High-energy neutrino physics & astrophysics

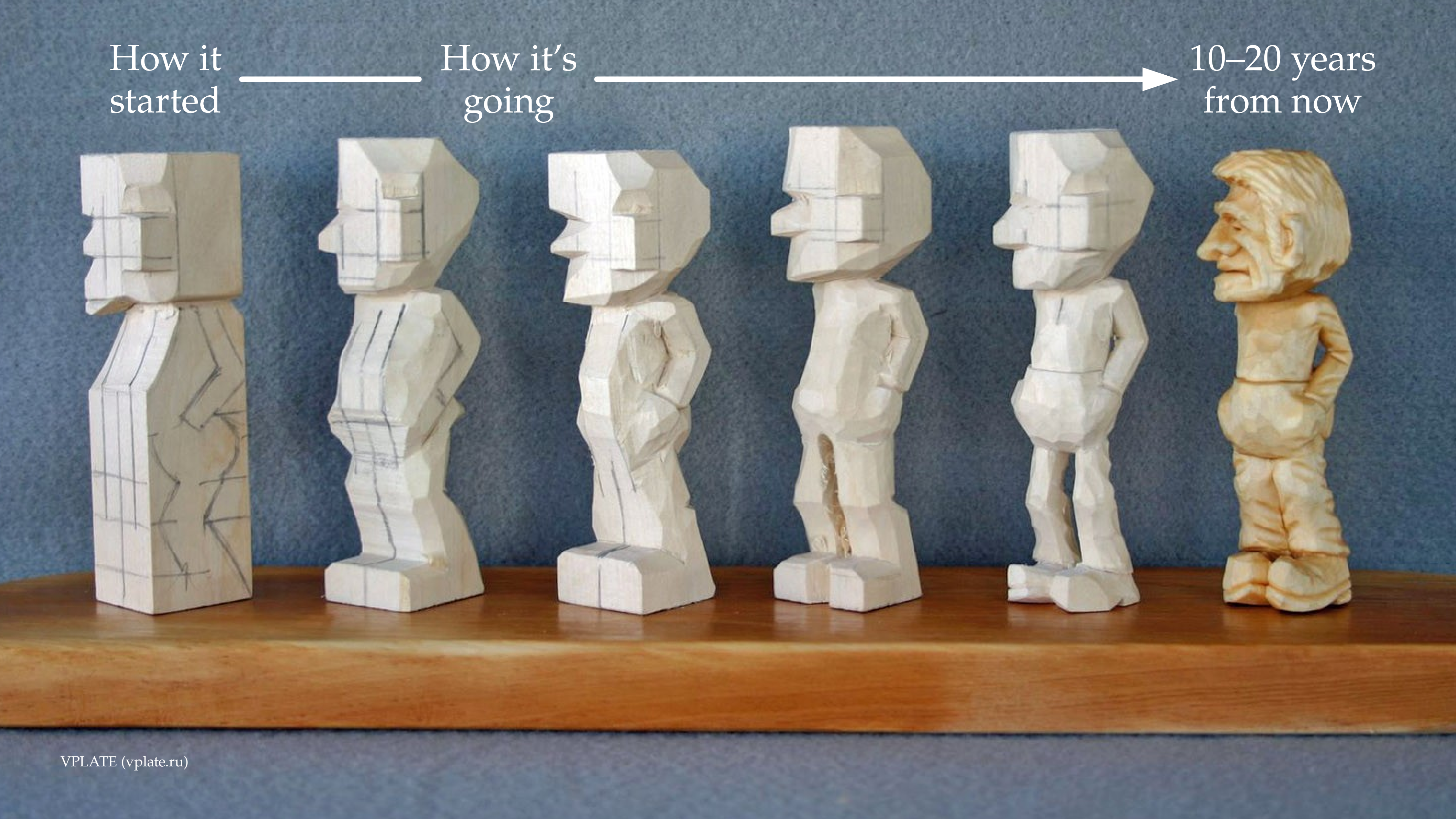
Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

UCL Workshop on Multimessenger Astronomy
London, July 03, 2024

UNIVERSITY OF
COPENHAGEN

VILLUM FONDEN

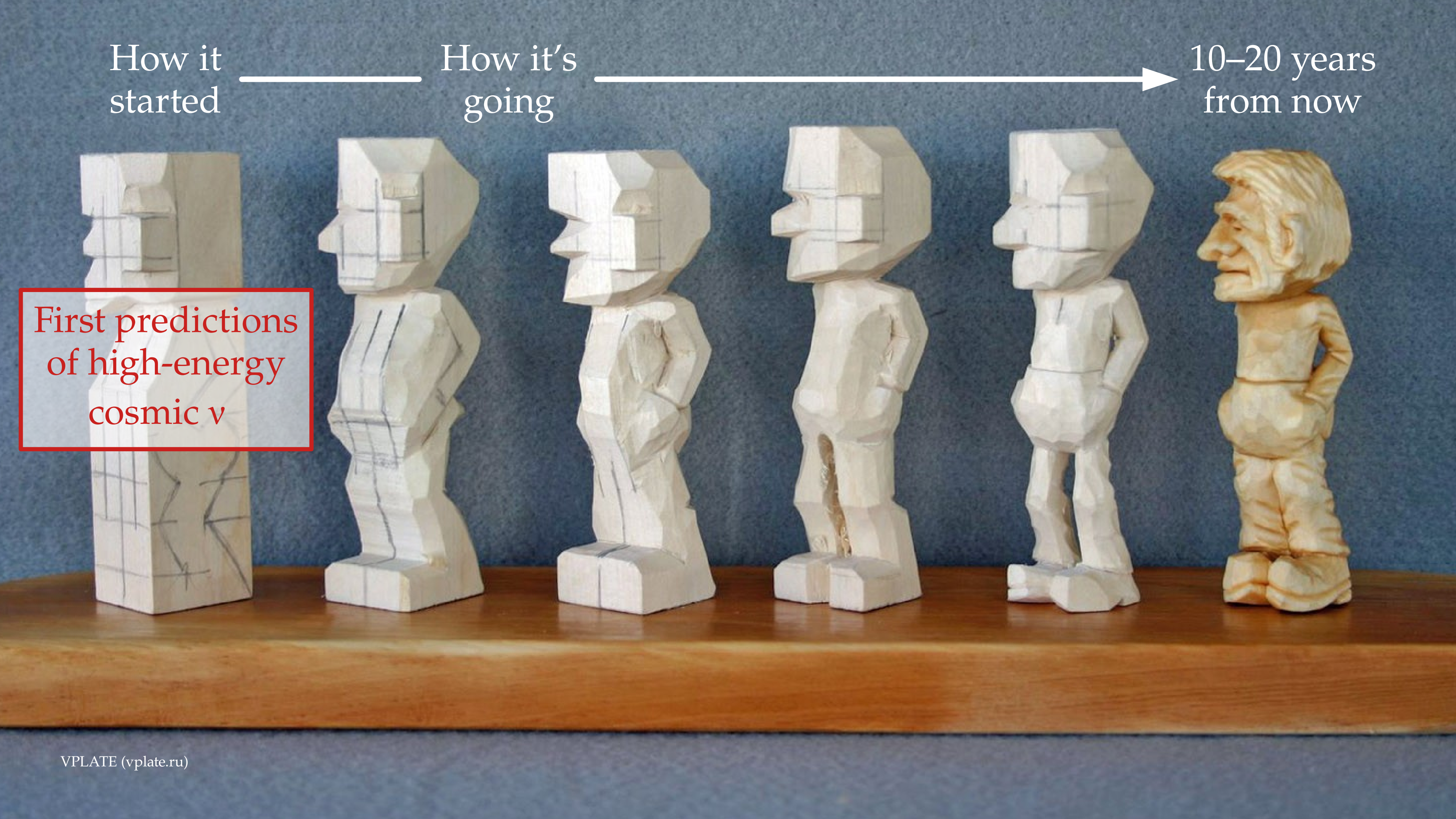


How it started

How it's going

10–20 years from now

VPLATE (vplate.ru)



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First predictions of high-energy cosmic ν

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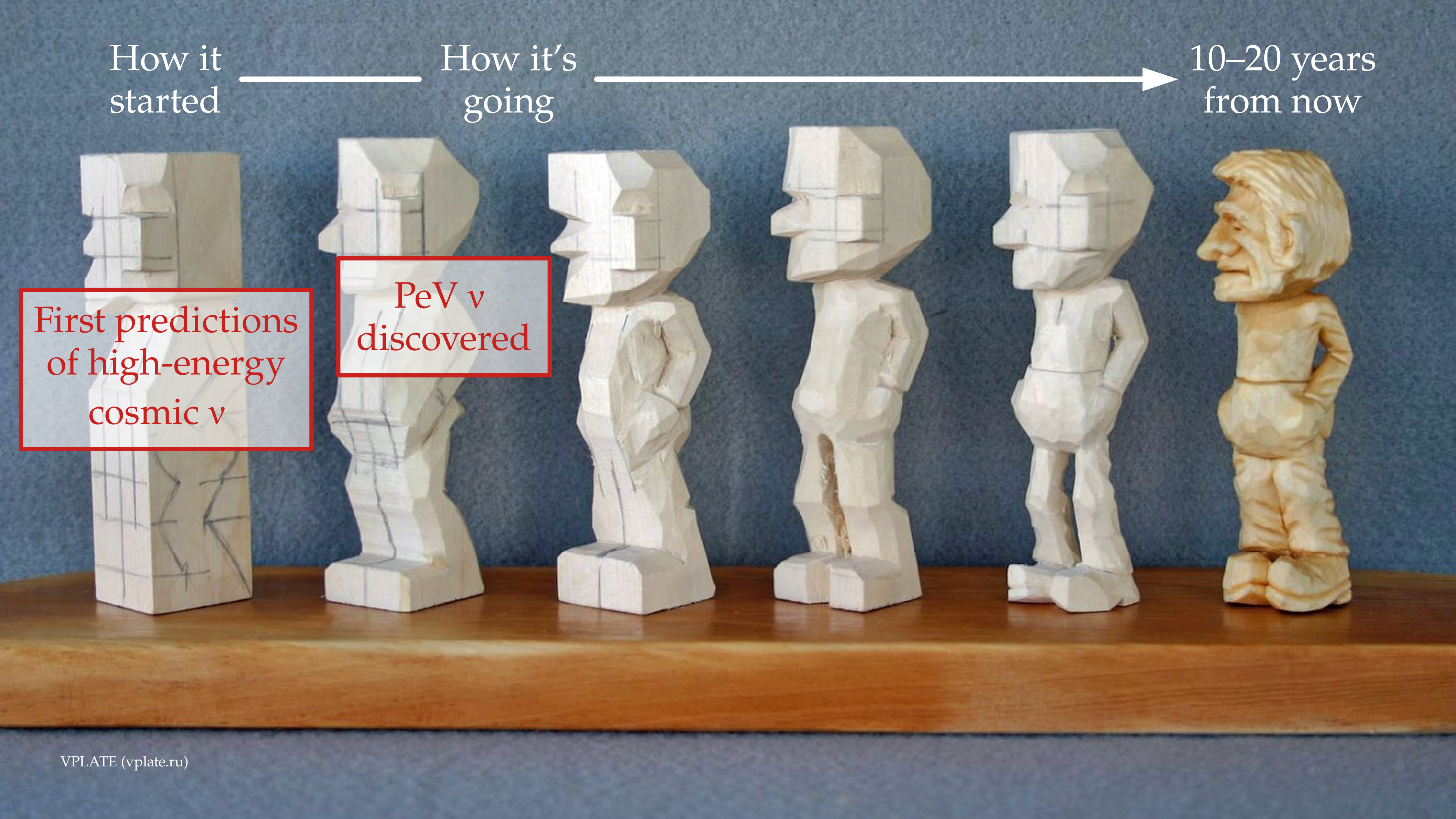

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First predictions of high-energy cosmic ν

PeV ν discovered

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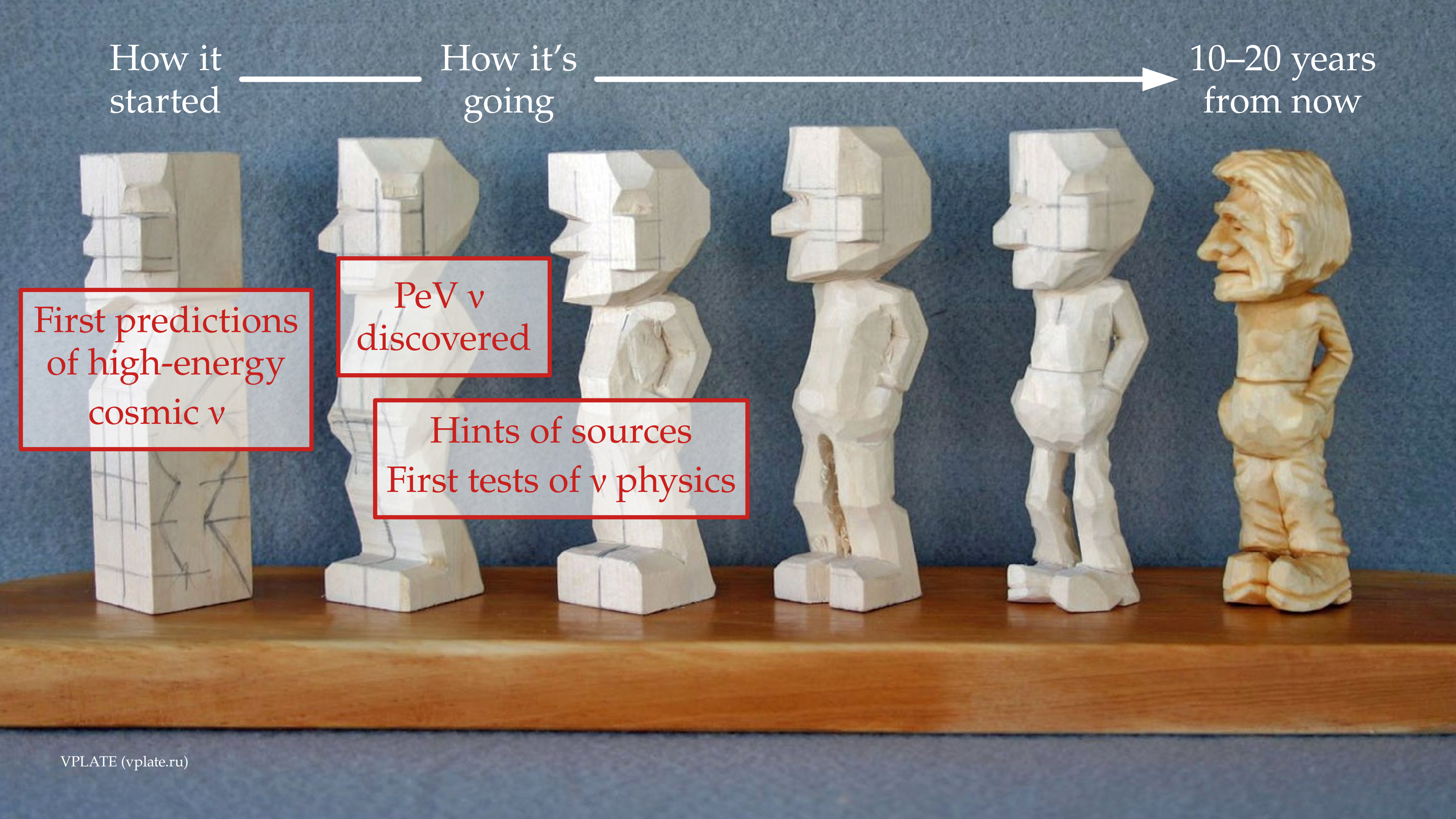

How it started → How it's going → 10–20 years from now

First predictions of high-energy cosmic ν

PeV ν discovered

Hints of sources
First tests of ν physics

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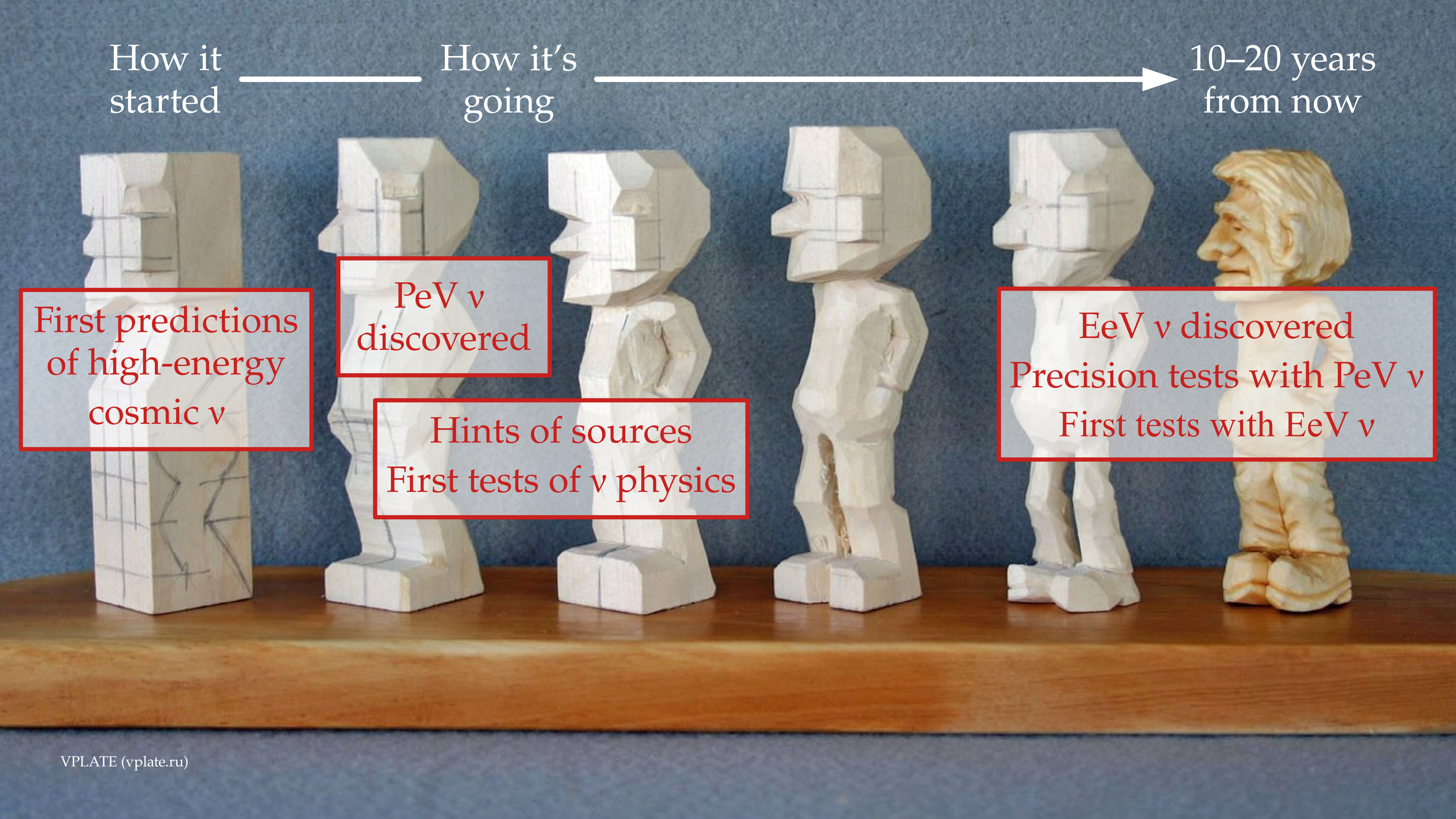

How it started → How it's going → 10–20 years from now

First predictions of high-energy cosmic ν

PeV ν discovered

Hints of sources
First tests of ν physics

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

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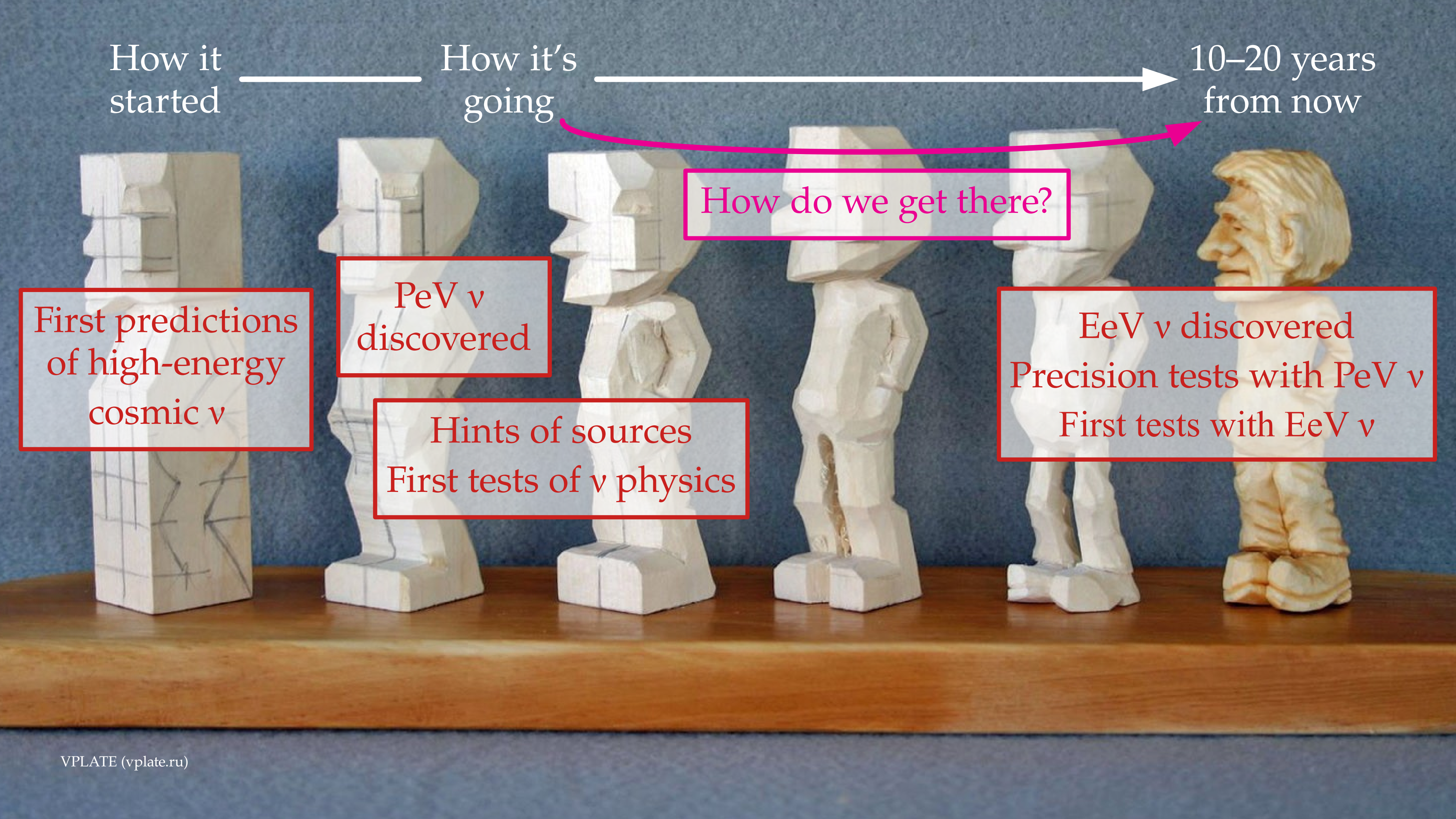

How it started → How it's going → 10–20 years from now

How do we get there?

First predictions of high-energy cosmic ν

PeV ν discovered

Hints of sources

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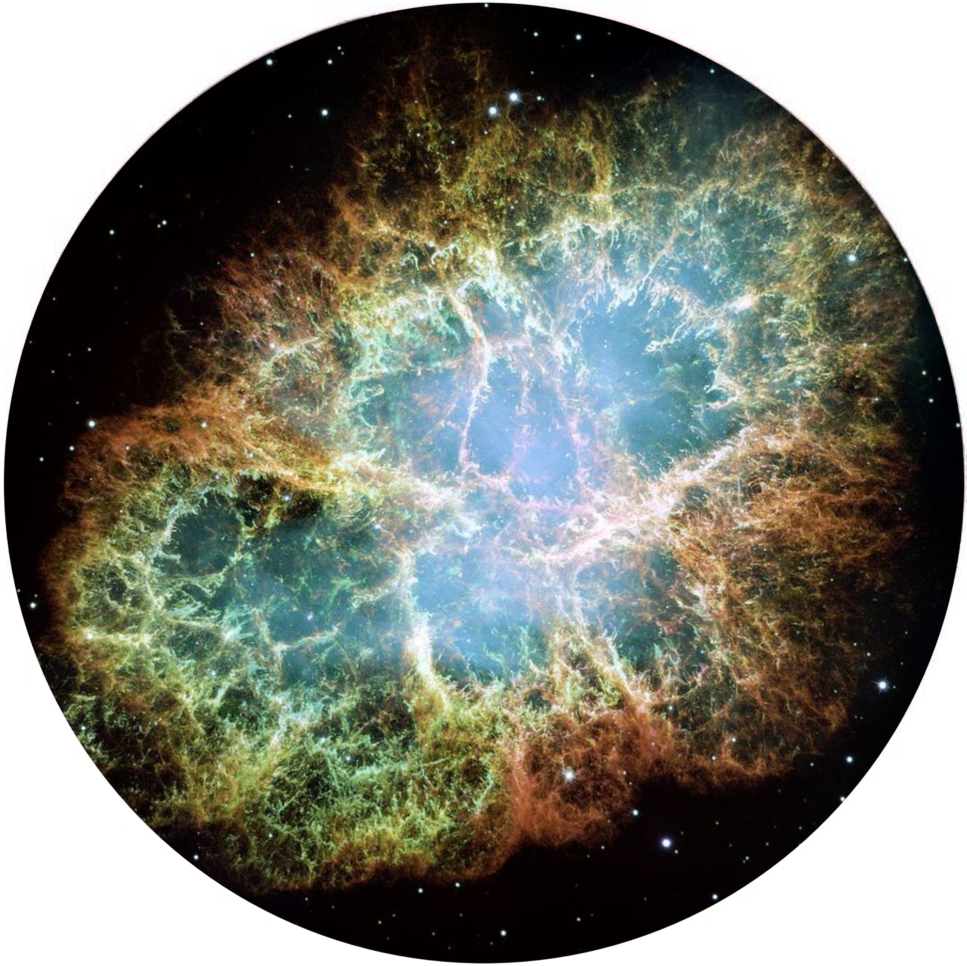
First tests with EeV ν

VPLATE (vplate.ru)

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



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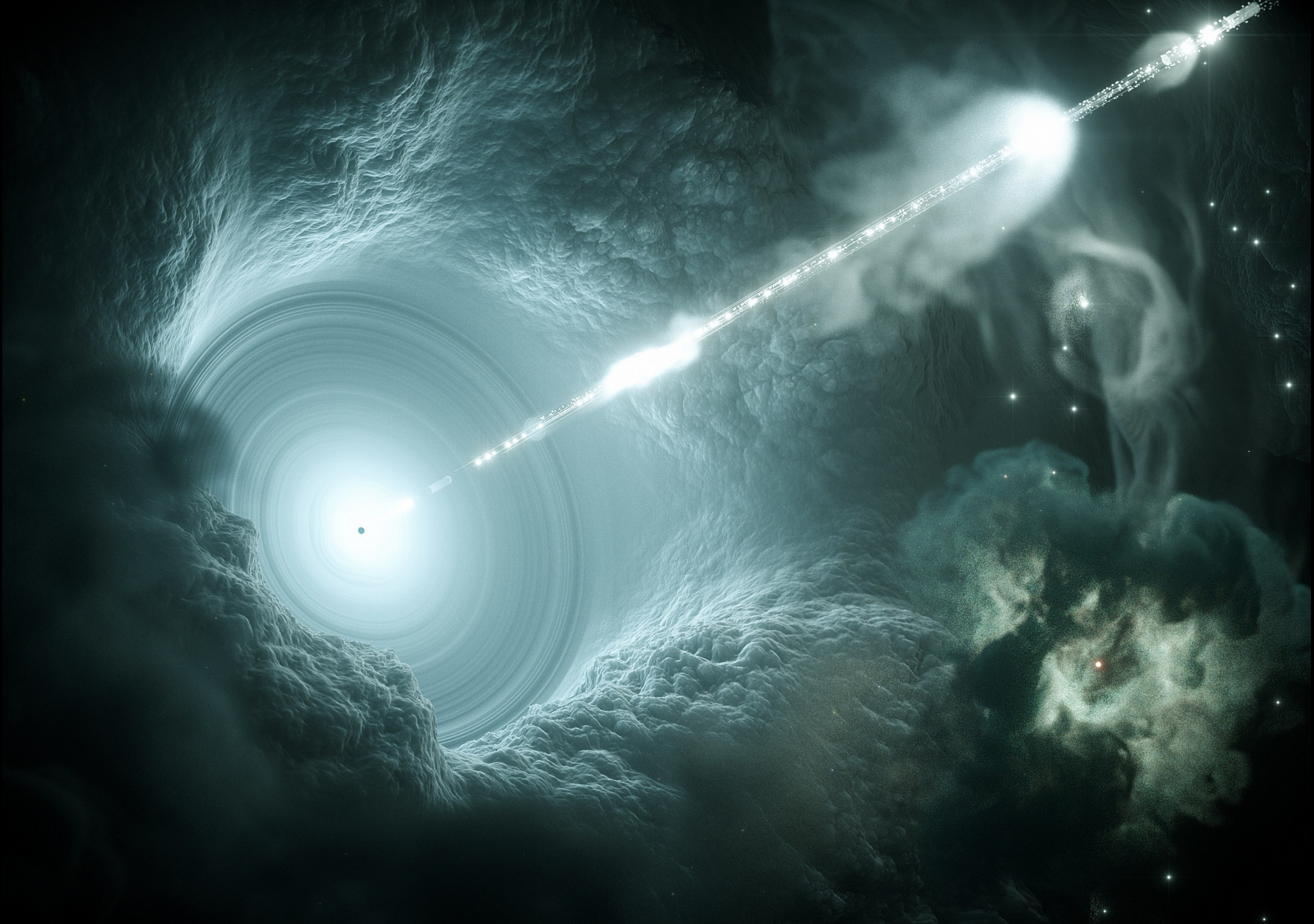
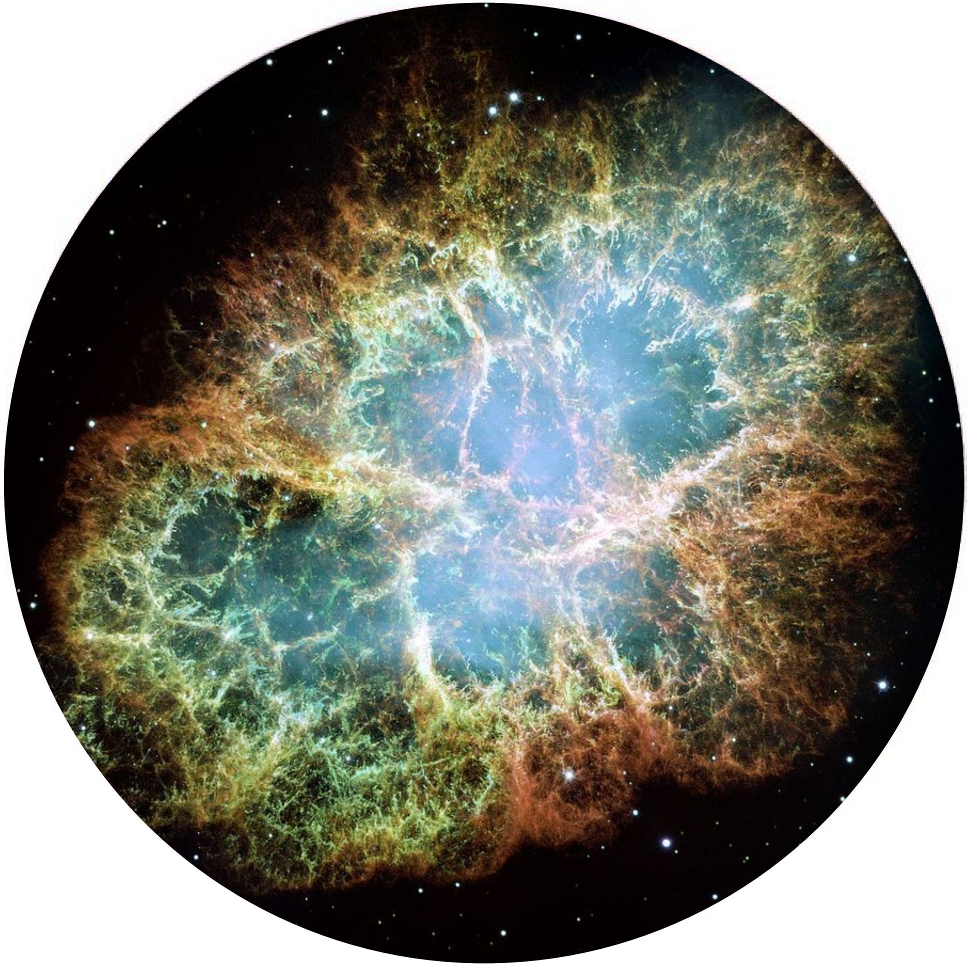


DESY

DESY



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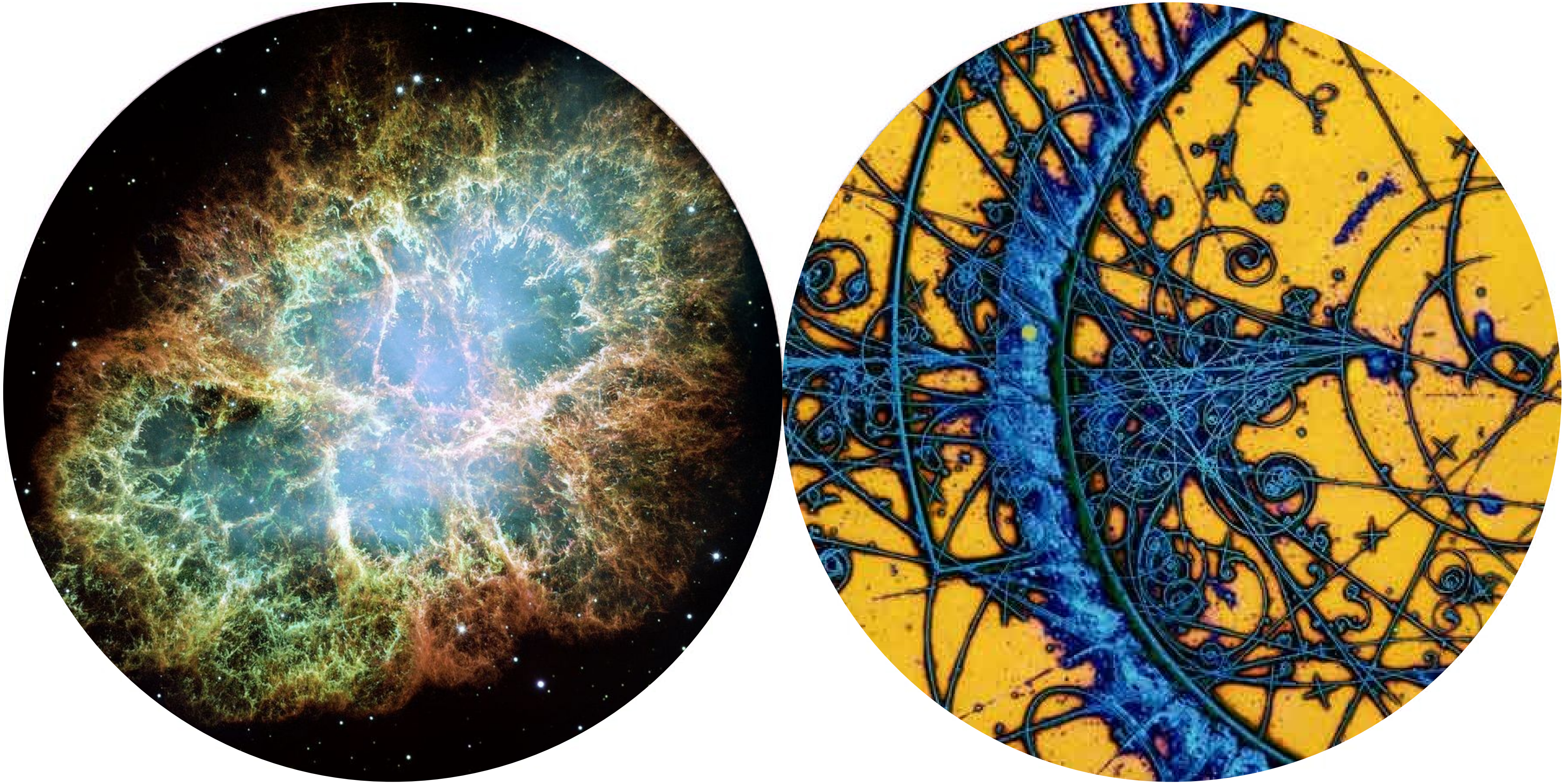

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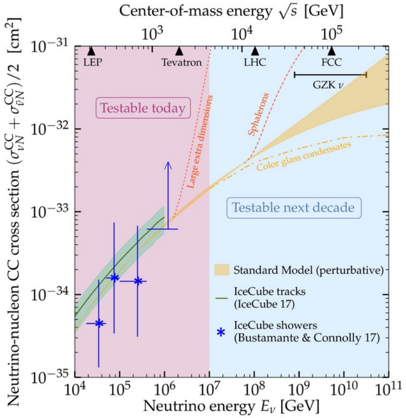
TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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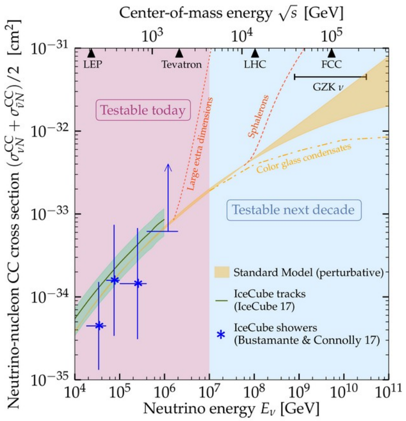
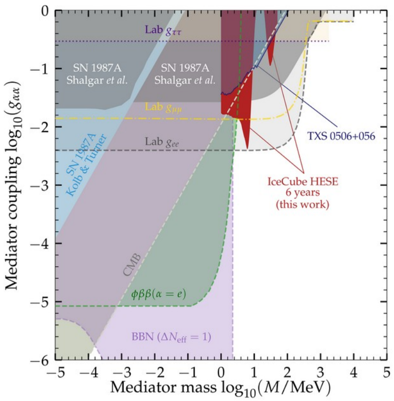


MB & Connolly, *PRL* 2019

ν self-interactions



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

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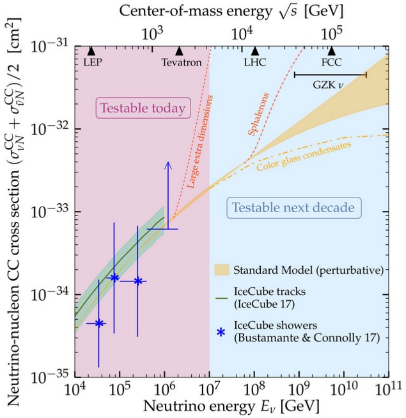

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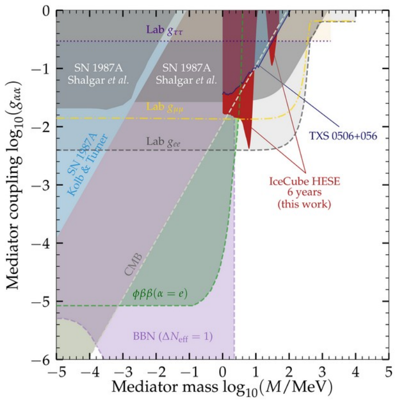

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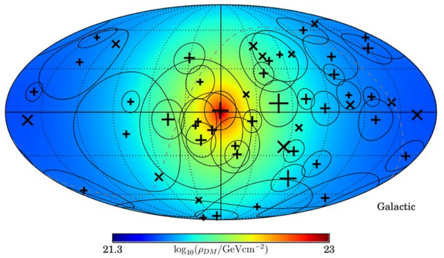
ν scattering on Galactic DM



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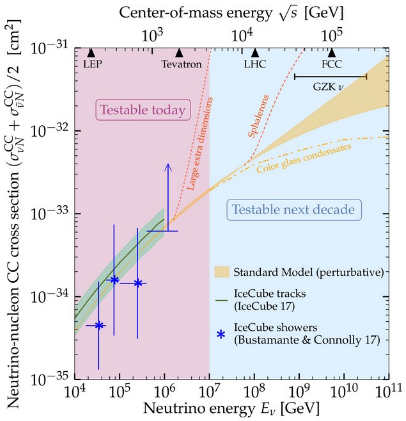

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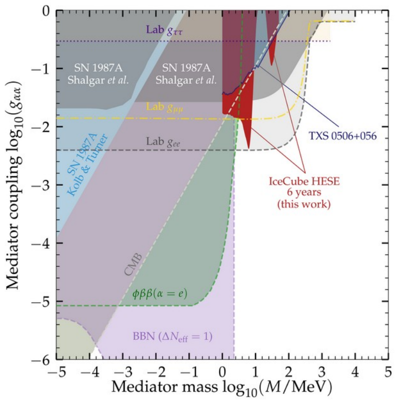

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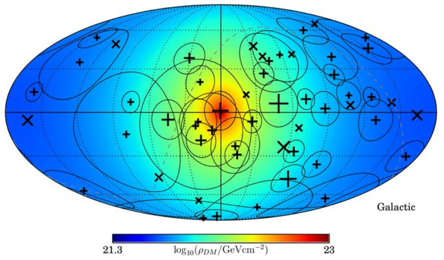

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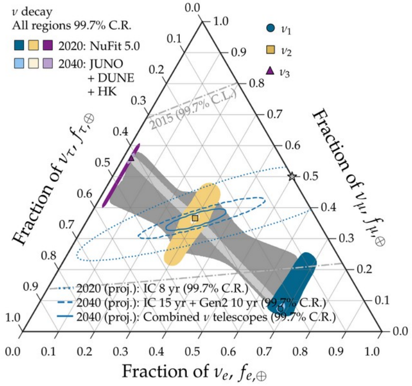
ν decay



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

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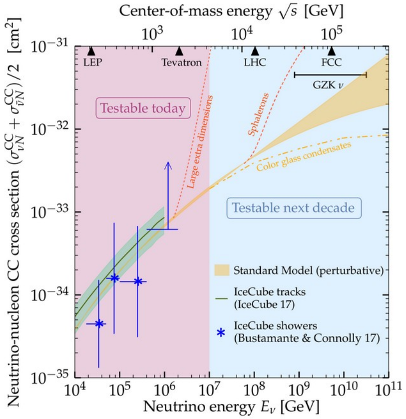

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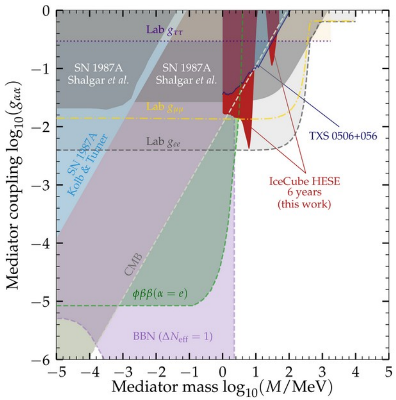

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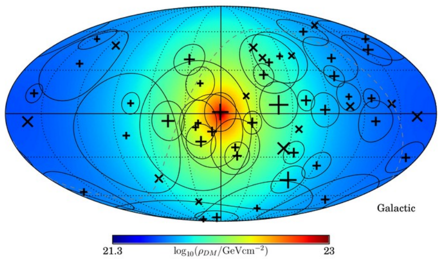

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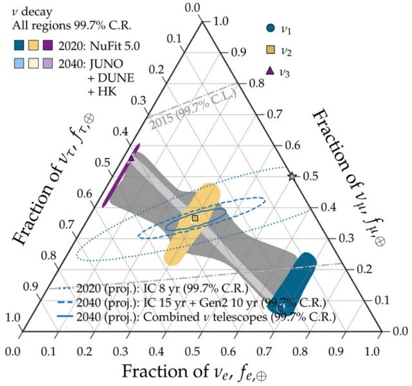

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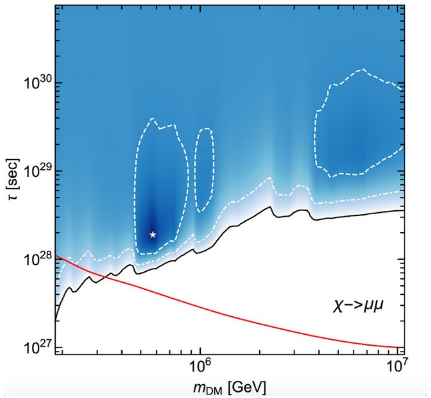
Dark matter decay



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

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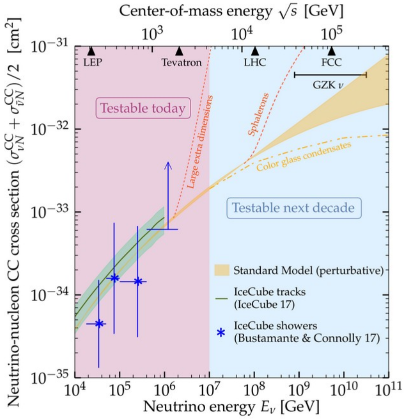

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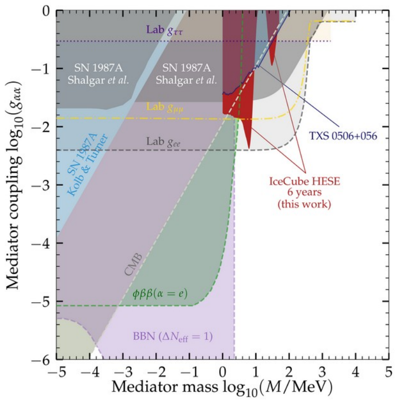

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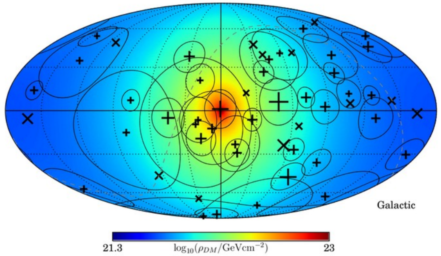

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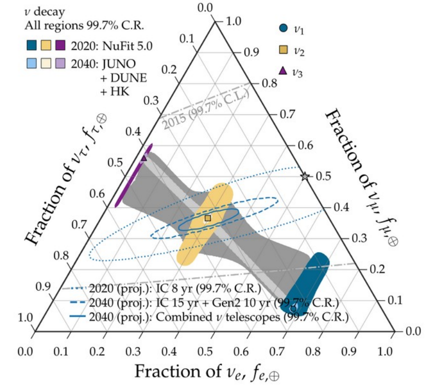

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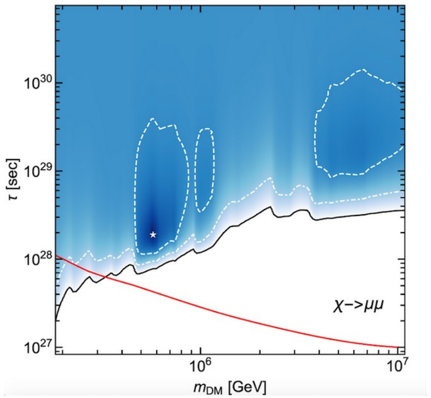

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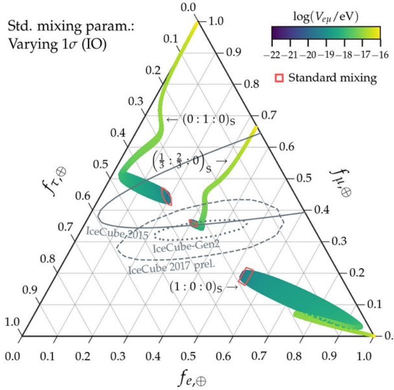
ν-electron interaction



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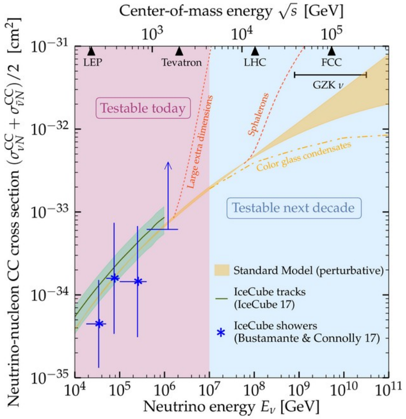

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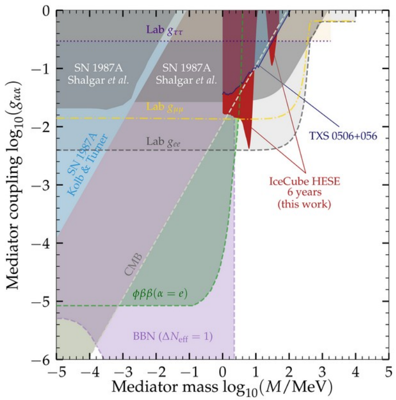

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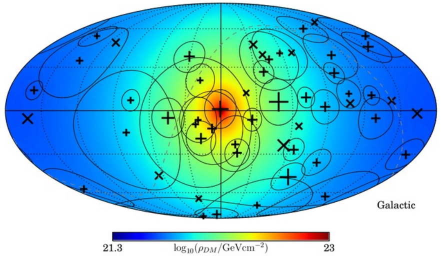

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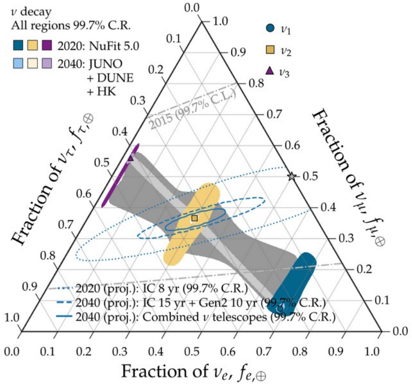

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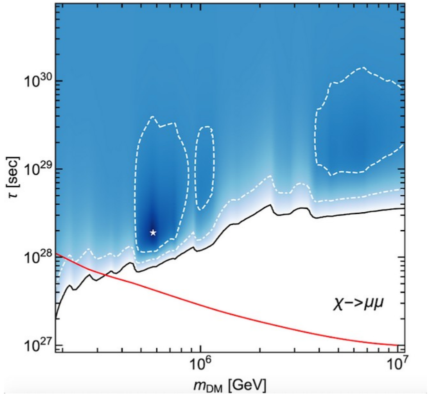

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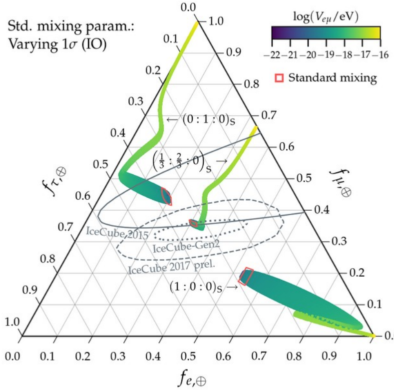
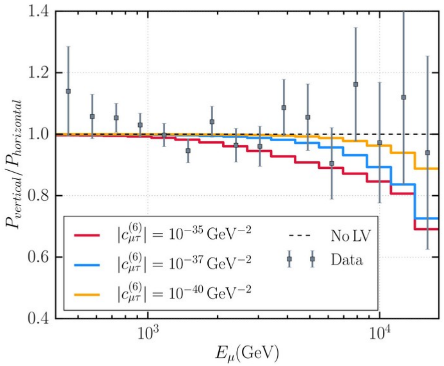


MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



IceCube, *Nature Phys.* 2018

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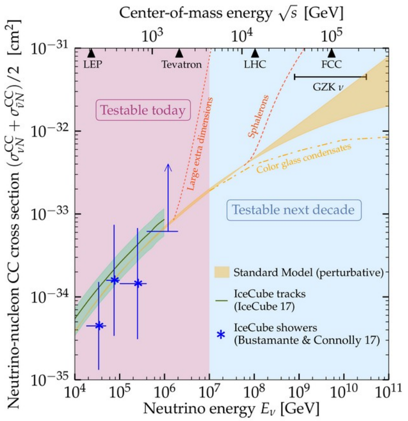

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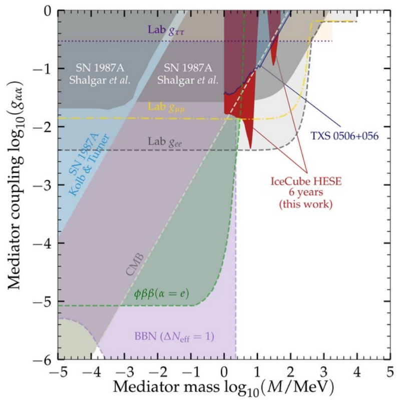

MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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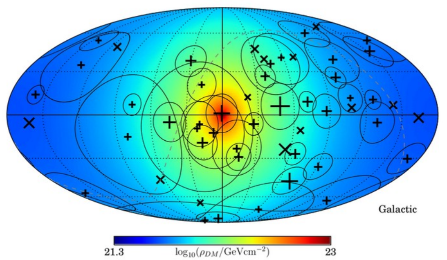

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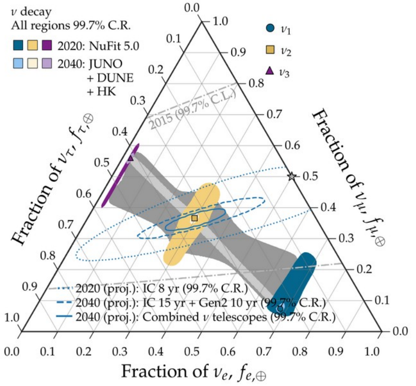

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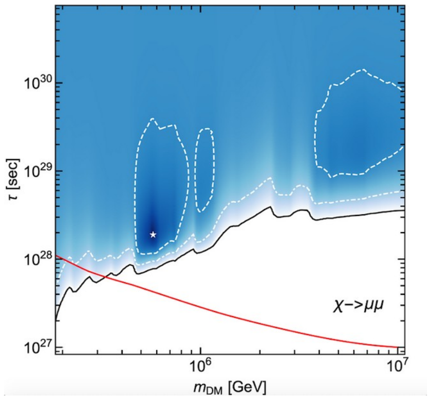

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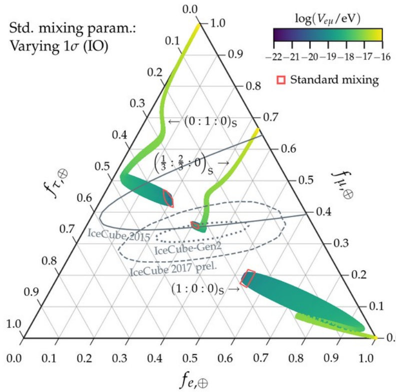

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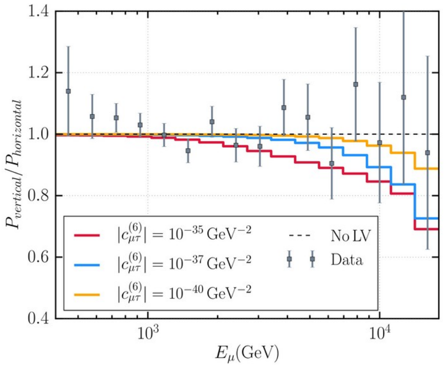
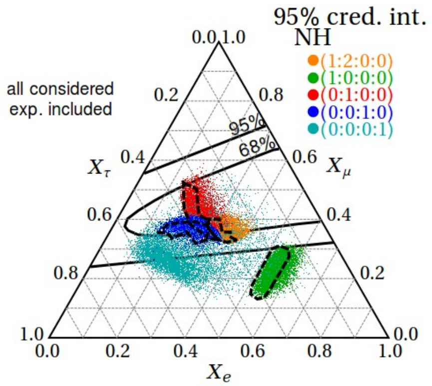
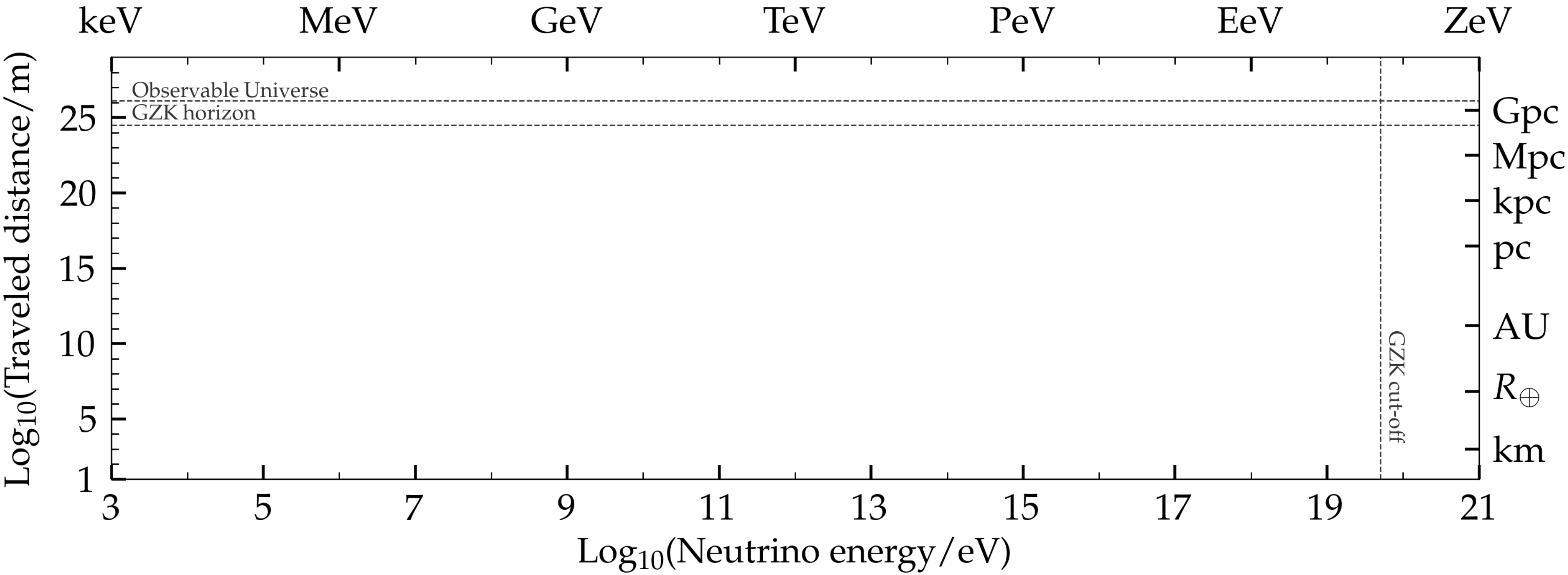


IceCube, *Nature Phys.* 2018

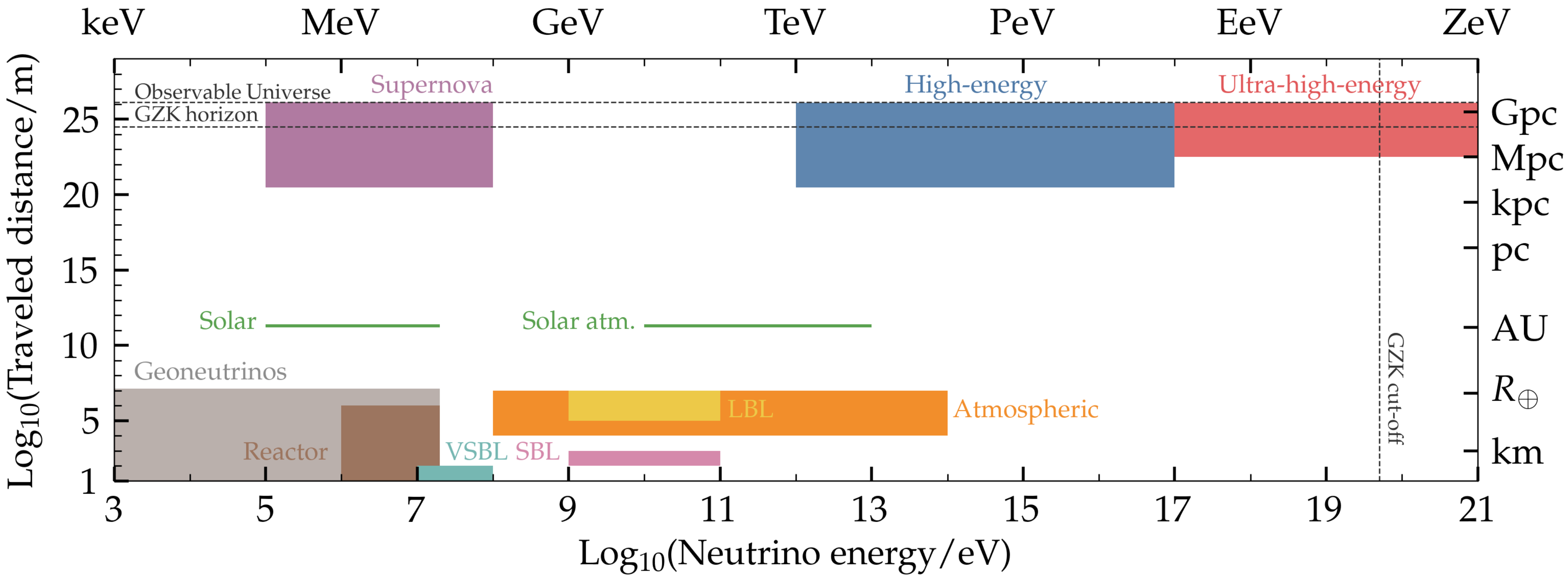
Sterile neutrinos



Brdar, Kopp, Wang, *JCAP* 2017



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



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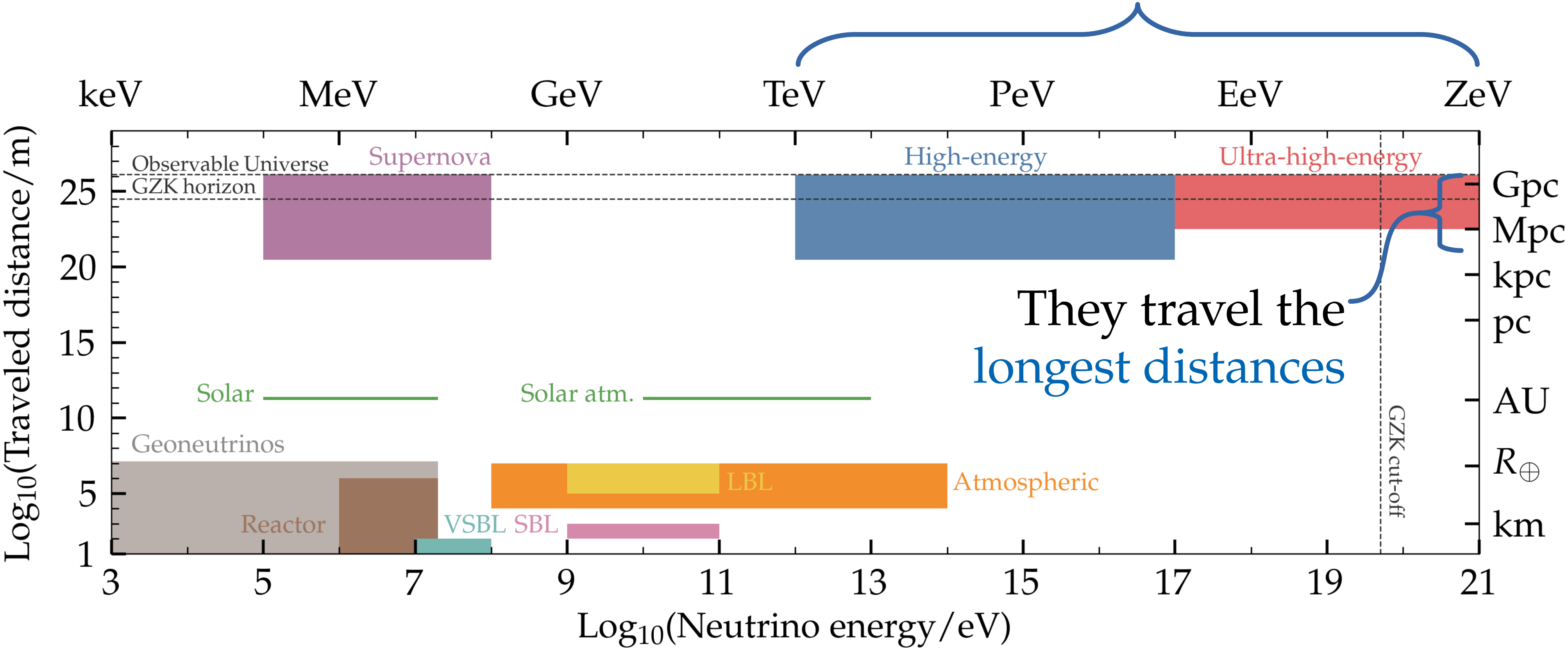
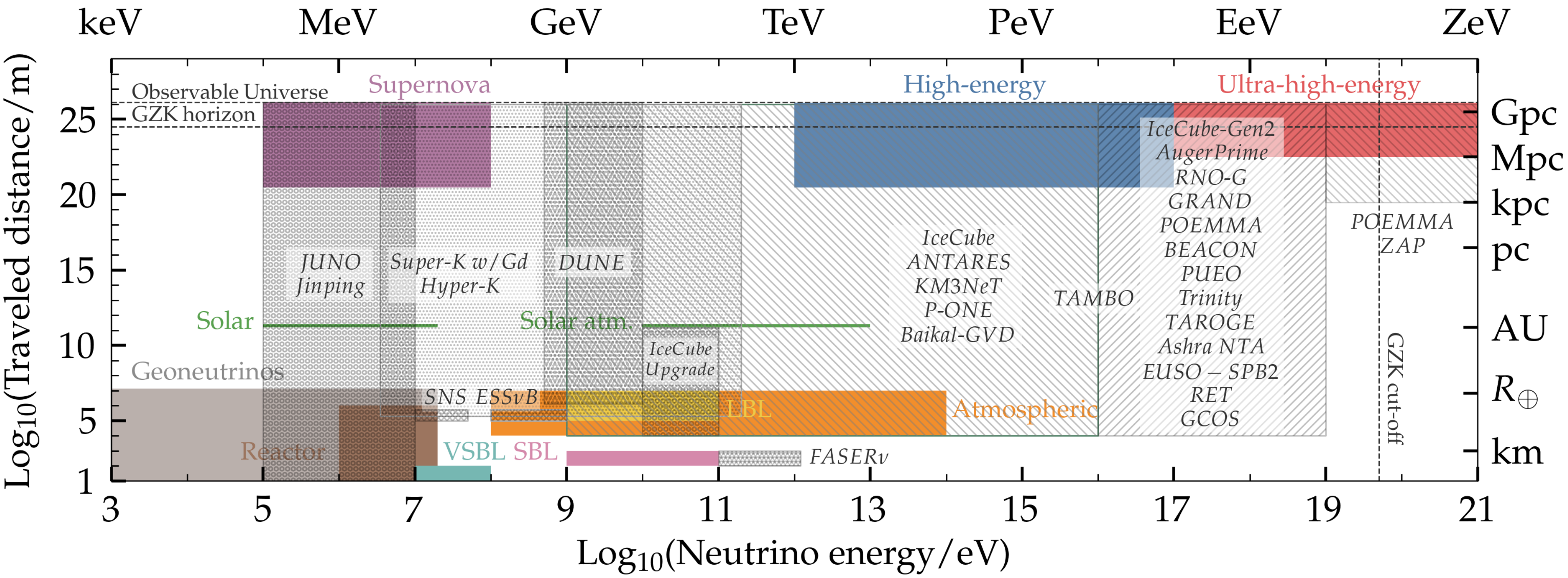
They have the highest energies



They travel the longest distances

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



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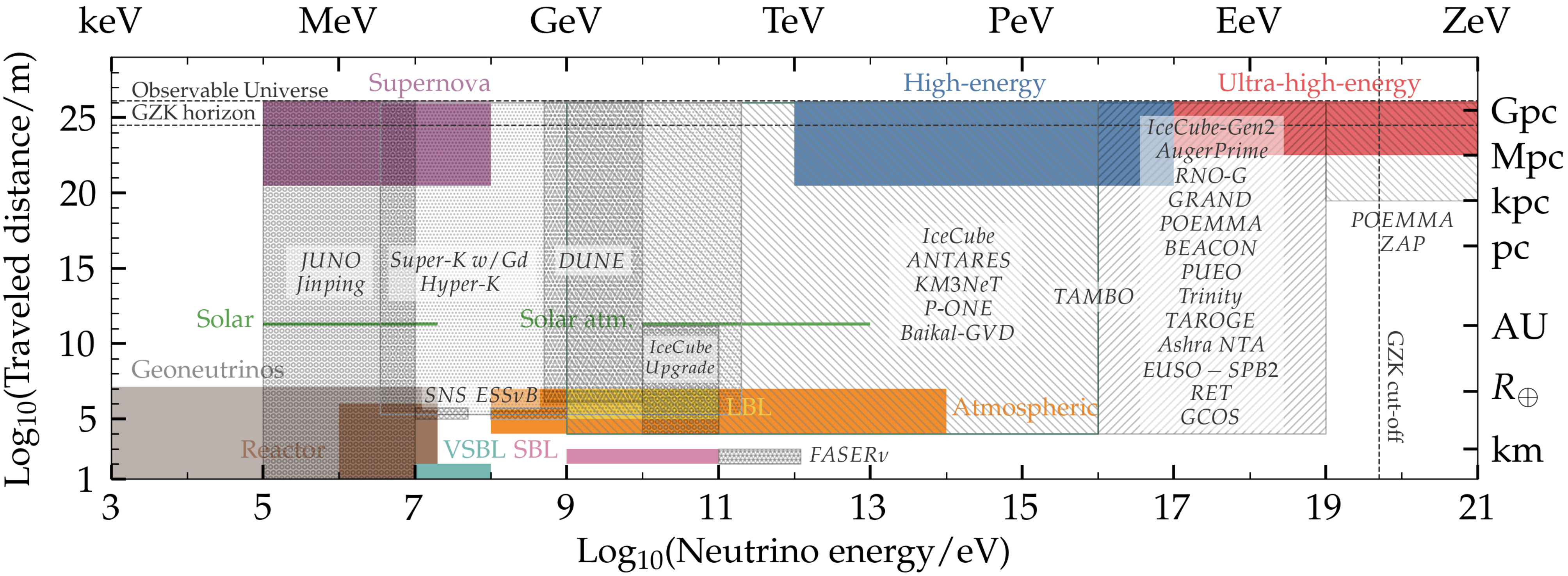

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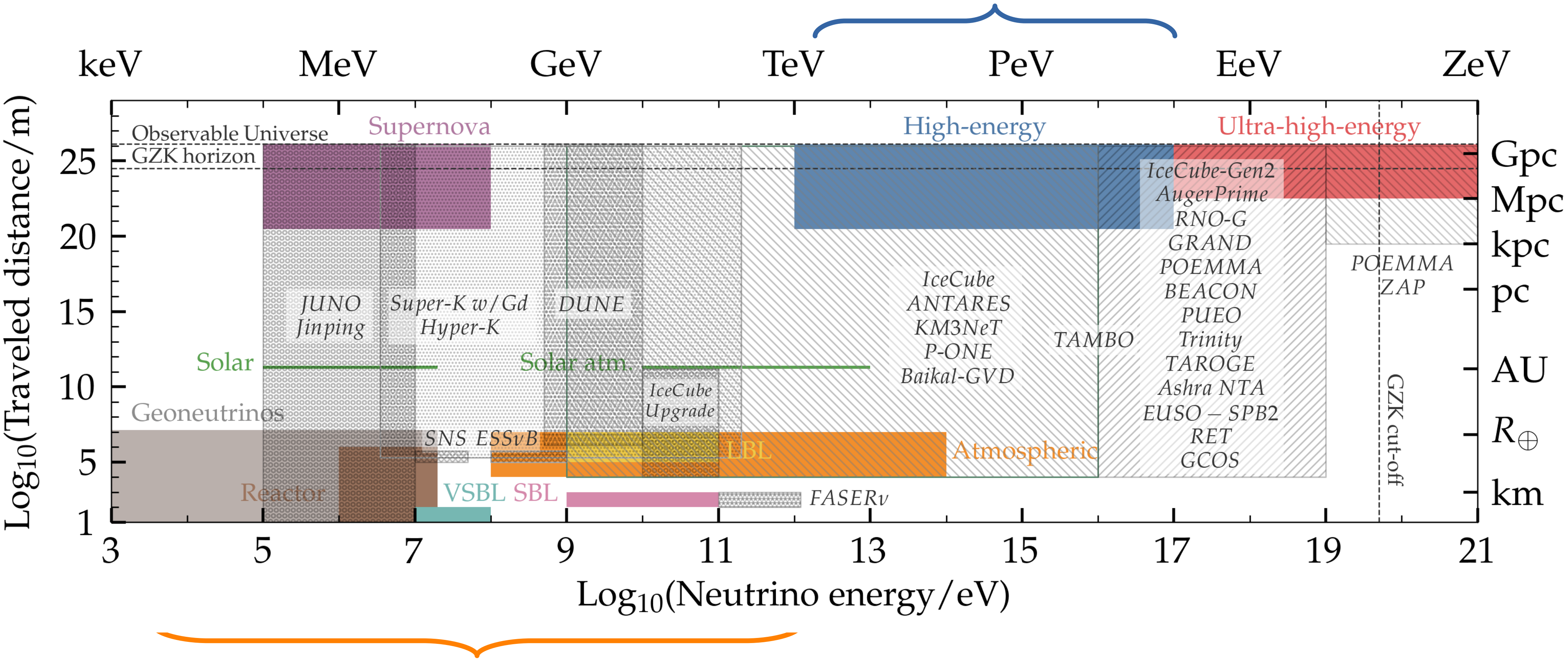

Synergies with lower energies

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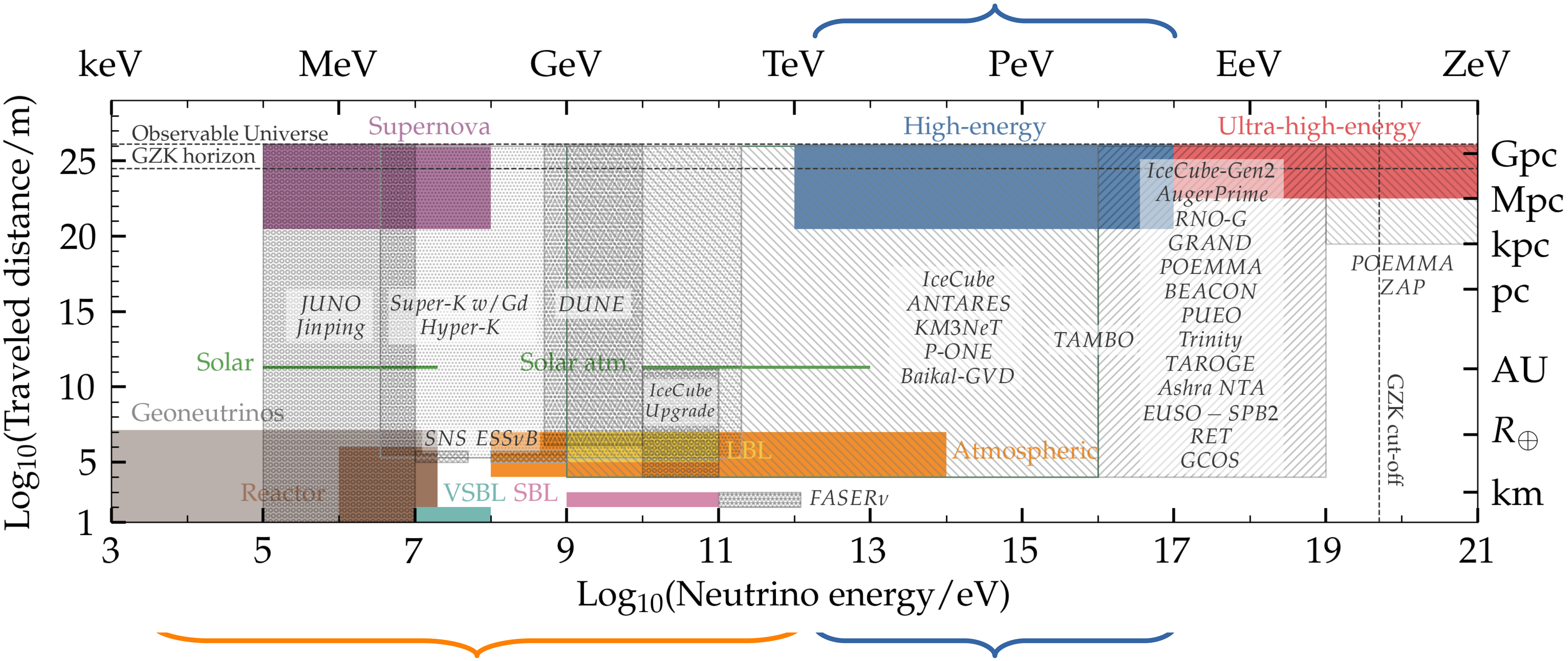

Synergies with lower energies

Increase TeV–PeV
ν statistics

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

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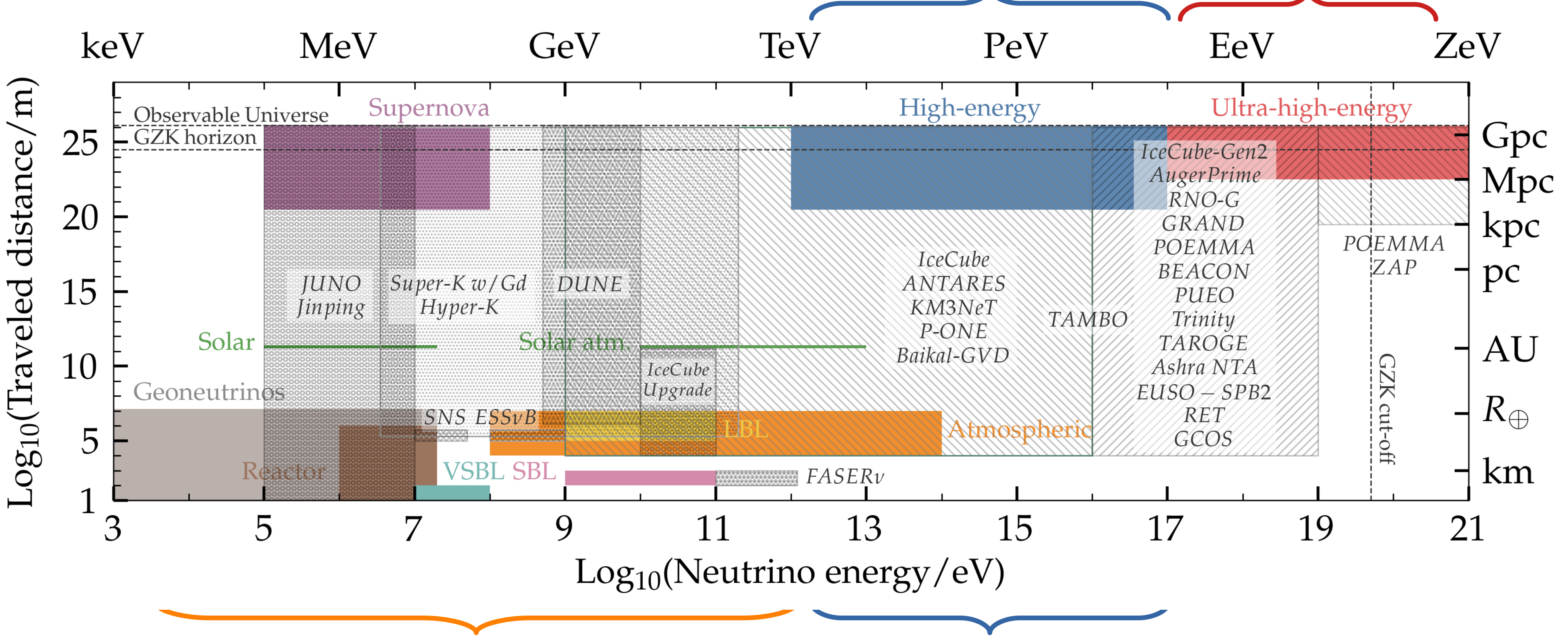
Predicted in 1969
by Berezinksy



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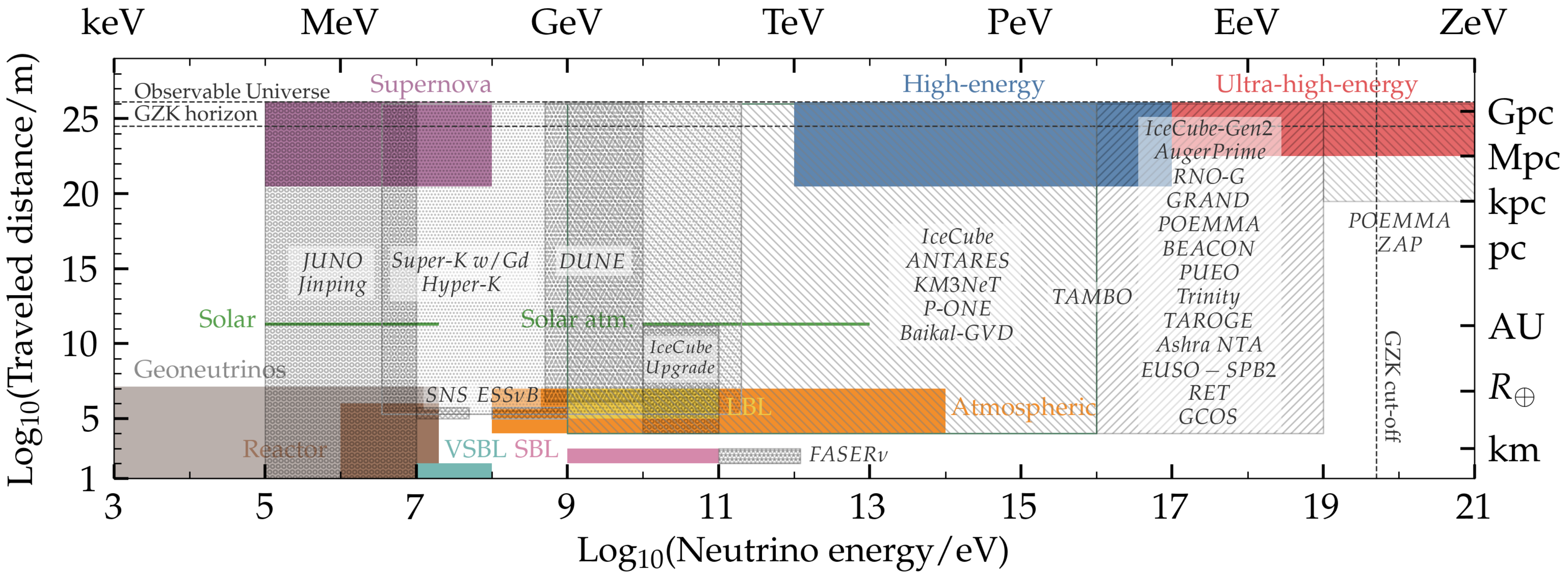

Synergies with lower energies

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Discover > EeV ν

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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

I.

The story so far

Making high-energy astrophysical neutrinos: a toy model

(or $p + p$)

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

Making high-energy astrophysical neutrinos: a toy model

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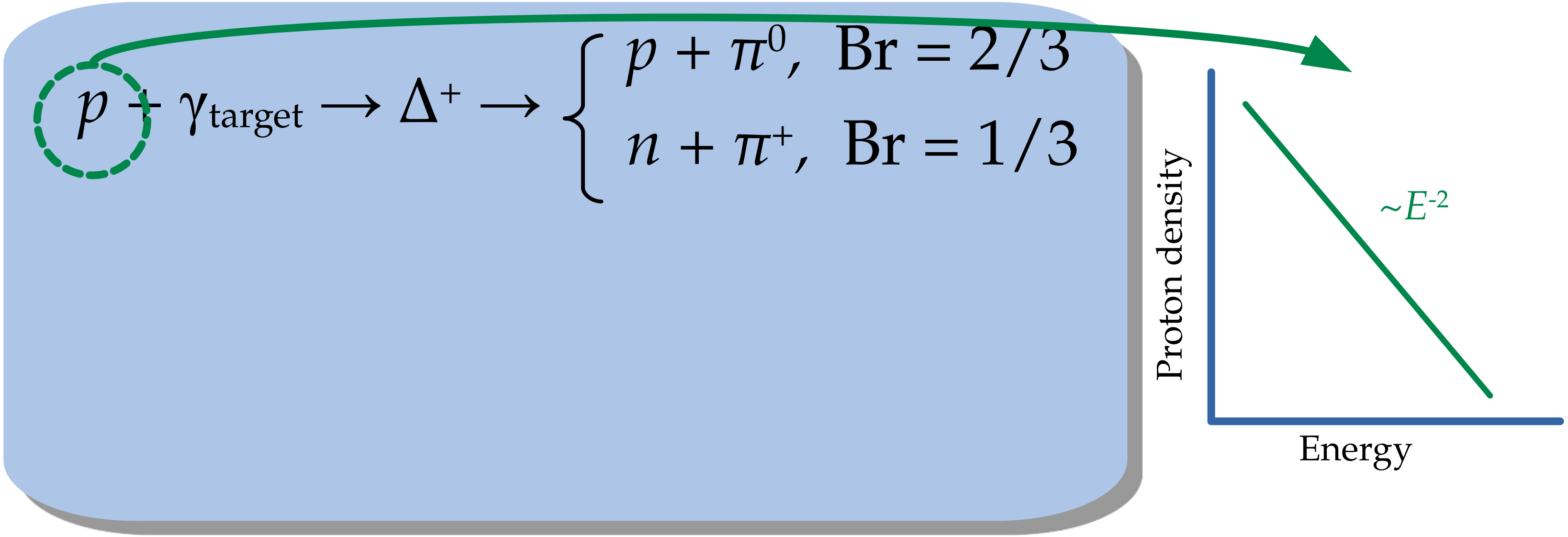

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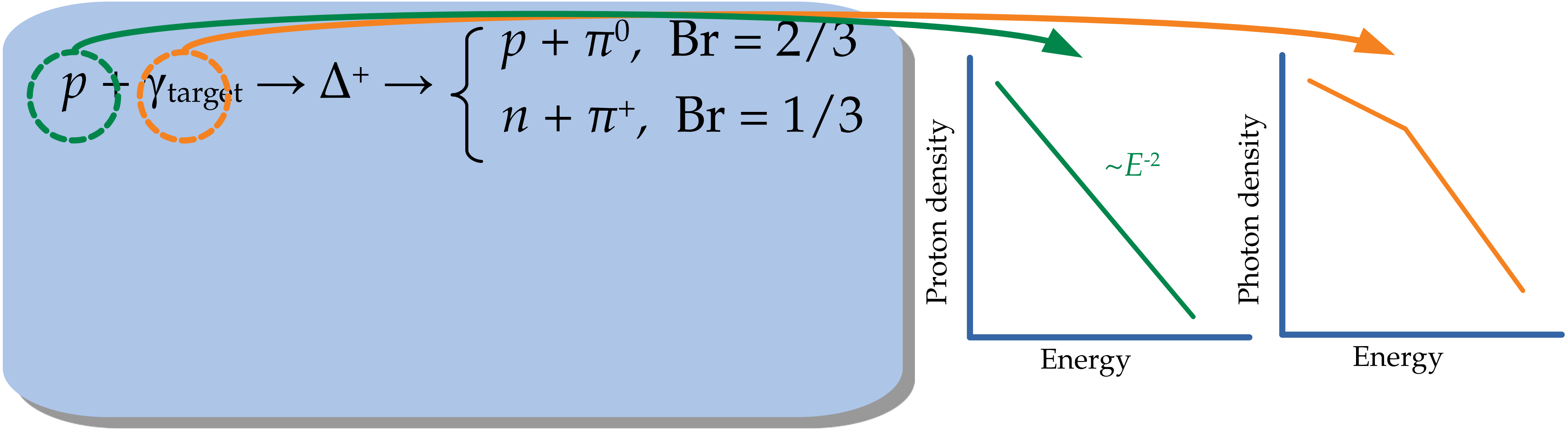

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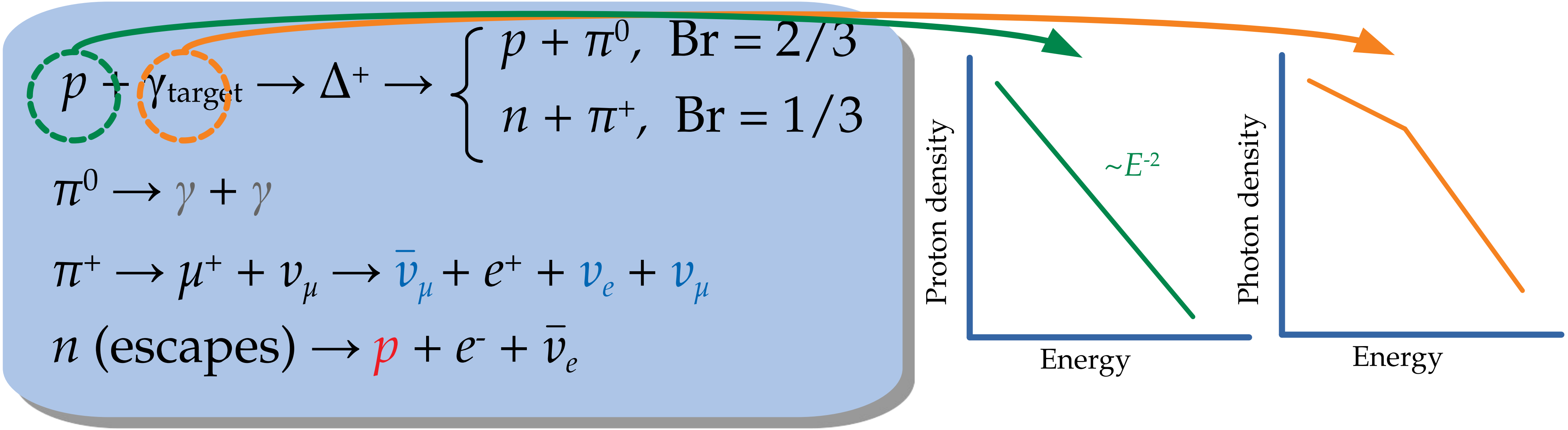
Making high-energy astrophysical neutrinos: a toy model

(or $p + p$)



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

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

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

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

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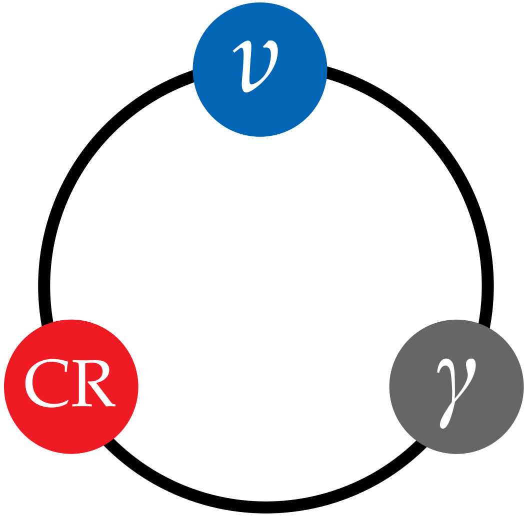
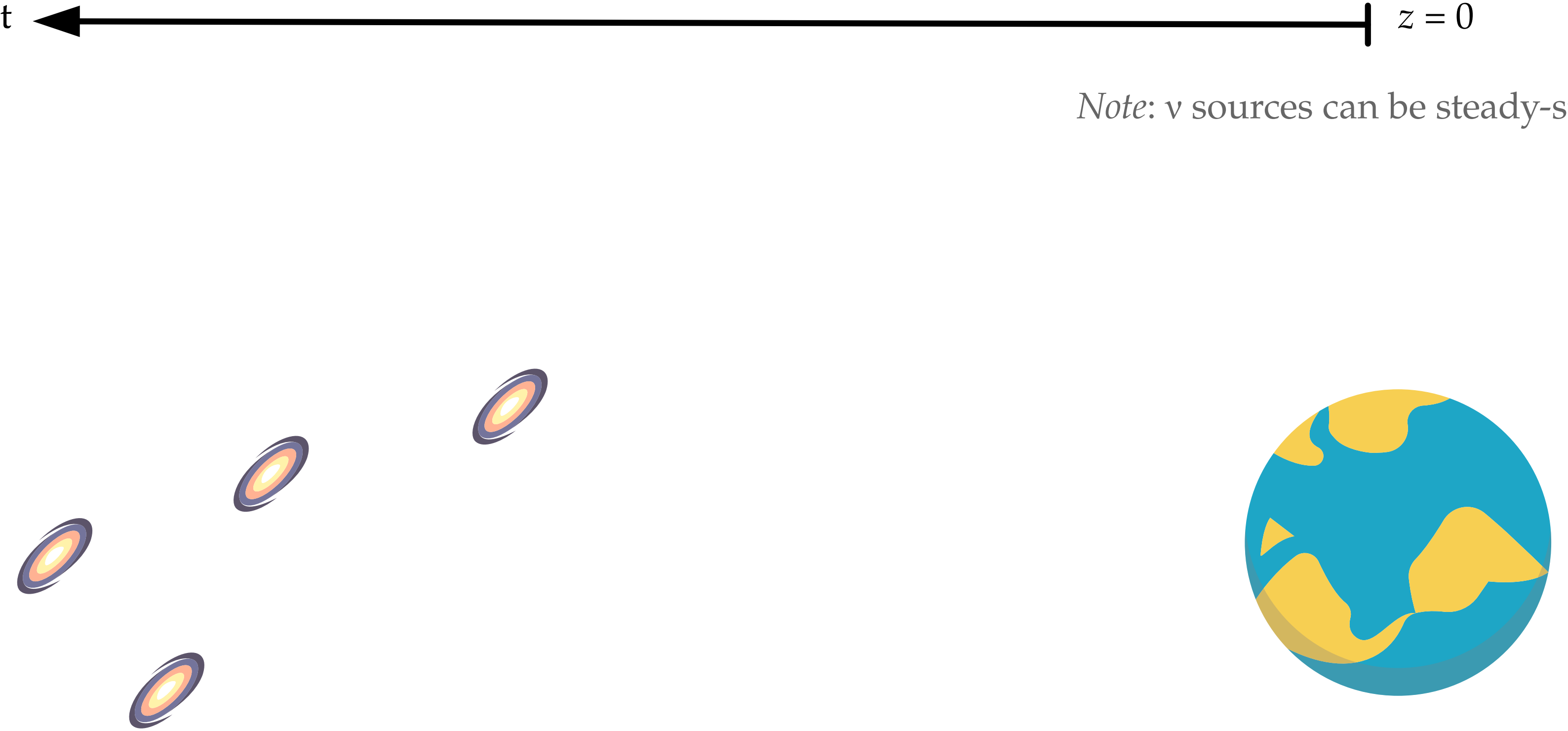


Neutrino energy = Proton energy / 20

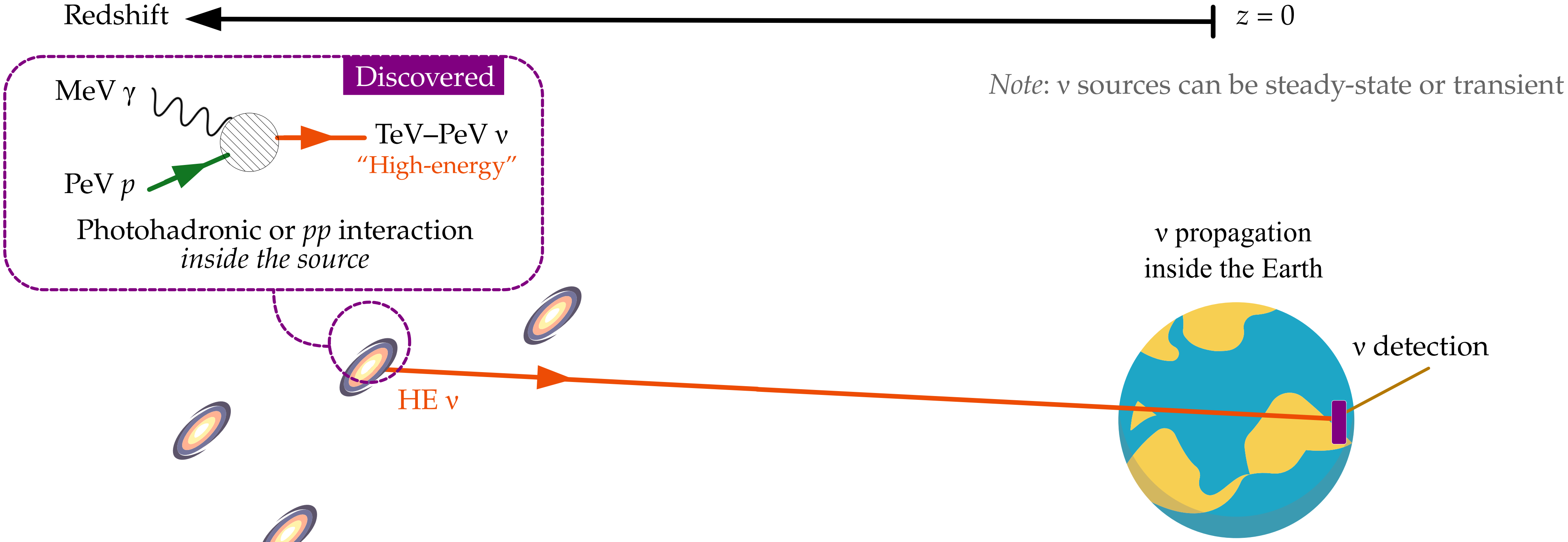
Gamma-ray energy = Proton energy / 10



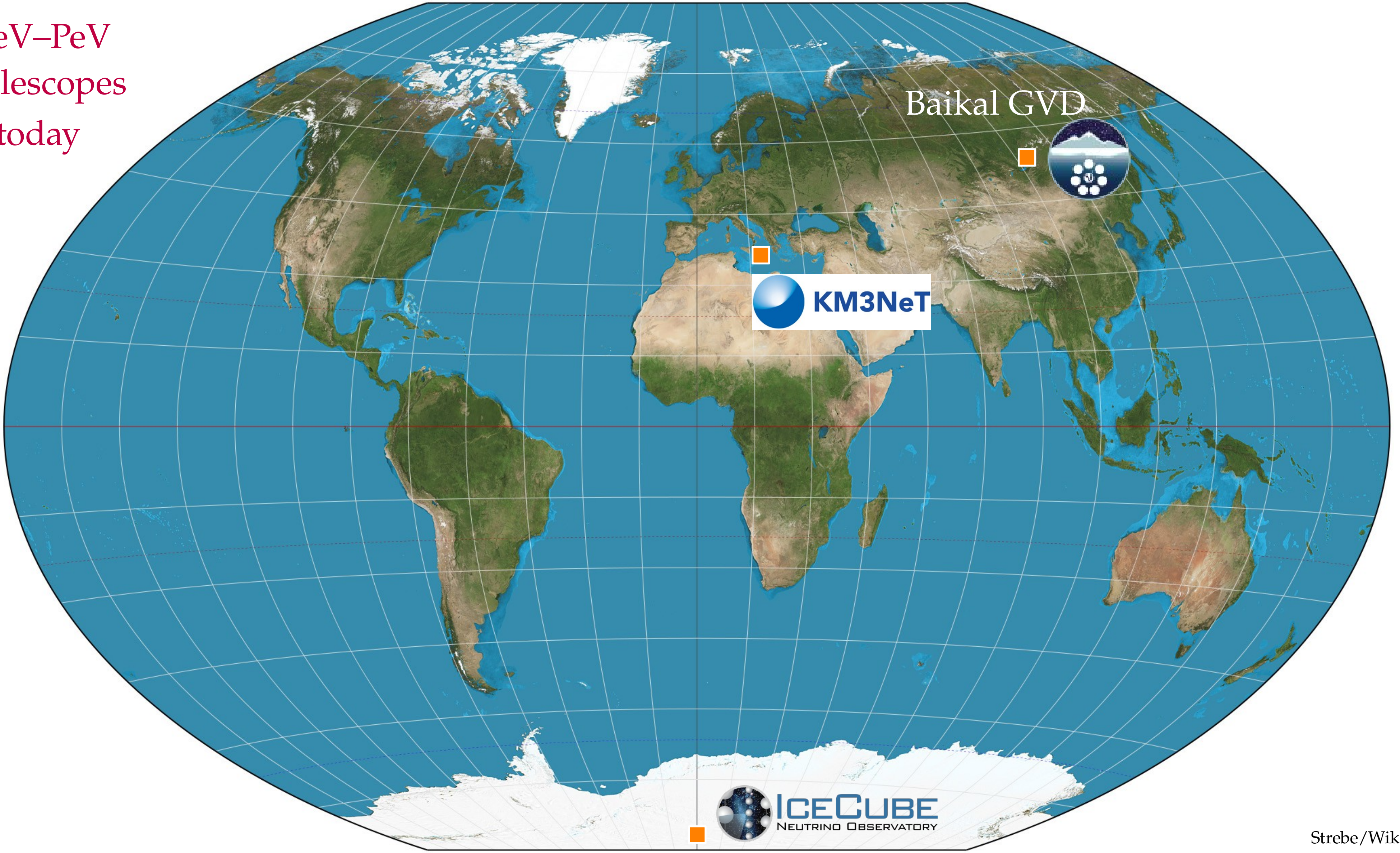
Redshift

$z = 0$

Note: ν sources can be steady-state or transient

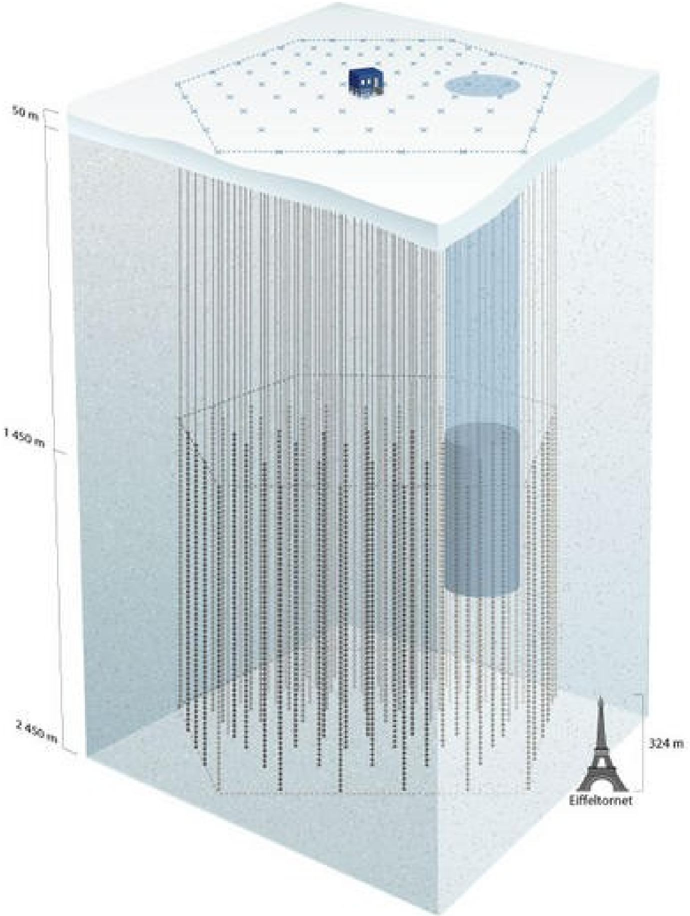

Redshift
$z = 0$
Discovered
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or *pp* interaction
inside the source
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν

TeV–PeV ν telescopes today



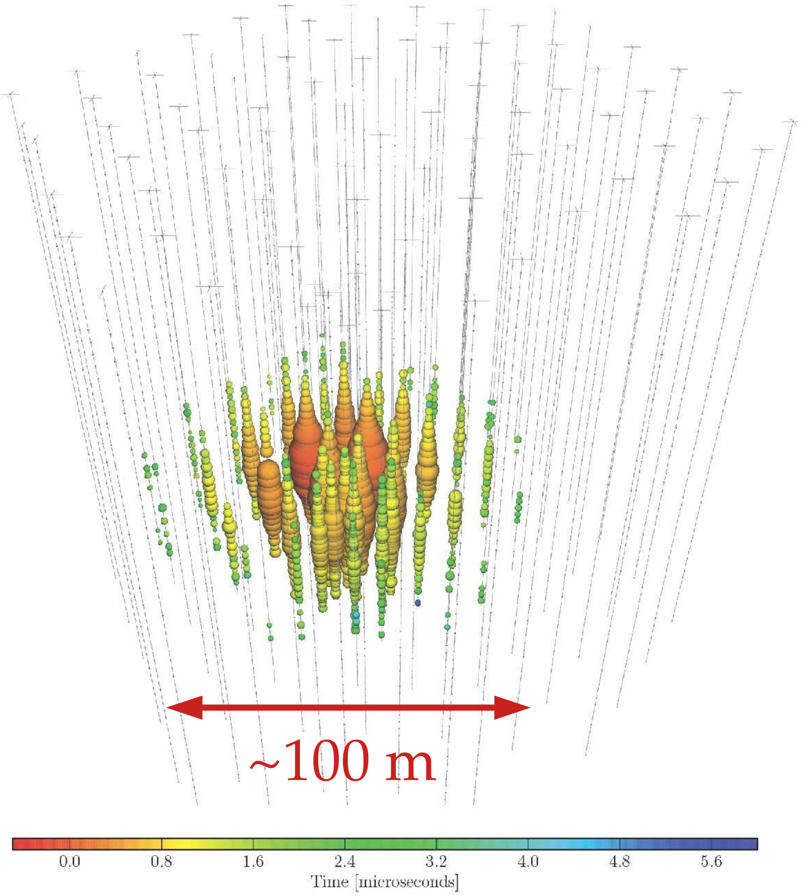
Strebe/Wikipedia

IceCube – What is it?



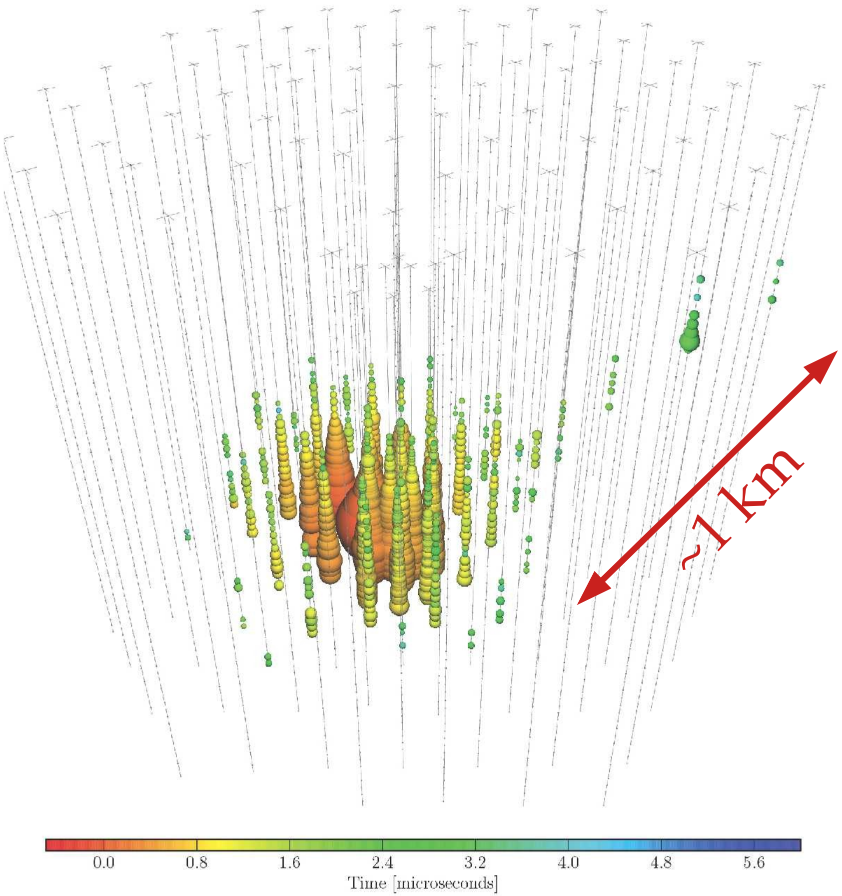
- Km^3 in-ice Cherenkov detector in Antarctica
- $>$ 5000 PMTs at 1.5–2.5 km of depth
- Sensitive to neutrino energies $>$ 10 GeV

Shower
(mainly from ν_e and ν_τ)

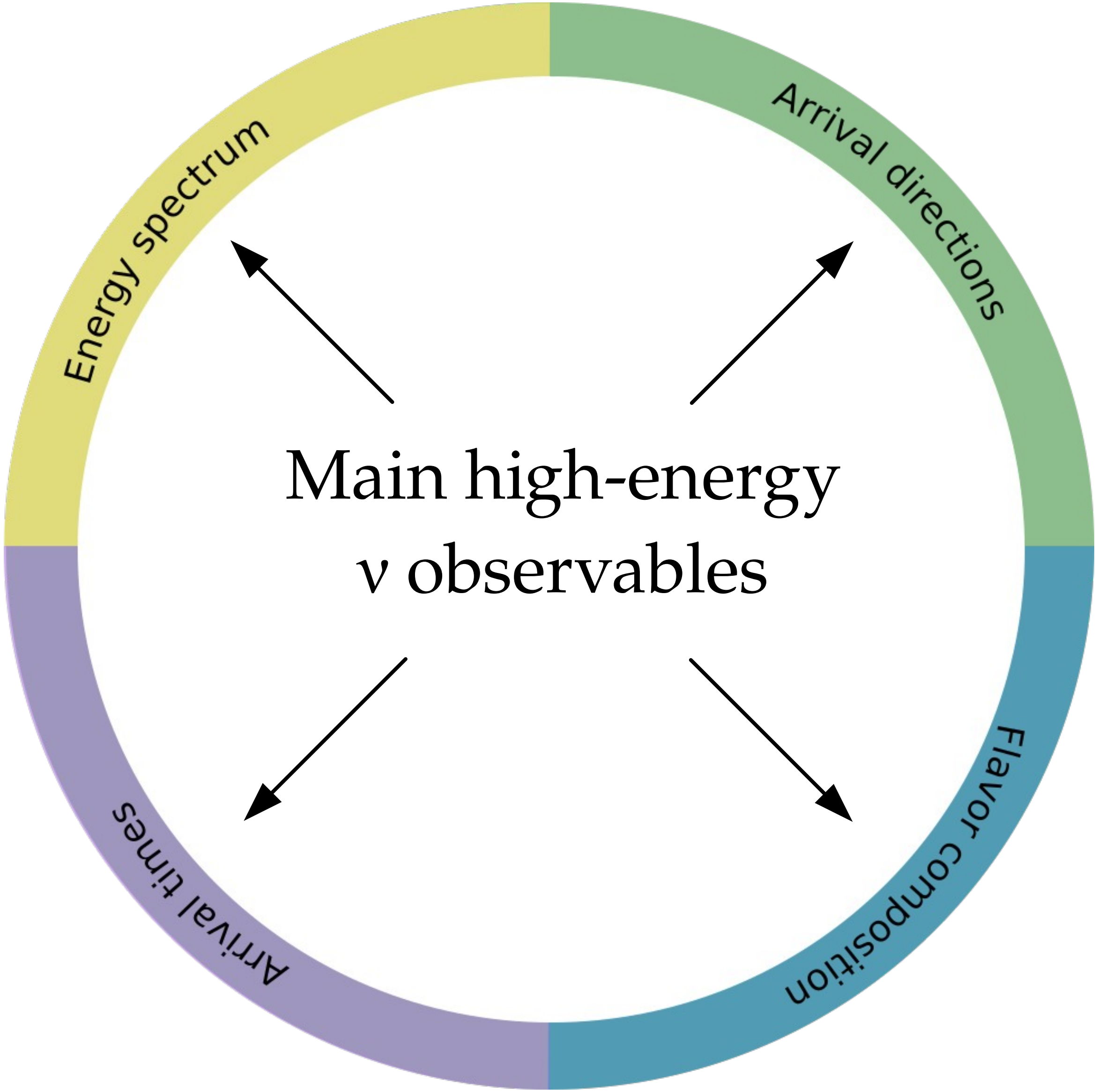


Poor angular resolution: ~10°

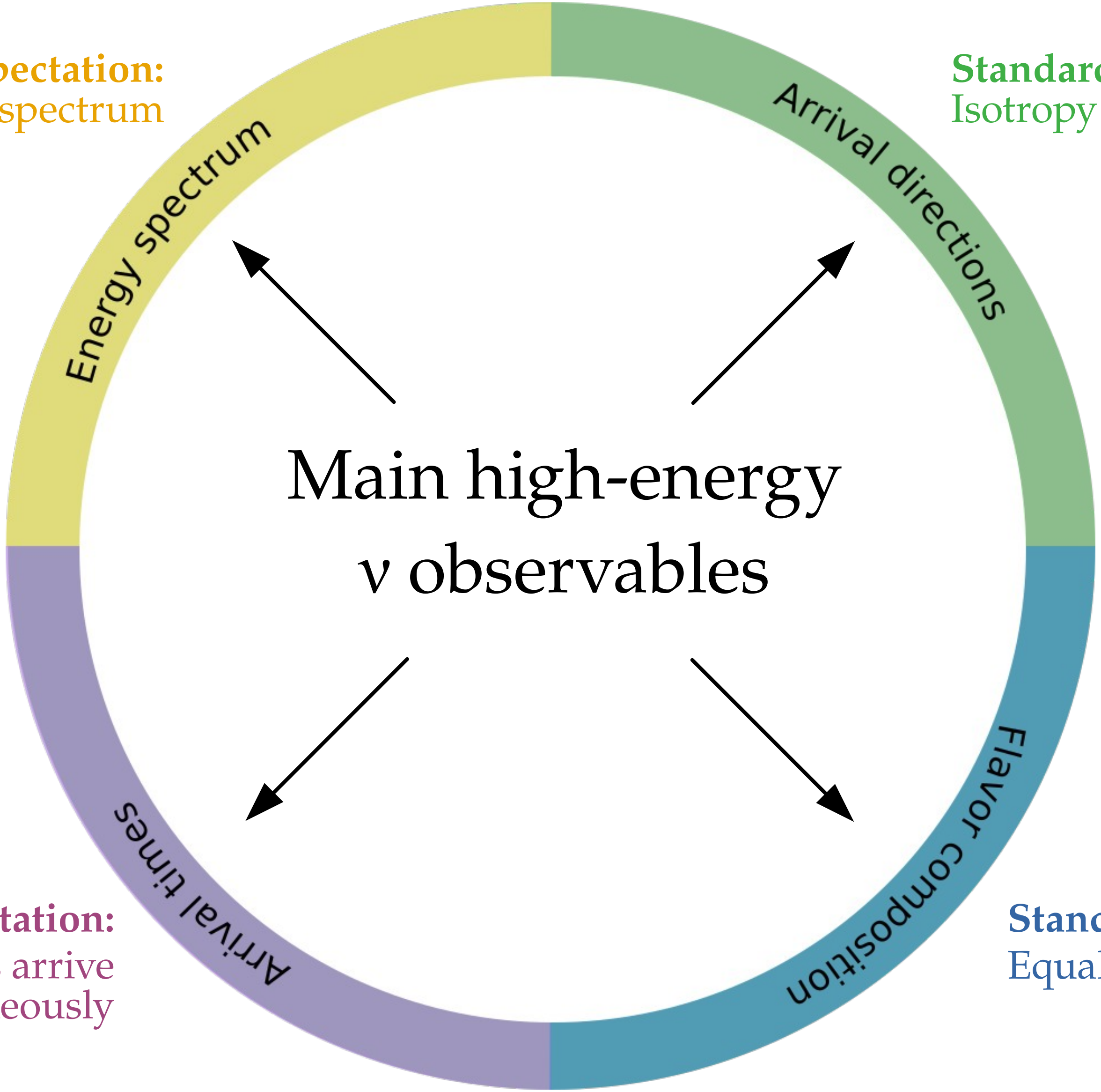
Track
(mainly from ν_μ)



Angular resolution: < 1°



Main high-energy
ν observables



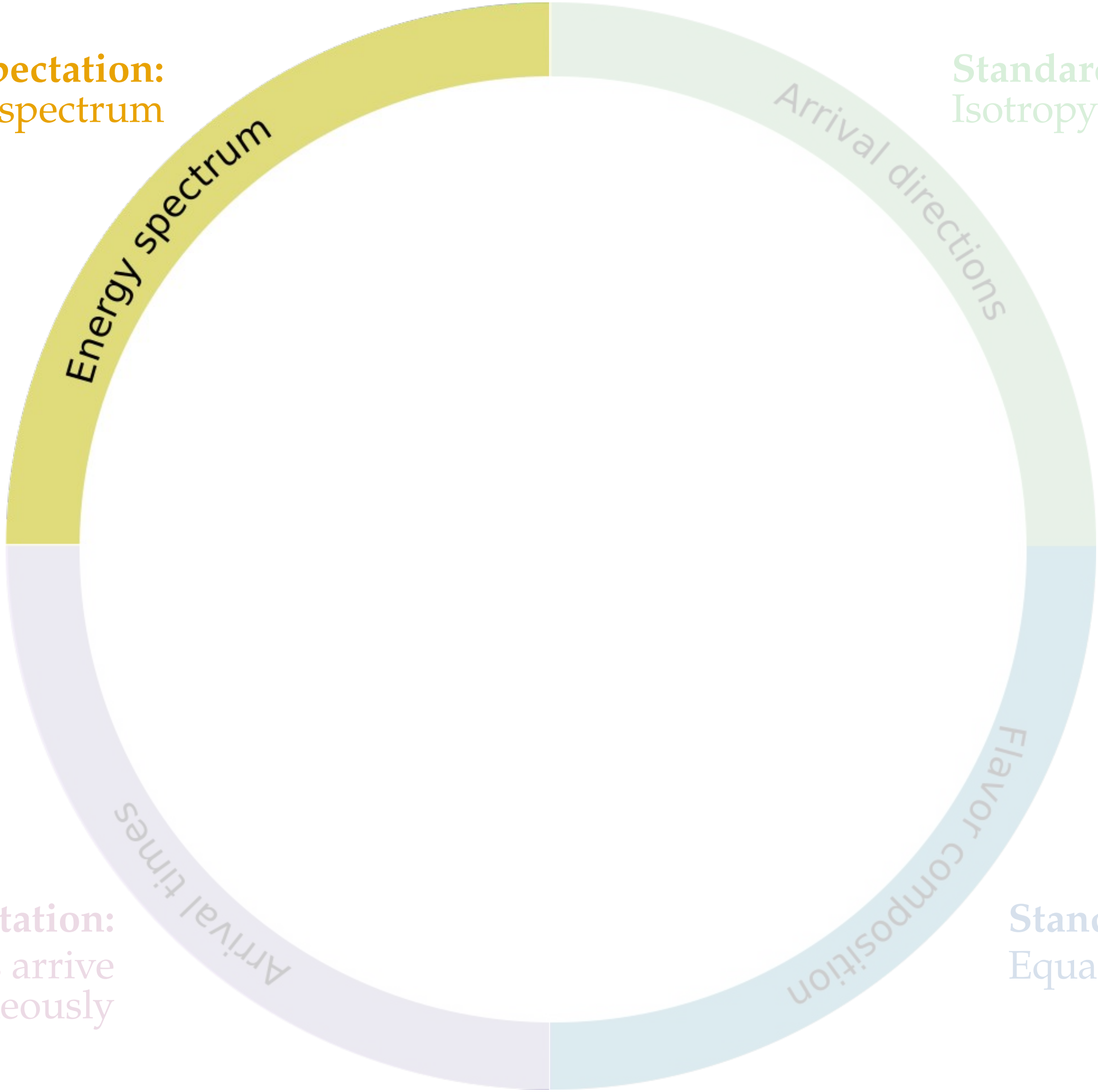
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Main high-energy
ν observables

Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ



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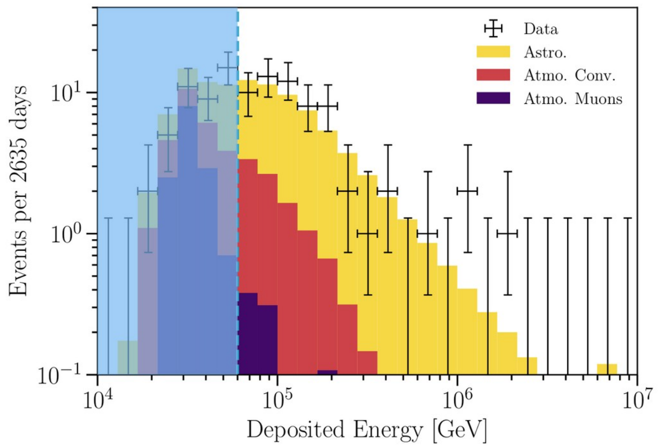
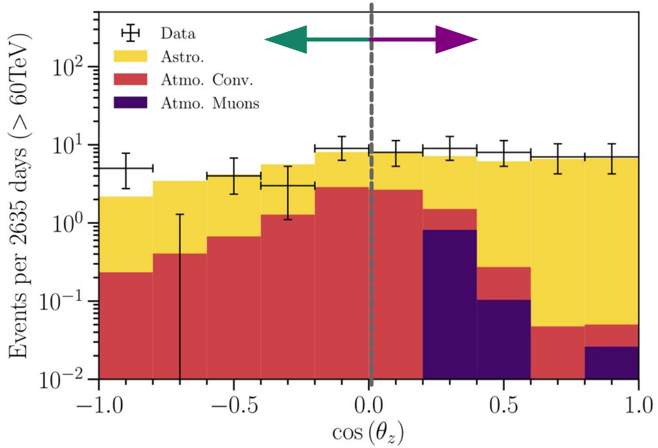
Neutrino energy spectrum (7.5 yr)

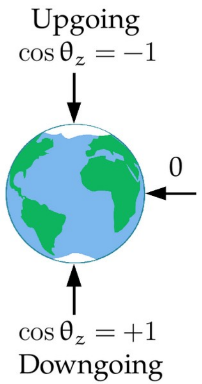
100+ contained events above 60 TeV:



ν attenuated by Earth

Atm. ν and μ vetoed





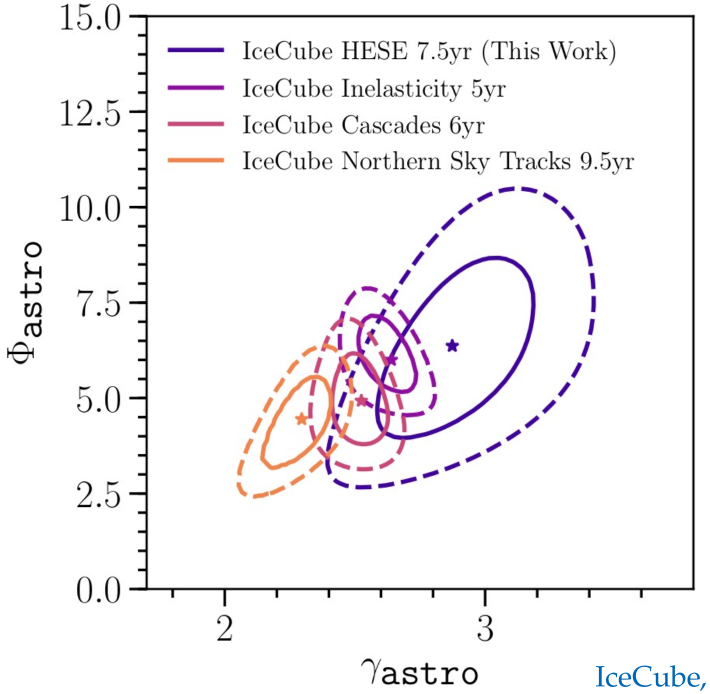
Upgoing
$\cos\theta_z = -1$

0

$\cos\theta_z = +1$
Downgoing

Data is fit well by a single power law:

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



IceCube, 2011.03545

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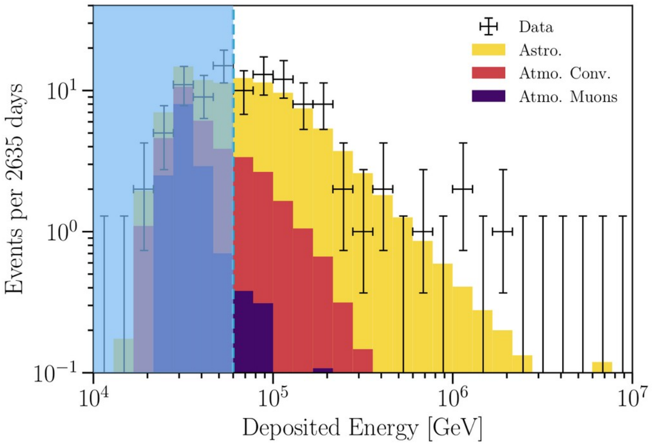

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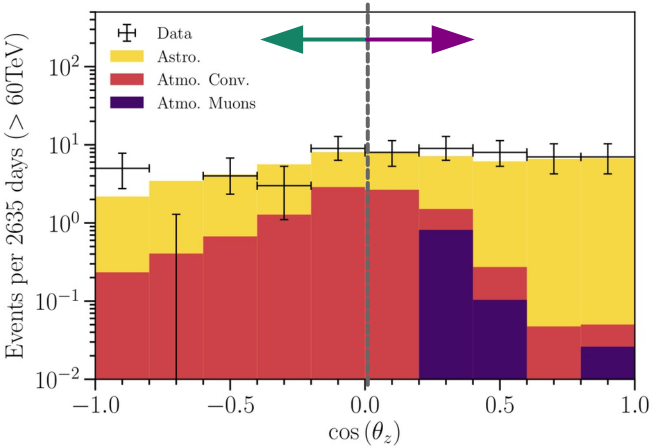

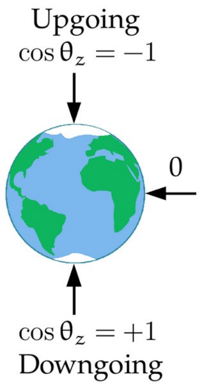

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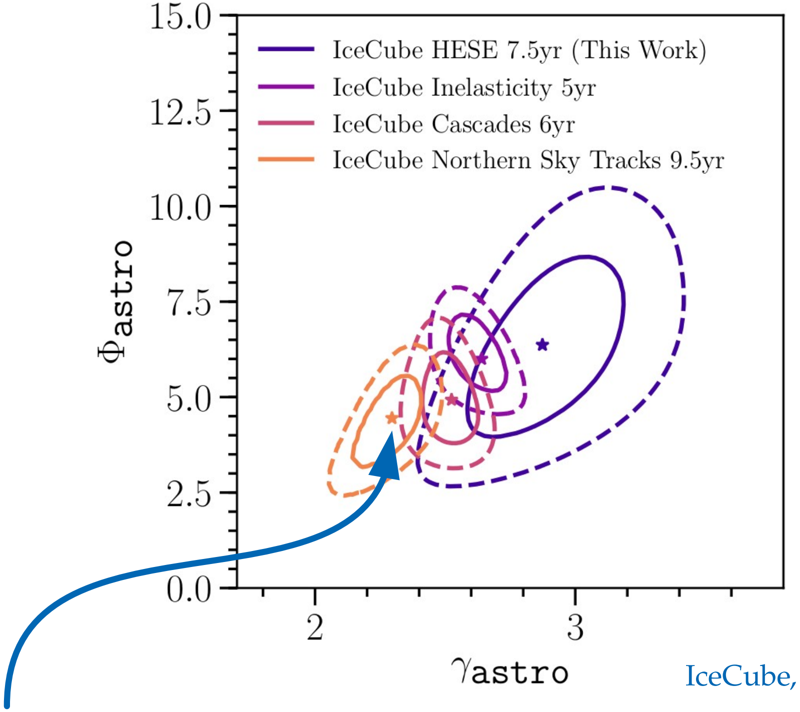
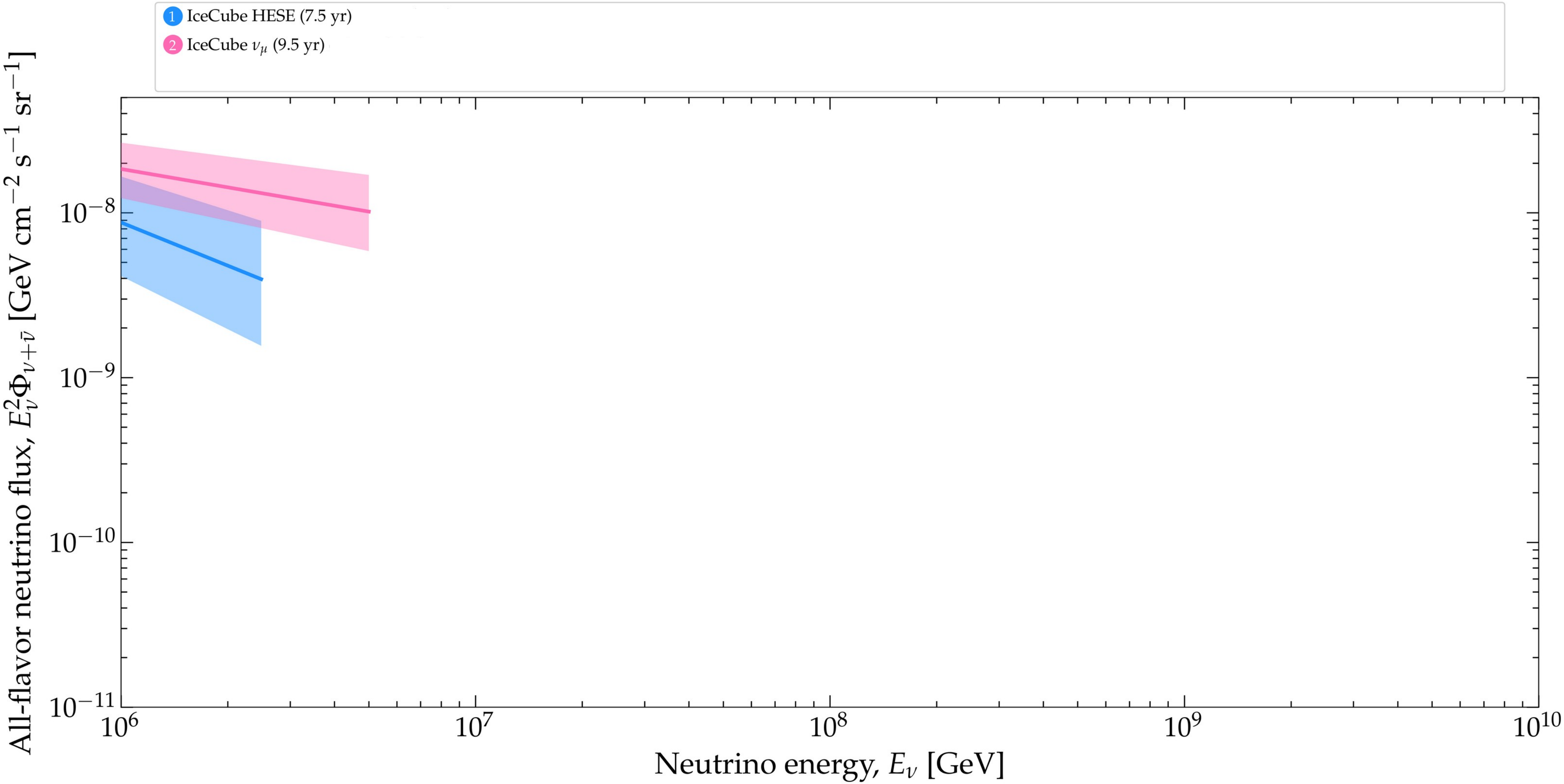


IceCube, 2011.03545

Spectrum looks harder for through-going ν_μ


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

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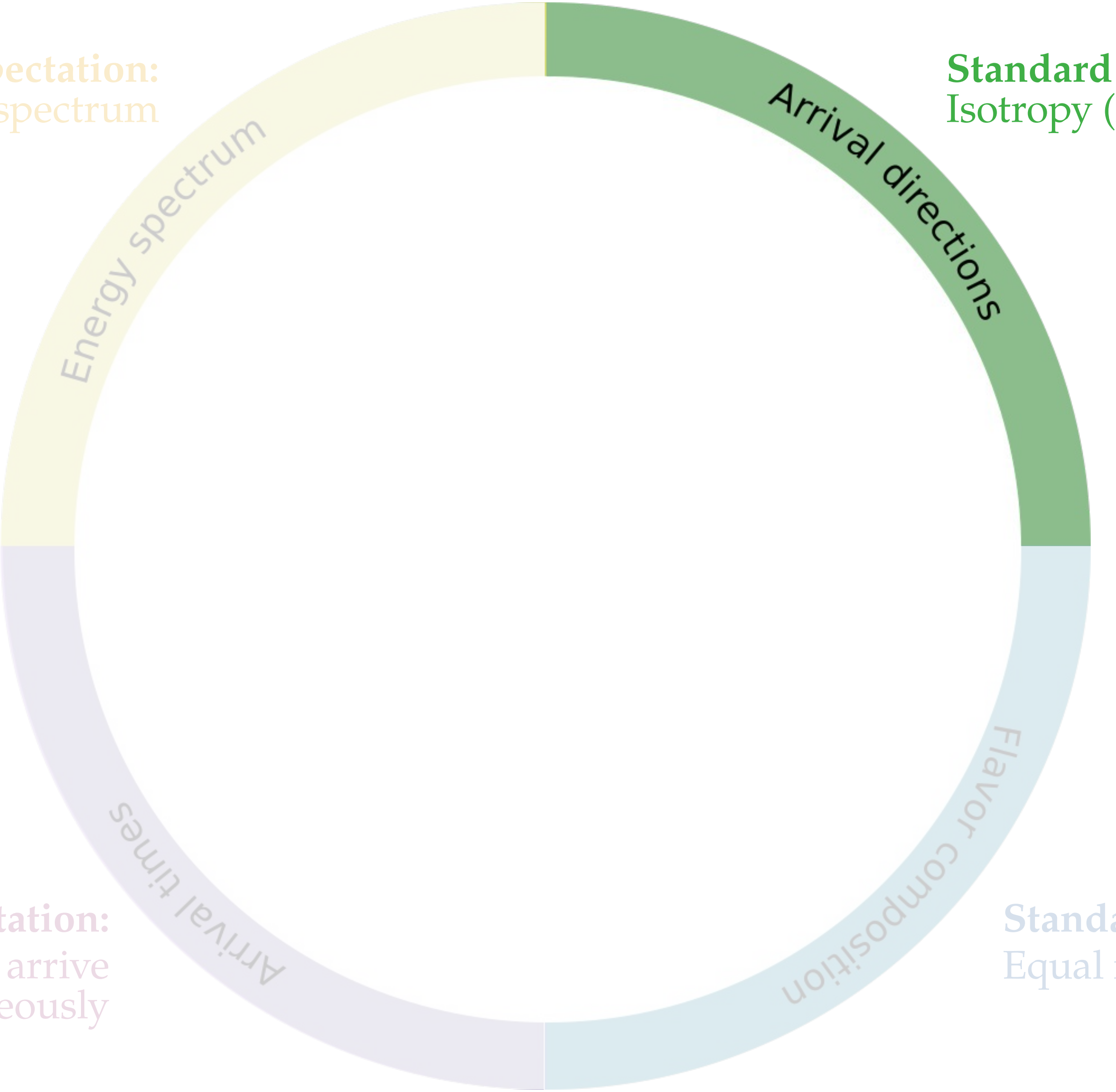

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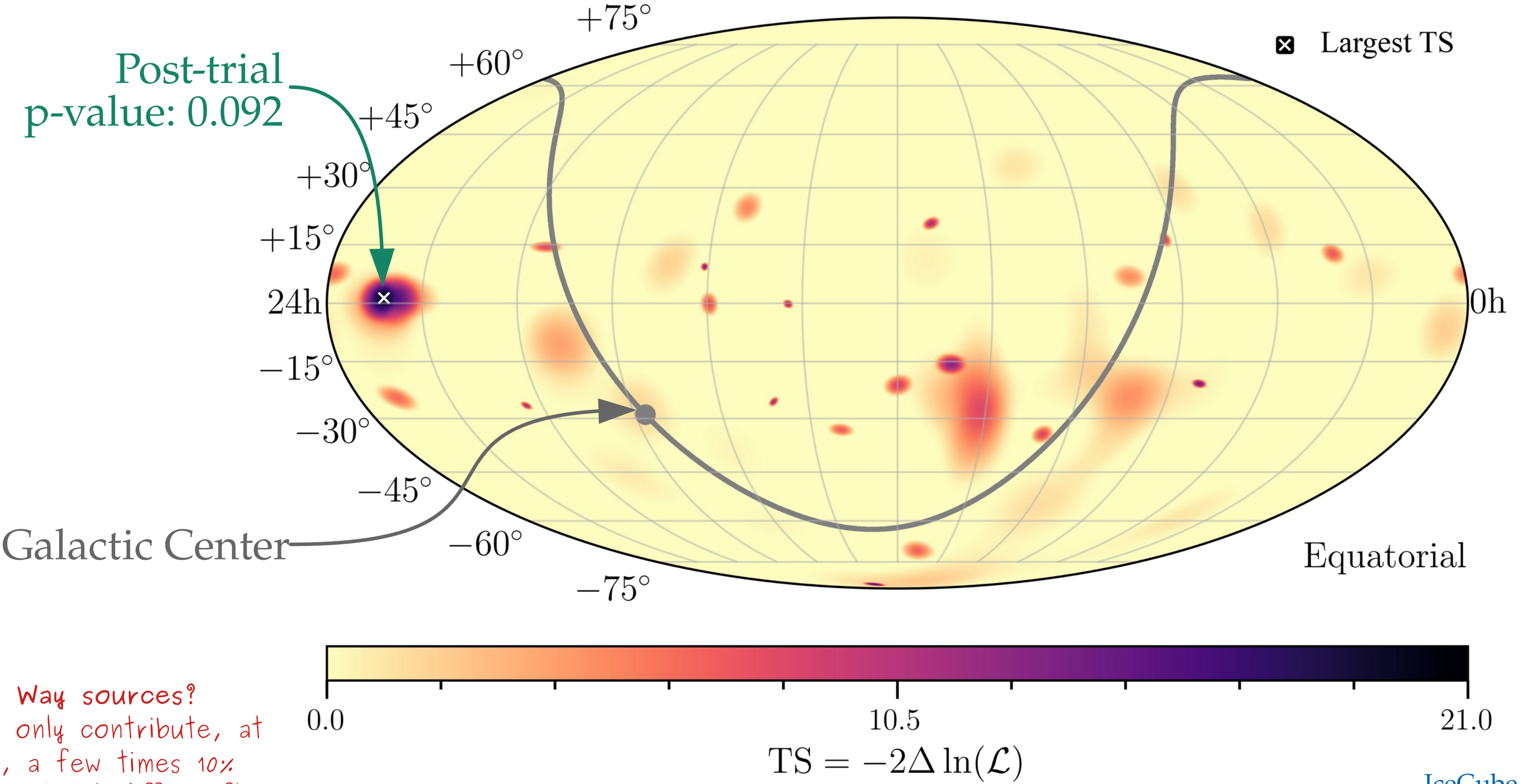
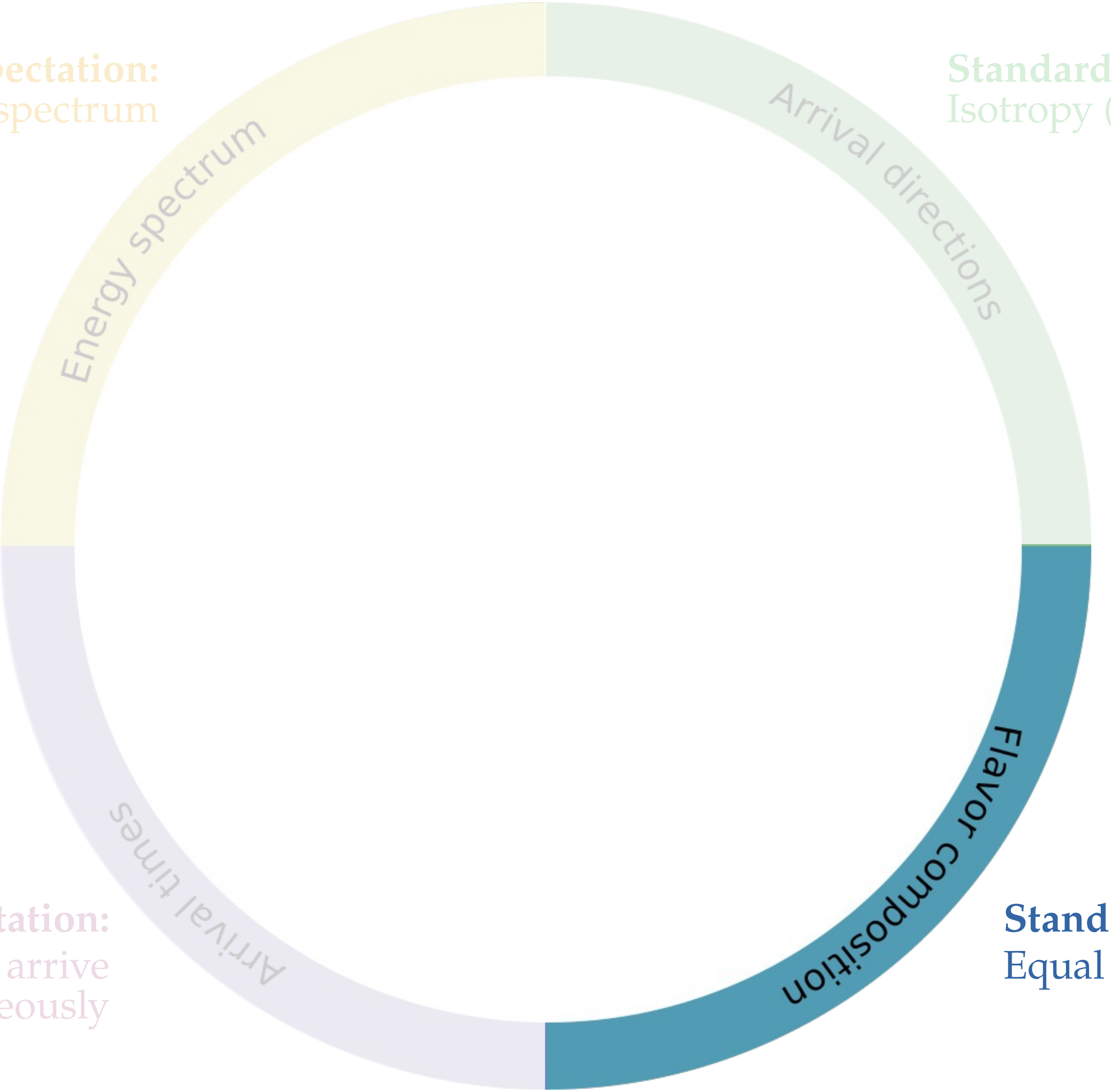
Distribution of arrival directions (7.5 yr)

No significant excess in the neutrino skymap:



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

IceCube, 2011.03545



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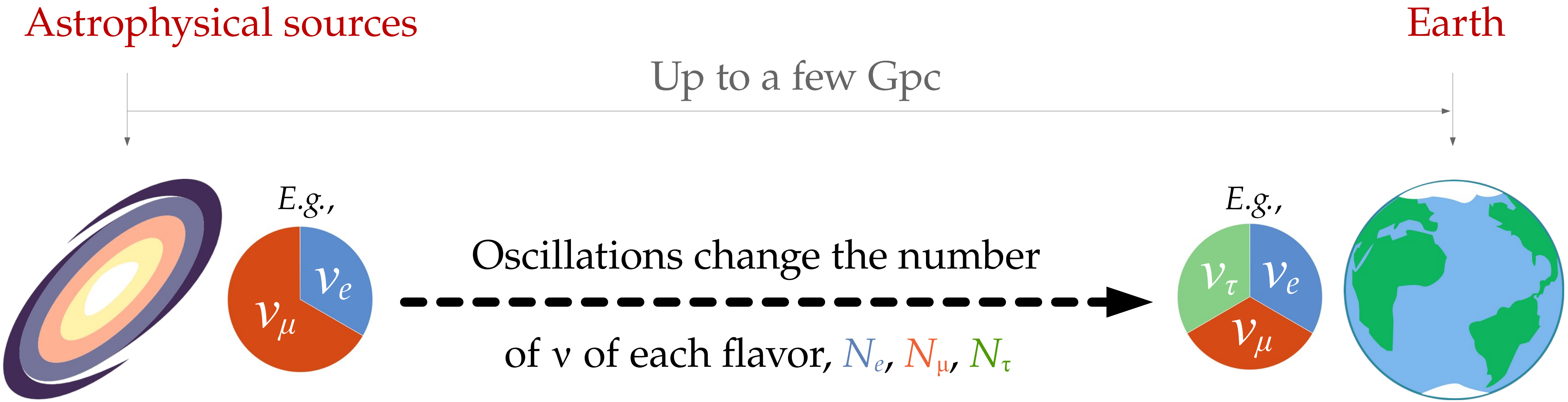


Astrophysical sources

Earth

Up to a few Gpc

Oscillations change the number

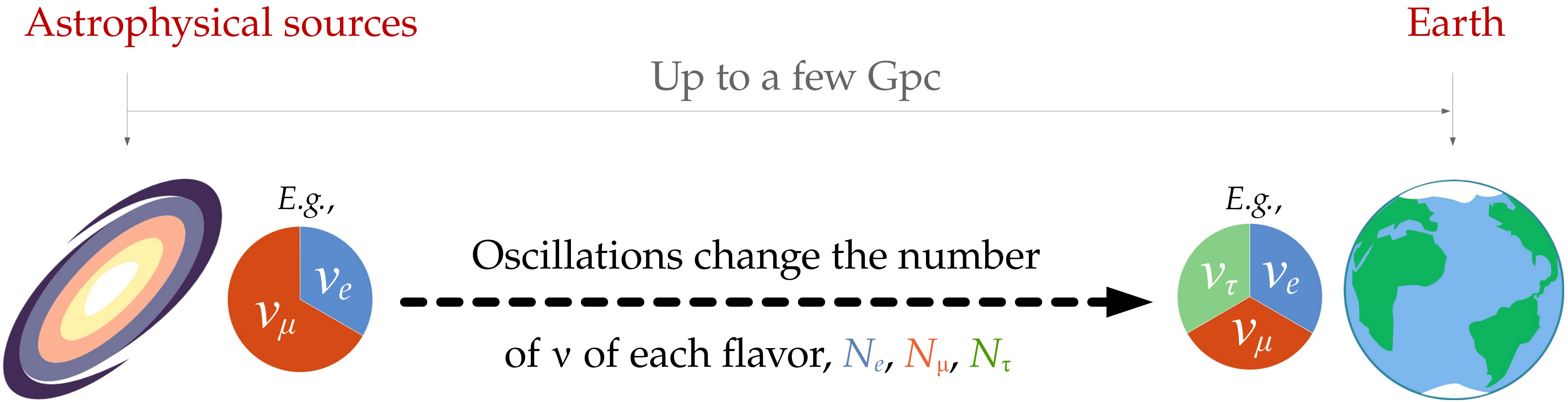
of ν of each flavor, N_e, N_μ, N_τ

Different production mechanisms yield different flavor ratios:

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

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

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



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Standard oscillations
or
new physics

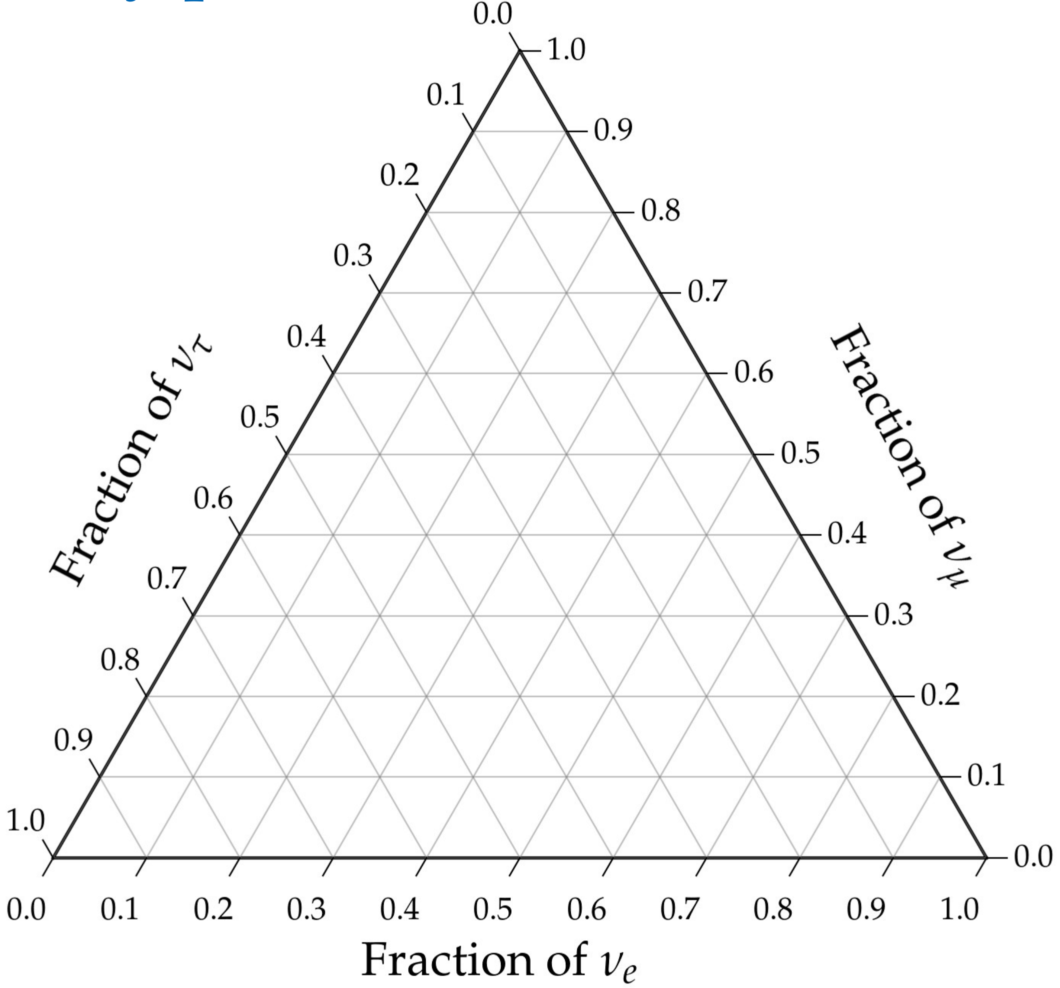
Quick aside: how to read a ternary plot

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

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



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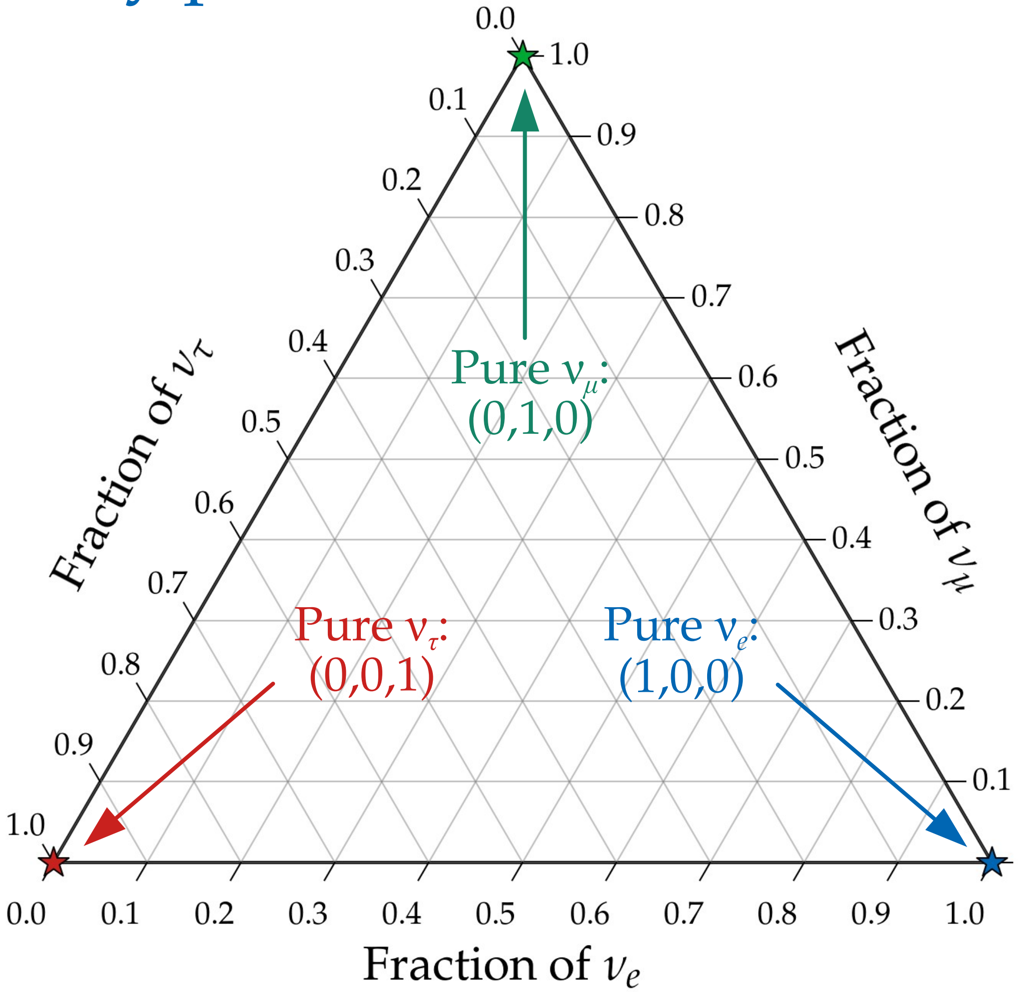

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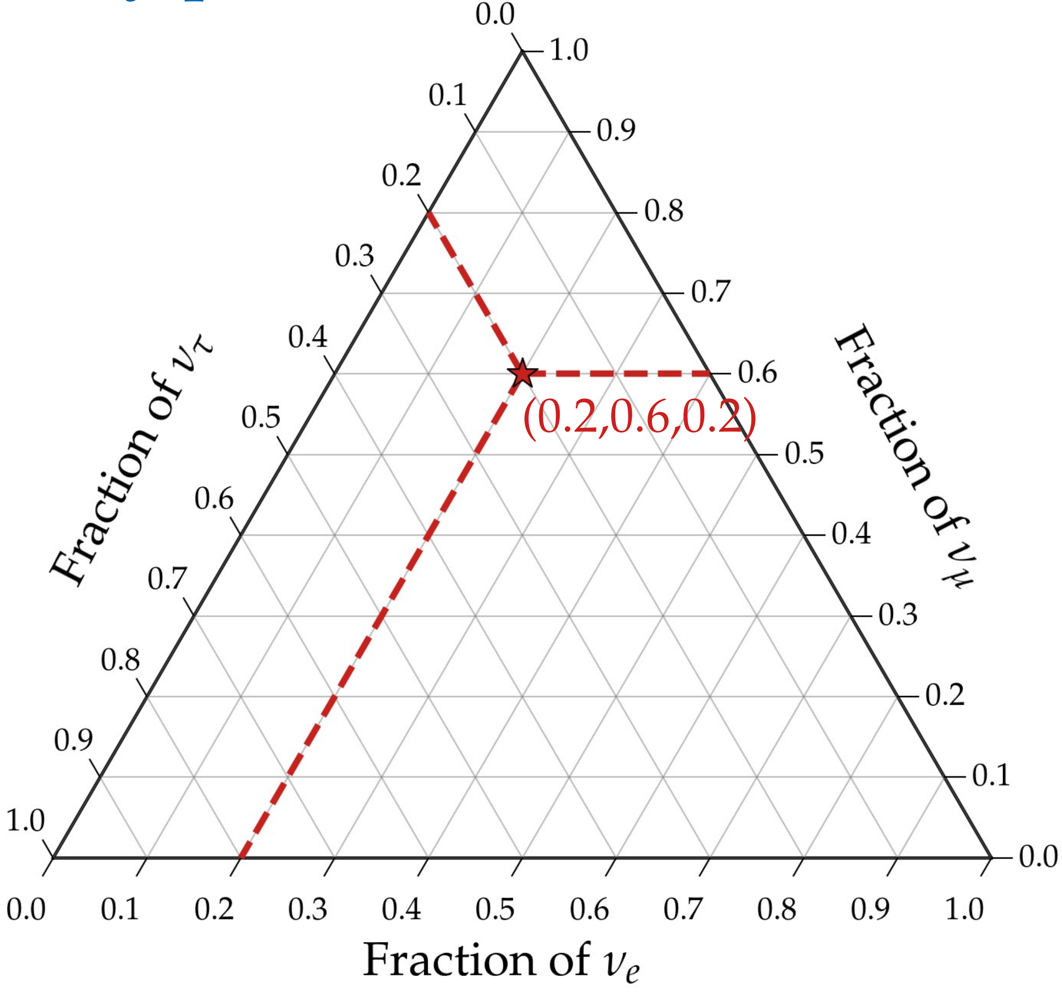

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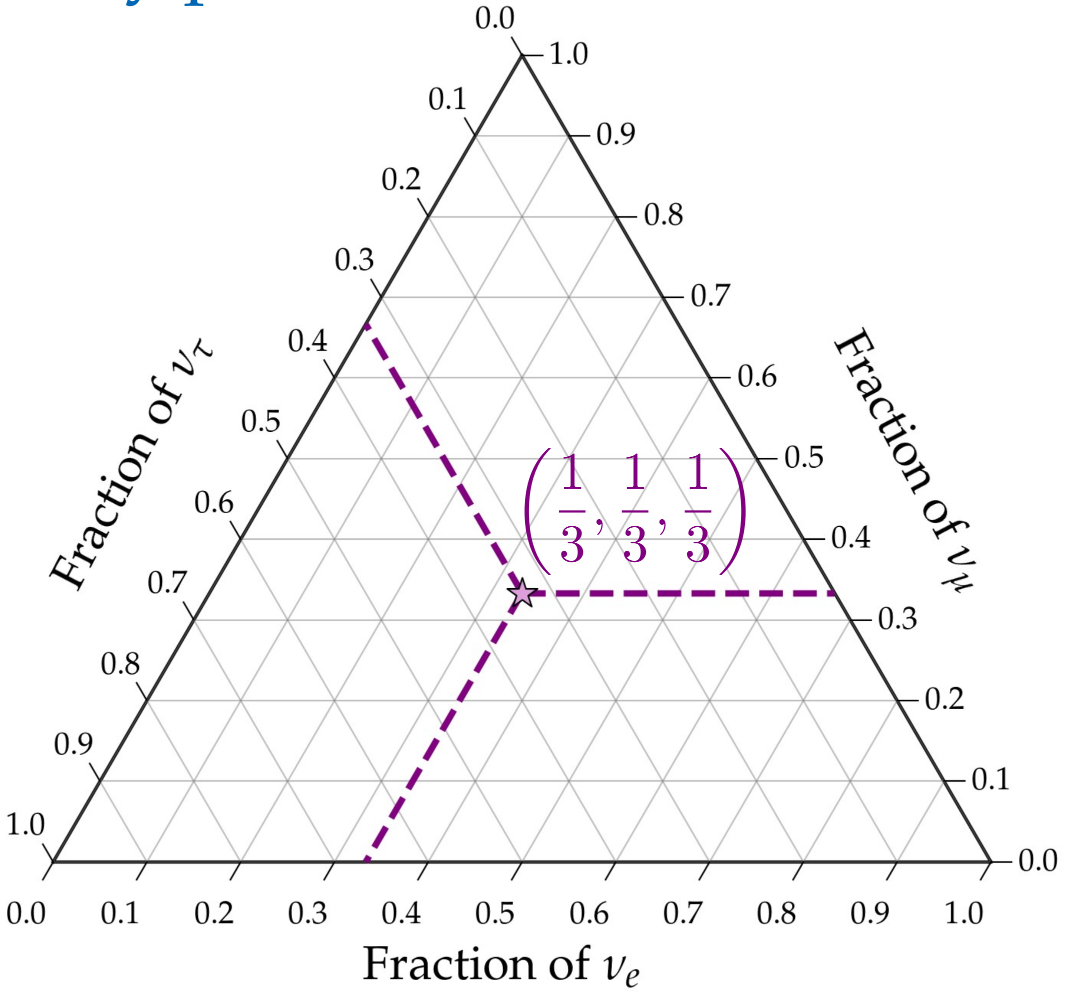

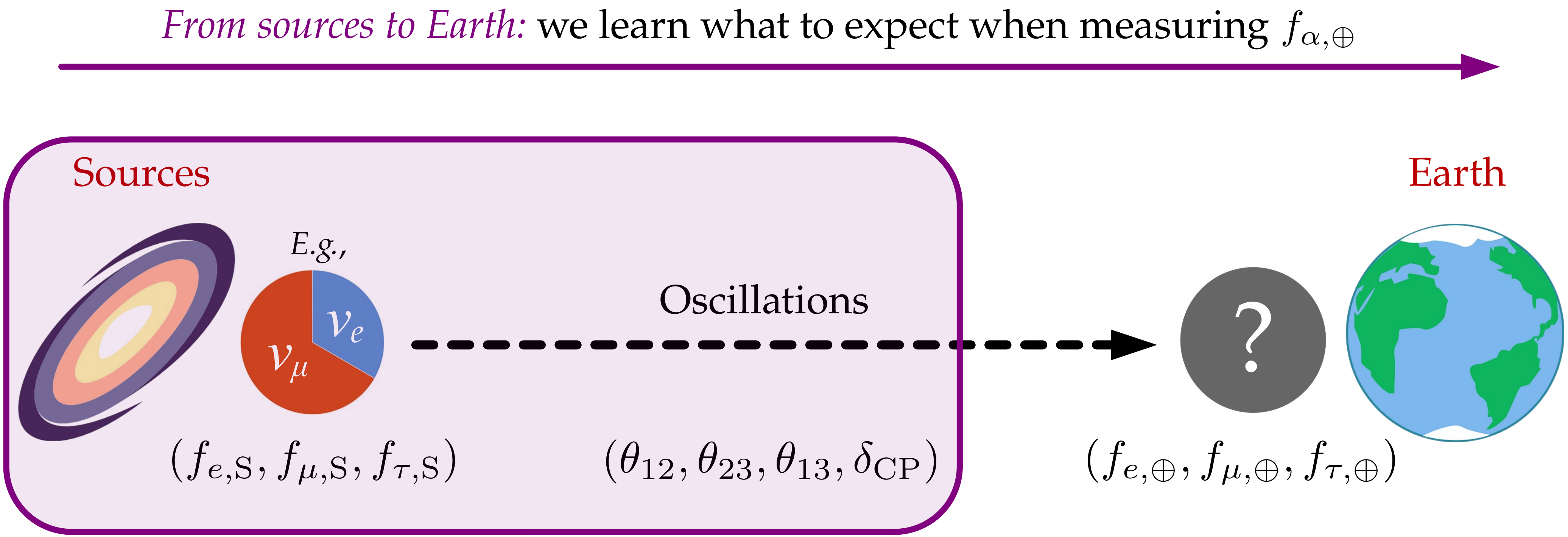

From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$

Sources

E.g.,

ν_e

ν_μ

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

Oscillations

$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$

Earth

?

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

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

$(1/3:2/3:0)_\mathrm{S}$

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

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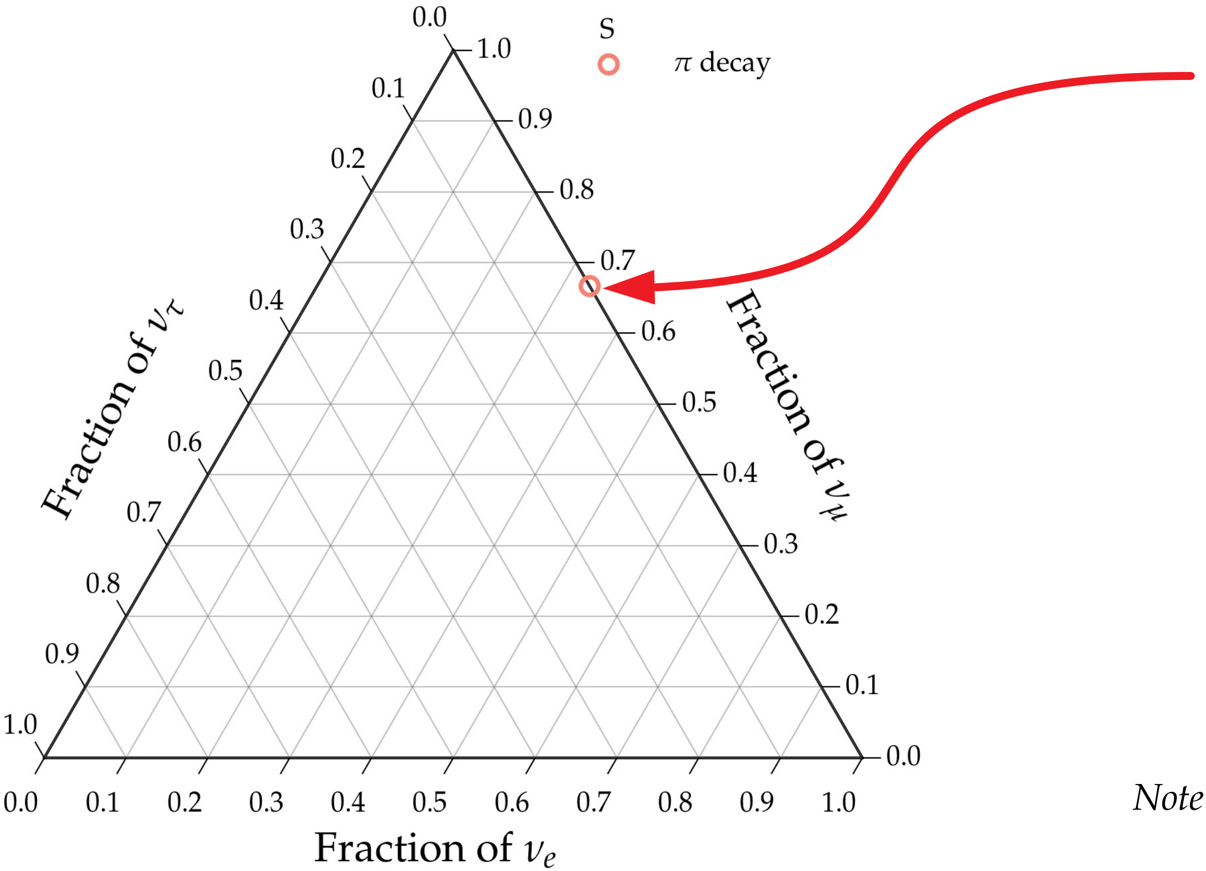

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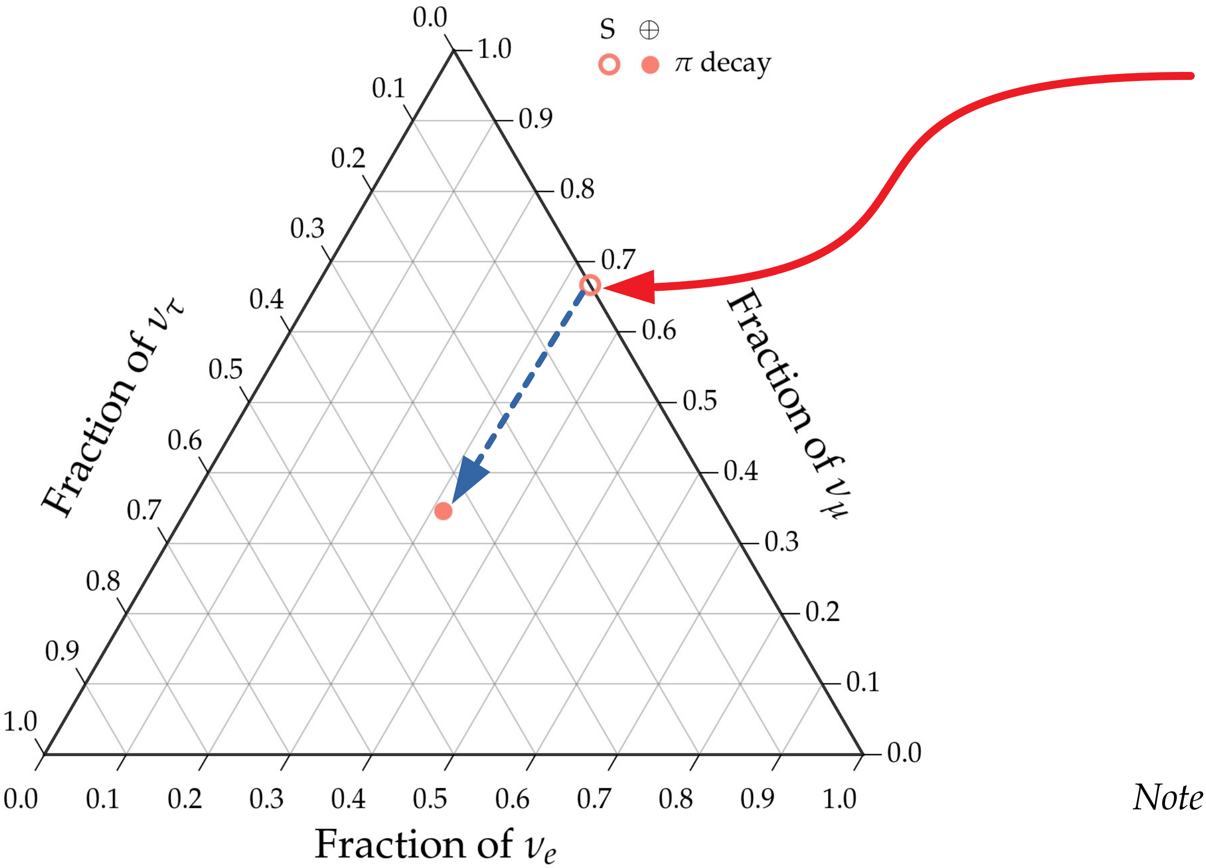

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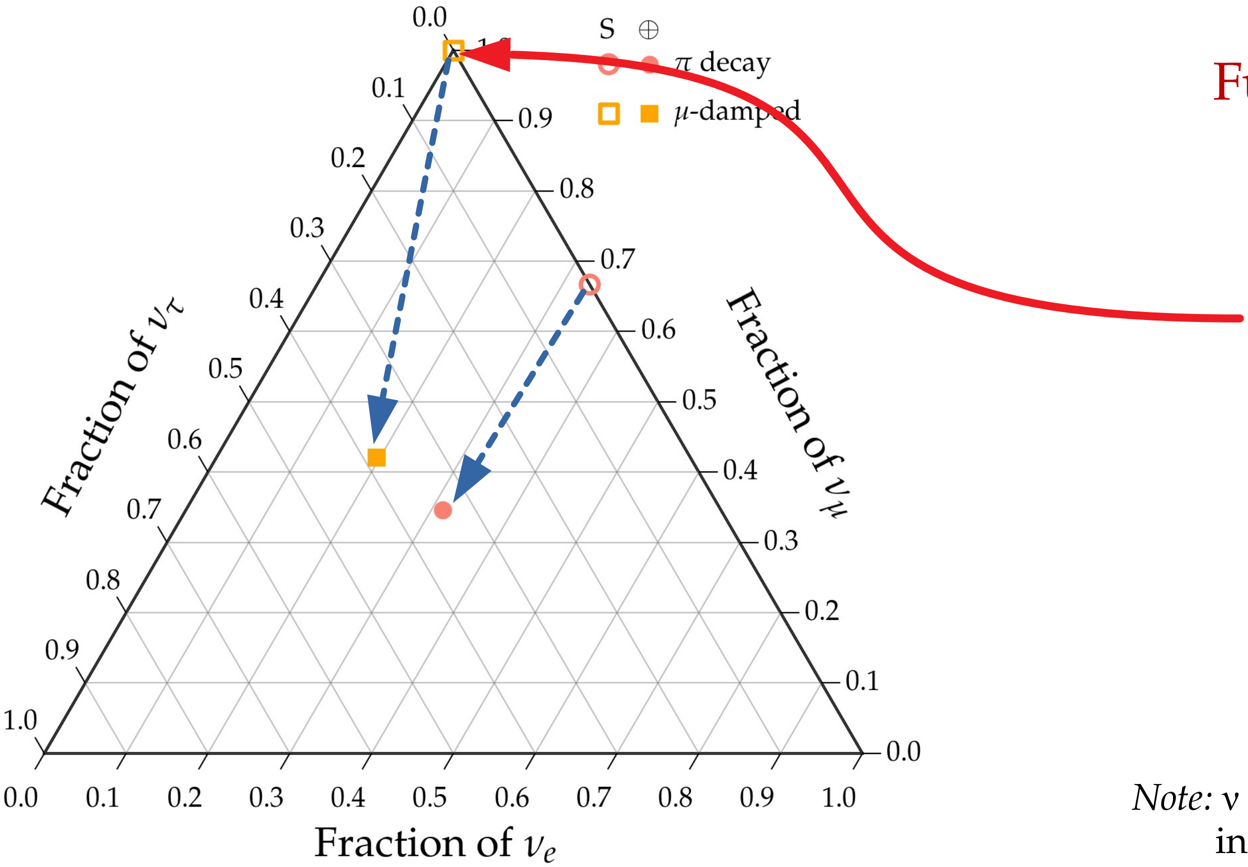

Full π decay chain

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Muon damped

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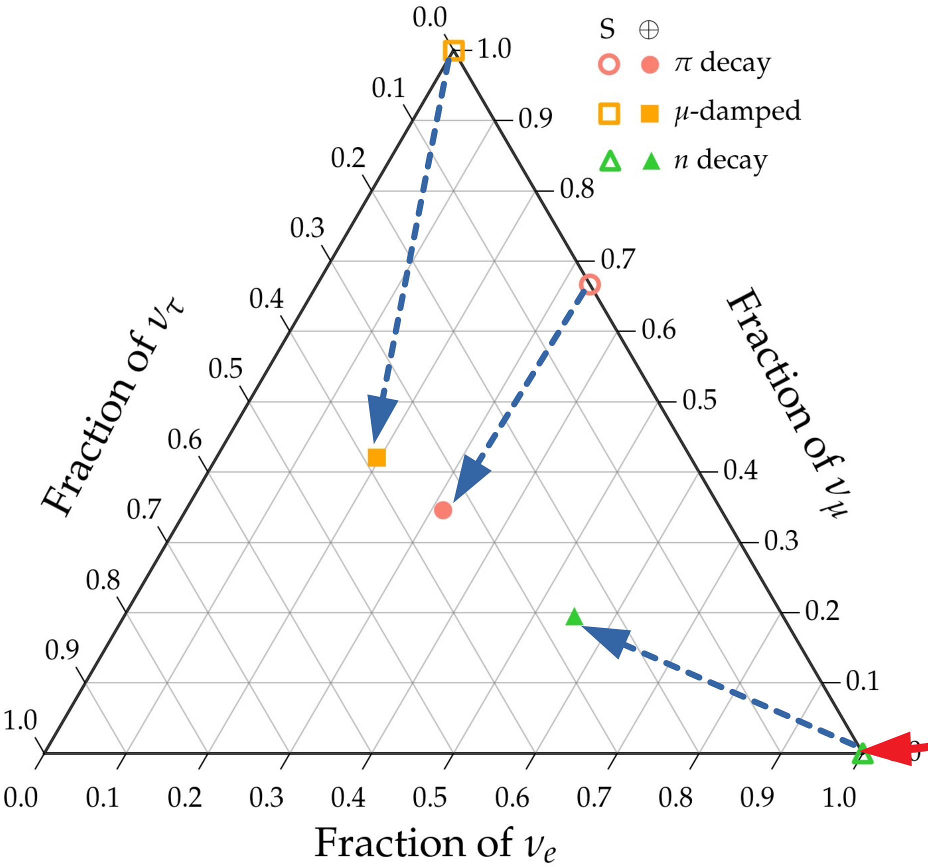

Full π decay chain

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Muon damped

$(0:1:0)_\mathrm{S}$

Neutron decay

$(1:0:0)_\mathrm{S}$

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

Measuring flavor composition: 2015–2020

IceCube Collab., *EPJC* 2022
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

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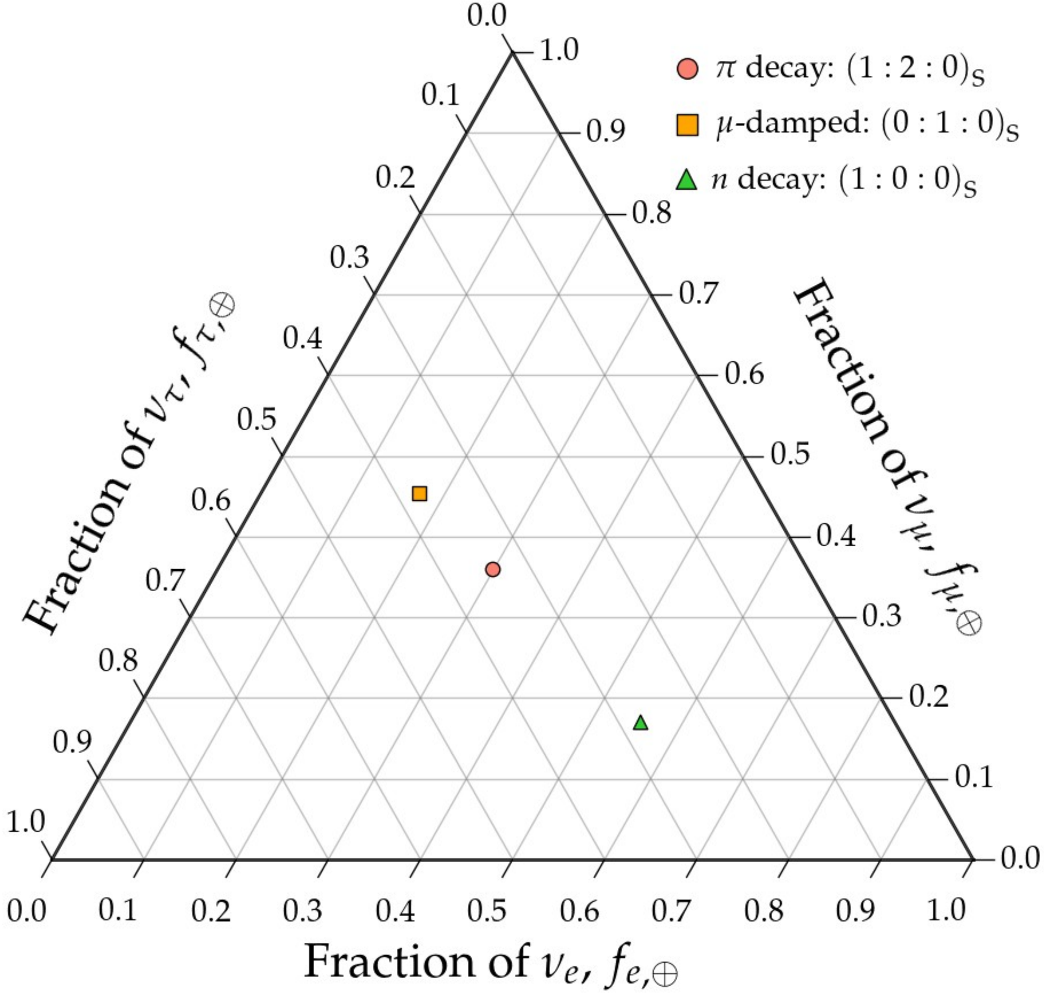

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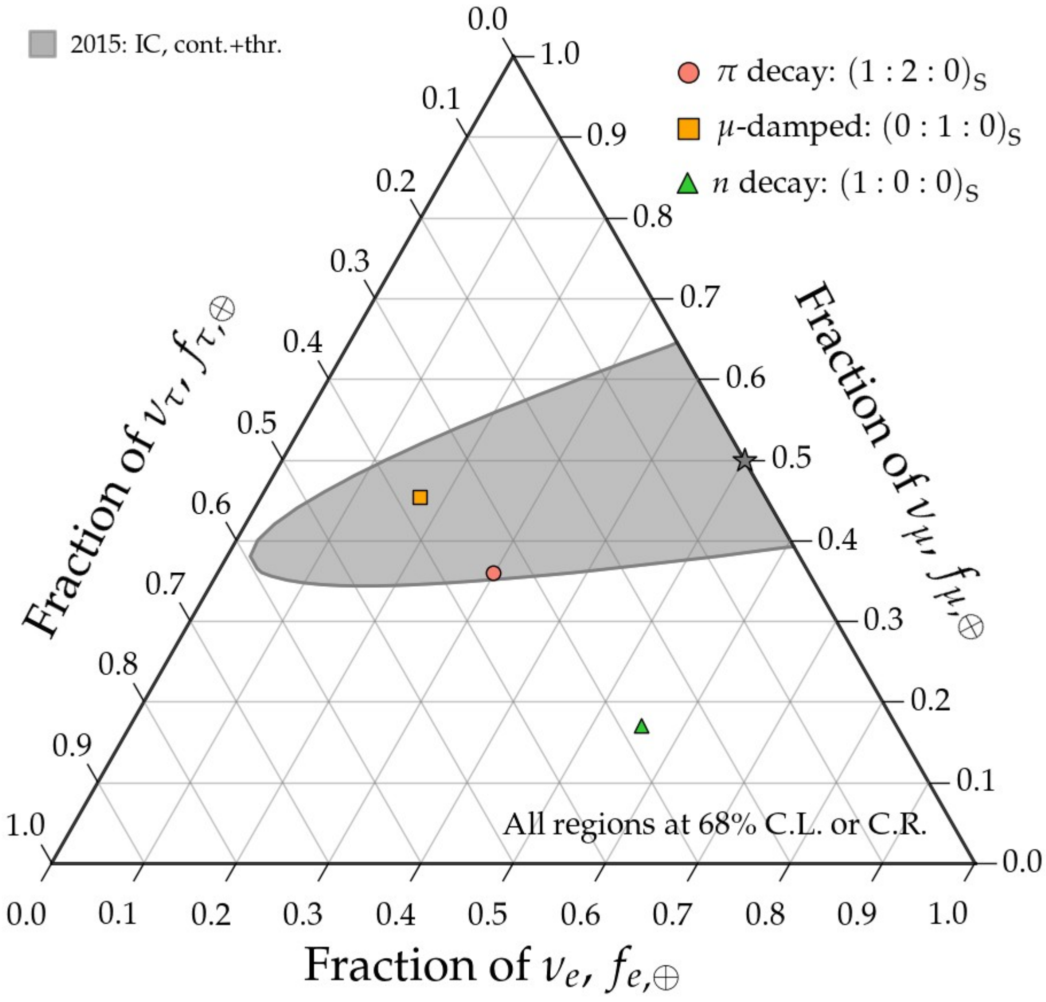

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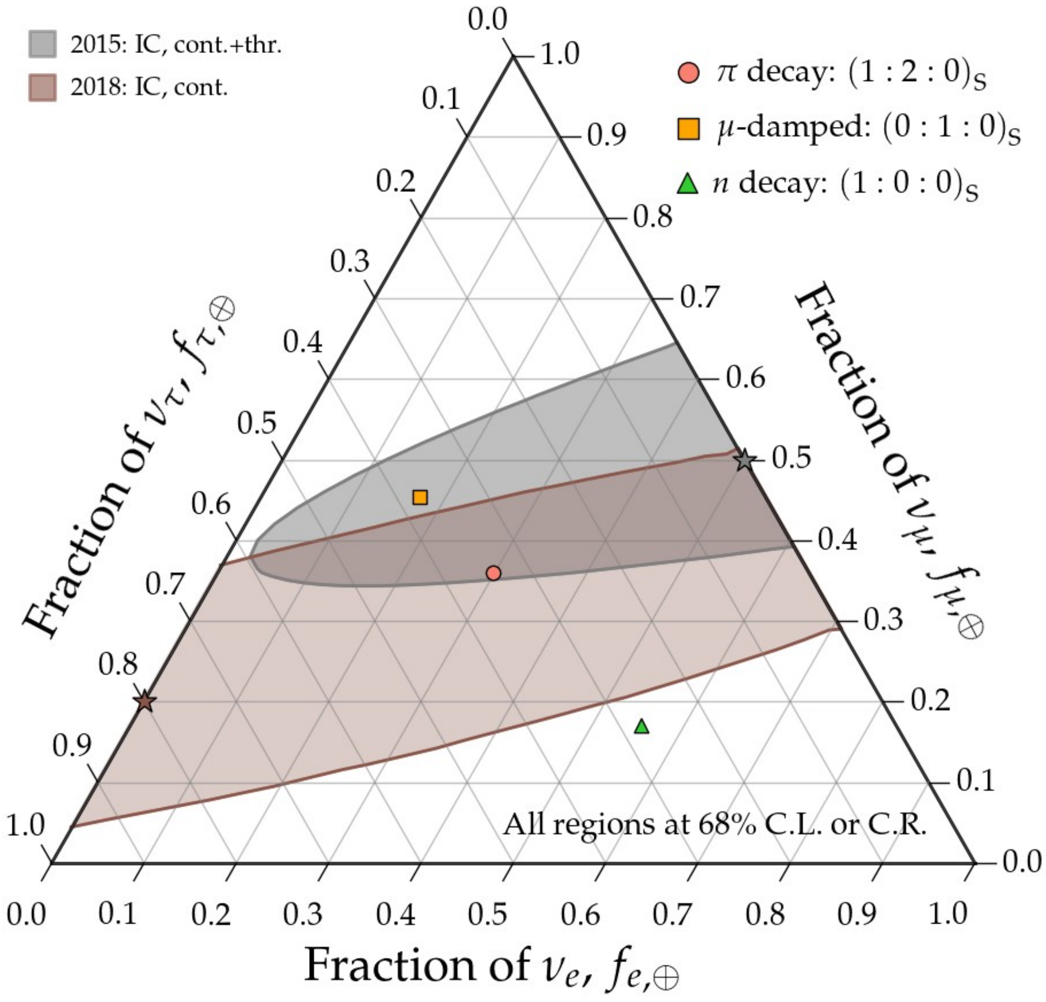

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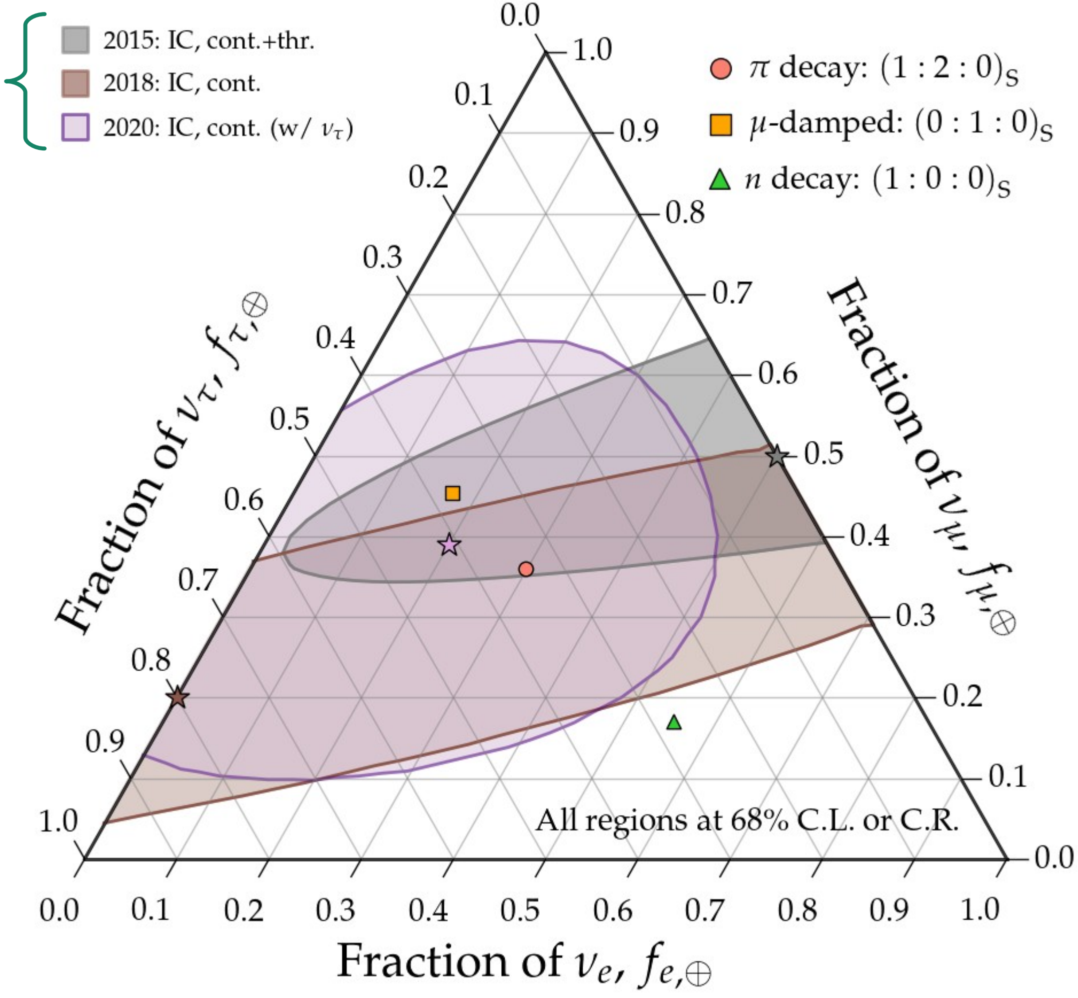
Based on real data



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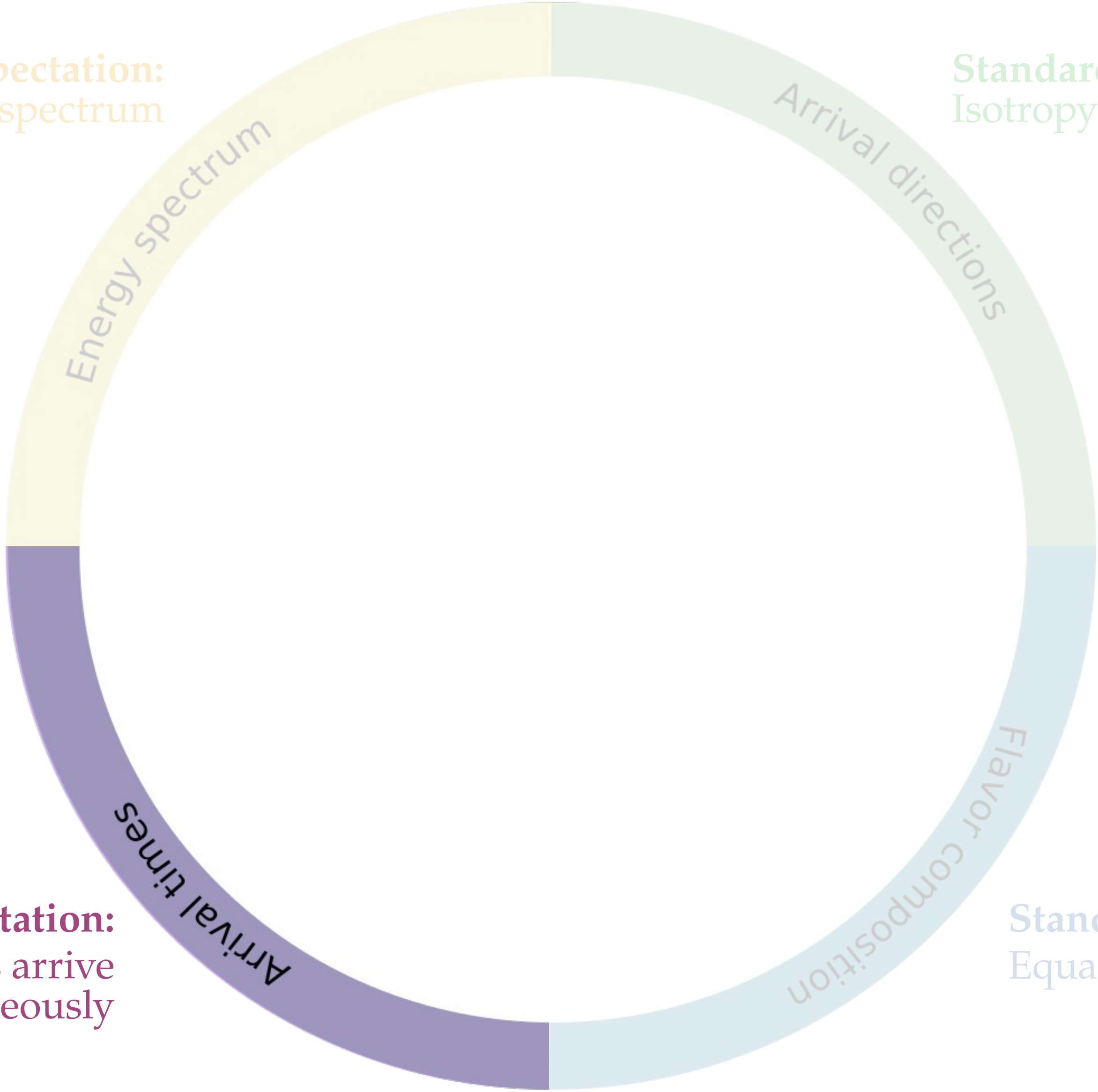

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Bright in gamma rays, bright in high-energy neutrinos

Energy in neutrinos ∝ energy in gamma rays

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

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

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Energy in neutrinos $\propto$ energy in gamma rays

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in one interaction (~20%)

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$$\overbrace{\int_0^\infty \mathrm{d}E_\nu E_\nu F_\nu(E_\nu)} = \frac{1}{8}\underbrace{\left[1-\left(1-\langle x_{p\to\pi}\rangle\right)^{\tau_{p\gamma}}\right]}_{\text{Fraction of total } p \text{ energy given to pions}} \frac{f_p}{f_e} \overbrace{\int_{1\ \mathrm{keV}}^{10\ \mathrm{MeV}} \mathrm{d}E_\gamma E_\gamma F_\gamma(E_\gamma)}$$

Baryonic loading

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

Bright in gamma rays, bright in high-energy neutrinos

Energy in neutrinos ∝ energy in gamma rays

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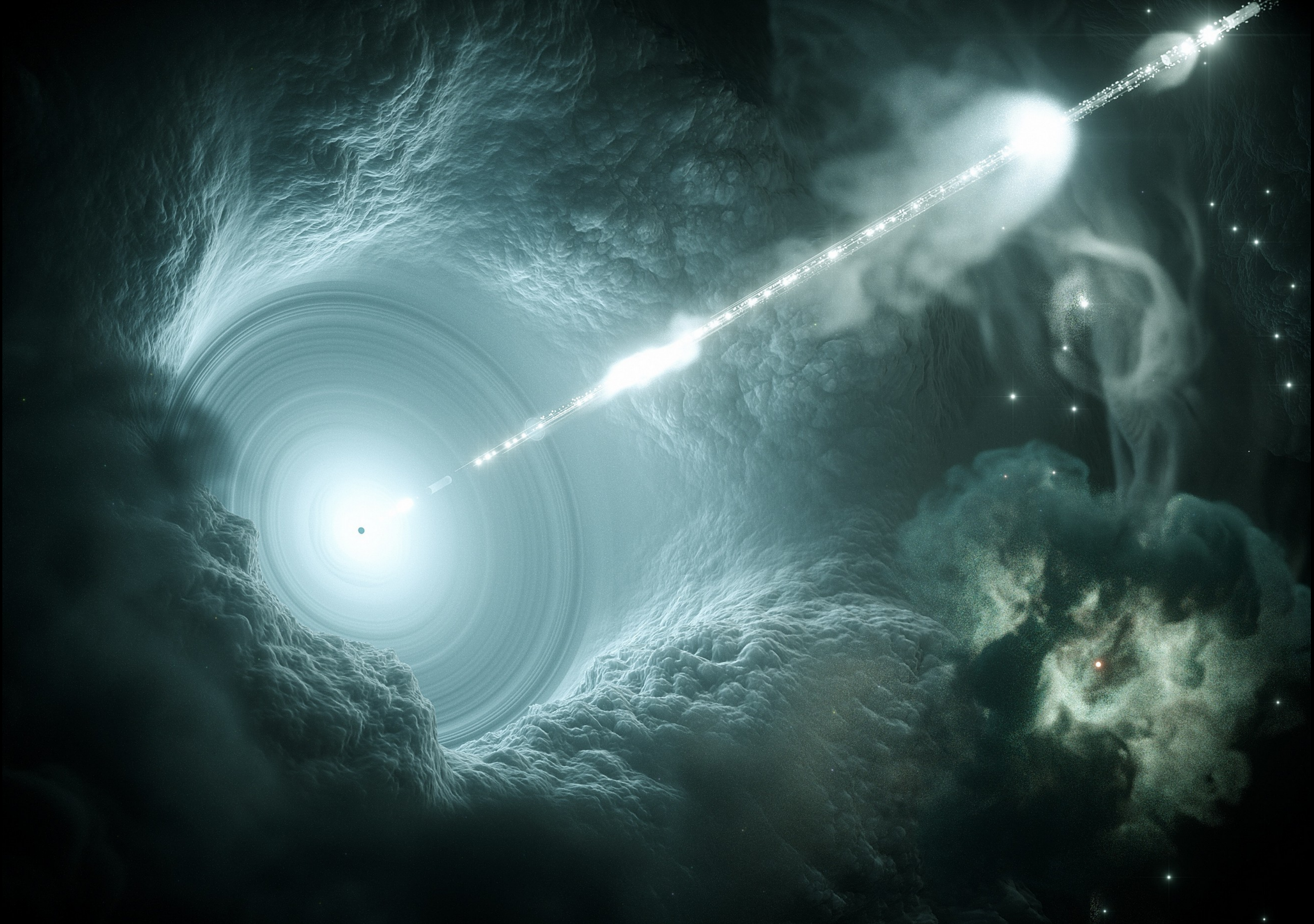
Baryonic loading

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

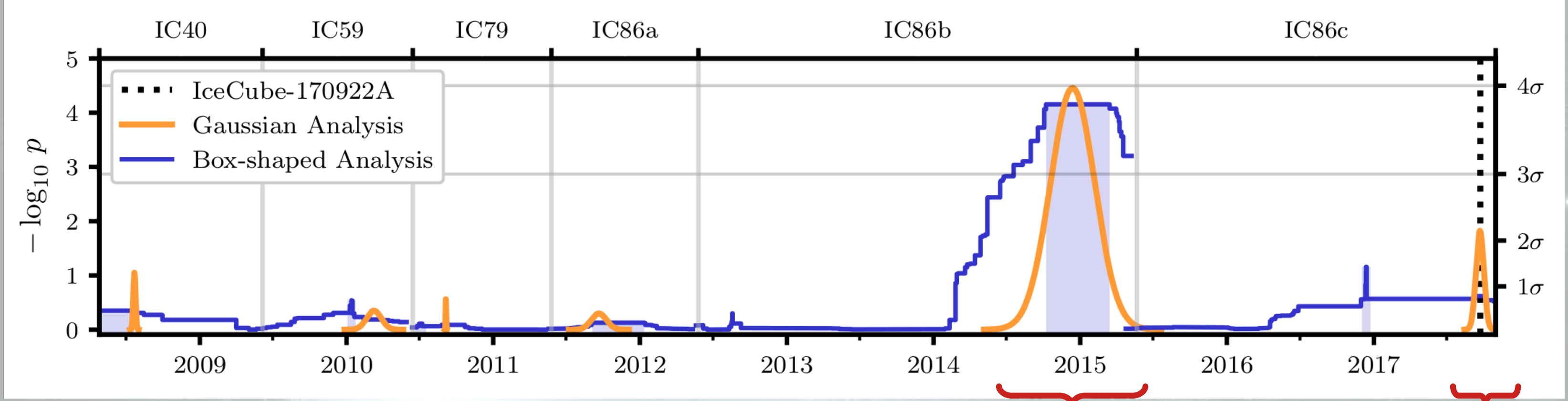
E. Waxman & J. Bahcall, *PRL* 1997
D. Guetta *et al.*, *Astropart. Phys.* 2004



DESY

Blazar TXS 0506+056:

IceCube, *Science* 2018



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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

Key developments:

Bigger detectors → larger statistics

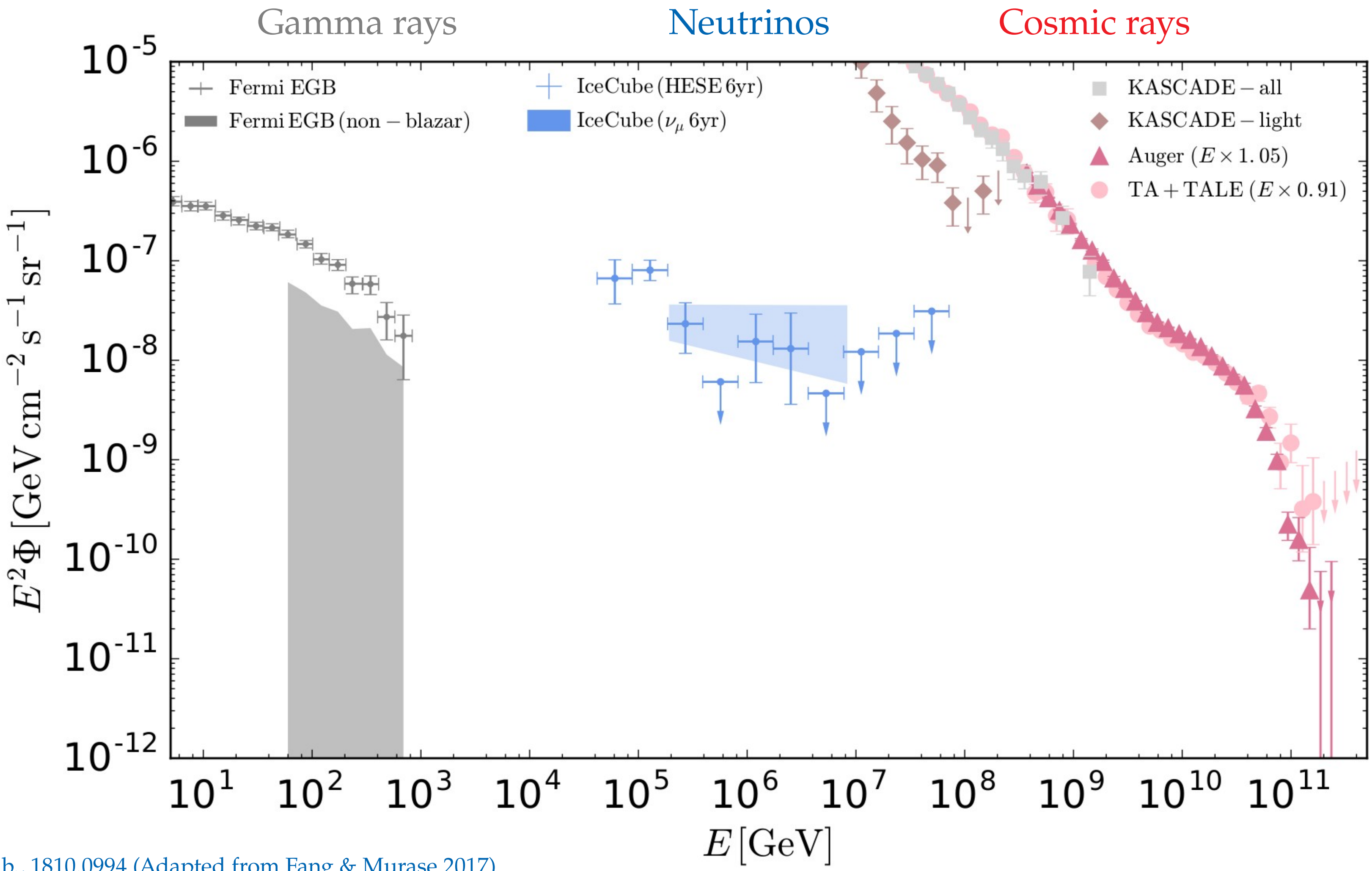
Better reconstruction

Smaller astrophysical uncertainties

II.

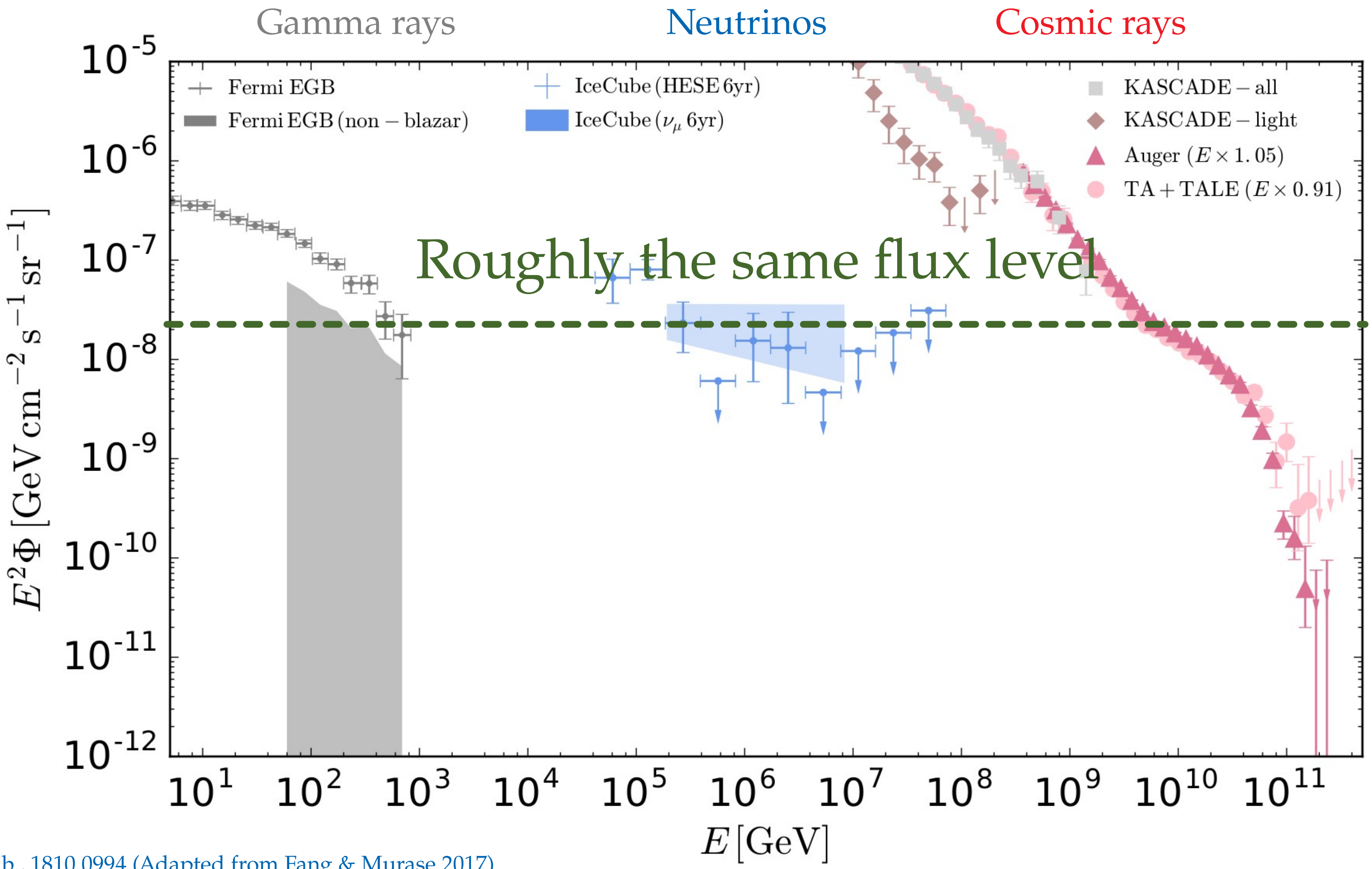
What have we learned about *astrophysics*

Fluxes at Earth



GRAND Collab., 1810.0994 (Adapted from Fang & Murase 2017)

Fluxes at Earth



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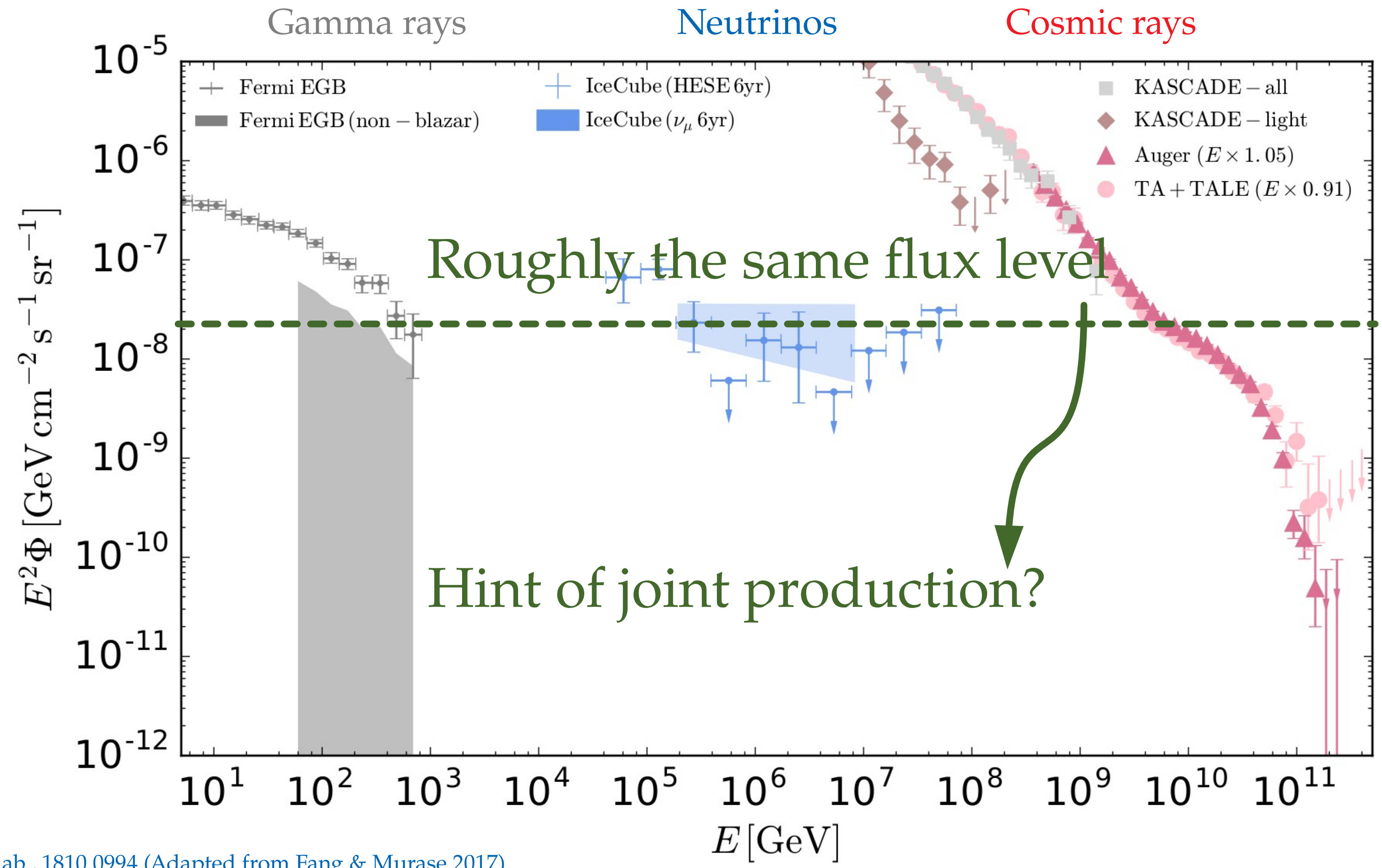
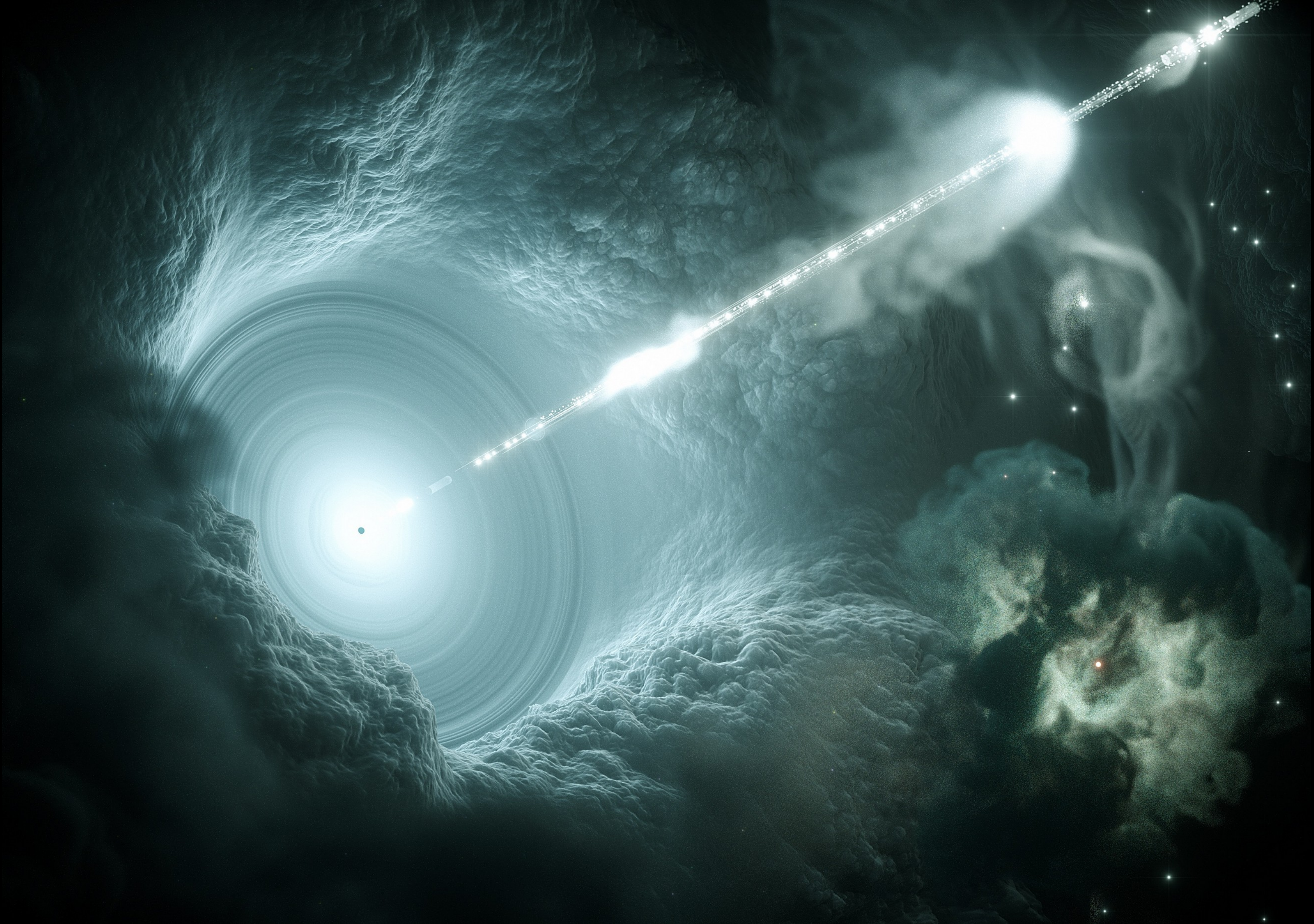


Roughly the same flux level

Hint of joint production?

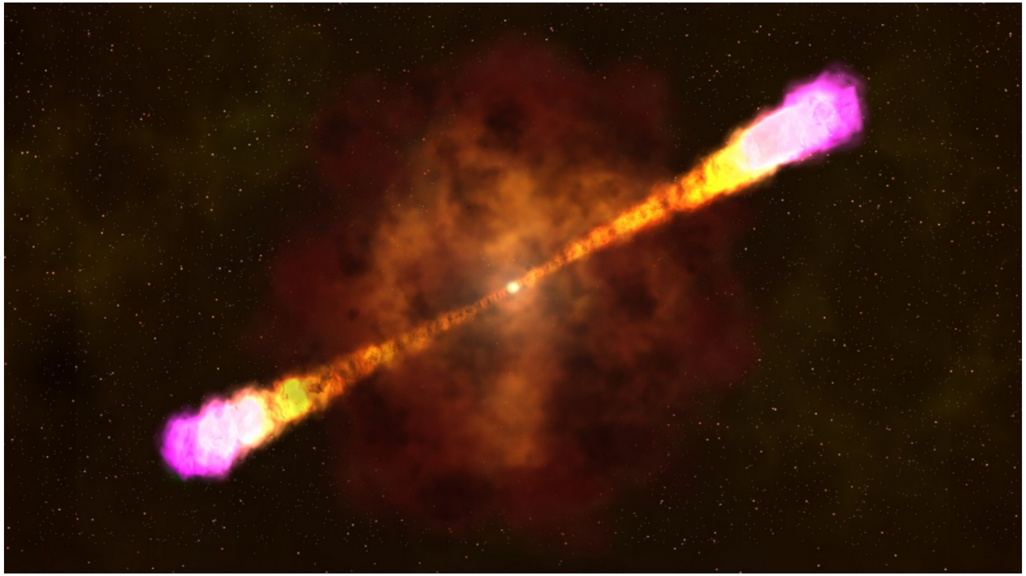
GRAND Collab., 1810.0994 (Adapted from Fang & Murase 2017)



DESY

Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts



Blazars

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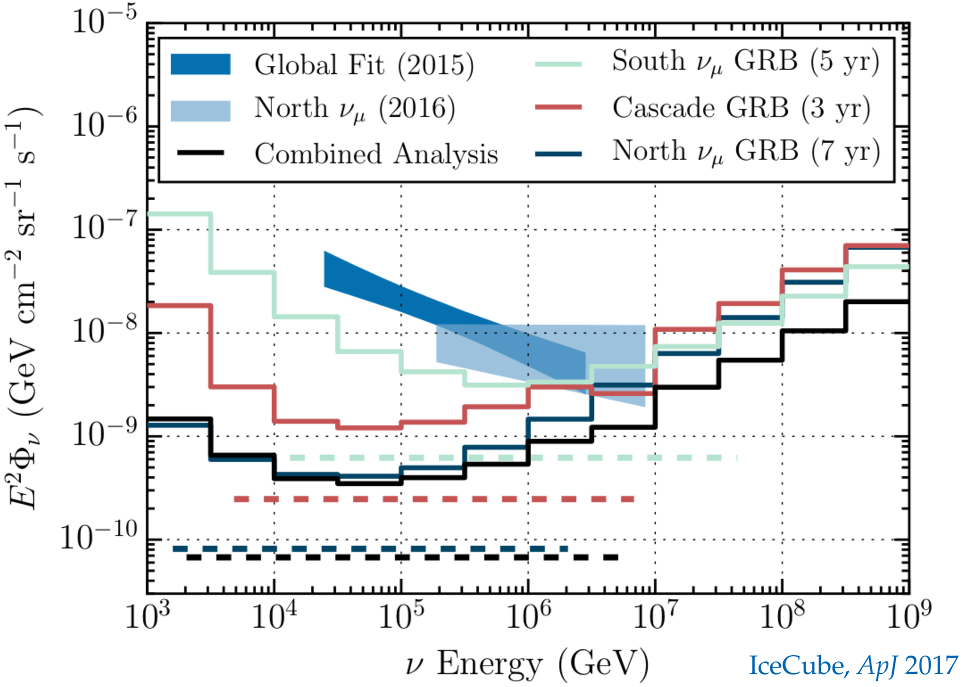
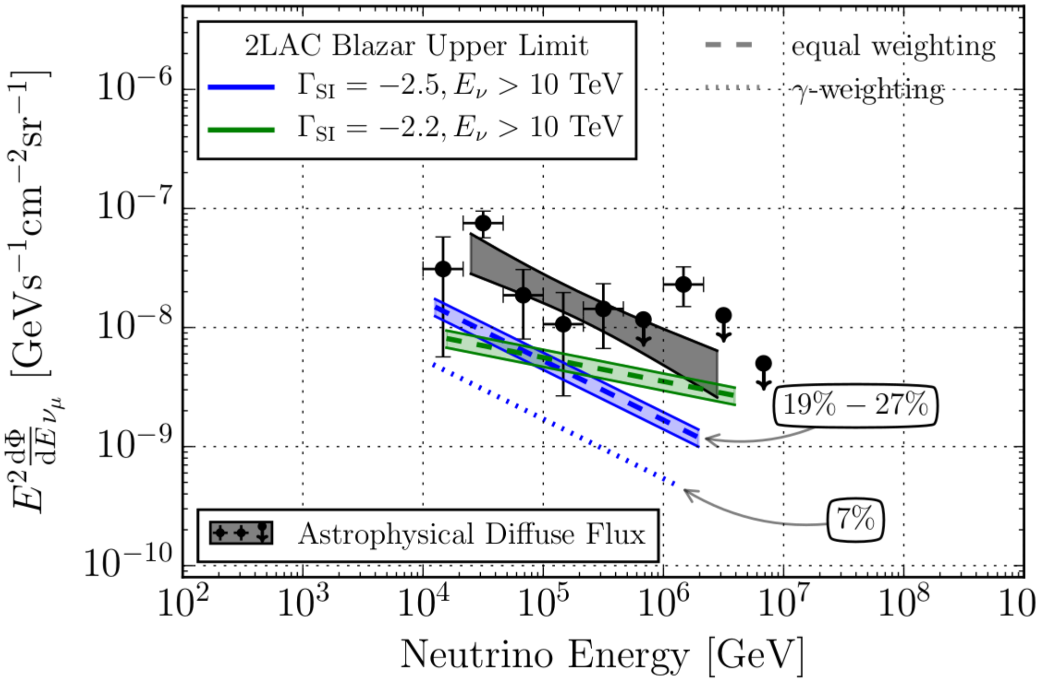


IceCube, *ApJ* 2017

1172 GRBs inspected, no correlation found

< 1% contribution to diffuse flux

Blazars

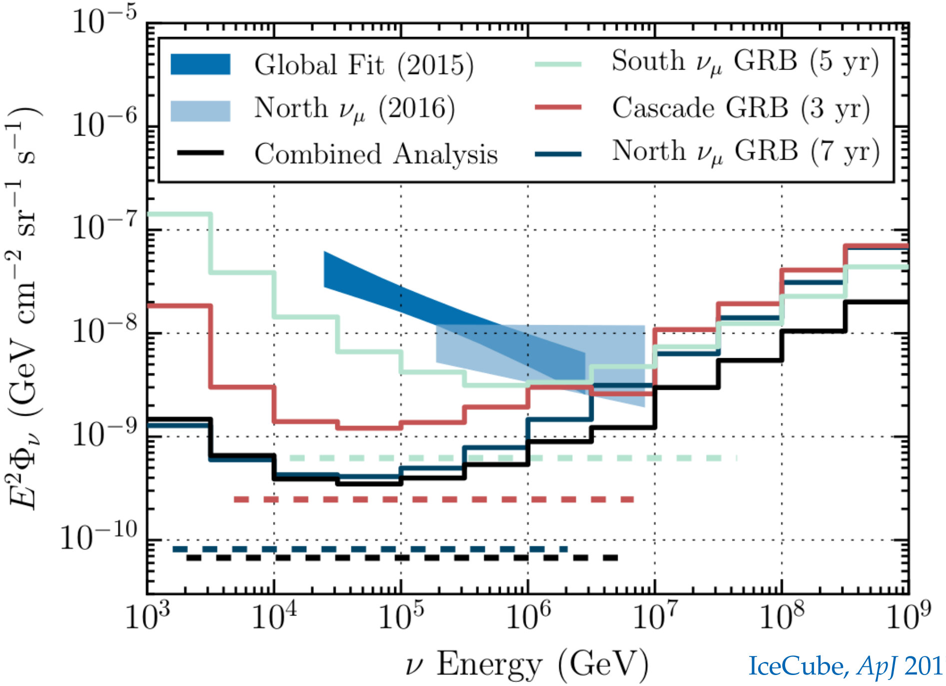


862 blazars inspected, no correlation found

< 27% contribution to diffuse flux

Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts



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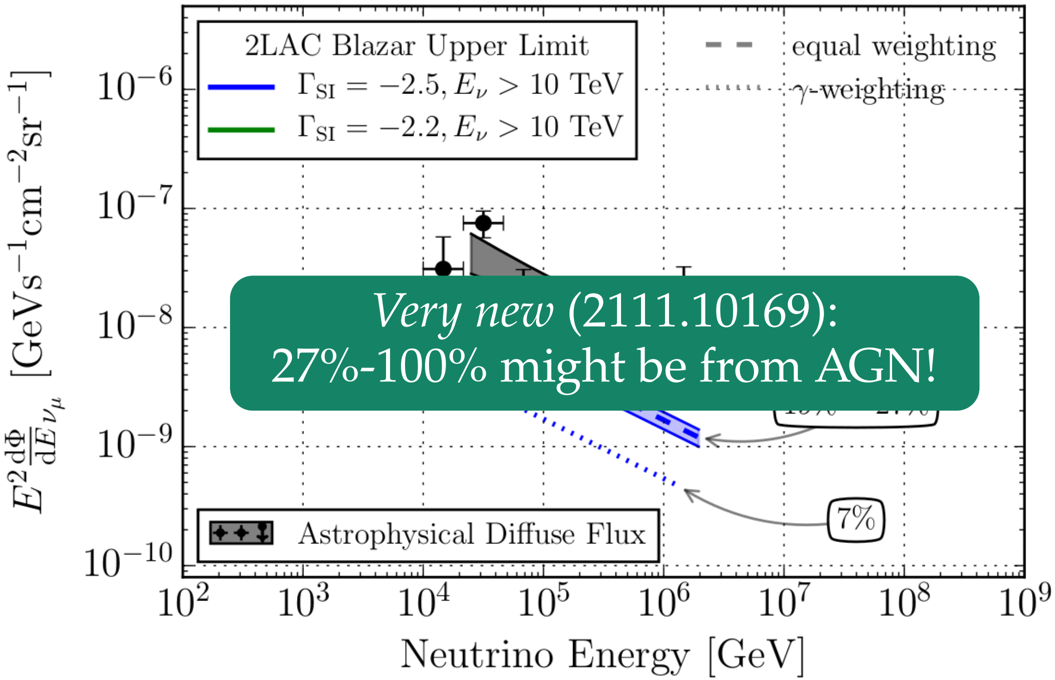
Blazars



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

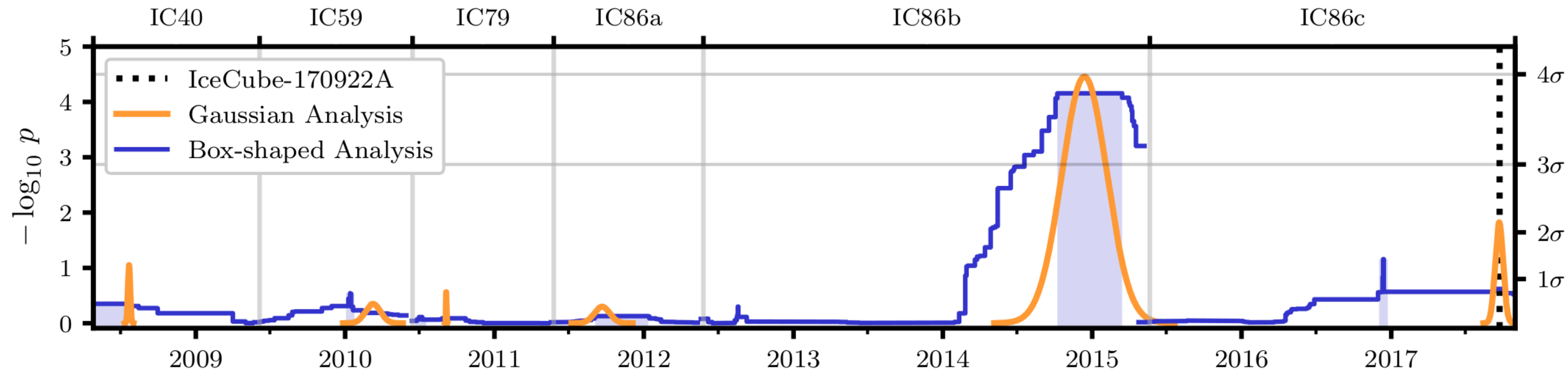
862 blazars inspected, no correlation found

$<$ 27% contribution to diffuse flux

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

Blazar TXS 0506+056:

IceCube, *Science* 2018



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3.5σ significance of correlation (post-trial)

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1.4σ significance of correlation

Combined (pre-trial): 4.1σ

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

Joint modeling of the two periods is challenging!

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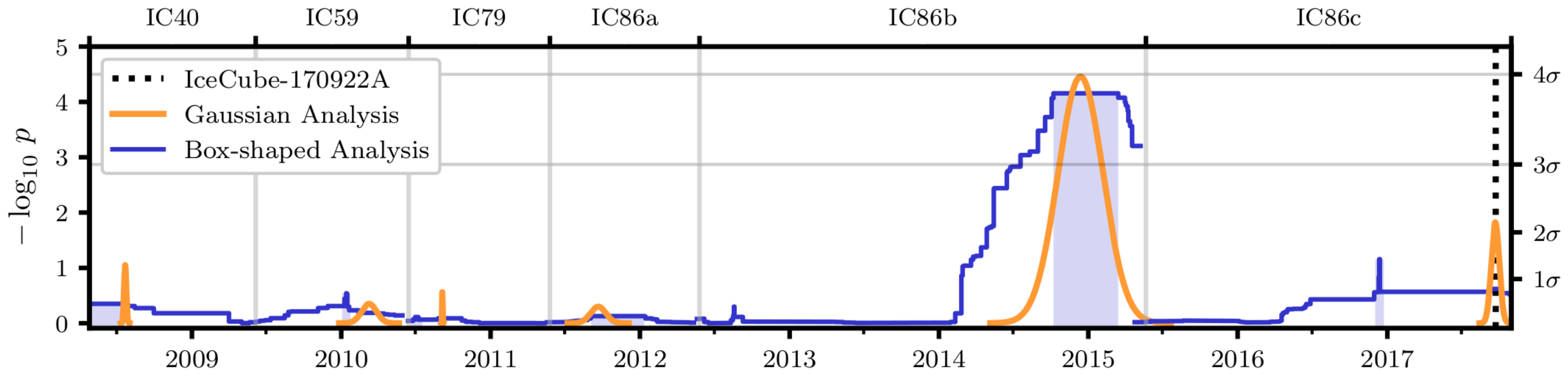

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as TXS 0506+056, the diffuse ν flux
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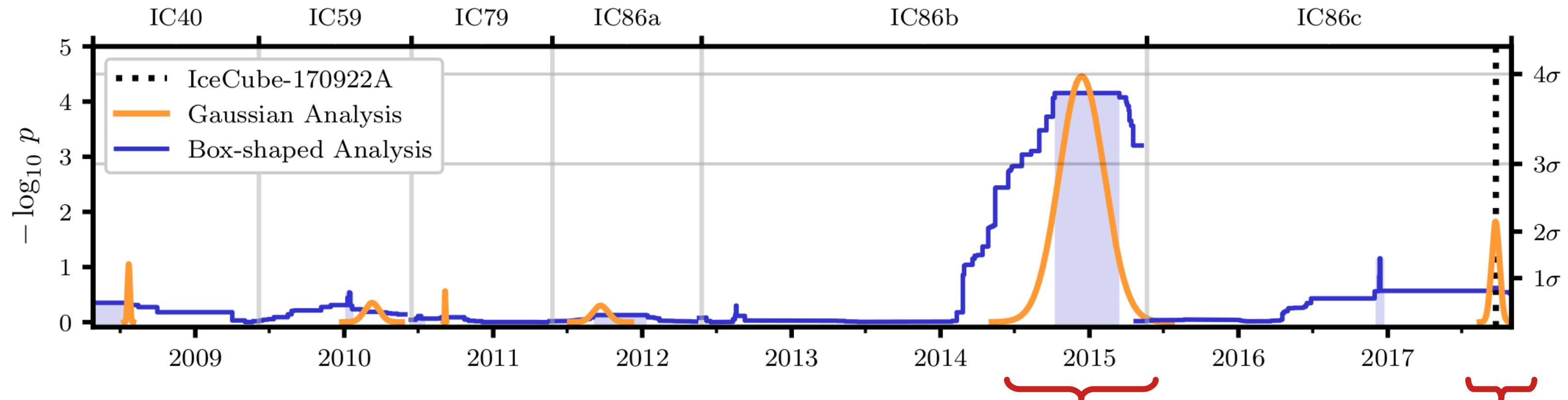

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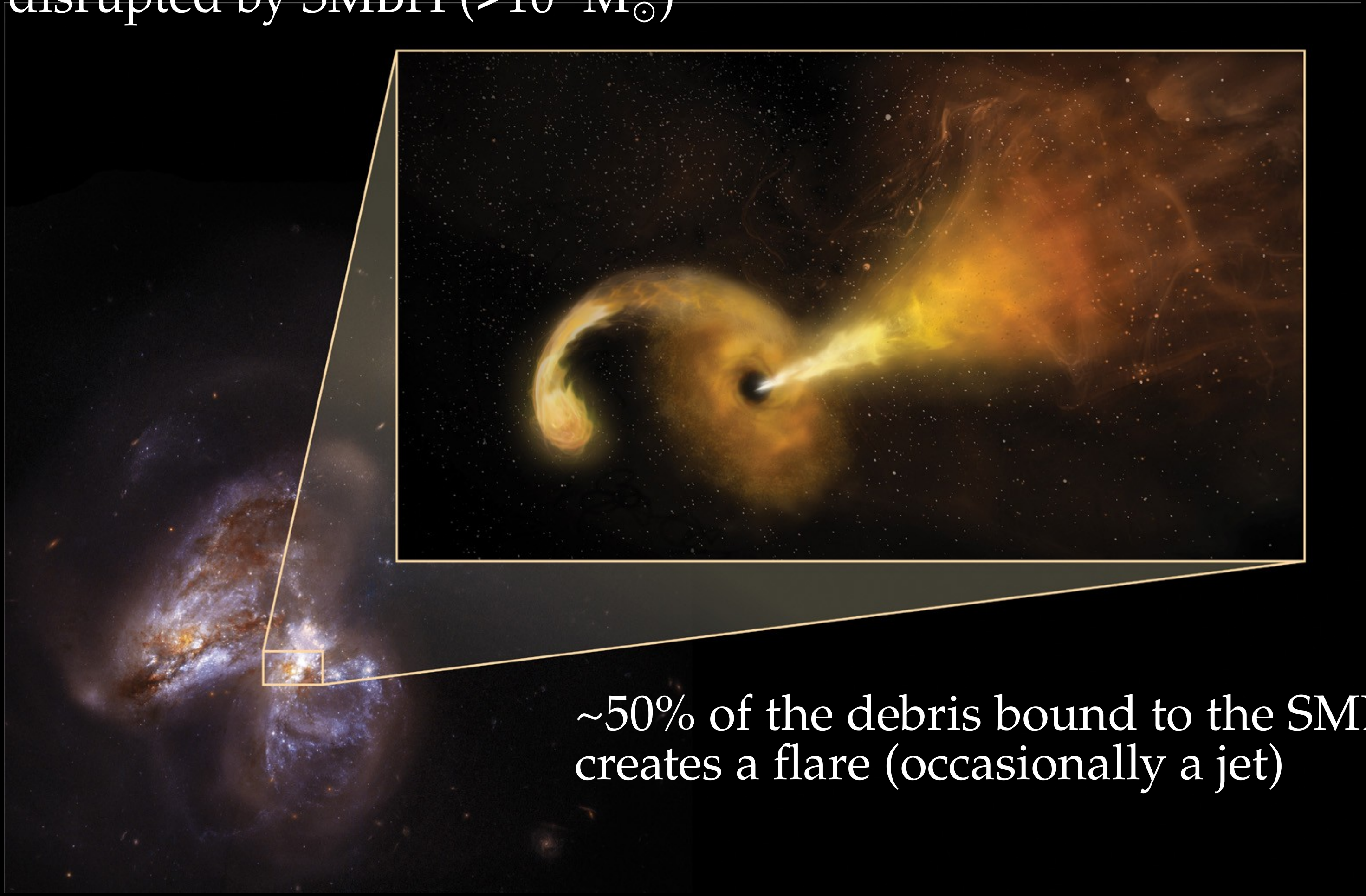
Tidal disruption events

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



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

NASA

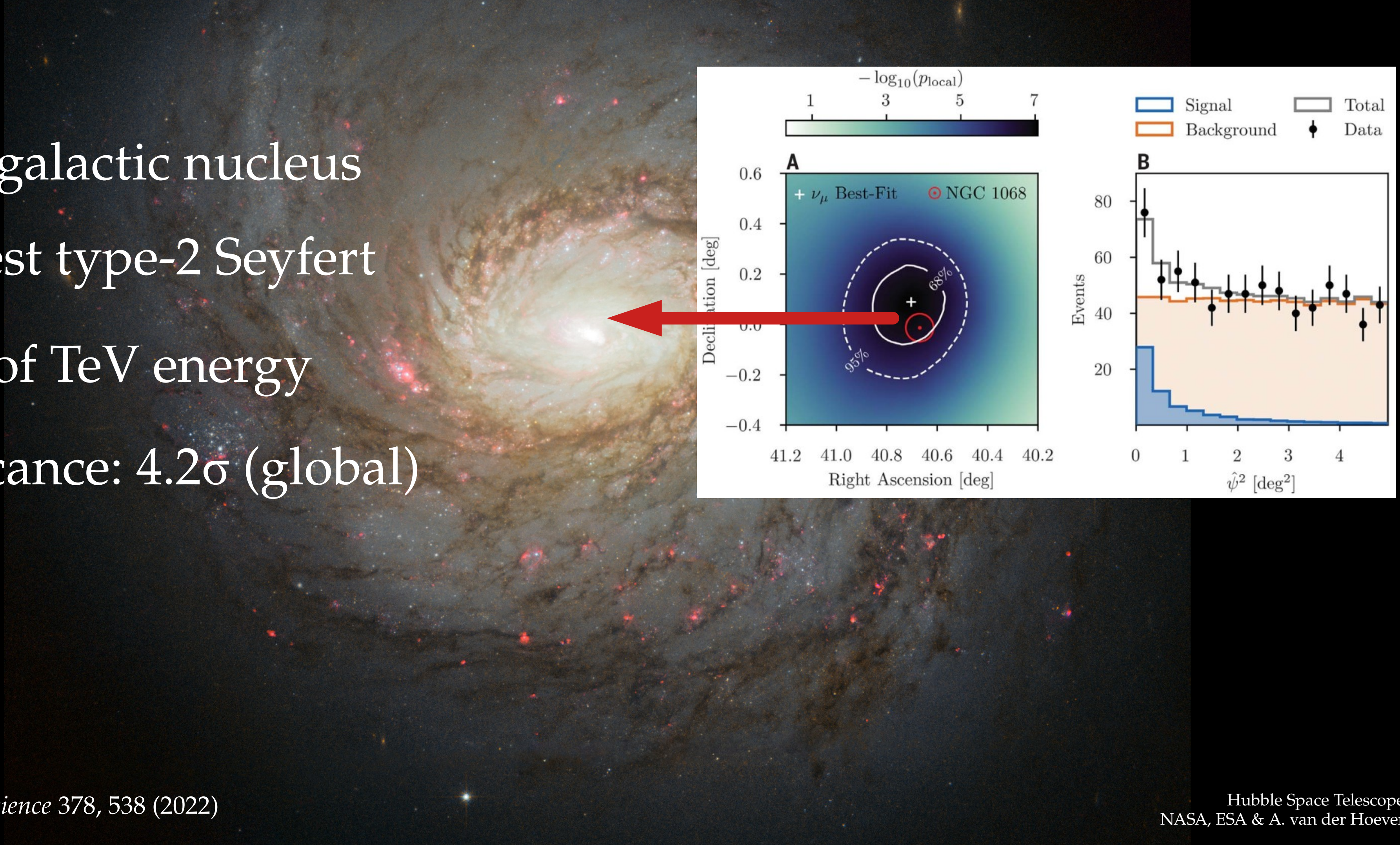
NGC1068: The first *steady-state* source of high-energy ν

Active galactic nucleus

Brightest type-2 Seyfert

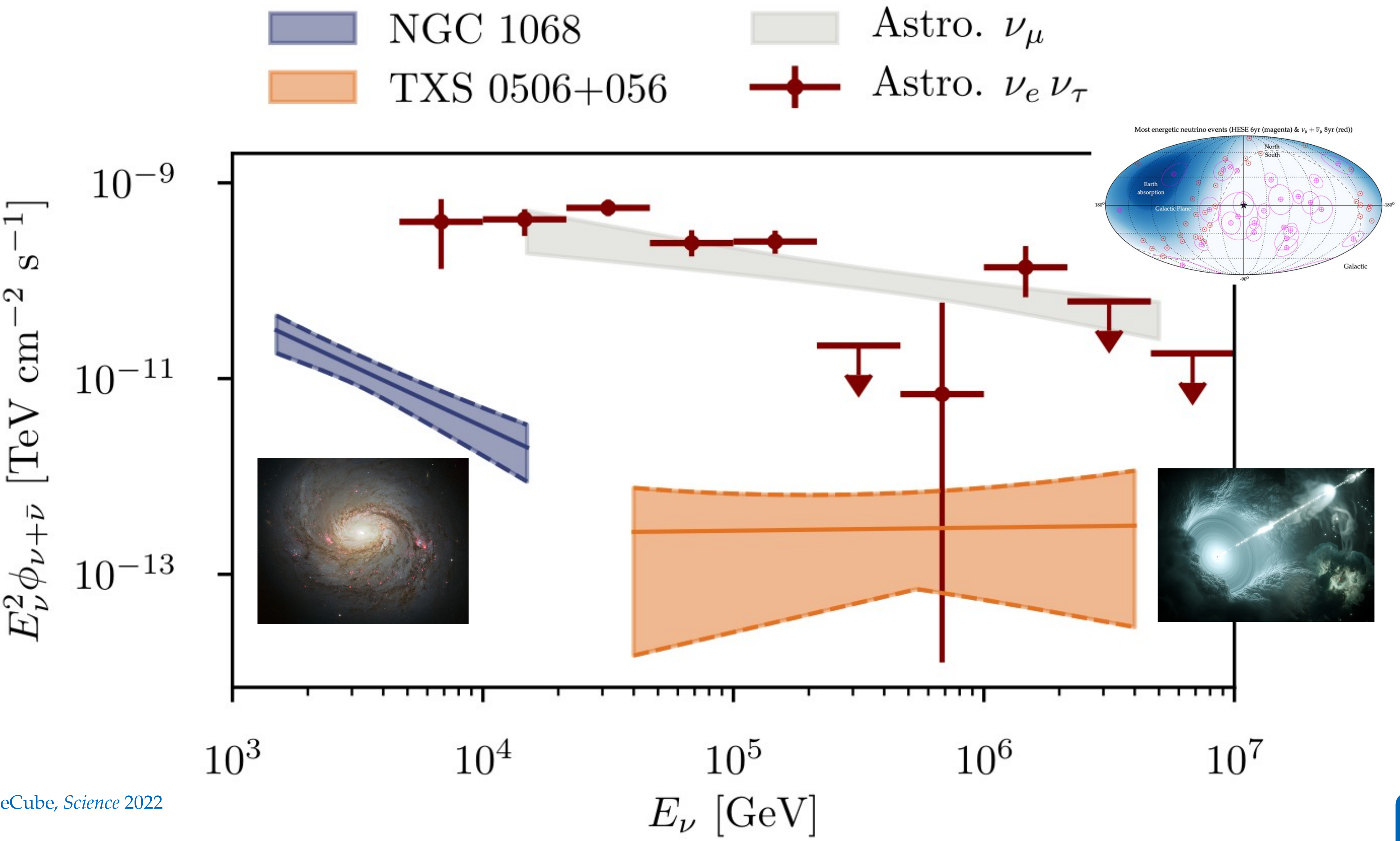
79^{+22}_{-20} ν of TeV energy

Significance: 4.2σ (global)



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

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

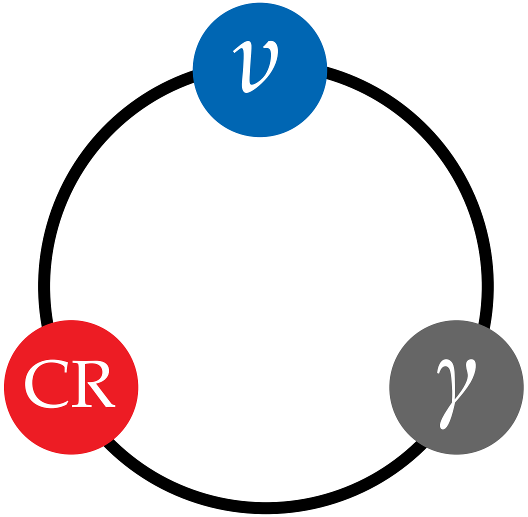


IceCube, *Science* 2022

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

Energy in neutrinos $\propto$ energy in gamma rays

Waxman & Bahcall, *PRL* 1997



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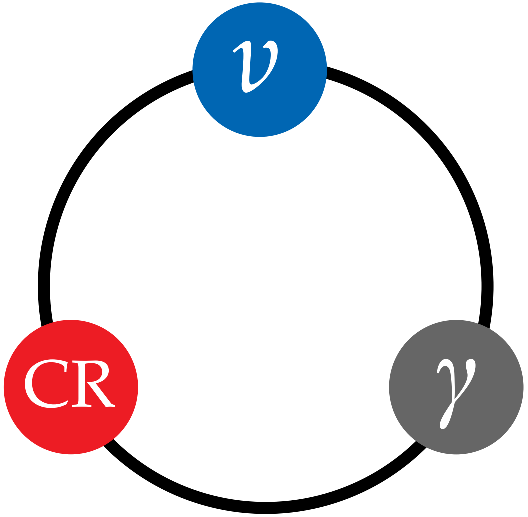
Fudge factors:

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

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



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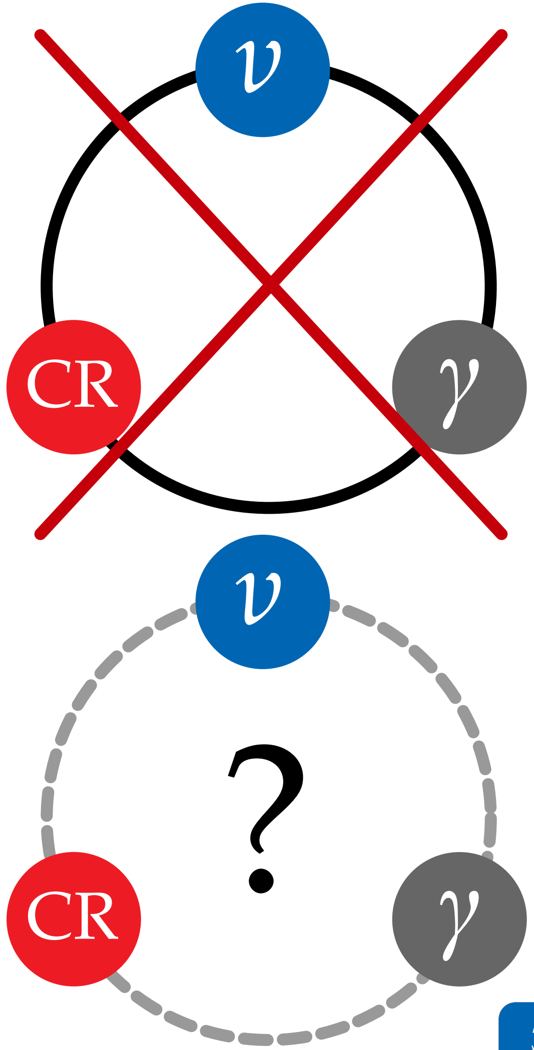
Gao, Pohl, Winter, *ApJ* 2017



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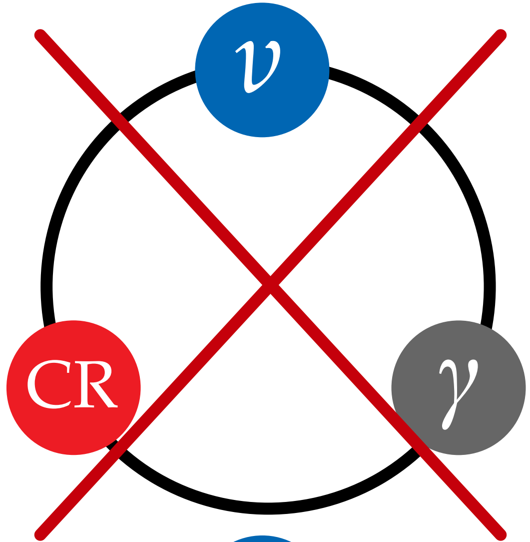


But the correlation between ν and γ may be more nuanced:

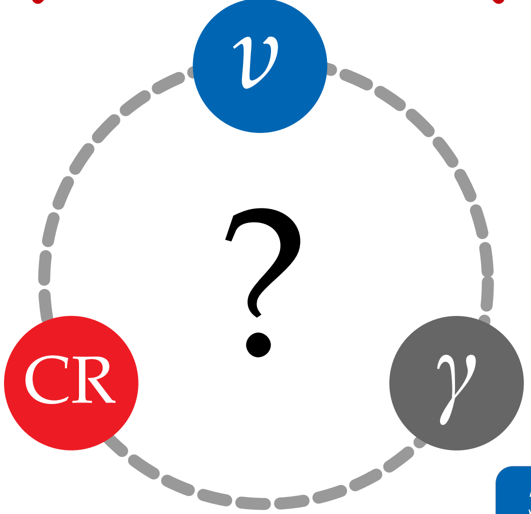
Gao, Pohl, Winter, *ApJ* 2017

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

Murase, Guetta, Ahlers, *PRL* 2016

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

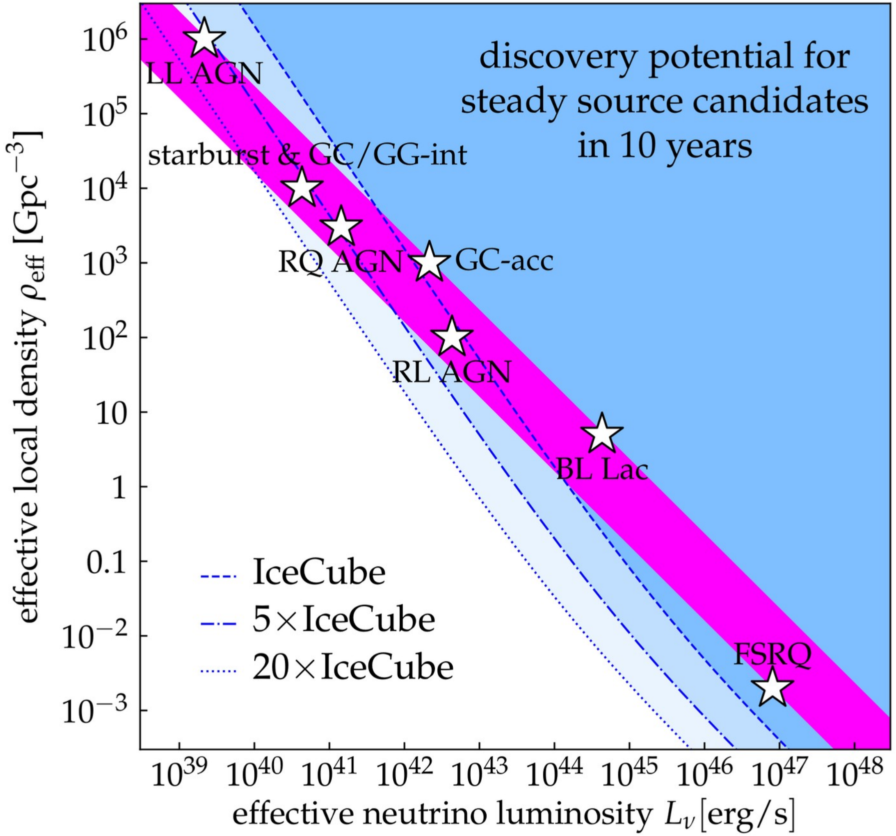
Morejon, Fedynitch, Boncioli, Winter, *JCAP* 2019
Boncioli, Fedynitch, Winter, *Sci. Rep.* 2017



Source discovery potential: today and in the future

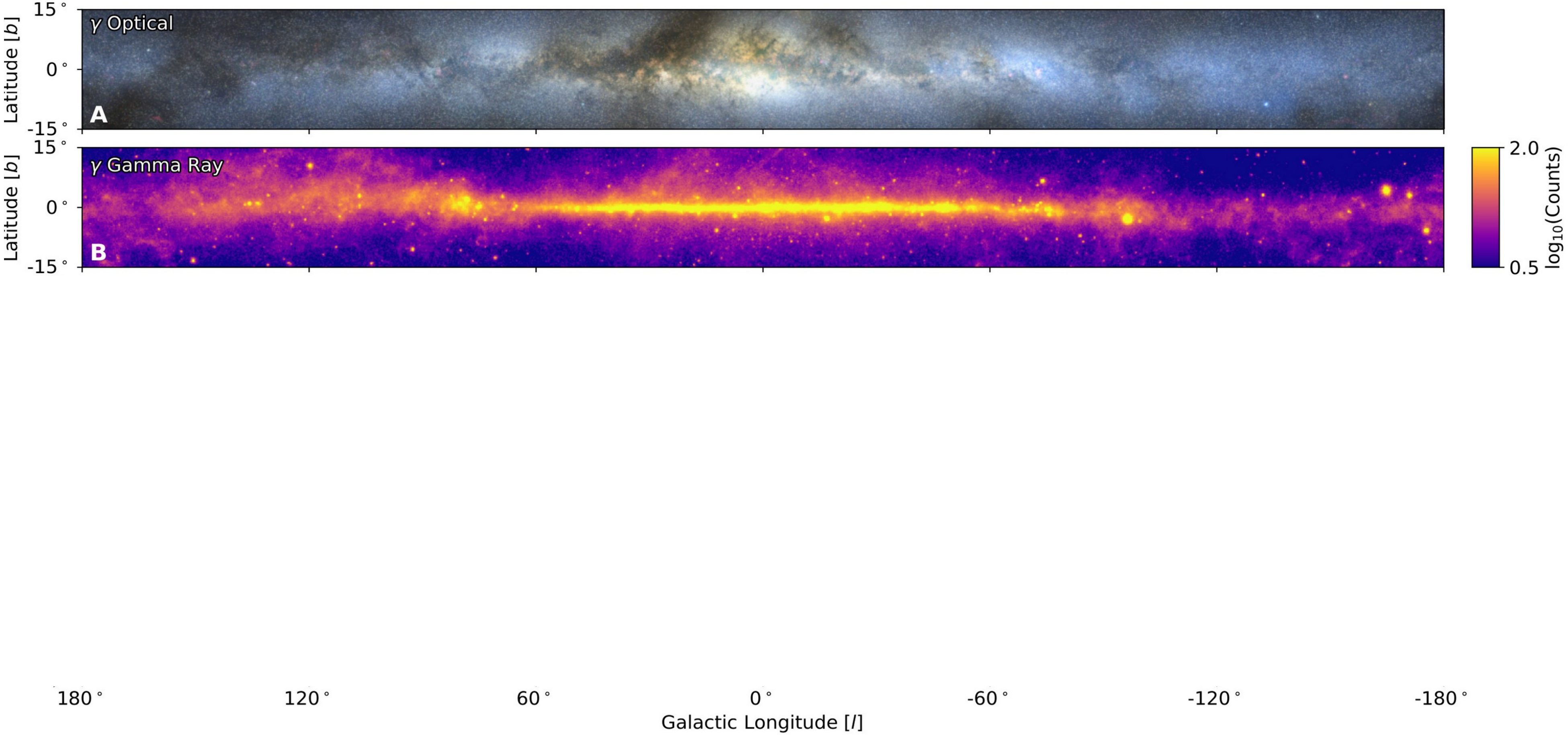
🟪 Accounts for the observed diffuse ν flux (lower/upper edge: rapid/no redshift evolution)

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



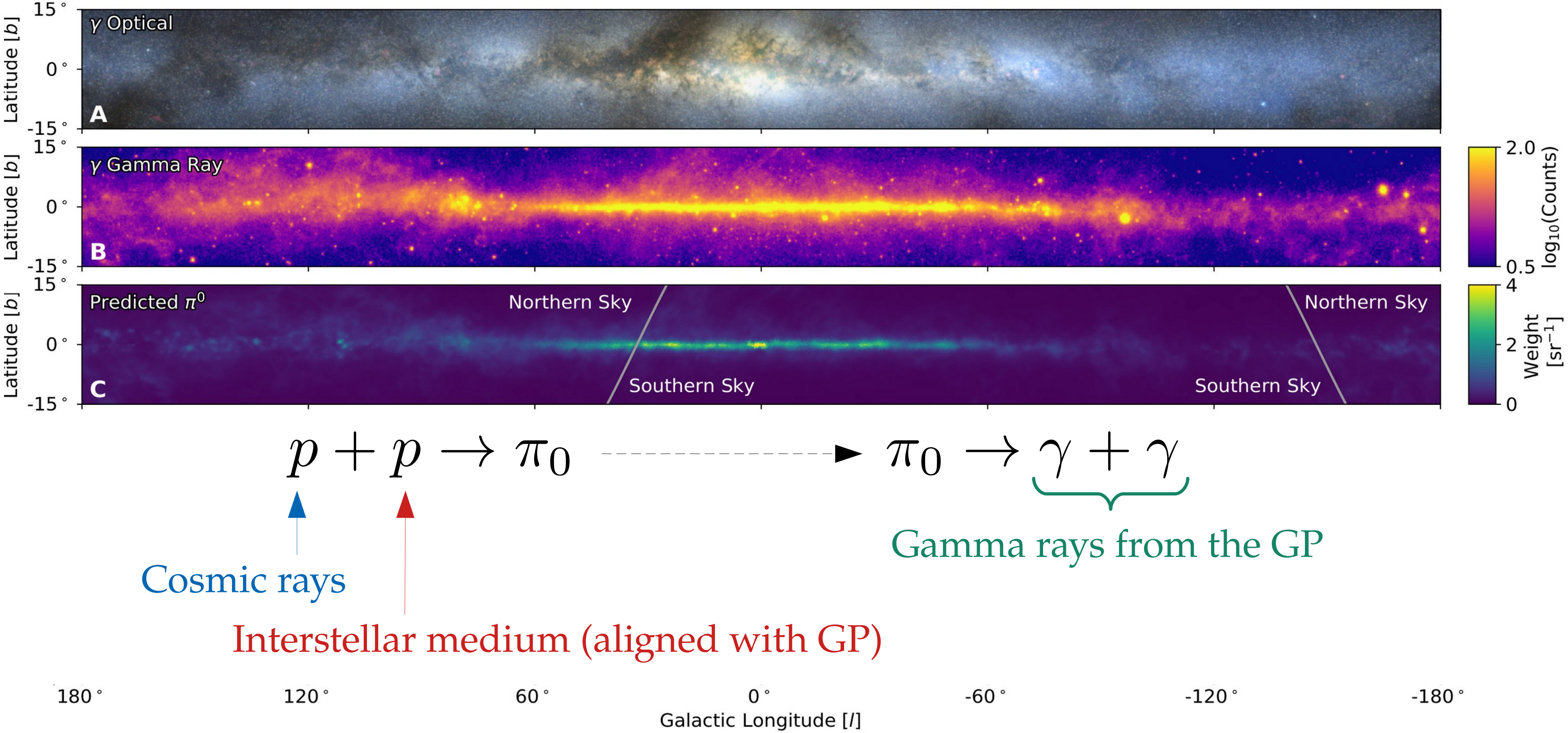
Ackermann, **MB** *et al.*, Astro2020 Survey (1903.04333) – See also: Silvestri & Barwick, *PRD* 2010; Murase & Waxman, *PRD* 2016

High-energy neutrinos from the Galactic Plane



IceCube Collab., *Science* 2023

High-energy neutrinos from the Galactic Plane



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

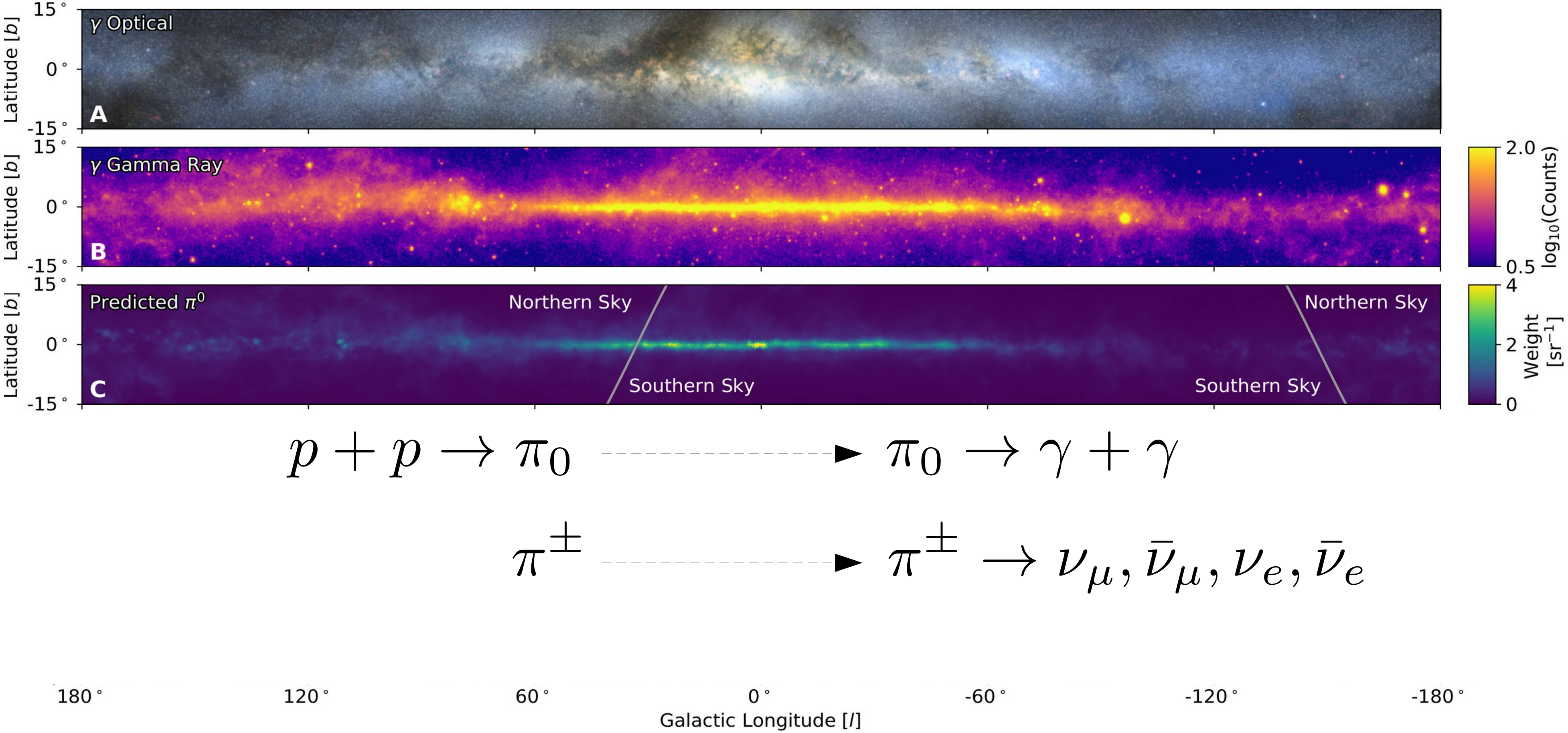
Gamma rays from the GP

Cosmic rays

Interstellar medium (aligned with GP)

IceCube Collab., *Science* 2023

High-energy neutrinos from the Galactic Plane

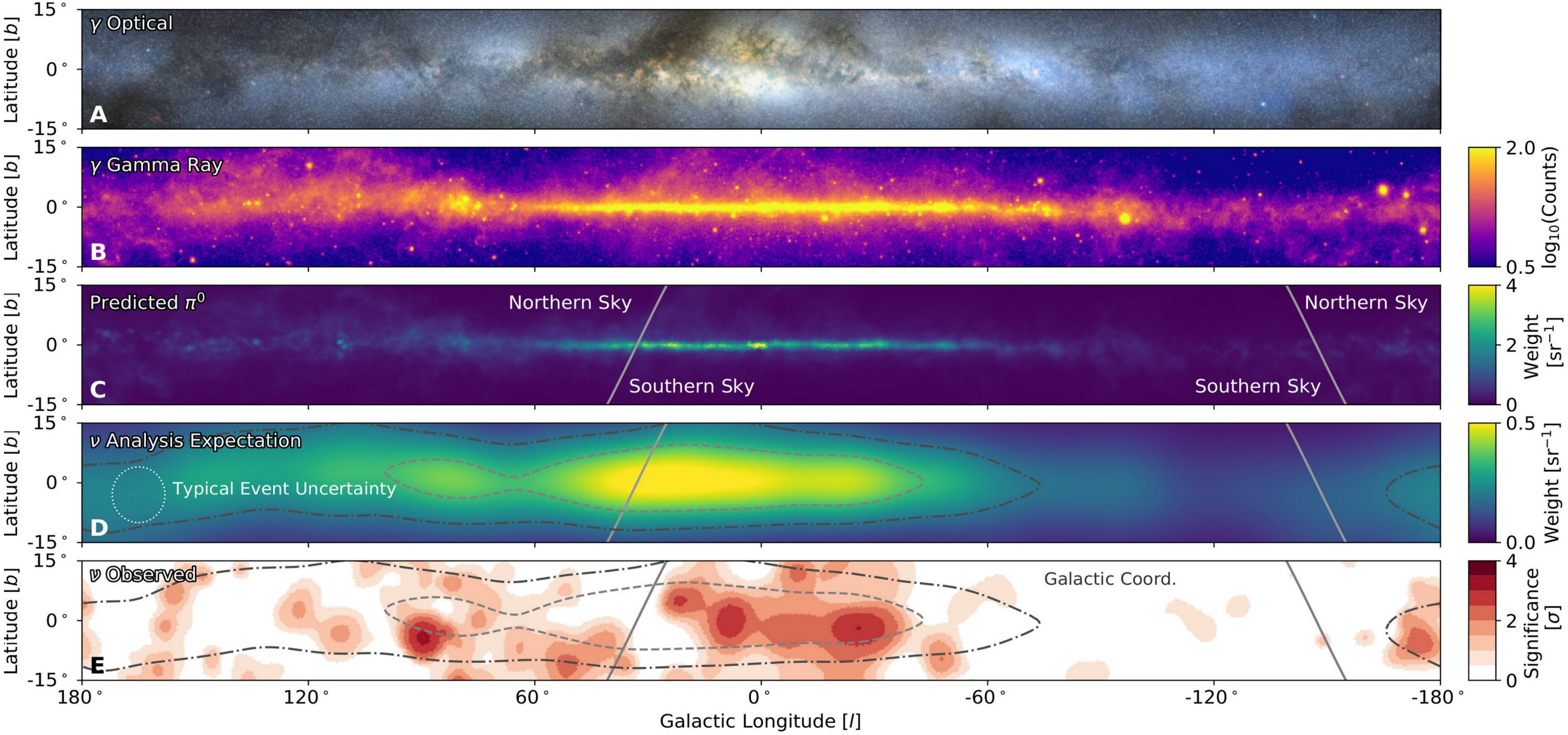


$$p + p \rightarrow \pi_0 \dashrightarrow \pi_0 \rightarrow \gamma + \gamma$$

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

IceCube Collab., *Science* 2023

High-energy neutrinos from the Galactic Plane



IceCube Collab., *Science* 2023

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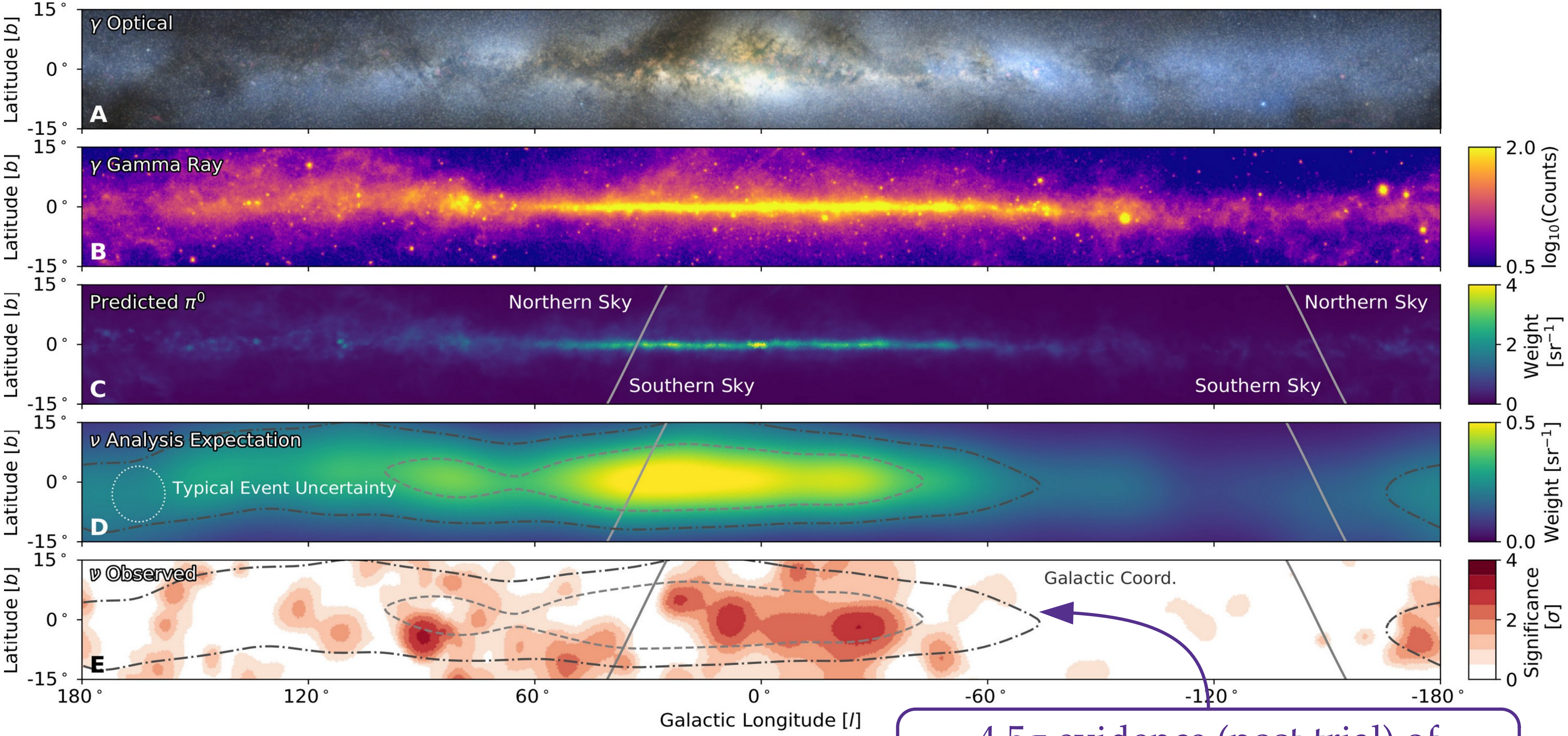
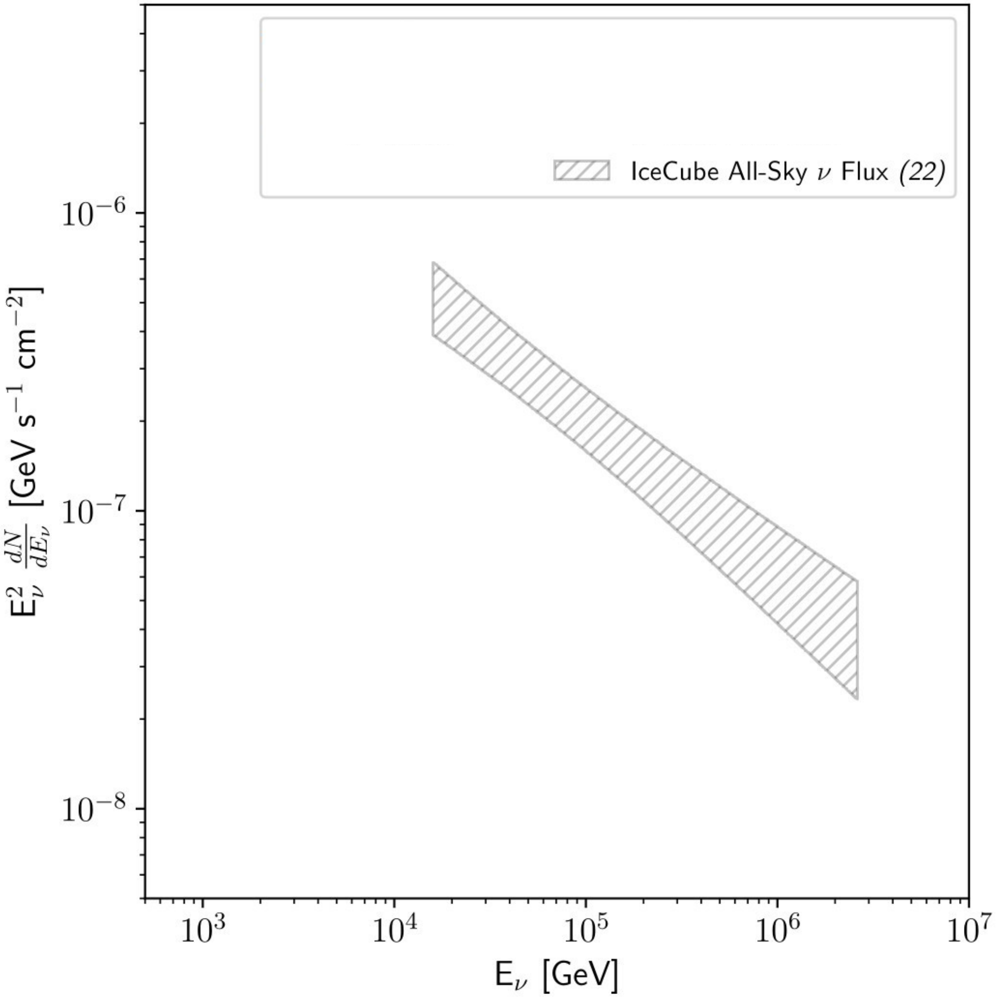


4.5σ evidence (post-trial) of diffuse flux of > TeV ν from the GP

IceCube Collab., *Science* 2023

High-energy neutrinos from the Galactic Plane



IceCube Collab., *Science* 2023

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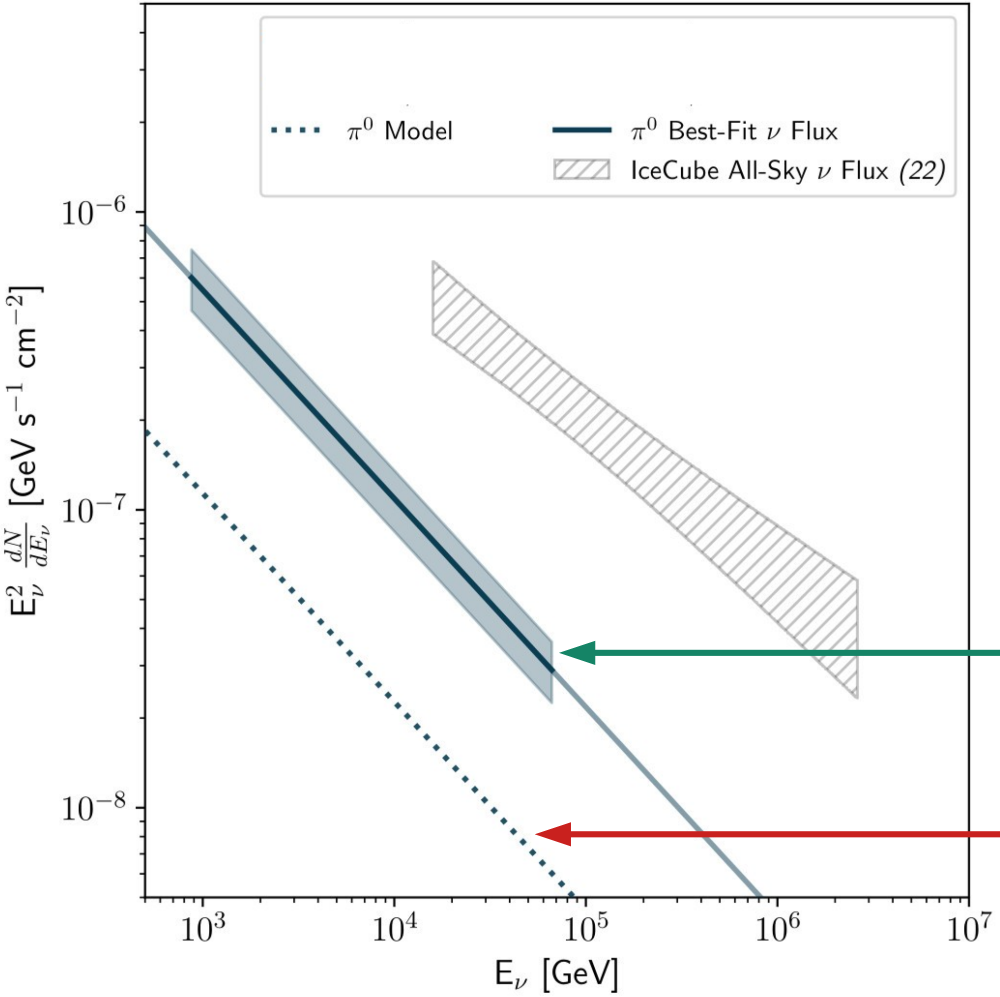


Three models of Galactic diffuse ν:

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

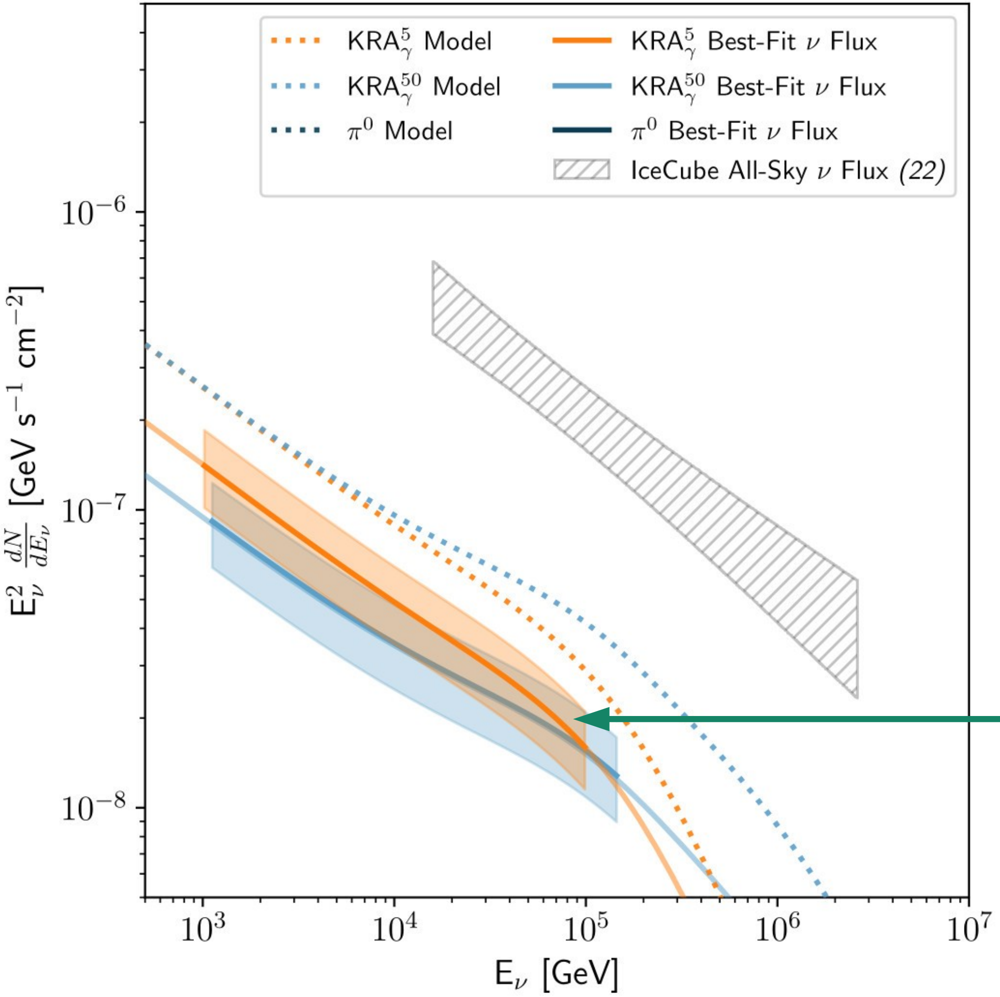
Observed (× 5 model)

Consistent with 100-TeV observations by Tibet Air Shower Array

Model

IceCube Collab., *Science* 2023

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

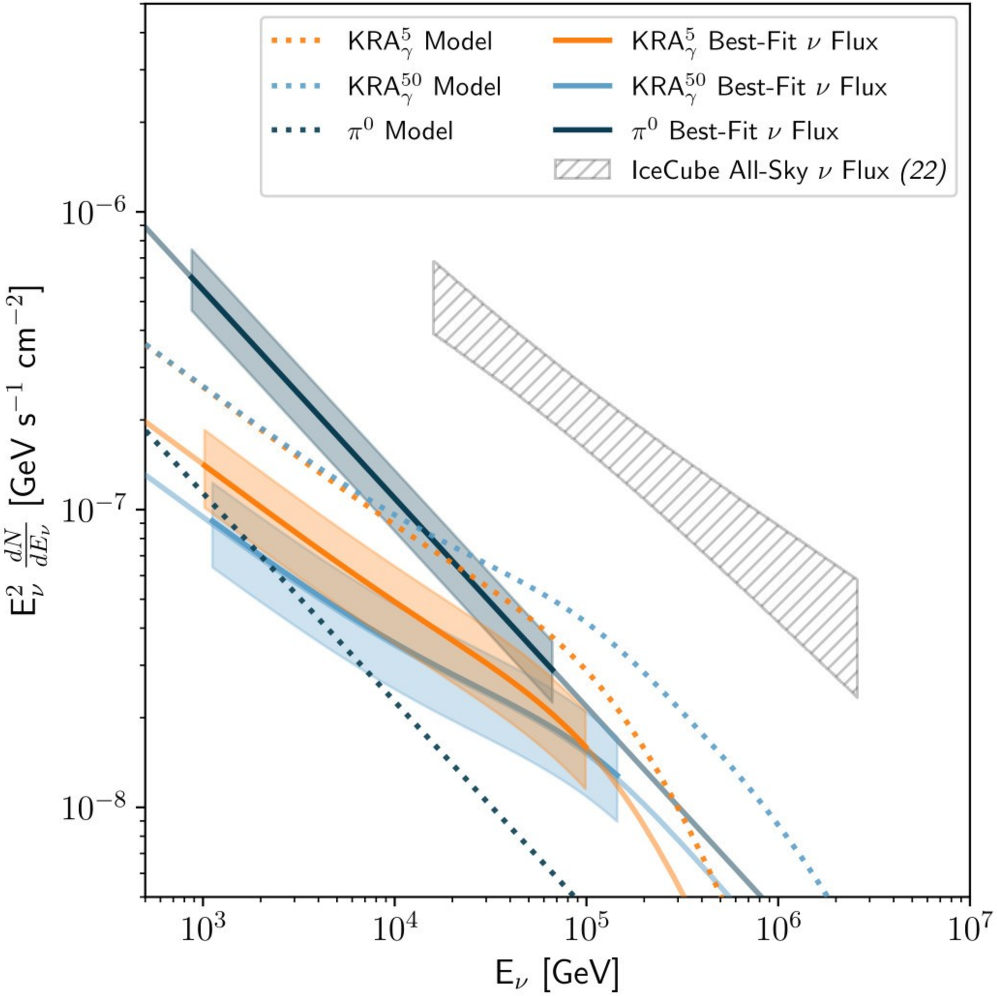
KRA_γ^{50} : Cut-off at 50 PeV in CR energy

Observed (× 0.5 model)

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

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 π⁰ template inferred from gamma rays extrapolated to TeV

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

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

None of the models matched data

(caveat: there are relatively simple models)

No Galactic ν source identified

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

GP flux is 6–13% of all-sky at 30 TeV

III.

What have we learned about *particle physics*

DM-ν interaction

DE-ν interaction

Lorentz+CPT violation

Neutrino decay

Heavy relics

Long-range interactions

DM annihilation

Secret νν interactions

Supersymmetry

DM decay

Sterile ν

Effective operators

Leptoquarks

Boosted DM

NSI

Extra dimensions

Superluminal ν

Monopoles

Note: Not an exhaustive list

Acts at production

- Heavy relics
- DM annihilation
- DM decay
- Sterile ν
- Boosted DM
- NSI

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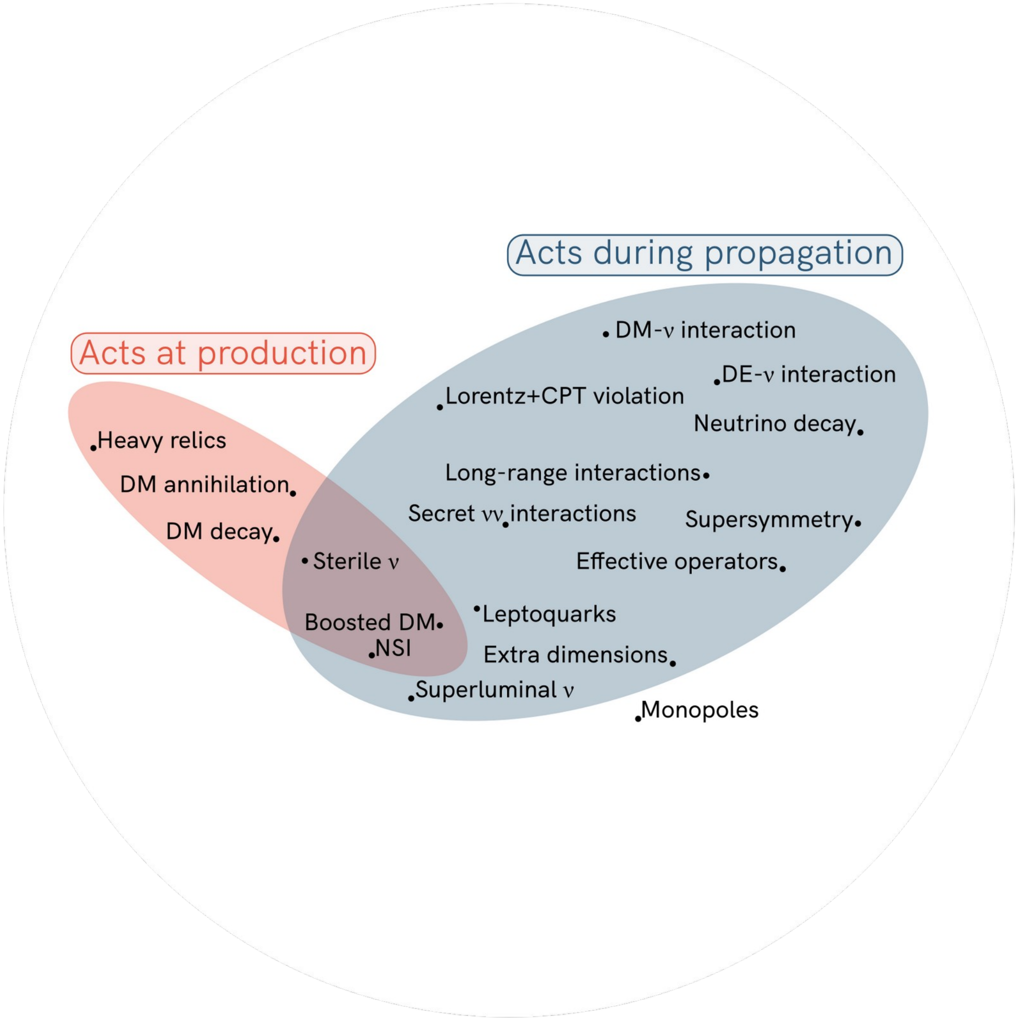

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Acts during propagation

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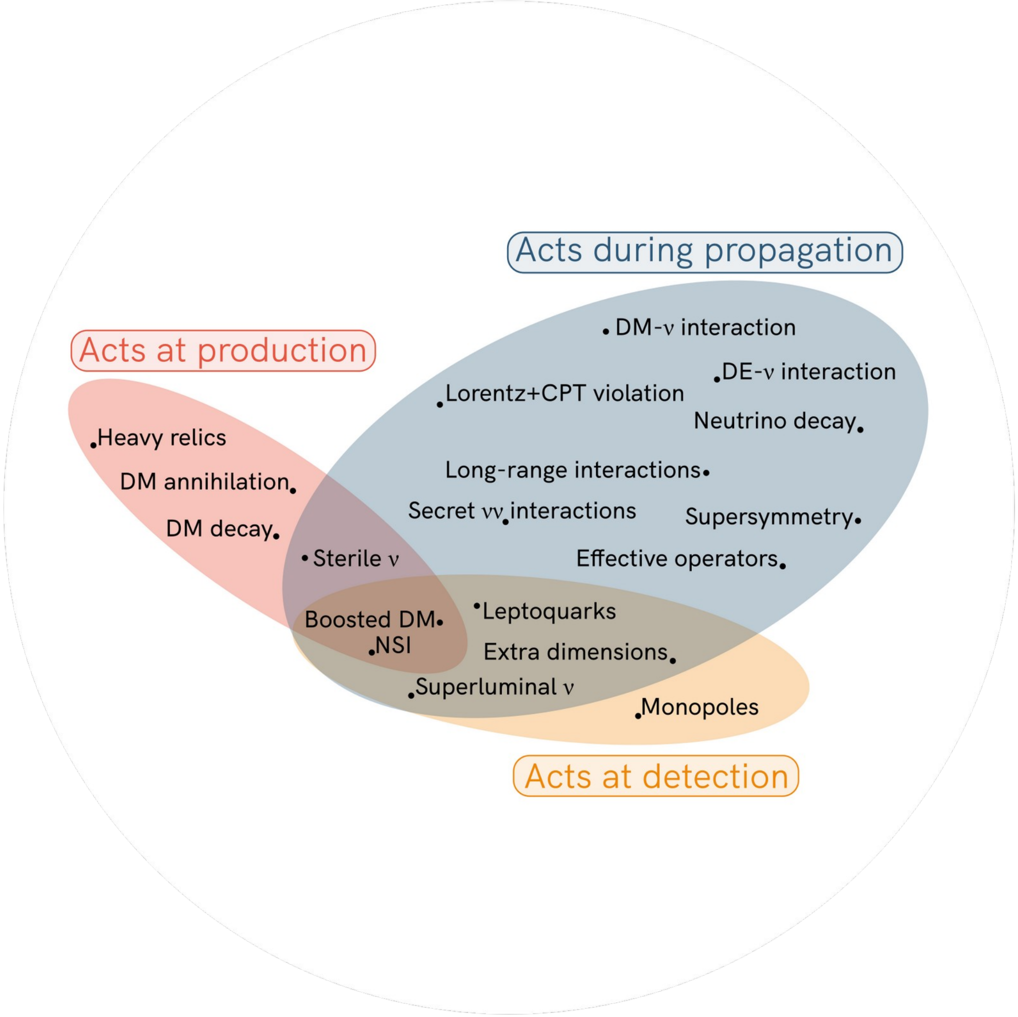
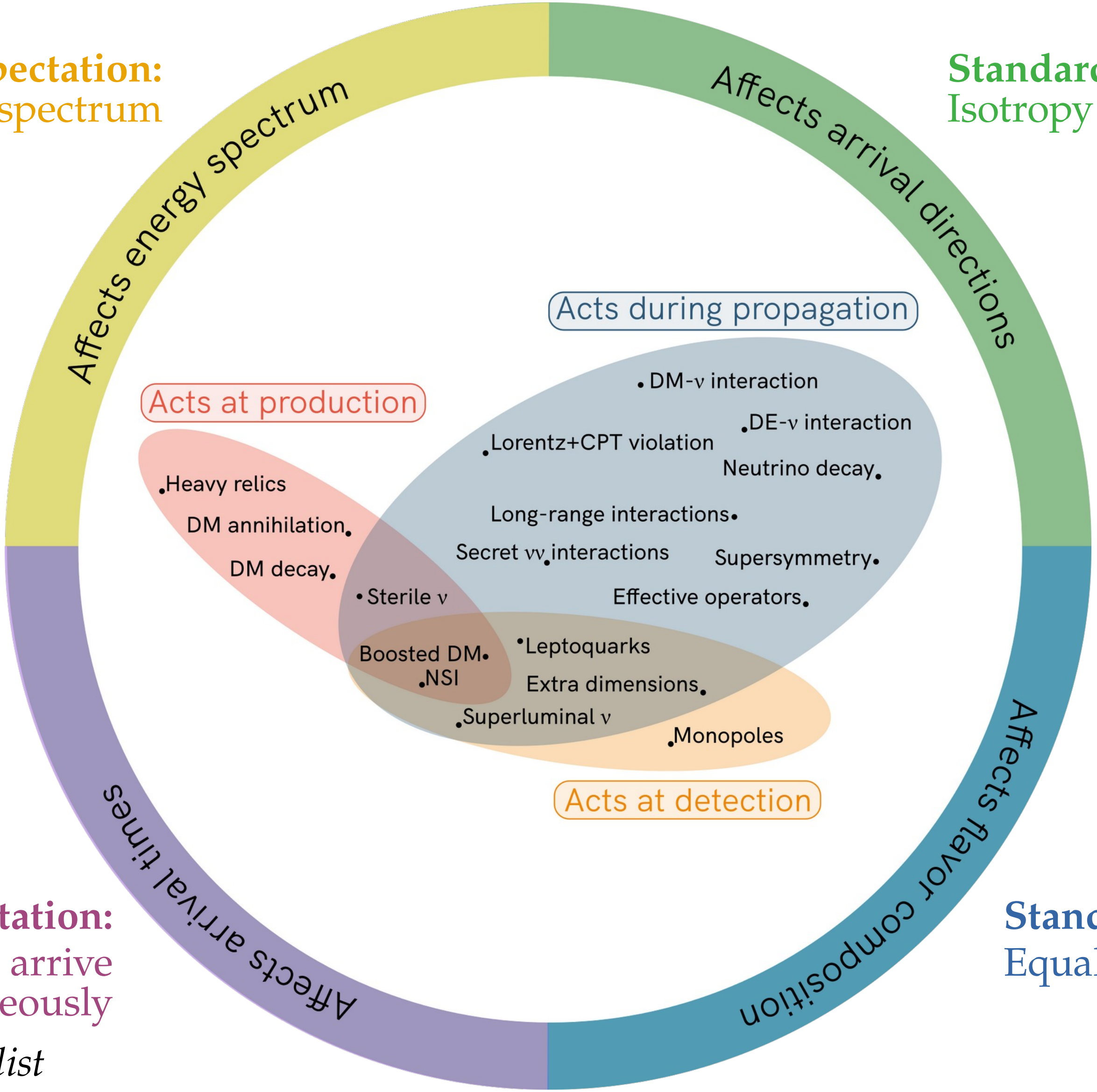


Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Affects energy spectrum

Affects arrival directions

Affects flavor composition

Affects arrival times

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- Heavy relics
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- DM decay

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Acts at detection

Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

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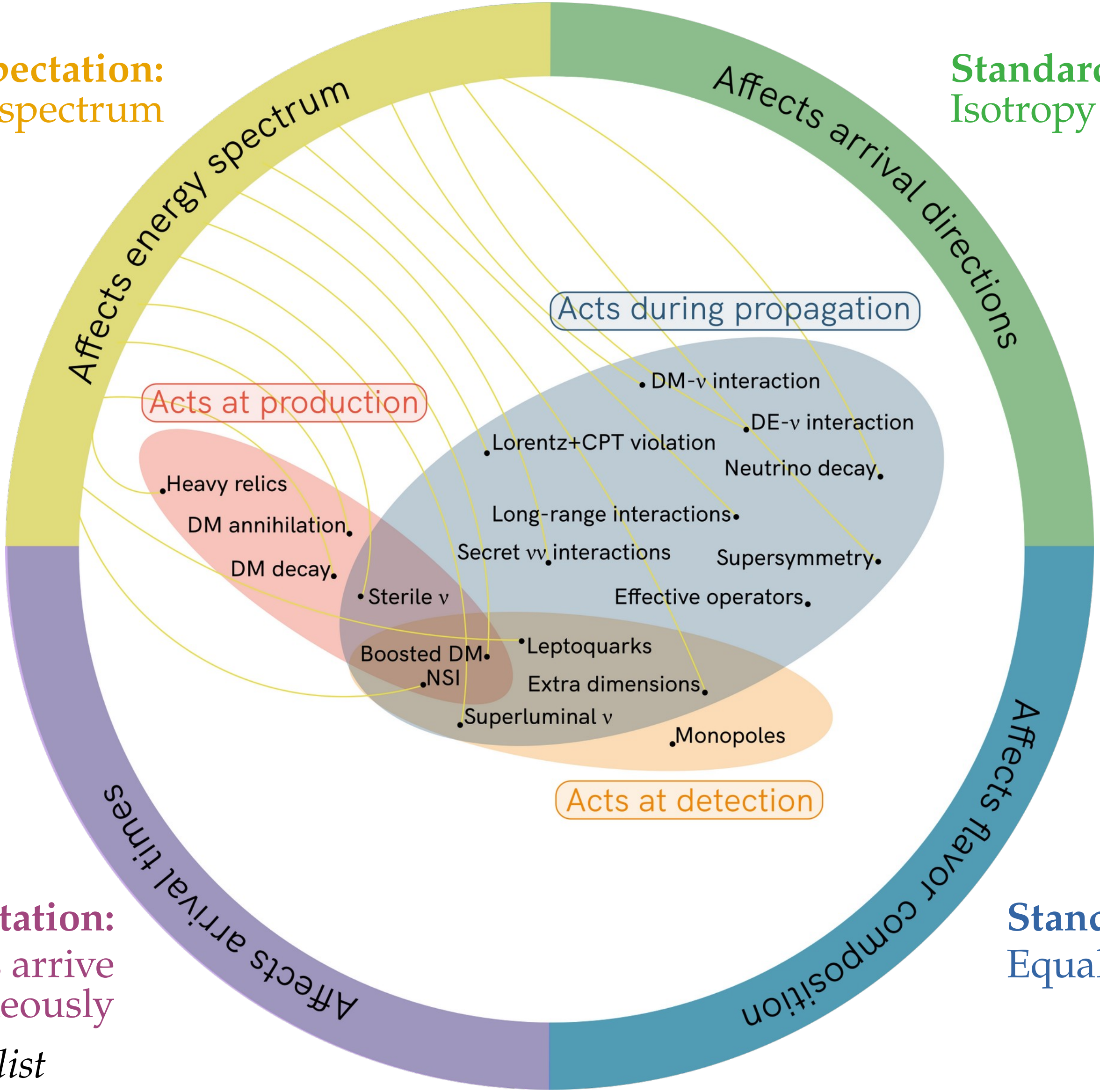

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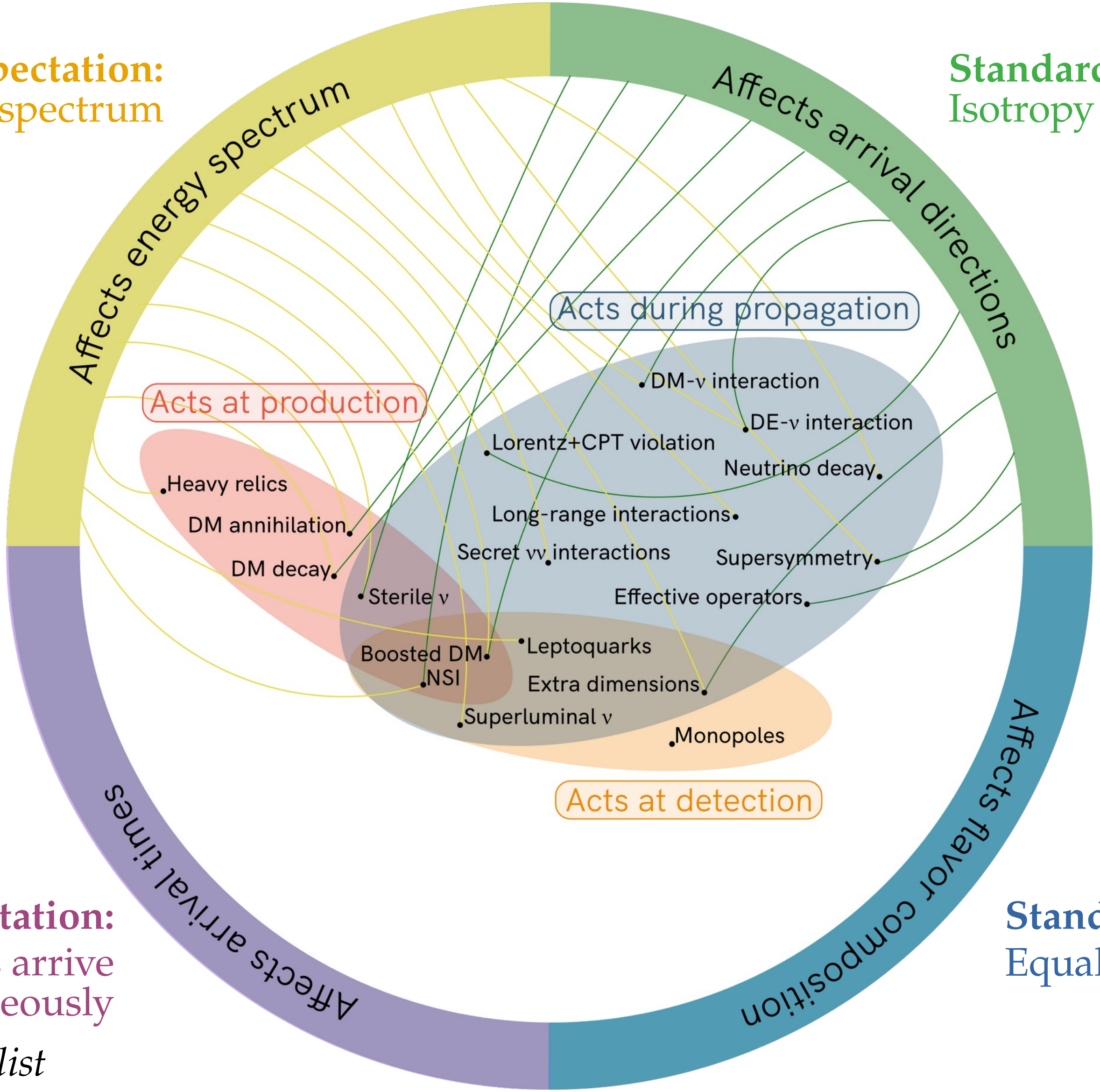

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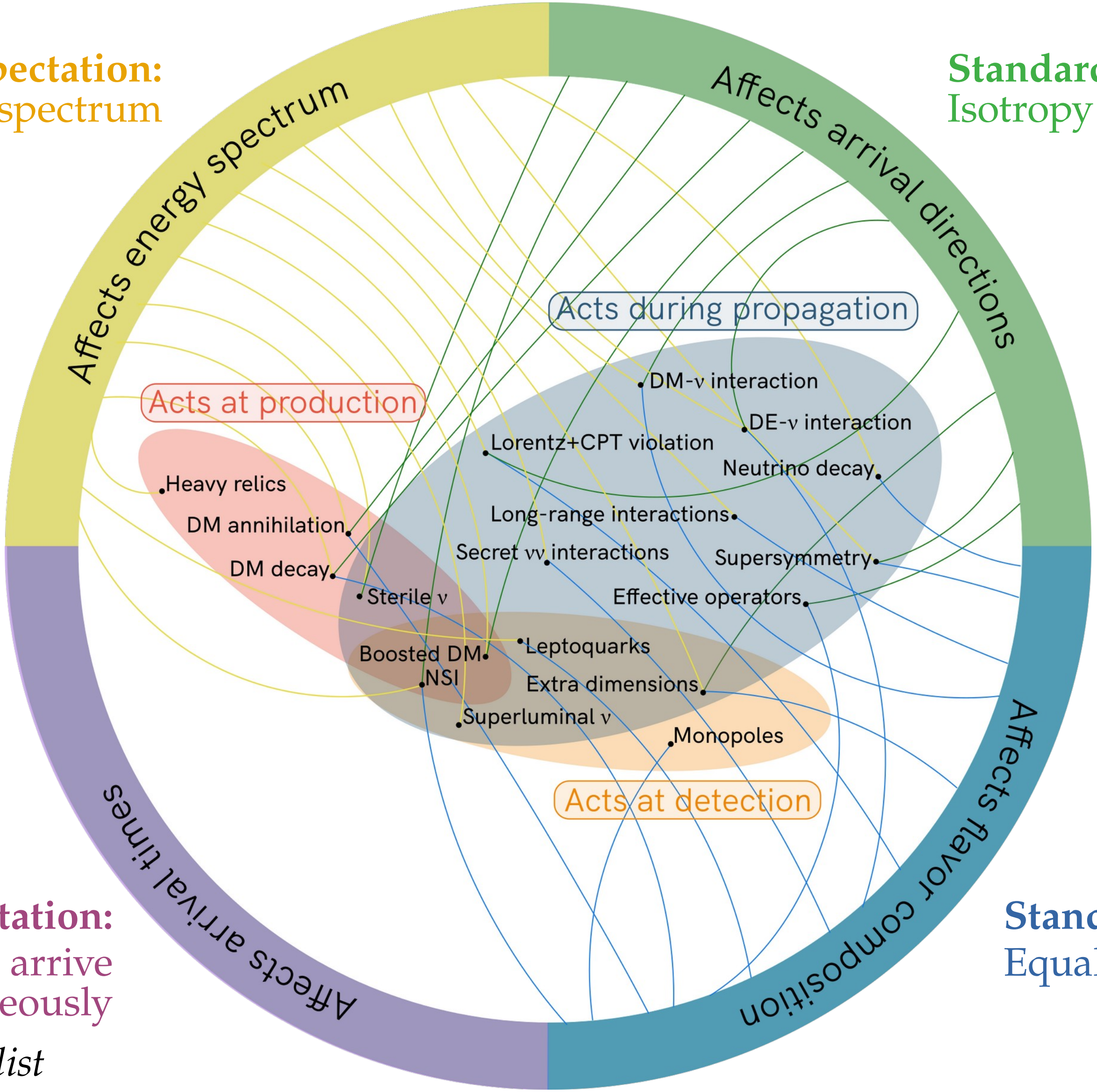

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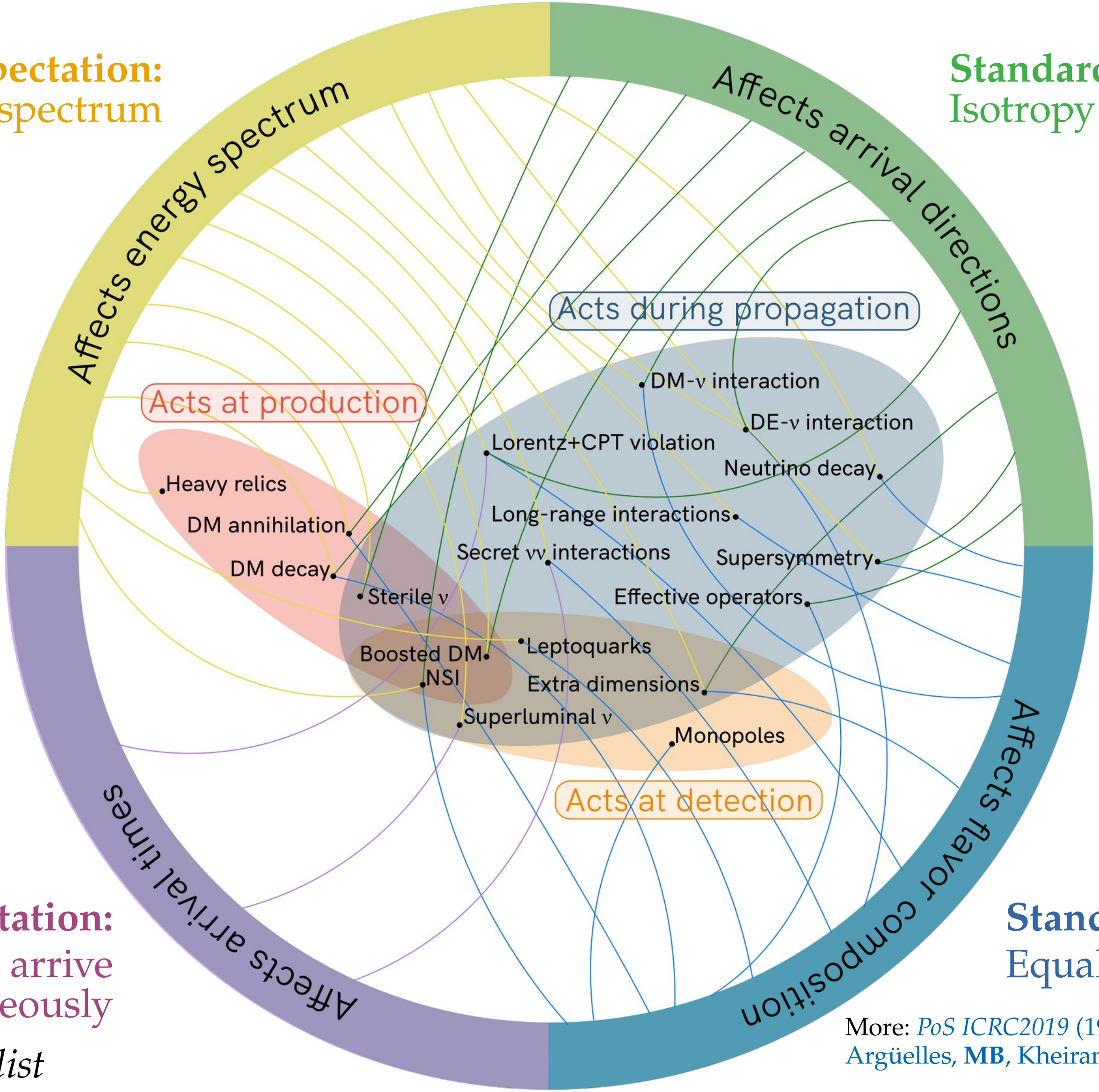
Power-law energy spectrum

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

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

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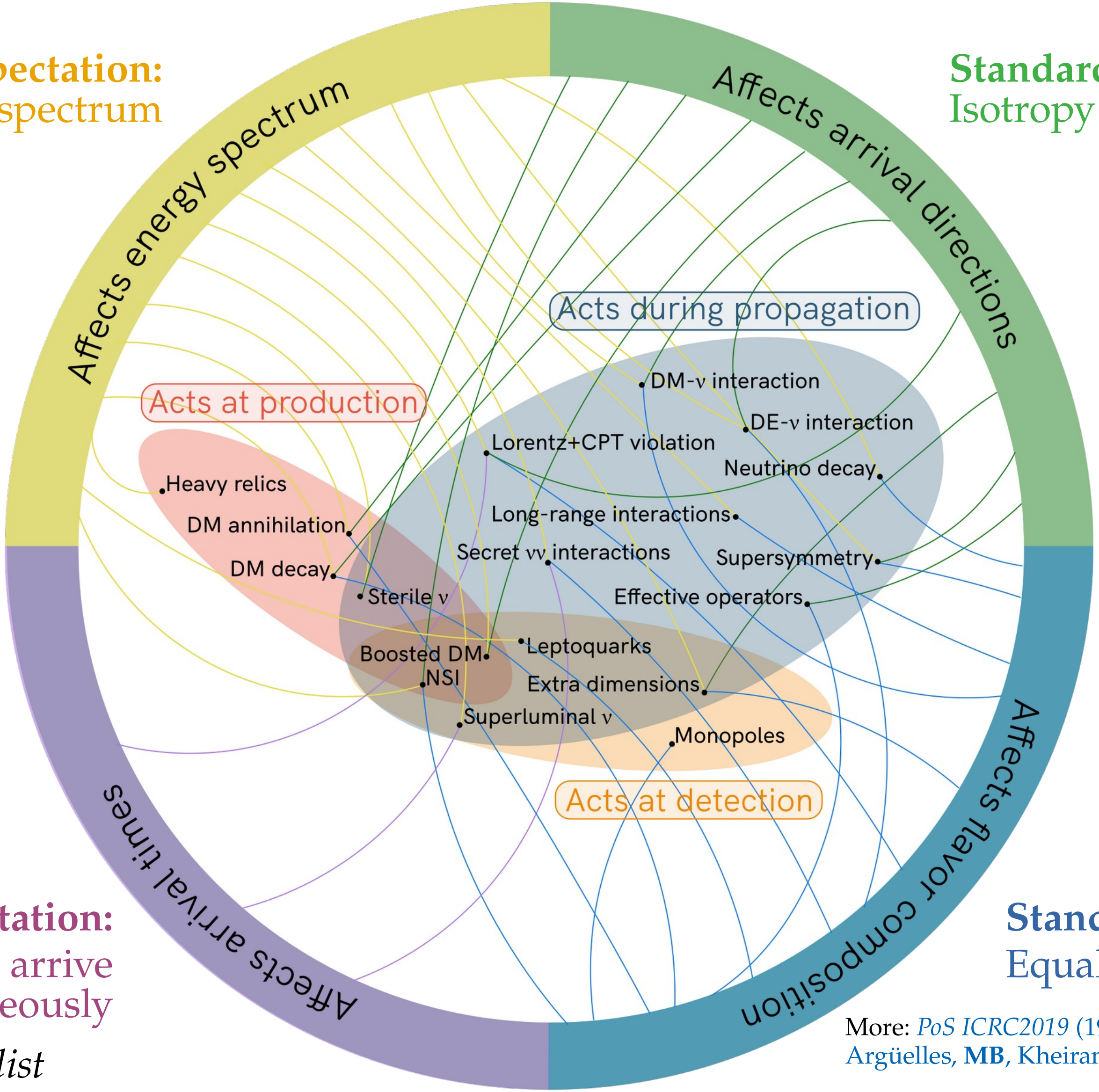

Affects energy spectrum

Affects arrival directions

Affects flavor composition

Affects arrival times

Acts during propagation

Acts at production

Acts at detection

DM-ν interaction

DE-ν interaction

Lorentz+CPT violation

Neutrino decay

Heavy relics

DM annihilation

Long-range interactions

DM decay

Secret νν interactions

Supersymmetry

Sterile ν

Effective operators

Leptoquarks

Boosted DM

NSI

Extra dimensions

Superluminal ν

Monopoles

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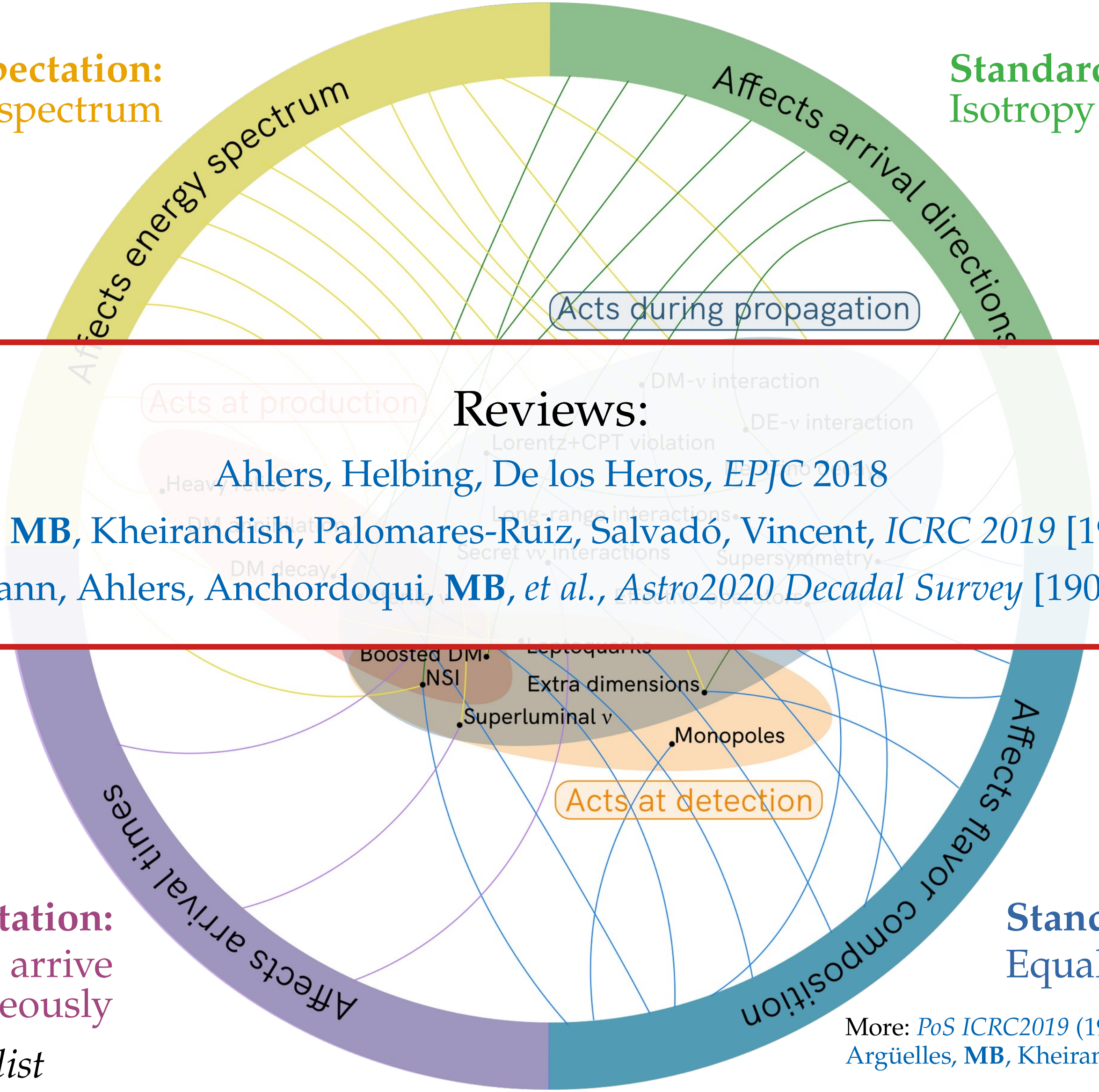
Reviews:

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

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

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



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Fundamental physics with high-energy cosmic neutrinos

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

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

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

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

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E.g.,
n = -1: neutrino decay
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In spite of
poor energy, angular, flavor reconstruction
& astrophysical unknowns

Two examples

1. Flavor stuff
2. Cross-section stuff

Good chances of discovery or setting strong bounds

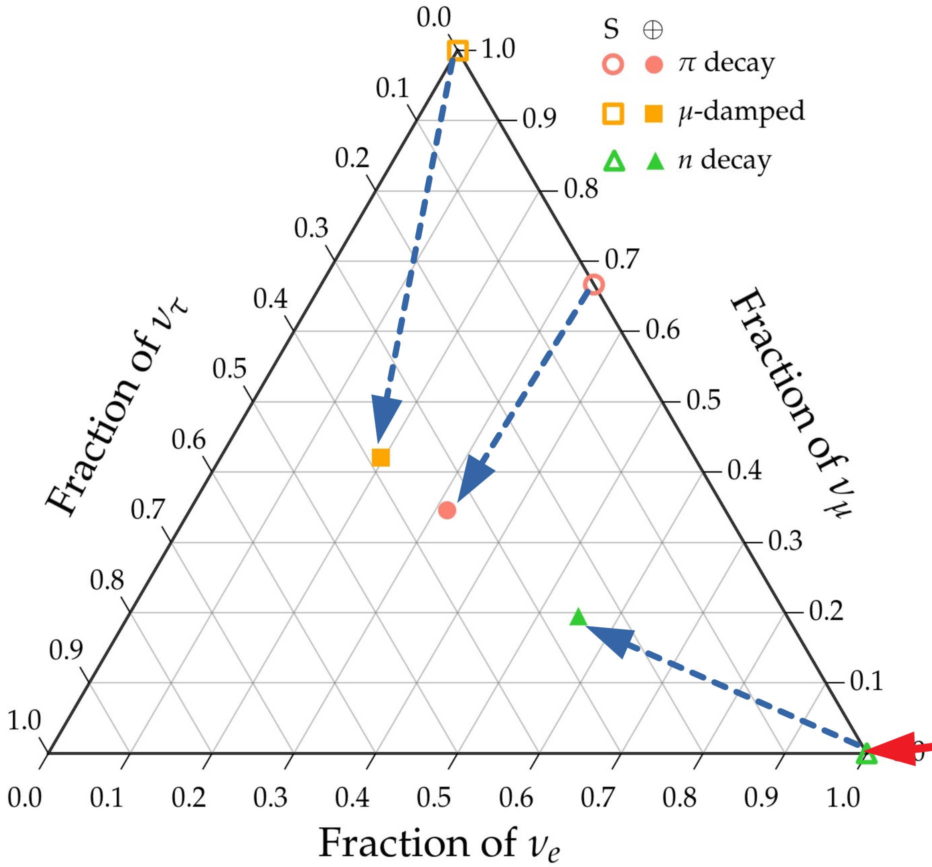
Flavor:

Towards precision, finally

(with the help of lower-energy experiments)

One likely TeV–PeV ν production scenario:

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



Full π decay chain

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

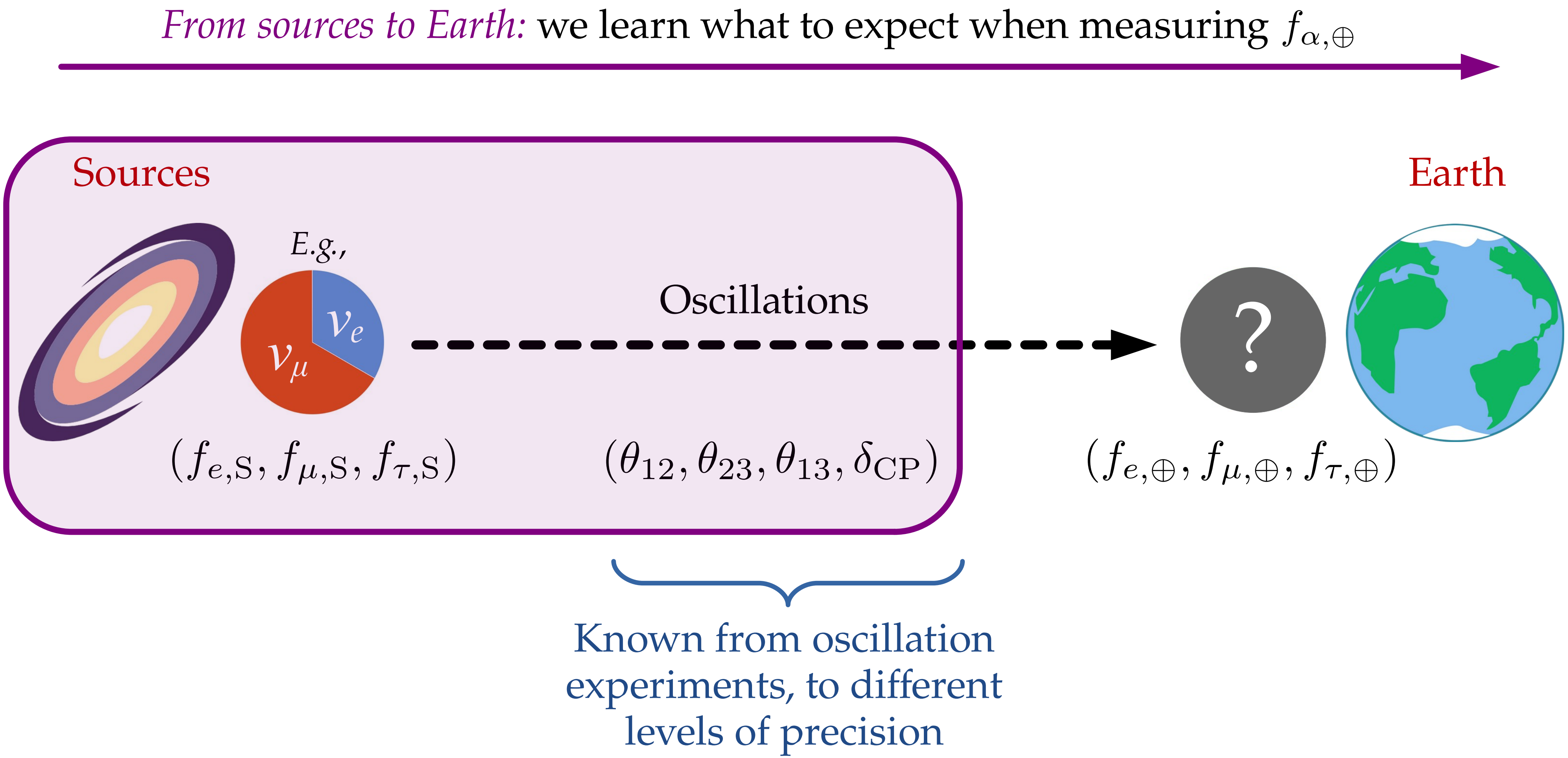
Muon damped

$(0:1:0)_S$

Neutron decay

$(1:0:0)_S$

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



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

Sources

E.g.,

ν_e

ν_μ

Oscillations

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

$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$

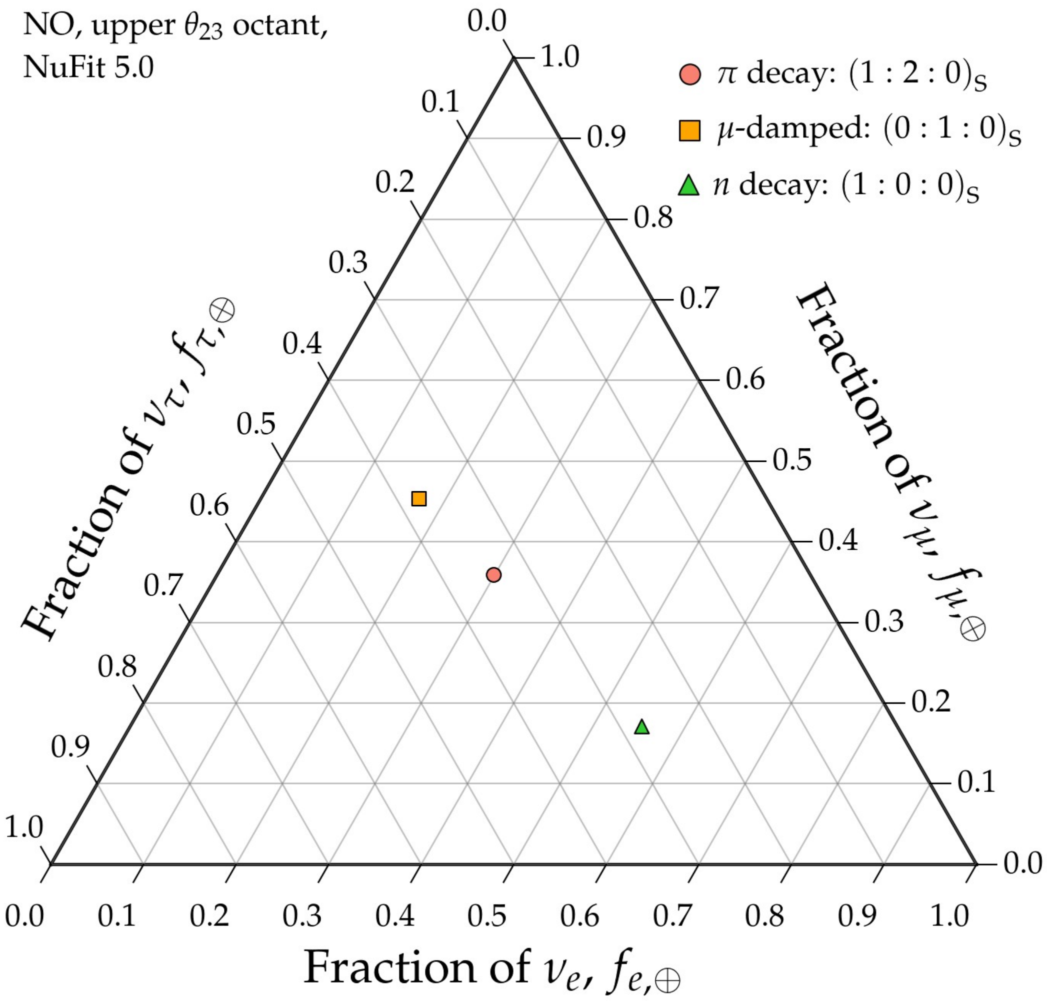
Earth

?

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

Known from oscillation
experiments, to different
levels of precision

Theoretically palatable regions: today (2021)



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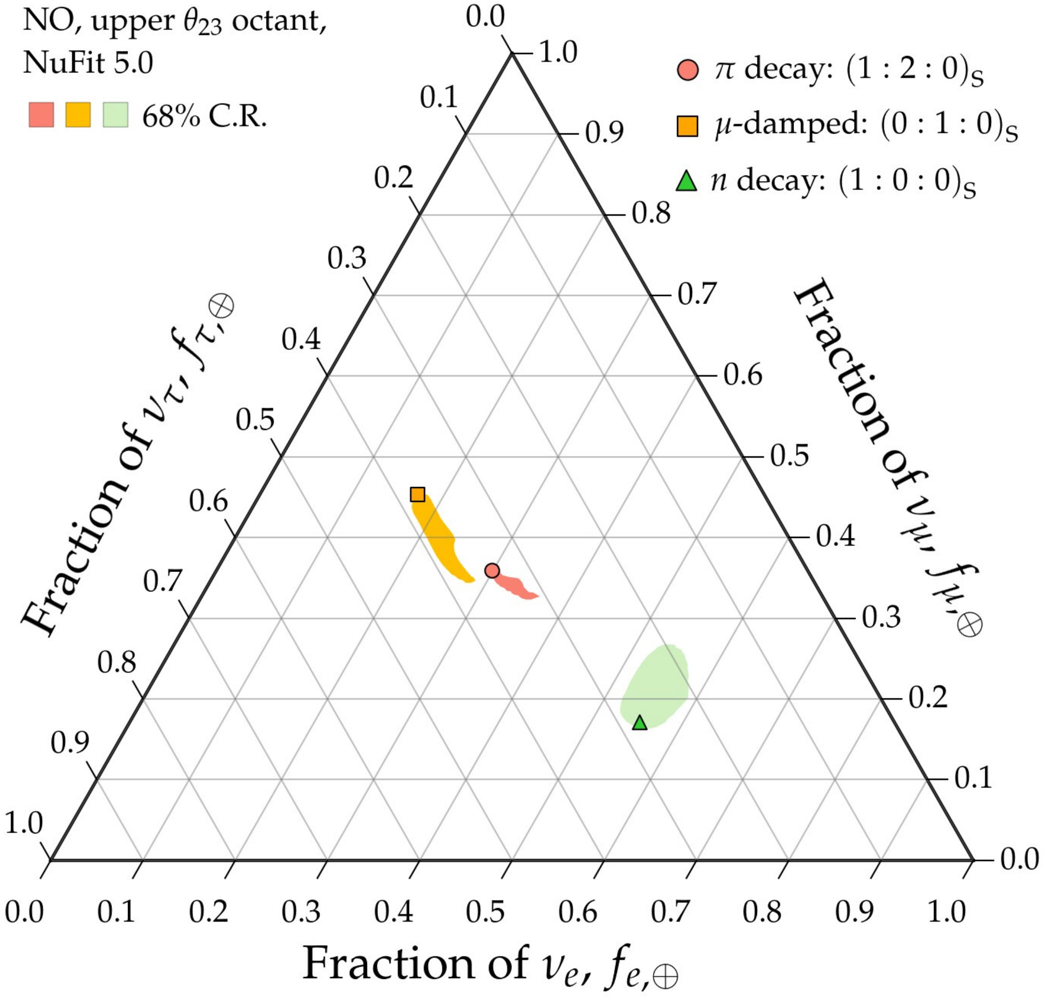
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: today (2021)



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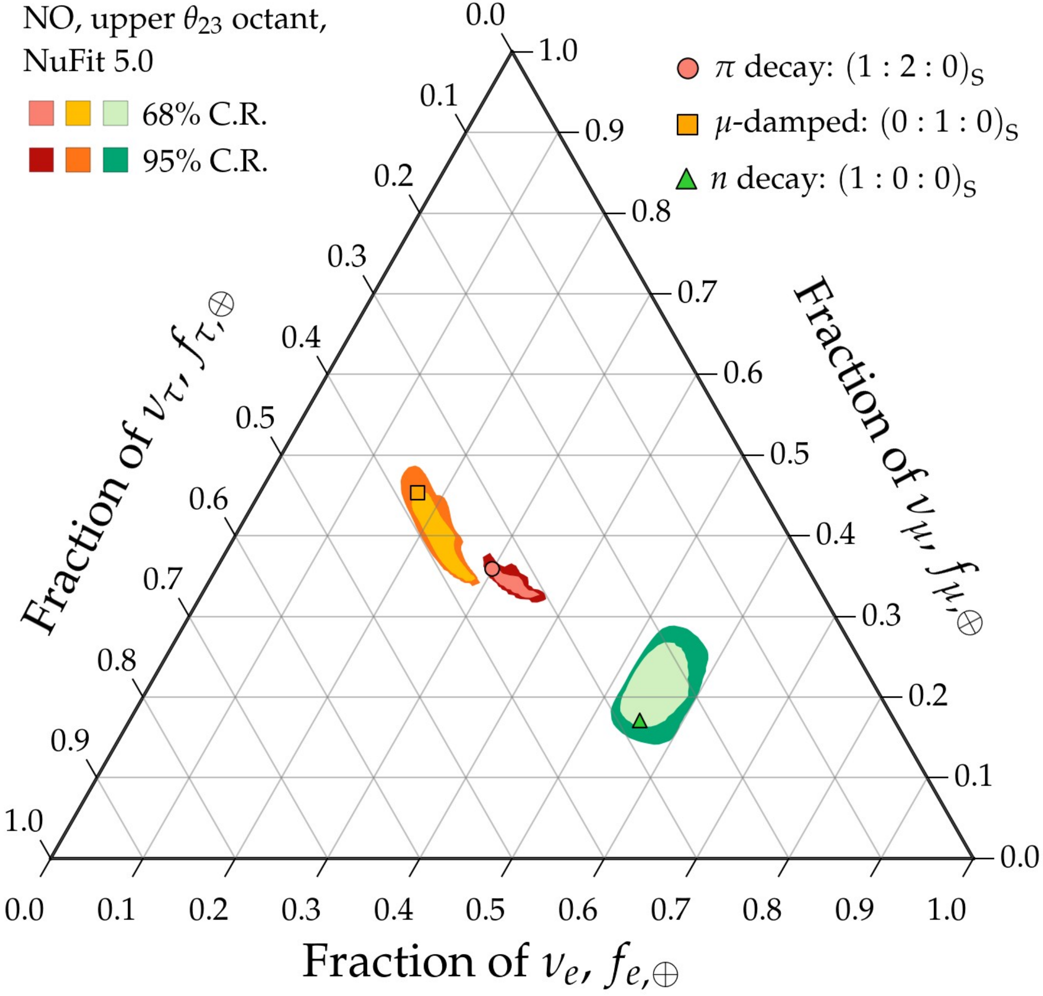
Theoretically palatable regions: today (2021)



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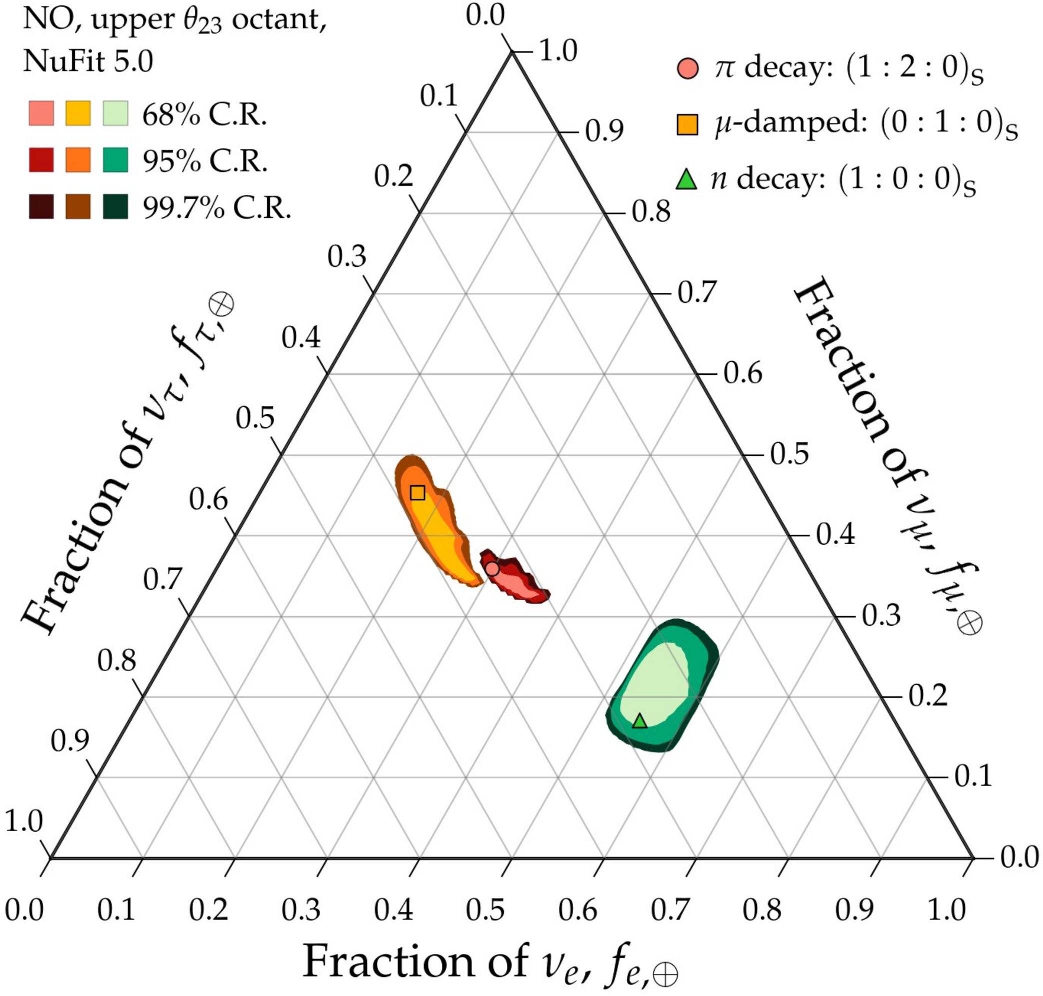
Theoretically palatable regions: today (2021)



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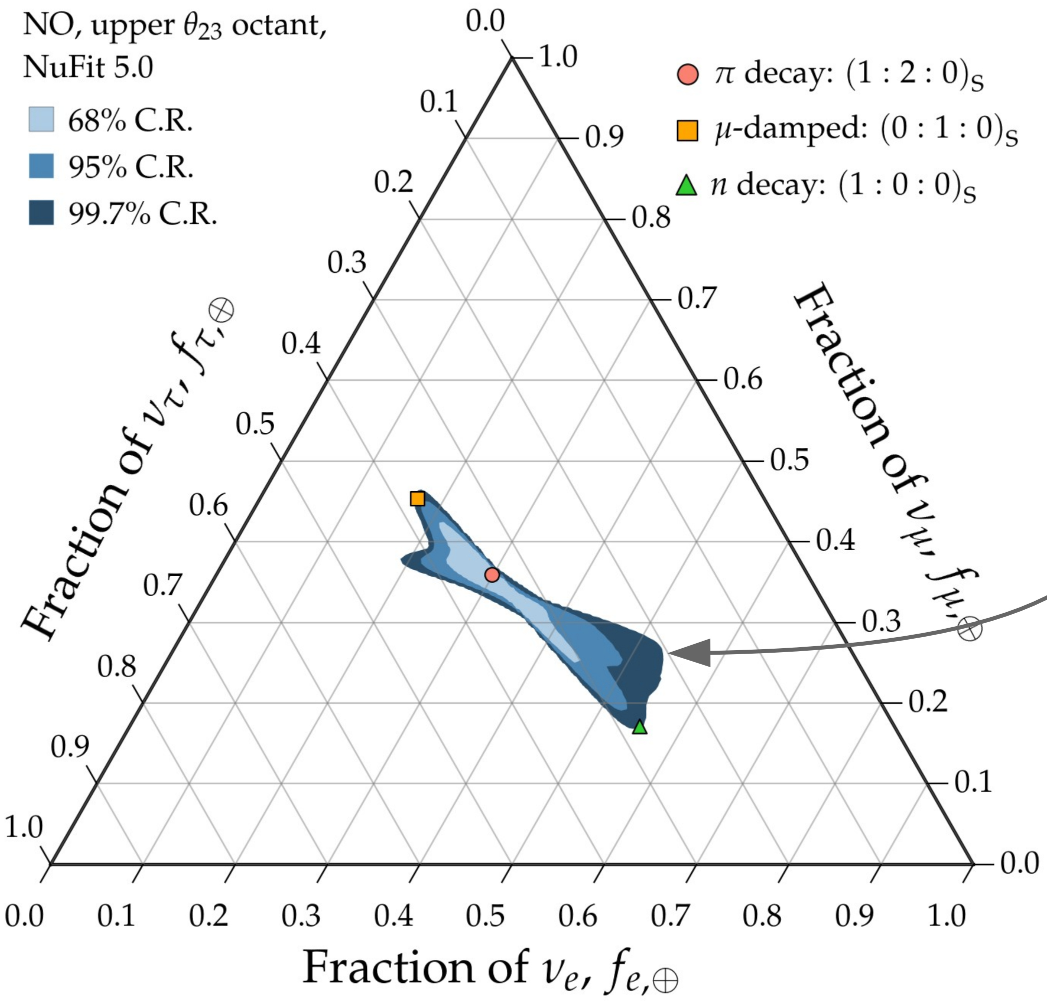

Varying over all possible flavor ratios at the source

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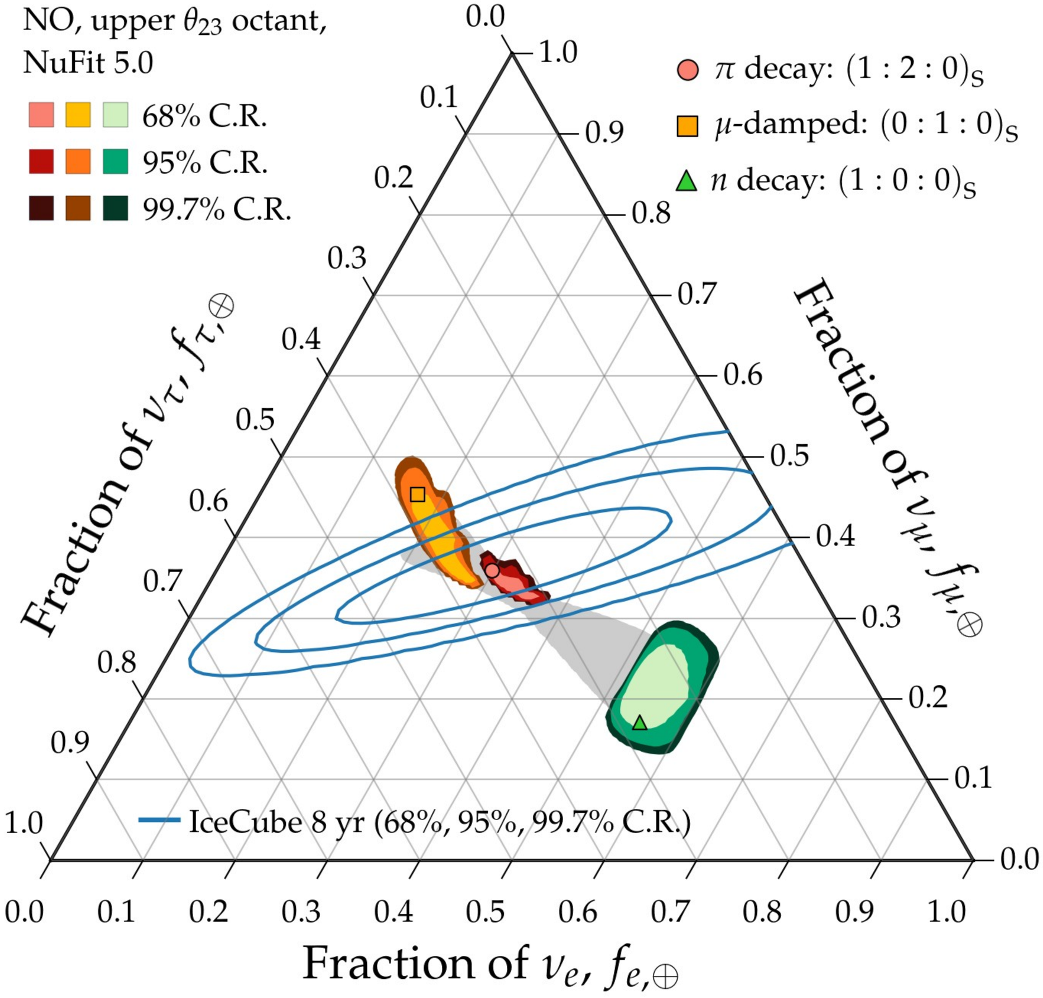
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: today (2021)



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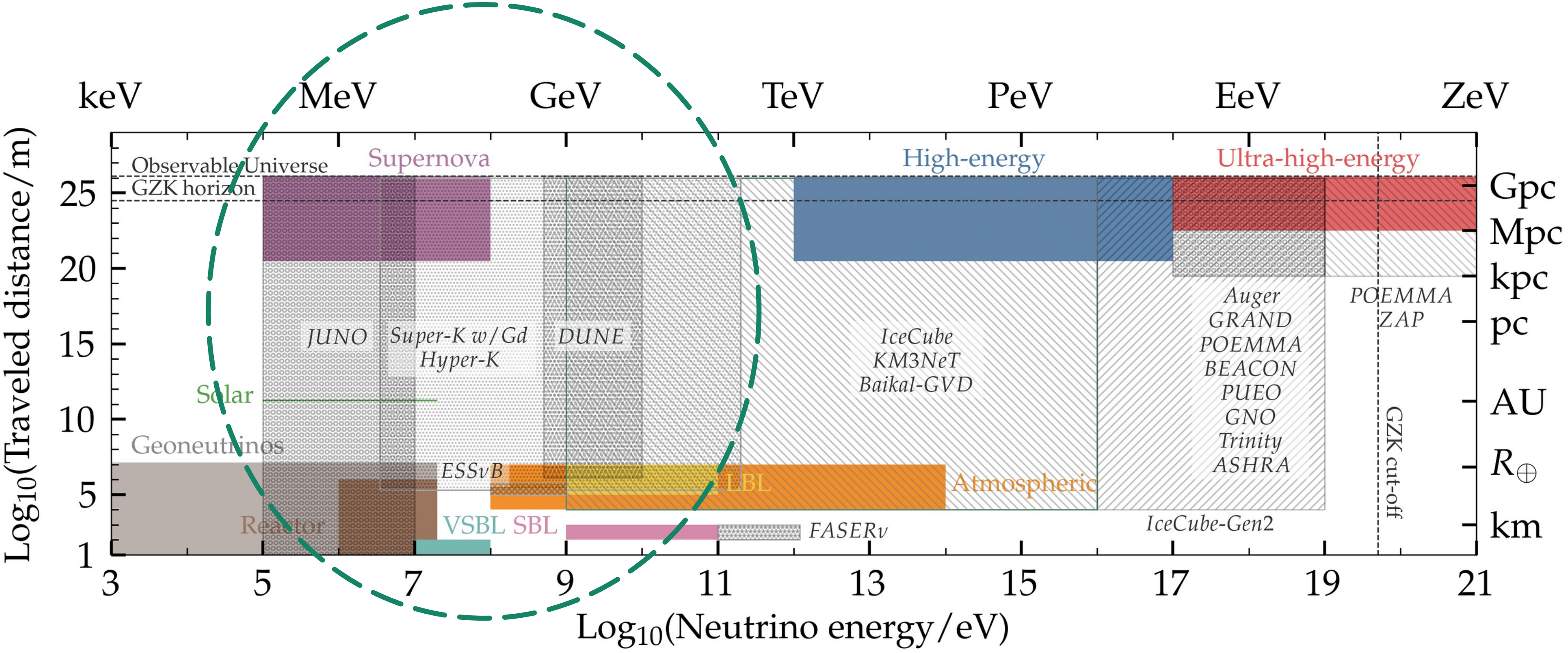
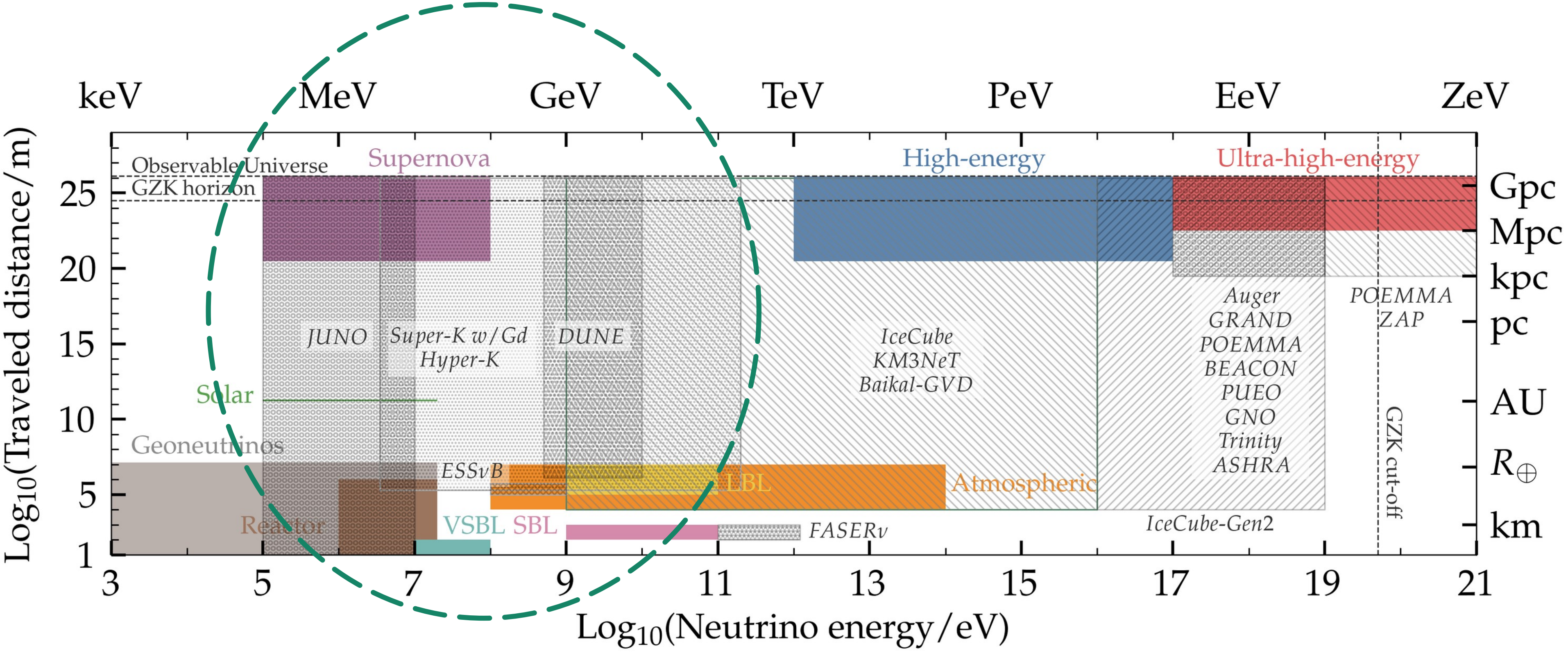
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Next decade: a host of planned neutrino detectors



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

Next decade: a host of planned neutrino detectors



Increase TeV–PeV
ν statistics

Discover > EeV ν

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

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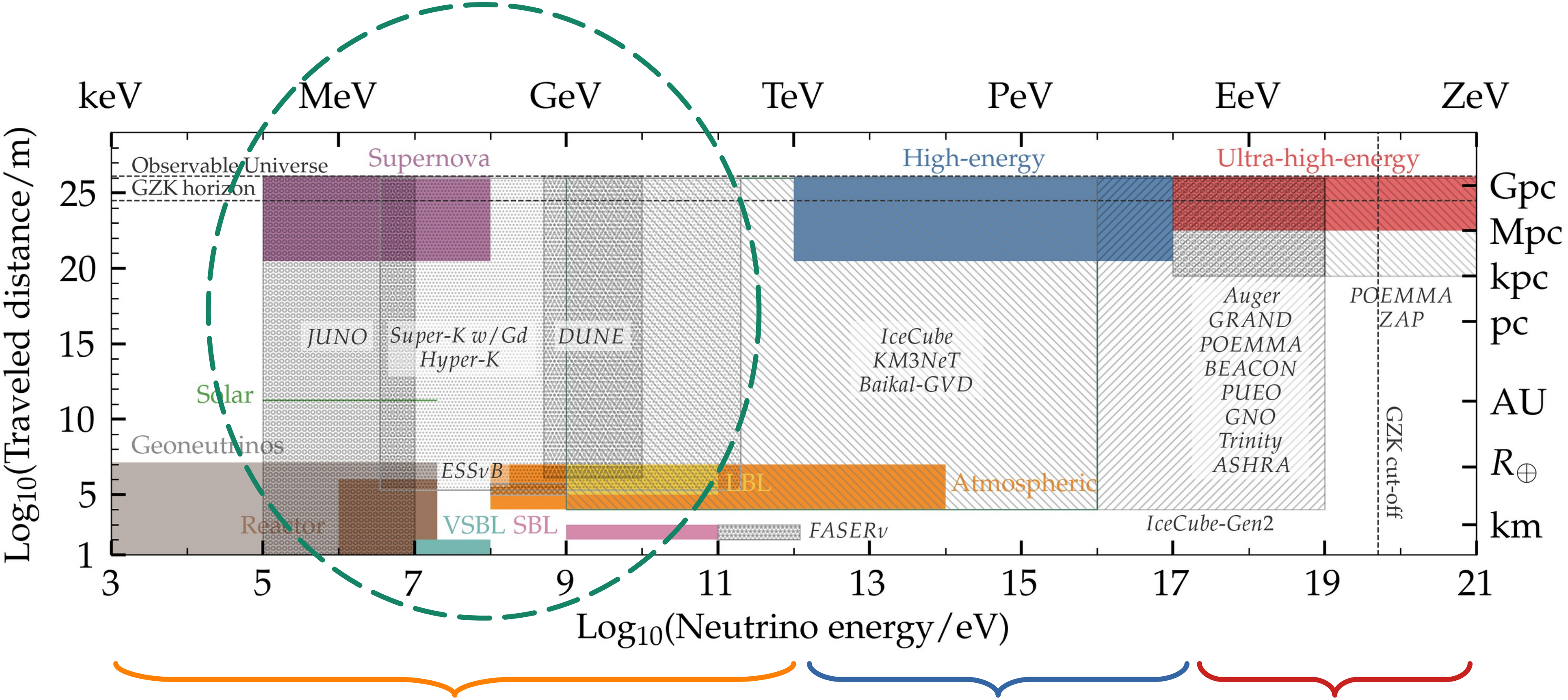


Synergies with lower energies

Increase TeV–PeV
ν statistics

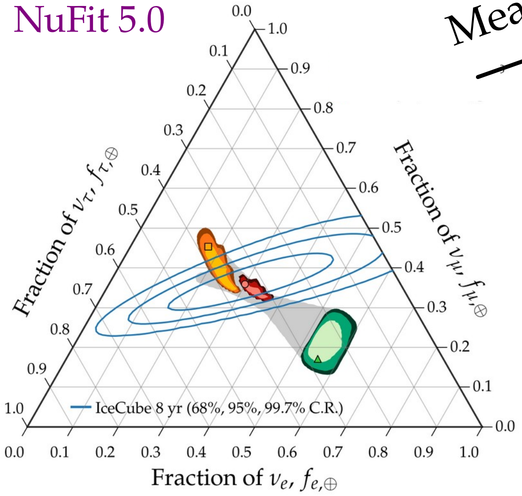
Discover > EeV ν

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

Knowing the mixing parameters better helps

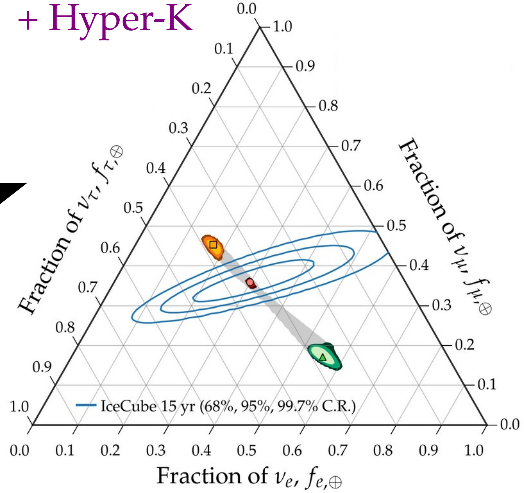
2020

NuFit 5.0

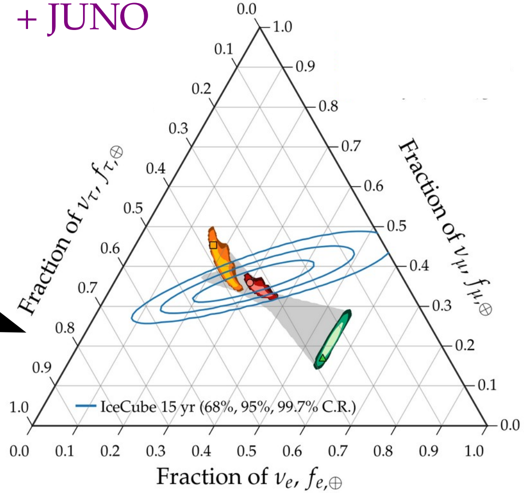


Measure θ_{23} better

+ Hyper-K



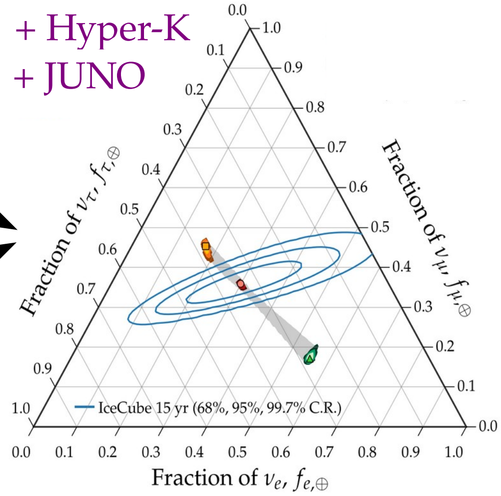
+ JUNO



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

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Power-law energy spectrum

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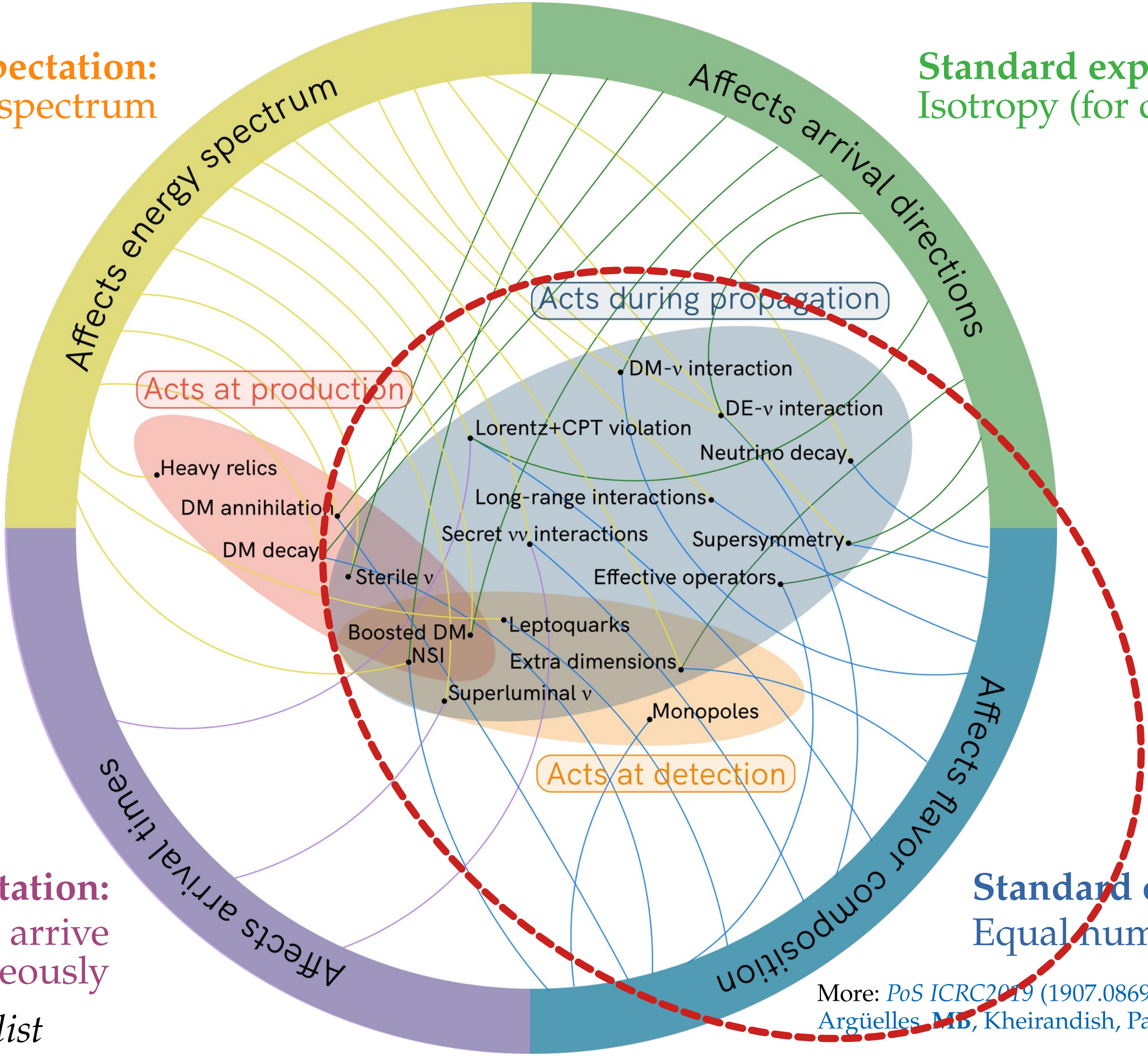

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New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

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Reviews:
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- Neutrino decay
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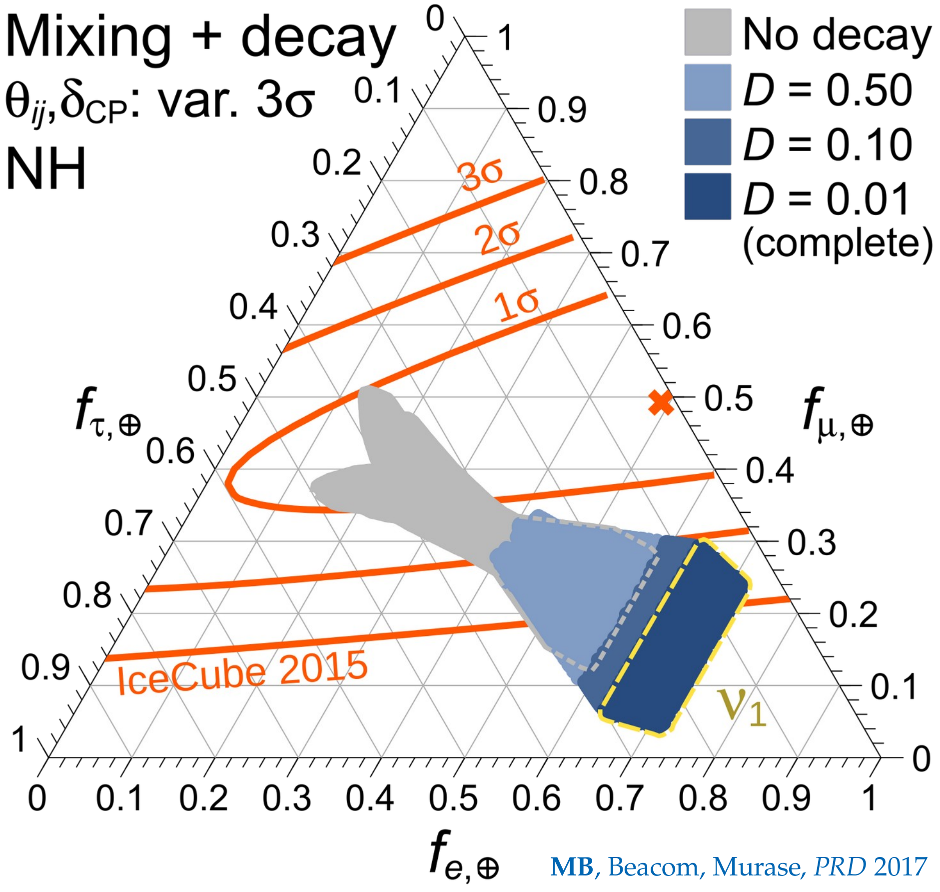

MB, Beacom, Murase, *PRD* 2017

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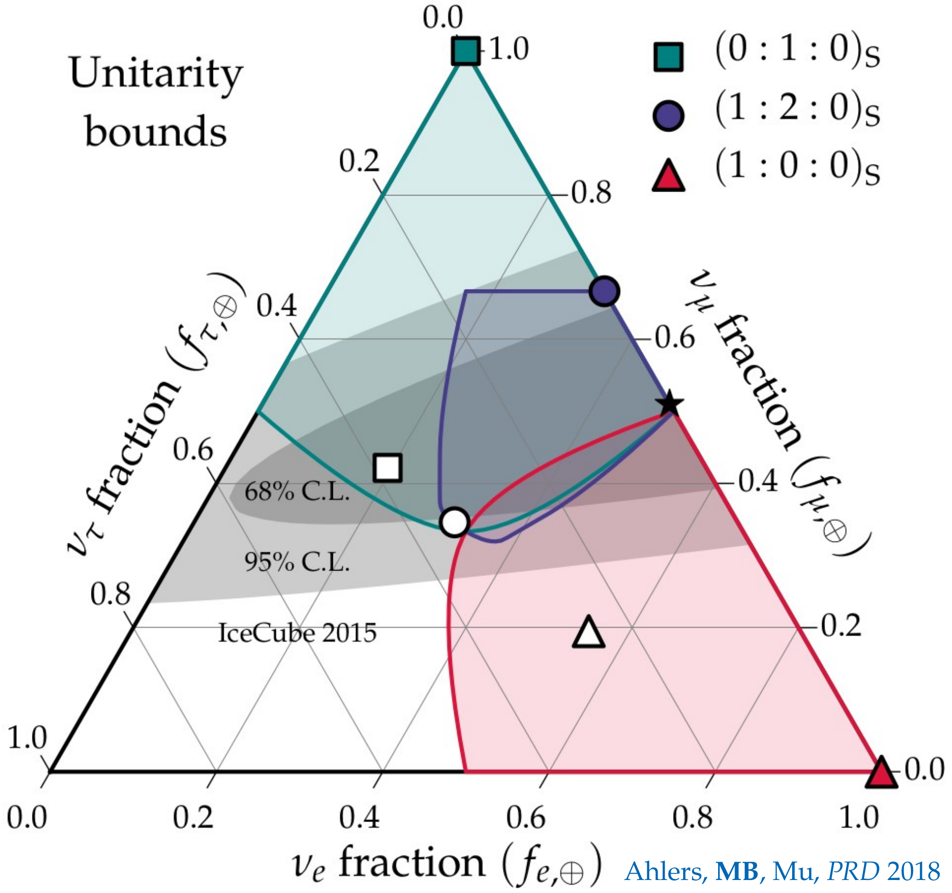

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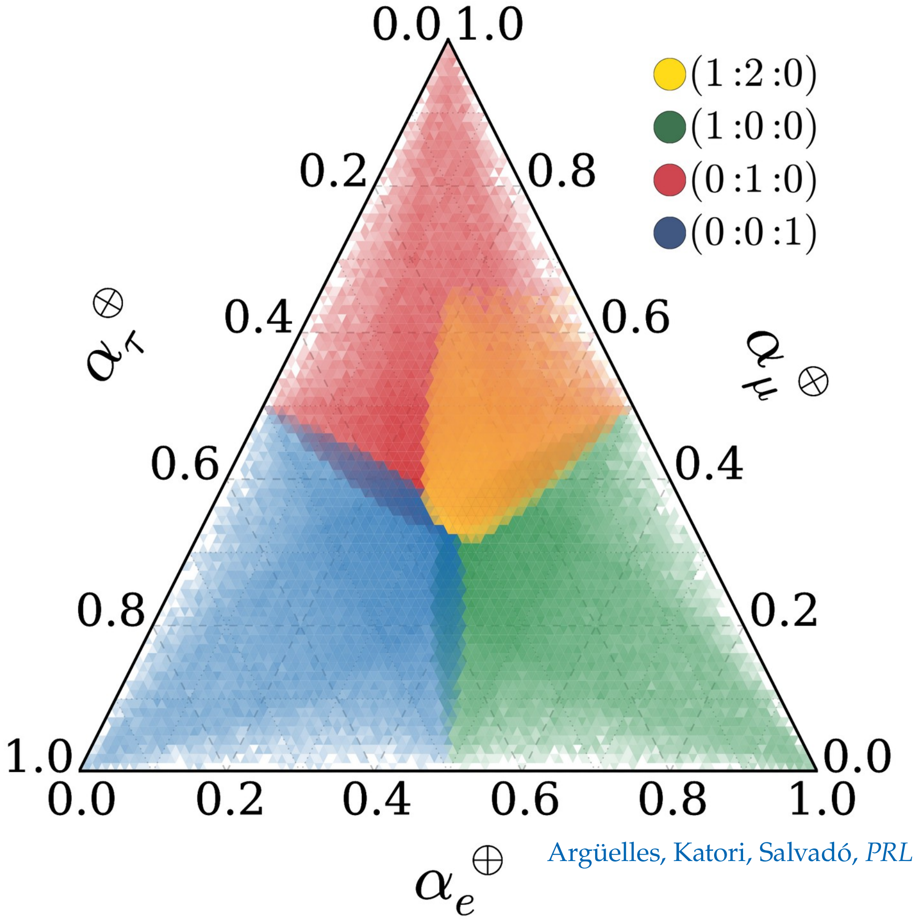

Argüelles, Katori, Salvadó, *PRL* 2015

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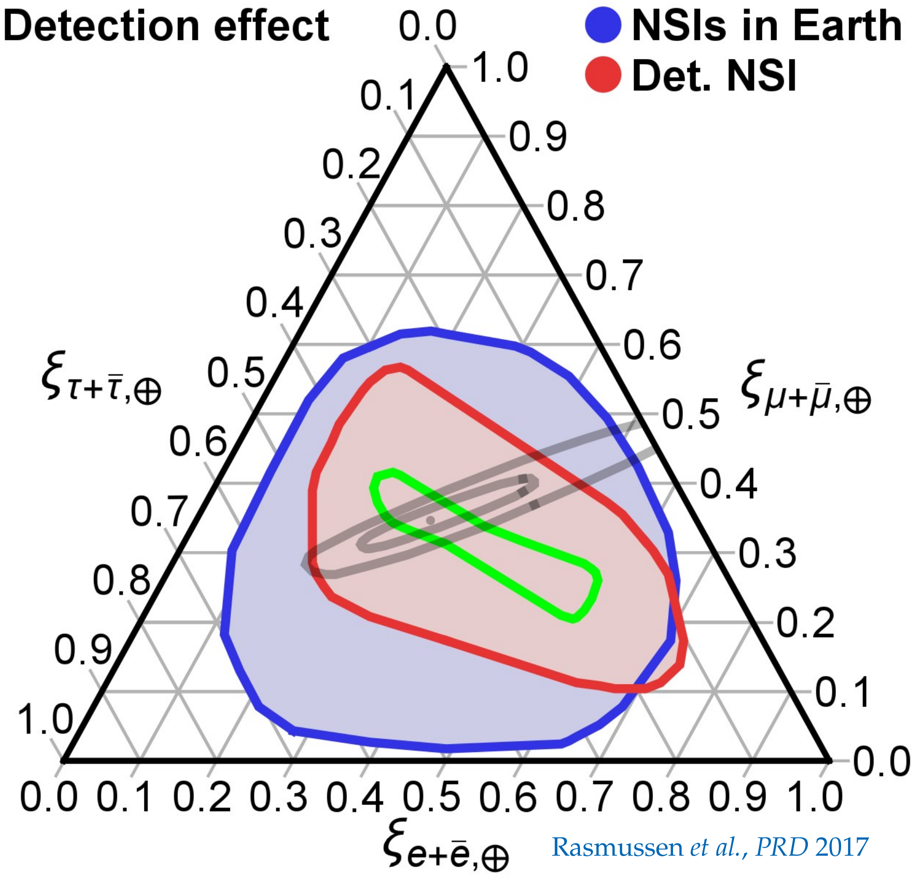

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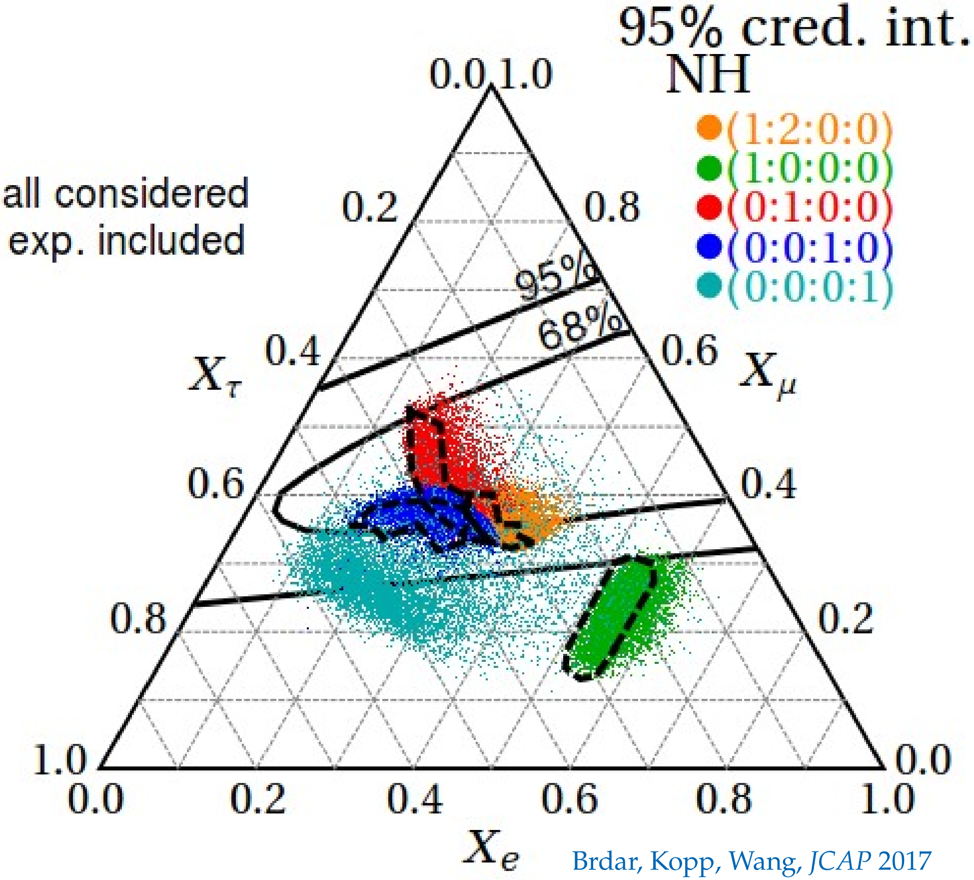

Brdar, Kopp, Wang, *JCAP* 2017

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

Reviews:
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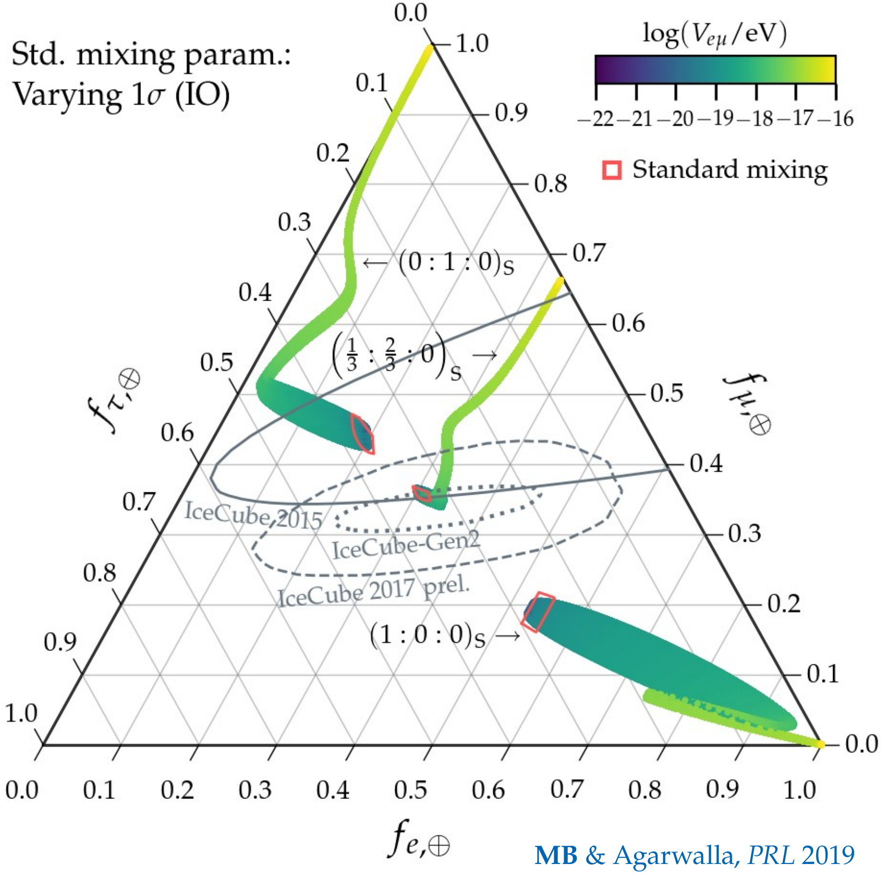
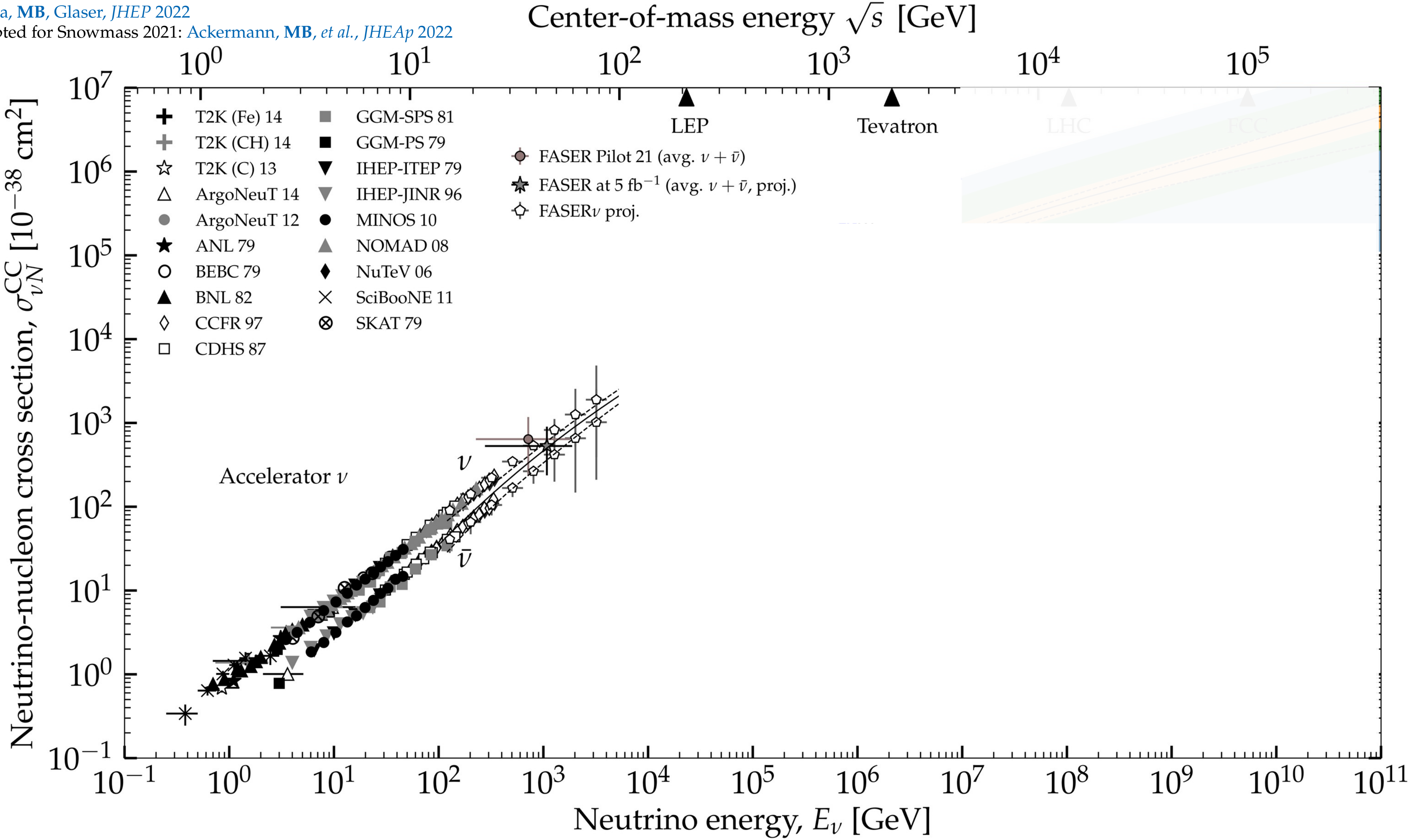


MB & Agarwalla, *PRL* 2019

Neutrino-nucleon cross section:

From high to ultra-high energies



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

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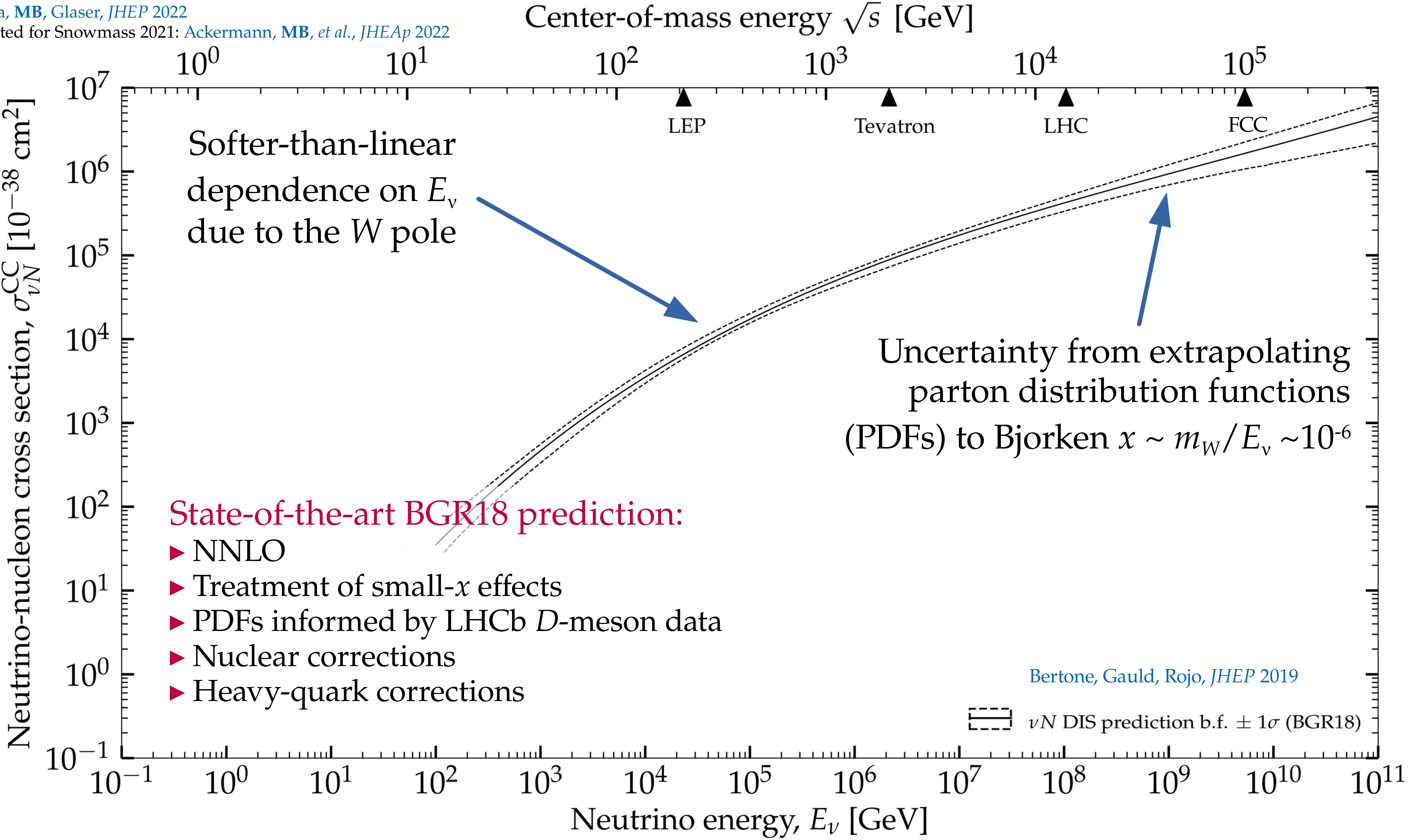


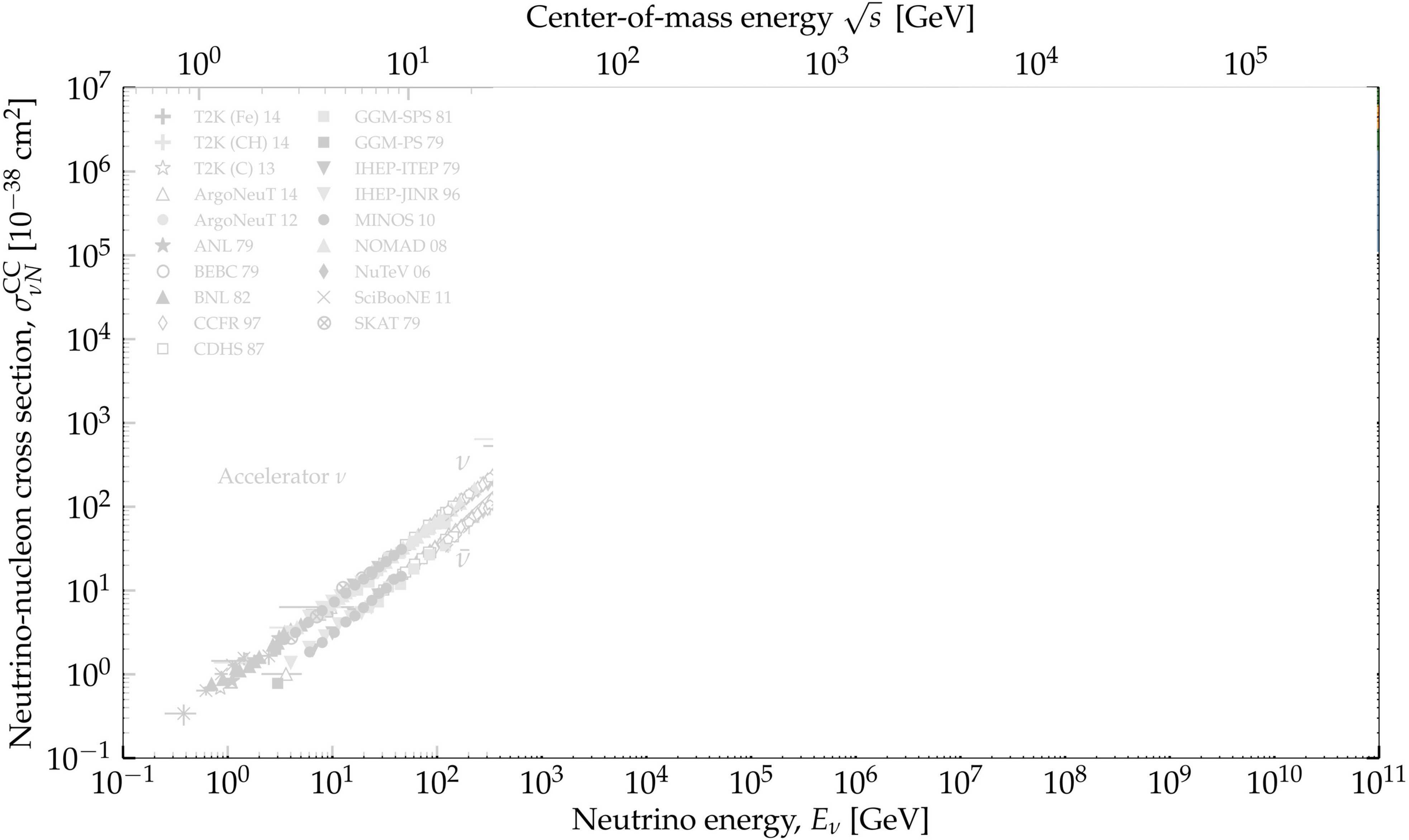
Softer-than-linear dependence on E_ν due to the W pole

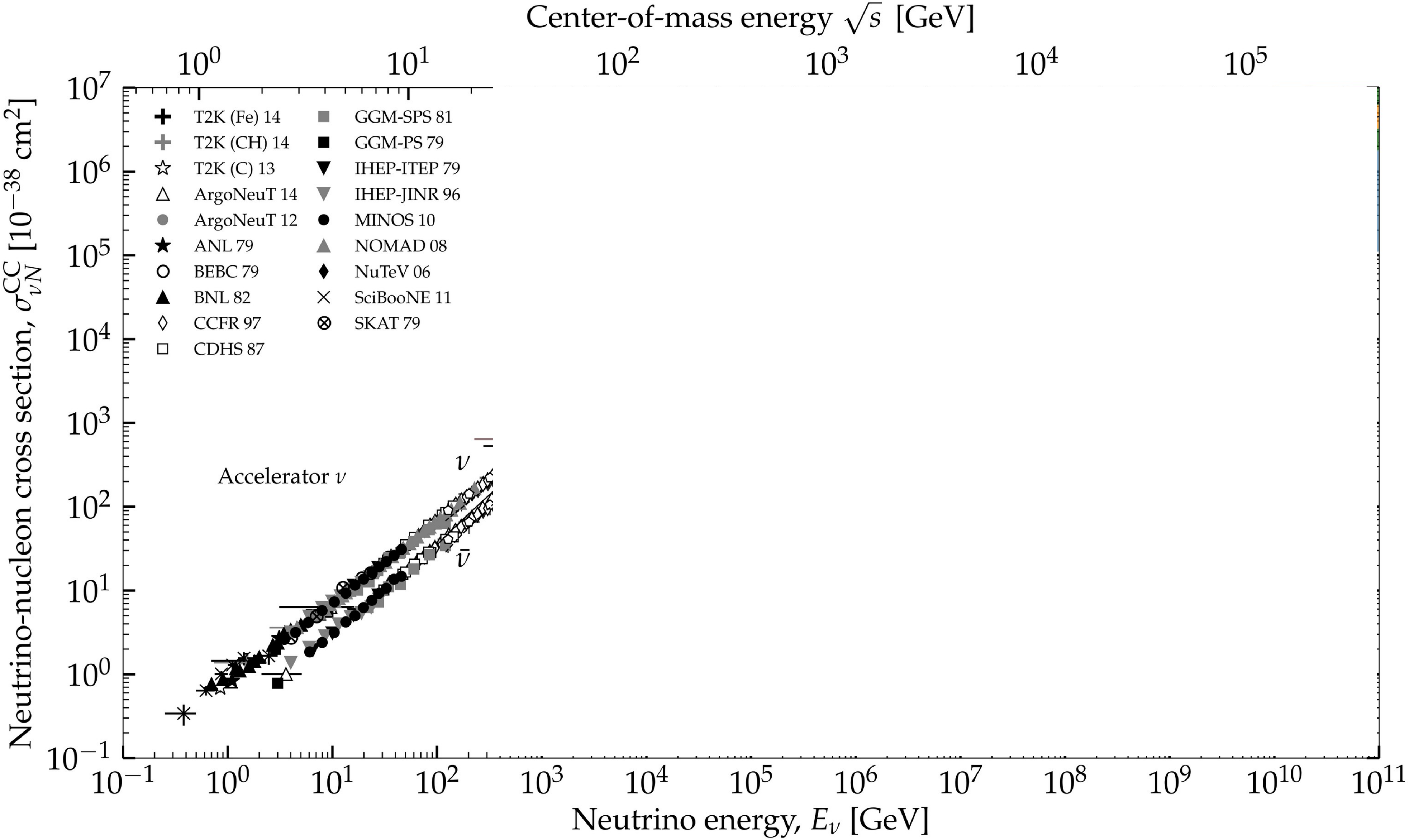
Uncertainty from extrapolating parton distribution functions (PDFs) to Bjorken $x \sim m_W/E_\nu \sim 10^{-6}$

State-of-the-art BGR18 prediction:

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

Bertone, Gauld, Rojo, *JHEP* 2019


Center-of-mass energy $\sqrt{s}$ [GeV]
10^0
10^1
10^2
10^3
10^4
10^5
Neutrino-nucleon cross section, $\sigma_{\nu N}^{\mathrm{CC}}$ [10^{-38} cm^2]
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
GGM-PS 79
IHEP-ITEP 79
IHEP-JINR 96
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
Accelerator ν
ν
$\bar{\nu}$
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
Neutrino energy, E_ν [GeV]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10^0
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10^7
10^6
10^5
10^4
10^3
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10^1
10^0
10^{-1}
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
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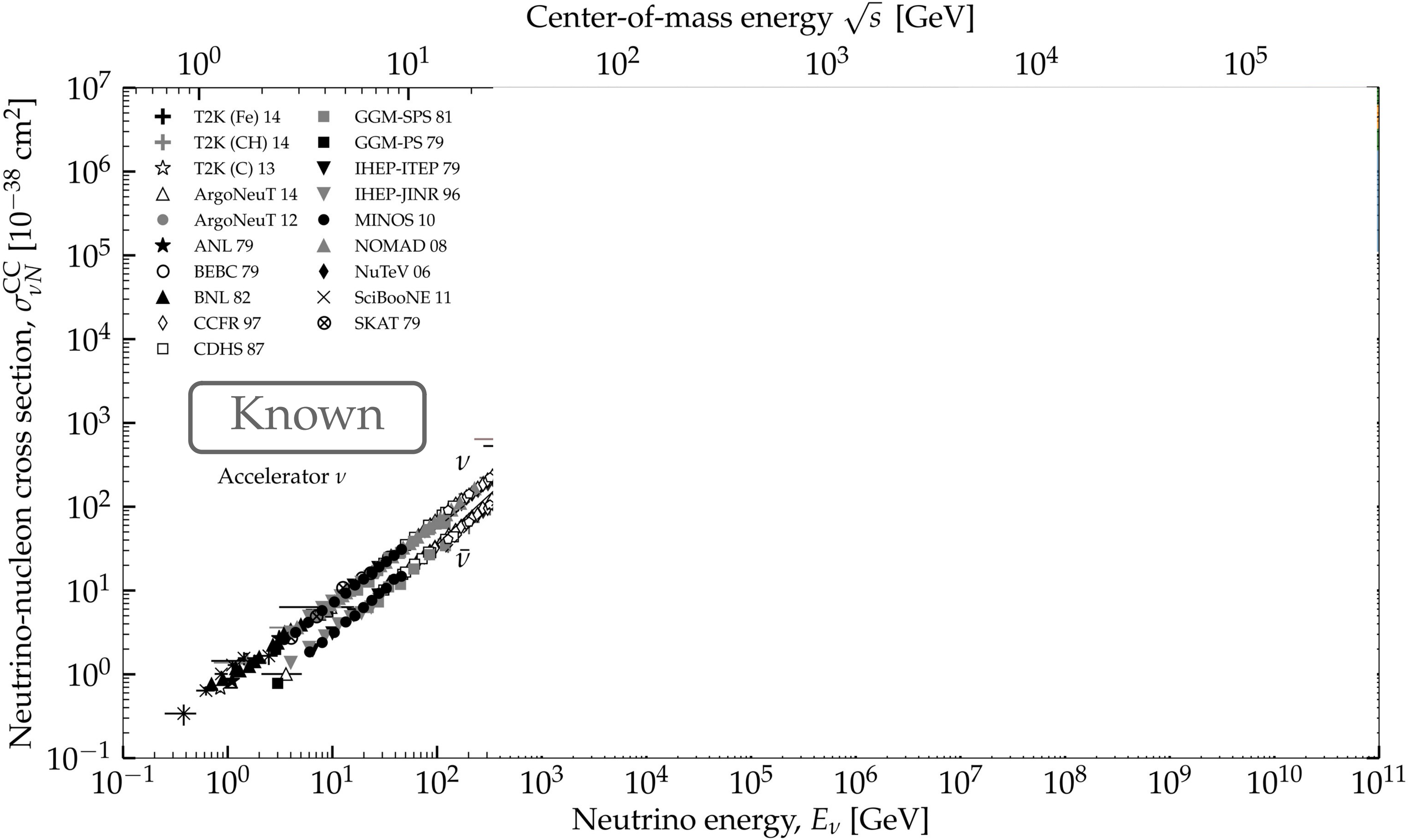
BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
GGM-PS 79
IHEP-ITEP 79
IHEP-JINR 96
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
Accelerator ν
ν
$\bar{\nu}$
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
Neutrino energy, E_ν [GeV]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10^0
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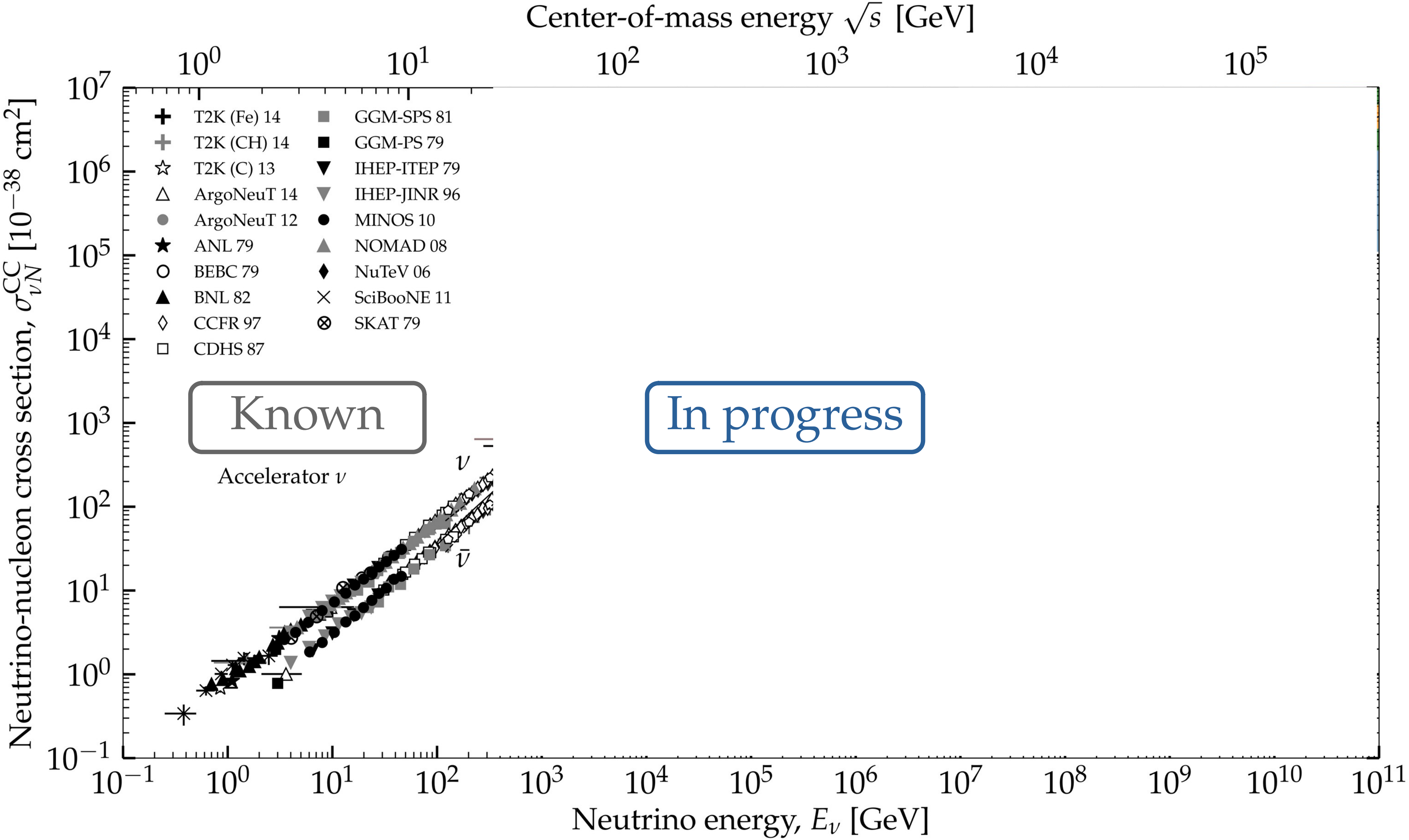
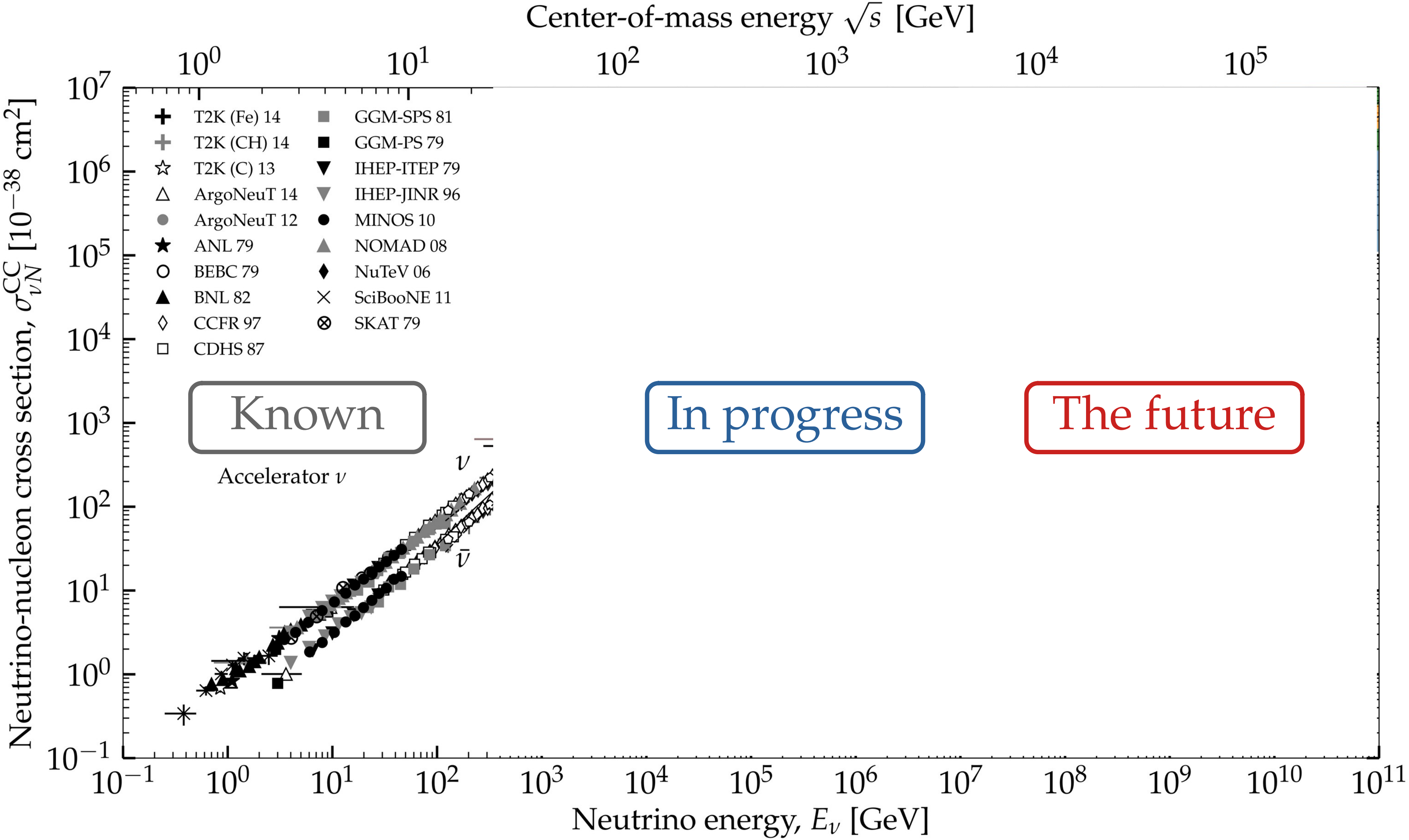
10^4
10^5
Neutrino-nucleon cross section, $\sigma_{\nu N}^{\rm CC}$ [10^{-38} cm^2]
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
GGM-PS 79
IHEP-ITEP 79
IHEP-JINR 96
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
Known
Accelerator ν
ν
$\bar{\nu}$
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
Neutrino energy, E_ν [GeV]



Known

In progress


Center-of-mass energy $\sqrt{s}$ [GeV]
10^0
10^1
10^2
10^3
10^4
10^5
Neutrino-nucleon cross section, $\sigma_{\nu N}^{\mathrm{CC}}$ [10^{-38} cm^2]
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
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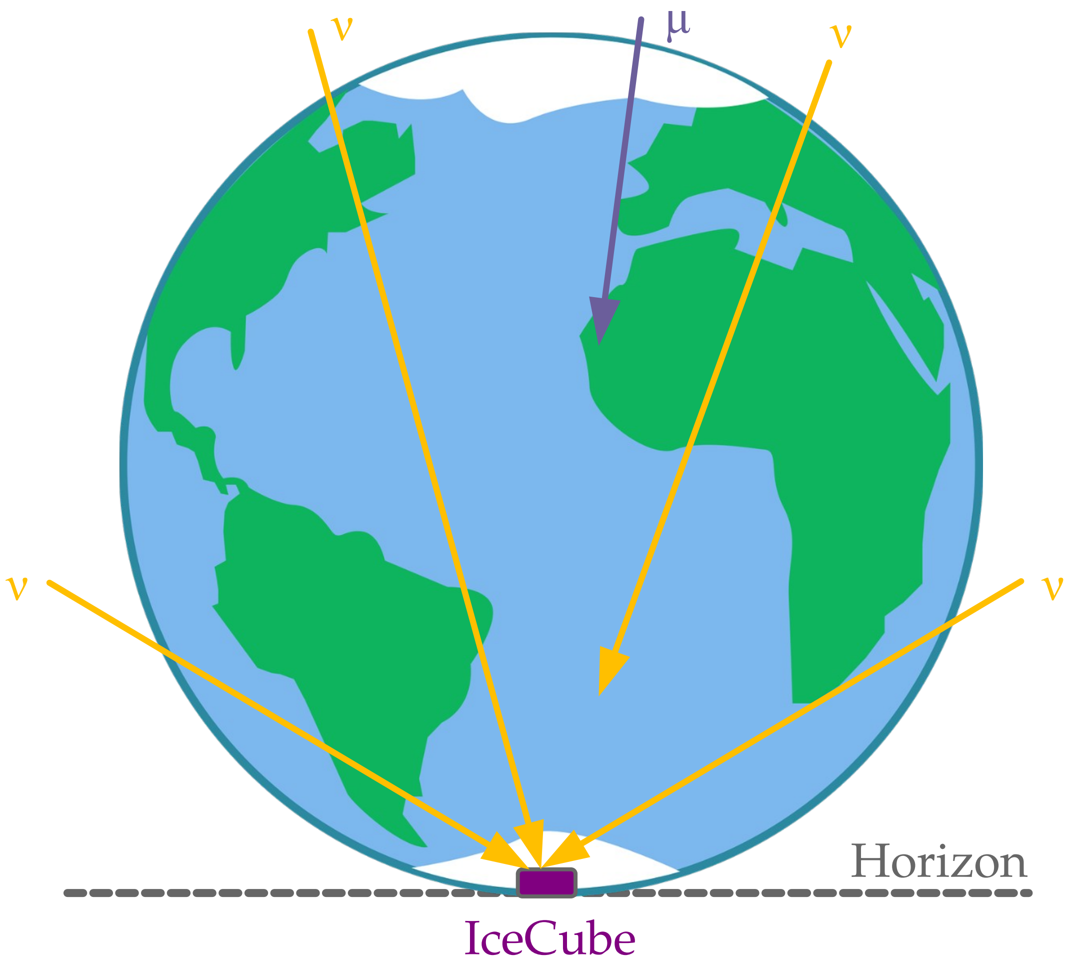
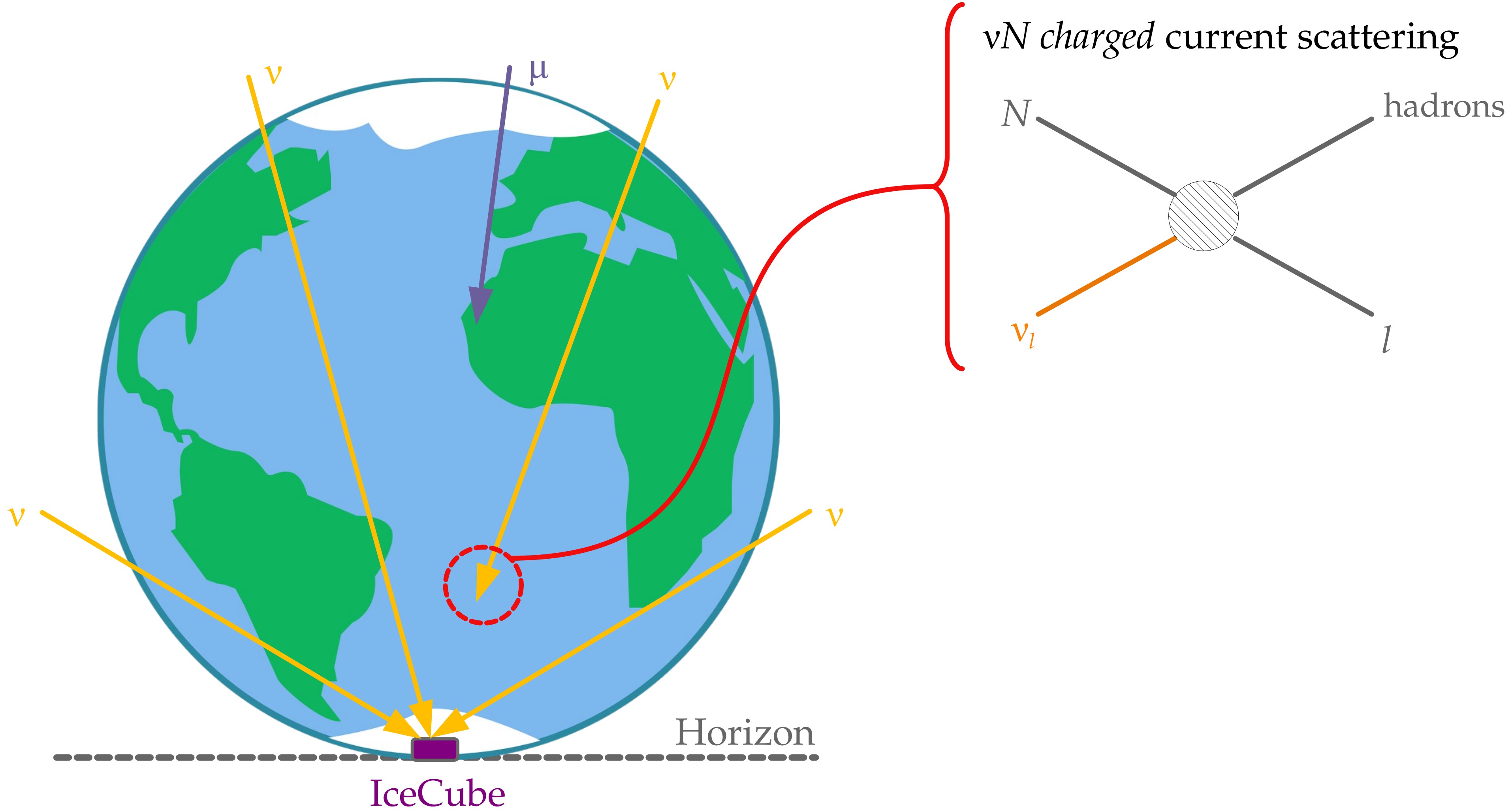
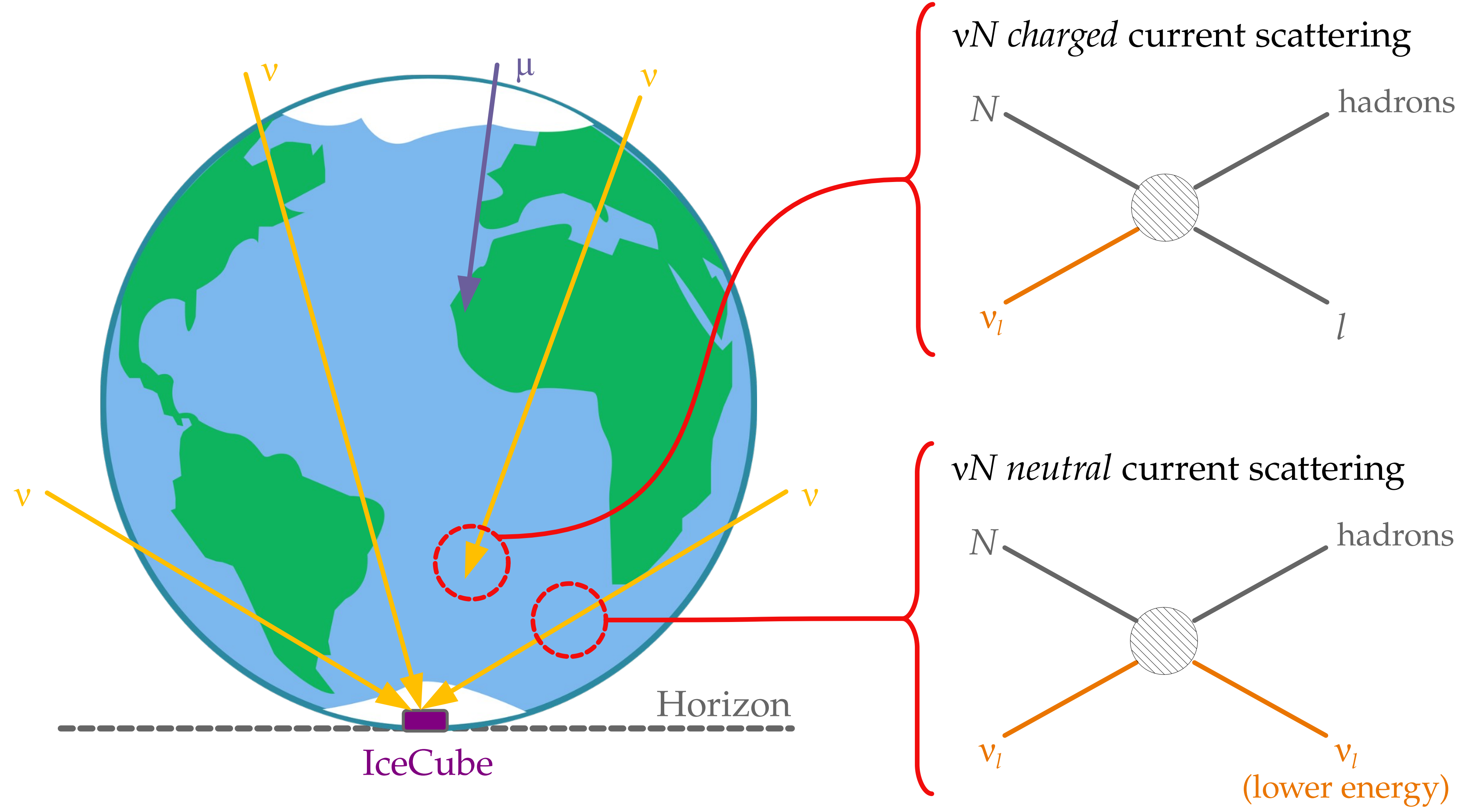
Known
In progress
The future
Accelerator ν
ν
$\bar{\nu}$
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
Neutrino energy, E_ν [GeV]

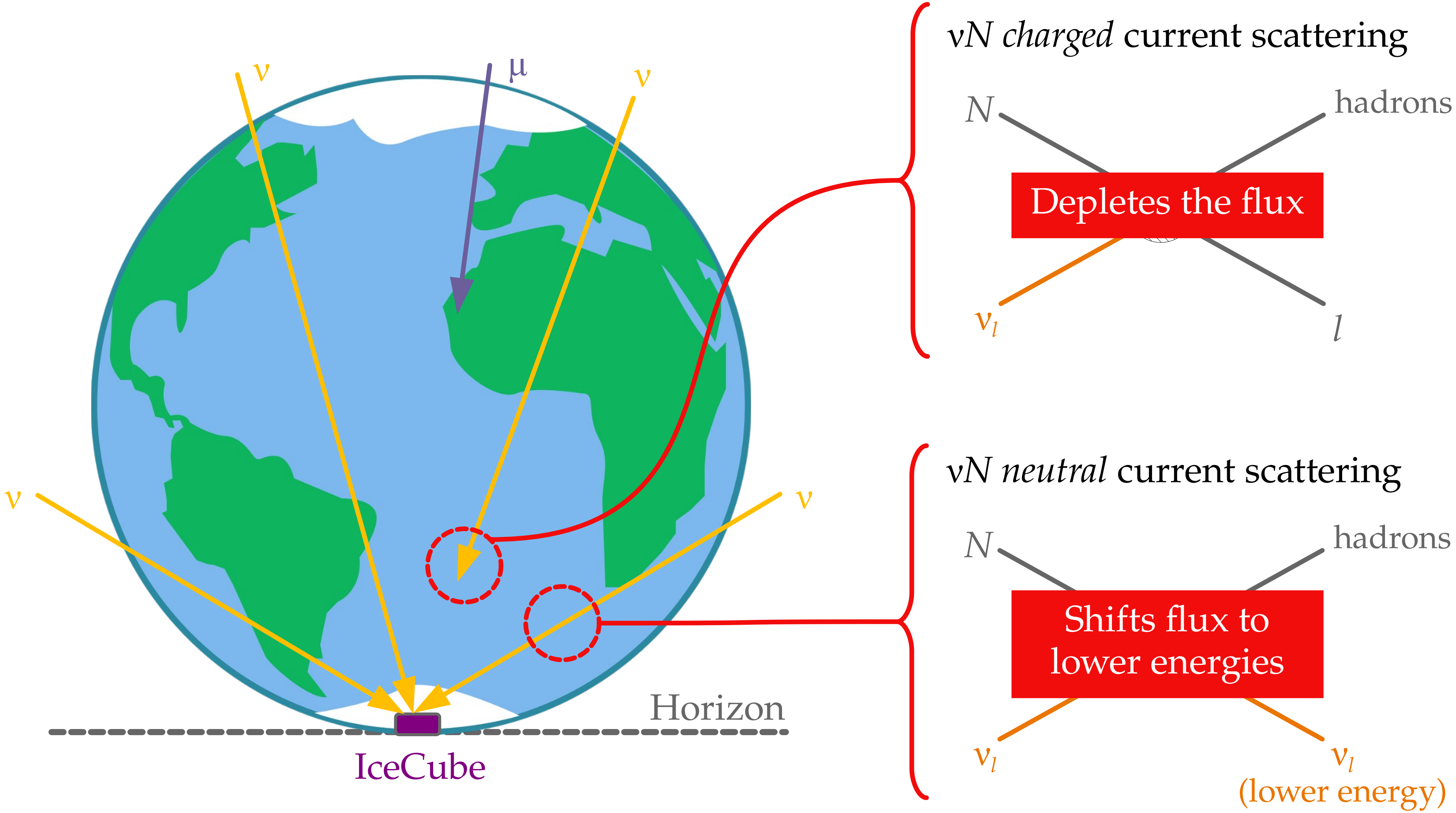

ν
μ
ν
ν
ν
Horizon
IceCube


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



νN *charged* current scattering

νN *neutral* current scattering



νN *charged* current scattering

Depletes the flux

νN *neutral* current scattering

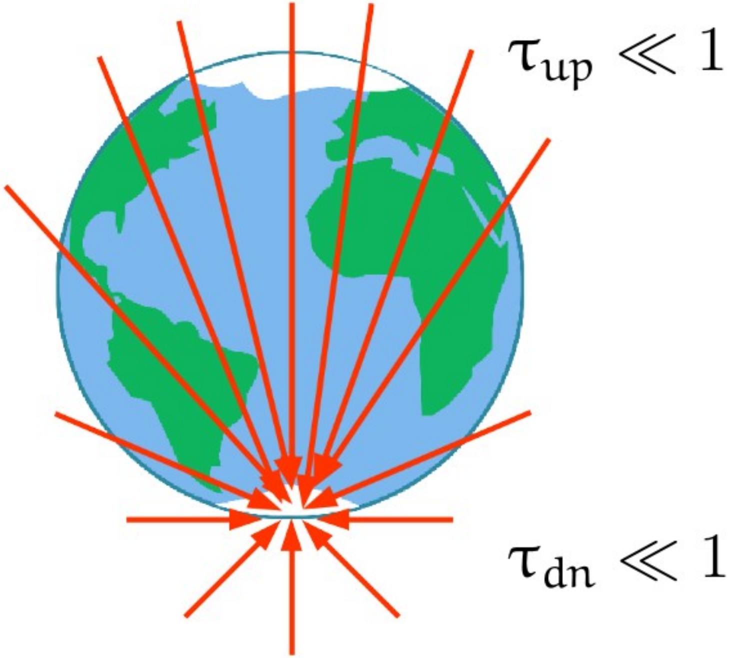
Shifts flux to lower energies

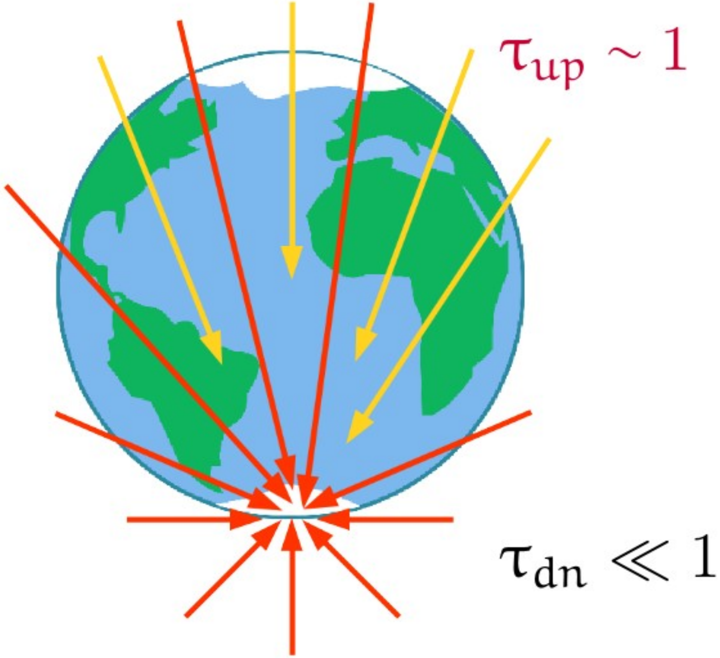
Measuring the high-energy *νN* cross section

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

Below ~ 10 TeV: Earth is transparent

Above ~ 10 TeV: Earth is opaque



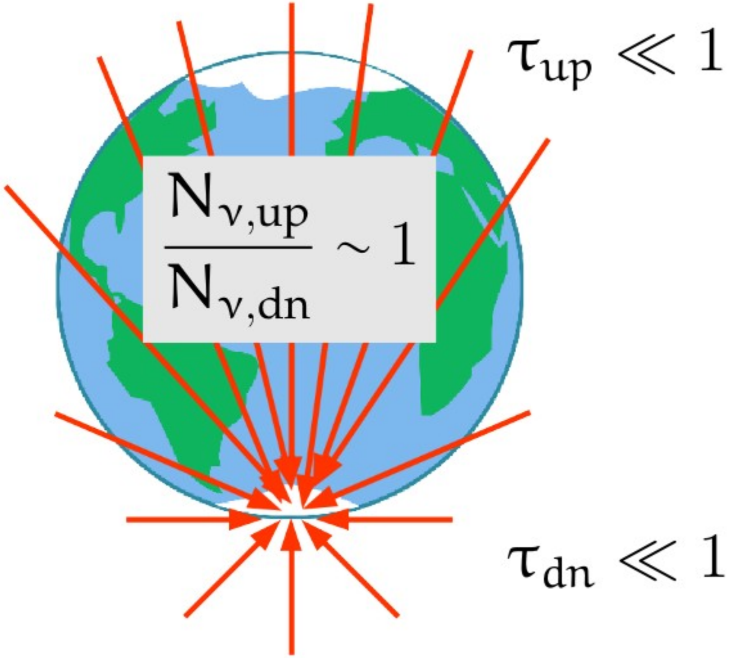


Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008 Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

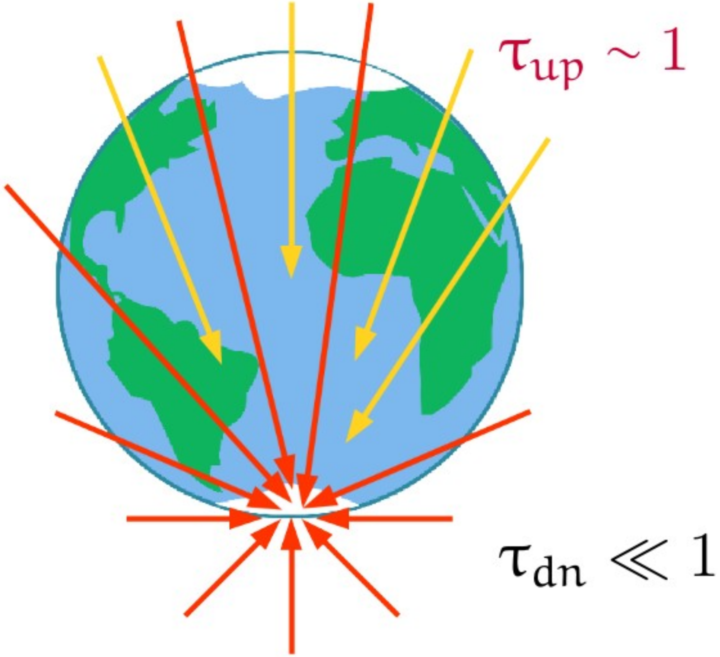
Measuring the high-energy νN cross section

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

Below ~ 10 TeV: Earth is transparent



Above ~ 10 TeV: Earth is opaque



Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
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Measuring the high-energy *νN* cross section

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

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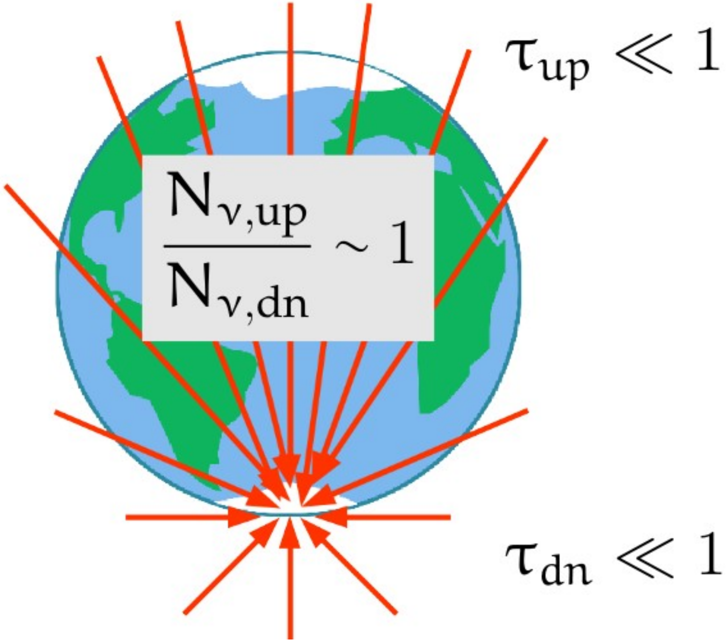
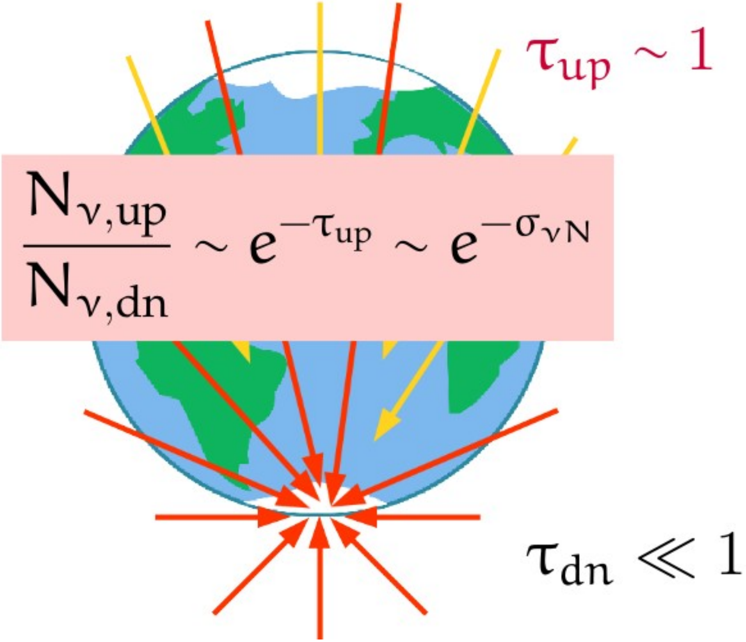


$\tau_{up} \ll 1$

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

$\tau_{dn} \ll 1$

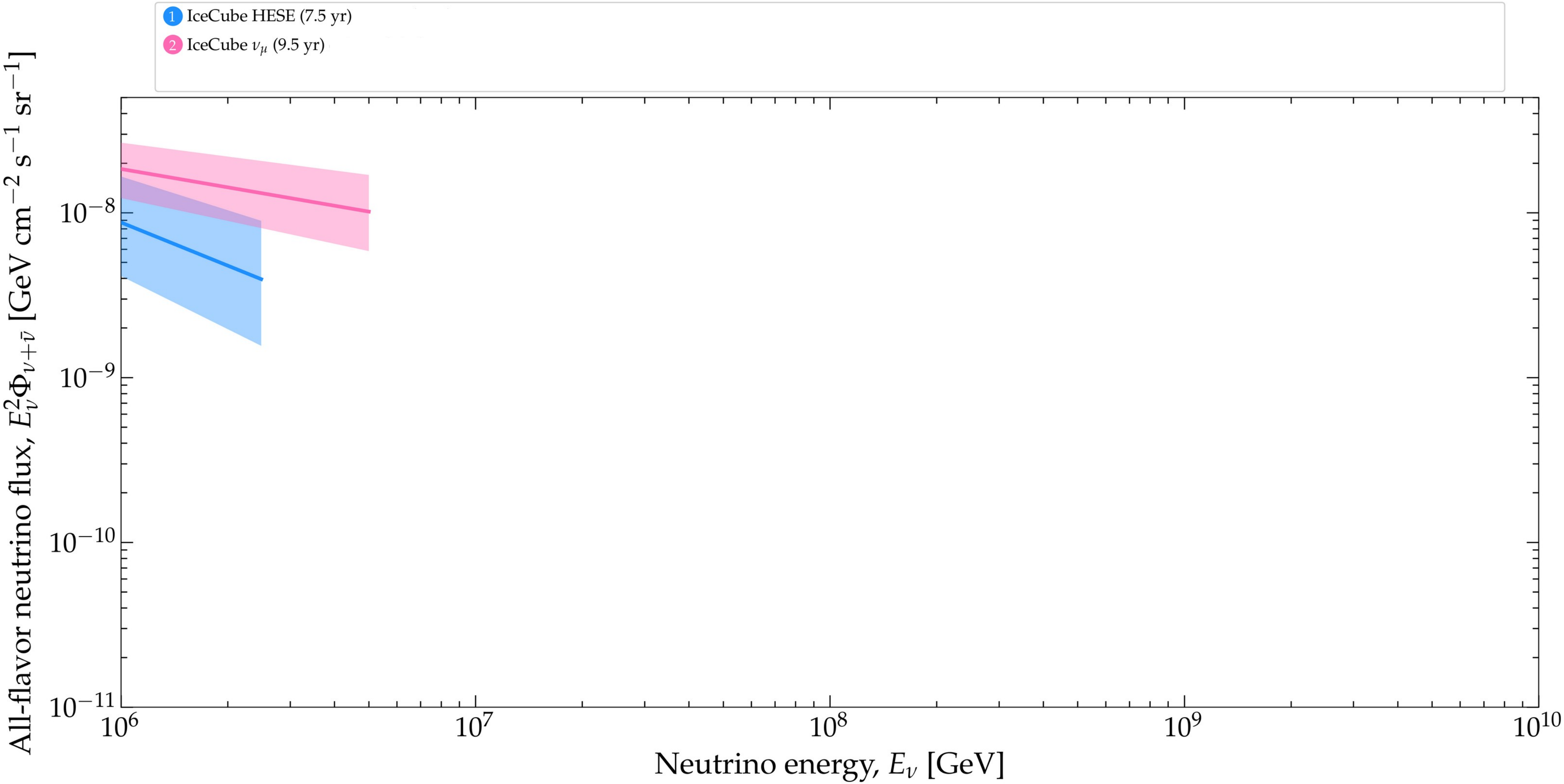


$\tau_{up} \sim 1$

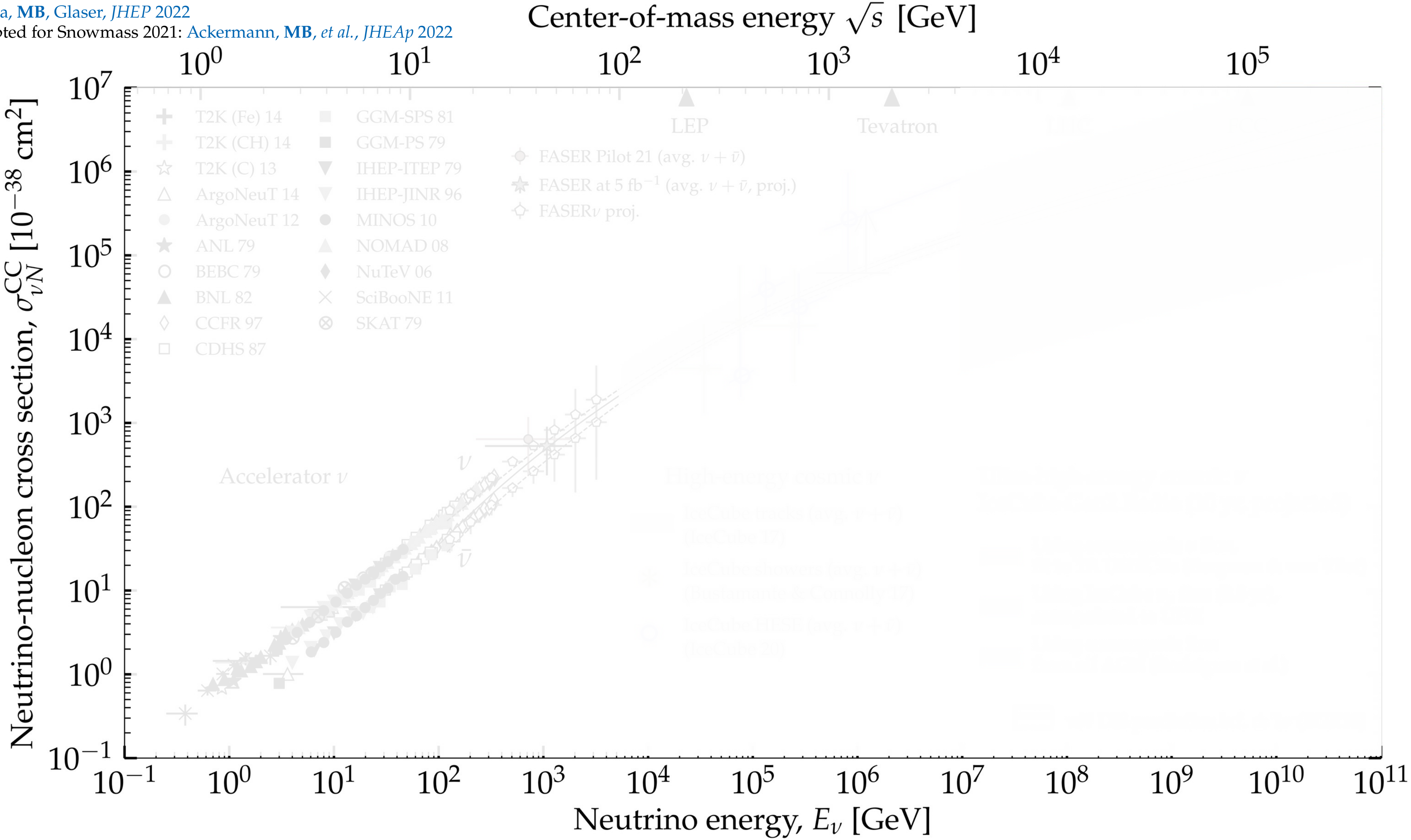
$$\frac{N_{\nu,up}}{N_{\nu,dn}} \sim e^{-\tau_{up}} \sim e^{-\sigma_{\nu N}}$$

$\tau_{dn} \ll 1$

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



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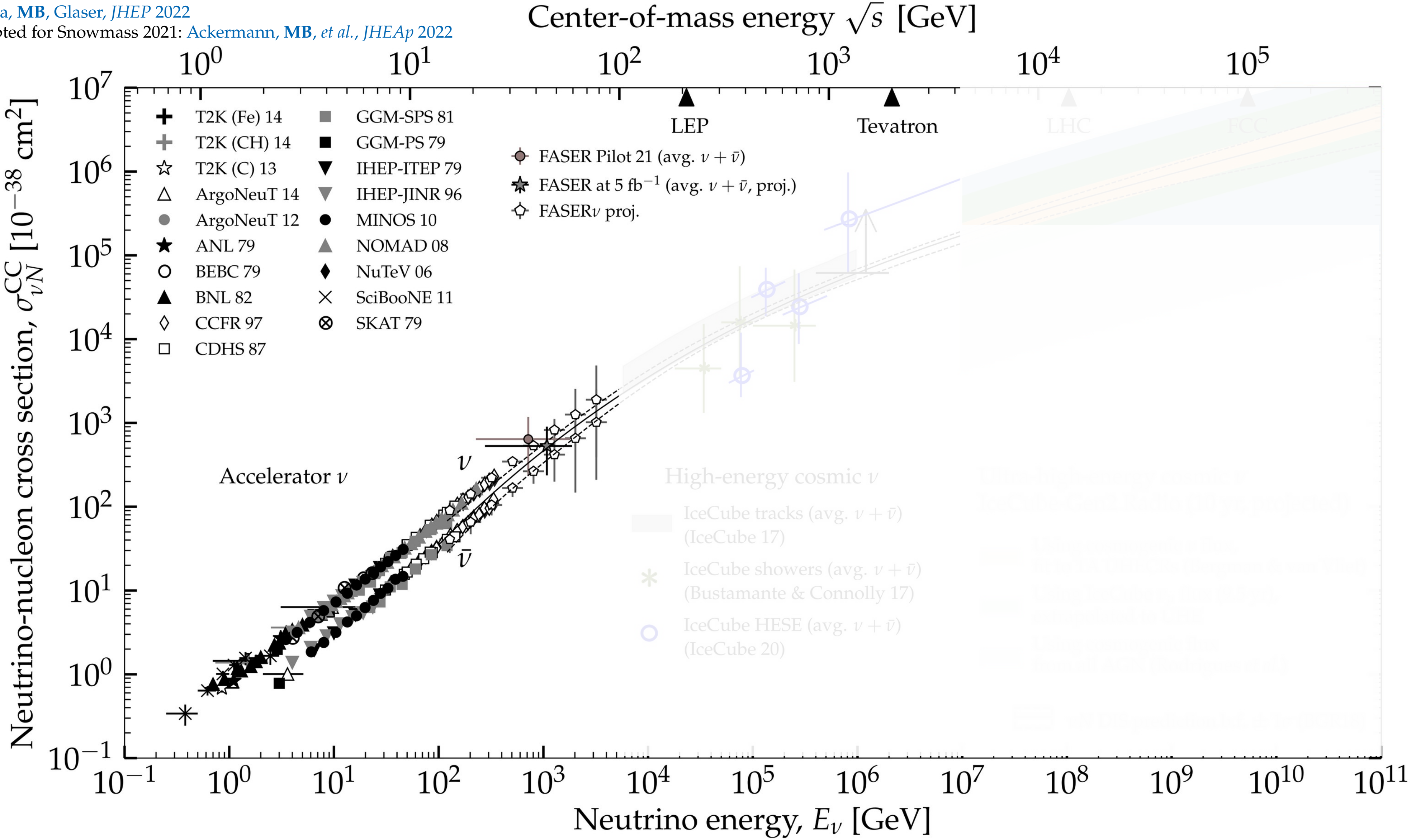

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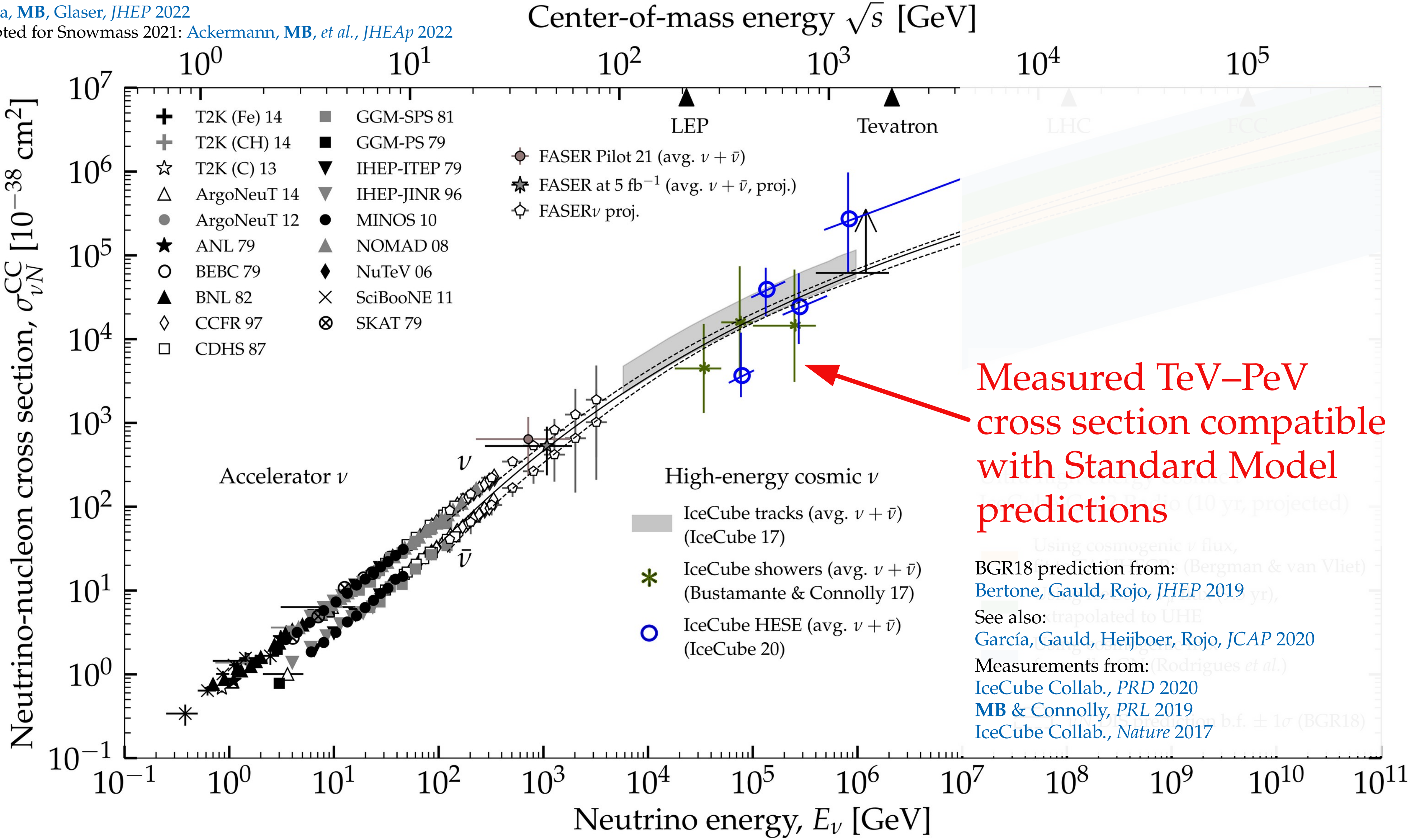
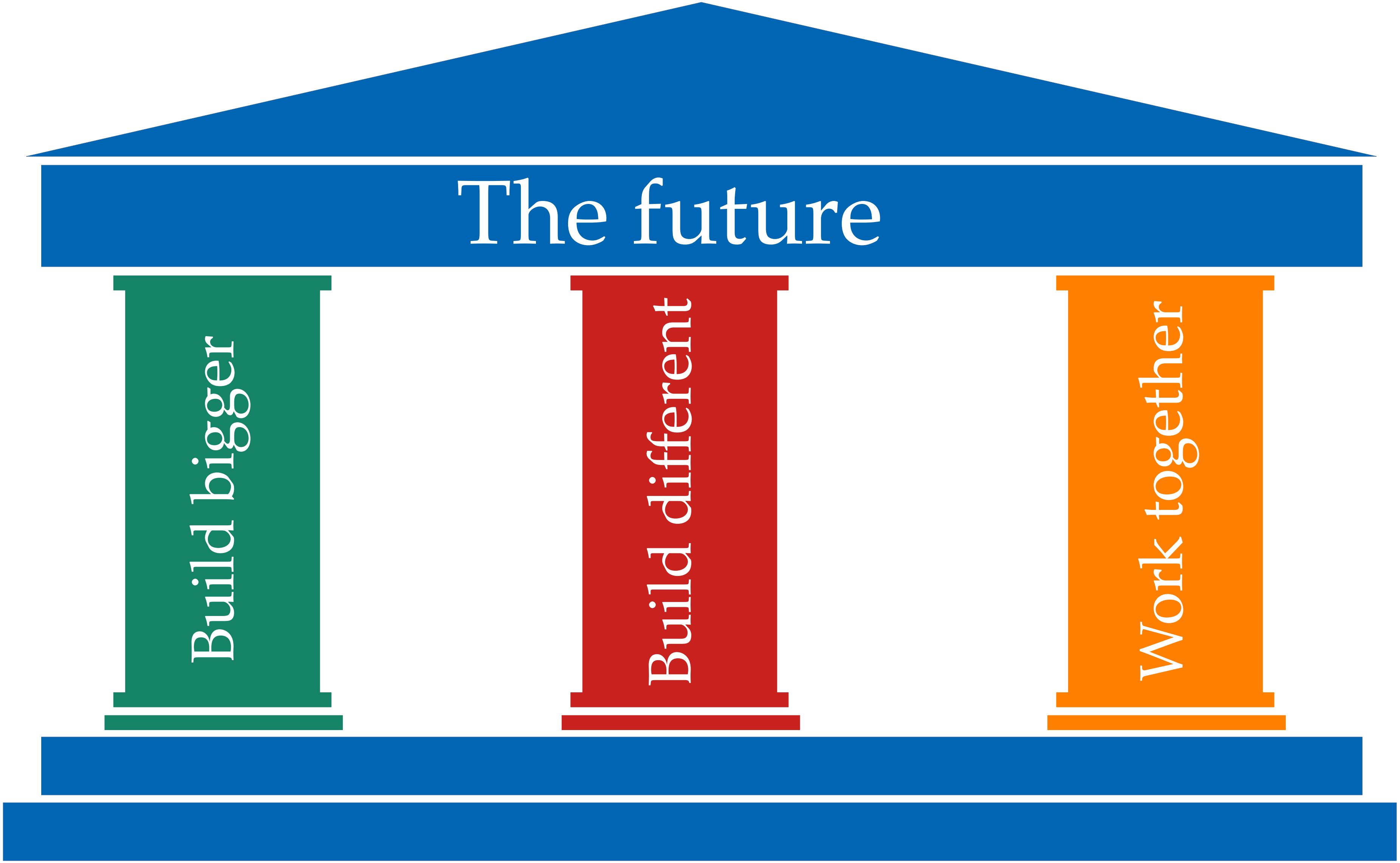


Measured TeV–PeV cross section compatible with Standard Model predictions

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

IV.
The future

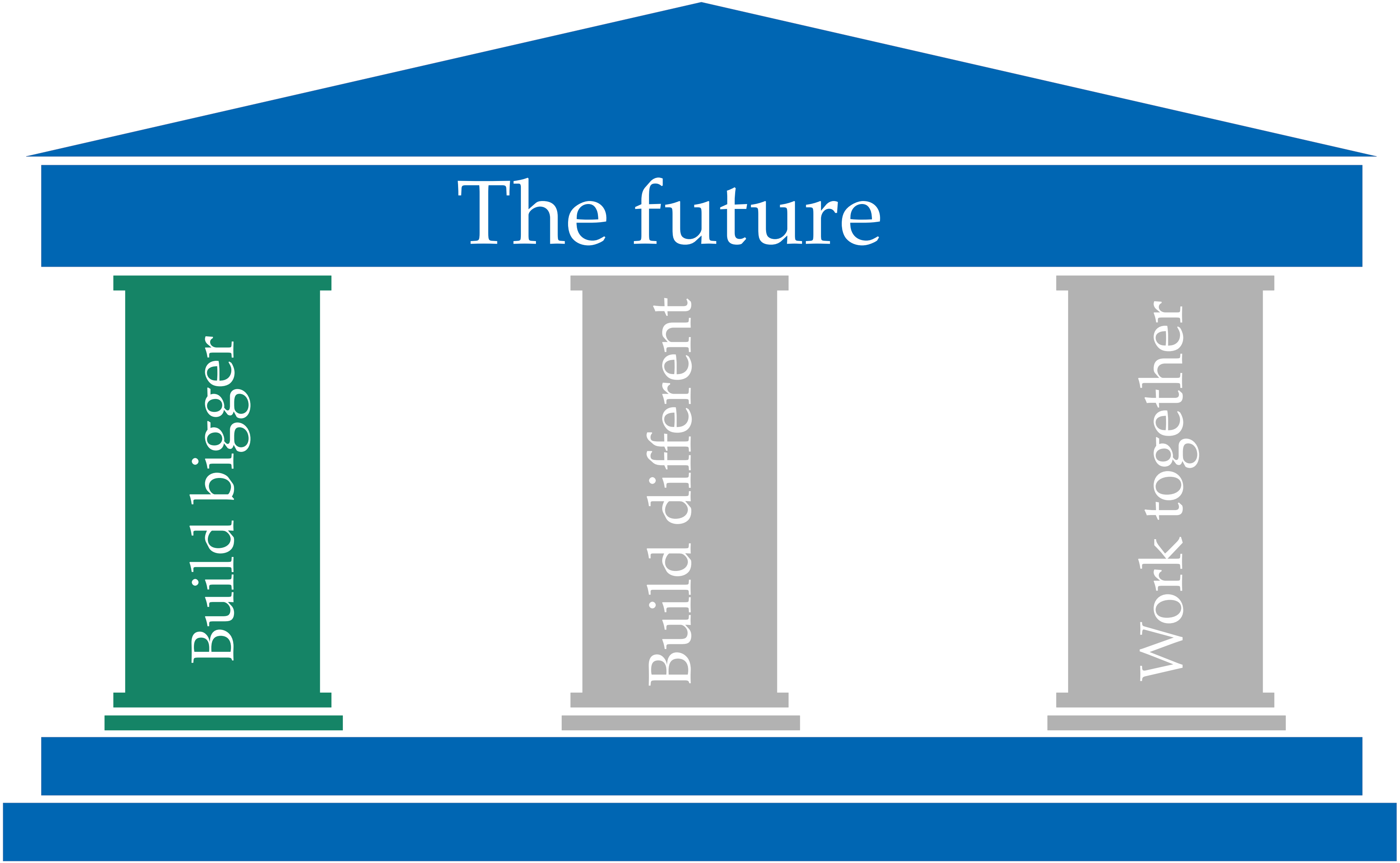


The future

Build bigger

Build different

Work together

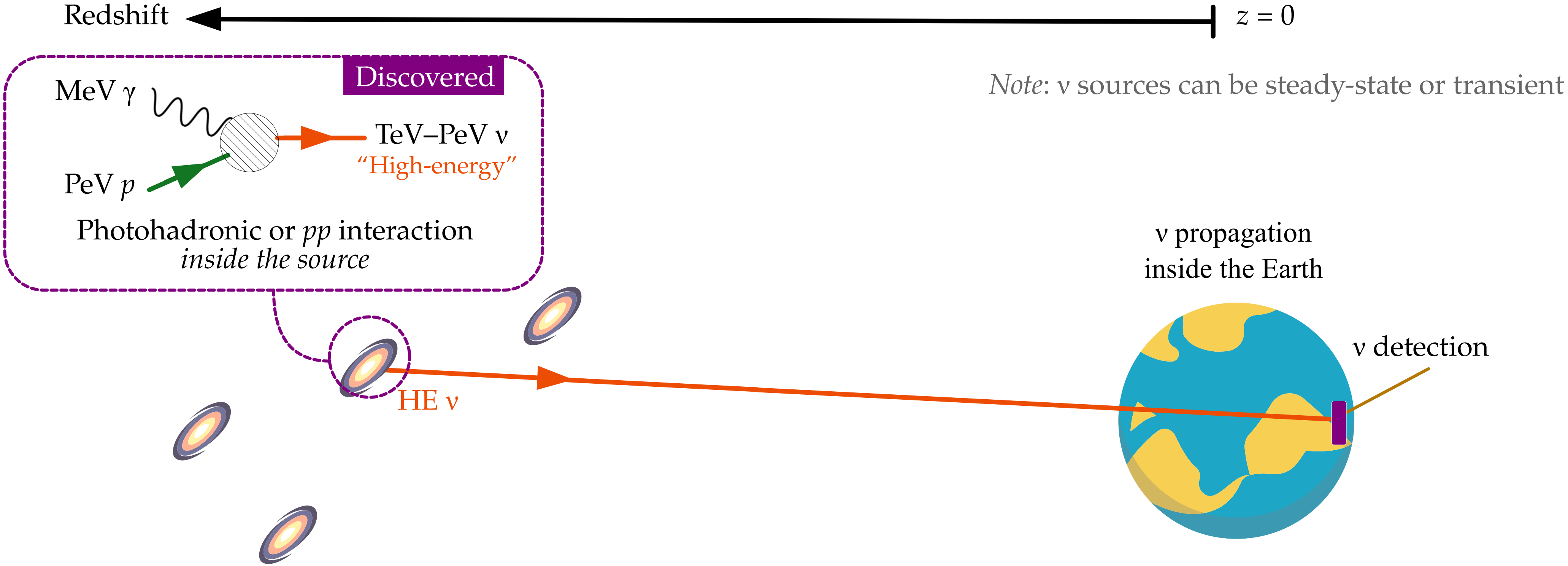


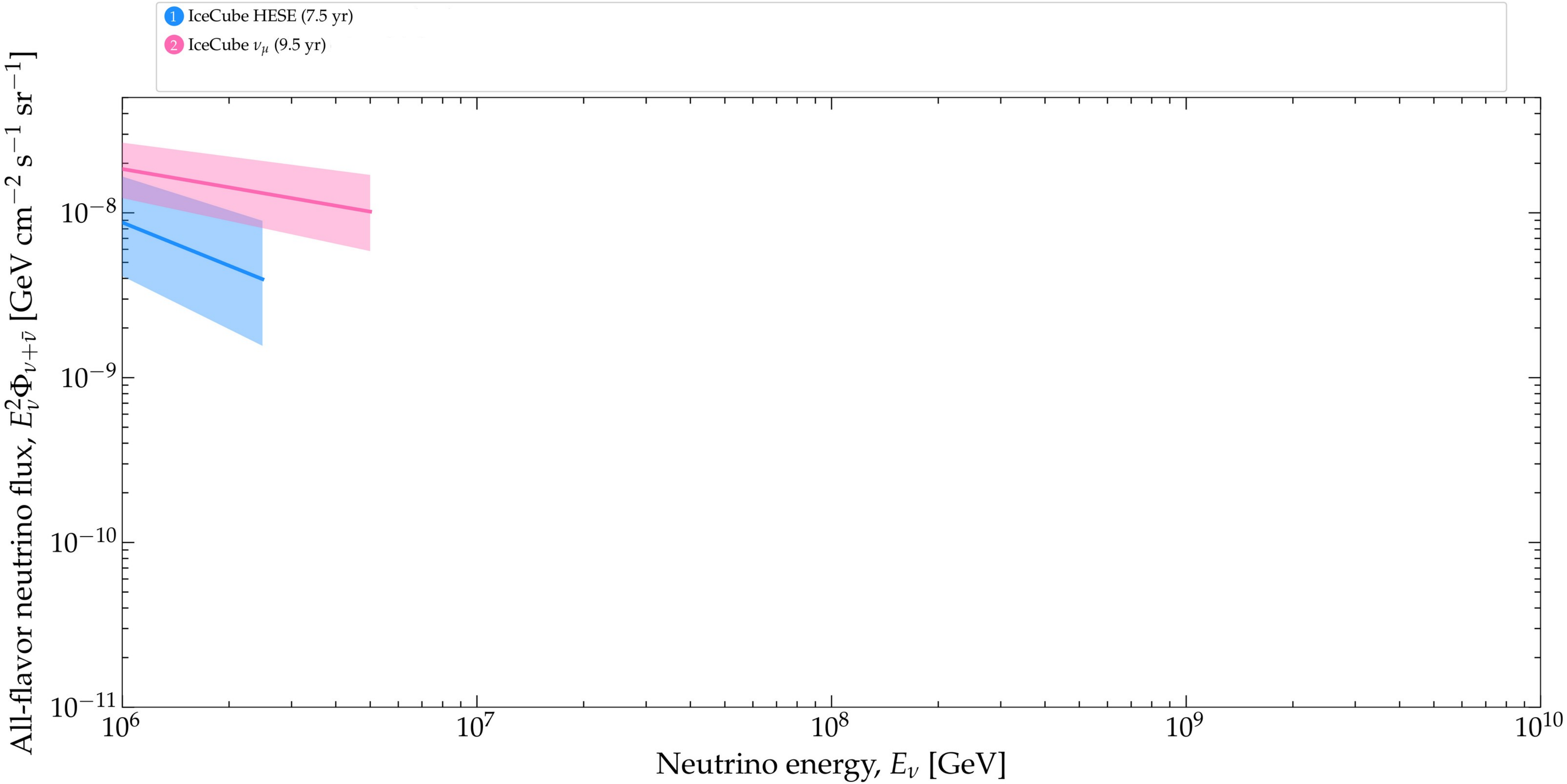
The future

Build bigger

Build different

Work together


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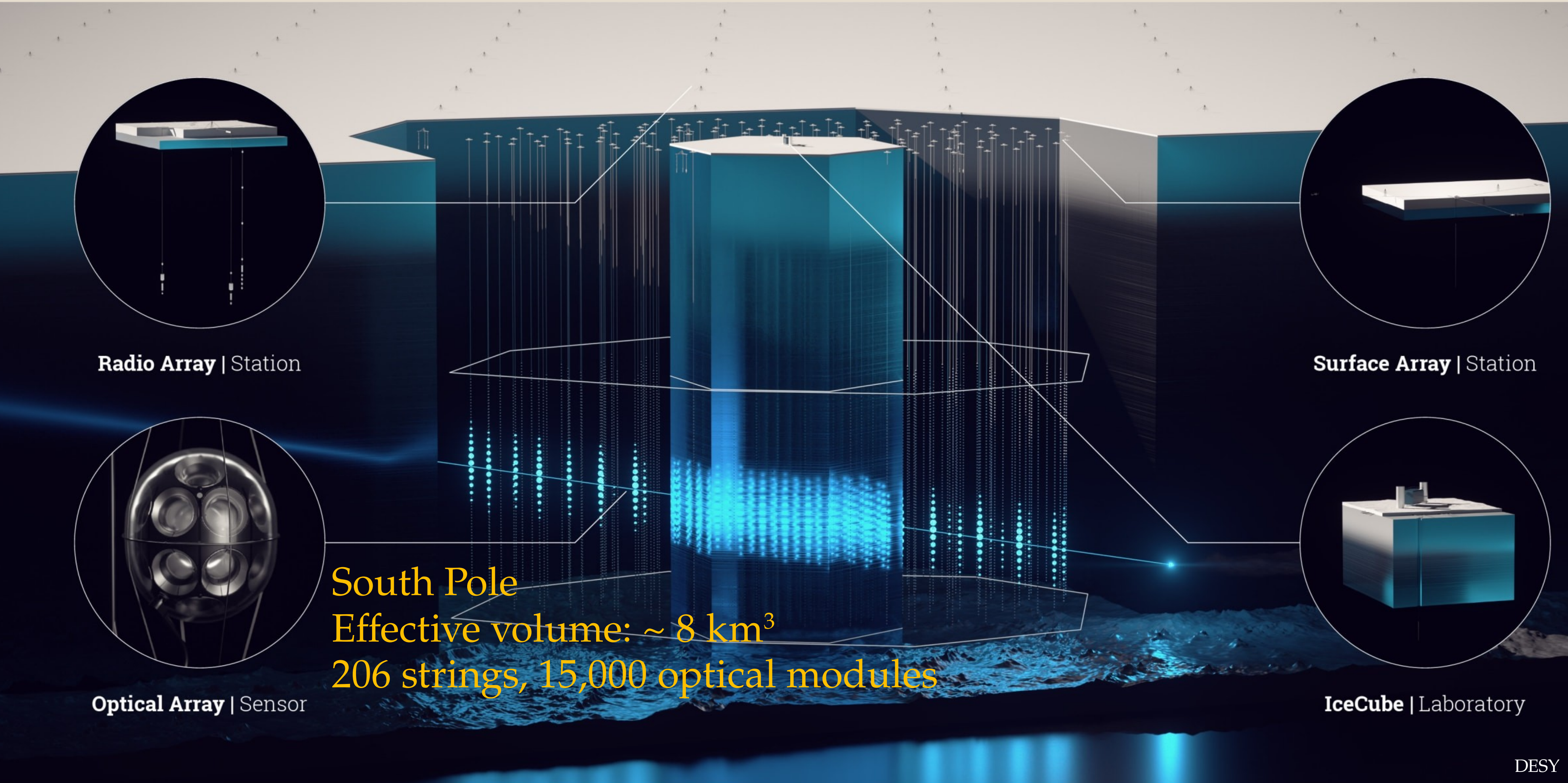
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]

TeV–PeV
ν telescopes
2030s

Strebe/Wikipedia

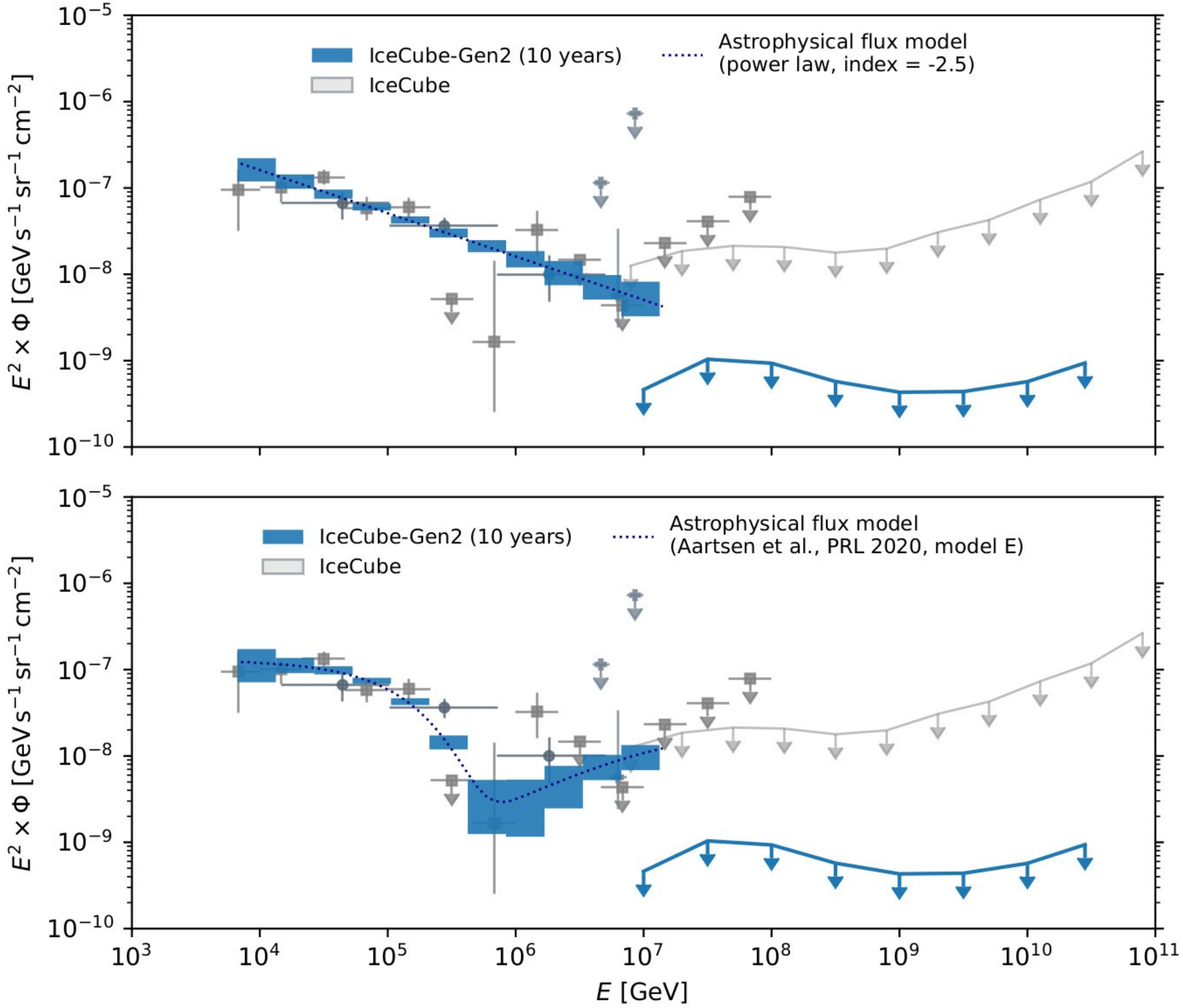
IceCube-Gen2



South Pole
Effective volume: ~ 8 km^3
206 strings, 15,000 optical modules

DESY

Measuring the diffuse flux *precisely*

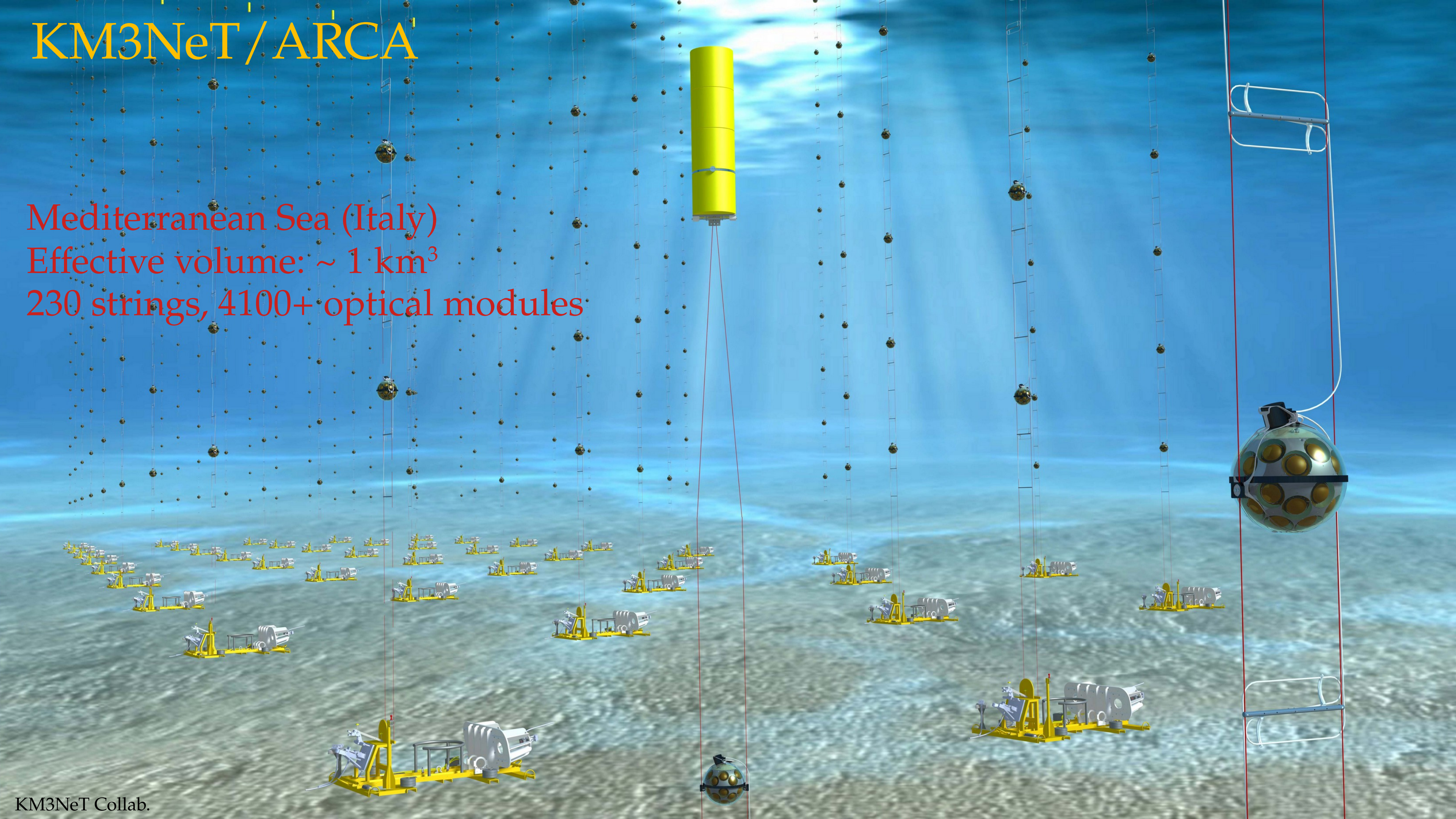


Assuming a power-law ν flux ∝ $E^{-2.5}$

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

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

KM3NeT/ARCA



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

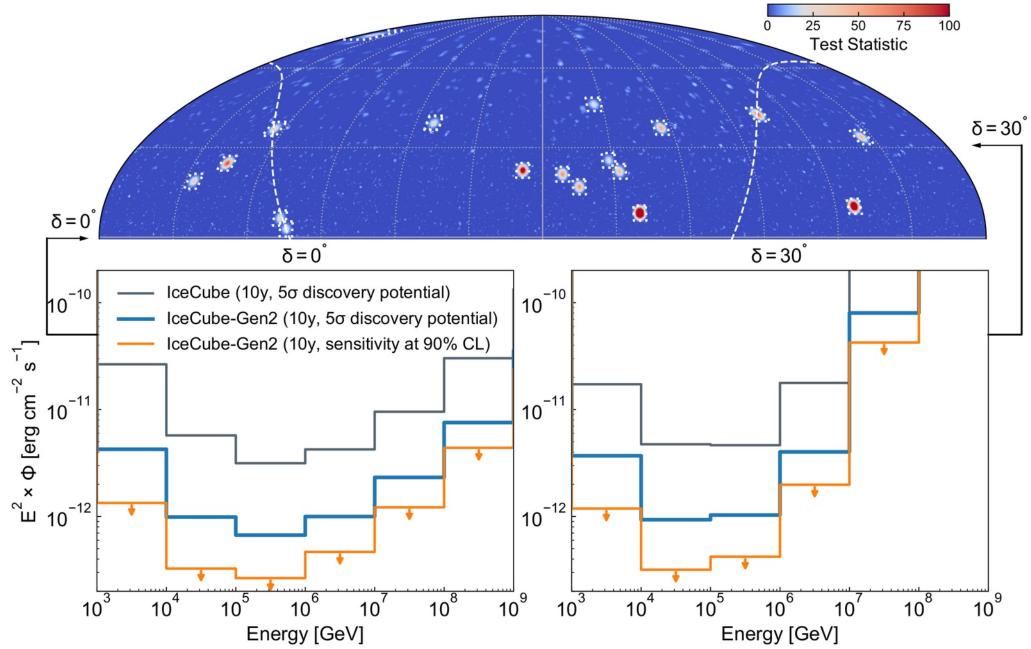
KM3NeT Collab.

Point-source limits

Point-source limits

IceCube-Gen2 (optical)

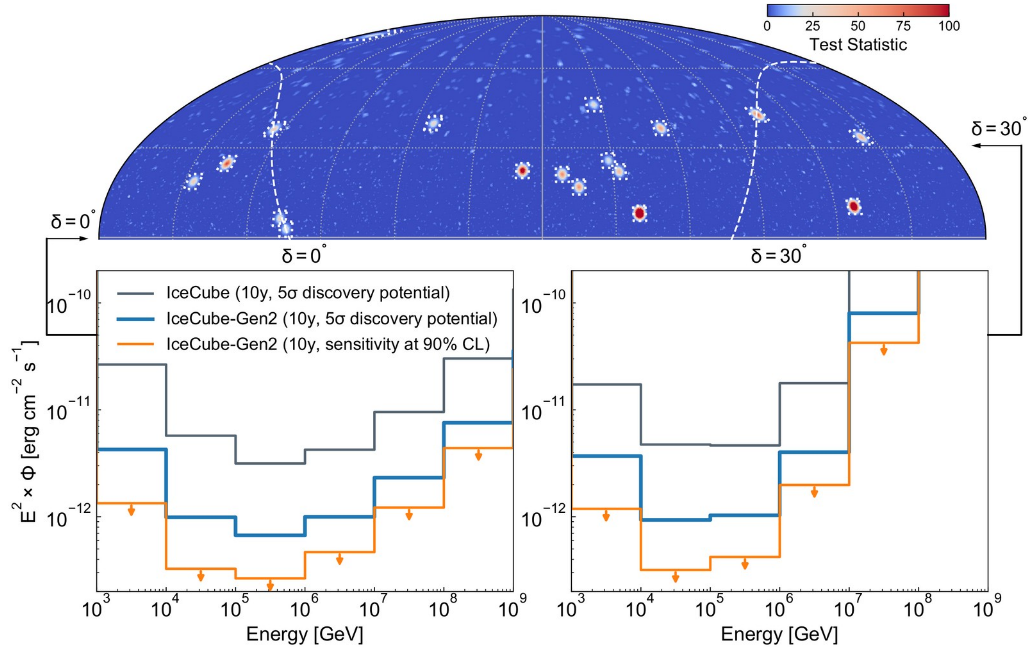
Northern sky



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

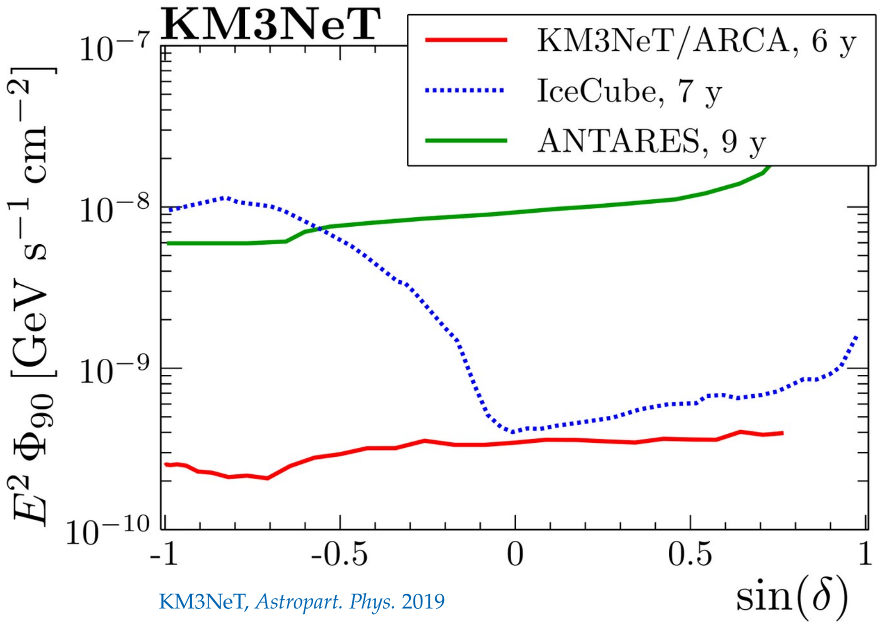
Point-source limits

IceCube-Gen2 (optical)
Northern sky



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

KM3NeT
Southern sky

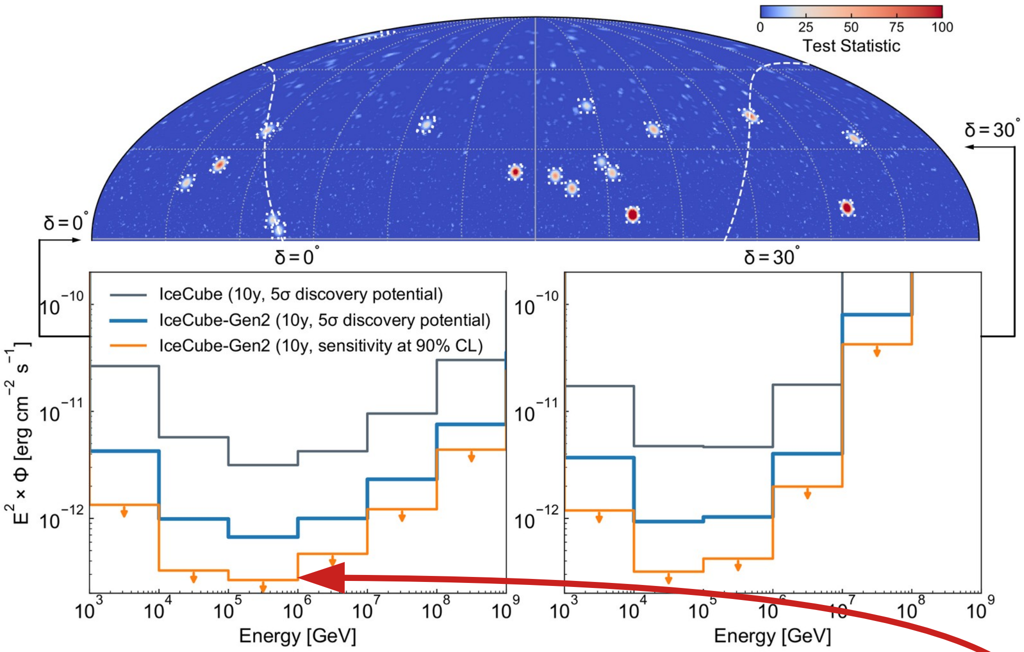


KM3NeT, *Astropart. Phys.* 2019

Point-source limits

IceCube-Gen2 (optical)

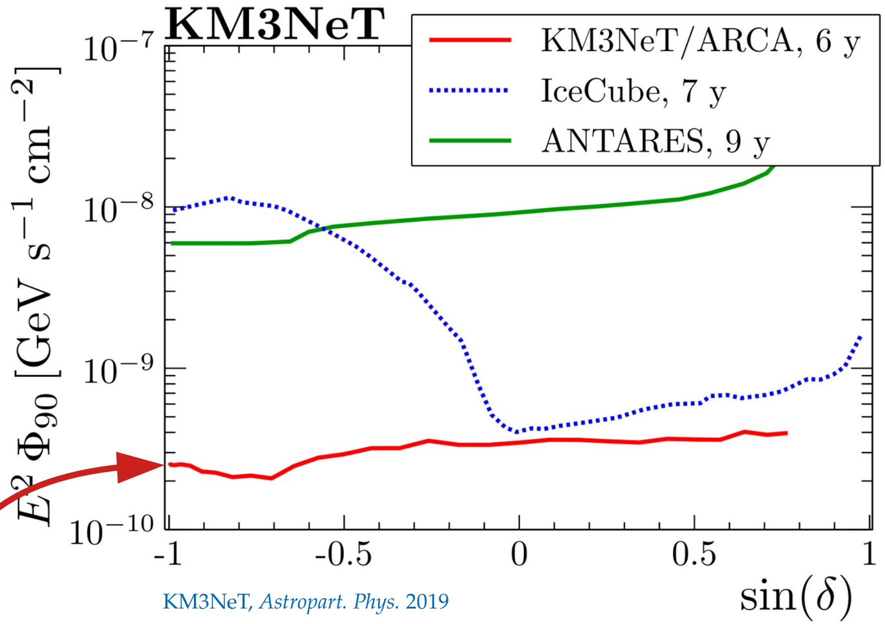
Northern sky



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

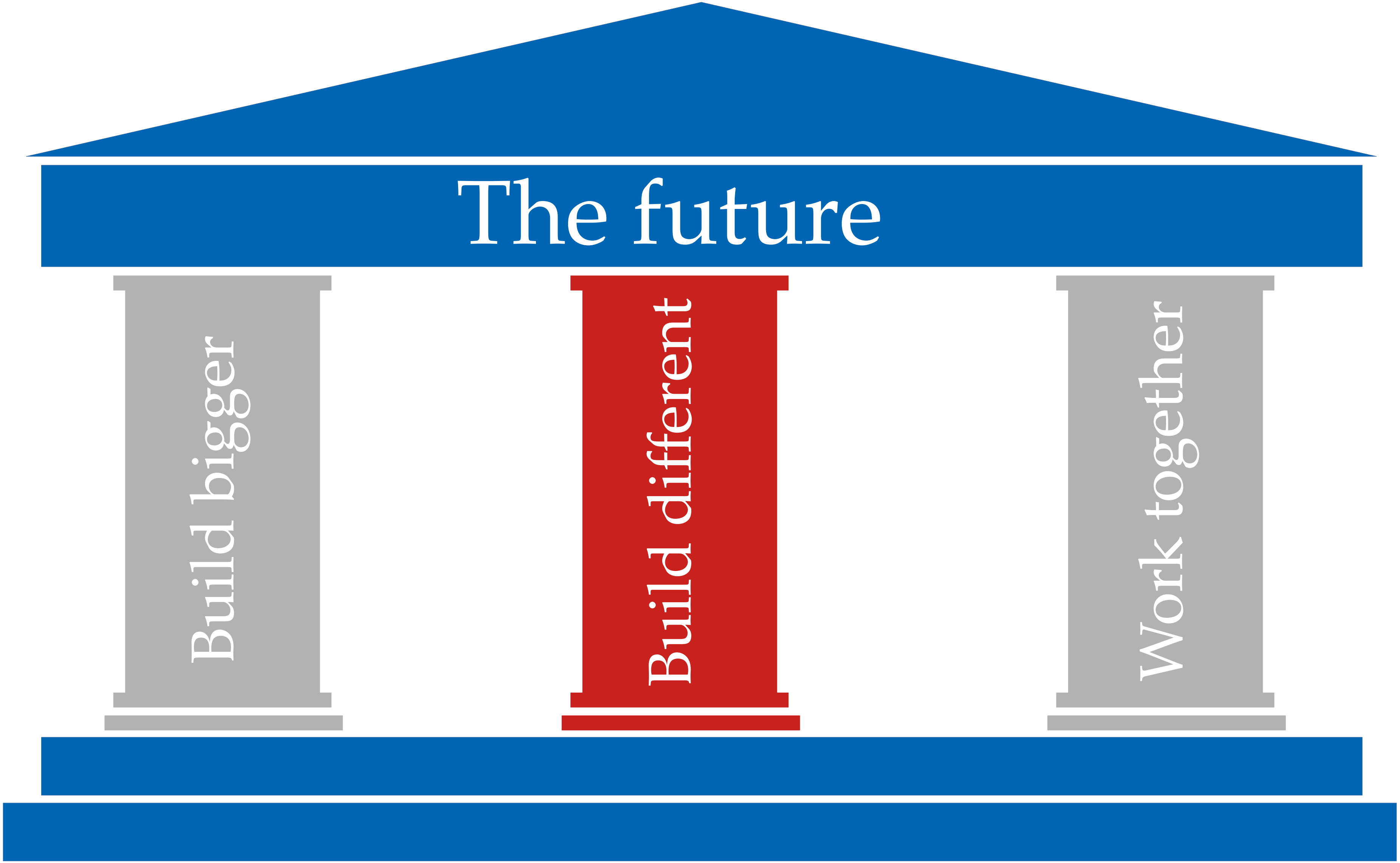
KM3NeT

Southern sky



KM3NeT, *Astropart. Phys.* 2019

We will reach comparable sensitivity in both hemispheres

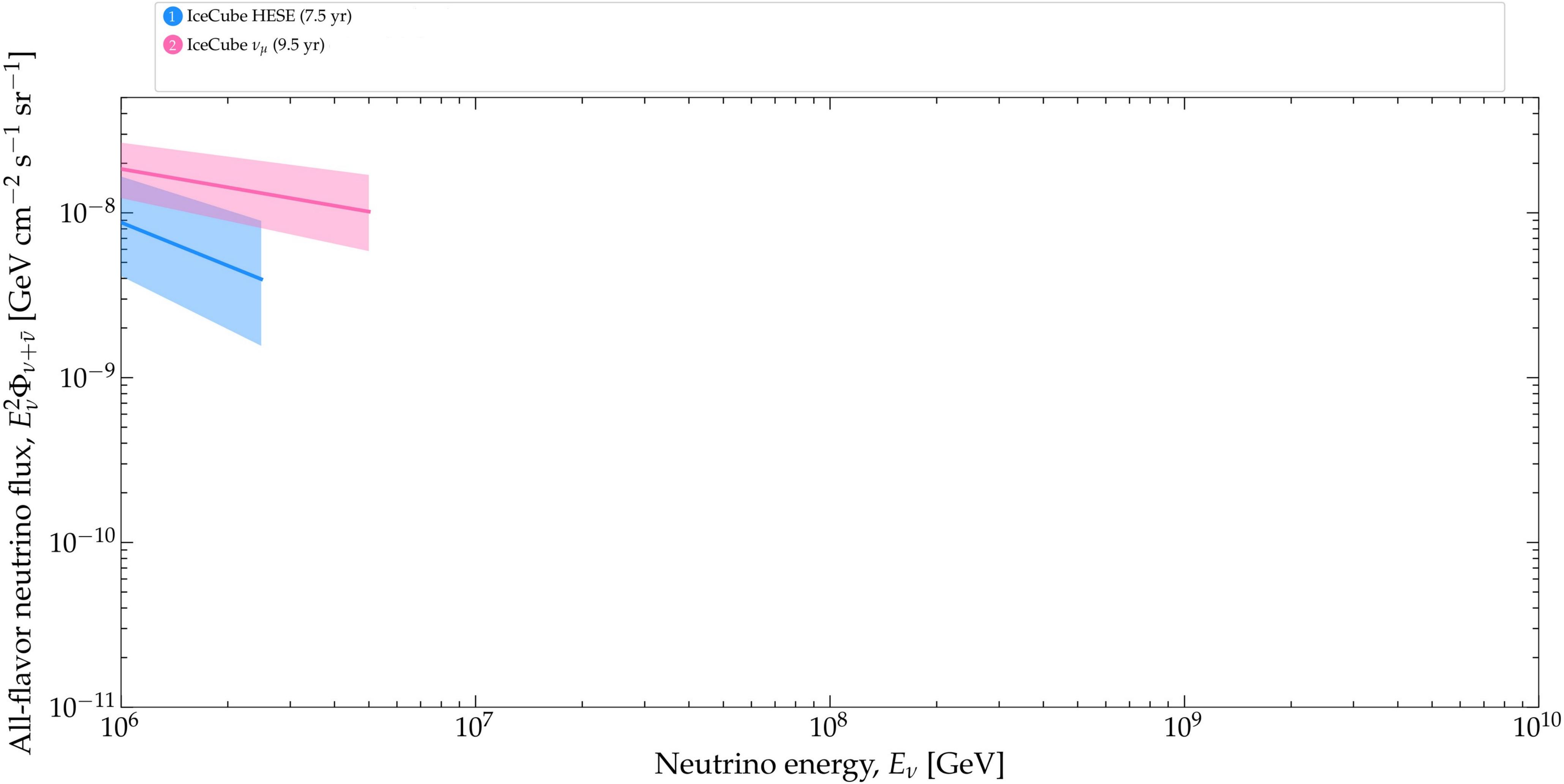


The future

Build bigger

Build different

Work together



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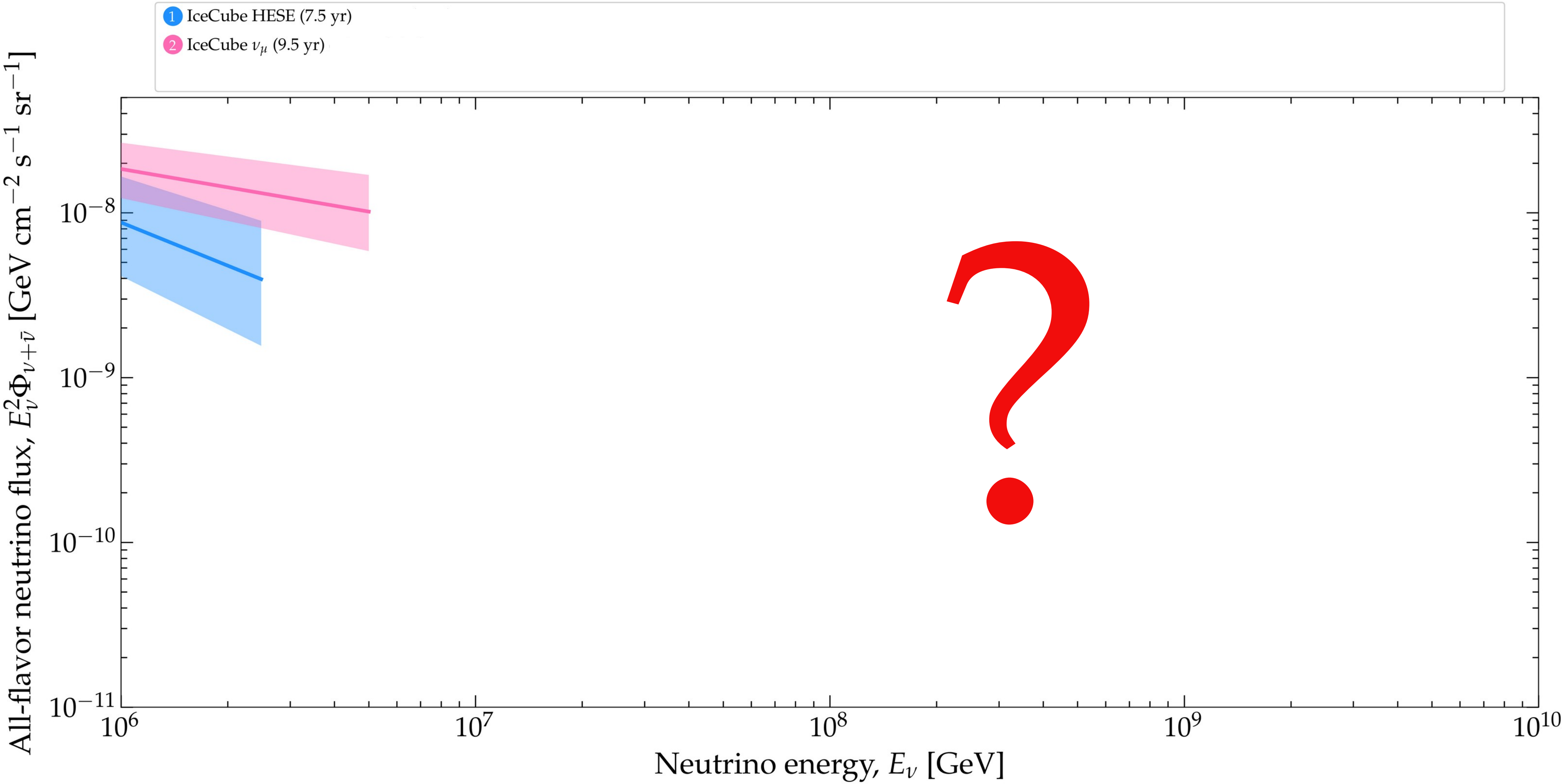
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]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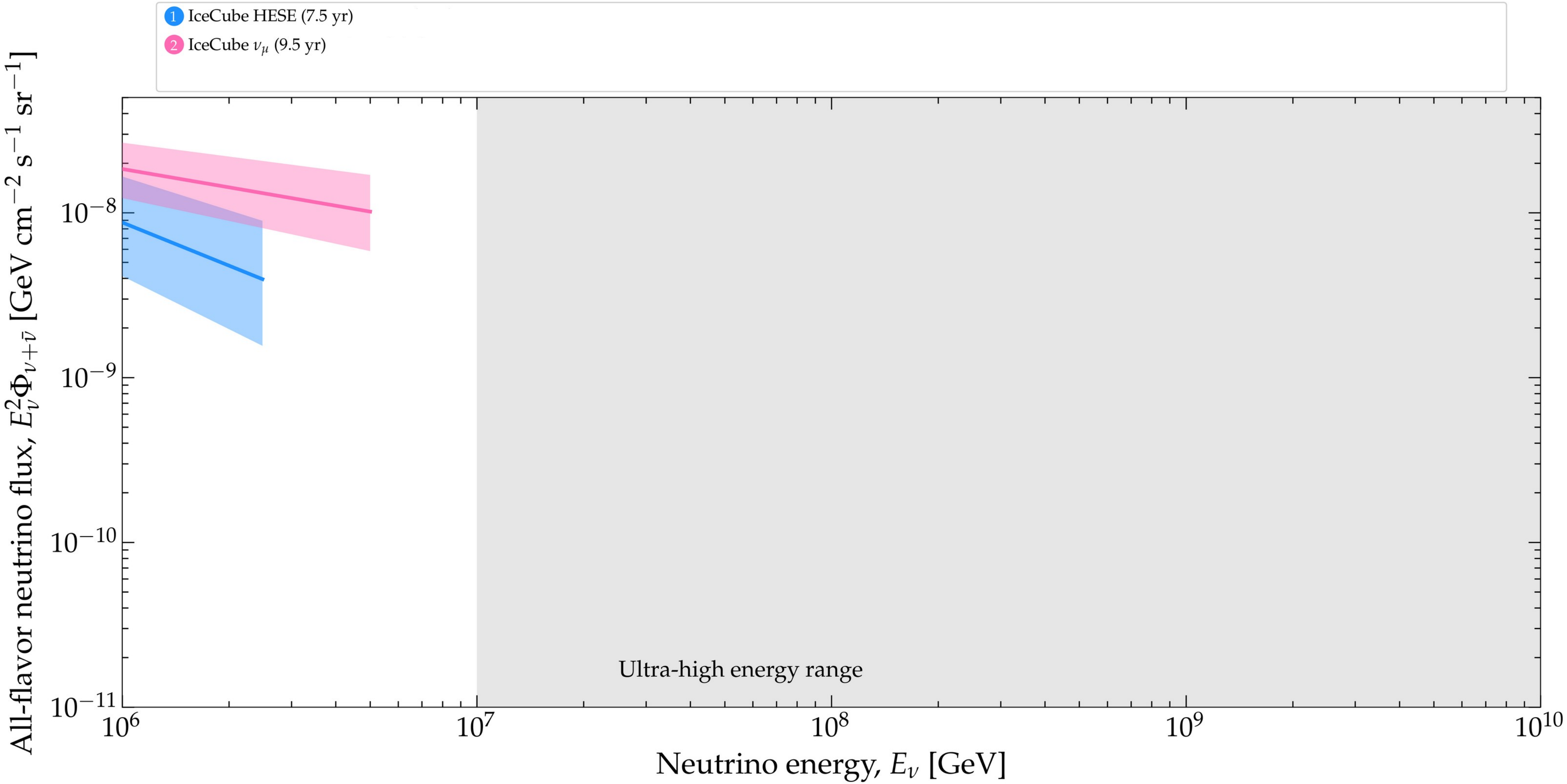
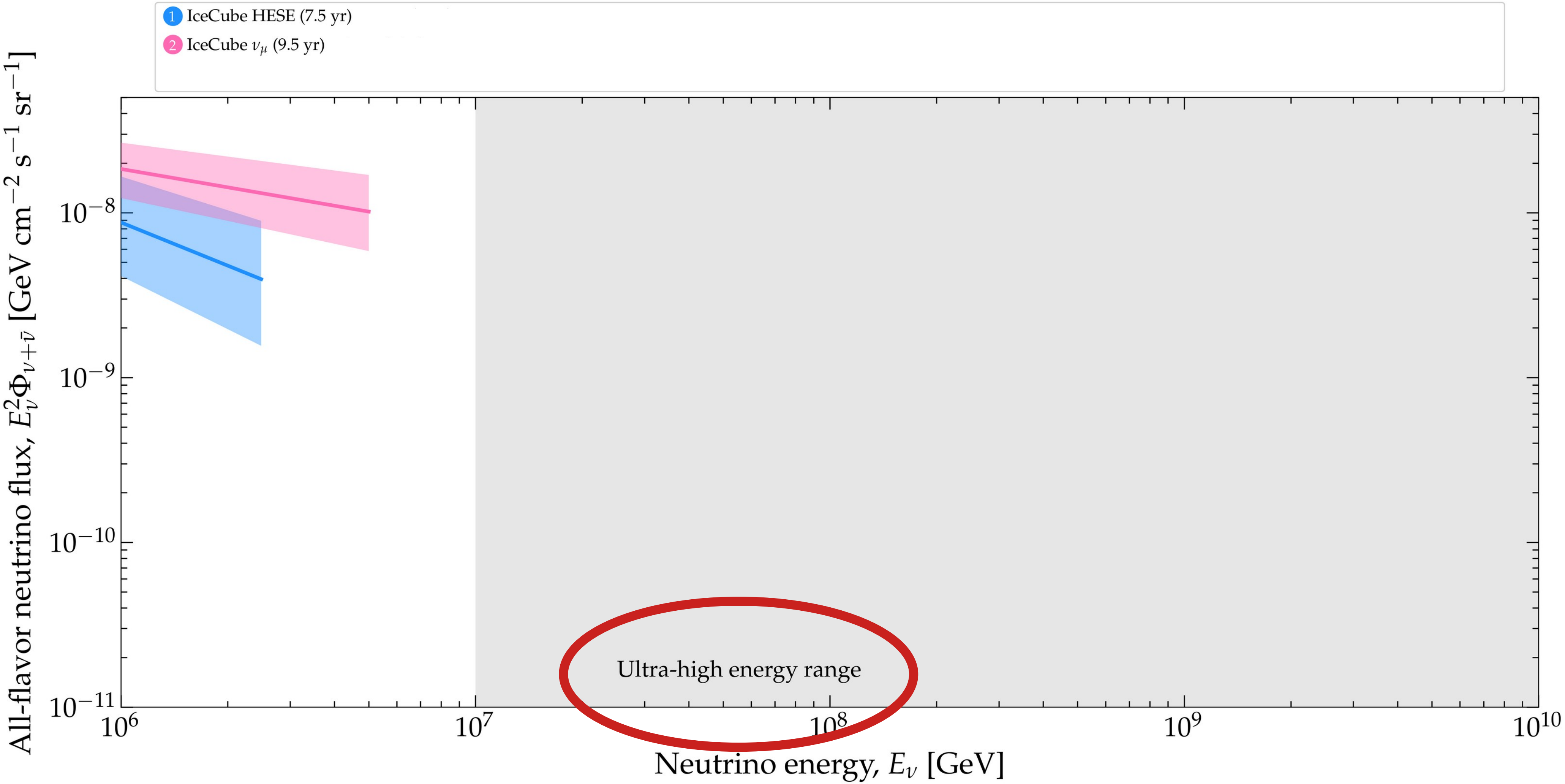
10^{-9}
10^{-10}
10^{-11}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
Neutrino energy, E_ν [GeV]
?



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



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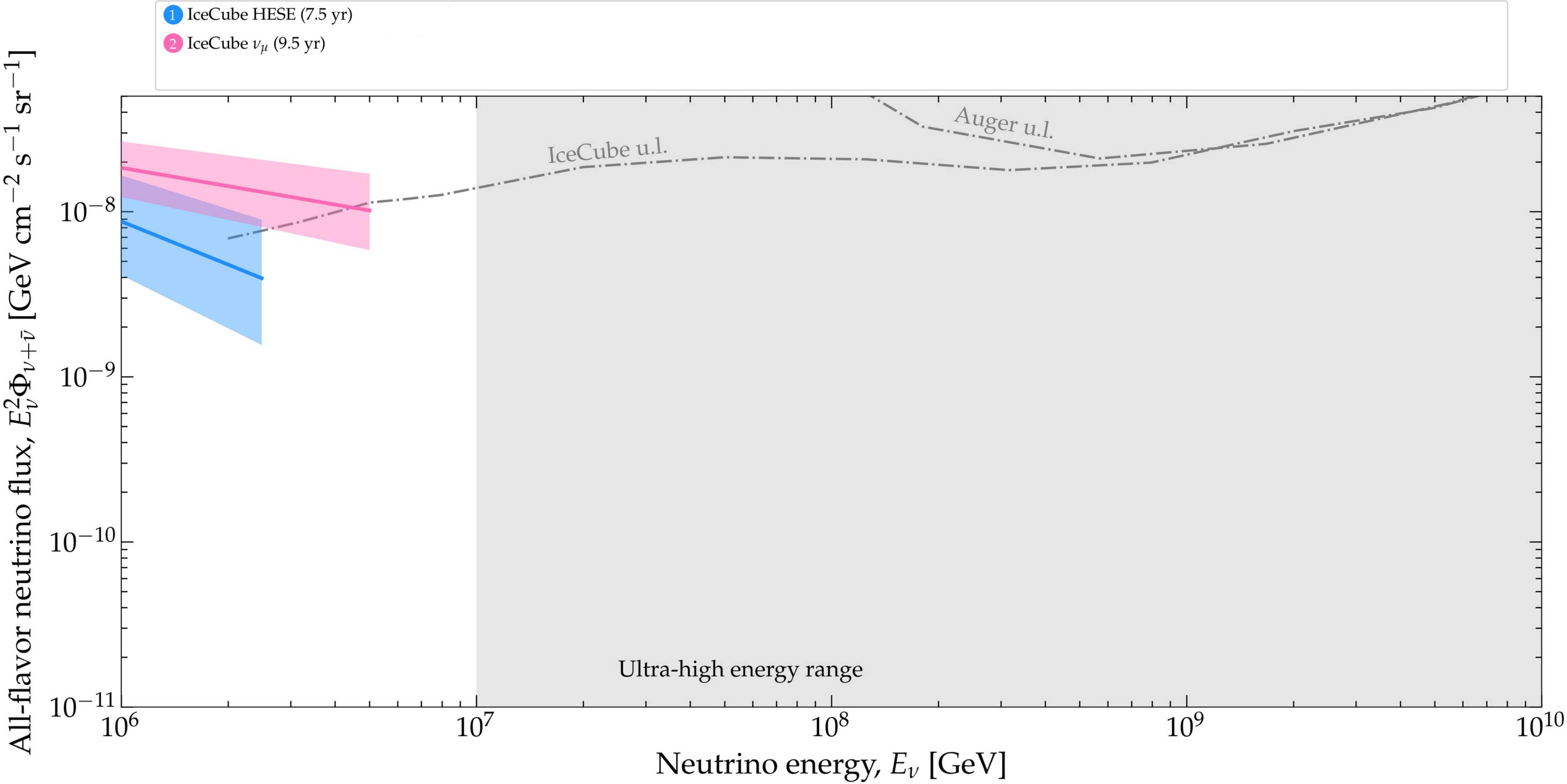

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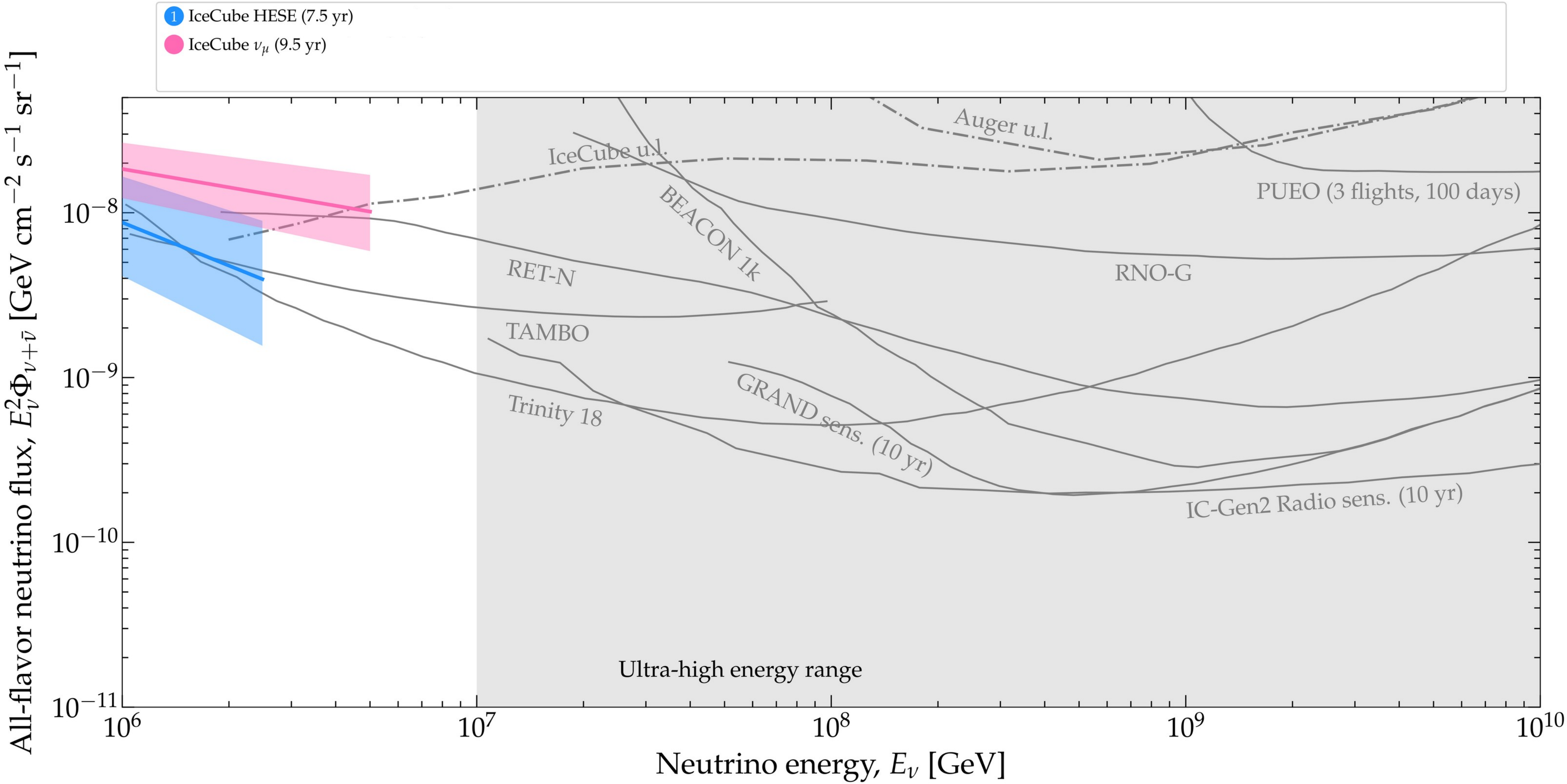
IceCube u.l.
Auger u.l.
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]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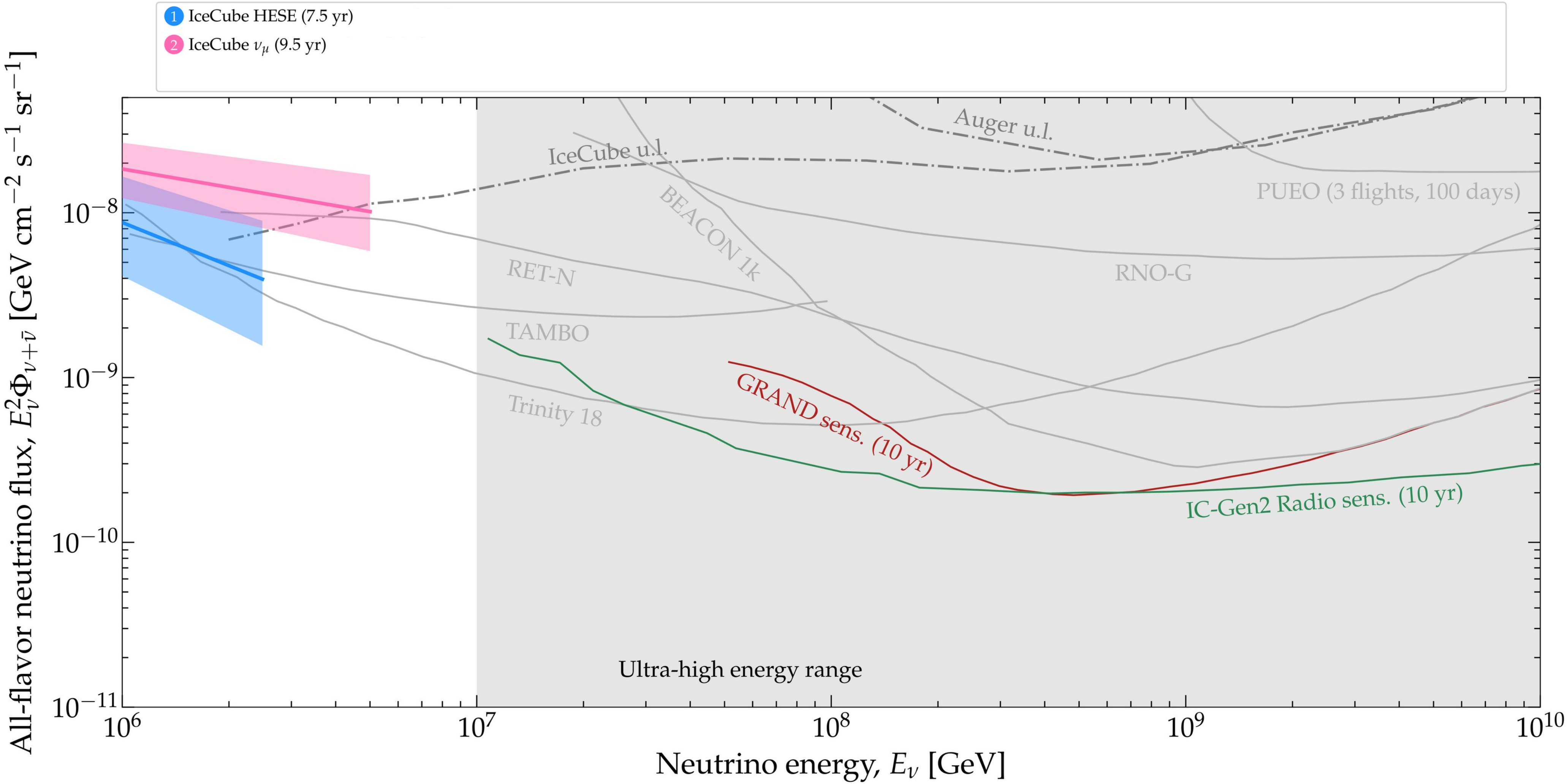
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]
Auger u.l.
IceCube u.l.
PUEO (3 flights, 100 days)
BEACON 1k
RNO-G
RET-N
TAMBO
GRAND sens. (10 yr)
Trinity 18
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range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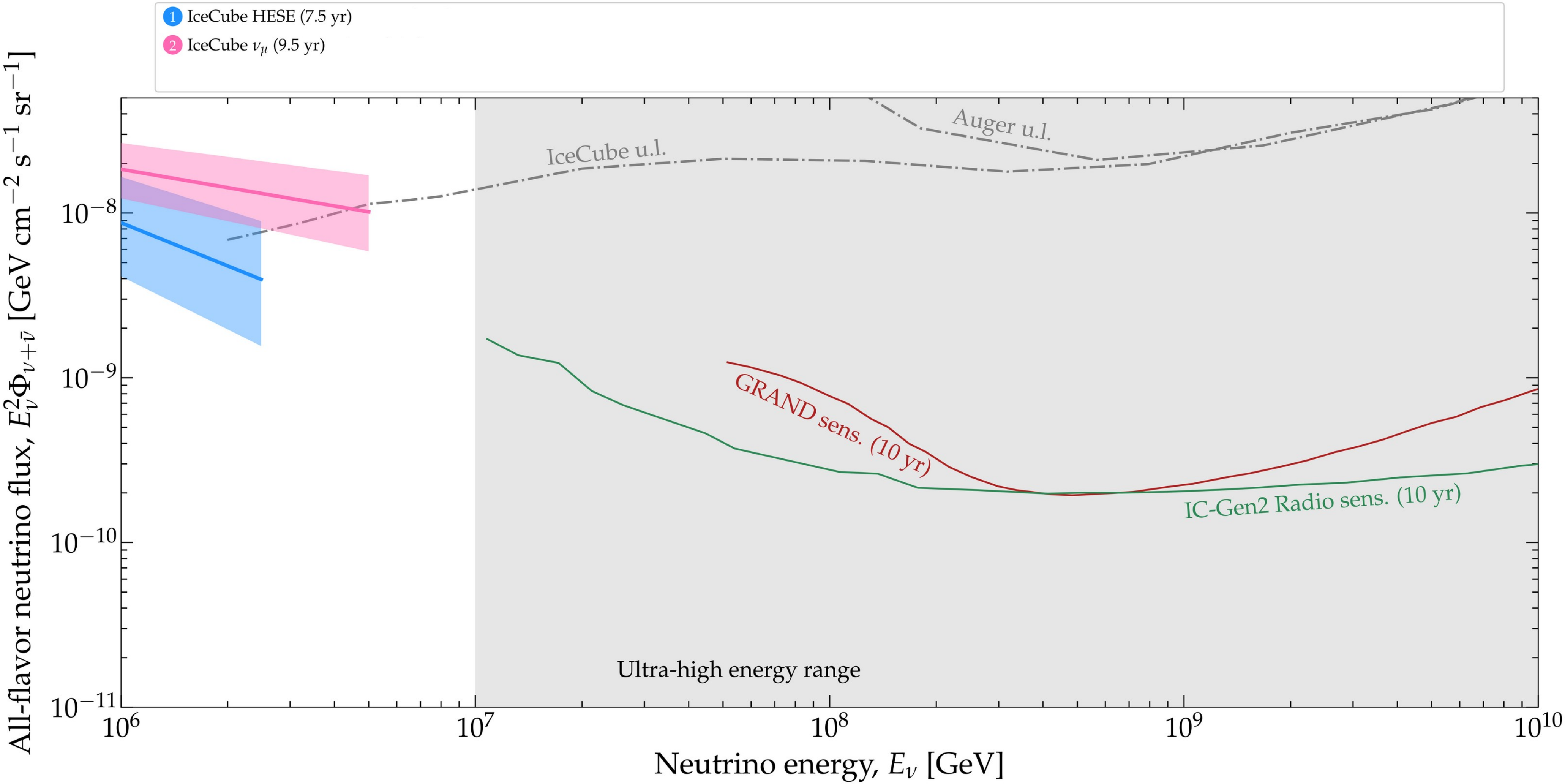
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Auger u.l.
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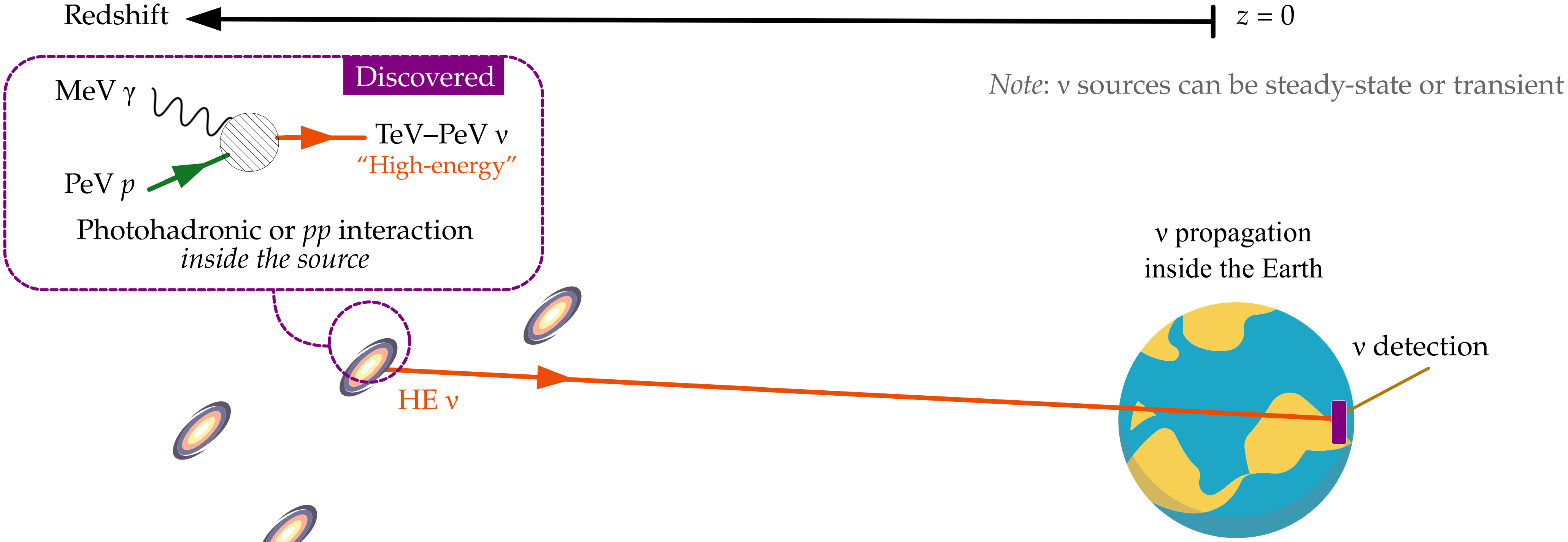
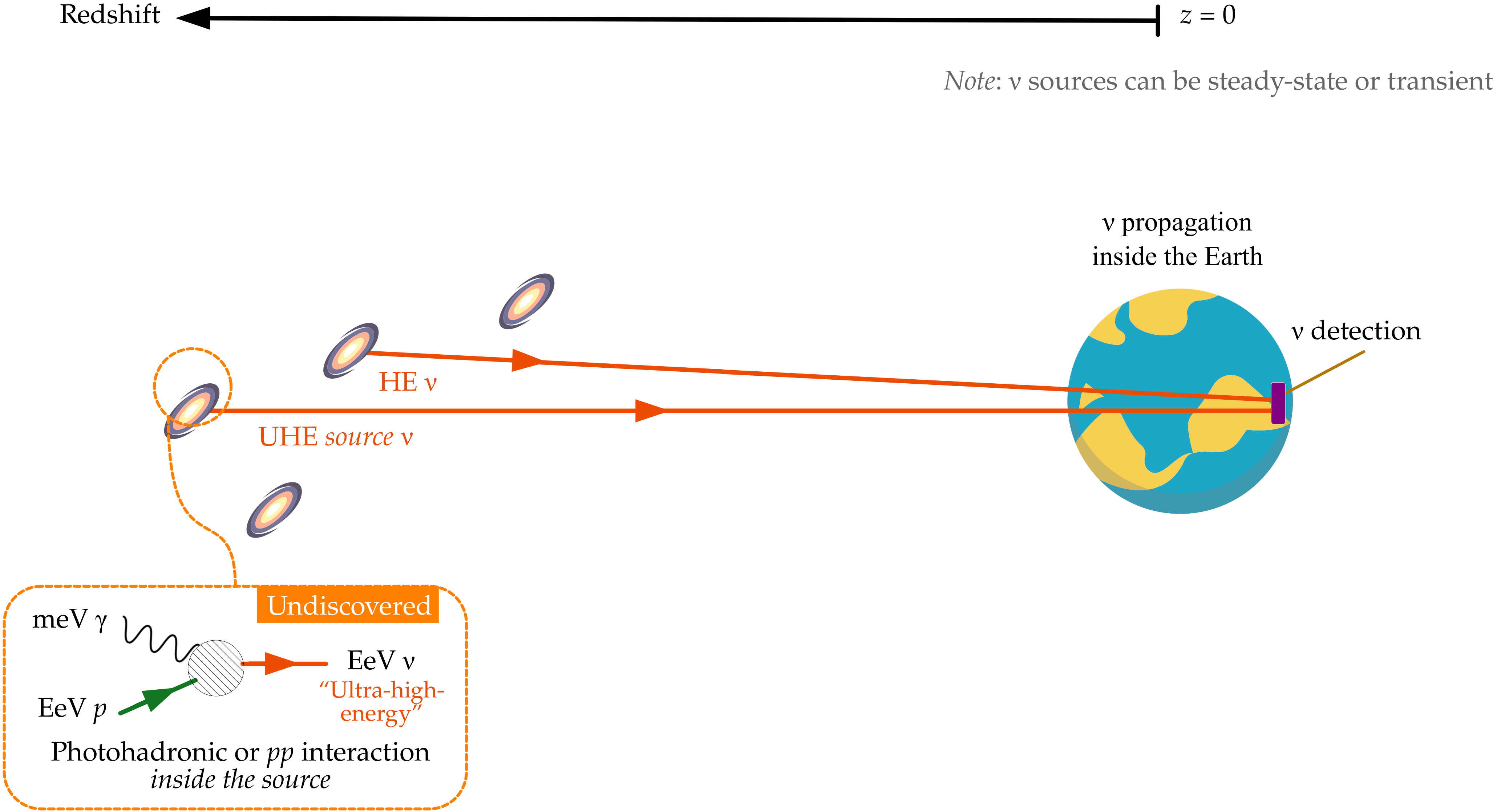
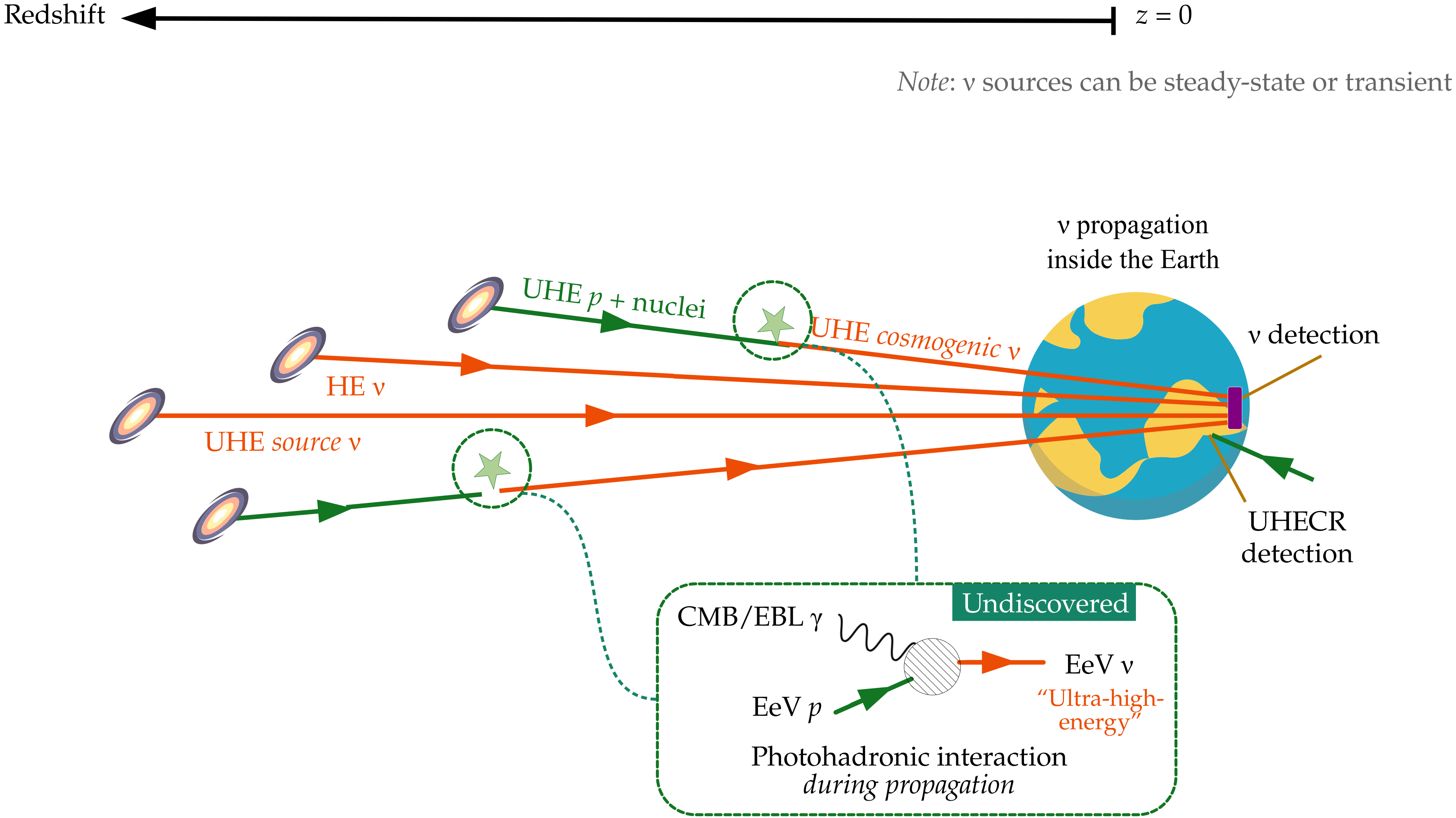
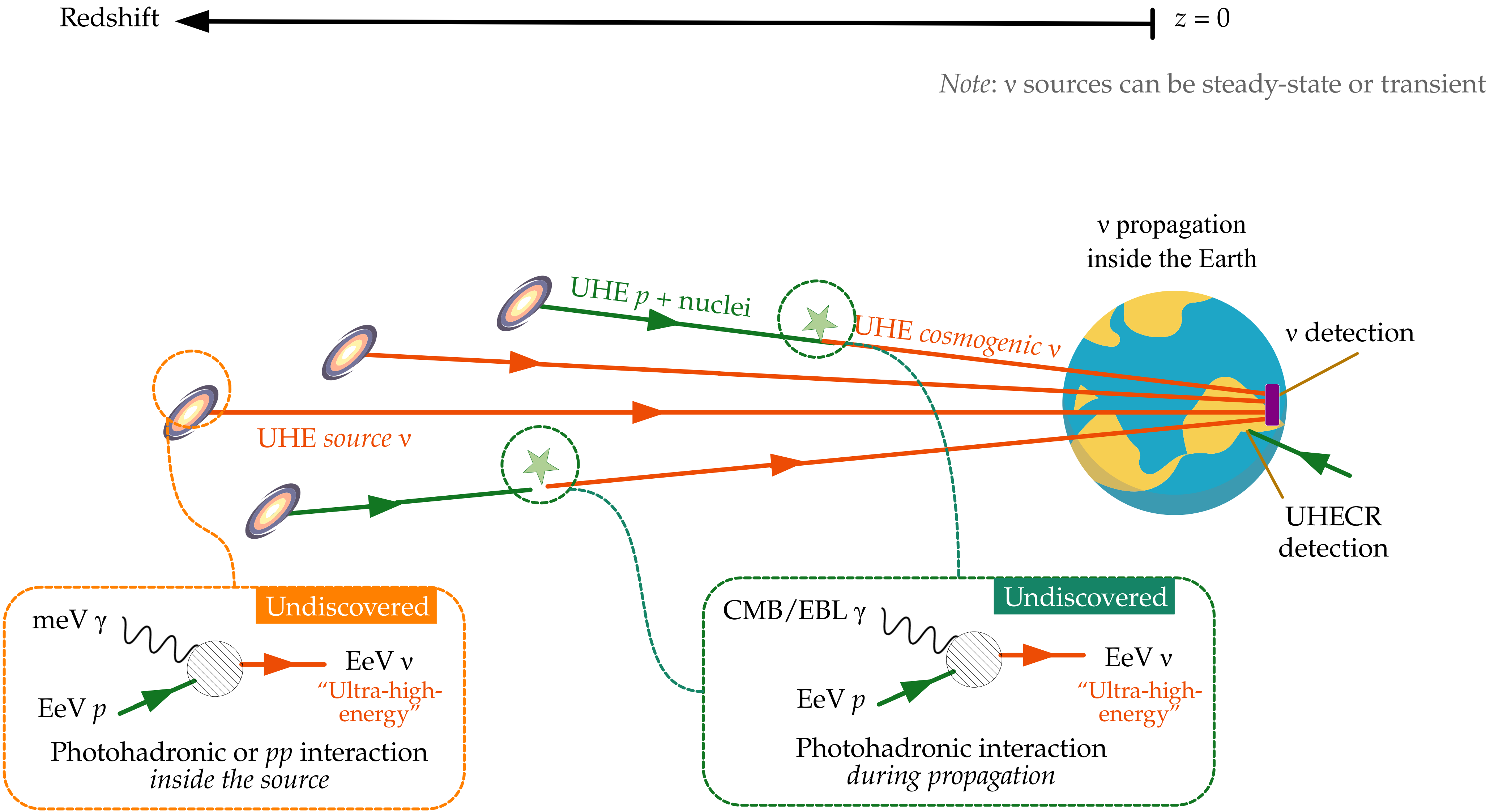
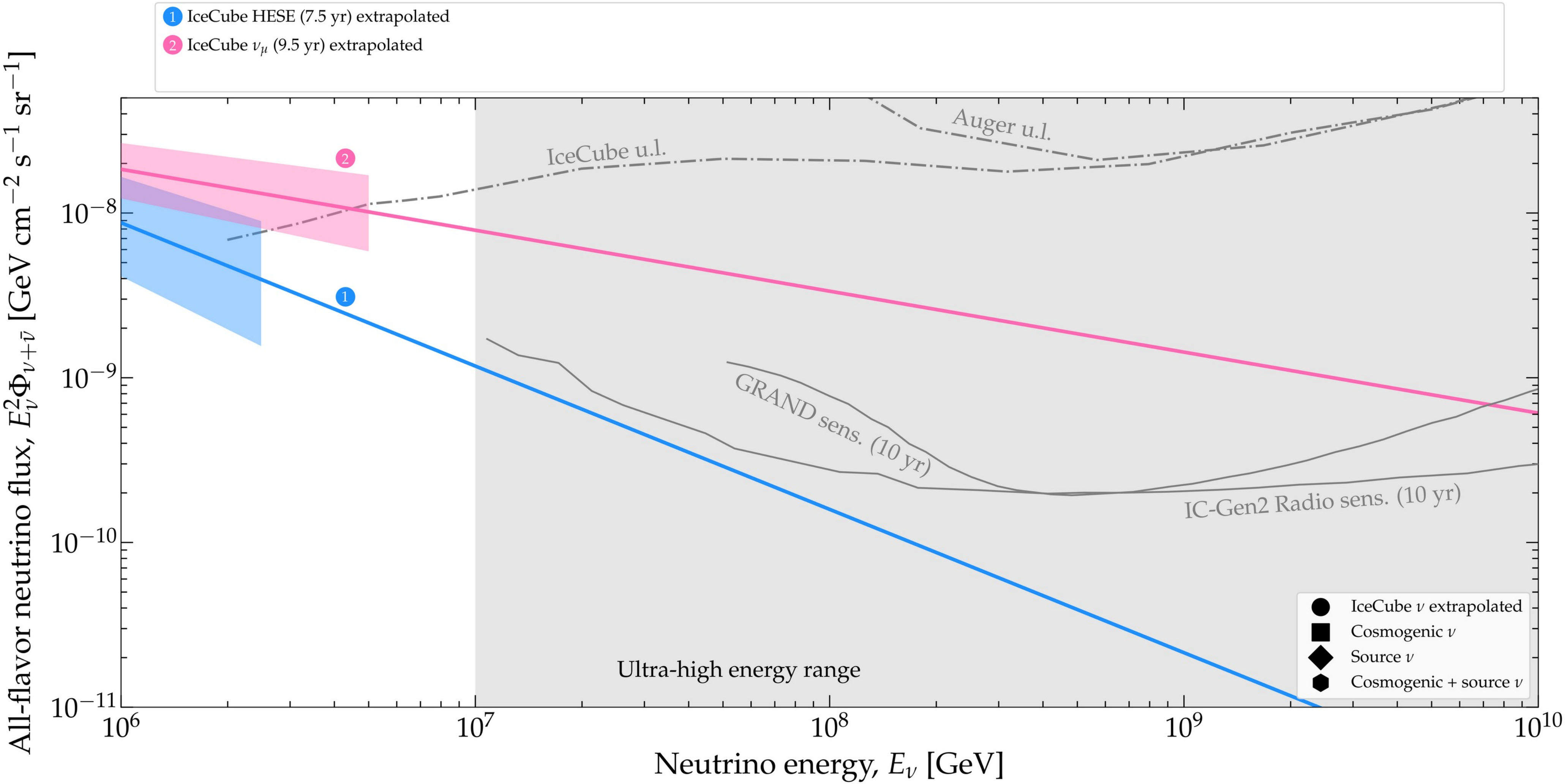

Redshift
$z = 0$
Discovered
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or *pp* interaction
inside the source
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν


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
EeV p
"Ultra-high-energy"
Photohadronic interaction
during propagation


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



① IceCube HESE (7.5 yr) extrapolated
② IceCube ν_μ (9.5 yr) extrapolated
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
● IceCube ν extrapolated
■ Cosmogenic ν
◆ Source ν
⬢ Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
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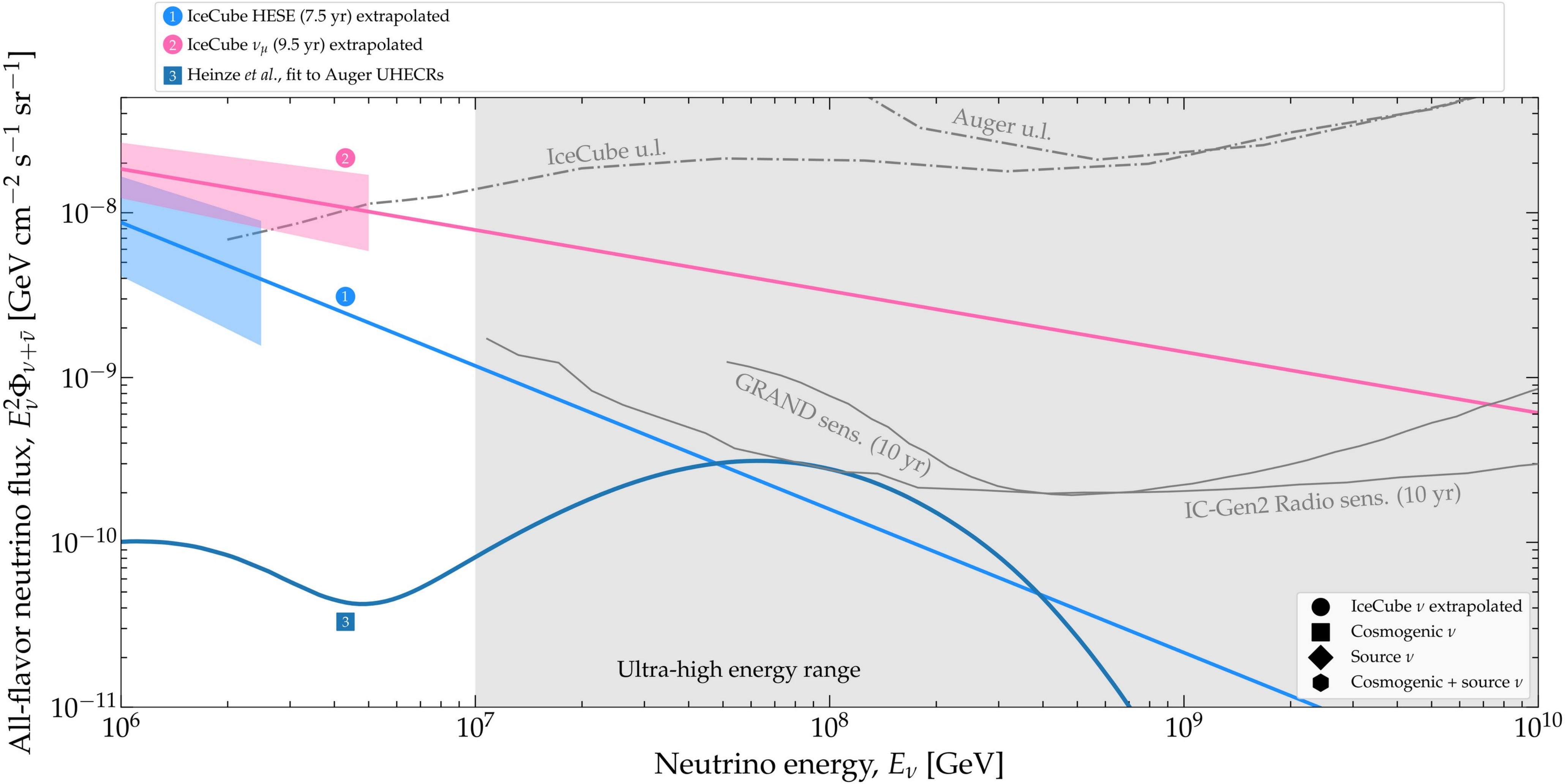
10^{10}
Neutrino energy, E_ν [GeV]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Auger u.l.
IceCube u.l.
②
①
3
GRAND sens. (10 yr)
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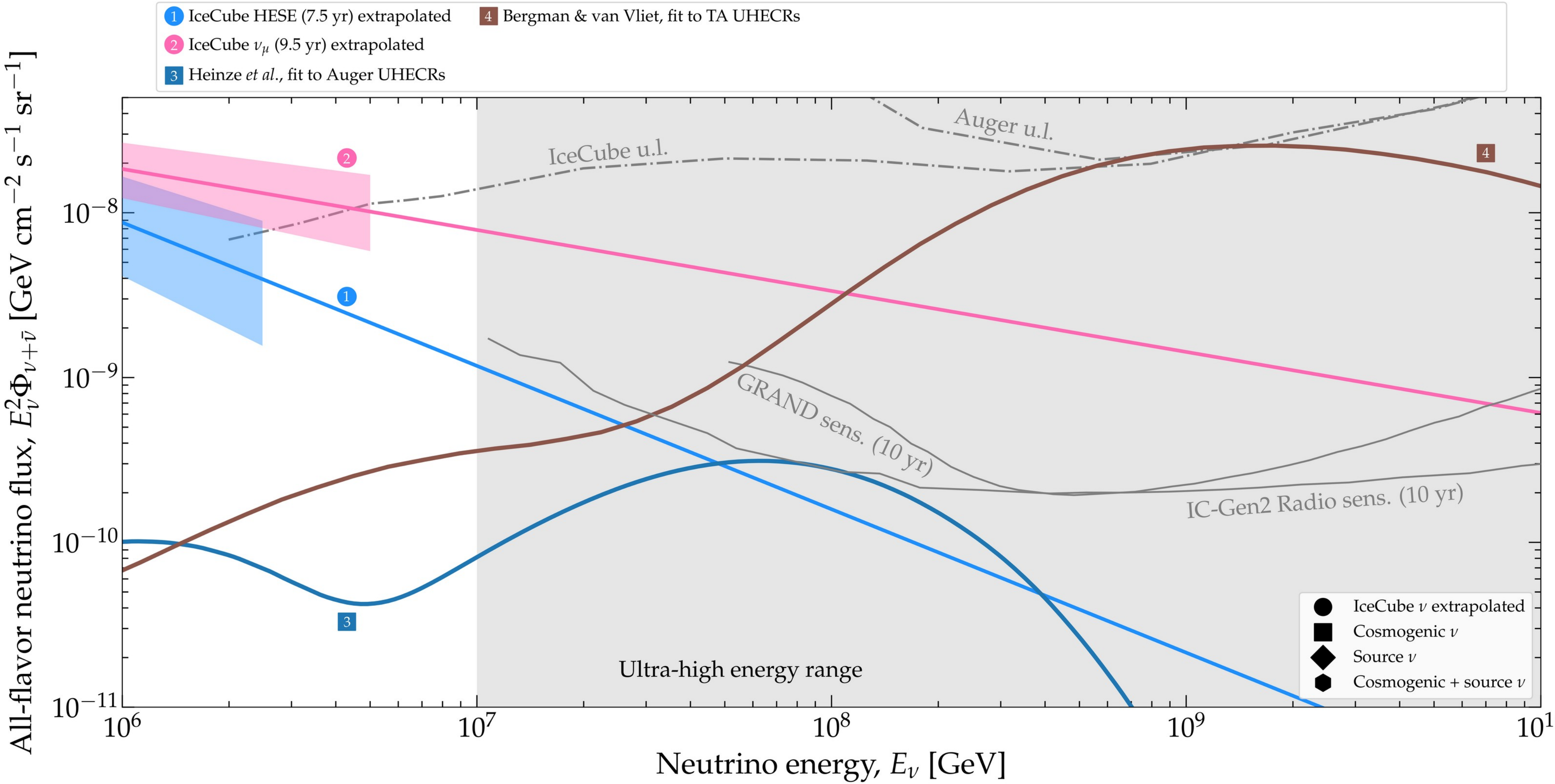
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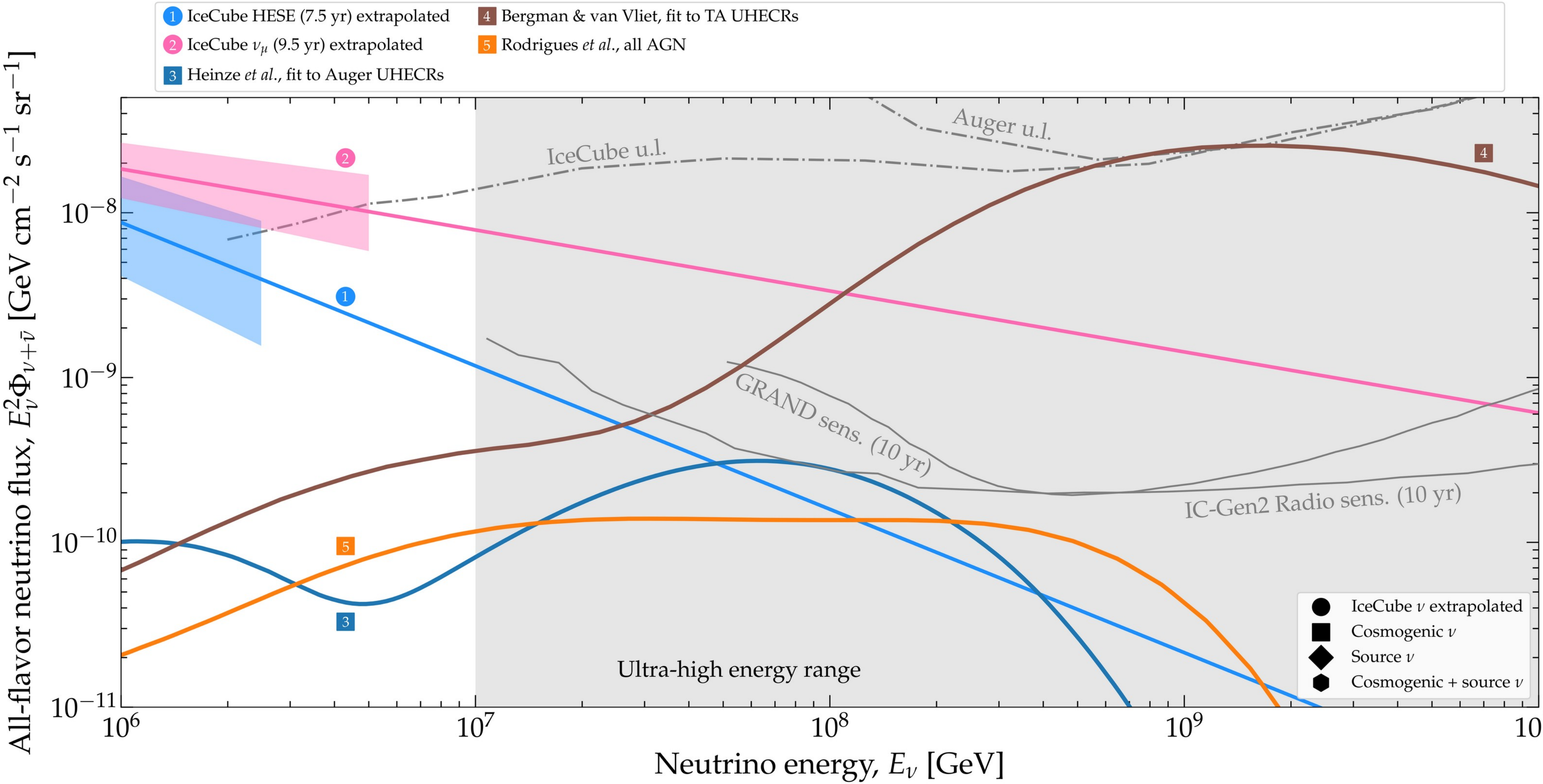
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Neutrino energy, E_ν [GeV]
10^6
10^7
10^8
10^9
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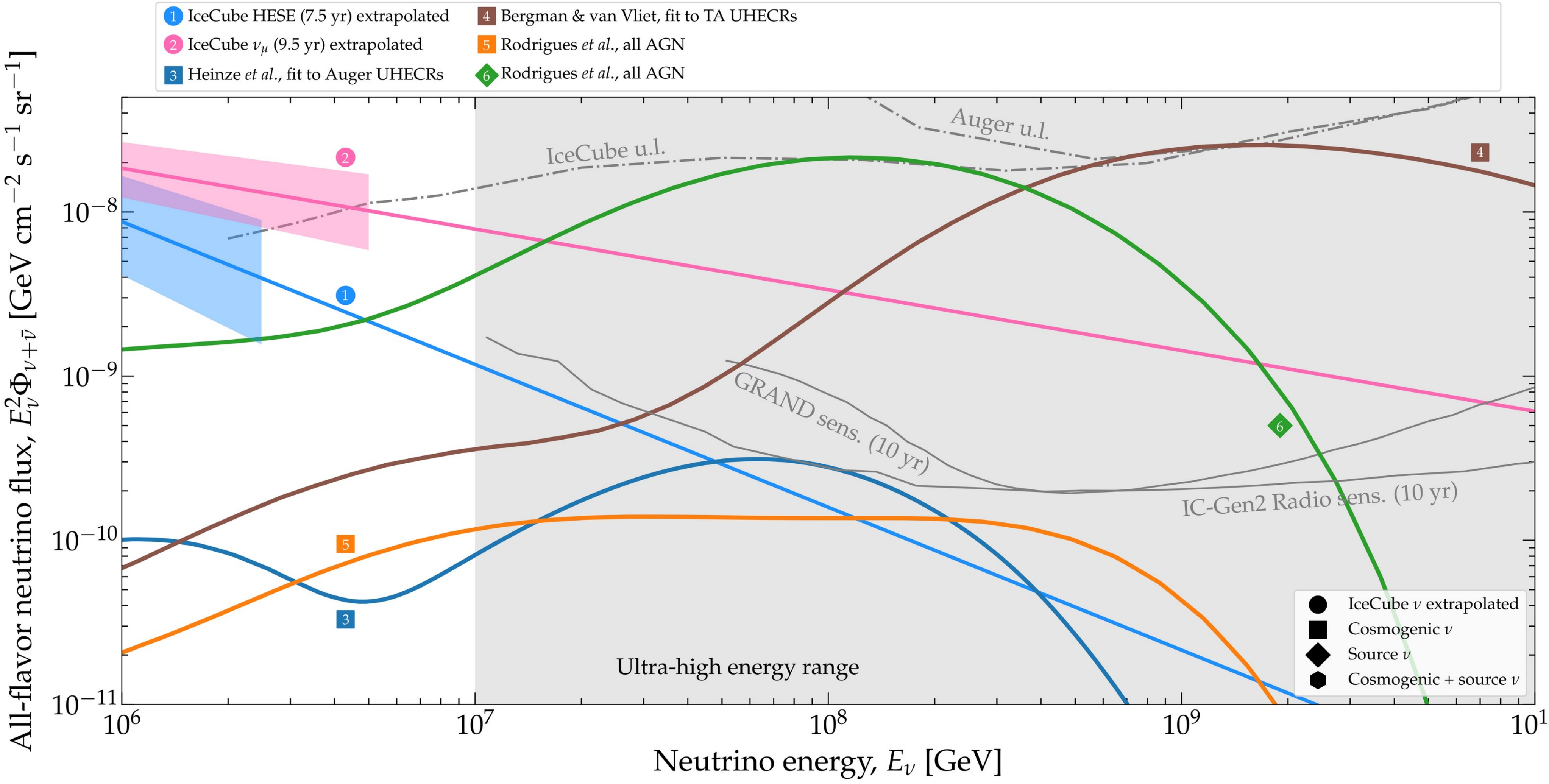
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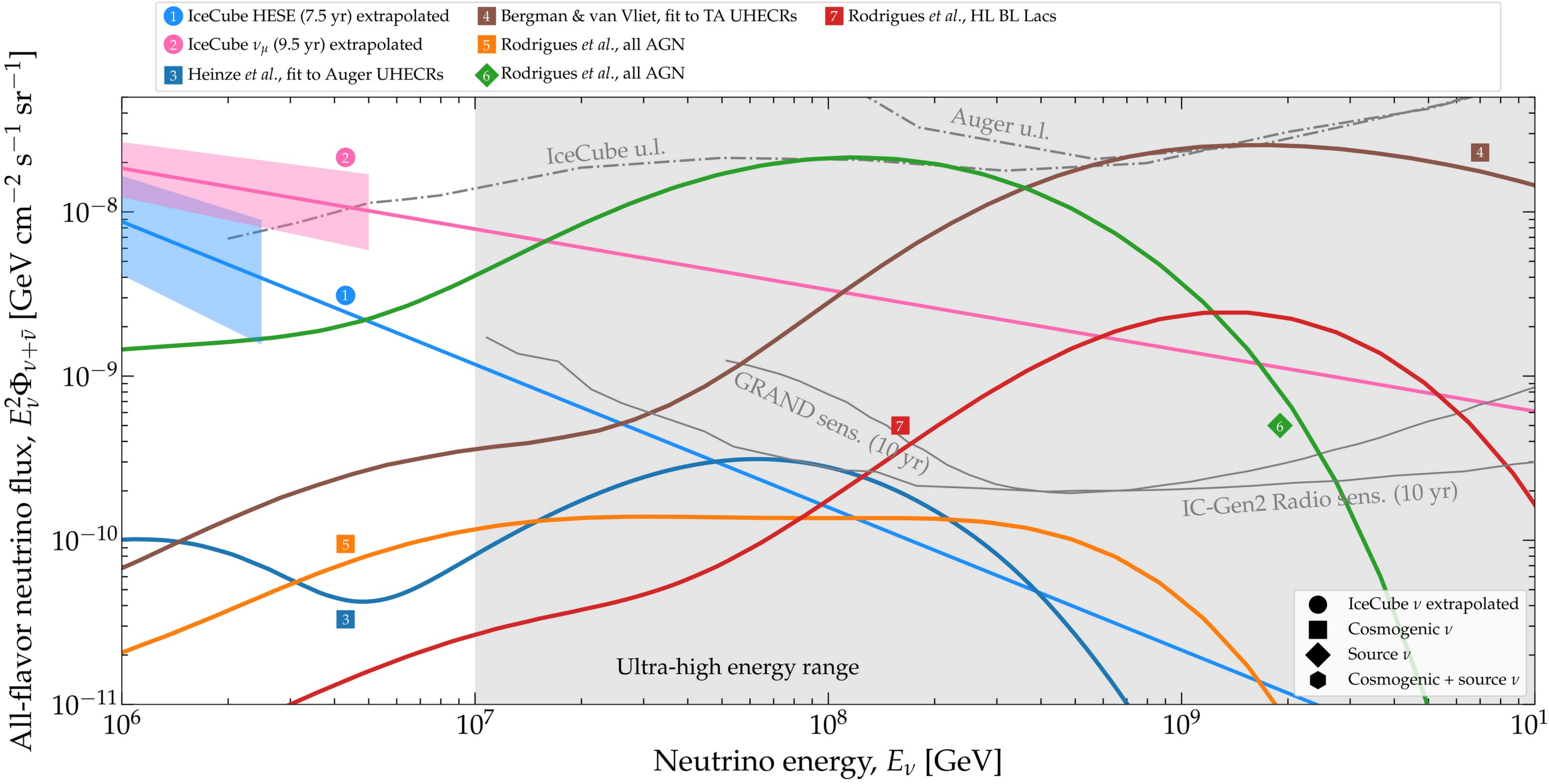
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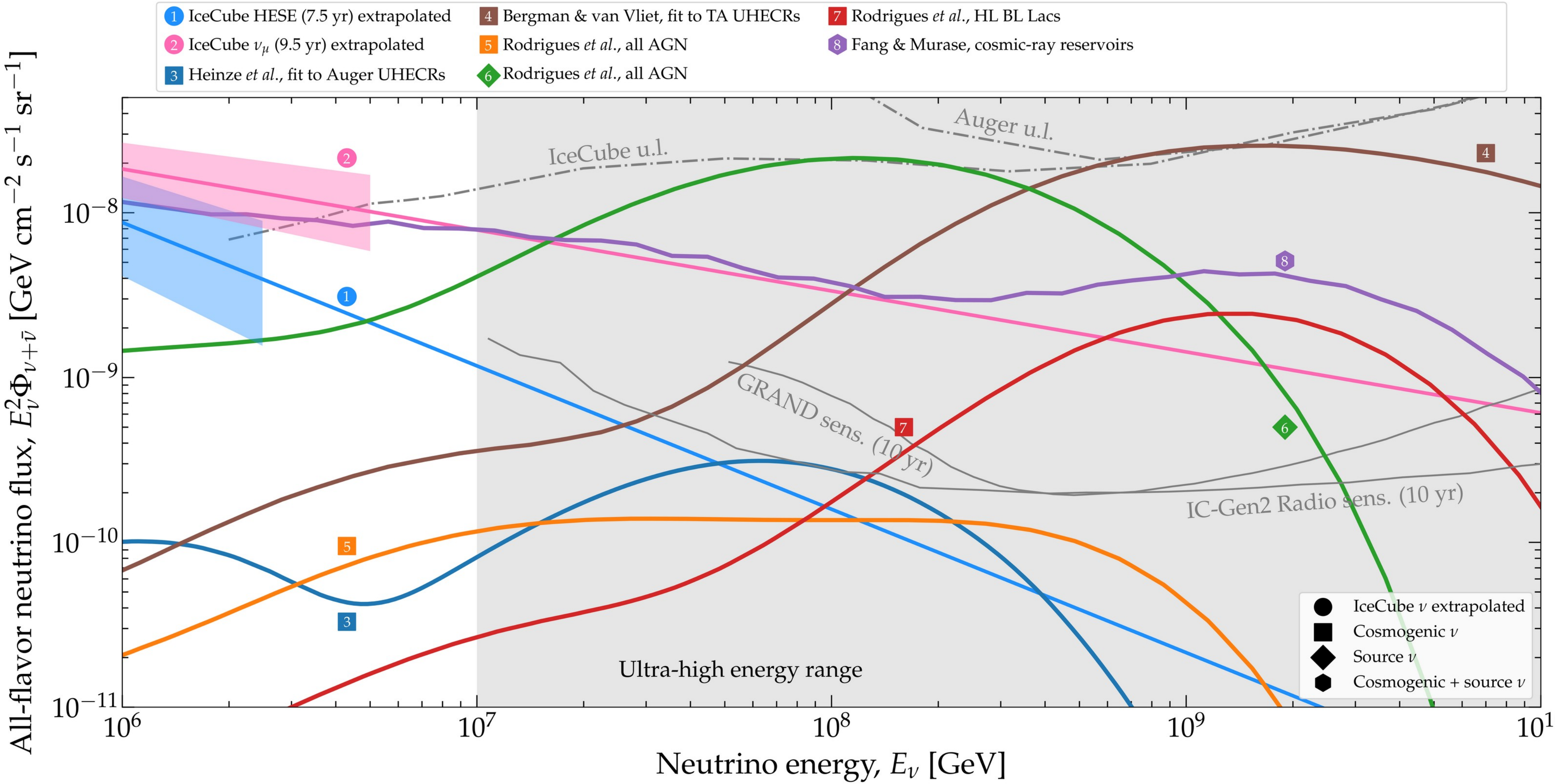
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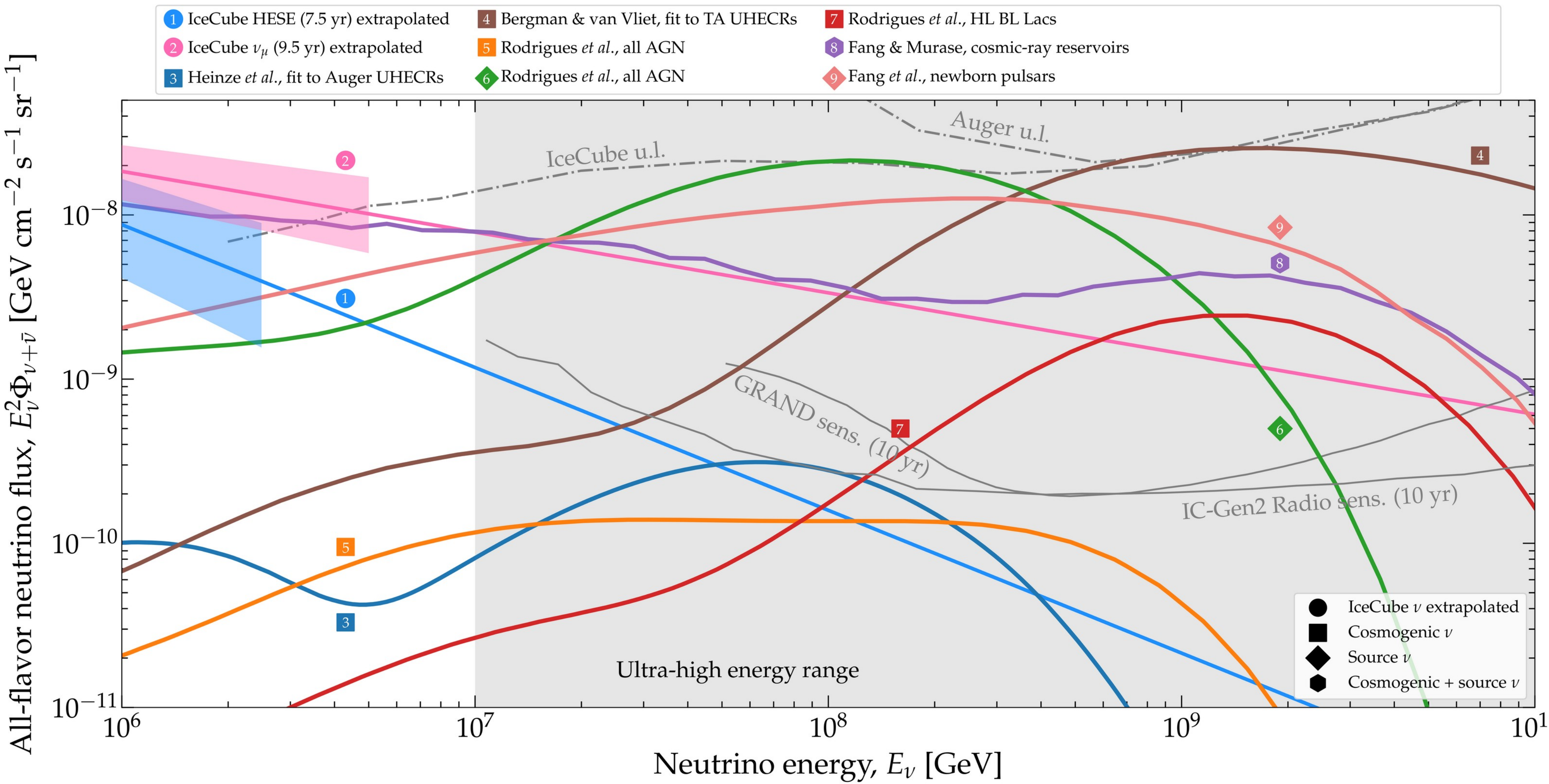
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Ultra-high energy range
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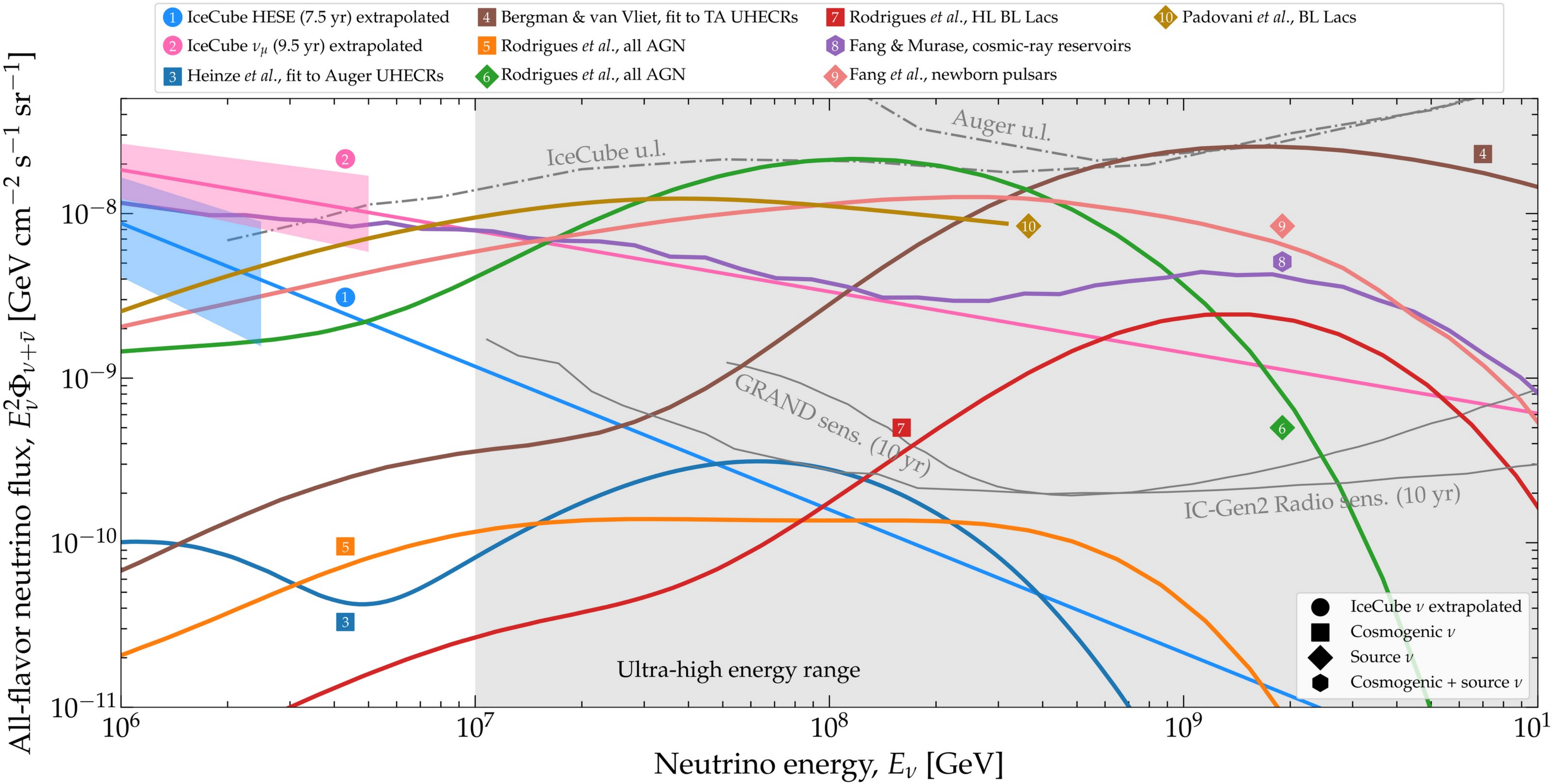
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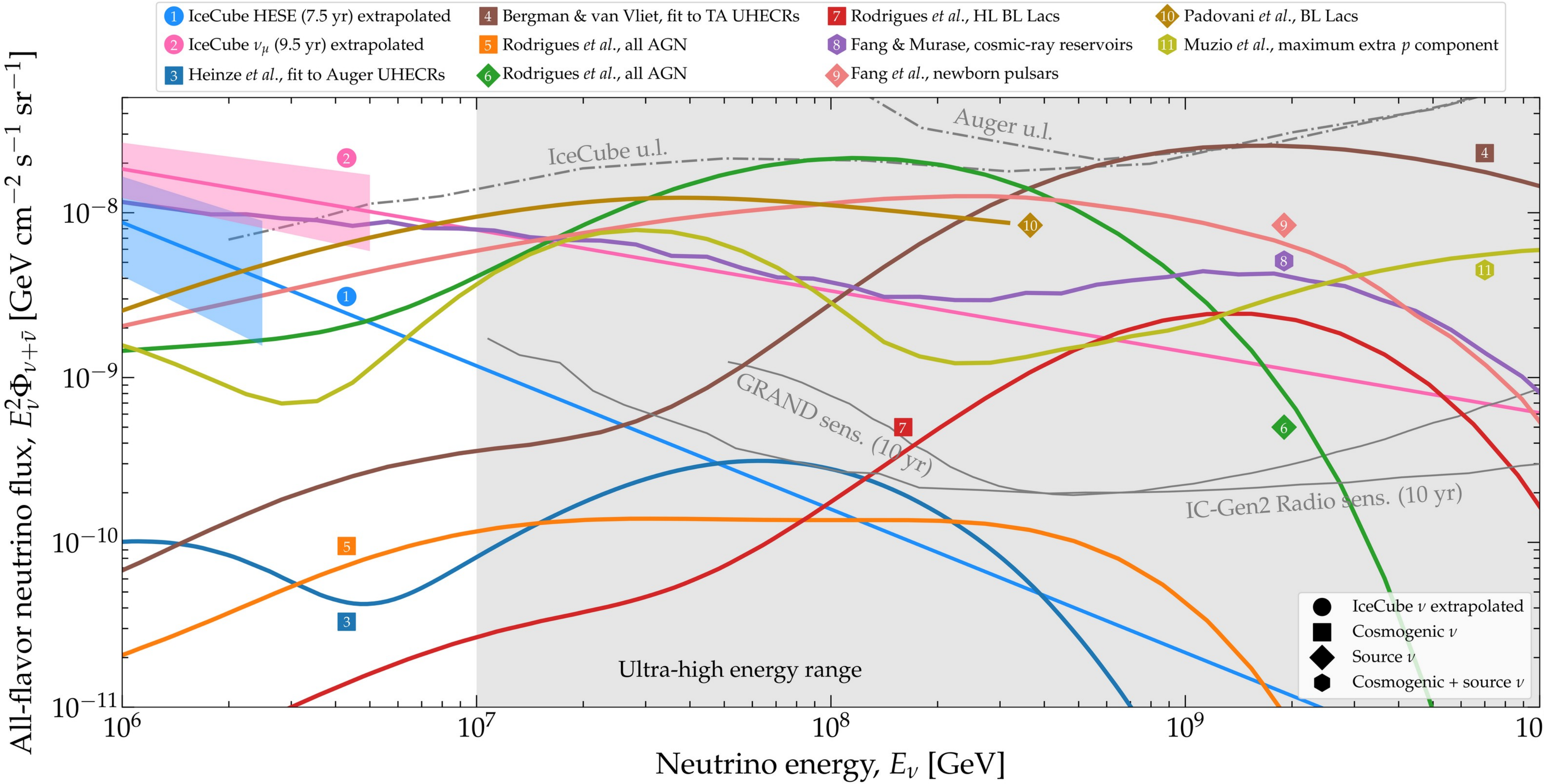

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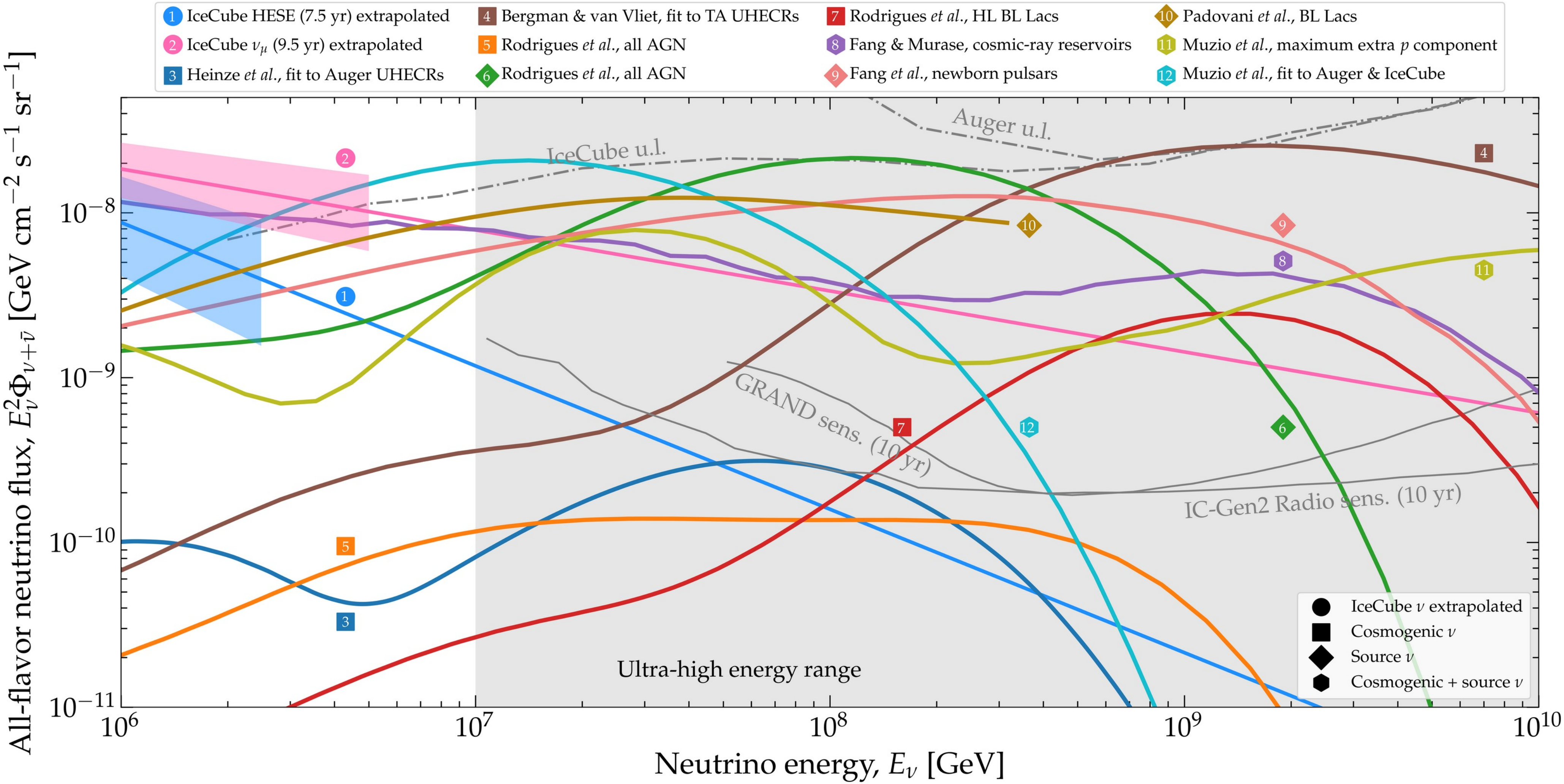
Neutrino energy, E_ν [GeV]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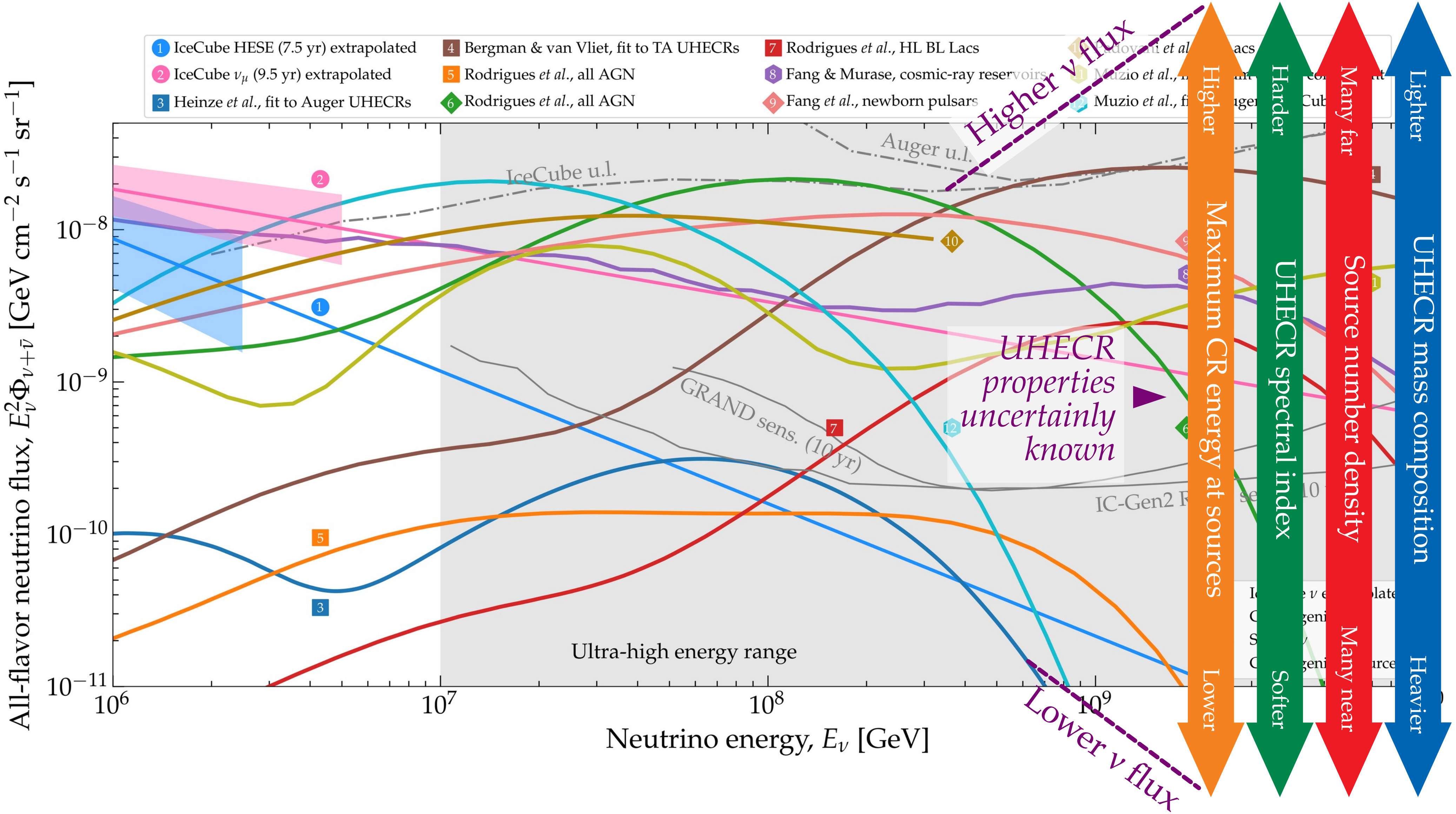

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12 Muzio *et al.*, fi… Auger … Cub…
All-flavor neutrino flux, $E_\nu^2\Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
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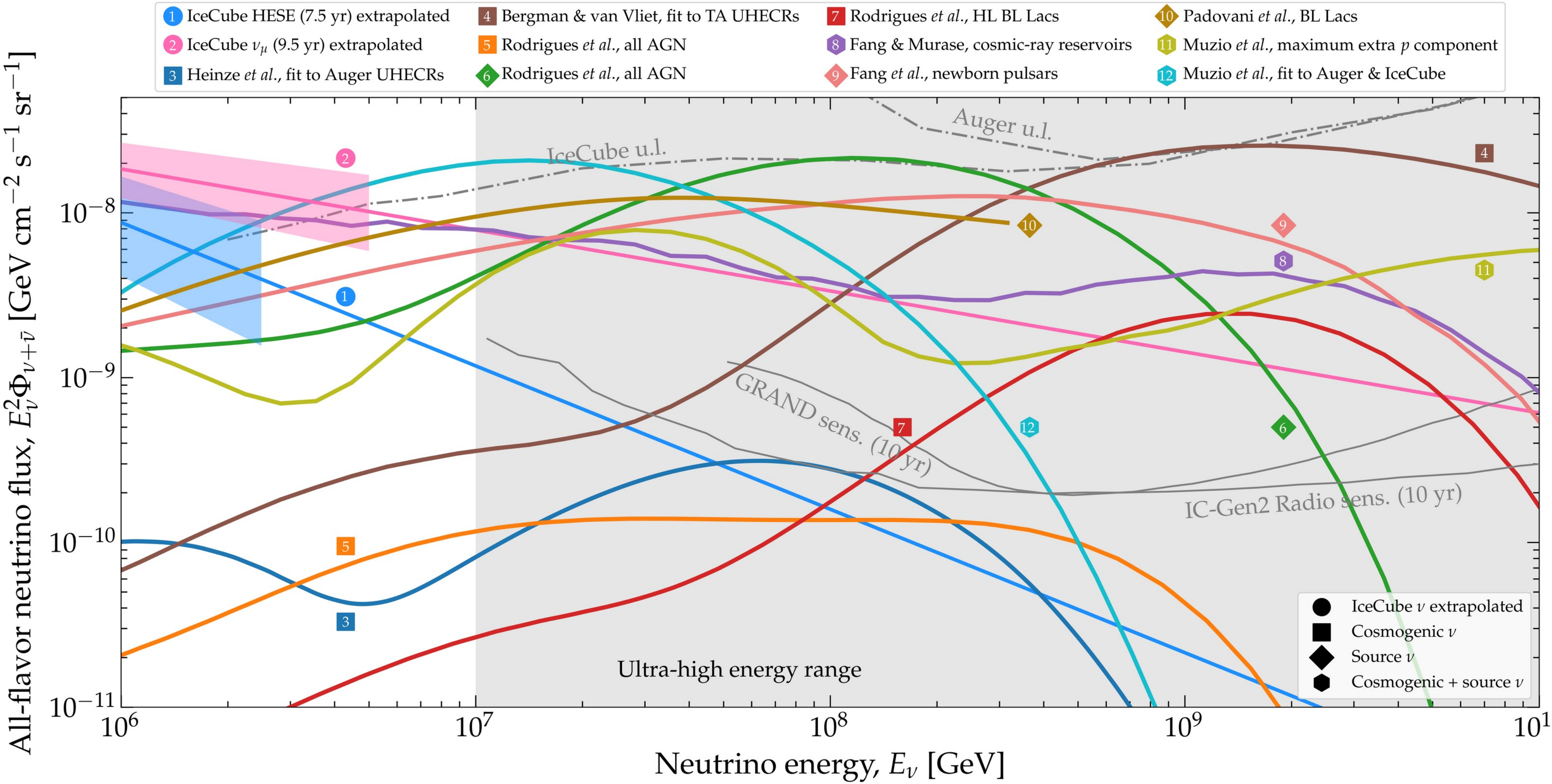
Neutrino energy, E_ν [GeV]
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 R… se… 10
Ultra-high energy range
Ic… e ν e… plate
C… geni…
S… ν
C… geni… urce
Higher ν flux
Lower ν flux
UHECR properties uncertainly known
Higher
Maximum CR energy at sources
Lower
Harder
UHECR spectral index
Softer
Many far
Source number density
Many near
Lighter
UHECR mass composition
Heavier



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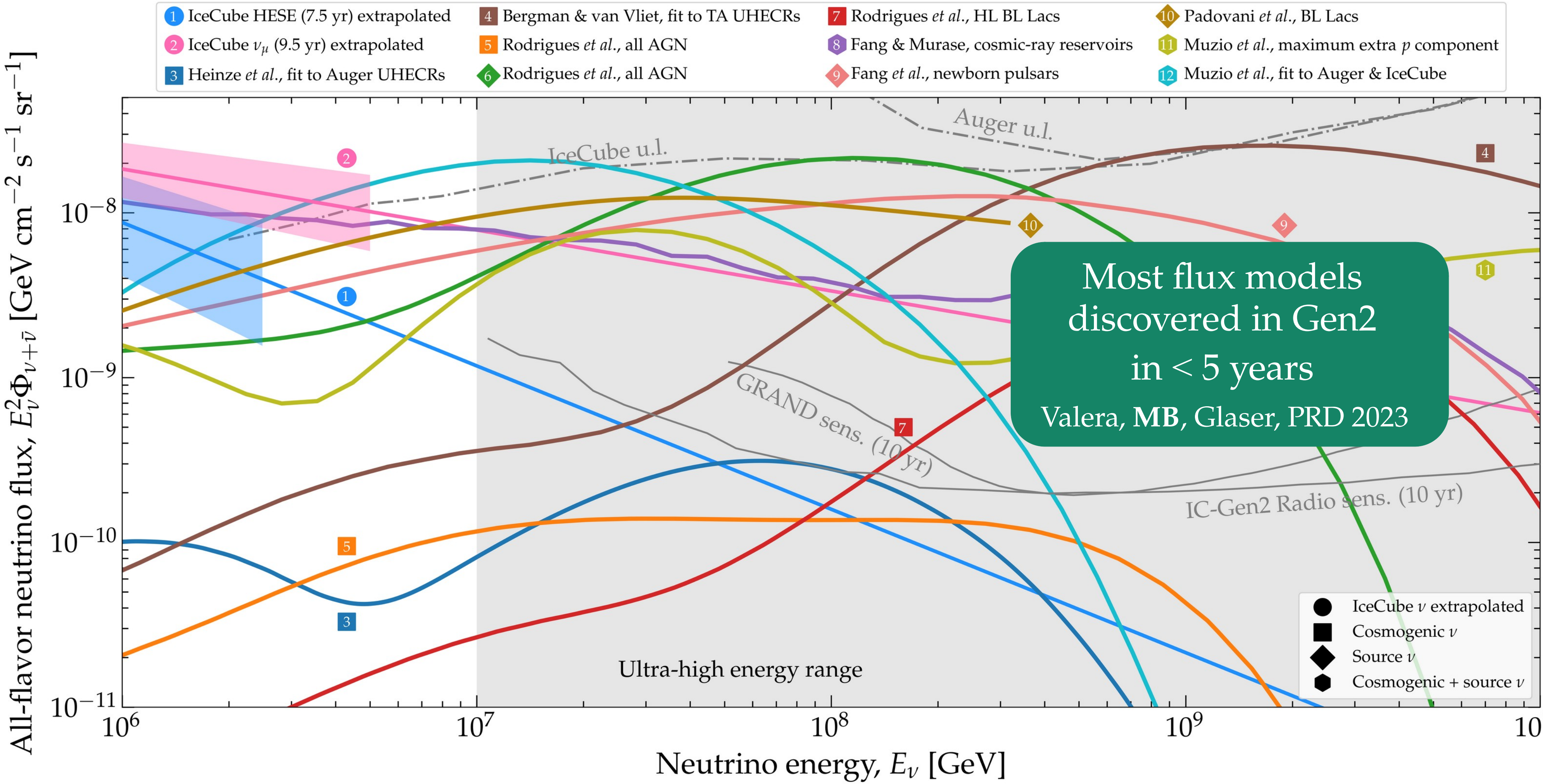
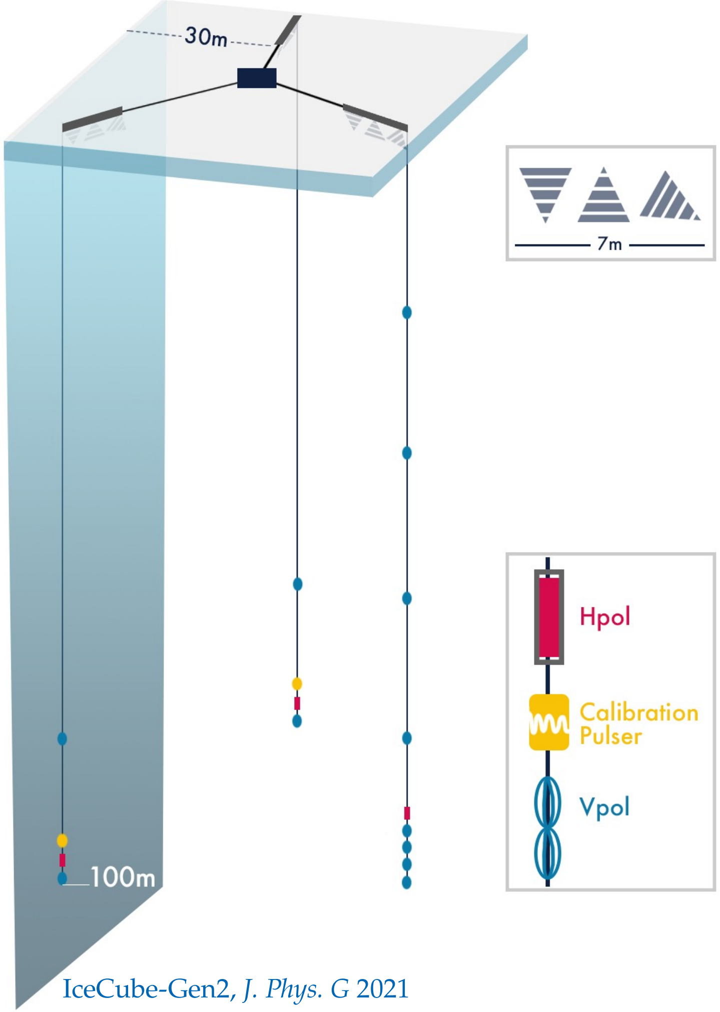


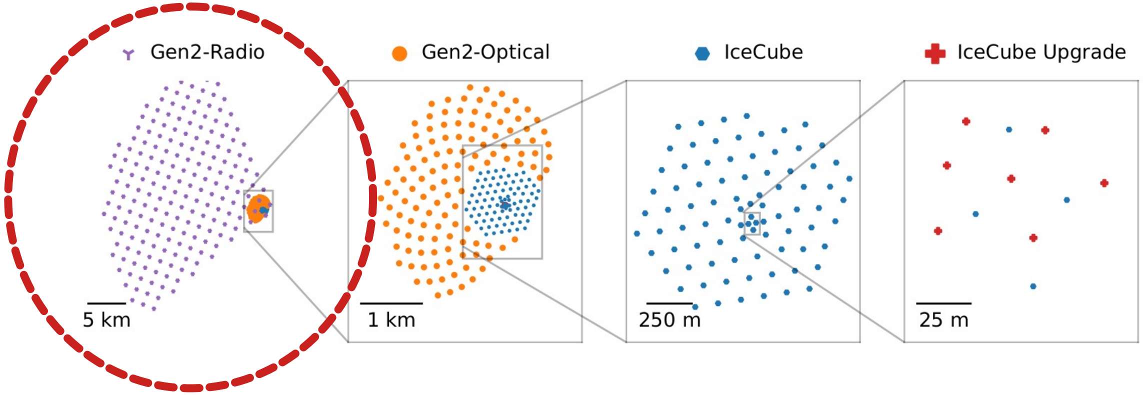
Most flux models discovered in Gen2 in < 5 years

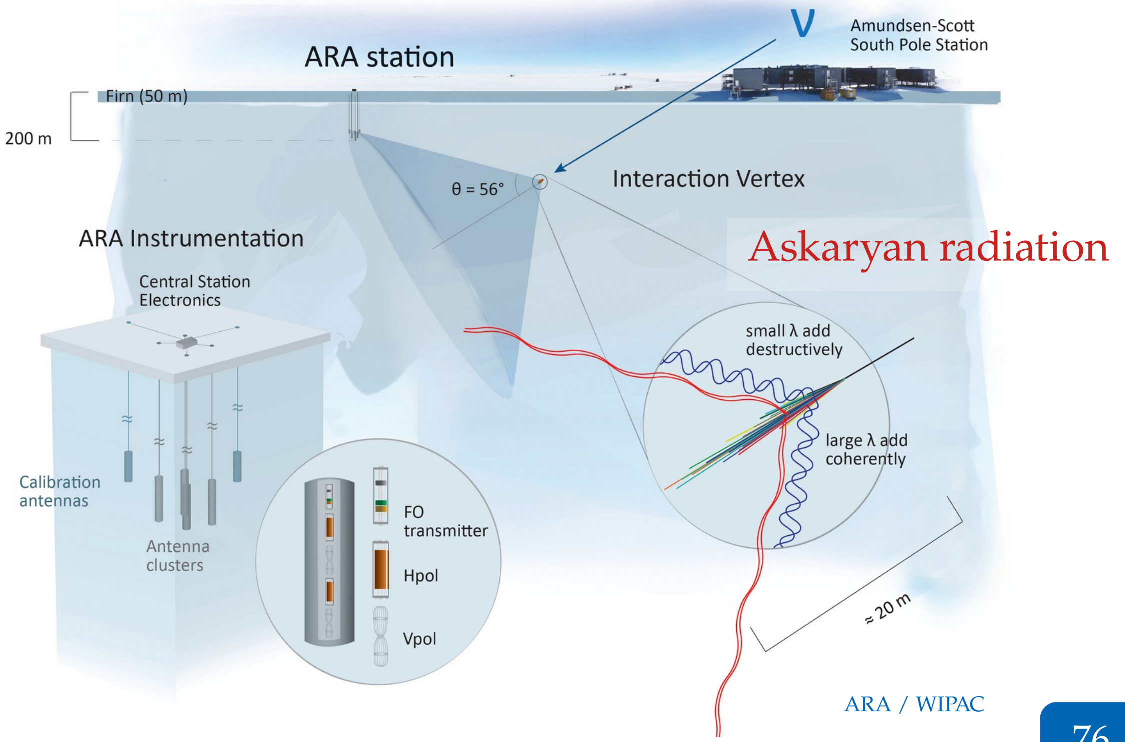
Valera, **MB**, Glaser, PRD 2023

IceCube-Gen2 Radio



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

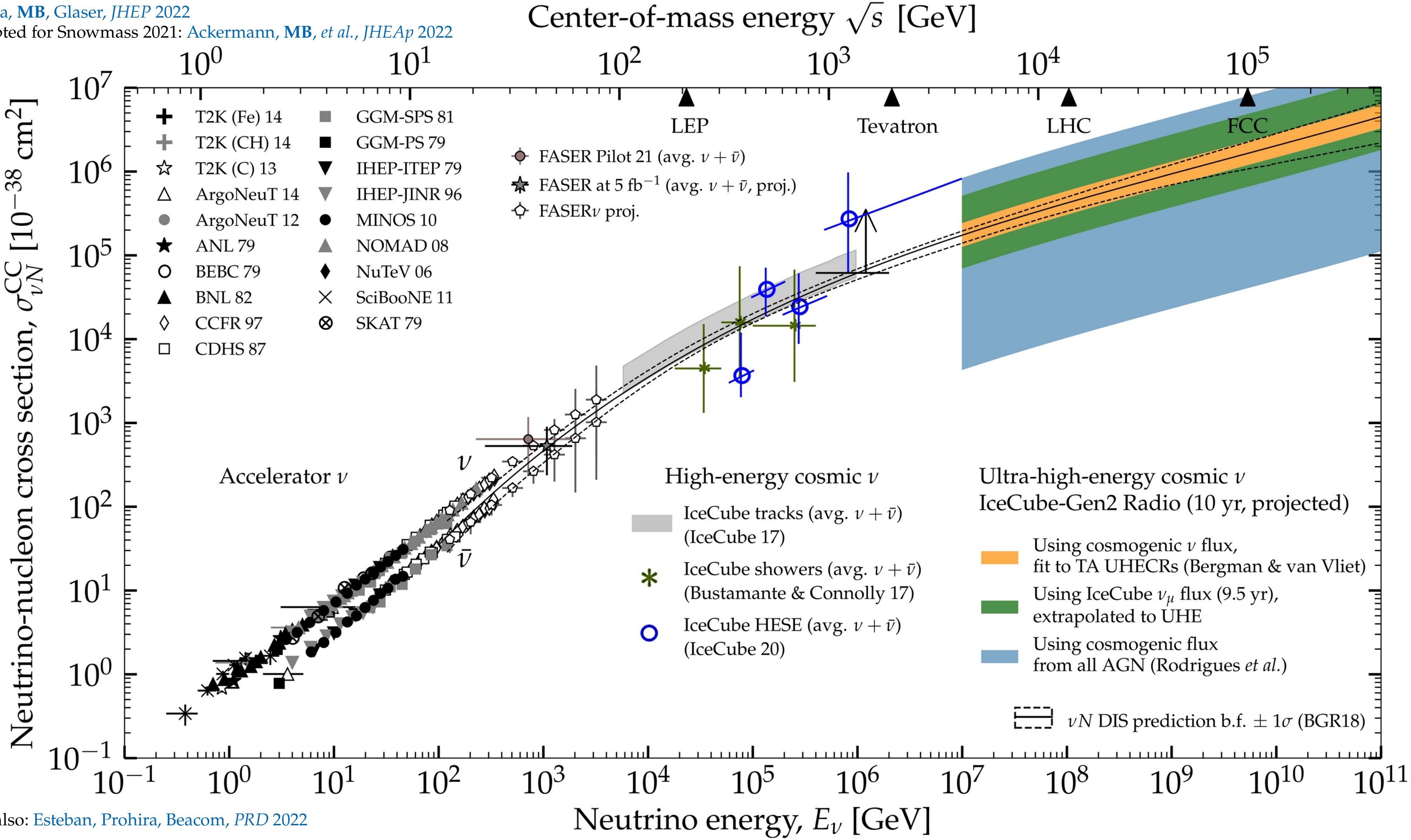




Askaryan radiation

ARA / WIPAC

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



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

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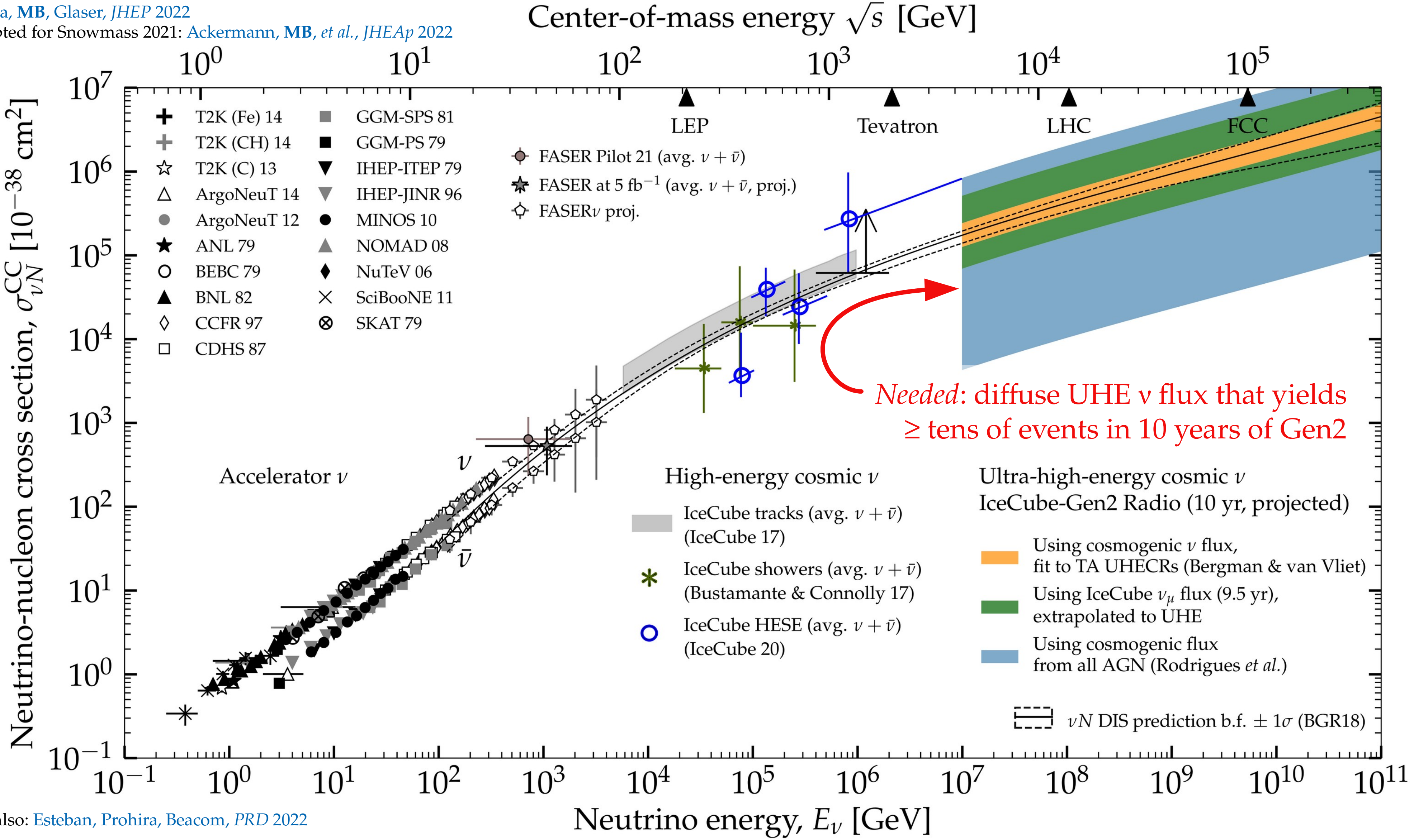
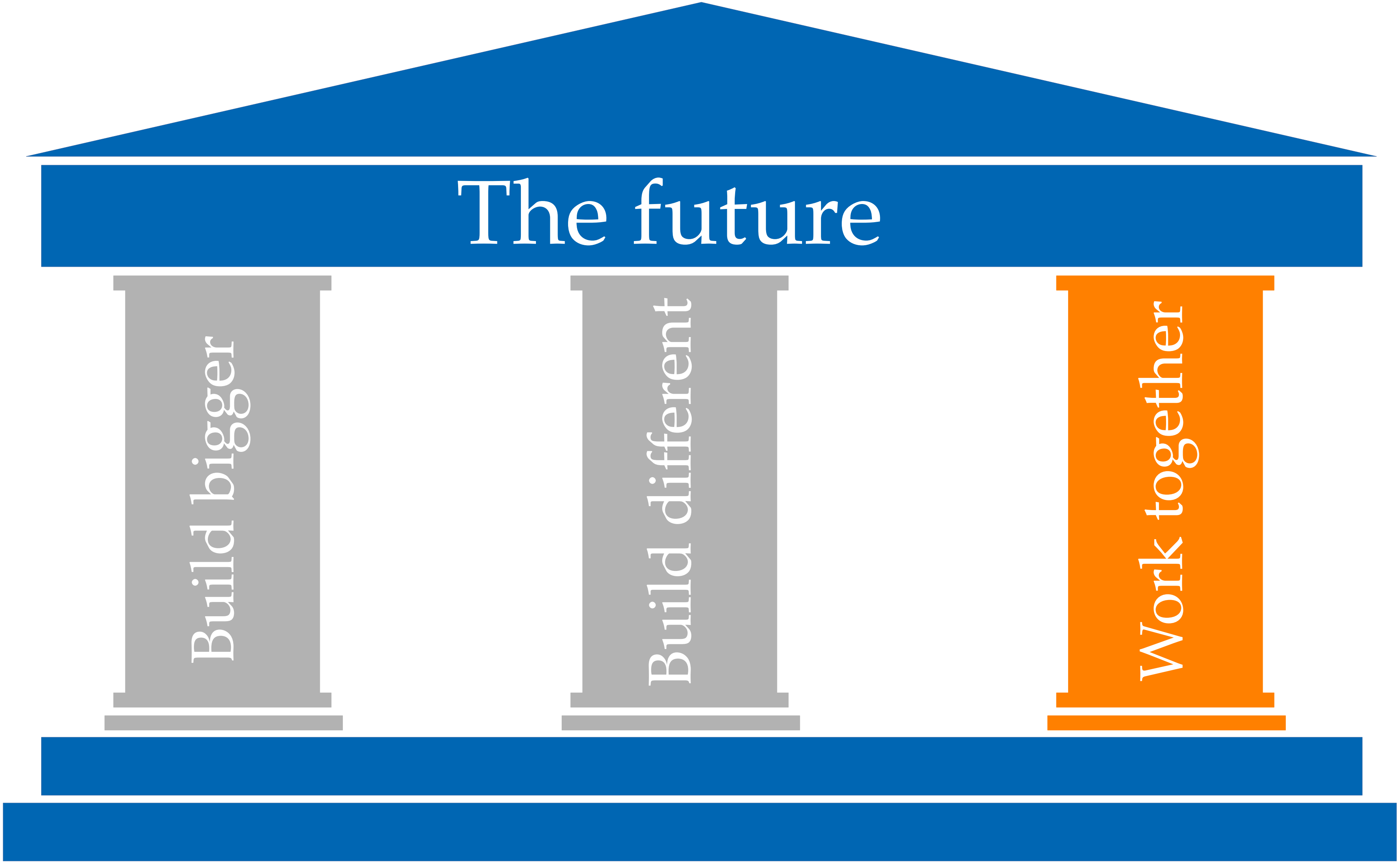


Needed: diffuse UHE ν flux that yields
≥ tens of events in 10 years of Gen2

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



The future

Build bigger

Build different

Work together

TeV–PeV ν telescopes, ~2030

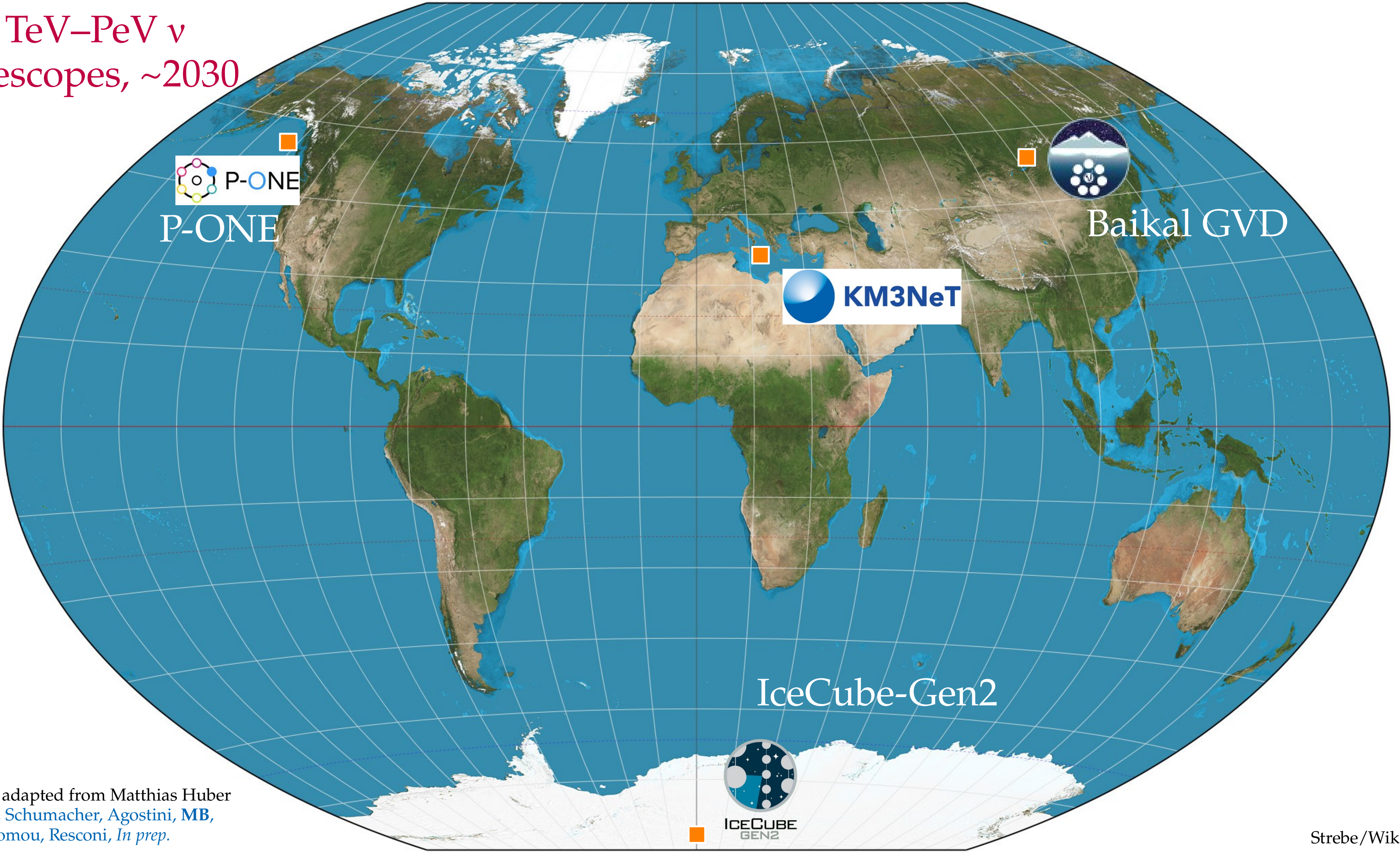
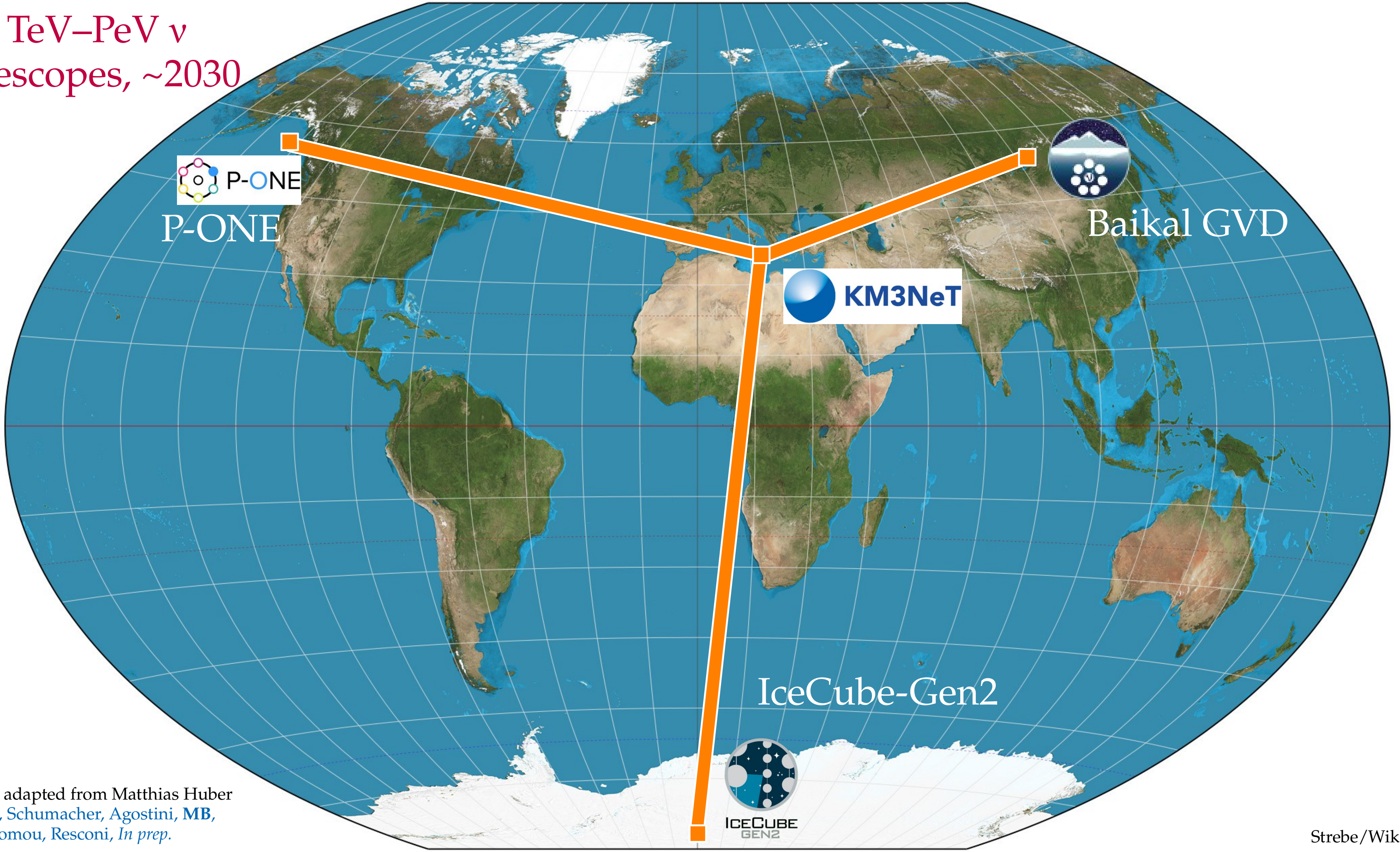


Figure adapted from Matthias Huber
Huber, Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

Strebe/Wikipedia

TeV–PeV ν telescopes, ~2030



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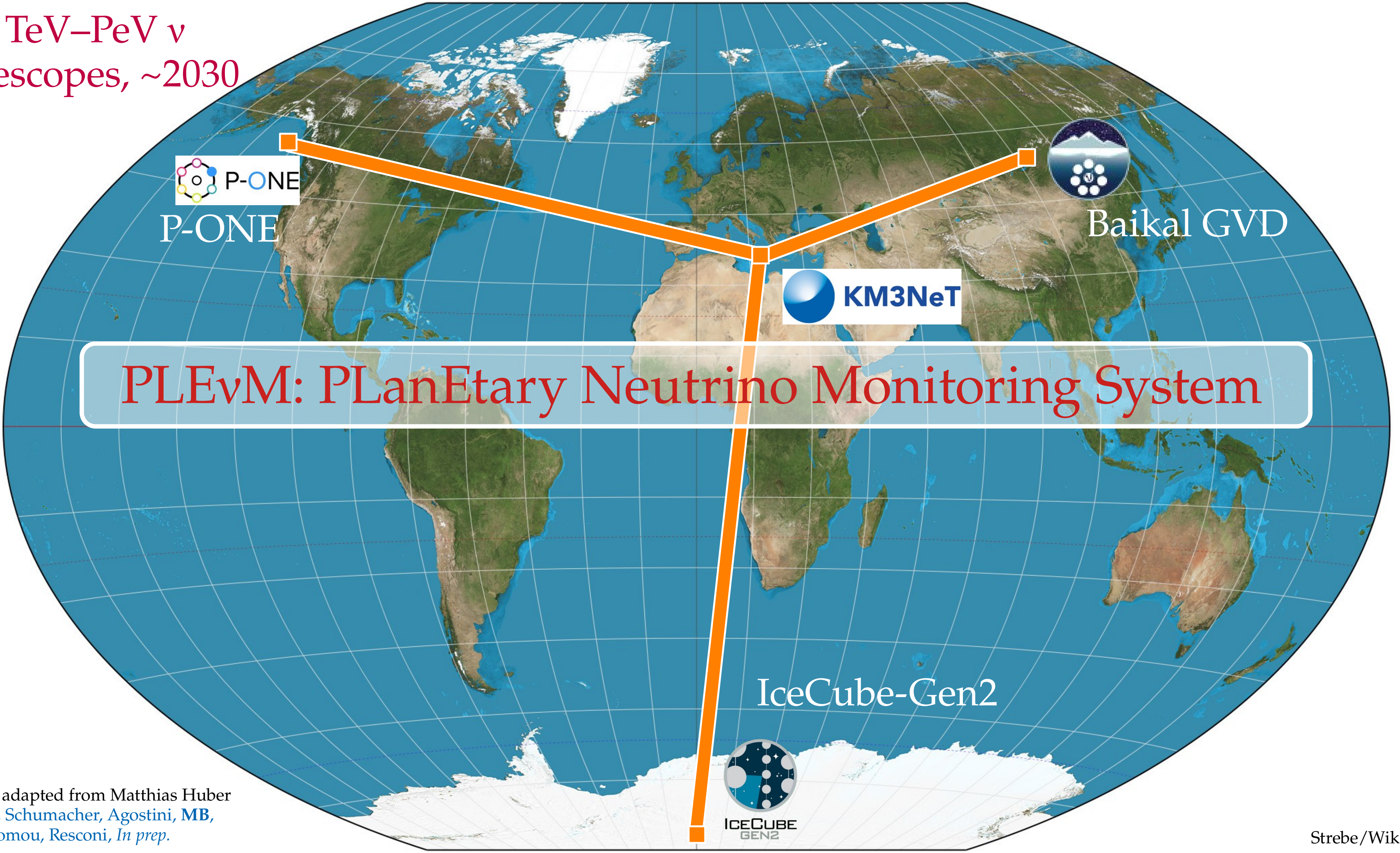

PLEνM: PLanEtary Neutrino Monitoring System

Figure adapted from Matthias Huber
Huber, Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

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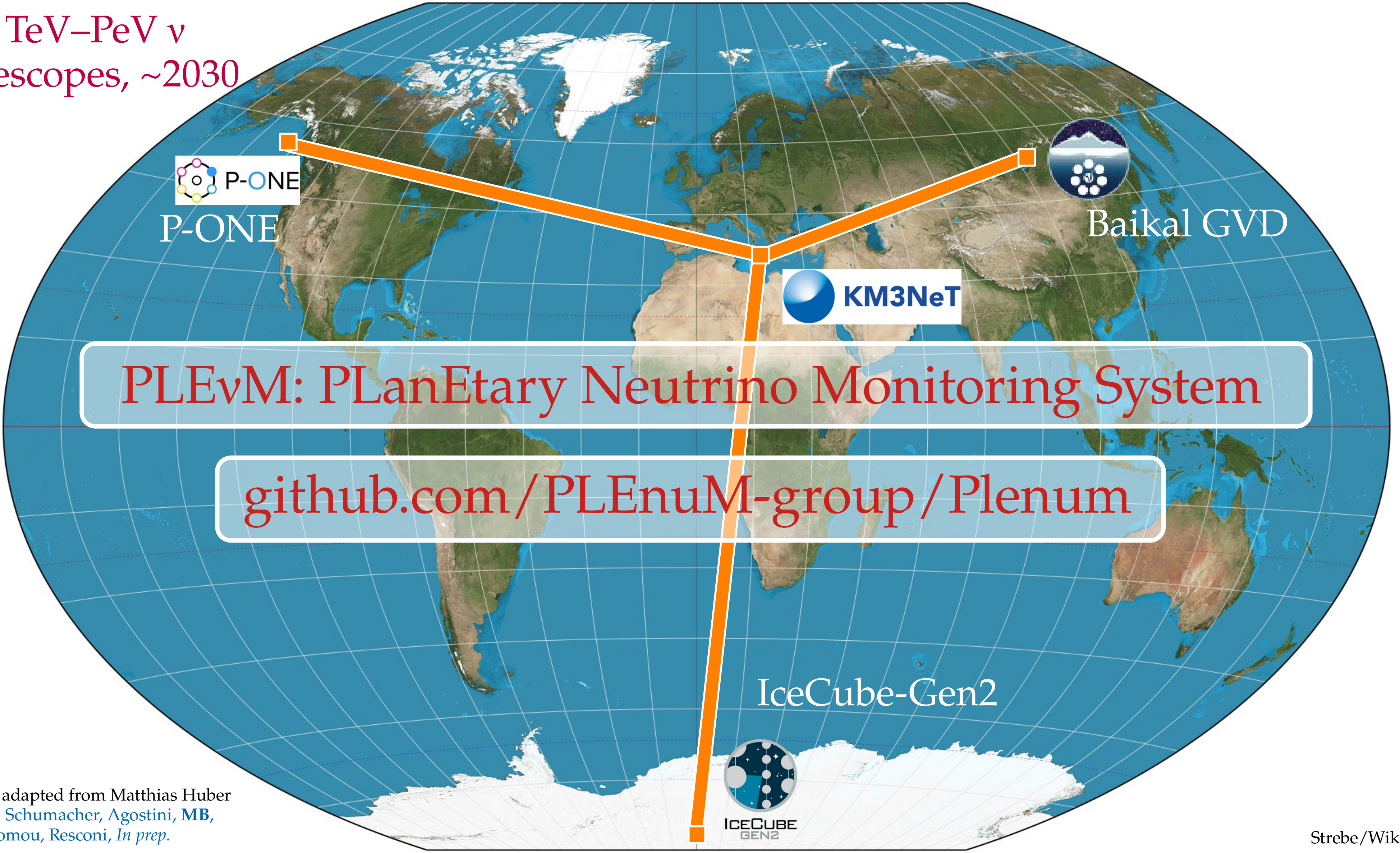
TeV–PeV ν telescopes, ~2030



PLEνM: PLanEtary Neutrino Monitoring System

github.com/PLEnuM-group/Plenum

Figure adapted from Matthias Huber
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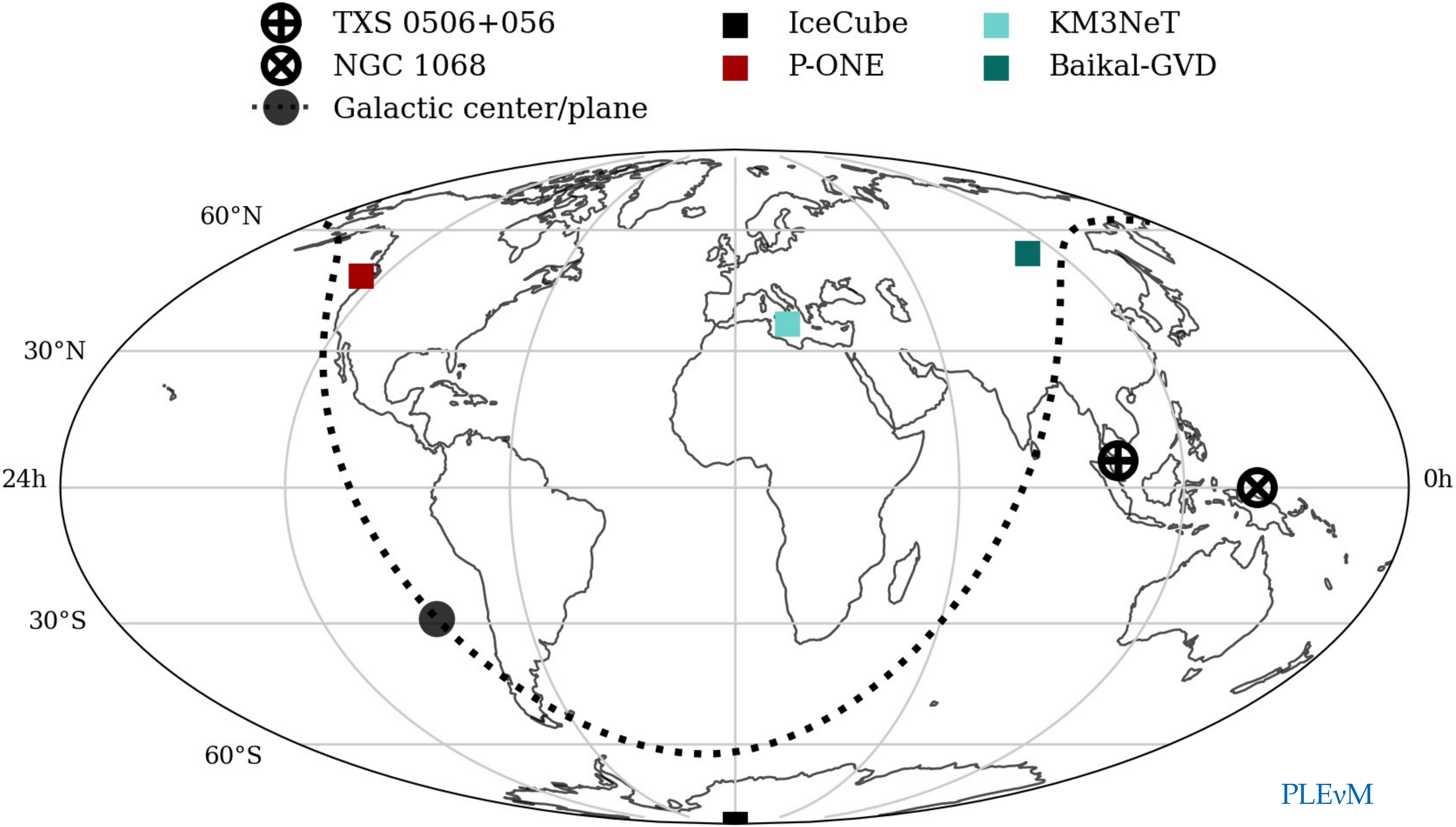
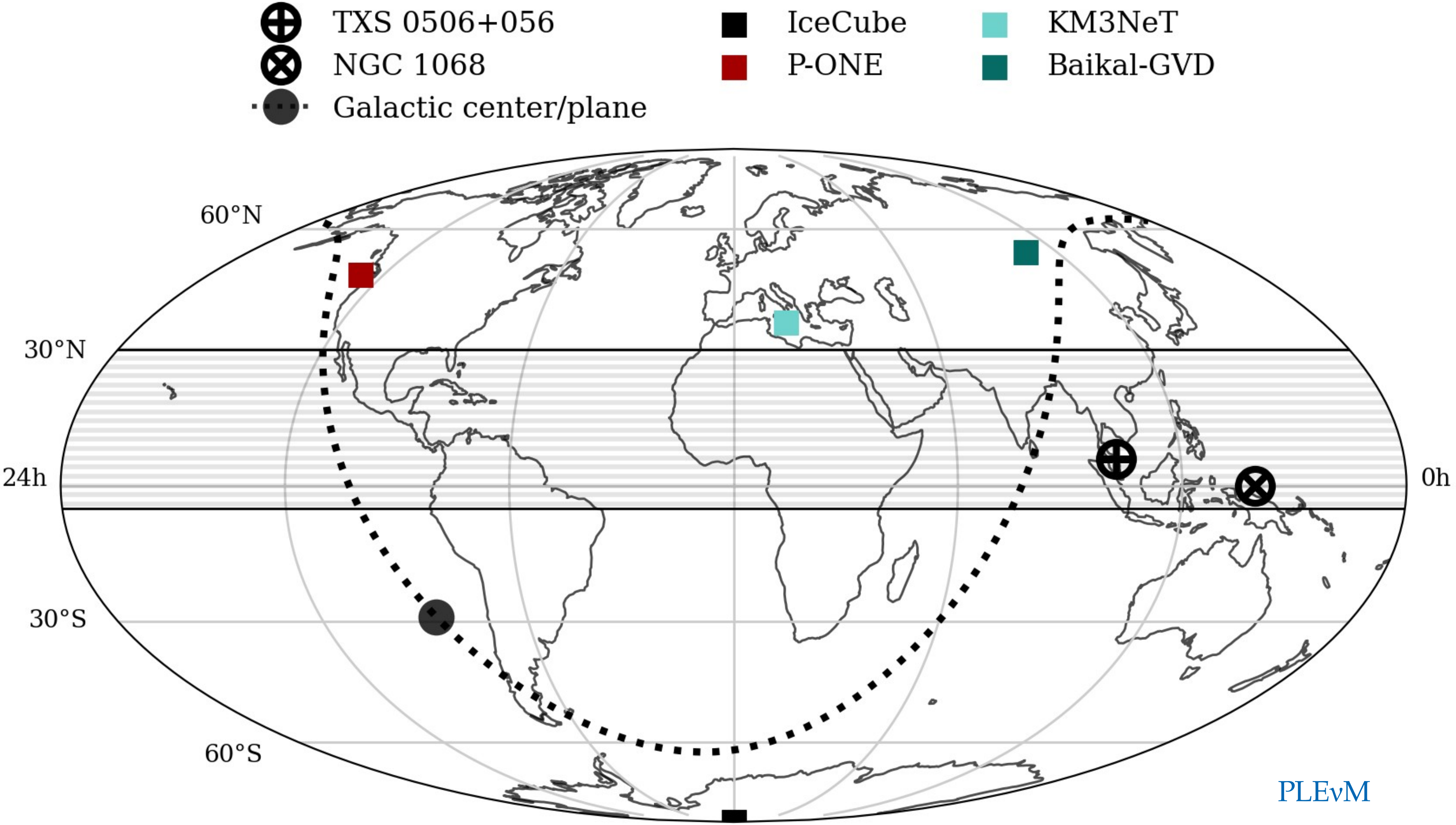
Strebe/Wikipedia


TXS 0506+056
NGC 1068
Galactic center/plane
IceCube
P-ONE
KM3NeT
Baikal-GVD
60°N
30°N
24h
30°S
60°S
0h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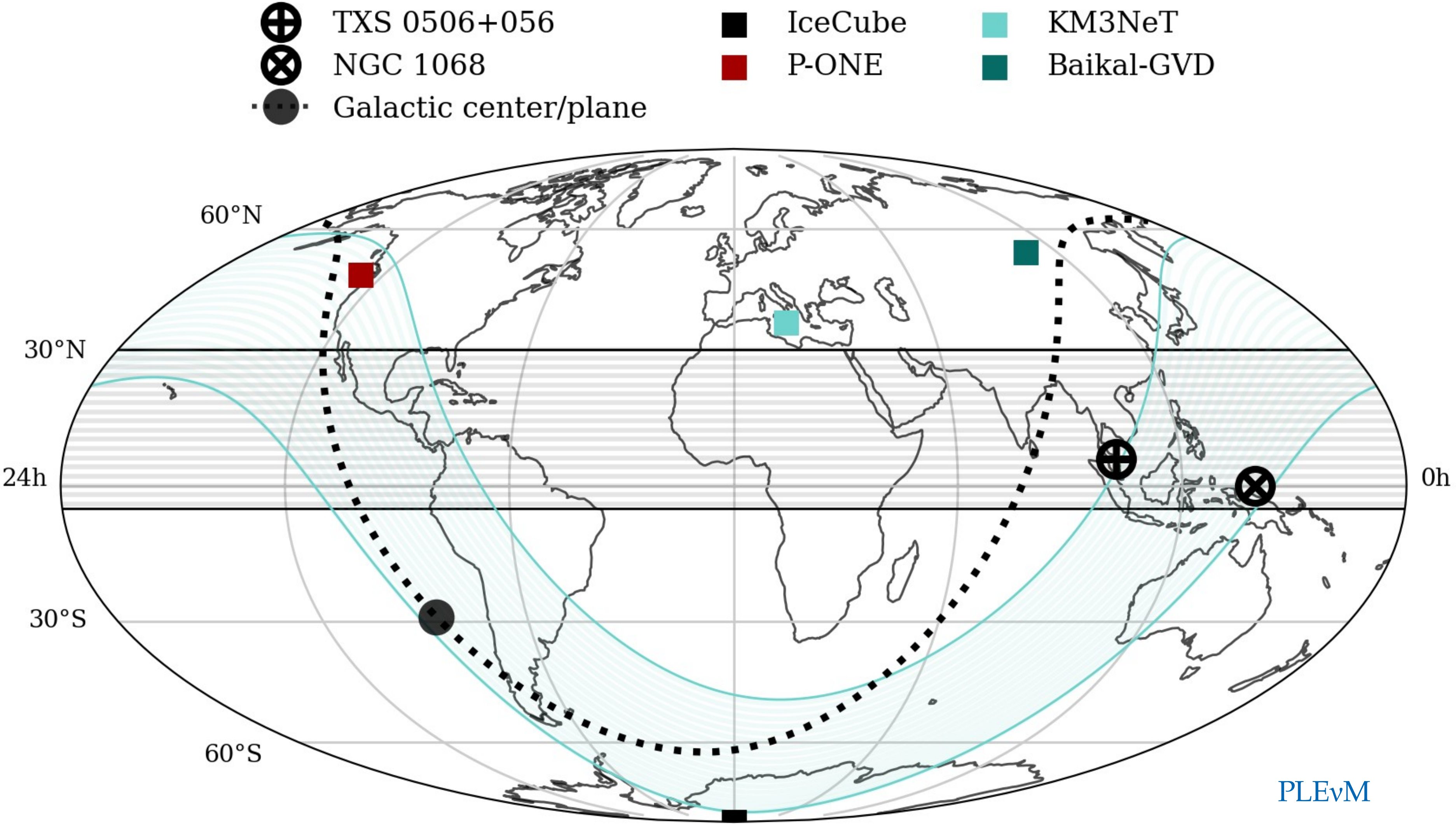
PLEνM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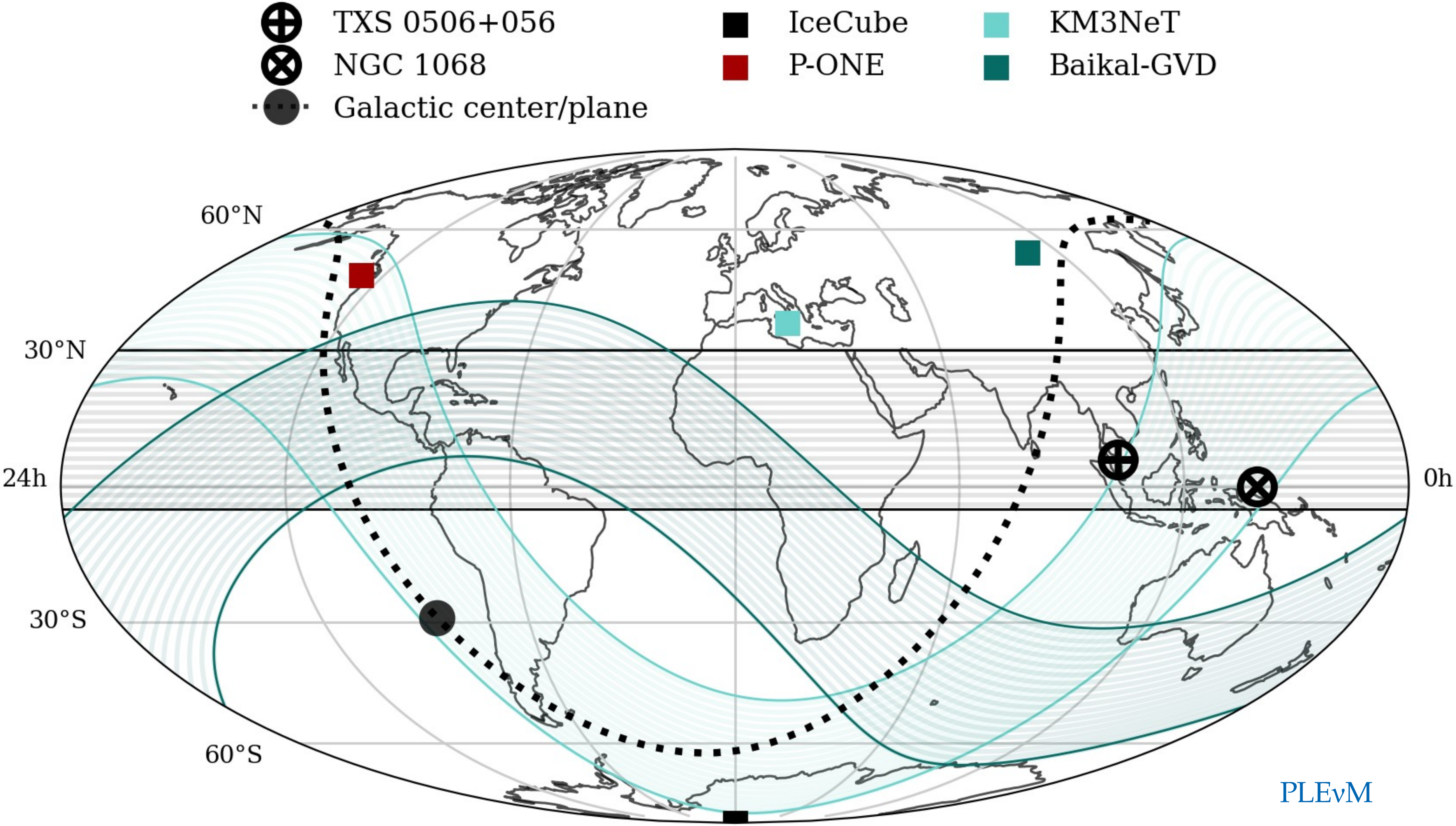
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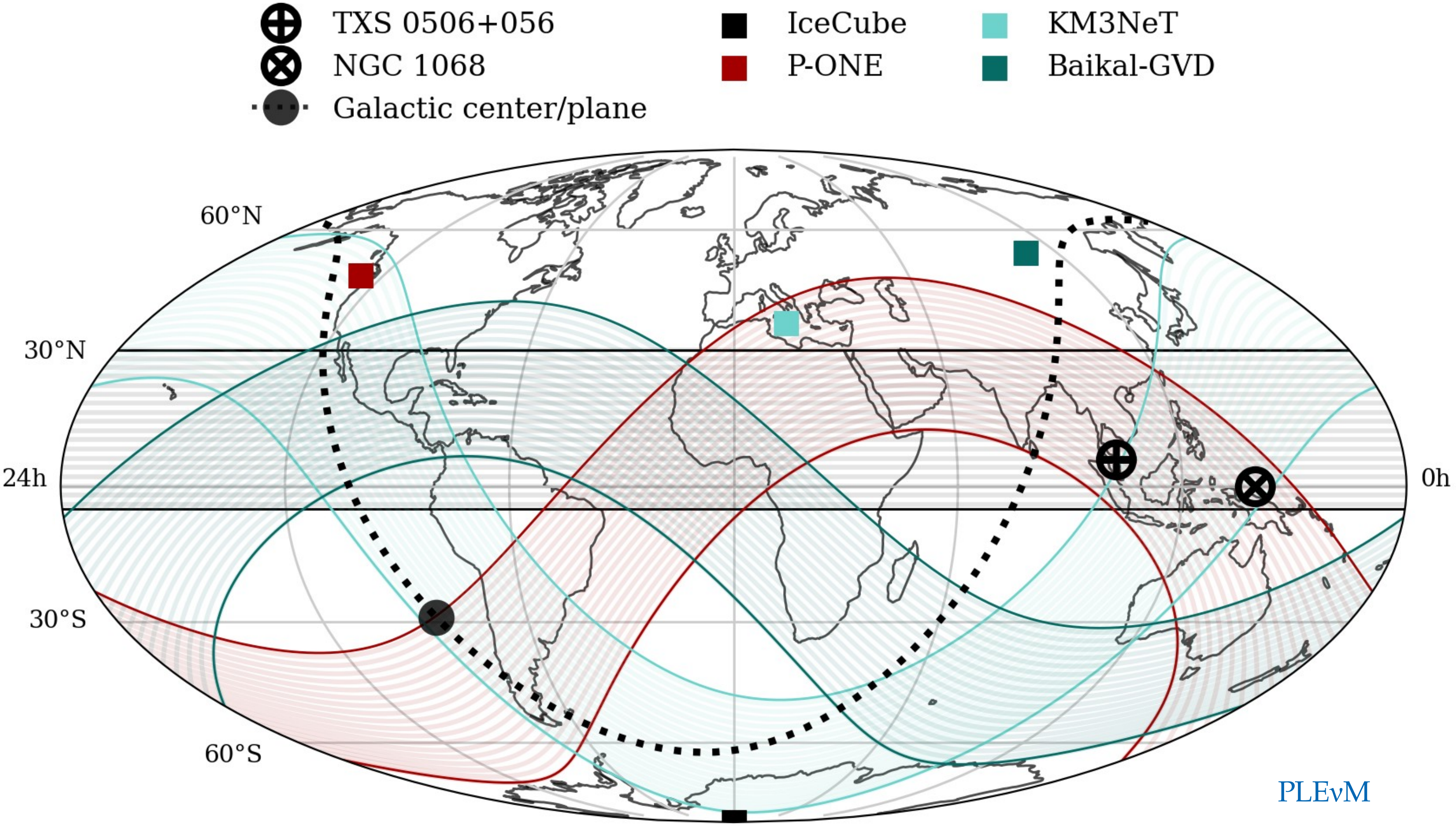
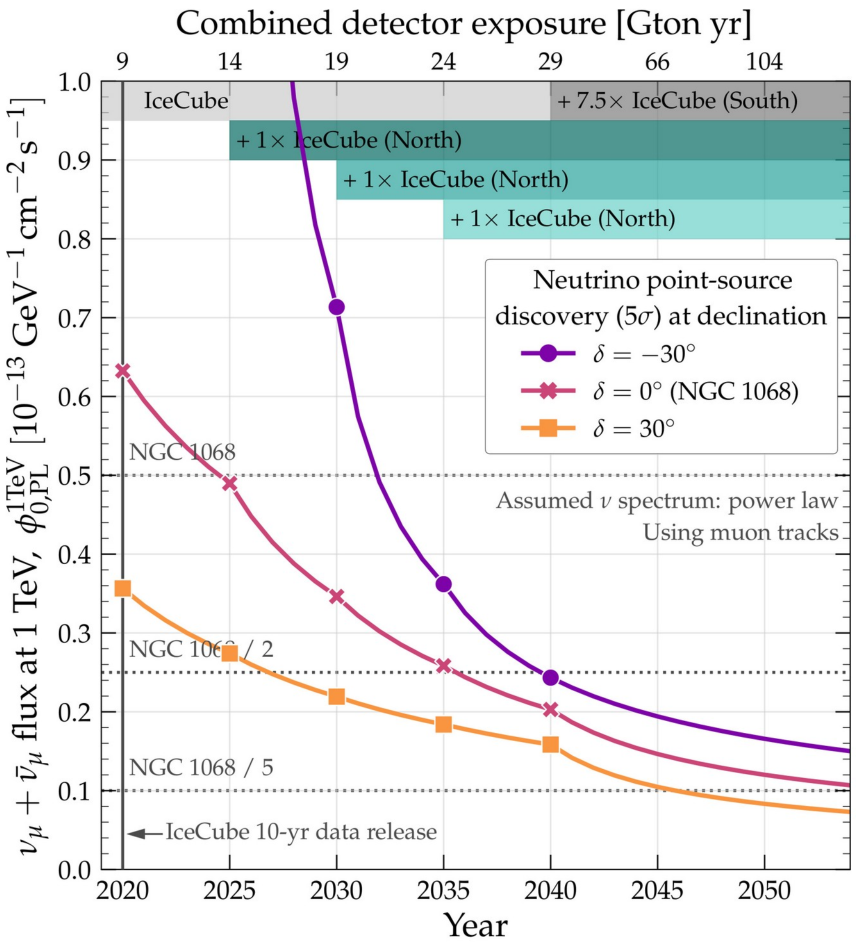
60°S

PLEνM

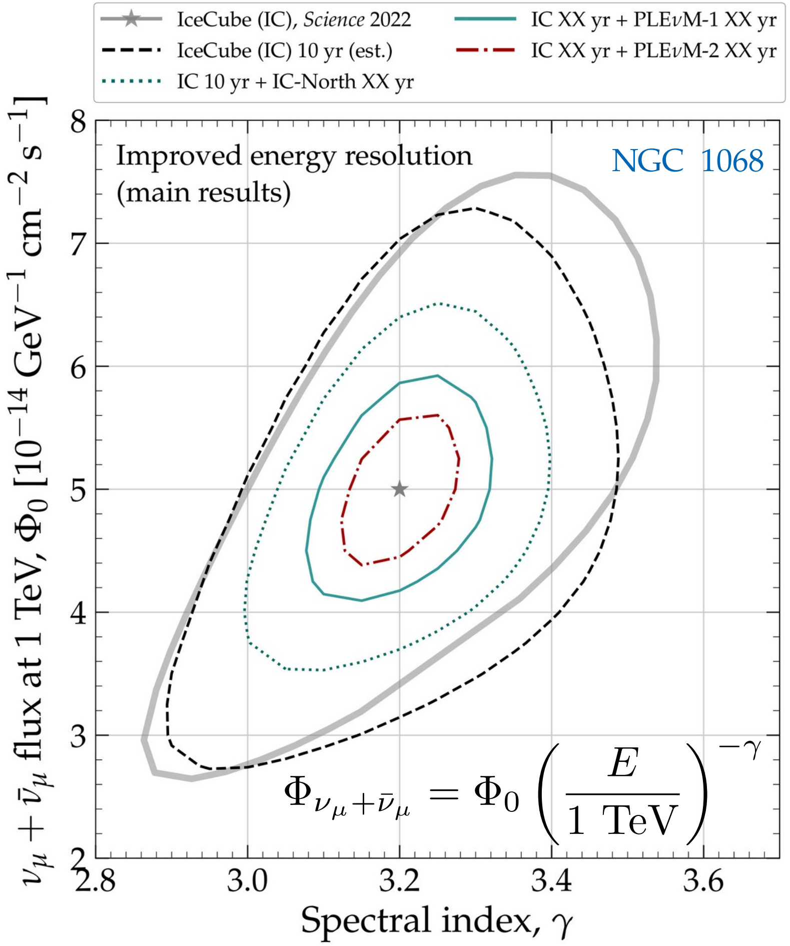

TXS 0506+056
NGC 1068
Galactic center/plane
IceCube
P-ONE
KM3NeT
Baikal-GVD
60°N
30°N
24h
0h
30°S
60°S
PLEνM

High-statistics, full-sky neutrino astronomy

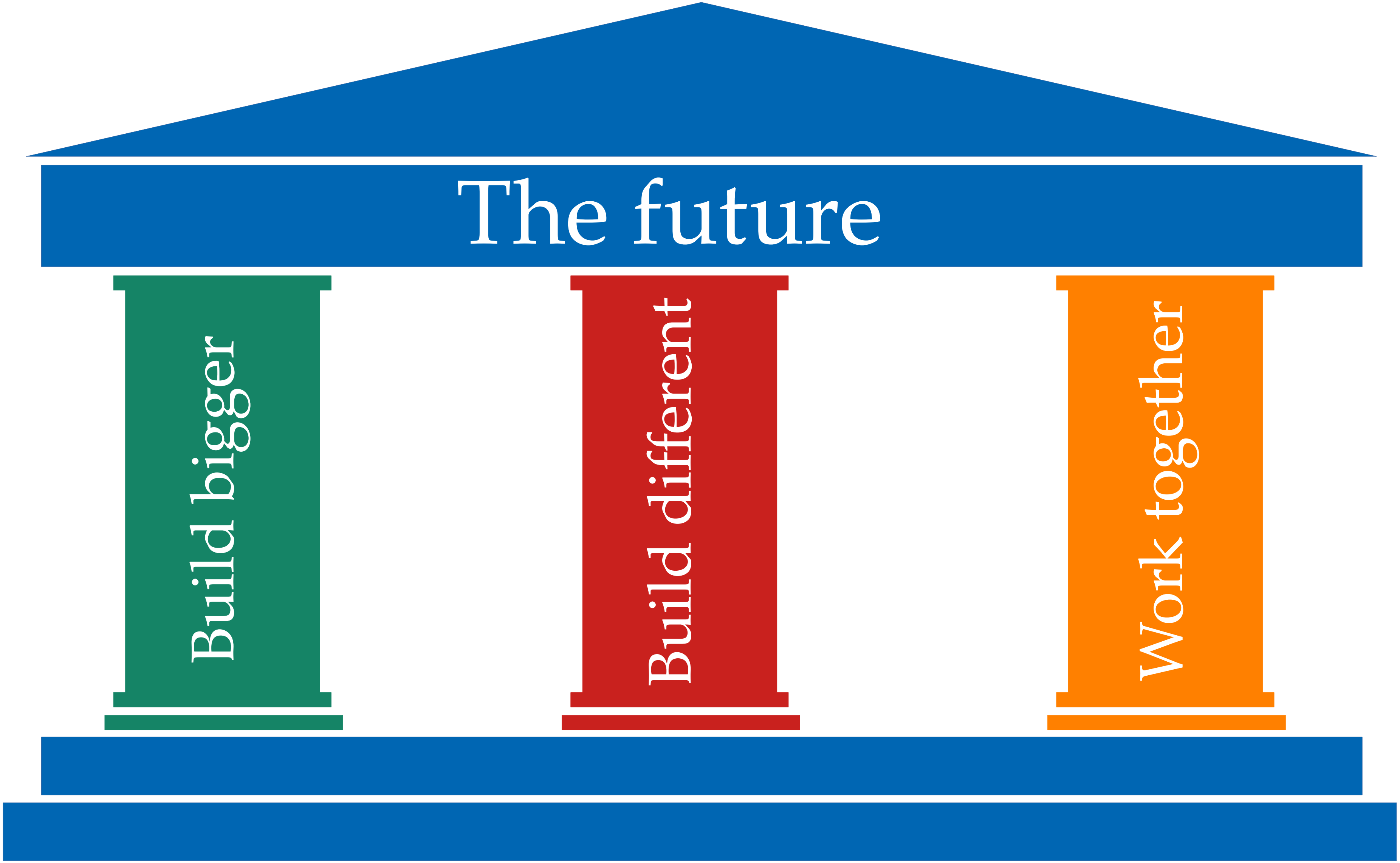
Discovering dimmer sources, faster



Fitting the ν spectrum from a source



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



The future

Build bigger

Build different

Work together

Today
TeV–PeV ν

Astro: Find & understand sources
Particle: Turn predictions into tests

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

Today

TeV–PeV ν

Astro: Find & understand sources

Particle: Turn predictions into tests

Key developments:

Bigger detectors → larger statistics

Better reconstruction

Smaller astrophysical uncertainties

Next decade

> 100-PeV ν

Today

TeV–PeV ν

Astro: Find & understand sources
Particle: Turn predictions into tests

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

Next decade

$>$ 100-PeV ν

Make predictions for
a new energy regime

Today

TeV–PeV ν

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

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Next decade
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Make predictions for
a new energy regime

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

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

Today
TeV–PeV ν

Astro: Find & understand sources
Particle: Turn predictions into tests

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

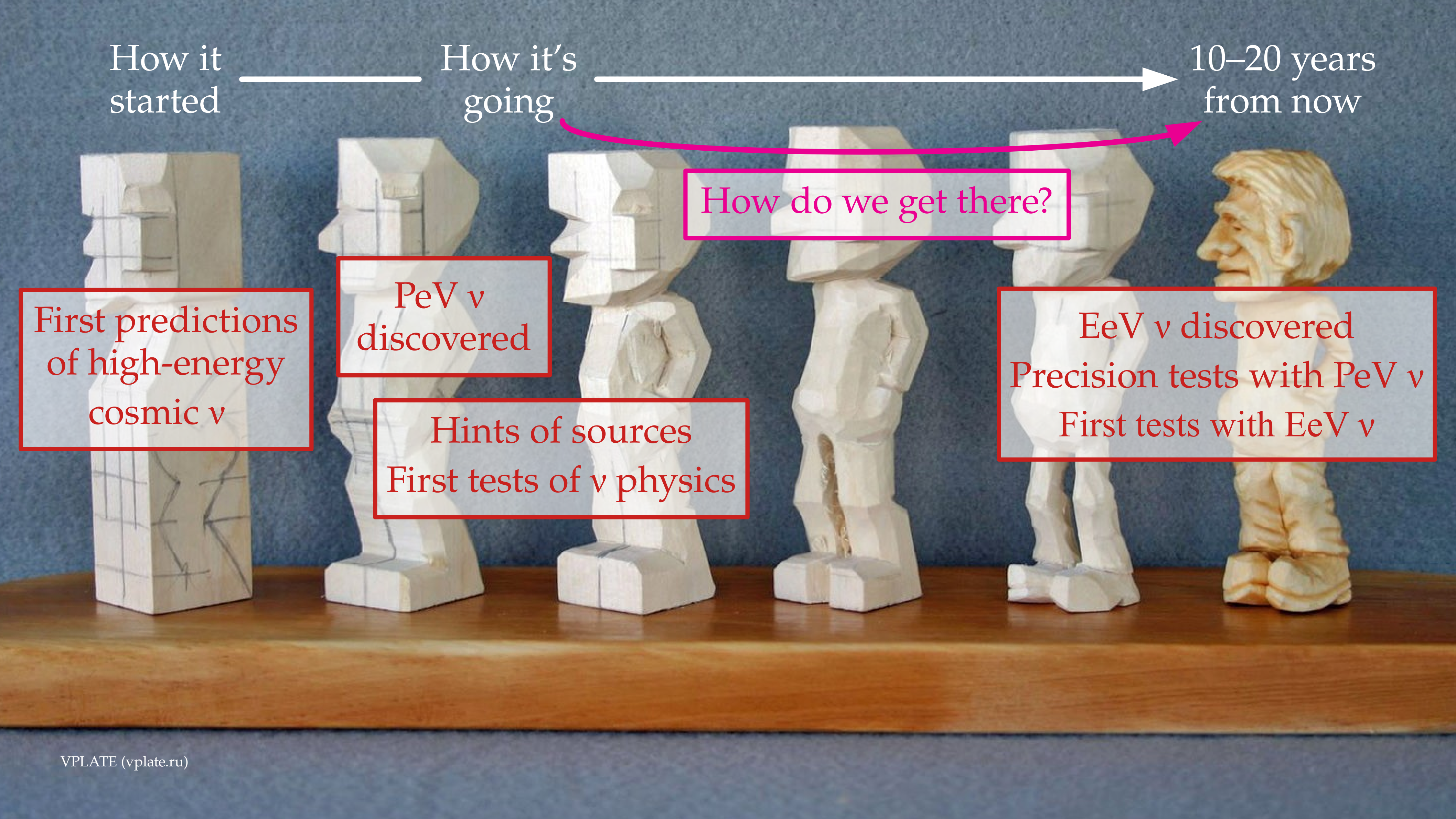
Next decade
$>$ 100-PeV ν

Make predictions for
a new energy regime

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

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



How it started

How it's going

10–20 years from now

How do we get there?

First predictions of high-energy cosmic ν

PeV ν discovered

Hints of sources

First tests of ν physics

EeV ν discovered

Precision tests with PeV ν

First tests with EeV ν

VPLATE (vplate.ru)

Thanks!

Backup slides

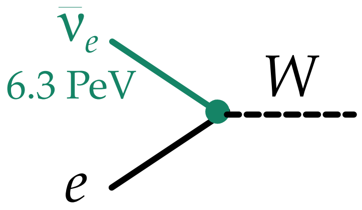
First observation of a Glashow resonance

Predicted in 1960:

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

First observation of a Glashow resonance

Predicted in 1960:



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

First observation of a Glashow resonance

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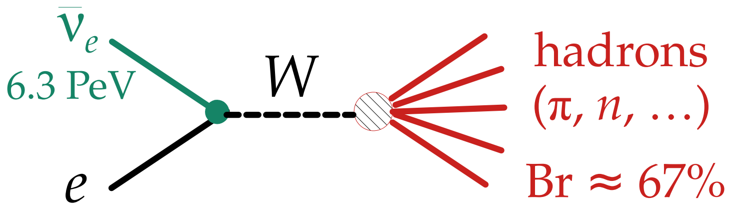

IceCube, *Nature* 2021
Glashow, *PR* 1960

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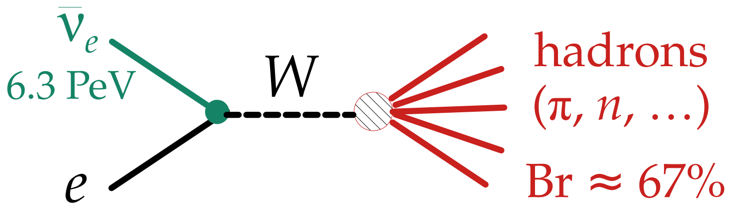

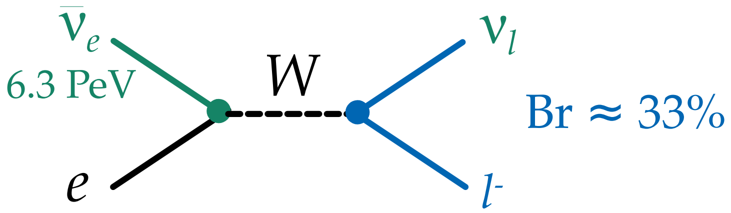

IceCube, *Nature* 2021
Glashow, *PR* 1960

First observation of a Glashow resonance

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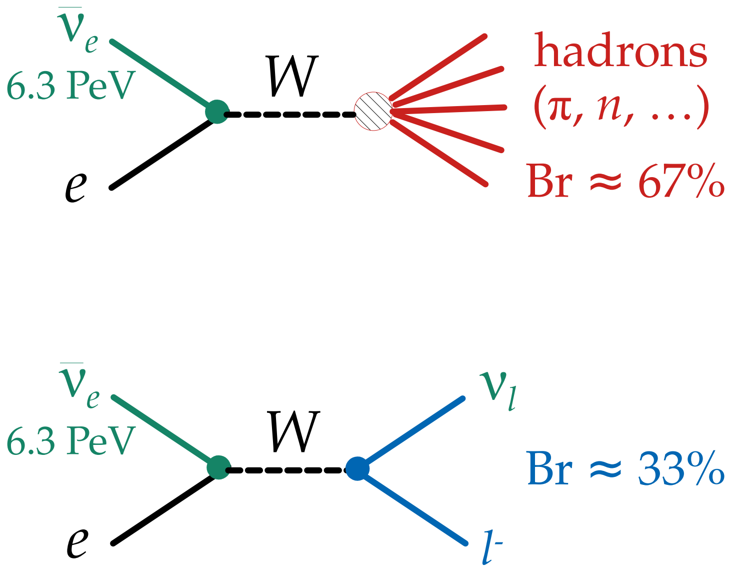
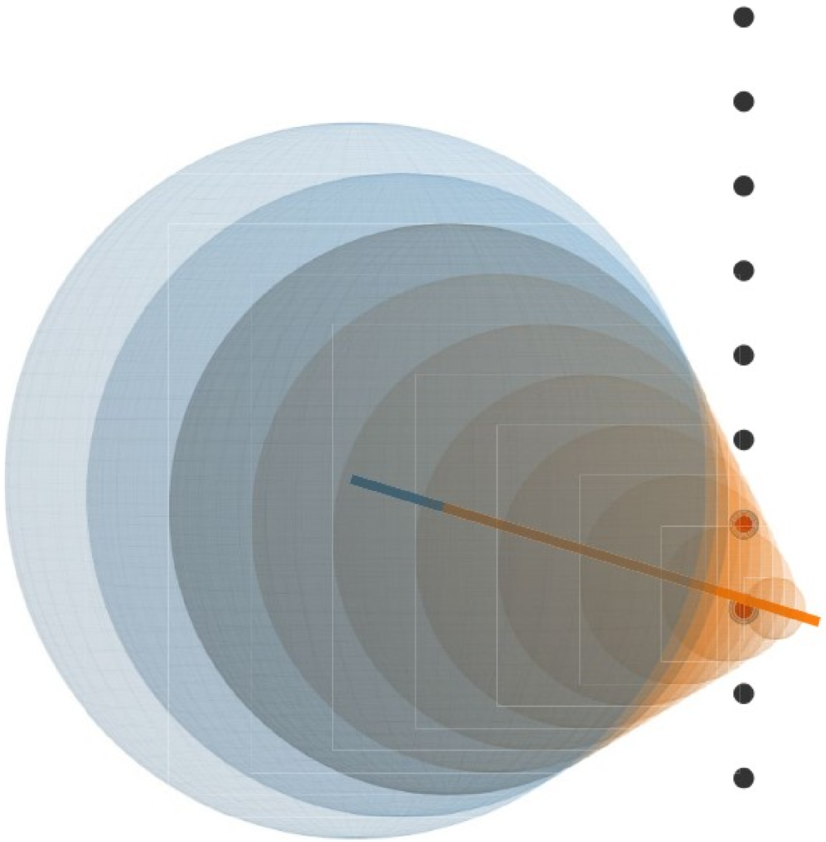


First reported by IceCube in 2021:



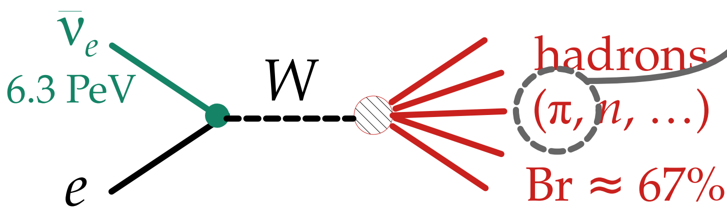
IceCube, *Nature* 2021
Glashow, *PR* 1960

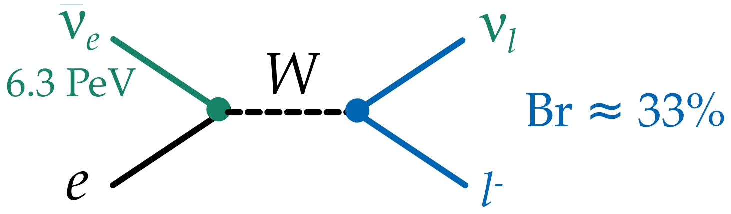
First observation of a Glashow resonance

Predicted in 1960:

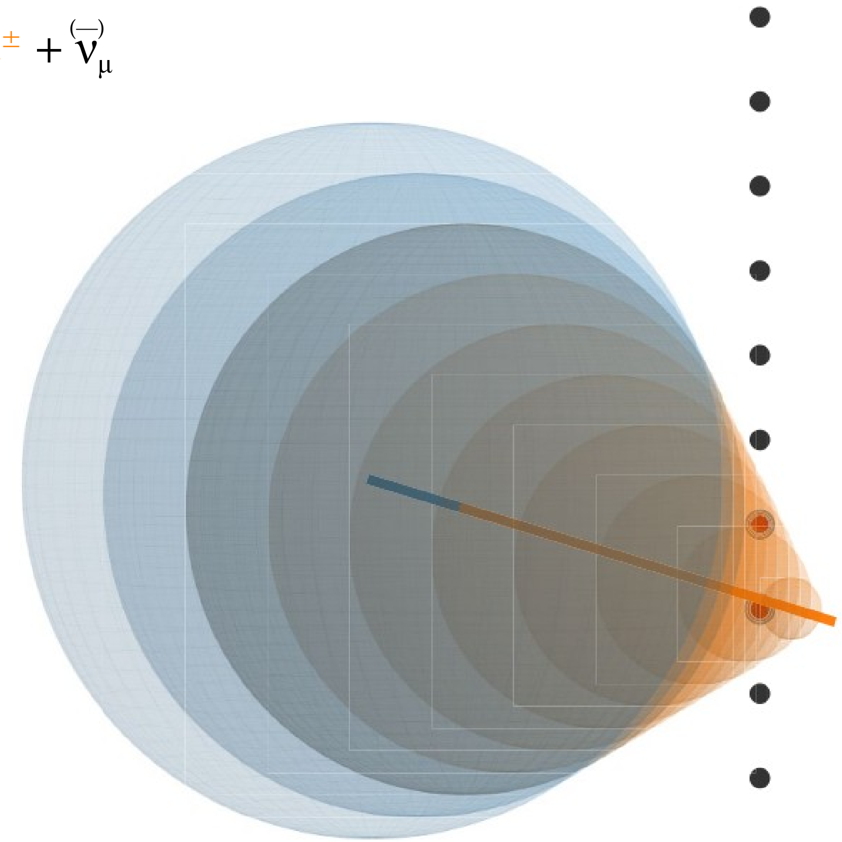
Pions decay promptly

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





First reported by IceCube in 2021:



IceCube, *Nature* 2021
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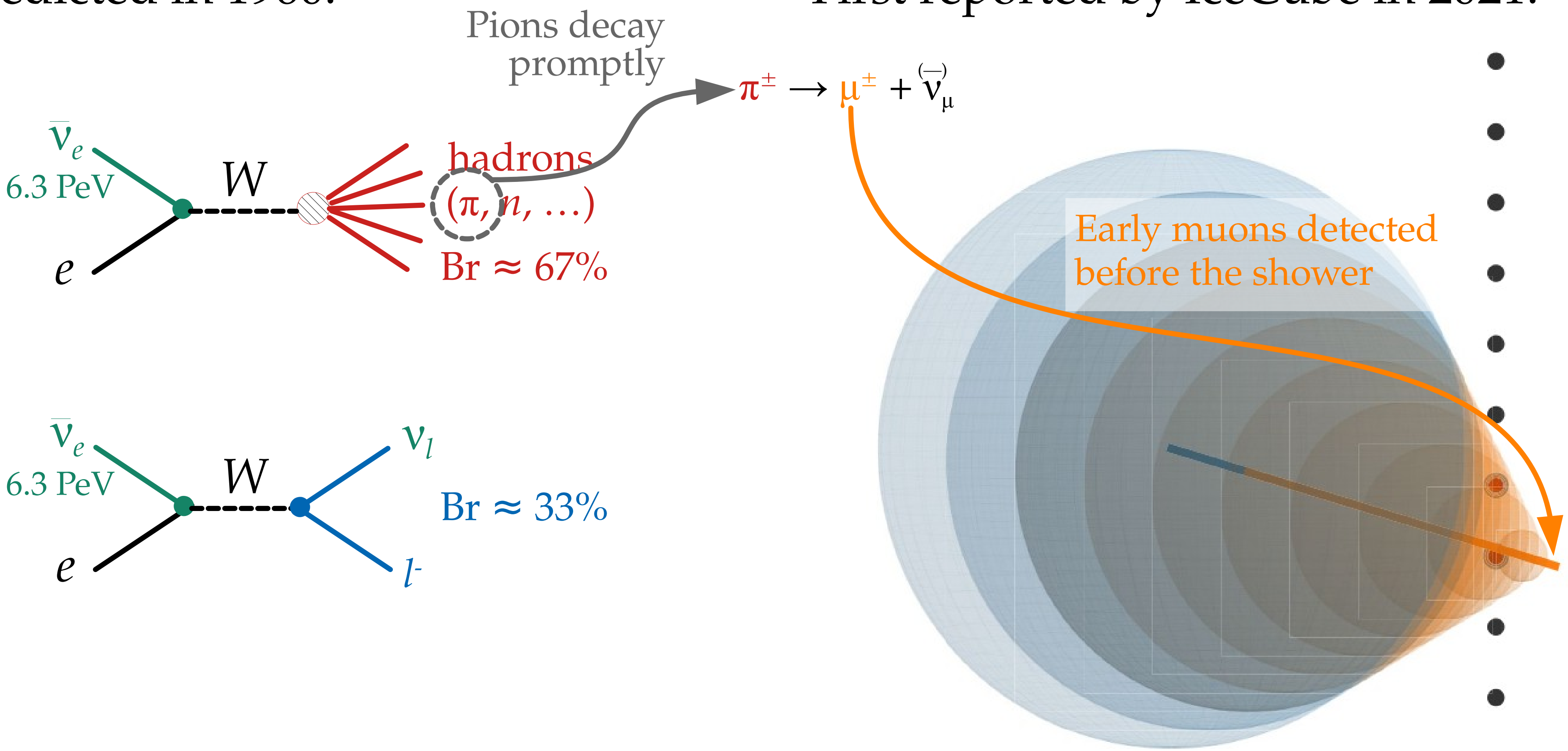

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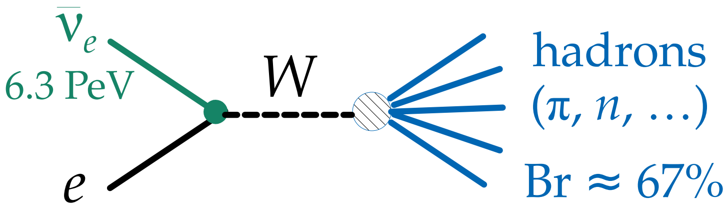

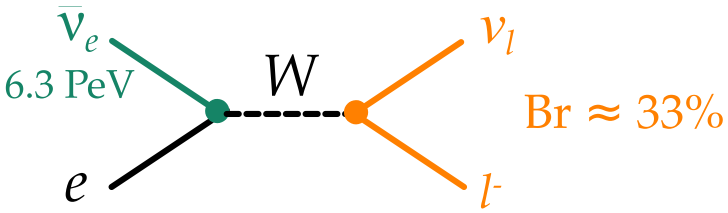

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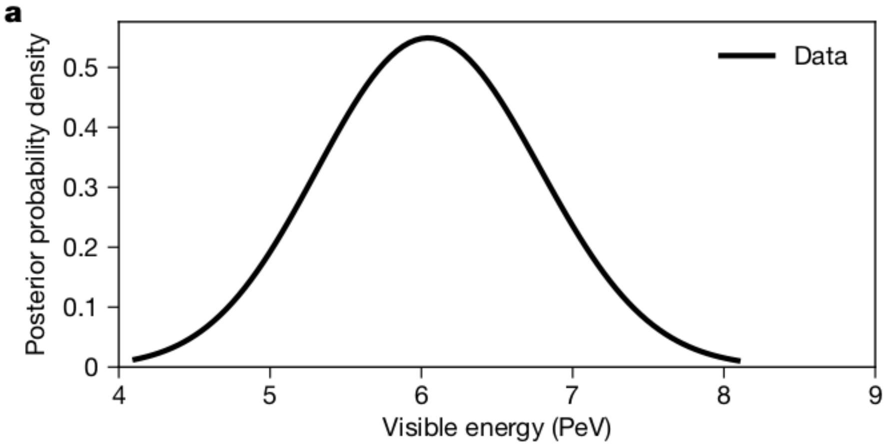

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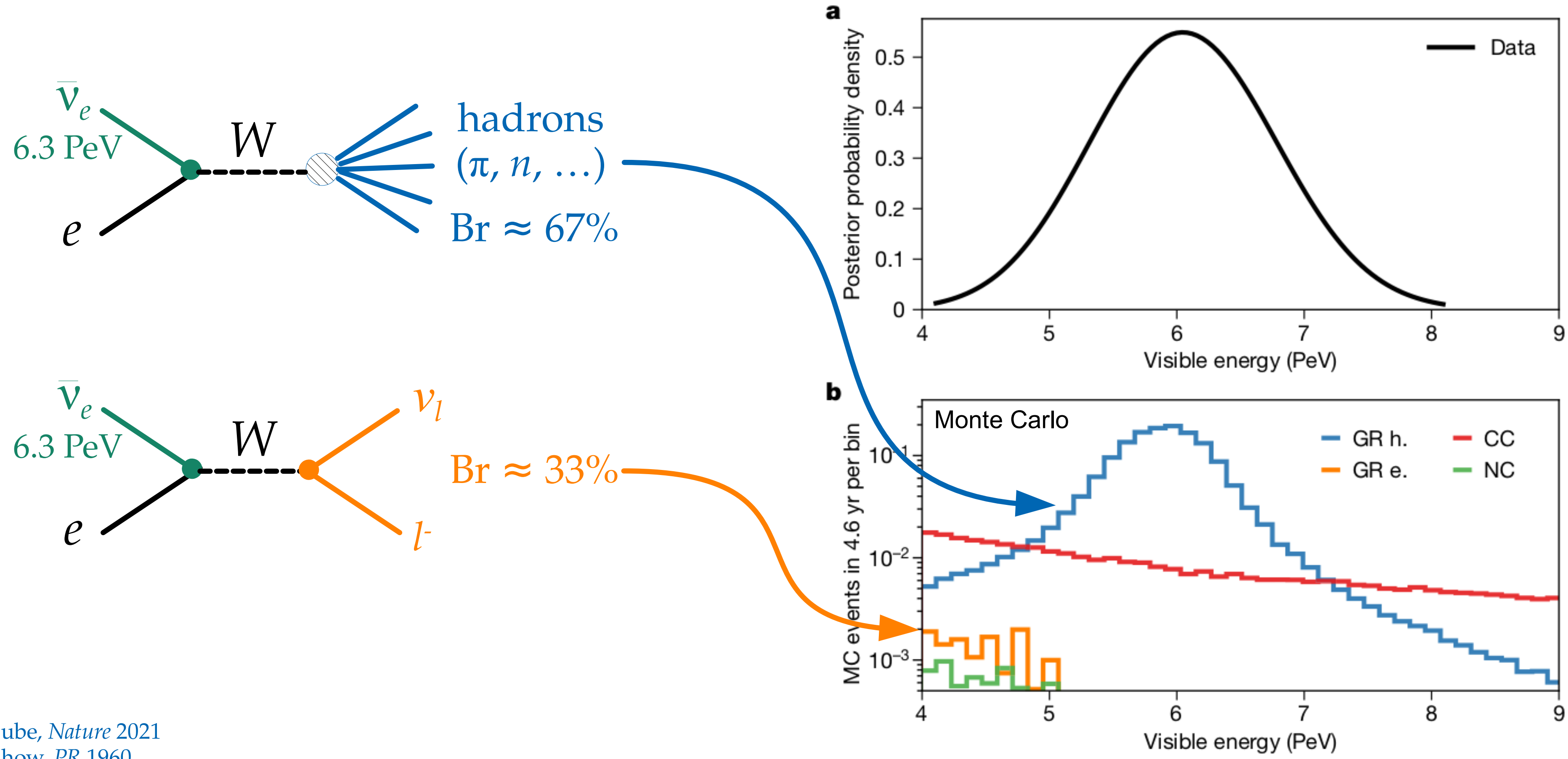
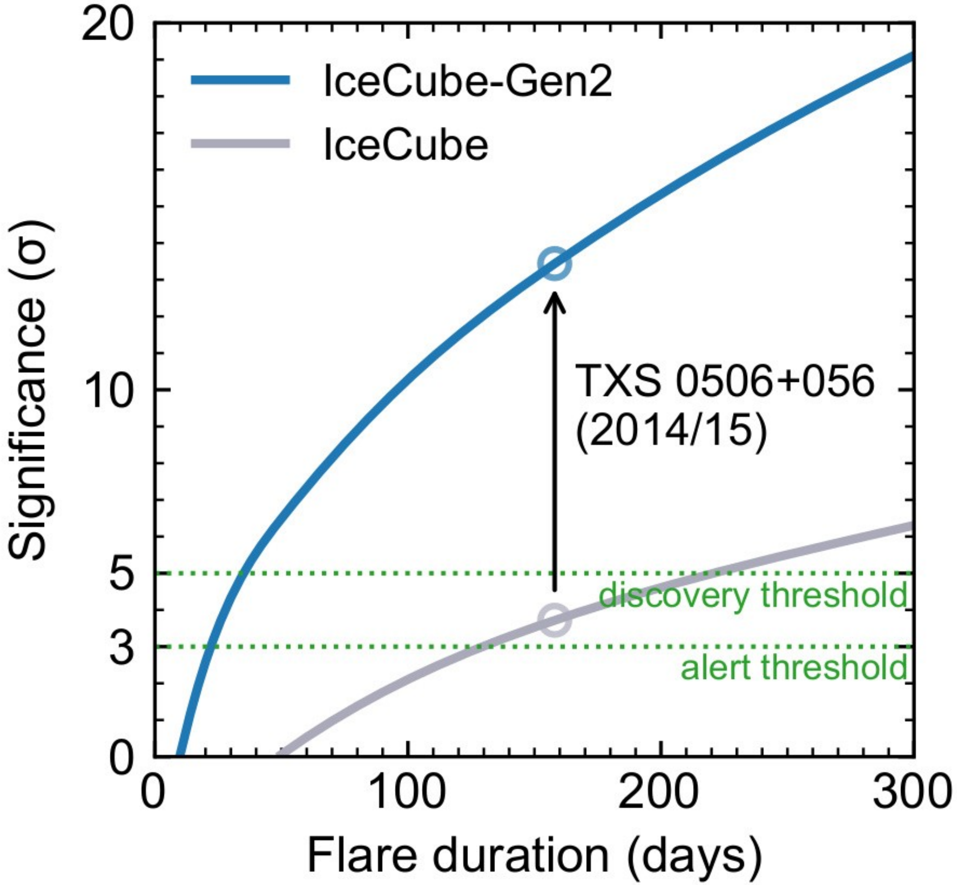


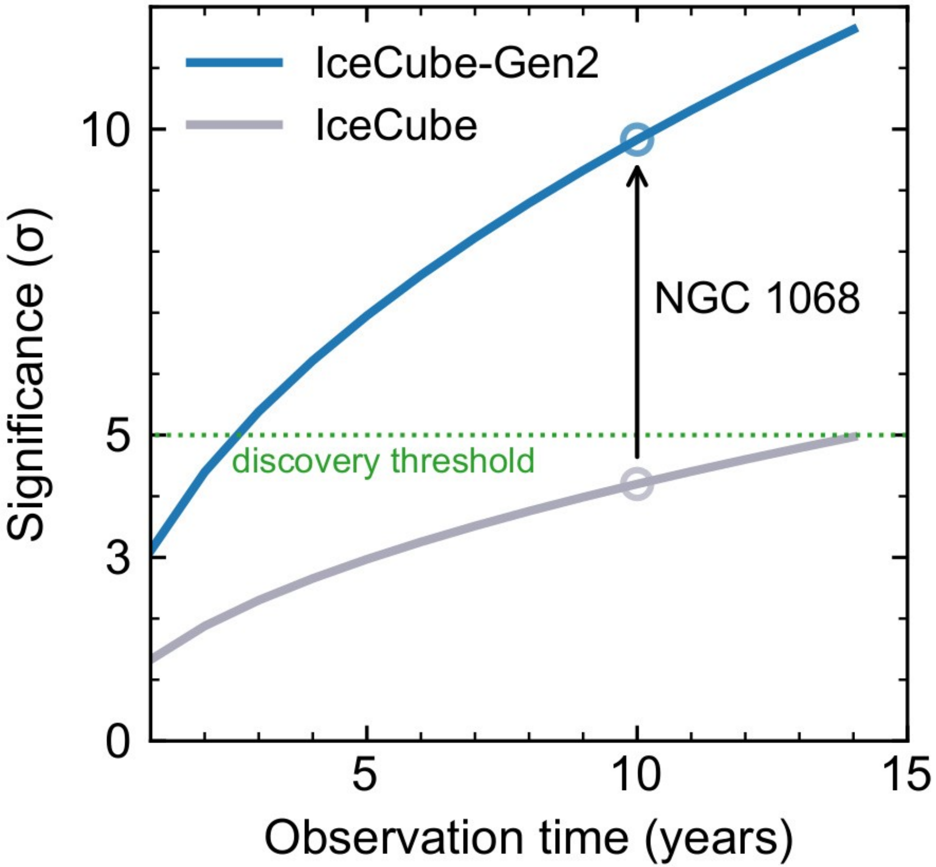
IceCube, *Nature* 2021
Glashow, *PR* 1960

Discovering sources fast, with high significance

TXS 0506+056

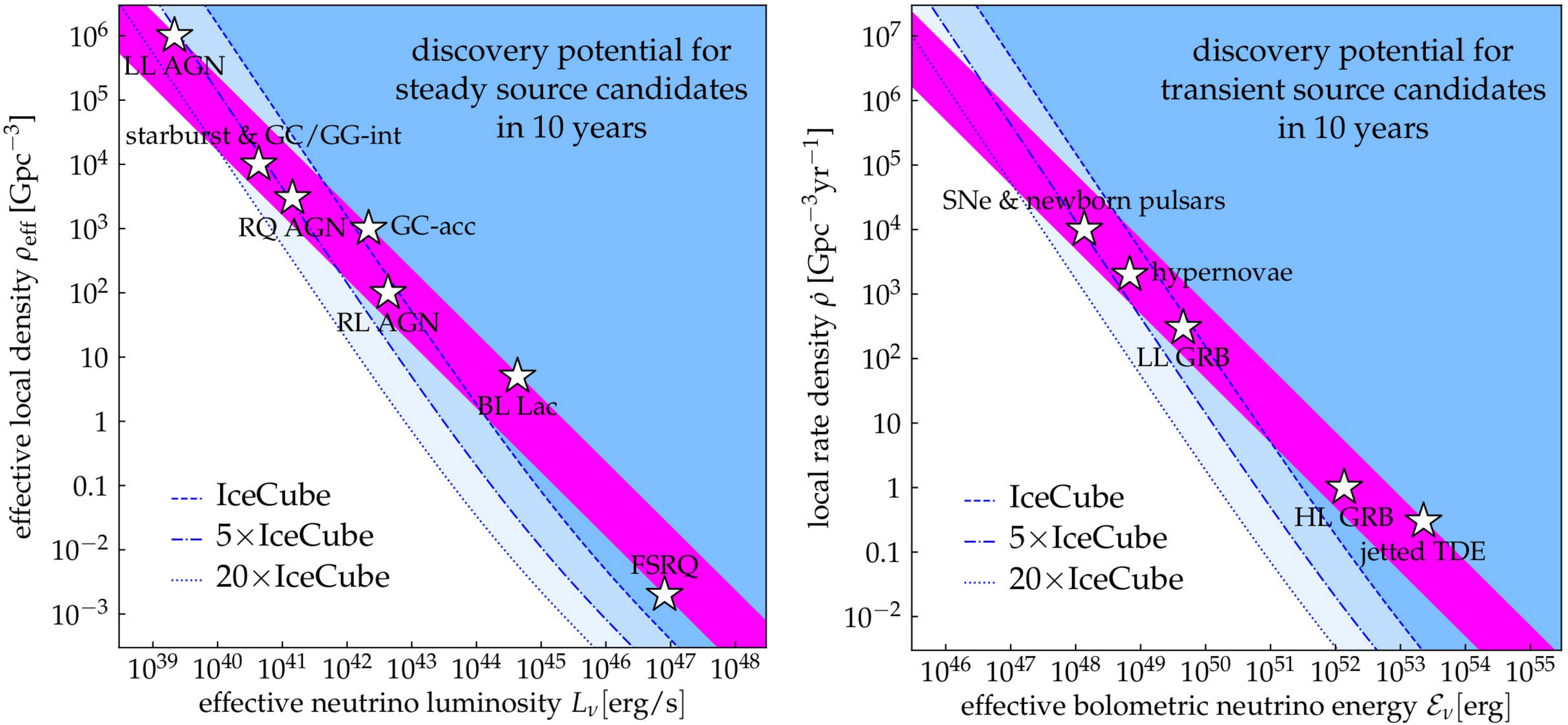


NGC 1068



IceCube-Gen2 Collab. Technical Design Report Part I

Constraining candidate source populations

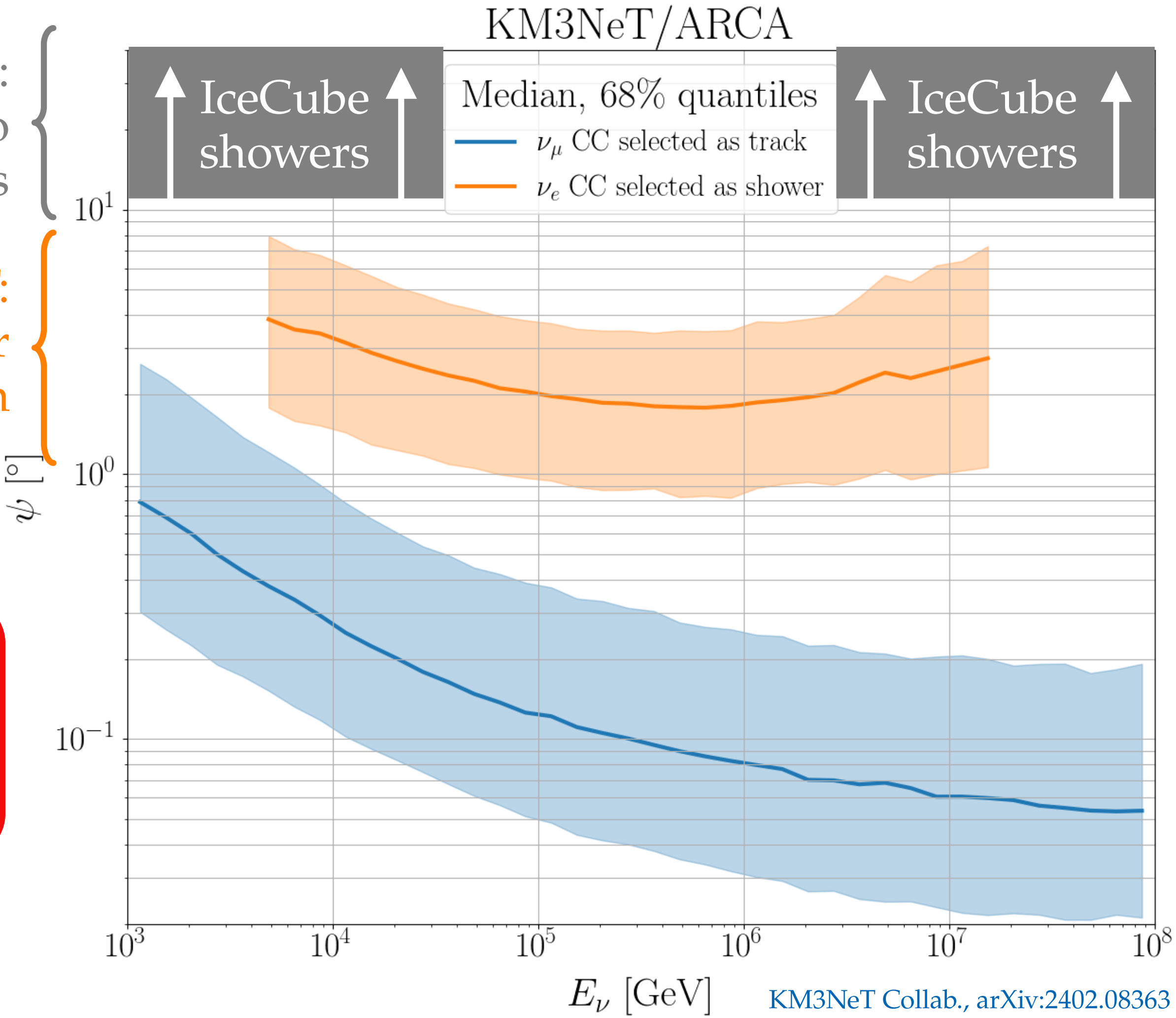


Boosting source searches with showers

IceCube:
Hard to use showers to
find point sources

KM3NeT:
Degree-scale shower
Angular resolution

Light scattering length
in water > in ice
(100–300 m *vs.* 4–40 m)



KM3NeT Collab., arXiv:2402.08363

IceCube Collab., *NIM* 2013
ANTARES Collab., *Astropart. Phys.* 2005

Characterizing the diffuse power-law flux in PLEνM

$$E^2\phi = \phi_{100\text{TeV}} \left(\frac{E}{100\ \text{TeV}}\right)^{2-\gamma}$$

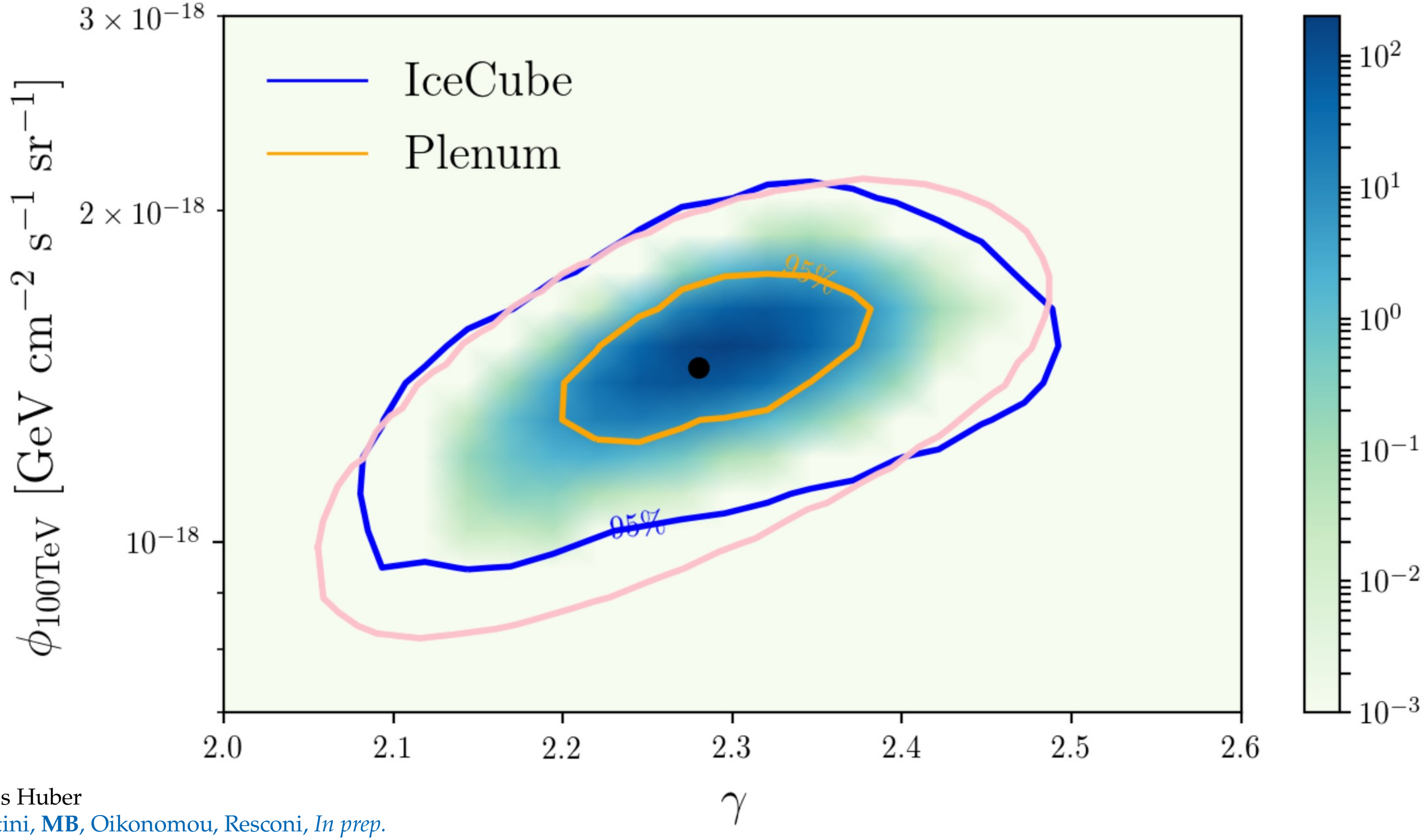
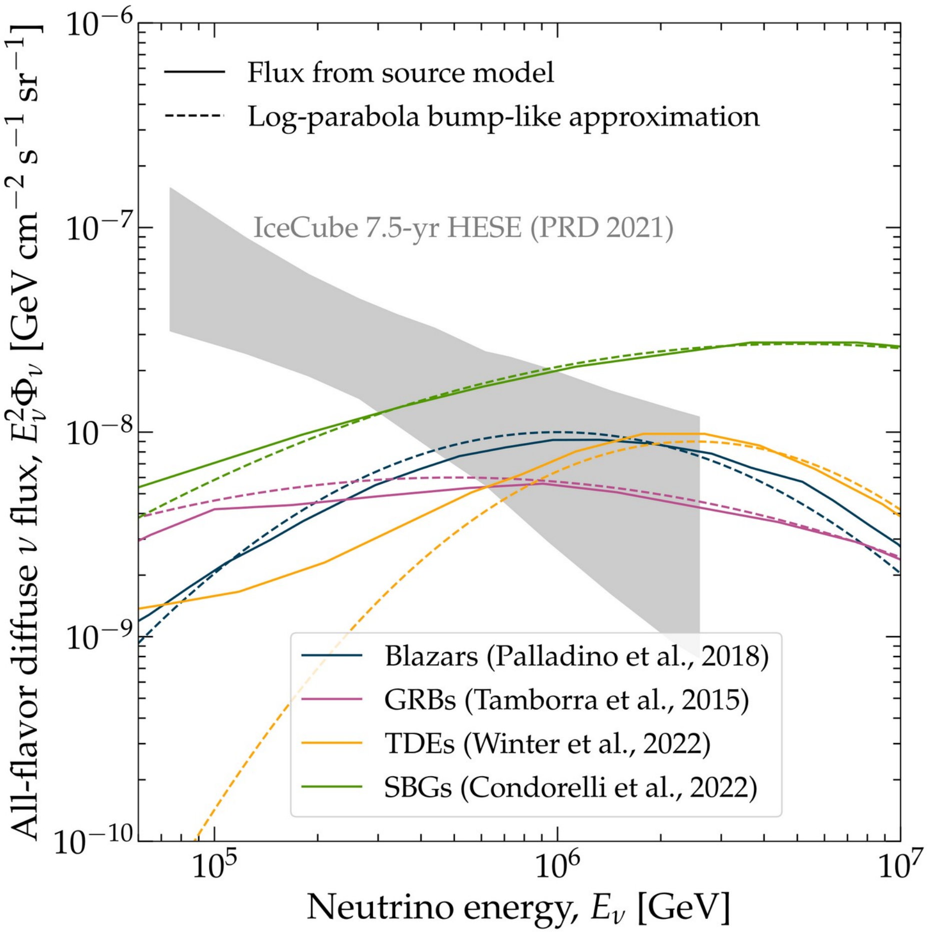


Figure courtesy of Matthias Huber

Huber, 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 *pγ*:



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

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

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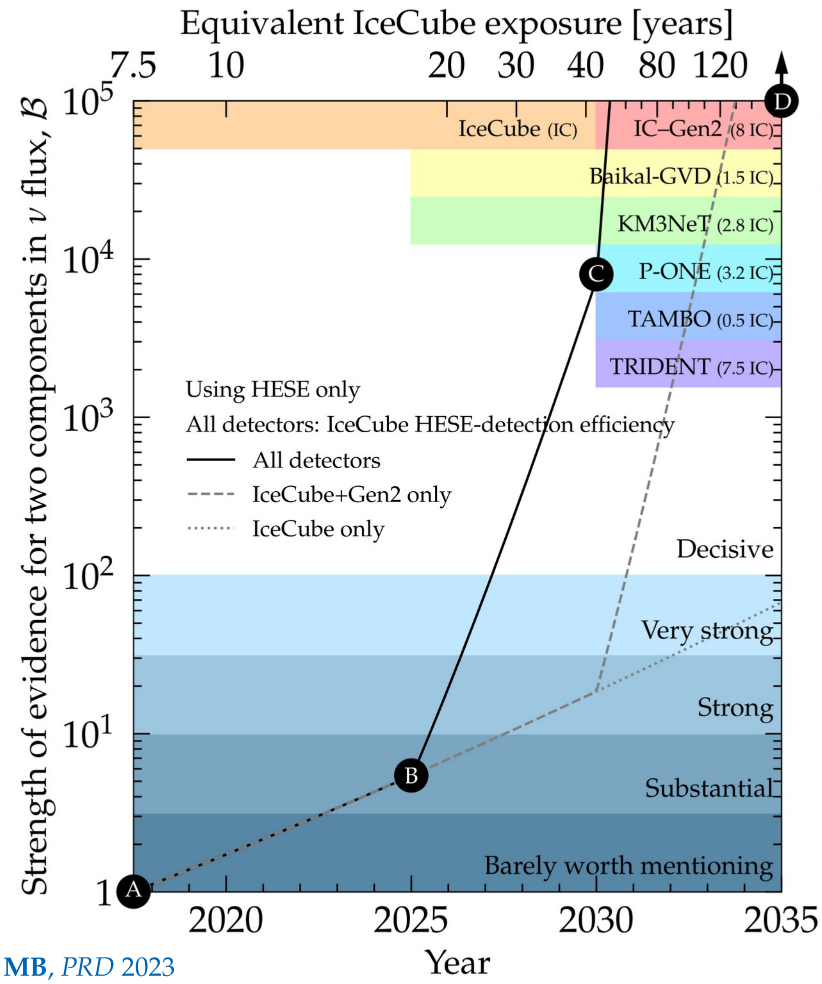
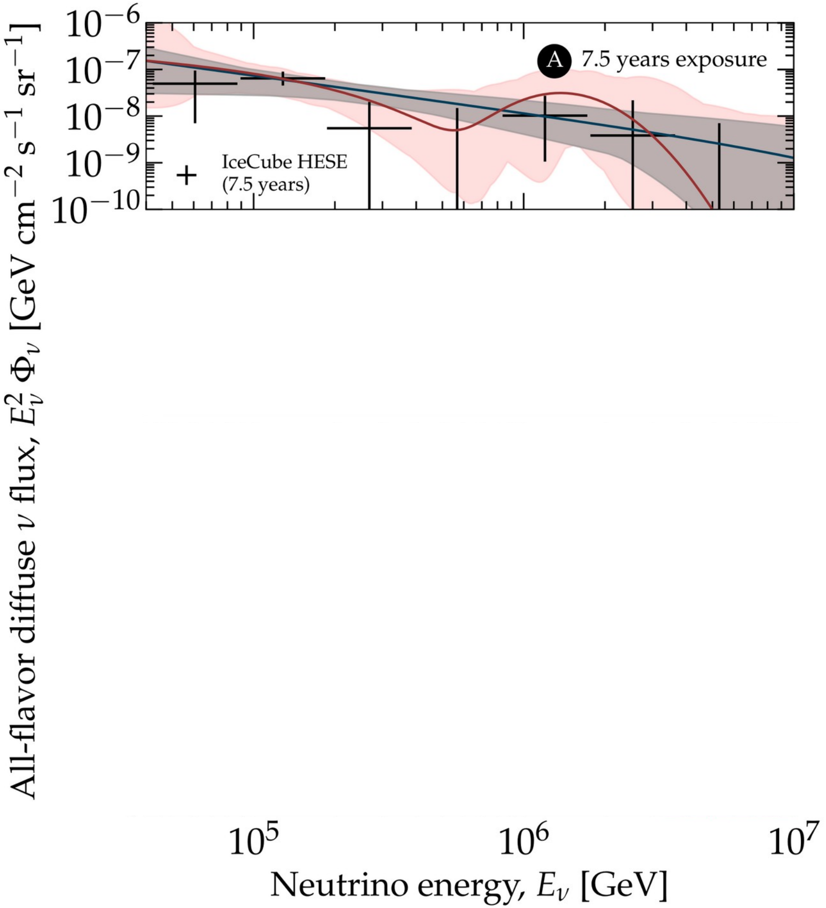
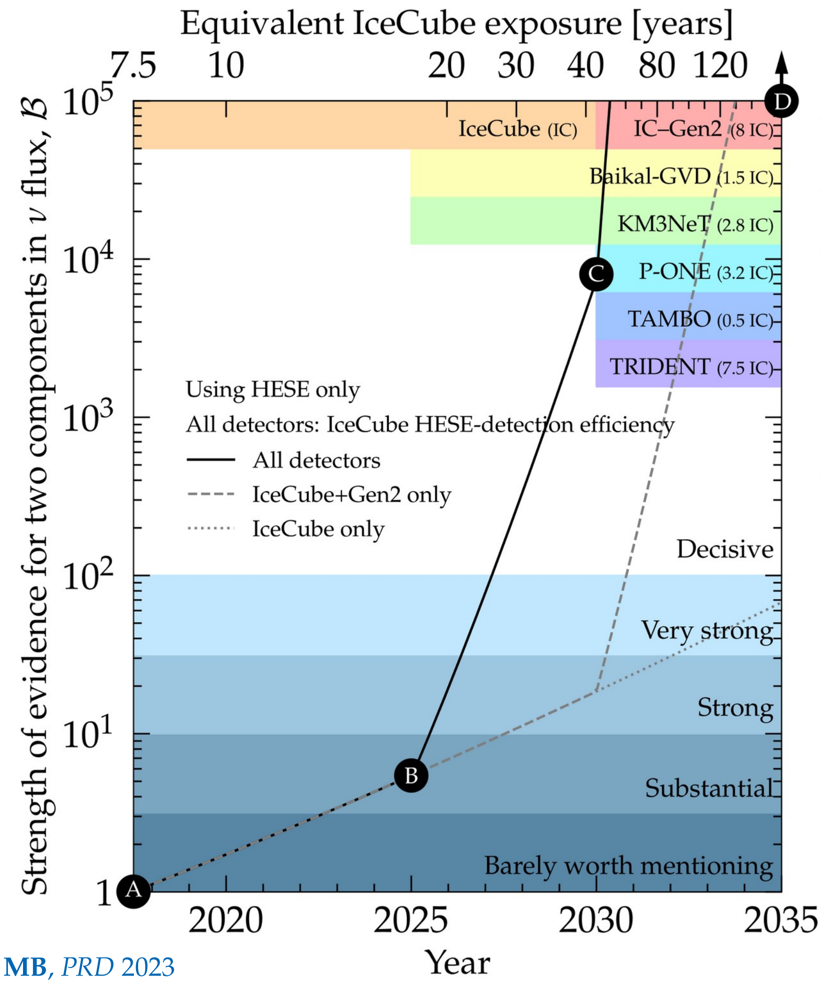


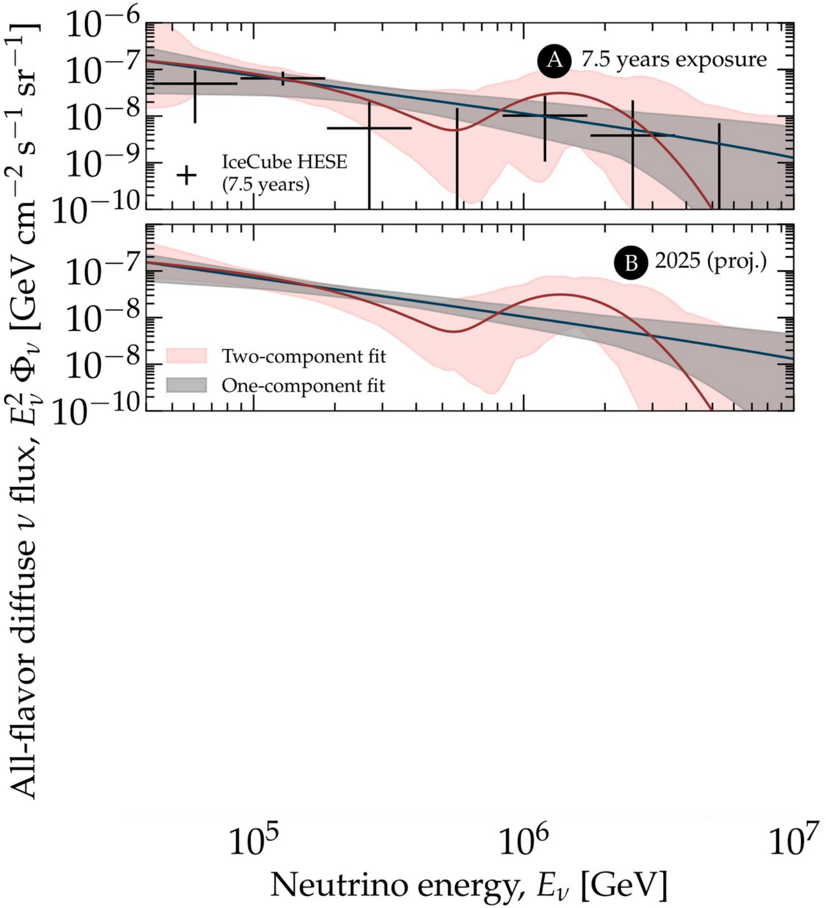


D. F. G. Fiorillo, **MB**, *PRD* 2023

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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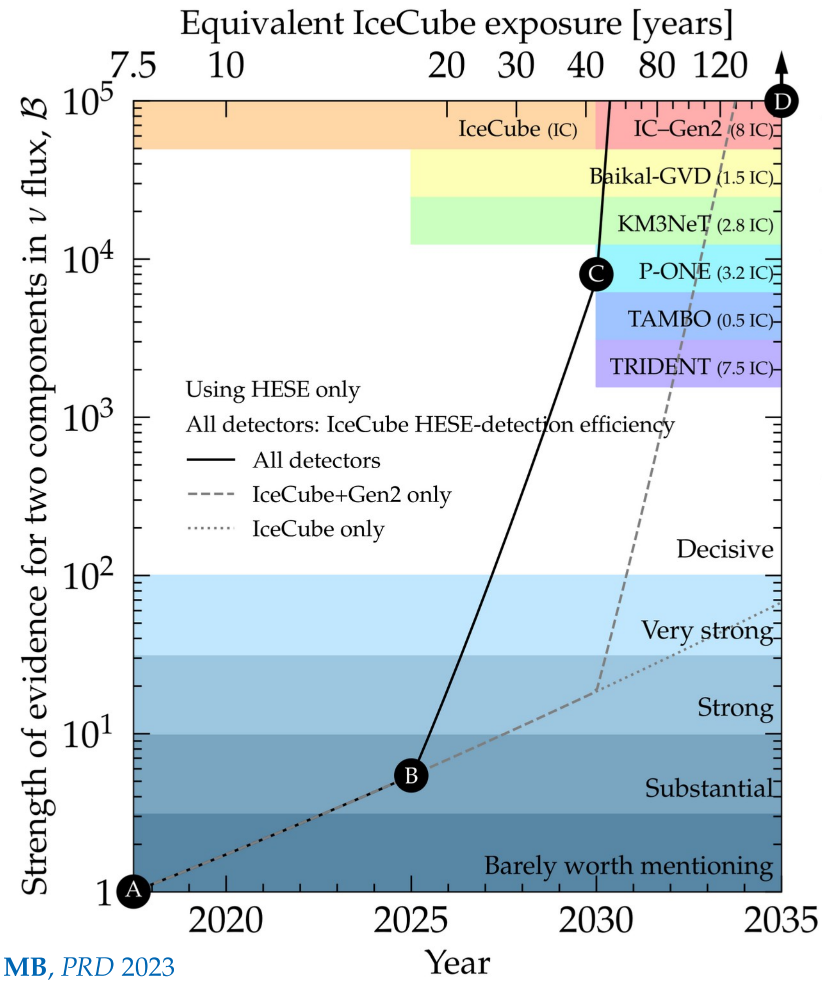
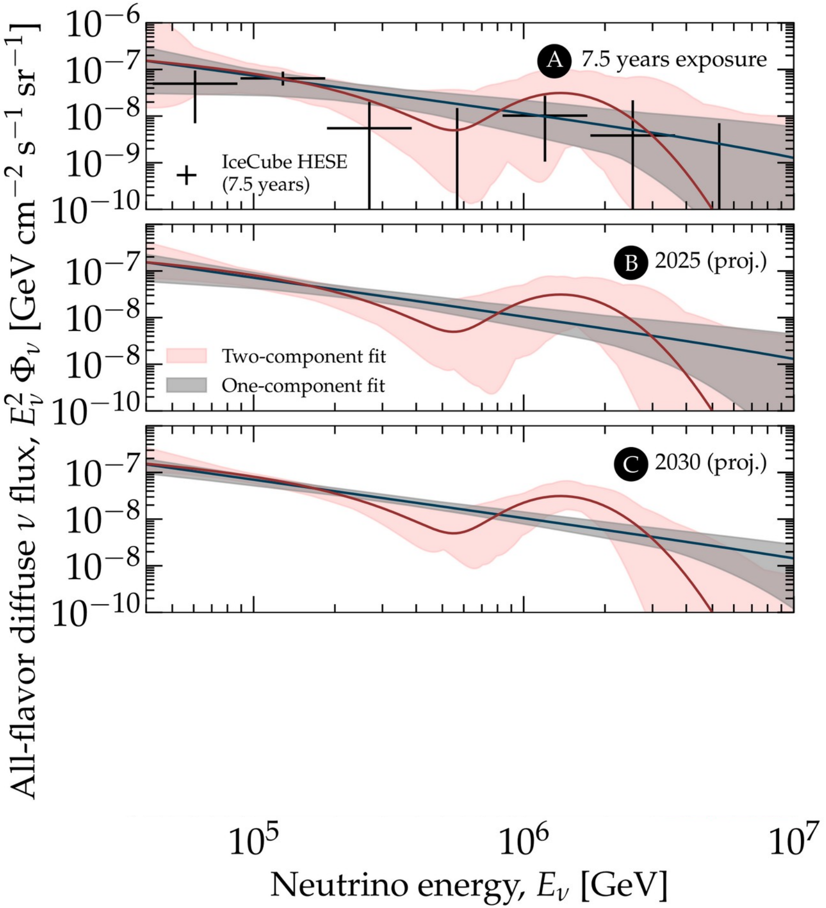
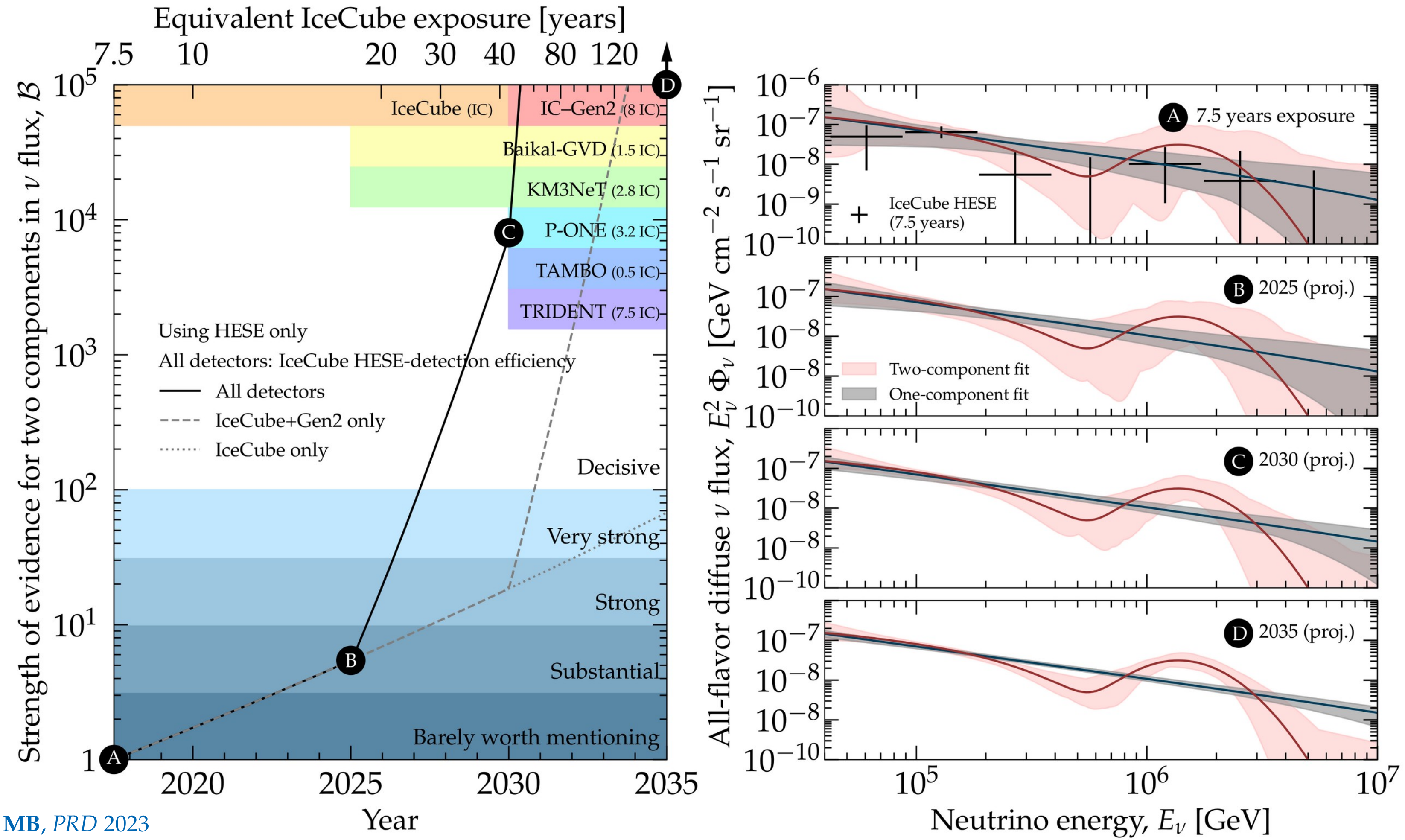




D. F. G. Fiorillo, **MB**, *PRD* 2023

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

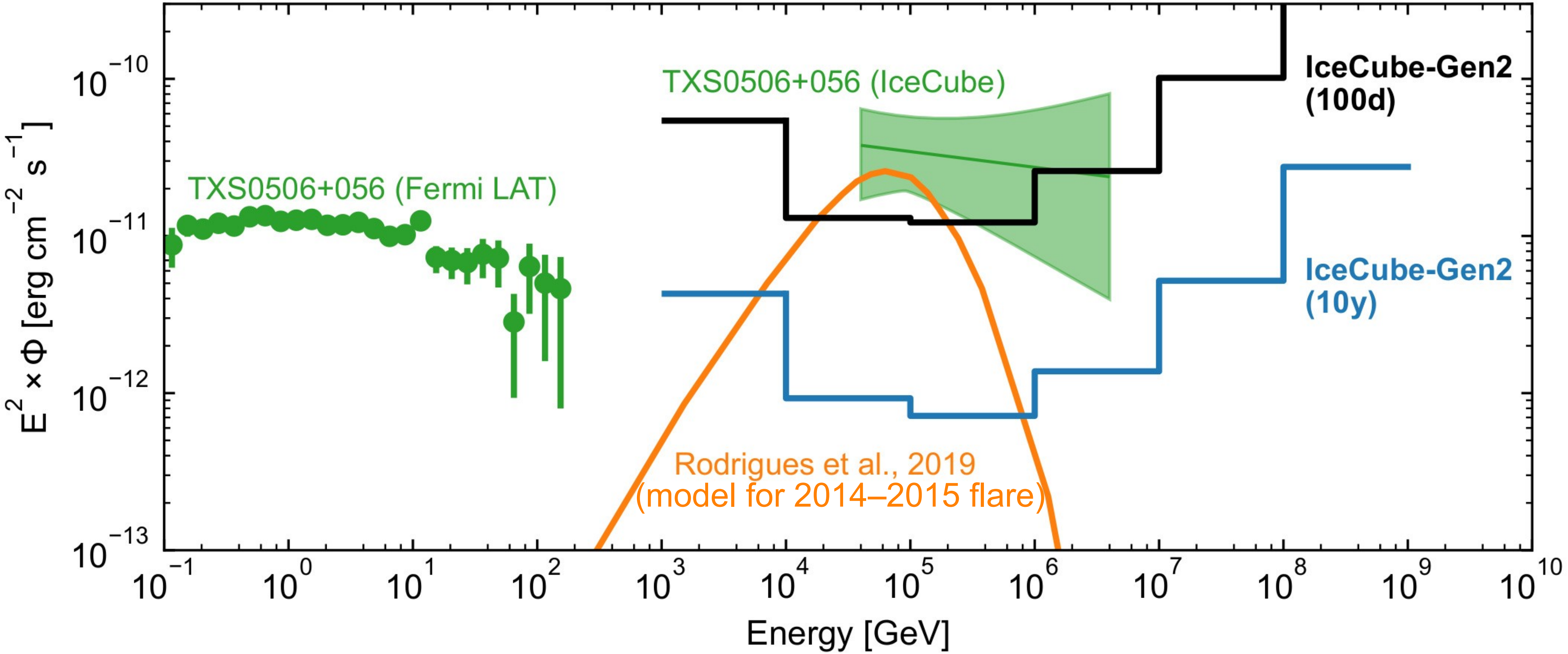
Bump-like spectra can reveal the presence of ν production via *pγ*:



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

High-statistics neutrino blazar flares

Observing the 2014–2015 TXS 0506+056 at 5σ:



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

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

Operational	☐	Date full operations began
Prototype	░	Date protoype operations began or begin
Planning	▓	Projected full operations

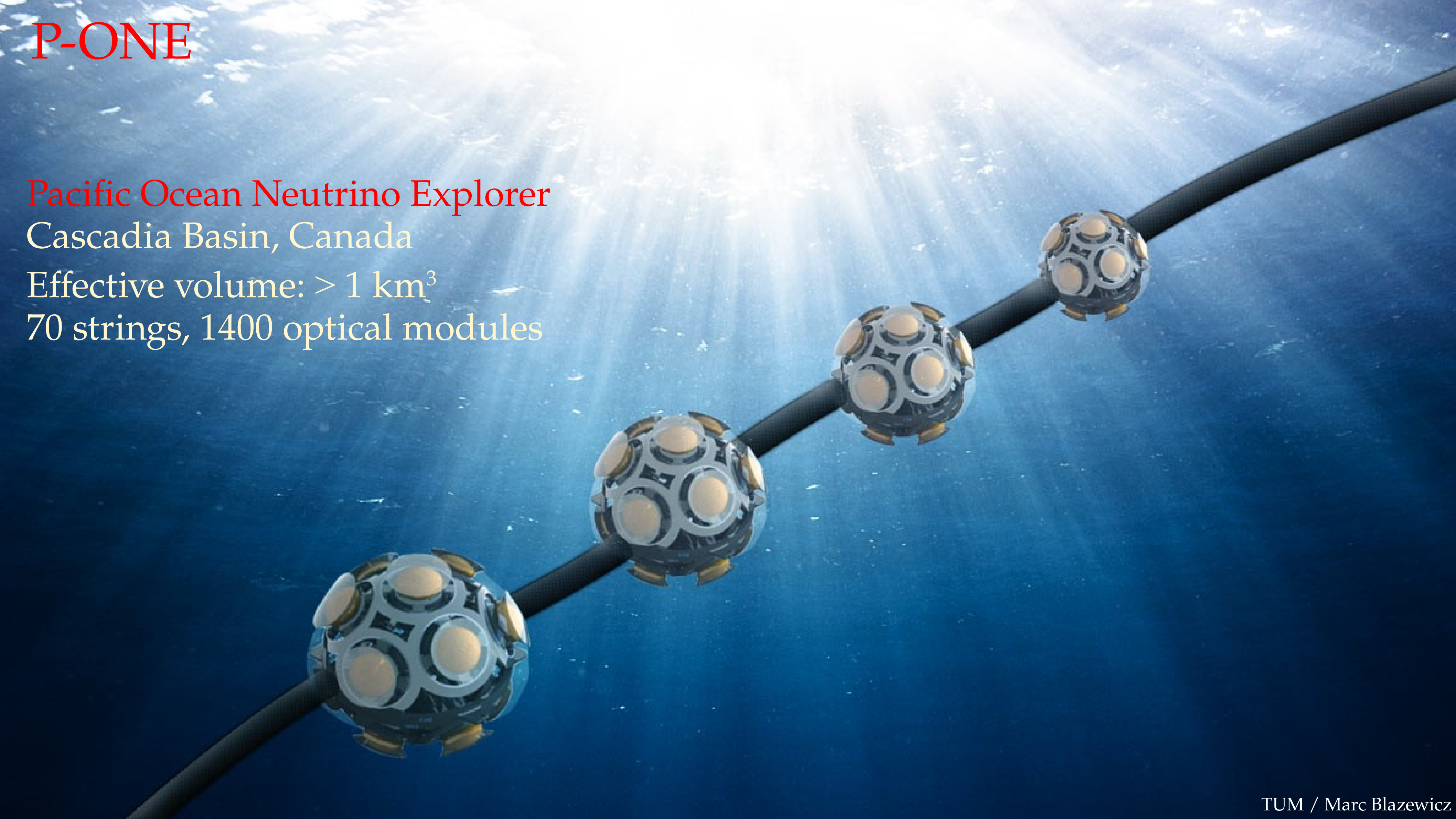
Abraham *et al.* (inc. **MB**),
J. Phys. G: Nucl. Part. Phys. 59, 11 (2022) [2203.05591]

Baikal-GVD

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

JINR

P-ONE

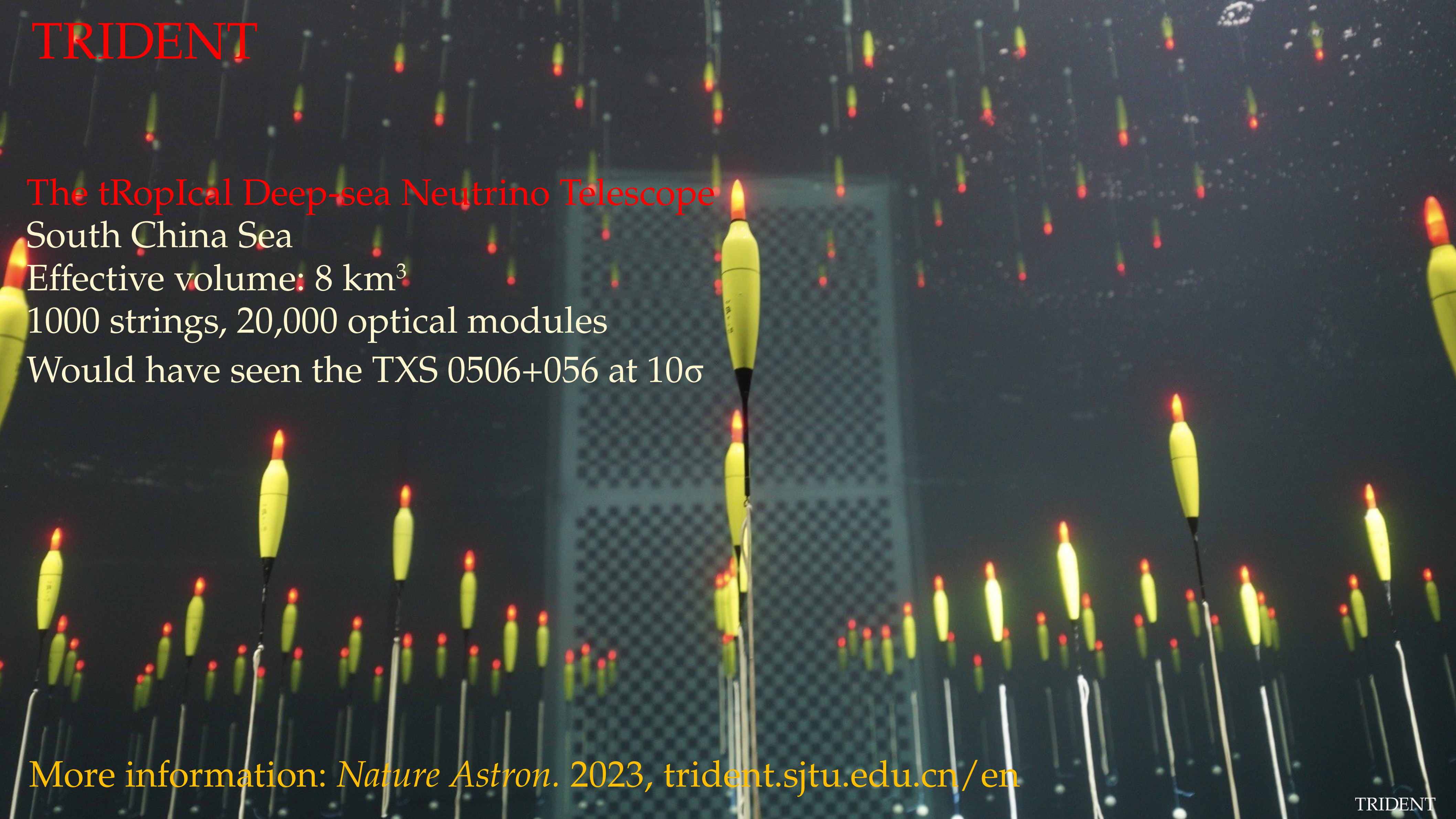


Pacific Ocean Neutrino Explorer
Cascadia Basin, Canada

Effective volume: > 1 km^3
70 strings, 1400 optical modules

TUM / Marc Blazewicz

TRIDENT



The tRopIcal Deep-sea Neutrino Telescope

South China Sea

Effective volume: 8 km^3

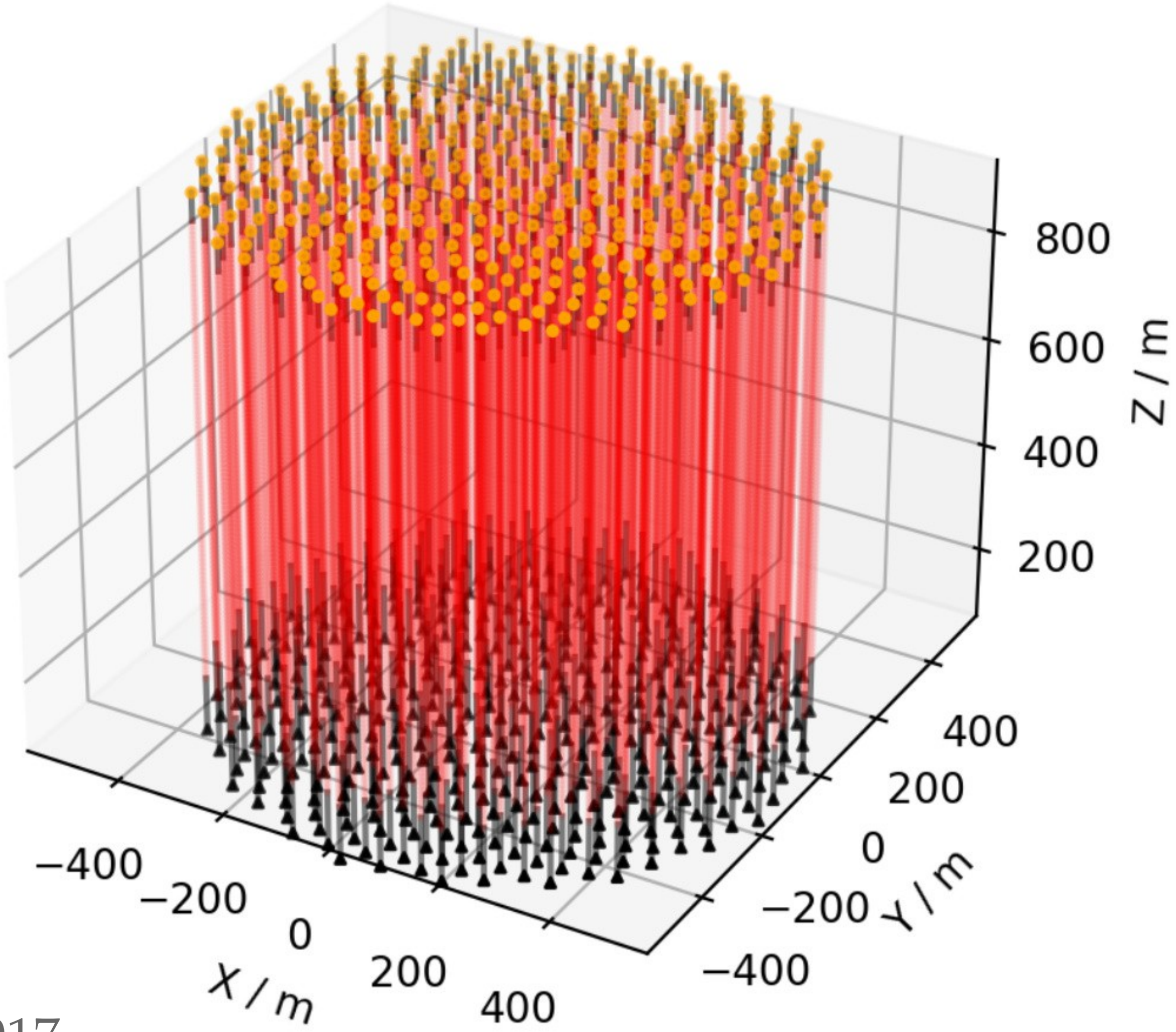
1000 strings, 20,000 optical modules

Would have seen the TXS 0506+056 at 10σ

More information: *Nature Astron.* 2023, trident.sjtu.edu.cn/en

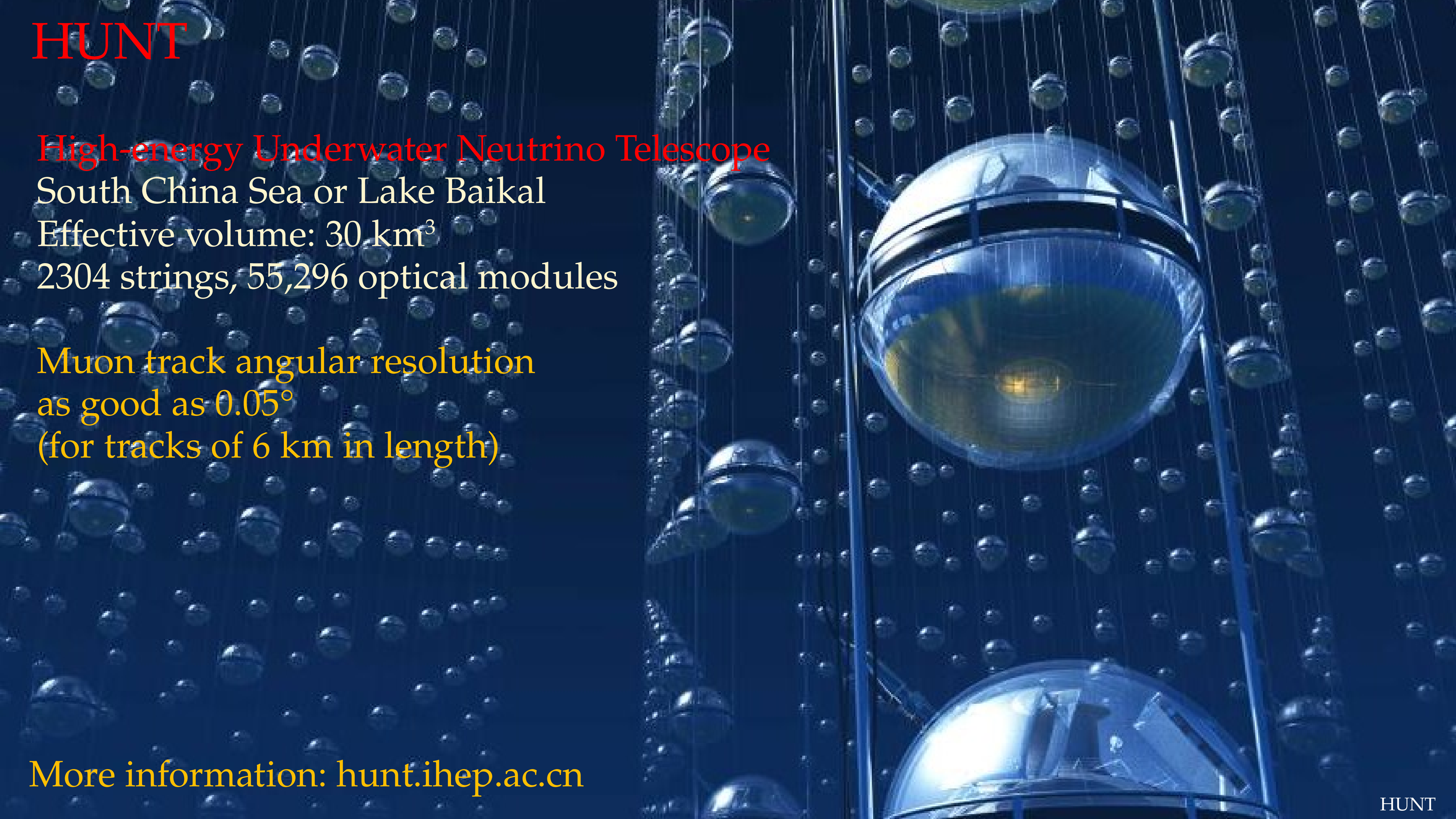
NEON

Neutrino Observatory in the Nanhai
South China Sea
Effective volume: 0.8 km^3 (dense!)
400 strings, 40,000 optical modules



More information: PoS (ICRC2023) 1017

HUNT

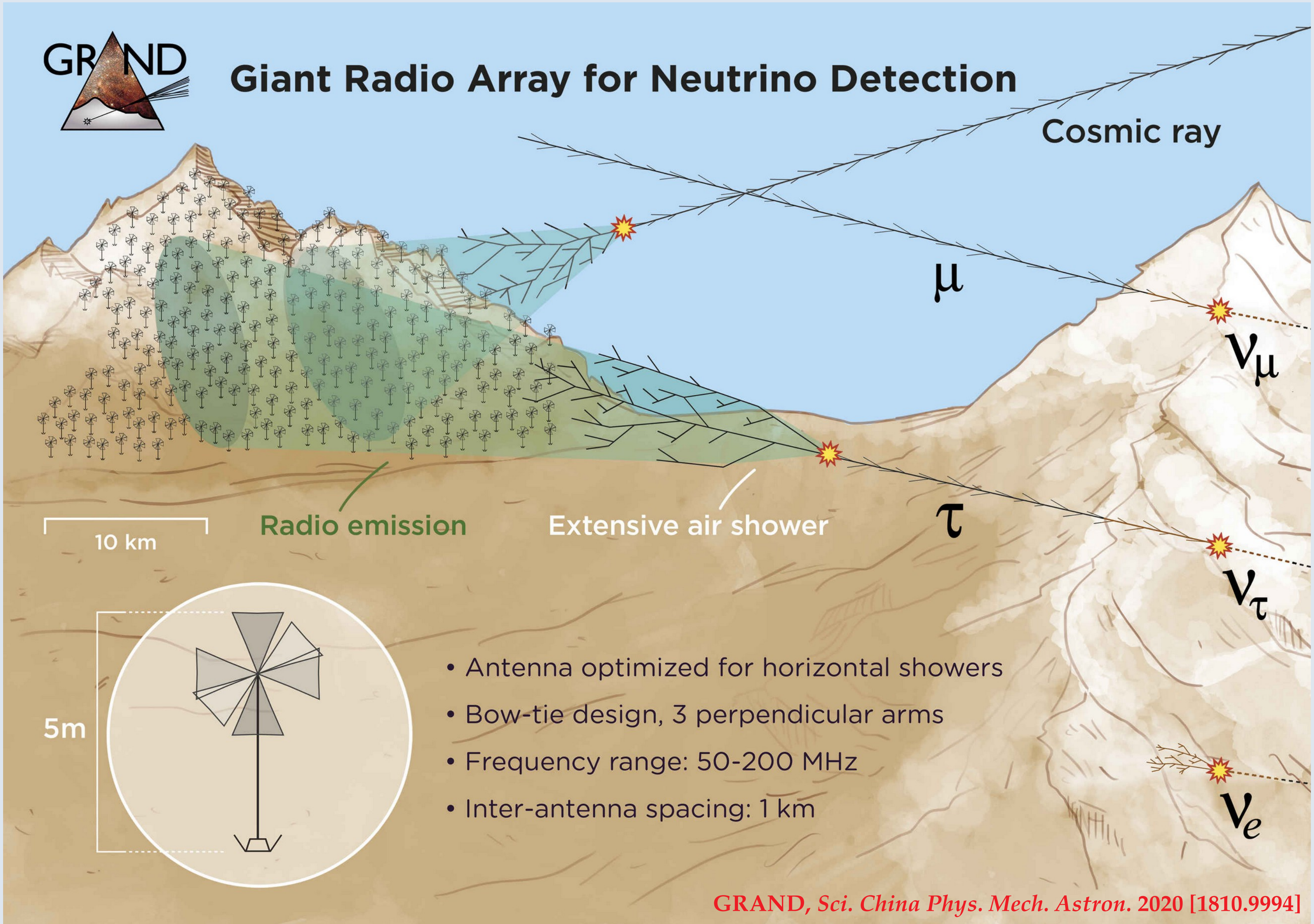


High-energy Underwater Neutrino Telescope
South China Sea or Lake Baikal
Effective volume: 30 km^3
2304 strings, 55,296 optical modules

Muon track angular resolution
as good as 0.05°
(for tracks of 6 km in length)

More information: hunt.ihep.ac.cn

Giant Radio Array for Neutrino Detection



- Antenna optimized for horizontal showers
- Bow-tie design, 3 perpendicular arms
- Frequency range: 50-200 MHz
- Inter-antenna spacing: 1 km

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

GRANDProto300@China

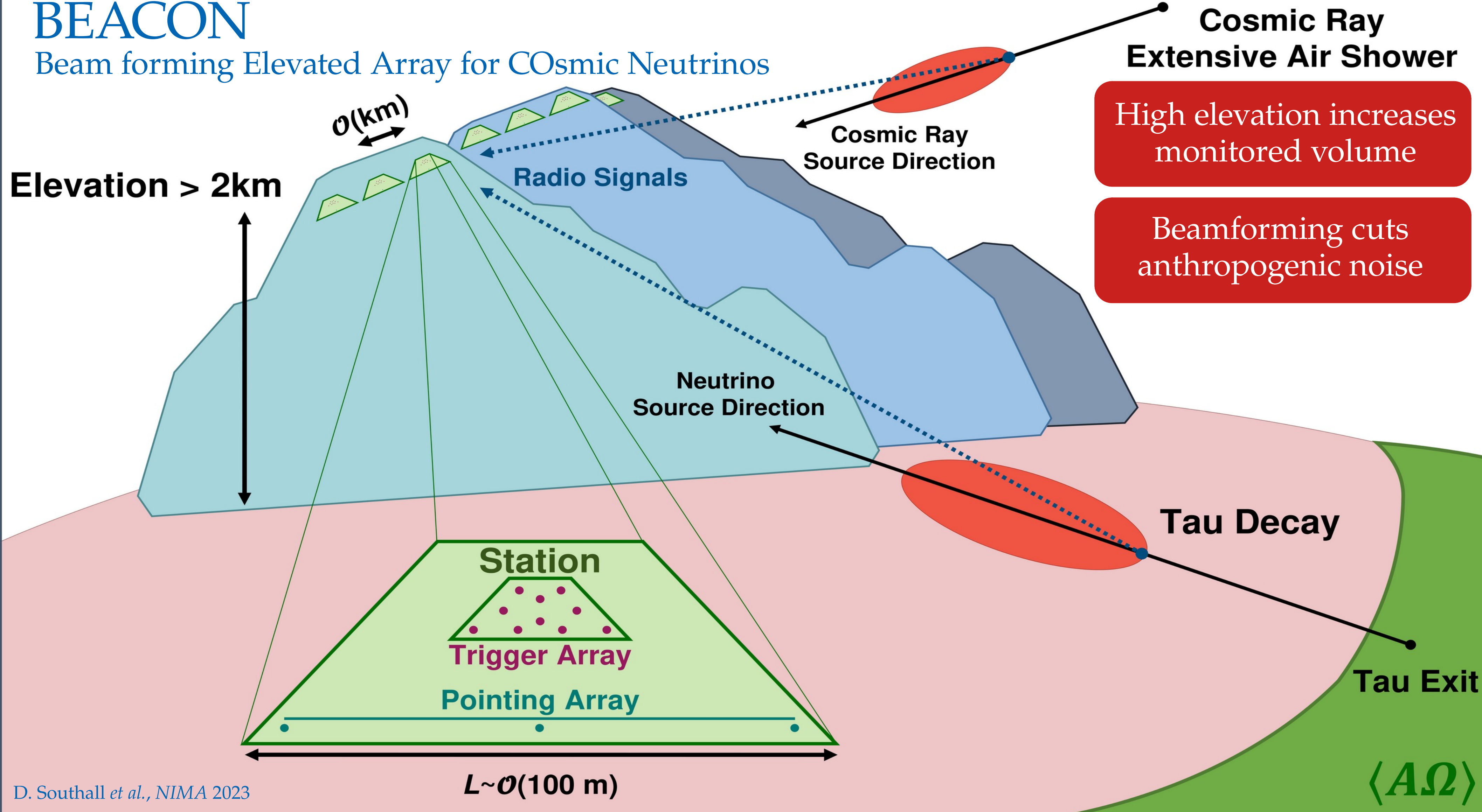
GRAND@Nançay

GRAND@Auger

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

BEACON

Beam forming Elevated Array for COsmic Neutrinos



High elevation increases monitored volume

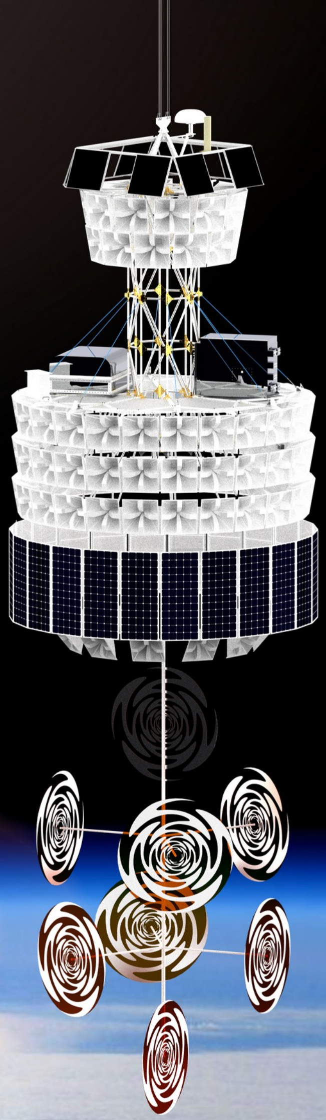
Beamforming cuts anthropogenic noise

D. Southall *et al.*, *NIMA* 2023

⟨*AΩ*⟩

PUEO

Payload for Ultrahigh Energy Observations



30-day flight above Antarctica

Builds on earlier ANITA I–IV flights

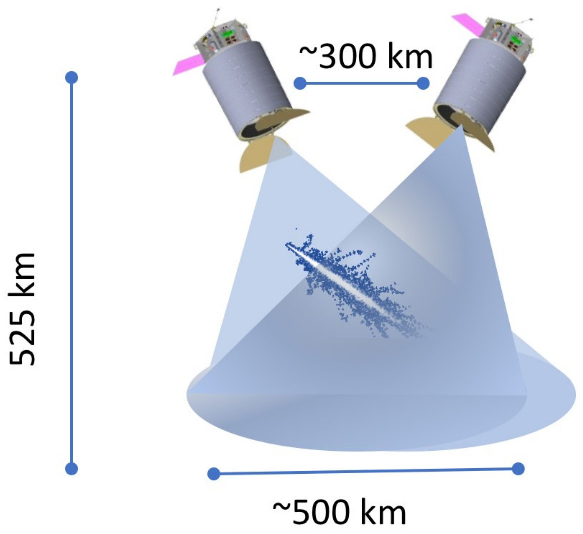
PUEO Collaboration

POEMMA:
Probe of Extreme
Multi-Messenger Astrophysics

Observing fluorescence
and Cherenkov radiation from space
using twin satellites

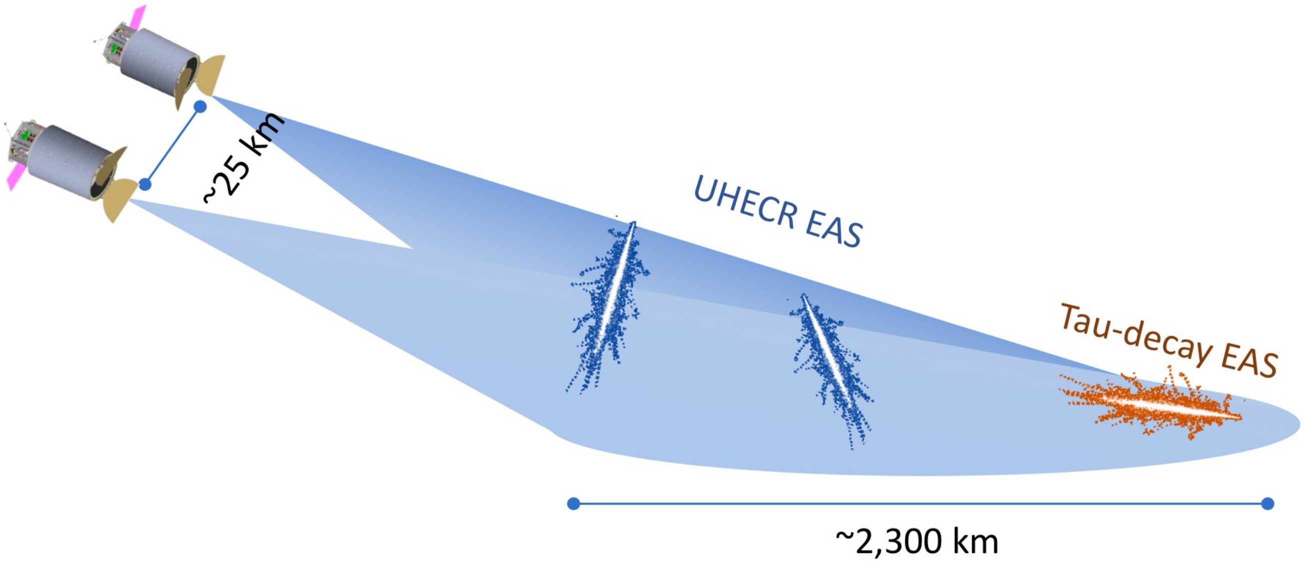
Fluorescence

POEMMA-Stereo



Cherenkov radiation

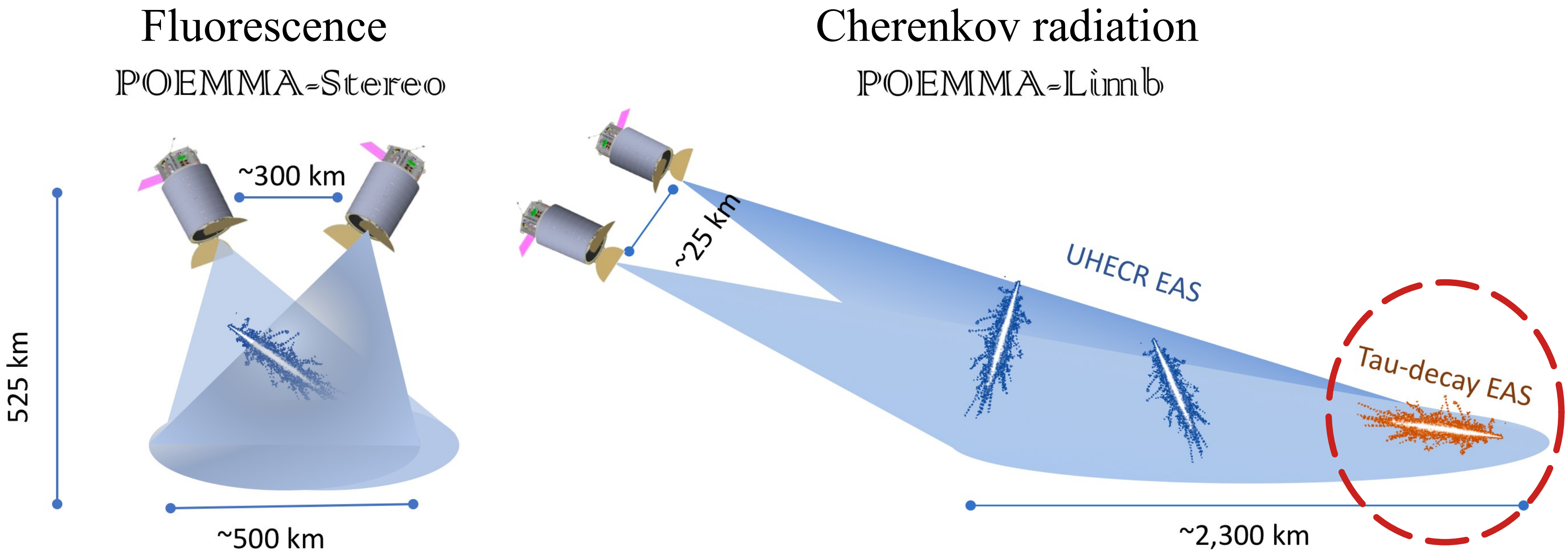
POEMMA-Limb



POEMMA, *JCAP* 2021 (2012.07945)

POEMMA: Probe of Extreme Multi-Messenger Astrophysics

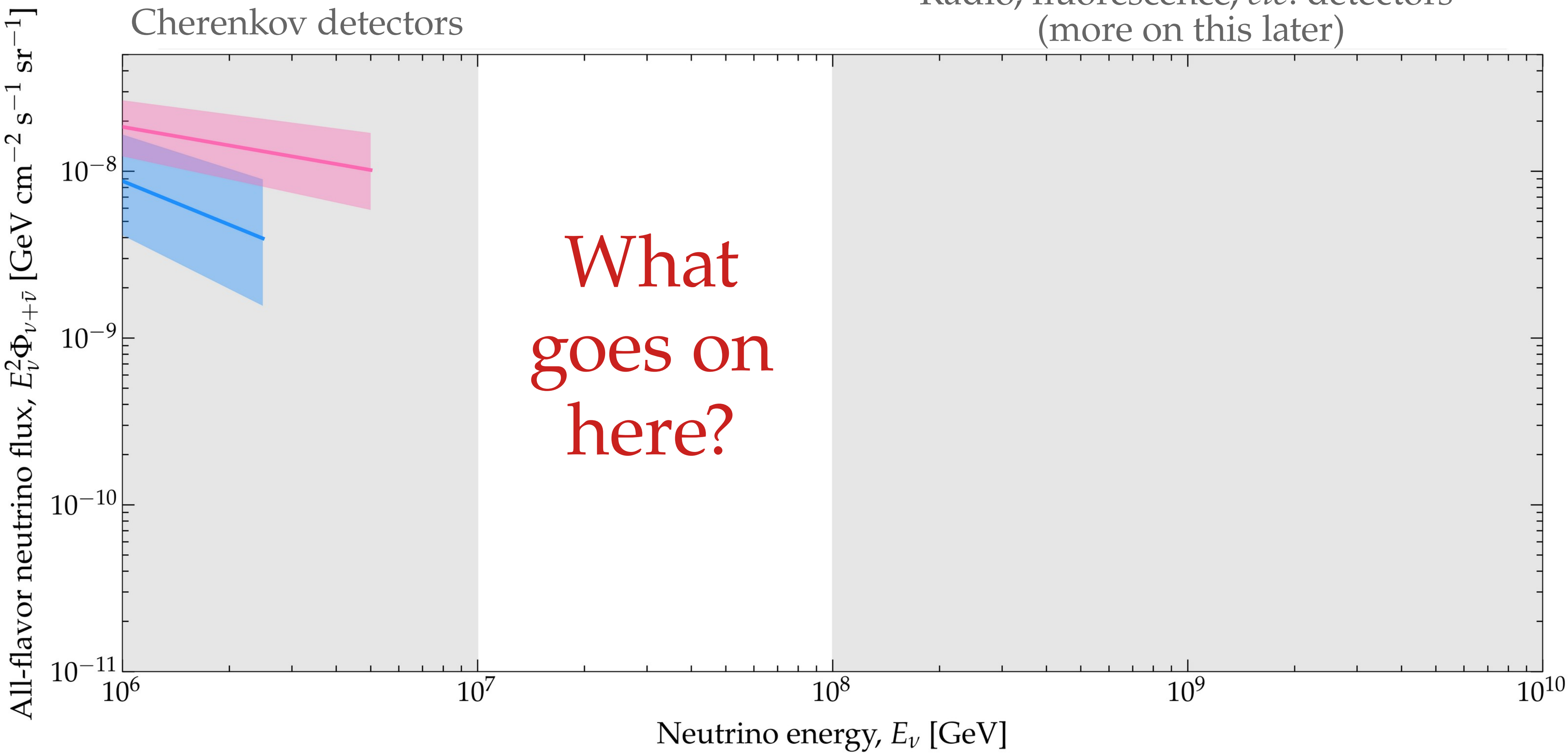
Observing fluorescence
and Cherenkov radiation from space
using twin satellites



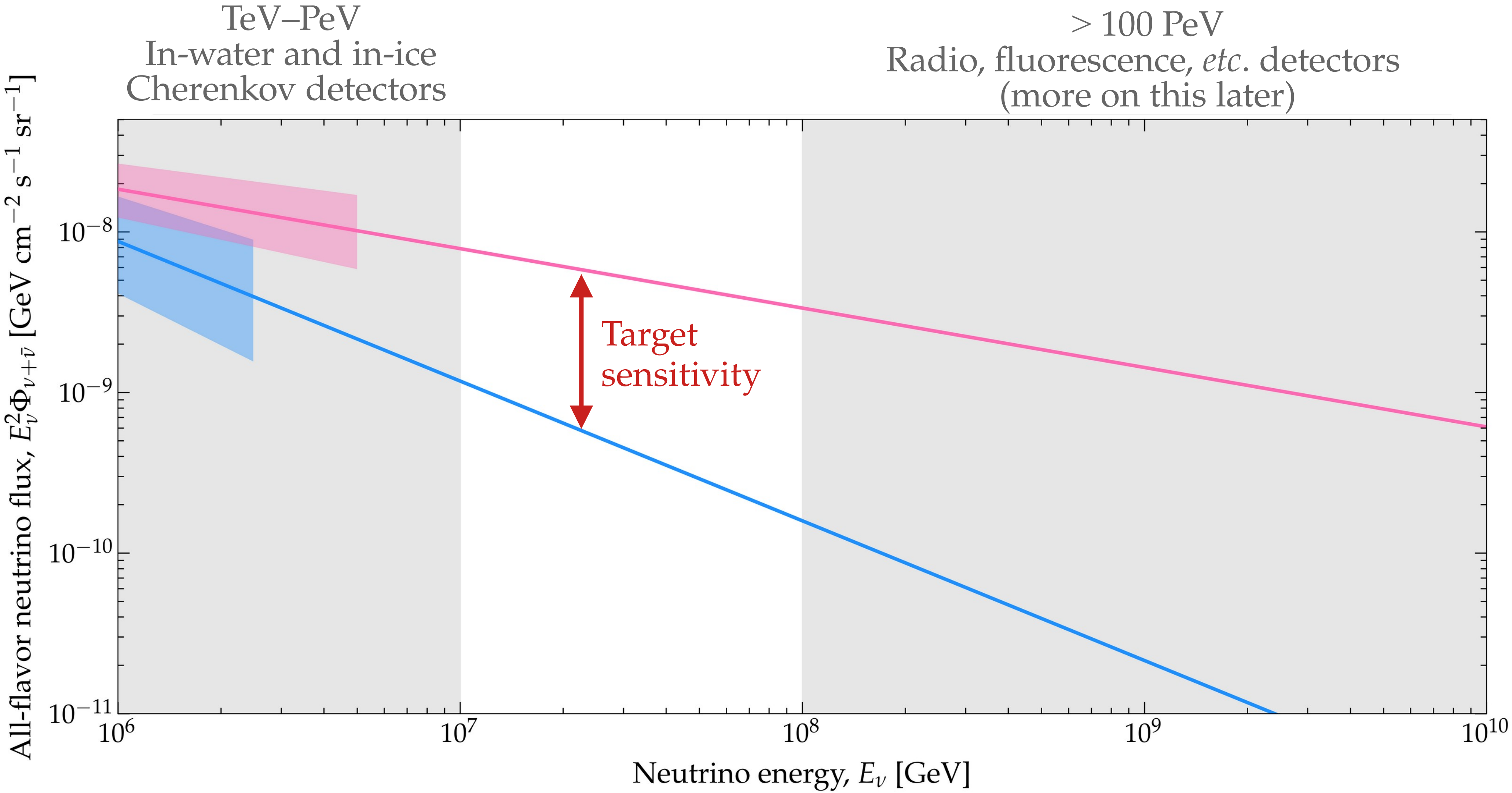
POEMMA, *JCAP* 2021 (2012.07945)

TeV–PeV
In-water and in-ice
Cherenkov detectors

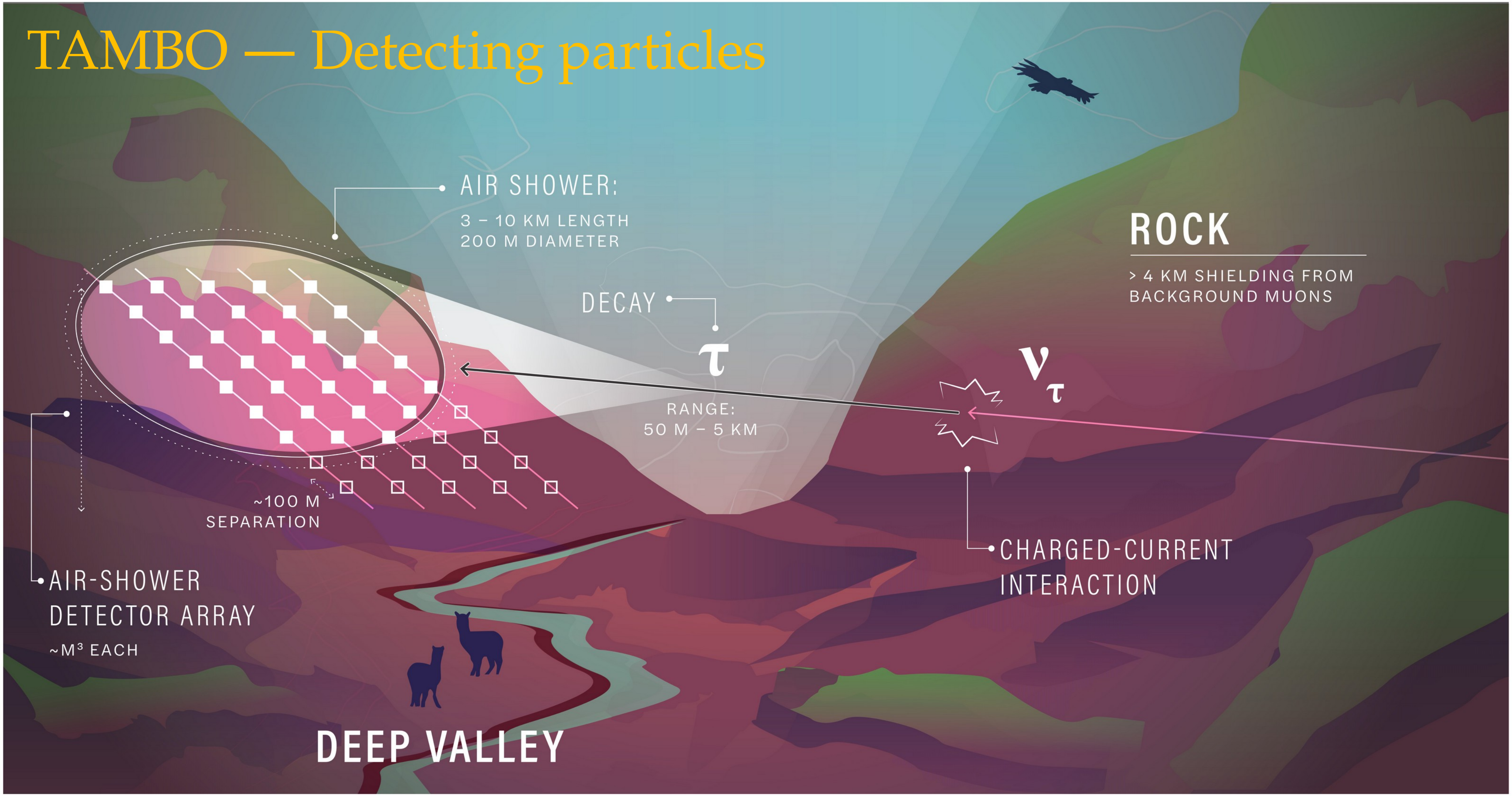
> 100 PeV
Radio, fluorescence, *etc.* detectors
(more on this later)



What goes on here?


TeV–PeV
In-water and in-ice
Cherenkov detectors
> 100 PeV
Radio, fluorescence, *etc*. detectors
(more on this later)
Target
sensitivity
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]

TAMBO — Detecting particles



AIR SHOWER:

3 – 10 KM LENGTH
200 M DIAMETER

DECAY

τ

RANGE:
50 M – 5 KM

ROCK

> 4 KM SHIELDING FROM
BACKGROUND MUONS

ν_τ

CHARGED-CURRENT
INTERACTION

~100 M
SEPARATION

AIR-SHOWER
DETECTOR ARRAY

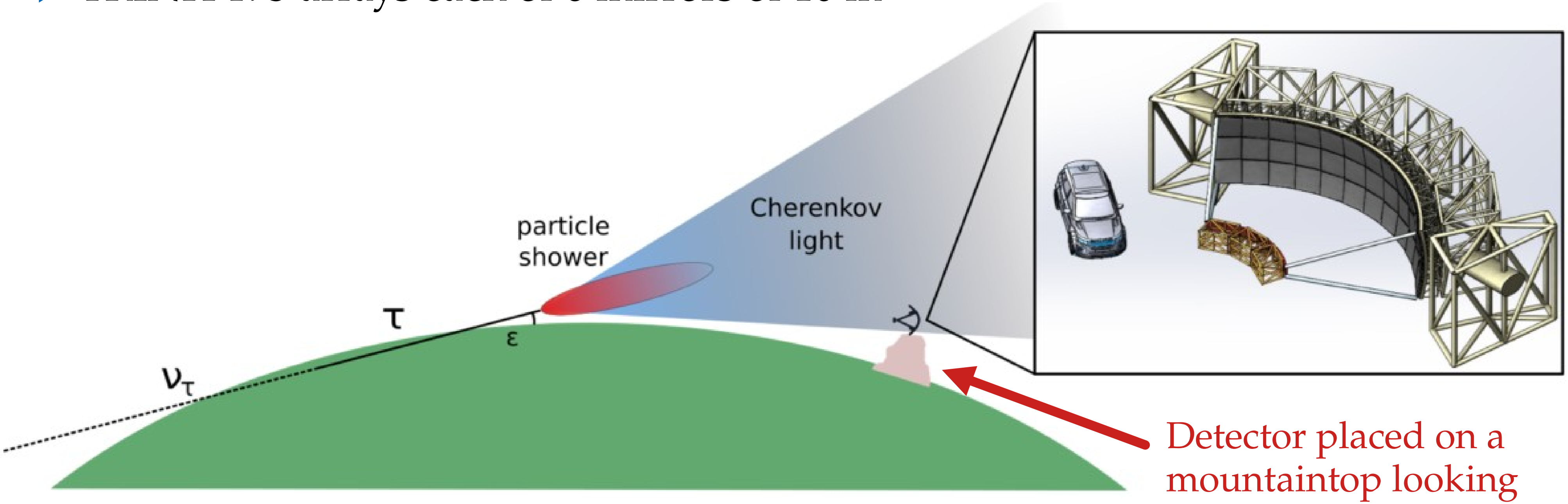
~M^3 EACH

DEEP VALLEY

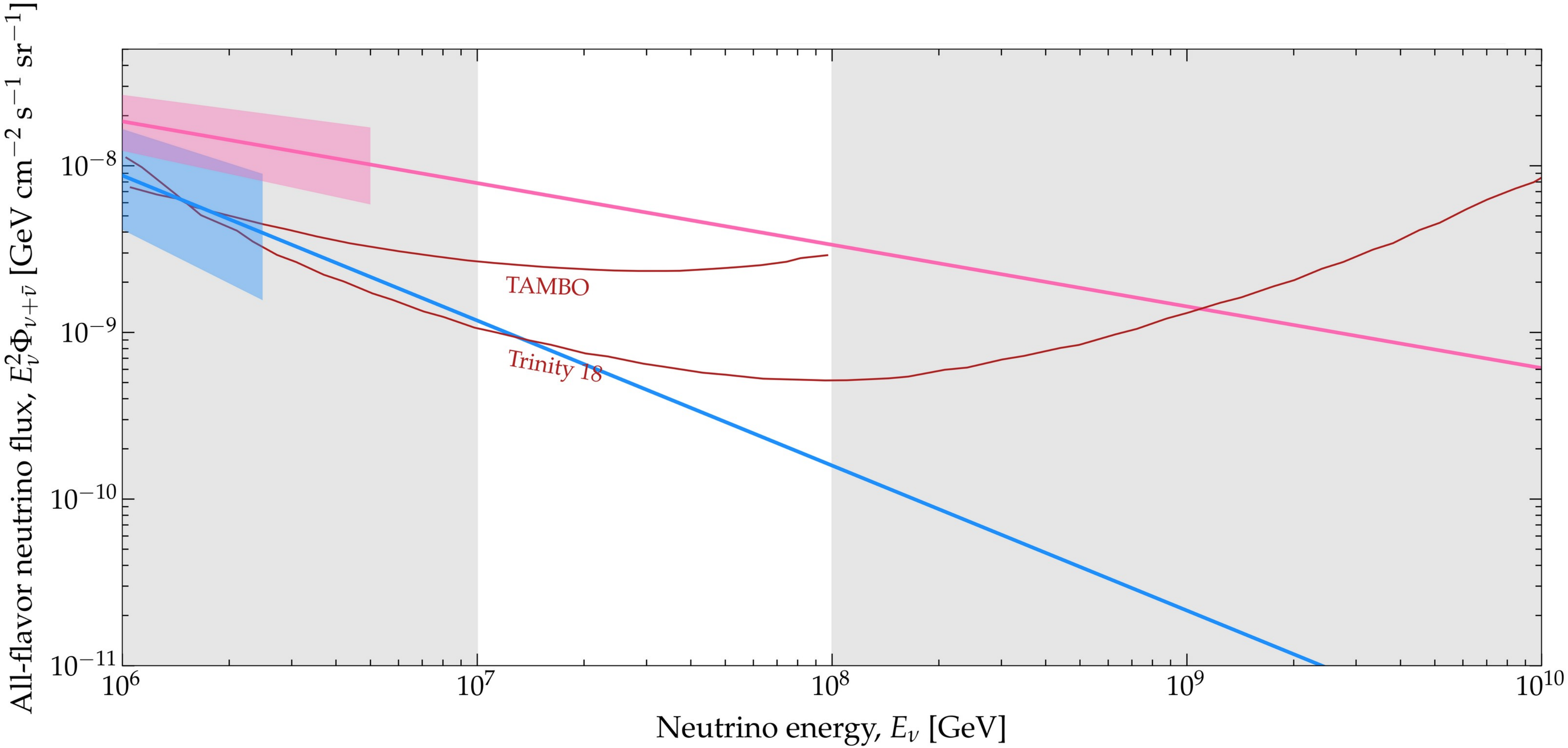
TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) · COLCA VALLEY, PERU

TRINITY — Detecting Cherenkov light

- Atmospheric Cherenkov imaging applied to PeV neutrinos
- Pioneered by MAGIC (pointing at Atlantic), ASHRA, and NTA (Mauna Kea)
- TRINITY: 3 arrays each of 6 mirrors of 10 m^2



Detector placed on a mountaintop looking towards the horizon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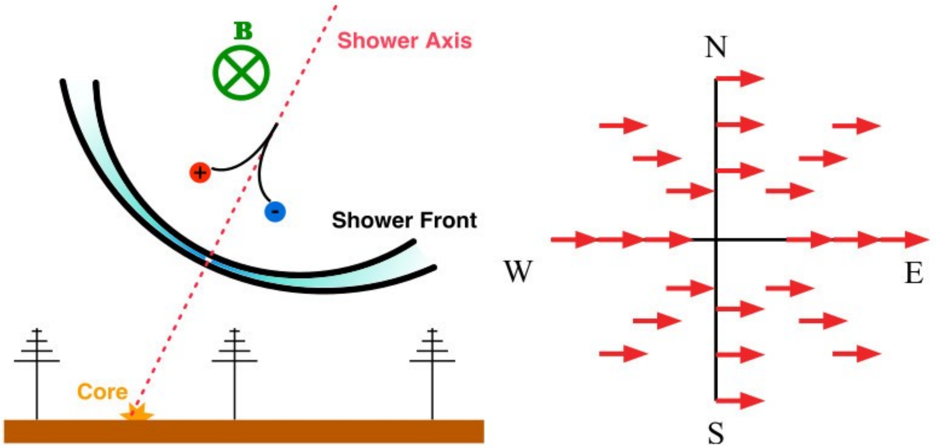
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
TAMBO
Trinity 18

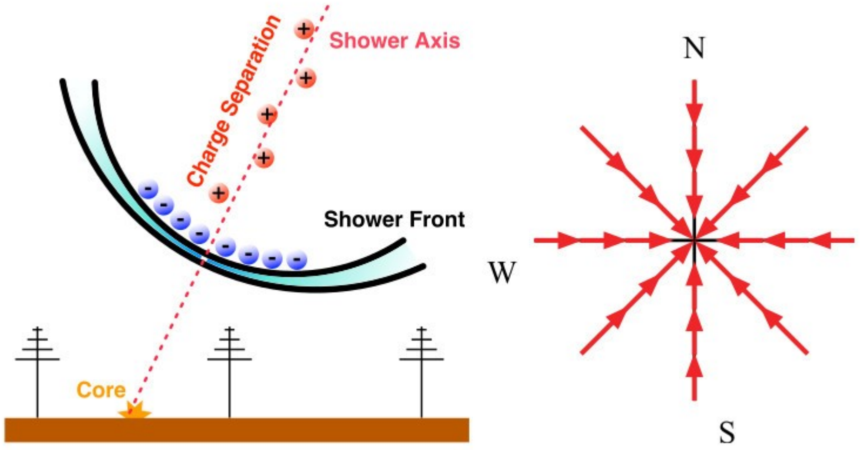
Radio emission: geomagnetic and Askaryan

Geomagnetic



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

Askaryan



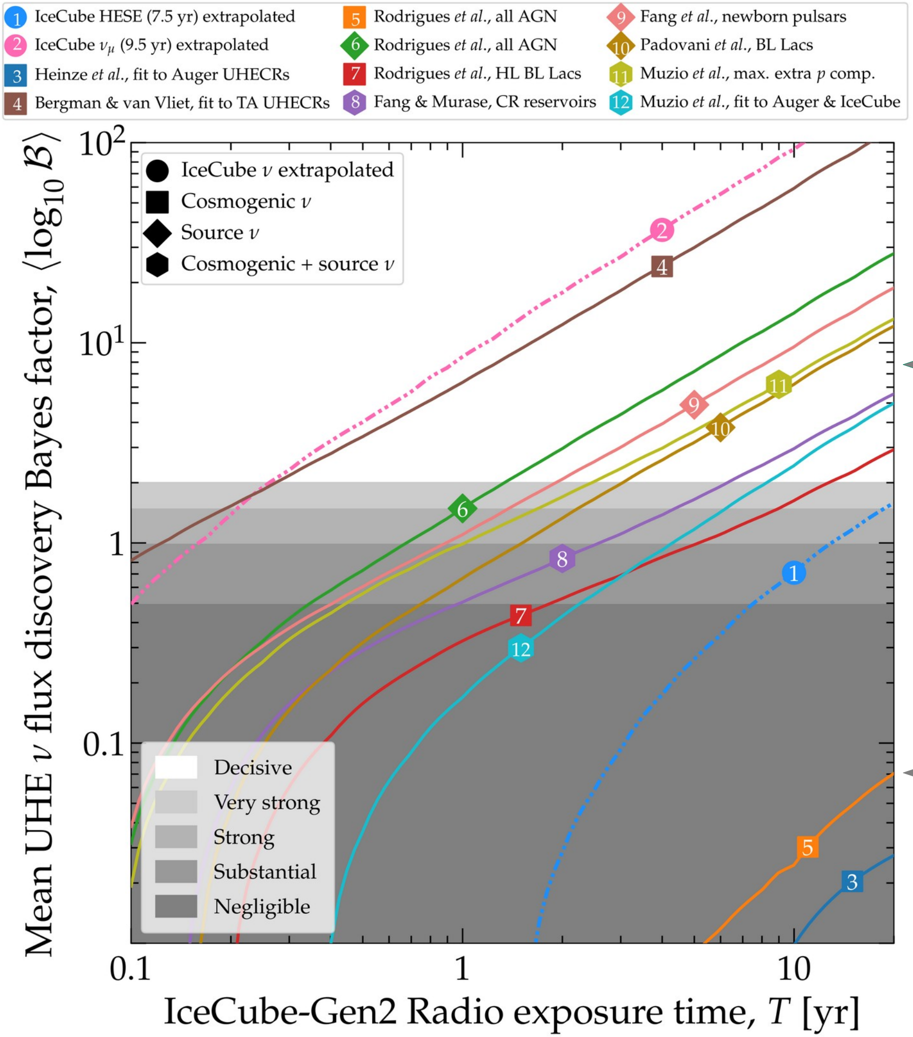
- Time-varying negative-charge ~20% excess
- Linearly polarized towards axis
- Sub-dominant in air showers

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

Radio emission: geomagnetic and Askaryan

Discovering the diffuse flux of UHE neutrinos

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



High Bayes factor
→ Decisive flux discovery

Low Bayes factor
→ No flux discovered

Valera, **MB**, Glaser,
PRD 2023 [2210.03756]

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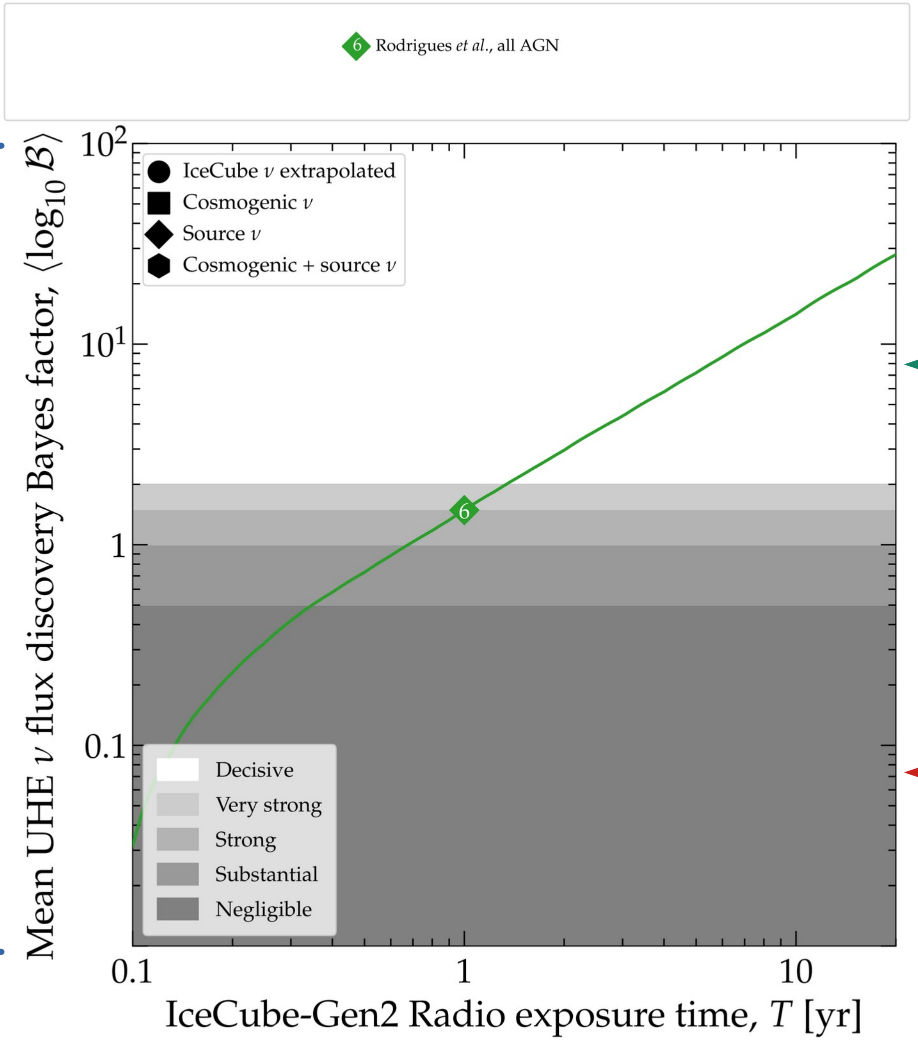

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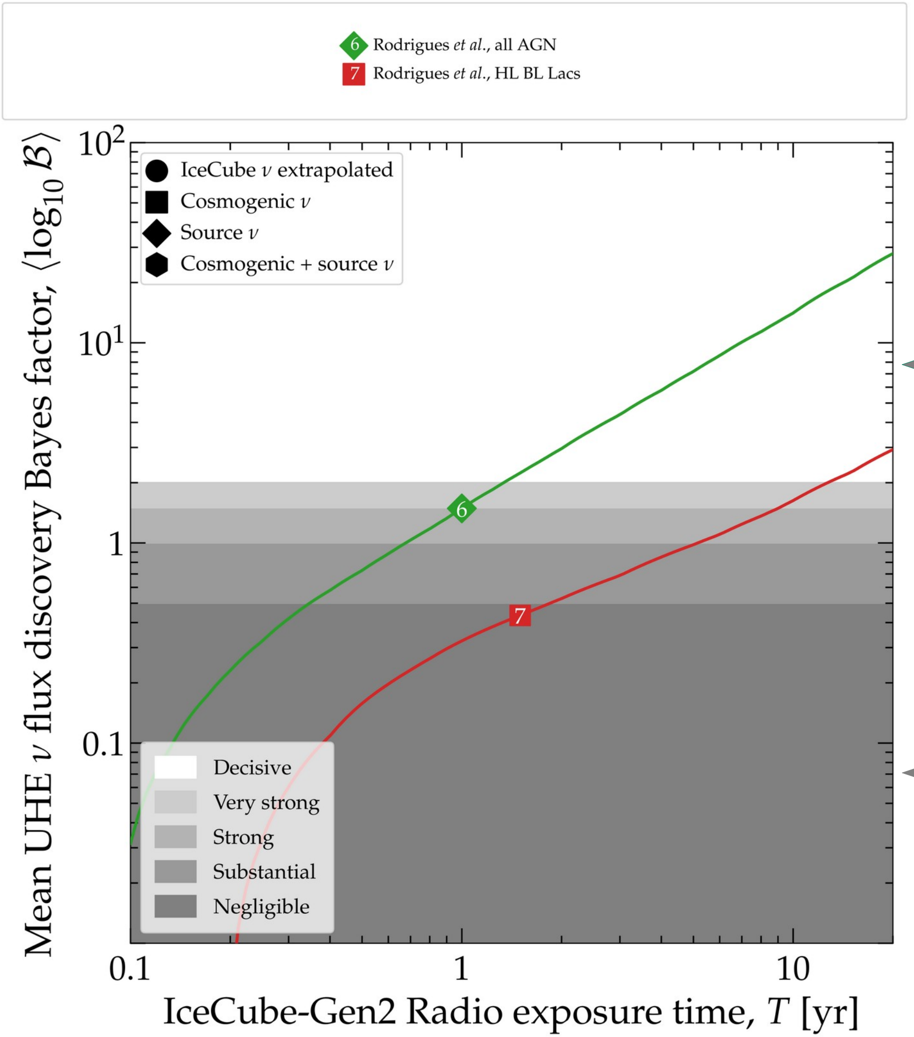

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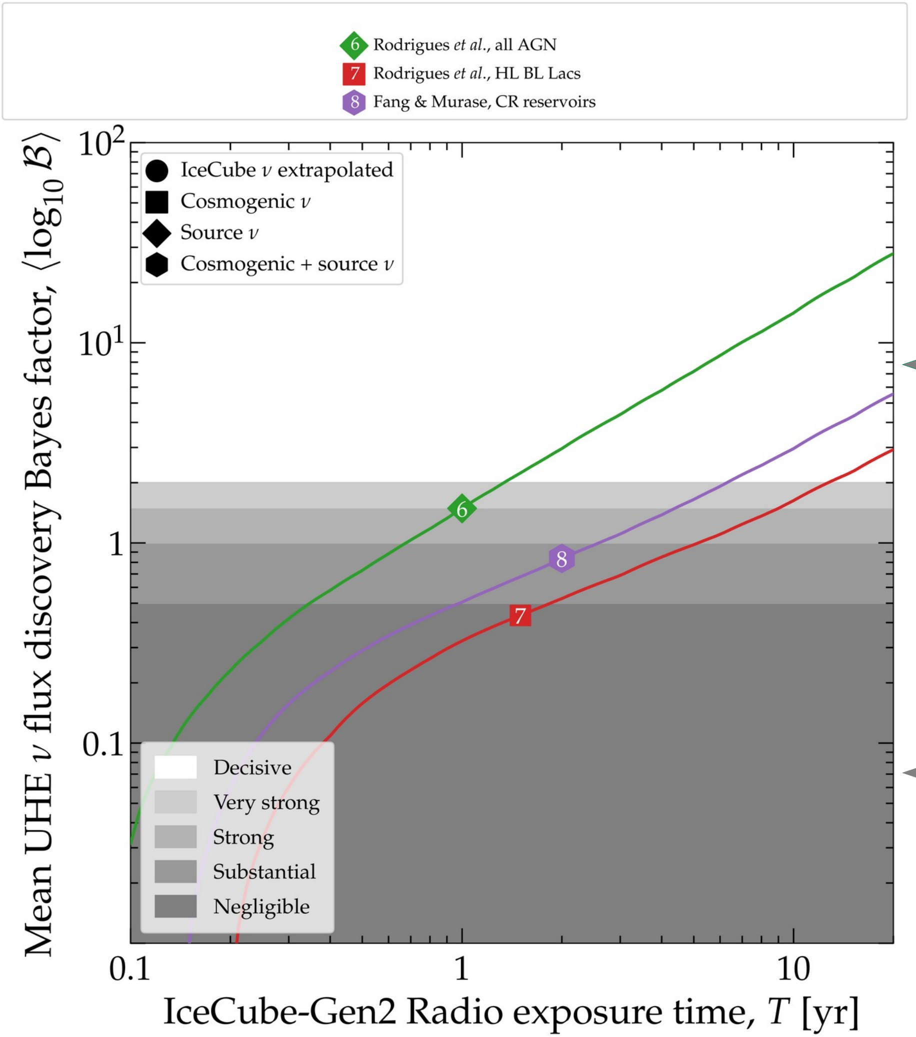

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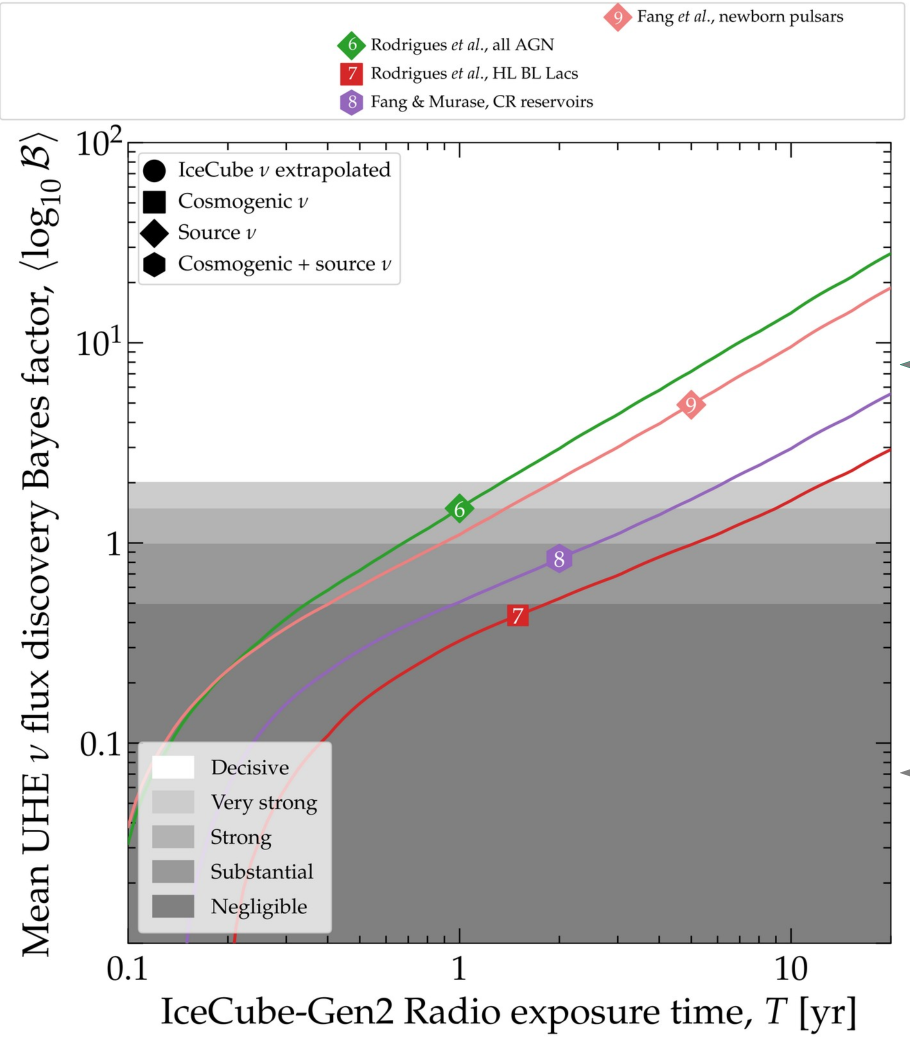

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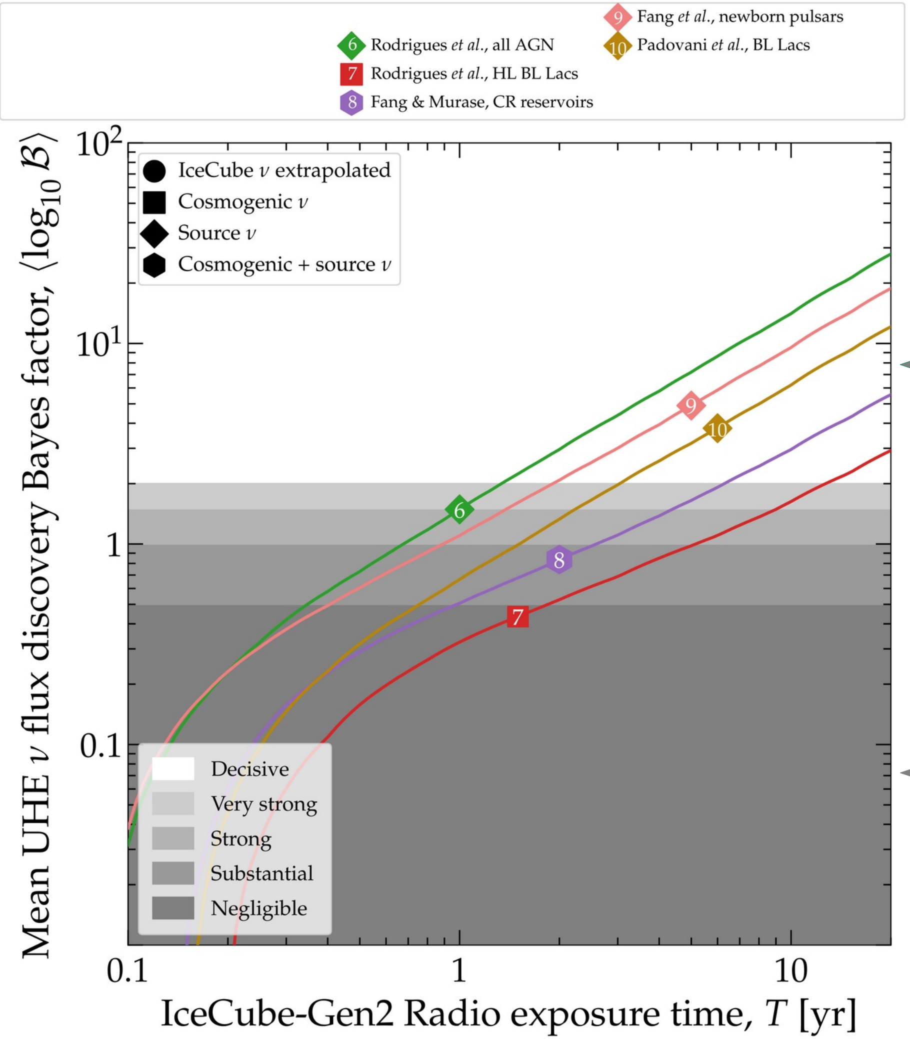

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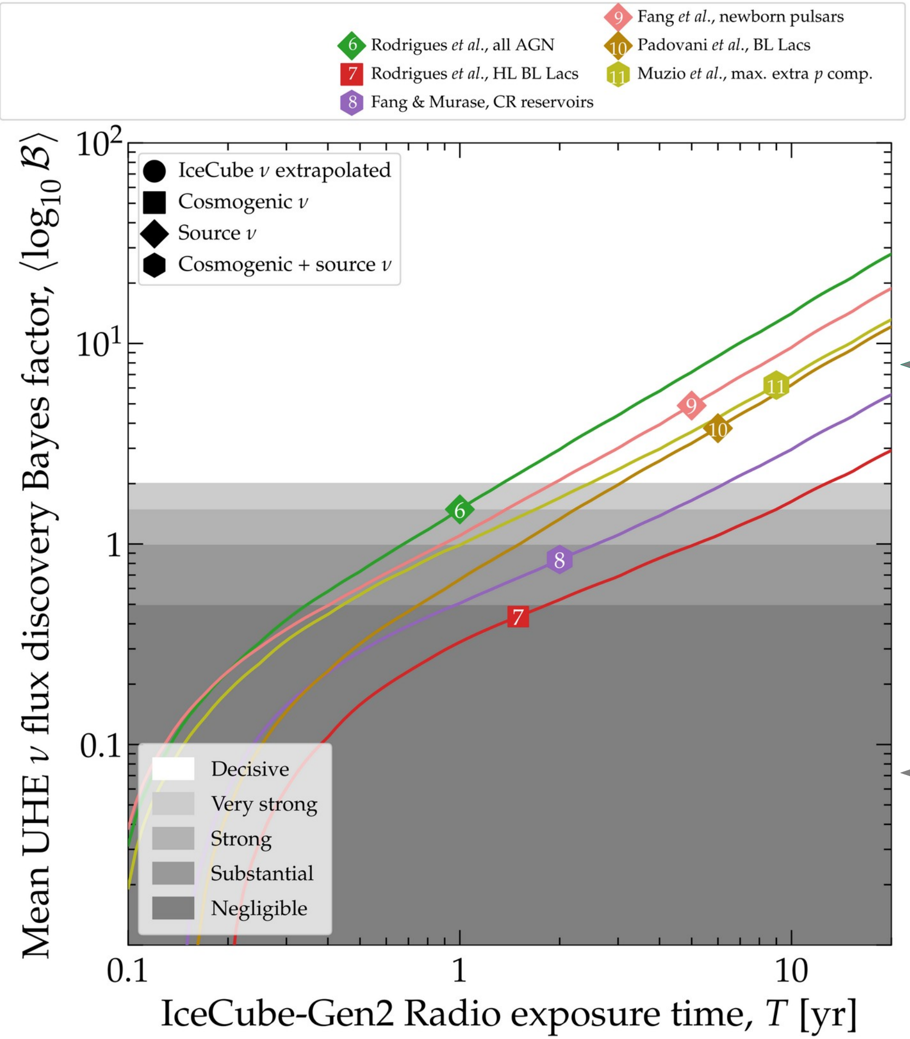

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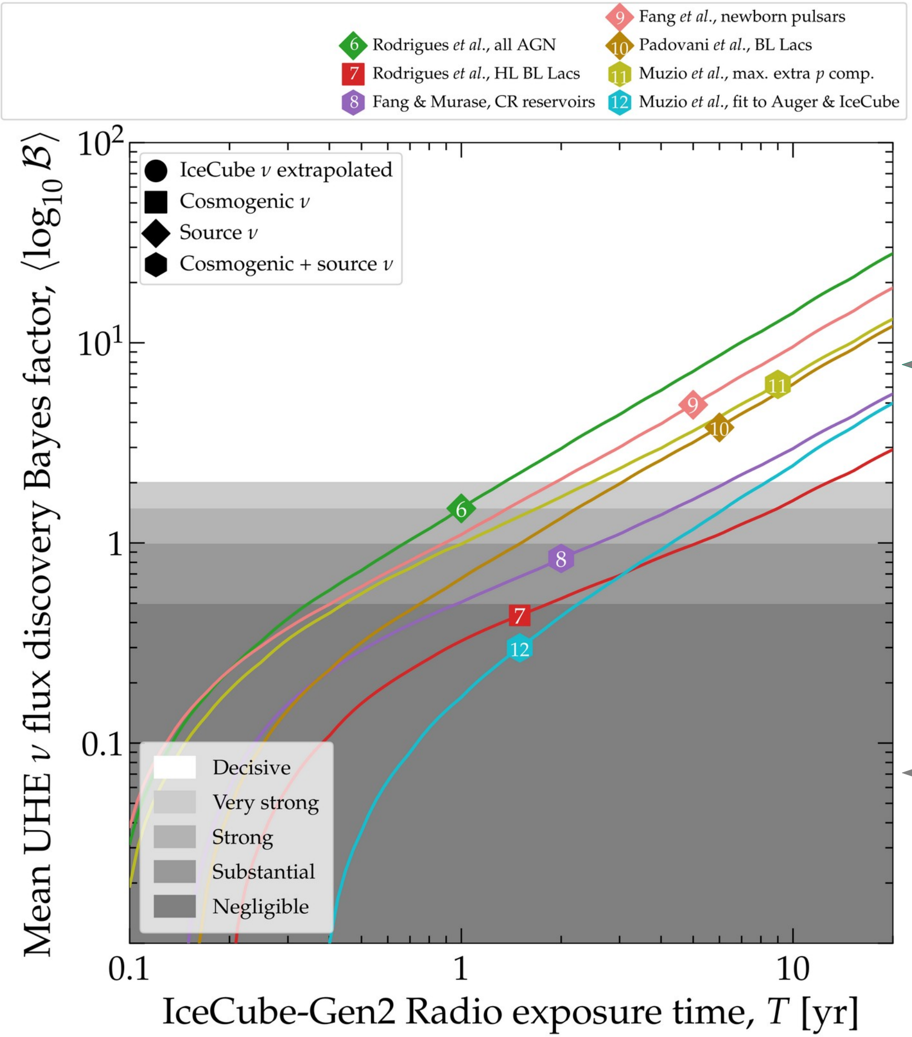

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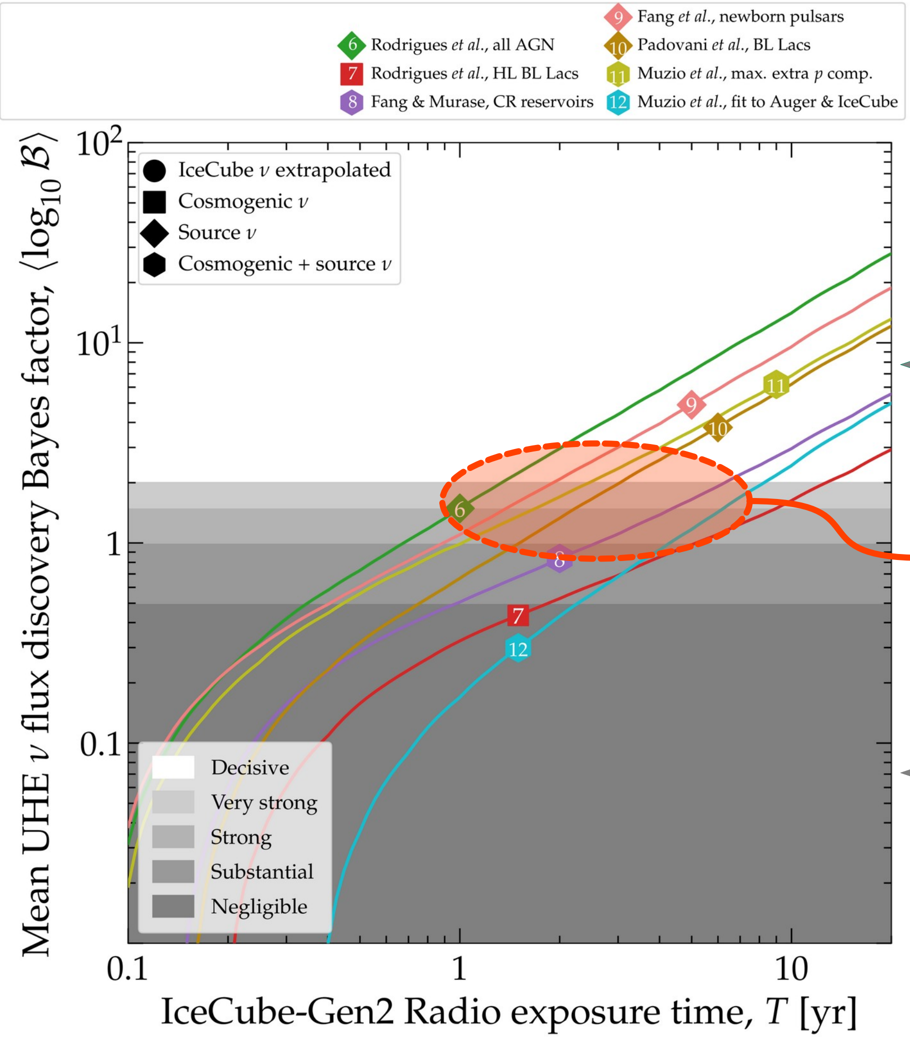


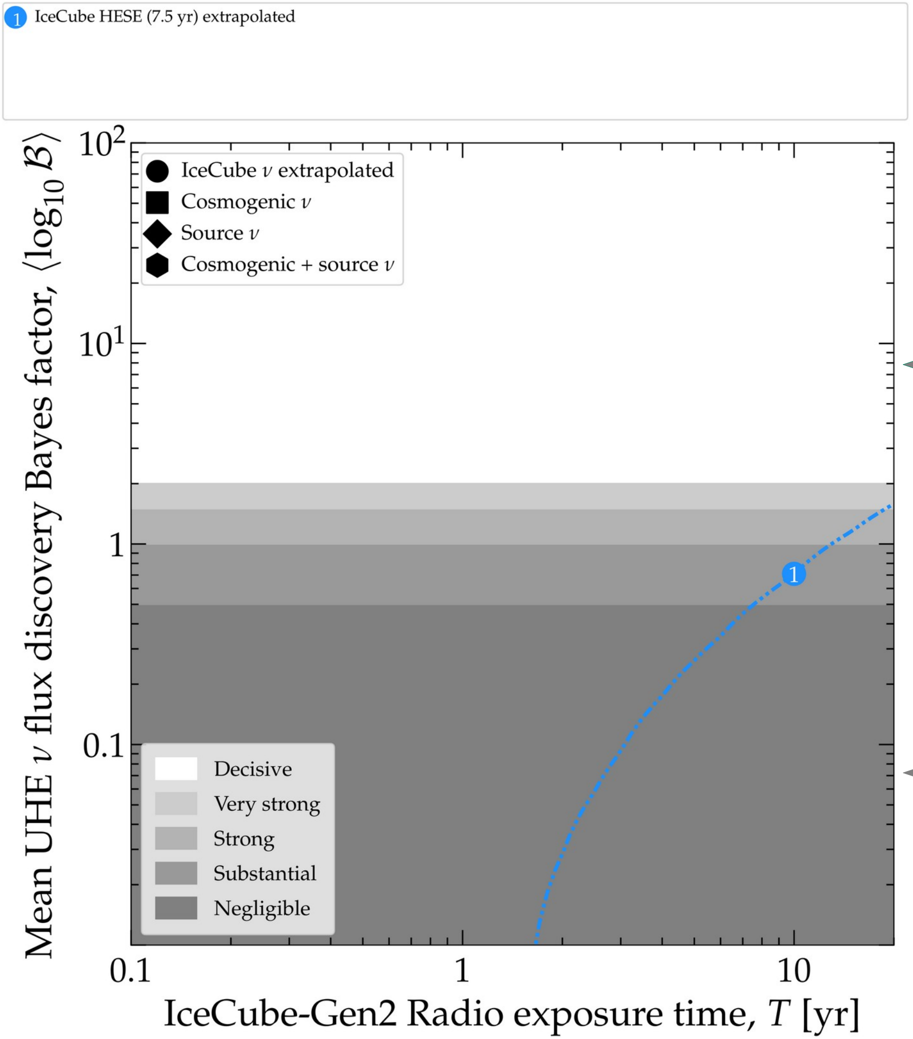
High Bayes factor → Decisive flux discovery

Most flux models are discoverable within a few years

Low Bayes factor → No flux discovered

Valera, **MB**, Glaser, *PRD* 2023 (to appear) [2210.03756]

Discovering the diffuse flux of UHE neutrinos



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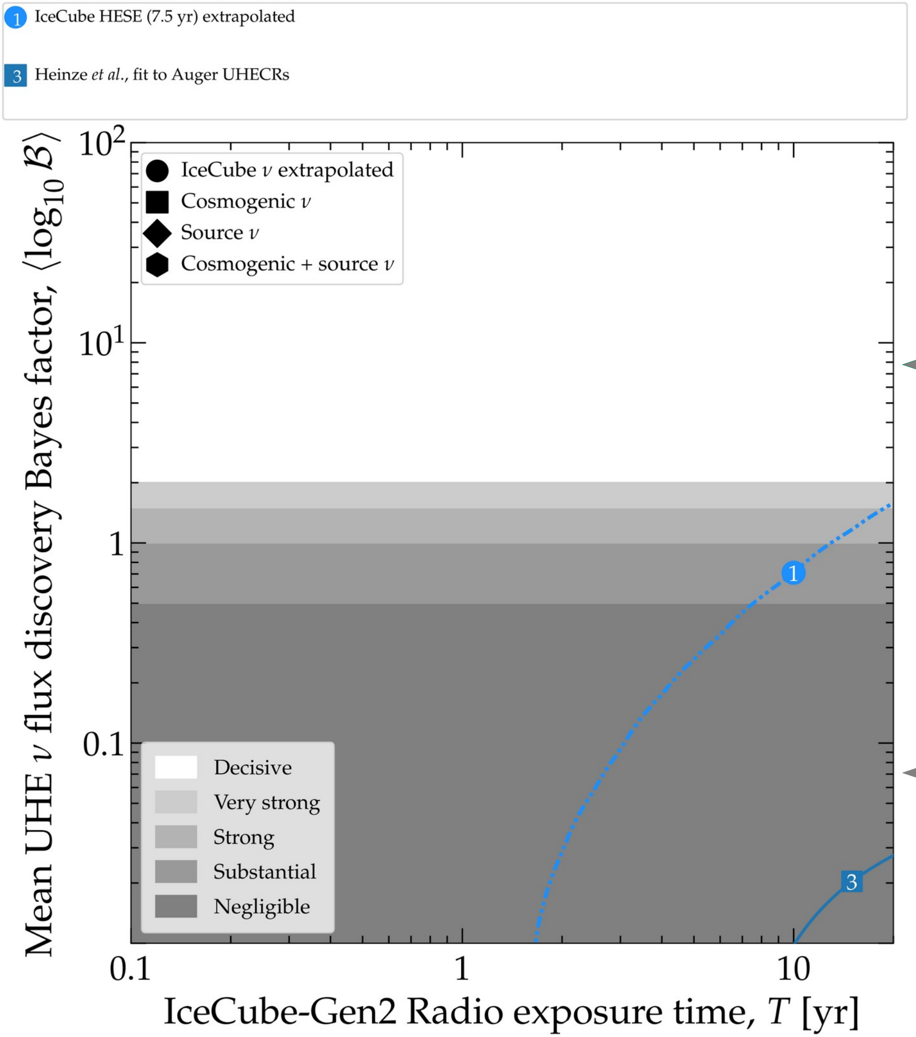

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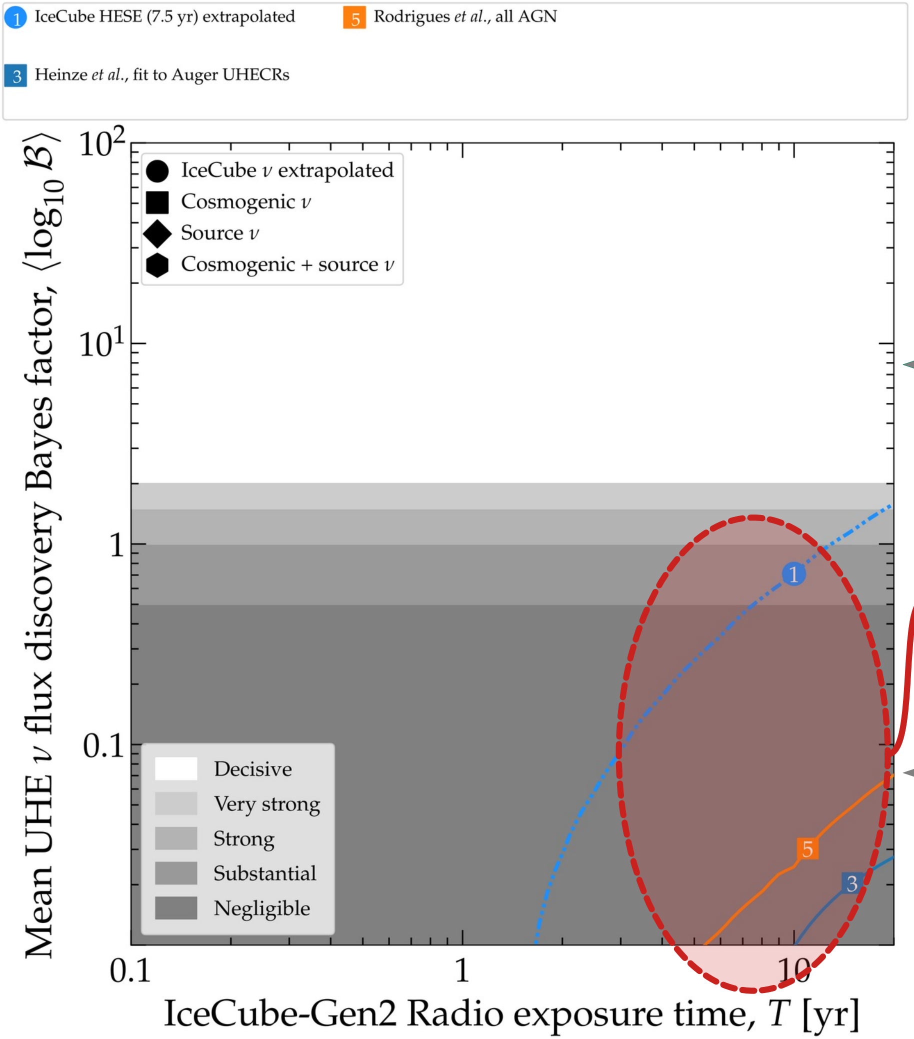

High Bayes factor
→ Decisive flux discovery

Some models will
not be discovered

Low Bayes factor
→ No flux discovered

Valera, **MB**, Glaser,
PRD 2023 (to appear) [2210.03756]

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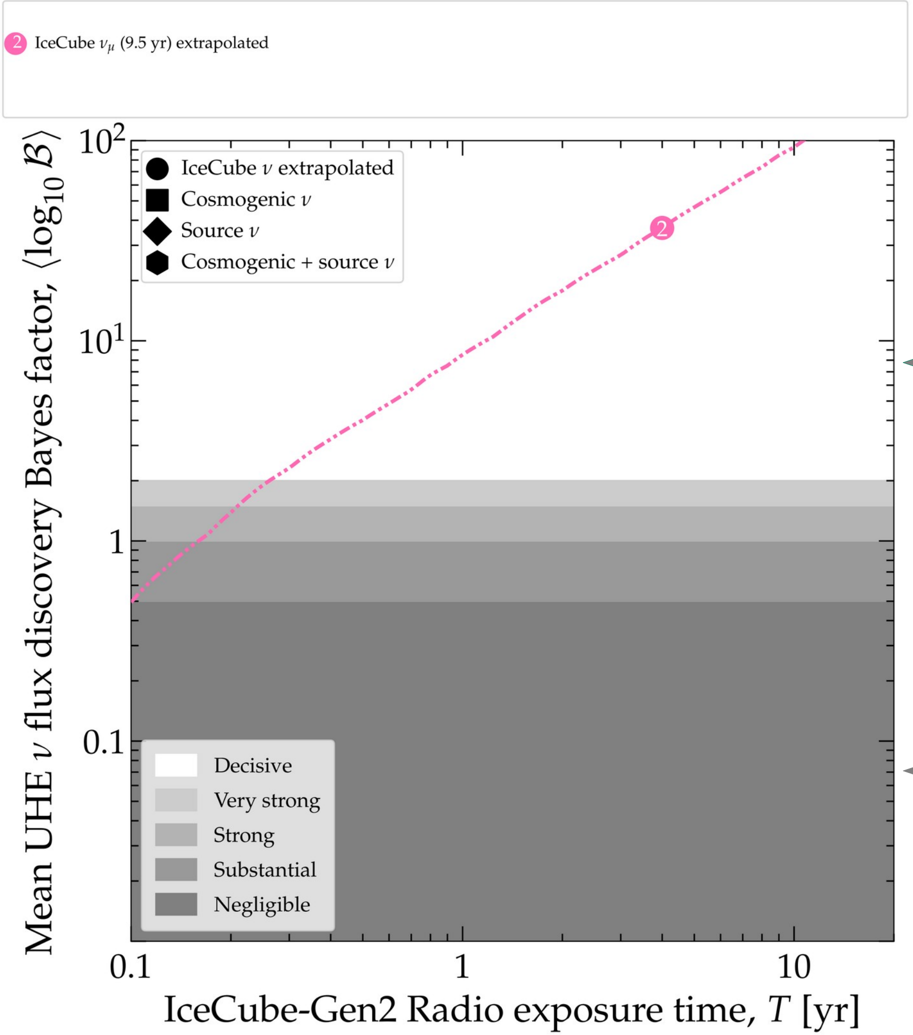

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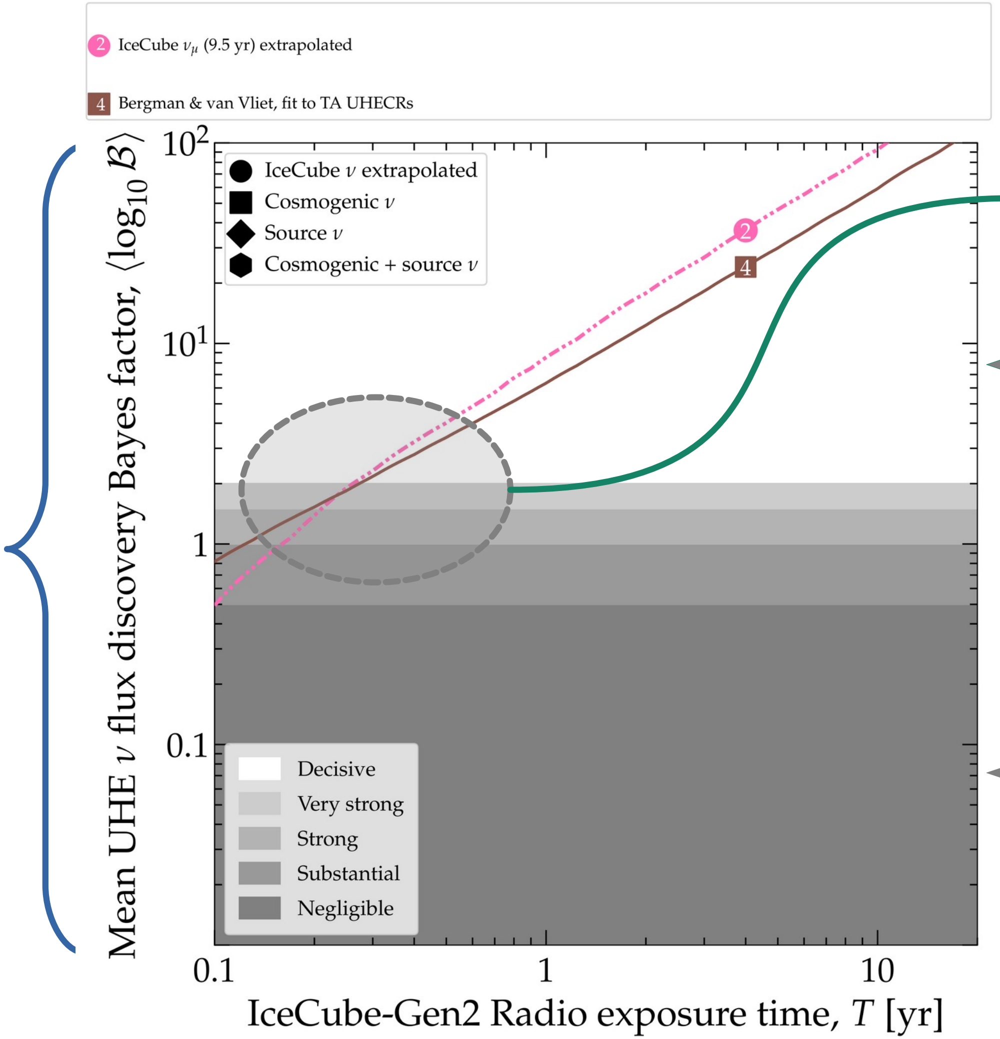

Some models will be discovered right away

High Bayes factor
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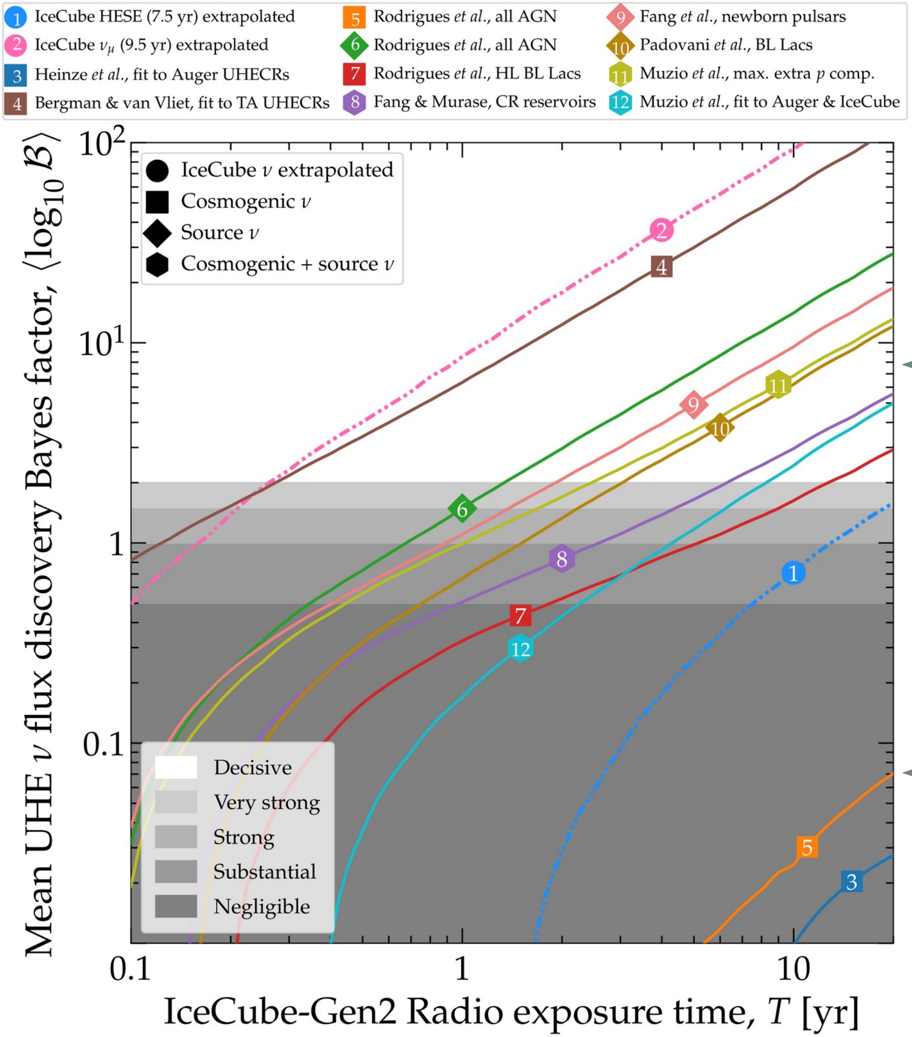

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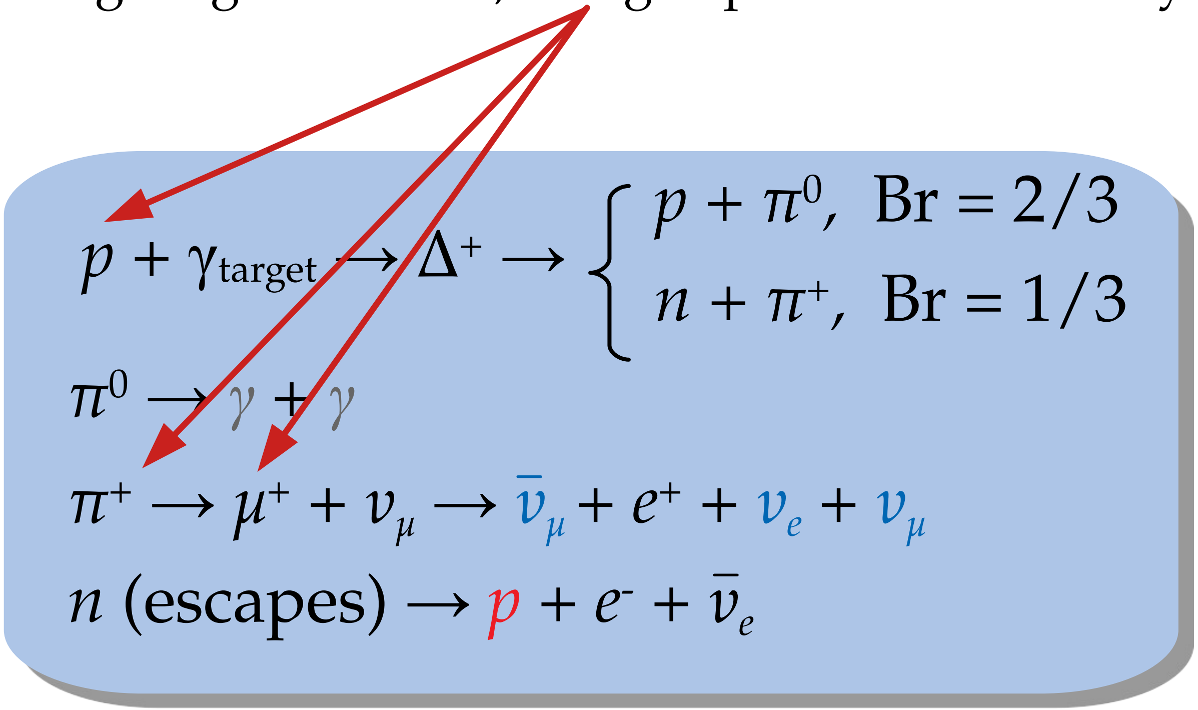
Valera, **MB**, Glaser,
PRD 2023 [2210.03756]

Using high-energy neutrinos as magnetometers

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



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

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

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

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

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

Using high-energy neutrinos as magnetometers

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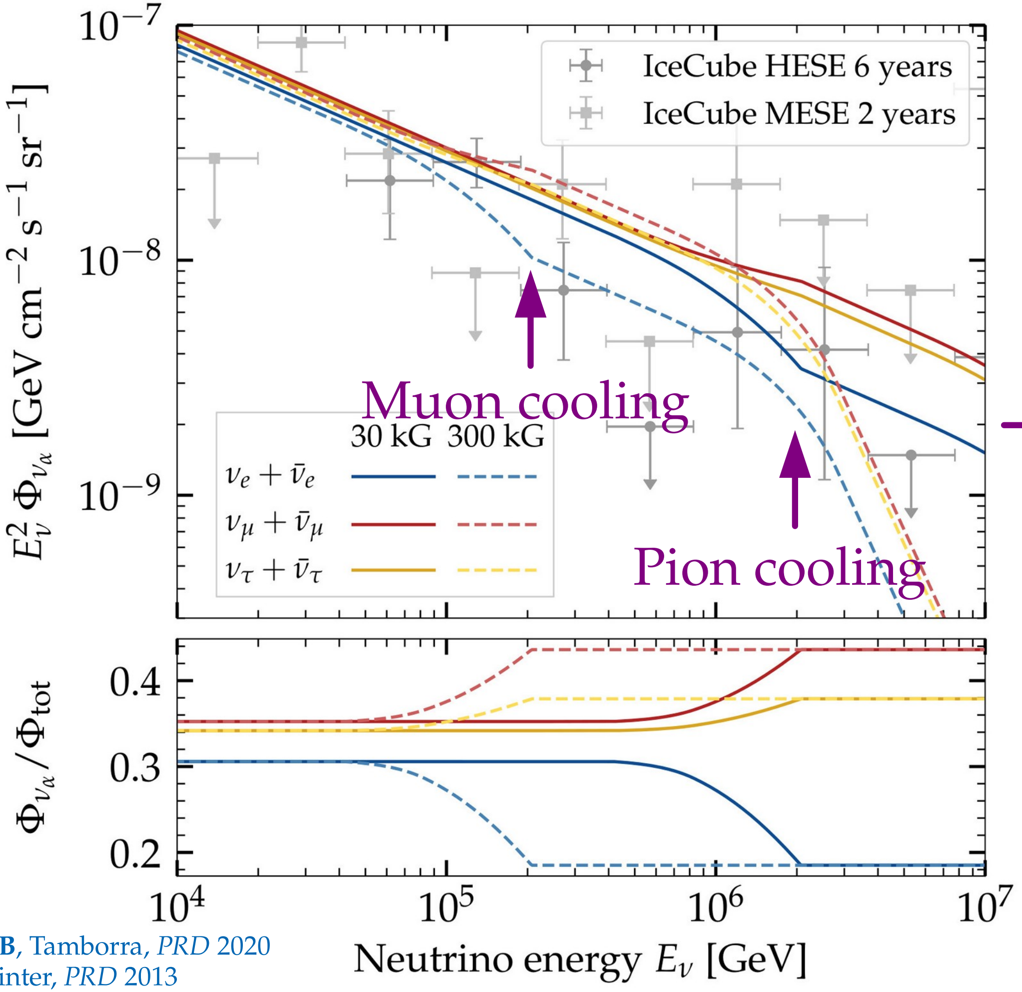

Muon cooling

Pion cooling

Proton cooling

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

Using high-energy neutrinos as magnetometers

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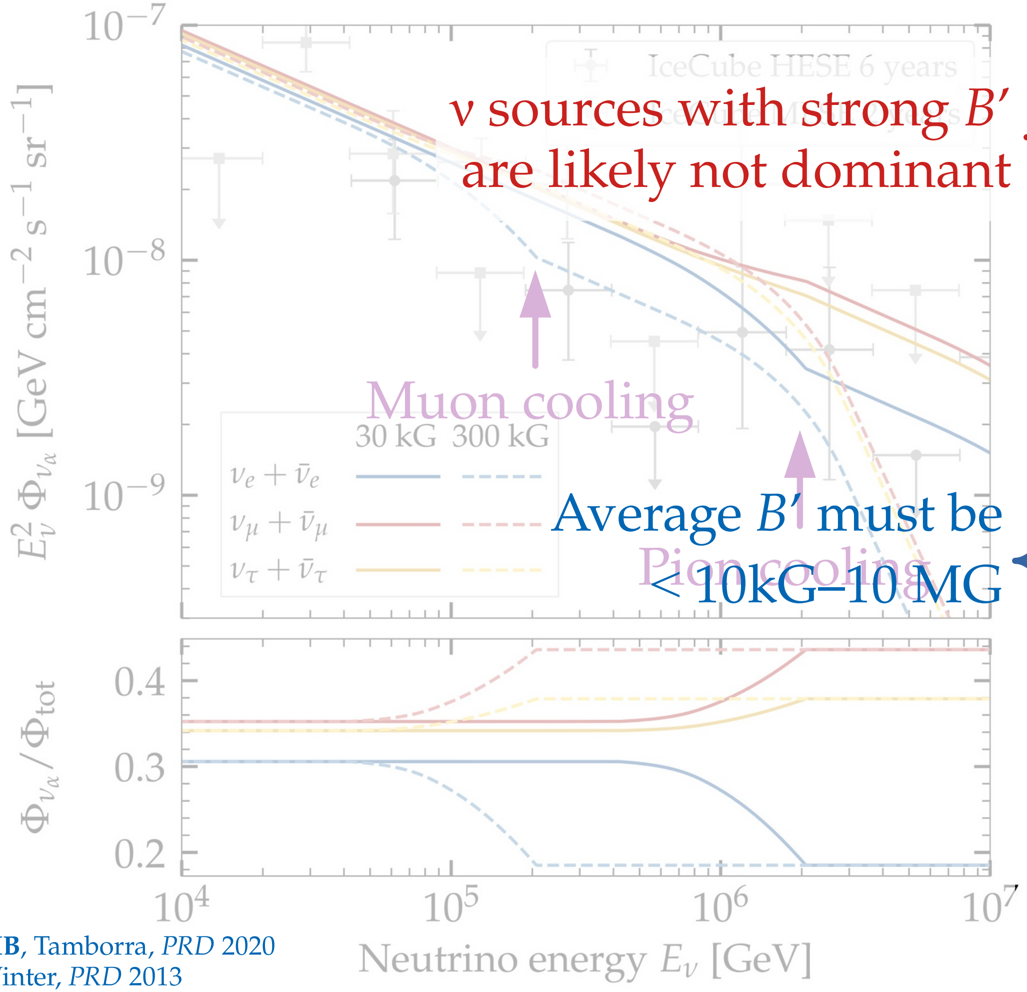
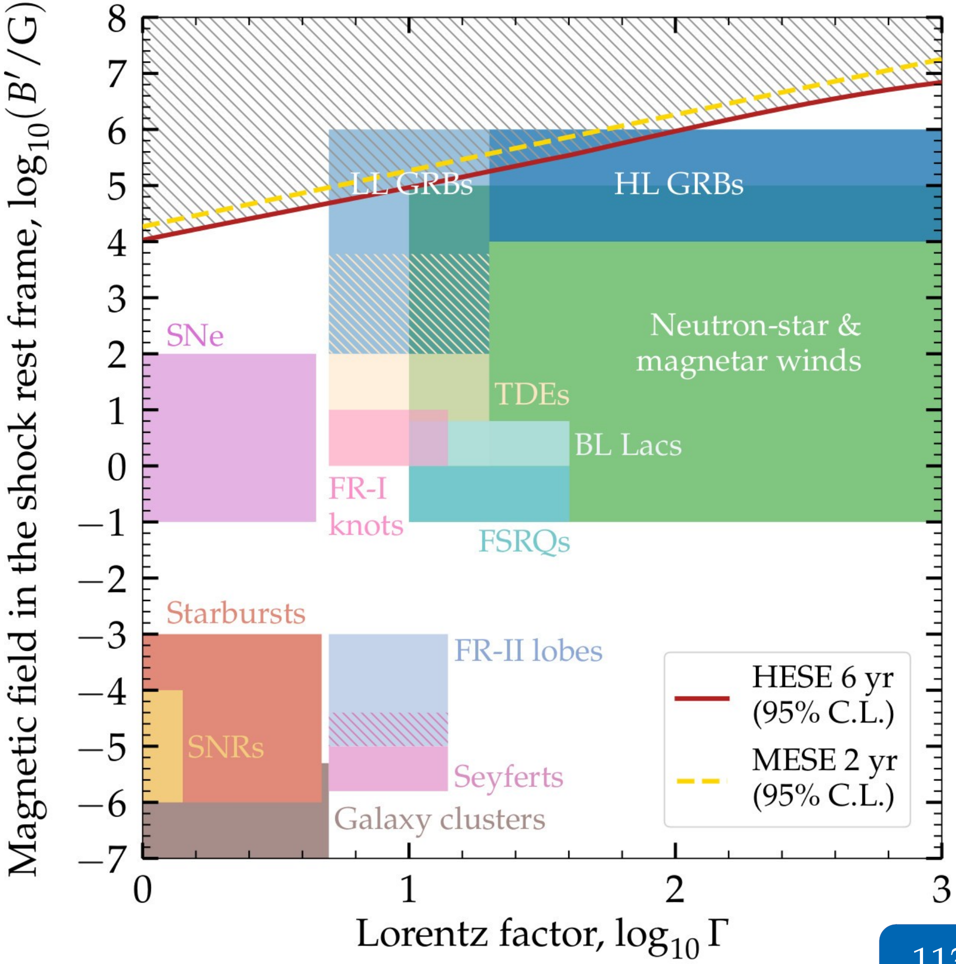


ν sources with strong B' are likely not dominant

Average B' must be $<$ 10kG–10 MG



MB, Tamborra, *PRD* 2020
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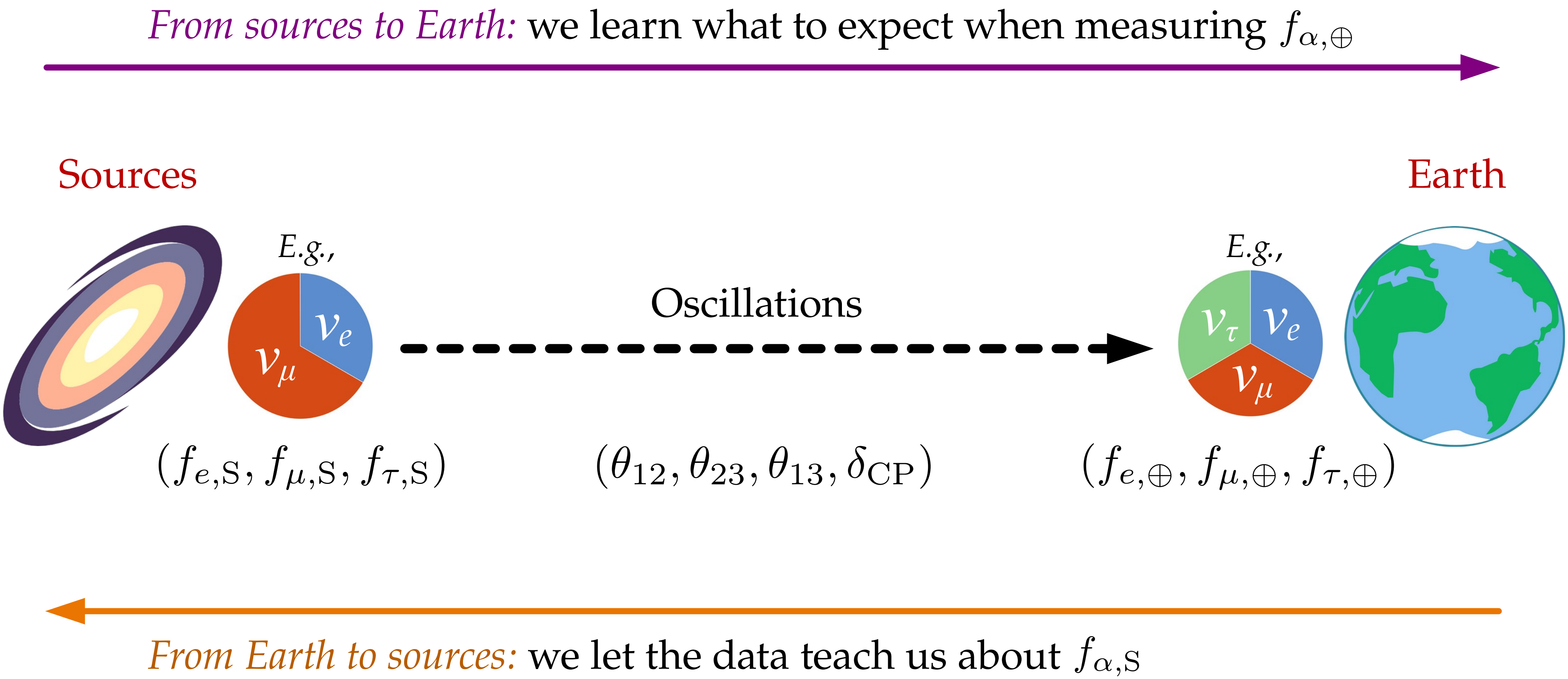


From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$

Sources

E.g.,

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

Oscillations

$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$

Earth

E.g.,

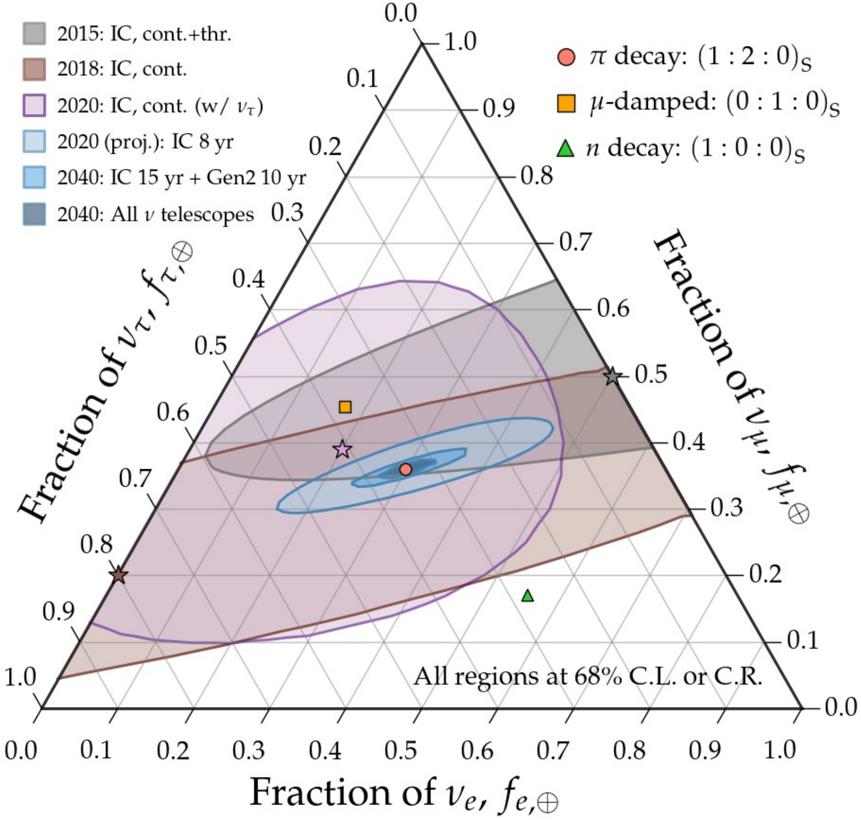
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

From Earth to sources: we let the data teach us about $f_{\alpha,\mathrm{S}}$

Inferring the flavor composition at the sources

Ingredient #1:

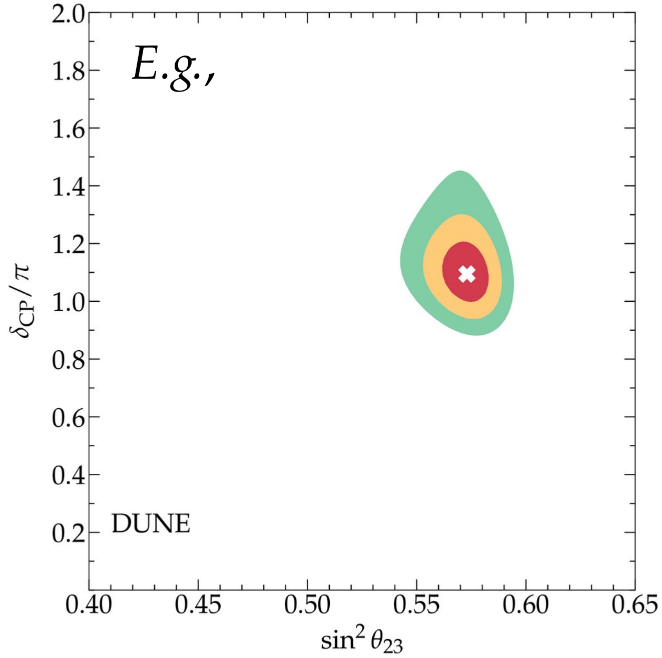
Flavor ratios measured at Earth, $(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$



Ingredient #2:

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

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



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

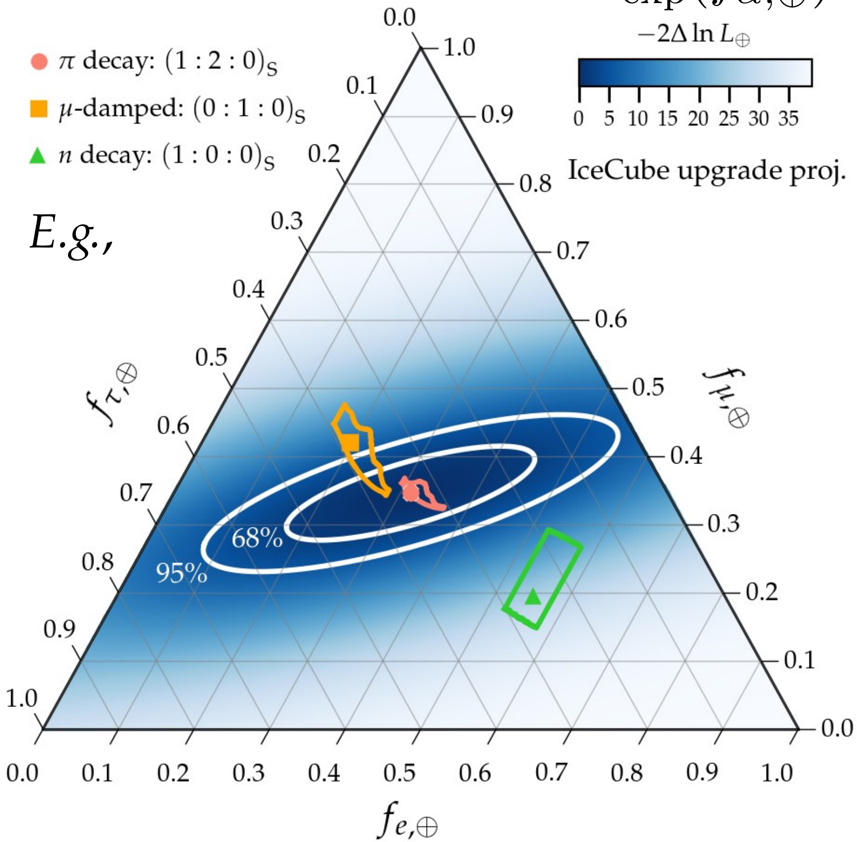
Inferring the flavor composition at the sources

Ingredient #1:

Flavor ratios measured at Earth,

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

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



E.g.,

Ingredient #2:

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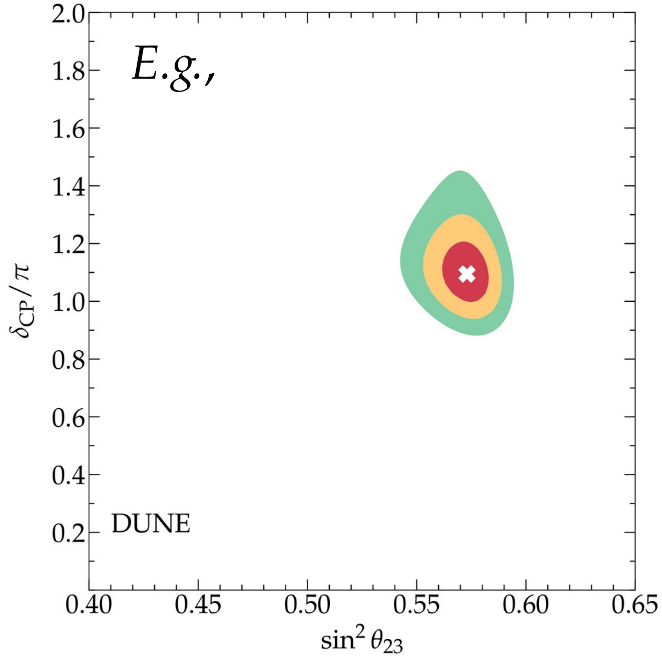

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Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
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Inferring the flavor composition at the sources

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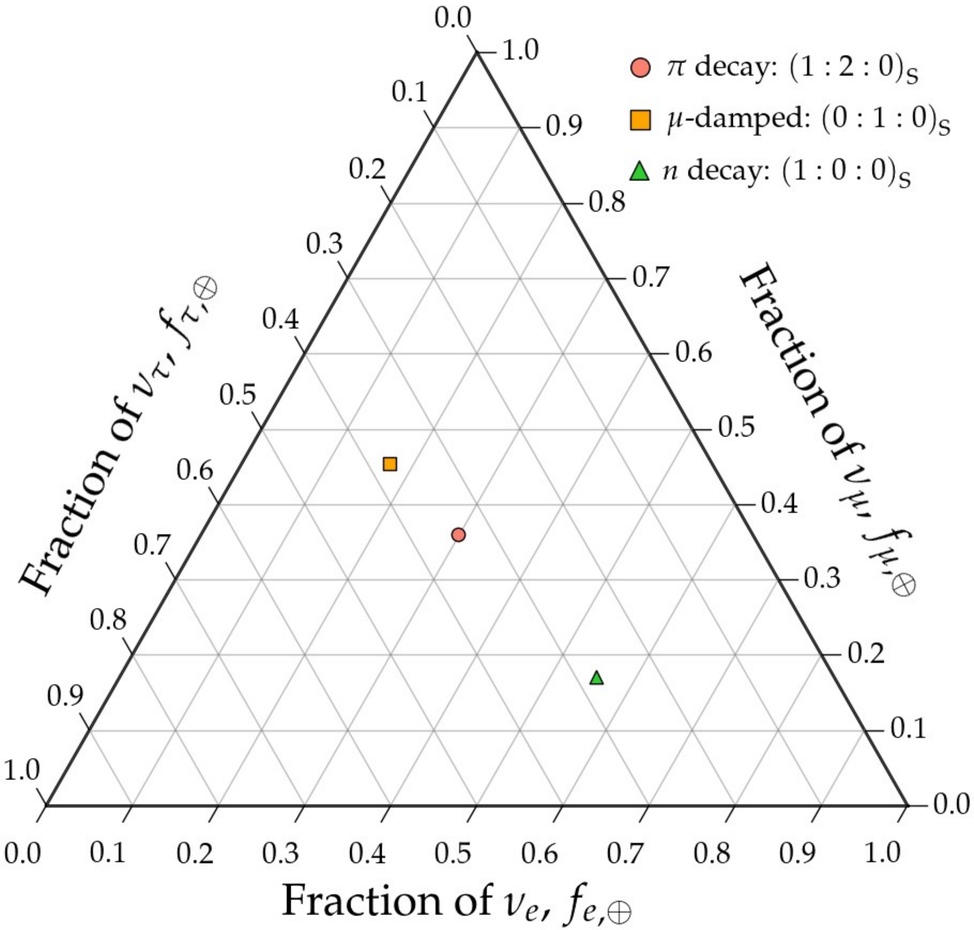

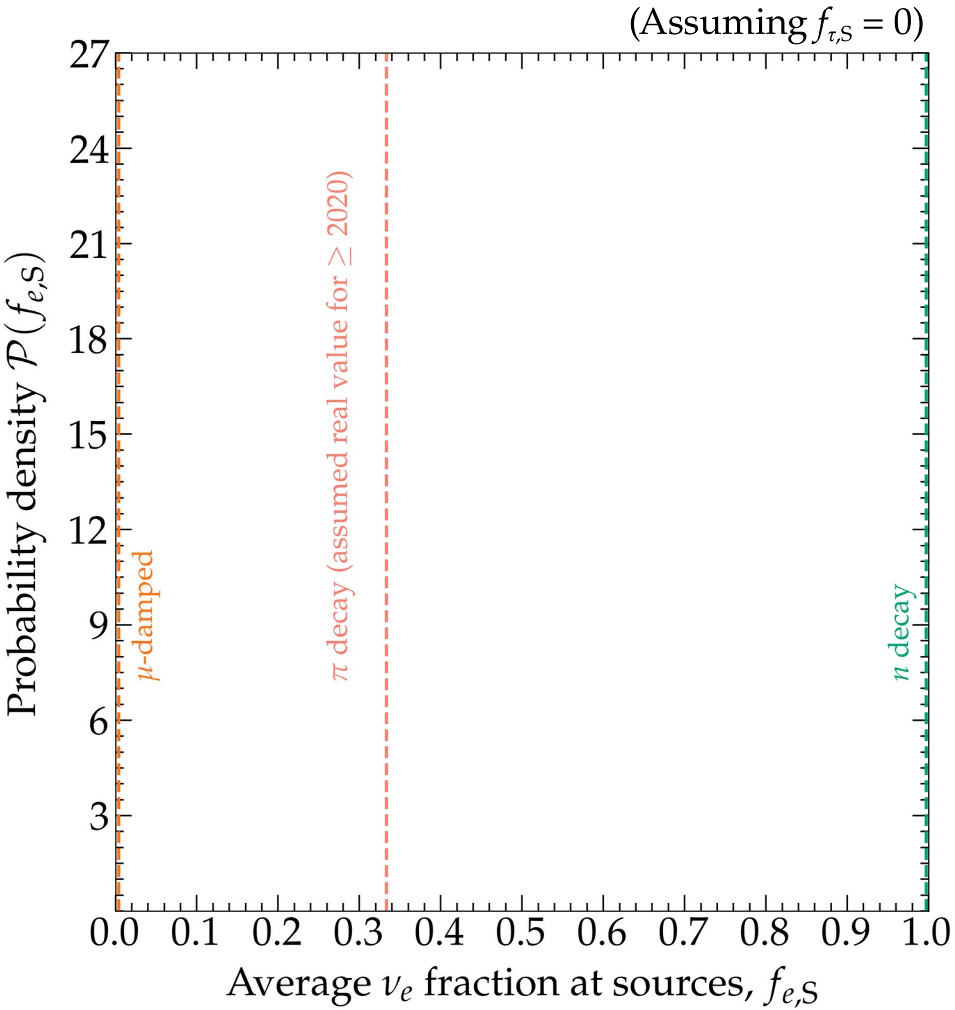

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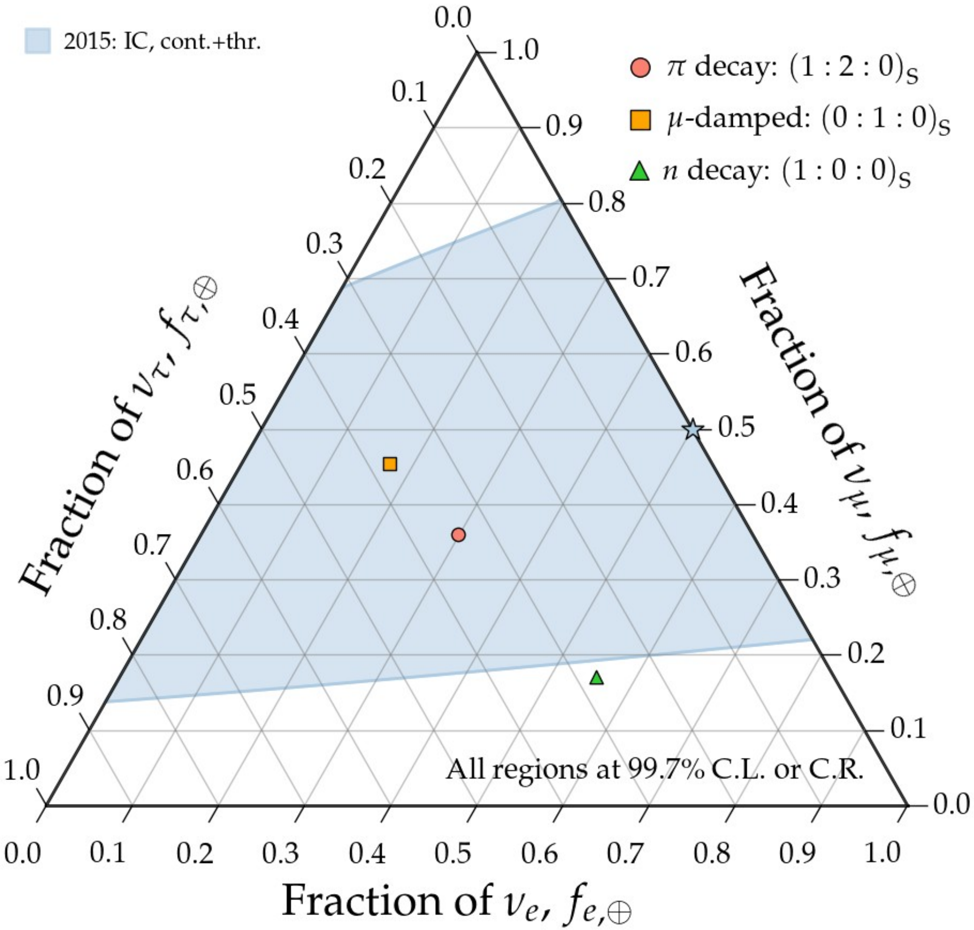

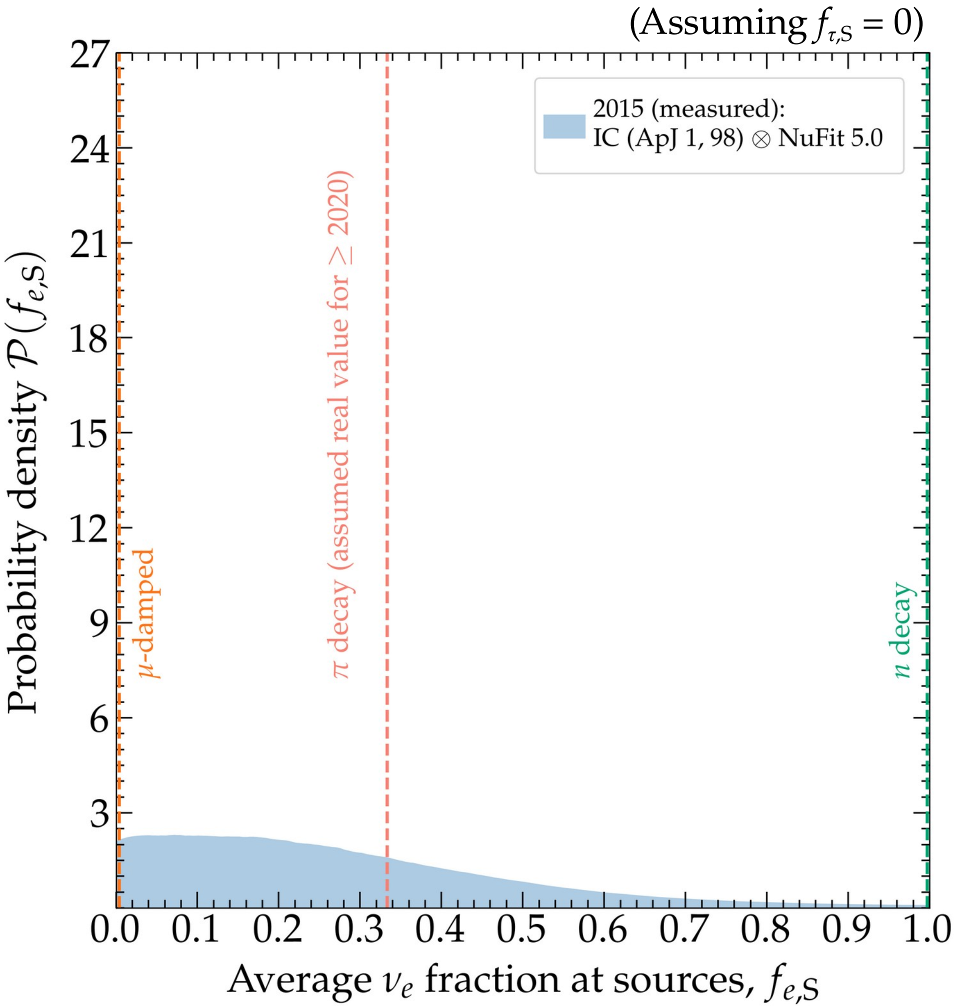

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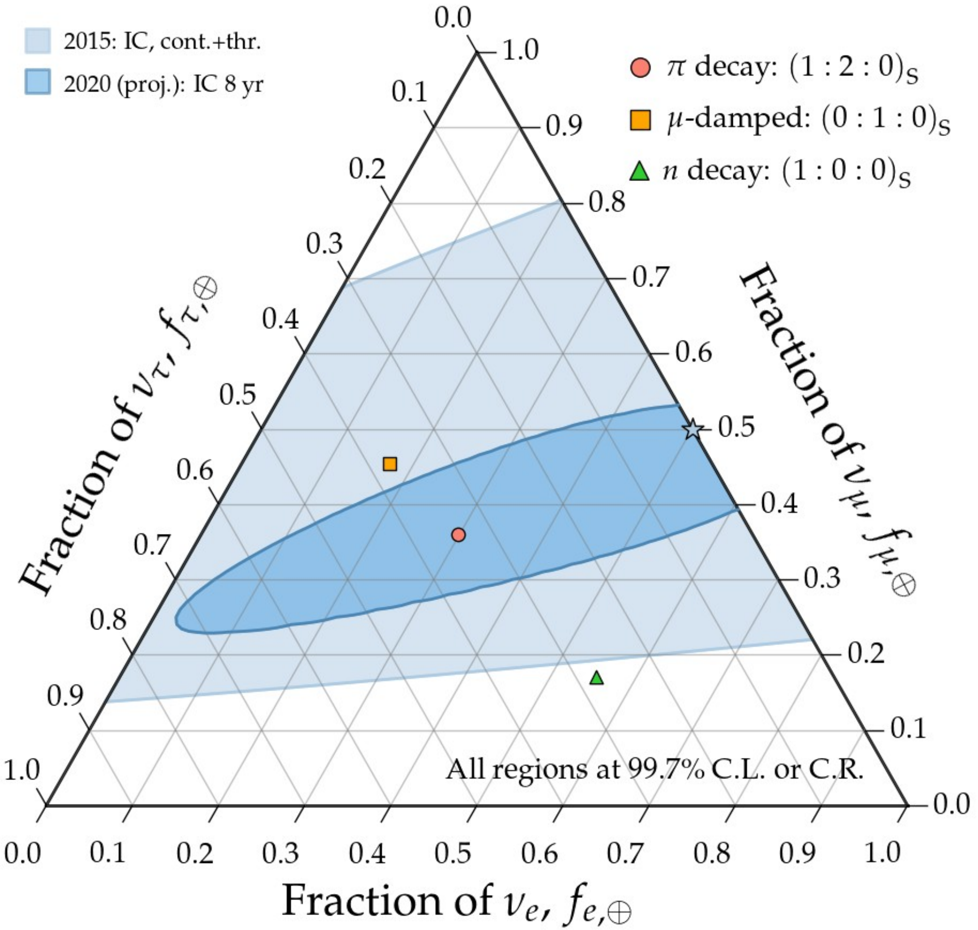
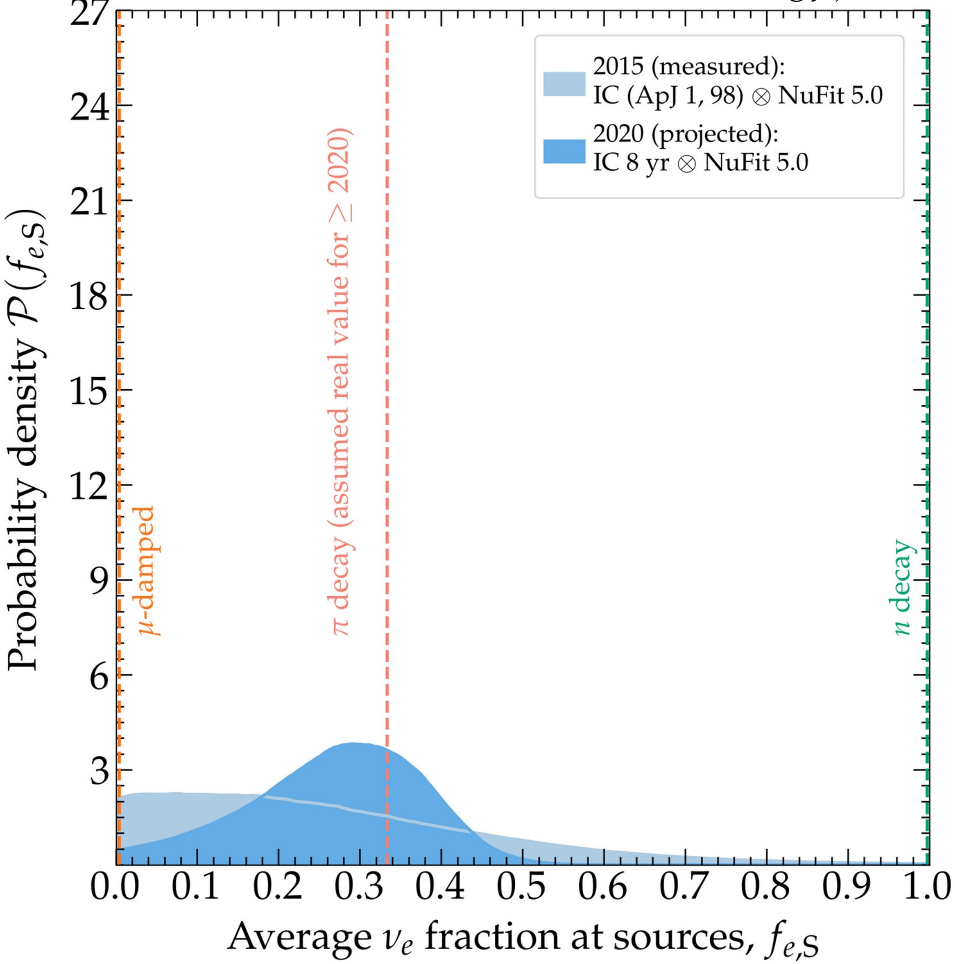


(Assuming $f_{\tau,\mathrm{S}} = 0$)



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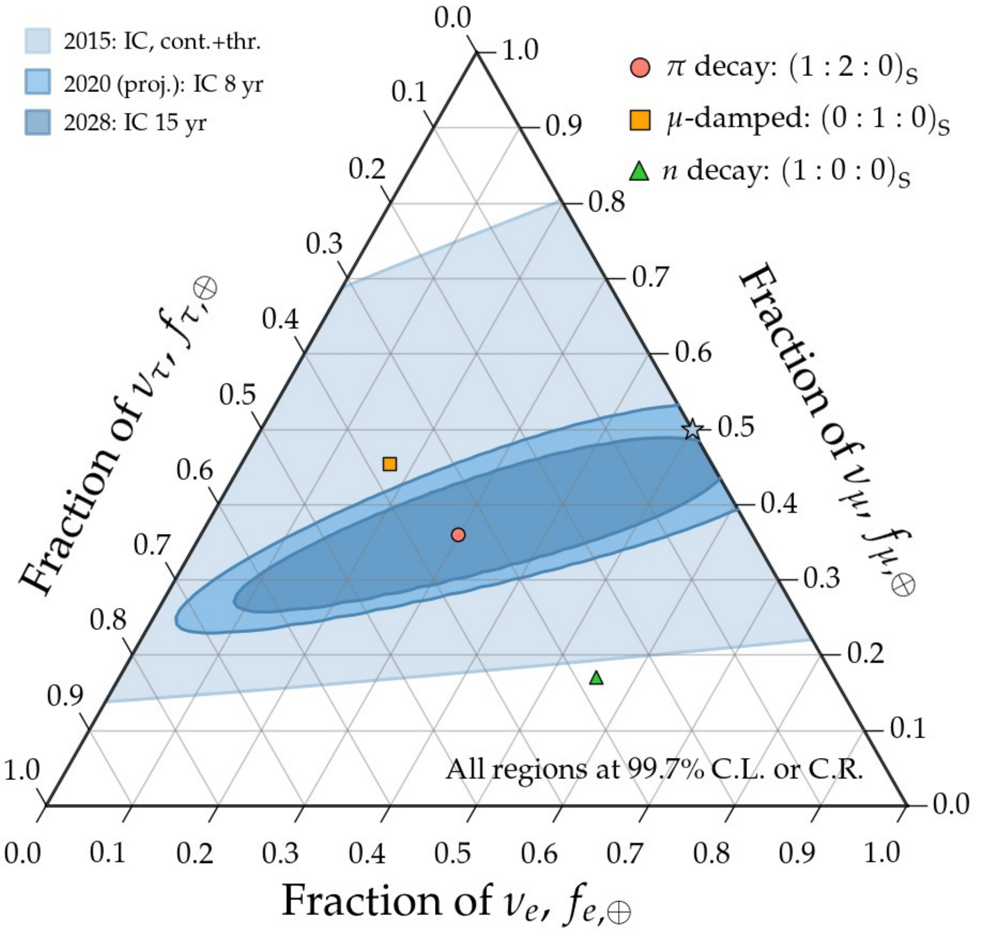

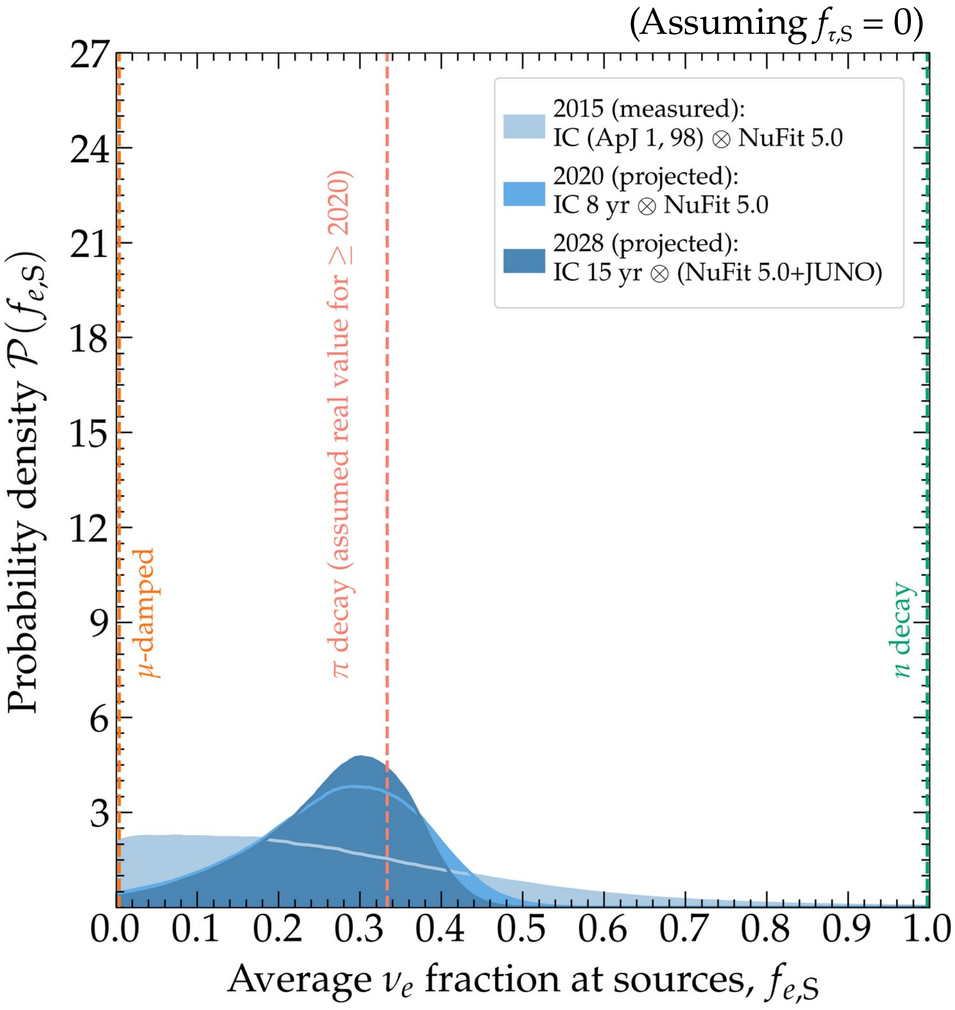

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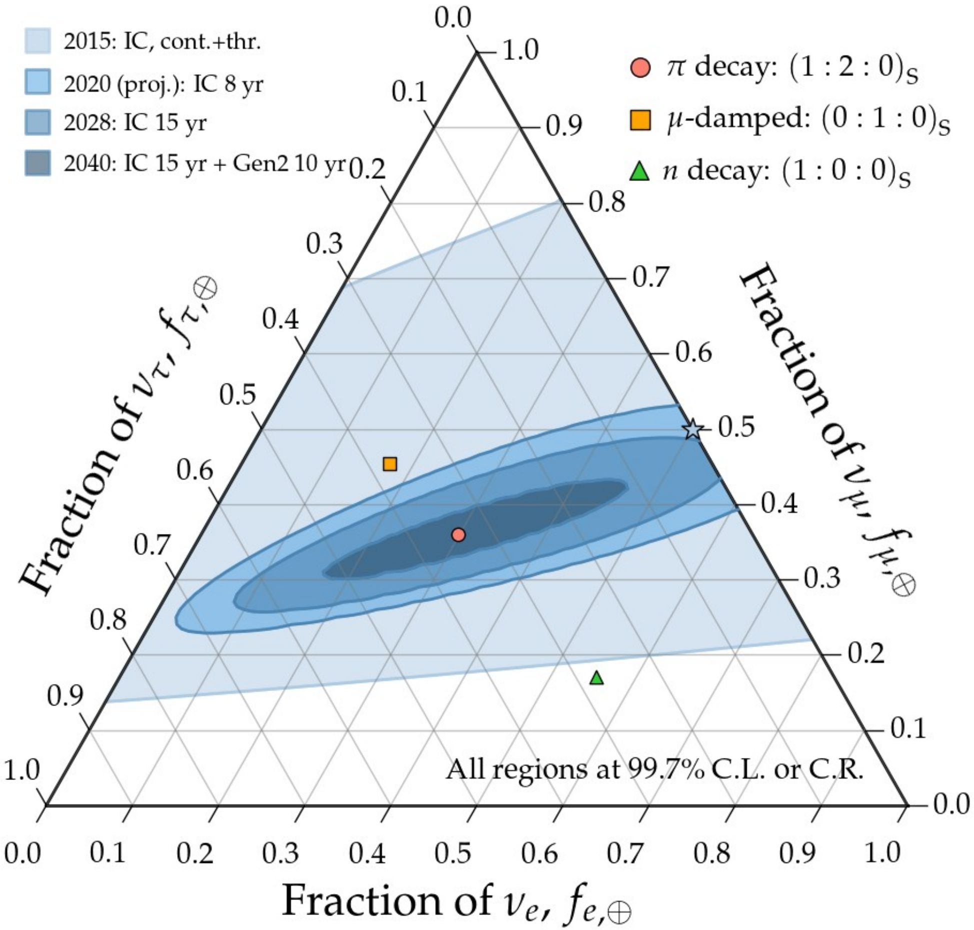

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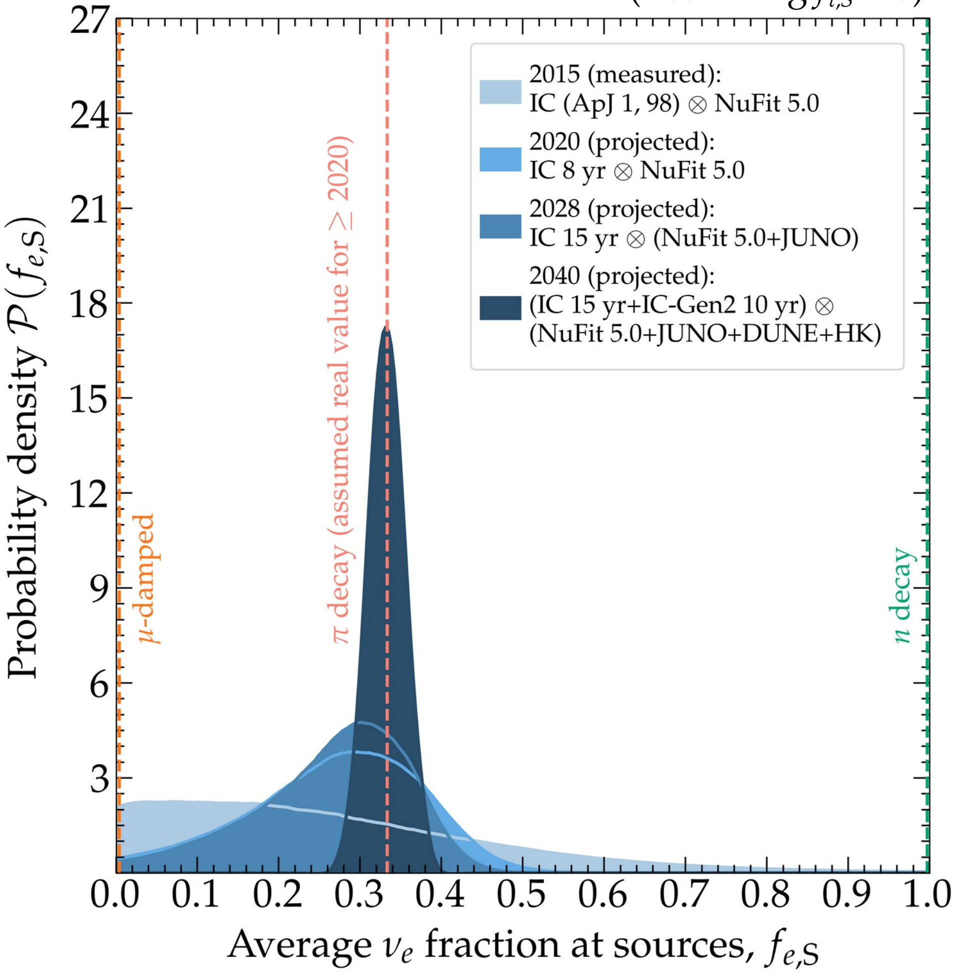

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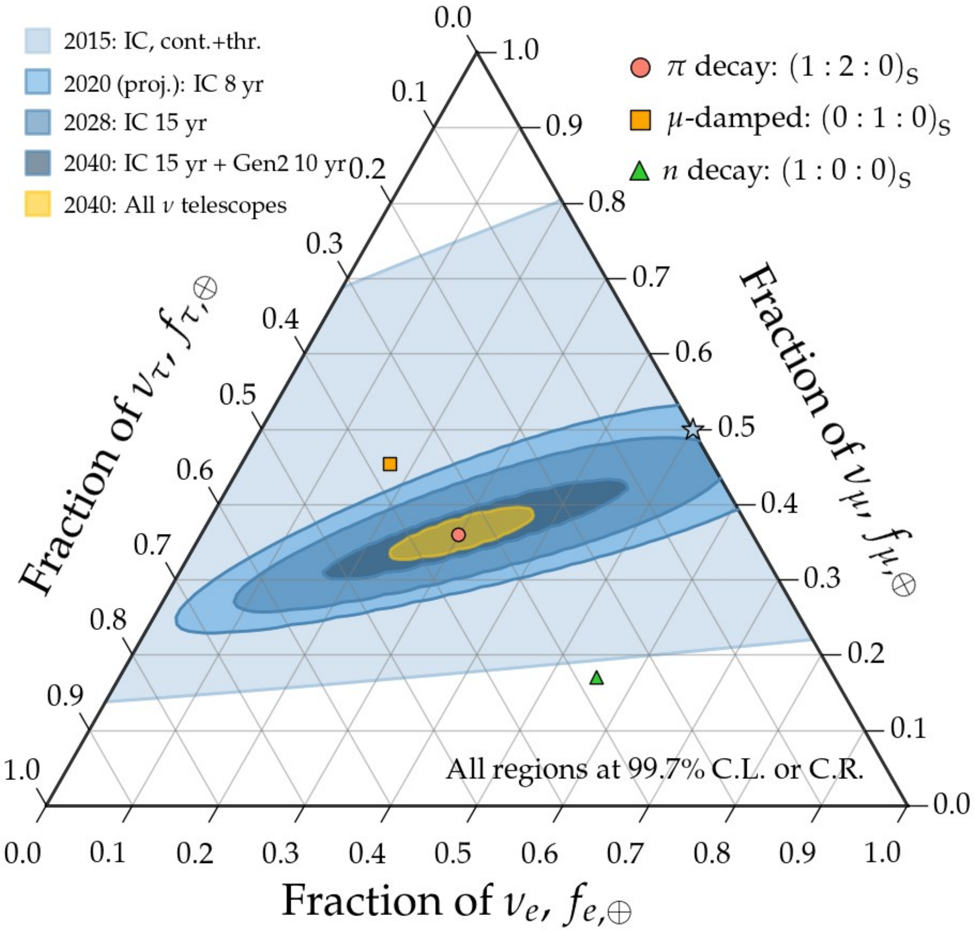

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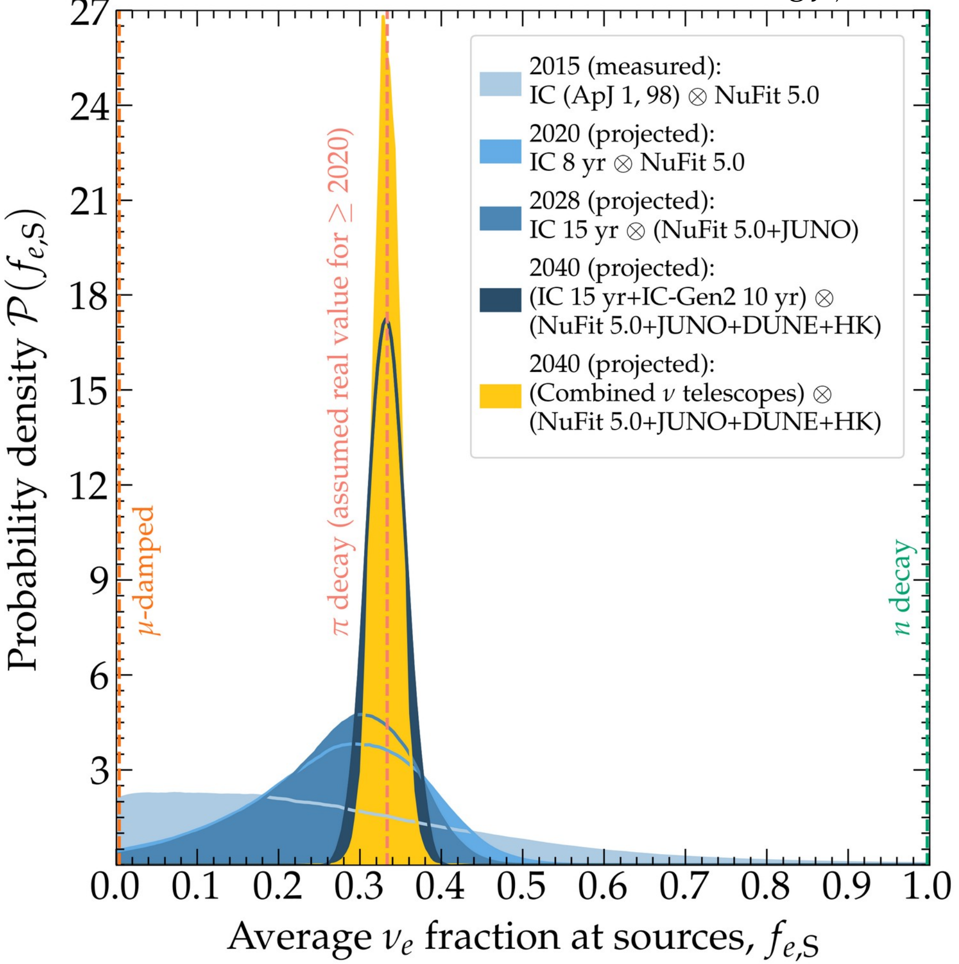

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