High-energy neutrino physics from high-energy astrophysical neutrinos

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VILLUM FONDEN

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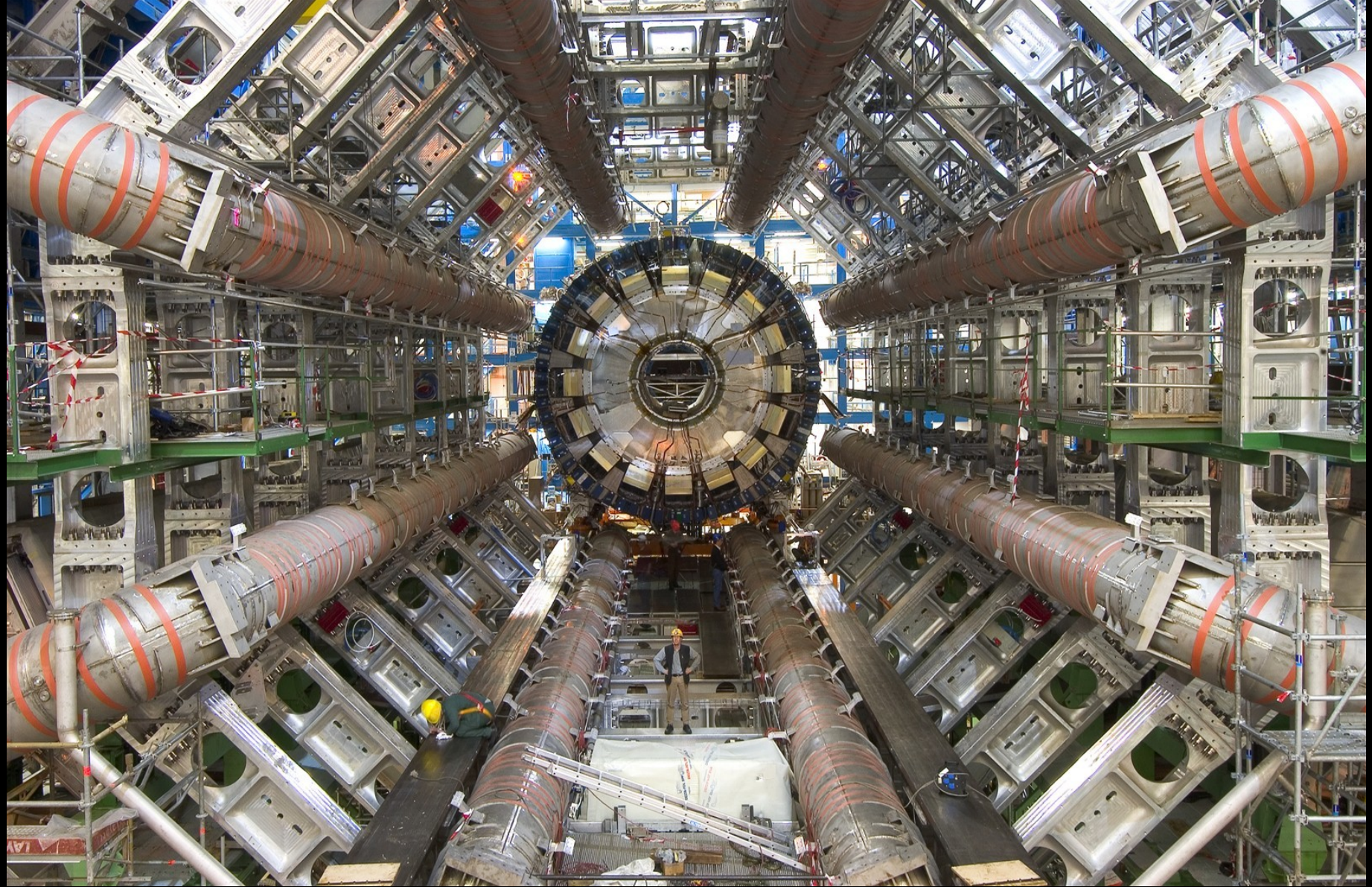
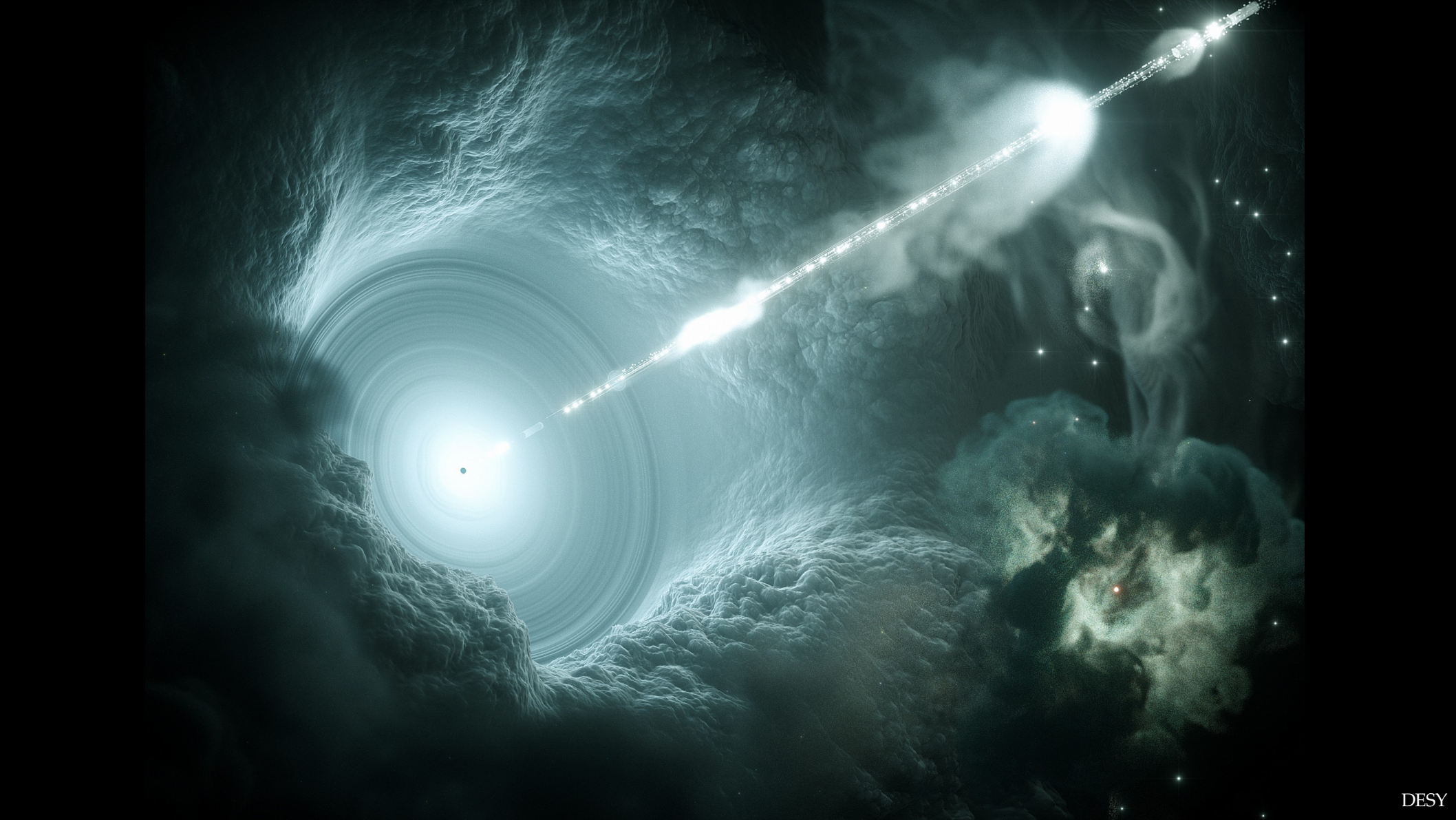


ATLAS



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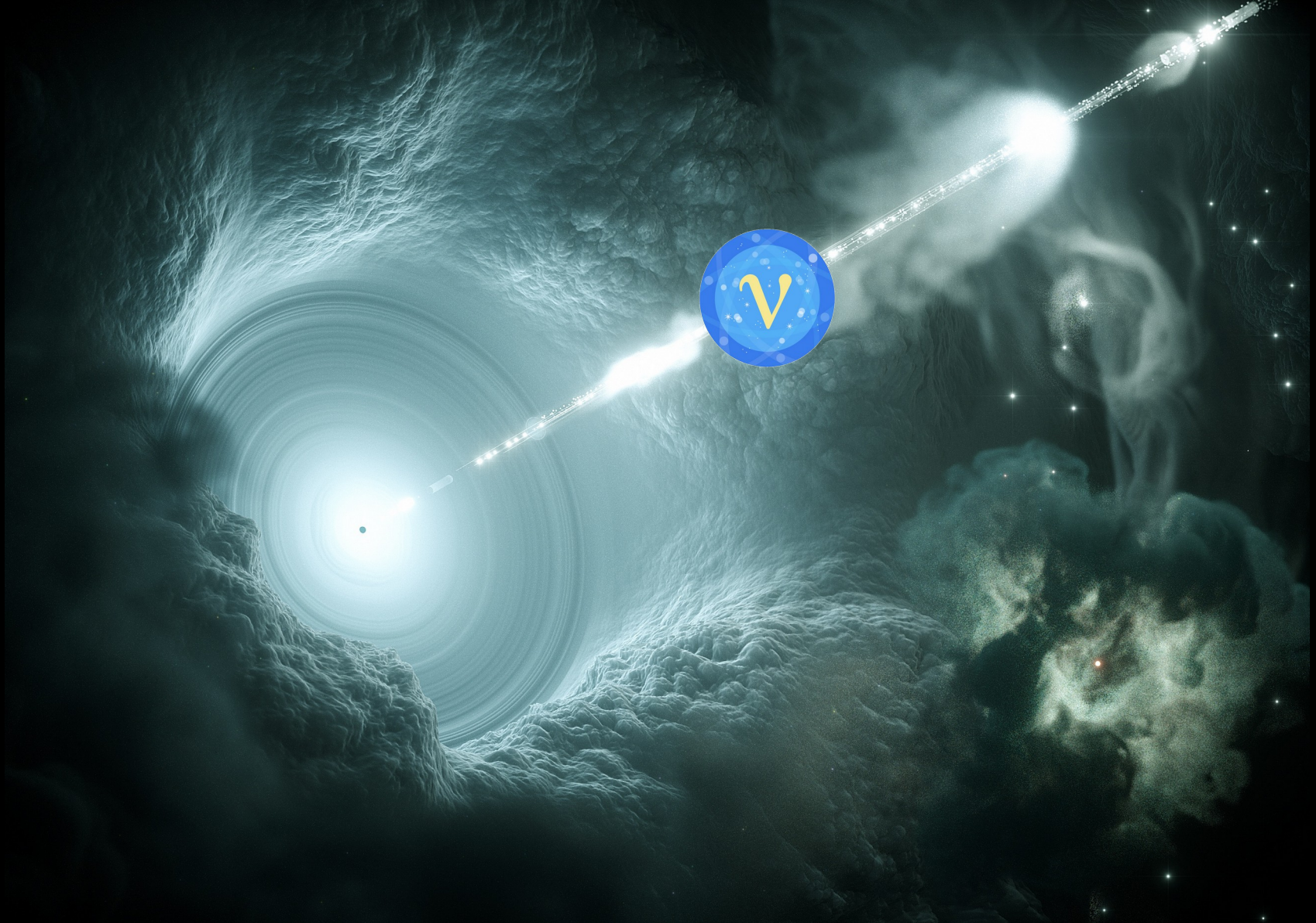

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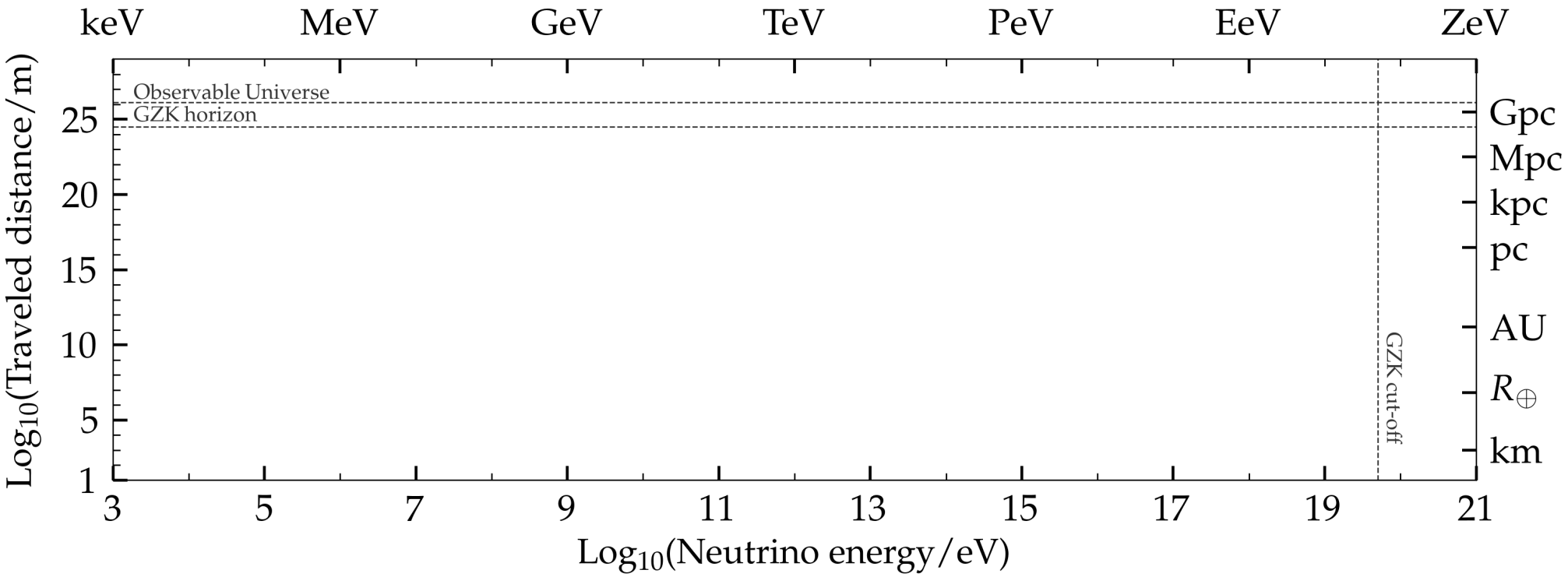
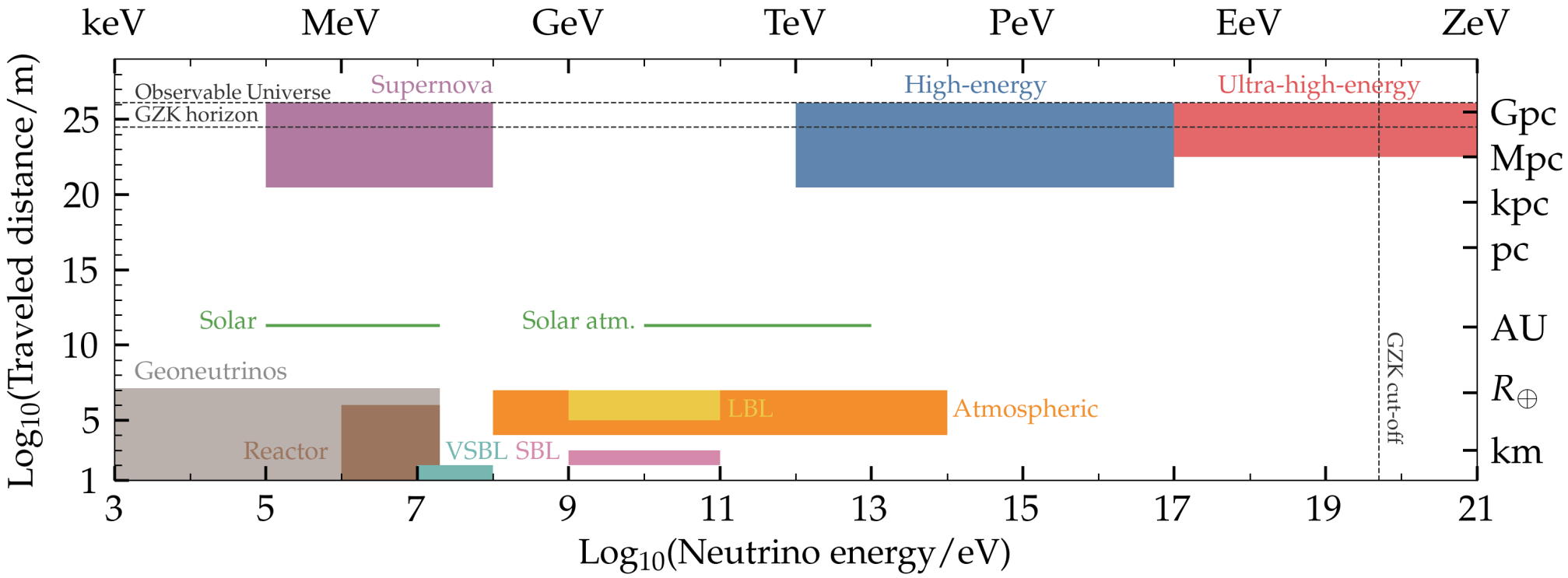


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



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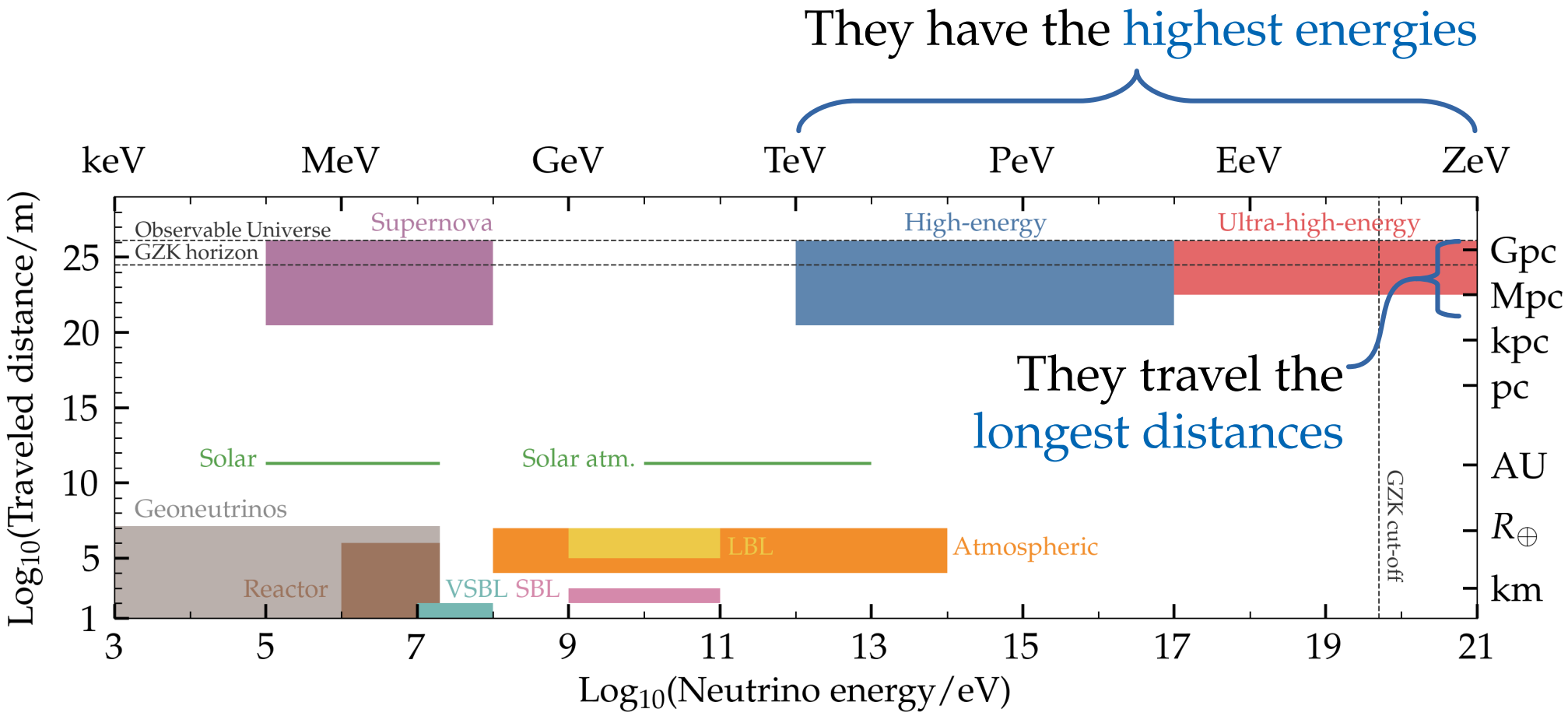

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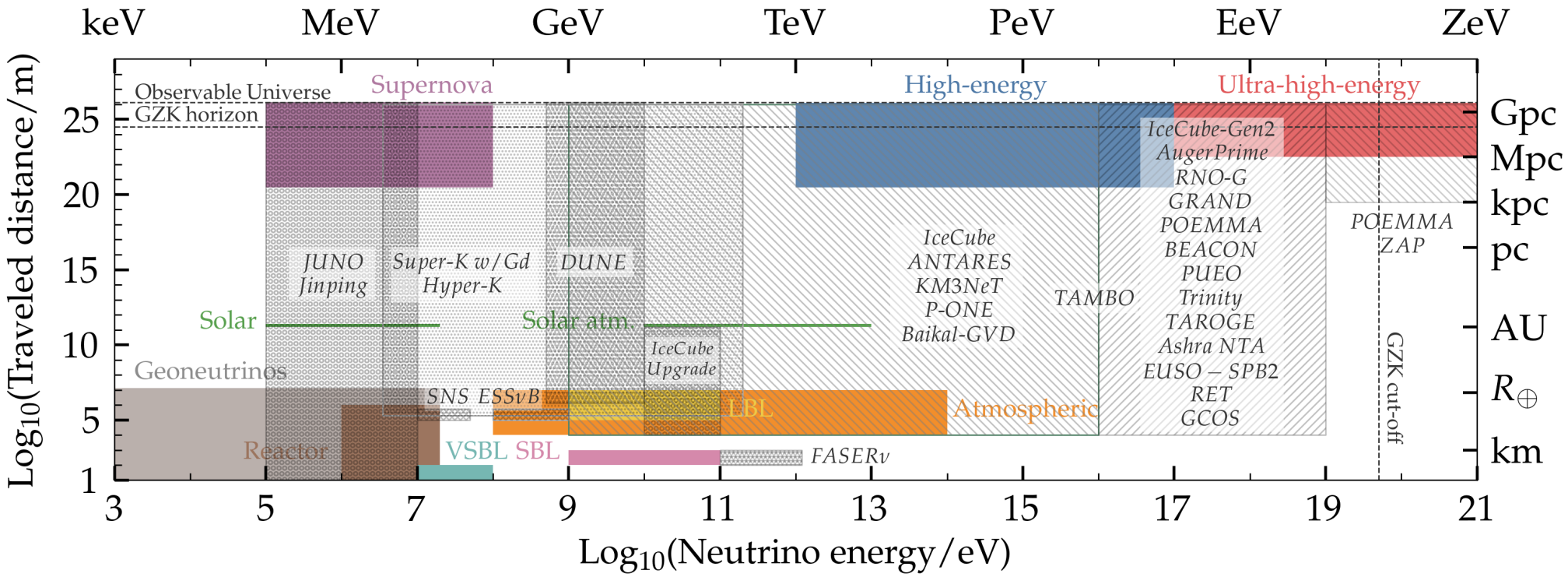

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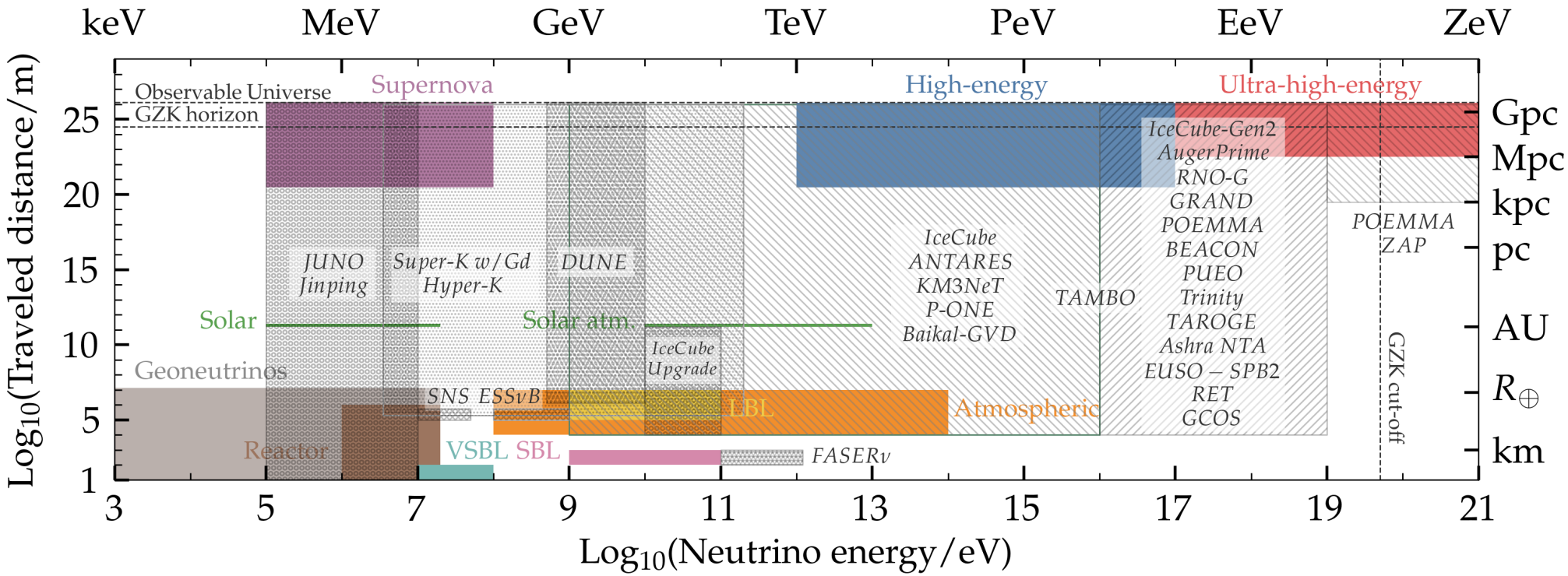
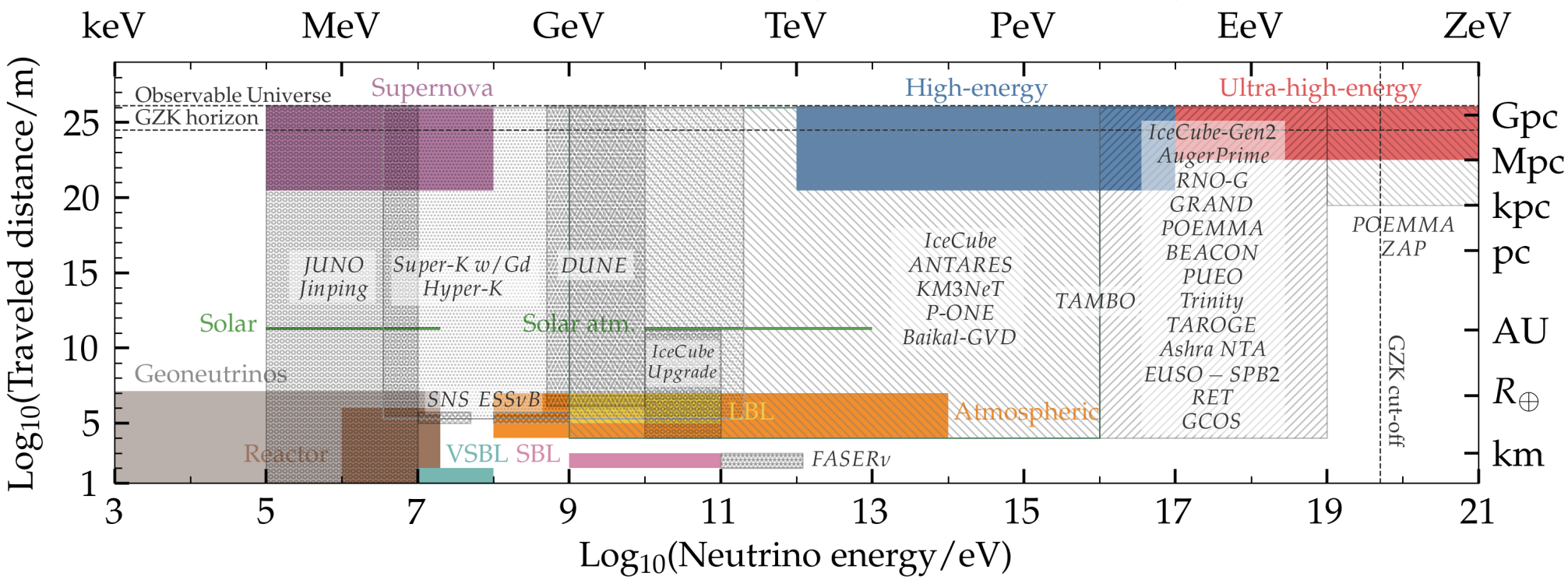


Synergies with lower energies

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

Discovered in 2013
by IceCube



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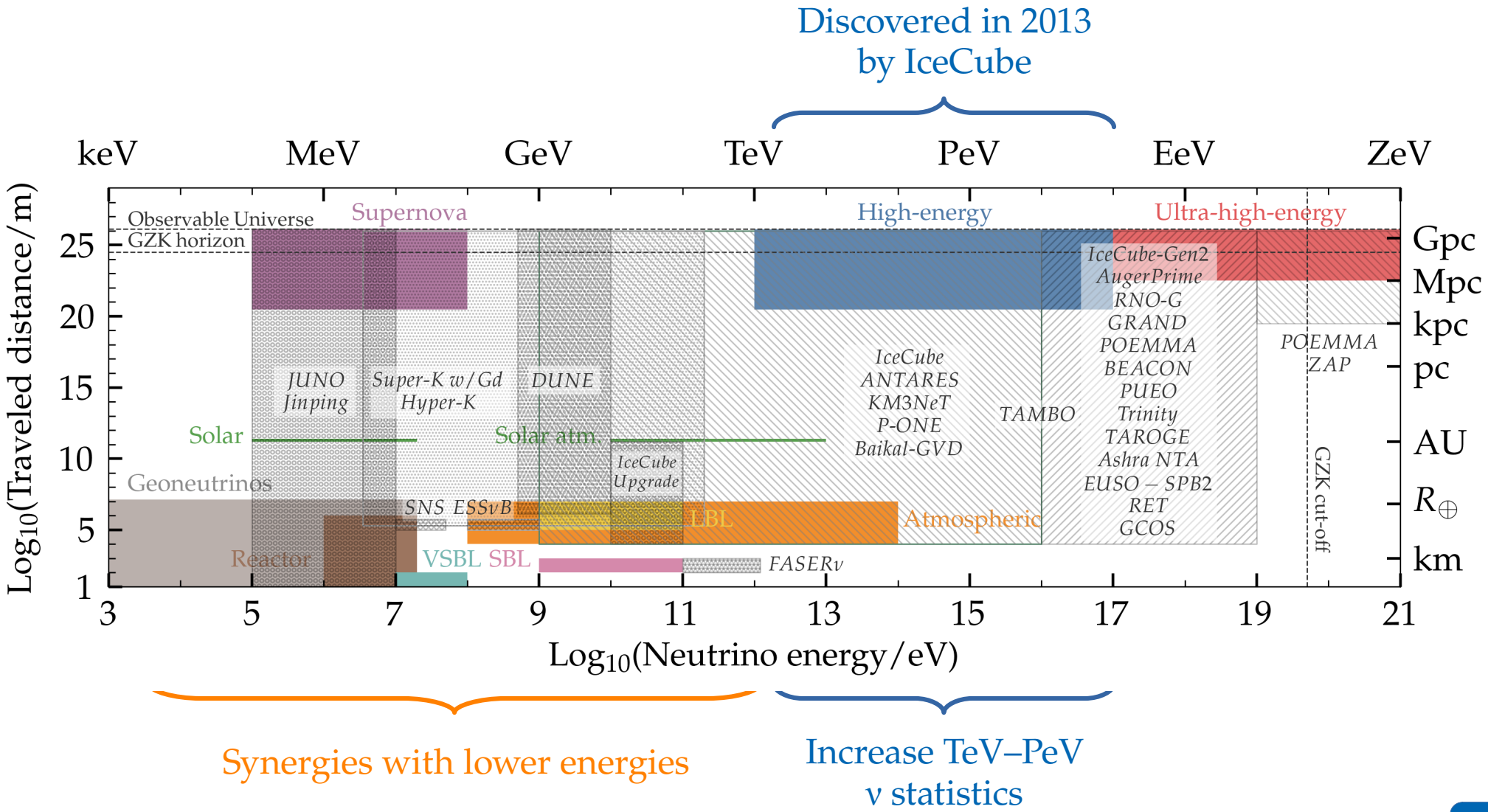

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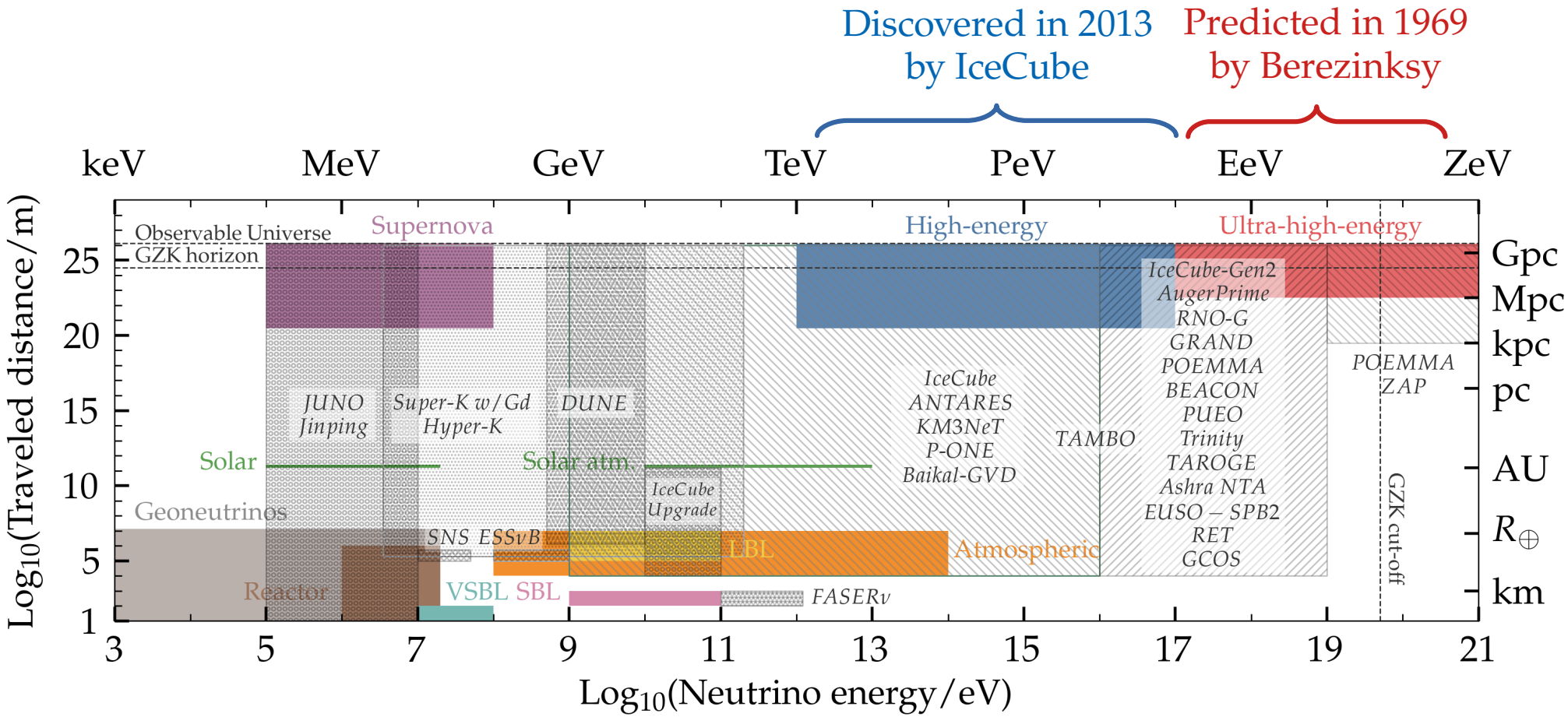

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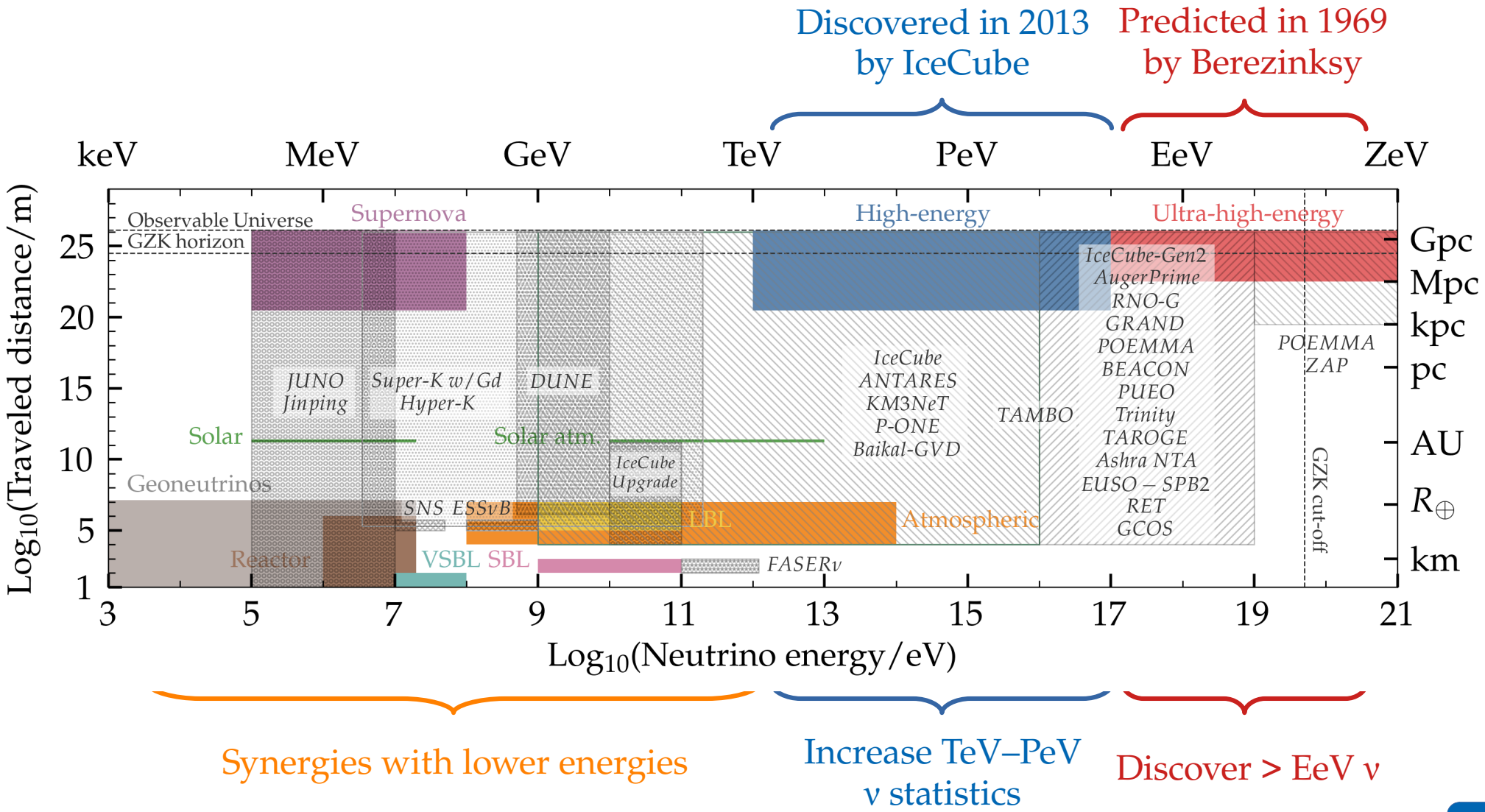

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Today

TeV–PeV ν

Astro: Find & understand sources

Particle: Turn predictions into tests

Next decade

> 100-PeV ν

Make predictions for a new energy regime

The story so far

Making high-energy astrophysical neutrinos: a toy model

(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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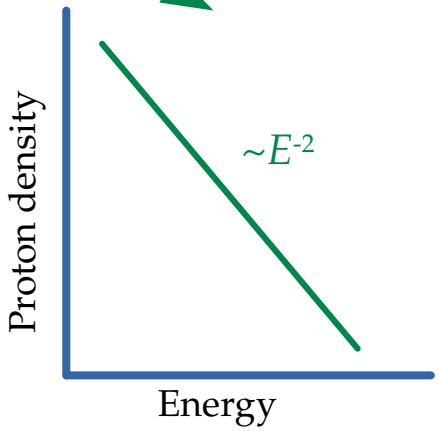

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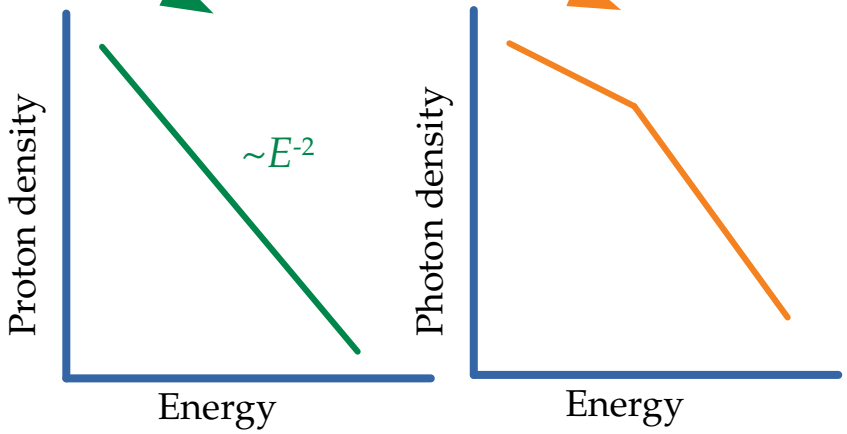

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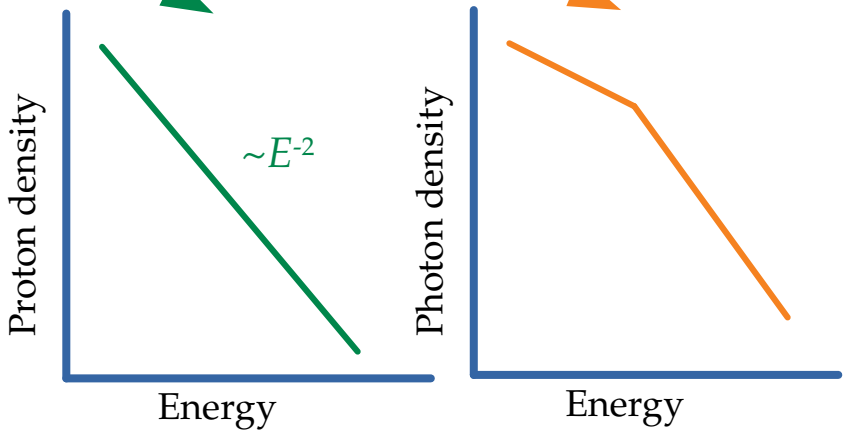
$$\pi^0 \rightarrow \gamma + \gamma$$

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

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



Making high-energy astrophysical neutrinos: a toy model

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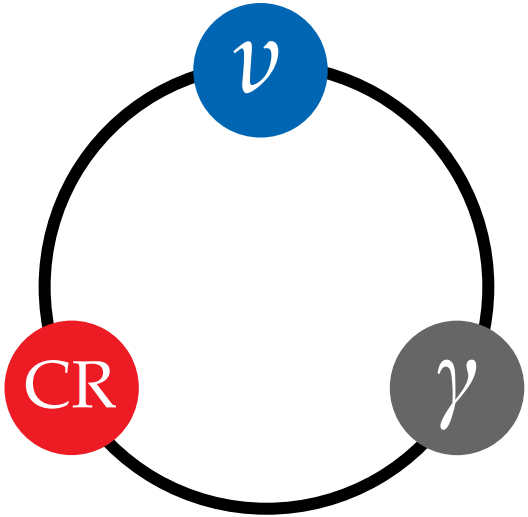
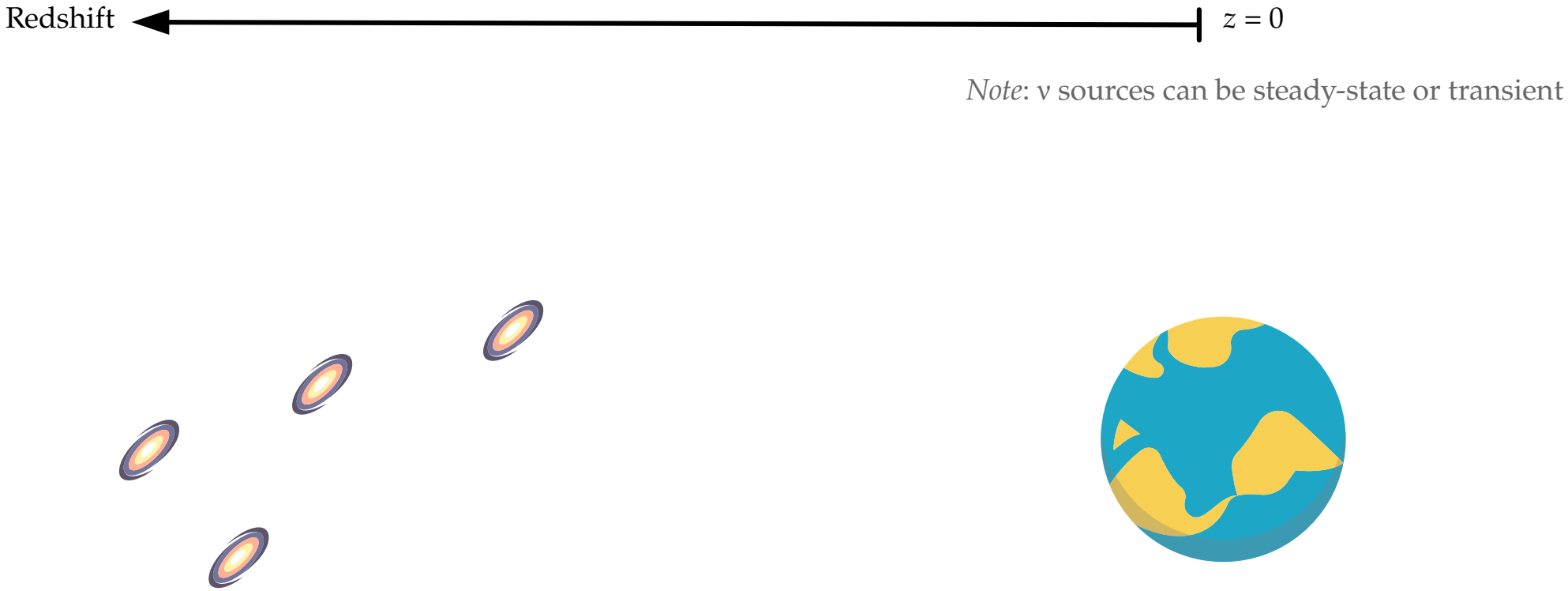
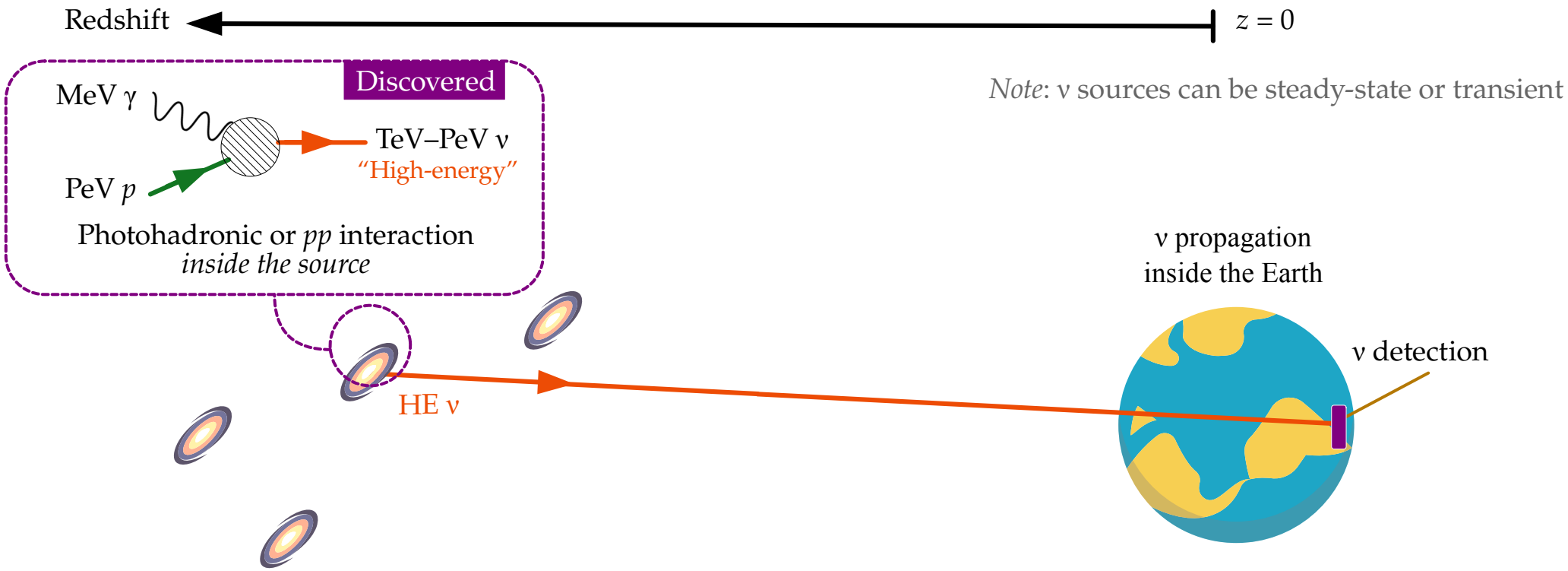


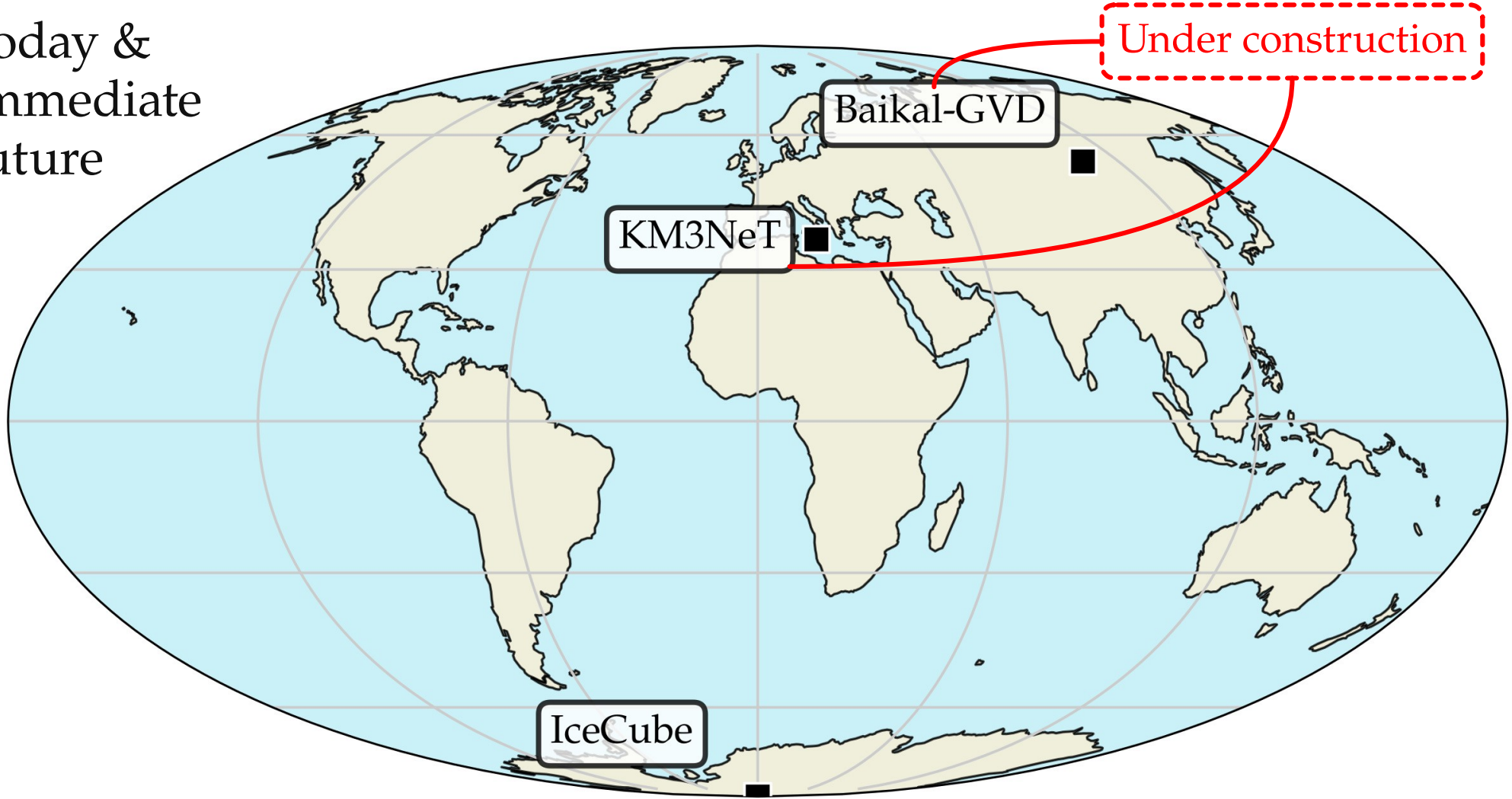
Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10


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

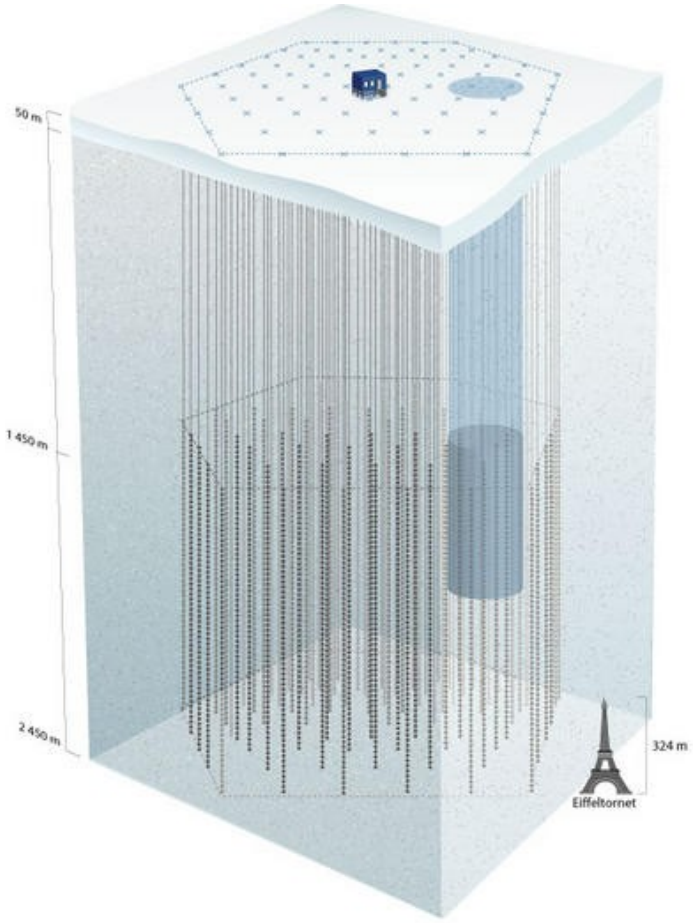

Redshift
z = 0
Discovered
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or pp interaction
inside the source
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν

Today & immediate future



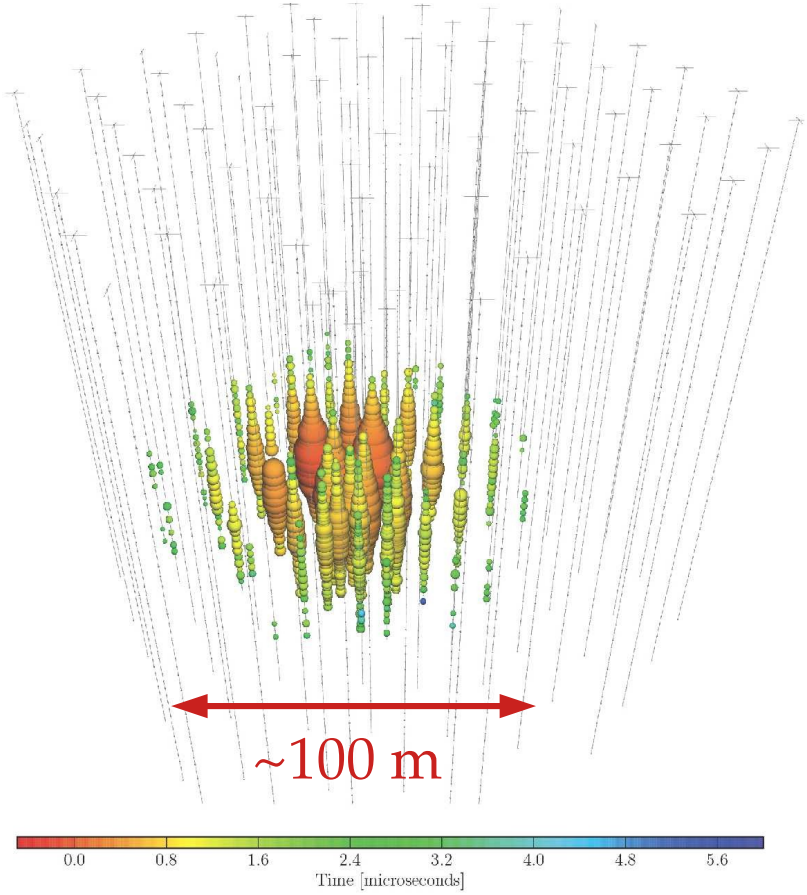
Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

IceCube – What is it?



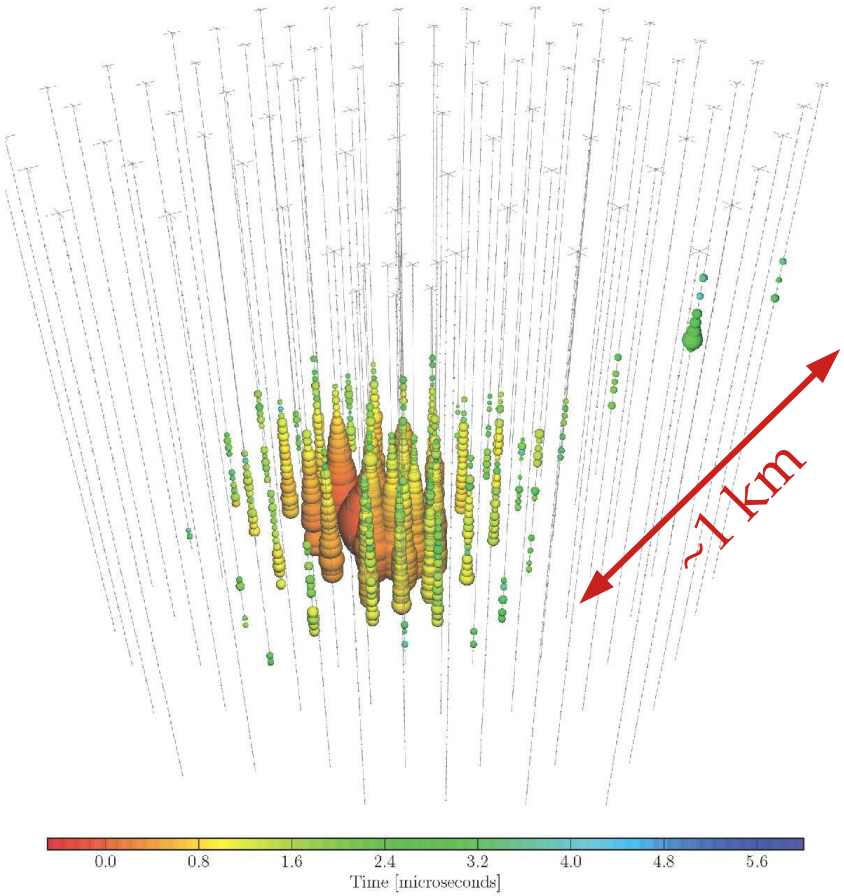
- Km^3 in-ice Cherenkov detector in Antarctica
- > 5000 PMTs at 1.5–2.5 km of depth
- Sensitive to neutrino energies > 10 GeV

Shower
(mainly from ν_e and ν_τ)

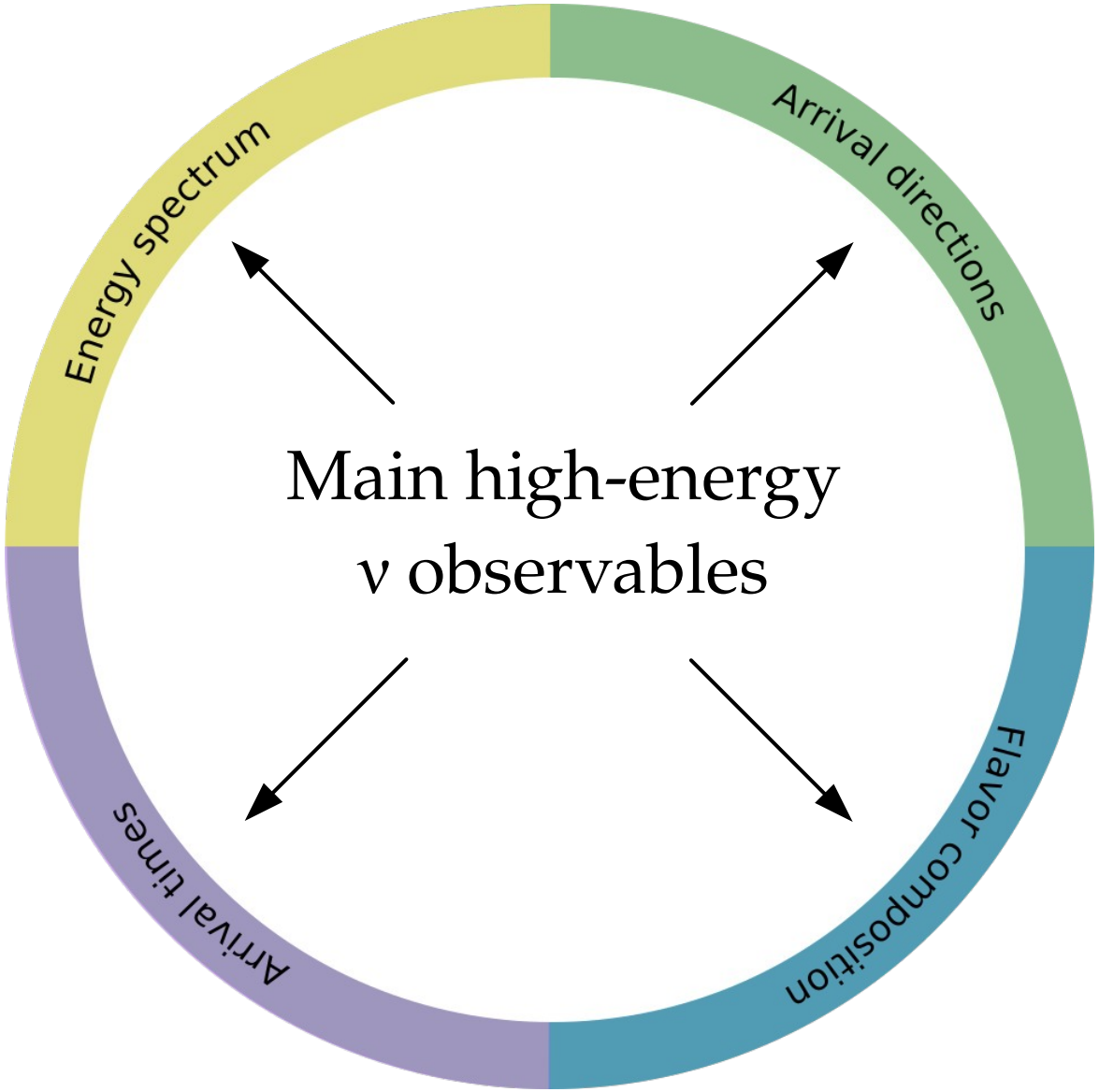


Poor angular resolution: ≥ 5°

Track
(mainly from ν_μ)

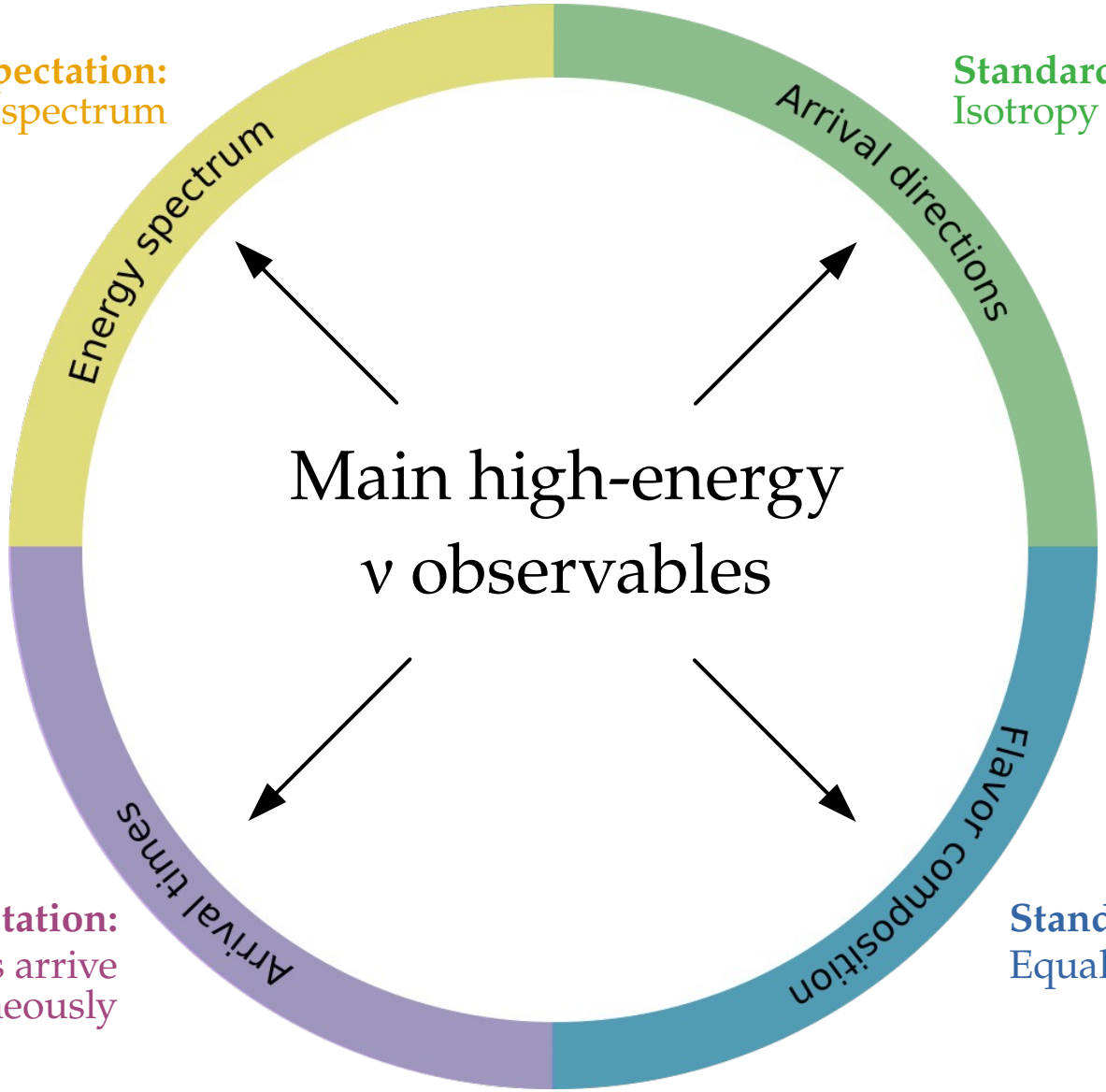


Angular resolution: < 1°


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

Standard expectation:
Power-law energy spectrum

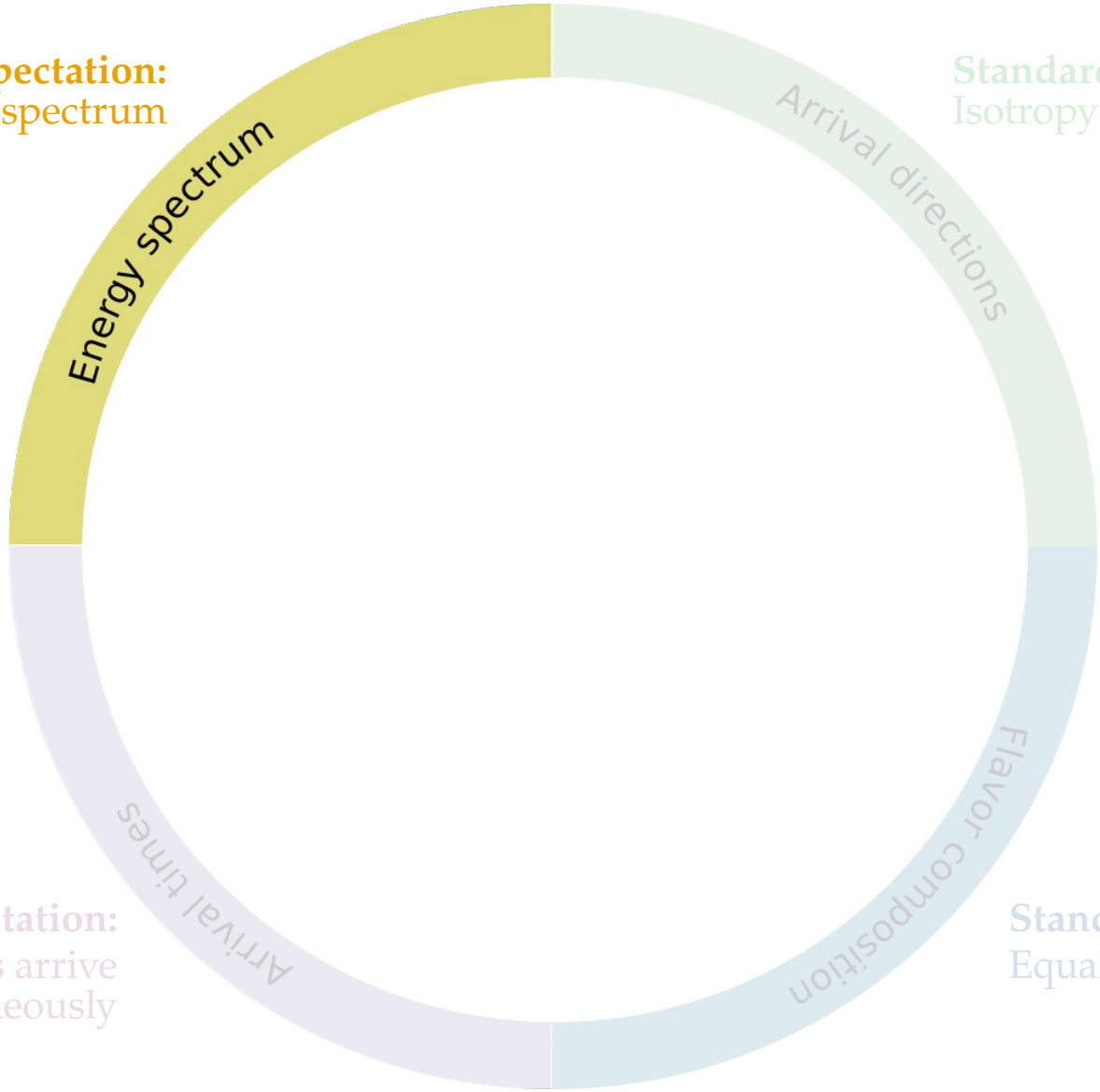
Standard expectation:
Isotropy (for diffuse flux)



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)

Standard expectation:
ν and γ from transients arrive simultaneously

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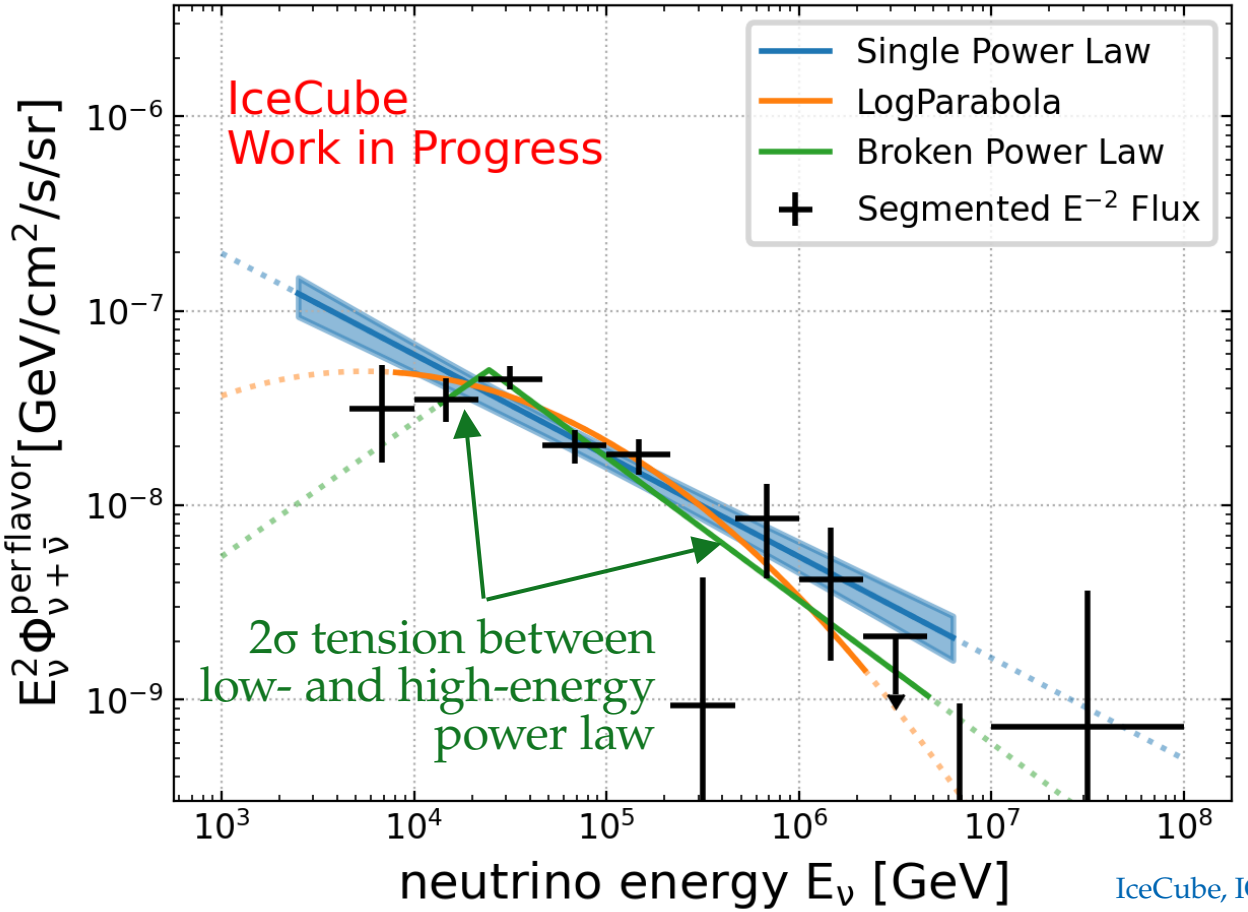
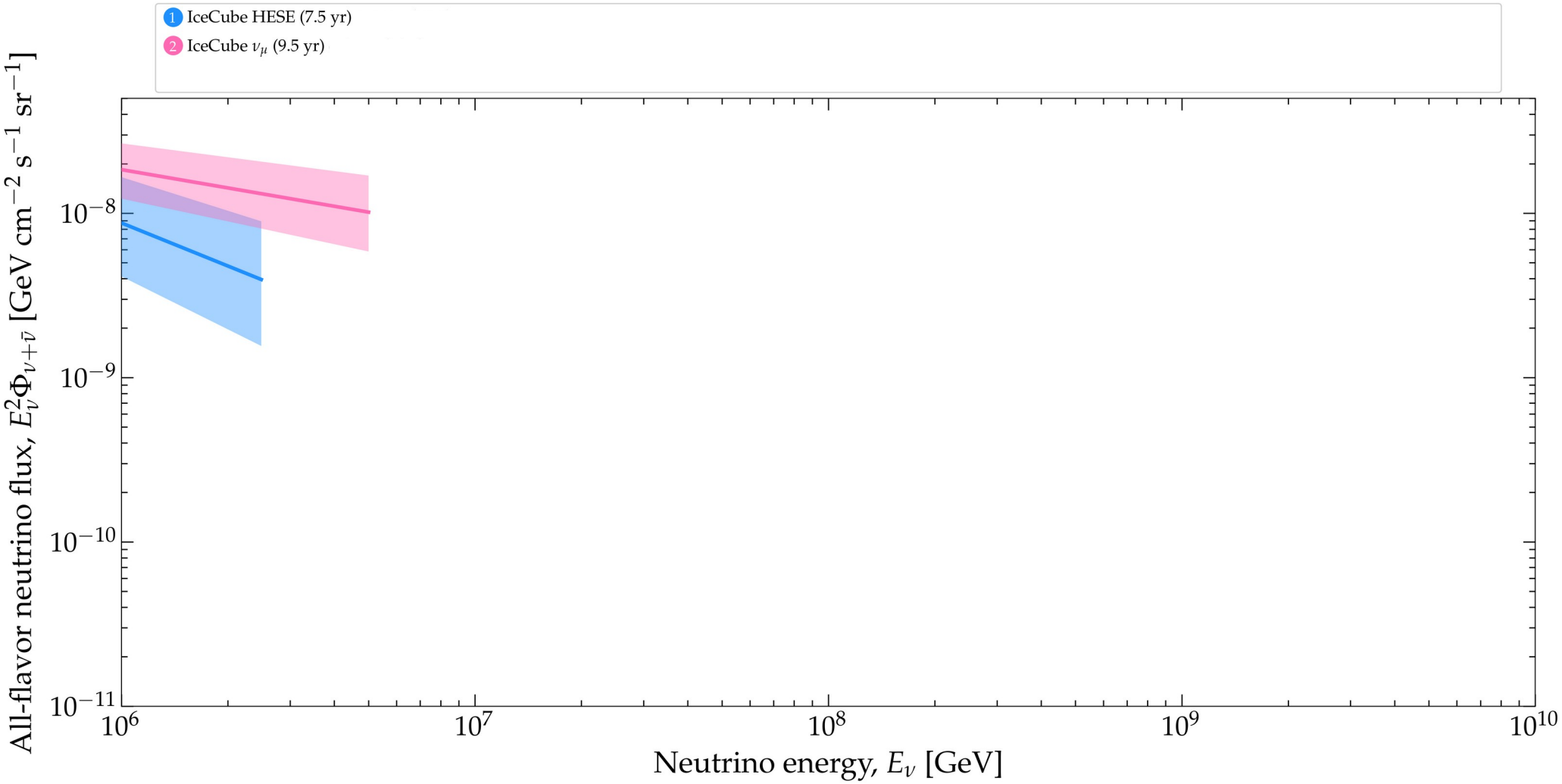
Neutrino energy spectrum

With > 10 years of data, deviations from a power law start to be testable:



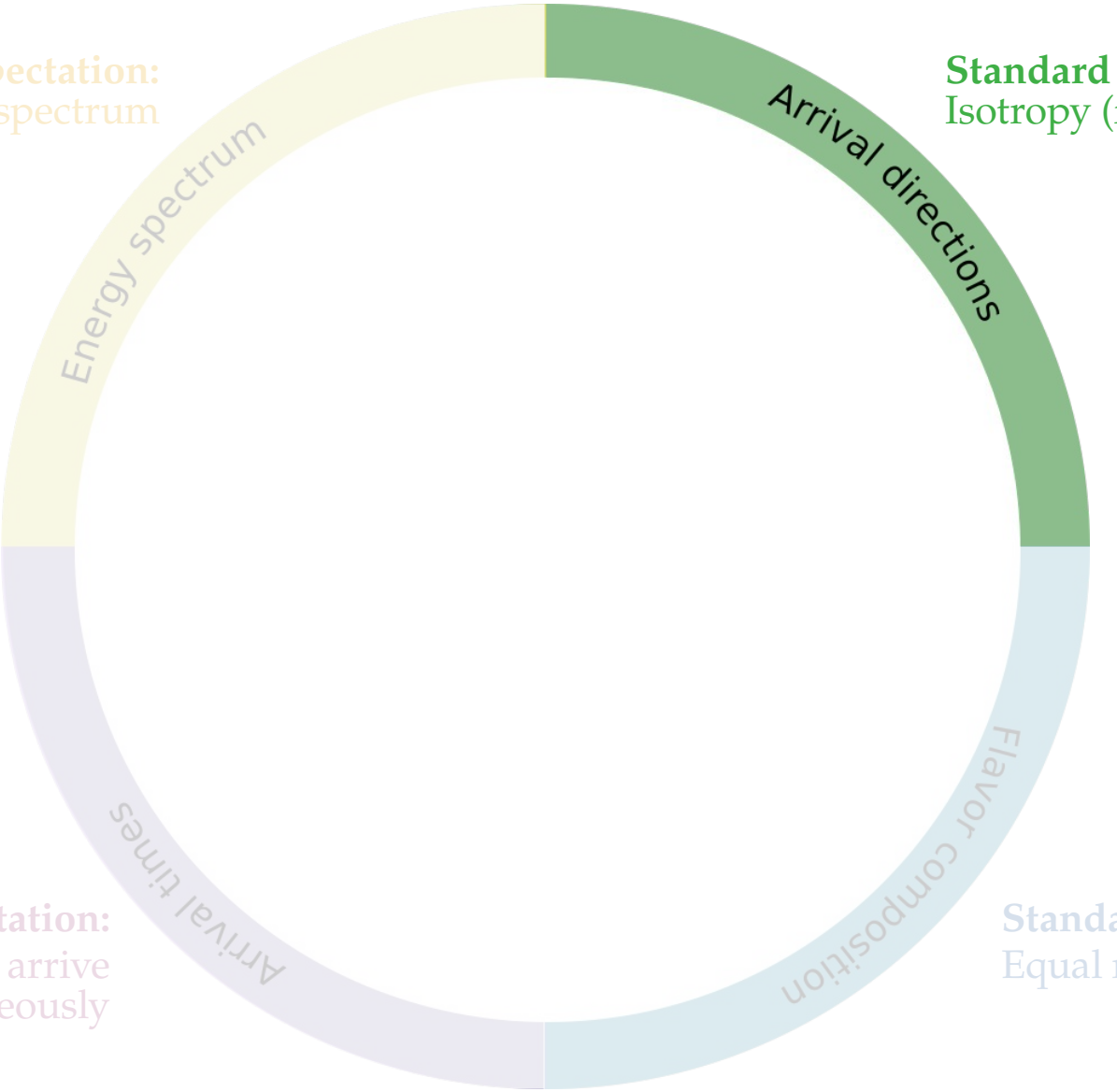
Different spectra might reflect different source populations

IceCube, ICRC 2023


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]

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



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Standard expectation:
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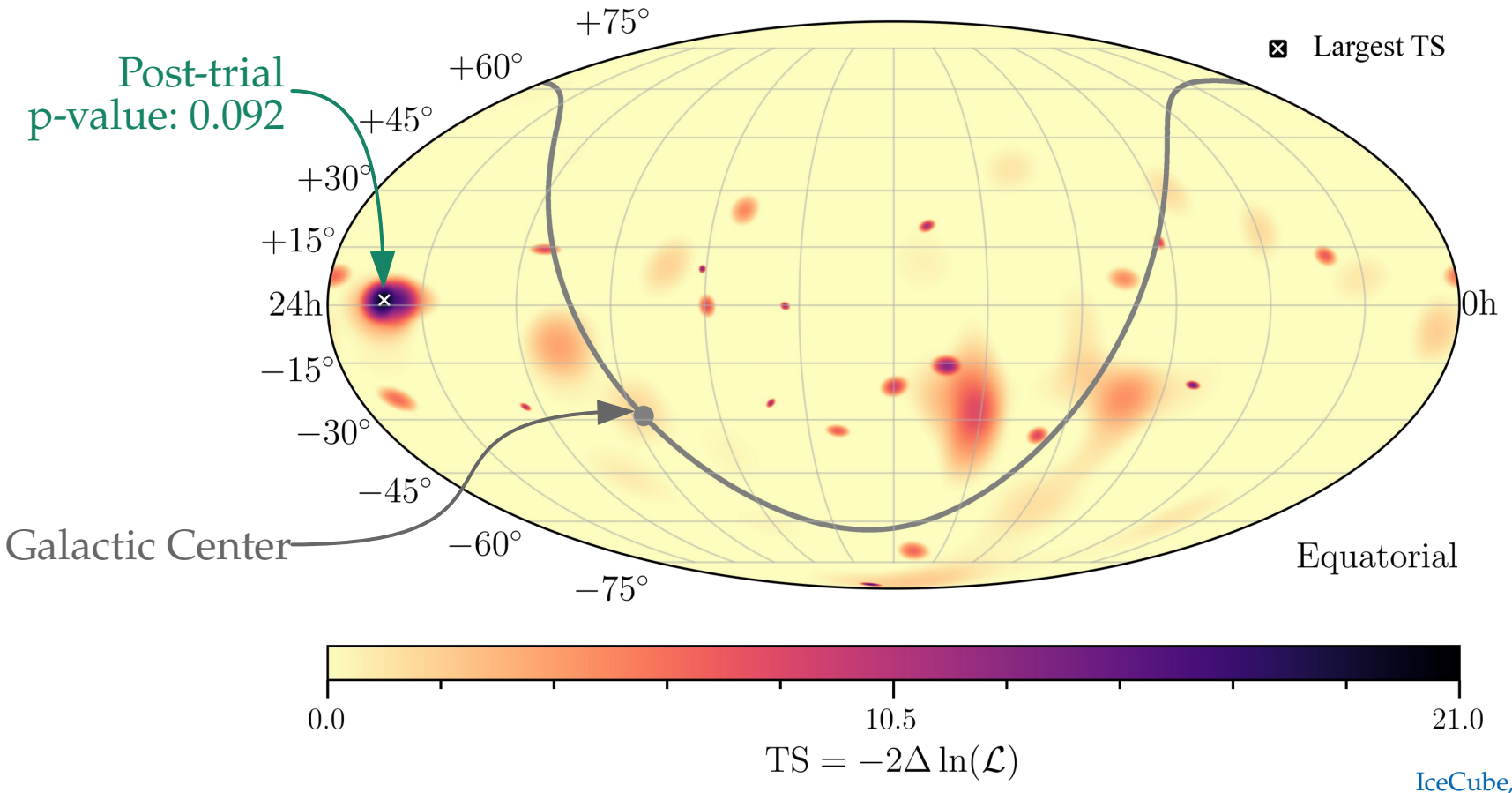
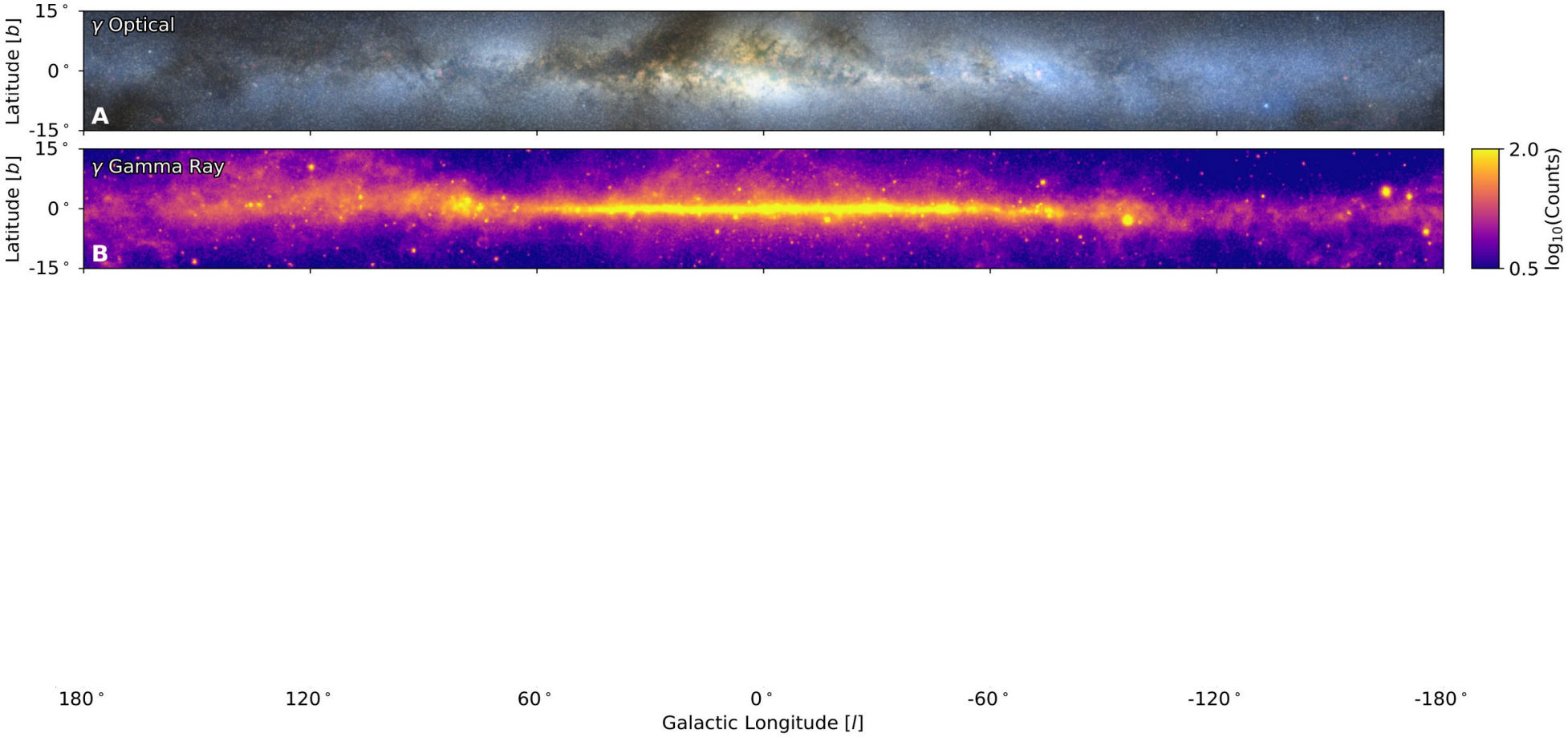
Distribution of arrival directions (7.5 yr)

No significant excess in the neutrino skymap:



IceCube, 2011.03545

High-energy neutrinos from the Galactic Plane



IceCube Collab., *Science* 2023

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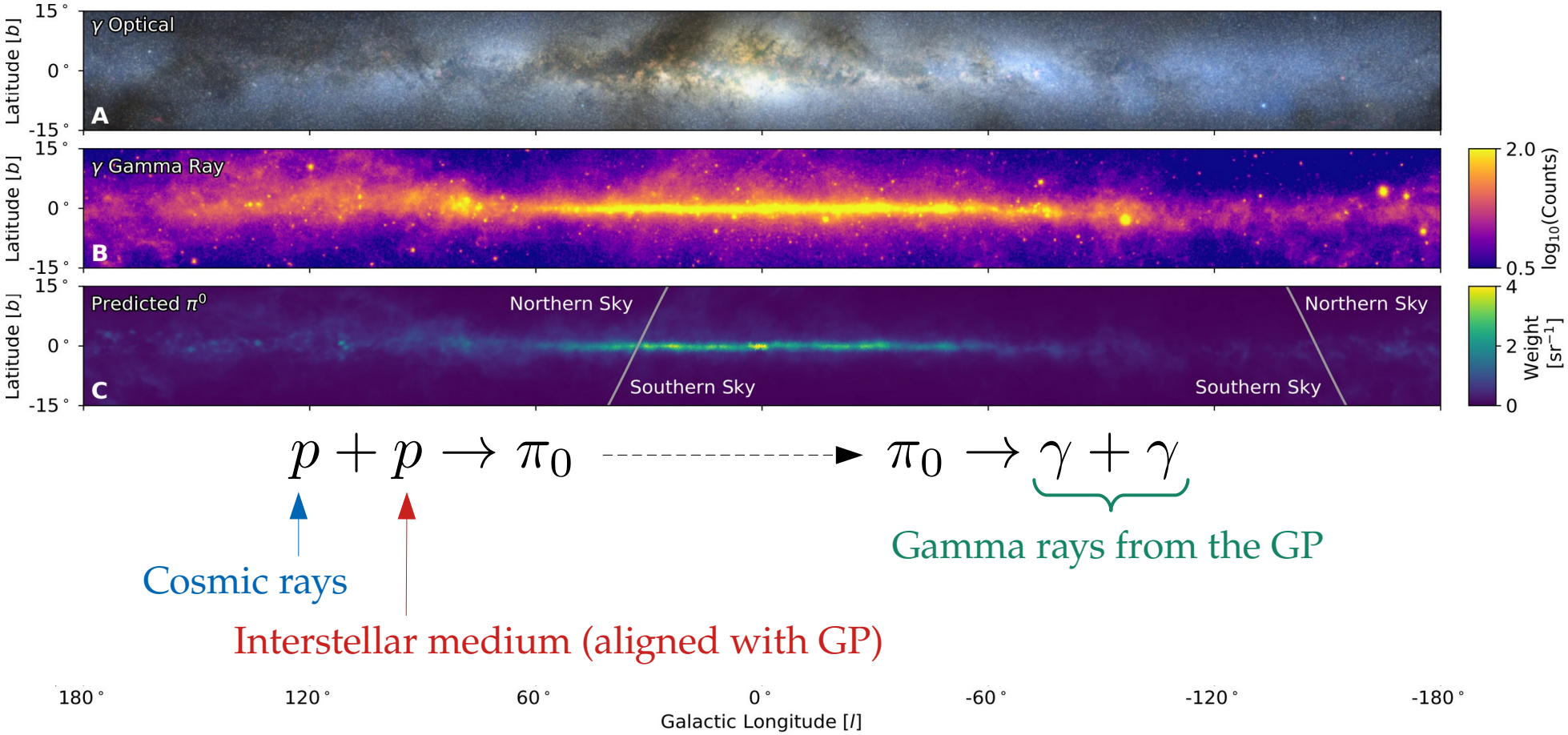


$$p + p \rightarrow \pi_0 \dashrightarrow \pi_0 \rightarrow \underbrace{\gamma + \gamma}$$

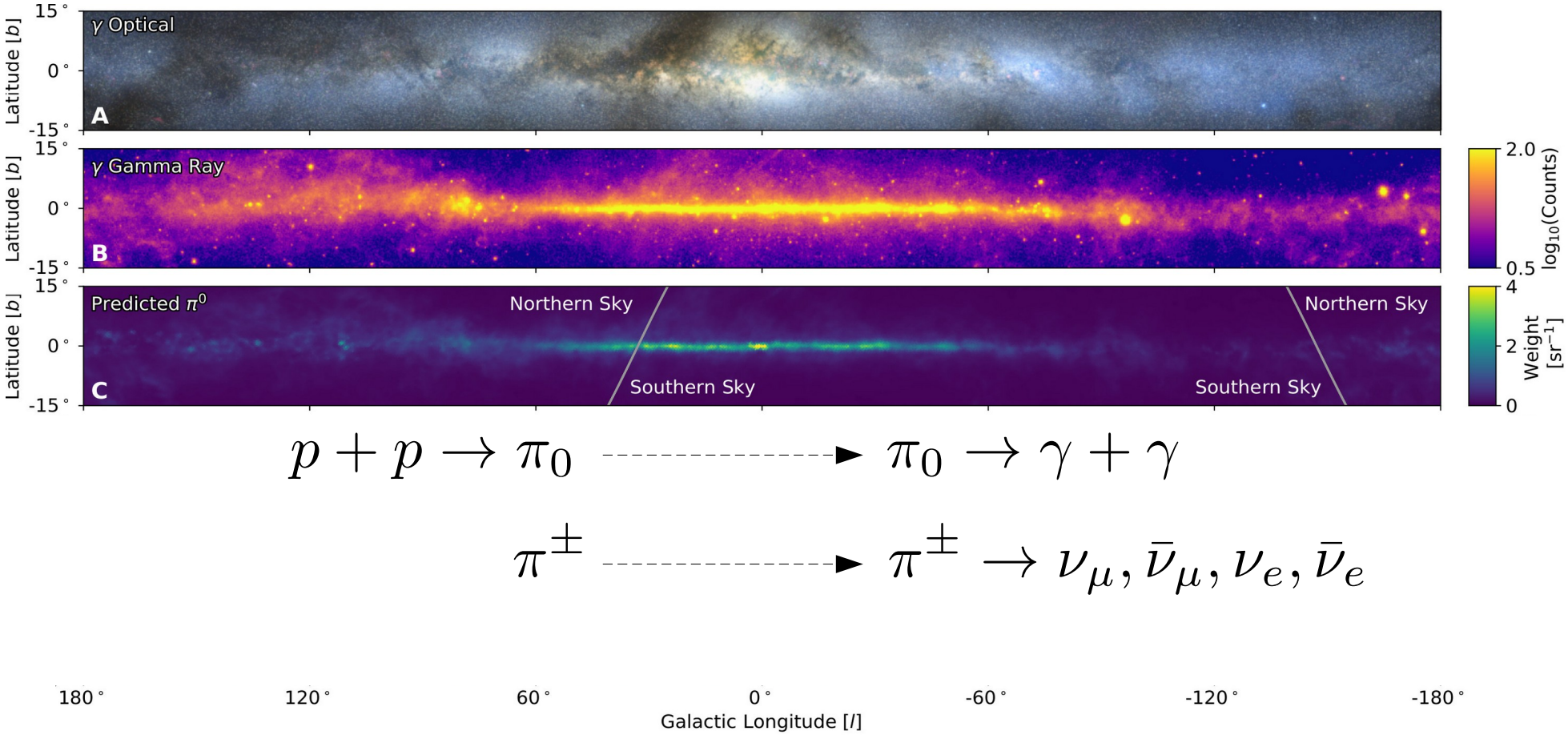
Cosmic rays

Interstellar medium (aligned with GP)

Gamma rays from the GP

IceCube Collab., *Science* 2023

High-energy neutrinos from the Galactic Plane

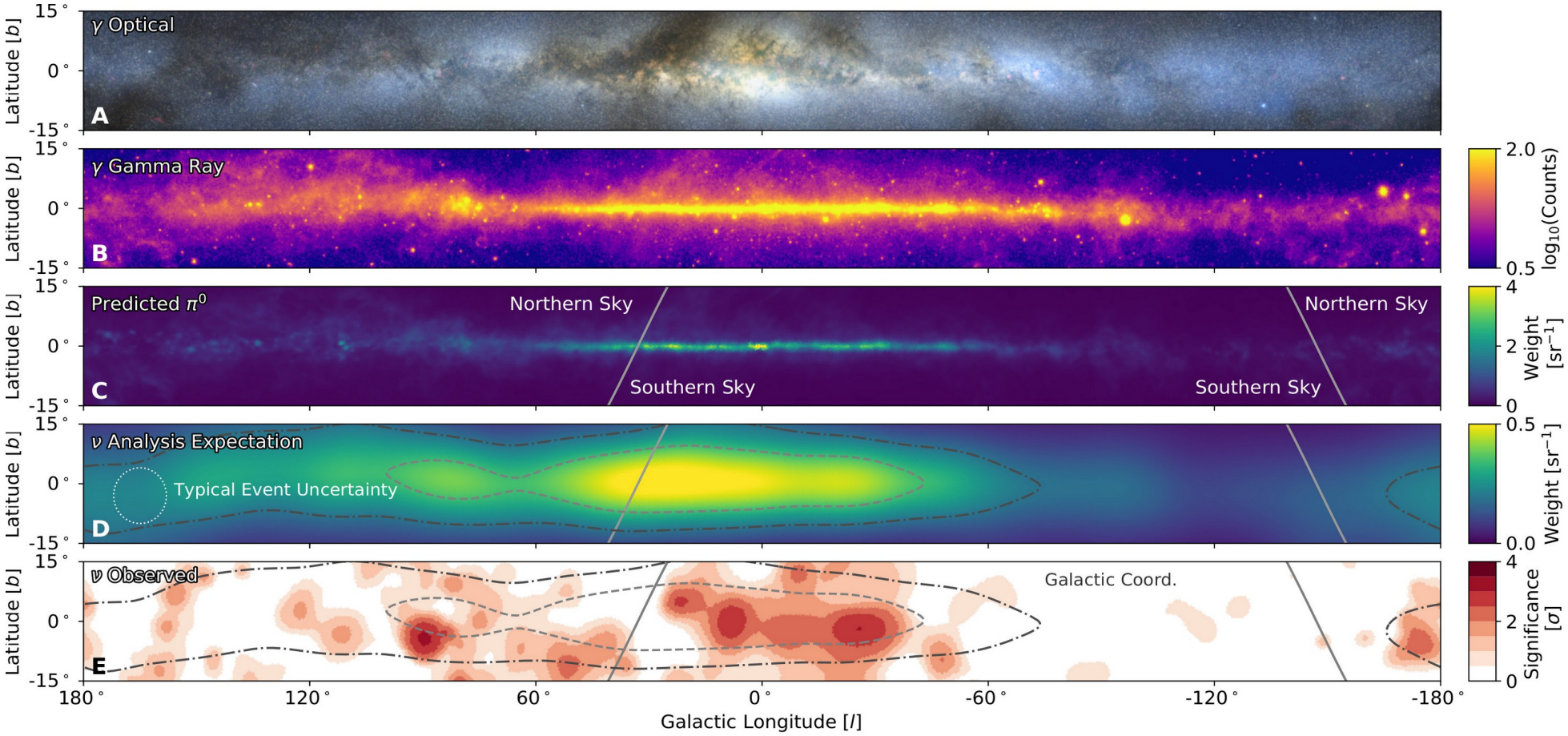


$$p + p \rightarrow \pi_0 \dashrightarrow \pi_0 \rightarrow \gamma + \gamma$$

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

IceCube Collab., *Science* 2023

High-energy neutrinos from the Galactic Plane



IceCube Collab., *Science* 2023

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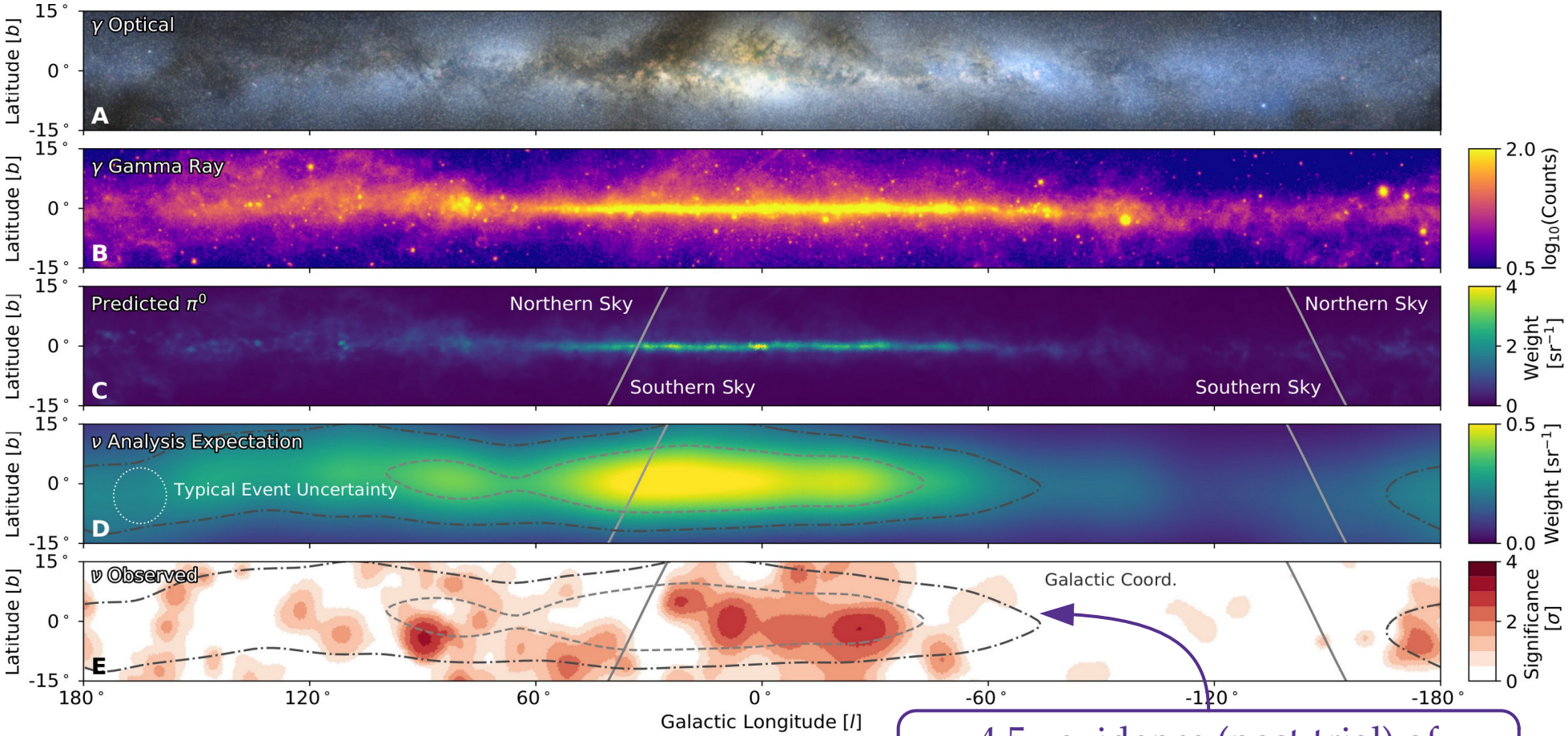

4.5σ evidence (post-trial) of diffuse flux of > TeV ν from the GP

IceCube Collab., *Science* 2023

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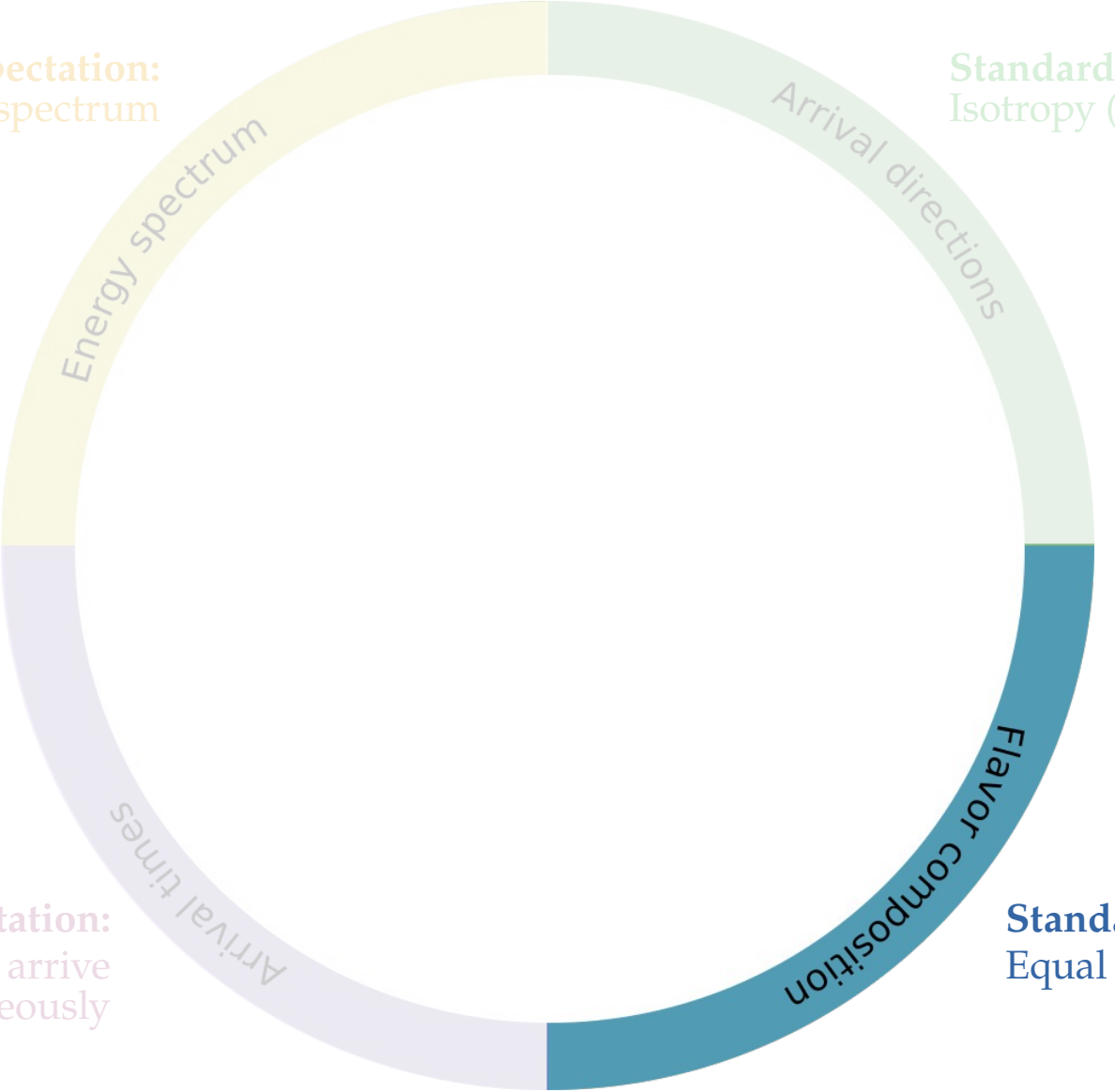

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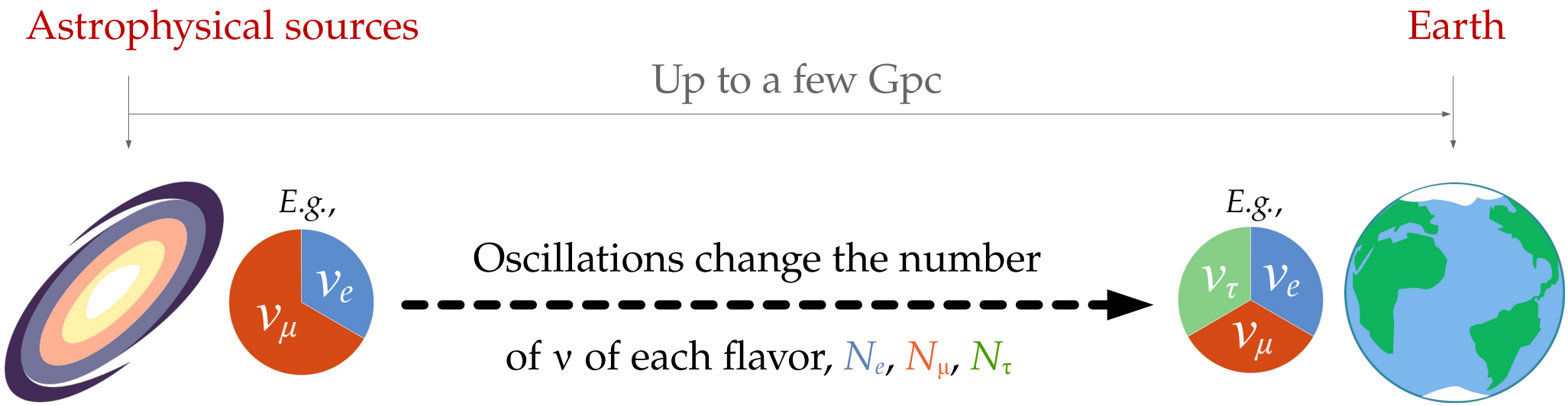


Different production mechanisms yield different flavor ratios:

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

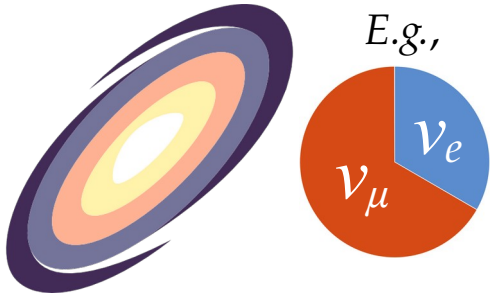
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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

Astrophysical sources

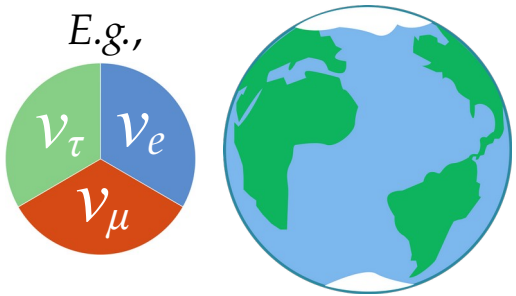
Earth

Up to a few Gpc



Oscillations change the number

of ν of each flavor, N_e, N_μ, N_τ



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Standard oscillations
or
new physics

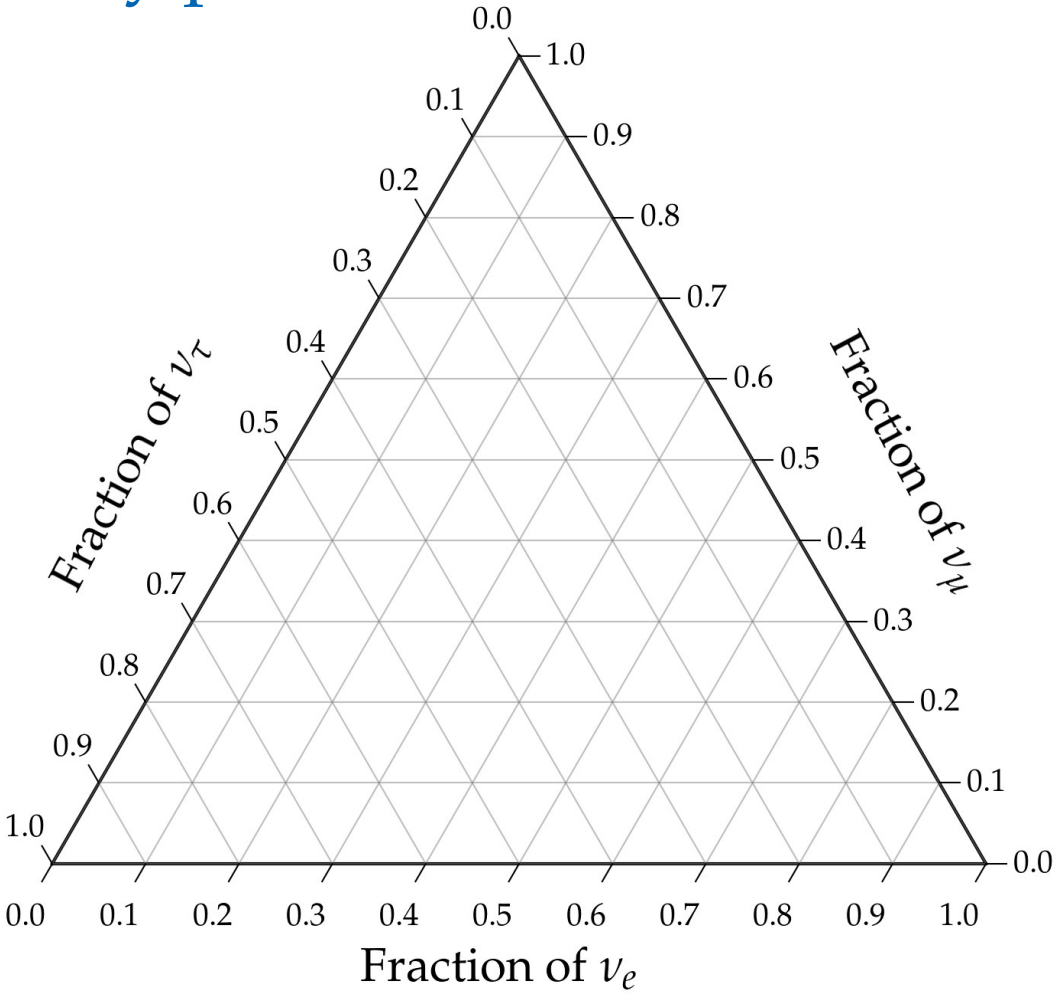
Quick aside: how to read a ternary plot

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

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



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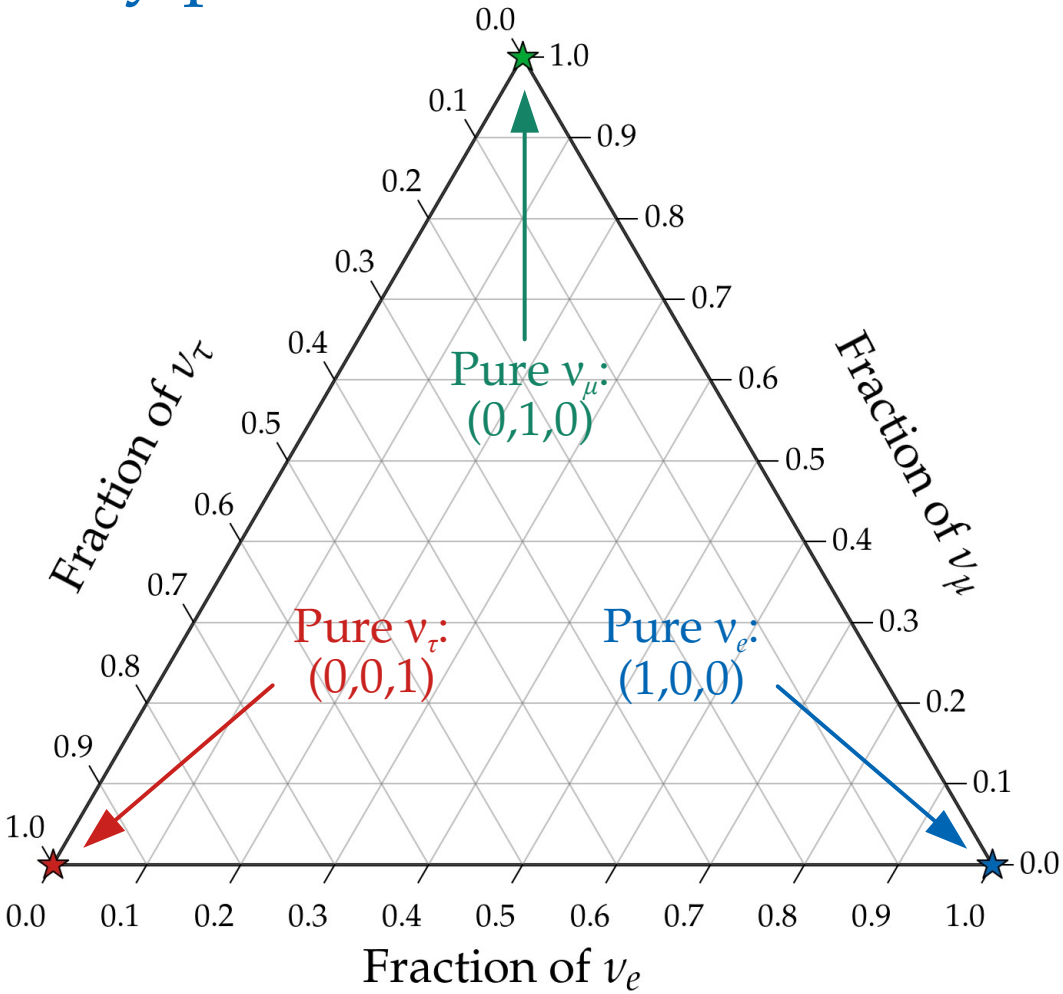

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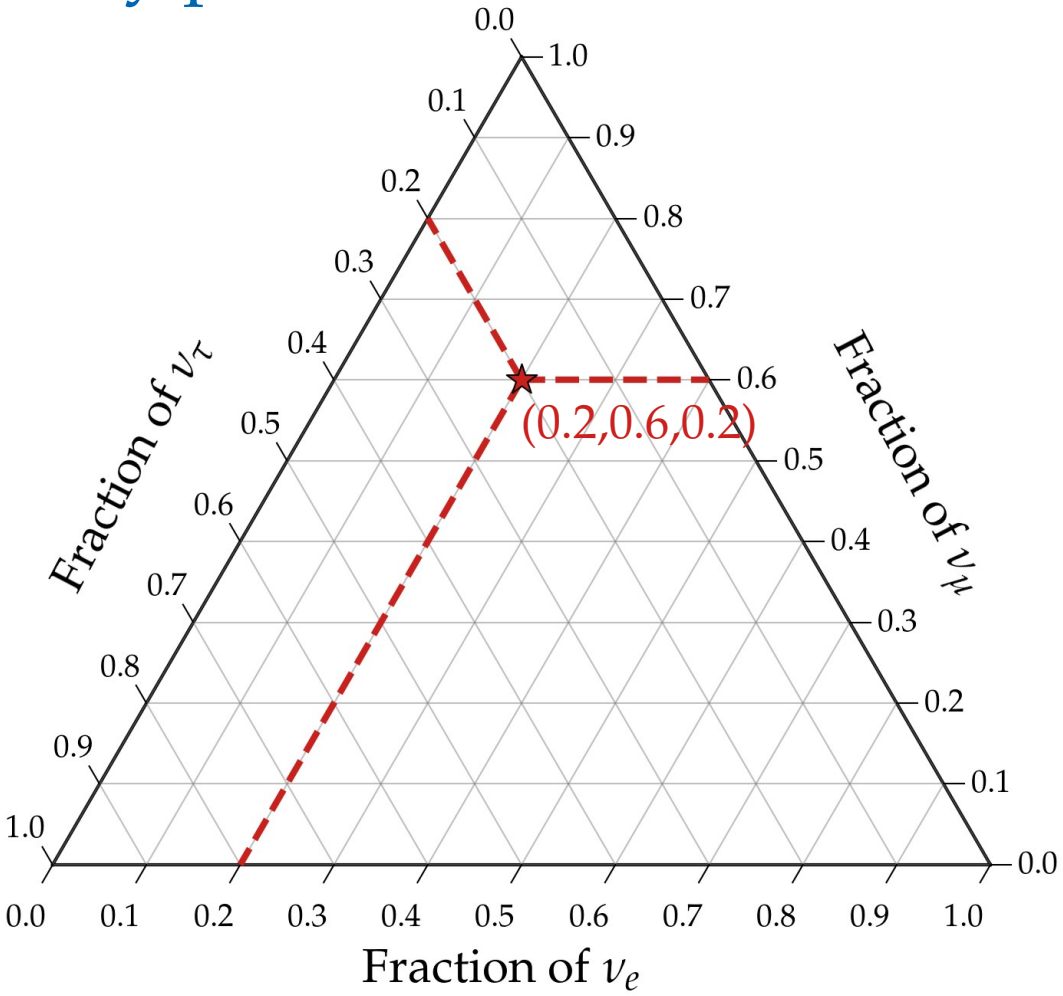

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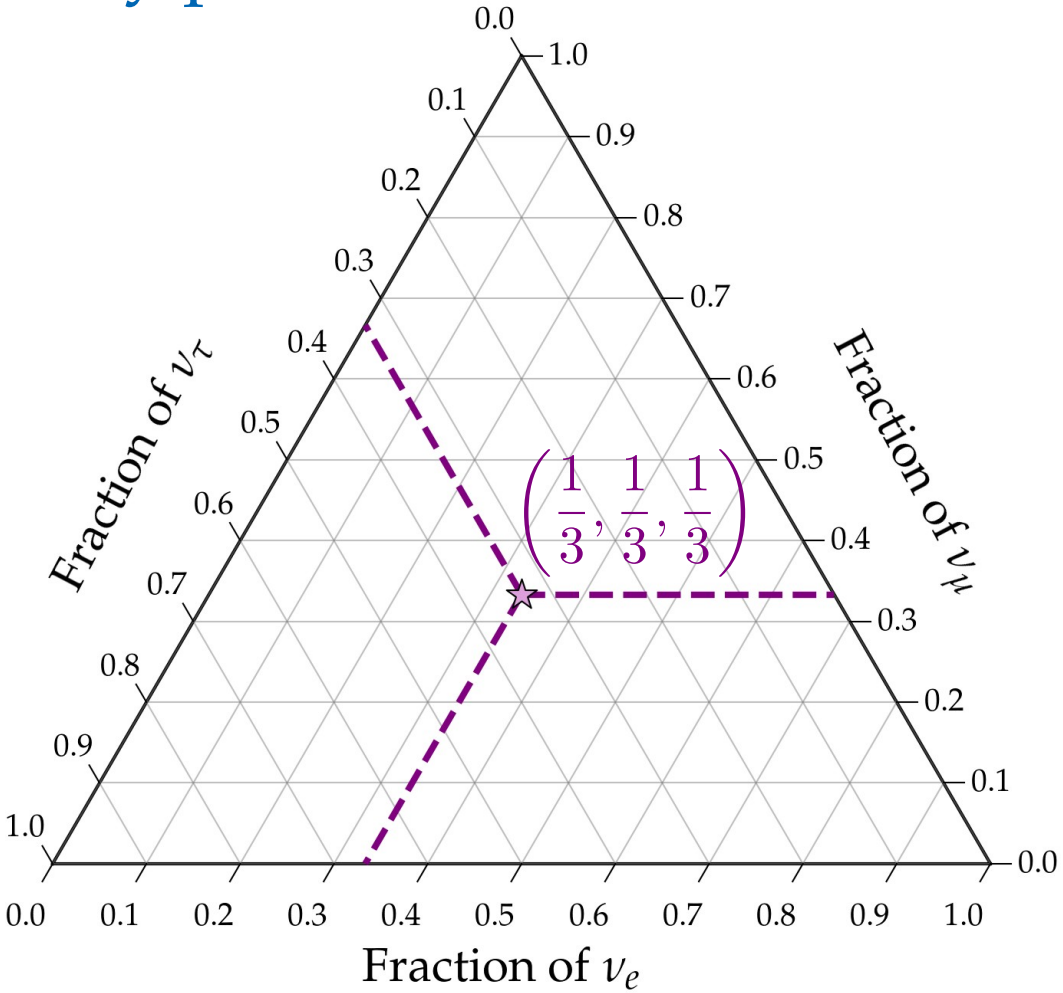
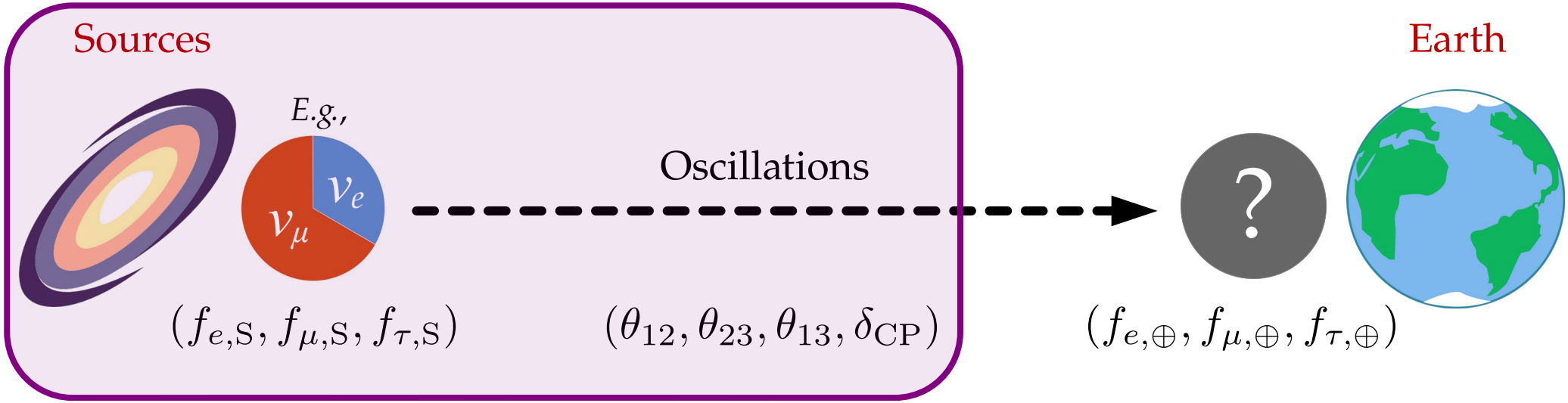


From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$



One likely TeV–PeV ν production scenario:

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

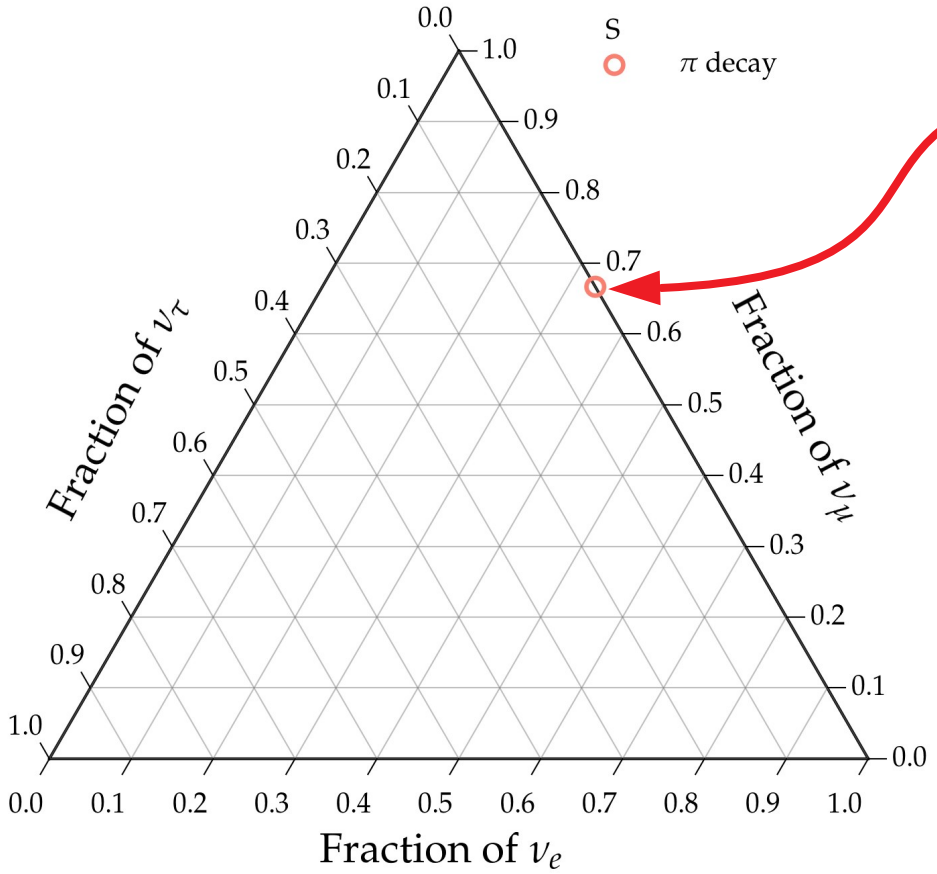
Full π decay chain

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

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

One likely TeV–PeV ν production scenario:

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



Full π decay chain

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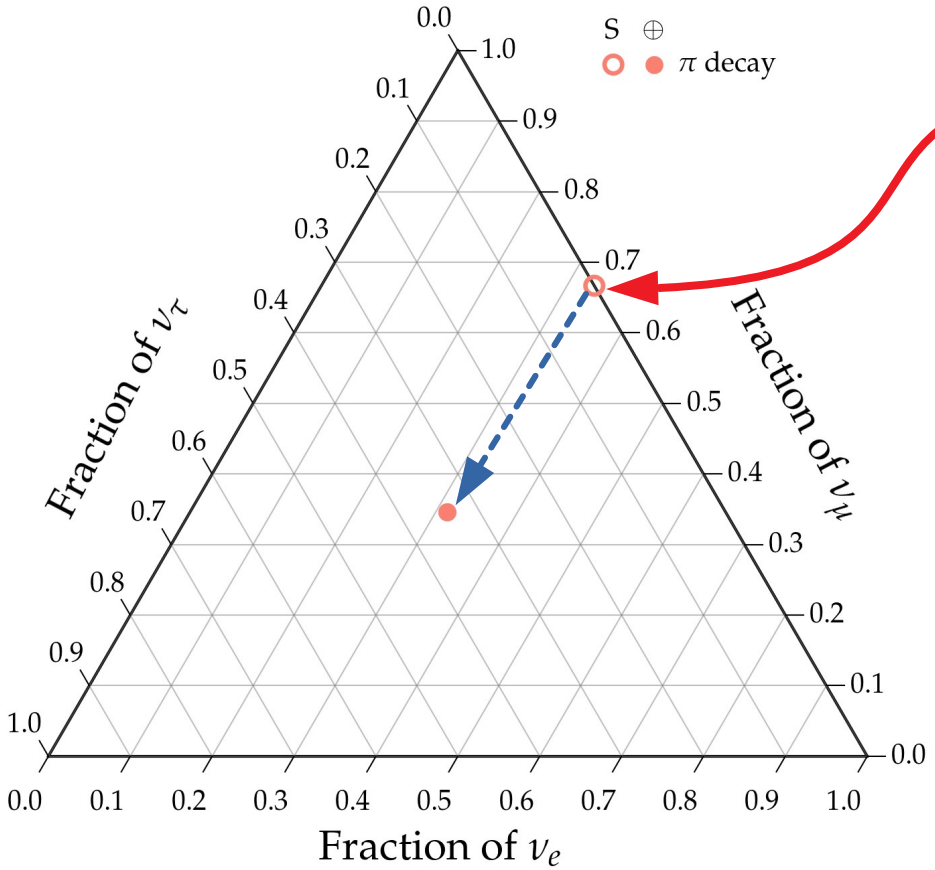

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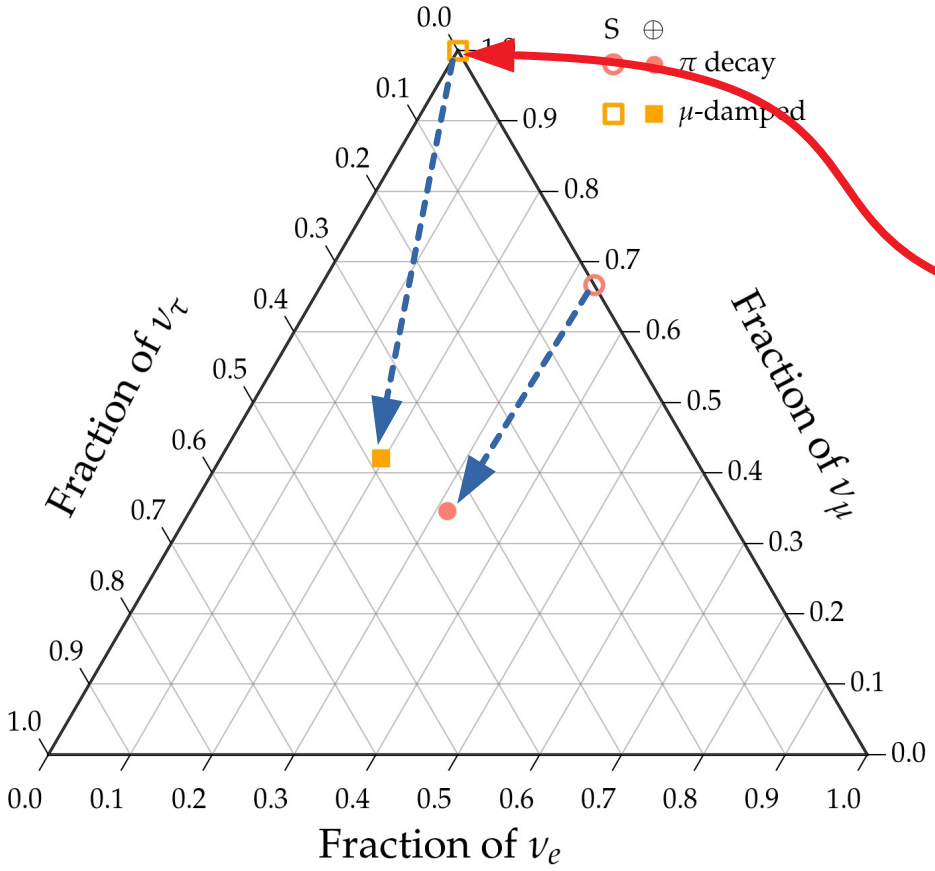

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Muon damped

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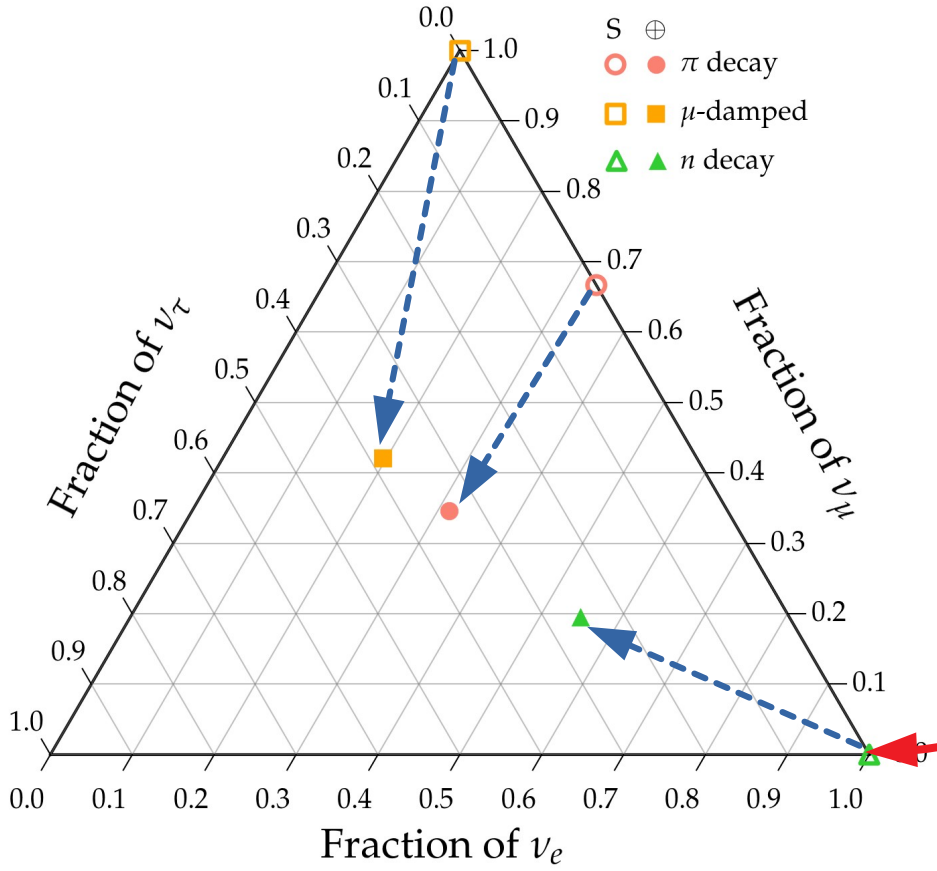

Full π decay chain

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Neutron decay

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Measuring flavor composition: 2015–2020

IceCube Collab., *EPJC* 2022
IceCube Collab., *PRD* 2019
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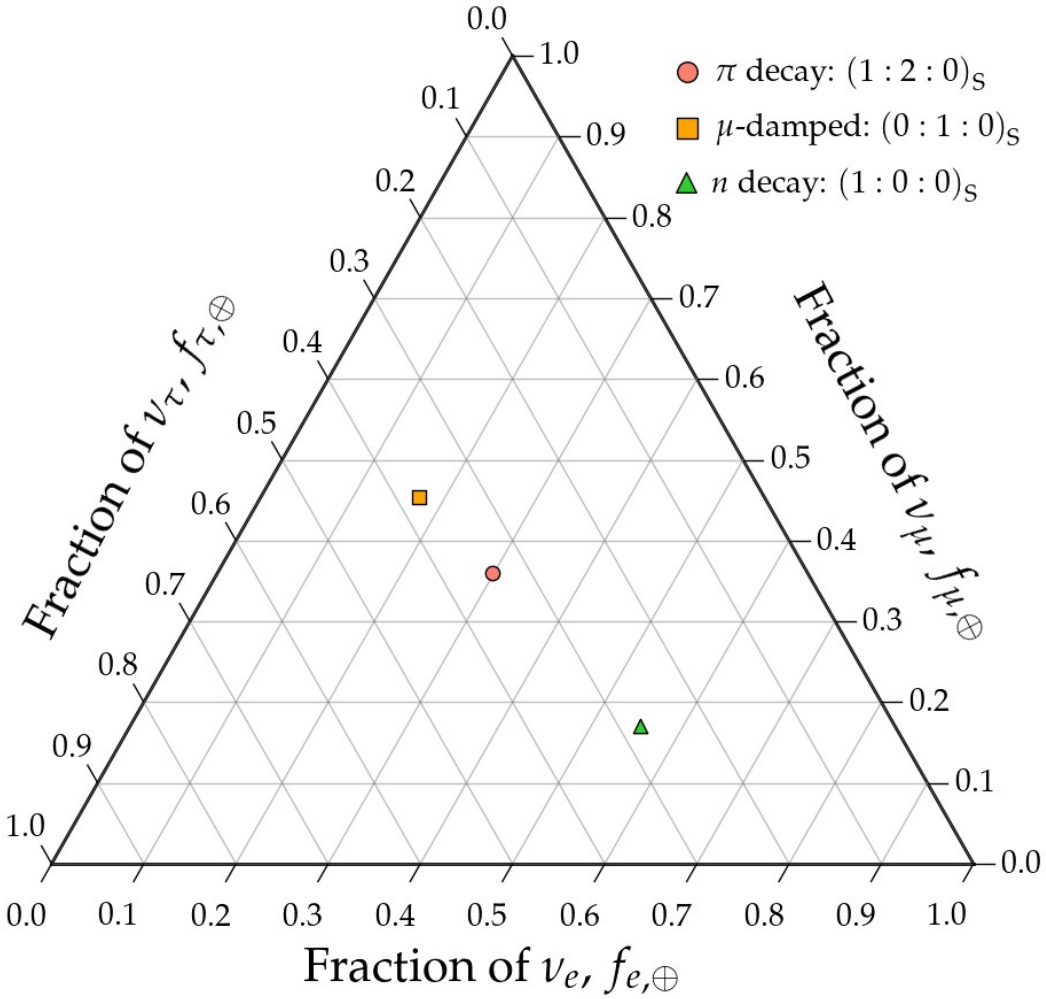

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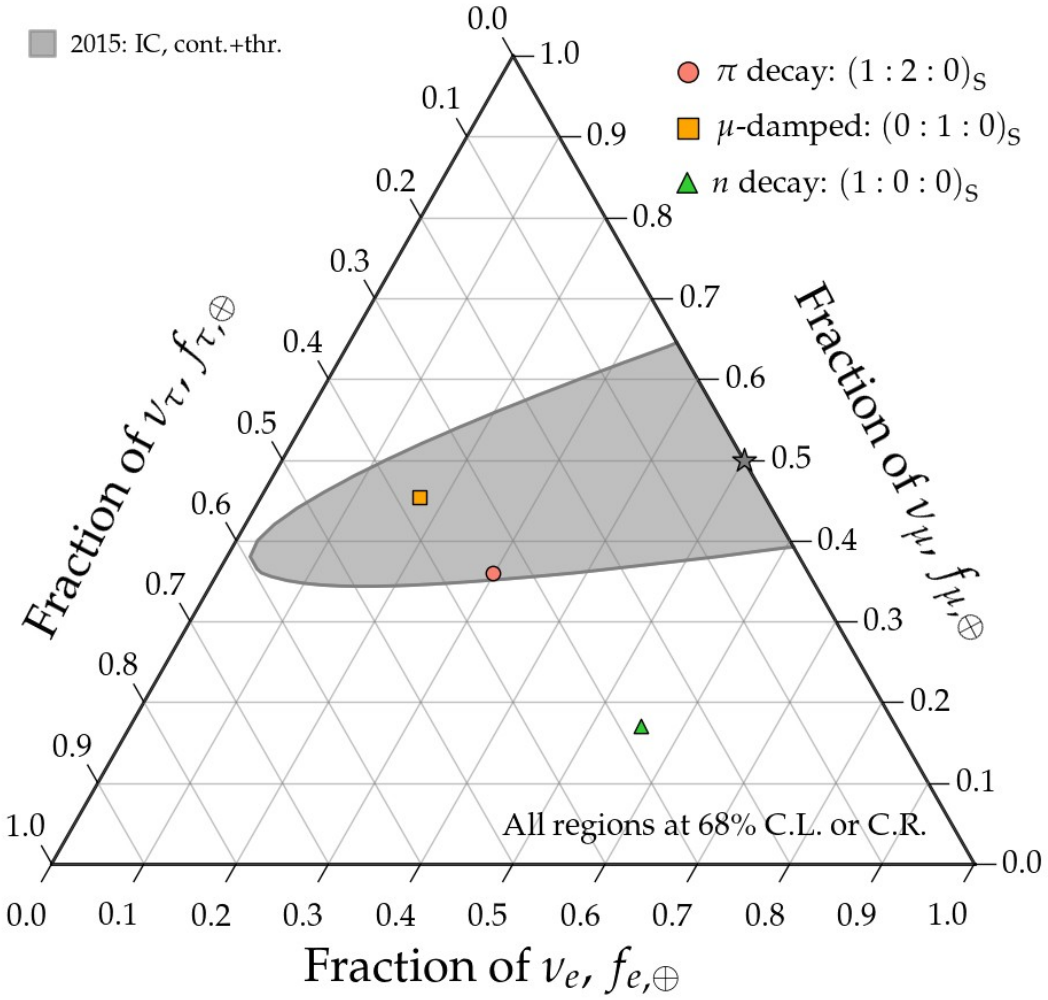

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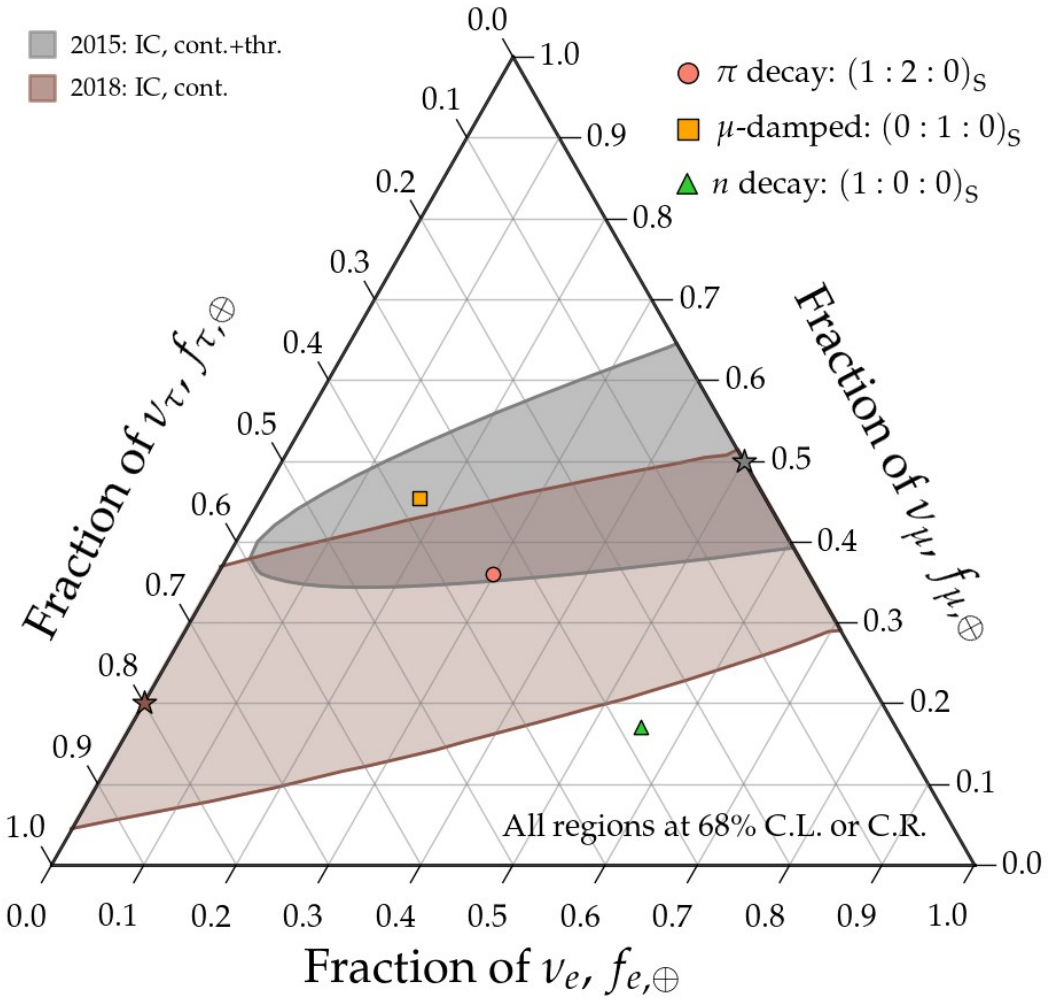

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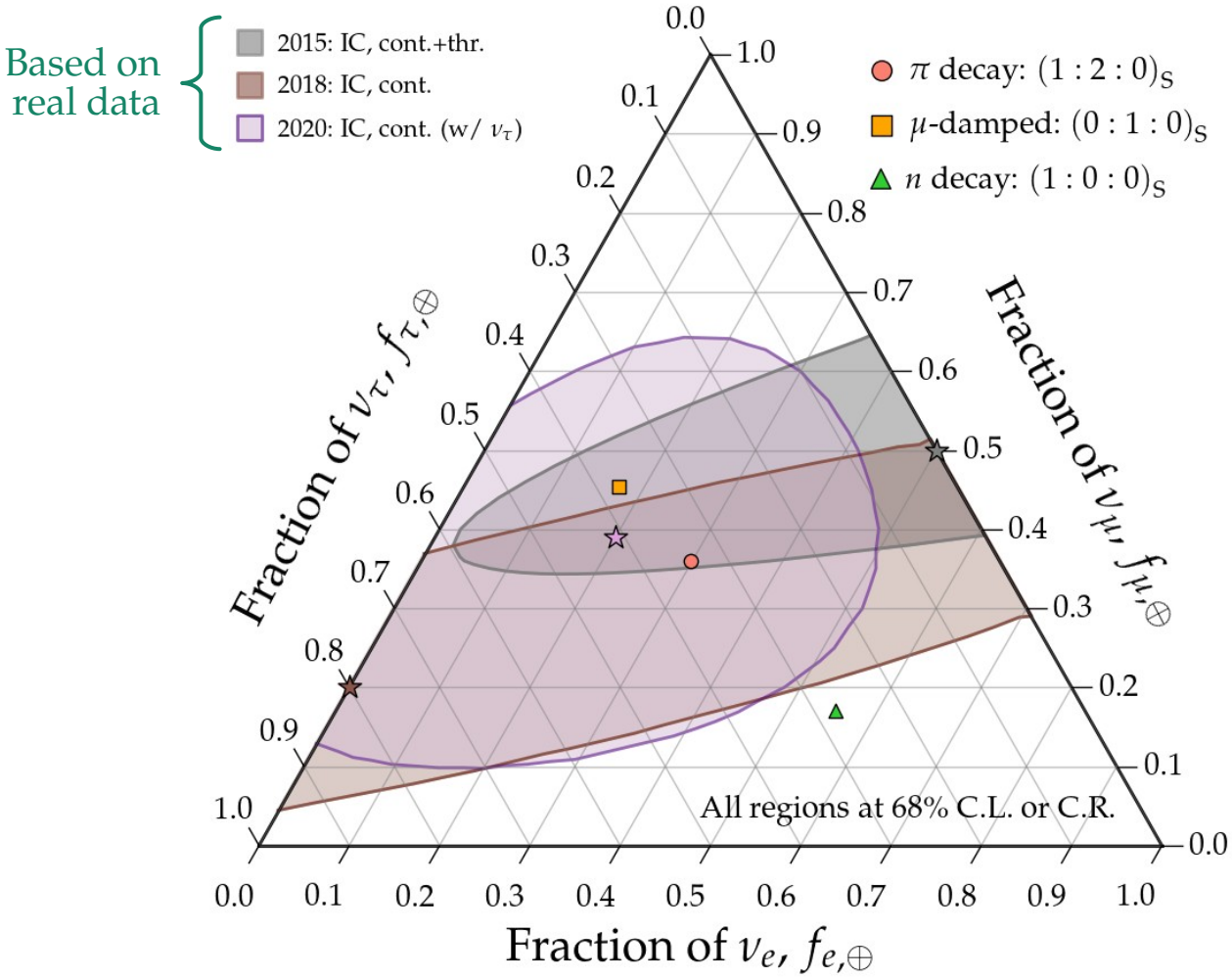

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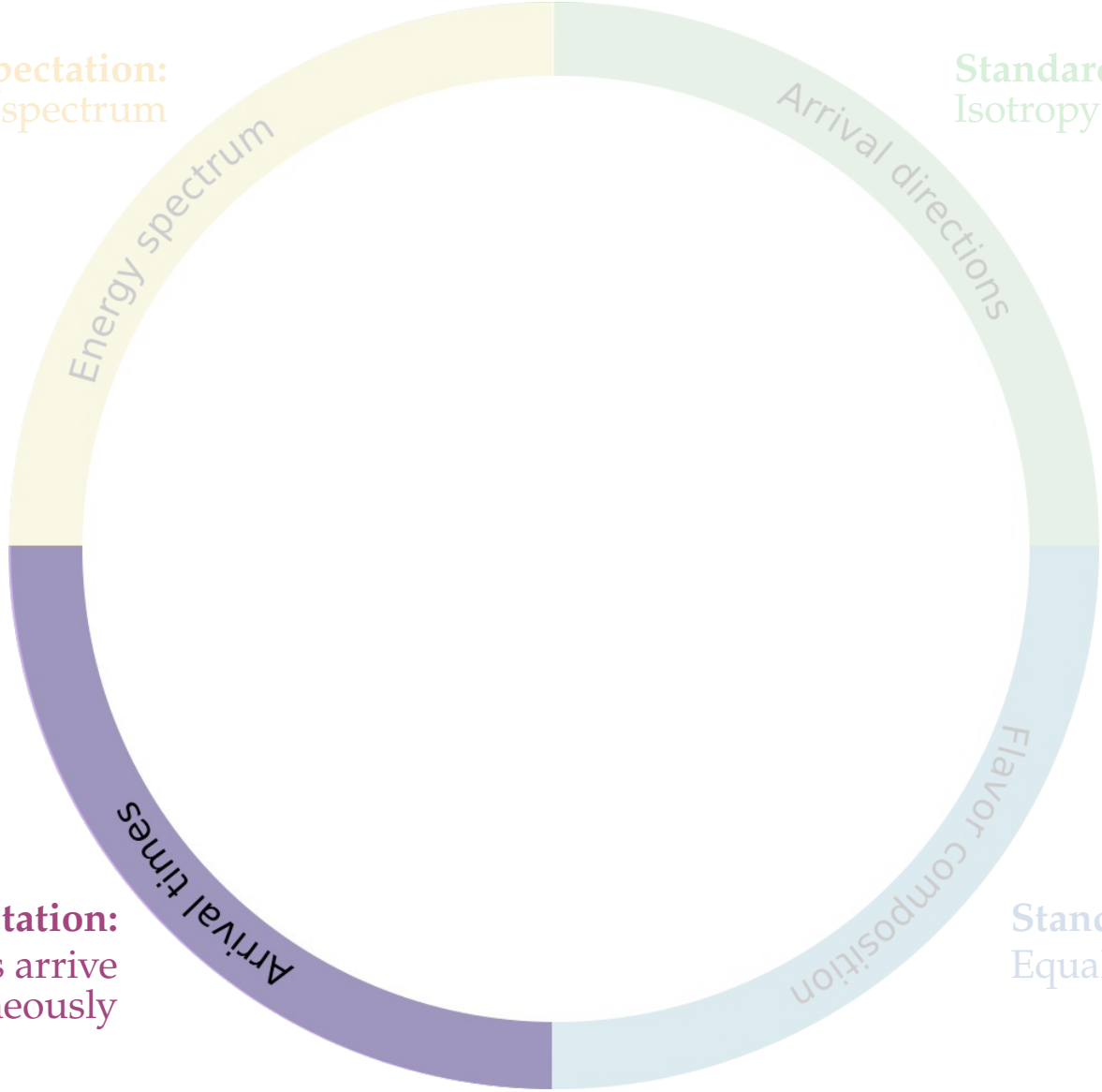

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Bright in gamma rays, bright in high-energy neutrinos

Energy in neutrinos ∝ energy in gamma rays

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

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Baryonic loading

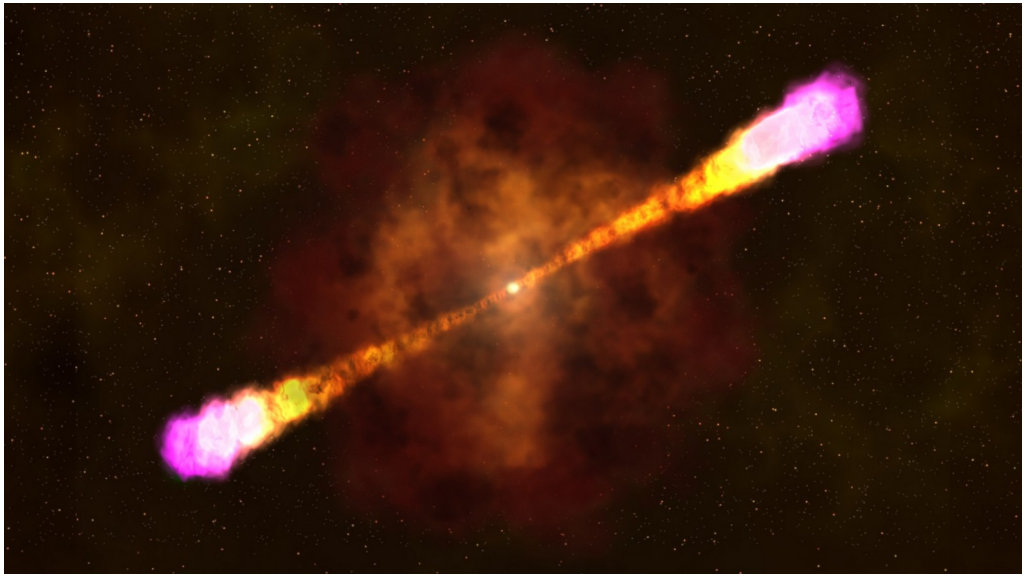
Optical depth to $p\gamma$:

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

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

Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts



Blazars

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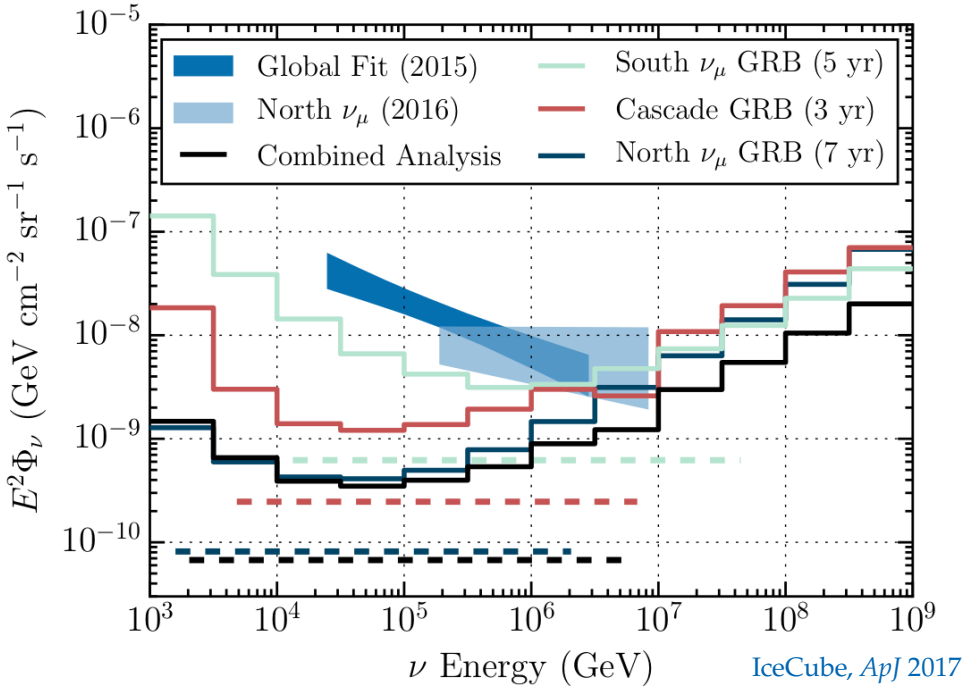
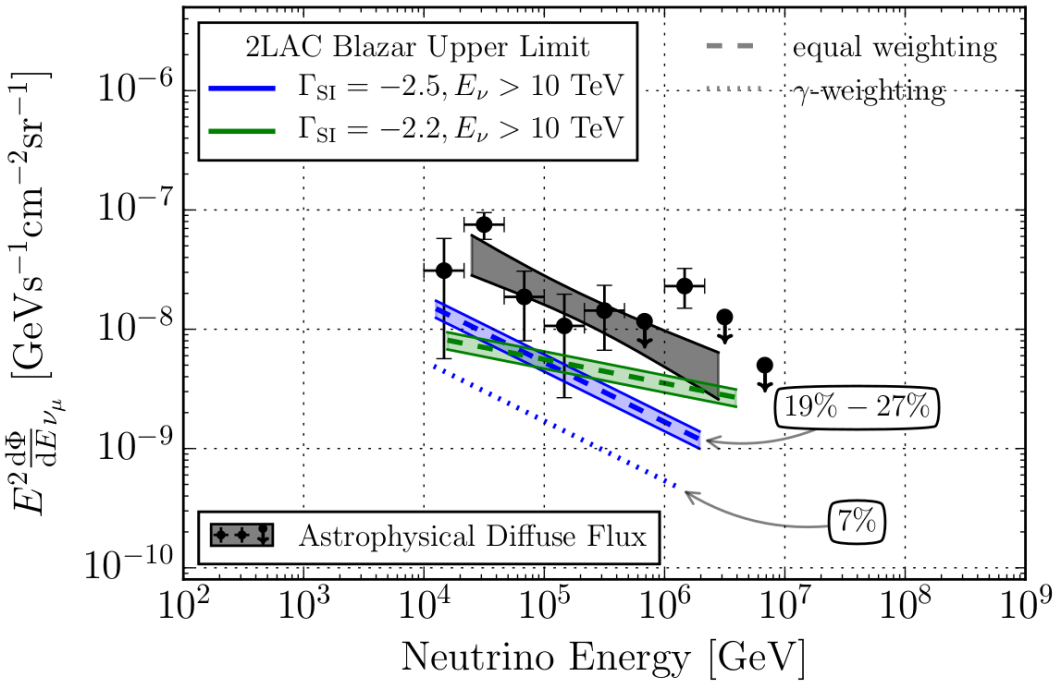


IceCube, *ApJ* 2017

1172 GRBs inspected, no correlation found

< 1% contribution to diffuse flux

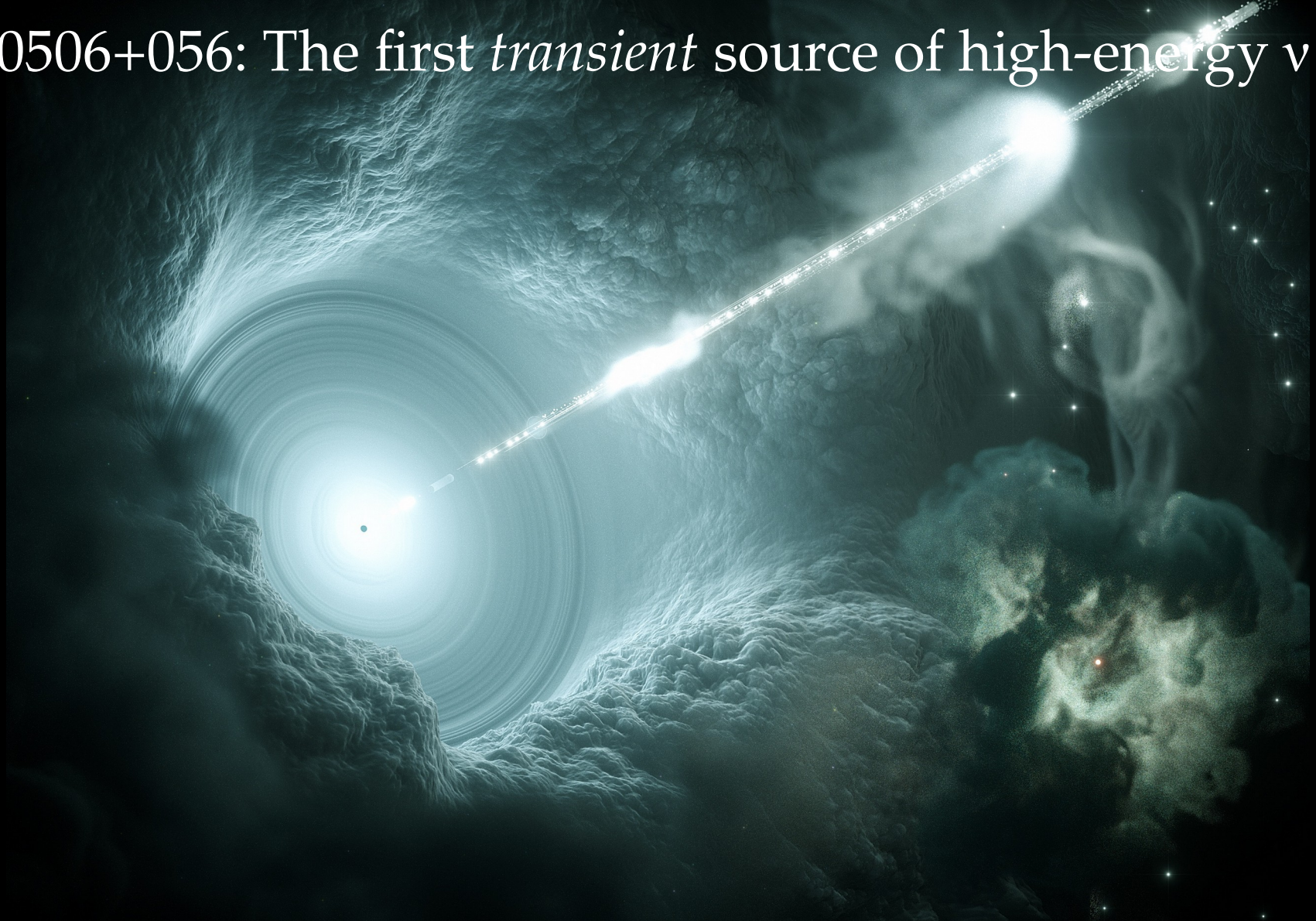
Blazars



862 blazars inspected, no correlation found

< 27% contribution to diffuse flux

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

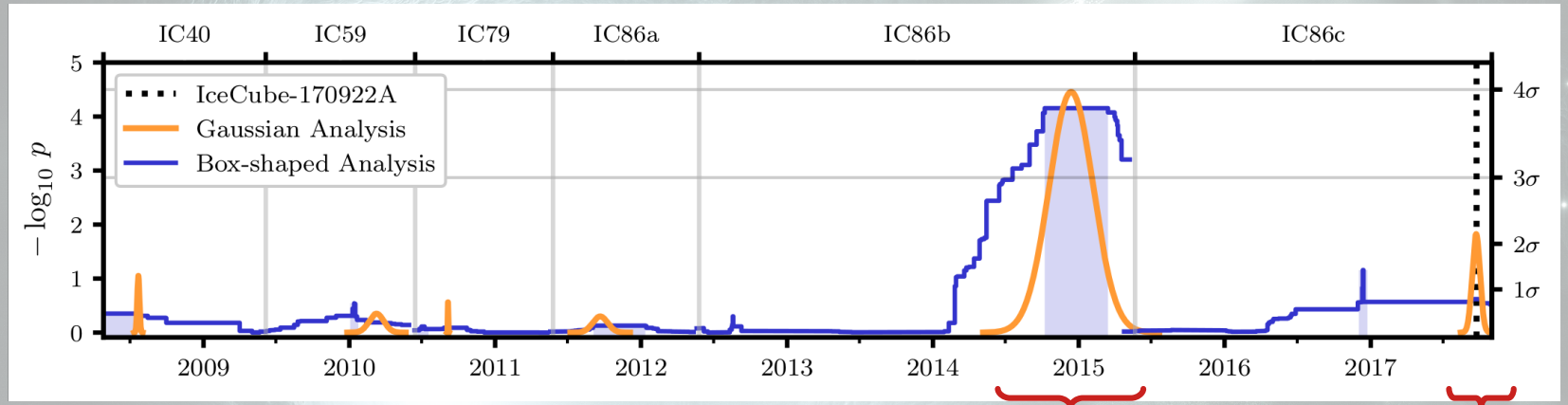


DESY

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

Blazar TXS 0506+056:

IceCube, *Science* 2018



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

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

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

Combined (pre-trial): 4.1σ

Today
TeV–PeV ν

Astro: Find & understand sources

Particle: Turn predictions into tests

<u>Key developments</u>:

Larger statistics

Better reconstruction

Smaller astrophysical uncertainties

High-energy neutrino physics

today

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 $\kappa_n \sim 4 \cdot 10^{-47}\,(E/\mathrm{PeV})^{-n}\,(L/\mathrm{Gpc})^{-1}\,\mathrm{PeV}^{1-n}$
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Note: Not an exhaustive list

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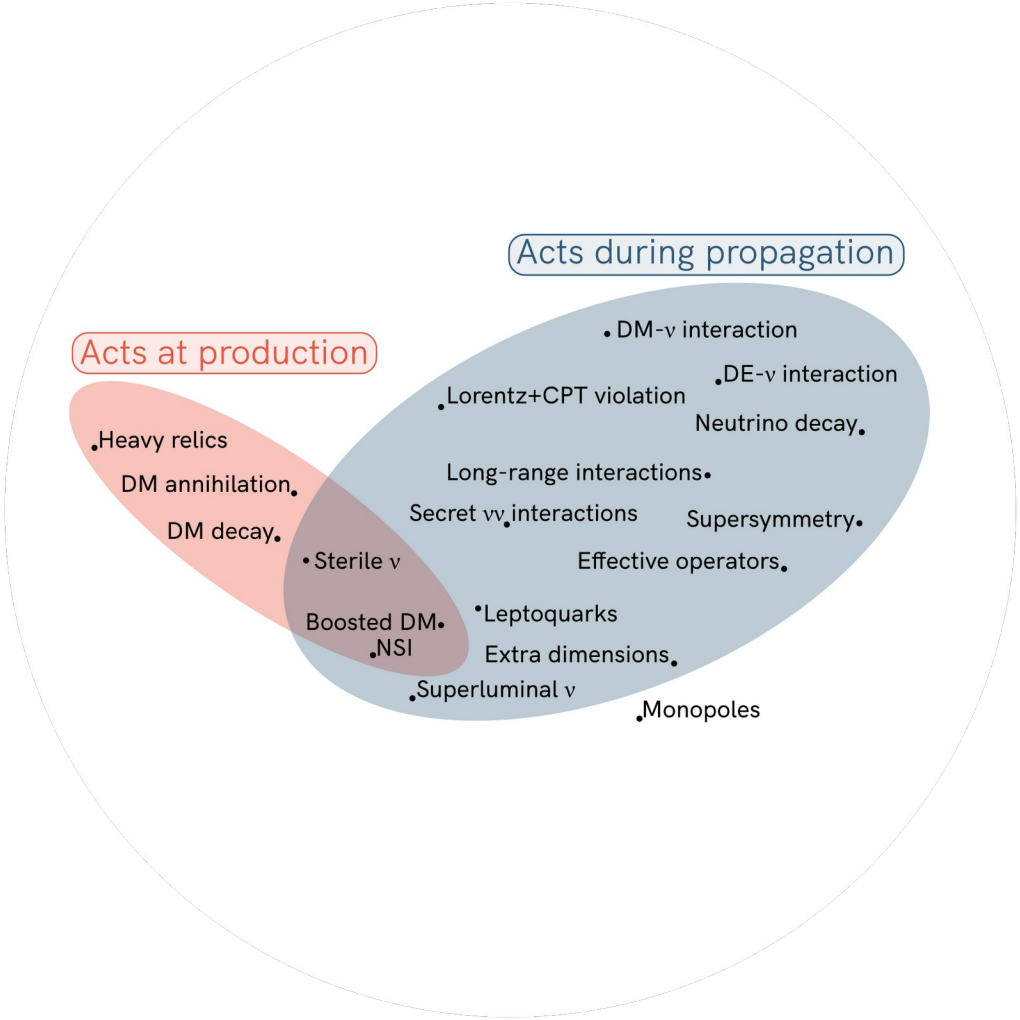

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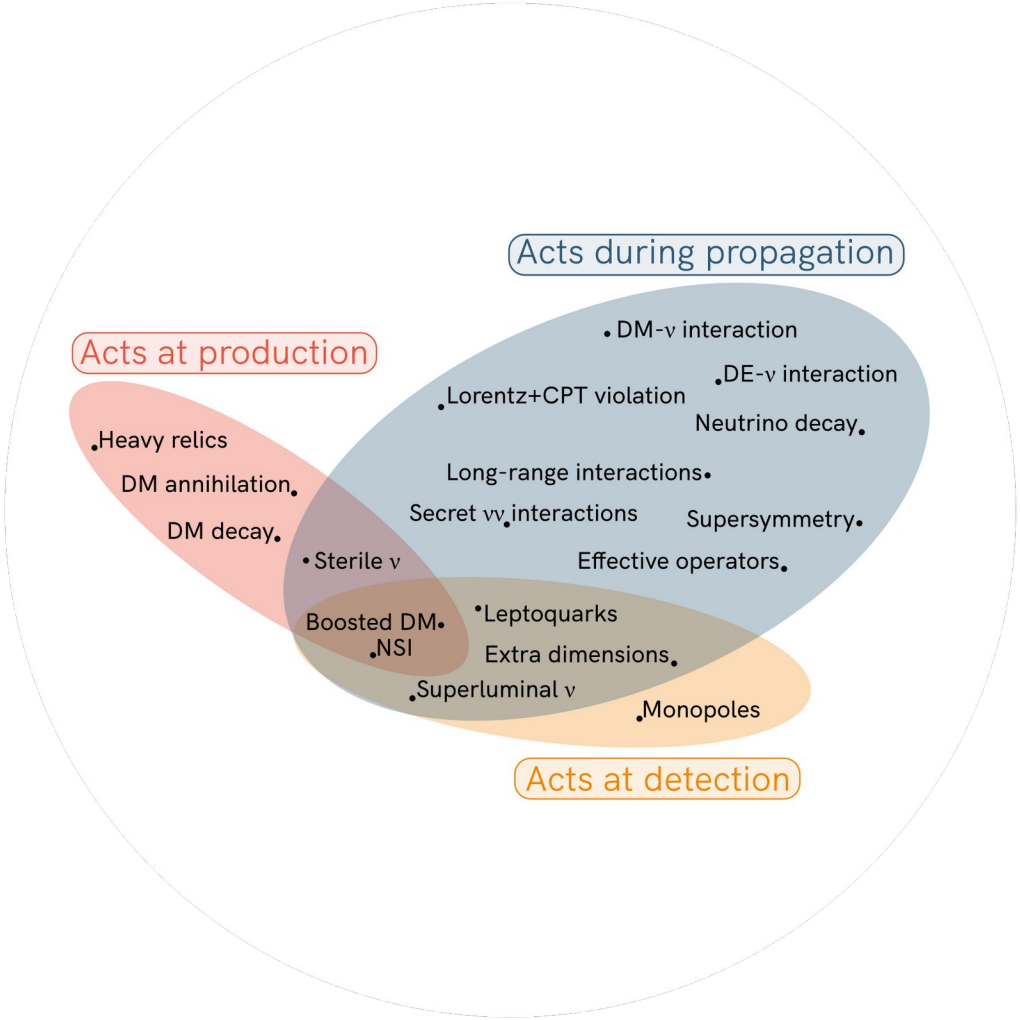

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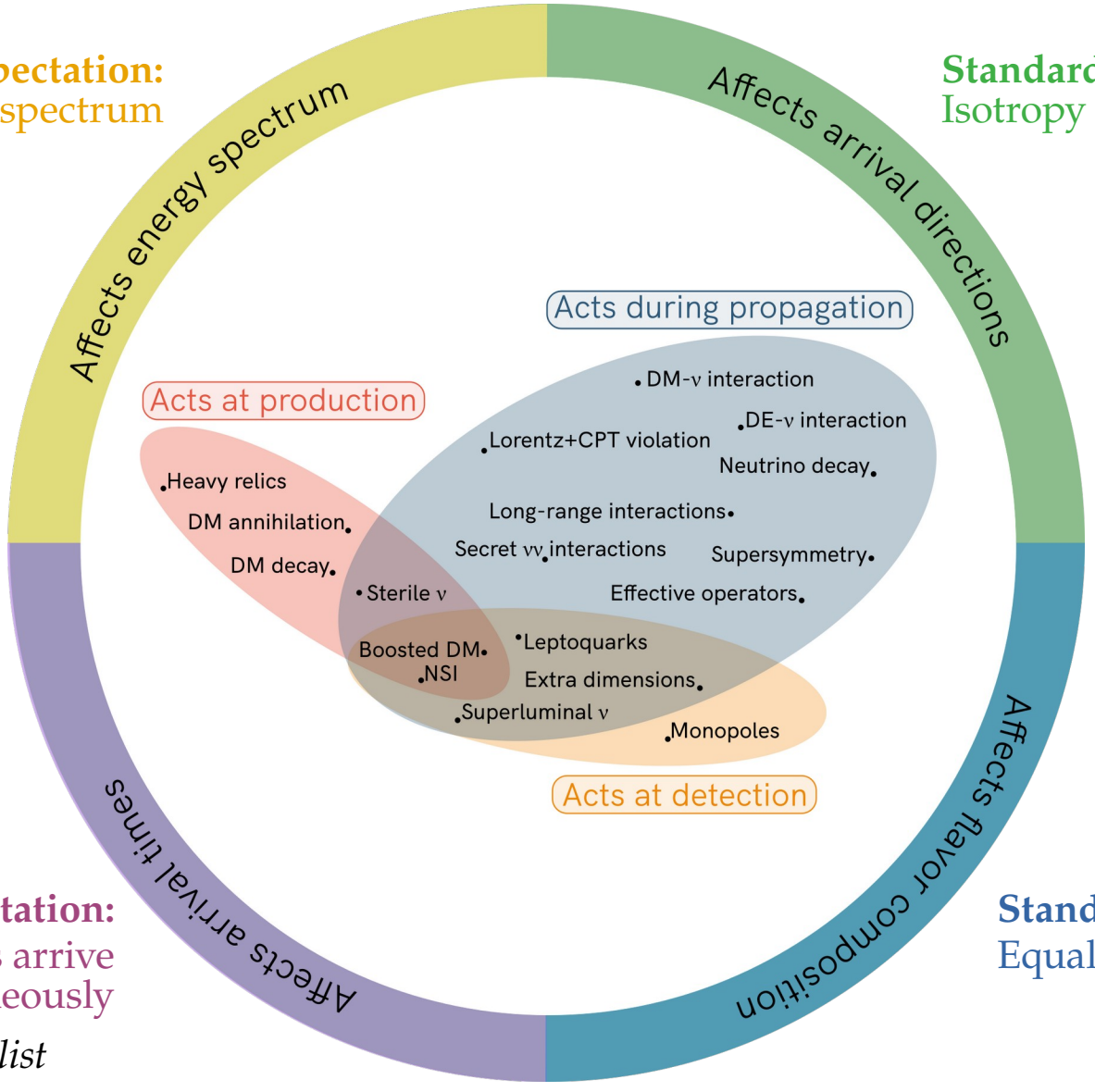
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



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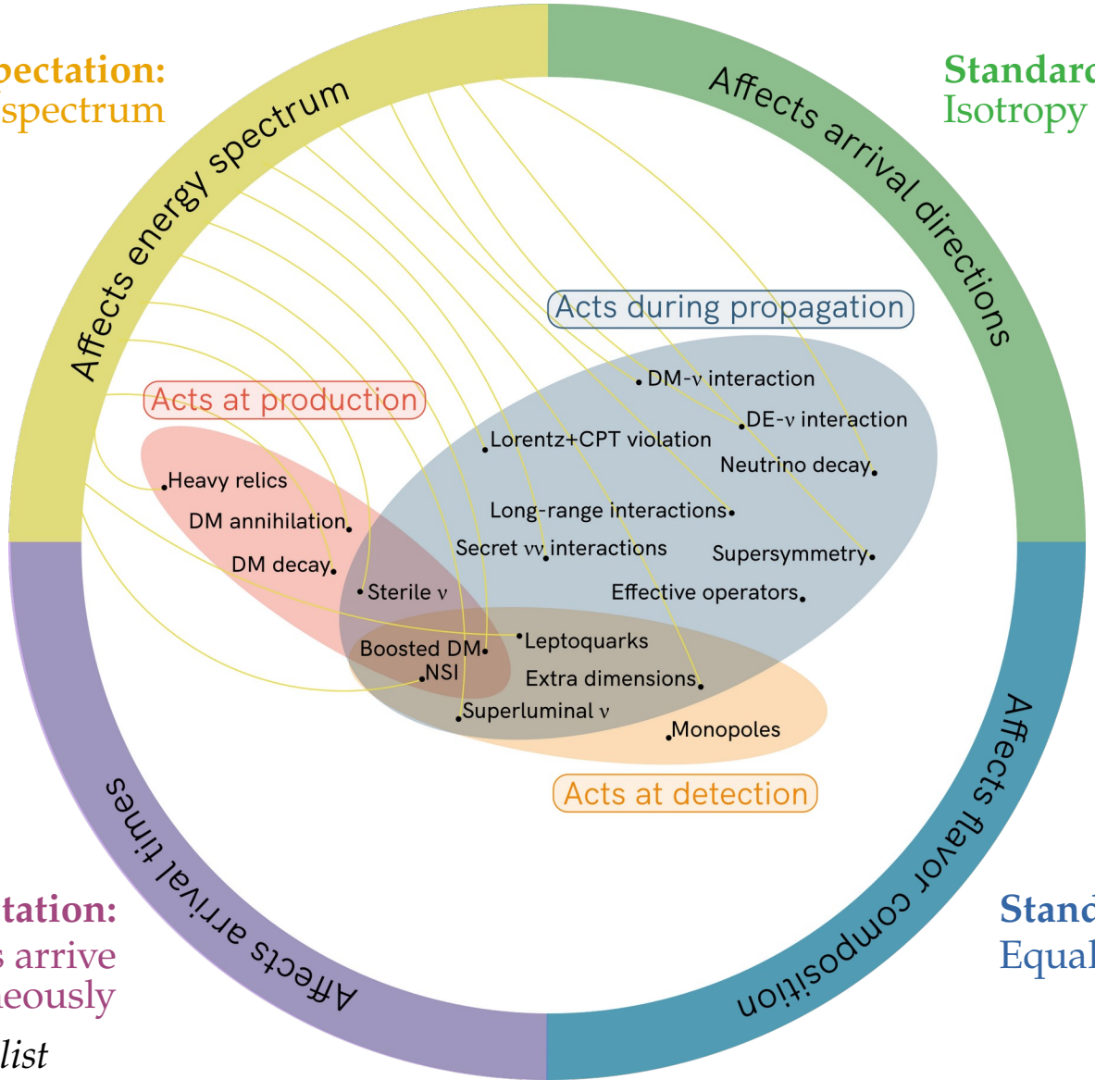

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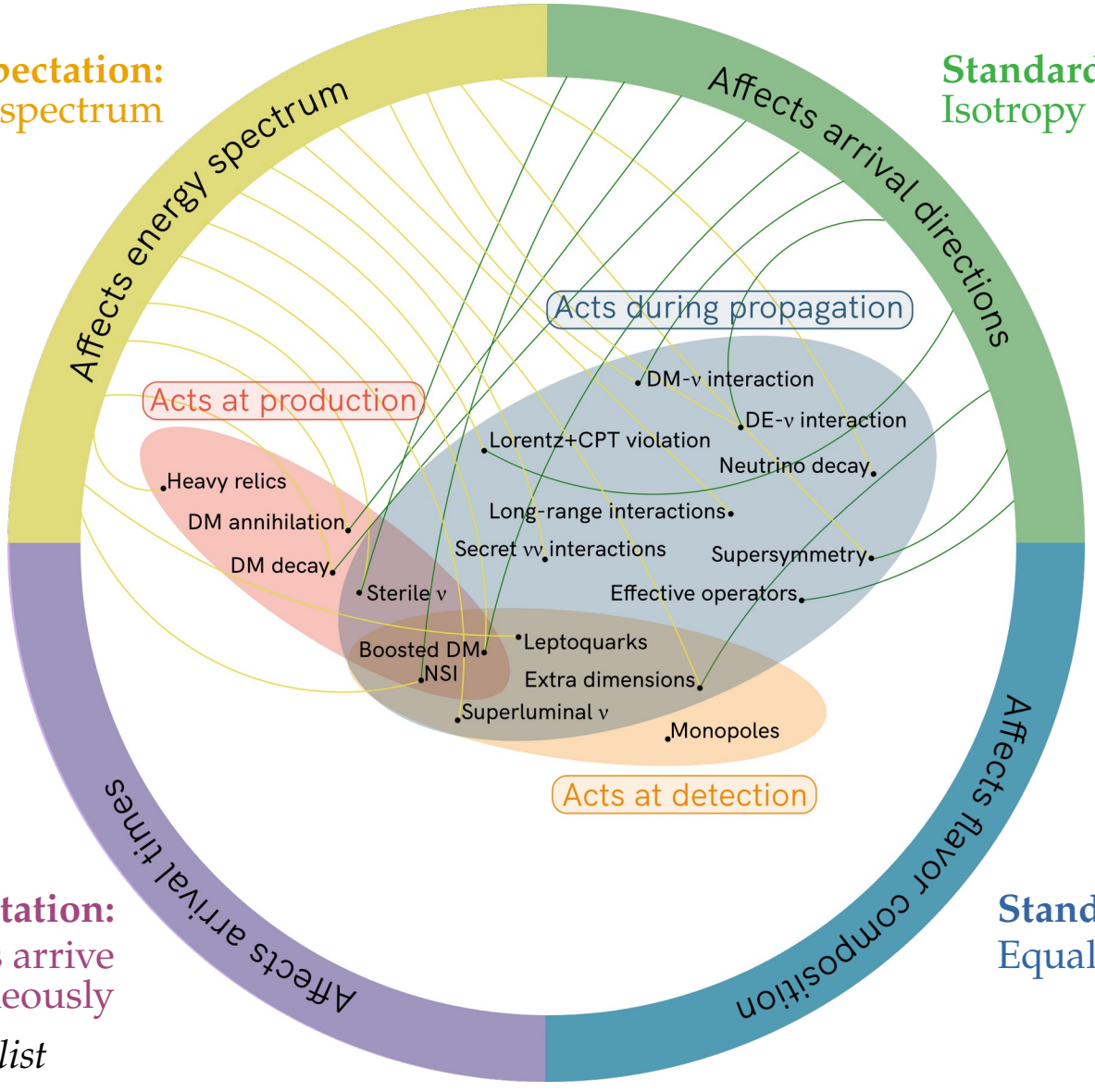

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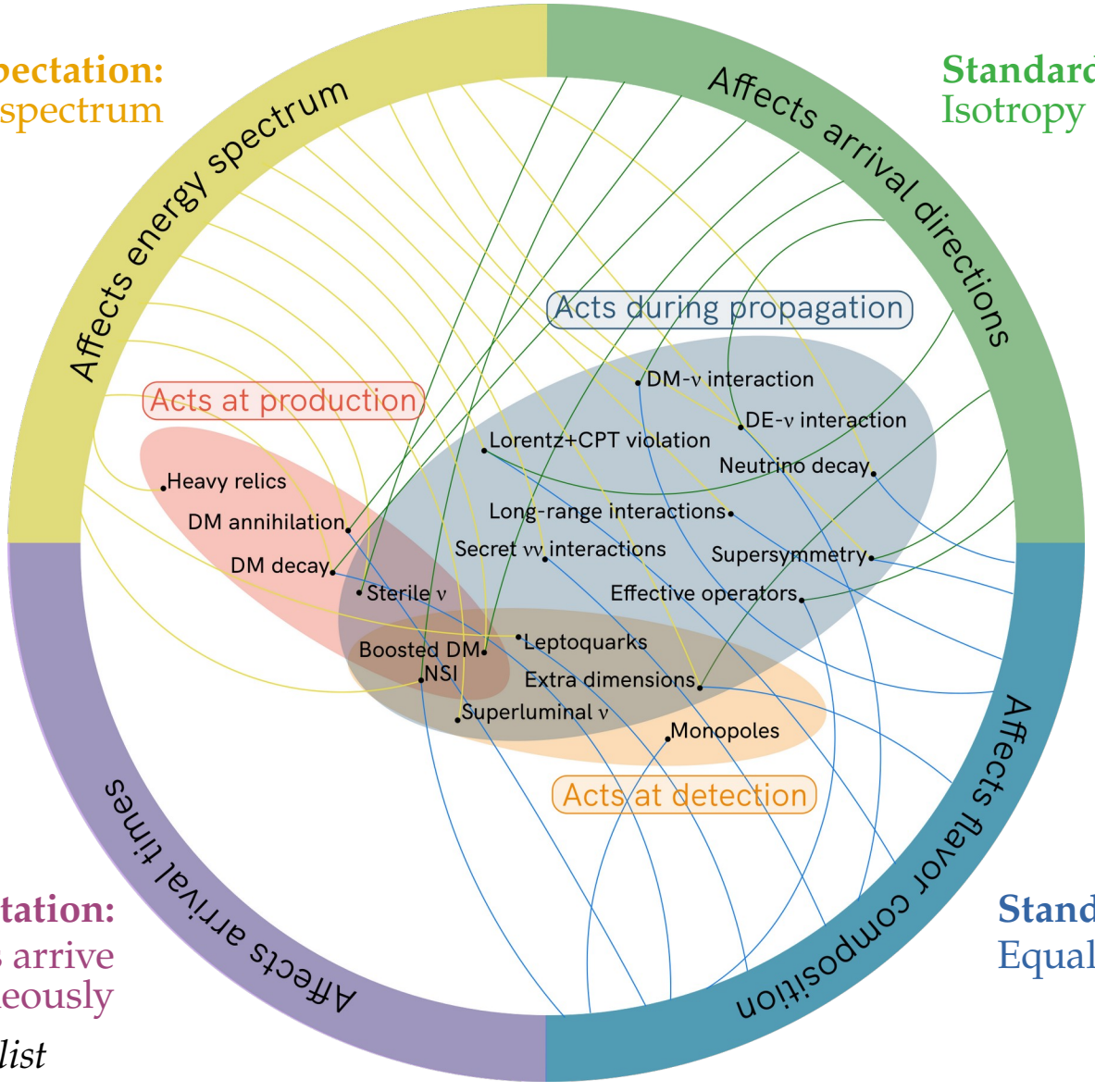

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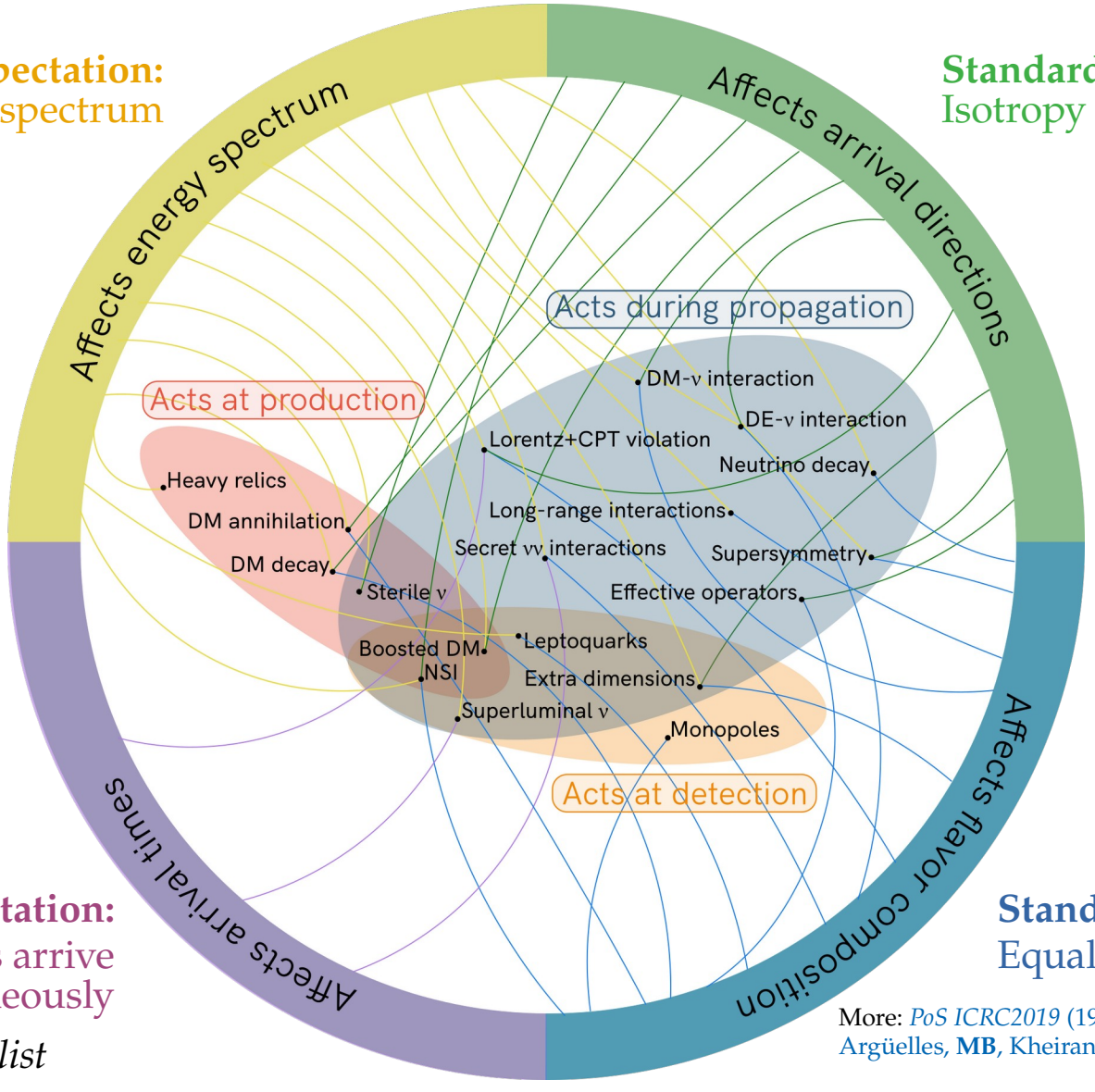

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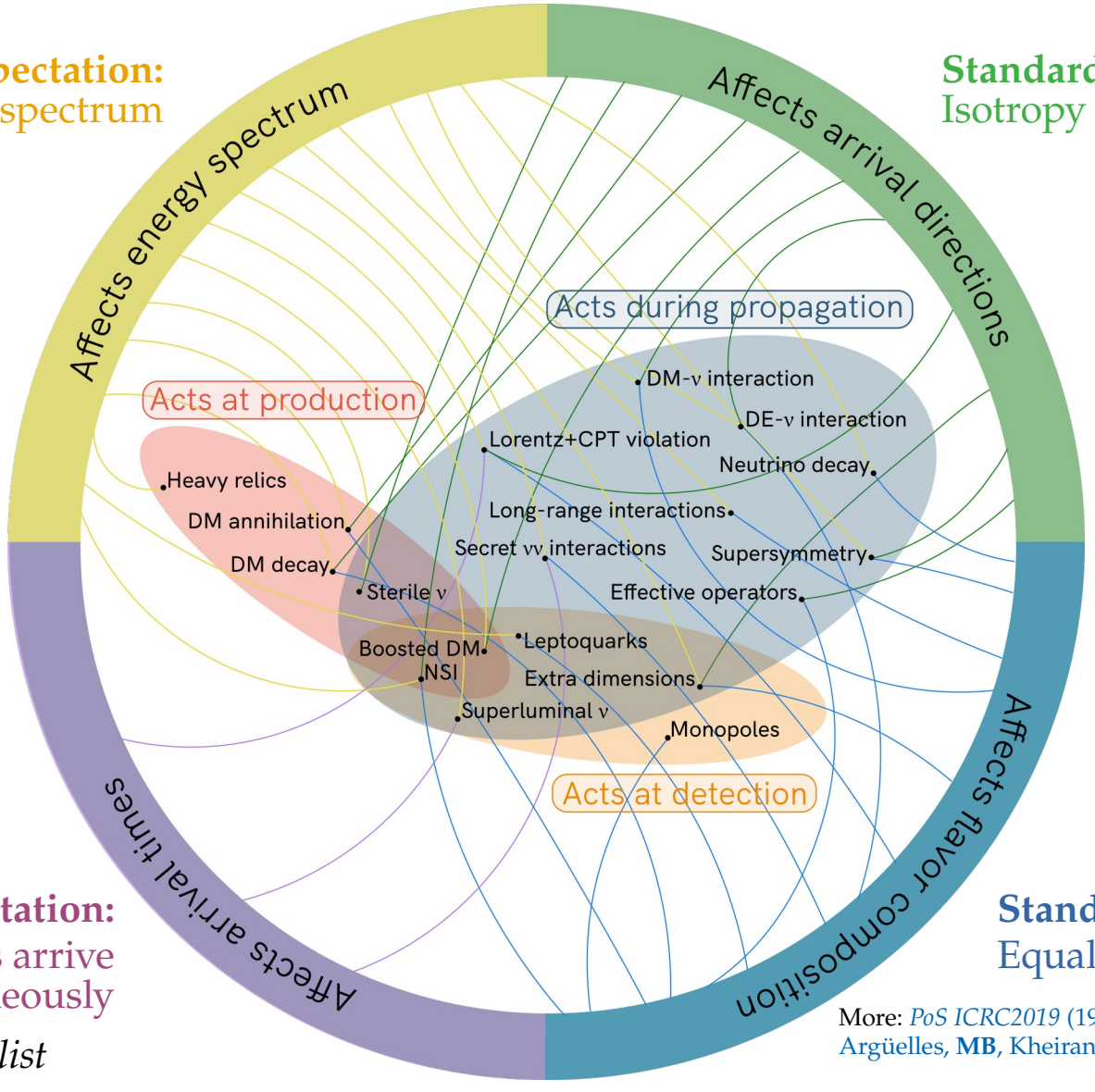

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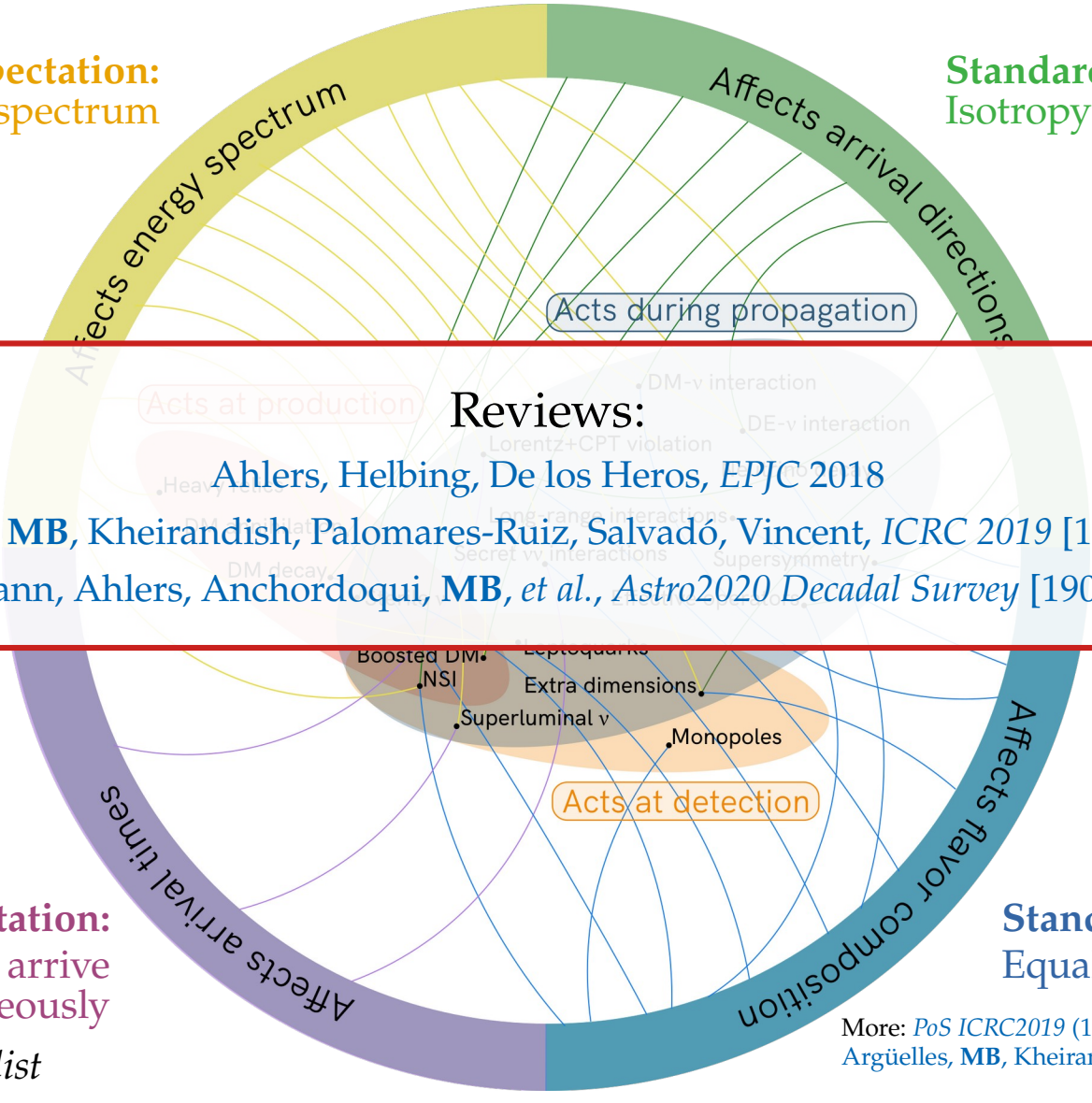

Reviews:

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

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

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

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A selection of neutrino physics

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

Find this in the backup slides

1. Glashow resonance:
Long-sought, finally seen

First observation of a Glashow resonance

Predicted in 1960:

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

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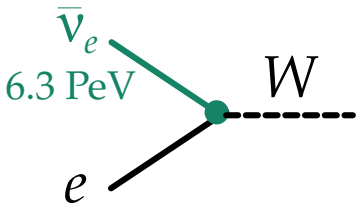

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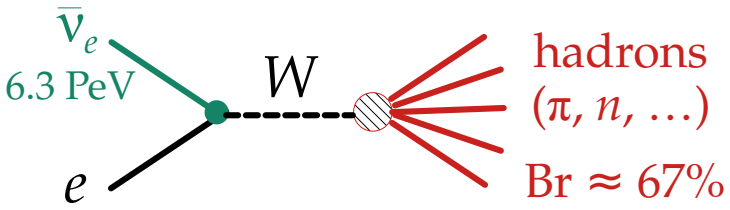

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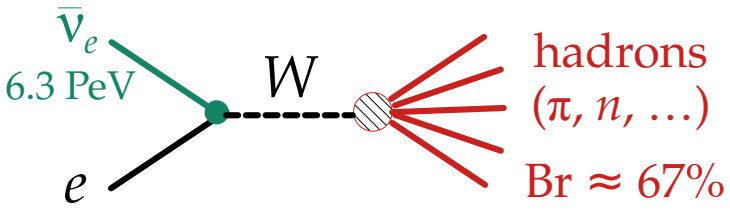

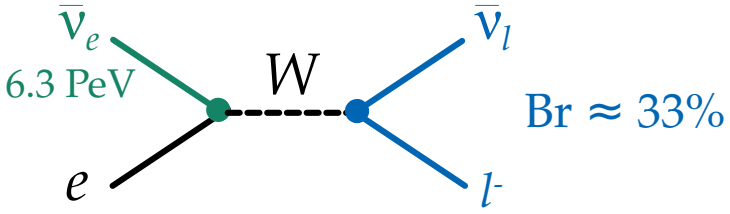

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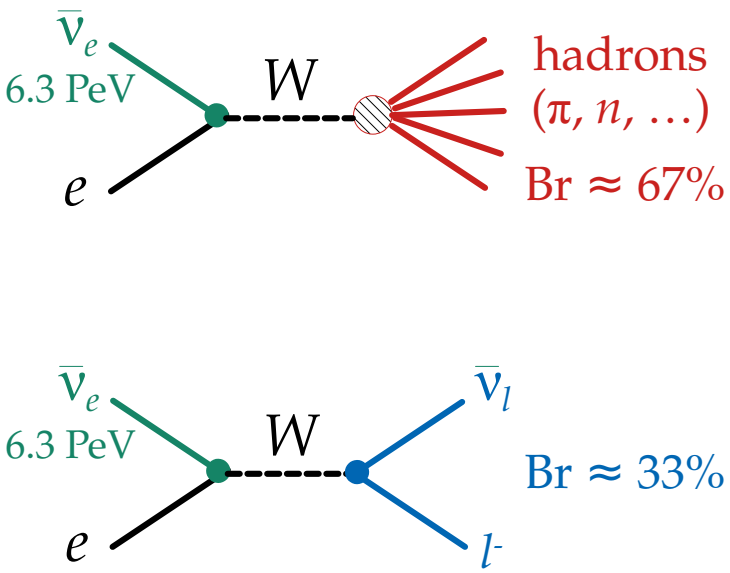

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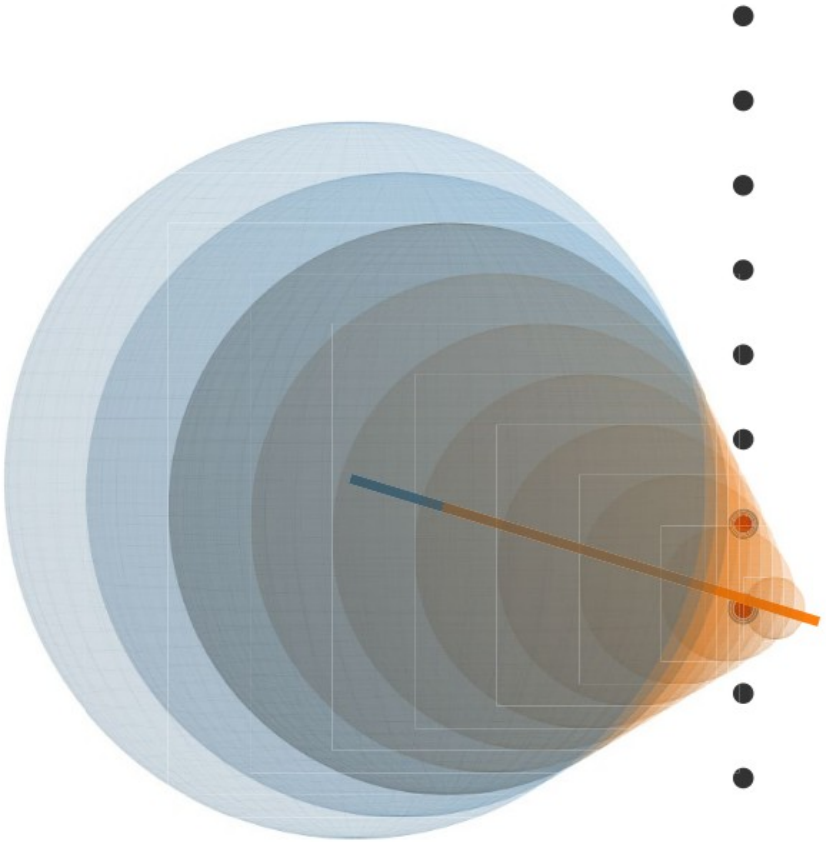

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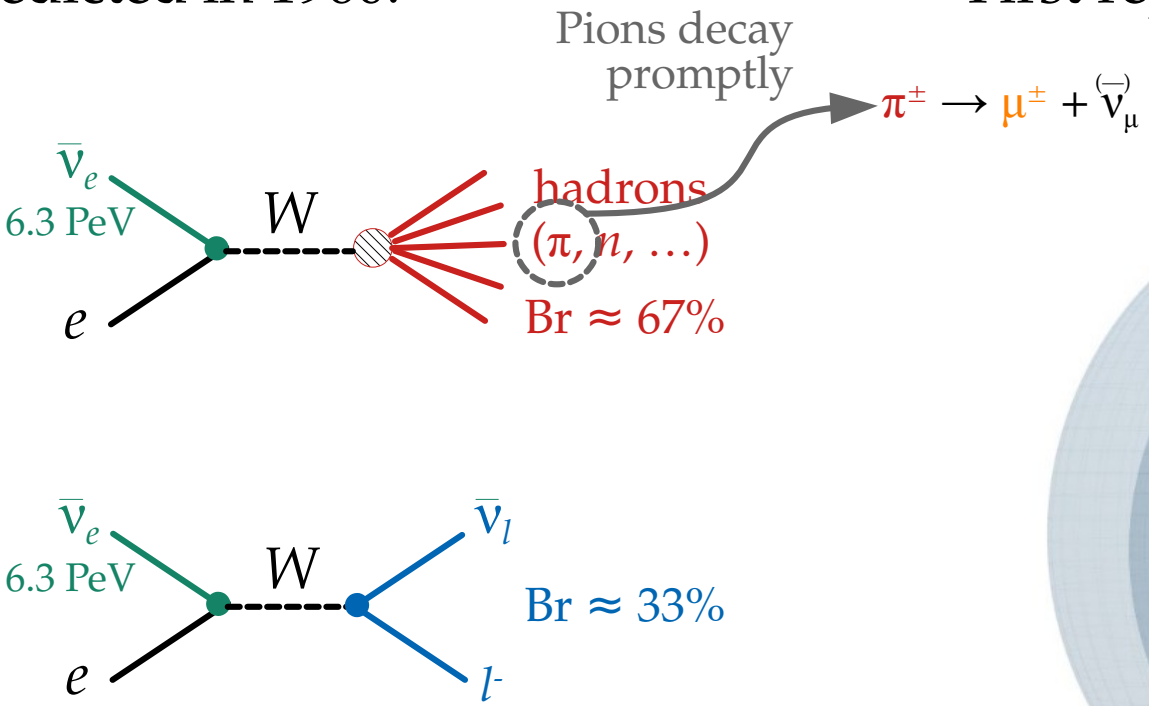

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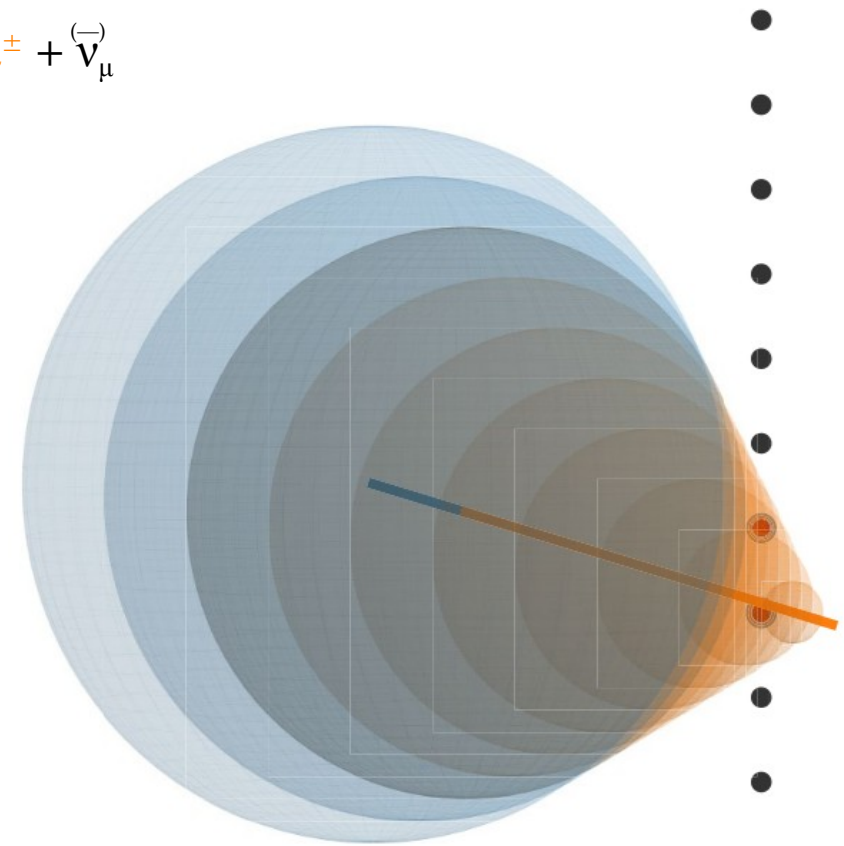

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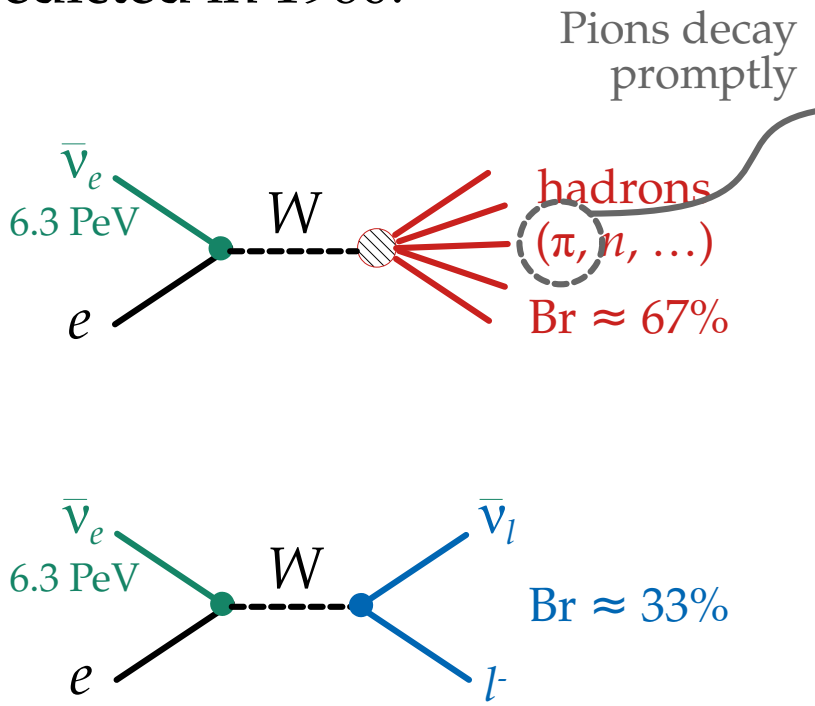
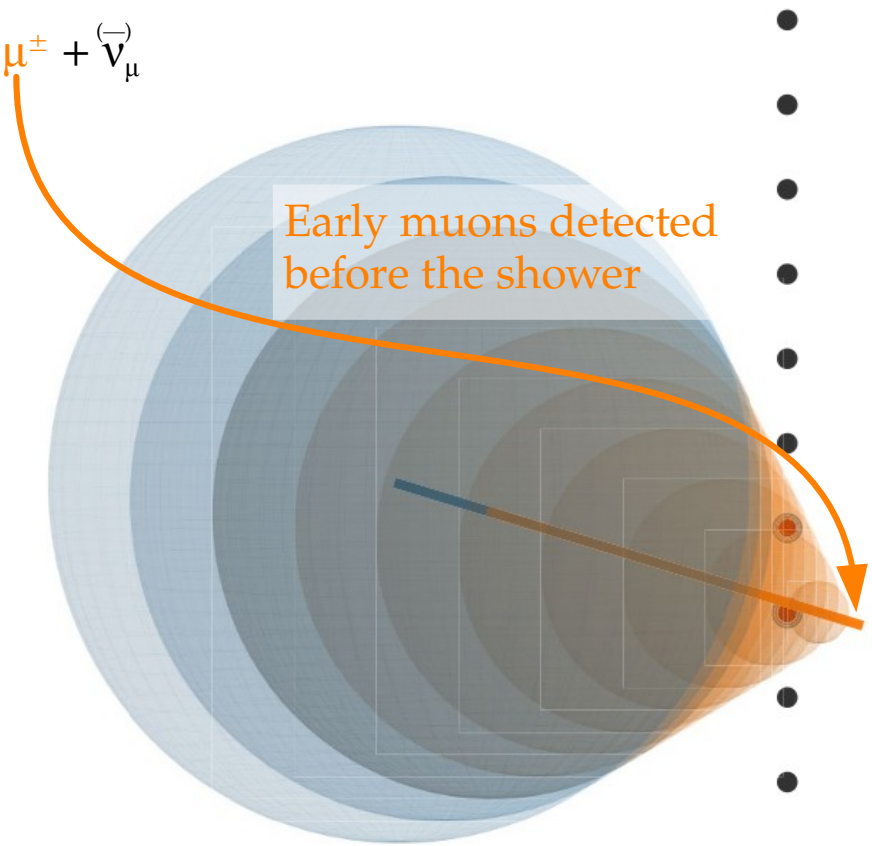


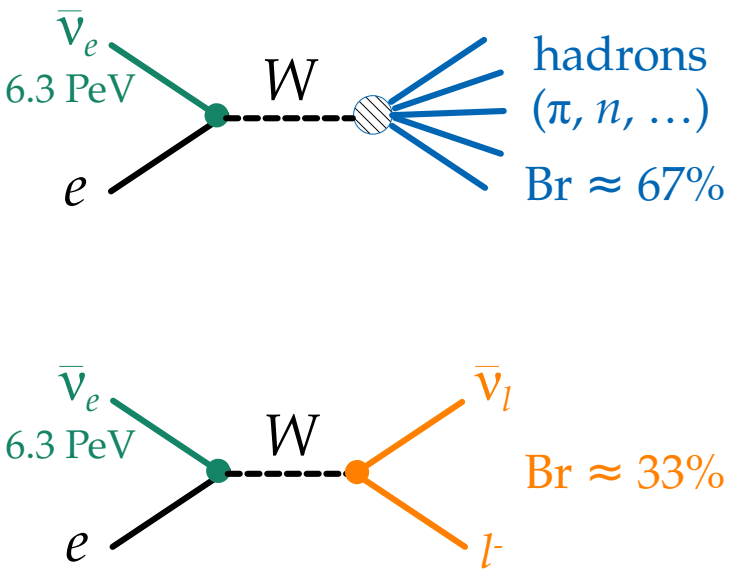
First reported by IceCube in 2021:



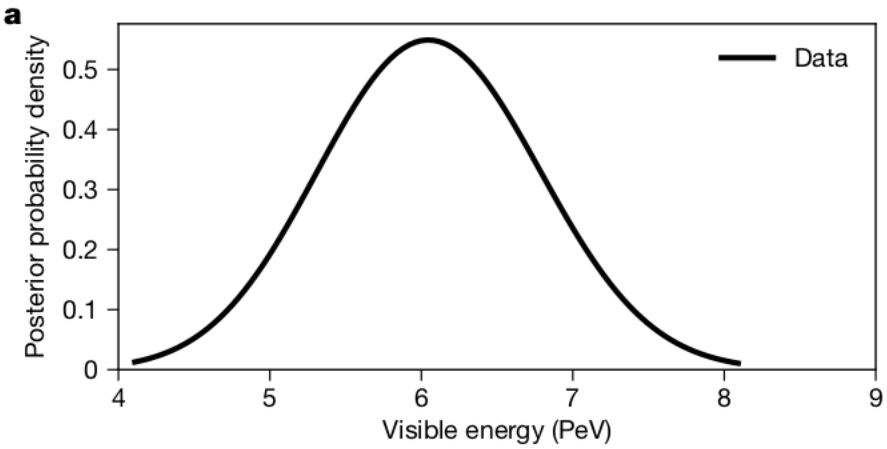
IceCube, *Nature* 2021
Glashow, *PR* 1960

First observation of a Glashow resonance

Predicted in 1960:



First reported by IceCube in 2021:



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

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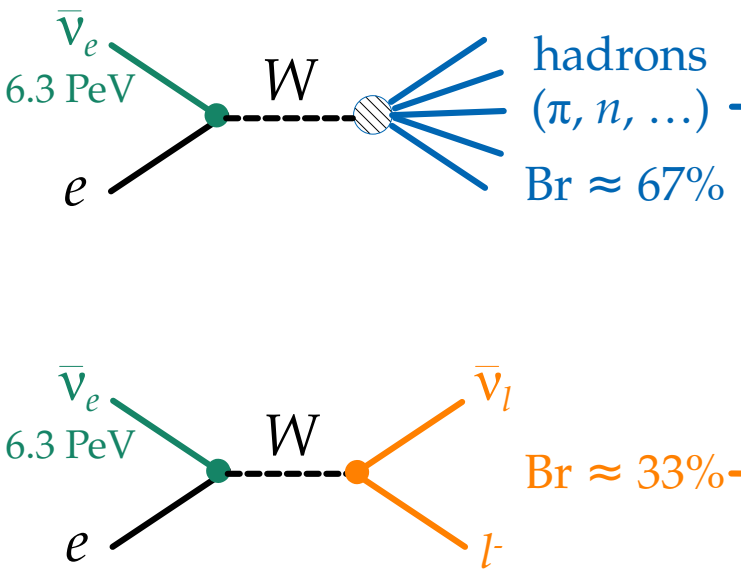

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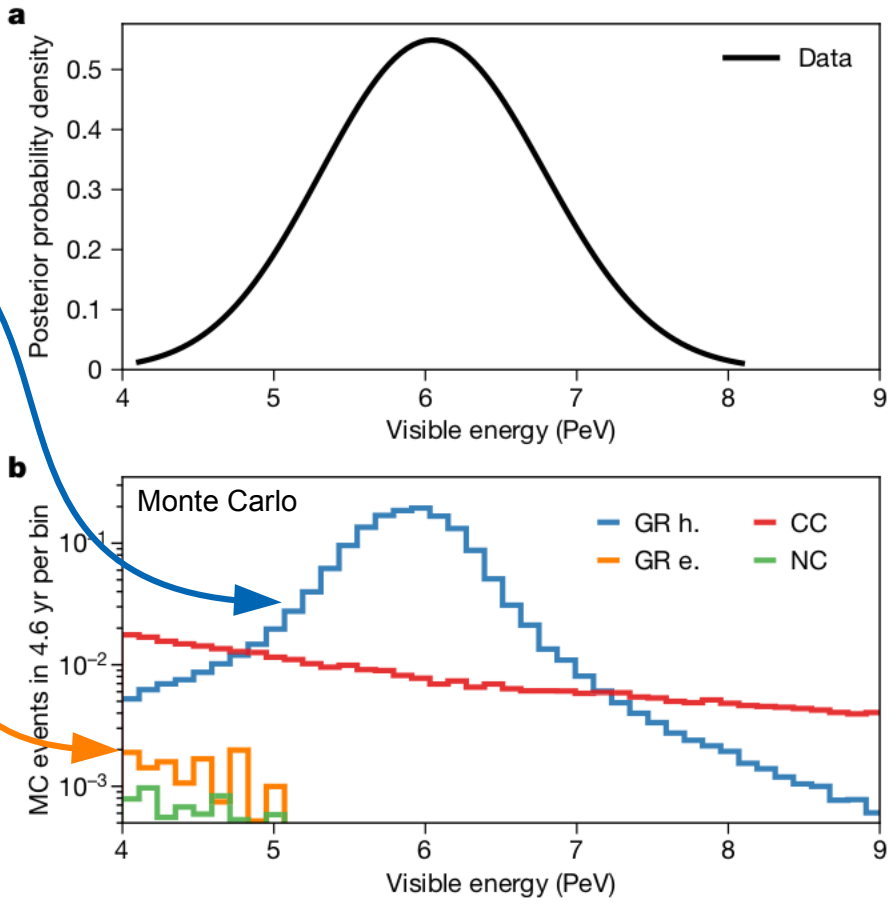
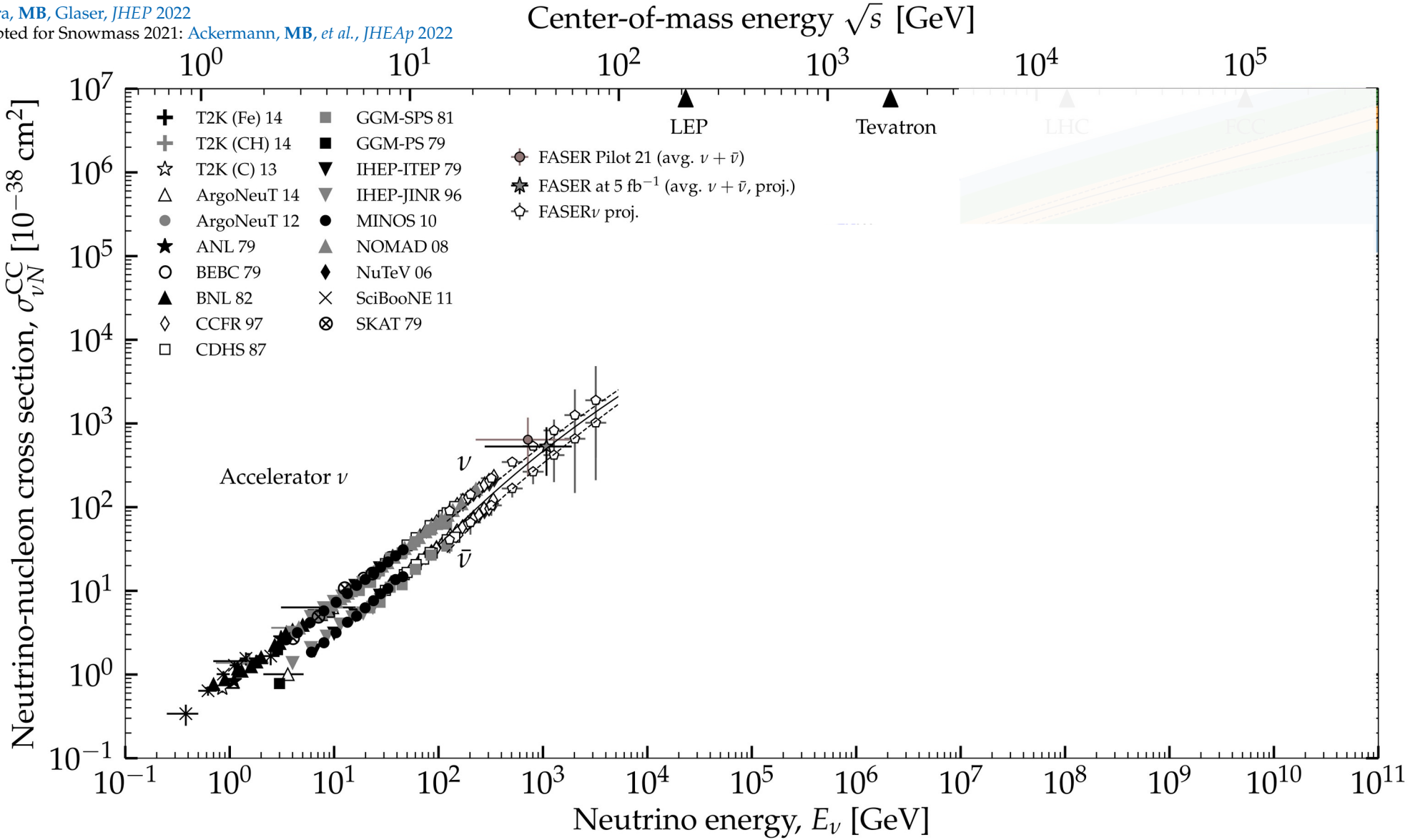


IceCube, *Nature* 2021
Glashow, *PR* 1960

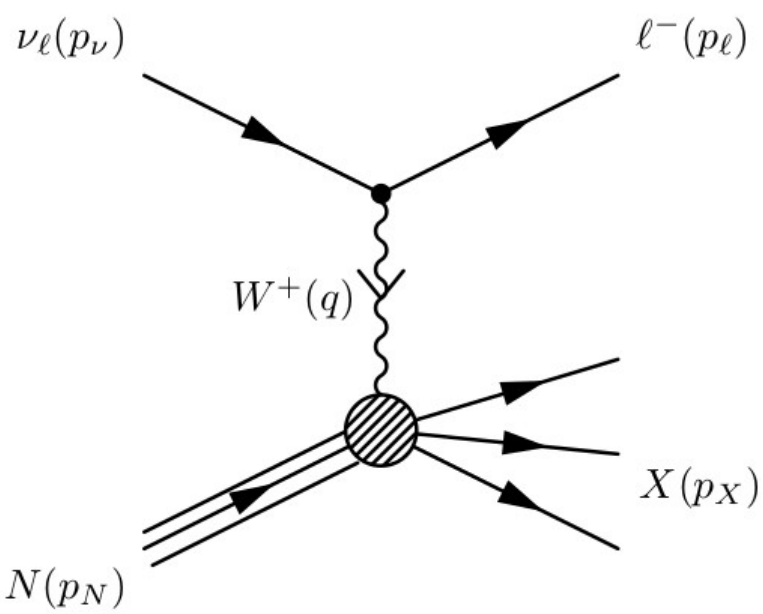
2. Neutrino-matter cross section:
From TeV to PeV

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

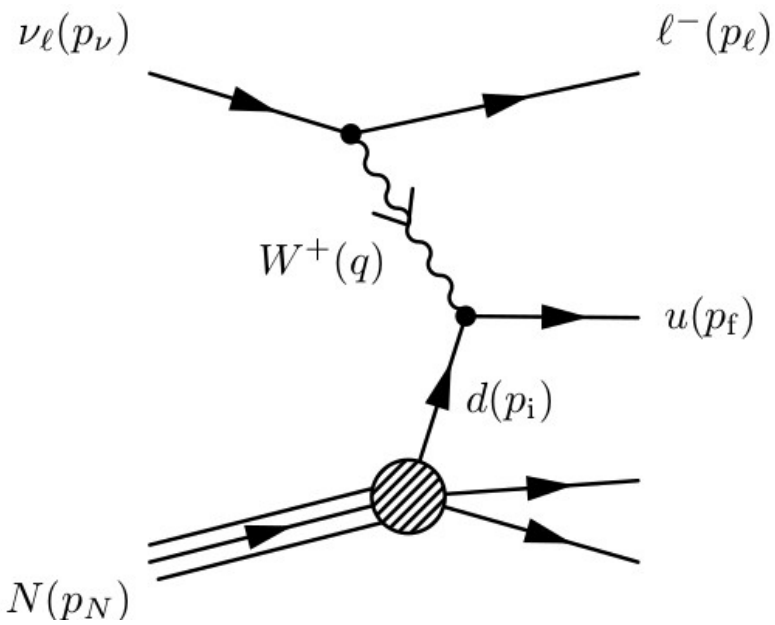


How does DIS probe nucleon structure?

What you see



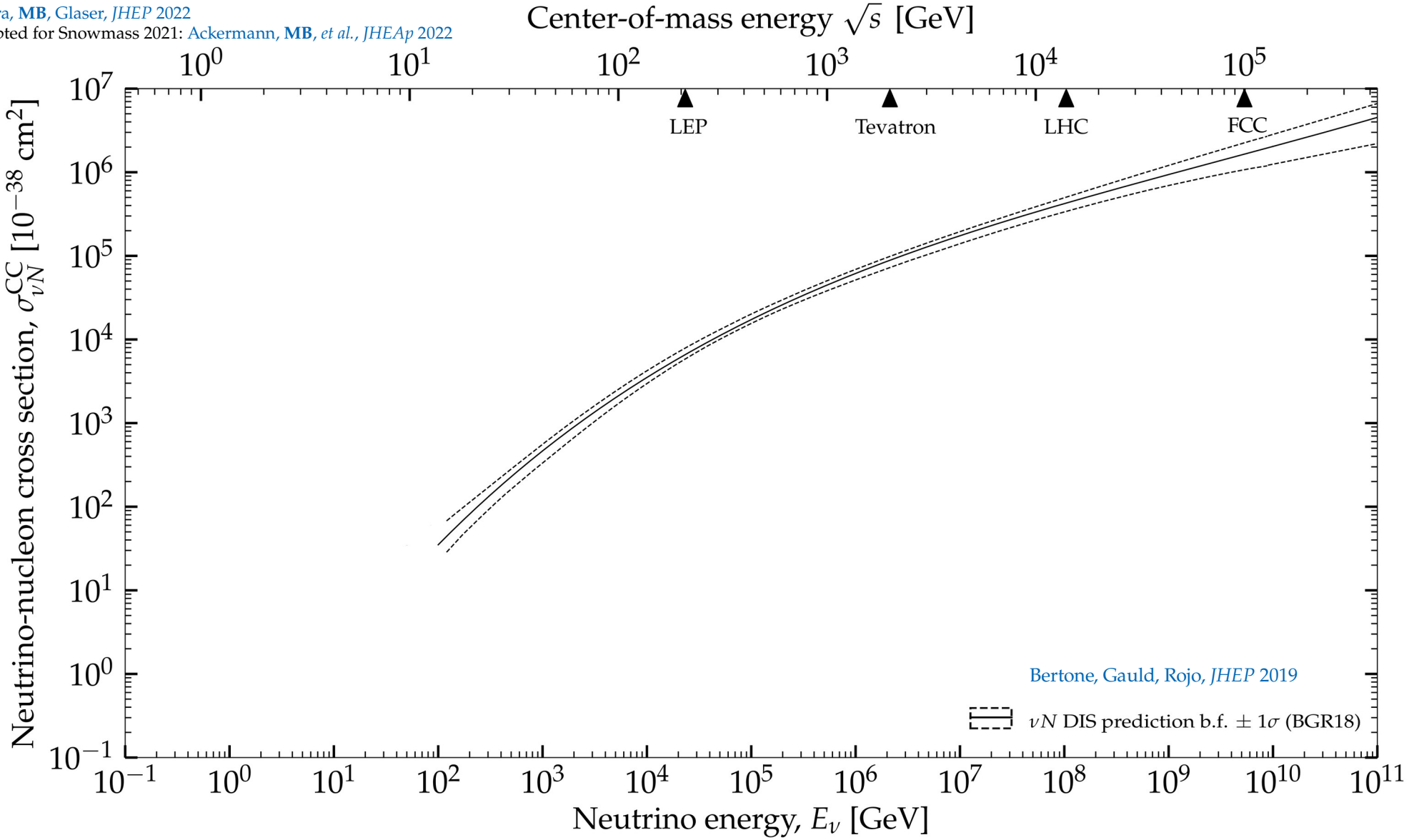
Beneath the hood

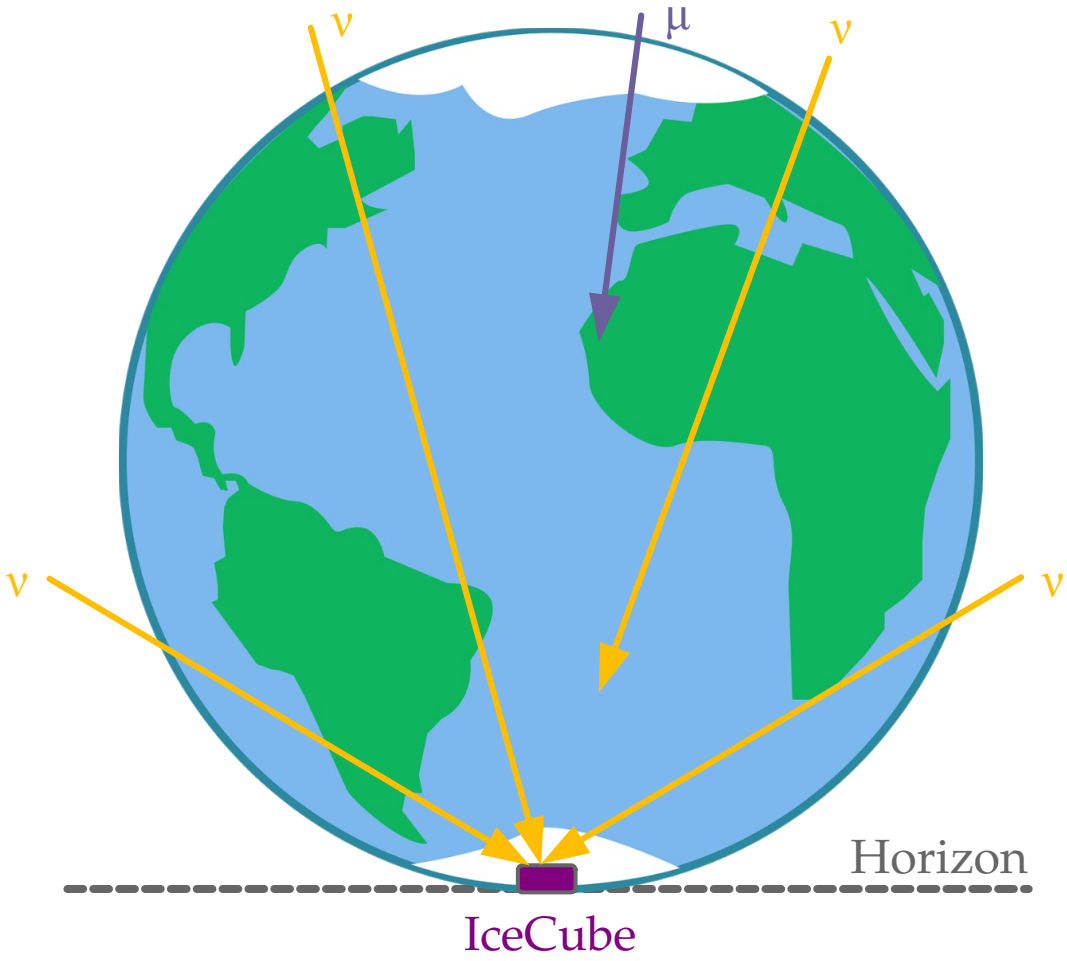


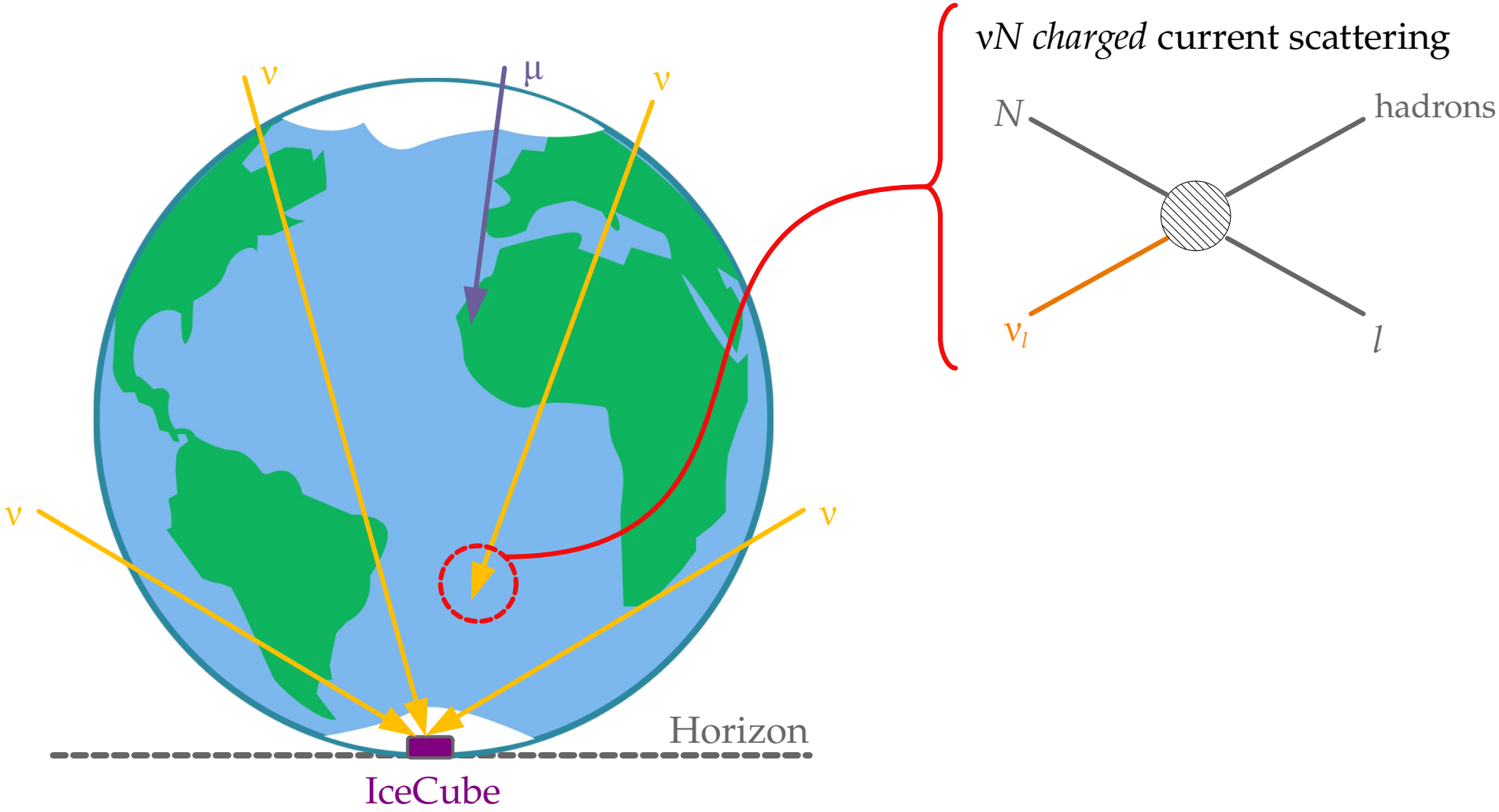
(Plus the equivalent neutral-current process (Z-exchange))

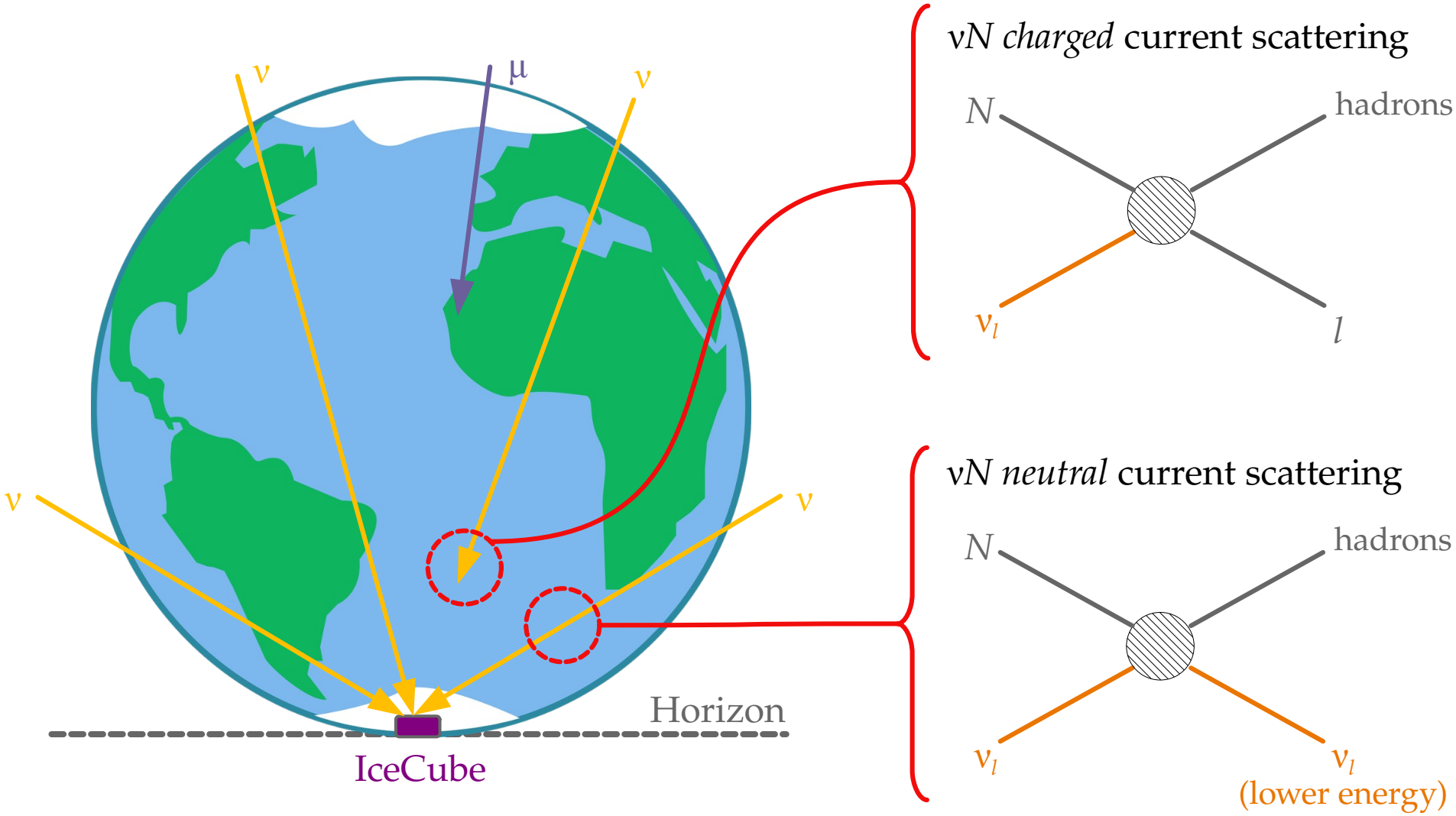
Giunti & Kim, *Fundamentals of Neutrino Physics & Astrophysics*

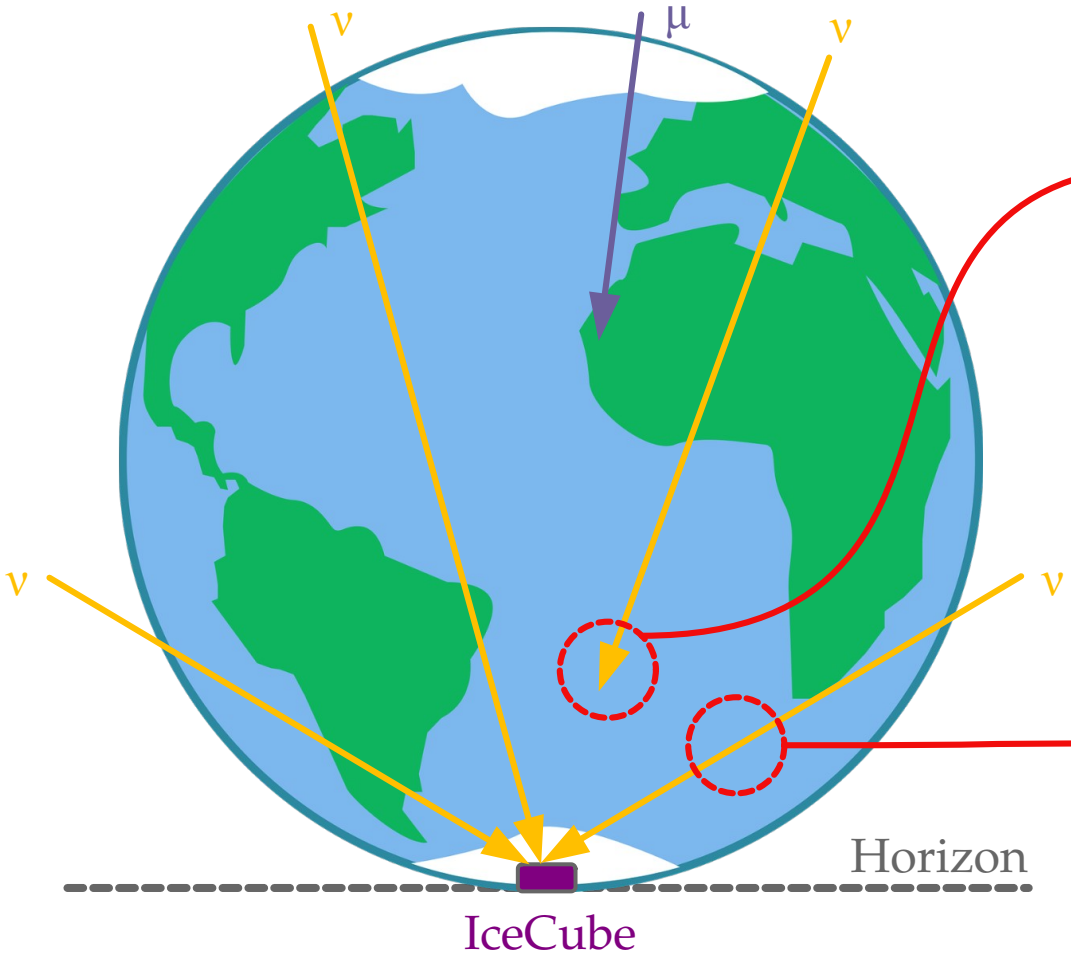
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022

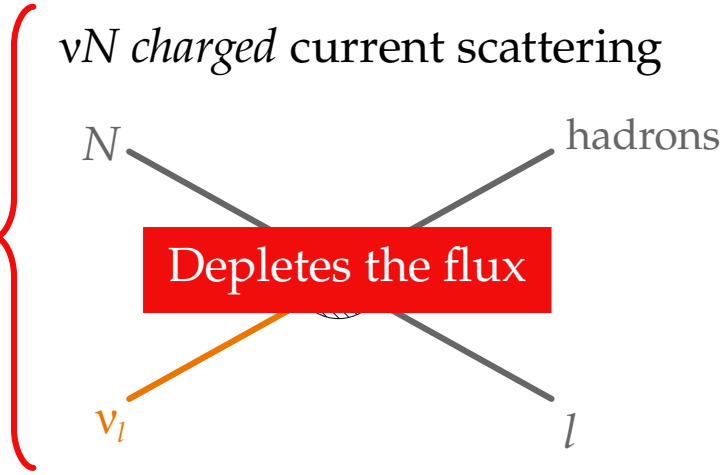


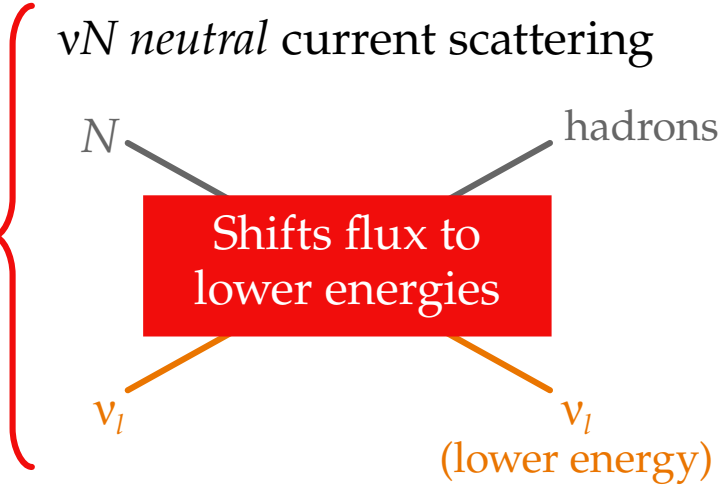

ν
μ
ν
ν
ν
Horizon
IceCube


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


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

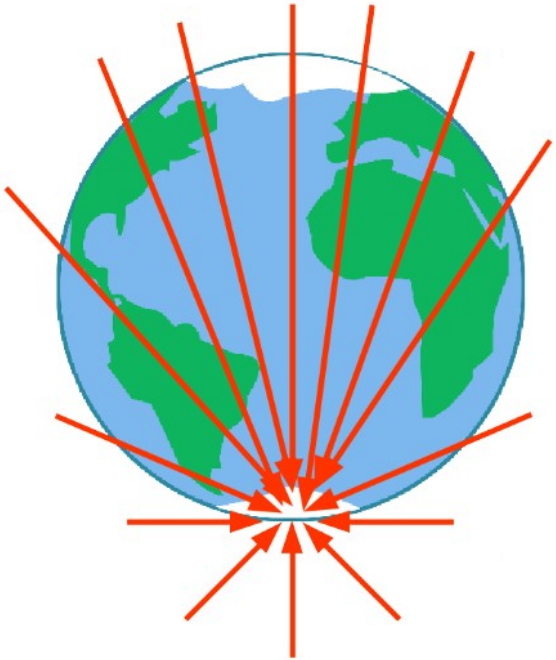

ν
μ
ν
ν
ν
Horizon
IceCube


νN *charged* current scattering
N
hadrons
Depletes the flux
ν_l
l

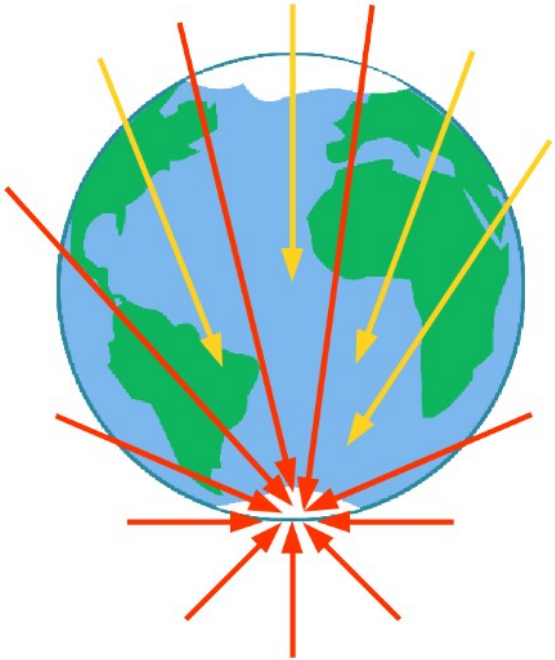

νN *neutral* current scattering
N
hadrons
Shifts flux to lower energies
ν_l
ν_l
(lower energy)

Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent



Above ~ 10 TeV: Earth is opaque



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

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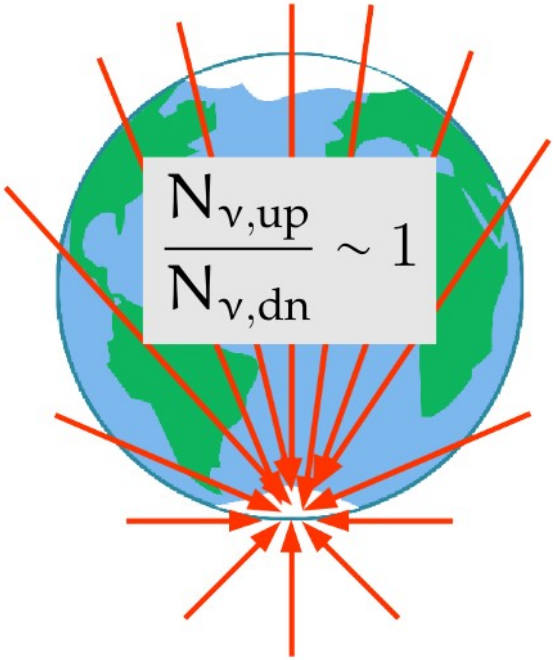

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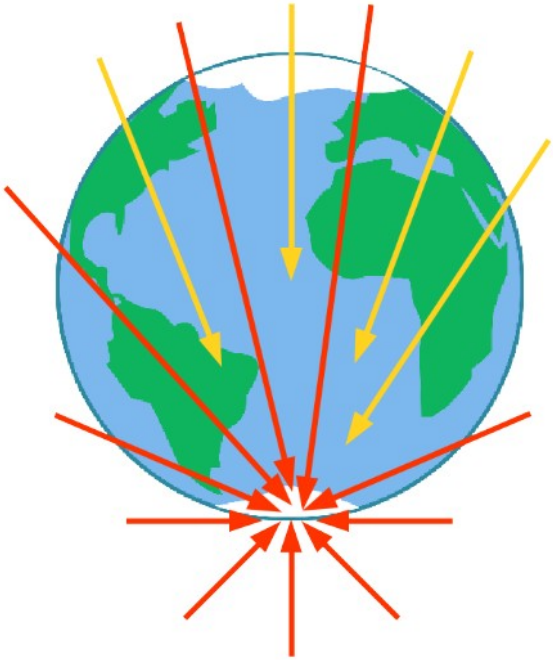

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008; Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

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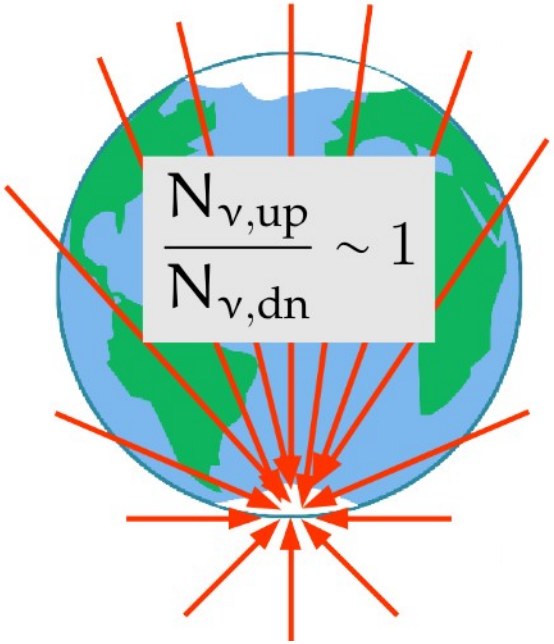
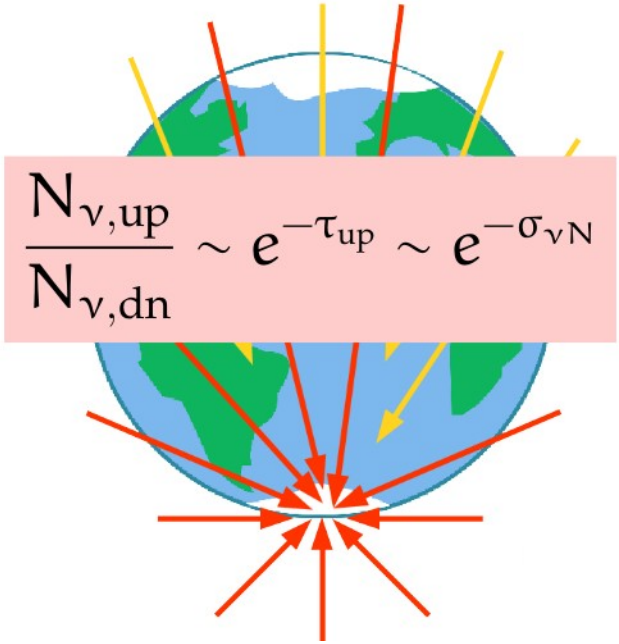
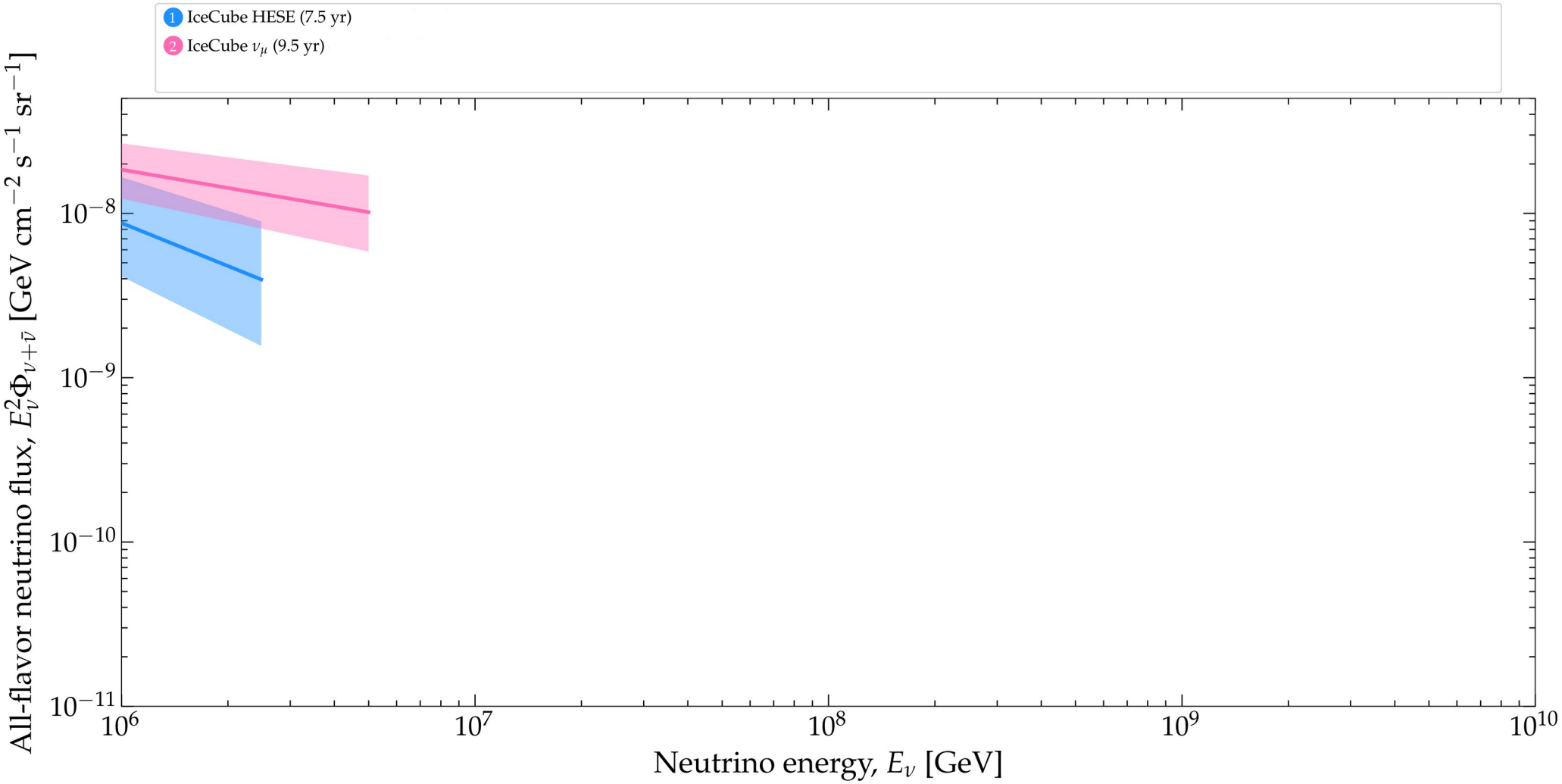


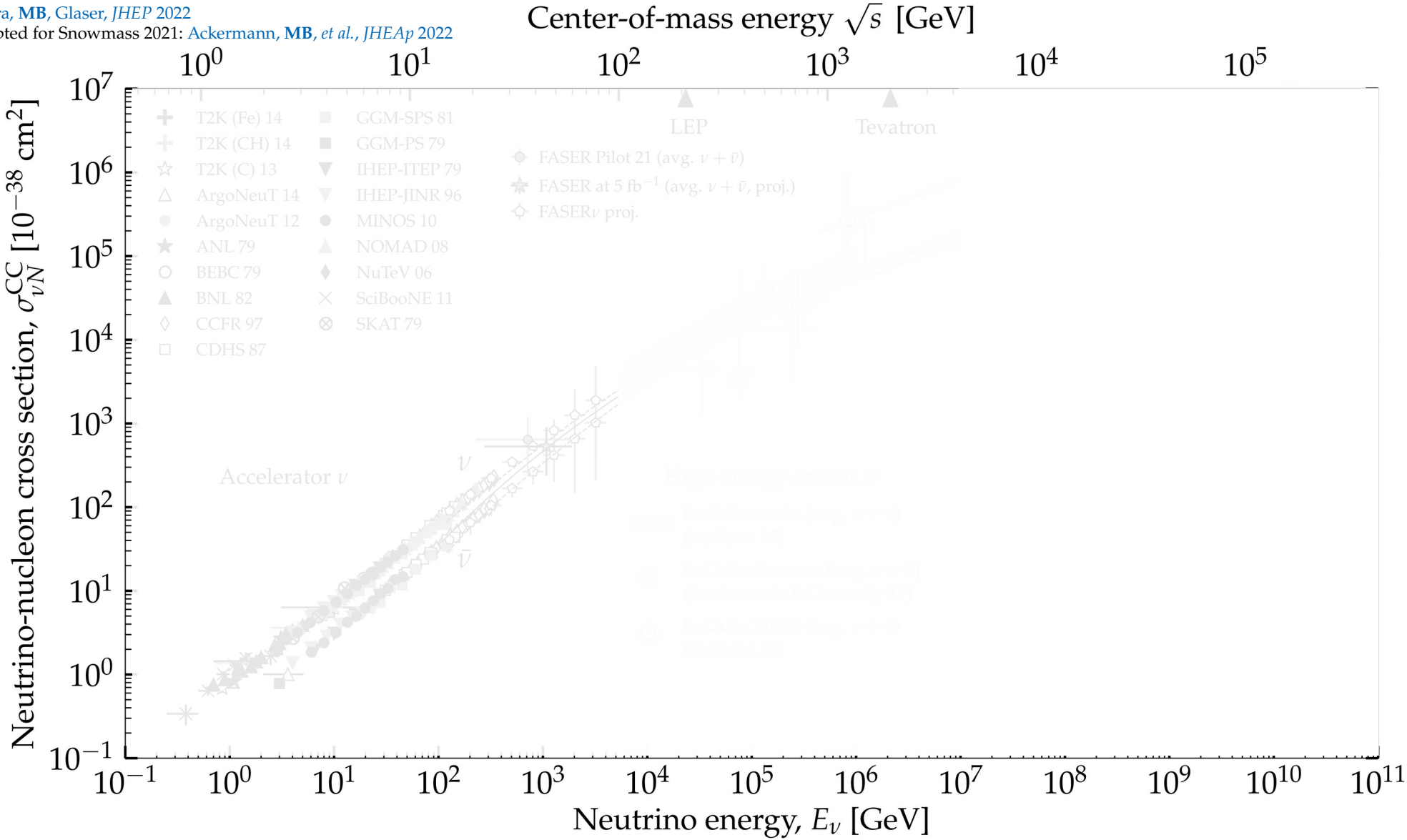
Above ~ 10 TeV: Earth is opaque



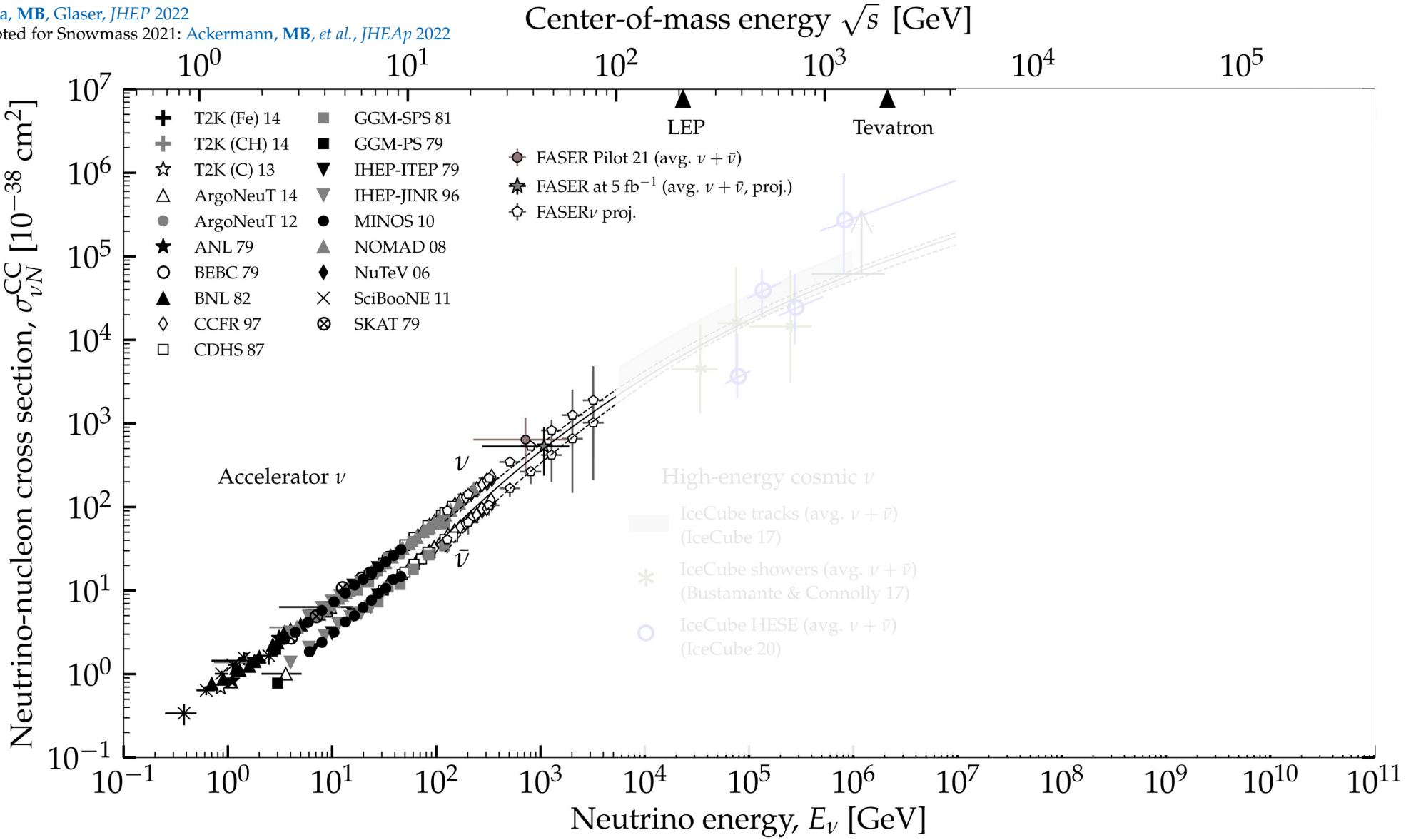
Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008; Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015


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]

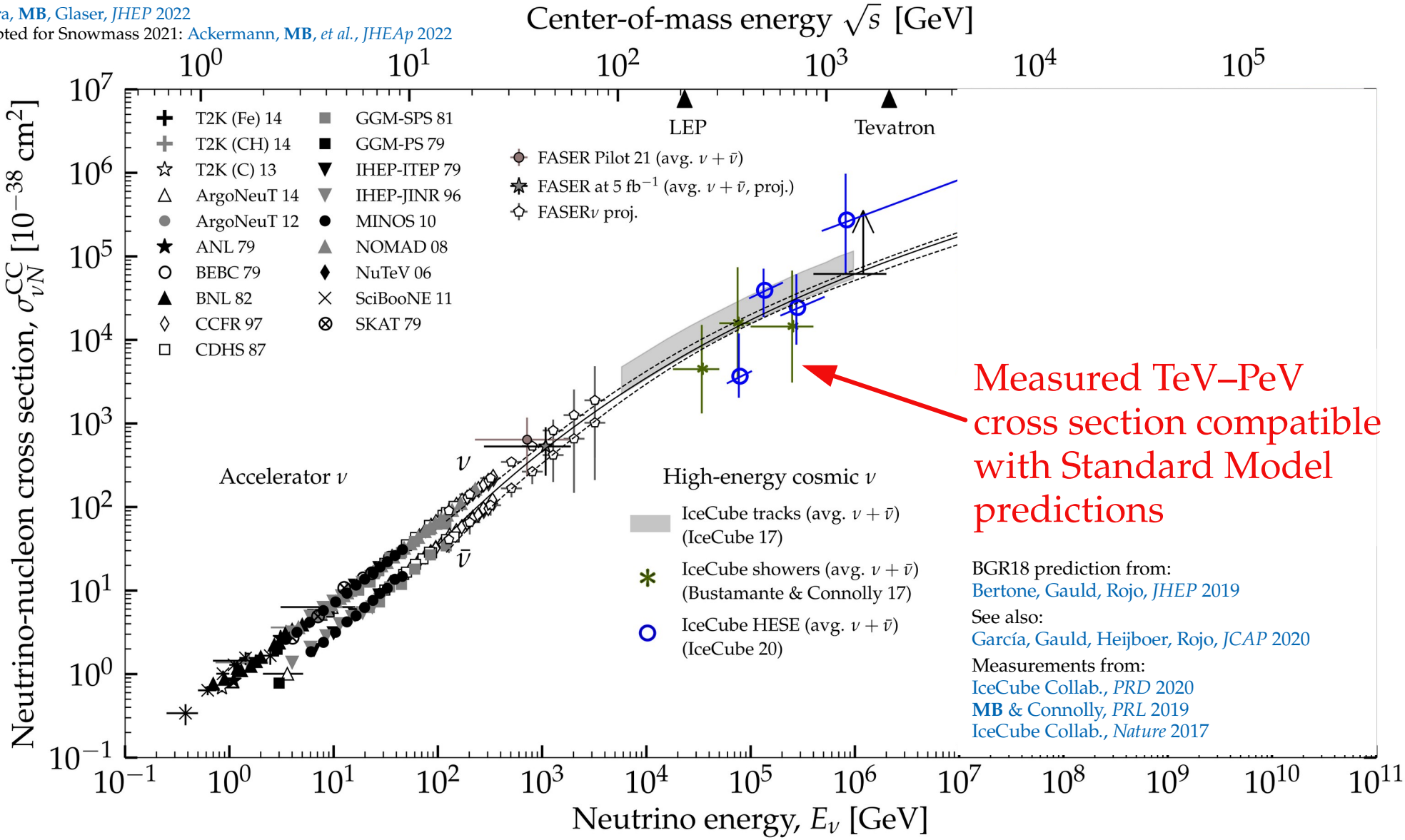
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



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



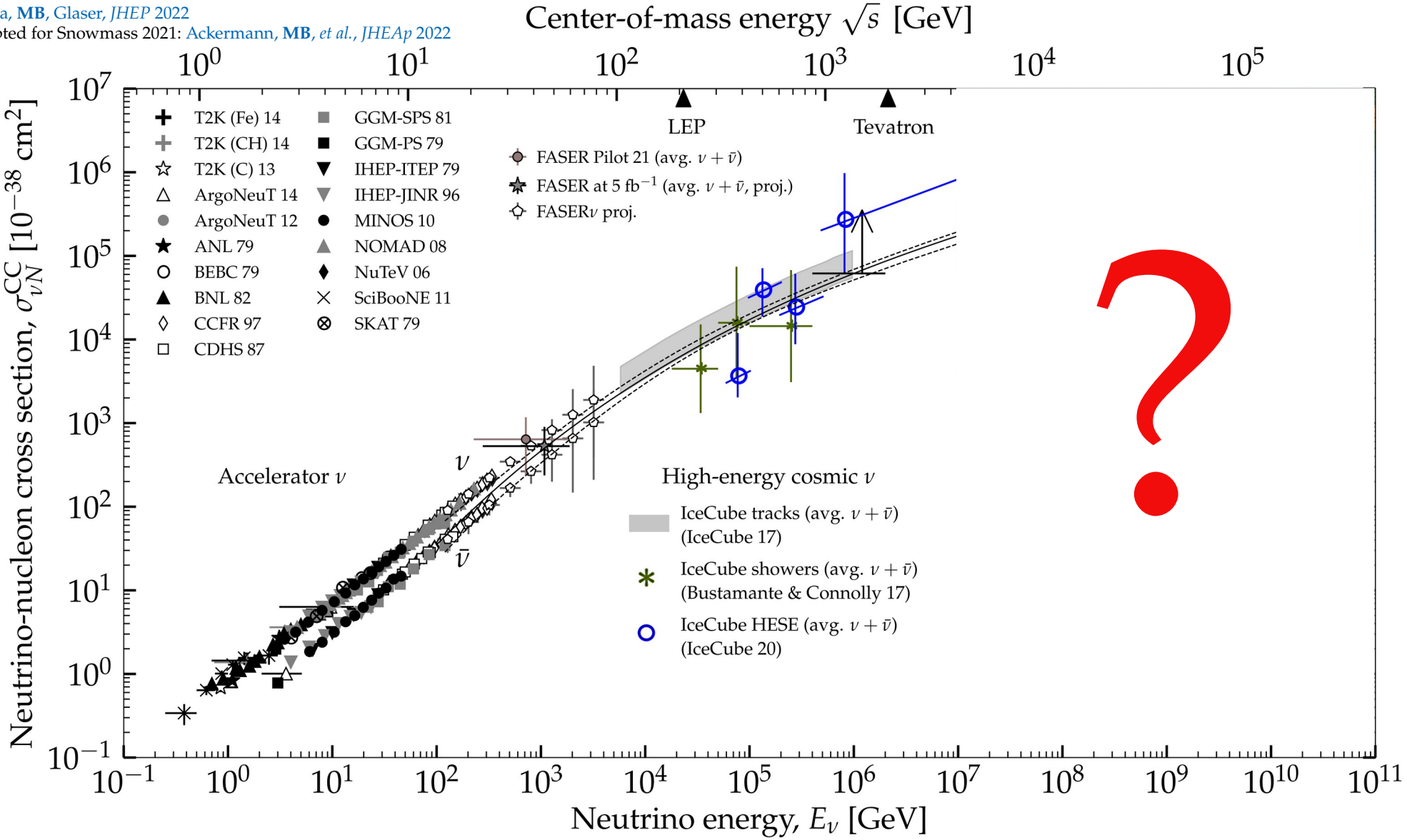
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



Measured TeV–PeV cross section compatible with Standard Model predictions

BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019
See also:
García, Gauld, Heijboer, Rojo, *JCAP* 2020
Measurements from:
IceCube Collab., *PRD* 2020
MB & Connolly, *PRL* 2019
IceCube Collab., *Nature* 2017

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



3. Dark matter:

Annihilation and decay into ν

High-energy neutrinos from dark matter

Dark matter co-annihilation:

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

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

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

Dark matter decay:

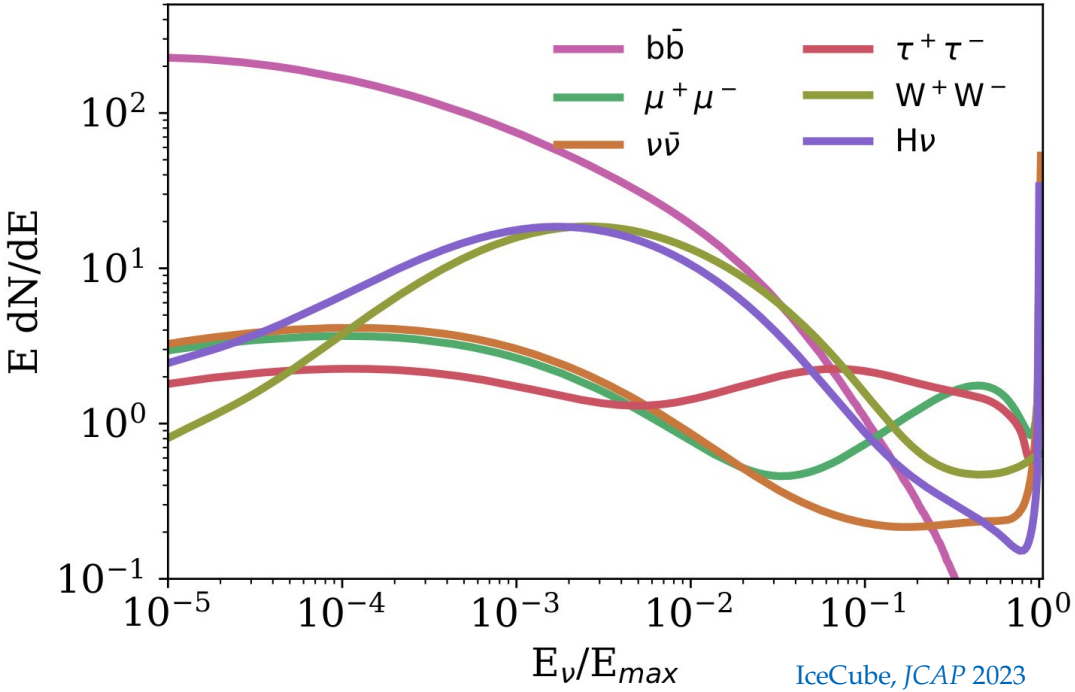
$$\chi \to \nu + \bar{\nu}$$

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

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

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

ν + ν̄ yield from DM (at source)

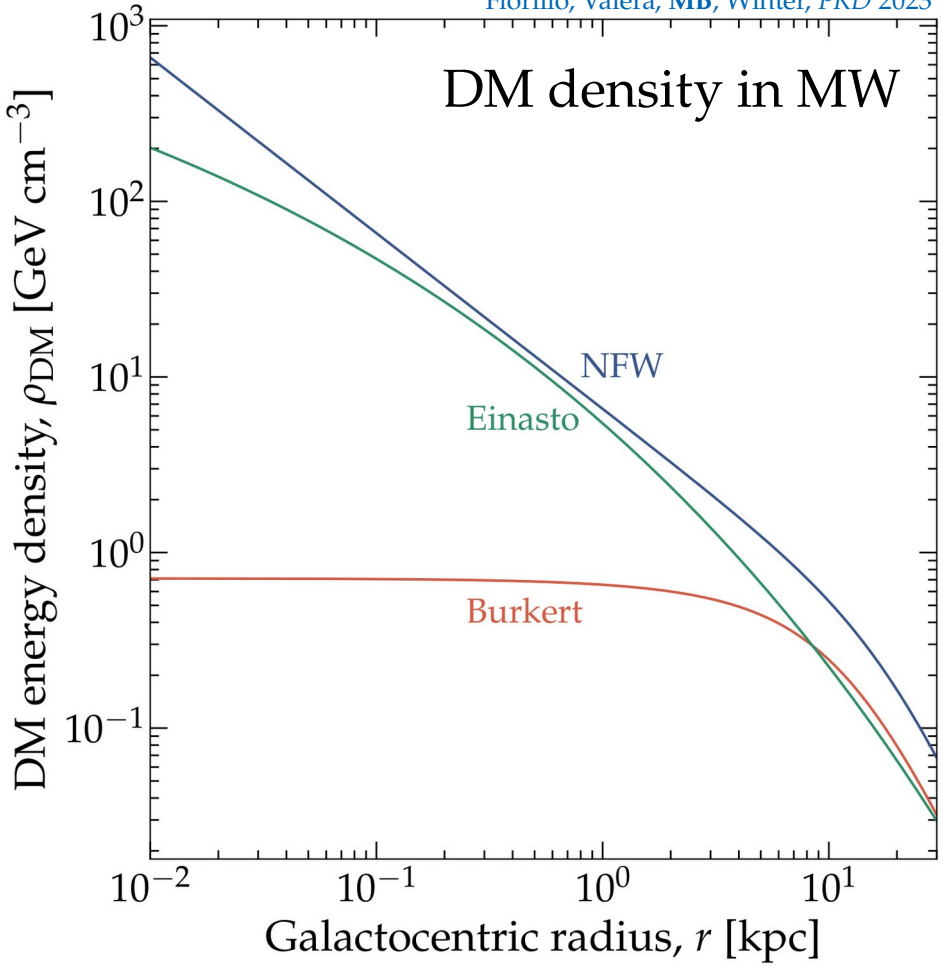


IceCube, *JCAP* 2023

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

Dark matter in the Milky Way

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



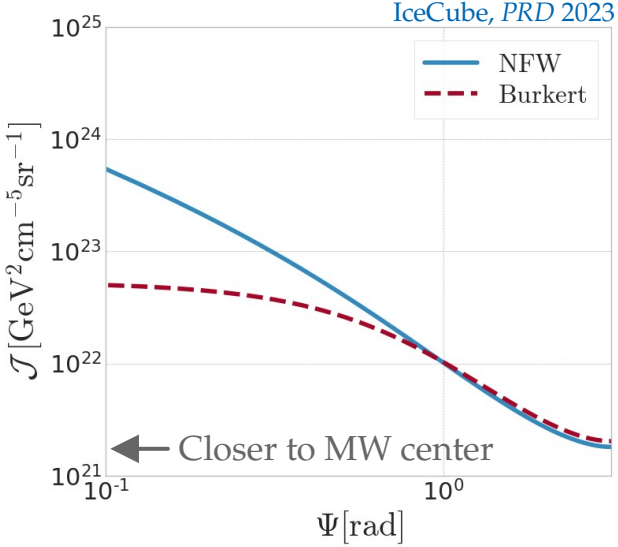
DM annihilation

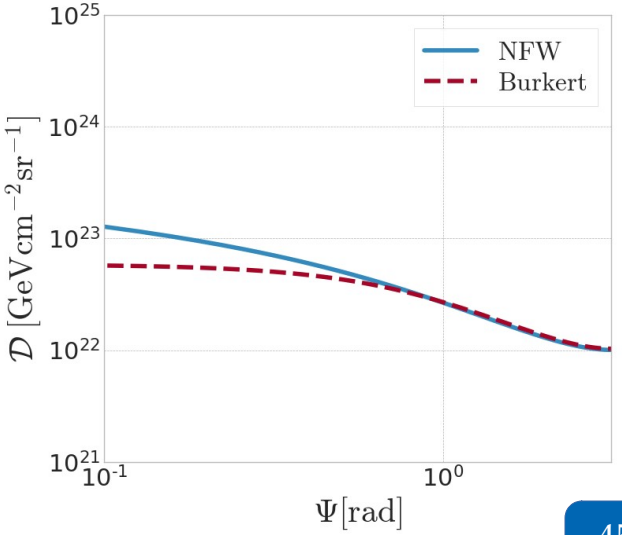
$\Phi_\nu \propto \mathcal{I} \propto \rho_{DM}^2$

DM decay

$\Phi_\nu \propto \mathcal{D} \propto \rho_{DM}$

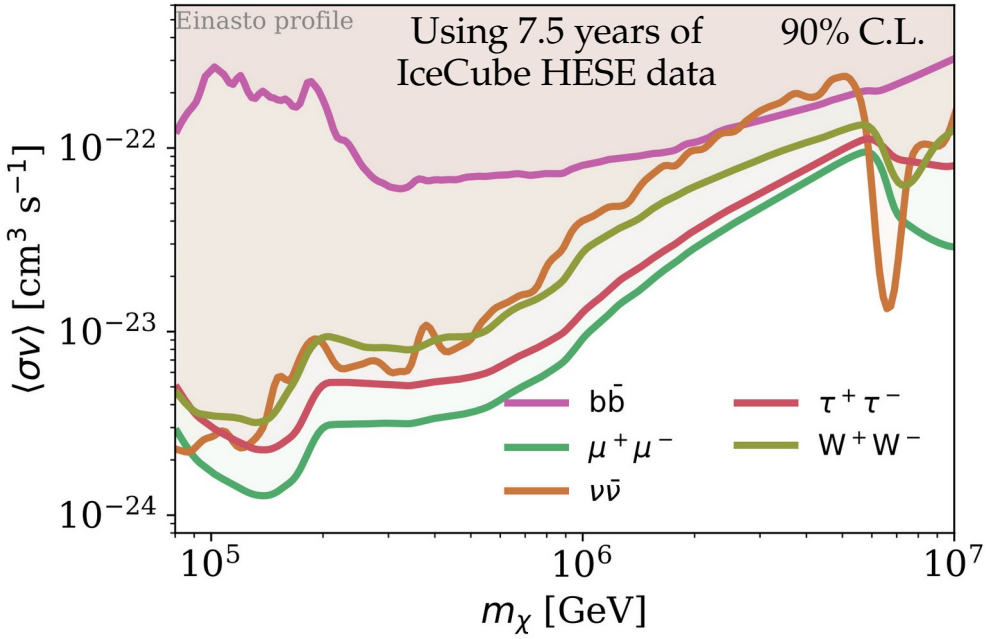
IceCube, *PRD* 2023





Limits on dark matter annihilation

Per annihilation channel
(assuming 100% branching ratio)



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

Plus background of atmospheric neutrinos (anisotropic, but different)

Limits on dark matter annihilation

Per annihilation channel
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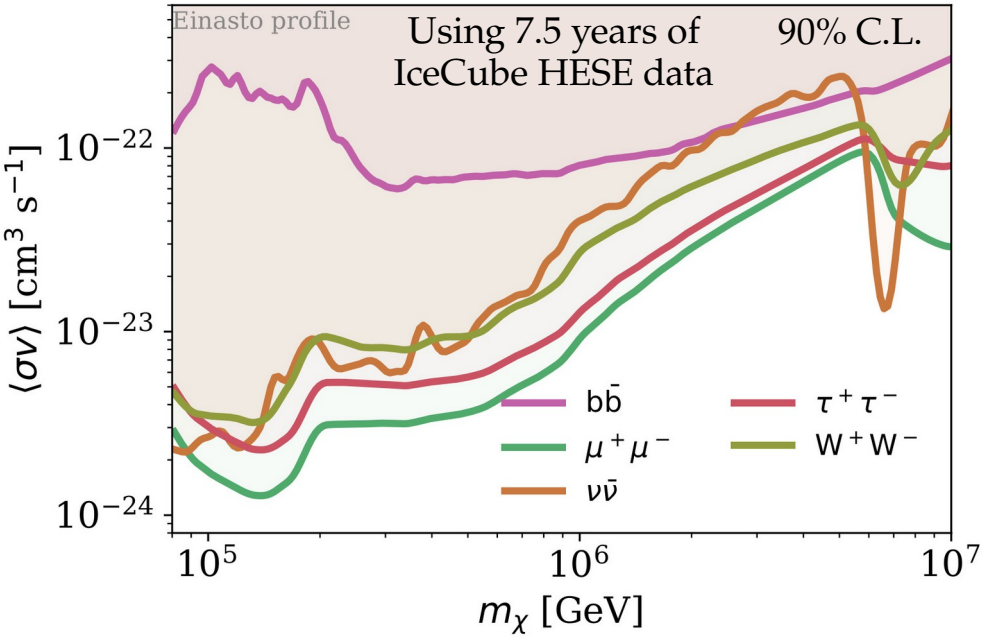
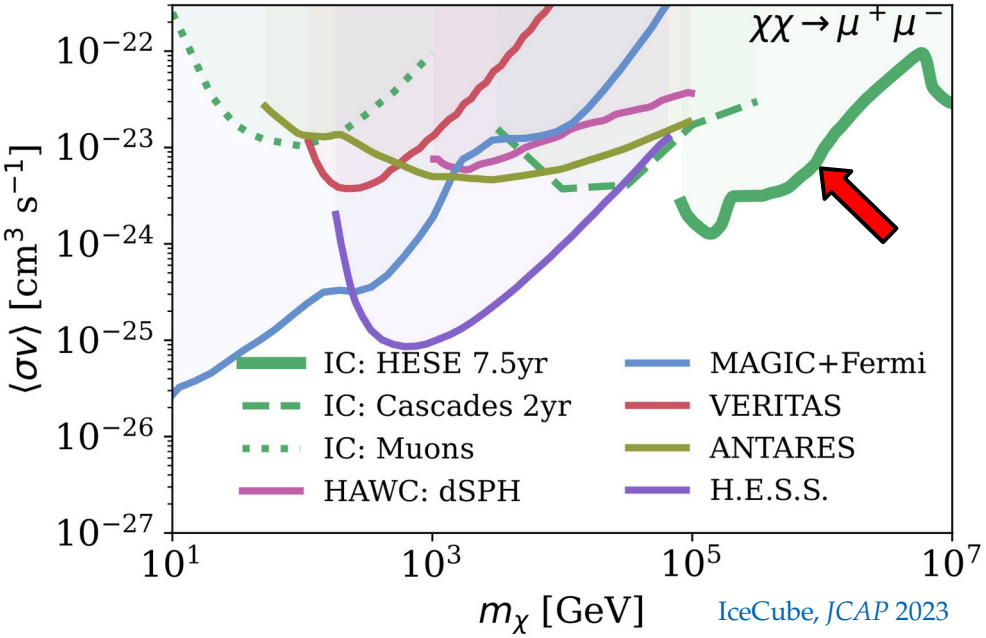


Compared to other limits
(assuming annihilation to muons)



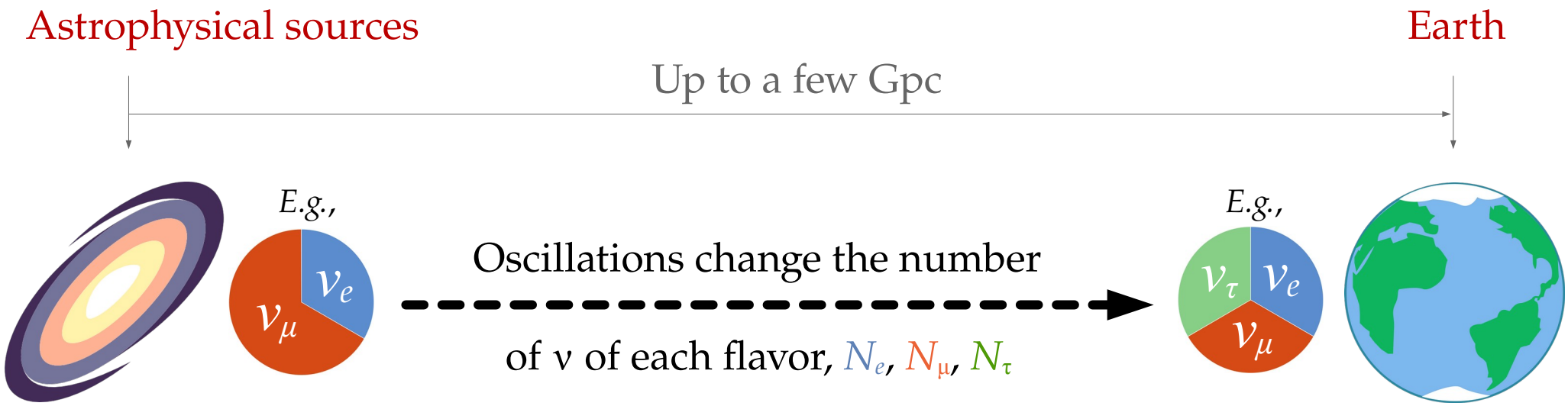
IceCube, *JCAP* 2023

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

Plus background of atmospheric neutrinos (anisotropic, but different)

4. New physics via flavor

Hard to do, but worth it



Different production mechanisms yield different flavor ratios:

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

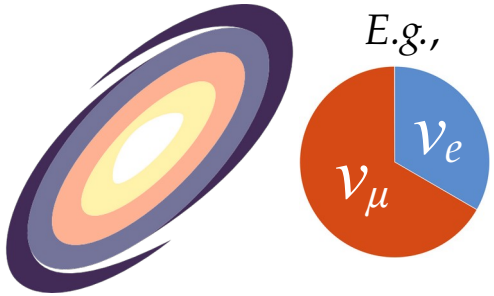
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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

Astrophysical sources

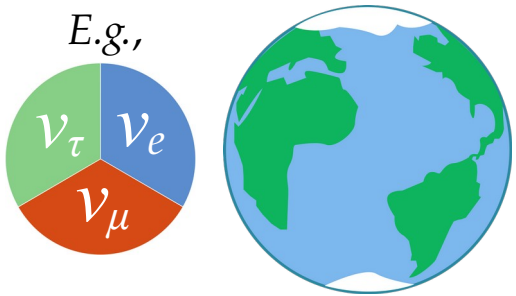
Earth

Up to a few Gpc



Oscillations change the number

of ν of each flavor, N_e, N_μ, N_τ



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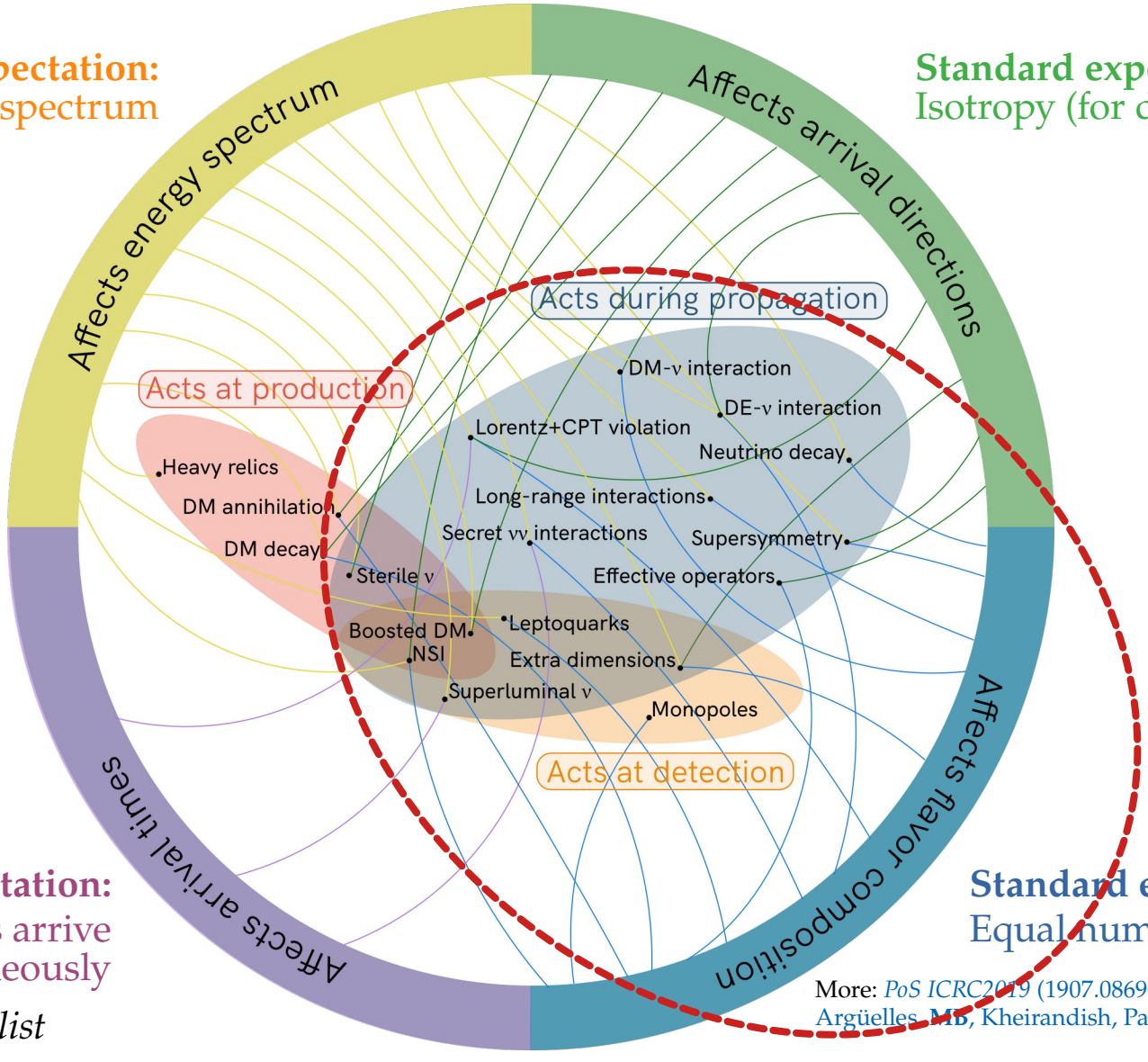
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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

Standard oscillations
or
new physics

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

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

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

New physics in flavor composition

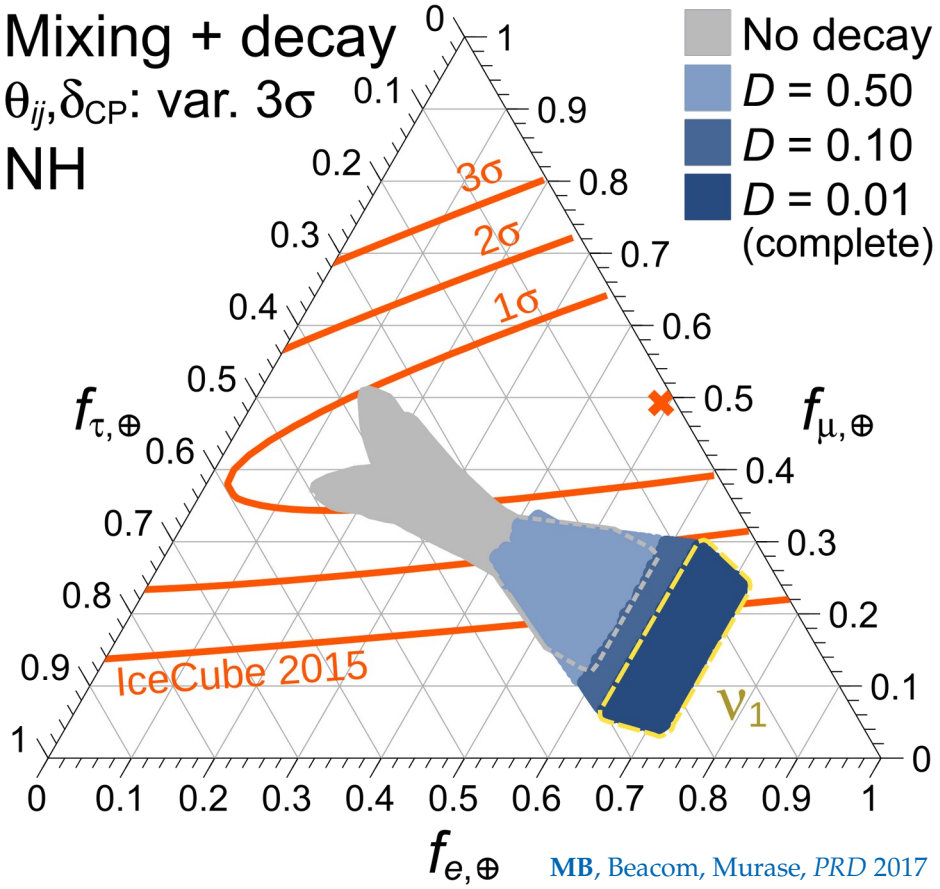
Repurpose the flavor sensitivity to test new physics:

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

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

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



MB, Beacom, Murase, *PRD* 2017

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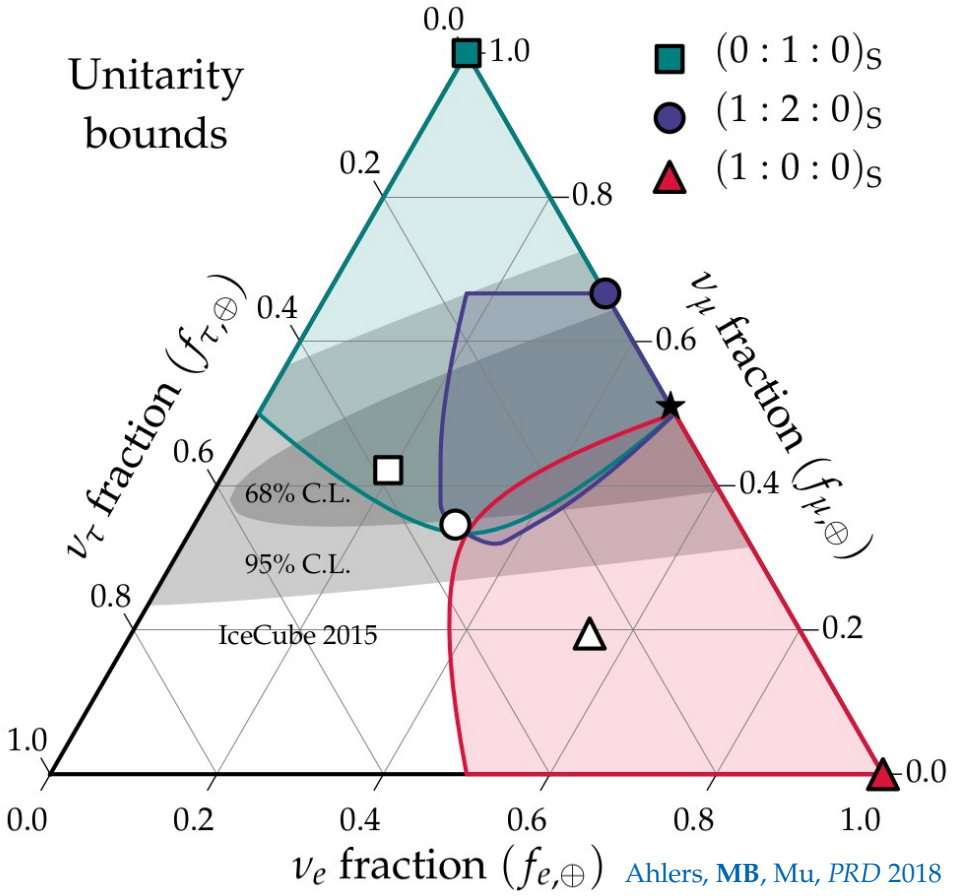
  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018; Ahlers, **MB**, Nortvig, *JCAP* 2021]



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

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

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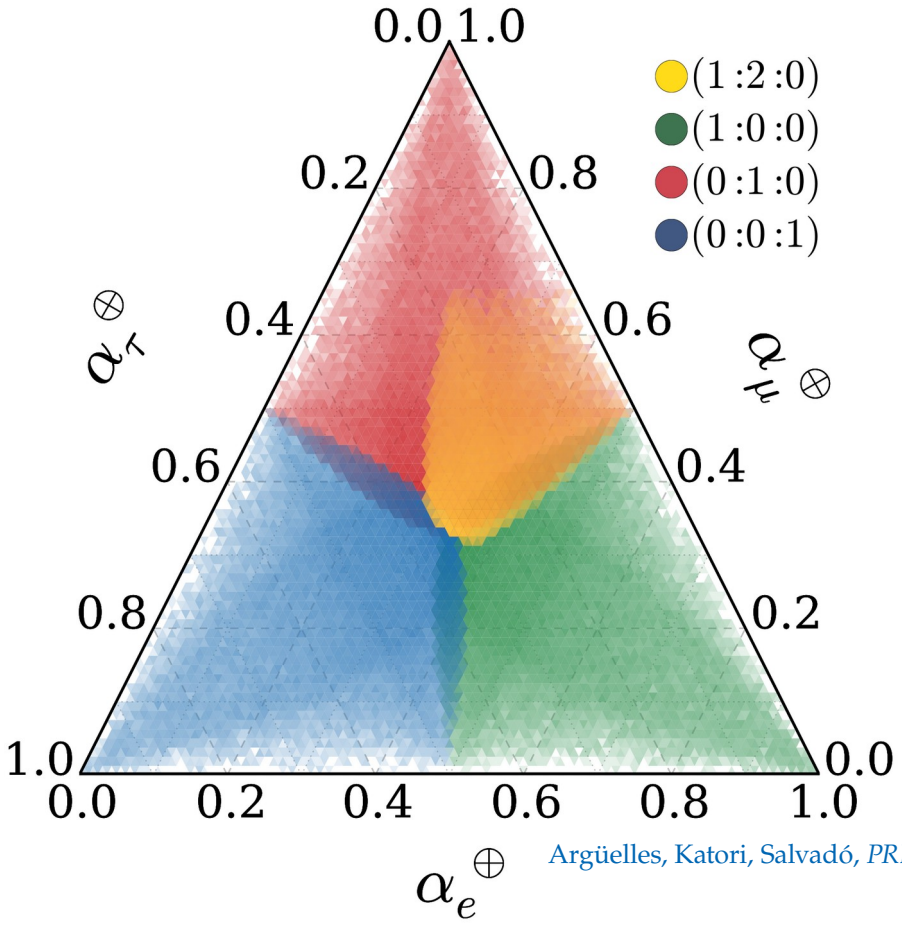
  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018; Ahlers, **MB**, Nortvig, *JCAP* 2021]
- Lorentz- and CPT-invariance violation
  [Barenboim & Quigg, *PRD* 2003; **MB**, Gago, Peña-Garay, *JHEP* 2010; Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]



Argüelles, Katori, Salvadó, *PRL* 2015

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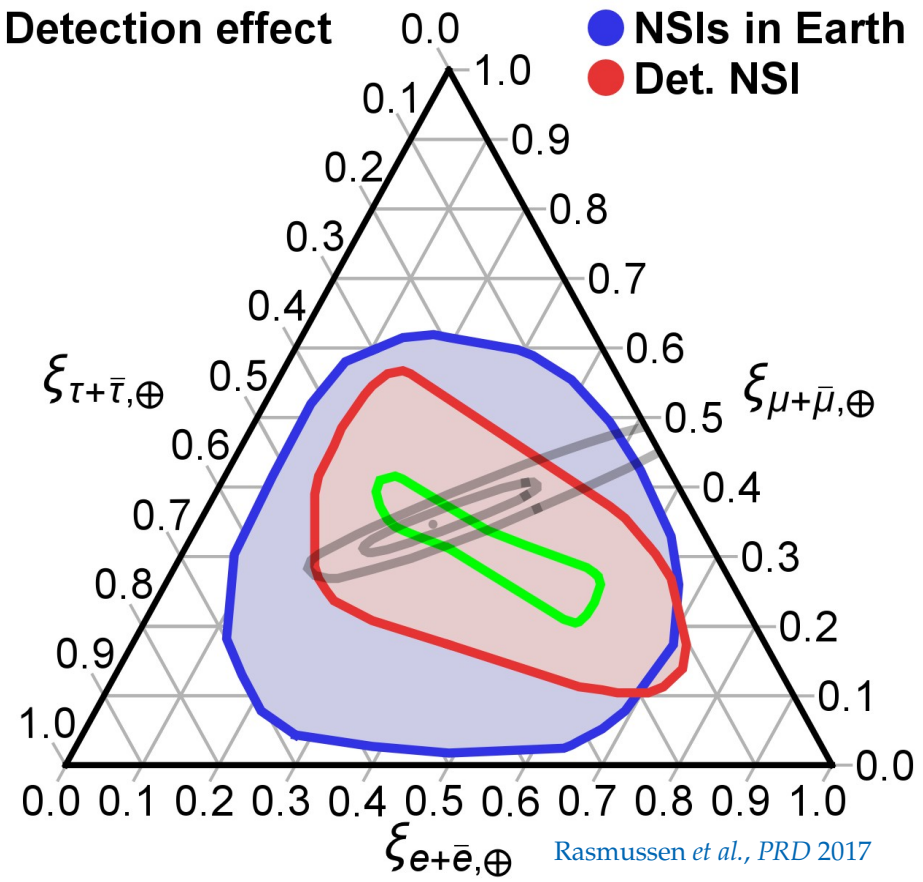

Rasmussen *et al.*, *PRD* 2017

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

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

- Neutrino decay
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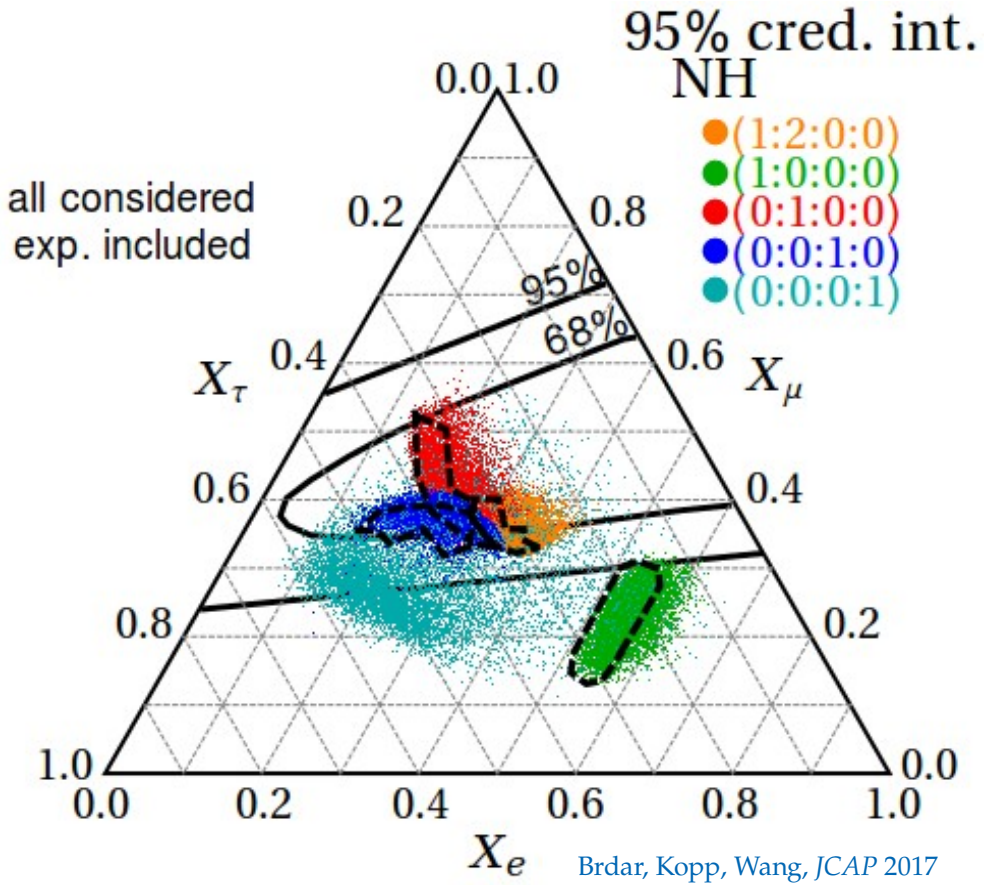

Brdar, Kopp, Wang, *JCAP* 2017

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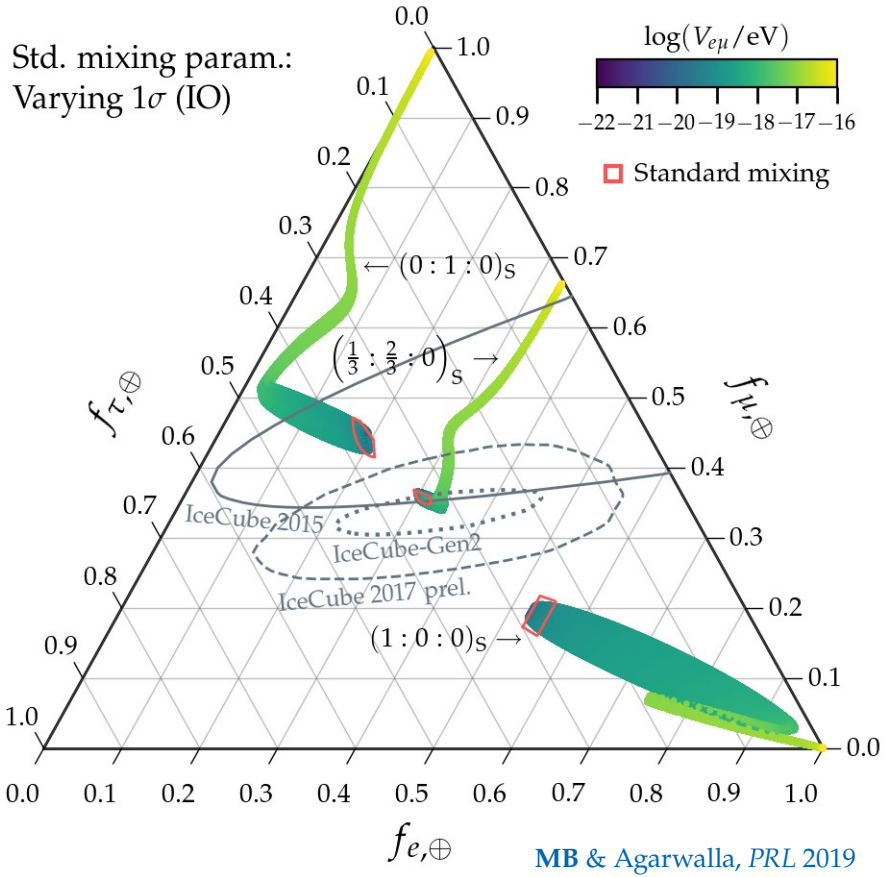
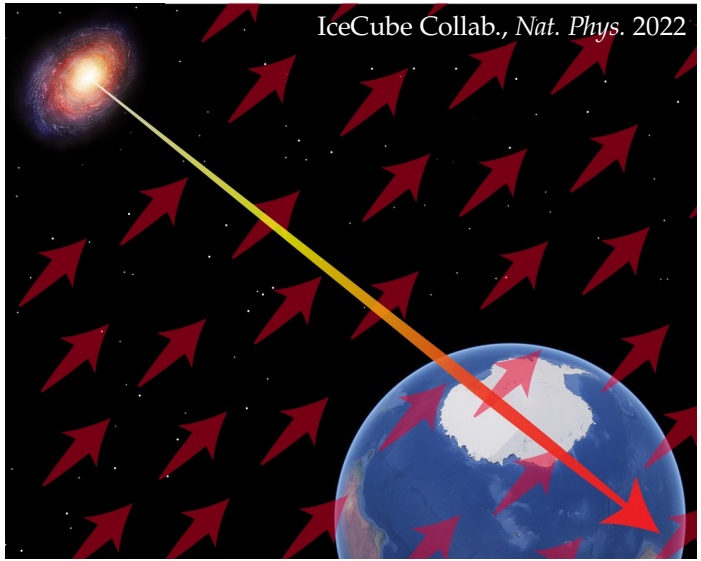
- Long-range *e*ν interactions
  [**MB** & Agarwalla, *PRL* 2019]

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



MB & Agarwalla, *PRL* 2019

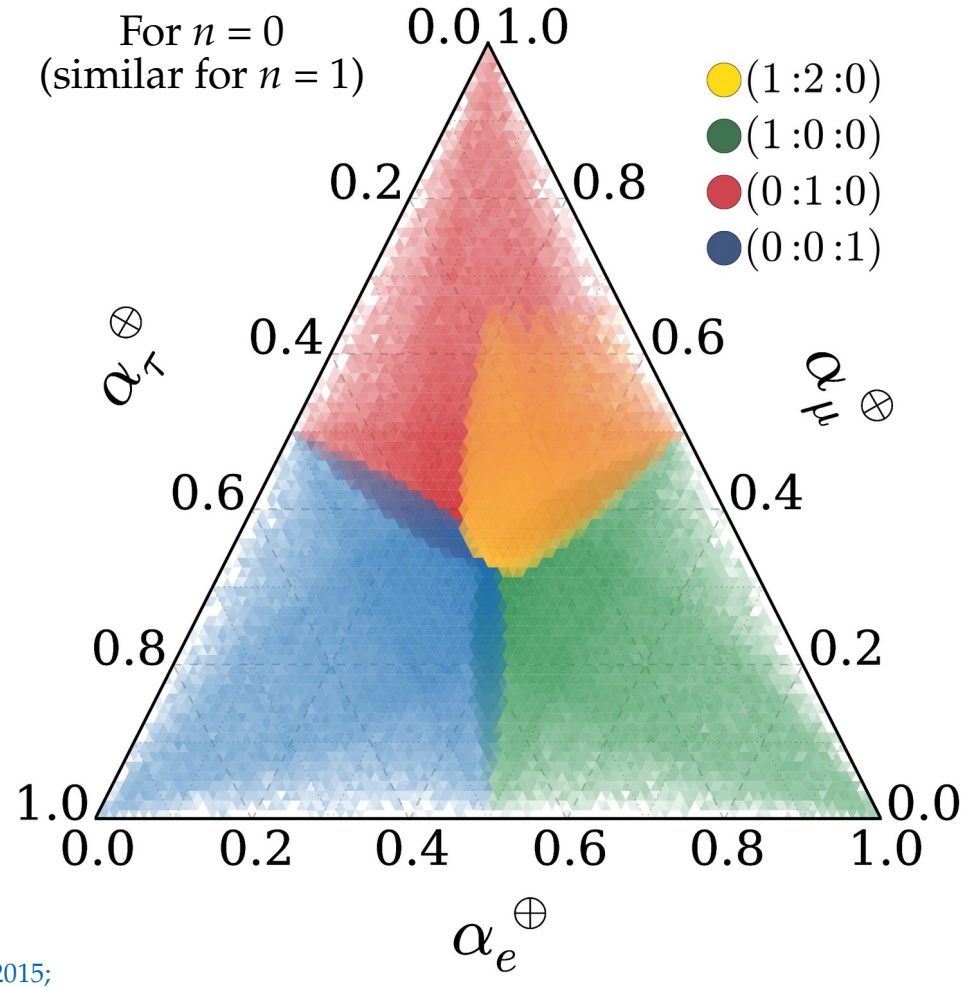
Lorentz-invariance violation can fill up the flavor triangle



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

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

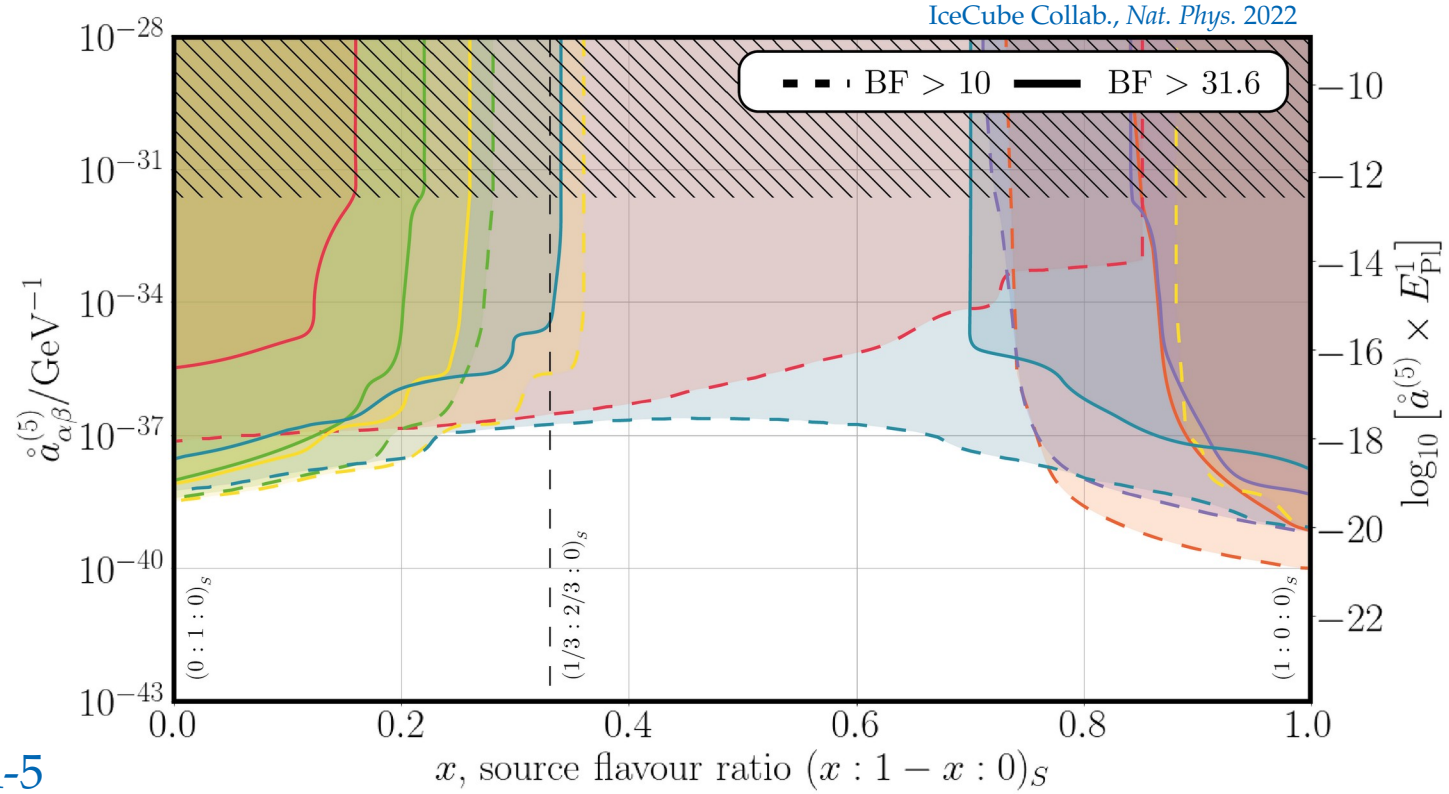
$$H_{\text{NP}} = \sum_n \left(\frac{E}{\Lambda_n}\right)^n U_n^{\dagger} \, \text{diag}\left(O_{n,1}, O_{n,2}, O_{n,3}\right) U_n$$



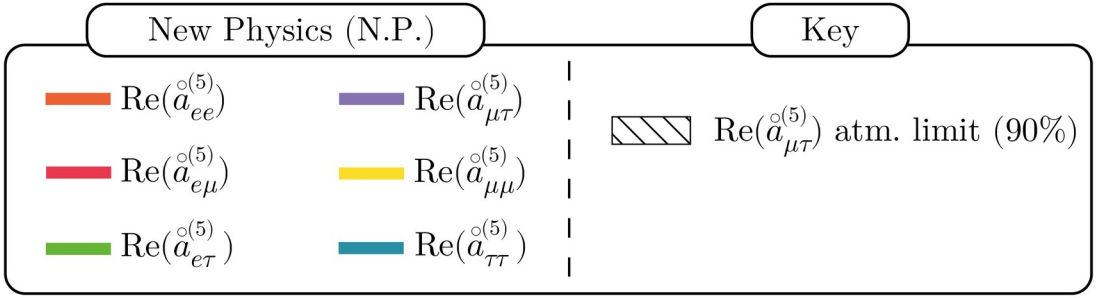
See also: Ahlers, **MB**, Mu, *PRD* 2018; Rasmusen *et al.*, *PRD* 2017; **MB**, Beacom, Winter *PRL* 2015; **MB**, Gago, Peña-Garay *JCAP* 2010; Bazo, **MB**, Gago, Miranda *IJMPA* 2009; + many others

Argüelles, Katori, Salvadó, *PRL* 2015

IceCube Collab., *Nat. Phys.* 2022

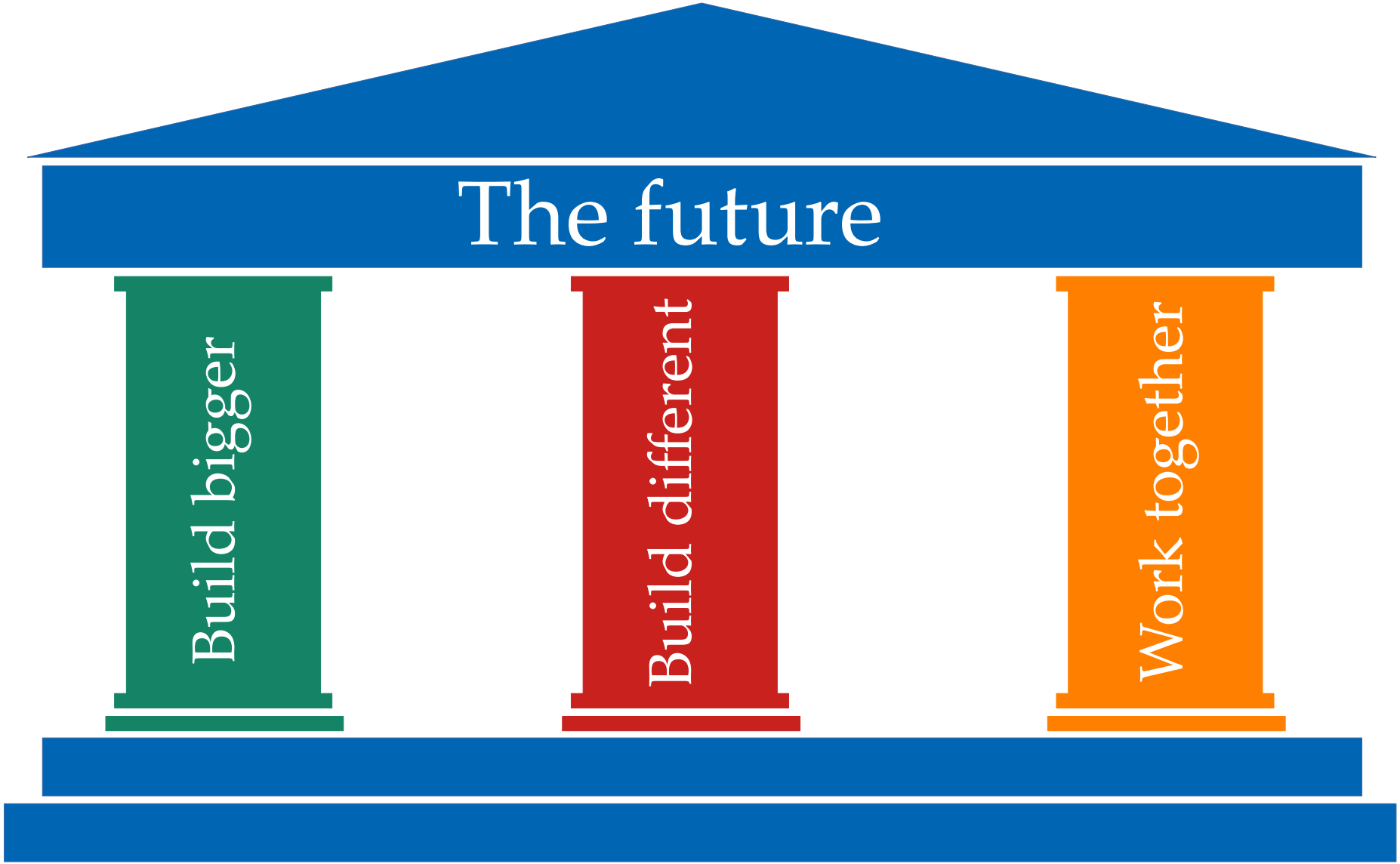


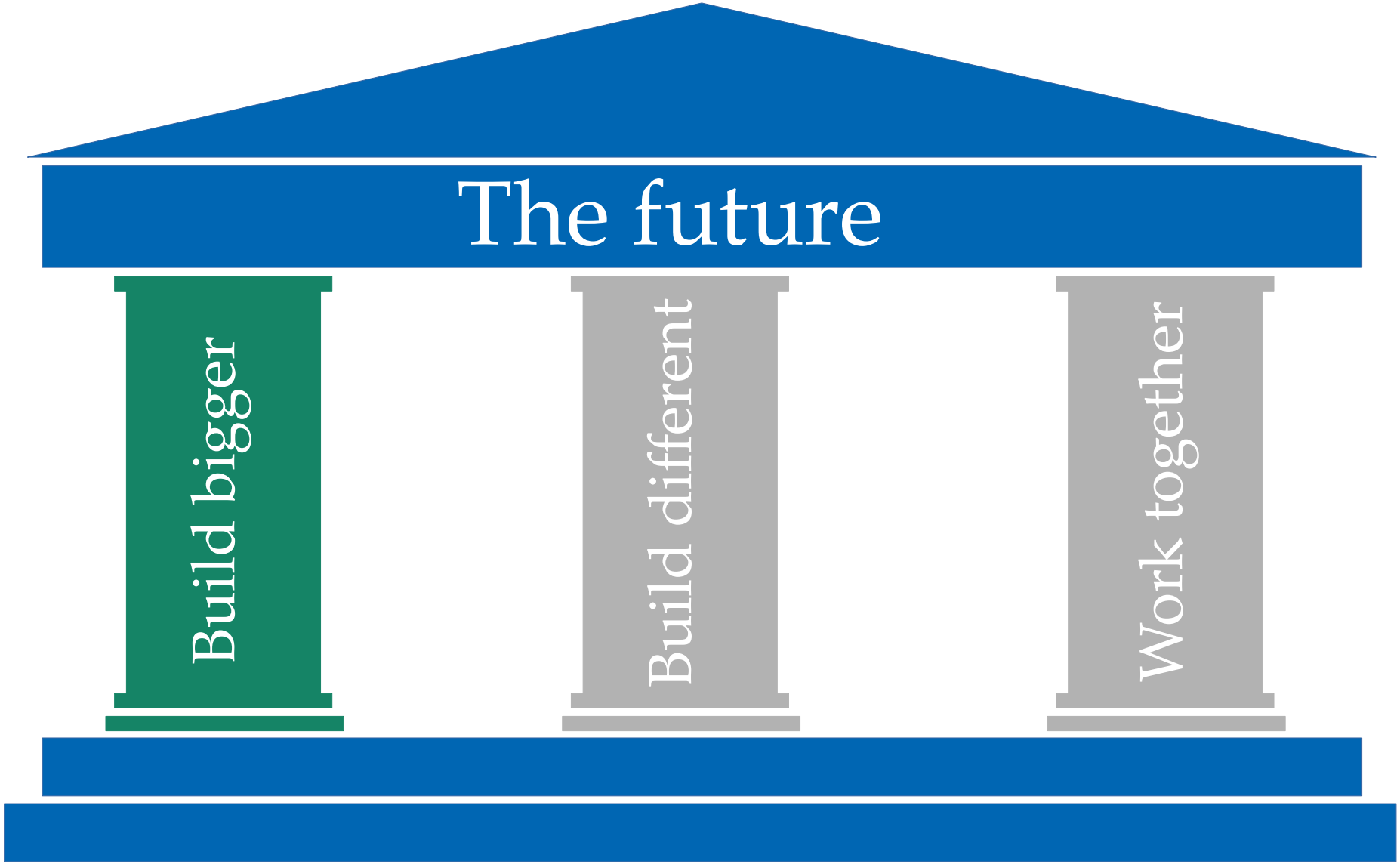
Dimension-5
CPT-odd
Isotropic
Lorentz-invariance
-violating
coefficient



High-energy neutrino physics

in the future


The future
Build bigger
Build different
Work together


The future
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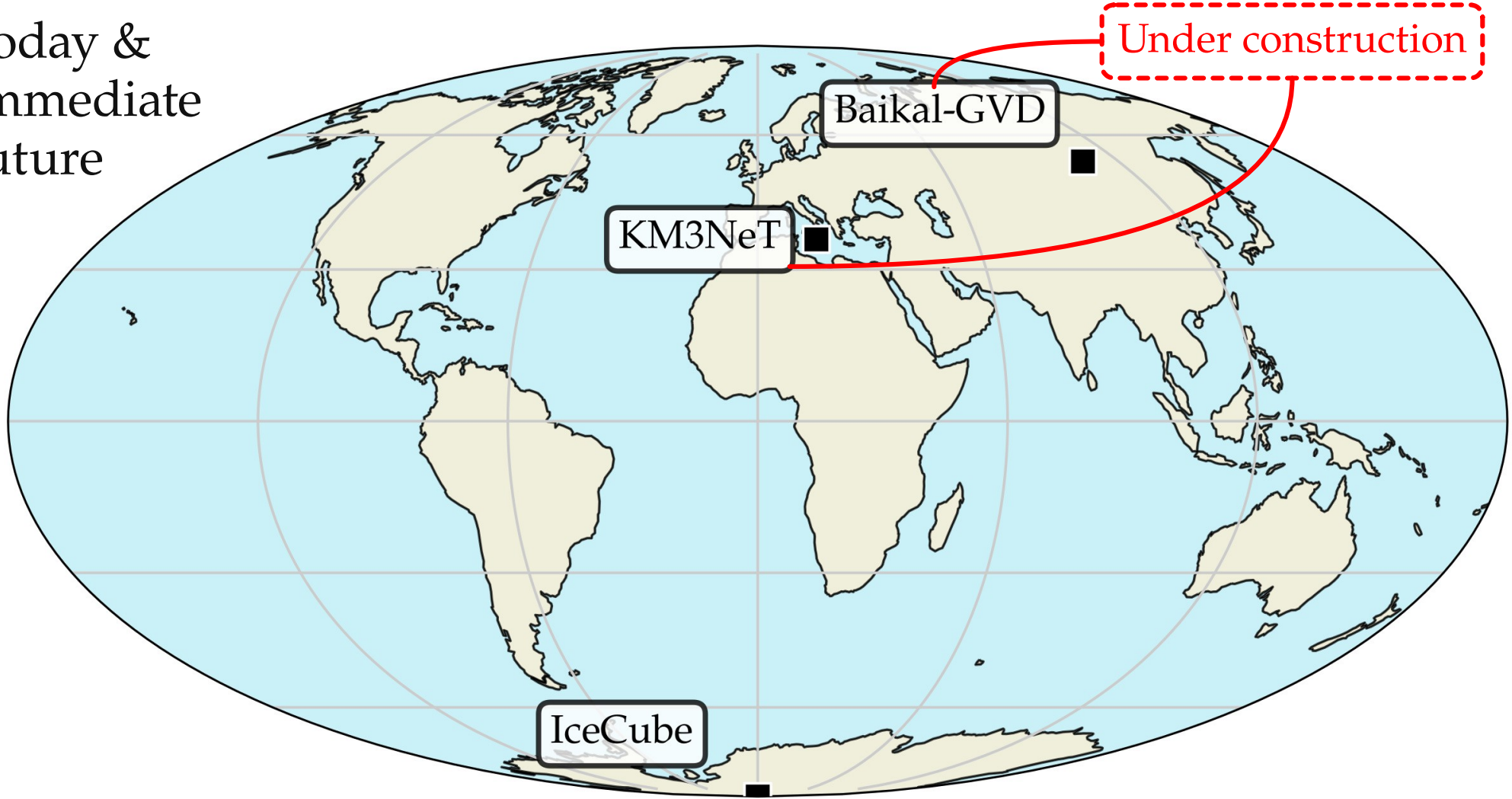
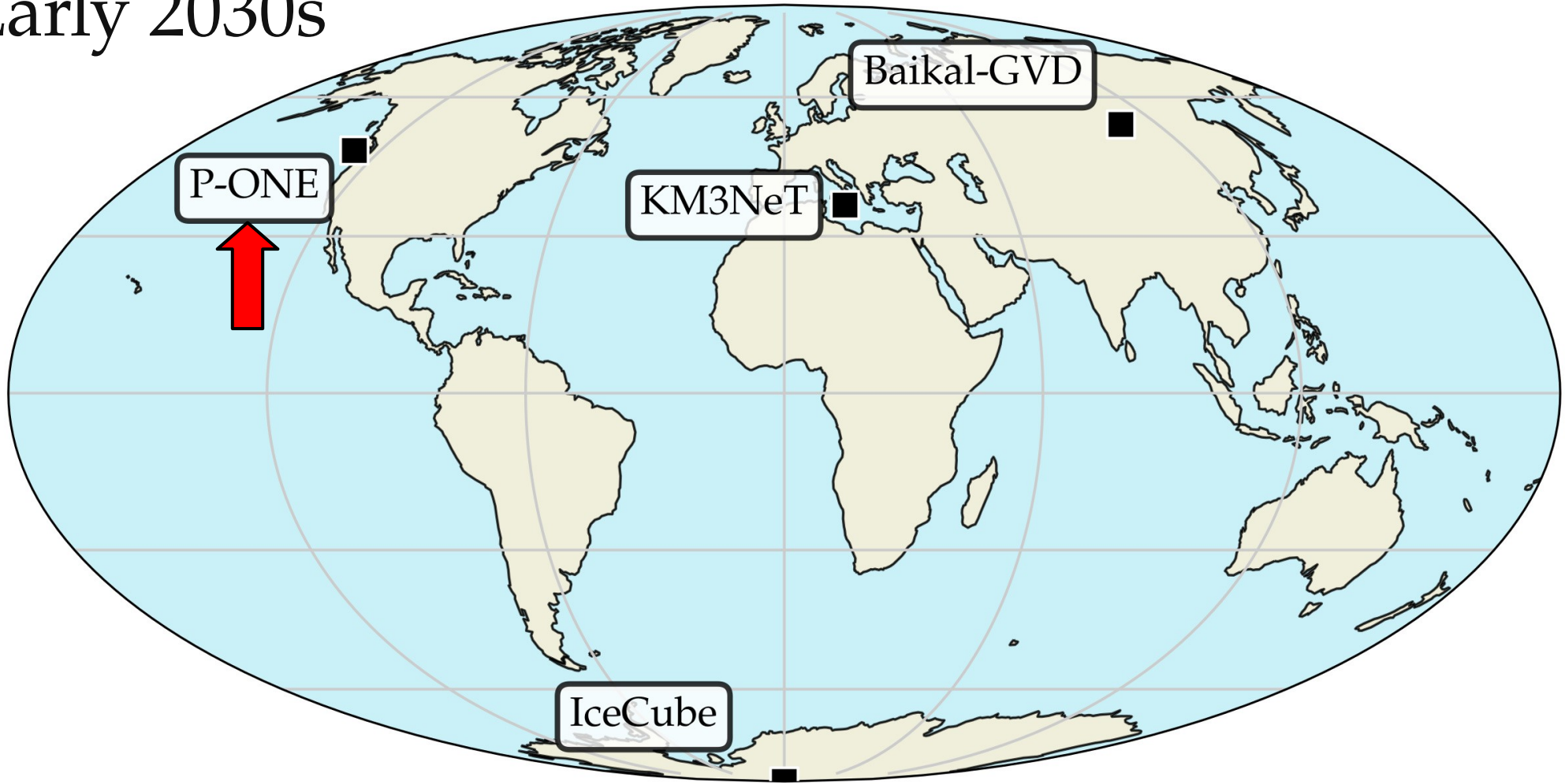
Today & immediate future



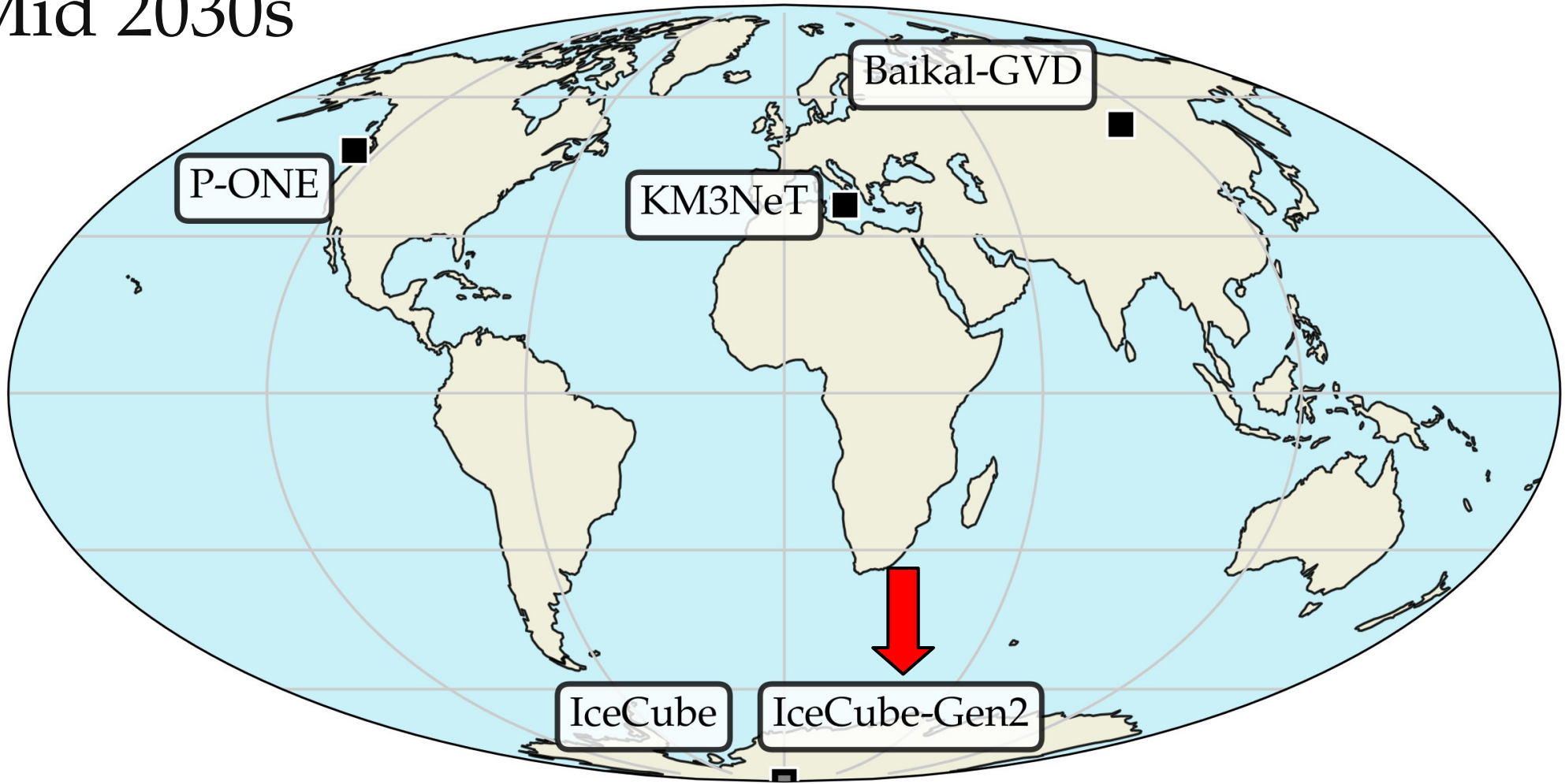
Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

Early 2030s



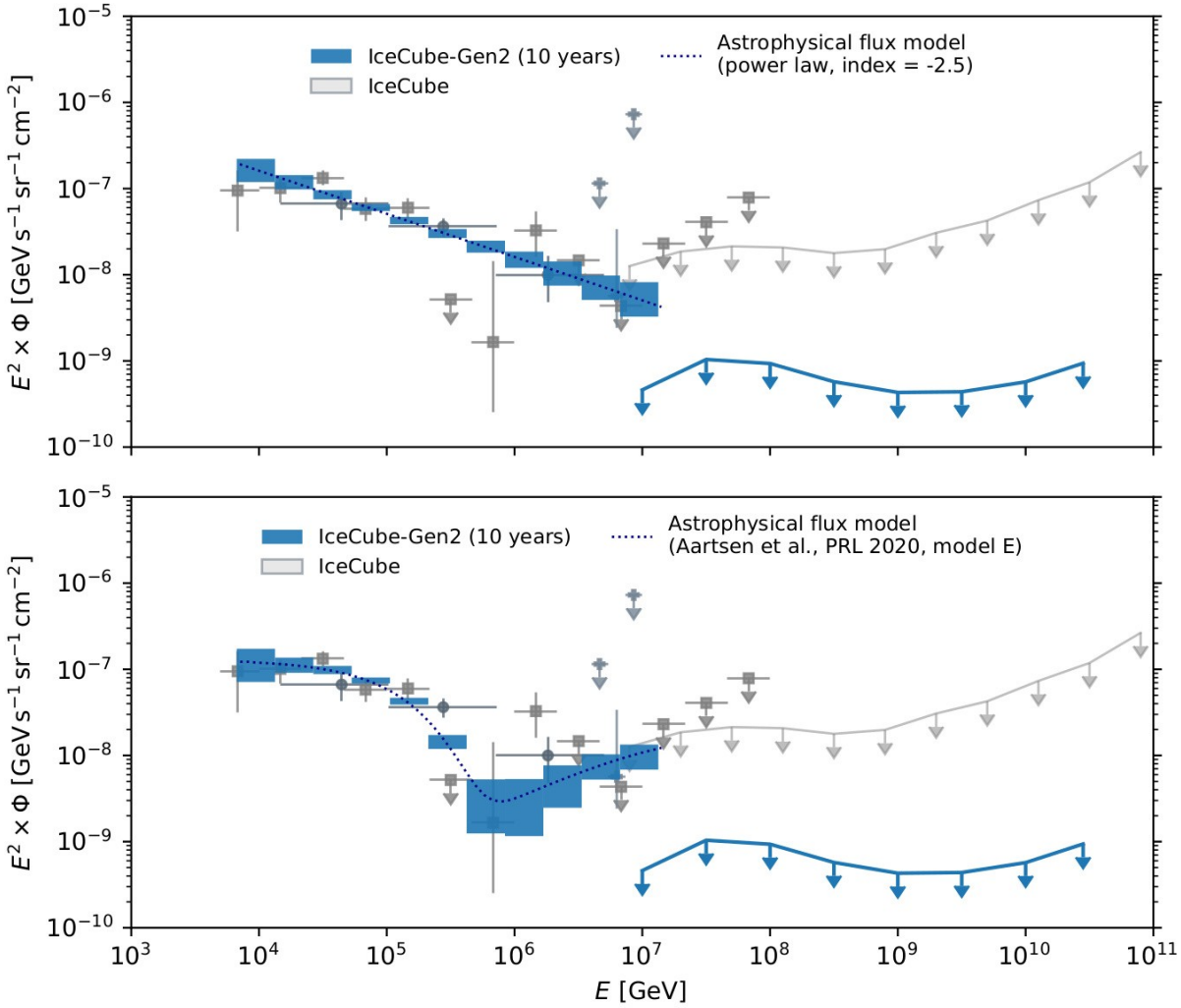
Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

Mid 2030s



Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

Measuring the diffuse flux *precisely*

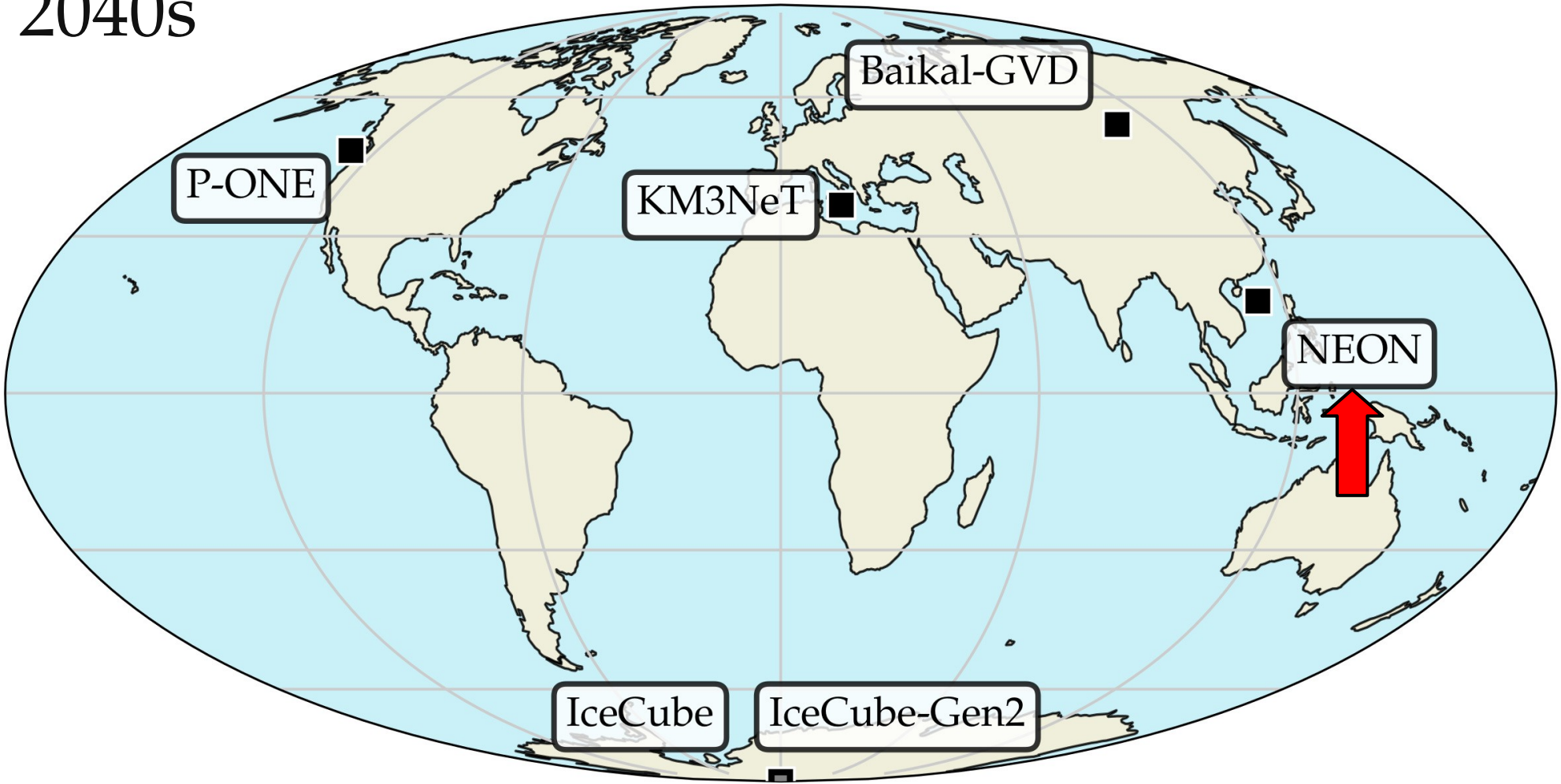


Assuming a power-law ν flux ∝ $E^{-2.5}$

Assuming a power-law ν flux with 100-TeV cut-off + $p\gamma$ bump at tens of TeV

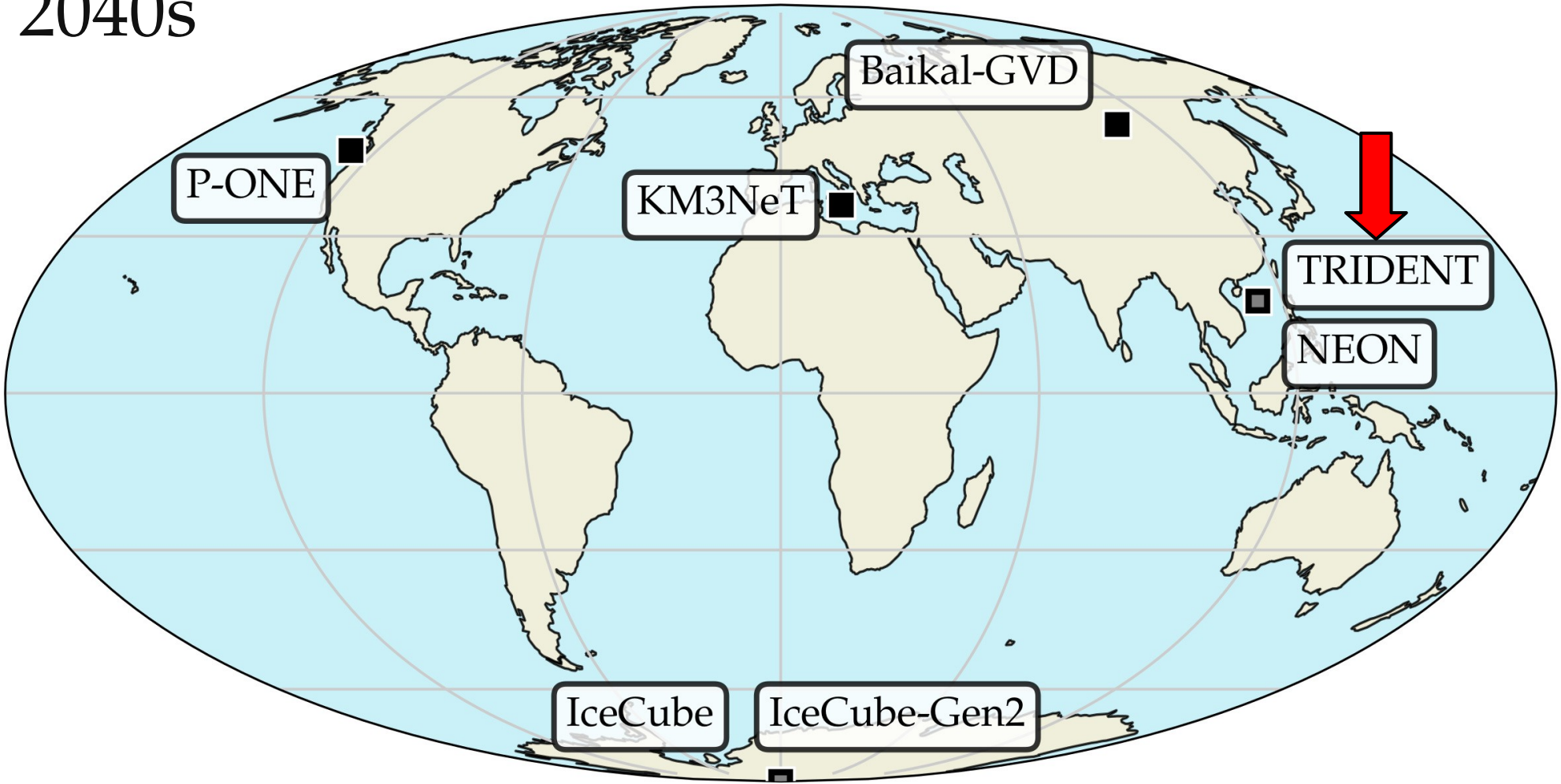
Ackermann, **MB** *et al.*, *JHEAp* 2022

2040s

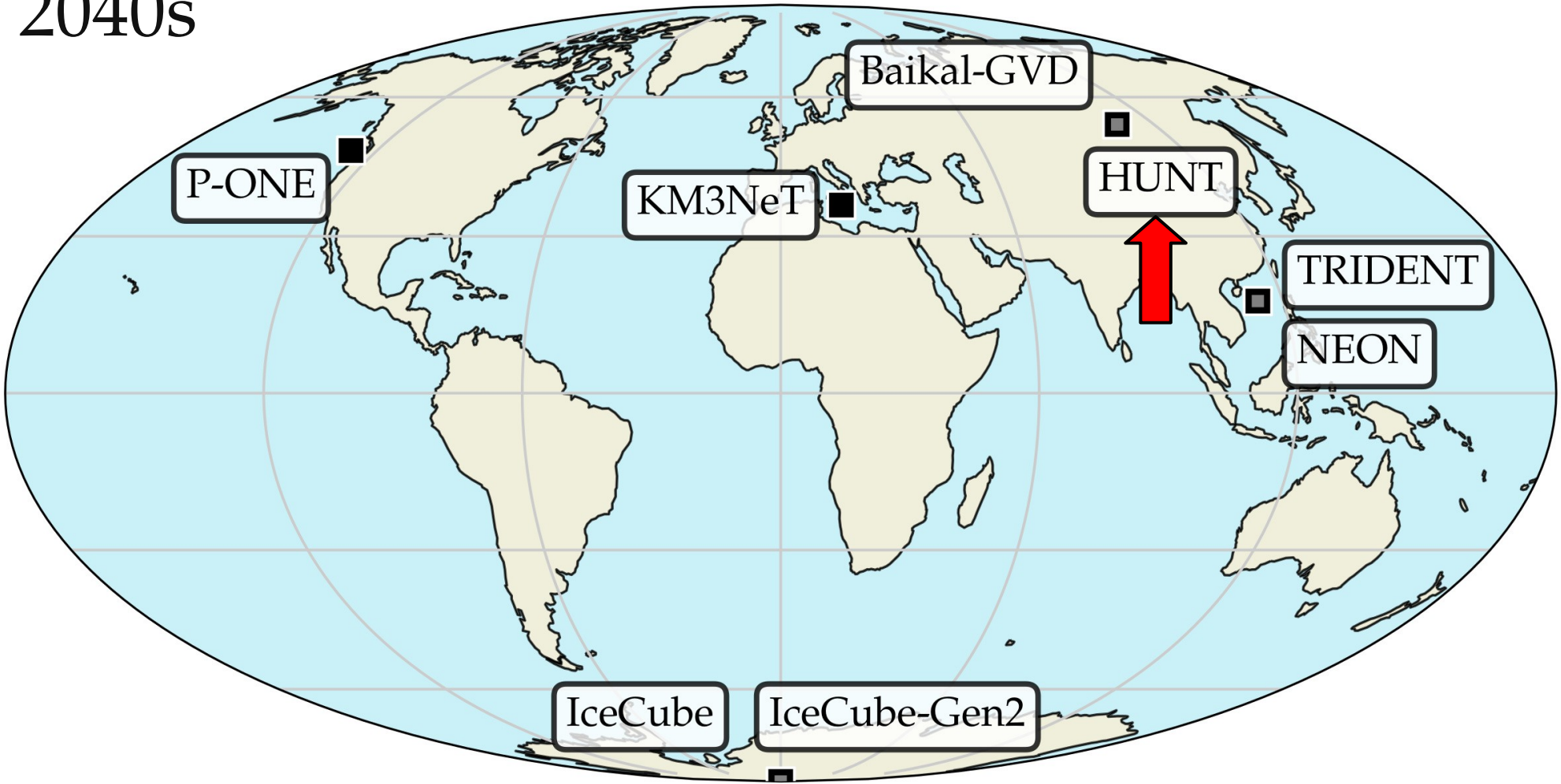


Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

2040s

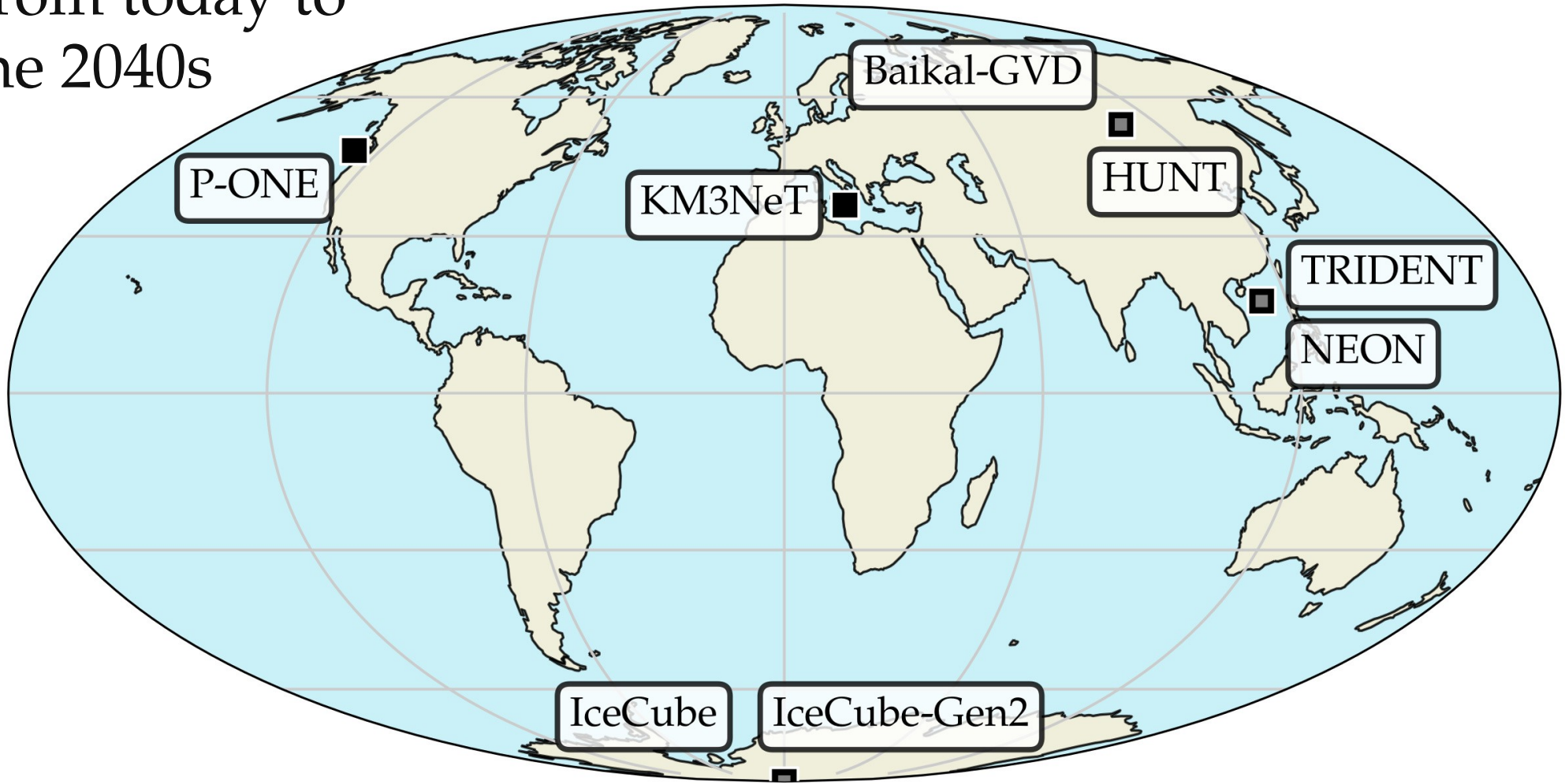


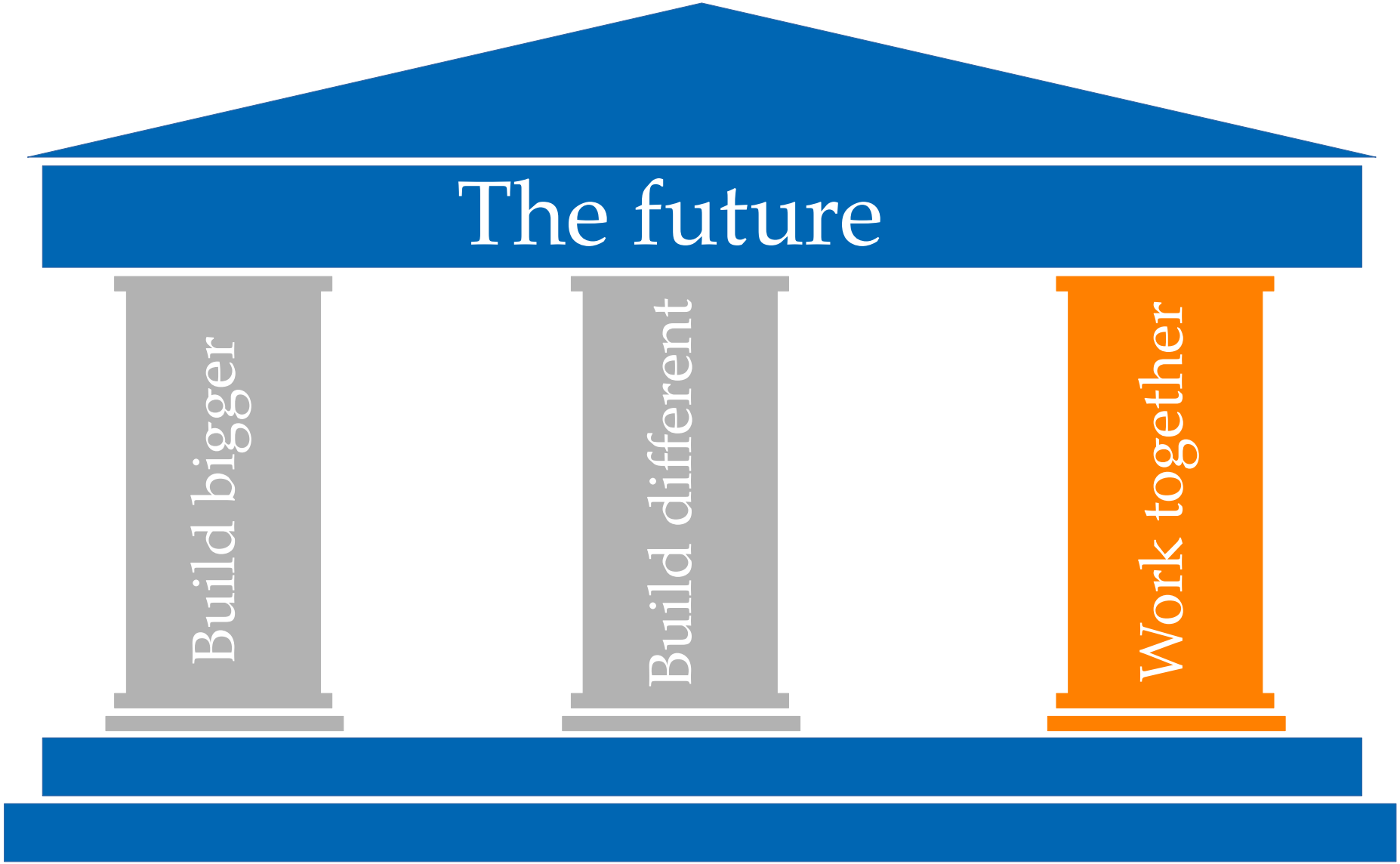
2040s



Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

From today to the 2040s

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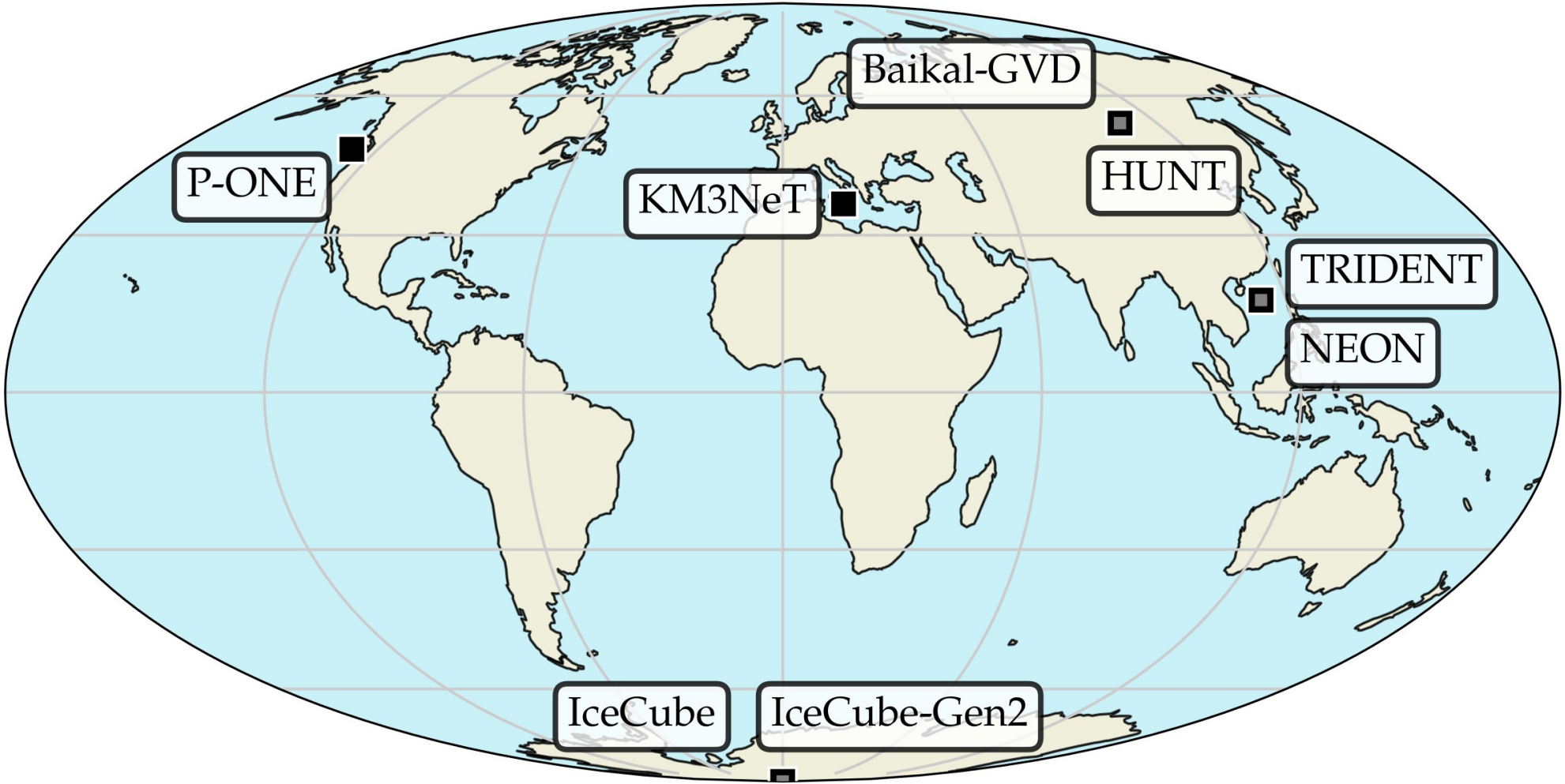

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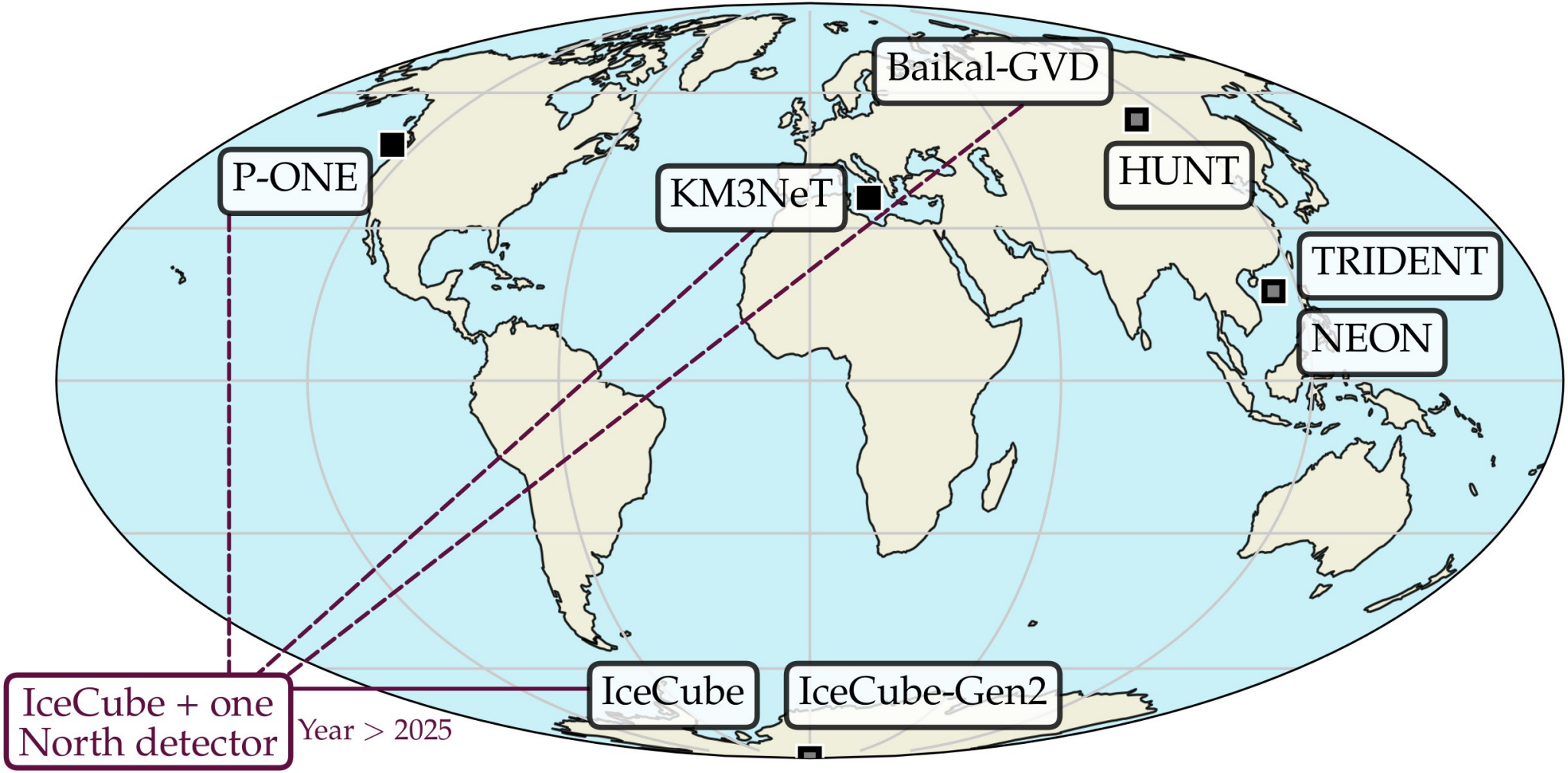

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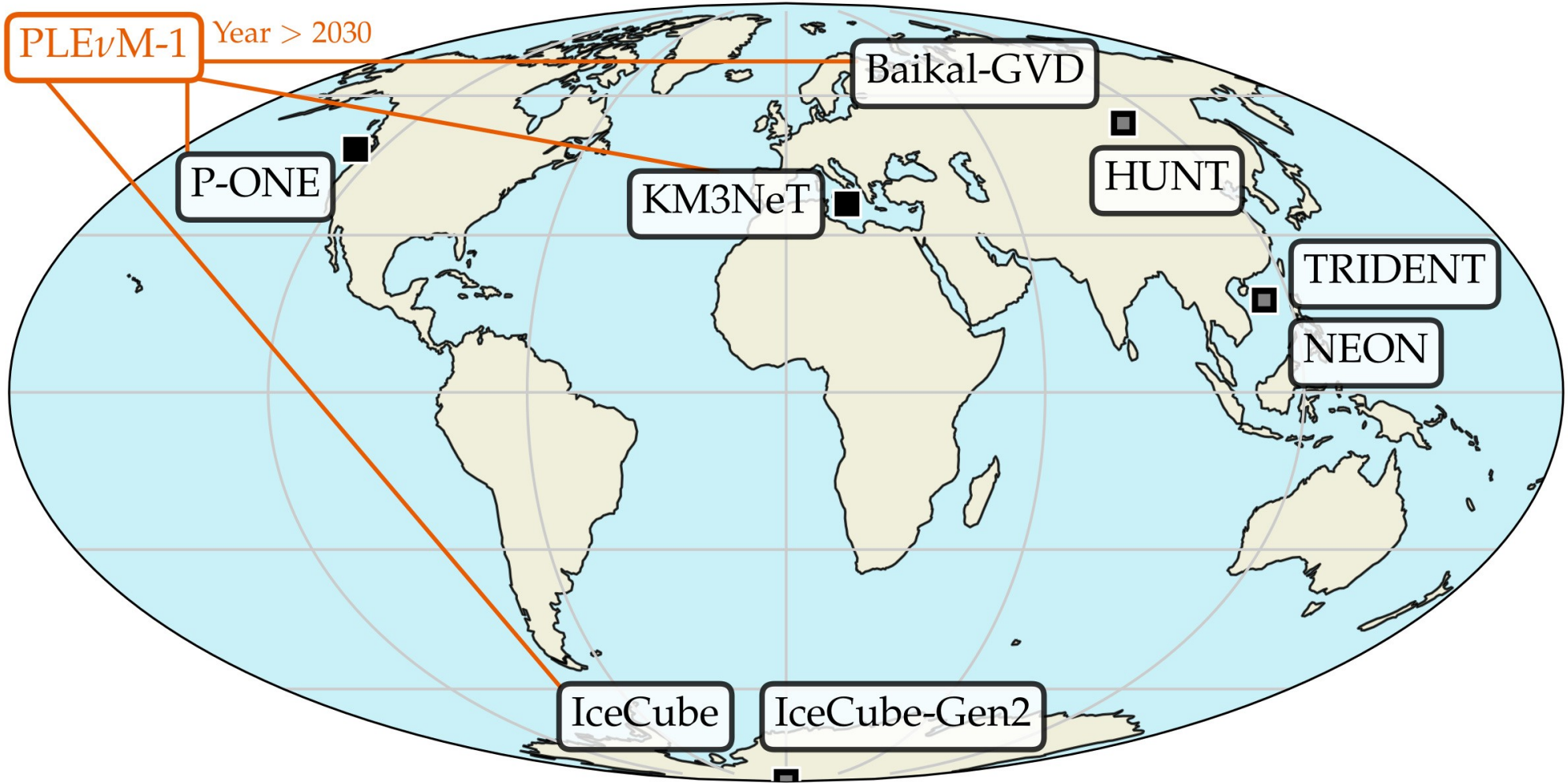

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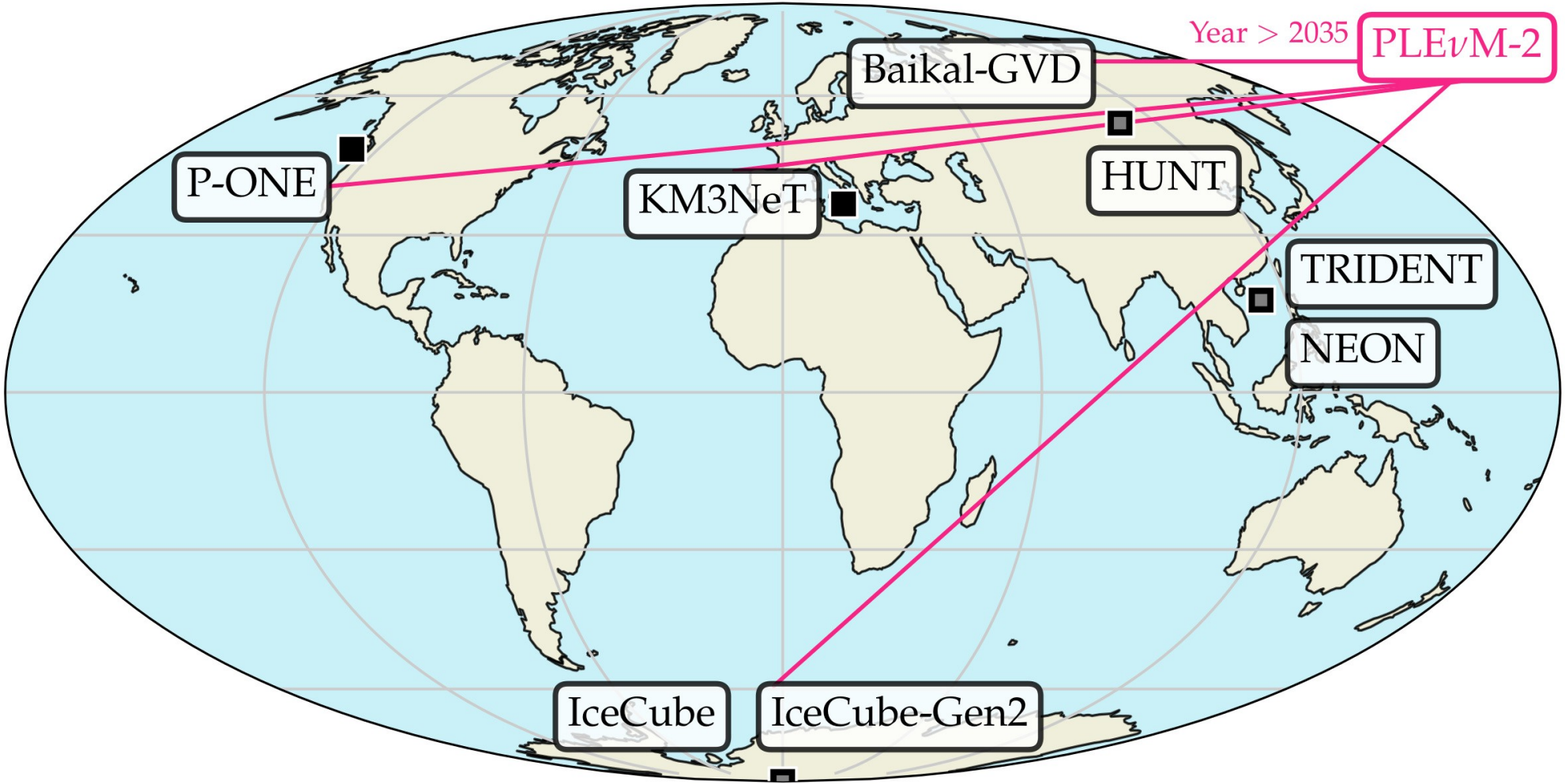

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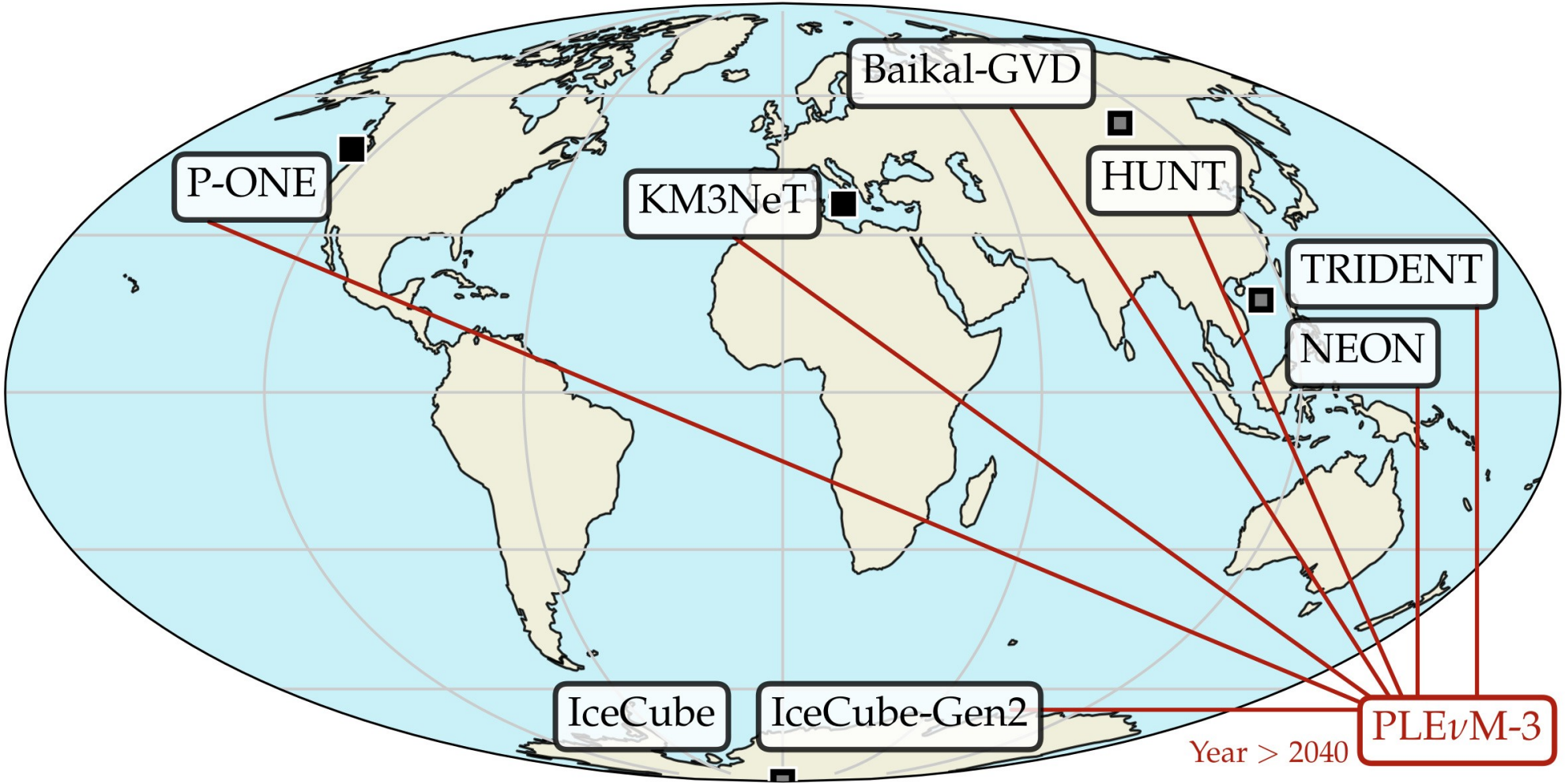
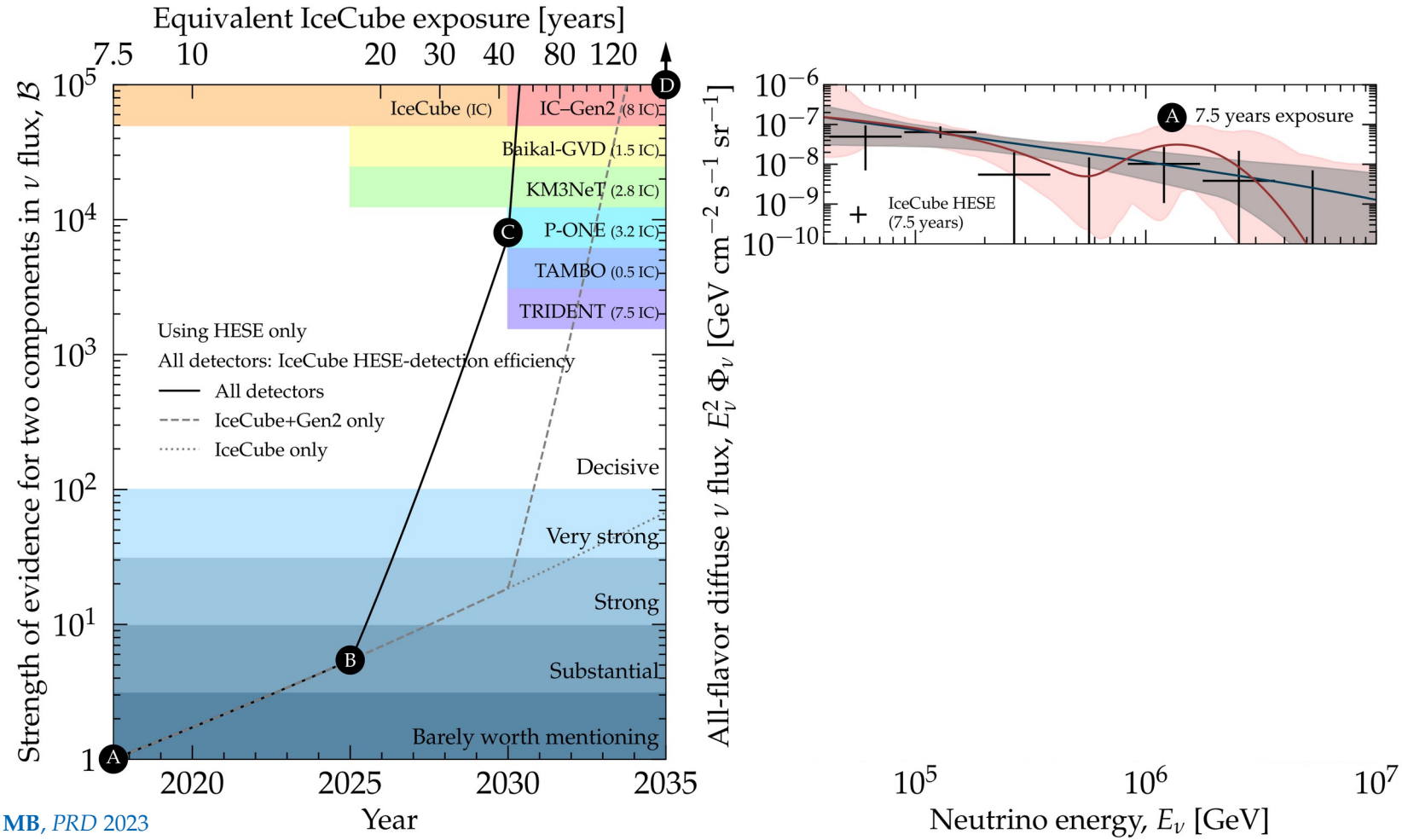


Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

Bump-hunting in the diffuse flux of high-energy neutrinos

Bump-like spectra can reveal the presence of ν production via $p\gamma$:



D. F. G. Fiorillo, **MB**, *PRD* 2023

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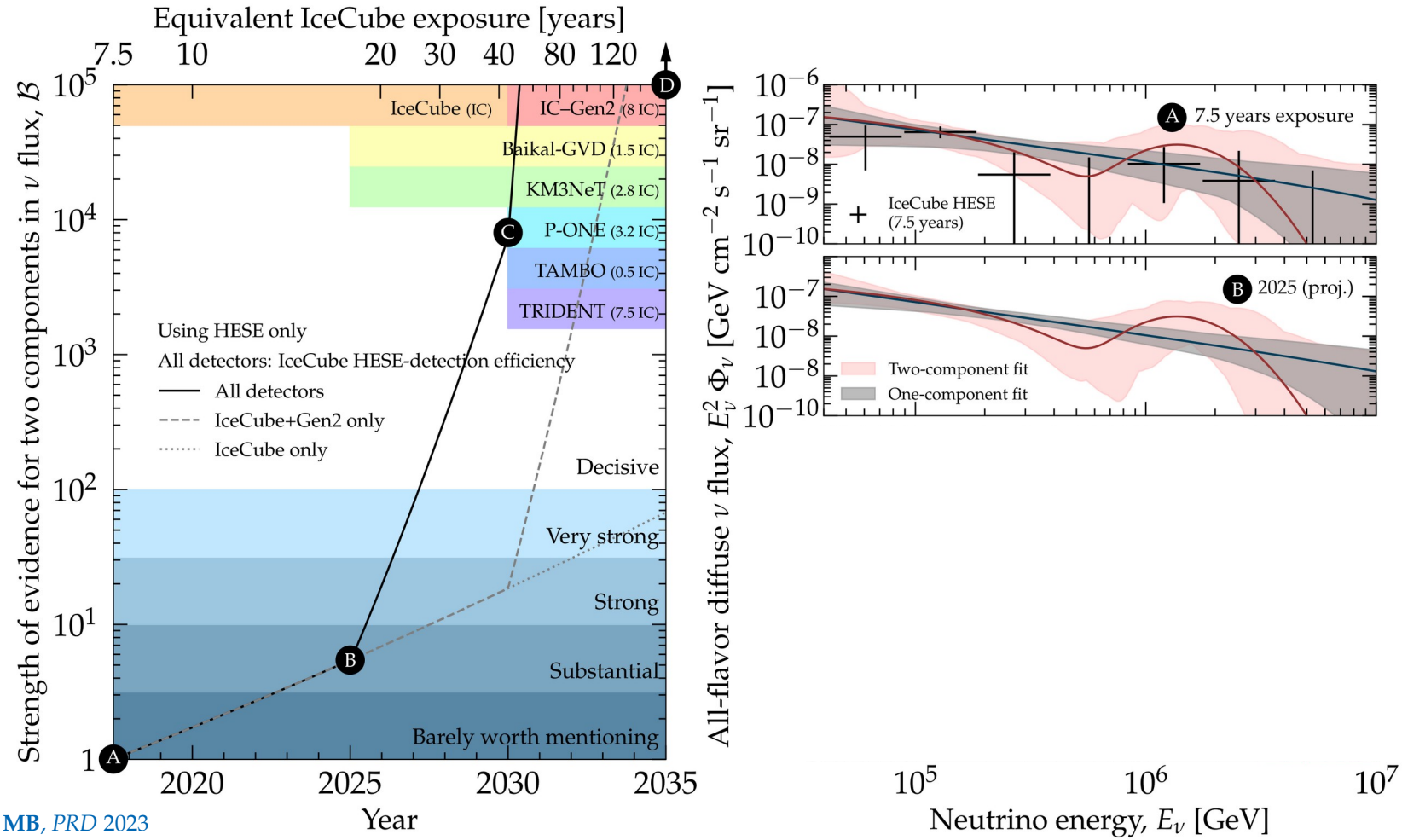

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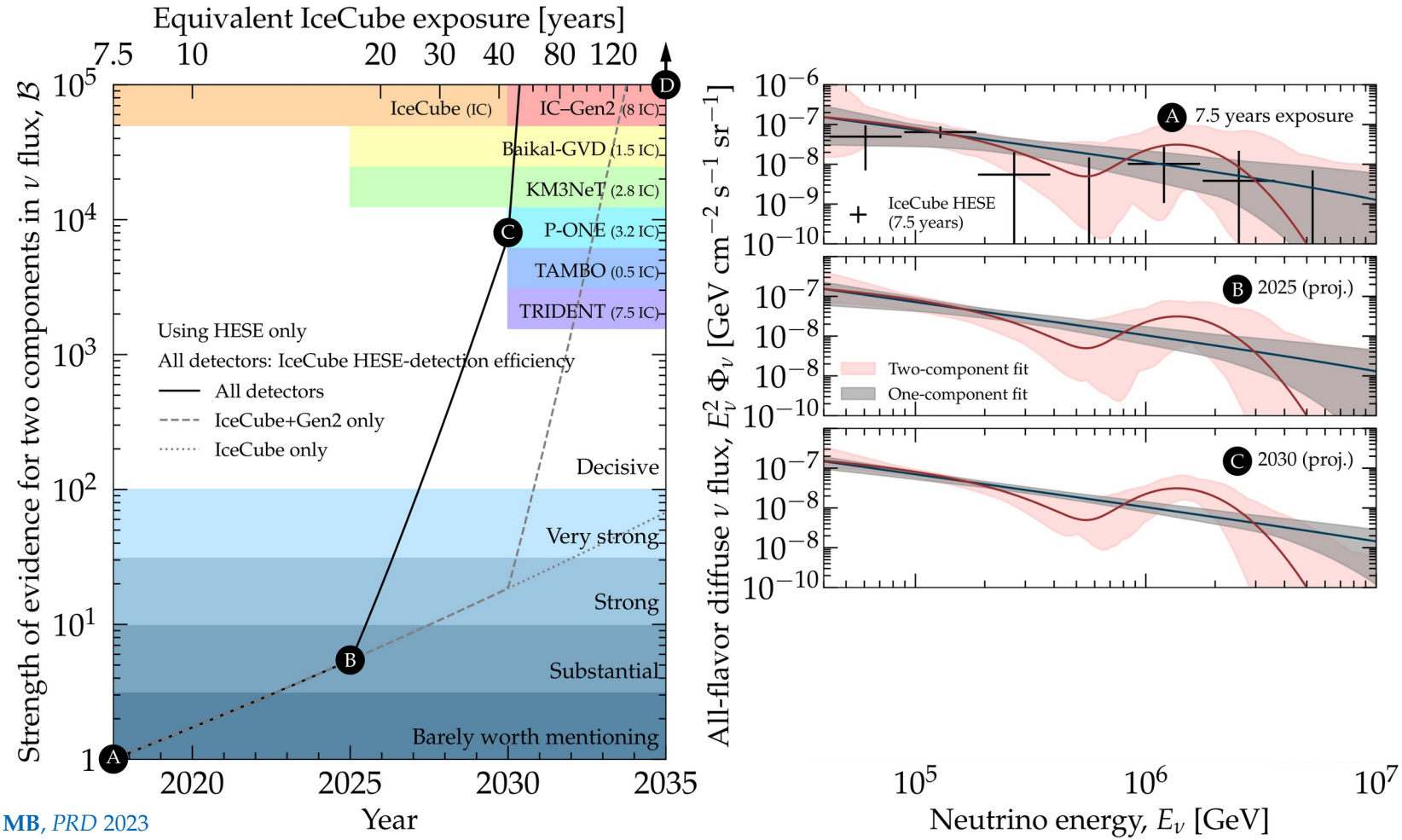

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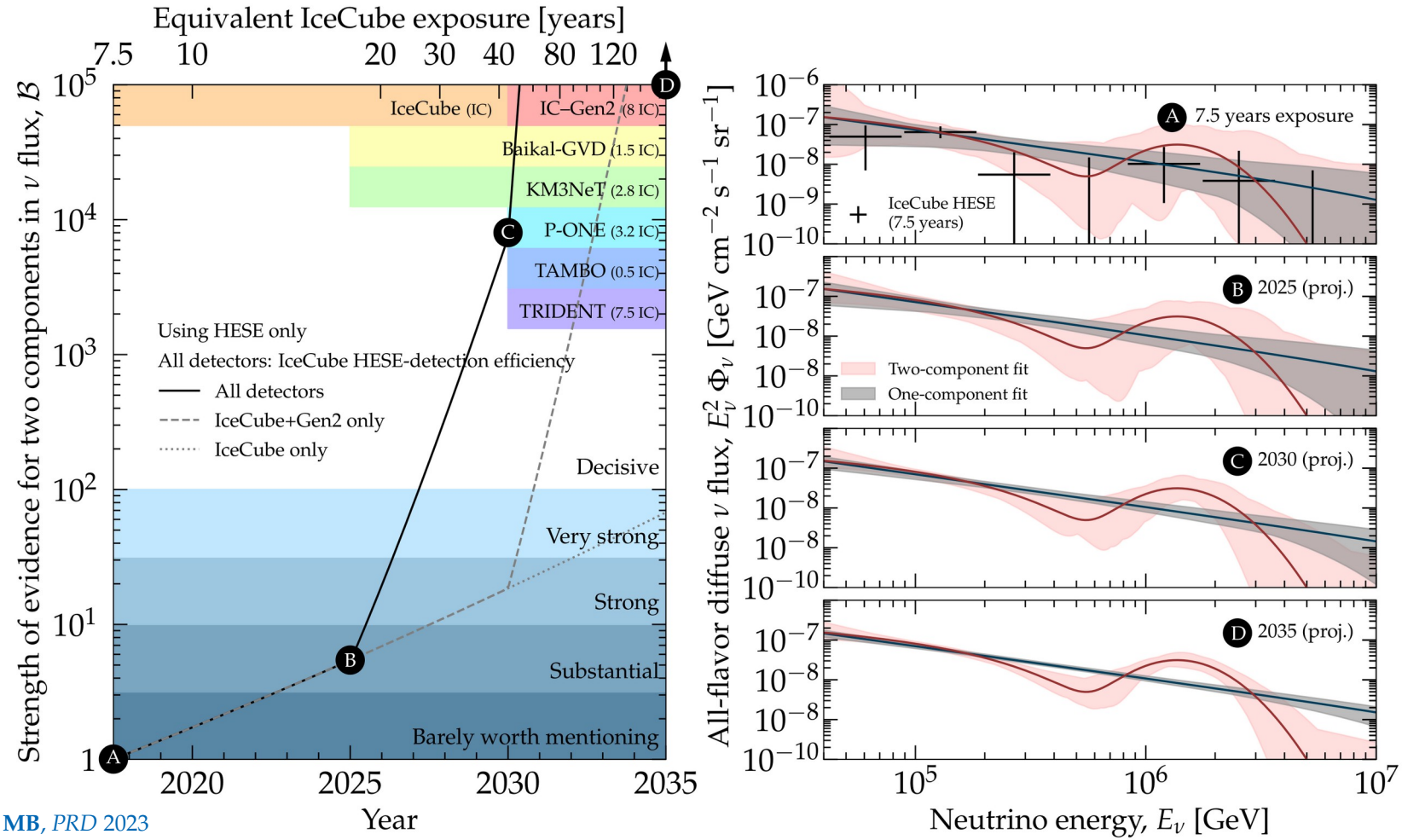

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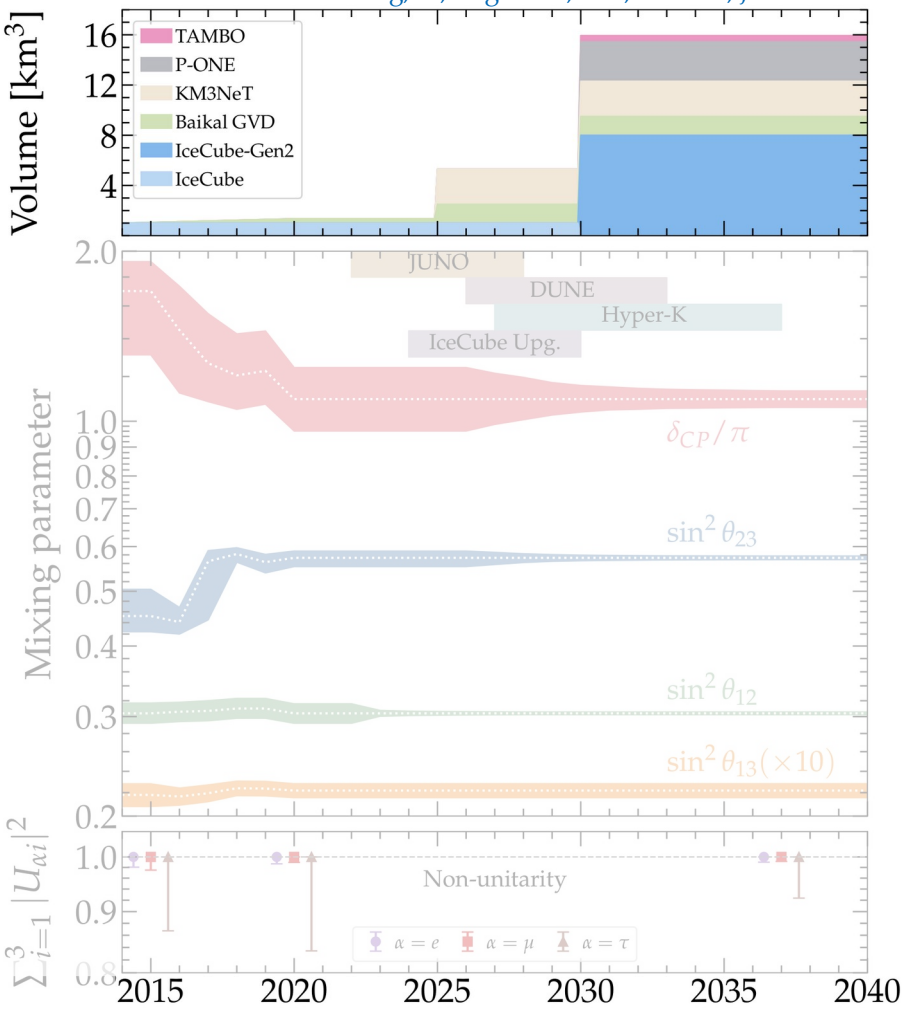
Measuring flavor composition: 2015–2040

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



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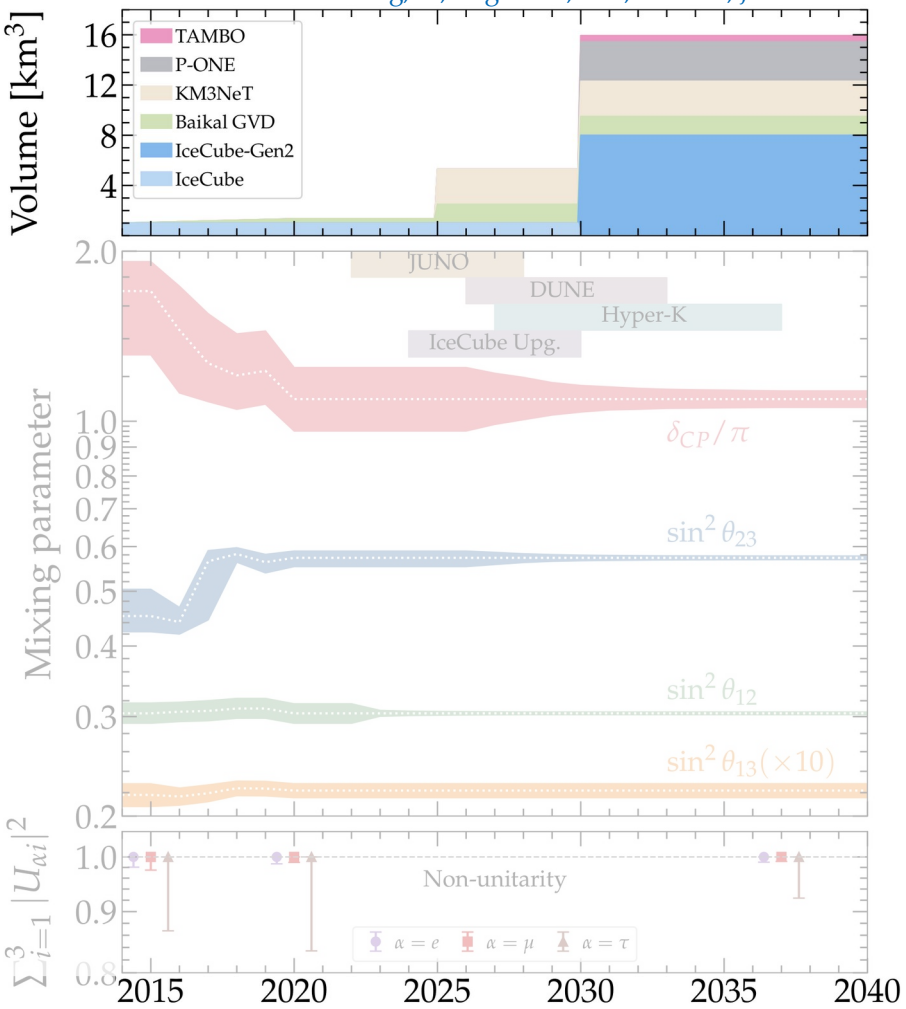

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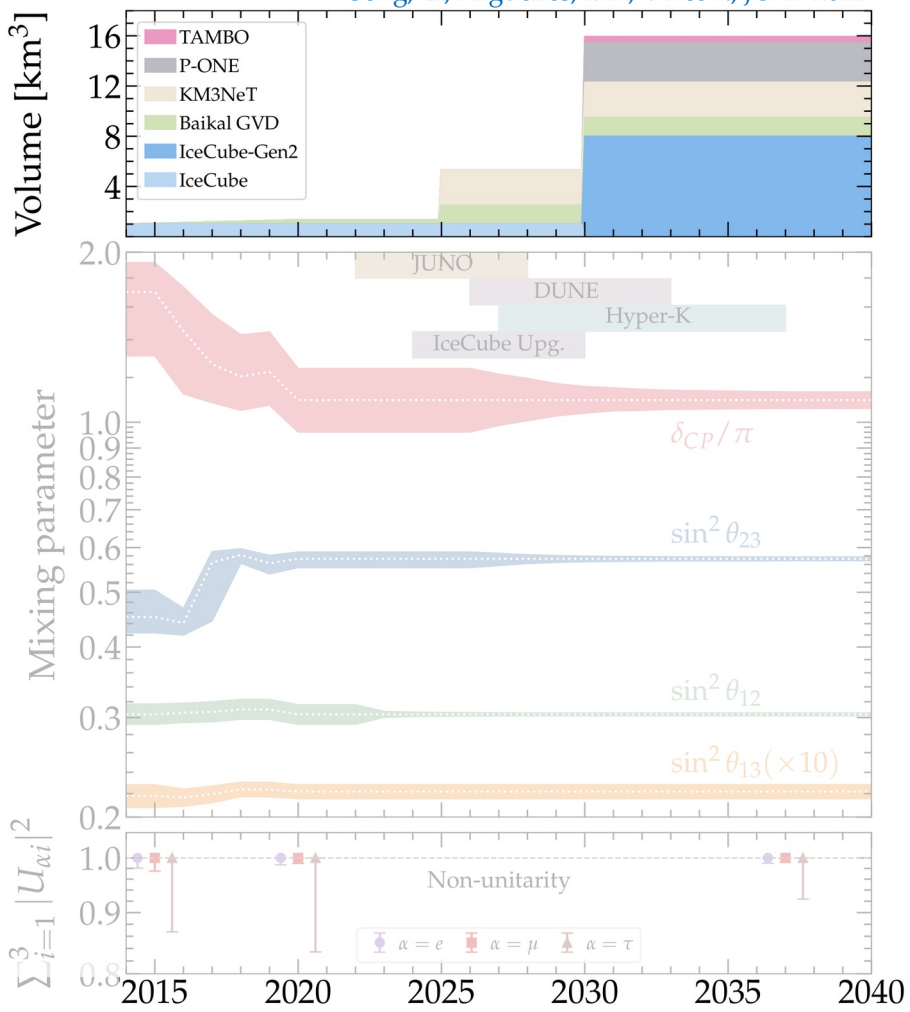

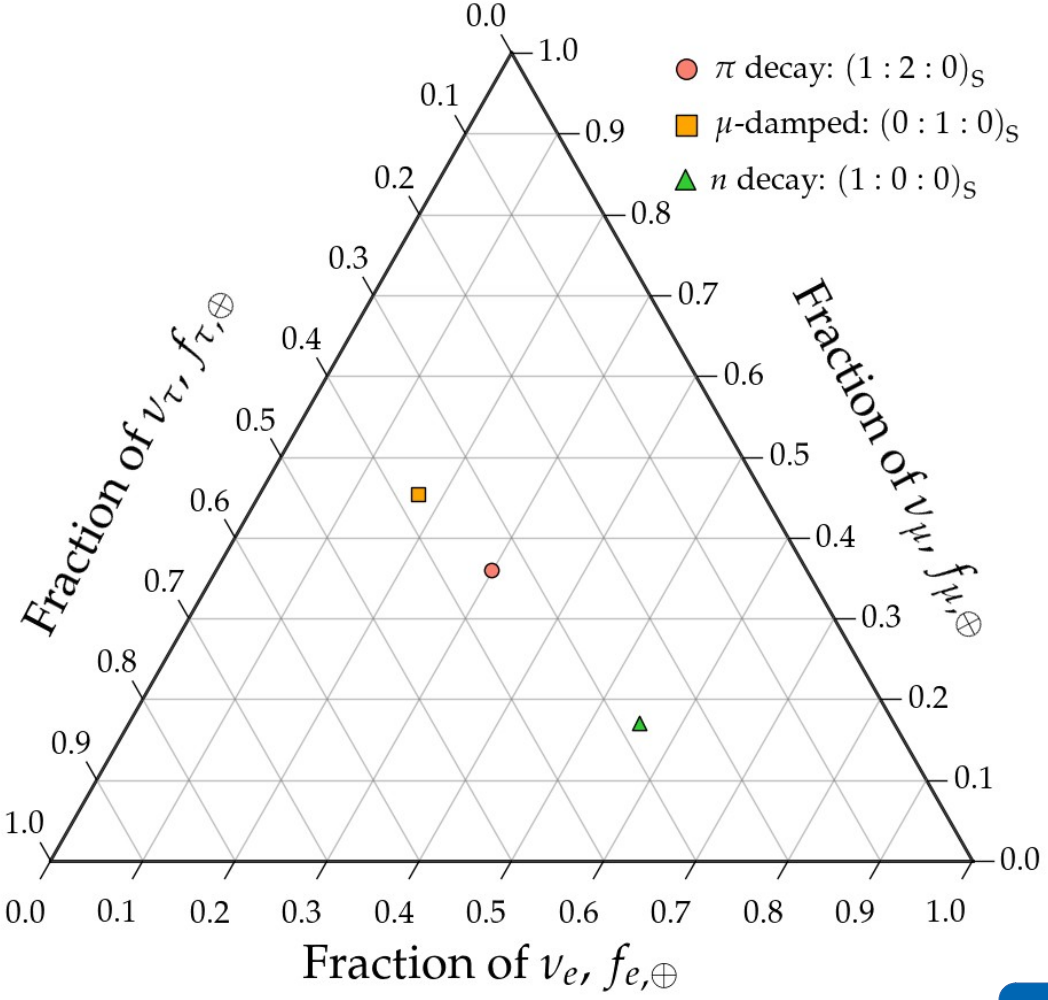

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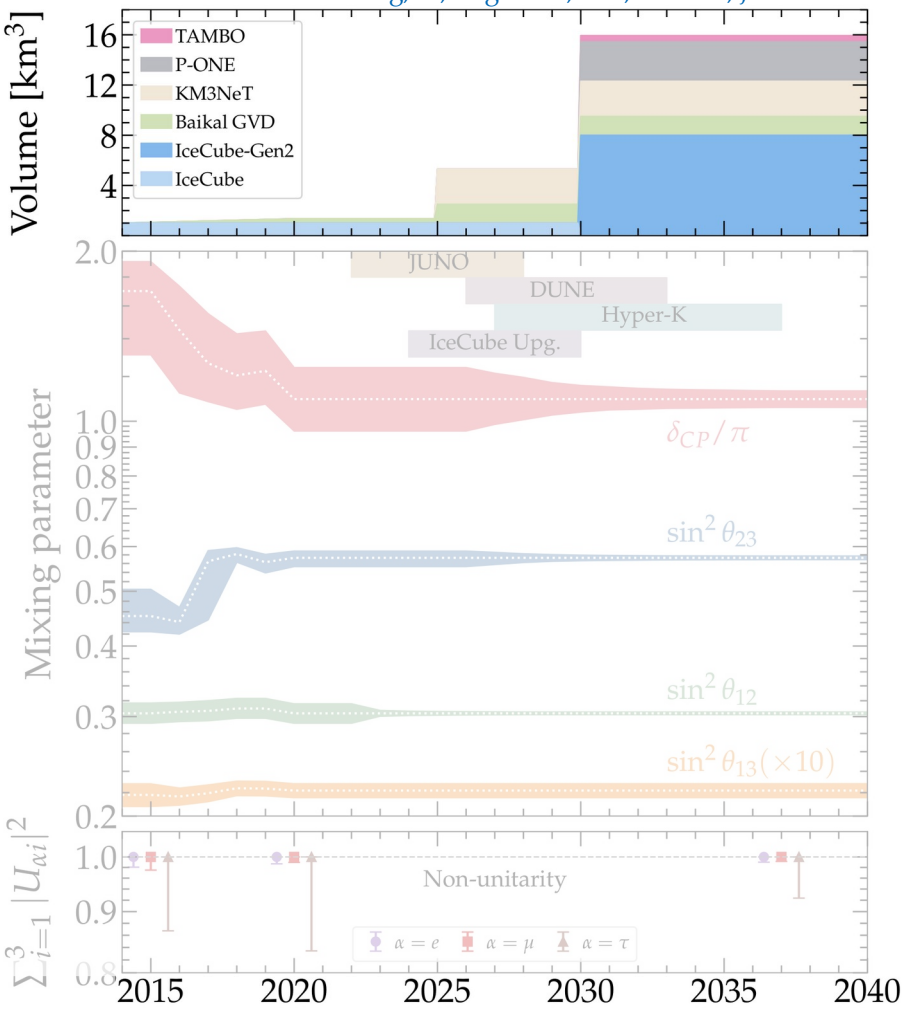

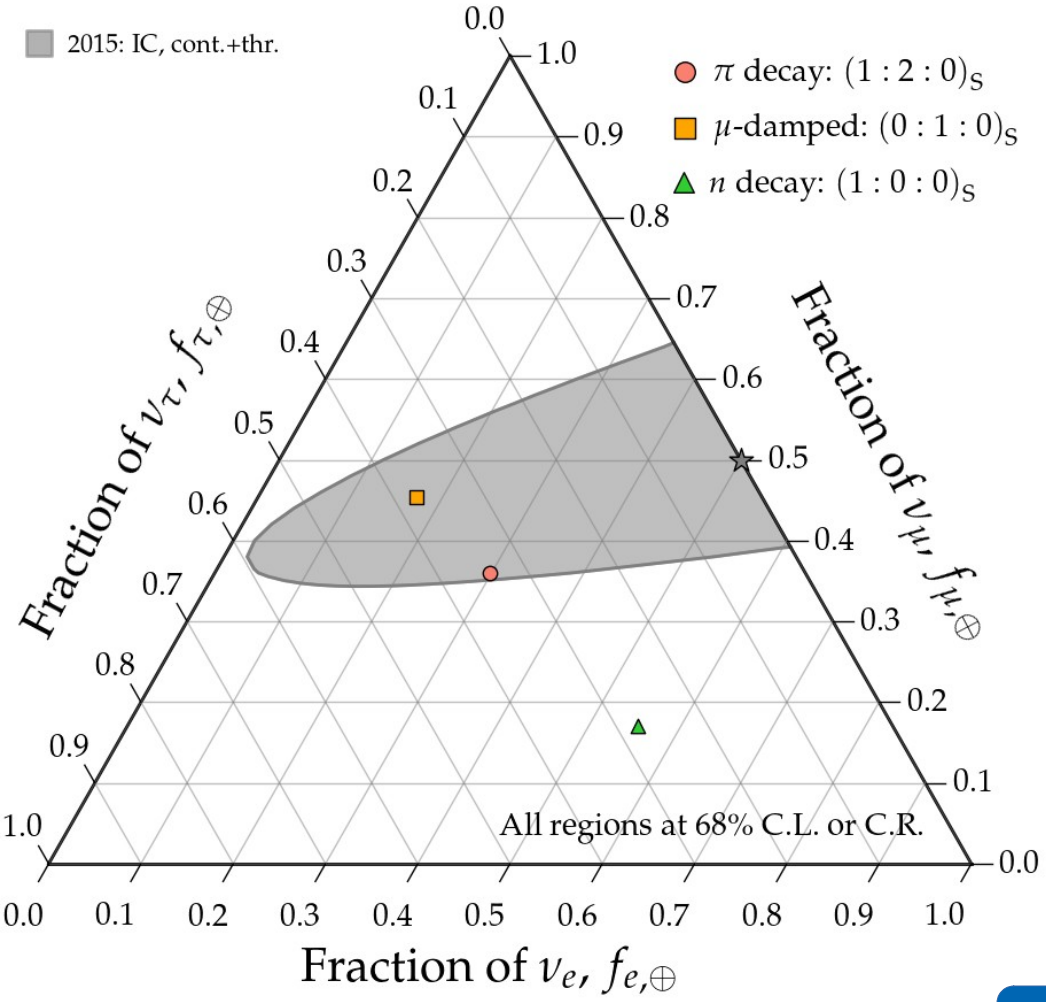

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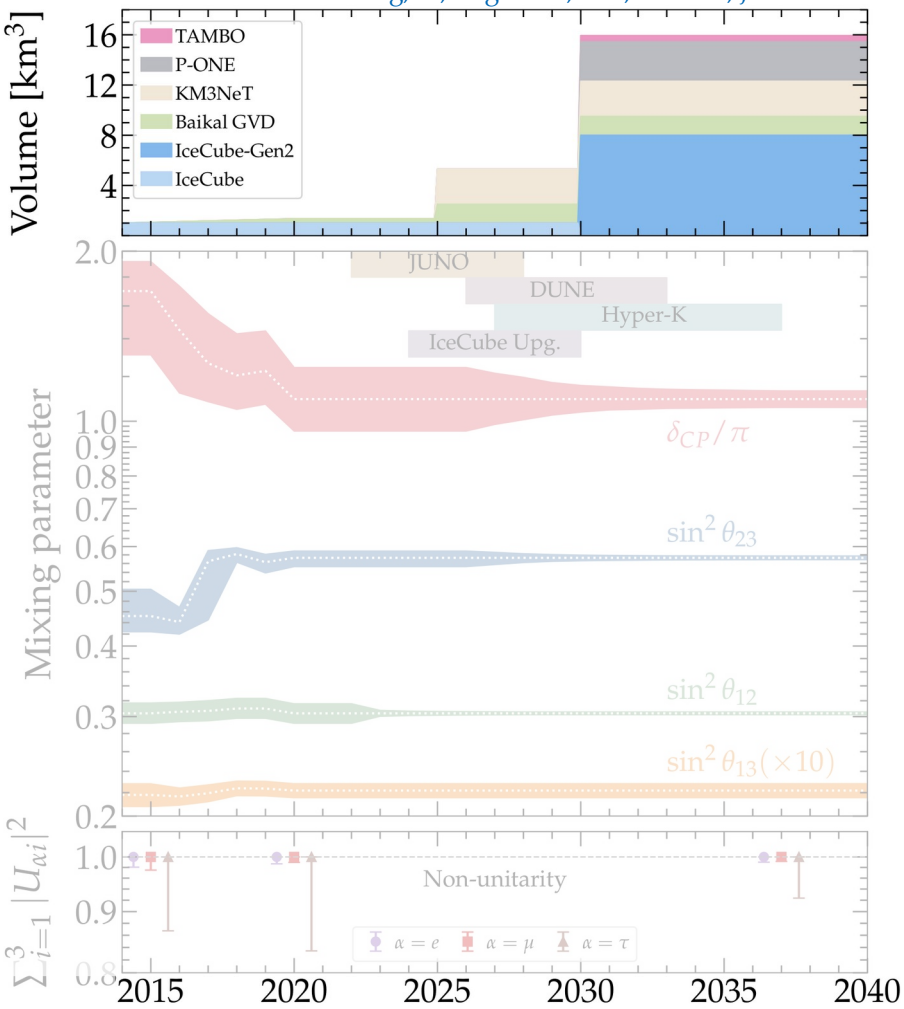

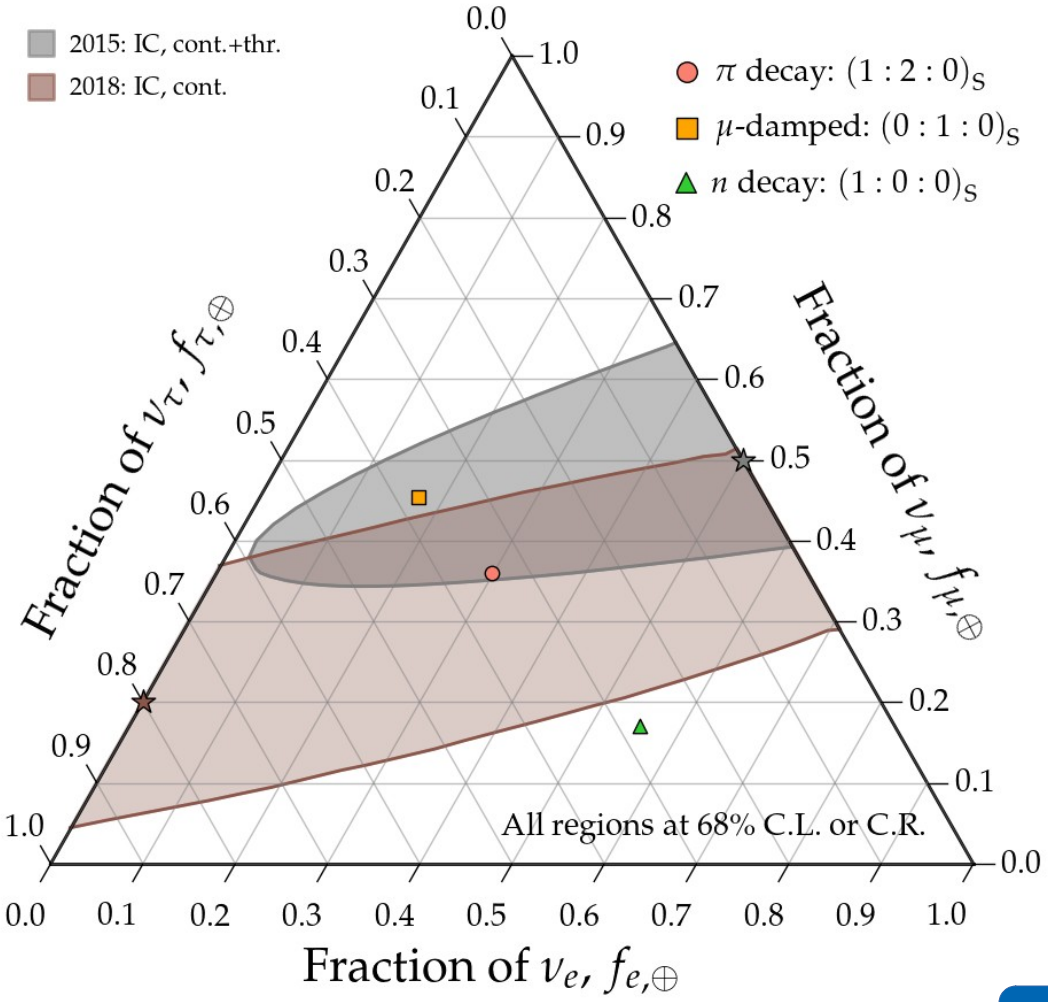

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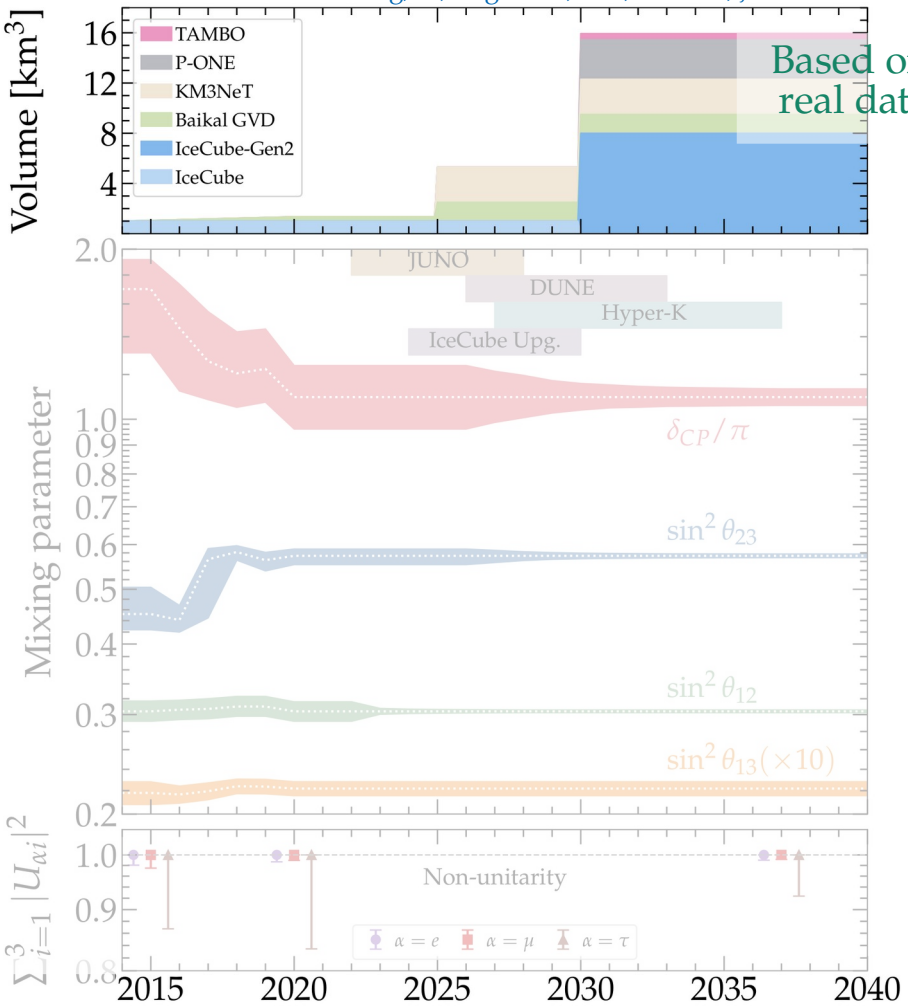
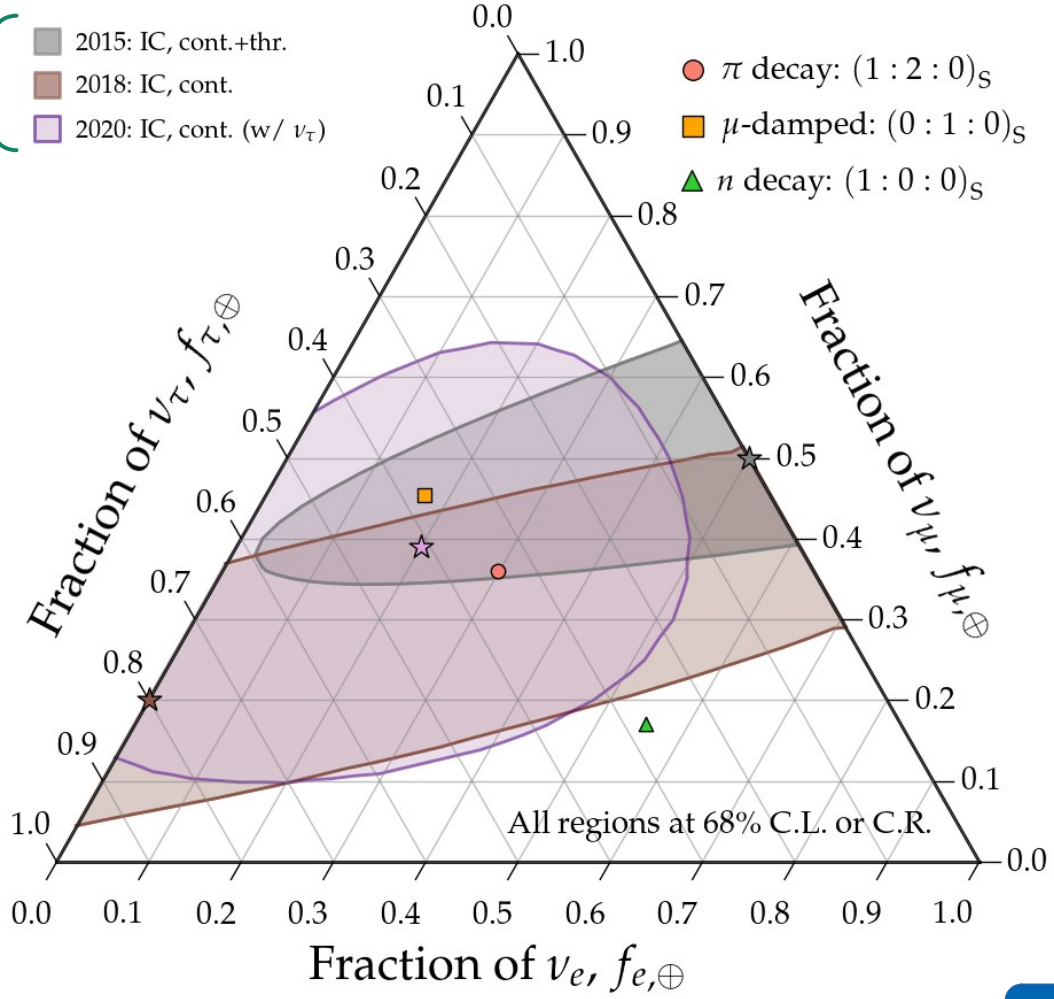


Based on real data



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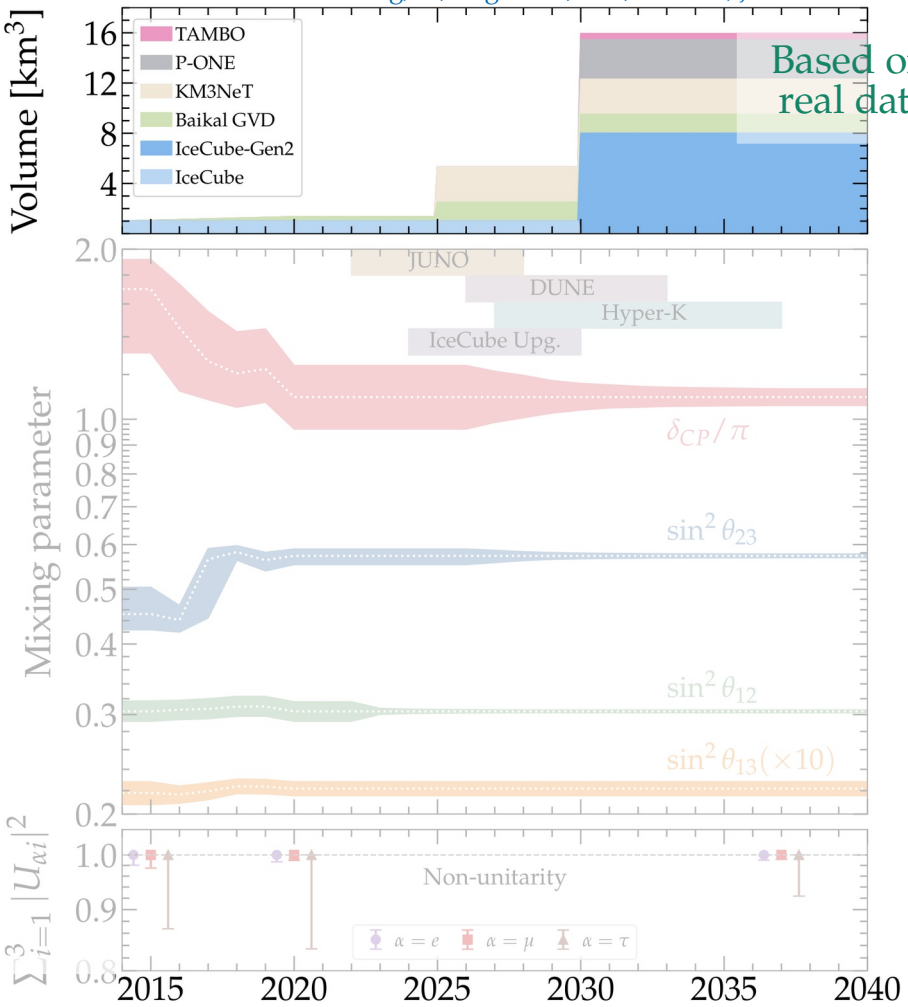

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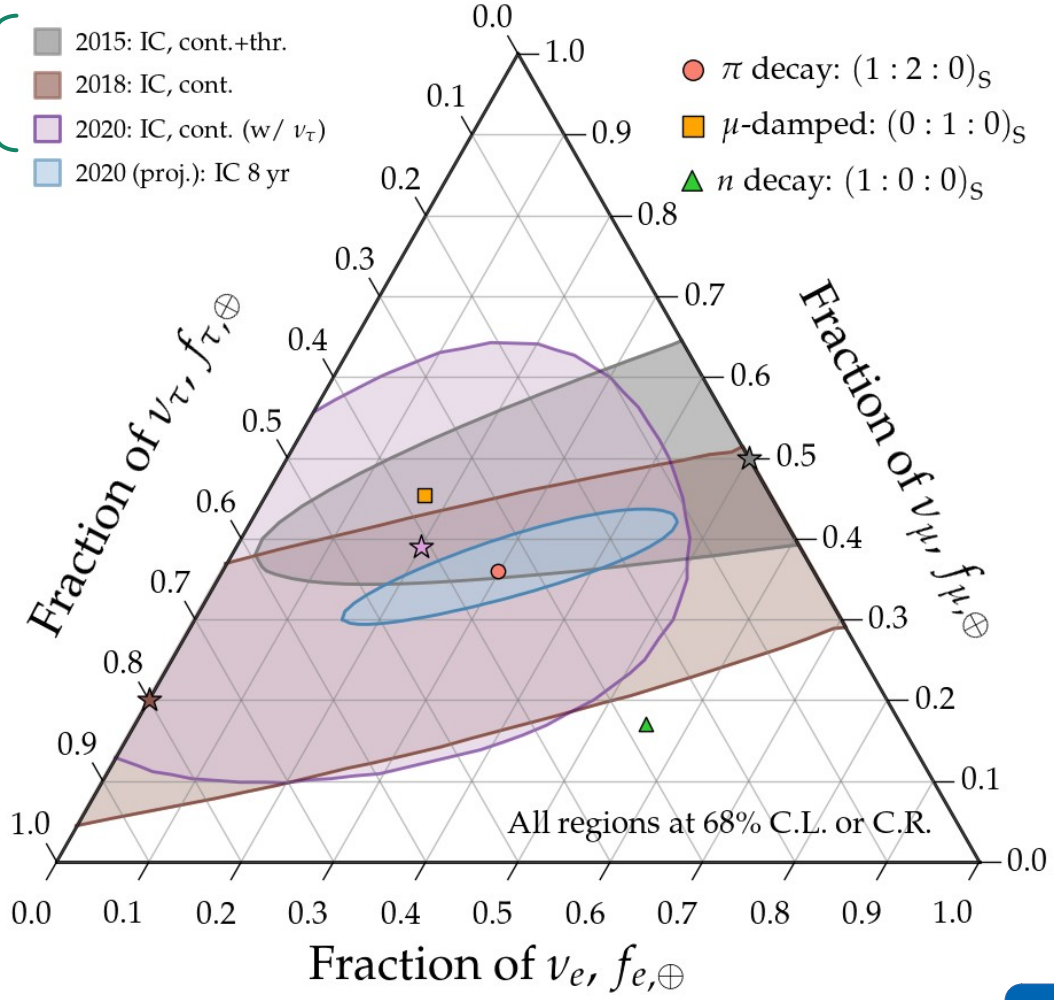

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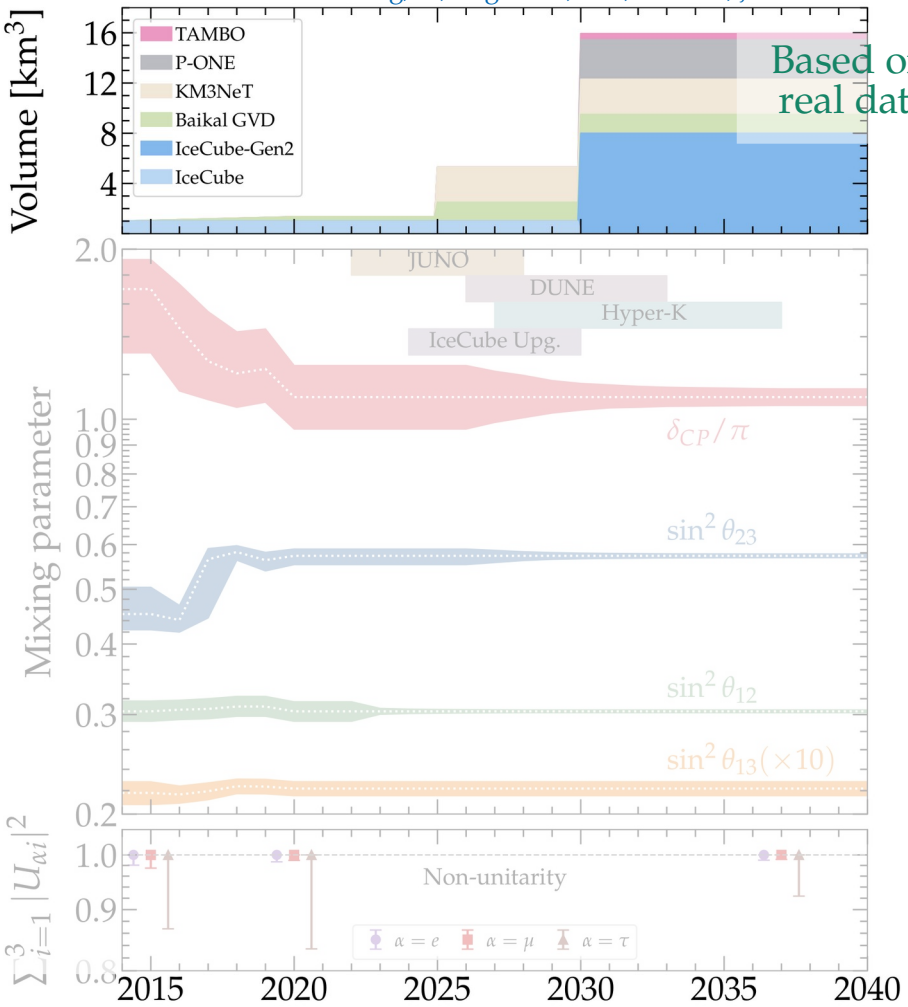

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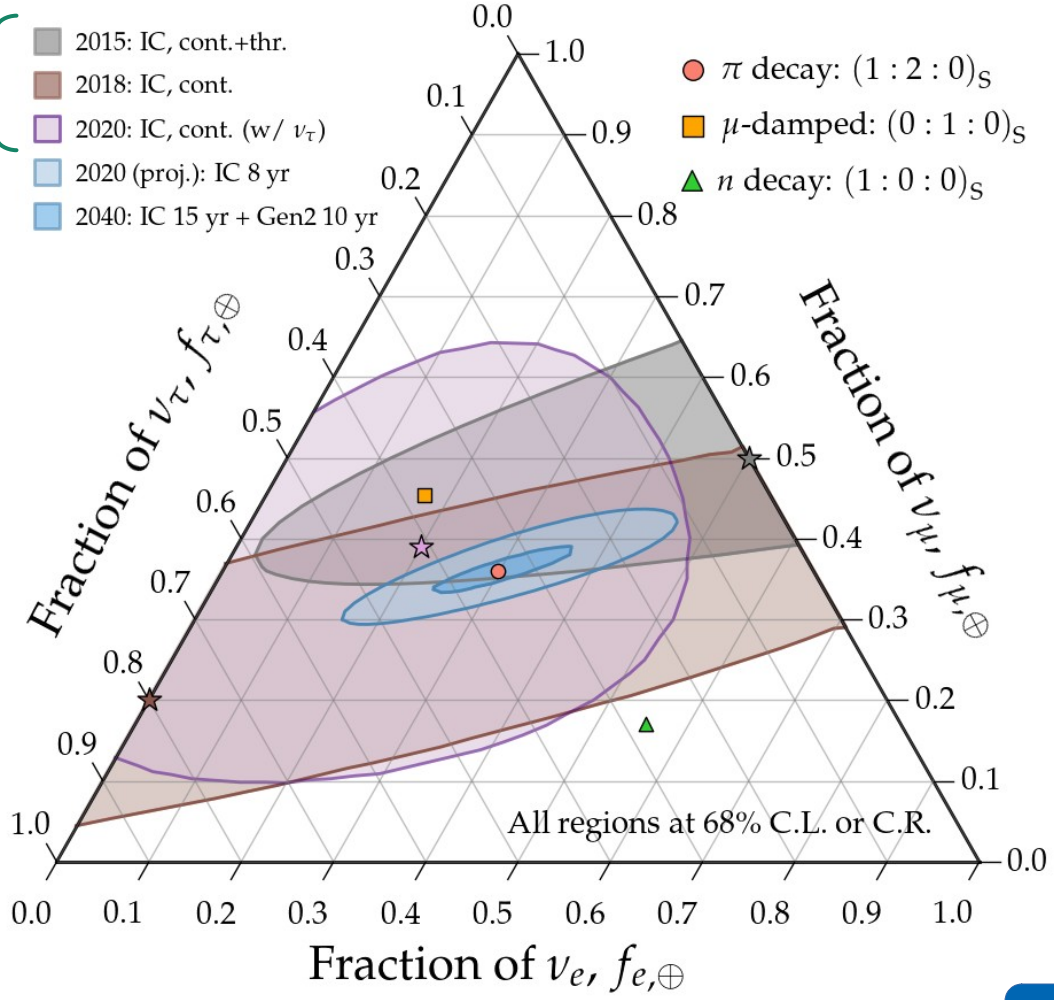

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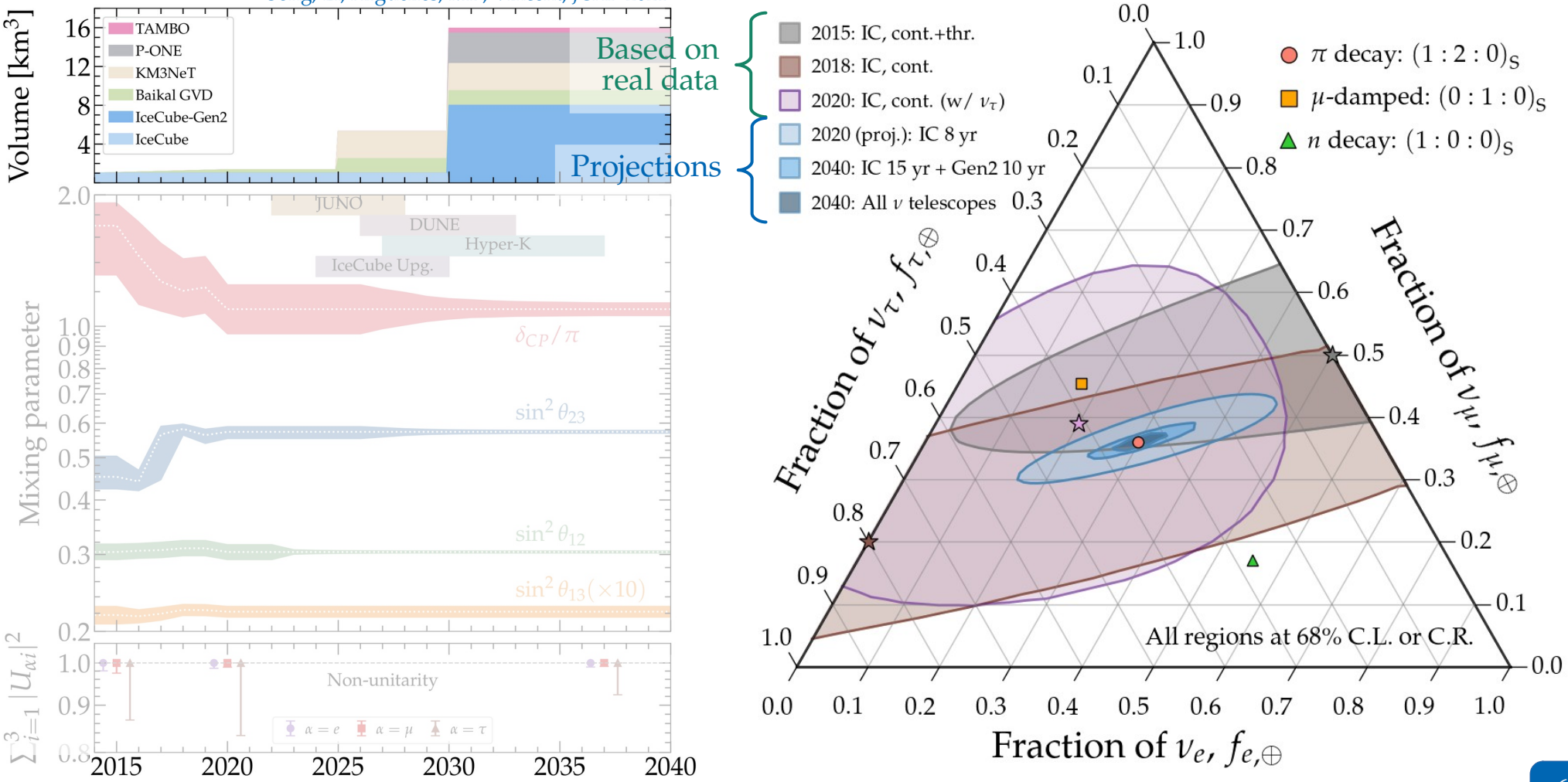
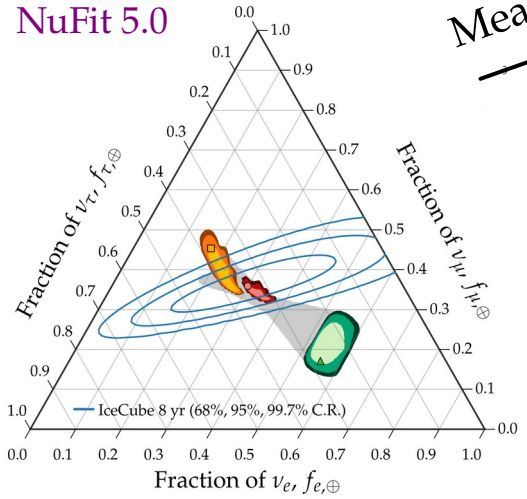


How knowing the mixing parameters better helps

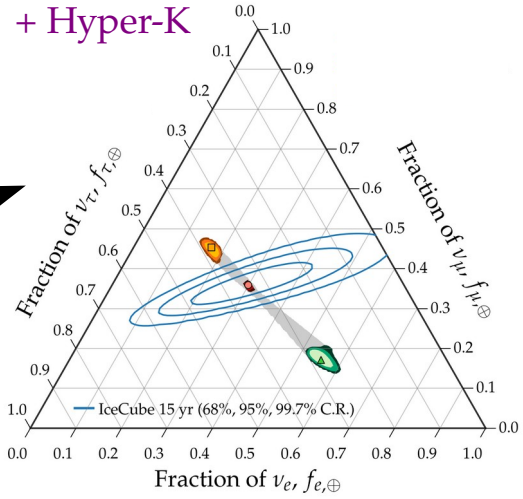
2020

NuFit 5.0

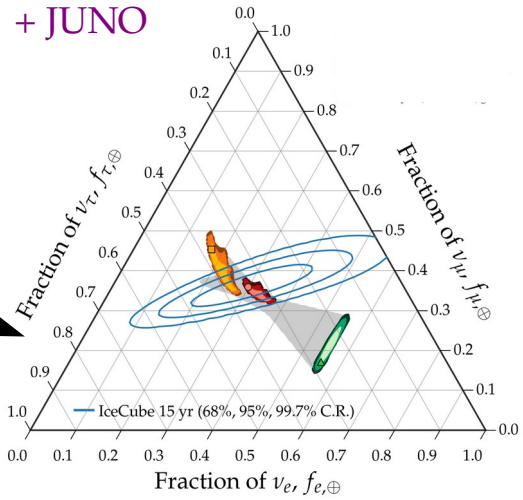


Measure θ_{23} better

+ Hyper-K



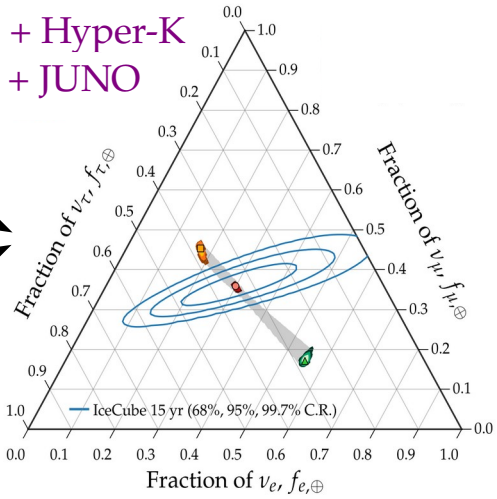
+ JUNO



Measure θ_{12} better

~2030

+ Hyper-K
+ JUNO

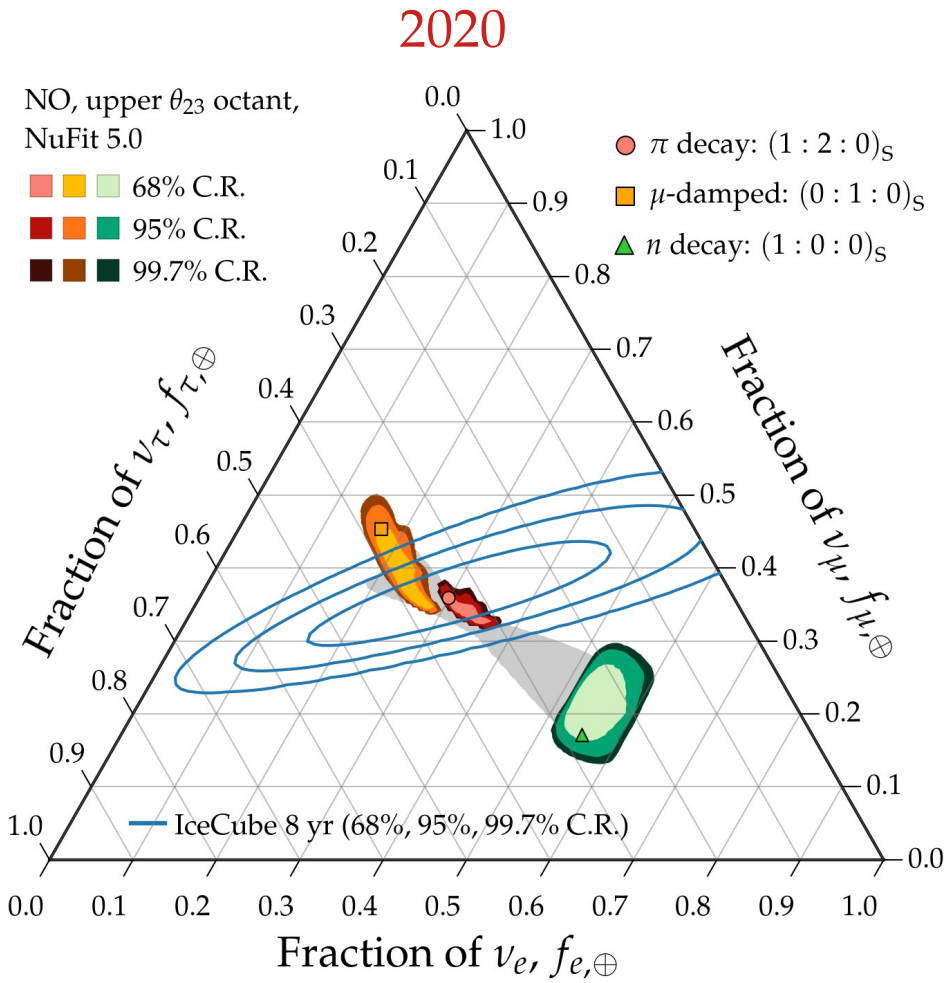


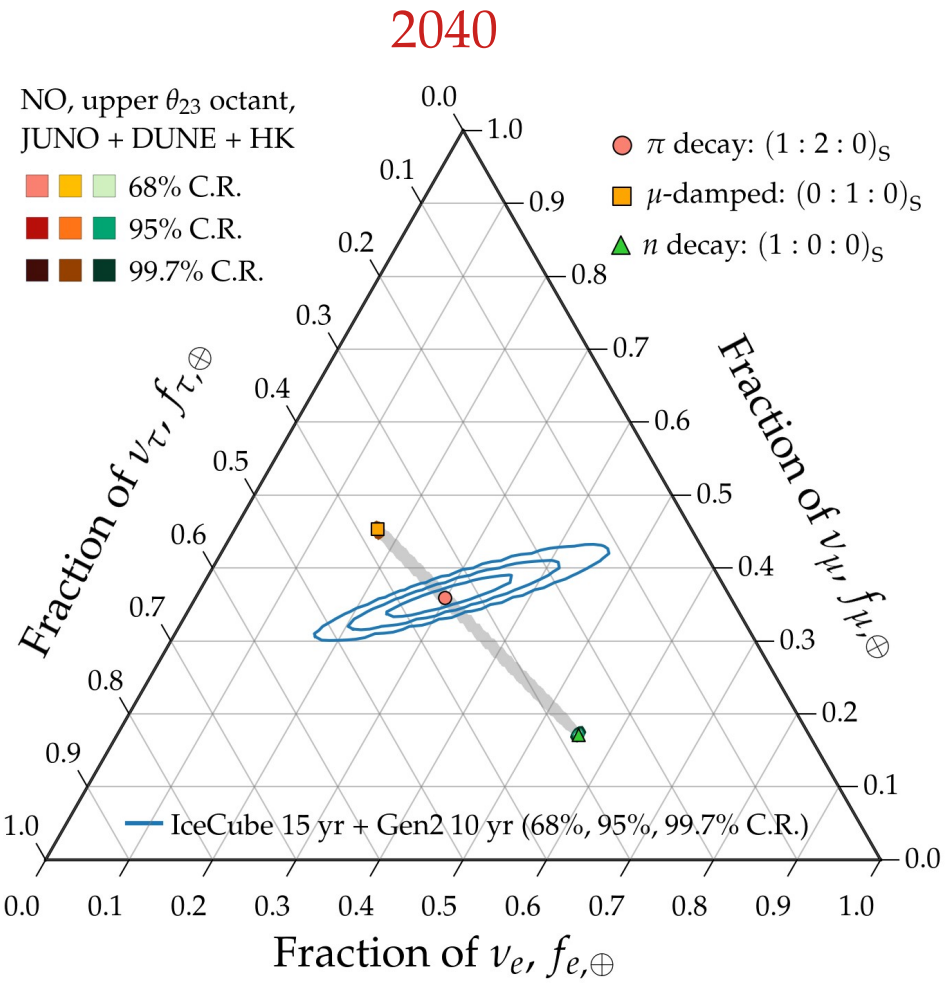
In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

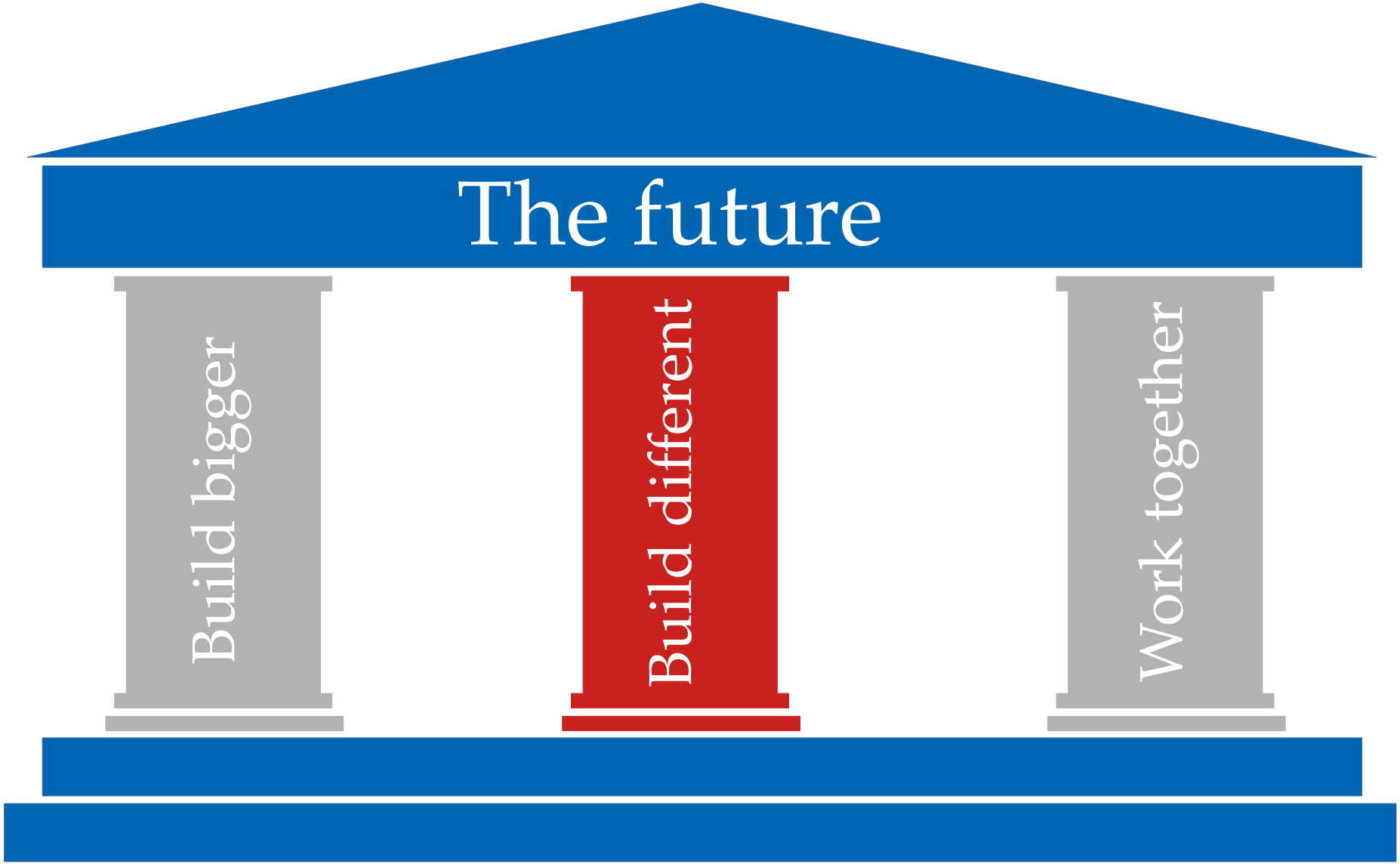
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

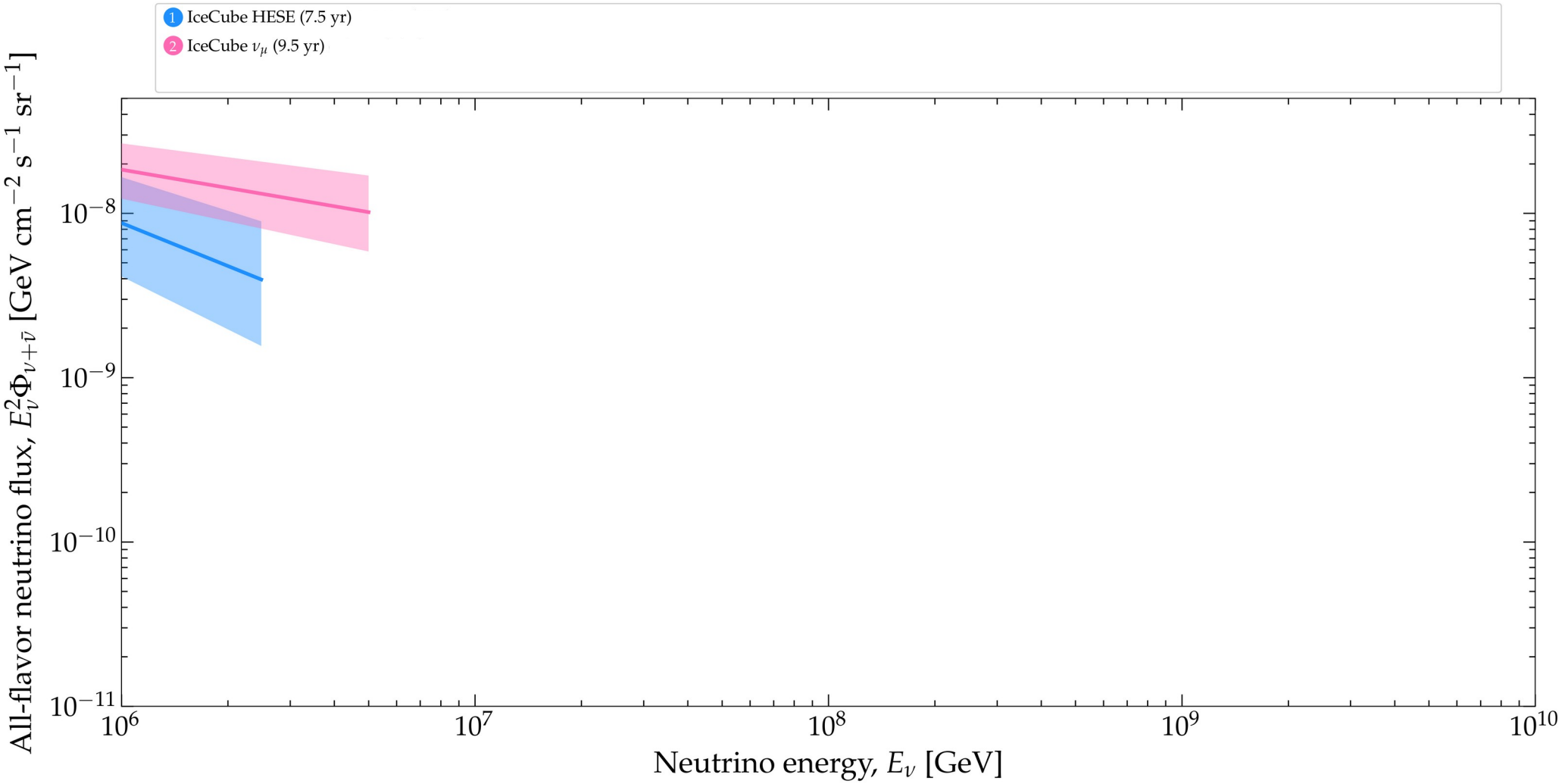
Theoretically palatable regions: 2020 → 2040





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


The future
Build bigger
Build different
Work together


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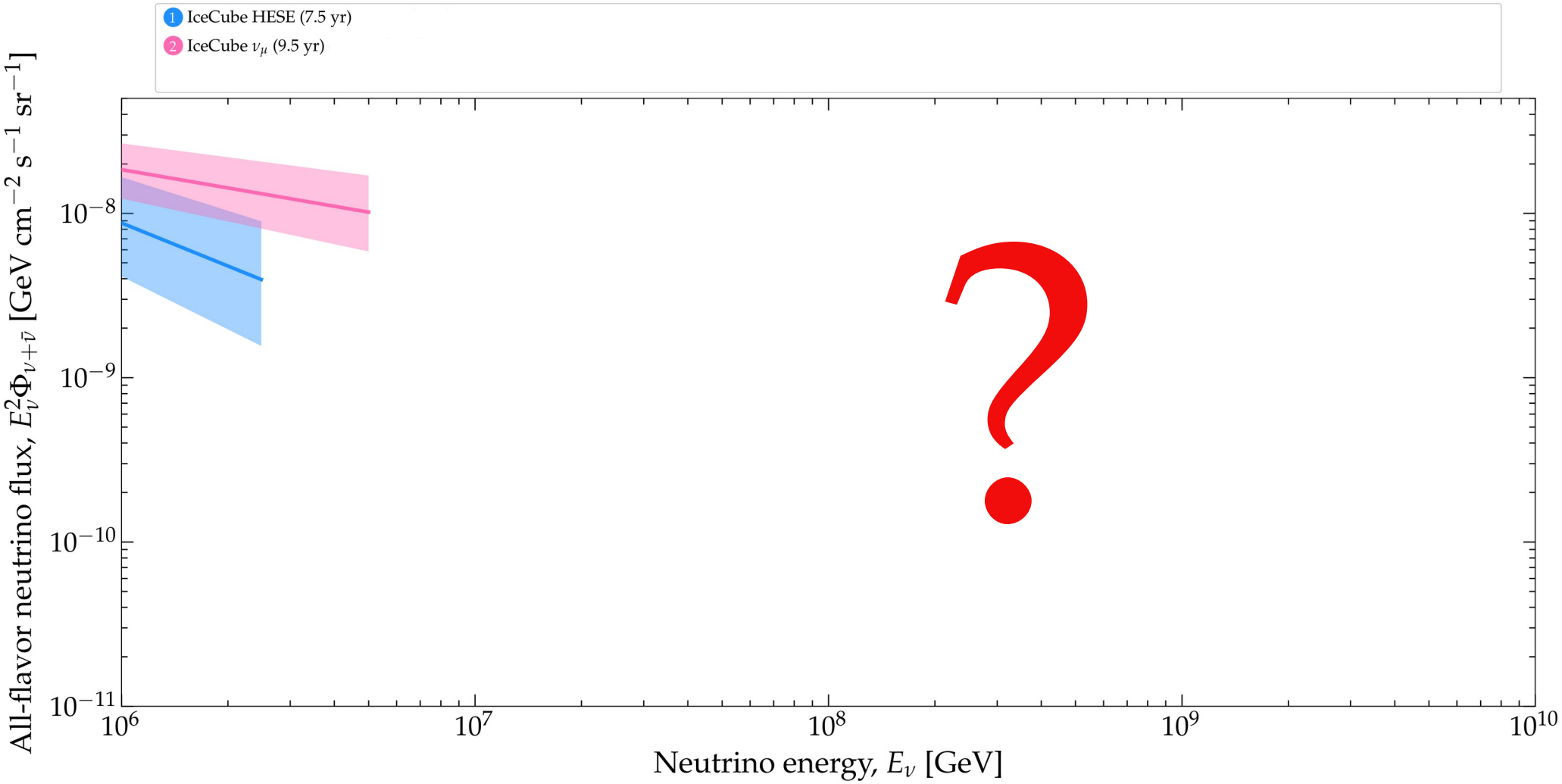
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]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All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
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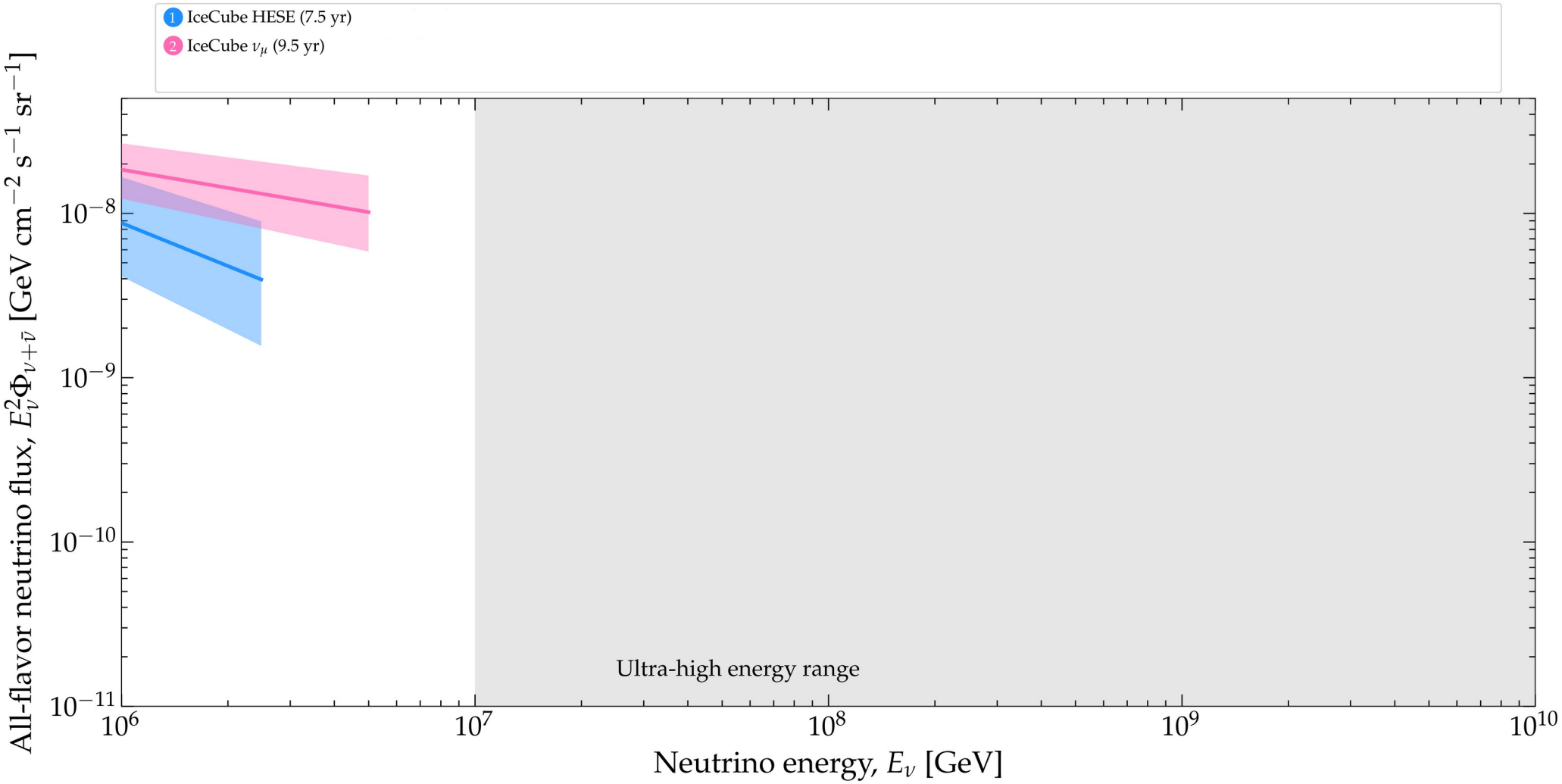
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]
?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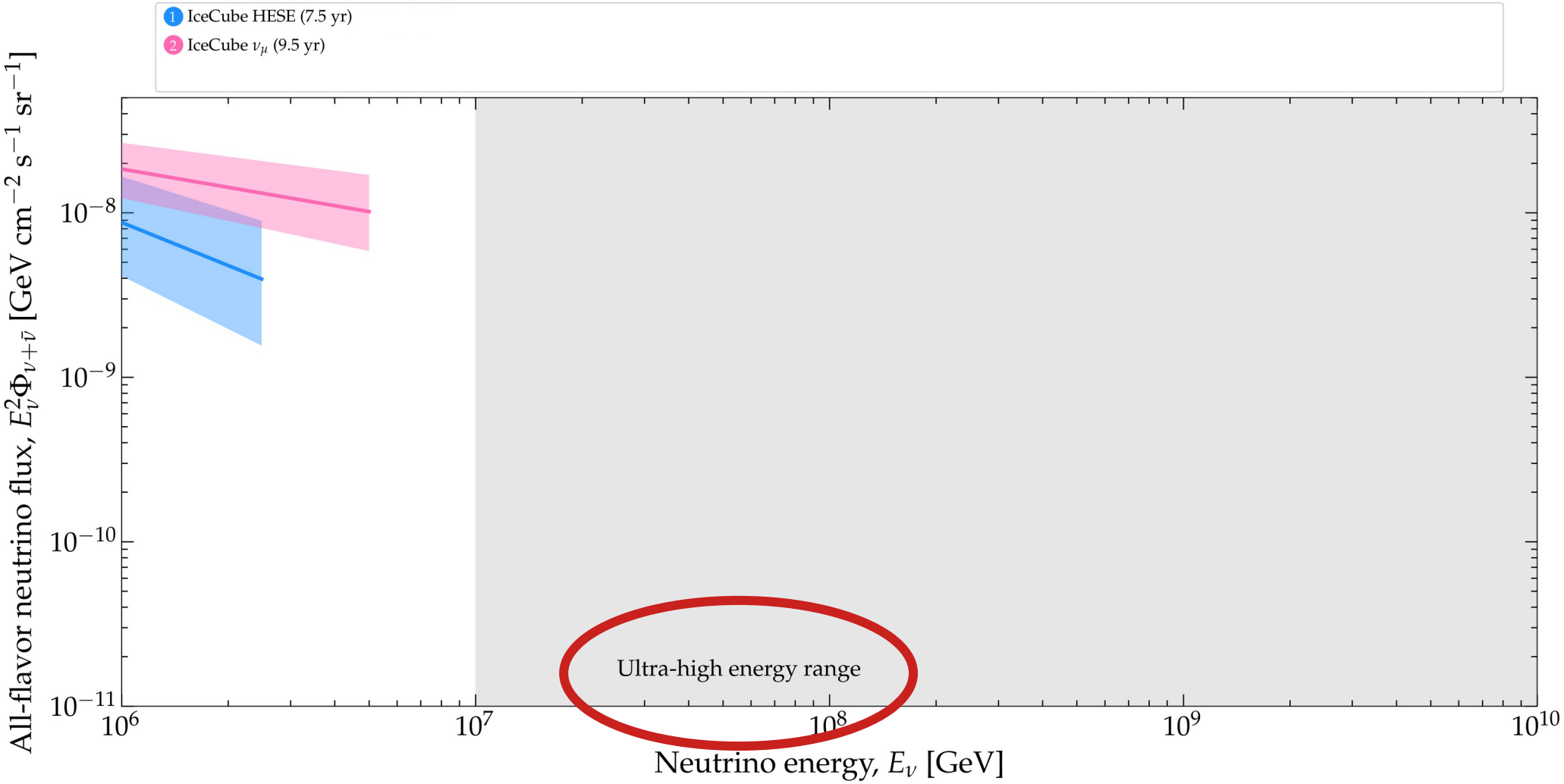
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Ultra-high energy range
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]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10^{-8}
10^{-9}
10^{-10}
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10^6
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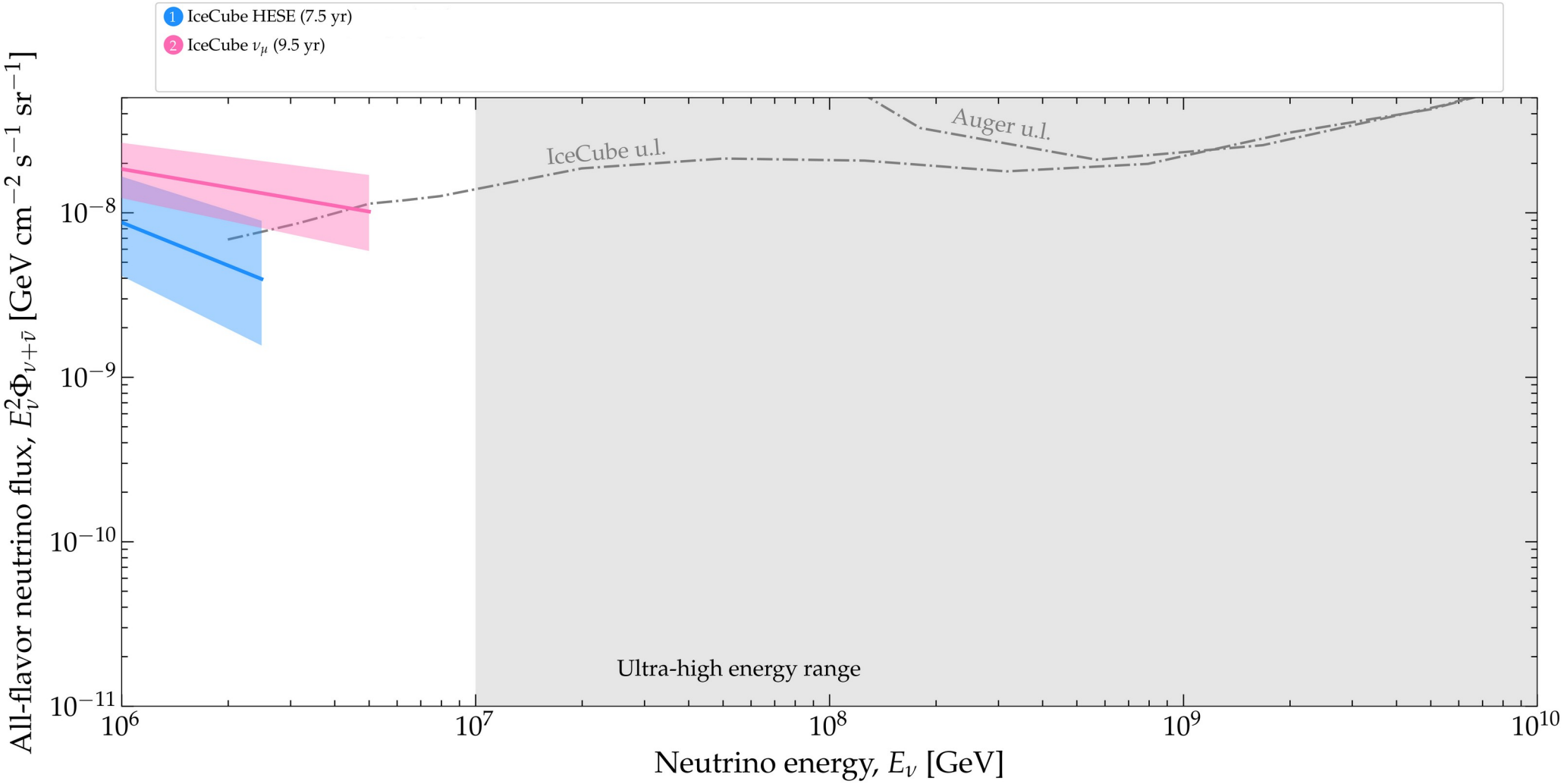
10^8
10^9
10^{10}
Ultra-high energy range
Neutrino energy, E_ν [GeV]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2 IceCube ν_μ (9.5 yr)
Auger u.l.
IceCube u.l.
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
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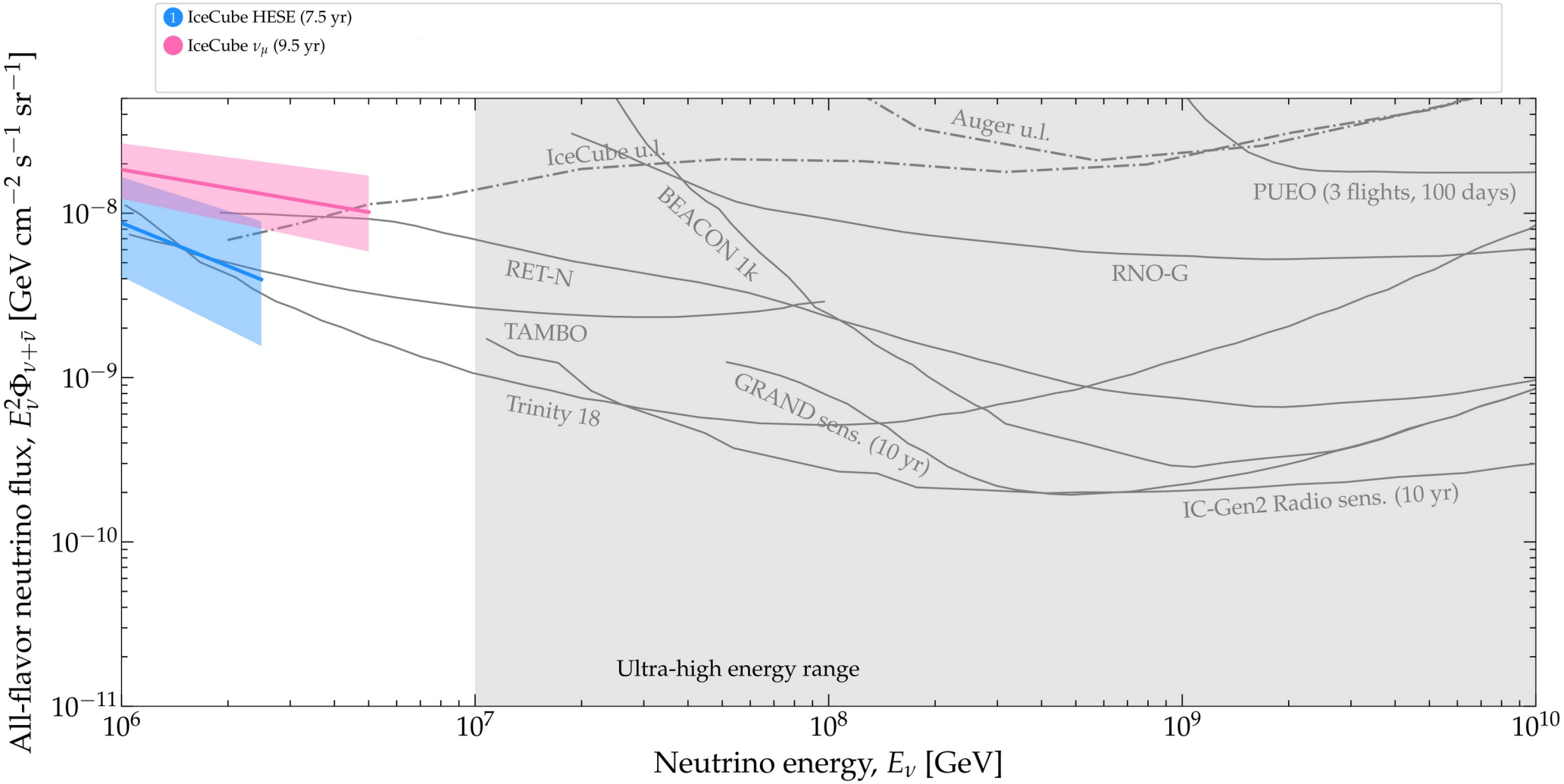
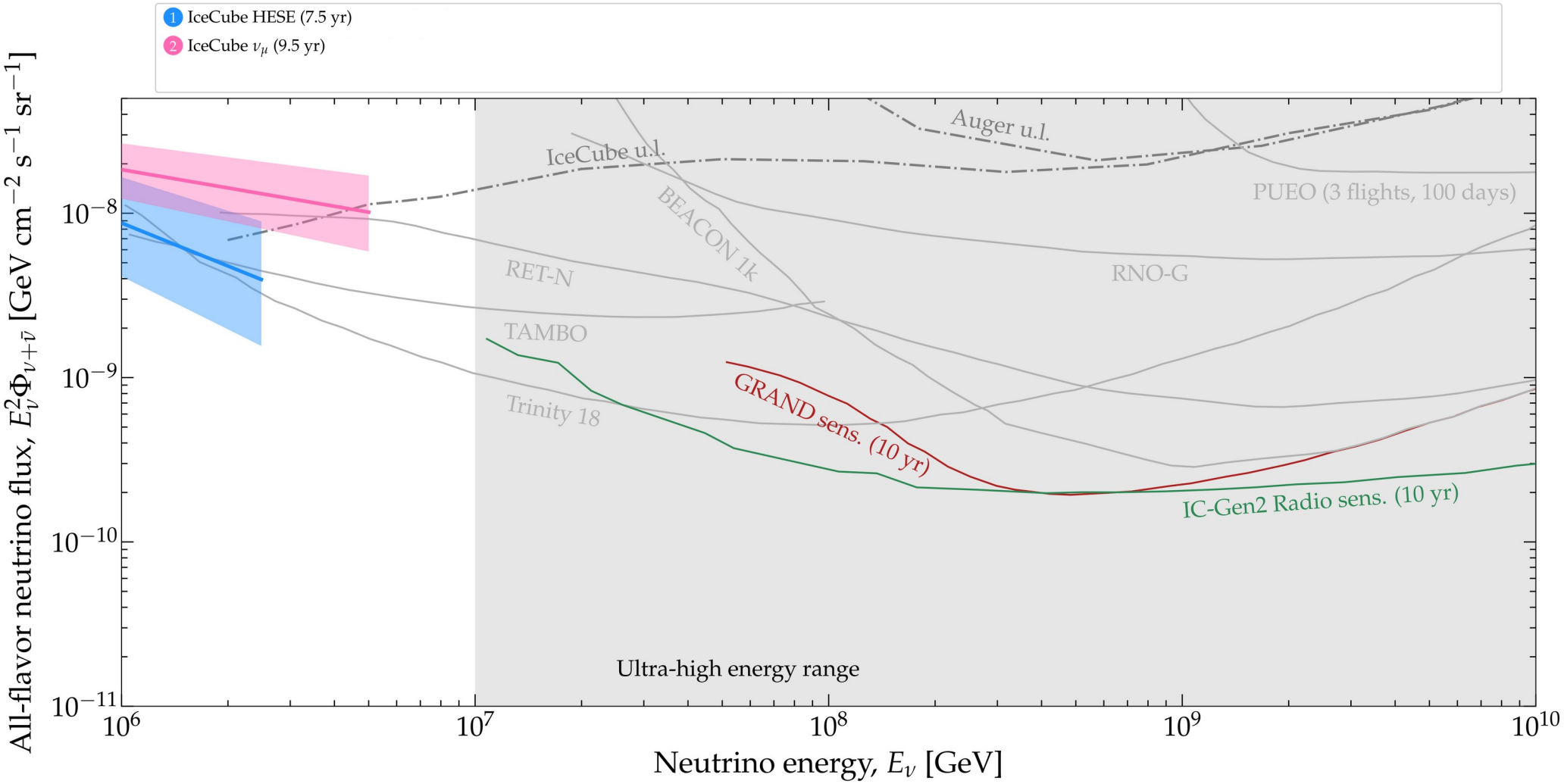
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]


IceCube HESE (7.5 yr)
IceCube ν_μ (9.5 yr)
Auger u.l.
IceCube u.l.
BEACON 1k
PUEO (3 flights, 100 days)
RET-N
RNO-G
TAMBO
GRAND sens. (10 yr)
Trinity 18
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
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}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10^6
10^7
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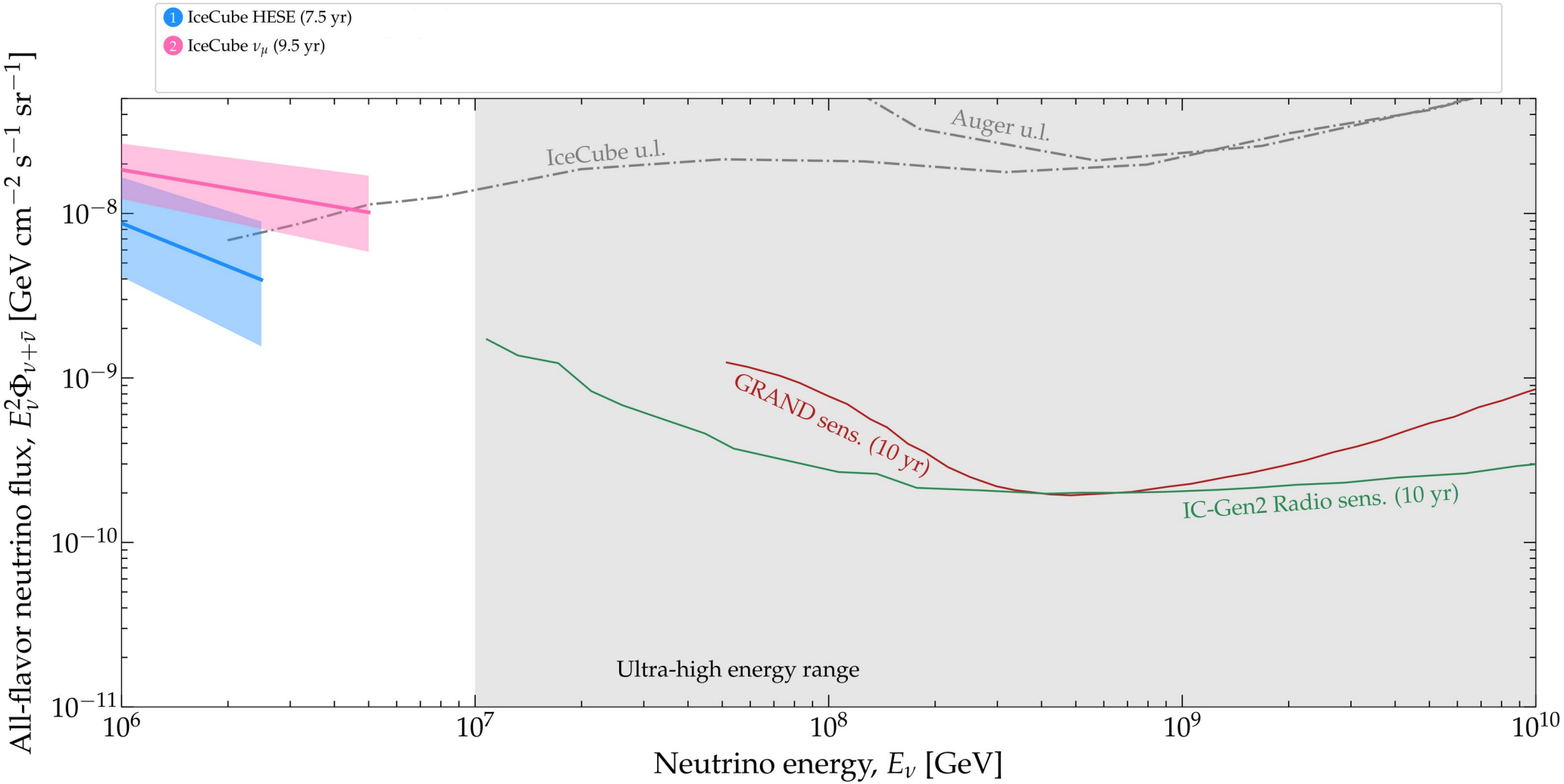
10^{10}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IceCube u.l.
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10^6
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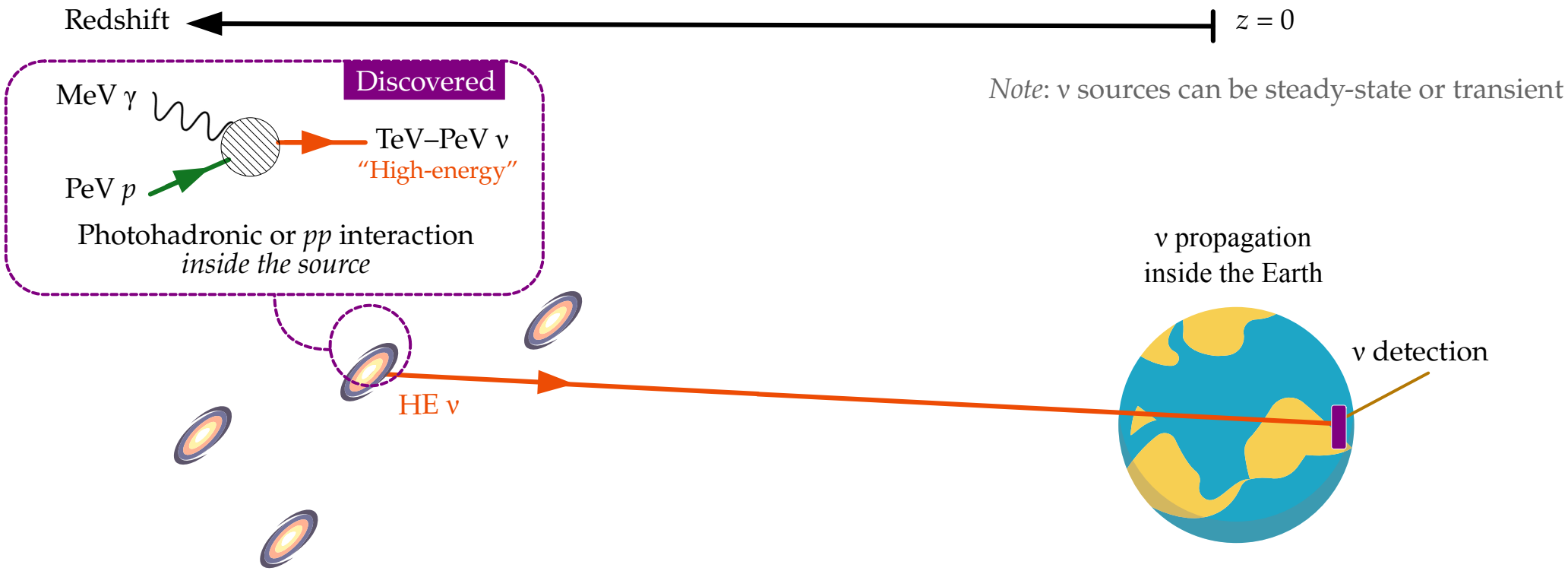
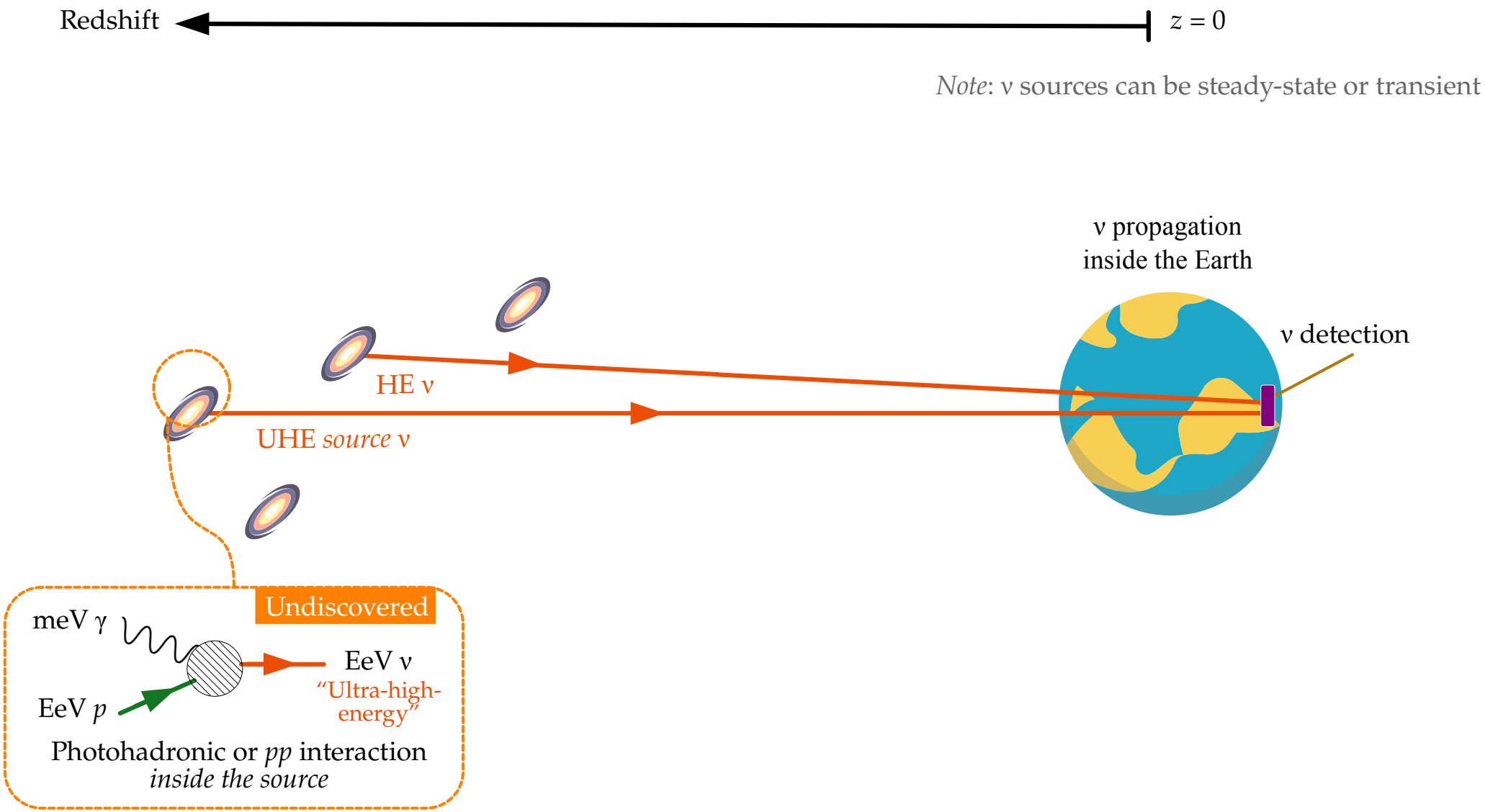
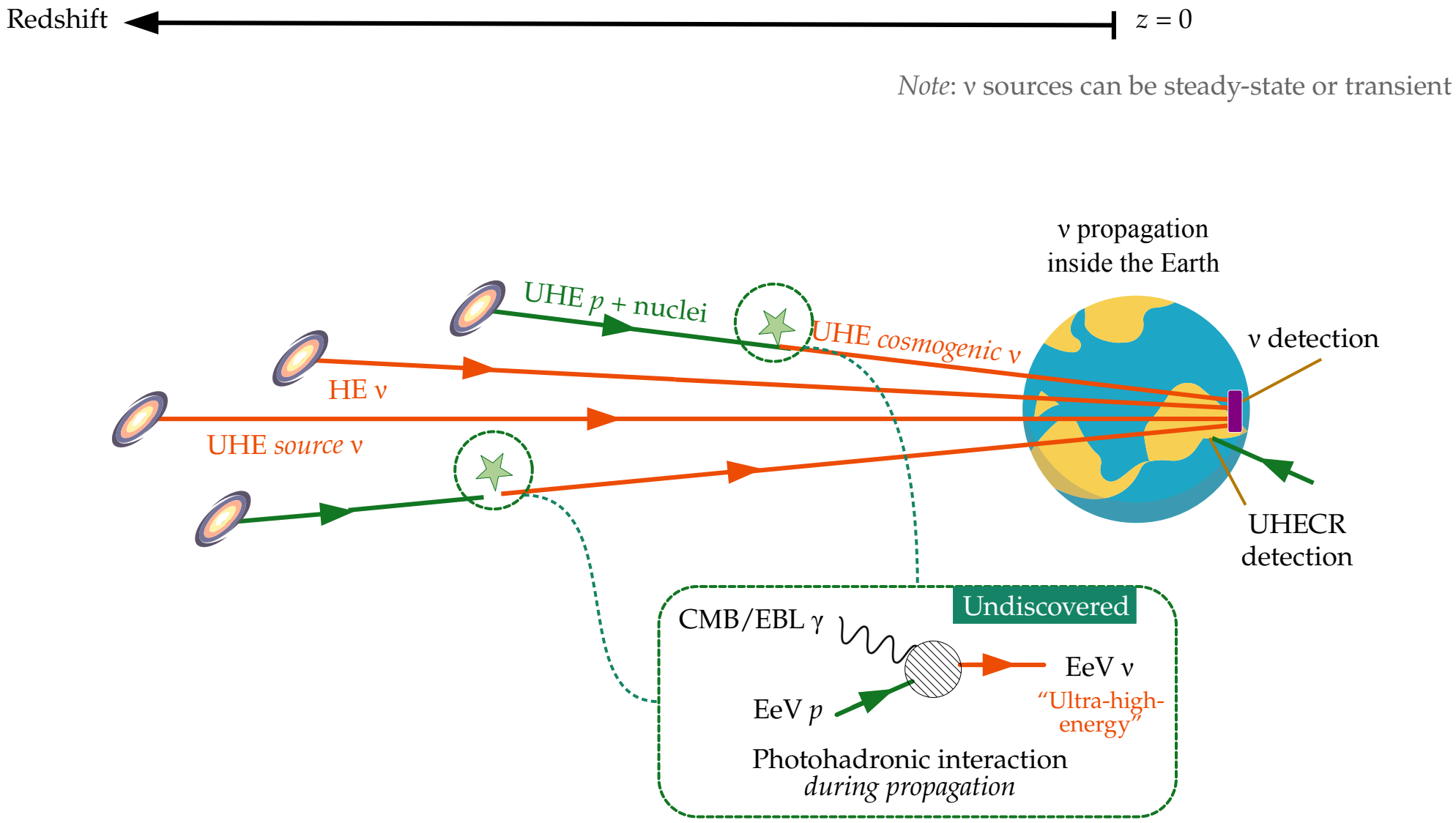
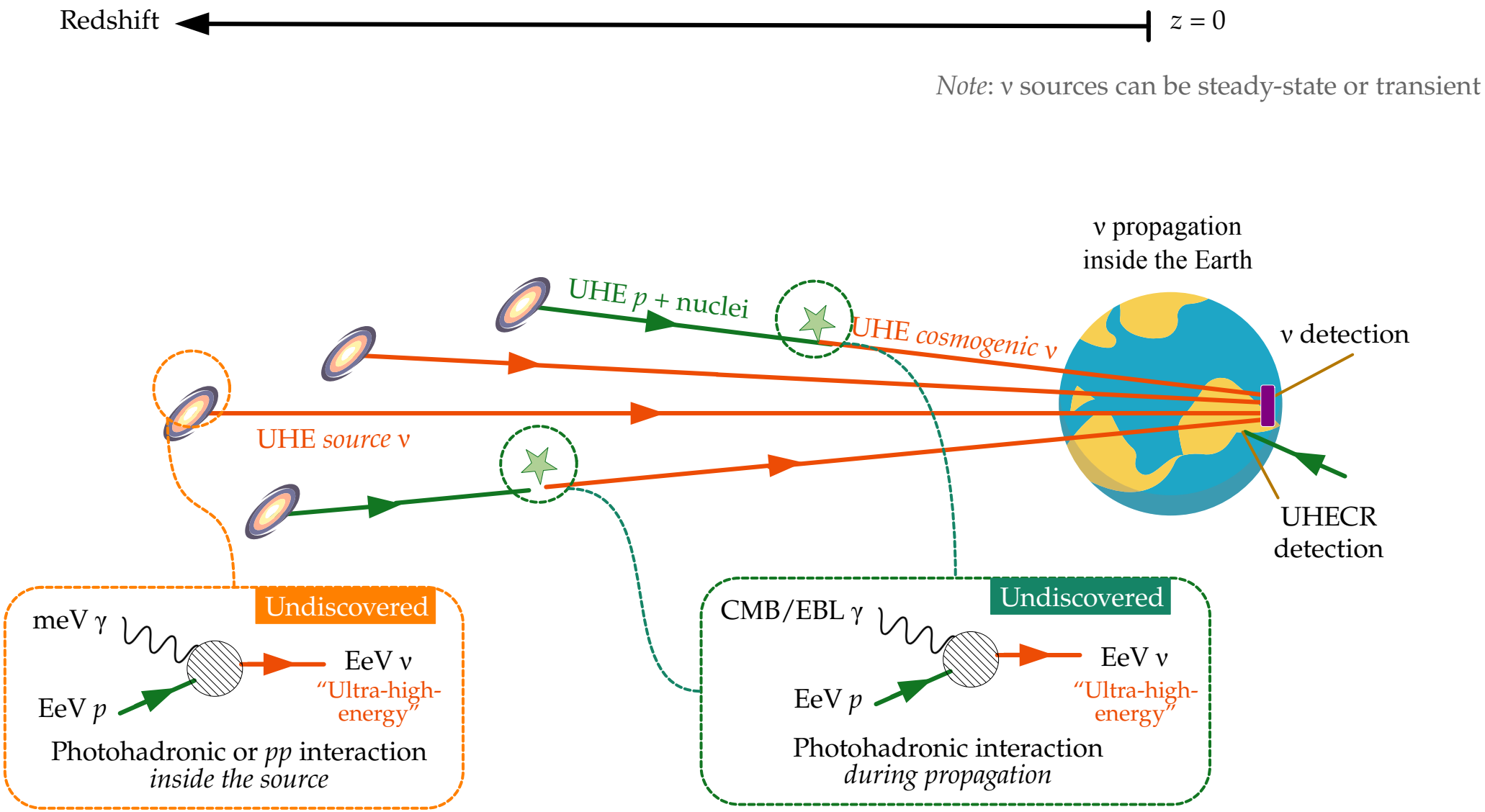
Neutrino energy, E_ν [GeV]


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


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


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


Redshift
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ν propagation
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UHE p + nuclei
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Undiscovered
meV γ
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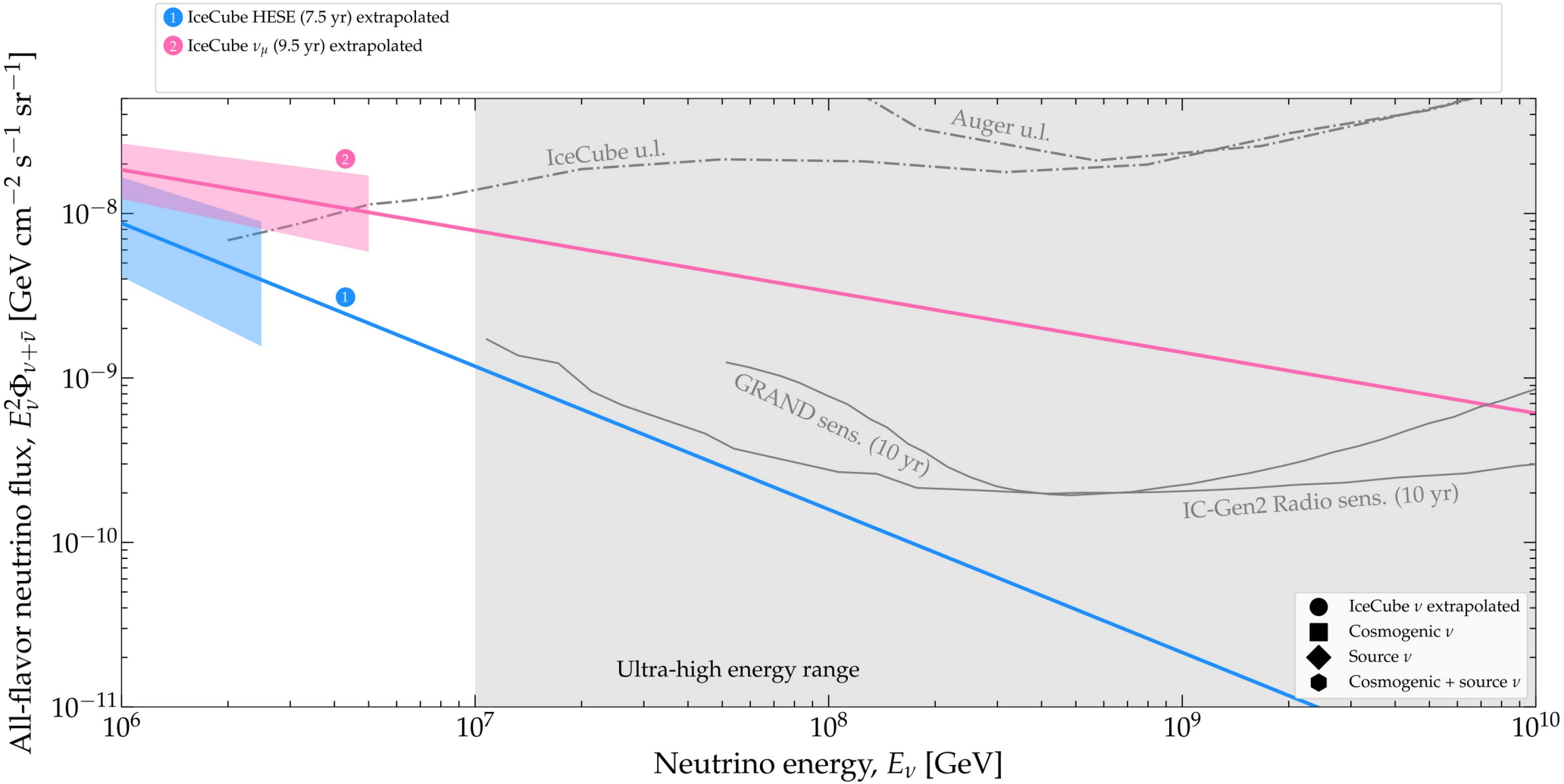
1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
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10^6
10^7
10^8
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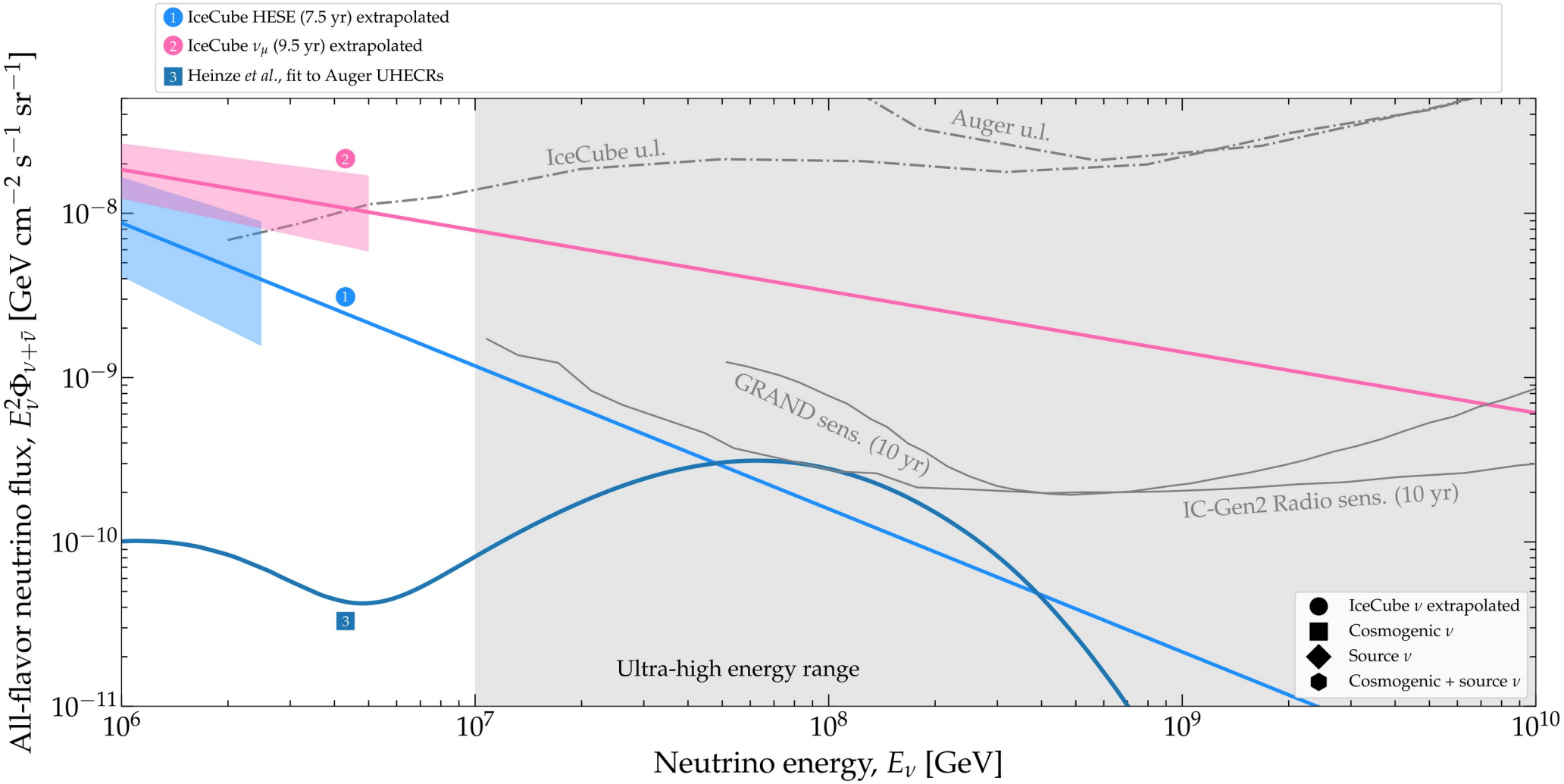
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Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
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IceCube ν extrapolated
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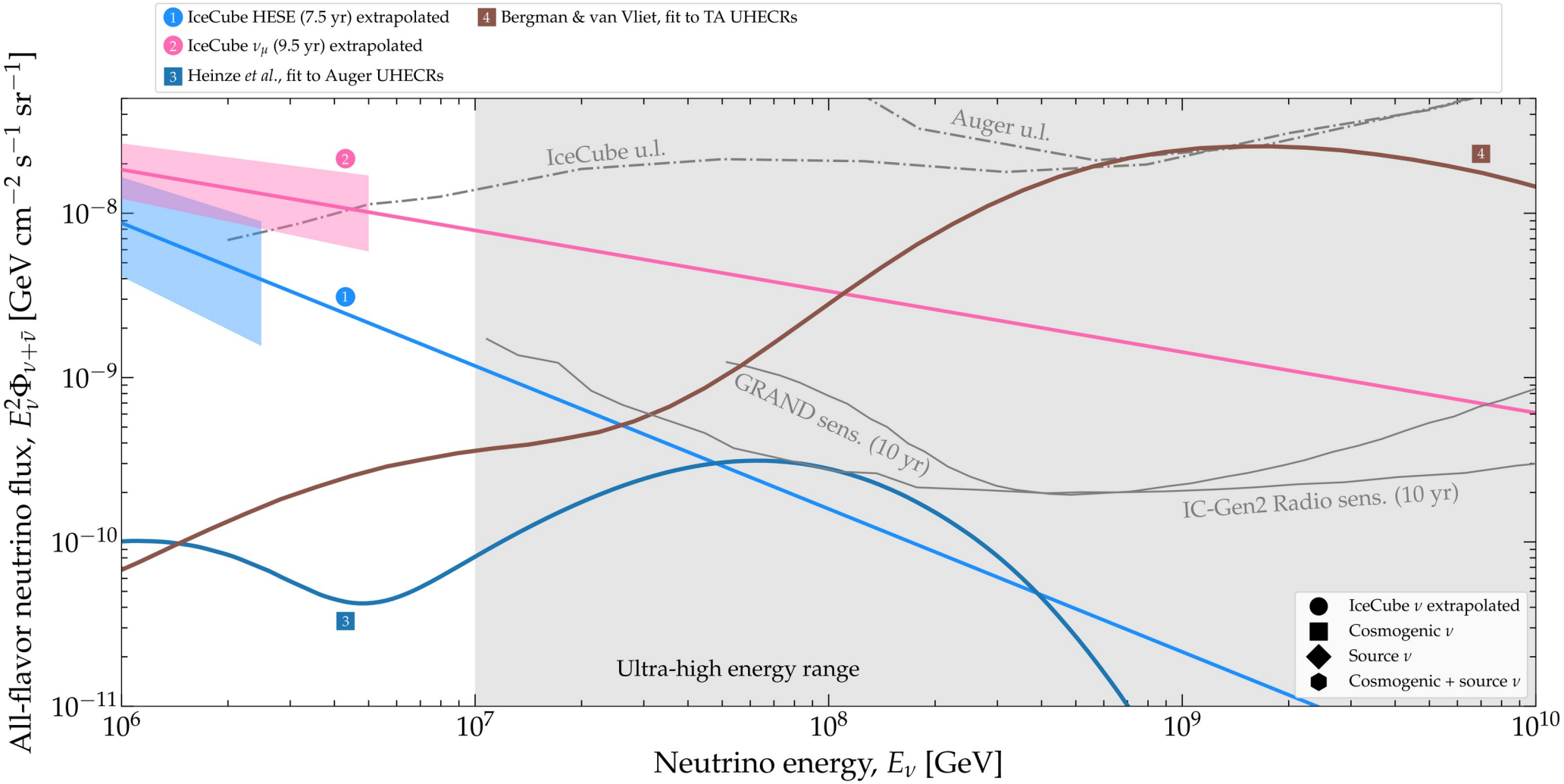
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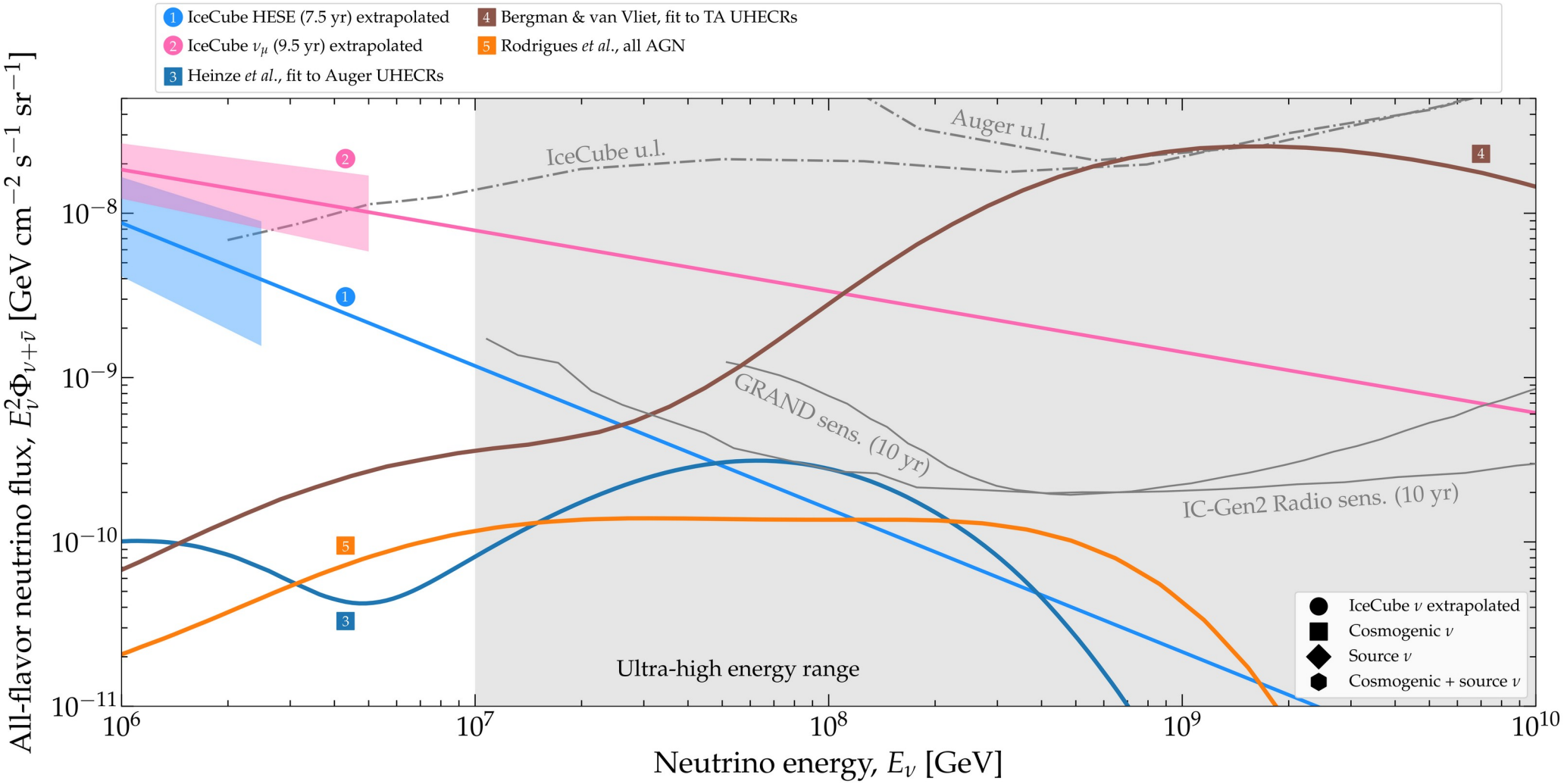
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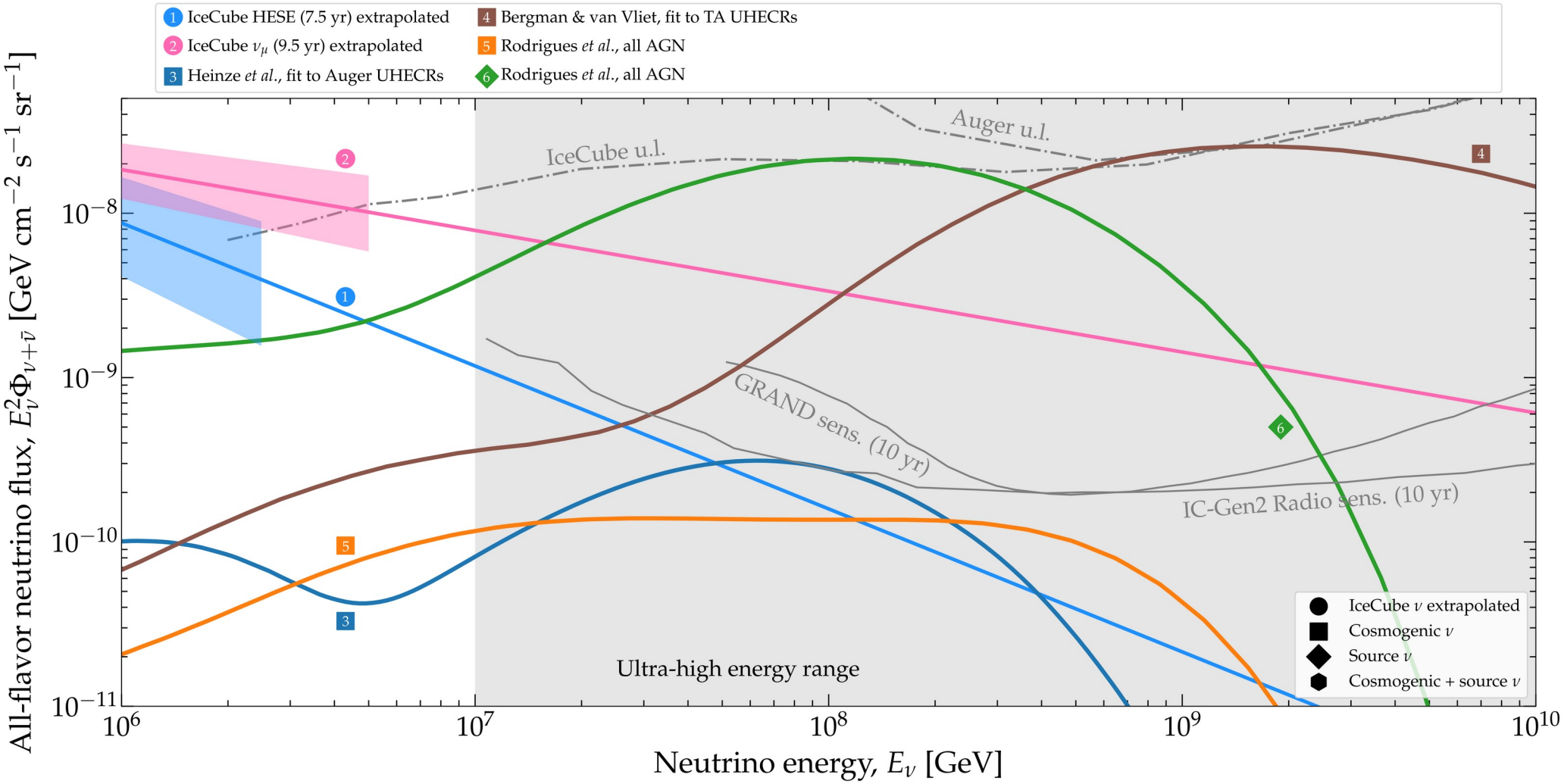
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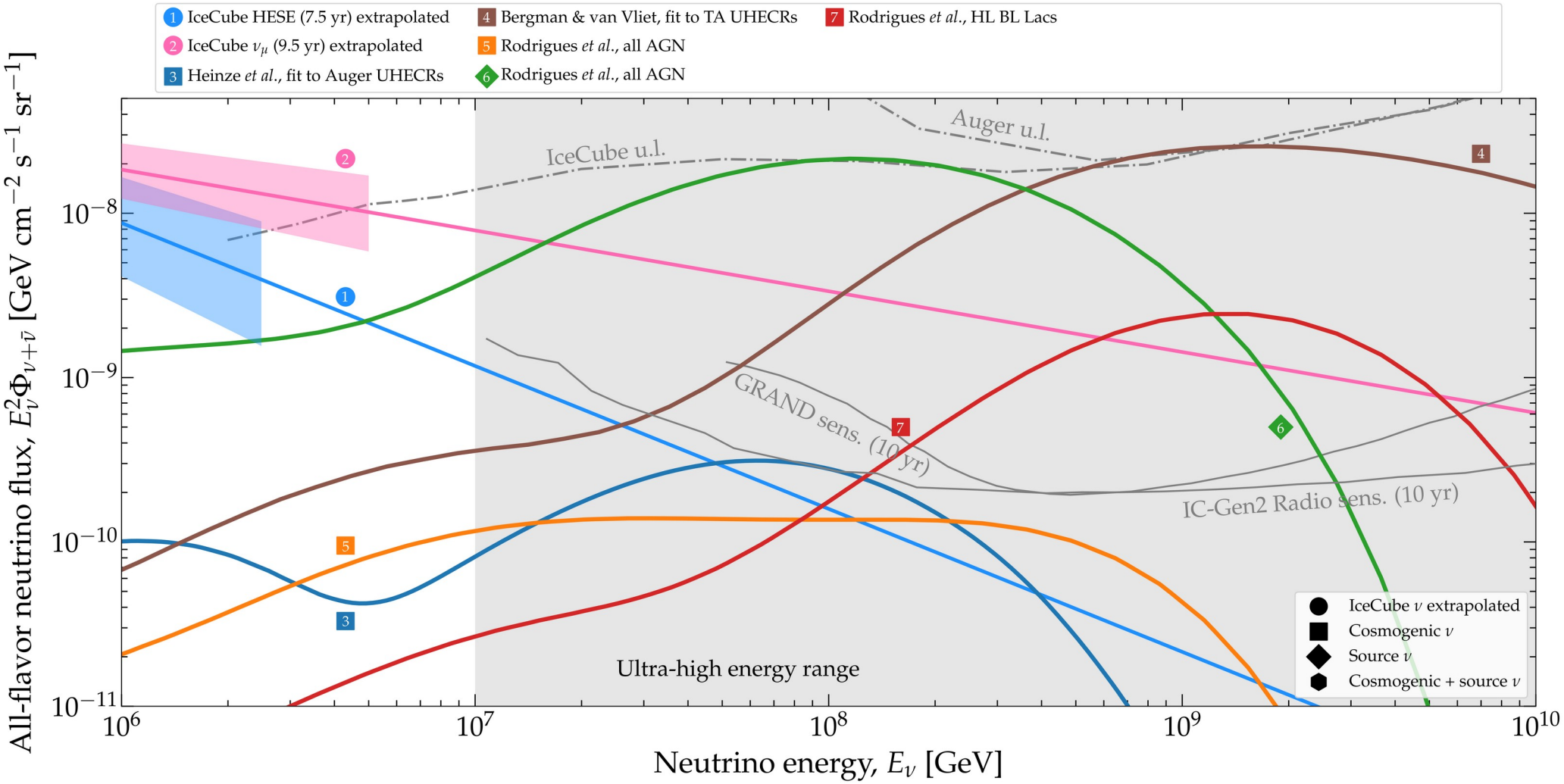
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IceCube u.l.
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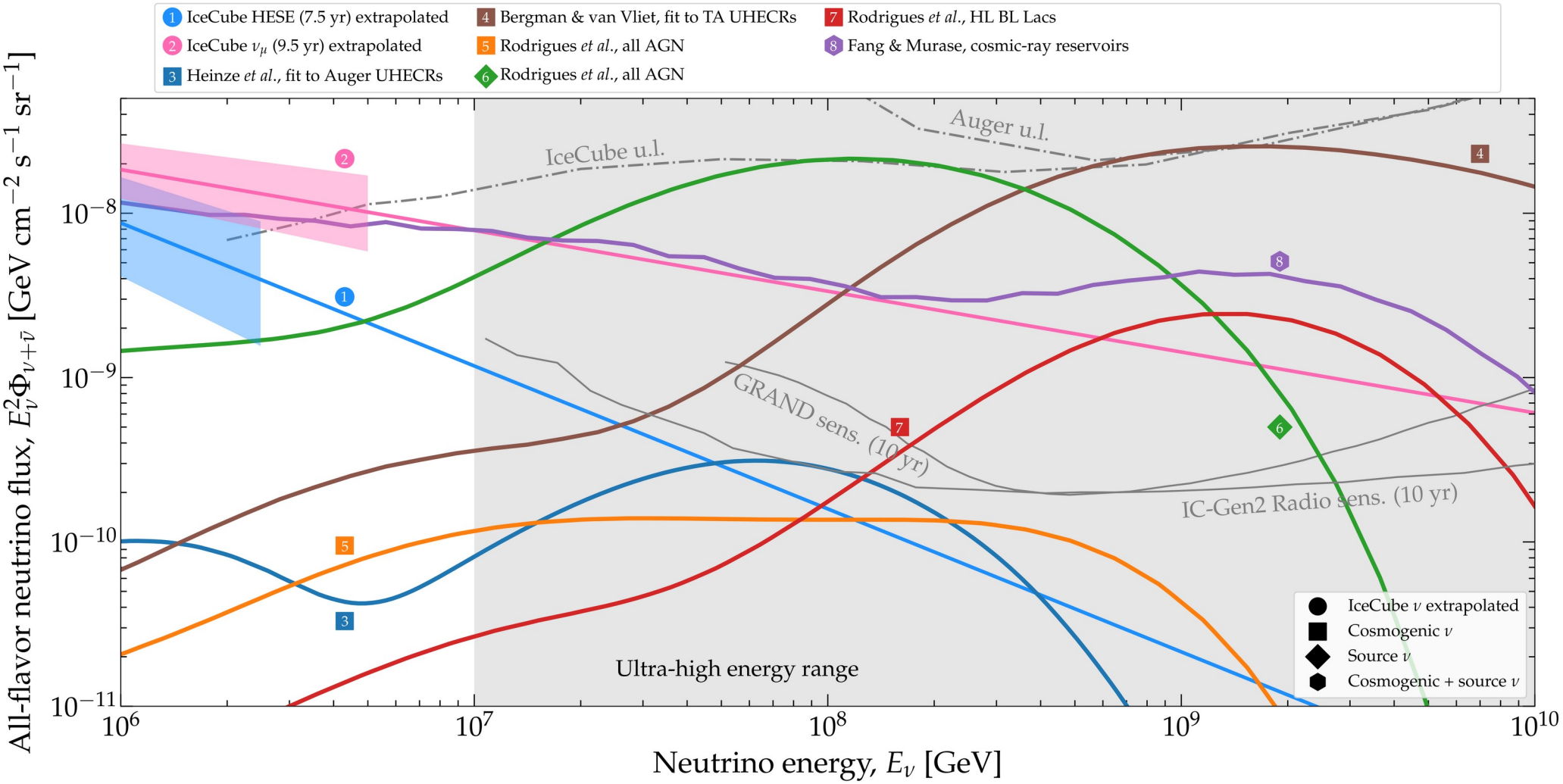
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IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
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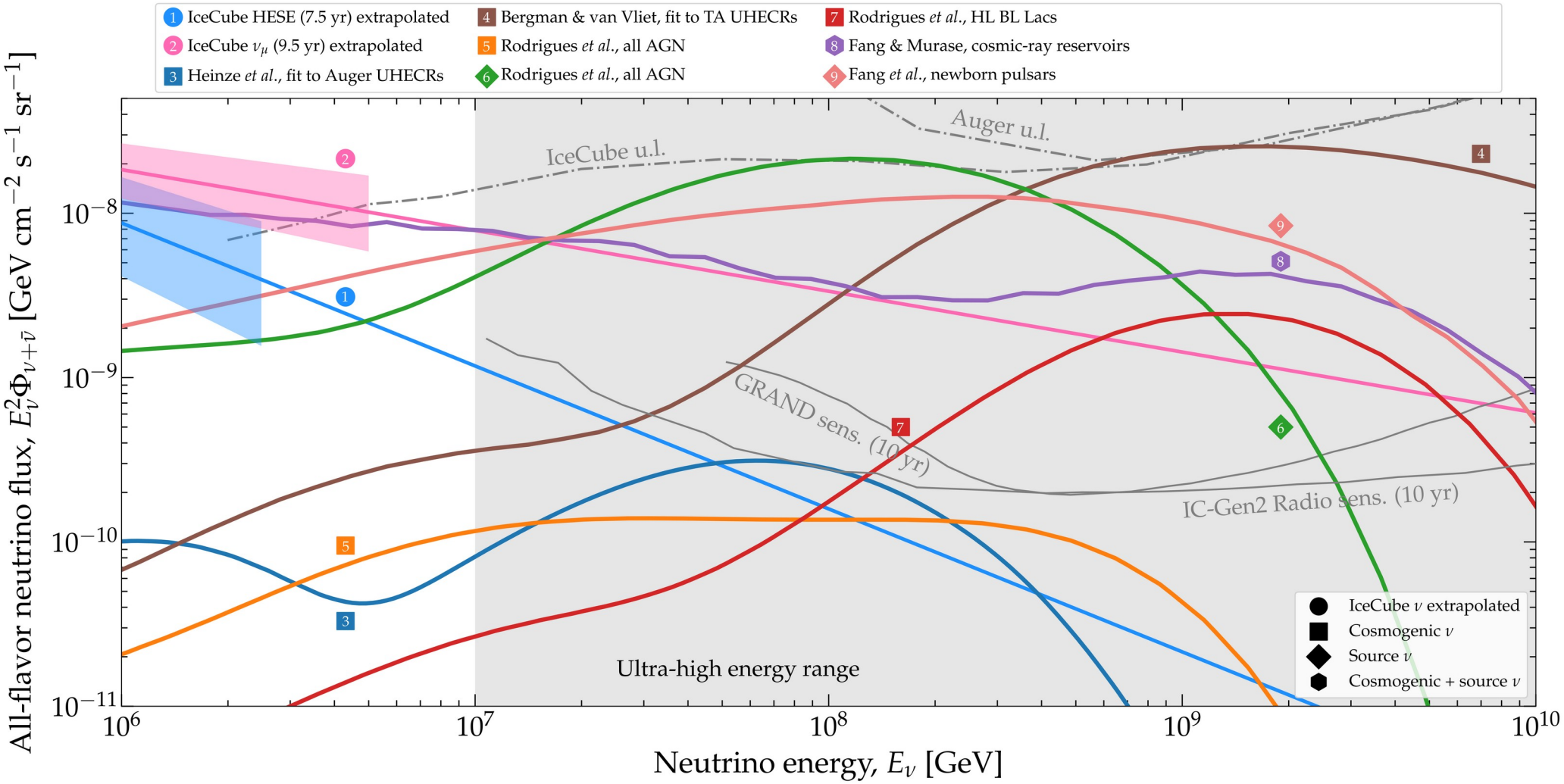
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Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
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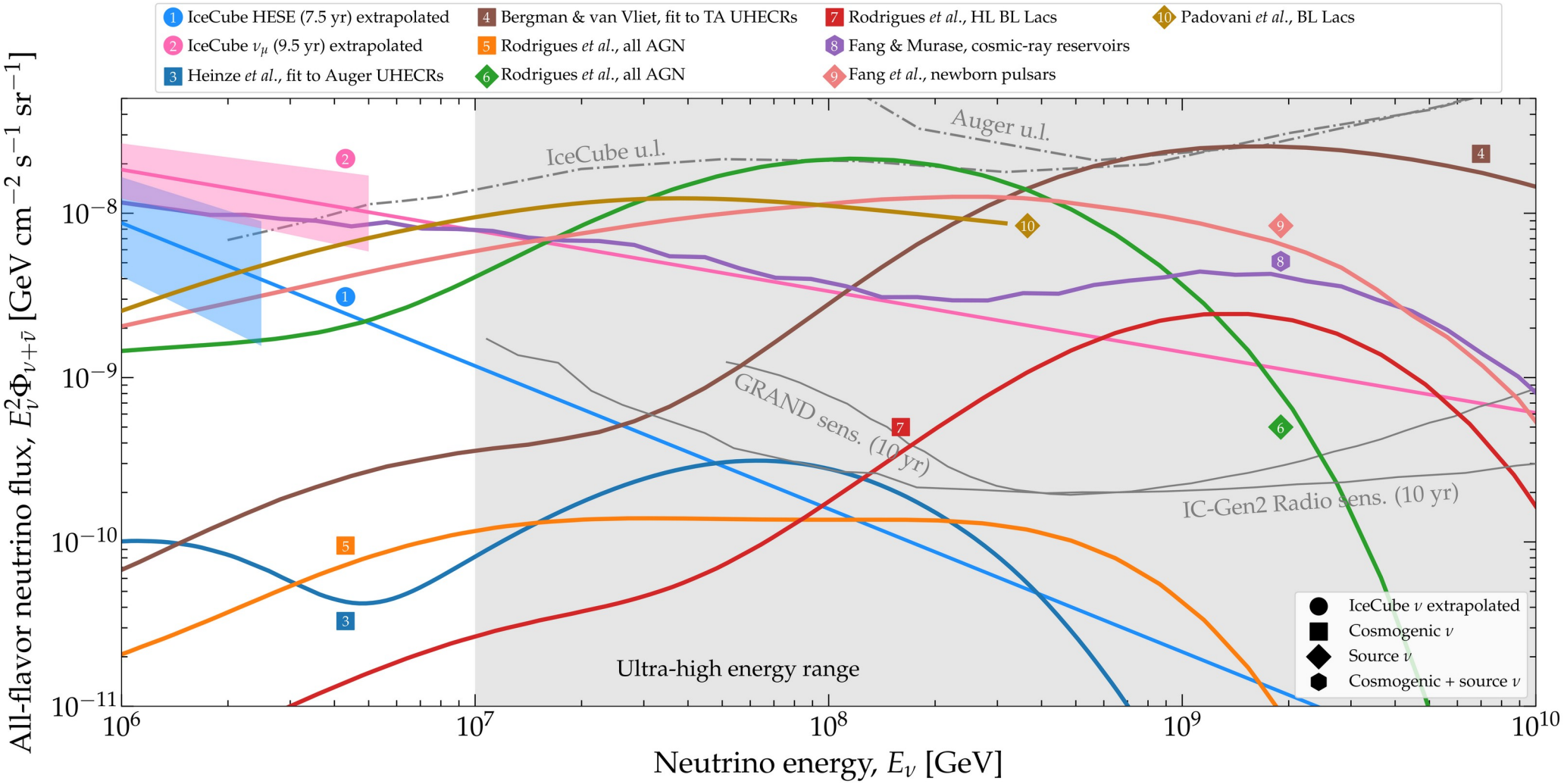
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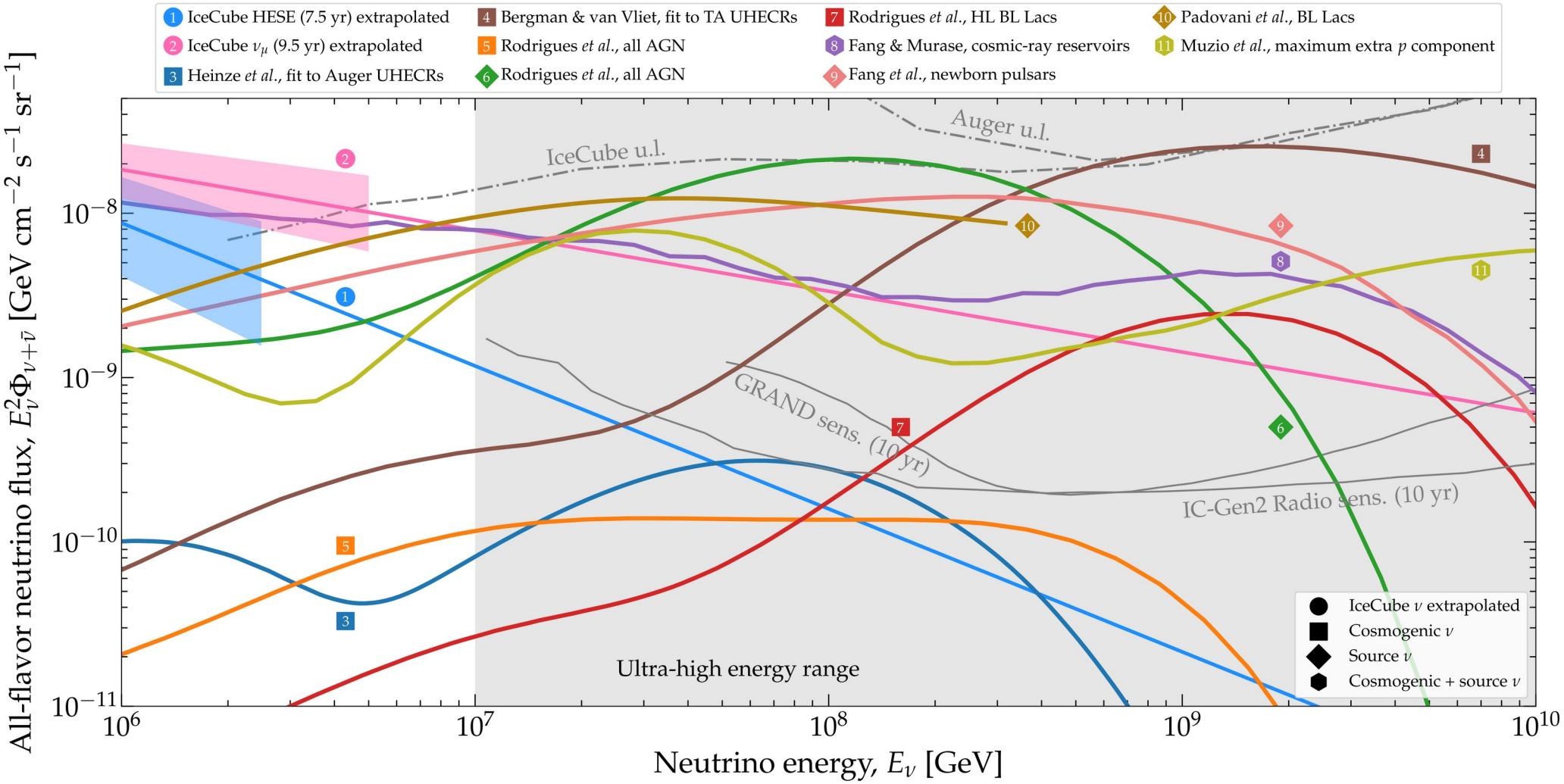
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Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
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Source ν
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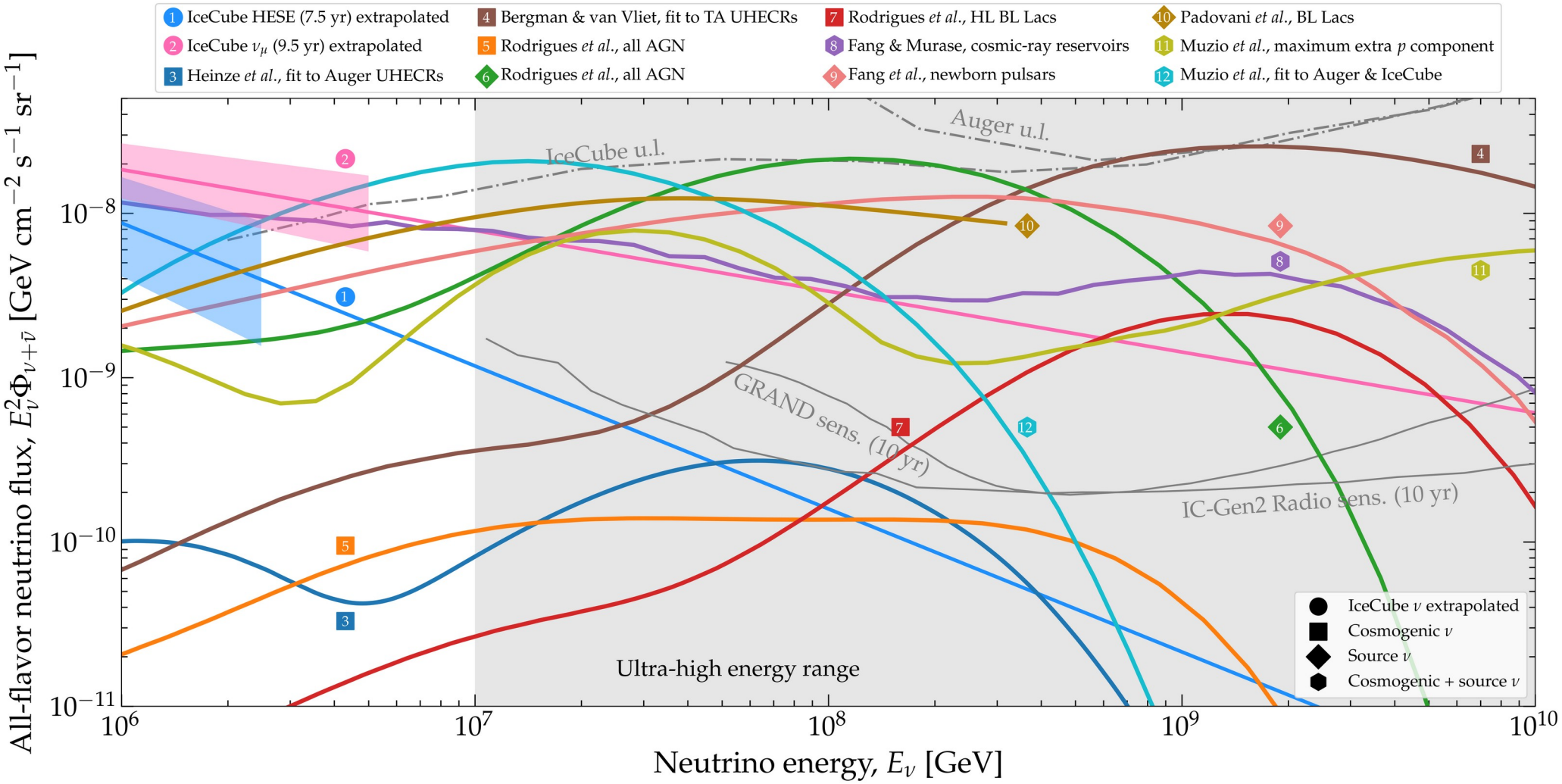
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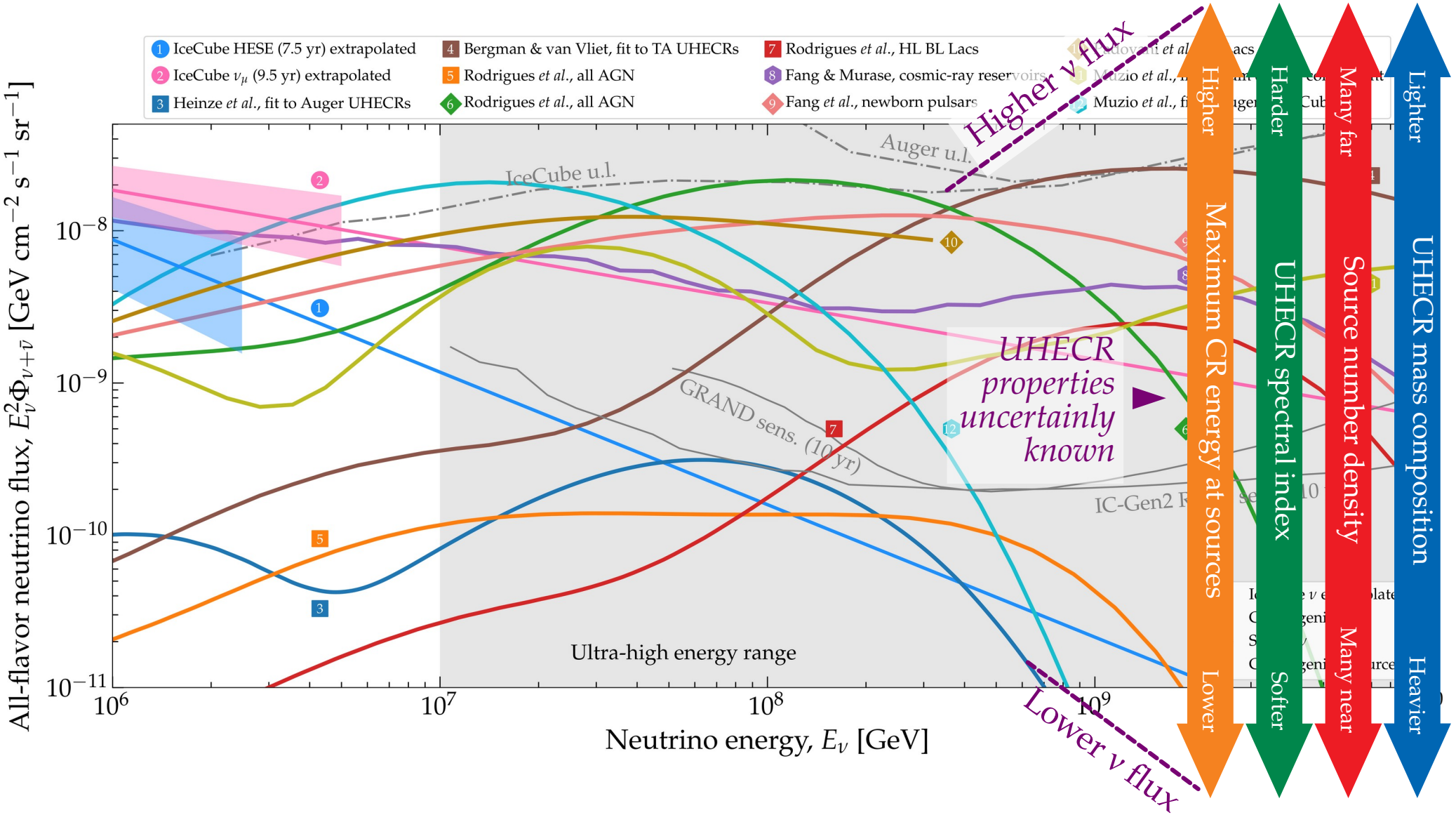
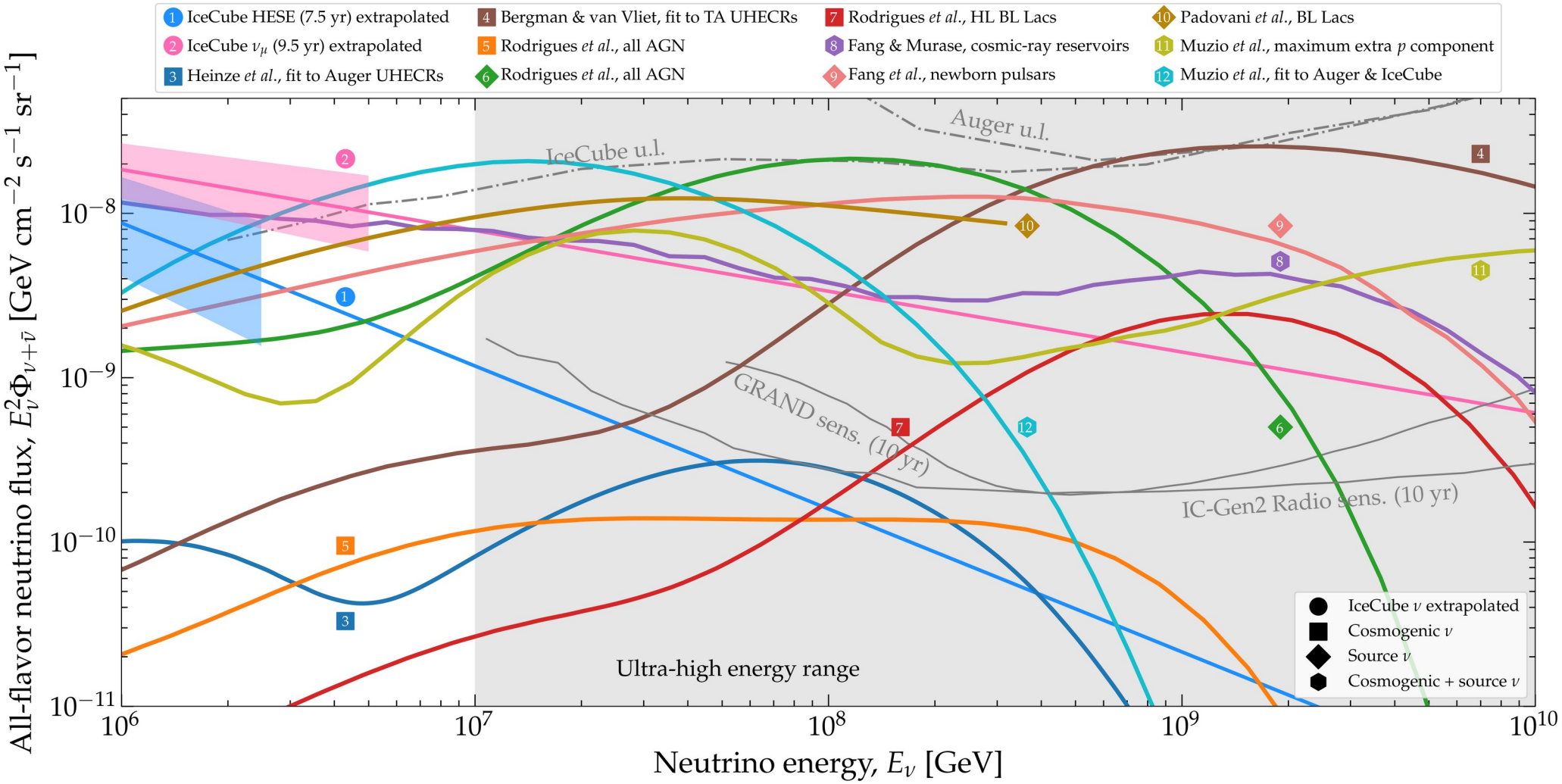
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}


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
Higher ν flux
Lower ν flux
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2
UHECR properties uncertainly known
Ultra-high energy range
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
Higher
Maximum CR energy at sources
Lower
Harder
UHECR spectral index
Softer
Many far
Source number density
Many near
Lighter
UHECR mass composition
Heavier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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)
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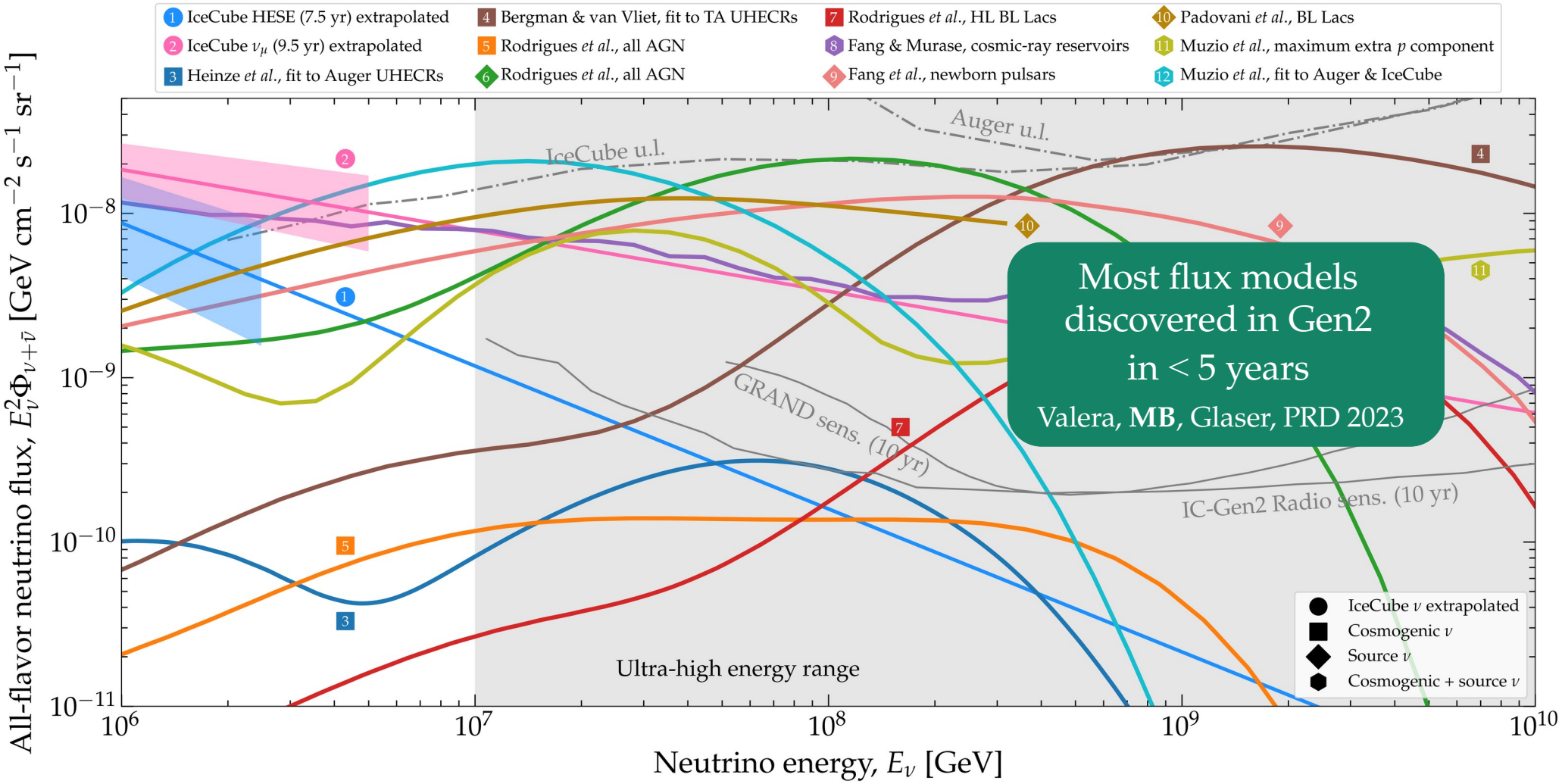
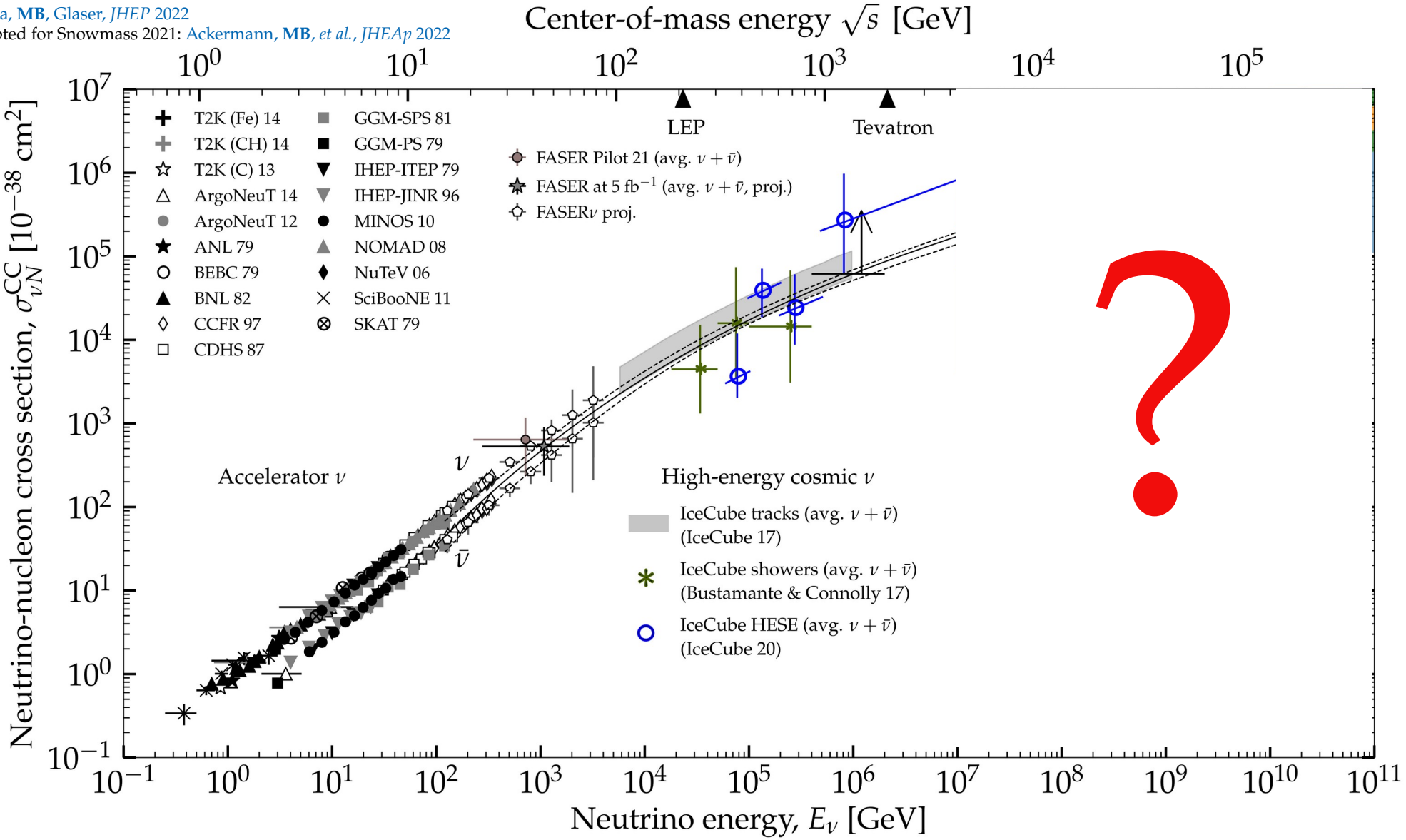


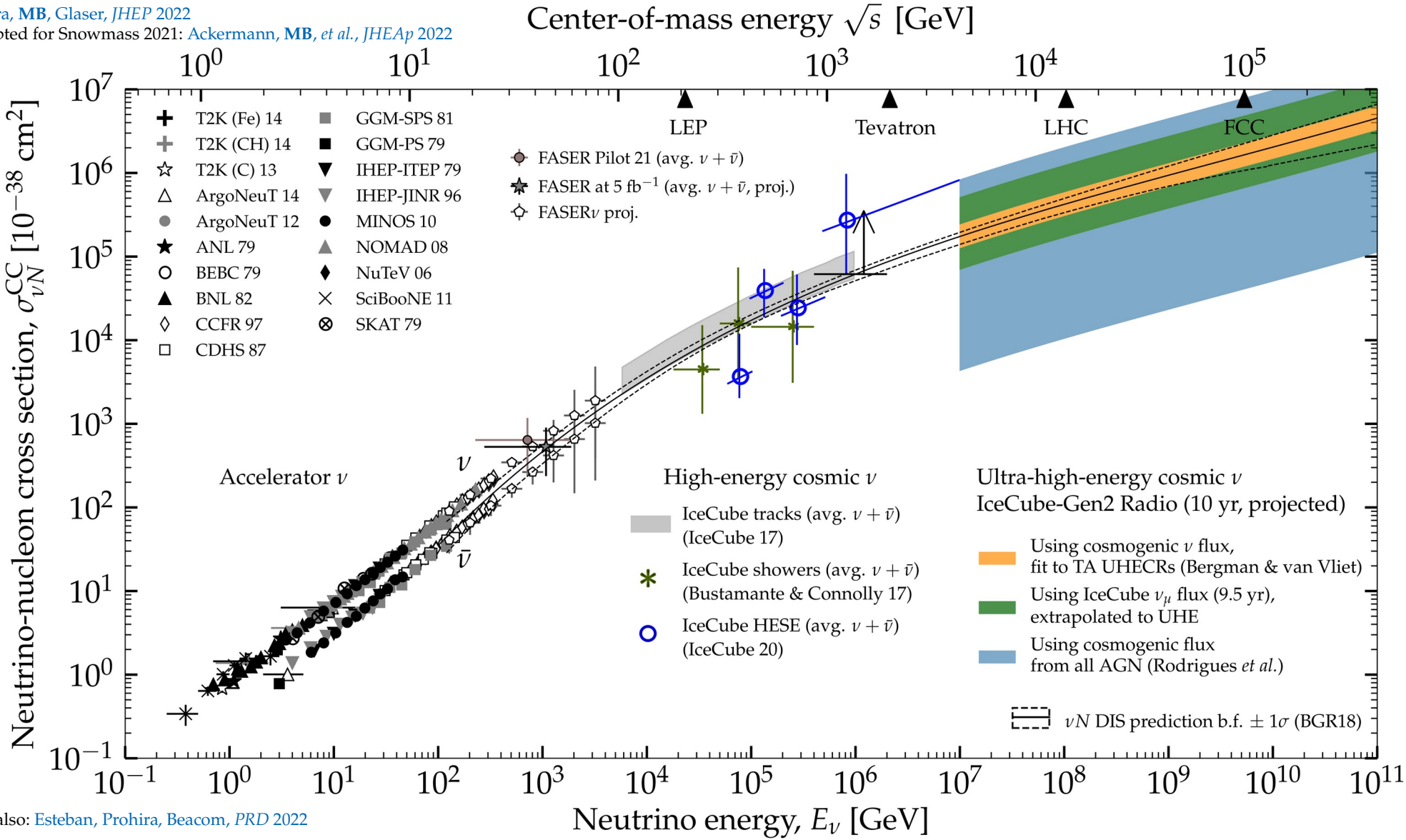
Most flux models discovered in Gen2 in < 5 years

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

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

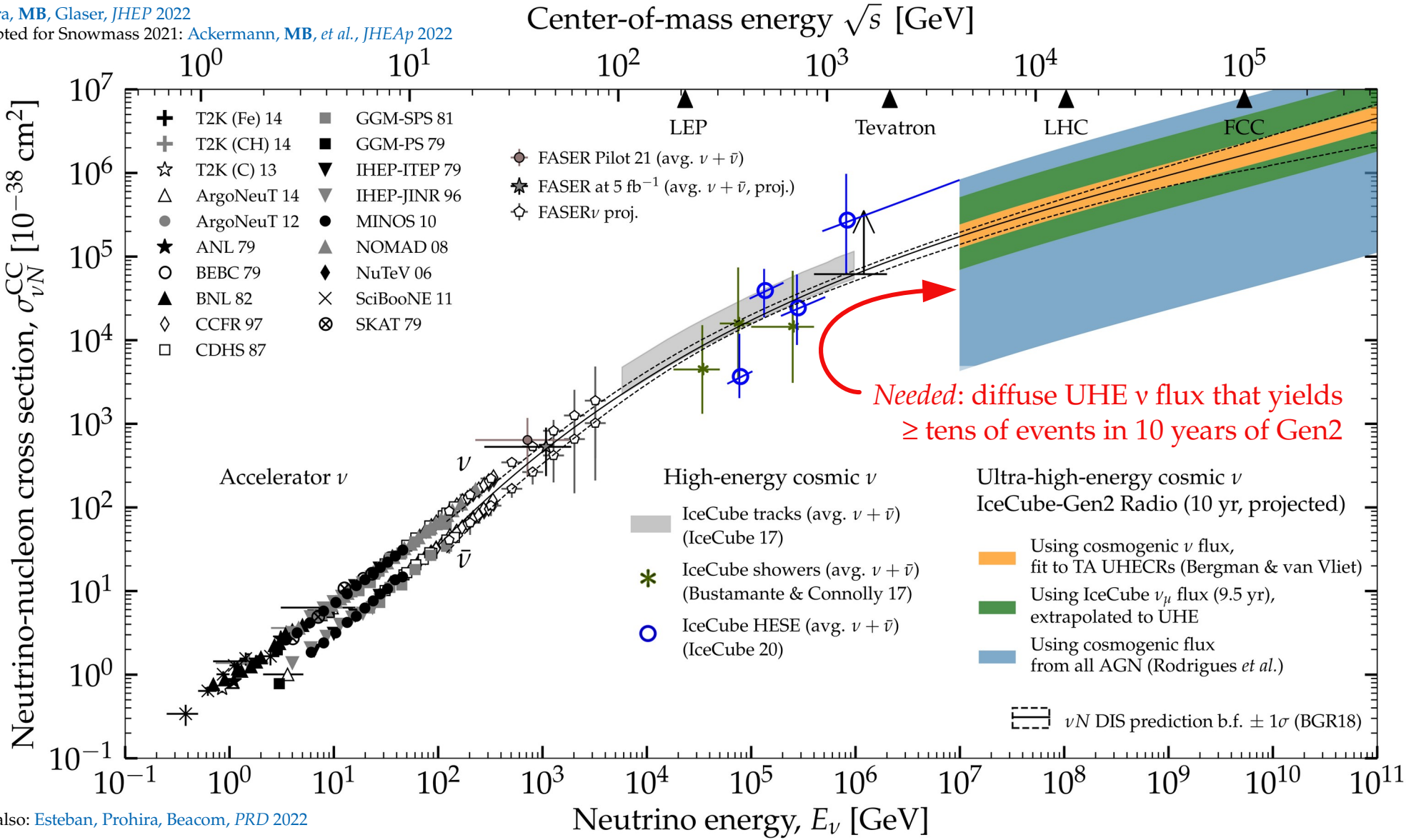


Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



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

Today

TeV–PeV ν

Turn predictions
into data-driven tests

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

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Next decade

> 100-PeV ν

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New detection techniques
Better UHE ν flux predictions

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

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

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TeV–PeV ν

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

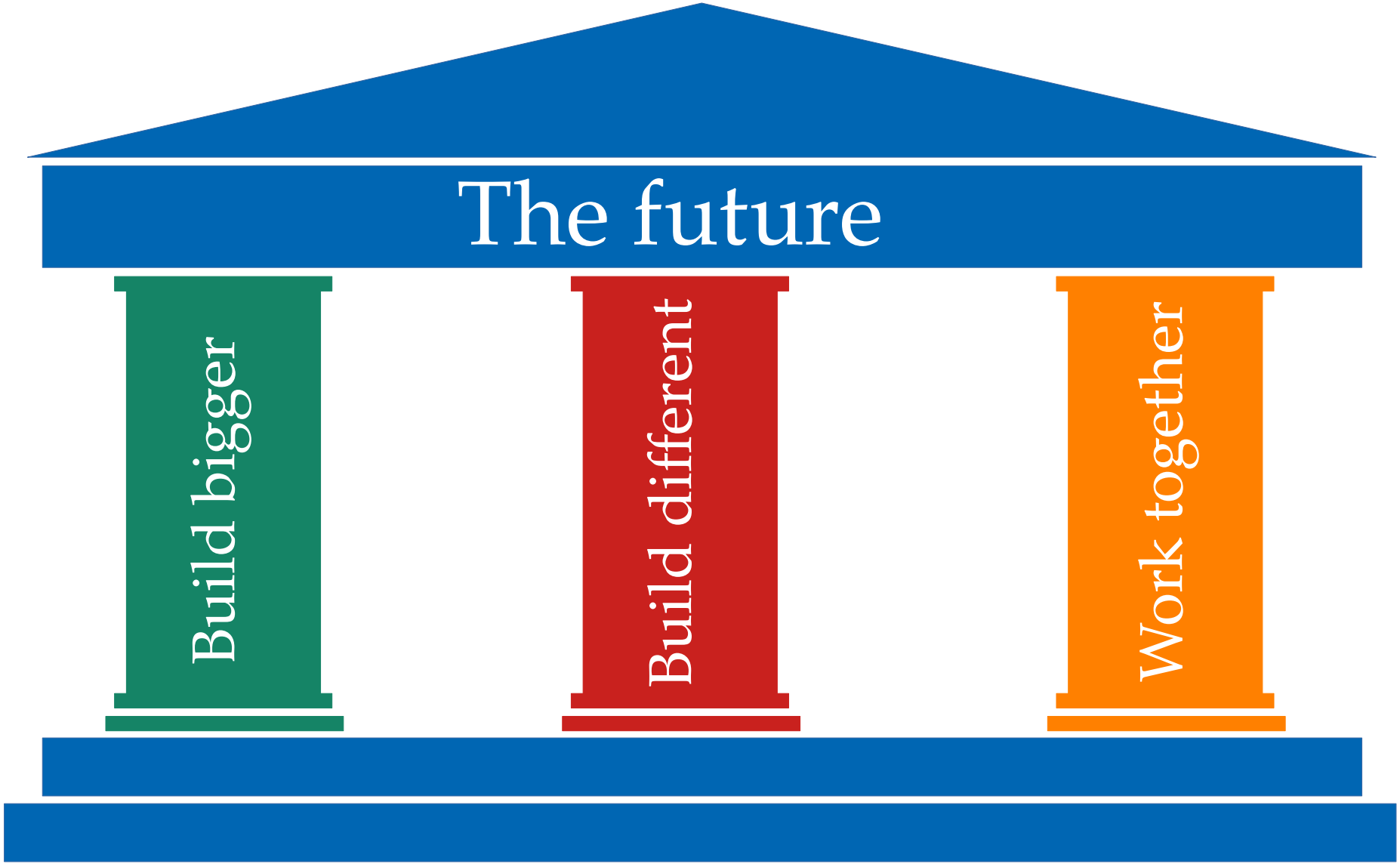
Next decade
> 100-PeV ν

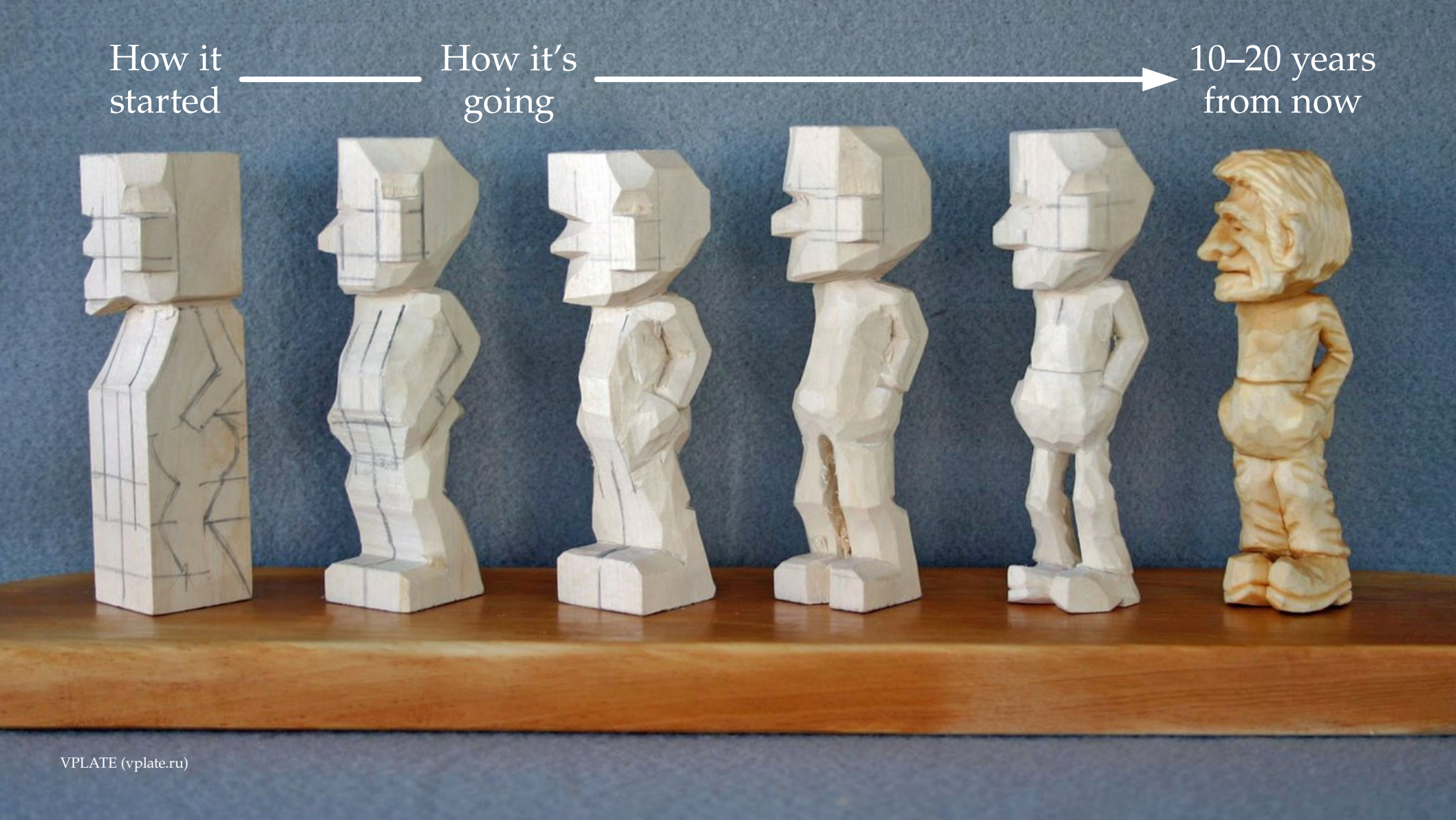
Make predictions for
a new energy regime

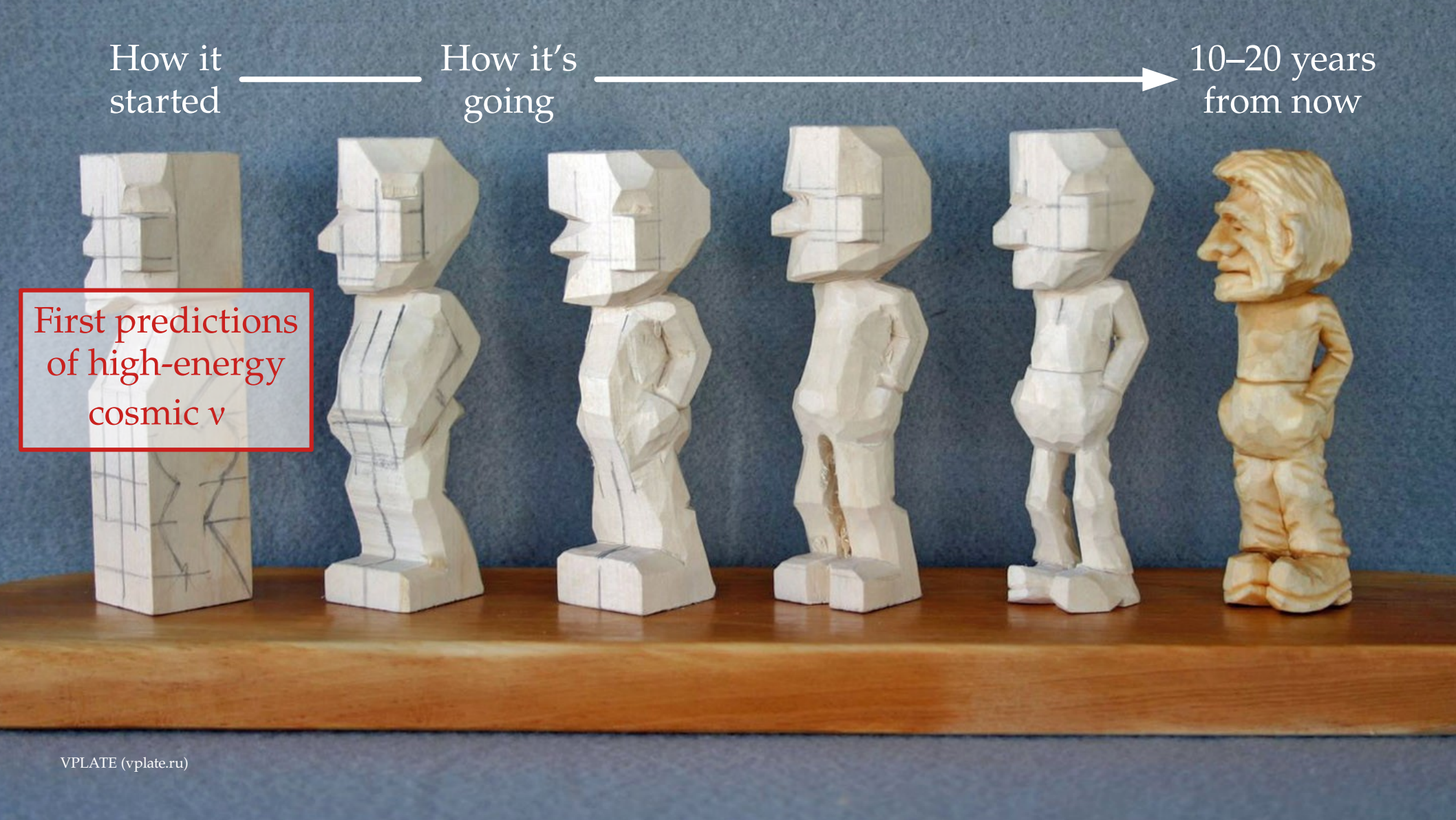
<u>Key developments</u>:
Discovery
New detection techniques
Better UHE ν flux predictions

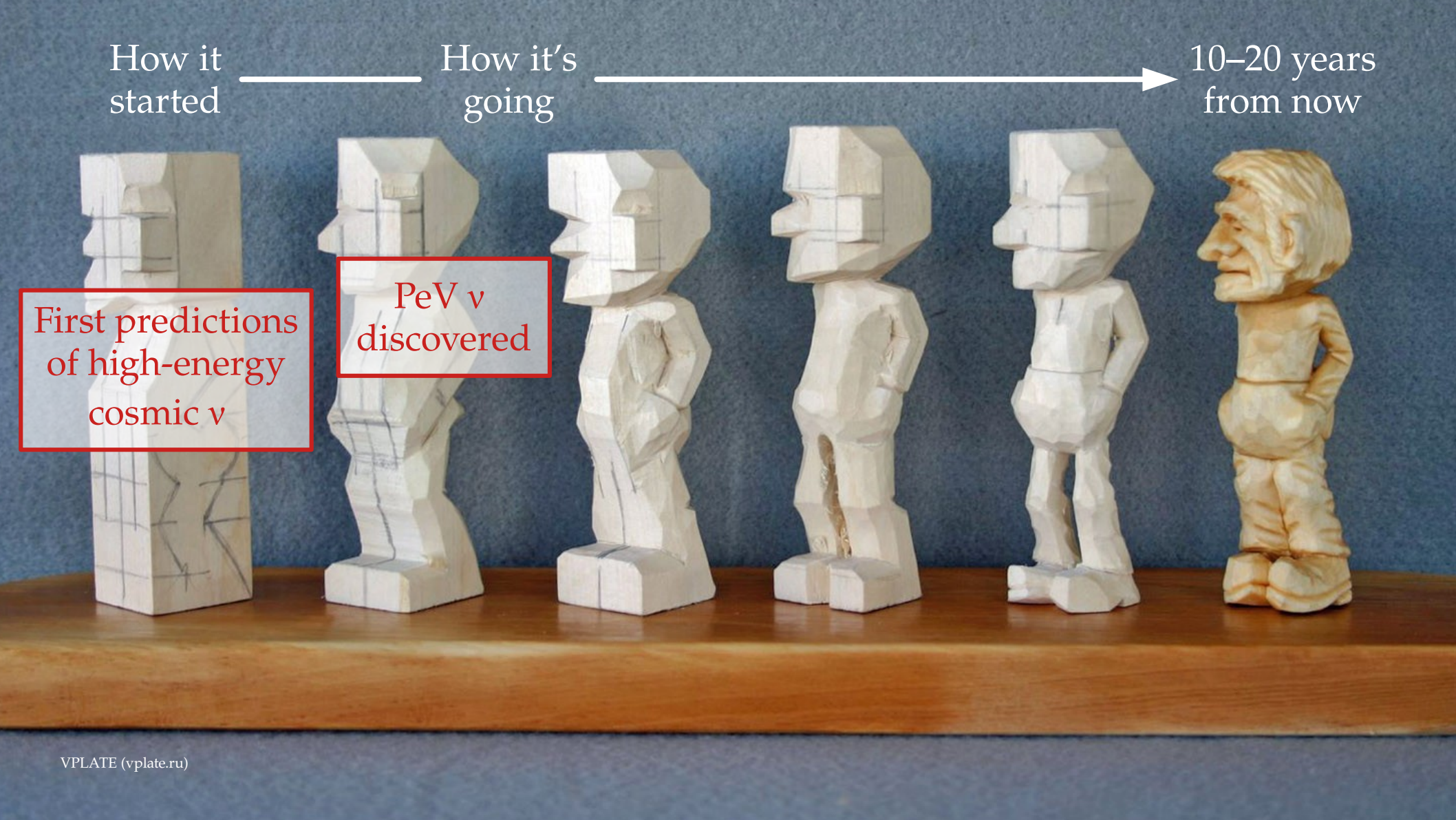
Similar to the evolution of cosmology to a high-precision field in the 1990s

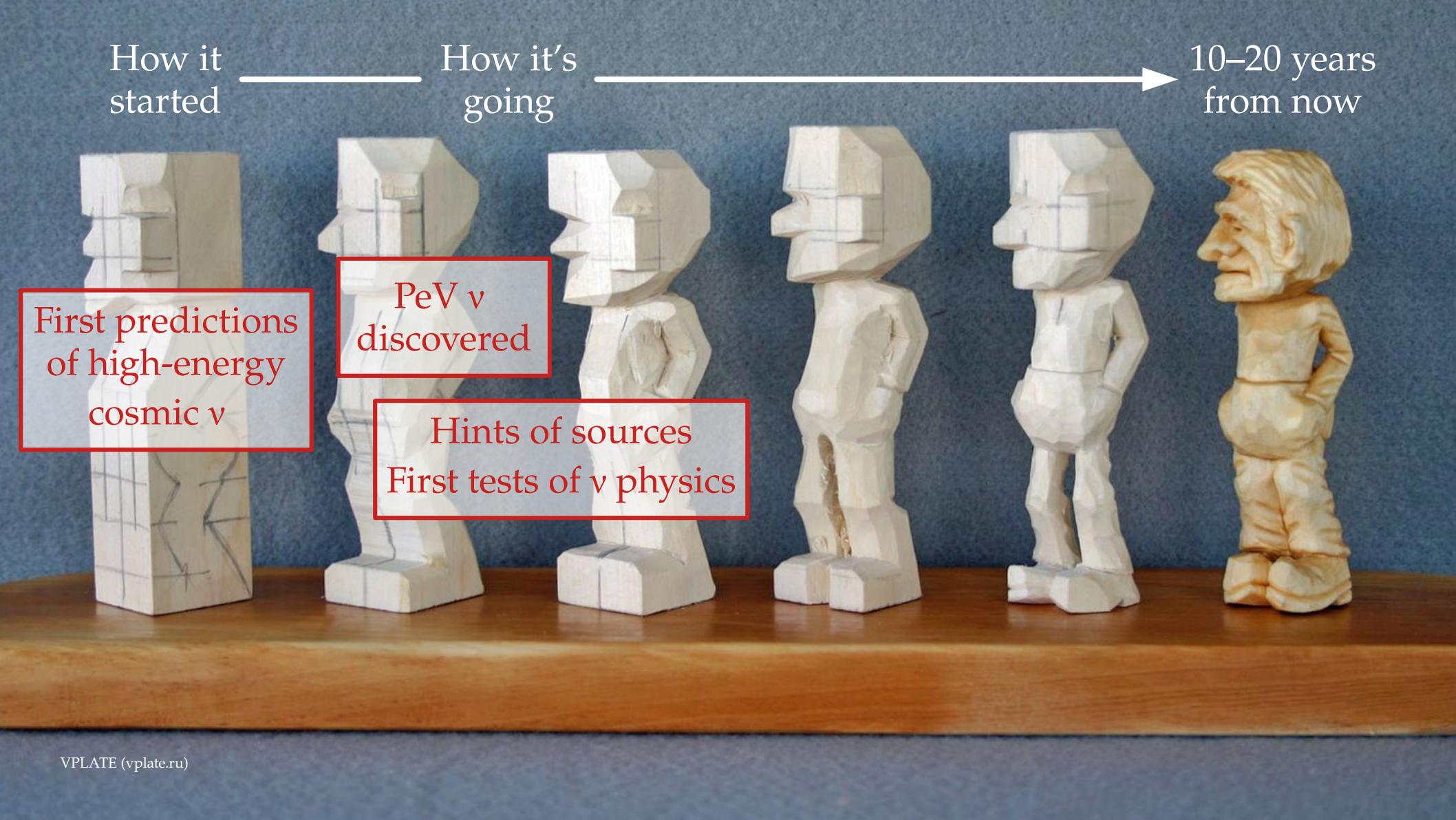
Made robust and meaningful by accounting
for all relevant particle and astrophysics uncertainties

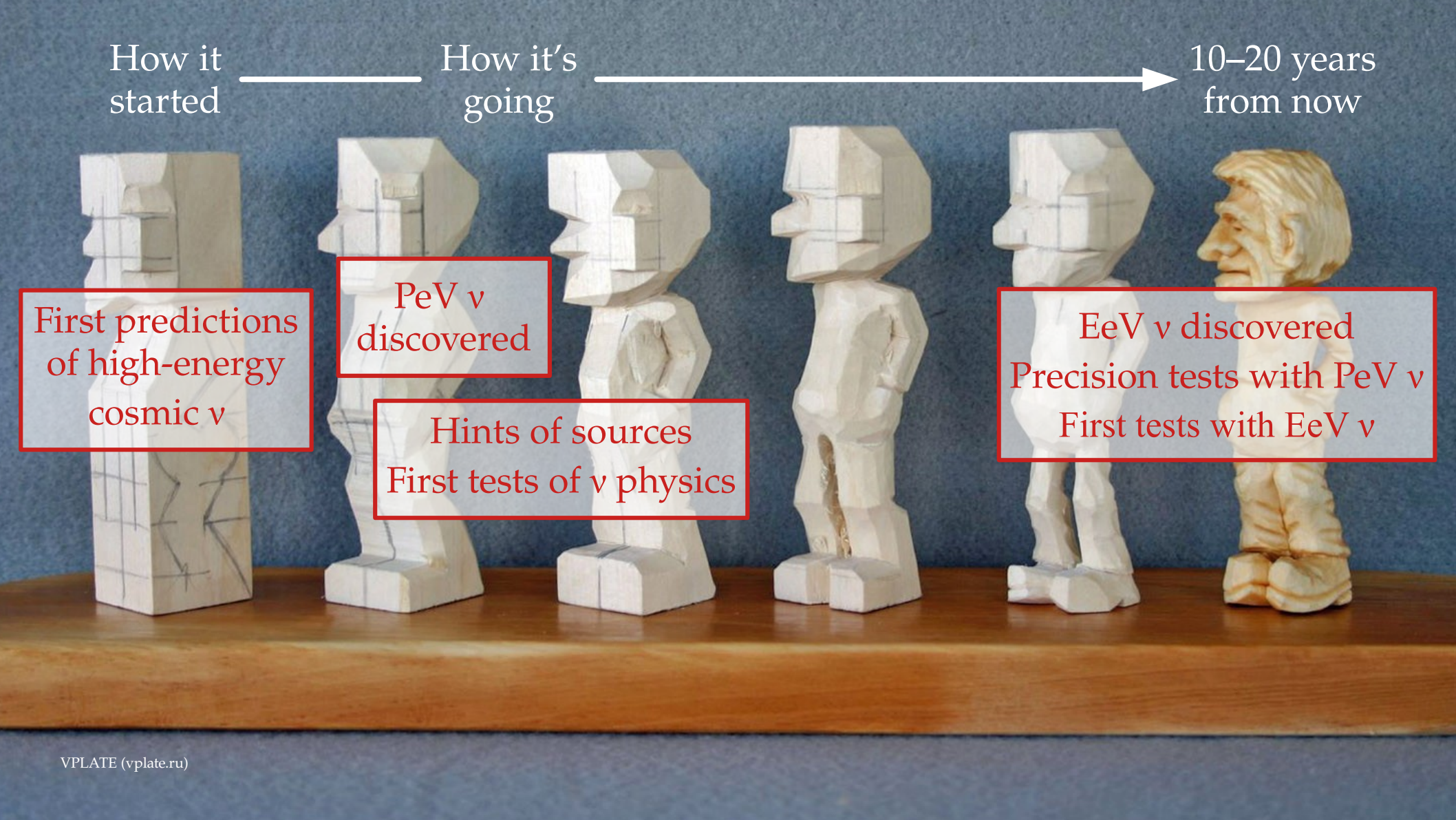

The future
Build bigger
Build different
Work together


How it started
How it's going
10–20 years from now
VPLATE (vplate.ru)


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


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


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


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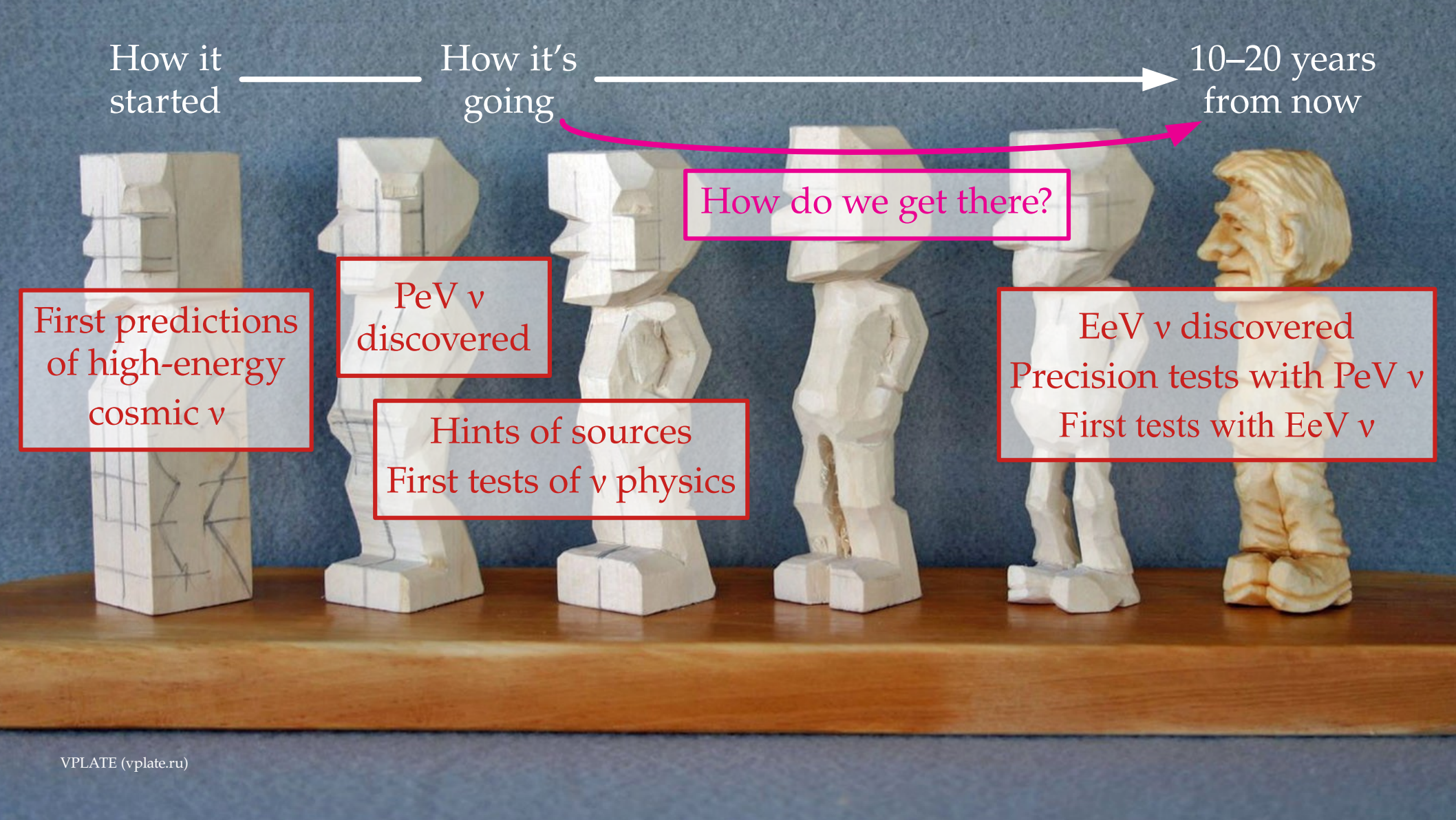
EeV ν discovered
Precision tests with PeV ν
First tests with EeV ν
VPLATE (vplate.ru)


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

Thanks!

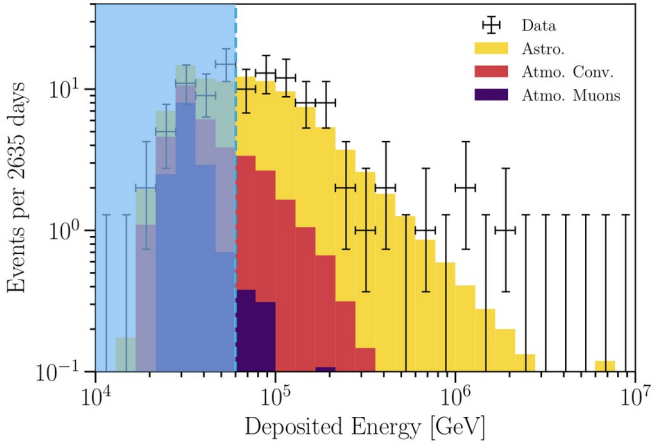
- One week
- Three tracks:
  - Neutrino phenomenology: Mariam Tórtola (Valencia)
  - Neutrino astrophysics: Maria Petropoulou (Athens)
  - Neutrino cosmology: Vivian Poulin (Montepellier)
- Plus topical seminars & student talks
- Registration will open soon

nbia.dk/neutrino2025

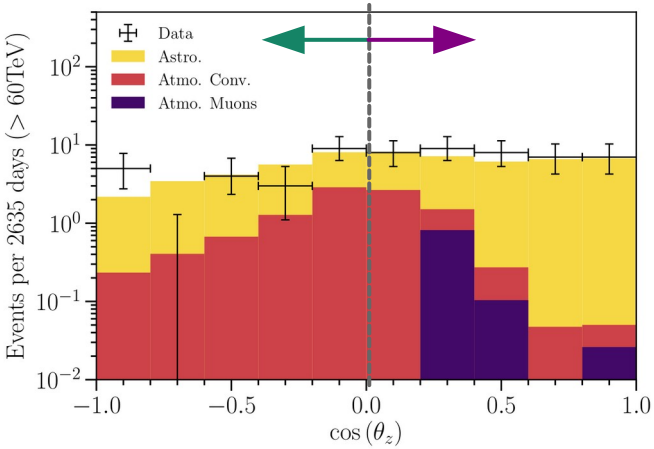
Backup slides

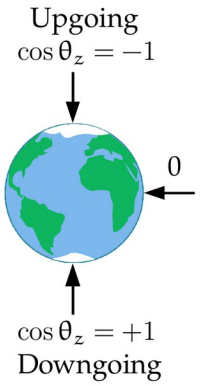
Neutrino energy spectrum

7.5 yr: 100+ contained events > 60 TeV:



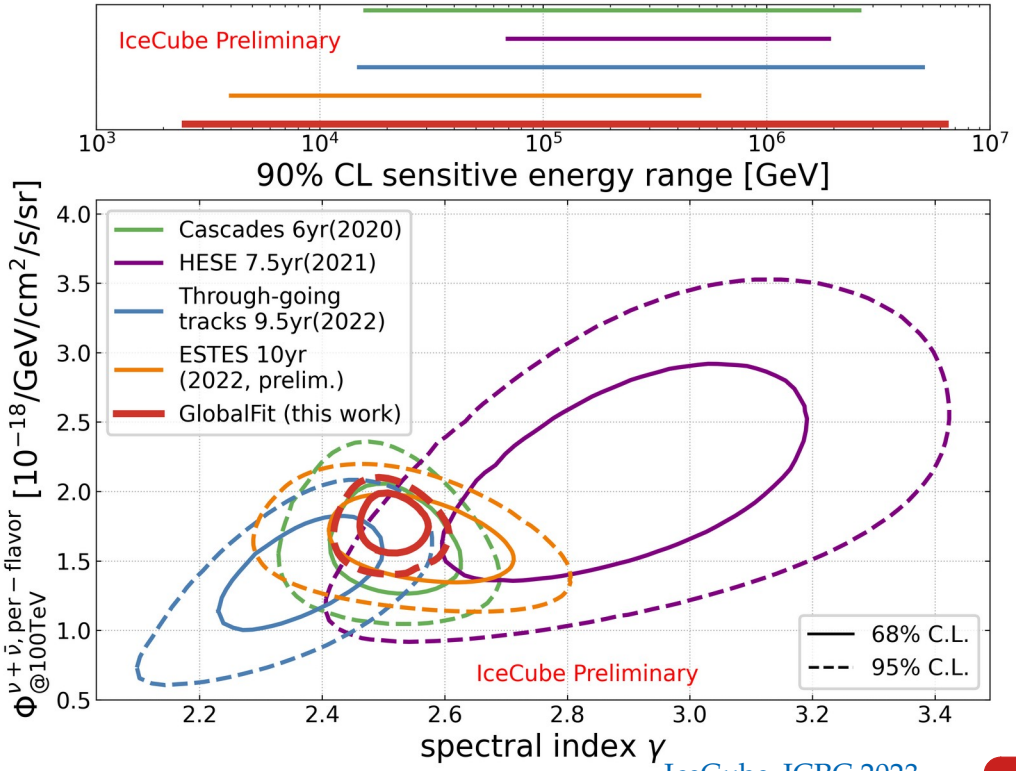
ν attenuated by Earth Atm. ν and μ vetoed





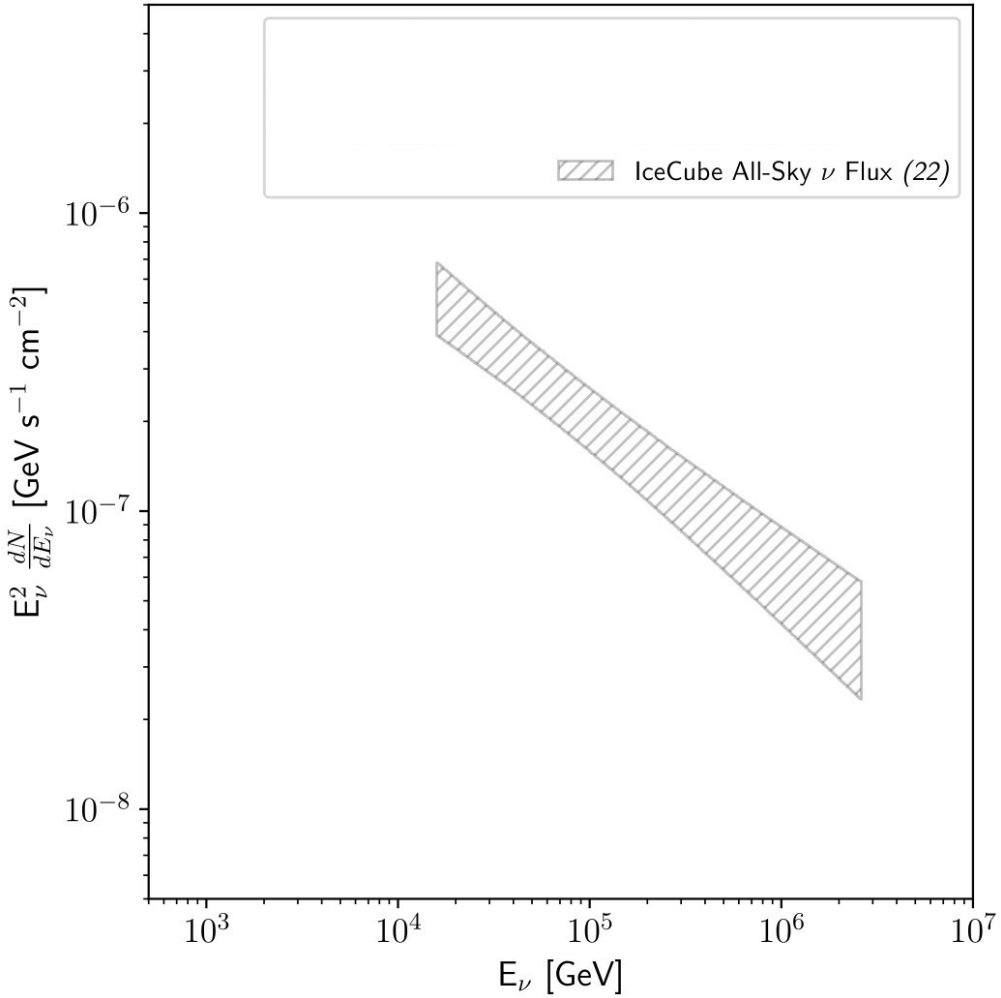
Data is fit well by a single power law:

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



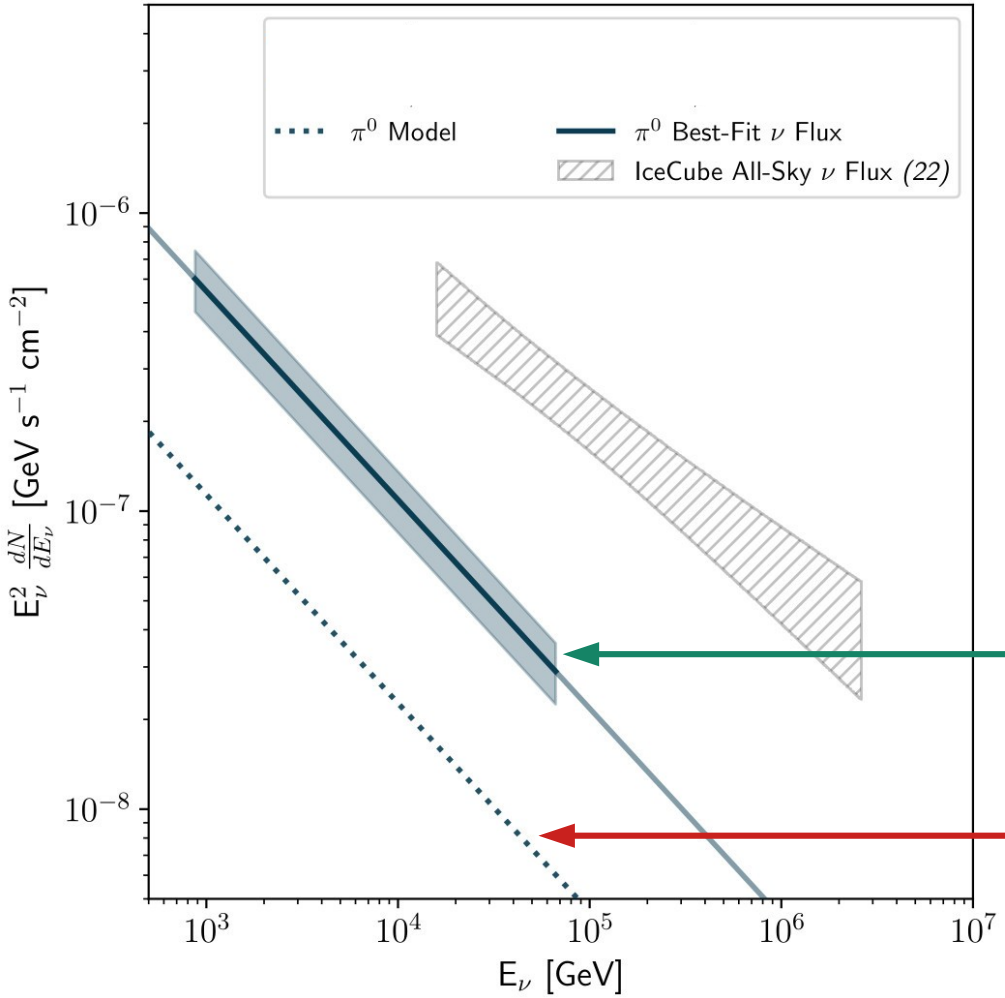
IceCube, ICRC 2023

High-energy neutrinos from the Galactic Plane



IceCube Collab., *Science* 2023

High-energy neutrinos from the Galactic Plane



Three models of Galactic diffuse ν:

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

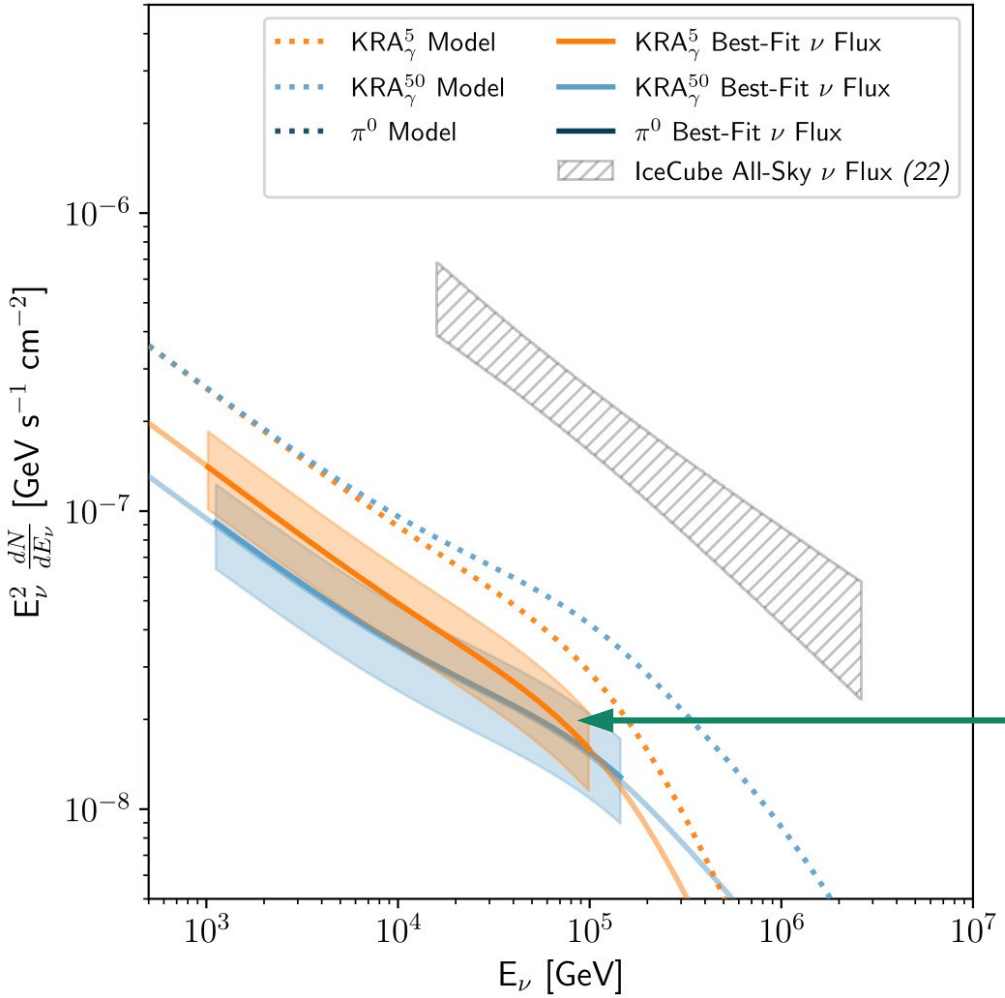
Observed (× 5 model)

Consistent with 100-TeV observations by Tibet Air Shower Array

Model

IceCube Collab., *Science* 2023

High-energy neutrinos from the Galactic Plane



Three models of Galactic diffuse ν:

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

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

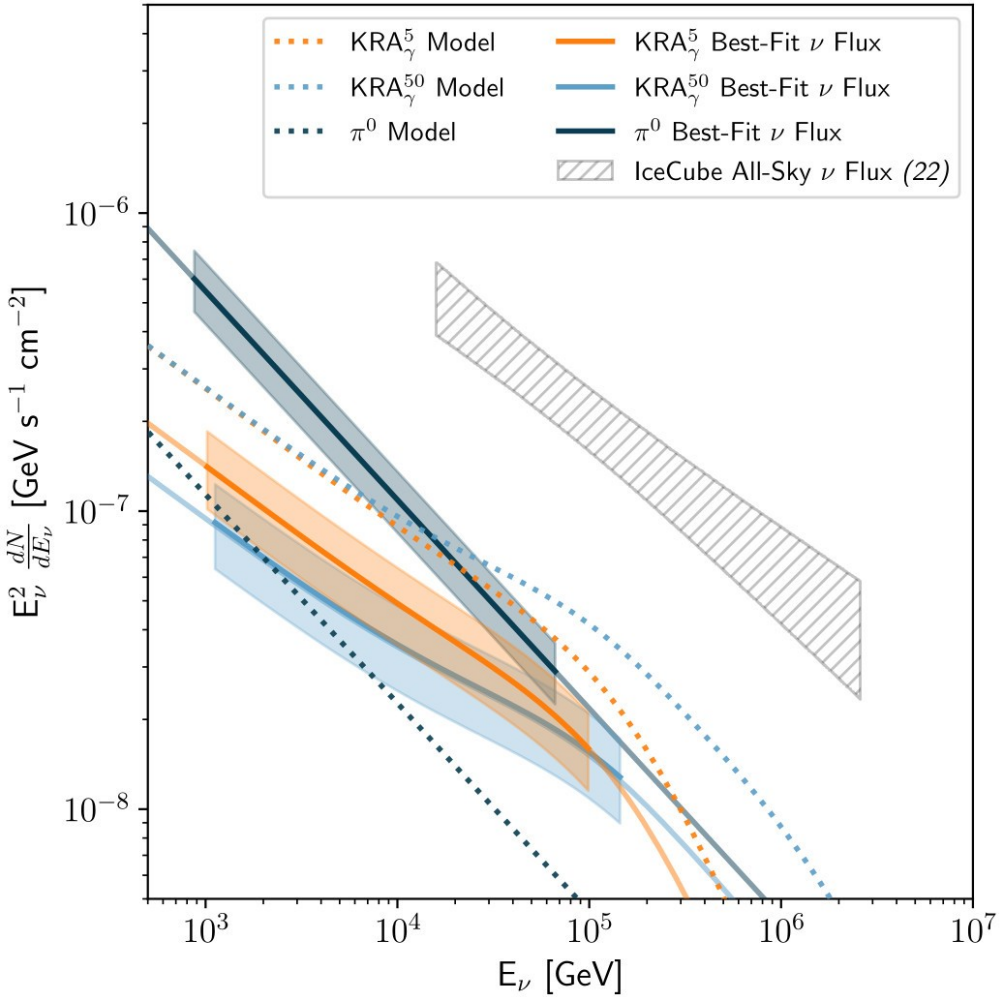
KRA$_\gamma^{50}$: Cut-off at 50 PeV in CR energy

Observed (× 0.5 model)

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

IceCube Collab., *Science* 2023

High-energy neutrinos from the Galactic Plane



IceCube Collab., *Science* 2023

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

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

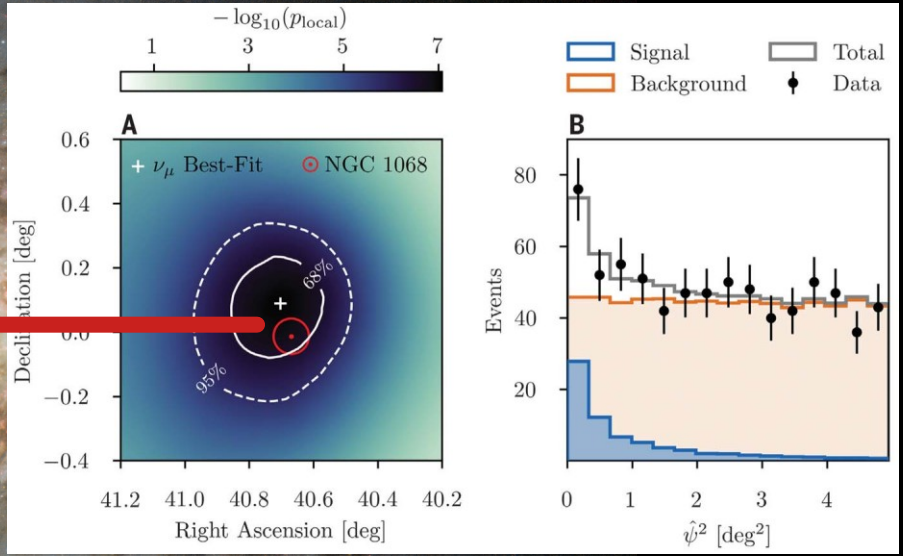
NGC1068: The first *steady-state* source of high-energy ν

Active galactic nucleus

Brightest type-2 Seyfert

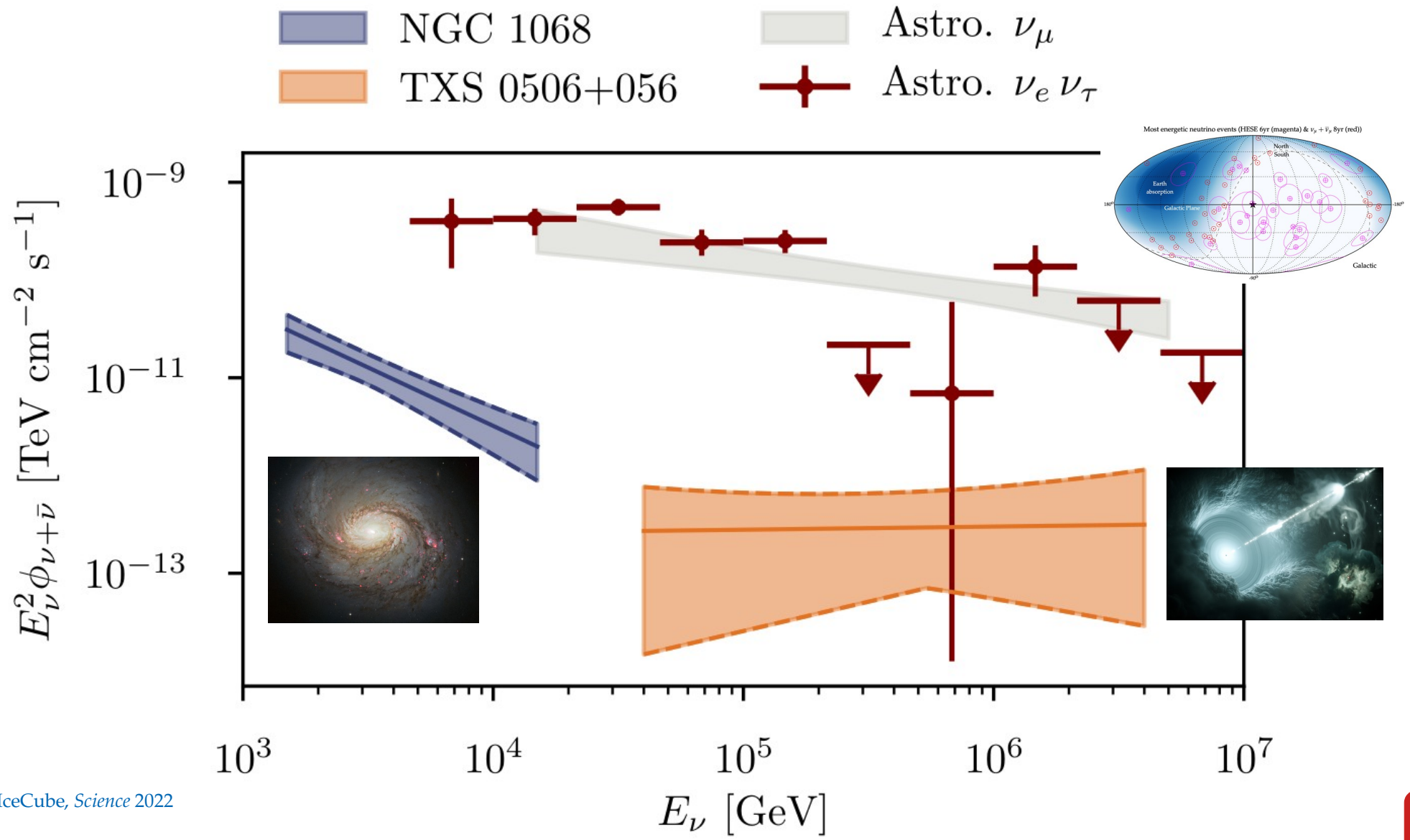
79^{+22}_{-20} ν of TeV energy

Significance: 4.2σ (global)



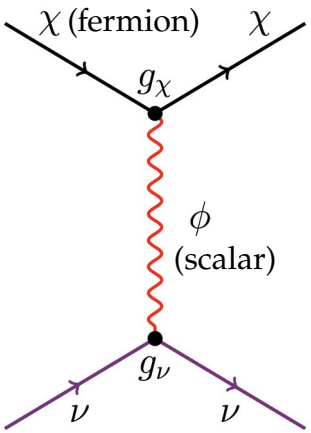
IceCube Collab., *Science* 378, 538 (2022)

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



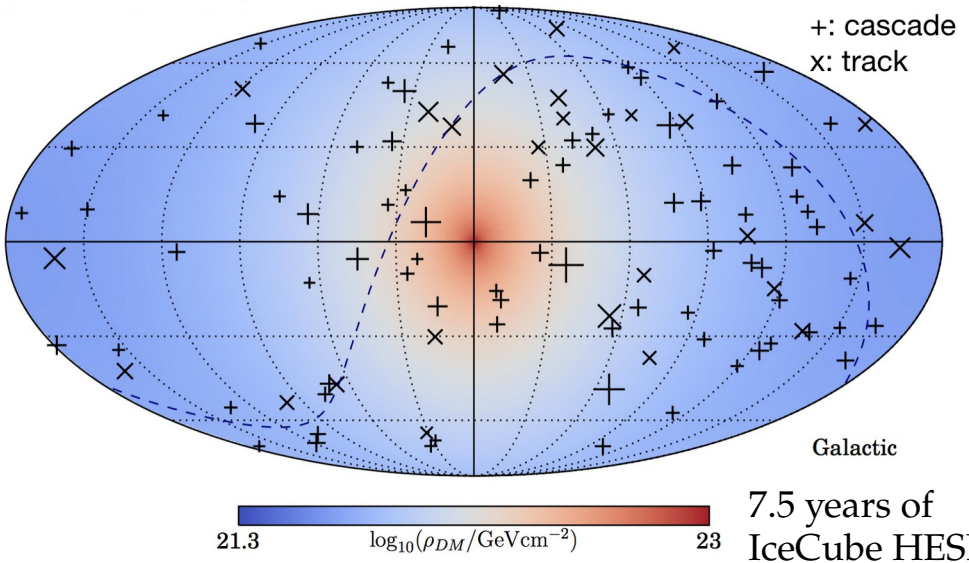
IceCube, *Science* 2022

Neutrino-dark matter scattering



Signature:

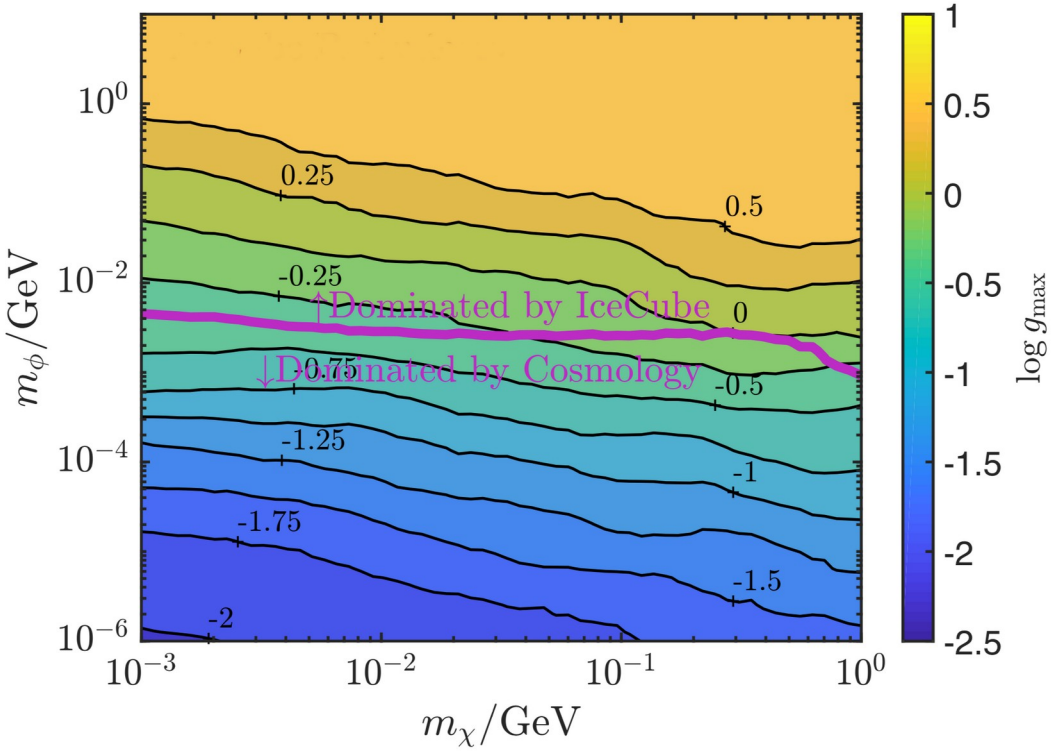
Deficit of high-energy ν from the Galactic Center



7.5 years of IceCube HESE data

Upper limits (90% C.L.) on

$$g_{\max} = \sqrt{g_\chi g_\nu}$$



IceCube, *JCAP* 2023
Argüelles, Kheirandish, Vincent, *PRL* 2017

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 $\rightarrow$ no matter)

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

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Hussain, Mafatia, McKay, *PRD* 2008 Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

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

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

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

$$N \propto \Phi_\nu \sigma_{\nu N} e^{-L \sigma_{\nu N} n_N}$$

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

Measuring the high-energy νN cross section

Number of detected neutrinos (simplified for presentation):

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

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

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

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

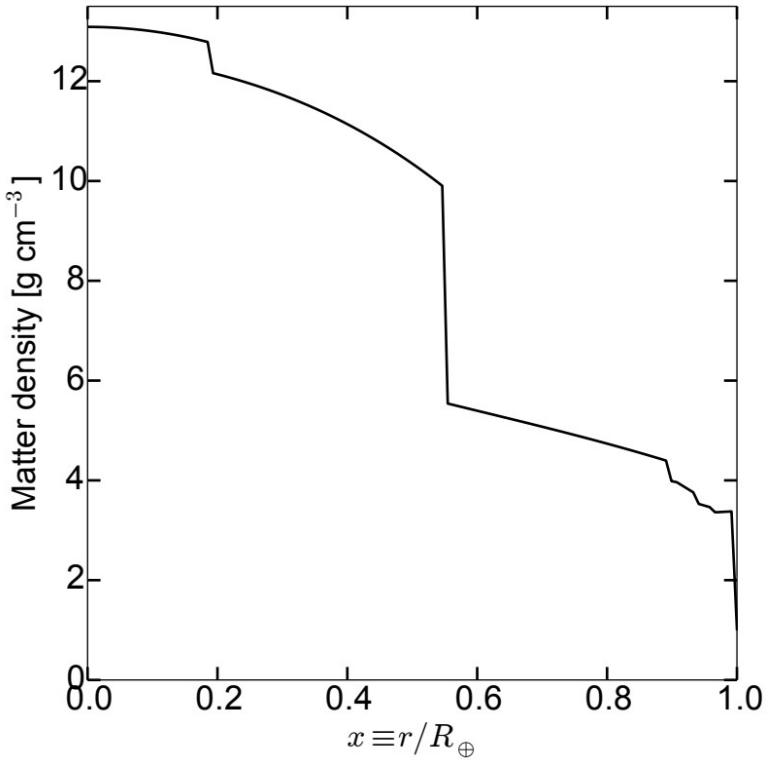
$$N \propto \Phi_\nu \sigma_{\nu N} \underbrace{e^{-L\sigma_{\nu N} n_N}}_{\text{Breaks the degeneracy}}$$

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

A feel for the in-Earth attenuation

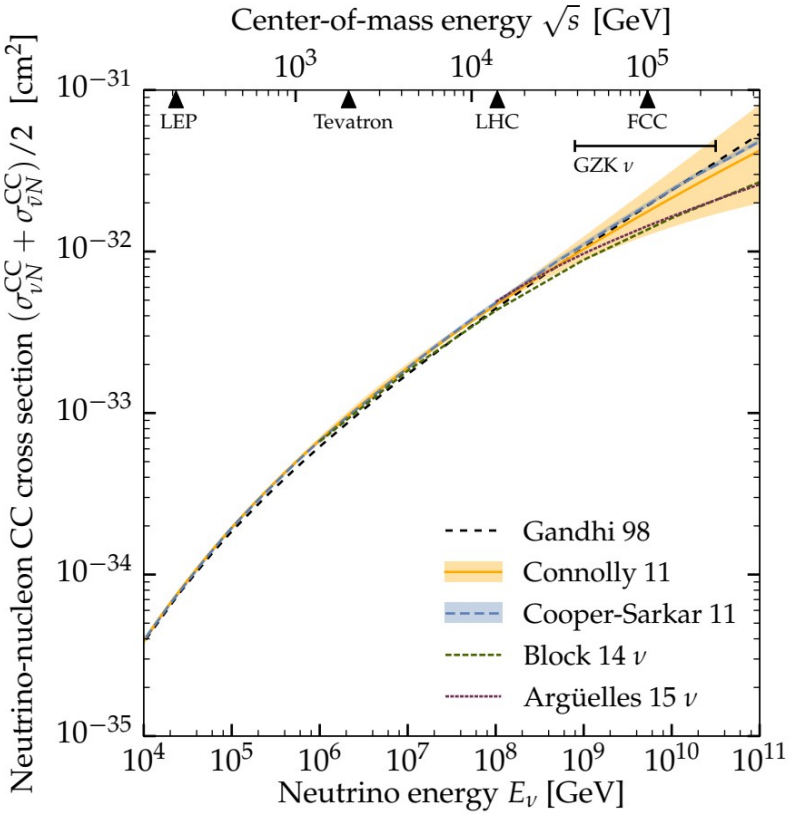
Earth matter density

(Preliminary Reference Earth Model)



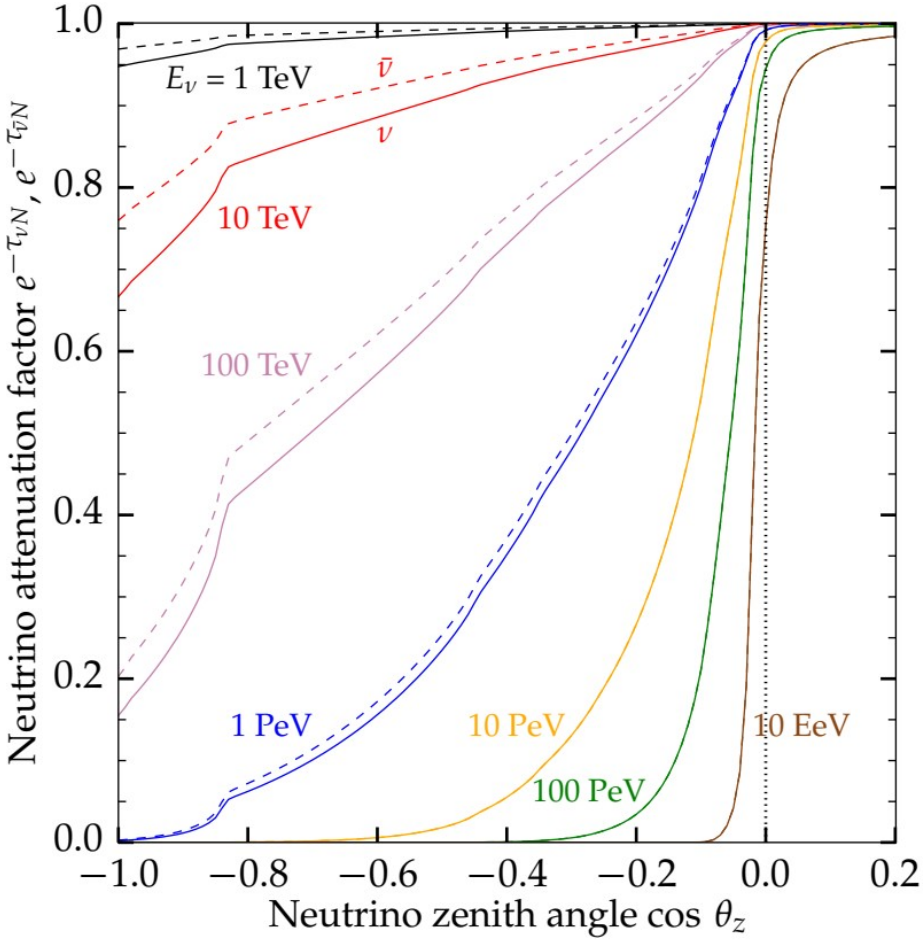
+

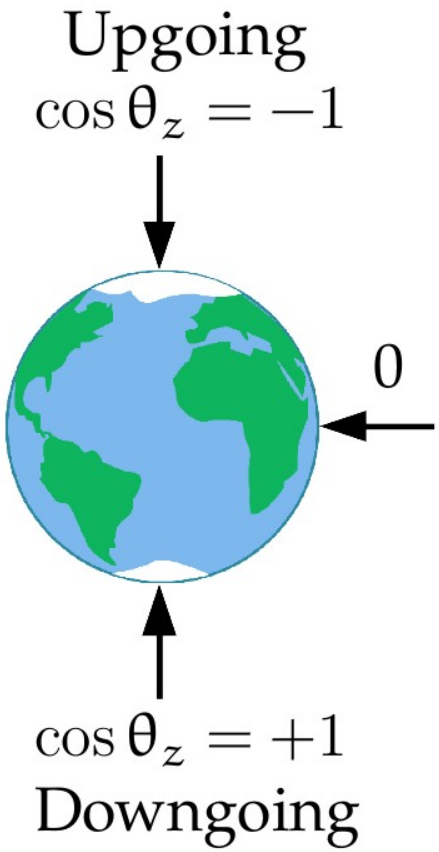
Neutrino-nucleon cross section

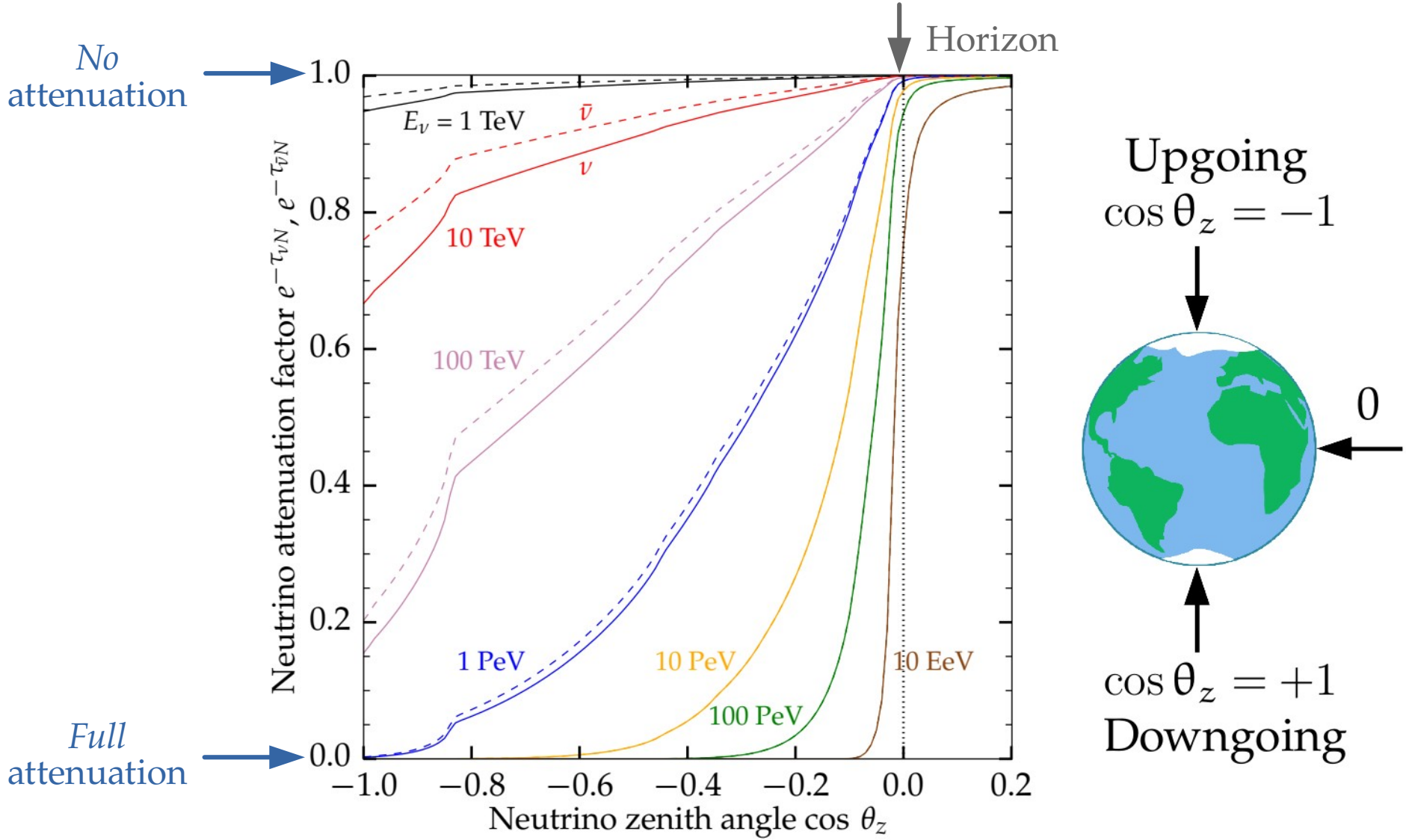


A feel for the in-Earth attenuation

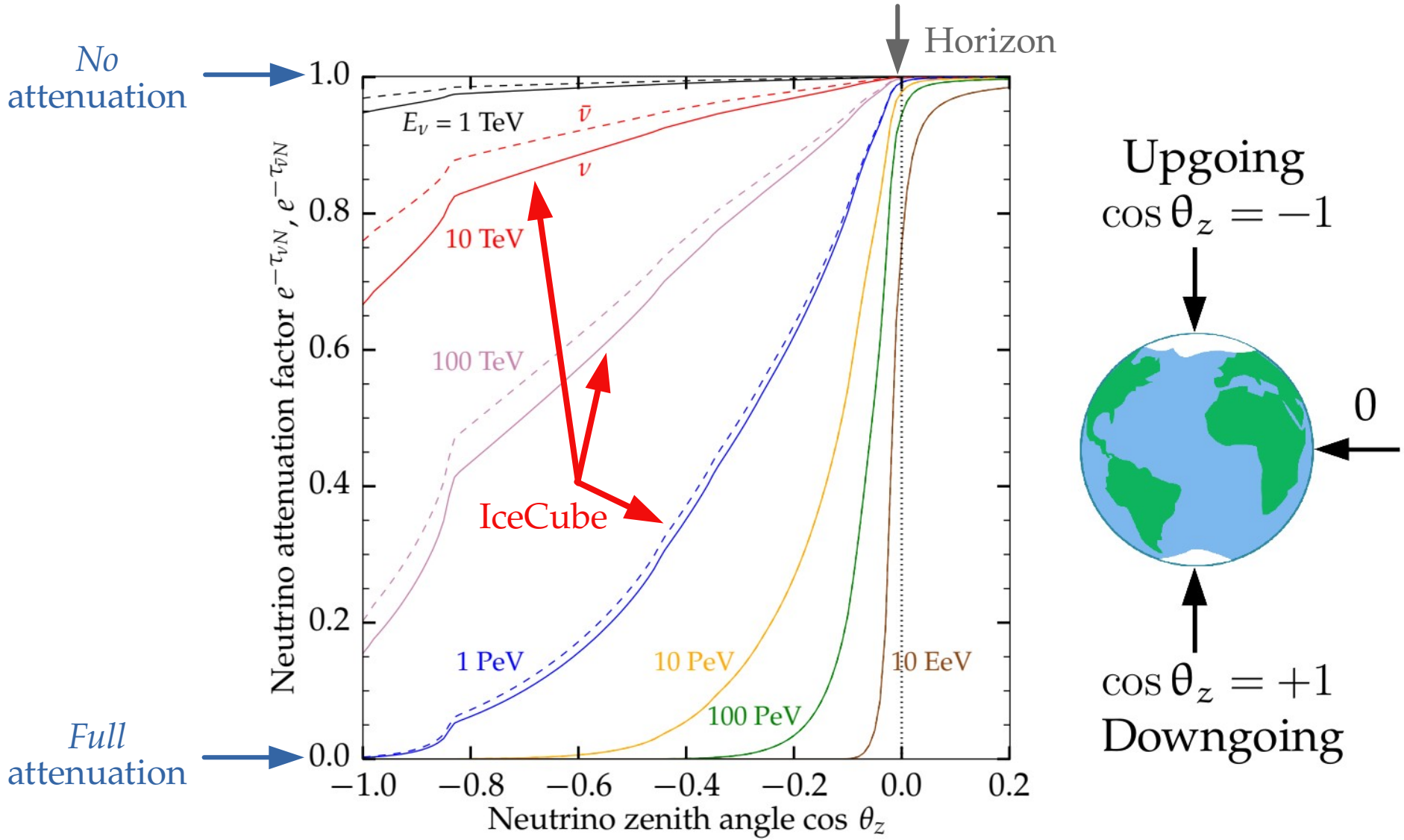
=



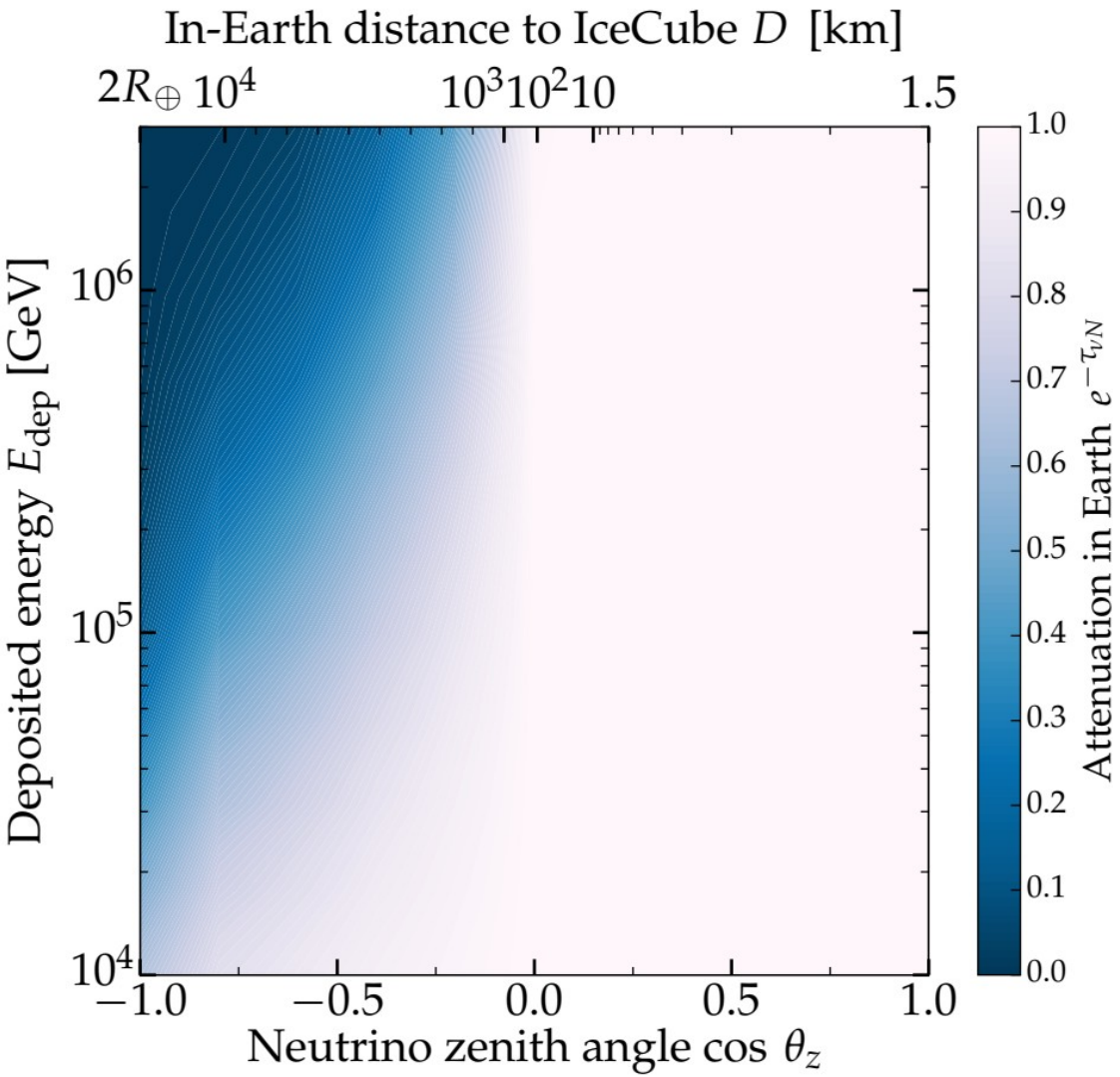


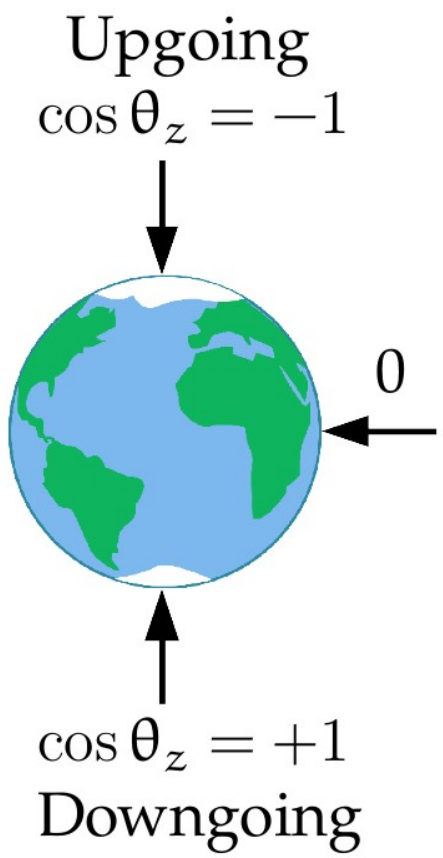


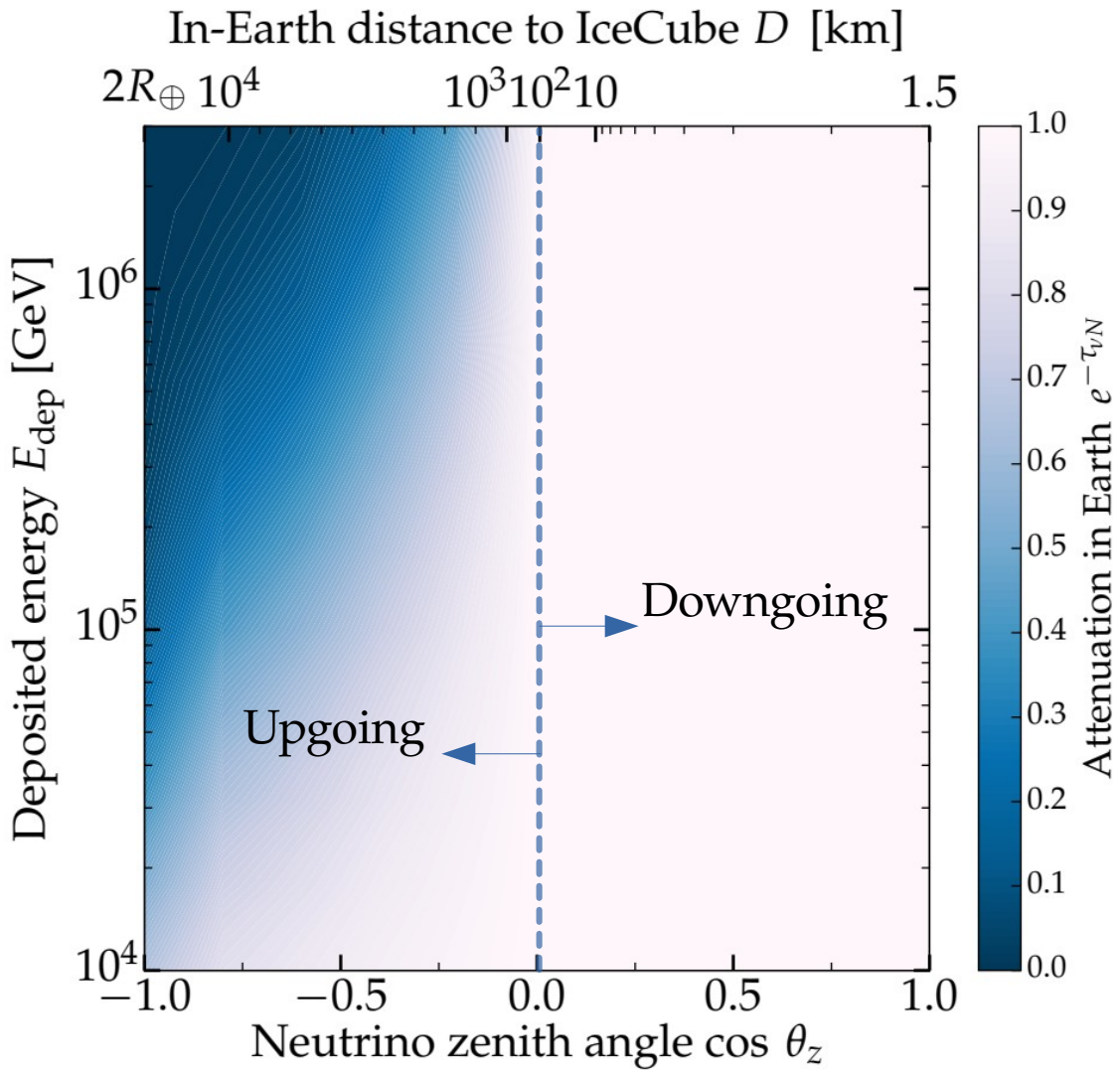
MB & Connolly, *PRL* 2019

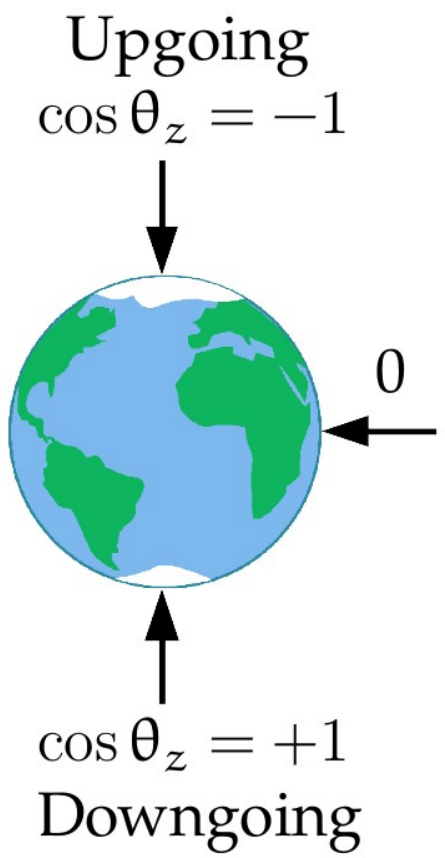


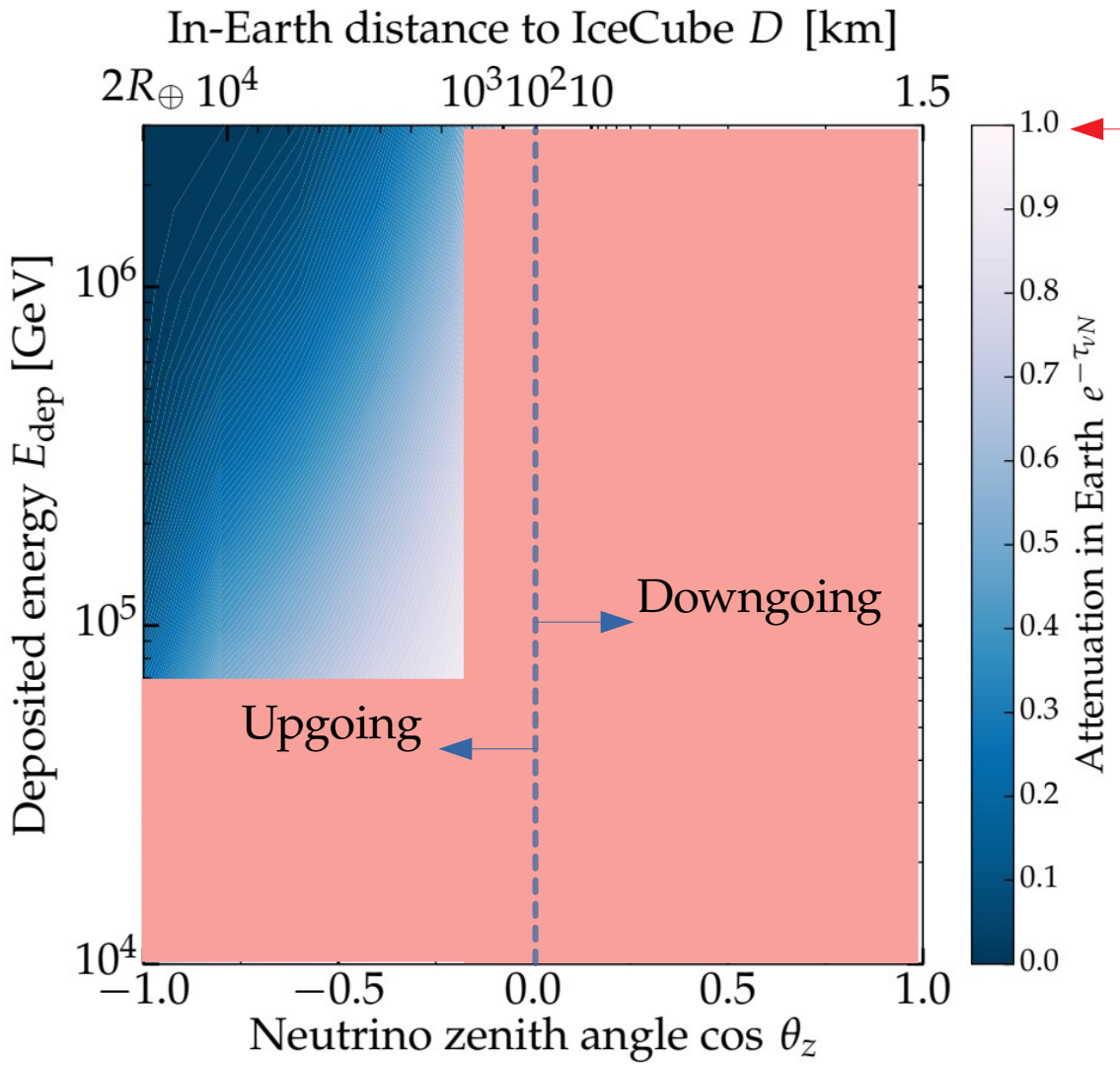
MB & Connolly, *PRL* 2019


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

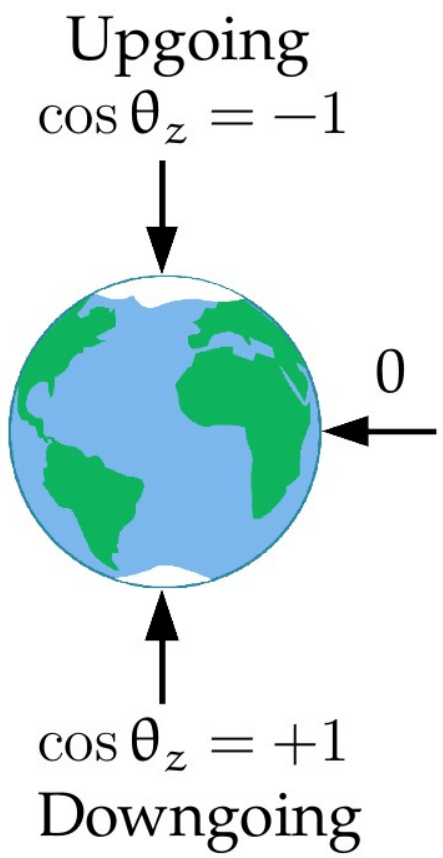

Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing

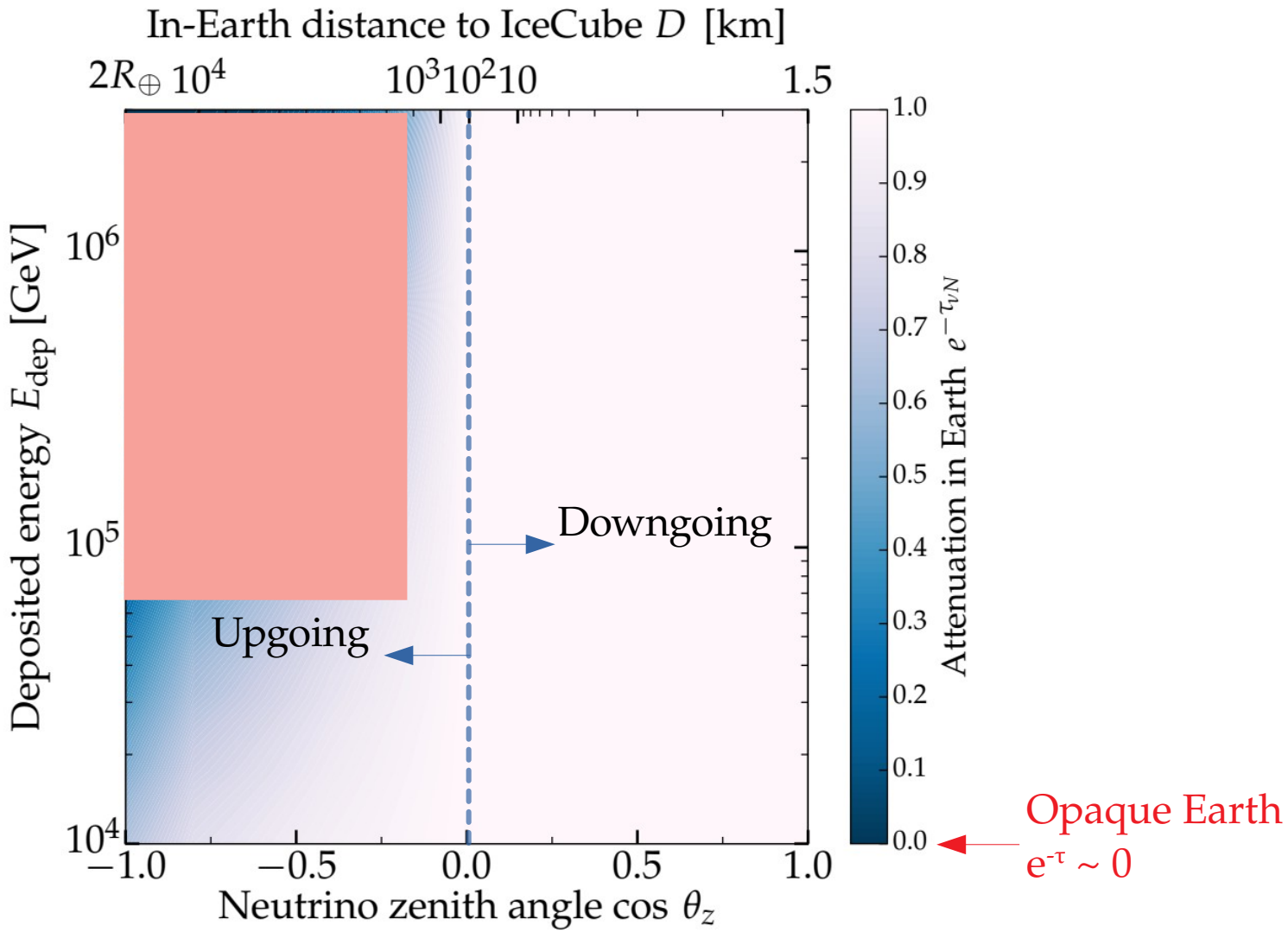

In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle $\cos\,\theta_z$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Attenuation in Earth $e^{-\tau_{\nu N}}$

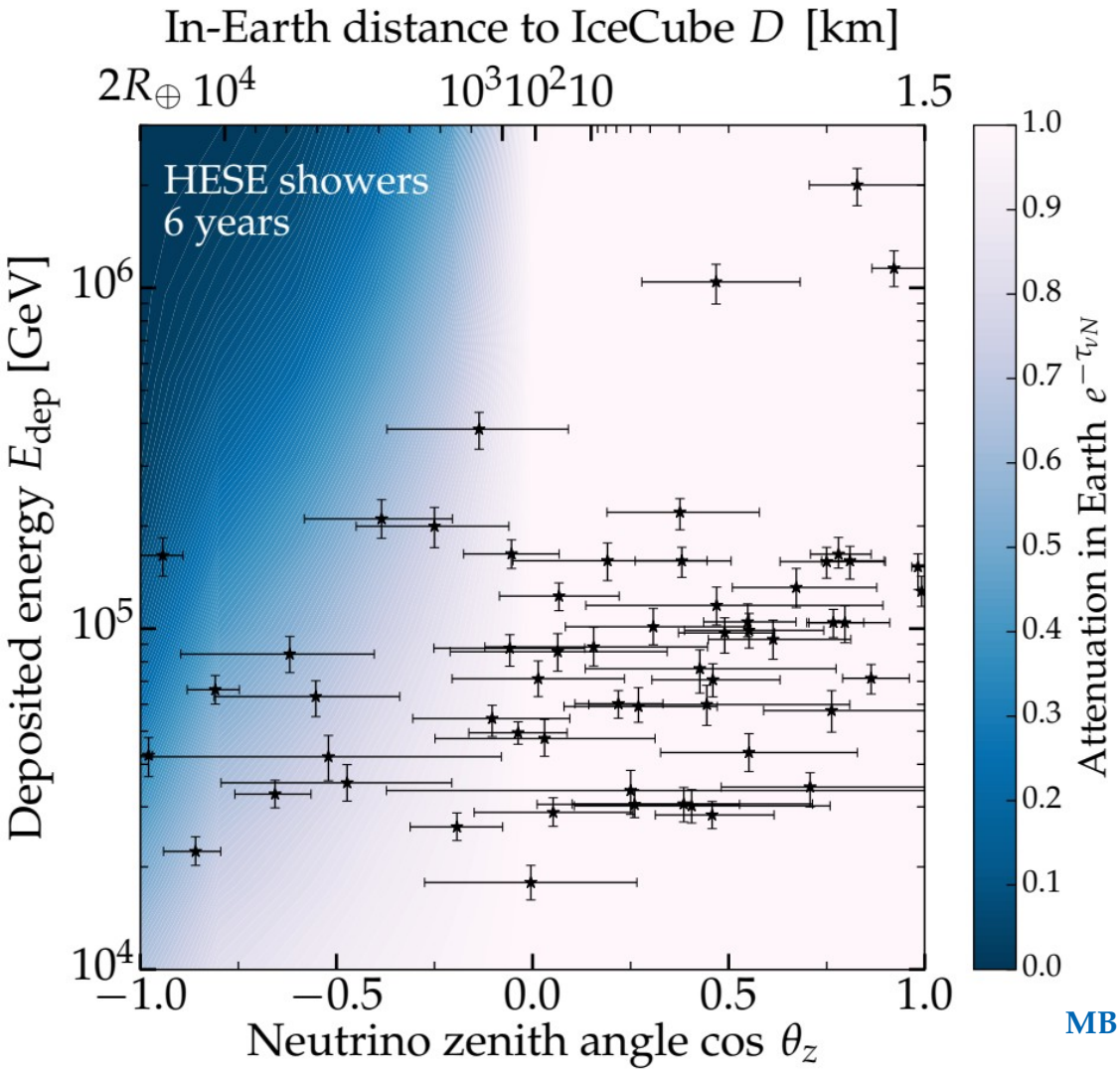




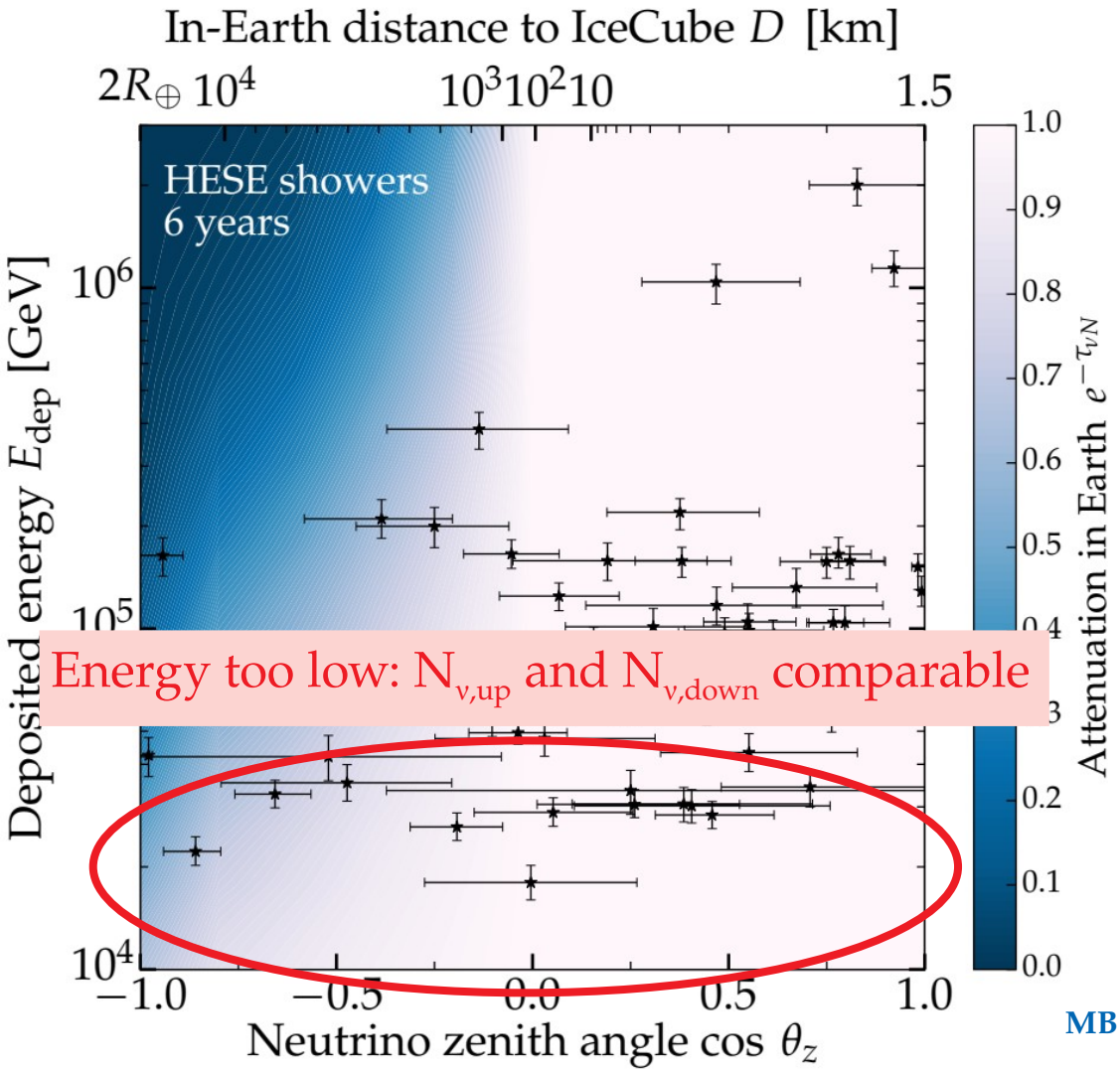
Transparent Earth
$e^{-\tau} \sim 1$


Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing


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

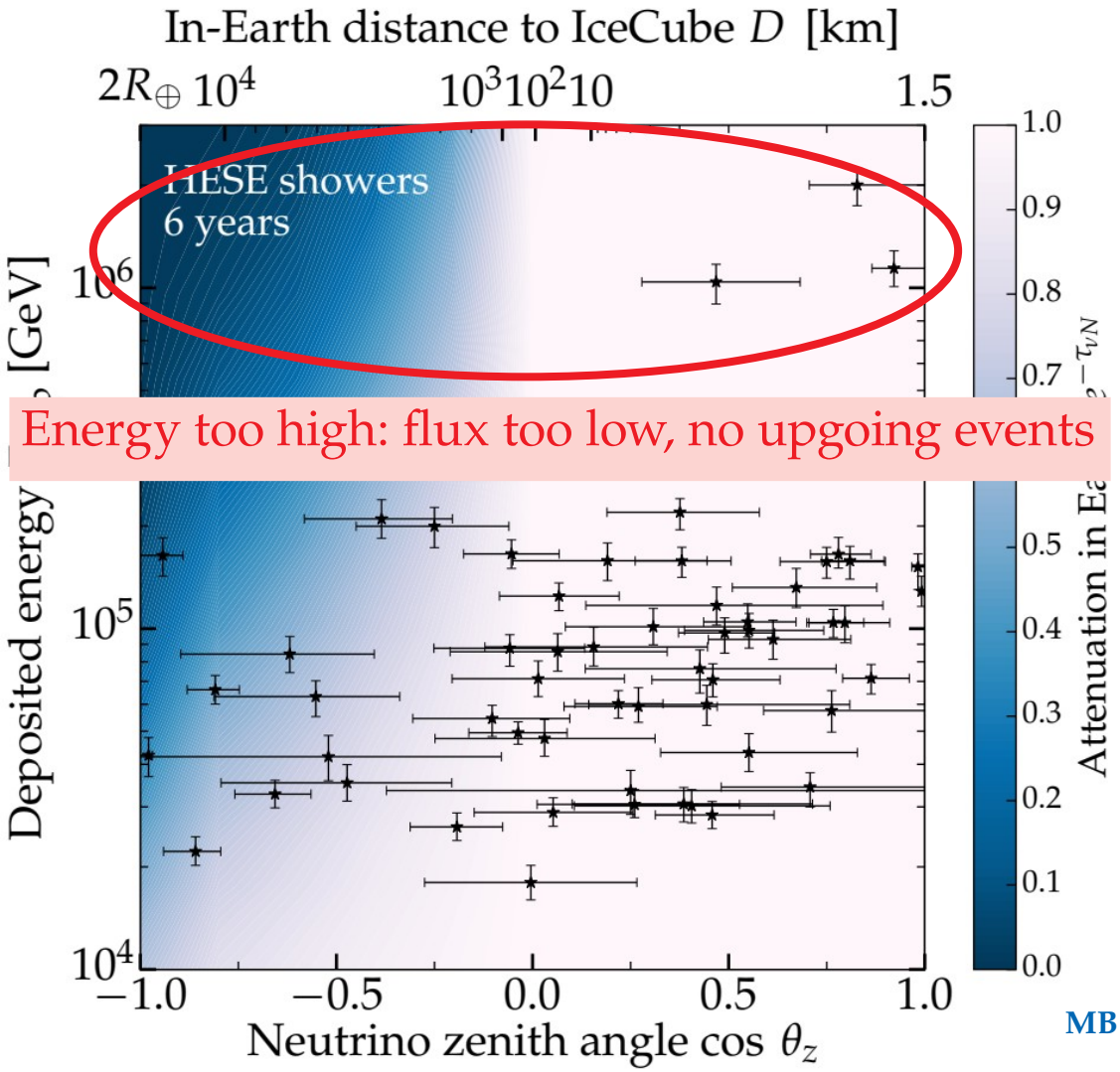


MB & Connolly, *PRL* 2019



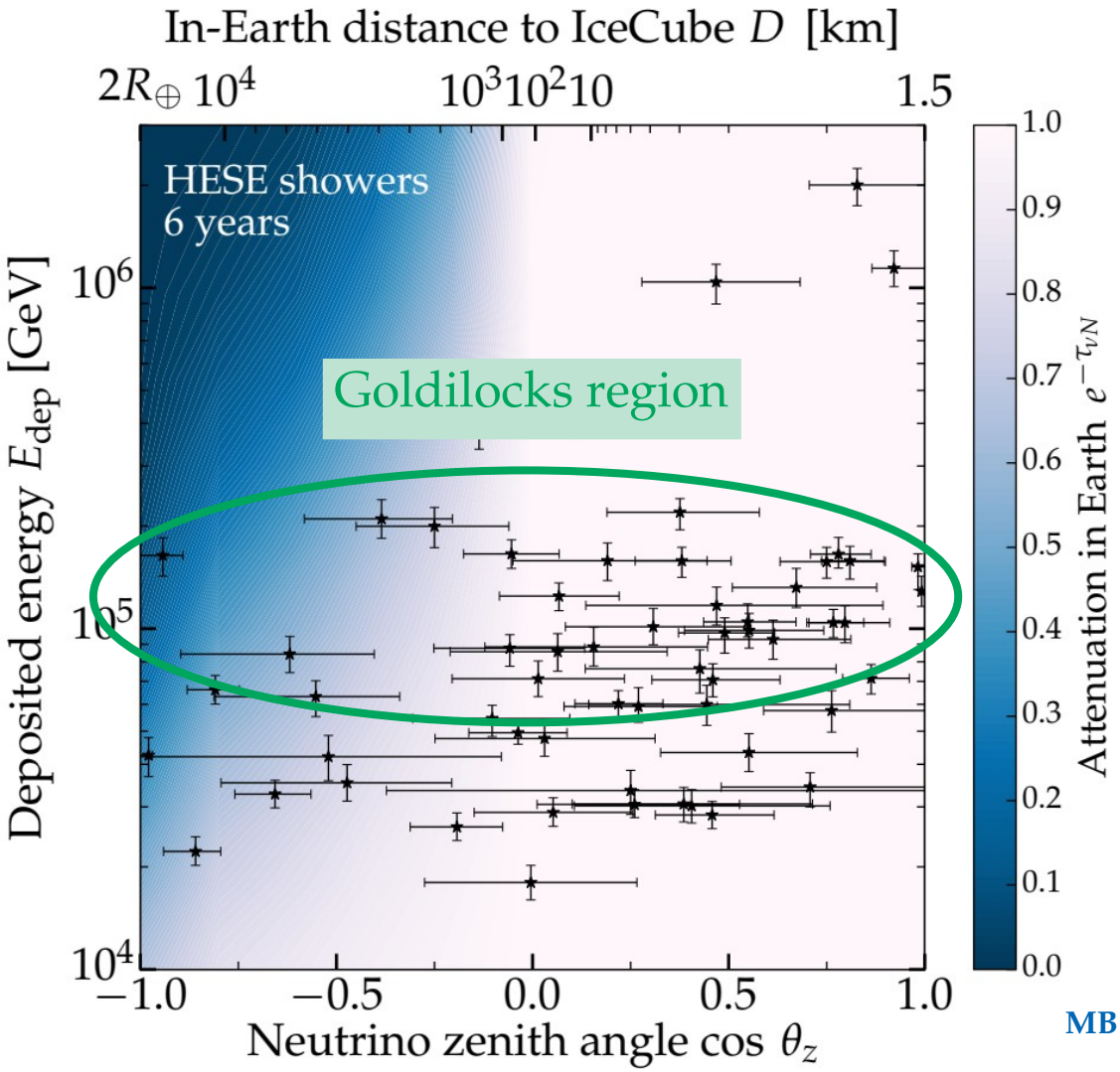
Energy too low: $N_{\nu,up}$ and $N_{\nu,down}$ comparable

MB & Connolly, *PRL* 2019



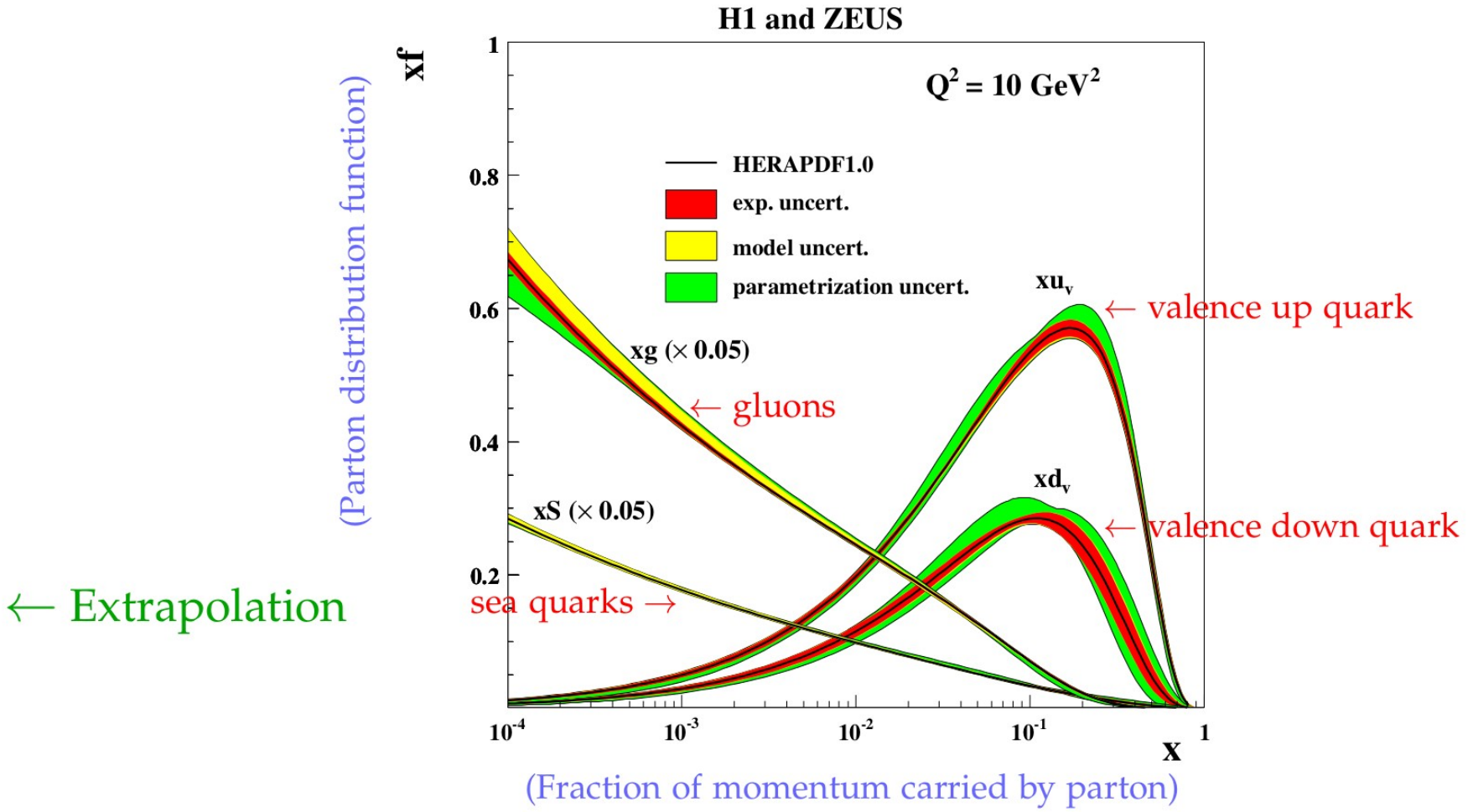
Energy too high: flux too low, no upgoing events

MB & Connolly, *PRL* 2019



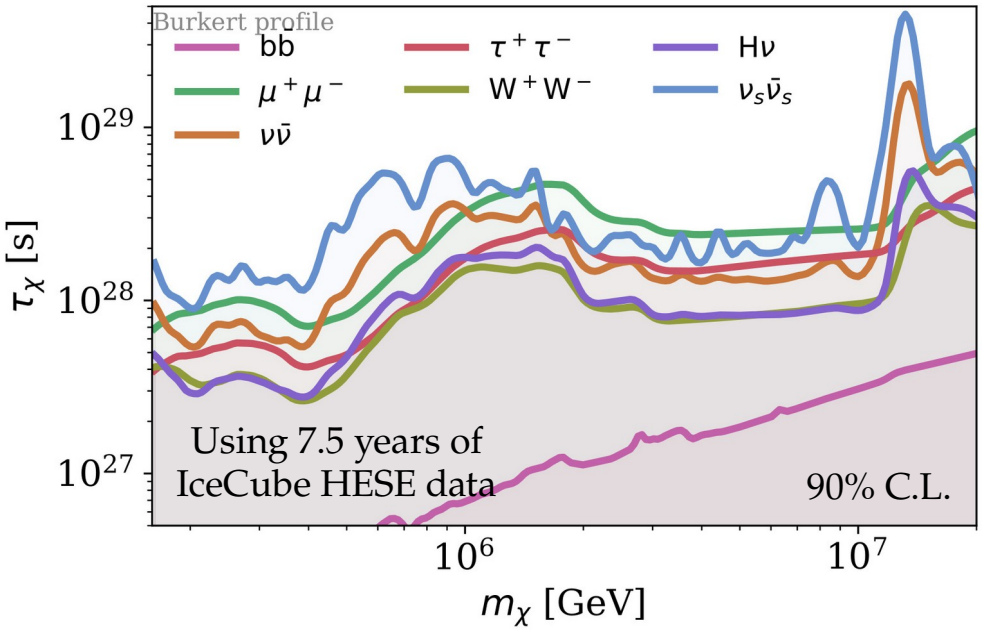
MB & Connolly, *PRL* 2019

Peeking inside a proton

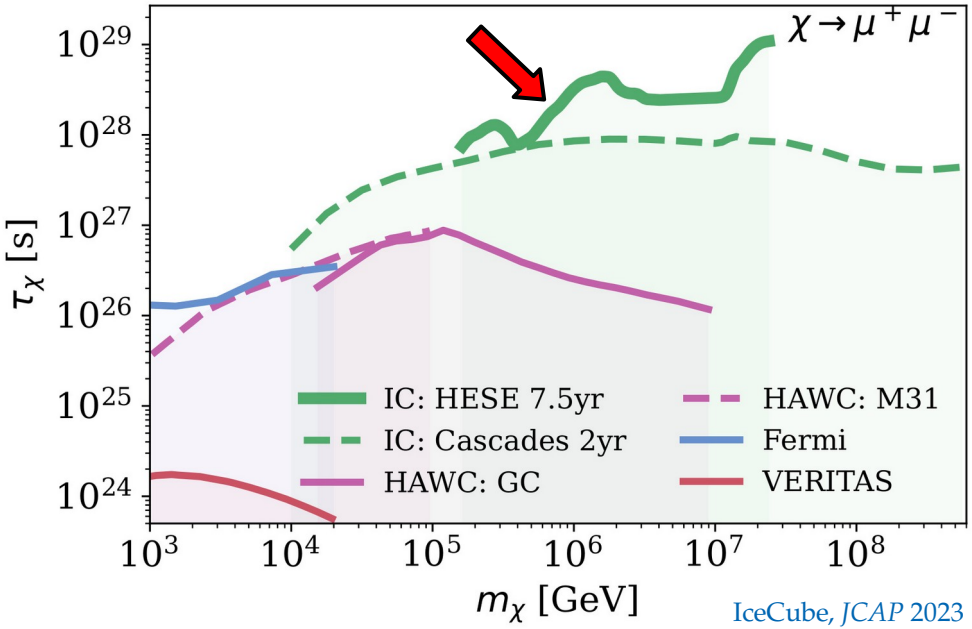


Limits on dark matter decay

Per annihilation channel
(assuming 100% branching ratio)



Compared to other limits
(assuming decay into muons)

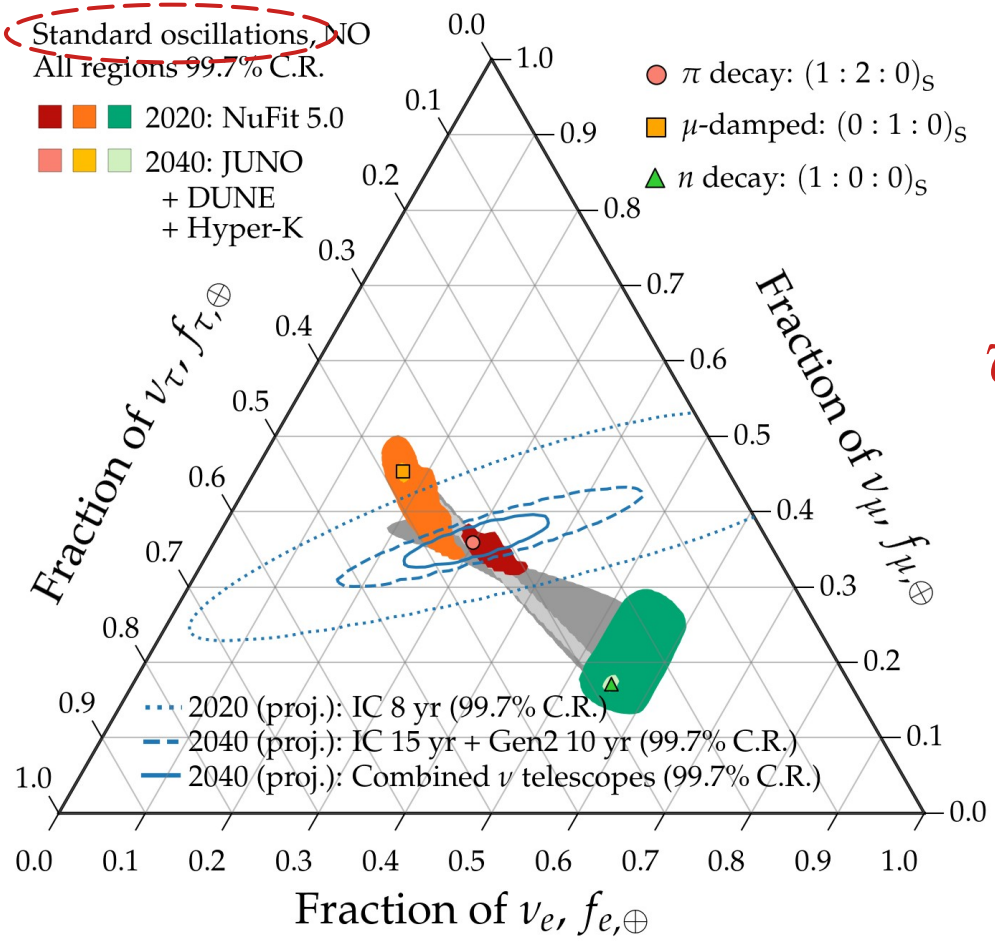


IceCube, *JCAP* 2023

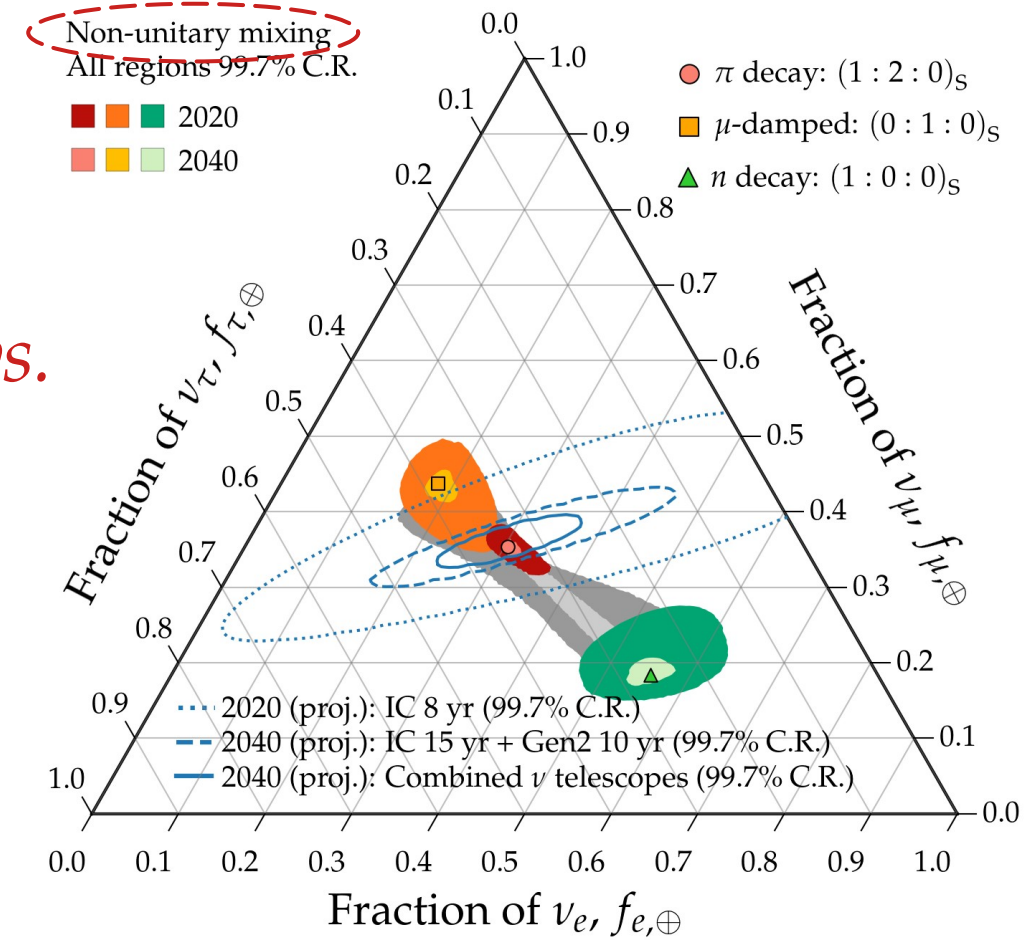
Two DM contributions: Galactic (anisotropic) + extragalactic (isotropic)

Plus background of atmospheric neutrinos (anisotropic, but different)

No unitarity? *No problem*

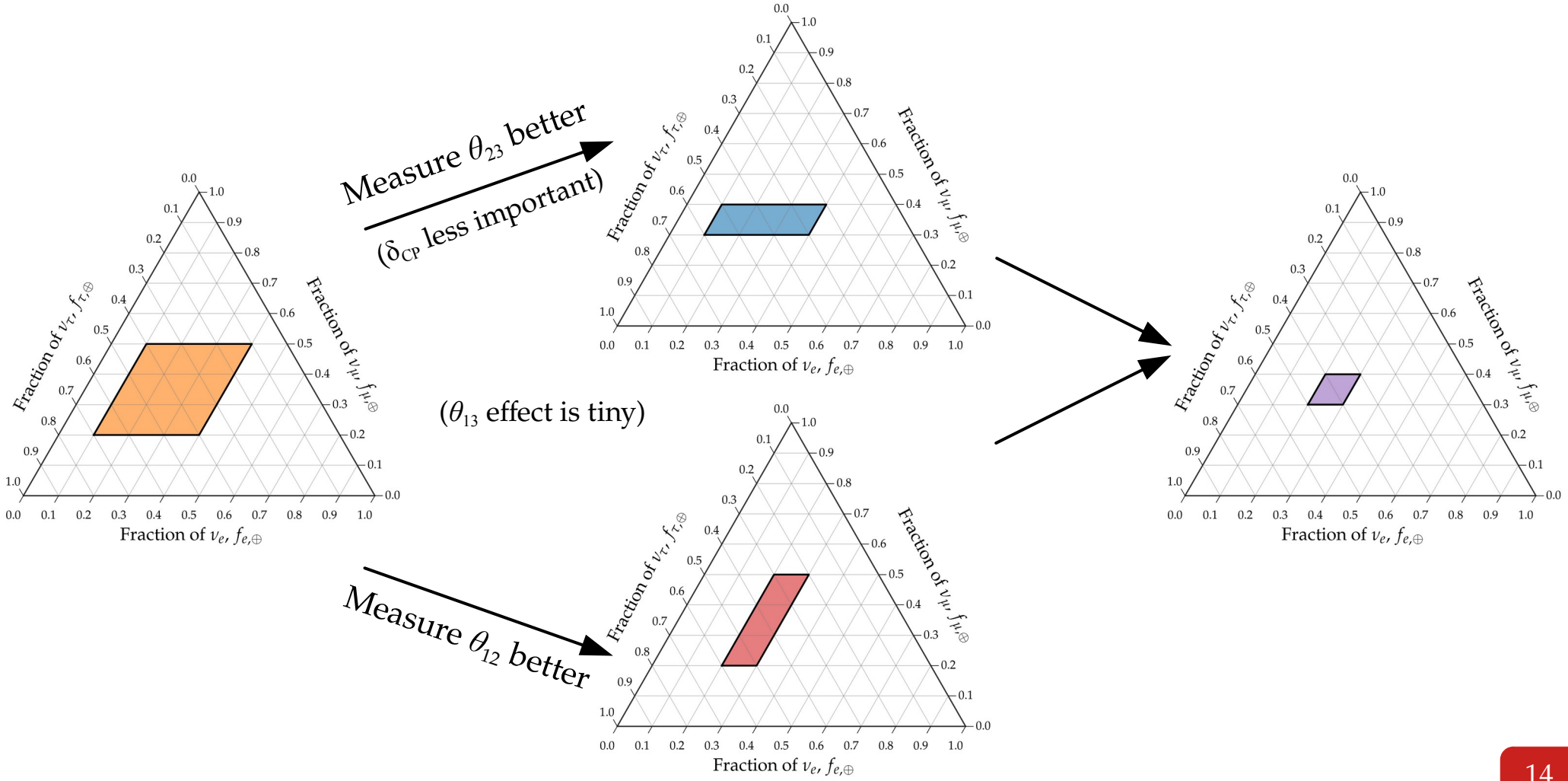


vs.



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

How knowing the mixing parameters better helps



5. New neutrino interactions:

Are there secret νν interactions?

Astrophysical neutrino sources

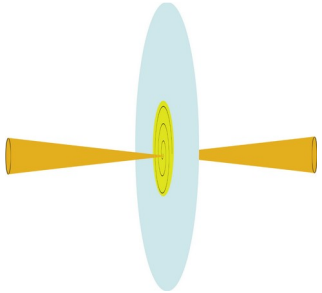
Earth

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

Astrophysical neutrino sources

Earth

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



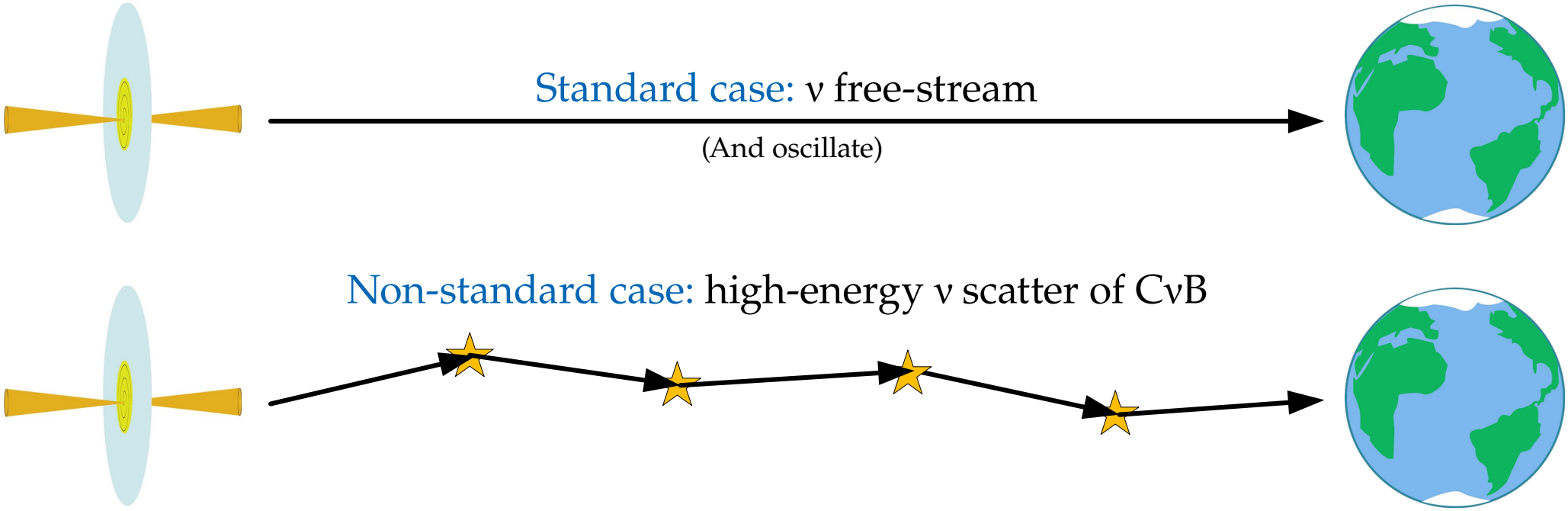
Standard case: ν free-stream

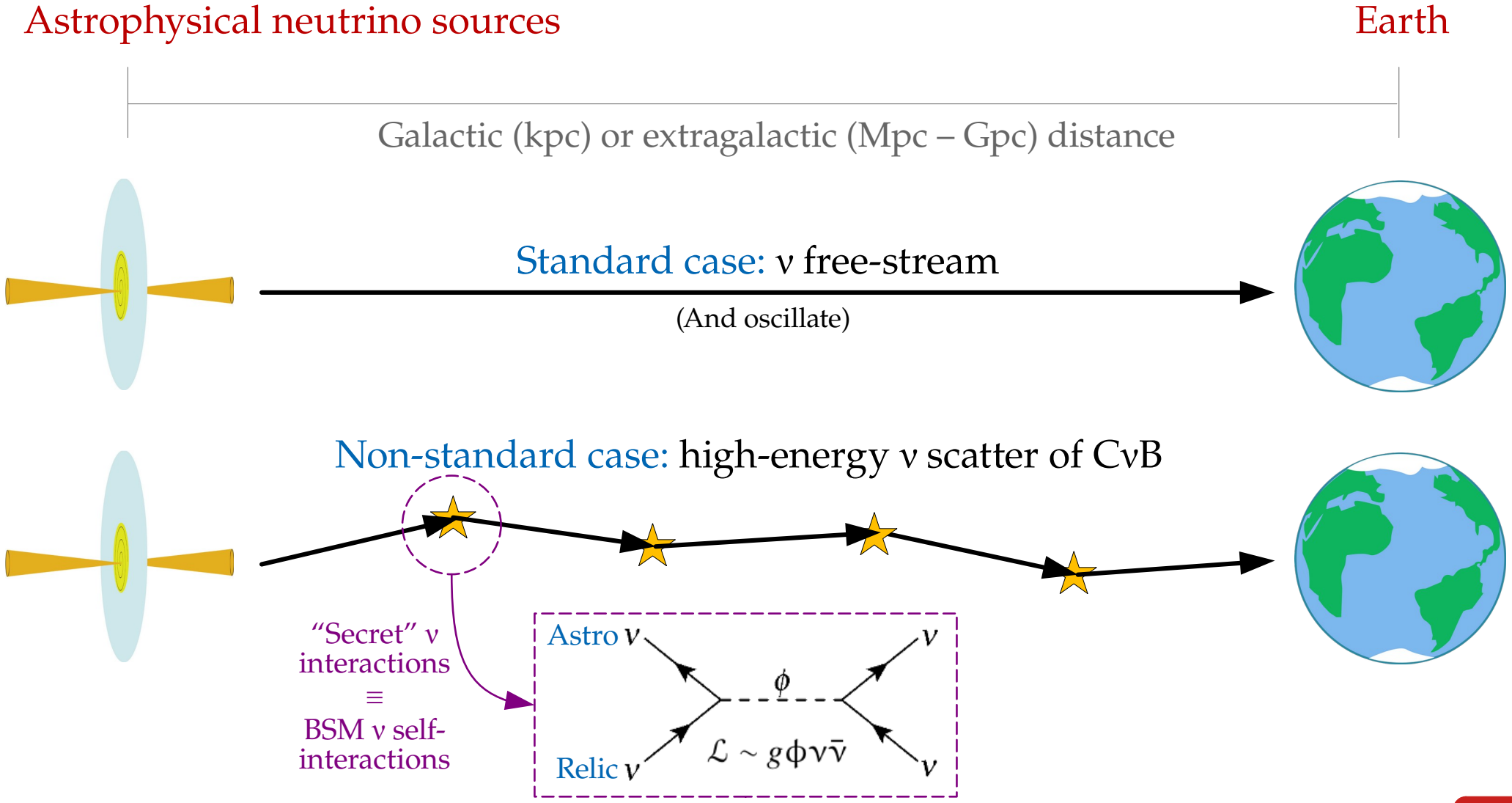
(And oscillate)

Astrophysical neutrino sources

Earth

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

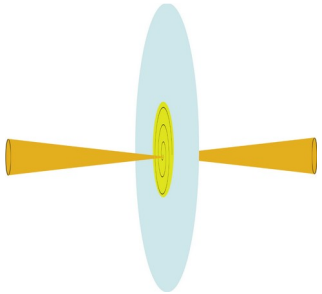



Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
(And oscillate)
Non-standard case: high-energy ν scatter of CνB
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ϕ
ν
ν
$\mathcal{L} \sim g\phi\nu\bar{\nu}$

Astrophysical neutrino sources

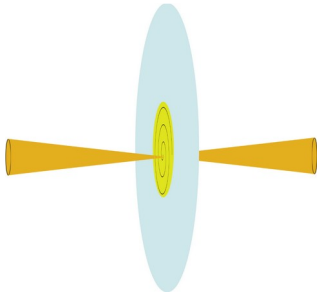
Earth

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

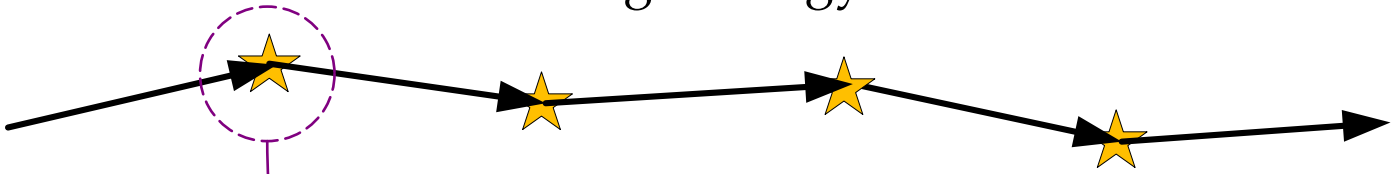


Standard case: ν free-stream

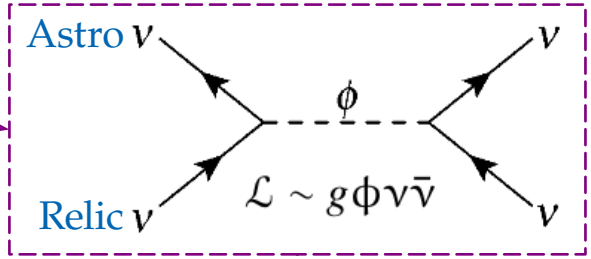
(And oscillate)



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



"Secret" ν interactions ≡ BSM ν self-interactions

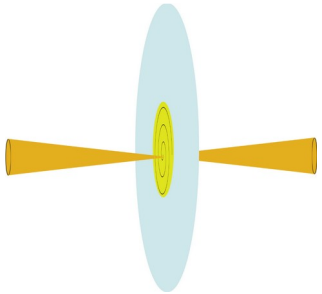


Can change:

Astrophysical neutrino sources

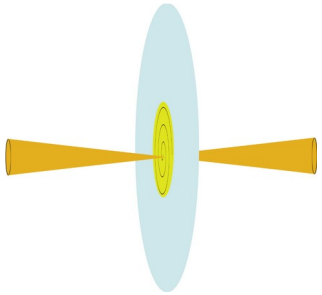
Earth

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



Standard case: ν free-stream

(And oscillate)



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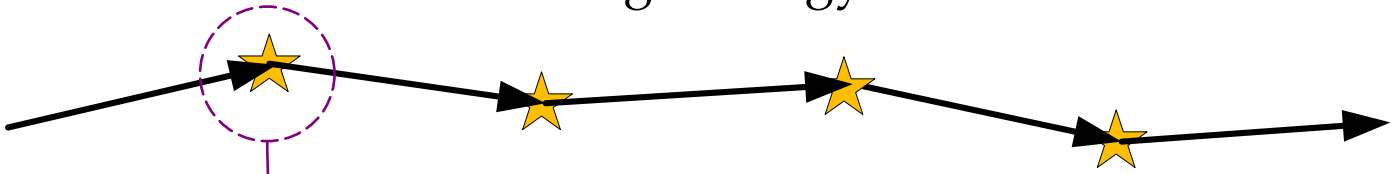

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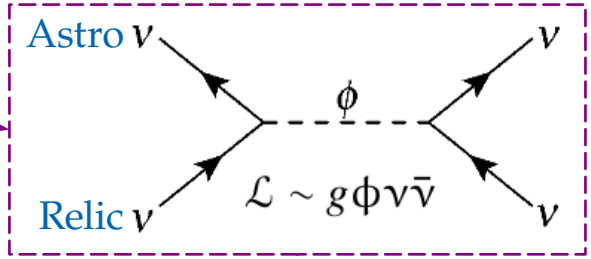
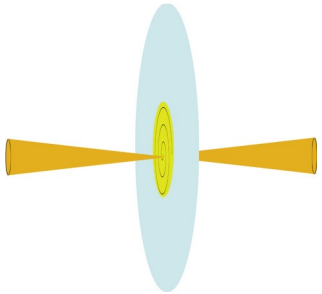


Can change:
- Energy spectrum

Astrophysical neutrino sources

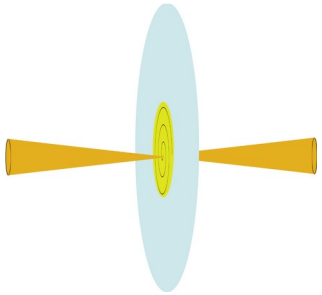
Earth

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

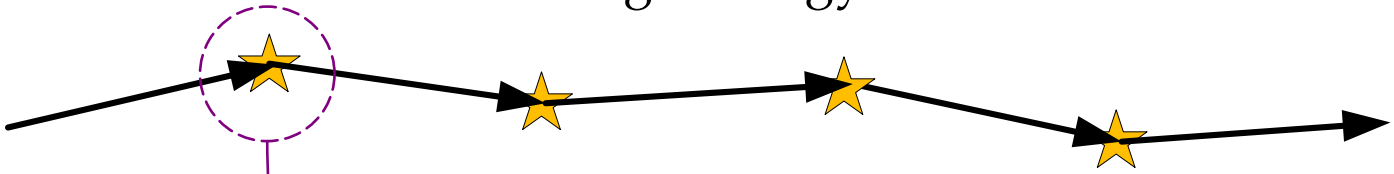


Standard case: ν free-stream

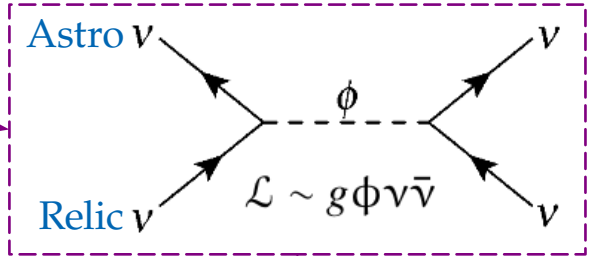
(And oscillate)



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



"Secret" ν interactions ≡ BSM ν self-interactions



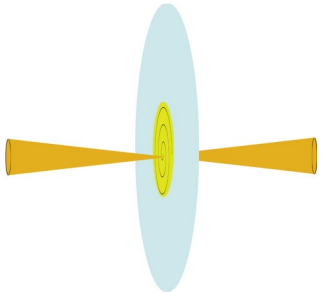
Can change:

- Energy spectrum
- Flavor composition

Astrophysical neutrino sources

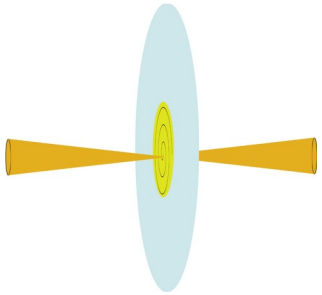
Earth

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

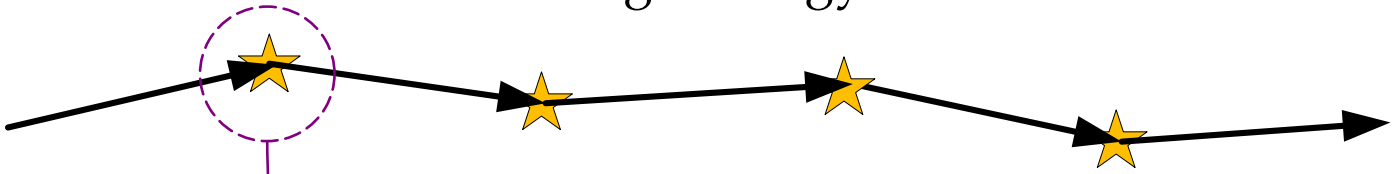


Standard case: ν free-stream

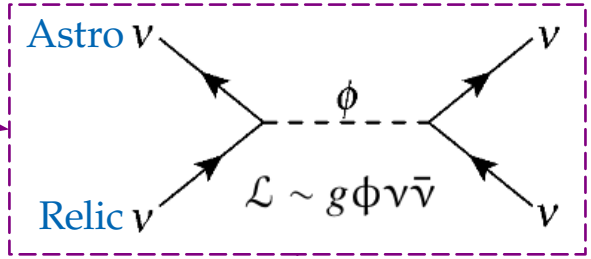
(And oscillate)



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



"Secret" ν interactions ≡ BSM ν self-interactions



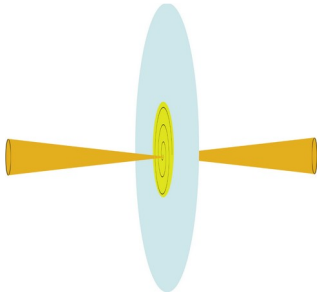
Can change:

- Energy spectrum
- Flavor composition
- Direction

Astrophysical neutrino sources

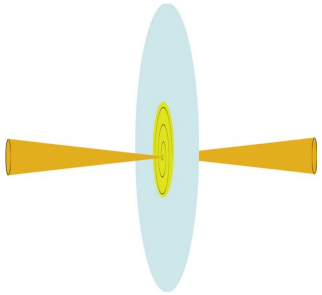
Earth

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

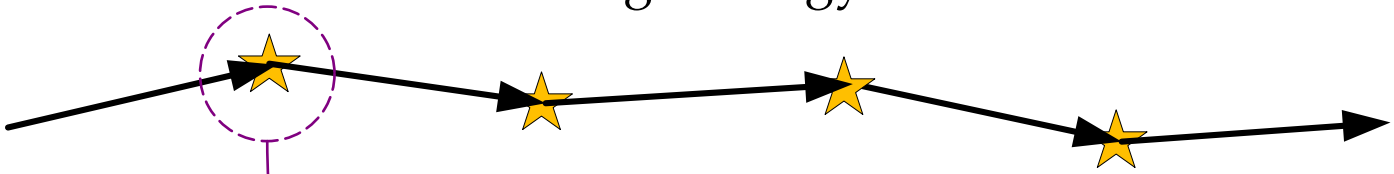


Standard case: ν free-stream

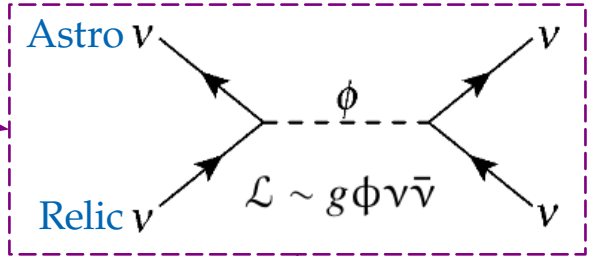
(And oscillate)



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



"Secret" ν interactions ≡ BSM ν self-interactions

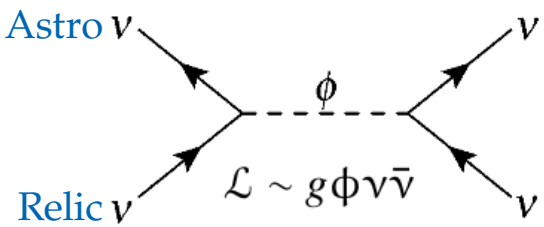


Can change:

- Energy spectrum
- Flavor composition
- Direction
- Arrival times

Secret interactions of high-energy astrophysical neutrinos

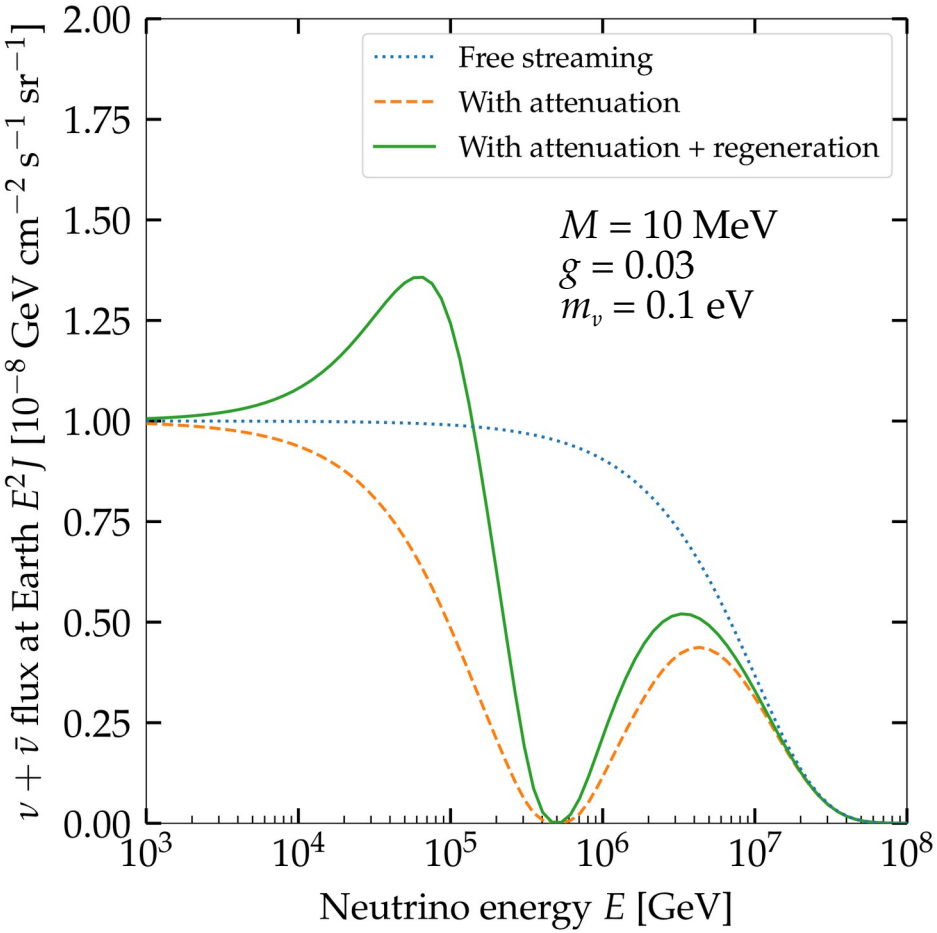
"Secret" neutrino interactions between astrophysical ν (PeV) and relic ν (0.1 meV):



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

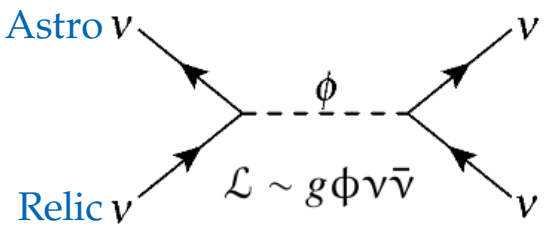
Resonance energy: $$E_{\rm res} = \frac{M^2}{2m_\nu}$$

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):

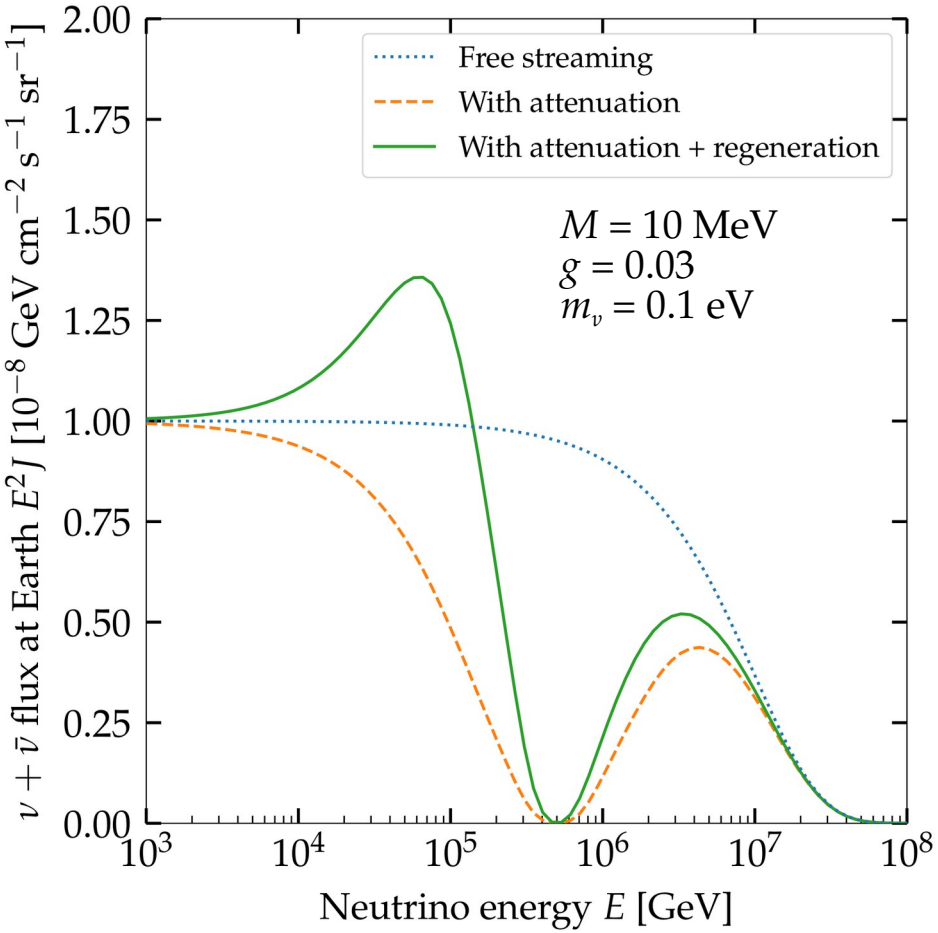


New coupling

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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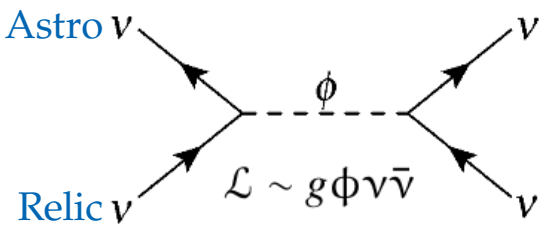

New coupling

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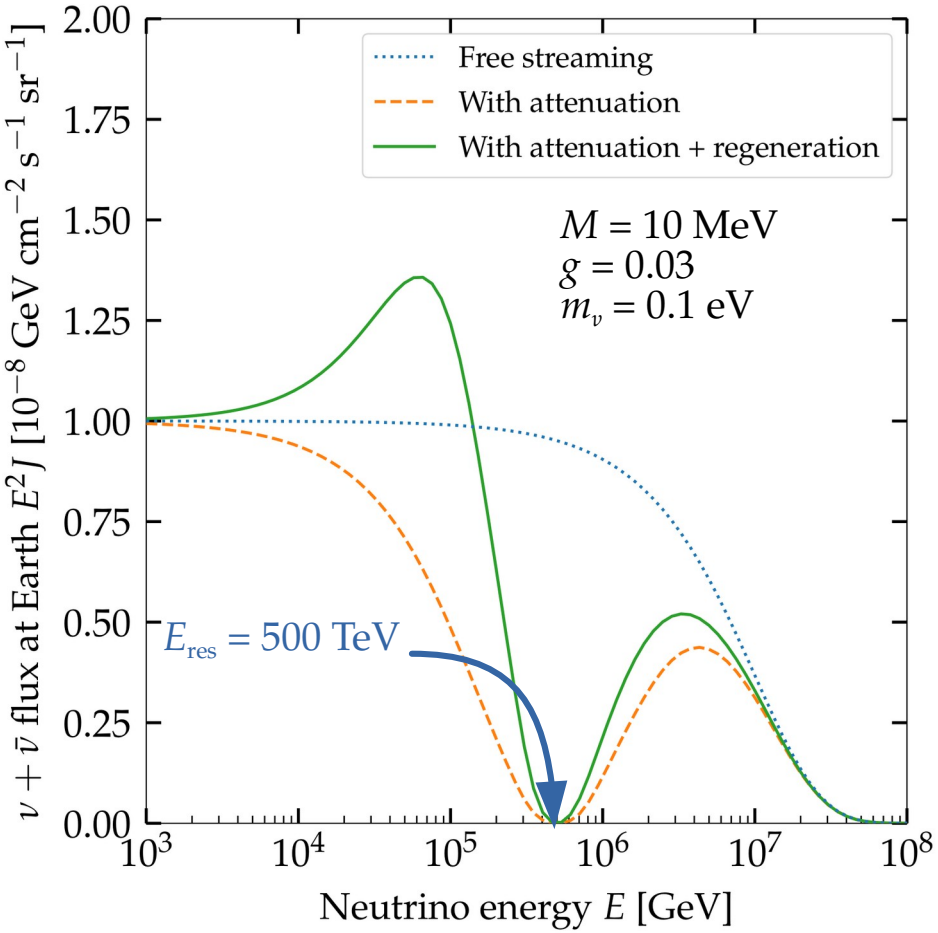
Mediator mass

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



MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
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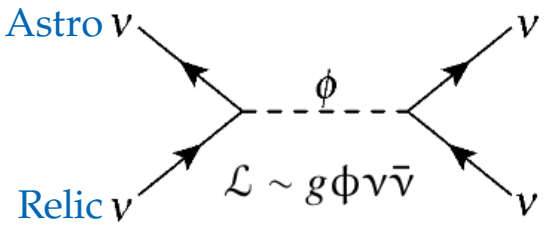
Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

Secret interactions of high-energy astrophysical neutrinos

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

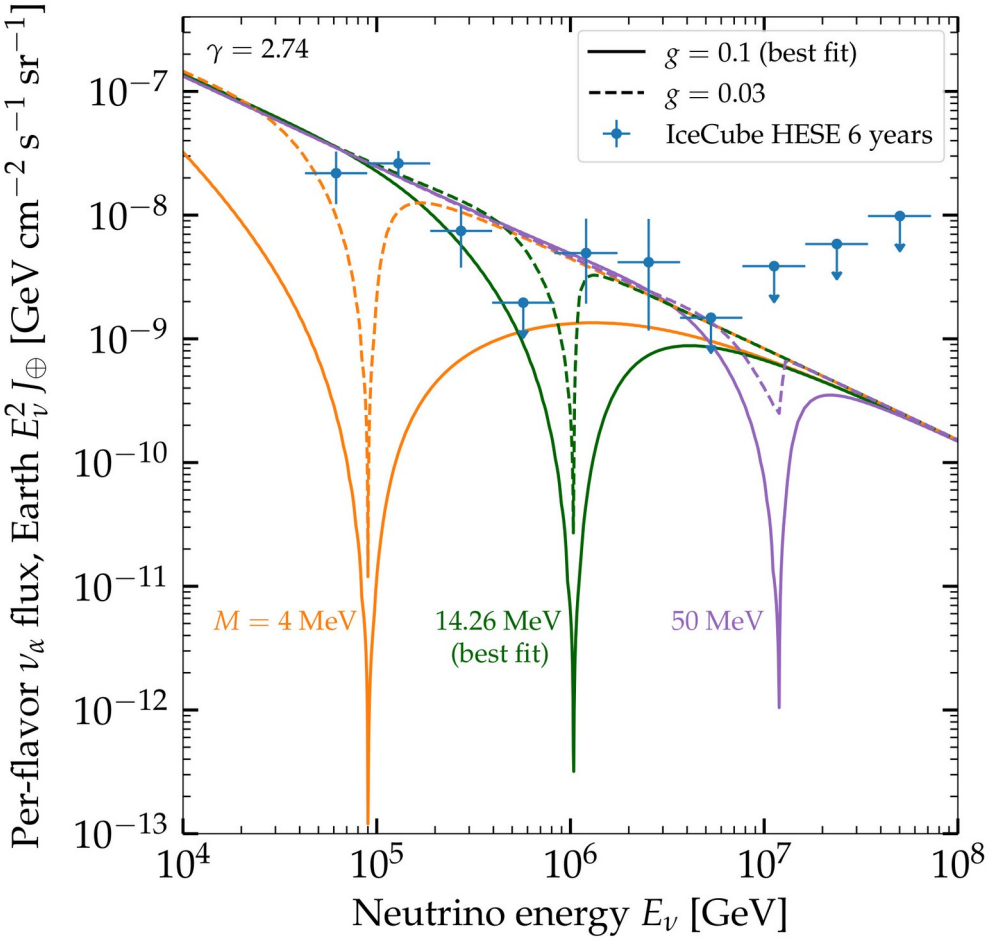


New coupling

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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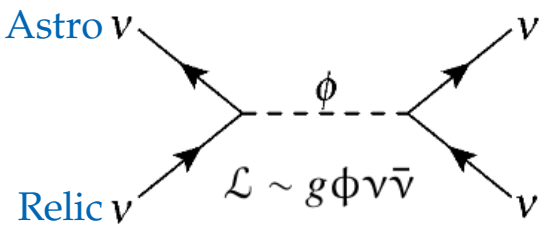

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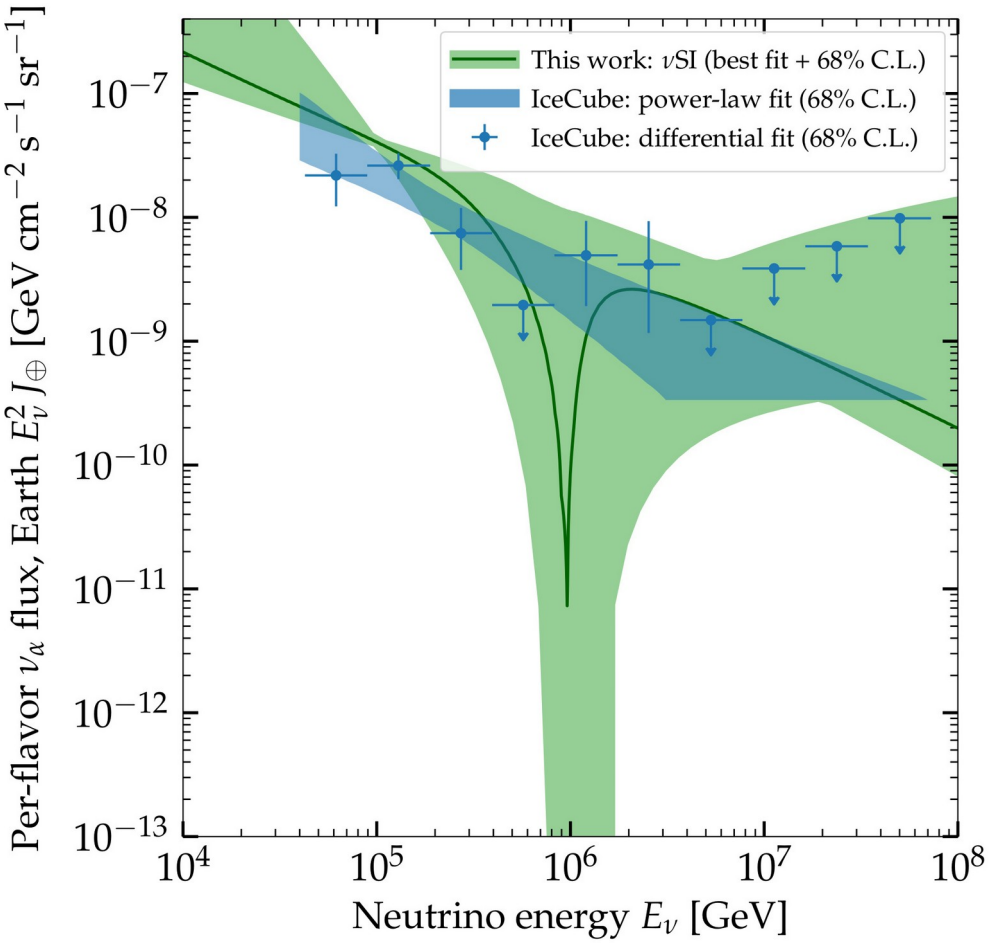
Looking for evidence of νSI

- 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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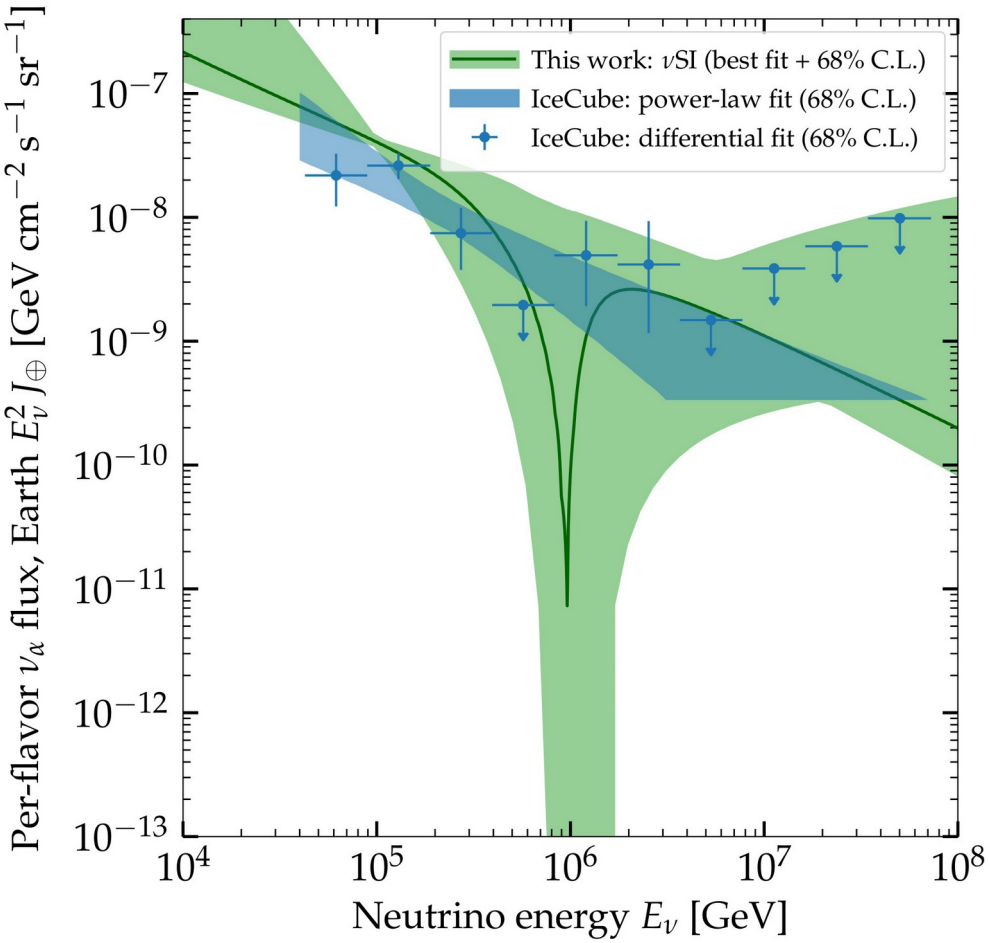

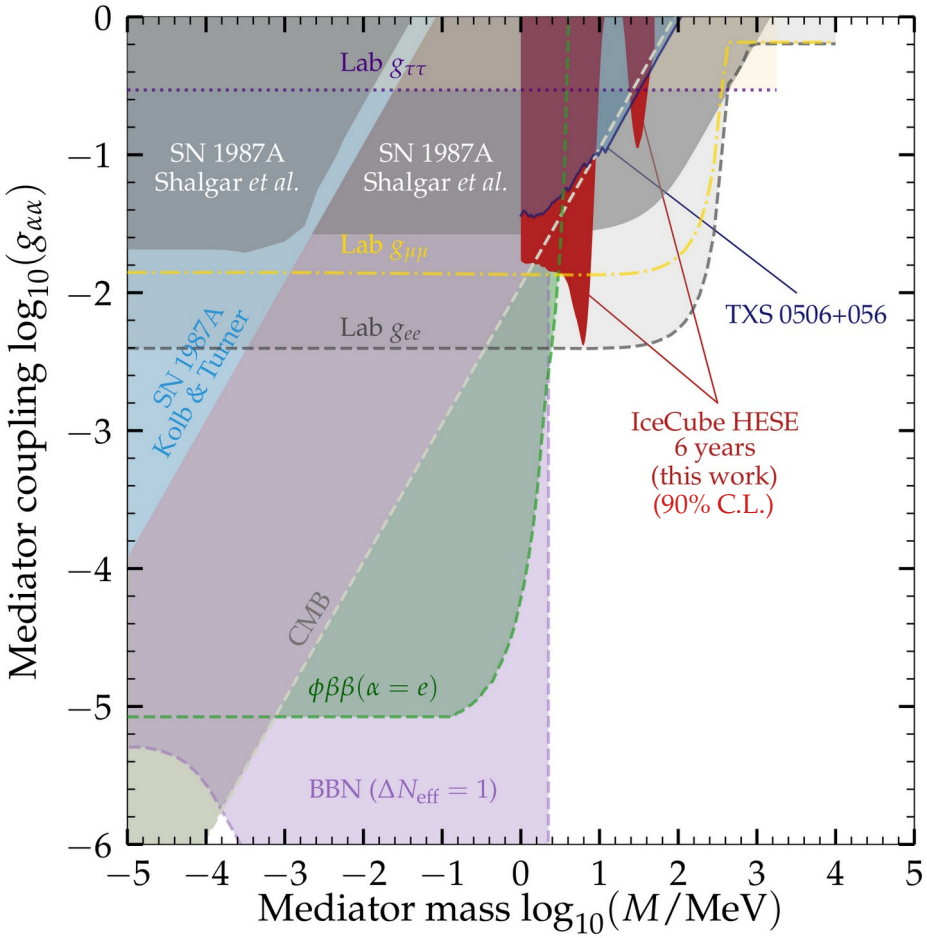

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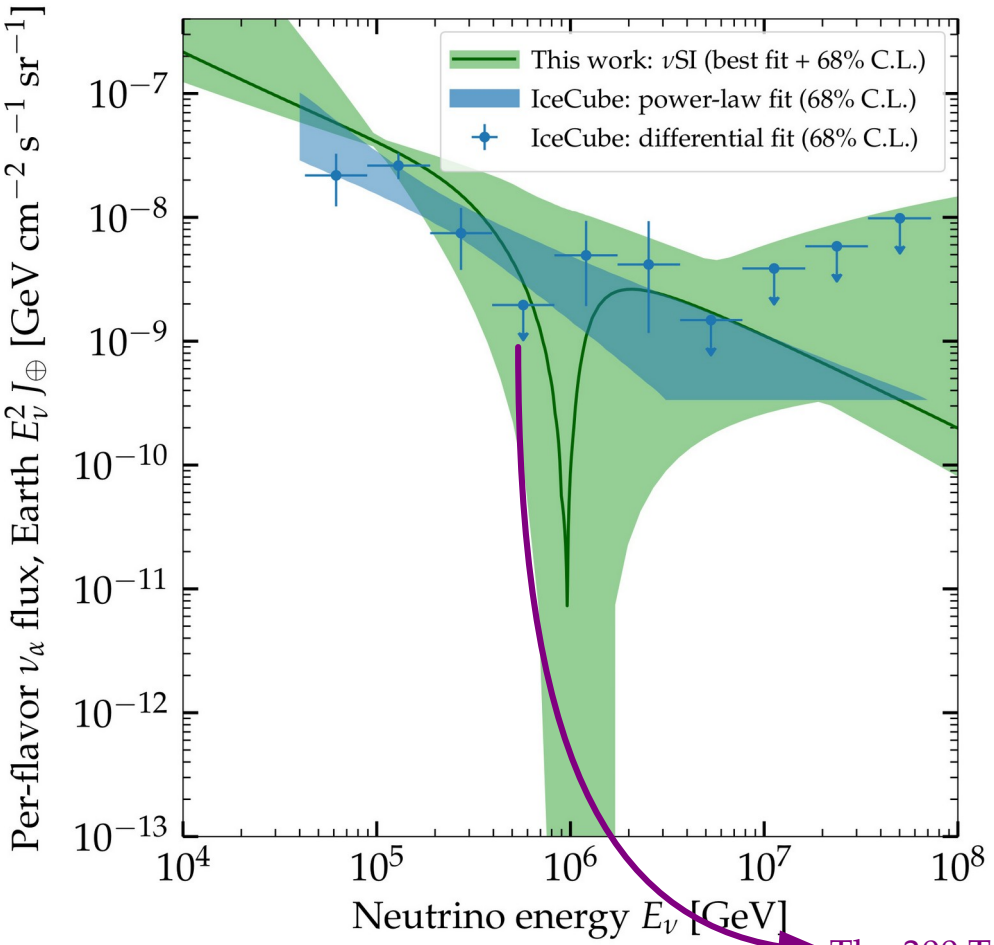

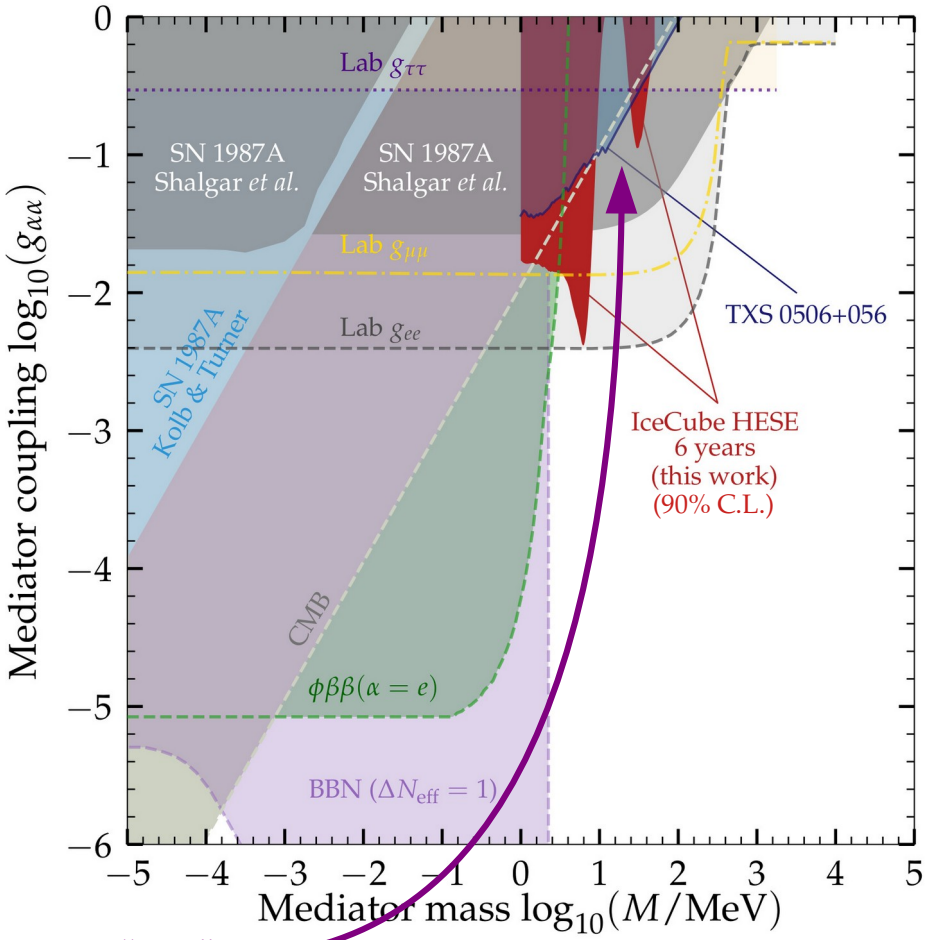

The 300 TeV–1 PeV "gap" degrades the limit at ~10 MeV

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Shalgar, **MB**, Tamborra, *PRD* 2020

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)

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  the nature of φ is unimportant if it is invisible to neutrino detectors

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- BSM decays may have significantly higher rates: $\nu_i \to \nu_j + \varphi$ — Nambu-Goldstone boson of a broken symmetry

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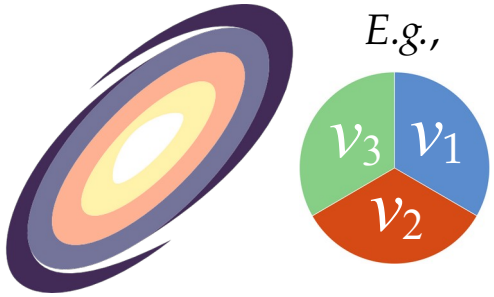
Astrophysical sources

Earth

L ~ up to a few Gpc



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

Astrophysical sources

Earth

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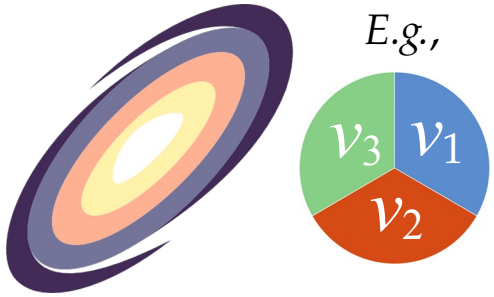

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Only sensitive to their ratio

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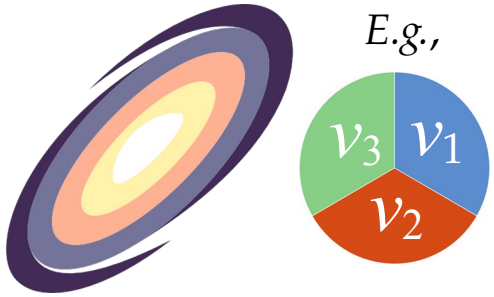

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?

Lower-E ν are longer-lived…

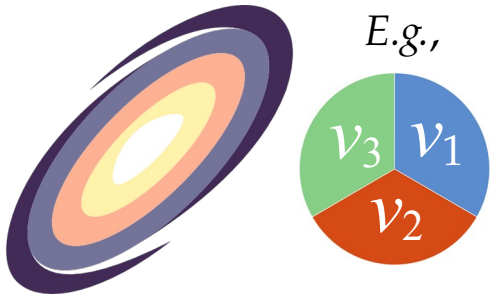
The flux of ν_i is attenuated by $\exp[-(L/E)\cdot(m_i/\tau_i)]$

… but ν that travel longer L are more attenuated!

Astrophysical sources

Earth

$L \sim$ up to a few Gpc



Astrophysical sources

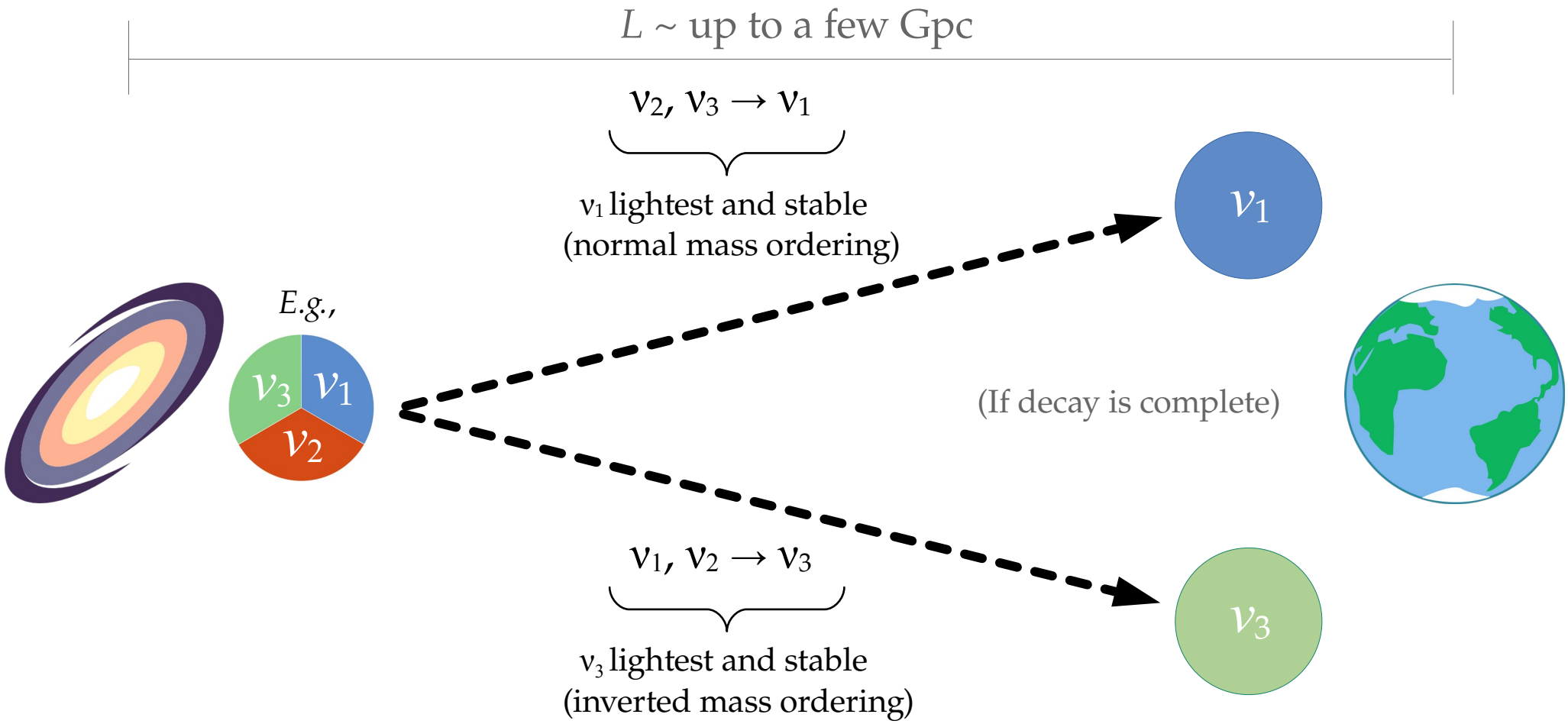
Earth

$L \sim$ up to a few Gpc

$$\underbrace{\nu_2, \nu_3 \to \nu_1}_{\substack{\nu_1 \text{ lightest and stable} \\ \text{(normal mass ordering)}}}$$

E.g.,

(If decay is complete)


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

Astrophysical sources

Earth

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E.g.,

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$\nu_1, \nu_2 \rightarrow \nu_3$

ν_3 lightest and stable
(inverted mass ordering)

Fine print:

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

Astrophysical sources

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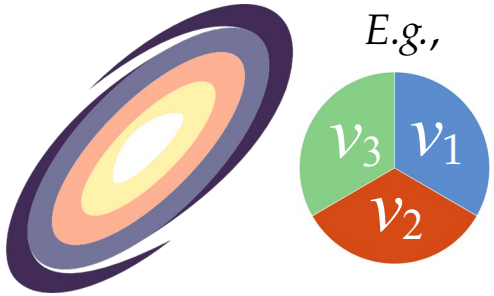
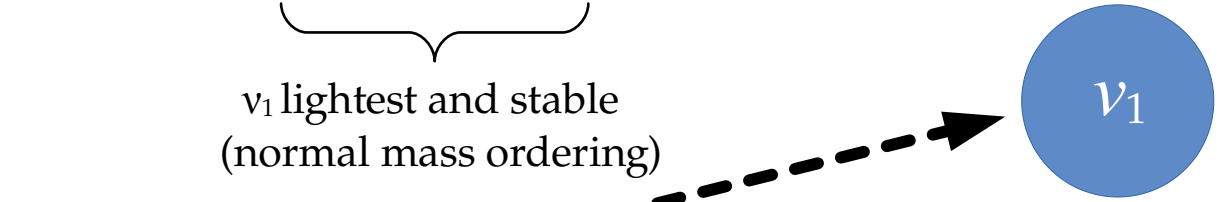
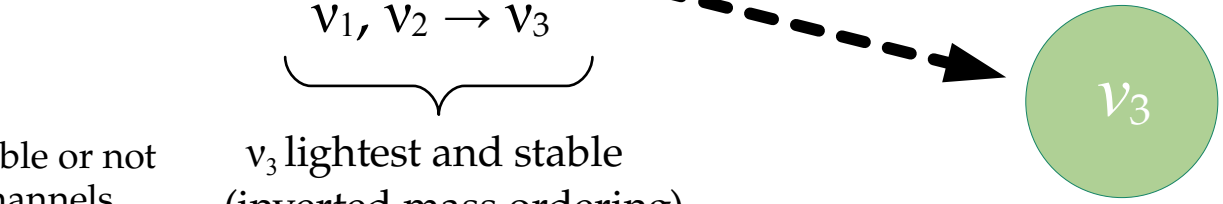




What does decay change?



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What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

What does neutrino decay change?

Flavor composition ⟷ Spectrum shape ⟷ Event rate

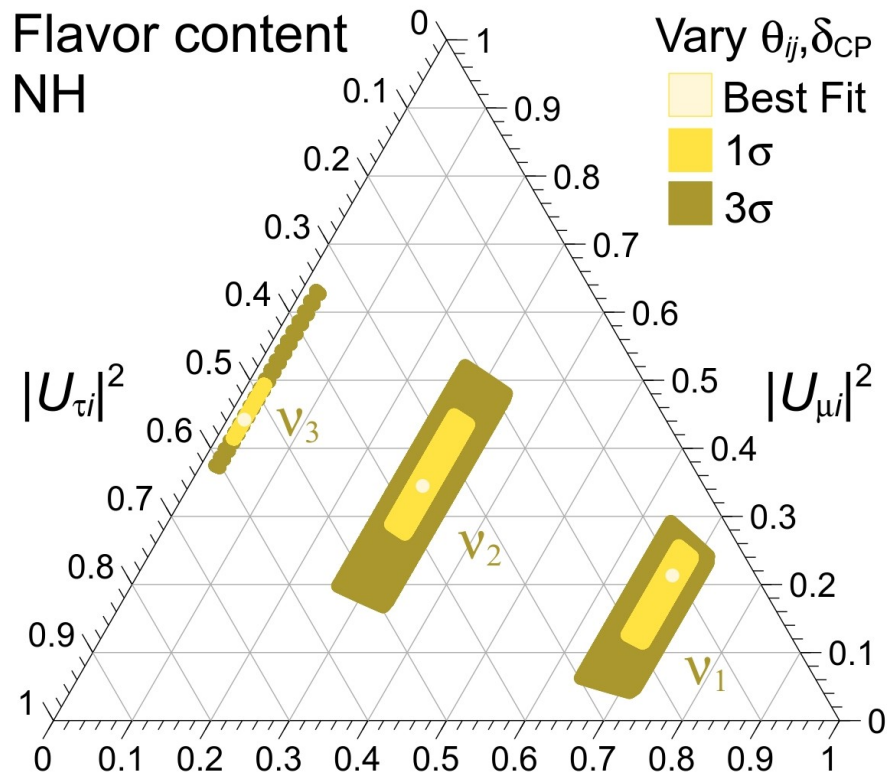
Flavor content of mass eigenstates:

Known to within 2%

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

Known to within 8%

Known to within 20% (or worse)



MB, Beacom, Winter *PRL* 2015

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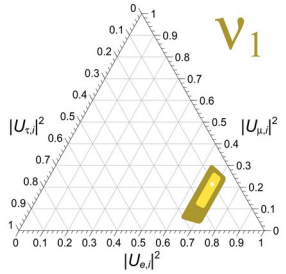

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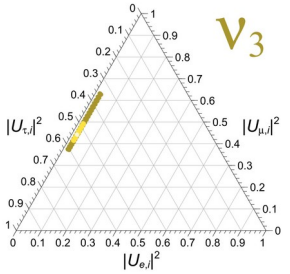

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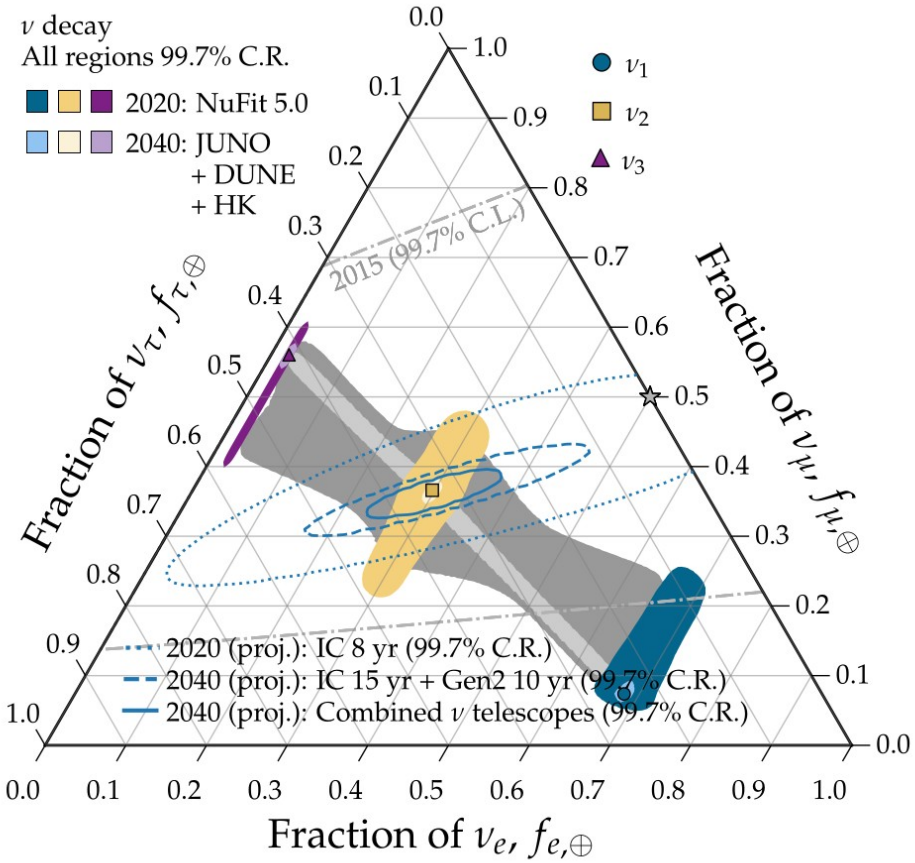

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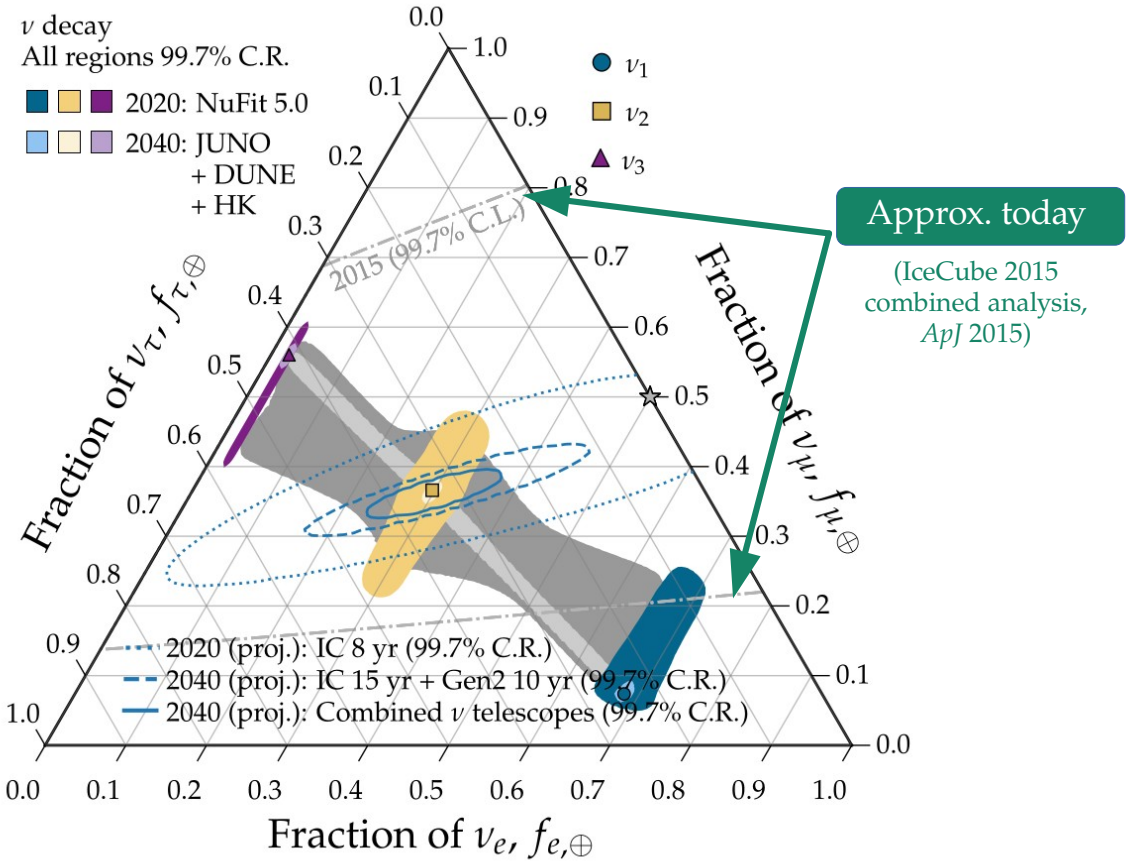

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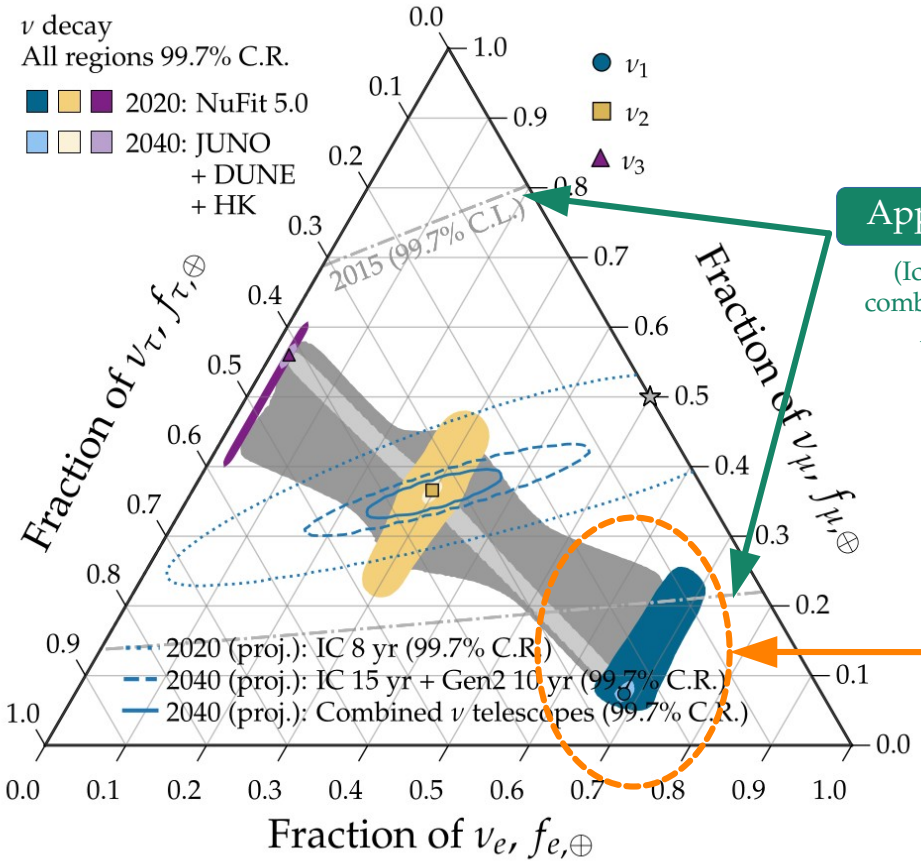

Approx. today

(IceCube 2015 combined analysis, *ApJ* 2015)

Complete decay into ν_1 disfavored by 2015 IceCube flavor measurement

What does neutrino decay change?

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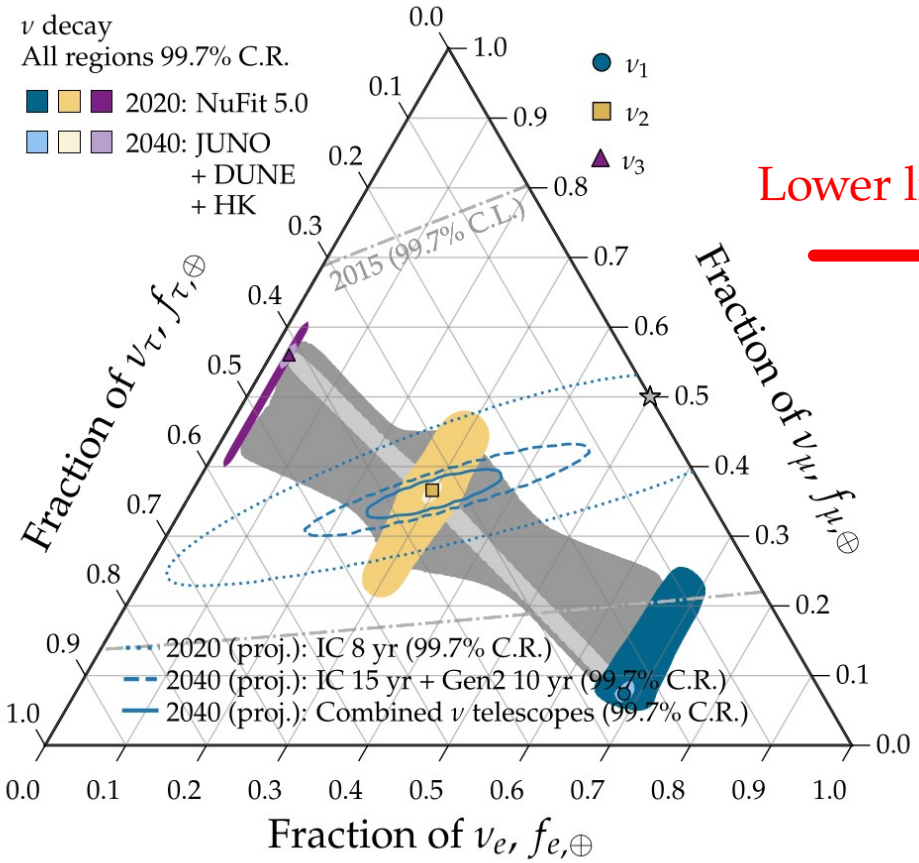

Lower limit on τ/m

What does neutrino decay change?

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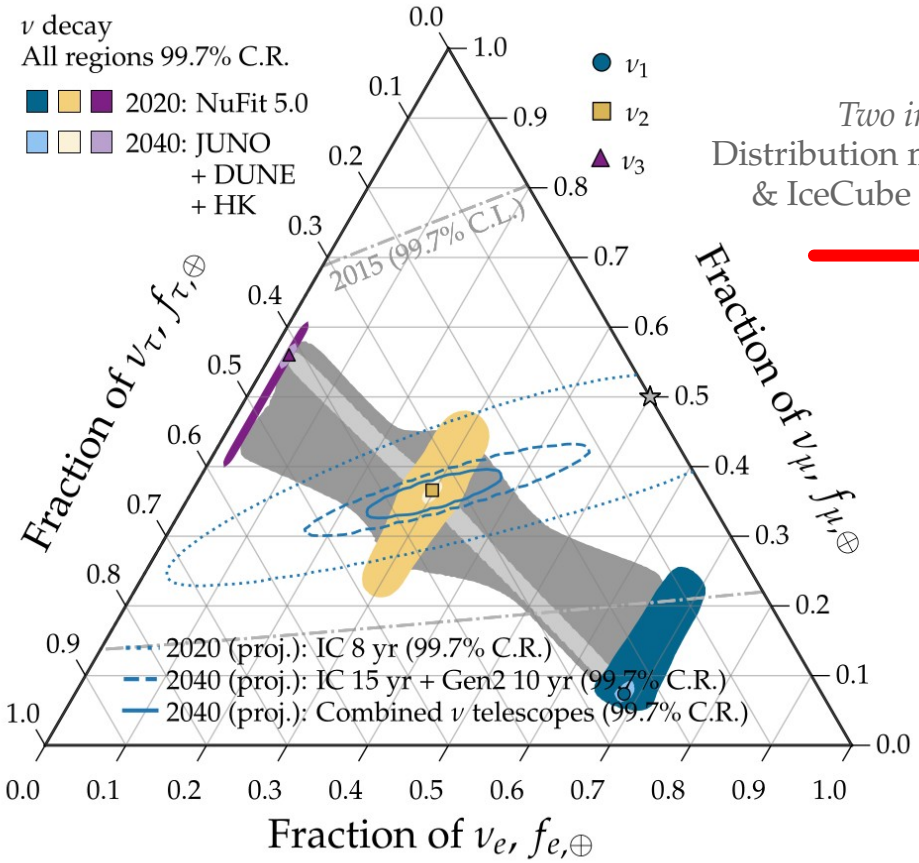

Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

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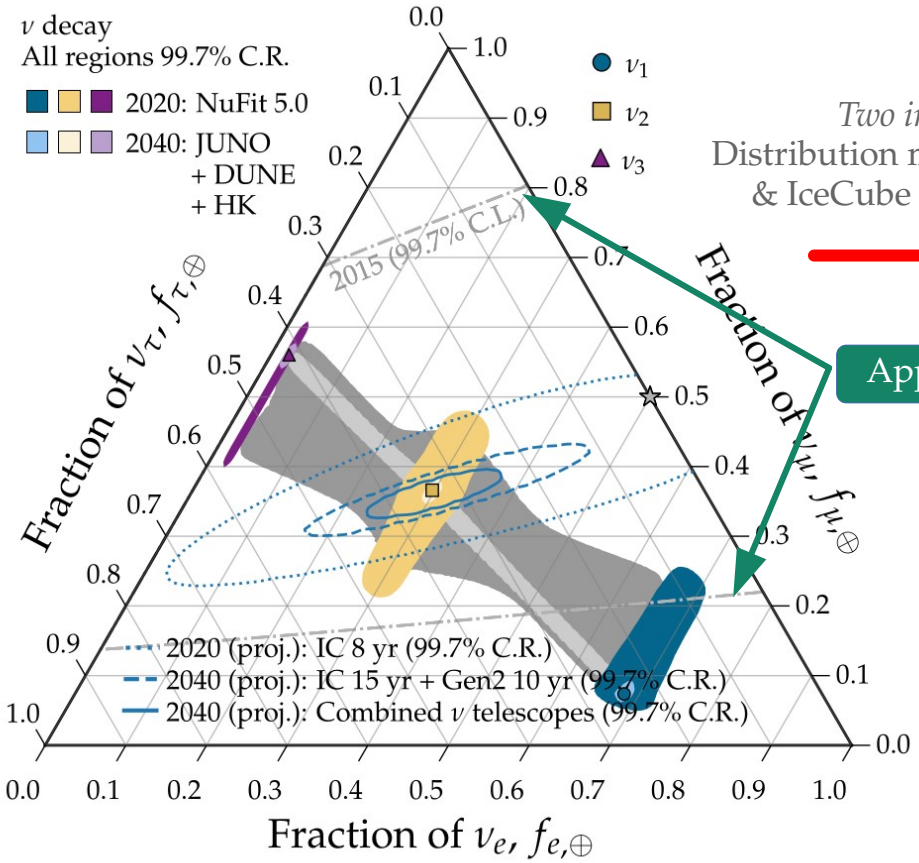

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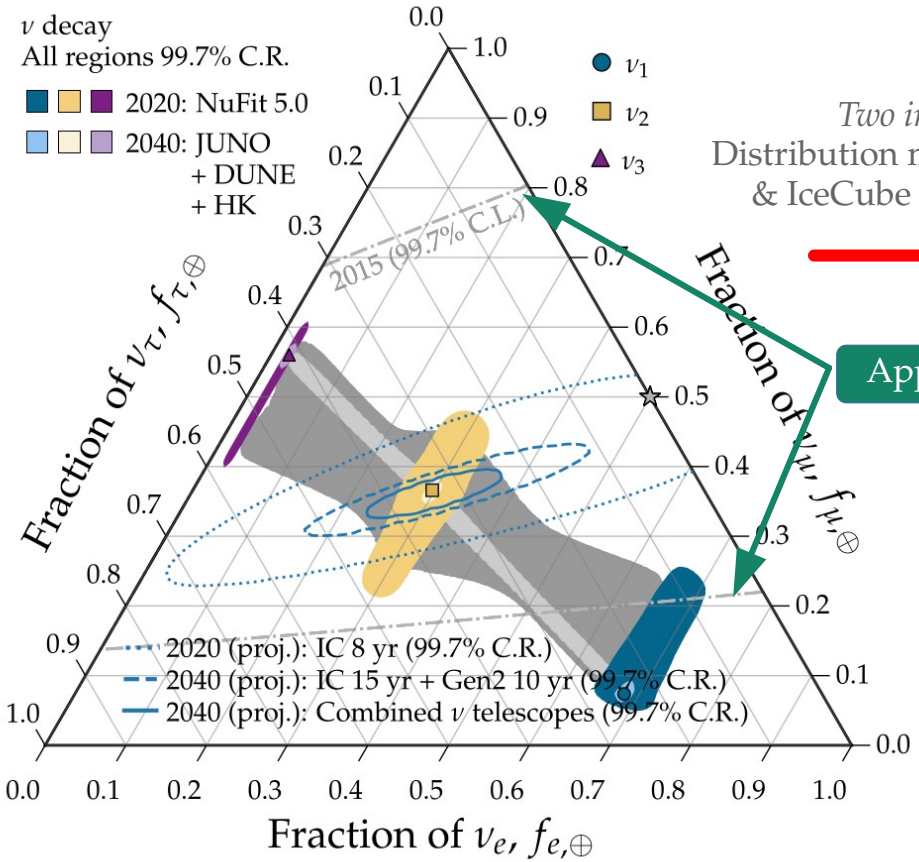

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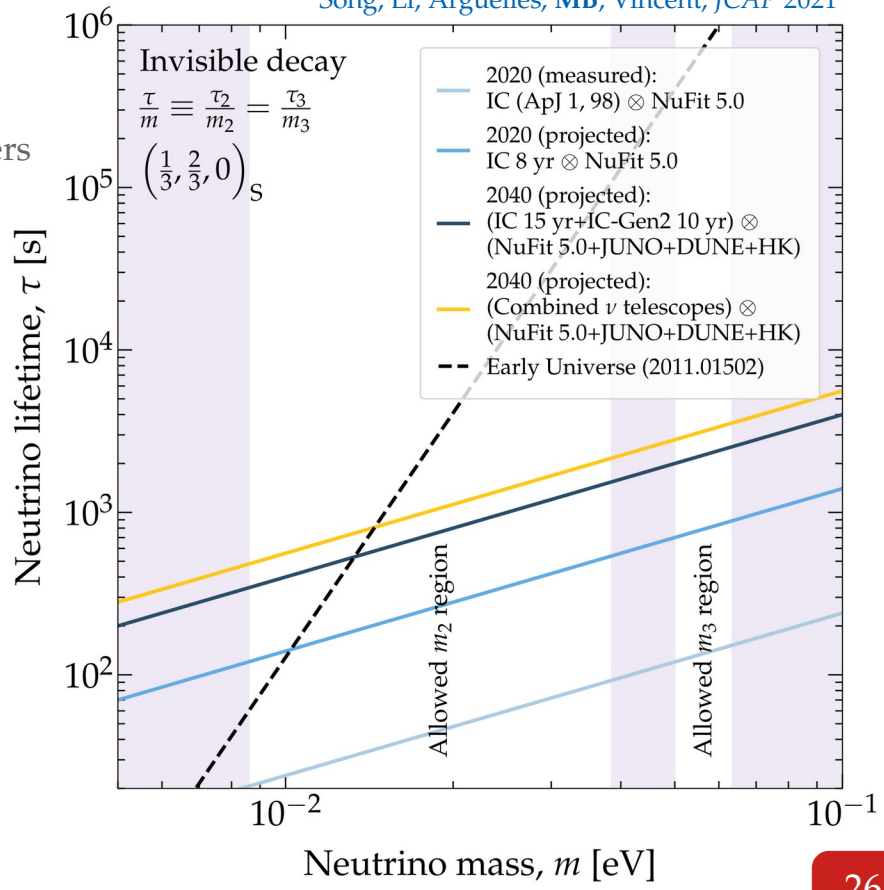
Approx. today

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



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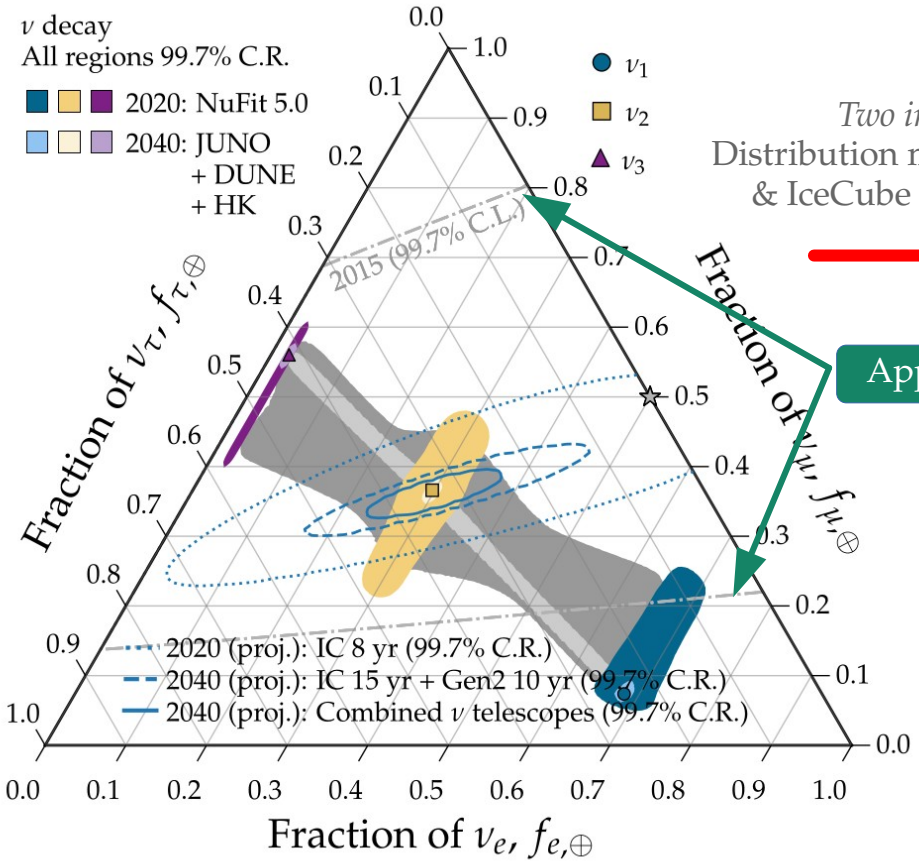

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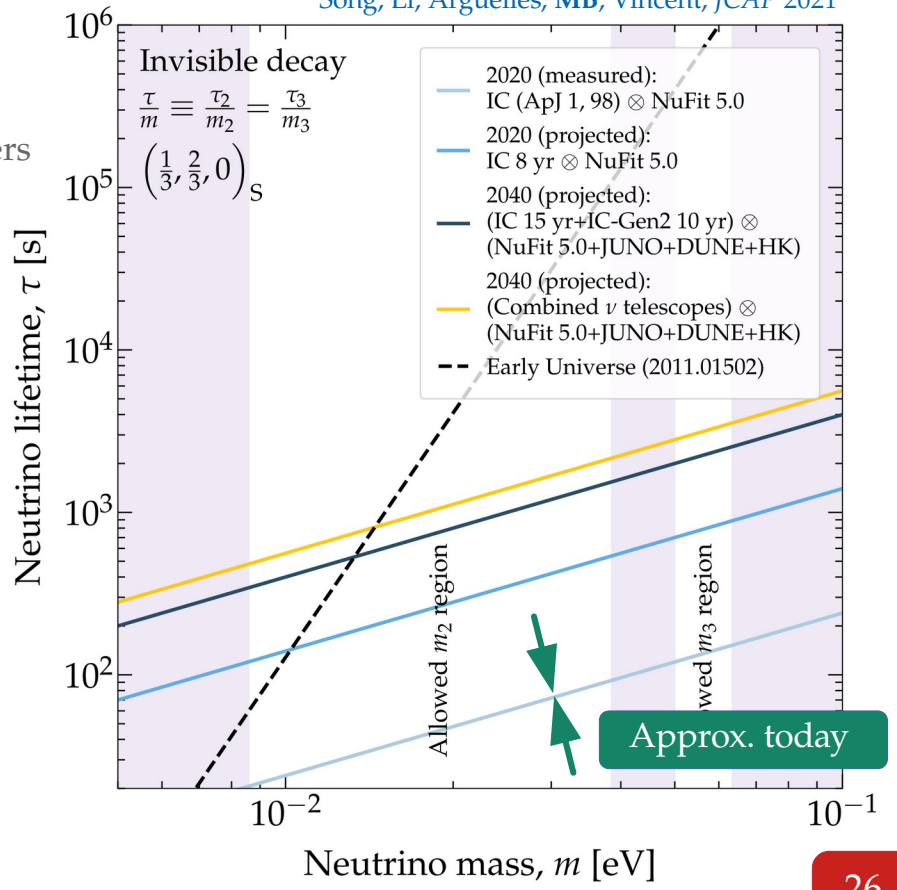

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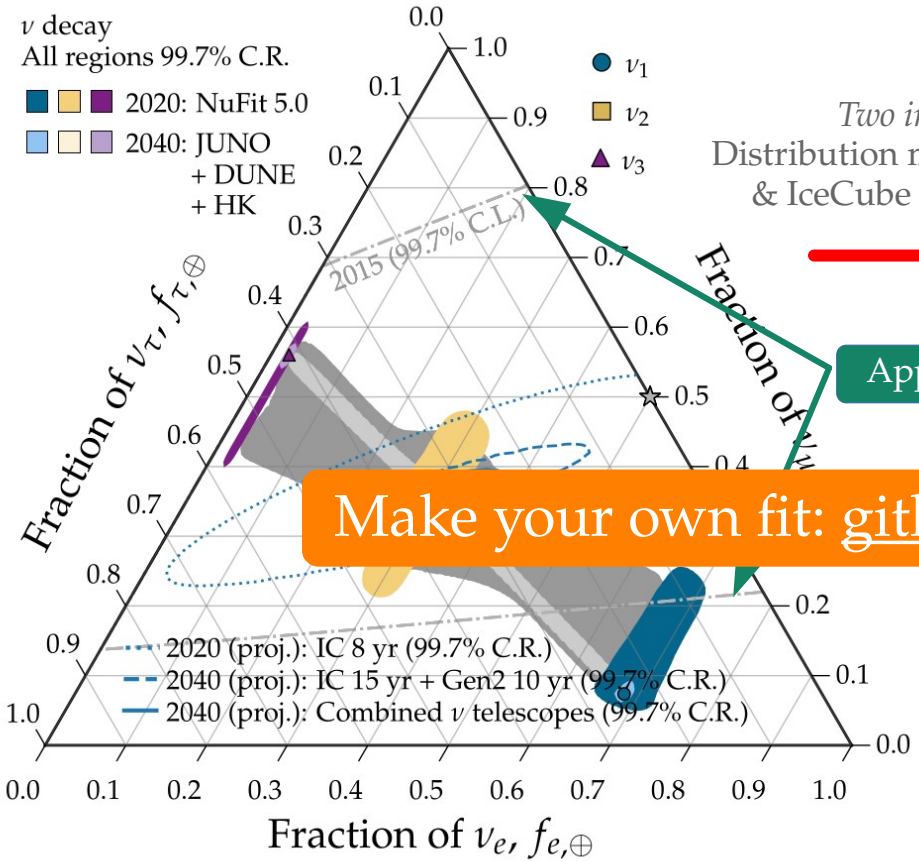

Two ingredients:
Distribution mixing parameters
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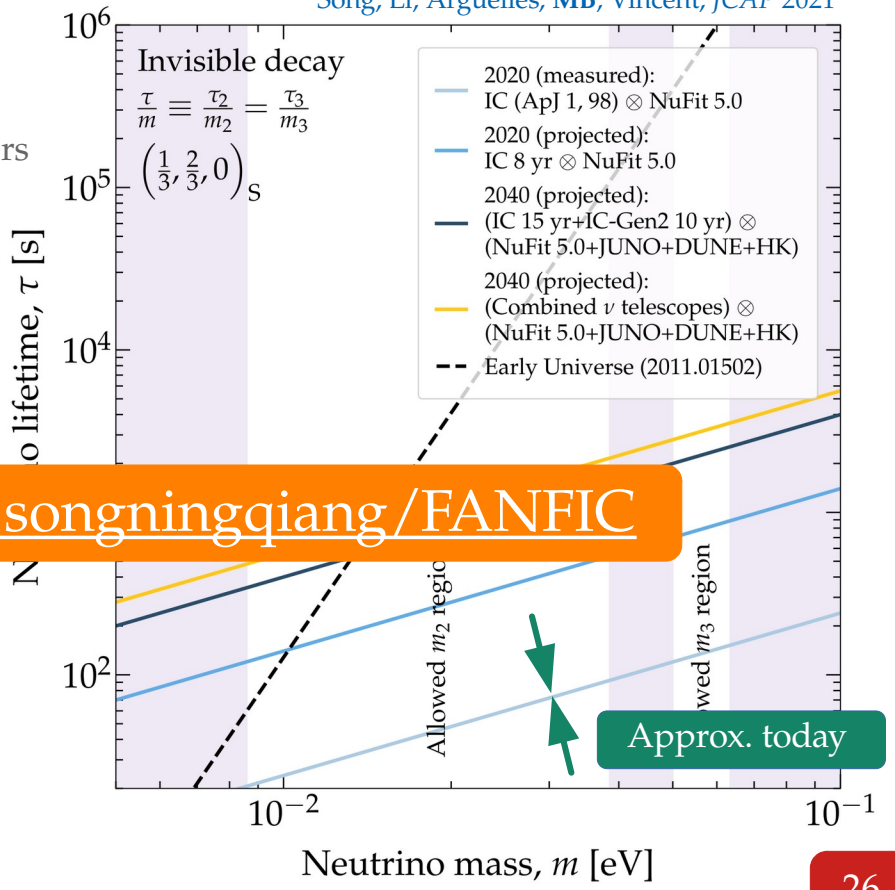
Approx. today

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

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



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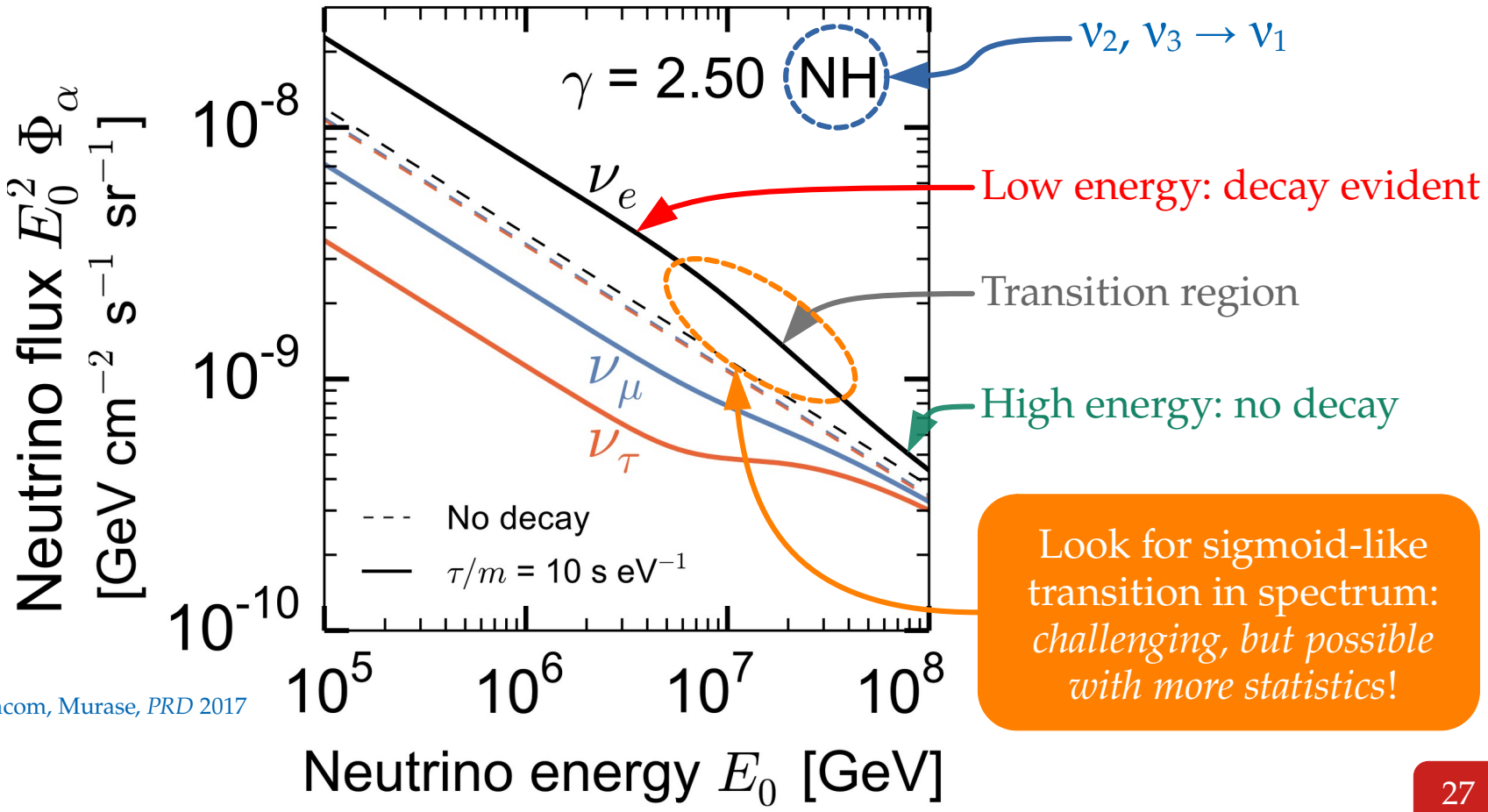
Flavor composition ⟷ **Spectrum shape** ⟷ Event rate



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

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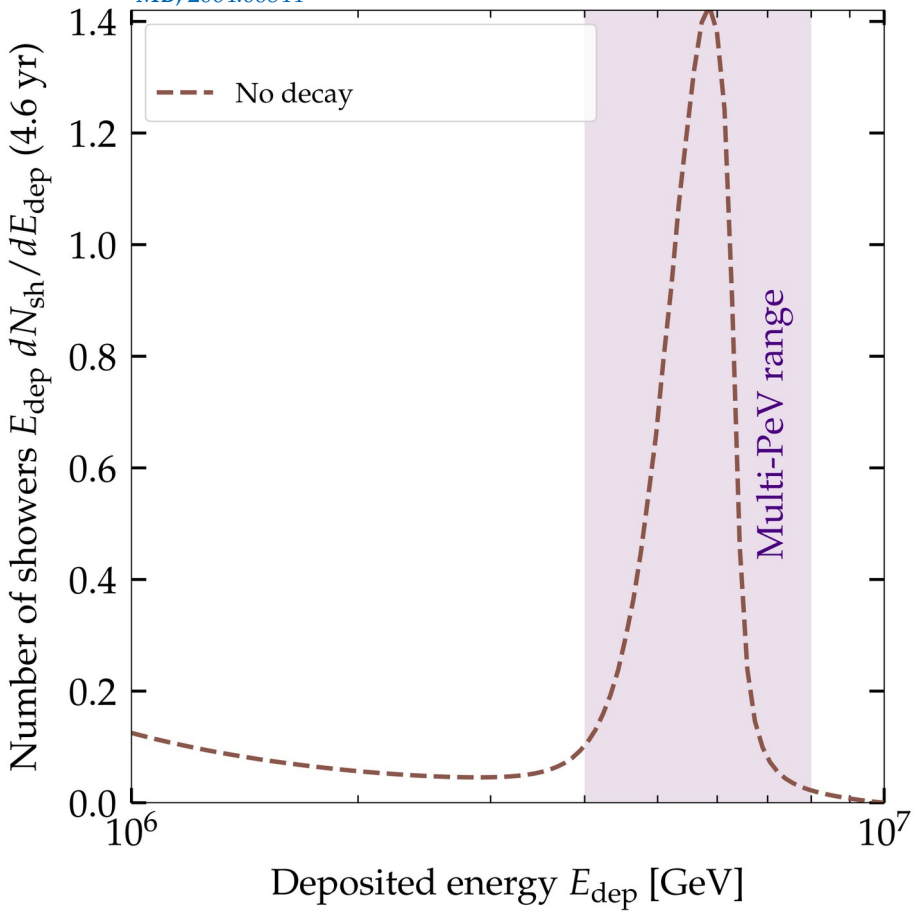
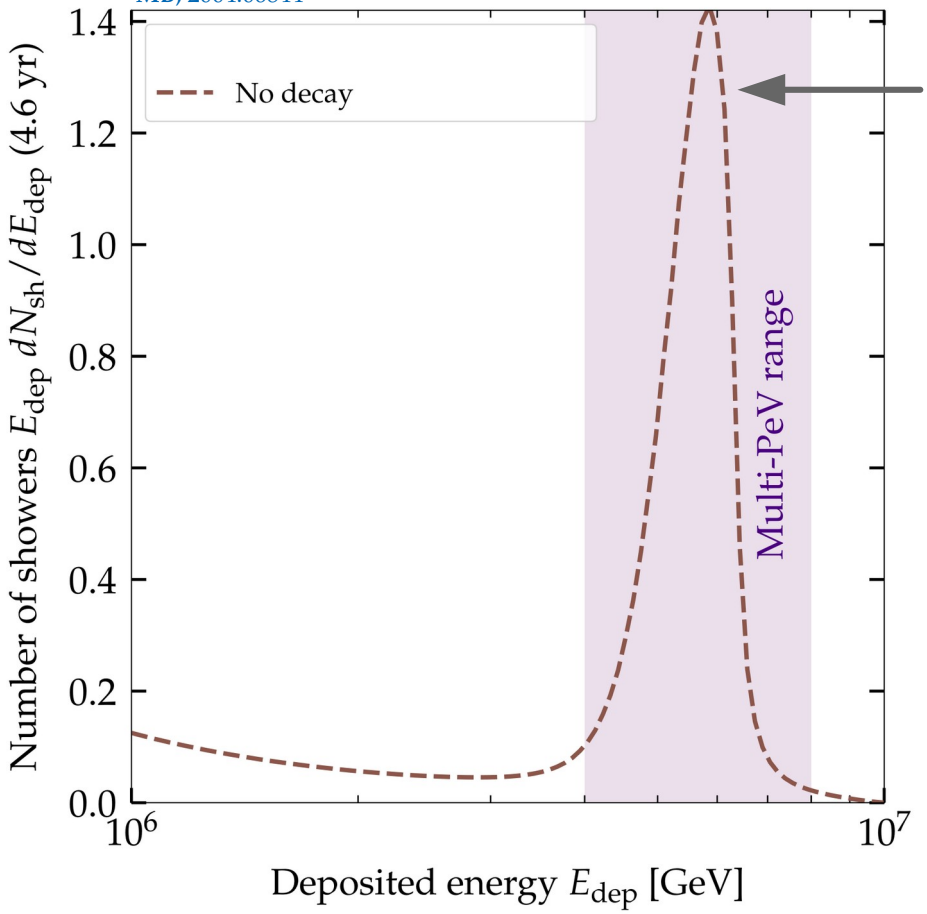


What does neutrino decay change?

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

Flavor composition ⟷ Spectrum shape ⟷ Event rate

MB, 2004.06844



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

What does neutrino decay change?

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Flavor composition ⟷ Spectrum shape ⟷ Event rate

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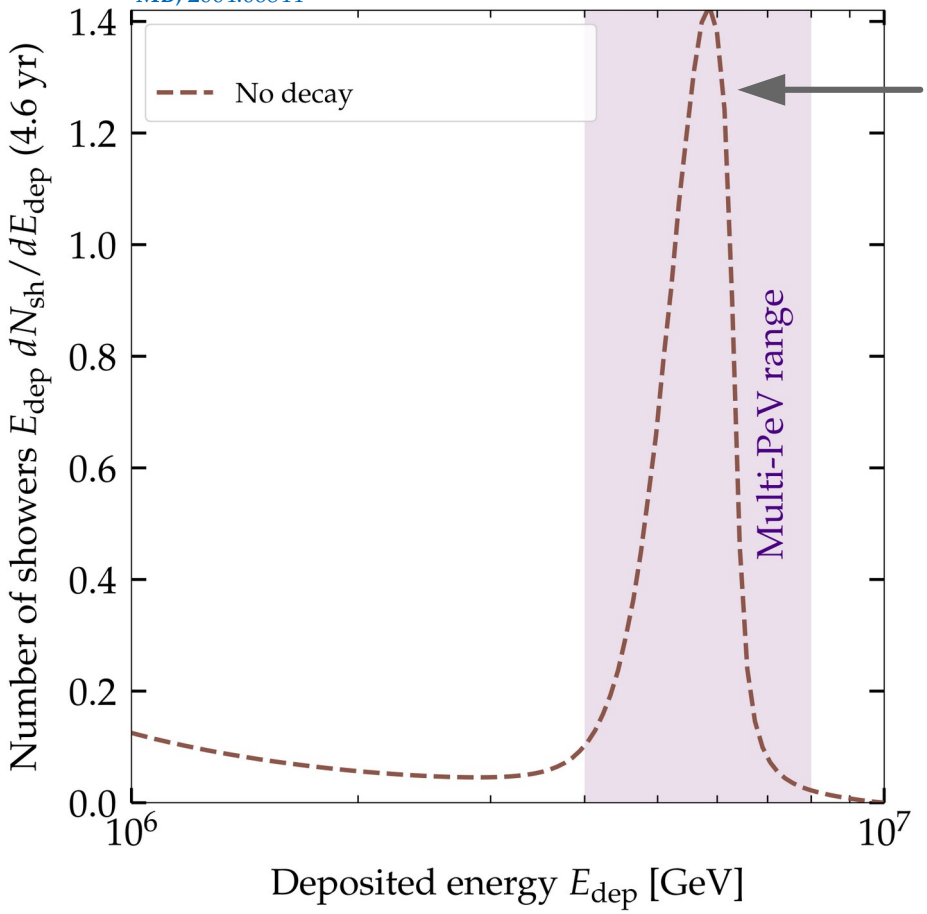
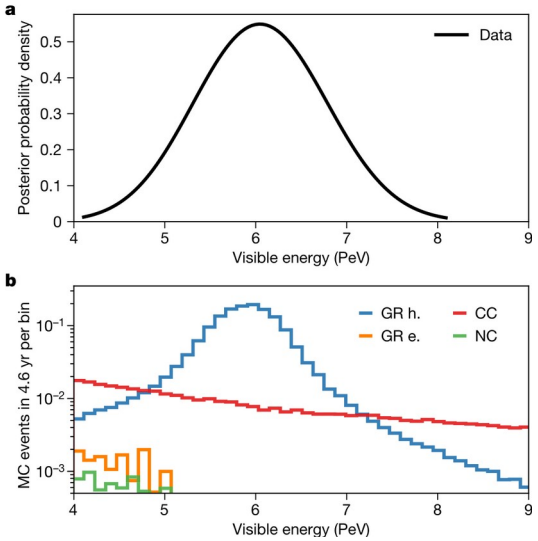
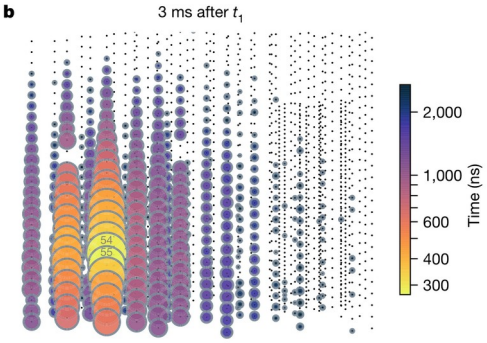


Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

IceCube has seen one GR candidate in 4.6 years:





IceCube Collab., *Nature* 2021

What does neutrino decay change?

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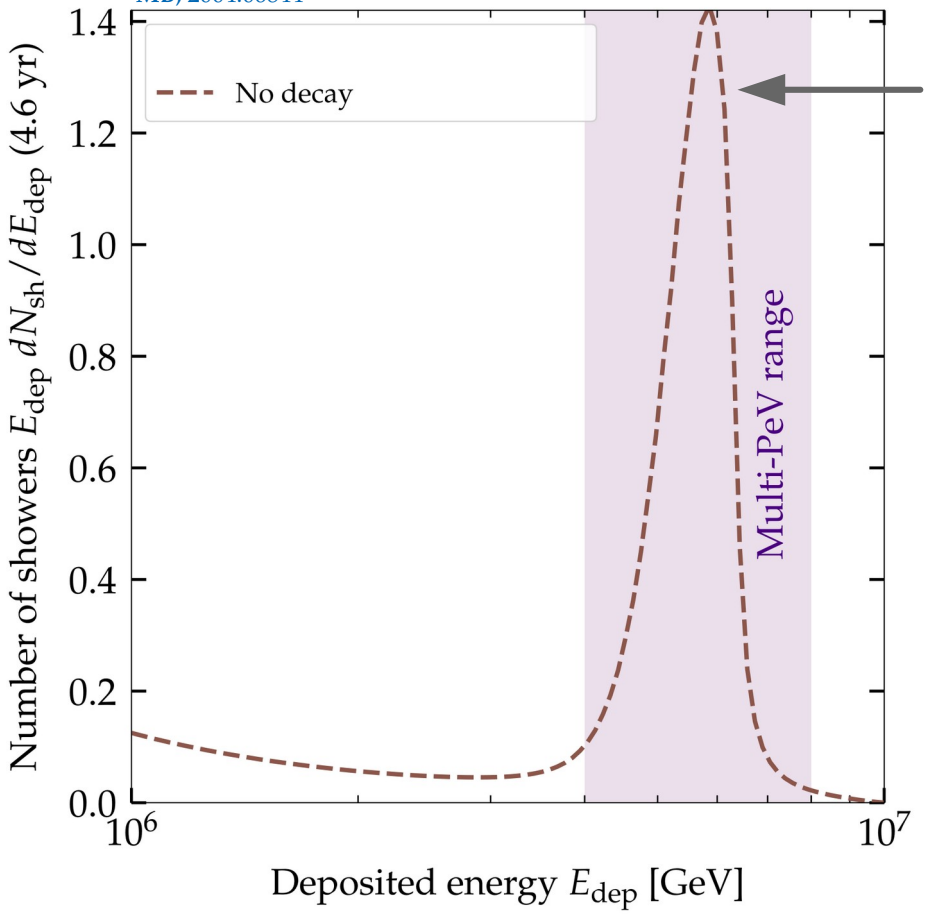
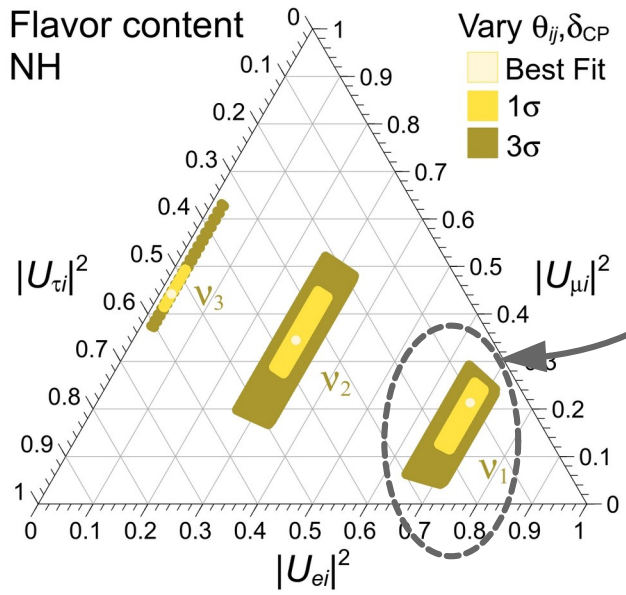


Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

ν_1 is the mass eigenstate with the most e flavor



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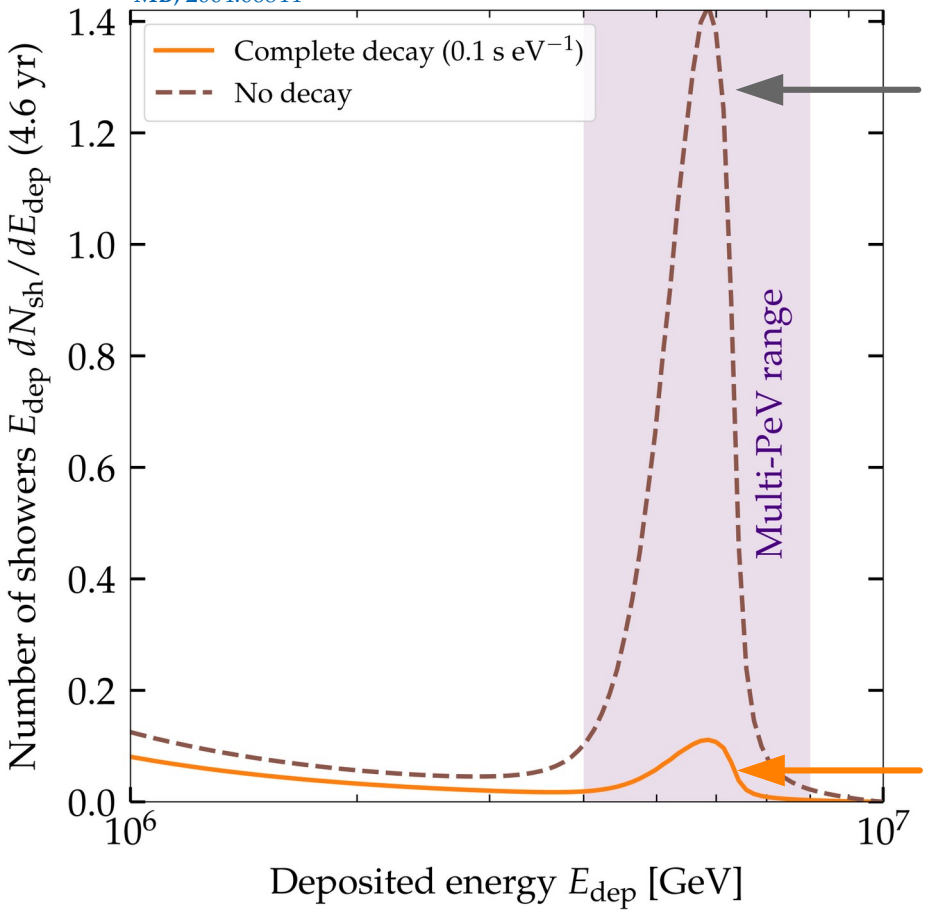

Glashow resonance (GR):
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If $\bar{\nu}_1$ had decayed en route to Earth,
there would not have been $\bar{\nu}_e$ left to trigger a GR

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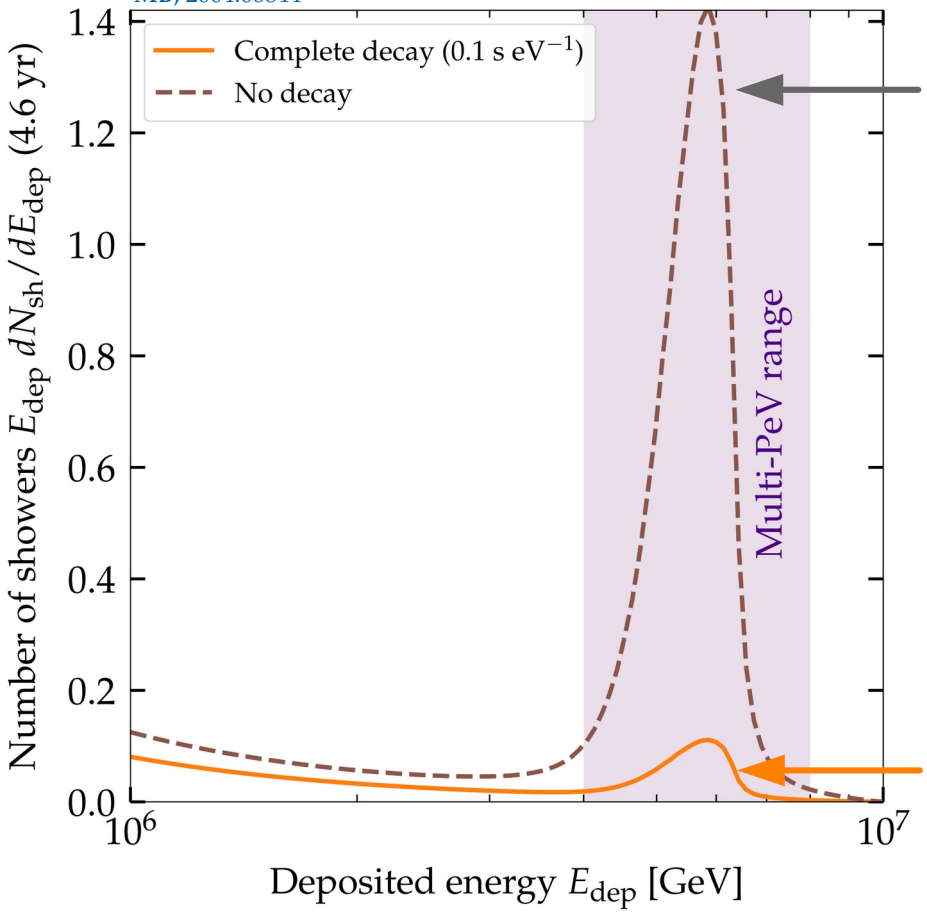

Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

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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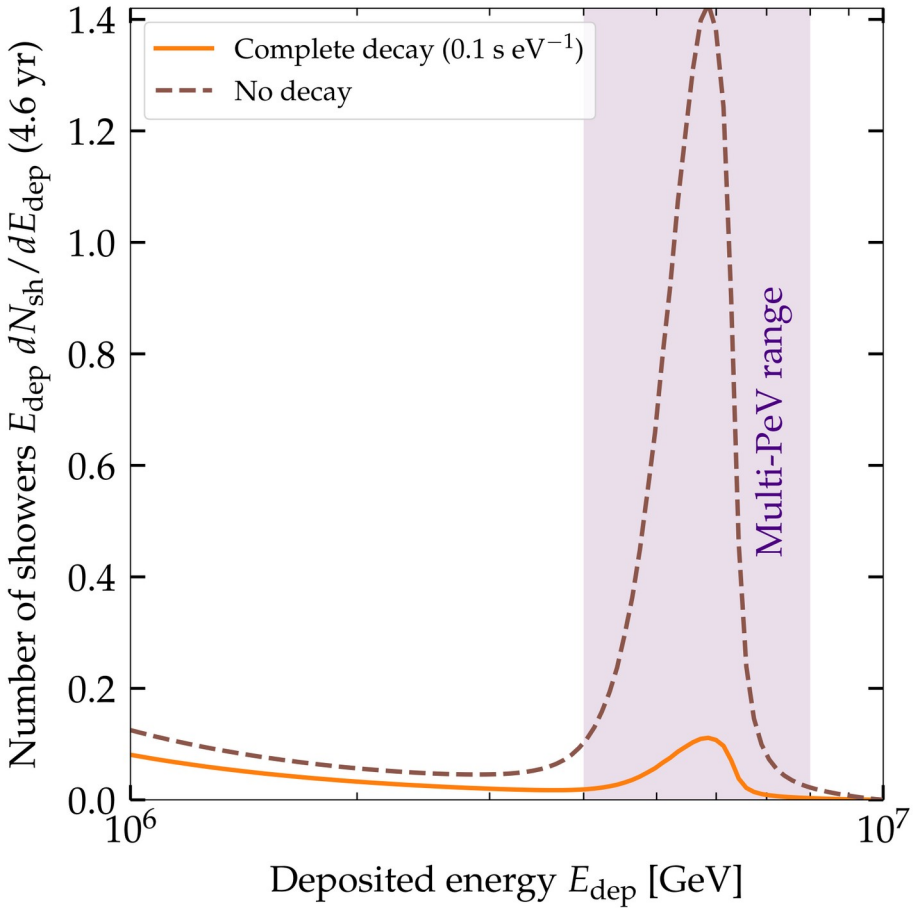

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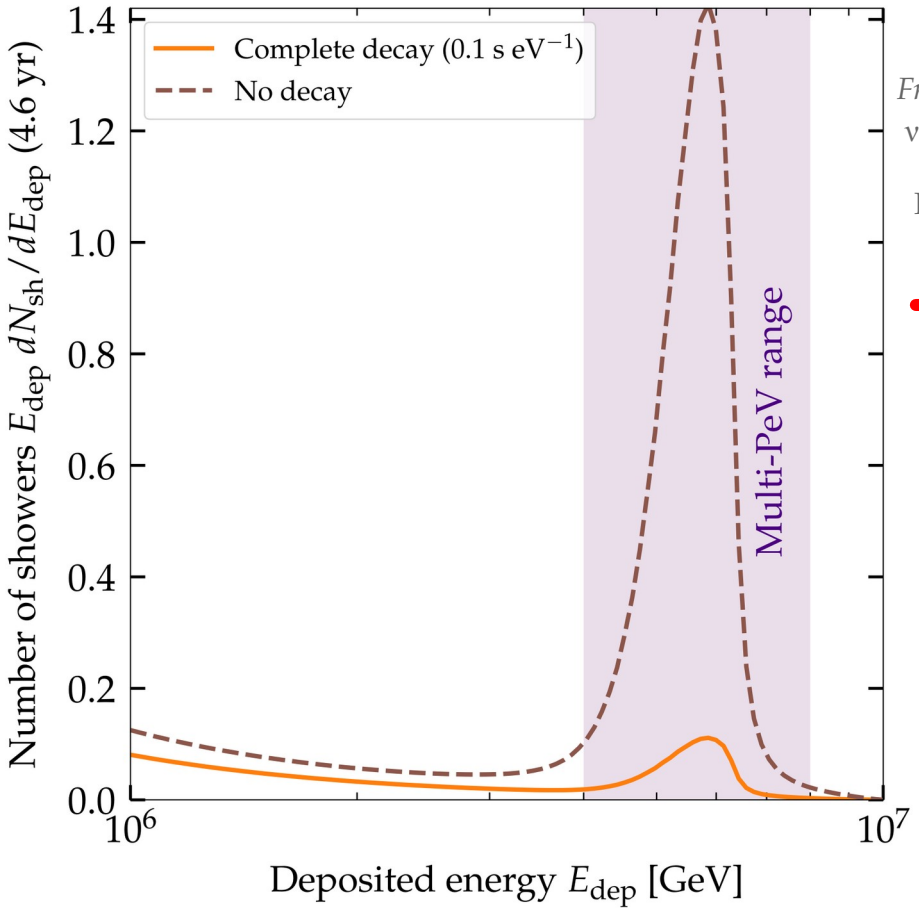

Free parameters:
ν_1, ν_2 lifetimes
Mix. par.
Flavor ratios
$\bar{\nu}/\nu$ ratio

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

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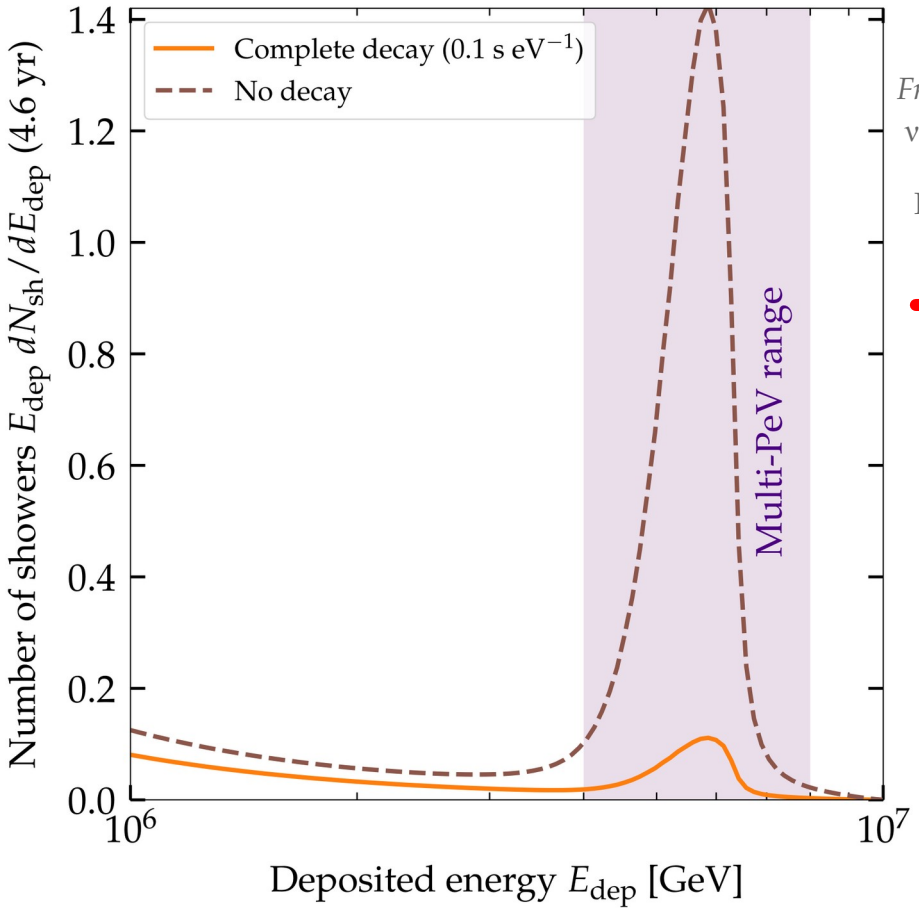

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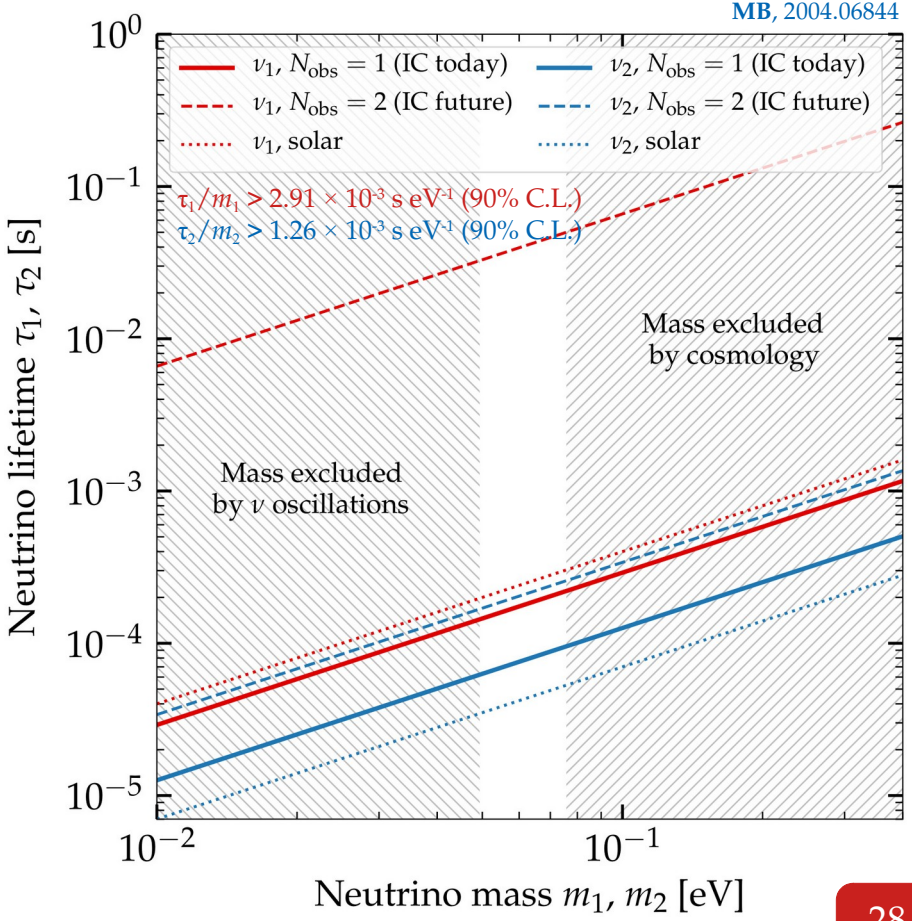

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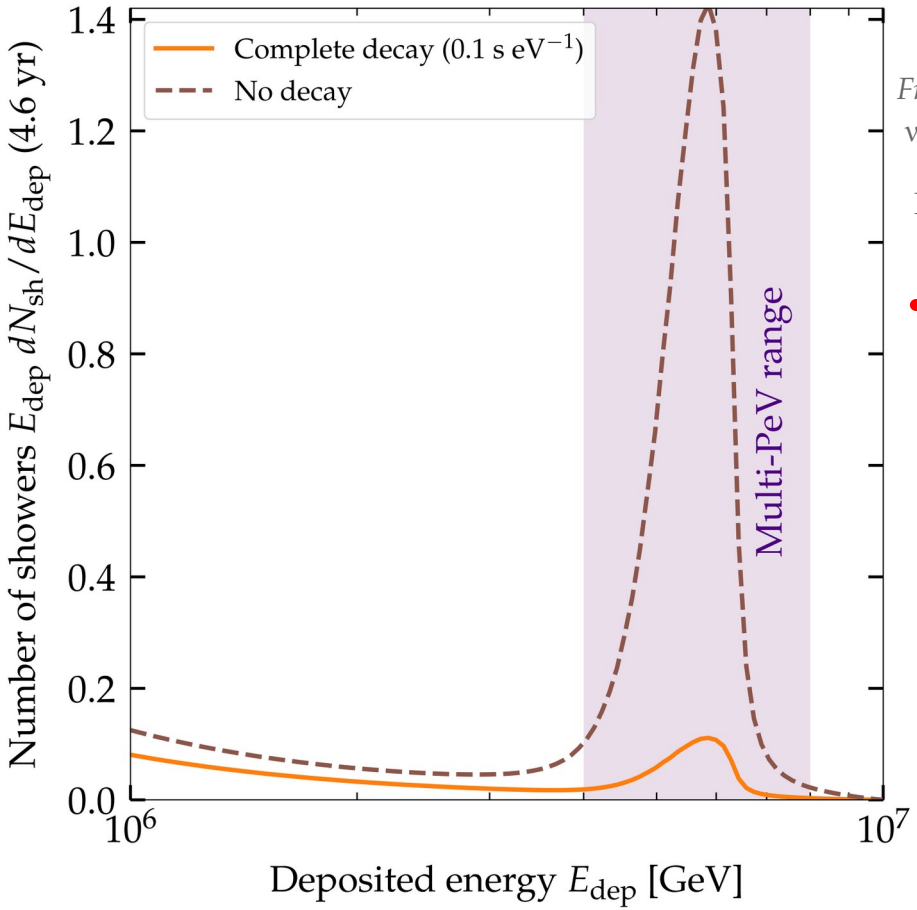

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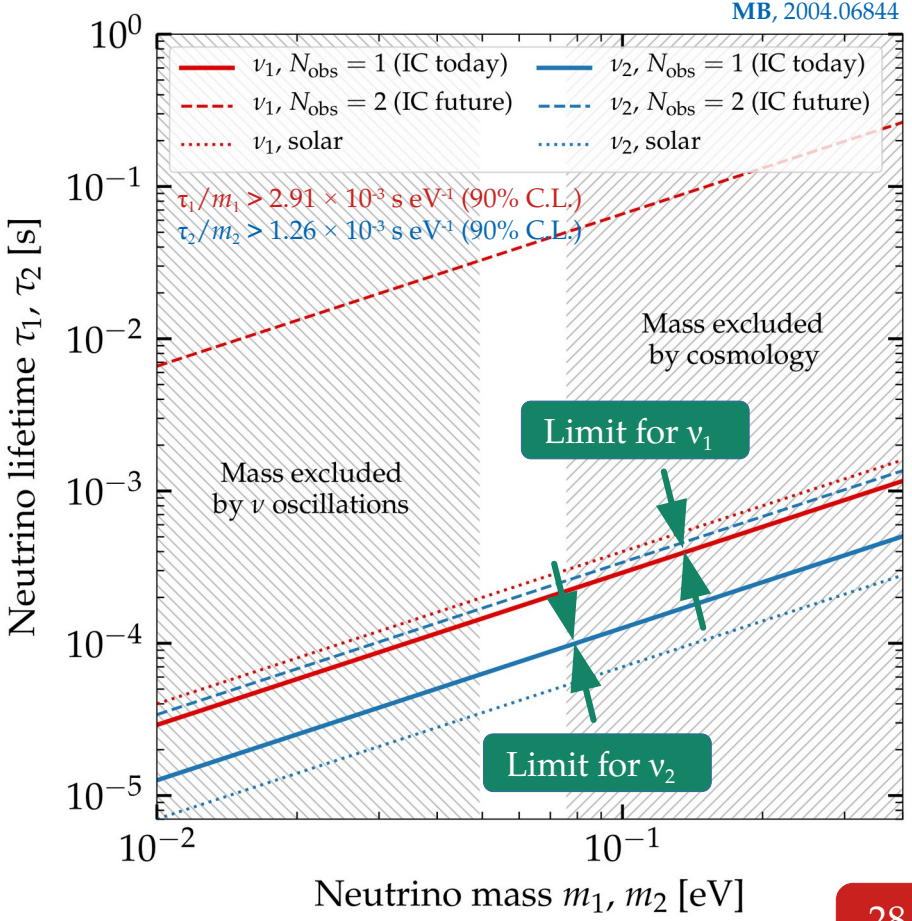
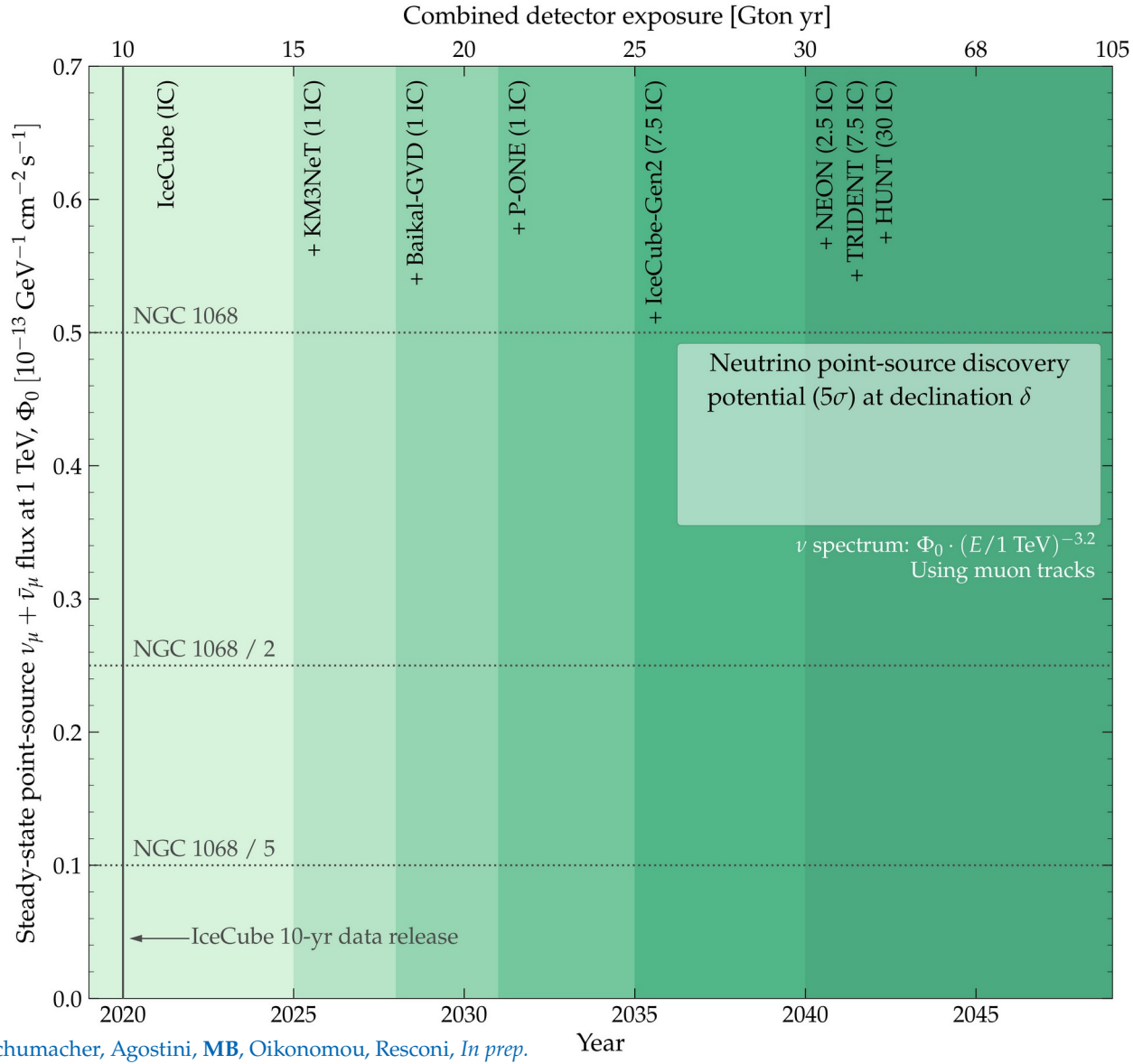
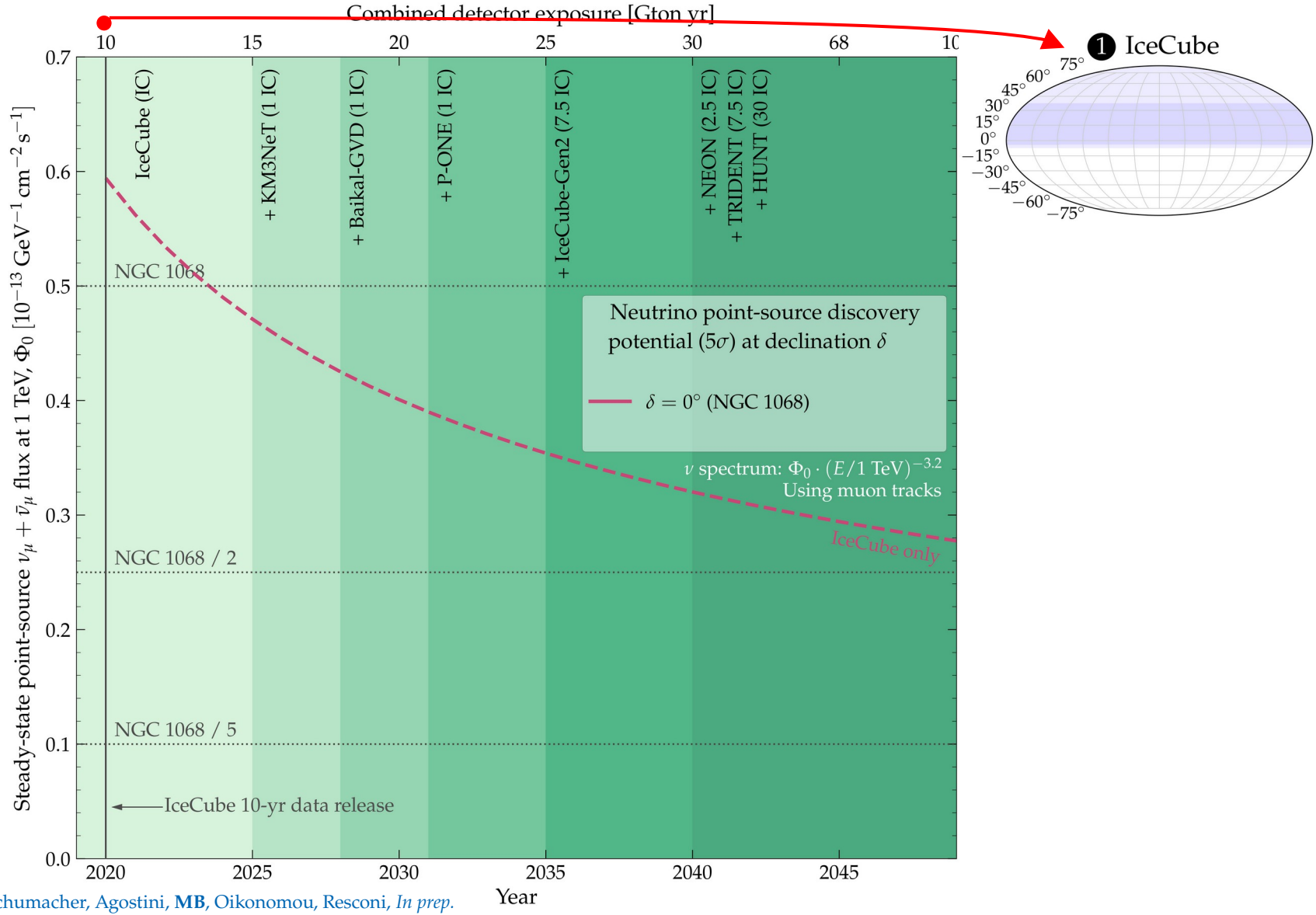




Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*



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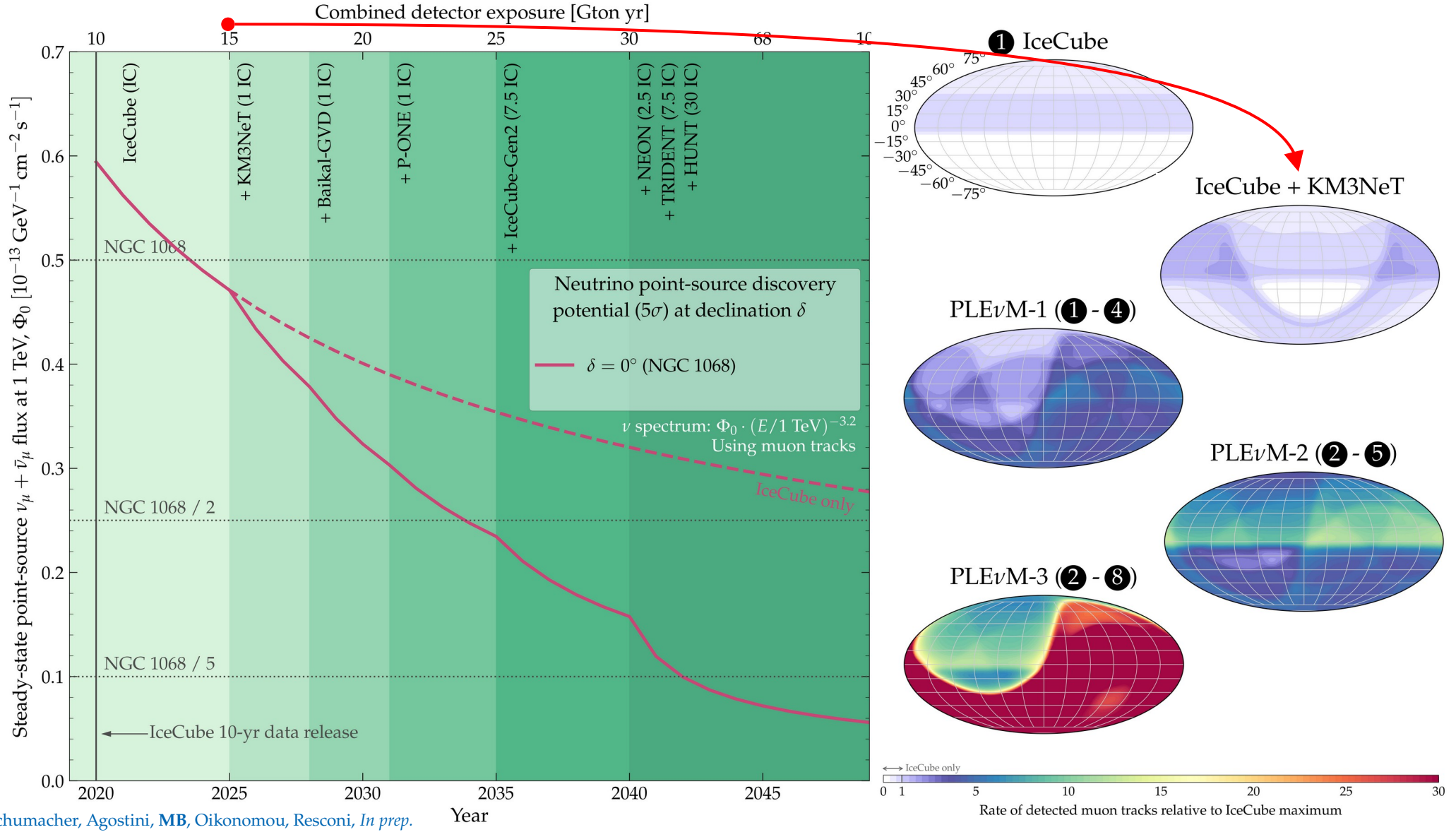

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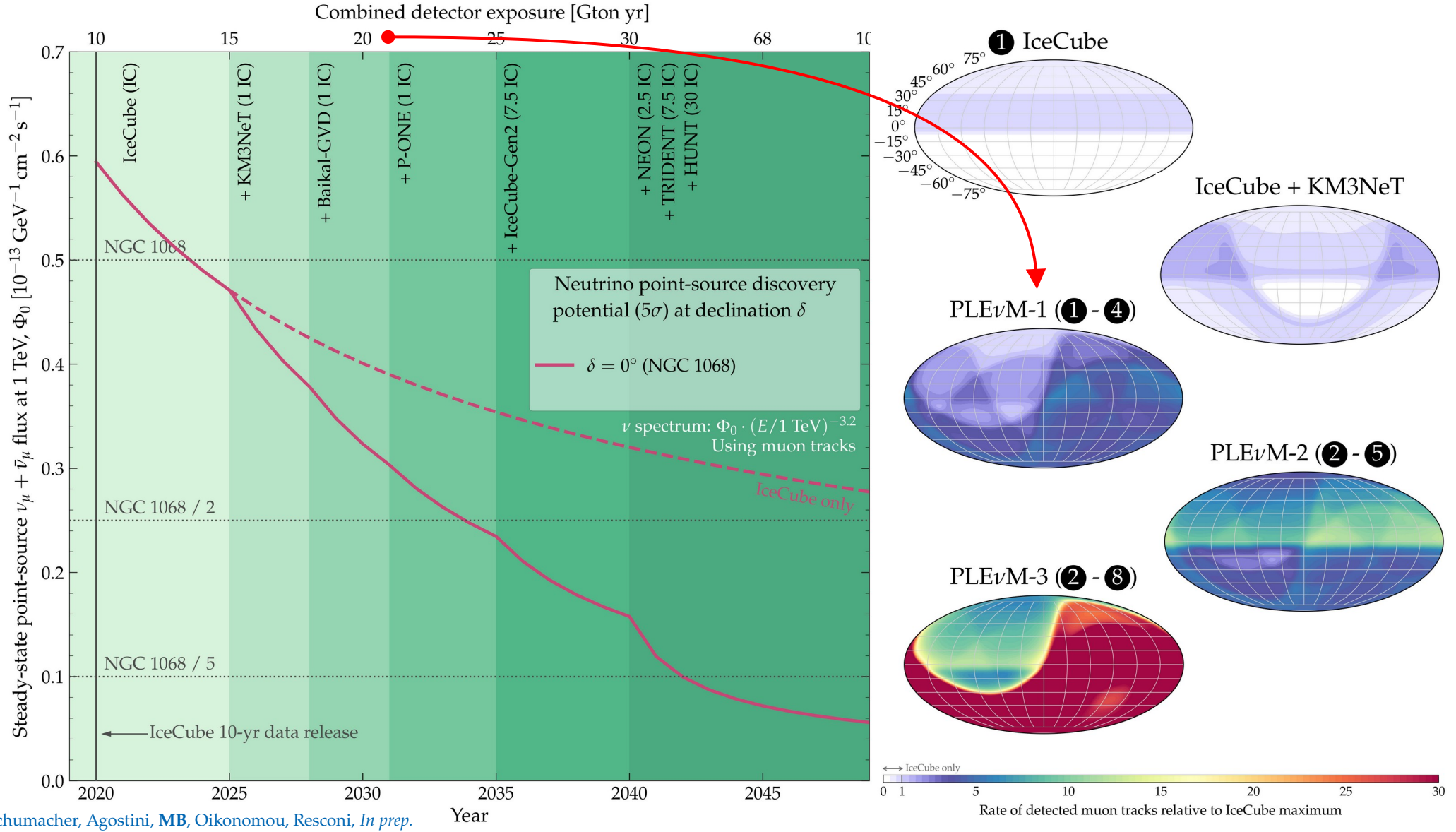

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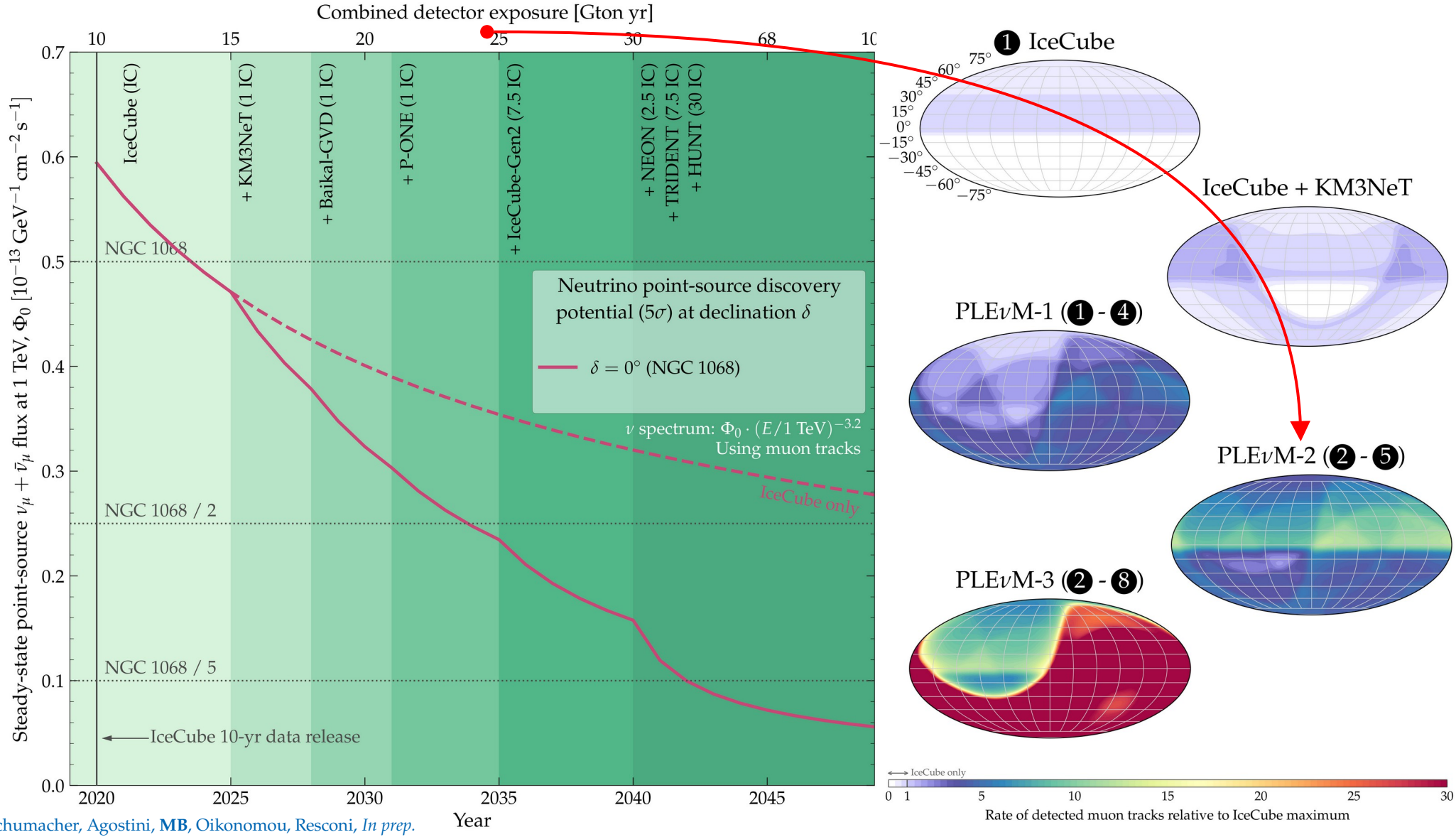

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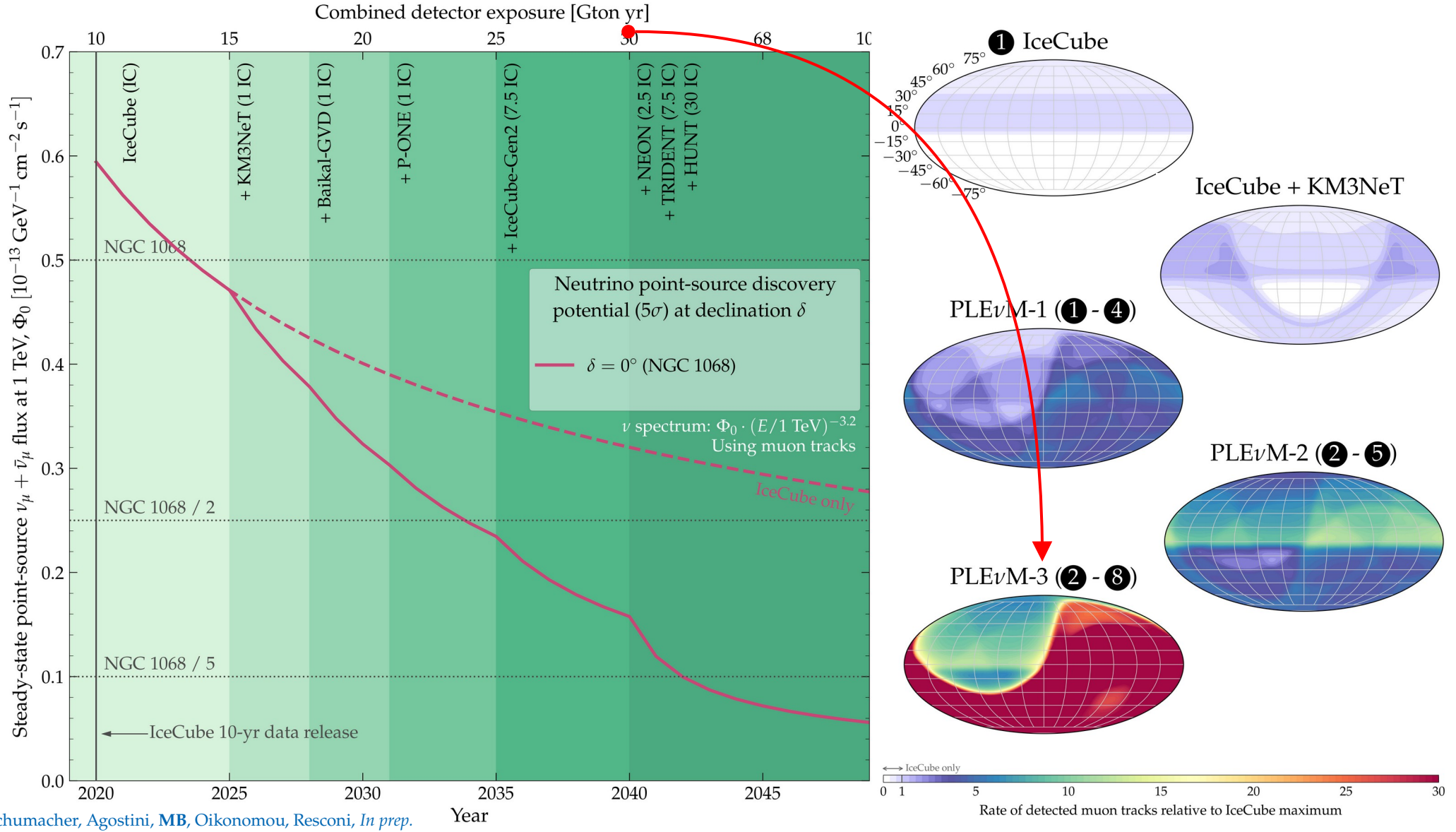

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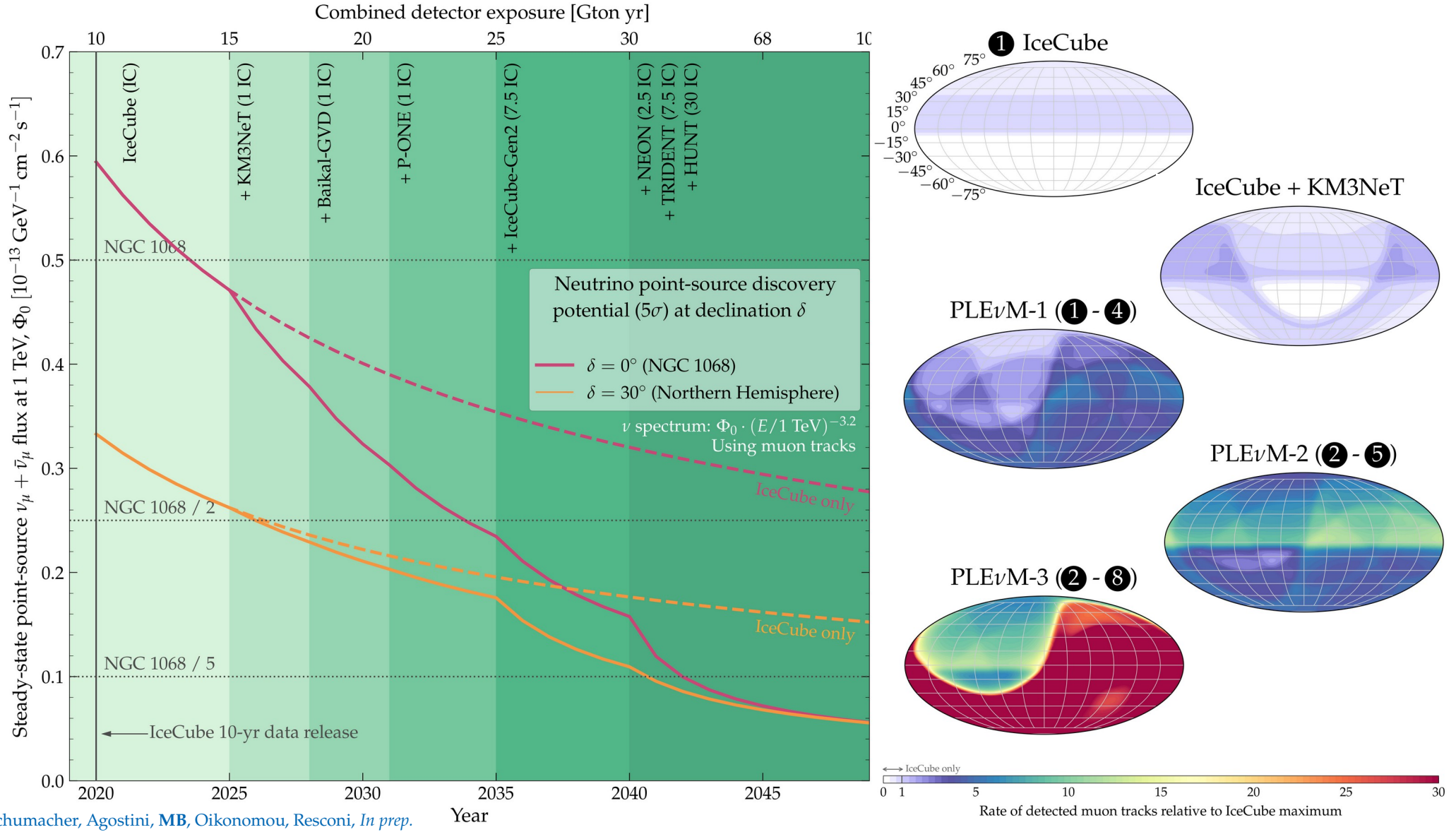

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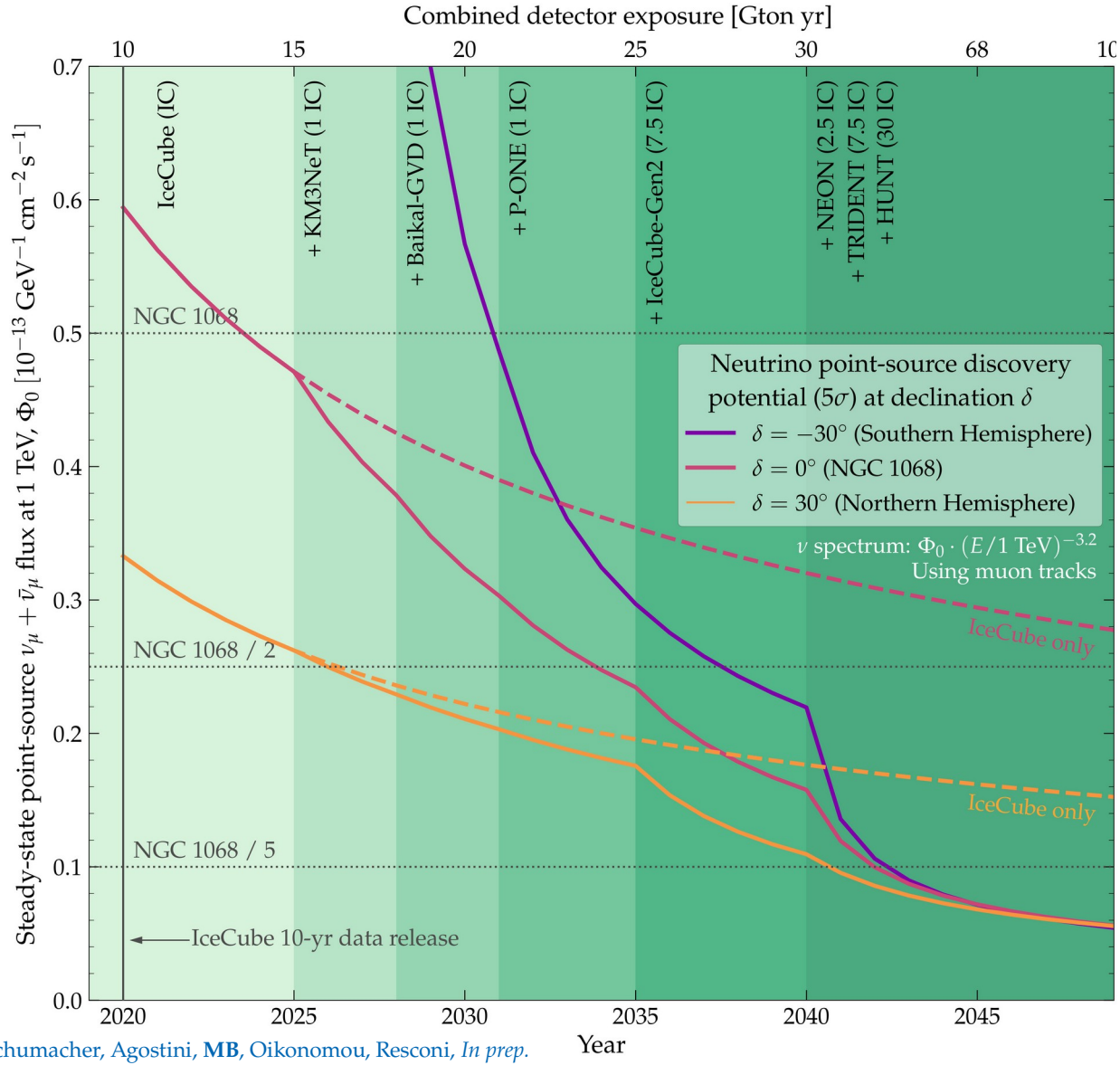
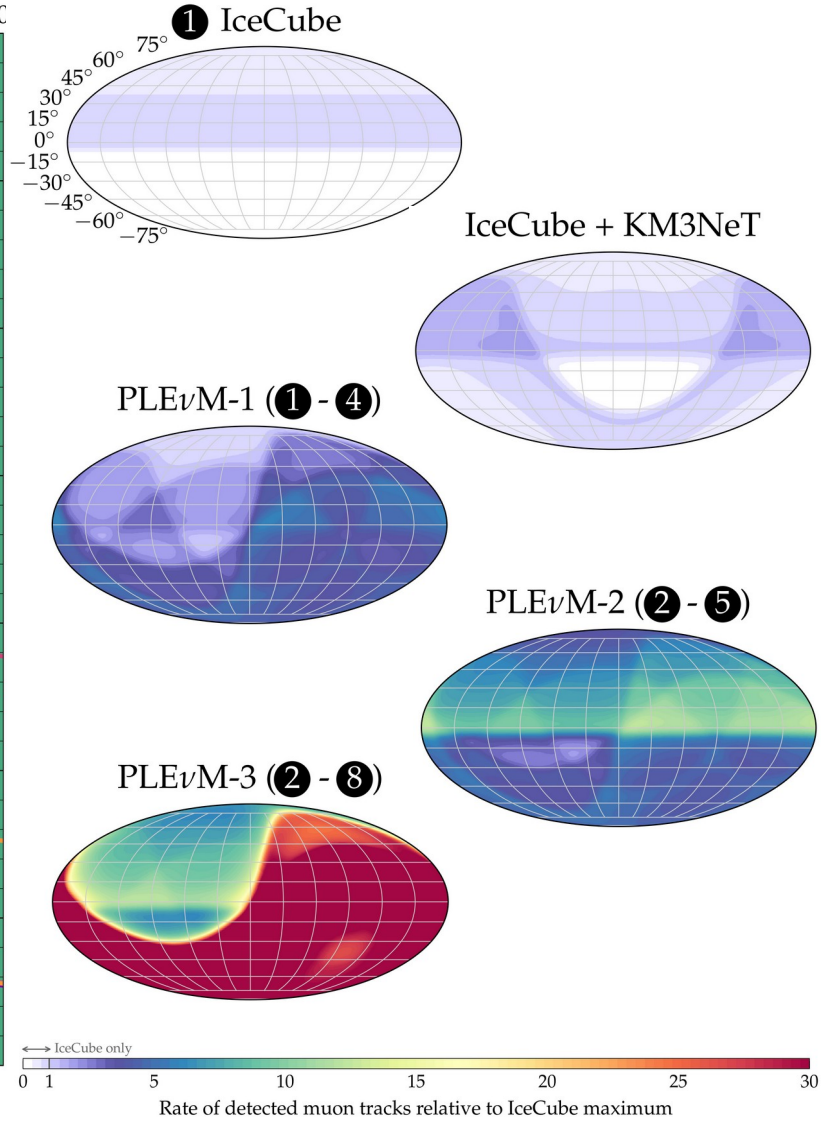
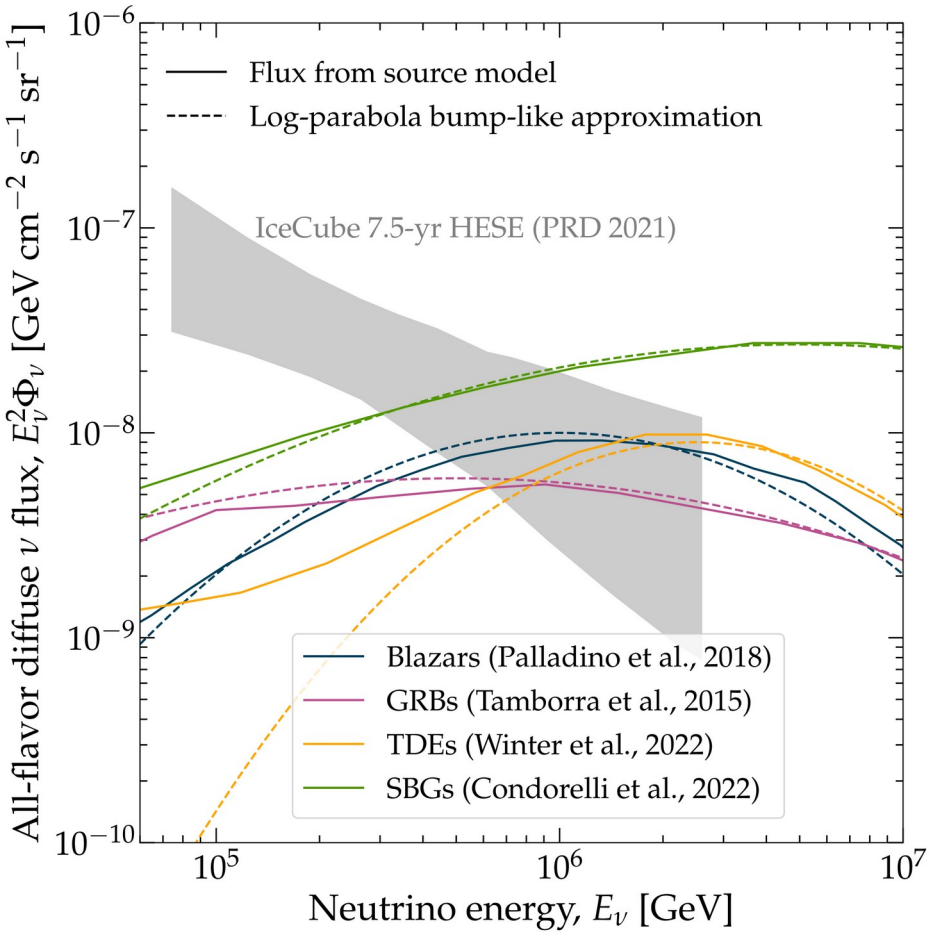




Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

Bump-hunting in the diffuse flux of high-energy neutrinos

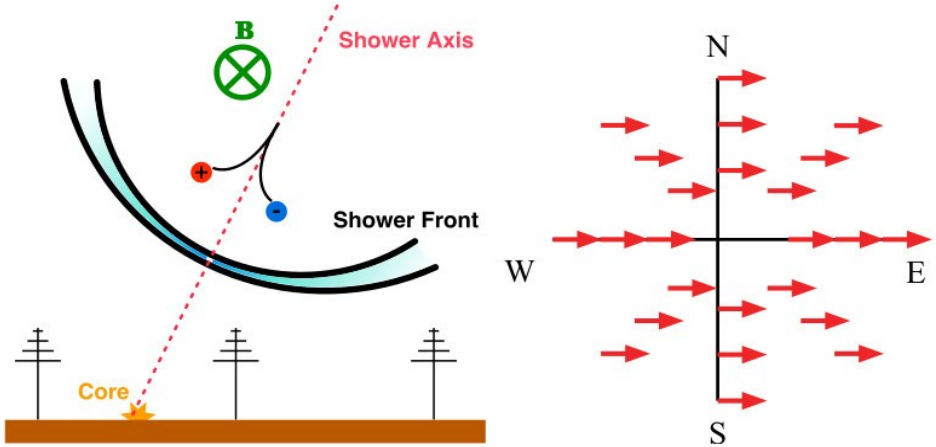
Bump-like spectra can reveal the presence of ν production via $p\gamma$:



D. F. G. Fiorillo, **MB**, *PRD* 2023

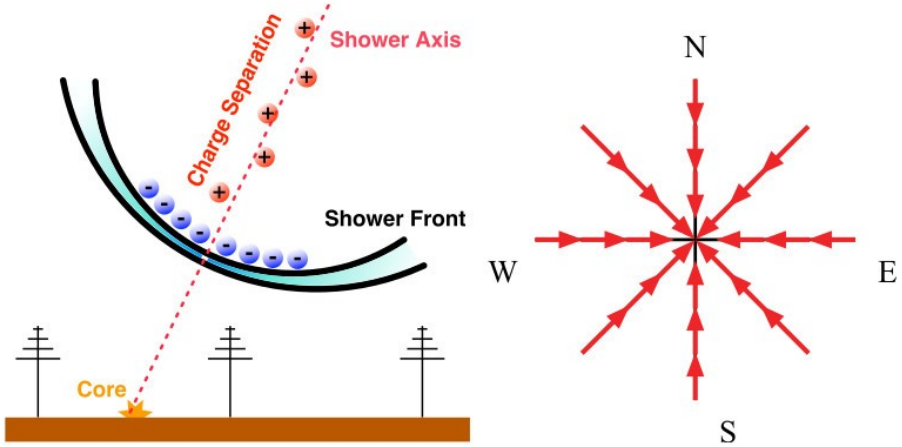
Radio emission: geomagnetic and Askaryan

Geomagnetic



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

Askaryan

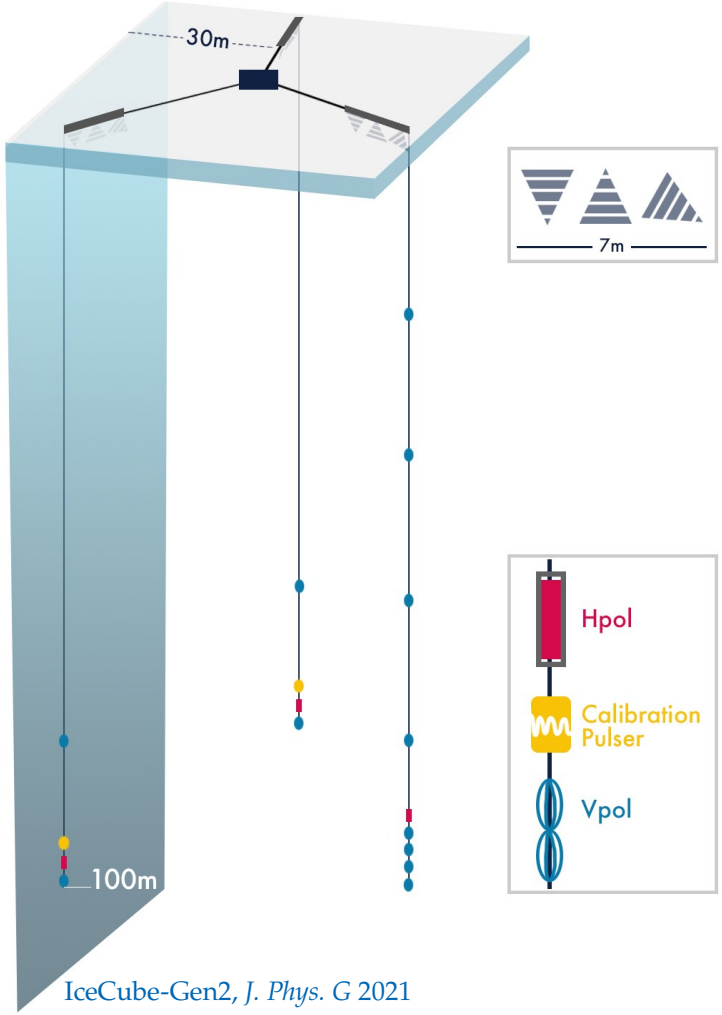


- Time-varying negative-charge ~20% excess
- Linearly polarized towards axis
- Sub-dominant in air showers

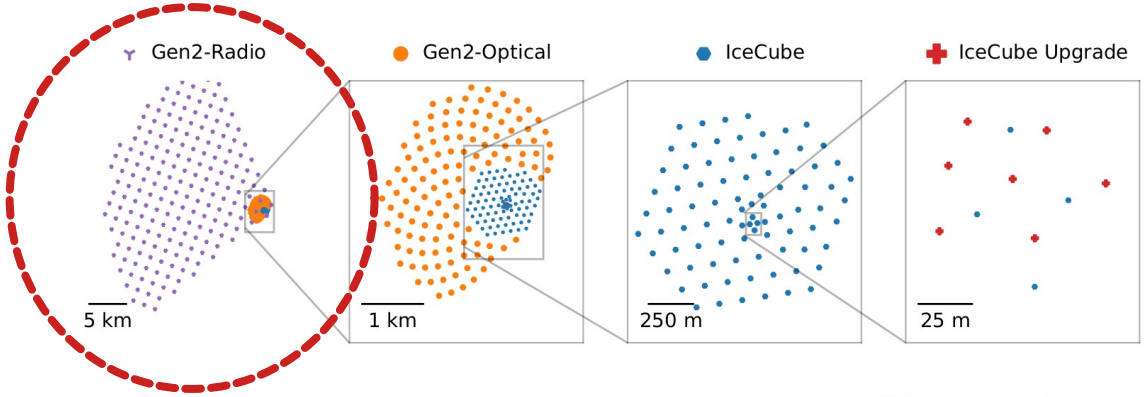
Figures by H. Schoorlemmer and K. D. de Vries

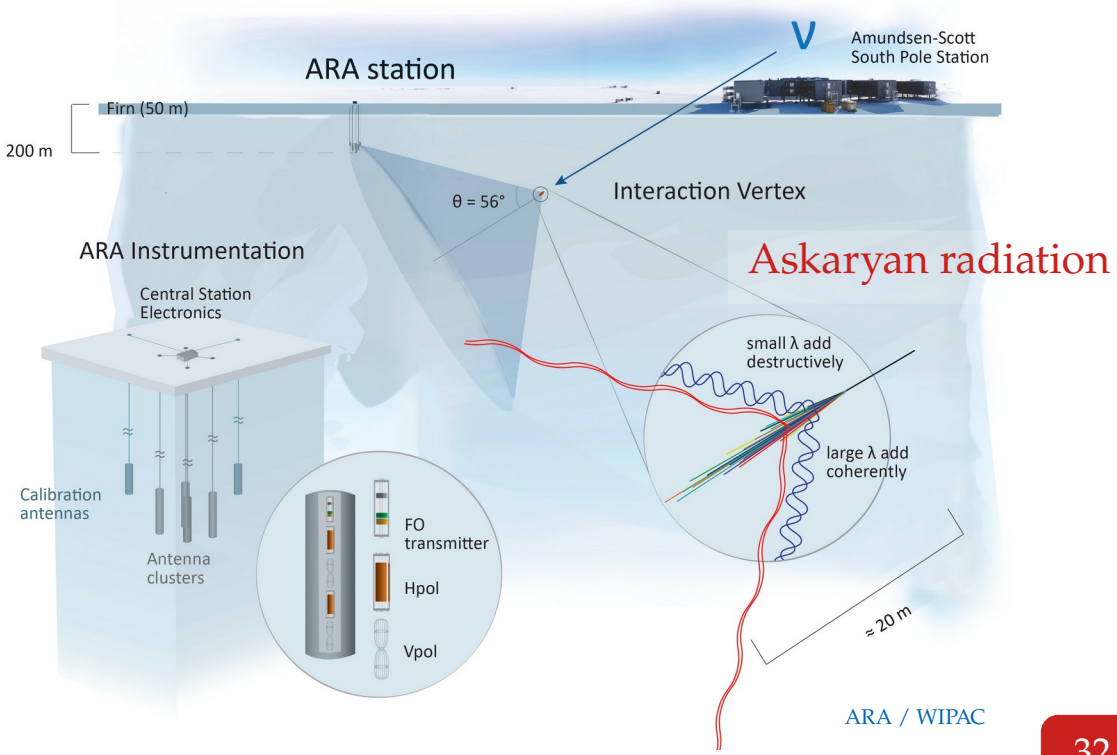
Radio emission: geomagnetic and Askaryan

IceCube-Gen2 Radio



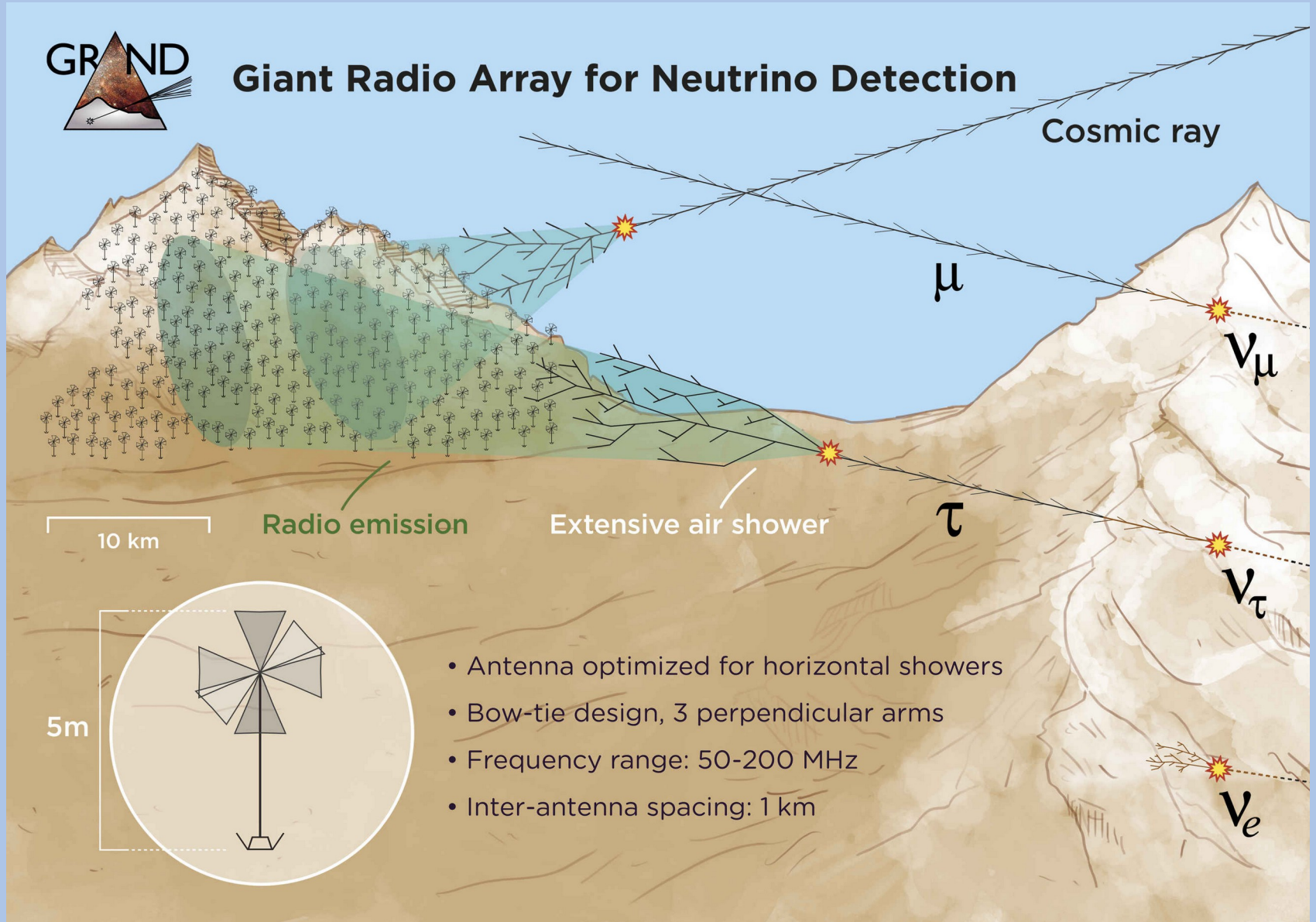
IceCube-Gen2, *J. Phys. G* 2021





Askaryan radiation

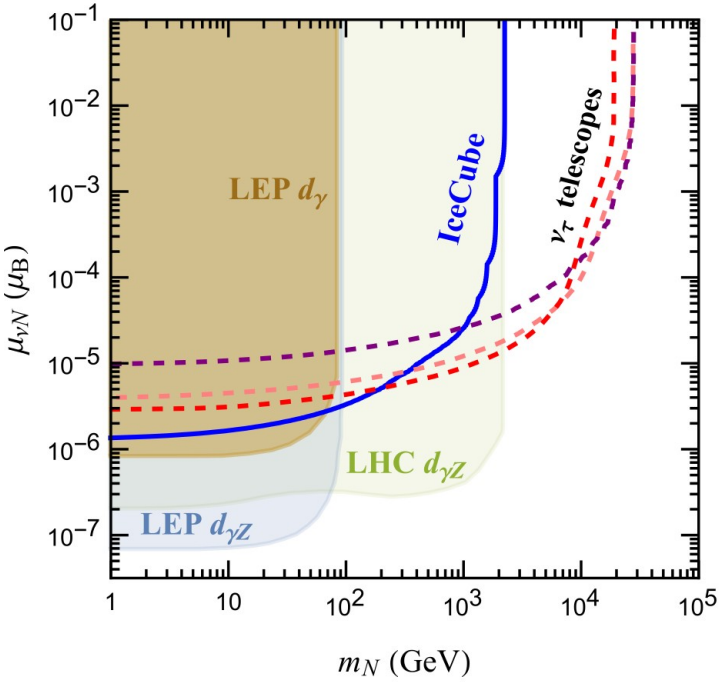
ARA / WIPAC


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

New physics in the UHE νN cross section

New physics in the UHE νN cross section

Heavy sterile neutrinos
via the dipole portal



Huang, Jana, Lindner, Rodejohann, 2204.10347

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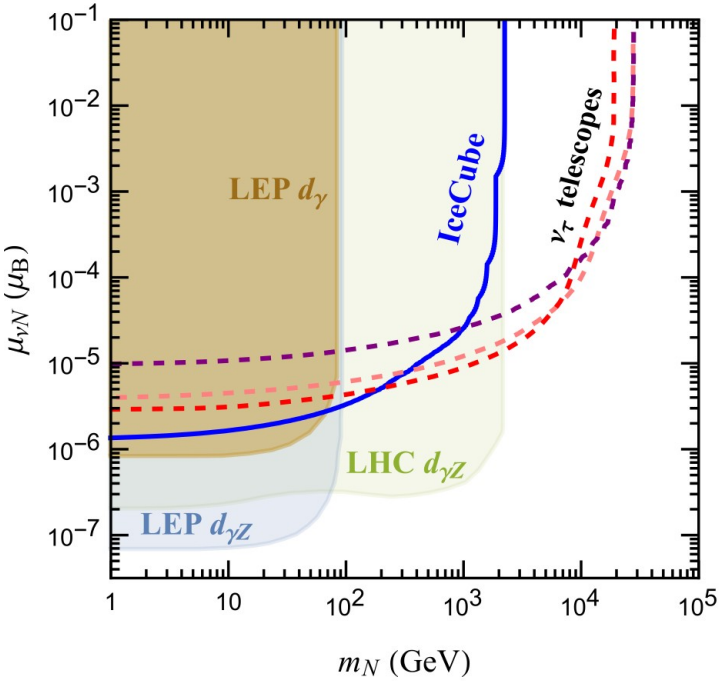
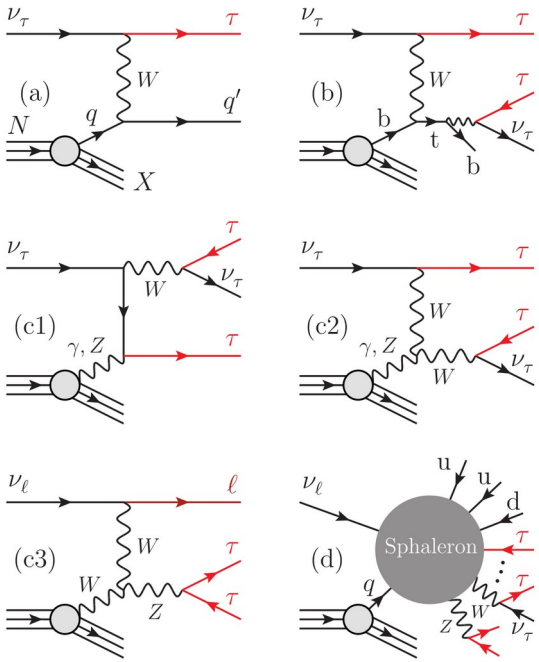


Huang, Jana, Lindner, Rodejohann, 2204.10347

Multiple ν_τ-induced bangs



Huang, *EPJC* 2022 [2207.02222]

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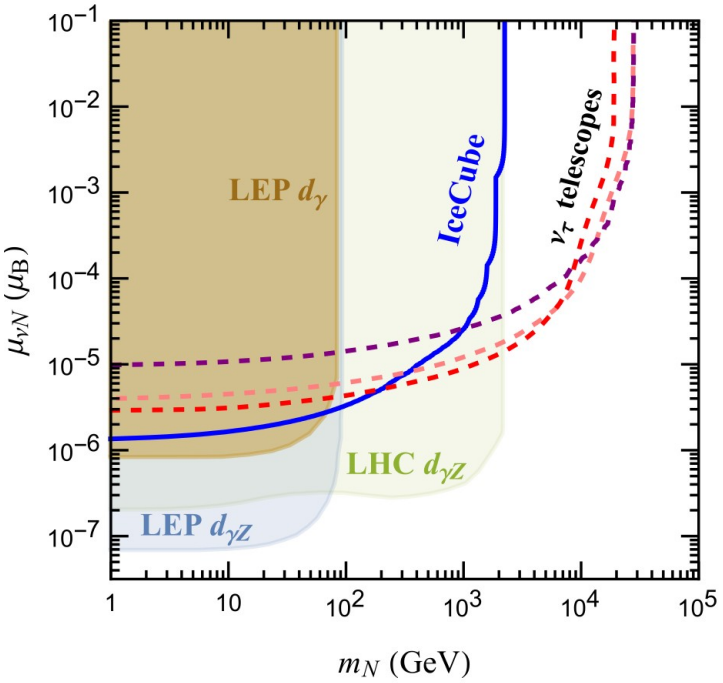

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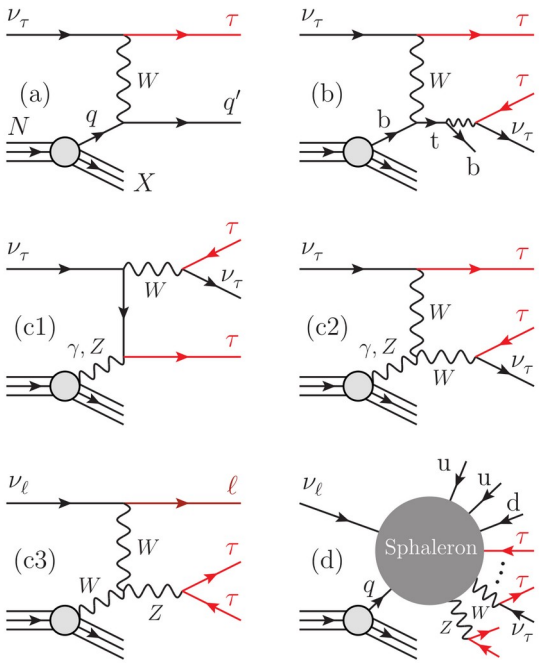
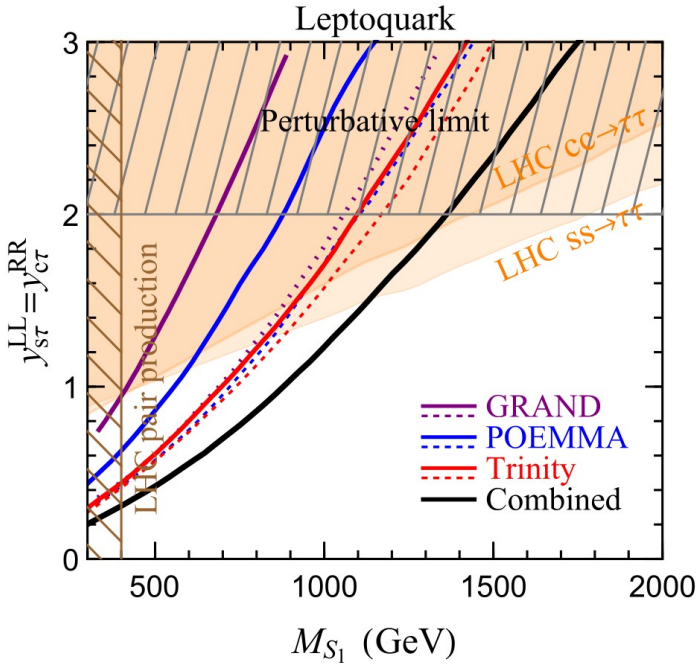


Huang, *EPJC* 2022 [2207.02222]

Leptoquarks, charged Higgs, *etc.*



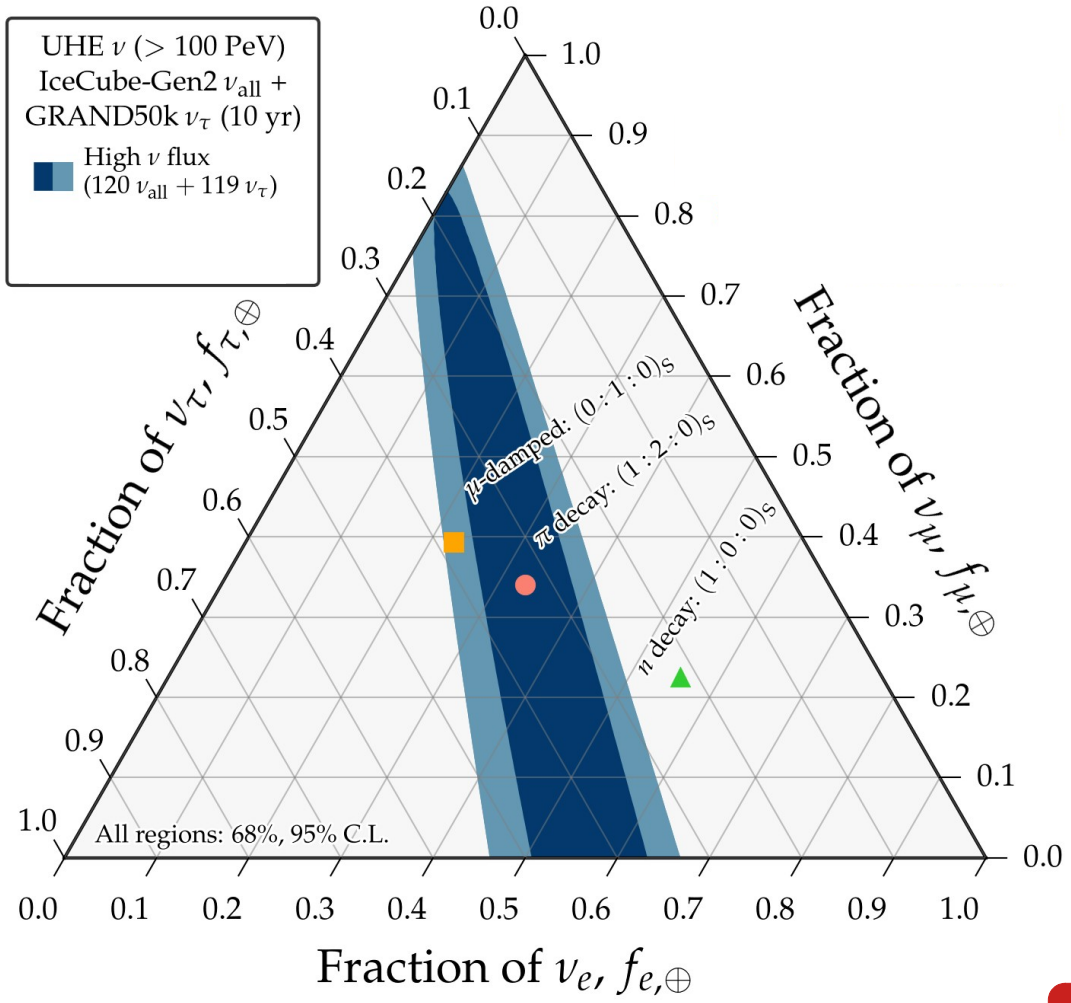
Huang, Jana, Lindner, Rodejohann, *JCAP* 2022 [2112.09476]

Flavor
at ultra-high energies

Manufacturing UHE flavor sensitivity with two detectors

What if future UHE radio-detection neutrino telescopes cannot see flavor?

Then we combine two of detectors:



Testagrossa, Fiorillo, **MB**, 2310.12215

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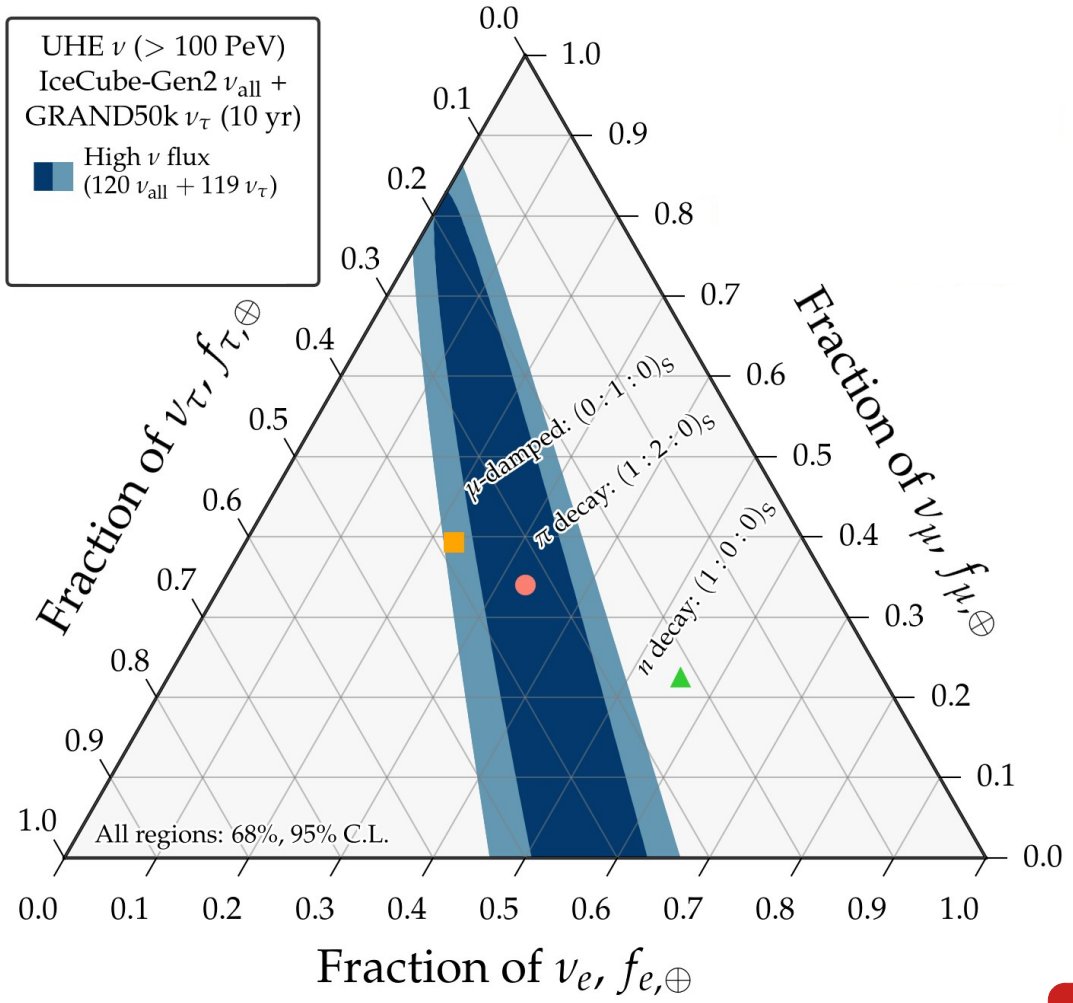

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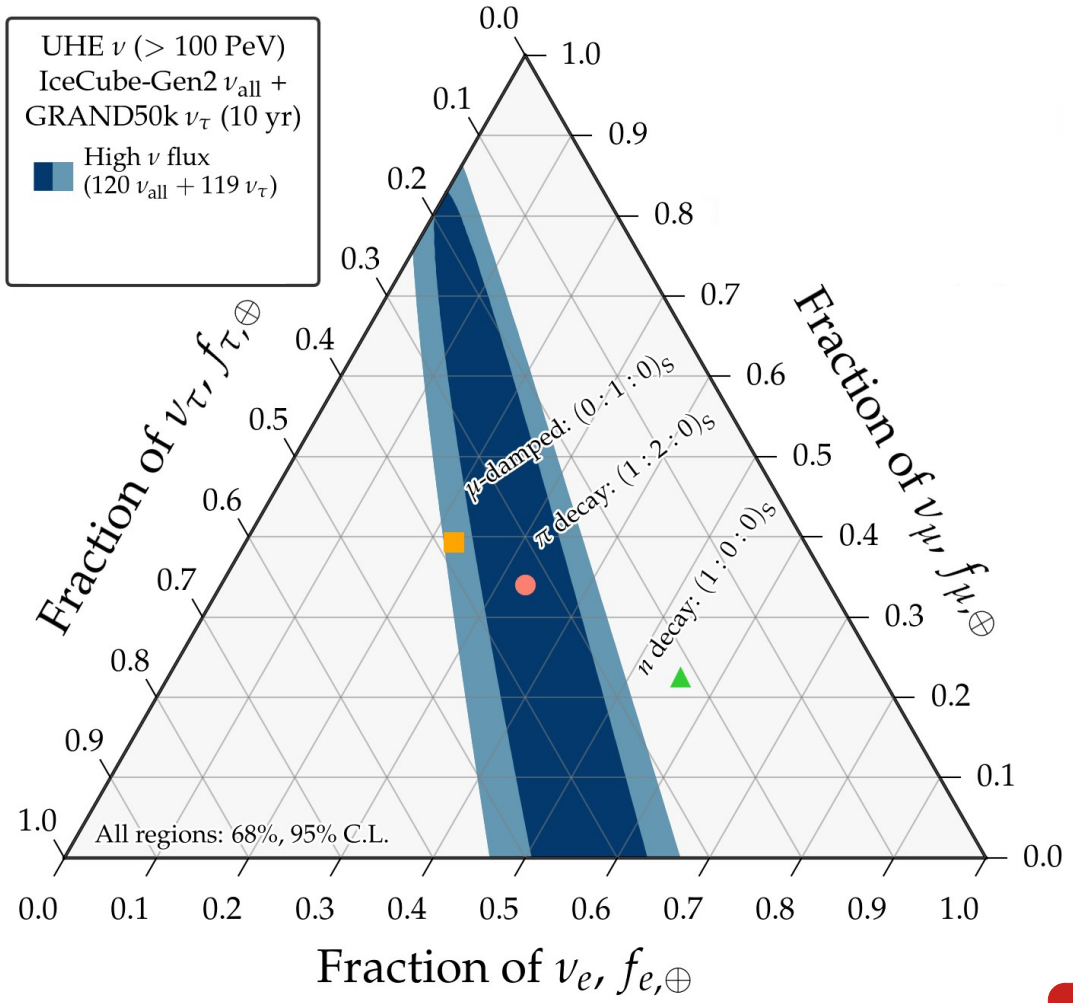
+

predominant detection of ν_τ by GRAND



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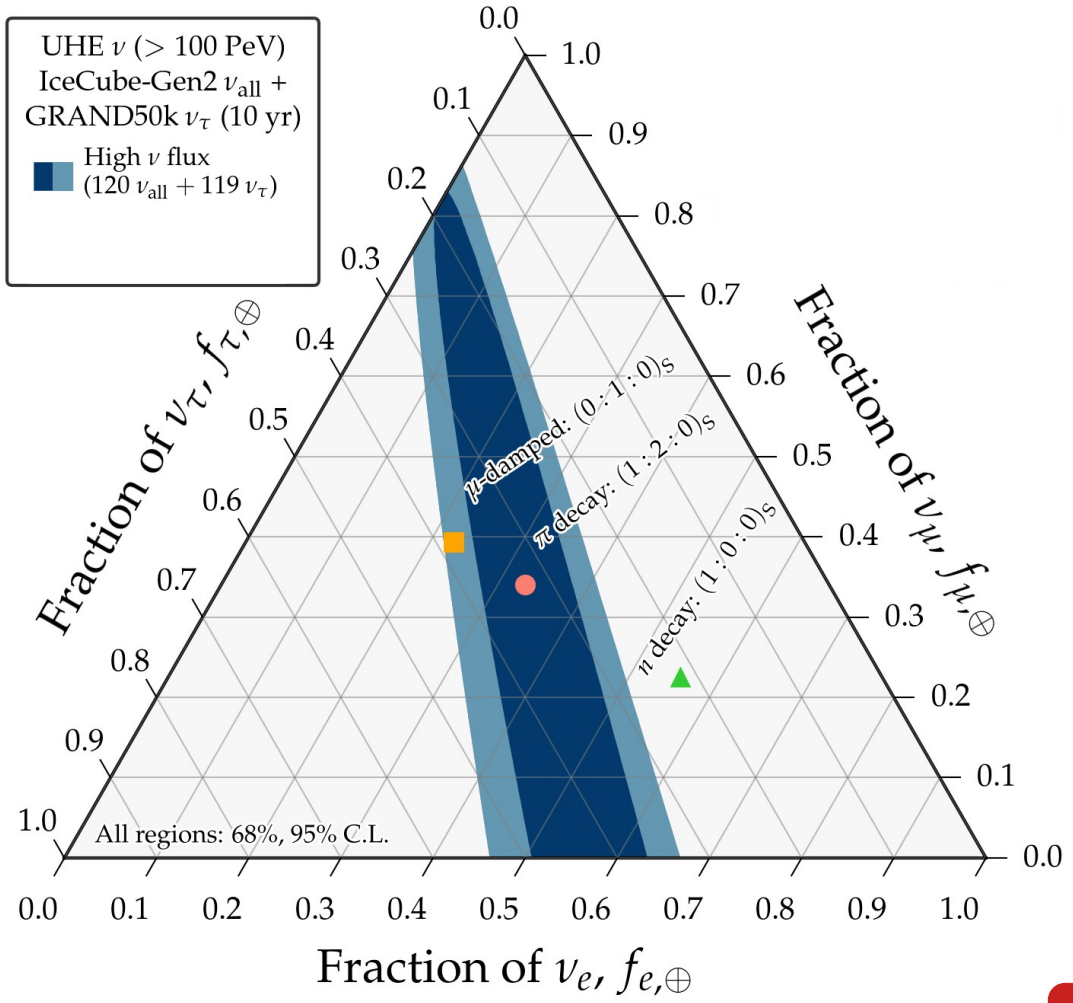
sensitivity to the fraction of UHE ν_τ



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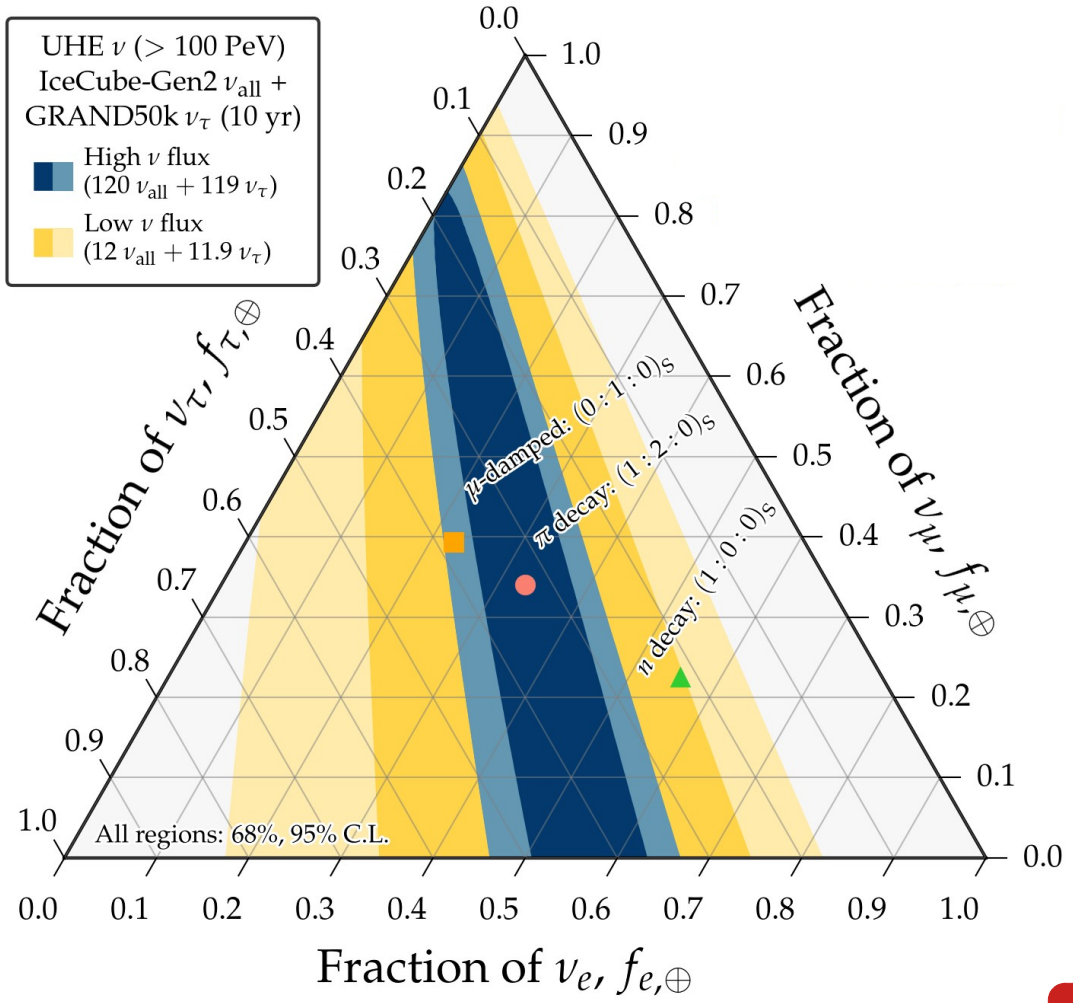

Testagrossa, Fiorillo, **MB**, 2310.12215

Manufacturing UHE flavor sensitivity with two detectors

What if future UHE radio-detection neutrino telescopes cannot see flavor?

Then we combine two of detectors:

indistinct detection of all flavors by IceCube-Gen2 (radio)

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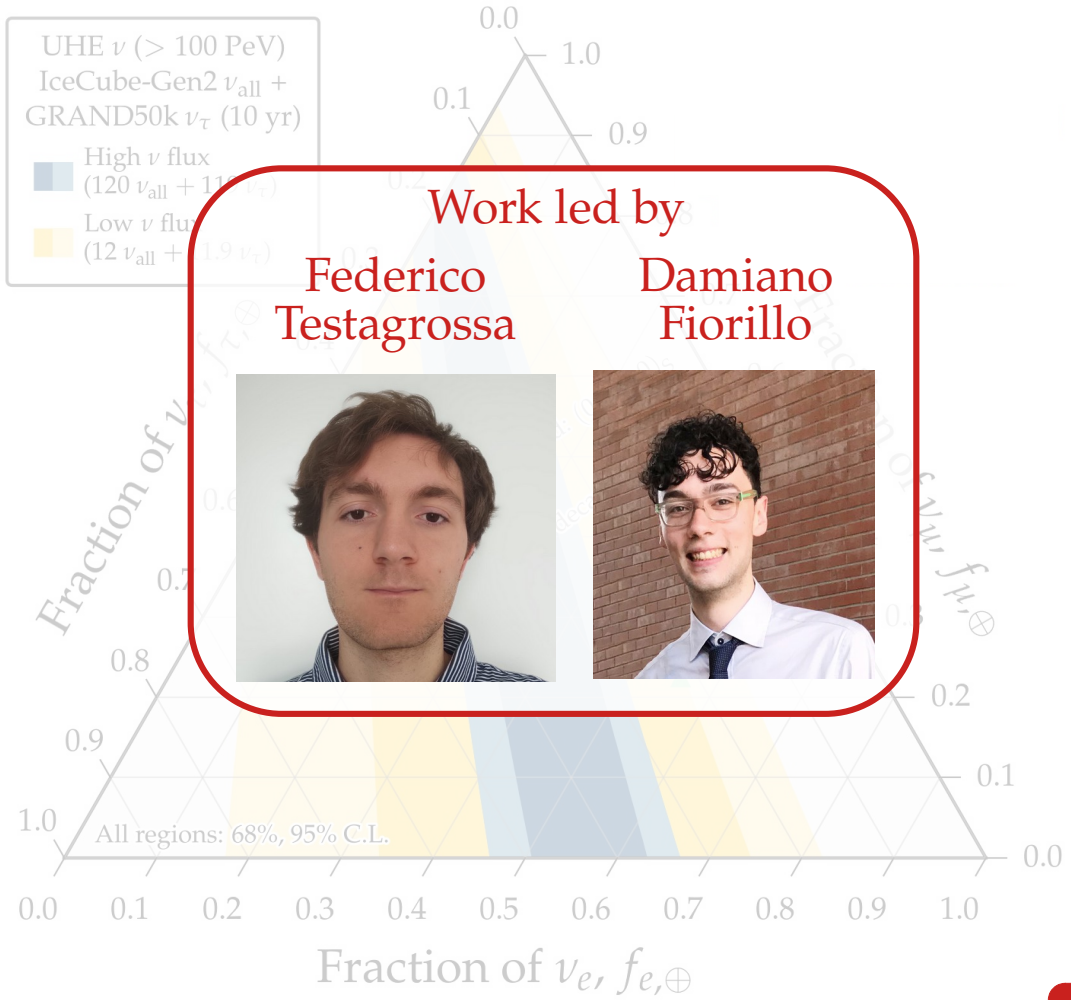

Work led by

Federico Testagrossa

Damiano Fiorillo

Testagrossa, Fiorillo, **MB**, 2310.12215

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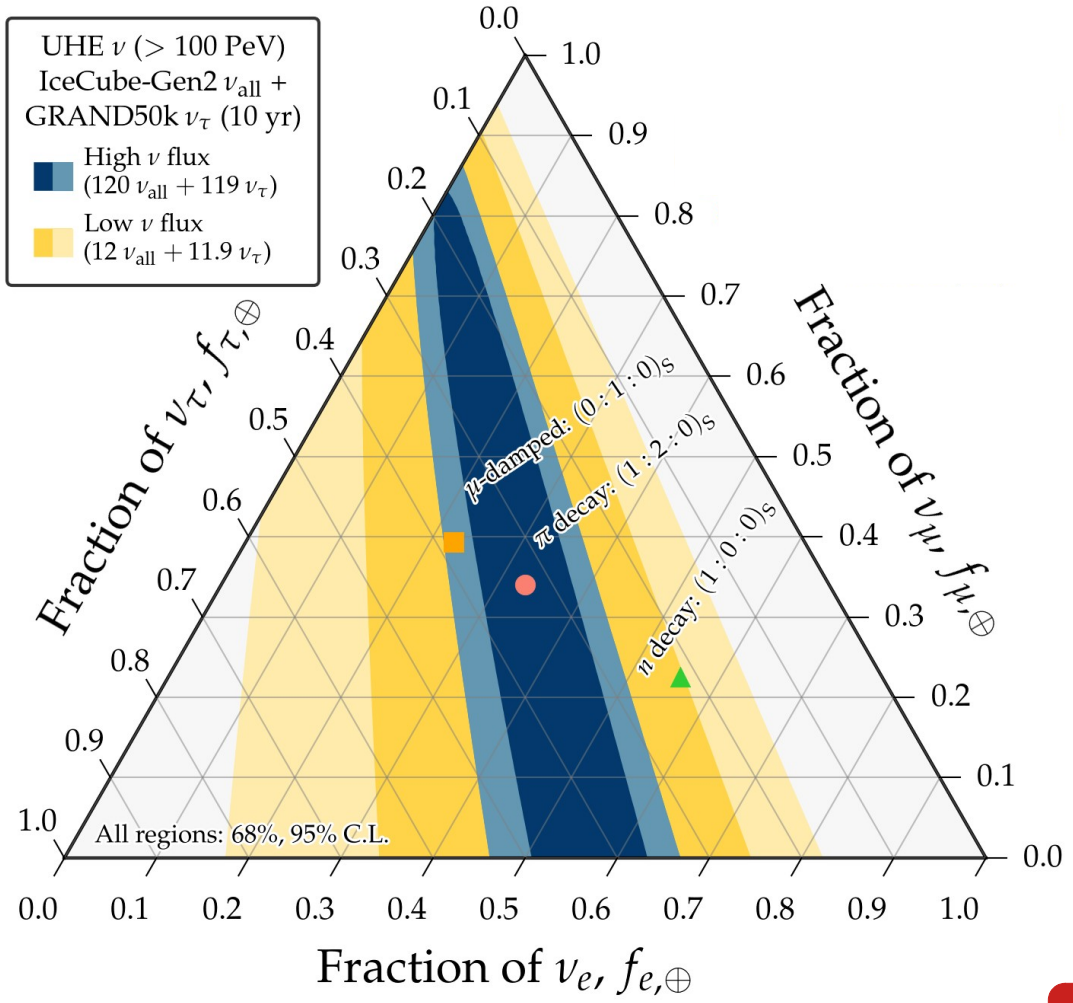

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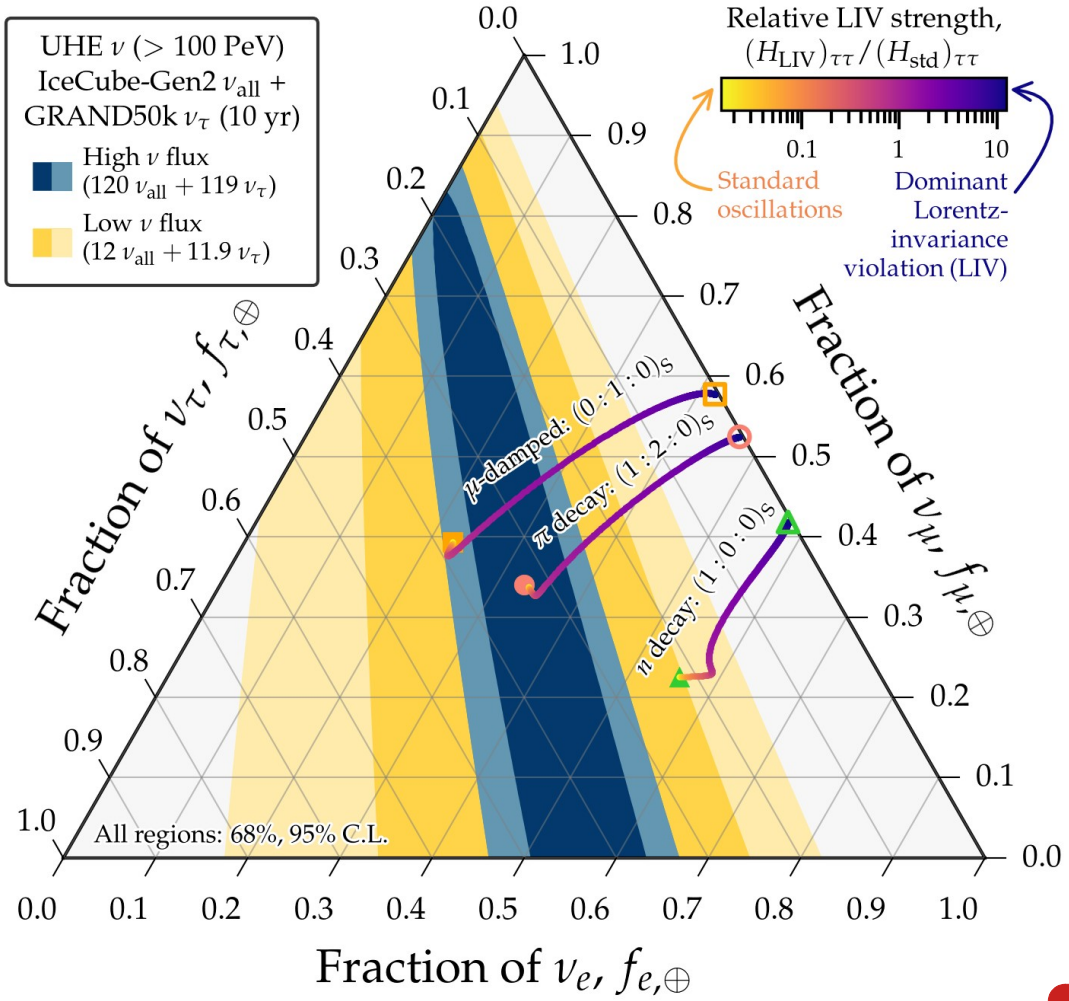

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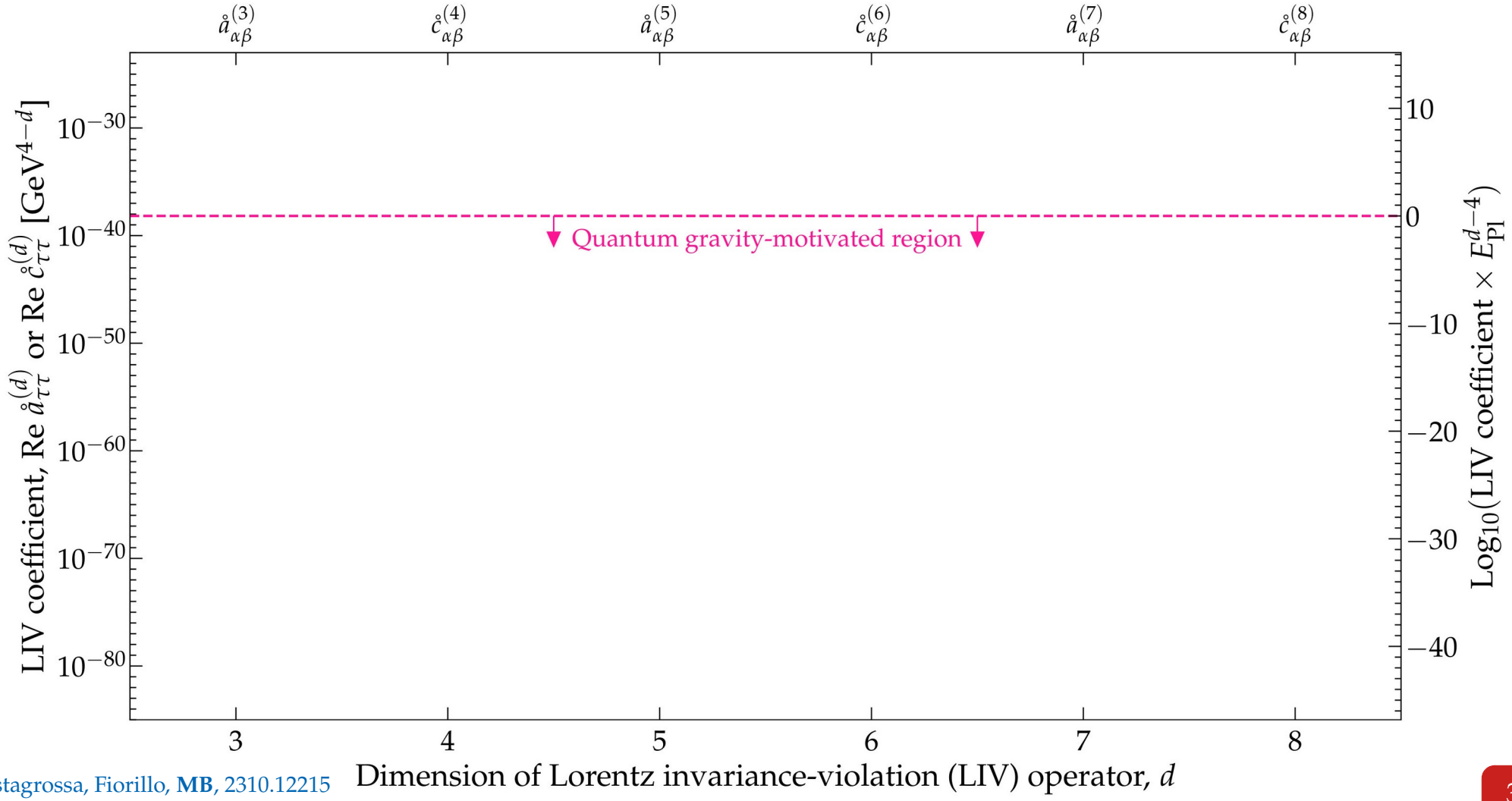
Lorentz-invariance violation at ultra-high energies



Testagrossa, Fiorillo, **MB**, 2310.12215

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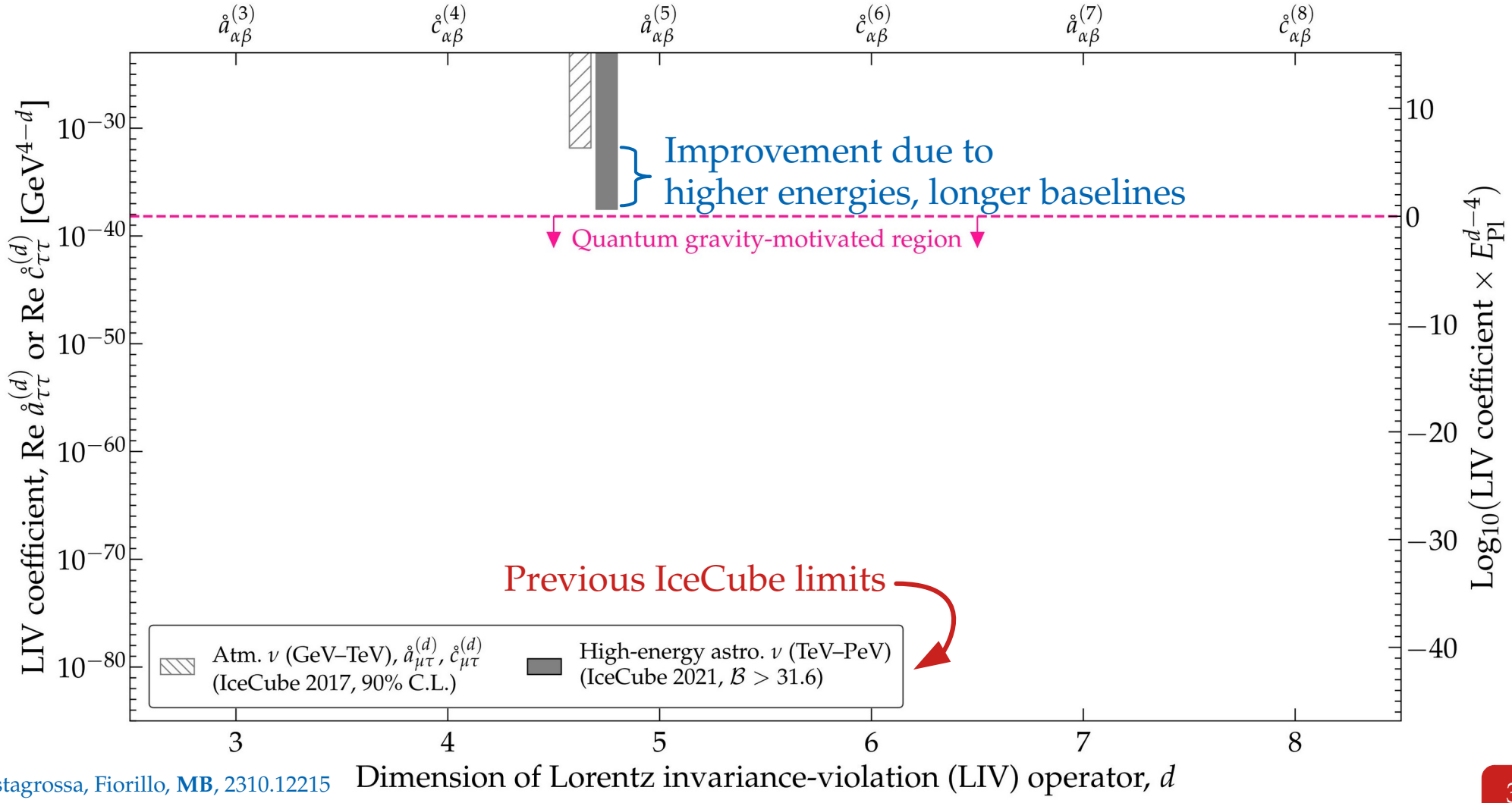

Testagrossa, Fiorillo, **MB**, 2310.12215

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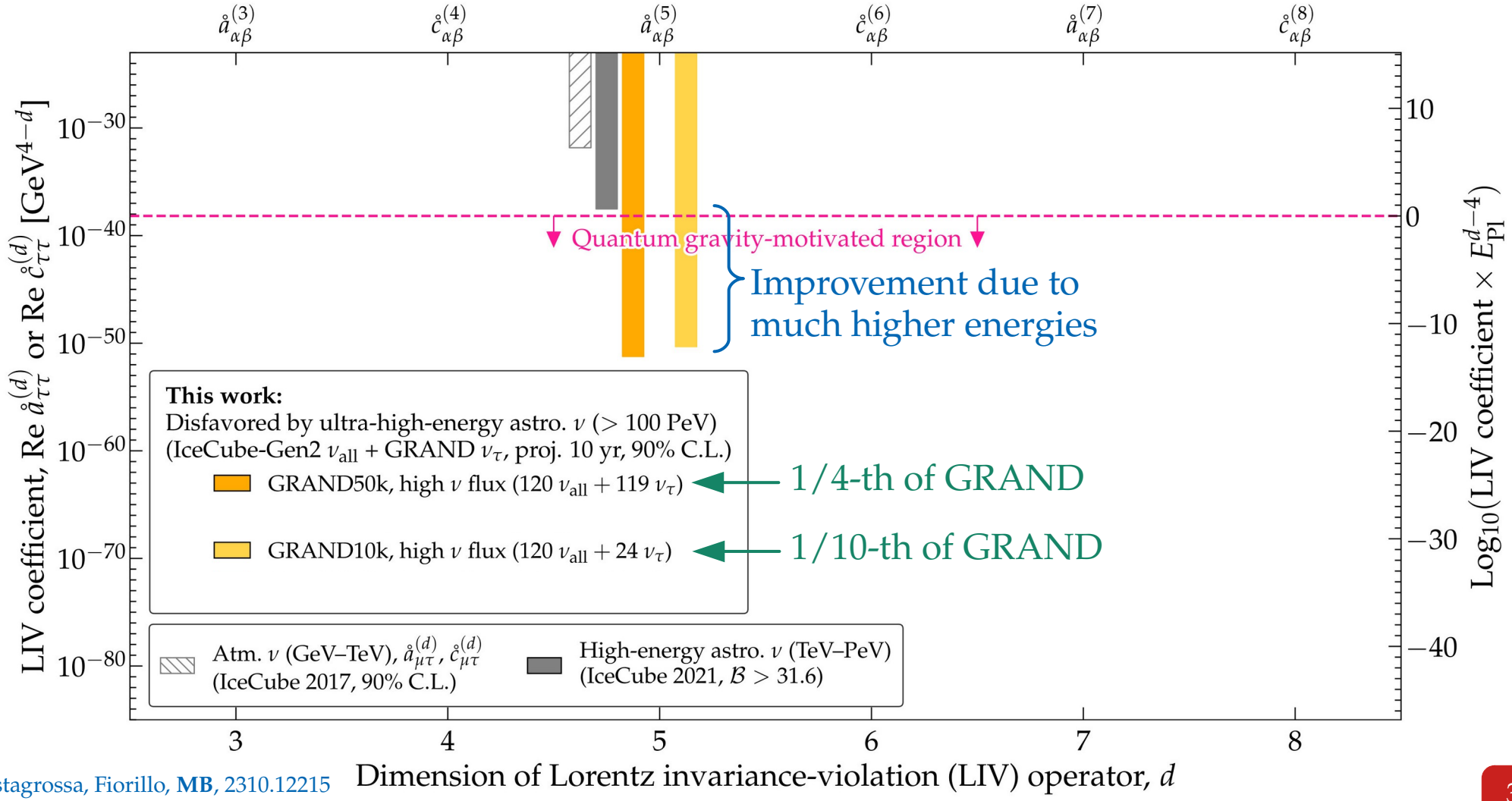

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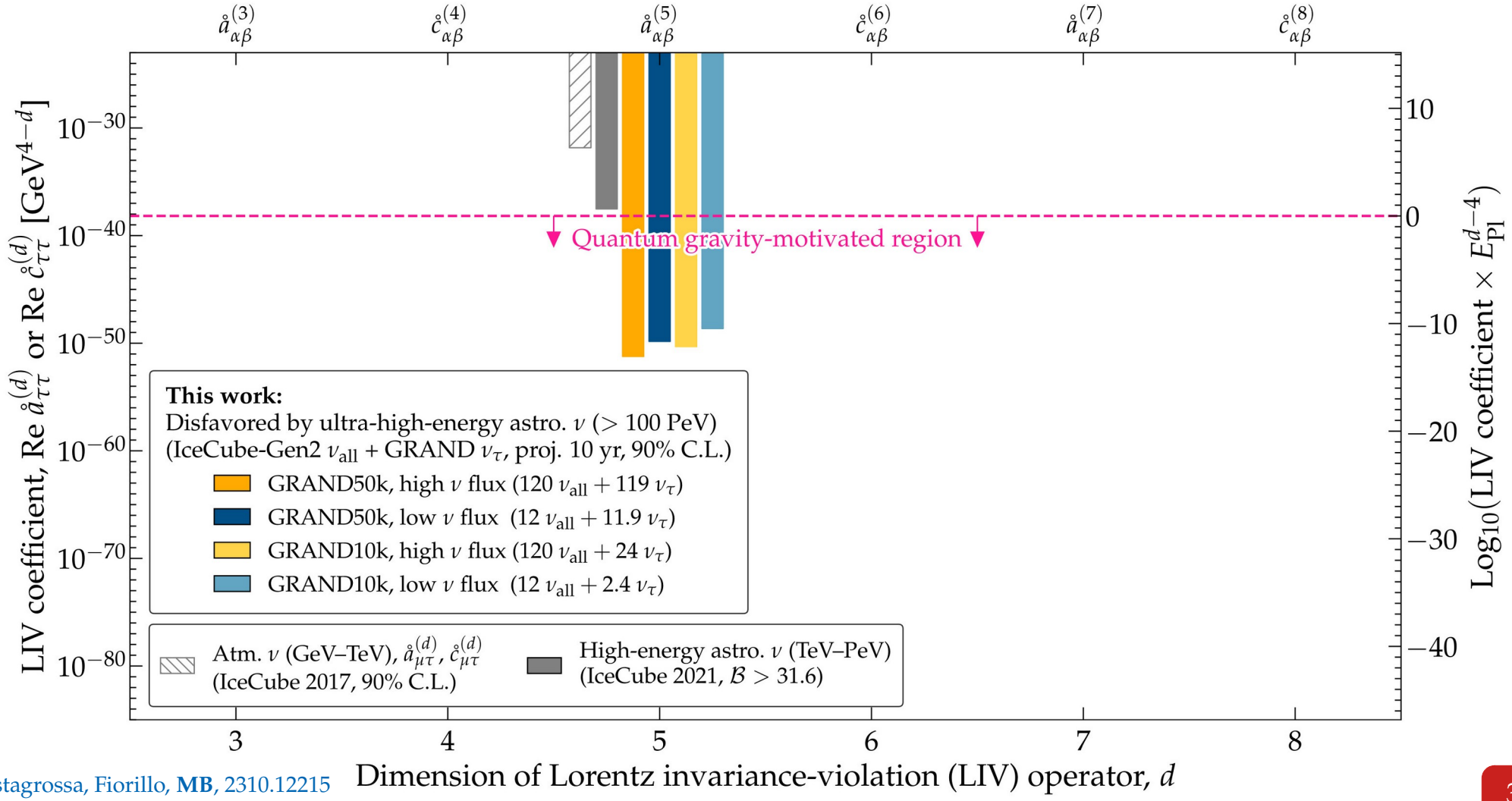

Testagrossa, Fiorillo, **MB**, 2310.12215

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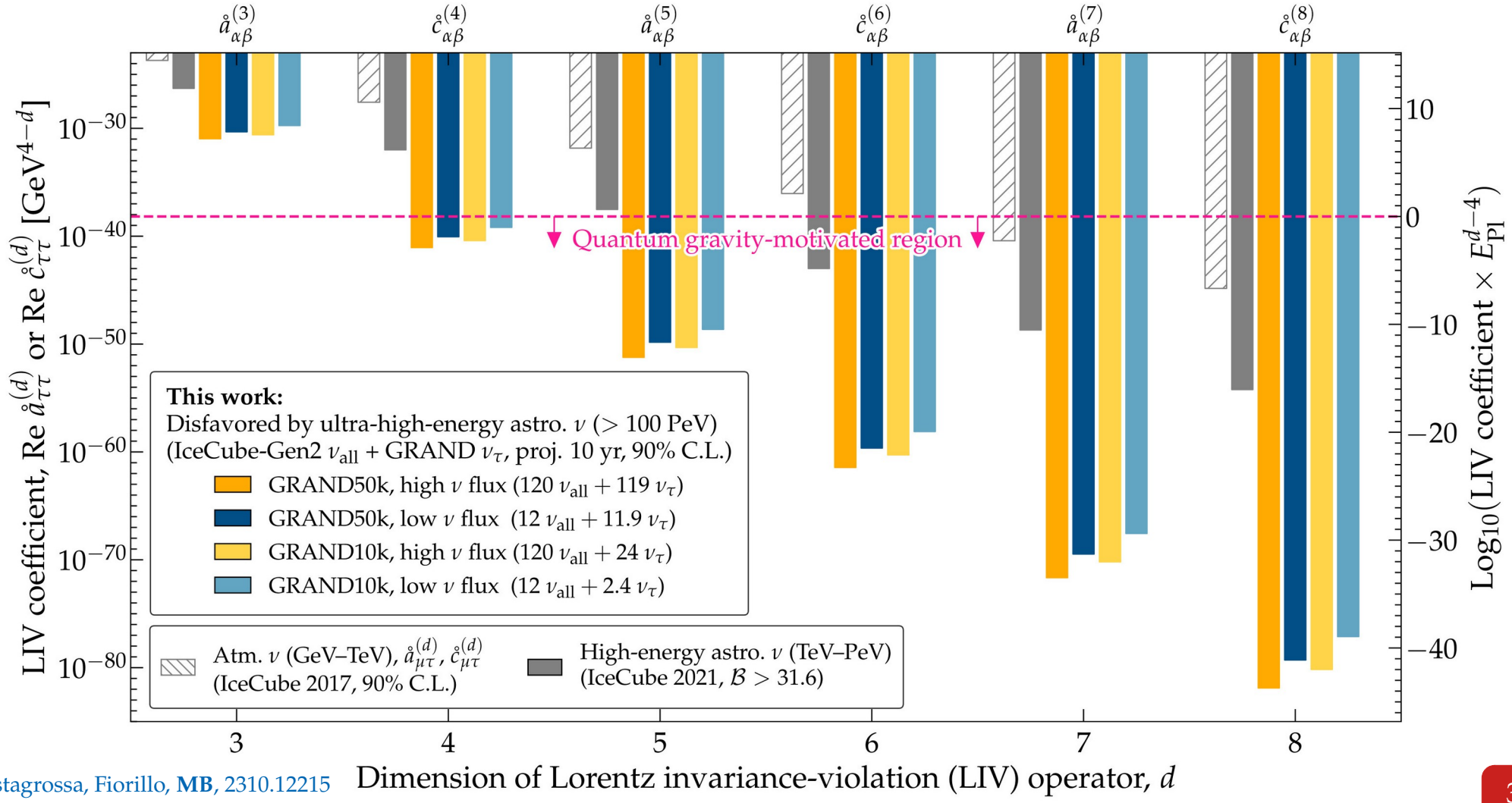

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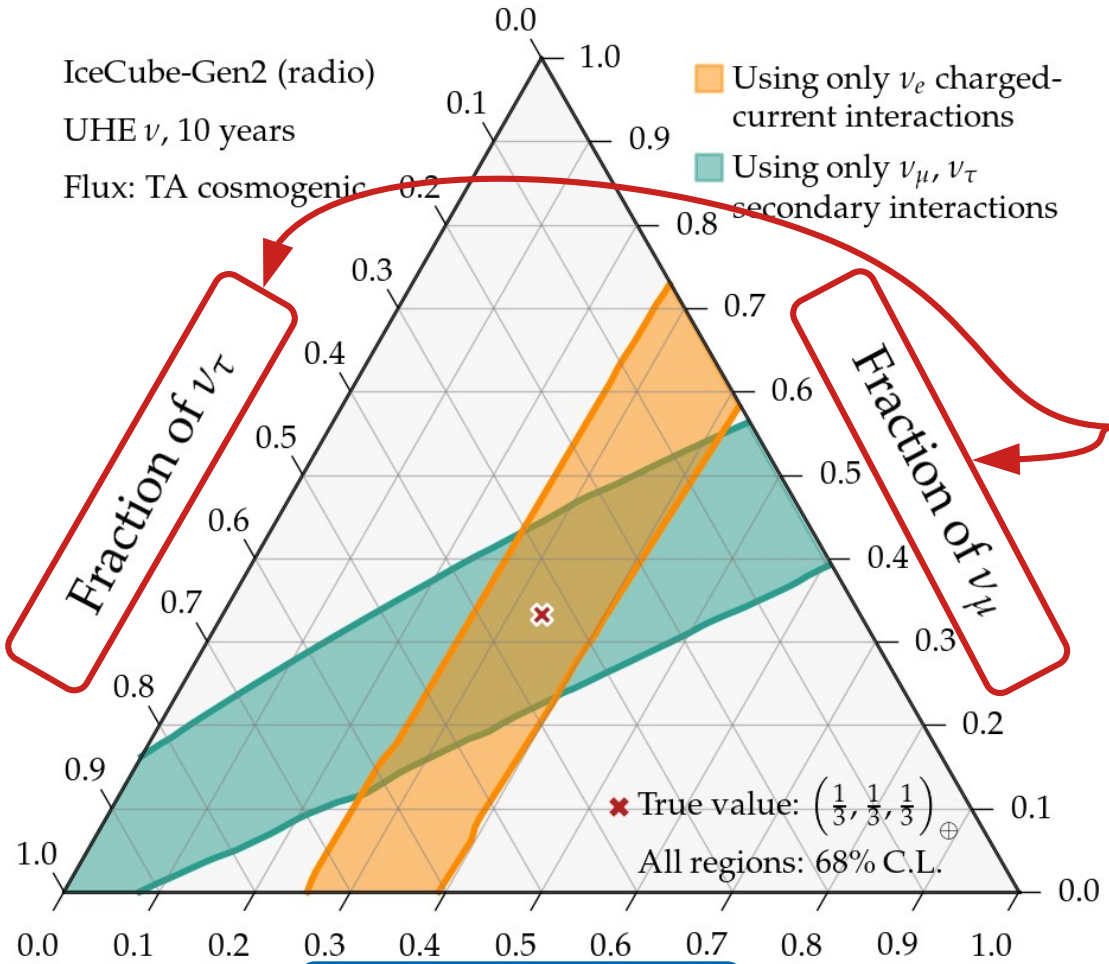
IceCube-Gen2 (radio) alone might measure flavor



Fraction of ν_e

Showers are elongated due to the LPM effect

Fraction of $\nu_\mu + \nu_\tau$

Secondary muons and tauons create showers that hit >1 radio station

Coleman, Ericsson, **MB**, Glaser, *In prep.*

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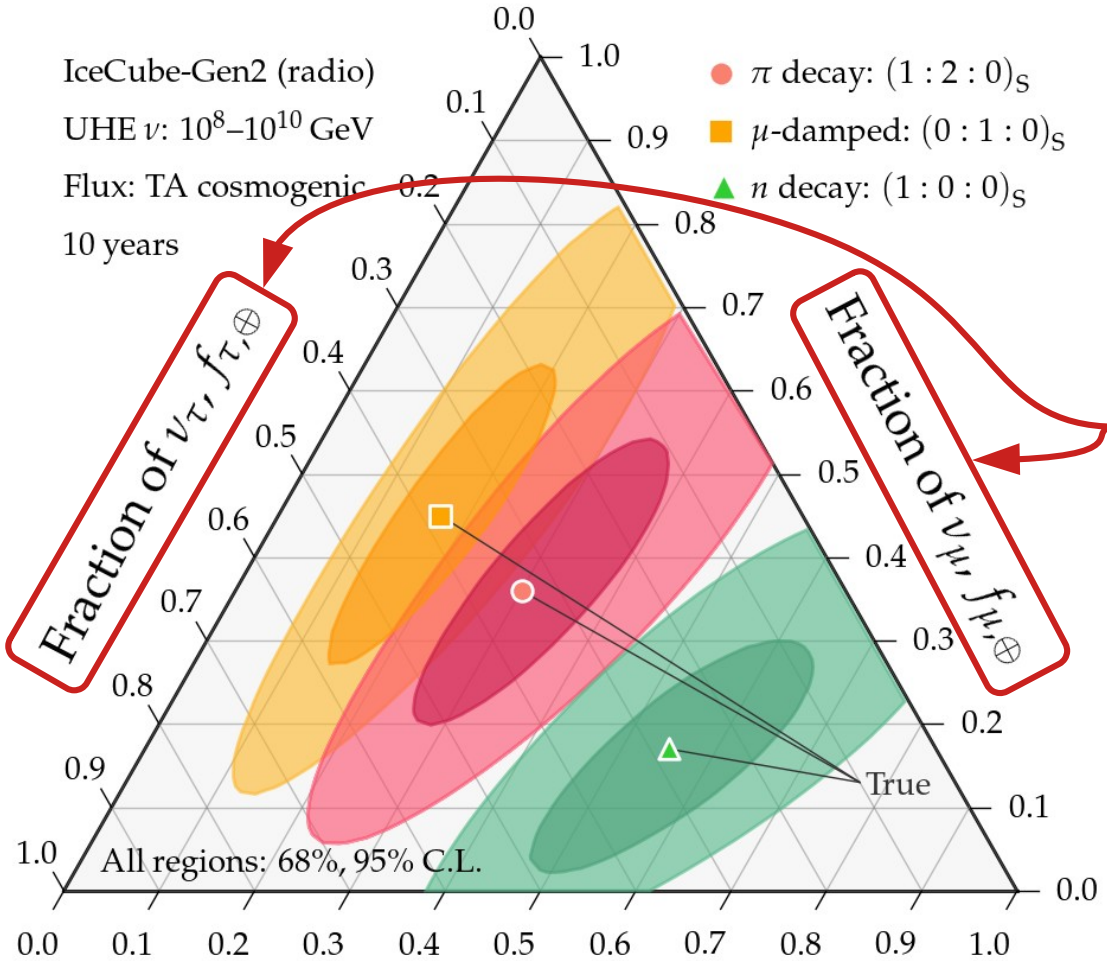

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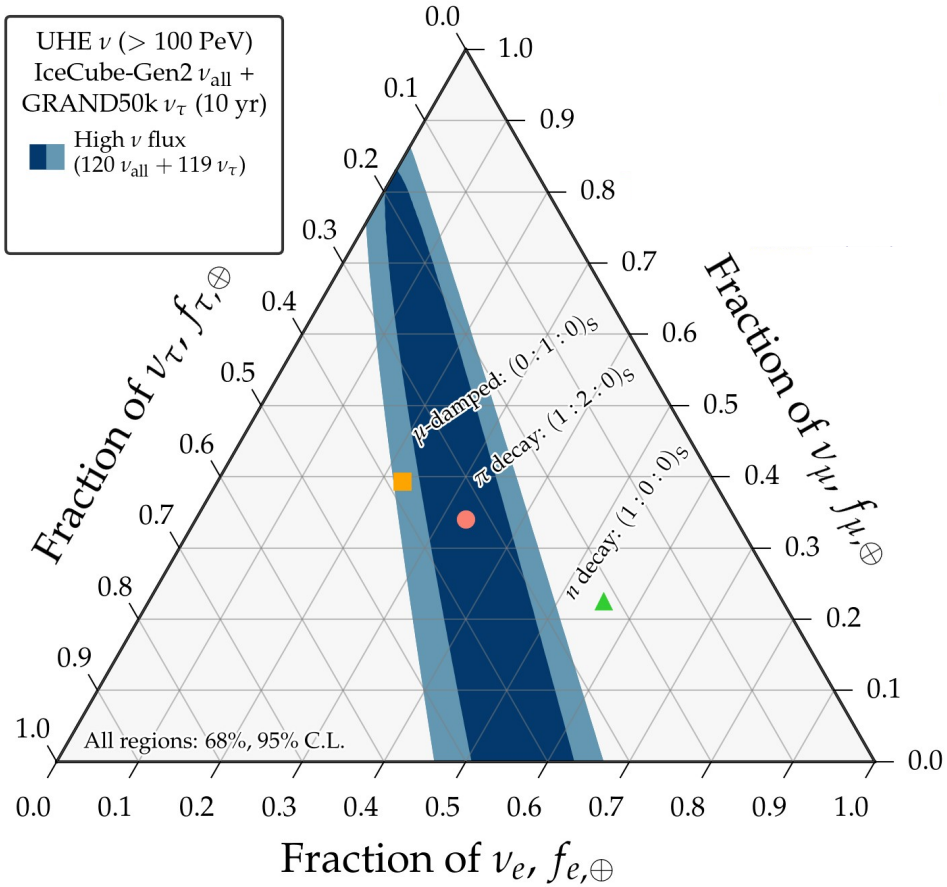
Accessing the full UHE flavor information

IceCube-Gen2 (no flavor-id) + GRAND:
Access to ν_τ fraction



IceCube-Gen2 (with flavor-id):
Access to ν_e fraction and $\nu_\mu+\nu_\tau$ fraction