A theory overview of high-energy cosmic neutrinos

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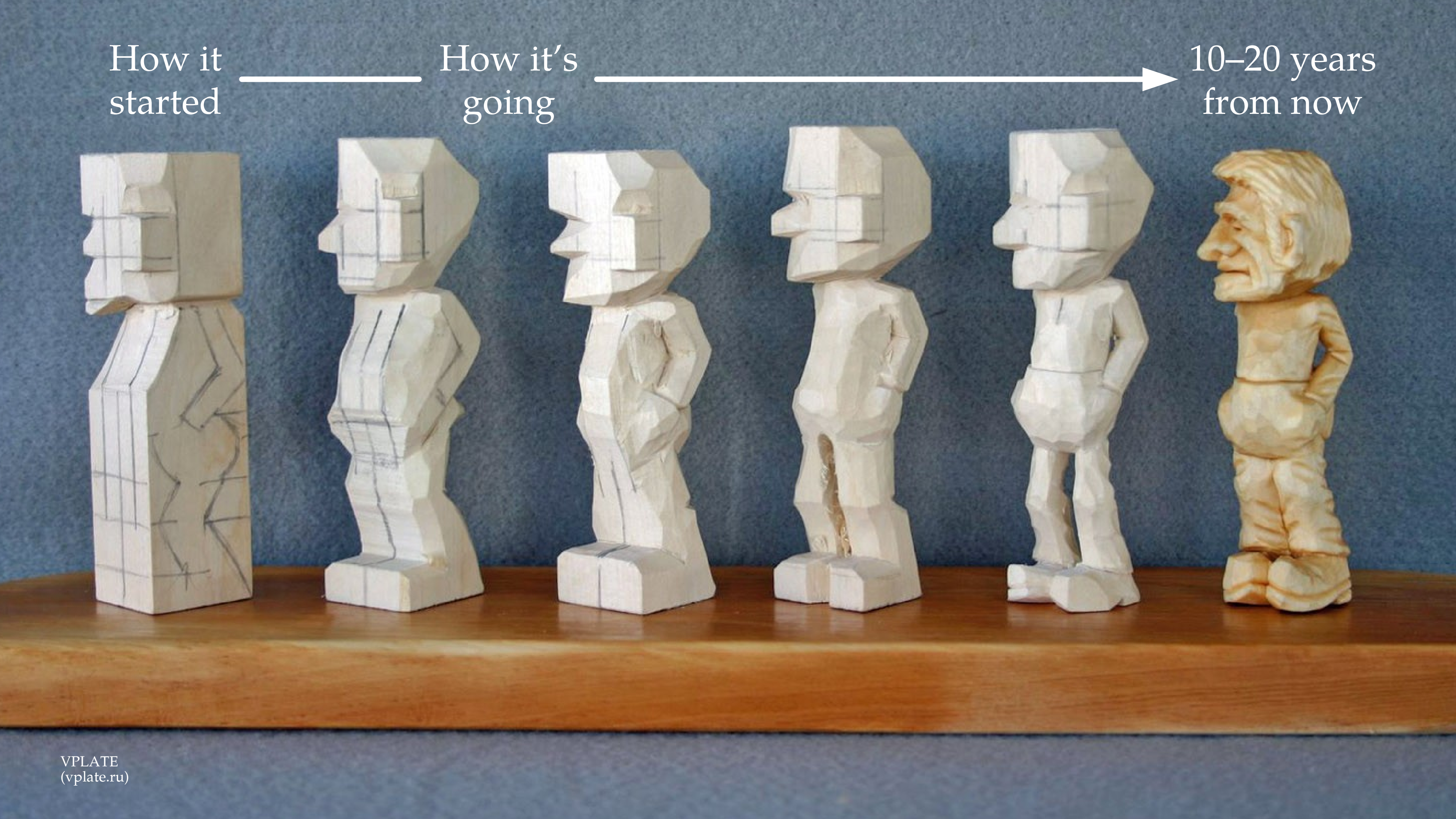
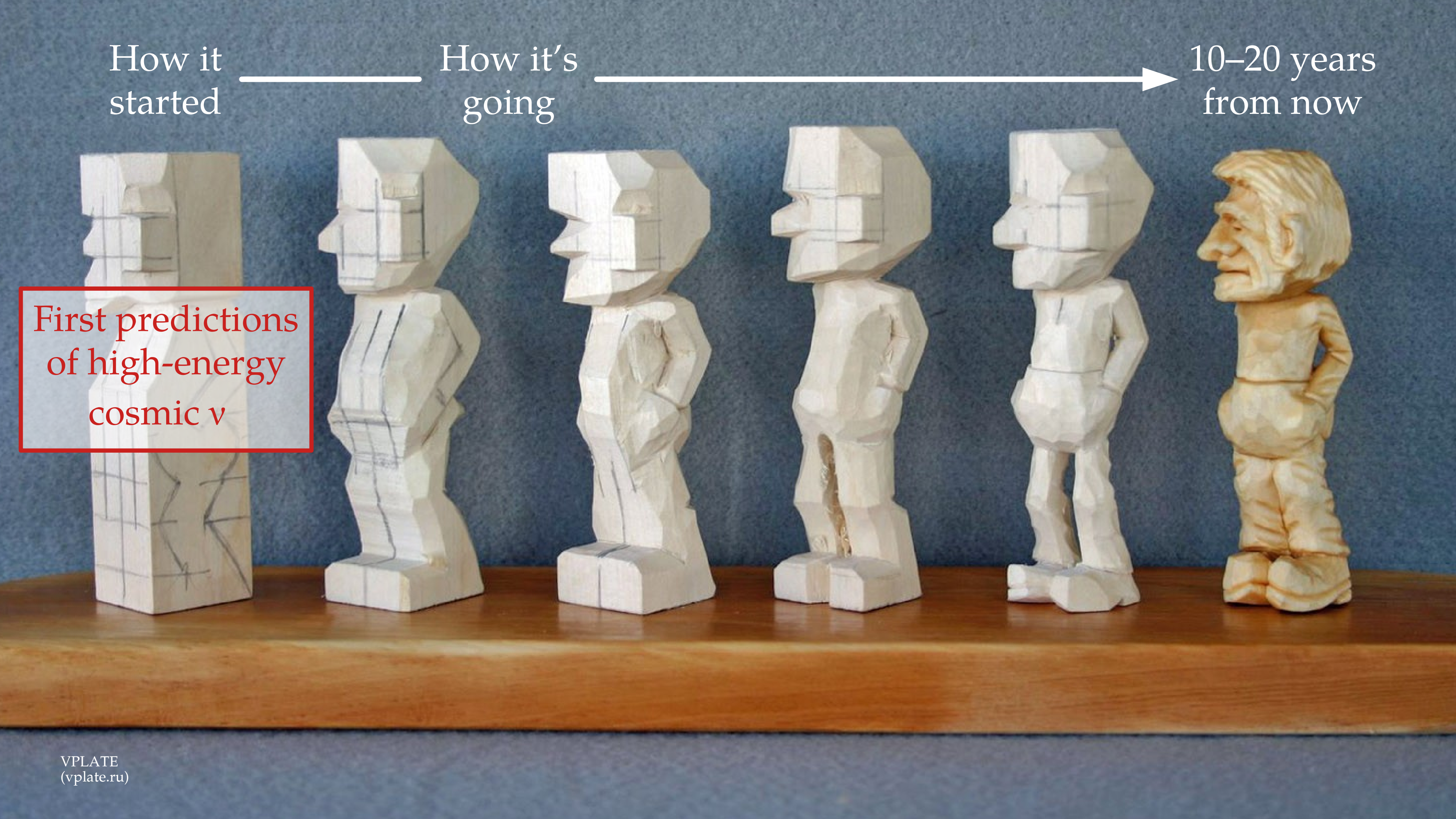
XIX TAUP
Xichang, China, August 25, 2025

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN


How it started
How it's going
10–20 years from now
VPLATE
(vplate.ru)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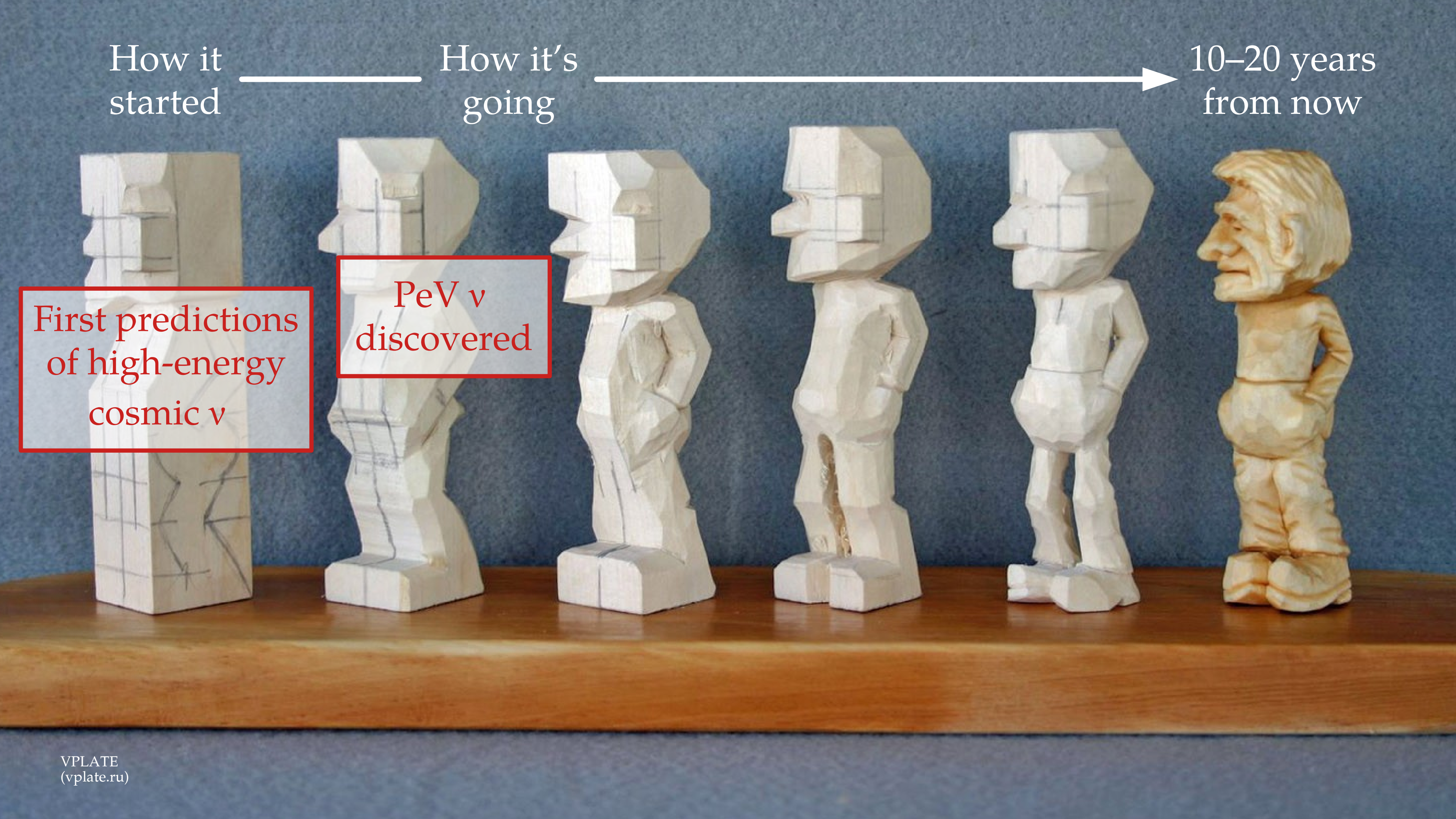
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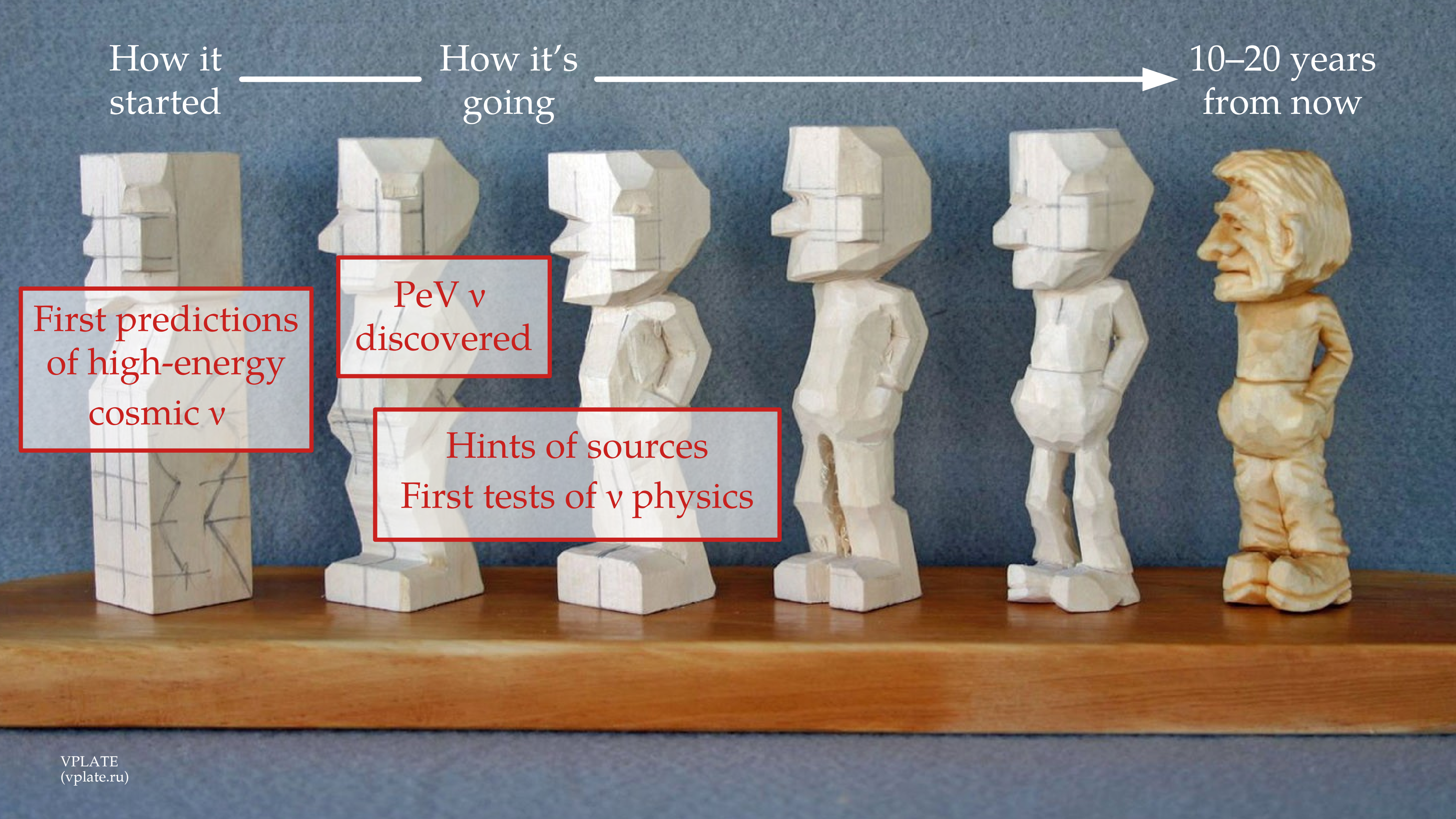
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Hints of sources
First tests of ν physics
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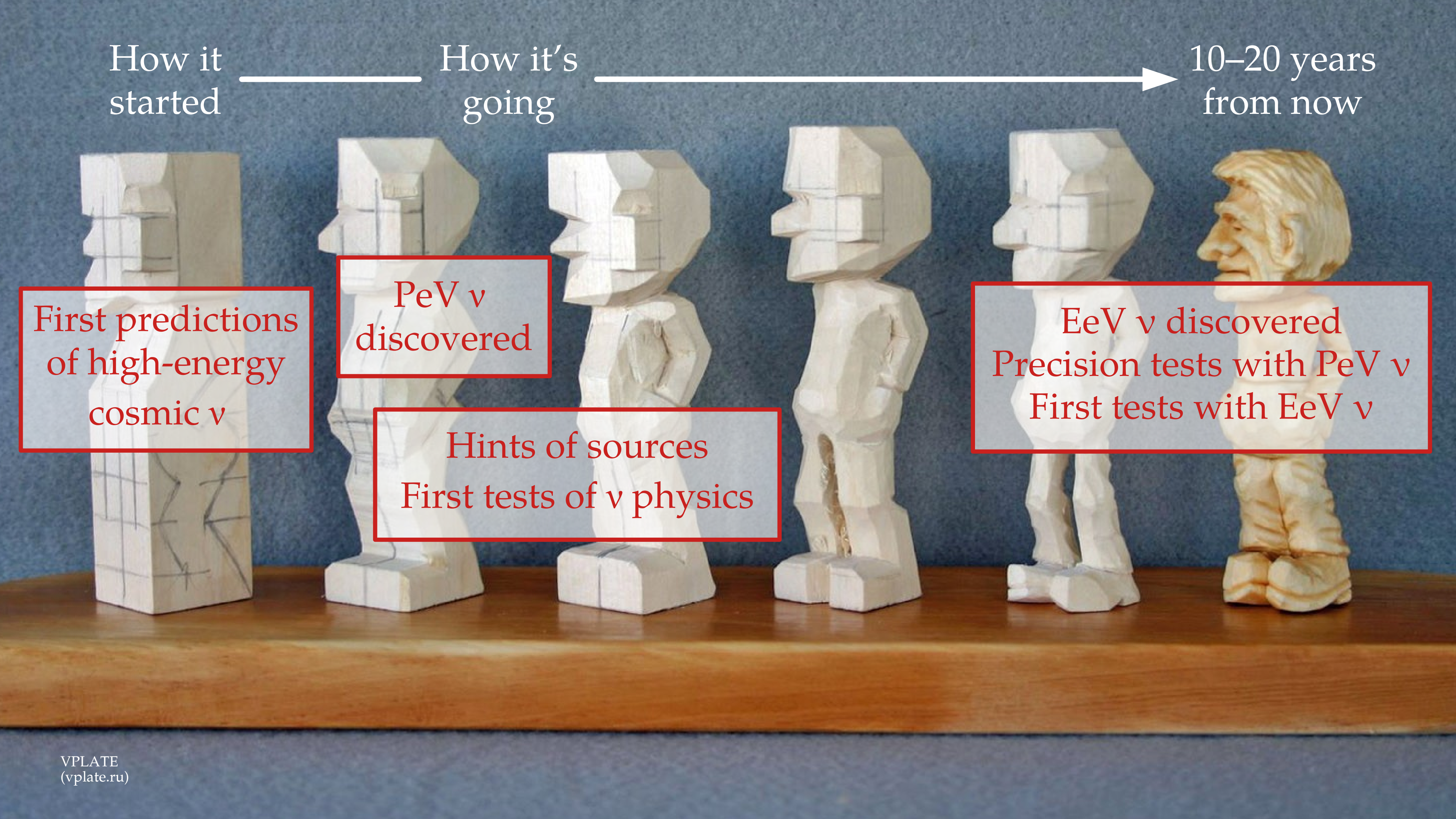
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First tests with EeV ν
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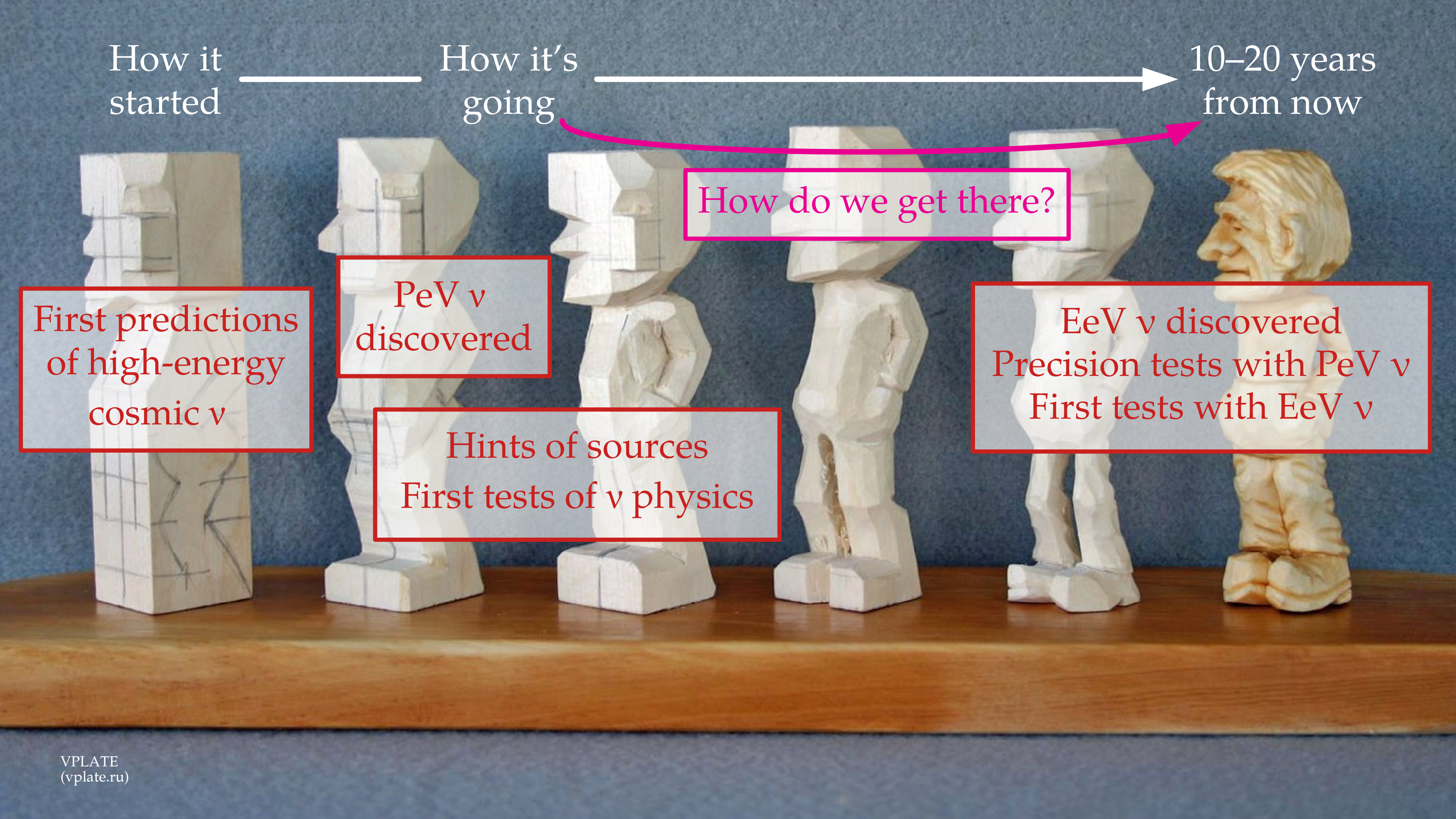
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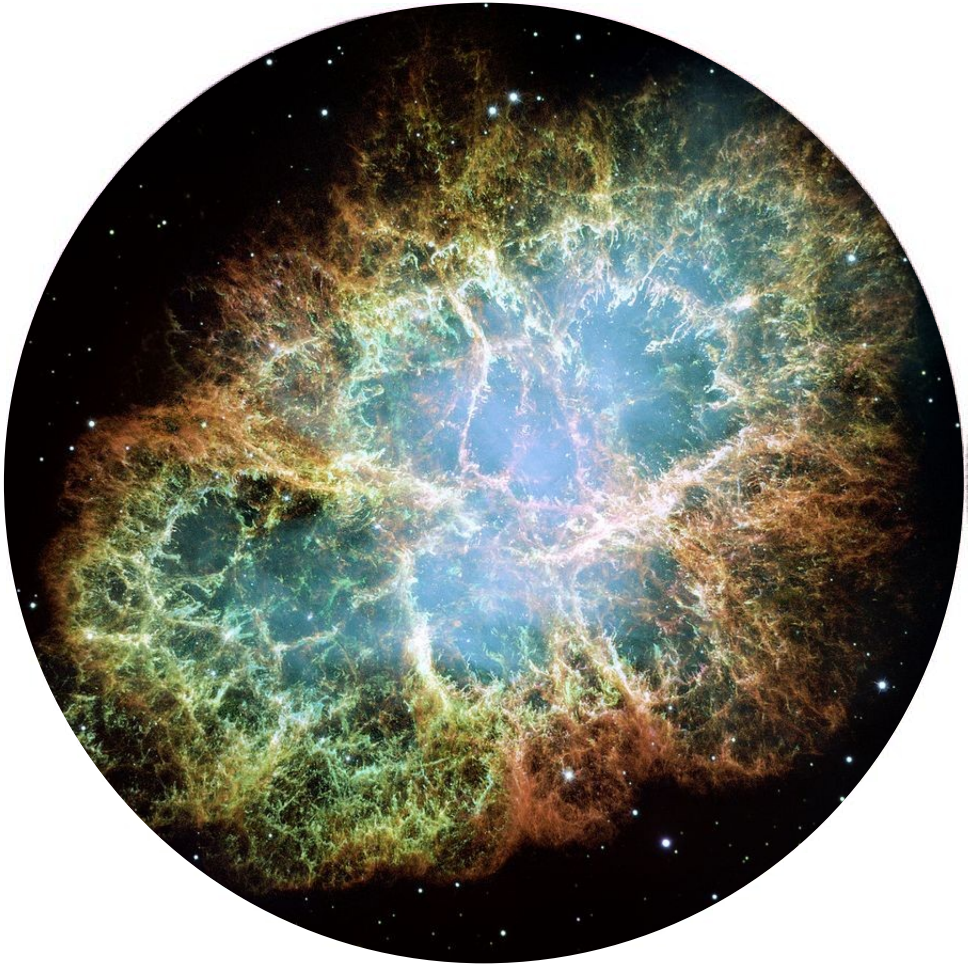
Banco Central de Reserva del Perú / NASA / ESA / CERN / Symmetry Magazine



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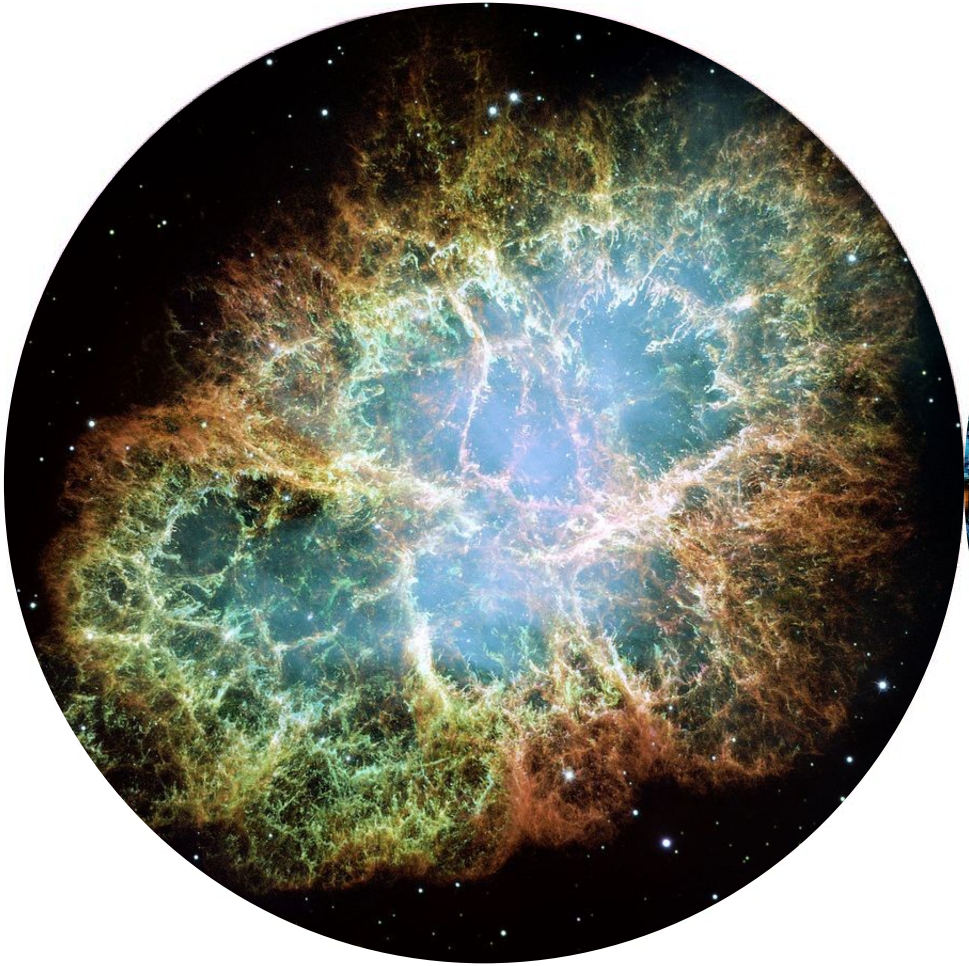

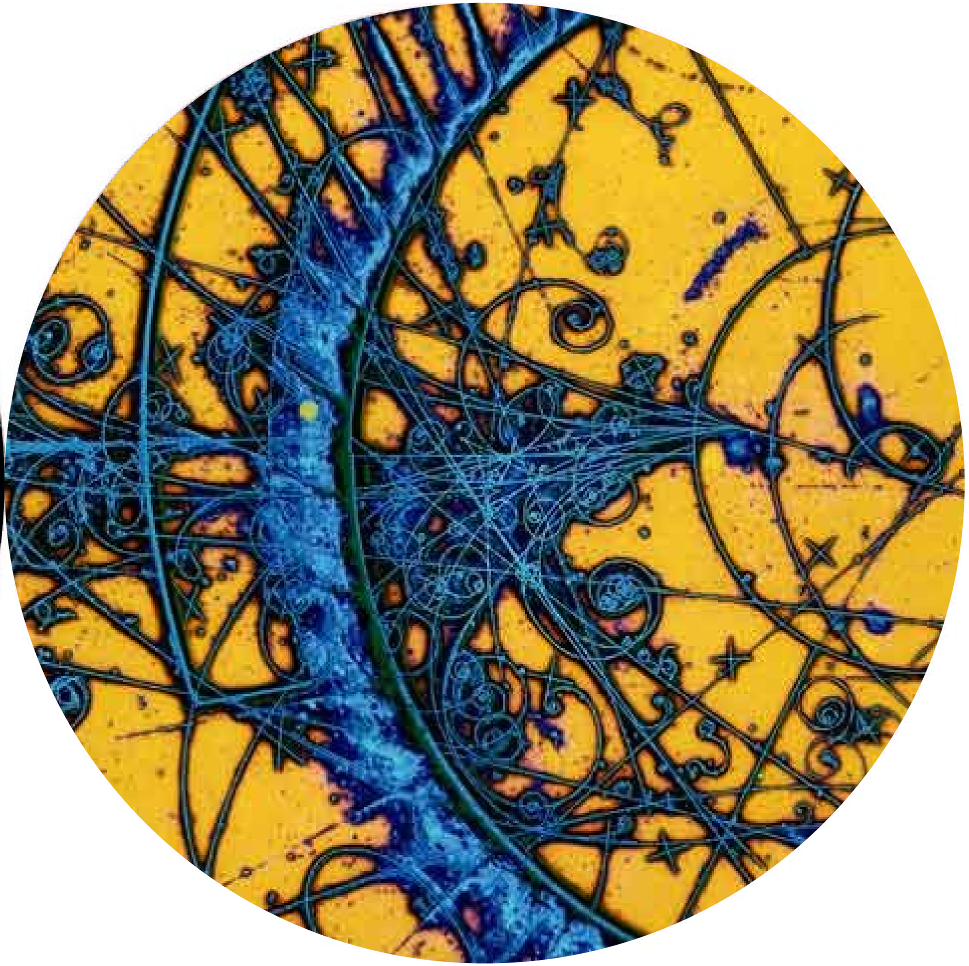

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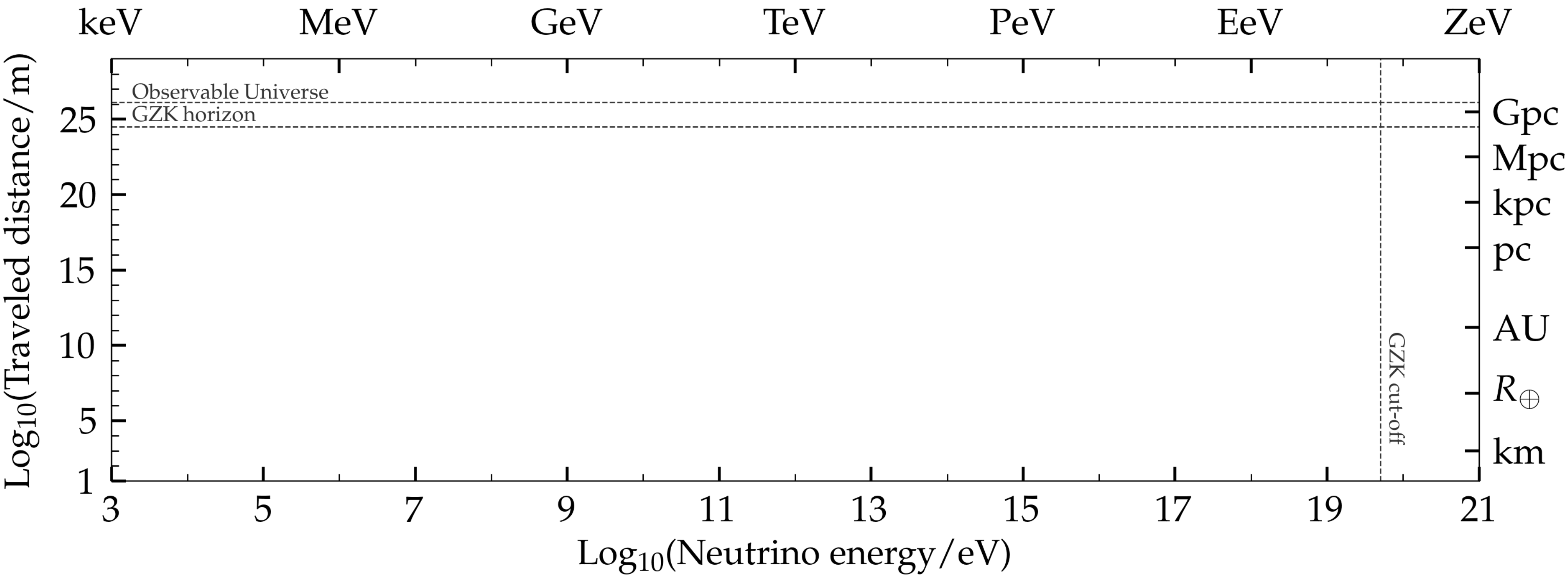
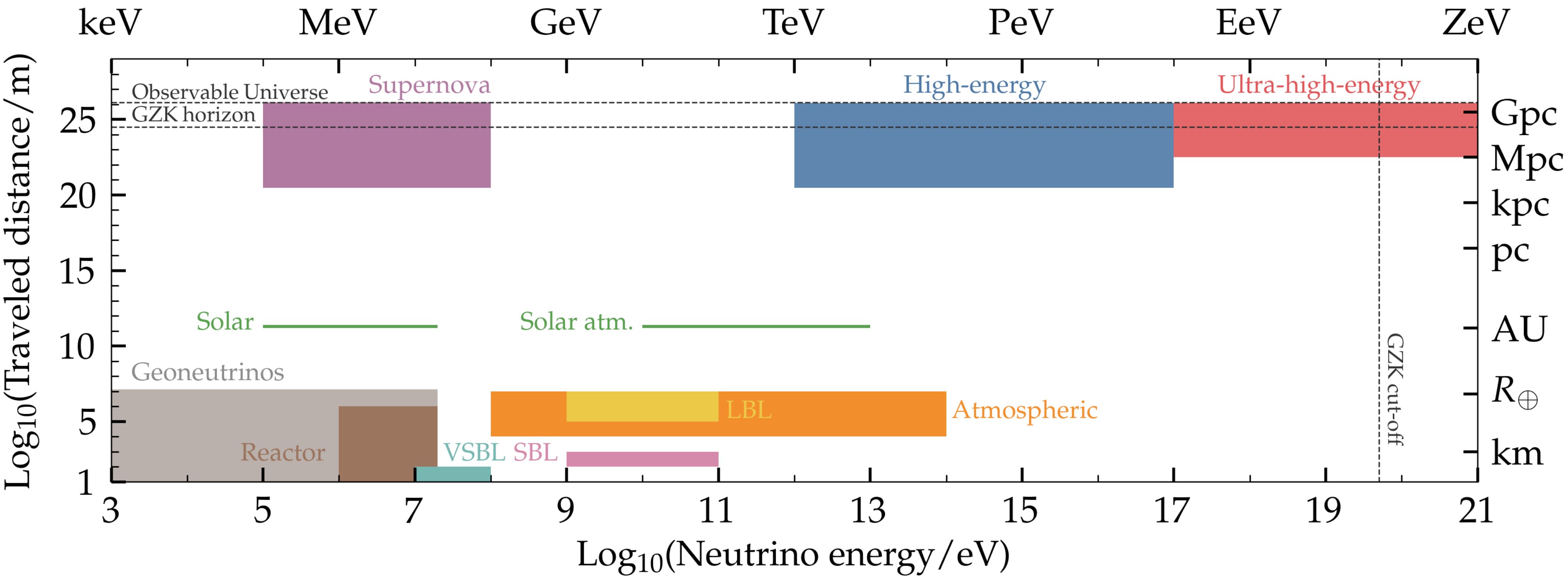
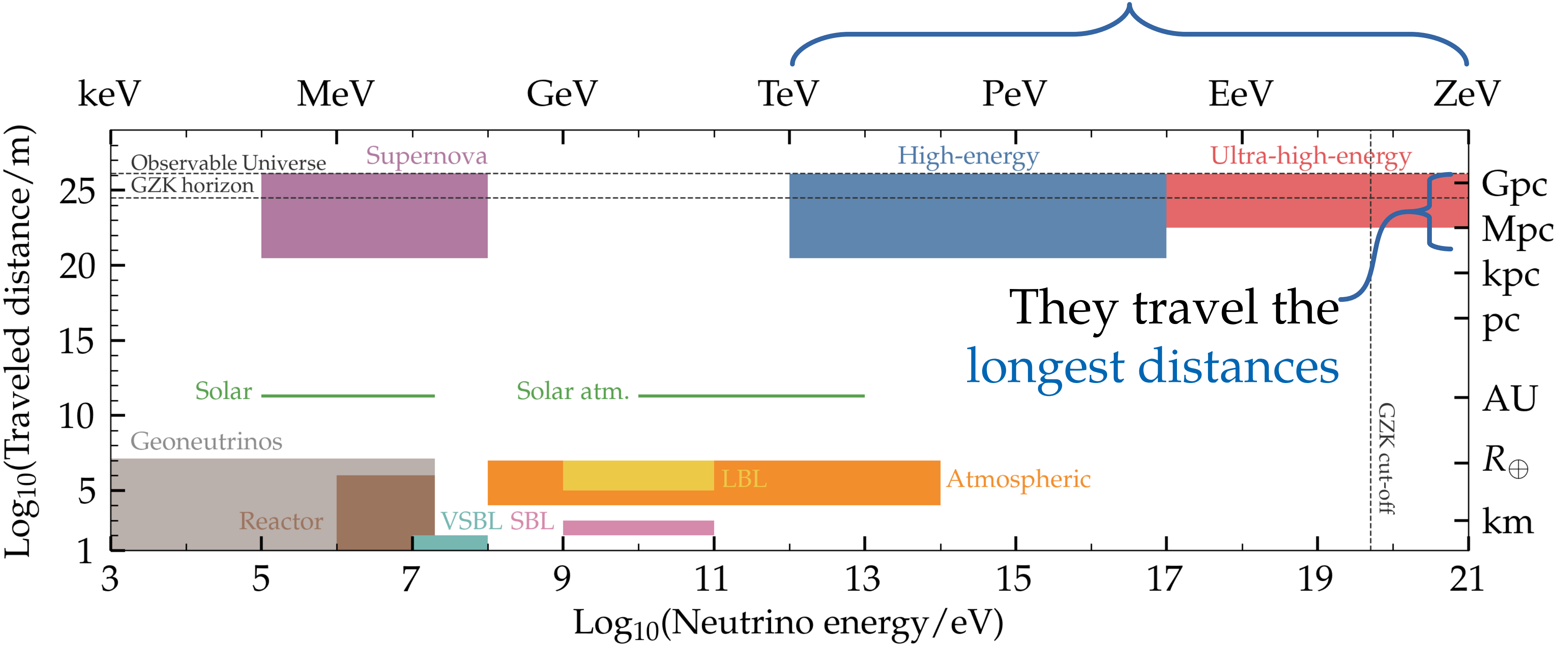


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



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

They have the highest energies



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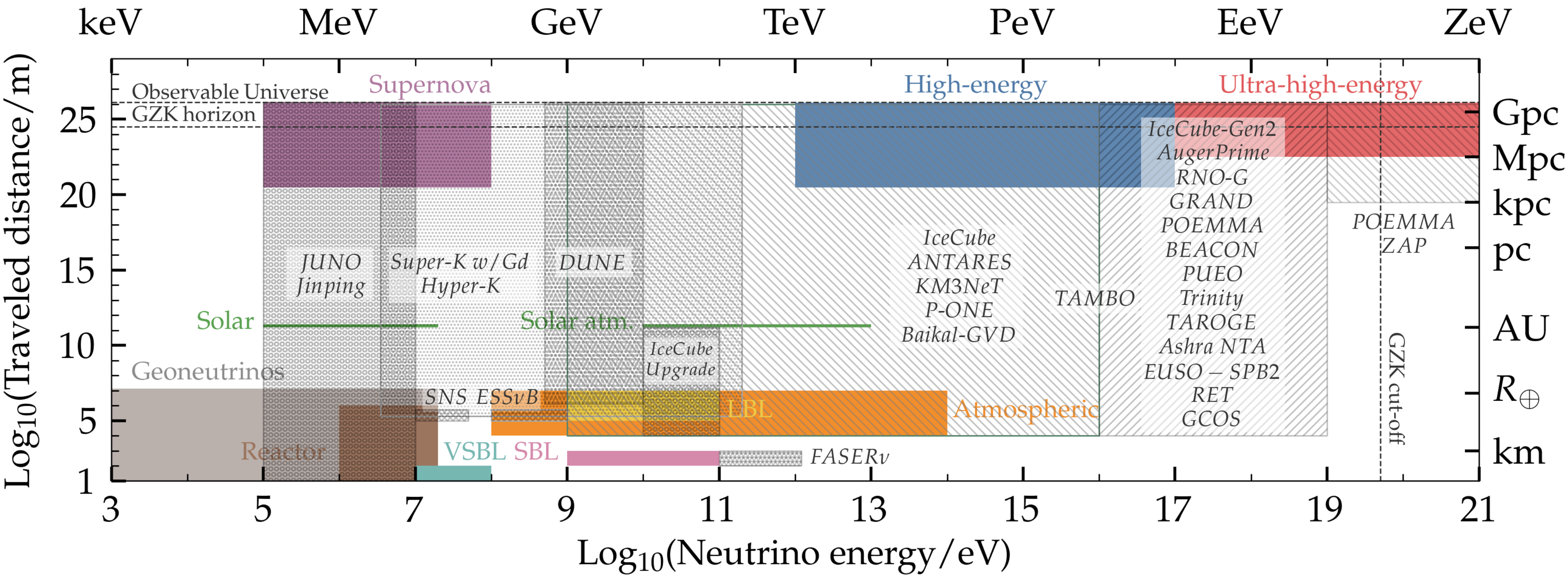

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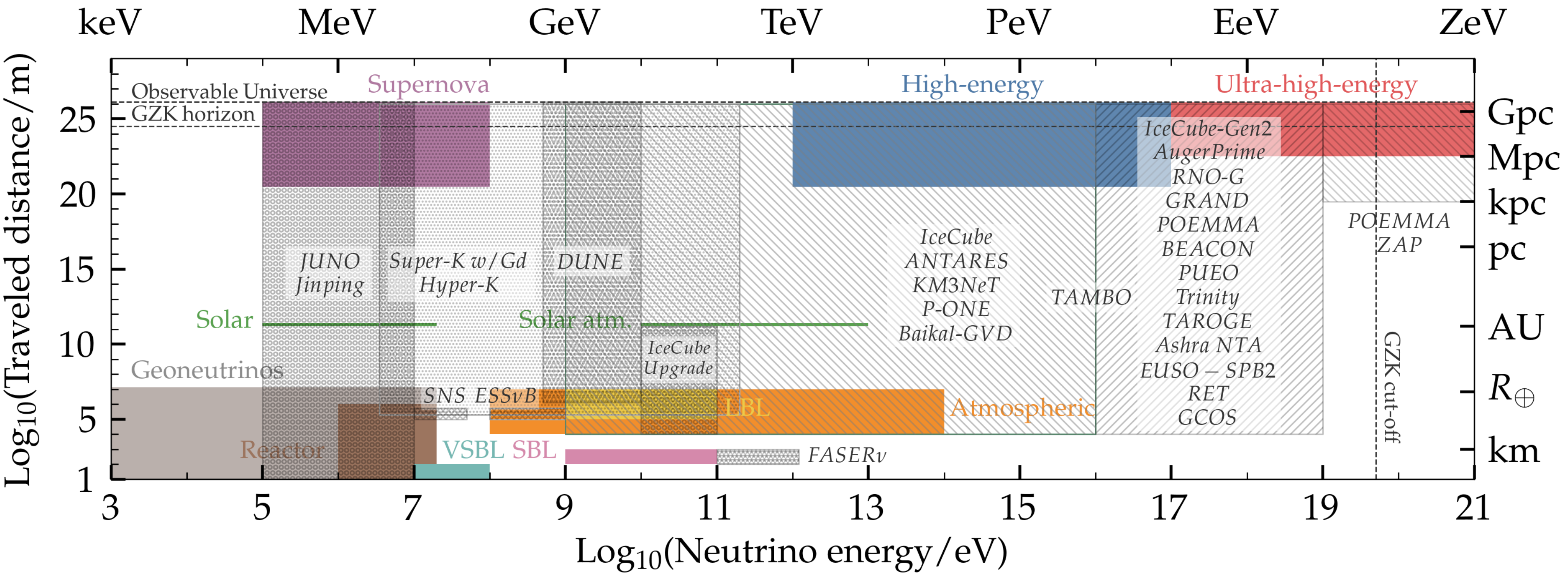
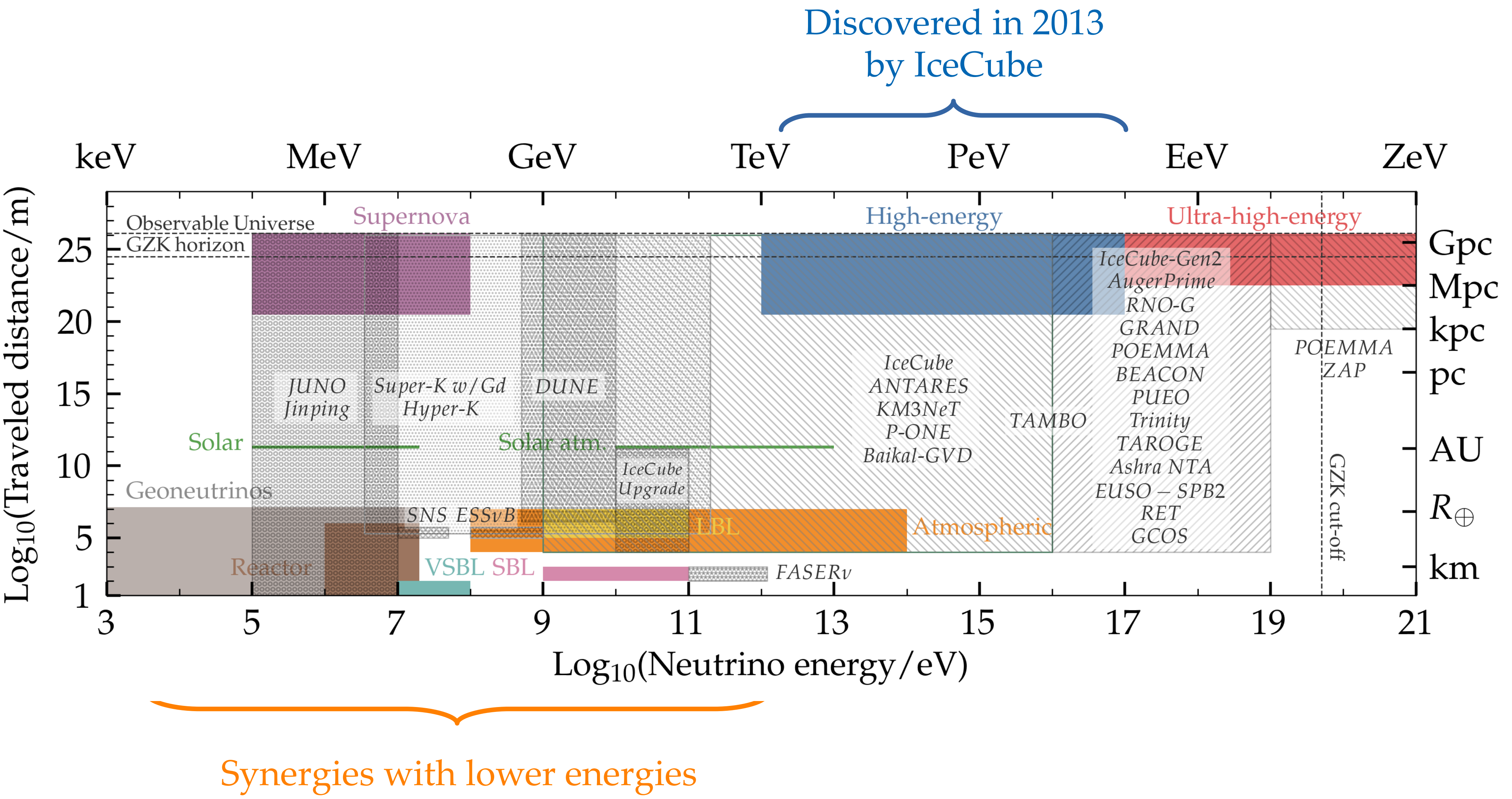


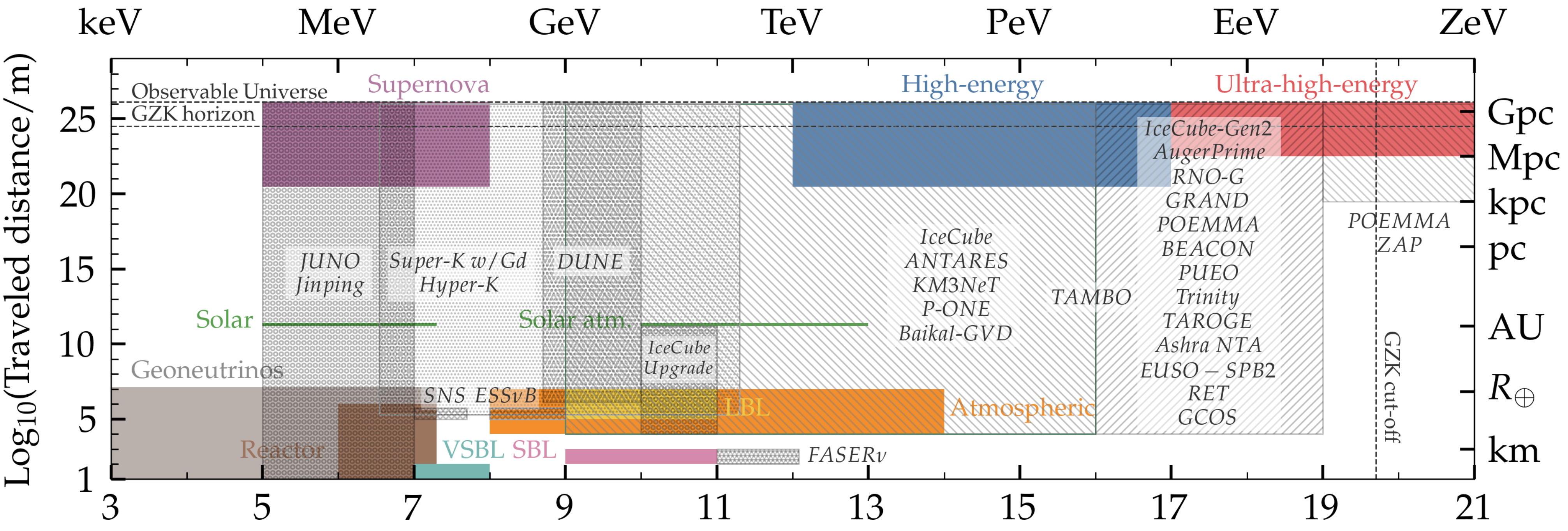
Synergies with lower energies

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



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

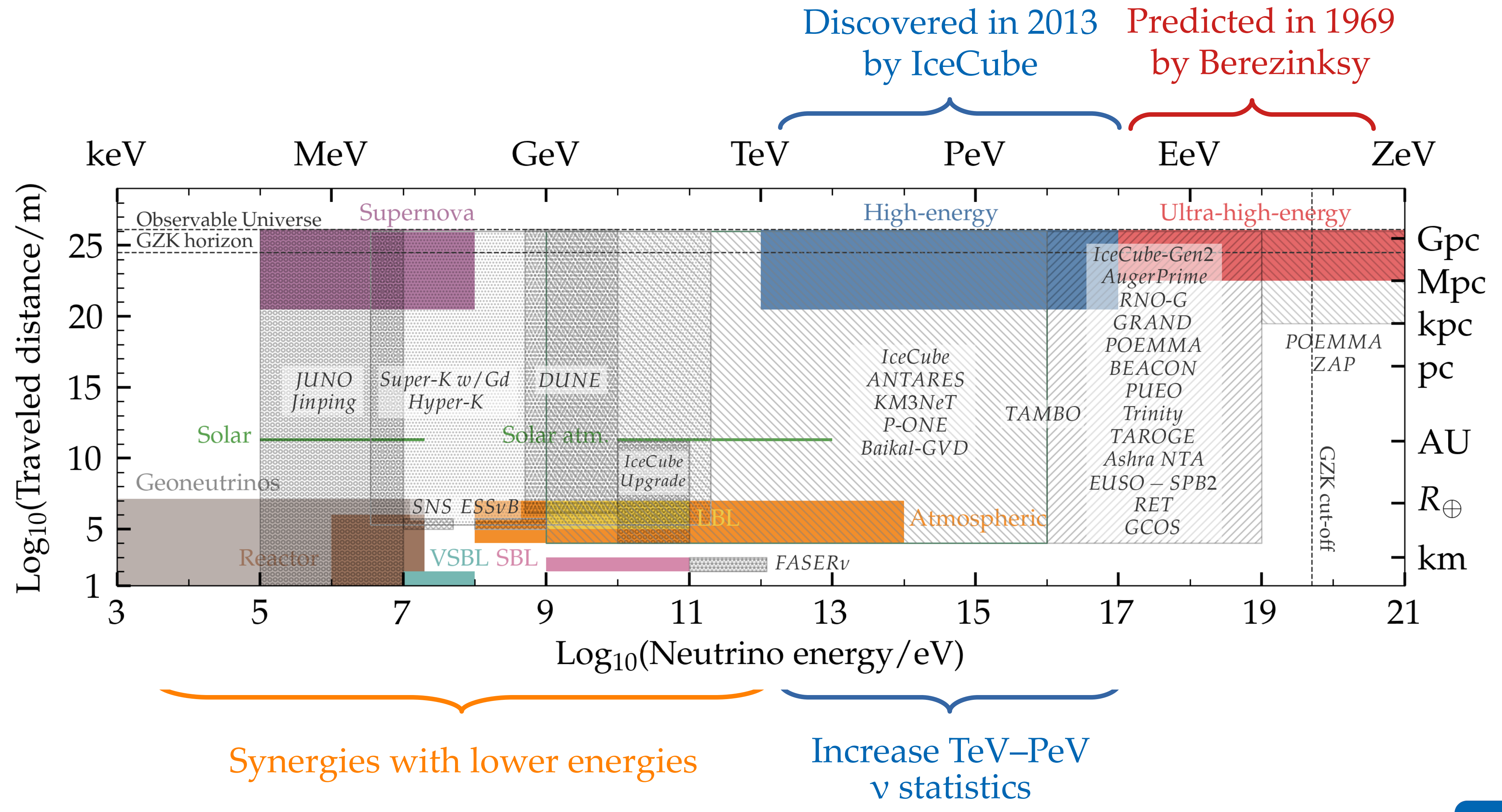
Discovered in 2013
by IceCube



Synergies with lower energies

Increase TeV–PeV
ν statistics

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



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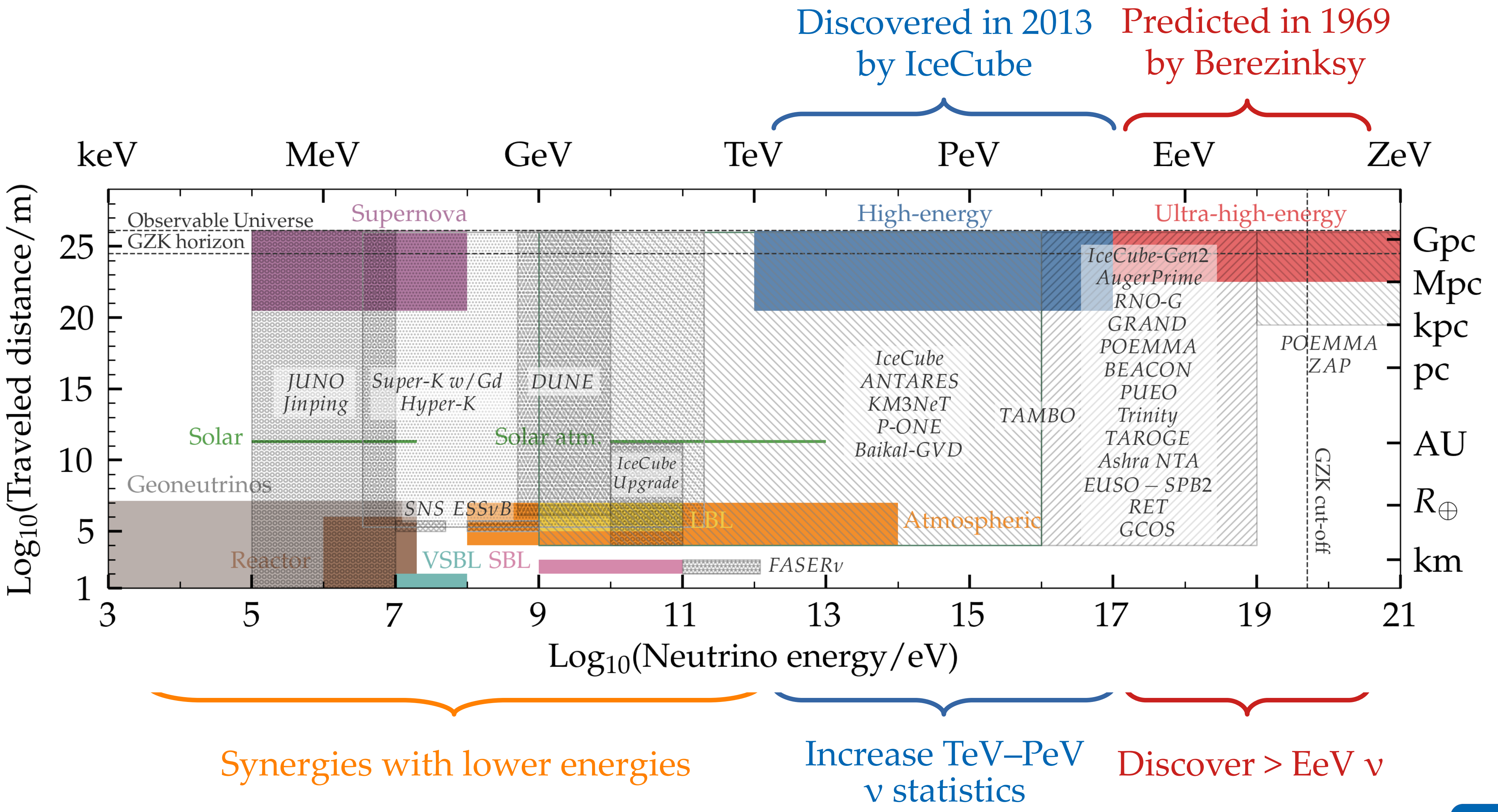

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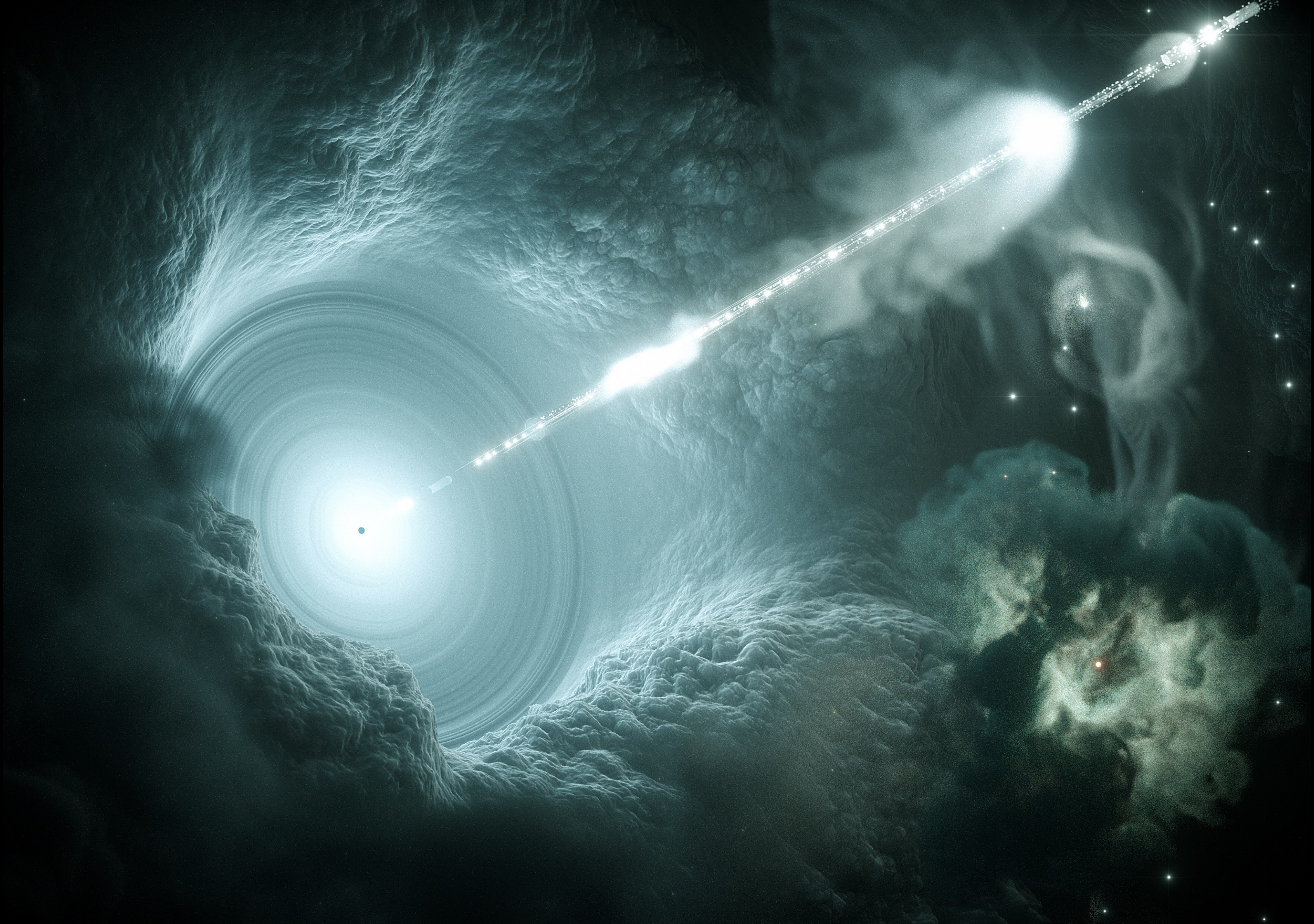
The story so far


DESY

The multi-messenger connection: a simple picture

(or $p + p$)

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

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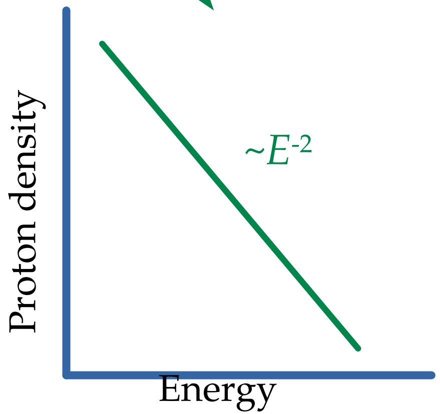

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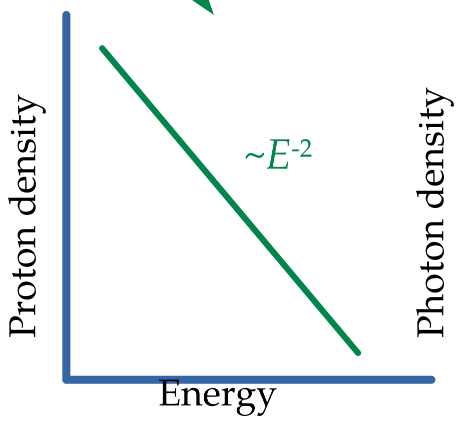

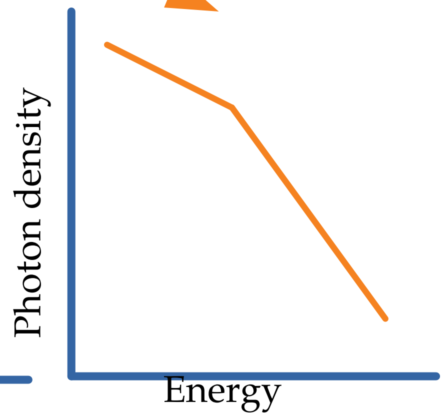

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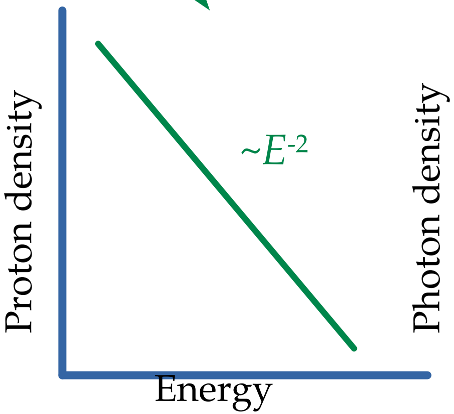
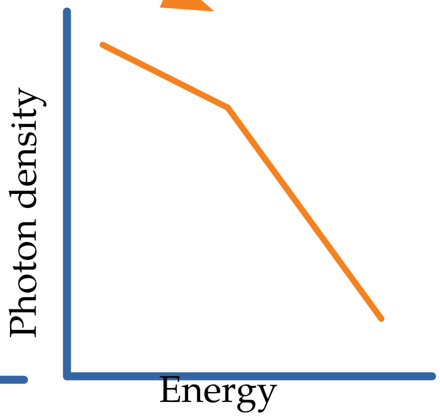
$$\pi^0 \longrightarrow \gamma + \gamma$$

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

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





The multi-messenger connection: a simple picture

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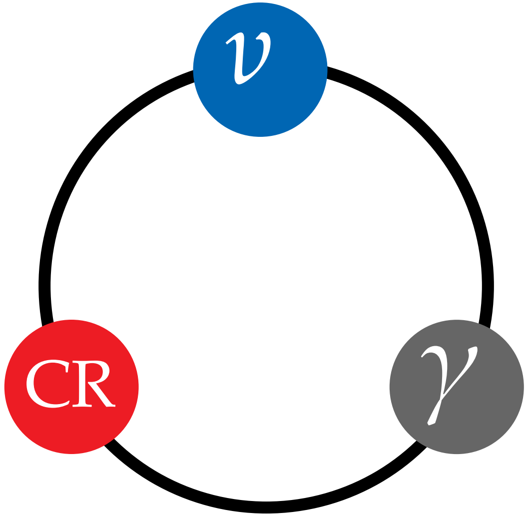

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

The multi-messenger connection: a simple picture

(or $p + p$)

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

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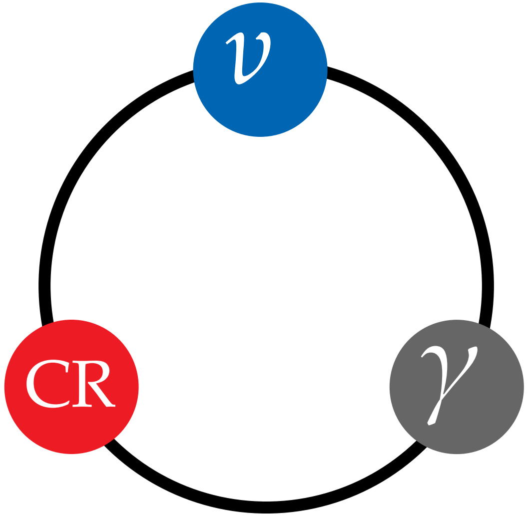

1 PeV 20 PeV

Neutrino energy = Proton energy / 20

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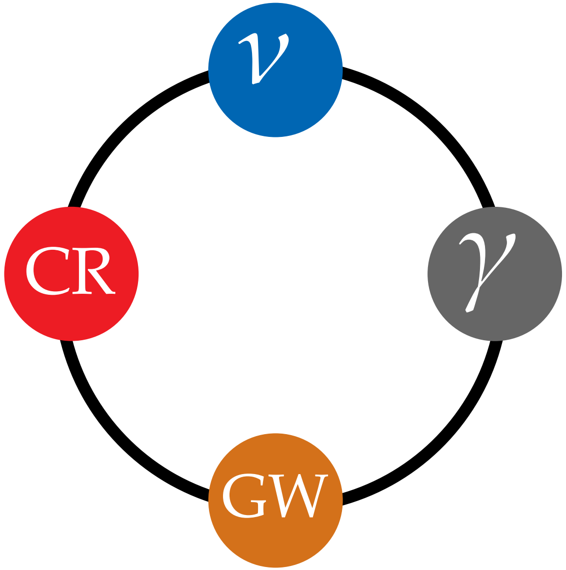

1 PeV — 20 PeV

Neutrino energy = Proton energy / 20

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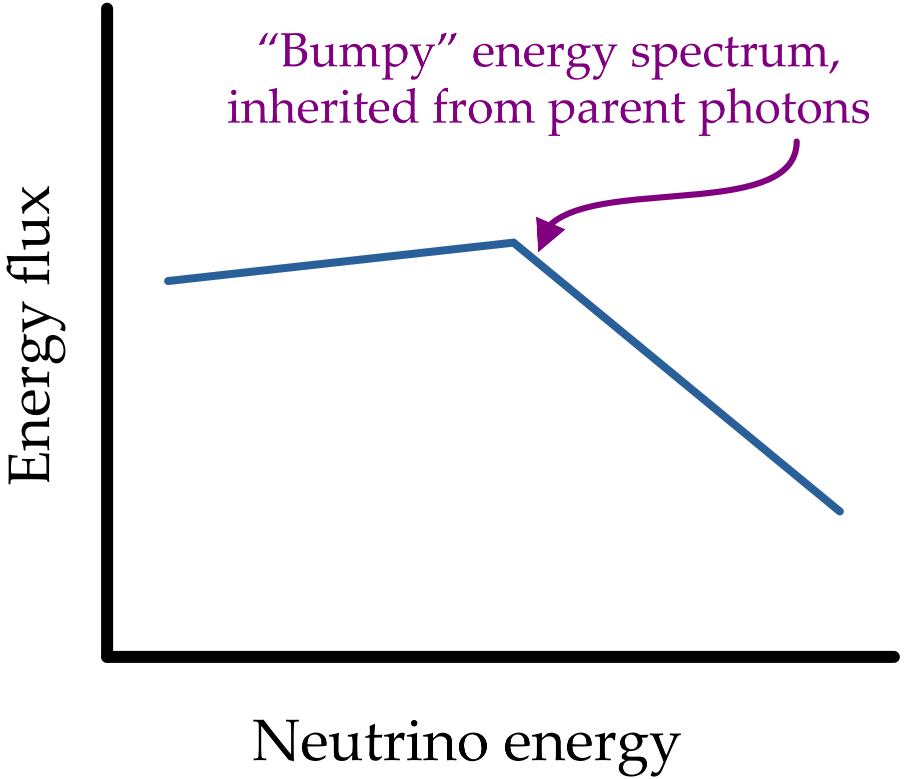
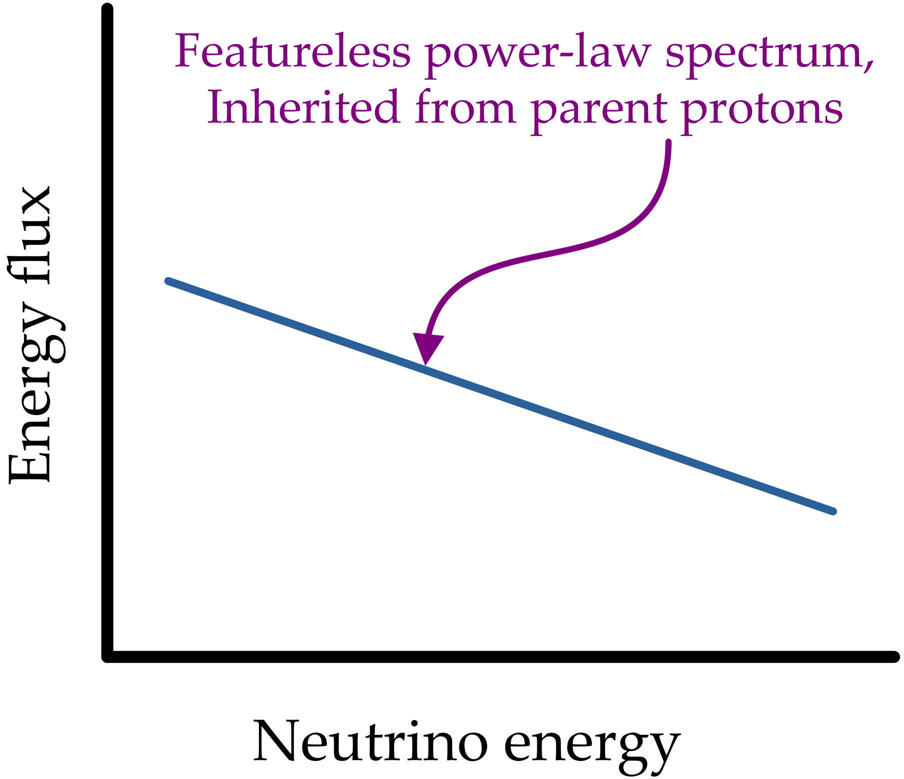
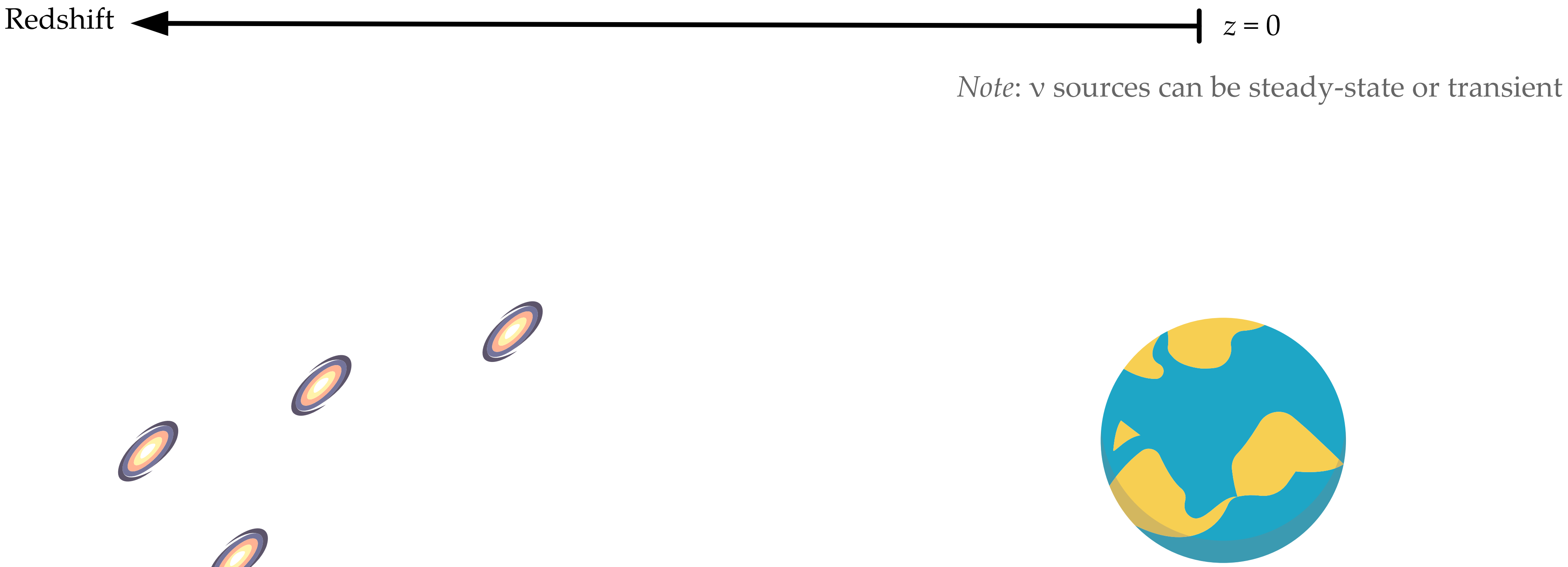
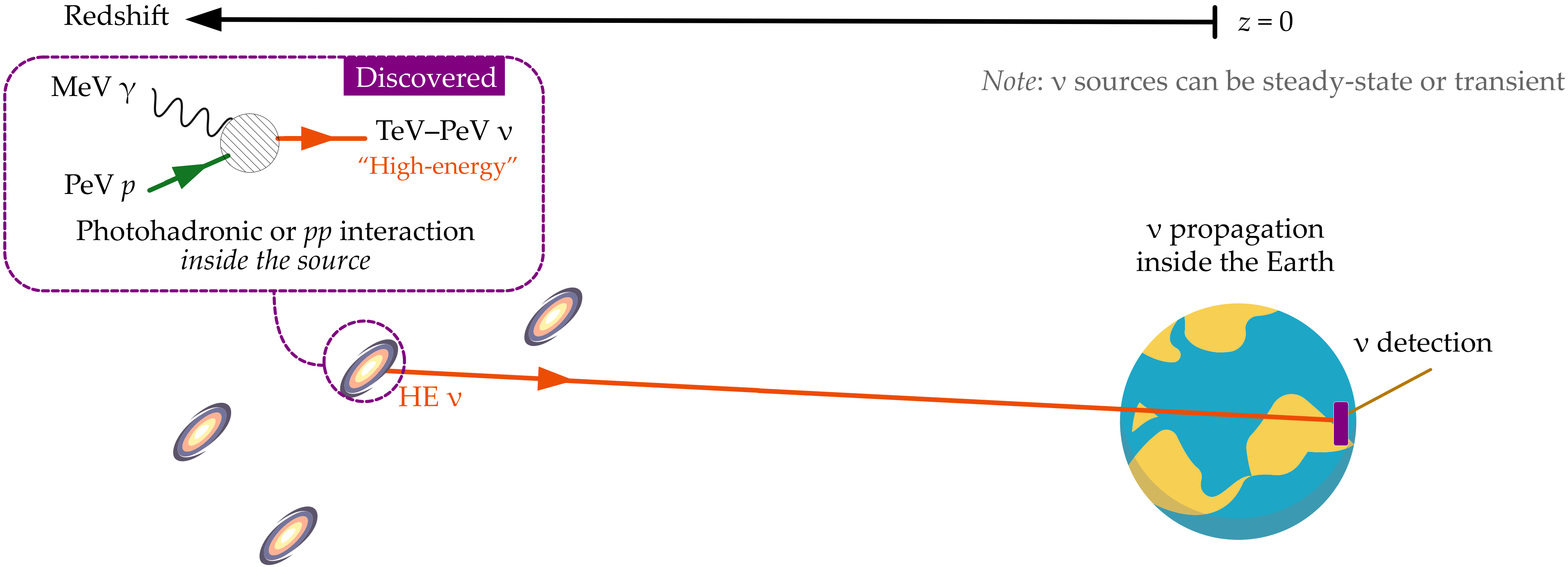
Neutrinos from *pγ* interactions



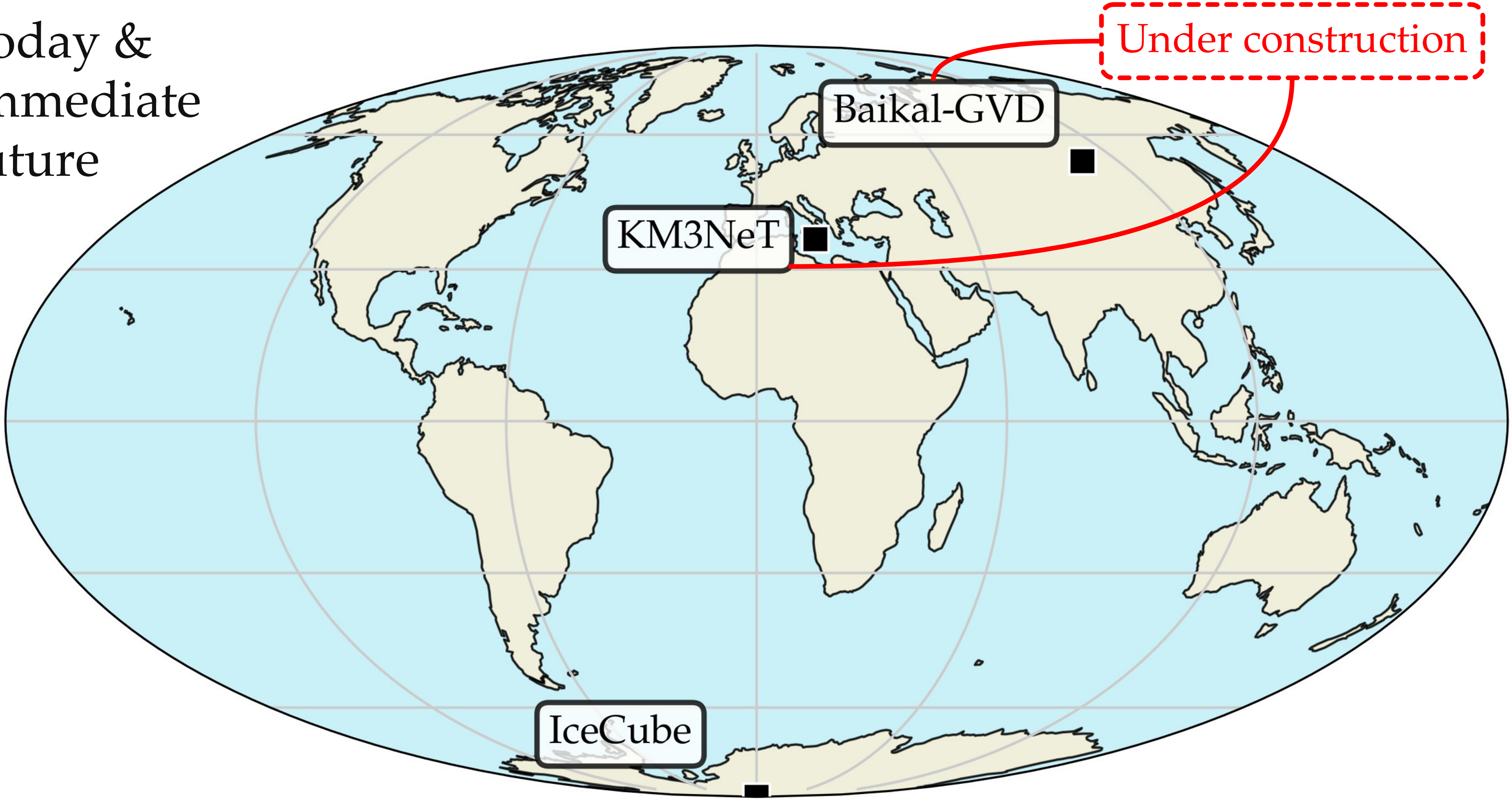
Neutrinos from *pp* interactions




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

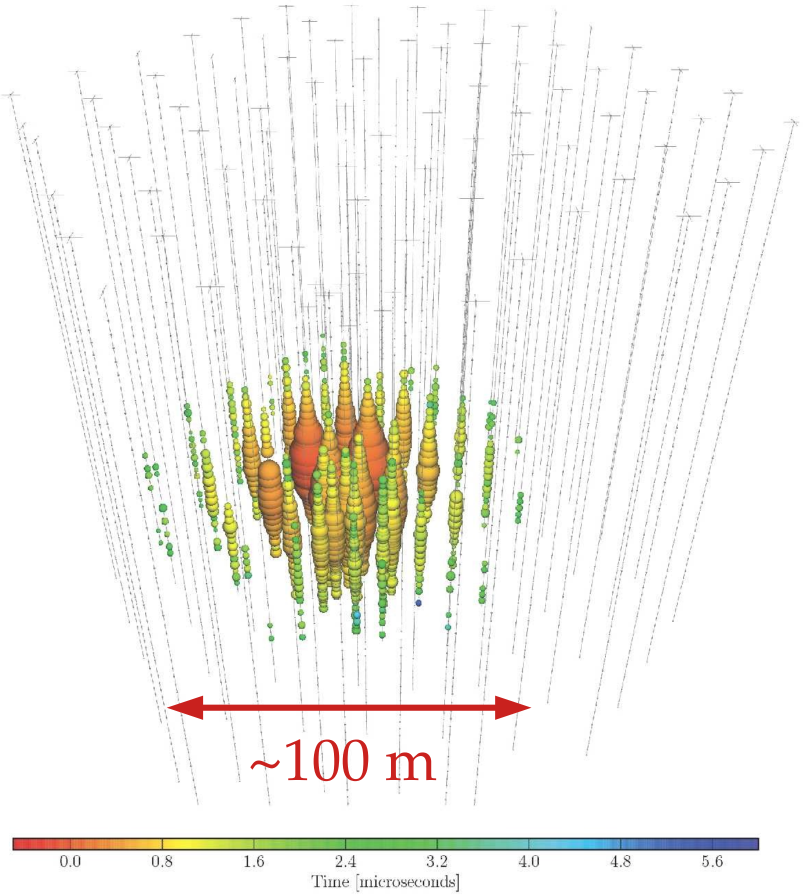

Redshift
$z = 0$
Discovered
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or pp interaction
inside the source
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν

Today & immediate future



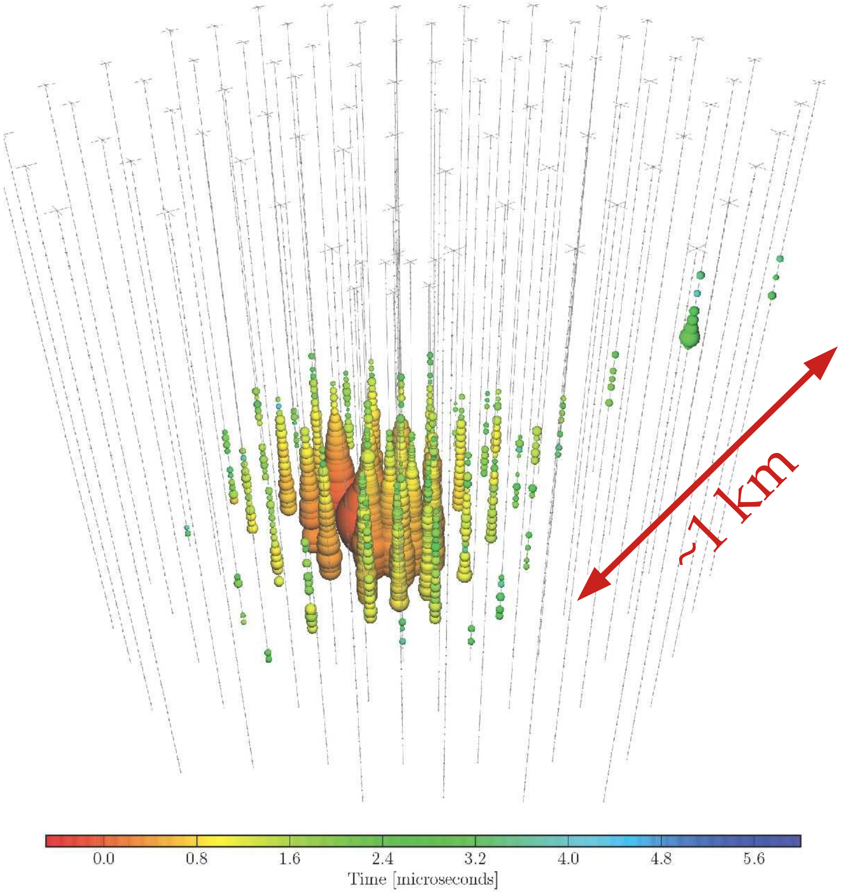
Schumacher, **MB**, Agostini, Oikonomou, Resconi, 2503.07549

Shower
(mainly from ν_e and ν_τ)

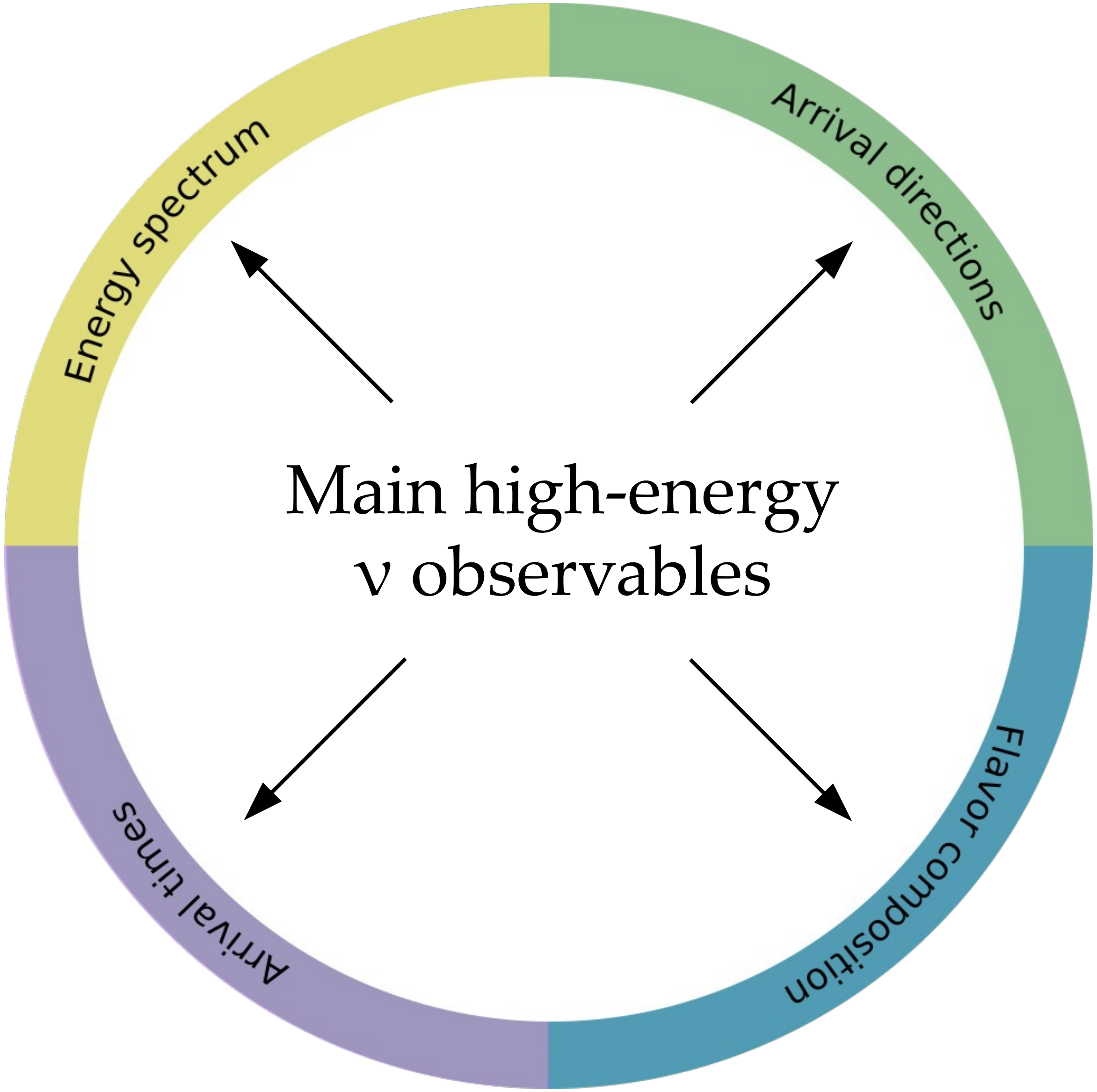


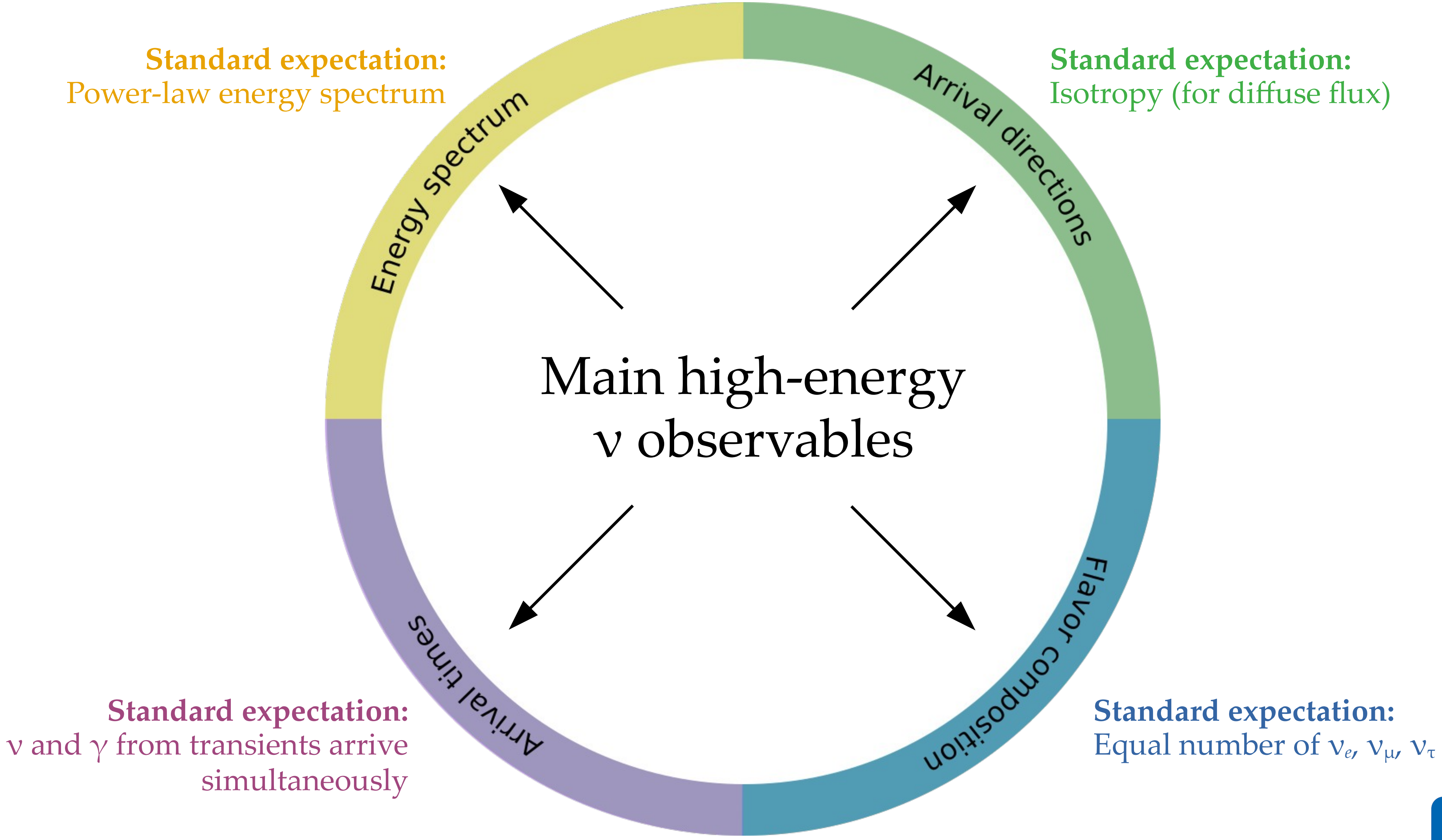
Poor angular resolution: < 5°

Track
(mainly from ν_μ)



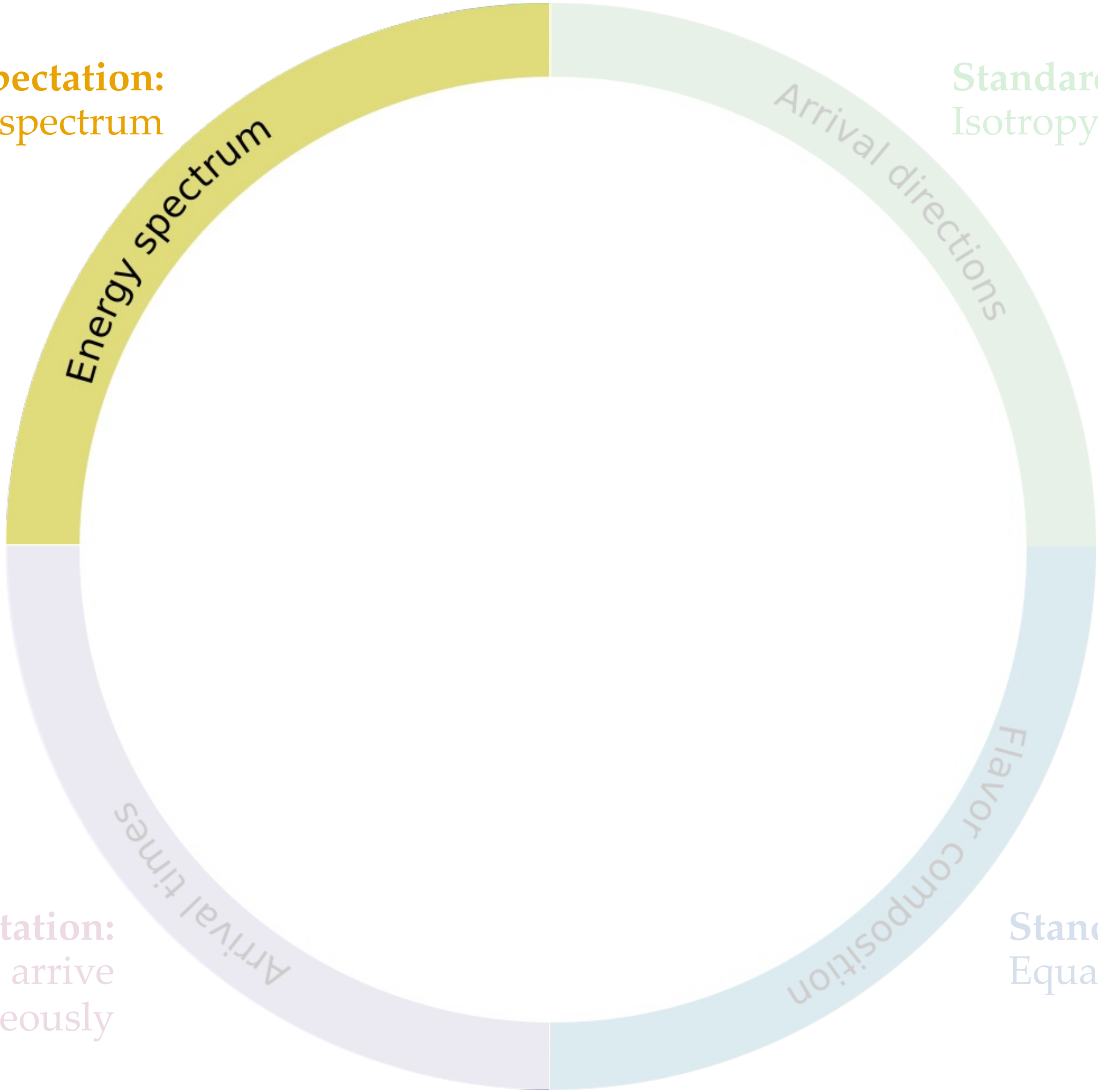
Angular resolution: < 1°


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


Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Energy spectrum
Arrival directions
Main high-energy
ν observables
Arrival times
Flavor composition
Standard expectation:
ν and γ from transients arrive simultaneously
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



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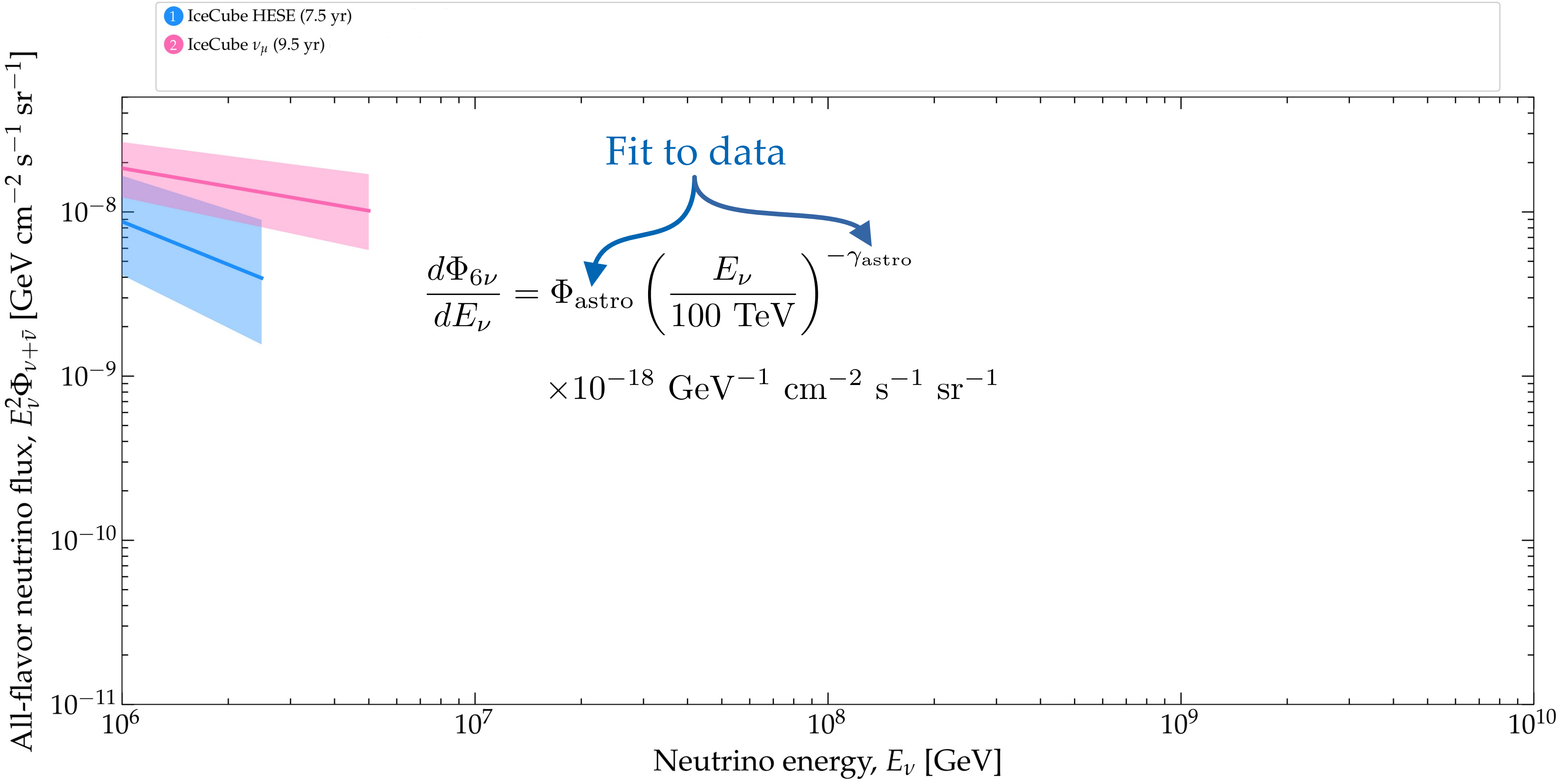


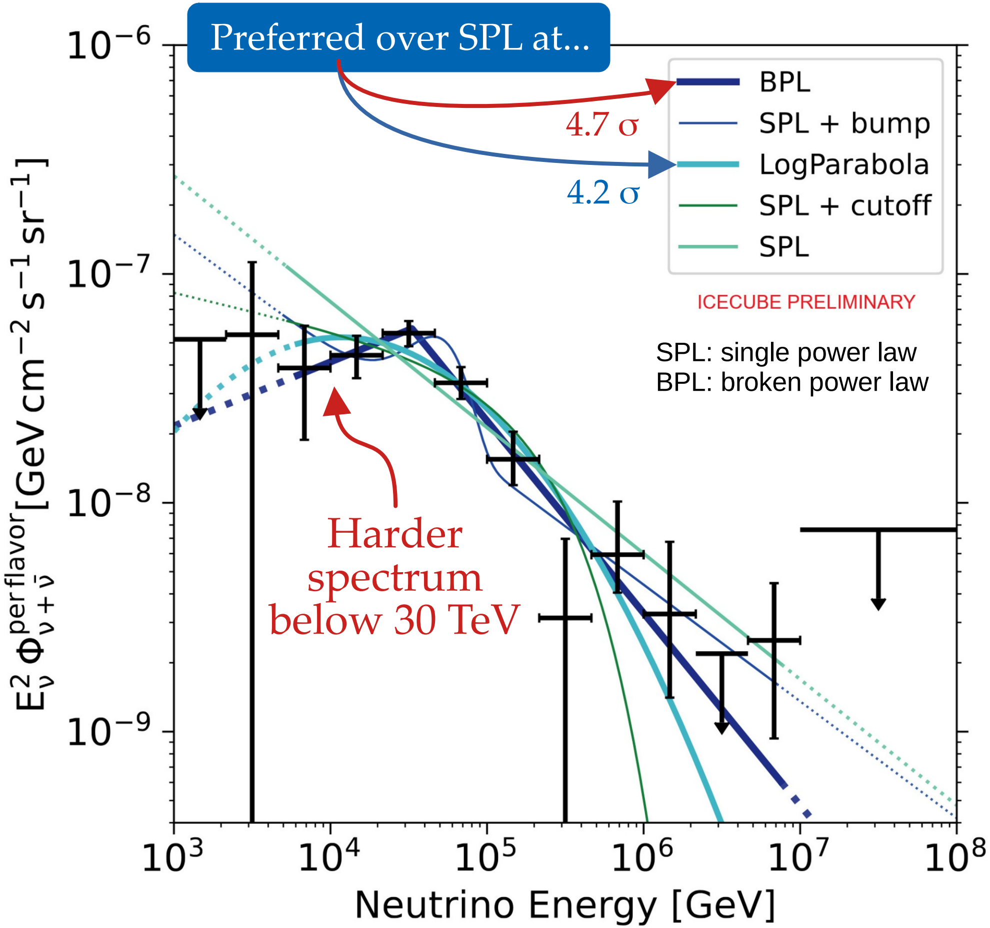
$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\mathrm{astro}} \left(\frac{E_\nu}{100~\mathrm{TeV}} \right)^{-\gamma_{\mathrm{astro}}}$$

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

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

Diffuse TeV–PeV υ flux: **IceCube**

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



11 yr of Medium Energy Starting Events (MESE)

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

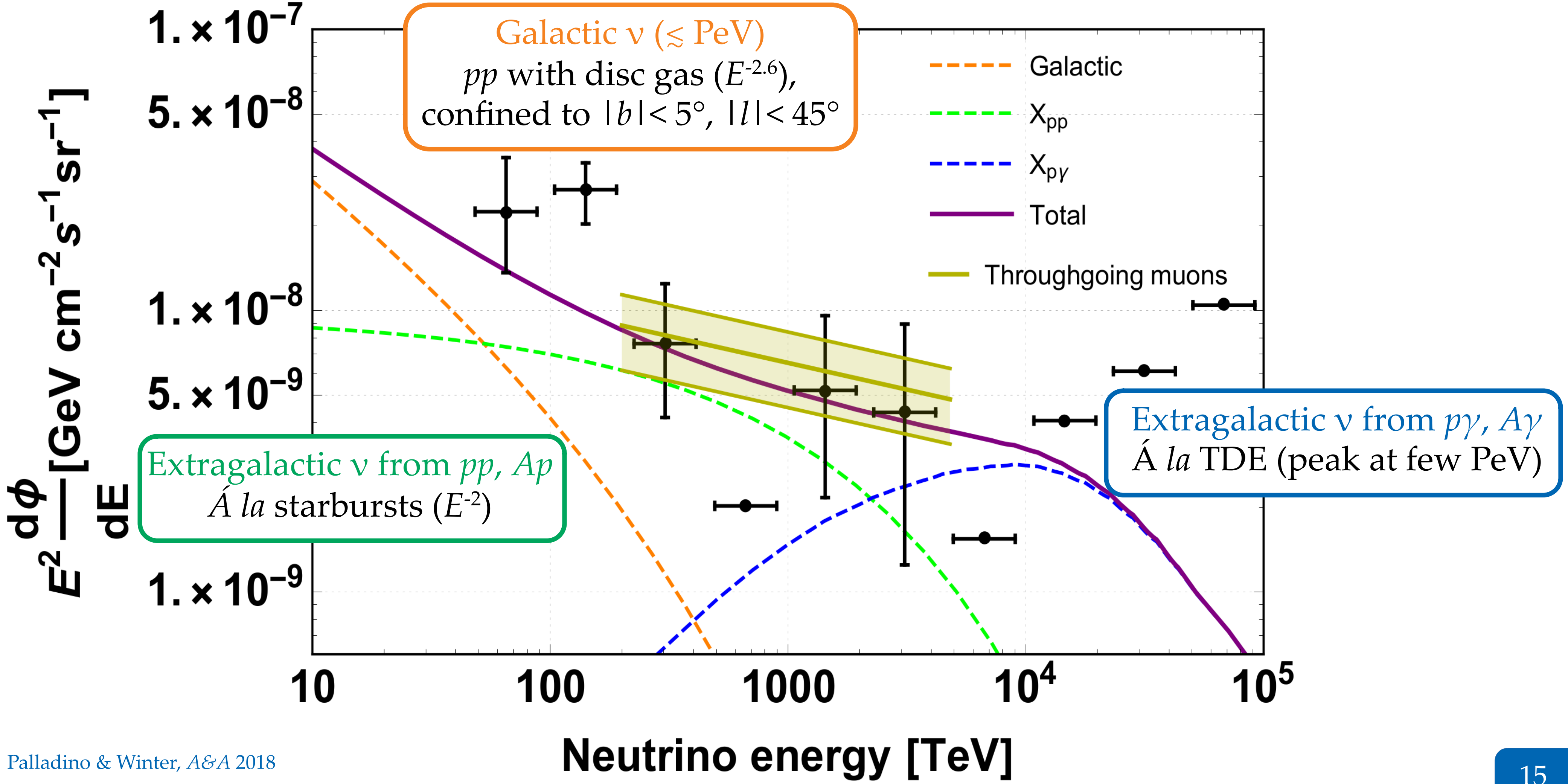
Resolved structure in the cosmic neutrino spectrum at > 4σ

Features of neutrino production?
Two source populations?
New physics? (*E.g.*, dark-matter decay/annihilation)

SPL b.f.: $\Phi \propto E^{-\gamma}$ ($\gamma = 2.55$)

BPL b.f.: $\Phi \propto \begin{cases} E^{-\gamma_1}, & E < E_b \\ E^{-\gamma_2}, & E > E_b \end{cases}$ ($\gamma_1 = 1.72$, $\gamma_2 = 2.84$, $E_b = 33$ TeV)

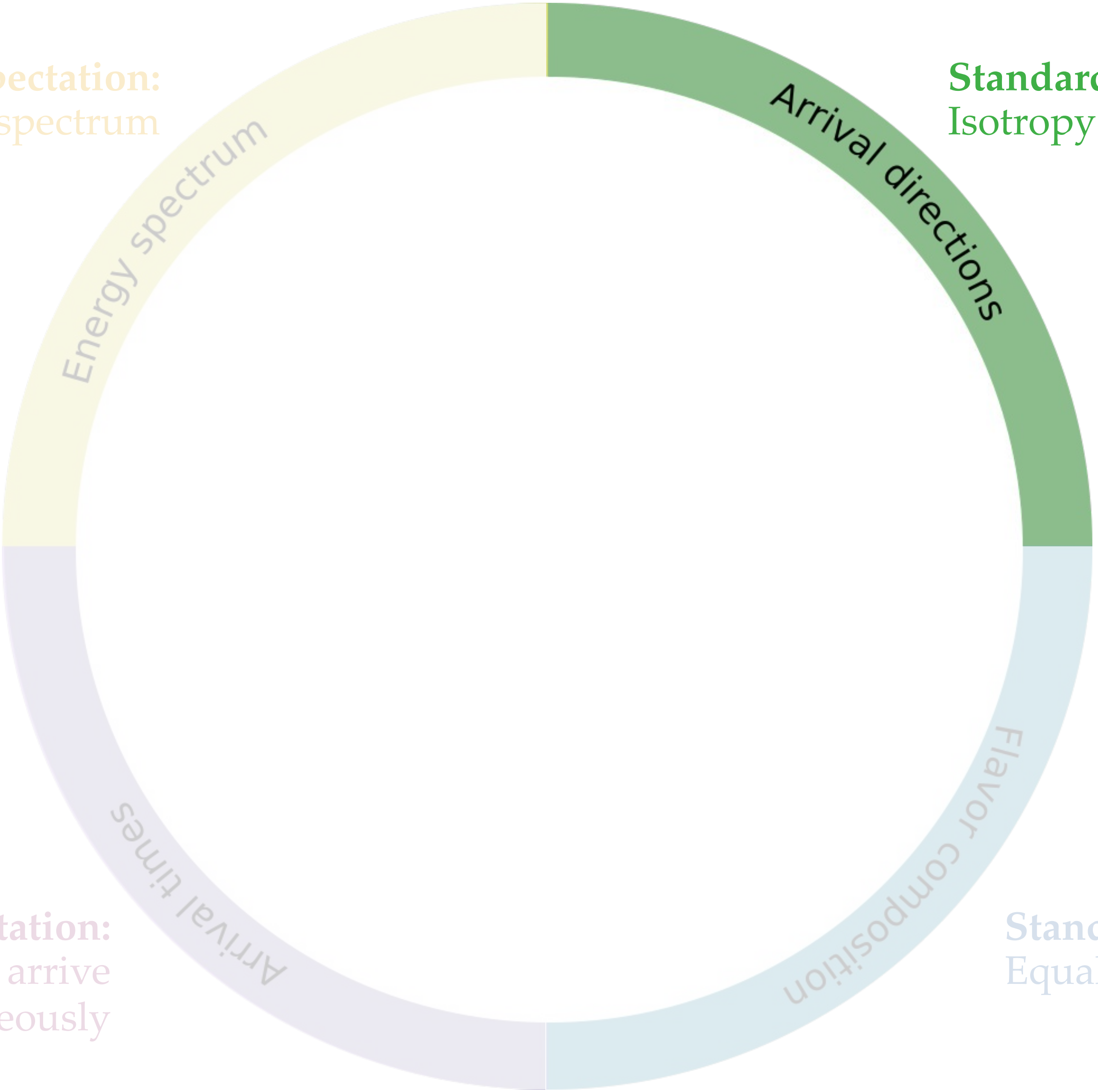
Multi-component model of astrophysical neutrinos



Palladino & Winter, *A&A* 2018

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

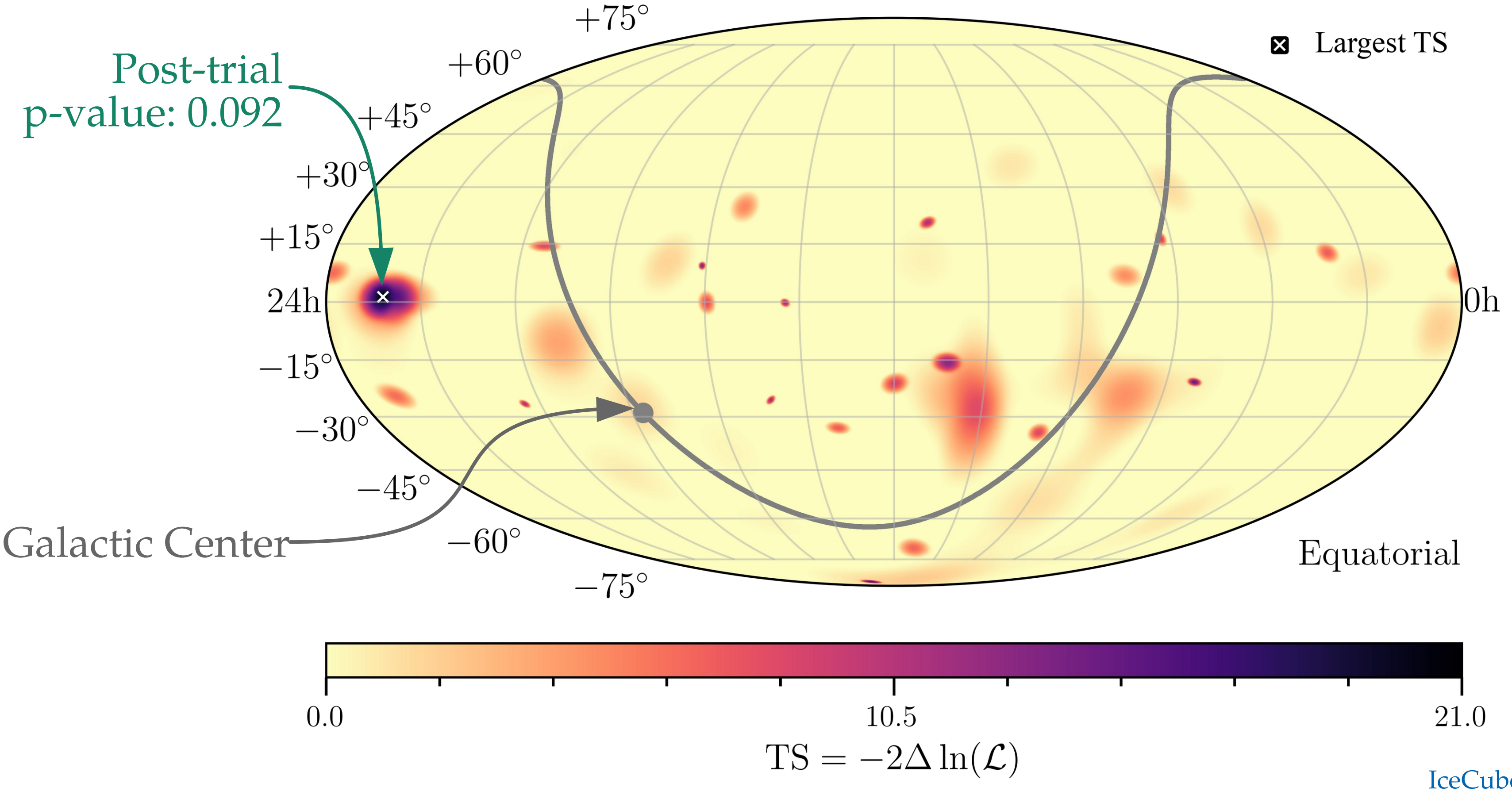


Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Arrival directions (7.5 yr)

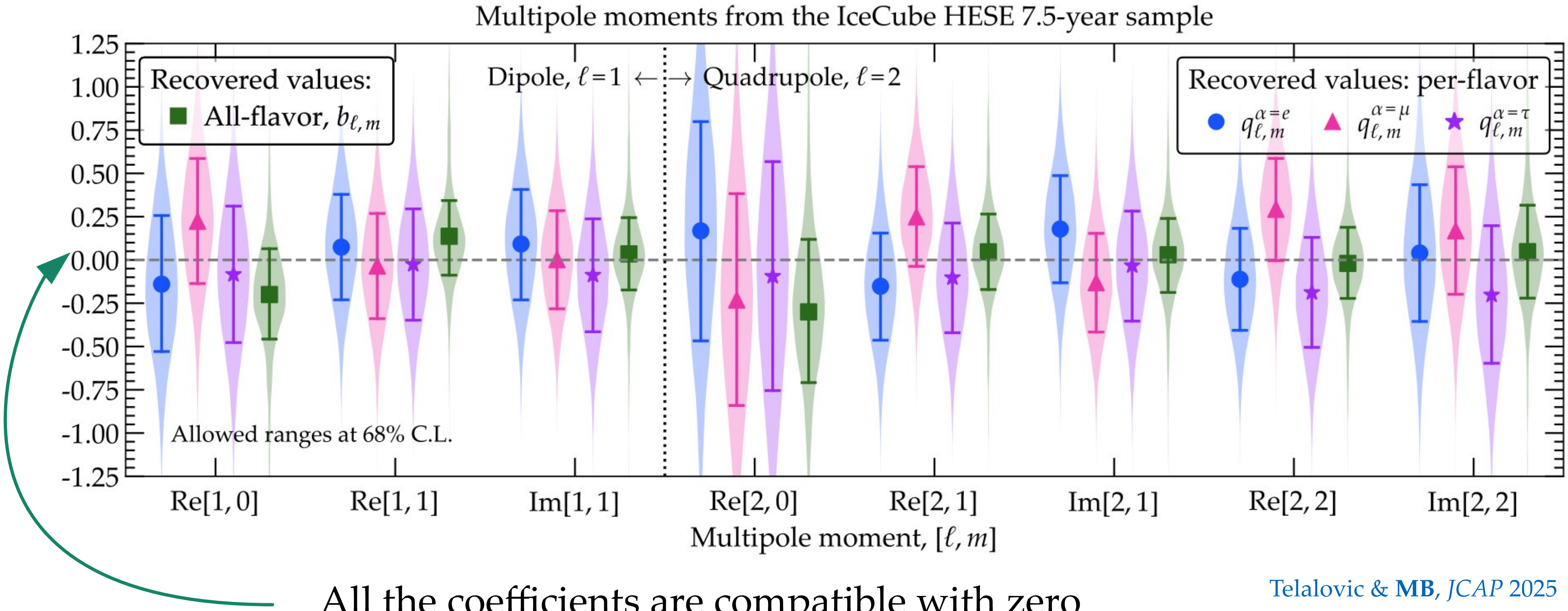
No significant excess in the neutrino sky map:



IceCube, *PRD* 2021

Arrival directions (7.5 yr)

A multipole analysis of the high-energy ν sky yields isotropy:



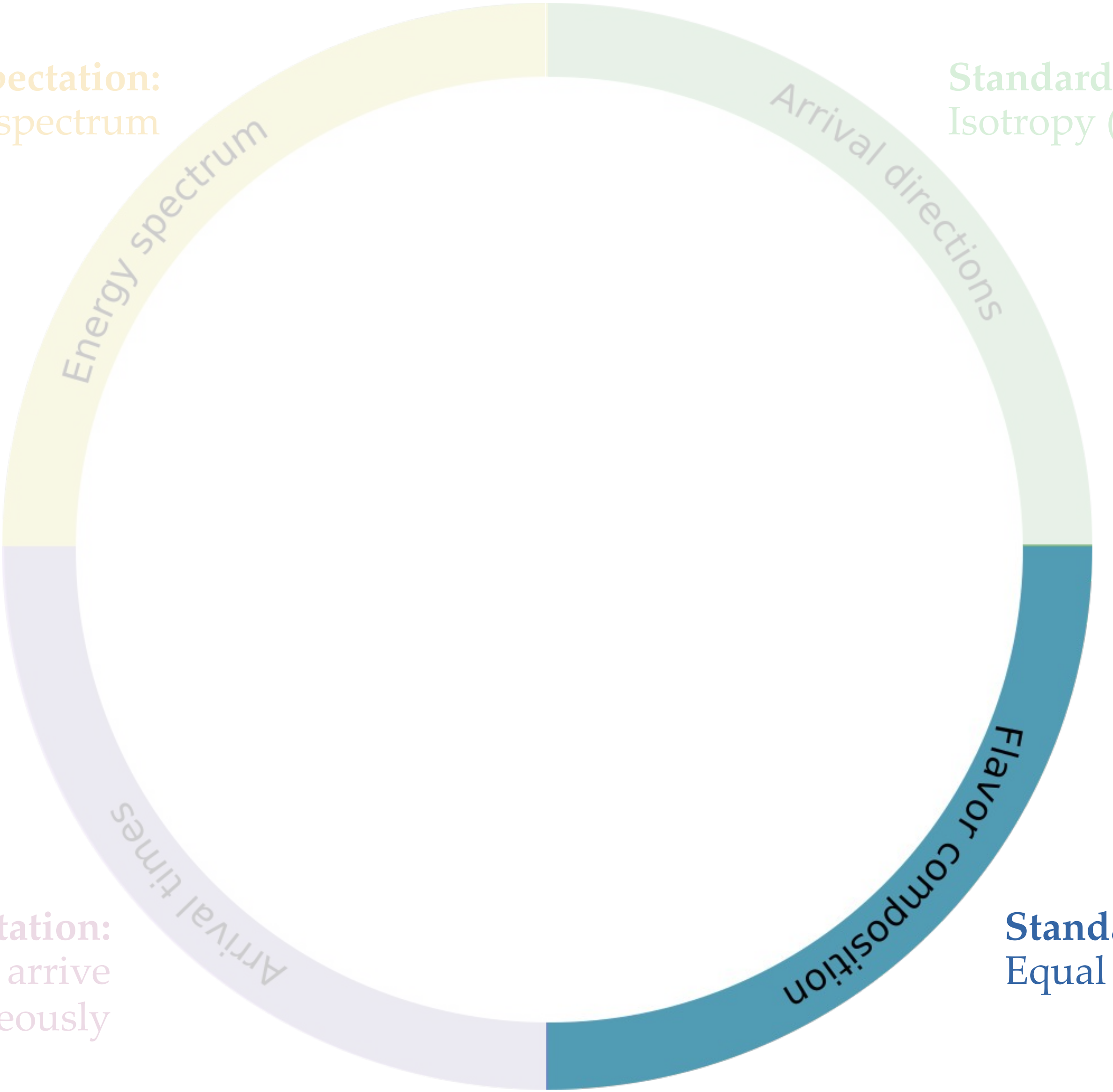
Telalovic & **MB**, *JCAP* 2025

All the coefficients are compatible with zero

$$\Phi_{\nu_\alpha}(\theta_z, \phi) \propto \sum_{i=1}^{\infty} \sum_{m=-\ell}^{\ell} q_{\ell,m}^{\alpha}(\theta_z, \phi)$$

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



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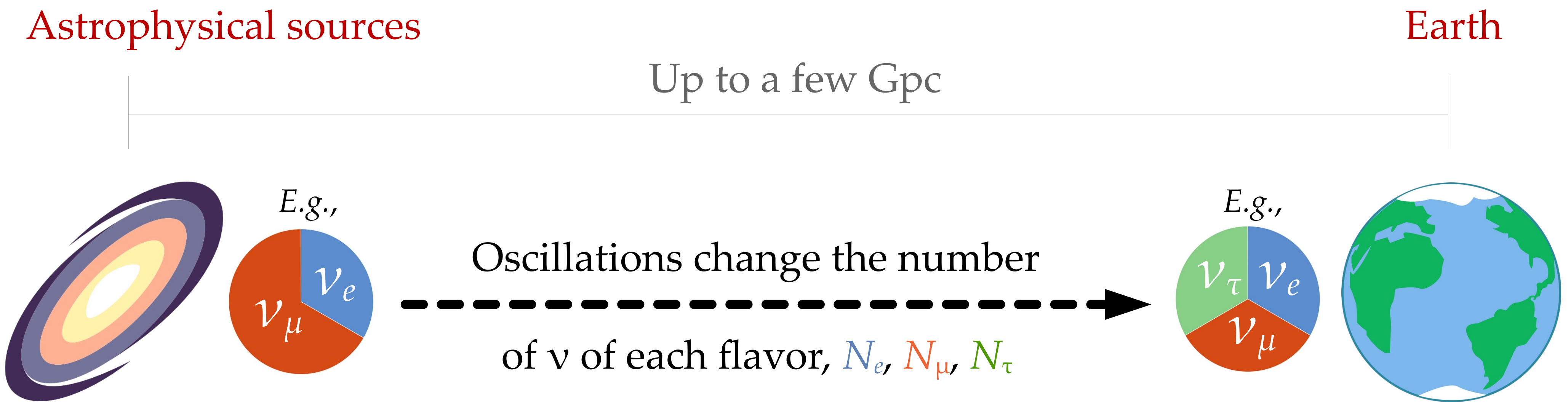
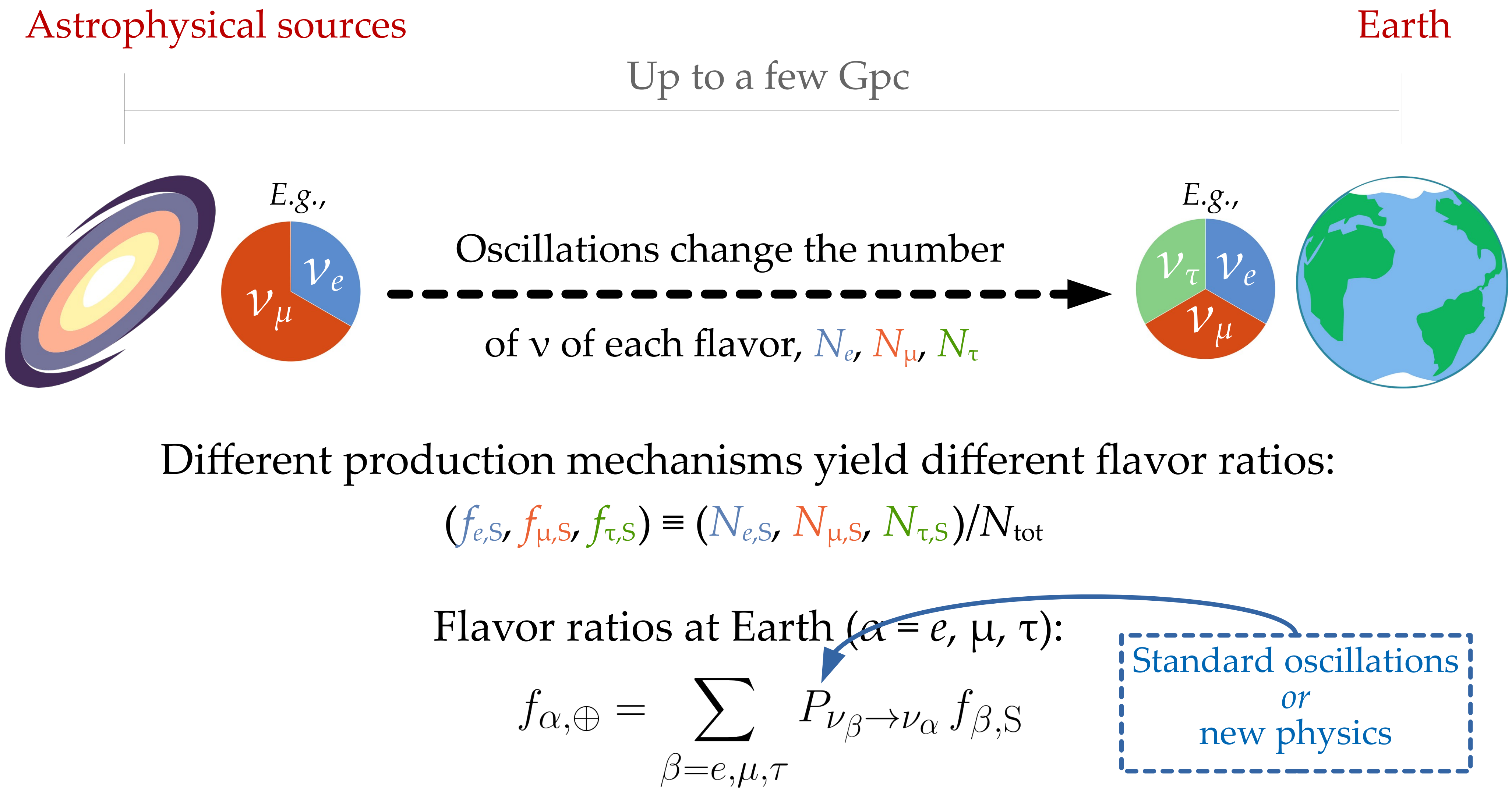


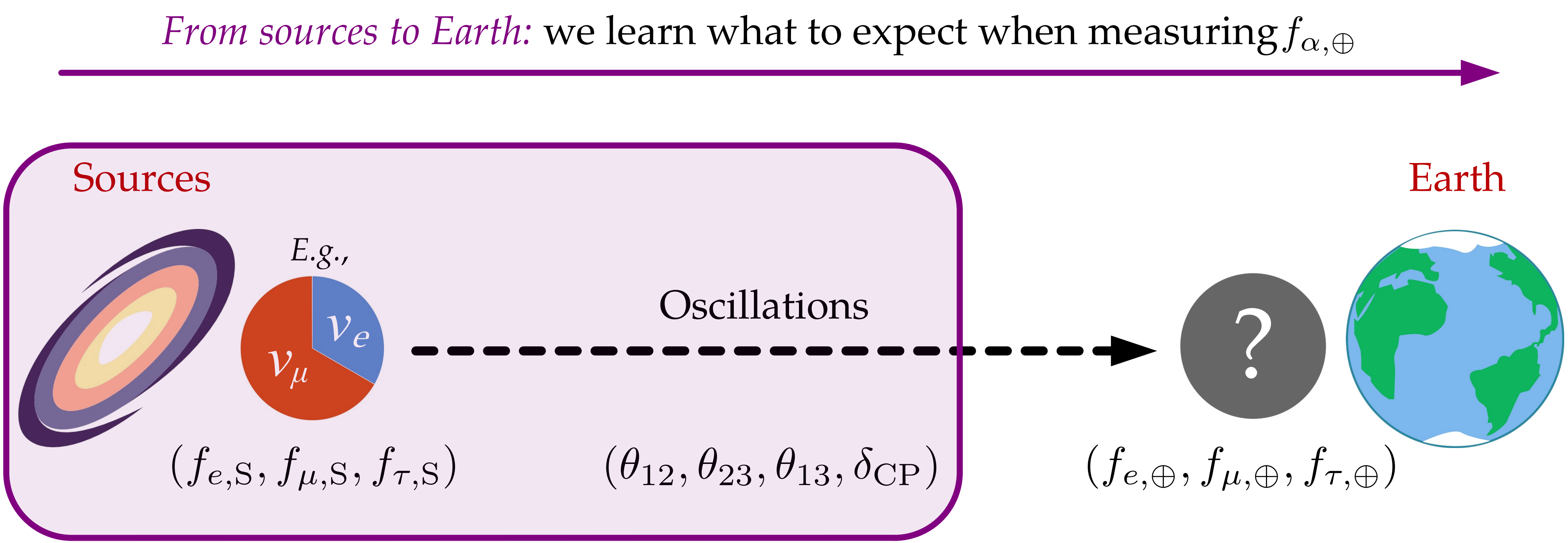
Different production mechanisms yield different flavor ratios:

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

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

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


Astrophysical sources
Earth
Up to a few Gpc
E.g.,
ν_e
ν_μ
Oscillations change the number
of ν of each flavor, N_e, N_μ, N_τ
E.g.,
ν_τ
ν_e
ν_μ
Different production mechanisms yield different flavor ratios:
$(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S})/N_{tot}$
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


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

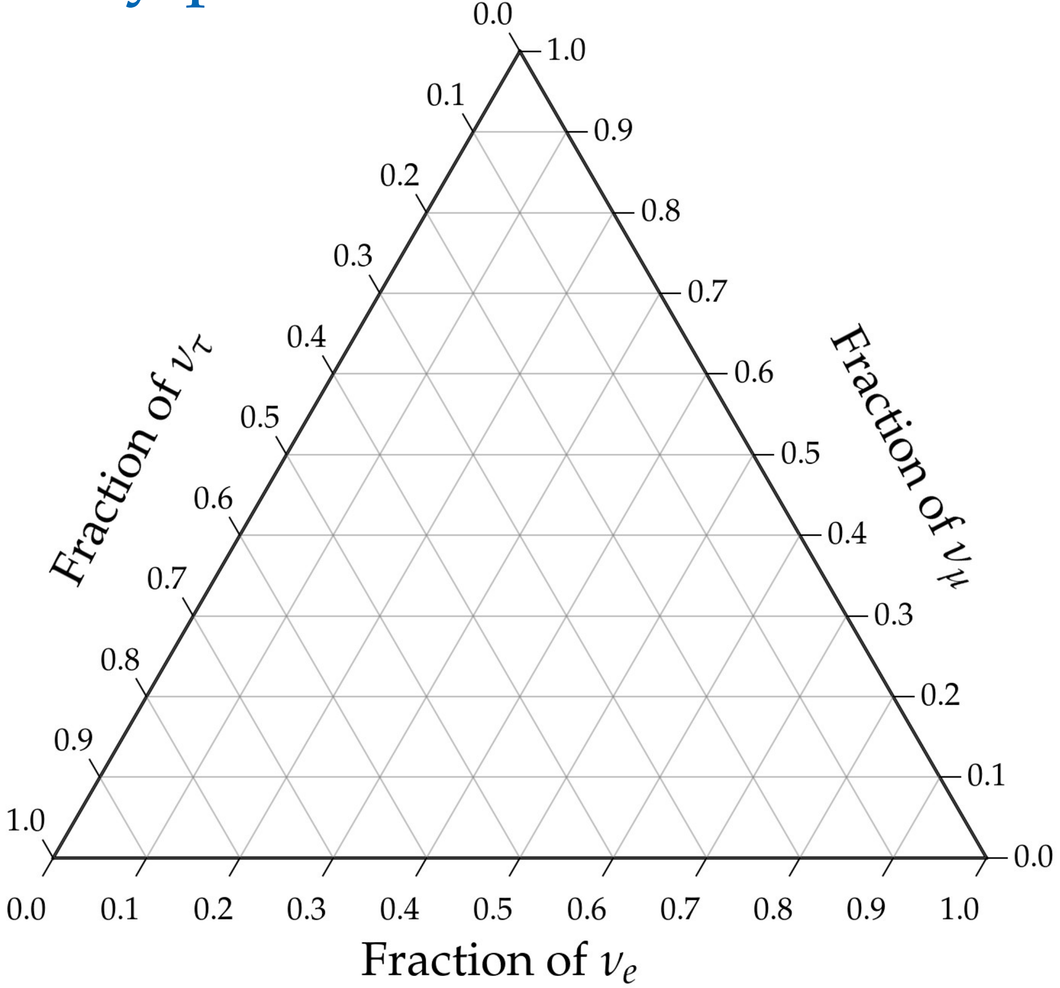
Quick aside: how to read a ternary plot

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

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



Quick aside: how to read a ternary plot

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

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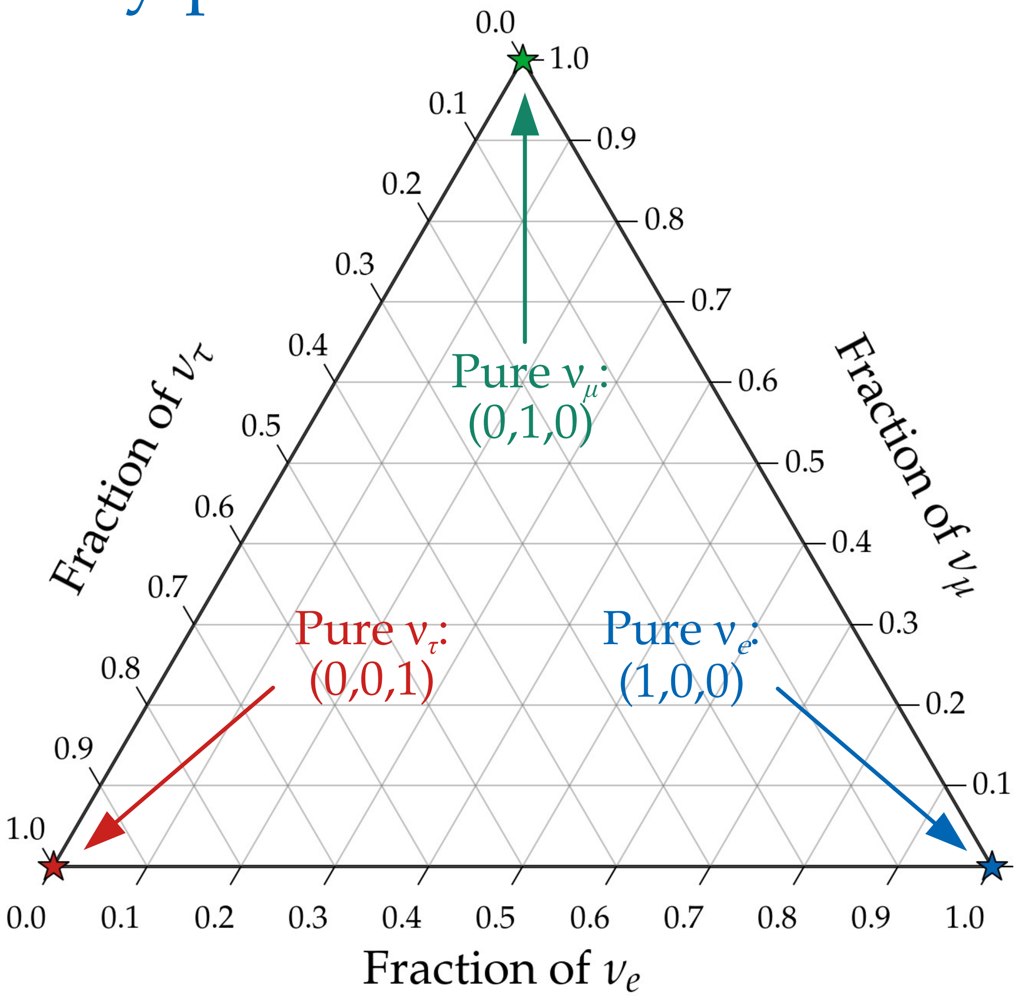

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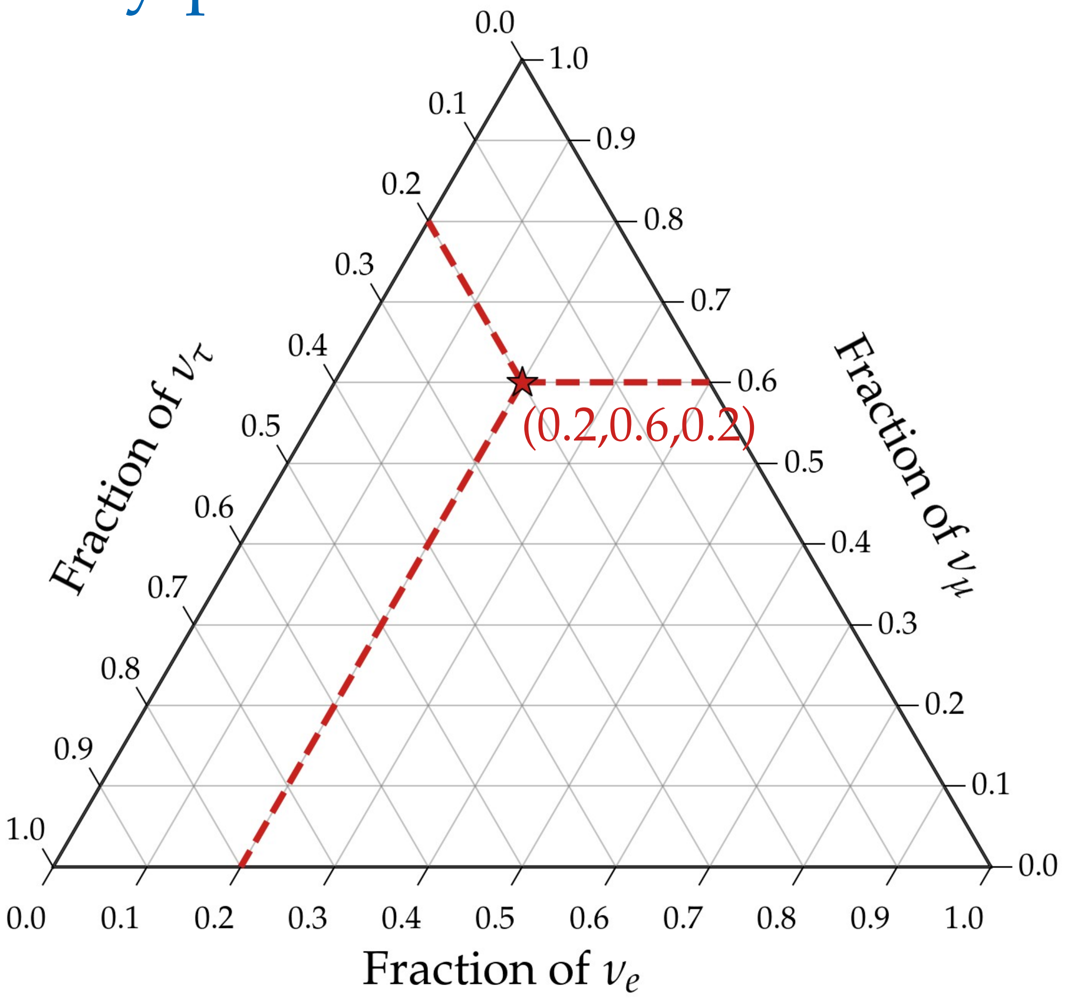

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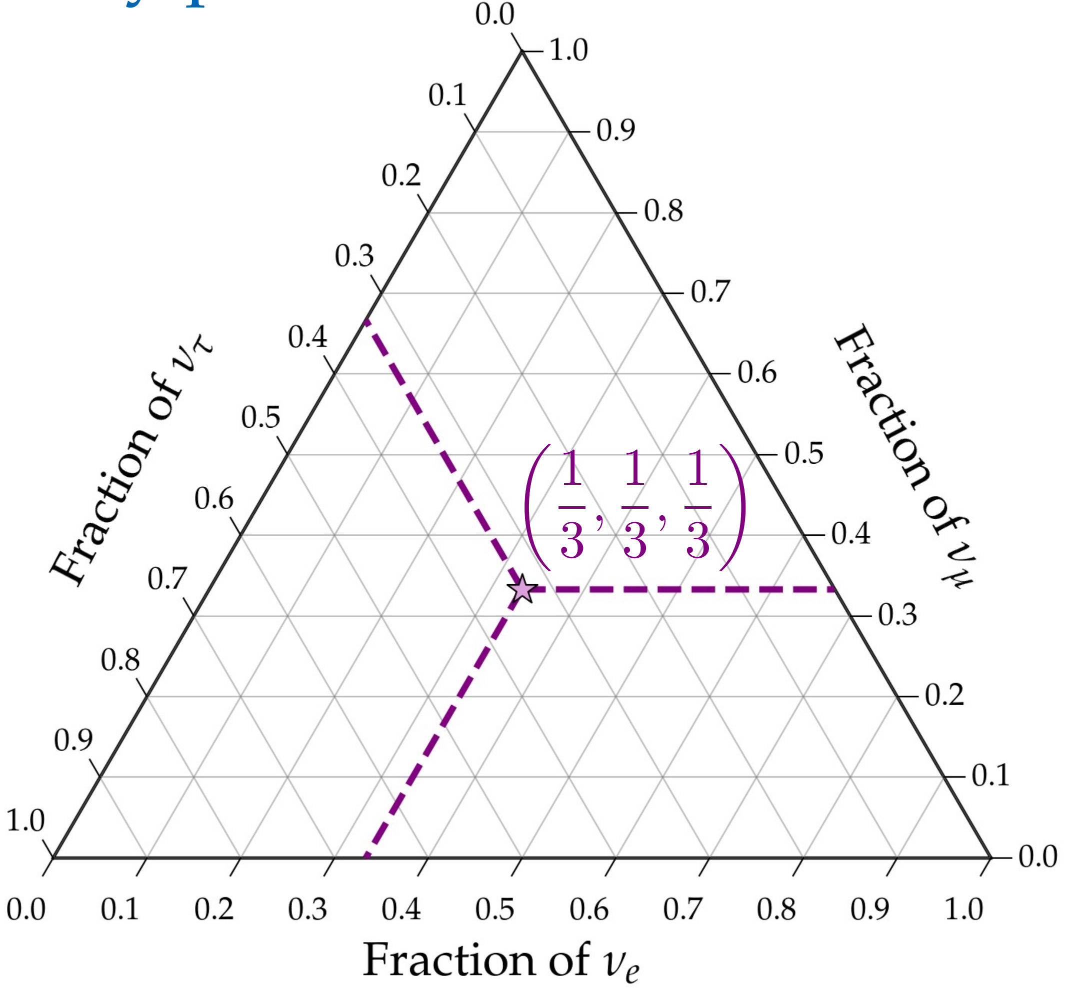

One likely TeV–PeV ν production scenario:

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

Full π decay chain

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

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

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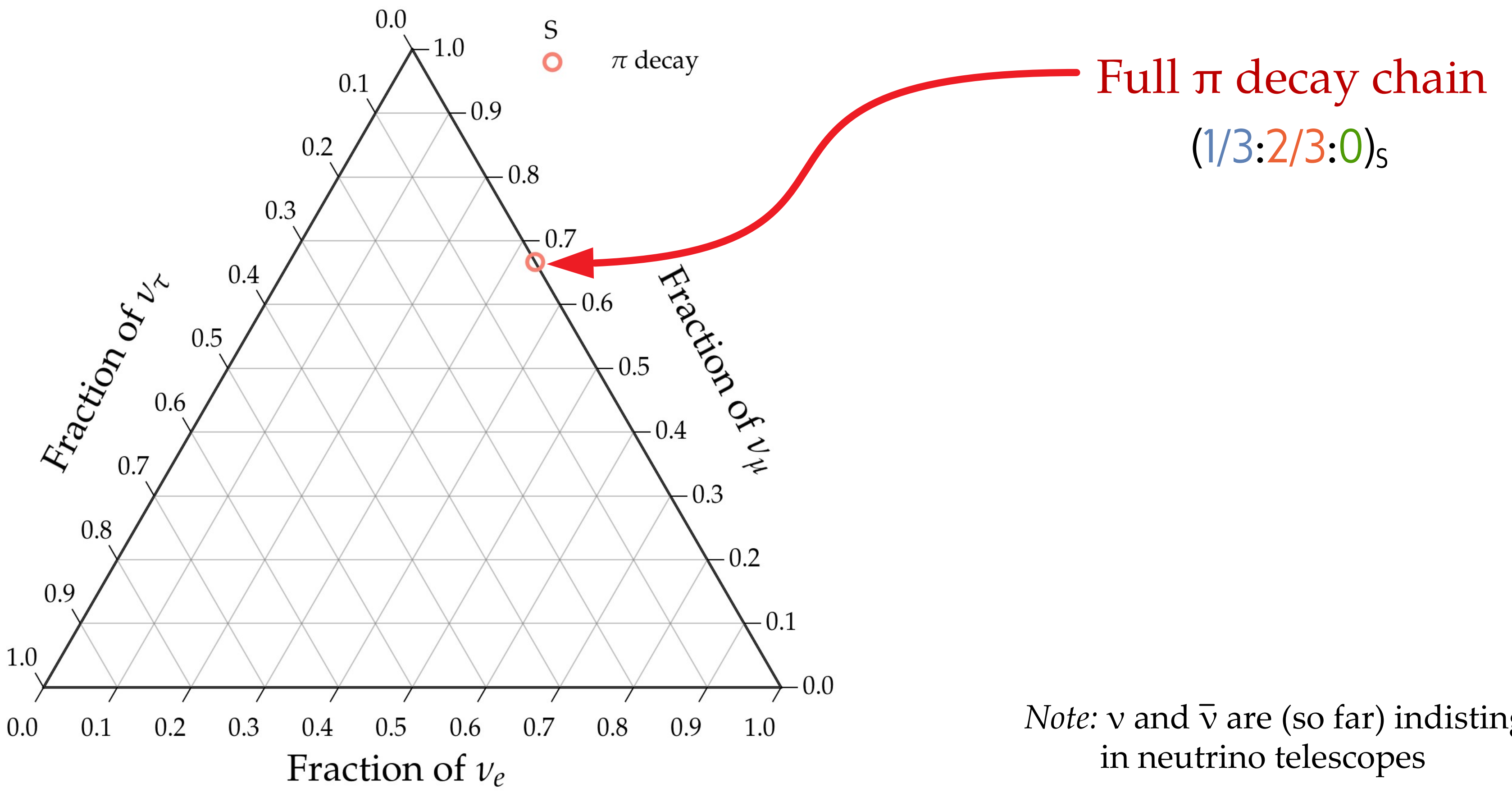

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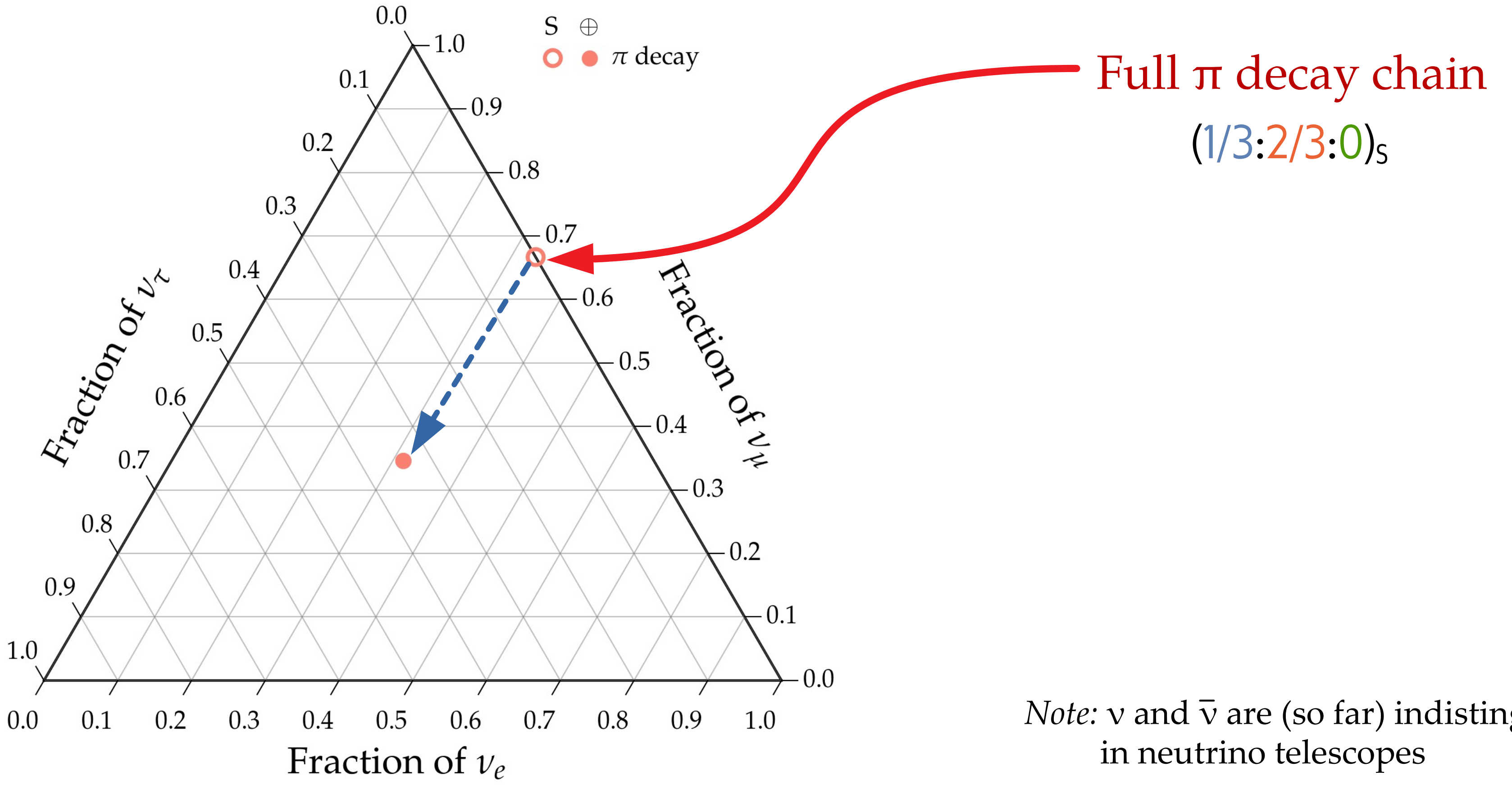

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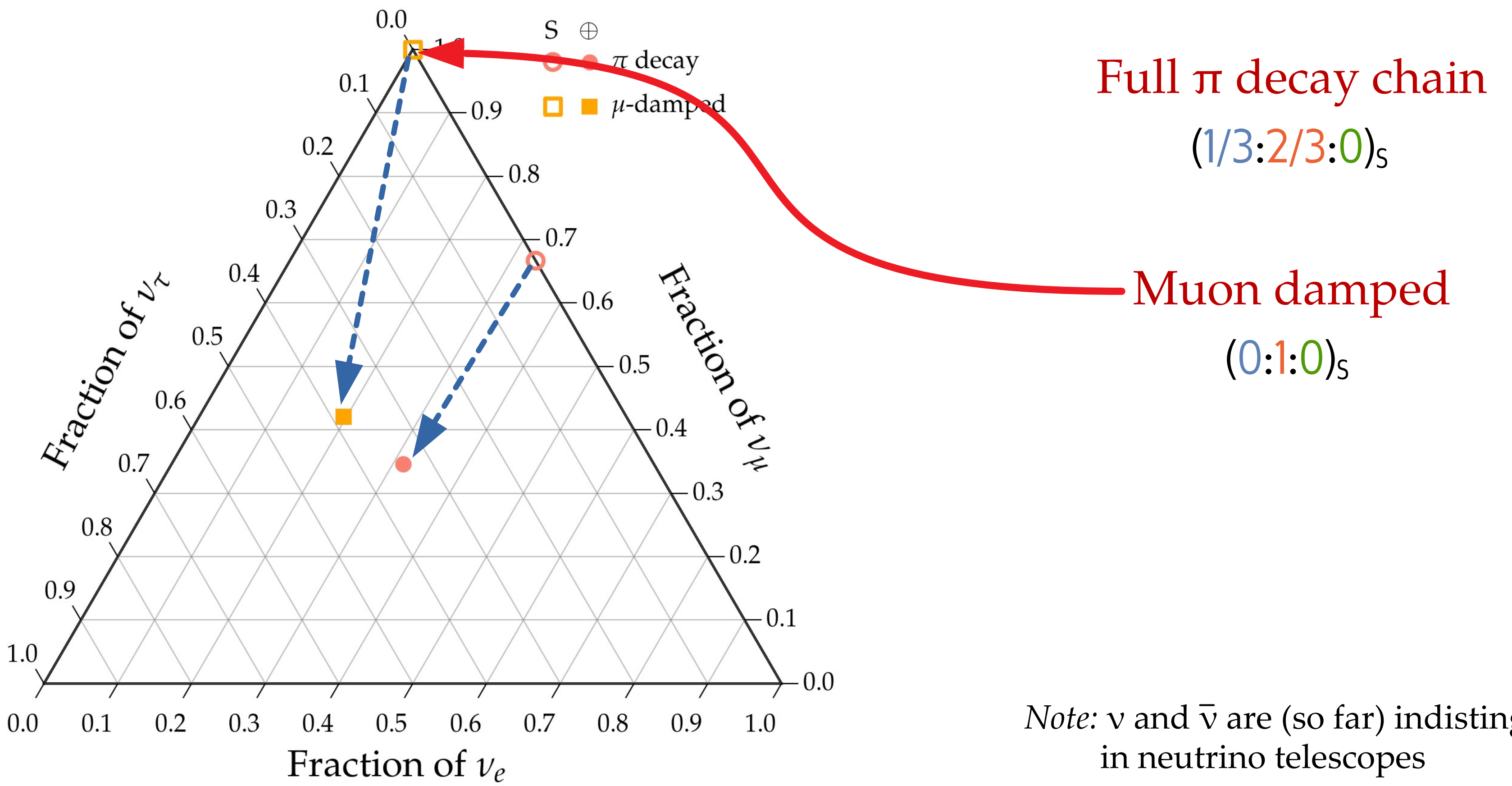

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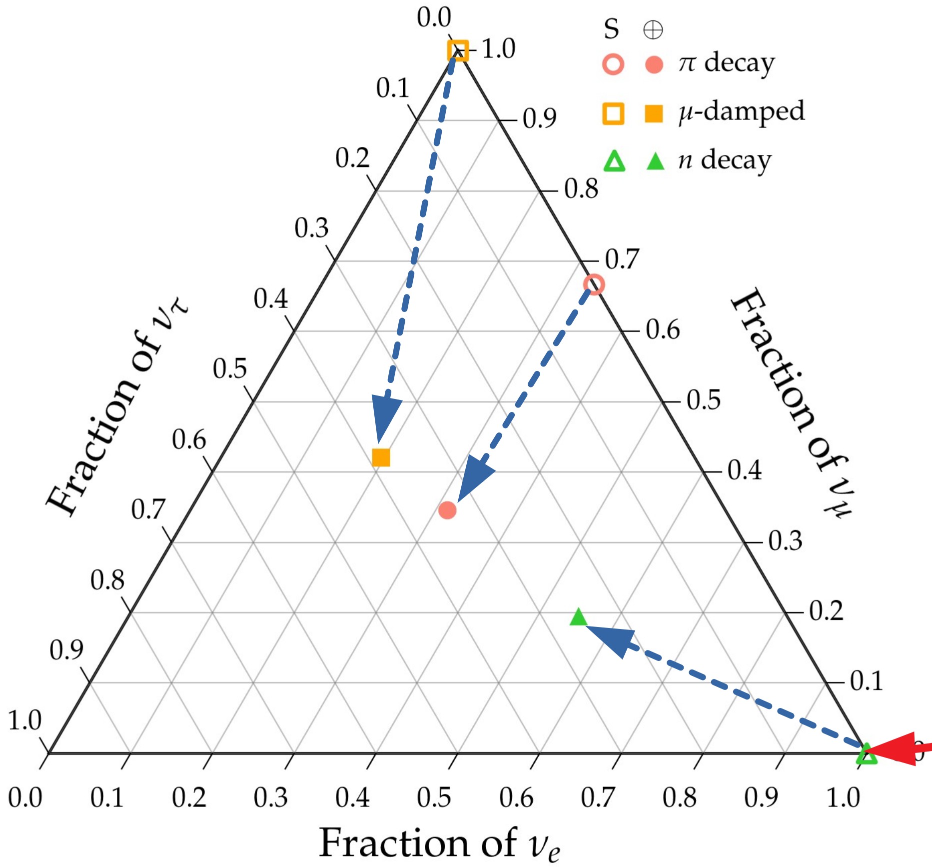


Full π decay chain

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

Muon damped

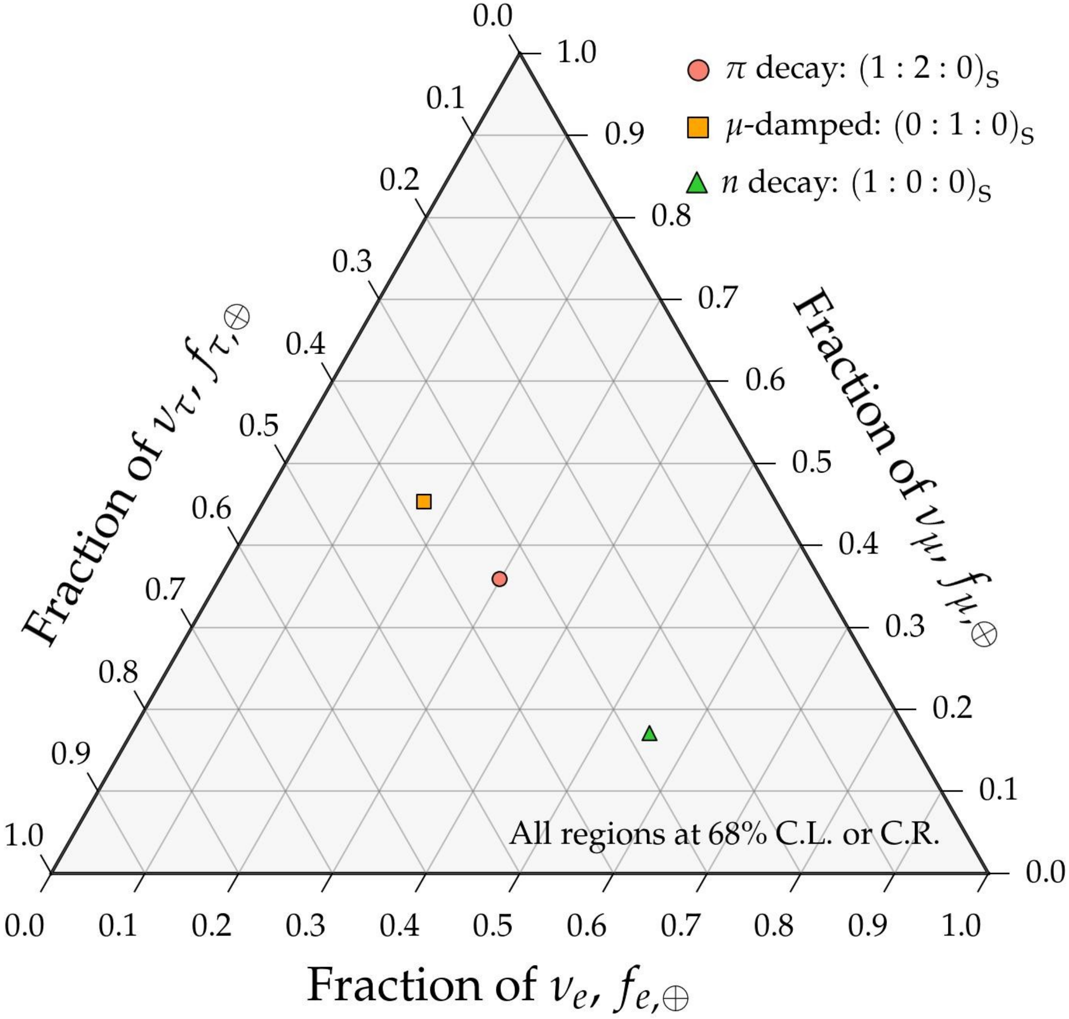
$(0:1:0)_S$

Neutron decay

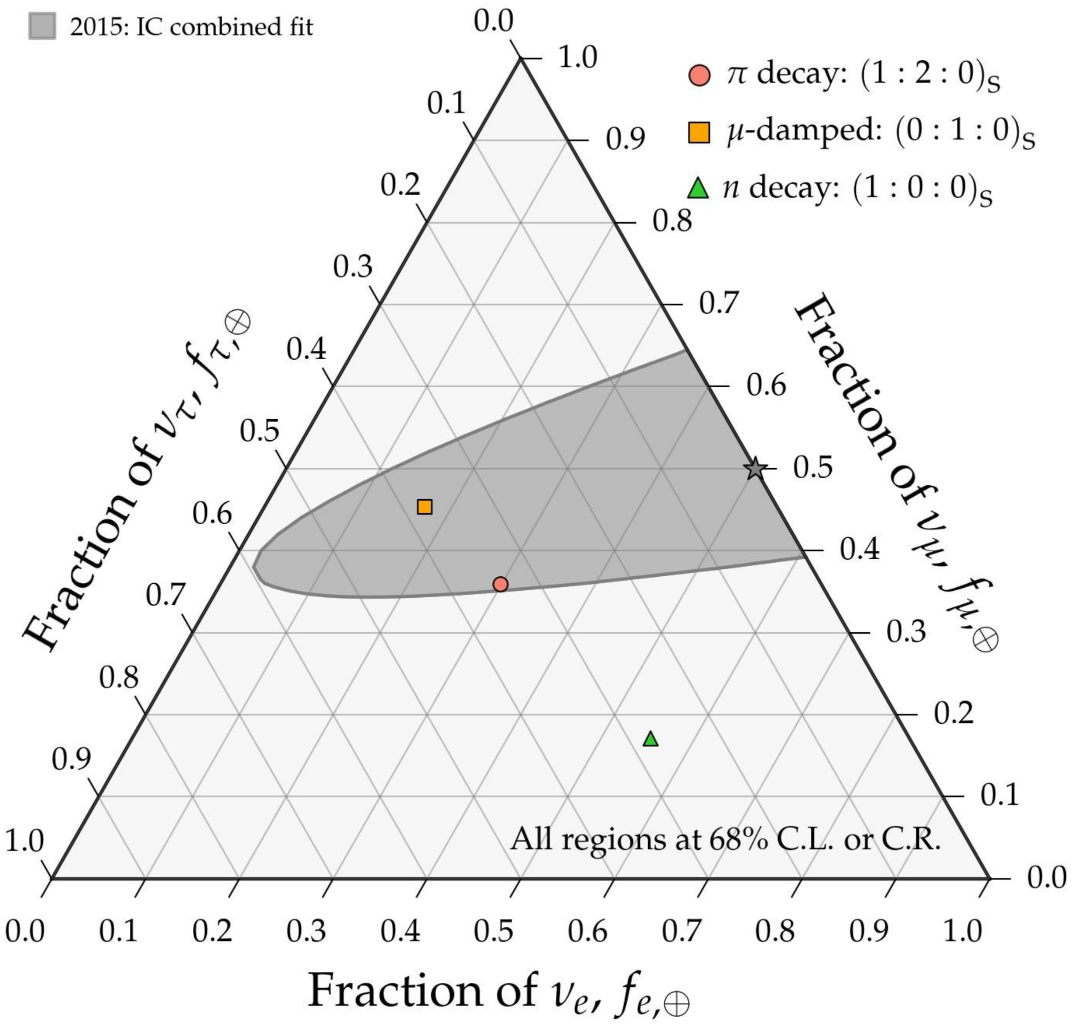
$(1:0:0)_S$

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

Measuring flavor composition 2015–2025



Measuring flavor composition 2015–2025



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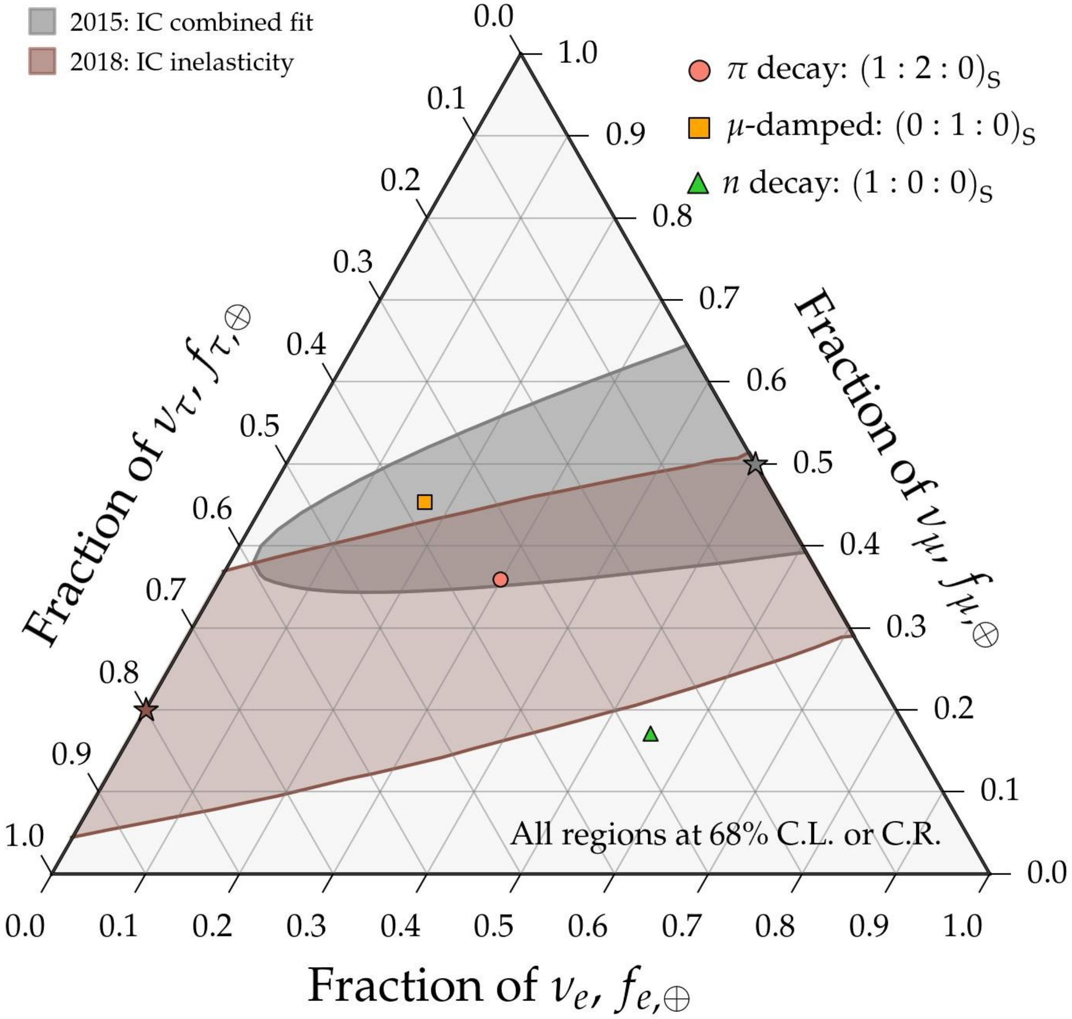

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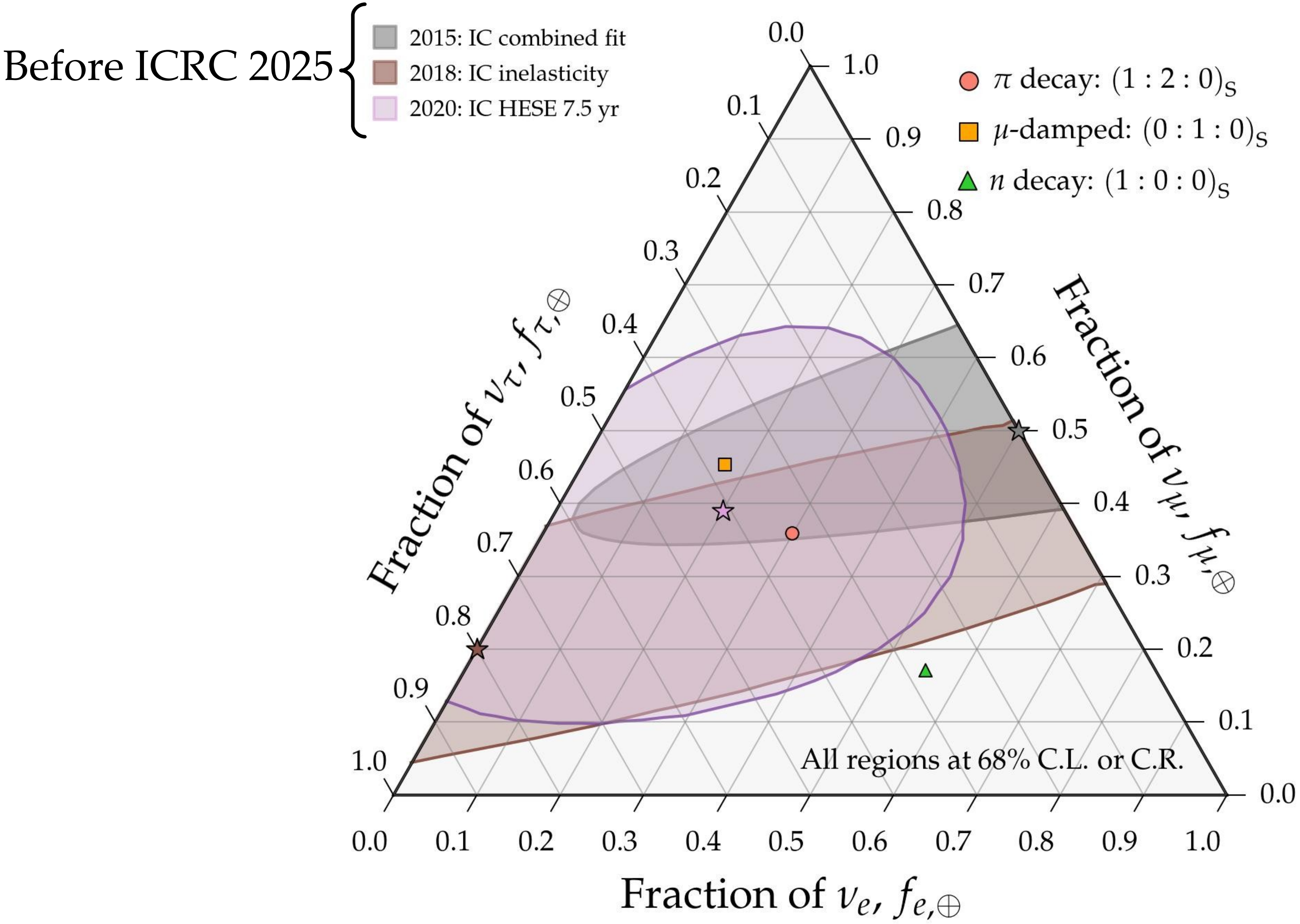
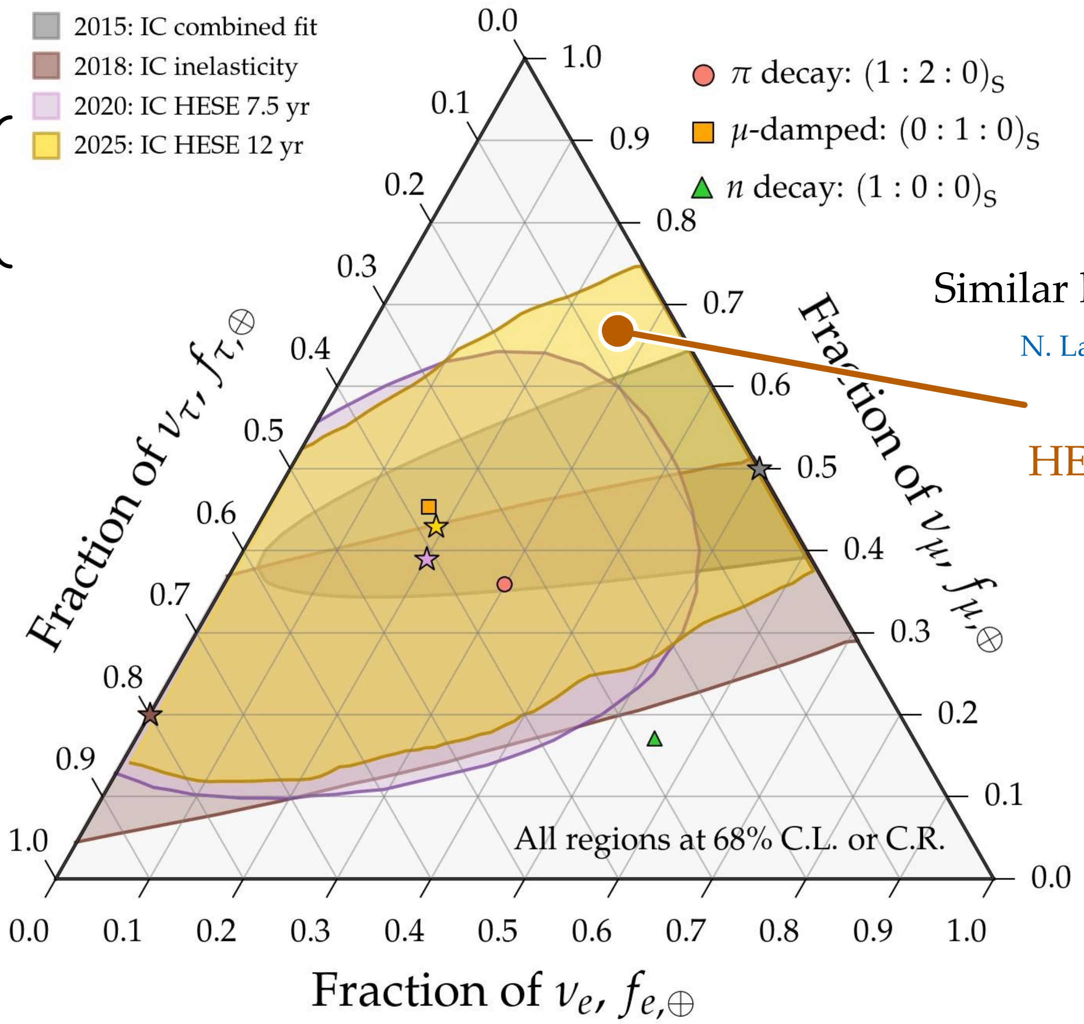


Measuring flavor composition 2015–2025

Presented at ICRC 2025



Similar likelihood as with 7.5 yr

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

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

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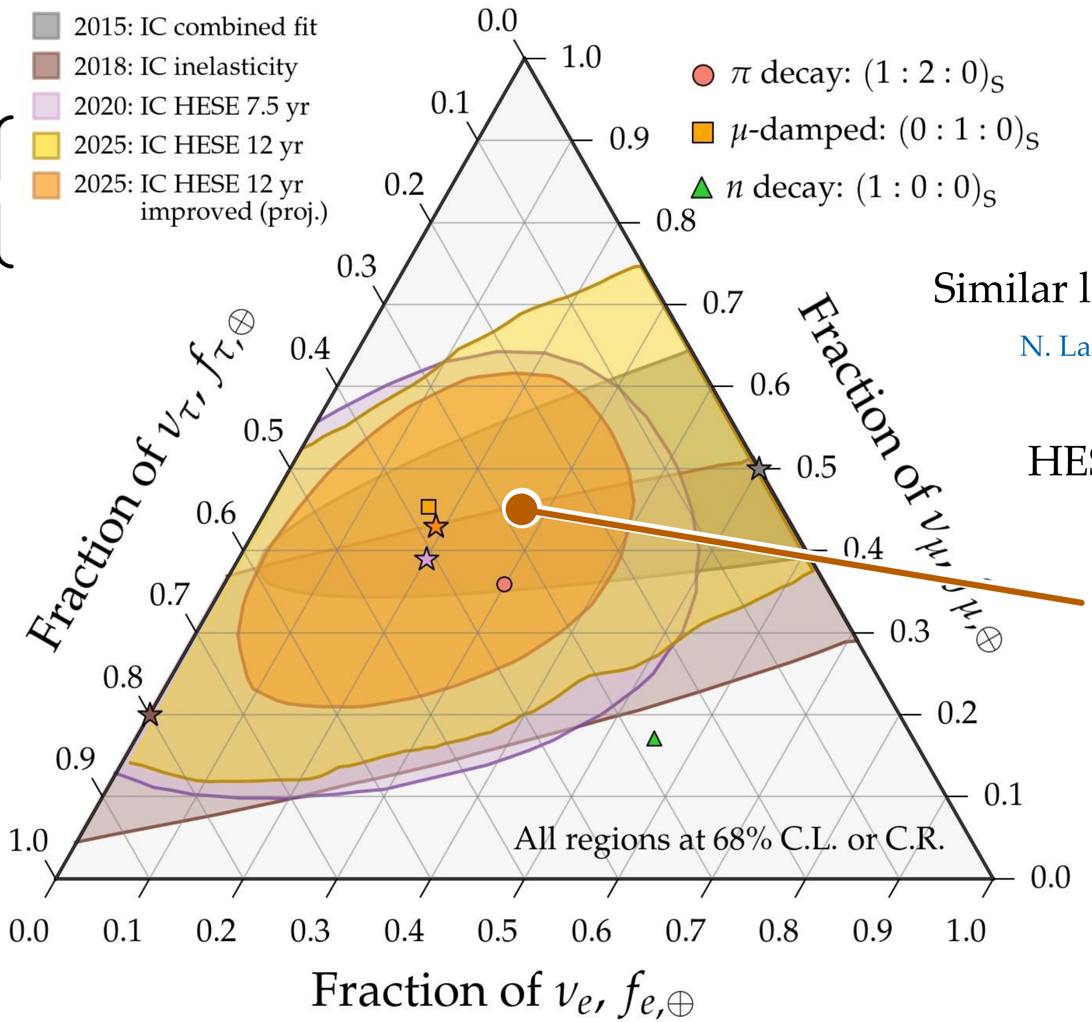

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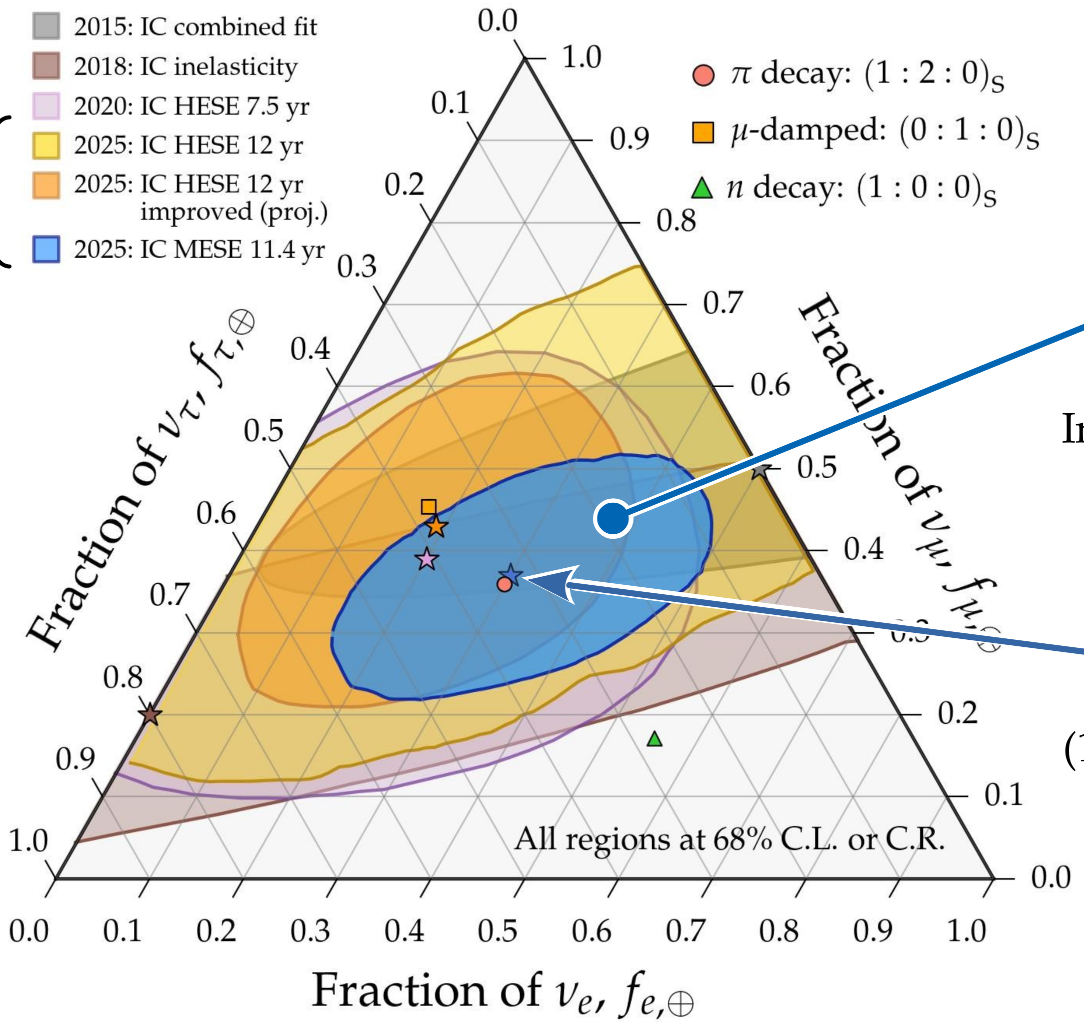
Improve via a neural network that uses the energy asymmetry of the two bangs and the direction

Measuring flavor composition 2015–2025

Presented at ICRC 2025



MESE events (> 1 TeV) are more abundant

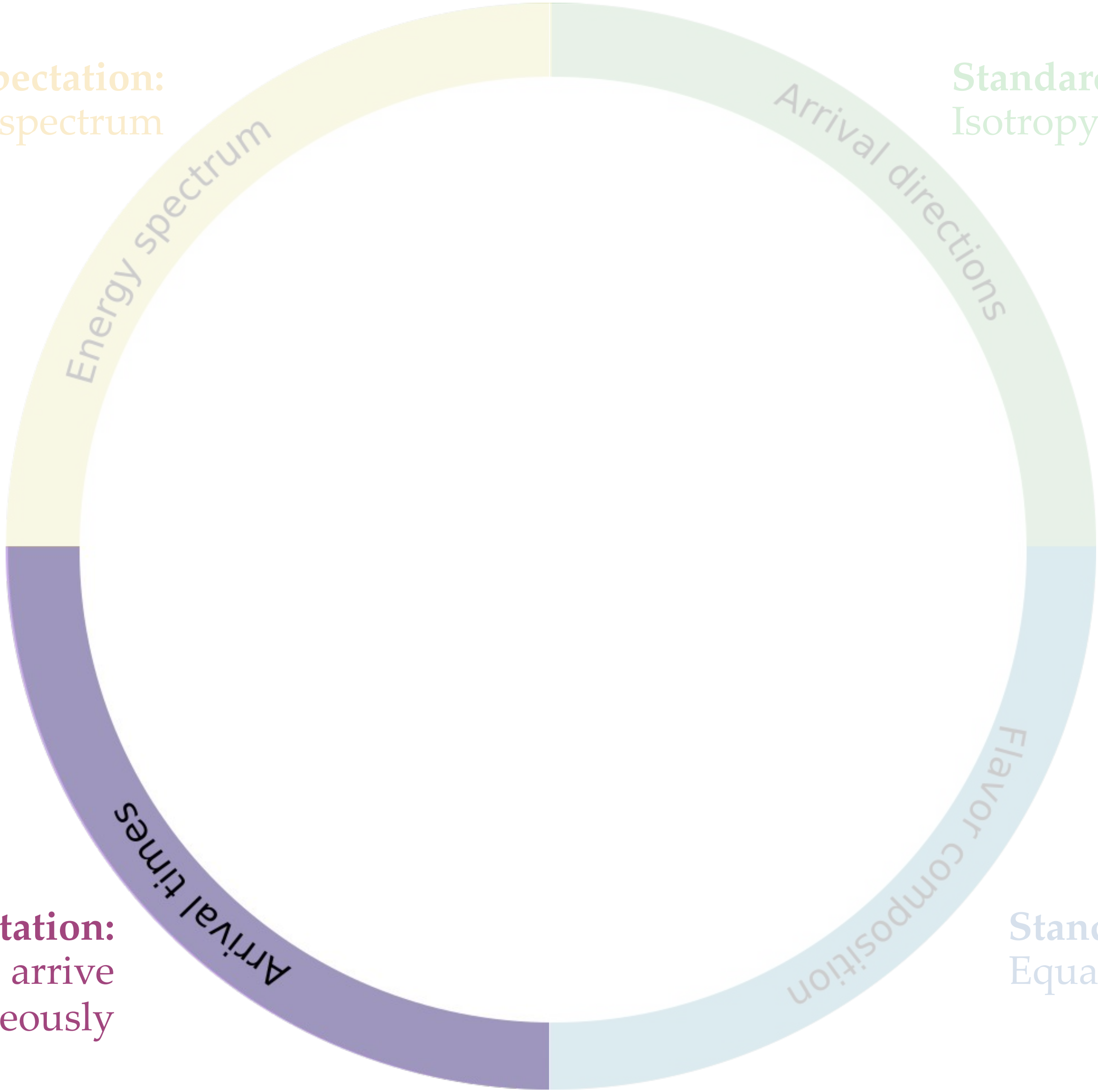
Includes classification of υ_τ

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

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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Bright in gamma rays, bright in high-energy neutrinos

Energy in neutrinos ∝ energy in gamma rays

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

E. Waxman & J. Bahcall, *PRL* 1997
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Fraction of total p energy given to pions

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Fraction of total p energy given to pions

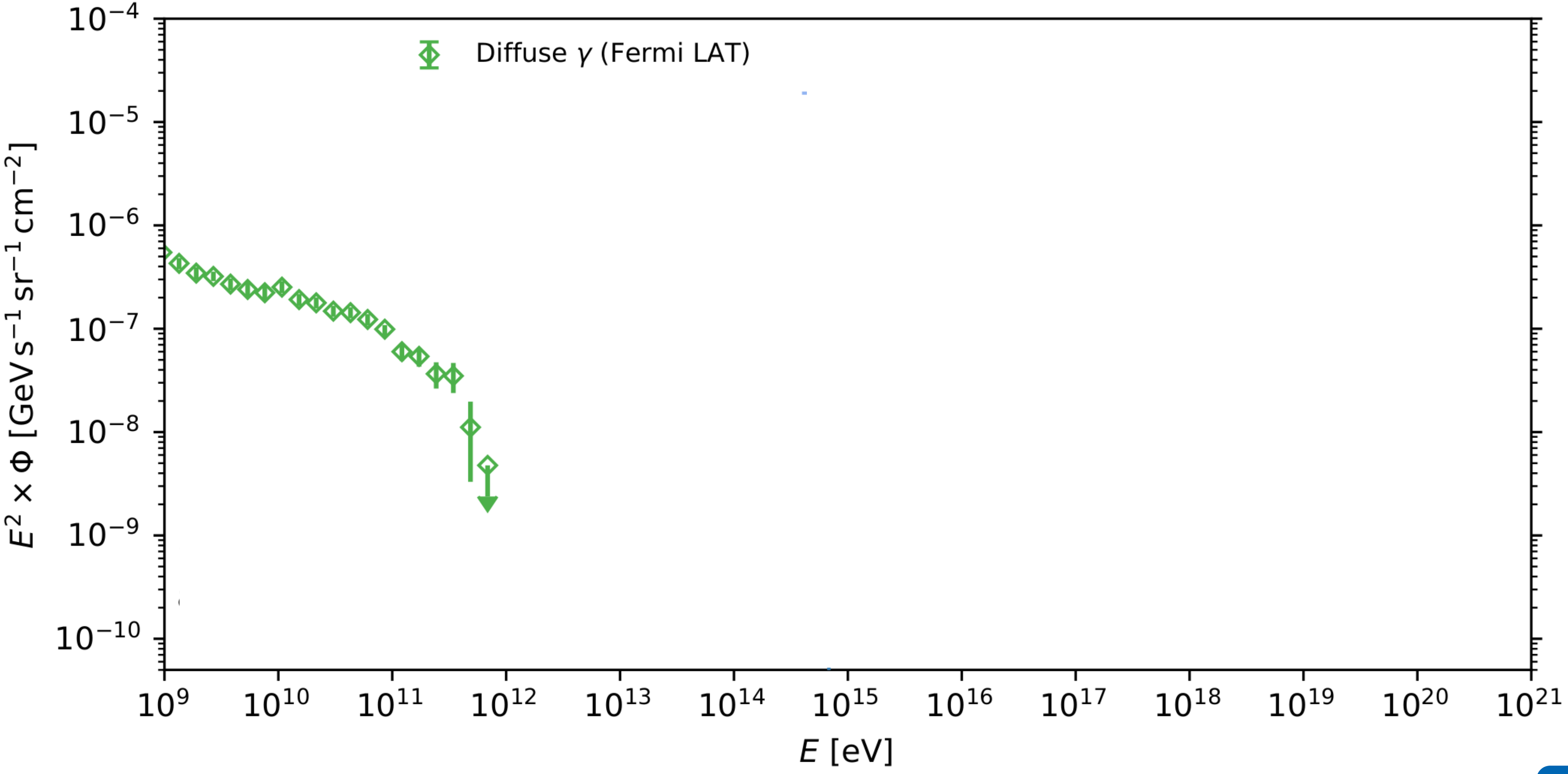
Baryonic loading

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

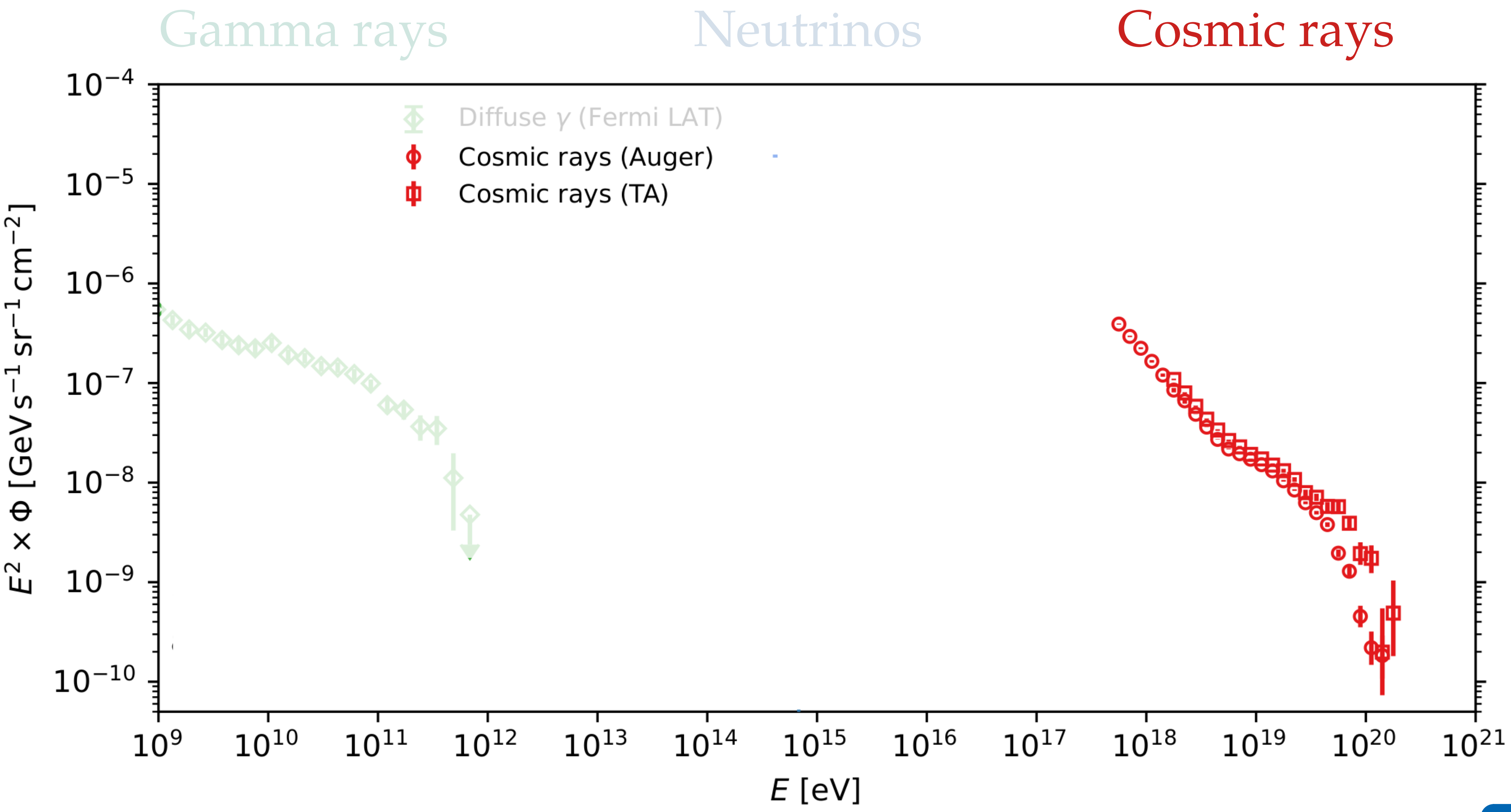
E. Waxman & J. Bahcall, *PRL* 1997
D. Guetta *et al.*, *Astropart. Phys.* 2004

What have we learned about *astrophysics*?

Gamma rays Neutrinos Cosmic rays



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



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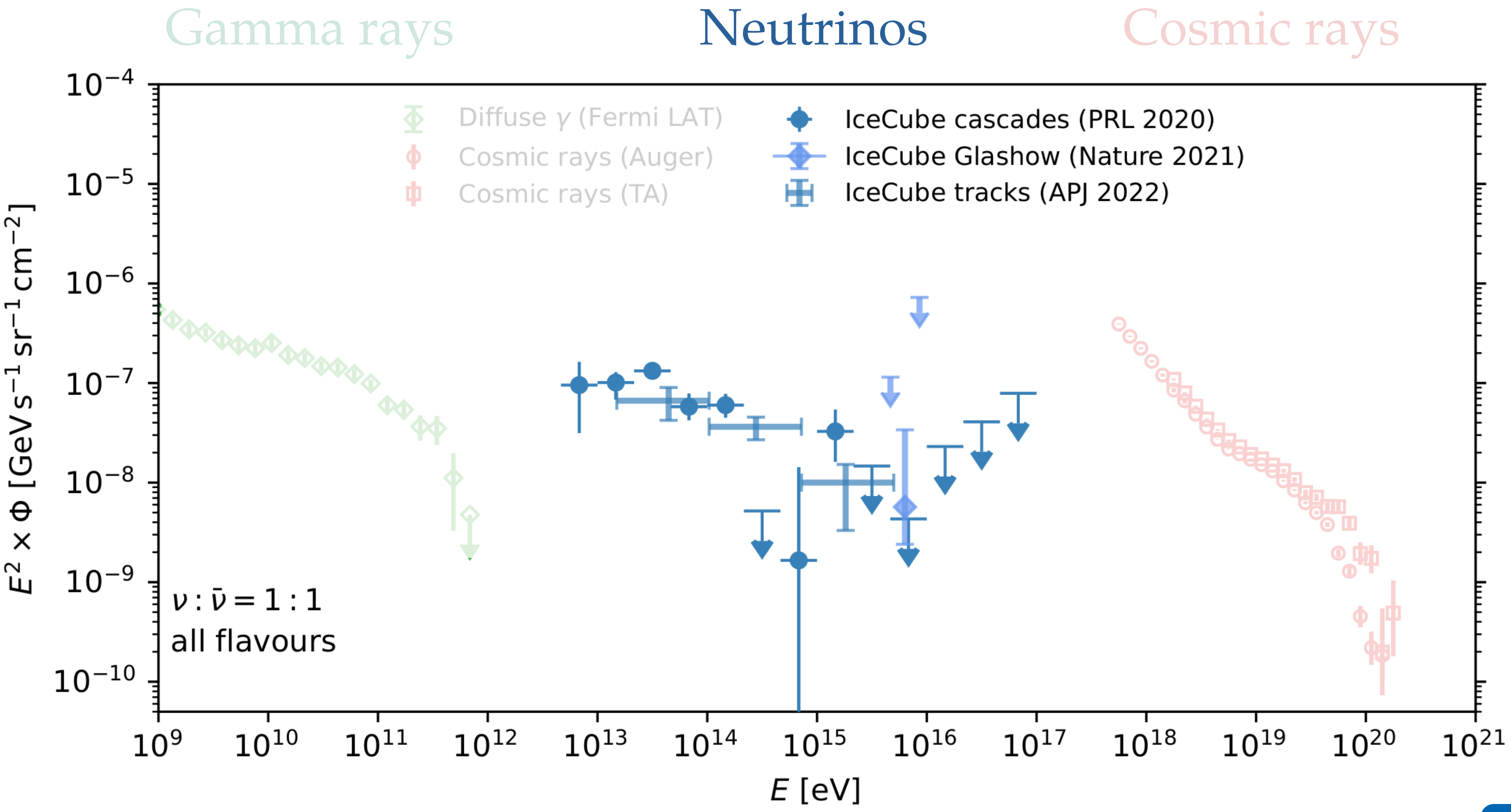

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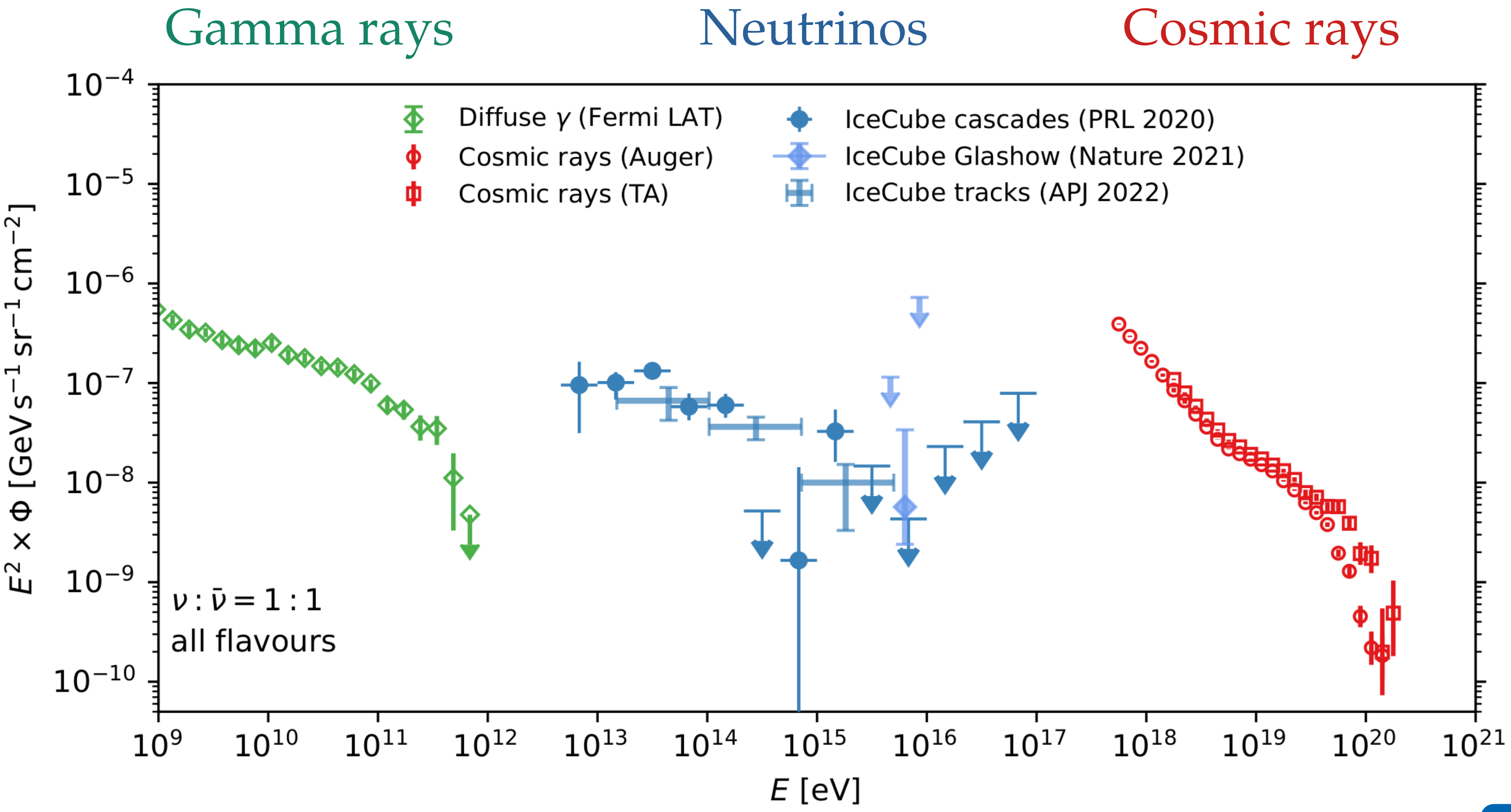

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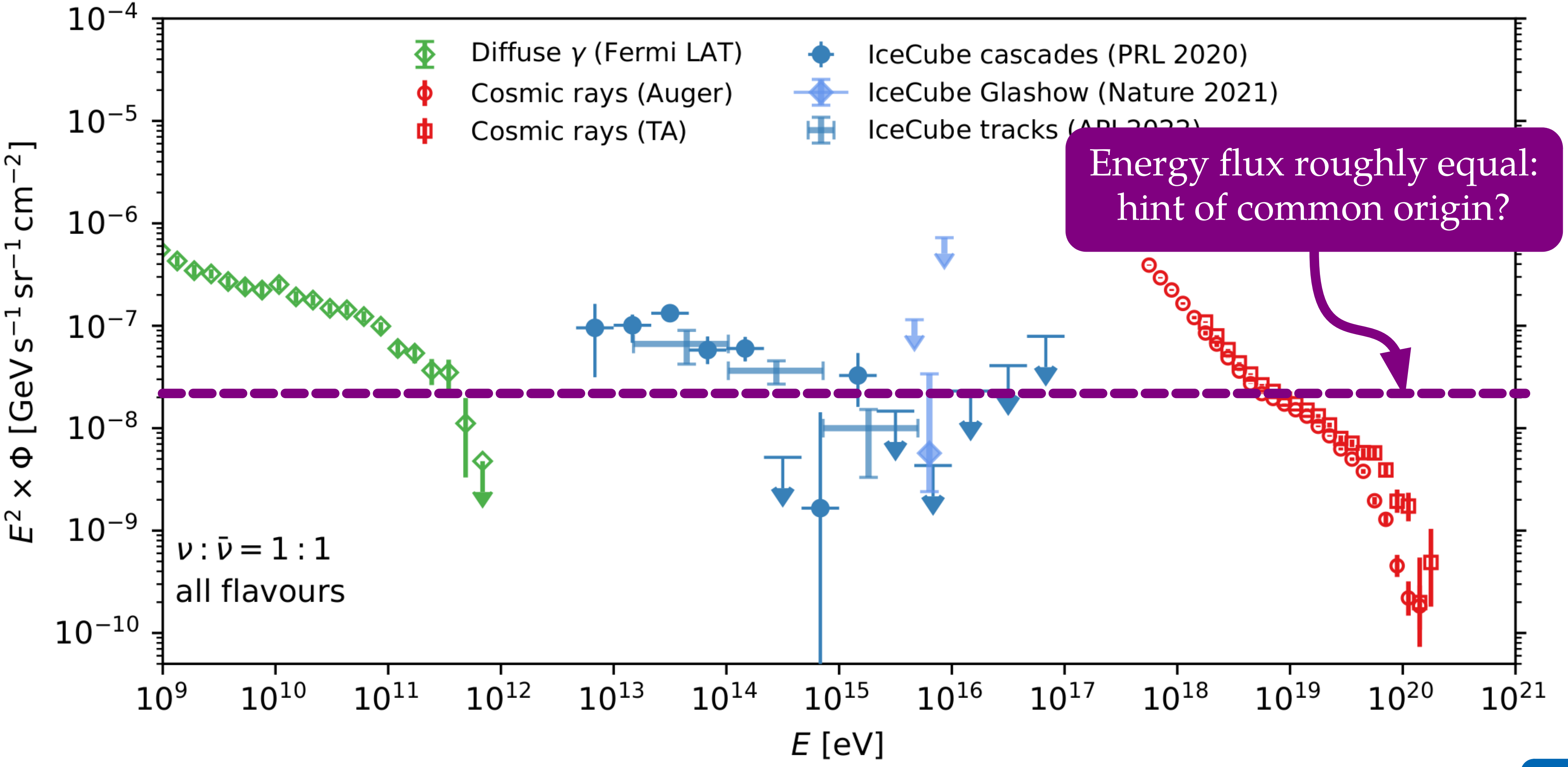
Gamma rays | Neutrinos | Cosmic rays



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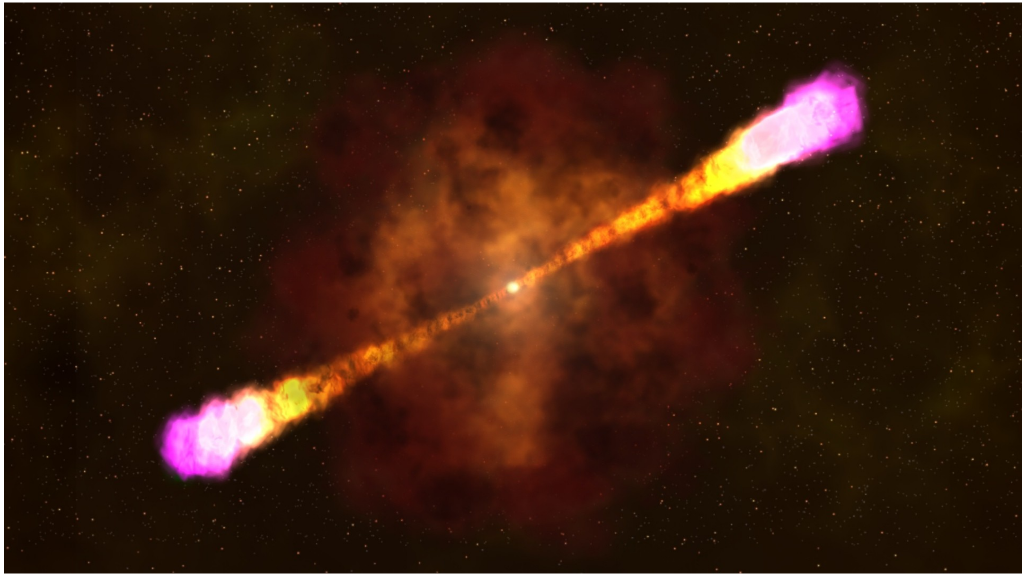
Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts



Blazars

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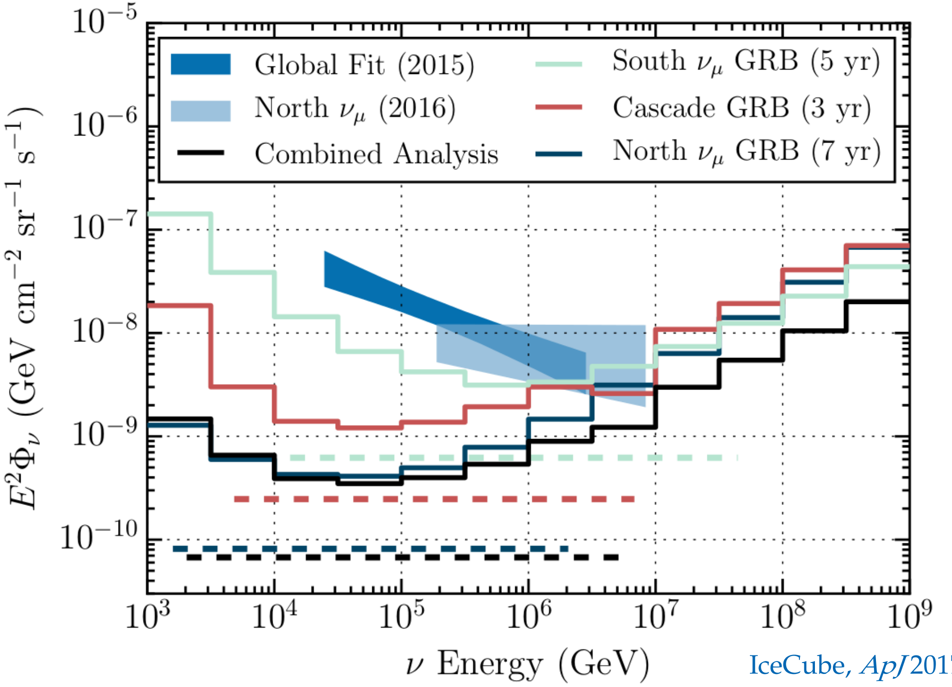
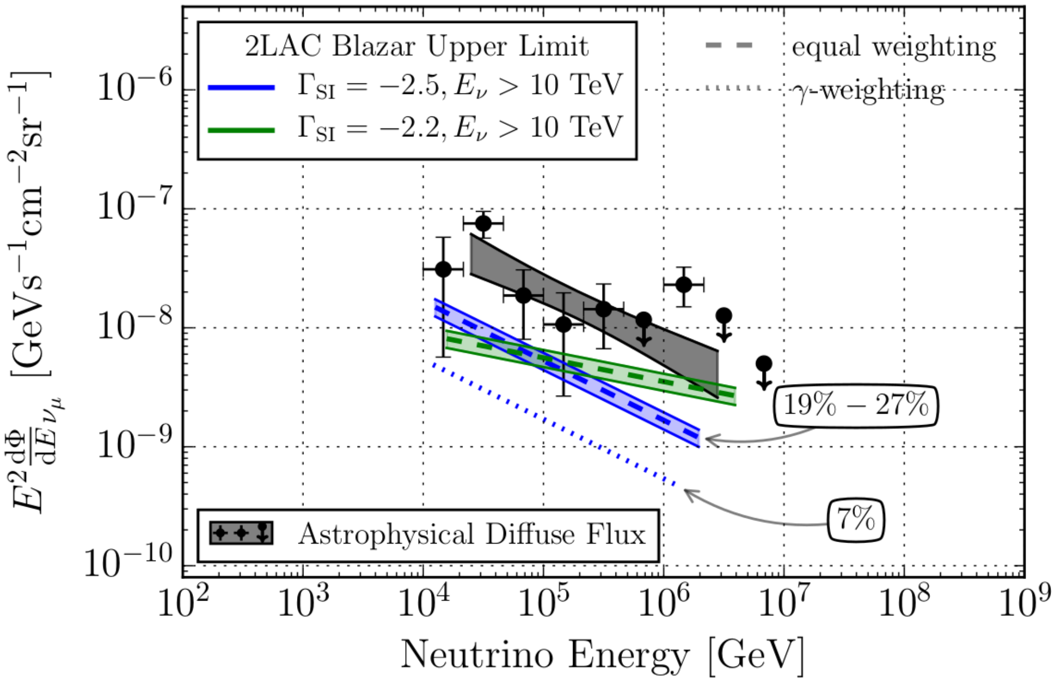


IceCube, *ApJ* 2017

1172 GRBs inspected, no correlation found

< 1% contribution to diffuse flux

Blazars

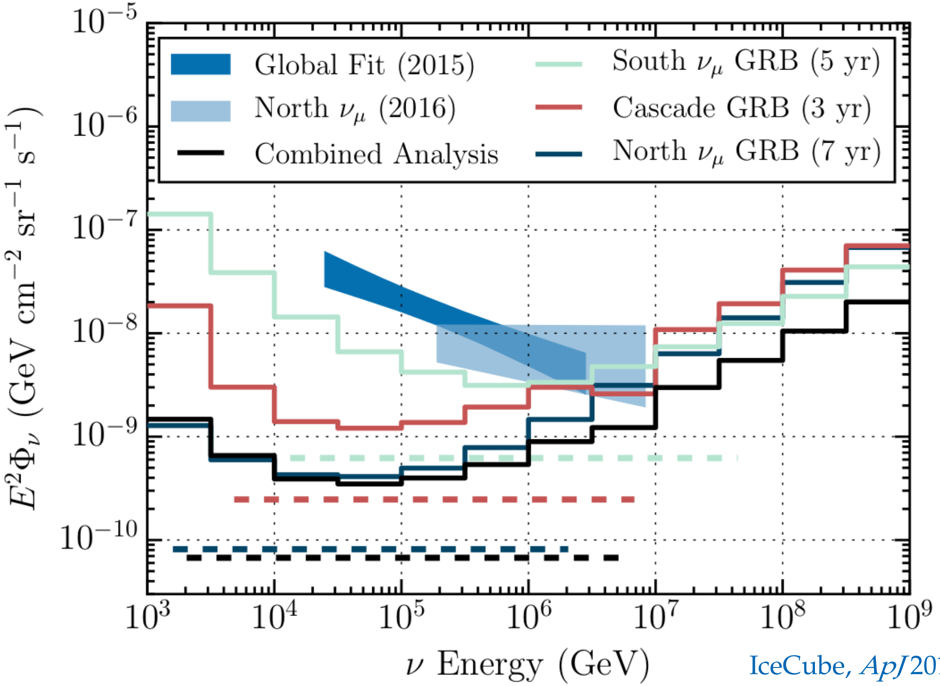


862 blazars inspected, no correlation found

< 27% contribution to diffuse flux

Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts



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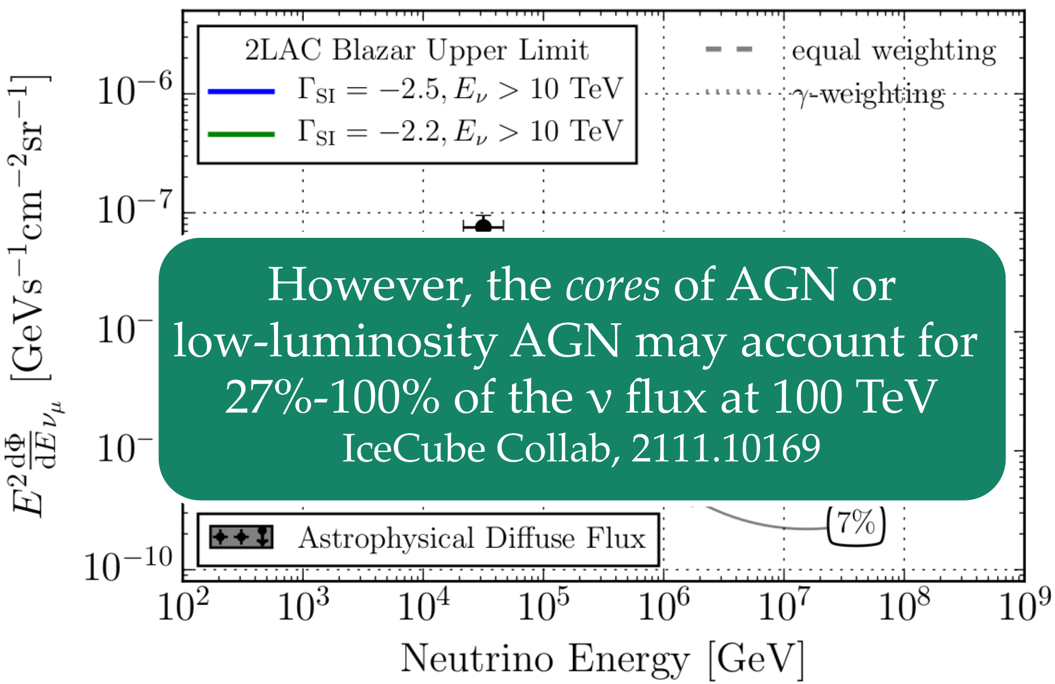
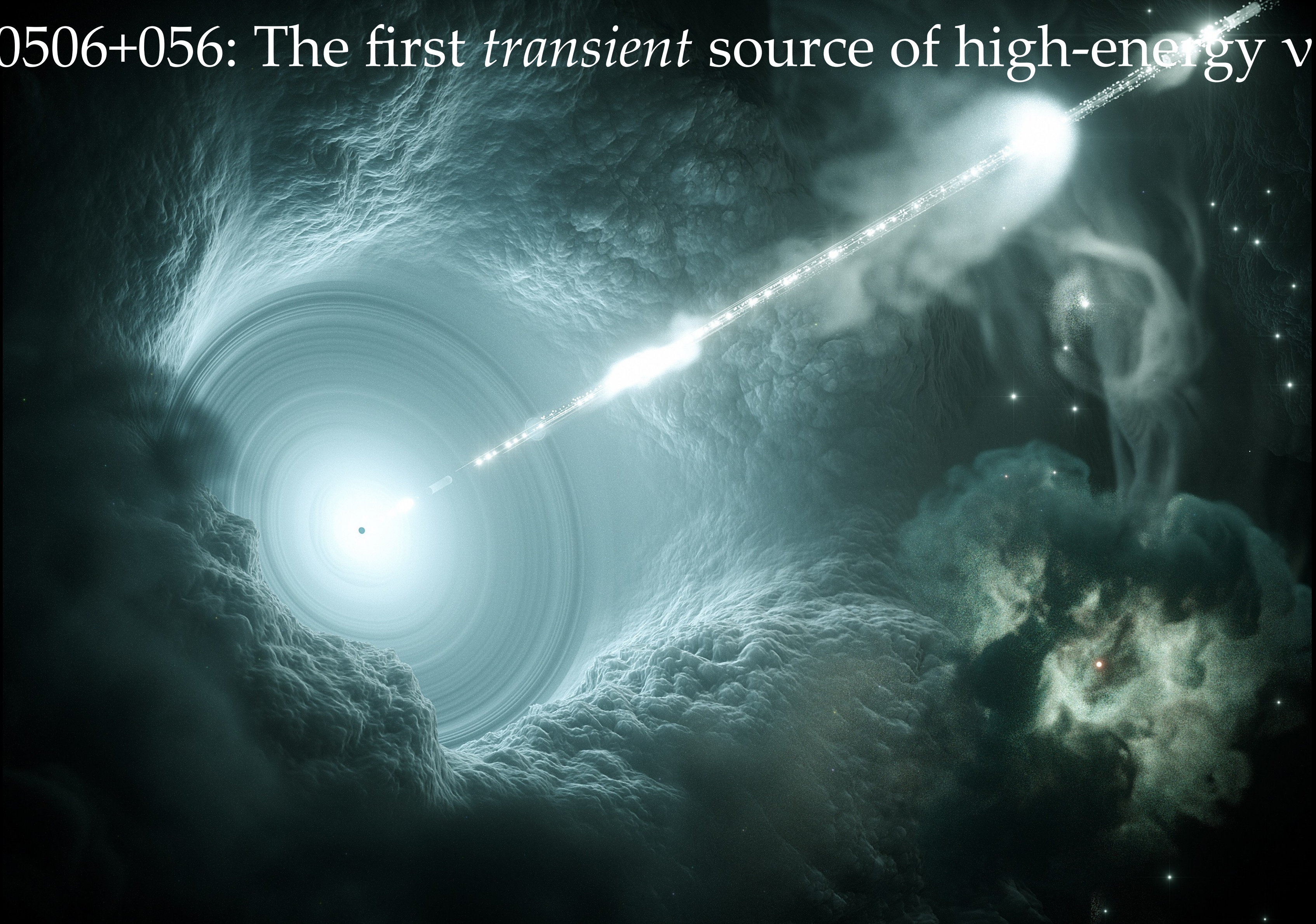


However, the *cores* of AGN or low-luminosity AGN may account for 27%-100% of the ν flux at 100 TeV
IceCube Collab, 2111.10169

862 blazars inspected, no correlation found

< 27% contribution to diffuse flux

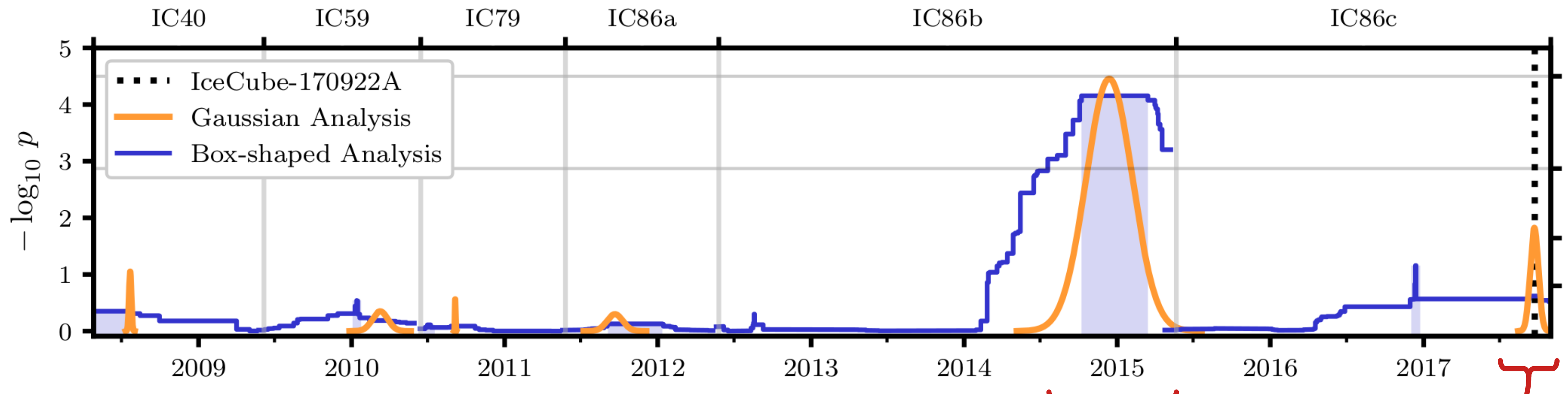
TXS 0506+056: The first *transient* source of high-energy ν



DESY

… but we have seen *one* blazar neutrino flare!

Blazar TXS 0506+056:



IceCube, *Science* 2018

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

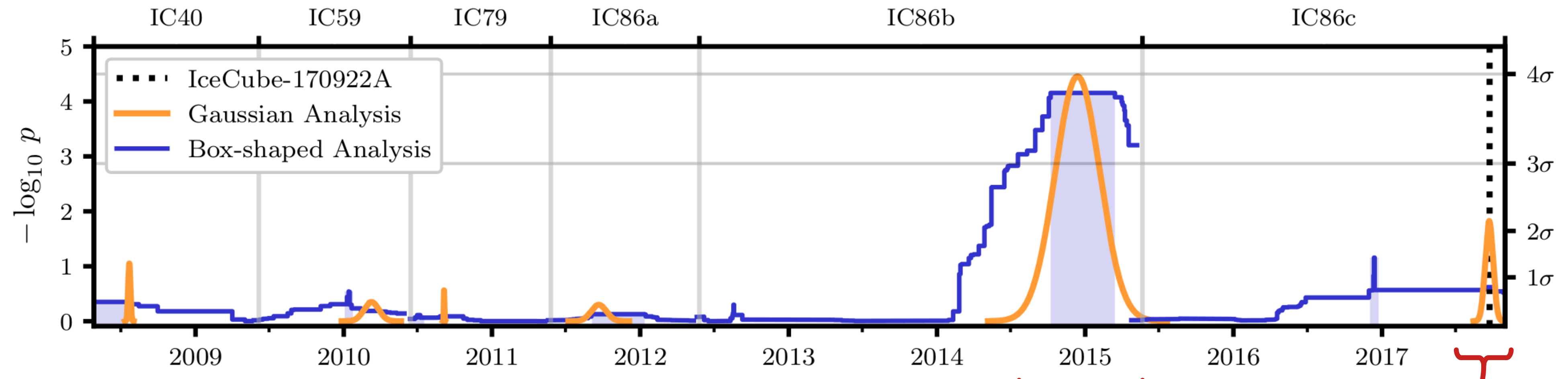
Combined (pre-trial): 4.1σ

Hard fluence: $E^2 J_{100} = 2.1^{+0.9}_{-0.7} \left(\frac{E}{100\ \text{TeV}}\right)^{-2.1\pm0.2}\ \text{TeV cm}^{-2}$

Joint modeling of the two periods is challenging!

… but we have seen *one* blazar neutrino flare!

Blazar TXS 0506+056:



IceCube, *Science* 2018

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

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Joint modeling of the two periods is challenging!

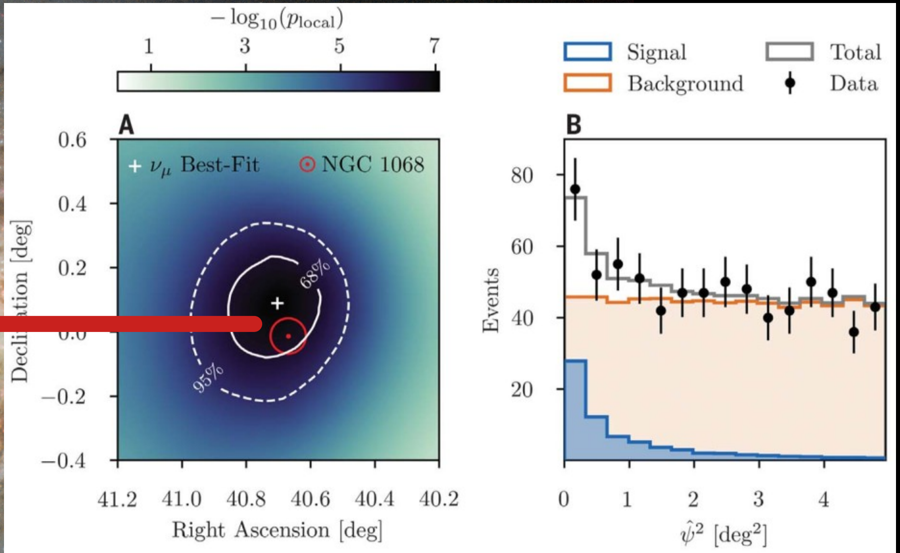
NGC1068: The first *steady-state* source of high-energy ν

Active galactic nucleus

Brightest type-2 Seyfert

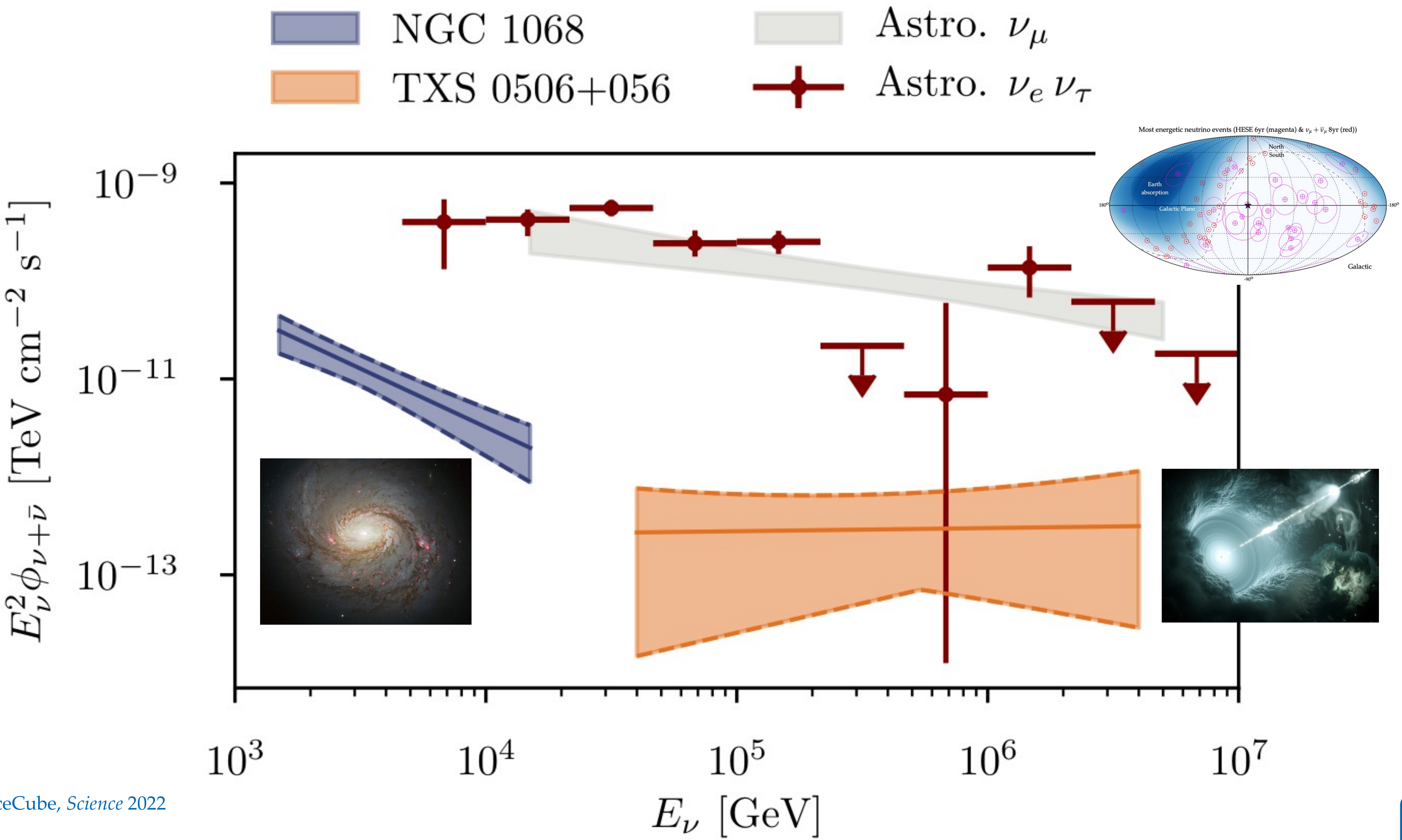
79^{+22}_{-20} ν of TeV energy

Significance: 4.2σ (global)



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

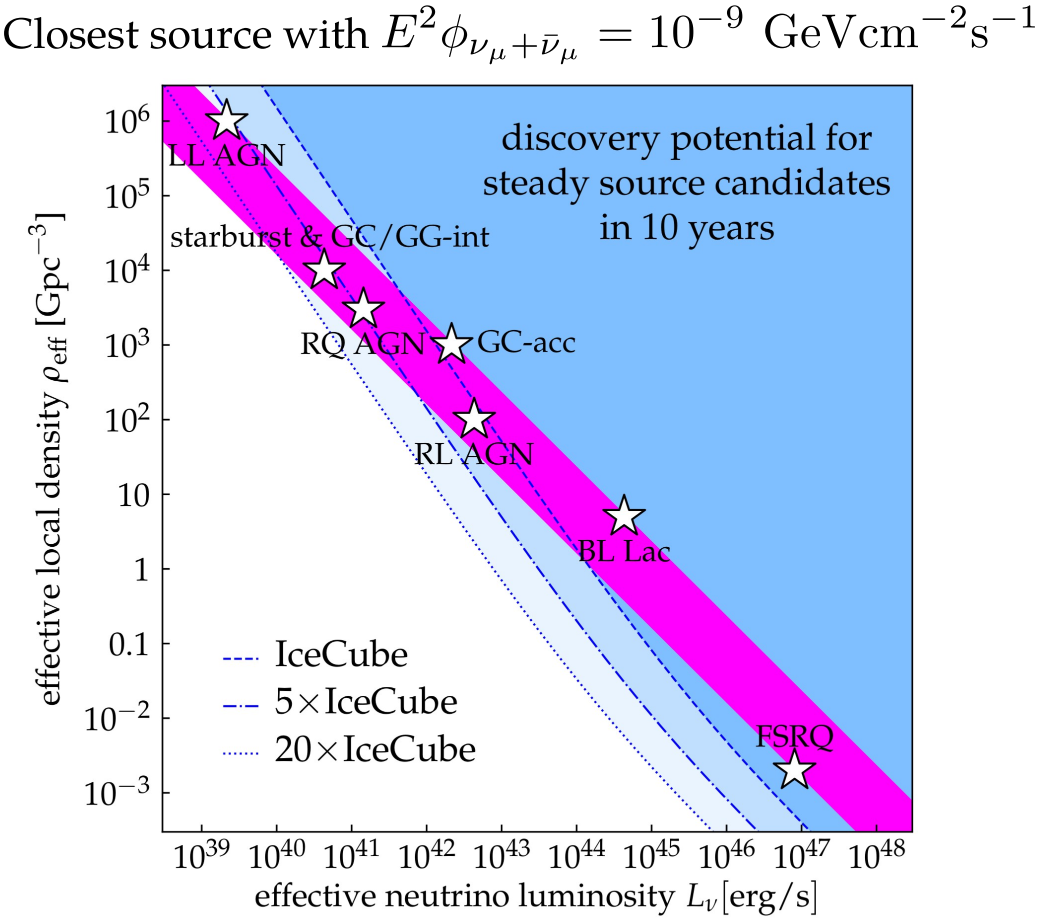
Hubble Space Telescope,
NASA, ESA & A. van der Hoeven



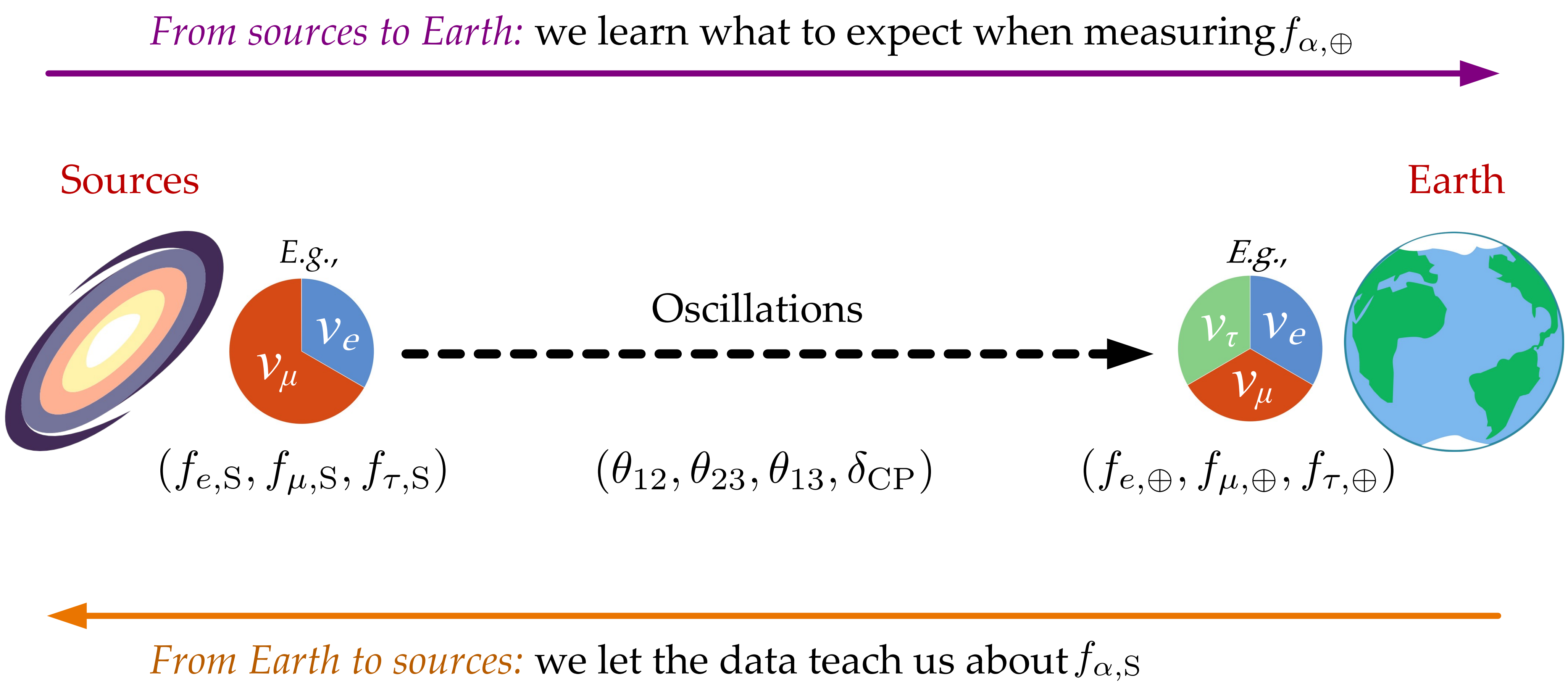
IceCube, *Science* 2022

Source discovery potential: today and in the future

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



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

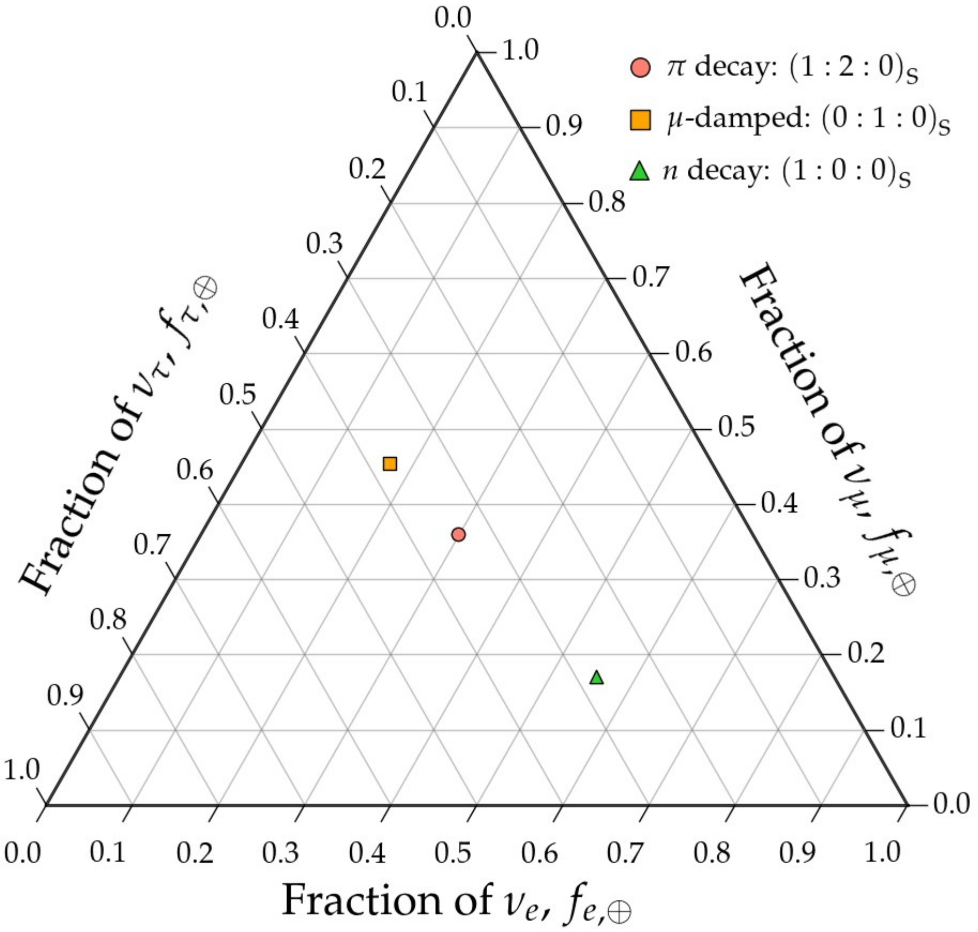


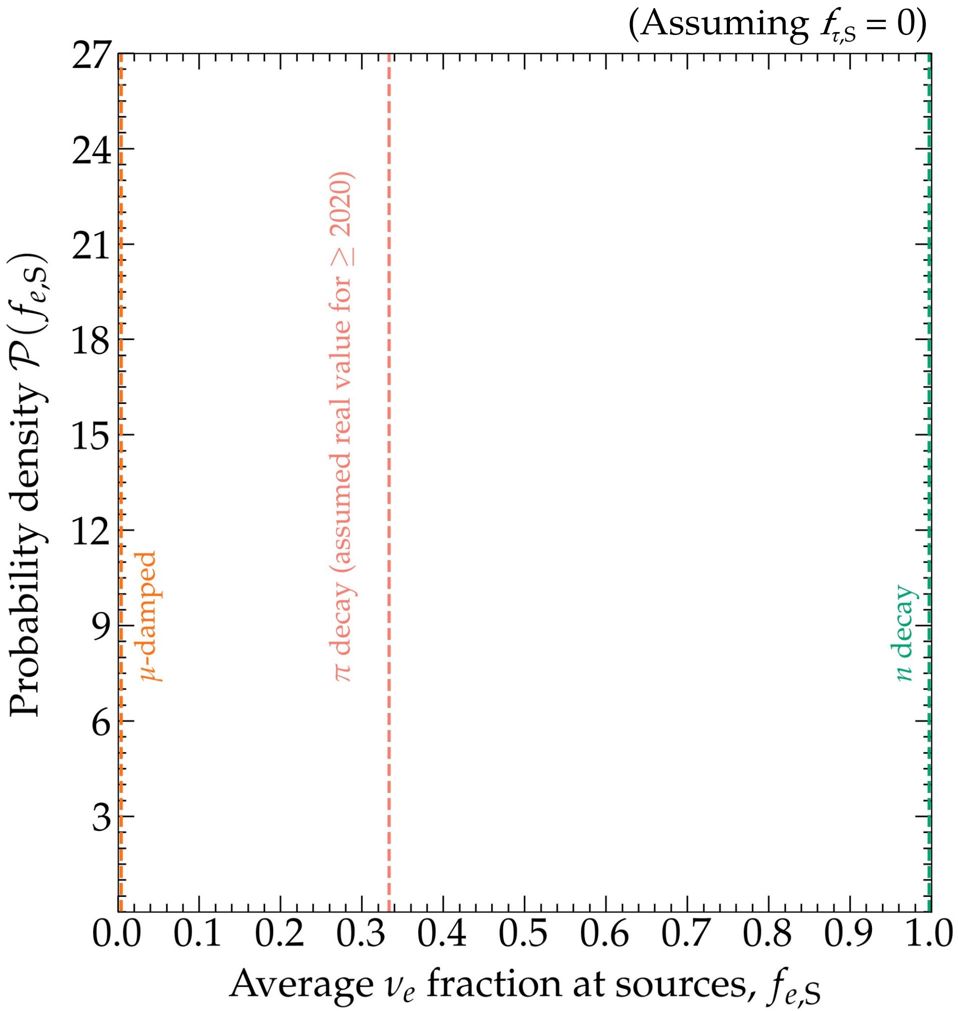
From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$
Sources
Earth
E.g.,
ν_e
ν_μ
Oscillations
E.g.,
ν_τ
ν_e
ν_μ
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$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

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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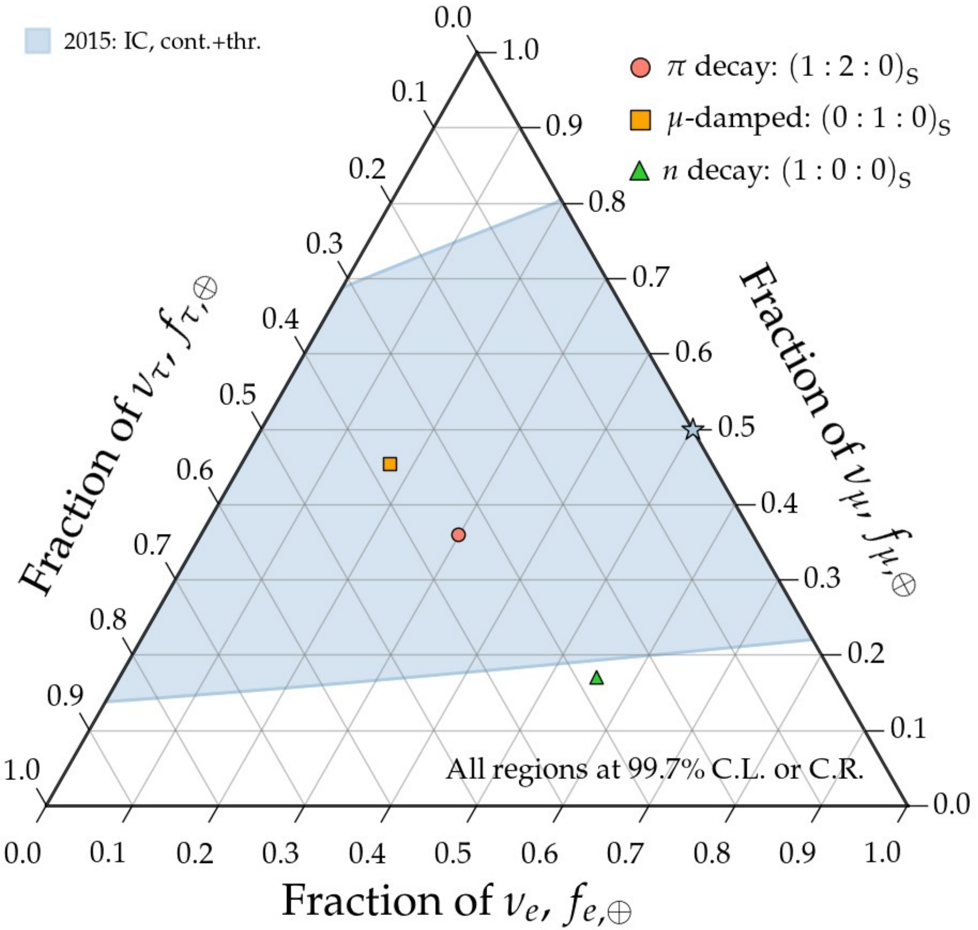
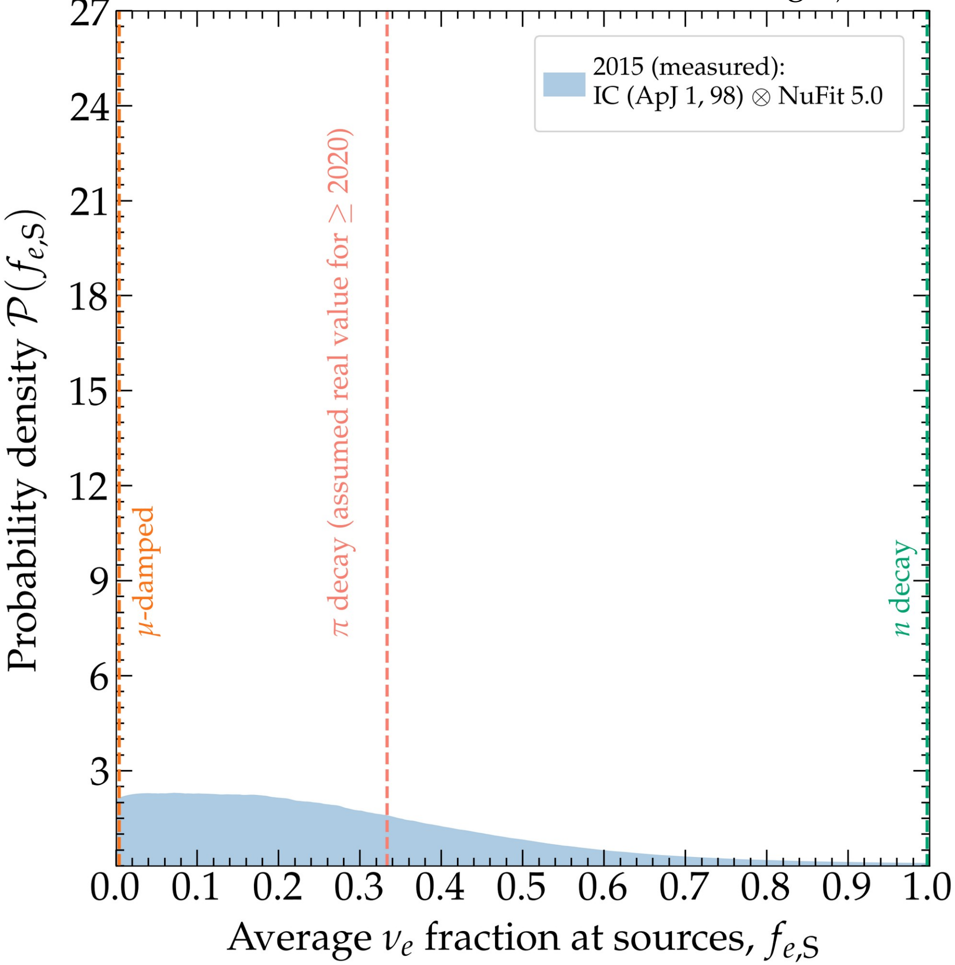


(Assuming $f_{\tau,S} = 0$)



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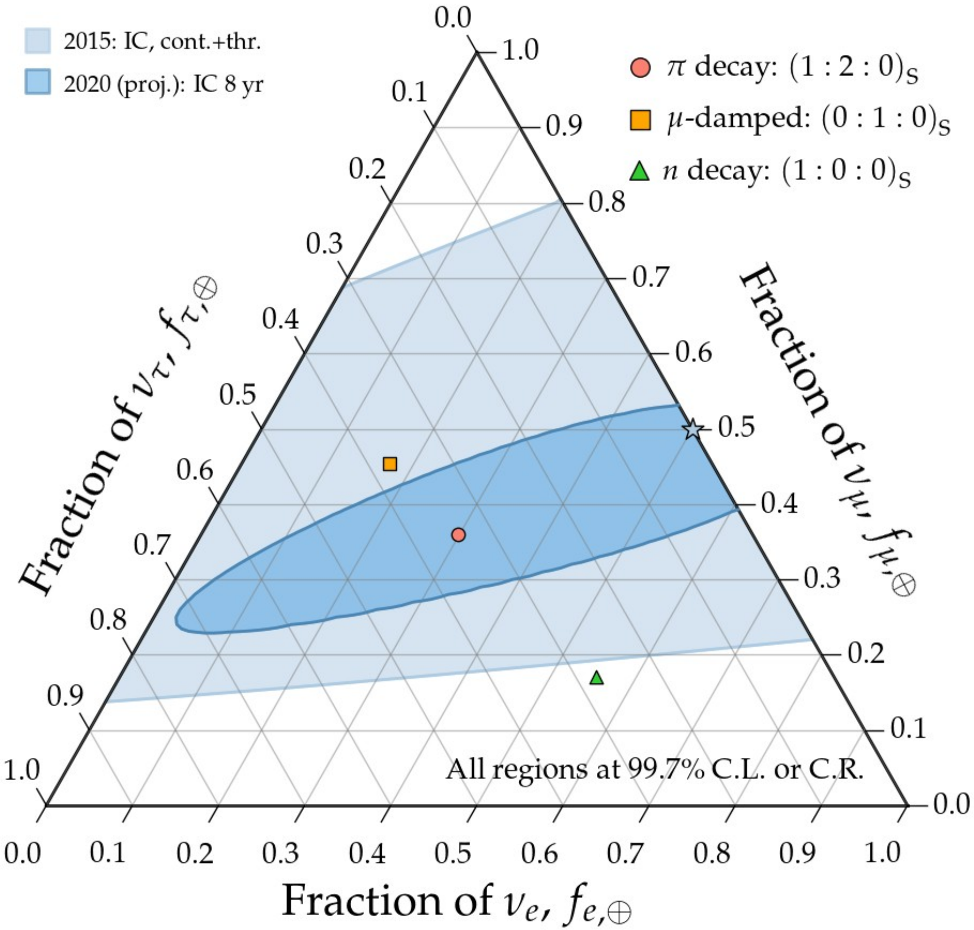

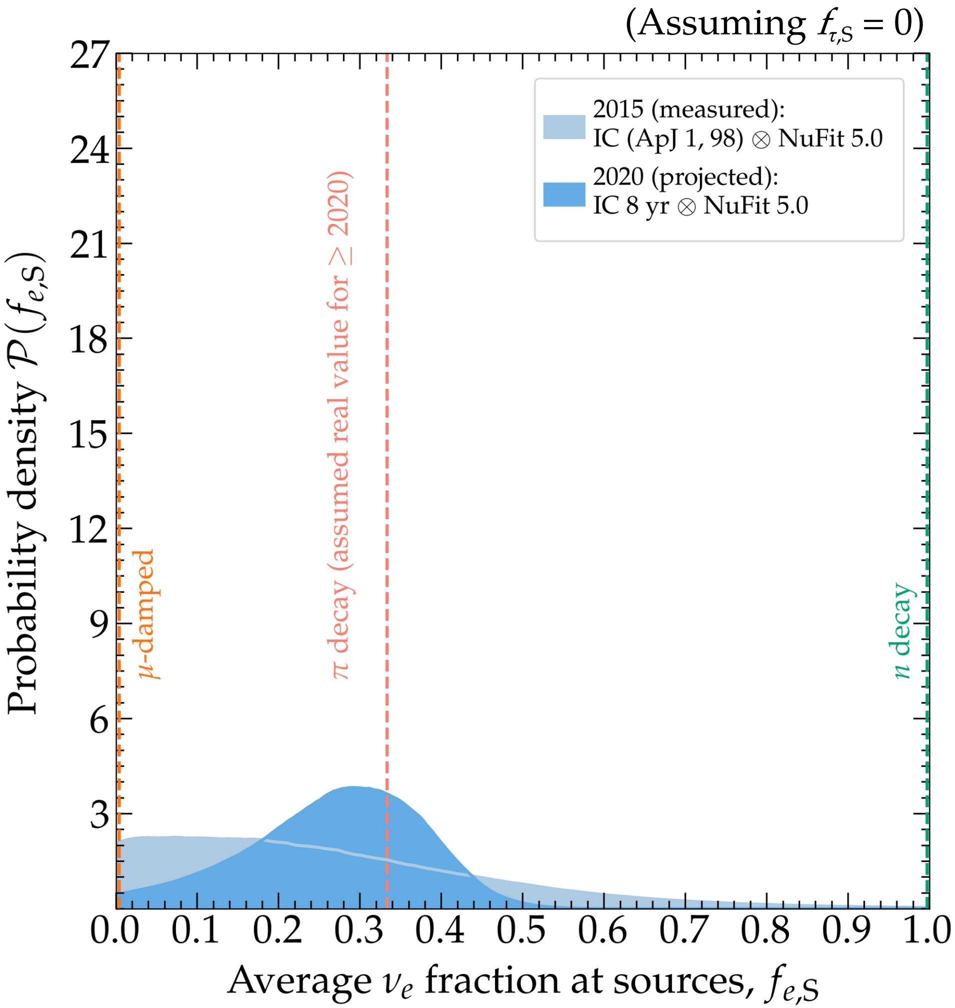

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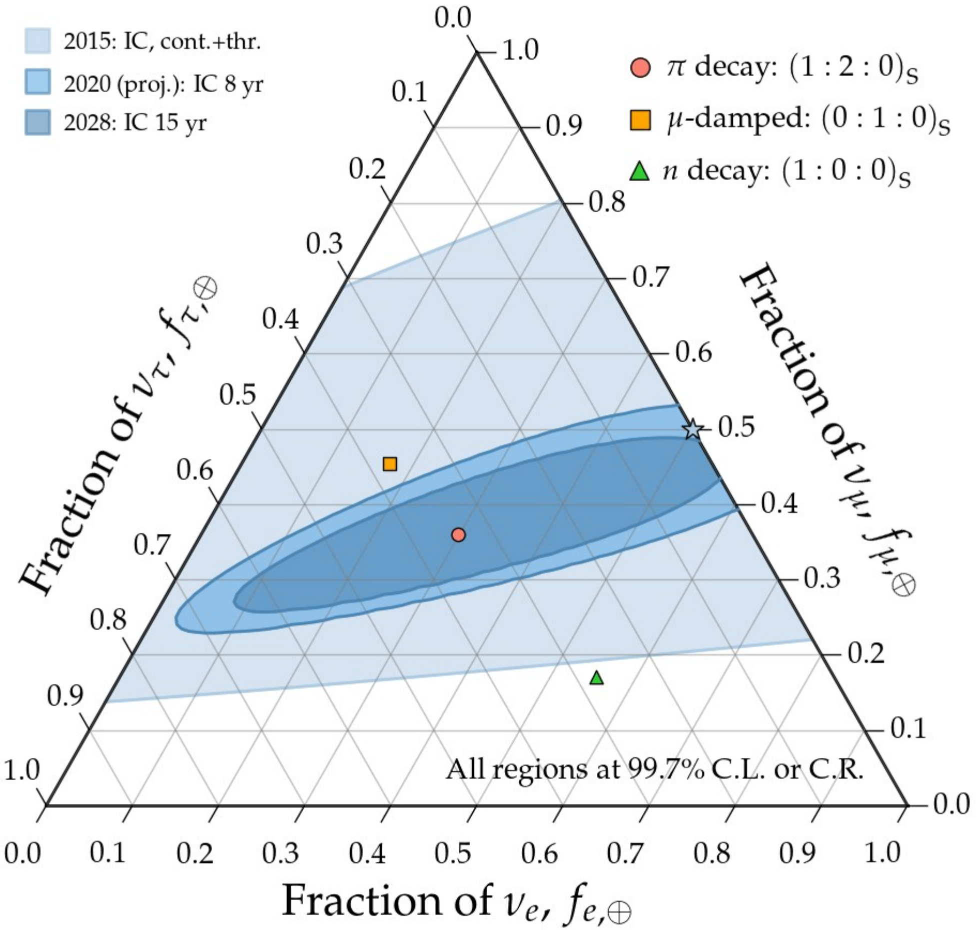

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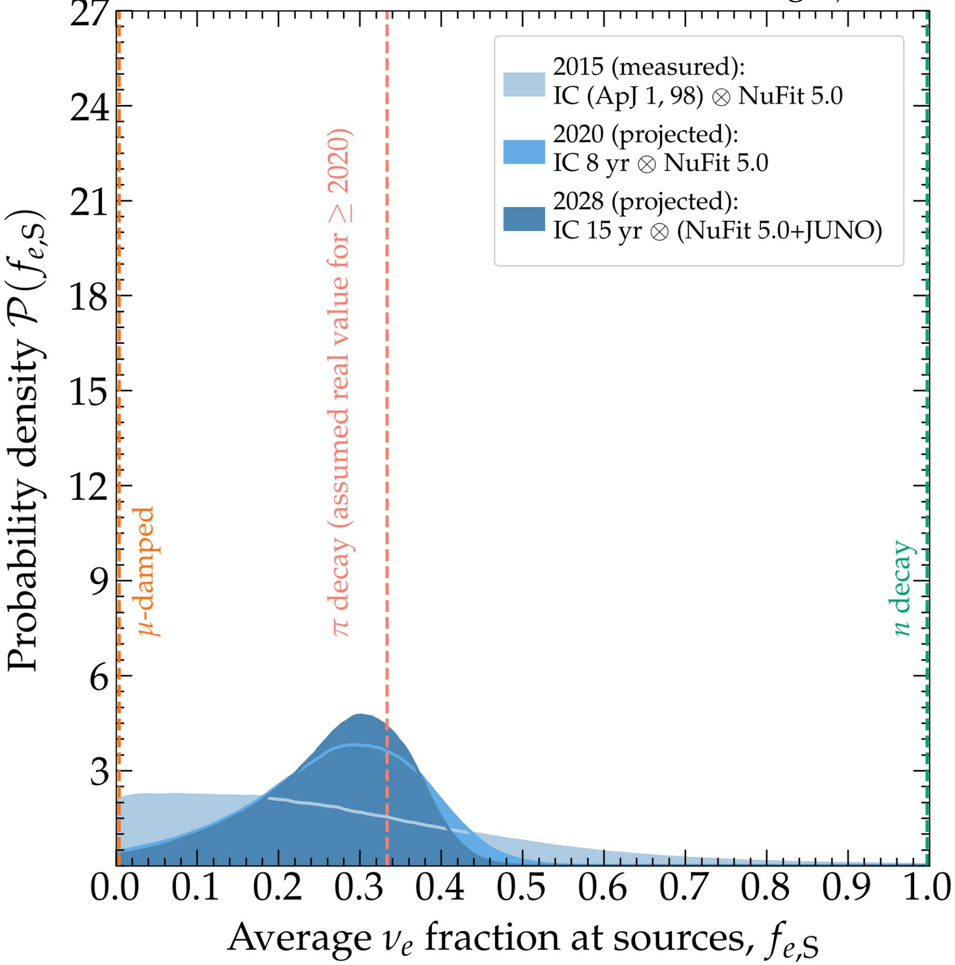

Song, Li, Argüelles, ***MB***, Vincent, *JCAP* 2021
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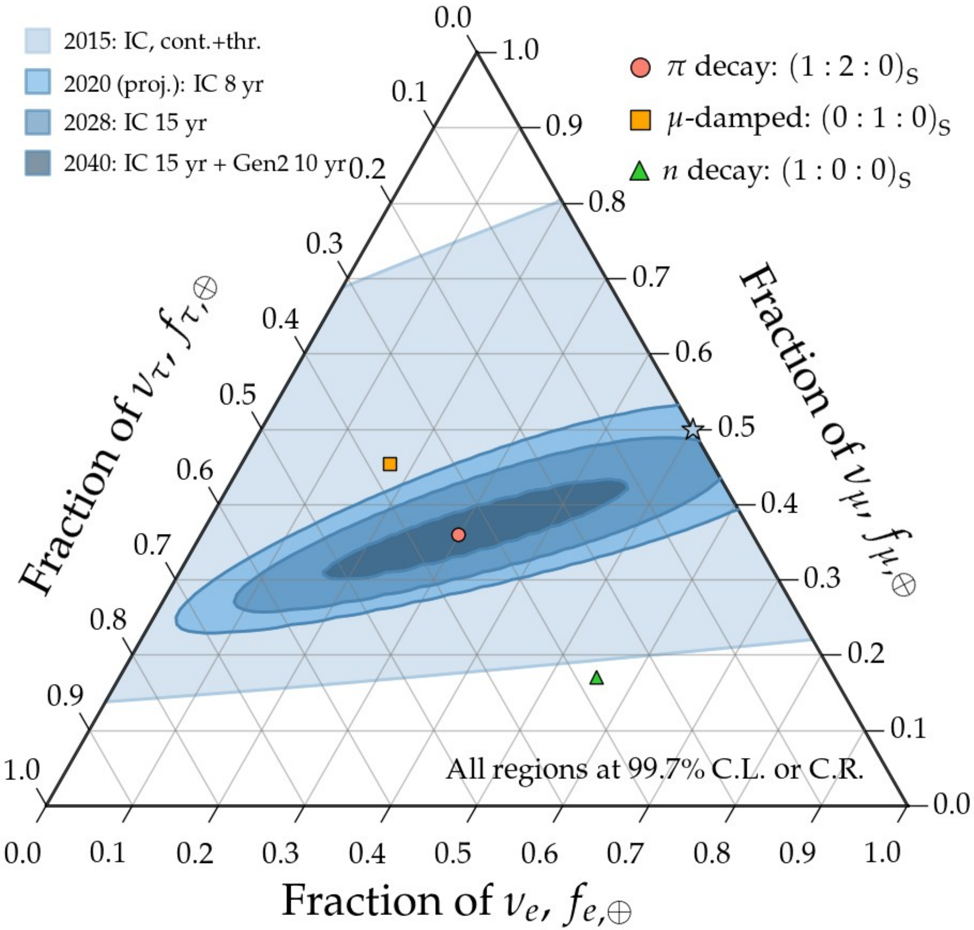
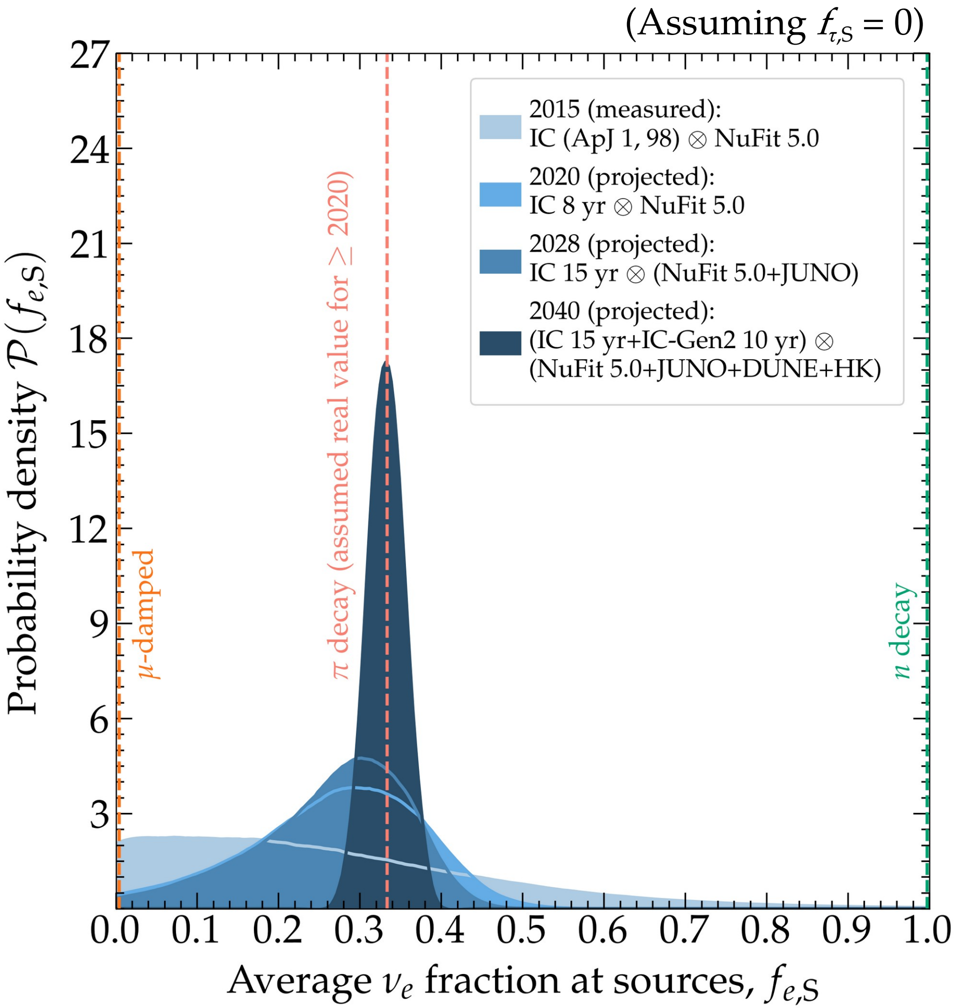
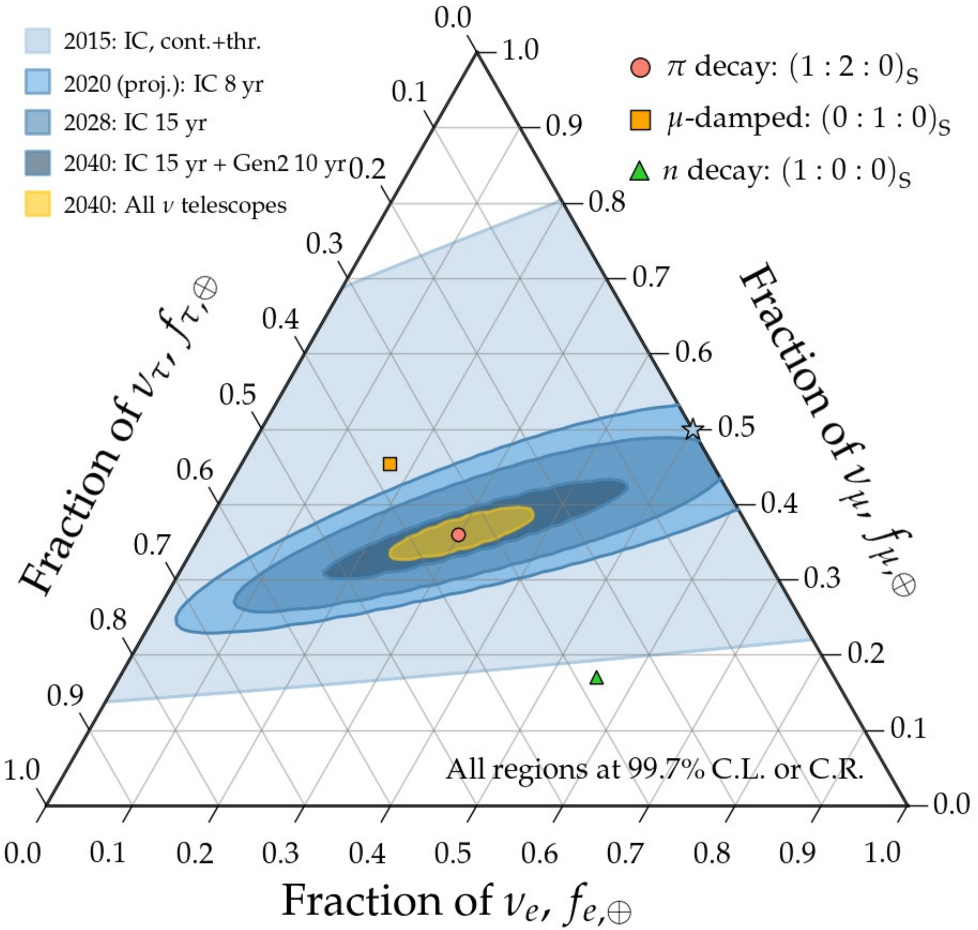
Inferring the flavor composition at the sources

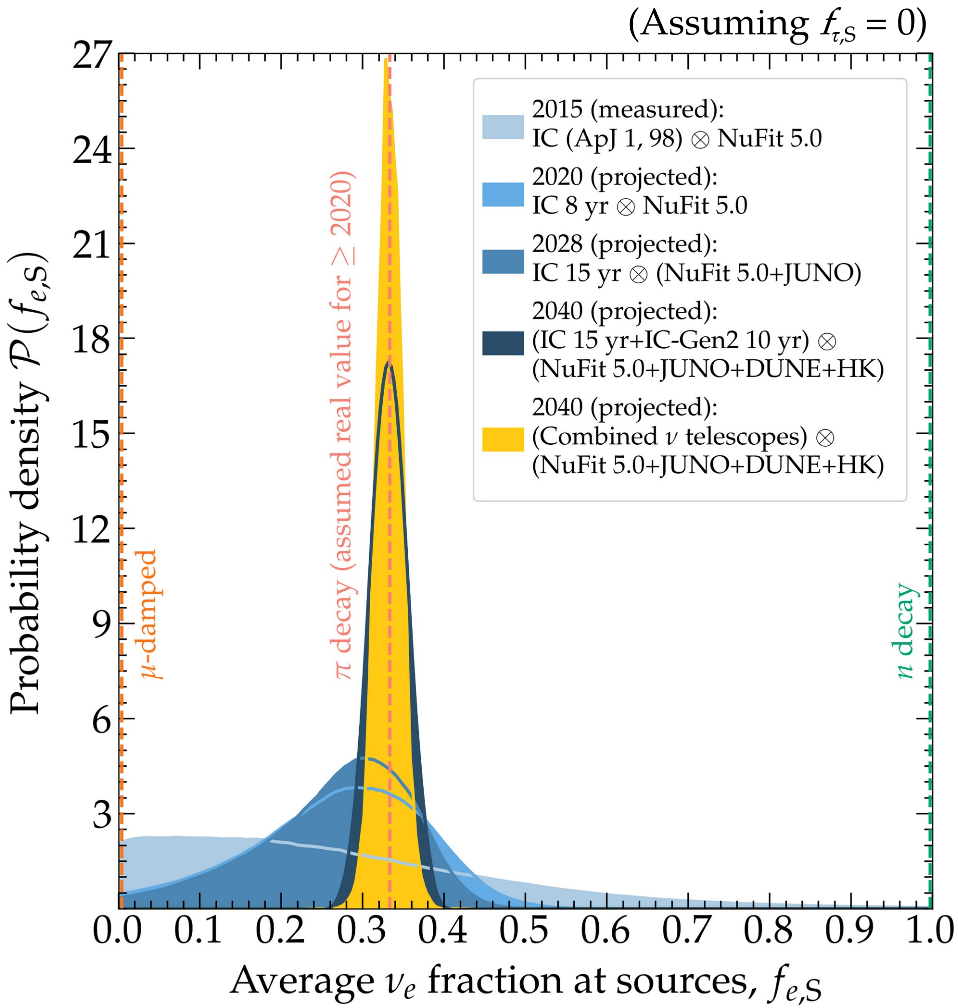




Song, Li, Argüelles, ***MB***, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

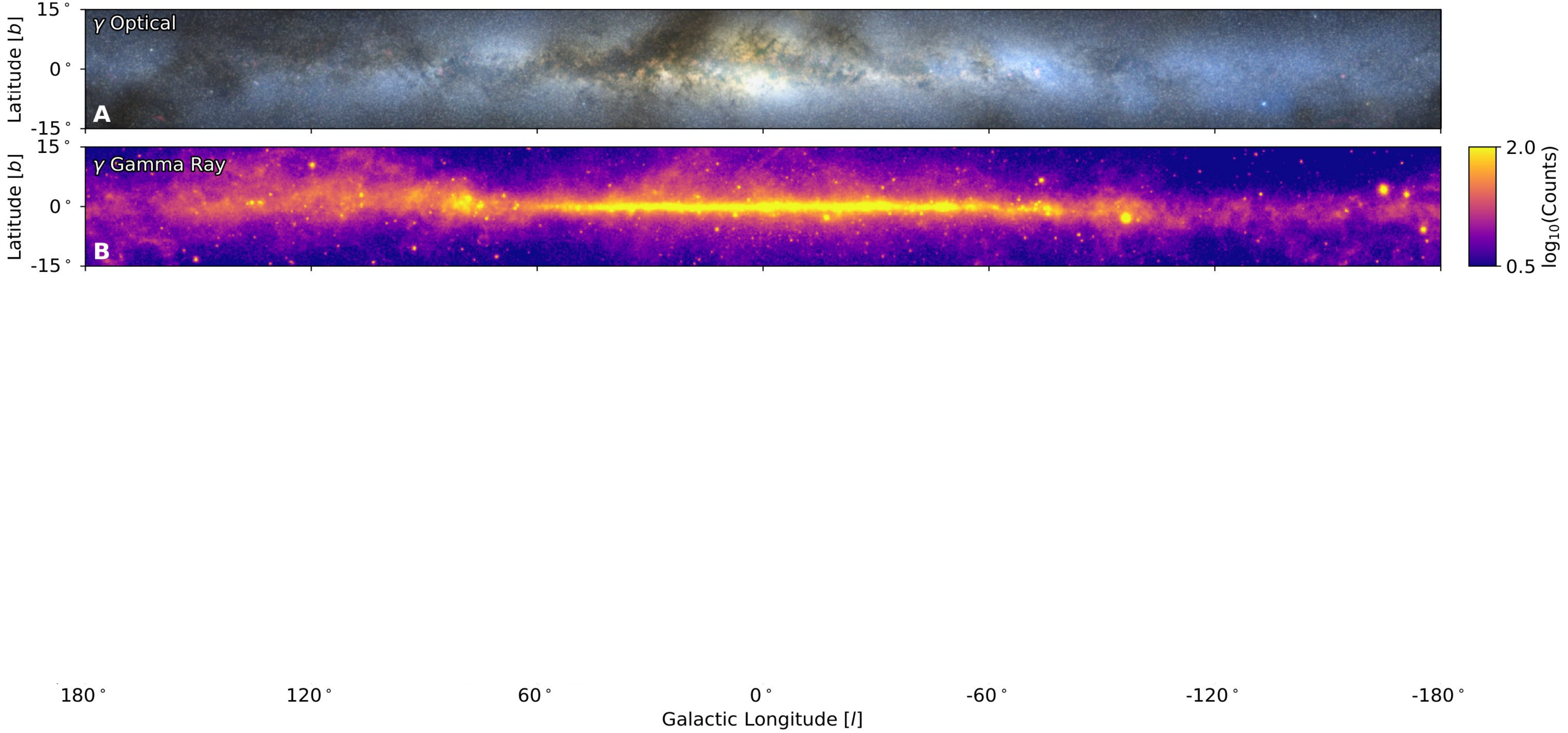
Inferring the flavor composition at the sources





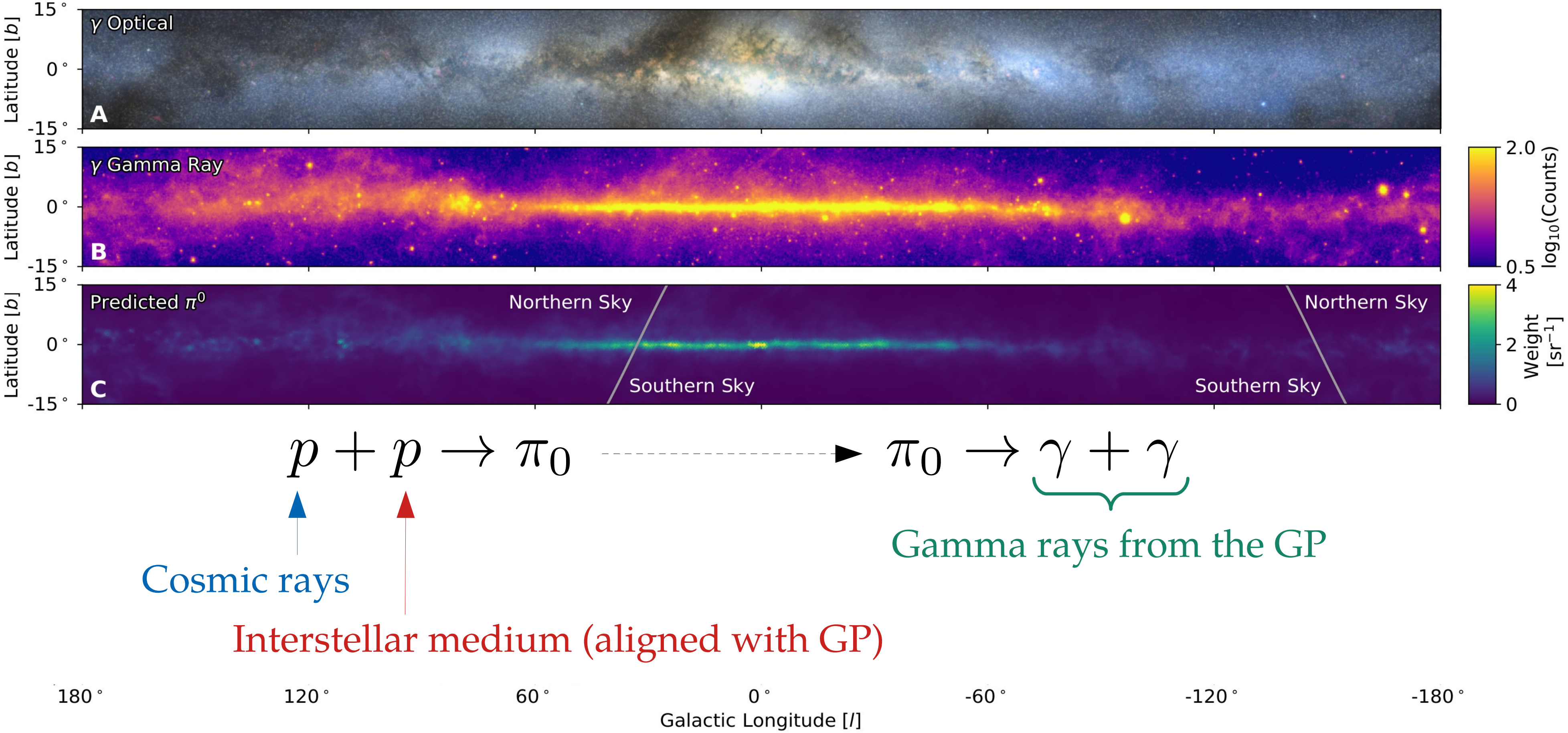
Song, Li, Argüelles, ***MB***, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Neutrinos from the Galaxy



IceCube Collab., *Science* 2023

Neutrinos from the Galaxy



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

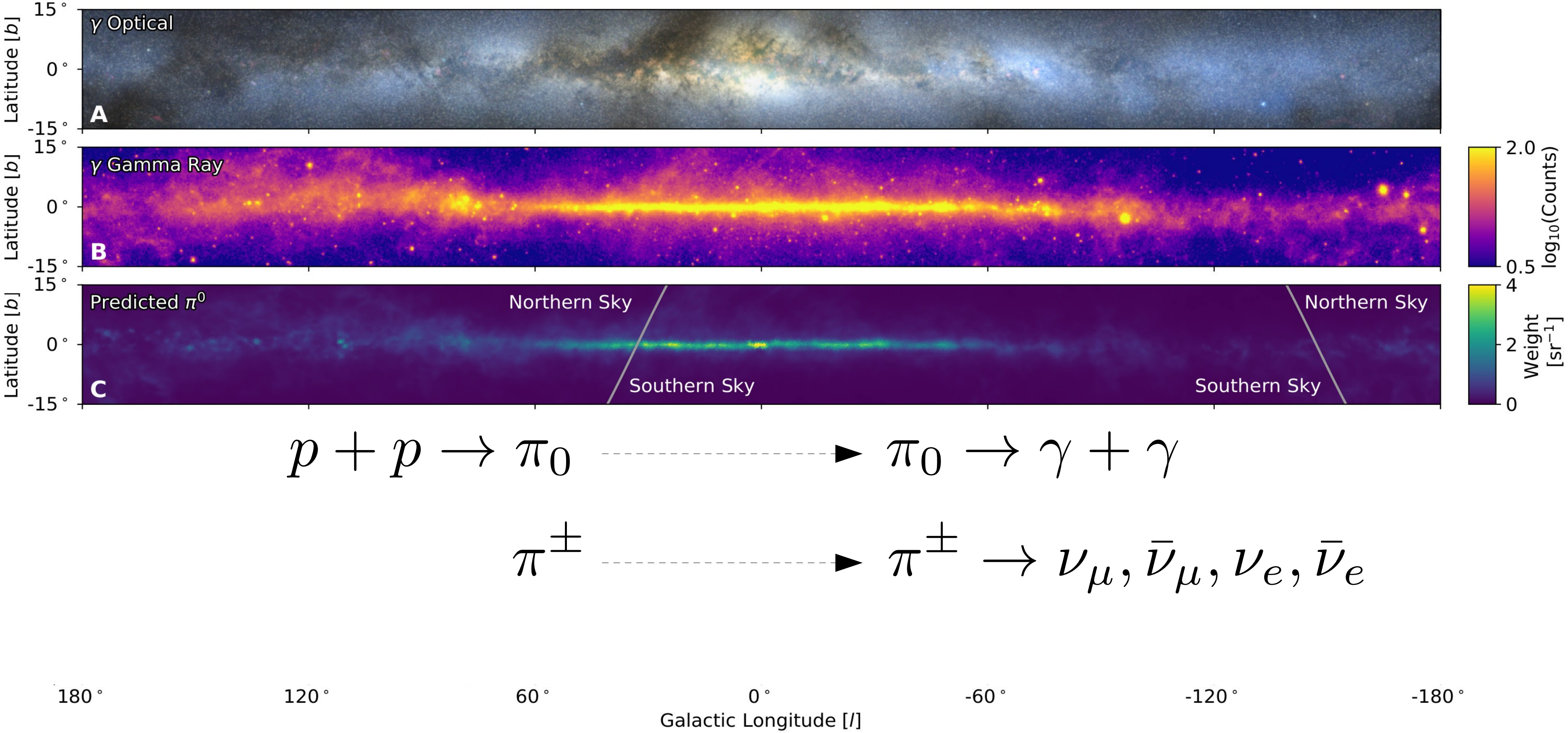
Cosmic rays

Interstellar medium (aligned with GP)

Gamma rays from the GP

IceCube Collab., *Science* 2023

Neutrinos from the Galaxy

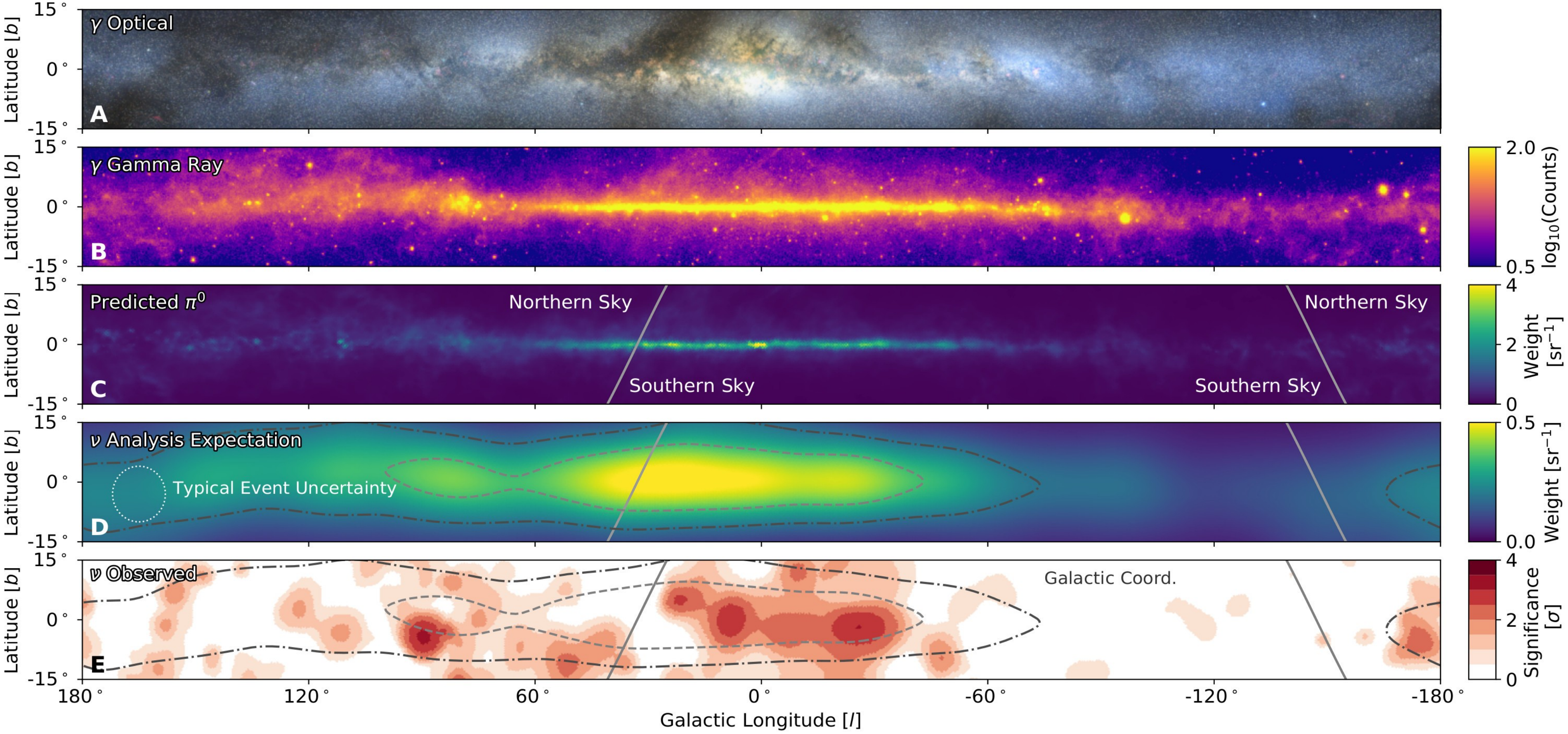


$$p + p \rightarrow \pi_0 \dashrightarrow \pi_0 \rightarrow \gamma + \gamma$$

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

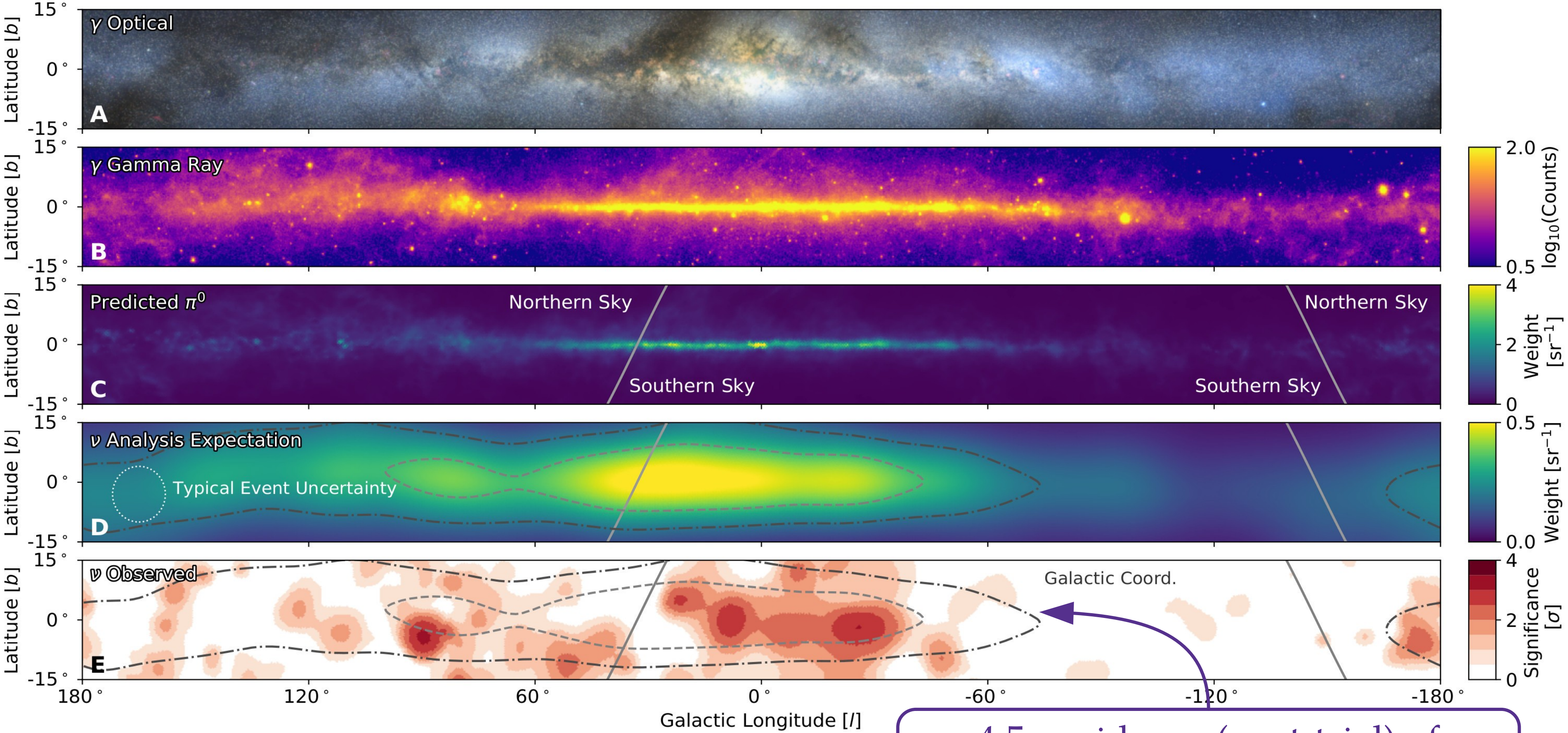
IceCube Collab., *Science* 2023

Neutrinos from the Galaxy



IceCube Collab., *Science* 2023

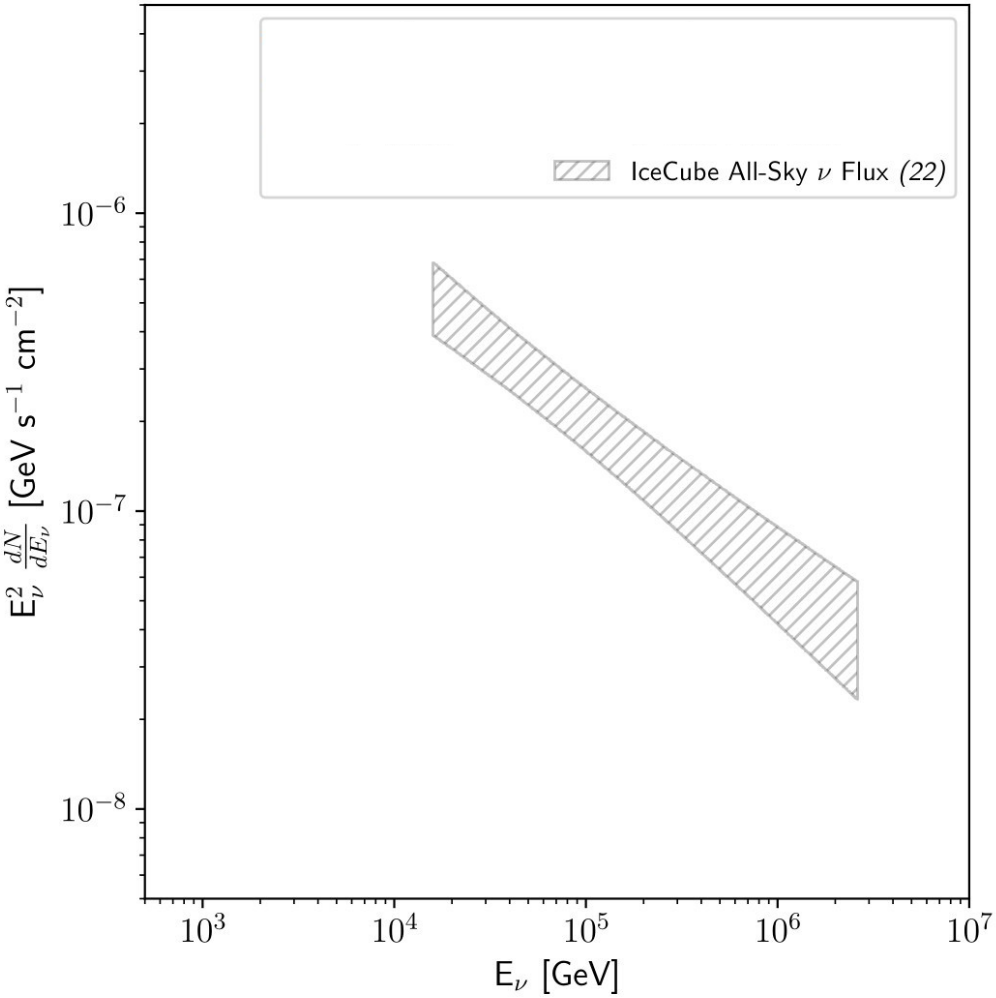
Neutrinos from the Galaxy



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

IceCube Collab., *Science* 2023

Neutrinos from the Galaxy



IceCube Collab., *Science* 2023

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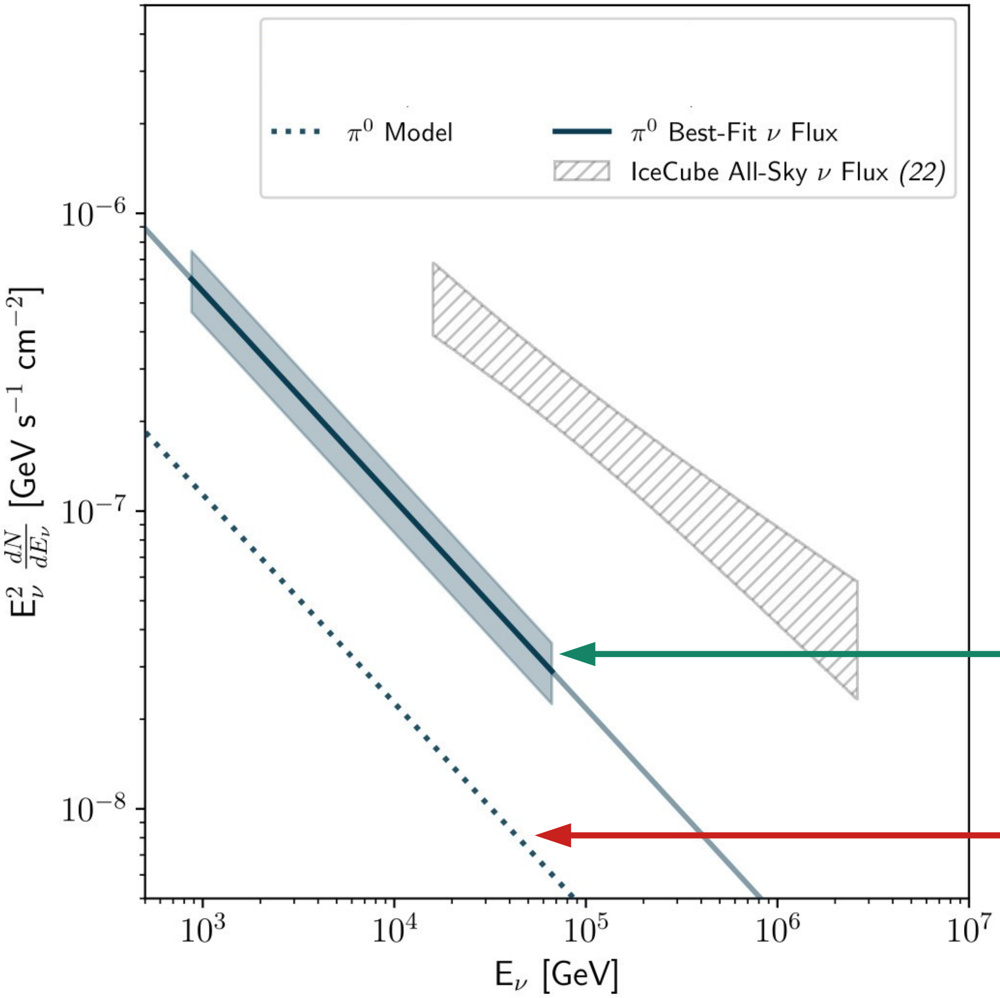

Three models of Galactic diffuse ν:

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

Observed (×5 model)

Consistent with 100-TeV observations by Tibet Air Shower Array

Model

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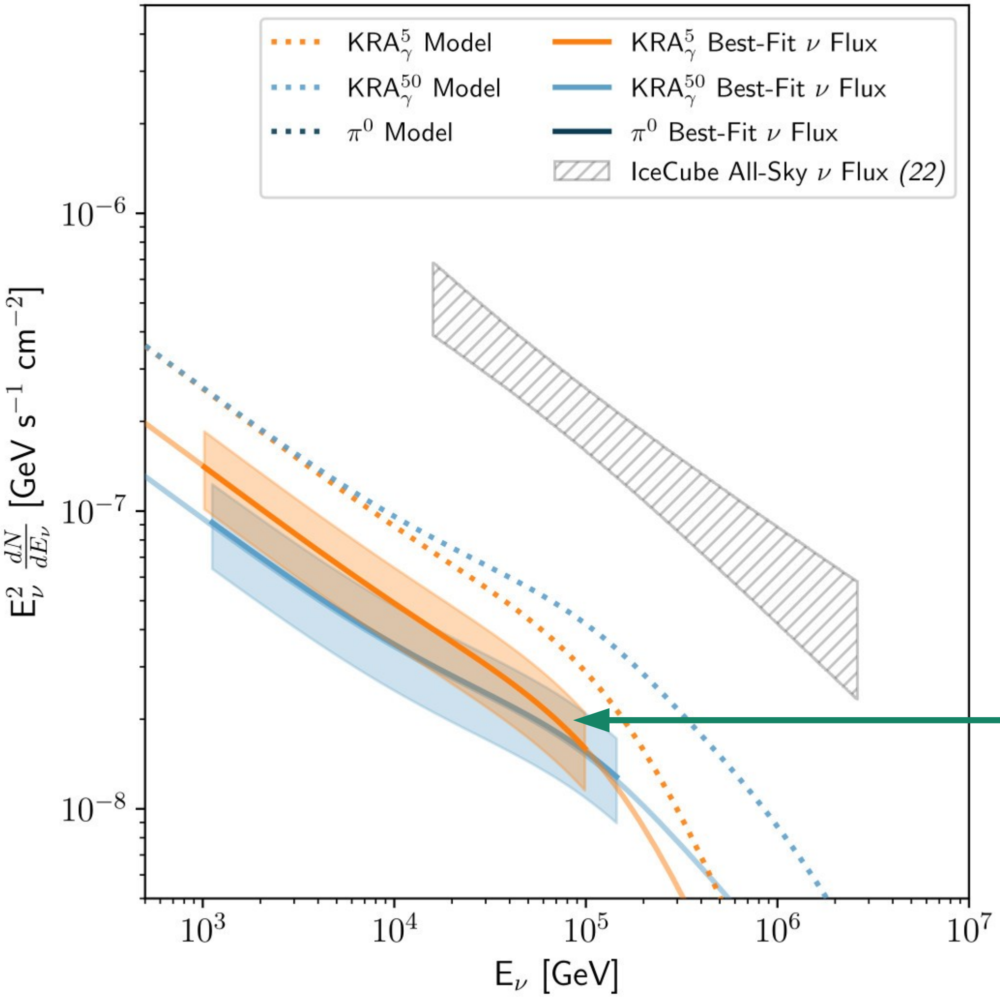
Neutrinos from the Galaxy



Three models of Galactic diffuse ν:

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

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

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

Observed (×0.5 model)

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

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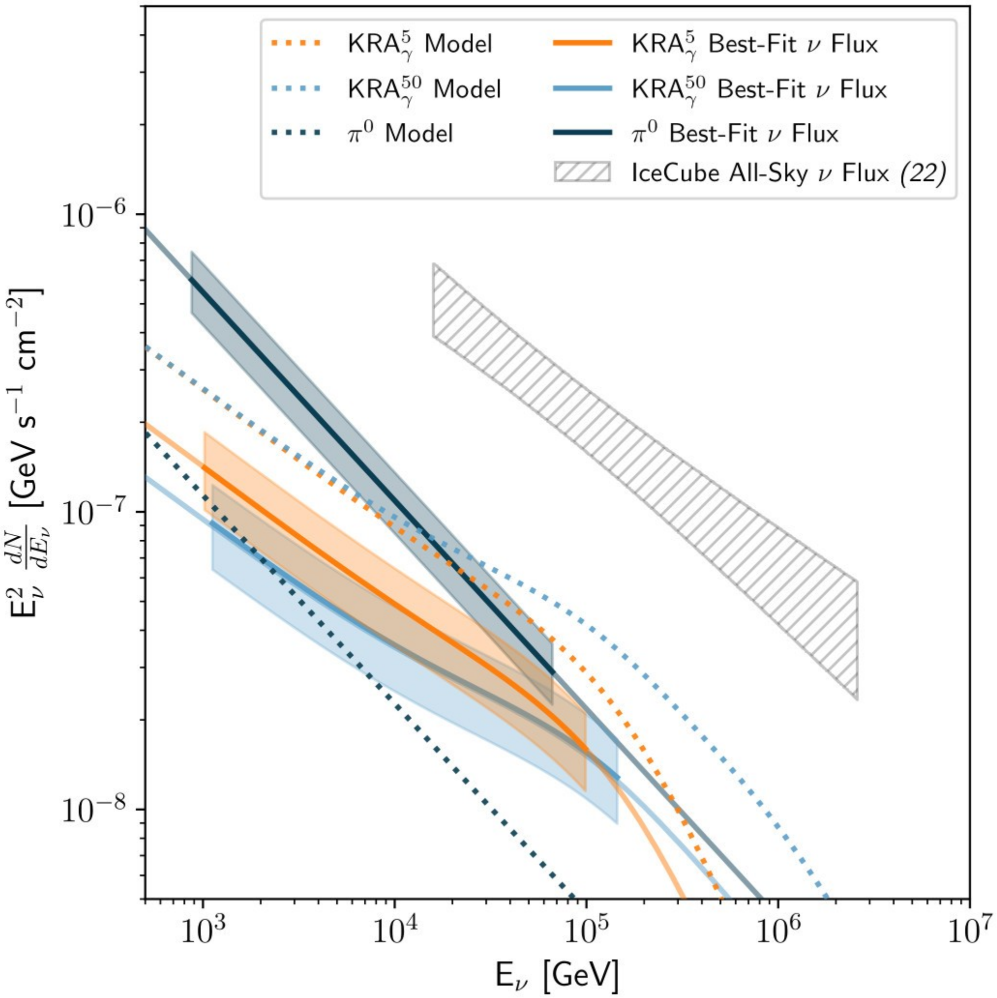
Neutrinos from the Galaxy



Three models of Galactic diffuse ν:

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

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

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

None of the models matched data

(caveat: there are relatively simple models)

No Galactic ν source identified

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

GP flux is 6–13% of all-sky at 30 TeV

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What have we learned about *particle physics*?

Fundamental physics with high-energy cosmic neutrinos

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

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

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

Fundamental physics with high-energy cosmic neutrinos

- Numerous new ν physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$
  - *E.g.*,
  - n = -1: neutrino decay
  - n = 0: CPT-odd Lorentz violation
  - n = +1: CPT-even Lorentz violation

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

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

Note: Not an exhaustive list

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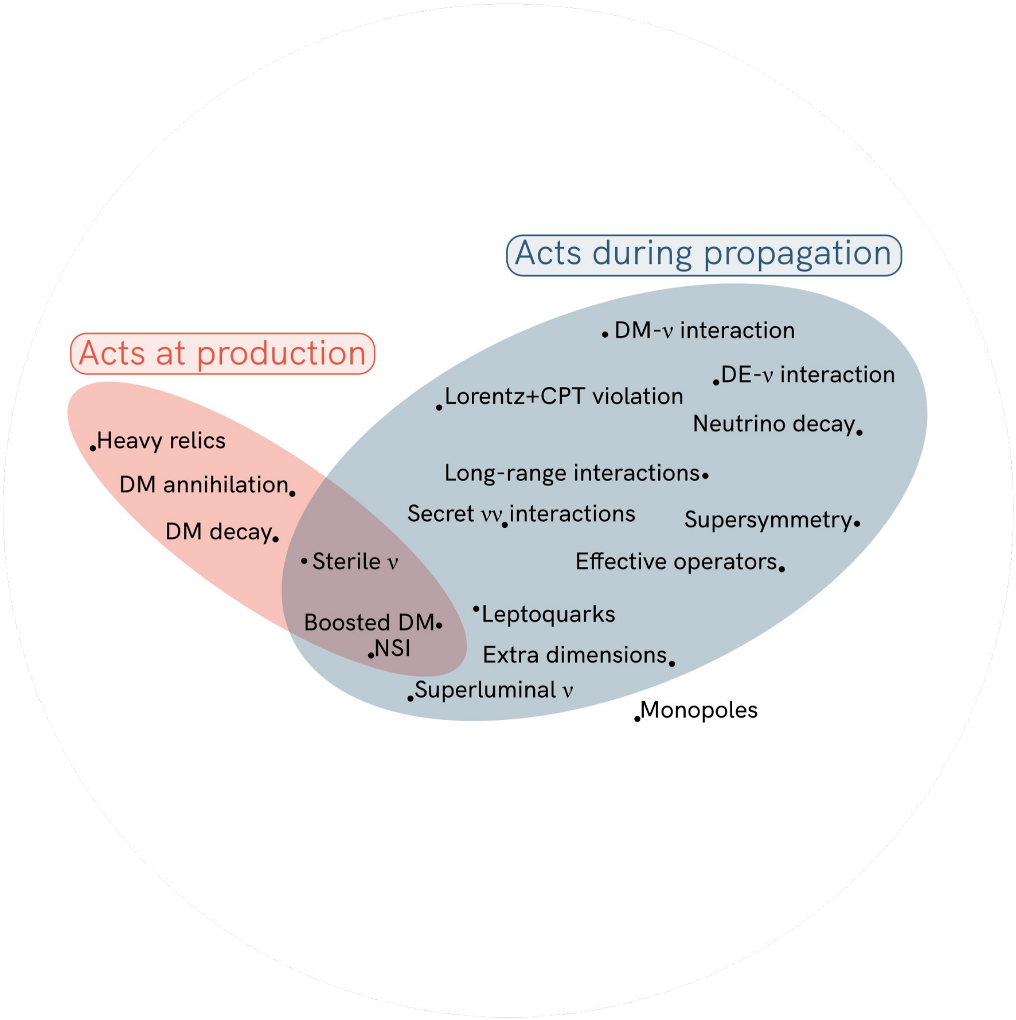

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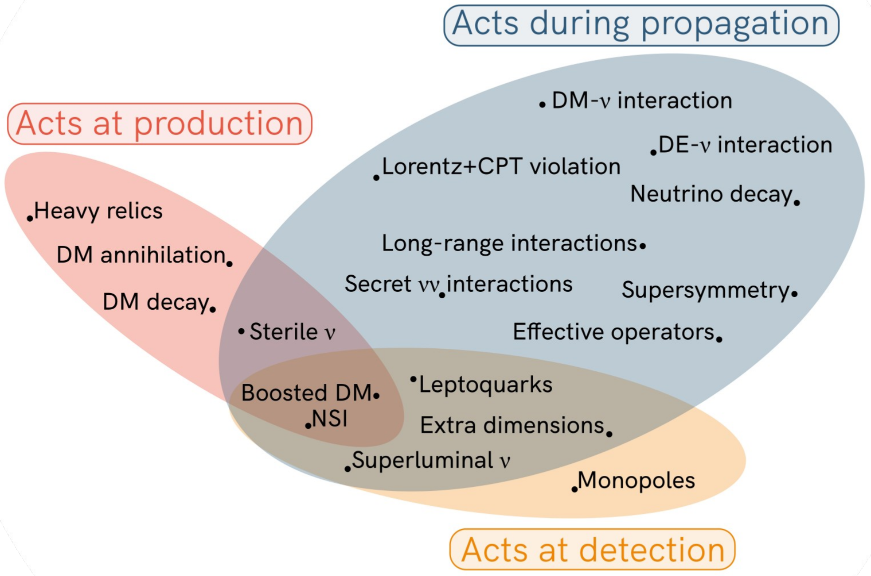

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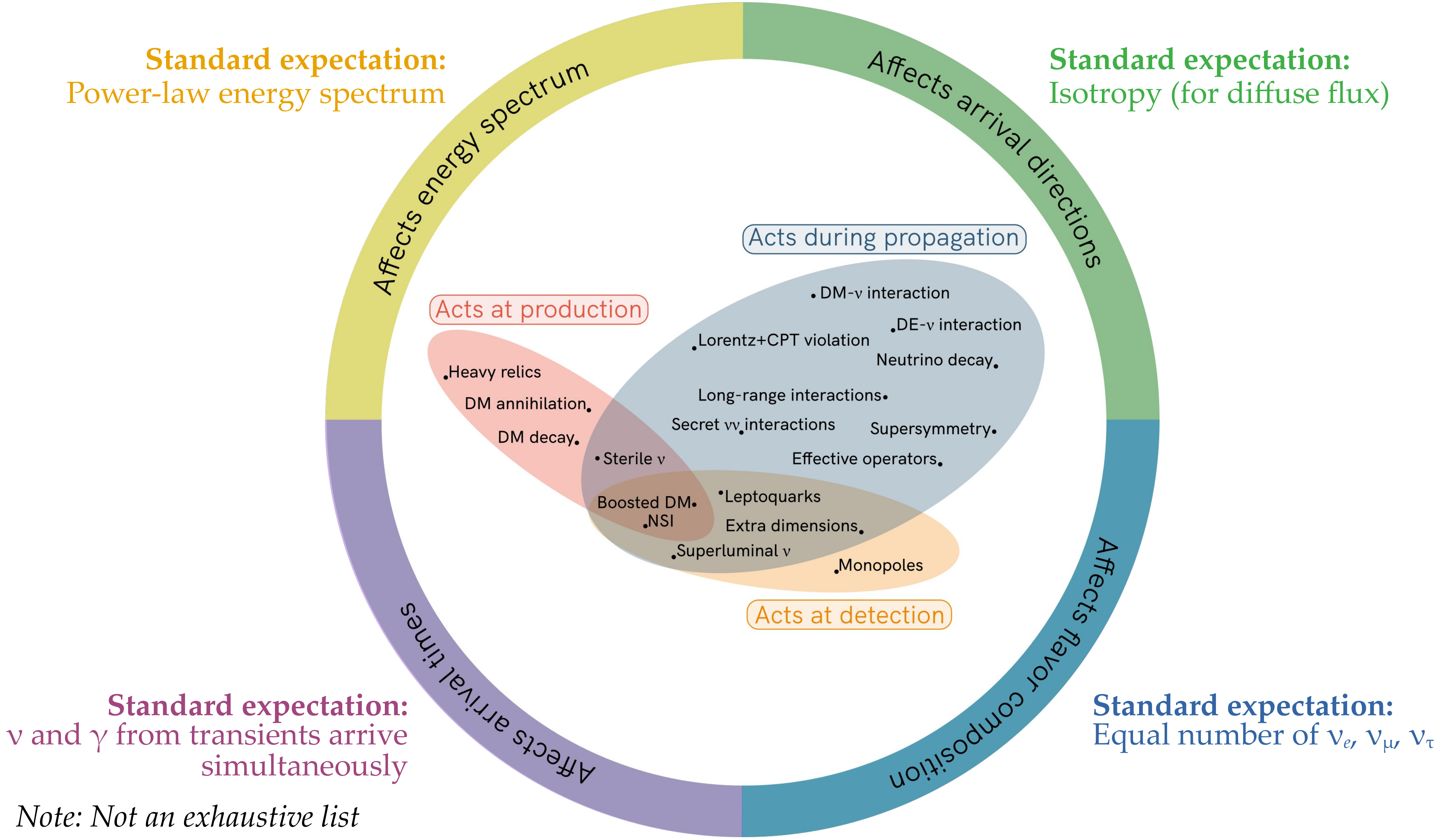

Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Standard expectation:
ν and γ from transients arrive simultaneously
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ
Affects energy spectrum
Affects arrival directions
Affects arrival times
Affects flavor composition
Acts at production
Acts during propagation
Acts at detection
Heavy relics
DM annihilation
DM decay
Sterile ν
Boosted DM
NSI
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Long-range interactions
Secret νν interactions
Supersymmetry
Effective operators
Leptoquarks
Extra dimensions
Superluminal ν
Monopoles
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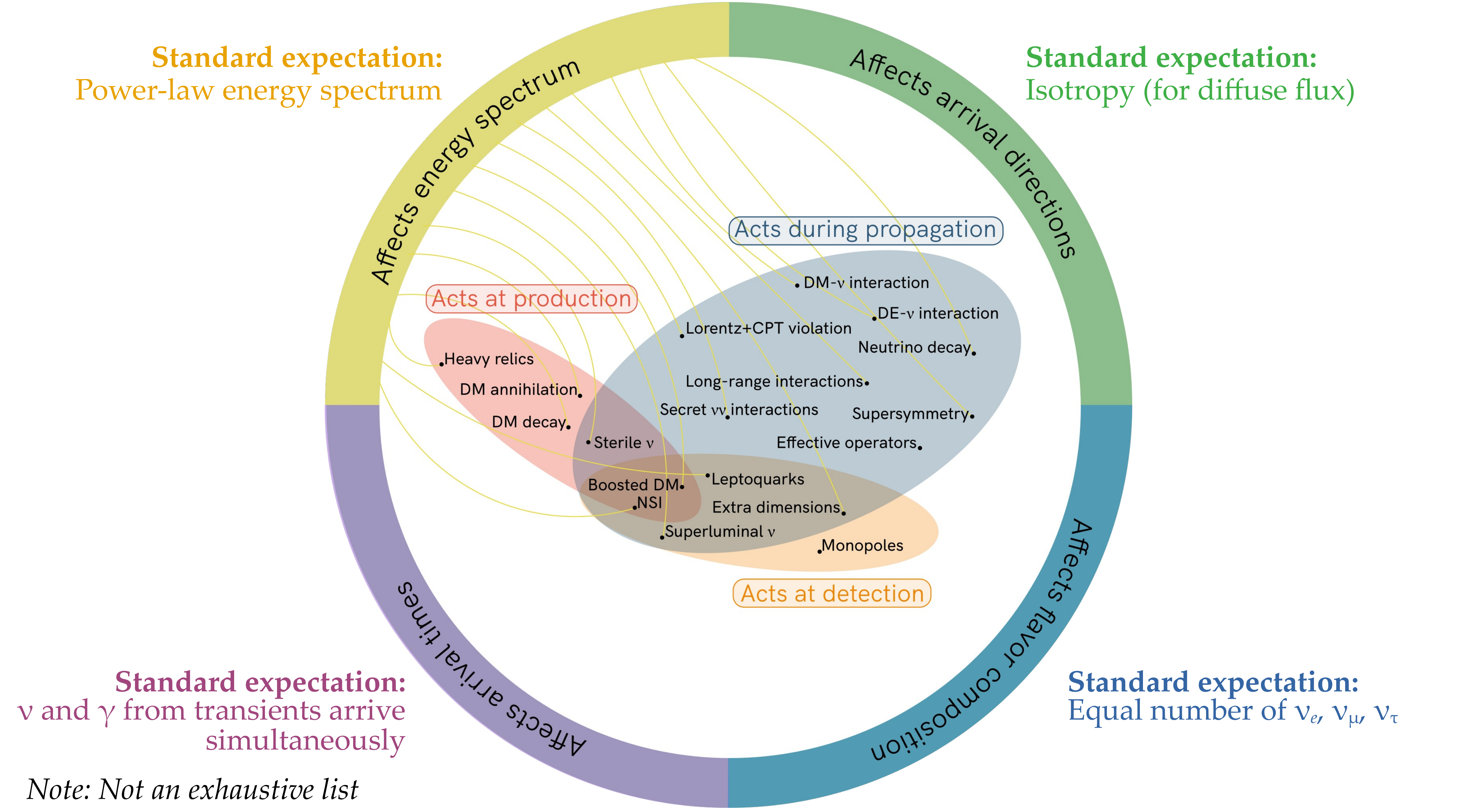
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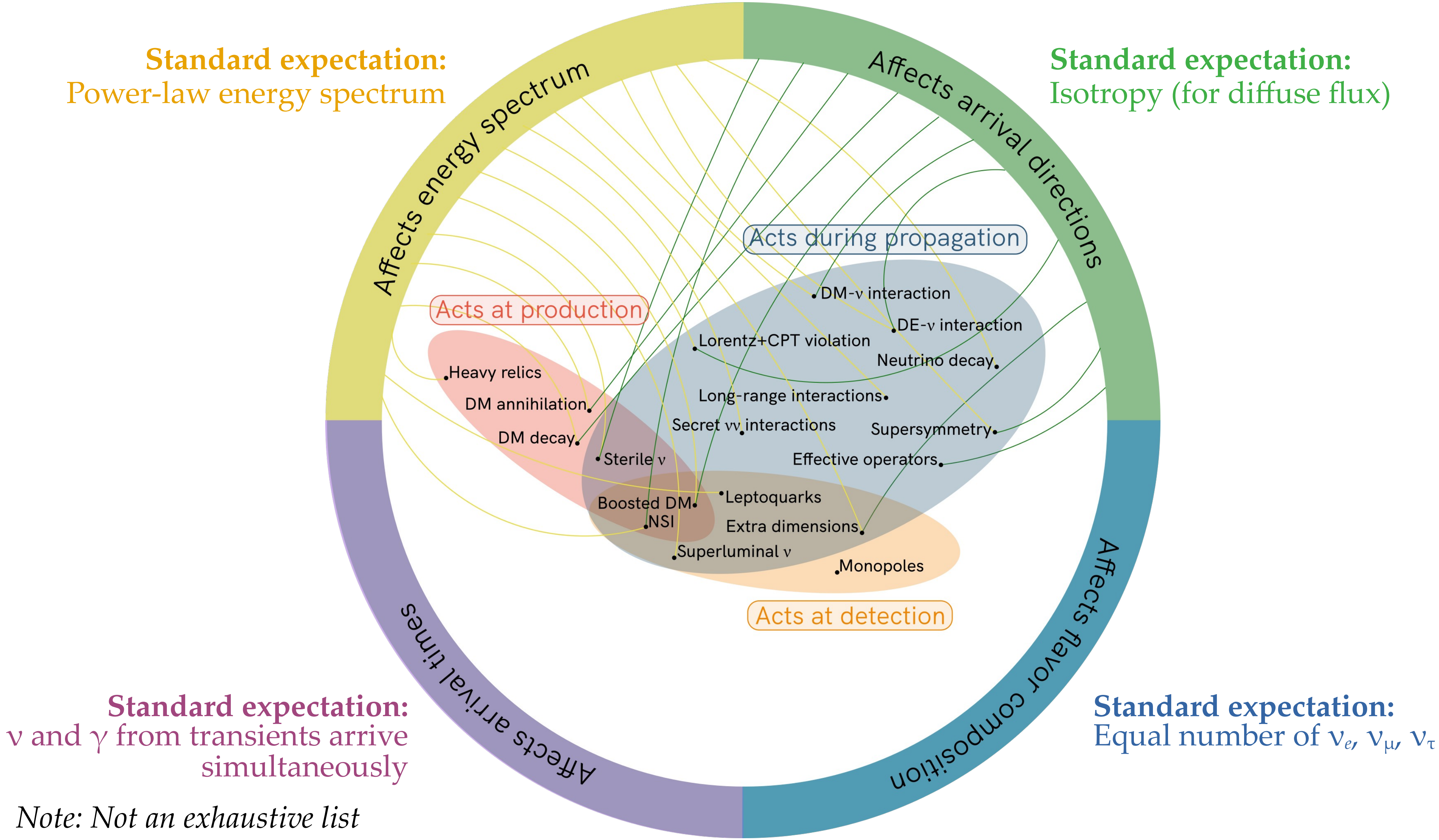
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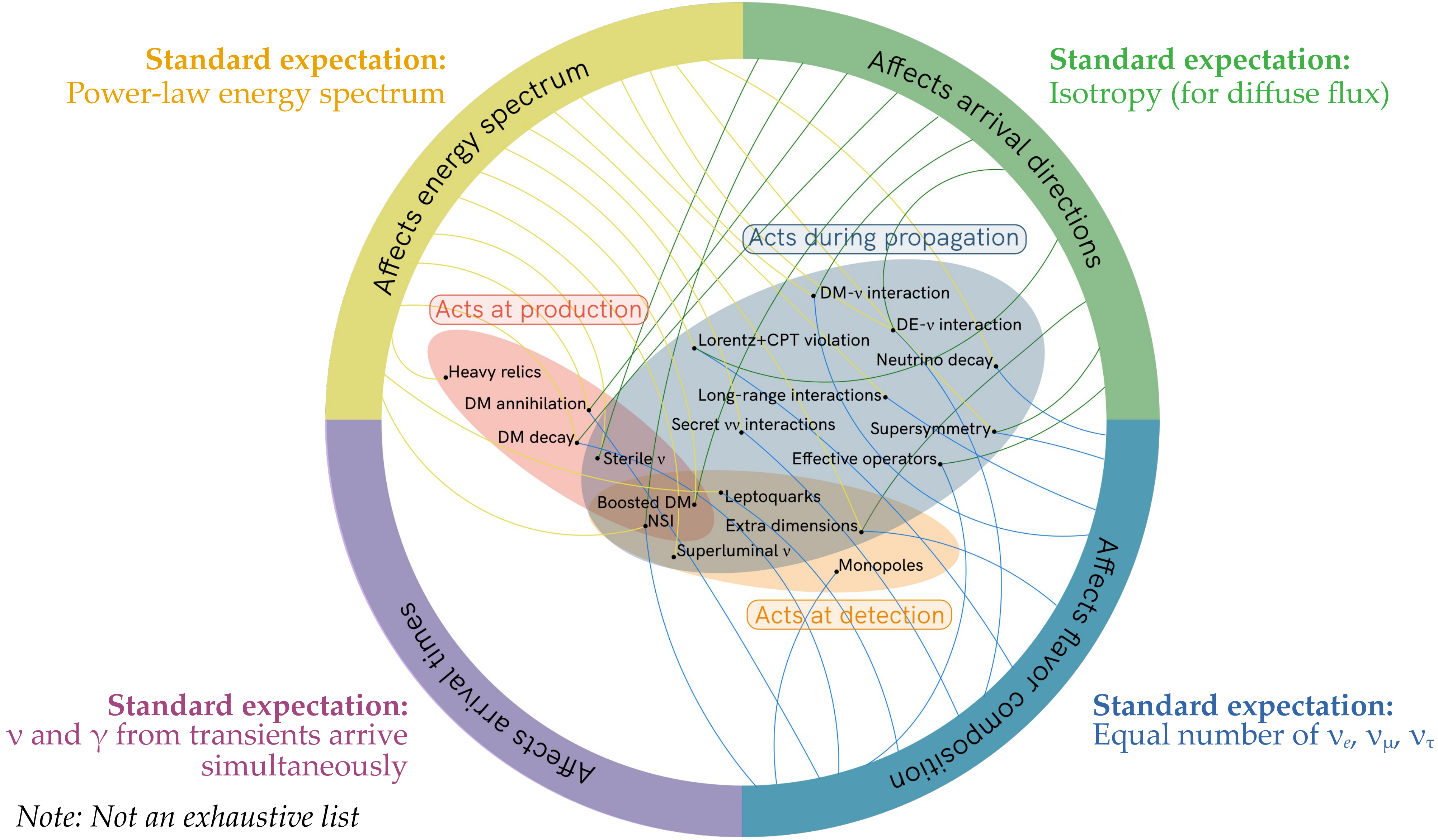

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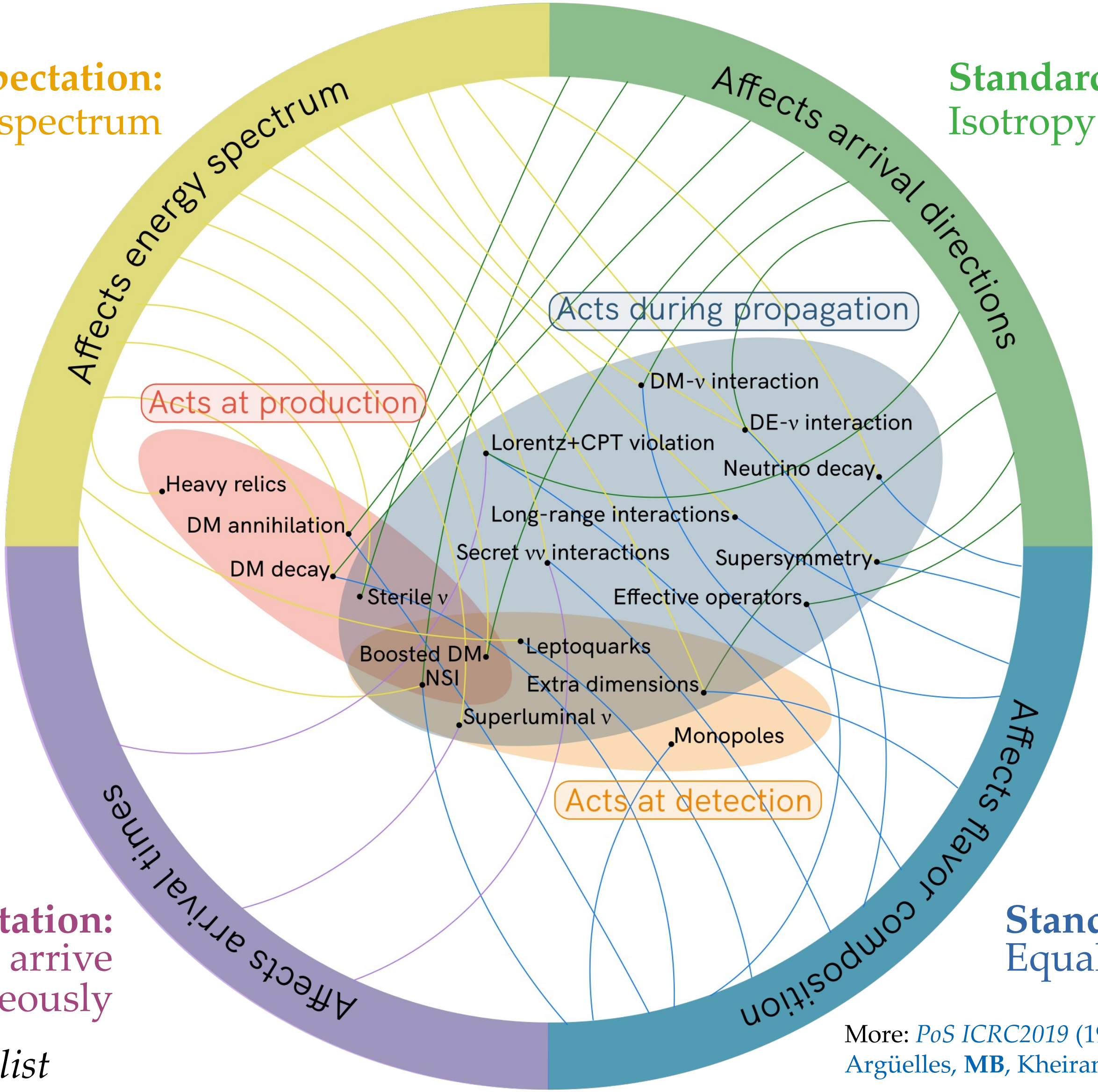

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Note: Not an exhaustive list

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

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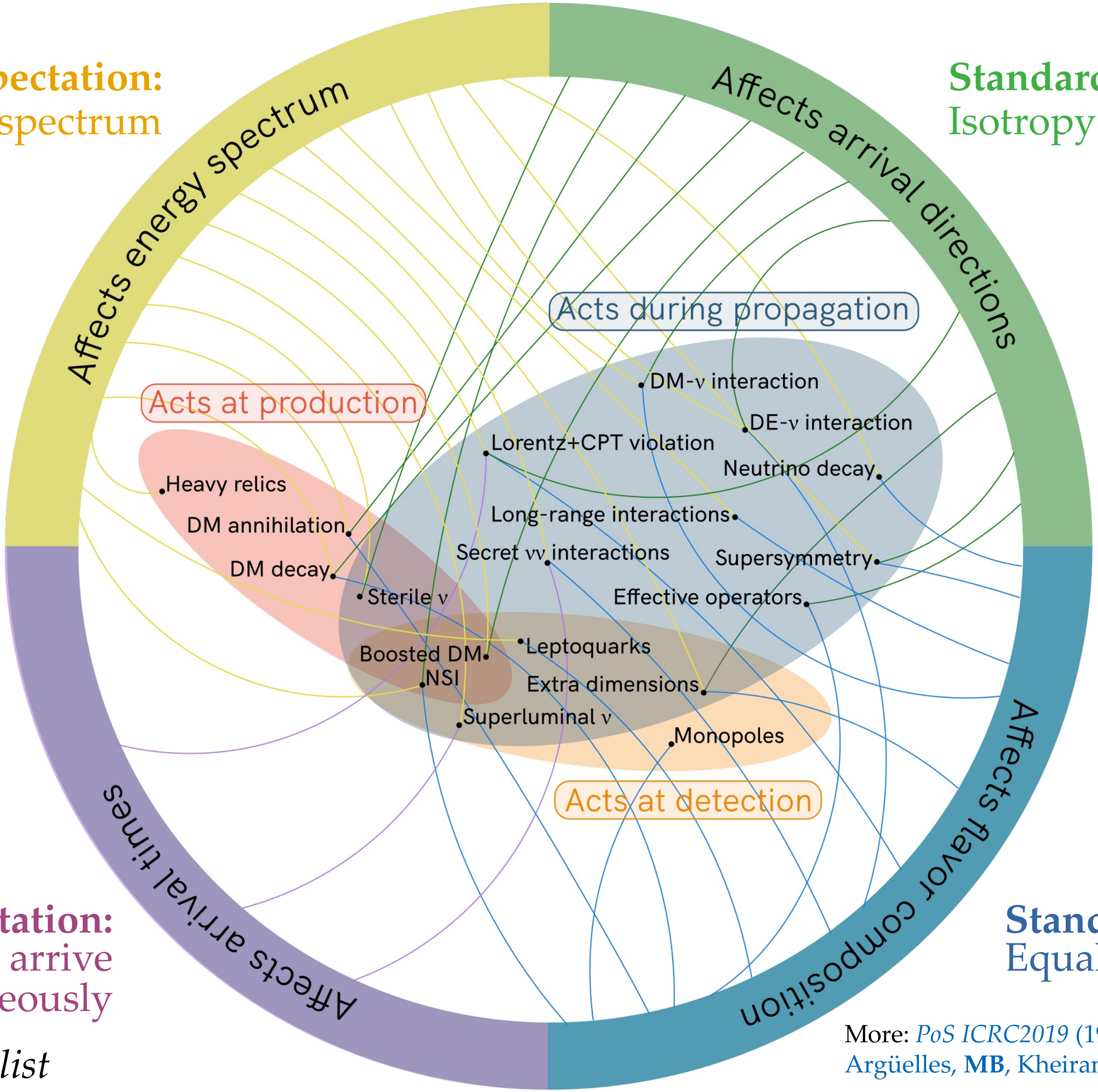

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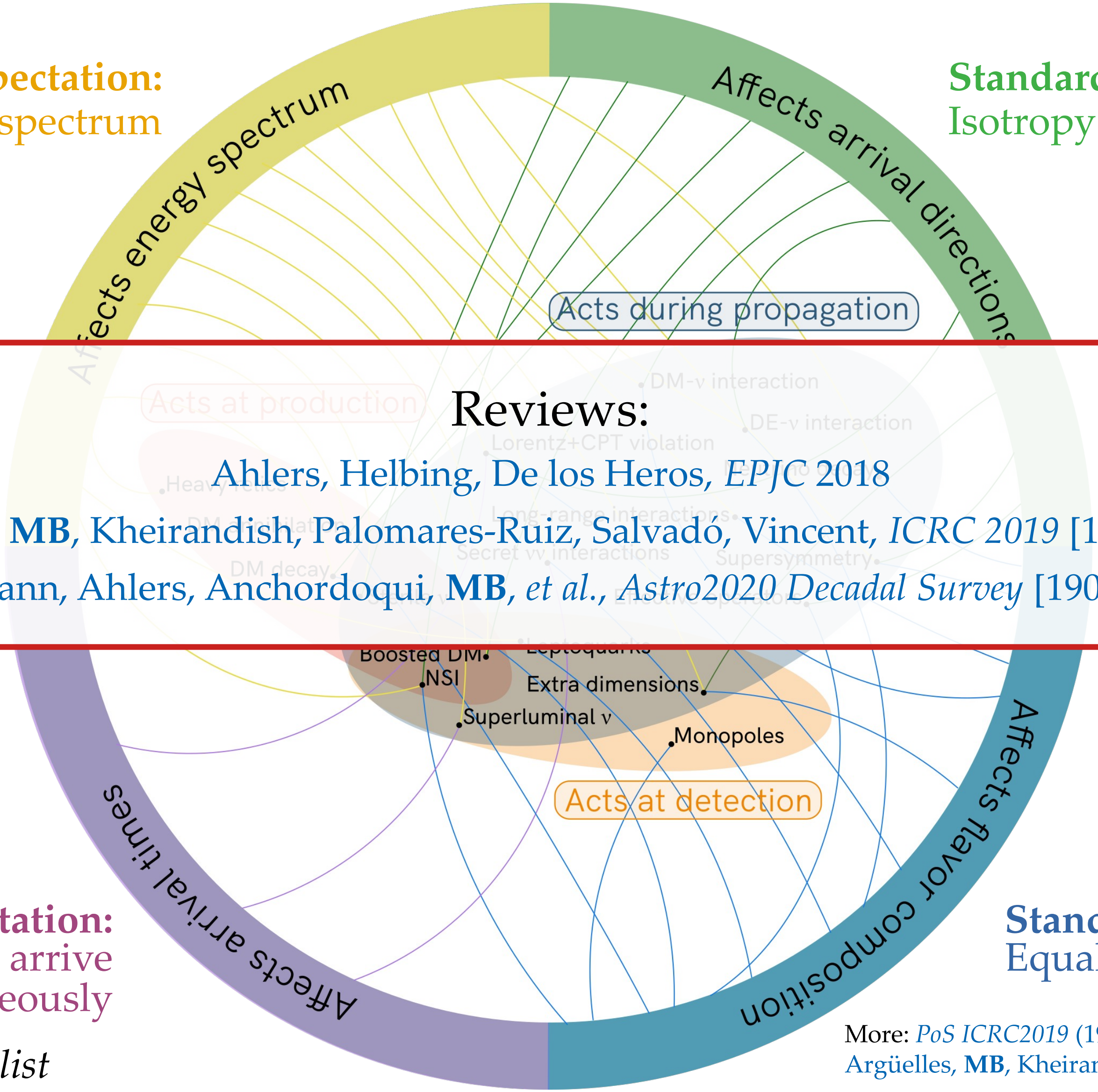

Reviews:

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

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

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

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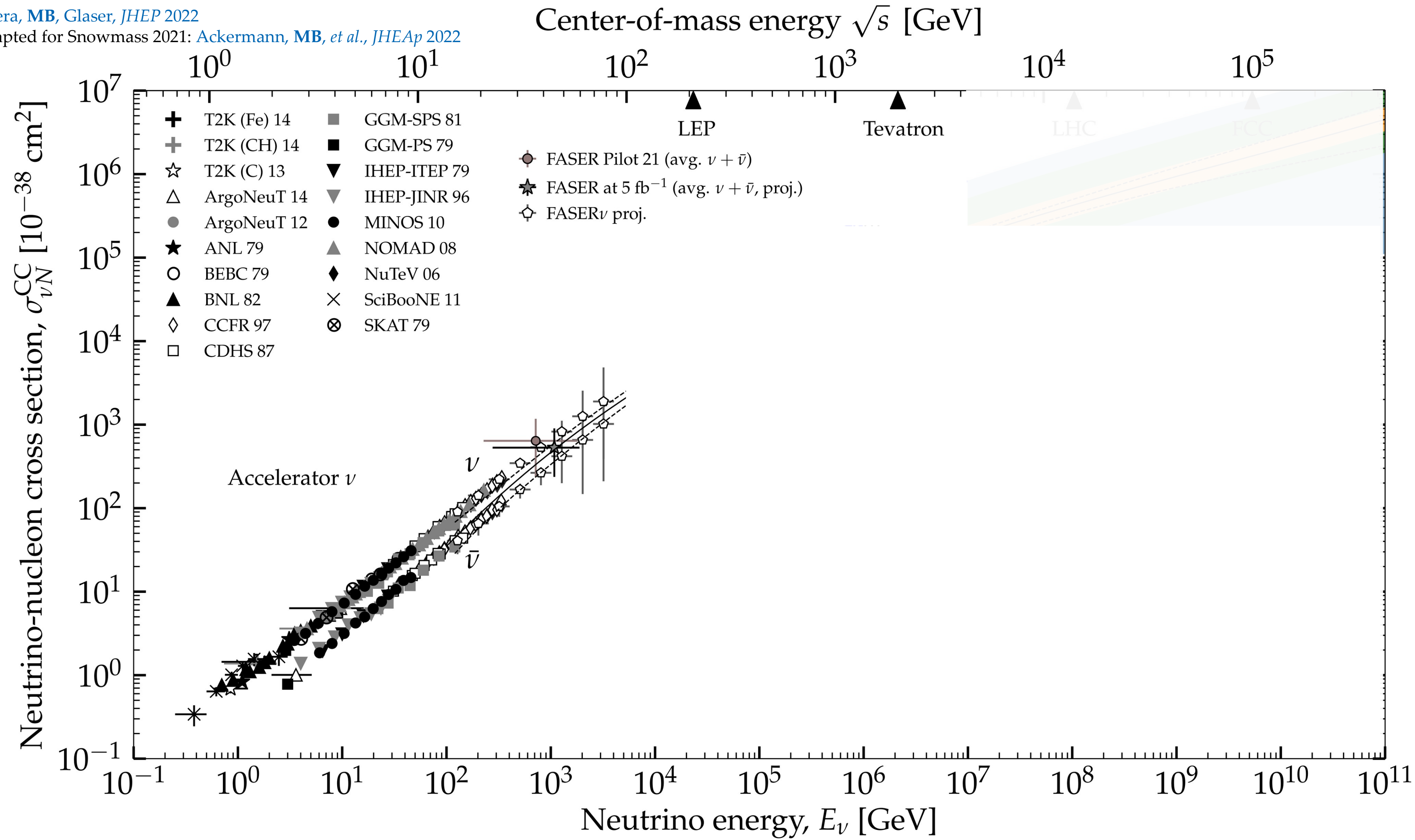
A selection of neutrino physics

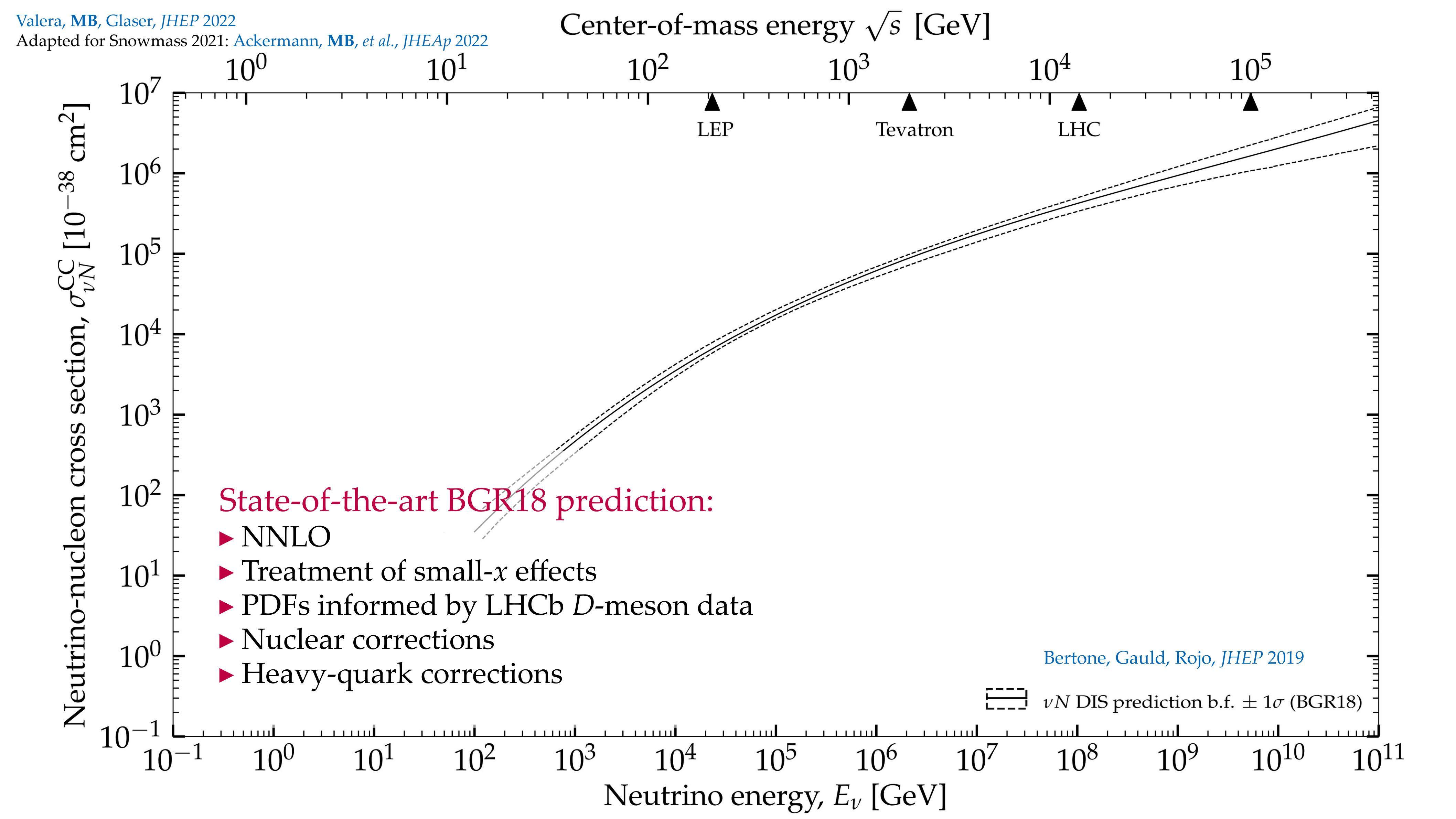
1. Neutrino-matter cross section
2. The Glashow resonance
3. Flavor physics
4. Secret neutrino interactions
5. Dark matter indirect detection
6. Neutrino decay

Find this in the backup slides

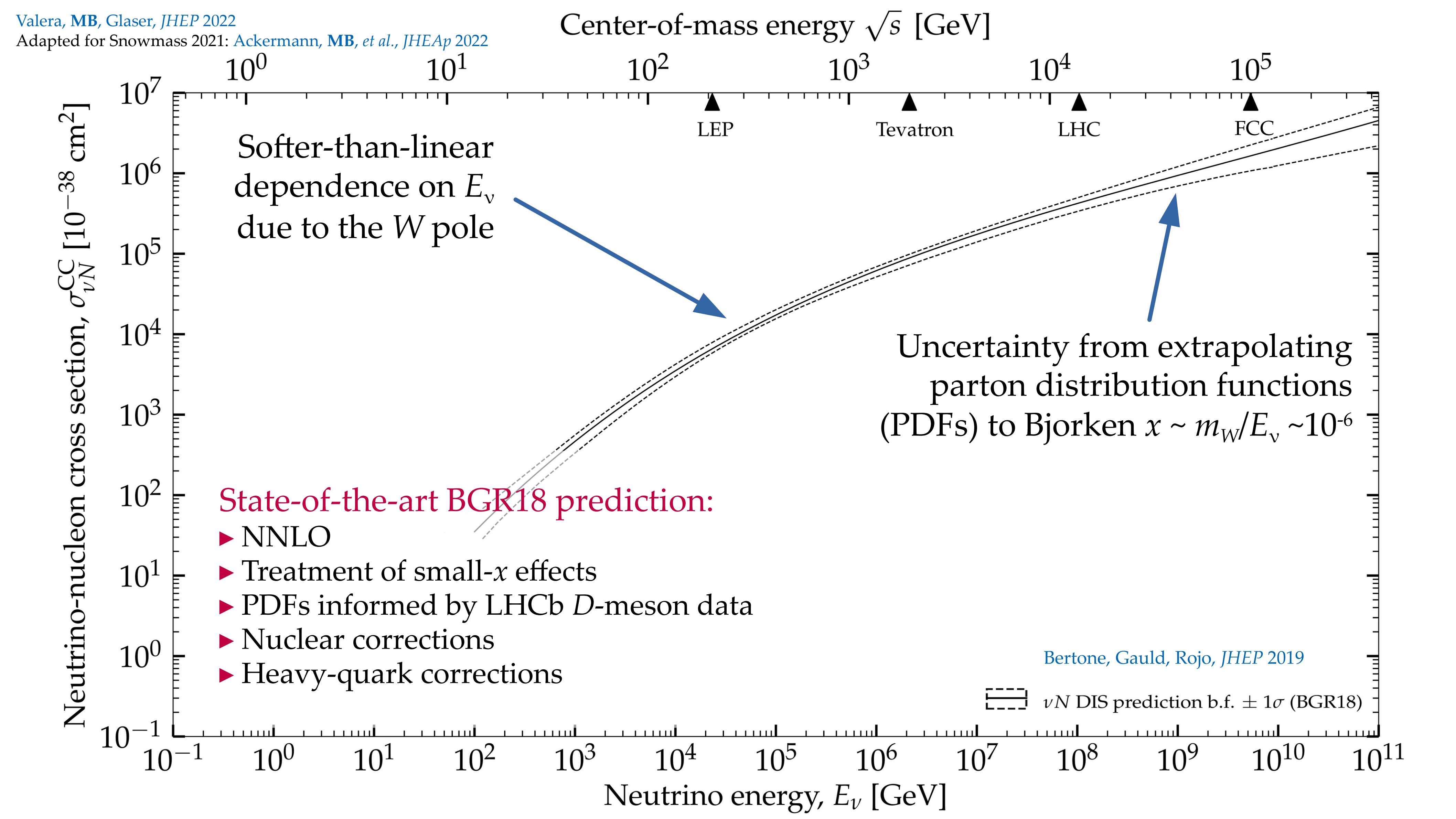
1. Neutrino-matter cross section: *From TeV to PeV*

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





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



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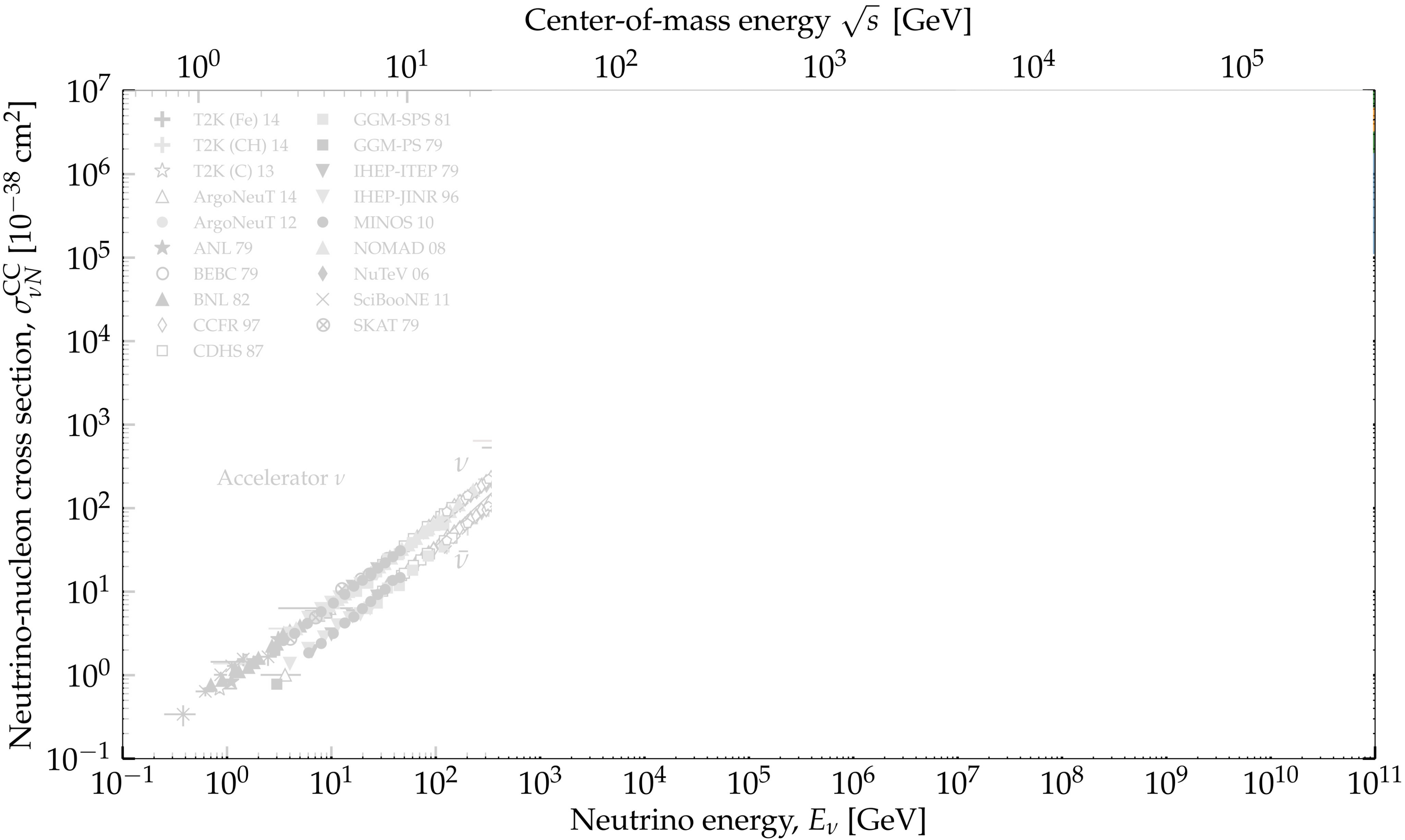
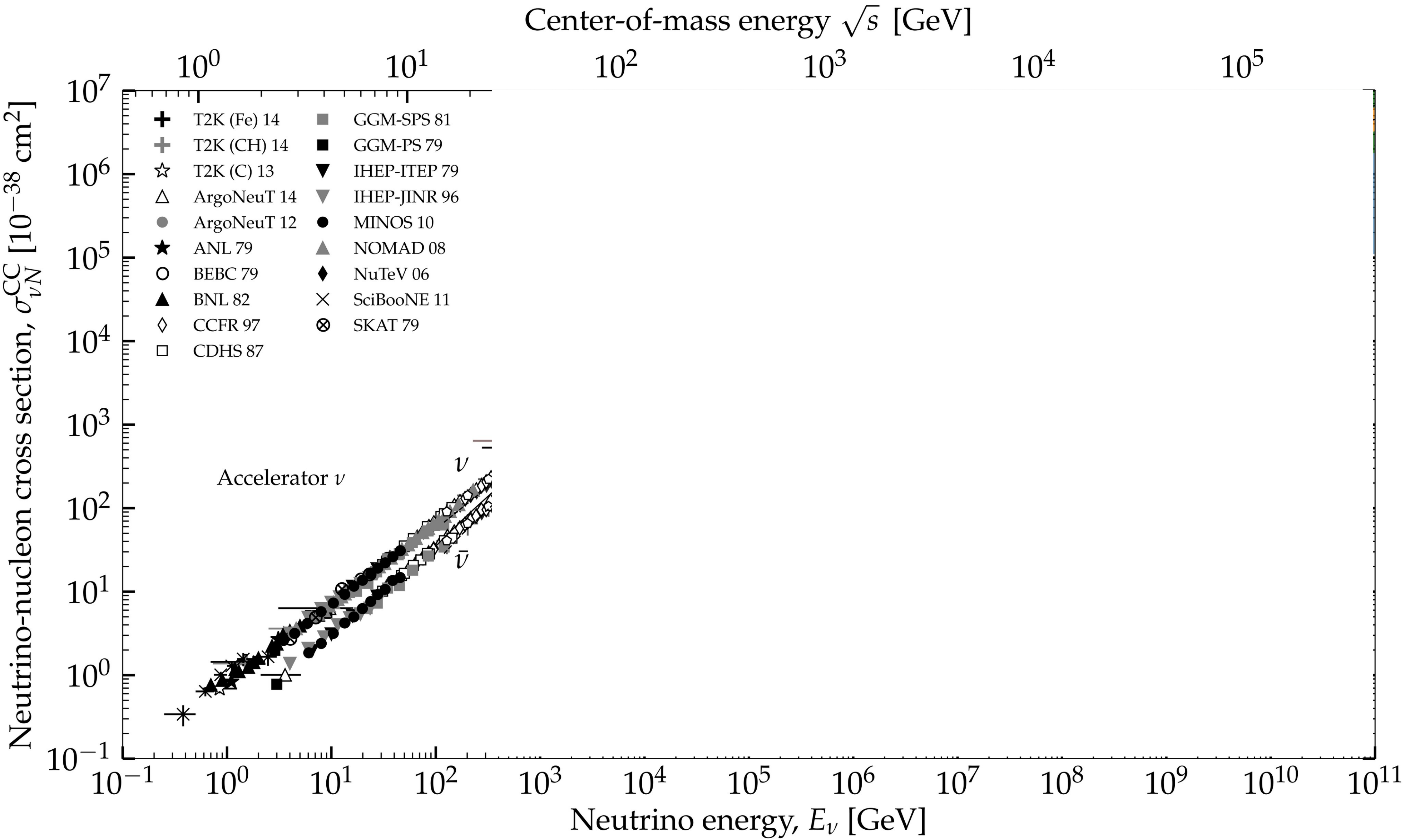


Center-of-mass energy $\sqrt{s}$ [GeV]
Neutrino-nucleon cross section, $\sigma_{\nu N}^{\mathrm{CC}}$ [10^{-38} cm^2]
Neutrino energy, E_ν [GeV]
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
GGM-PS 79
IHEP-ITEP 79
IHEP-JINR 96
MINOS 10
NOMAD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



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^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
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Accelerator ν
ν
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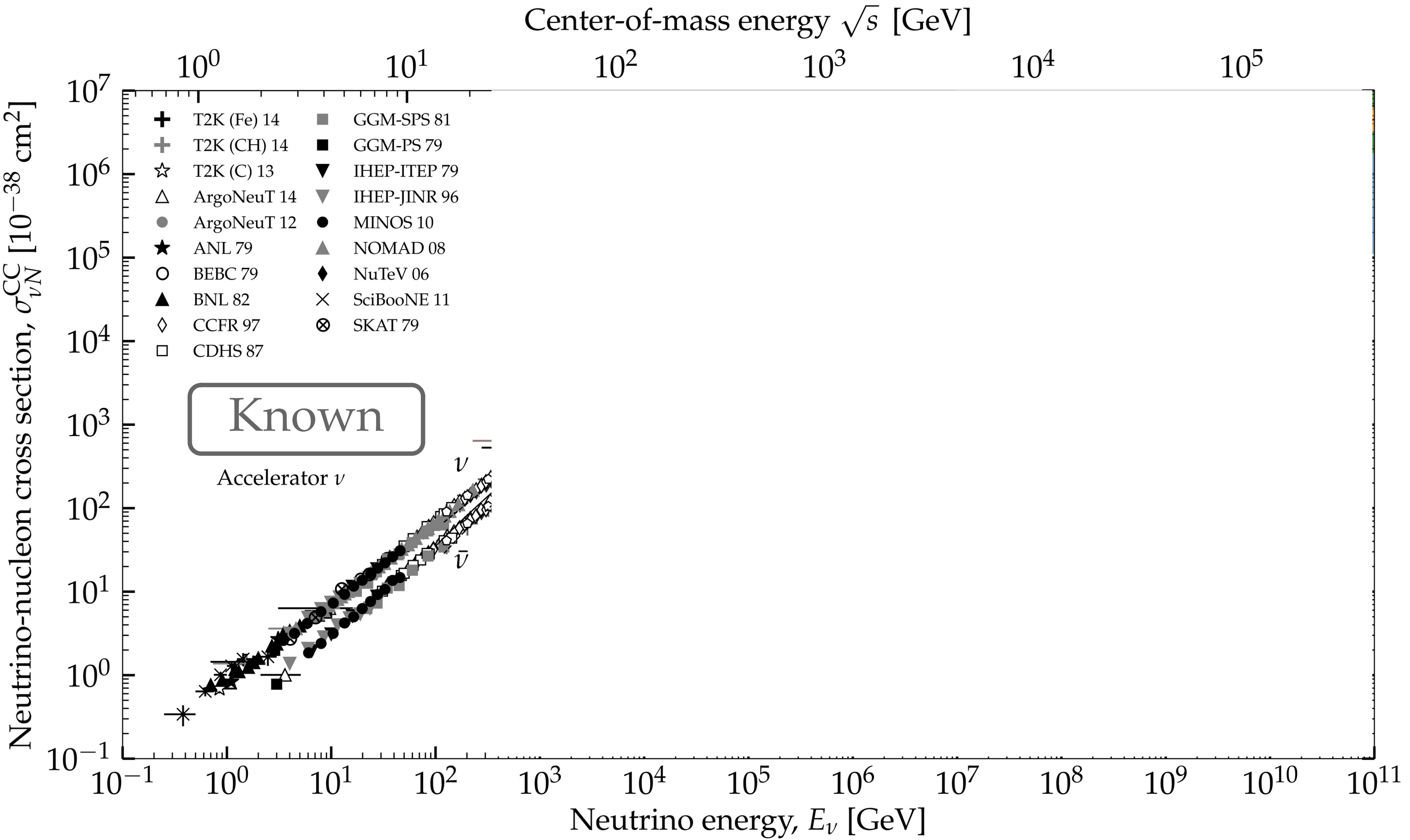
10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11}
Neutrino energy, E_ν [GeV]



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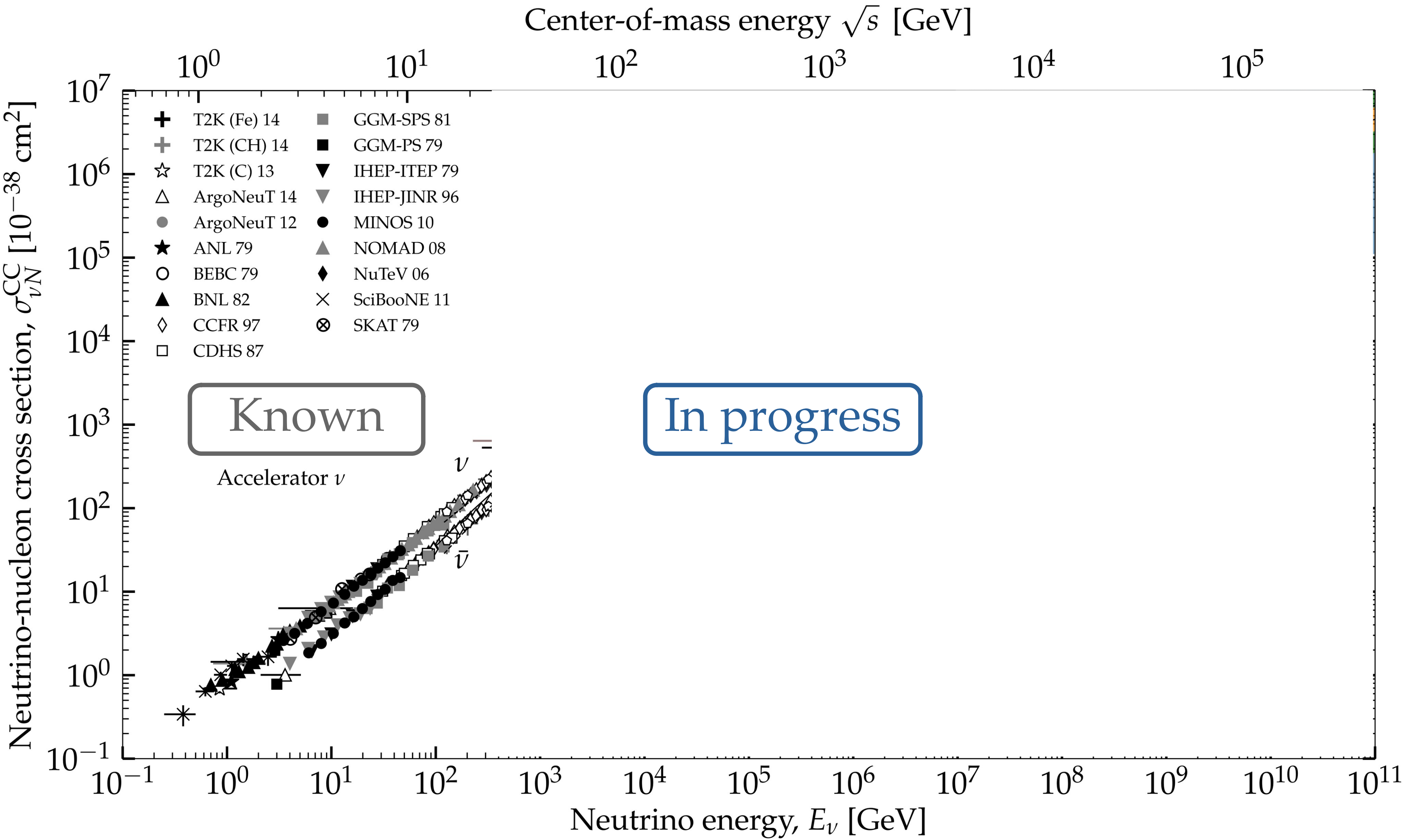
Known
Accelerator ν
ν
$\bar{\nu}$
Neutrino energy, E_ν [GeV]
10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11}



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T2K (Fe) 14
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T2K (C) 13
ArgoNeuT 14
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ANL 79
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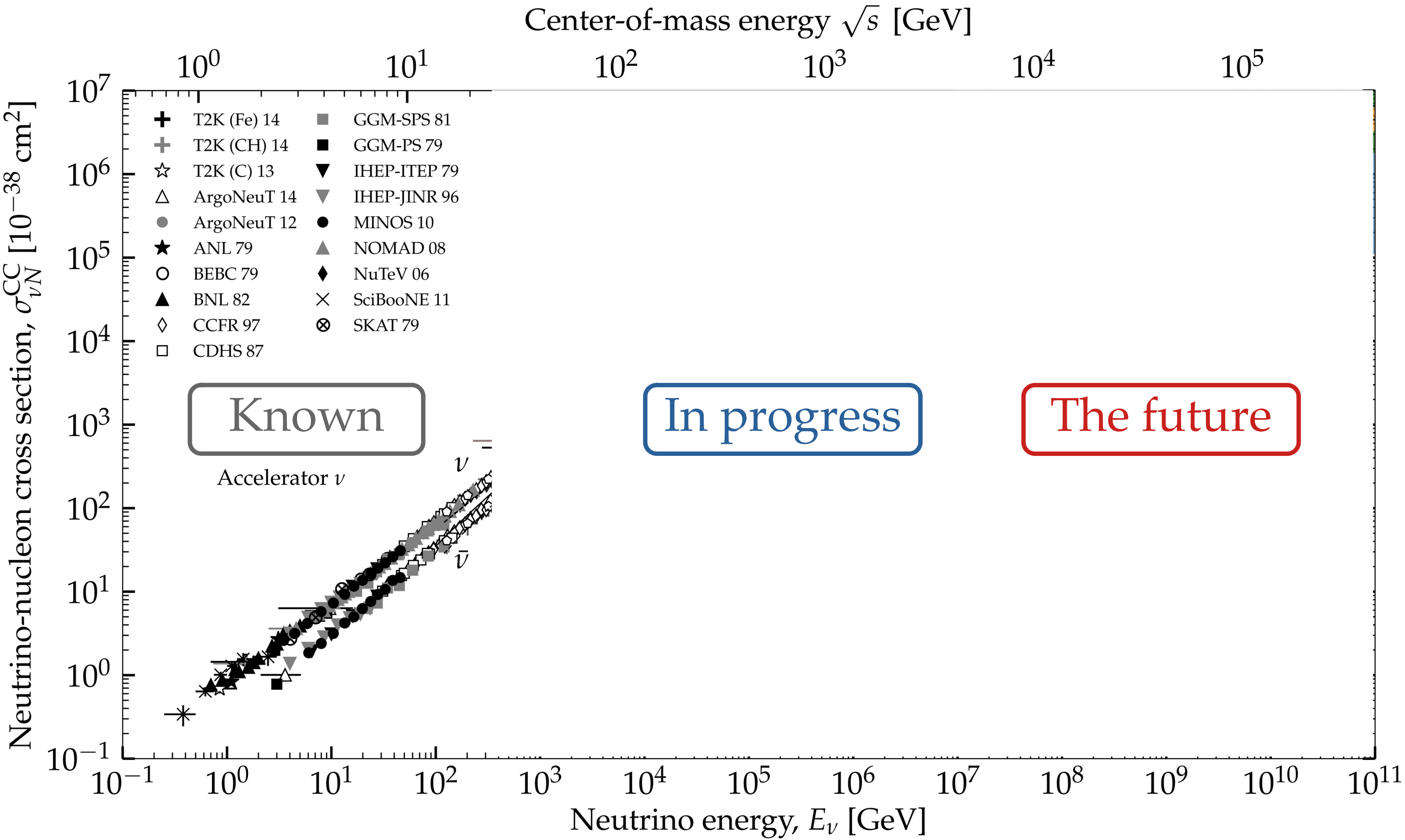
Accelerator ν
ν
$\bar{\nu}$



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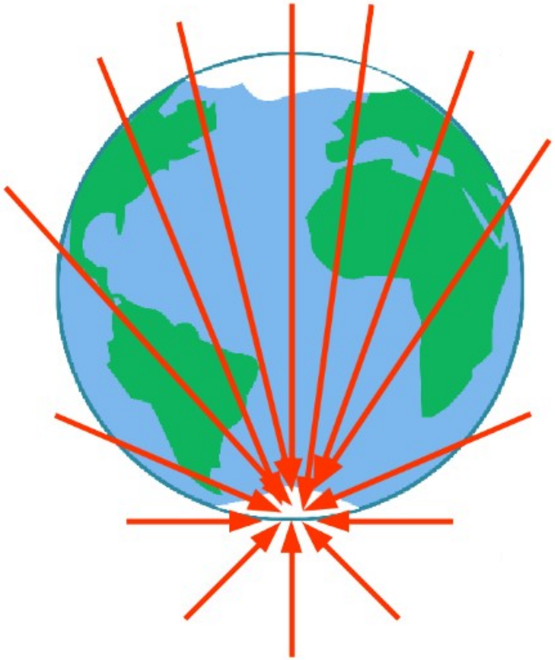
The future
Accelerator ν
ν
$\bar{\nu}$

Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent



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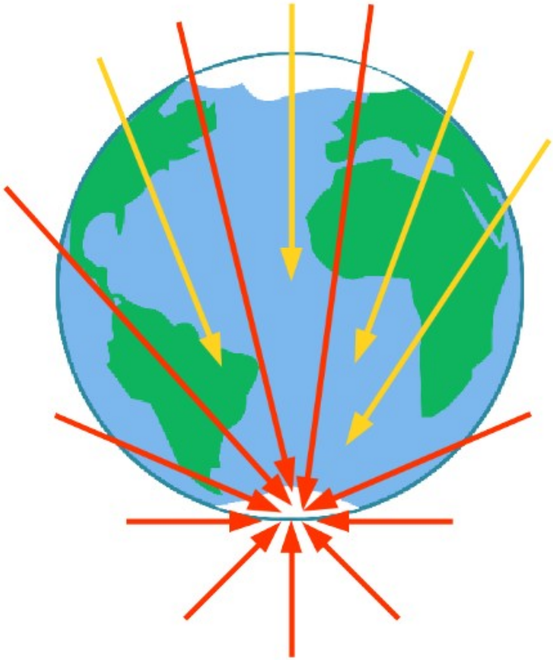

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008; Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

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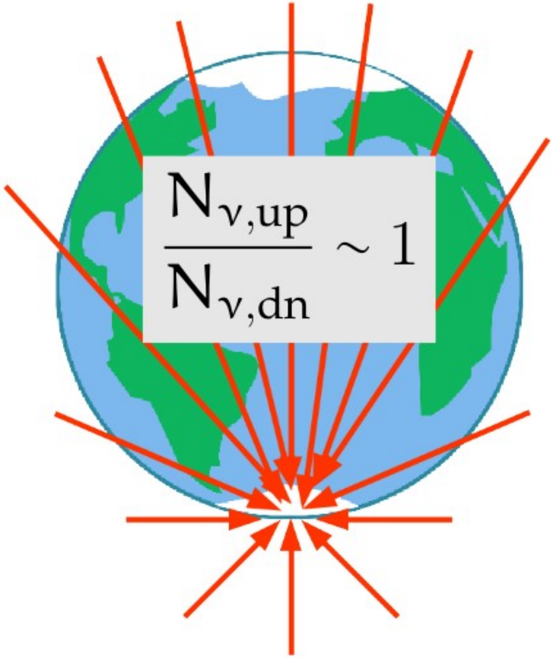

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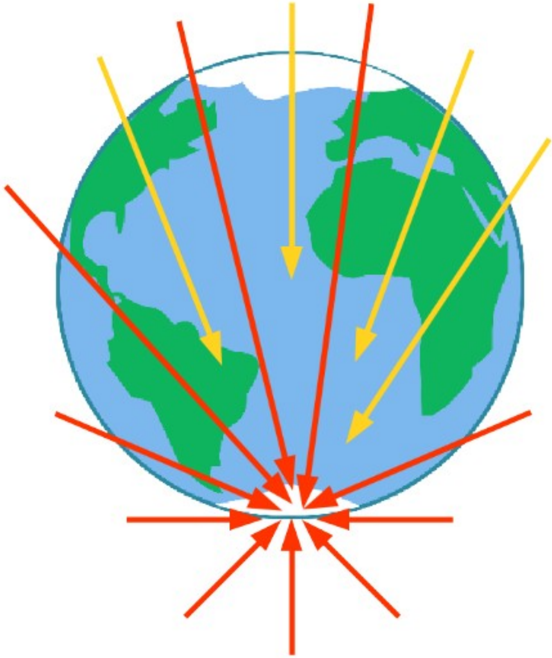

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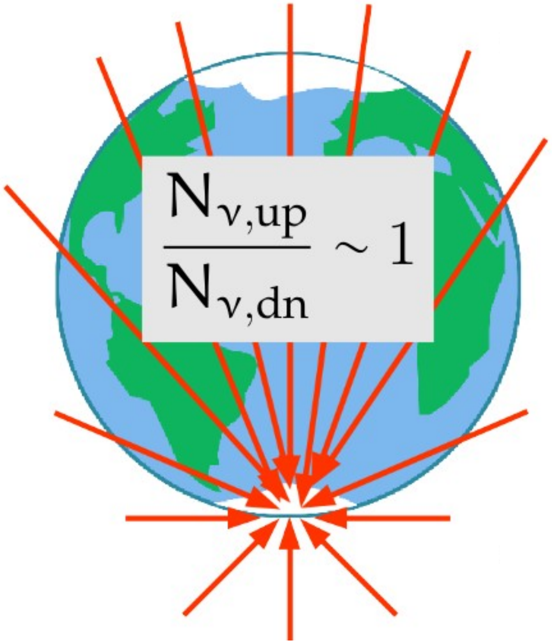

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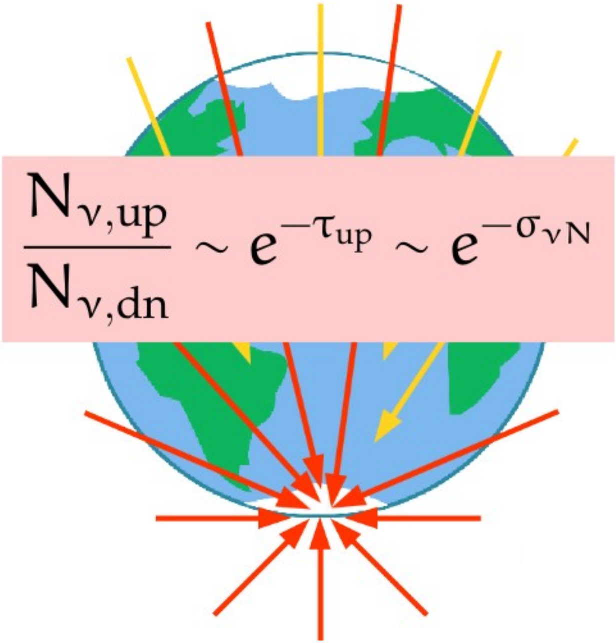

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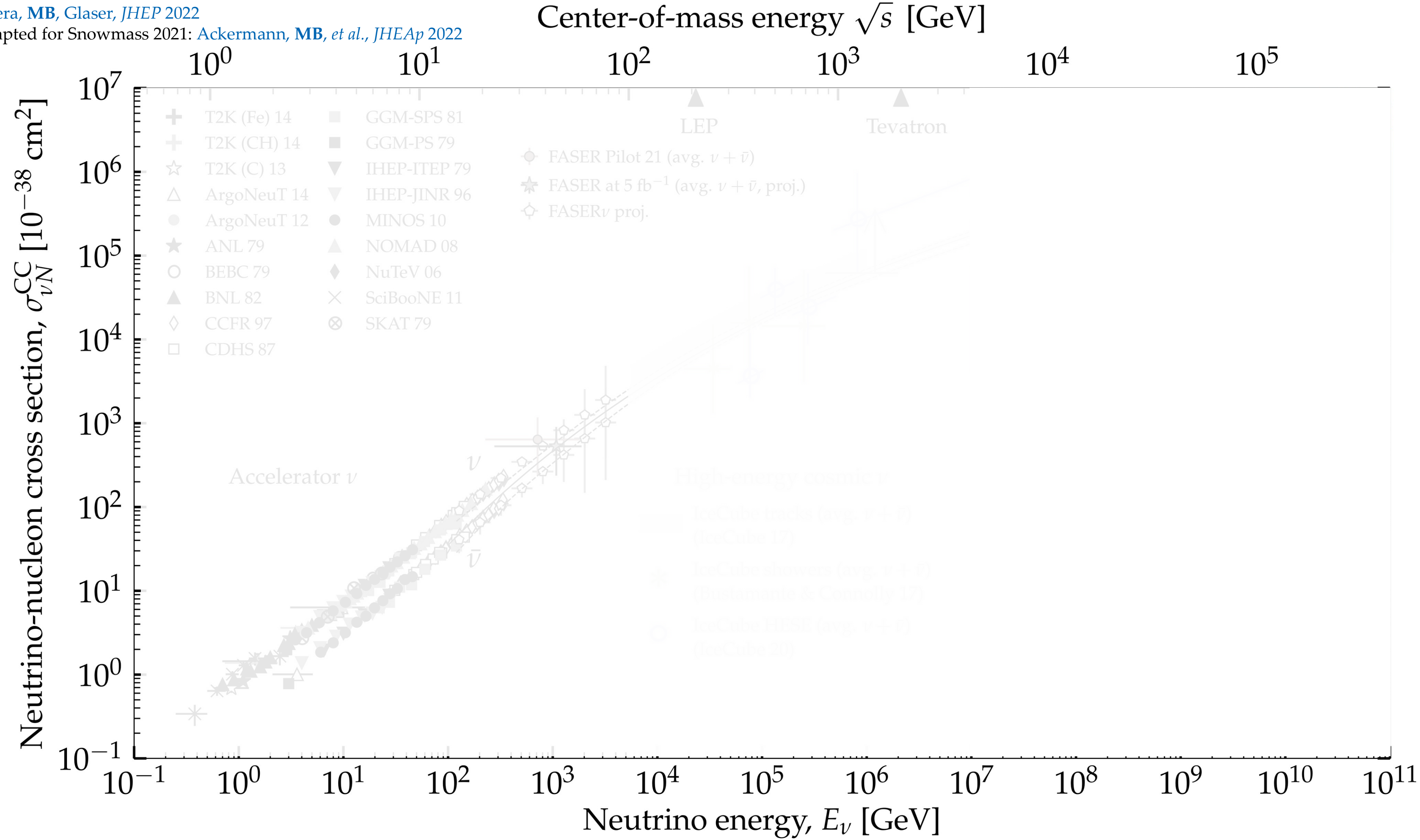
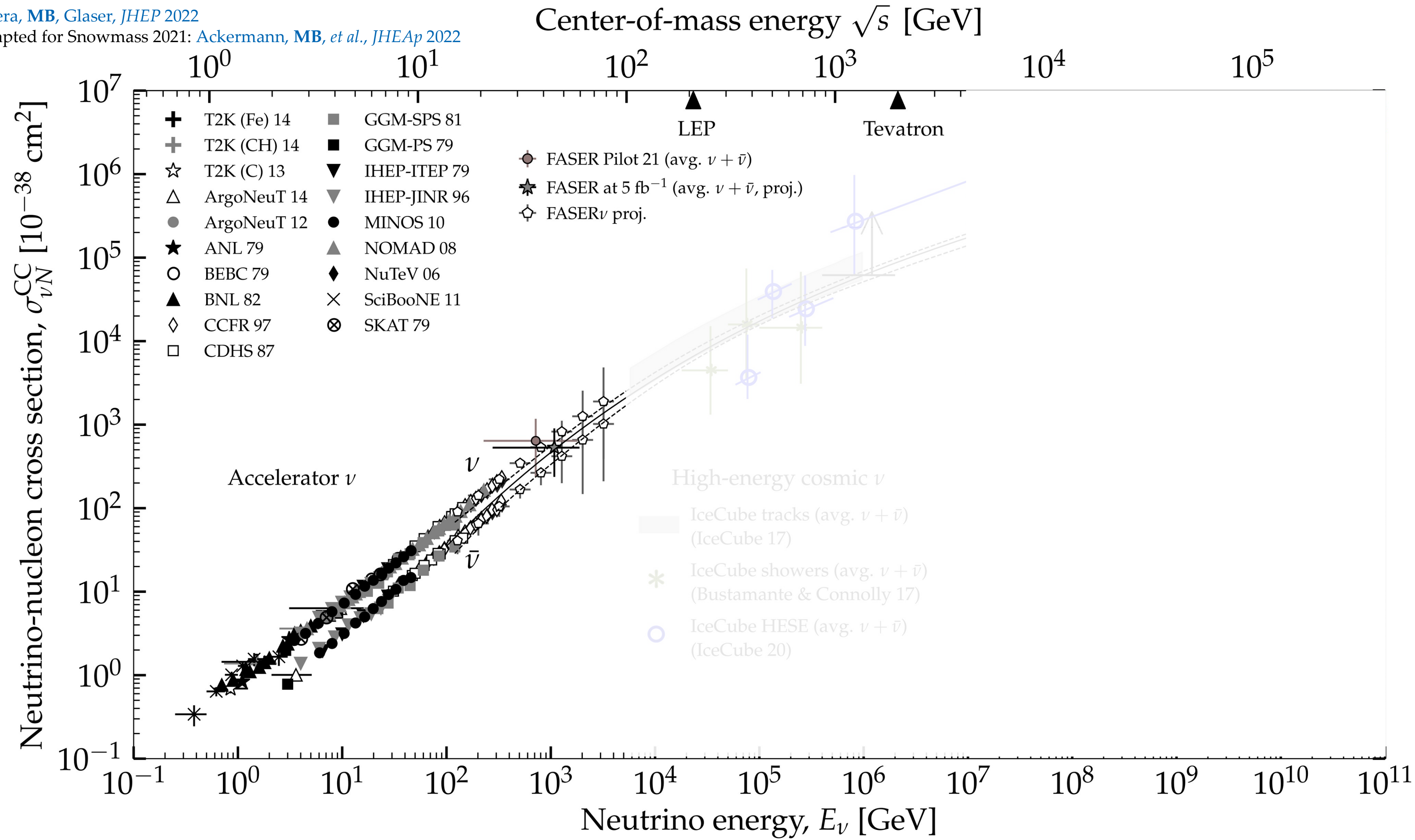
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



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

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



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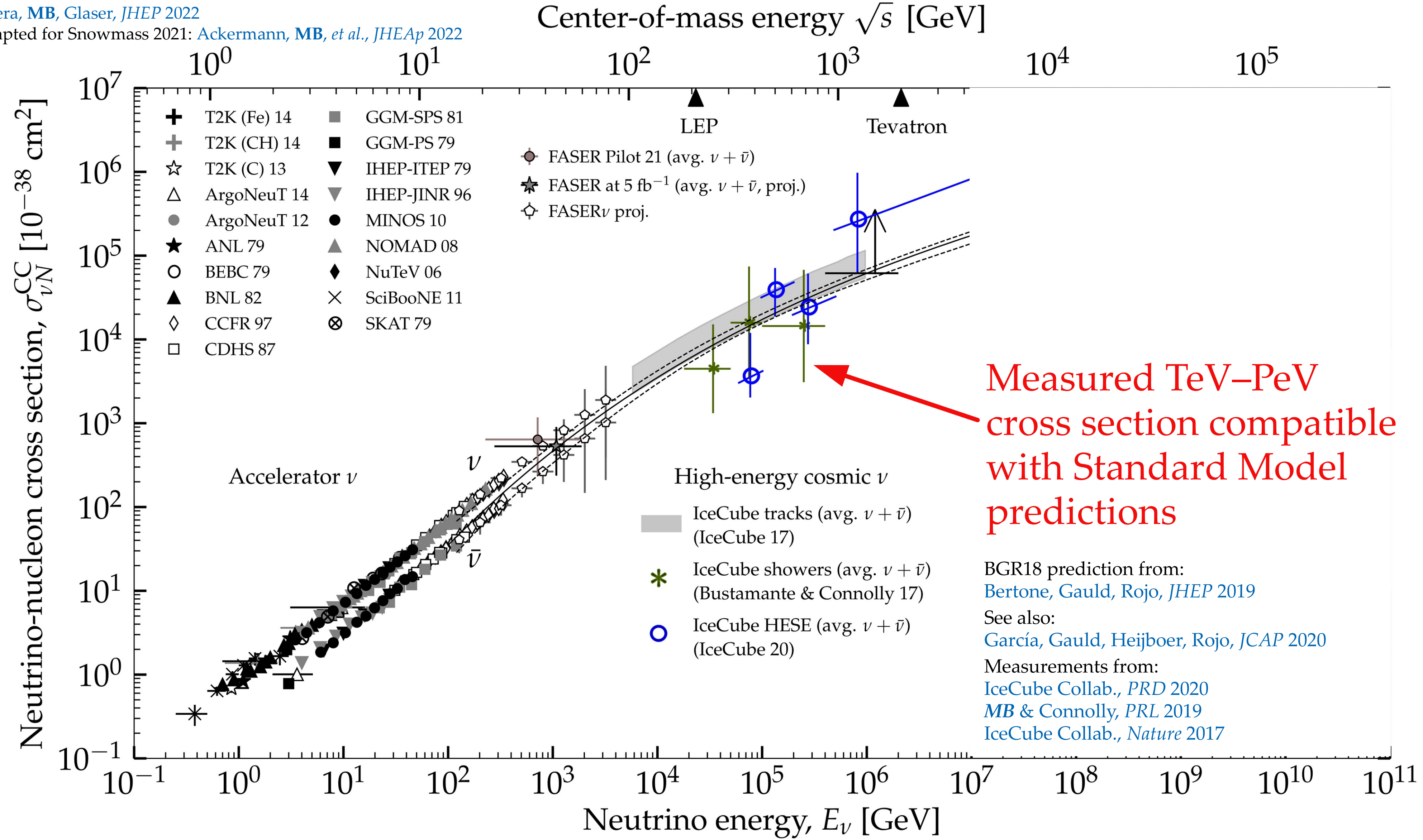
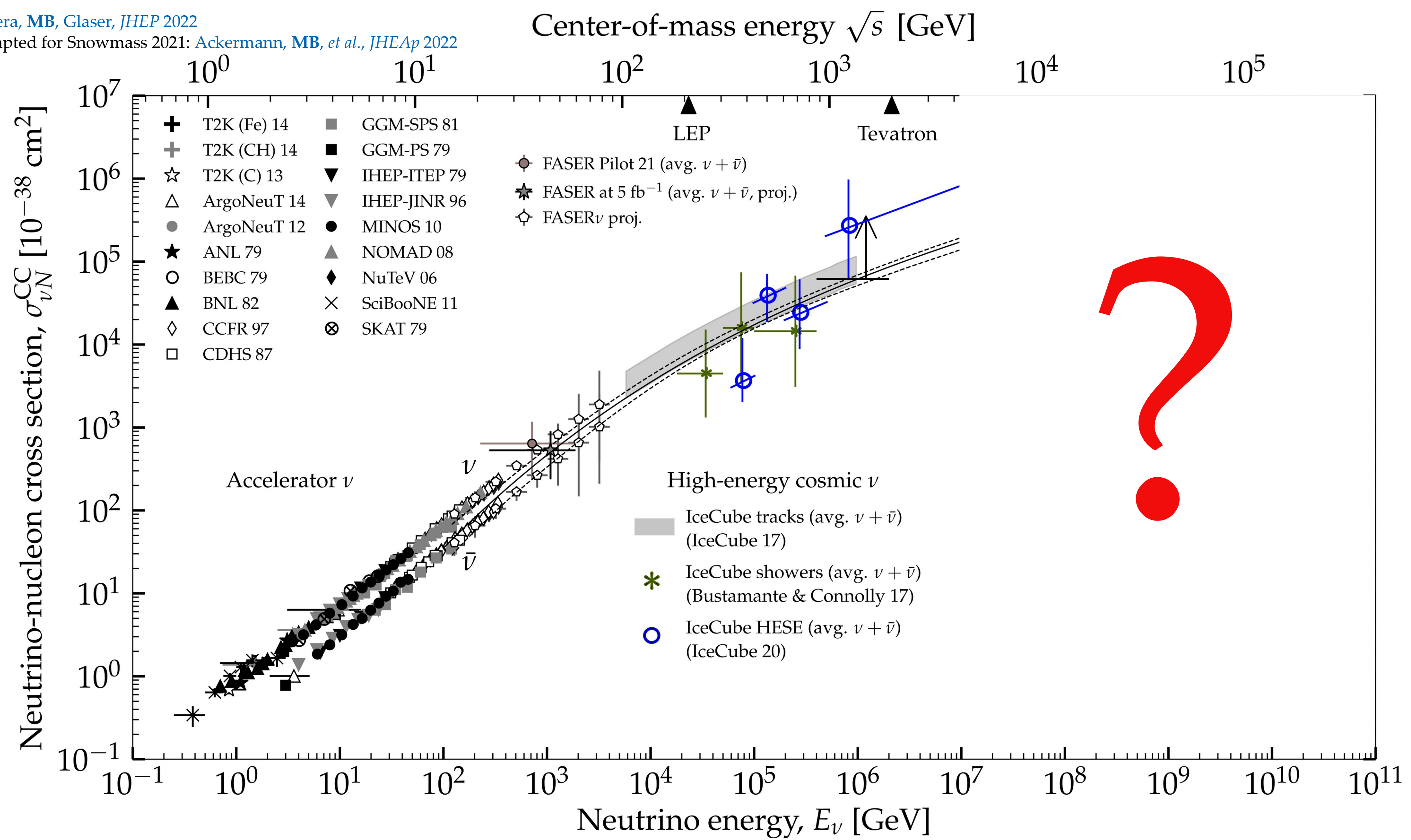


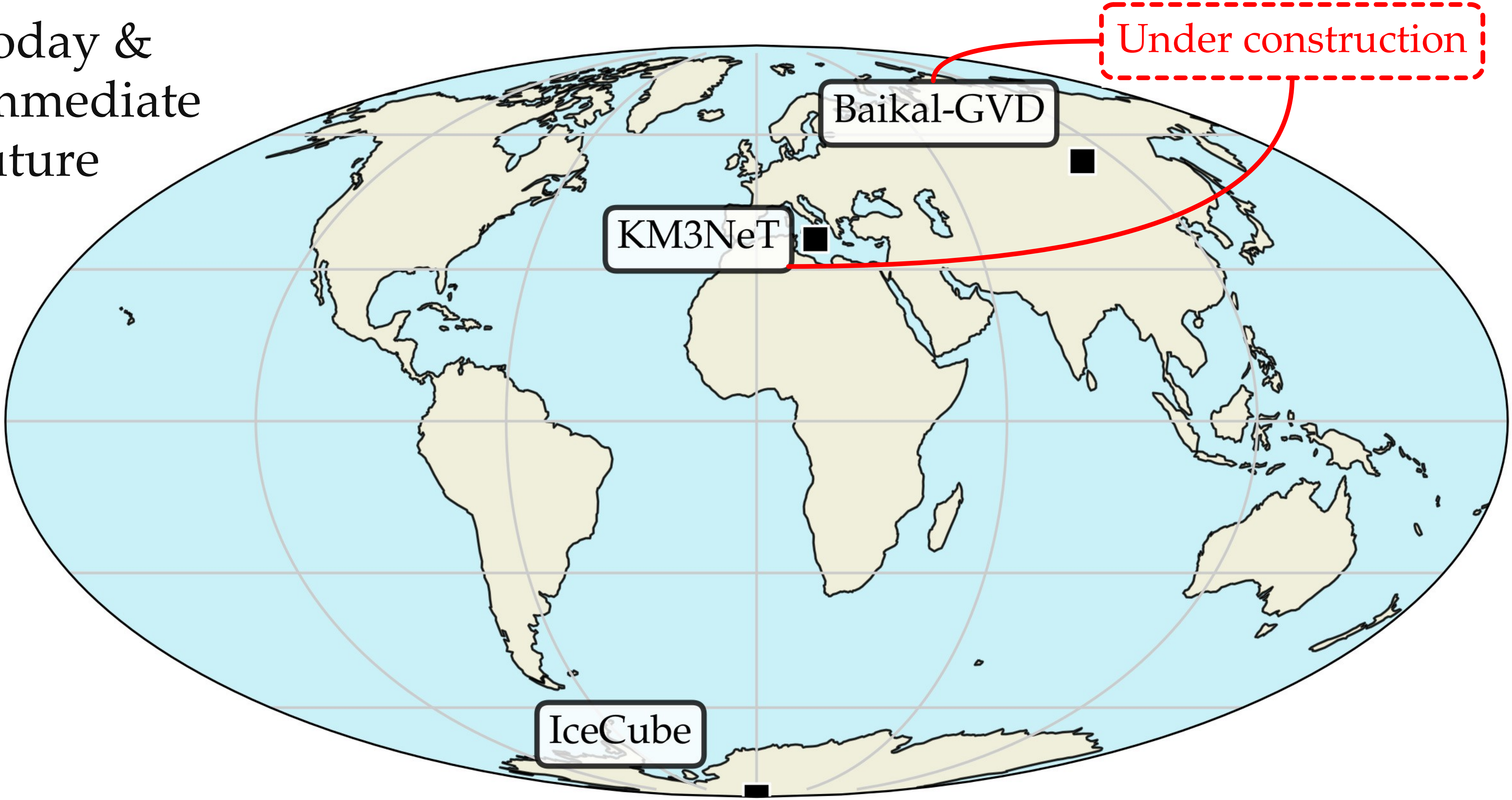
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



The future, now

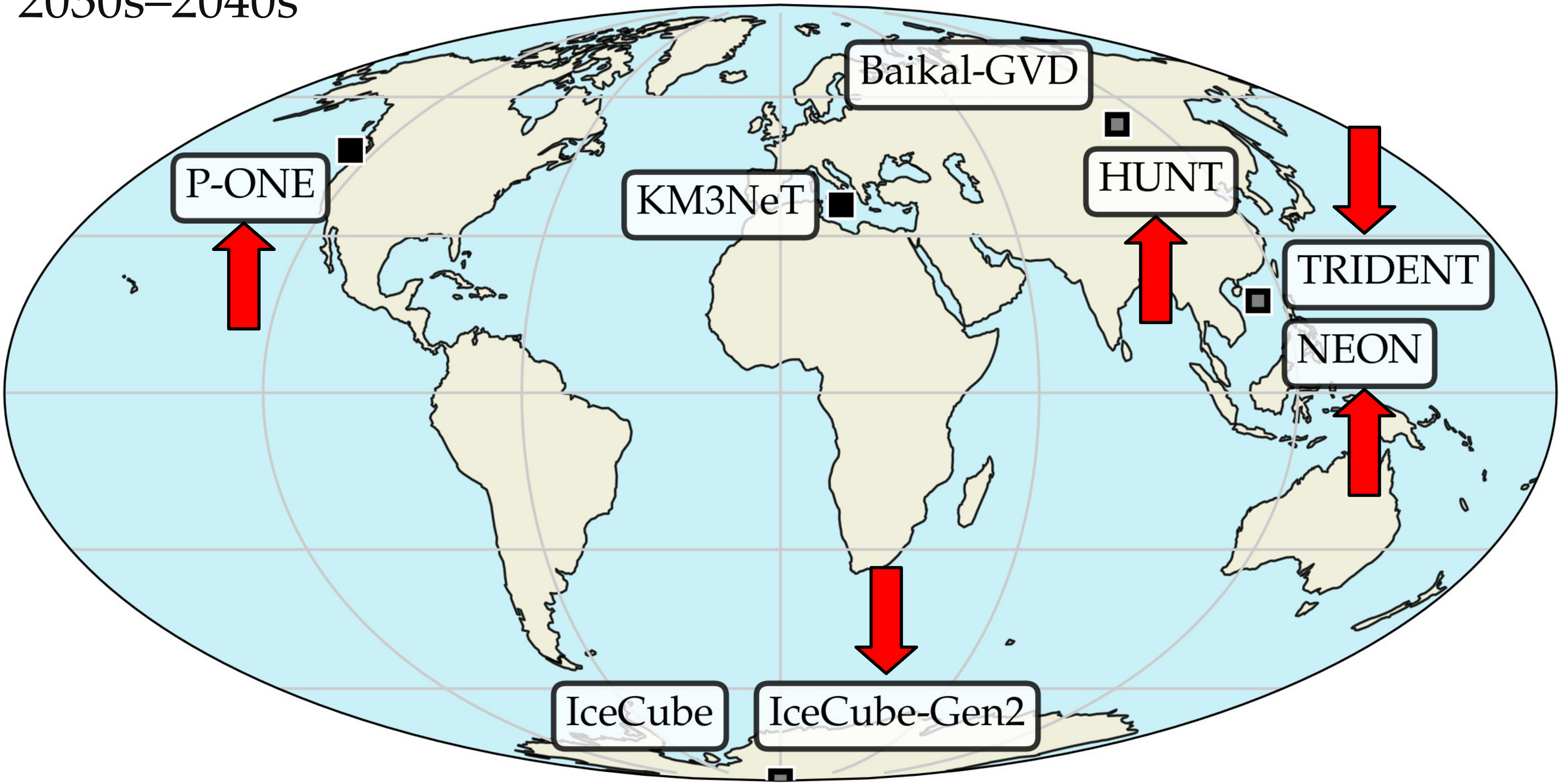
A global network of neutrino telescopes

Today & immediate future

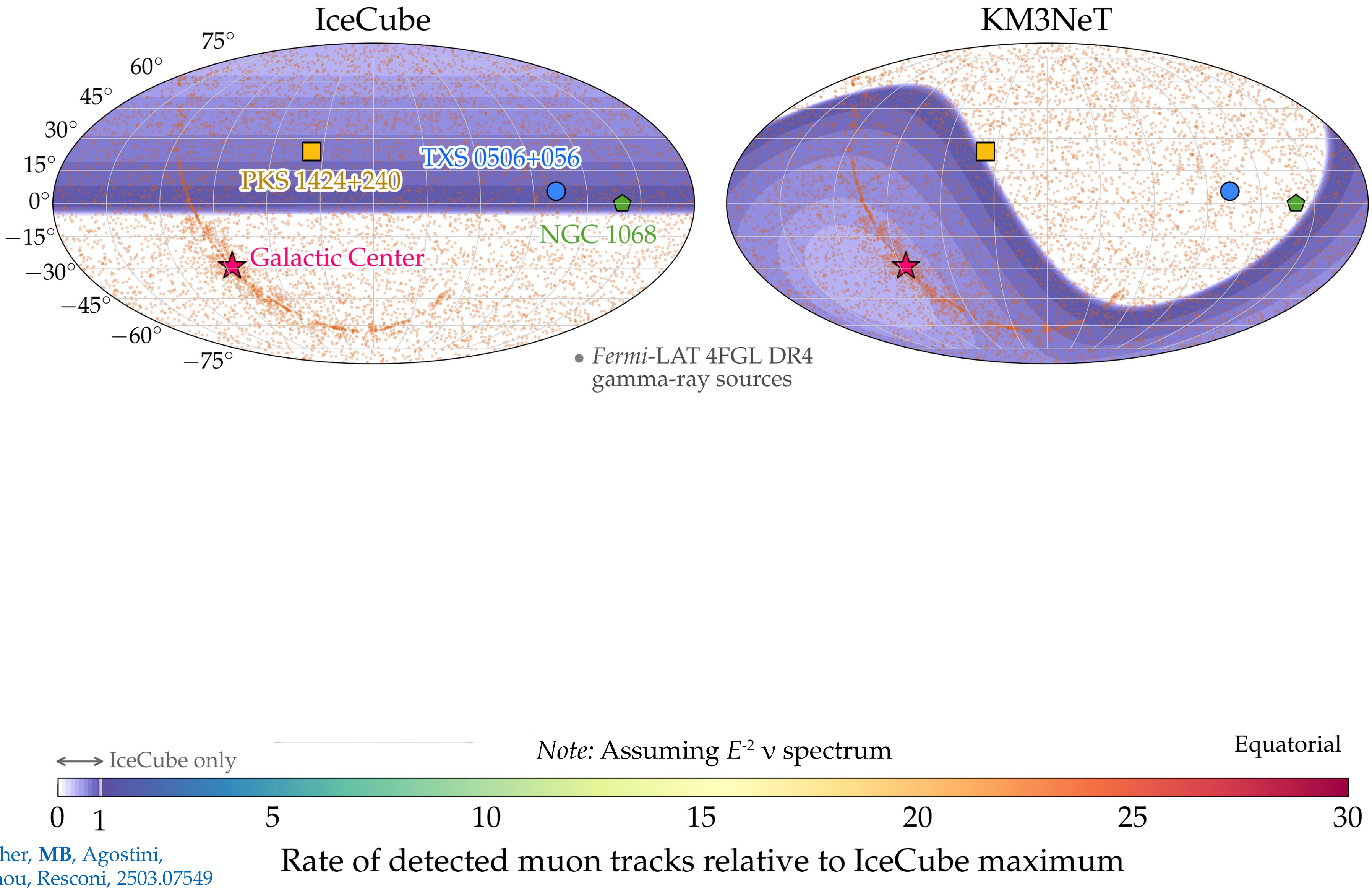


Schumacher, **MB**, Agostini, Oikonomou, Resconi, 2503.07549

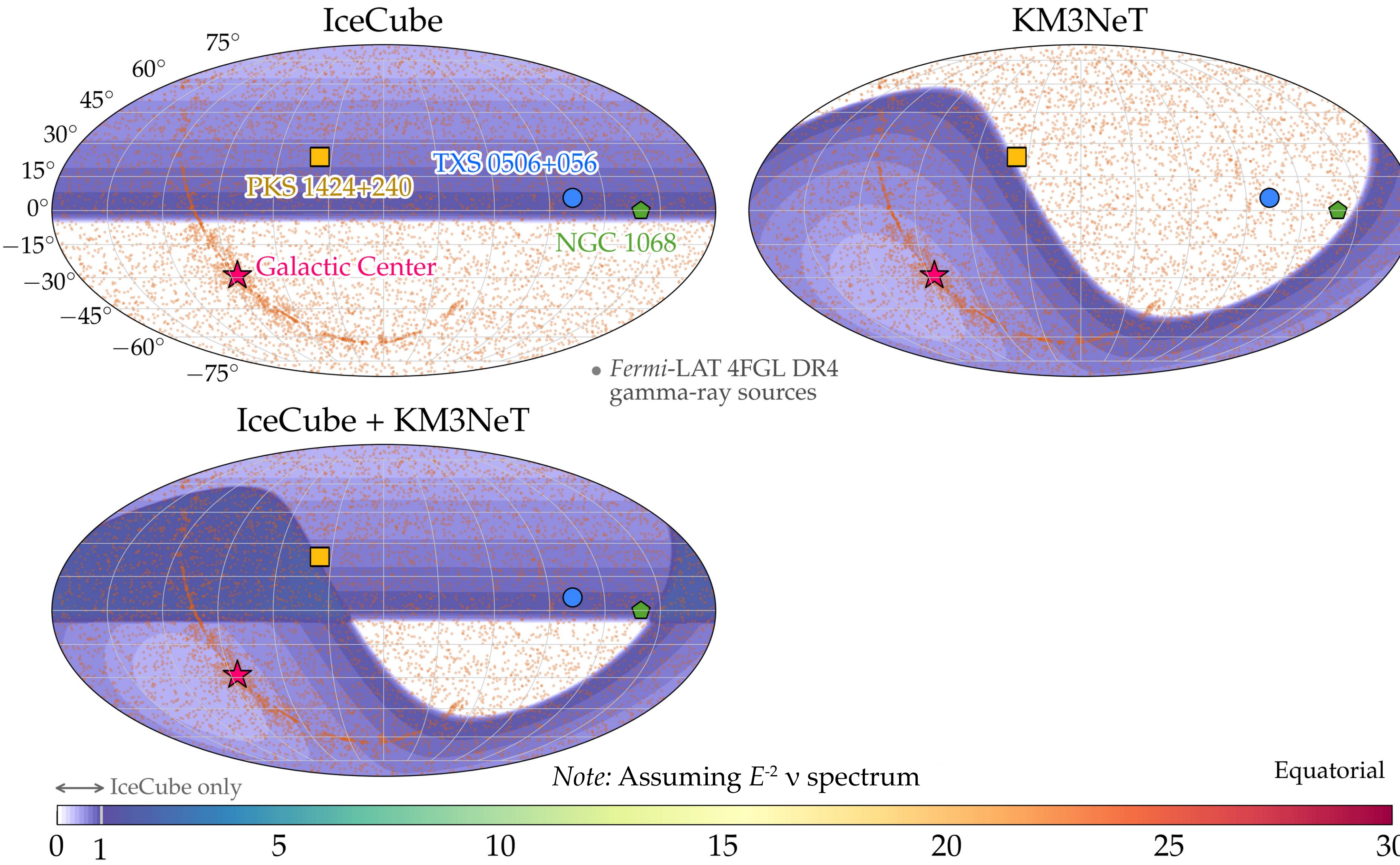
2030s–2040s



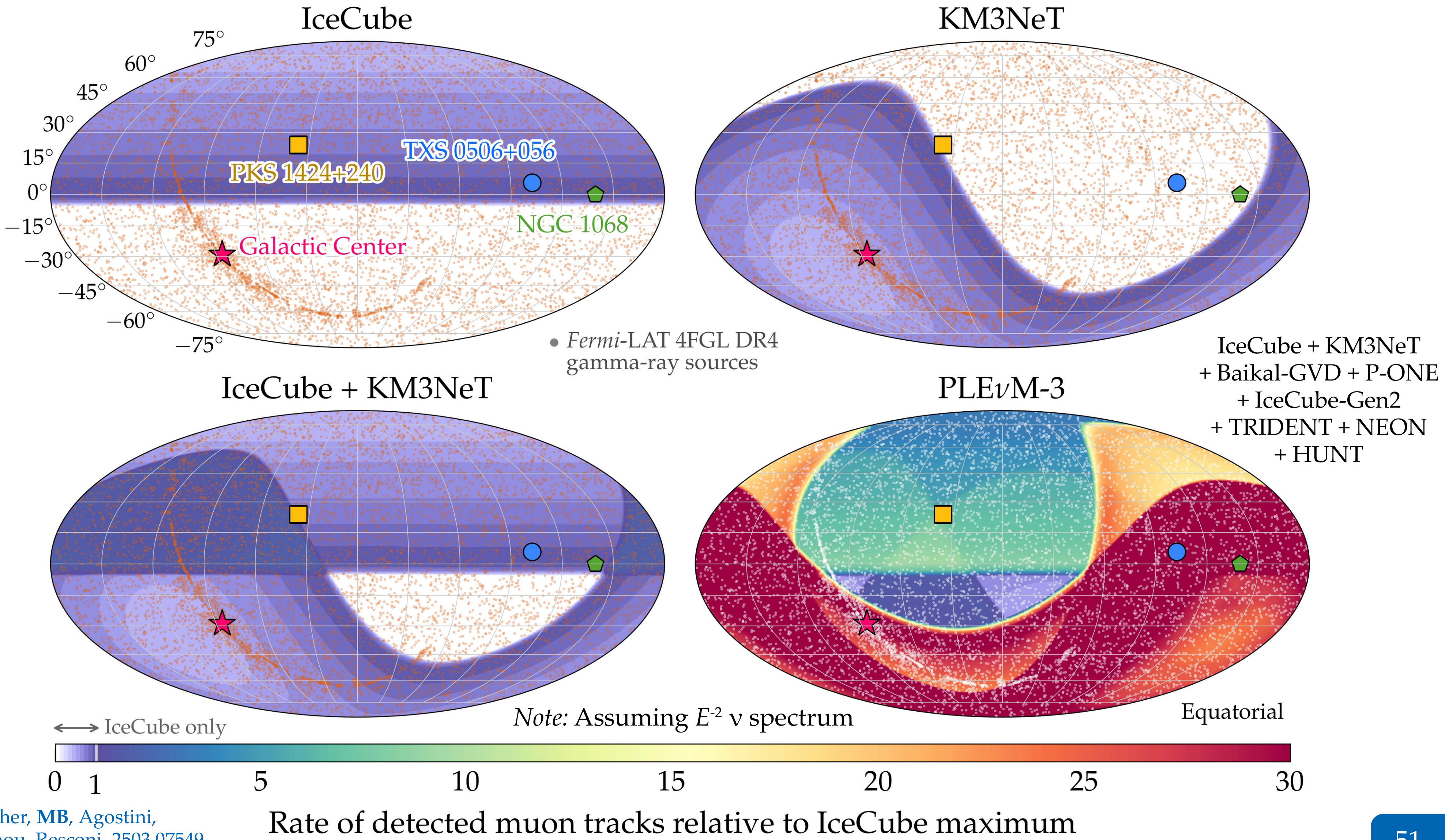
Schumacher, **MB**, Agostini, Oikonomou, Resconi, 2503.07549



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

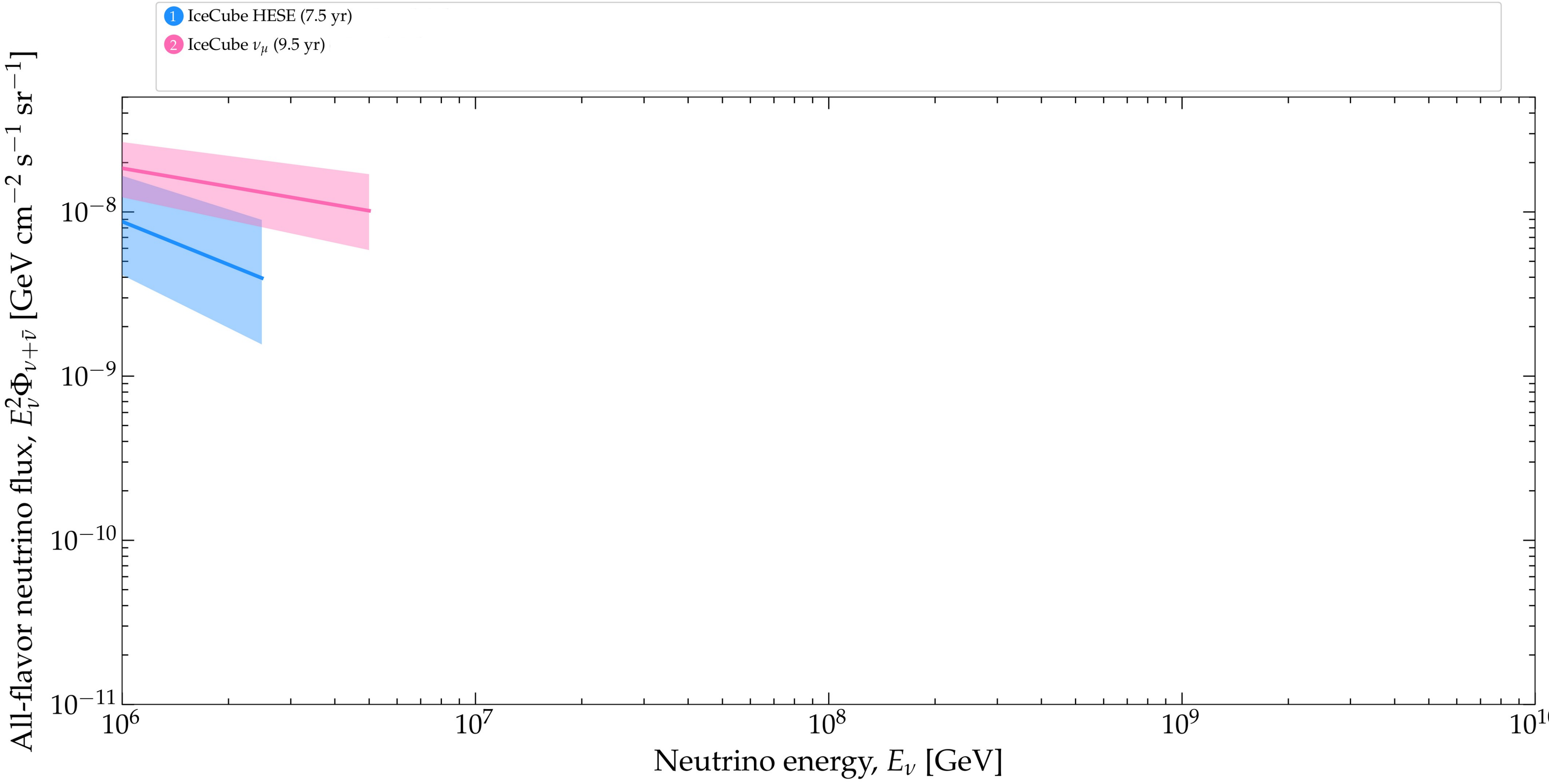


Schumacher, **MB**, Agostini, Oikonomou, Resconi, 2503.07549

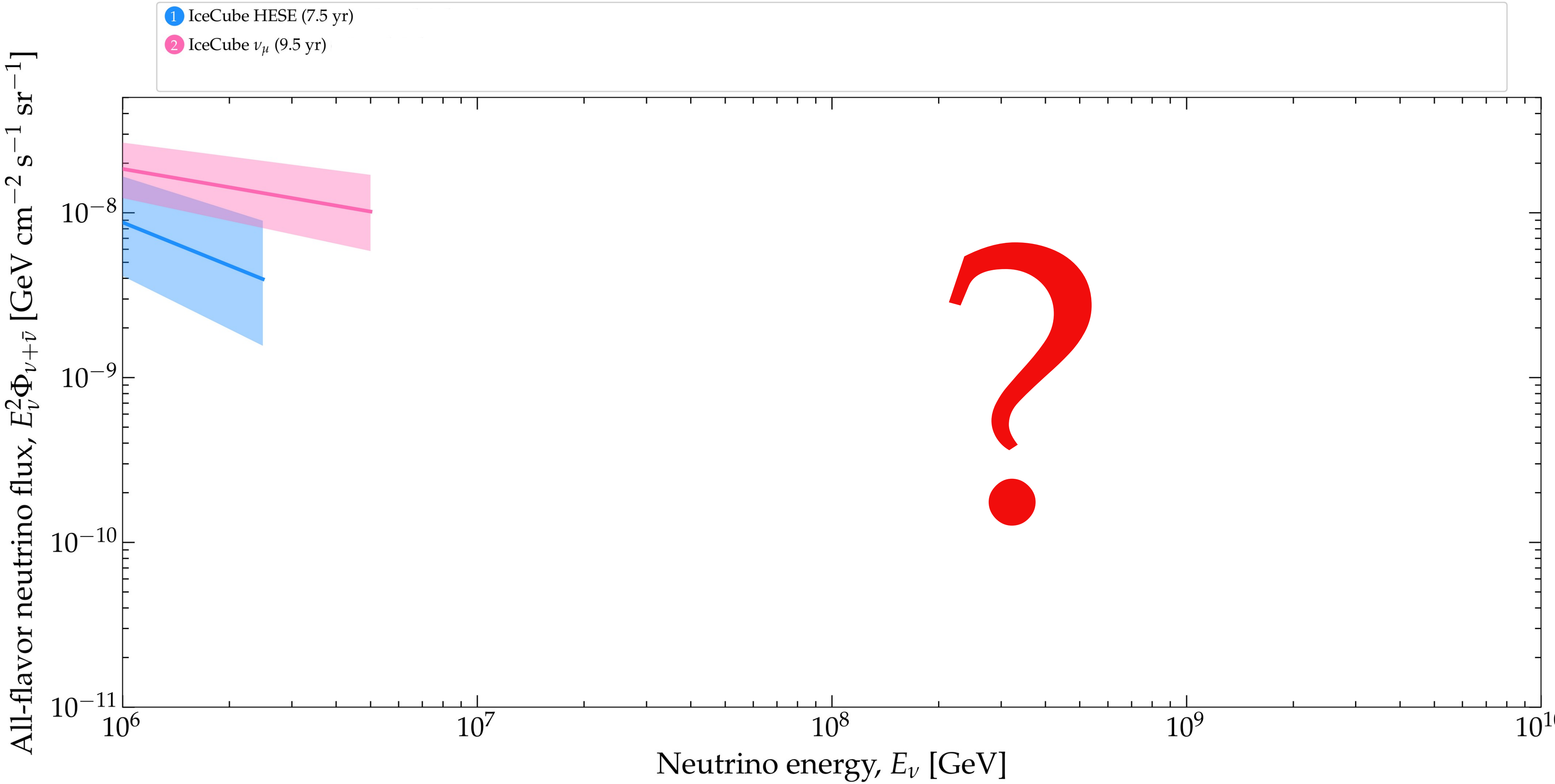


Schumacher, **MB**, Agostini, Oikonomou, Resconi, 2503.07549

Ultra-high energies



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



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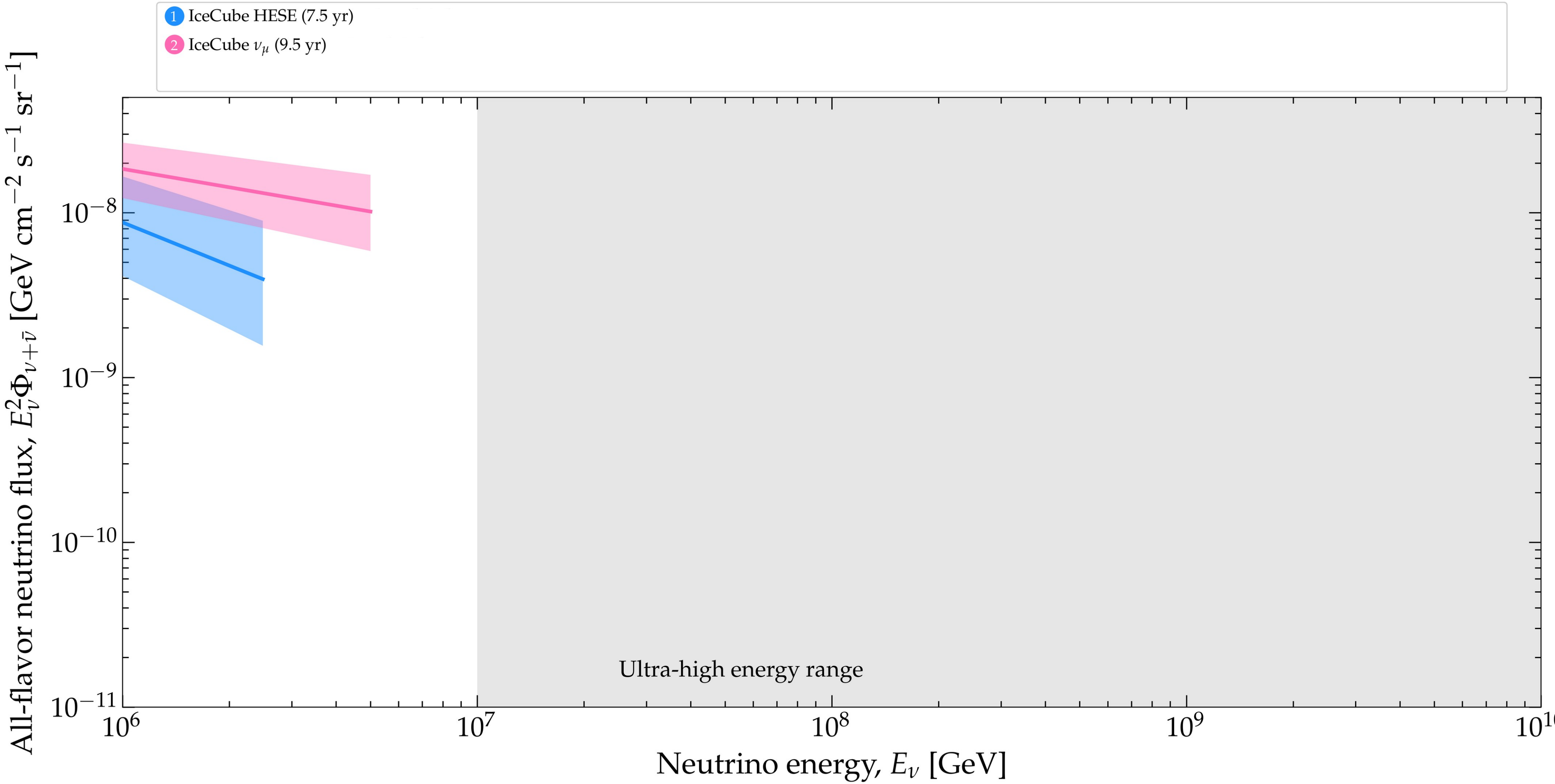
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]
?



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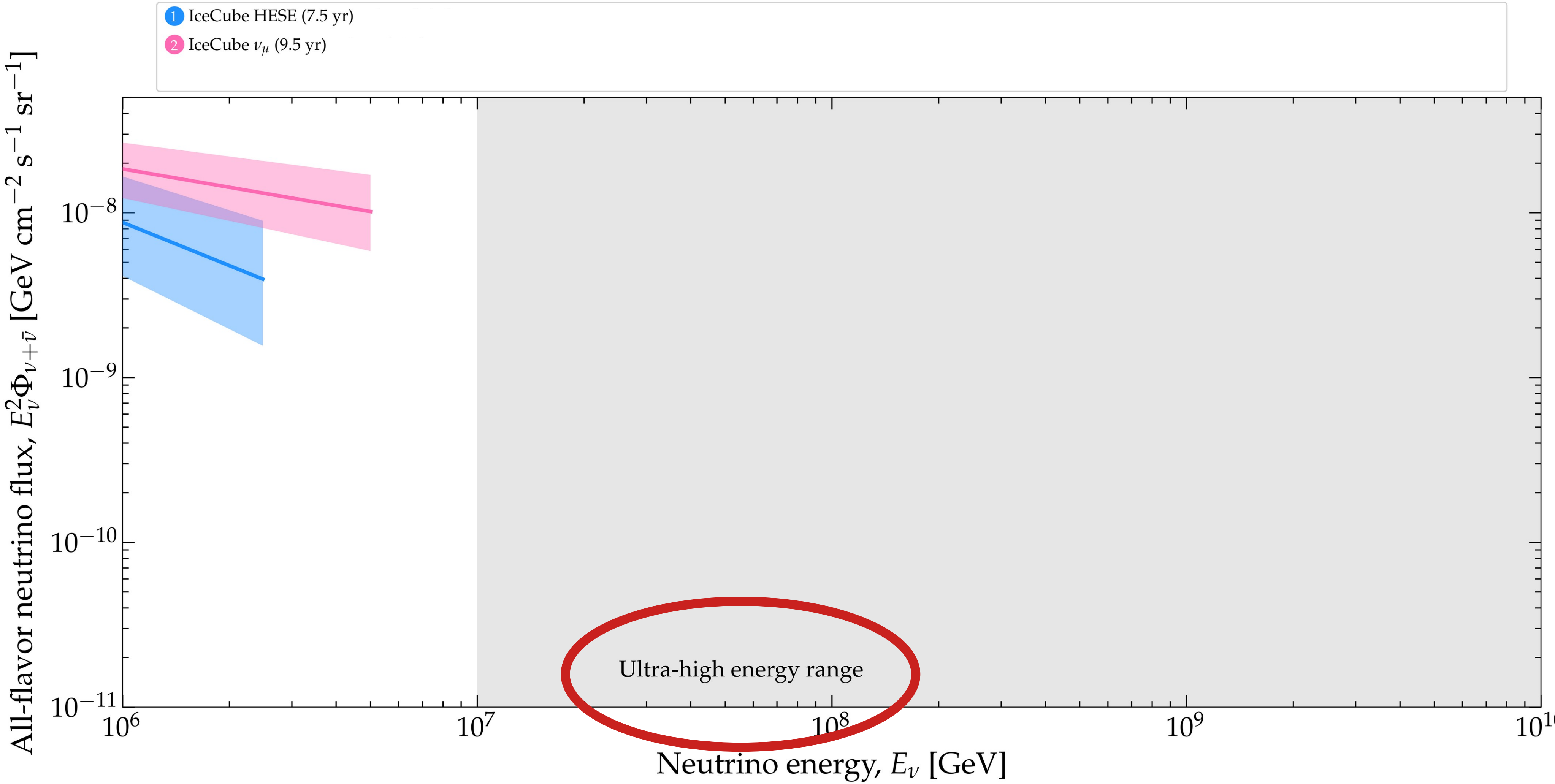
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Ultra-high energy range
Neutrino energy, E_ν [GeV]



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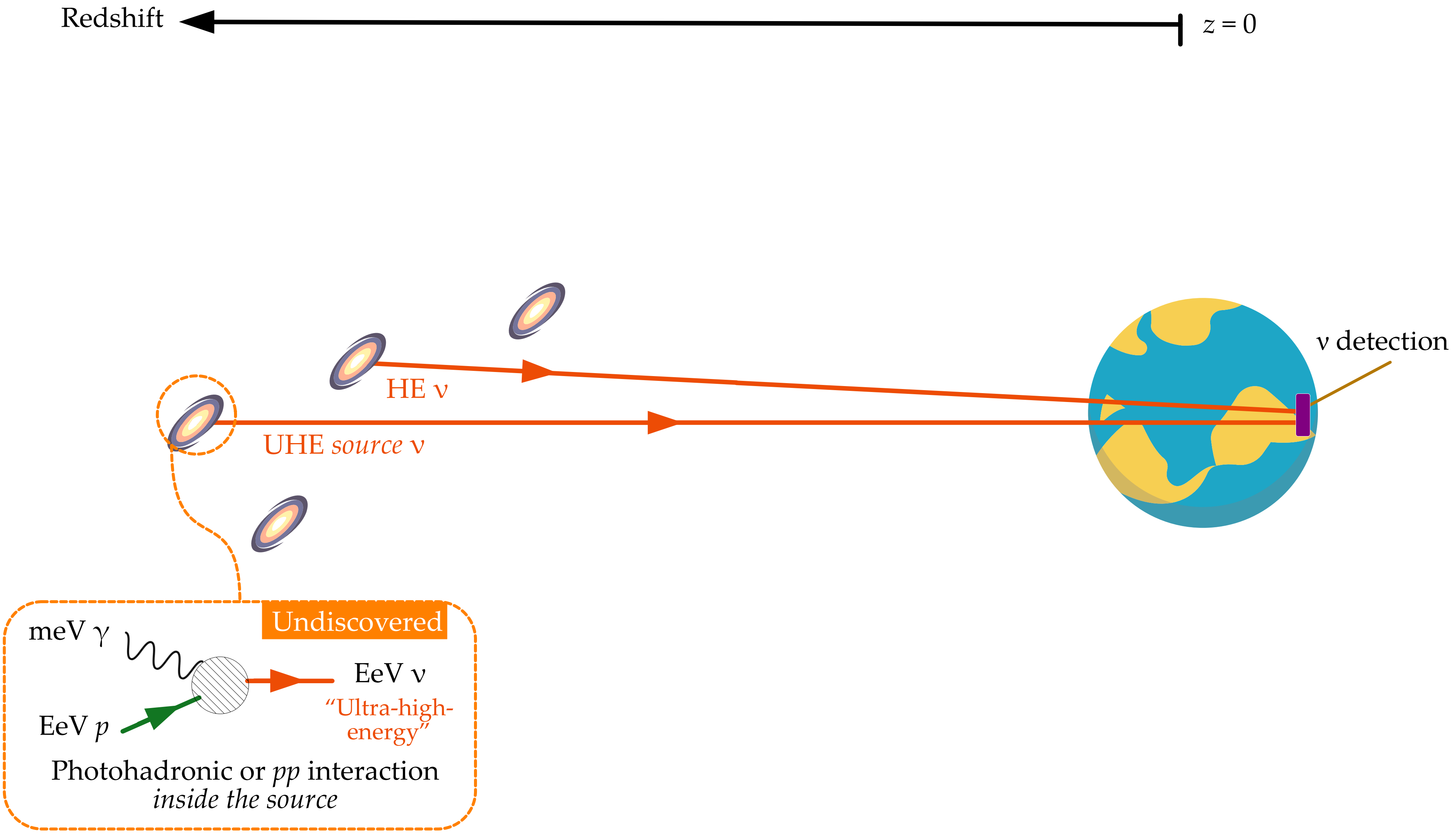
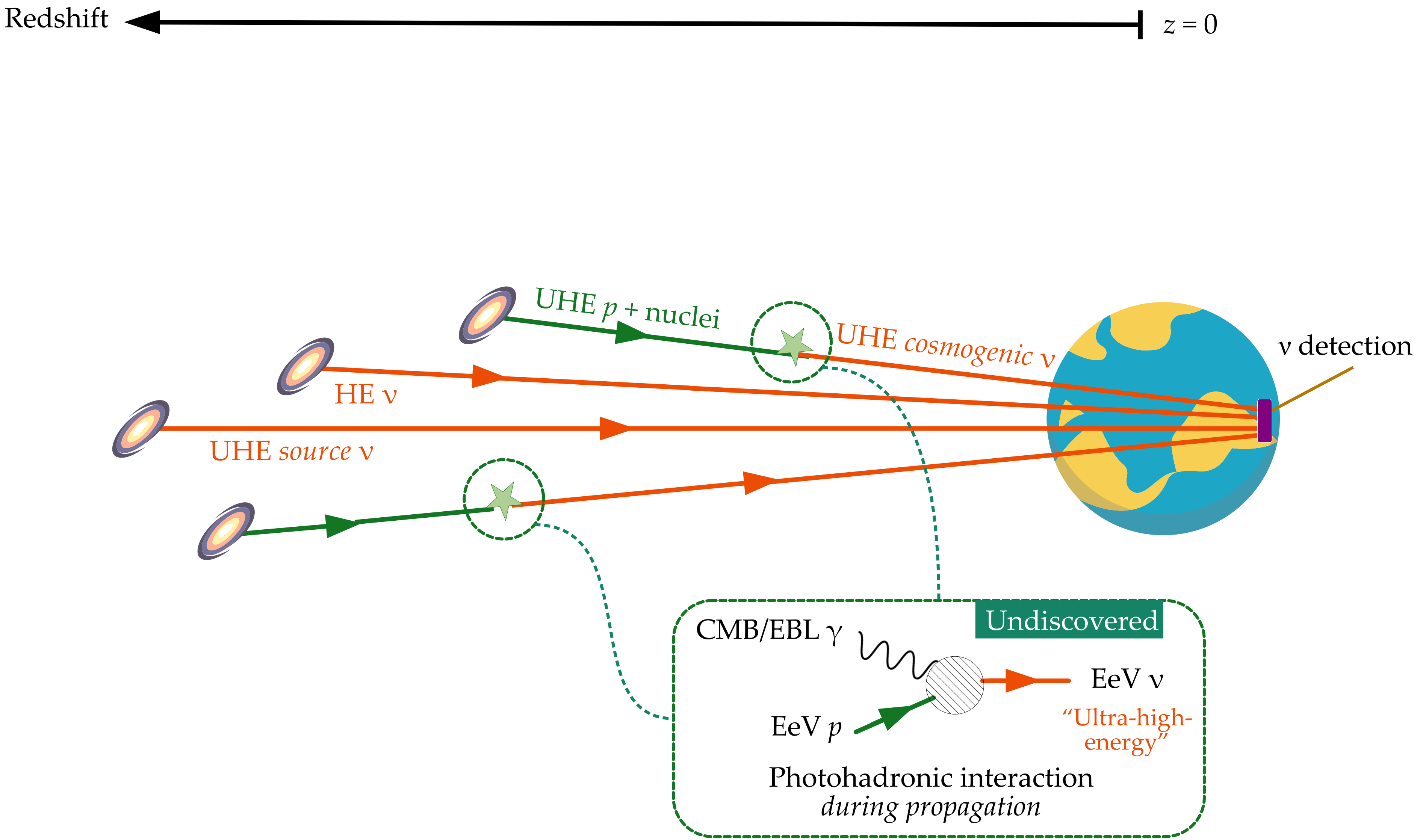
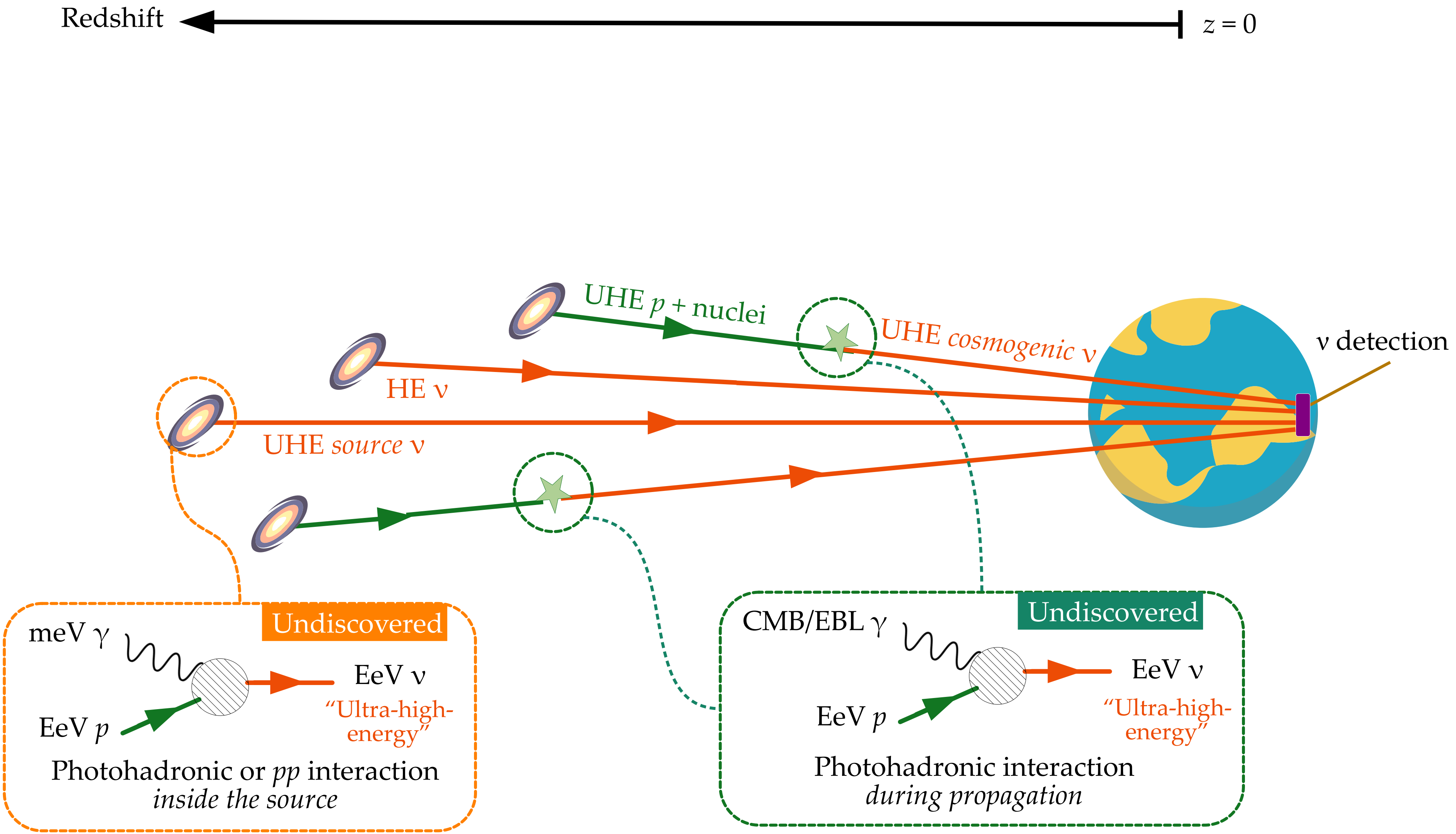
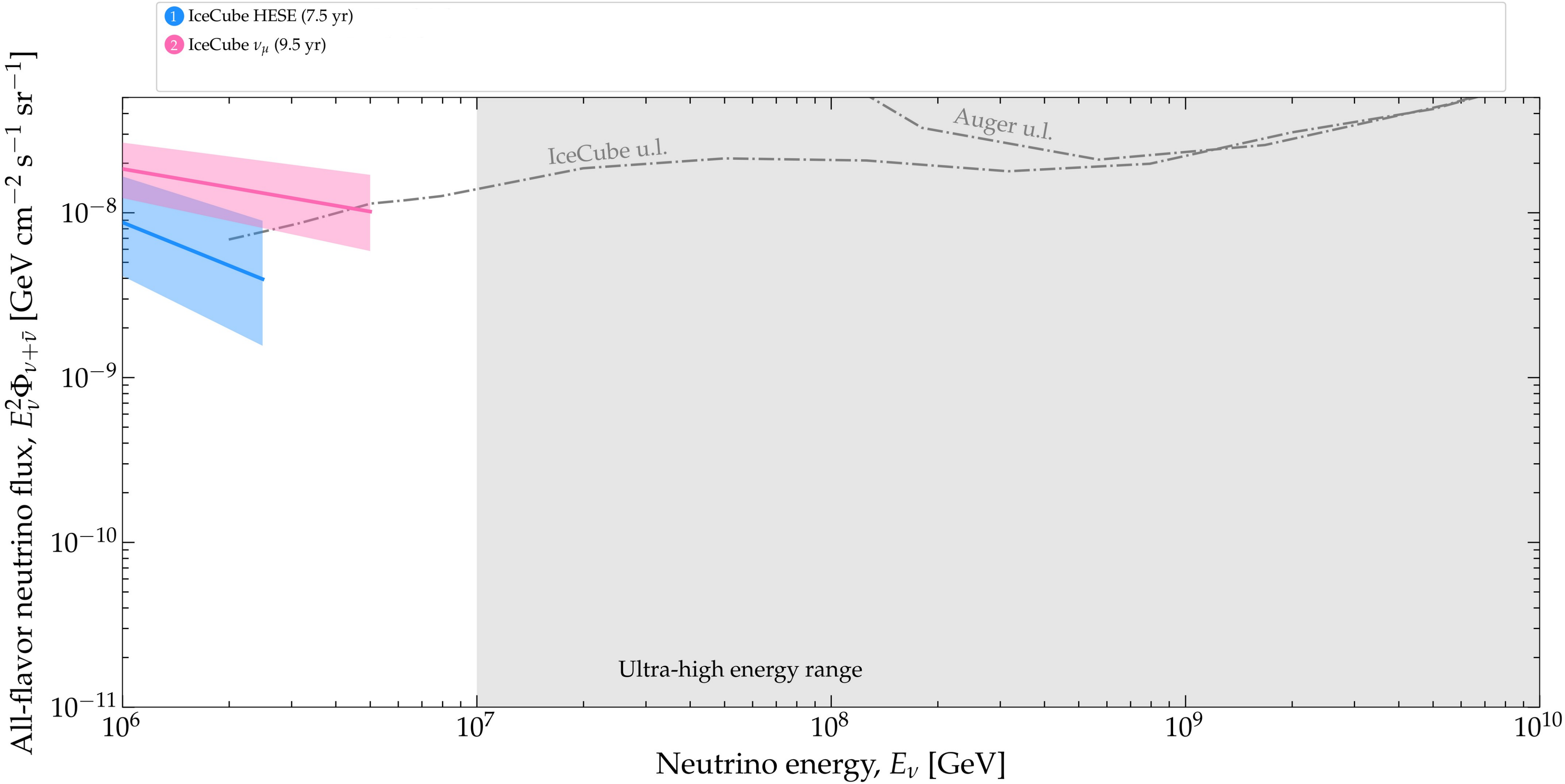
Ultra-high energy range
Neutrino energy, E_ν [GeV]


Redshift
$z = 0$
ν detection
HE ν
UHE *source* ν
Undiscovered
meV γ
EeV ν
EeV *p*
"Ultra-high-energy"
Photohadronic or *pp* interaction
inside the source


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



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



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

Article

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

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

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

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But is it due to a neutrino?

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

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

(Assuming E^{-2} spectrum)

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RECORD BREAKER

Where did it come from?

From the Southern Hemisphere
(RA = 94.3°, dec = -7.8°)

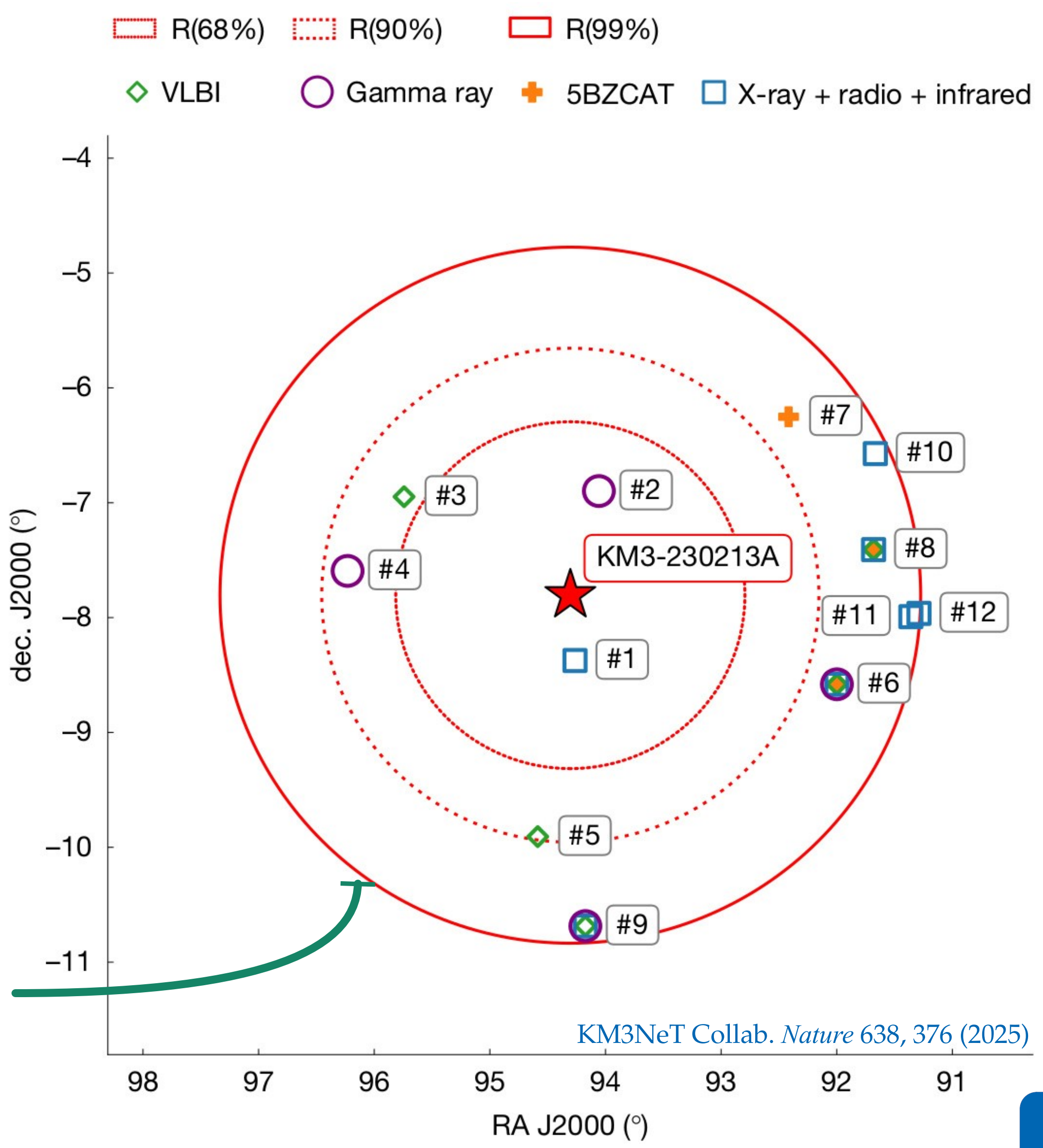
Not far from Milky Way plane
But likely not of Milky-Way origin

KM3NeT Collab. arXiv:2502.08387

Likely extragalactic origin

Few extragalactic sources (blazars) near event position, but no strong association

KM3NeT Collab. arXiv:2502.08484



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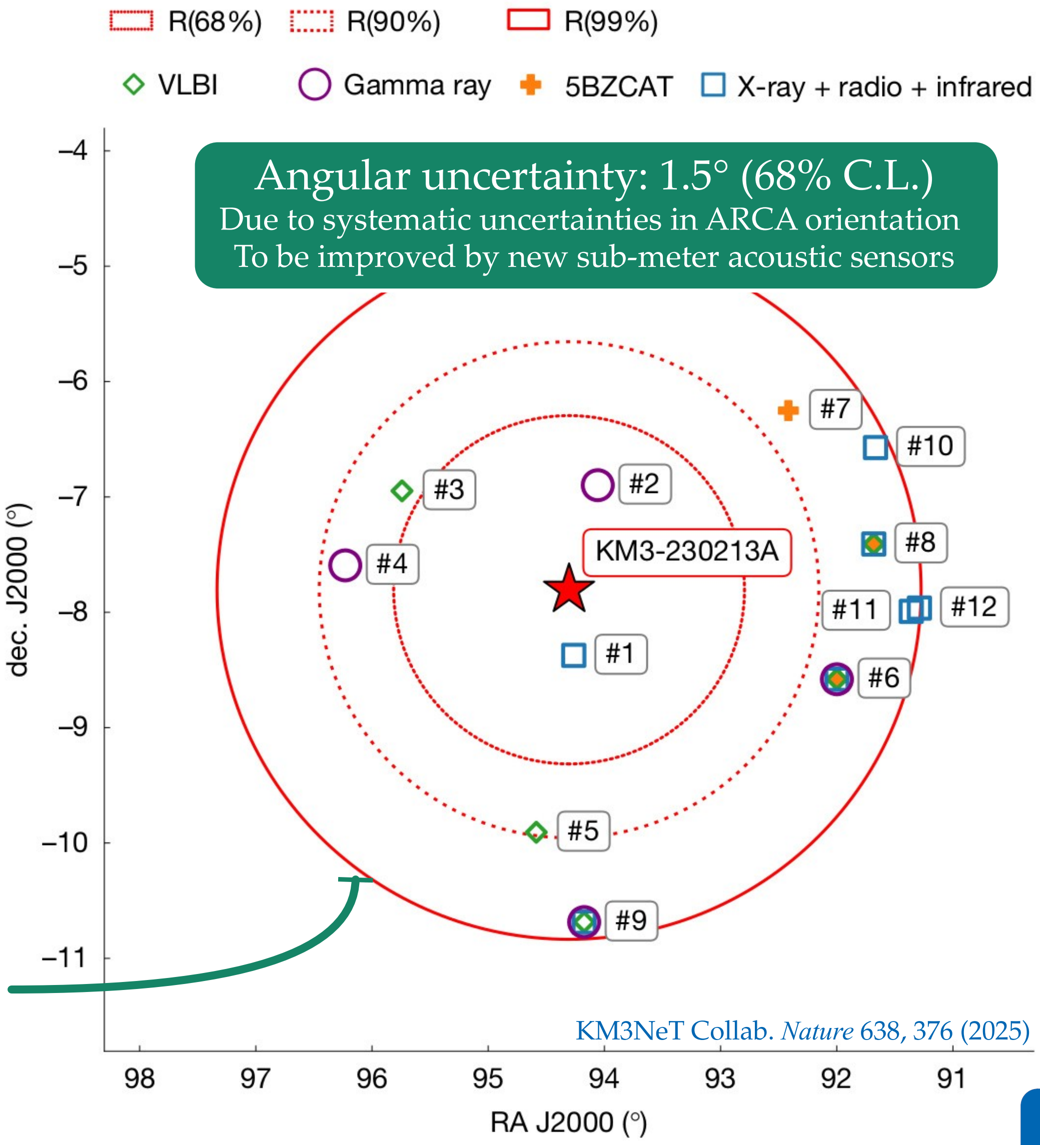
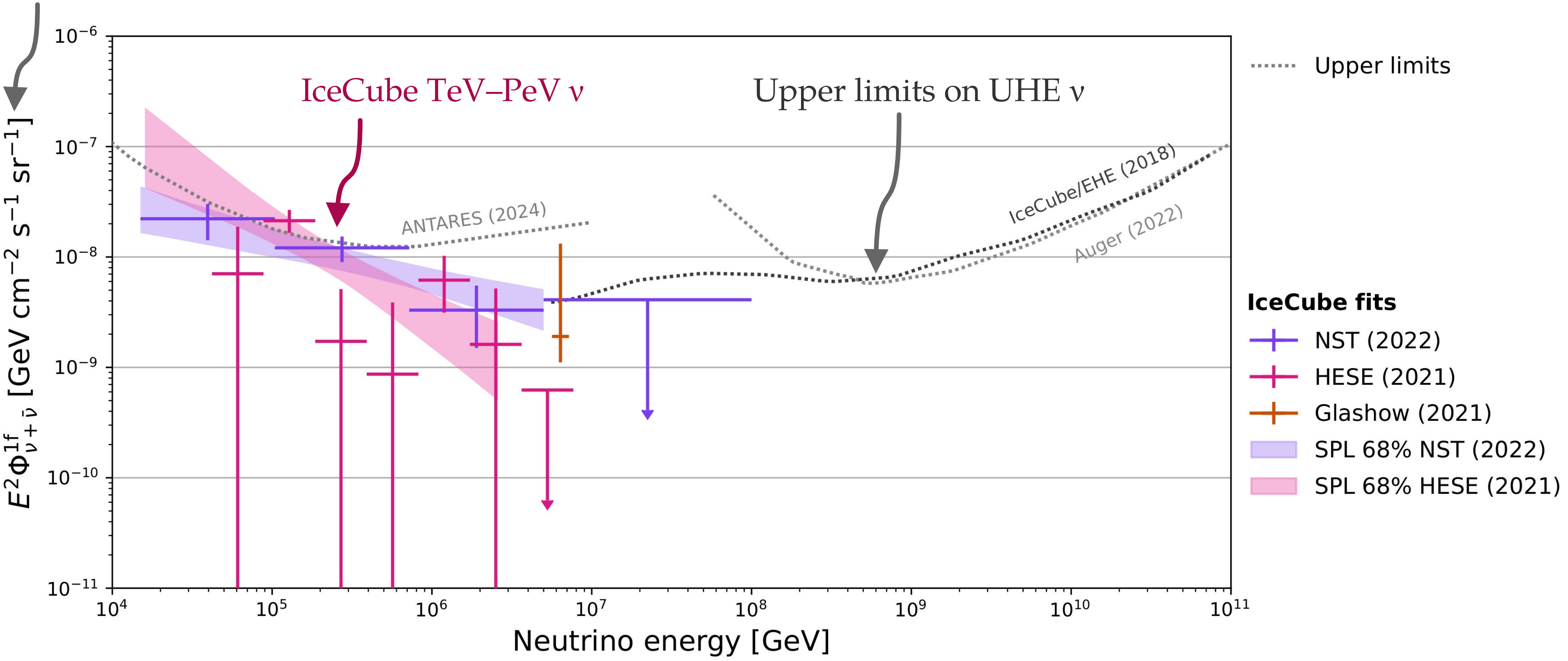


KM3NeT Collab. *Nature* 638, 376 (2025)

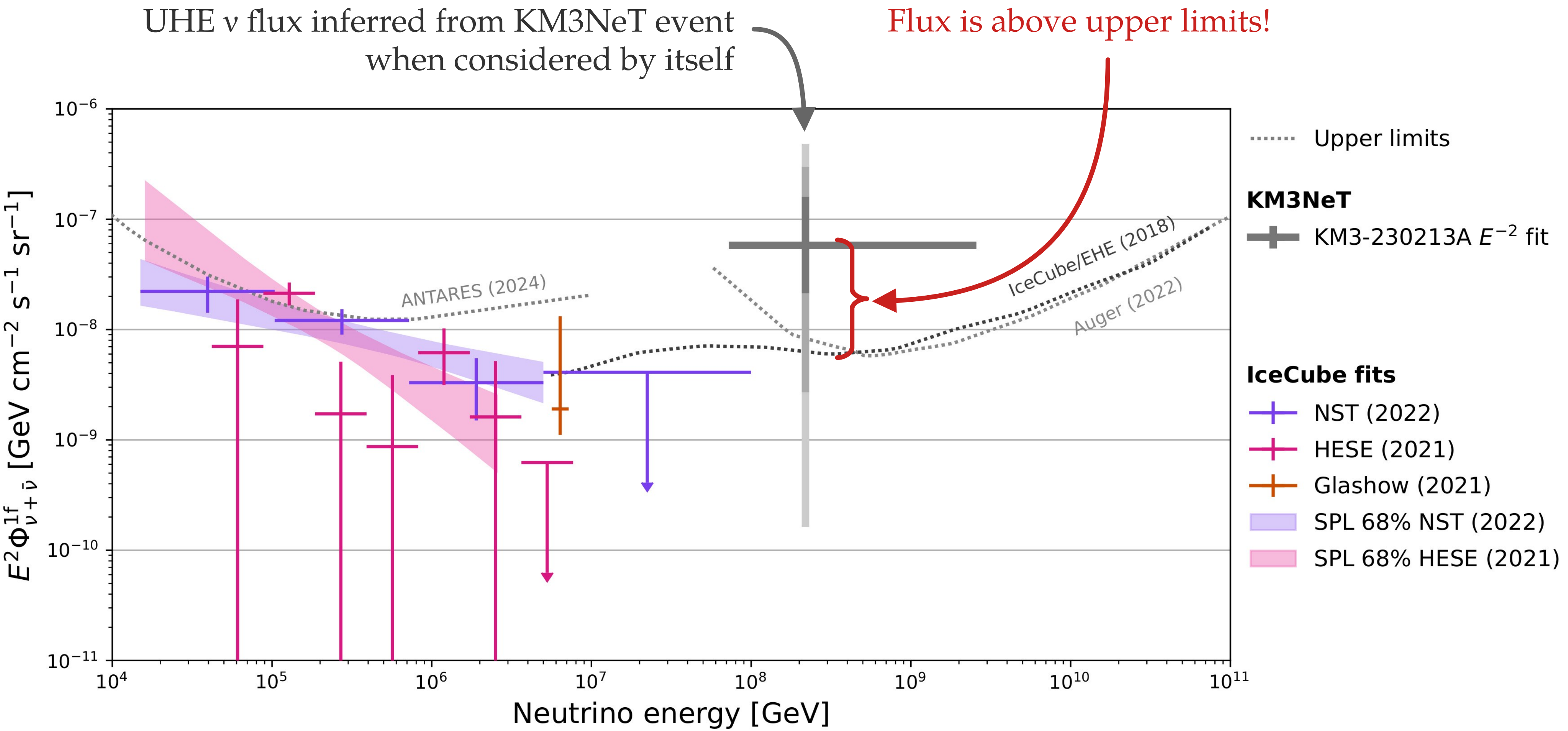
KM3NeT *vs.* IceCube & Auger

Diffuse flux of high-energy astrophysical ν



KM3NeT Collab., arXiv:2502.08173 (adapted)
KM3NeT Collab. *Nature* 638, 376 (2025)

KM3NeT *vs.* IceCube & Auger



KM3NeT Collab., arXiv:2502.08173 (adapted)
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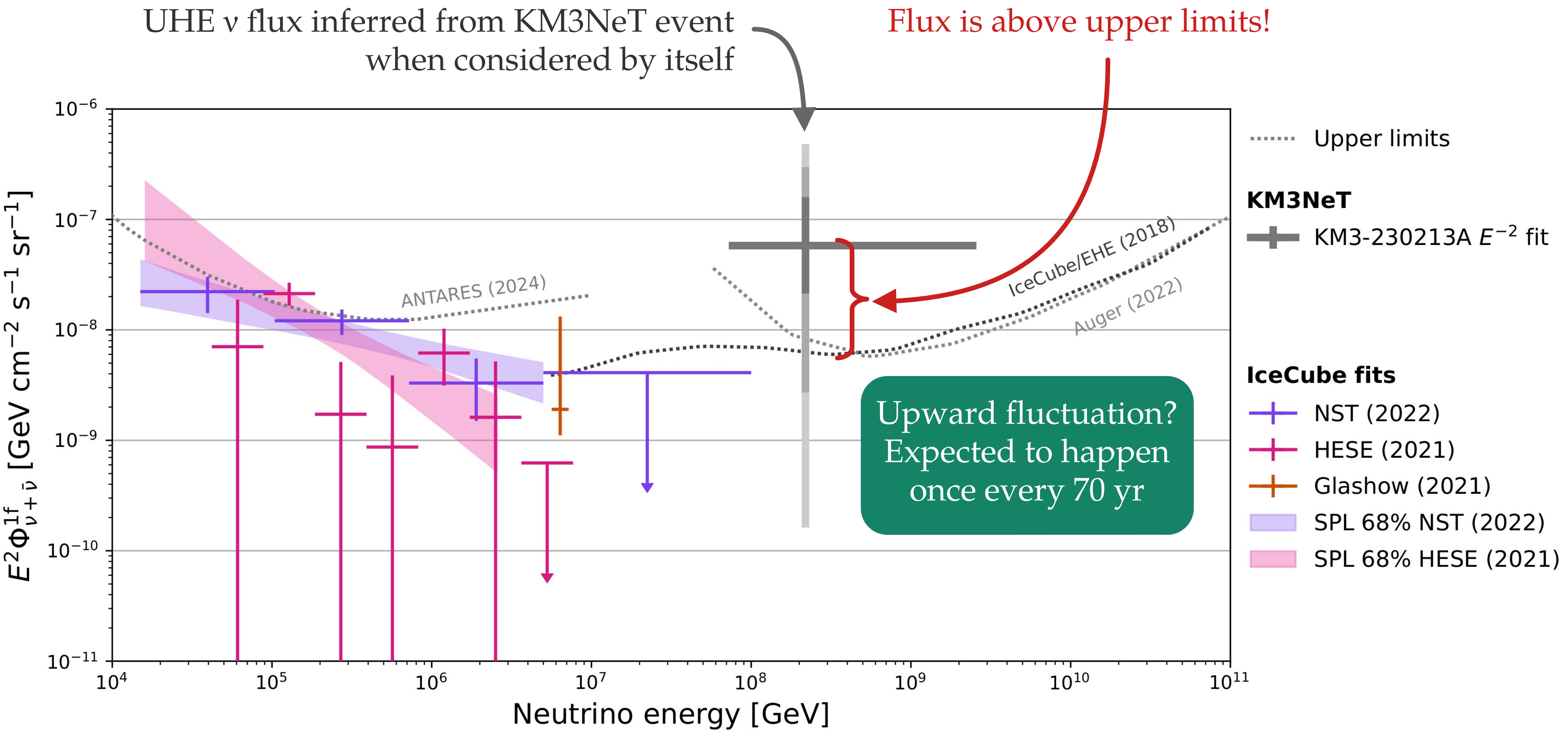
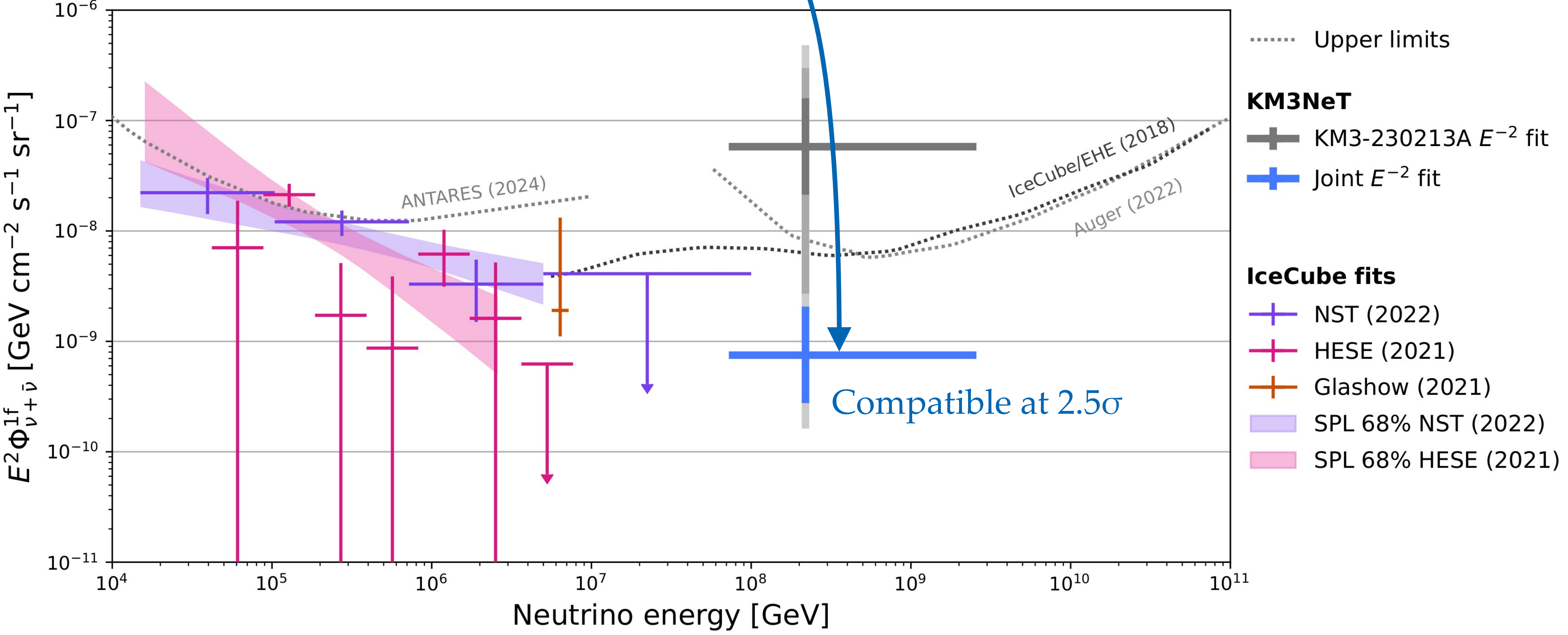


KM3NeT Collab., arXiv:2502.08173 (adapted)
KM3NeT Collab. *Nature* 638, 376 (2025)

KM3NeT *vs.* IceCube & Auger

UHE ν flux inferred when considering
non-observation by IceCube & Auger

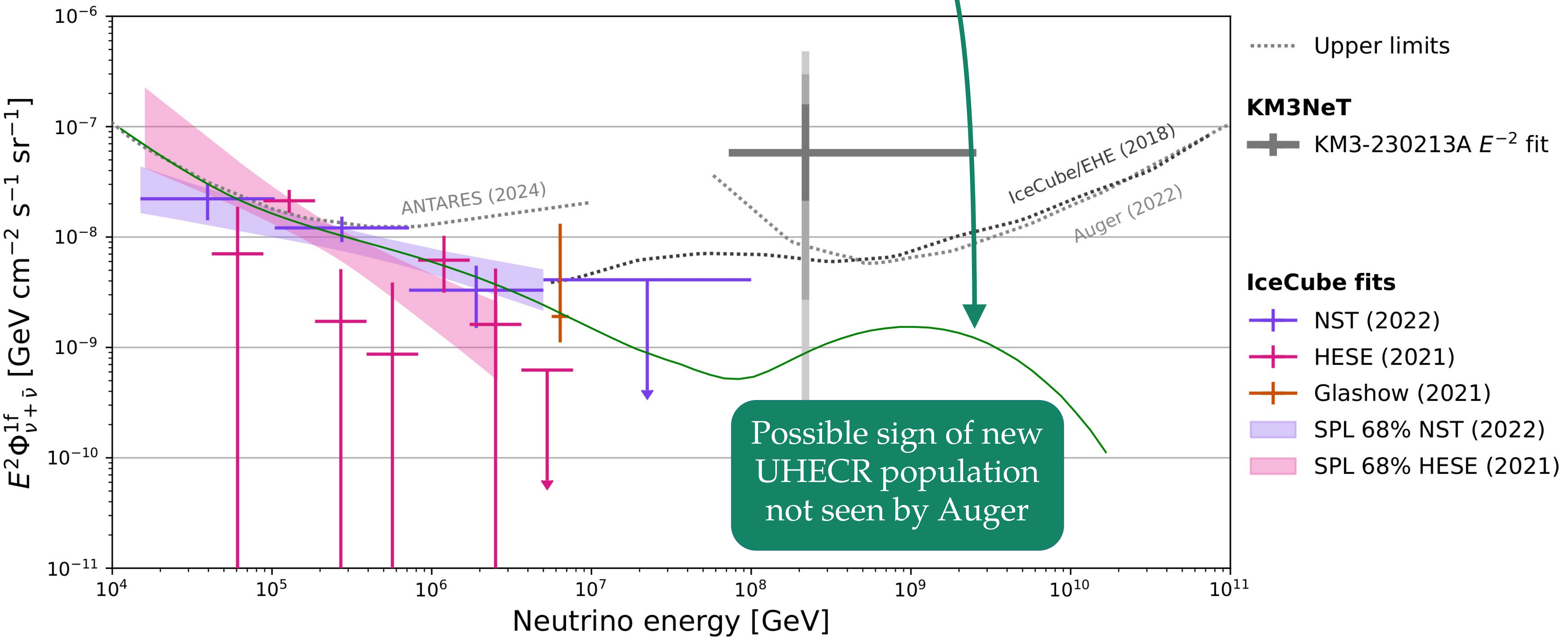


KM3NeT Collab. *Nature* 638, 376 (2025)

Joint neutrino + cosmic-ray interpretation

Muzio, Yuan, Lu, arXiv:2502.06944

Joint fit to IceCube and KM3NeT ν data + Auger UHECR data
(Assuming 100 PeV for KM3-230213A)



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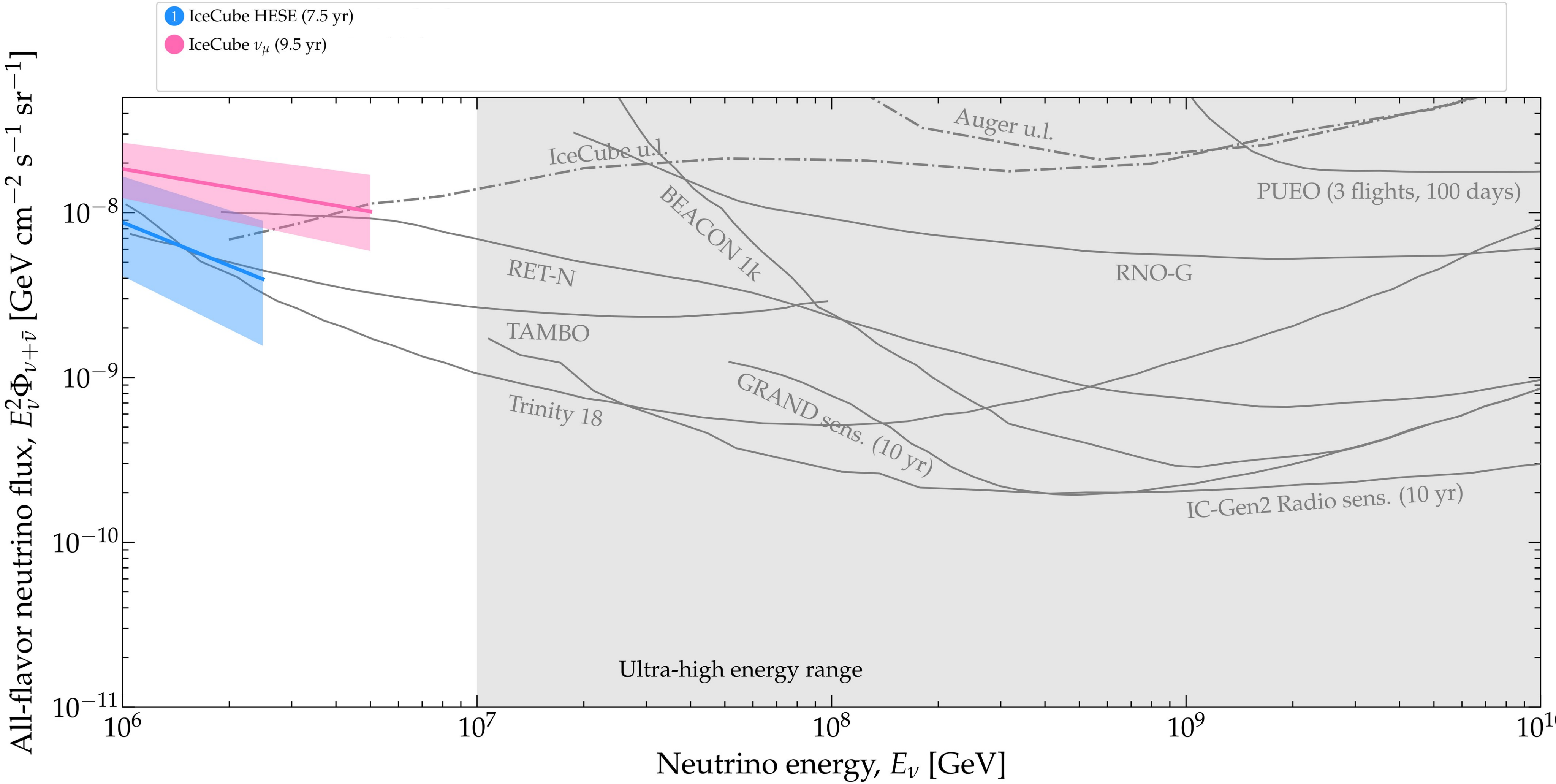
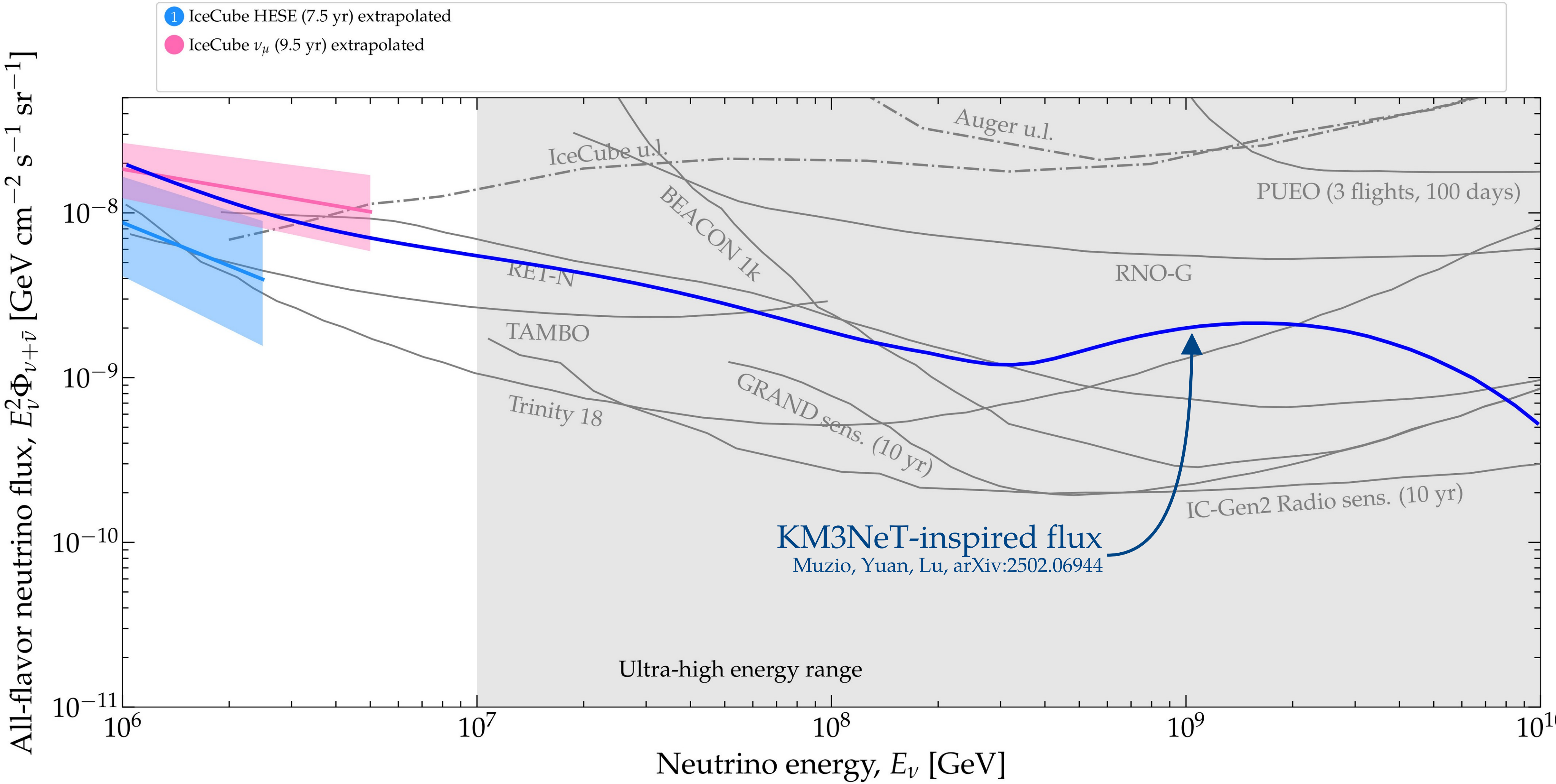


V. Valera, **MB**, C. Glaser, *PRD* 2023 [2210.03756]



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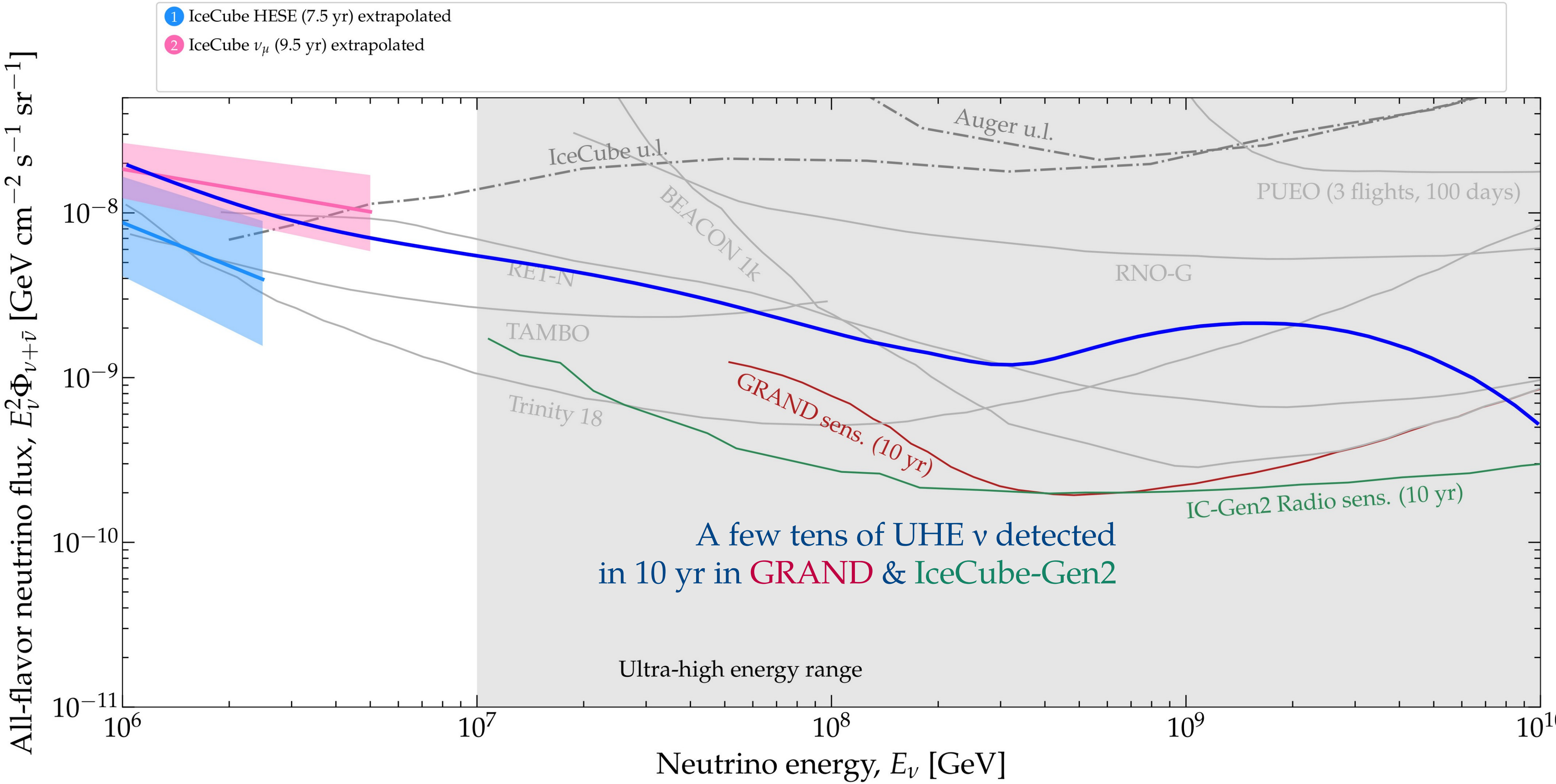

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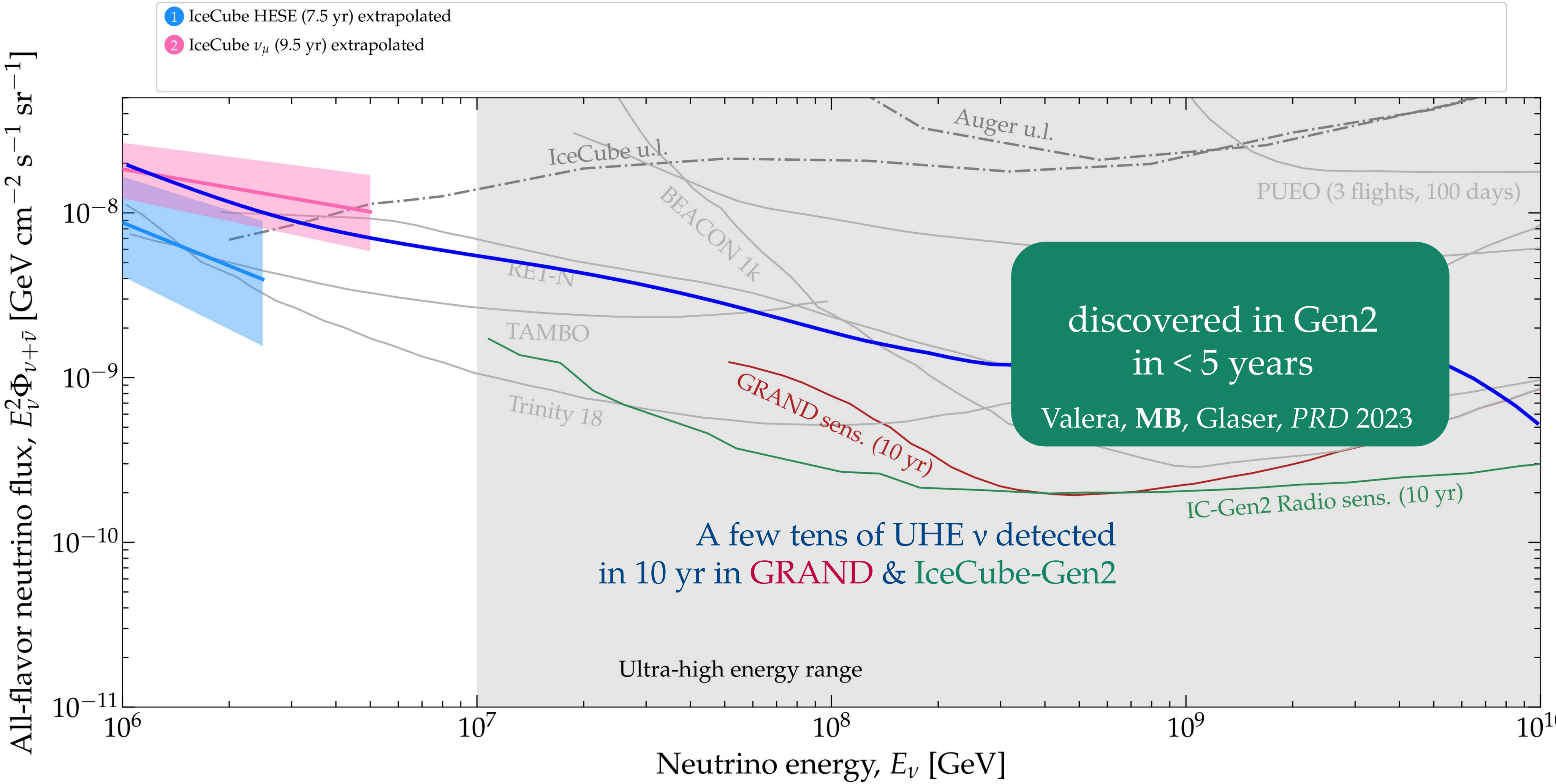

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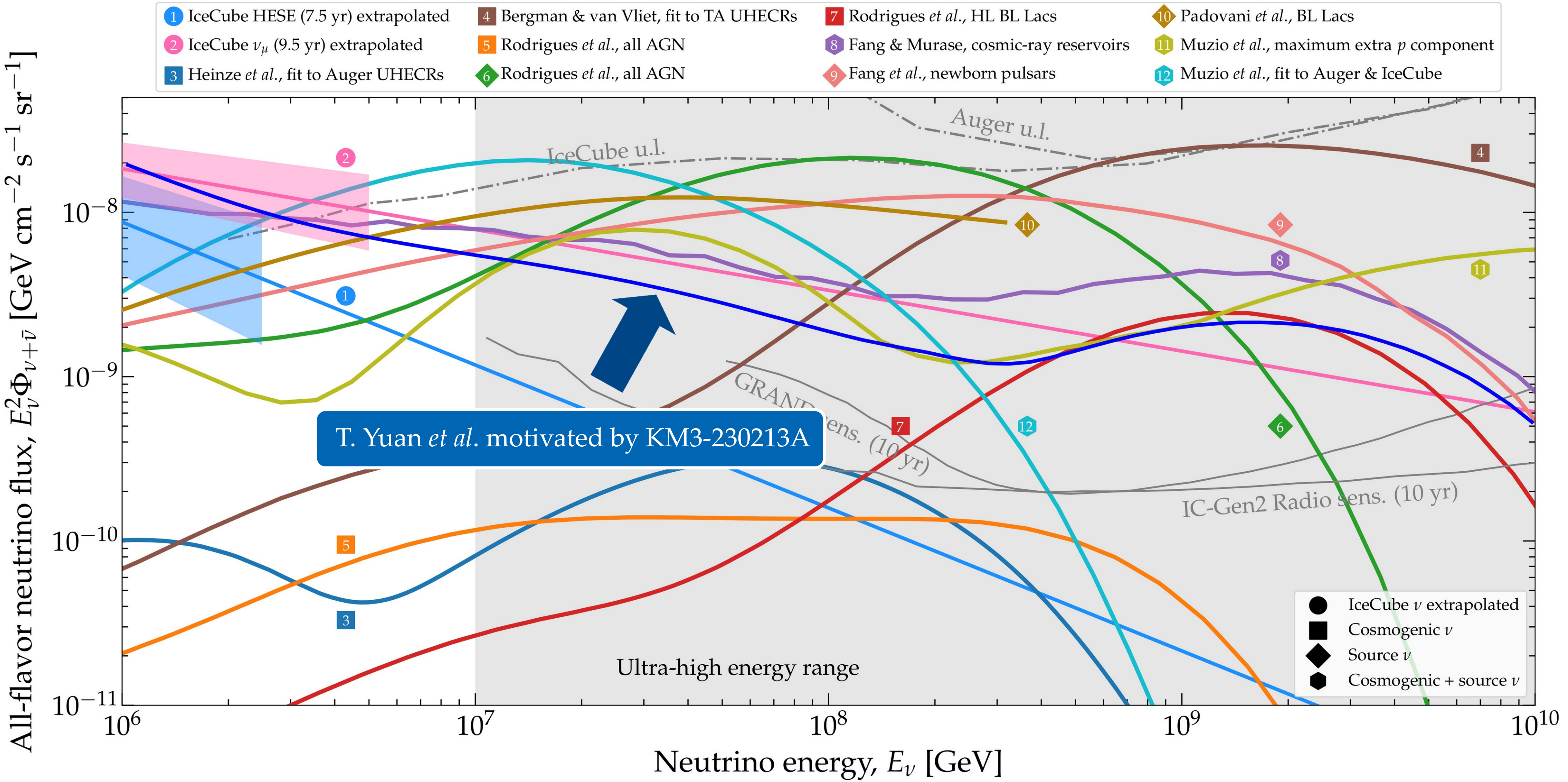

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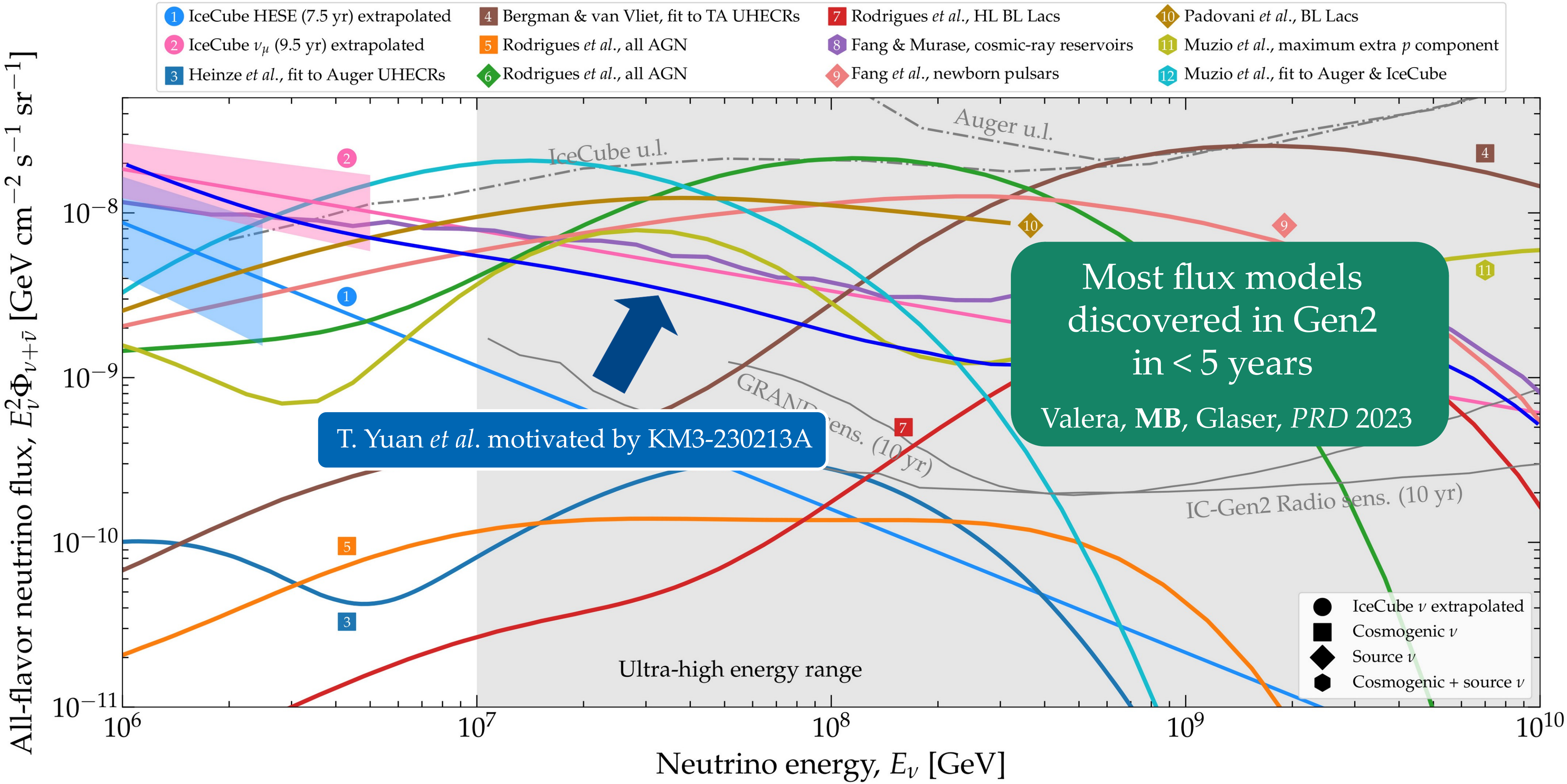

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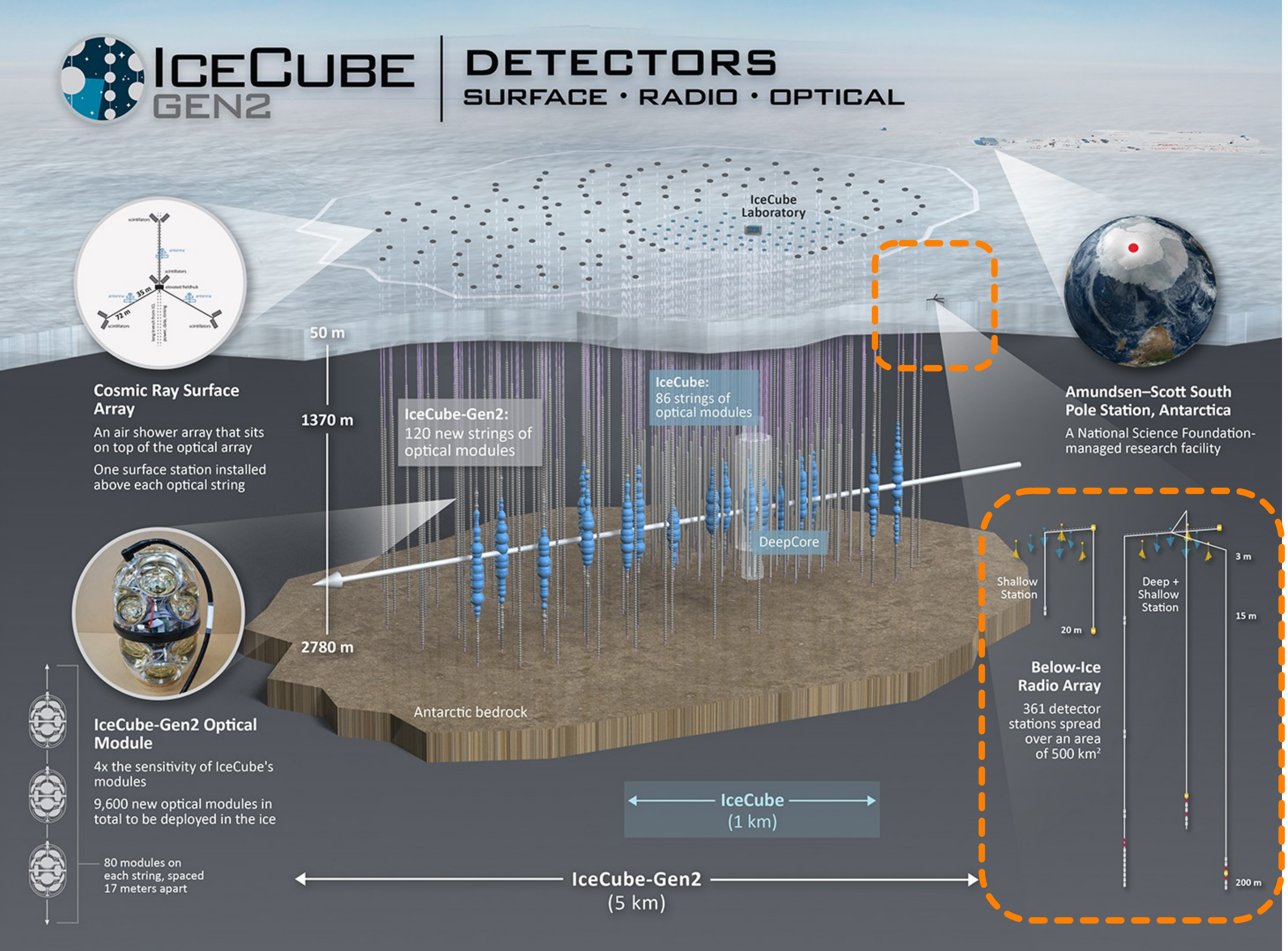
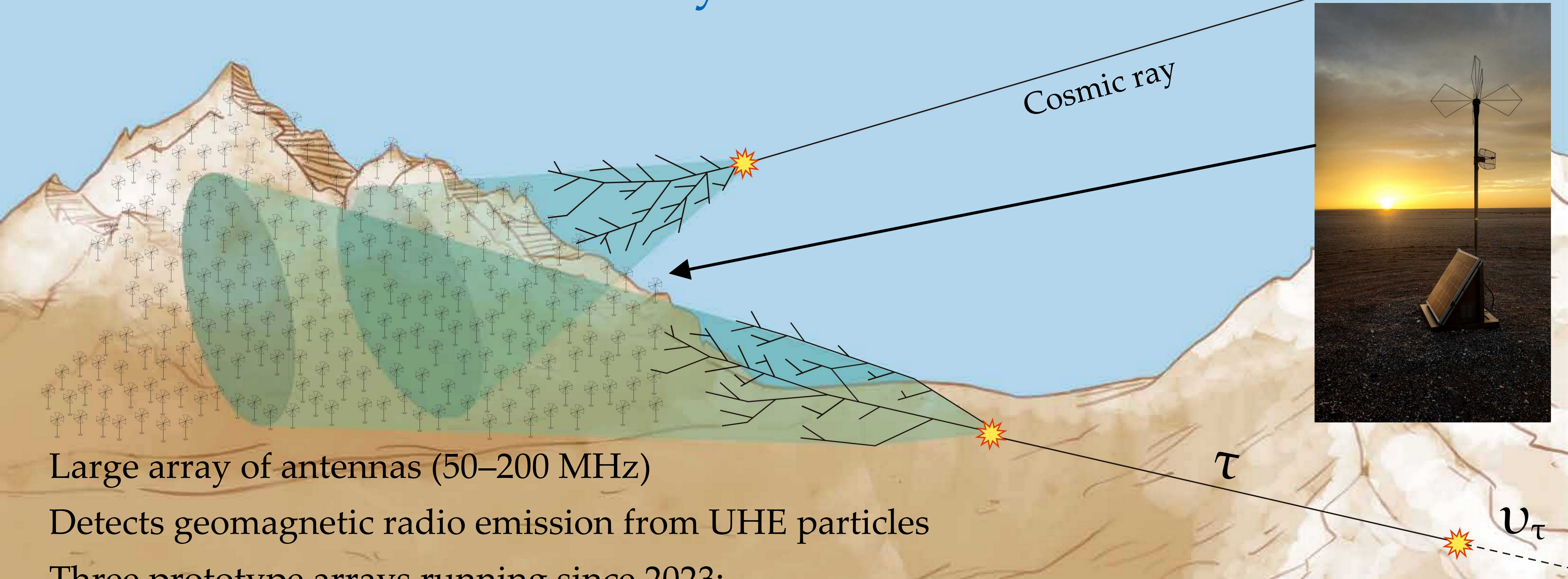


High-energy IceCube successor

Radio array:
> 100 PeV ν
Askaryan radiation
~310 stations
~500 km^2

~100× rate of EeV ν *vs.* IceCube

GRAND: Giant Radio Array for Neutrino Detection



Large array of antennas (50–200 MHz)

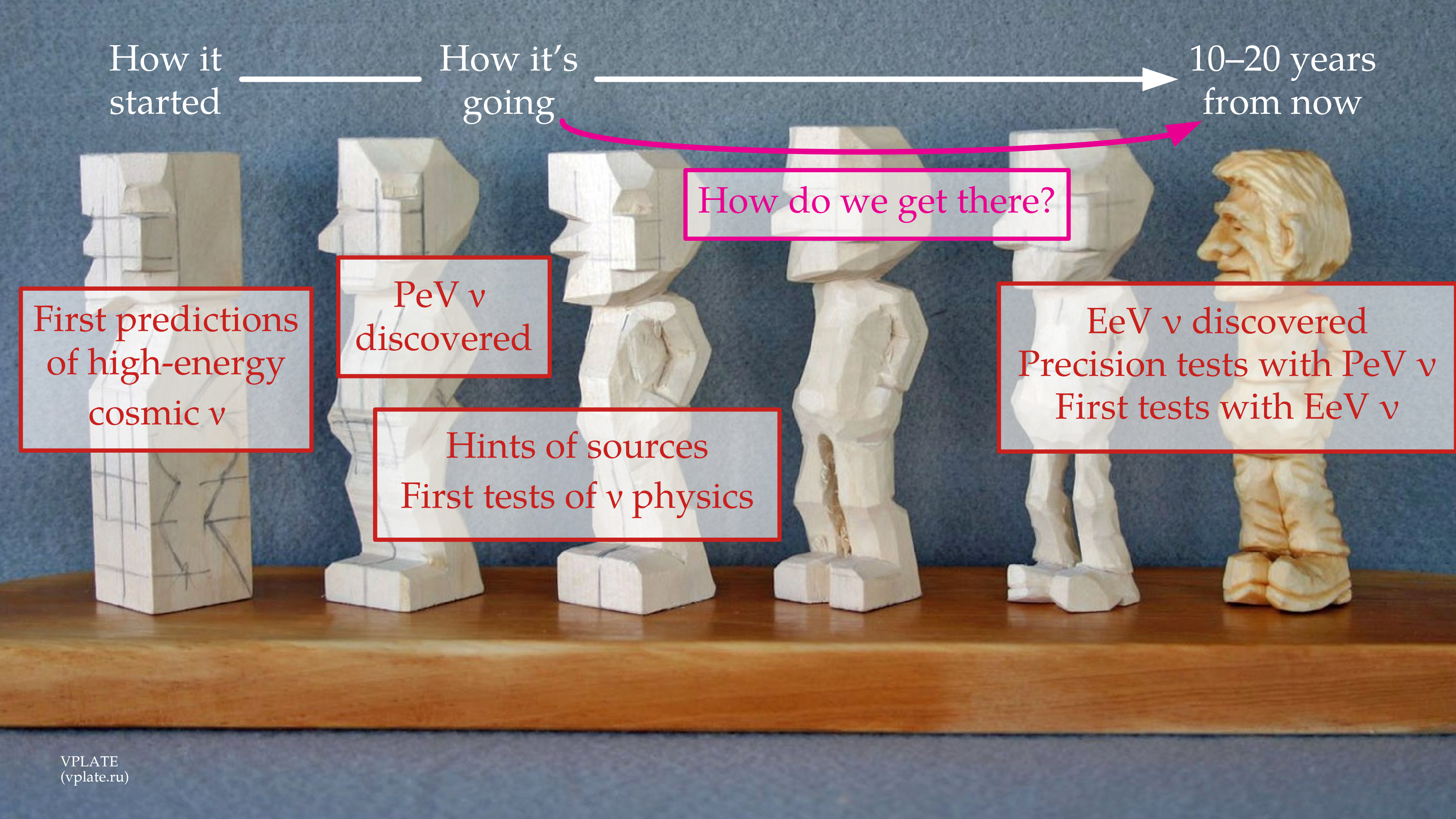
Detects geomagnetic radio emission from UHE particles

Three prototype arrays running since 2023:

GRANDProto300	GRAND@Auger	GRAND@Nançay
65 antennas, China	10 antennas, Argentina	5 antennas, France

First cosmic-ray candidates shown at ICRC 2025

GRAND talks:
Sei Kato, Thu 16:00
Guoyuan Huan, Thu 16:00


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)

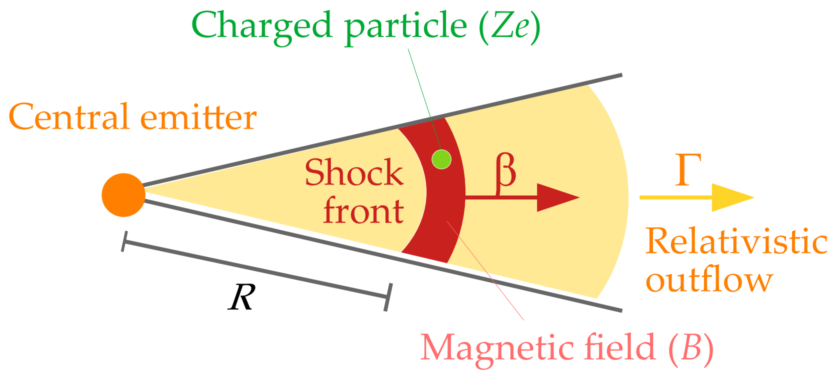
Thanks!

Backup slides

General stuff

Hillas criterion

A necessary condition to accelerate charged particles is confinement within the acceleration region.



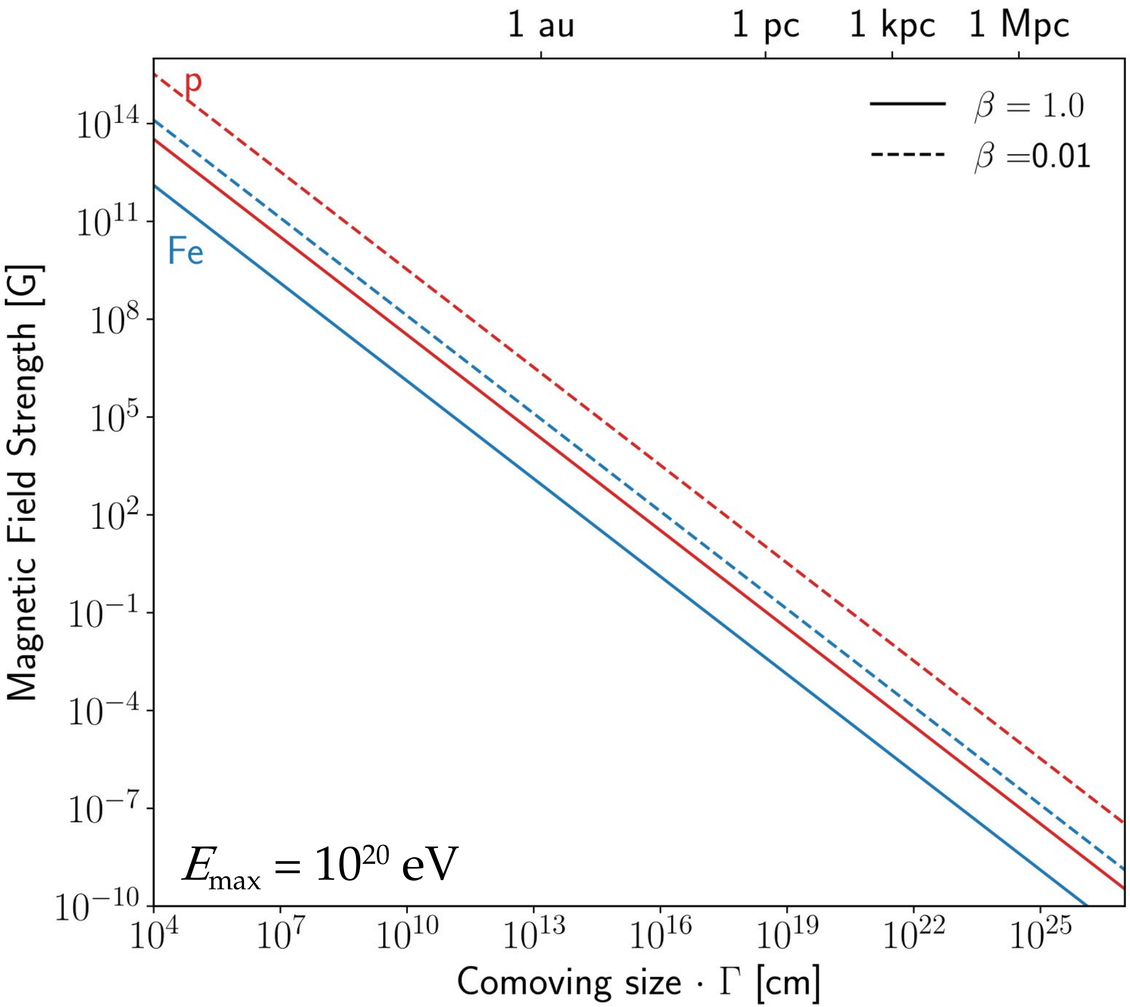
Confinement holds until

Larmor radius (R_L) = Size of region (R)

$$\frac{E_{\rm max}}{ZeB} = \beta\Gamma R$$

$$\Rightarrow E_{\rm max} = \eta^{-1}\beta\Gamma ZeBR$$

Acceleration efficiency



Hillas, *Ann. Rev. Astron. Astrophys.* 1984

Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019

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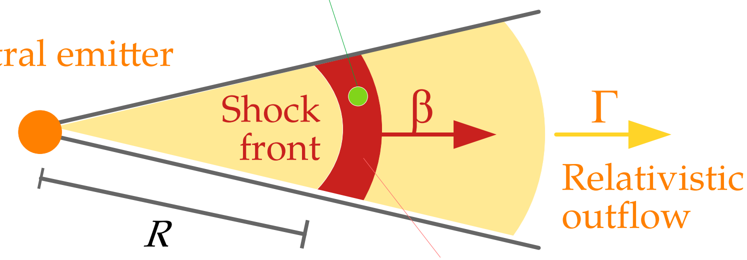

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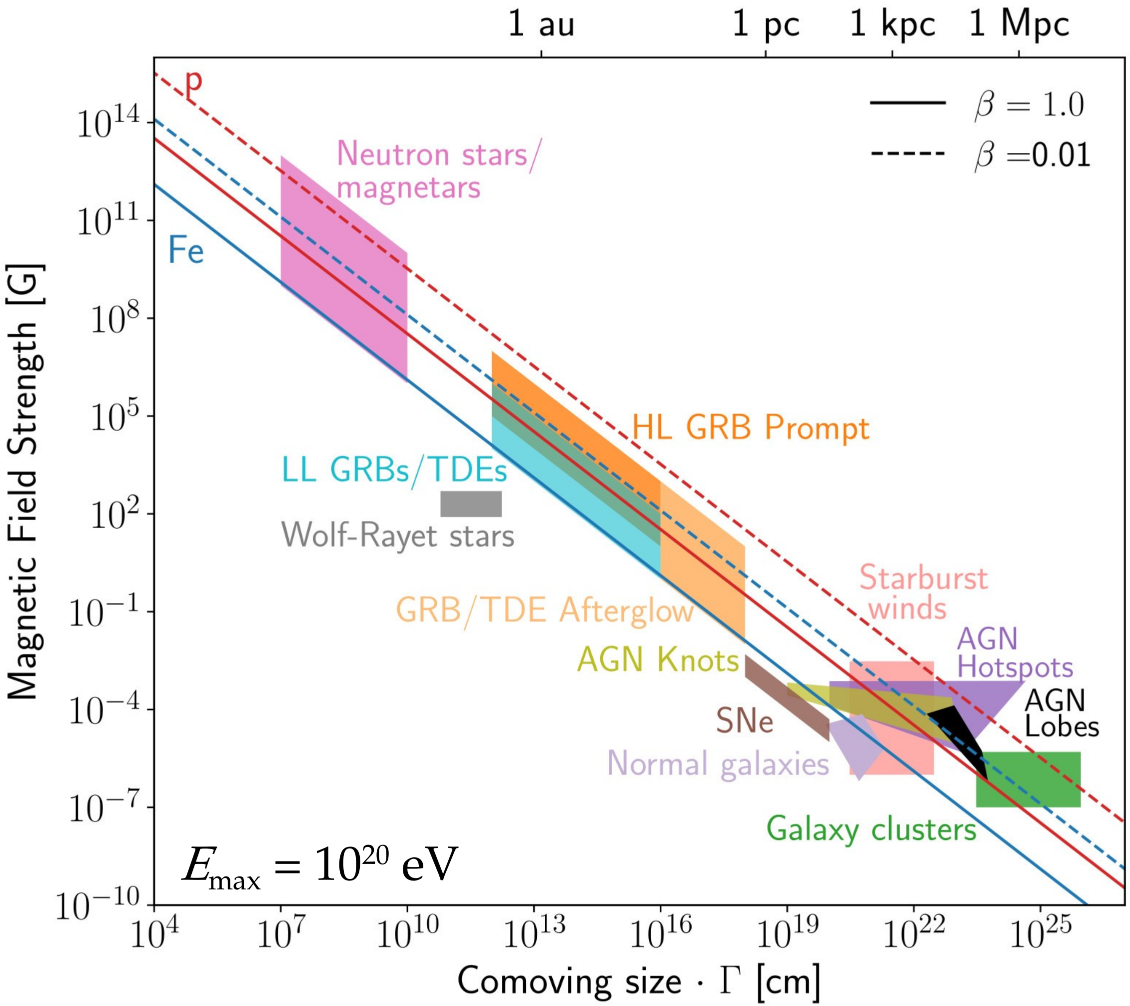


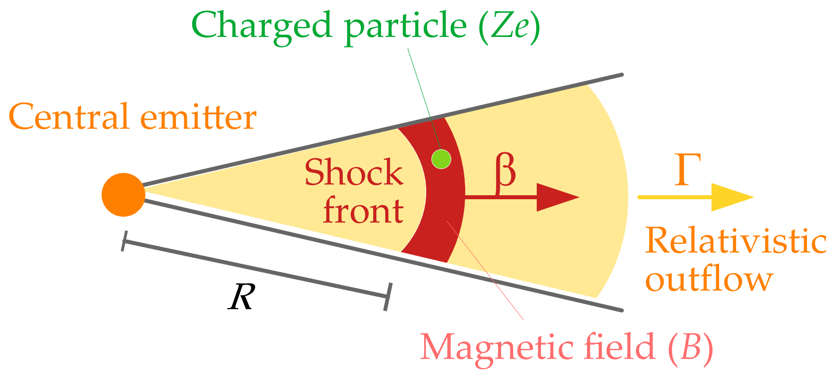
Hillas, *Ann. Rev. Astron. Astrophys.* 1984

Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019

Hillas criterion

But not sufficient!

A necessary condition to accelerate charged particles is confinement within the acceleration region



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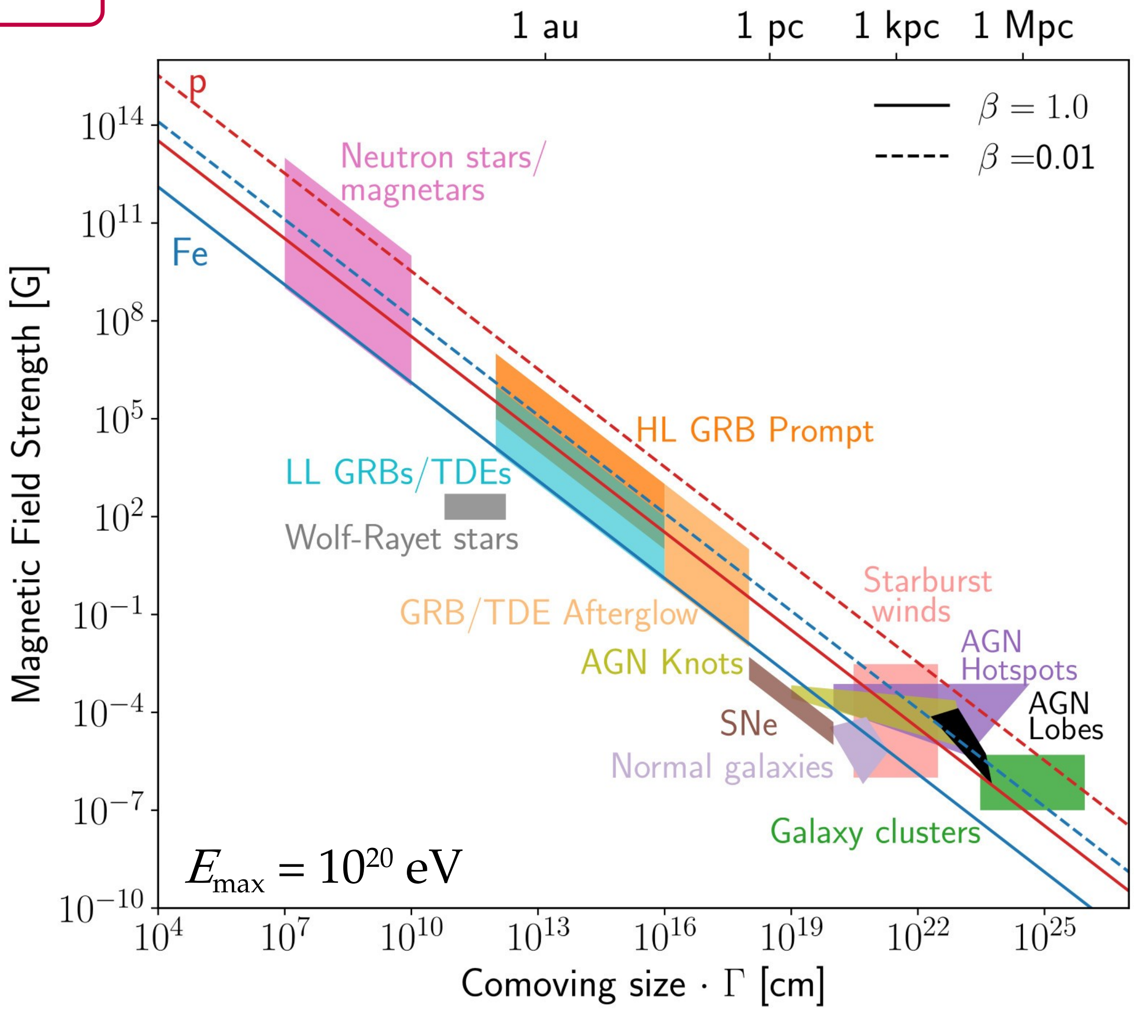
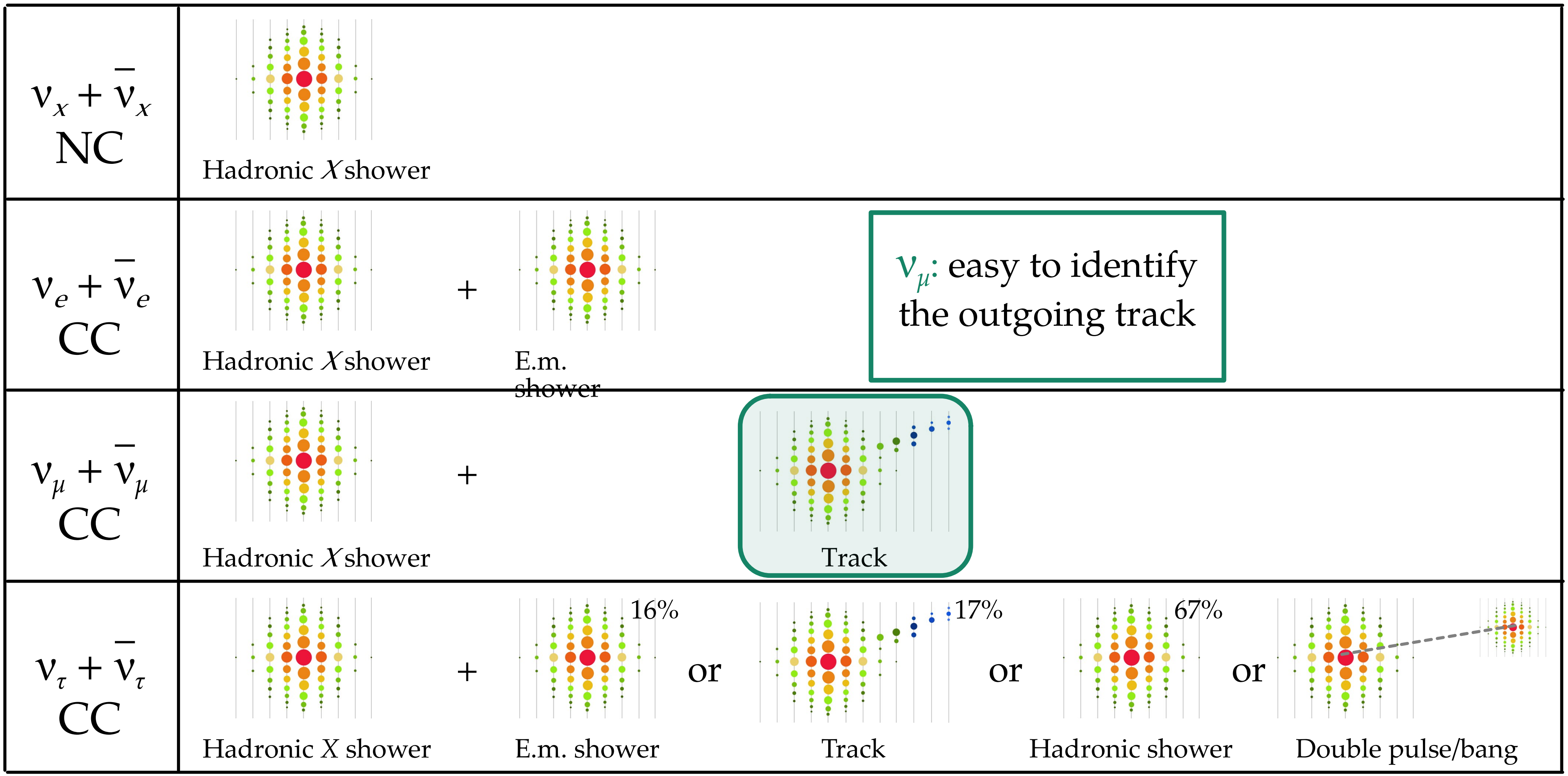
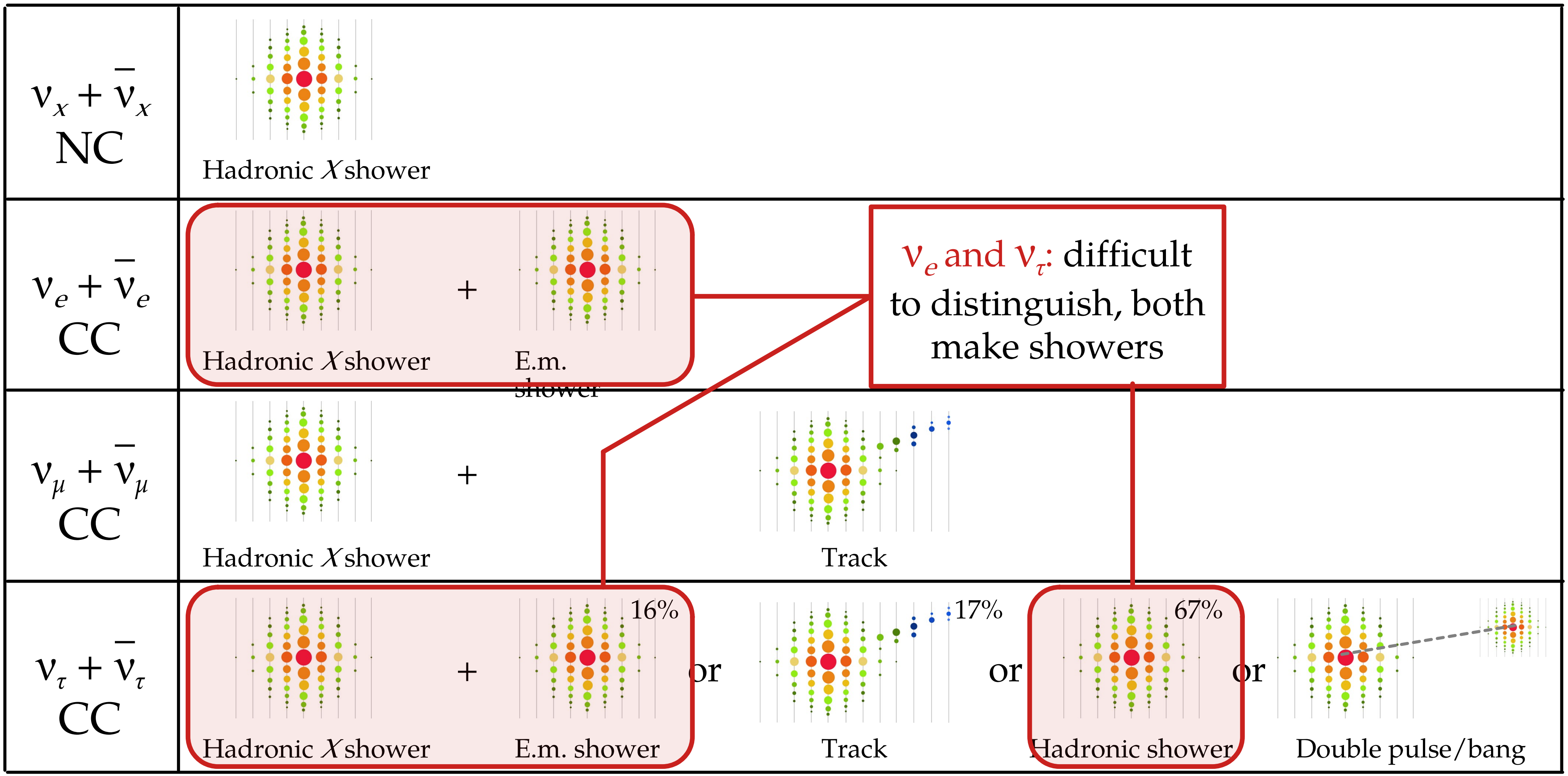


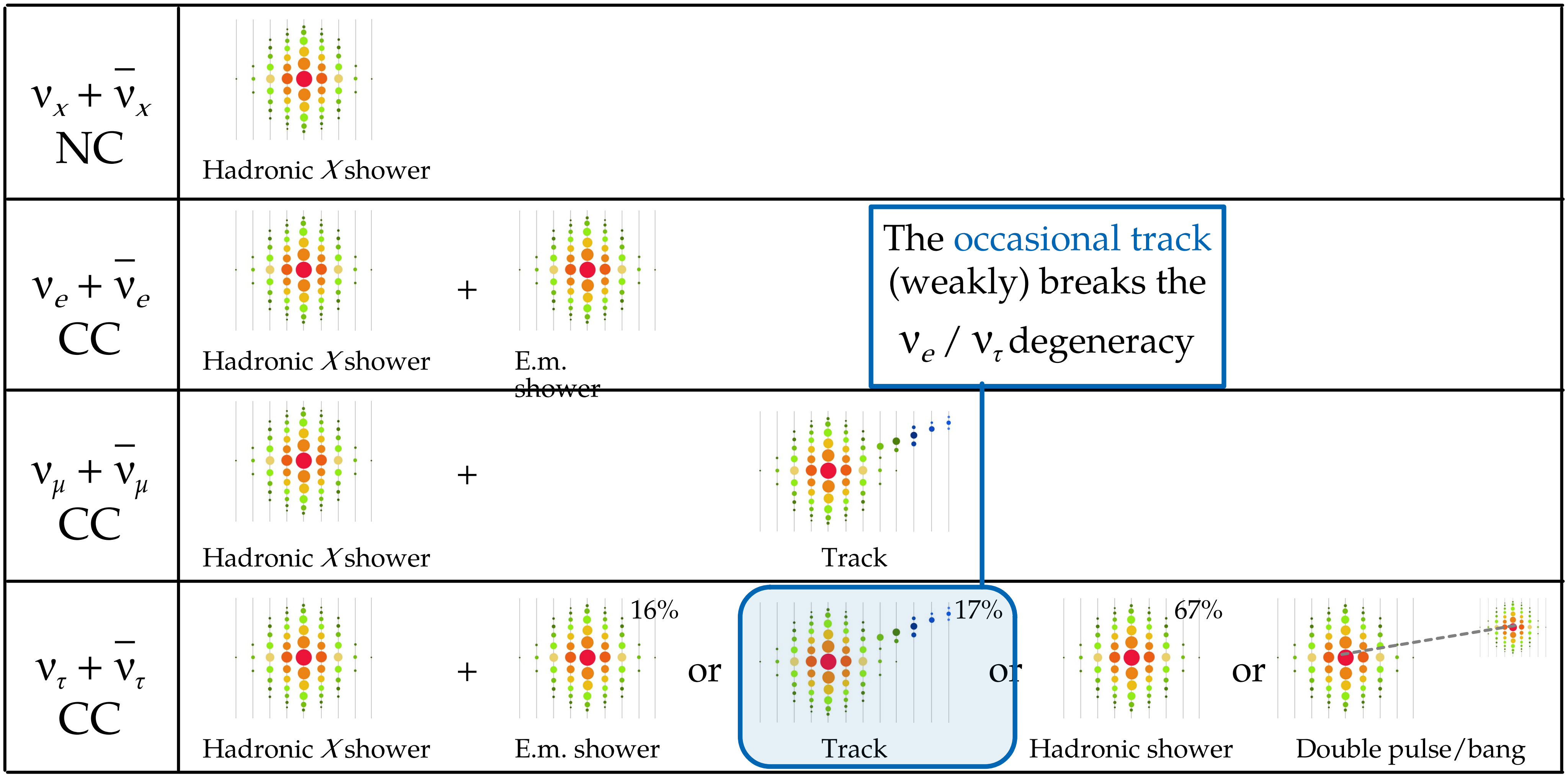
Hillas, *Ann. Rev. Astron. Astrophys.* 1984

Alves Batista *et al.* (inc. **MB**), *Front. Astron. Space Sci.* 2019


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



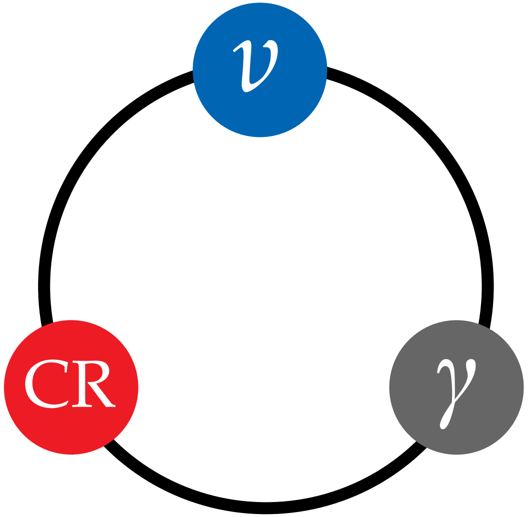
$\nu_x + \bar{\nu}_x$
NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$
CC
Hadronic X shower
+
E.m. shower
ν_e and ν_τ: difficult to distinguish, both make showers
$\nu_\mu + \bar{\nu}_\mu$
CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$
CC
Hadronic X shower
+
E.m. shower
16%
or
Track
17%
or
Hadronic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


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

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

Energy in neutrinos $\propto$ energy in gamma rays

Waxman & Bahcall, *PRL* 1997

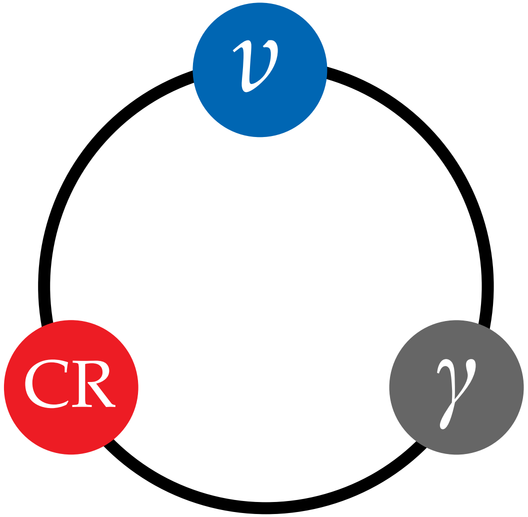


Bright in gamma rays, bright in high-energy neutrinos (?)

Energy in neutrinos $\propto$ energy in gamma rays

Waxman & Bahcall, *PRL* 1997

Fudge factors:
Source properties (*e.g.*, baryonic loading)
Particle effects (*e.g.*, ν-producing channels)

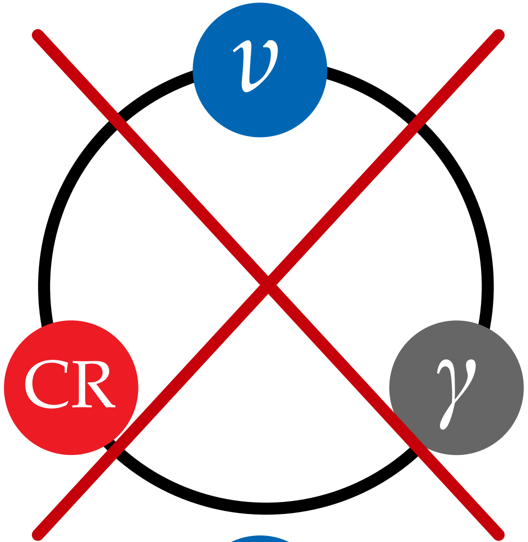


Bright in gamma rays, bright in high-energy neutrinos (?)

Energy in neutrinos ∝ energy in gamma rays

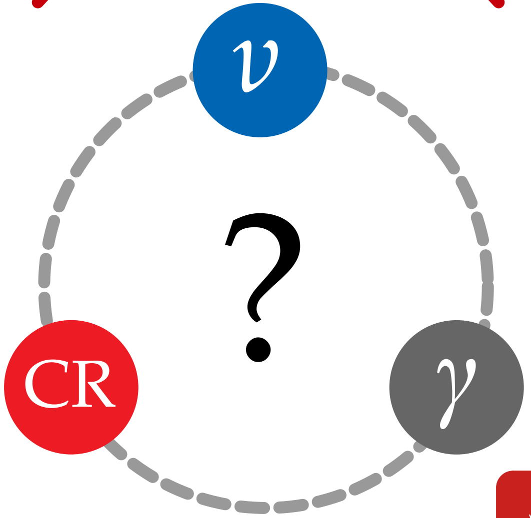
Waxman & Bahcall, *PRL* 1997

Fudge factors:
Source properties (*e.g.*, baryonic loading)
Particle effects (*e.g.*, ν-producing channels)



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

Gao, Pohl, Winter, *ApJ* 2017



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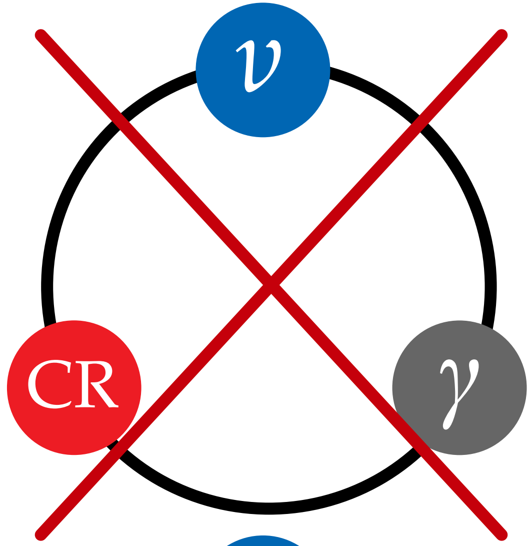


But the correlation between ν and γ may be more nuanced:

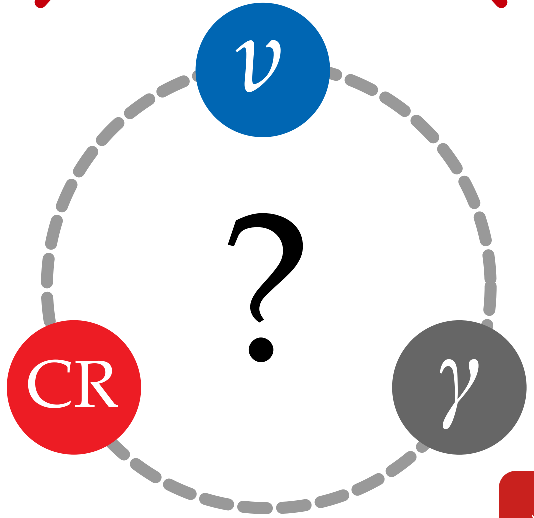
Gao, Pohl, Winter, *ApJ* 2017

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

Murase, Guetta, Ahlers, *PRL* 2016

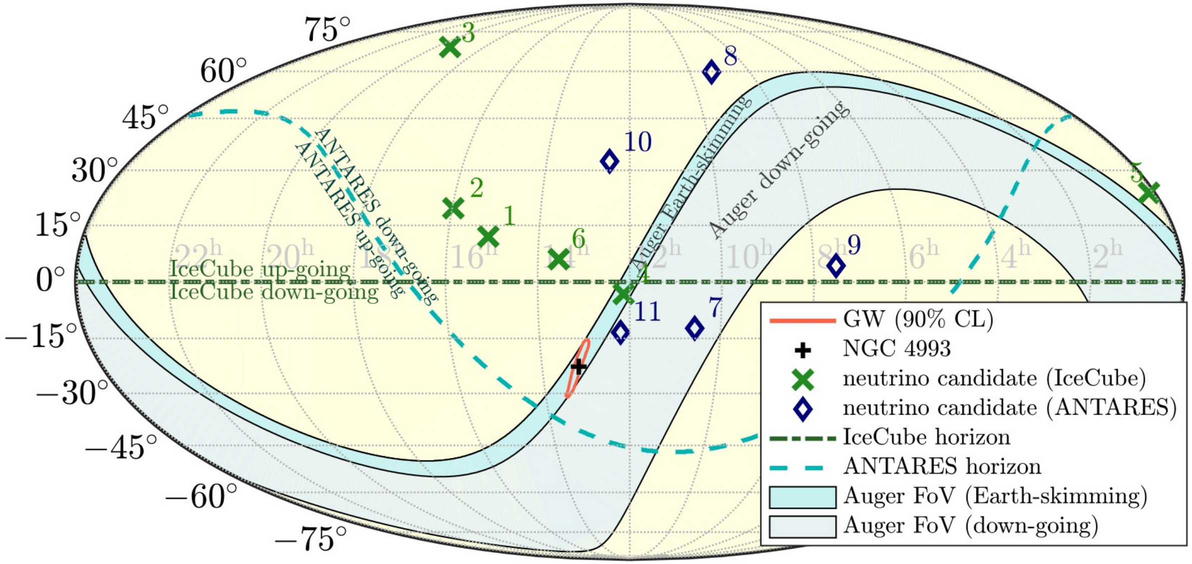
Modeling of *p*γ interactions & nuclear cascading
in the sources is complex and uncertain

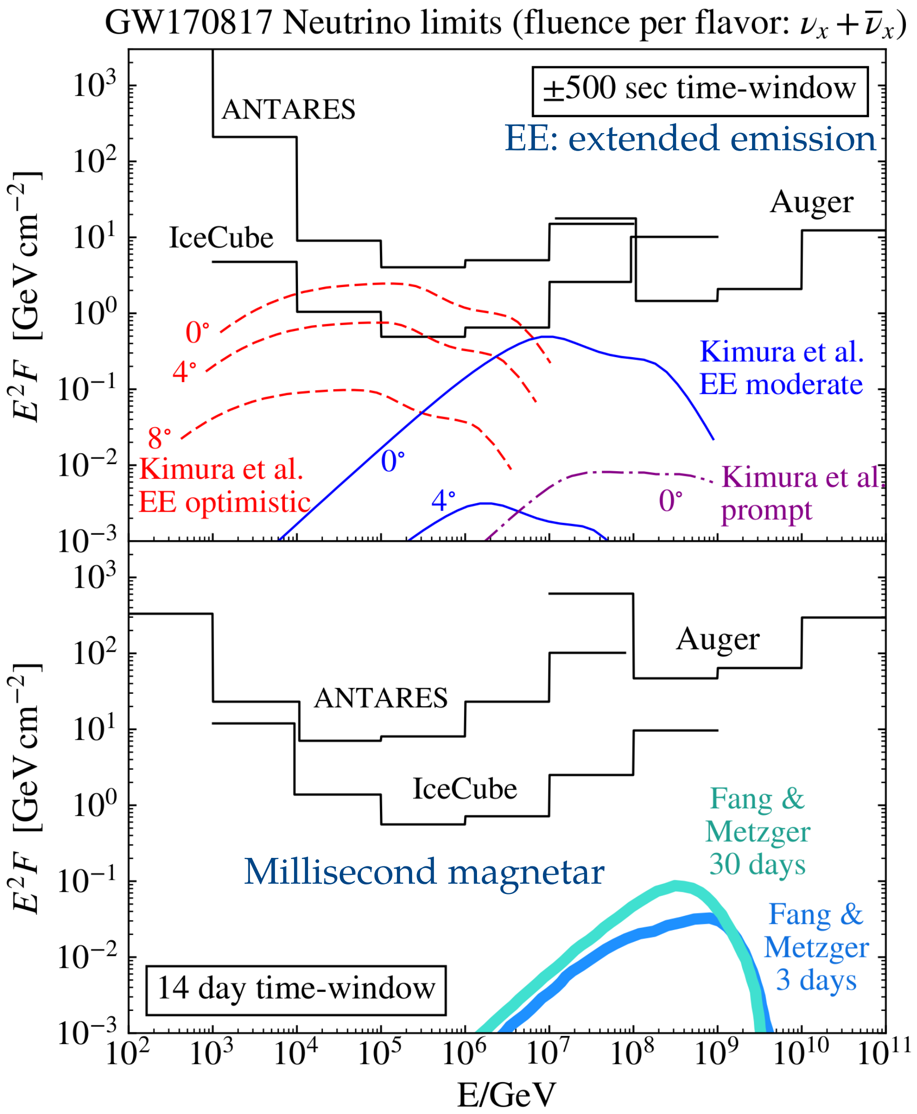
Morejon, Fedynitch, Boncioli, Winter, *JCAP* 2019
Boncioli, Fedynitch, Winter, *Sci. Rep.* 2017



GW170817 (NS-NS merger)

- Short GRB seen in *Fermi*-GBM, INTEGRAL
- Neutrino search by IceCube, ANTARES, and Auger
- MeV–EeV neutrinos, 14-day window
- Non-detection consistent with off-axis





ANTARES, IceCube, Pierre Auger Collab., *ApJL* 2017

Using high-energy neutrinos as magnetometers

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

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

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

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

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

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

Using high-energy neutrinos as magnetometers

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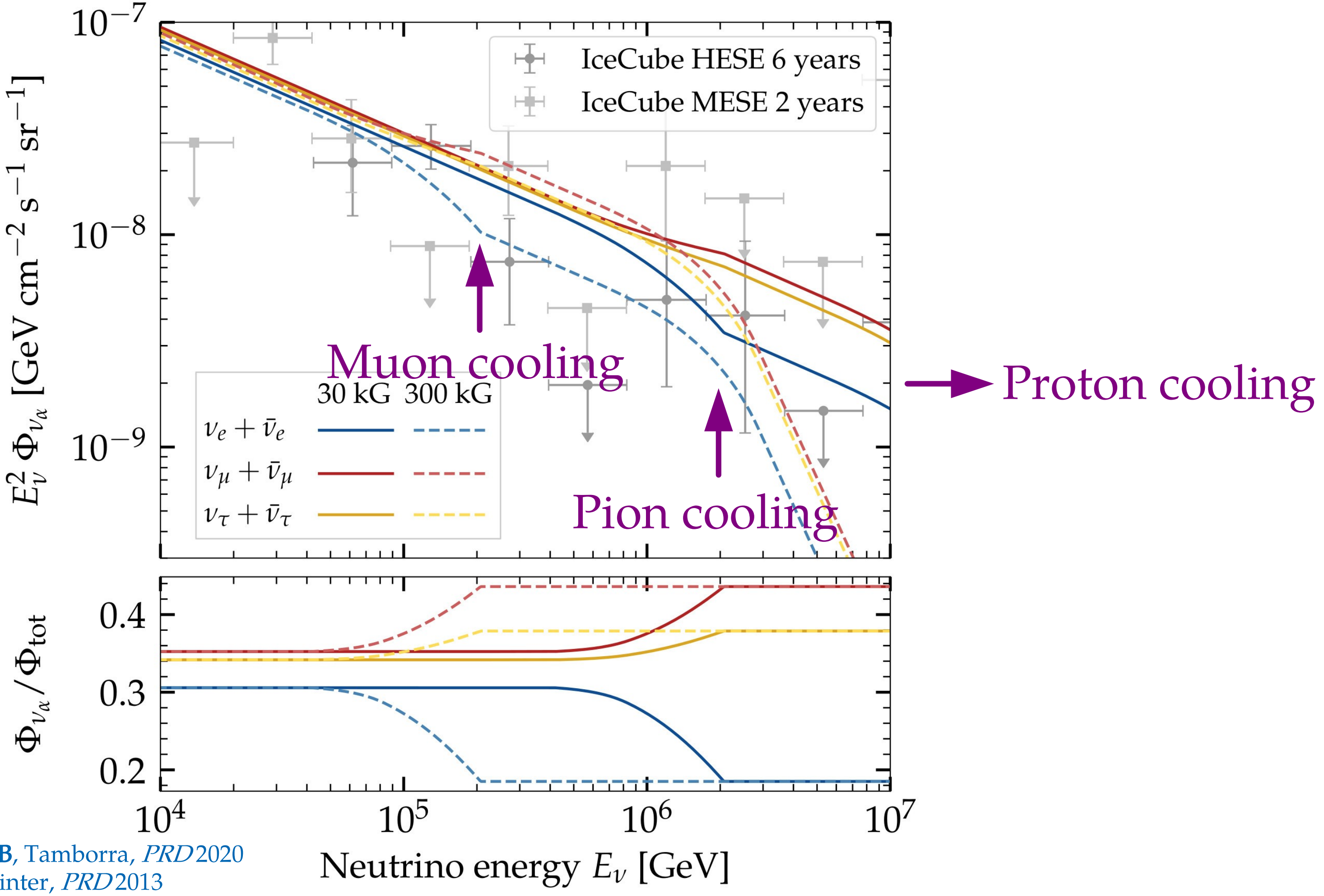

MB, Tamborra, *PRD* 2020
Winter, *PRD* 2013

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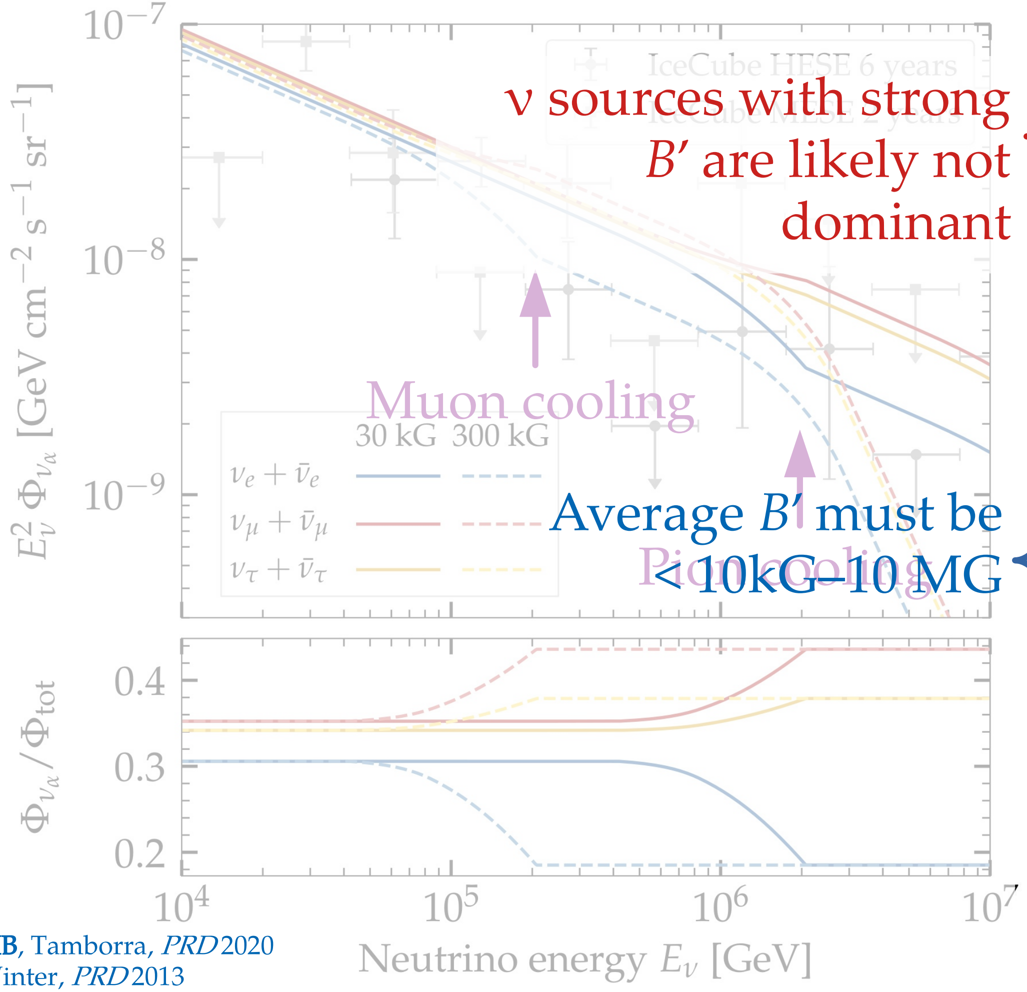

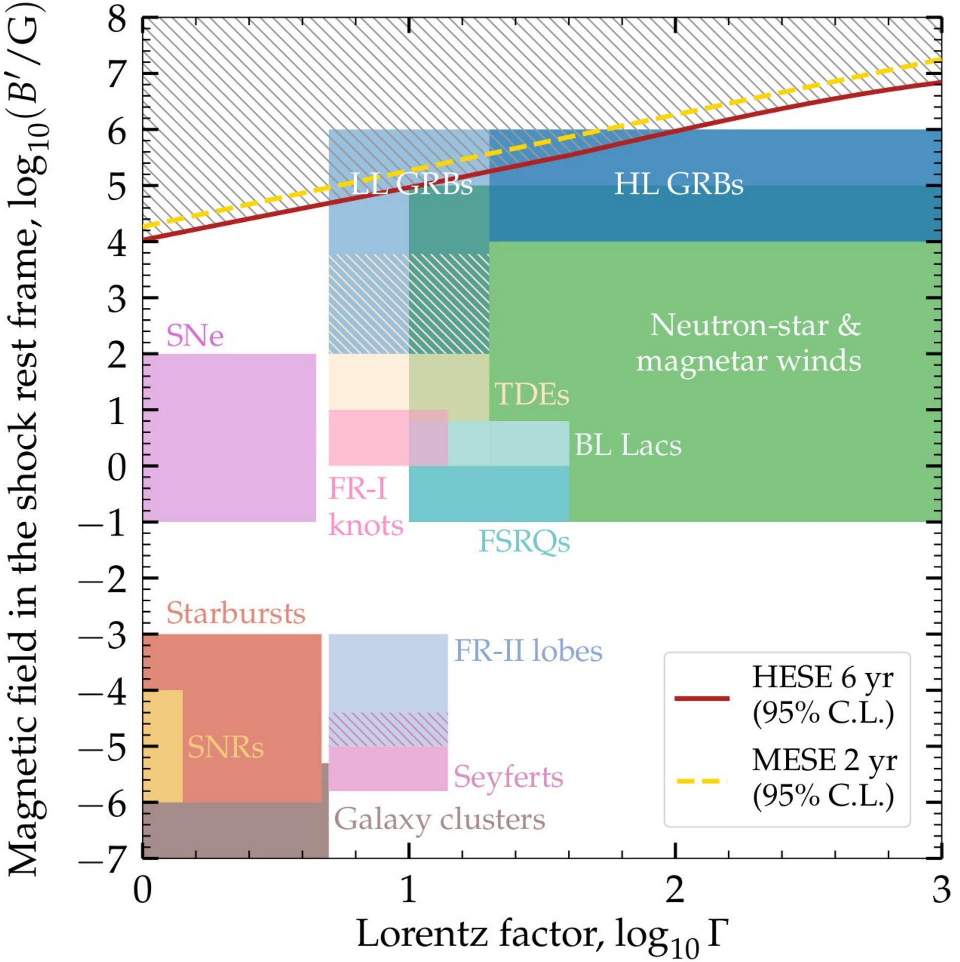

MB, Tamborra, *PRD* 2020
Winter, *PRD* 2013

Cross-section measurements

Measuring the high-energy νN cross section

Number of detected neutrinos (simplified for presentation):

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

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

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Downgoing neutrinos
(L short → no matter)

$$N \propto \Phi_\nu \sigma_{\nu N}$$

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
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(L long → lots of matter)

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Downgoing neutrinos
(L short → no matter)

$$N \propto \underbrace{\Phi_\nu \sigma_{\nu N}}_{\text{Degeneracy}}$$

Upgoing neutrinos
(L long → lots of matter)

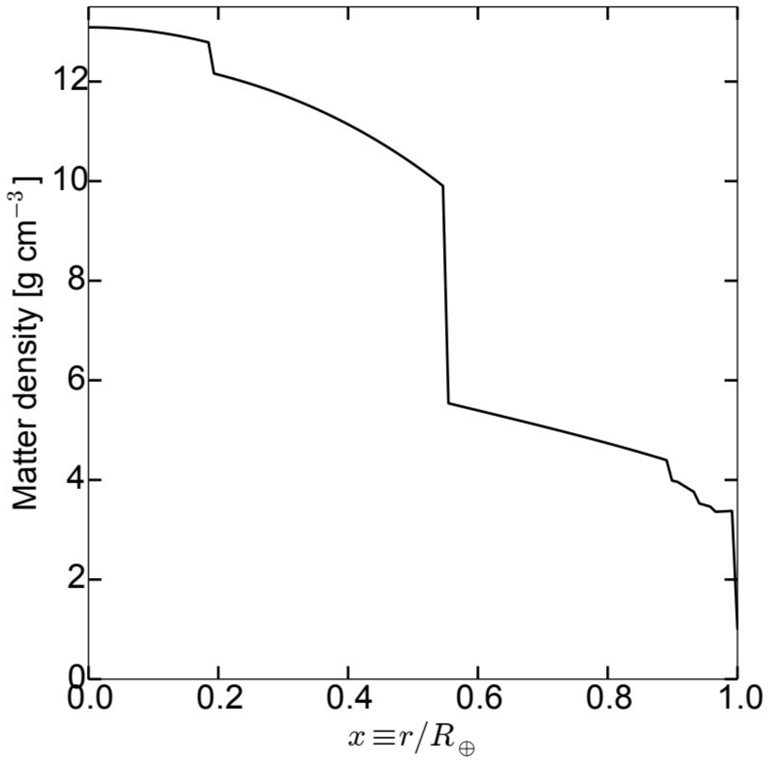
$$N \propto \Phi_\nu \sigma_{\nu N} \underbrace{e^{-L \sigma_{\nu N} n_N}}_{\text{Breaks the degeneracy}}$$

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

A feel for the in-Earth attenuation

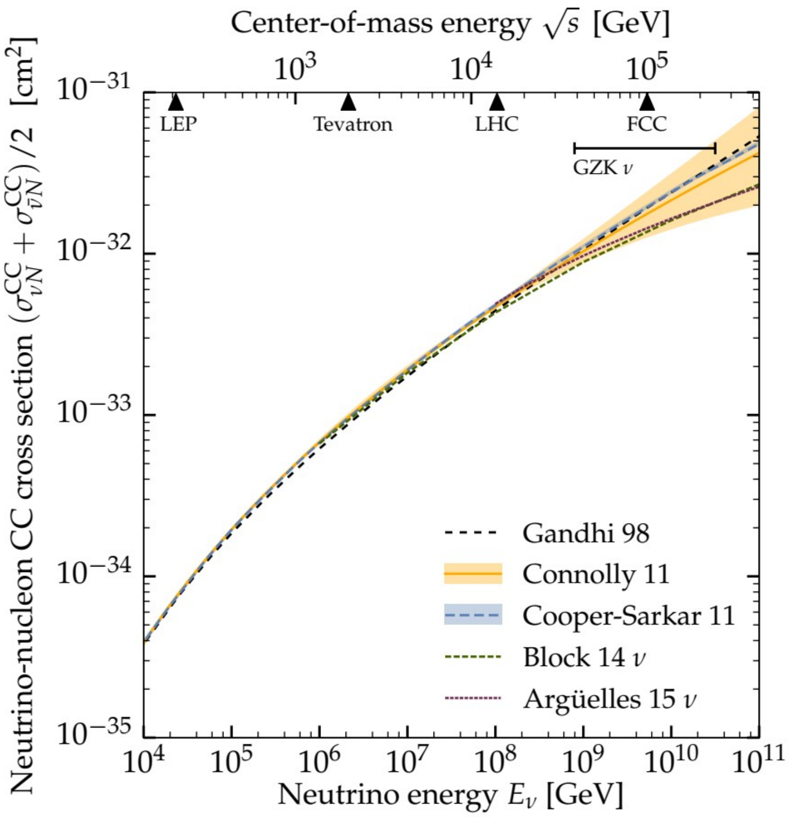
Earth matter density

(Preliminary Reference Earth Model)



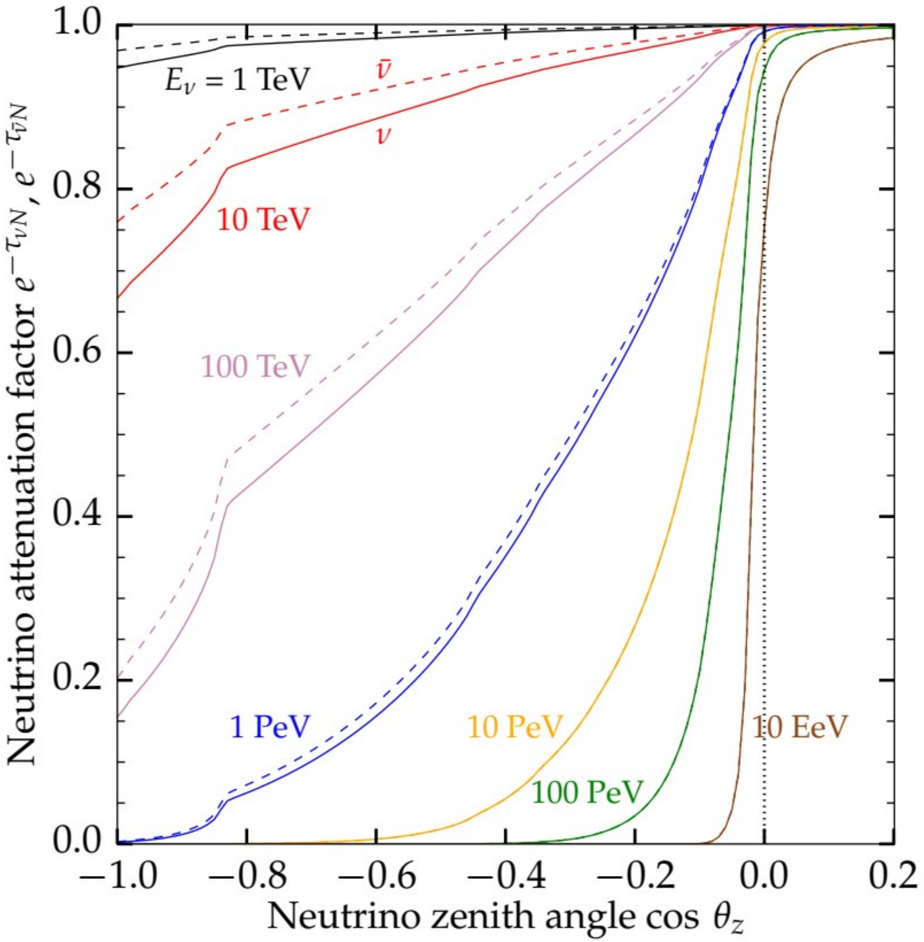
+

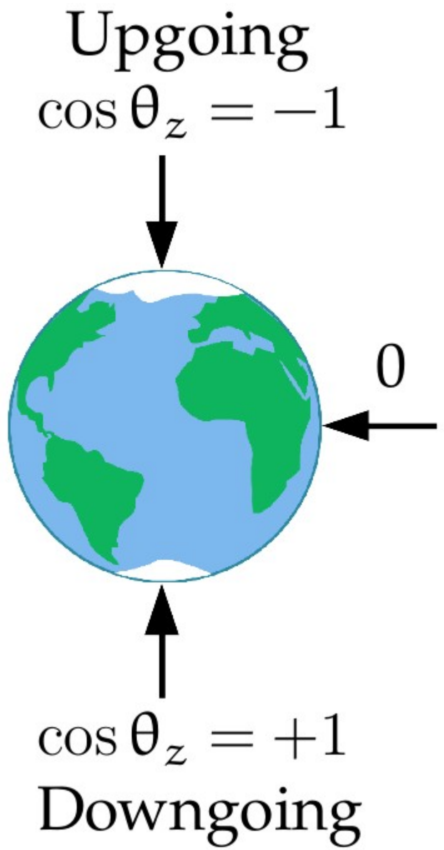
Neutrino-nucleon cross section

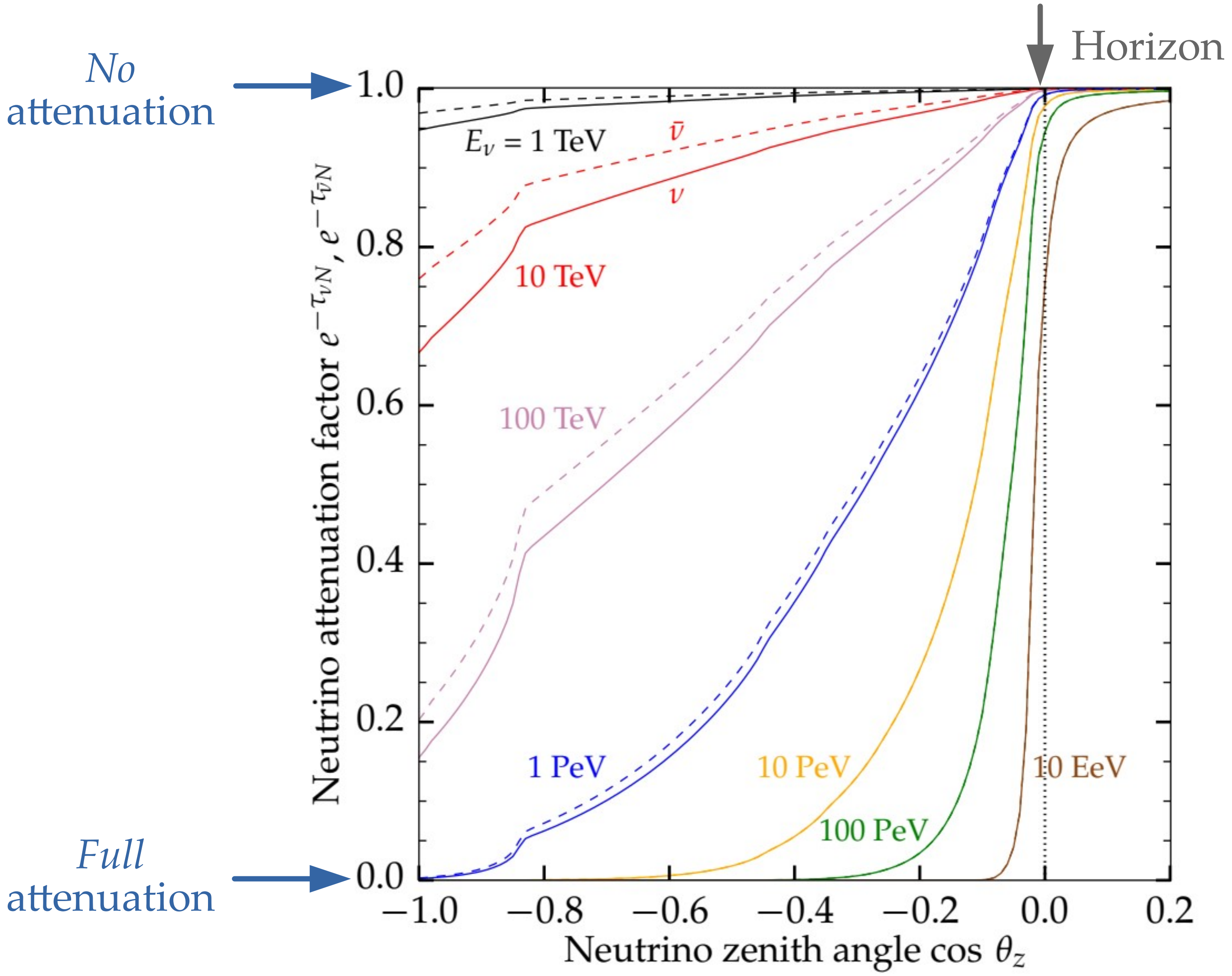


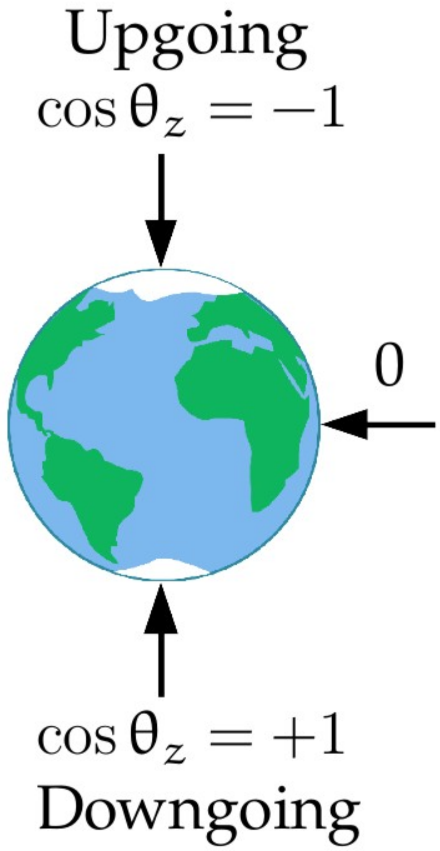
A feel for the in-Earth attenuation

=

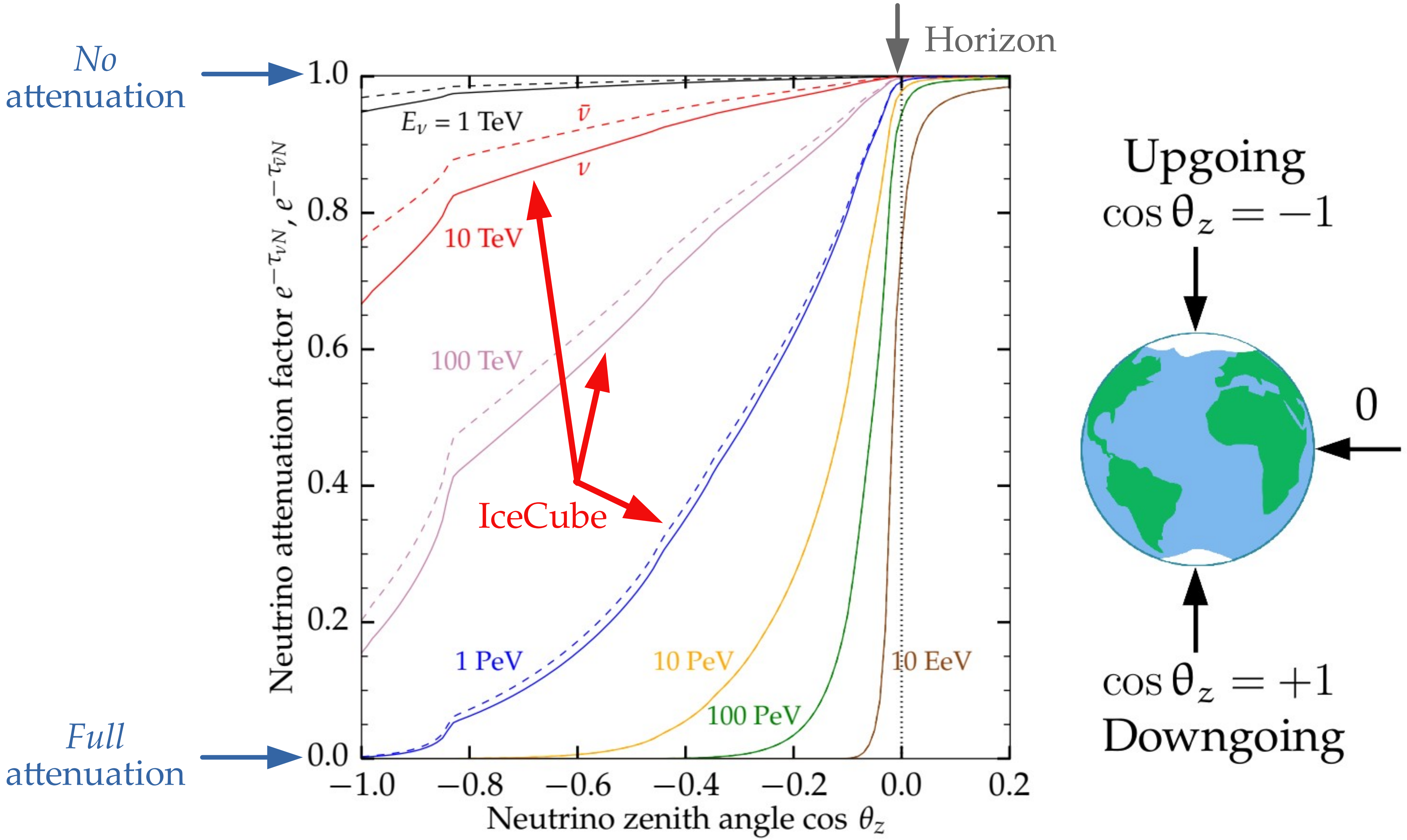




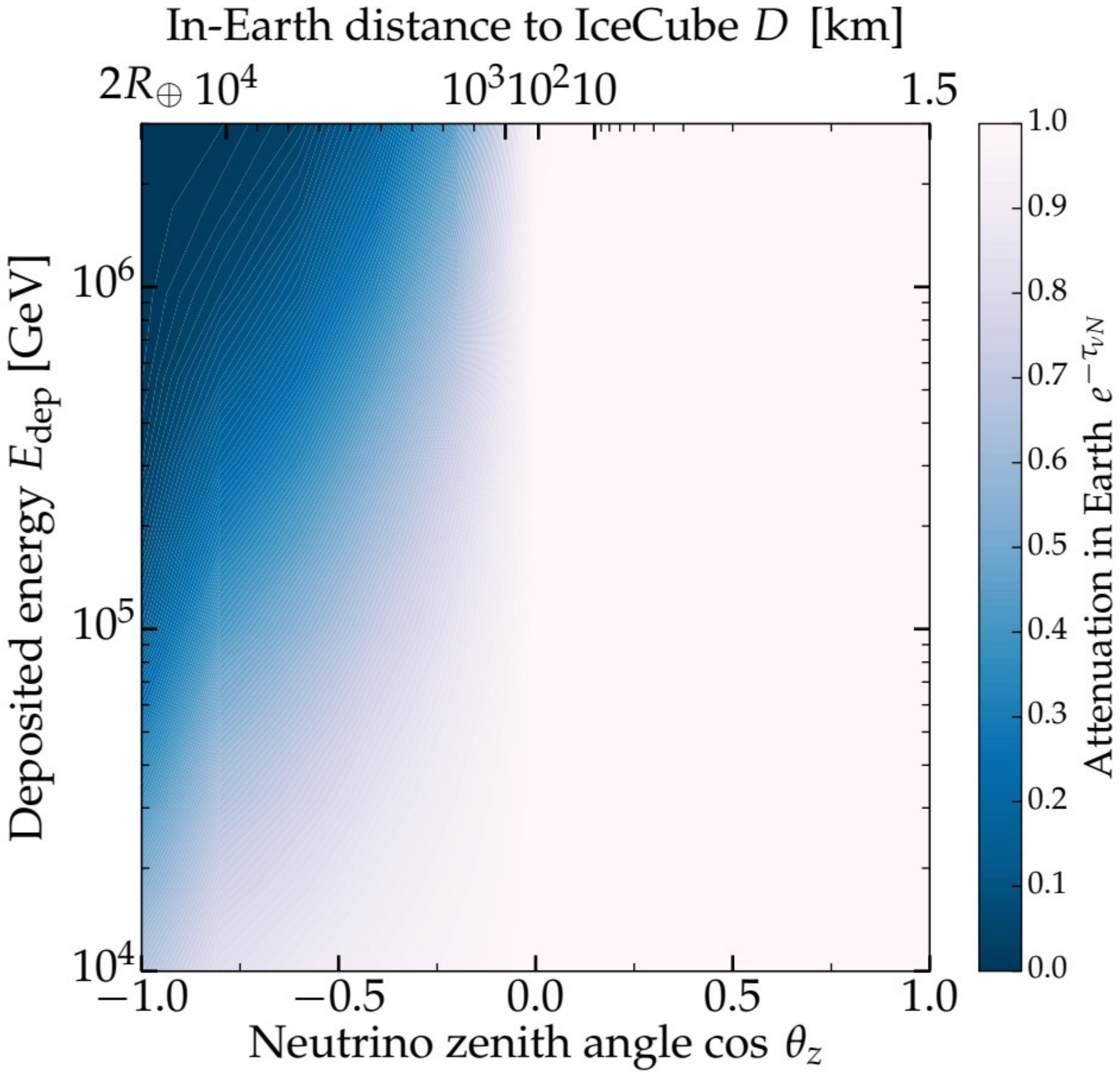


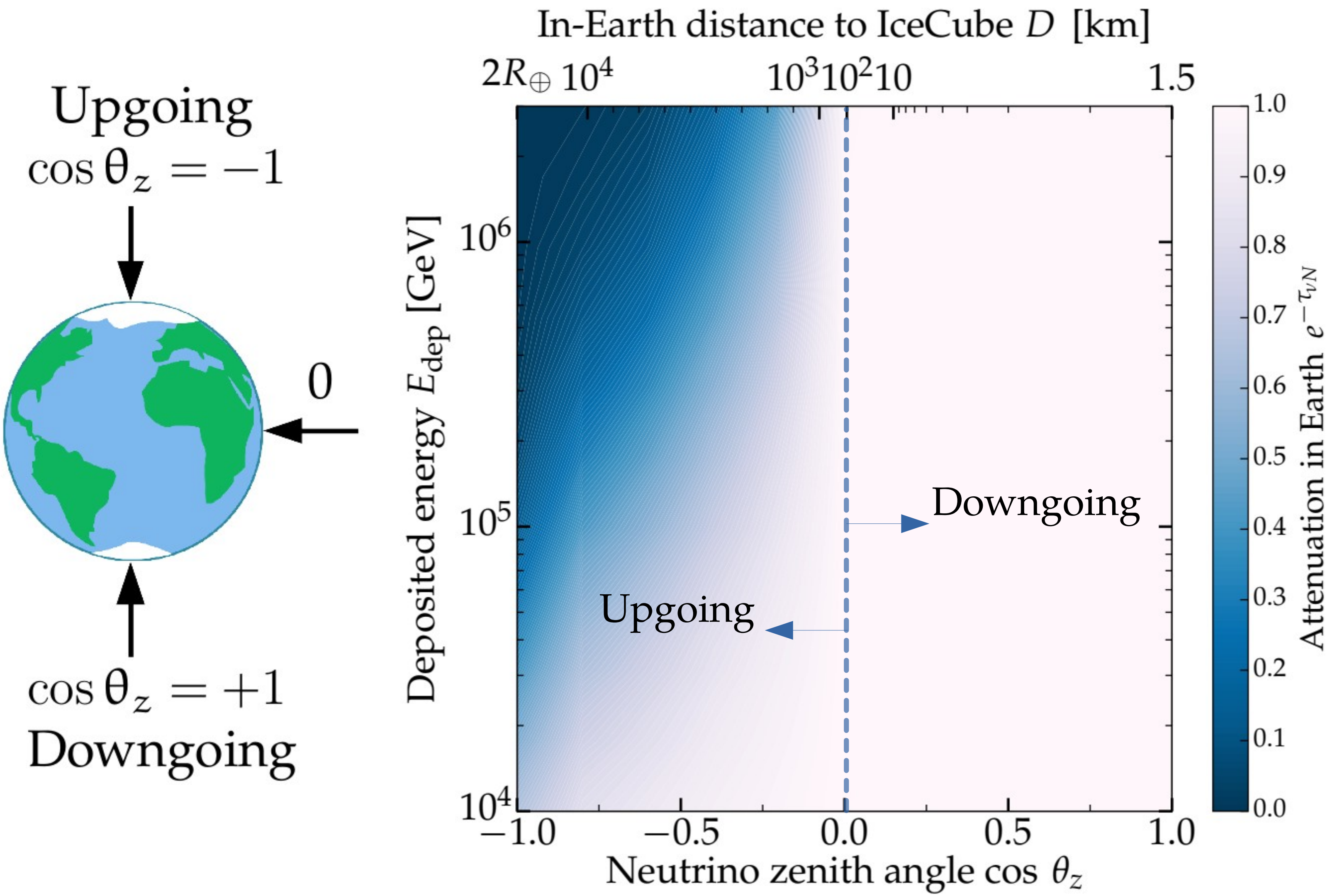


MB & Connolly, *PRL* 2019

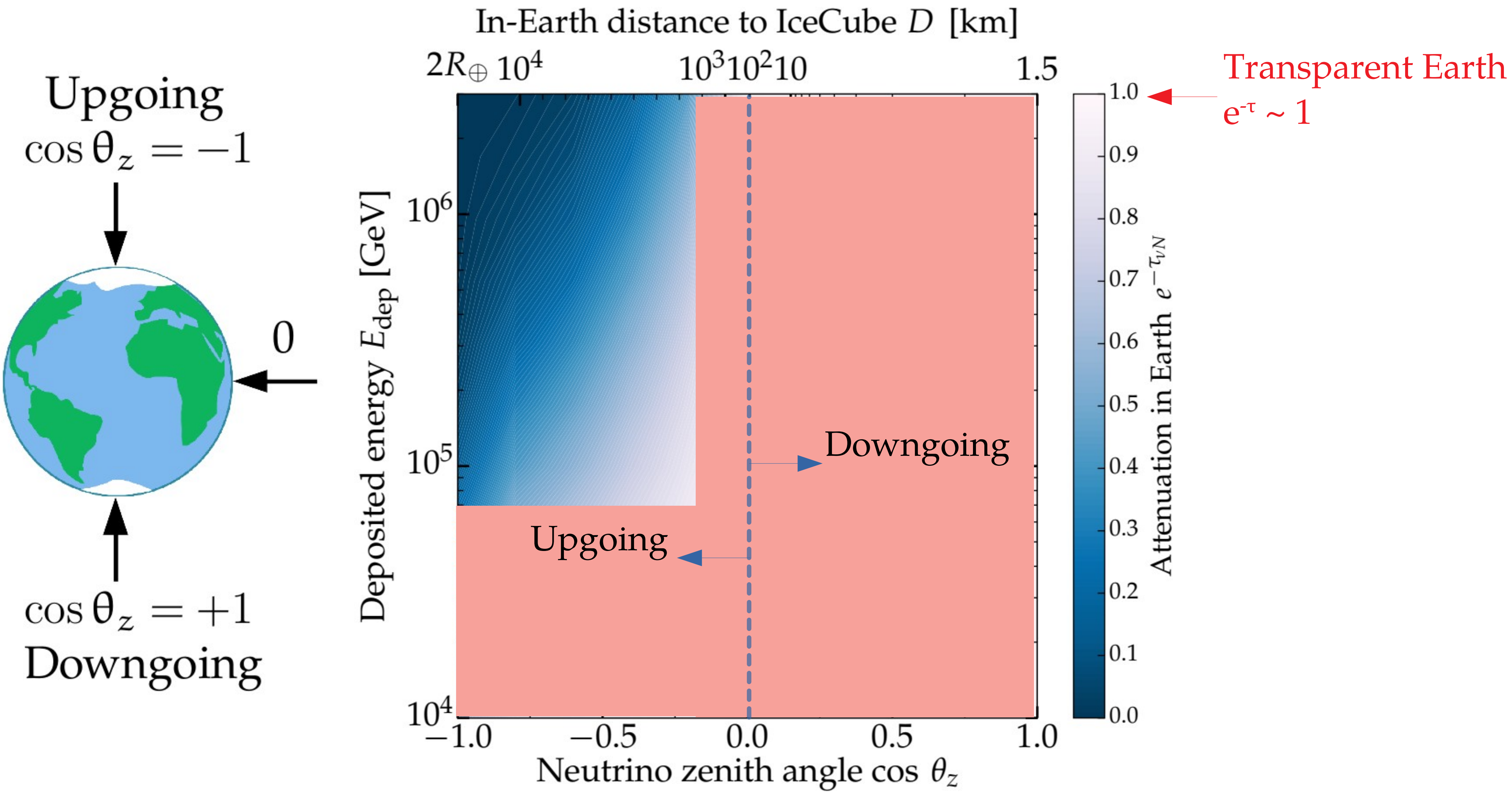


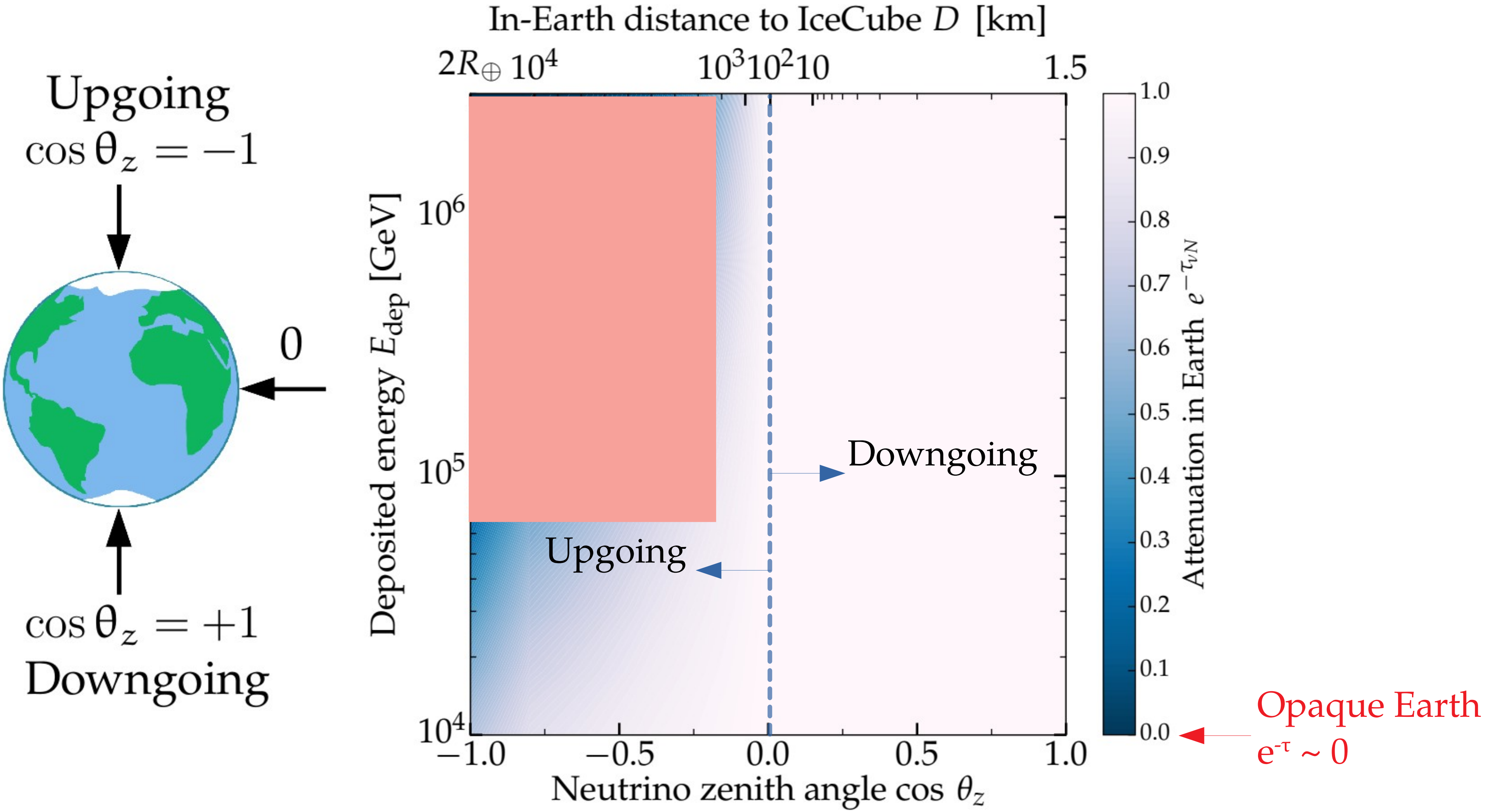
MB & Connolly, *PRL* 2019

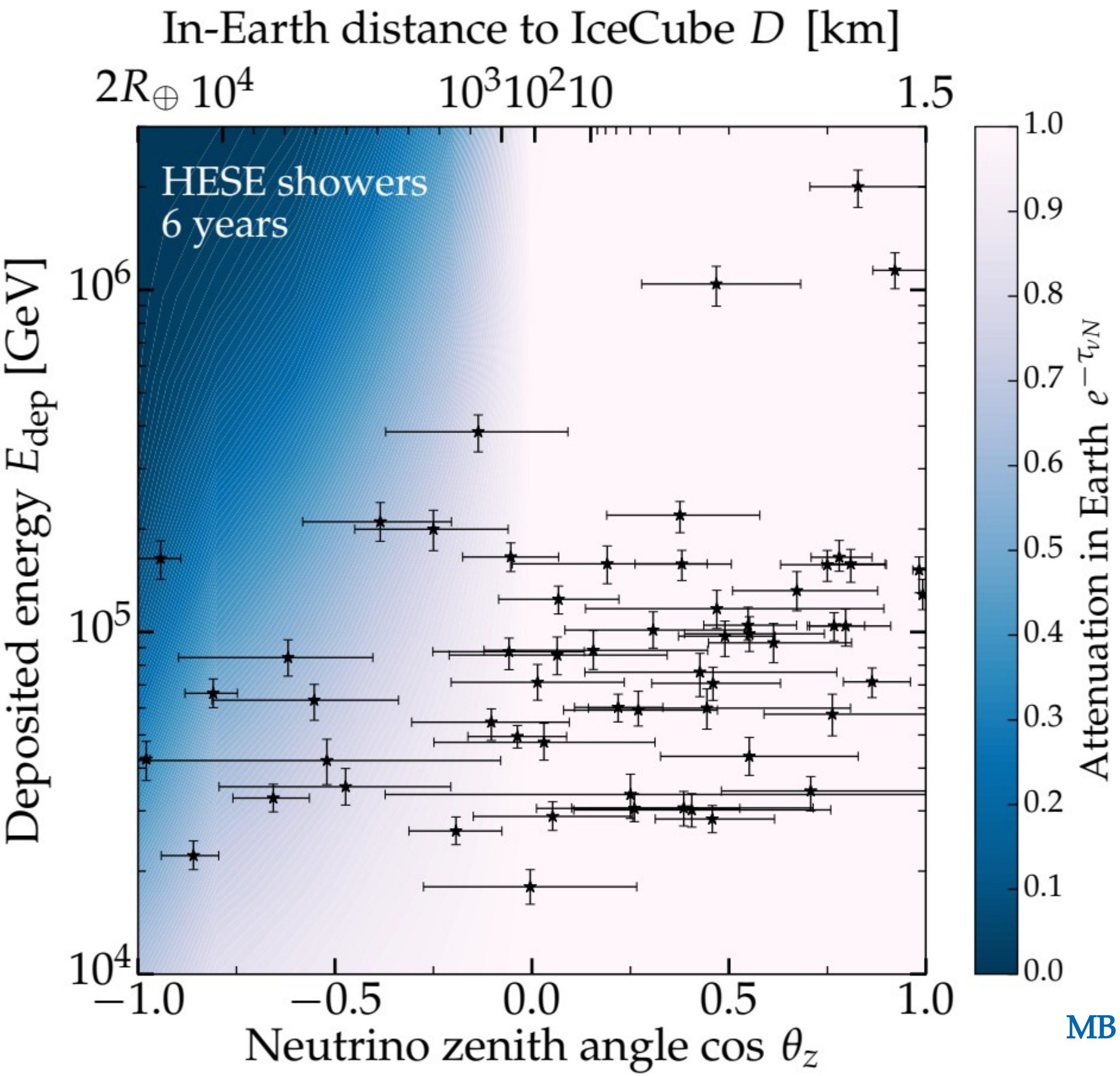

In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0



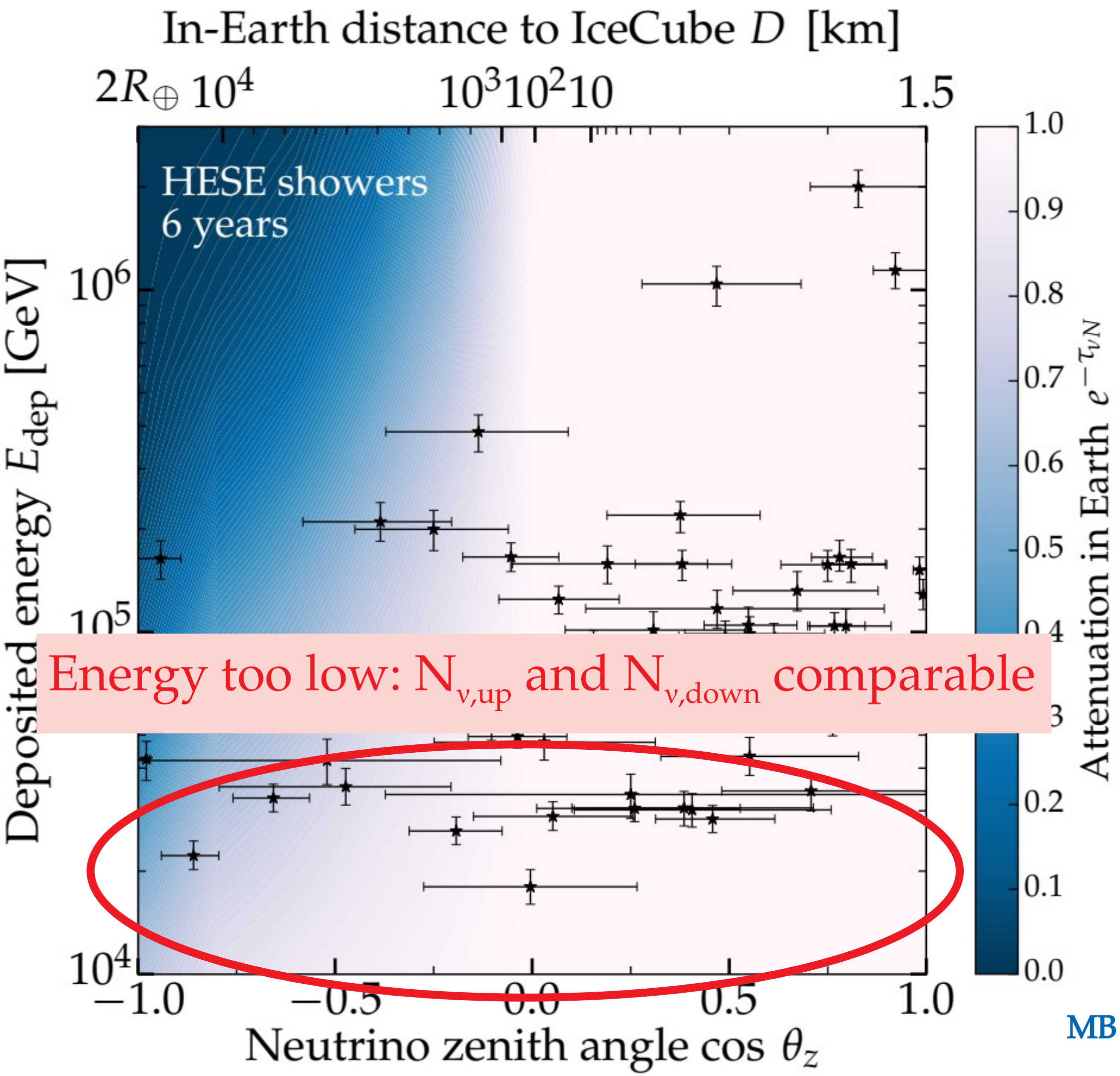
Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^4 10^5 10^6
Neutrino zenith angle $\cos\theta_z$
−1.0 −0.5 0.0 0.5 1.0
Downgoing
Upgoing
Attenuation in Earth $e^{-\tau_{\nu N}}$
0.0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


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


Upgoing
cos θ_z = −1
0
cos θ_z = +1
Downgoing
In-Earth distance to IceCube D [km]
2R⊕ 10^4 10^3 10^2 10 1.5
Deposited energy E_dep [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle cos θ_z
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Attenuation in Earth e^{−τ_{νN}}
Opaque Earth
e^{-τ} ~ 0

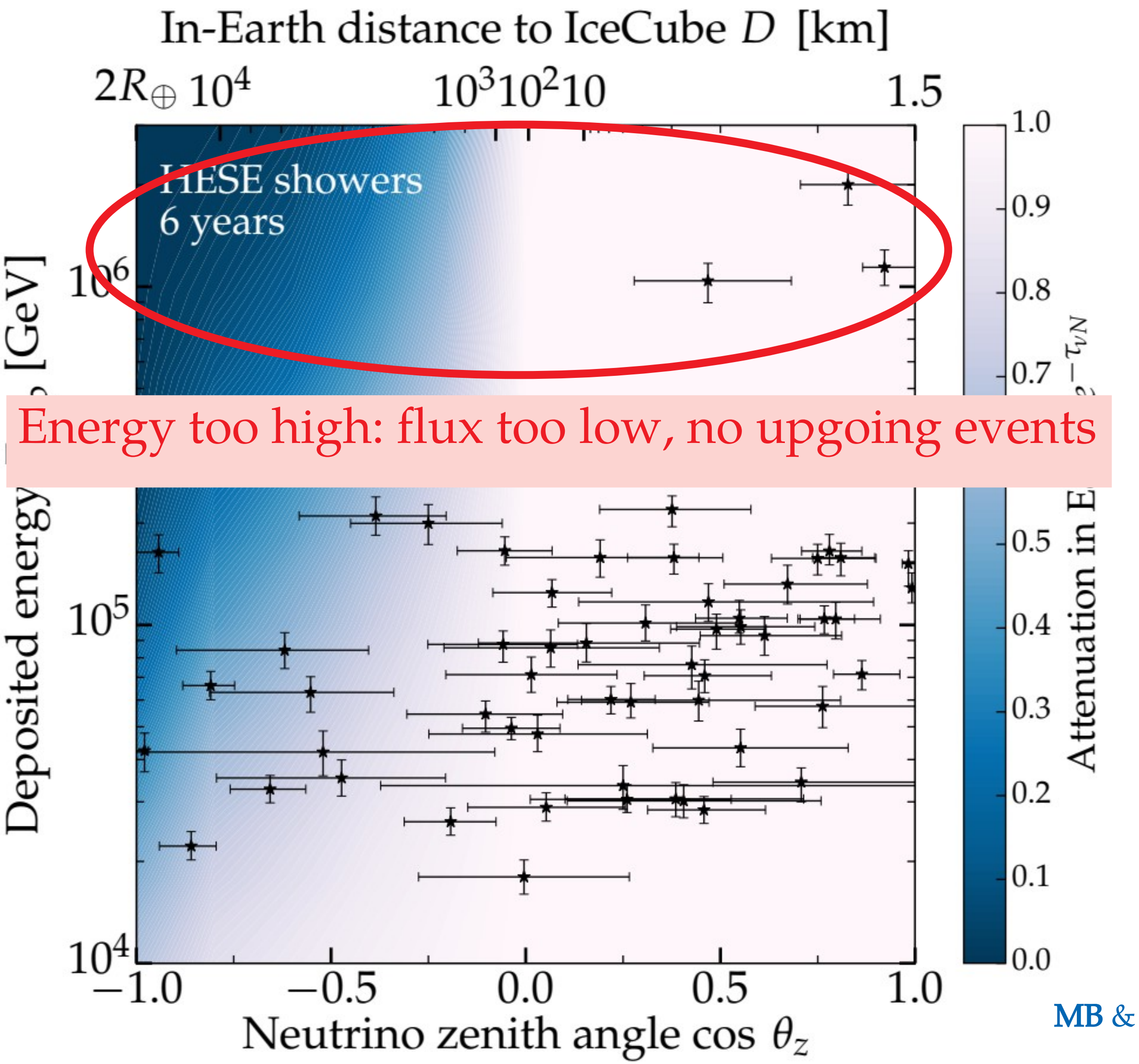


MB & Connolly, *PRL* 2019

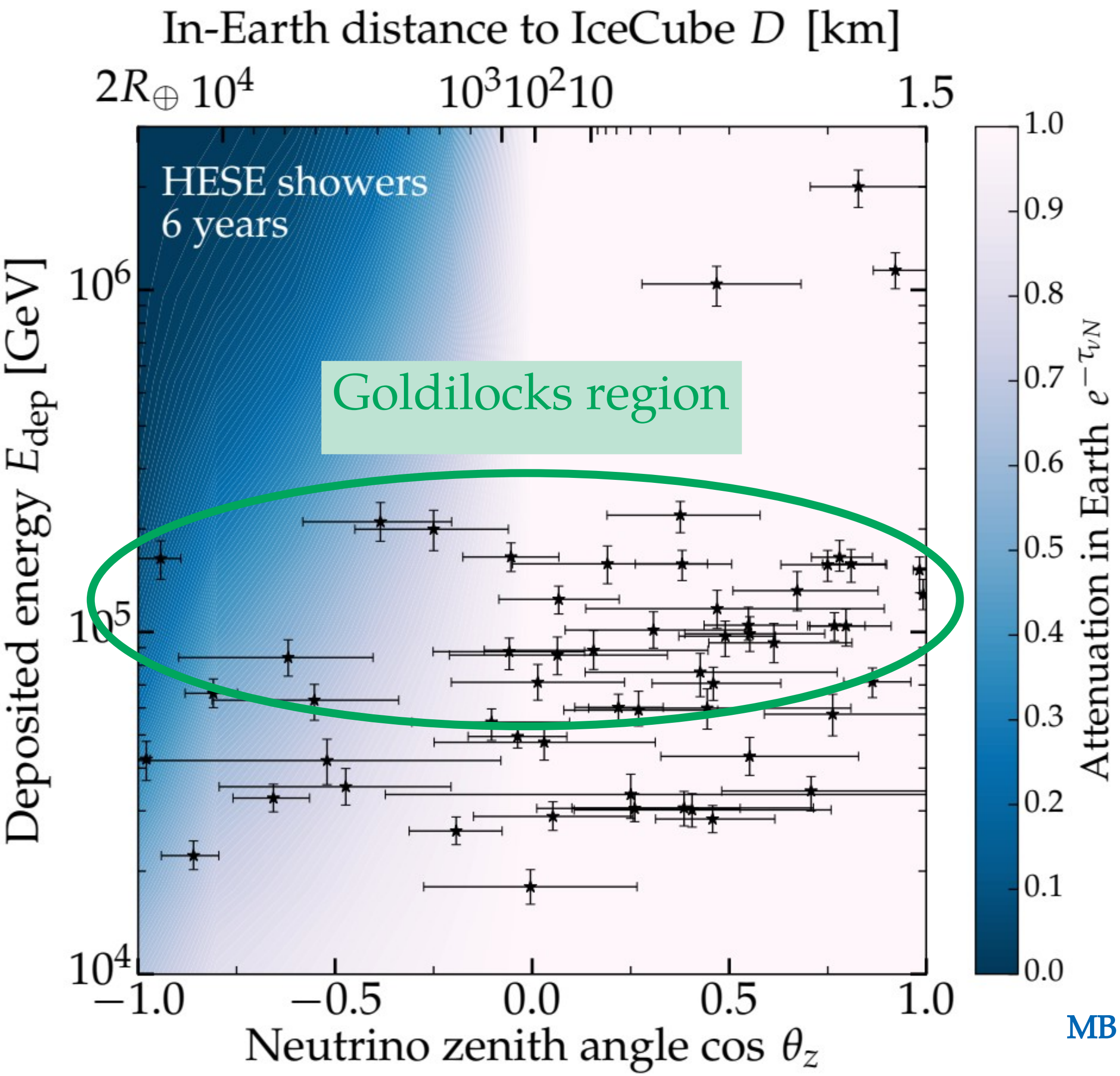


Energy too low: $N_{\nu,up}$ and $N_{\nu,down}$ comparable

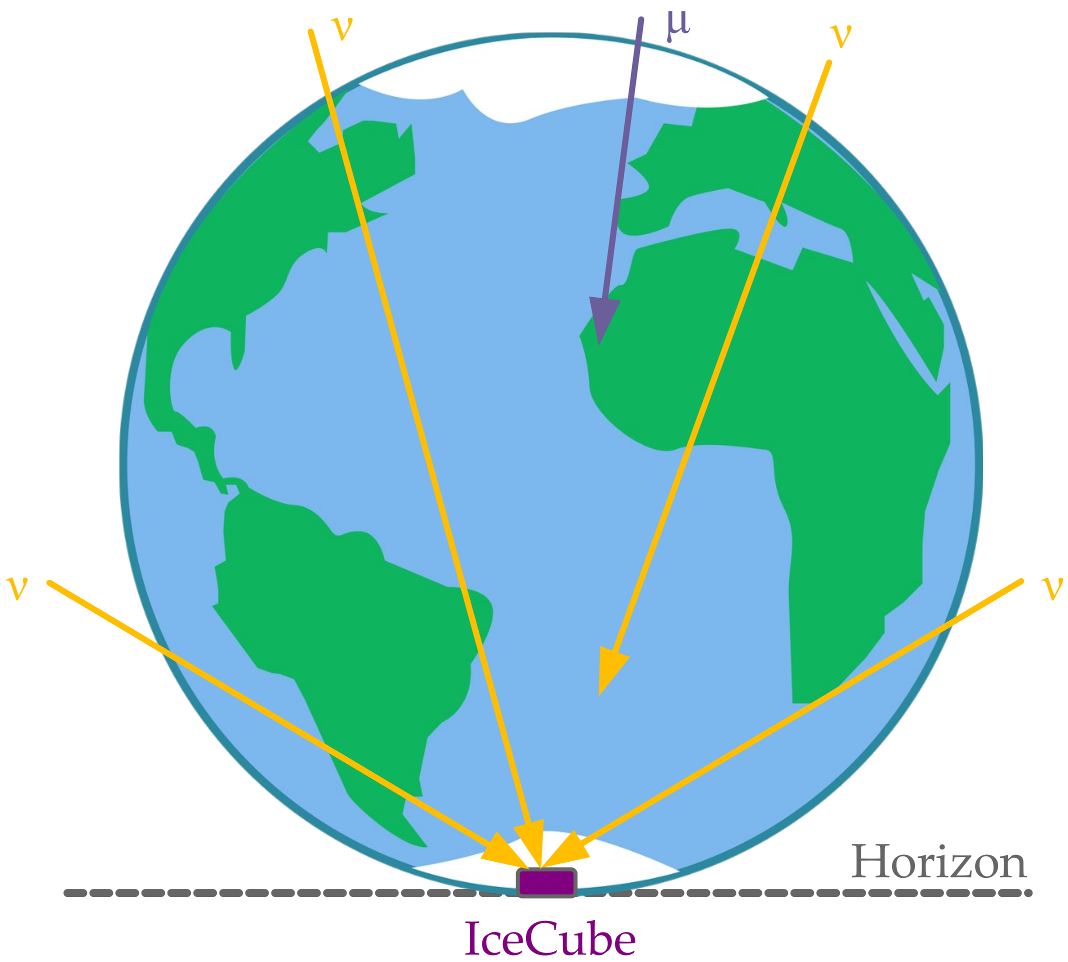
MB & Connolly, *PRL* 2019

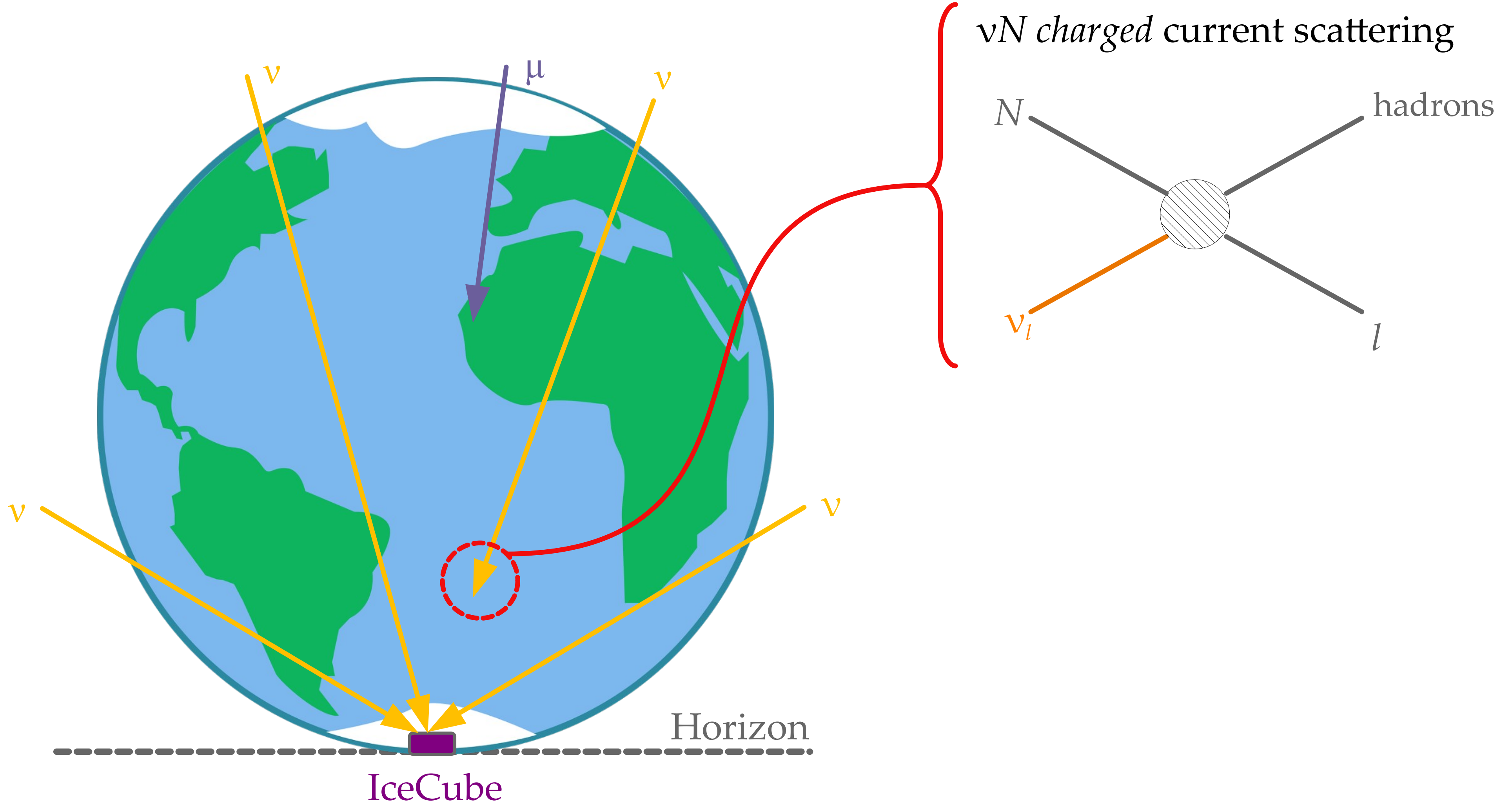


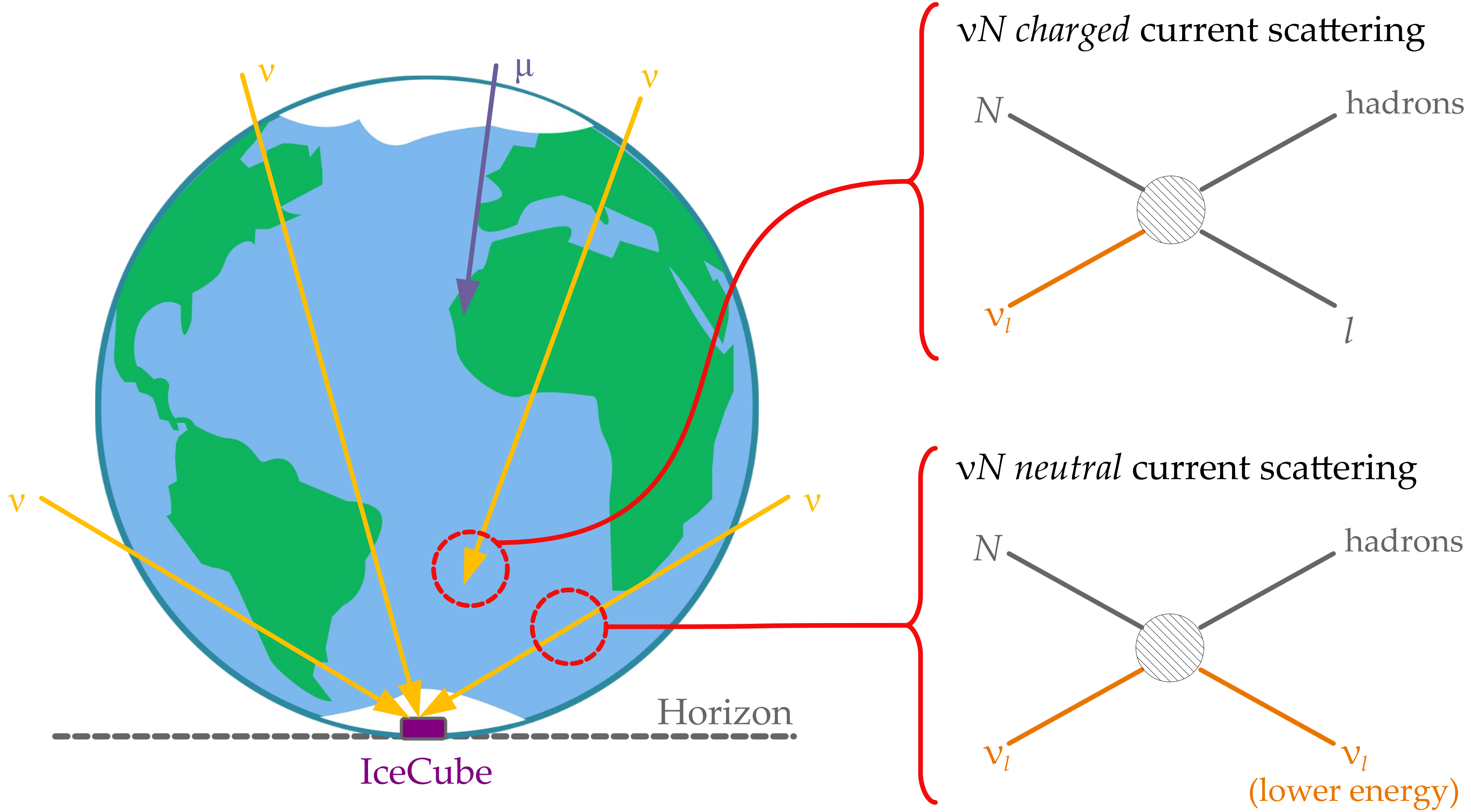
MB & Connolly, *PRL* 2019

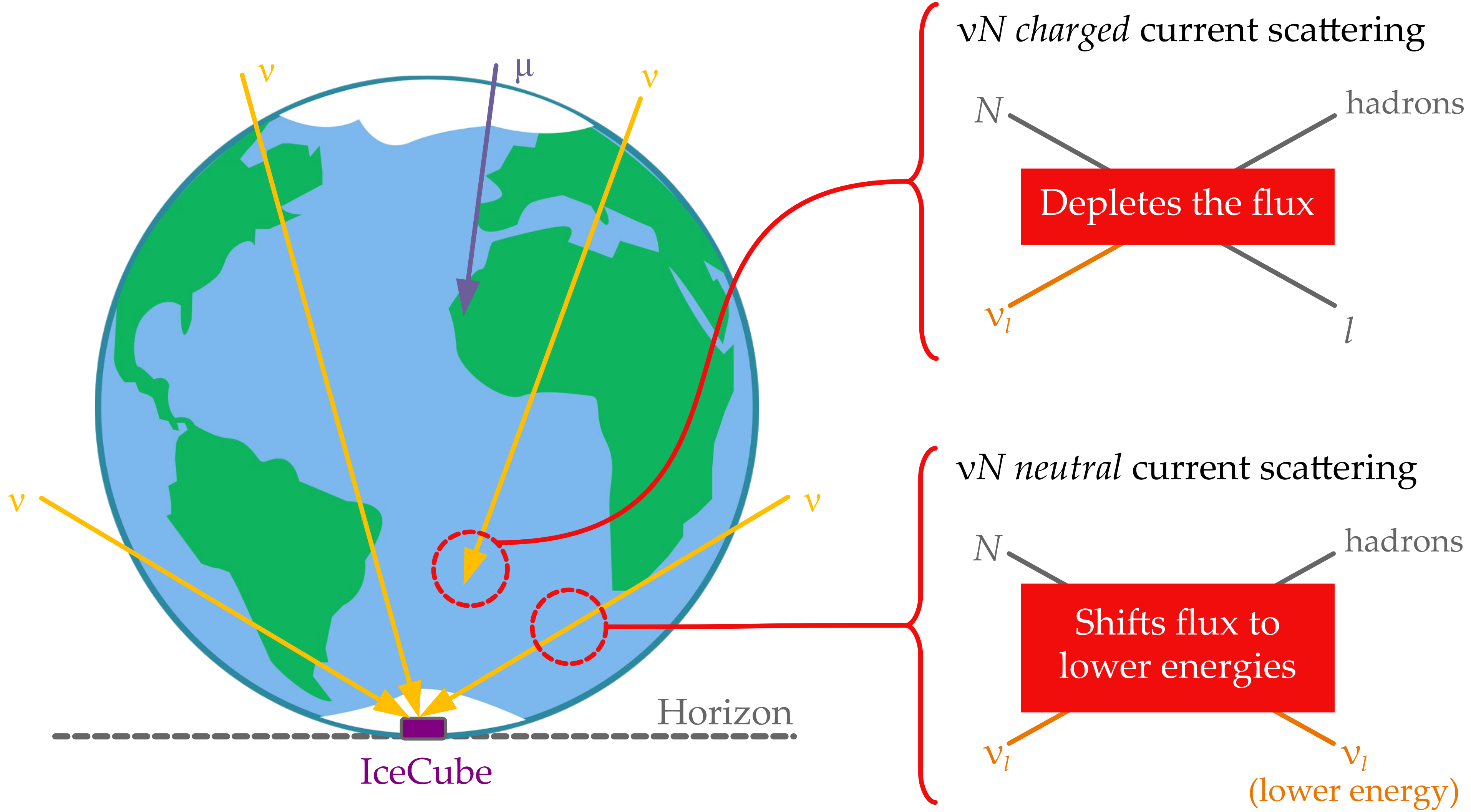


MB & Connolly, *PRL* 2019

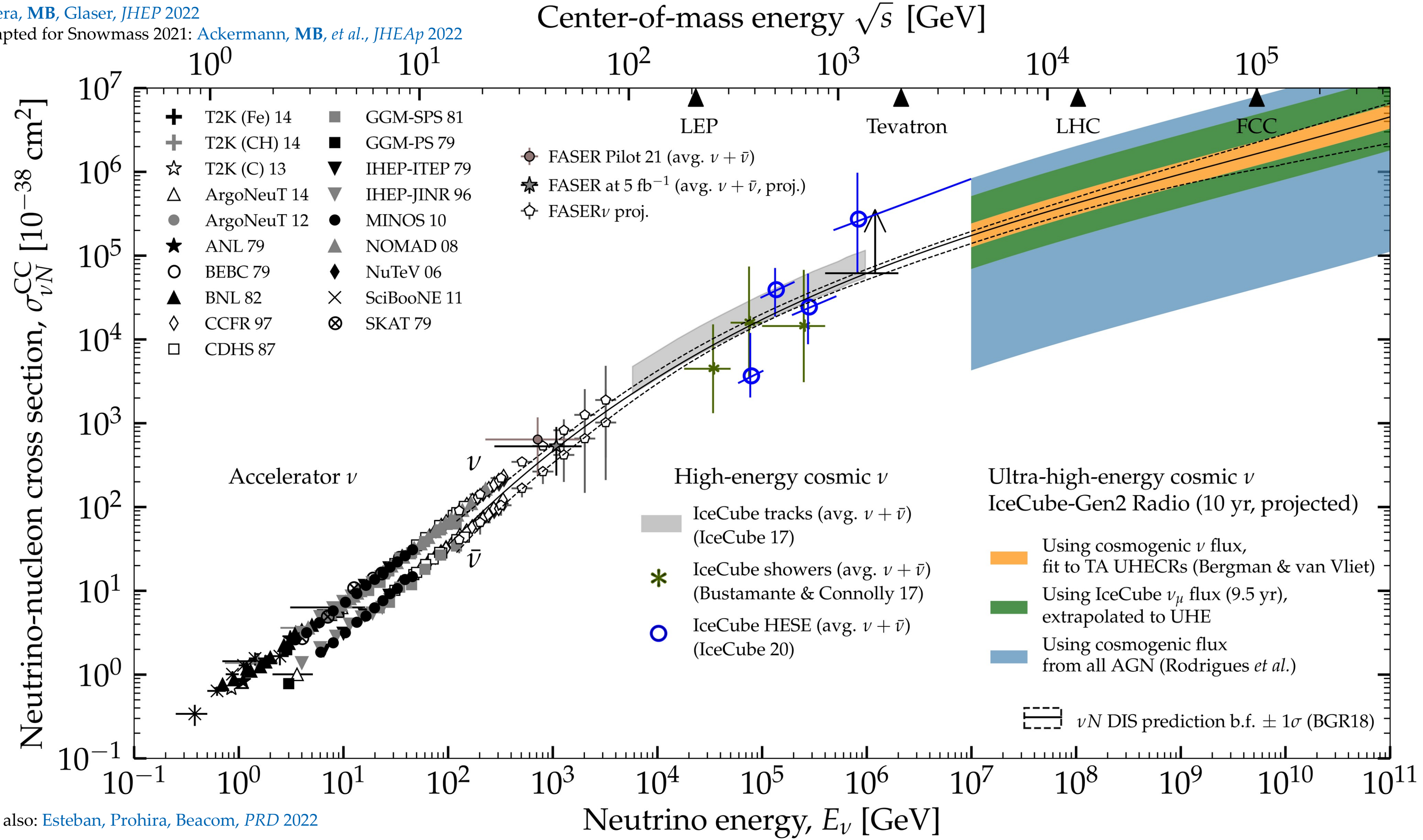

ν
μ
ν
ν
ν
Horizon
IceCube


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

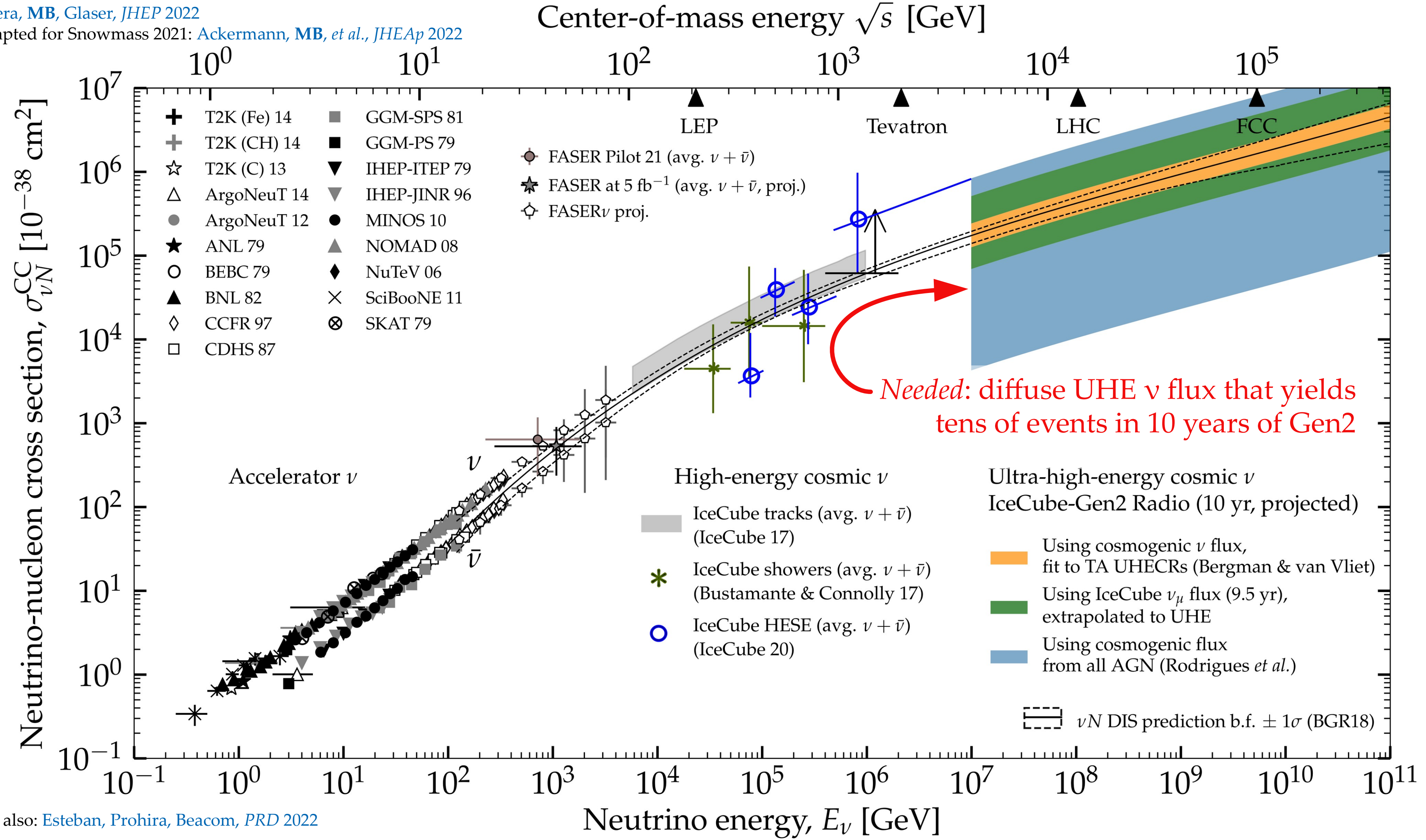

ν
μ
ν
ν
ν
Horizon
IceCube
νN *charged* current scattering
N
hadrons
Depletes the flux
ν_l
l
νN *neutral* current scattering
N
hadrons
Shifts flux to lower energies
ν_l
ν_l
(lower energy)

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



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

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



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

2. Glashow resonance:
Long-sought, finally seen

First observation of a Glashow resonance

Predicted in 1960:

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

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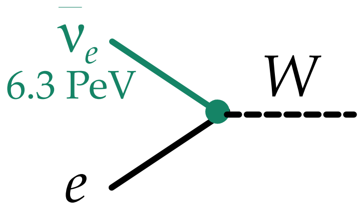
Predicted in 1960:



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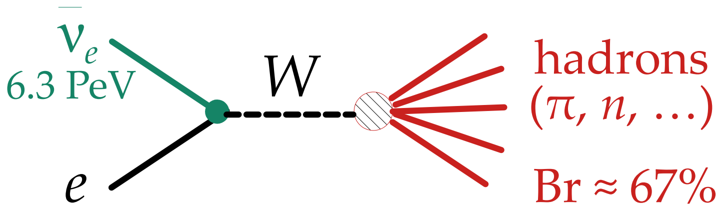

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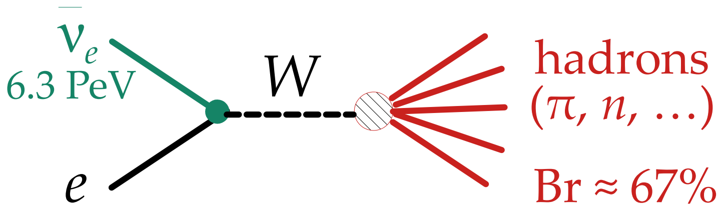

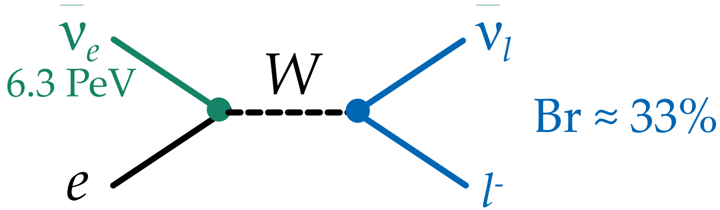

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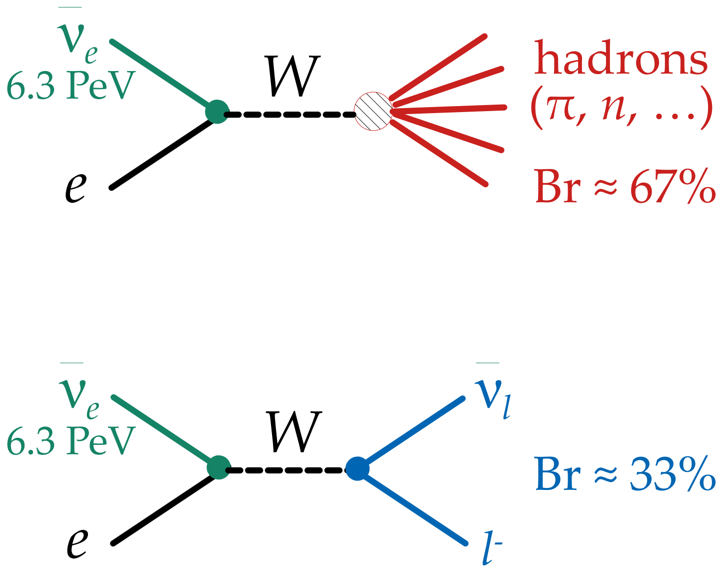
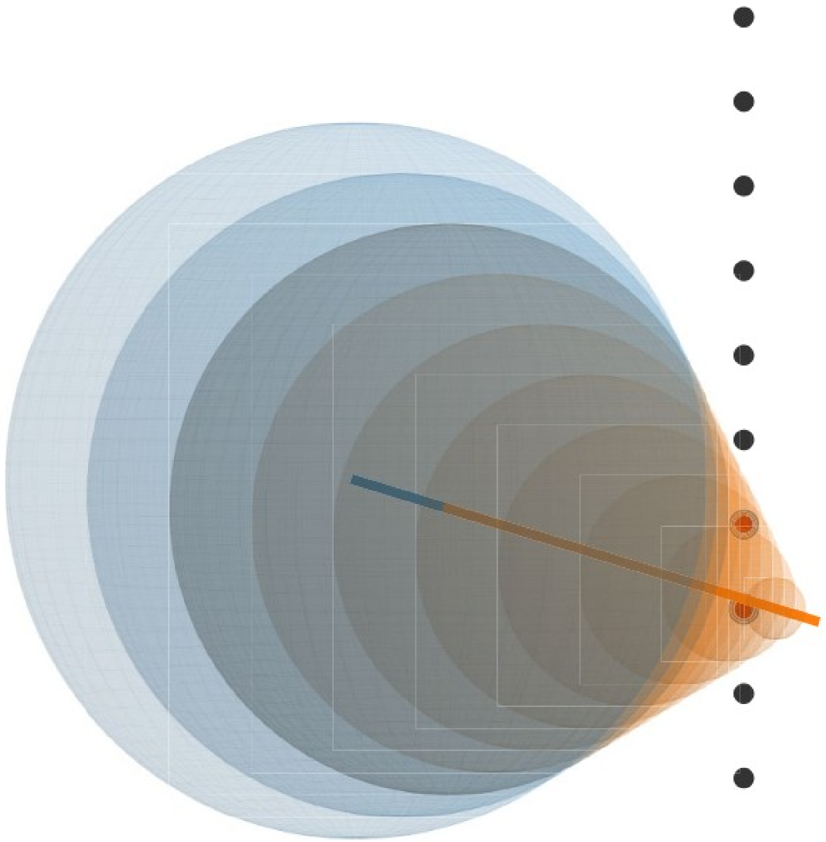


First reported by IceCube in 2021:



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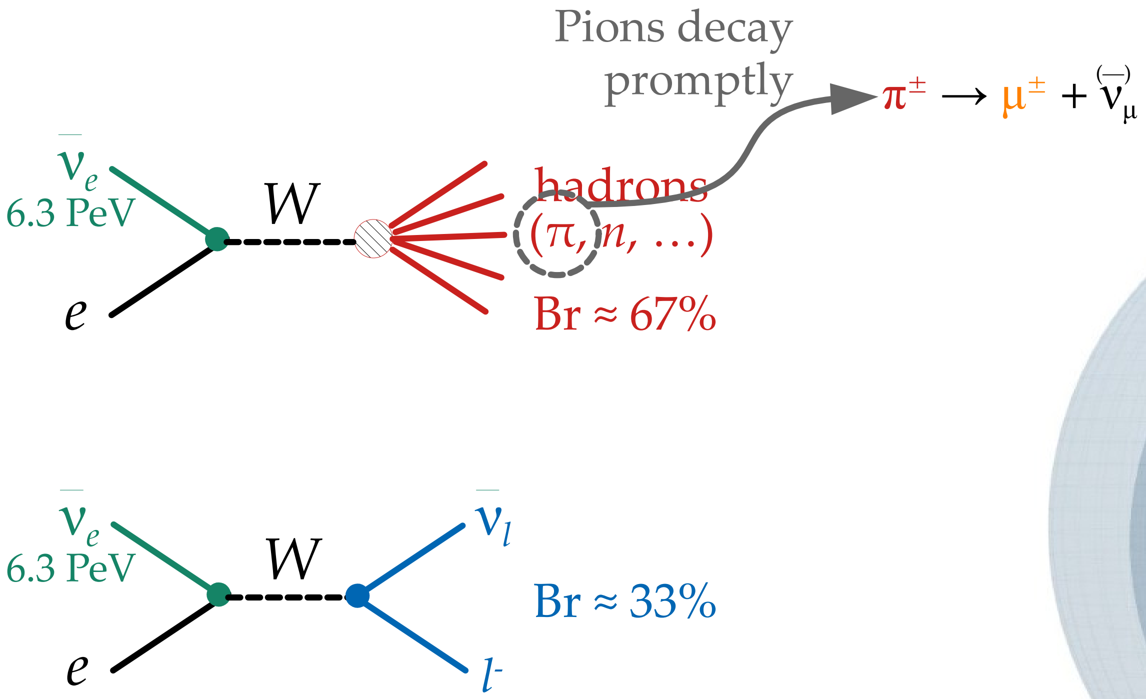
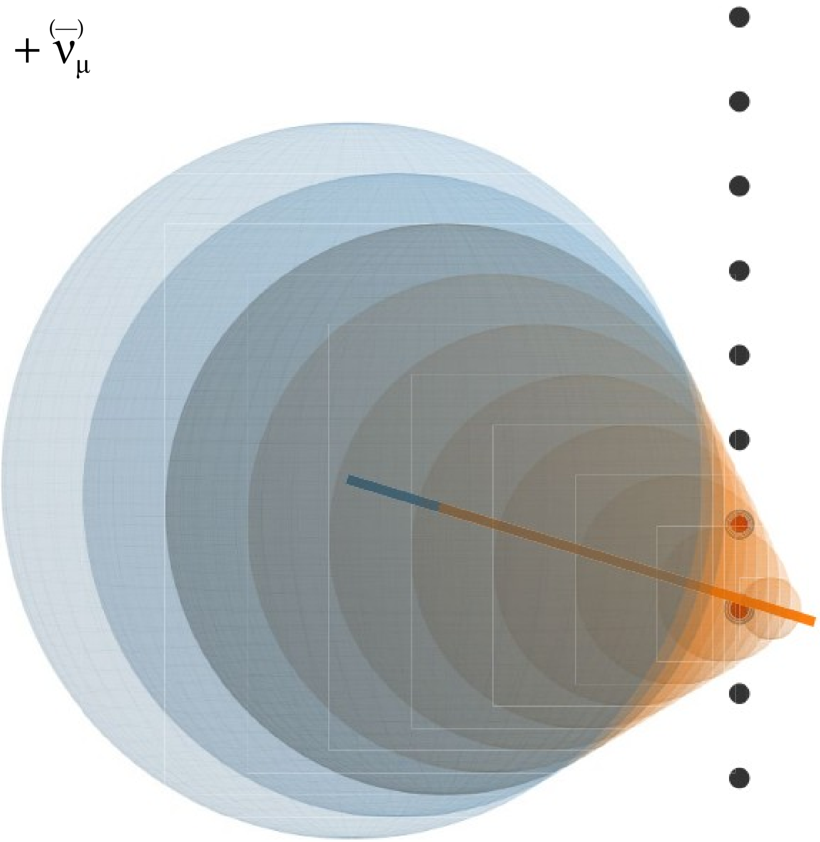


First reported by IceCube in 2021:

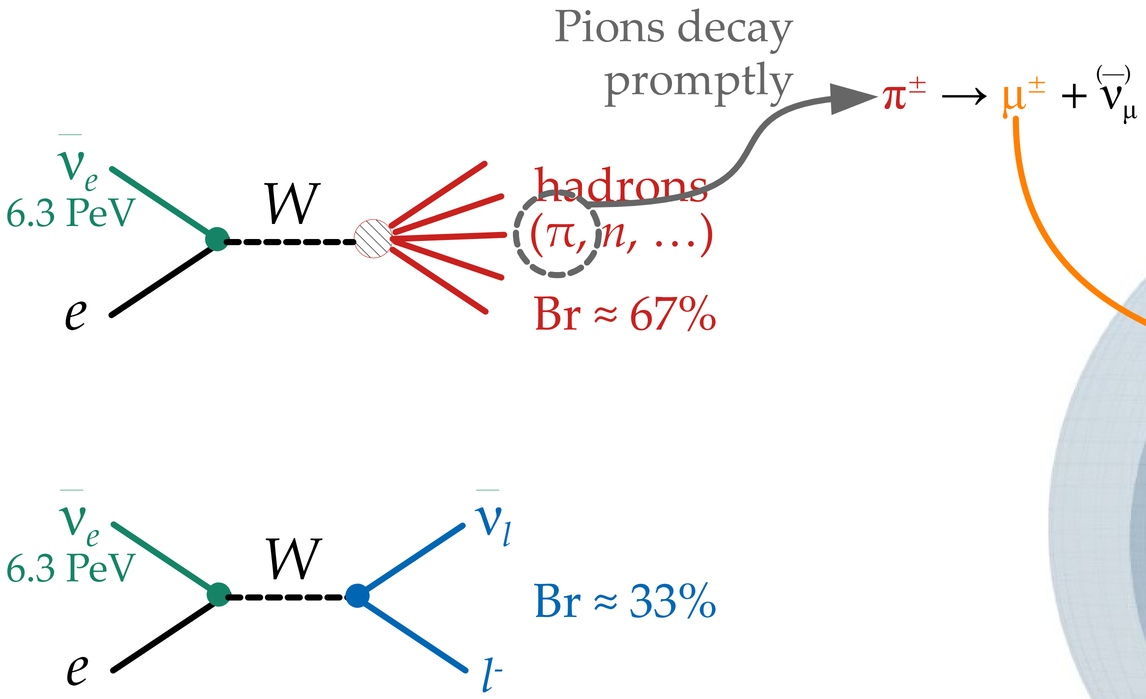


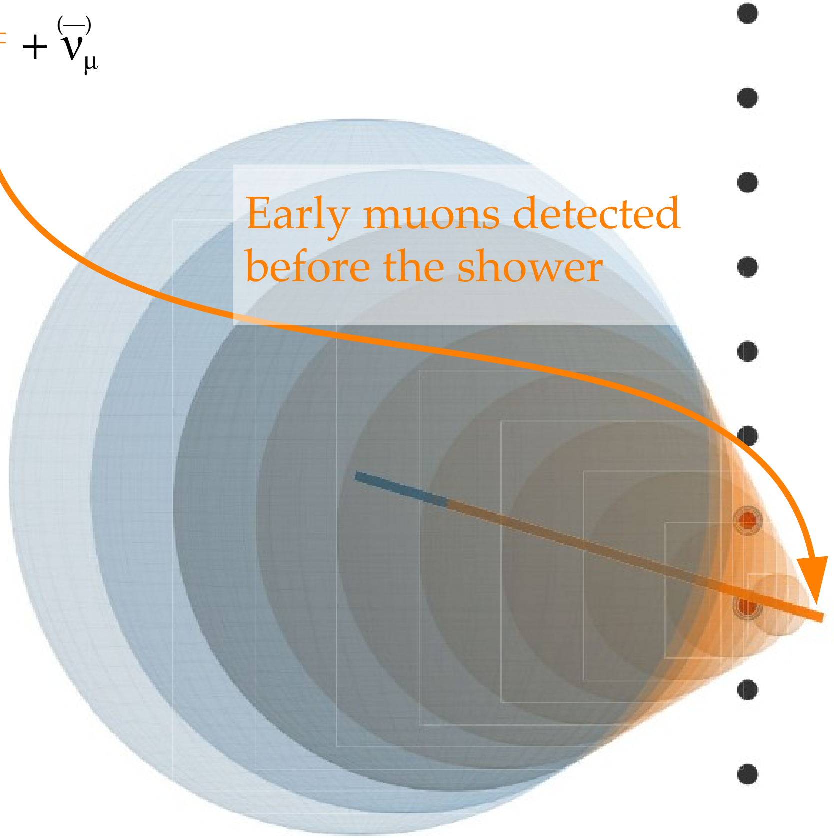
IceCube, *Nature* 2021
Glashow, *PR* 1960

First observation of a Glashow resonance

Predicted in 1960:

First reported by IceCube in 2021:





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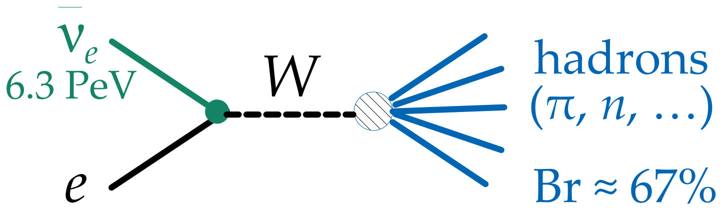

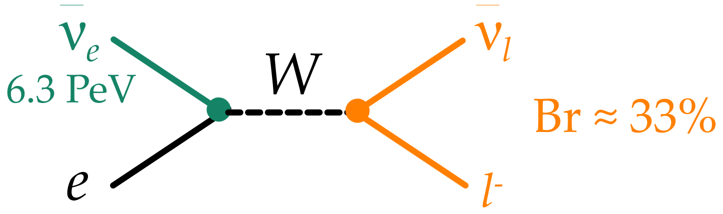

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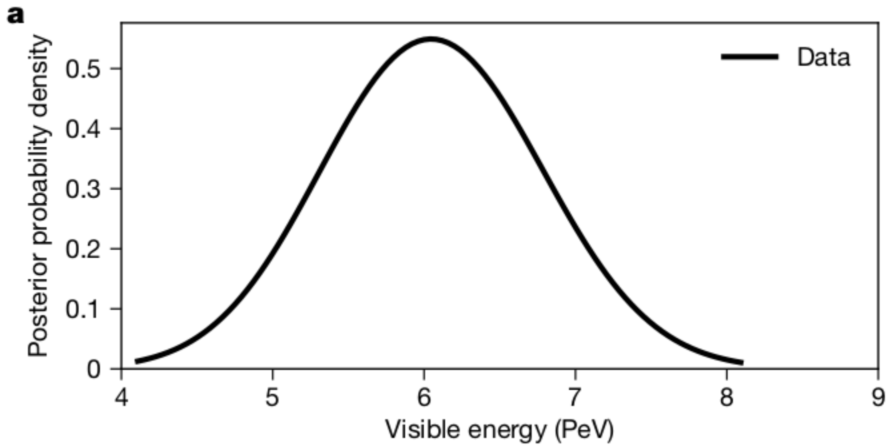

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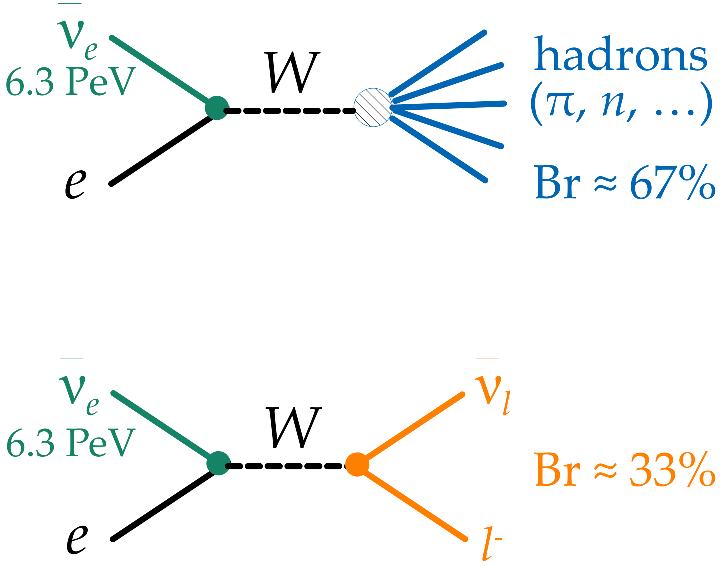
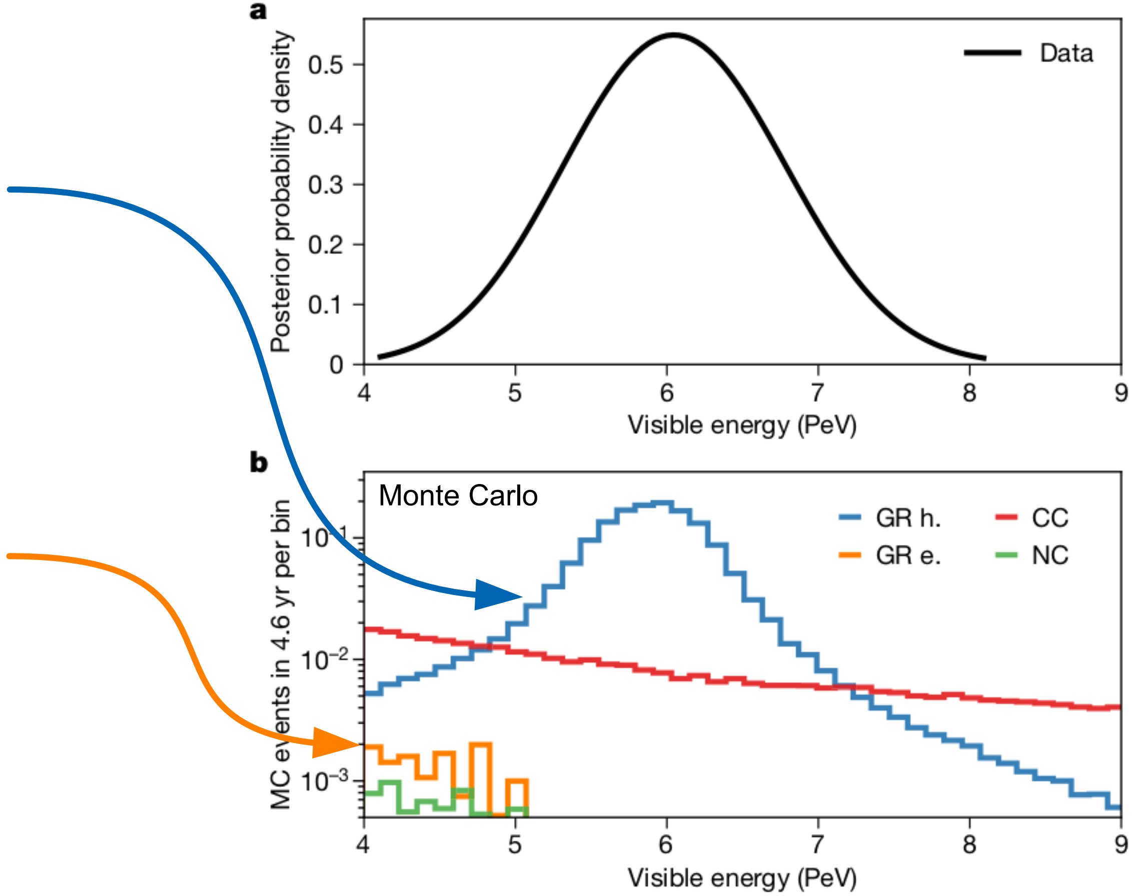


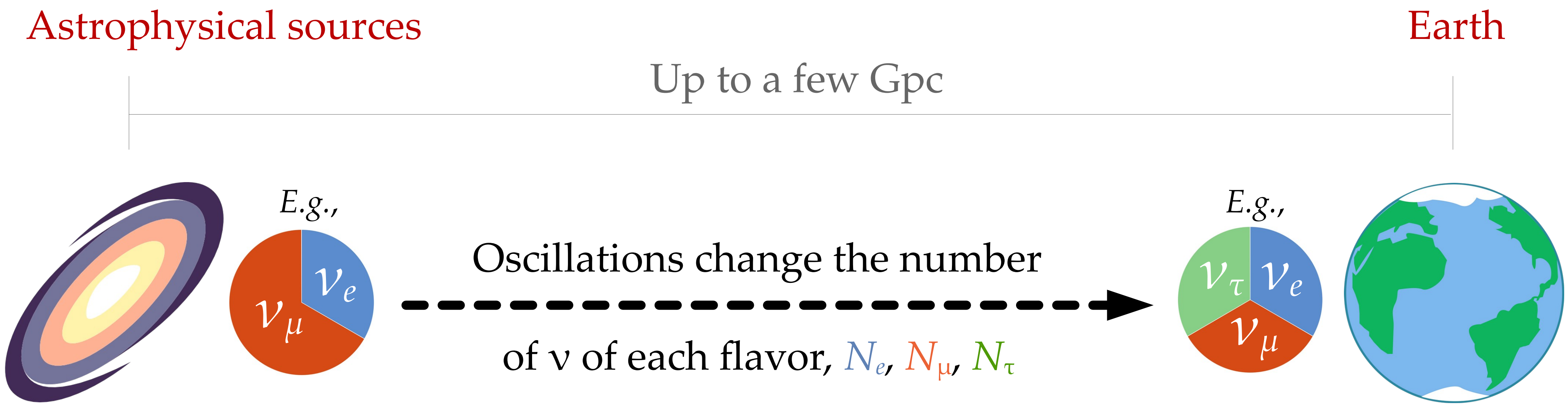
First reported by IceCube in 2021:



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

3. New physics via flavor

Hard to do, but worth it

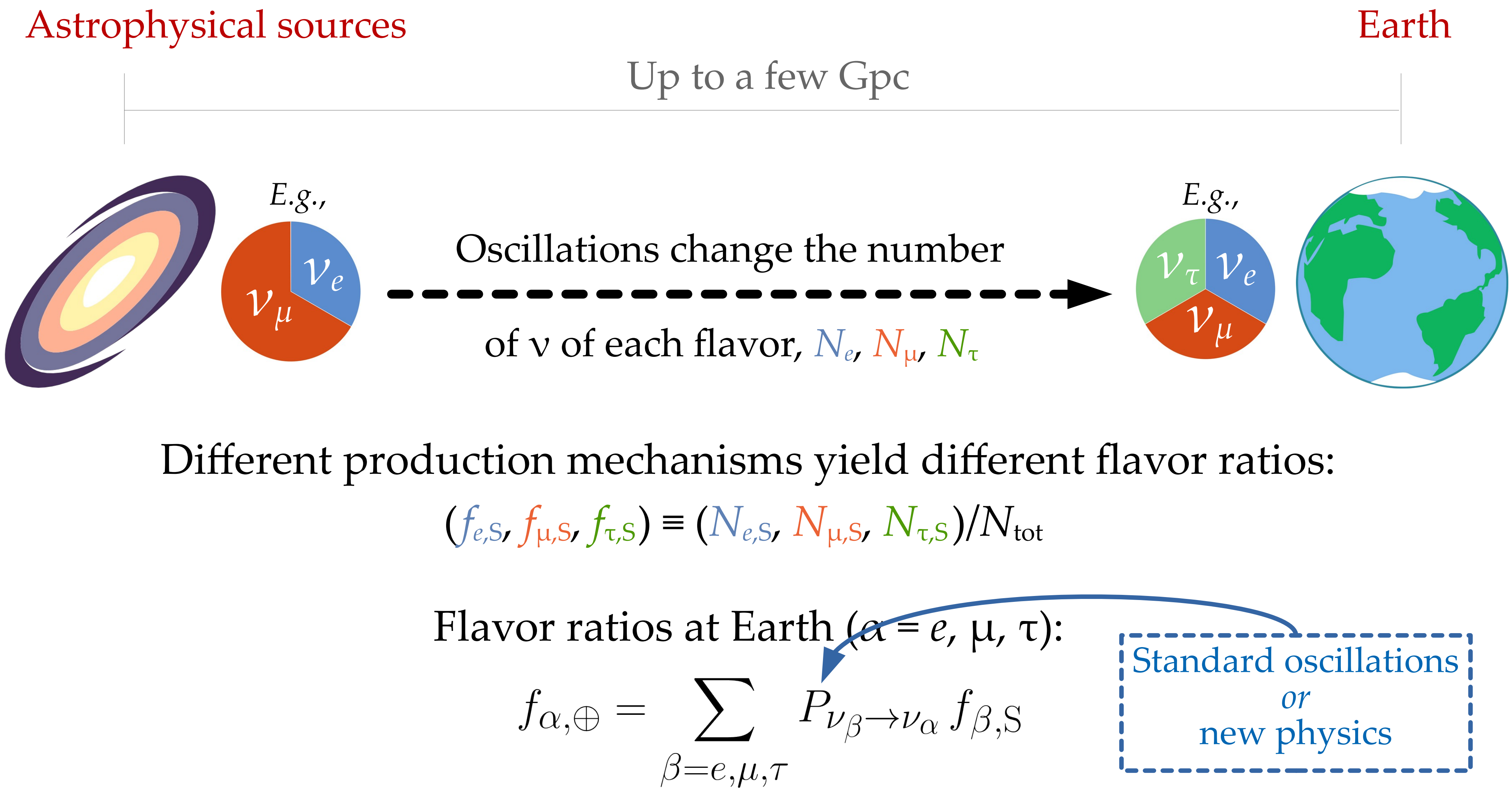


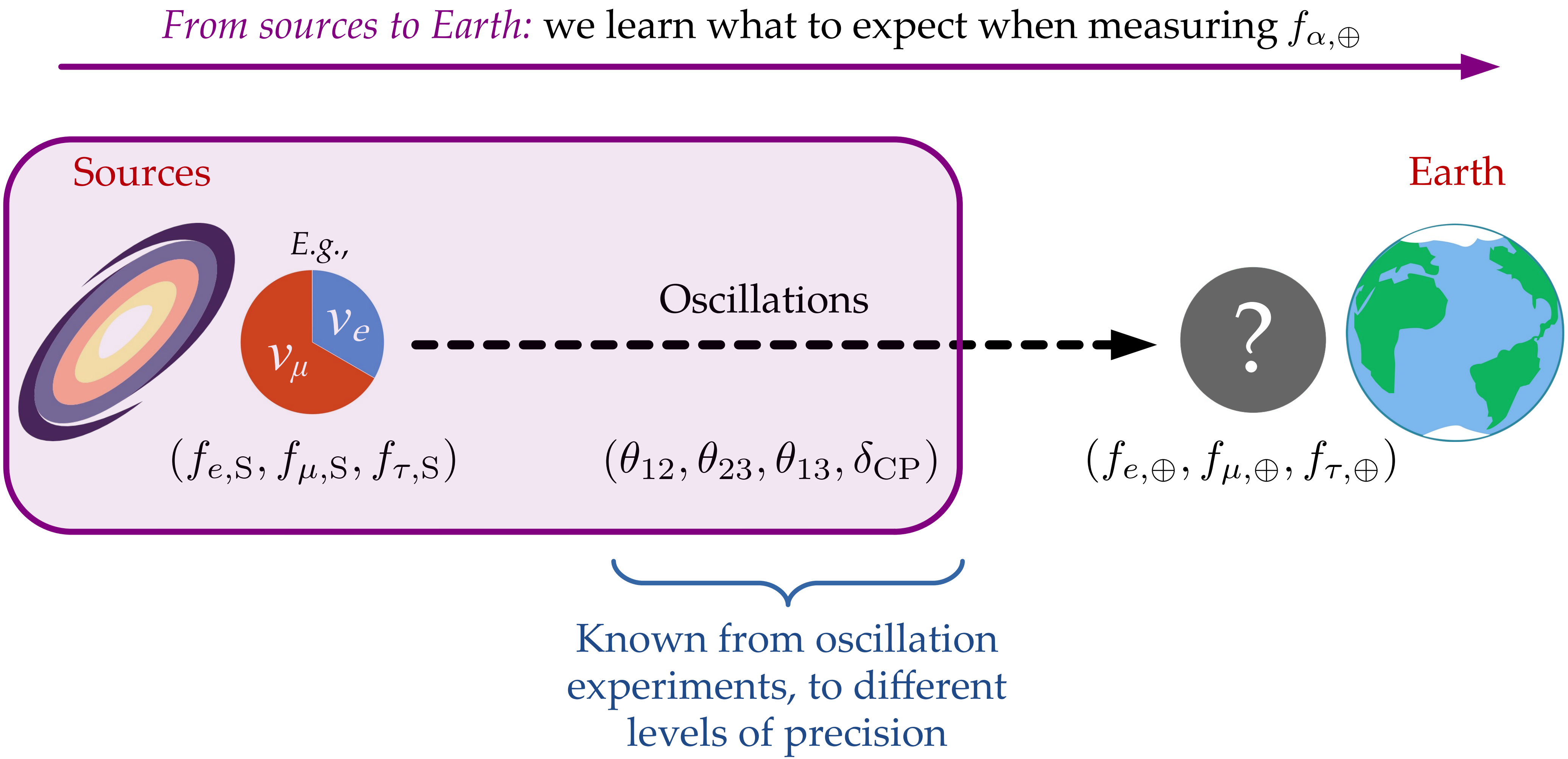
Different production mechanisms yield different flavor ratios:

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

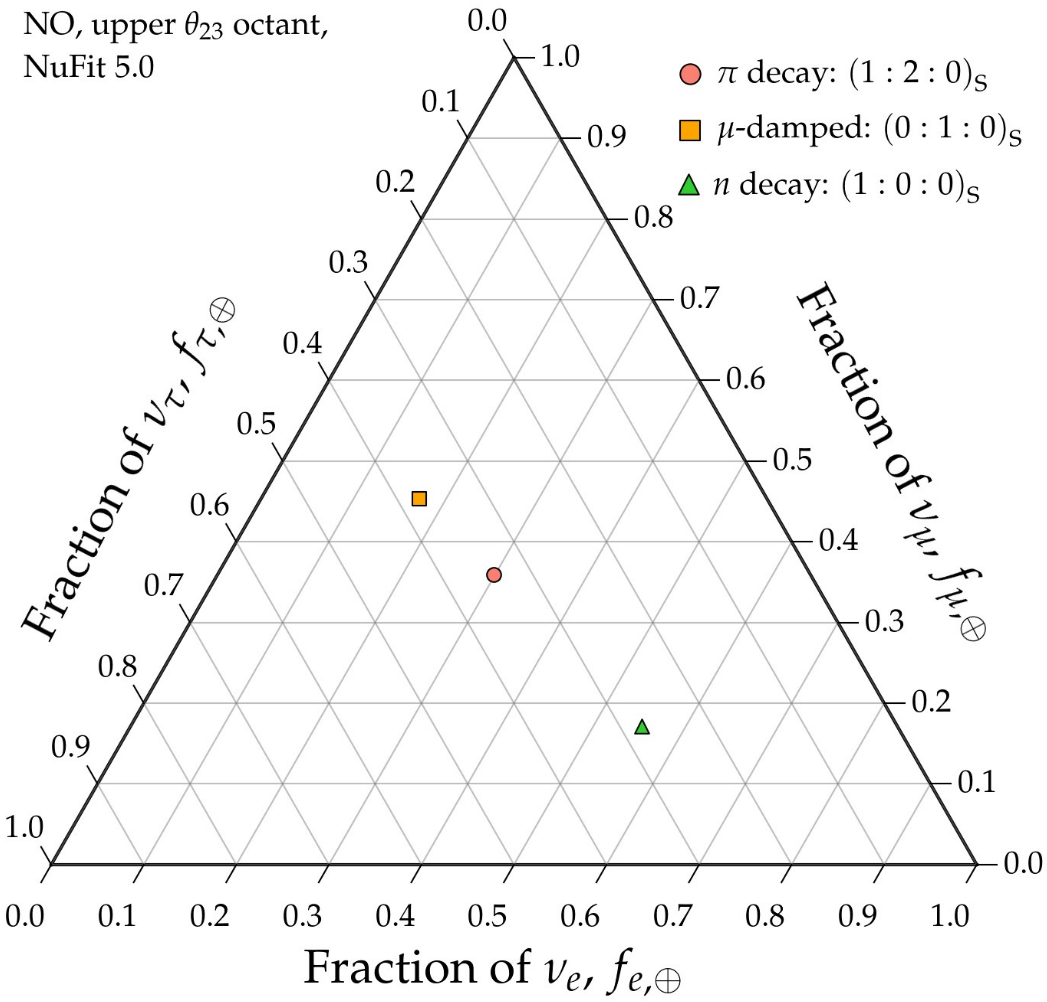
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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


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


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

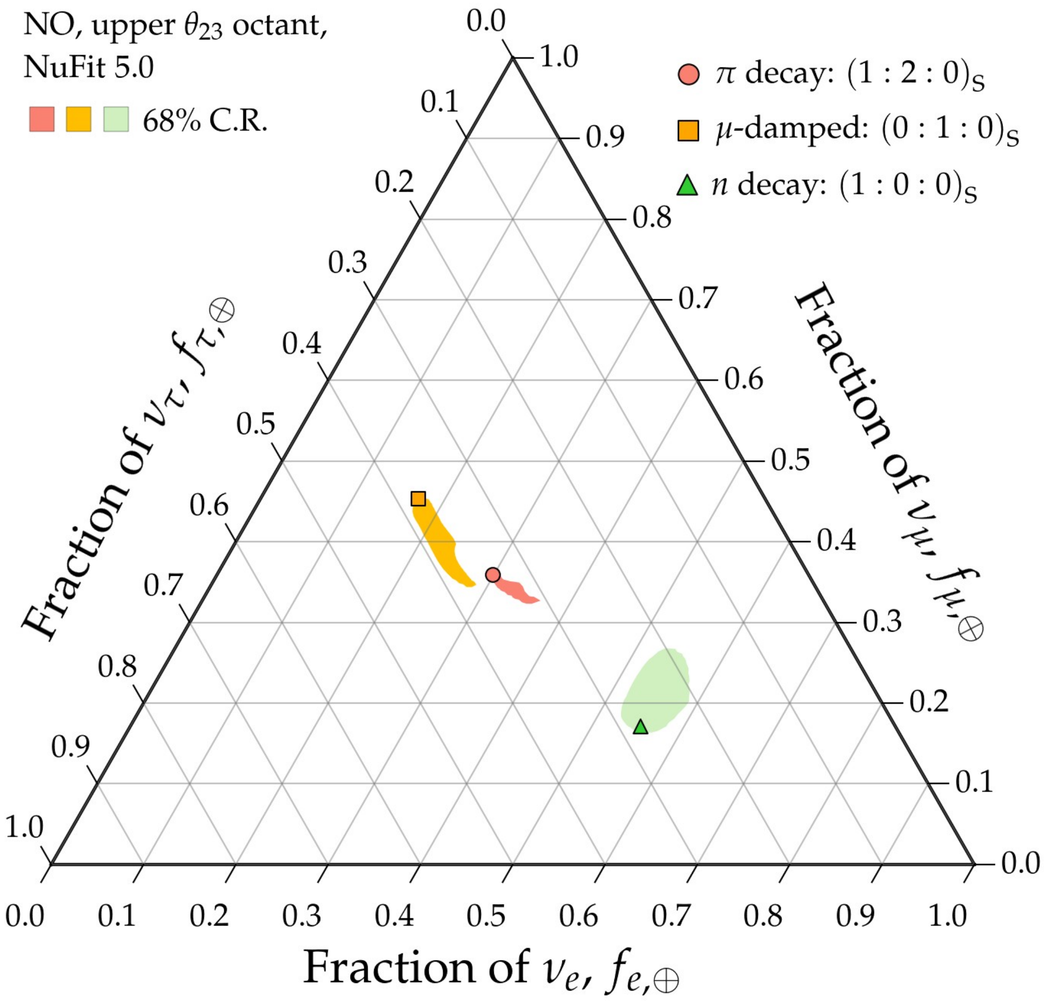
Theoretically palatable regions: today



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

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

Theoretically palatable regions: today



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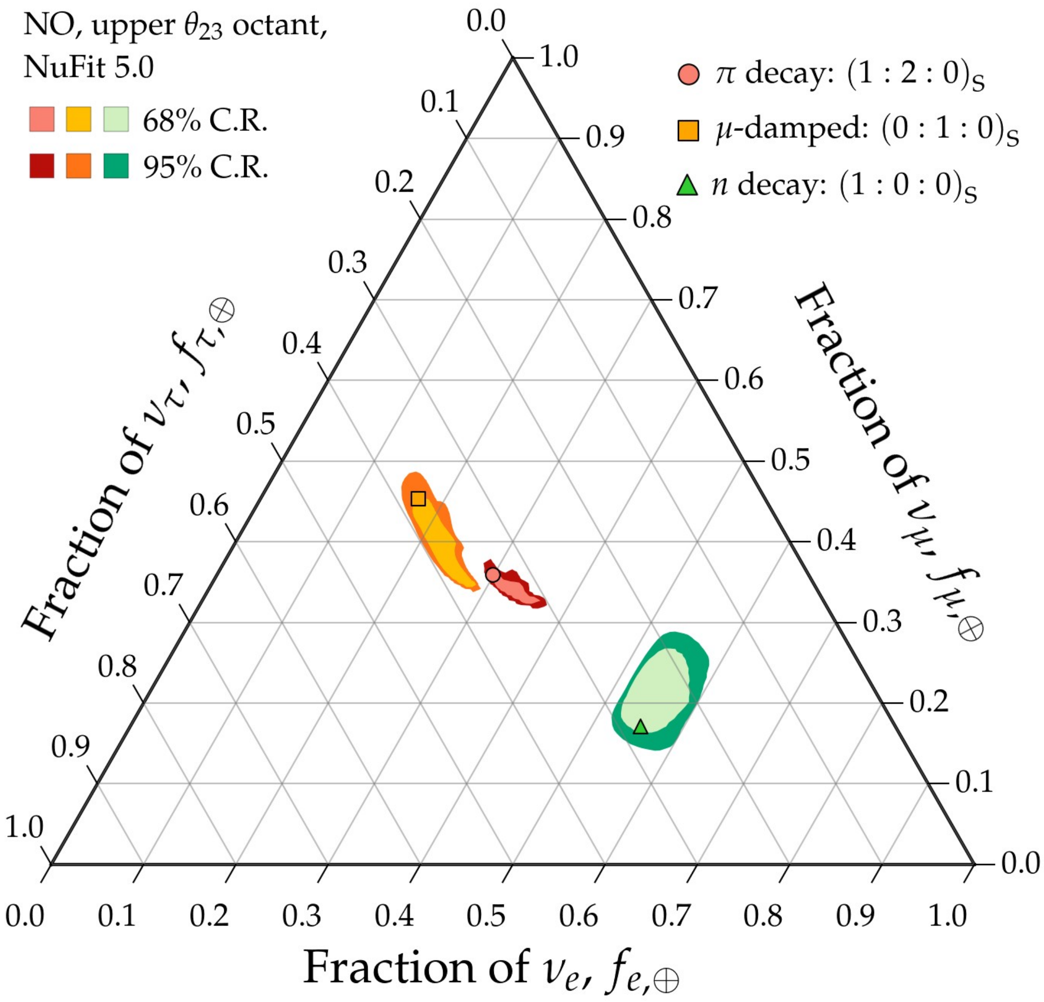

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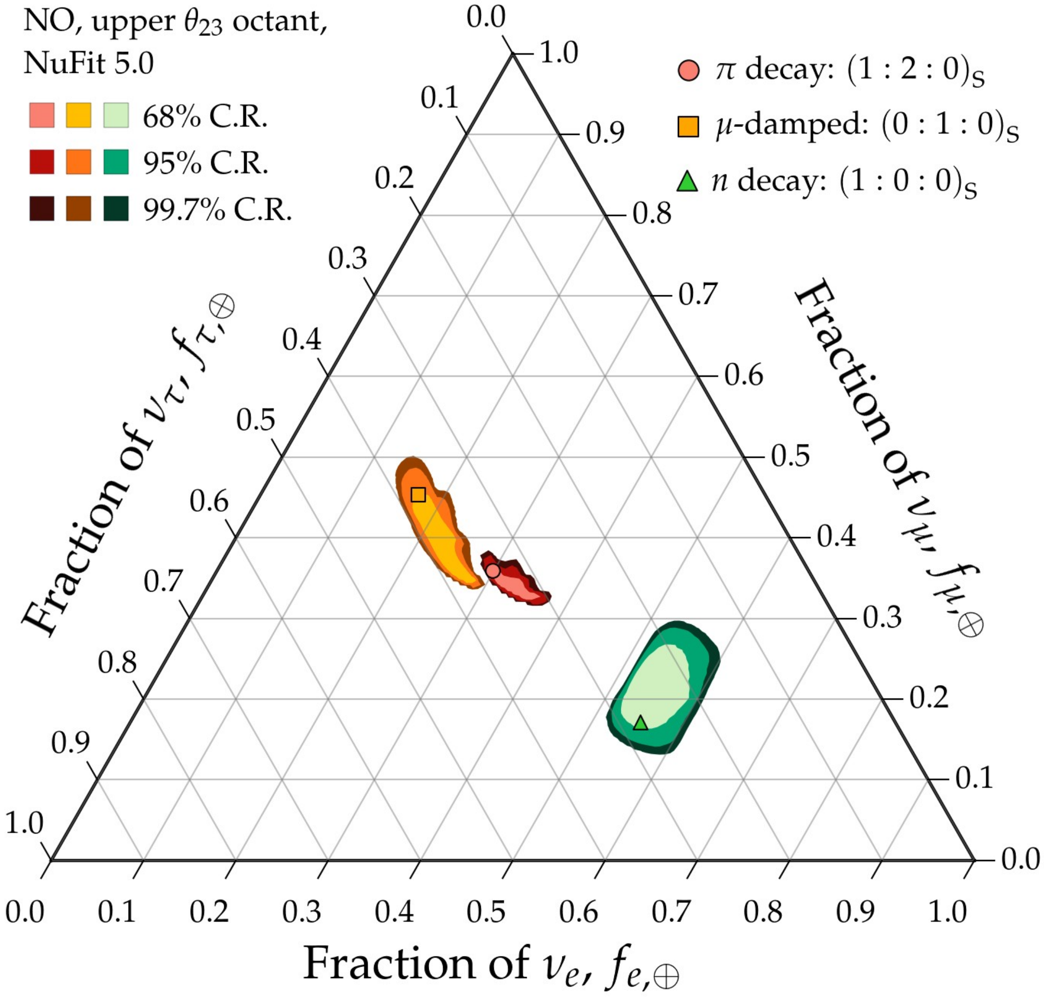
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: today



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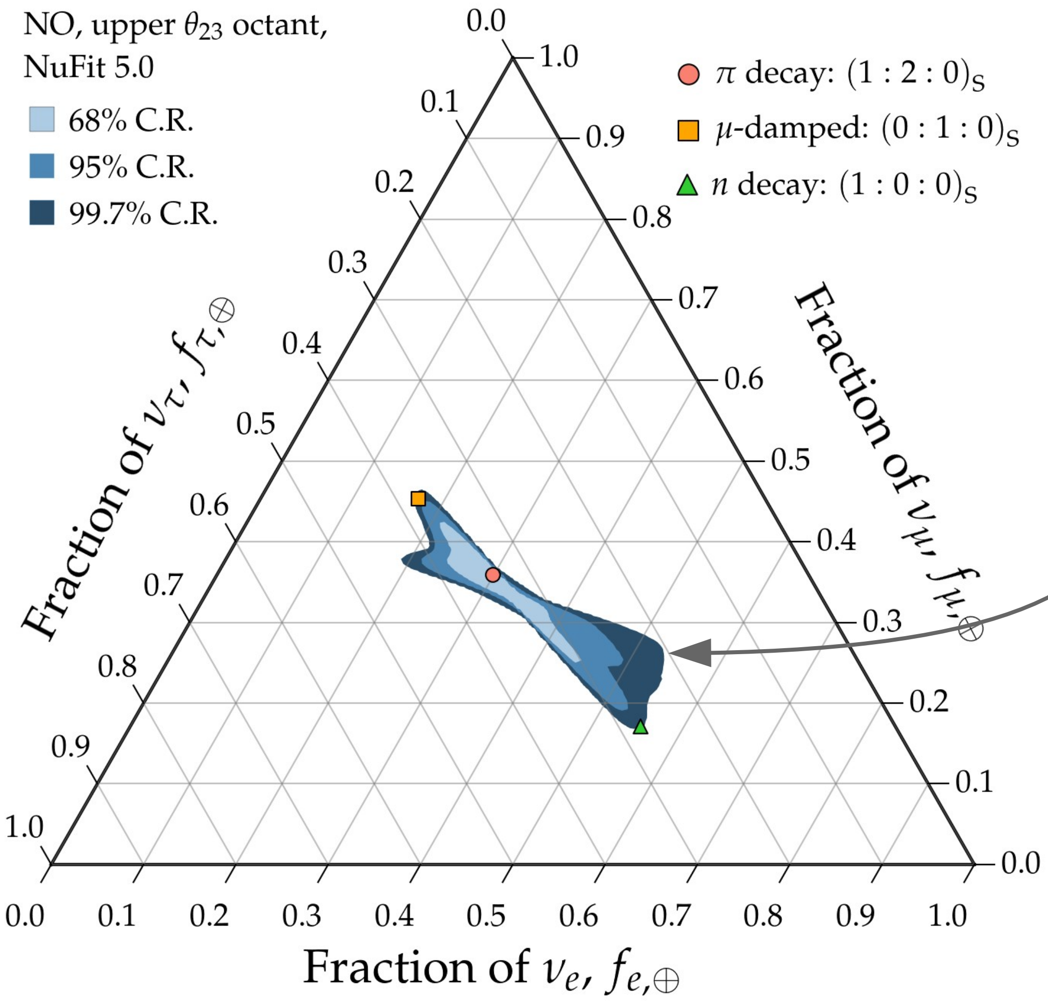


Varying over all possible flavor ratios at the source

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

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

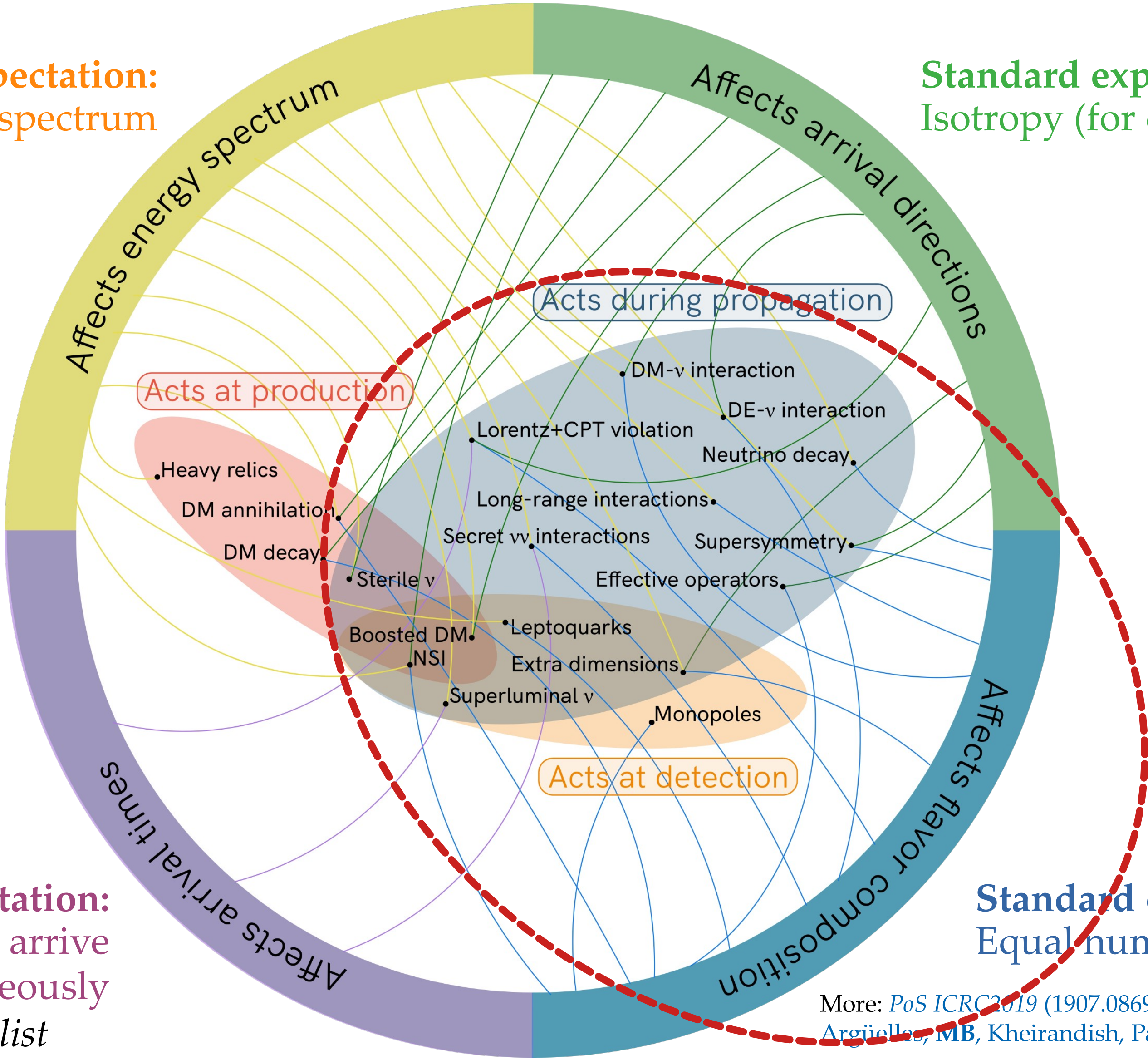
Theoretically palatable regions: today

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

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

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

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

Note: Not an exhaustive list

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

New physics in flavor composition

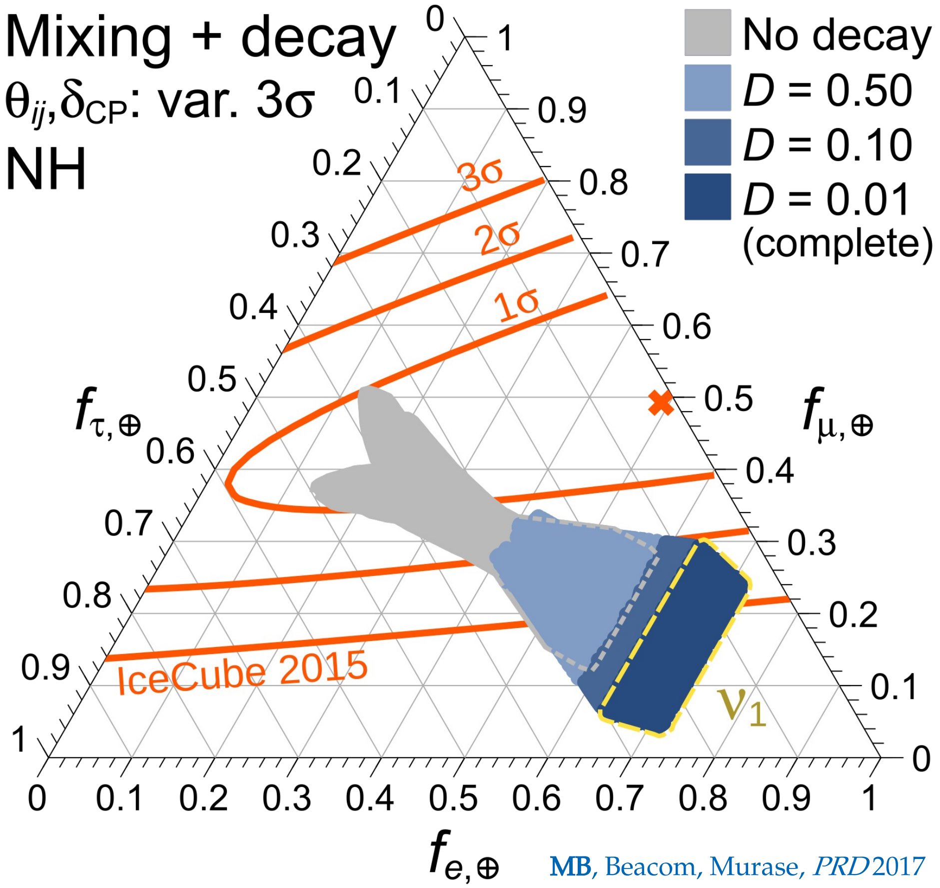
Use the flavor sensitivity to test new physics:

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

New physics in flavor composition

Use 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

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

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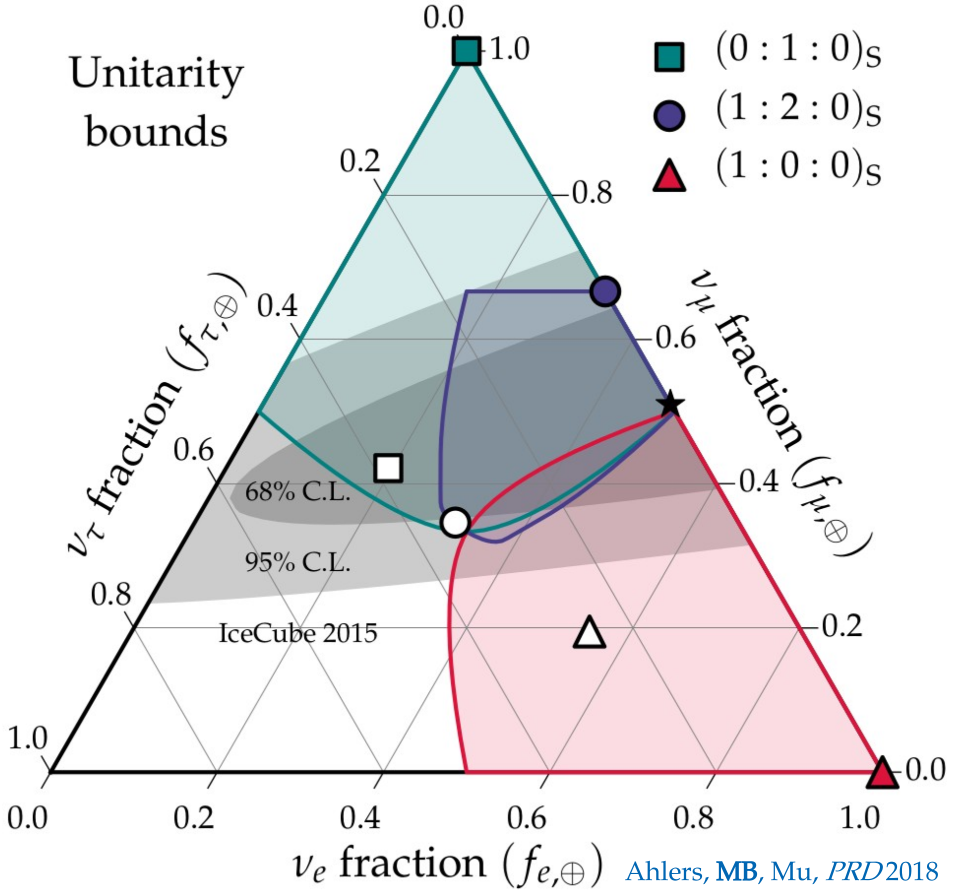
- ▸ Tests of unitarity at high energy
  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, ***MB***, Mu, *PRD* 2018; Ahlers, ***MB***, Nortvig, *JCAP* 2021]



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

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

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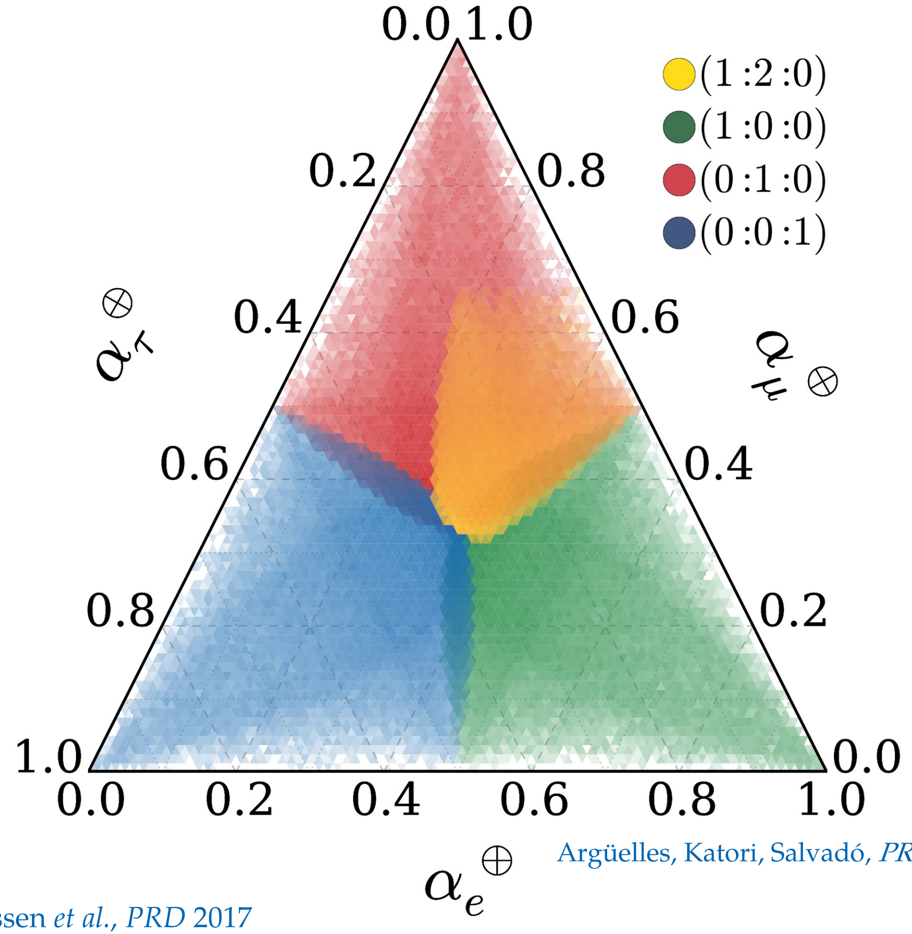
- Lorentz- and CPT-invariance violation
  [Barenboim & Quigg, *PRD* 2003; ***MB***, Gago, Peña-Garay, *JHEP* 2010; Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]



Argüelles, Katori, Salvadó, *PRL* 2015

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

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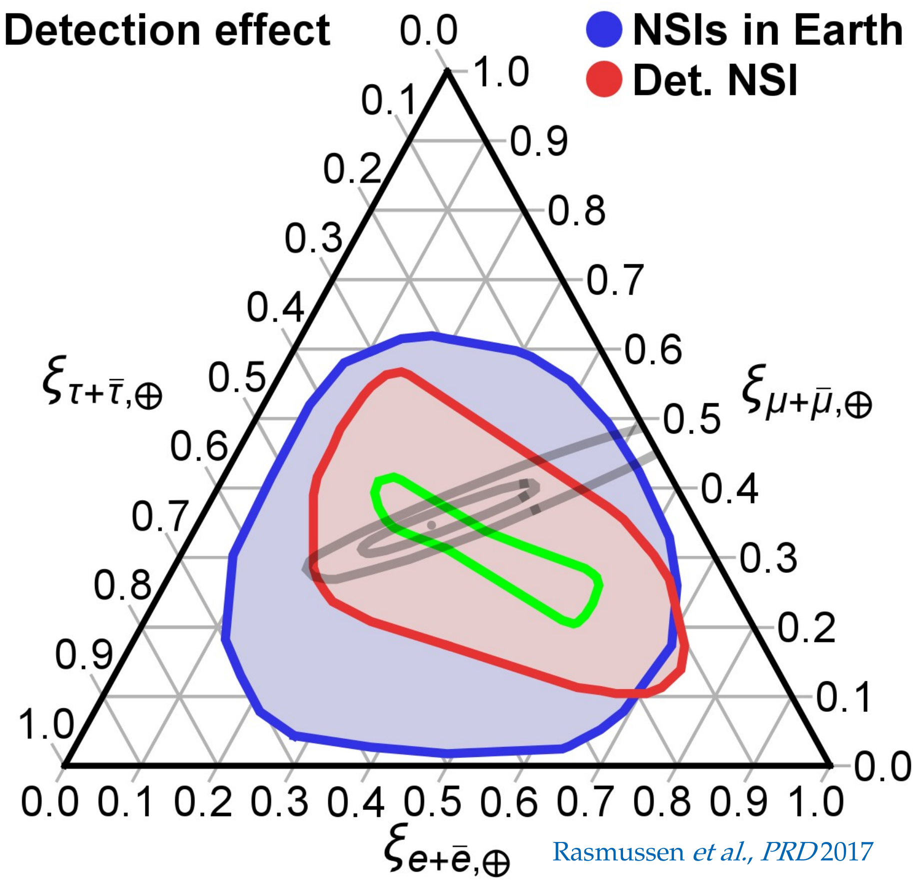
- ▸ Non-standard interactions
  [González-García *et al.*, *Astropart. Phys.* 2016; Rasmussen *et al.*, *PRD* 2017]



Rasmussen *et al.*, *PRD* 2017

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

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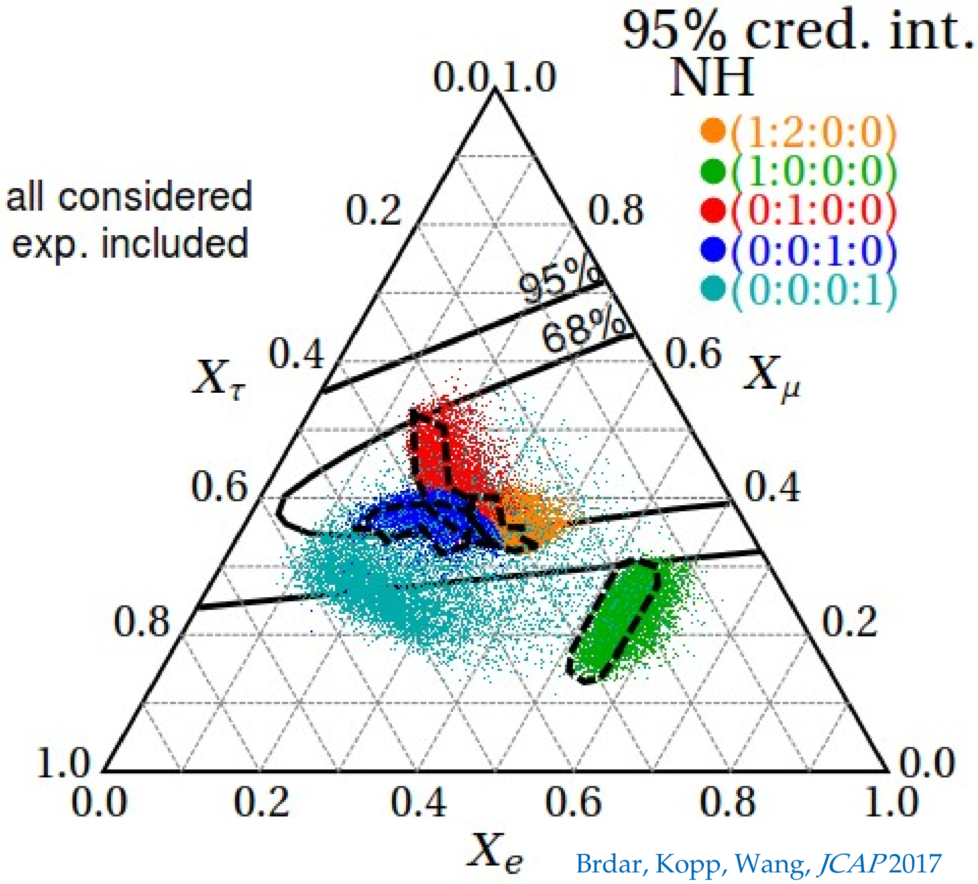
- **Active-sterile ν mixing**
  [Aeikens *et al.*, *JCAP* 2015; Brdar, Kopp, Wang, *JCAP* 2017; Argüelles *et al.*, *JCAP* 2020; Ahlers, ***MB***, *JCAP* 2021]



Brdar, Kopp, Wang, *JCAP* 2017

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

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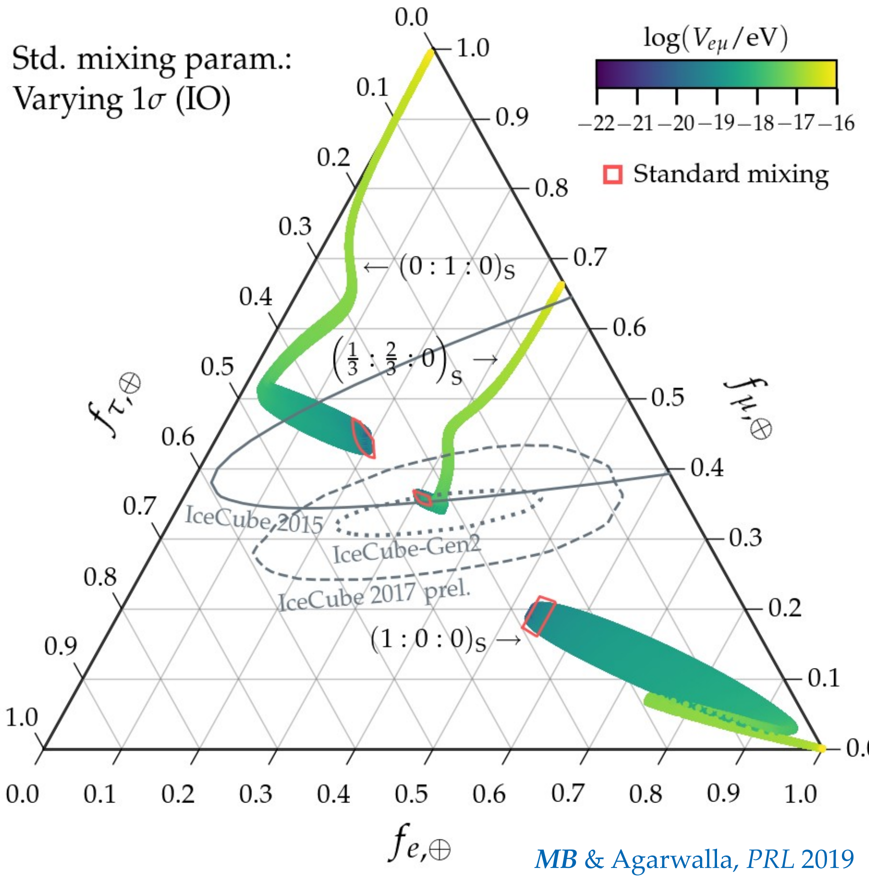
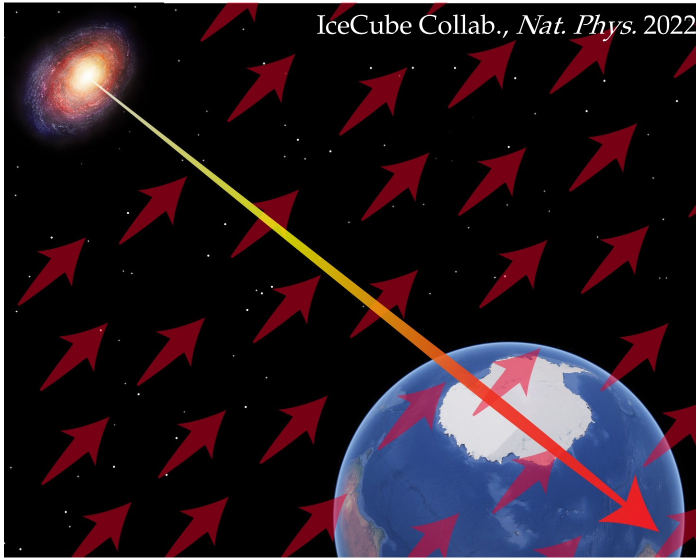
  [Aeikens *et al.*, *JCAP* 2015; Brdar, Kopp, Wang, *JCAP* 2017; Argüelles *et al.*, *JCAP* 2020; Ahlers, ***MB***, *JCAP* 2021]
- Long-range *e*ν interactions
  [***MB*** & Agarwalla, *PRL* 2019]



MB & Agarwalla, *PRL* 2019

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

Lorentz-invariance violation can fill up the flavor triangle

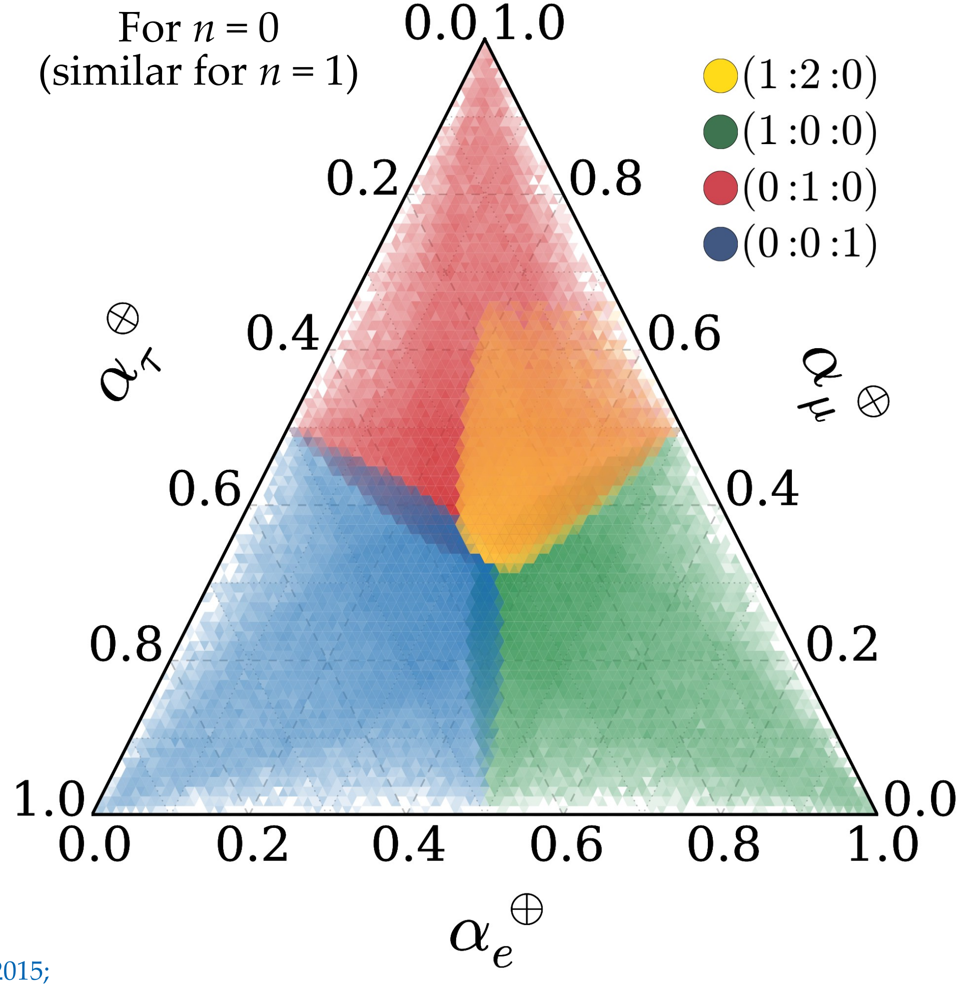


$$H_{\text{tot}} = H_{\text{std}} + H_{\text{NP}}$$

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

$$H_{\text{NP}} = \sum_n \left(\frac{E}{\Lambda_n}\right)^n U_n^{\dagger}\, \text{diag}\left(O_{n,1}, O_{n,2}, O_{n,3}\right) U_n$$

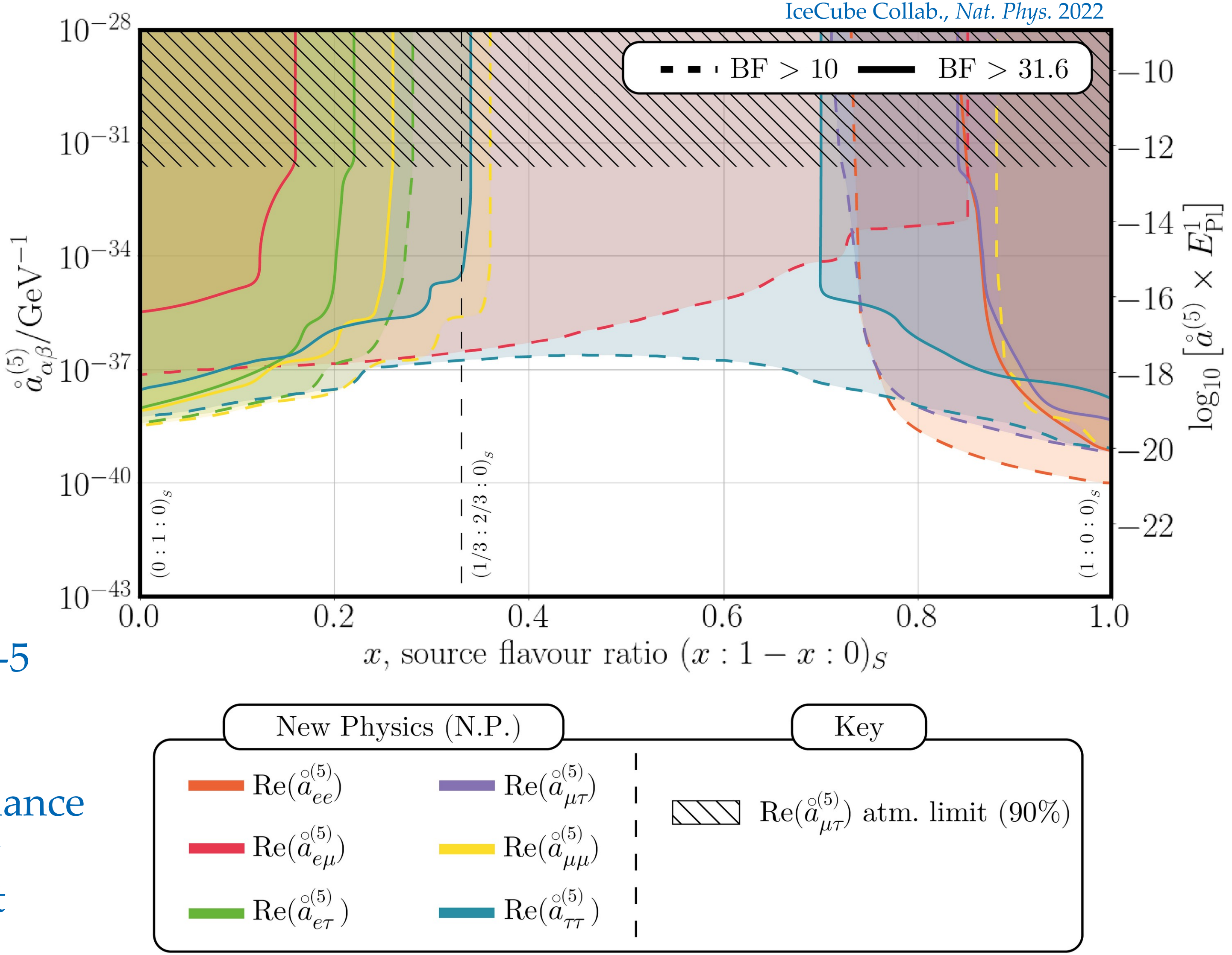
For $n = 0$
(similar for $n = 1$)



Argüelles, Katori, Salvadó, *PRL* 2015

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

IceCube Collab., *Nat. Phys.* 2022

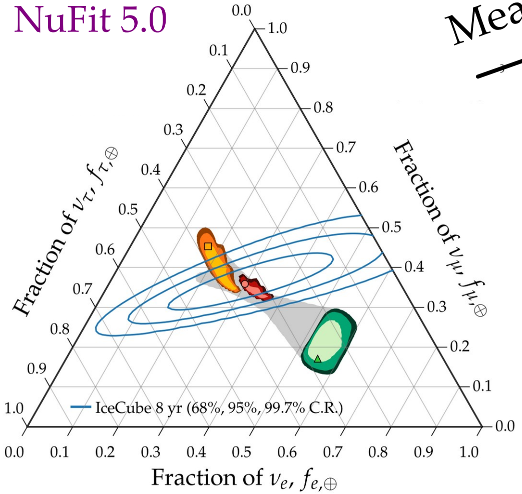


Dimension-5
CPT-odd
isotropic
Lorentz-invariance
-violating
coefficient

How knowing the mixing parameters better helps

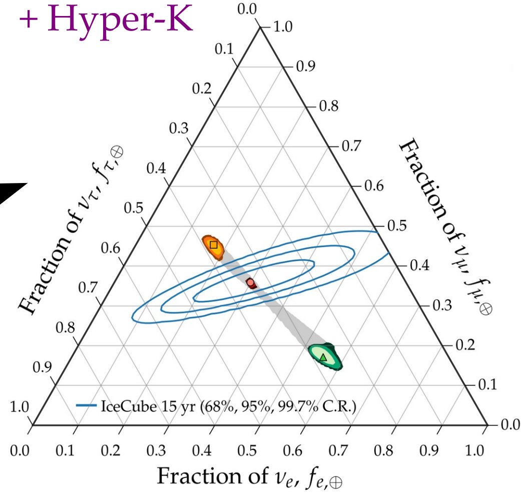
2020

NuFit 5.0



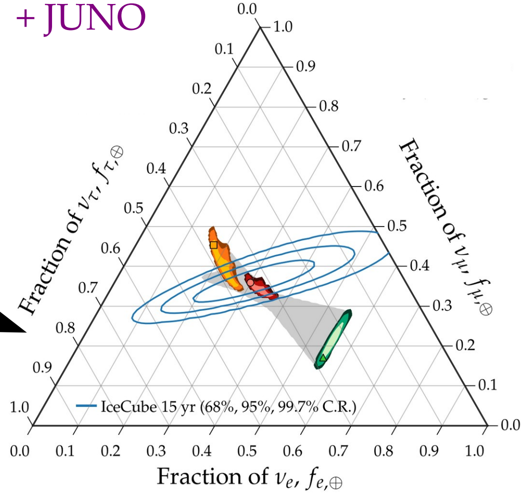
Measure θ_{23} better

+ Hyper-K



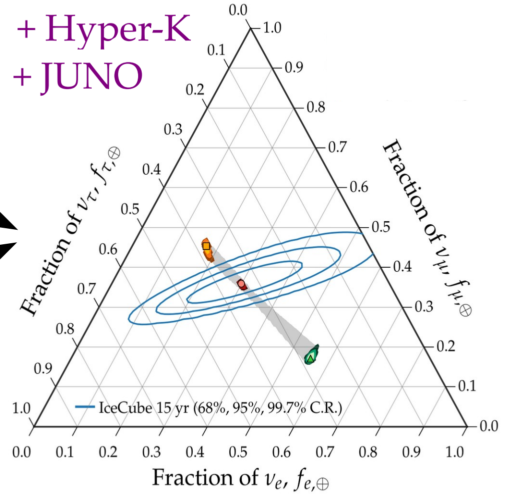
Measure θ_{12} better

+ JUNO



~2030

+ Hyper-K
+ JUNO



In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

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

4. New neutrino interactions:
Are there secret $\nu\nu$ *interactions?*

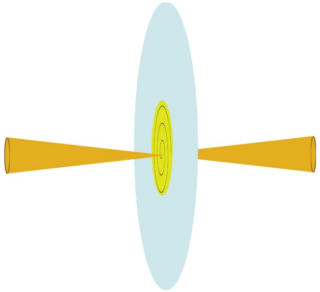
Astrophysical neutrino sources

Earth

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

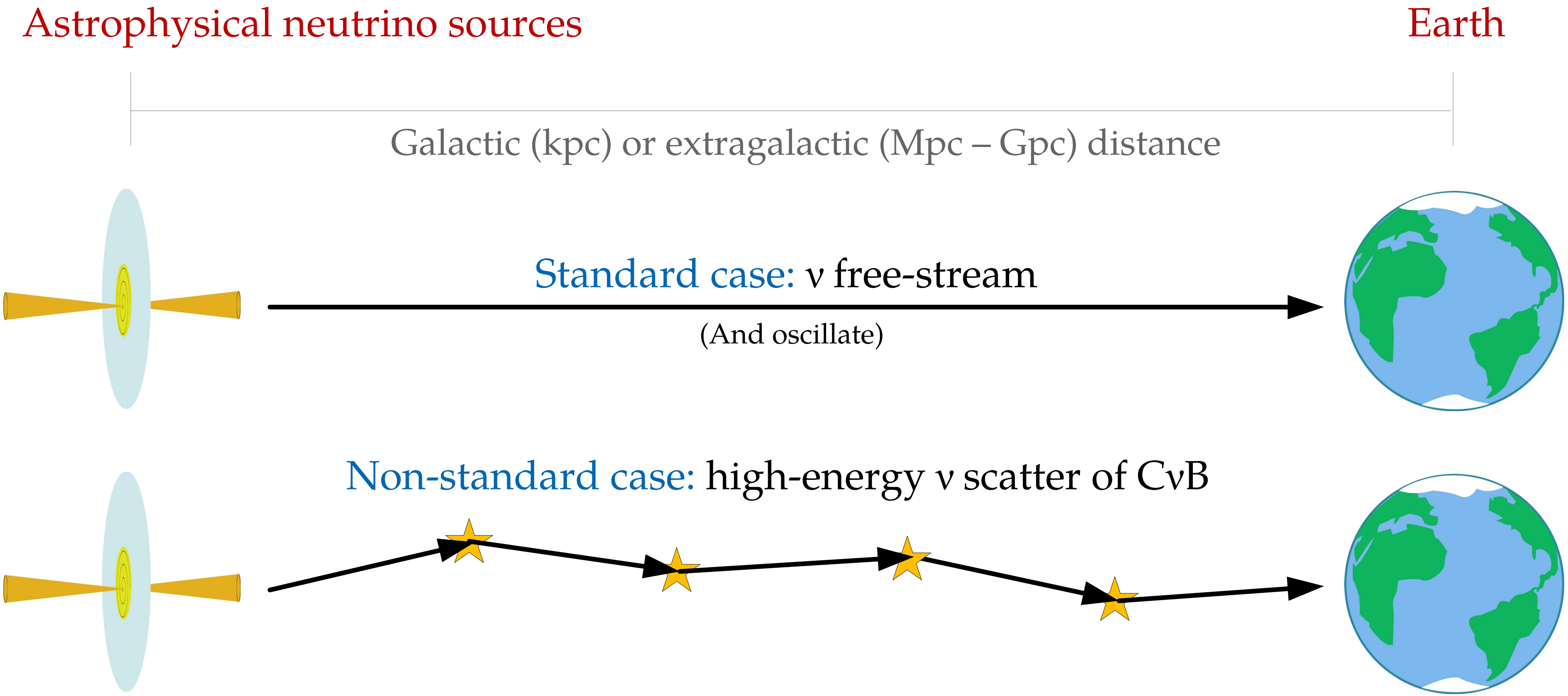
Astrophysical neutrino sources Earth

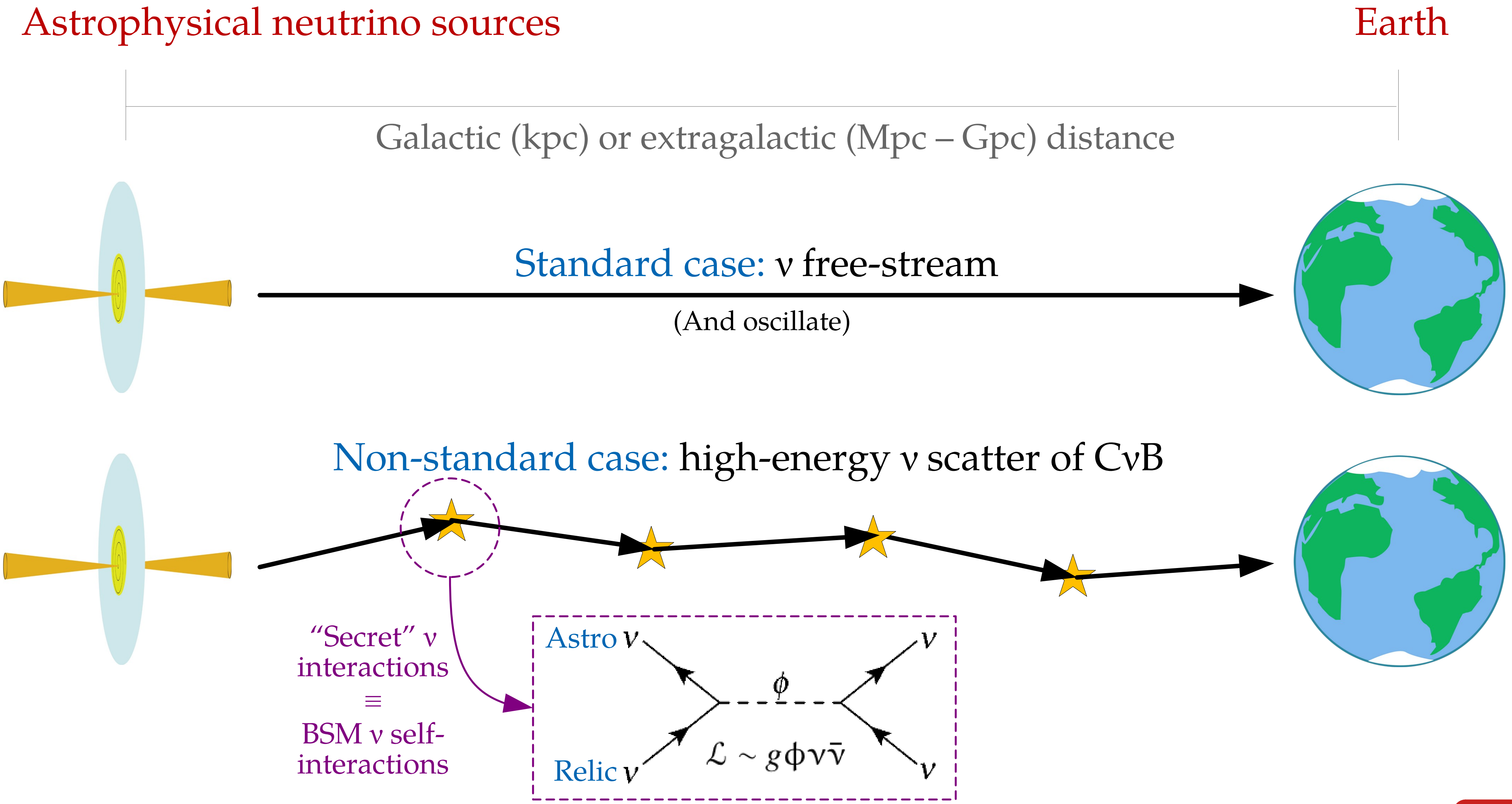
Galactic (kpc) or extragalactic (Mpc – Gpc) distance

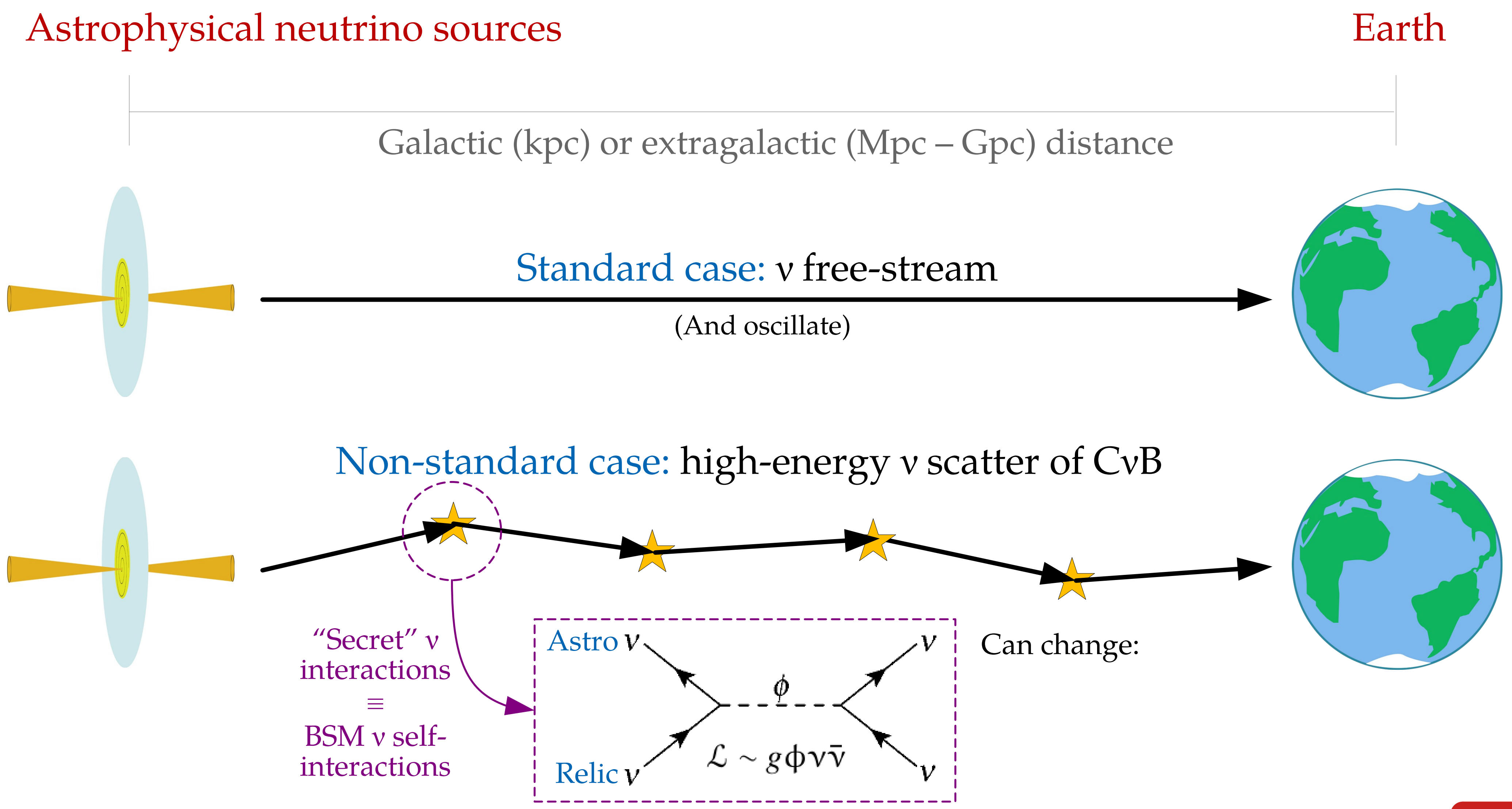


Standard case: ν free-stream

(And oscillate)


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


Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
(And oscillate)
Non-standard case: high-energy ν scatter of CνB
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$



Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
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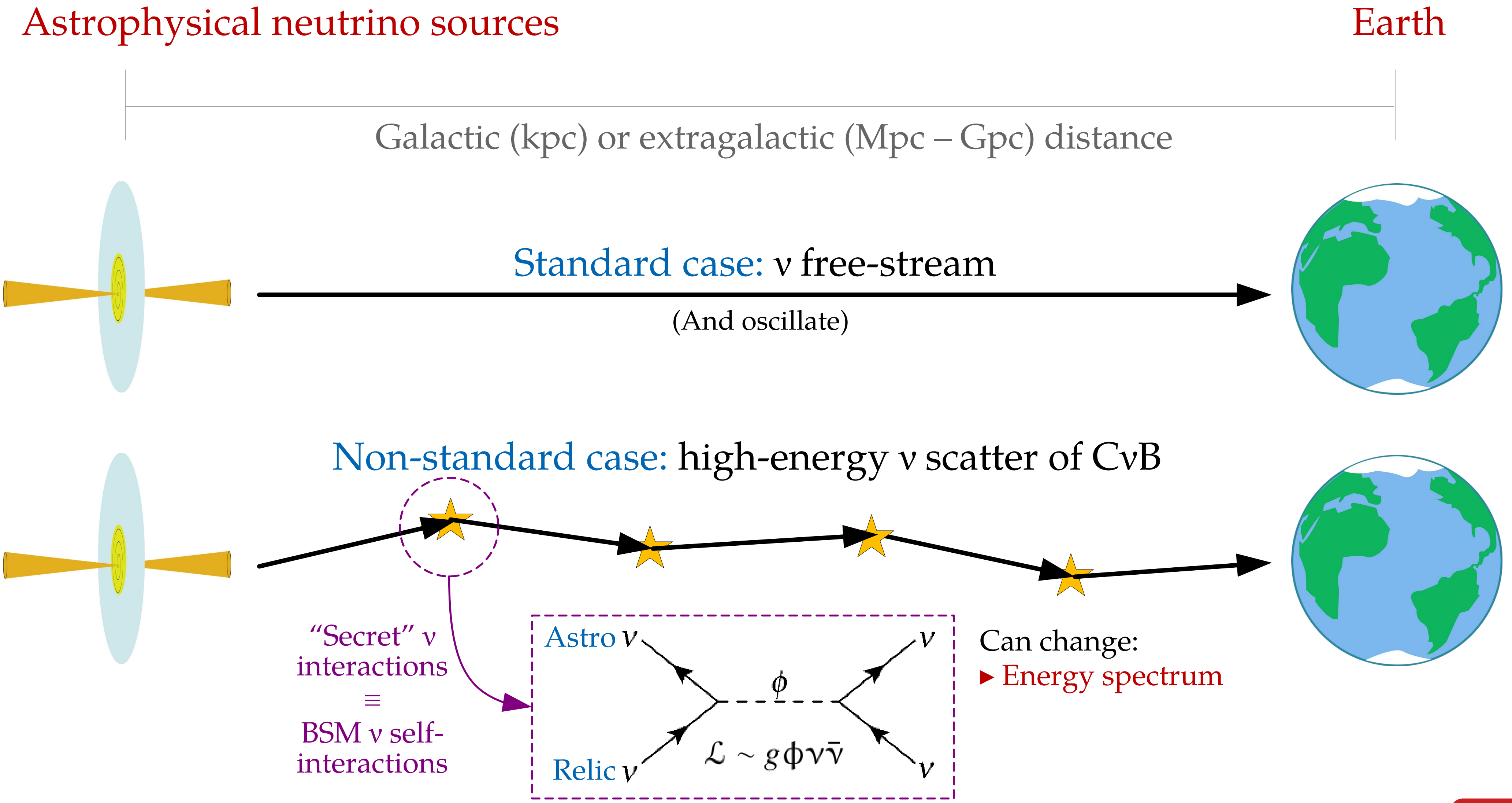
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
ν
ϕ
Relic ν
ν
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change: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Astro ν
Relic ν
ν
ν
ϕ
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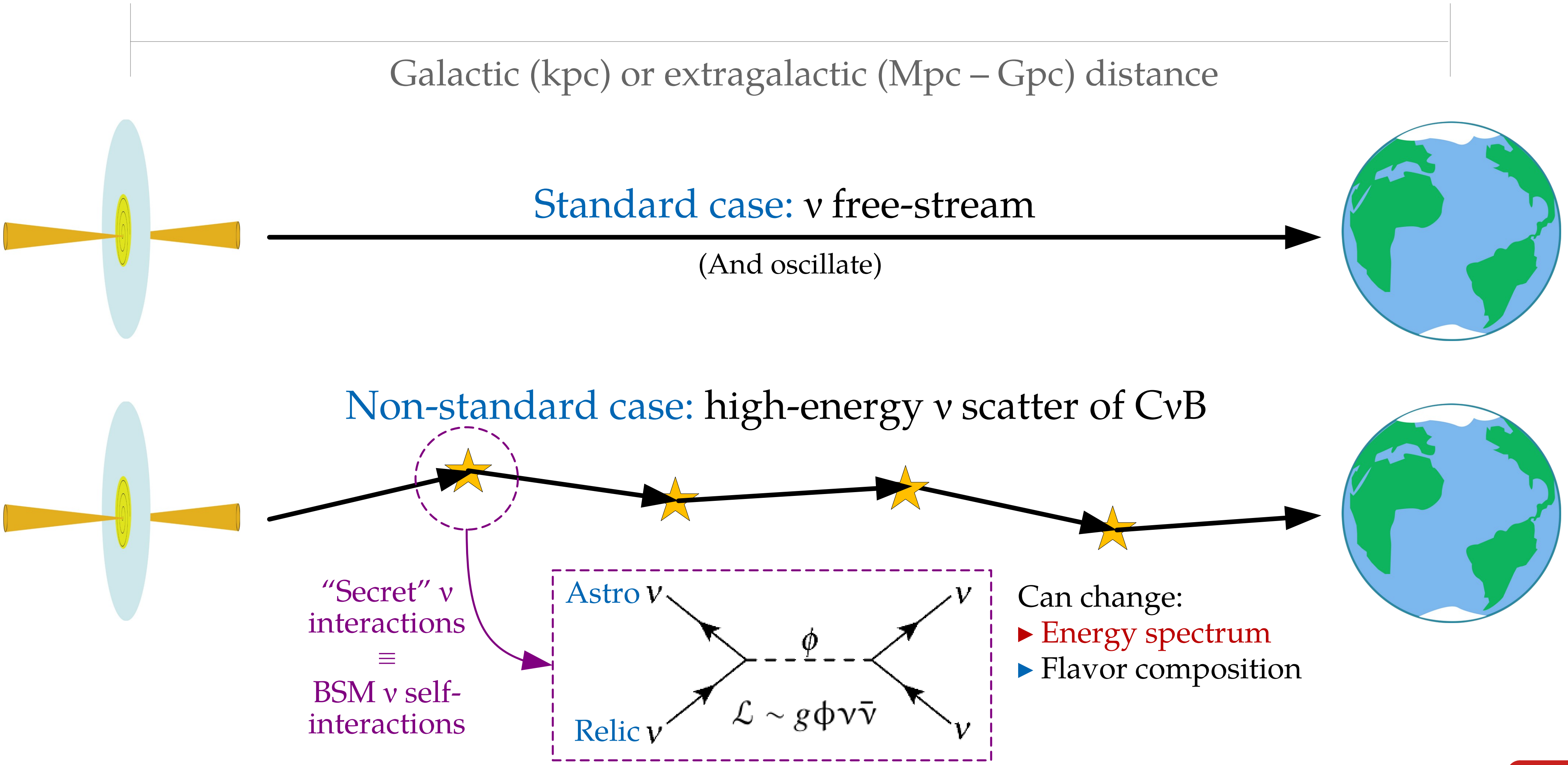
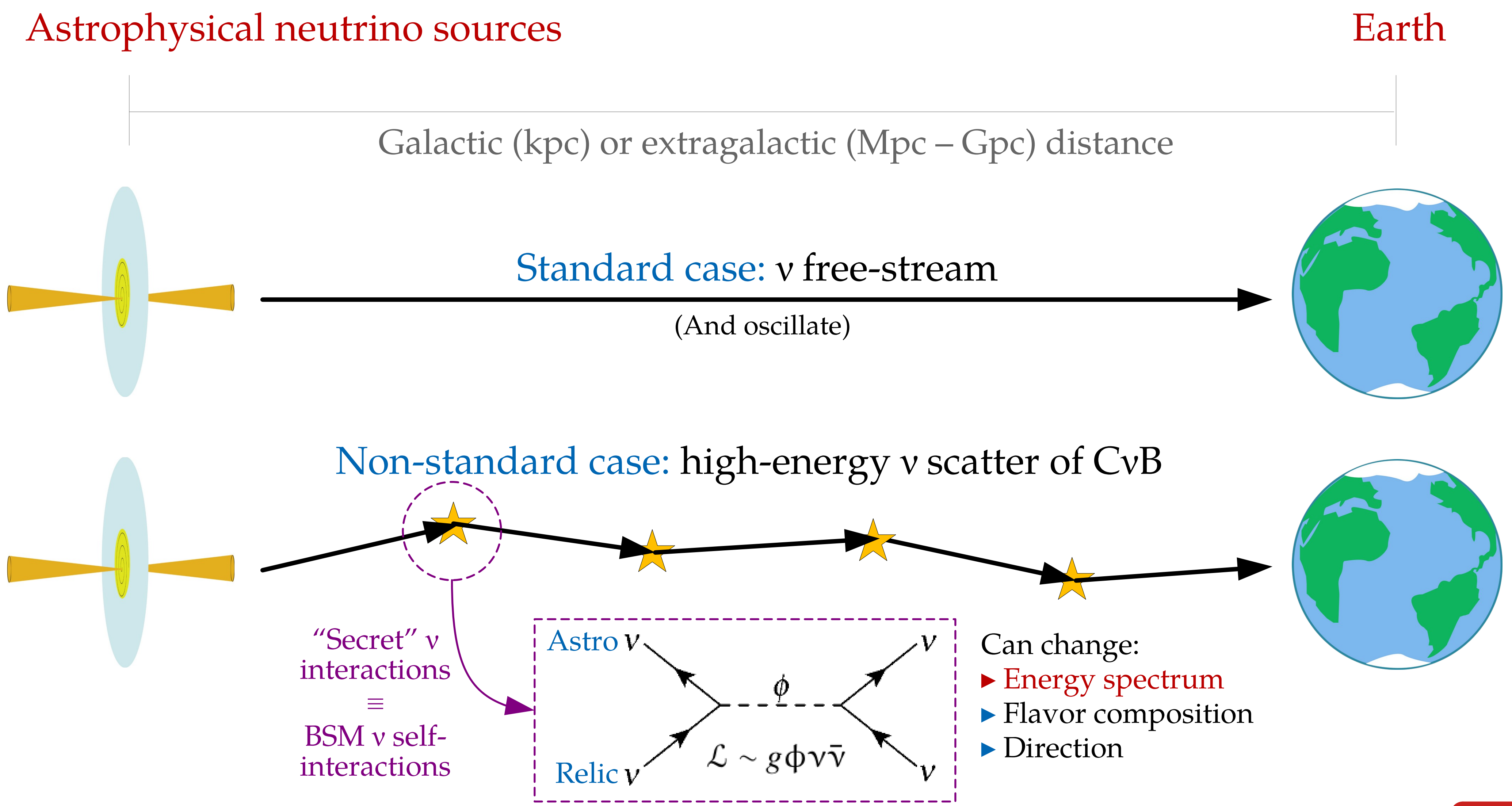
Can change:
▸ Energy spectrum

Astrophysical neutrino sources — Earth

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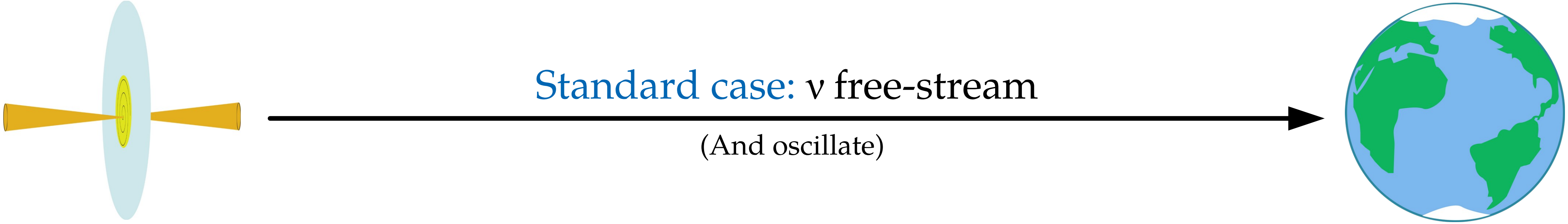
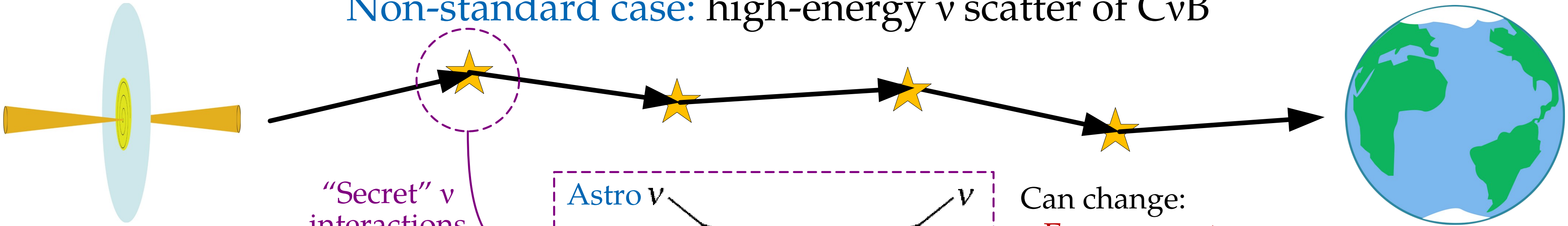
Astro ν
Relic ν
ν
ν
ϕ
ℒ ~ gϕνν̄
Can change:
▸ Energy spectrum
▸ Flavor composition
▸ Direction

Astrophysical neutrino sources — Earth

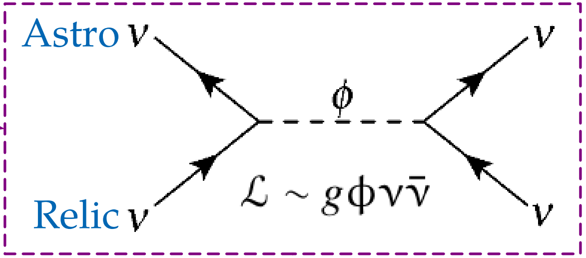
Galactic (kpc) or extragalactic (Mpc – Gpc) distance



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



"Secret" ν interactions
≡
BSM ν self-interactions

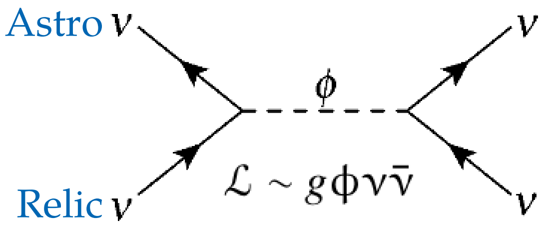


Can change:

- Energy spectrum
- Flavor composition
- Direction
- Arrival times

Secret interactions of high-energy astrophysical neutrinos

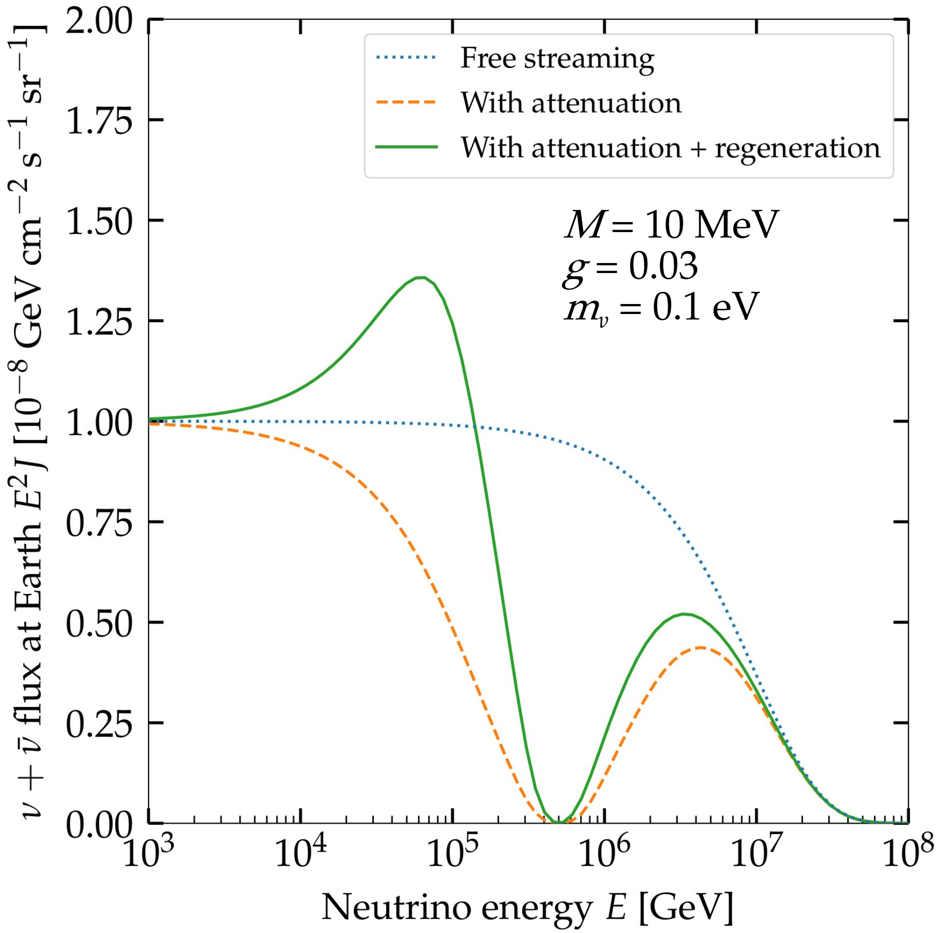
"Secret" neutrino interactions between astrophysical ν (PeV) and relic ν (0.1 meV):



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

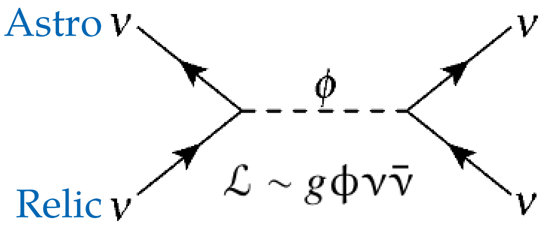
Resonance energy: $E_{\rm res} = \frac{M^2}{2m_\nu}$

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



Secret interactions of high-energy astrophysical neutrinos

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



New coupling

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

Mediator mass

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

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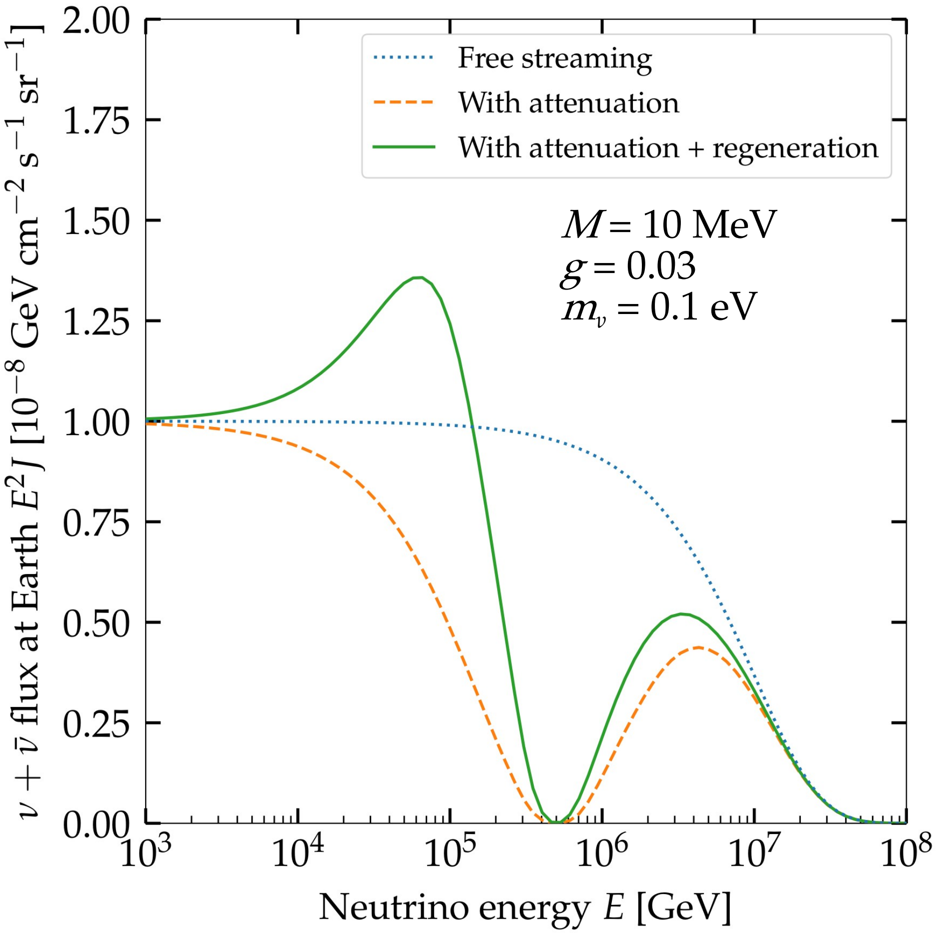

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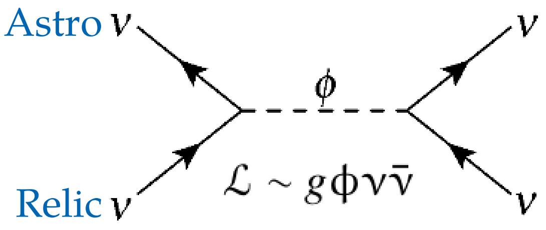

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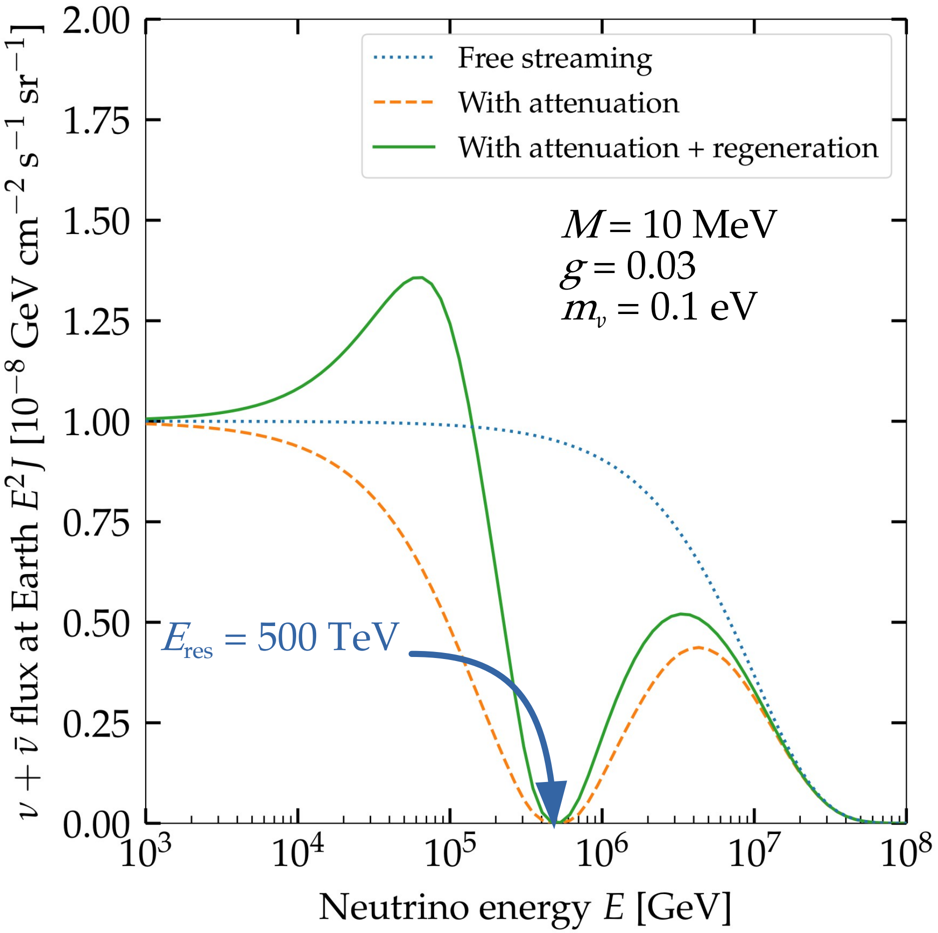

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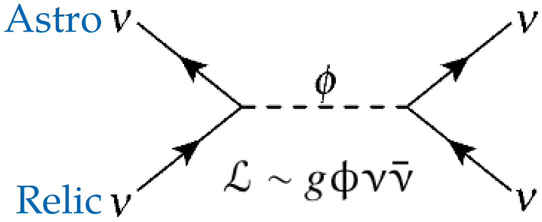

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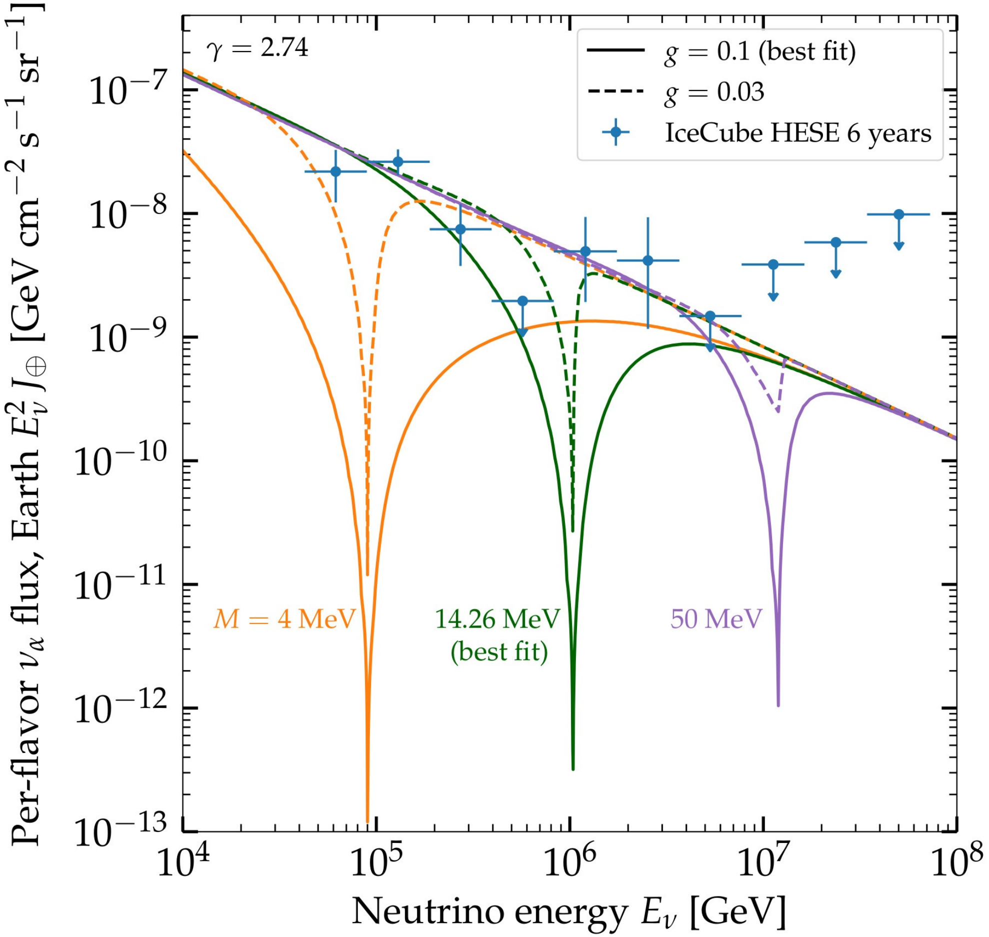

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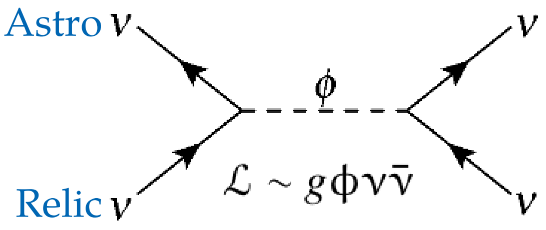

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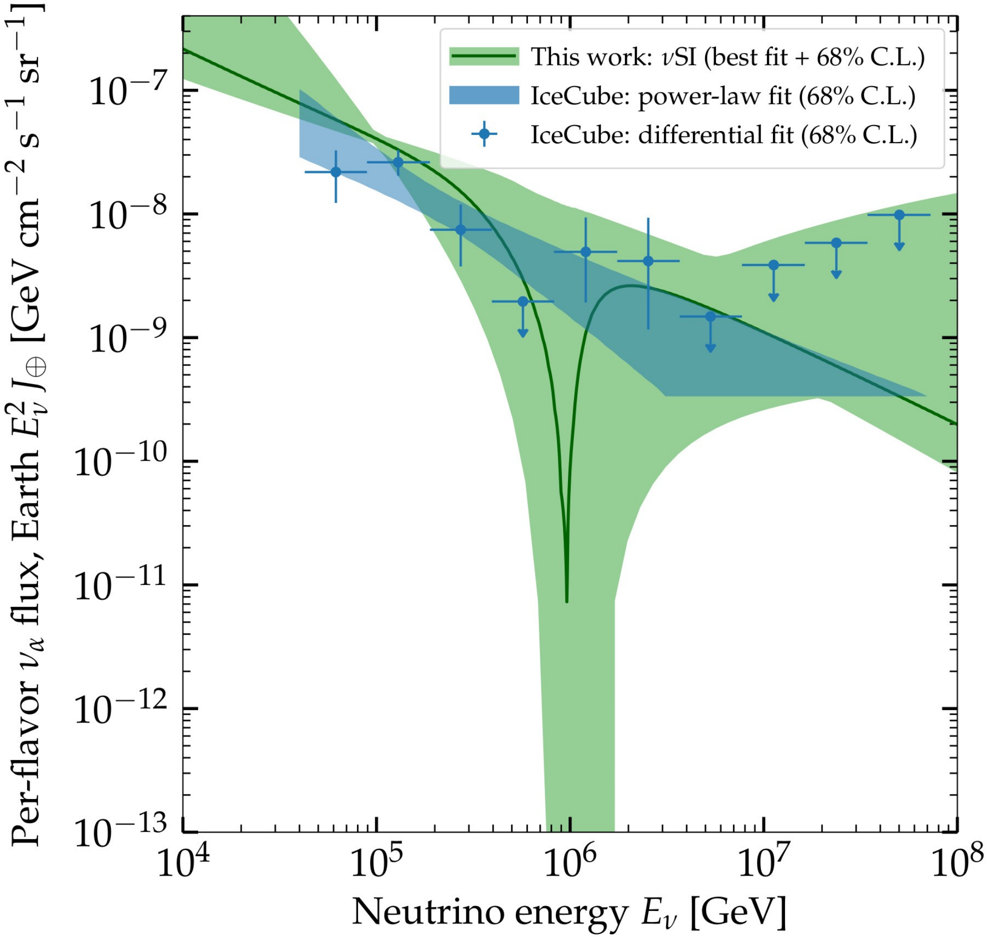
Looking for evidence of νSI

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

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



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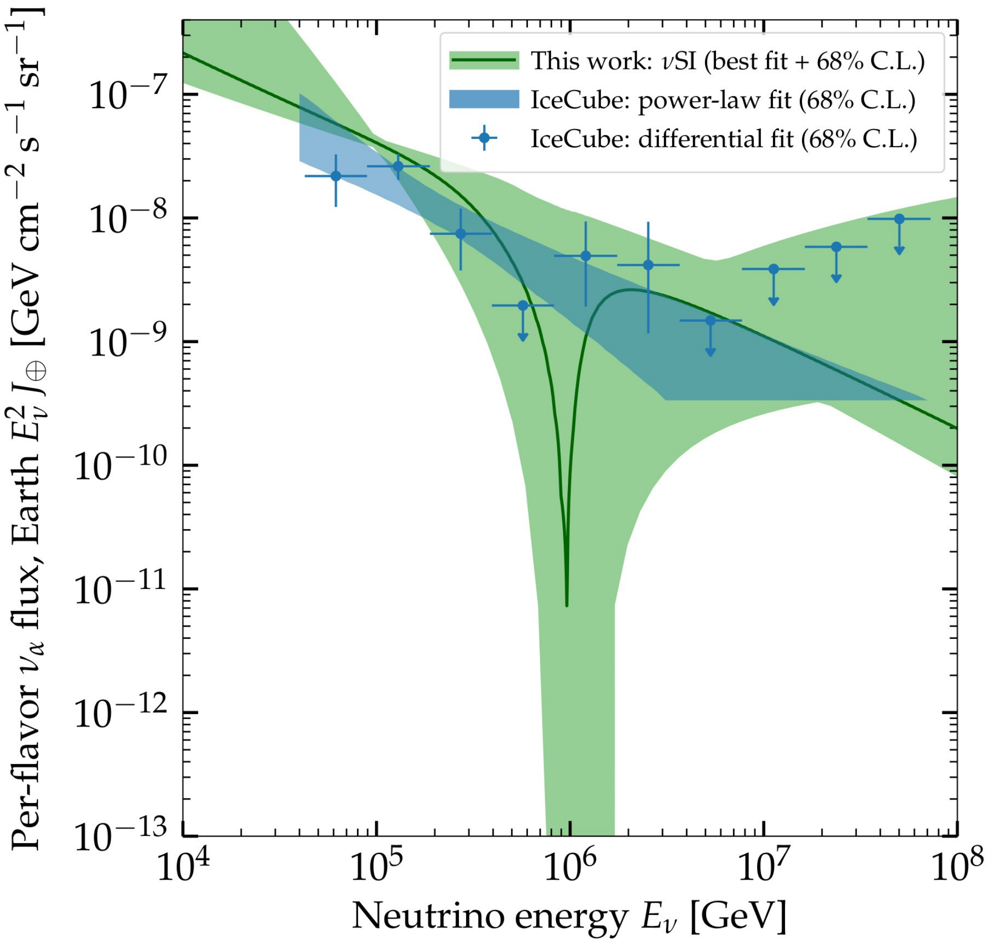

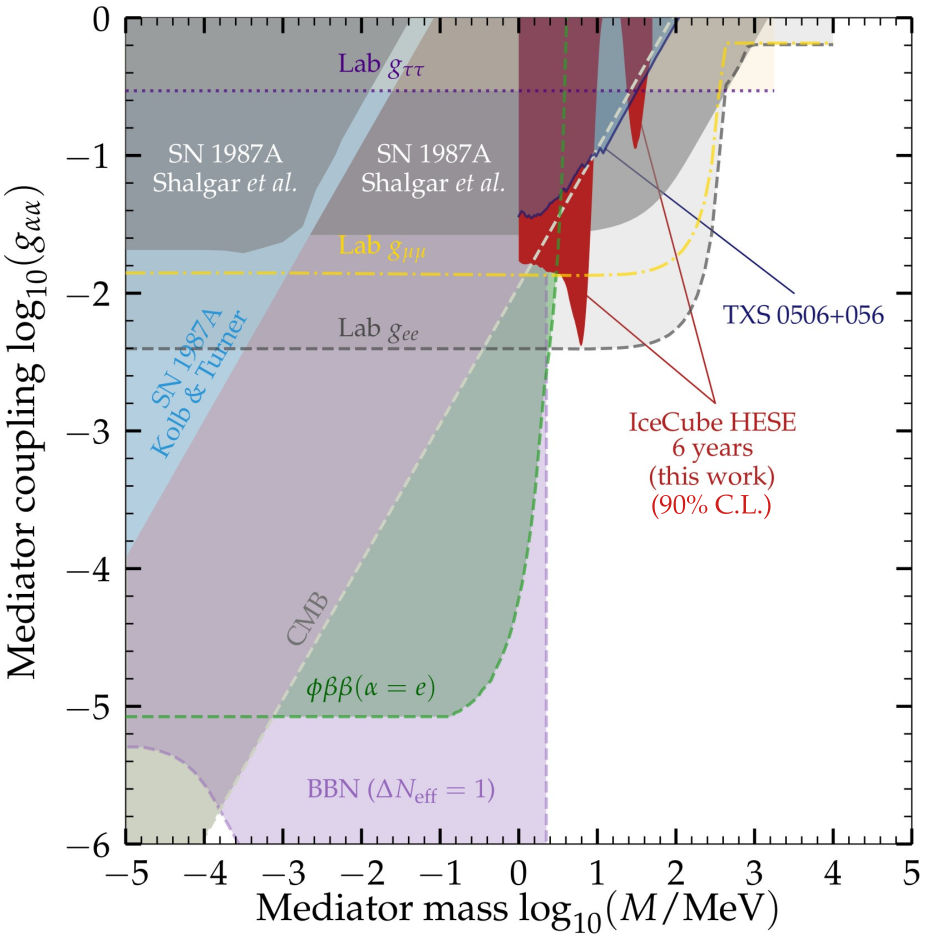

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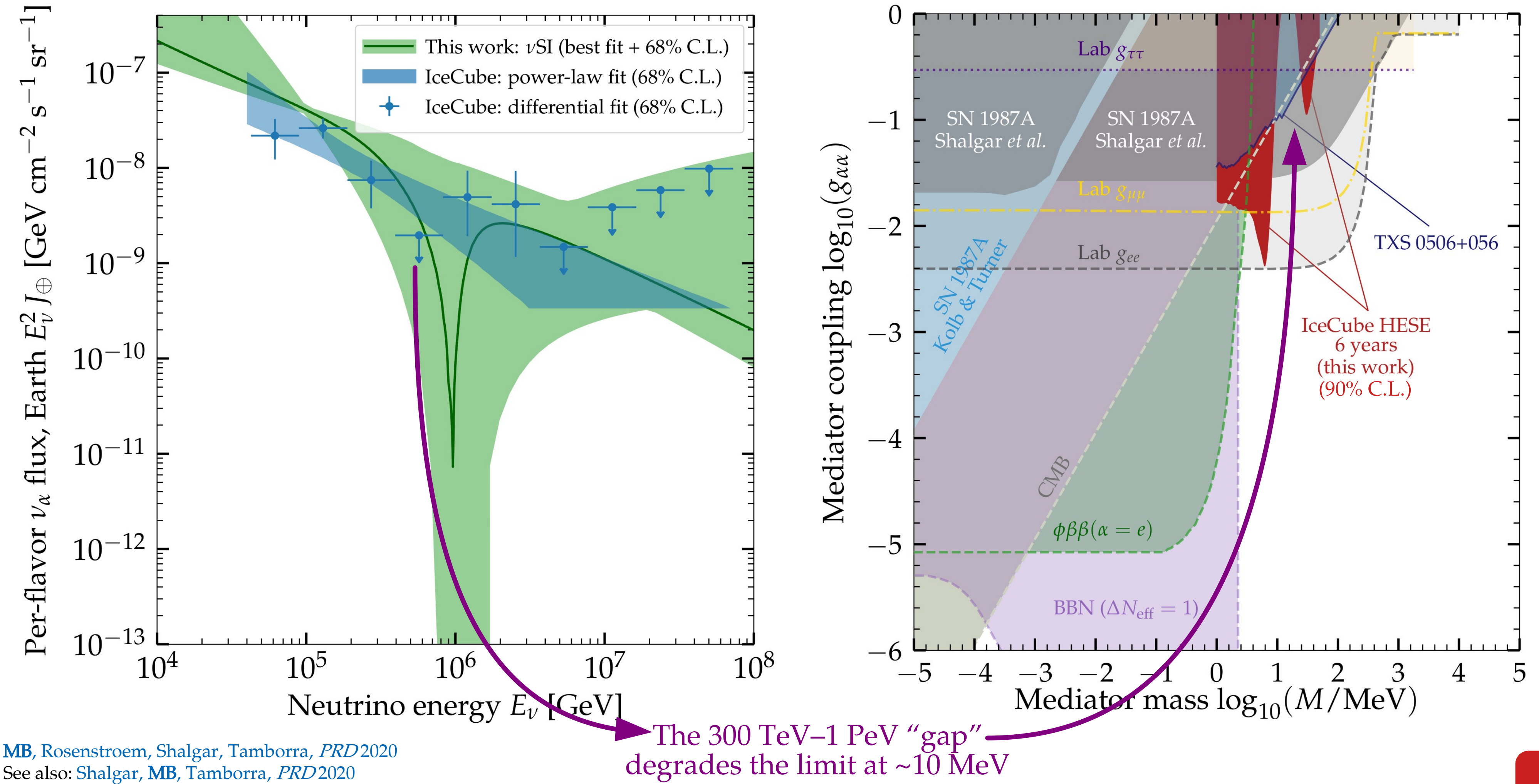

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5. Dark matter:
Annihilation and decay into ν

High-energy neutrinos from dark matter

Dark matter co-annihilation:

$$\chi + \chi \rightarrow \nu + \bar{\nu}$$

$$\chi + \chi \rightarrow \ldots \rightarrow \nu + \bar{\nu} + \ldots$$

$$E_{\max} = m_\chi$$

Dark matter decay:

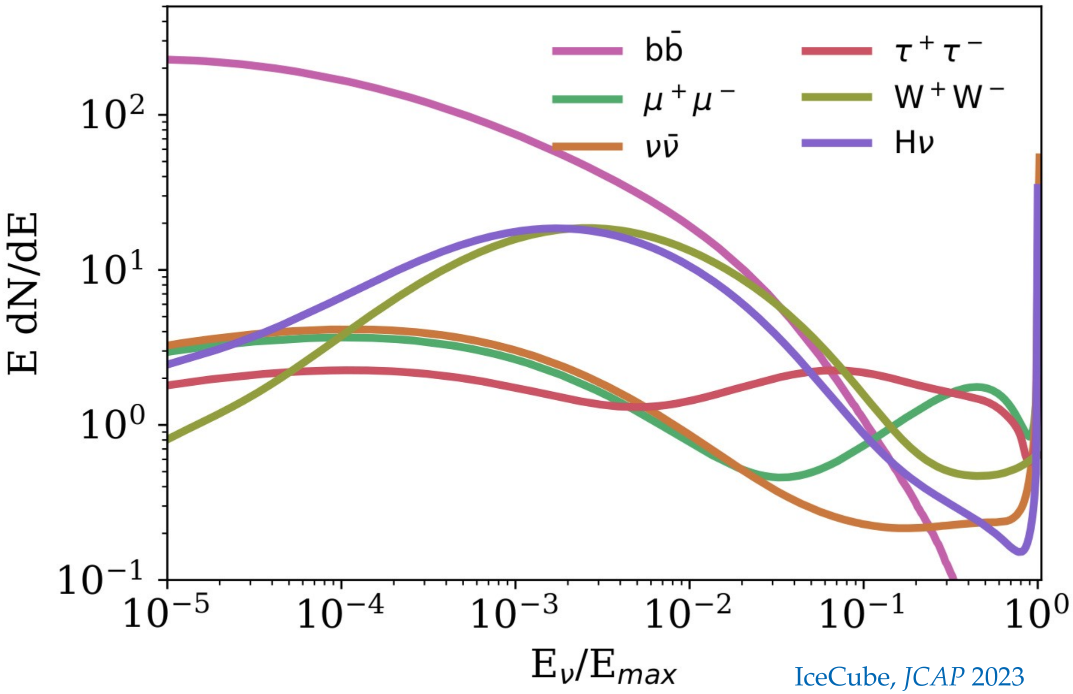
$$\chi \rightarrow \nu + \bar{\nu}$$

$$\chi \rightarrow \ldots \rightarrow \nu + \bar{\nu} + \ldots$$

$$E_{\max} = m_\chi / 2$$

Electroweak corrections (off-shell W and Z emission) broaden the ν spectrum

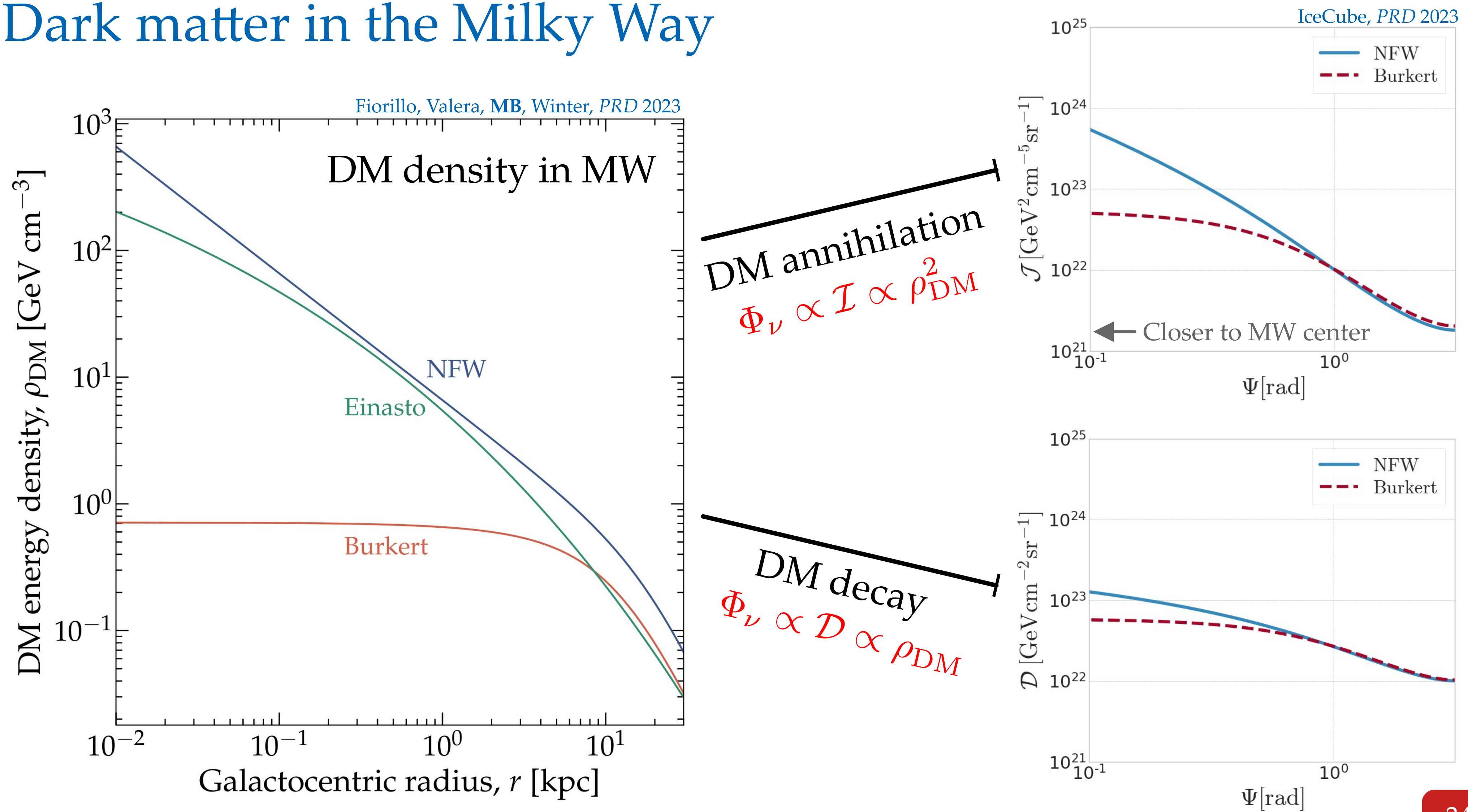
ν + ν yield from DM (at source)



IceCube, *JCAP* 2023

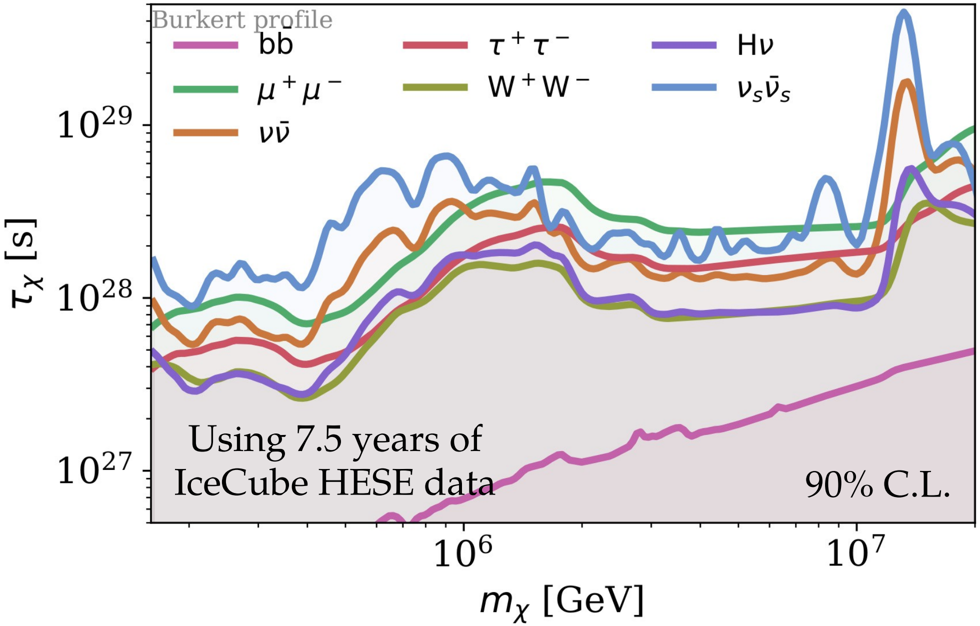
Approximate independence on m_χ valid for $m_\chi \approx$ 100 TeV–10 PeV

Dark matter in the Milky Way

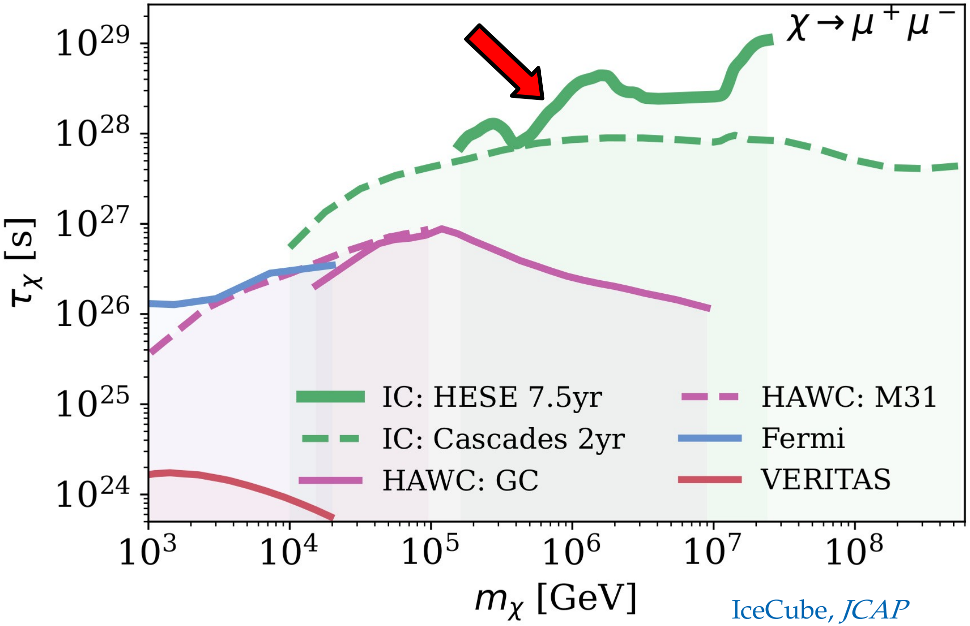


Limits on dark matter decay

Per annihilation channel
(assuming 100% branching ratio)



Compared to other limits
(assuming decay into muons)



IceCube, *JCAP* 2023

Two DM contributions: Galactic (anisotropic) + extragalactic (isotropic)

Plus background of atmospheric neutrinos (anisotropic, but different)

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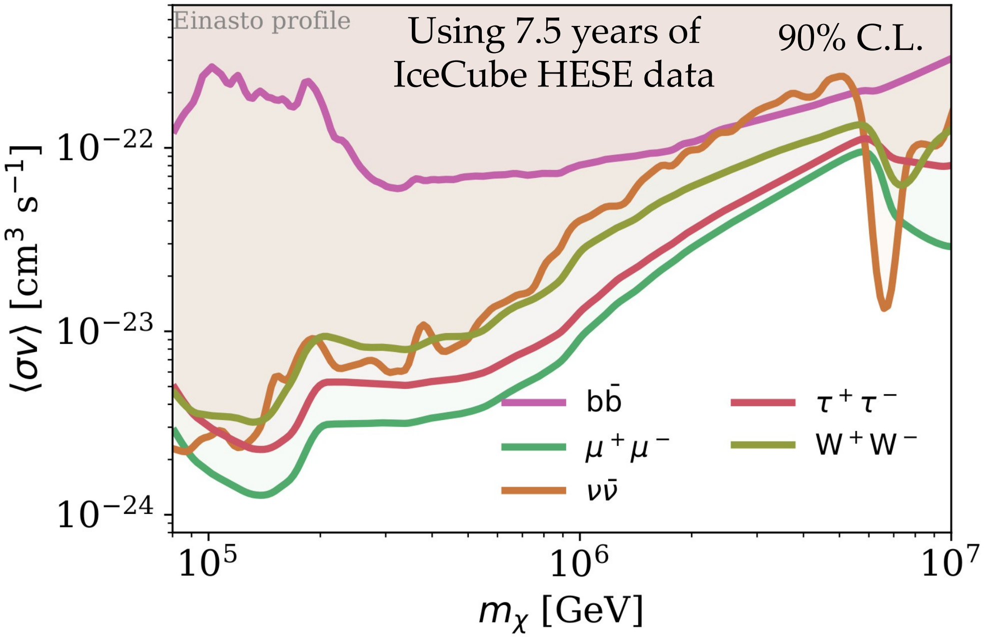

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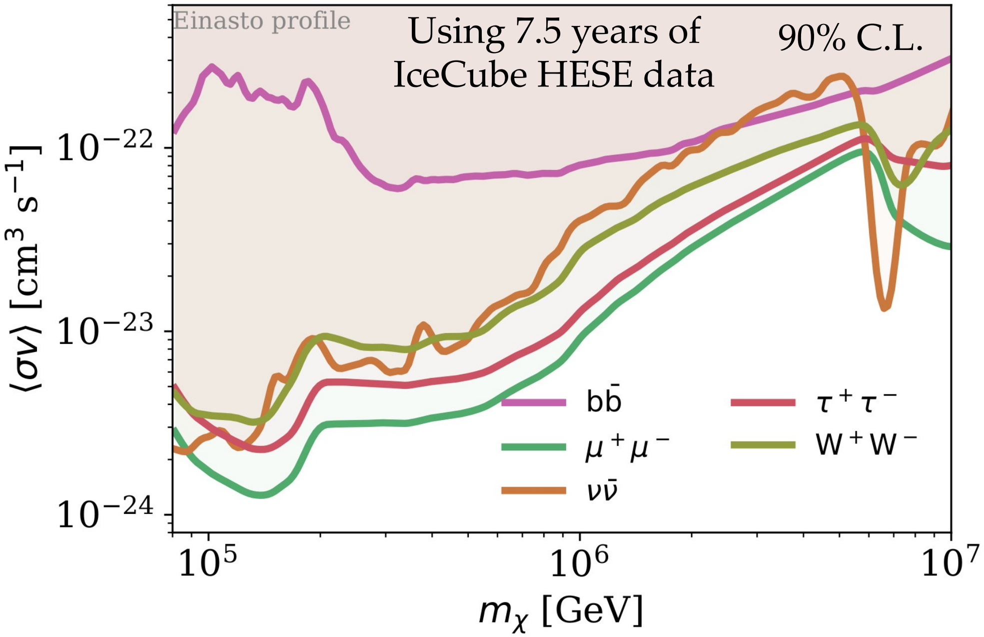

Compared to other limits
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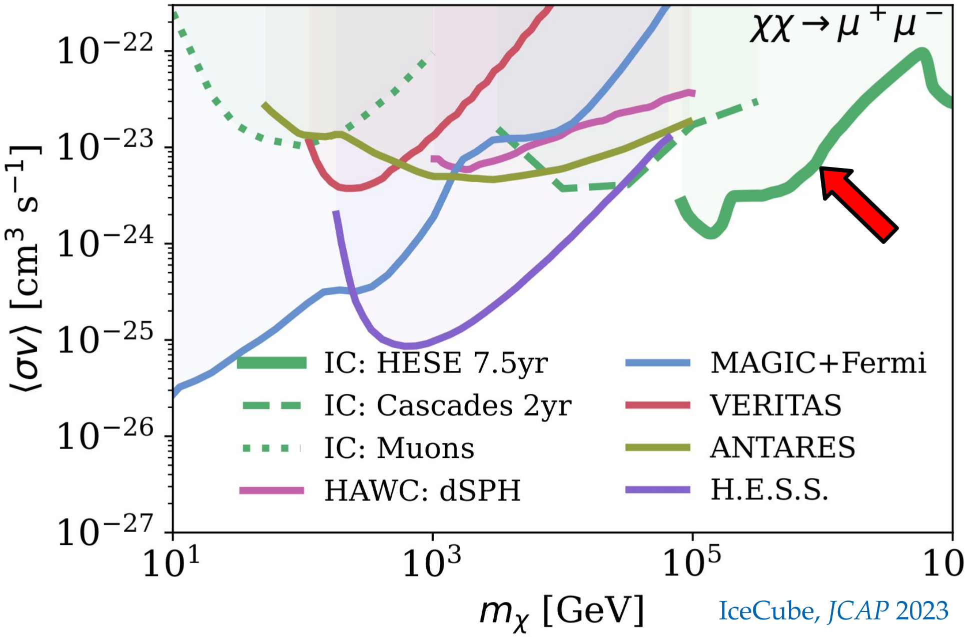

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6. Unstable neutrinos:
Are neutrinos for ever?

Are neutrinos forever?

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

  » Age of Universe (~ 14.5 Gyr)

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

- We work in a model-independent way:
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  Nambu-Goldstone boson of a broken symmetry

- We work in a model-independent way:
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Astrophysical sources — Earth

$L \sim$ up to a few Gpc

E.g.,

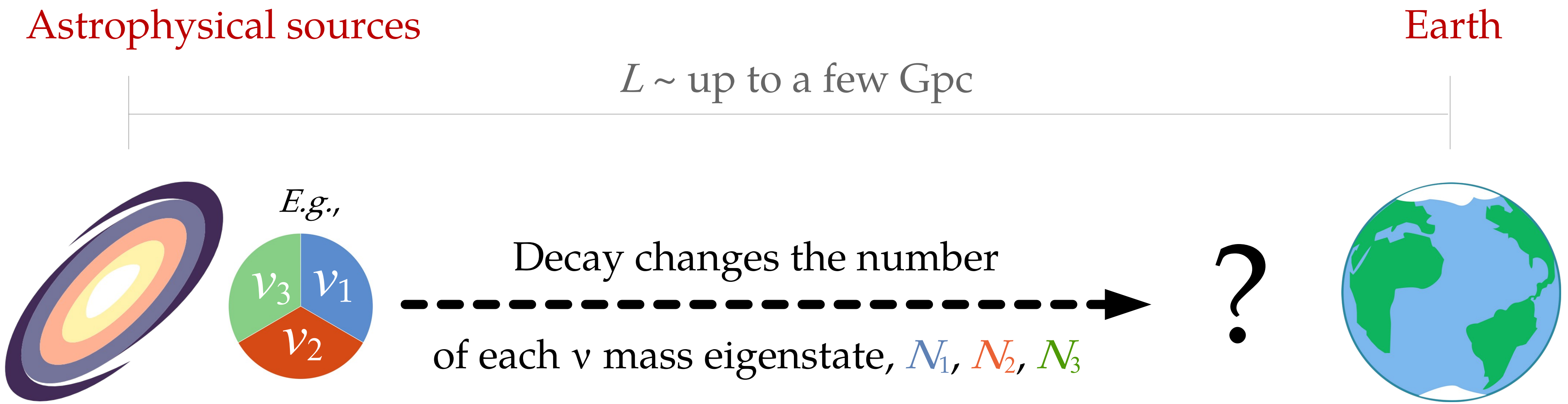
Decay changes the number

of each ν mass eigenstate, N_1, N_2, N_3

?

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

Mass of ν_i — Lifetime of ν_i



Only sensitive to their ratio

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Astrophysical sources

Earth

L ~ up to a few Gpc

E.g.,

Decay changes the number

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?

Lower-E ν are longer-lived…

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

… but ν that travel longer L are more attenuated!

Astrophysical sources

Earth

$L \sim$ up to a few Gpc

E.g.,

Astrophysical sources — Earth

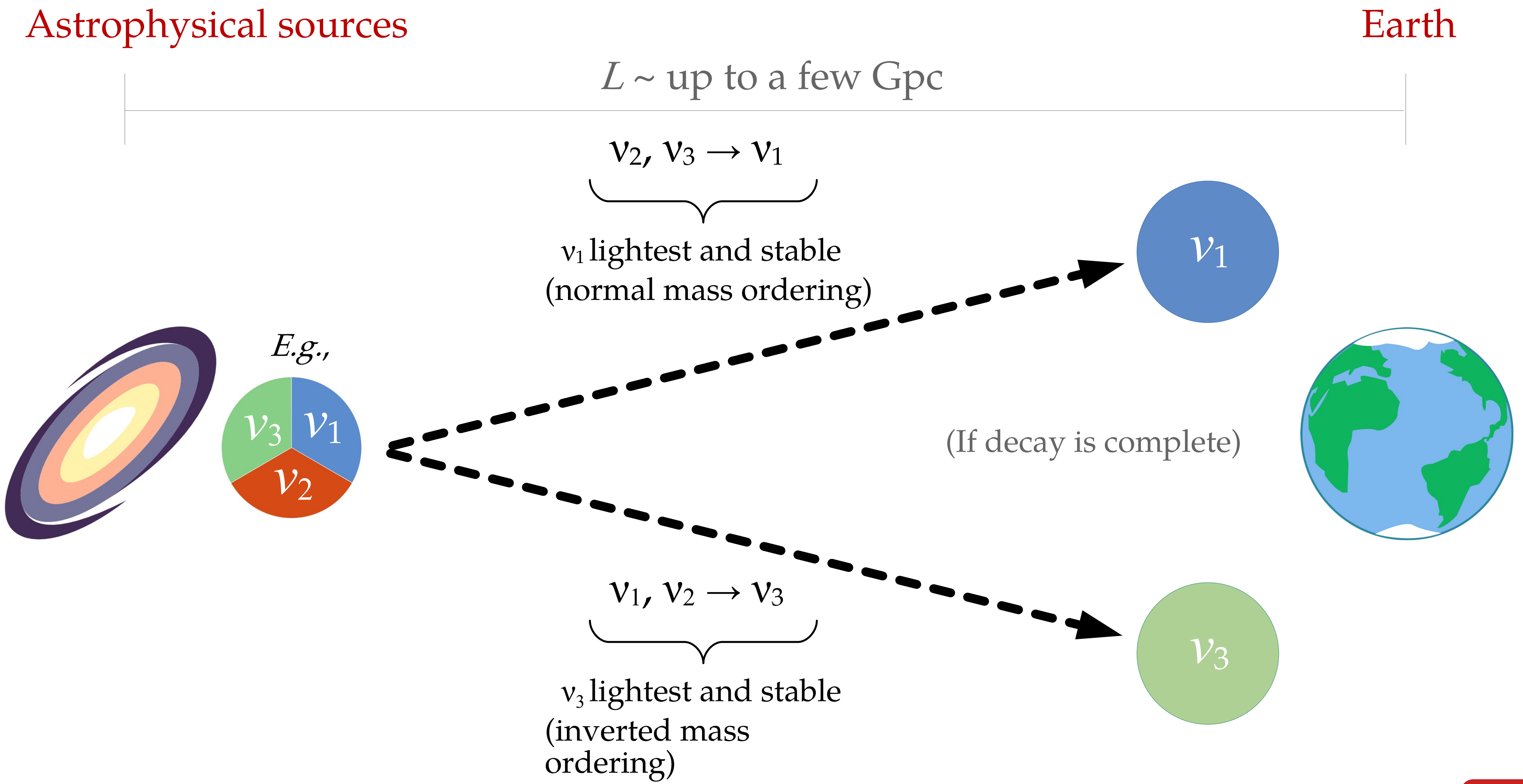
$L \sim$ up to a few Gpc

$\nu_2, \nu_3 \rightarrow \nu_1$

ν_1 lightest and stable
(normal mass ordering)

E.g.,

(If decay is complete)



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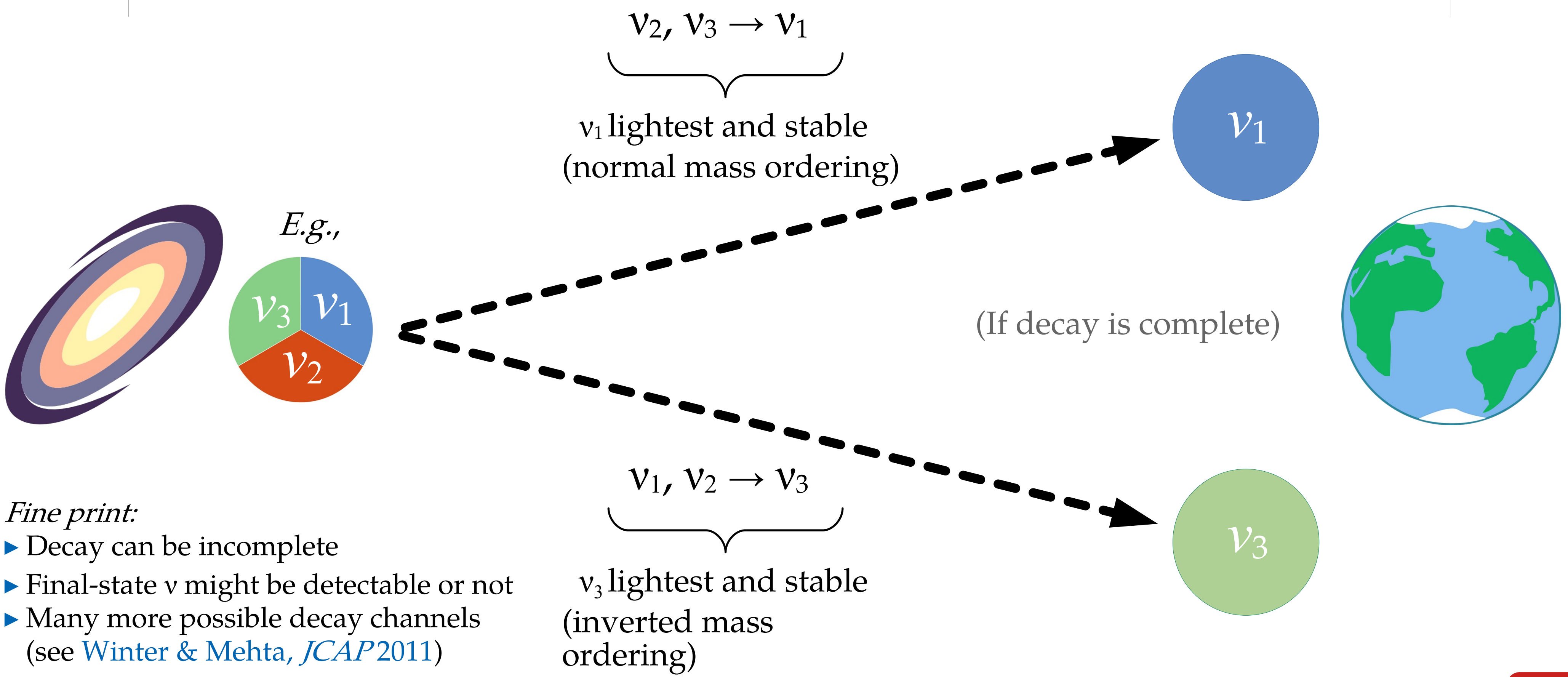
E.g.,
ν_3
ν_1
ν_2
ν_1
(If decay is complete)
$\nu_1, \nu_2 \rightarrow \nu_3$
ν_3 lightest and stable
(inverted mass
ordering)
ν_3

Astrophysical sources — Earth

$L \sim$ up to a few Gpc



Fine print:

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

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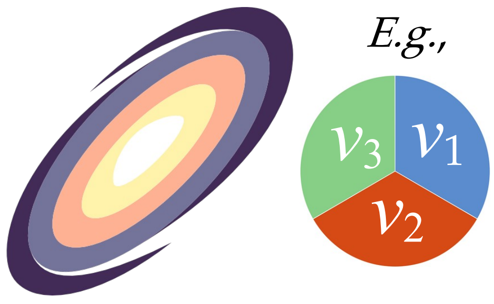

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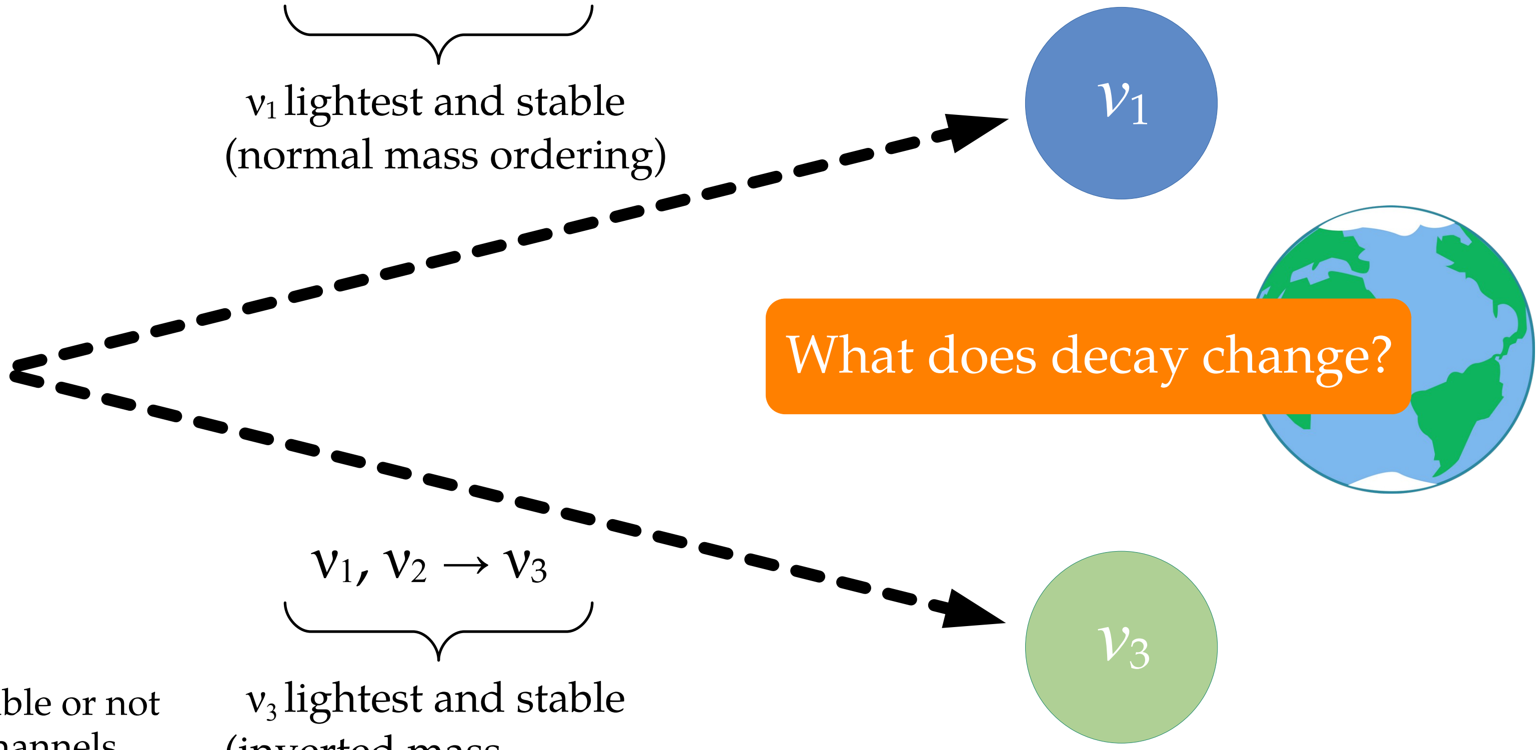

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What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

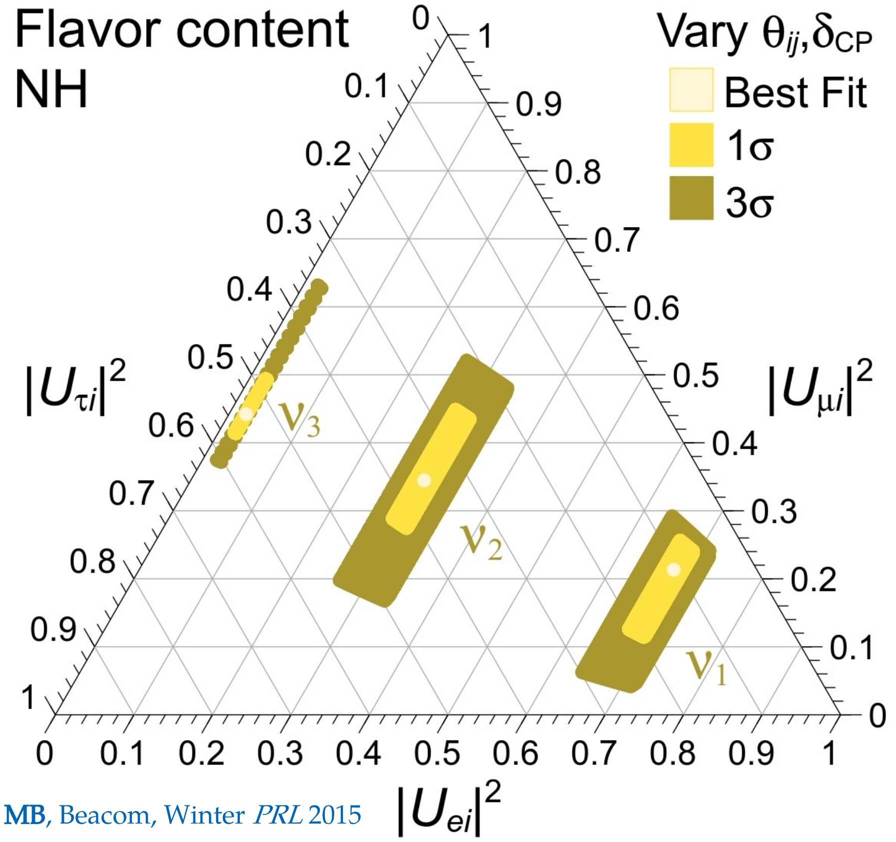
Flavor content of mass eigenstates:

Known to within 2% (arrows to θ_{12} and θ_{13})

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

Known to within 8%

Known to within 20% (or worse)



MB, Beacom, Winter *PRL* 2015

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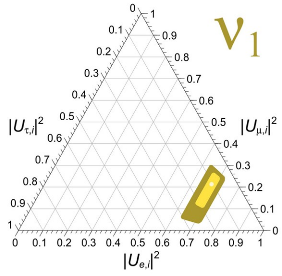

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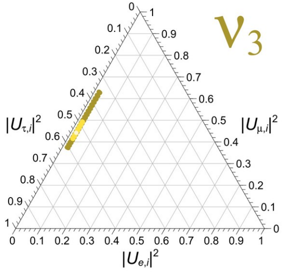

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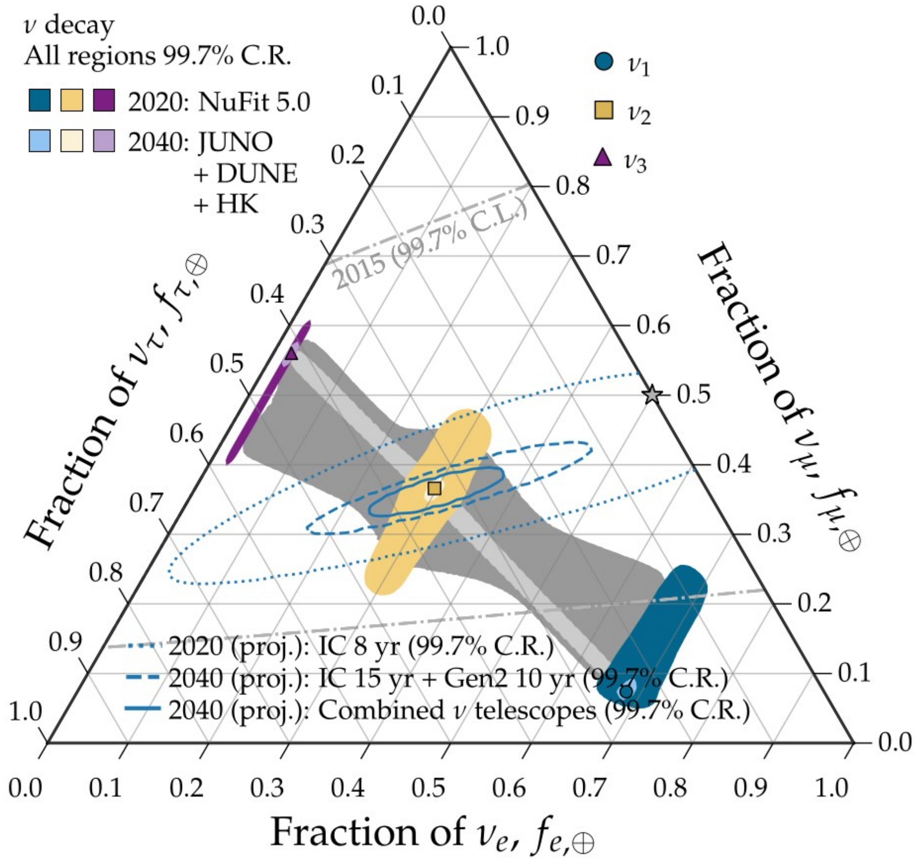
Flavor composition ⟺ Spectrum shape ⟺ Event rate



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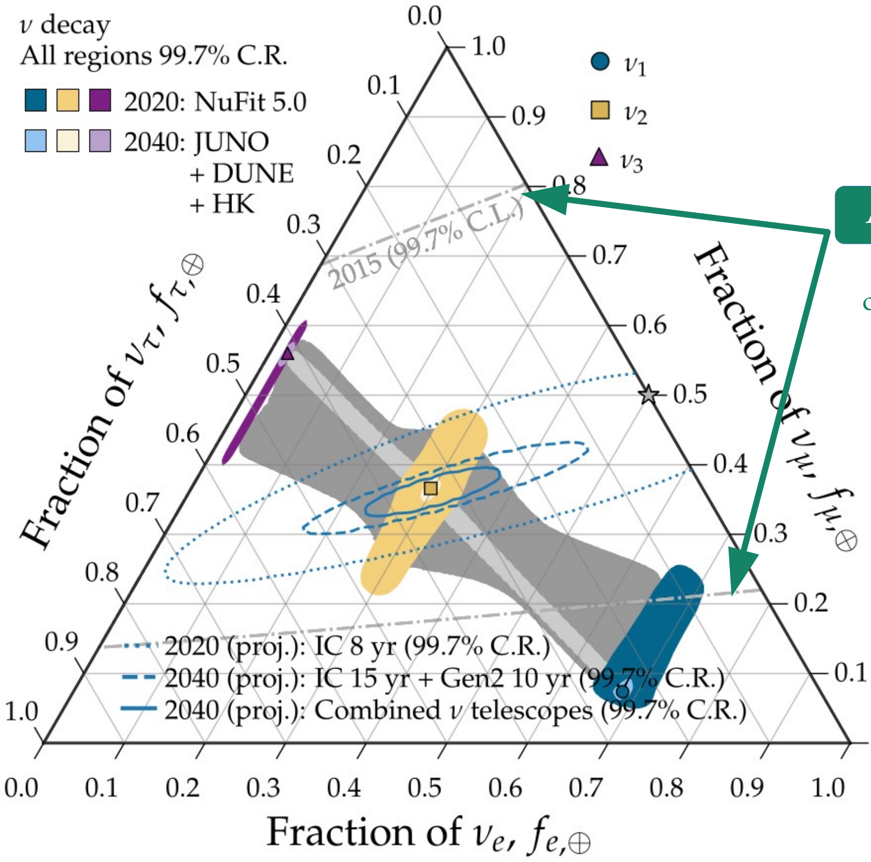

Approx. today

(IceCube 2015 combined analysis, *ApJ* 2015)

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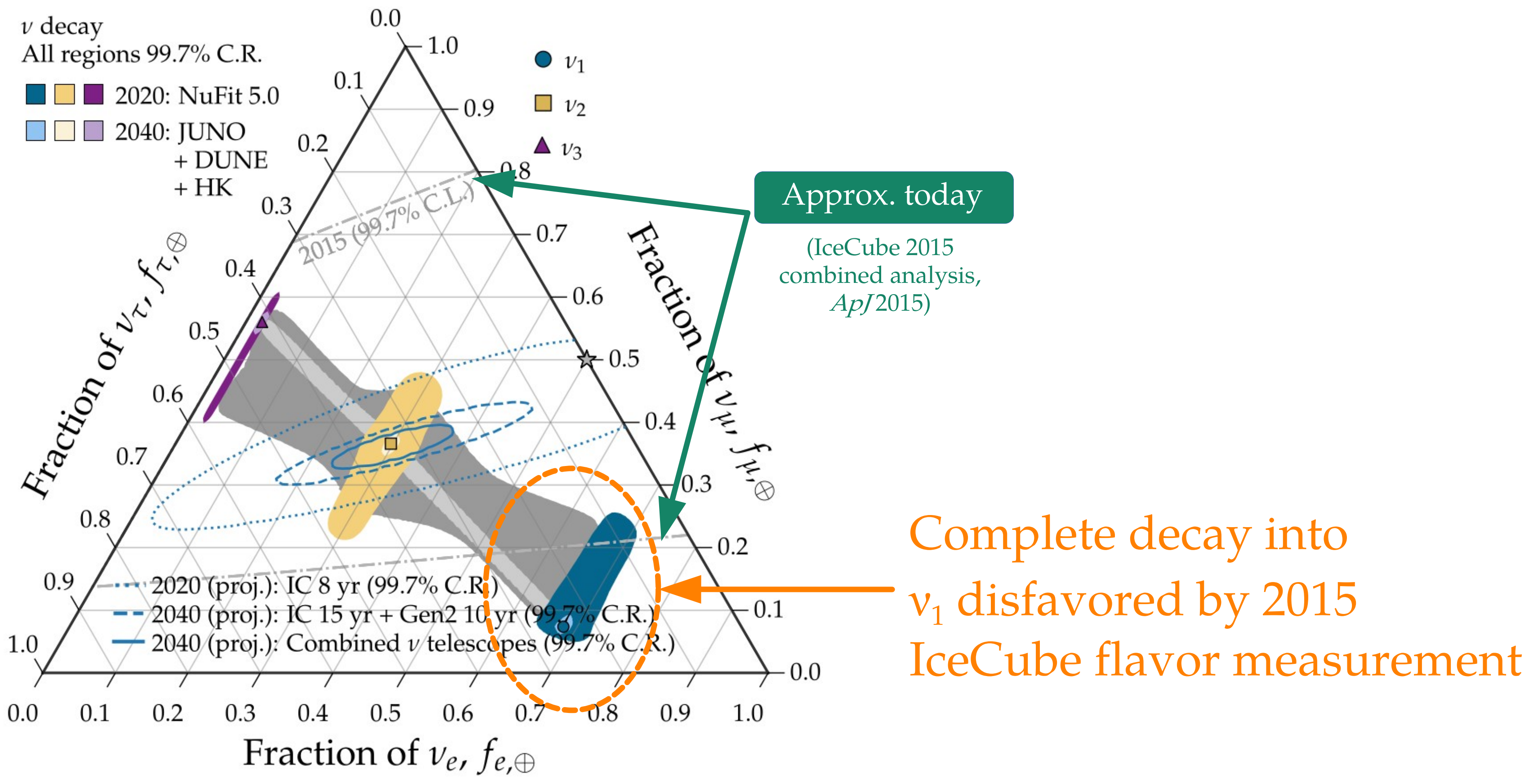

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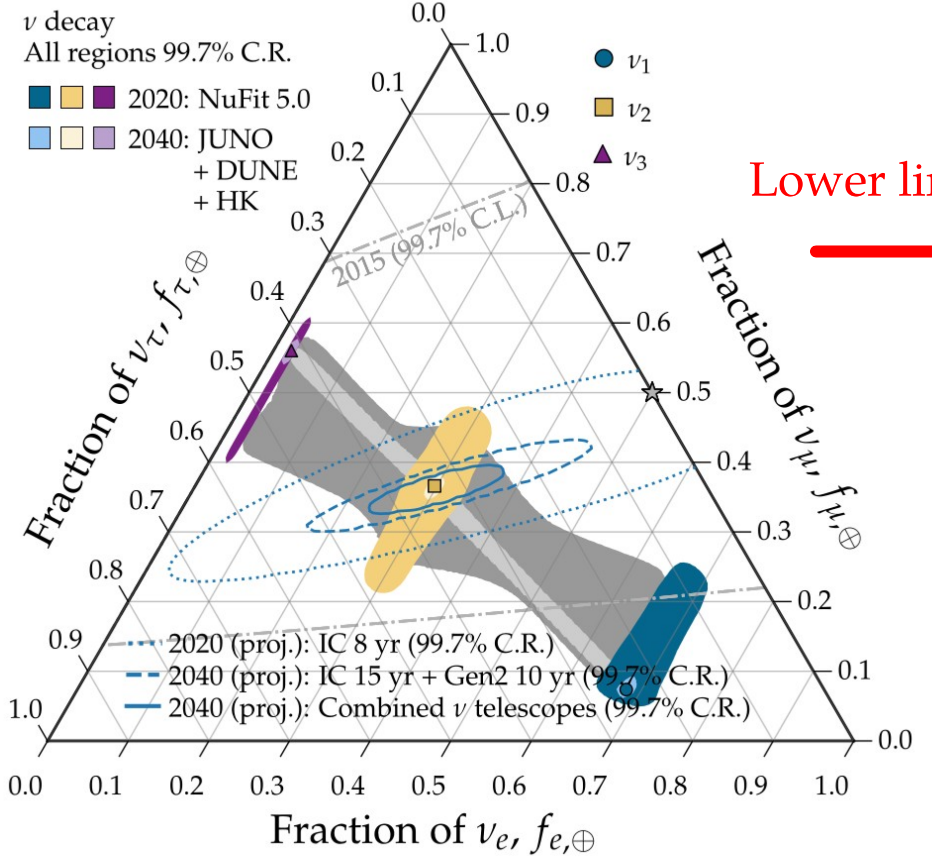

Lower limit on τ/m →

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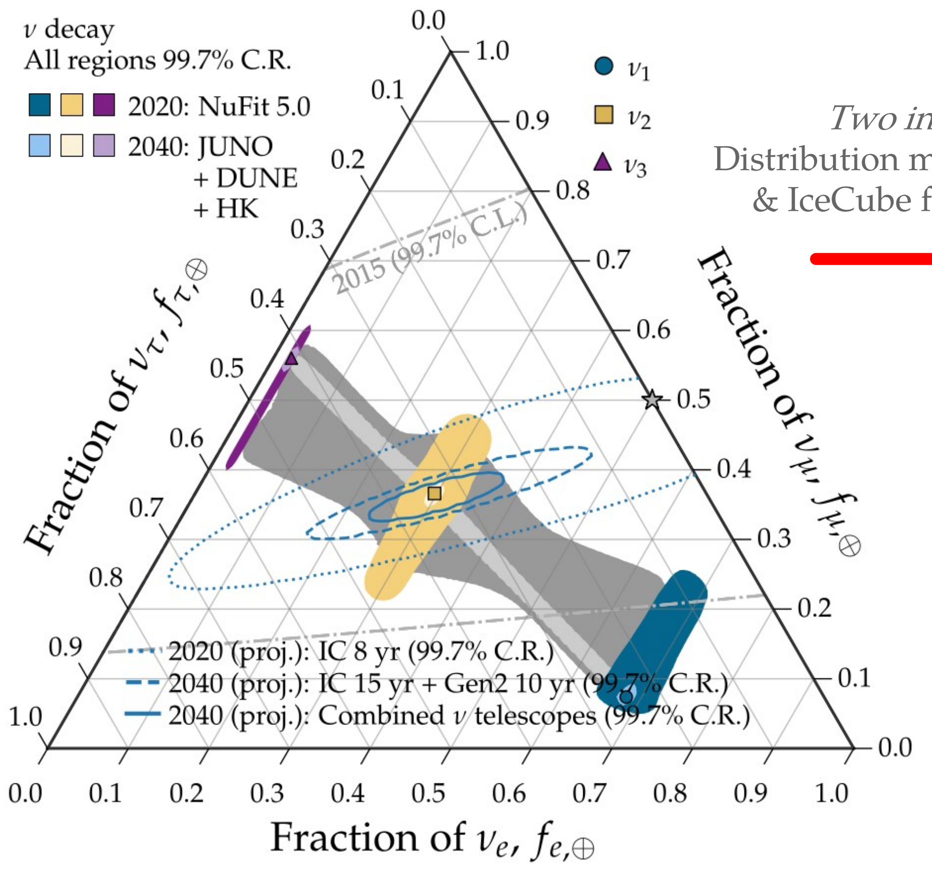

Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

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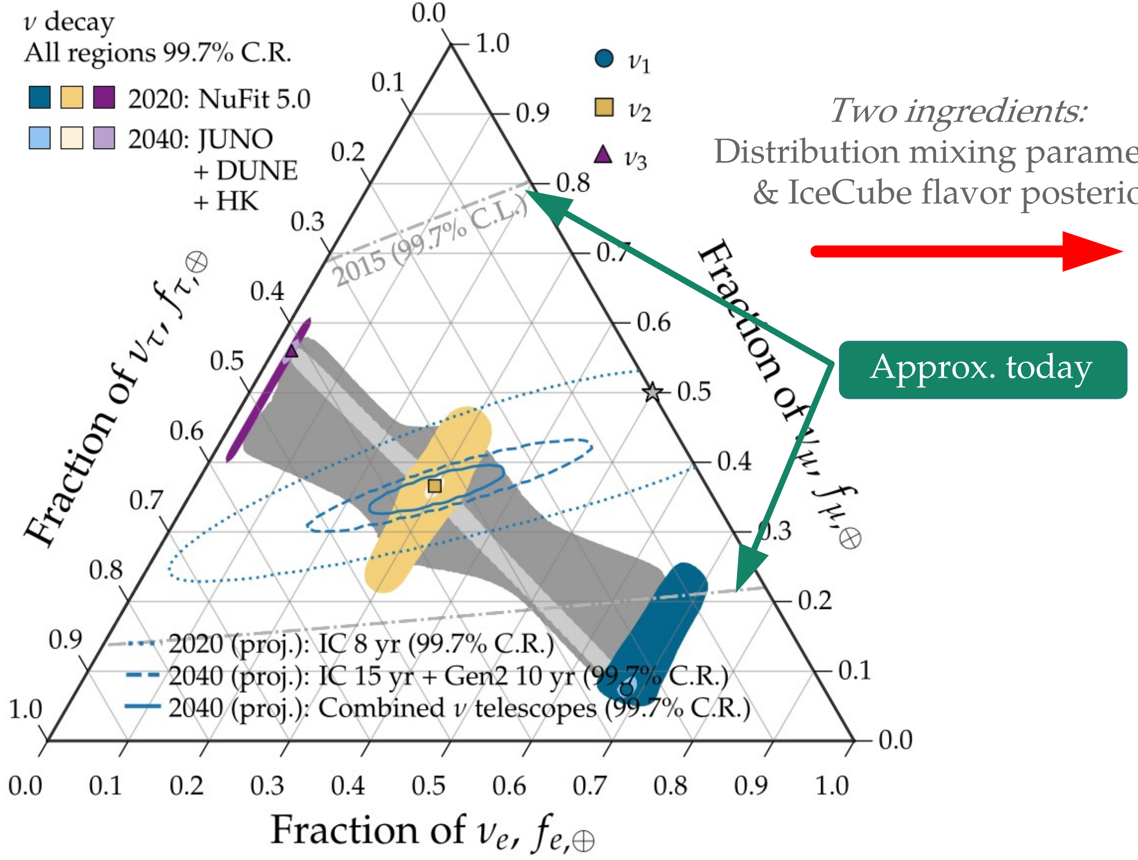

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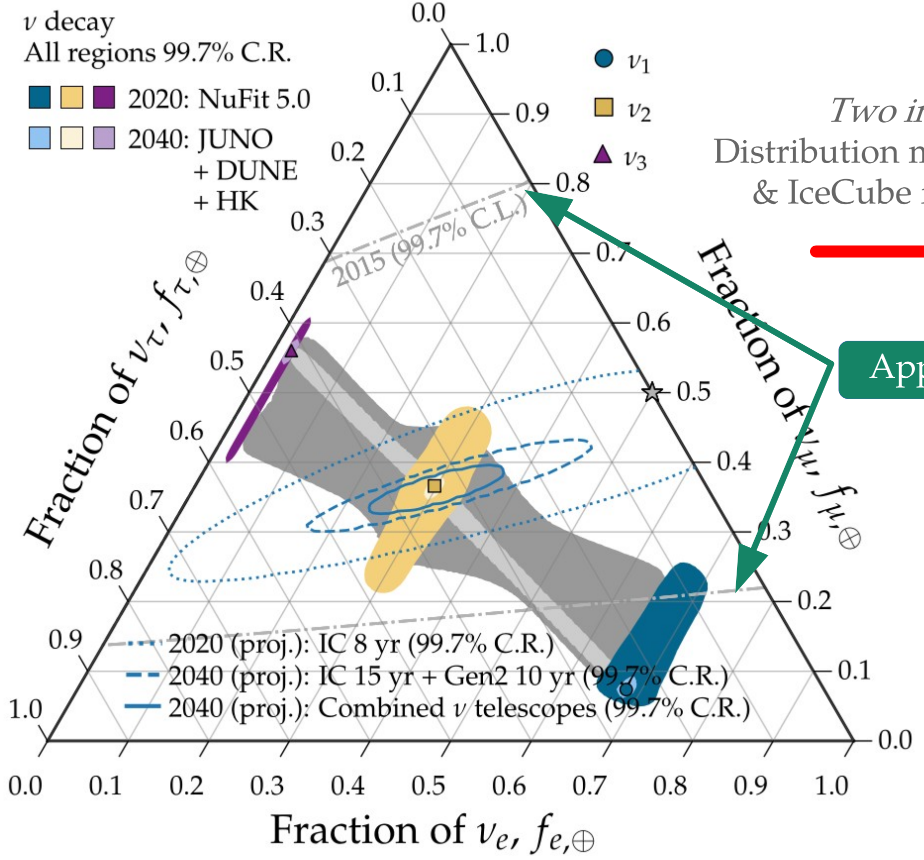

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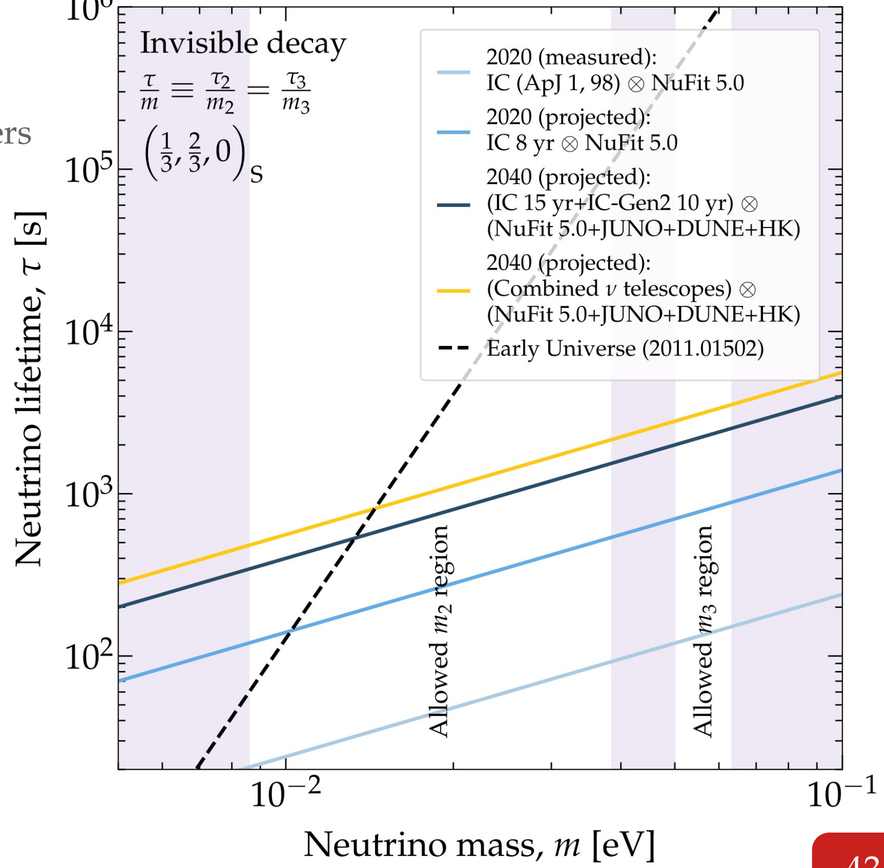
Approx. today

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



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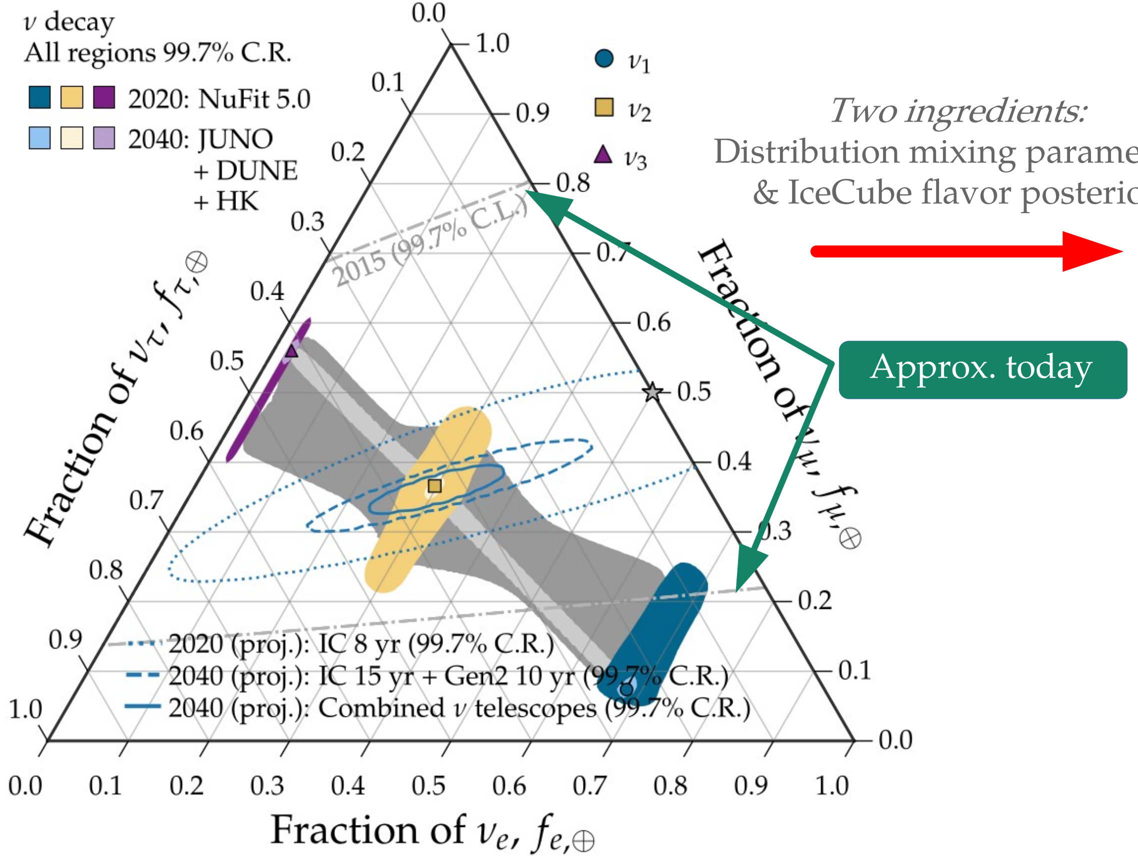

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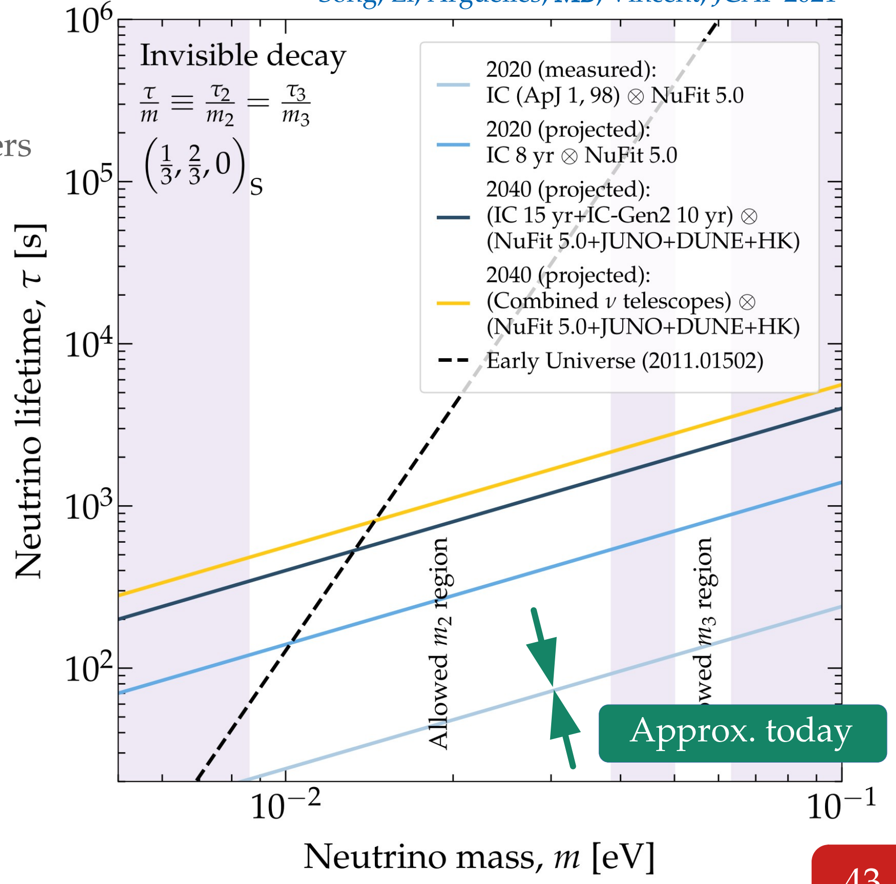

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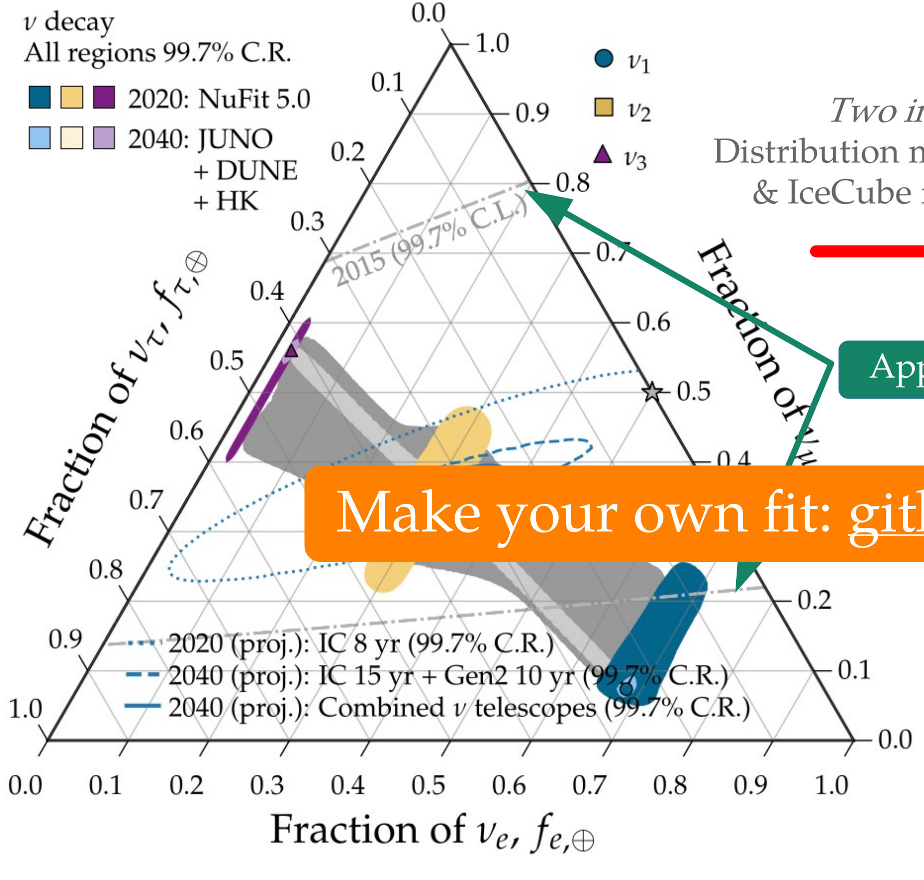

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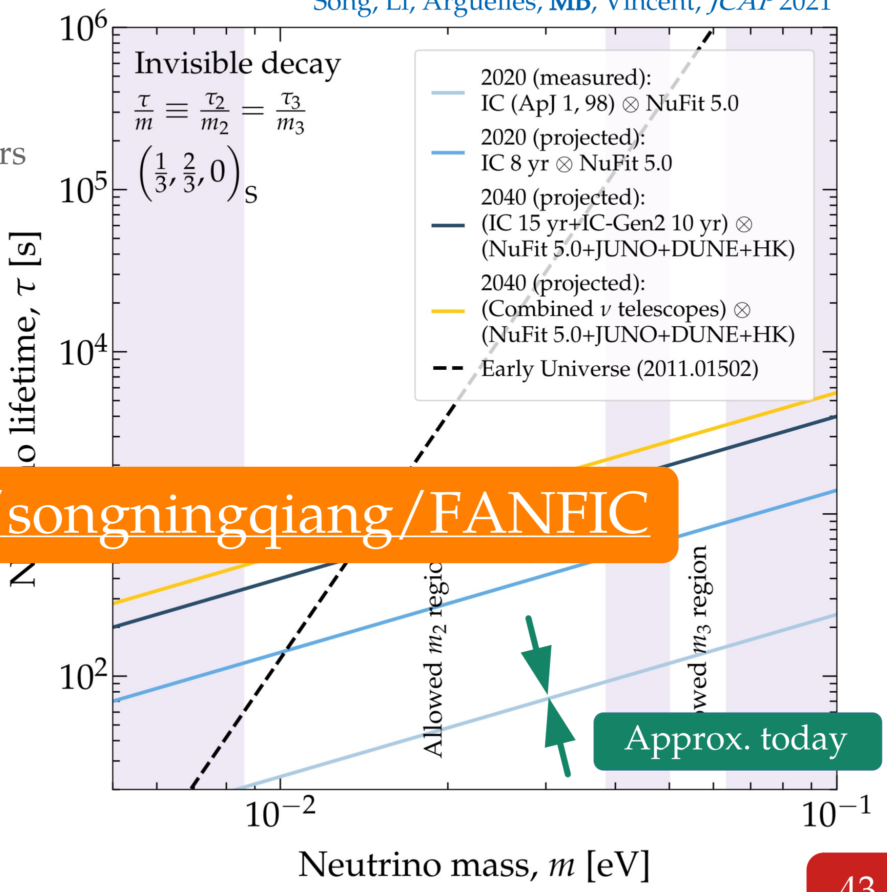
Distribution mixing parameters & IceCube flavor posterior

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

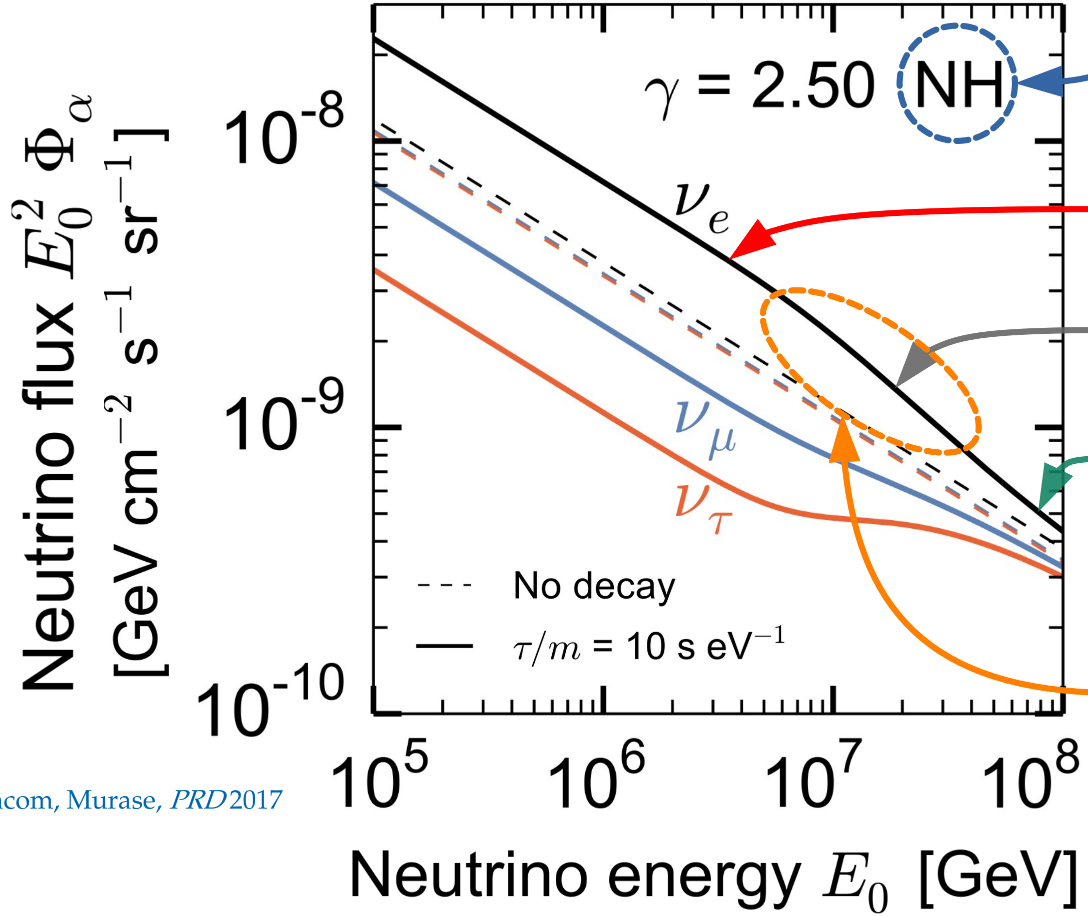


Make your own fit: github.com/songningqiang/FANFIC

What does neutrino decay change?

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

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



$\nu_2, \nu_3 \rightarrow \nu_1$

Low energy: decay evident

Transition region

High energy: no decay

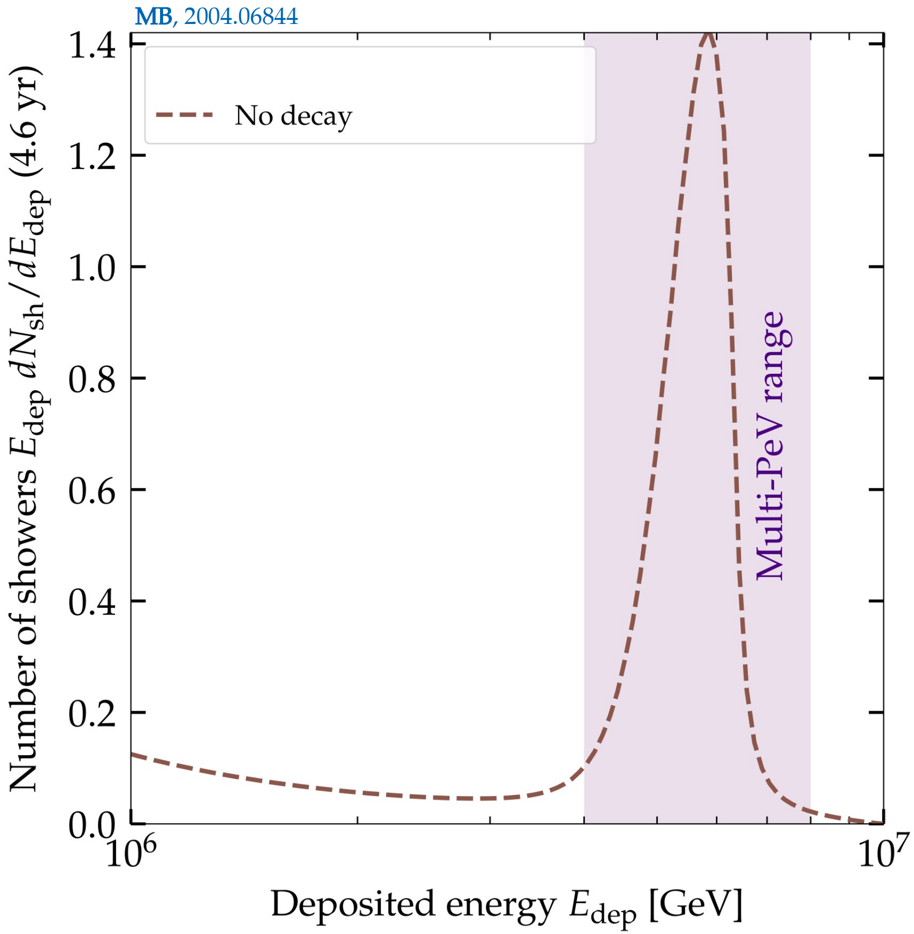
Look for sigmoid-like transition in spectrum: *challenging, but possible with more statistics!*

MB, Beacom, Murase, *PRD* 2017

What does neutrino decay change?

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

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



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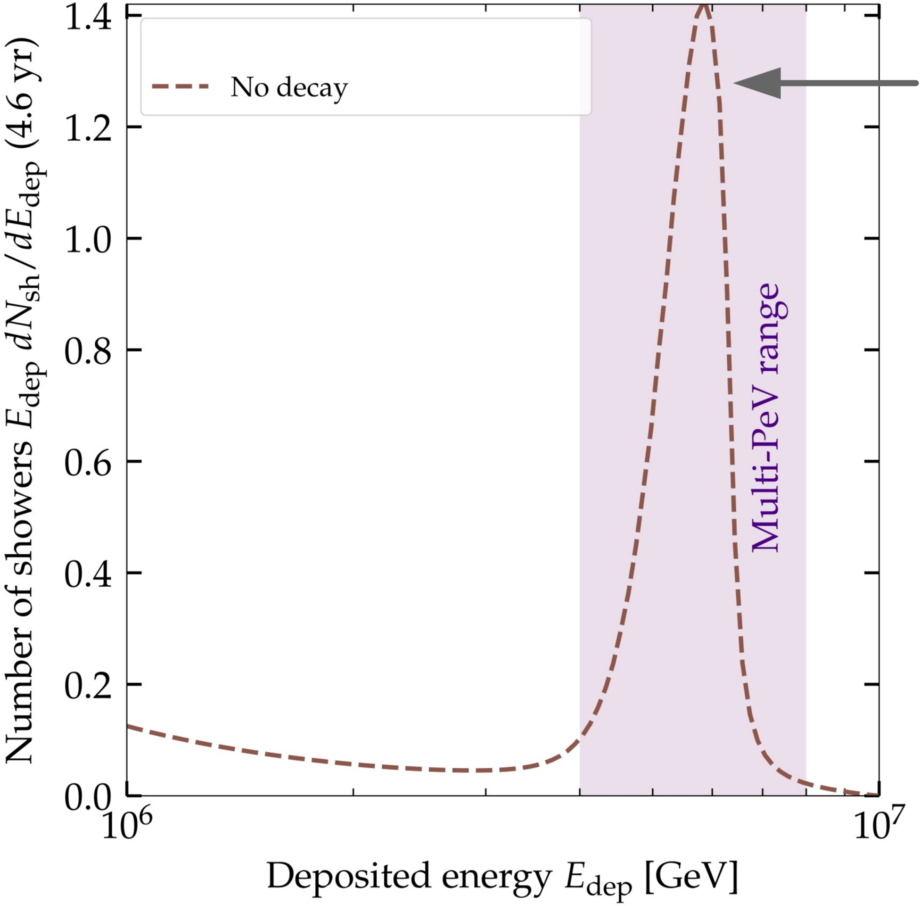
Flavor composition ⟺ Spectrum shape ⟺ **Event rate**

MB, 2004.06844



Glashow resonance (GR):

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

What does neutrino decay change?

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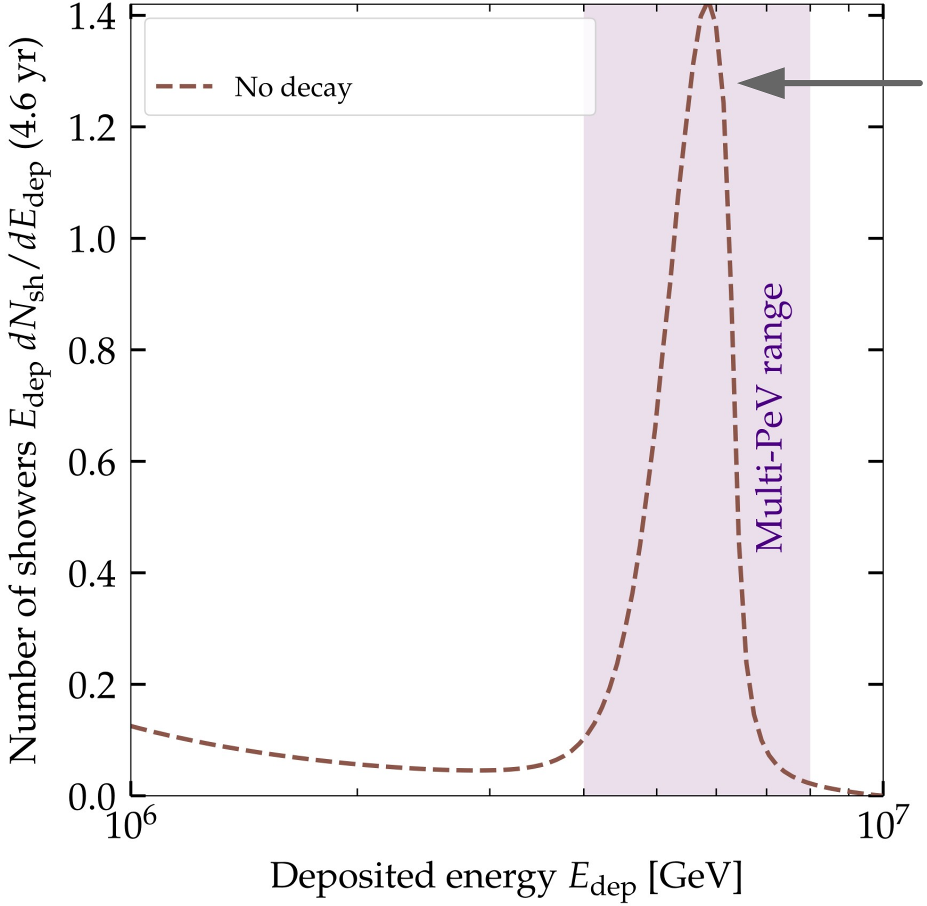
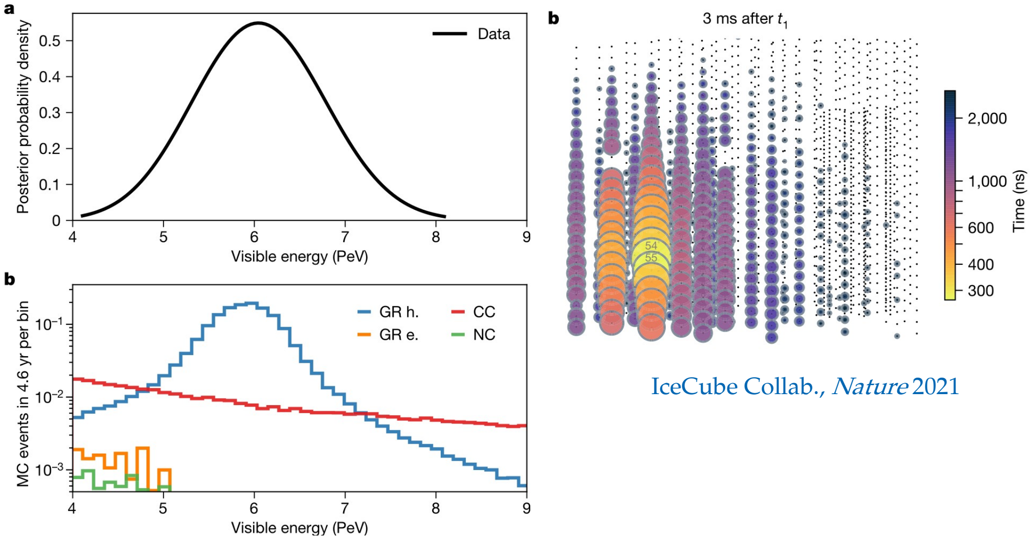


Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

IceCube has seen one GR candidate in 4.6 years:



IceCube Collab., *Nature* 2021

What does neutrino decay change?

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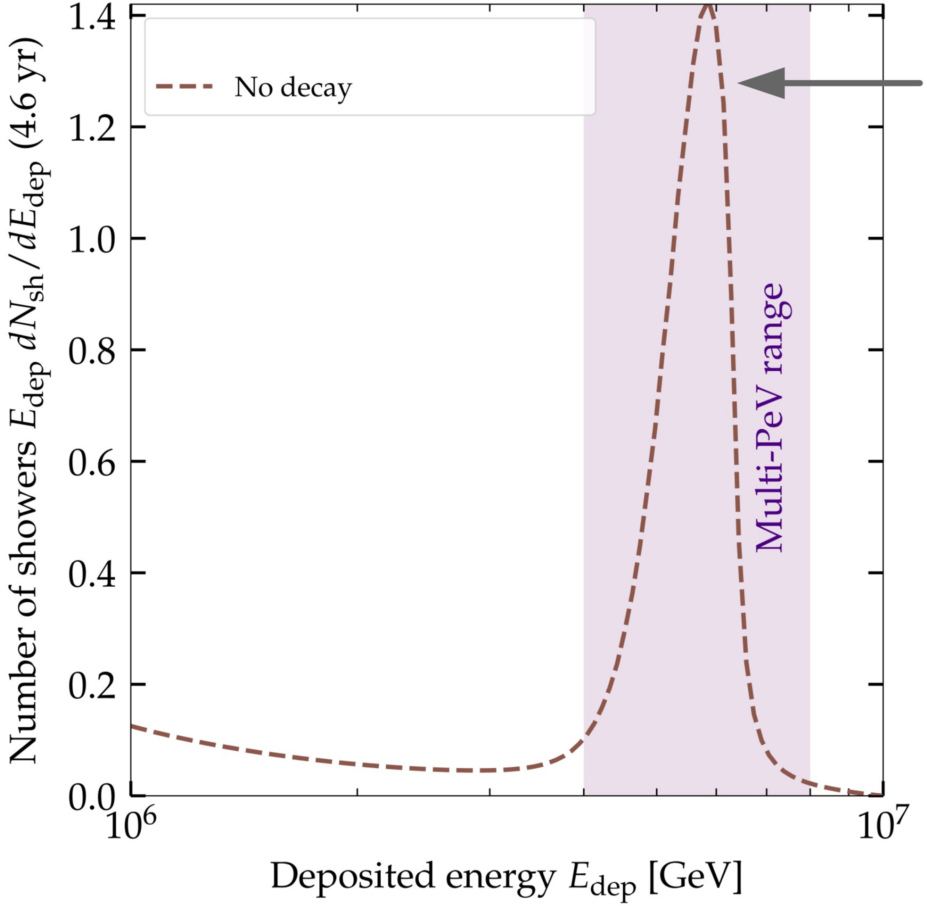
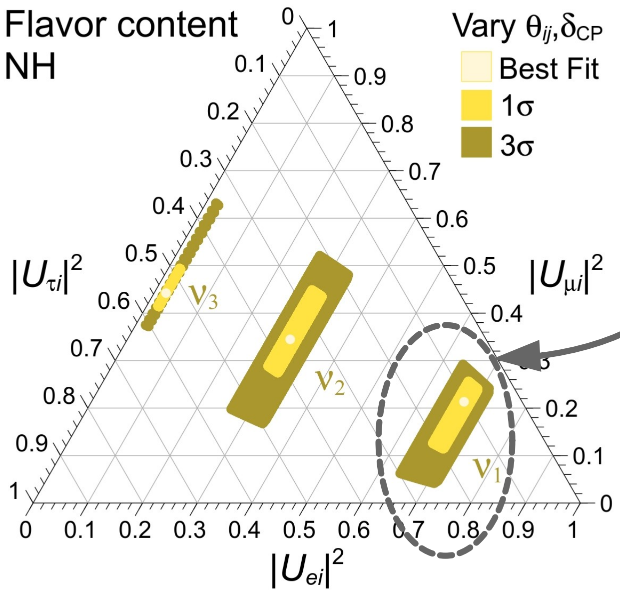


Glashow resonance (GR):
$\bar{\nu}_e + e \to W \to$ hadrons $\to$ shower

ν_1 is the mass eigenstate with the most e flavor



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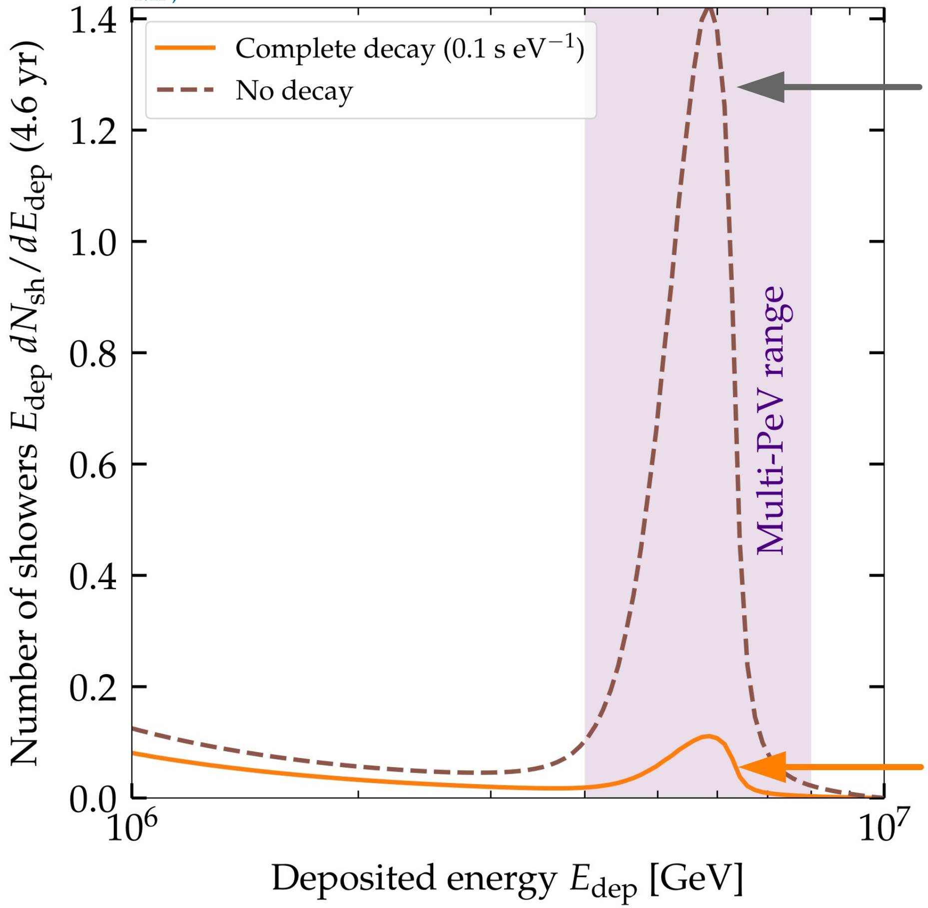

Glashow resonance (GR):
$\bar{\nu}_e + e \to W \to$ hadrons $\to$ shower

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

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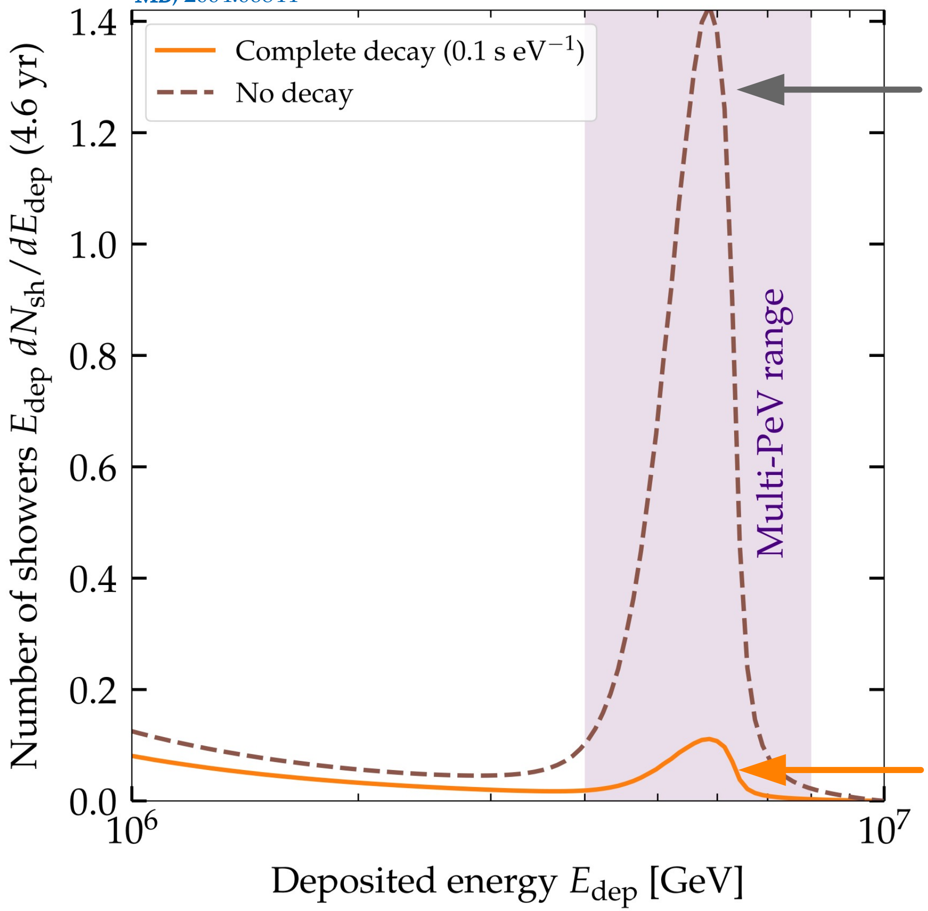

Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

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

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

What does neutrino decay change?

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

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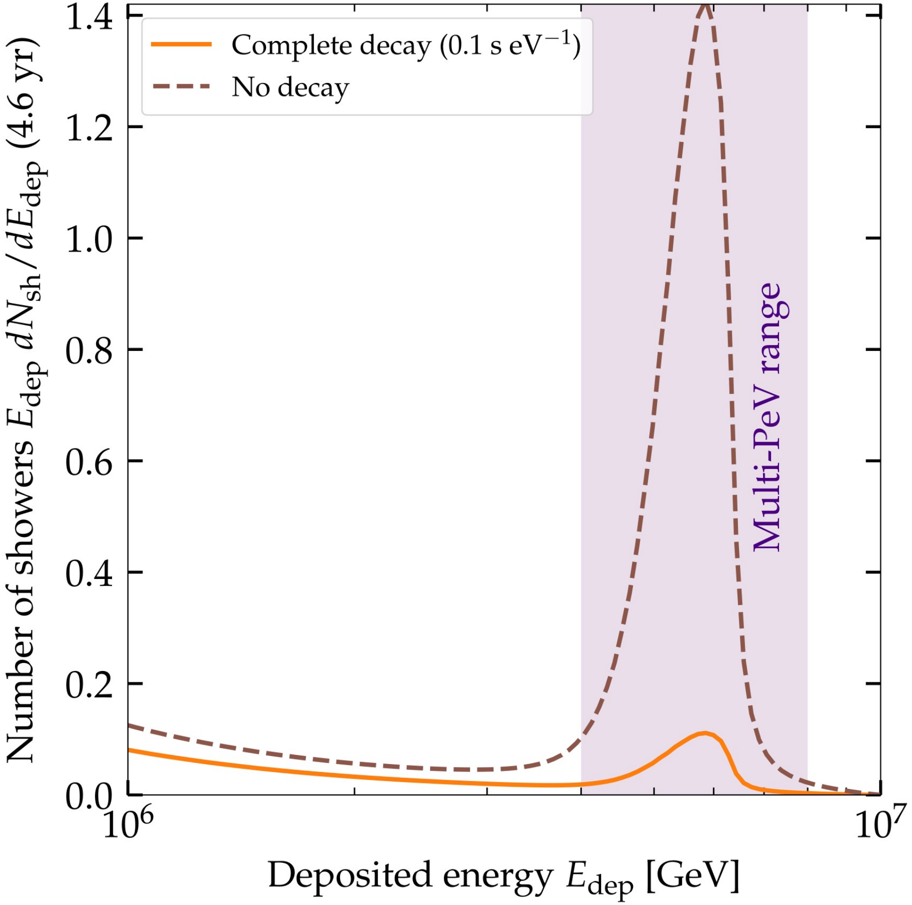

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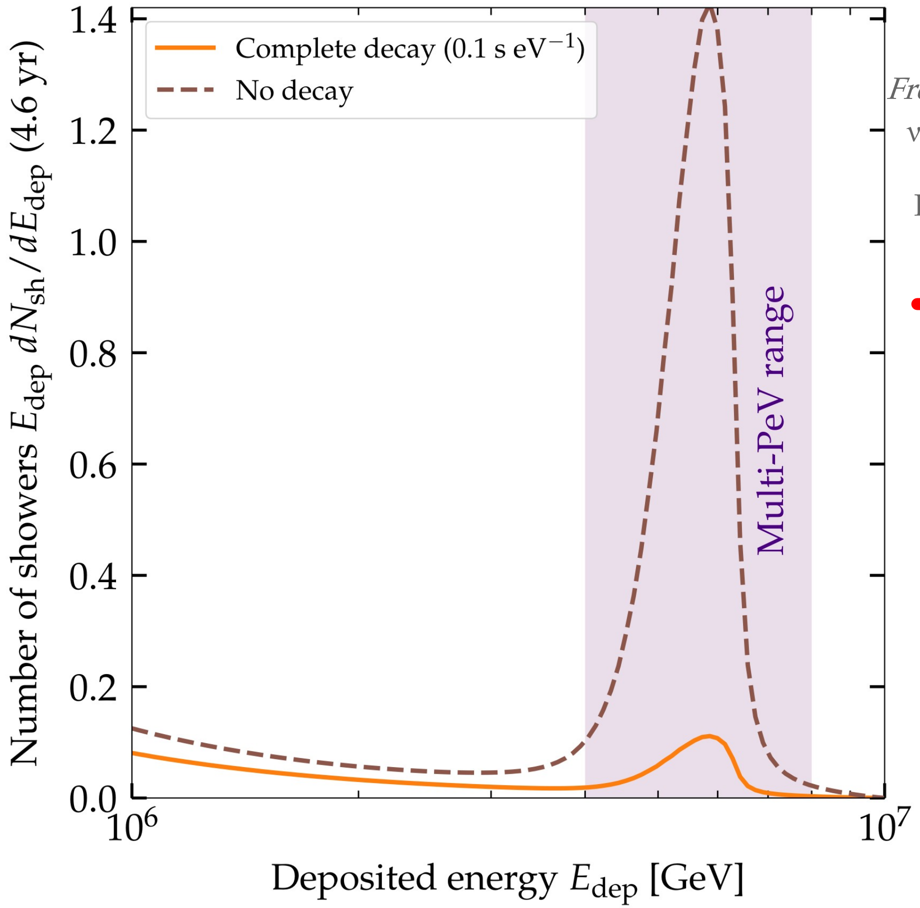

Free parameters:
ν_1, ν_2 lifetimes
Mix. par.
Flavor ratios
$\bar{\nu}/\nu$ ratio

→

What does neutrino decay change?

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

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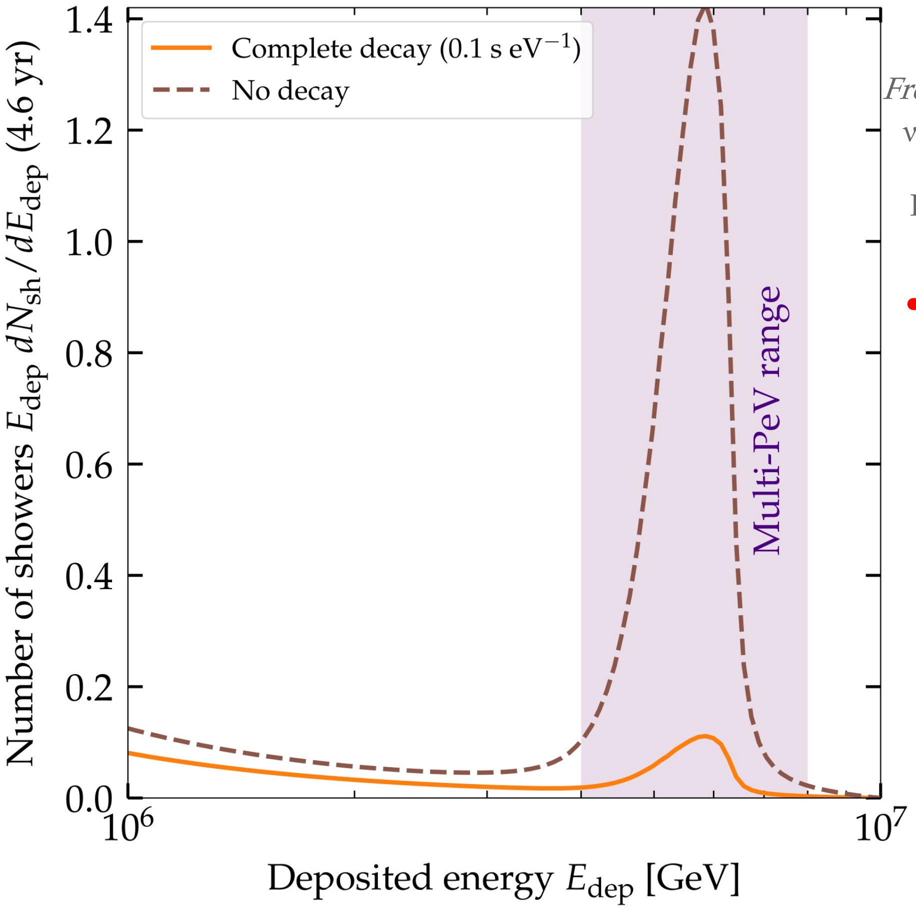

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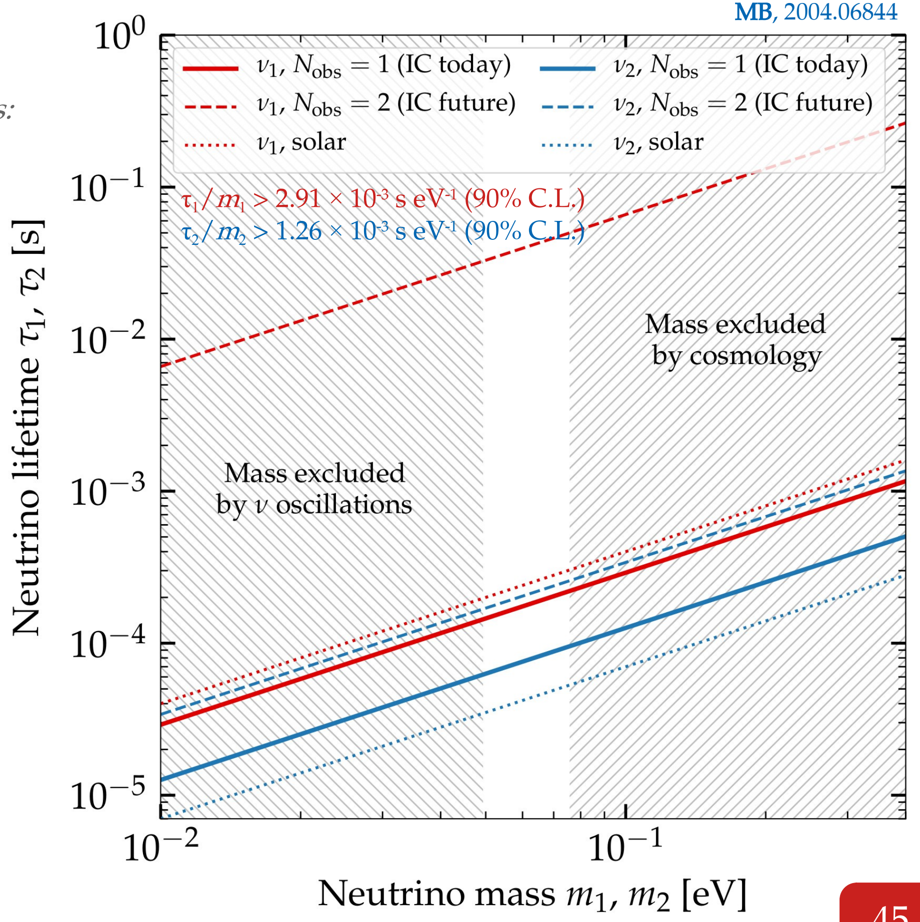

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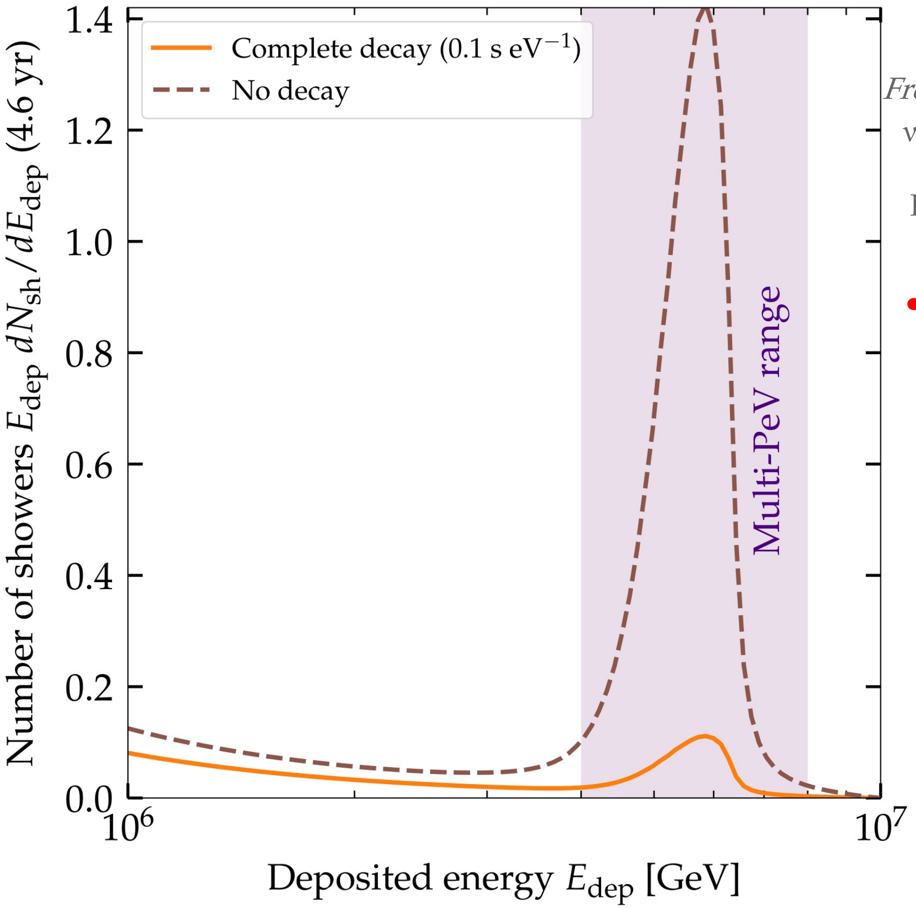

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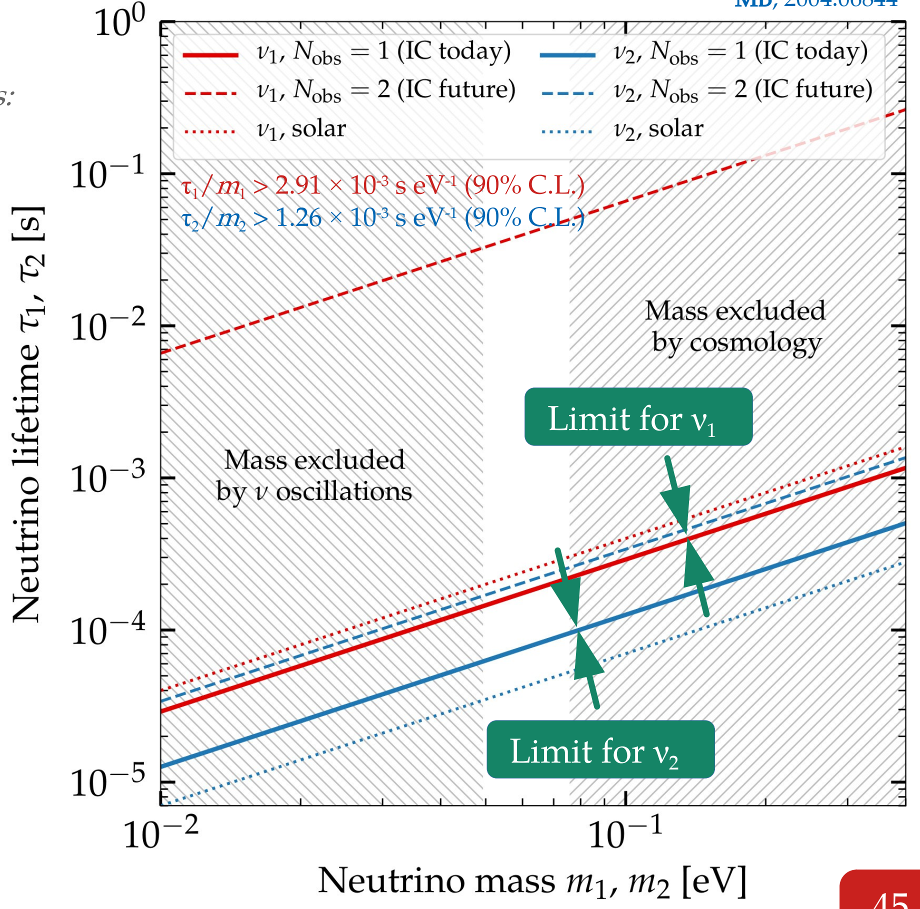
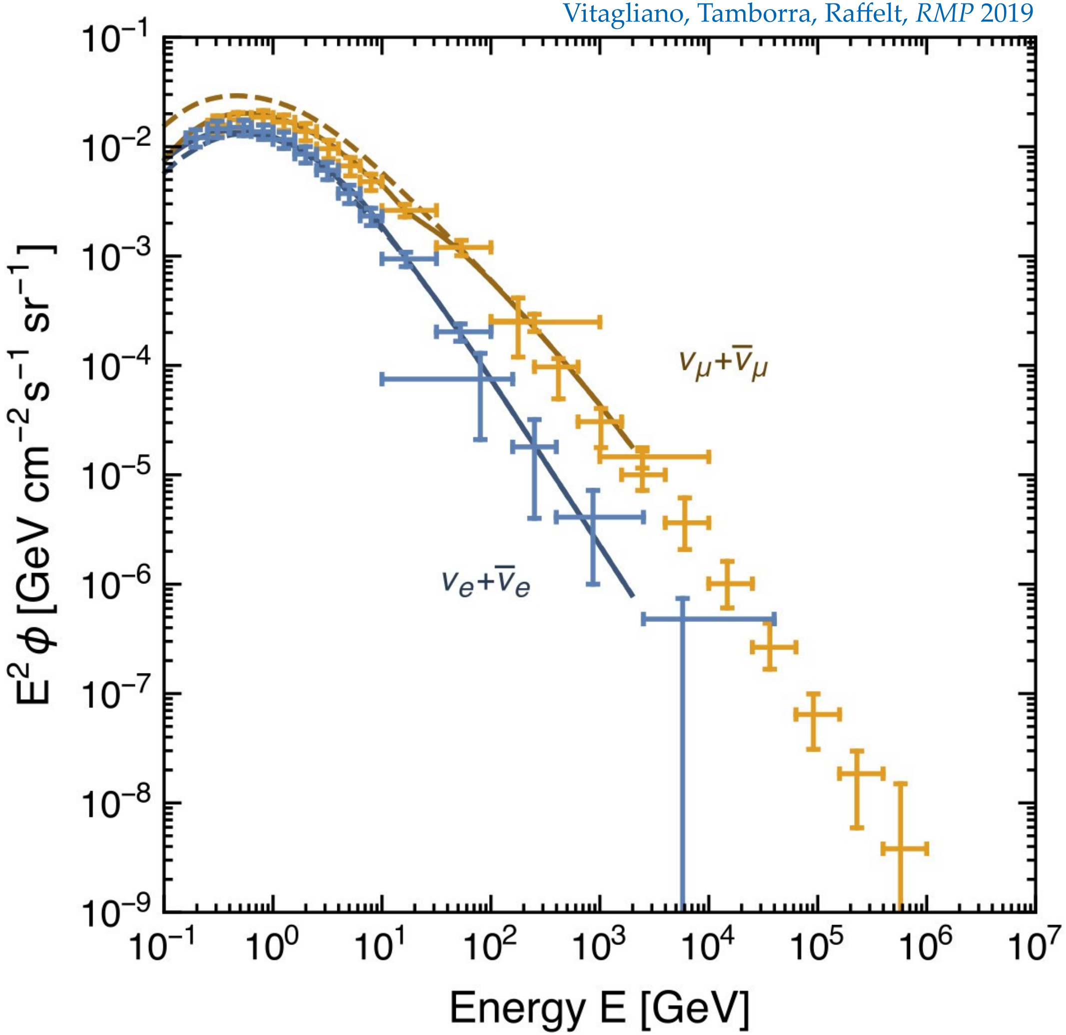


Source searches, Galactic neutrinos

Neutrinos from the Galaxy

Vitagliano, Tamborra, Raffelt, *RMP* 2019



See also: Beacom & Candia, *JCAP* 2004

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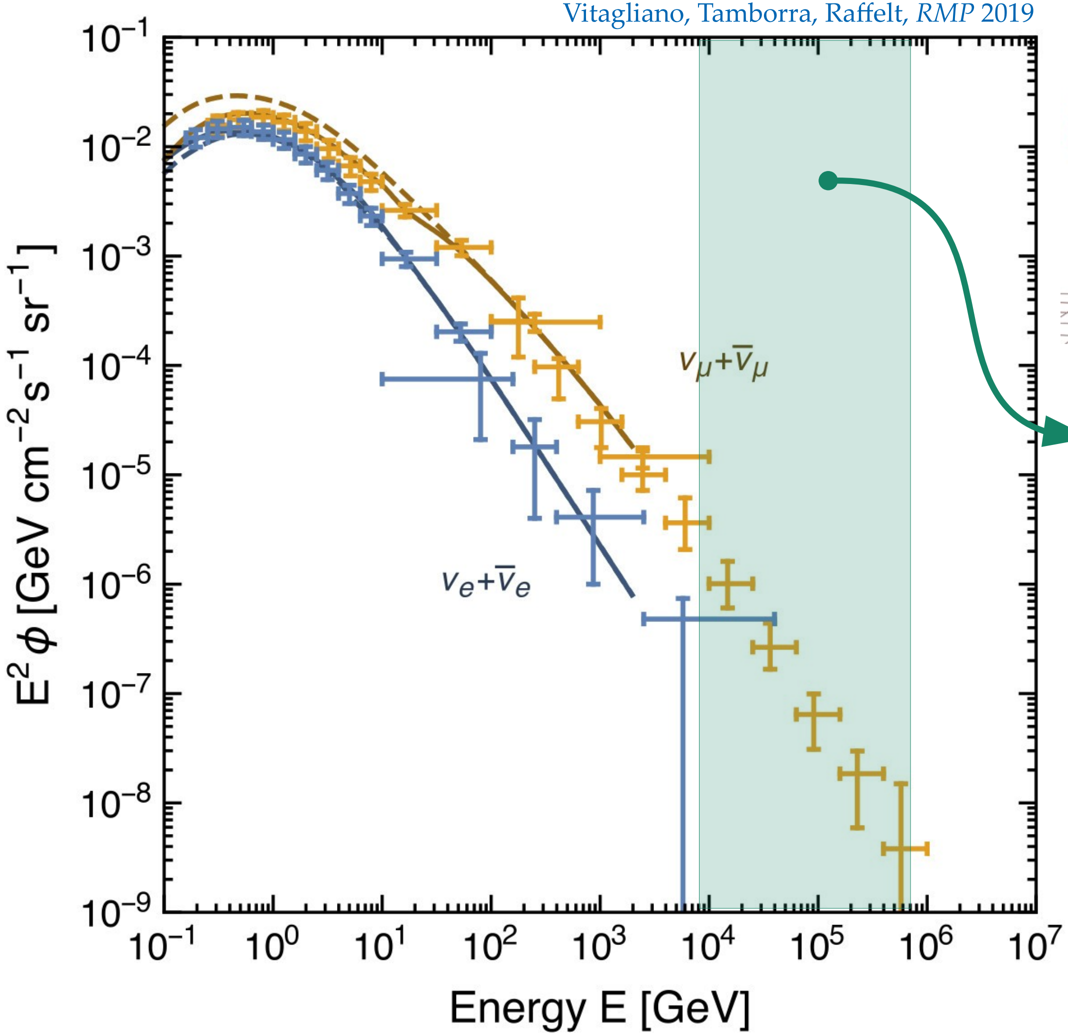
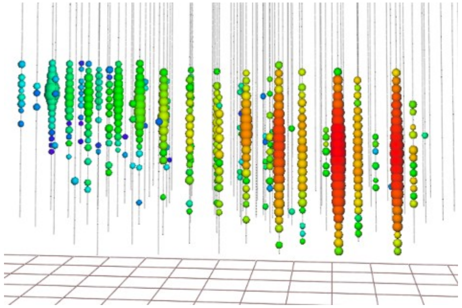


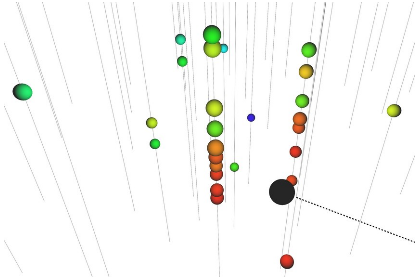


Search for **>10-TeV** astrophysical ν

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

See also: Beacom & Candia, *JCAP* 2004

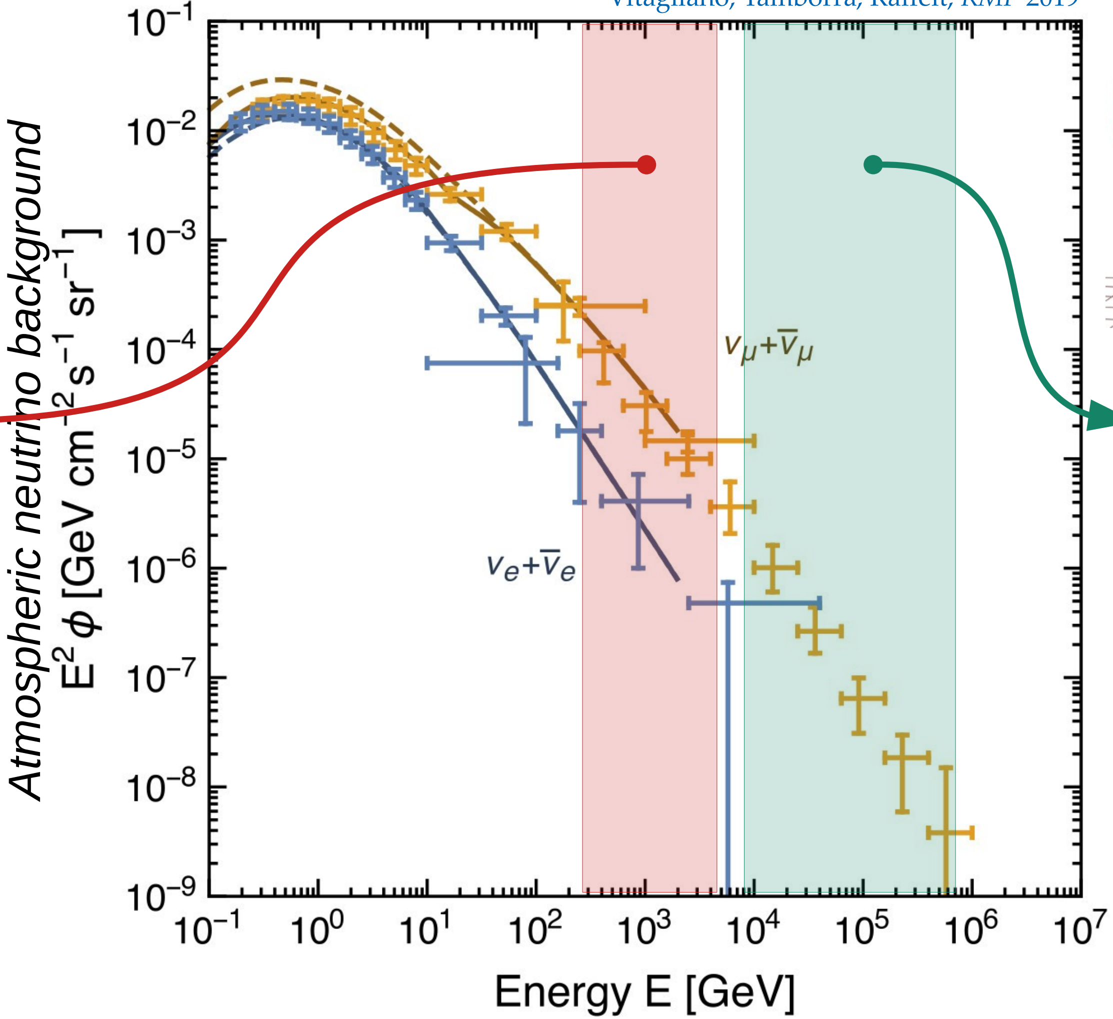
Neutrinos from the Galaxy

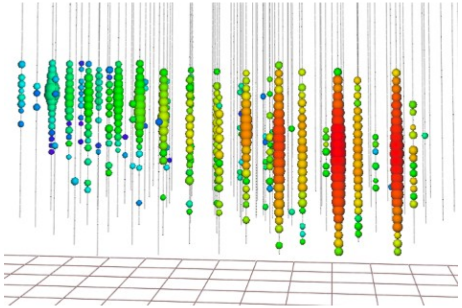


Search for **TeV** astrophysical ν

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

Vitagliano, Tamborra, Raffelt, *RMP* 2019





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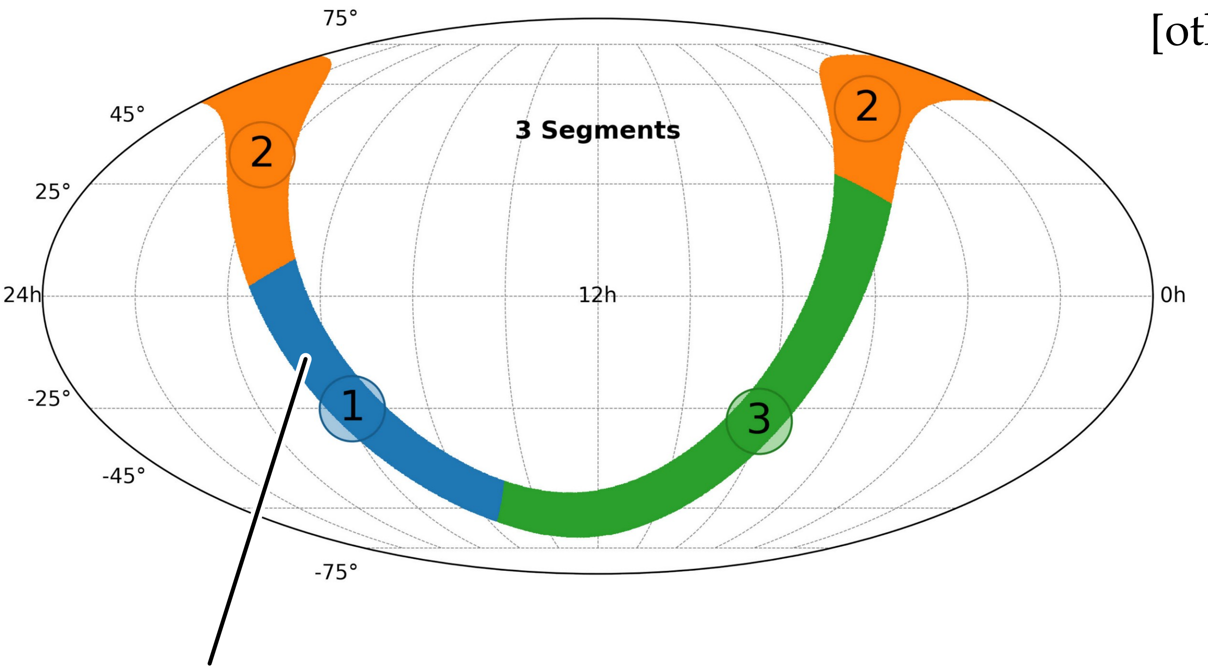
Neutrinos from the Galaxy: **IceCube**

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

Improvements **without** template fitting



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

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

Same cascade sample as 2023 discovery

Same unbinned maximum likelihood
… but now segmented

In each segment: single power law

Fit flux normalization and spectral index

Note: No systematics yet

Neutrinos from the Galaxy: **IceCube**

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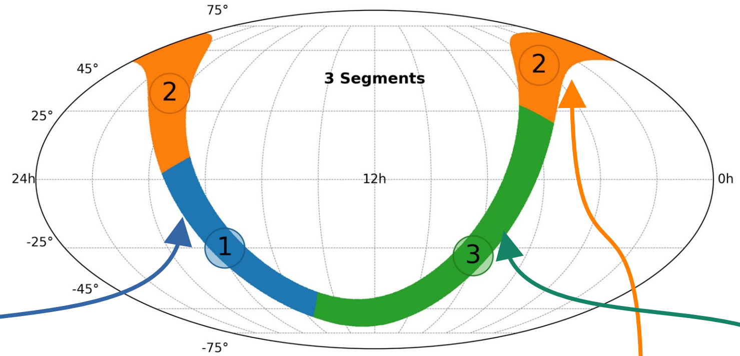
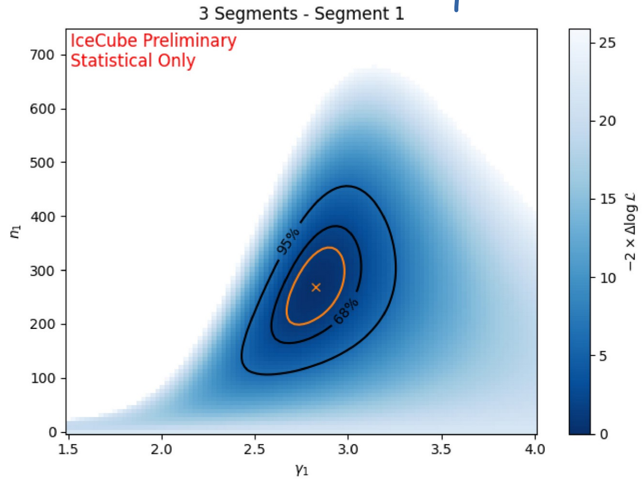
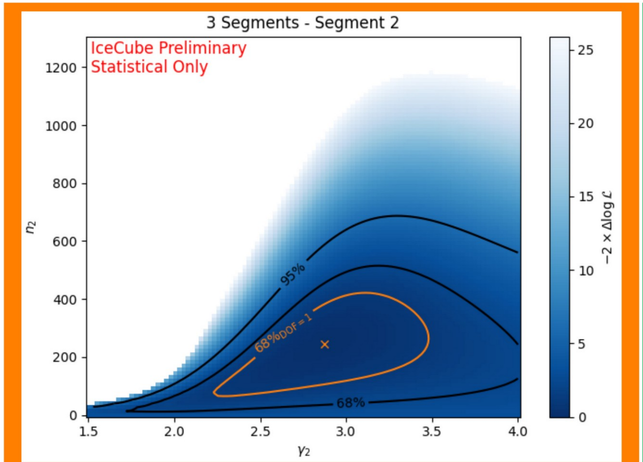


Inner galaxy

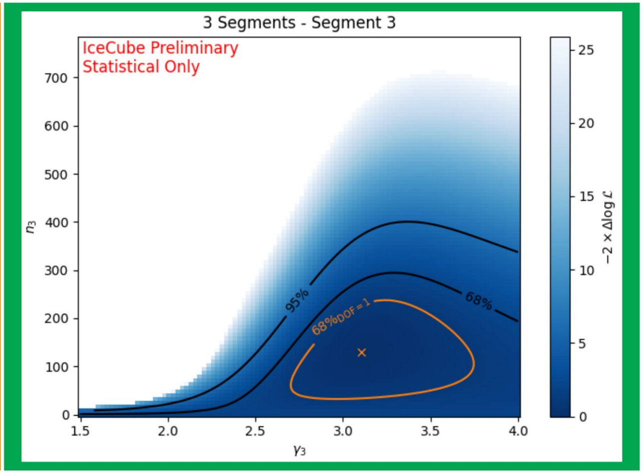
Outer galaxy



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



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



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

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

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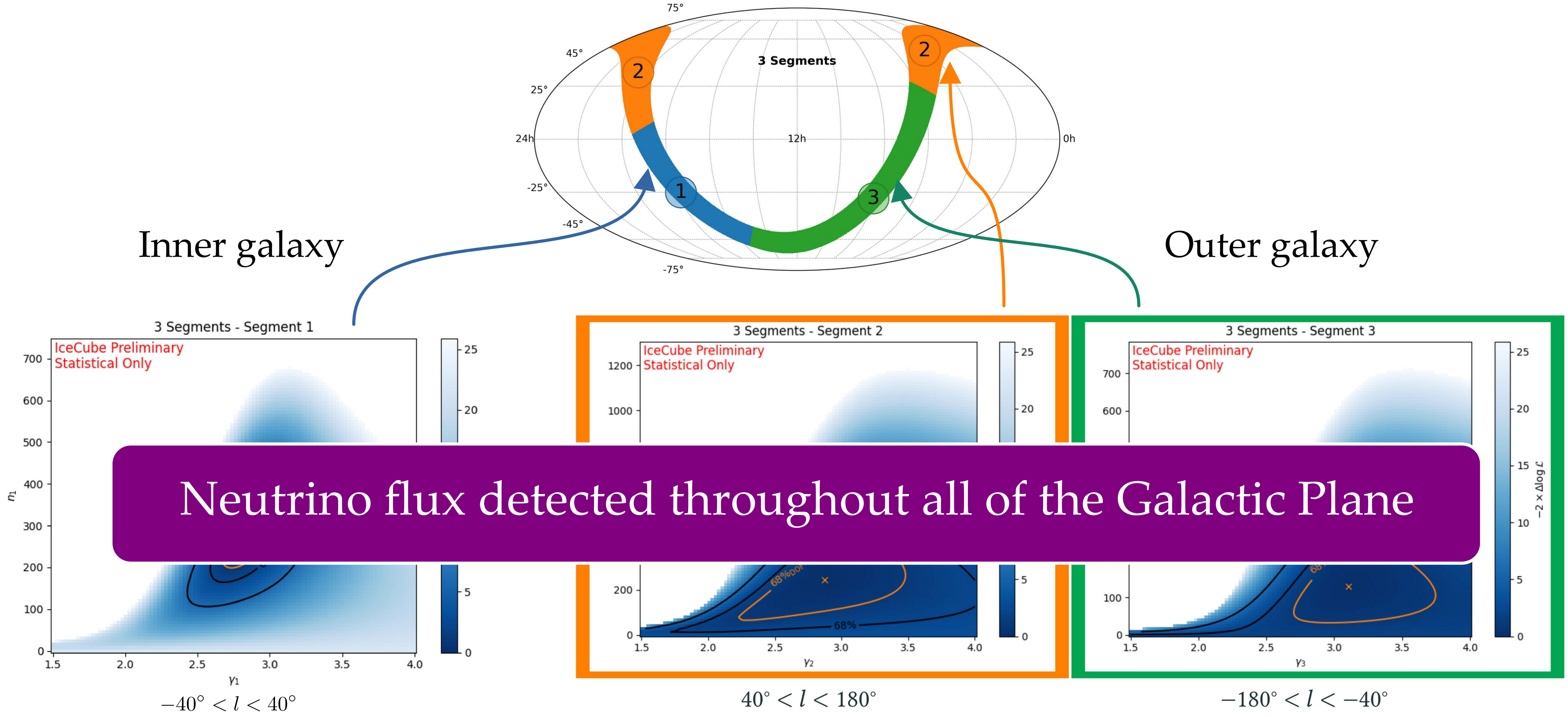
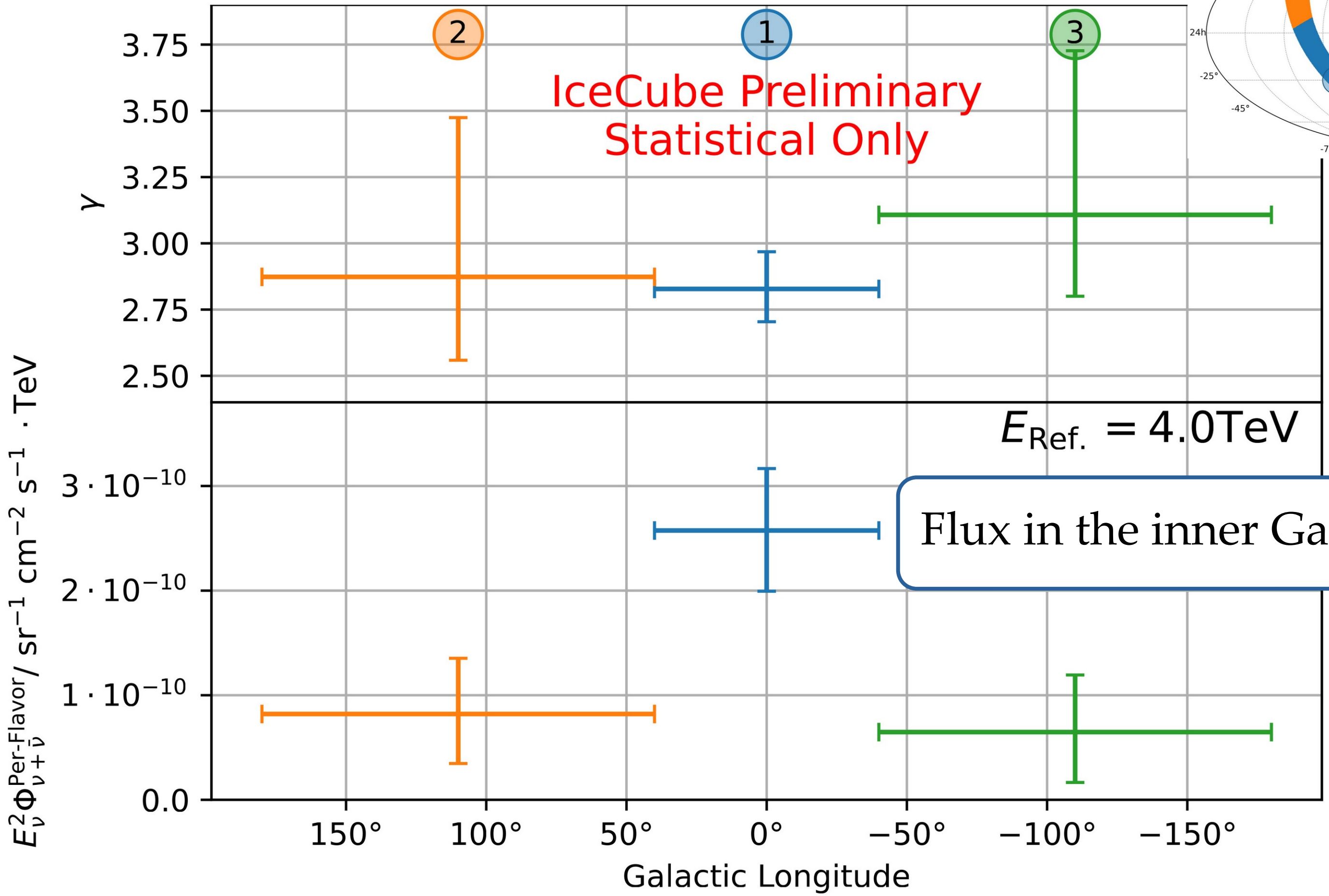
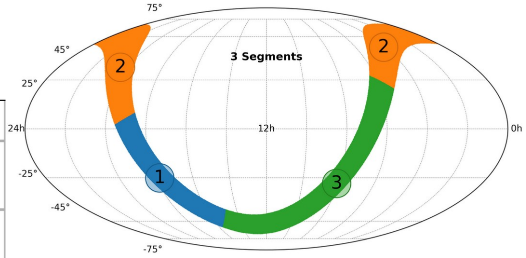


Neutrino flux detected throughout all of the Galactic Plane

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

Improvements **without** template fitting



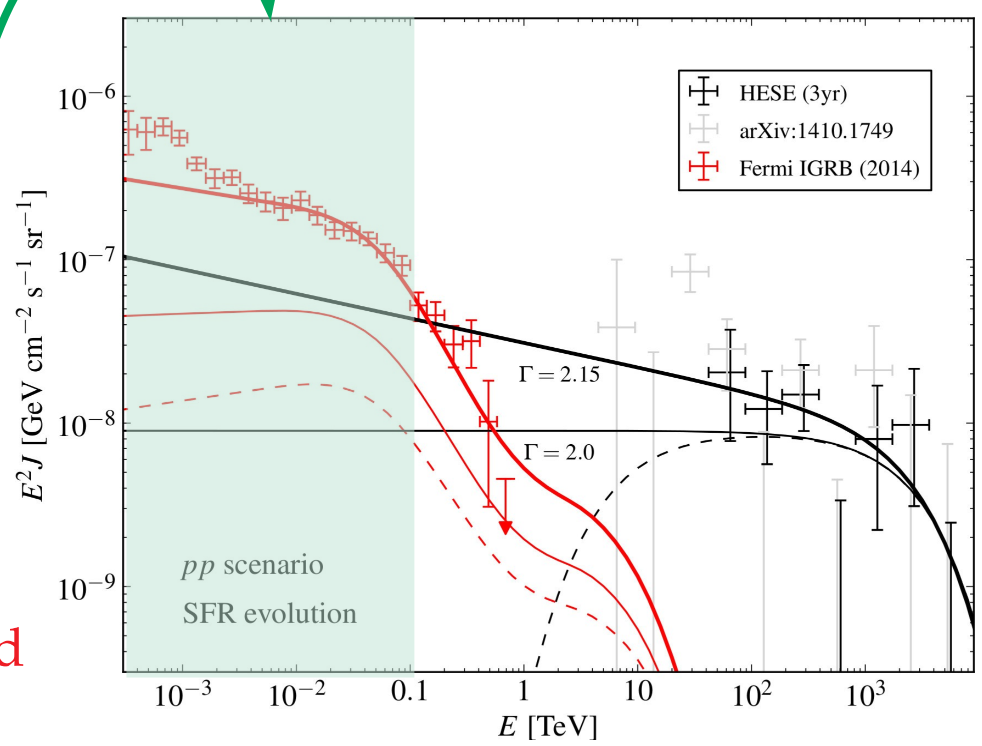


Flux in the inner Galaxy is 2× higher

Constraints from the gamma-ray background

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

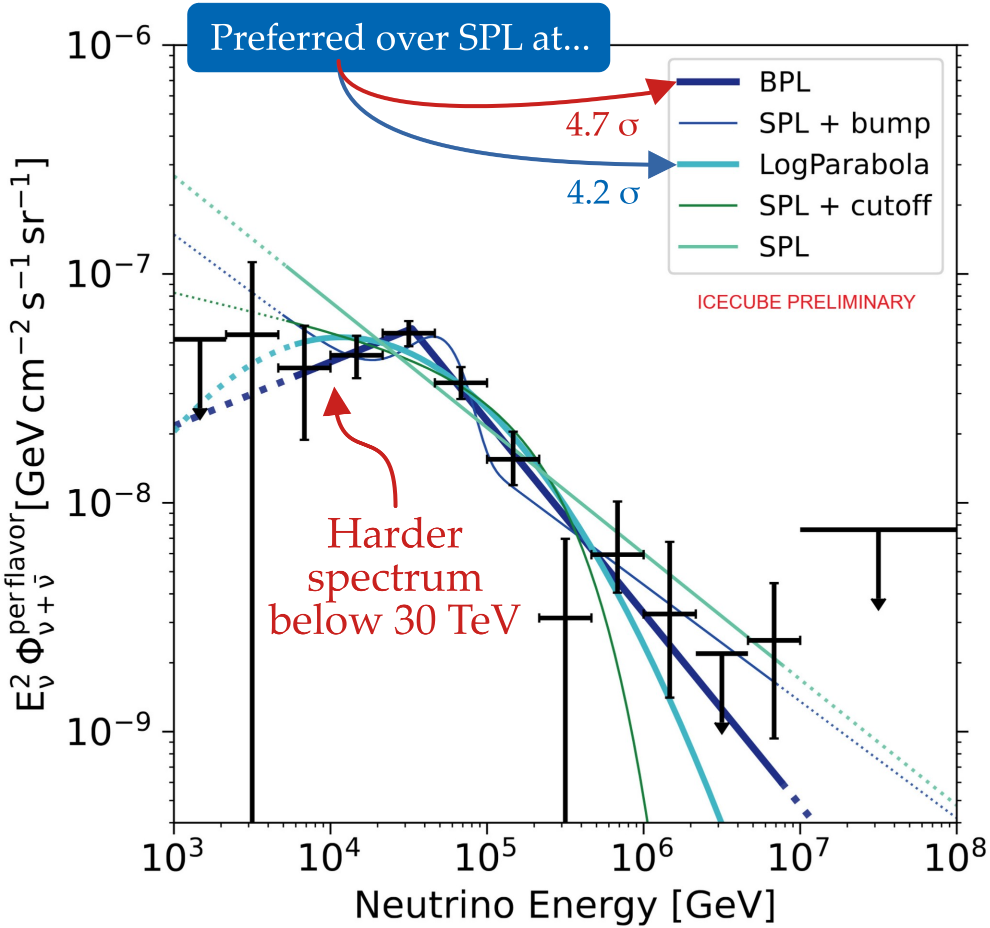
Murase, Ahlers, Lacki, *PRD* 2013

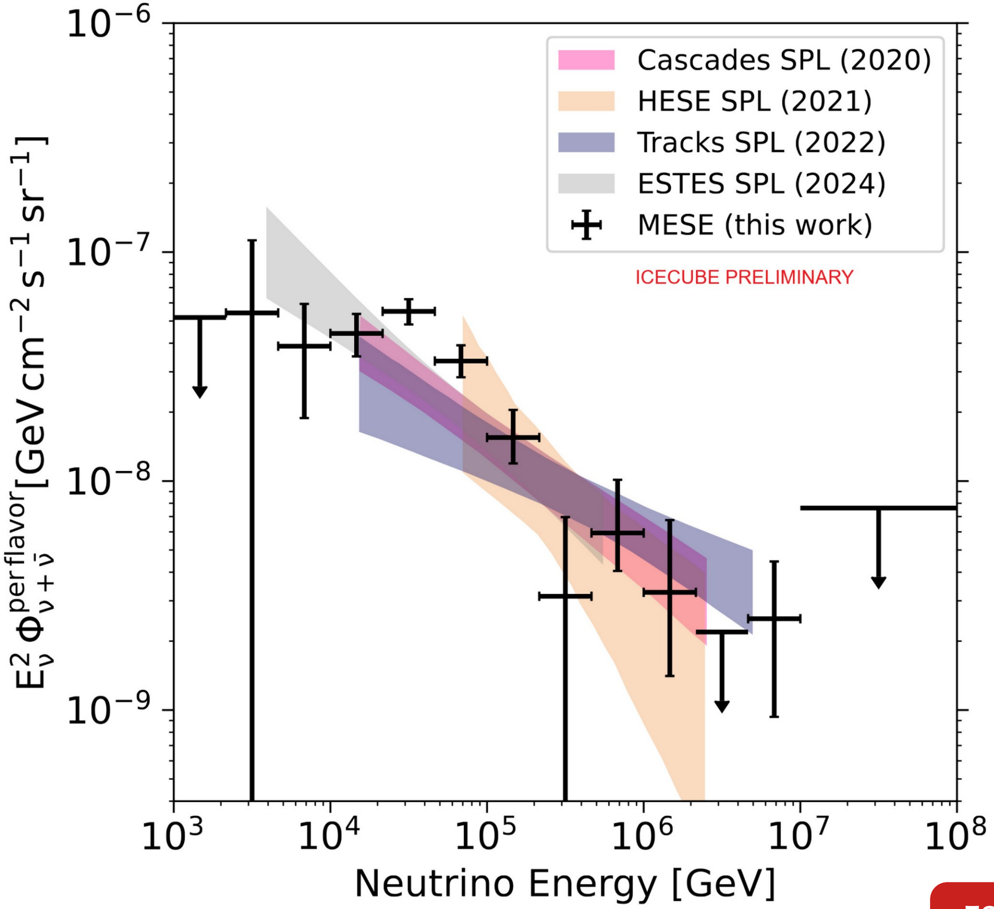


V. Basu, A. Balagopal, A. Karle,
PoS(ICRC2025)985

Diffuse TeV–PeV ν flux: **IceCube**

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

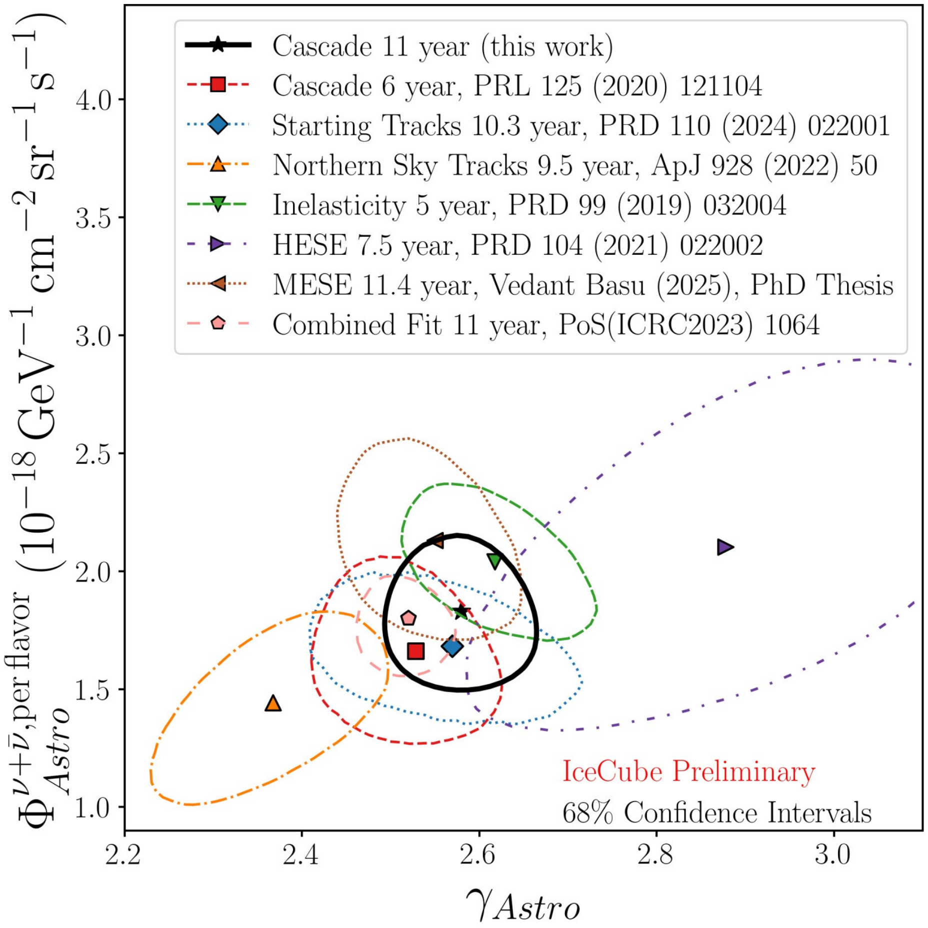


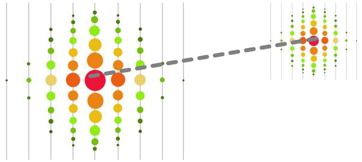


Diffuse TeV–PeV υ flux: **IceCube**

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

2 – New measurement using cascades at > 10 TeV





11 yr of cascade data

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

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

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

Produce υ_τ-enriched sample with 90% υ_τ purity

(Great for flavor measurements, see later)

Diffuse TeV–PeV υ flux: **IceCube**

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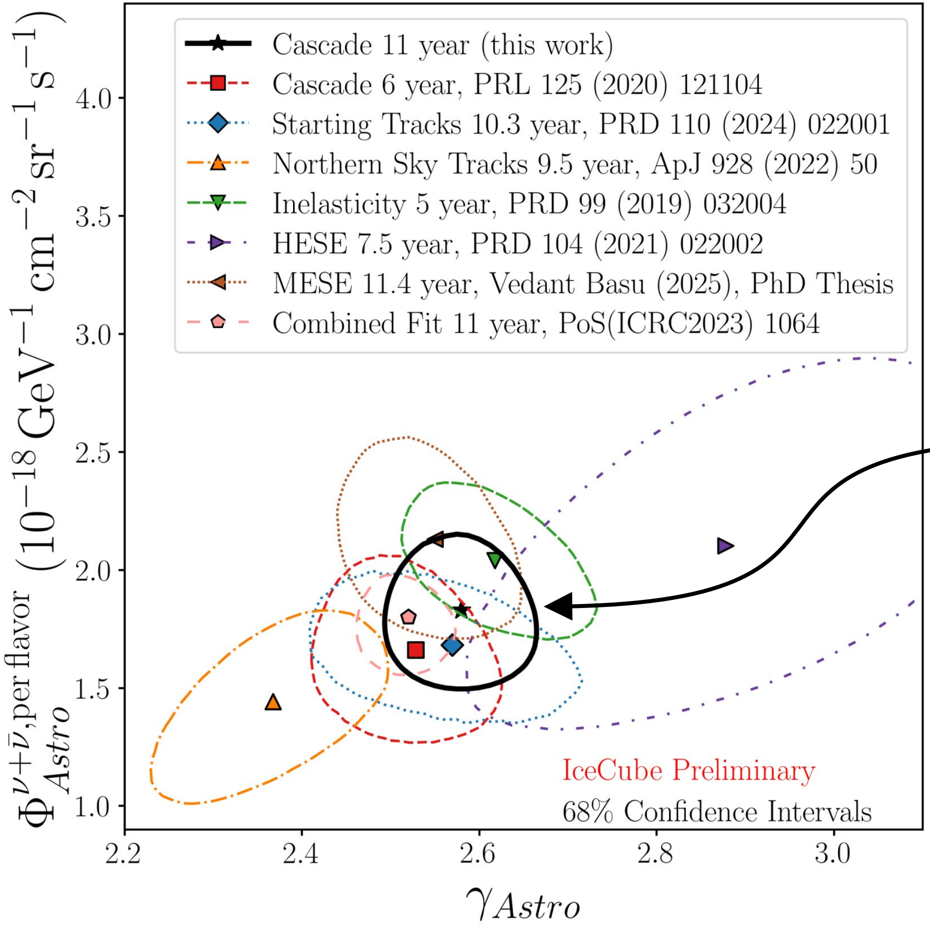
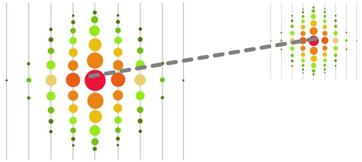




11 yr of cascade data

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

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

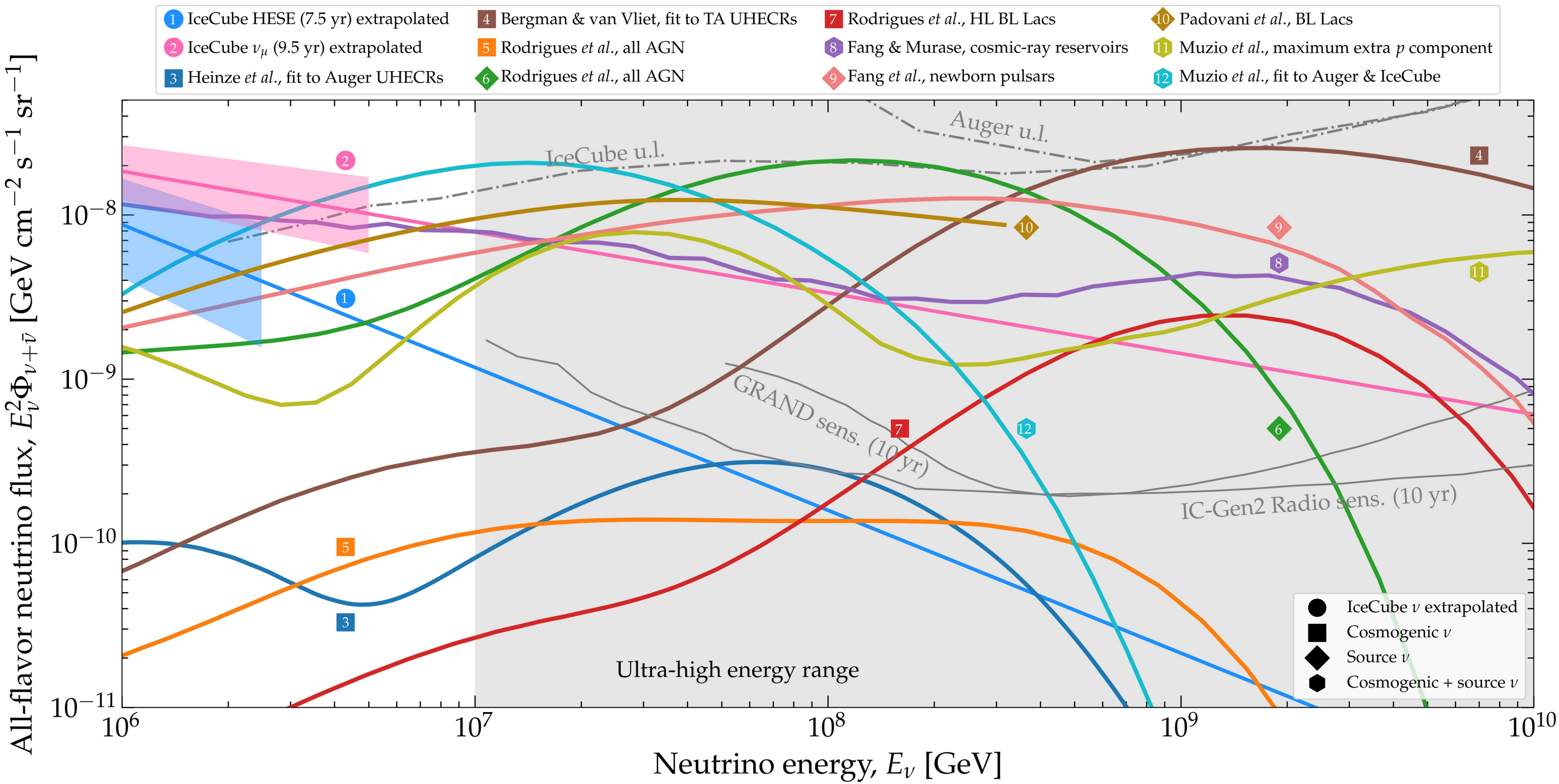
$$\Phi = \Phi_0 \times \left(\frac{E}{100\ \text{TeV}}\right)^{-\gamma},$$

agrees with previous results

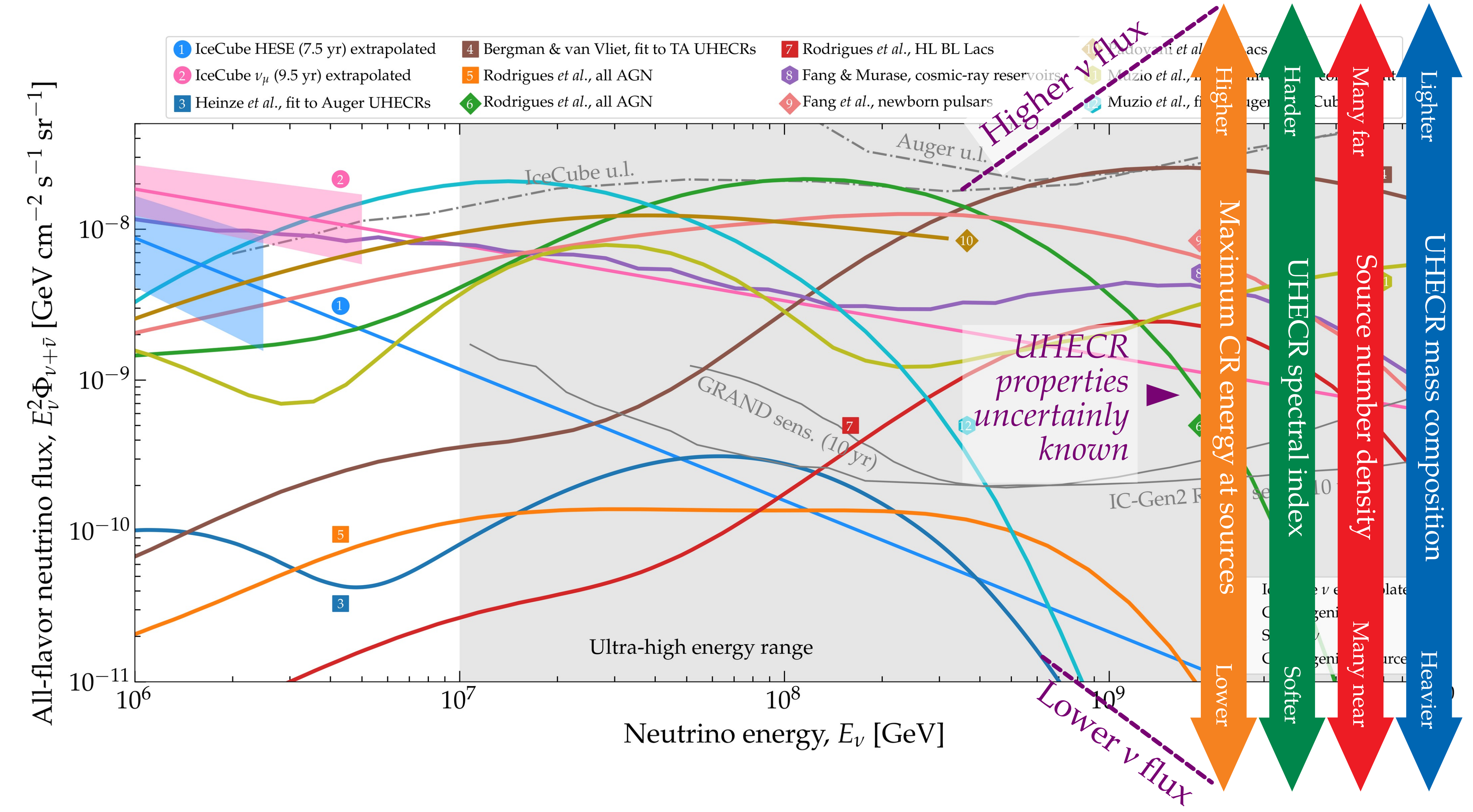
Best-fit values:

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

UHE neutrinos



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



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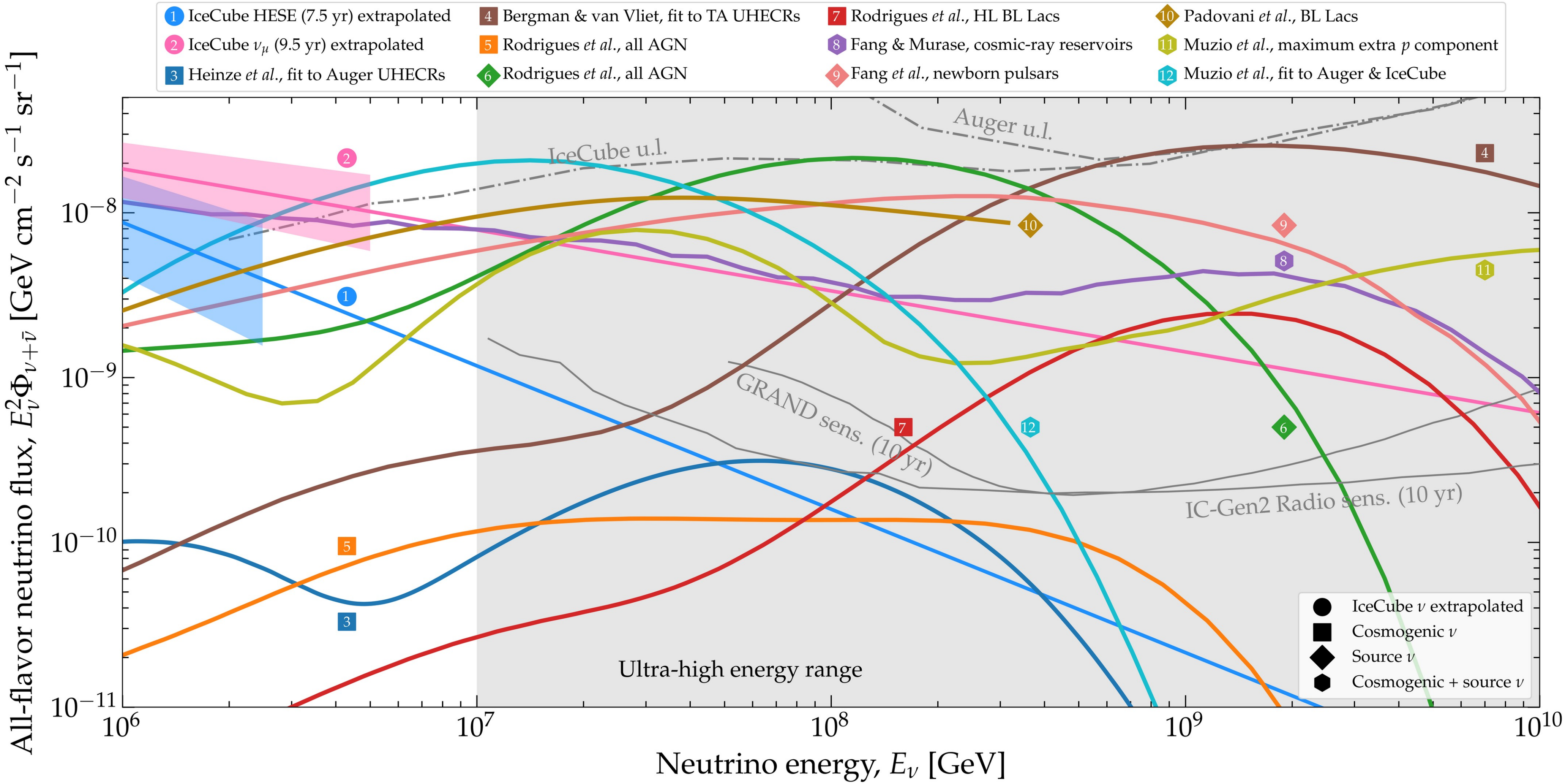
Higher ν flux
Lower ν flux
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
Ultra-high energy range
UHECR properties uncertainly known
Higher
Maximum CR energy at sources
Lower
Harder
UHECR spectral index
Softer
Many far
Source number density
Many near
Lighter
UHECR mass composition
Heavier
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]



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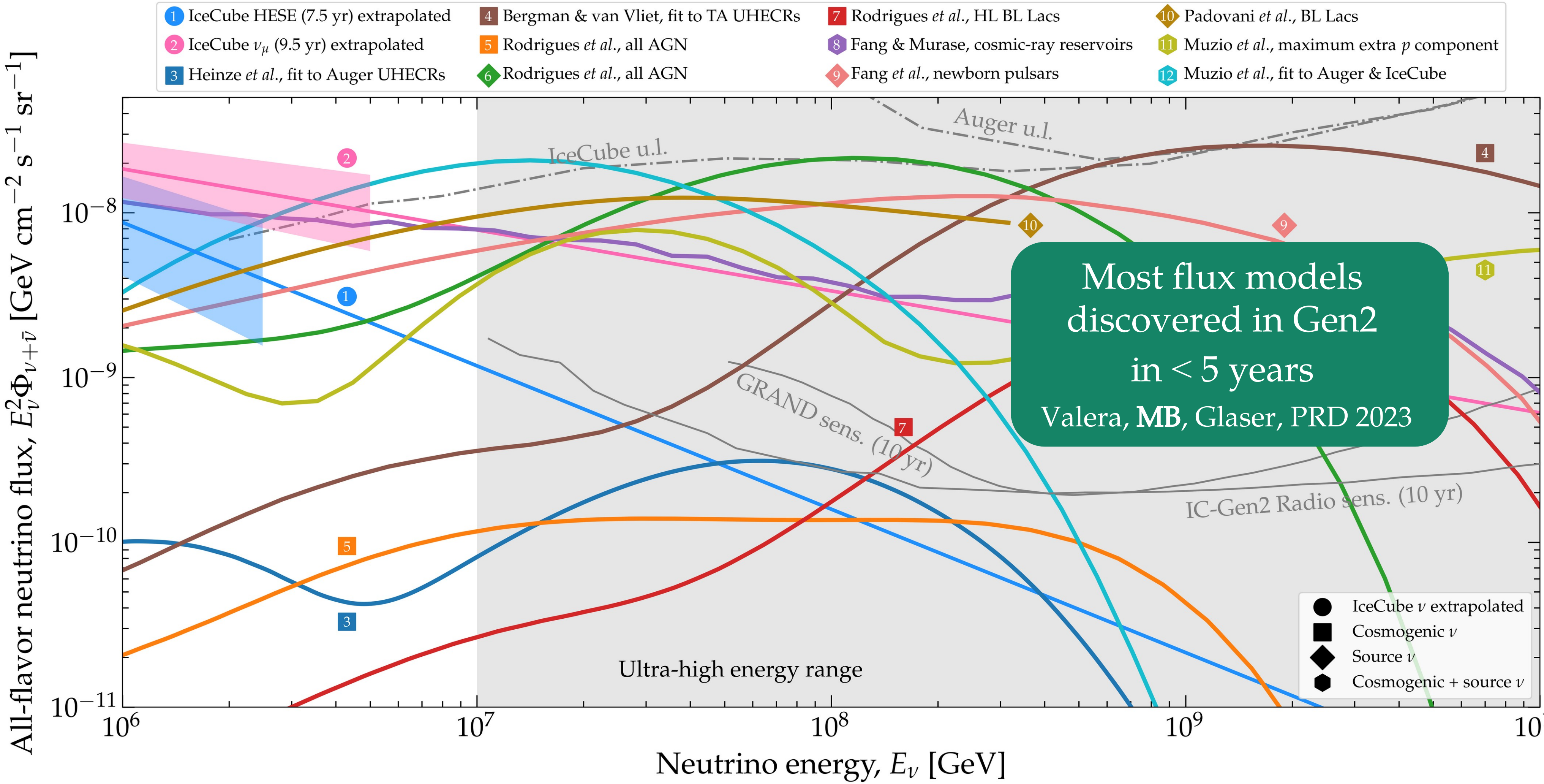
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze et al., fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
5 Rodrigues et al., all AGN
6 Rodrigues et al., all AGN
7 Rodrigues et al., HL BL Lacs
8 Fang & Murase, cosmic-ray reservoirs
9 Fang et al., newborn pulsars
10 Padovani et al., BL Lacs
11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

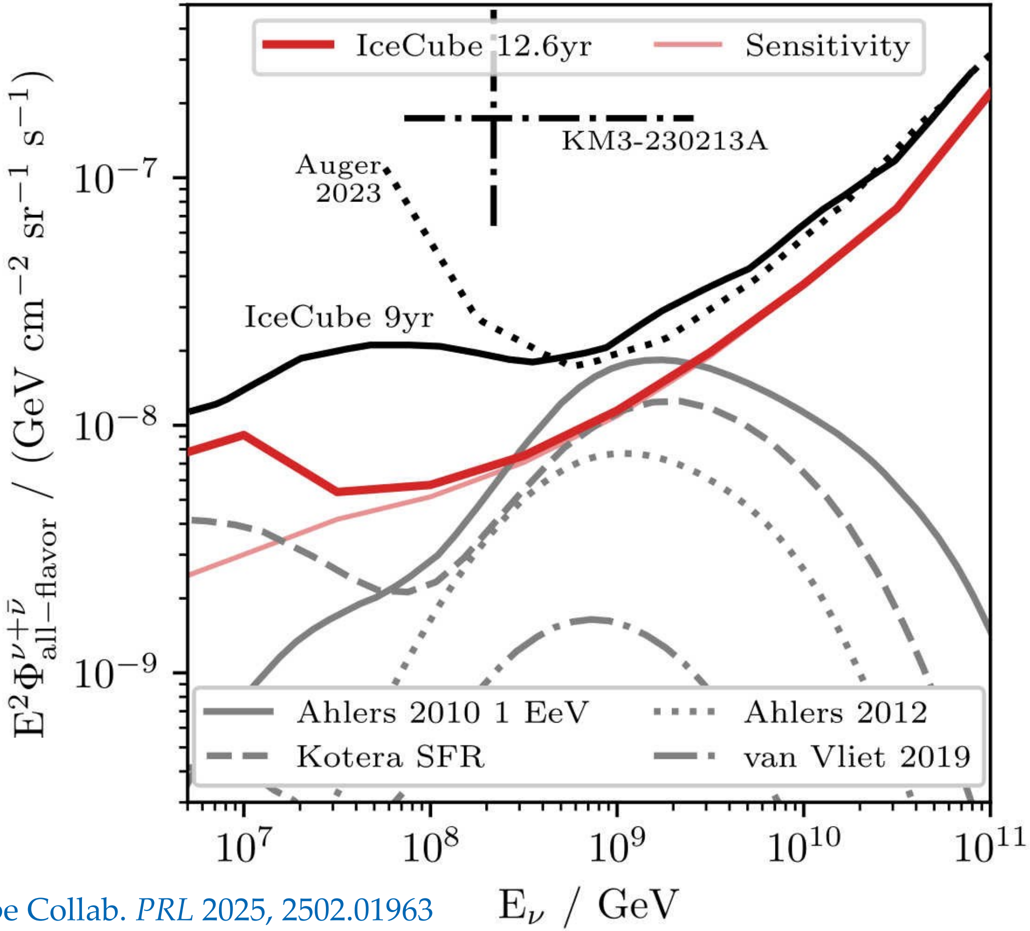


Most flux models discovered in Gen2 in < 5 years

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

New upper limits on UHE neutrinos: **IceCube**

Search for UHE ν updated from 9 to 12.6 yr



Strongest UHE limit today

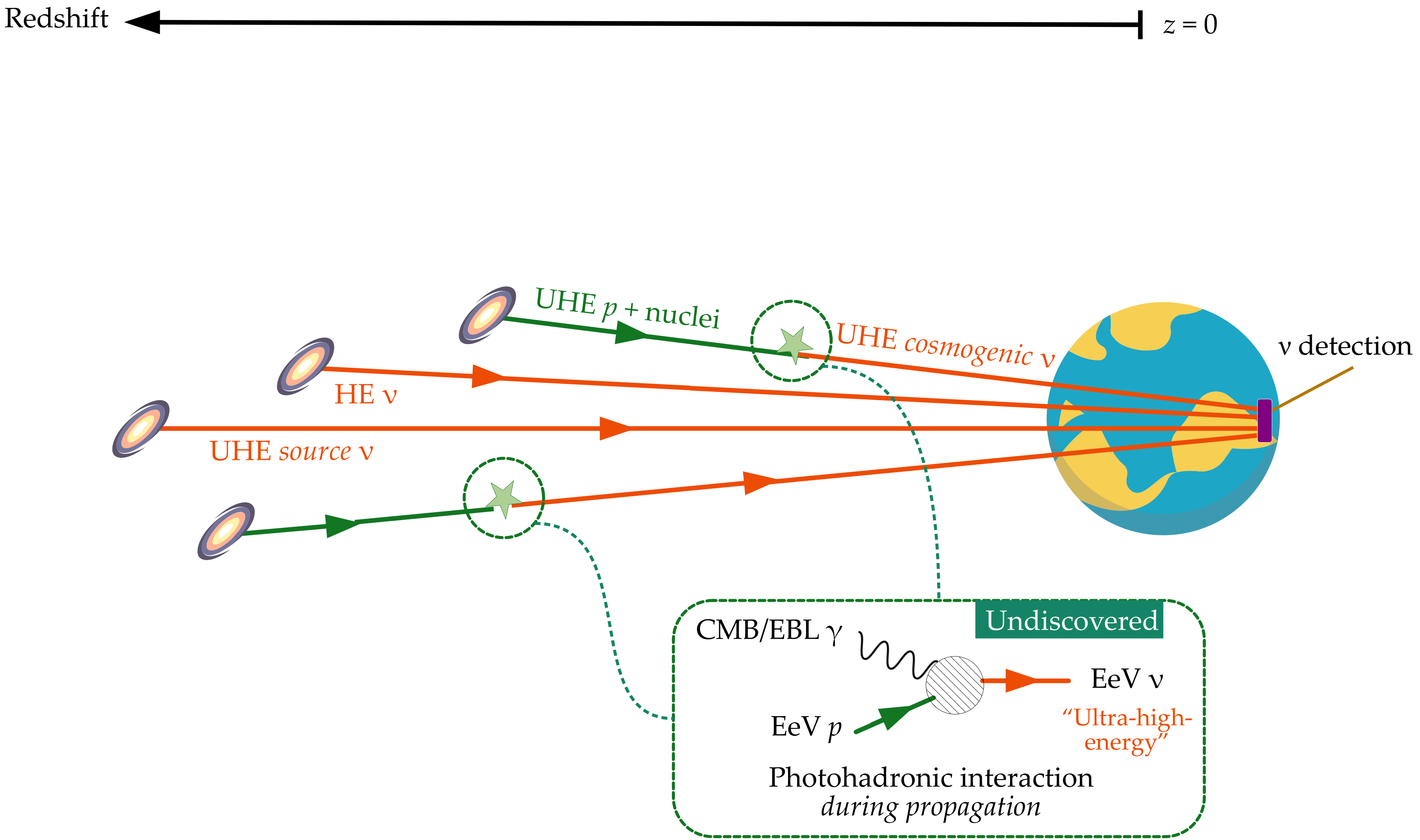
Improvement due to 40% higher ν_μ A_{eff}:
- Improved angular resolution
- Looser muon bundle cuts

Repeating the joint fit of the UHE KM3-230213A with IceCube and Auger increases the tension from 2.5σ to 2.9σ

Also: new limits on UHECR proton fraction

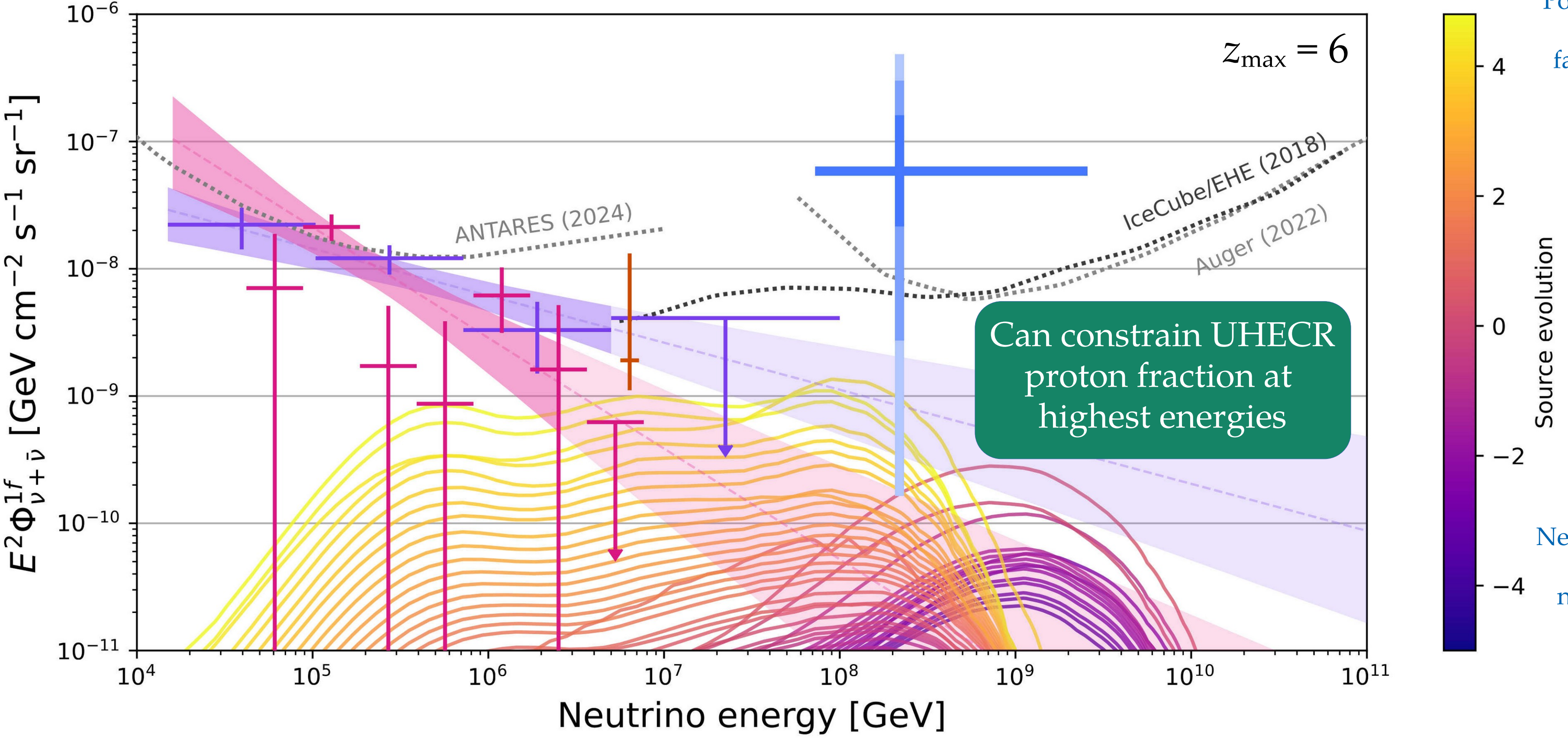
IceCube Collab. *PRL* 2025, 2502.01963

The KM3NeT UHE neutrino


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

Was it a cosmogenic neutrino?

Assume population of nondescript, identical UHECR sources
UHECR flux fit to Auger spectrum + mass composition, source abundance $(1+z)^m$



Positive evolution:
More sources faraway — more cosmogenic ν

Negative evolution:
More sources nearby — fewer cosmogenic ν

KM3NeT Collab. *ApJL* 2025

BSM with the KM3NeT UHE neutrino

Beyond the Standard Model

New energies represent new opportunities to look for BSM physics, *e.g.*,

UHE ν from decay of super-heavy dark matter
UHE ν from primordial black holes
Sterile-active ν transitions
Lorentz-invariance violation

Caveat emptor!
Being able to explain KM3-230213A with BSM physics ***does not*** mean that a BSM explanation is preferred (always compute your Bayes factors!)

See backup slides for BSM proposals inspired by KM3-230213A

Lorentz-invariance violation — from superluminal speeds

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

$$\nu \to \nu + e^+ + e^-$$

Cohen & Glashow, *PRL* 2011

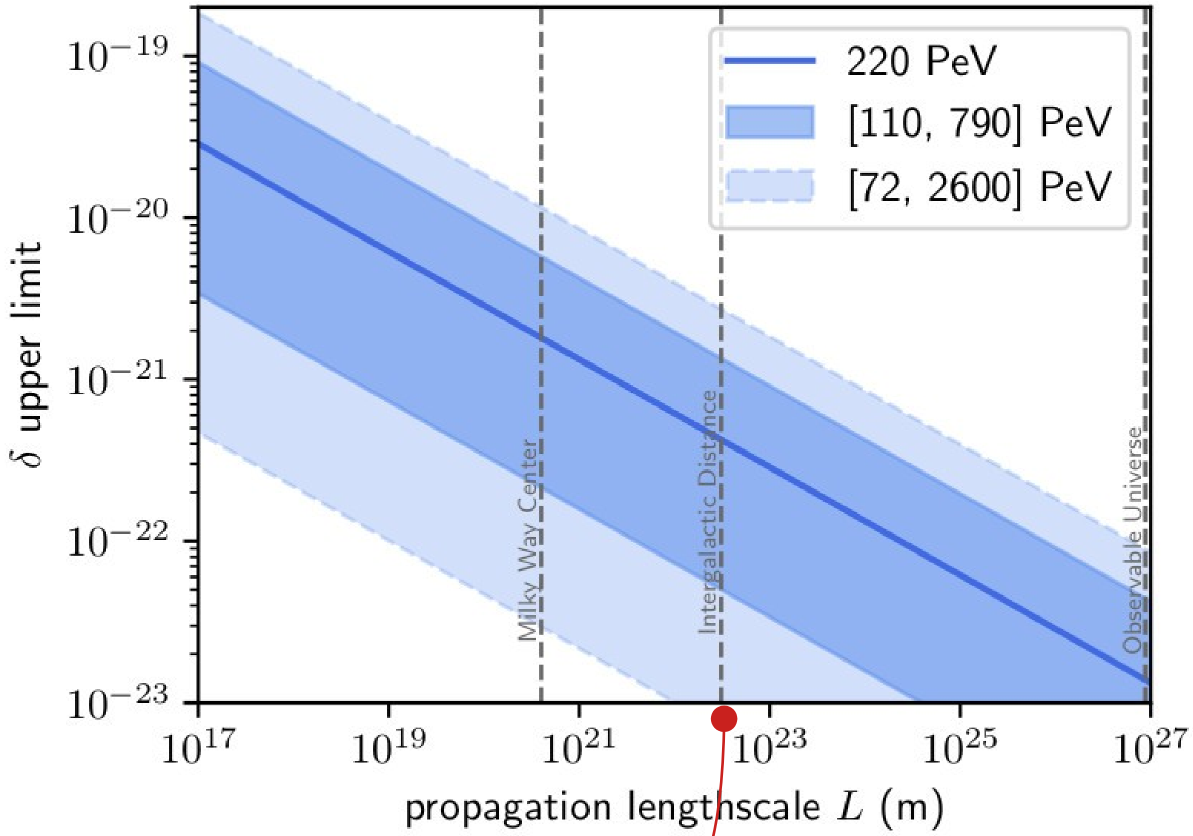
Excess over light speed: $\delta = c_\nu - 1$

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

Decay width (↑ Γ)

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

KM3NeT Collab., 2502.12070



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

Lorentz-invariance violation — from a GRB association

GRB emitted neutrinos & photons simultaneously

Time delay induced by dispersion of neutrinos on spacetime foam:

Neutrino energy

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

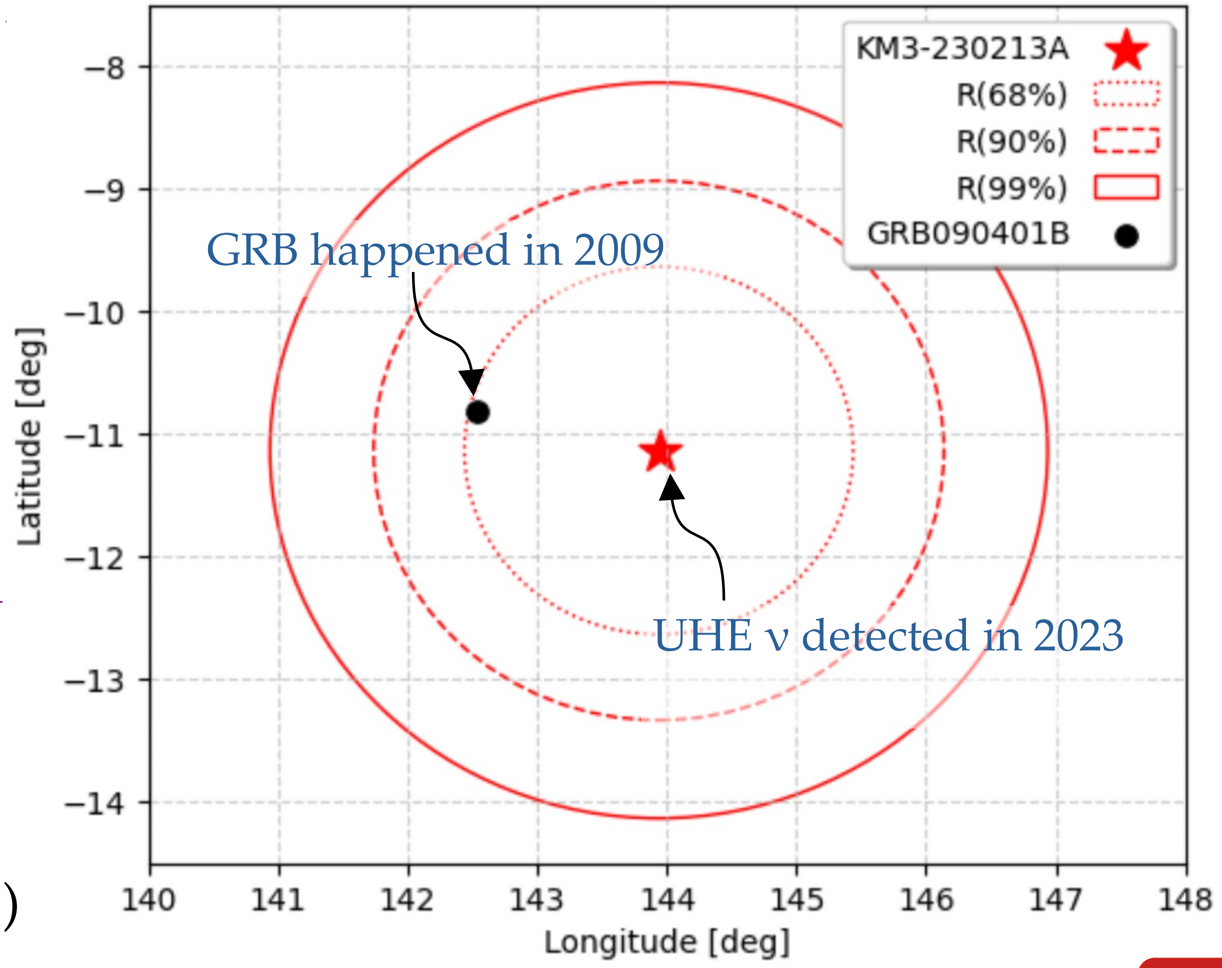
Cosmological expansion

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

GRB-ν association: 2.4σ

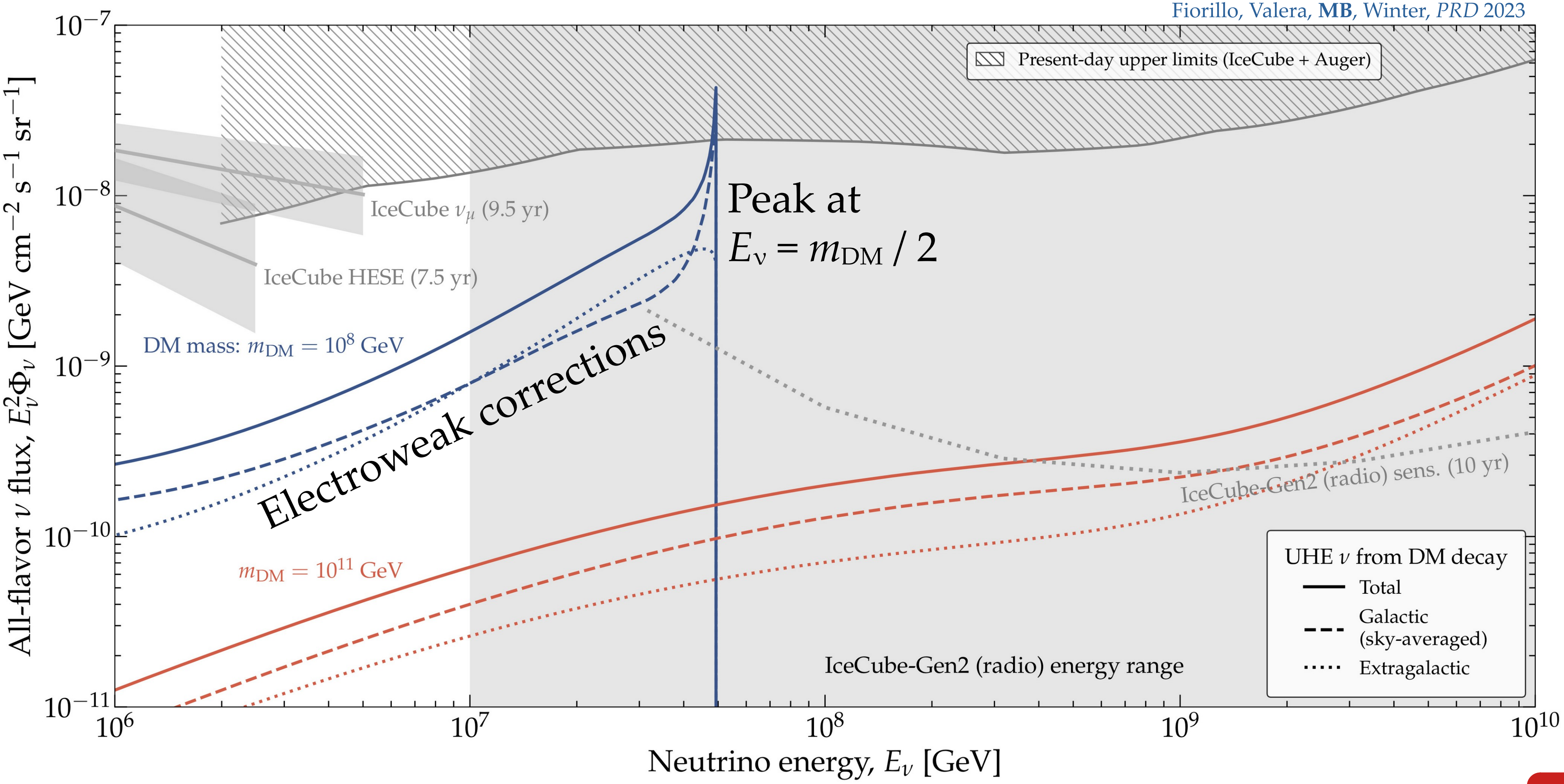
(p-value of 0.015)

Amelino-Camelia *et al.*, 2502.13093



Decay of heavy dark matter (DM → ν + ν)

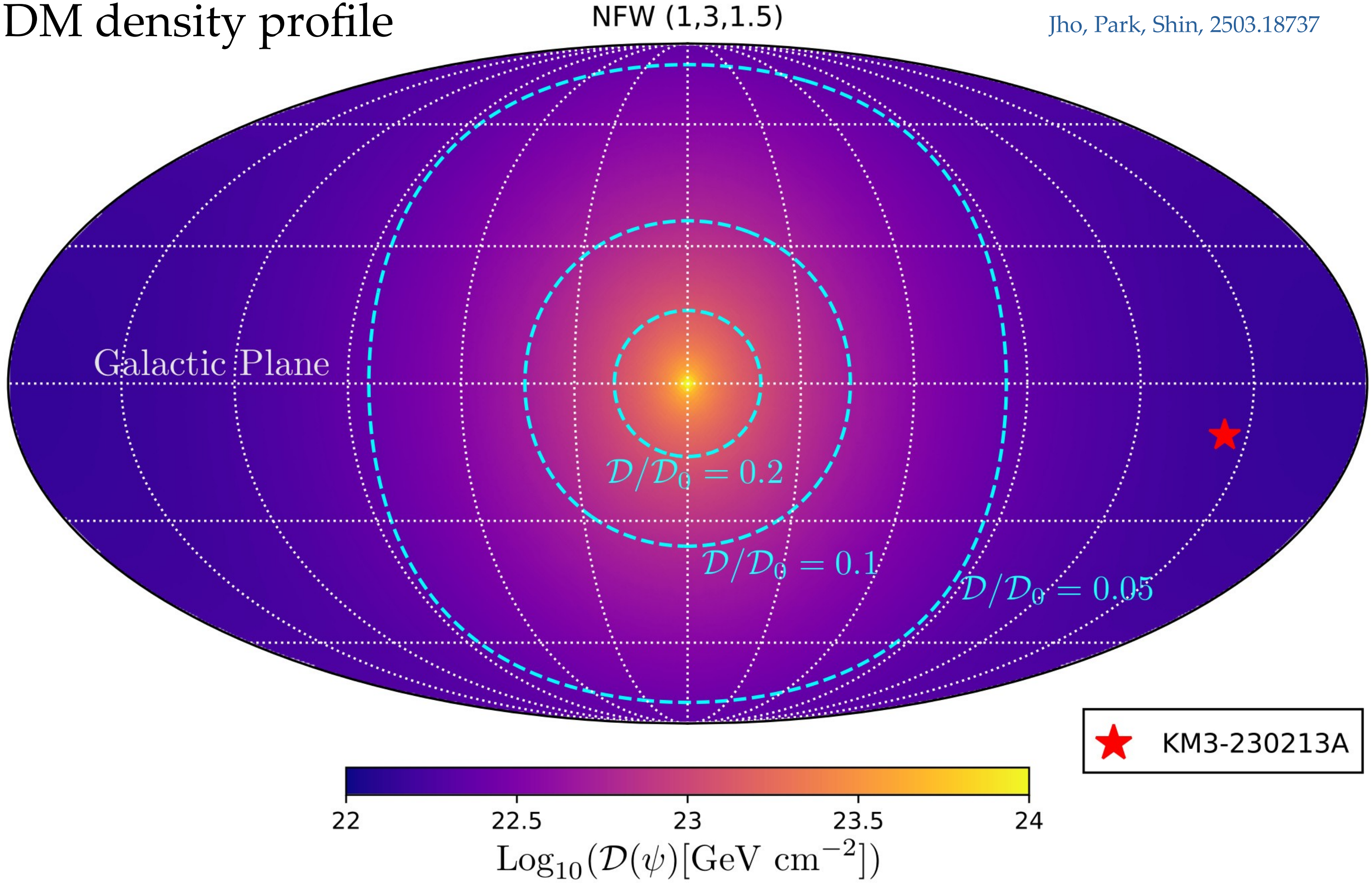
Fiorillo, Valera, **MB**, Winter, *PRD* 2023



Decay of heavy dark matter (DM → ν + ν)

Galactic DM density profile

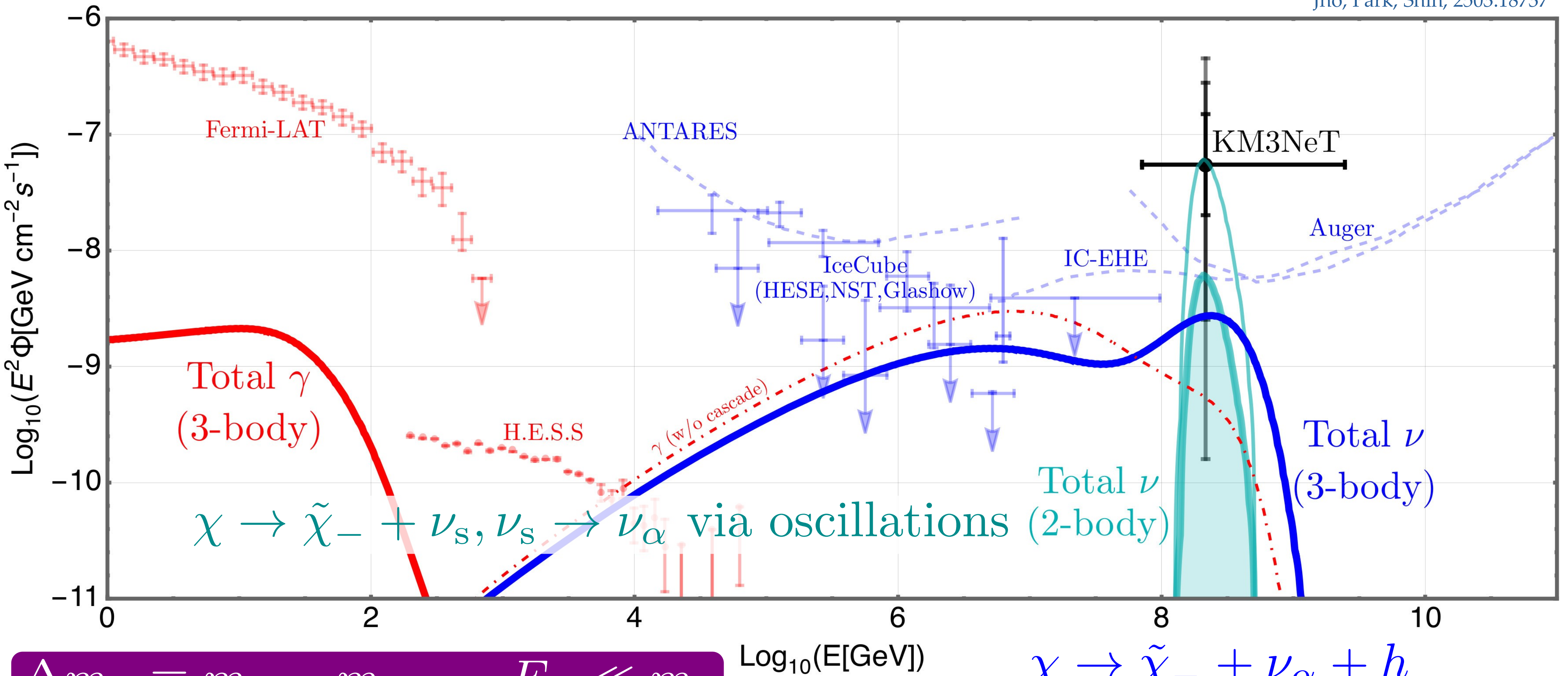
Jho, Park, Shin, 2503.18737



Decay of heavy dark matter — supersymmetric

Multi-component DM: heavy (χ, unstable) & lighter ($\tilde{\chi}_-$, stable)

Jho, Park, Shin, 2503.18737



$\chi \to \tilde{\chi}_- + \nu_s, \nu_s \to \nu_\alpha$ via oscillations

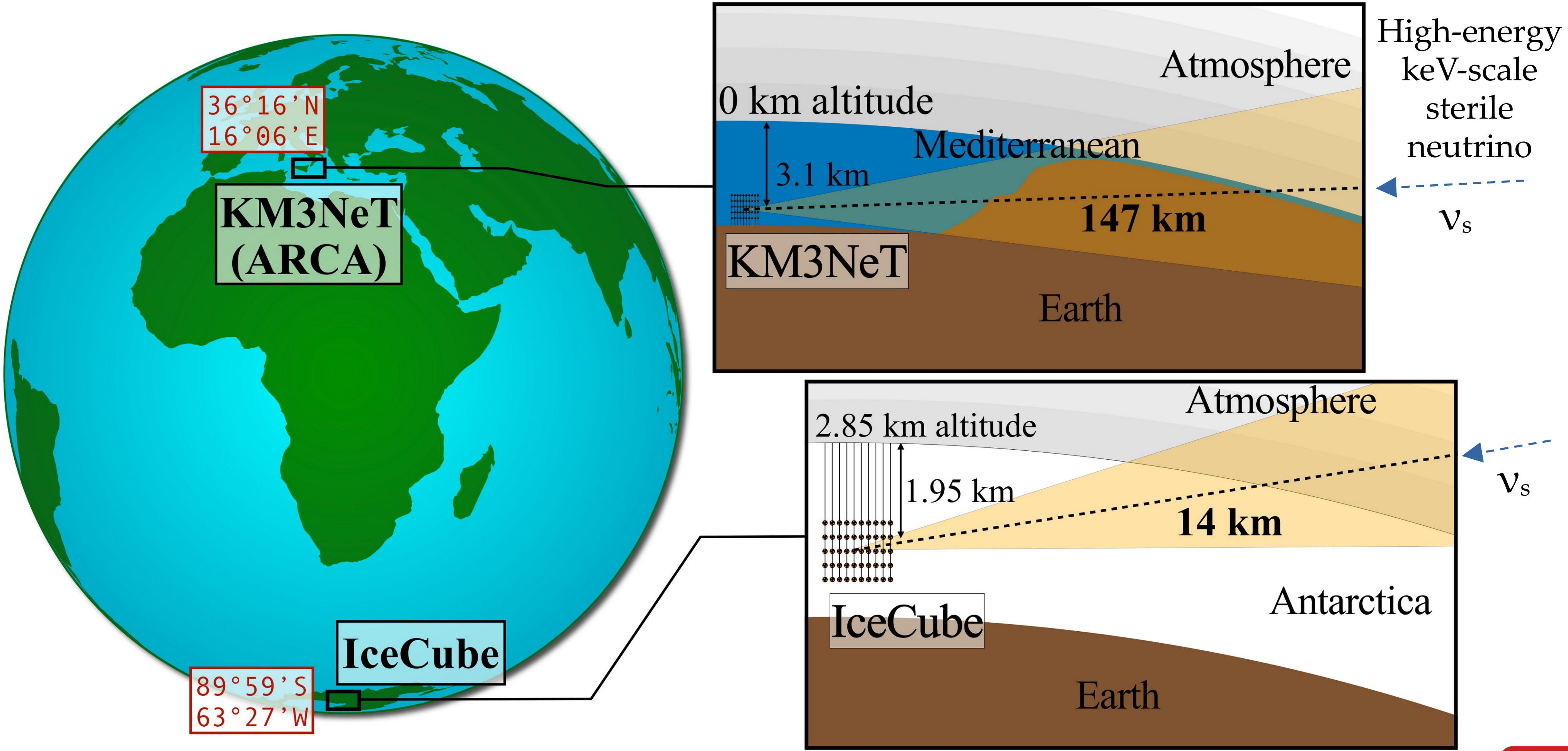
$\Delta m_\chi \equiv m_\chi - m_{\tilde{\chi}_-} \sim E_\nu \ll m_\chi$

$\chi \to \tilde{\chi}_- + \nu_\alpha + h$

(Higgs decays into γ)

Sterile-active ν transitions

Brdar & Chattopadhyay, 2502.21299



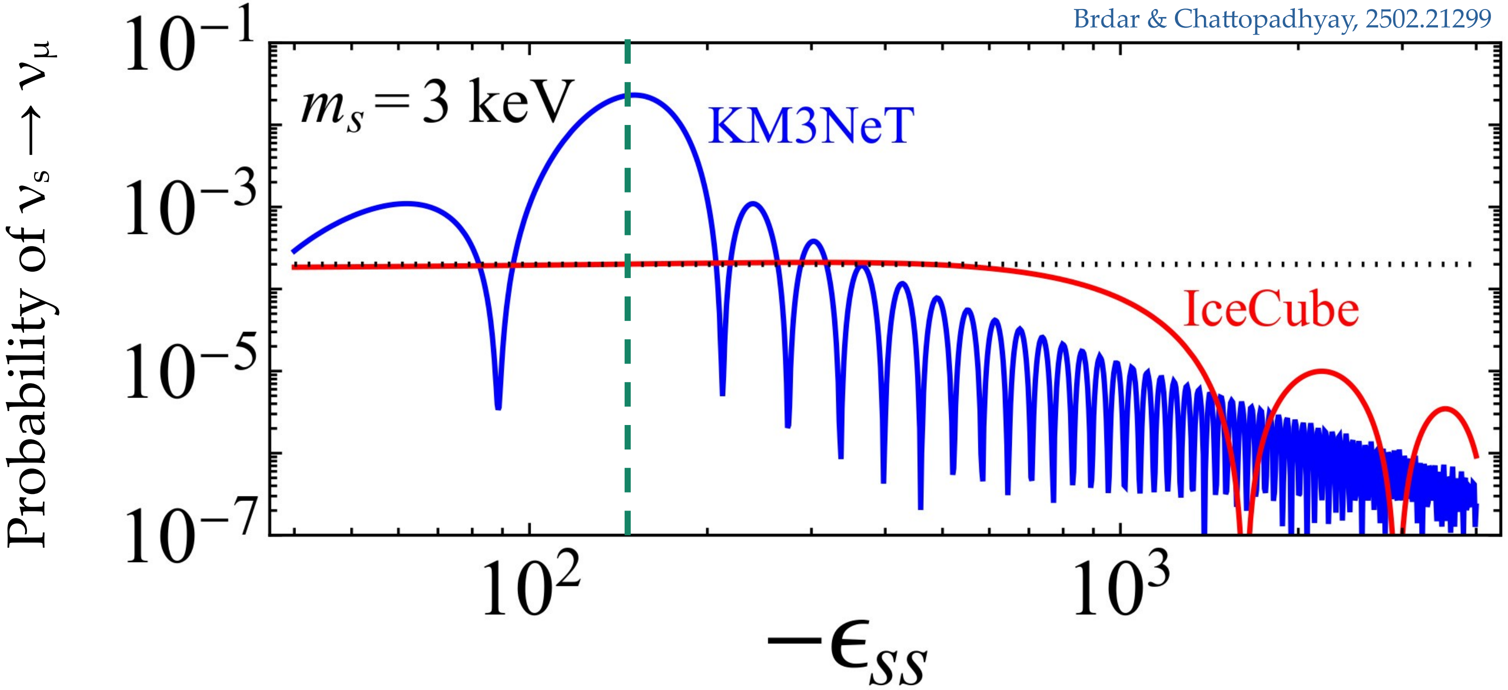
Sterile-active ν transitions

New neutrino-baryon interactions inside Earth (by gauging $U(1)_B$ symmetry)

Relative strength *vs.* standard weak interaction: $\epsilon_{ss} = G_B/(\sqrt{2}G_F)$

For $-\epsilon_{ss} = 150$, transitions are resonant in KM3NeT, but not in IceCube

Brdar & Chattopadhyay, 2502.21299



Primordial black hole evaporation

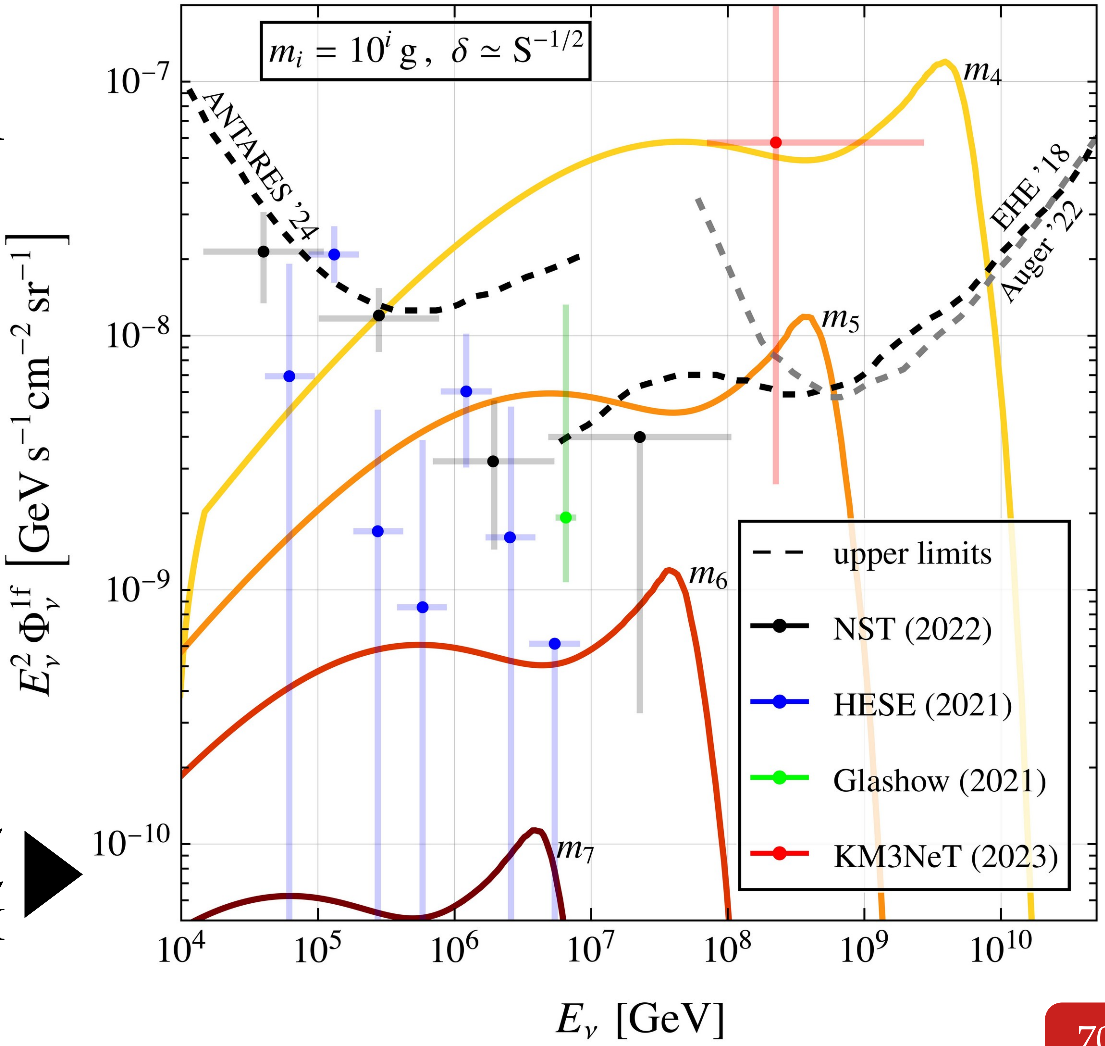
Primordial black holes (PBHs) evaporate through Hawking radiation

“Memory burden” effect: quantum back-reaction lengthens the life of the black hole

Most of the contribution is from intermediate-mass PBHs, transitioning to memory burden

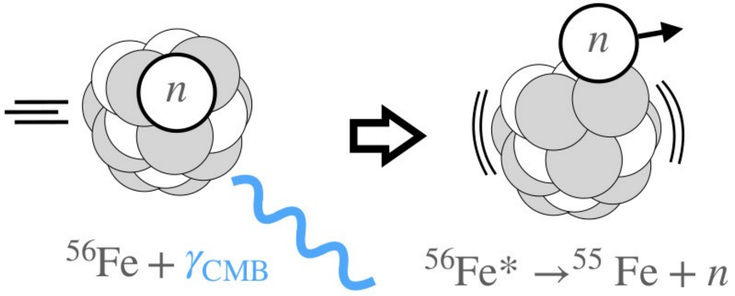
Galactic + extragalactic contributions, monochromatic mass spectrum, PBHs make up all of DM

Dvali, Zantedeschi, Zell, 2503.21740

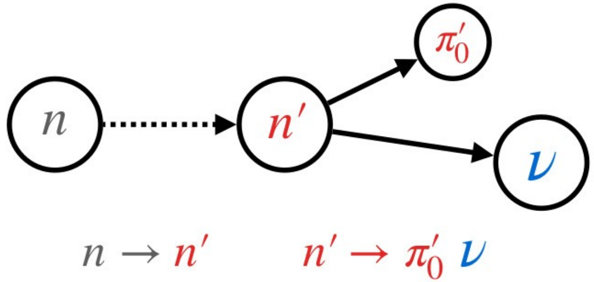


Mirror neutrons

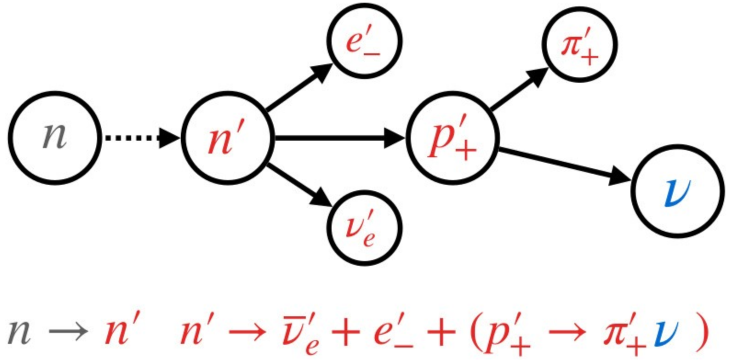
Can reconcile large cosmogenic ν flux inspired by KM3-230213A and heavy UHECR mass composition



But cannot explain lack of IceCube events

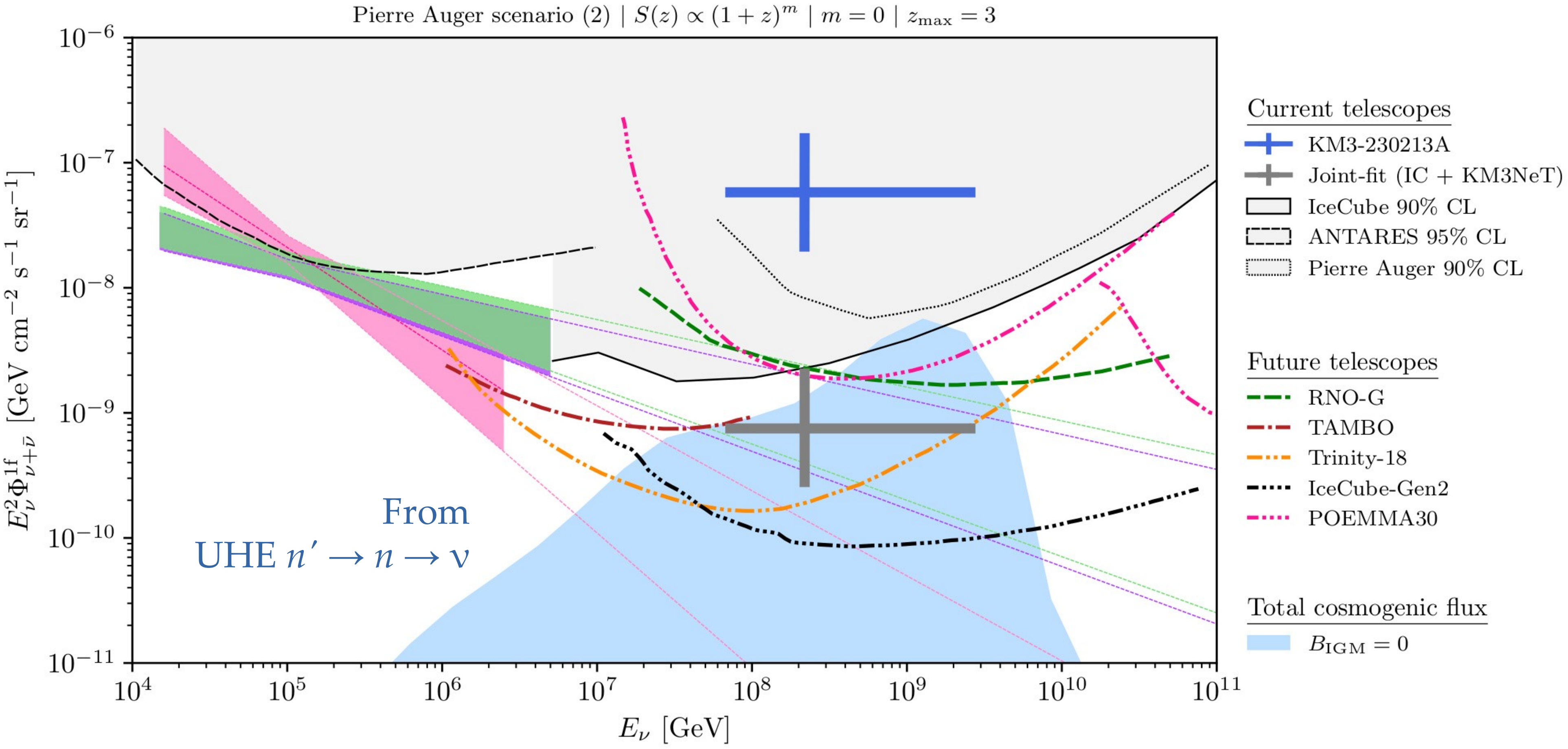


Joint fits to Auger UHECR data + neutrino data from IceCube and KM3NeT



Alves, Hostert, Pospelov, 2503.14419

Mirror neutrons



Alves, Hostert, Pospelov, 2503.14419