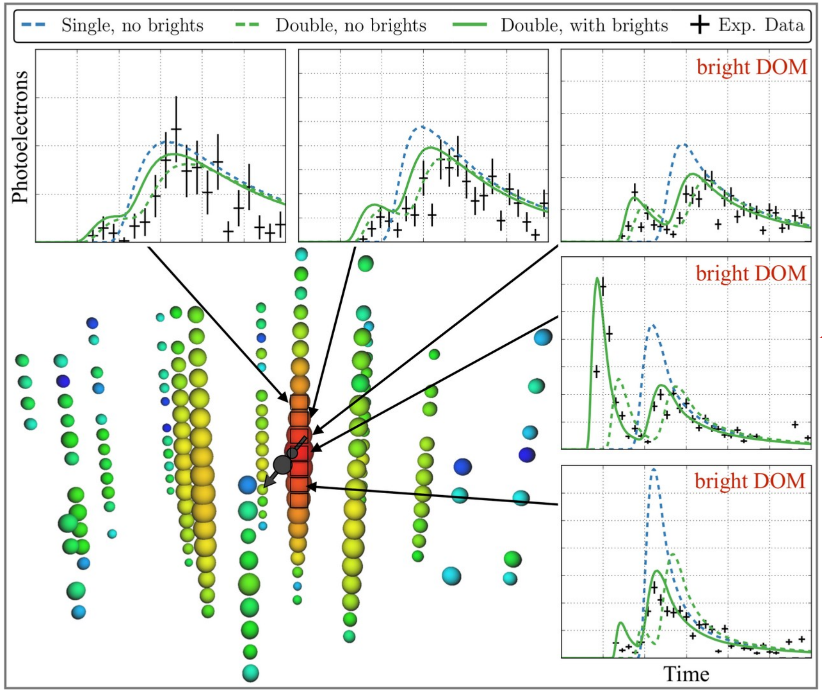
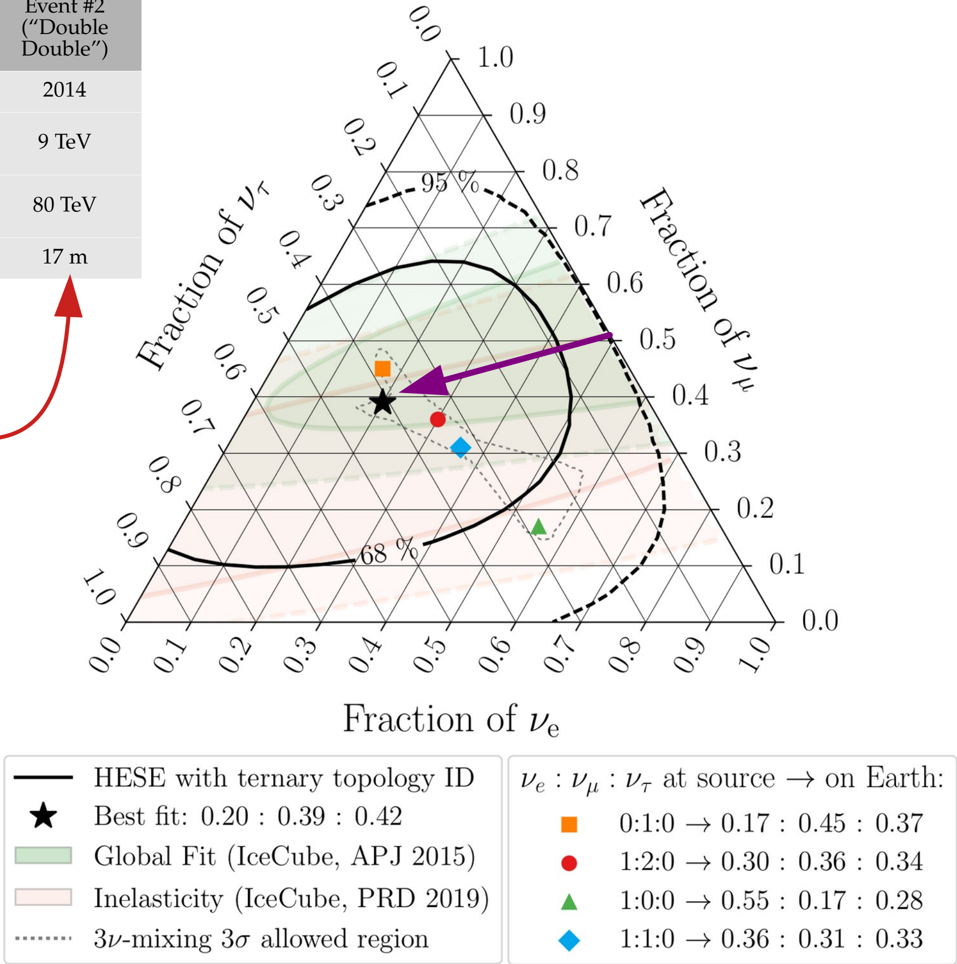
Length	16 m	17 m

Most likely to be a ν_τ





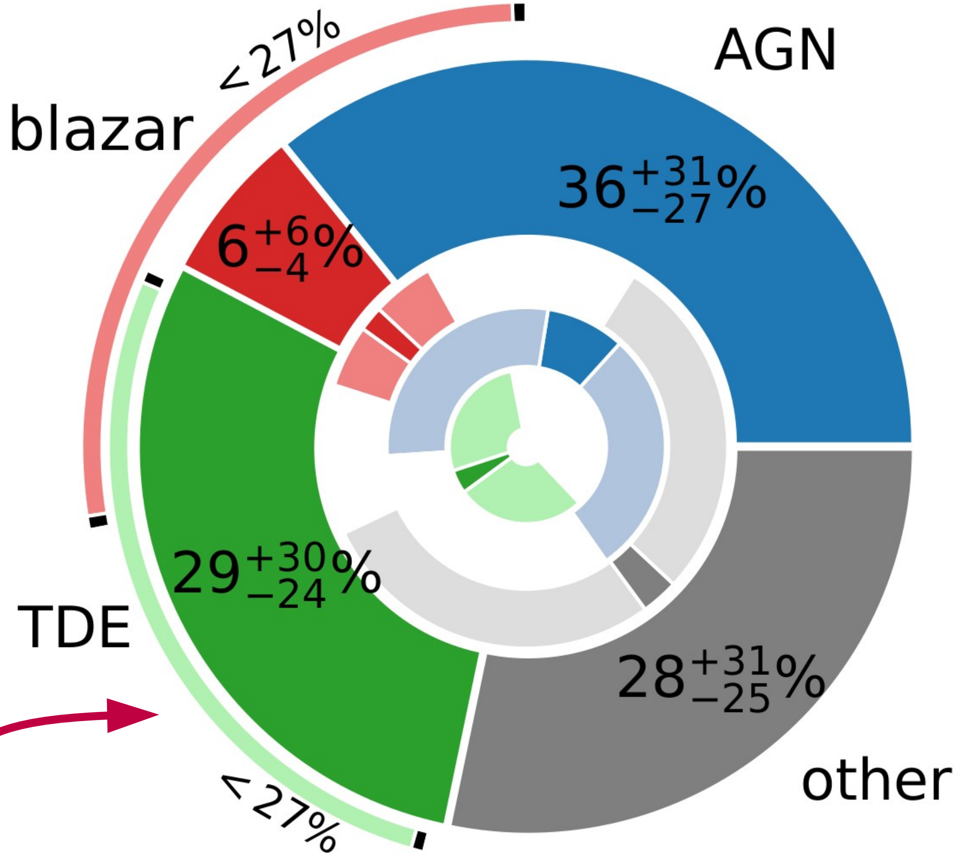
IceCube, 2011.03561

The IceCube pie chart

Sources with associated ν emission:

Name	Type	p
NGC 1068	AGN	0.008
TXS 0506+056	blazar	0.001
PKS 1502+106	blazar	0.01
PKS 1424-41	blazar	0.05
AT2019dsg	TDE	0.002

Fractional contribution of each source population to total diffuse flux (Bayesian analysis)



Note: Outer rings are from separate stacking analyses

I. Bartos *et al.*, *ApJ* 2021 [2105.03792]

Fundamental physics

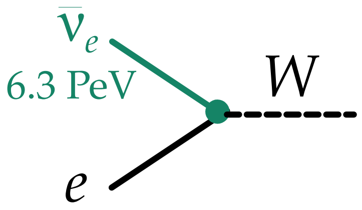
First observation of a Glashow resonance

Predicted in 1960:

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

First observation of a Glashow resonance

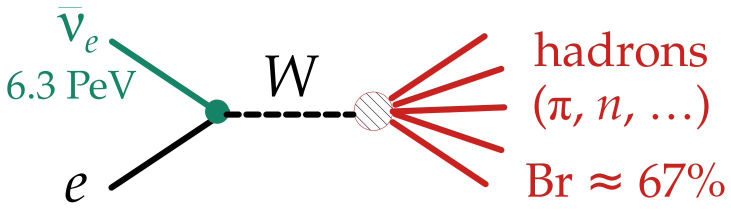
Predicted in 1960:



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

First observation of a Glashow resonance

Predicted in 1960:



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

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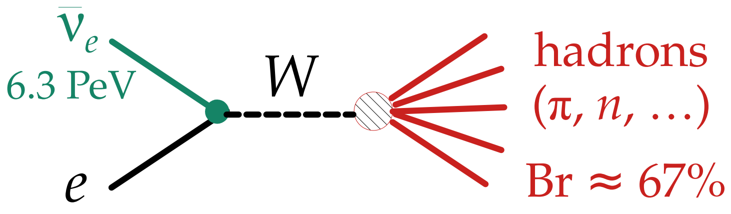

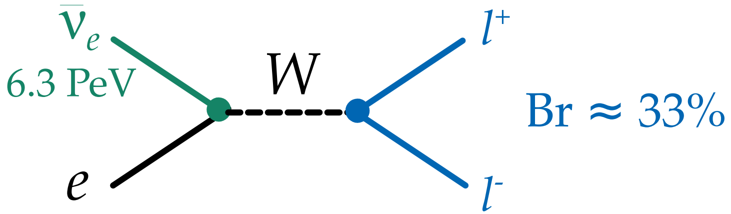

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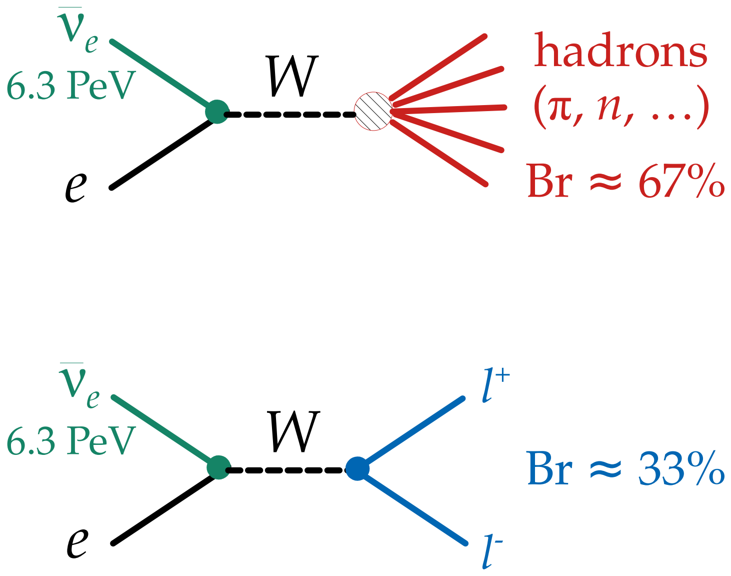
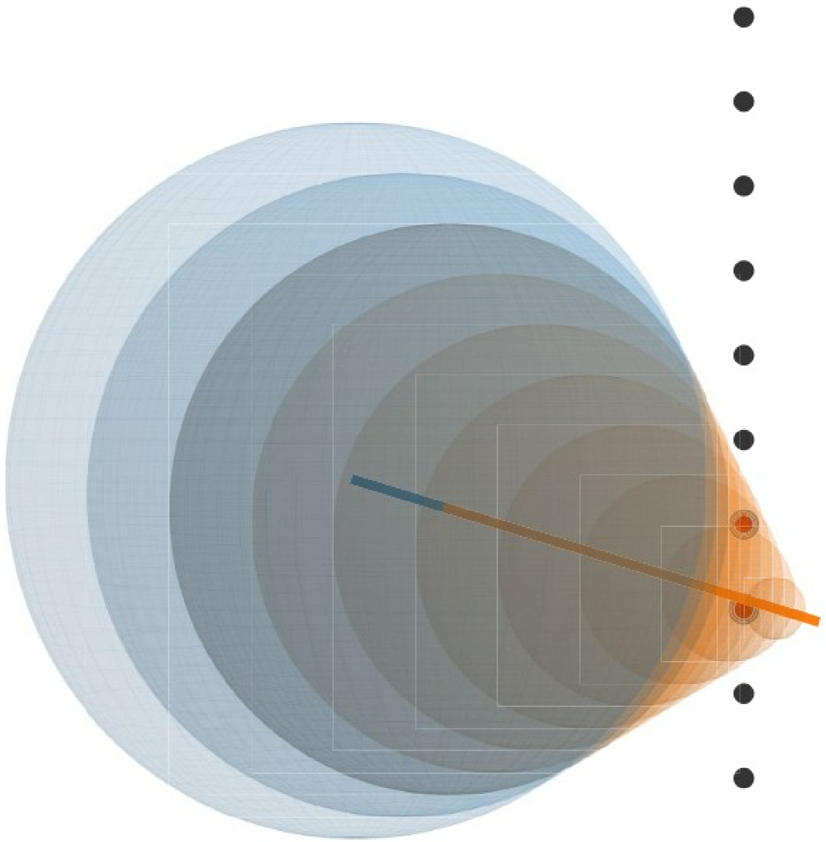


First reported by IceCube in 2021:



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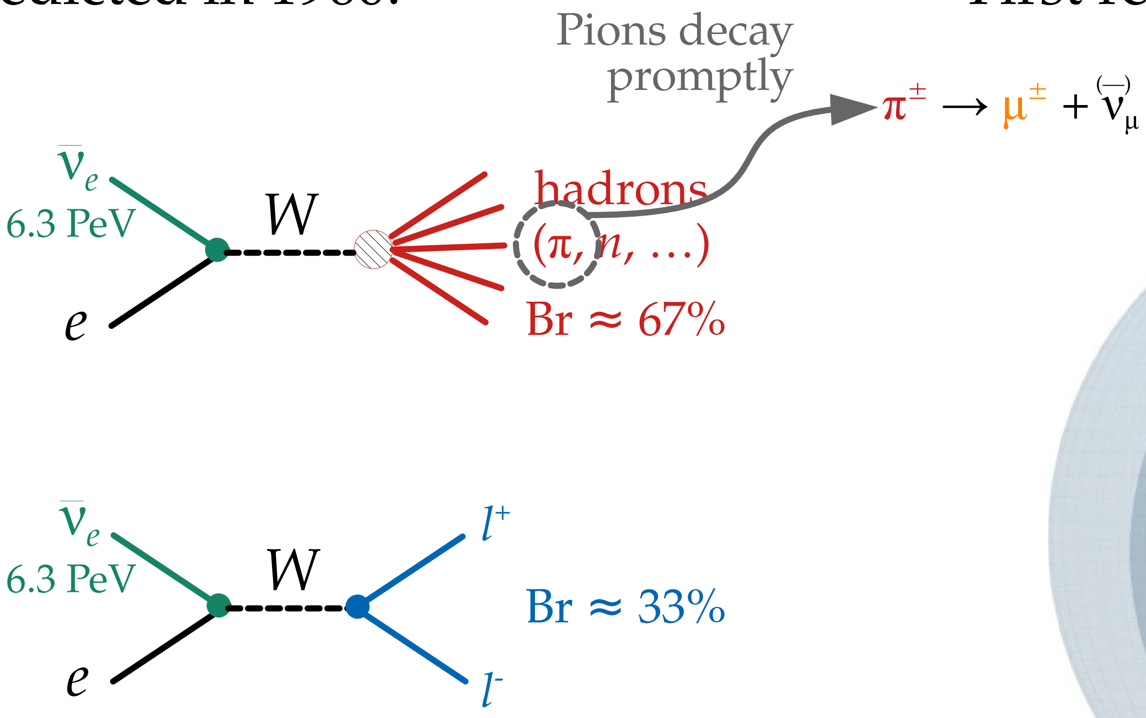

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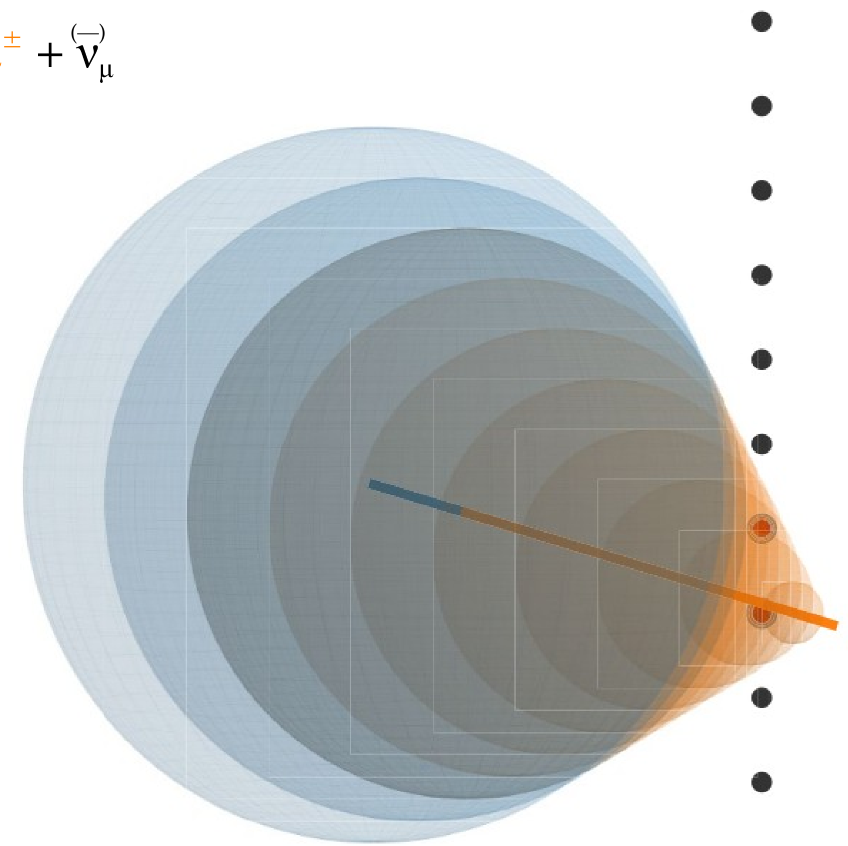

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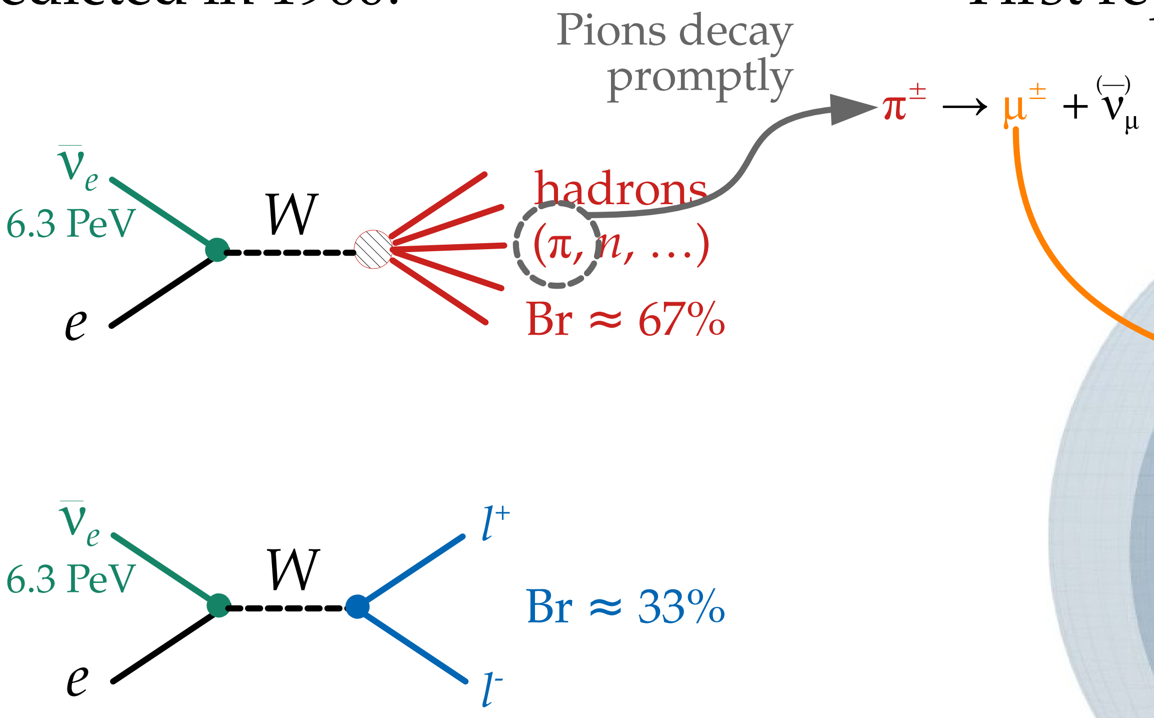

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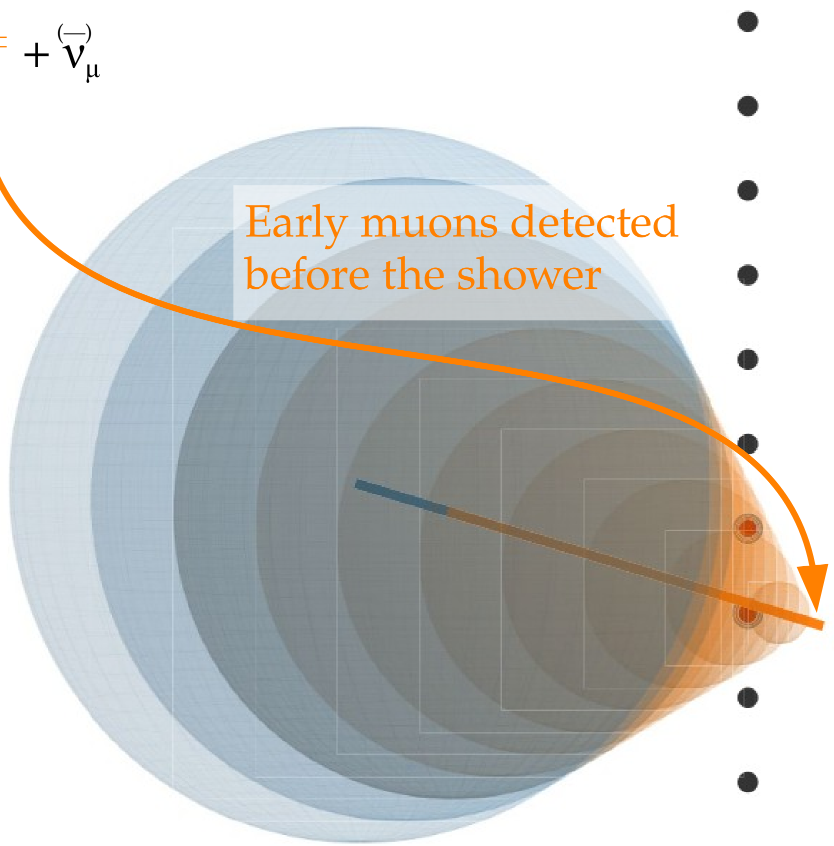

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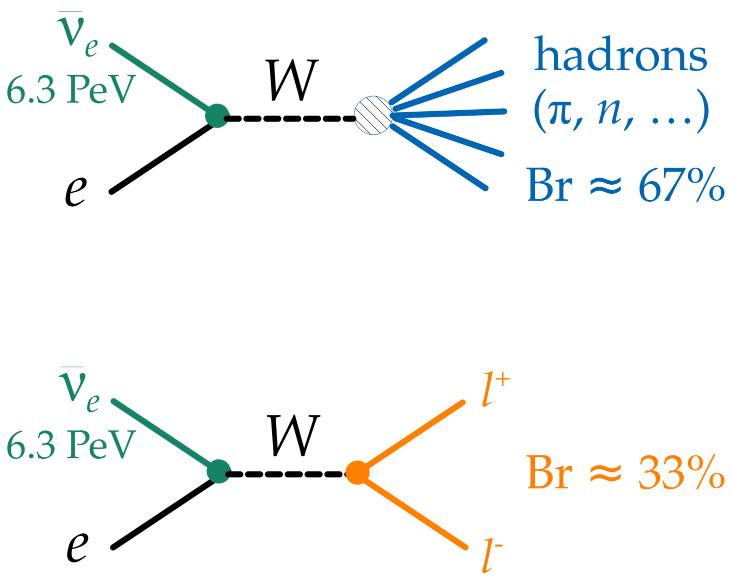

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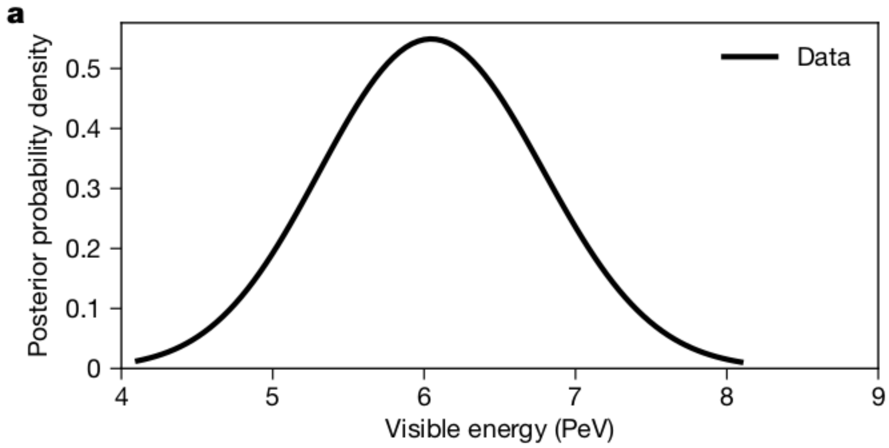

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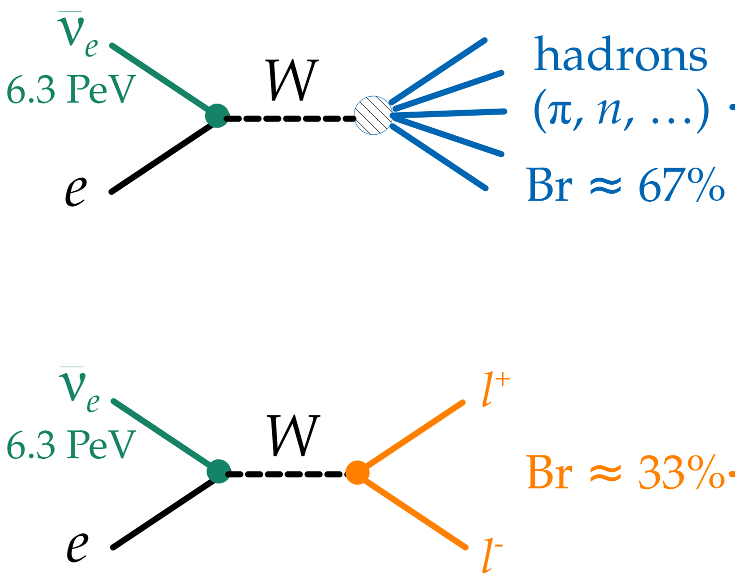

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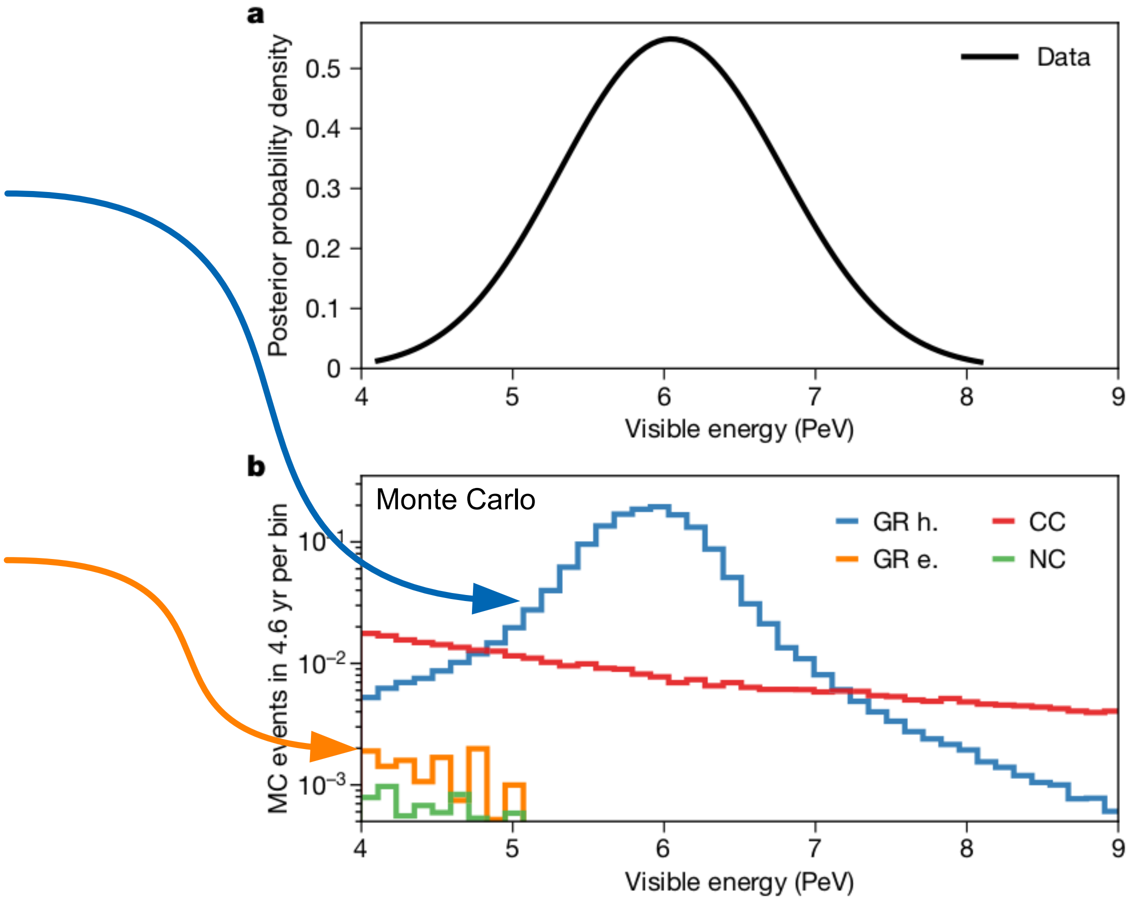


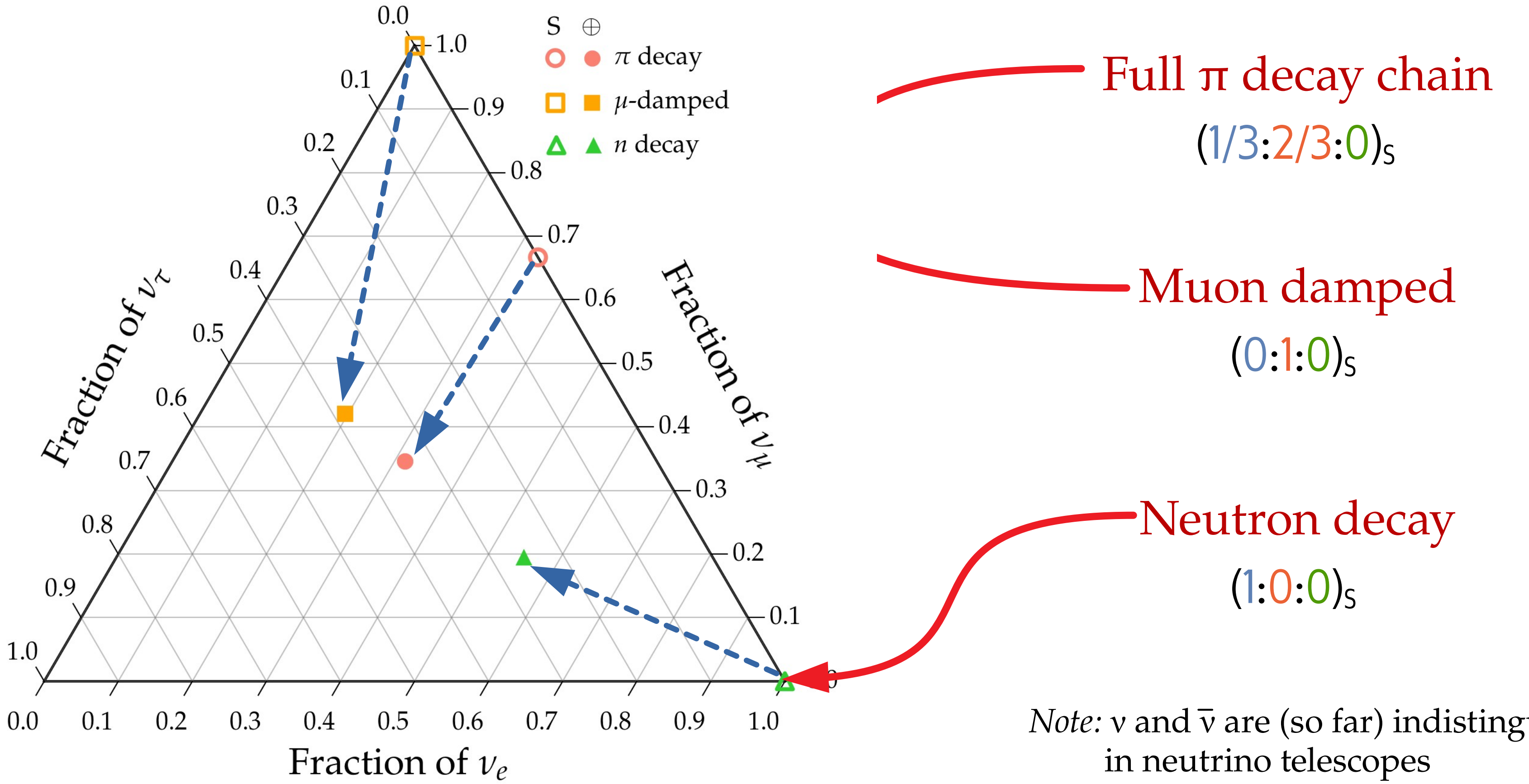
IceCube, *Nature* 2021
Glashow, *PR* 1960

Flavor:
Towards precision, finally

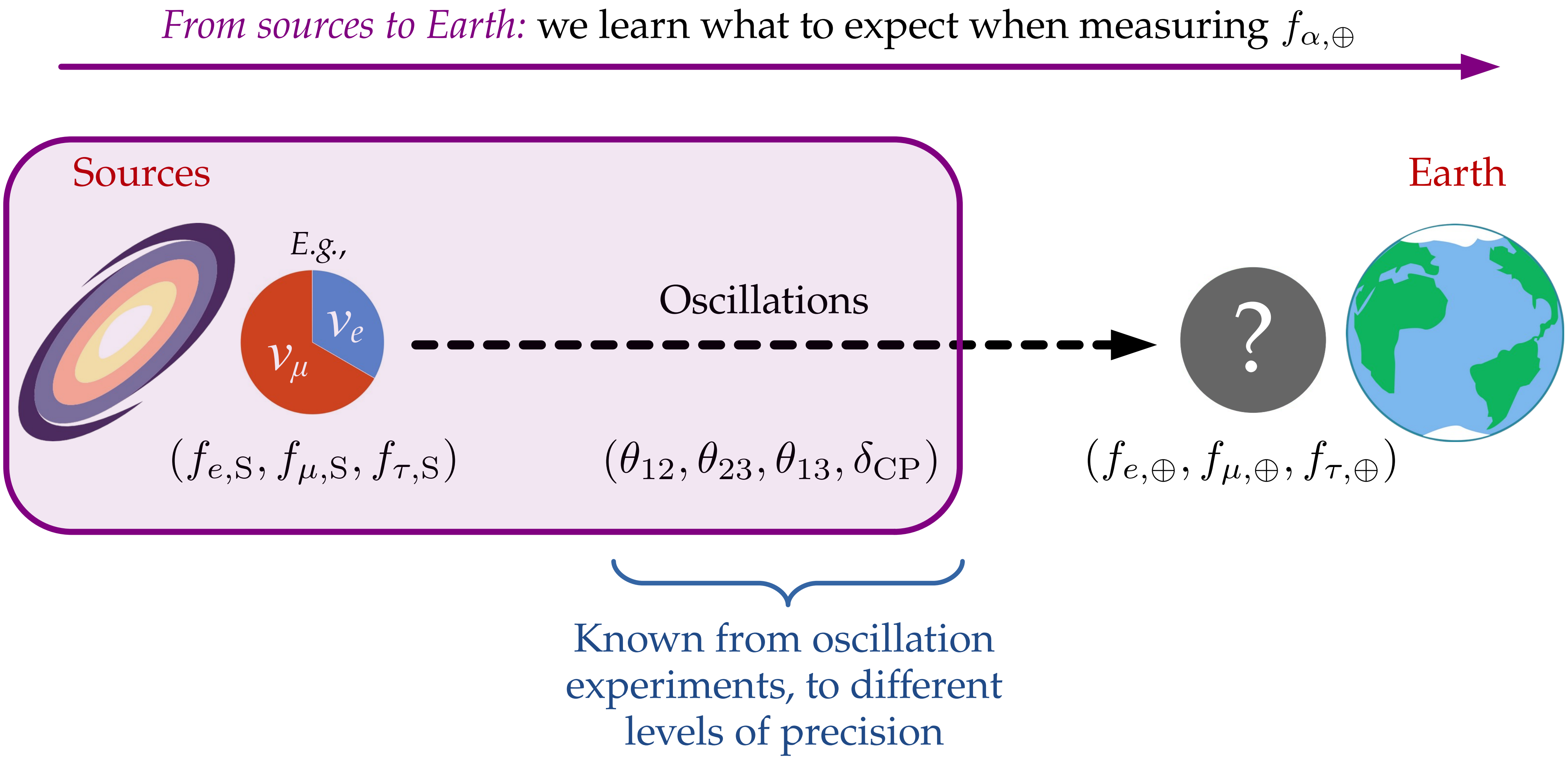
(with the help of lower-energy experiments)

One likely TeV–PeV ν production scenario:

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

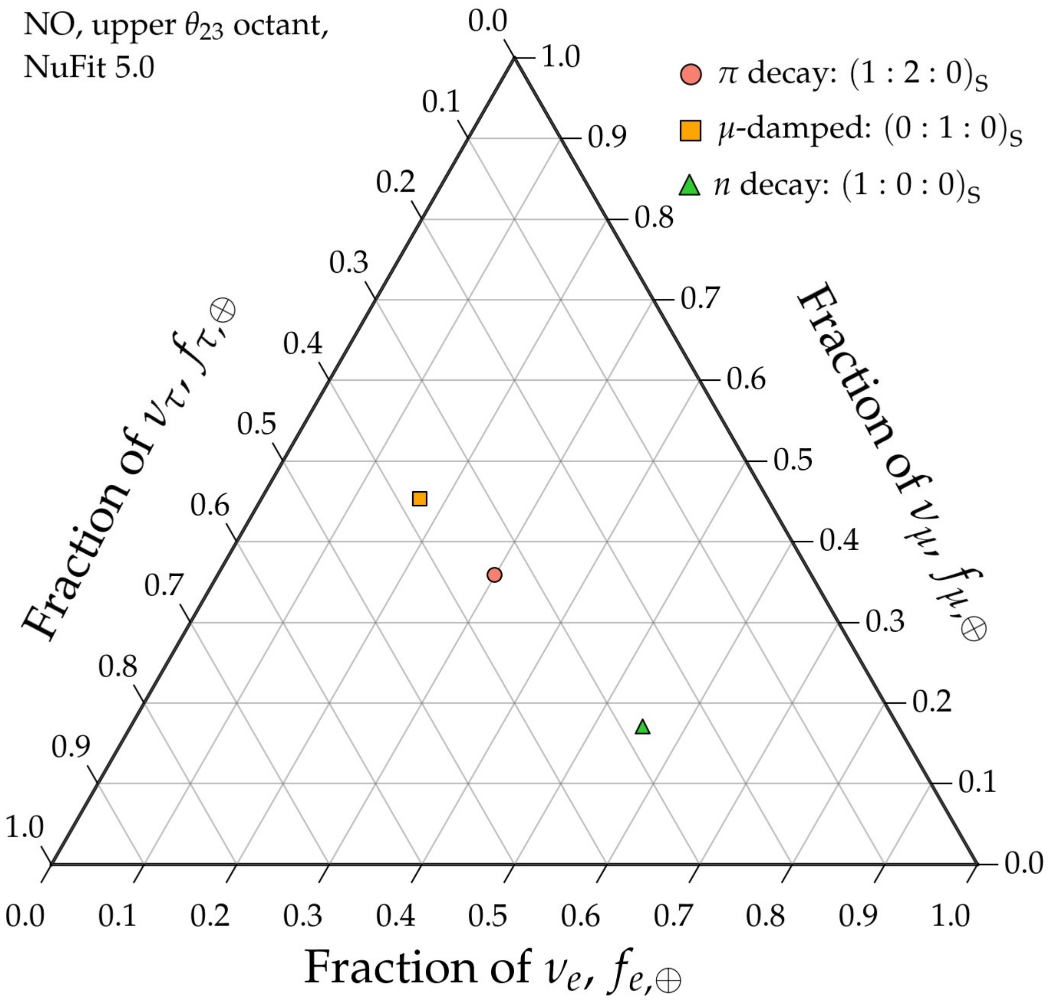


Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes



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 (2021)



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

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

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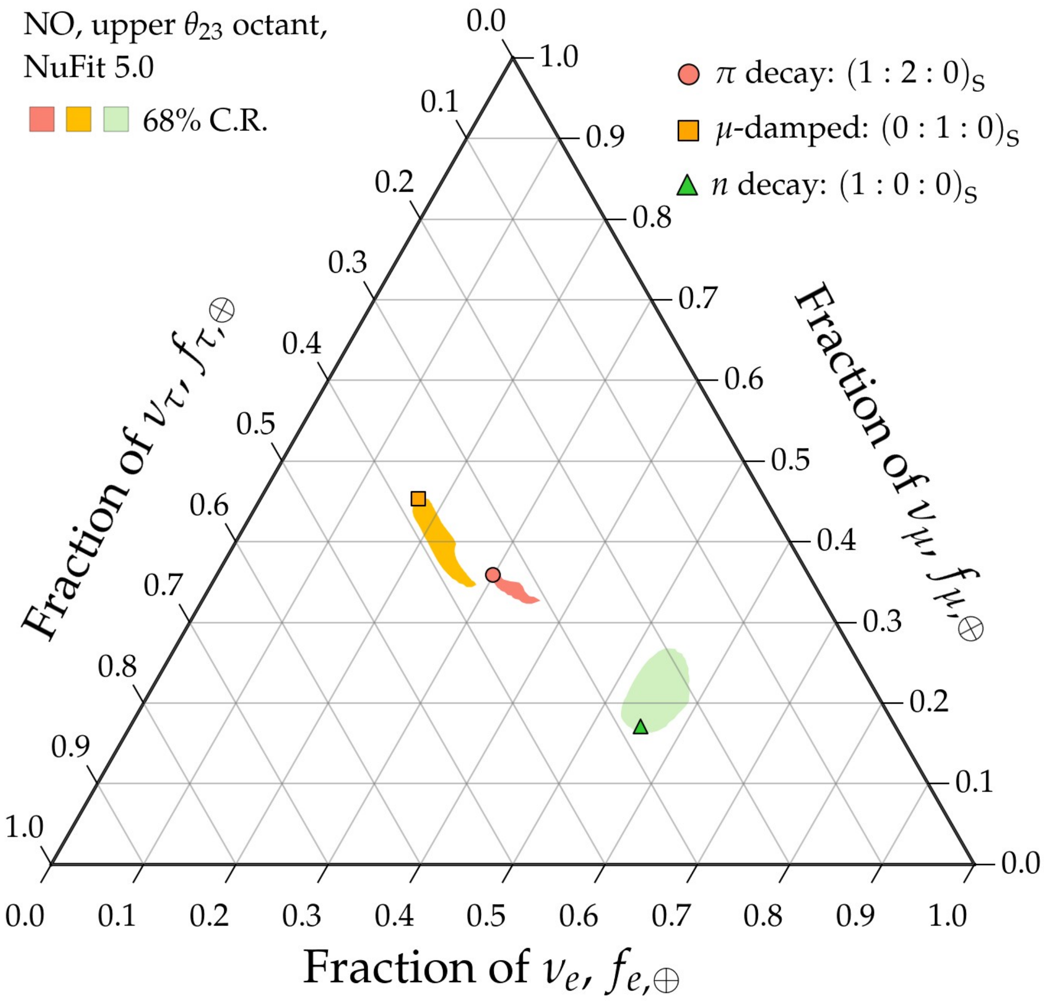

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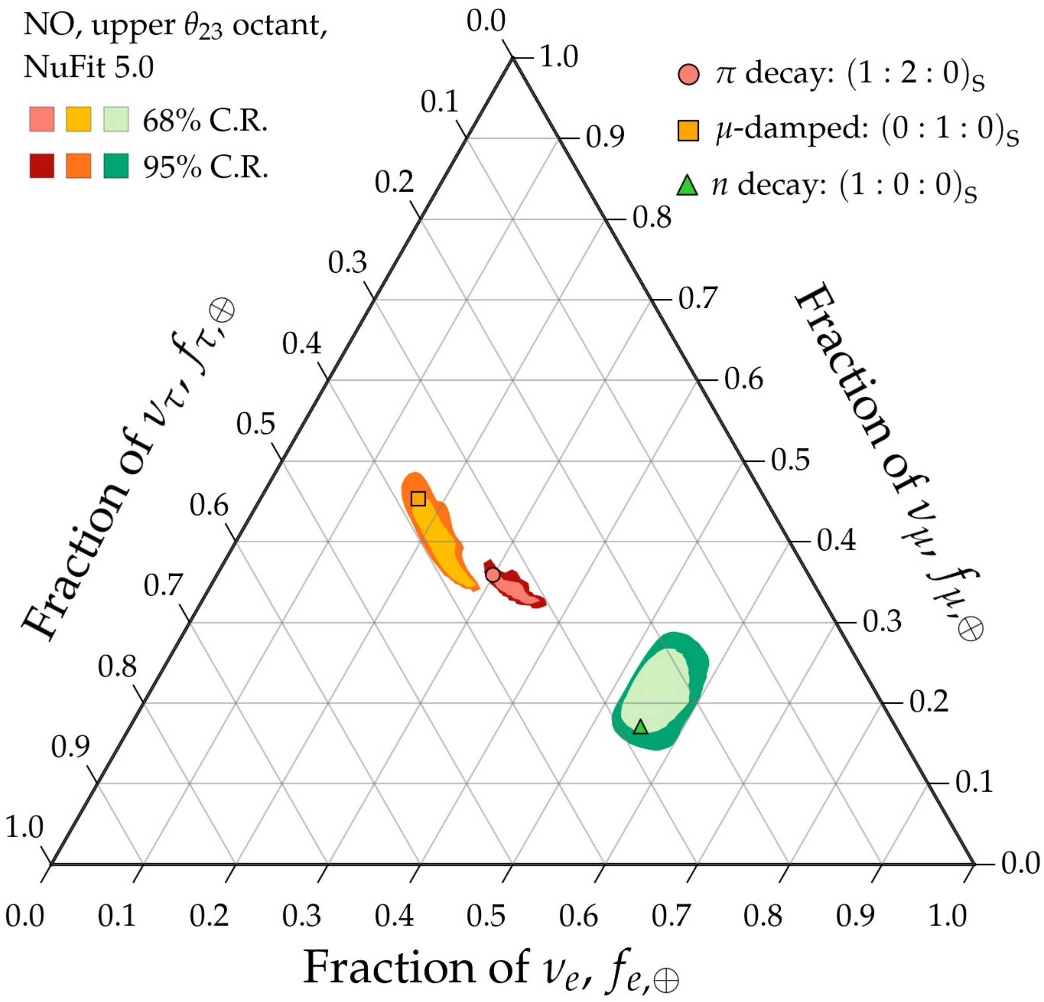

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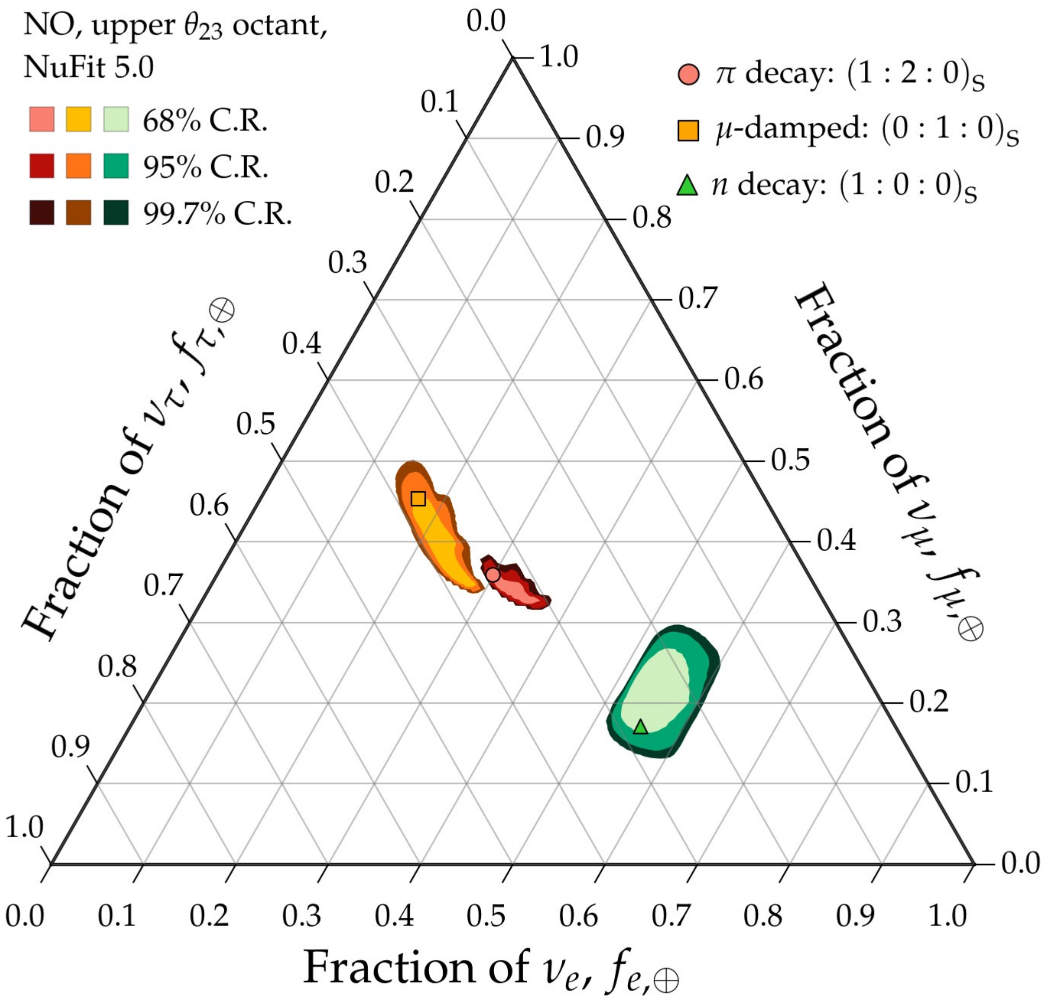

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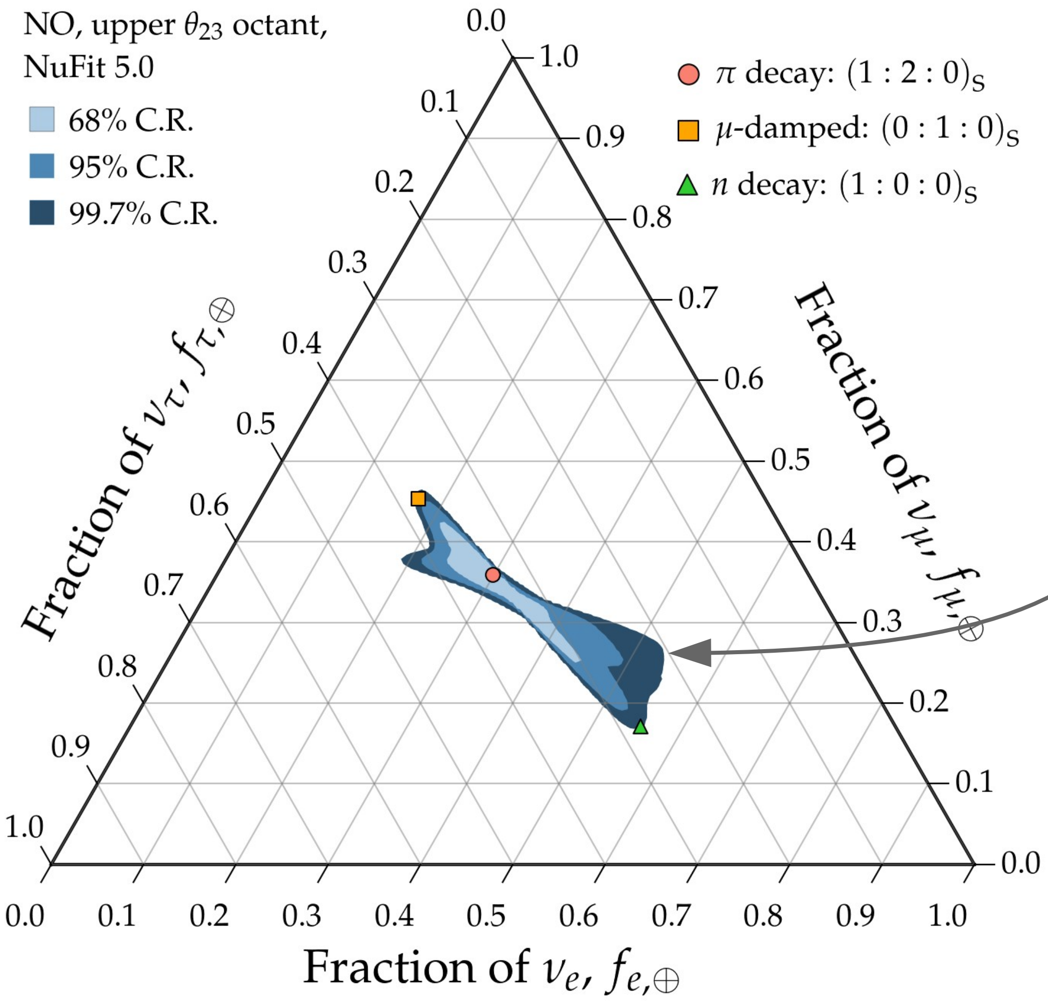

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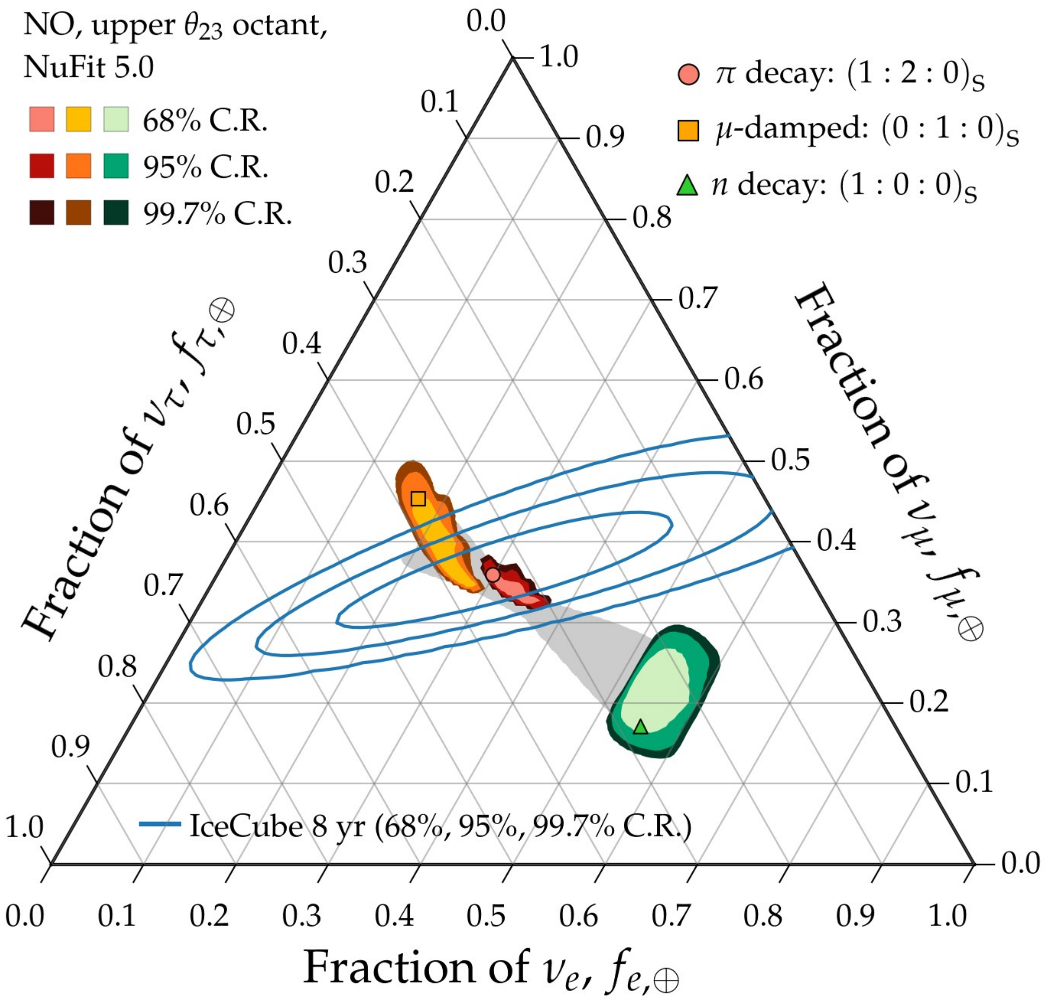

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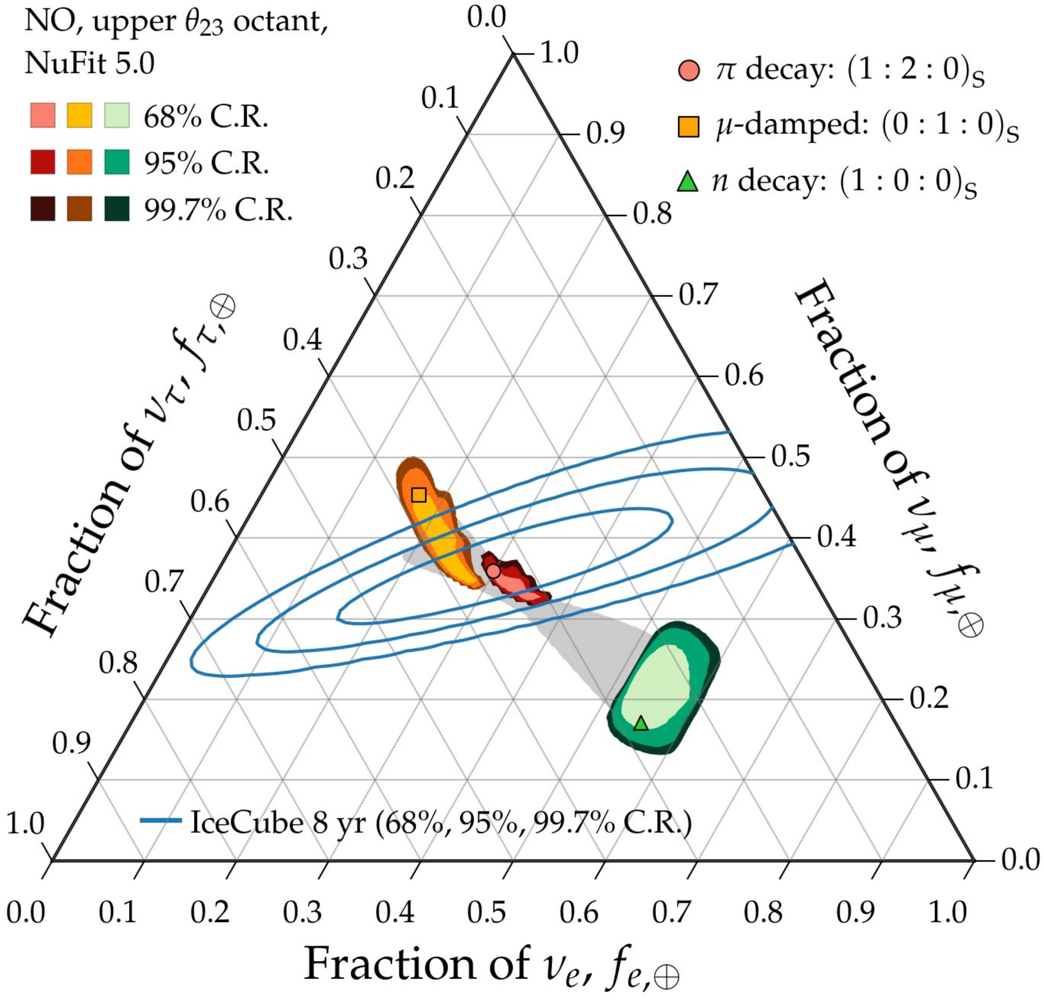


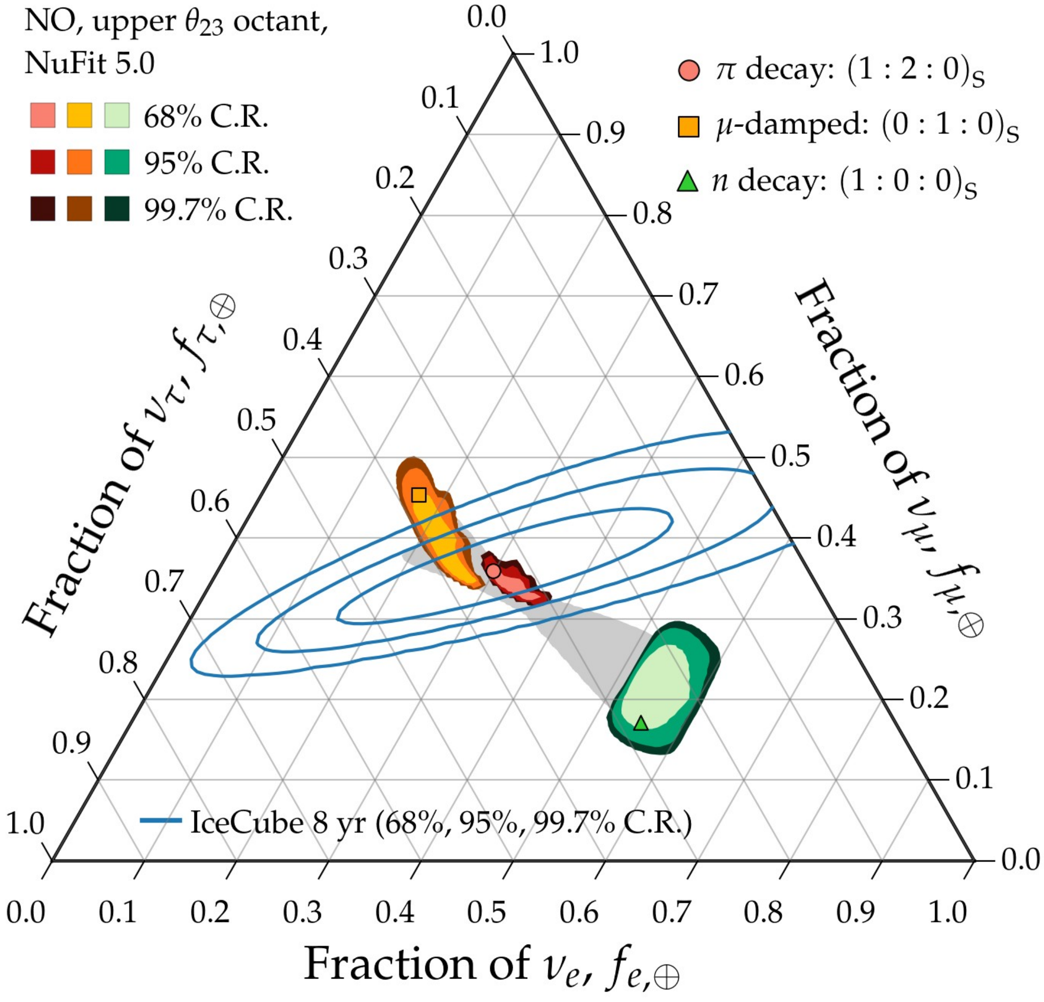
Two limitations:

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 (2021)



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Will be overcome by 2030

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

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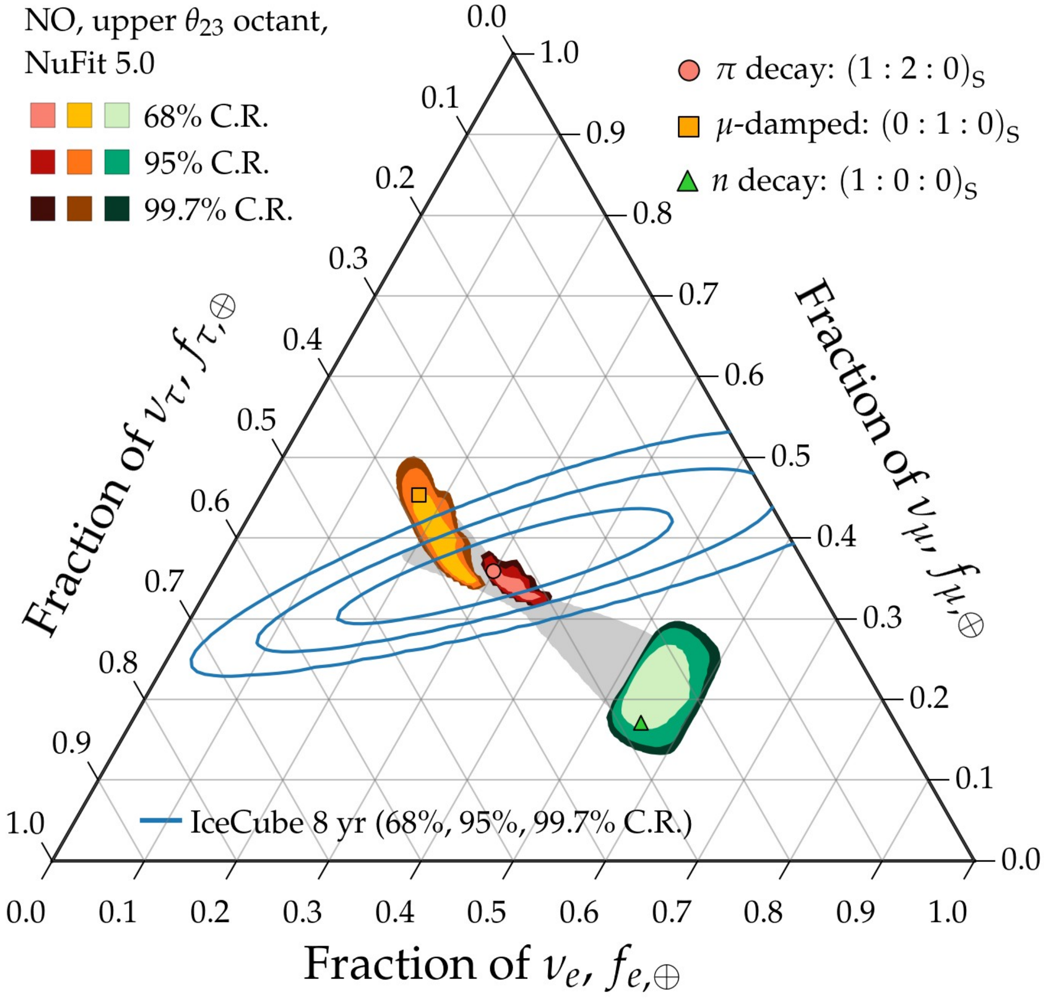

Two limitations:

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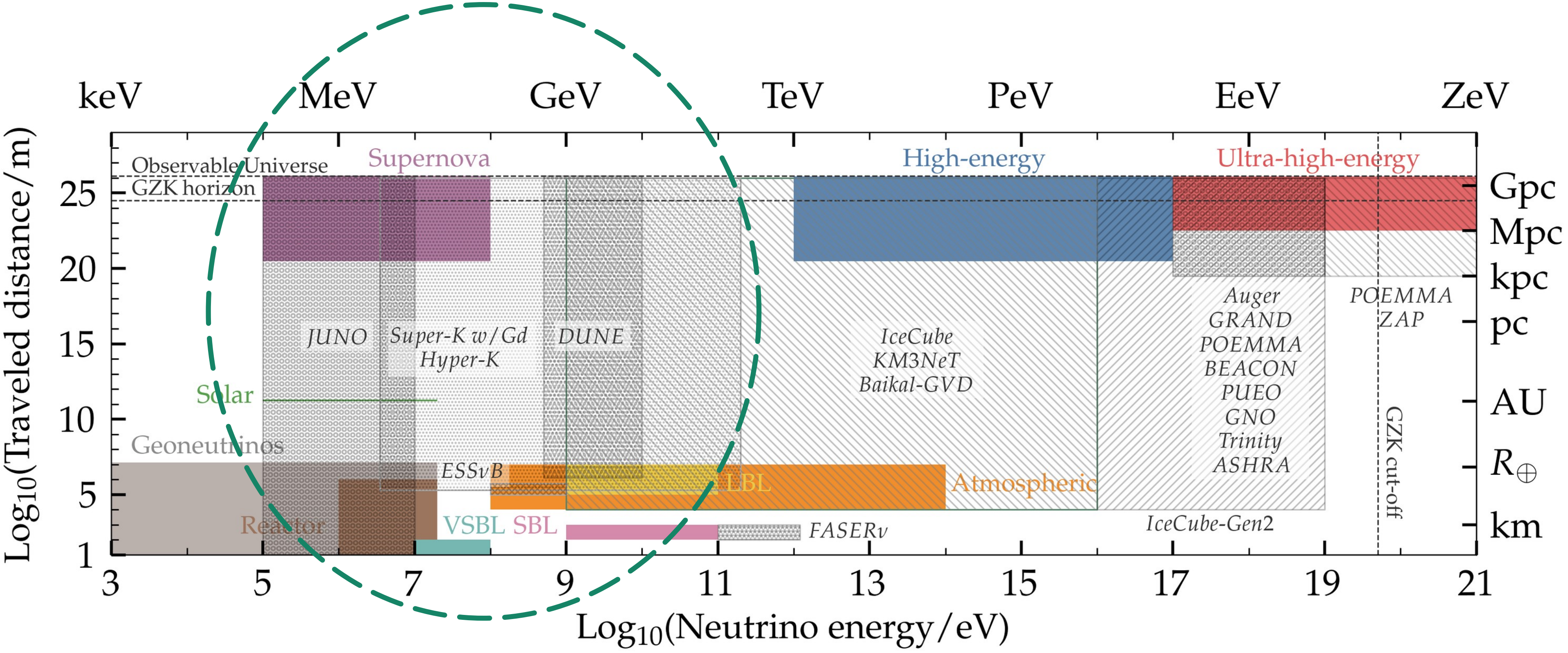
Will be overcome by 2030

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

Will be overcome by 2040

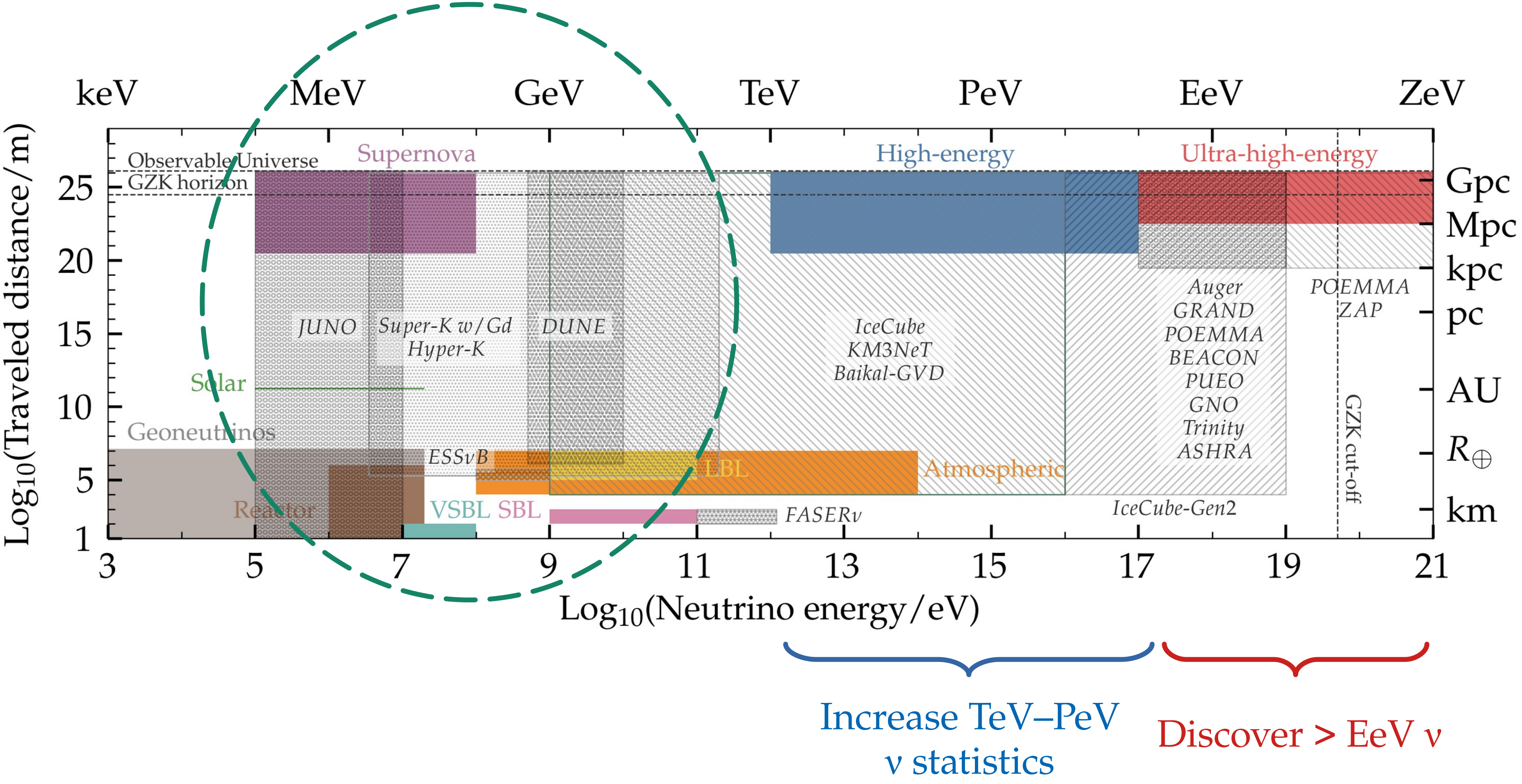
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Next decade: a host of planned neutrino detectors



MB *et al.*, Snowmass 2020 Letter of interest

Next decade: a host of planned neutrino detectors



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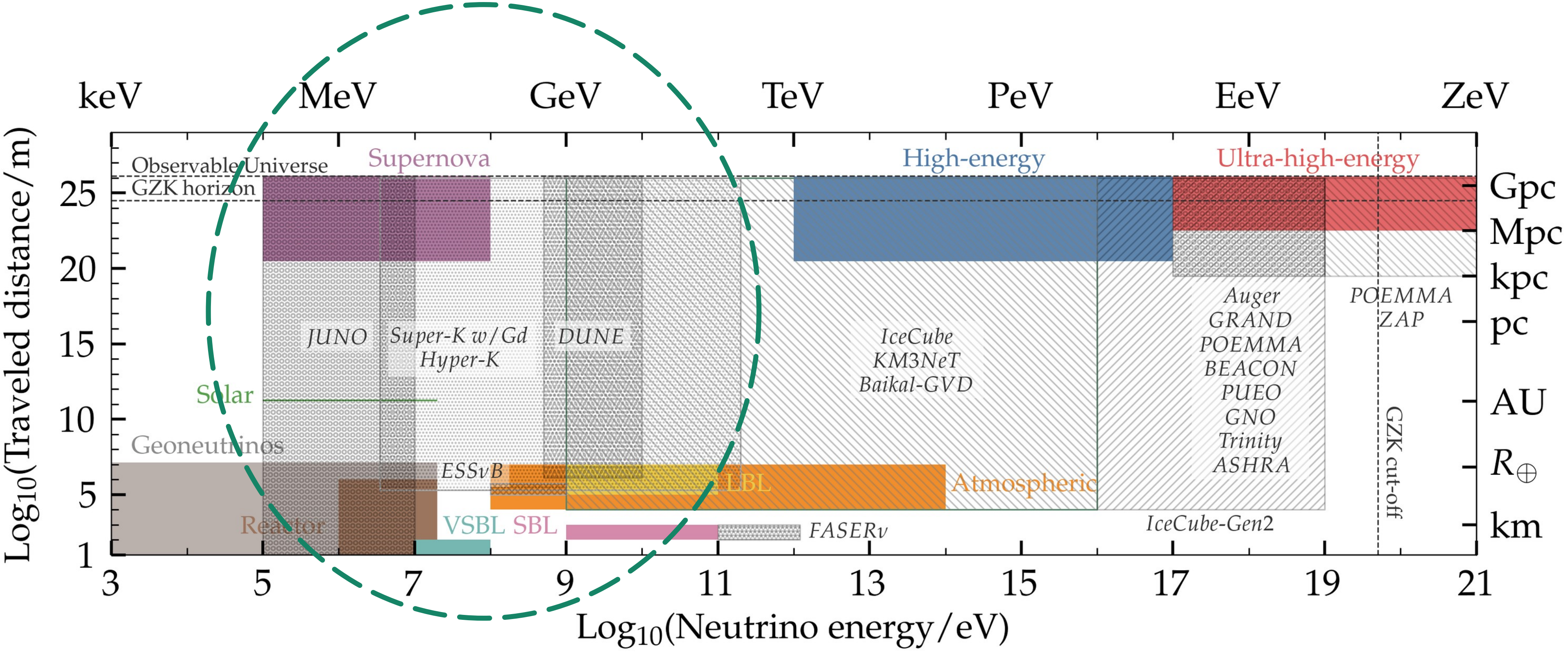


Synergies with lower energies

Increase TeV–PeV ν statistics

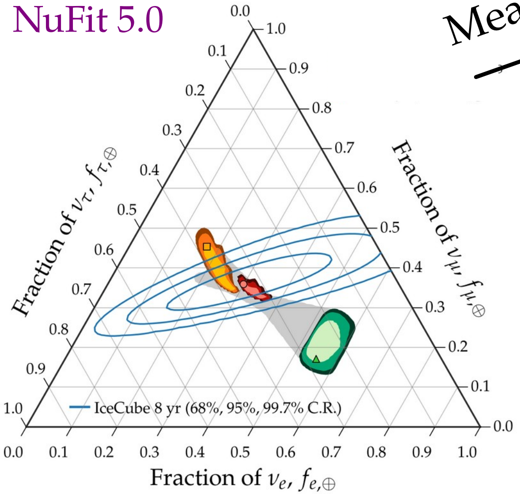
Discover > EeV ν

MB *et al.*, Snowmass 2020 Letter of interest

Knowing the mixing parameters better helps

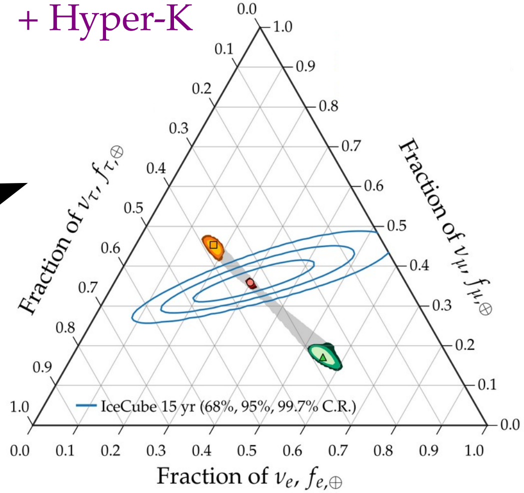
2020

NuFit 5.0



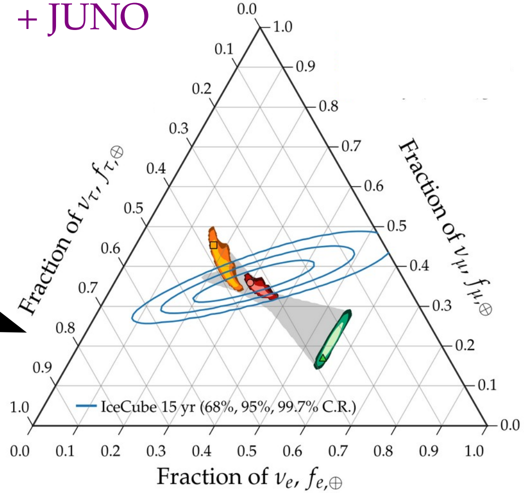
Measure θ_{23} better

\+ Hyper-K



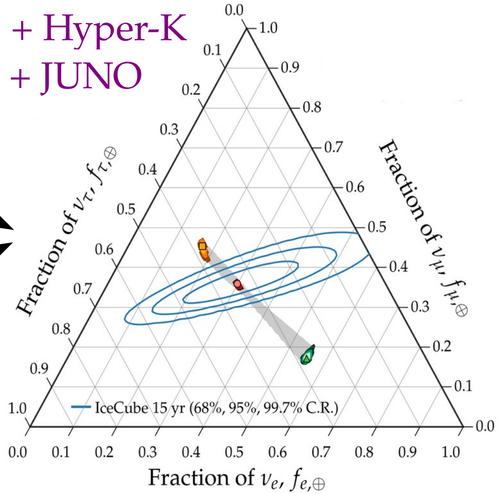
Measure θ_{12} better

\+ JUNO



~2030

\+ Hyper-K
\+ JUNO



In our results:
JUNO + Hyper-K + DUNE

\+ Marginal improvement til 2040

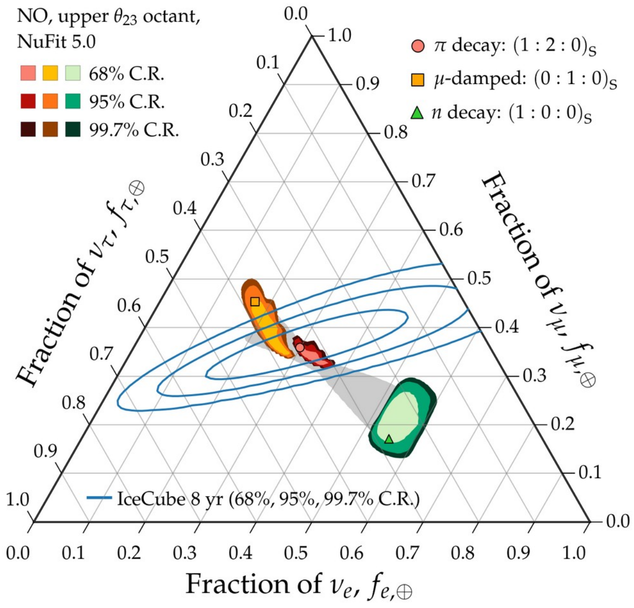
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: 2020 → 2030 → 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

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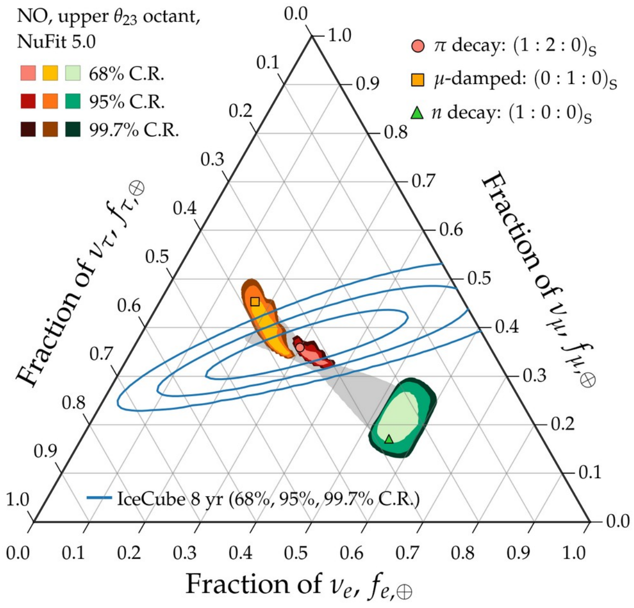
2020



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Measurement: imprecise

Not ideal

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

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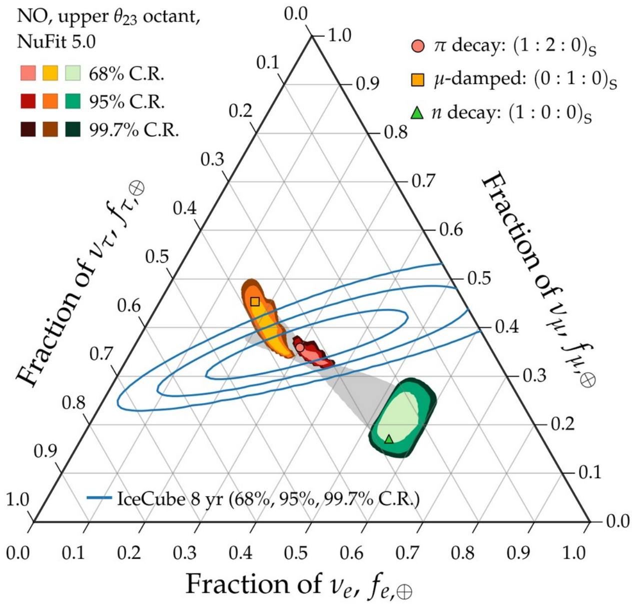
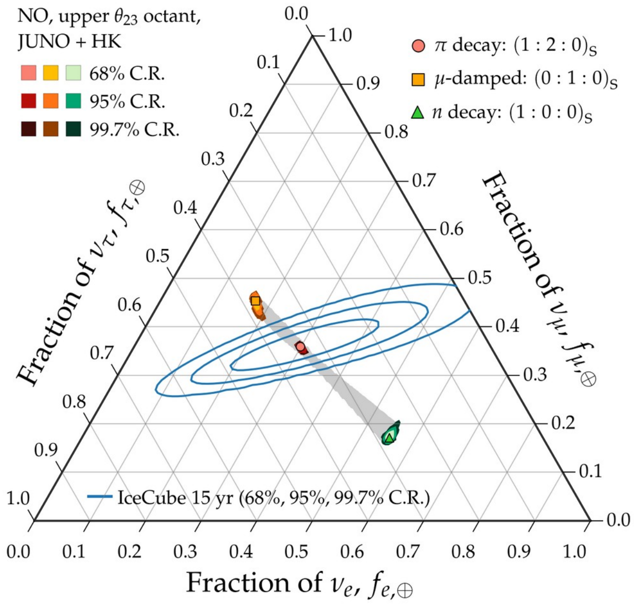


2030



Allowed regions: overlapping
Measurement: imprecise

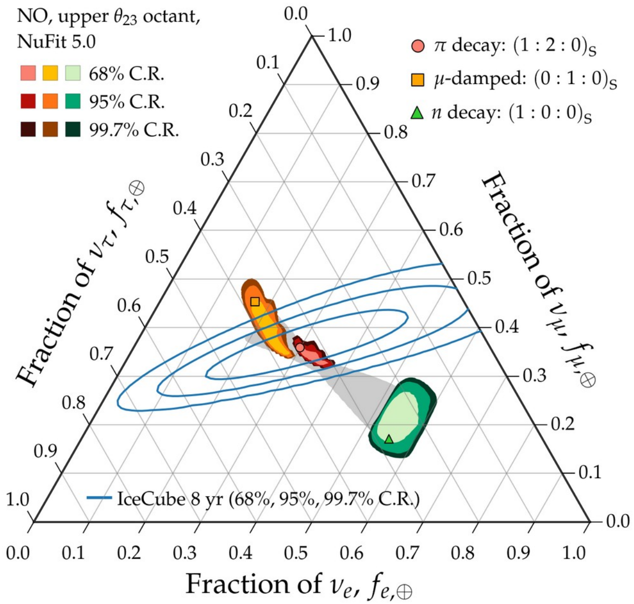
Not ideal

Allowed regions: well separated
Measurement: improving

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

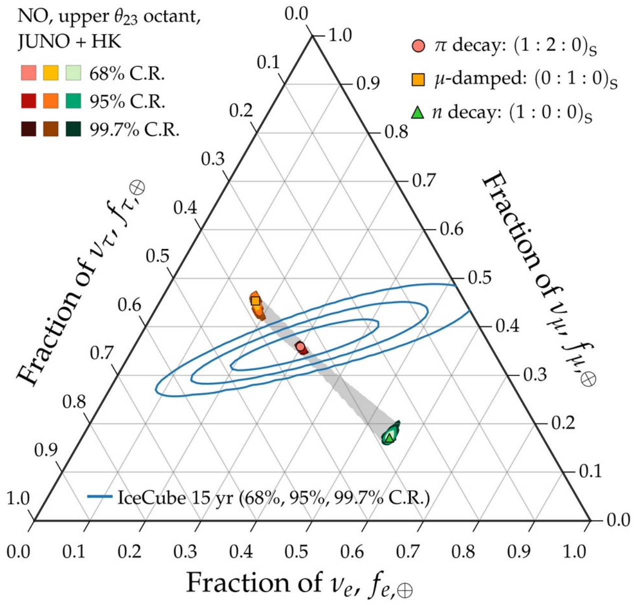


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



Allowed regions: well separated

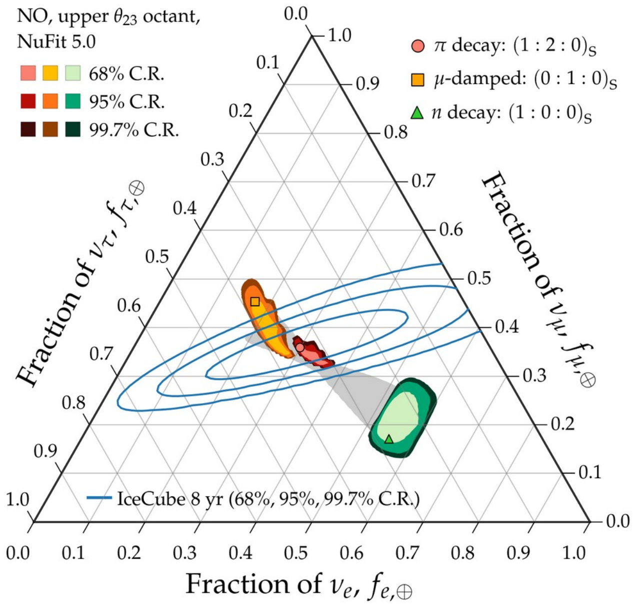
Measurement: improving

Nice

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

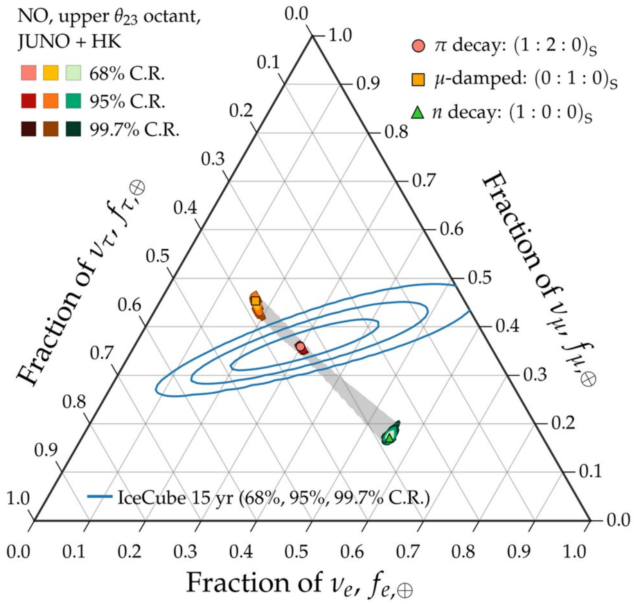


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



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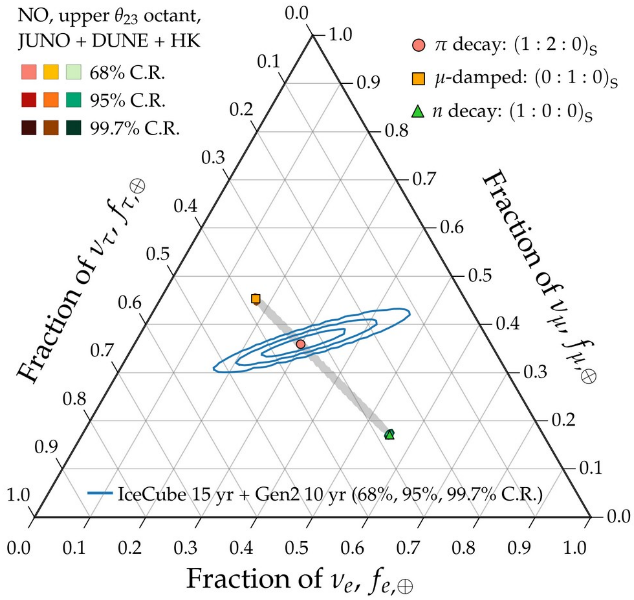
2040



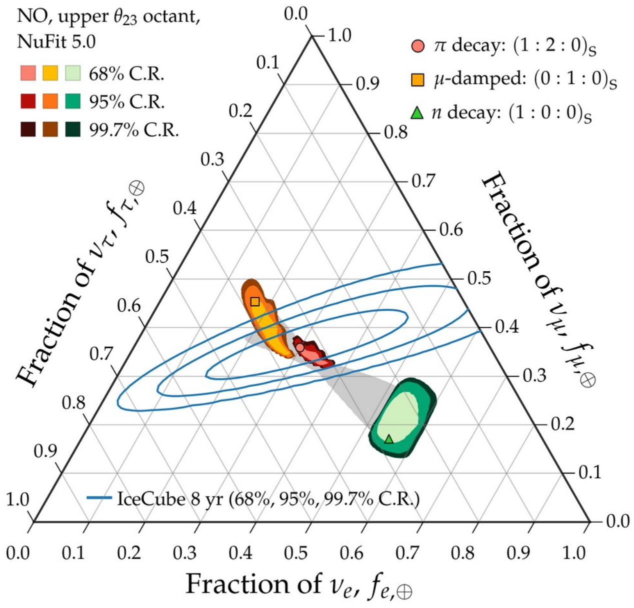
Allowed regions: well separated

Measurement: precise

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

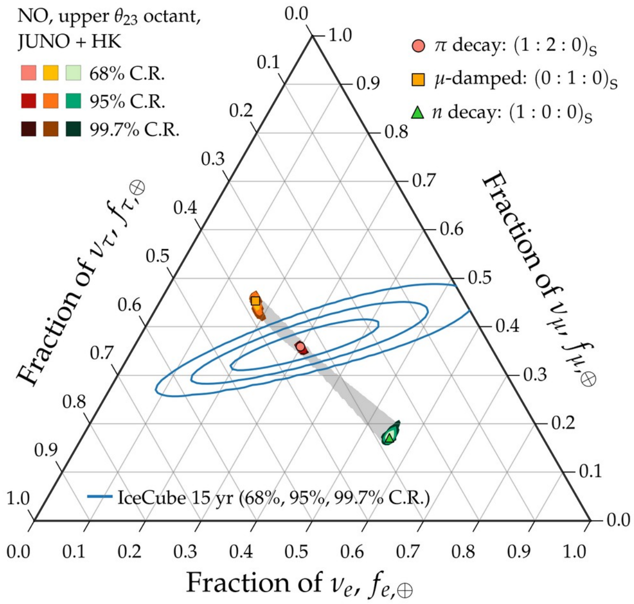


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030

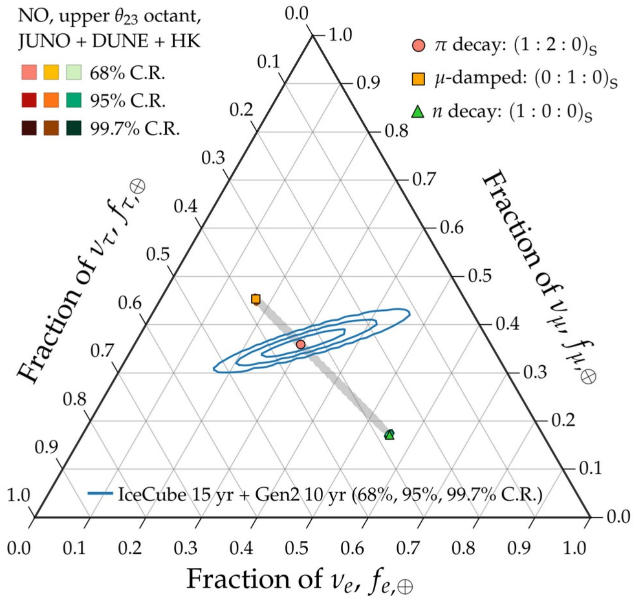


Allowed regions: well separated

Measurement: improving

Nice

2040



Allowed regions: well separated

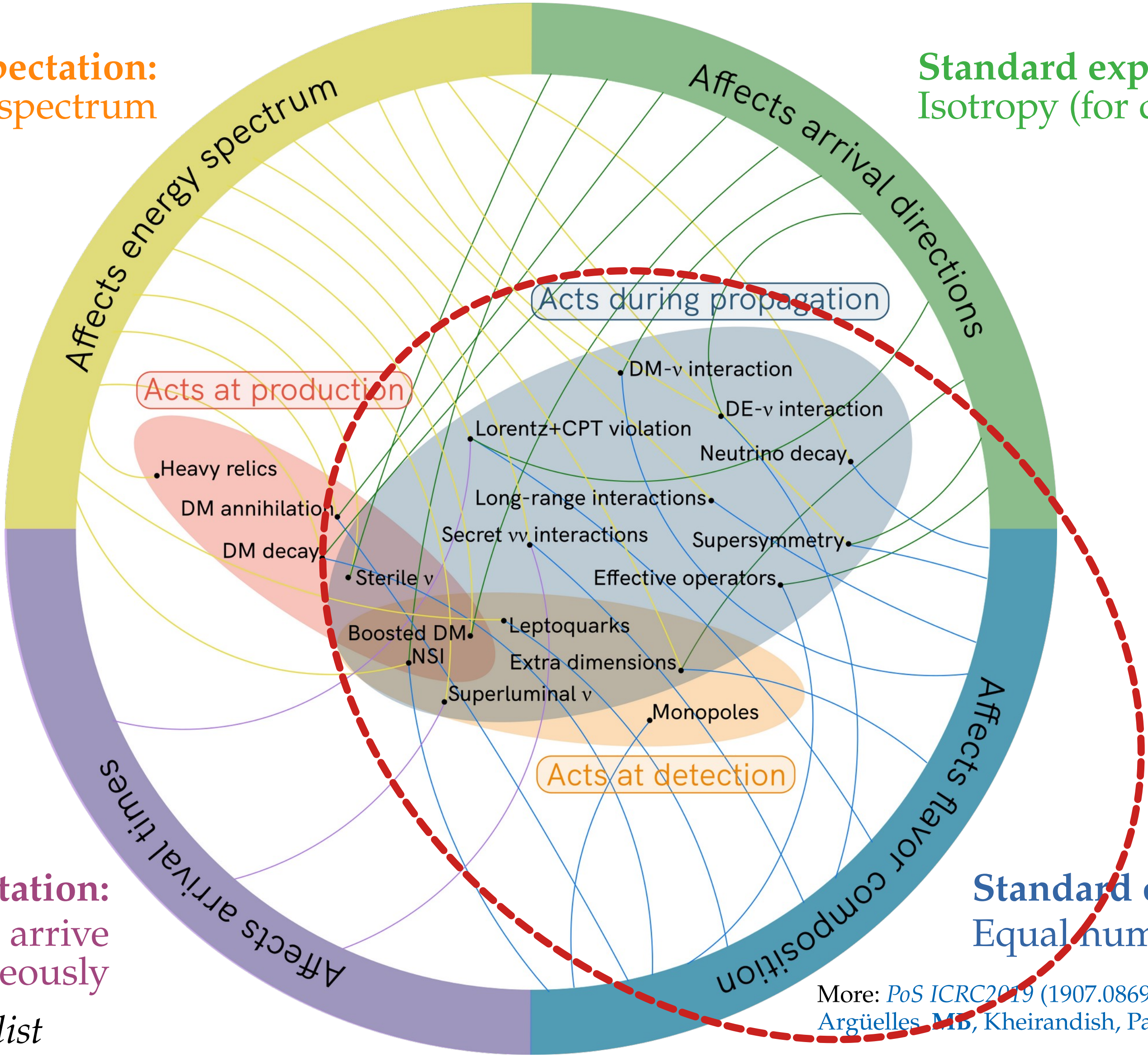
Measurement: precise

Success

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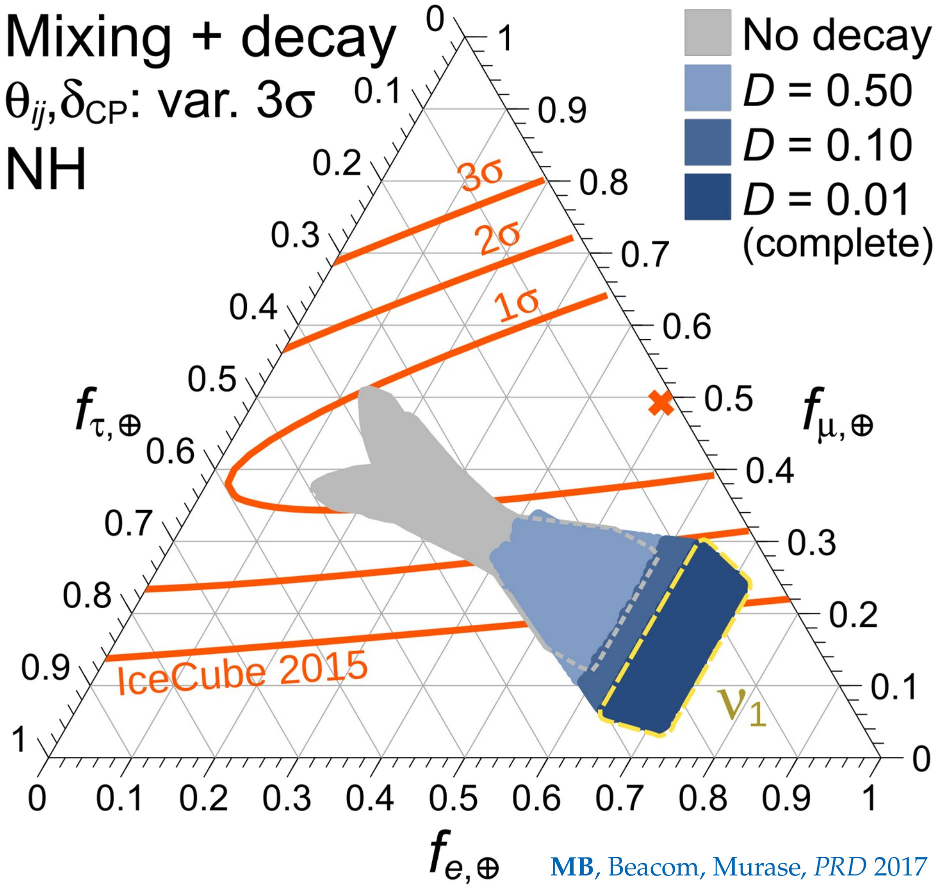
Reviews:
Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

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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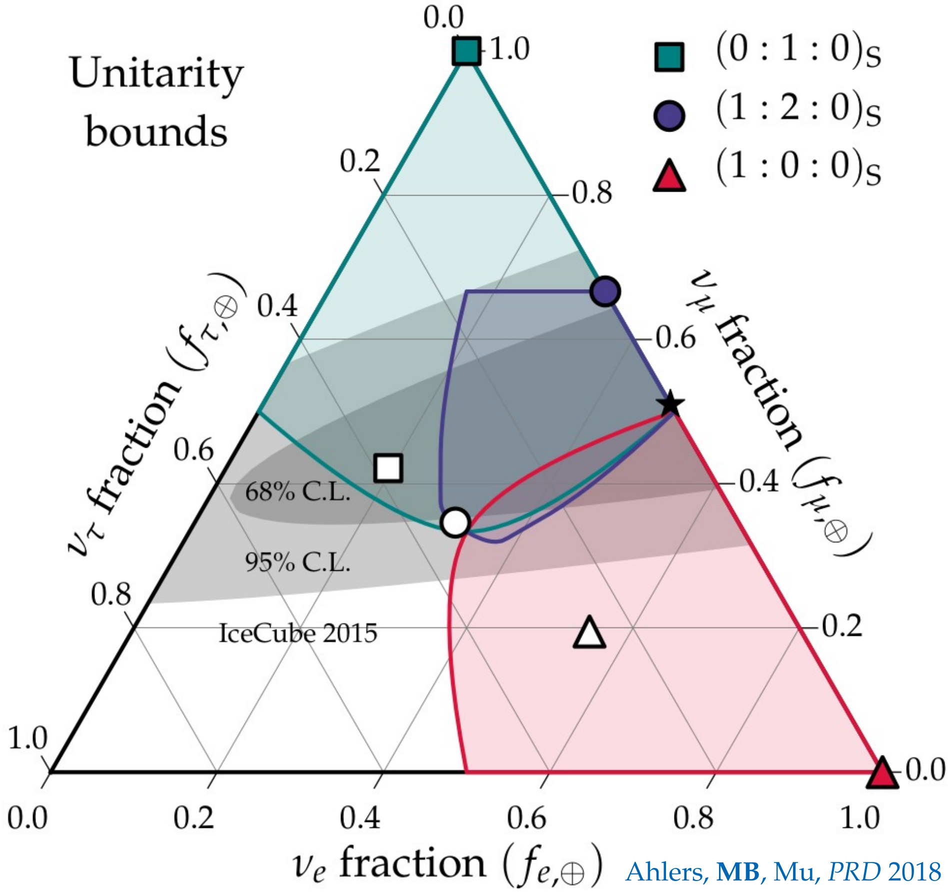

Ahlers, **MB**, Mu, *PRD* 2018

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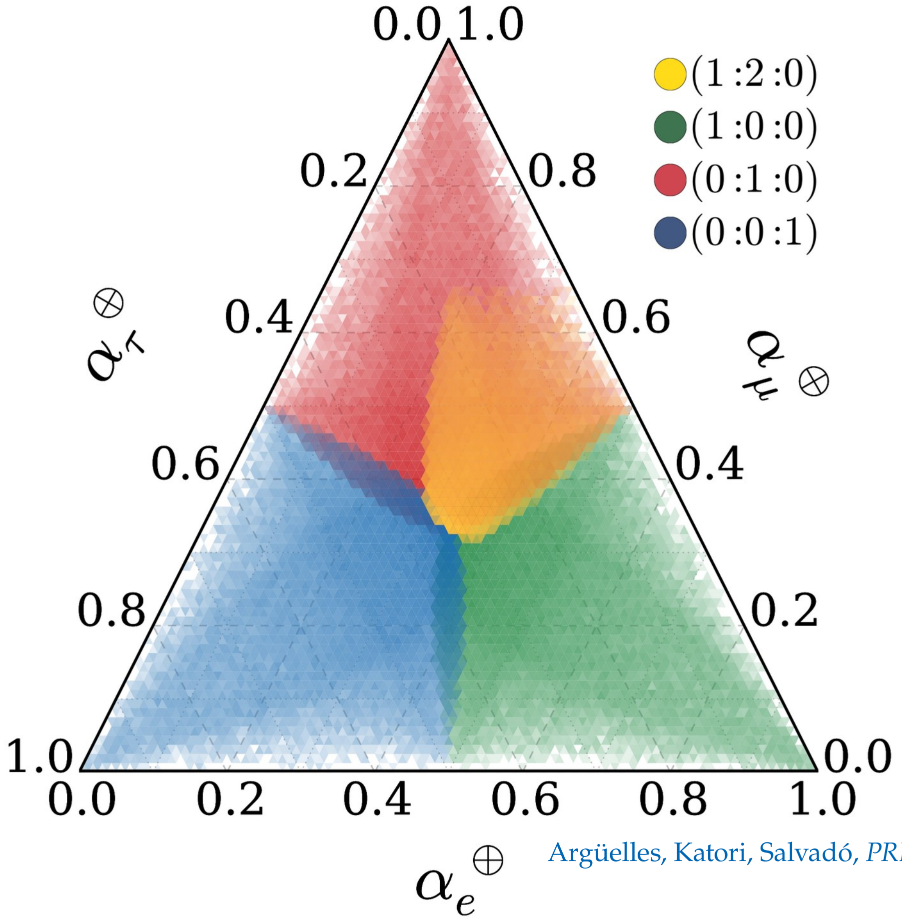

Argüelles, Katori, Salvadó, *PRL* 2015

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

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- ▸ Non-standard interactions
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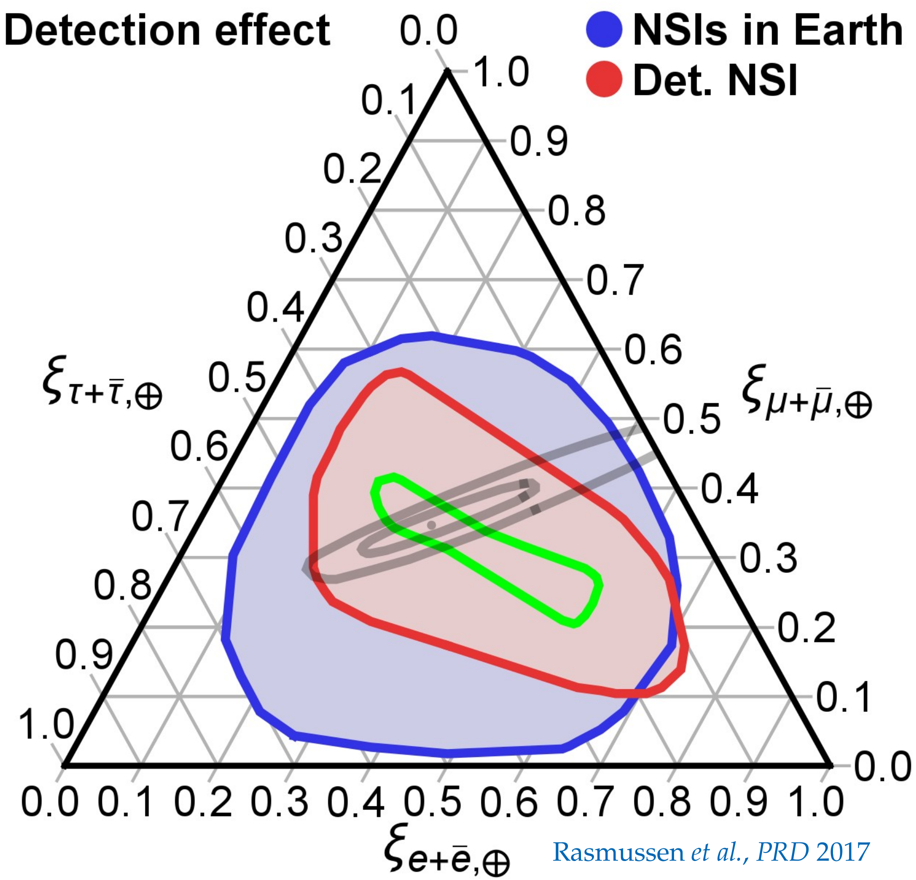

Rasmussen *et al.*, *PRD* 2017

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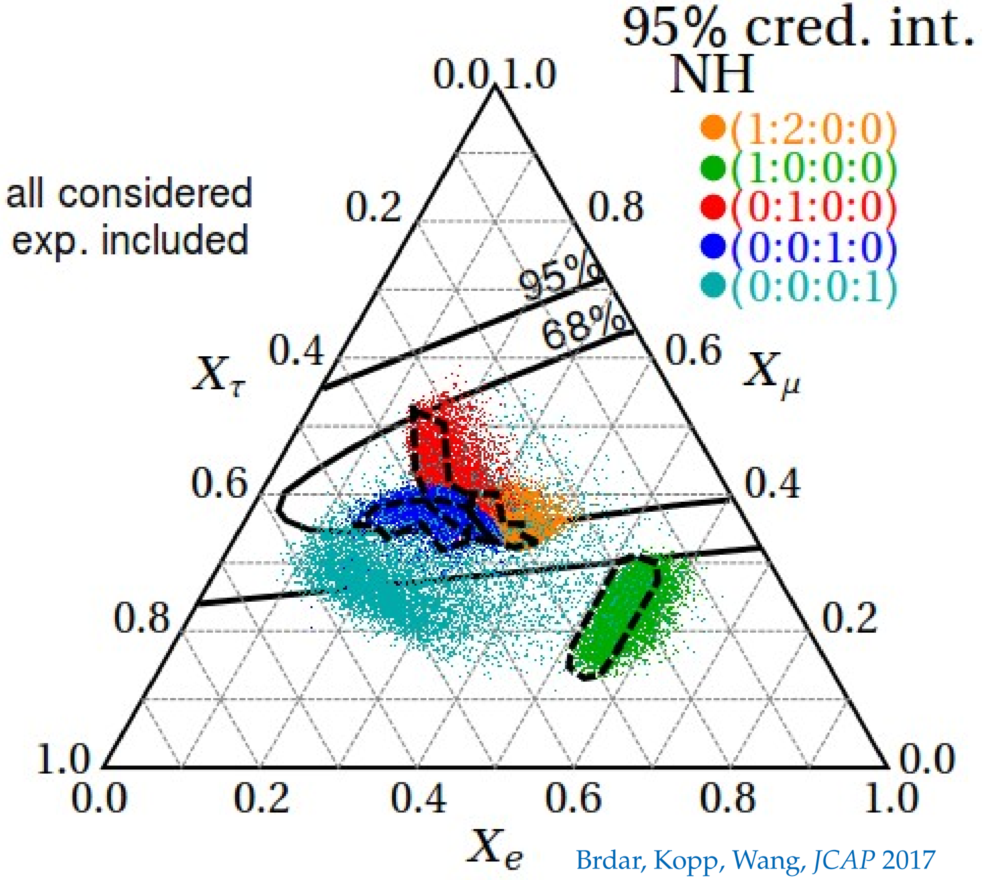
  [González-García *et al.*, *Astropart. Phys.* 2016;
  Rasmussen *et al.*, *PRD* 2017]
- Active-sterile ν mixing
  [Aeikens *et al.*, *JCAP* 2015; Brdar, Kopp, Wang, *JCAP* 2017;
  Argüelles *et al.*, *JCAP* 2020; Ahlers, **MB**, *JCAP* 2021]



Brdar, Kopp, Wang, *JCAP* 2017

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

New physics in flavor composition

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]
- **Tests of unitarity at high energy**
  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018; Ahlers, **MB**, Nortvig, *JCAP* 2021]
- **Lorentz- and CPT-invariance violation**
  [Barenboim & Quigg, *PRD* 2003; **MB**, Gago, Peña-Garay, *JHEP* 2010; Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]
- **Non-standard interactions**
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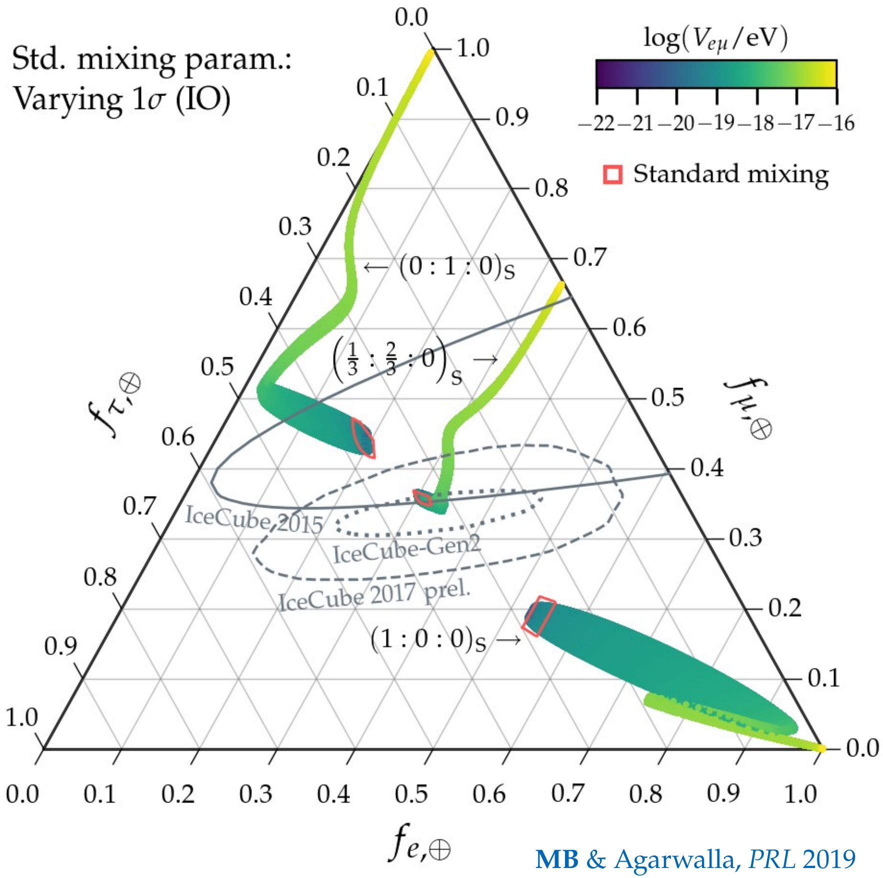
- **Long-range *e*ν interactions**
  [**MB** & Agarwalla, *PRL* 2019]

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



MB & Agarwalla, *PRL* 2019

Example 2:
Secret neutrino interactions

νSI with the UHE diffuse flux

Resonance energy: $E_{\text{res}} = \dfrac{M^2}{2m_\nu}$

Coupling matrix:

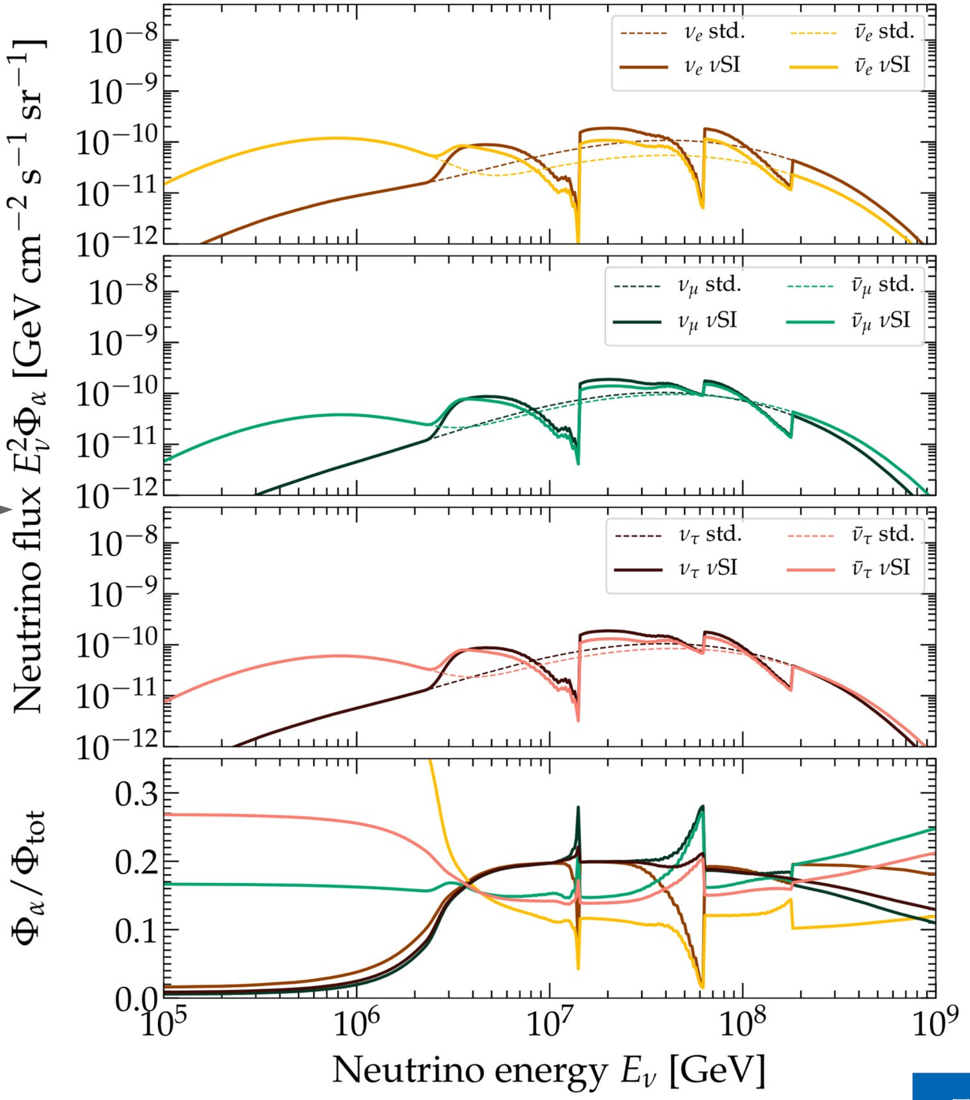
Different flavors can have different couplings

$$\mathbf{G} \equiv \begin{pmatrix} g_{ee} & g_{e\mu} & g_{e\tau} \\ g_{e\mu} & g_{\mu\mu} & g_{\mu\tau} \\ g_{e\tau} & g_{\mu\tau} & g_{\tau\tau} \end{pmatrix}$$

νSI dips and bumps in the diffuse UHE ν flux:

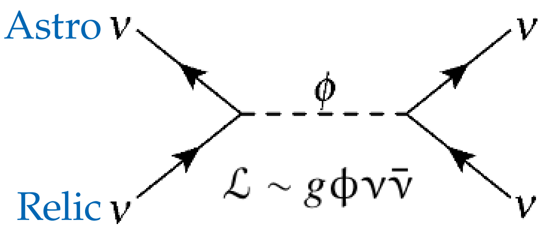
- In the cosmogenic flux
- In the flux from sources

But we need enough events to detect the spectral features – we need POEMMA-360!



MB, Másson, Valera, In prep.

νSI with the UHE transient flux



If this happens repeatedly, high-energy neutrinos disappear

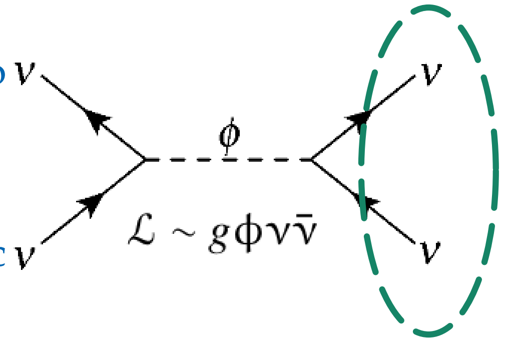
So, if we see high-energy neutrinos, we can set an upper limit on the νSI strength

Original idea by Kolb & Turner, using SN1987A (*PRD* 1987)

Mean free path of a ν of energy E: $l_{\rm int}(E) = [n_{\rm C\nu B}\sigma_{\nu\nu}(E)]^{-1}$

Estimated optical depth if emitted by a source at a distance L: $\tau(E) = \frac{l_{\rm int}(E)}{L}$

νSI with the UHE transient flux



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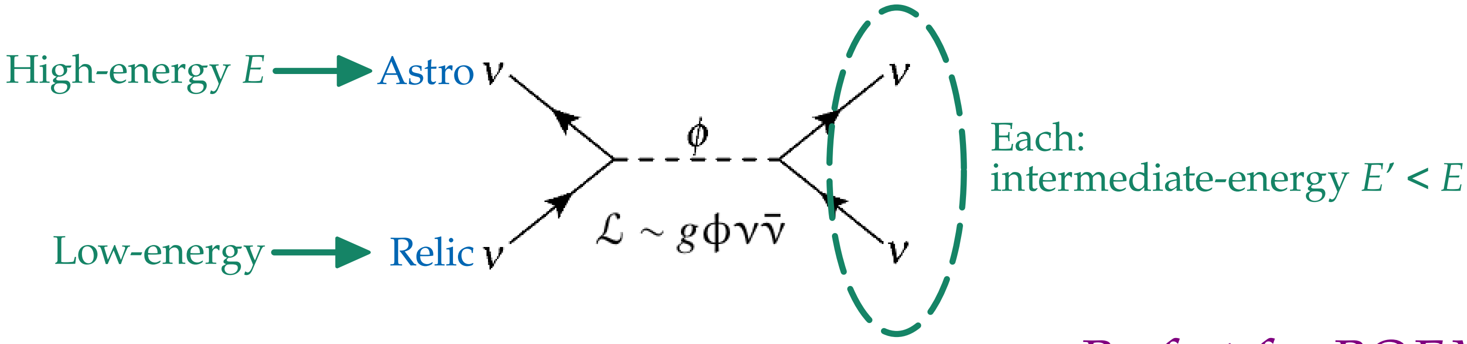

Perfect for POEMMA!

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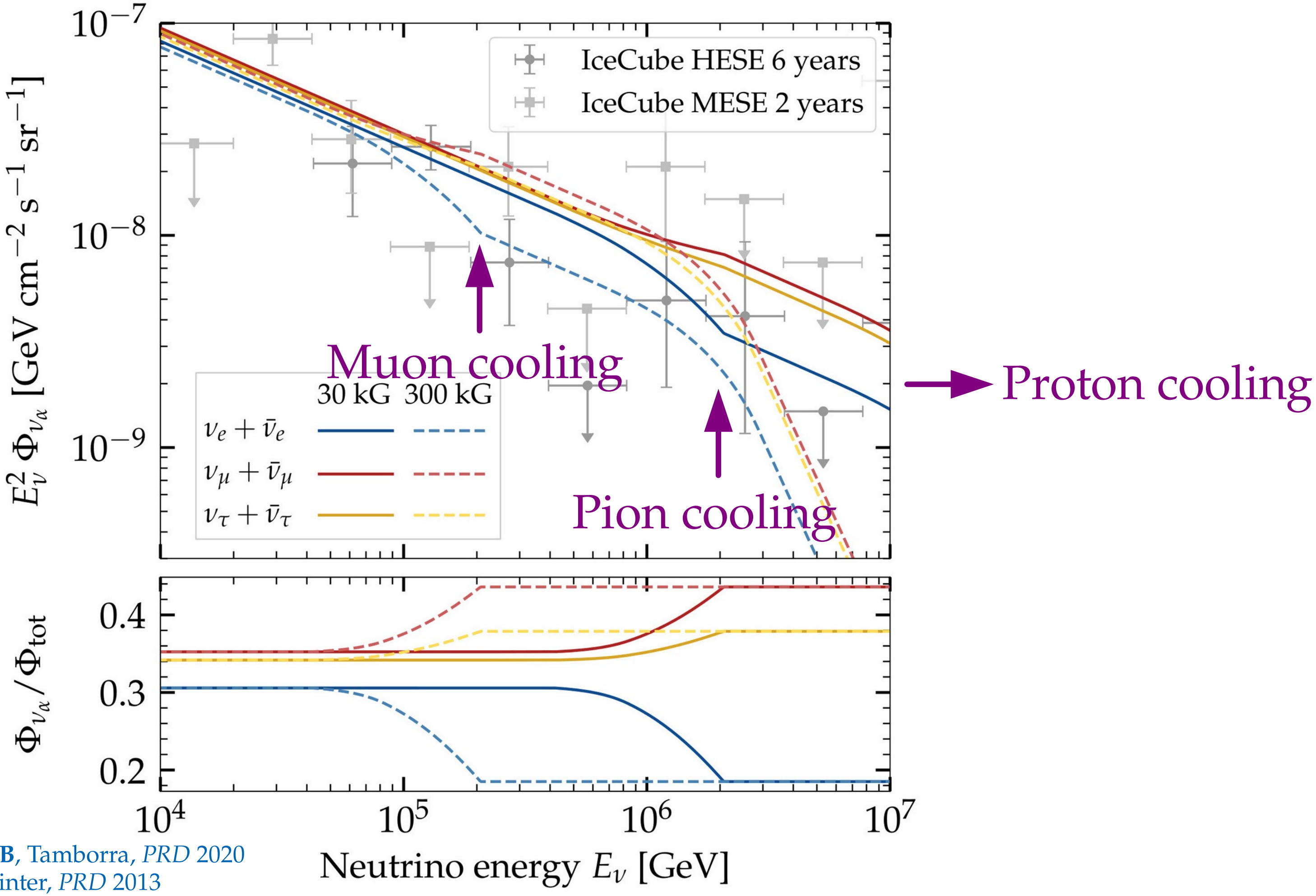
Flavor composition

Using high-energy neutrinos as magnetometers

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



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

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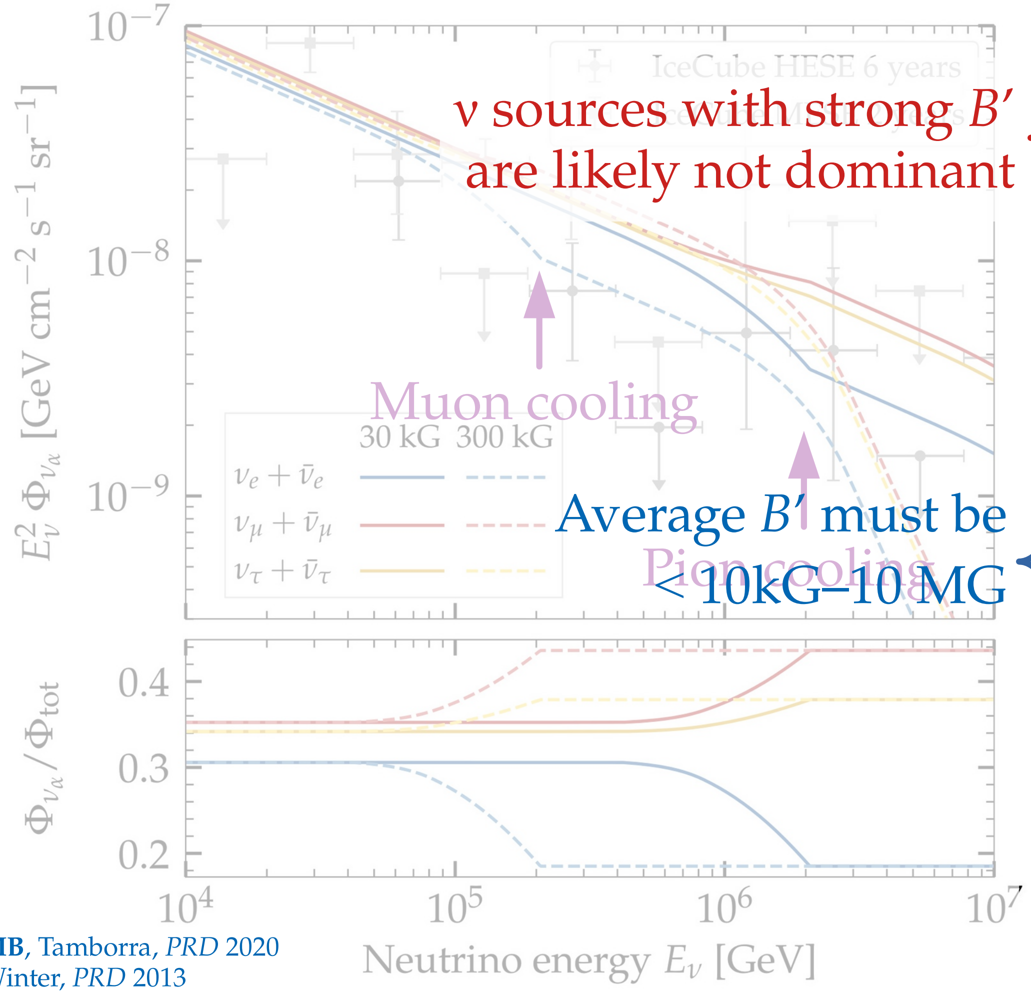
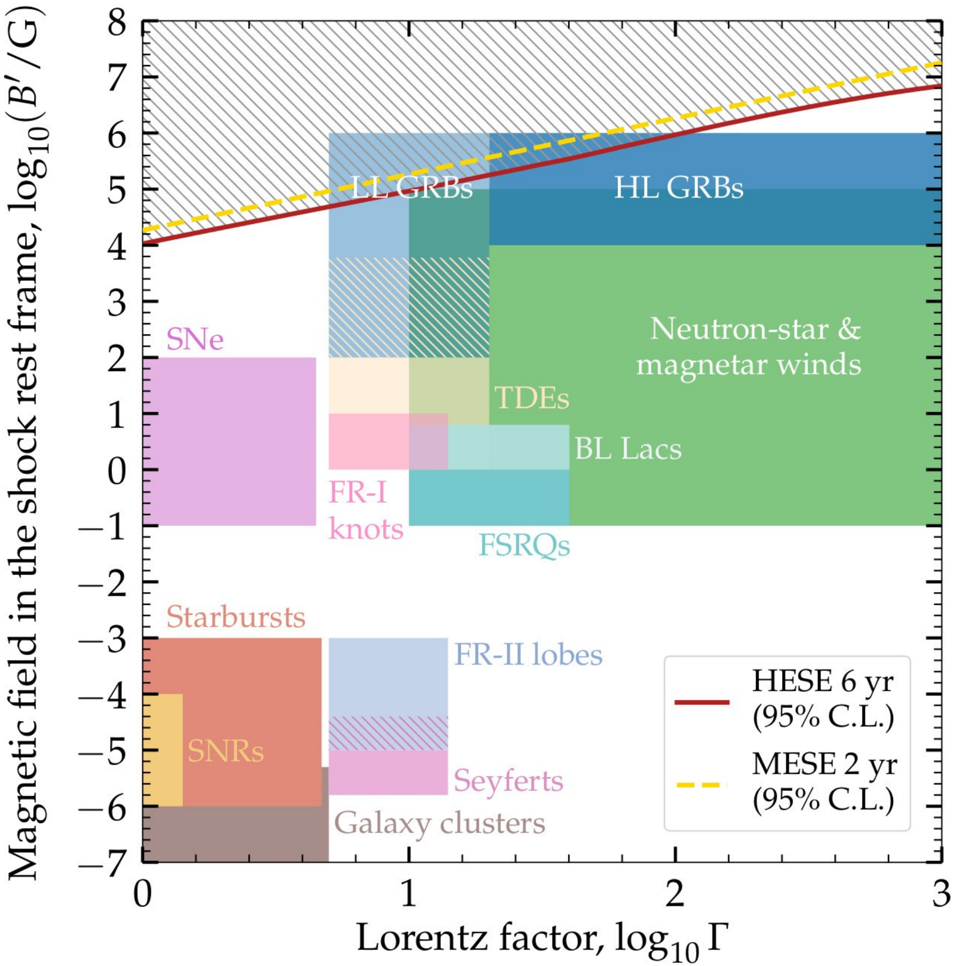
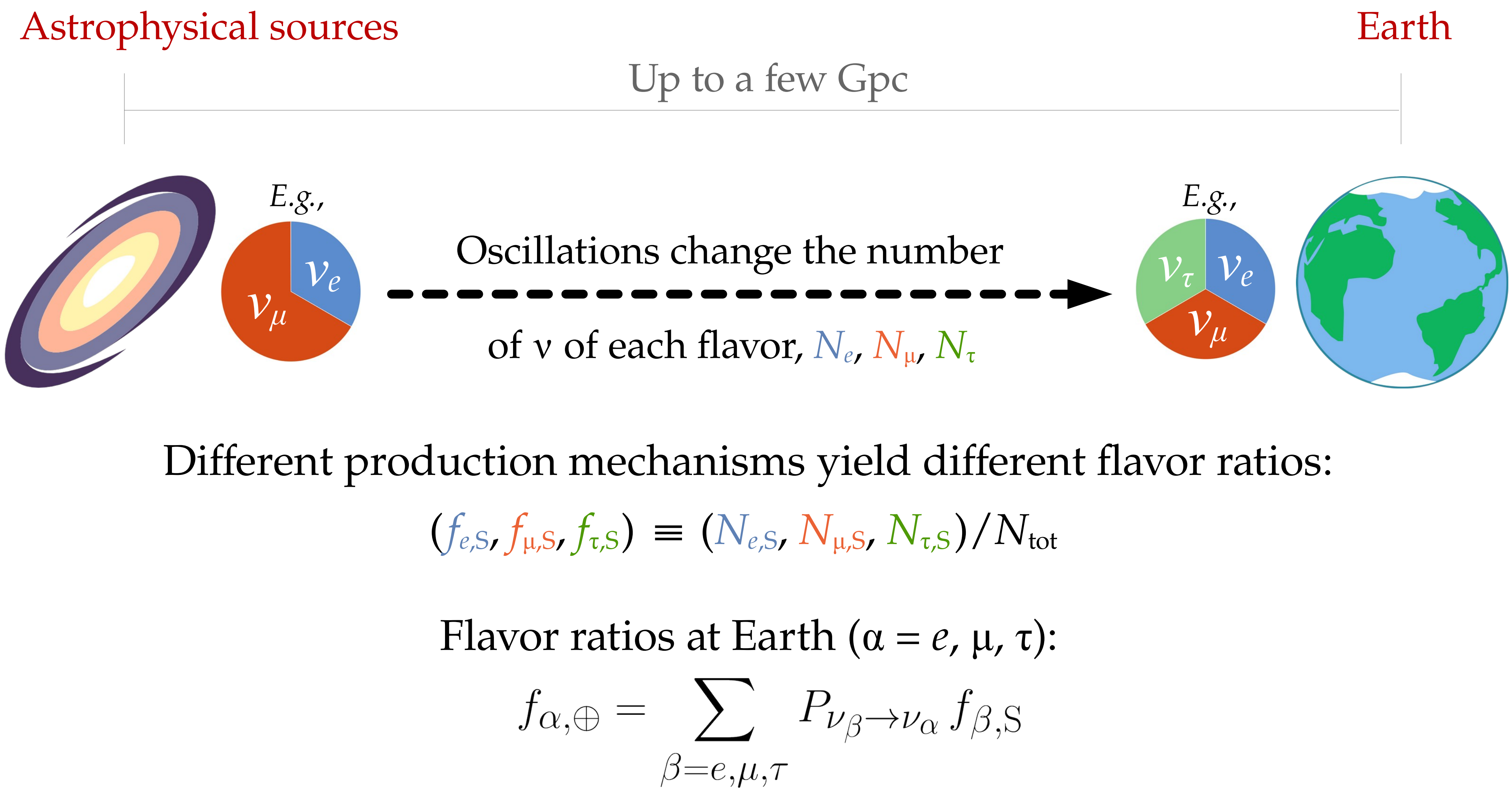


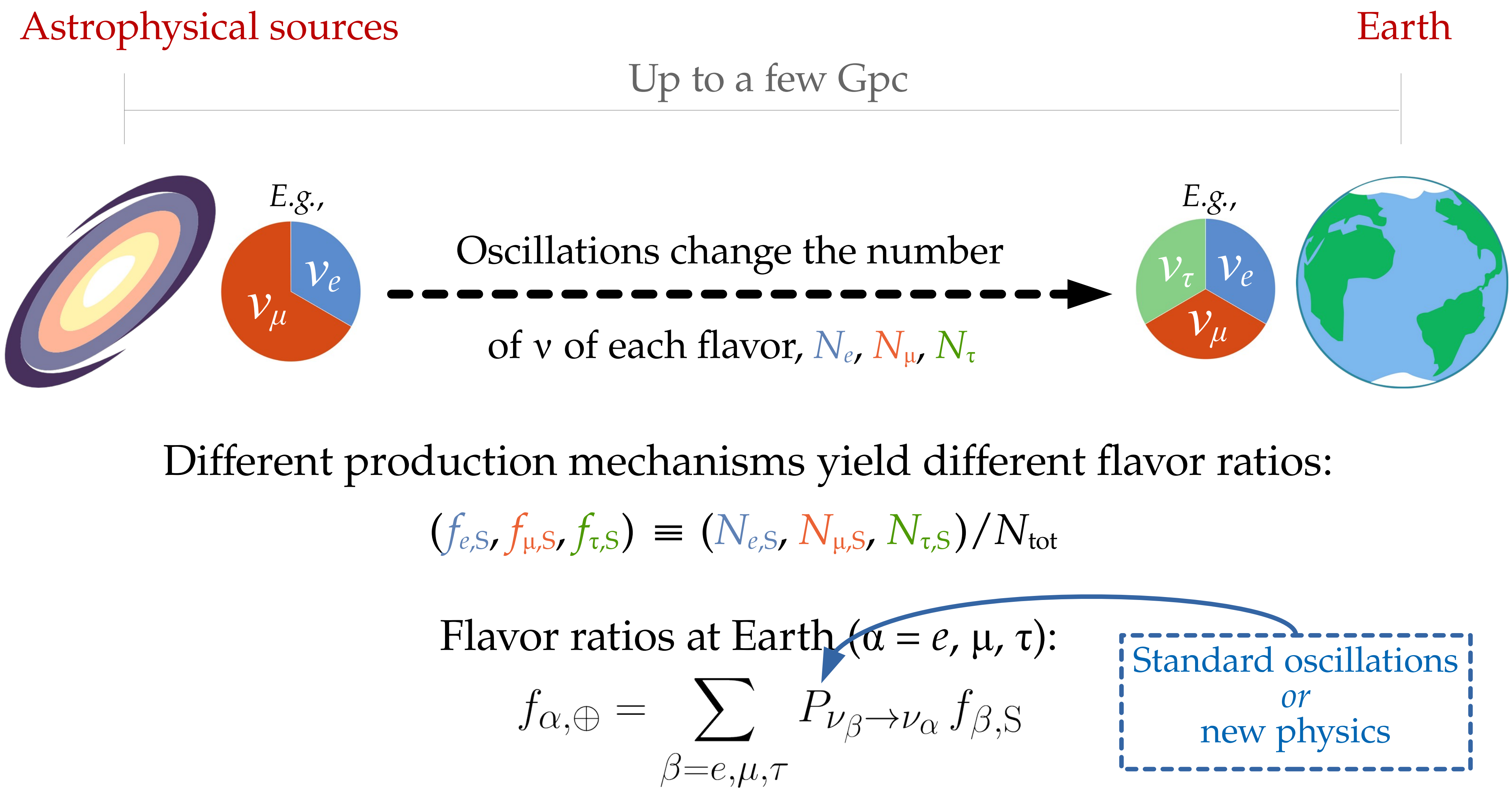
ν sources with strong B' are likely not dominant

Average B' must be < 10kG–10 MG



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


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 ($\alpha = e, \mu, \tau$):
$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,\mathrm{S}}$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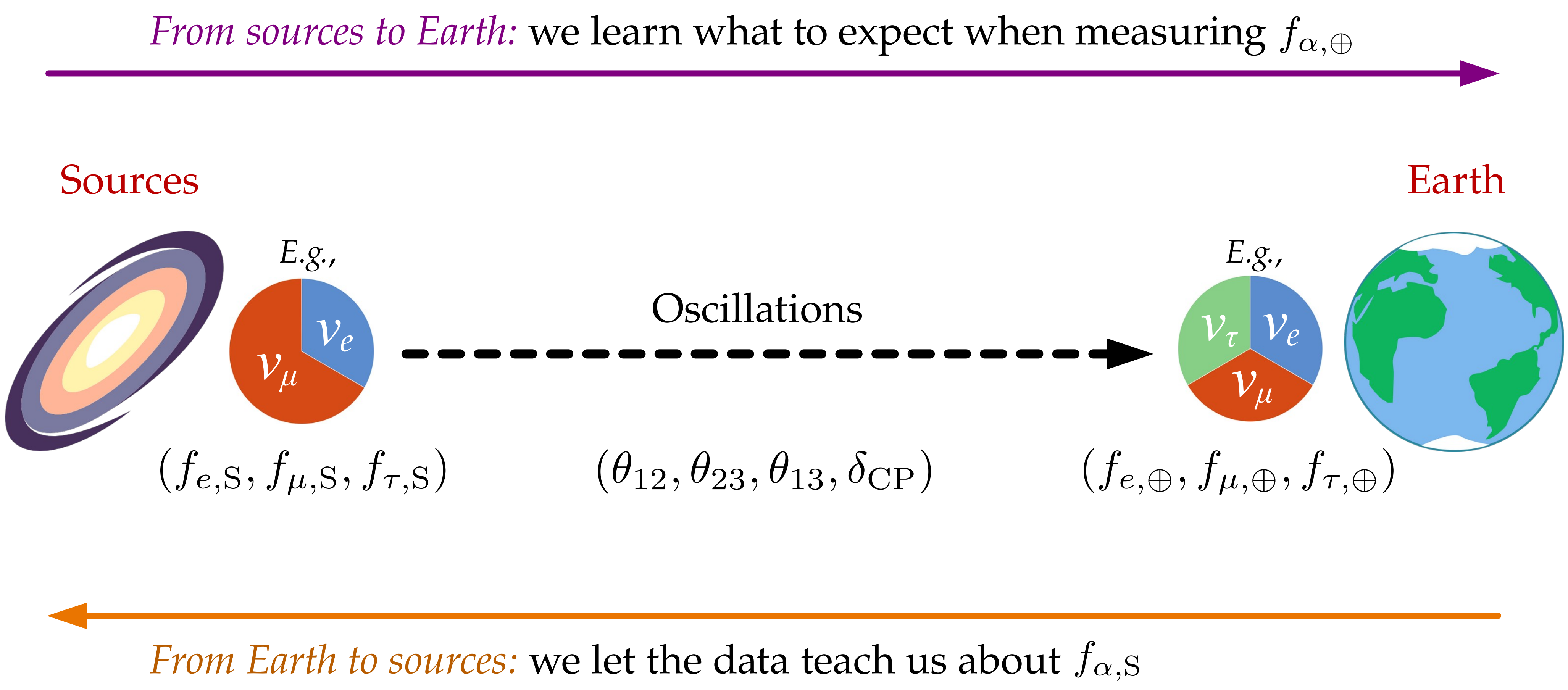
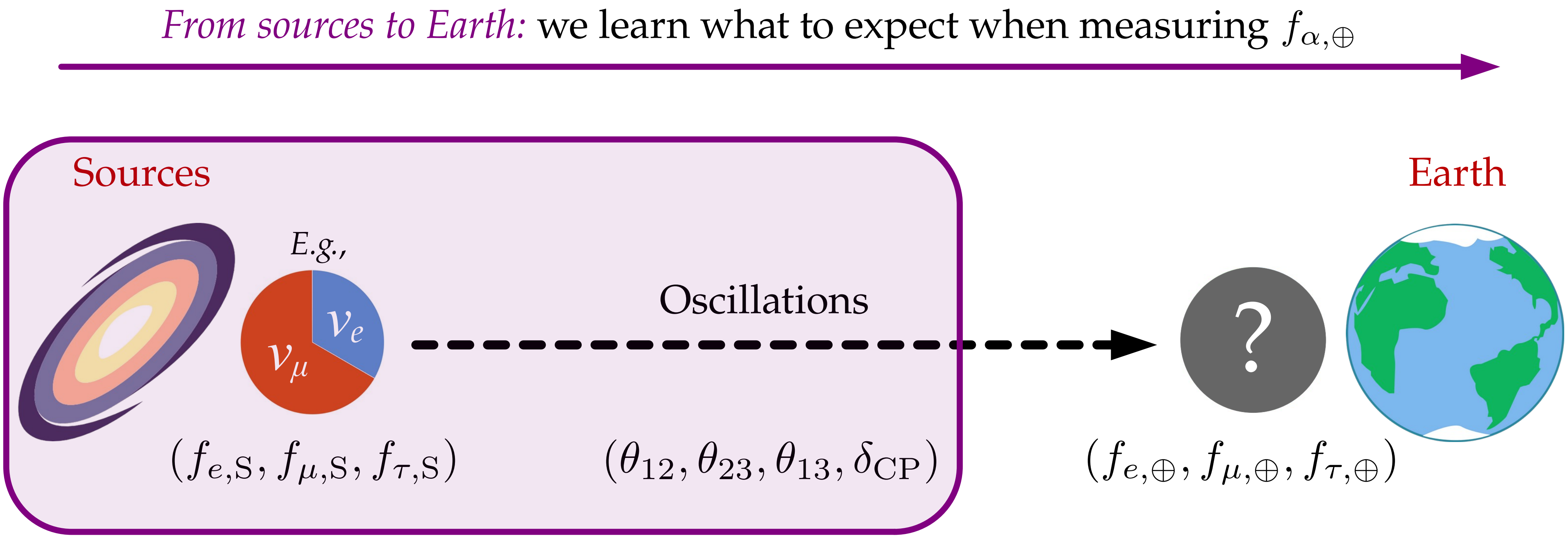
$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,S}$
Standard oscillations
or
new physics



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



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

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

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

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Ingredient #1:

Flavor ratios at the source,

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Fix at one of the benchmarks
(pion decay, muon-damped, neutron decay)

or

Explore all possible combinations

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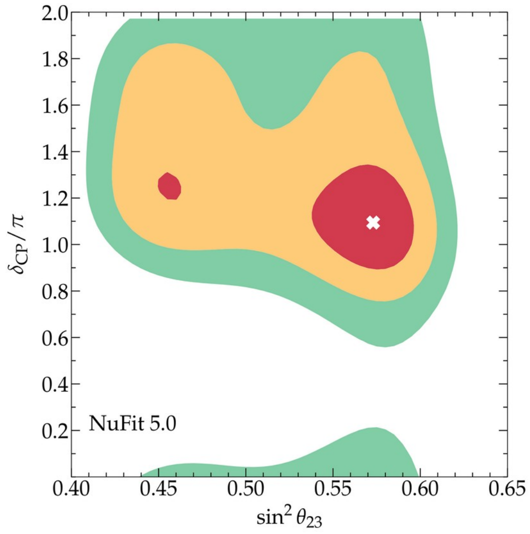
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

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



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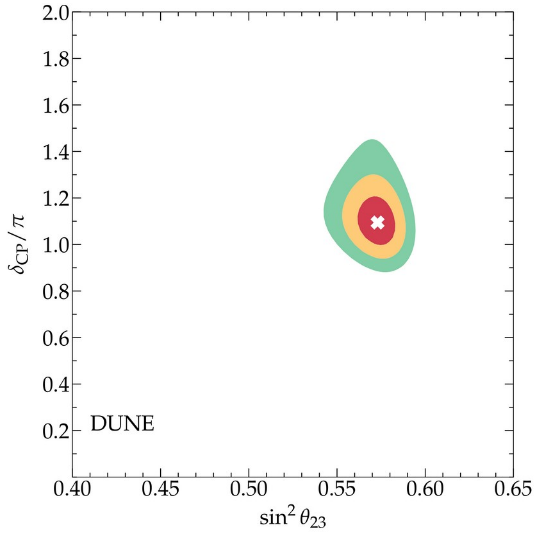
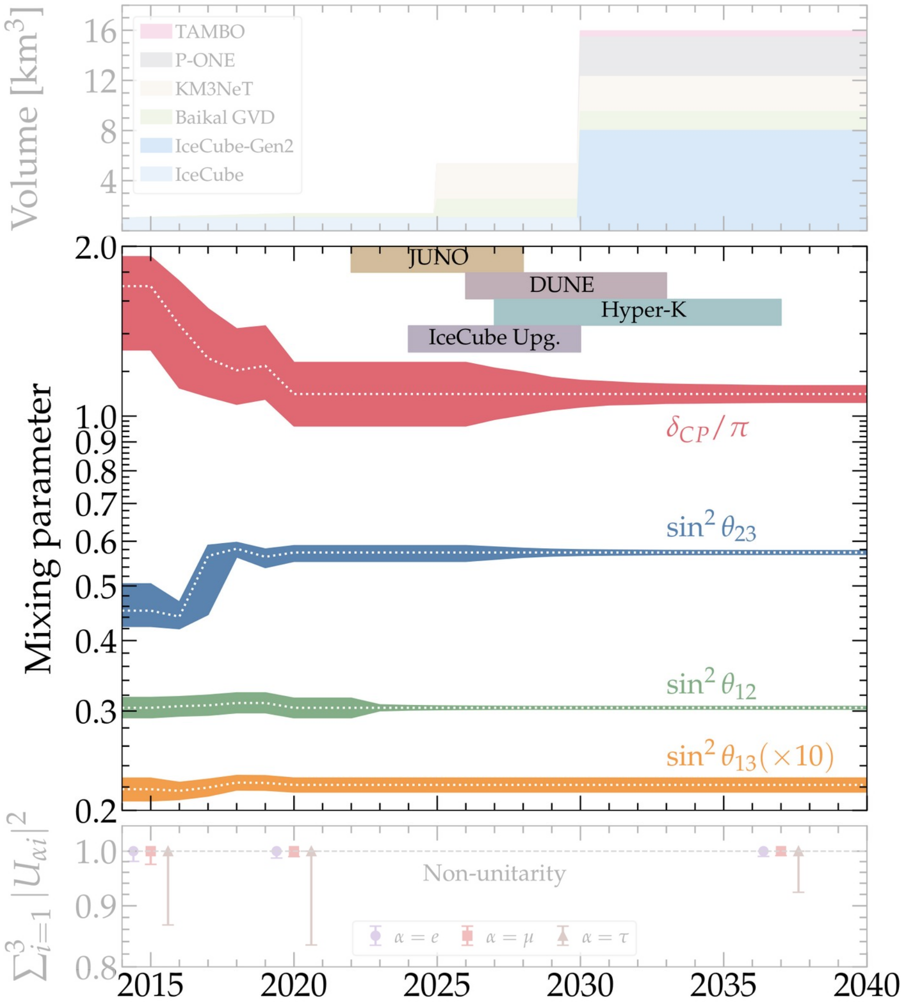
Esteban *et al.*, *JHEP* 2020
www.nu-fit.org

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



How knowing the mixing parameters better helps



For a future experiment
ε = JUNO, DUNE, Hyper-K:

Best fit from NuFit 5.0

$$\chi^2_\varepsilon(\boldsymbol{\vartheta}) = \sum_i \frac{(\vartheta_i - \bar{\vartheta}_i)^2}{\sigma^2_{i,\varepsilon}}$$

From our simulations

We combine experiments in a likelihood:

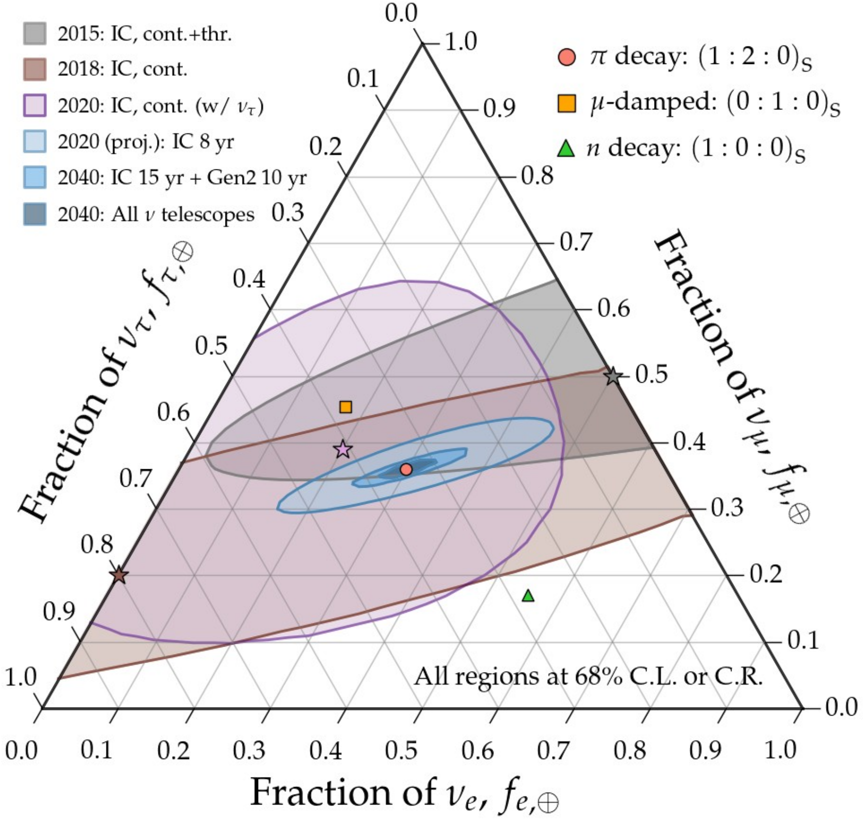
$$-2\log\mathcal{L}(\boldsymbol{\theta}) = \sum_\varepsilon \chi^2_\varepsilon(\boldsymbol{\vartheta})$$

Inferring the flavor composition at the sources

Ingredient #1:

Flavor ratios measured at Earth,

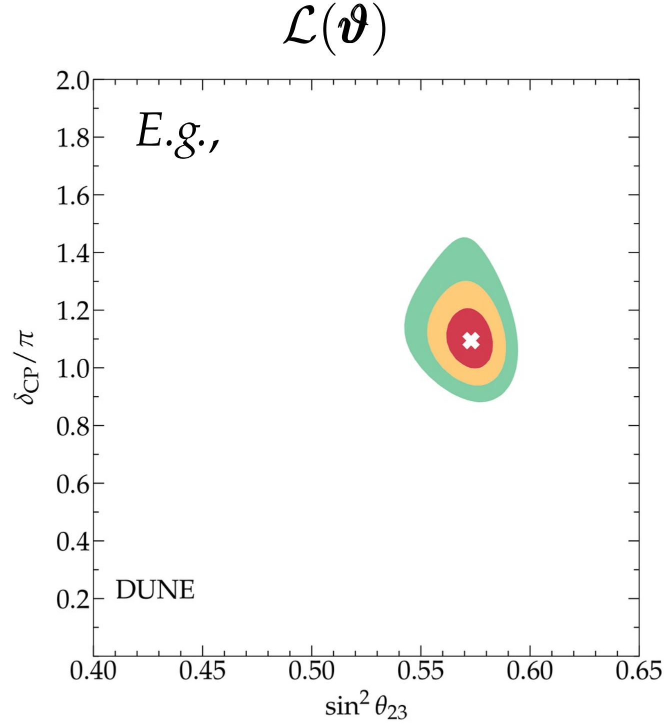
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$



Ingredient #2:

Probability density of mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$

$\mathcal{L}(\boldsymbol{\vartheta})$



Song, Li, Argüelles, **MB**, Vincent, 2012.12893
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

Ingredient #1:

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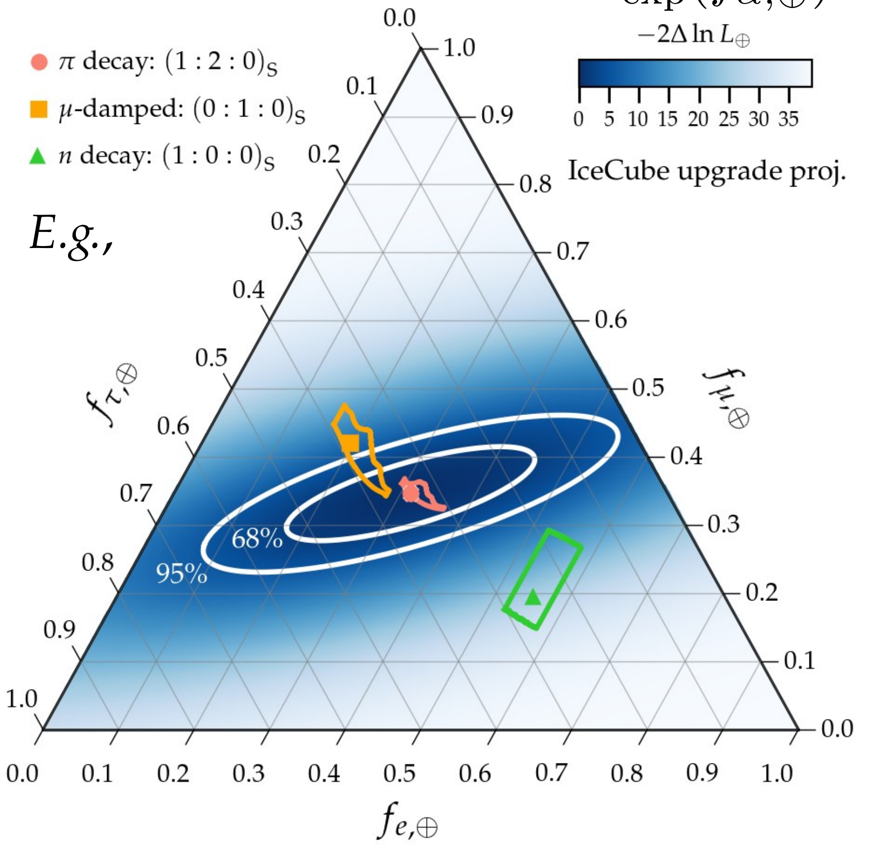
$\mathcal{P}_{\rm exp}(f_{\alpha,\oplus})$

E.g.,



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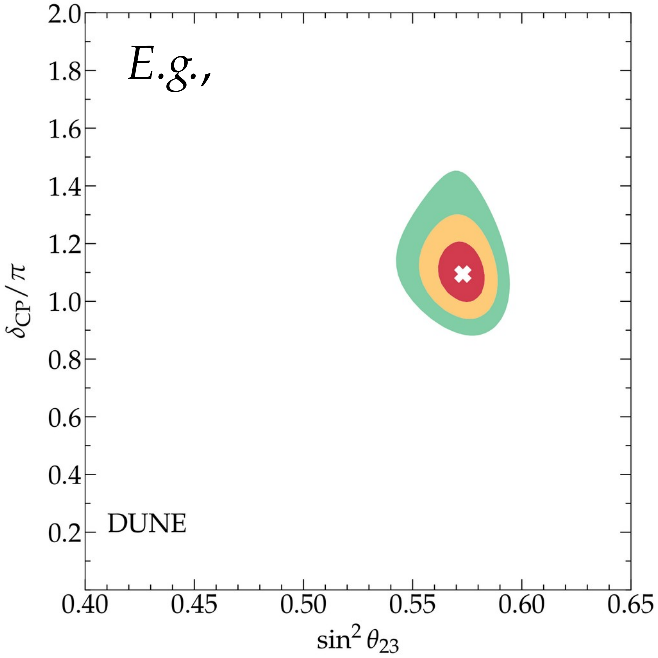

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Probability density of mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\rm CP})$

Posterior probability of $f_{\alpha,\rm S}$ [**MB** & Ahlers, *PRL* 2019]:

$$\mathcal{P}(\boldsymbol{f}_s) = \int d\boldsymbol{\vartheta} \mathcal{L}(\boldsymbol{\vartheta}) \mathcal{P}_{\rm exp}(\boldsymbol{f}_\oplus(\boldsymbol{f}_{\rm S}, \boldsymbol{\vartheta}))$$

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Song, Li, Argüelles, **MB**, Vincent, 2012.12893
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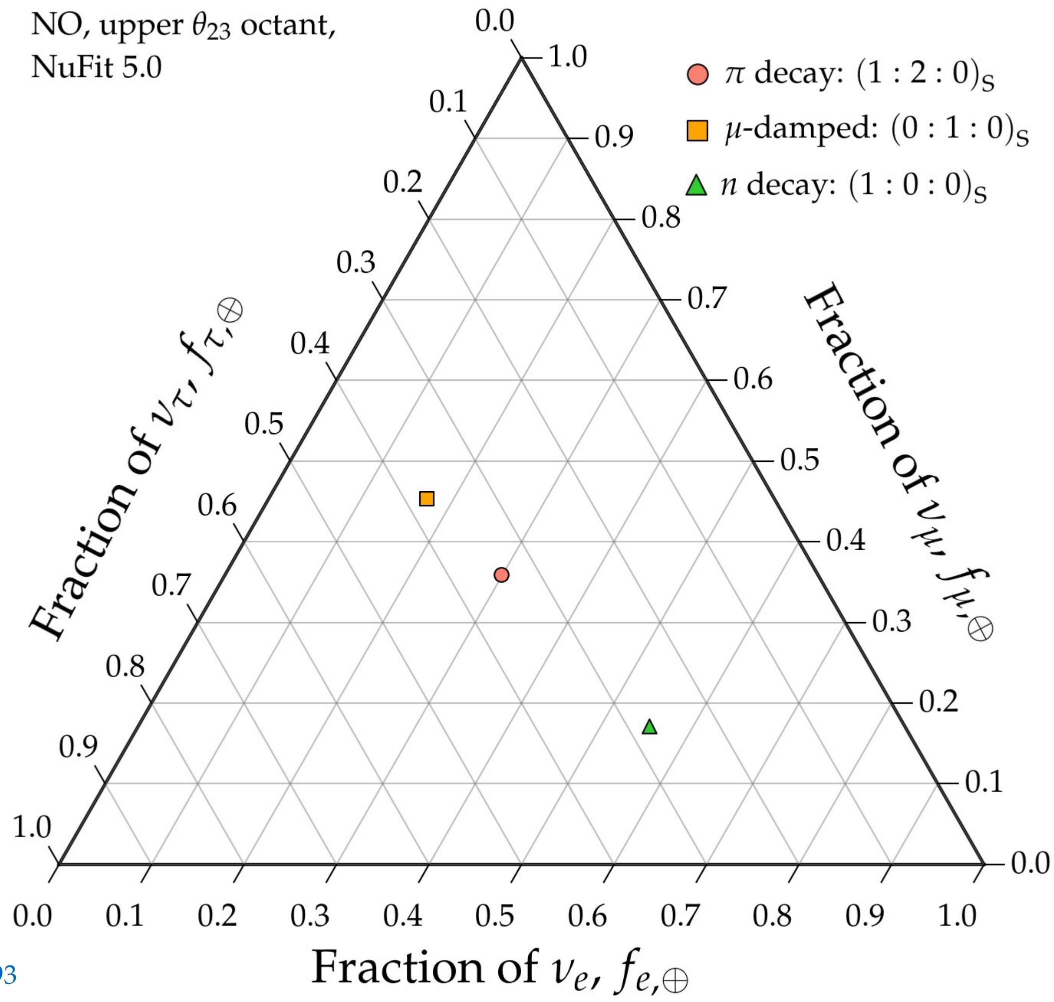
Oscillation experiments   Neutrino telescopes

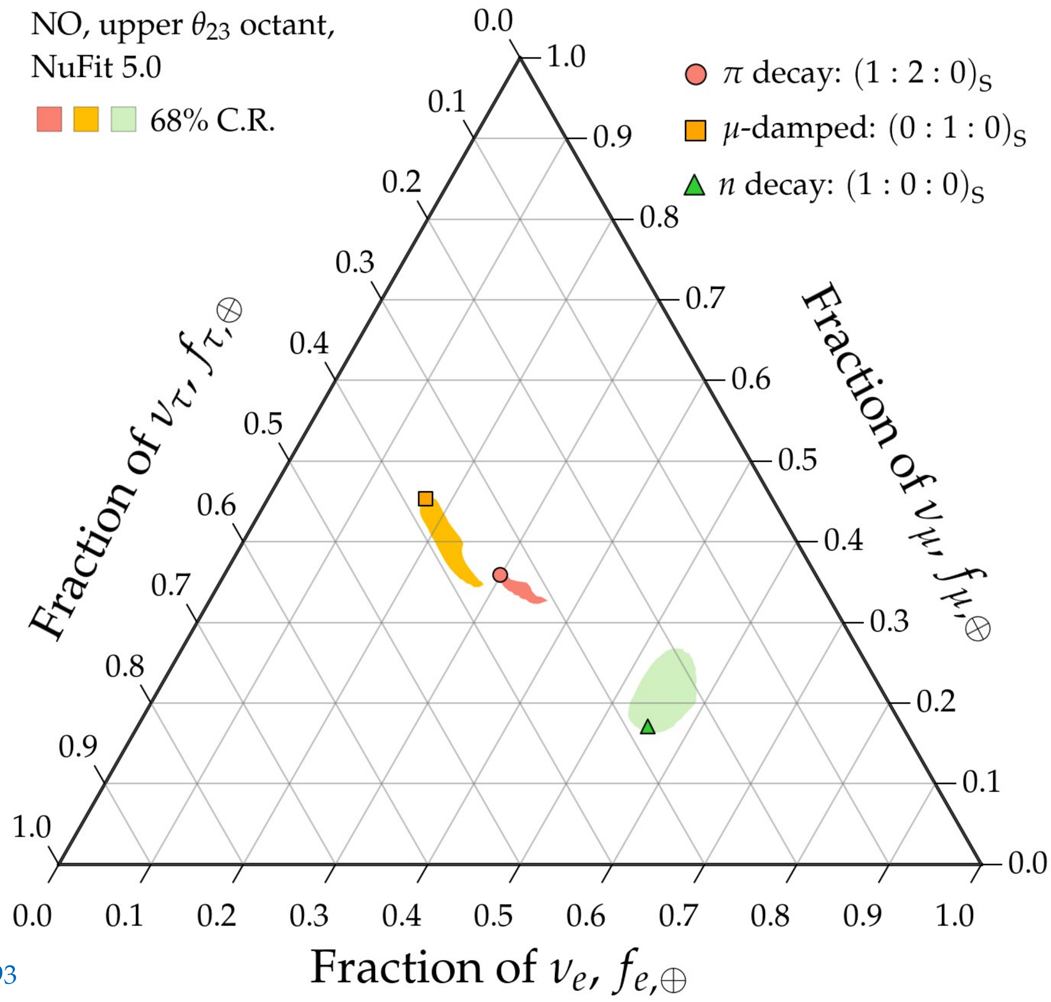
Theoretically palatable regions: today (2020)



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

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
See also: **MB**, Beacom, Winter, *PRL* 2015

Theoretically palatable regions: today (2020)



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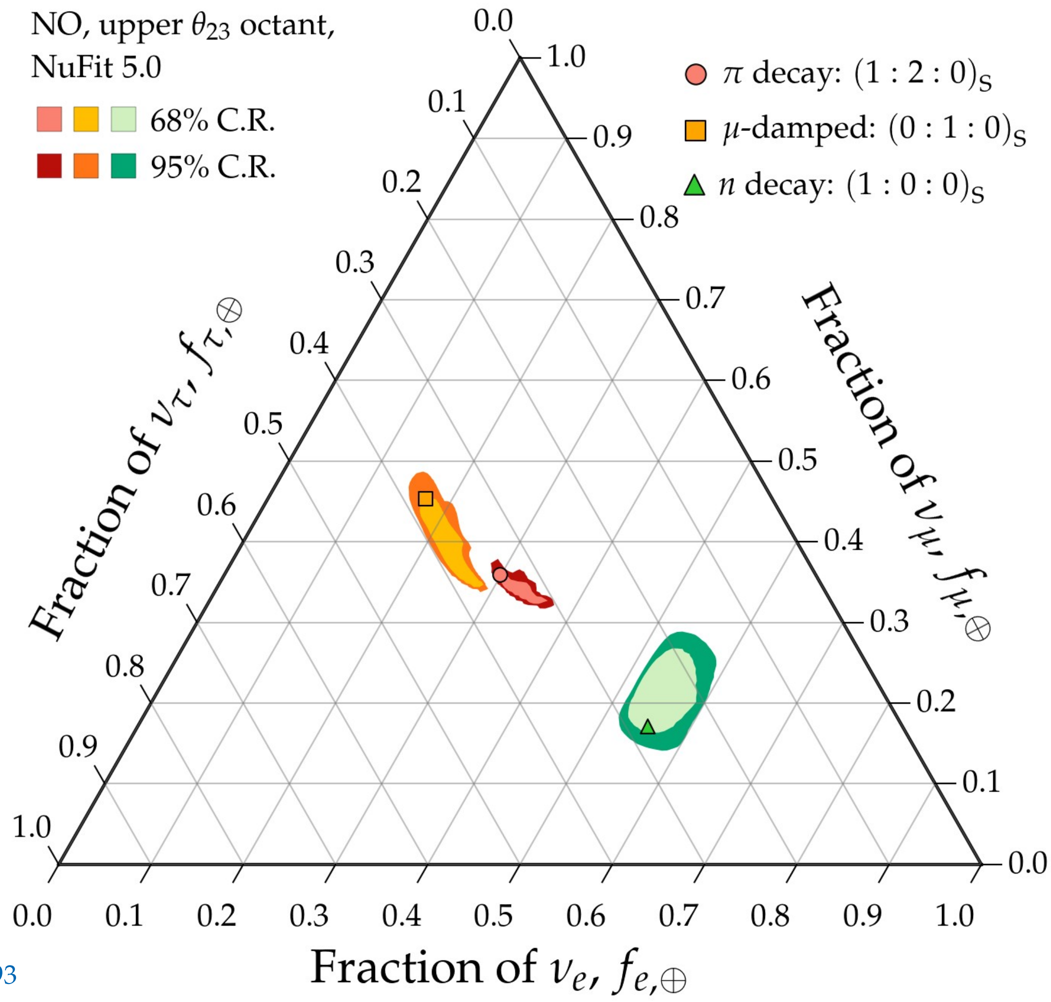

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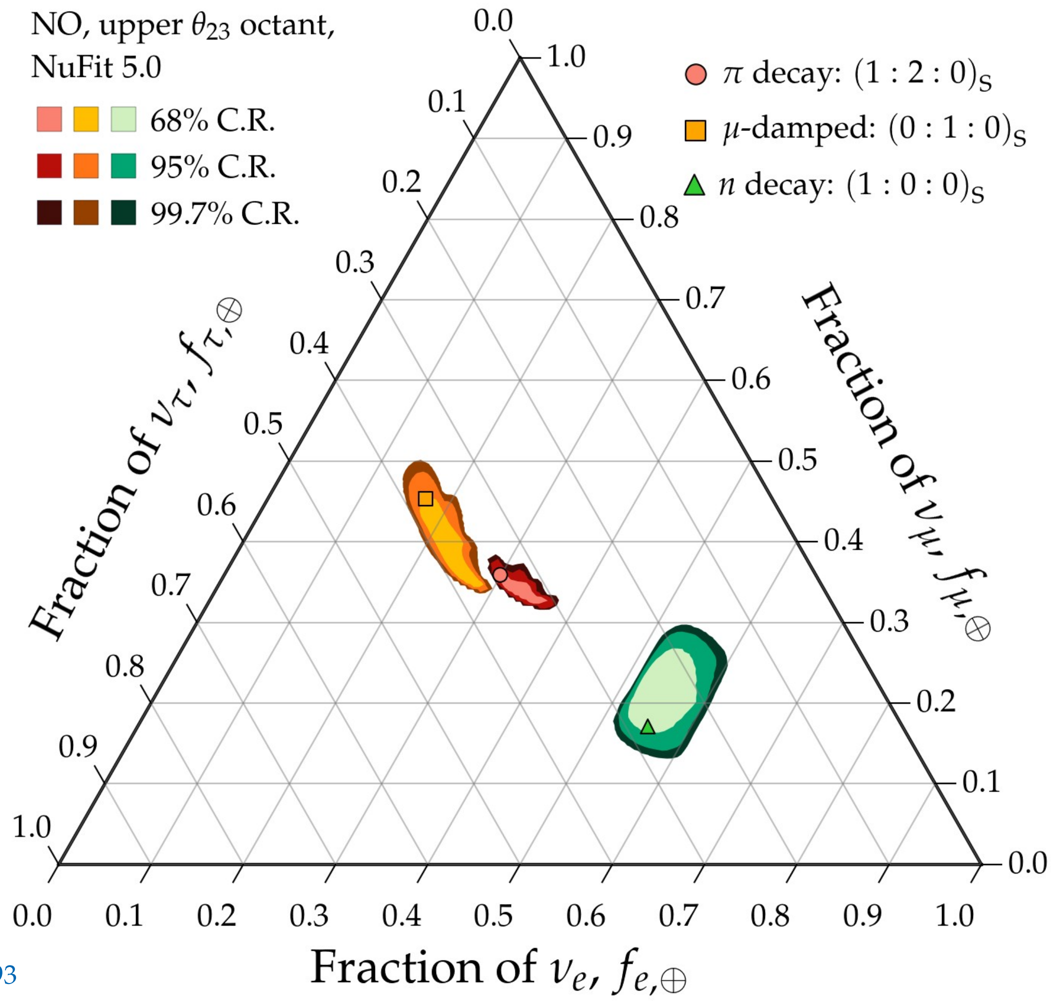

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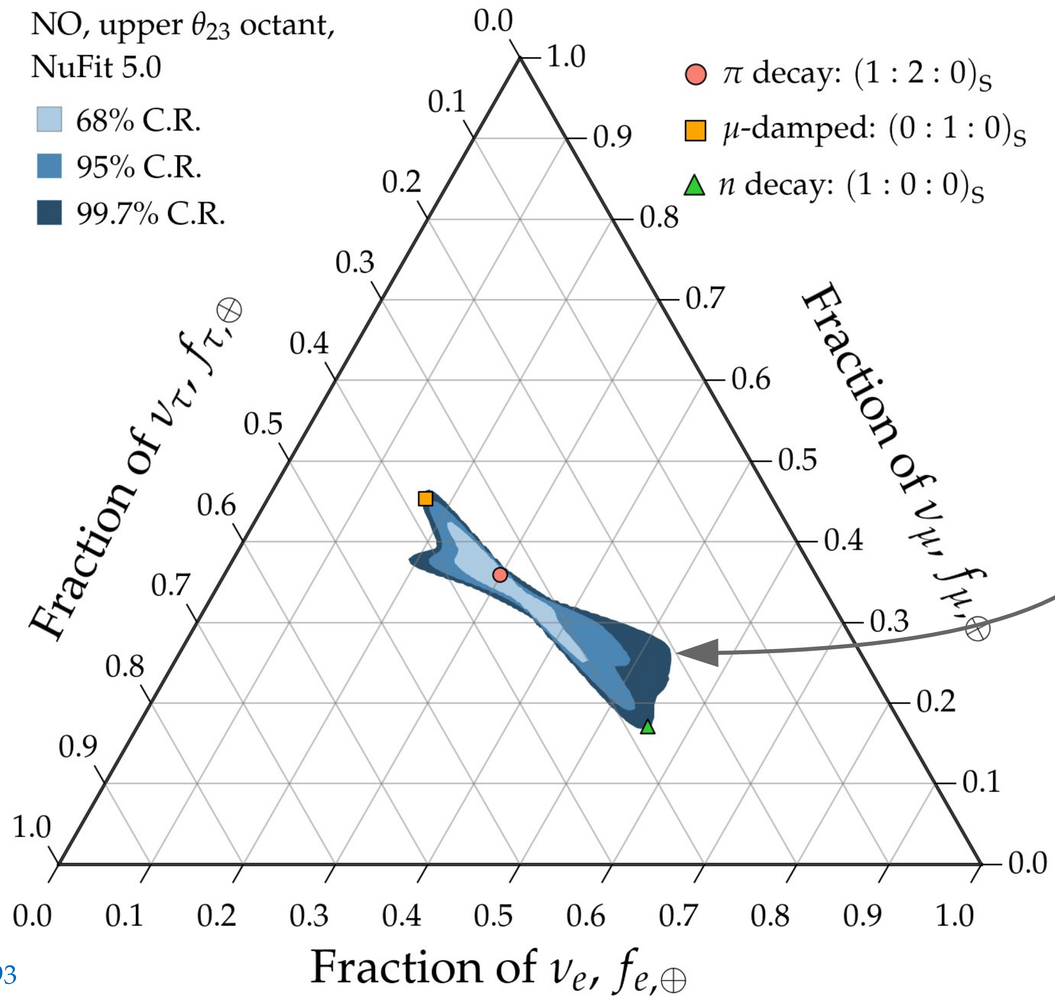

Varying over all possible flavor ratios at the source

Note:
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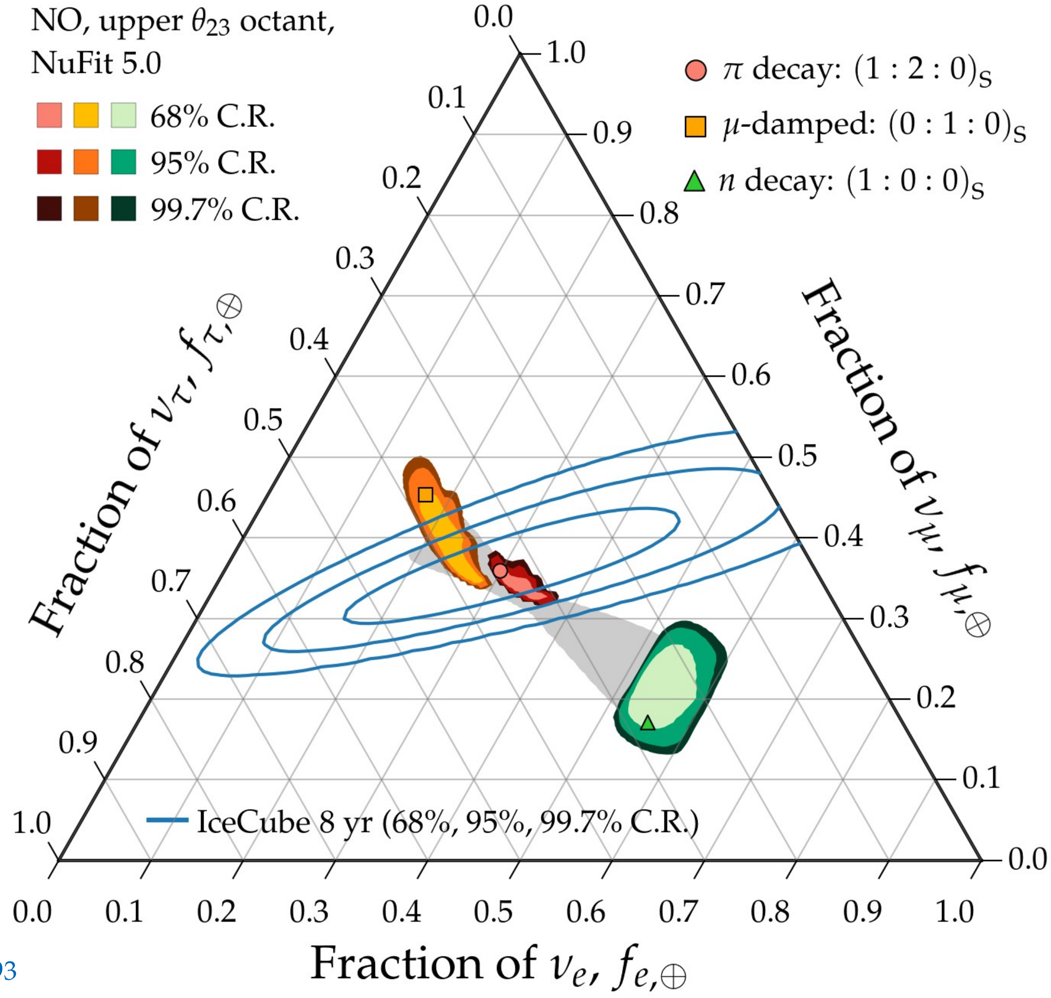
Song, Li, Argüelles, **MB**, Vincent, 2012.12893
See also: **MB**, Beacom, Winter, *PRL* 2015

Theoretically palatable regions: today (2020)



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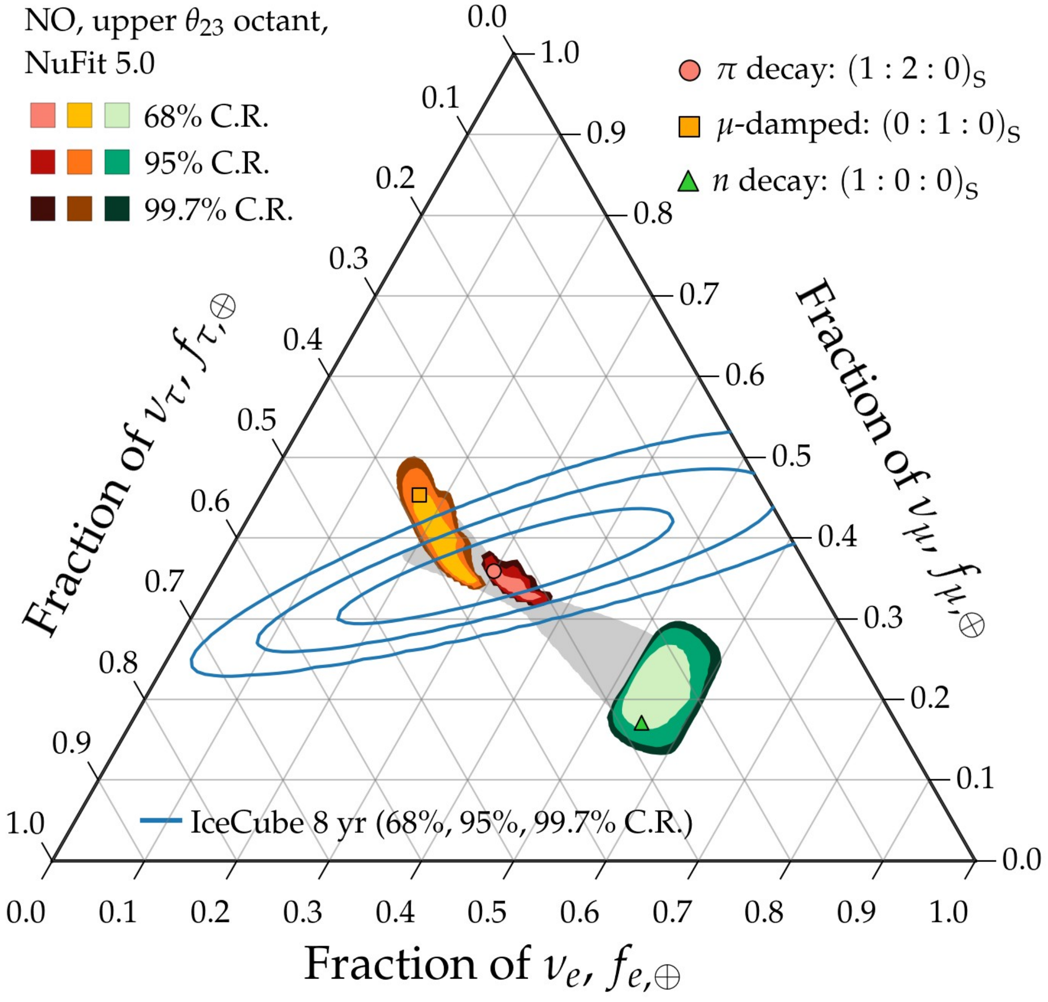
Theoretically palatable regions: today (2020)



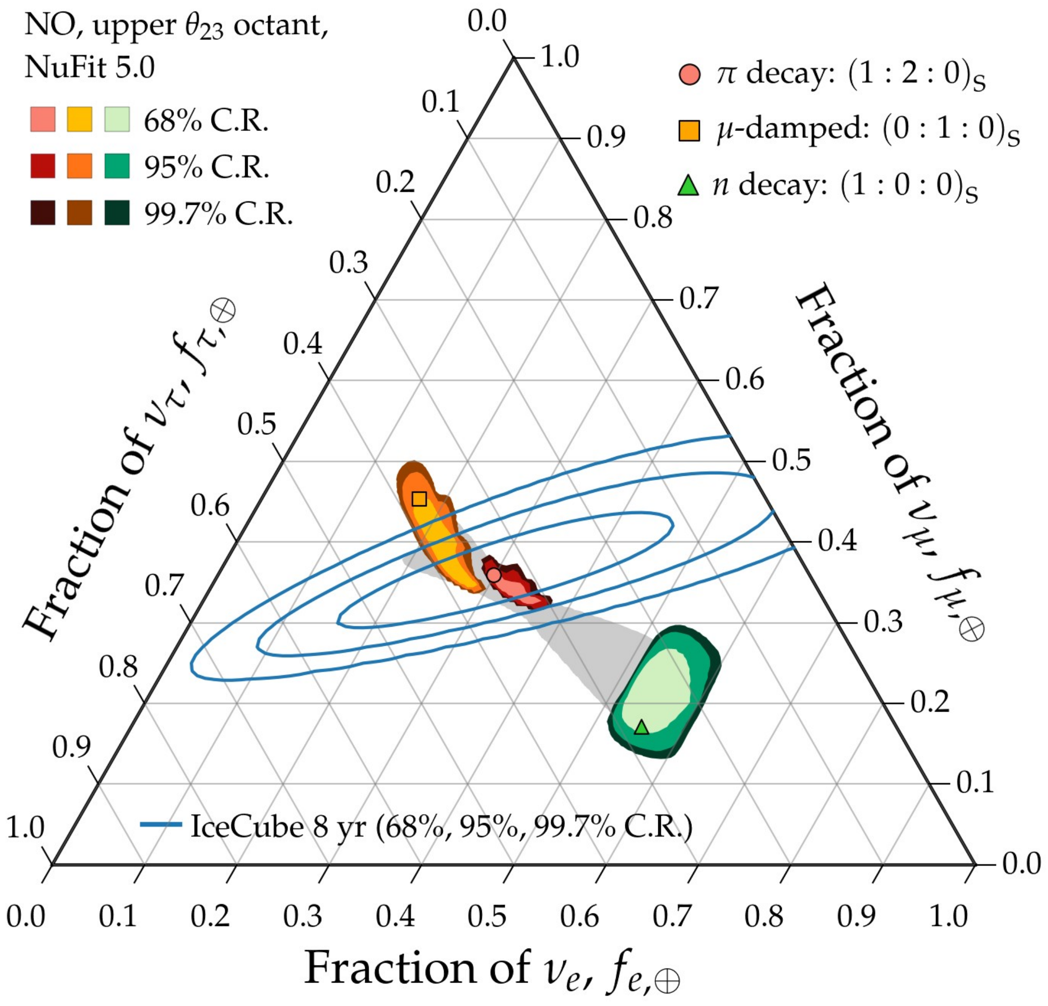
Two limitations:

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, 2012.12893
See also: **MB**, Beacom, Winter, *PRL* 2015

Theoretically palatable regions: today (2020)



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)

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See also: **MB**, Beacom, Winter, *PRL* 2015

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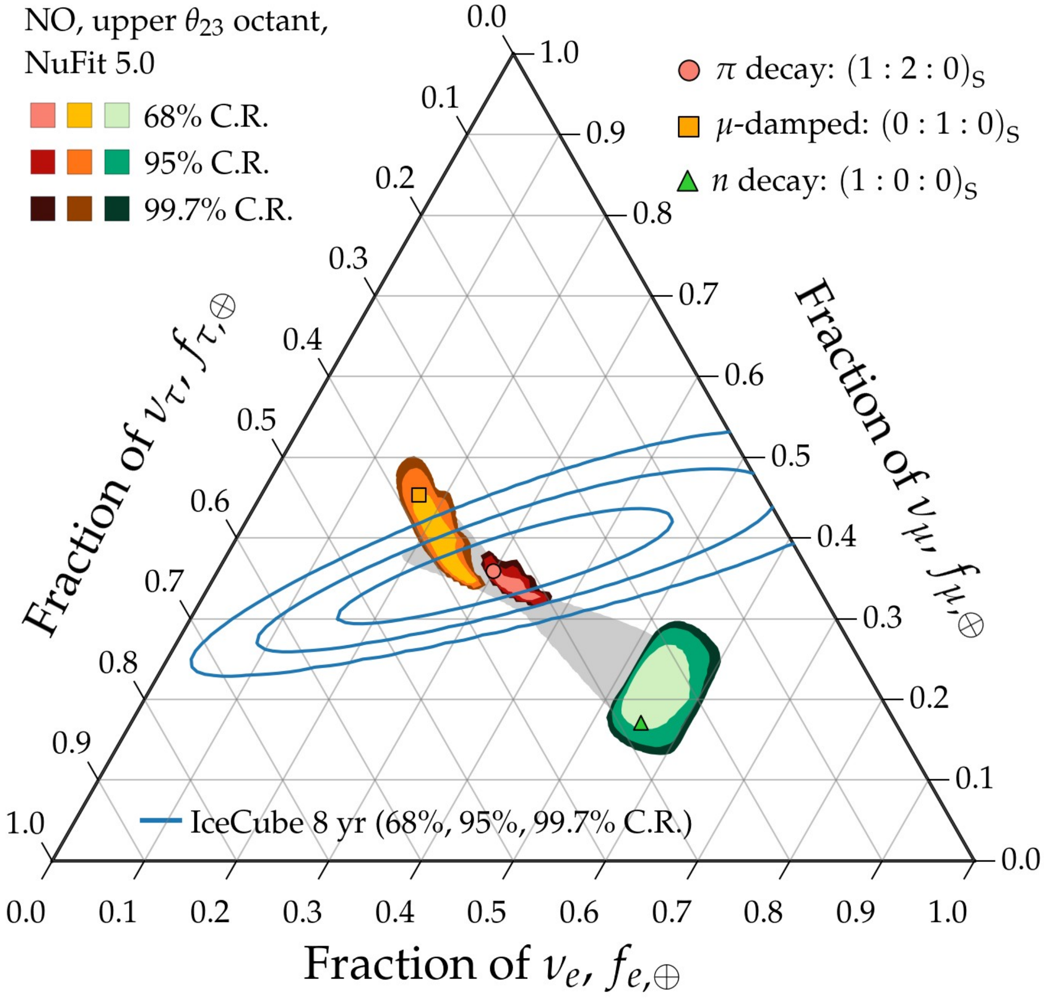

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Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

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, 2012.12893
See also: **MB**, Beacom, Winter, *PRL* 2015

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

Flavor at the Earth: *theoretically palatable regions*

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Allowed regions of flavor ratios at Earth derived from oscillations

Ingredient #1:

Flavor ratios at the source,

$(f_{e,S}, f_{\mu,S}, f_{\tau,S})$

Fix at one of the benchmarks
(pion decay, muon-damped, neutron decay)

or

Explore all possible combinations

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Theoretically palatable flavor regions

$\equiv$

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Explore all possible combinations

Ingredient #2:
Probability density of mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$

Note:
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Theoretically palatable flavor regions

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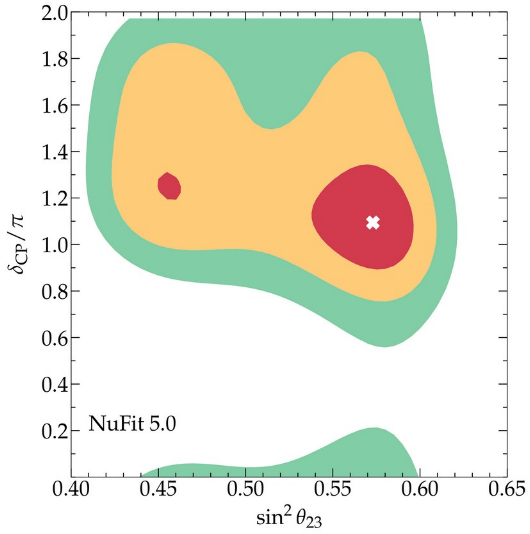
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

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



Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

$\equiv$

MB, Beacom, Winter, *PRL* 2015

Allowed regions of flavor ratios at Earth derived from oscillations

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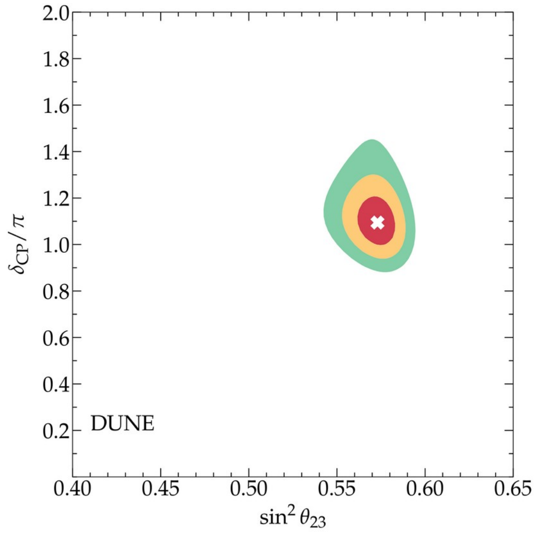
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

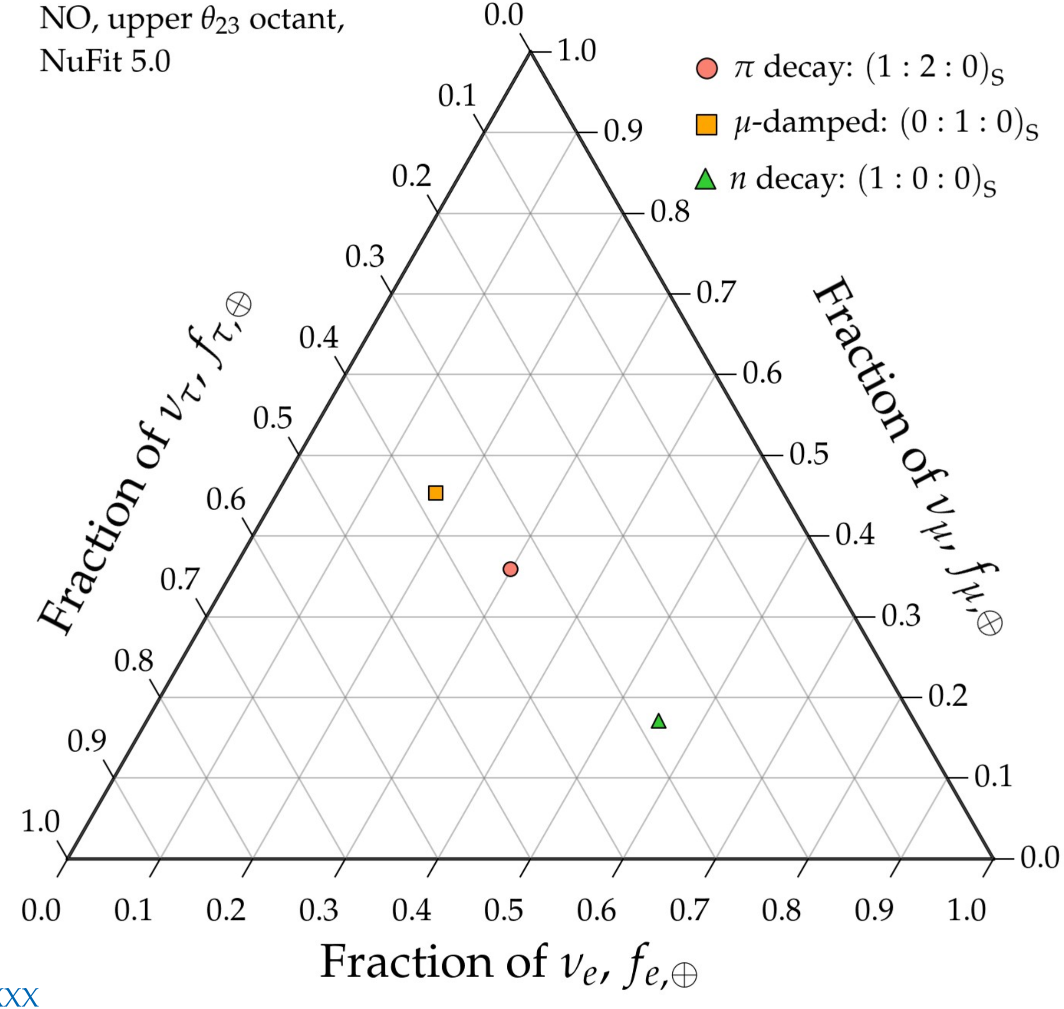
Esteban *et al.*, *JHEP* 2020
www.nu-fit.org

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



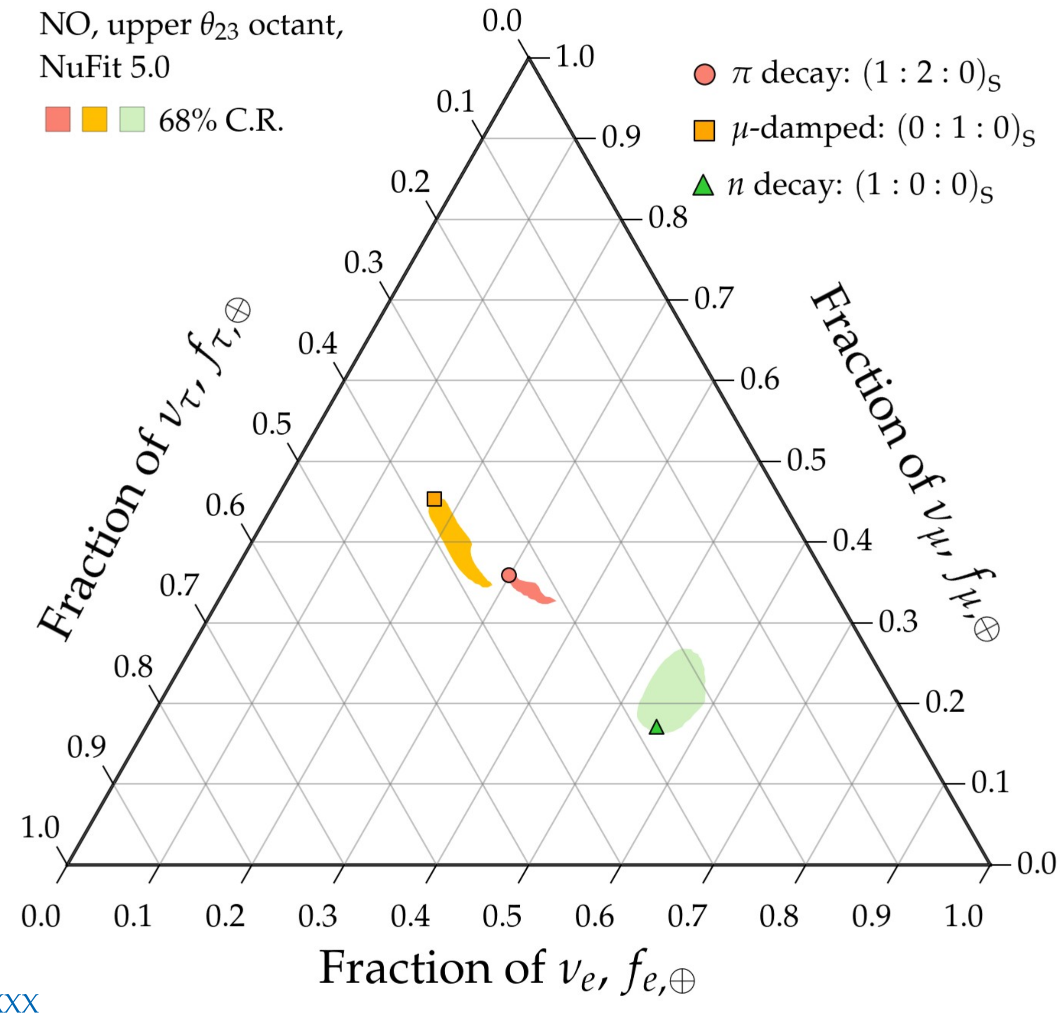
Theoretically palatable regions: today (2020)



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

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: today (2020)



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Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

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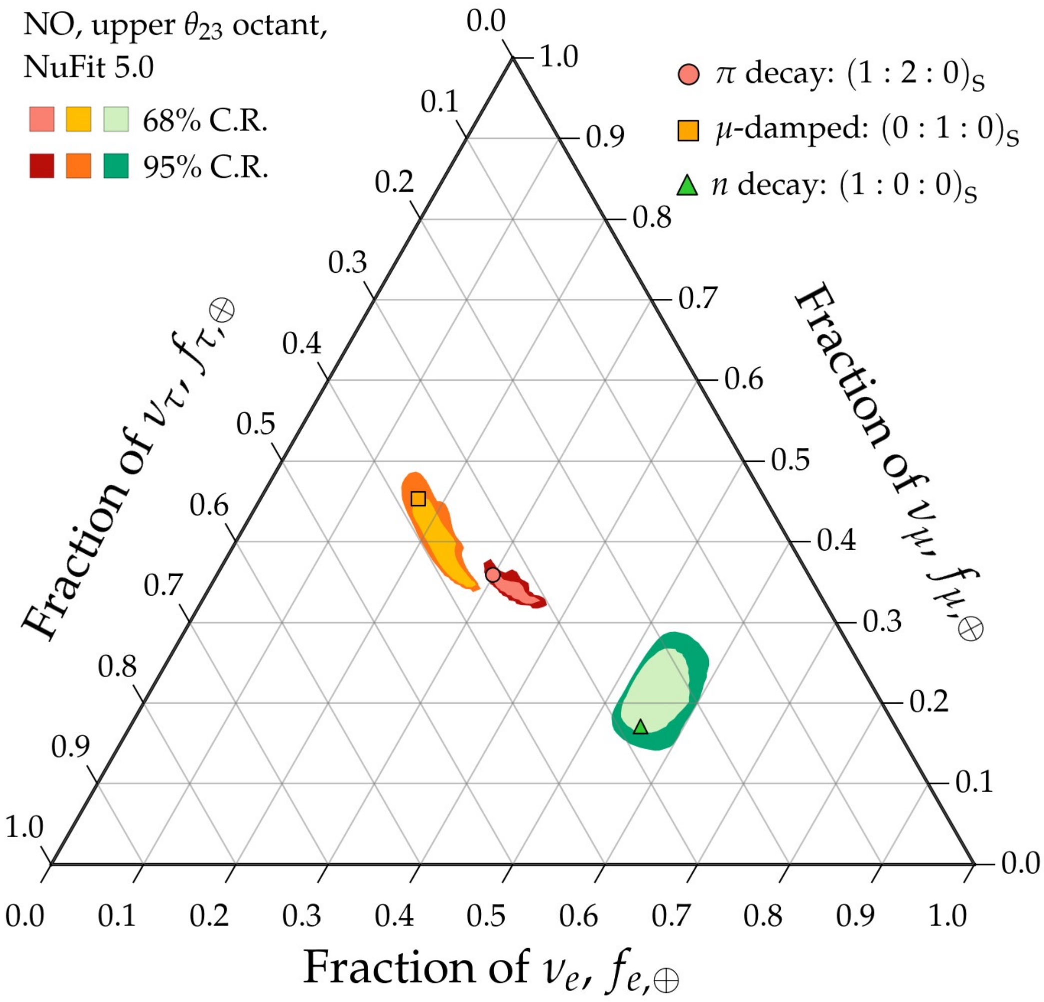

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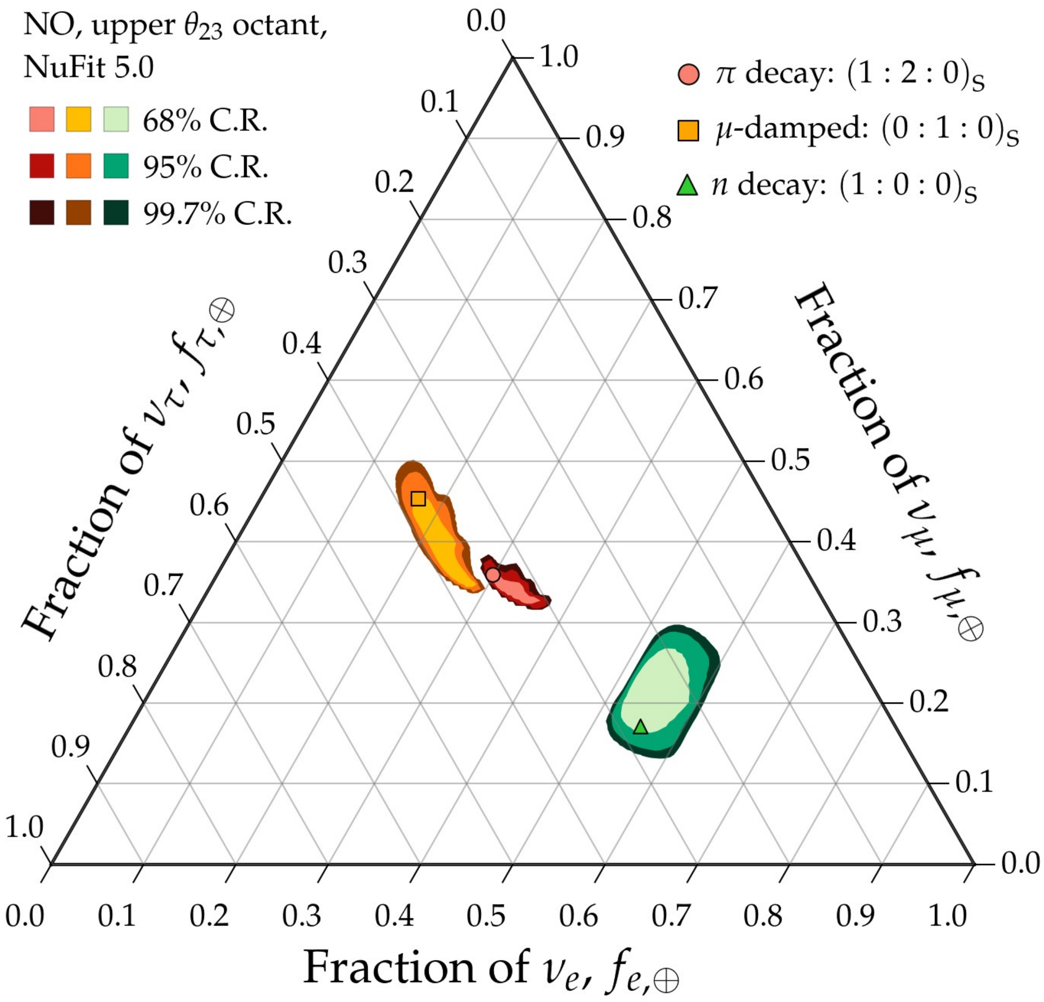

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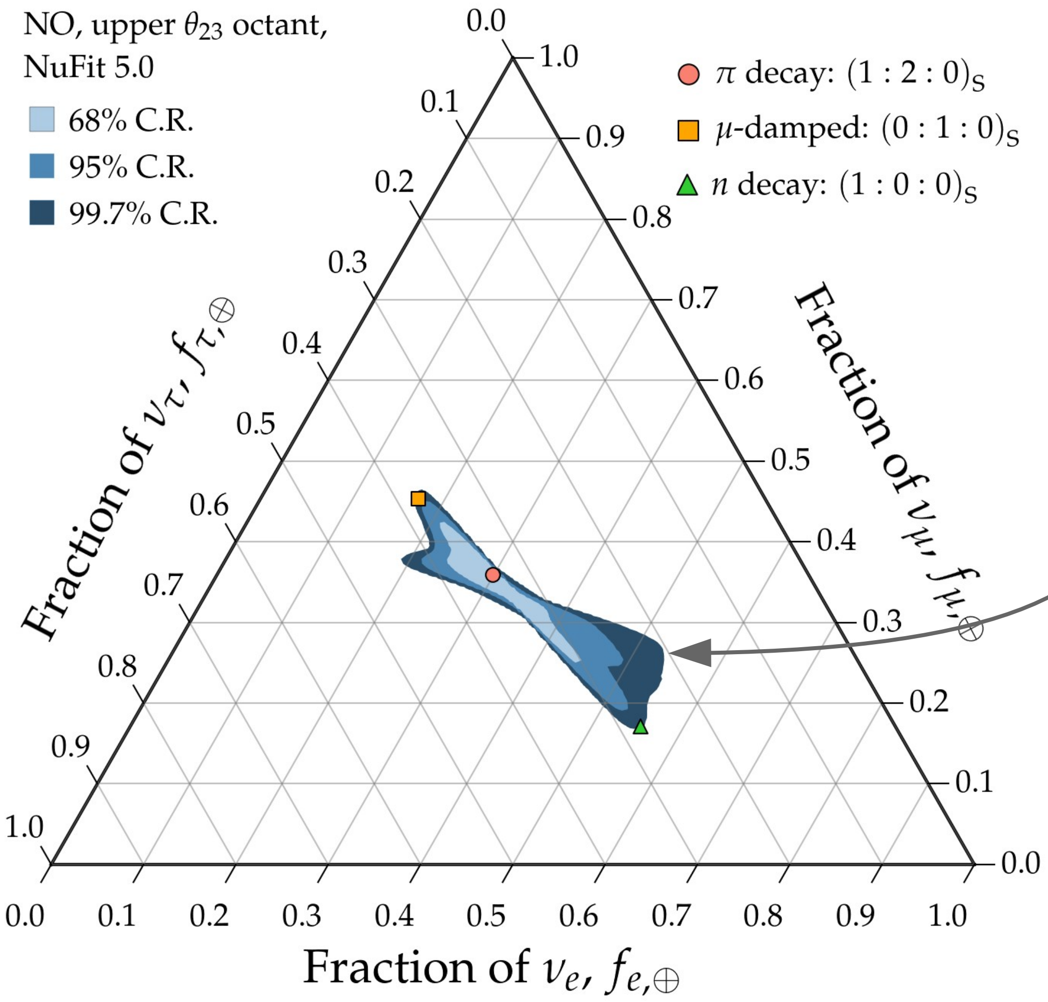
Song, Li, **MB**, Argüelles, Vincent, 2012.X

Theoretically palatable regions: today (2020)

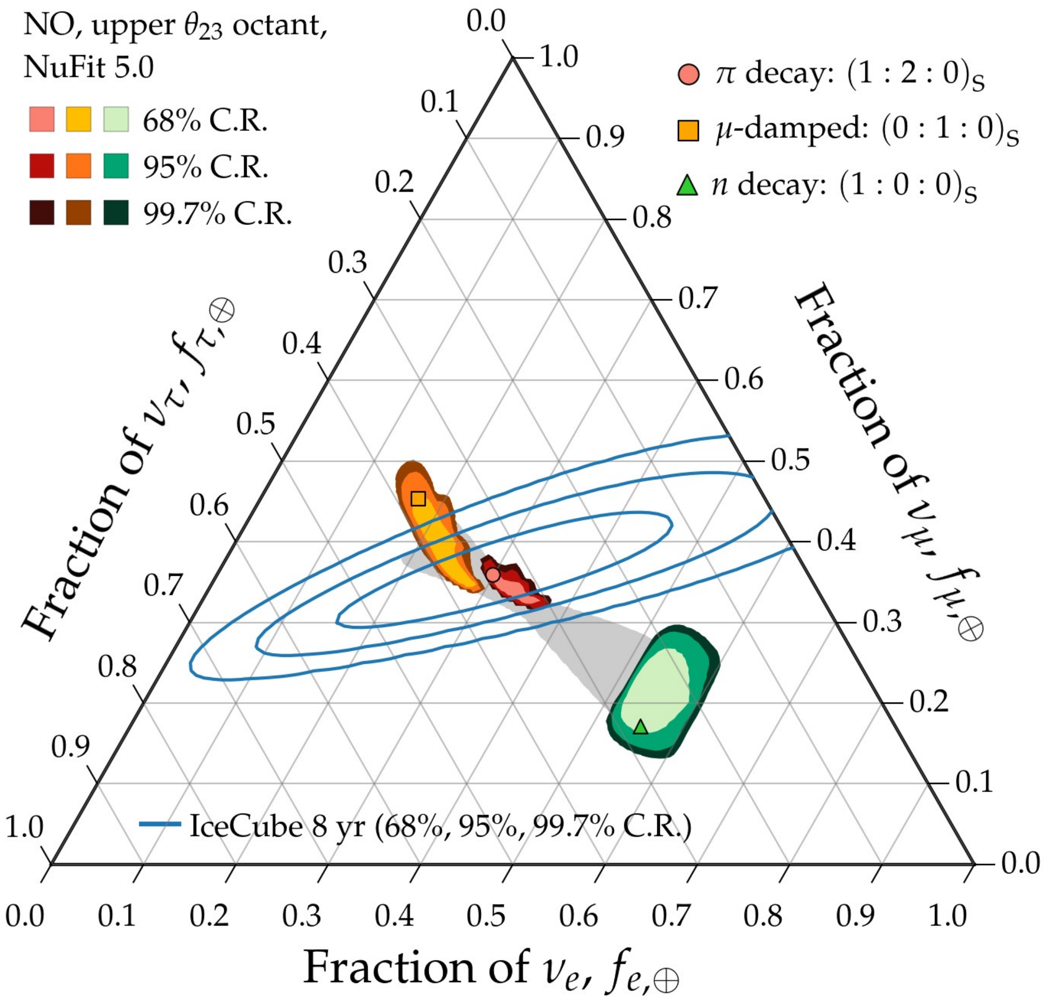


Varying over all possible flavor ratios at the source

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

Song, Li, **MB**, Argüelles, Vincent, 2012.X

Theoretically palatable regions: today (2020)



Note:
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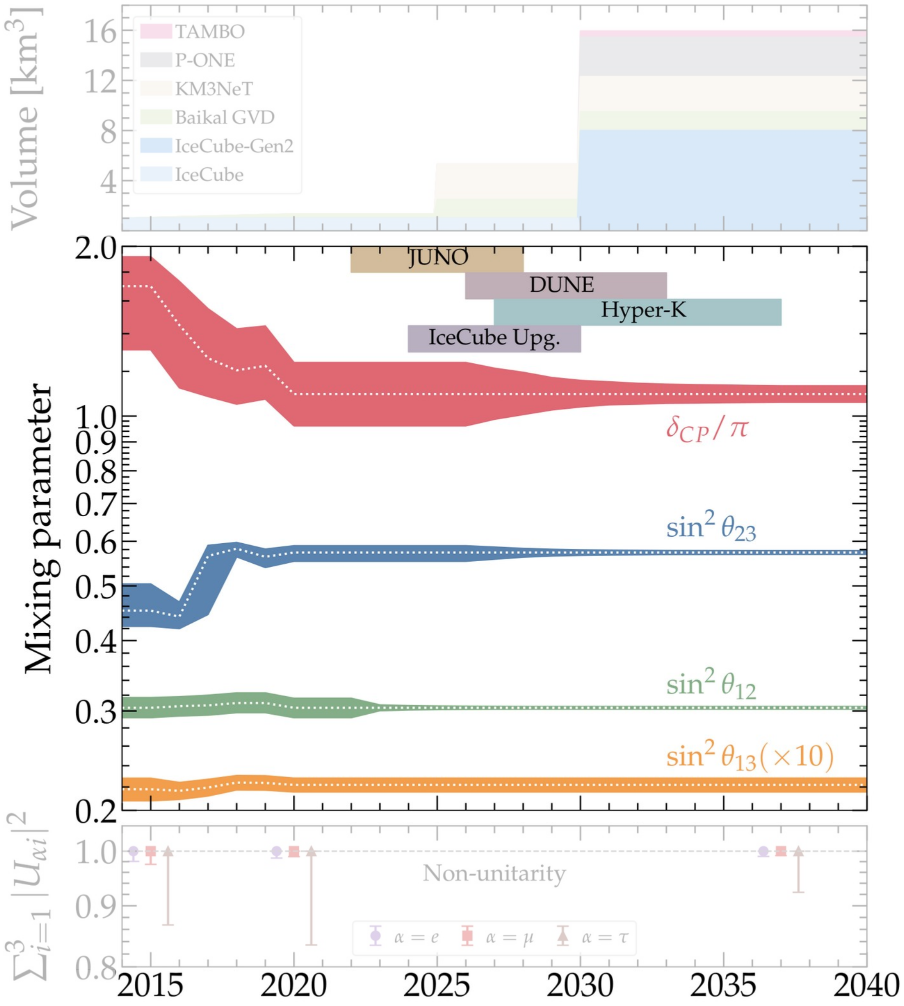
Song, Li, **MB**, Argüelles, Vincent, 2012.X

How knowing the mixing parameters better helps

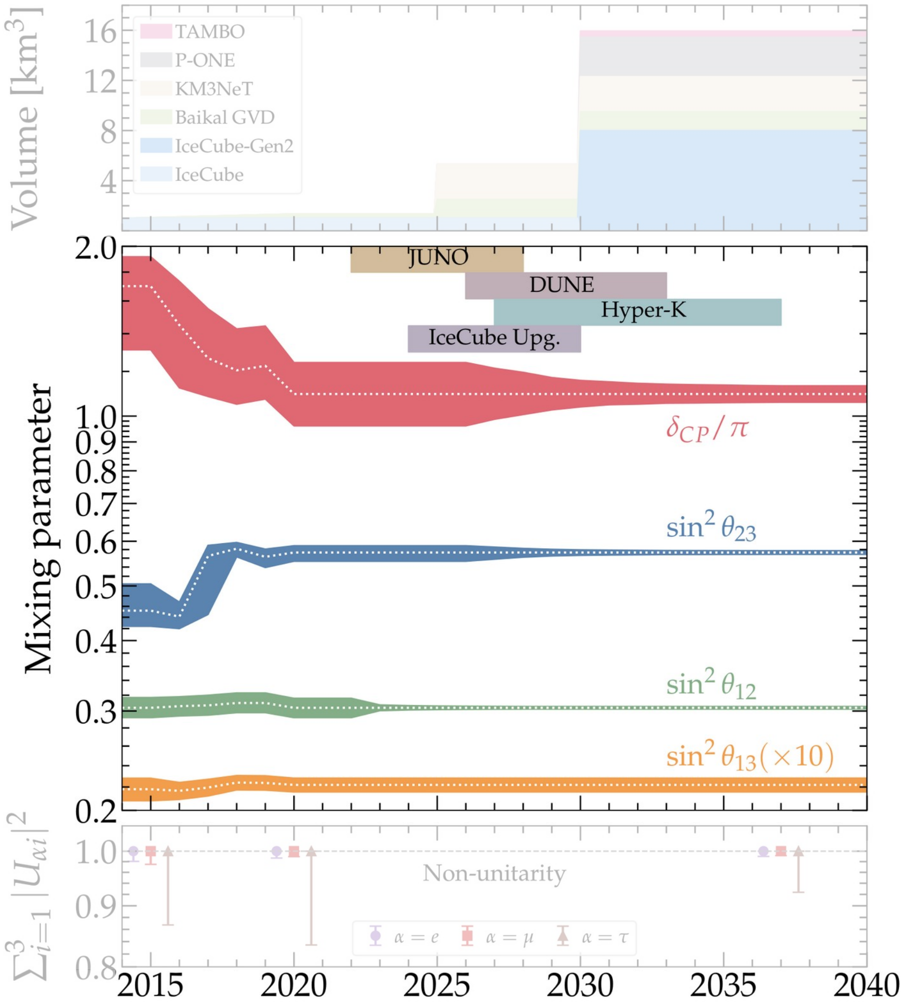


We can compute the oscillation probability more precisely:

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

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

How knowing the mixing parameters better helps



For a future experiment ε = JUNO, DUNE, Hyper-K:

Best fit from NuFit 5.0

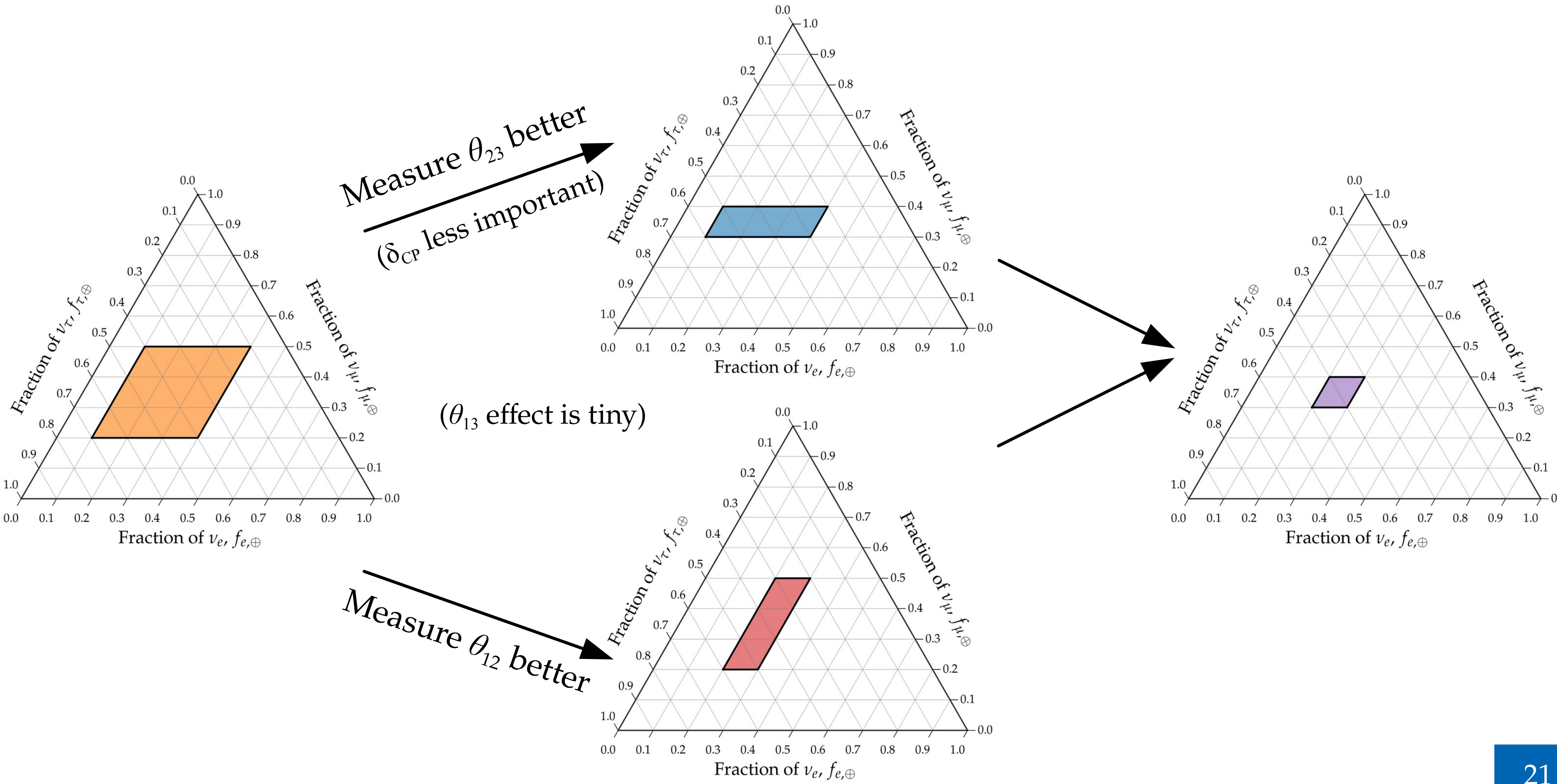
$$\chi^2_\varepsilon(\boldsymbol{\vartheta}) = \sum_i \frac{(\vartheta_i - \bar{\vartheta}_i)^2}{\sigma^2_{i,\varepsilon}}$$

From our simulations

We combine experiments in a likelihood:

$$-2\log\mathcal{L}(\boldsymbol{\theta}) = \sum_\varepsilon \chi^2_\varepsilon(\boldsymbol{\vartheta})$$

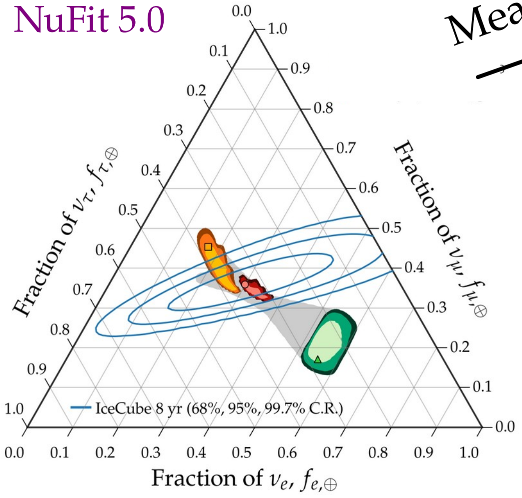
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

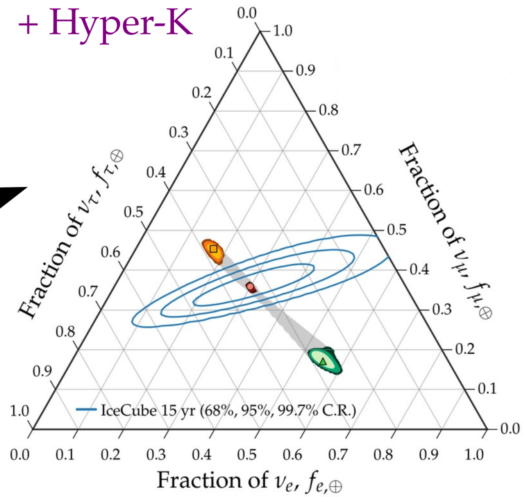
2020

NuFit 5.0



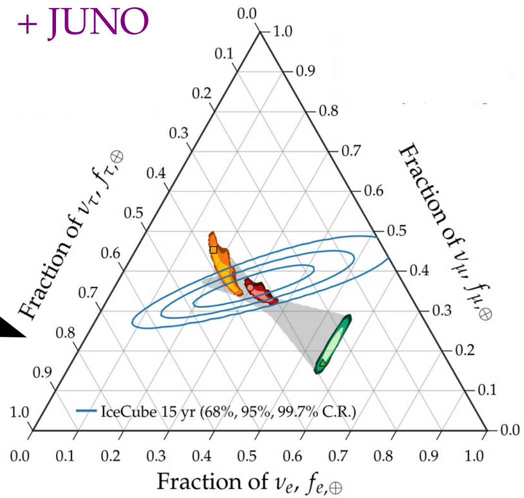
Measure θ_{23} better

+ Hyper-K



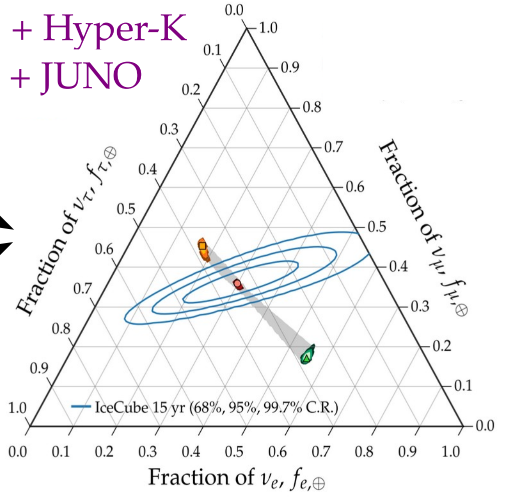
Measure θ_{12} better

+ JUNO



~2030

+ Hyper-K
+ JUNO



In our results:
JUNO + Hyper-K + DUNE

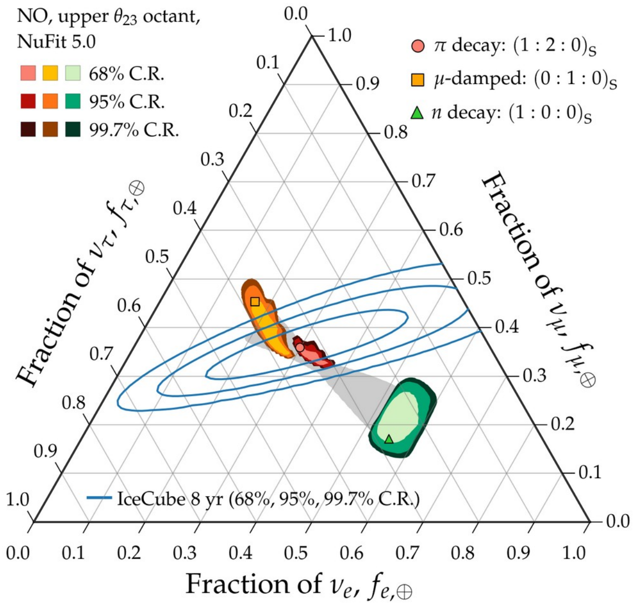
Marginal improvement til 2040

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



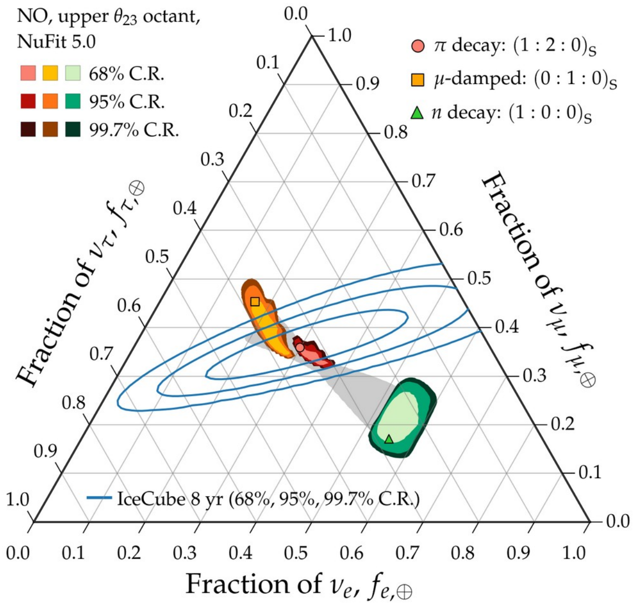
Allowed regions: overlapping

Measurement: imprecise

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020



Allowed regions: overlapping

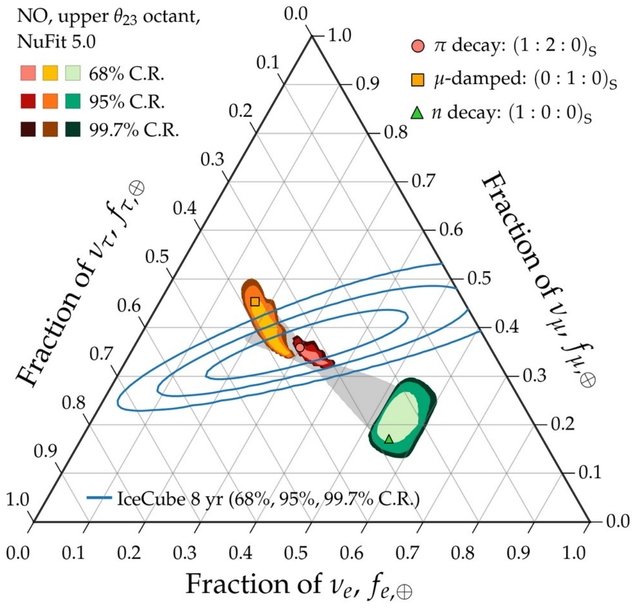
Measurement: imprecise

Not ideal

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020



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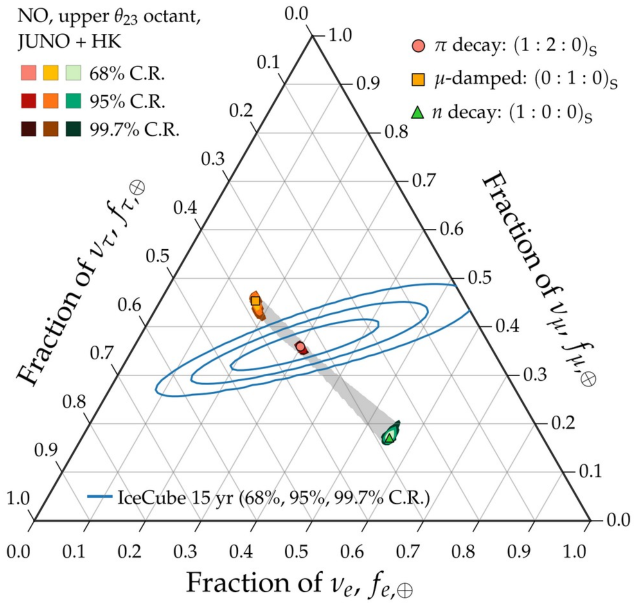
Not ideal

2030



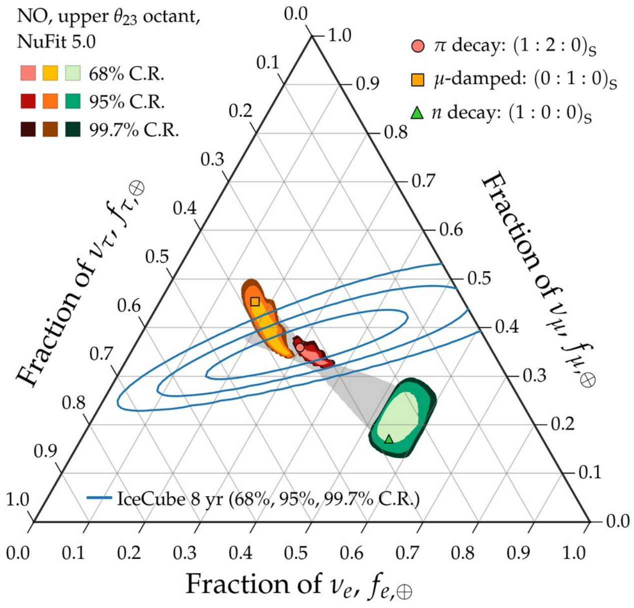
Allowed regions: well separated

Measurement: improving

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020

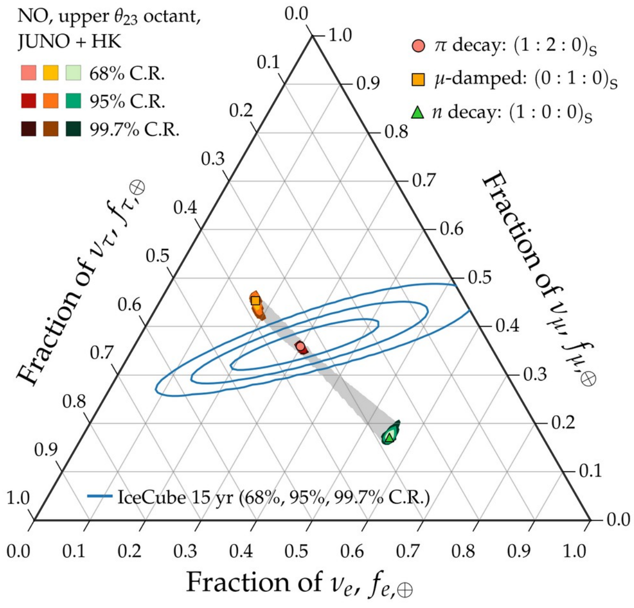


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



Allowed regions: well separated

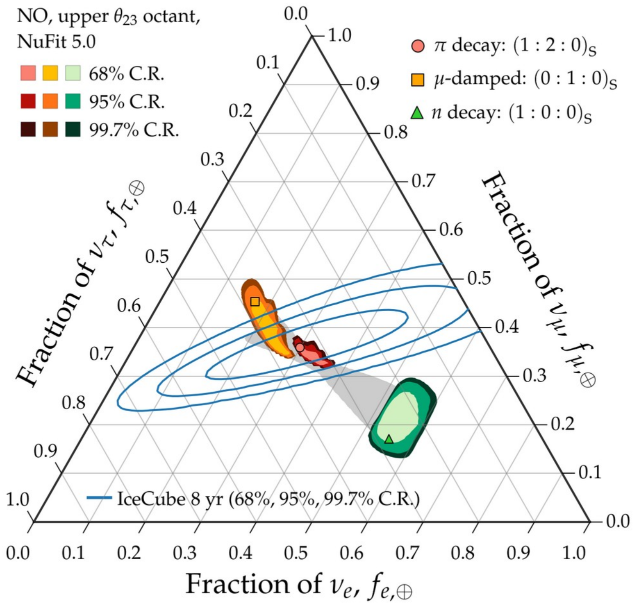
Measurement: improving

Nice

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020

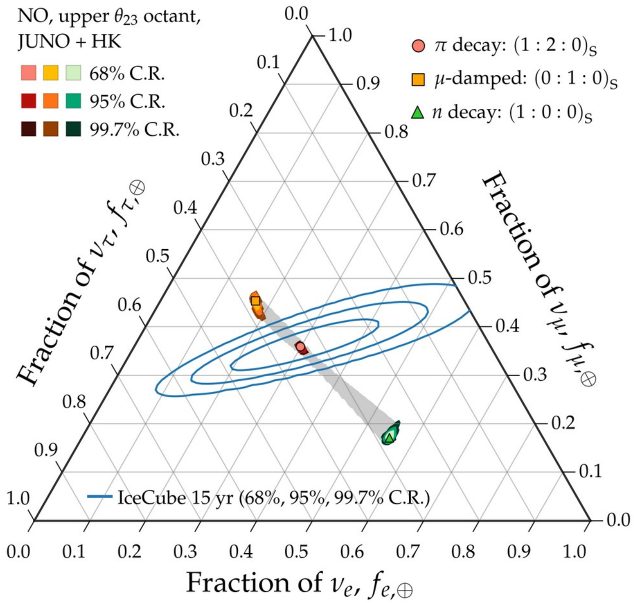


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030

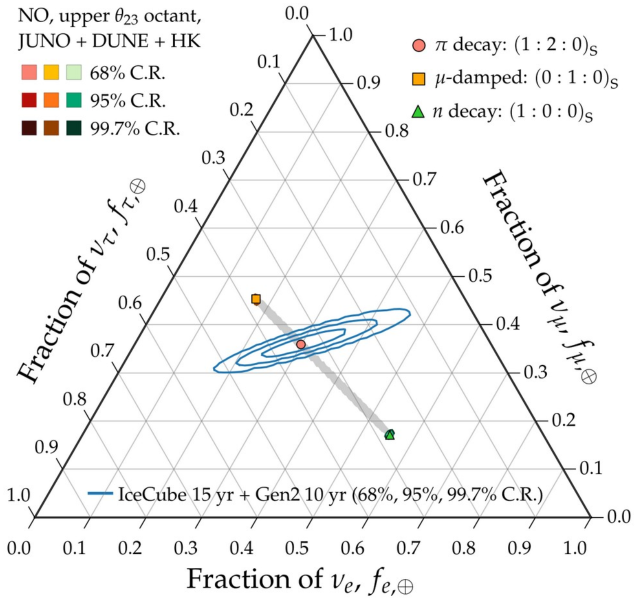


Allowed regions: well separated

Measurement: improving

Nice

2040



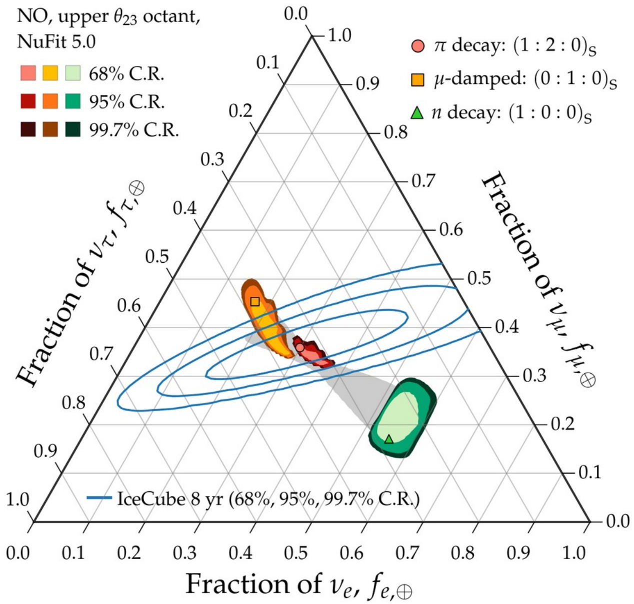
Allowed regions: well separated

Measurement: precise

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020

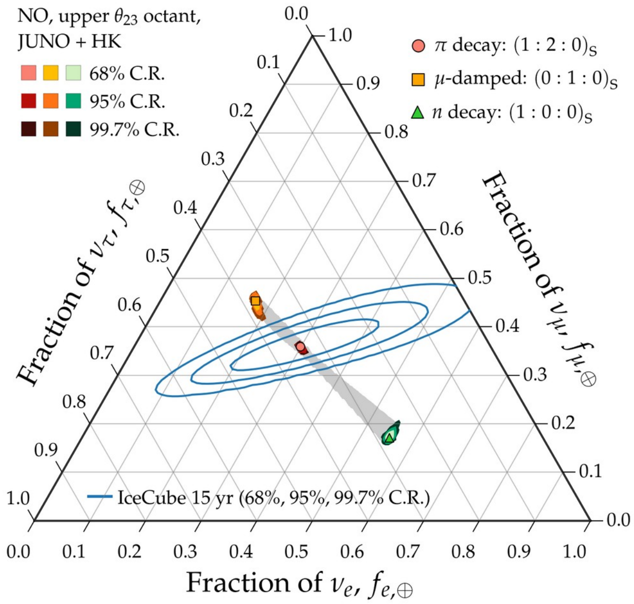


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030

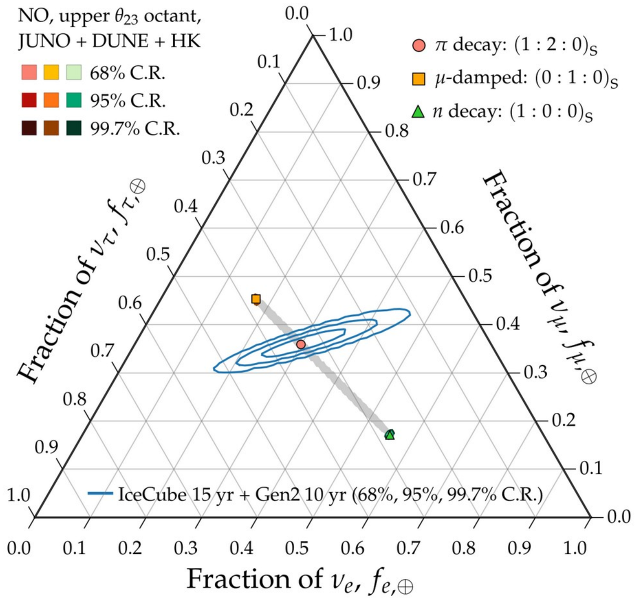


Allowed regions: well separated

Measurement: improving

Nice

2040



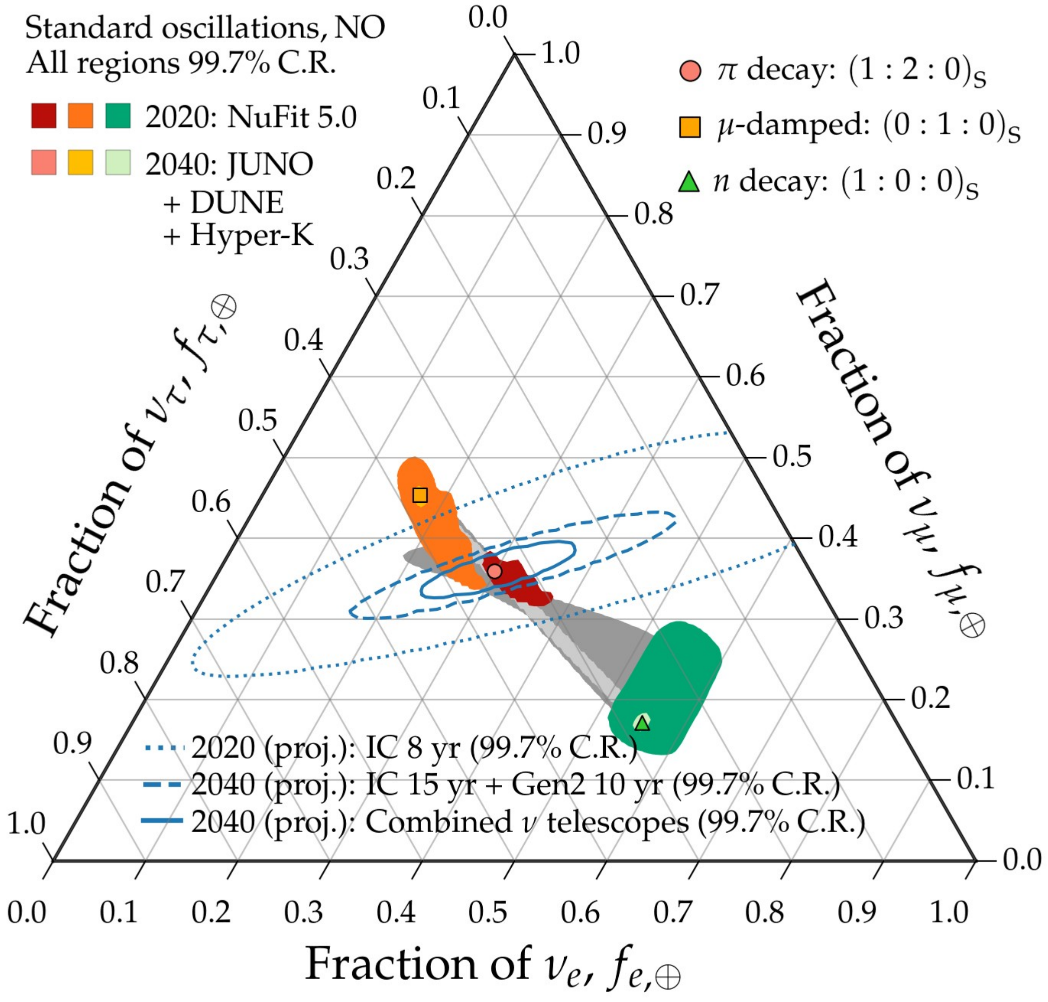
Allowed regions: well separated

Measurement: precise

Success

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 *vs.* 2040



By 2040:

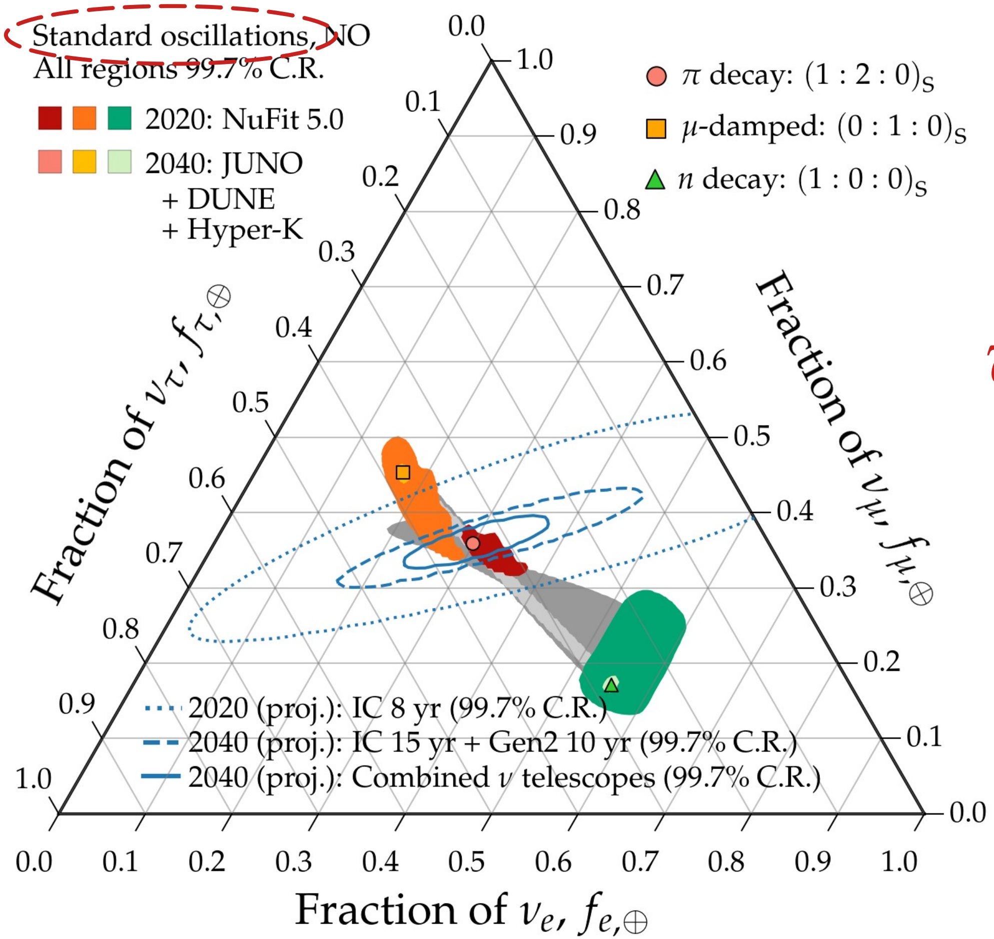
Theory –
Mixing parameters known precisely: allowed flavor regions are *almost* points (already by 2030)

Measurement of flavor ratios –
Can distinguish between similar predictions at 99.7% C.R. (3σ)

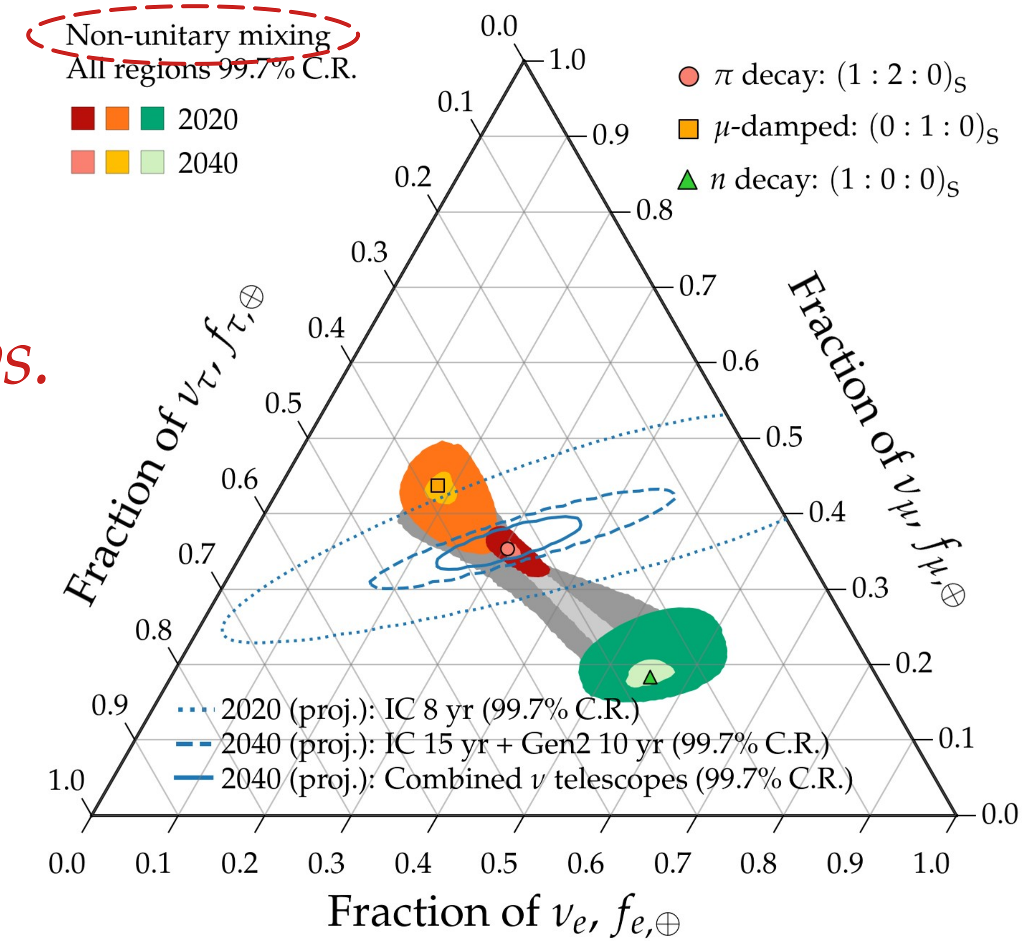
Can finally use the full power of flavor composition for astrophysics and neutrino physics

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

No unitarity? *No problem*



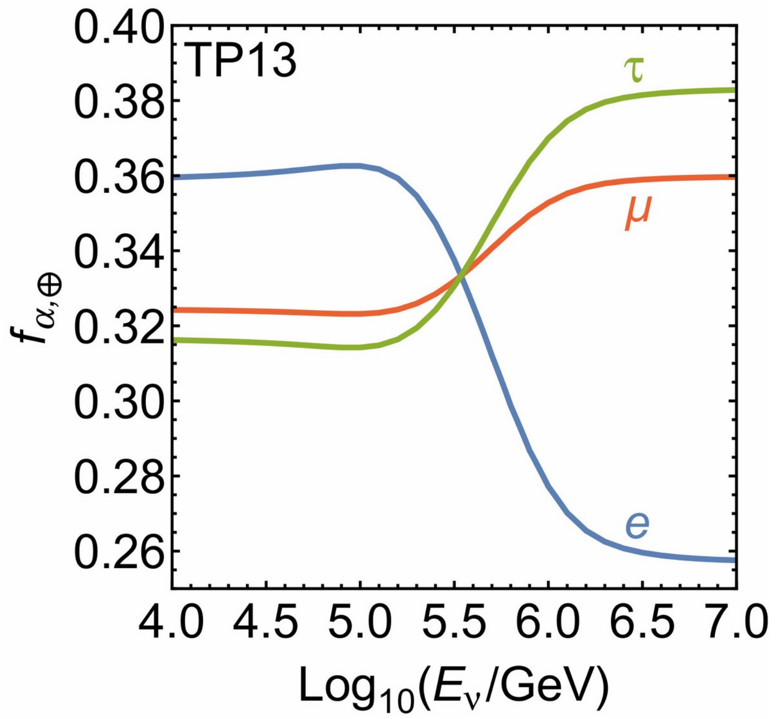
vs.

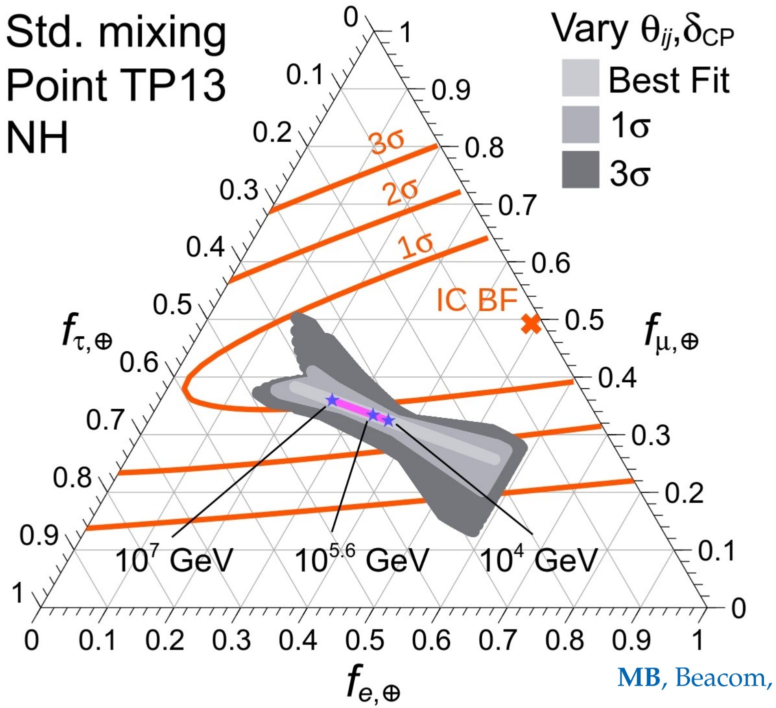


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –



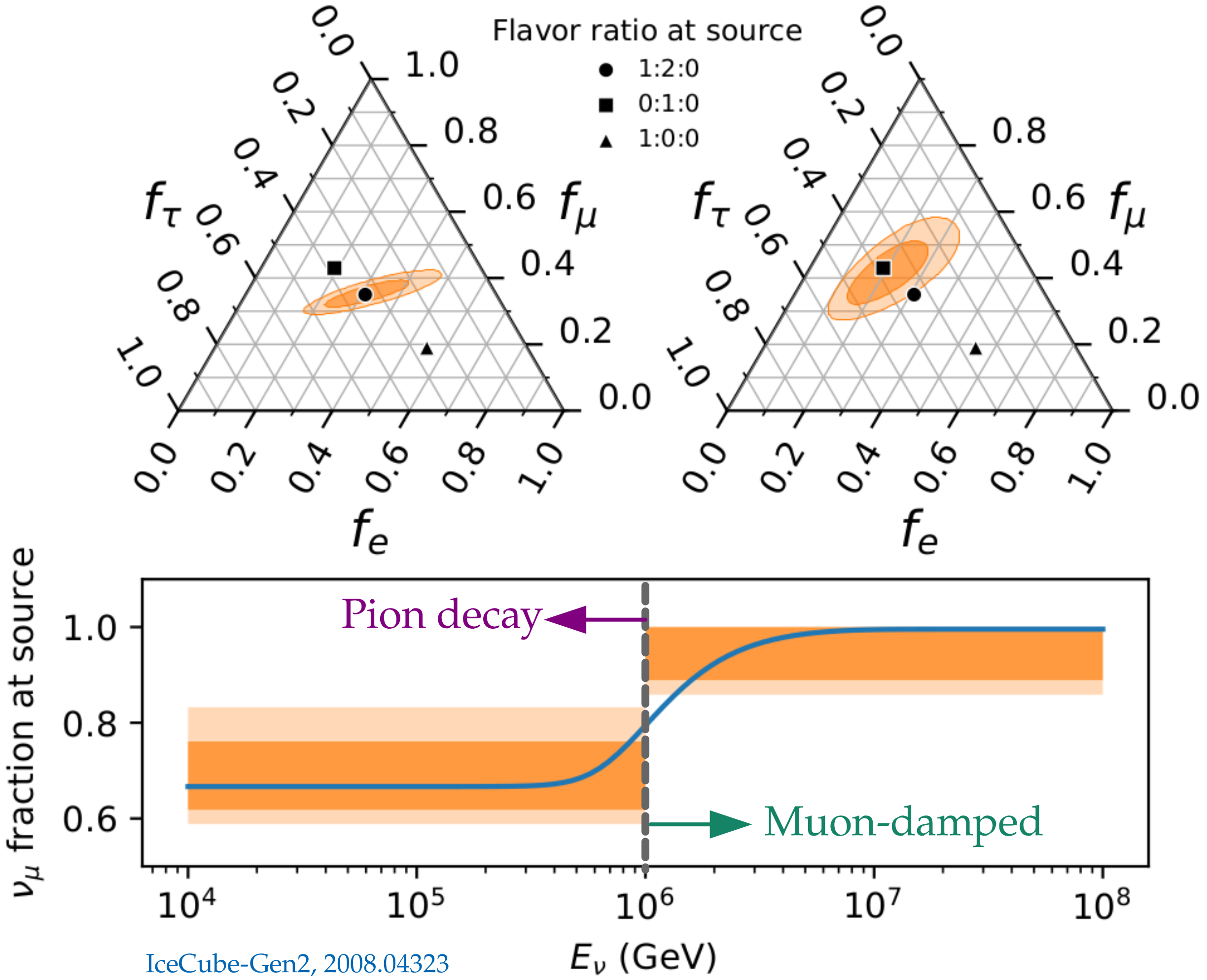


MB, Beacom, Winter, *PRL* 2015

- TP13: $p\gamma$ model, target photons from e^-e^+ annihilation [Hümmer+, *Astropart. Phys.* 2010]
- Will be difficult to resolve [Kashti, Waxman, *PRL* 2005; Lipari, Lusignoli, Meloni, *PRD* 2007]

Energy dependence of flavor ratios – in IceCube-Gen2

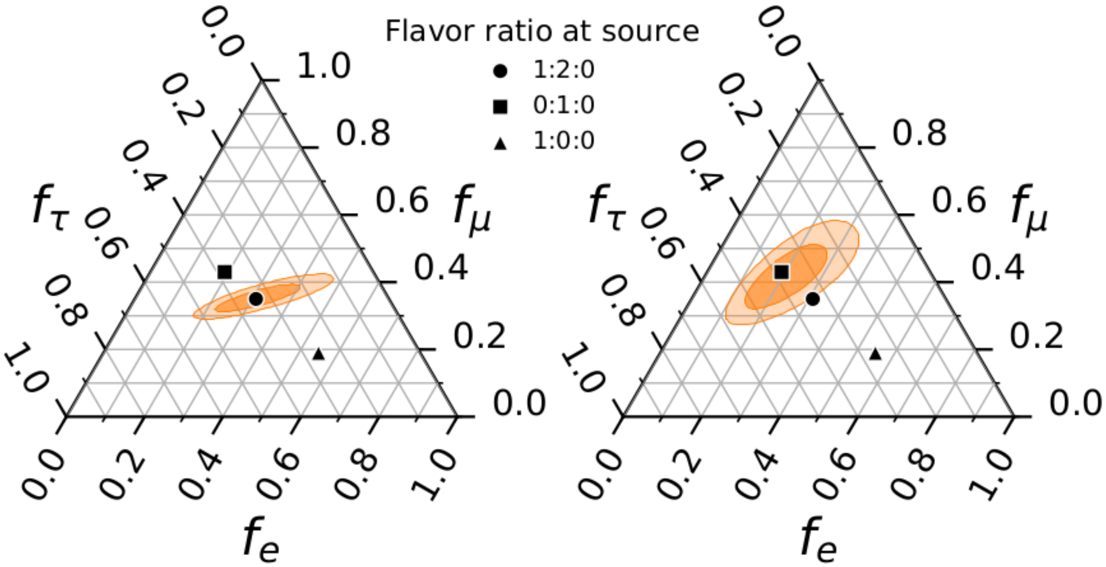
Measured:

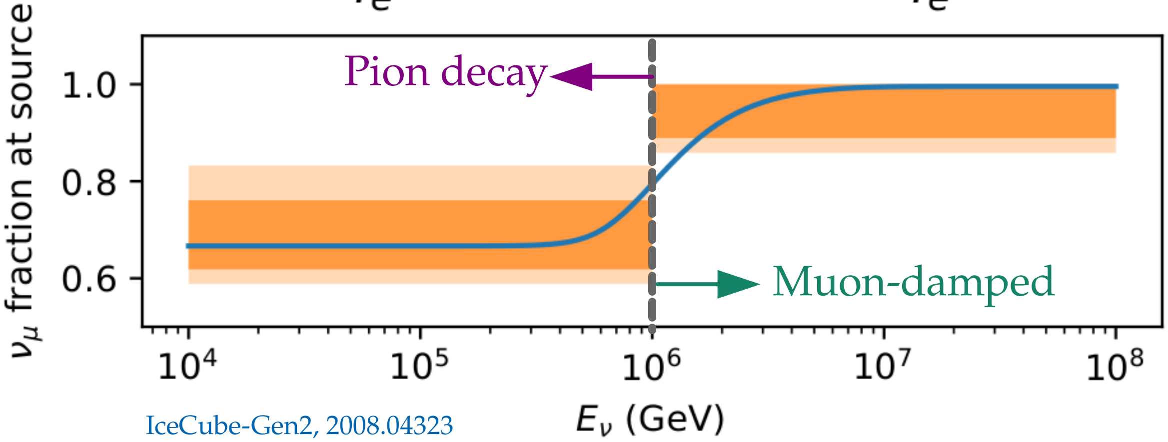


IceCube-Gen2, 2008.04323

Energy dependence of flavor ratios – in IceCube-Gen2

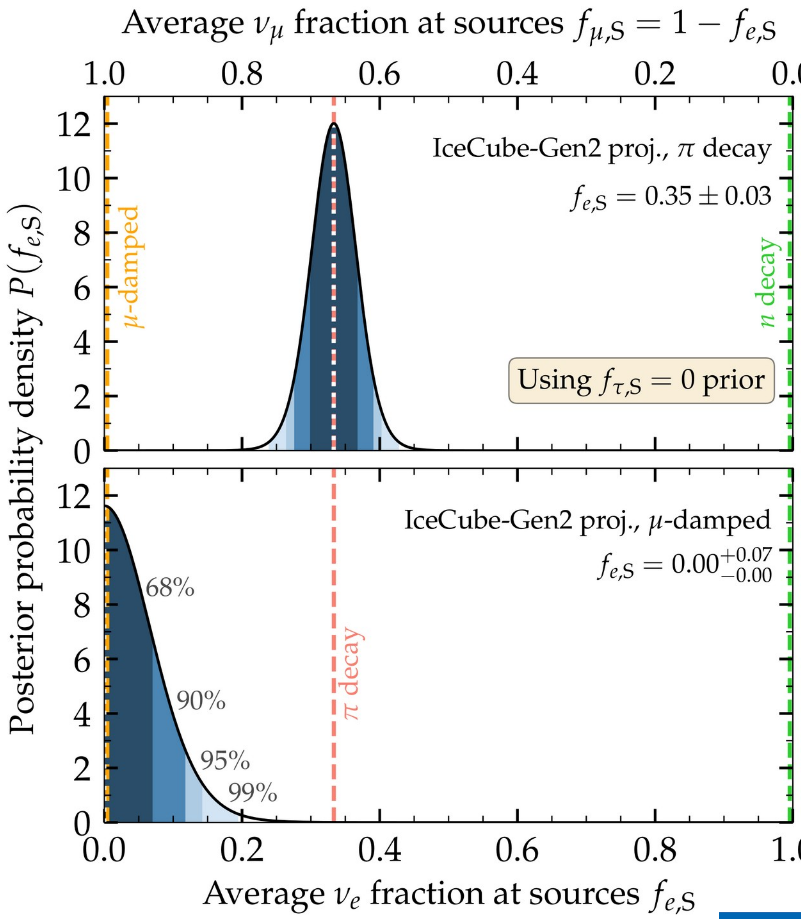
Measured:





IceCube-Gen2, 2008.04323

Inferred (at sources):



MB & Ahlers, *PRL* 2019

Energy dependence of flavor ratios – in IceCube-Gen2

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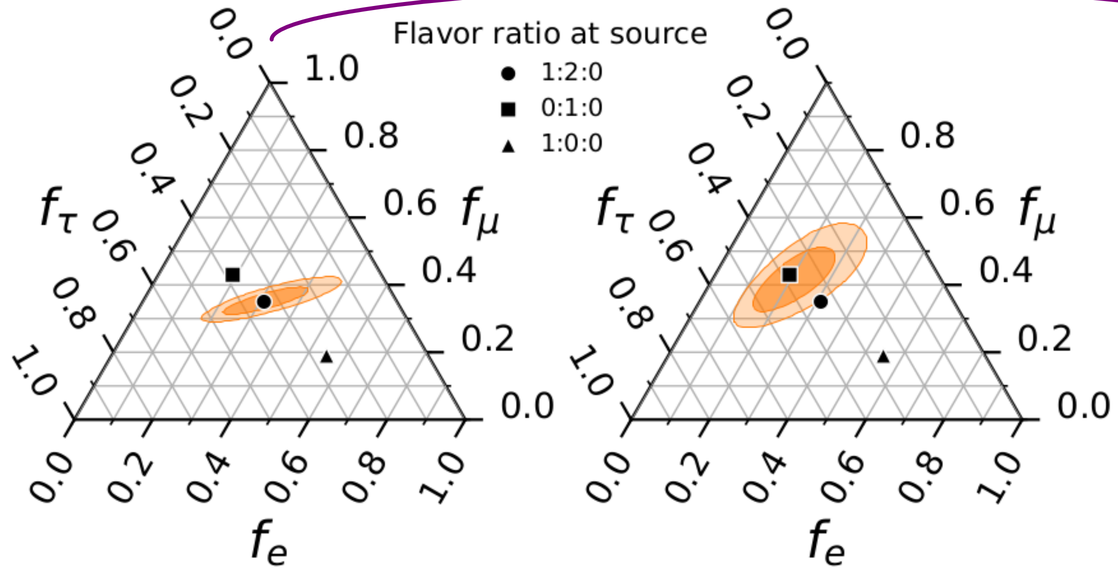

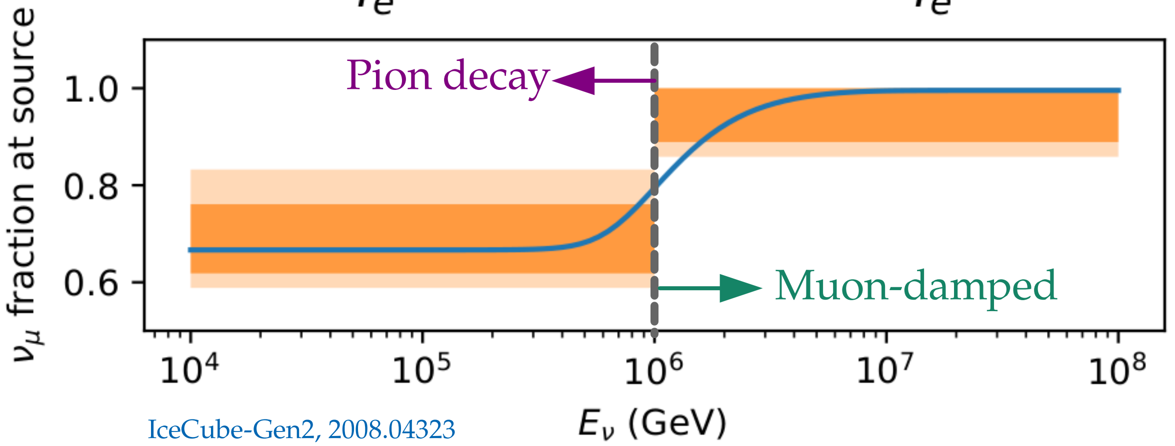

IceCube-Gen2, 2008.04323

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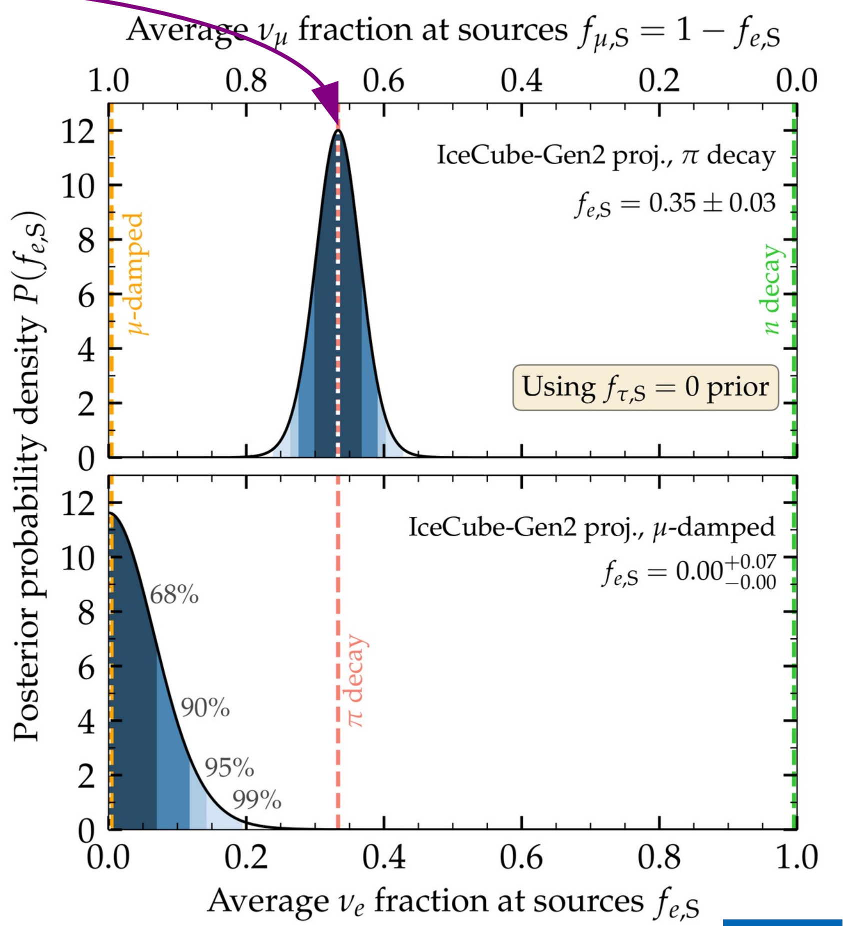
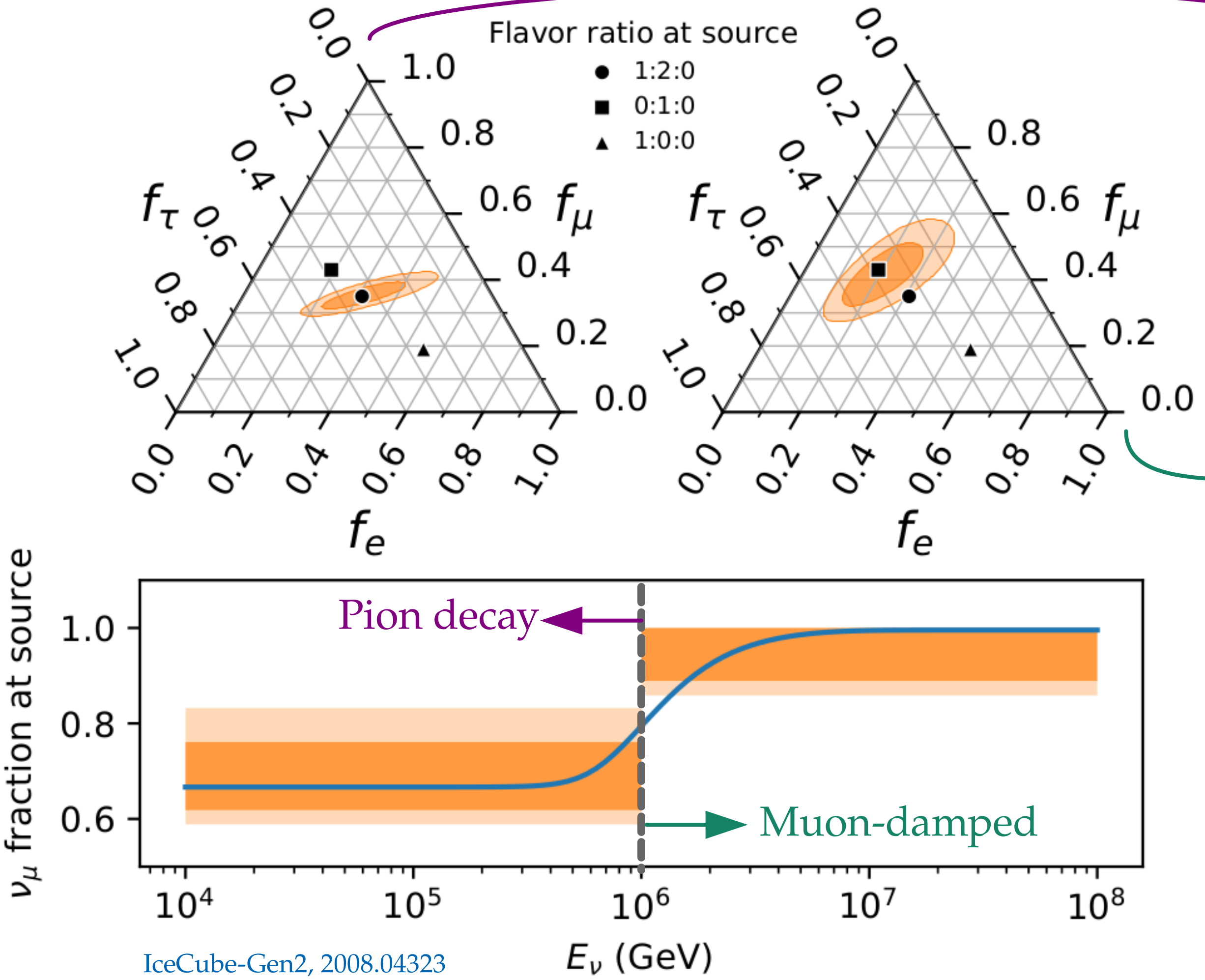


MB & Ahlers, *PRL* 2019

Energy dependence of flavor ratios – in IceCube-Gen2

Measured:



IceCube-Gen2, 2008.04323

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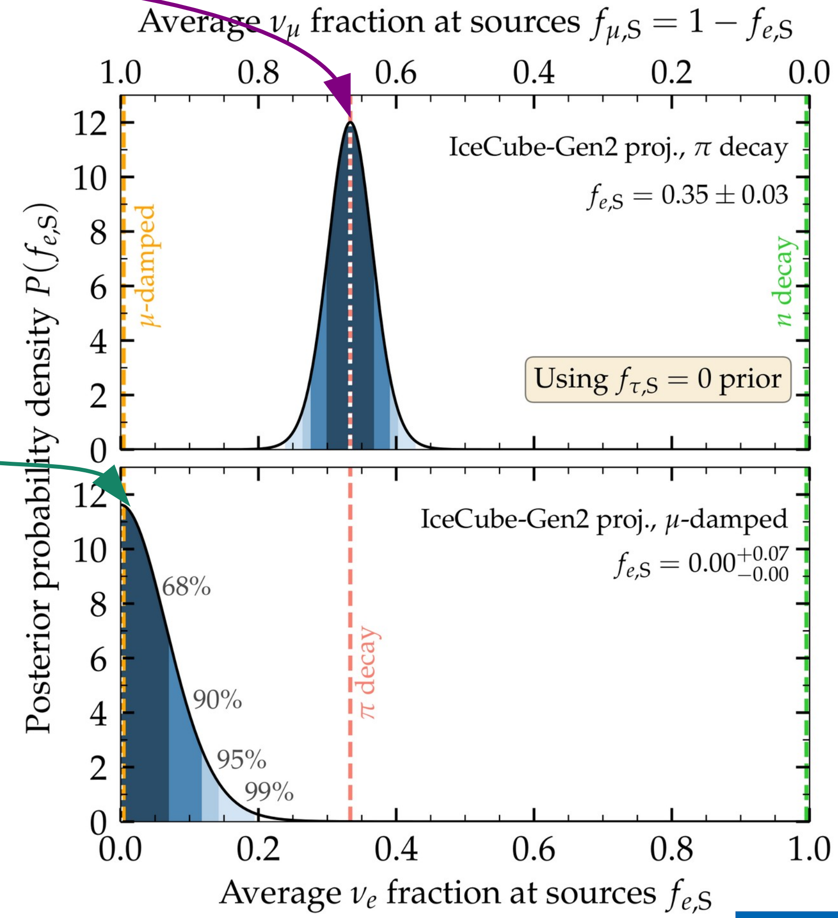
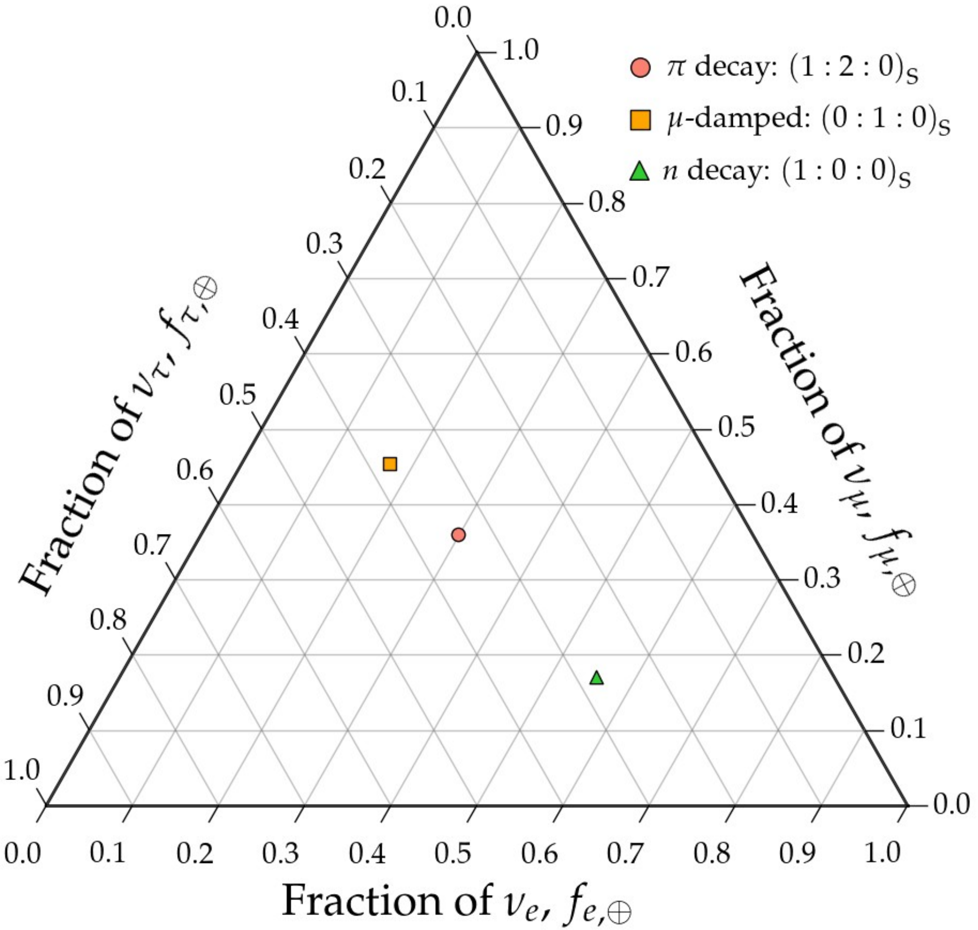


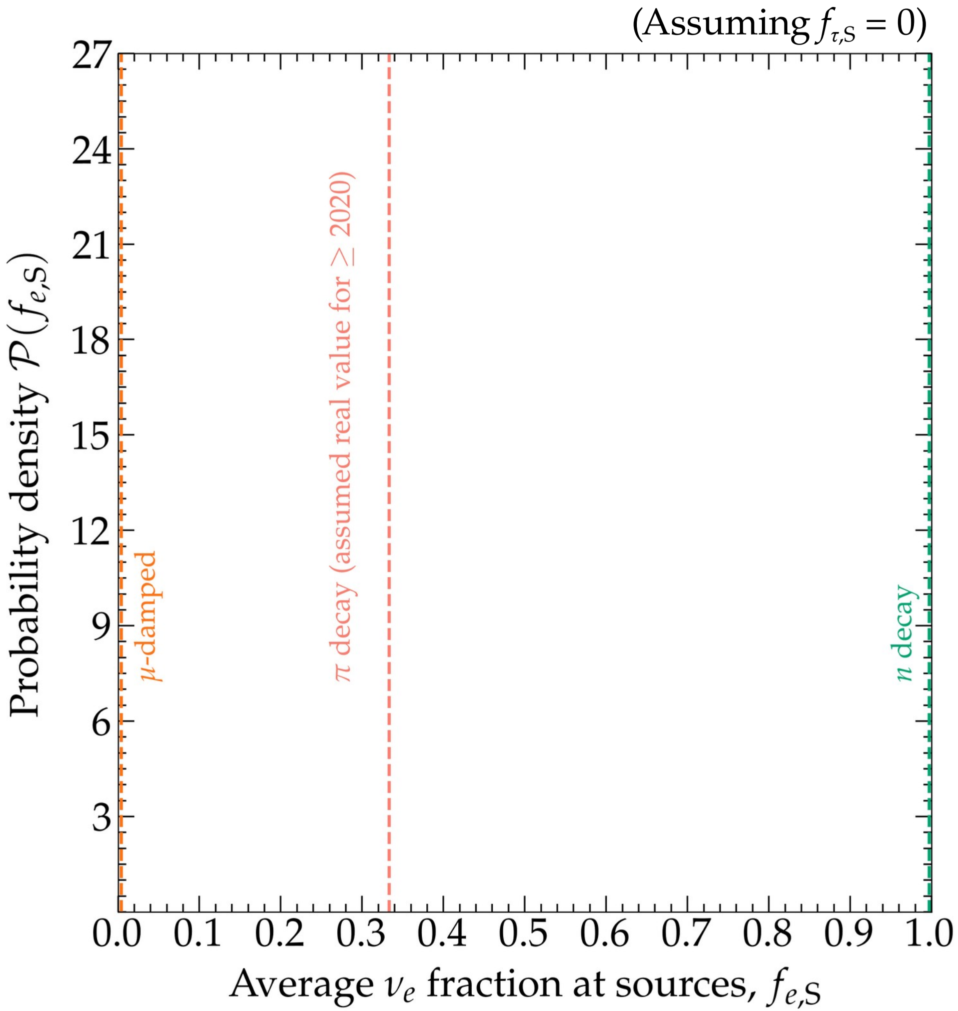
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

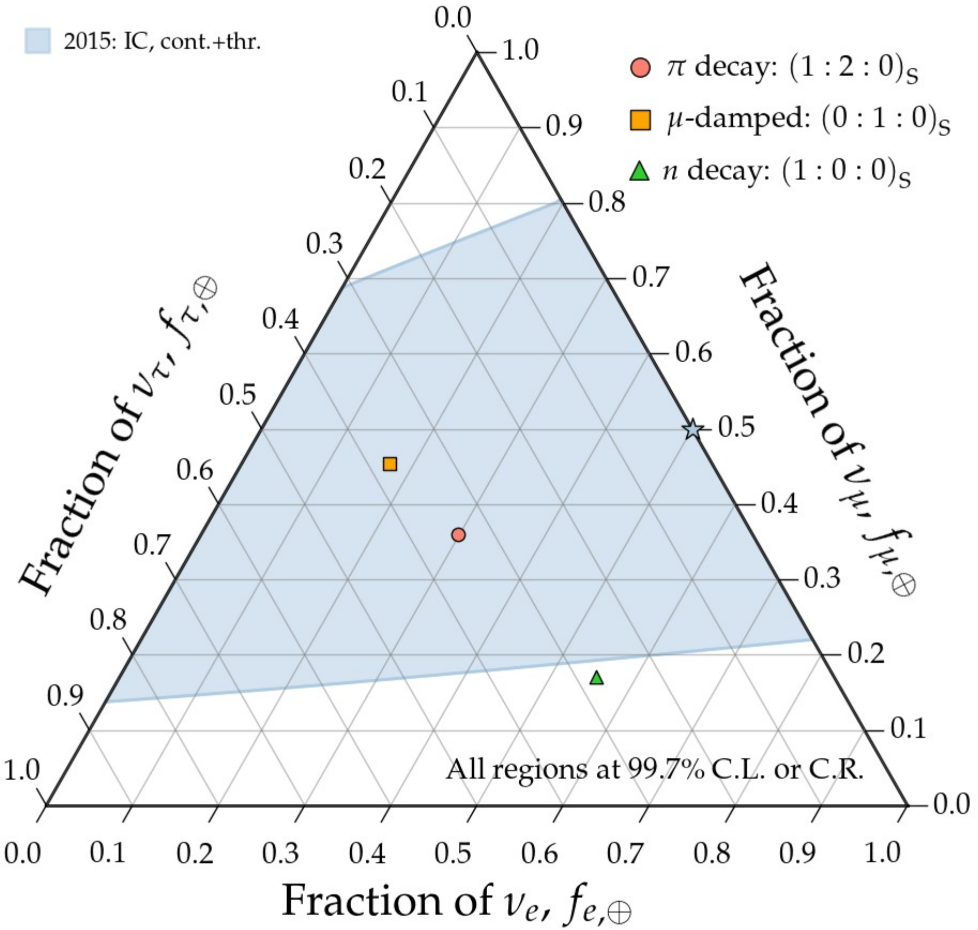
Inferring the flavor composition at the sources

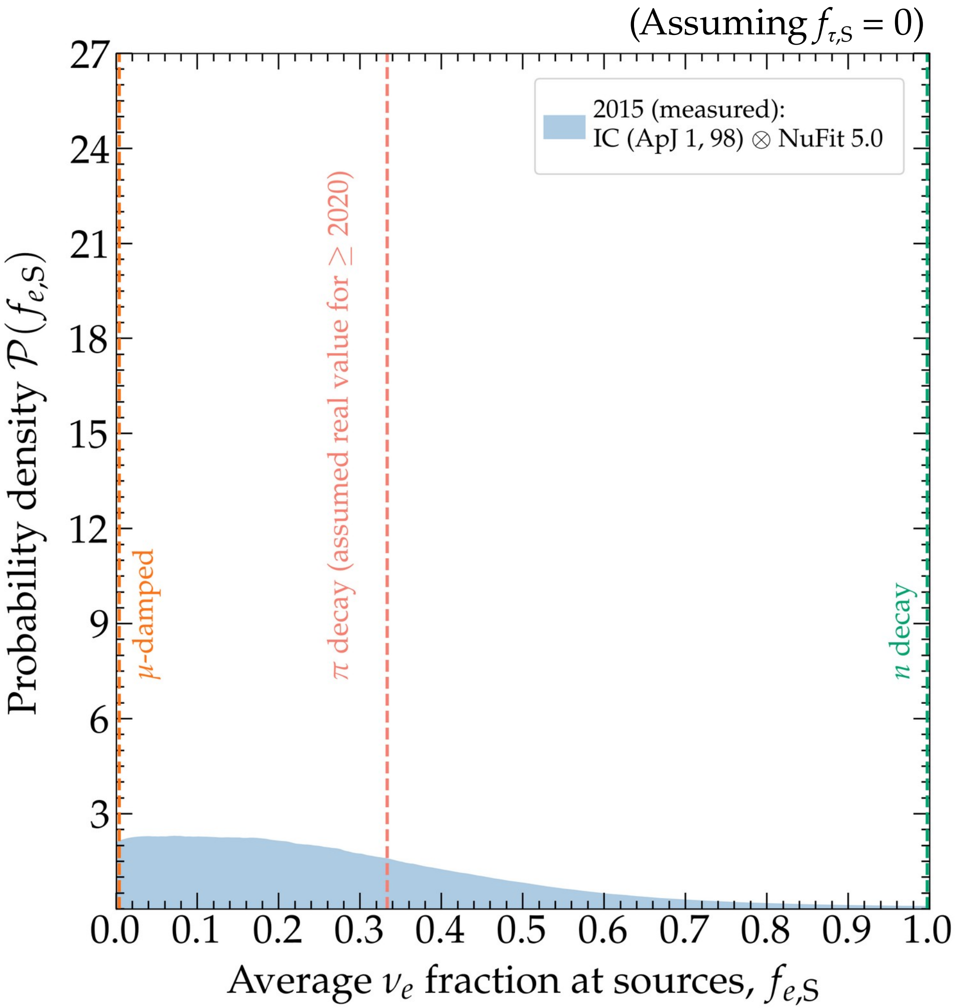




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

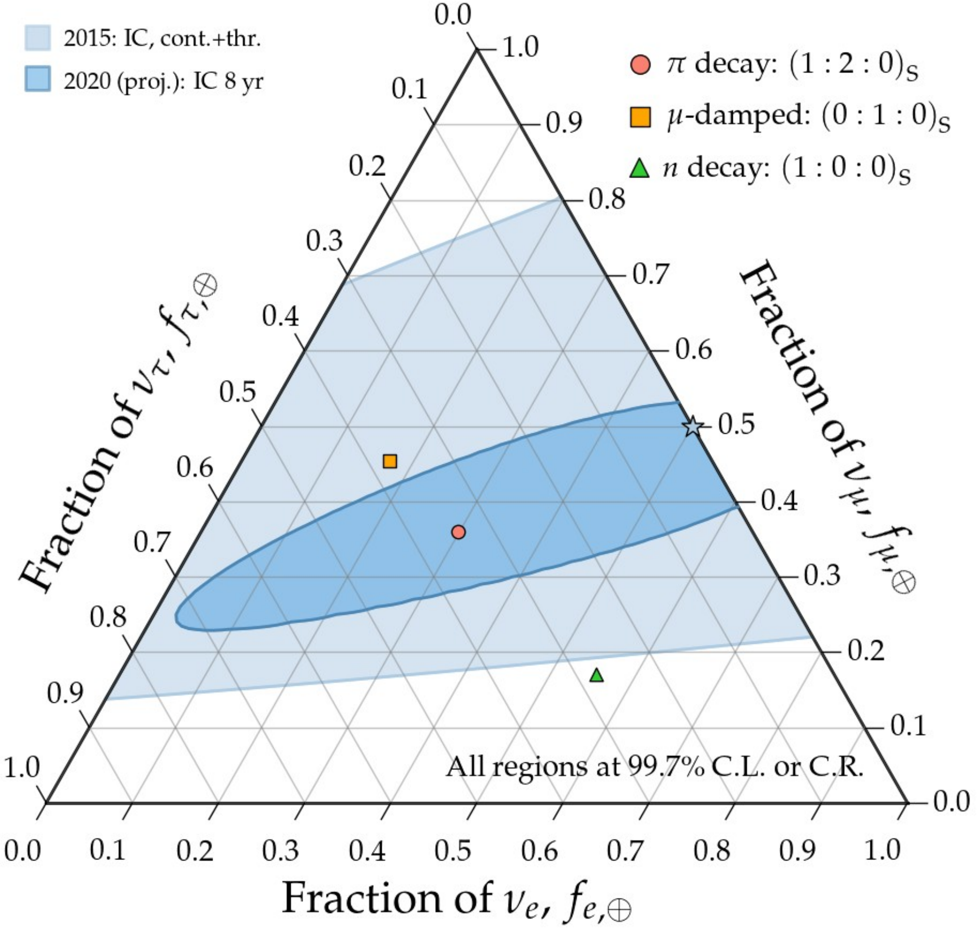
Inferring the flavor composition at the sources

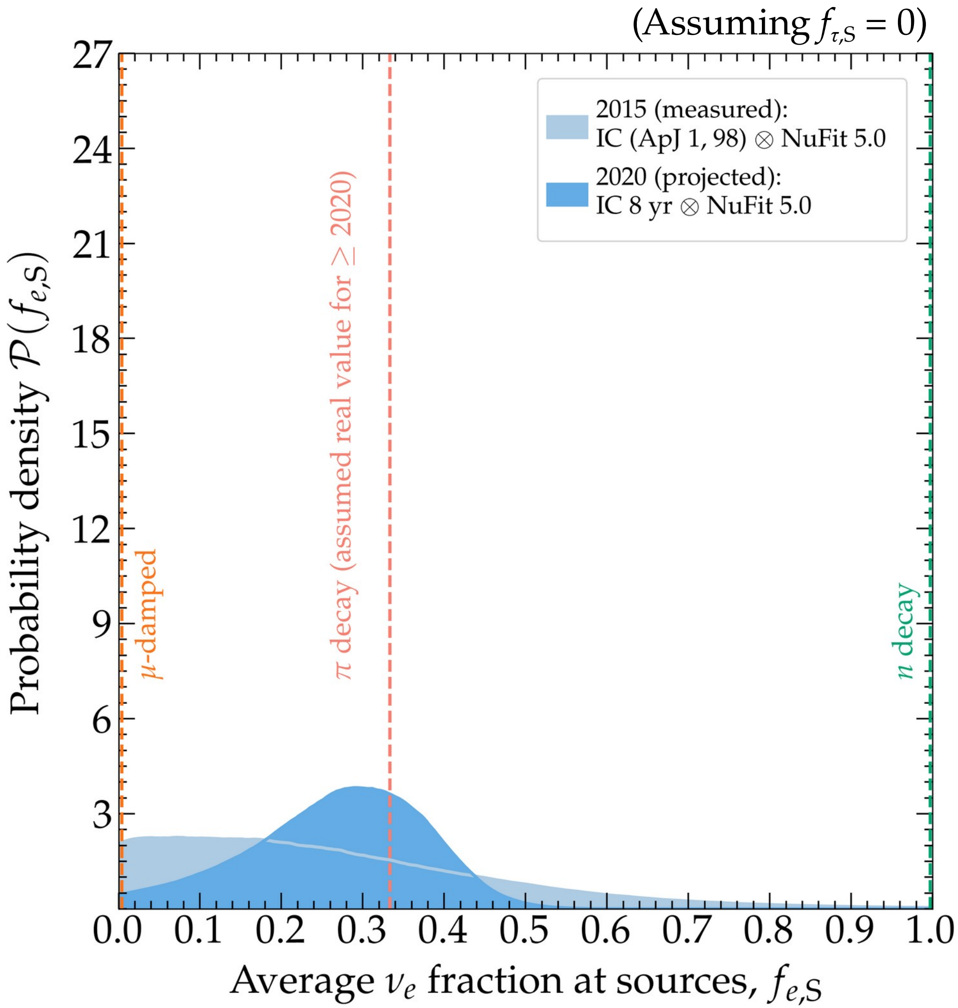




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources





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MB & Ahlers, *PRL* 2019

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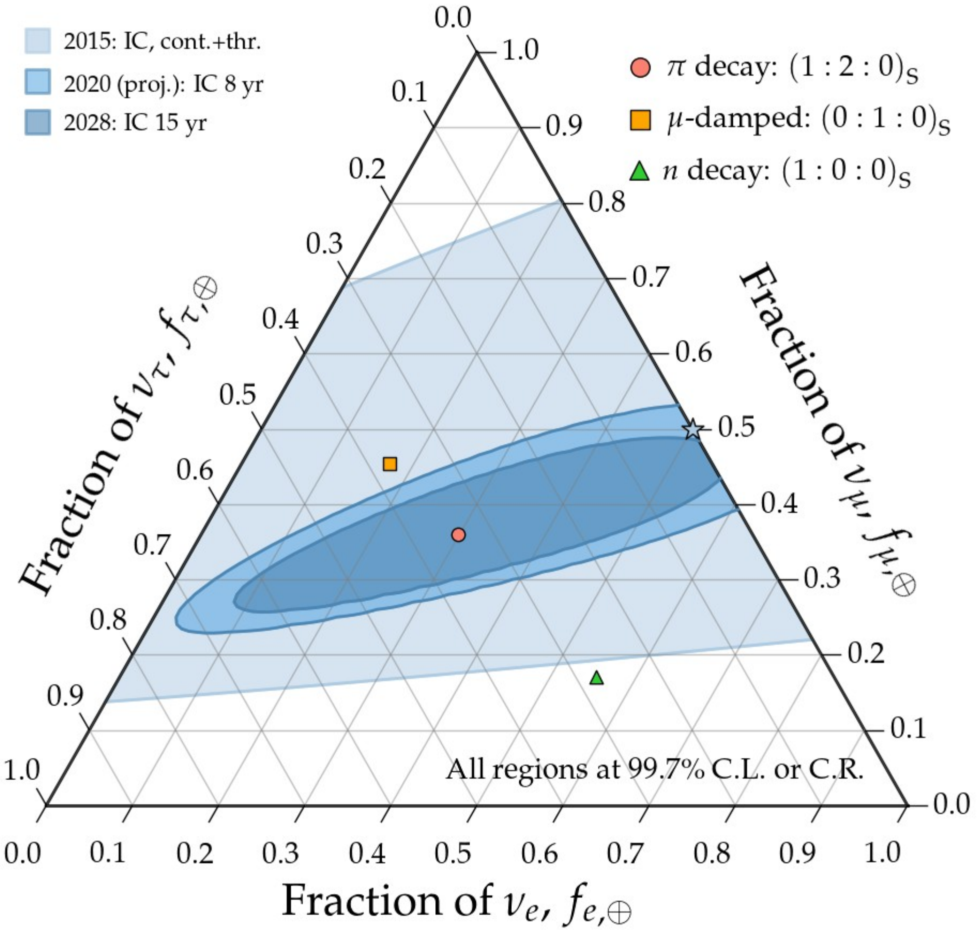

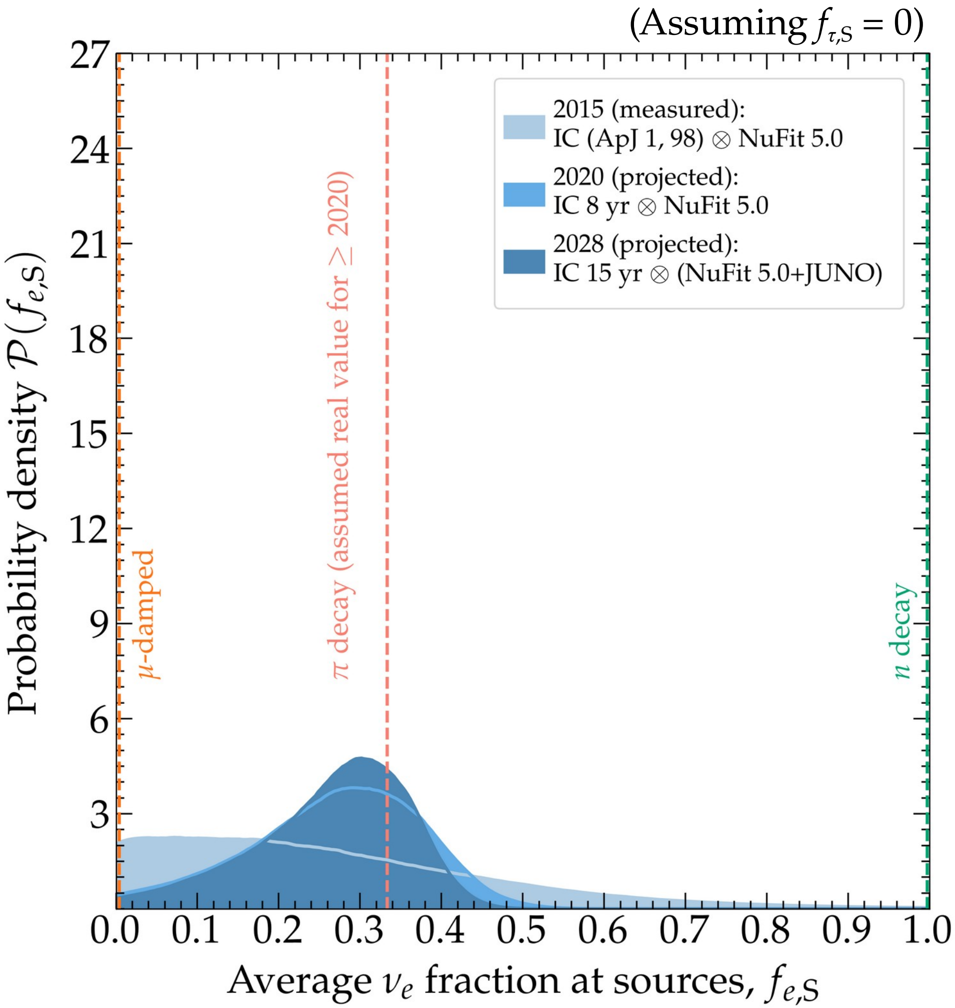

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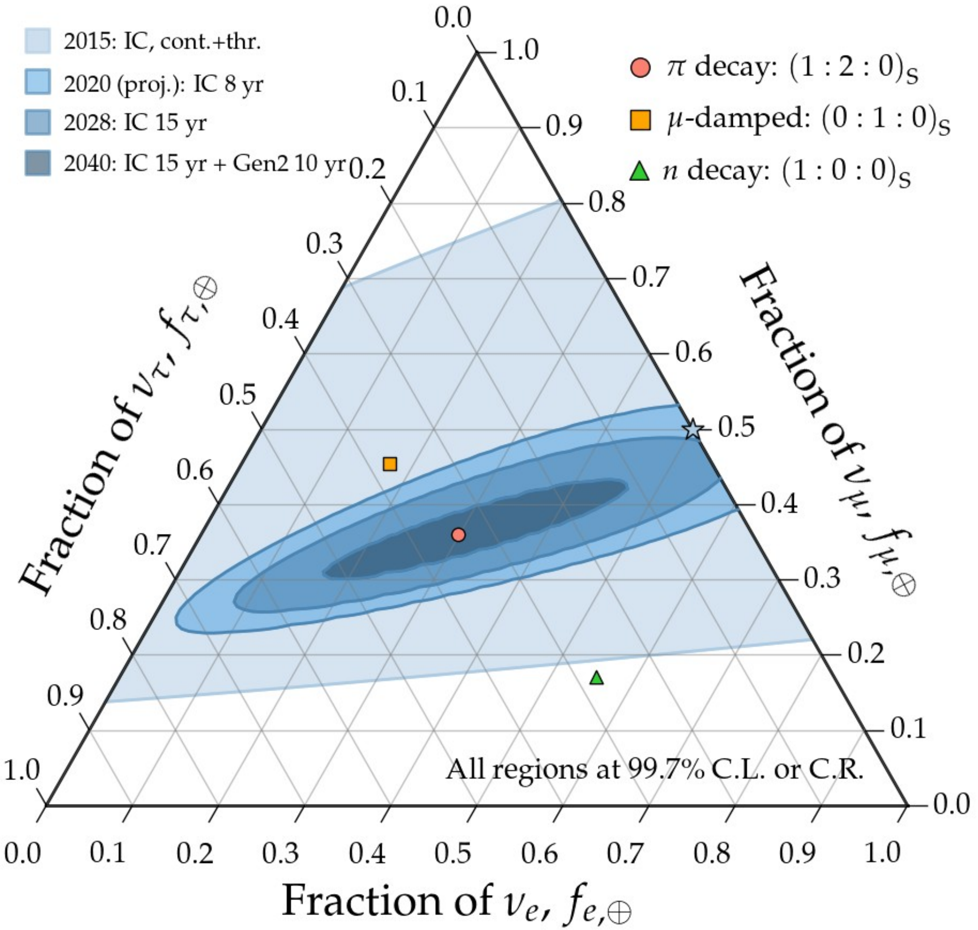
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources



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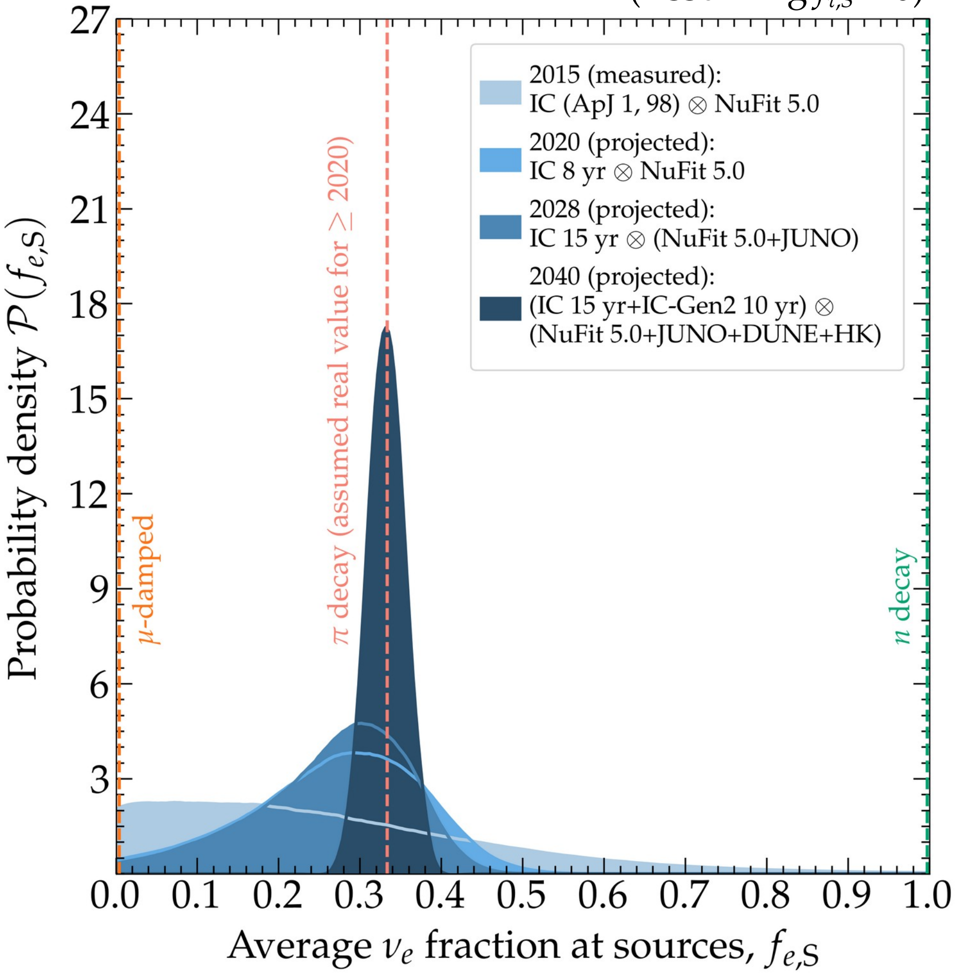

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
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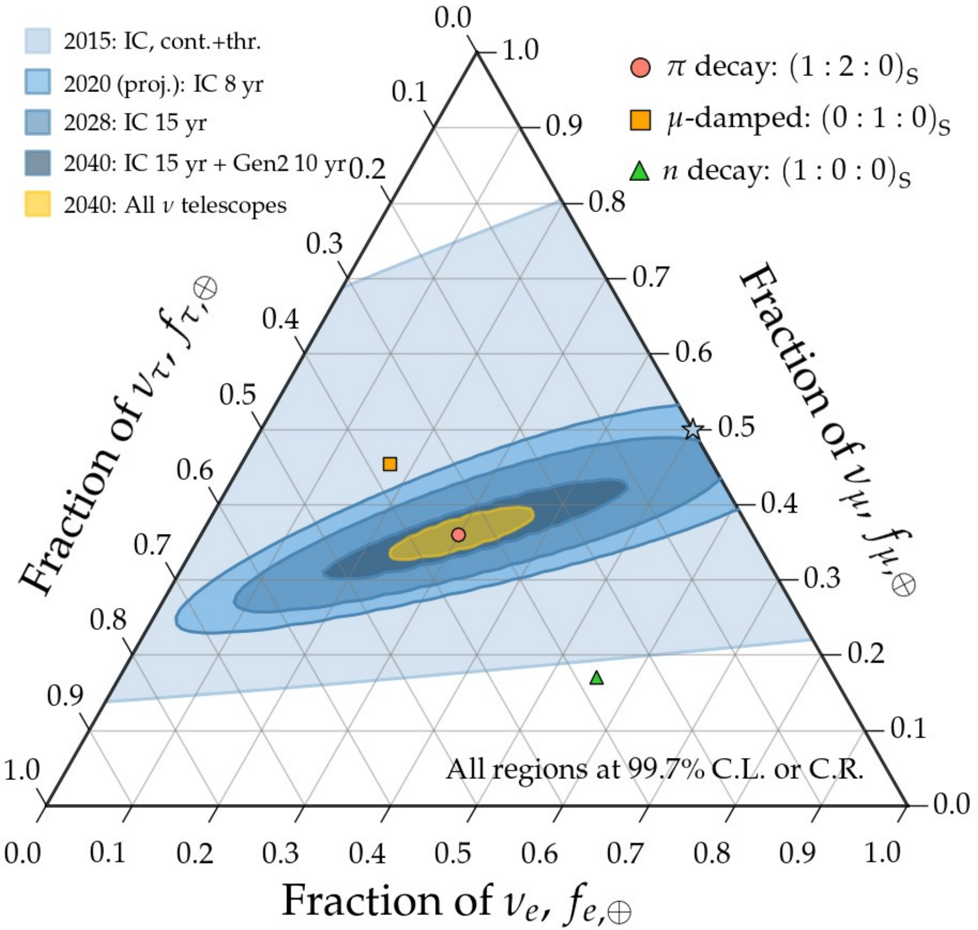

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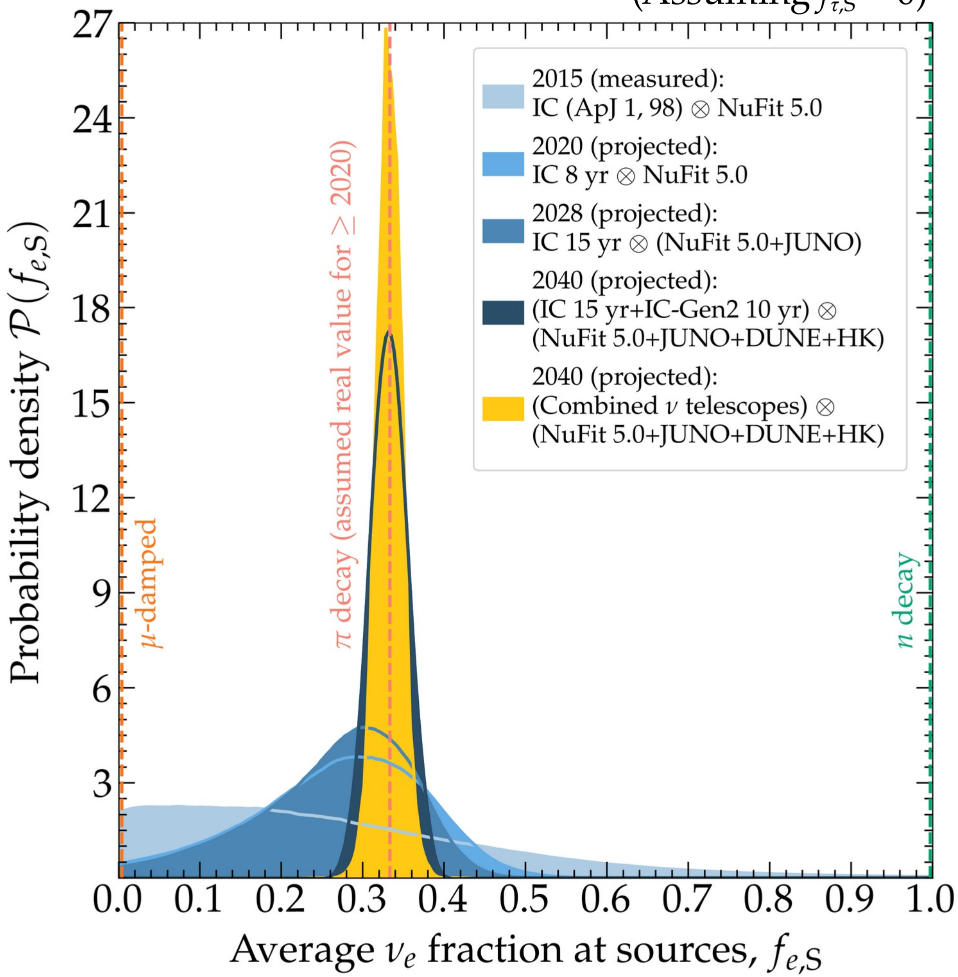

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
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Can we detect the contribution of multiple ν production mechanisms?

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π decay: (1/3, 2/3, 0) | μ damped: (0, 1, 0) | *n* decay: (1, 0, 0)

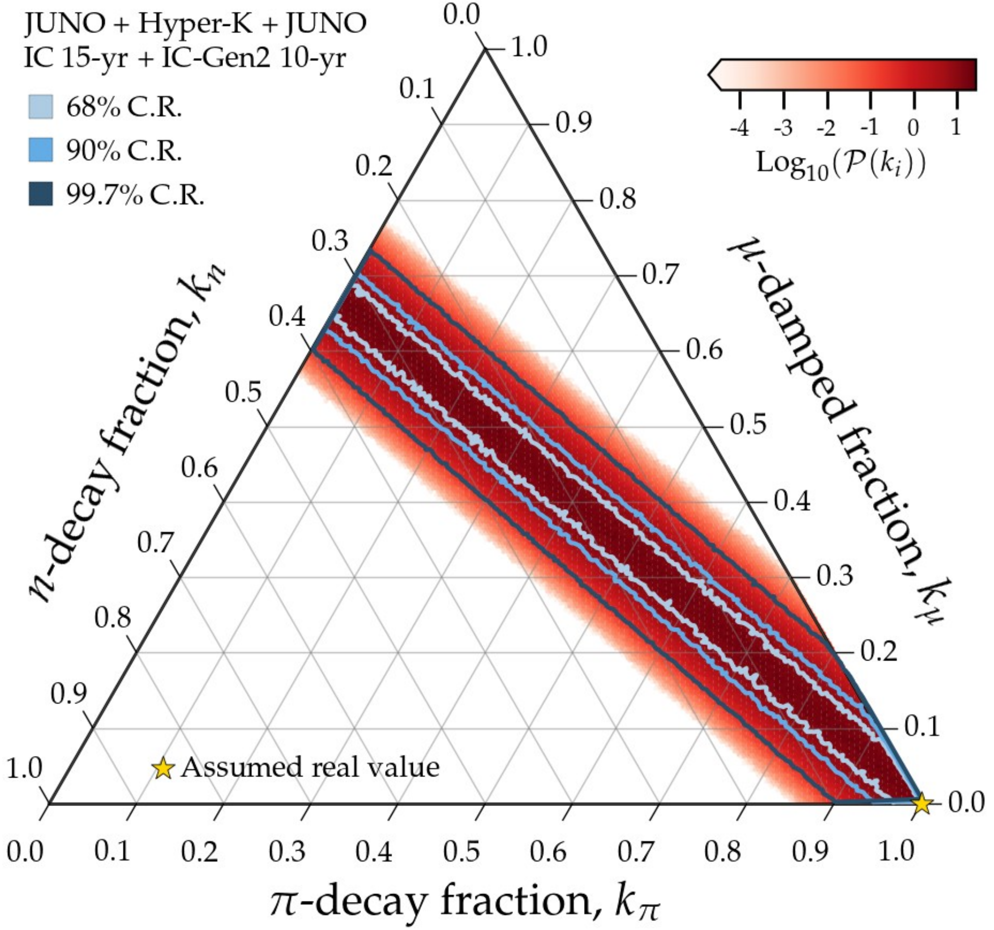
Propagate to Earth

$$\boldsymbol{f}_\oplus$$

Assume real value $k_\pi = 1$ ($k_\mu = k_n = 0$)

By 2040, how well will we recover the real value?

[Adding spectrum information (not shown) will likely help]



Song, Li, Argüelles, **MB**, Vincent, 2012.12893

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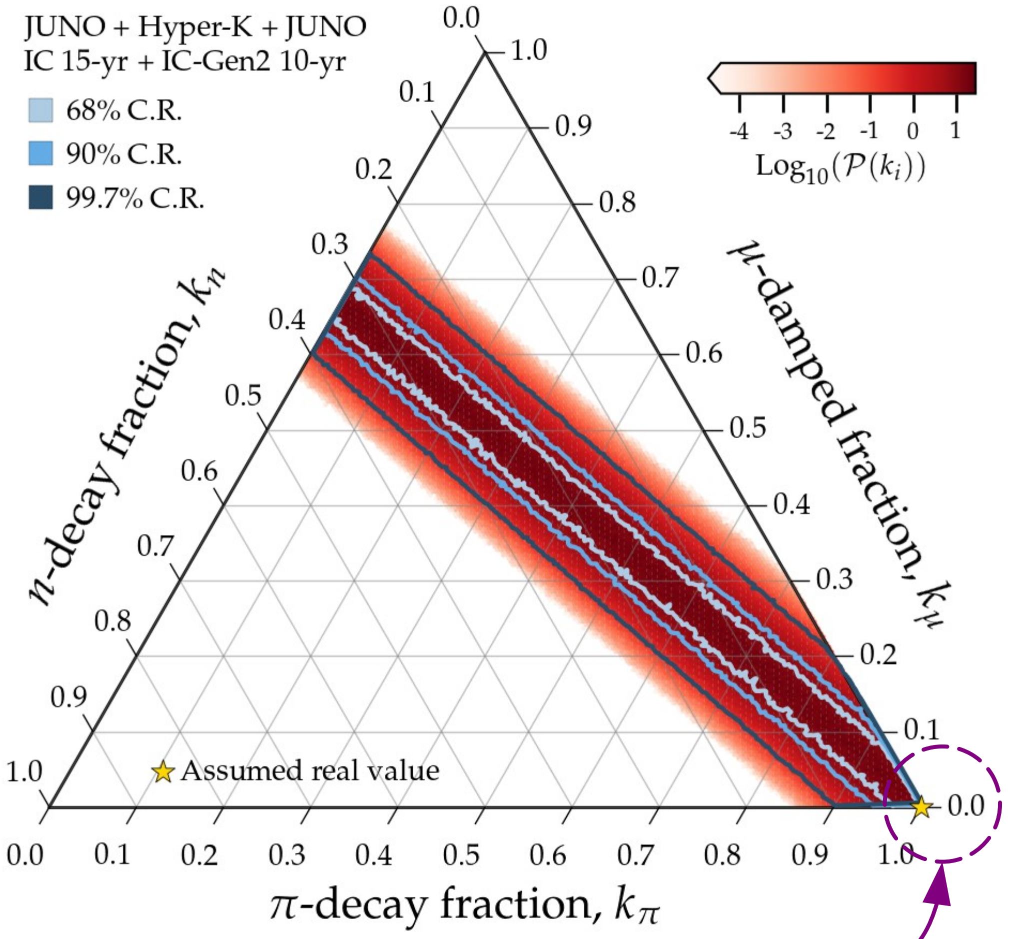

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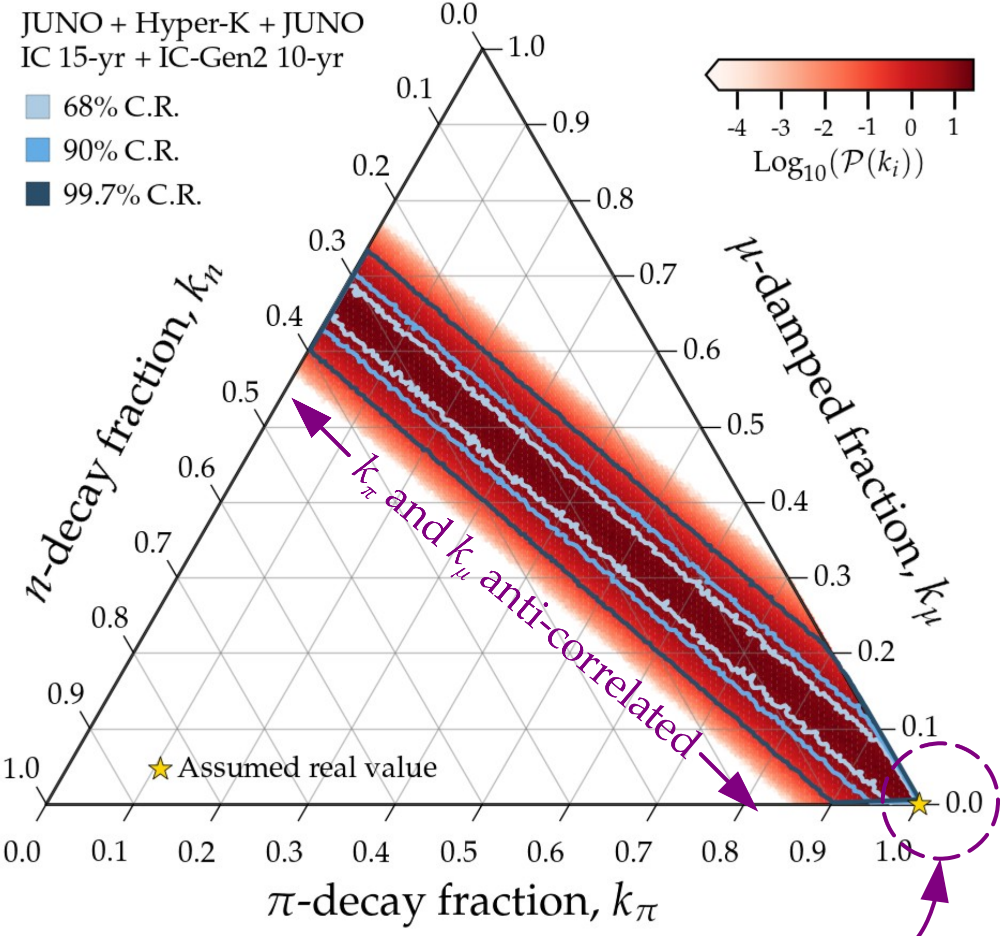

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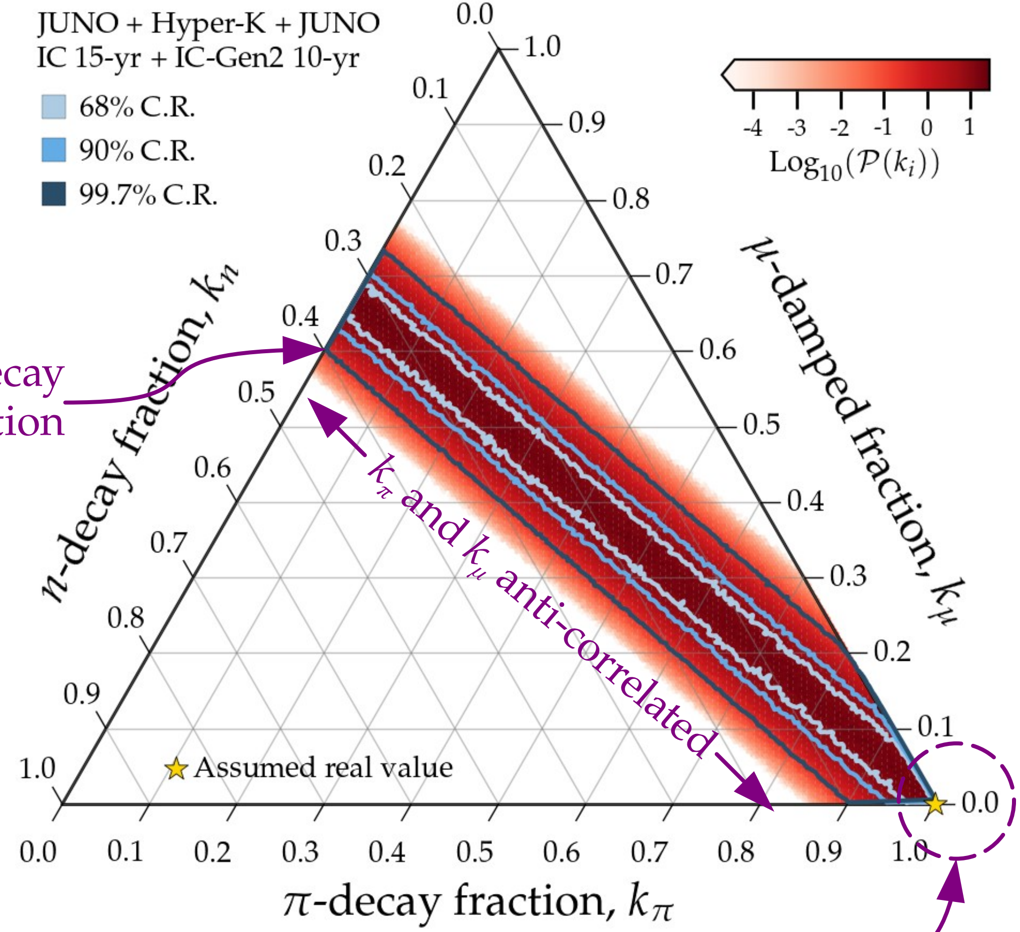

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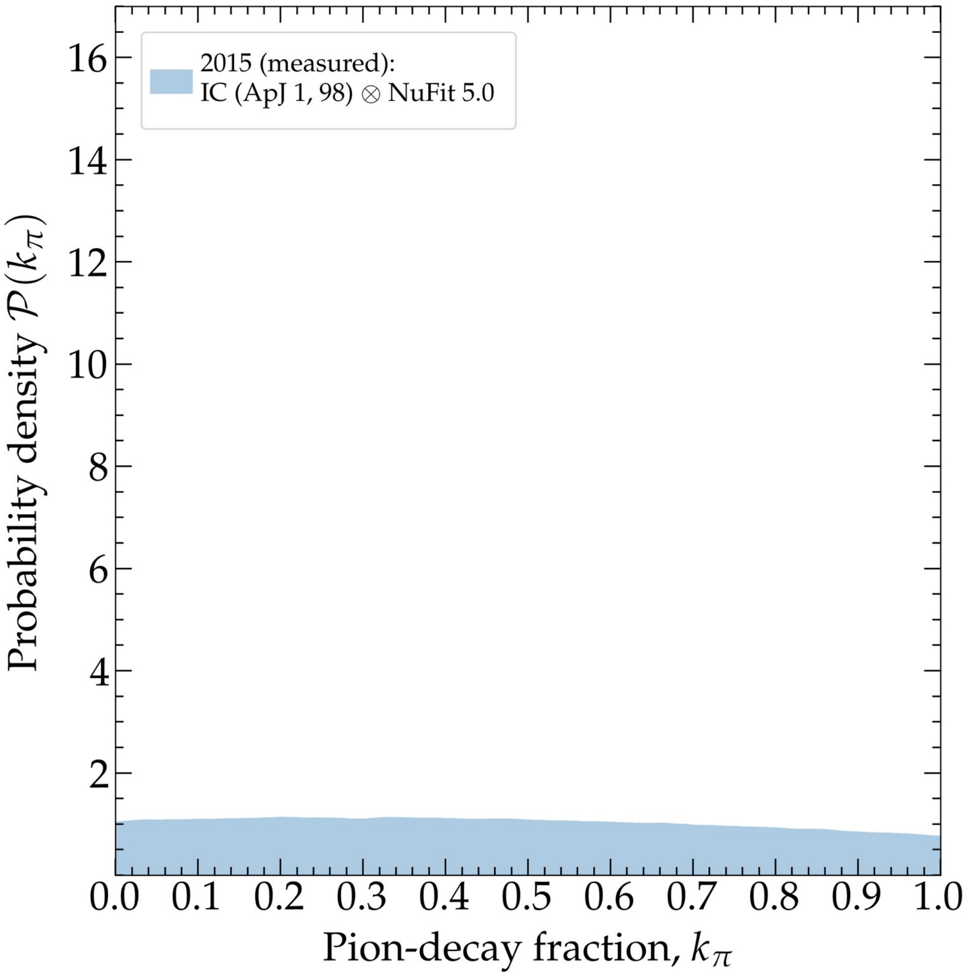

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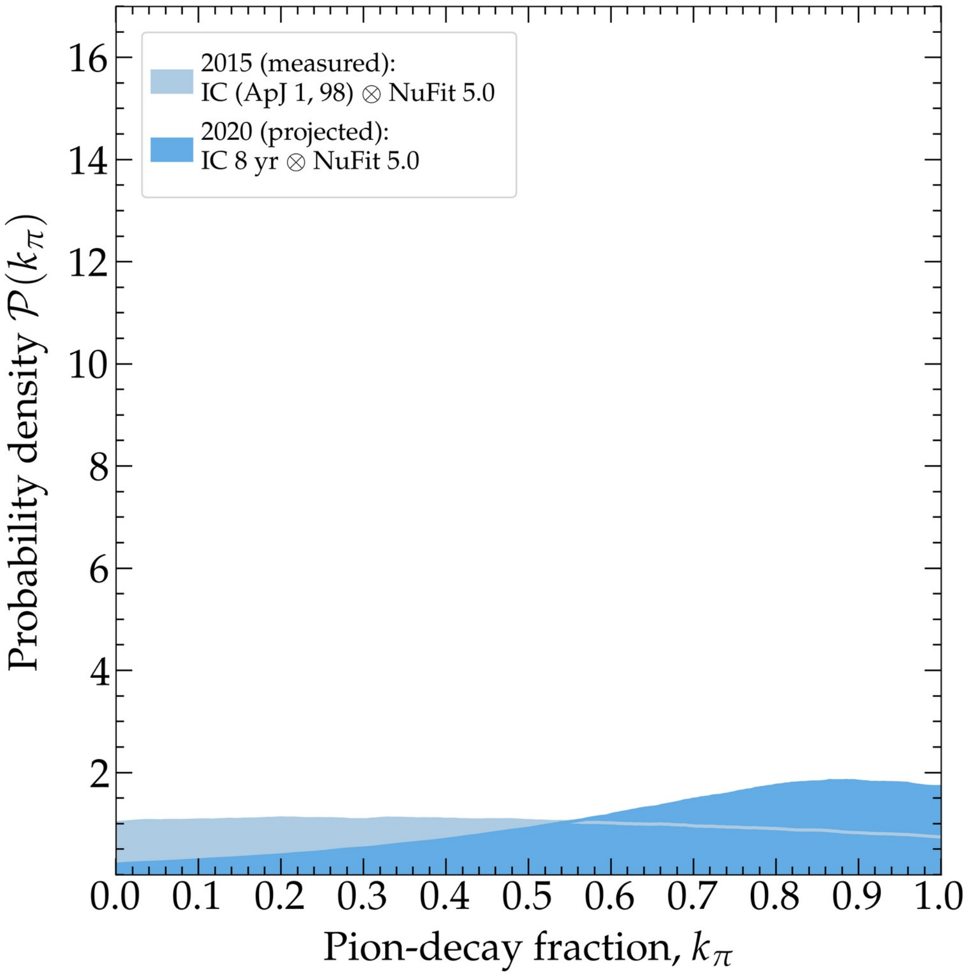

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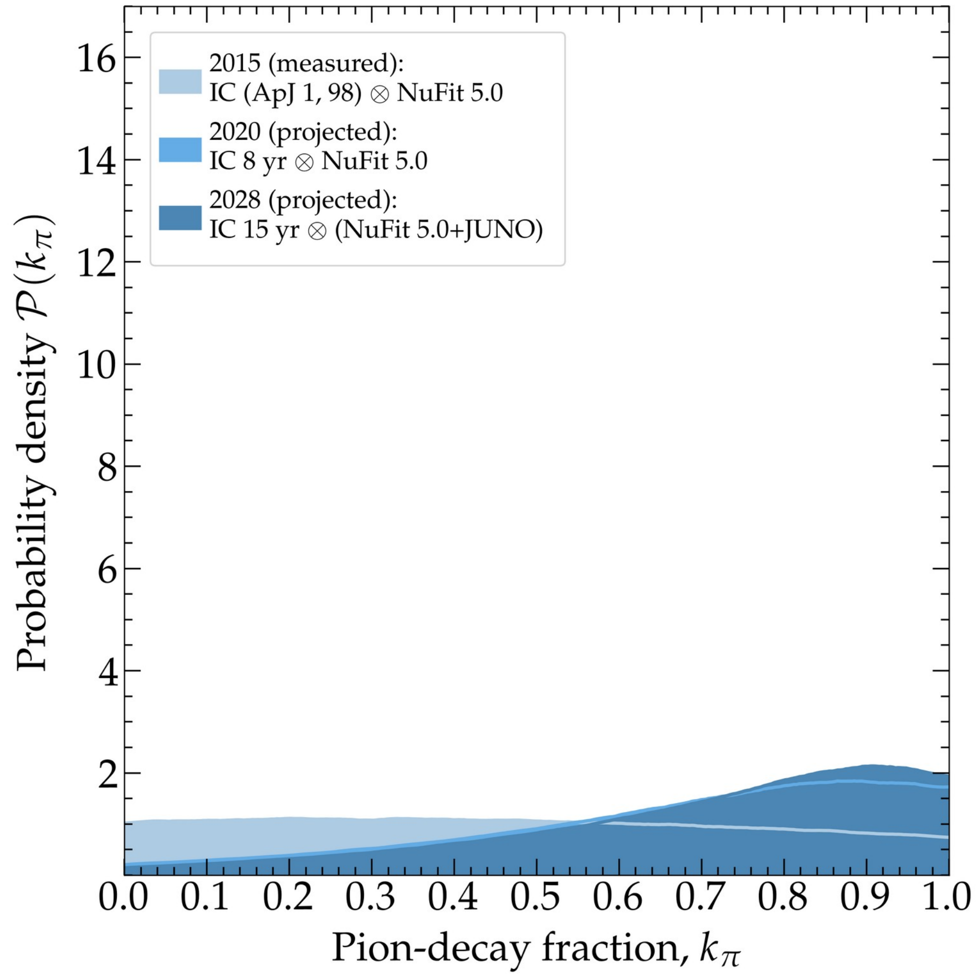

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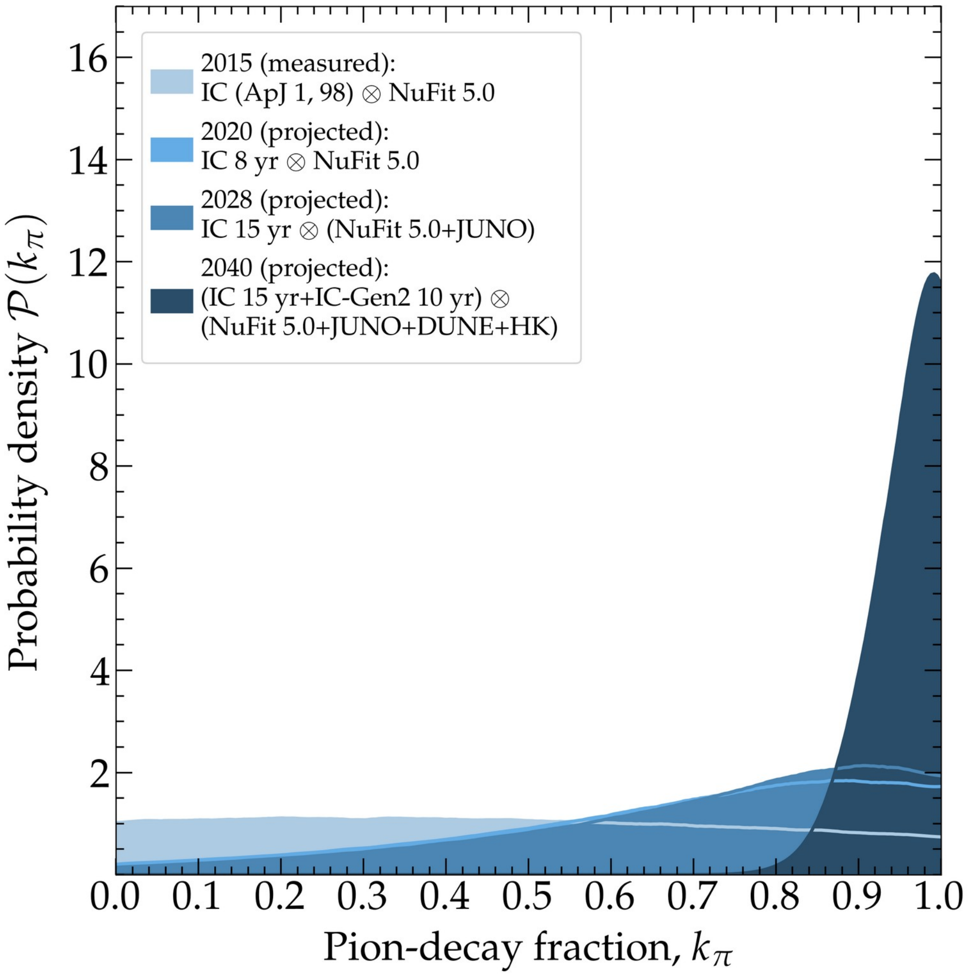

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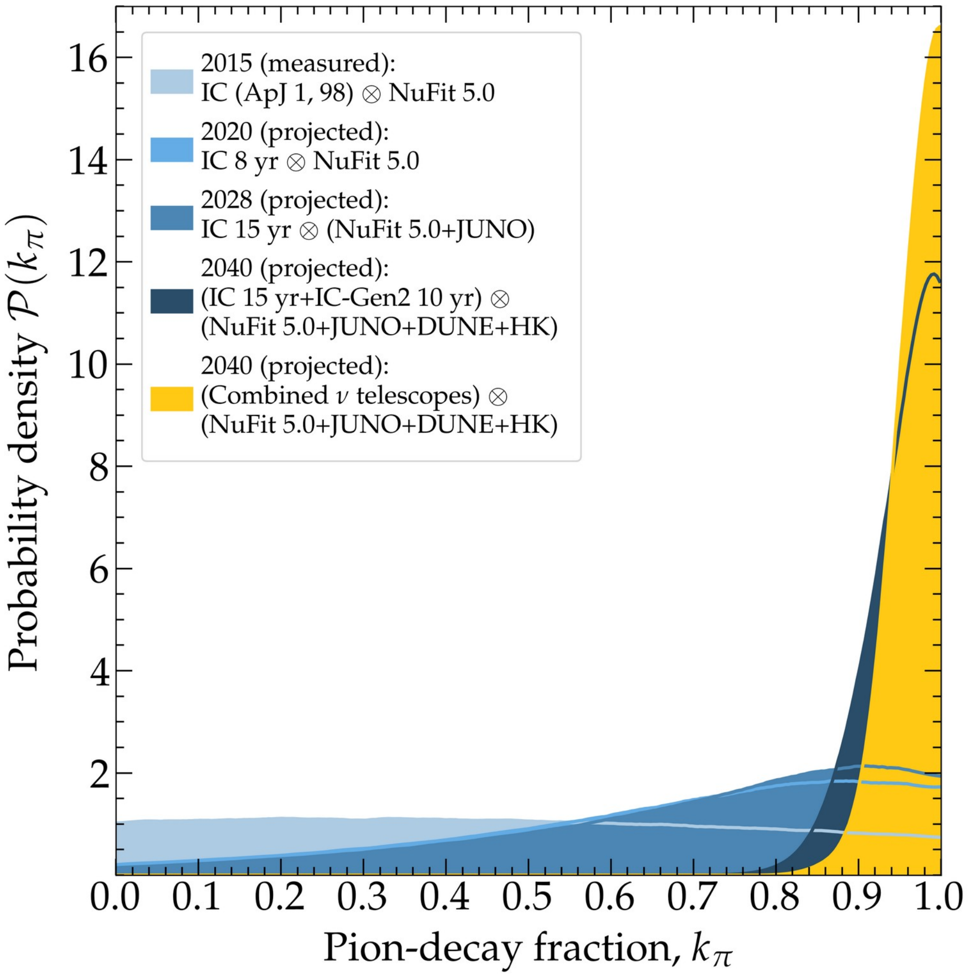

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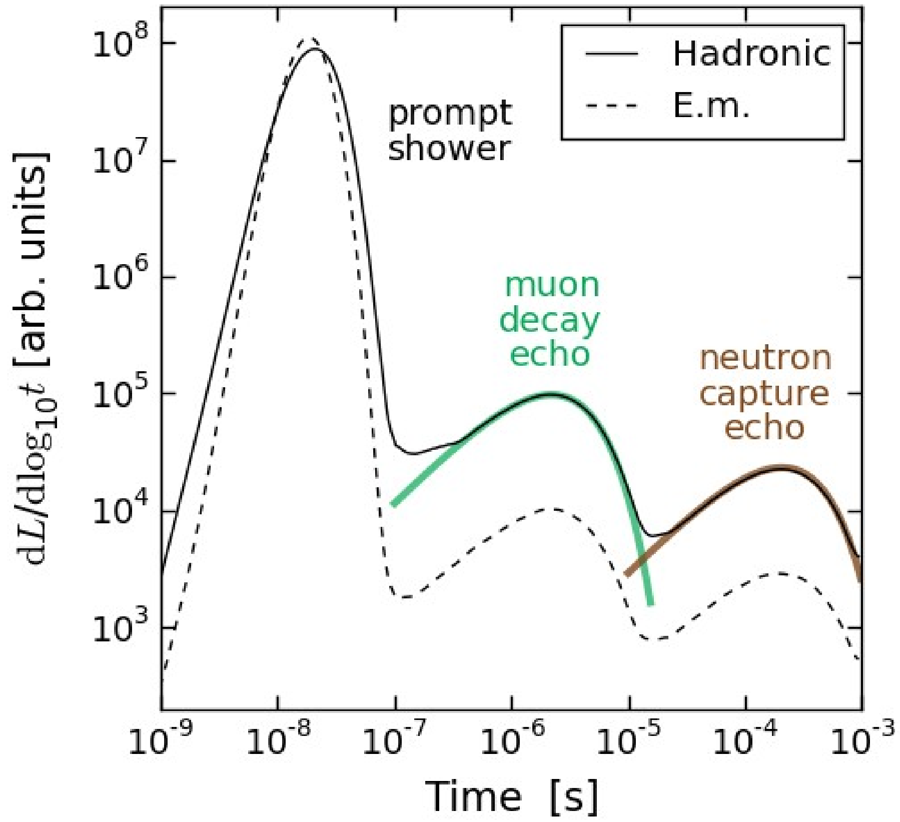
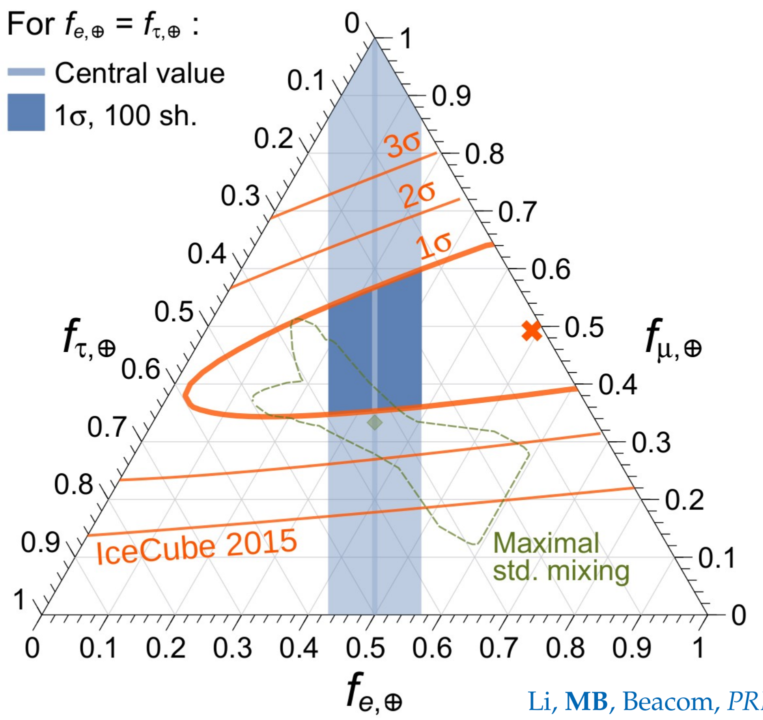
Side note: Improving flavor-tagging using *echoes*

Late-time light (*echoes*) from muon decays and neutron captures can separate showers made by ν_e and ν_τ –





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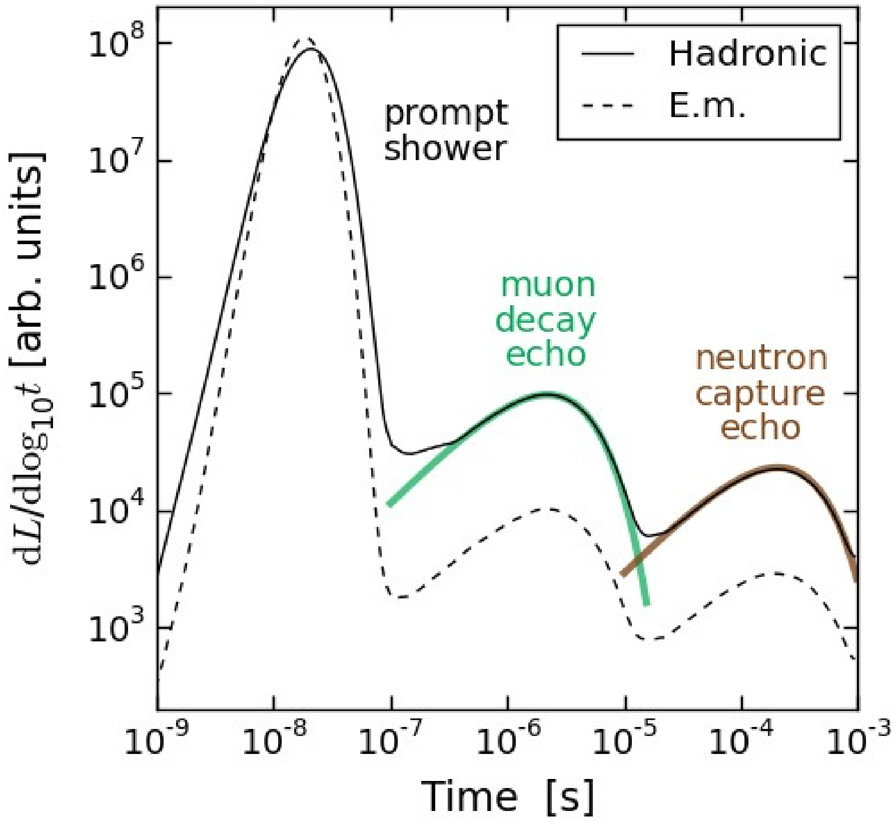
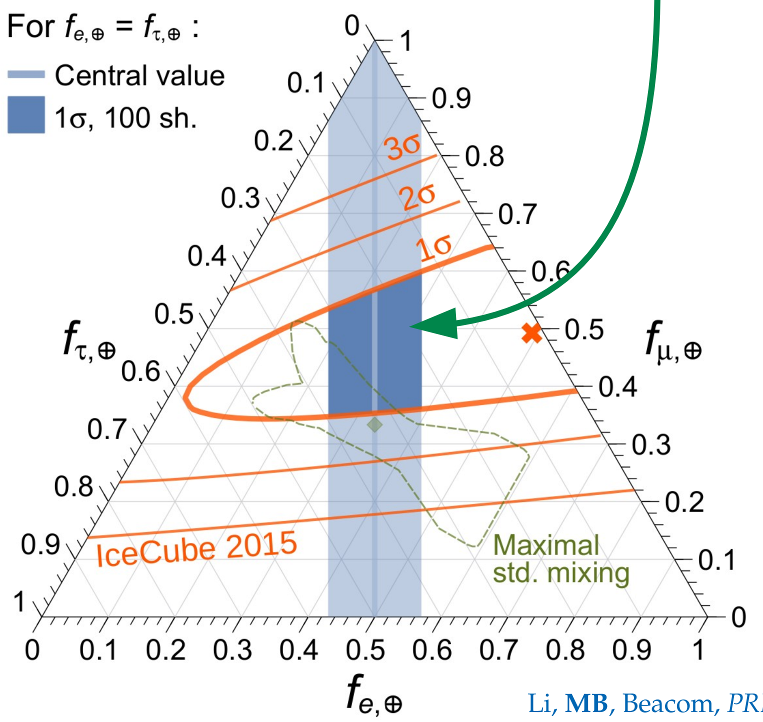


~10 × improvement over current measurement



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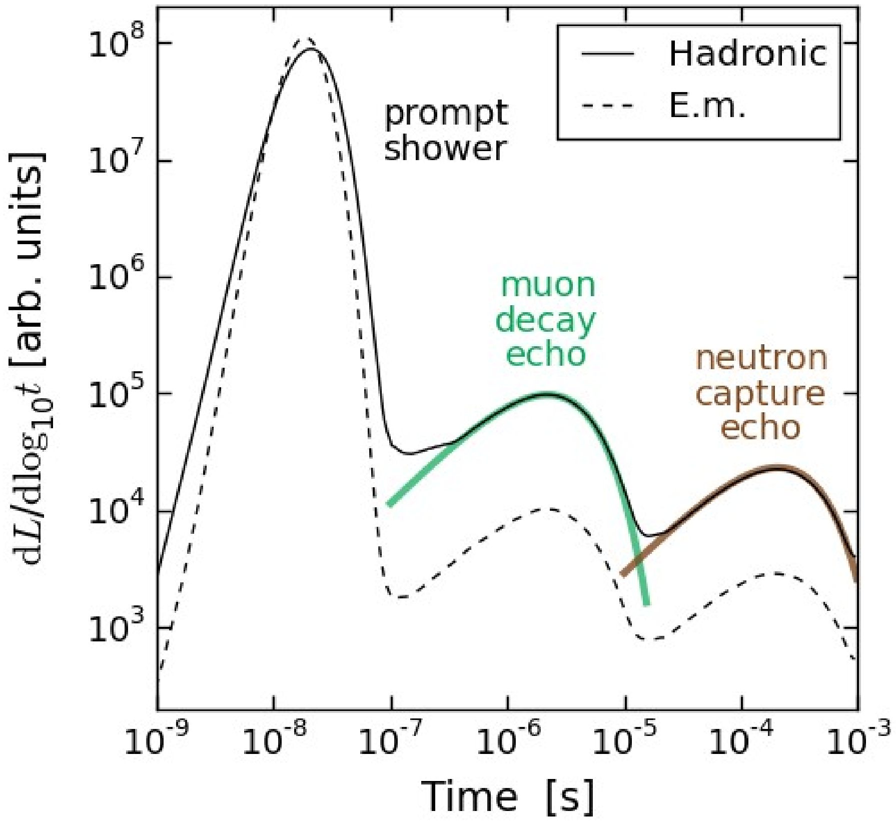

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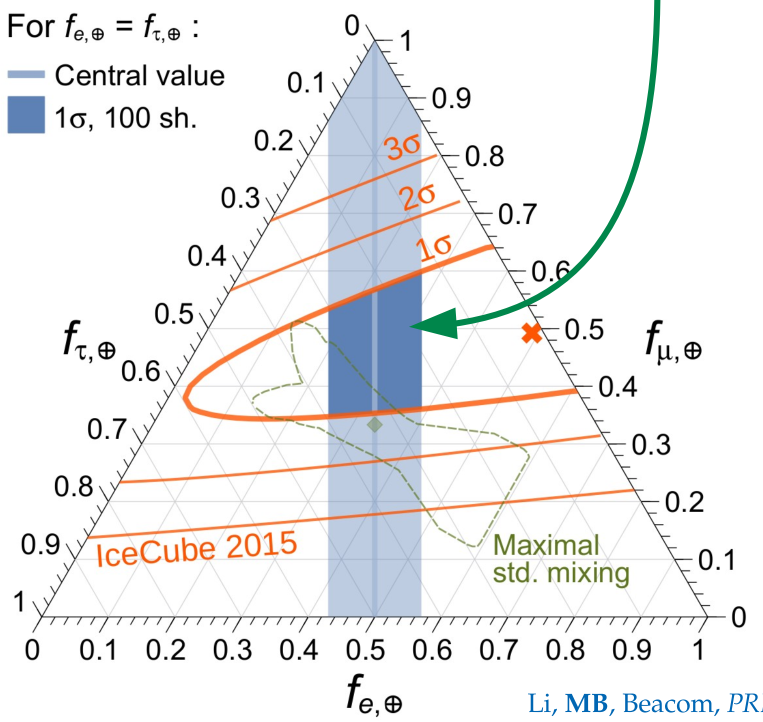
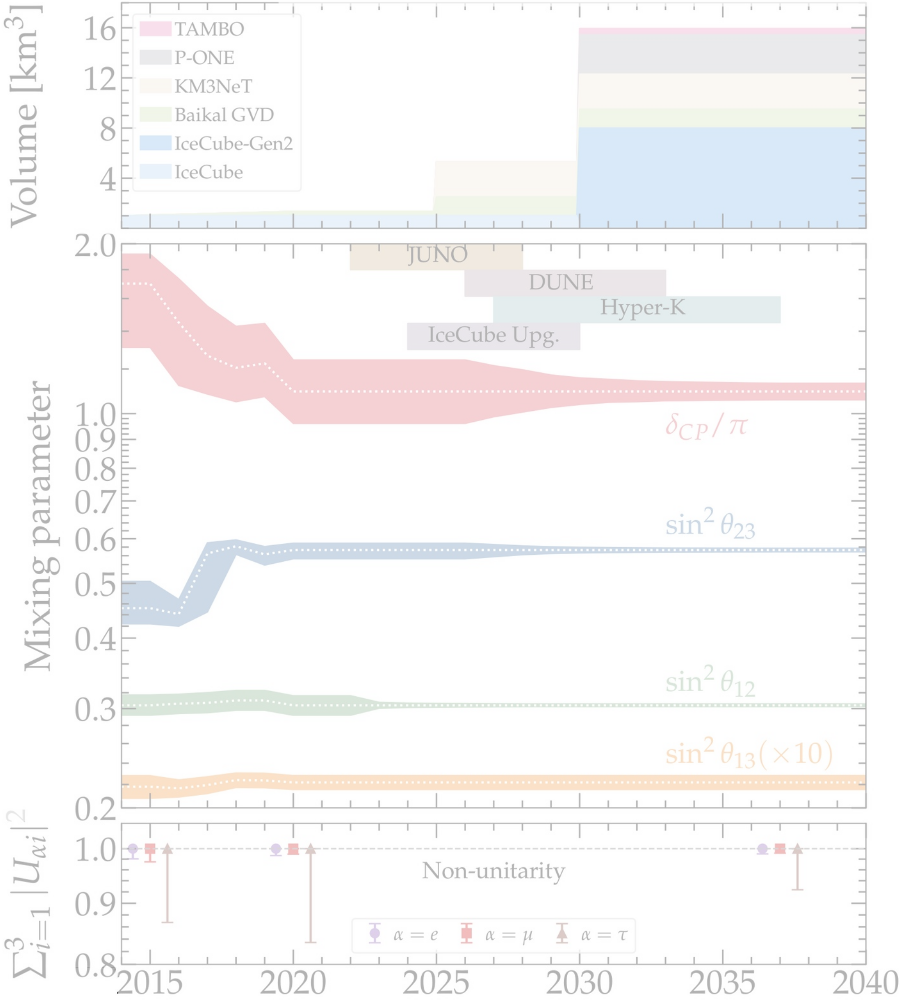


Li, **MB**, Beacom, *PRL* 2019

Three reasons to be excited

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



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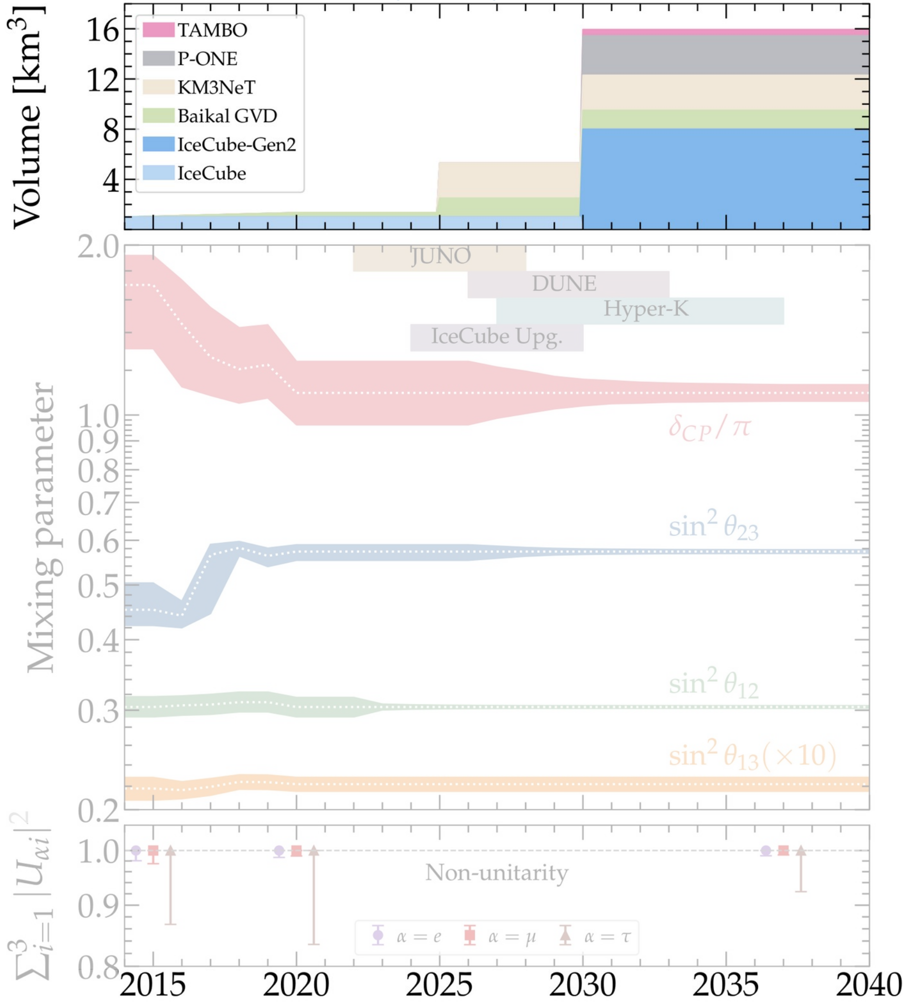

Flavor measurements:
New neutrino telescopes = more events, better flavor measurement

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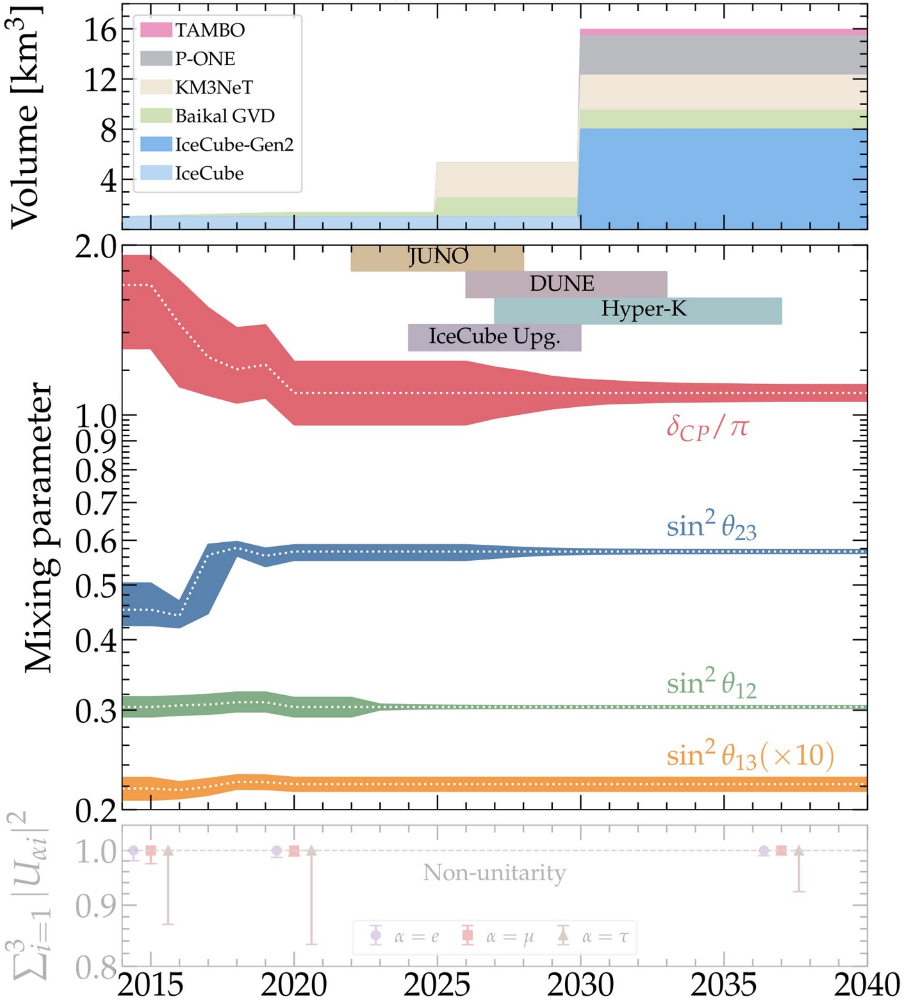

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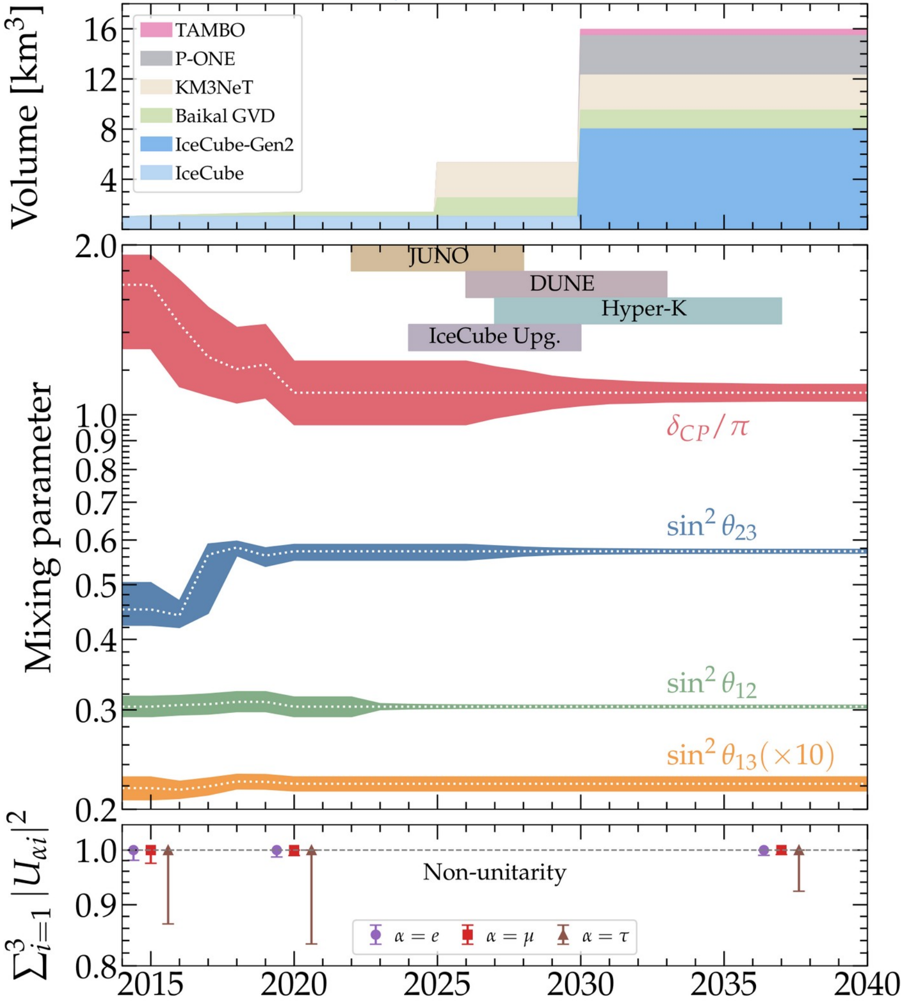

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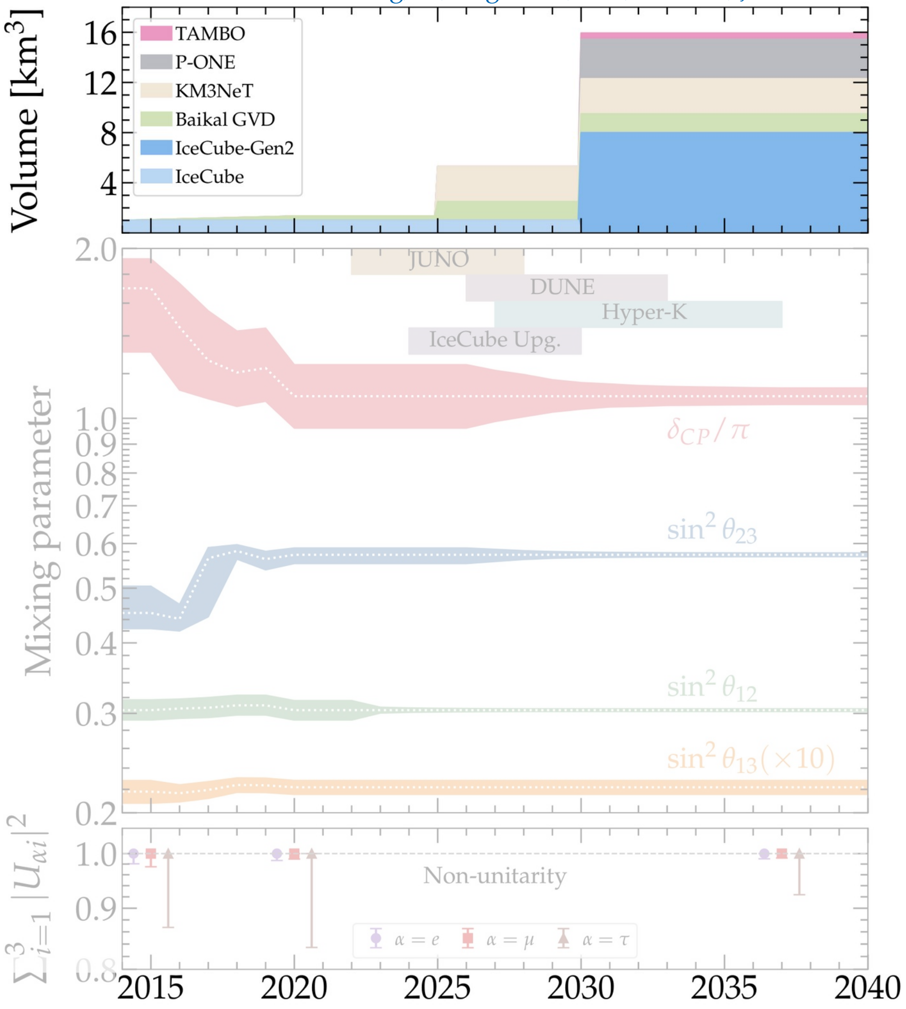
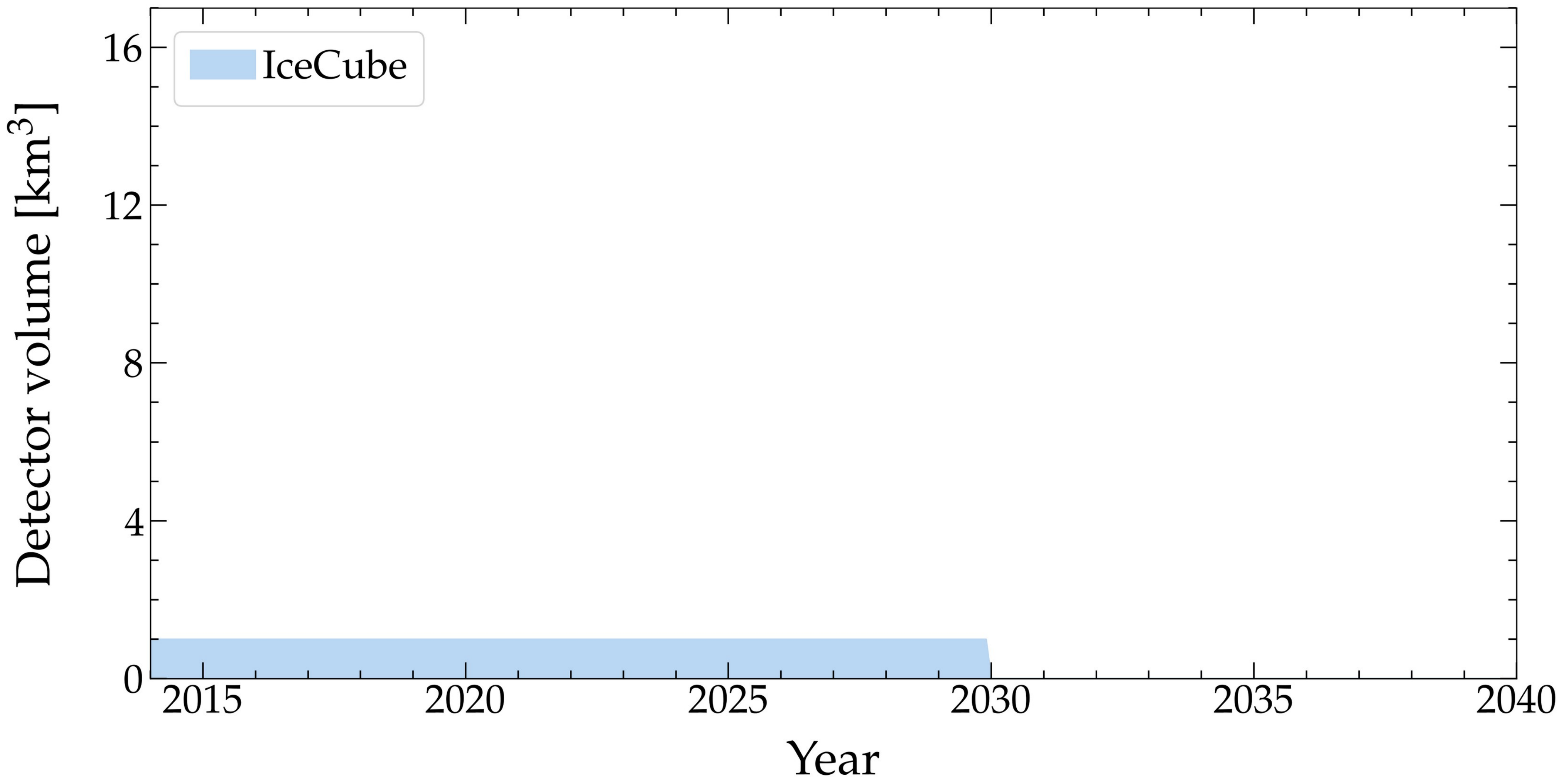
We will know the mixing parameters better (JUNO, DUNE, Hyper-K, IceCube Upgrade)

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





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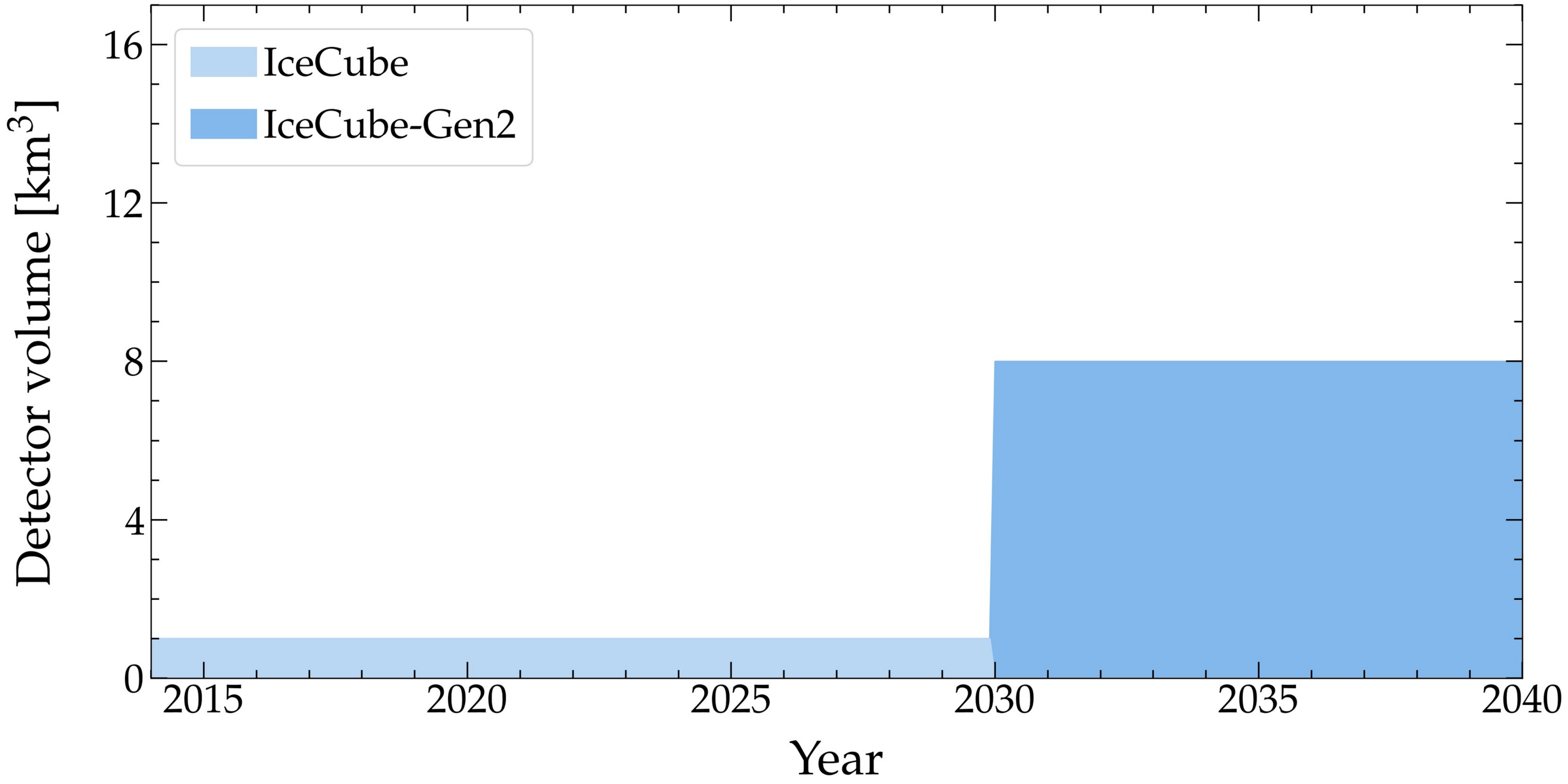

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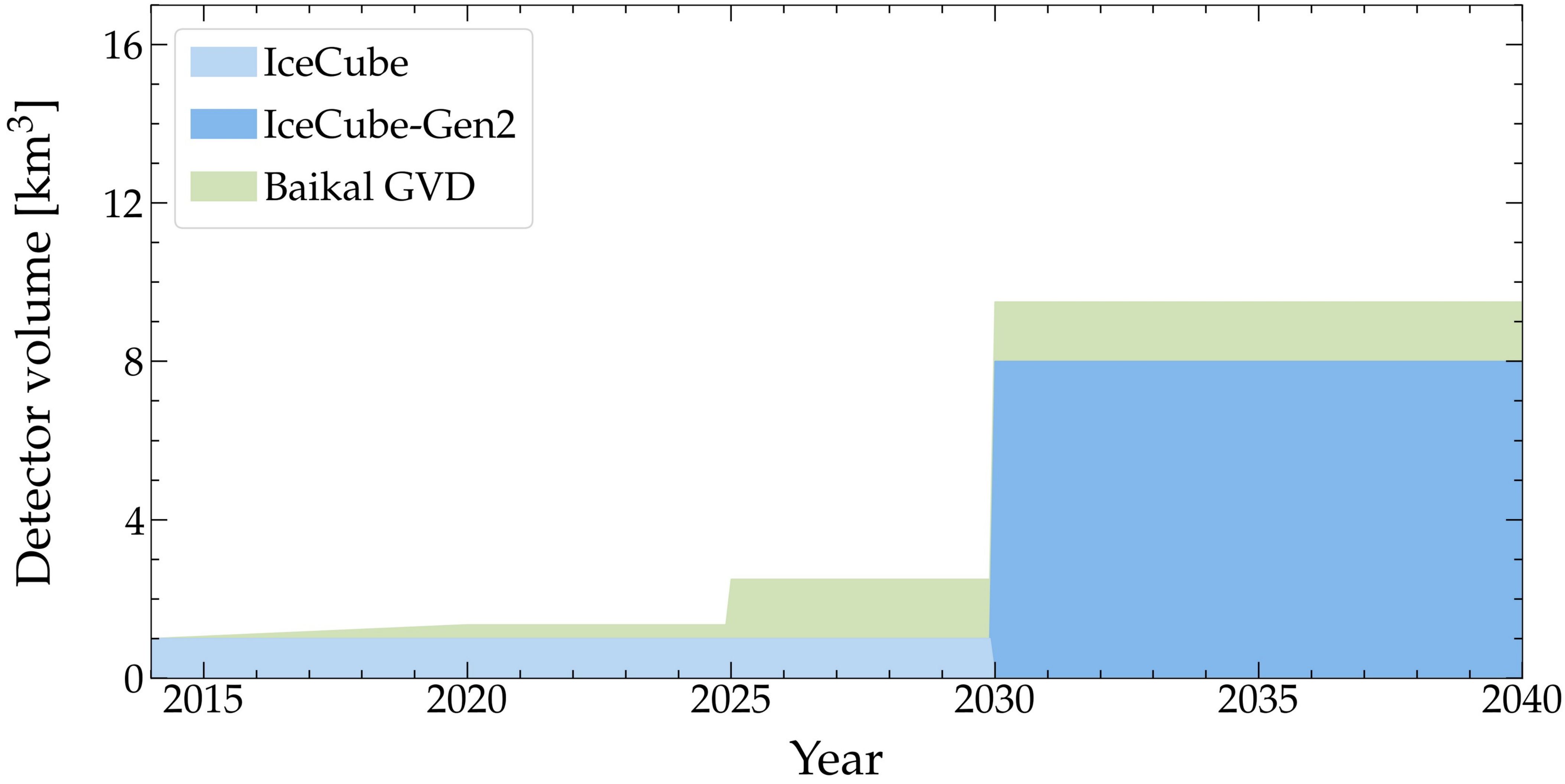

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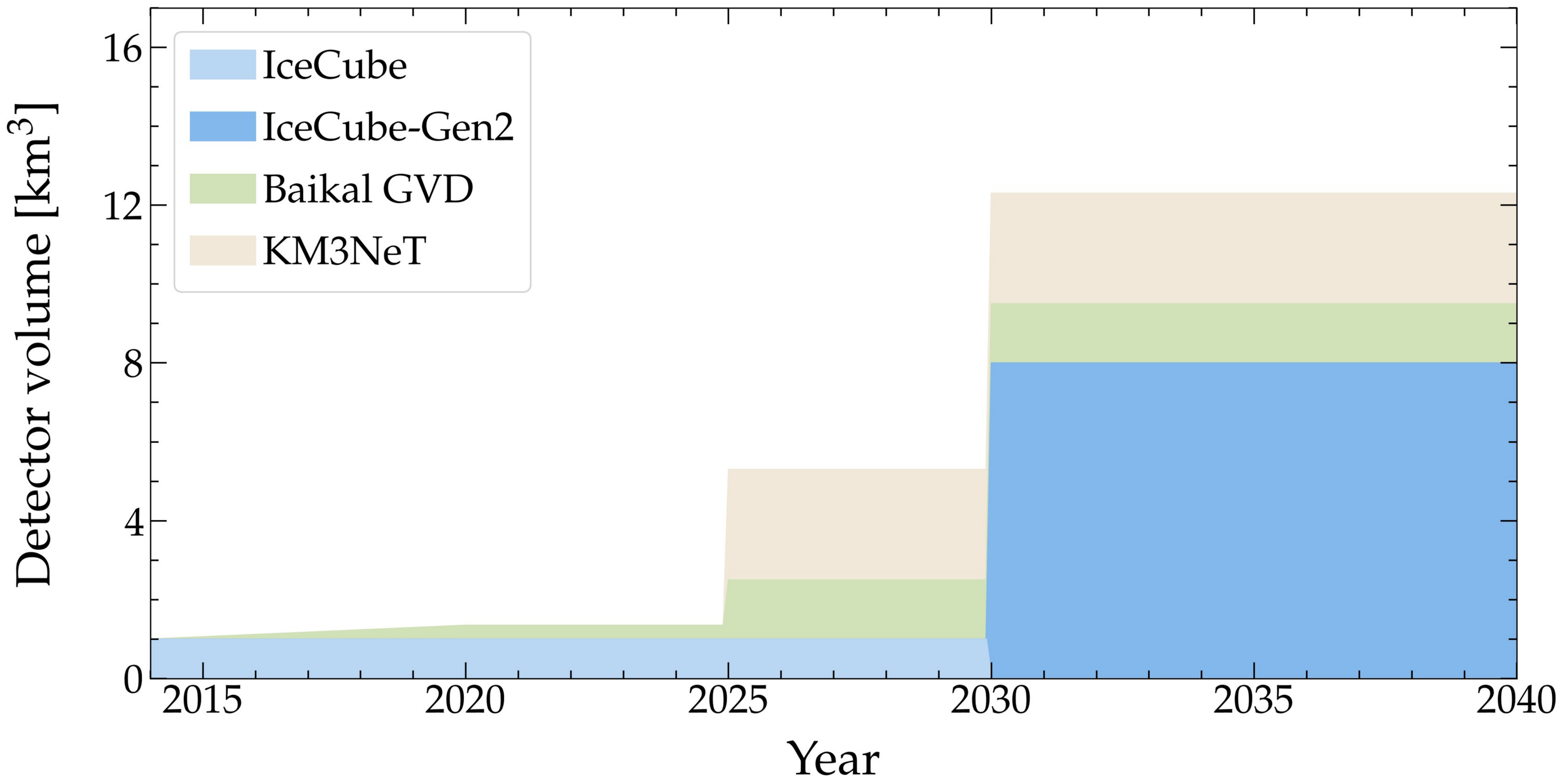

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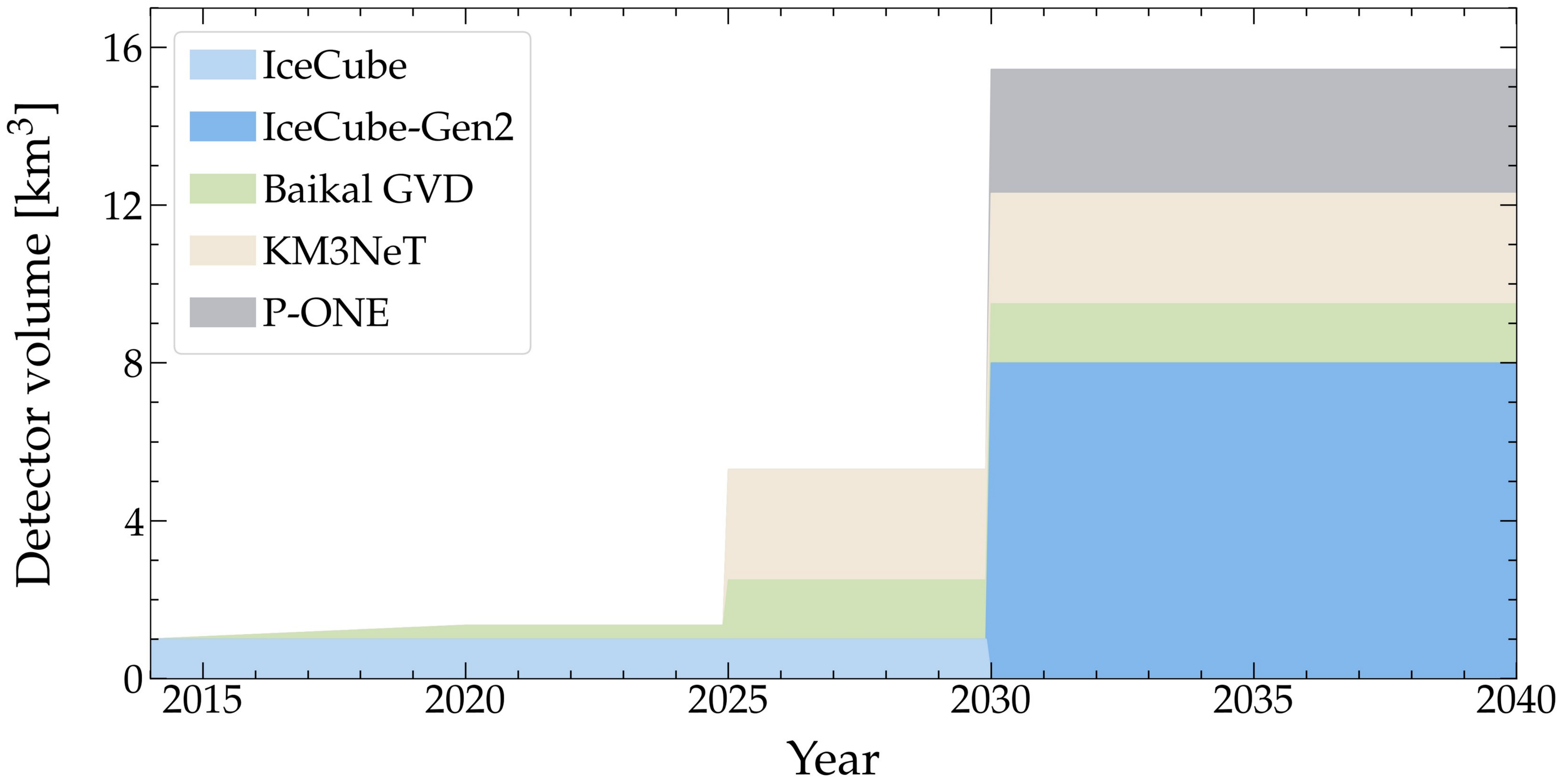

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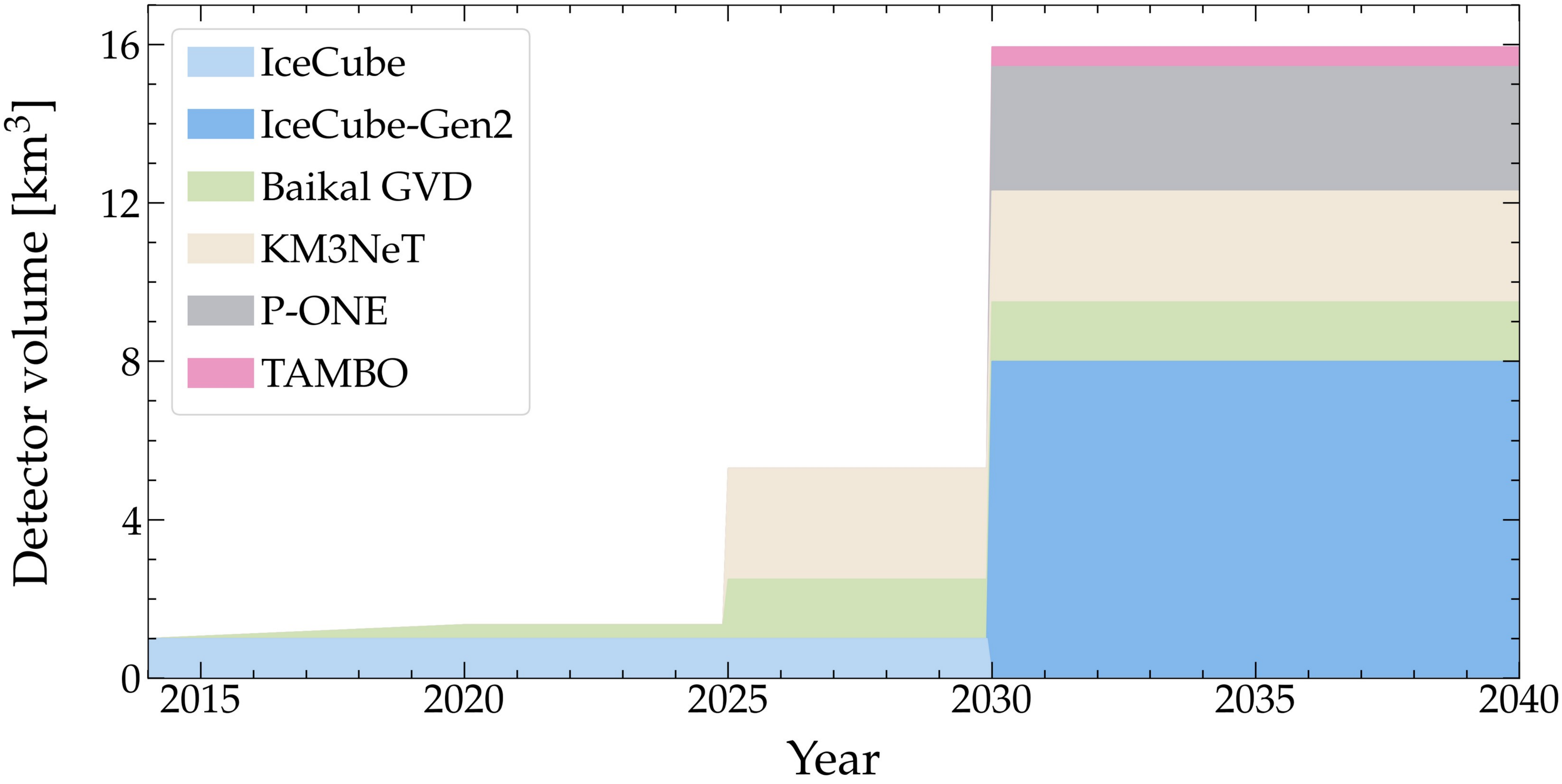

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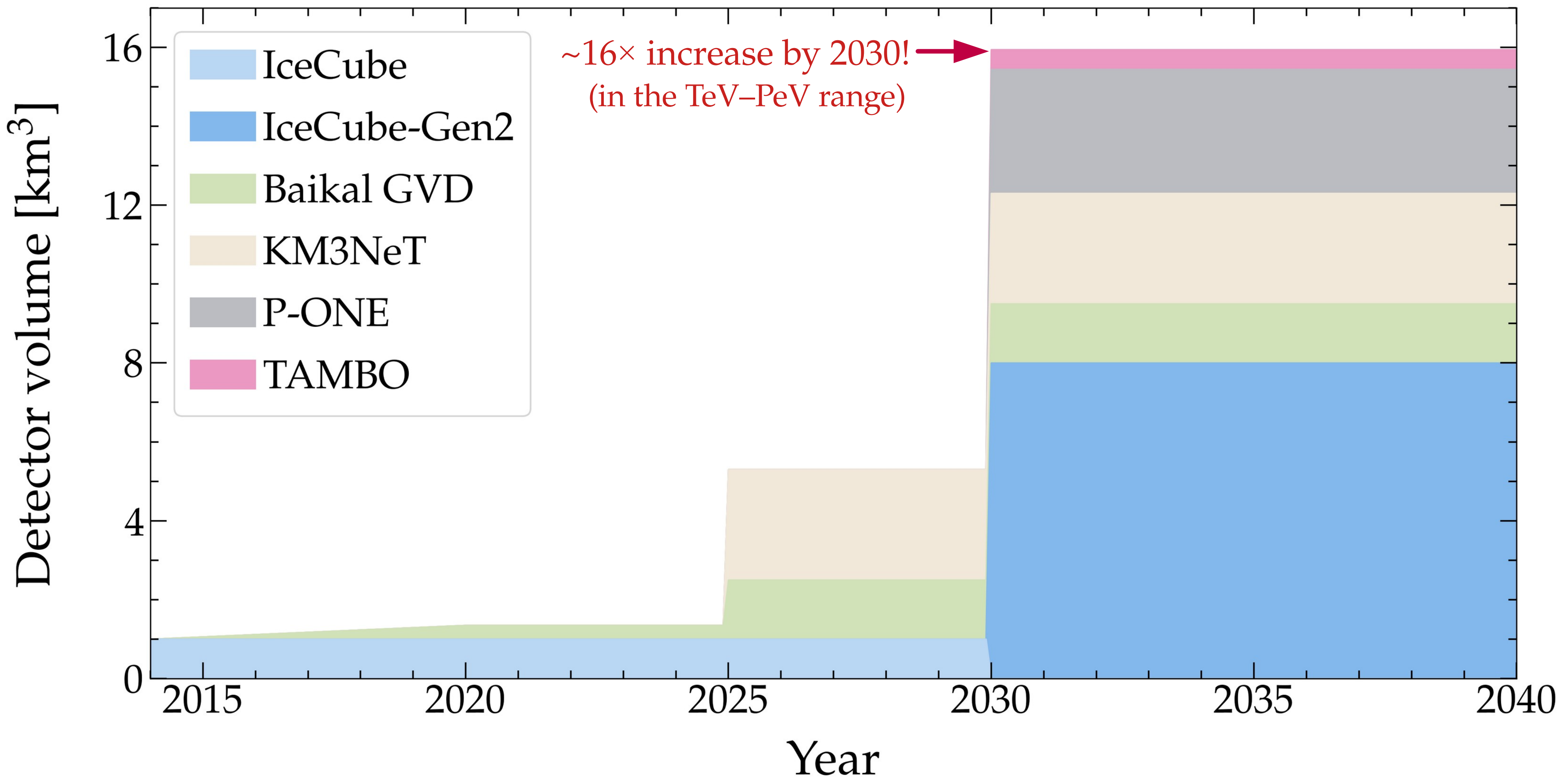
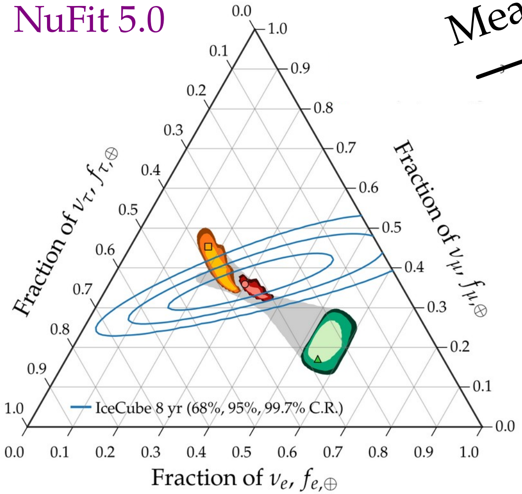


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

How knowing the mixing parameters better helps

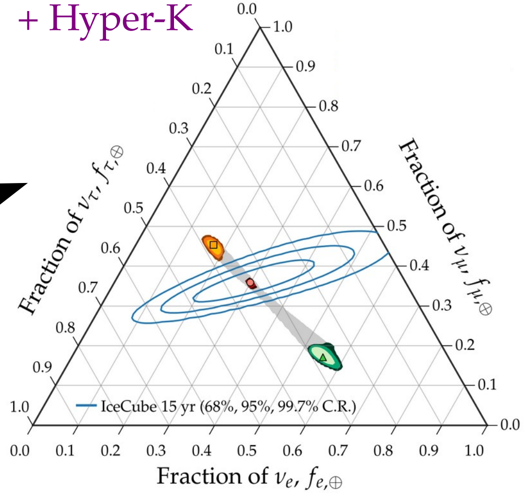
2020

NuFit 5.0



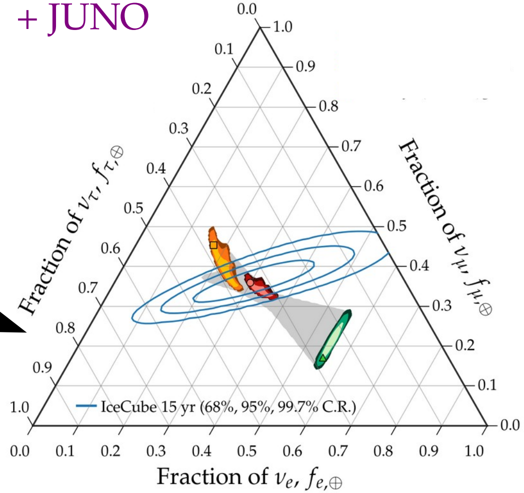
Measure θ_{23} better

\+ Hyper-K



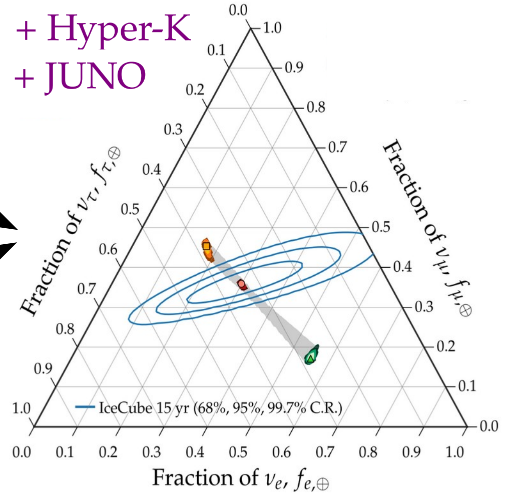
Measure θ_{12} better

\+ JUNO



~2030

\+ Hyper-K
\+ JUNO



In our results:
JUNO + Hyper-K + DUNE

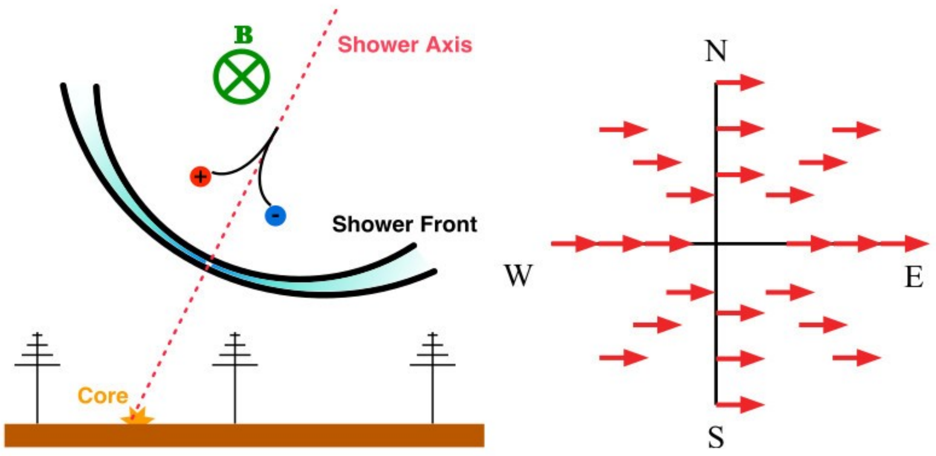
Marginal improvement til 2040

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

Detectors

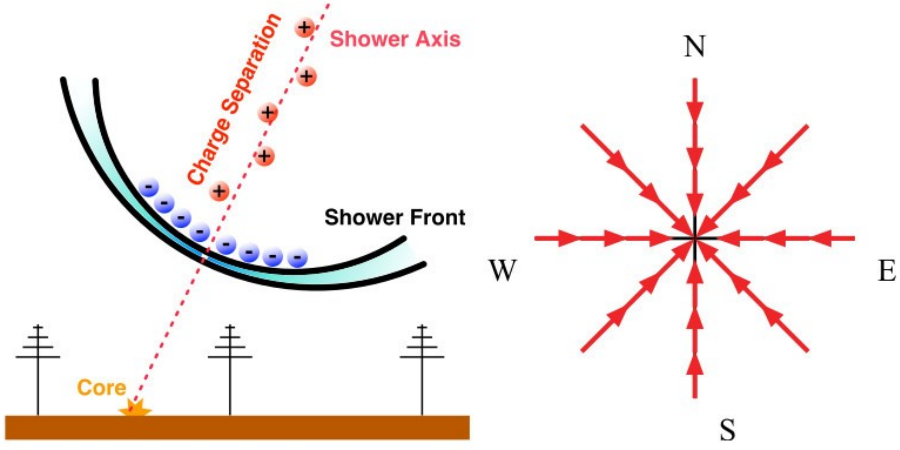
Radio emission: geomagnetic and Askaryan

Geomagnetic



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

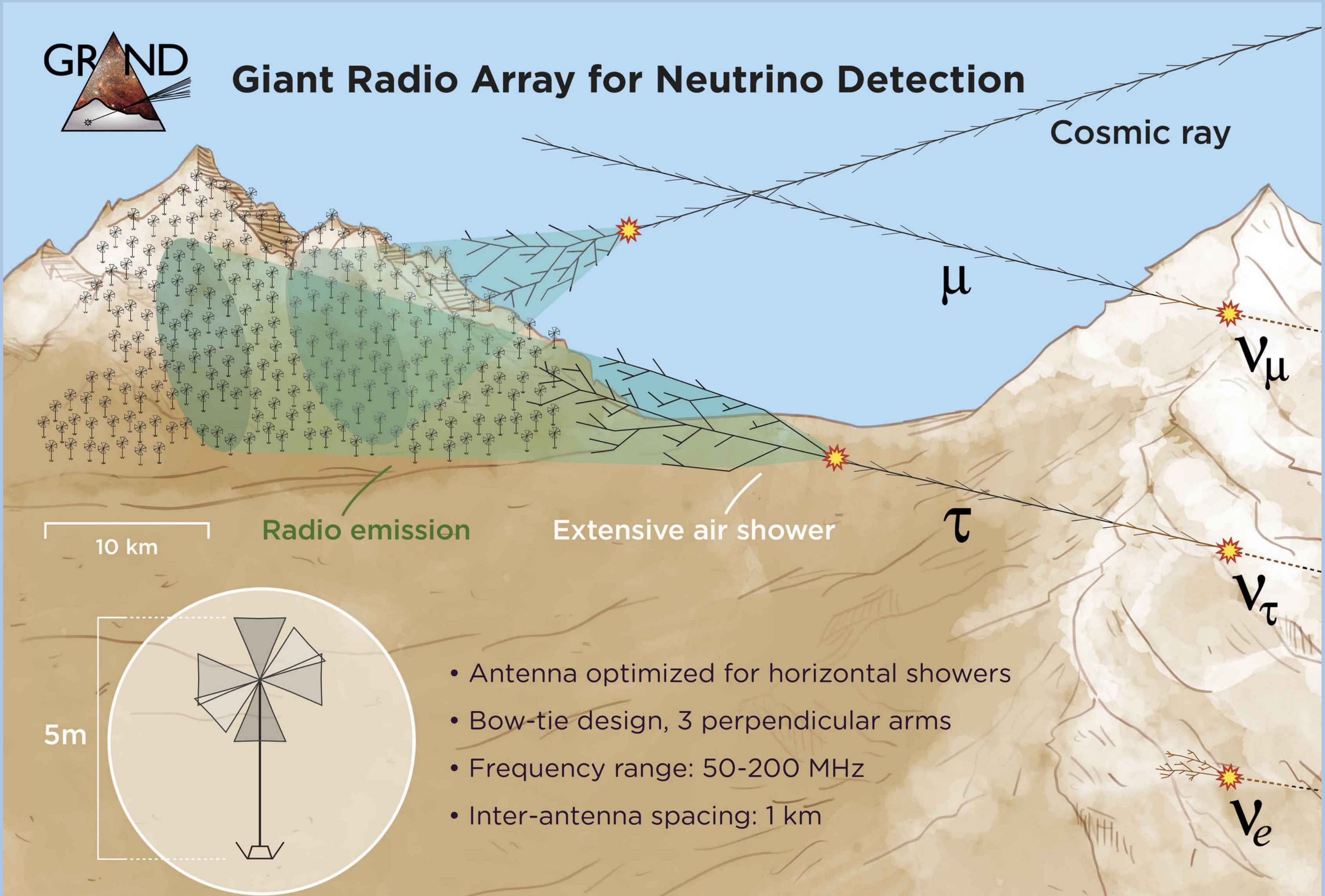
Askaryan



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

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

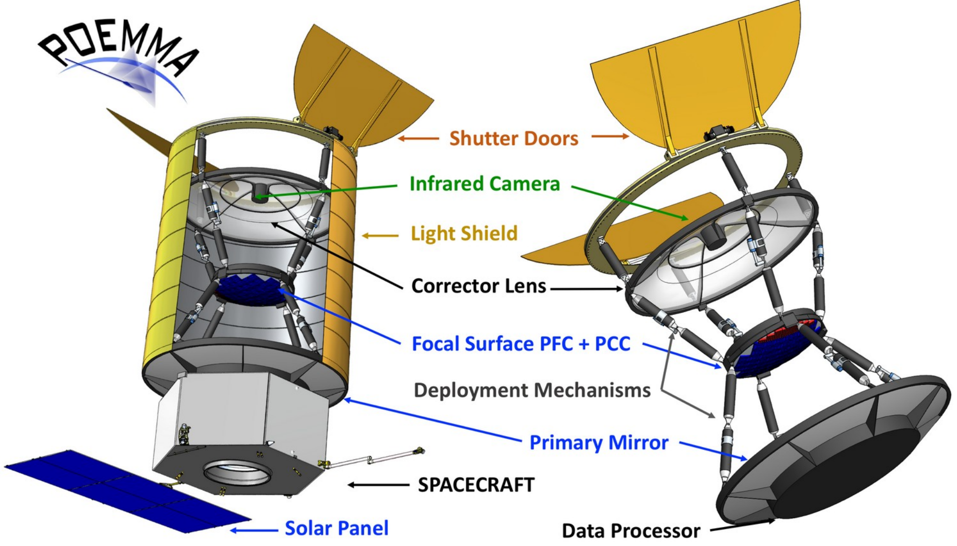
Radio emission: geomagnetic and Askaryan

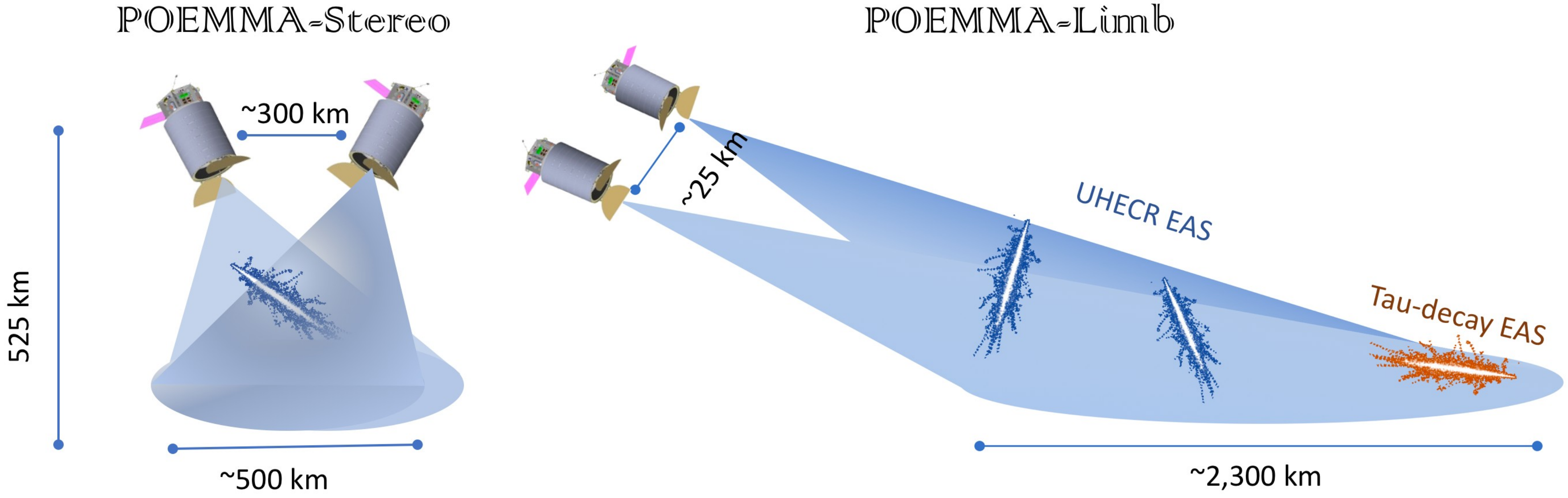


GRAND, *Sci. China Phys. Mech. Astron.* 2020 [1810.9994]

POEMMA:
Probe of Extreme Multi-Messenger Astrophysics

POEMMA, *JCAP* 2021 (2012.07945)





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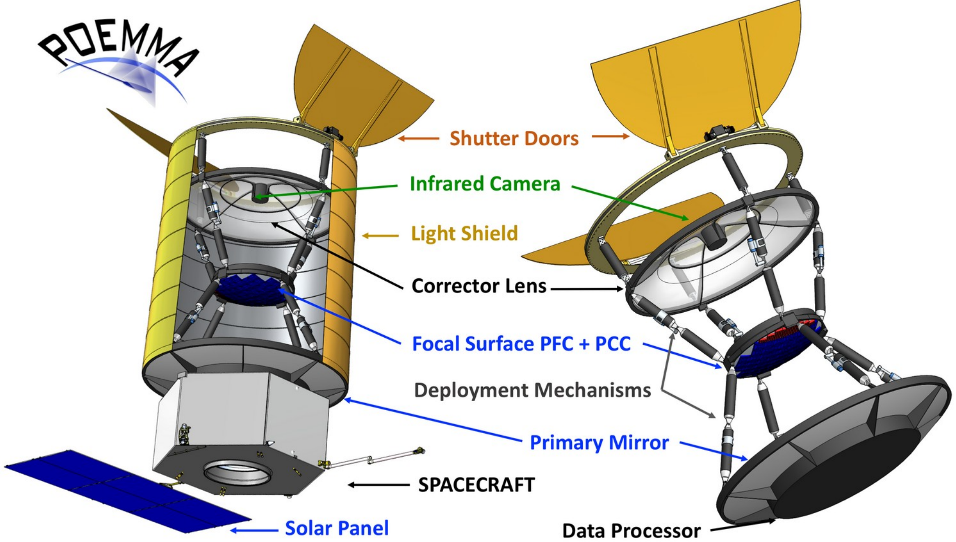
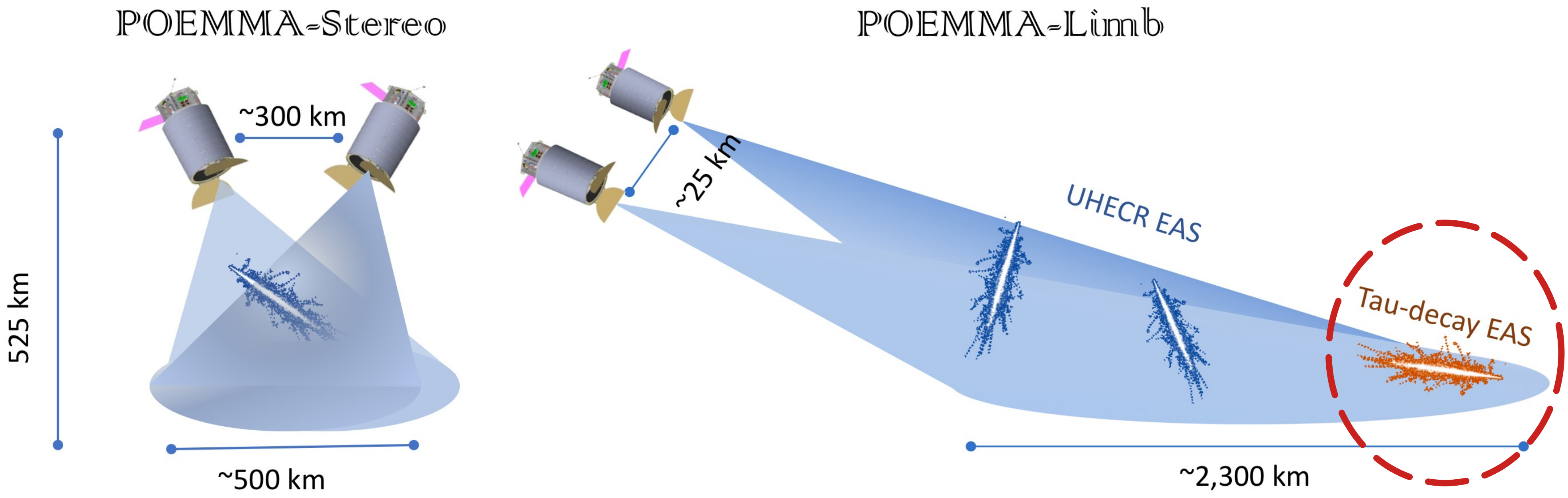
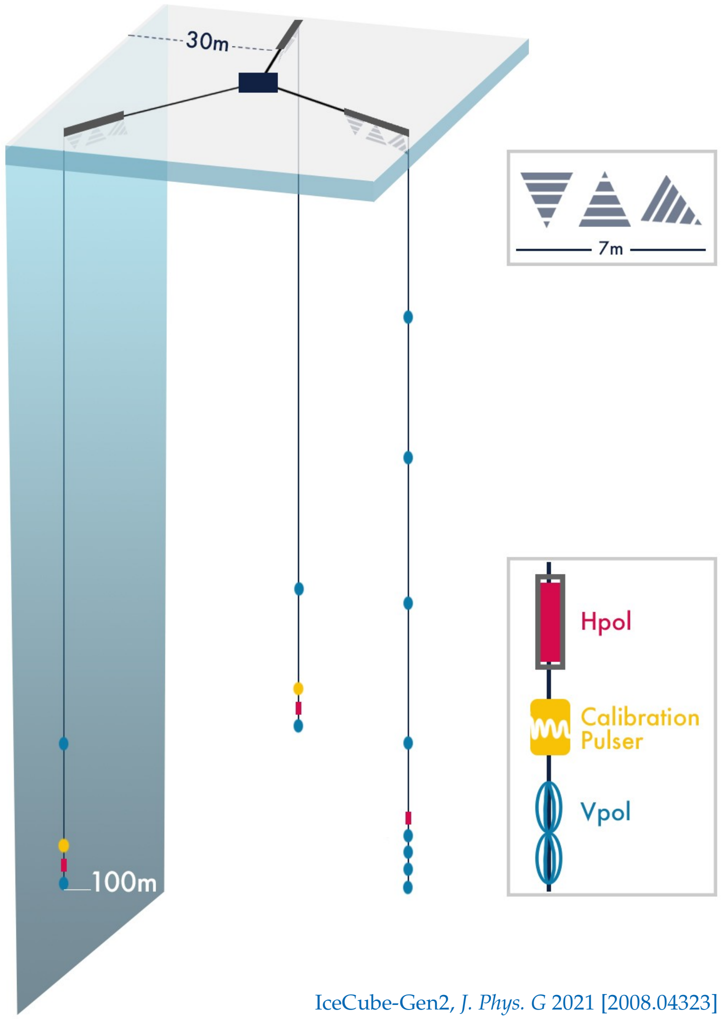
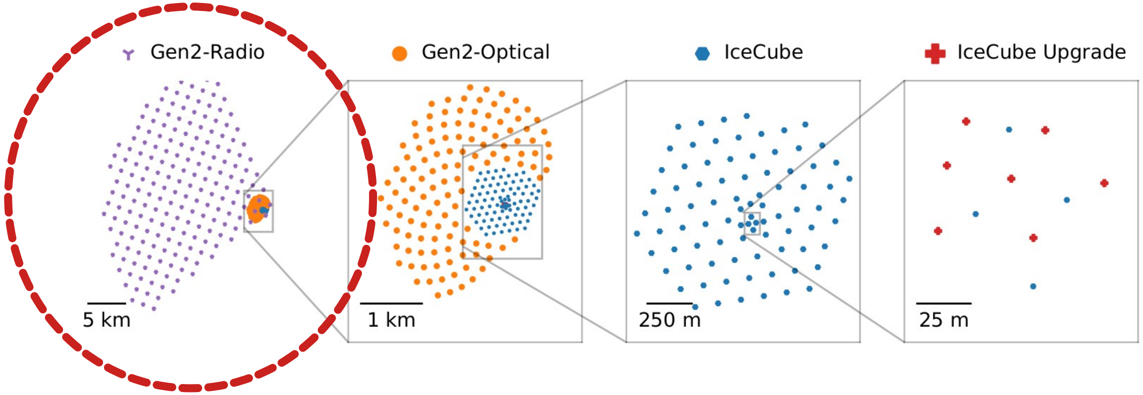


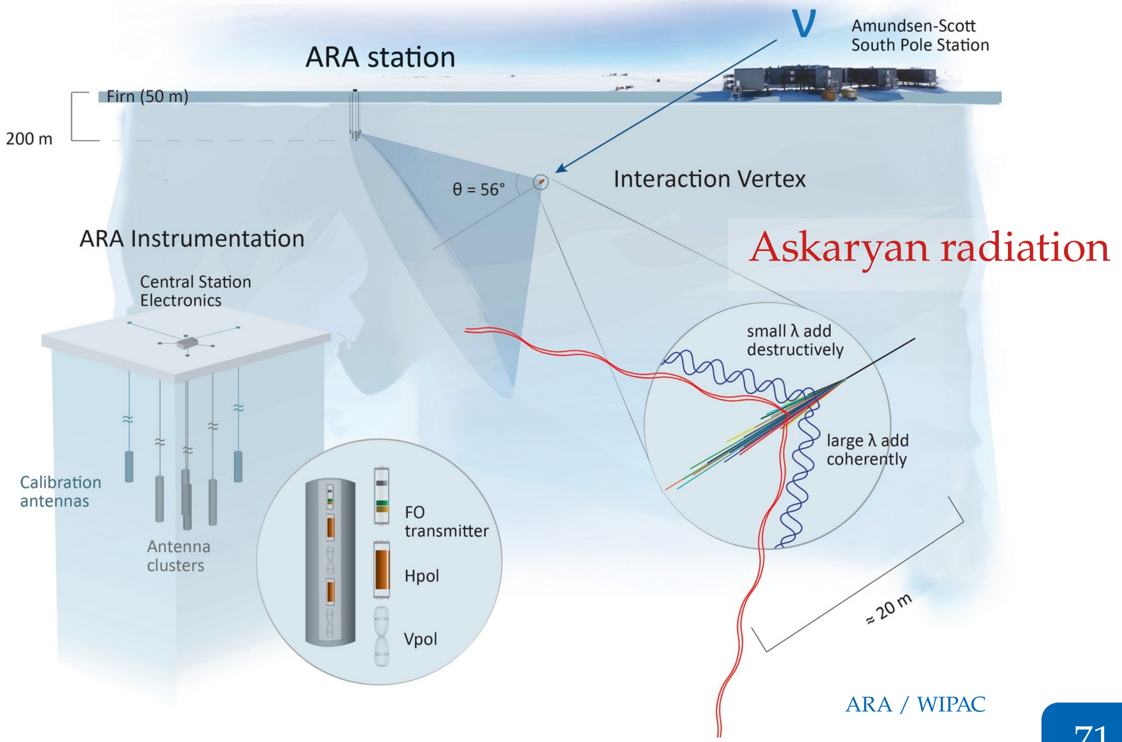


IceCube-Gen2 Radio



IceCube-Gen2, *J. Phys. G* 2021 [2008.04323]





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