

Neutrino physics at the cosmic and energy frontiers

Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

Science Coffee

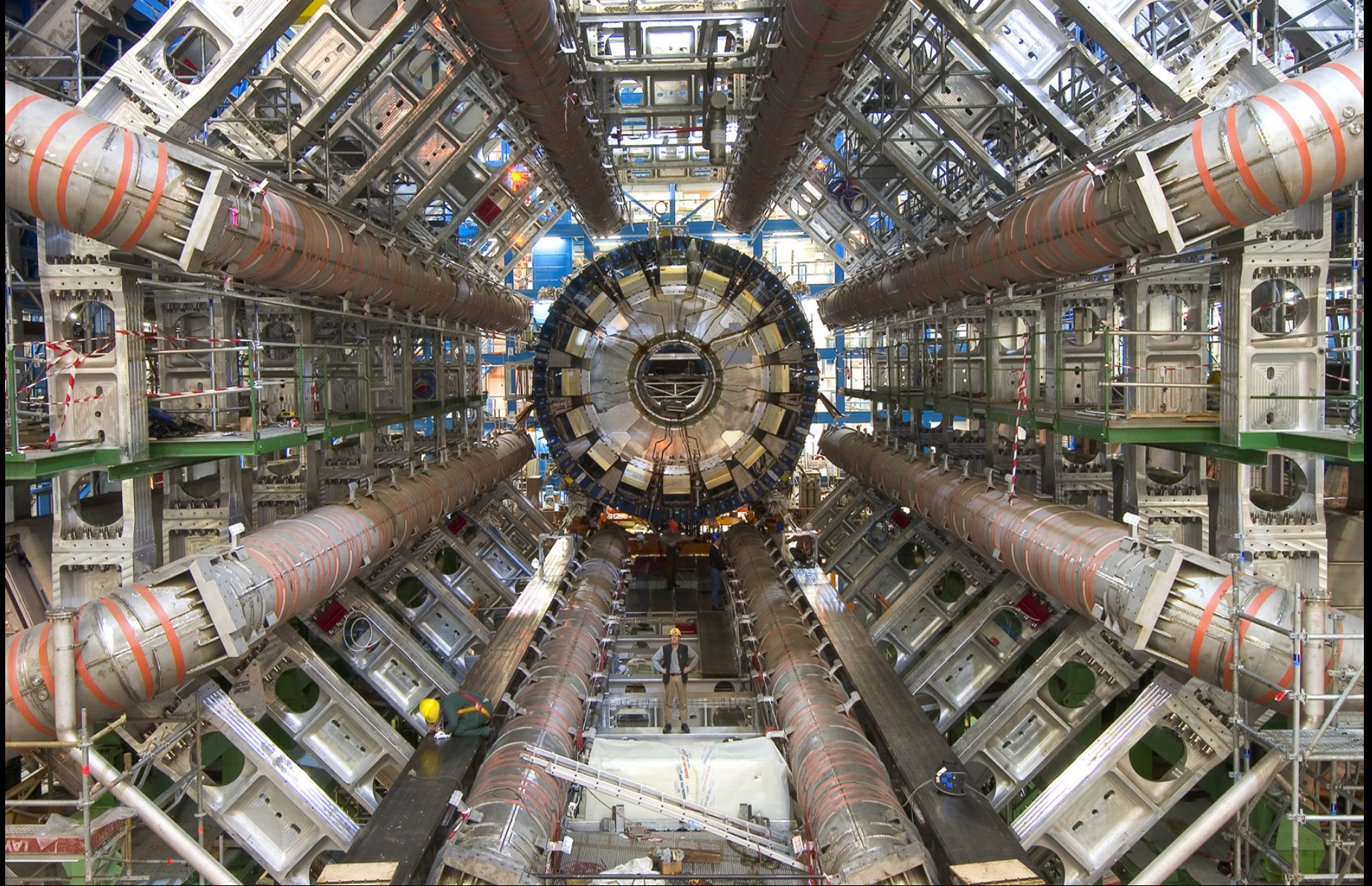
Lund University, May 20, 2025

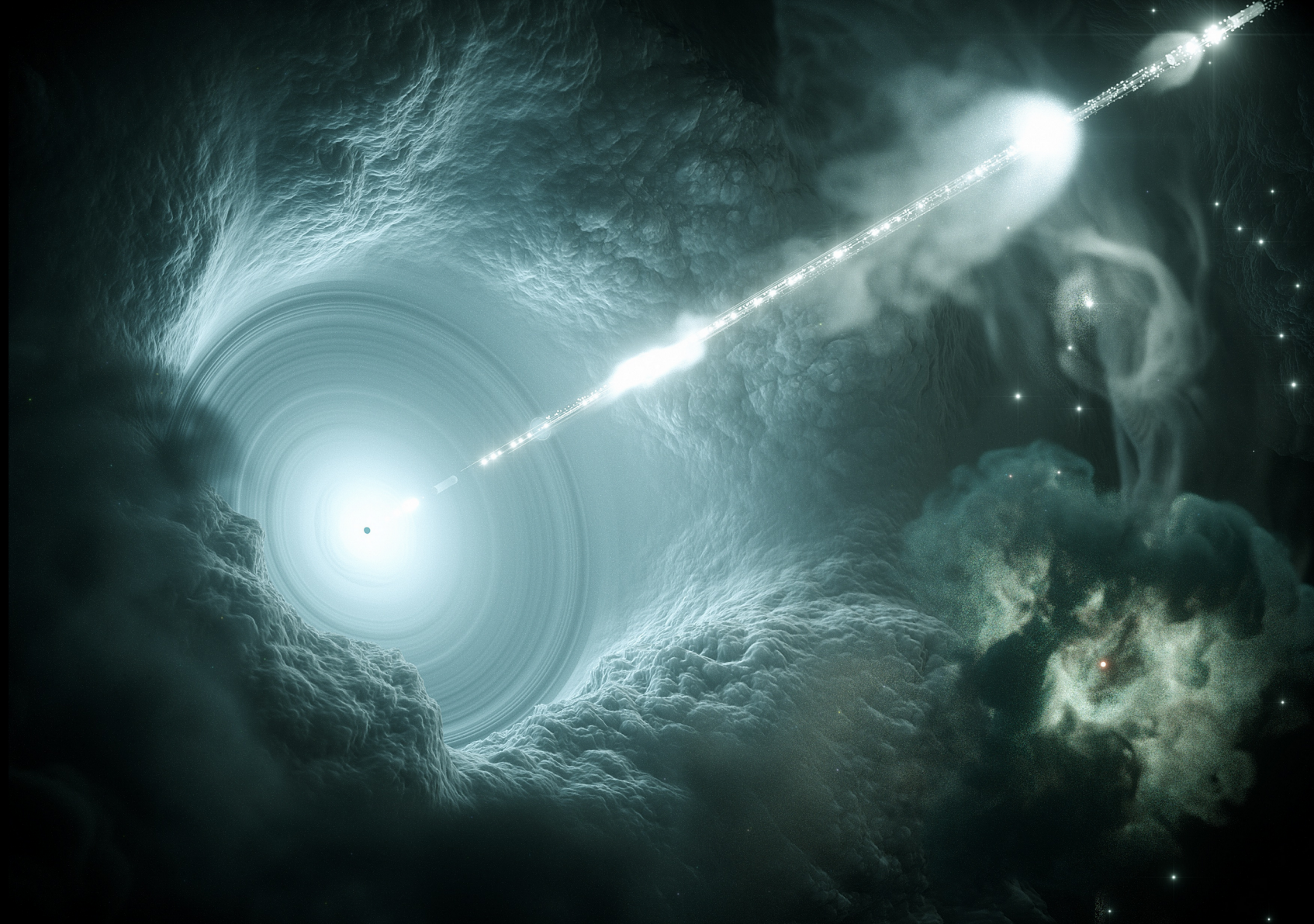
UNIVERSITY OF
COPENHAGEN

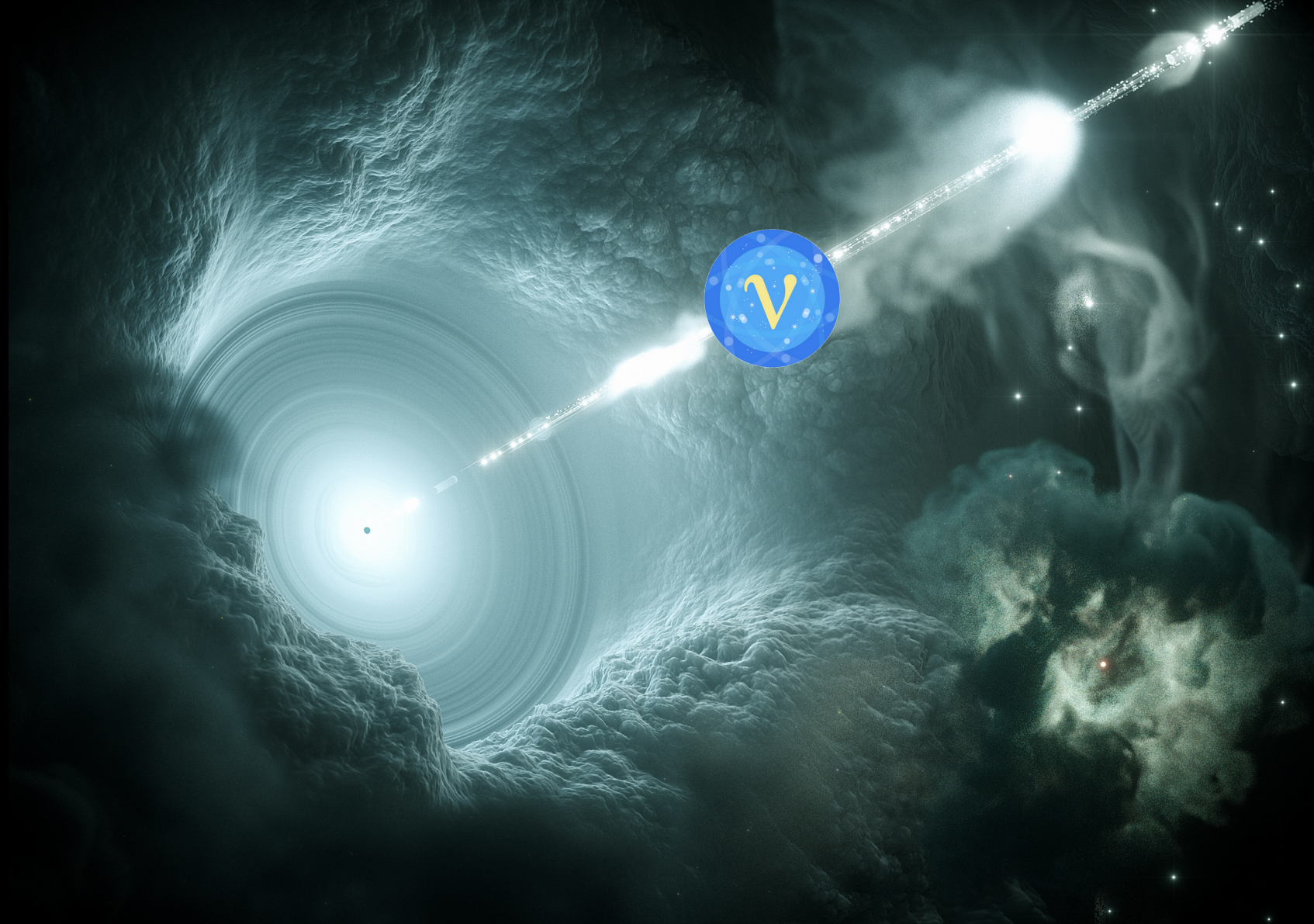


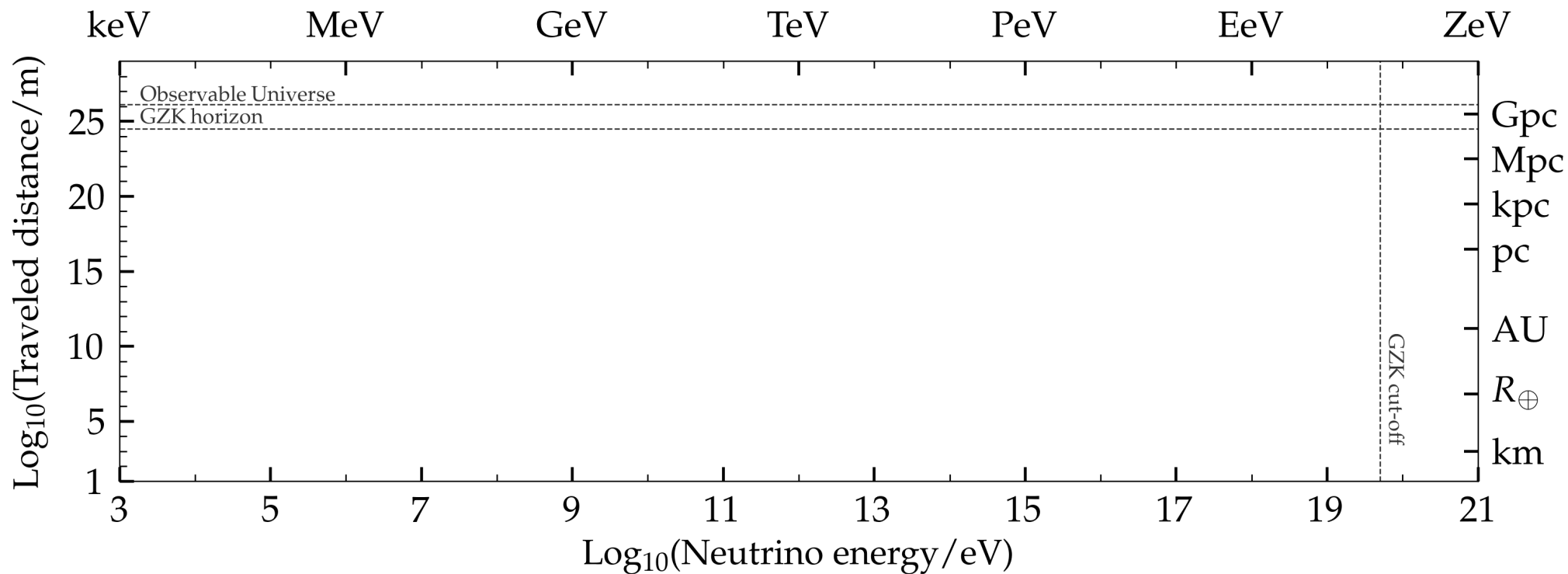
VILLUM FONDEN

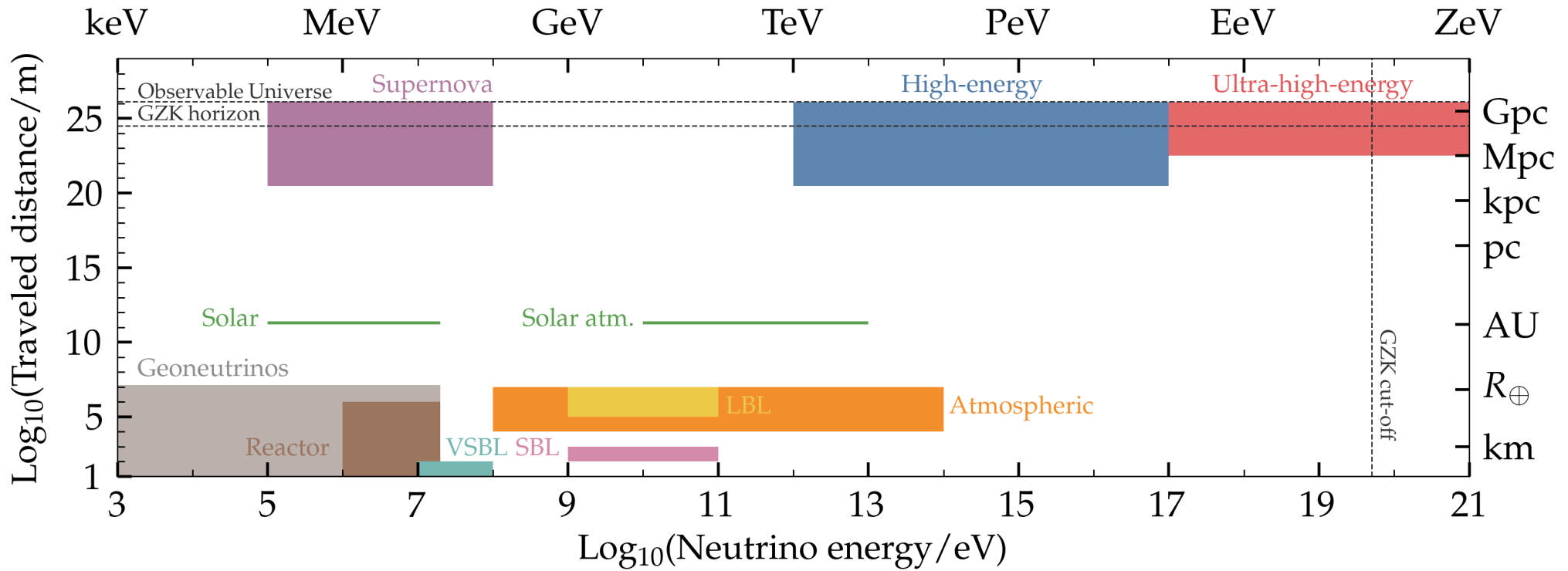




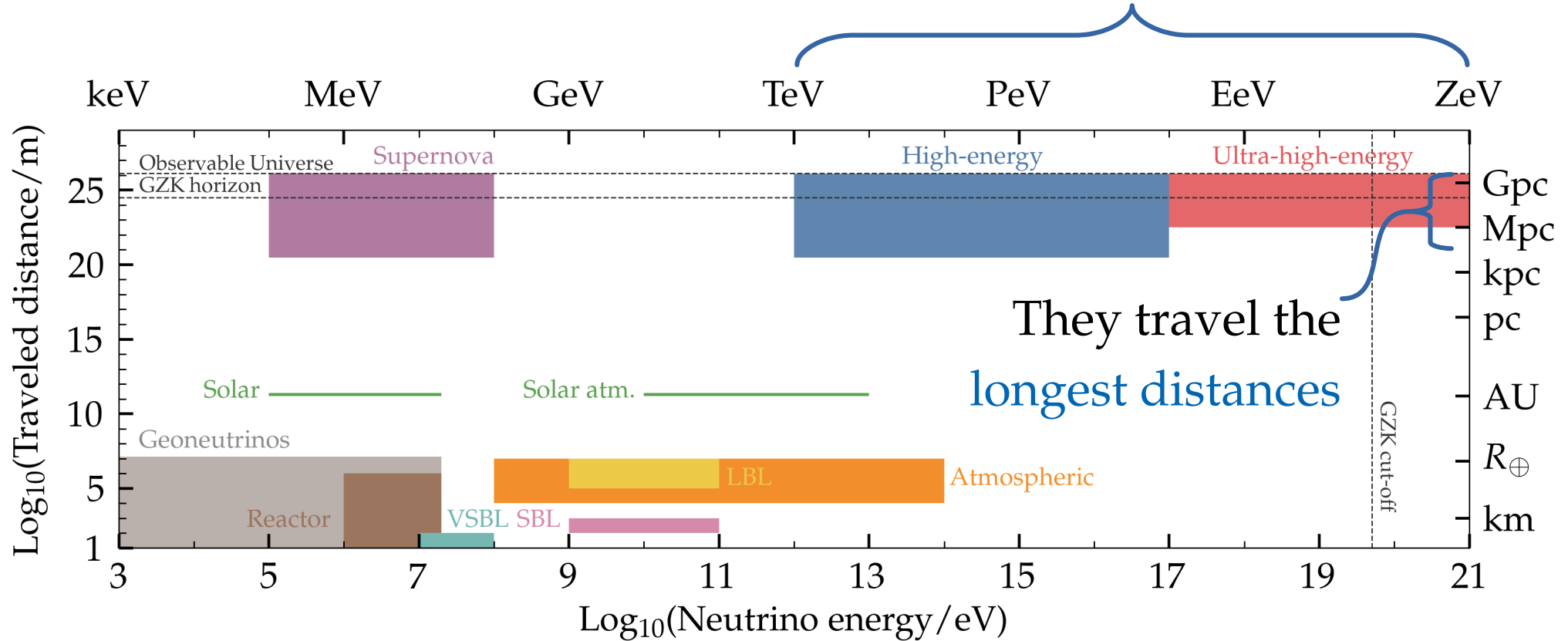


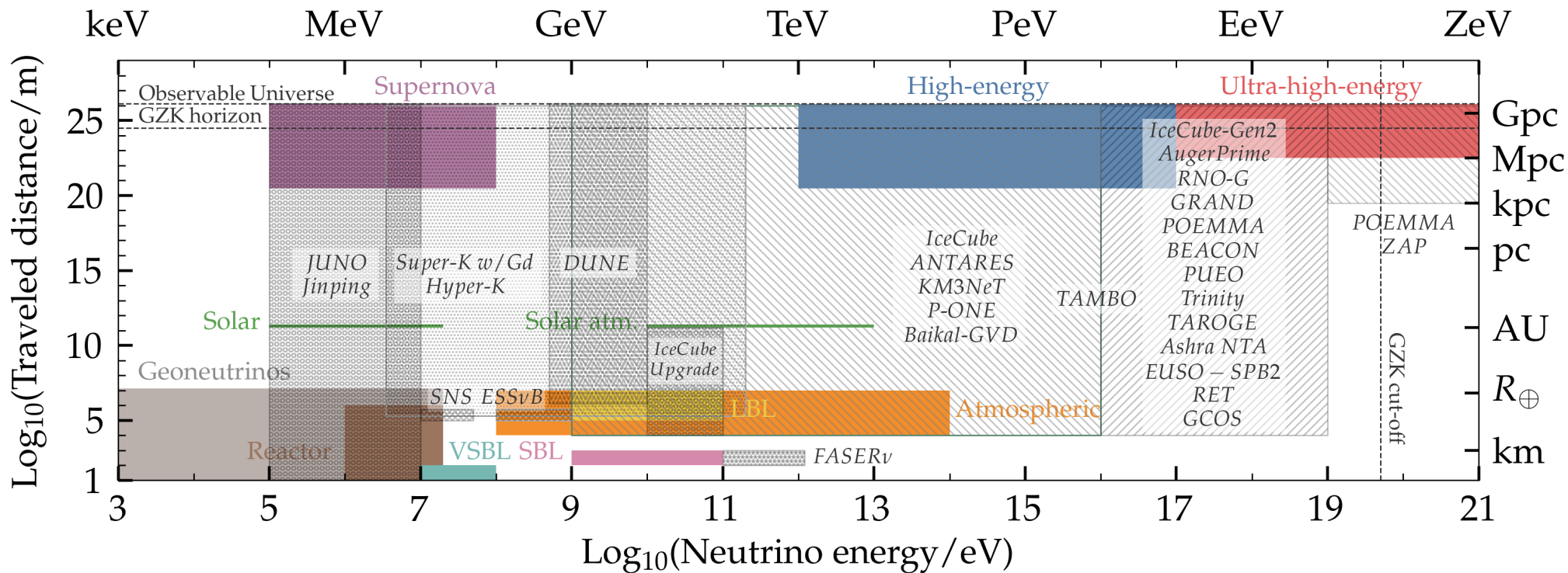


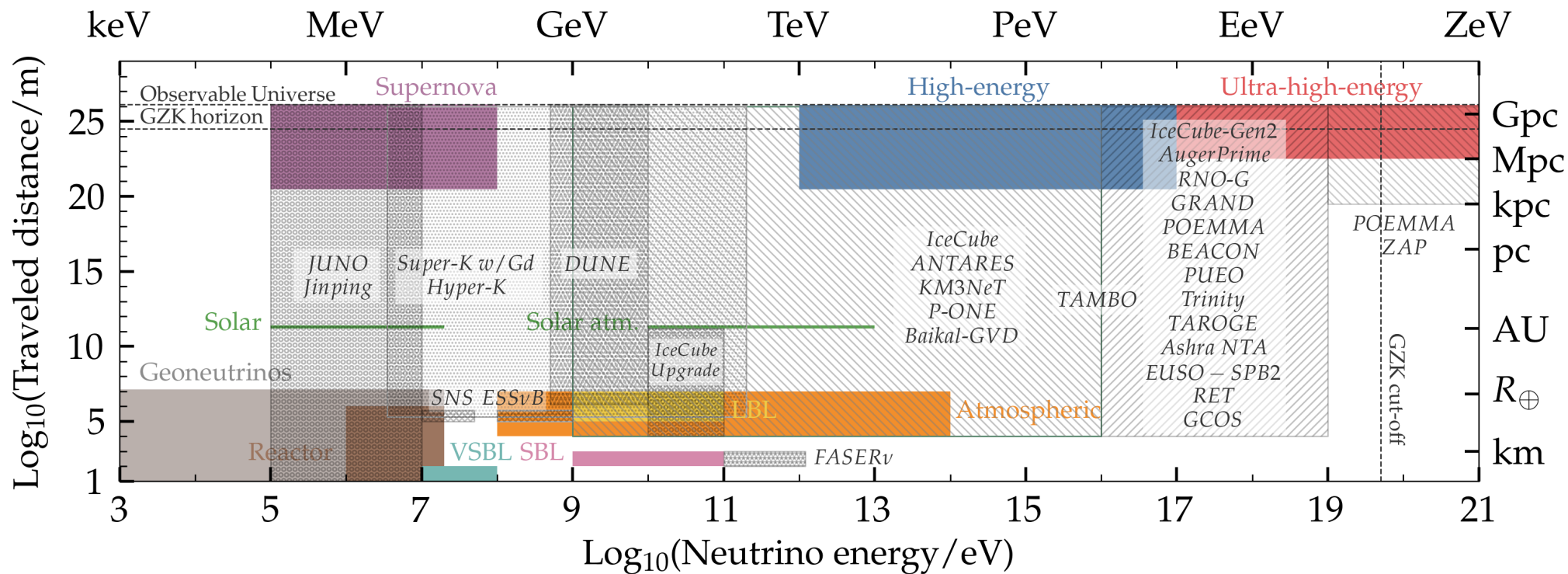




They have the **highest energies**

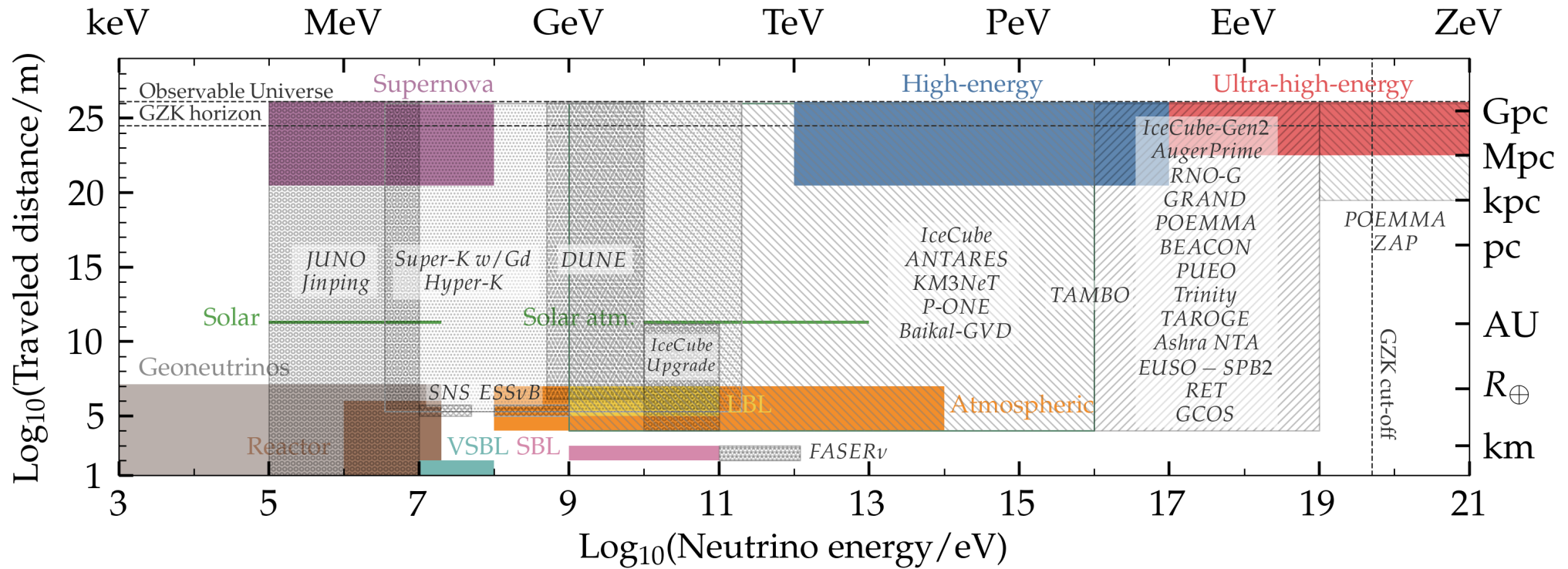






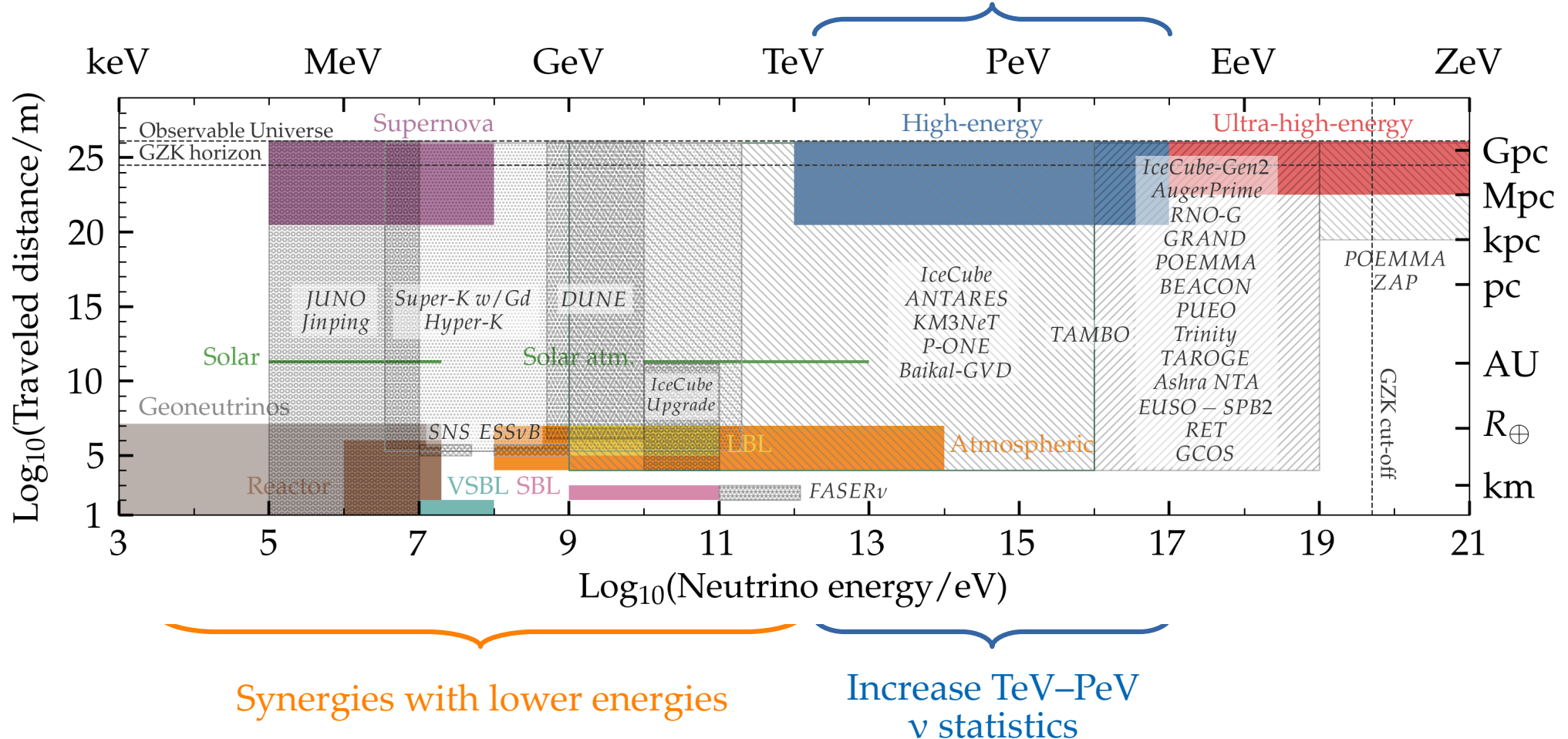
Synergies with lower energies

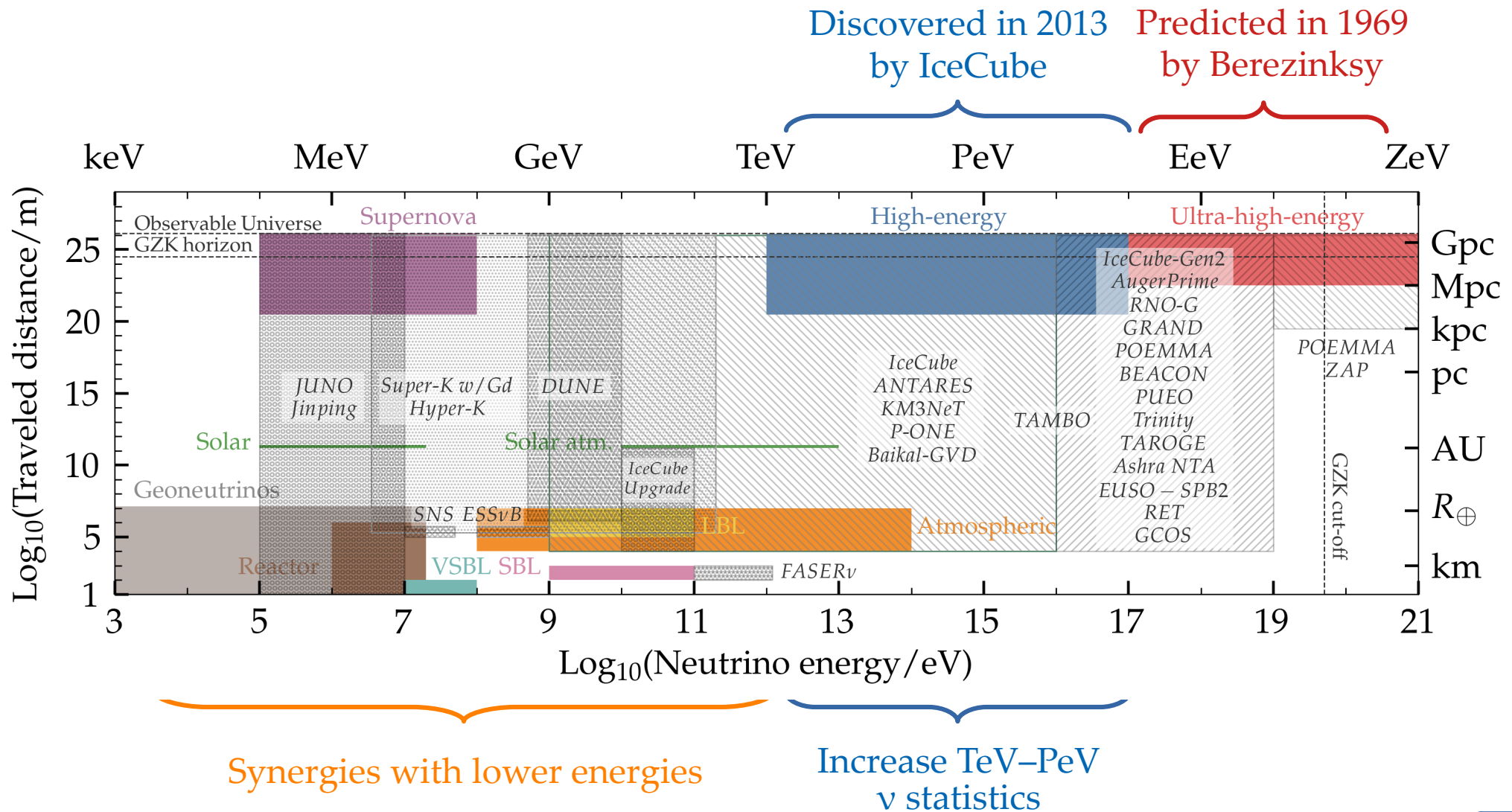
Discovered in 2013
by IceCube

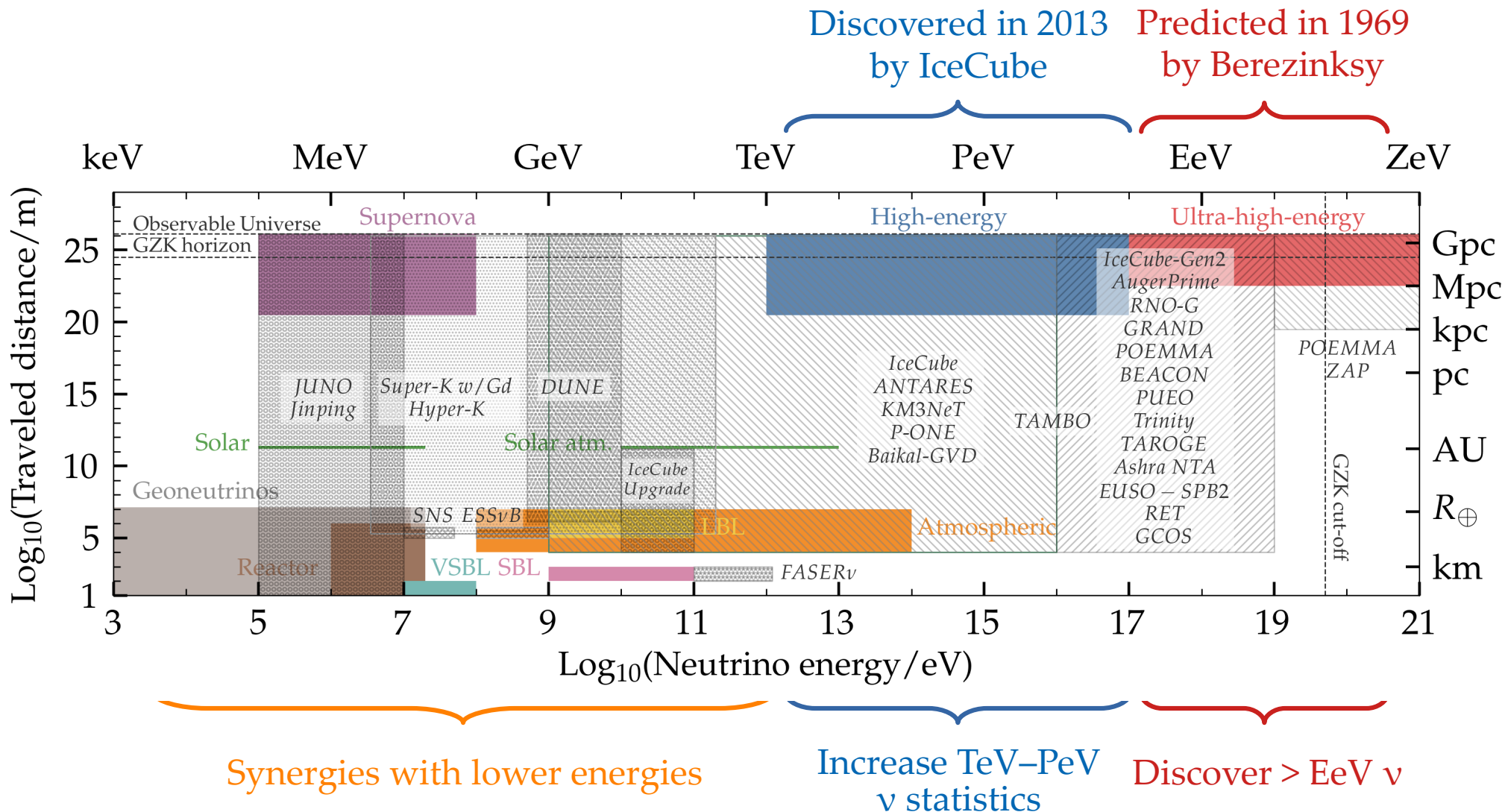


Synergies with lower energies

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The story so far

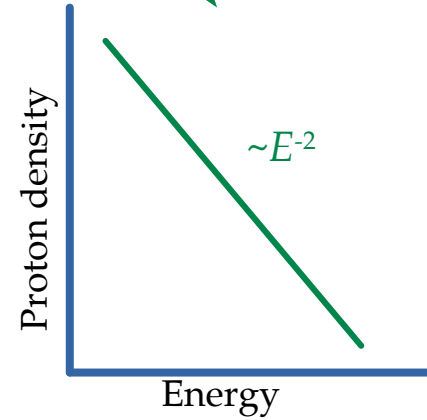
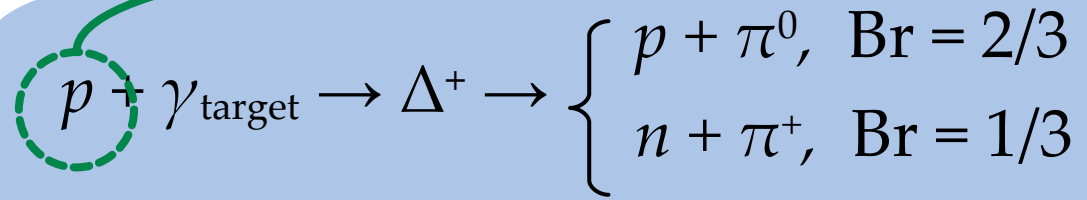
The multi-messenger connection: a simple picture

(or $p + p$)

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

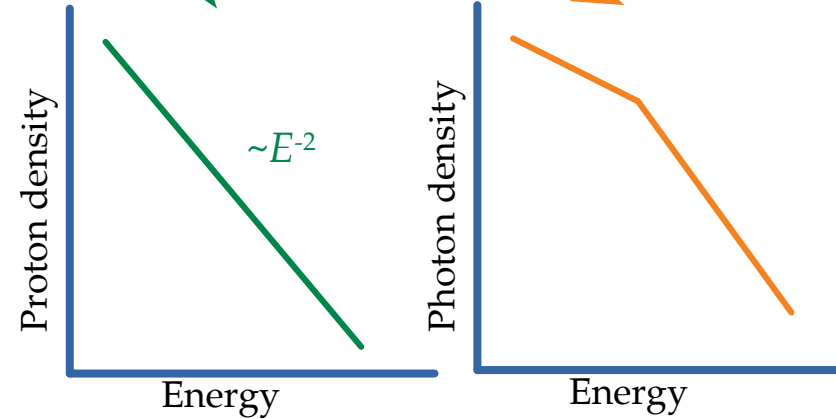
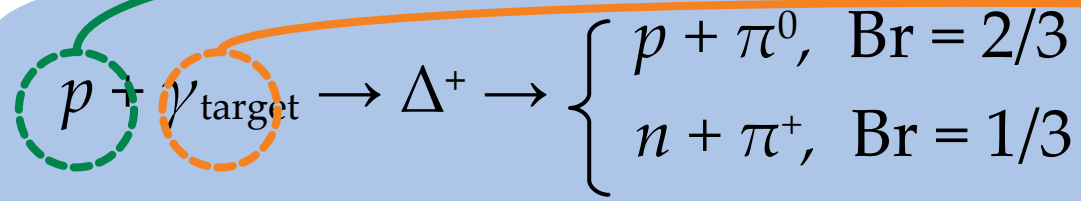
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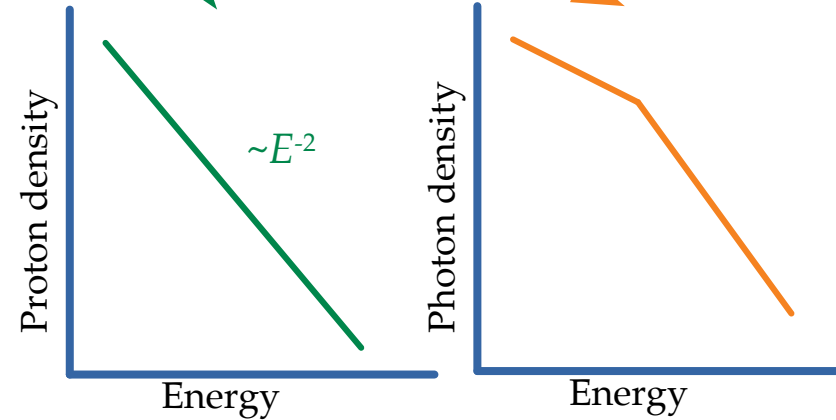
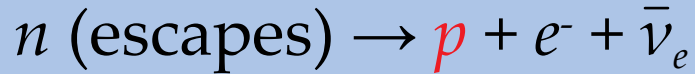
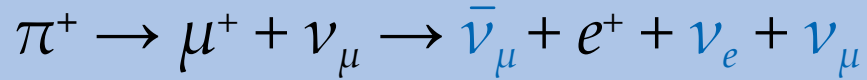
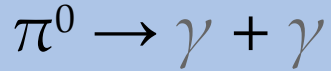
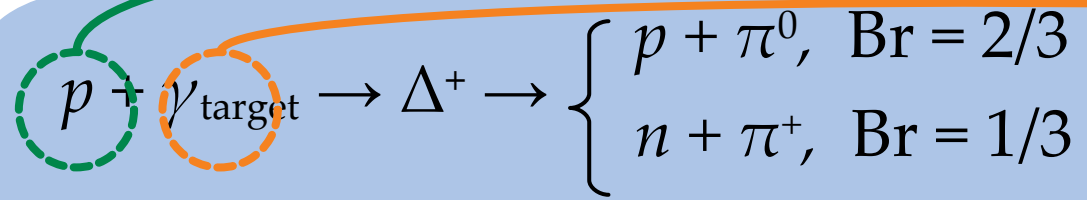
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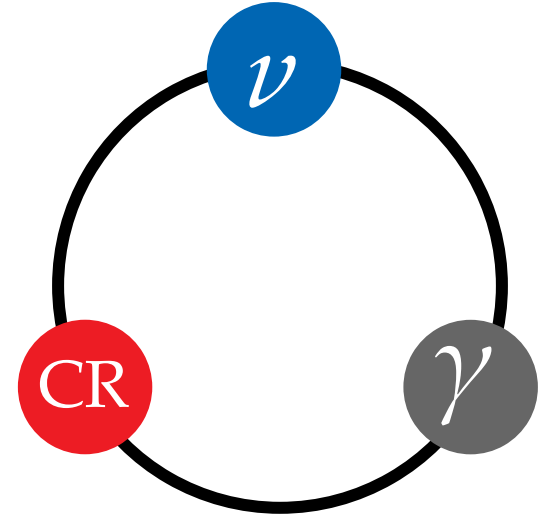
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$$\pi^0 \rightarrow \gamma + \gamma$$

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

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



Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

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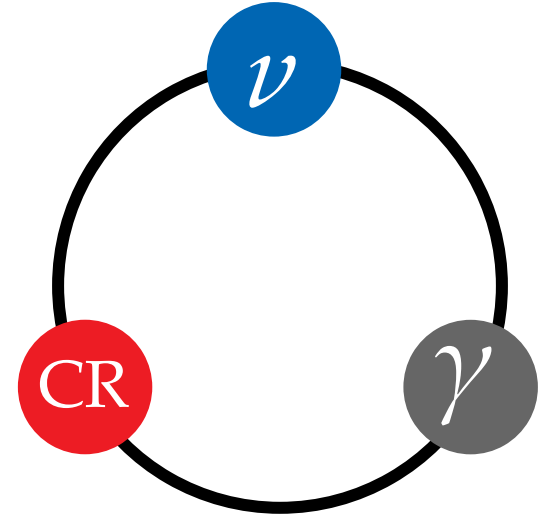
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1 PeV

20 PeV

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Gamma-ray energy = Proton energy / 10

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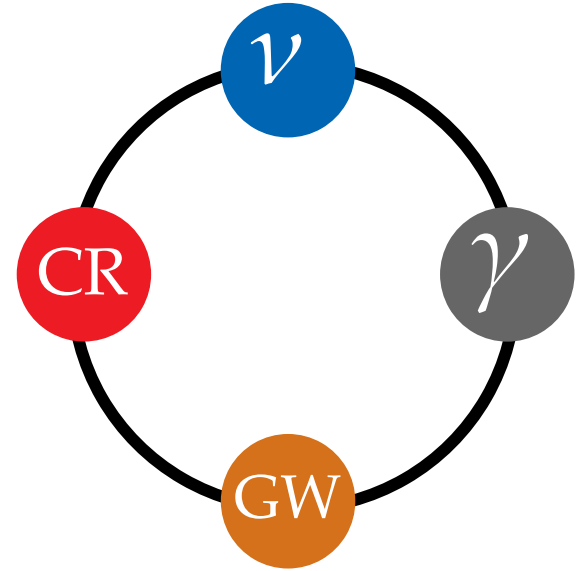
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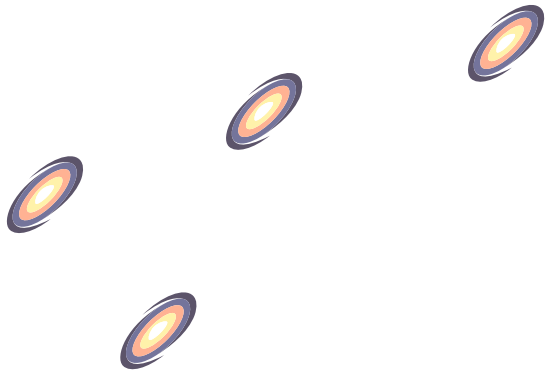
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Redshift



$z = 0$

Note: ν sources can be steady-state or transient



Redshift

$z = 0$

Note: ν sources can be steady-state or transient

MeV γ

PeV p

TeV–PeV ν

"High-energy"

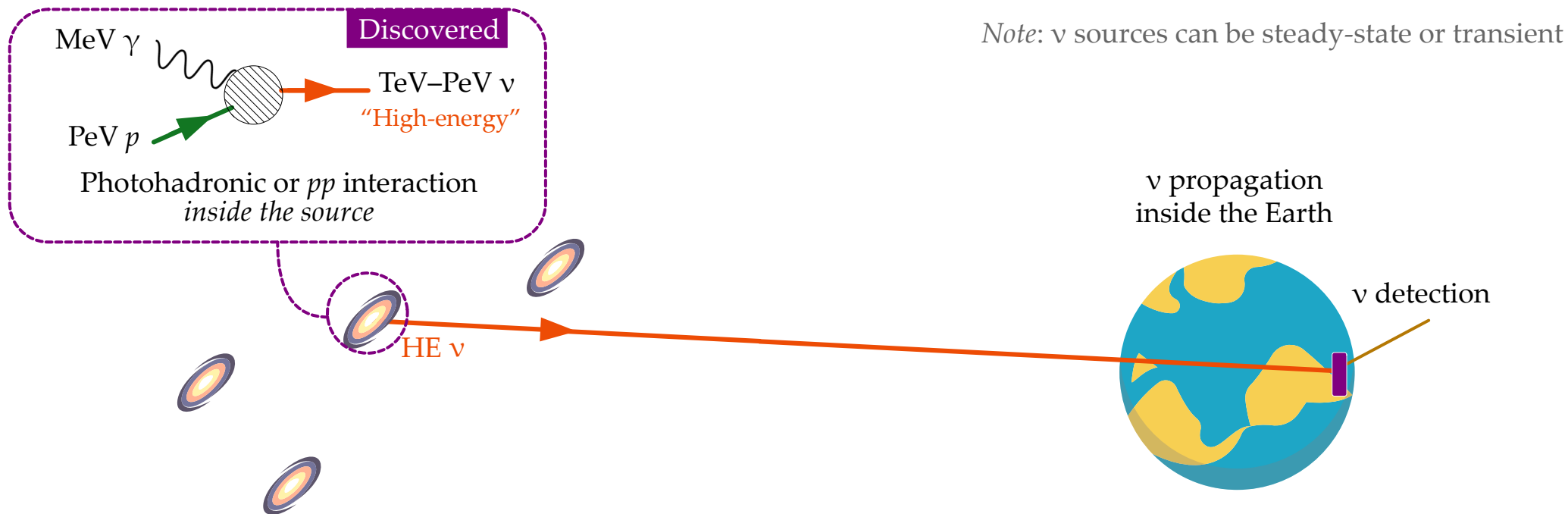
Photohadronic or pp interaction
inside the source

Discovered

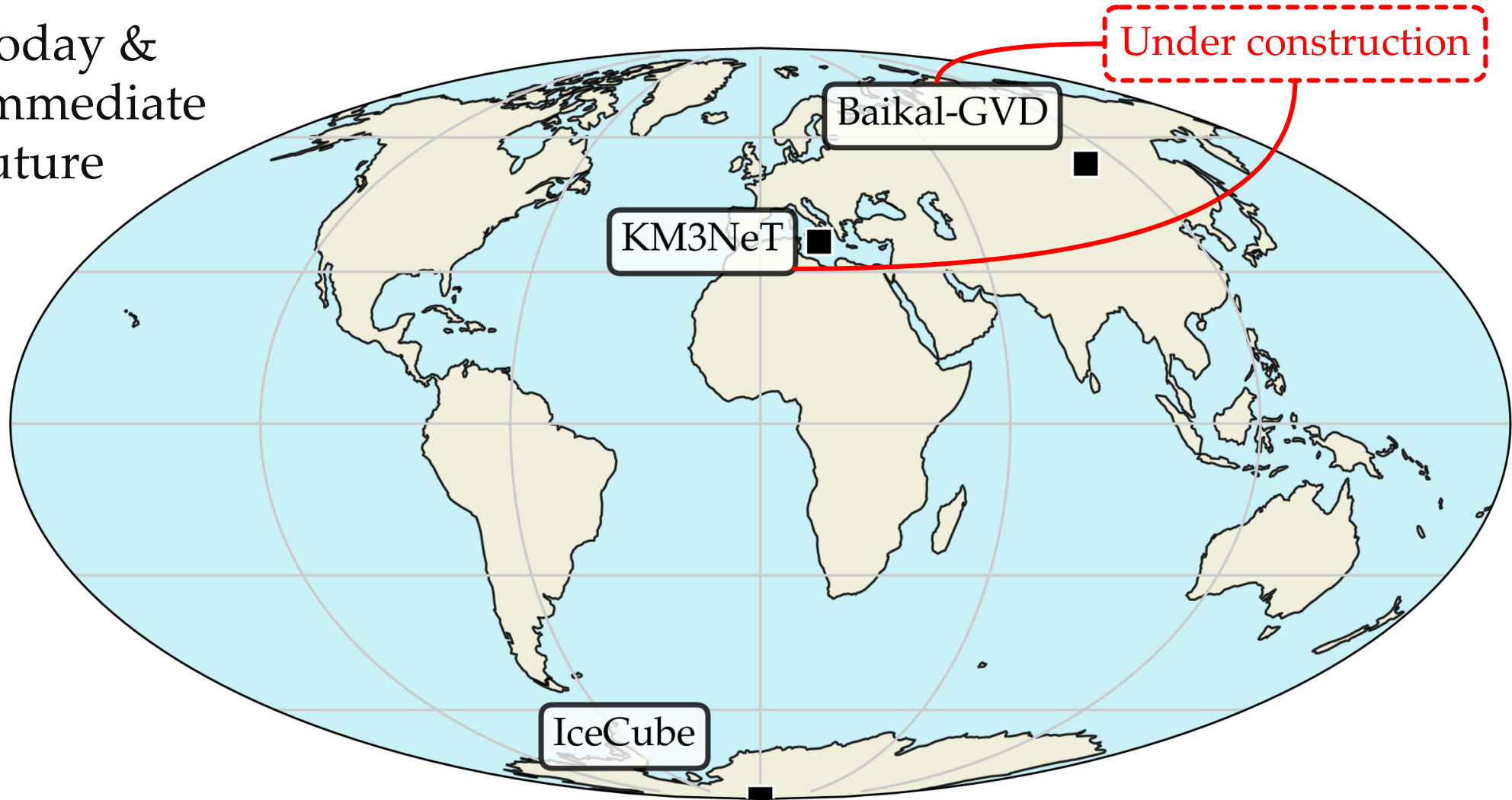
HE ν

ν propagation
inside the Earth

ν detection

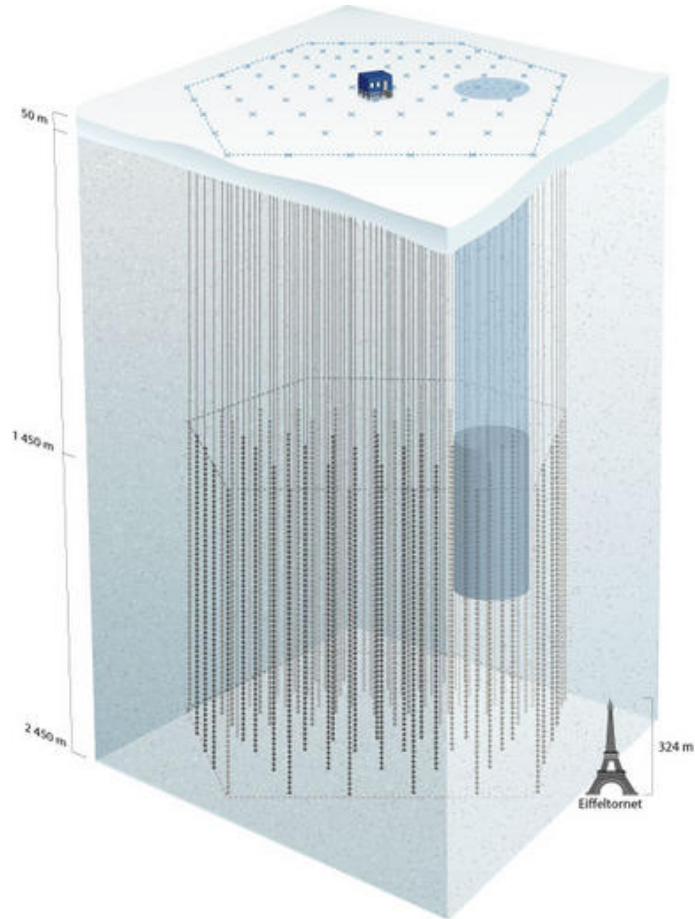


Today &
immediate
future

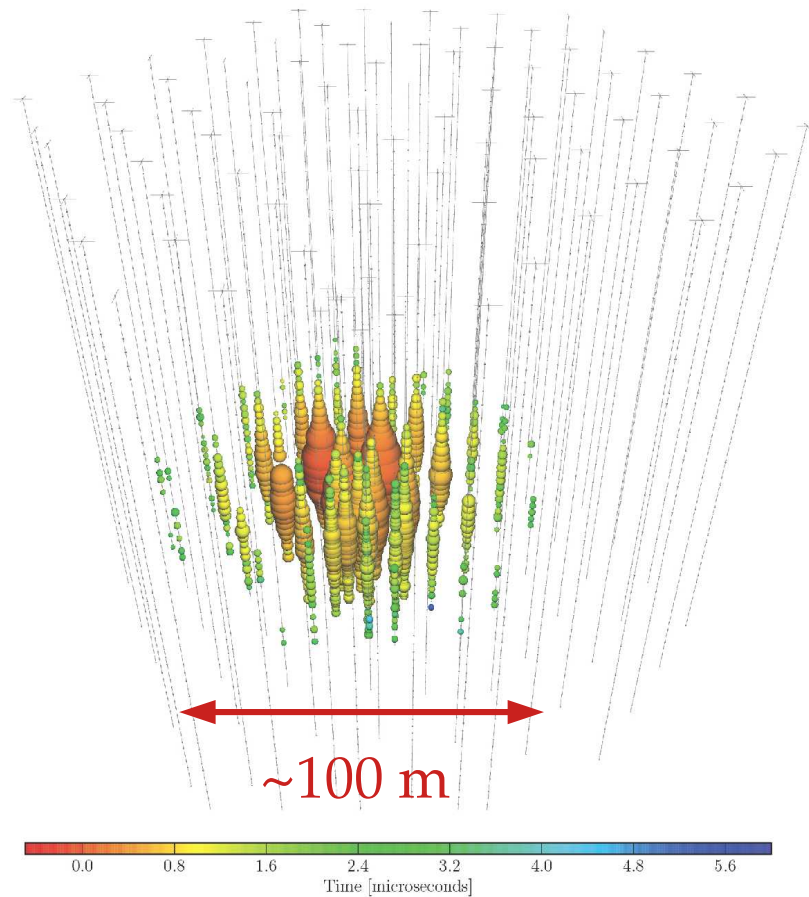


IceCube – What is it?

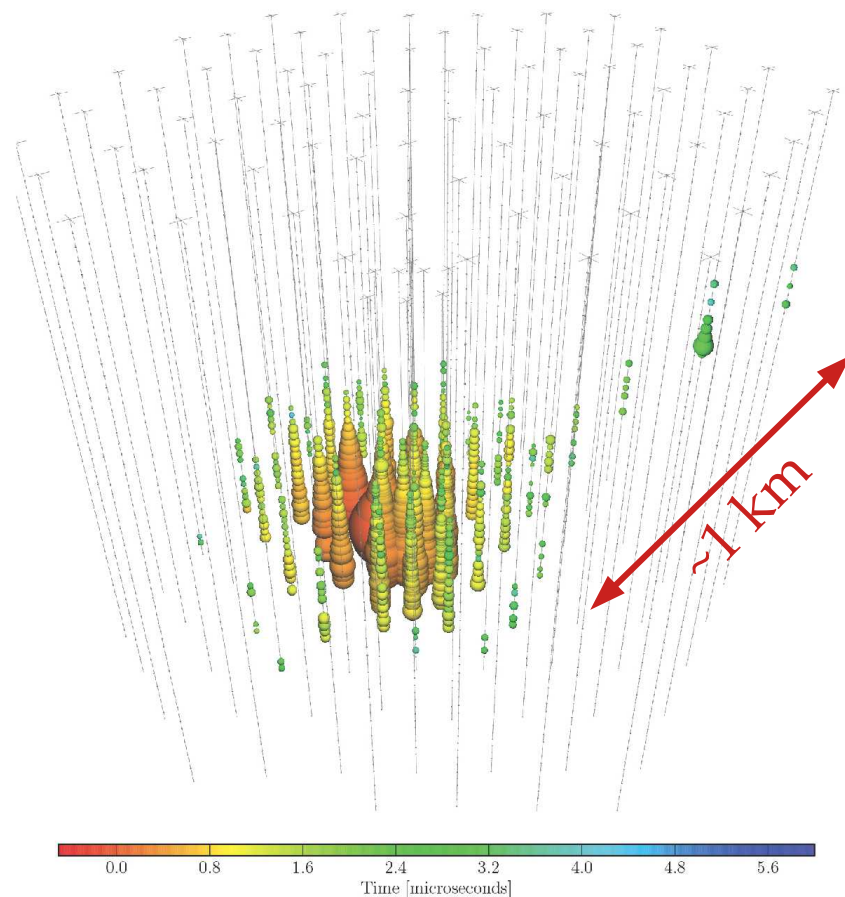
- ▶ Km^3 in-ice Cherenkov detector in Antarctica
- ▶ > 5000 PMTs at 1.5–2.5 km of depth
- ▶ Sensitive to neutrino energies > 10 GeV



Shower
(mainly from ν_e and ν_τ)

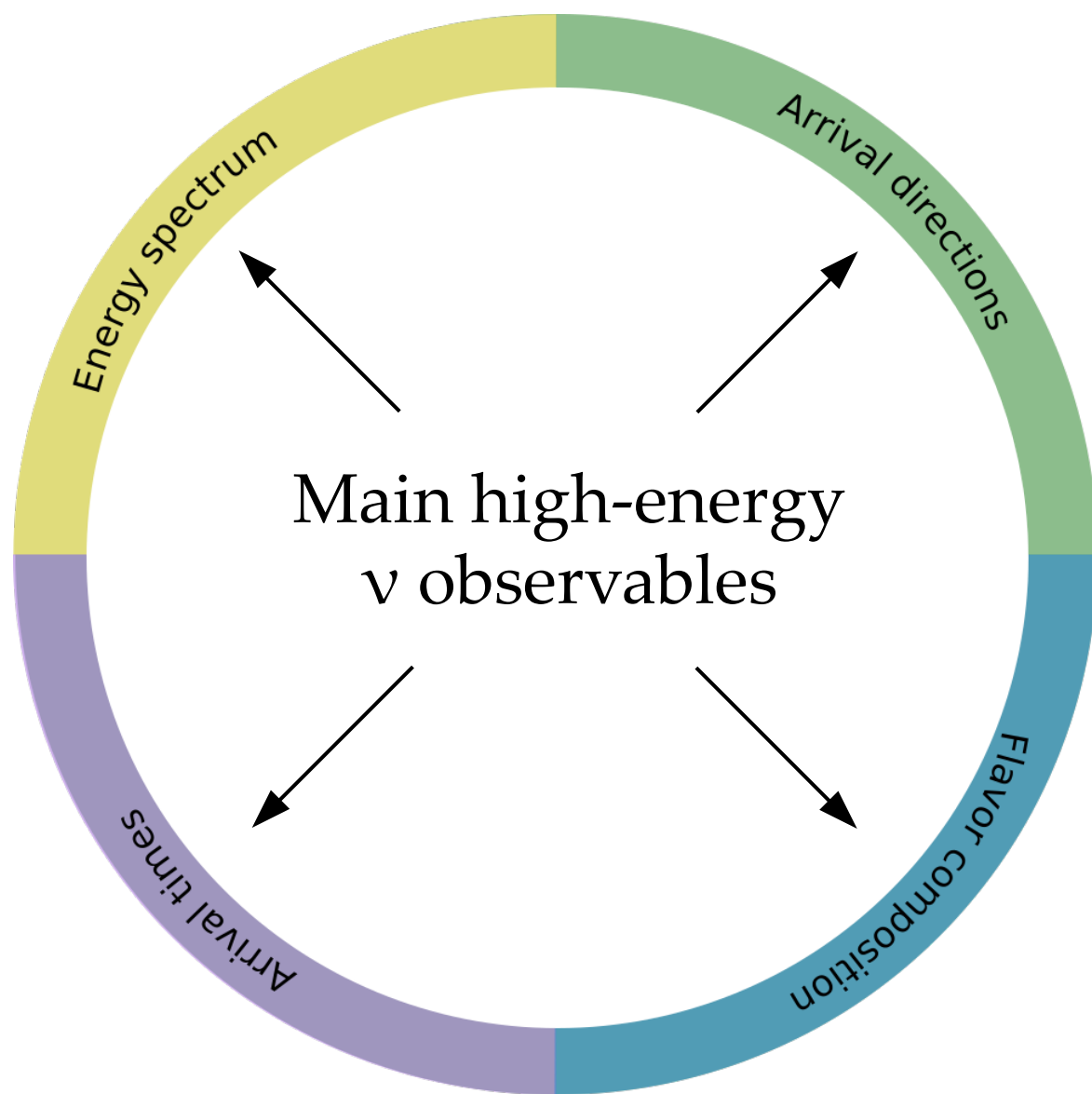


Track
(mainly from ν_μ)



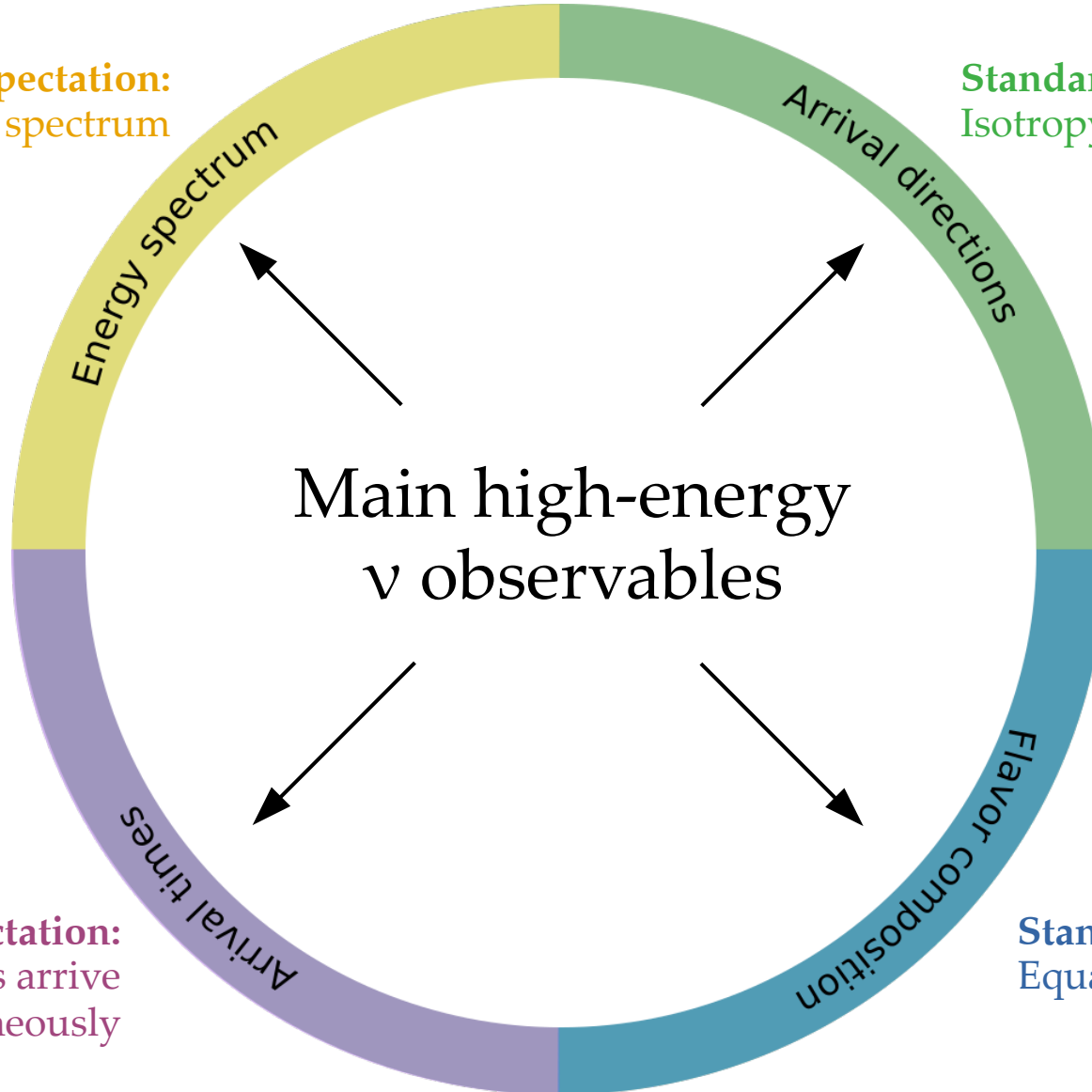
Poor angular resolution: $< 5^\circ$

Angular resolution: $< 1^\circ$



Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

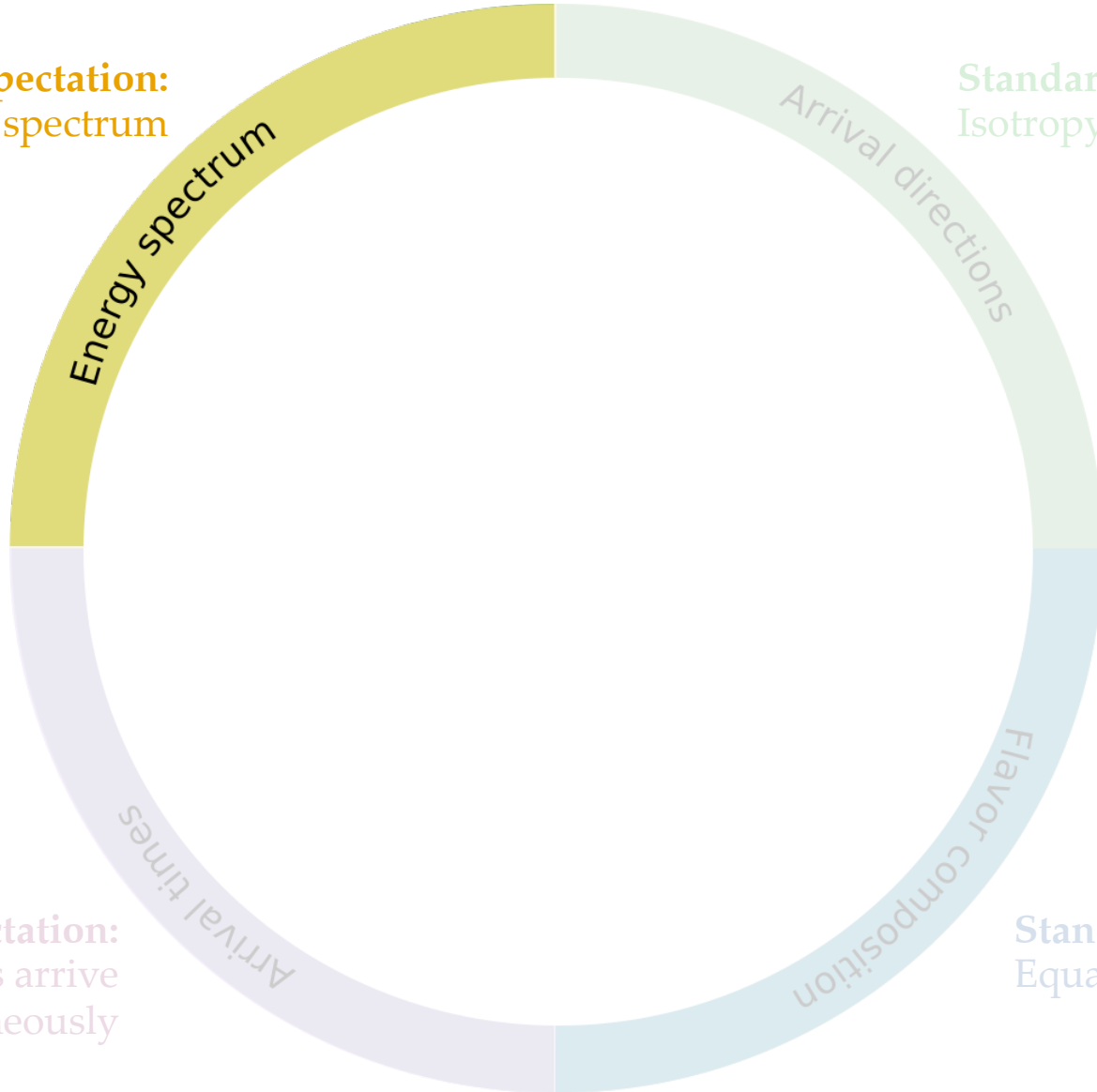


Standard expectation:
 ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

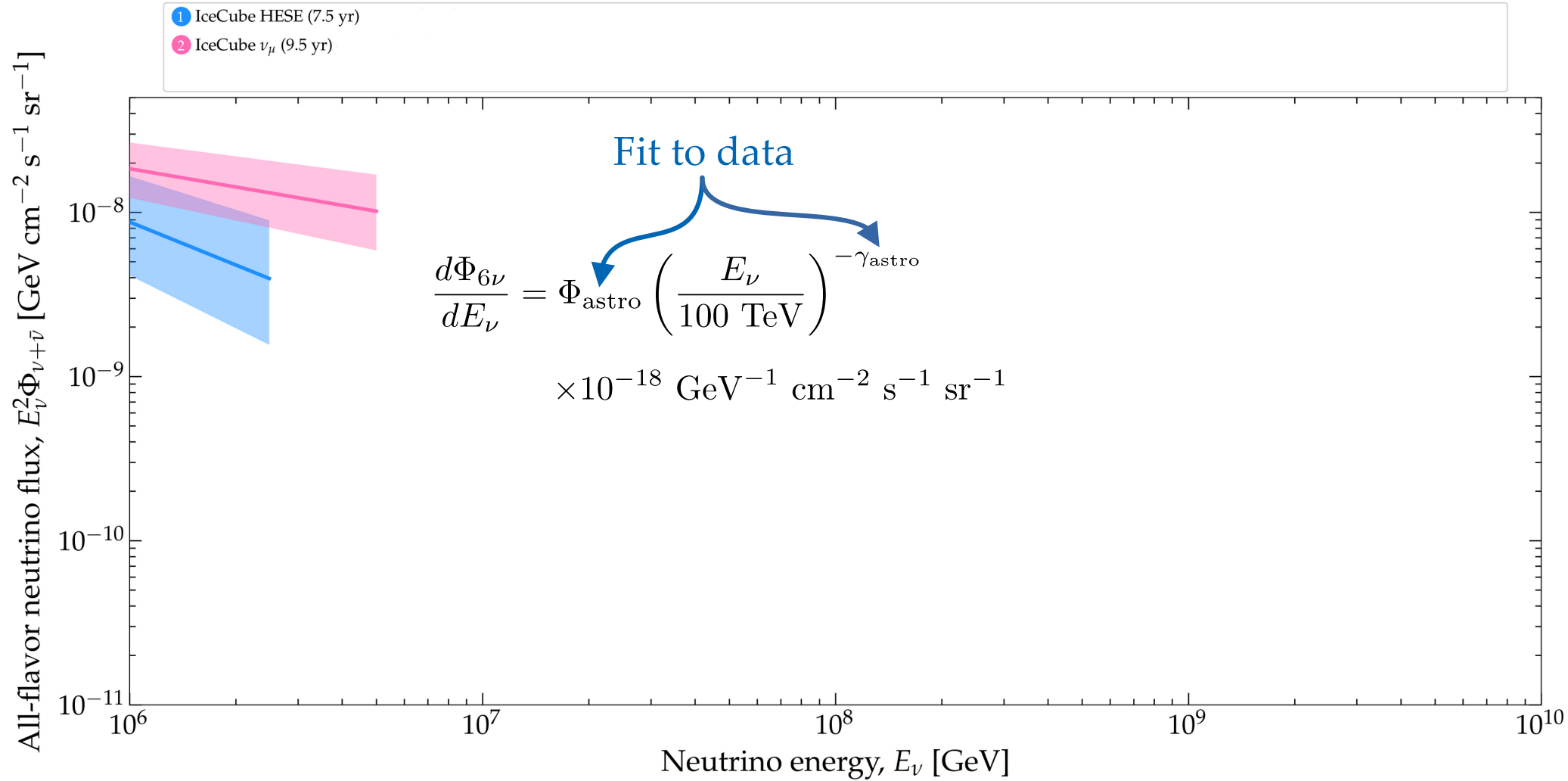
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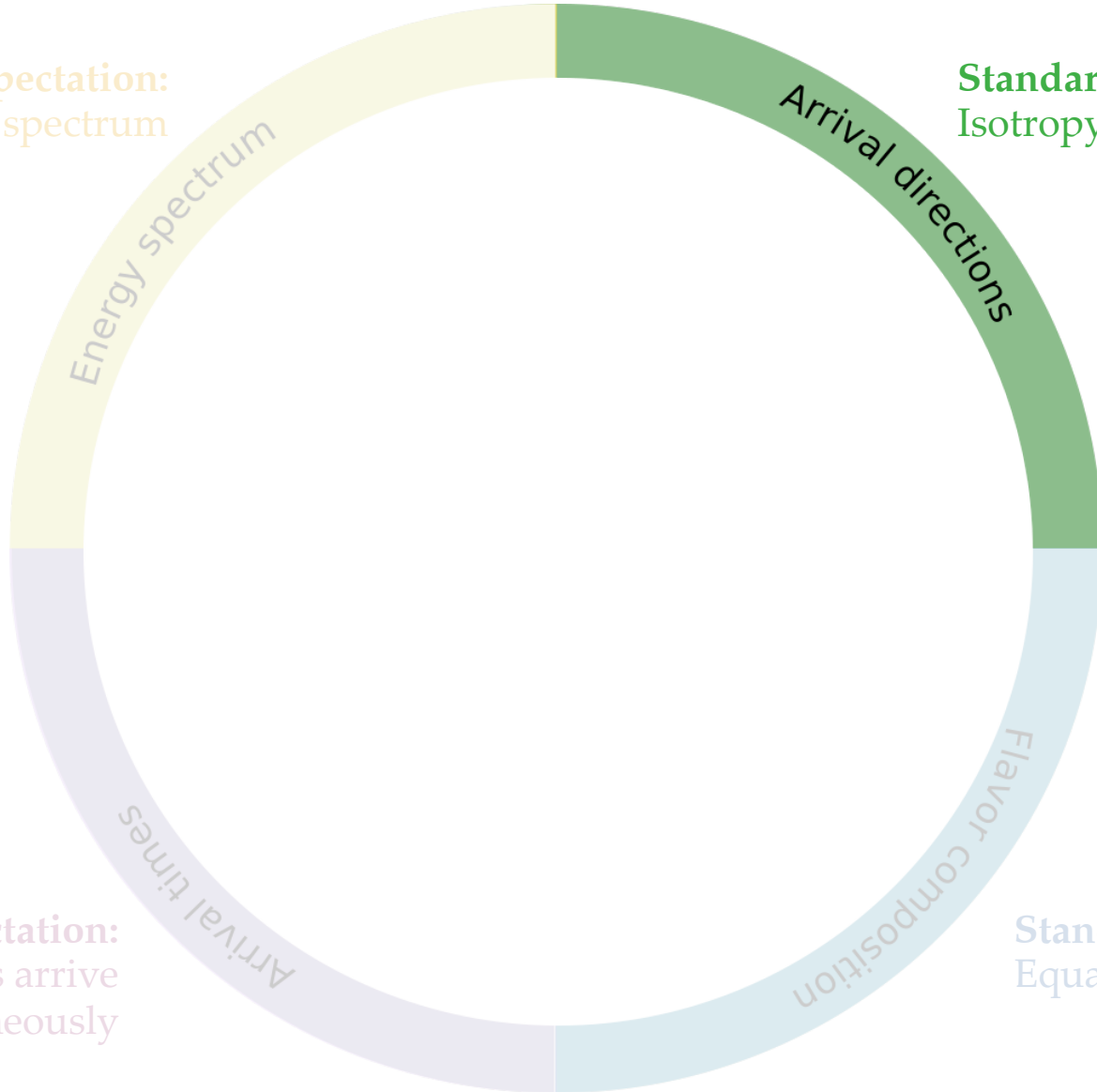


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Arrival directions

Flavor composition

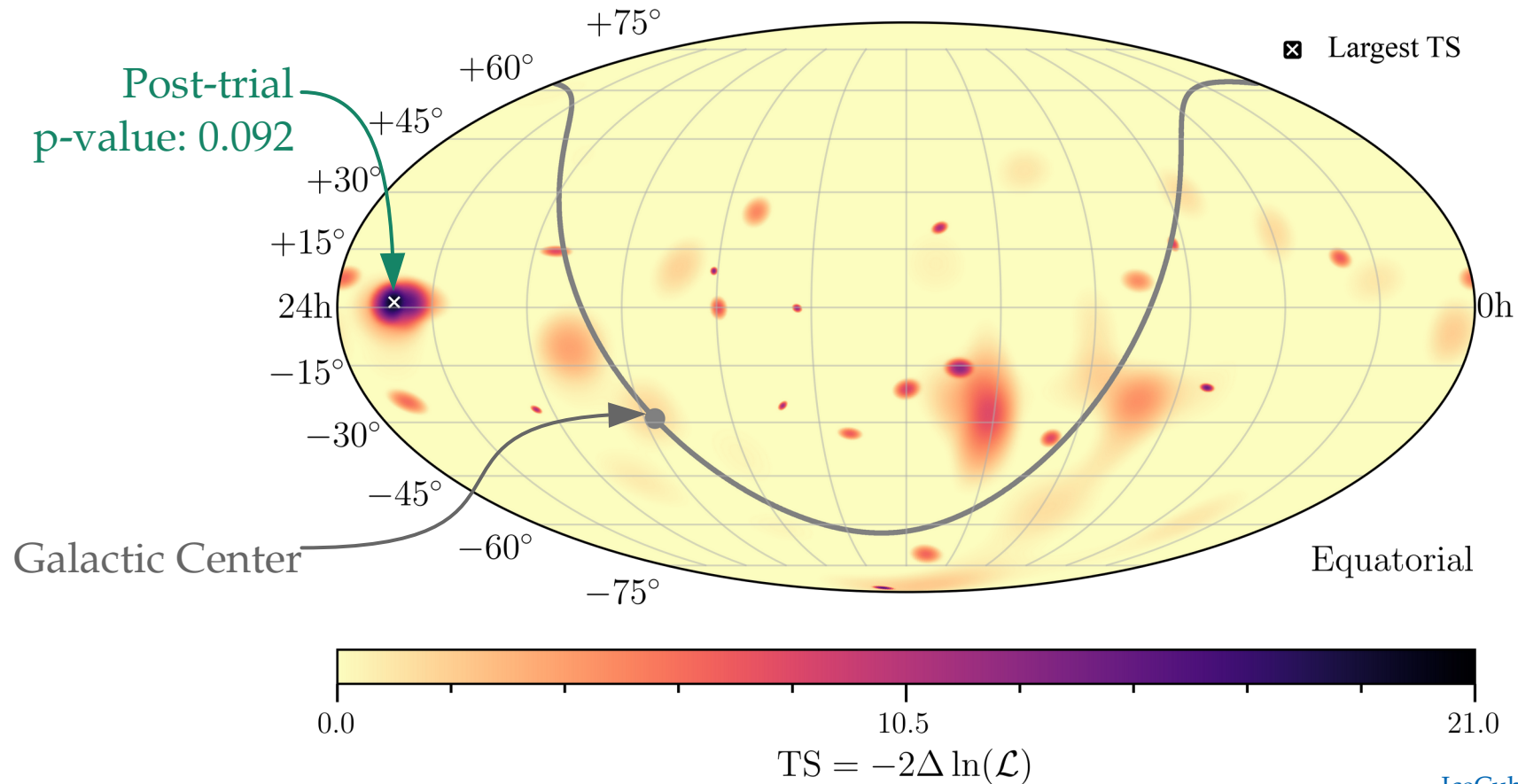
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Arrival times

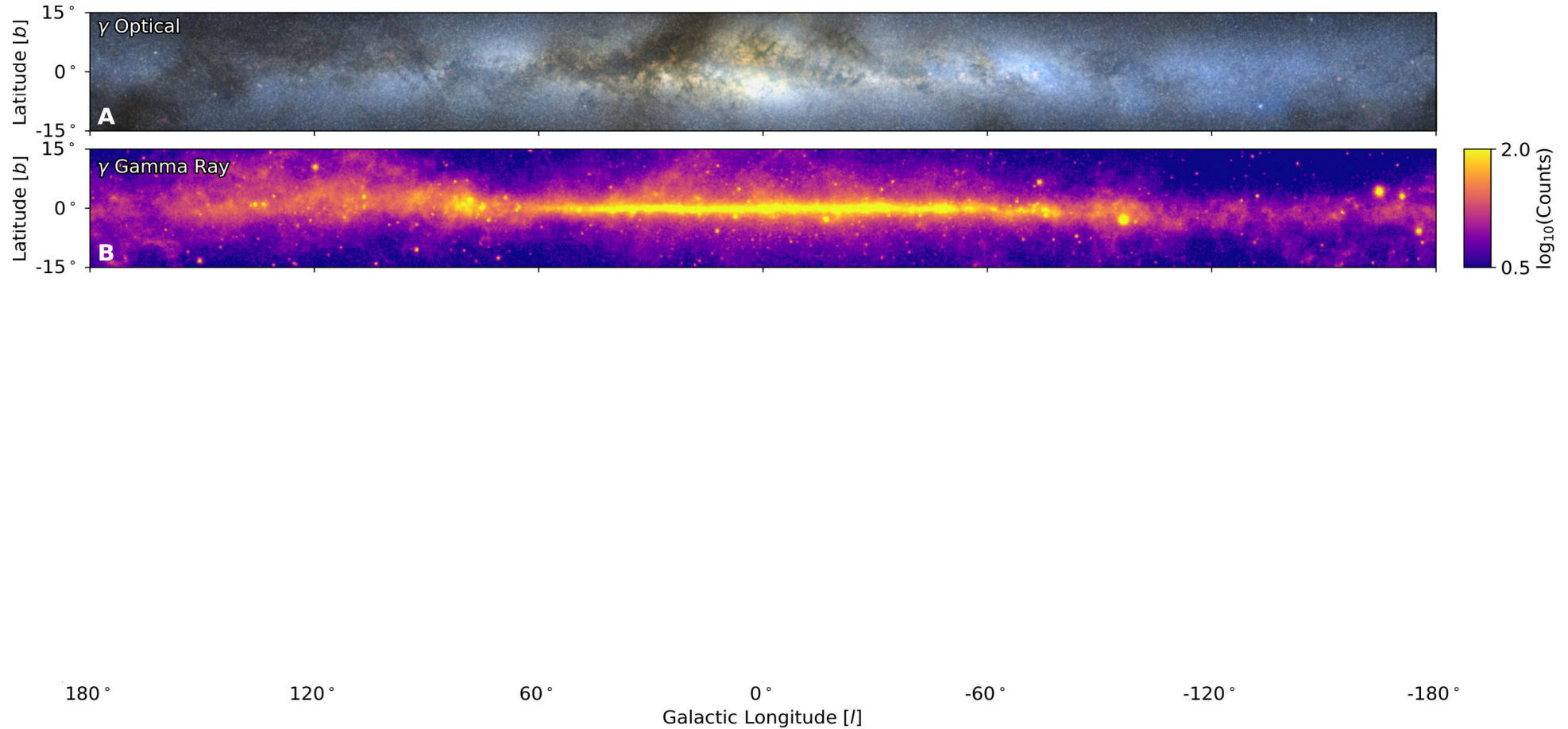
Arrival directions (7.5 yr)

No significant excess in the neutrino sky map:

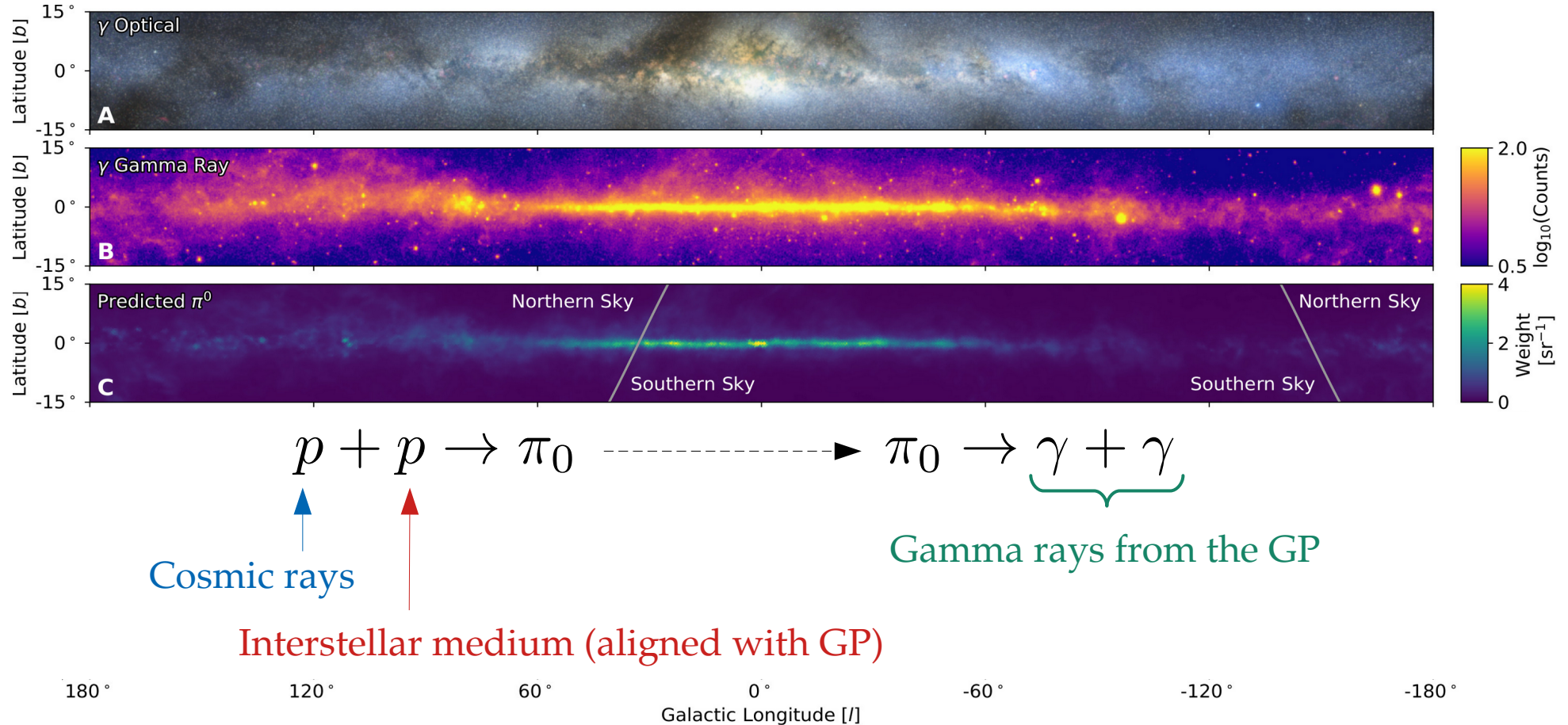


IceCube, PRD 2021

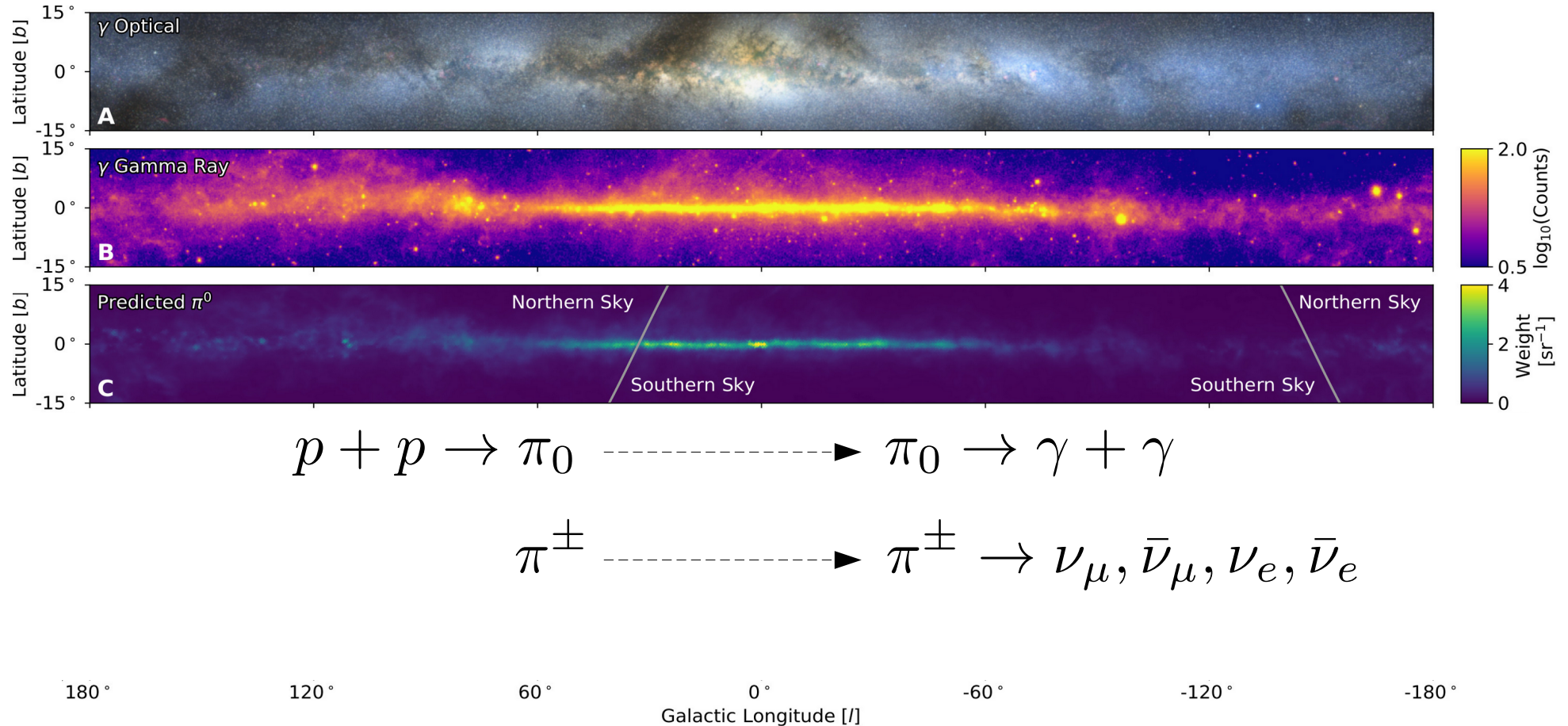
High-energy neutrinos from the Galactic Plane



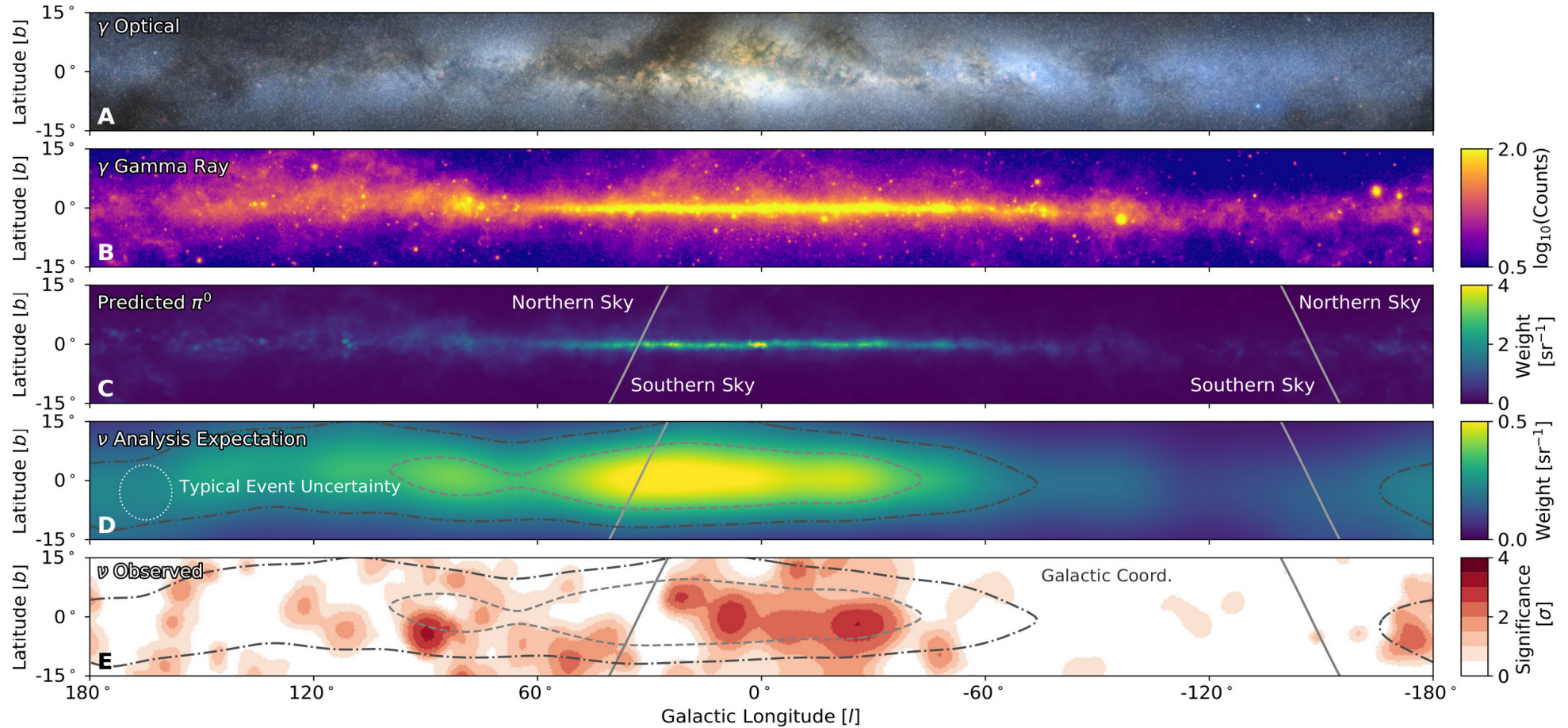
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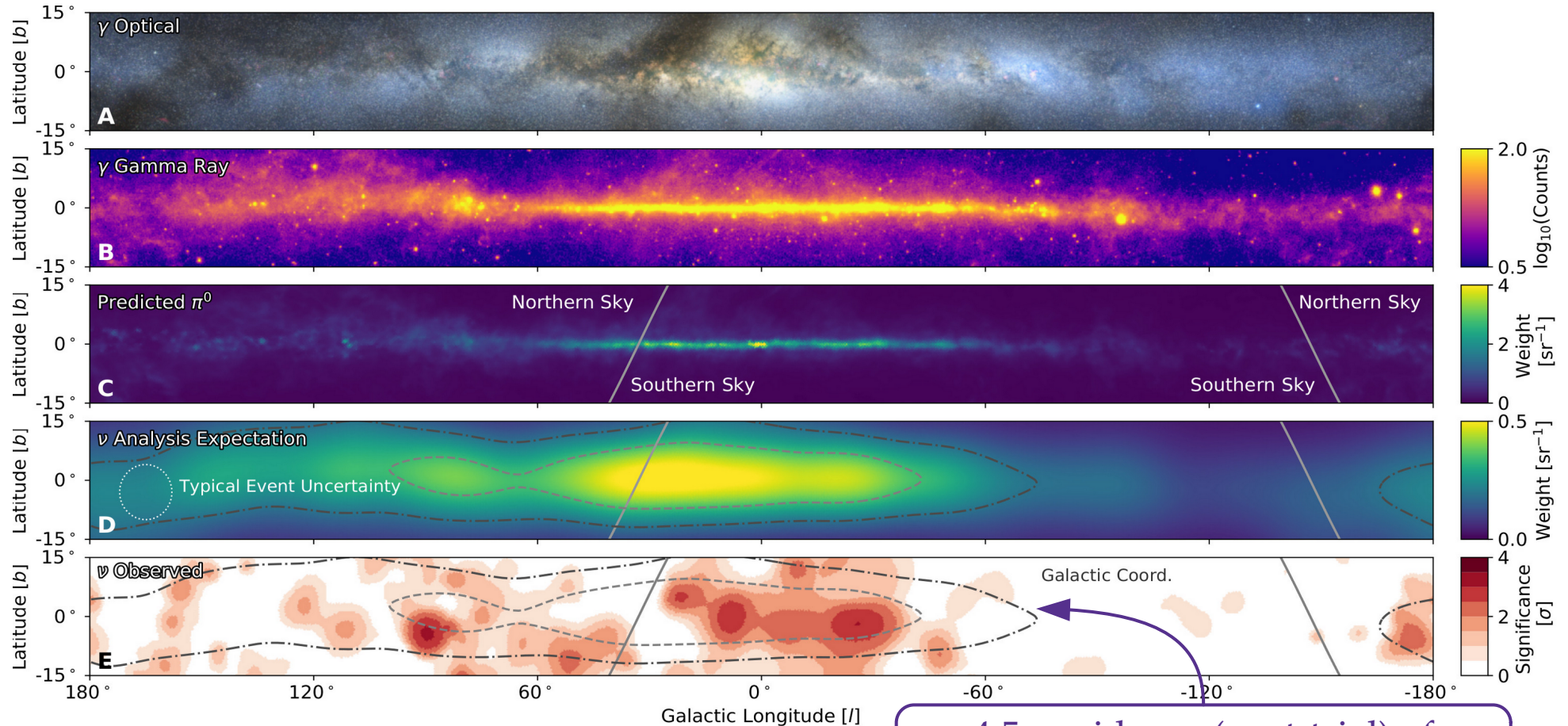
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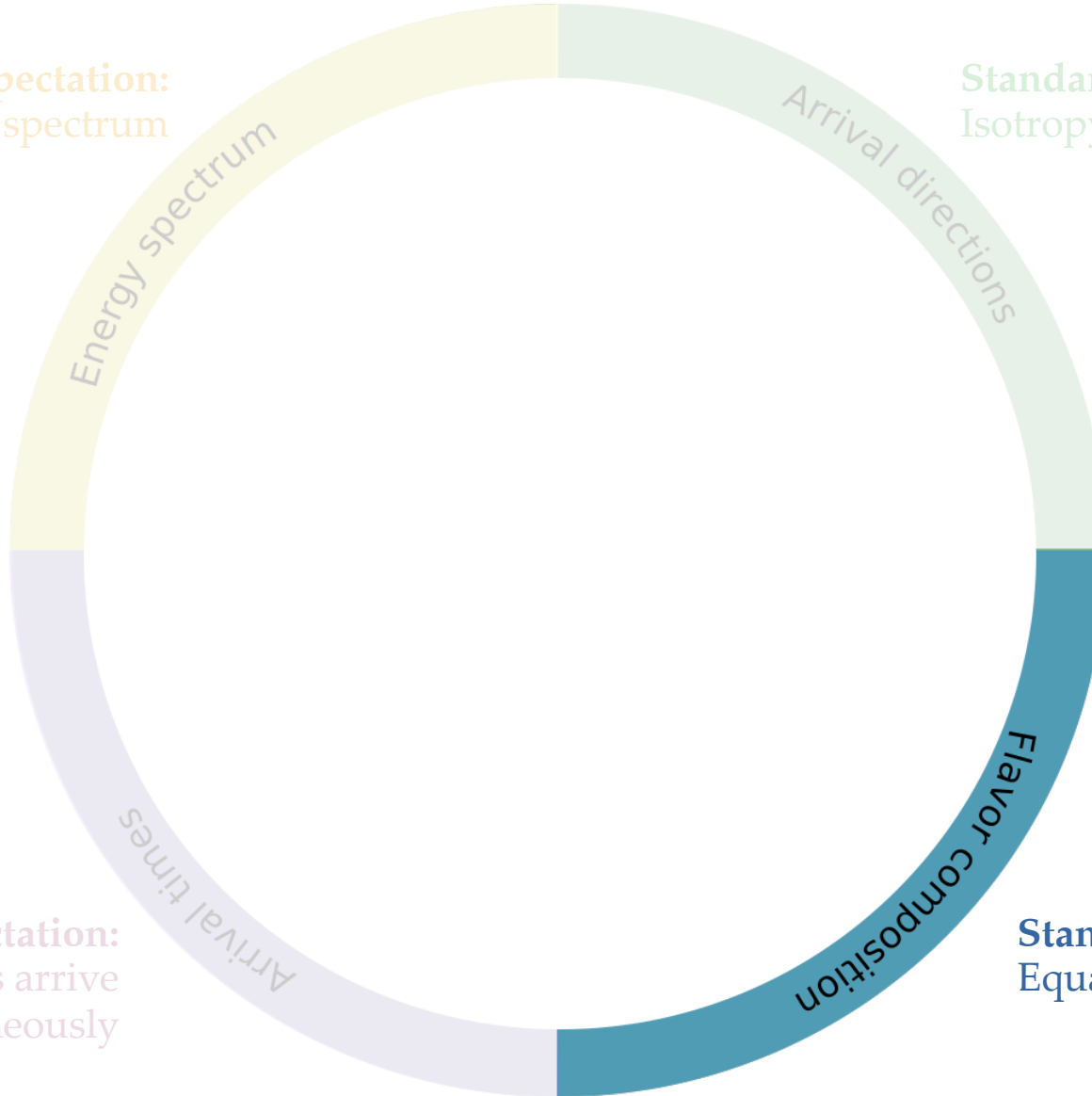
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4.5 σ evidence (post-trial) of
diffuse flux of > TeV ν from the GP

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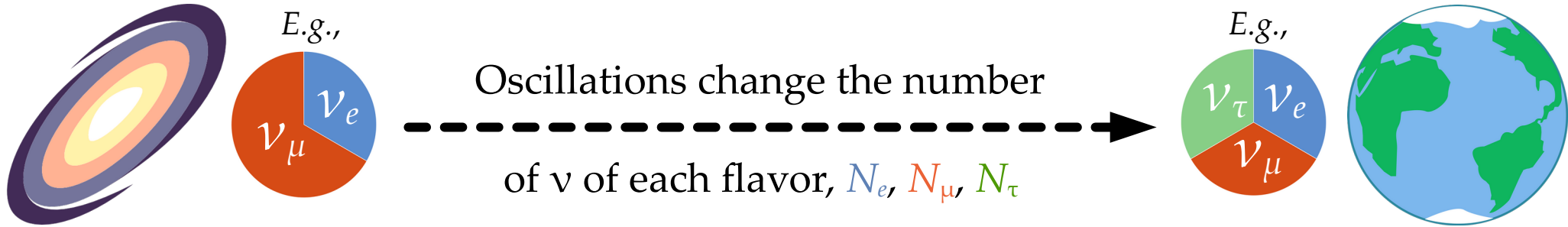
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Astrophysical sources

Earth

Up to a few Gpc



Different production mechanisms yield different flavor ratios:

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

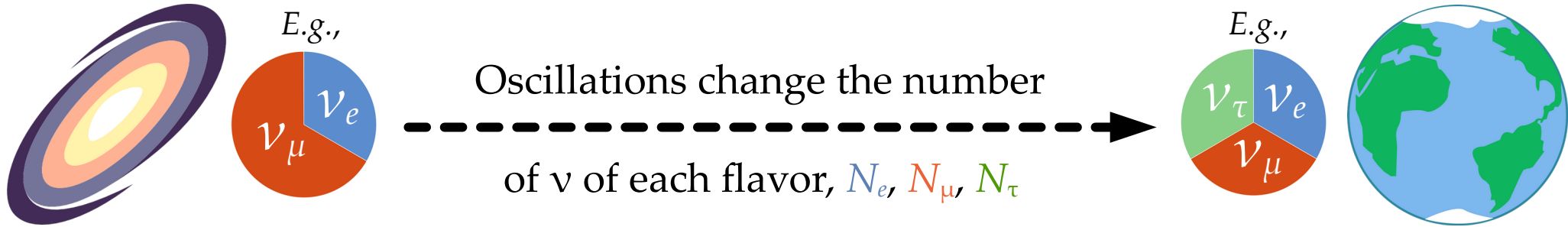
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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

Astrophysical sources

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Up to a few Gpc



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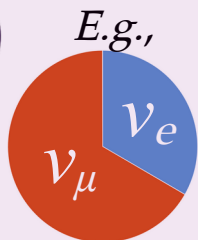
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Standard
oscillations
or
new physics

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

Sources



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

Oscillations

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

Earth



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

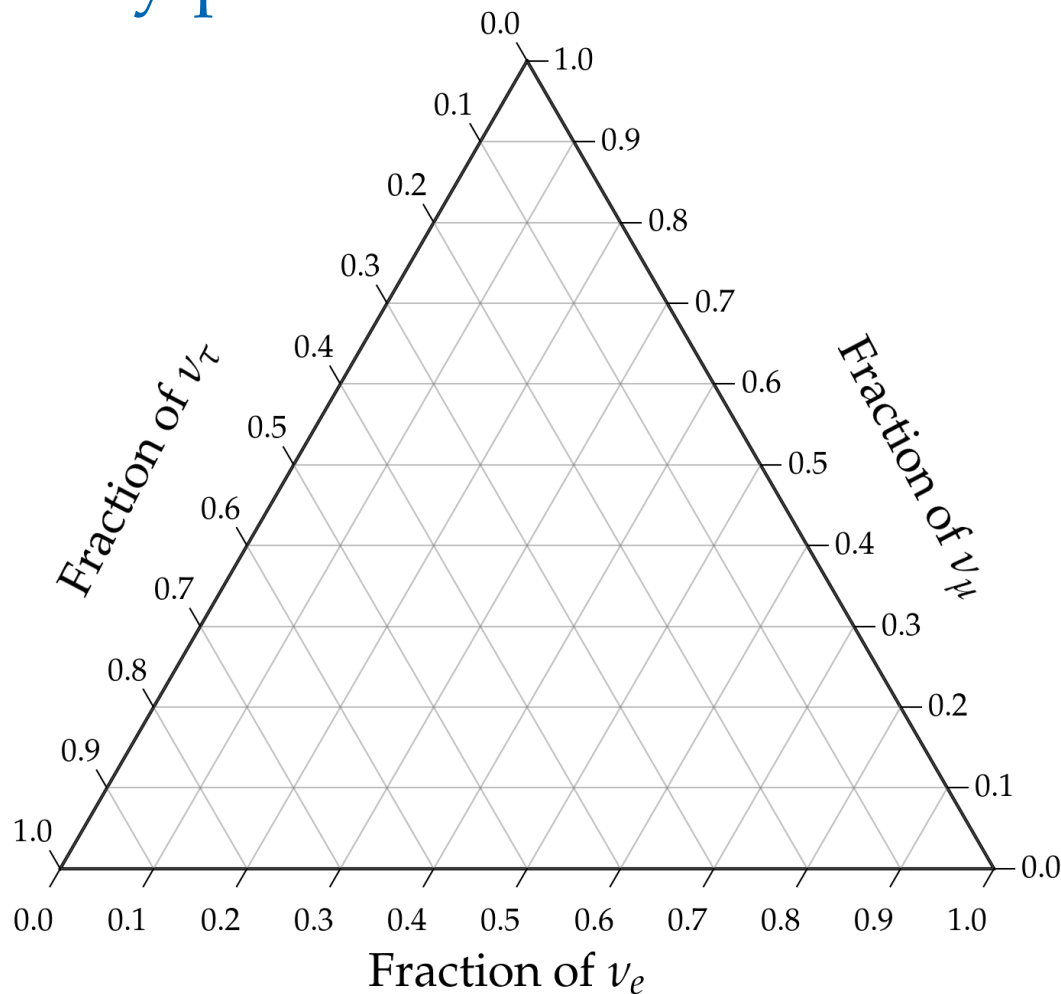
Quick aside: how to read a ternary plot

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

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



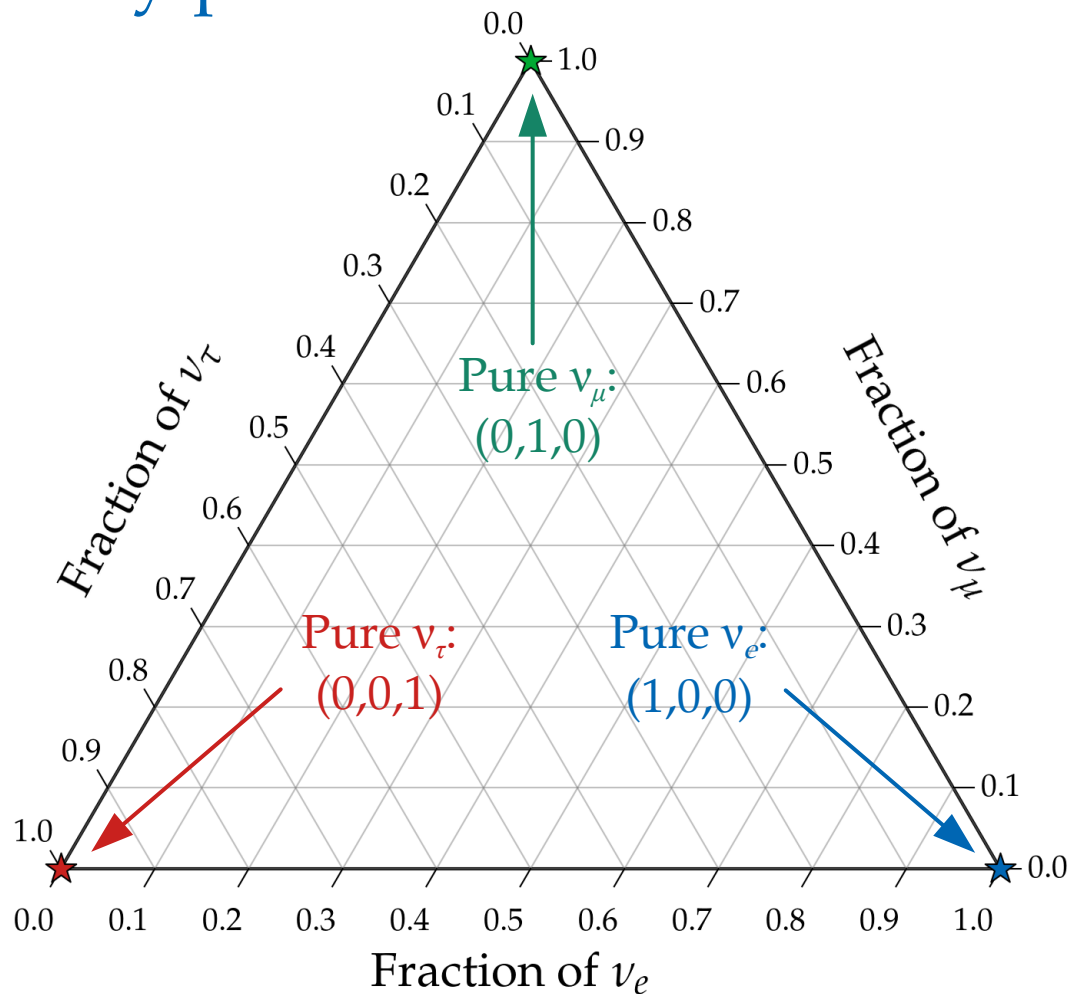
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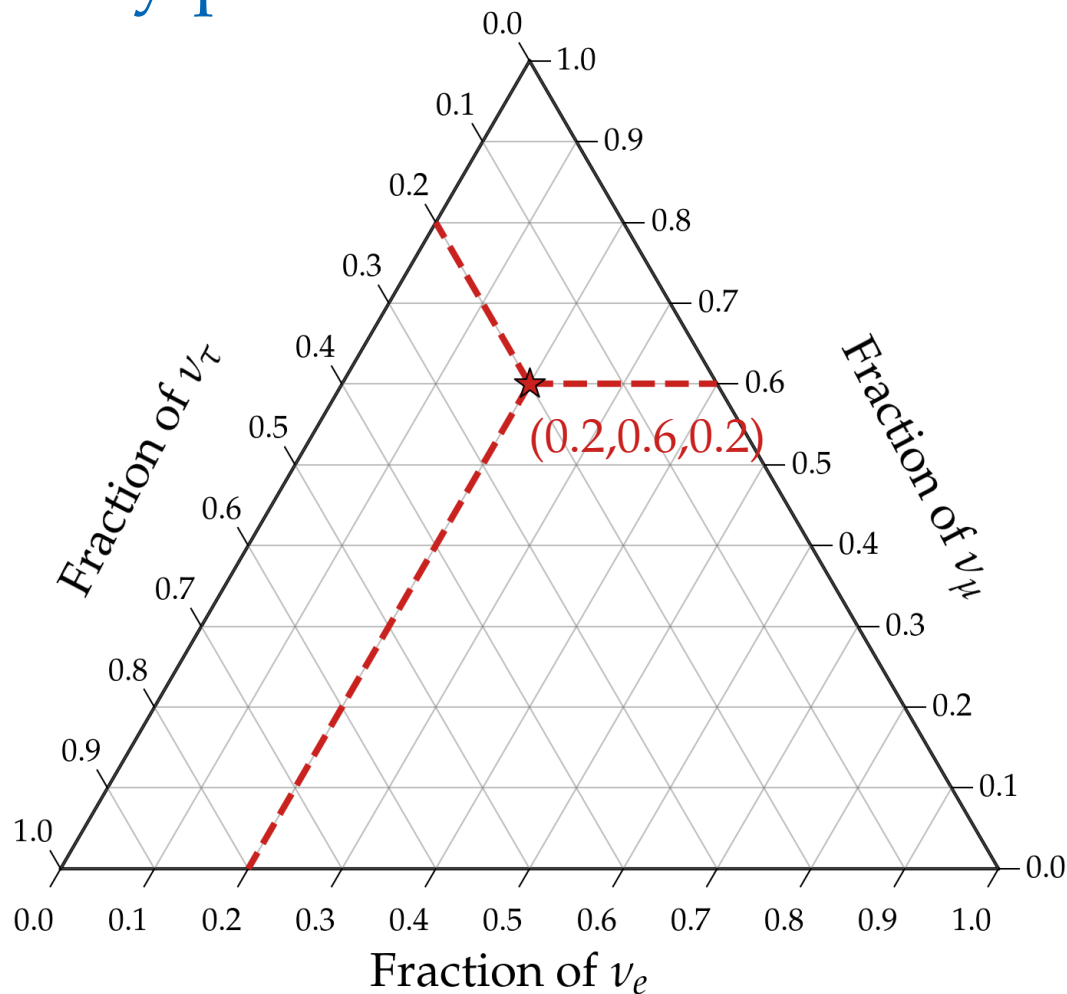
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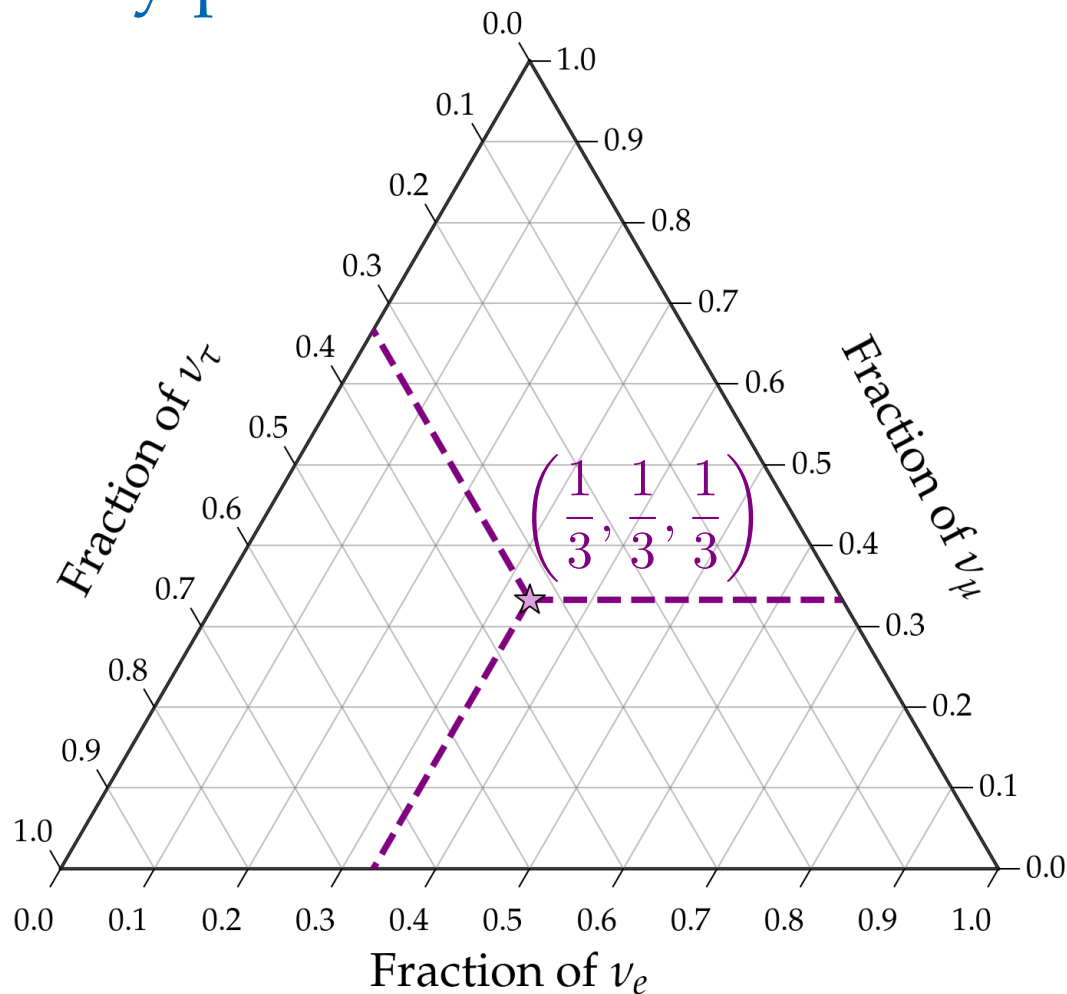
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One likely TeV–PeV ν production scenario:

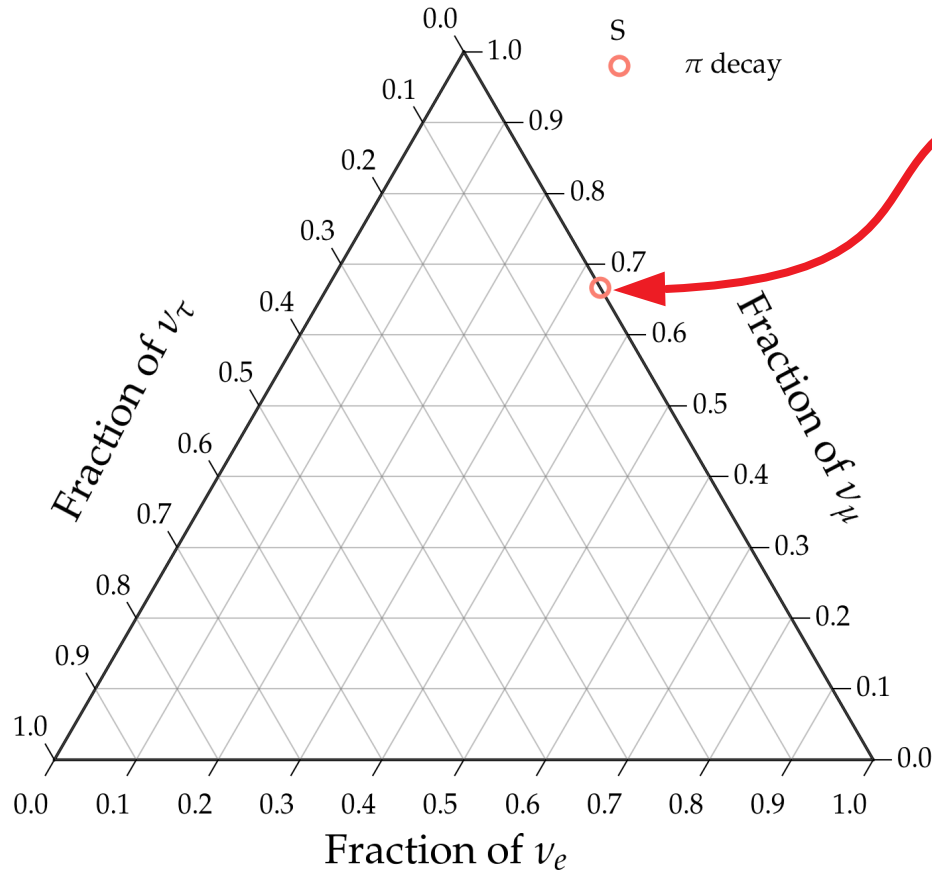
$$p + \gamma \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu \text{ followed by } \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Full π decay chain

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

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

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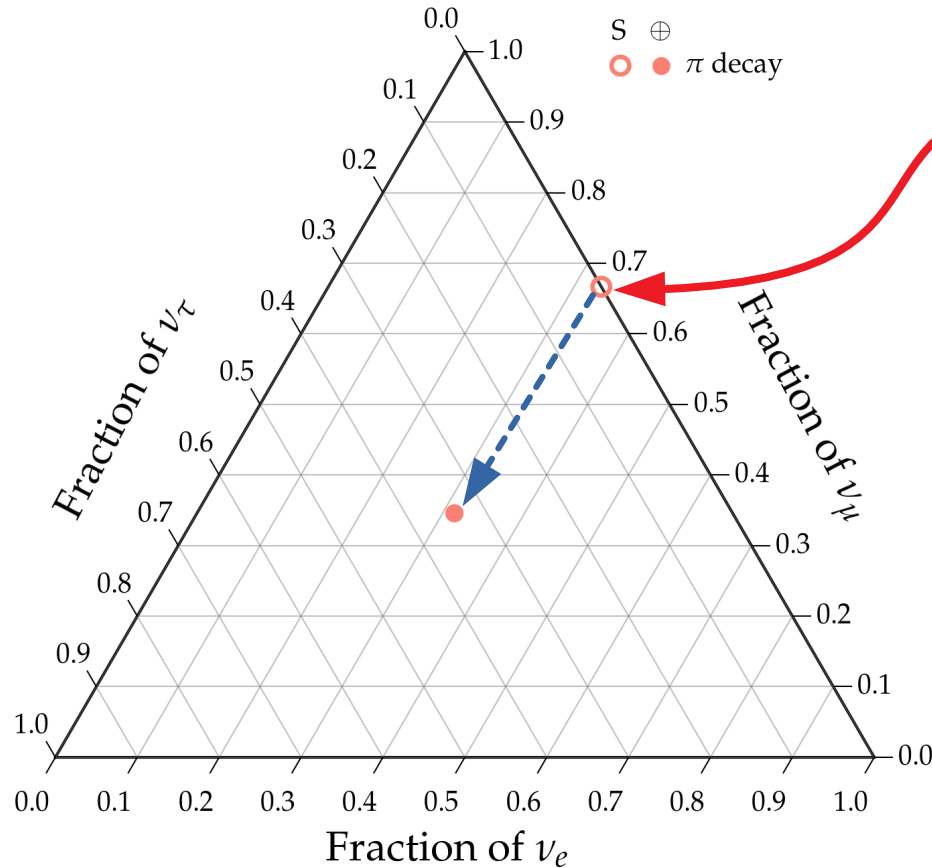


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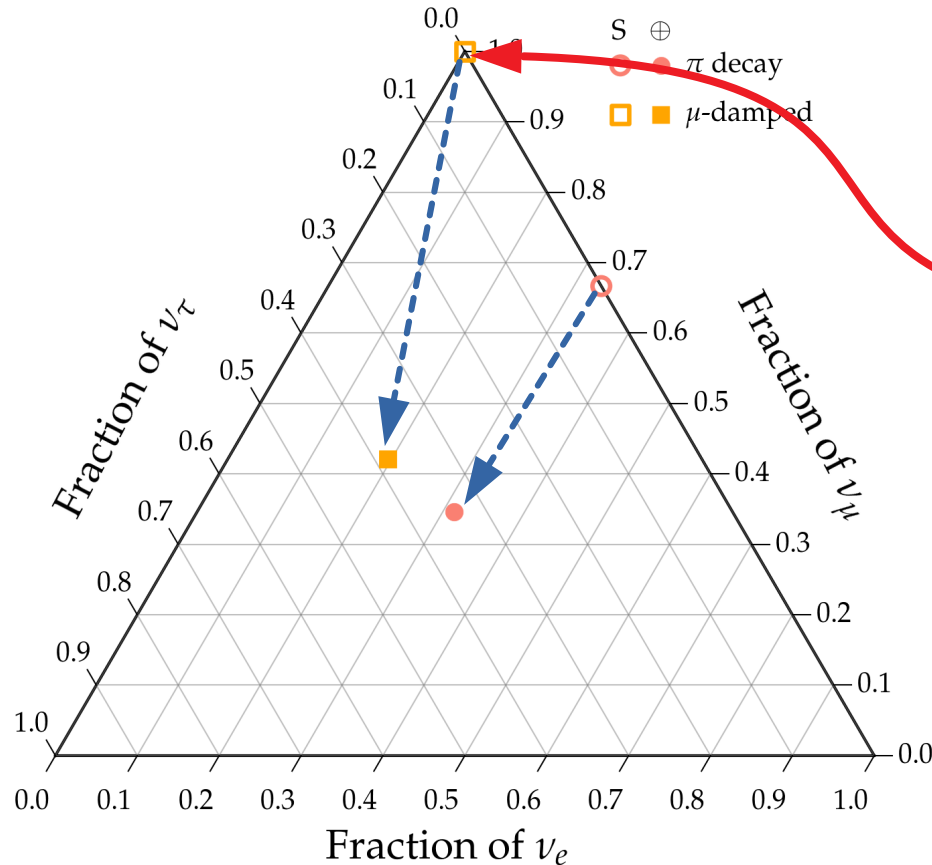
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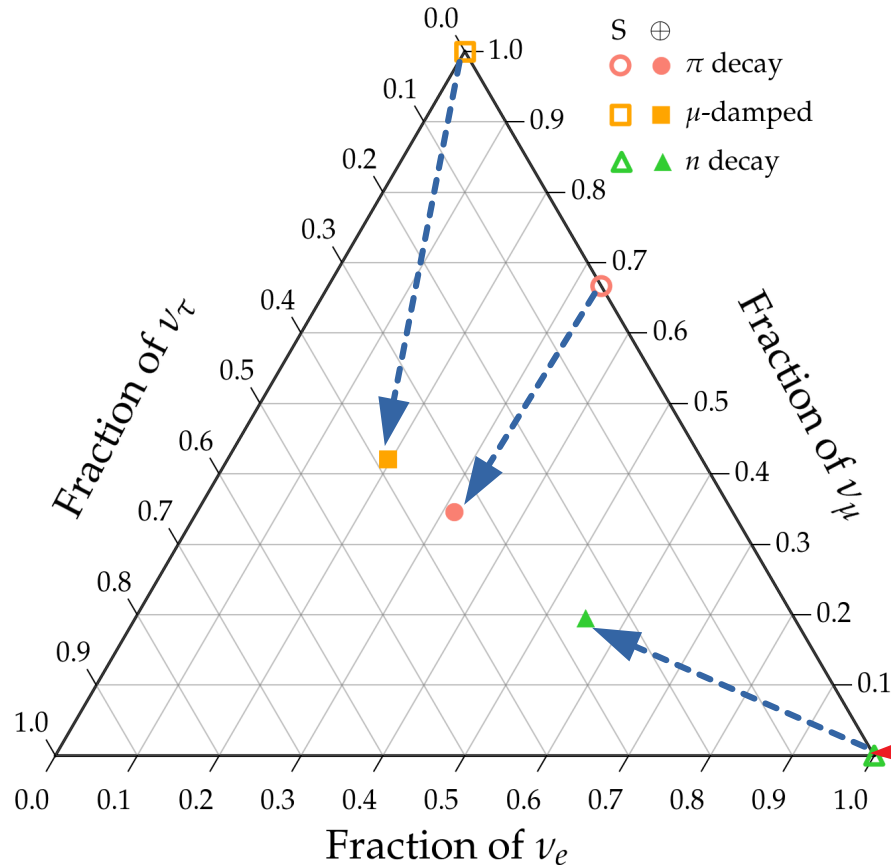
$(1/3:2/3:0)_S$

Muon damped

$(0:1:0)_S$

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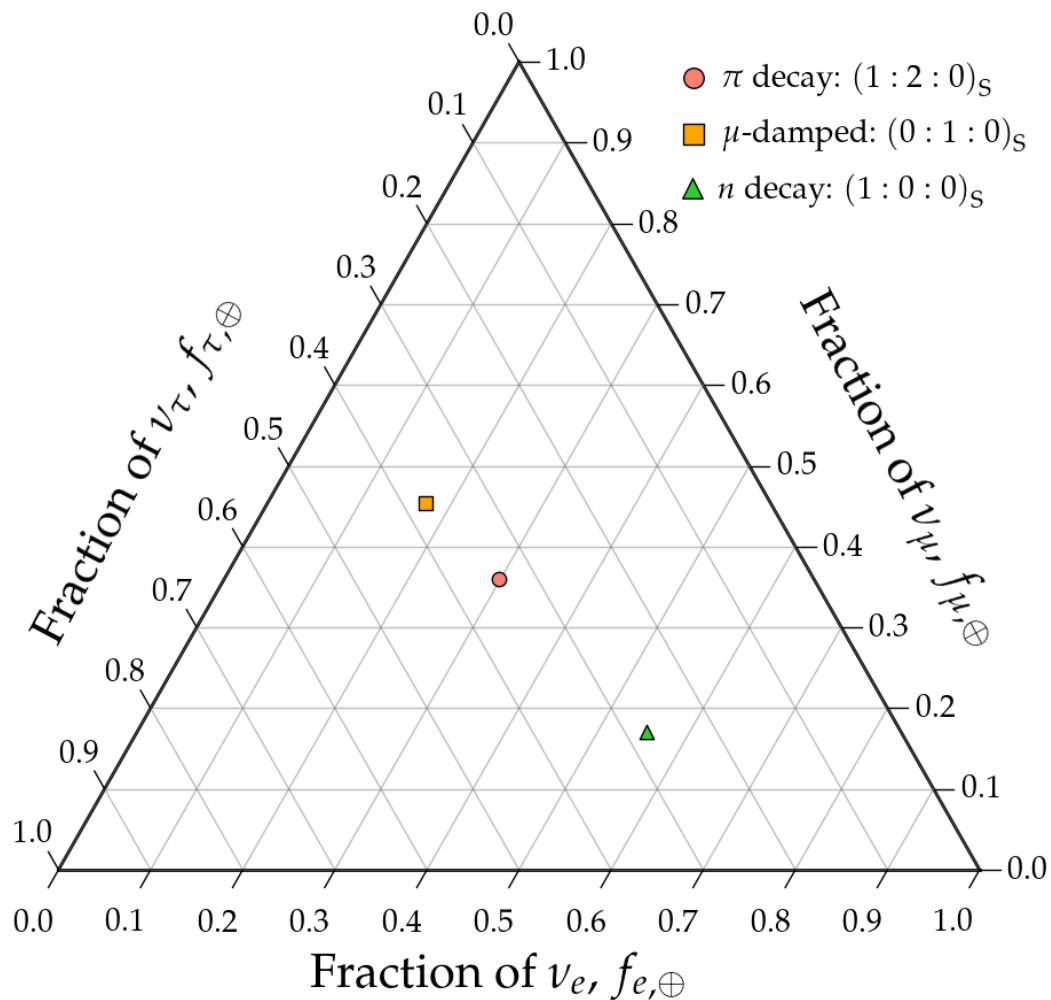
Neutron decay

$(1:0:0)_S$

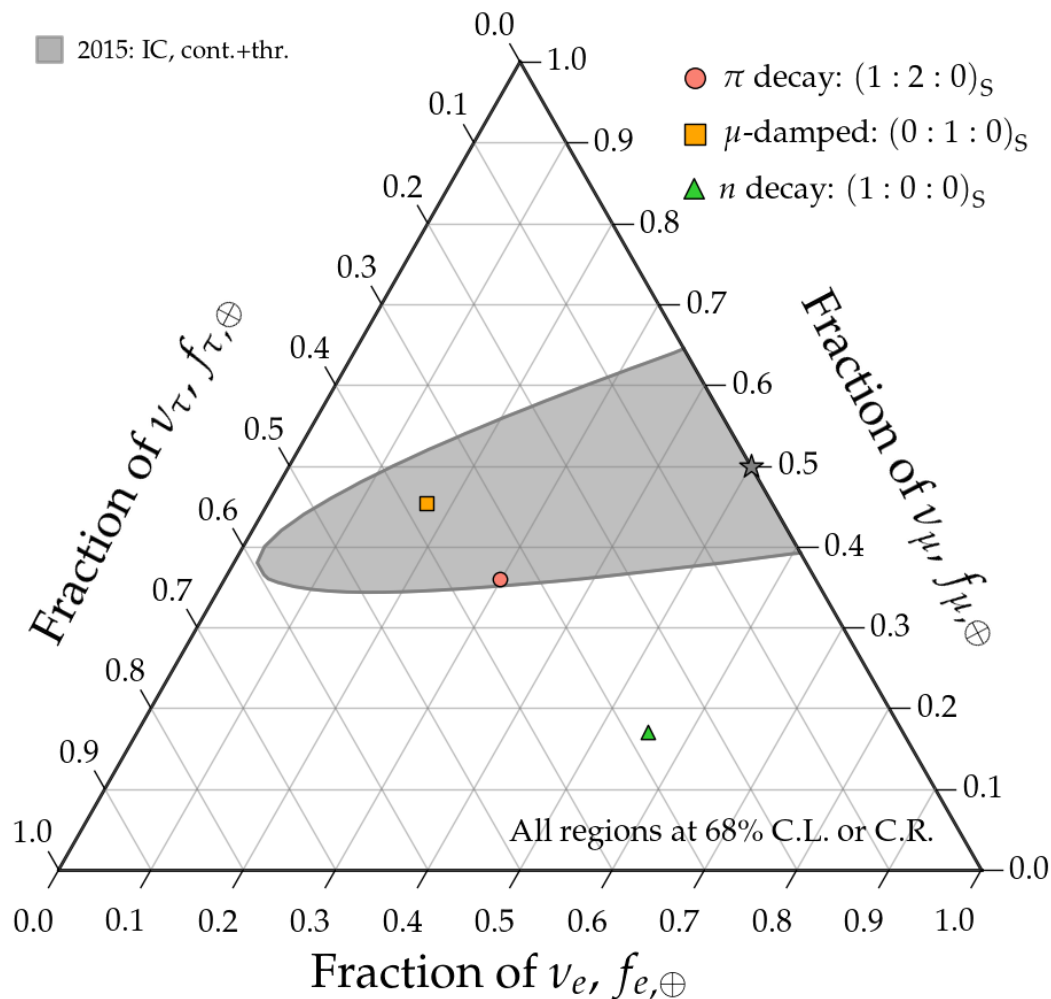
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Measuring flavor composition

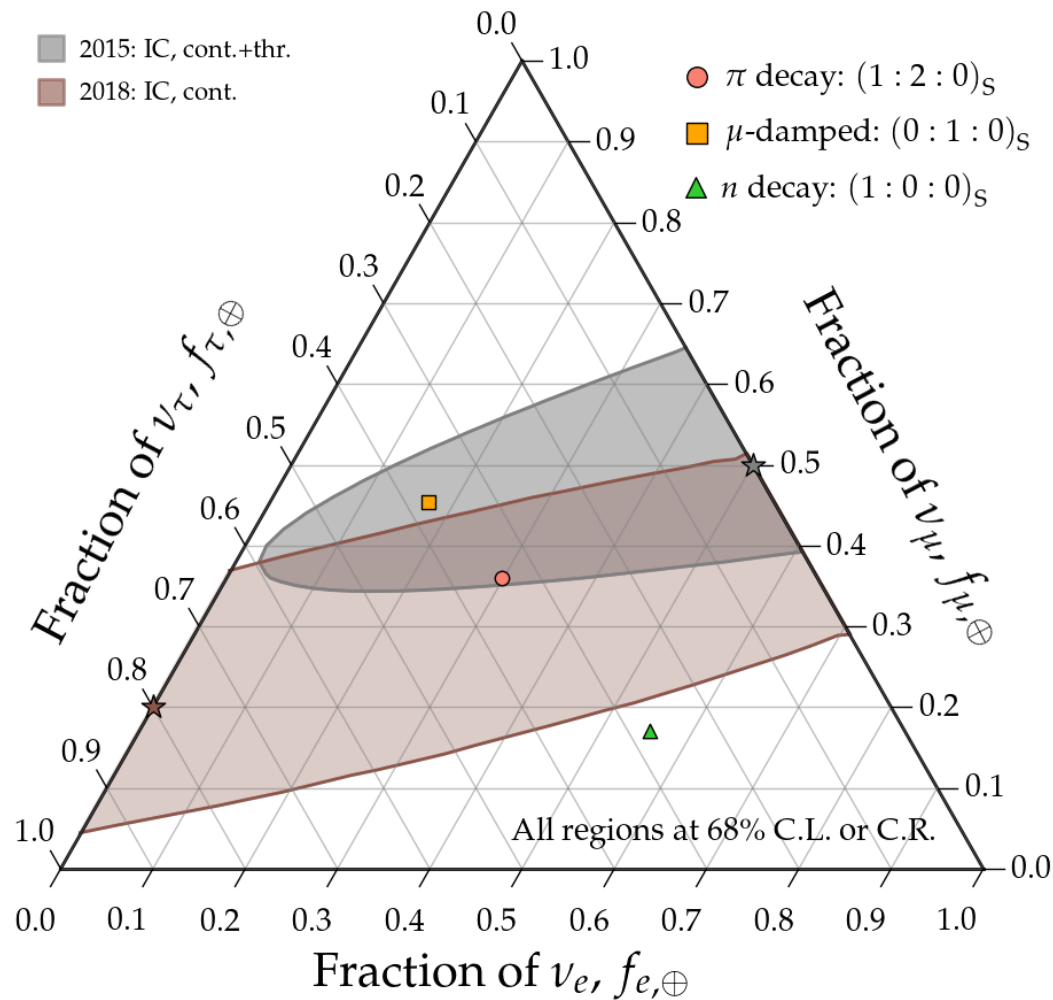
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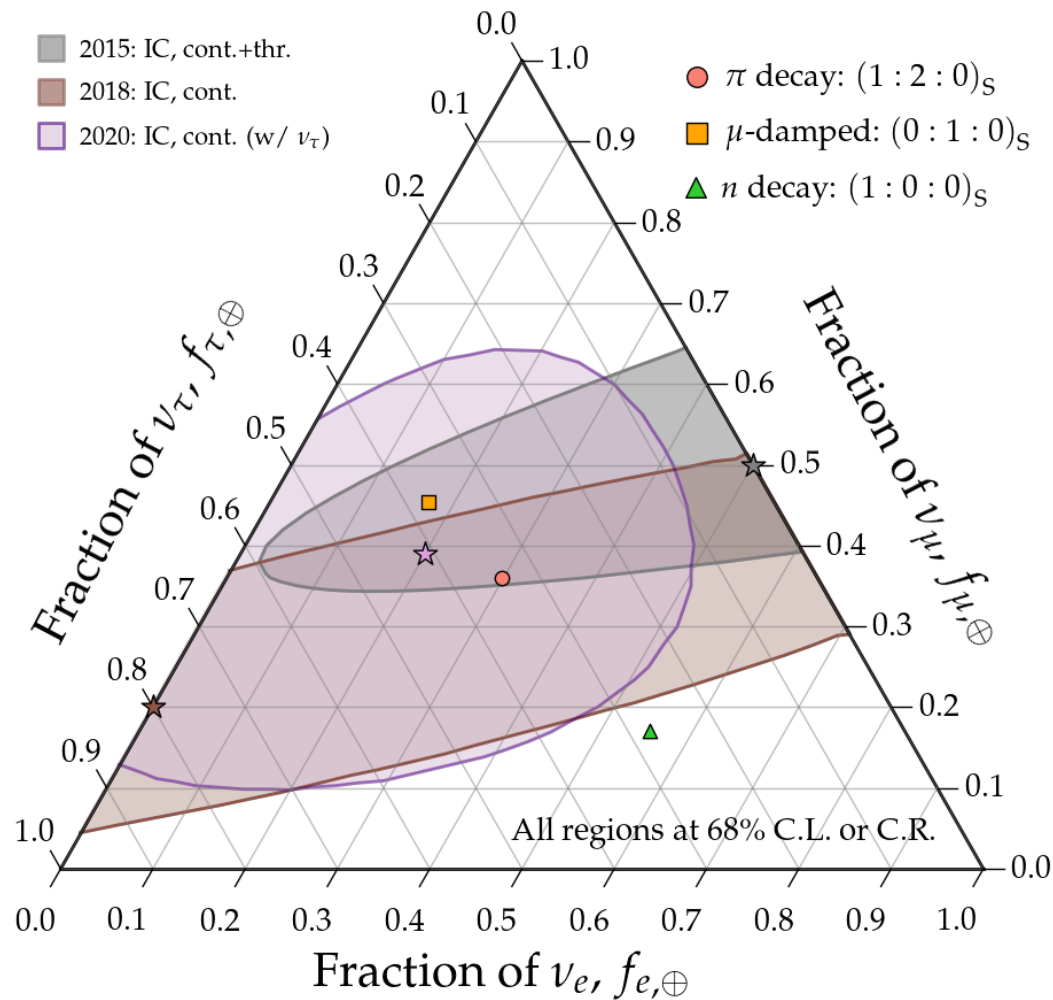
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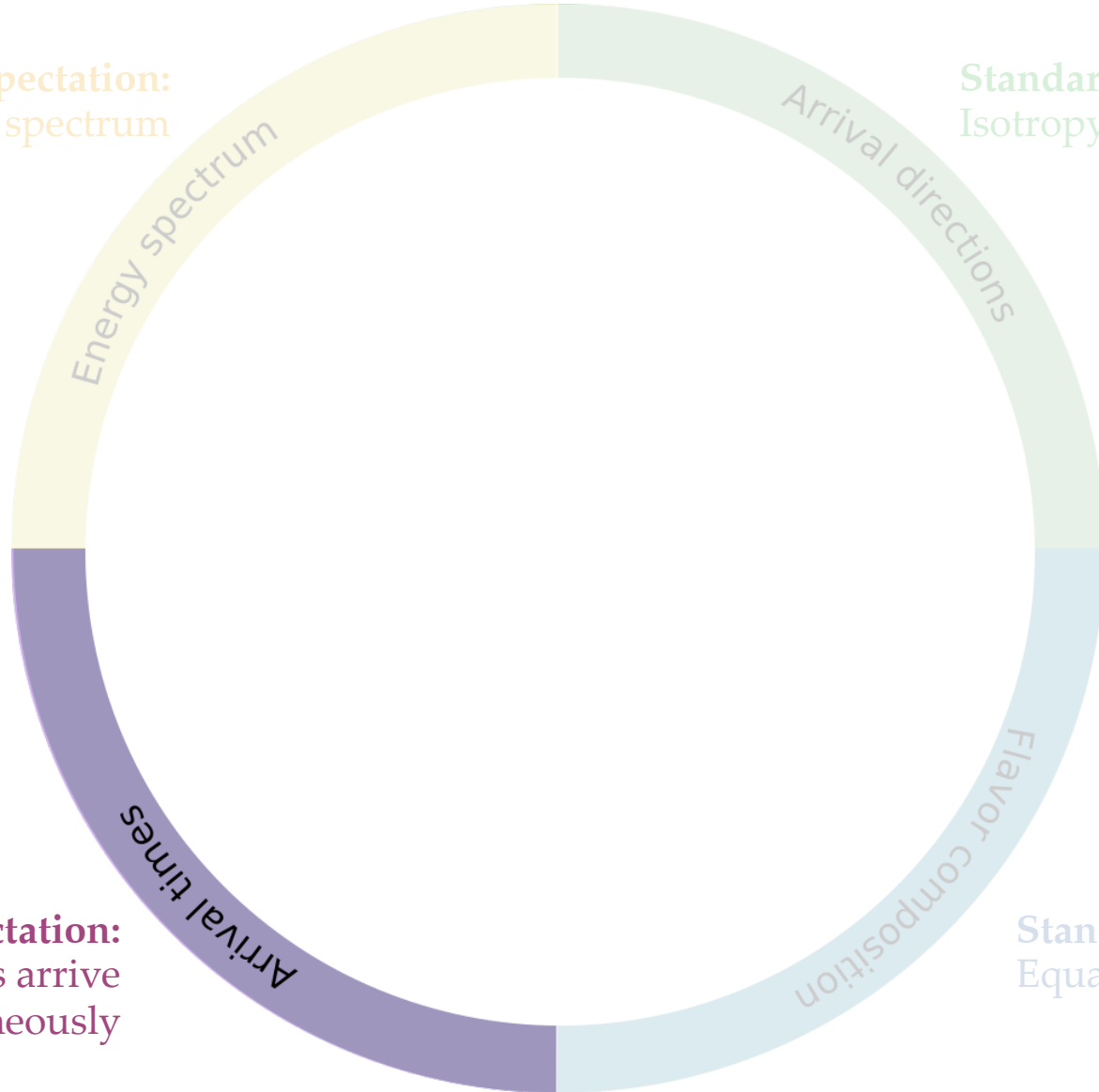


Measuring flavor composition



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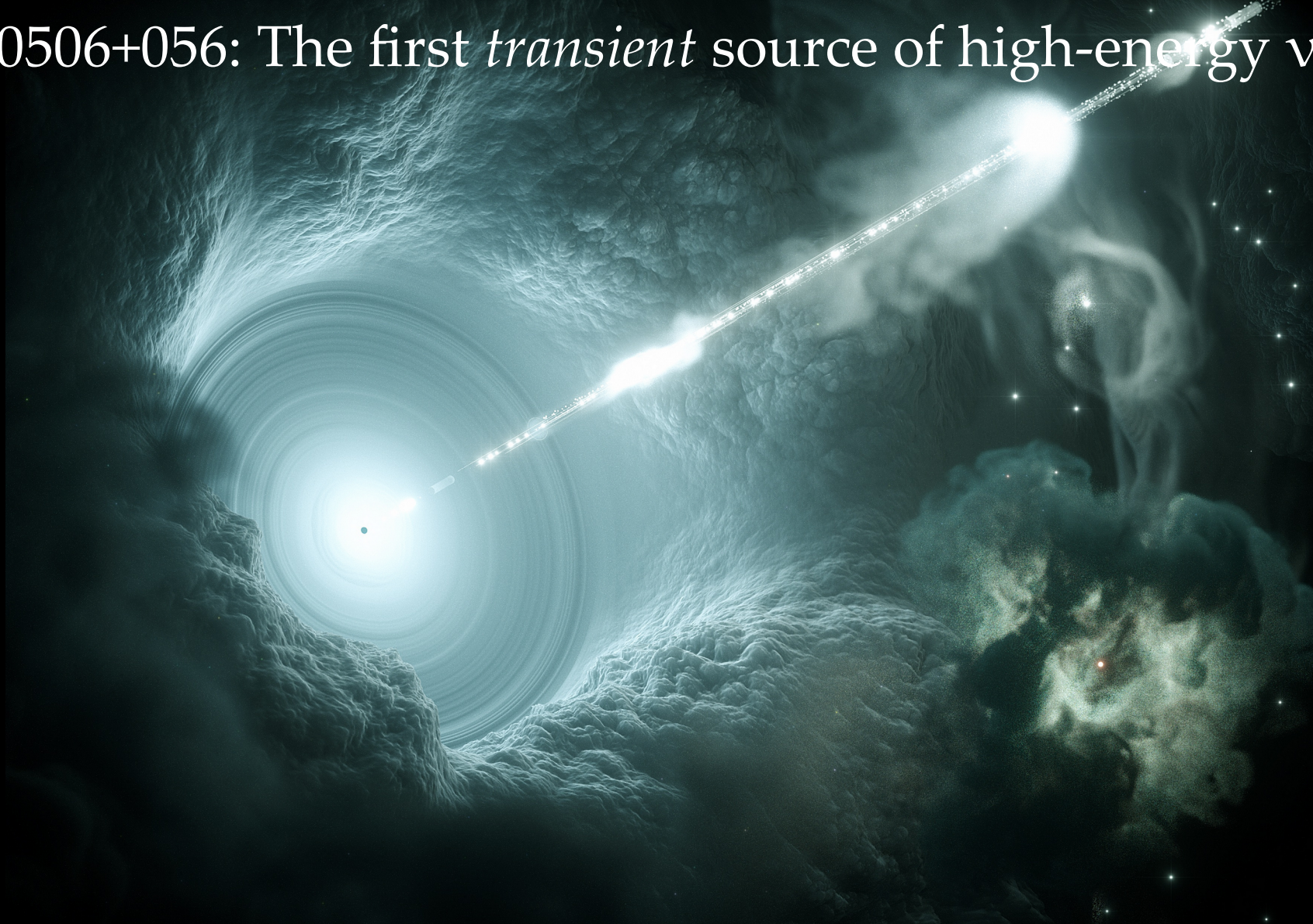
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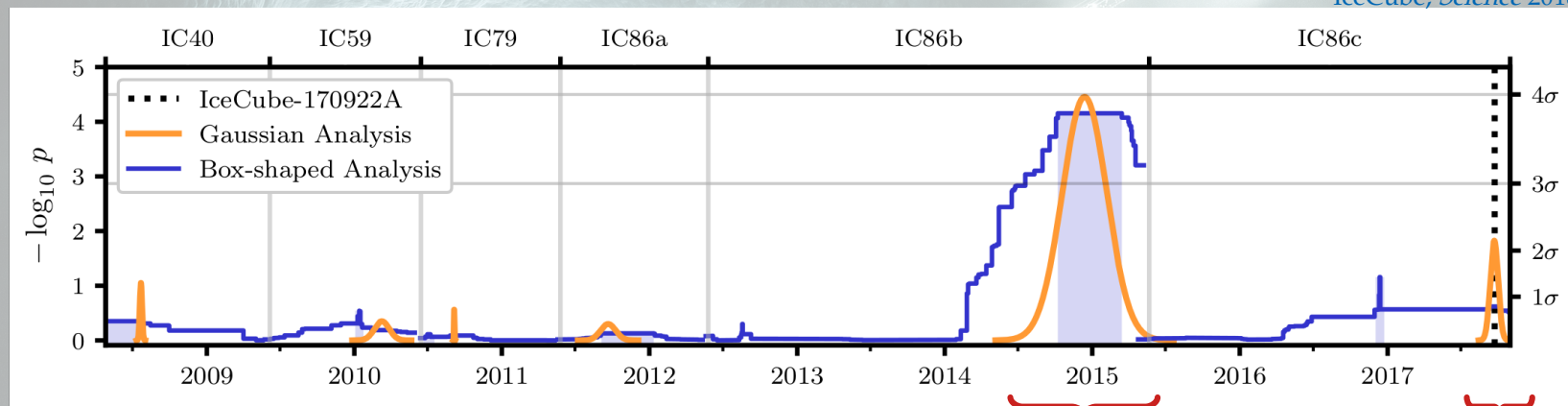
TXS 0506+056: The first *transient* source of high-energy ν



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

Blazar TXS 0506+056:

IceCube, *Science* 2018



After re-analysis (2101.09836),
significance dropped
from $p=7 \times 10^{-5}$ to $p=8 \times 10^{-3}$

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

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

Combined (pre-trial): 4.1σ

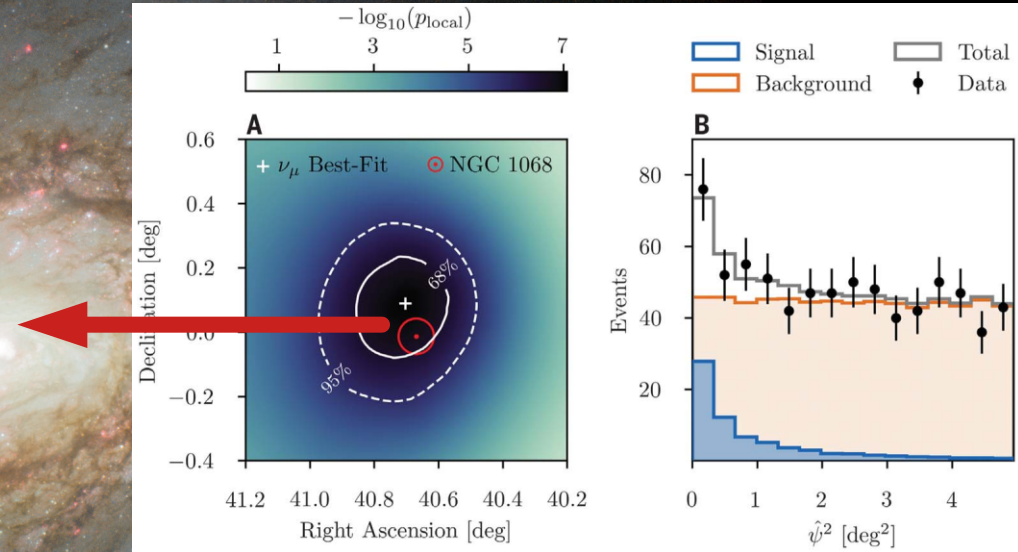
NGC1068: The first *steady-state* source of high-energy ν

Active galactic nucleus

Brightest type-2 Seyfert

79^{+22}_{-20} ν of TeV energy

Significance: 4.2σ (global)



What have we learned
about particle physics?

Fundamental physics with high-energy cosmic neutrinos

- ▶ Numerous new ν physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$
- ▶ So we can probe $\kappa_n \sim 4 \cdot 10^{-47} (E/\text{PeV})^{-n} (L/\text{Gpc})^{-1} \text{PeV}^{1-n}$
- ▶ Improvement over limits using atmospheric ν : $\kappa_0 < 10^{-29} \text{PeV}$, $\kappa_1 < 10^{-33}$

Fundamental physics with high-energy cosmic neutrinos

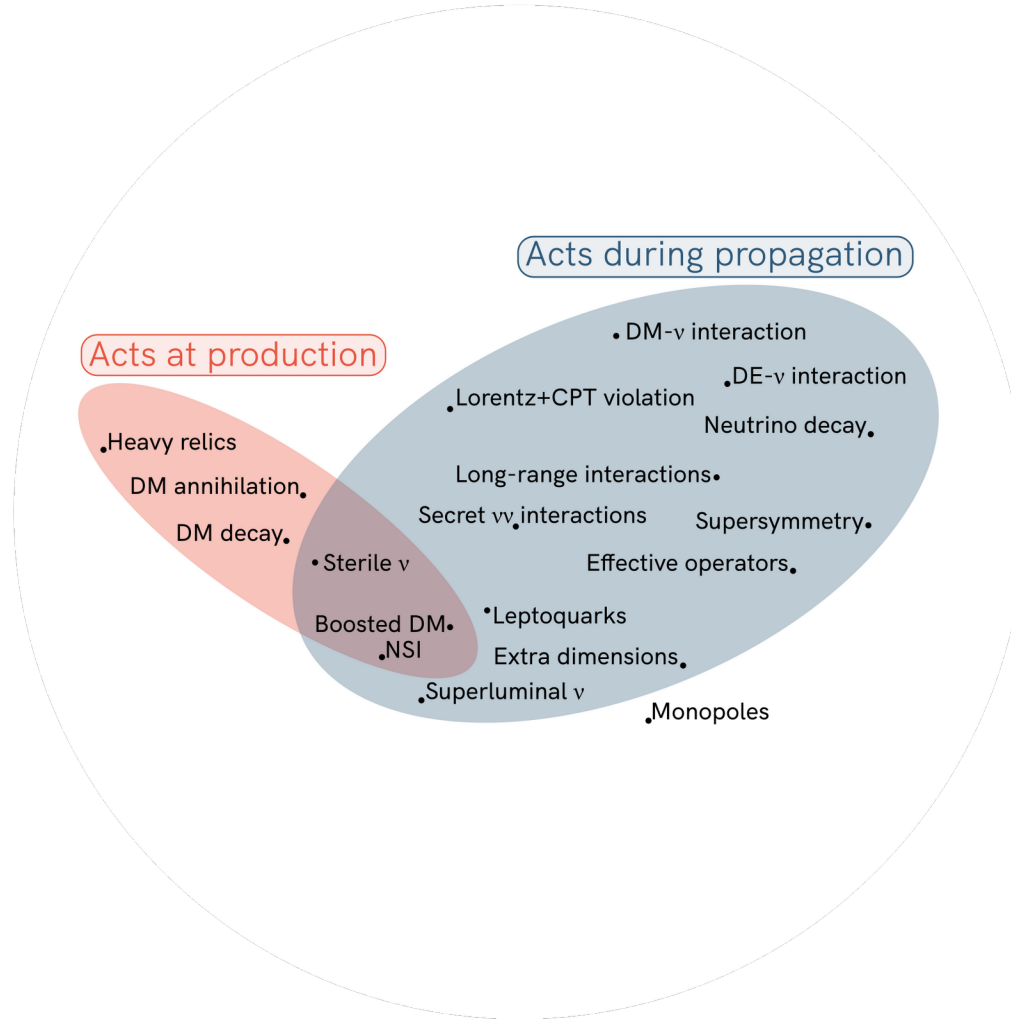
- ▶ Numerous new ν physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$ $\left. \begin{array}{l} \text{E.g.,} \\ n = -1: \text{neutrino decay} \\ n = 0: \text{CPT-odd Lorentz violation} \\ n = +1: \text{CPT-even Lorentz violation} \end{array} \right\}$
- ▶ So we can probe $\kappa_n \sim 4 \cdot 10^{-47} (E/\text{PeV})^{-n} (L/\text{Gpc})^{-1} \text{PeV}^{1-n}$
- ▶ Improvement over limits using atmospheric ν : $\kappa_0 < 10^{-29} \text{PeV}$, $\kappa_1 < 10^{-33}$



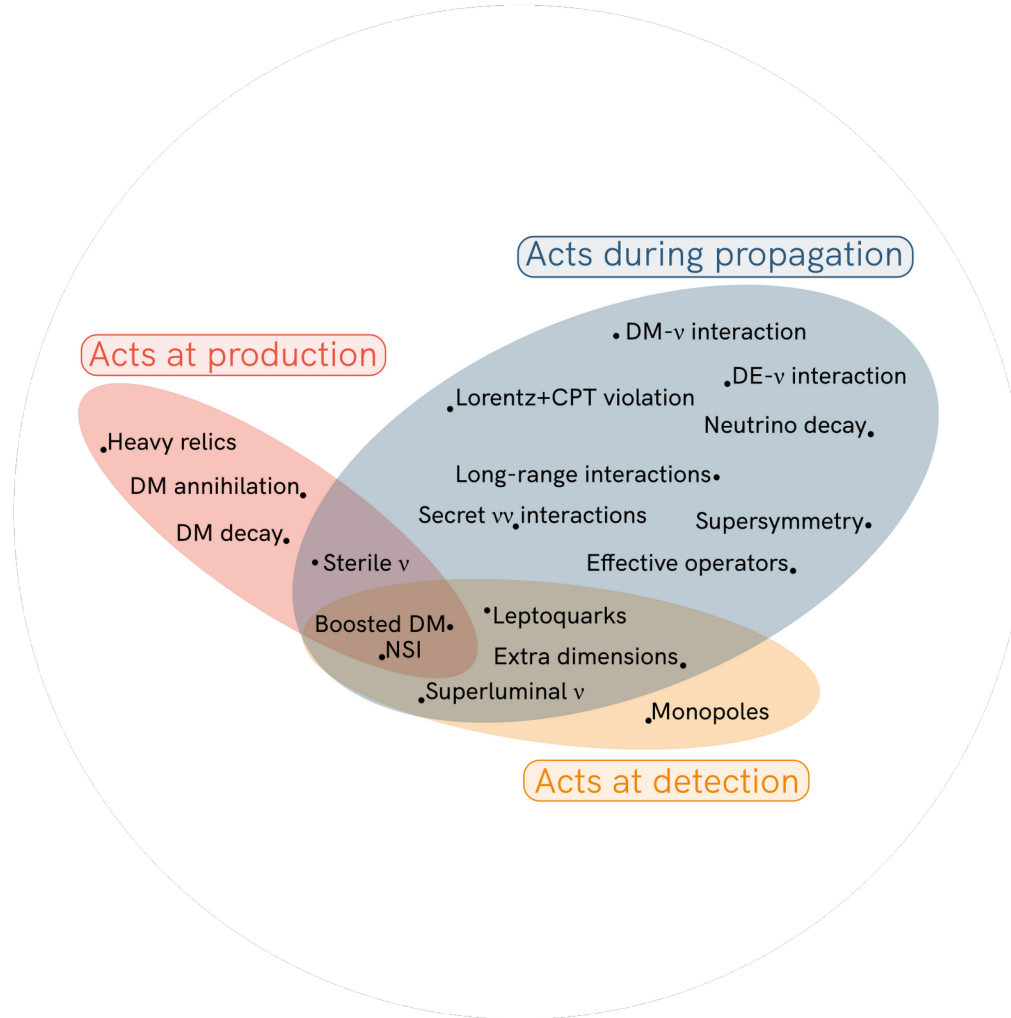
Note: Not an exhaustive list



Note: Not an exhaustive list



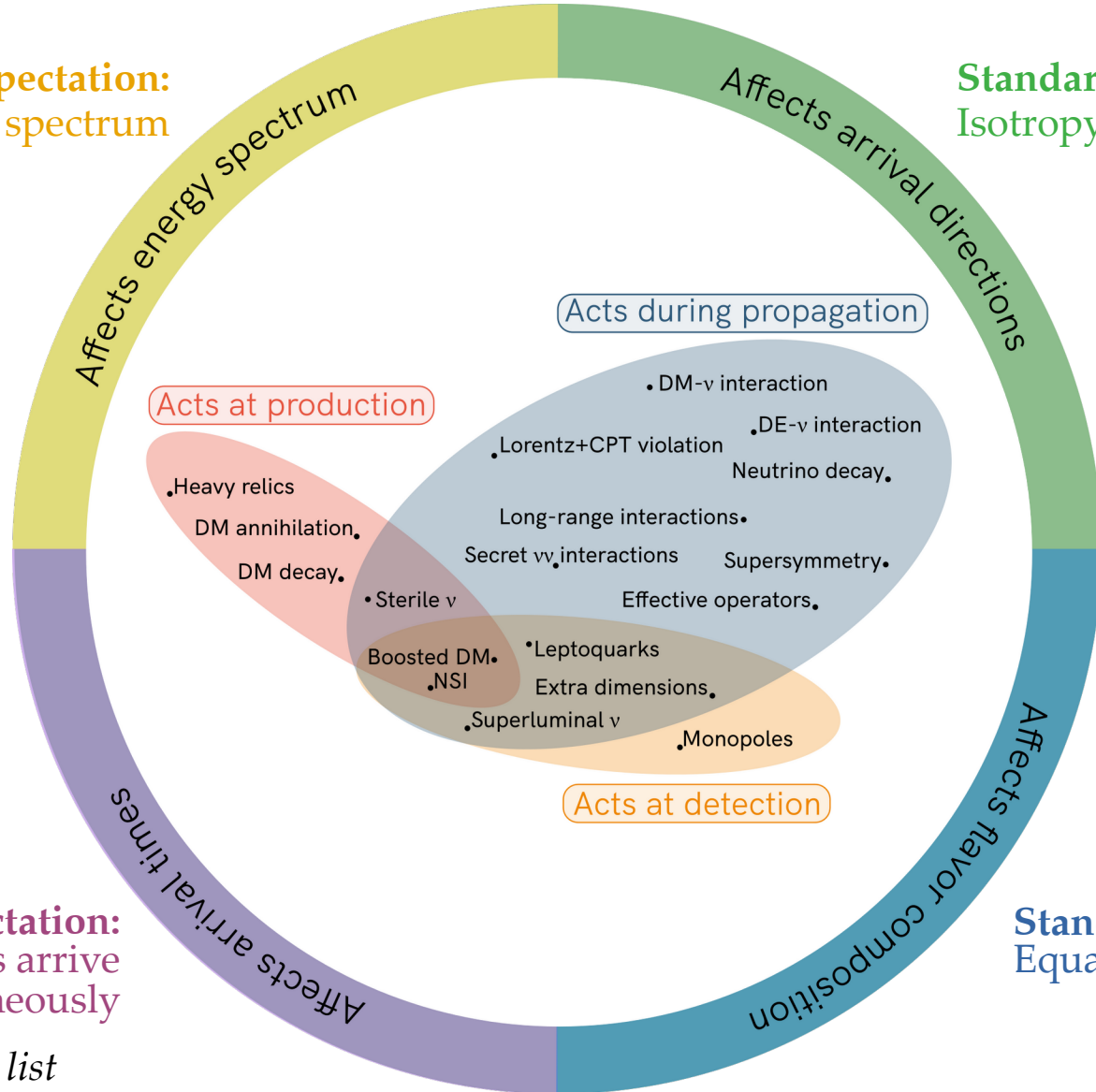
Note: Not an exhaustive list



Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



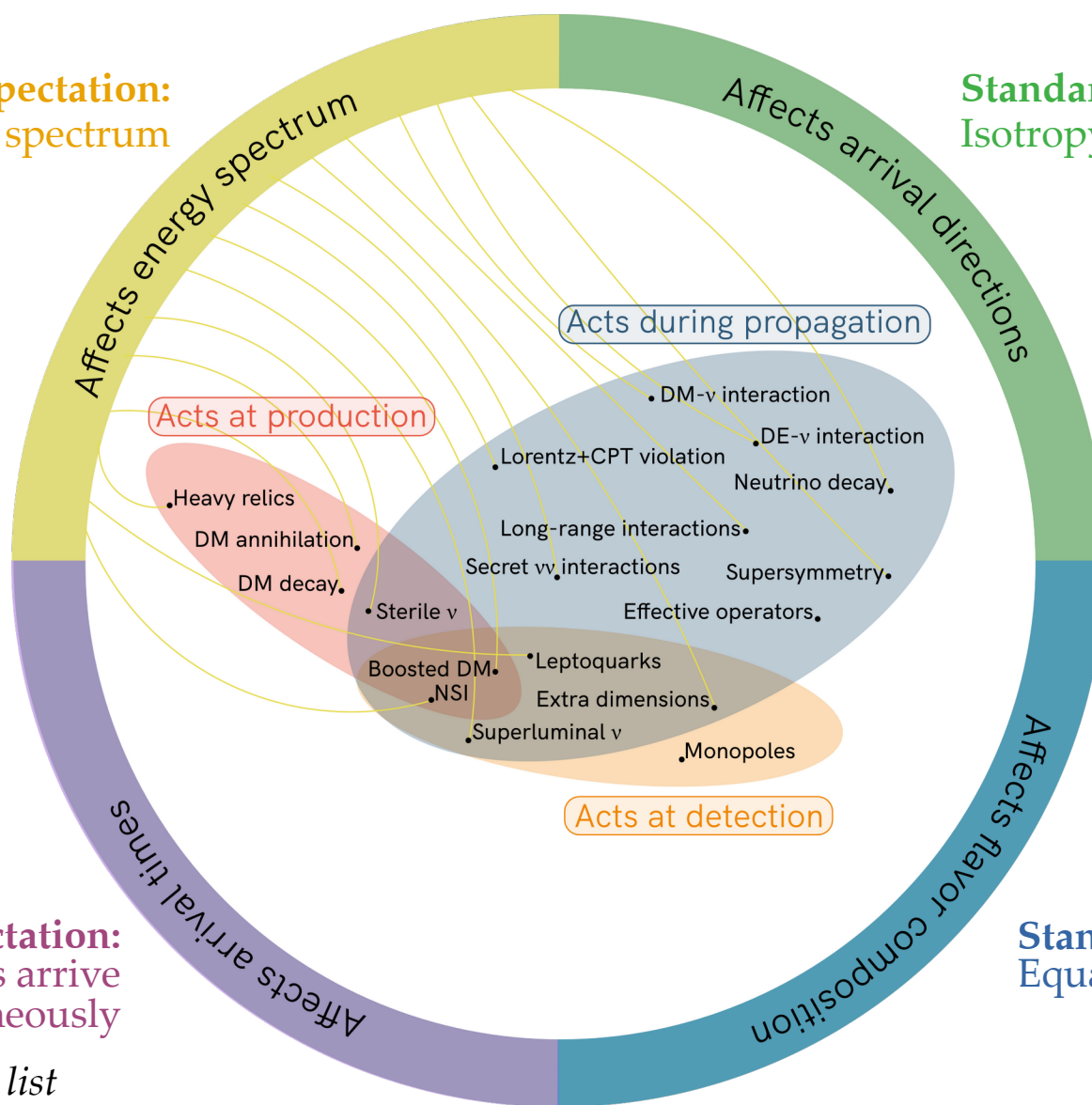
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Standard expectation:
 ν and γ from transients arrive simultaneously

Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



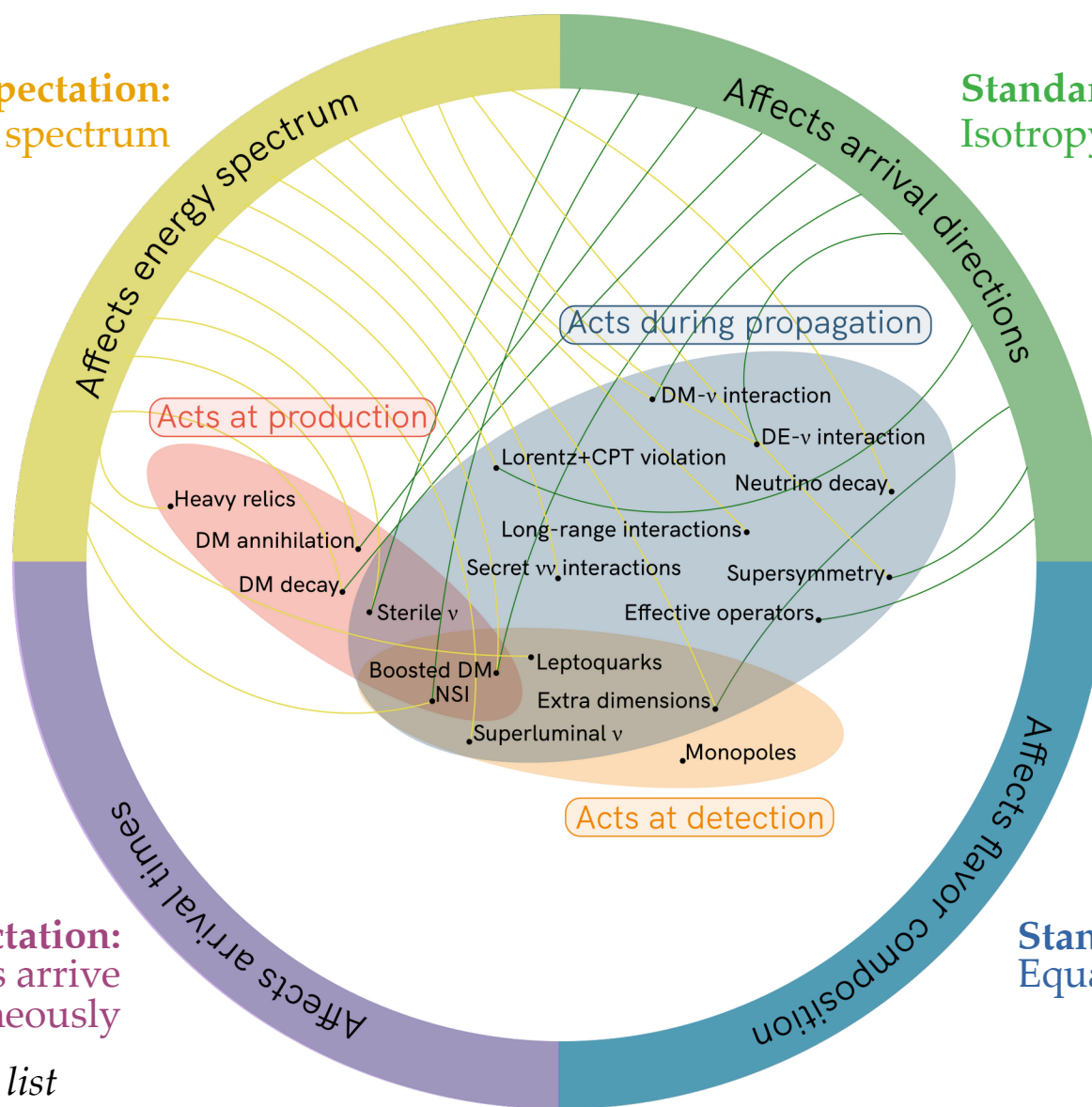
Standard expectation:
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Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
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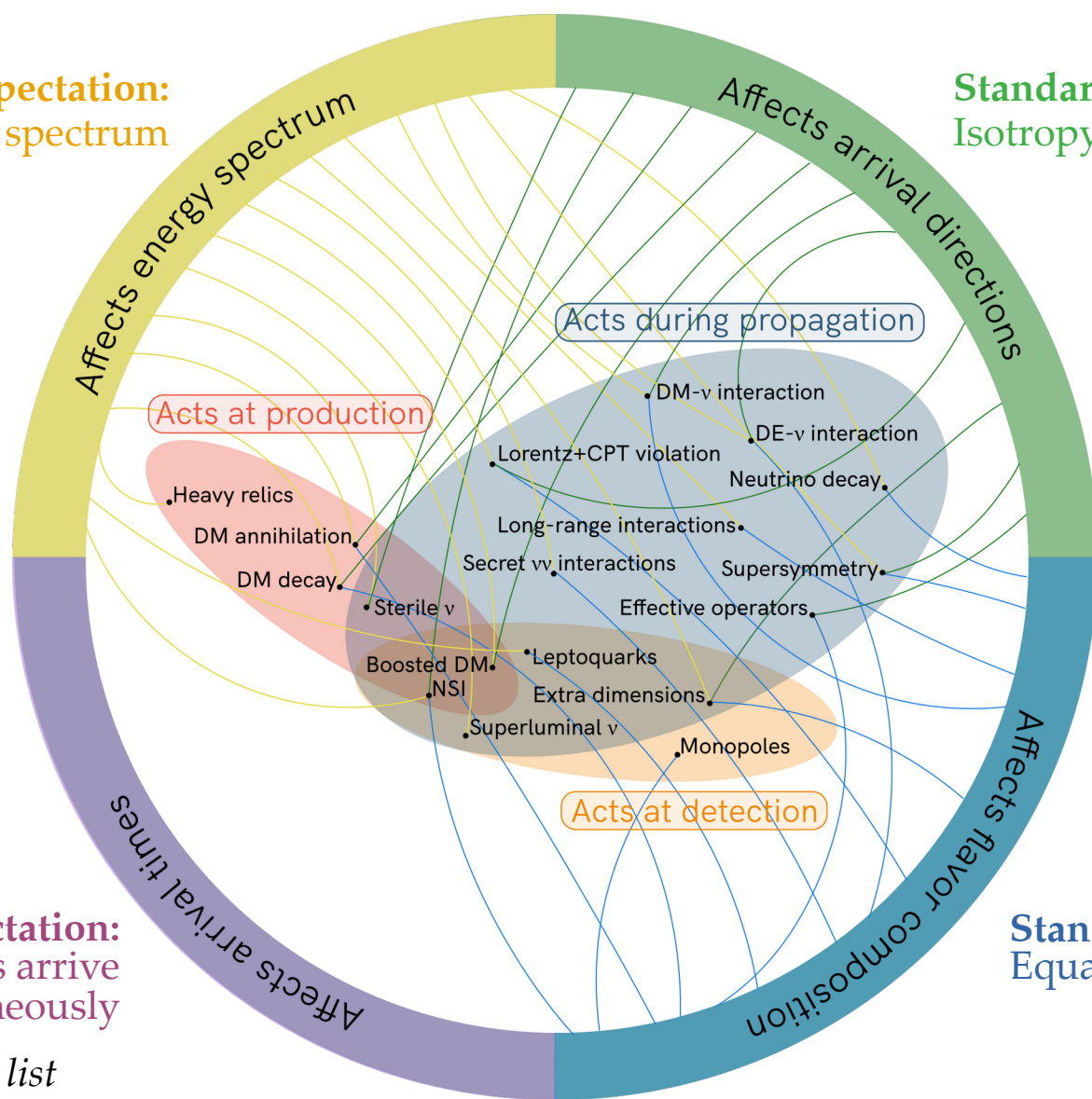
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

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Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



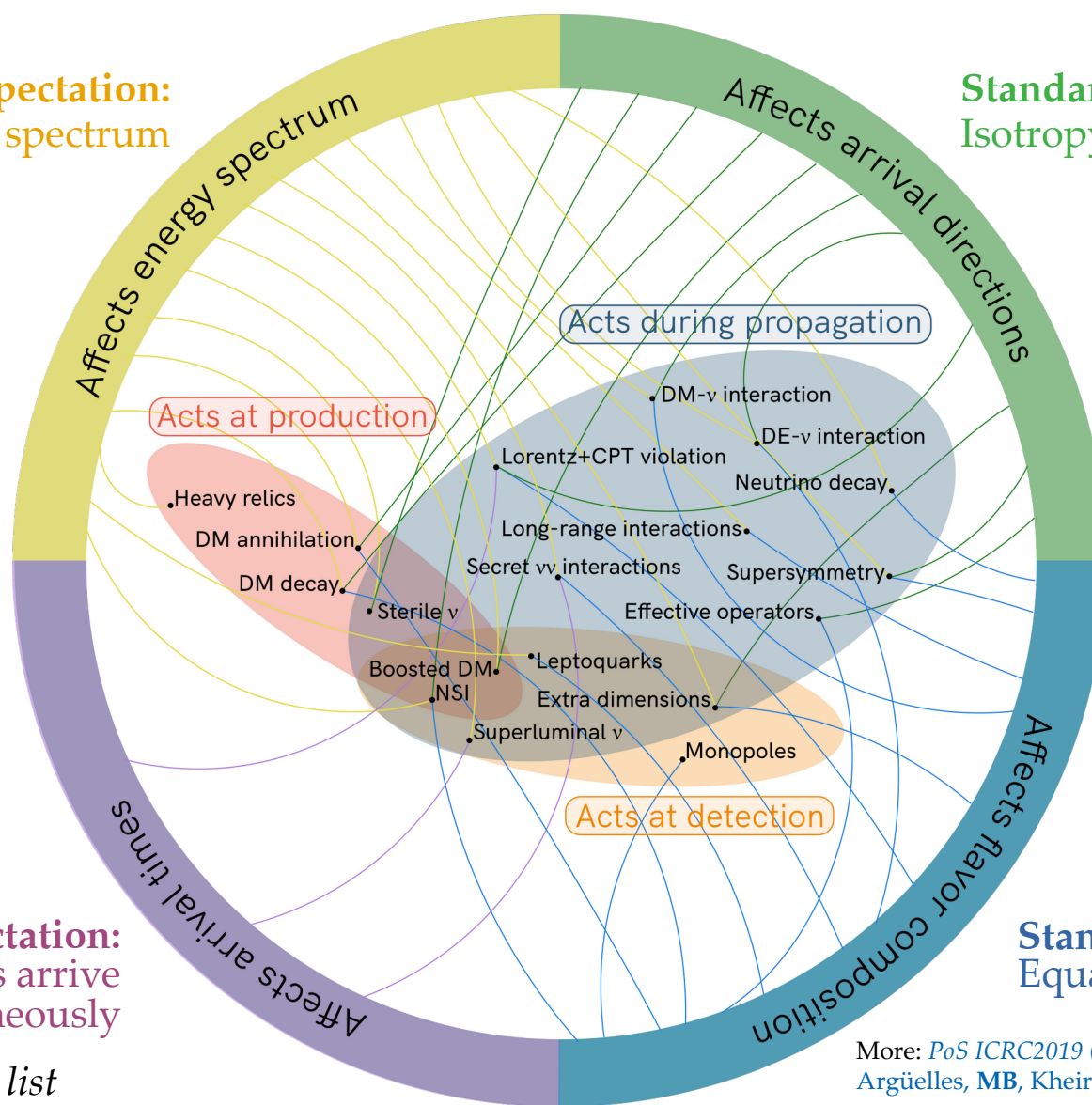
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Standard expectation:
 ν and γ from transients arrive
simultaneously

Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



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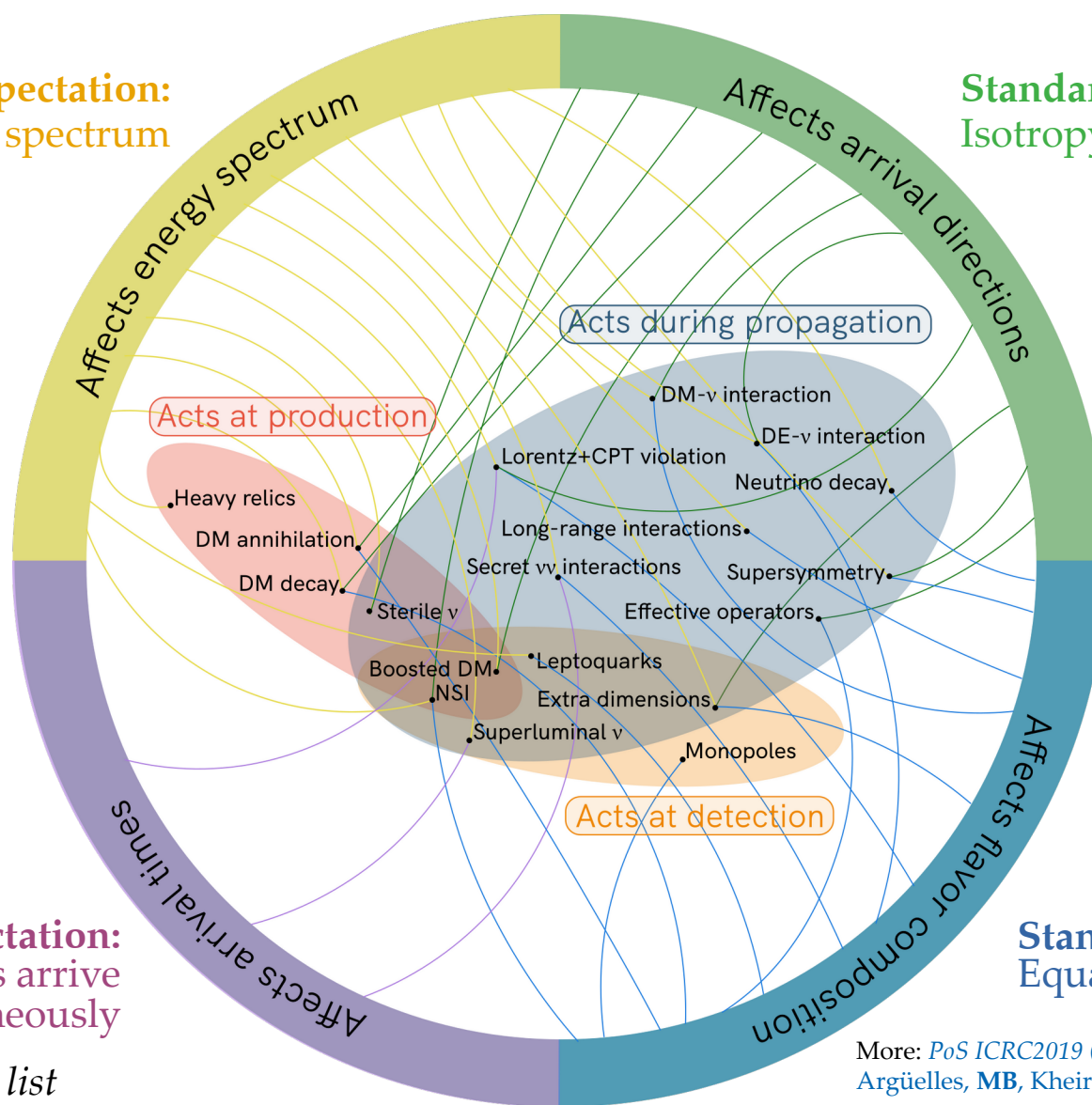
Standard expectation:
 ν and γ from transients arrive simultaneously

Note: Not an exhaustive list

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

Standard expectation:
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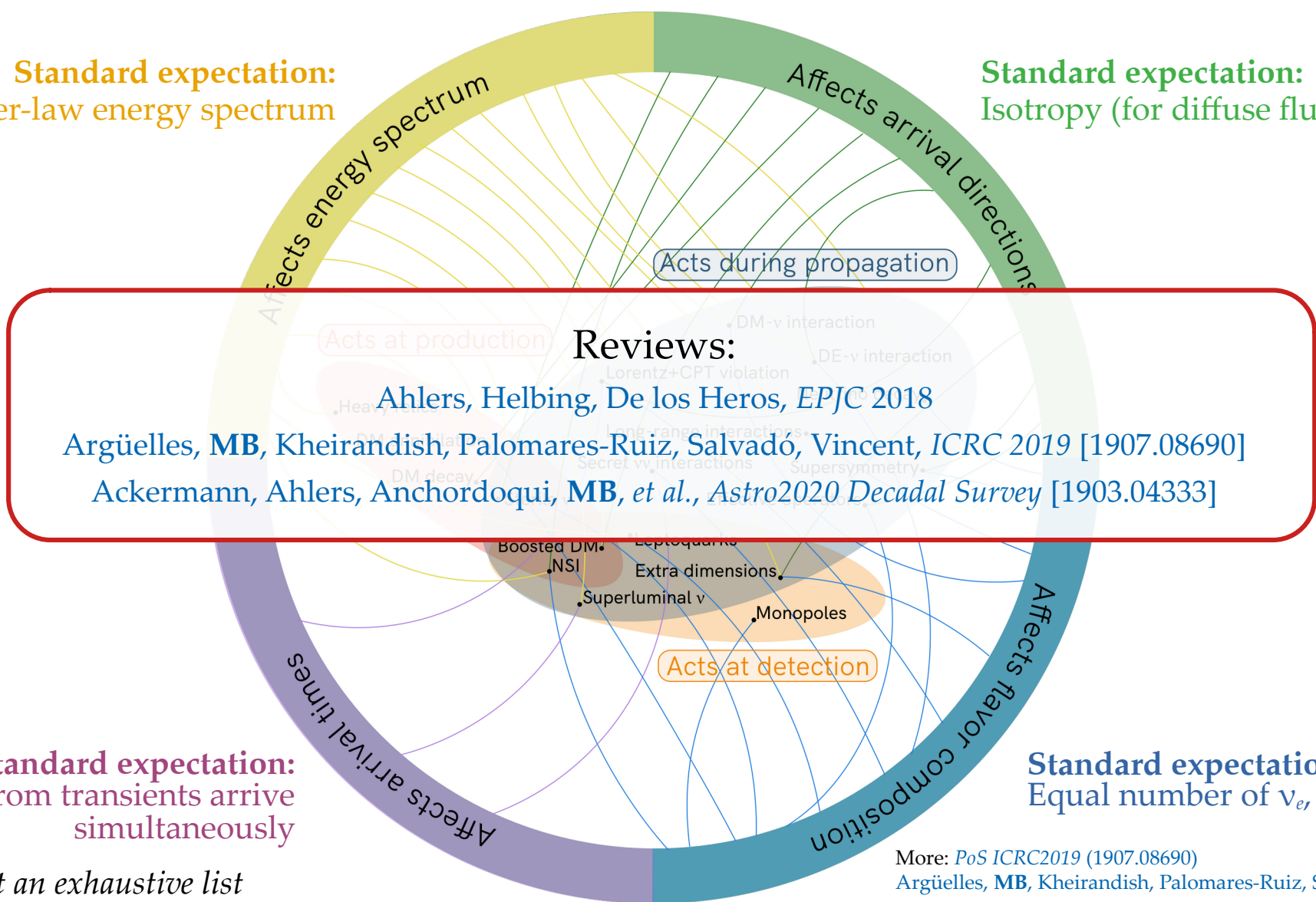
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Note: Not an exhaustive list

A selection of neutrino physics

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

} Find this in
the backup slides

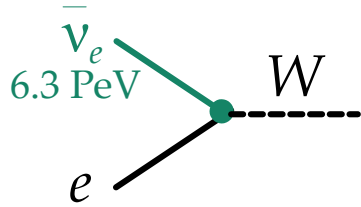
1. Glashow resonance:
Long-sought, finally seen

First observation of a Glashow resonance

Predicted in 1960:

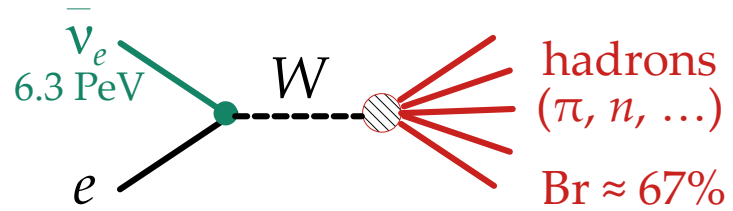
First observation of a Glashow resonance

Predicted in 1960:



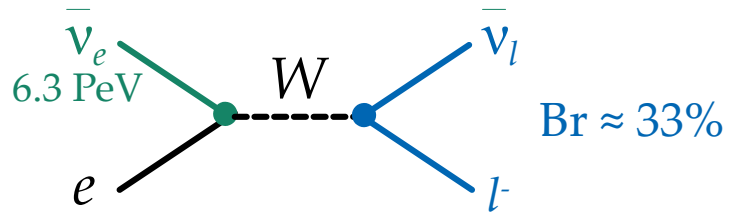
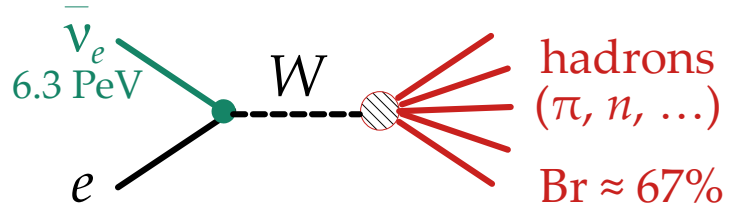
First observation of a Glashow resonance

Predicted in 1960:



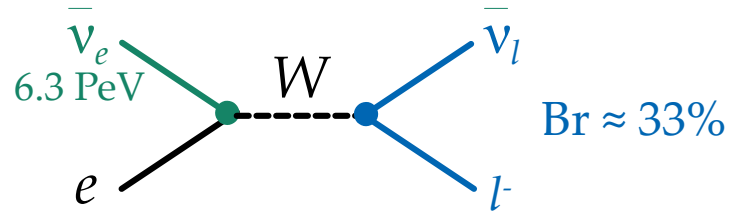
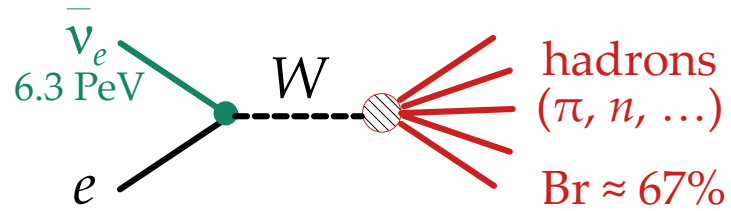
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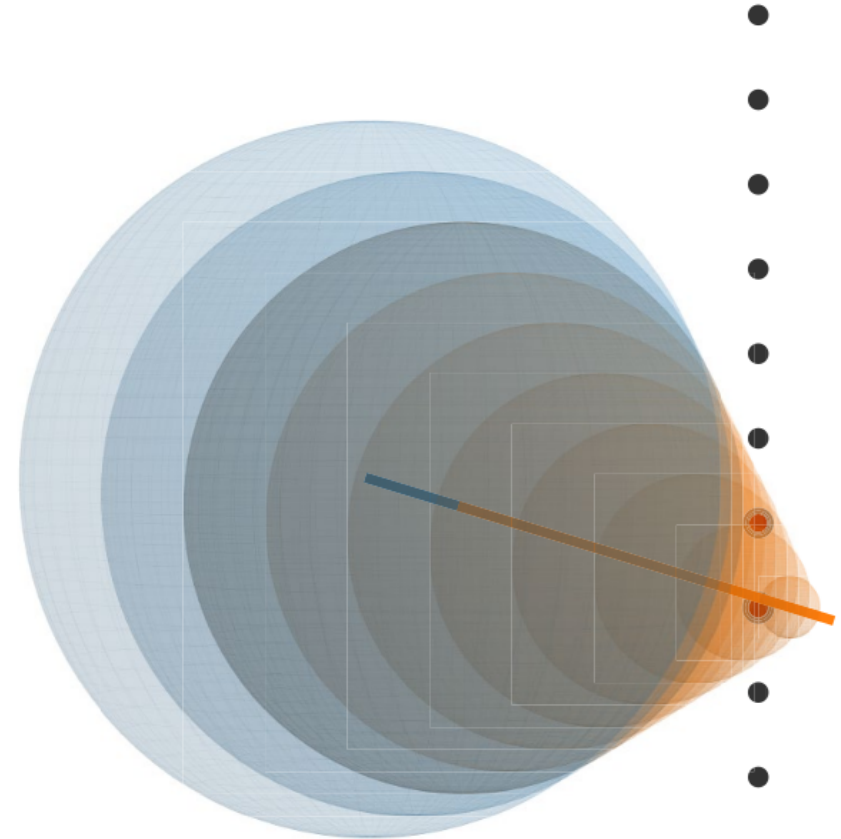


First observation of a Glashow resonance

Predicted in 1960:

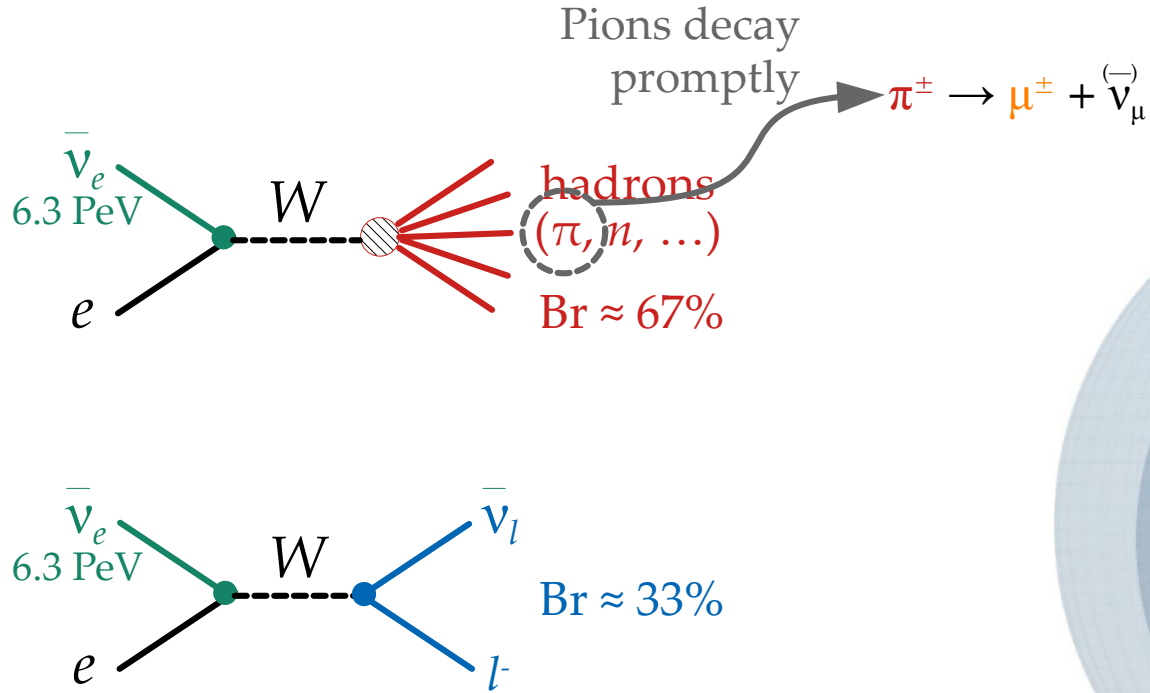


First reported by IceCube in 2021:

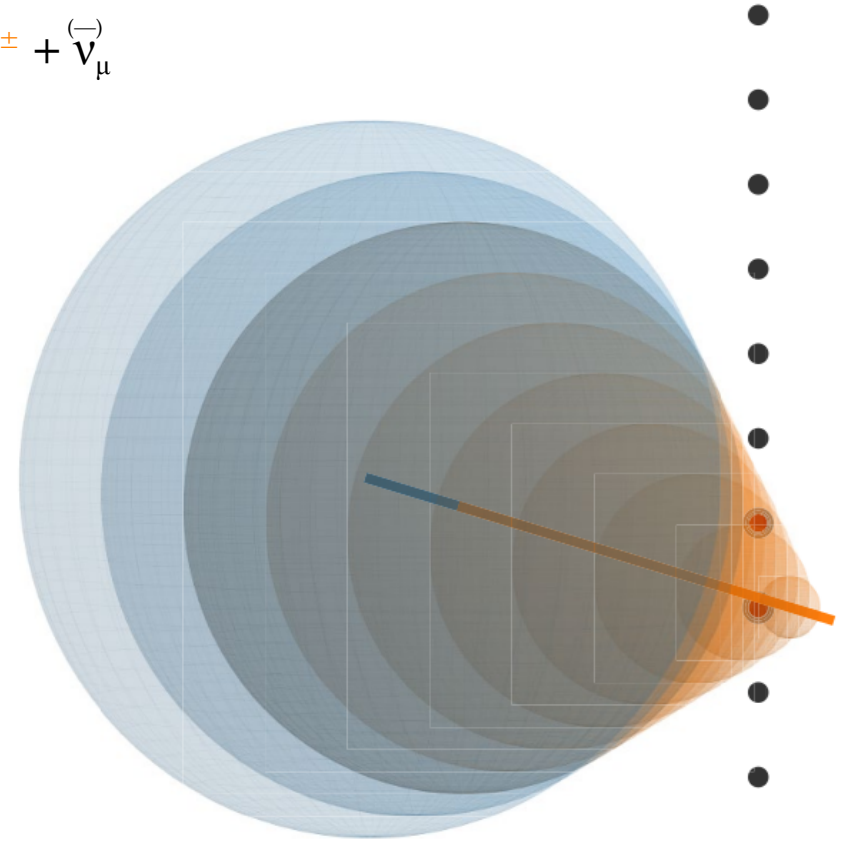


First observation of a Glashow resonance

Predicted in 1960:

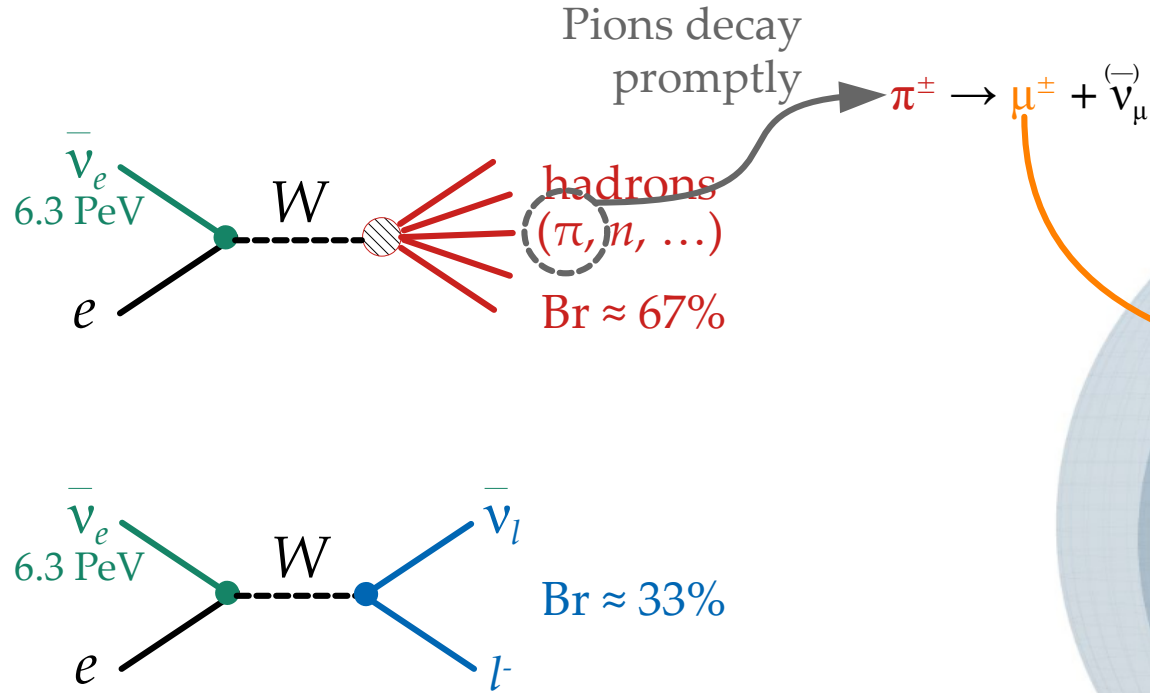


First reported by IceCube in 2021:

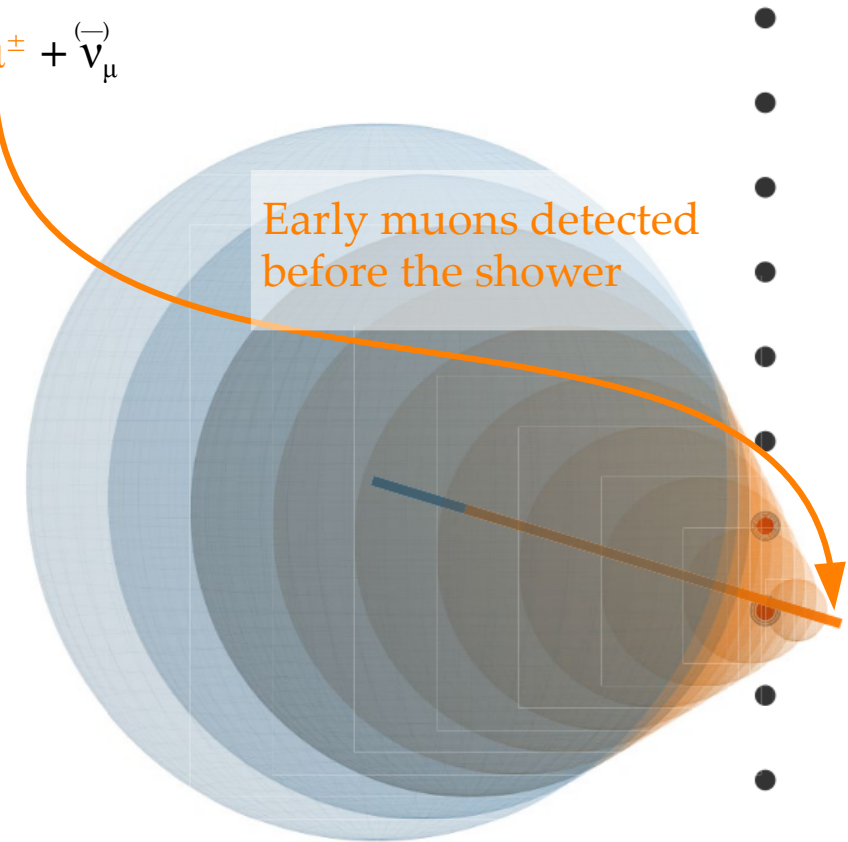


First observation of a Glashow resonance

Predicted in 1960:

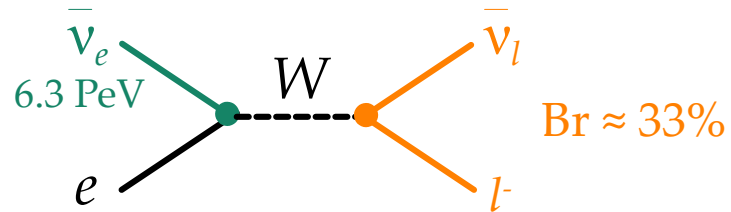
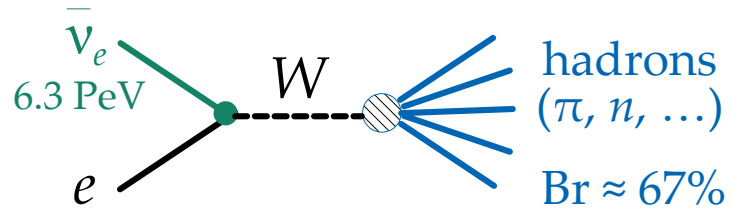


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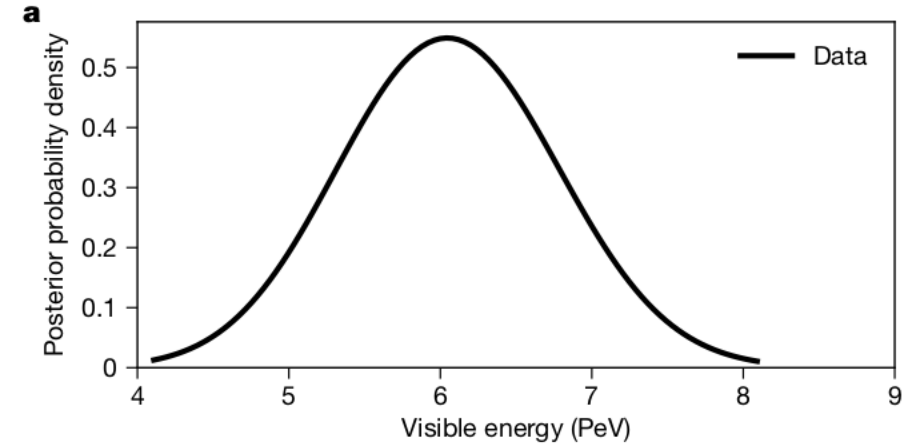


First observation of a Glashow resonance

Predicted in 1960:

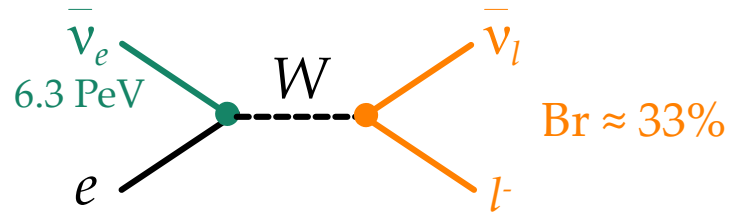
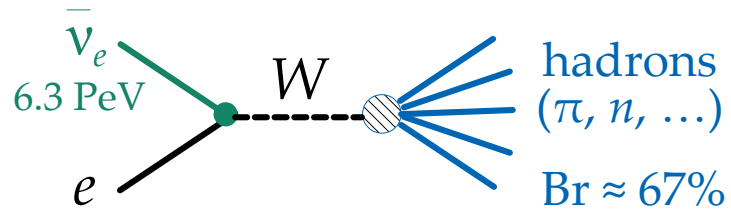


First reported by IceCube in 2021:

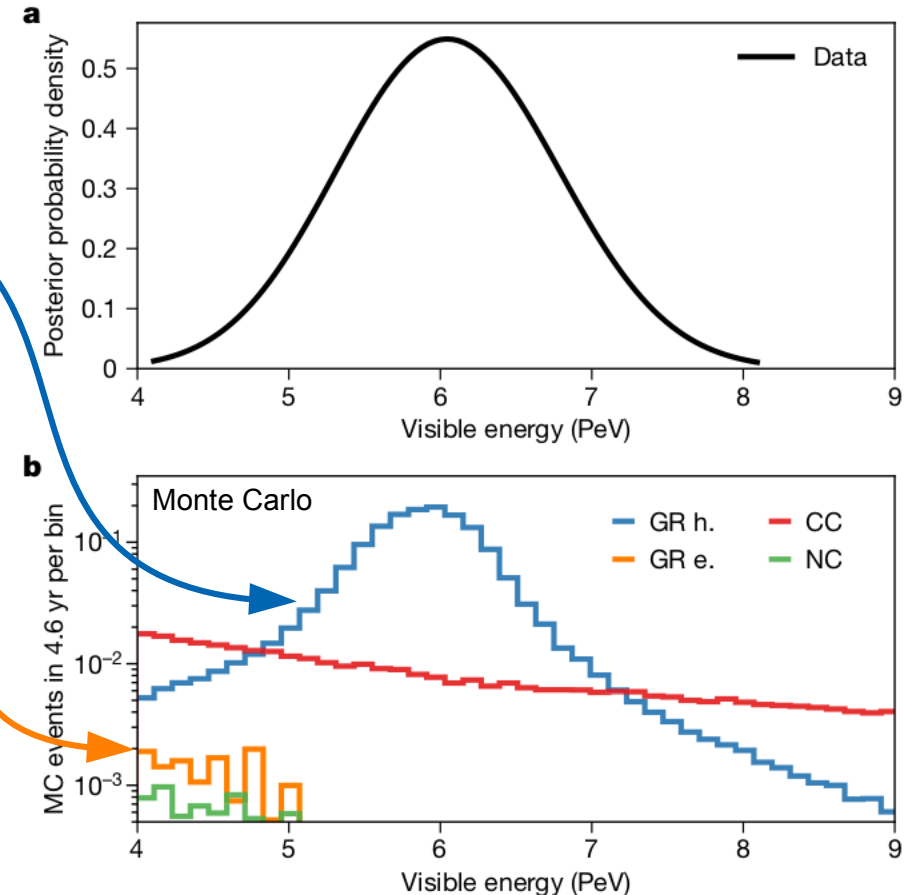


First observation of a Glashow resonance

Predicted in 1960:

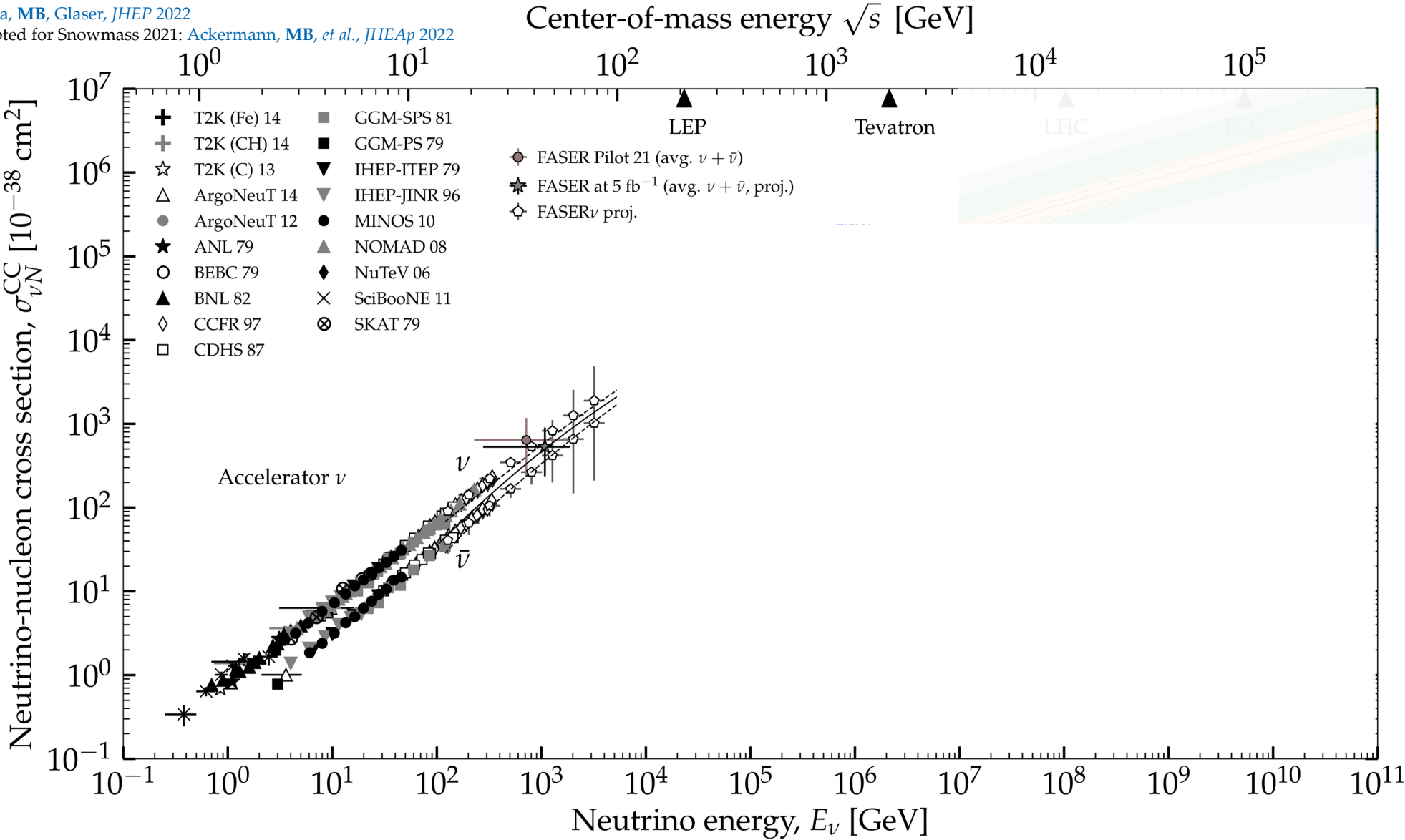


First reported by IceCube in 2021:

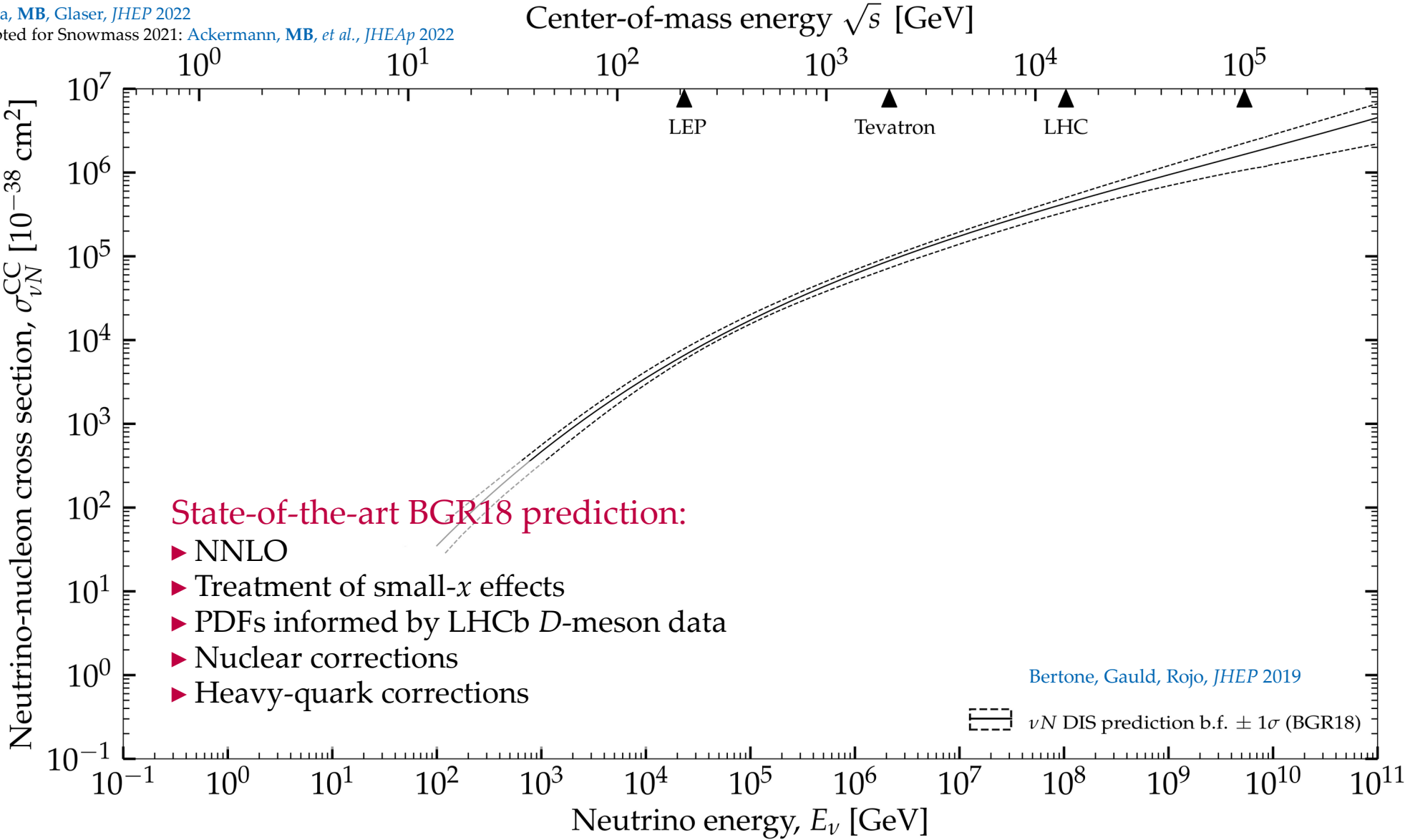


2. Neutrino-matter cross section: *From TeV to PeV*

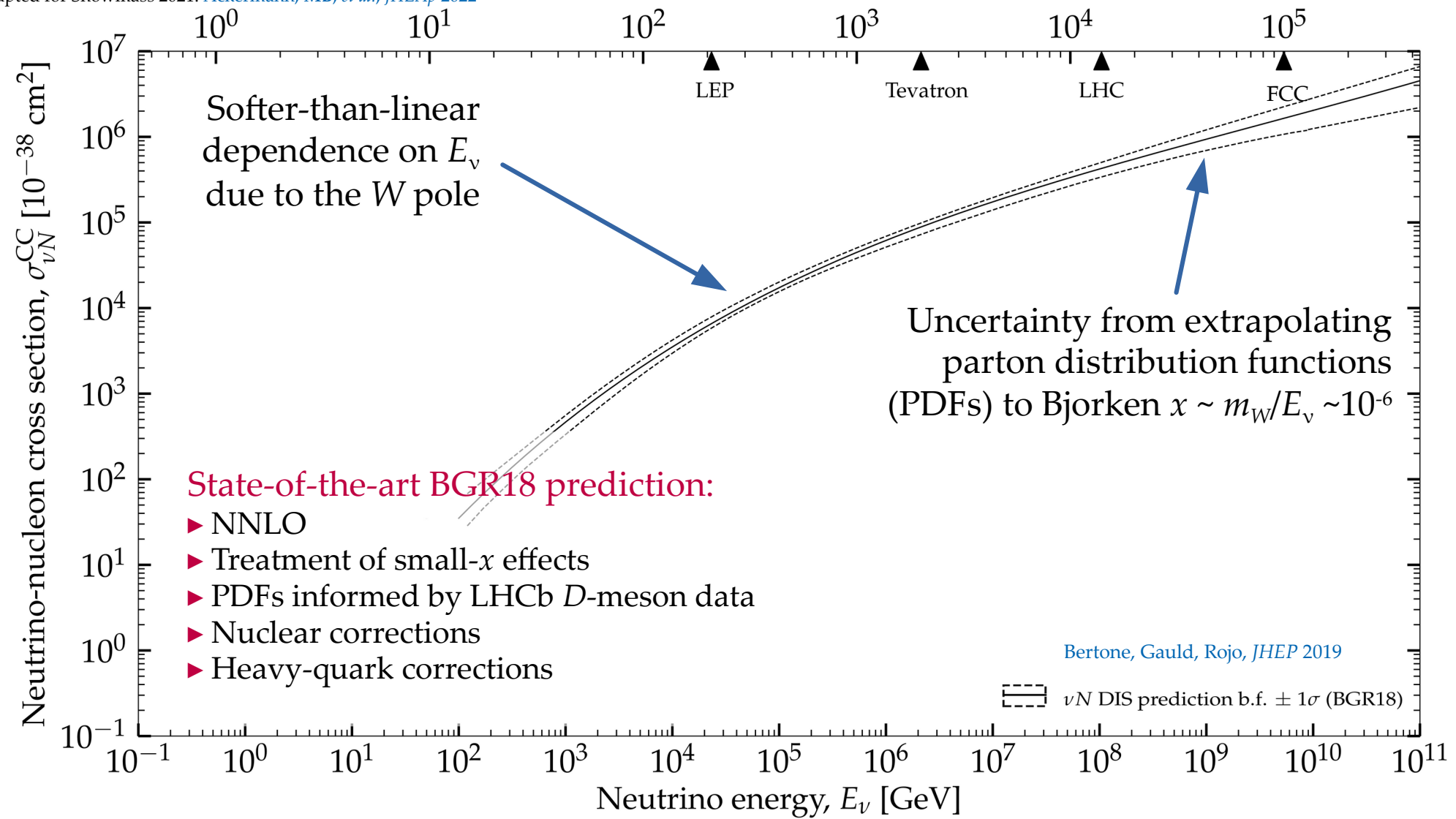
Center-of-mass energy $\sqrt{s}$ [GeV]

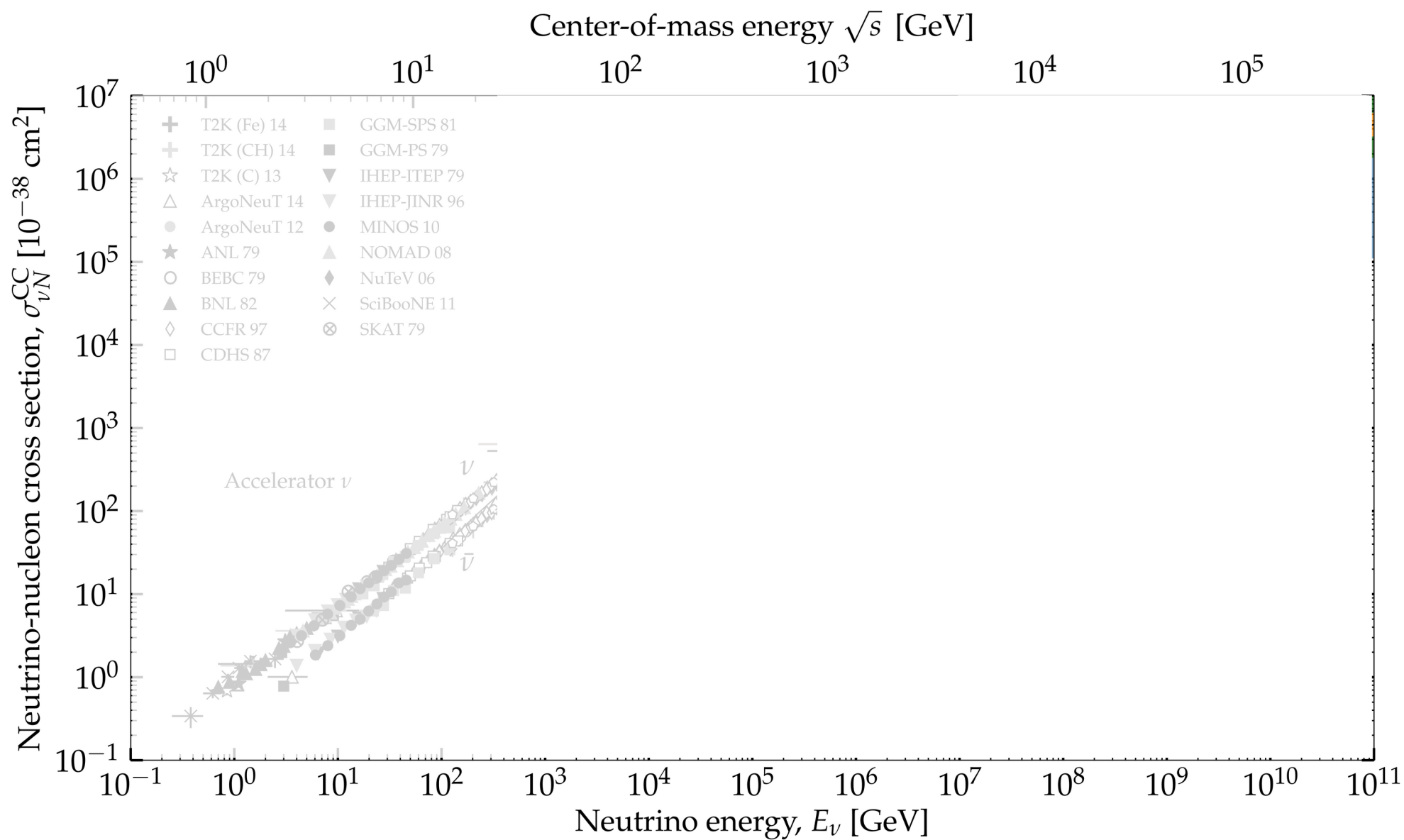


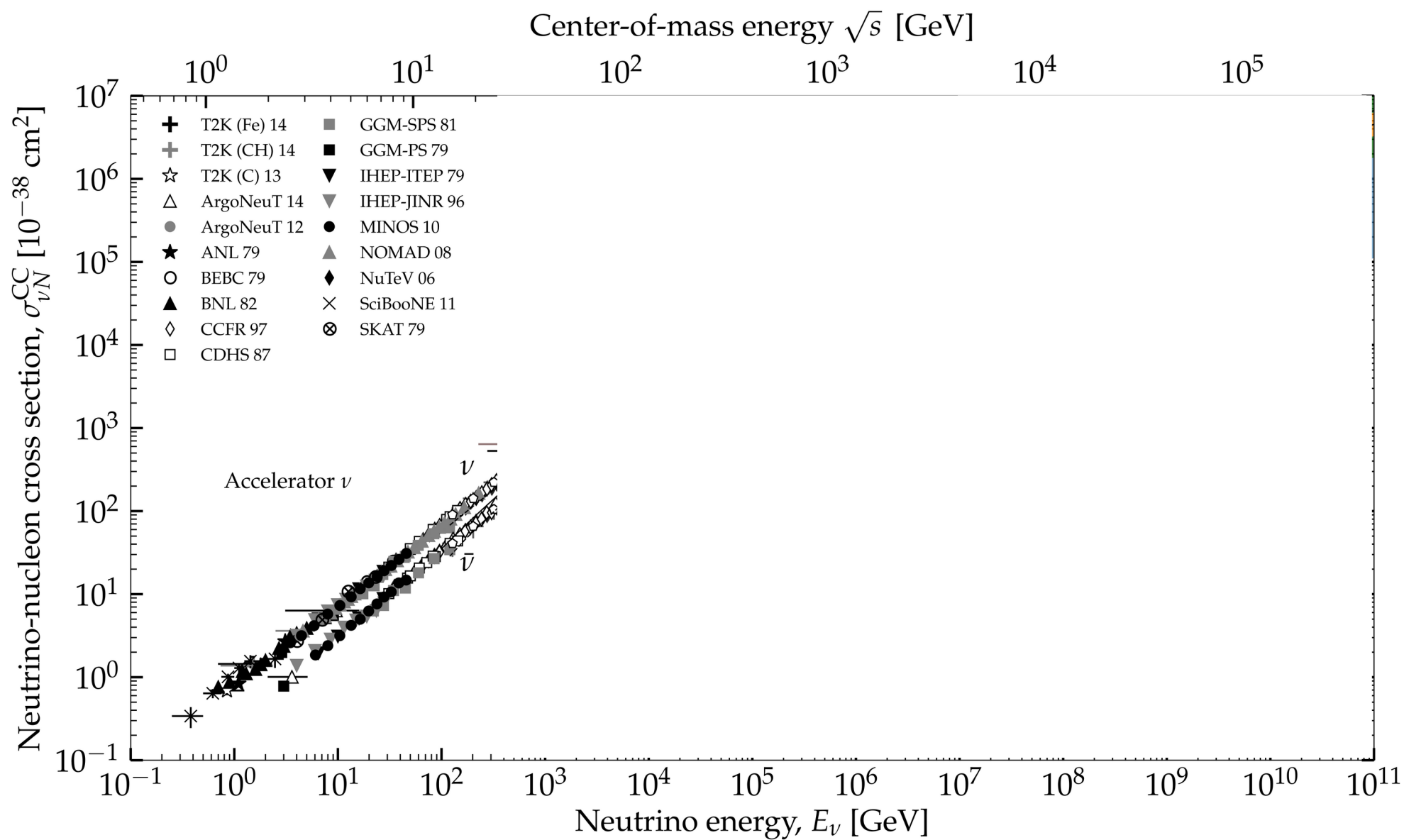
Center-of-mass energy $\sqrt{s}$ [GeV]

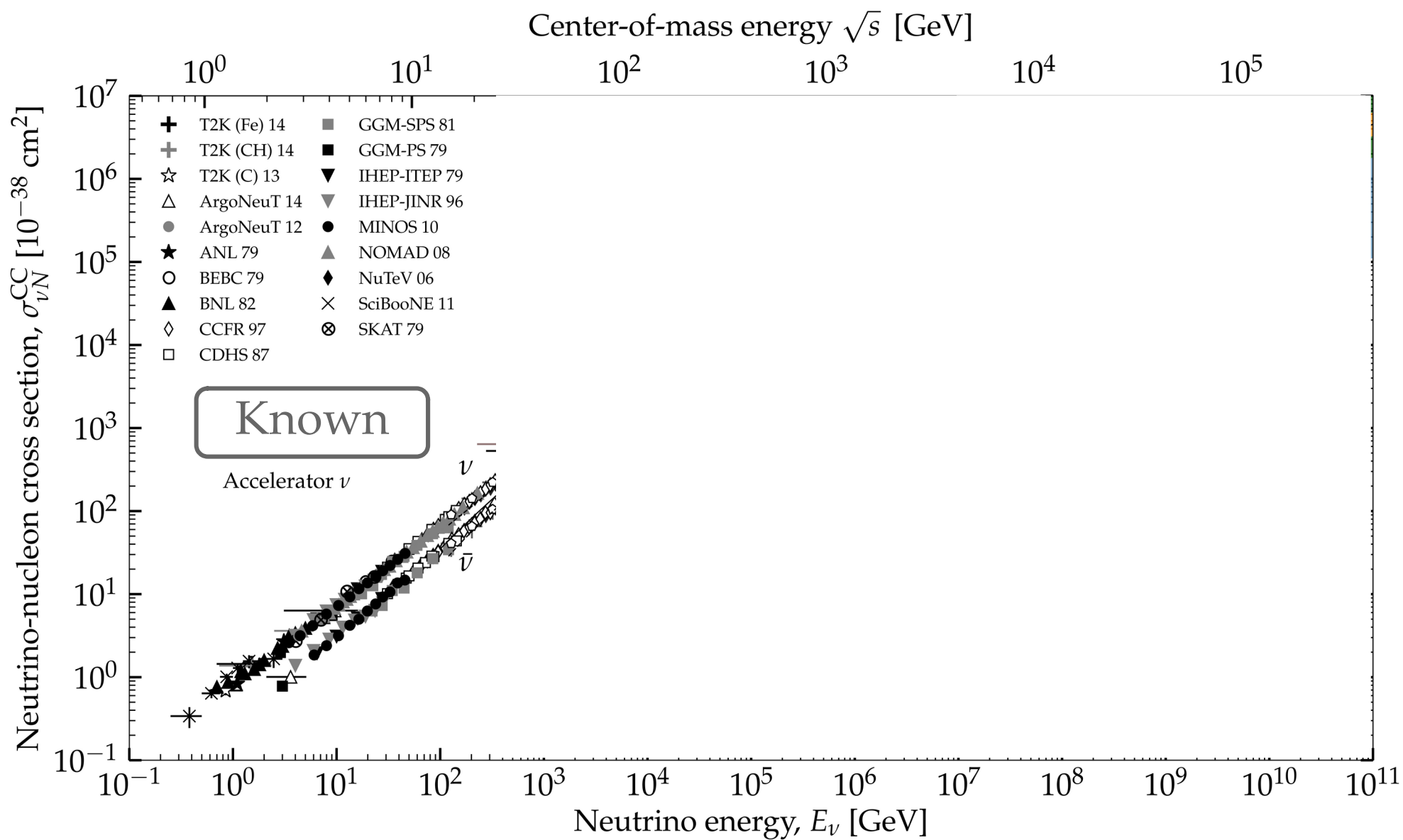


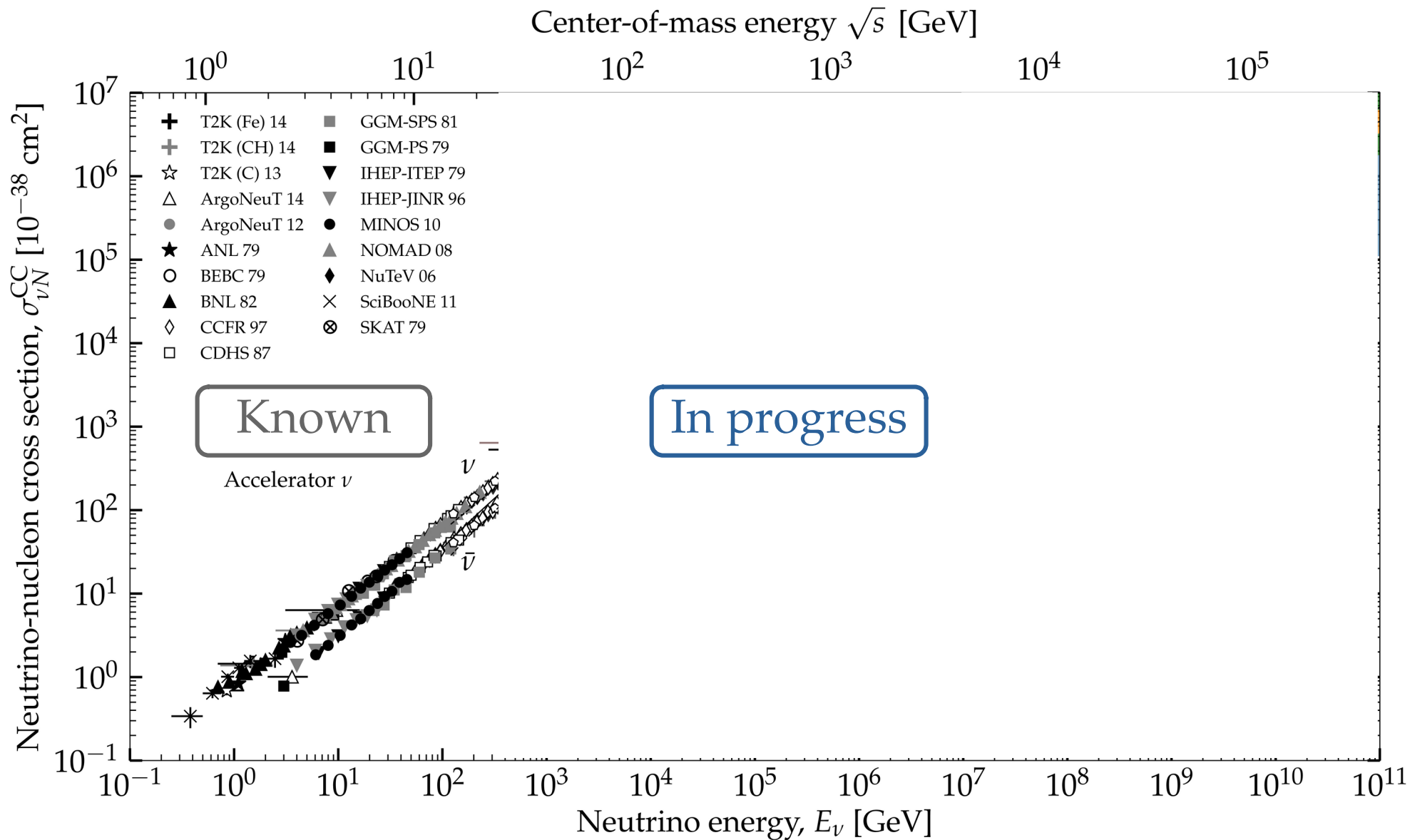
Center-of-mass energy $\sqrt{s}$ [GeV]

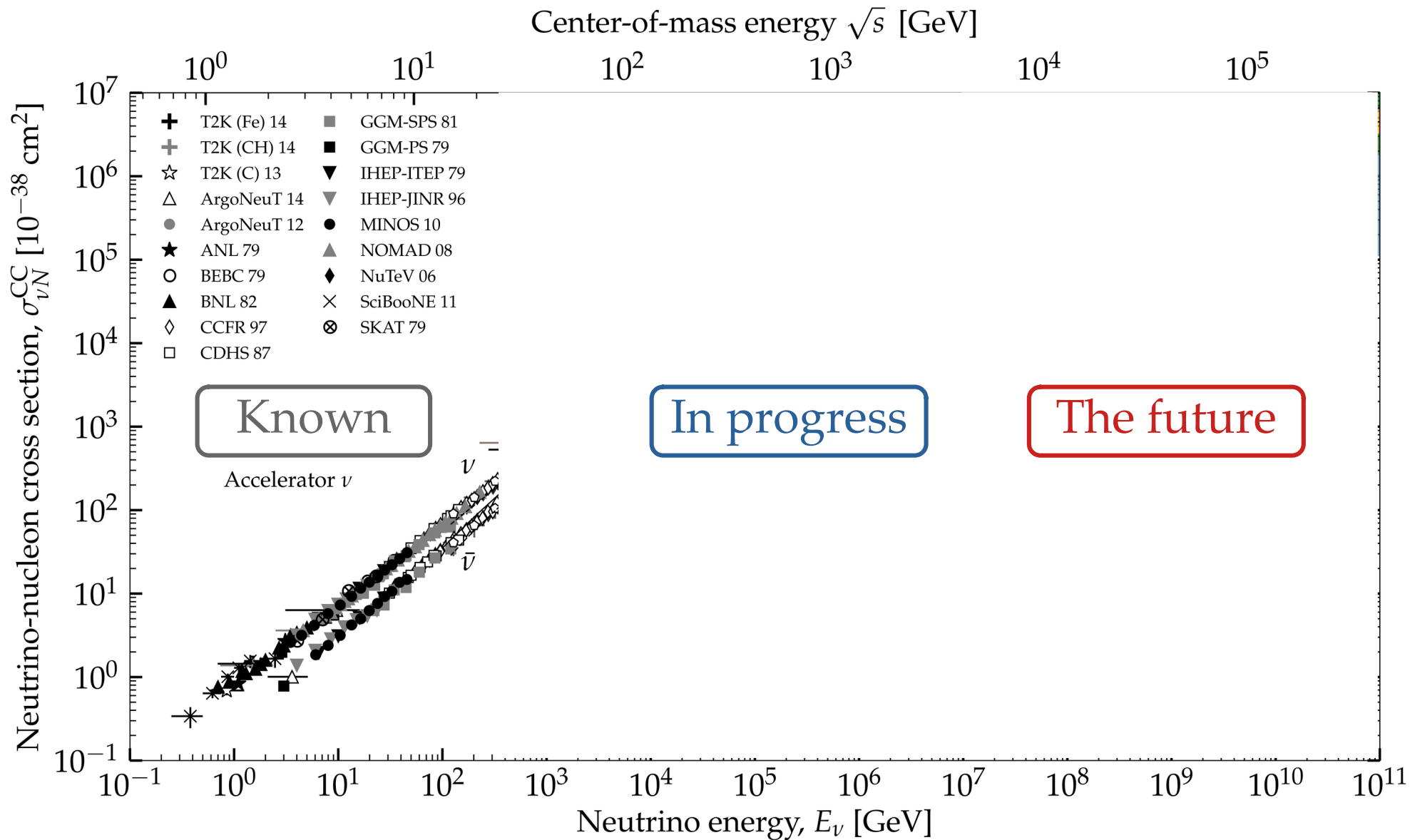






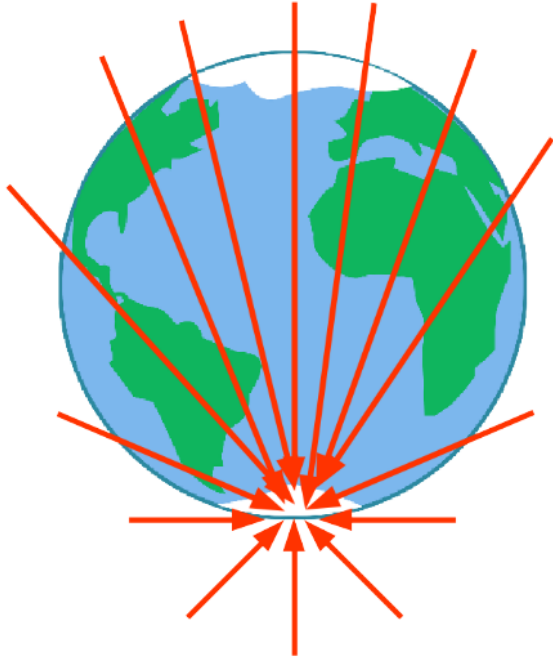




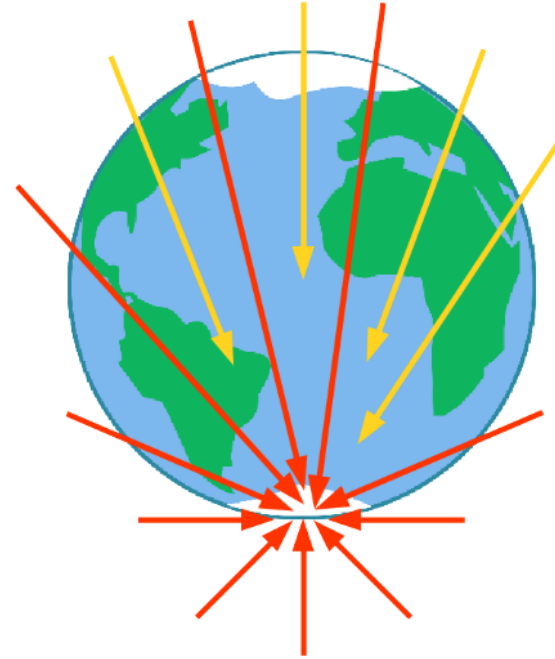


Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent

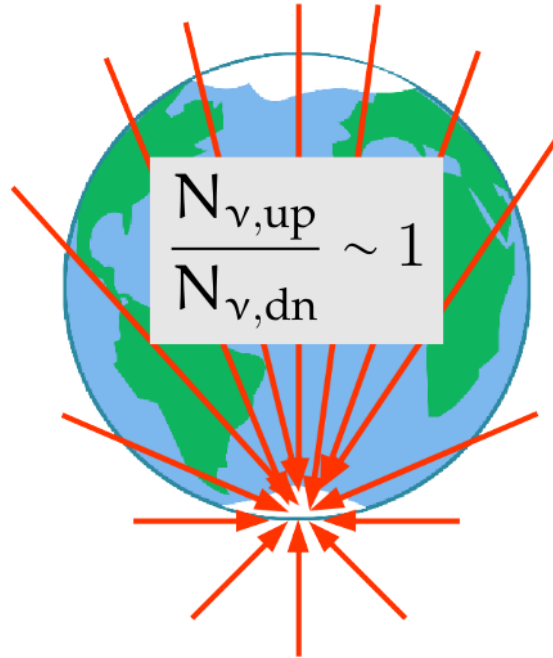


Above ~ 10 TeV: Earth is opaque

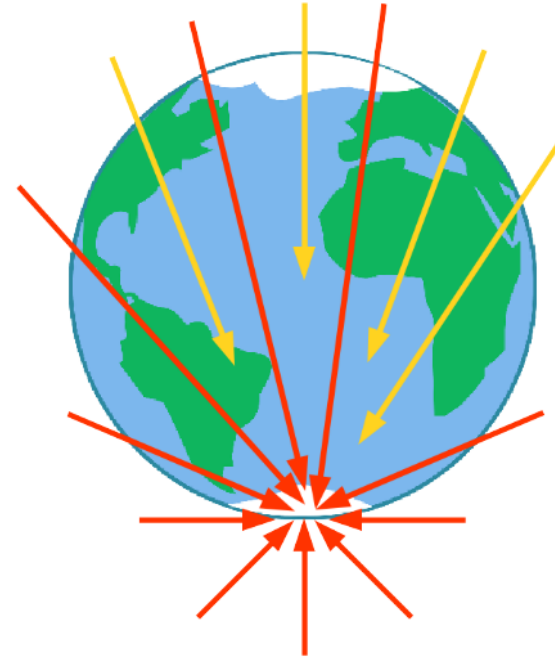


Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent

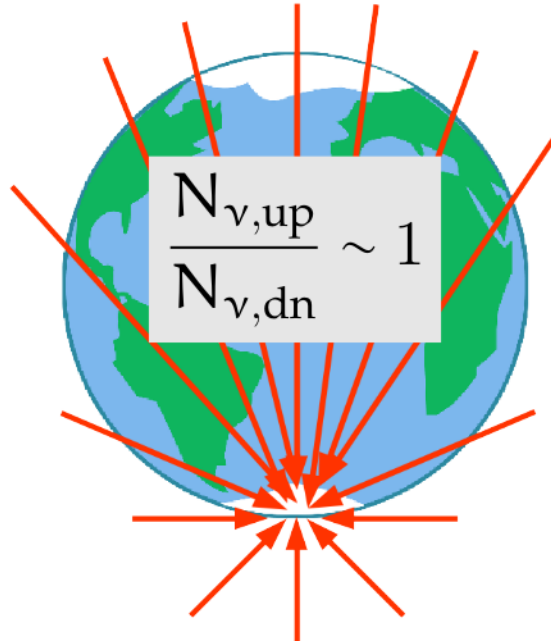


Above ~ 10 TeV: Earth is opaque

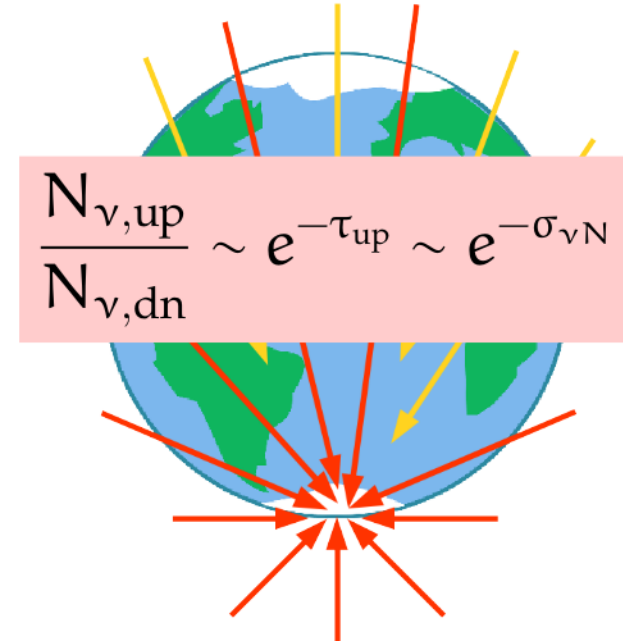


Measuring the high-energy νN cross section

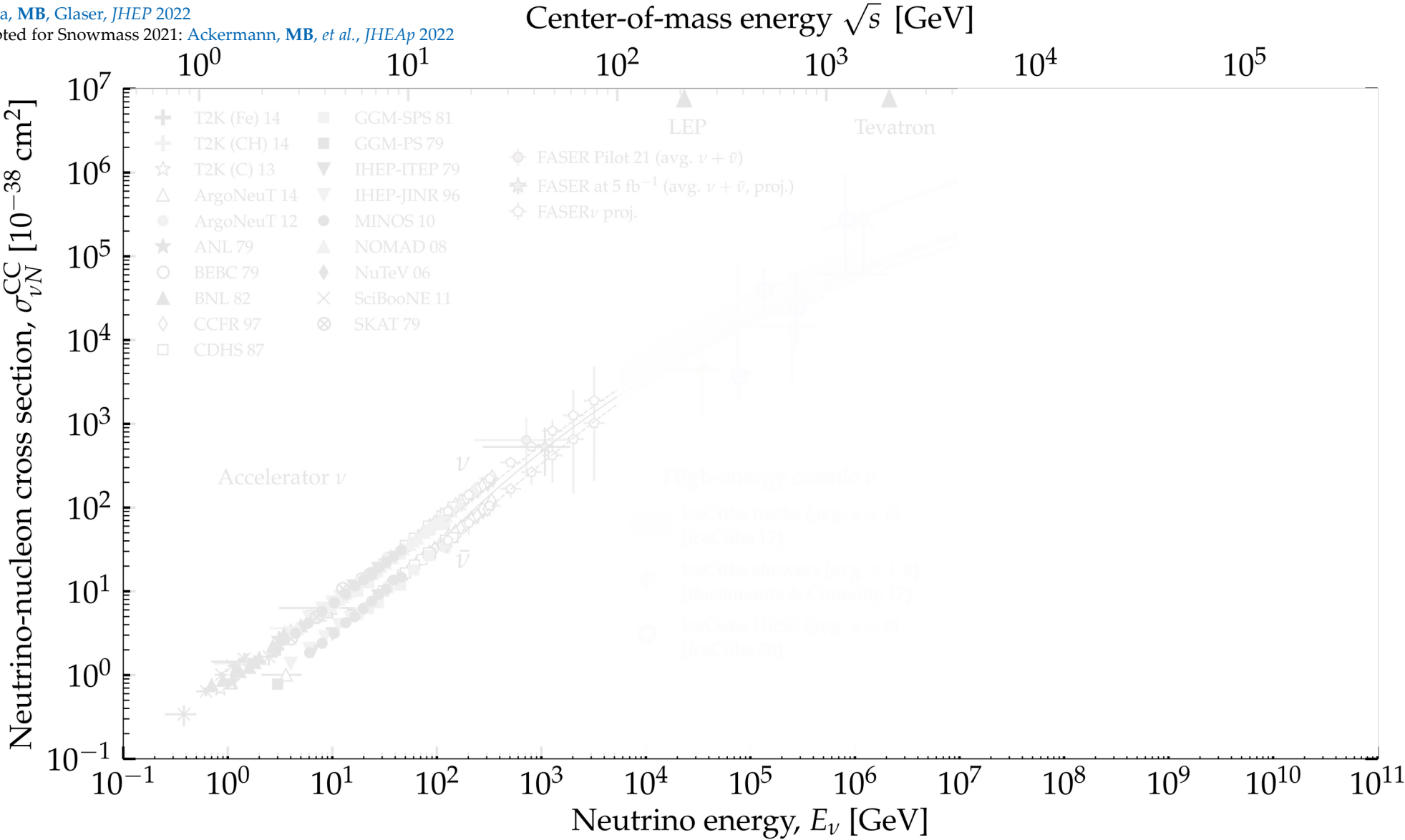
Below ~ 10 TeV: Earth is transparent



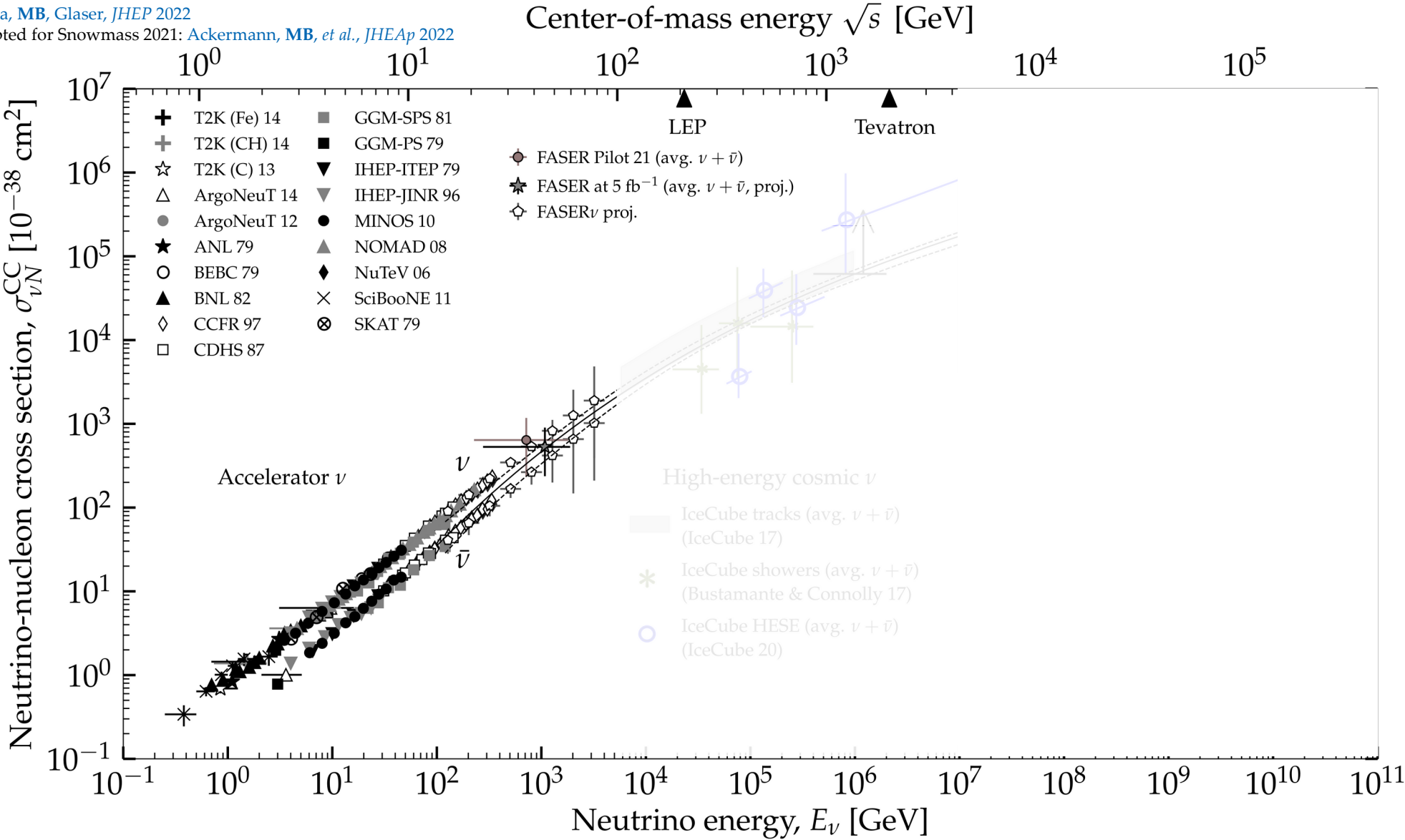
Above ~ 10 TeV: Earth is opaque



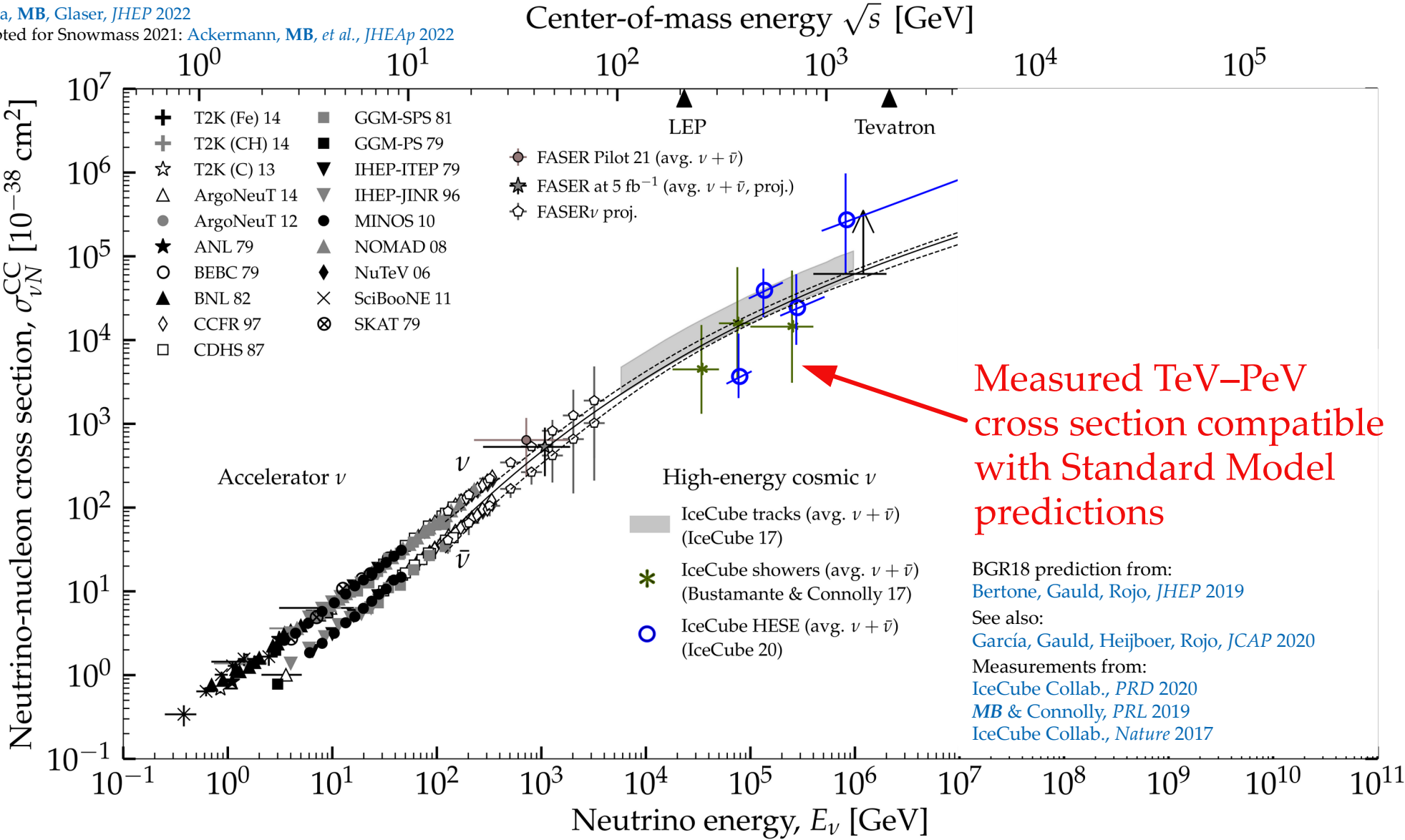
Center-of-mass energy $\sqrt{s}$ [GeV]



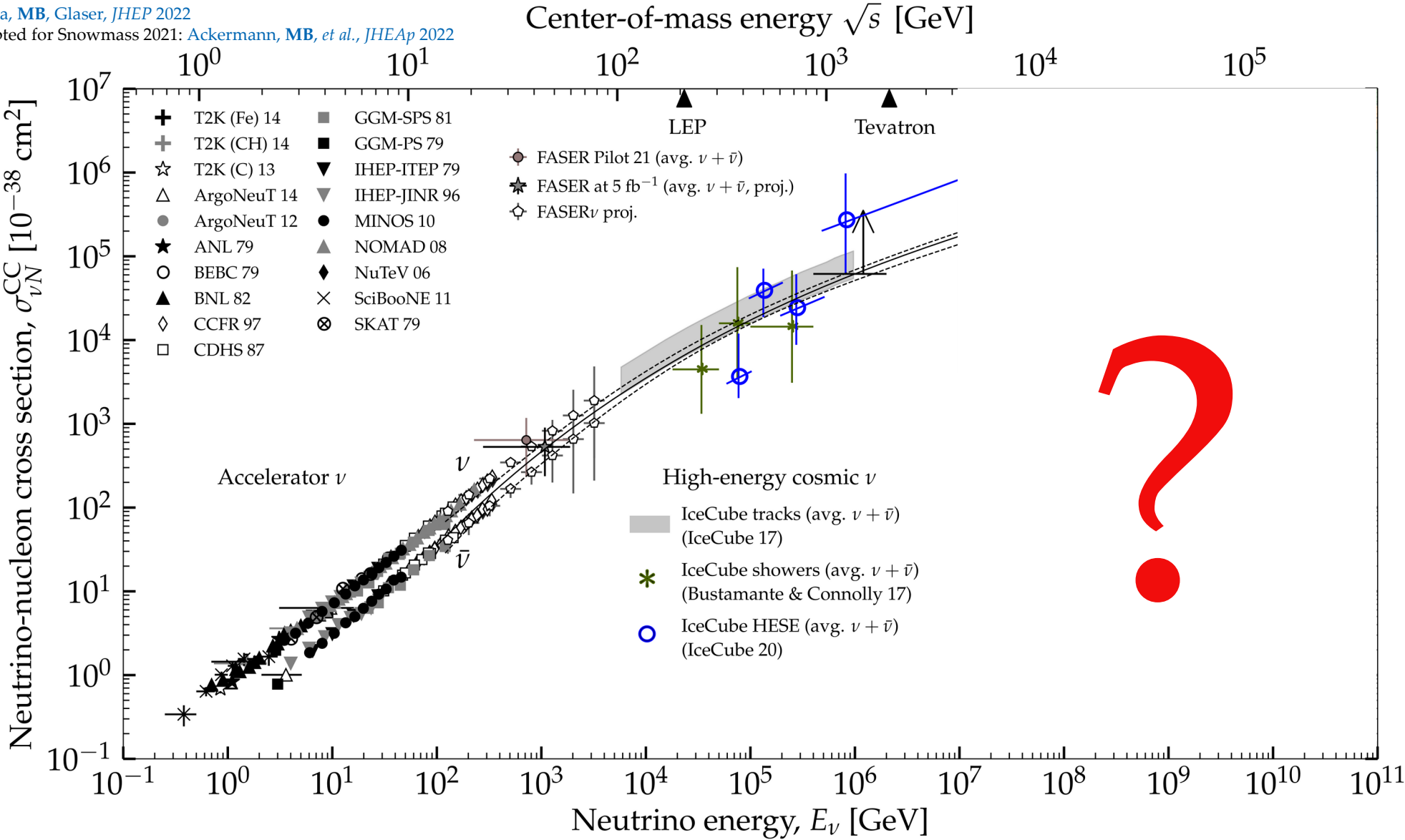
Center-of-mass energy $\sqrt{s}$ [GeV]



Center-of-mass energy $\sqrt{s}$ [GeV]



Center-of-mass energy $\sqrt{s}$ [GeV]



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

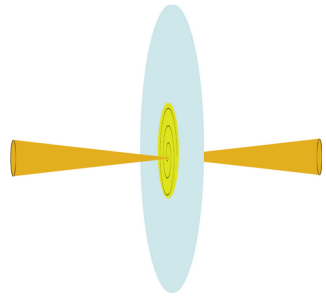


Galactic (kpc) or extragalactic (Mpc – Gpc) distance

Astrophysical neutrino sources

Earth

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

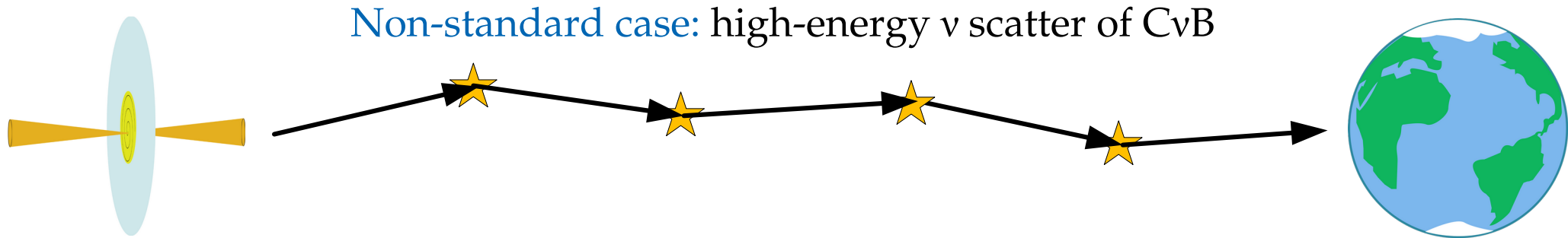
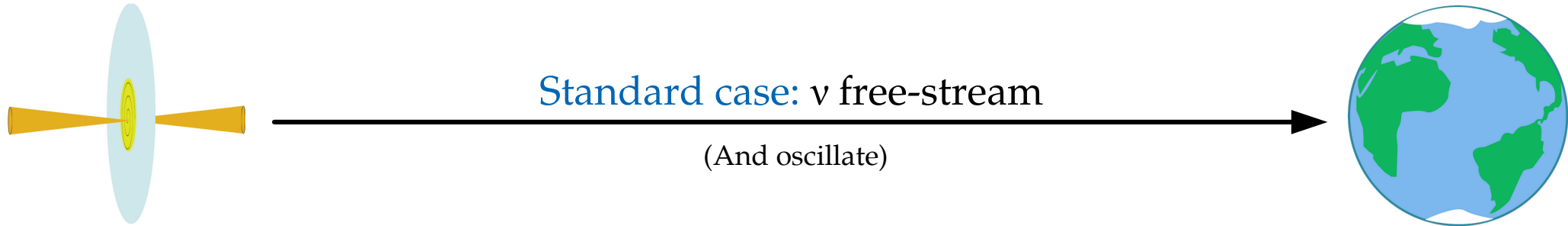


Standard case: ν free-stream

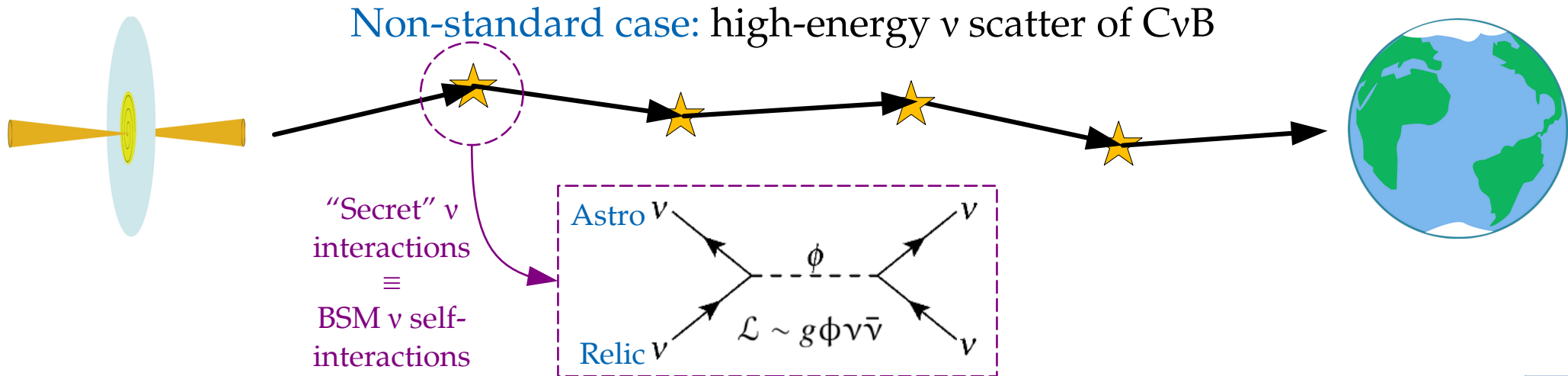
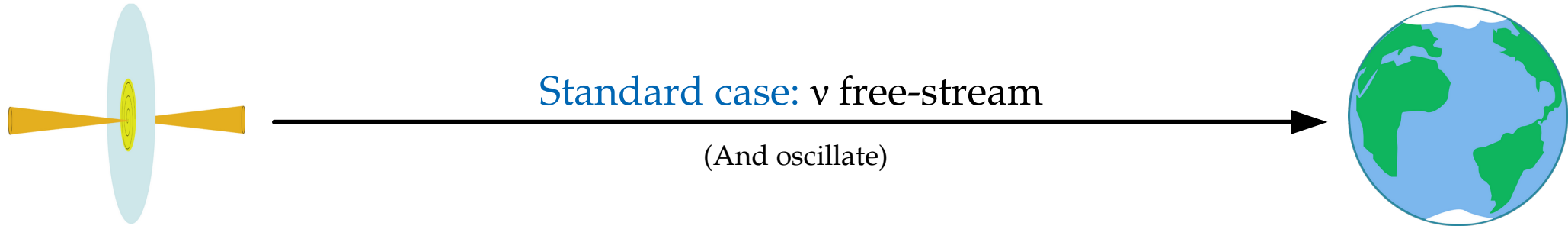
(And oscillate)



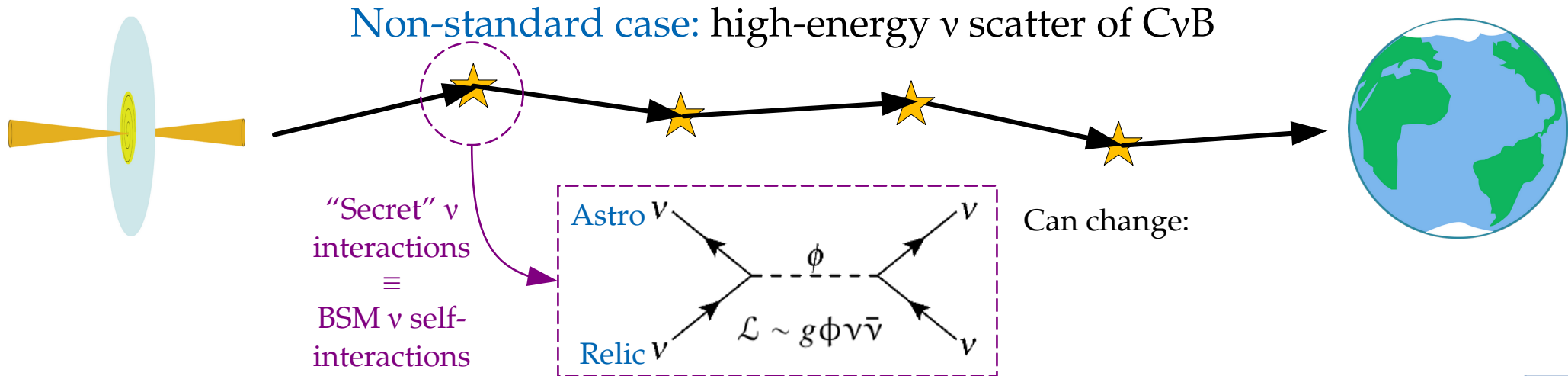
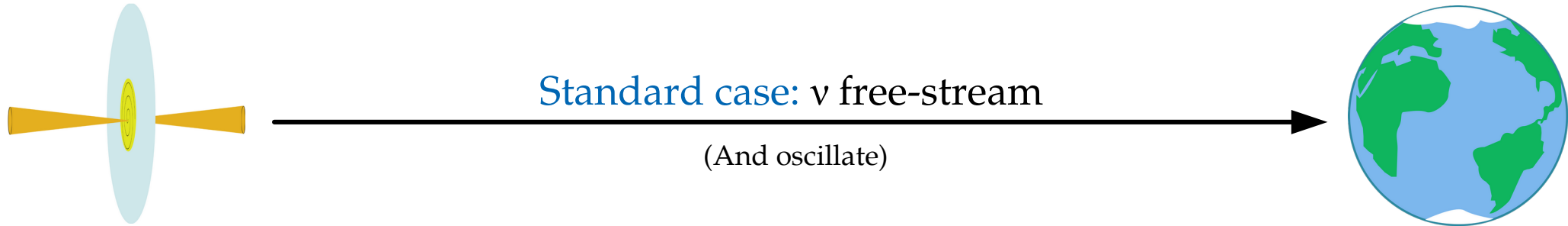
Galactic (kpc) or extragalactic (Mpc – Gpc) distance



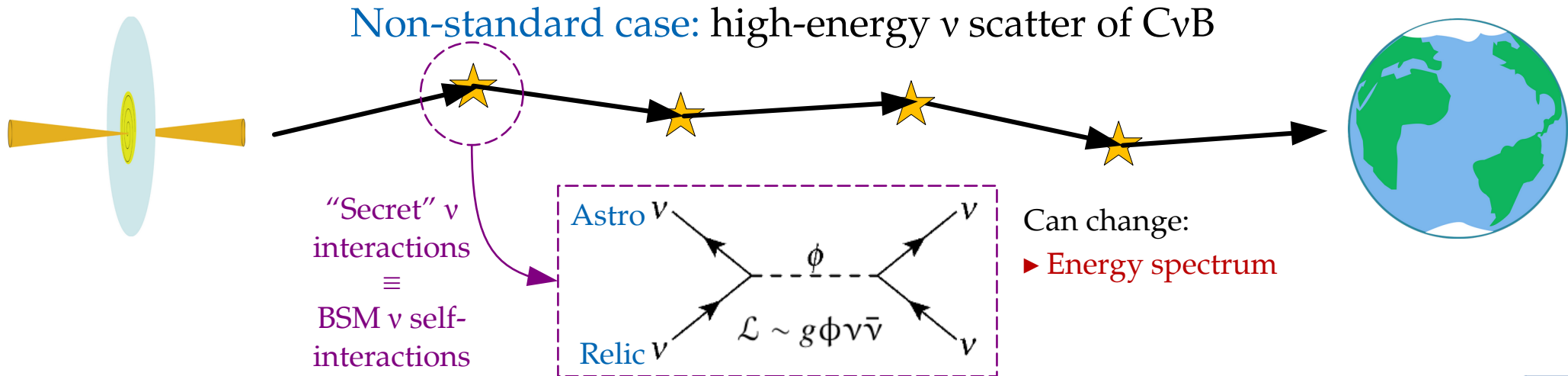
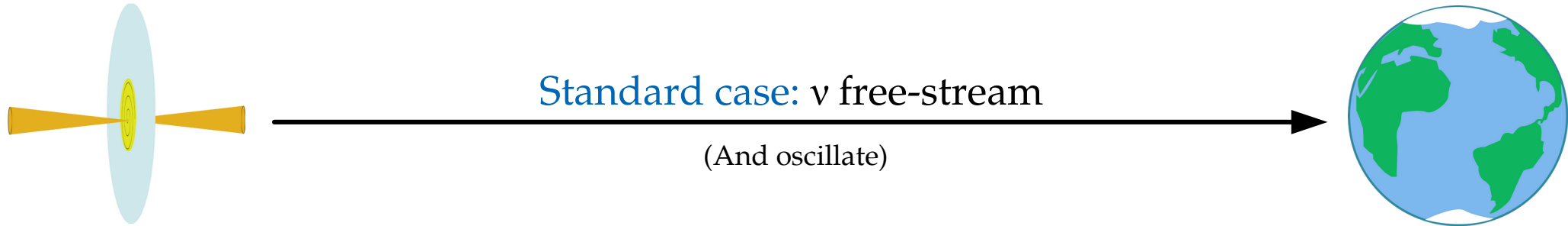
Galactic (kpc) or extragalactic (Mpc – Gpc) distance



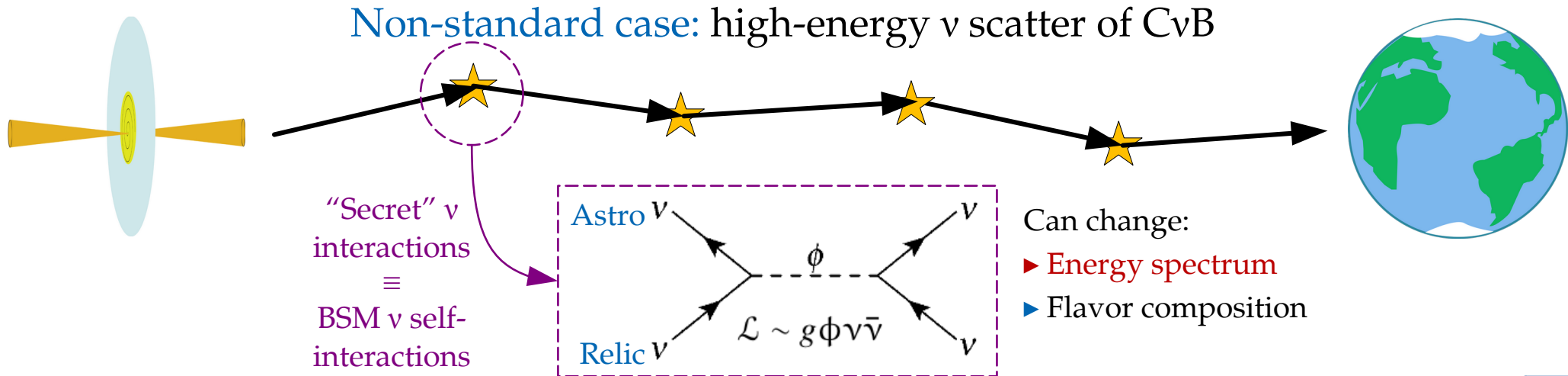
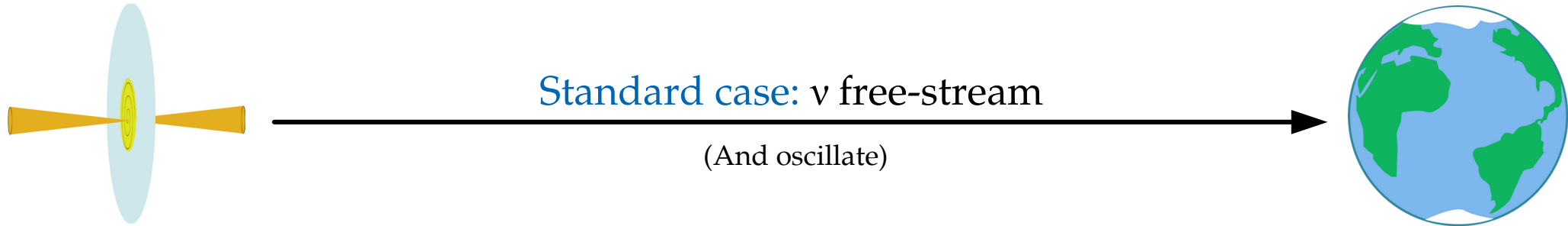
Galactic (kpc) or extragalactic (Mpc – Gpc) distance



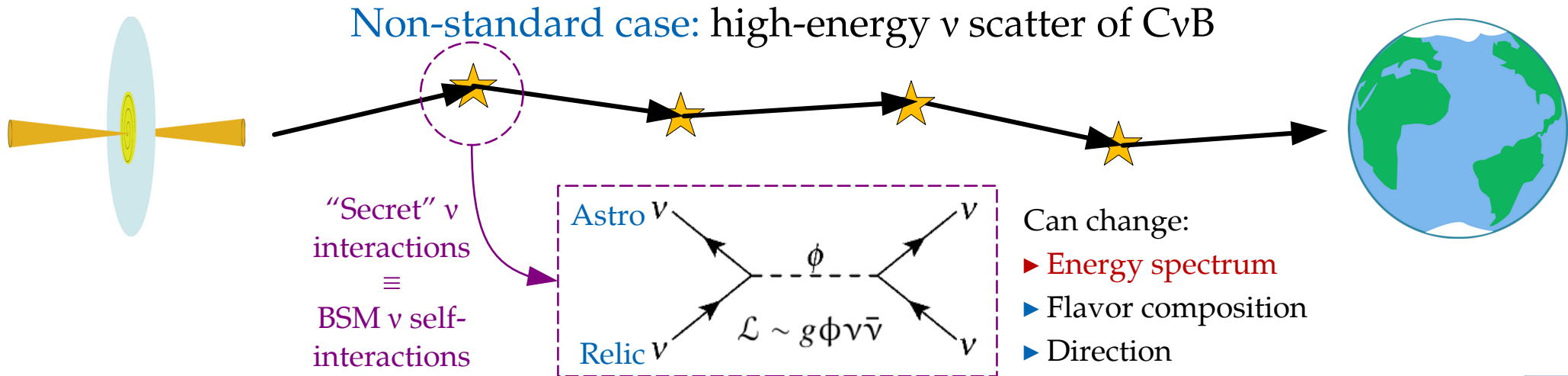
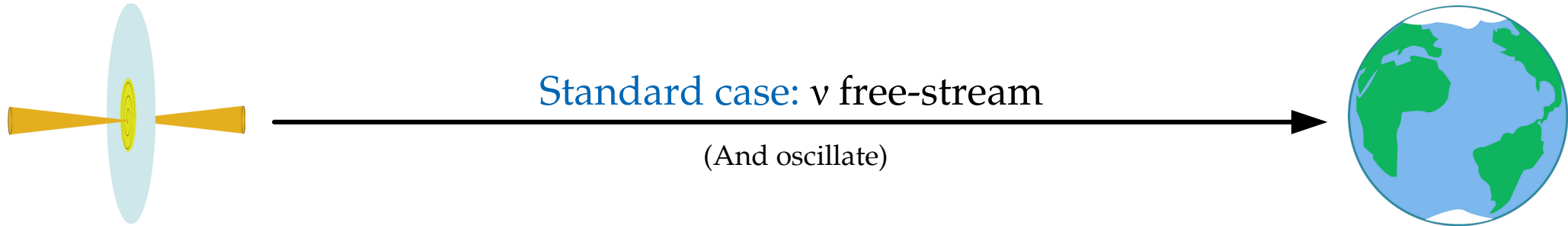
Galactic (kpc) or extragalactic (Mpc – Gpc) distance



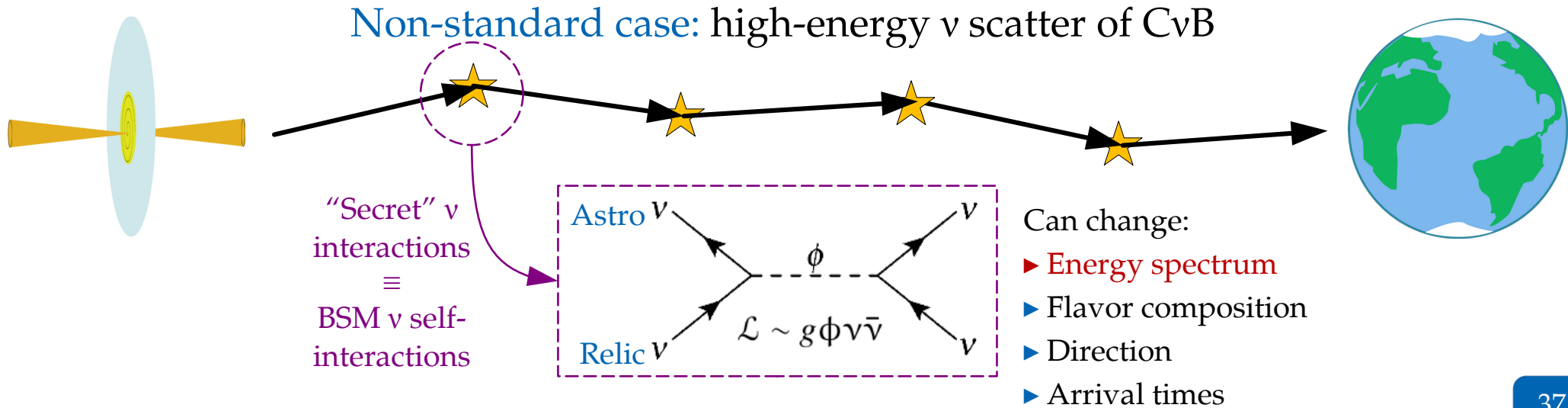
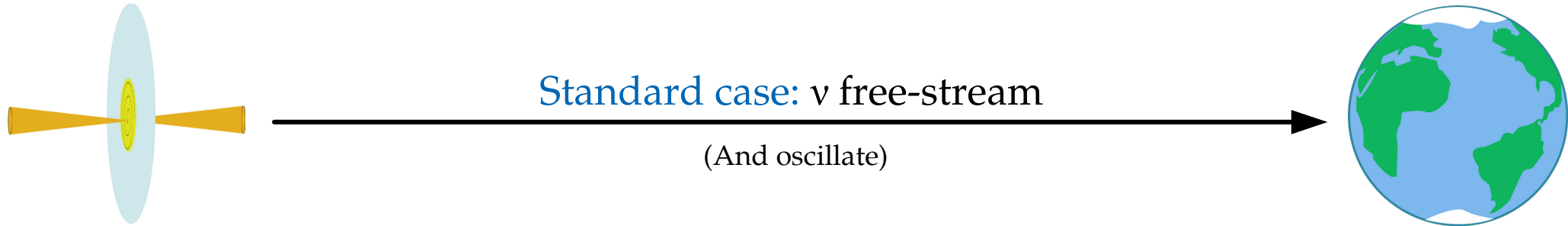
Galactic (kpc) or extragalactic (Mpc – Gpc) distance



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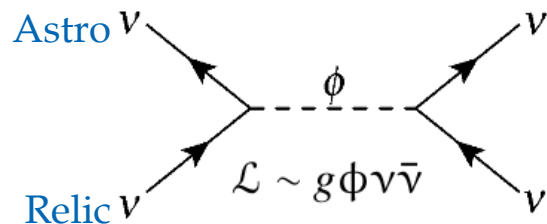


Galactic (kpc) or extragalactic (Mpc – Gpc) distance



Secret interactions of high-energy astrophysical neutrinos

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



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

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

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020

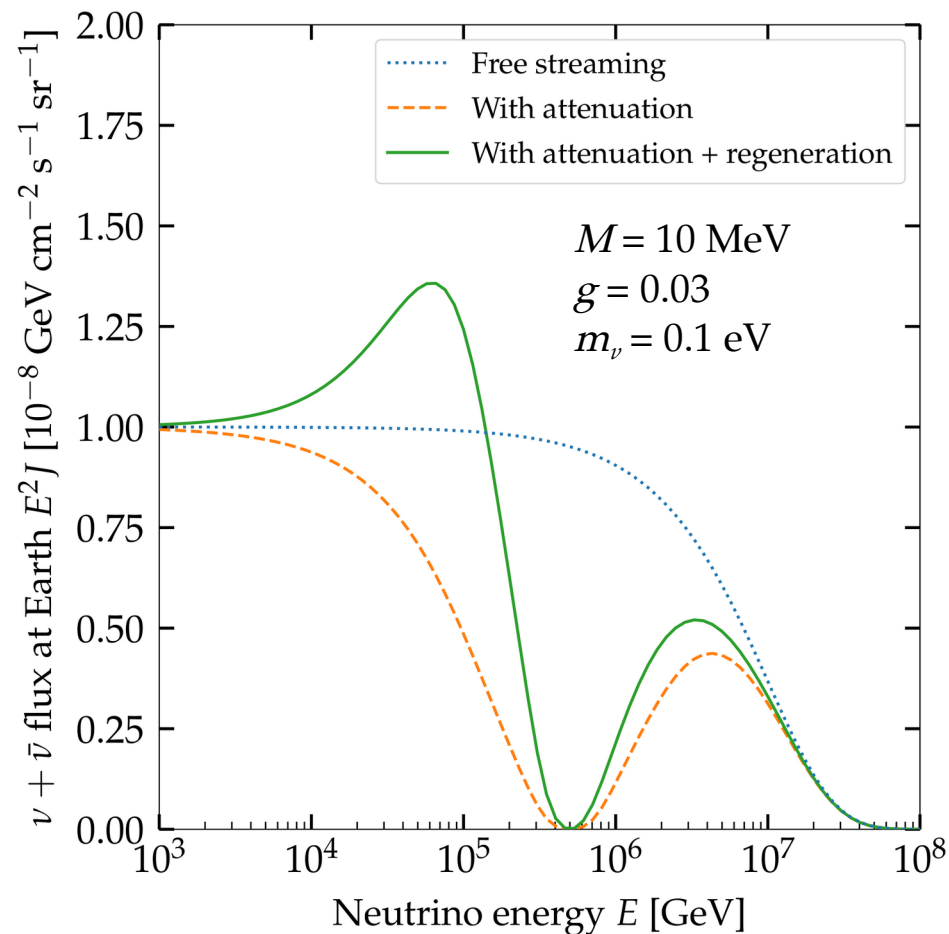
See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021

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

Ng & Beacom, *PRD* 2014

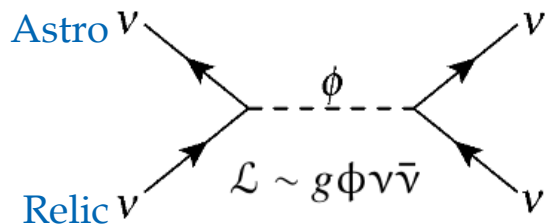
Cherry, Friedland, Shoemaker, 1411.1071

Blum, Hook, Murase, 1408.3799



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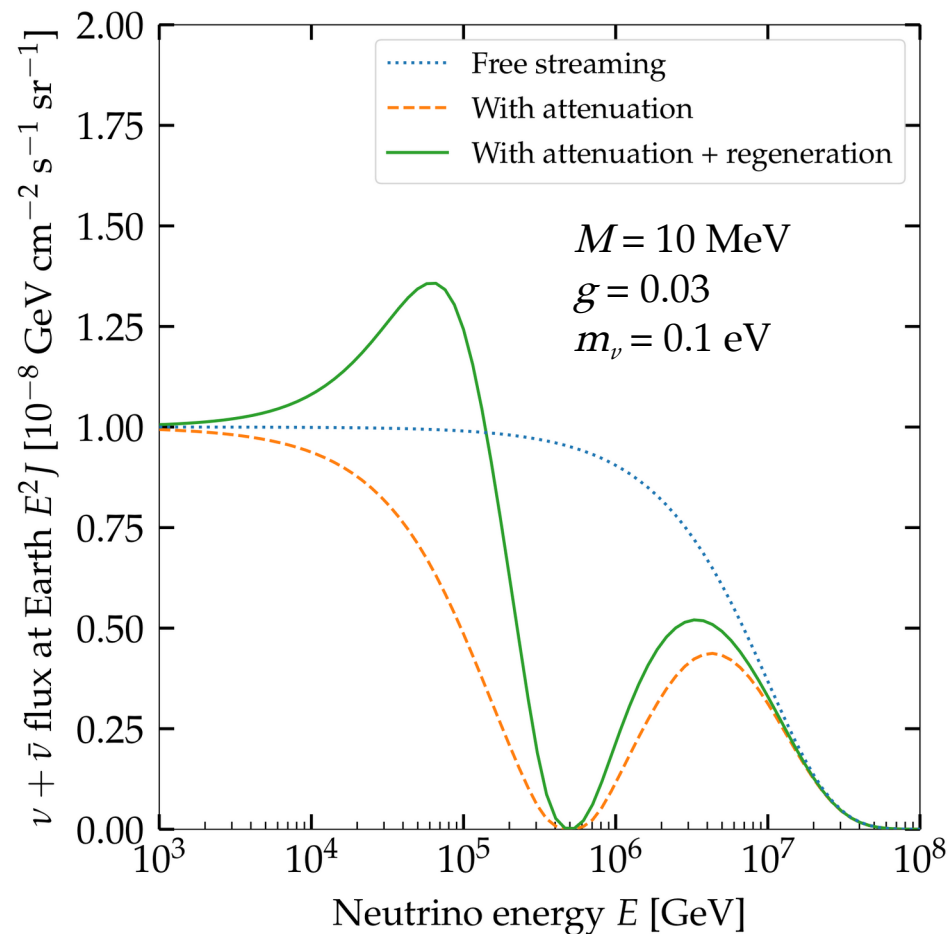


Cross section: $\sigma = \frac{g^4 s}{4\pi (s - M^2)^2 + M^2\Gamma^2}$

New coupling Mediator mass

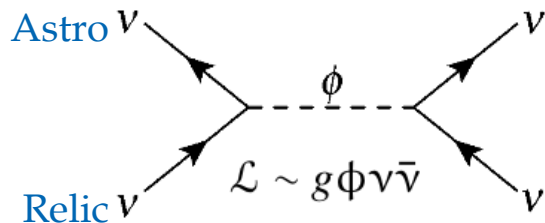
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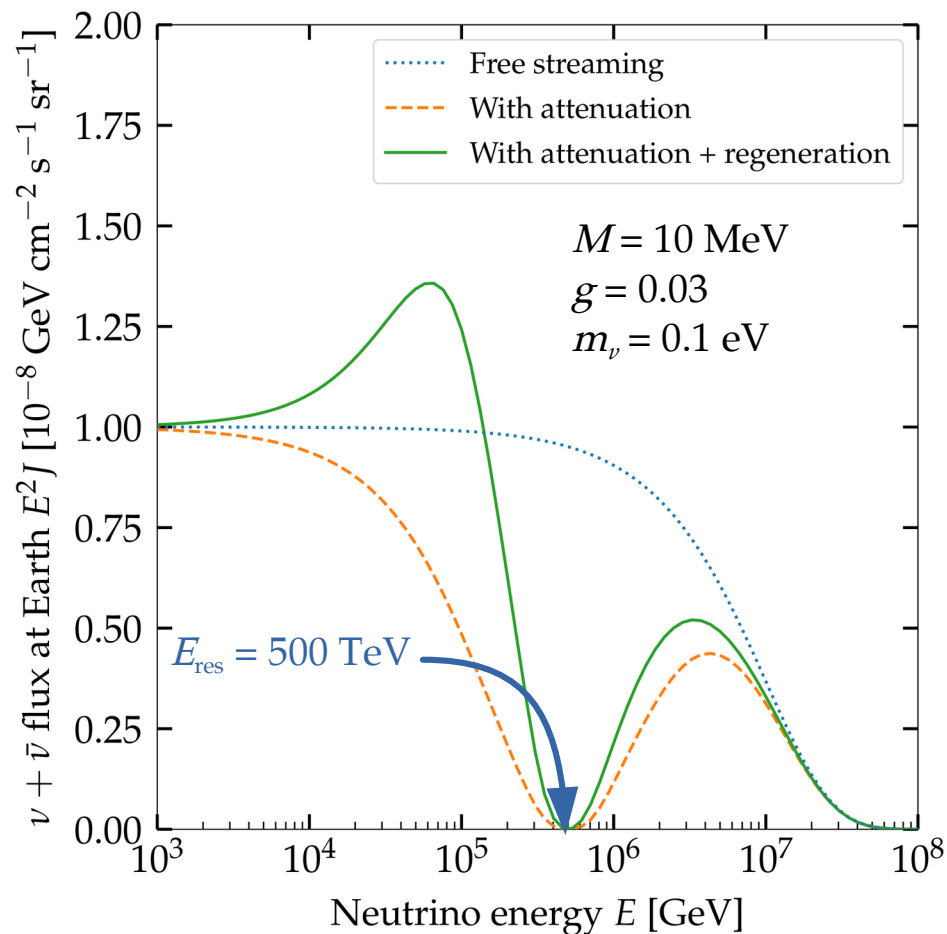


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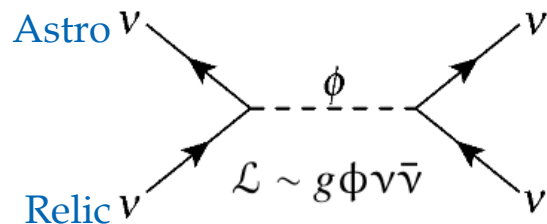
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MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021
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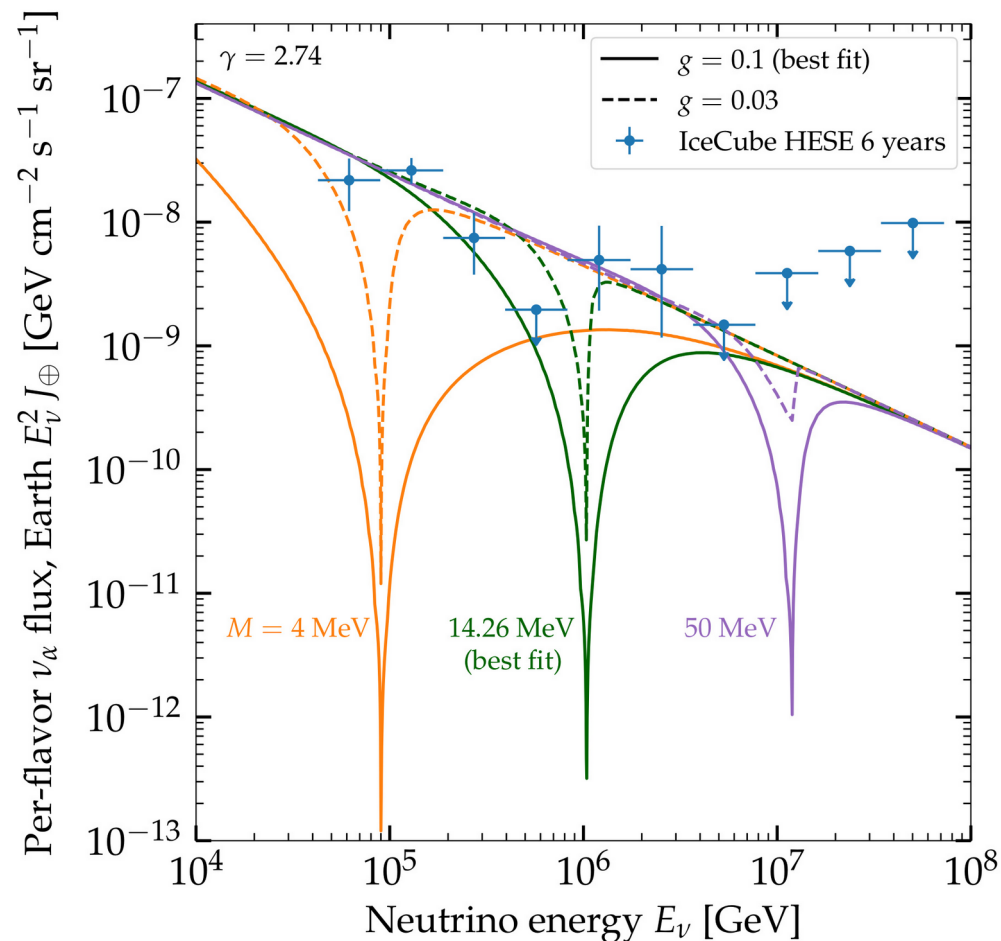


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New coupling Mediator mass

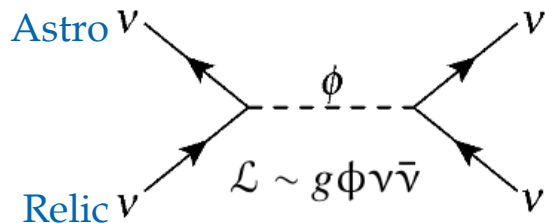
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See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021

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

Ng & Beacom, *PRD* 2014

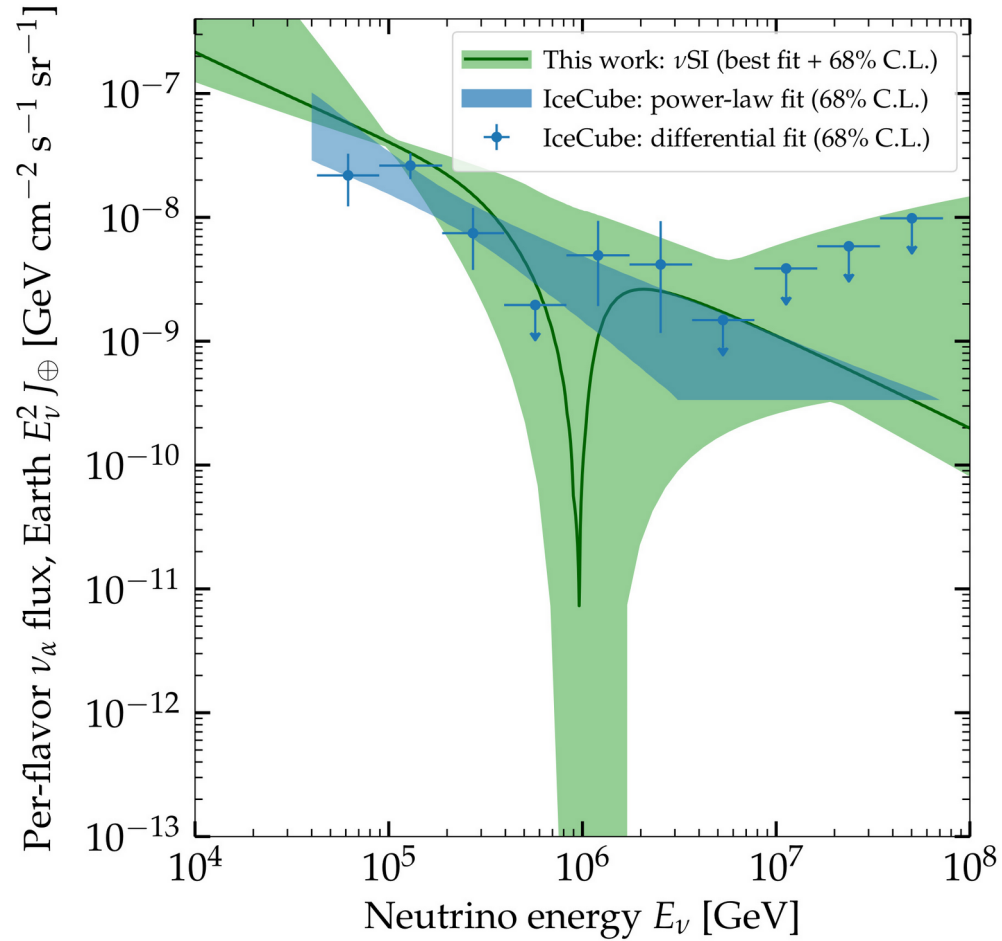
Cherry, Friedland, Shoemaker, 1411.1071

Blum, Hook, Murase, 1408.3799

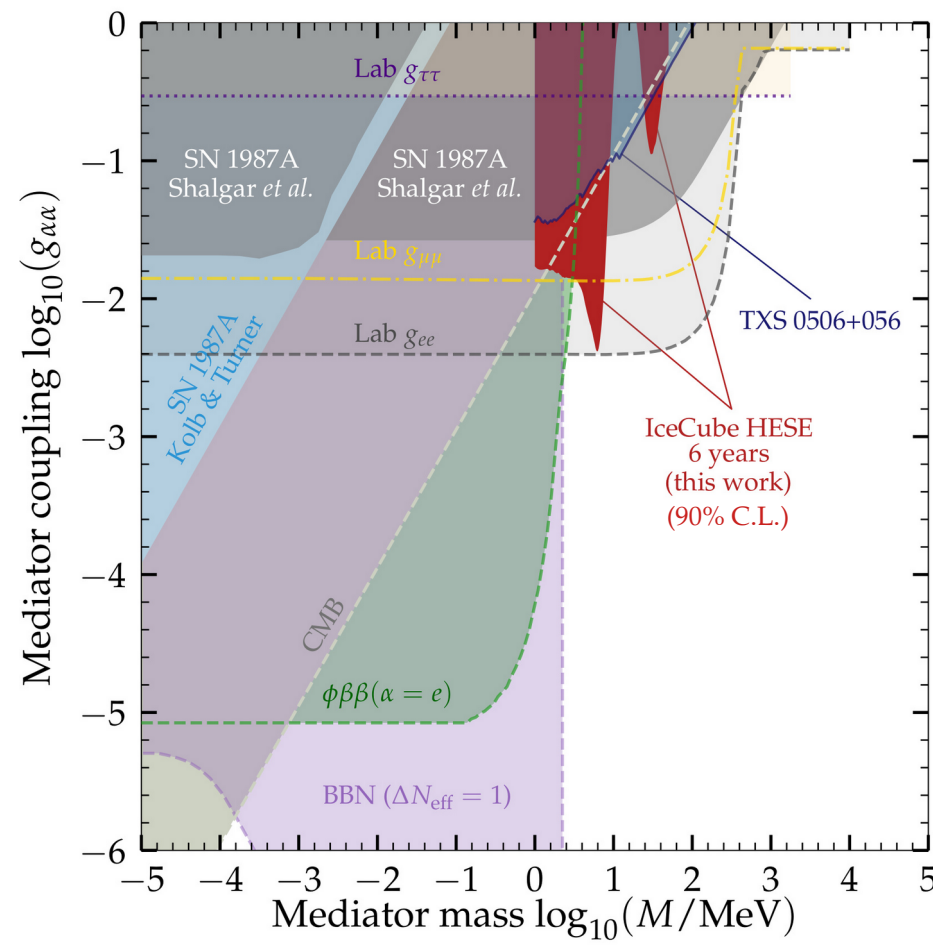
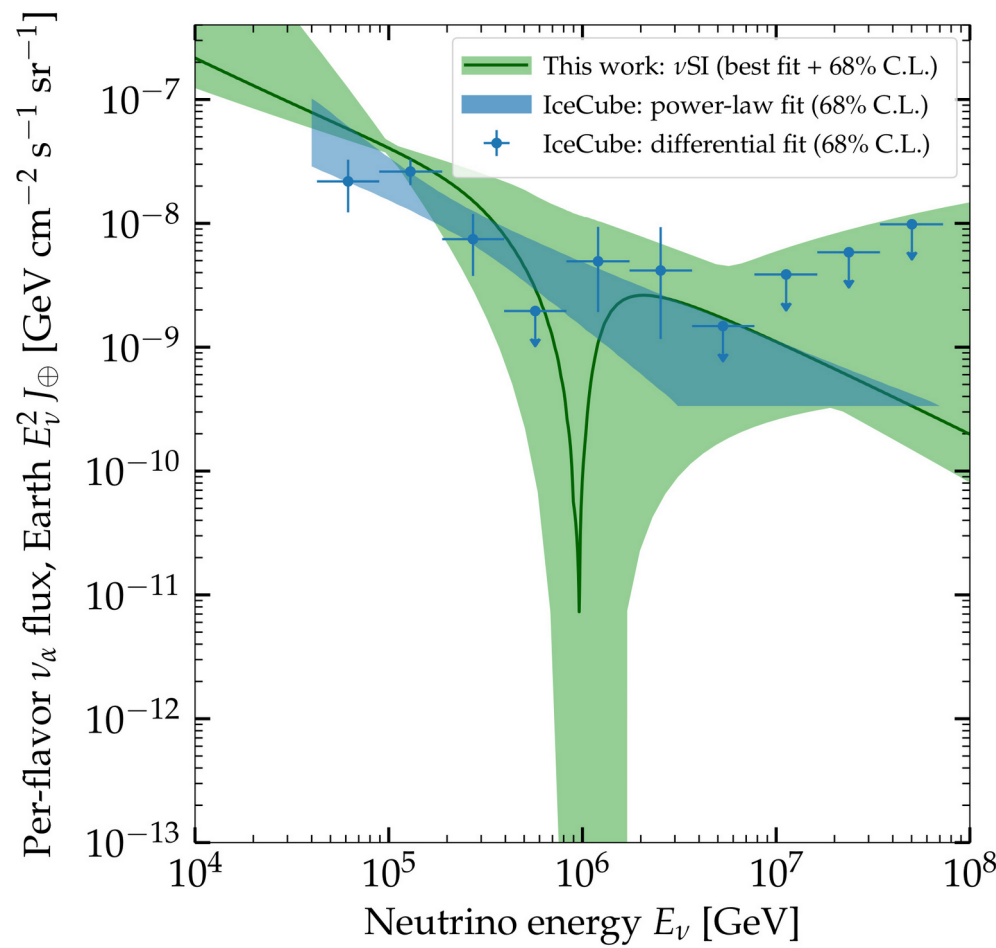
Looking for evidence of ν SI

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

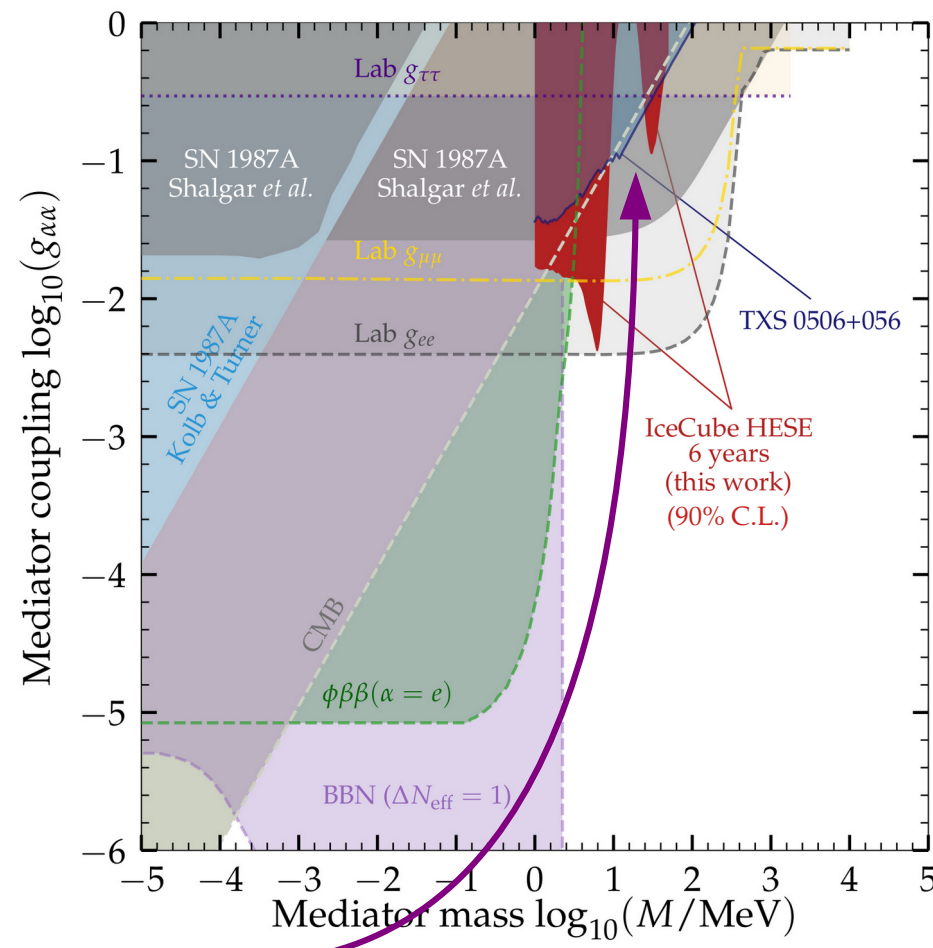
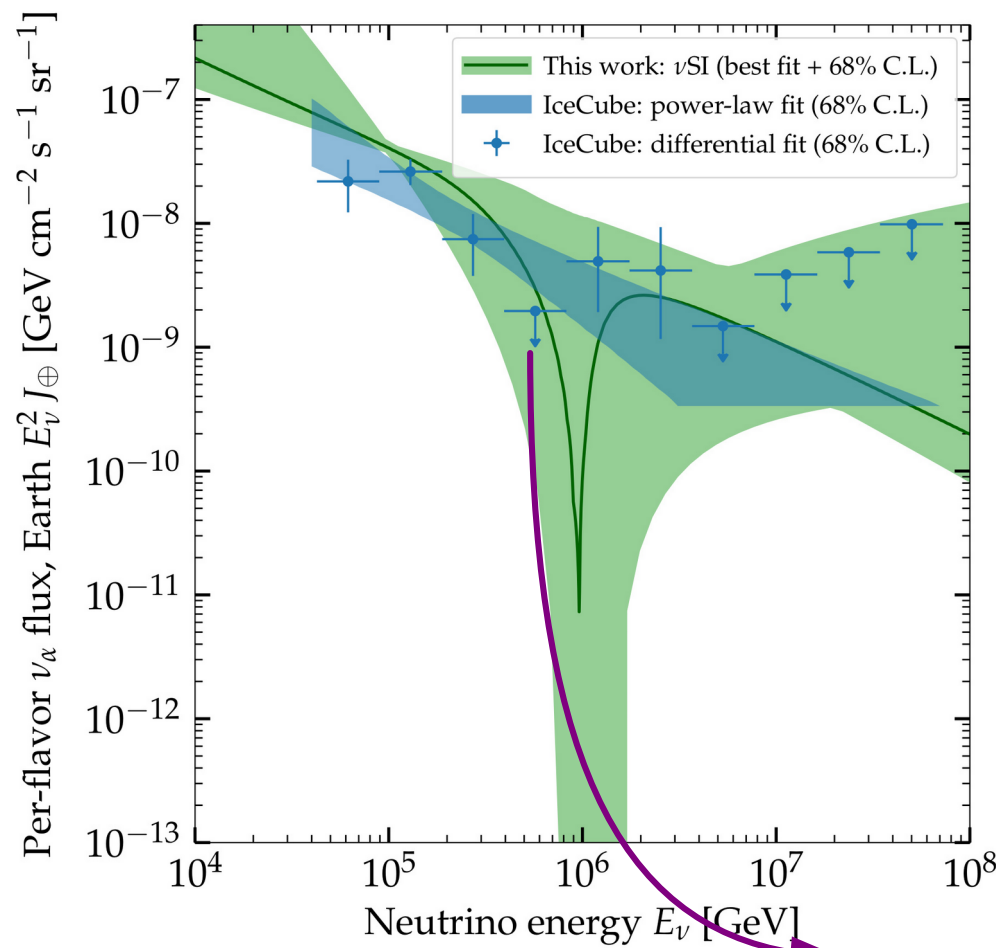
No significant ($> 3\sigma$) evidence for a spectral dip ...



No significant ($> 3\sigma$) evidence for a spectral dip so we set upper limits on the coupling g



No significant ($> 3\sigma$) evidence for a spectral dip so we set upper limits on the coupling g



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

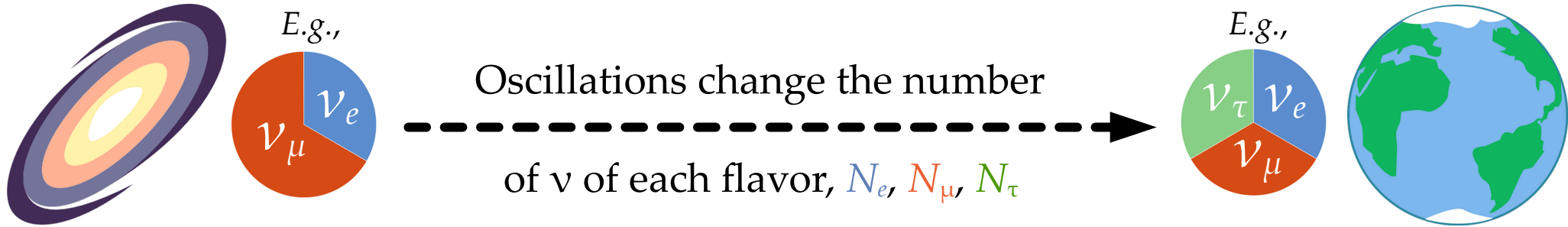
4. New physics via flavor

Hard to do, but worth it

Astrophysical sources

Earth

Up to a few Gpc



Different production mechanisms yield different flavor ratios:

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

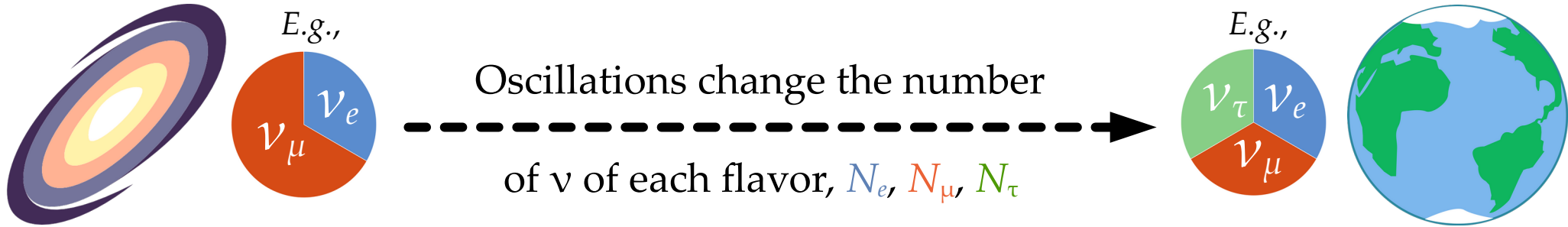
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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

Astrophysical sources

Earth

Up to a few Gpc



Different production mechanisms yield different flavor ratios:

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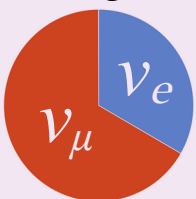
Standard
oscillations
or
new physics

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

Sources



E.g.,



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

Oscillations

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

Earth

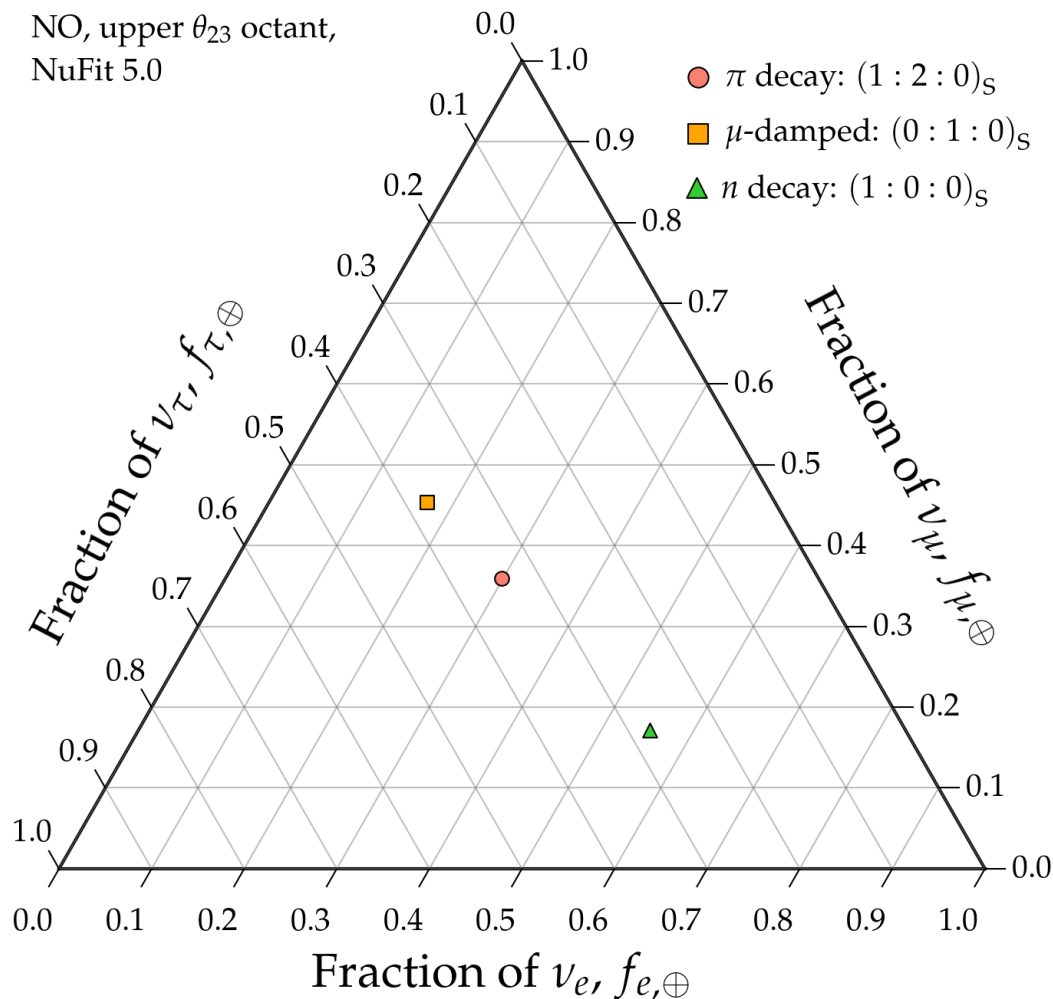


$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

Known from oscillation
experiments, to different
levels of precision

Theoretically palatable regions: today

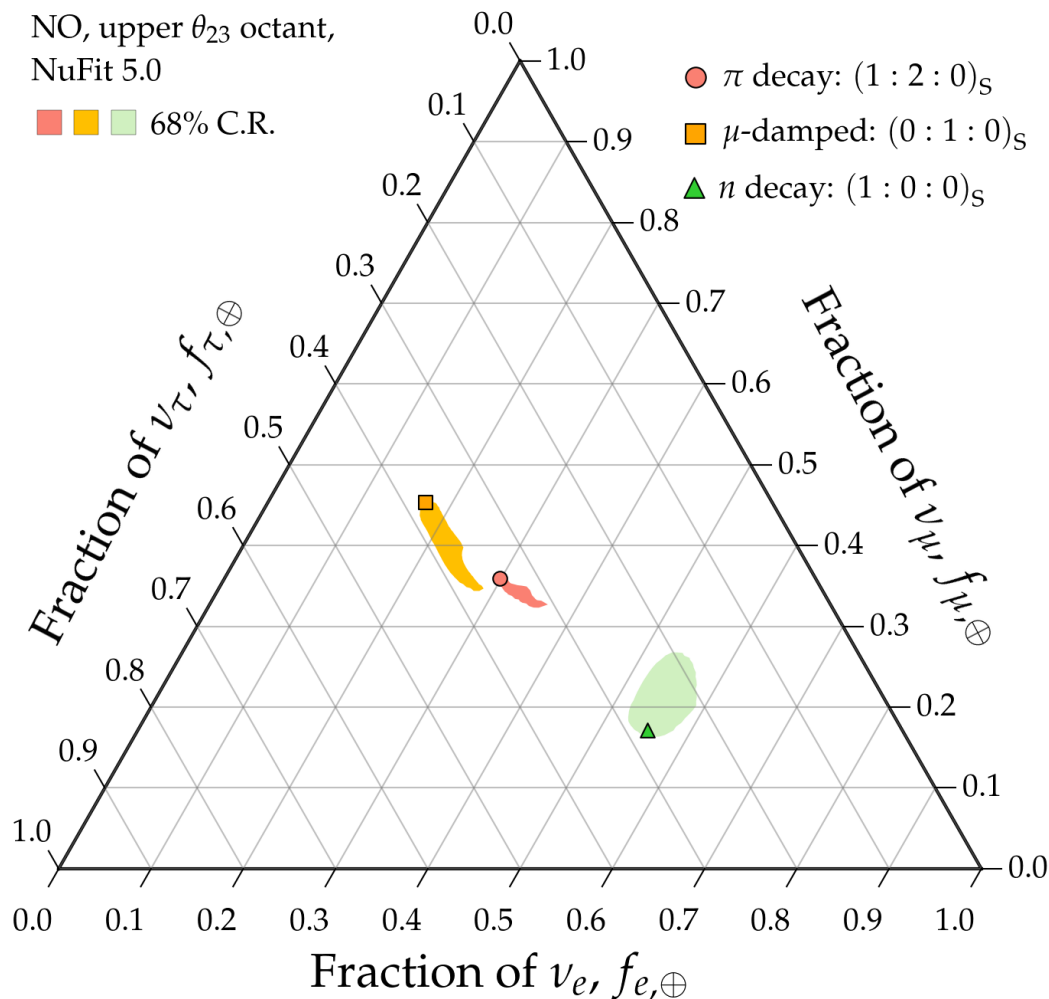
NO, upper θ_{23} octant,
NuFit 5.0



Note:

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

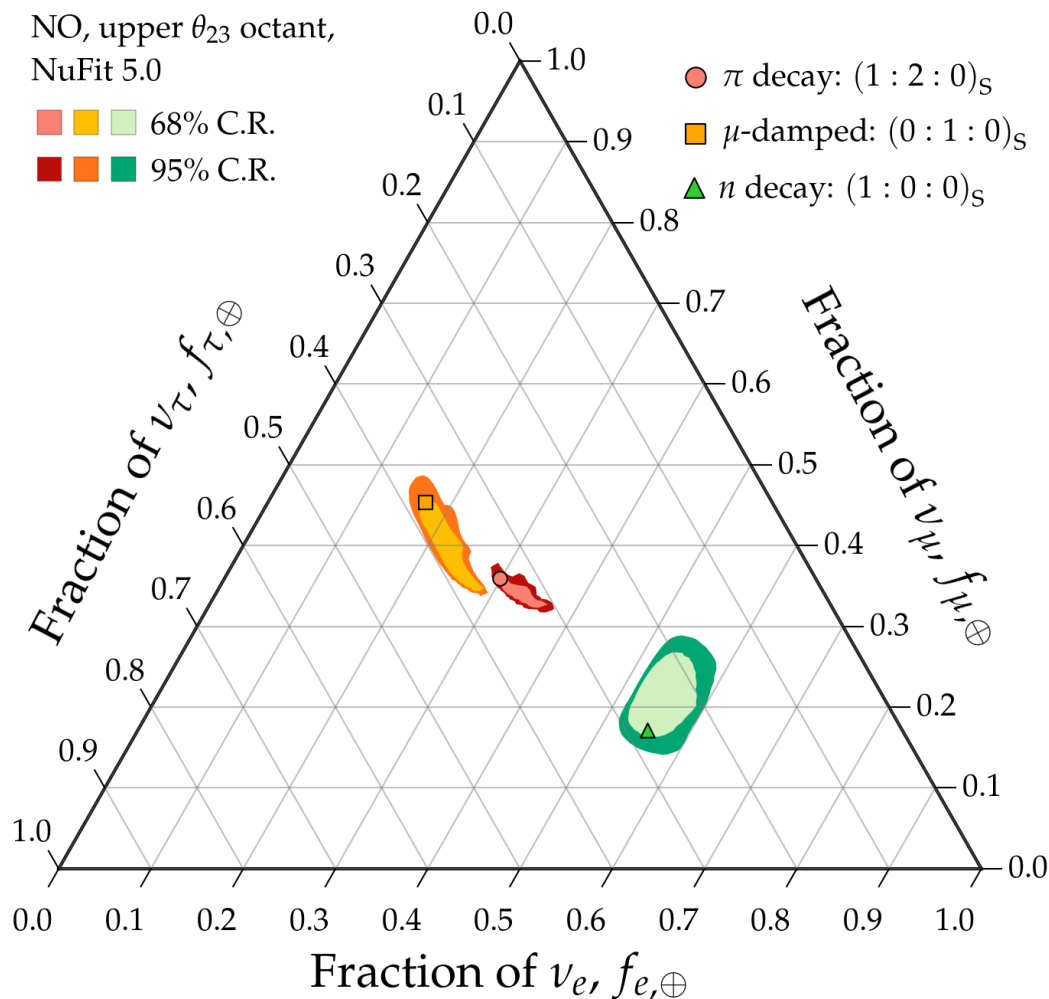
Theoretically palatable regions: today



Note:

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neutrino mass ordering (NO);
inverted ordering looks similar

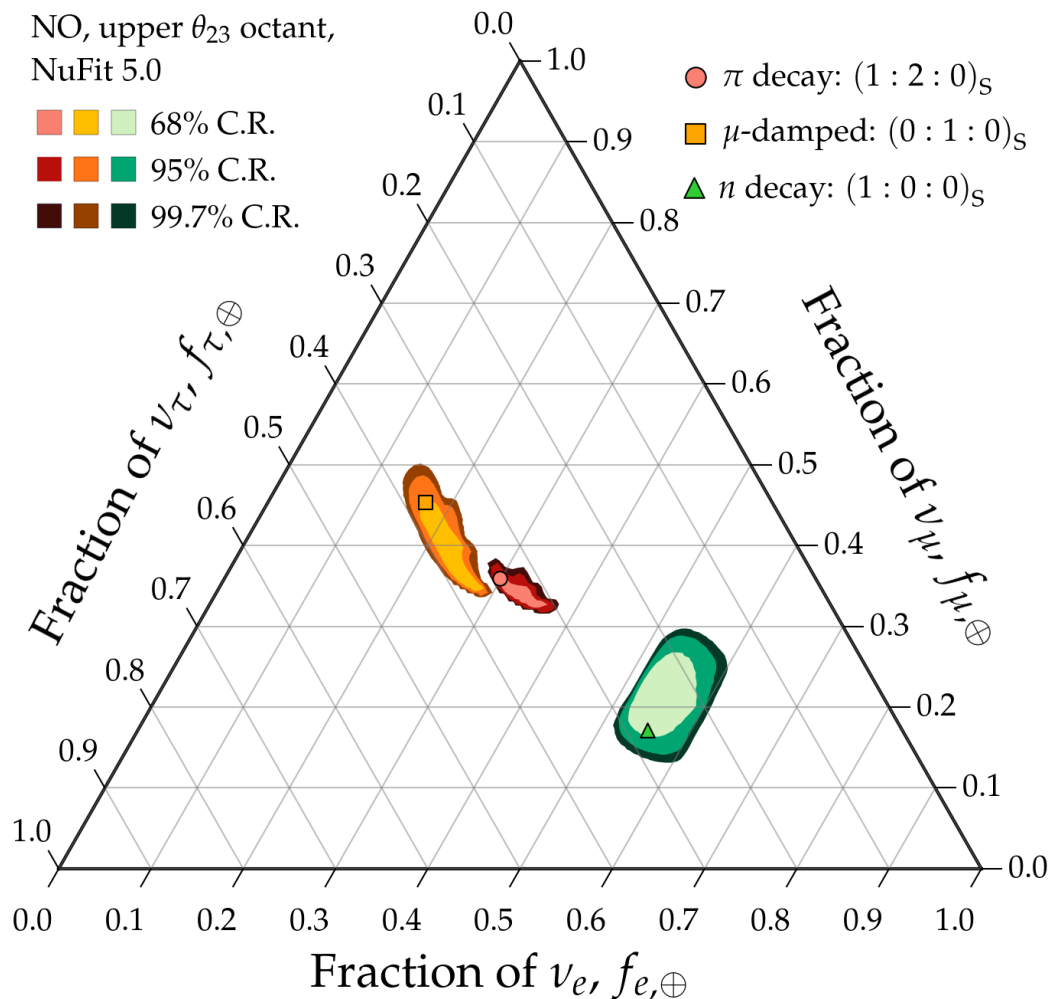
Theoretically palatable regions: today



Note:

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

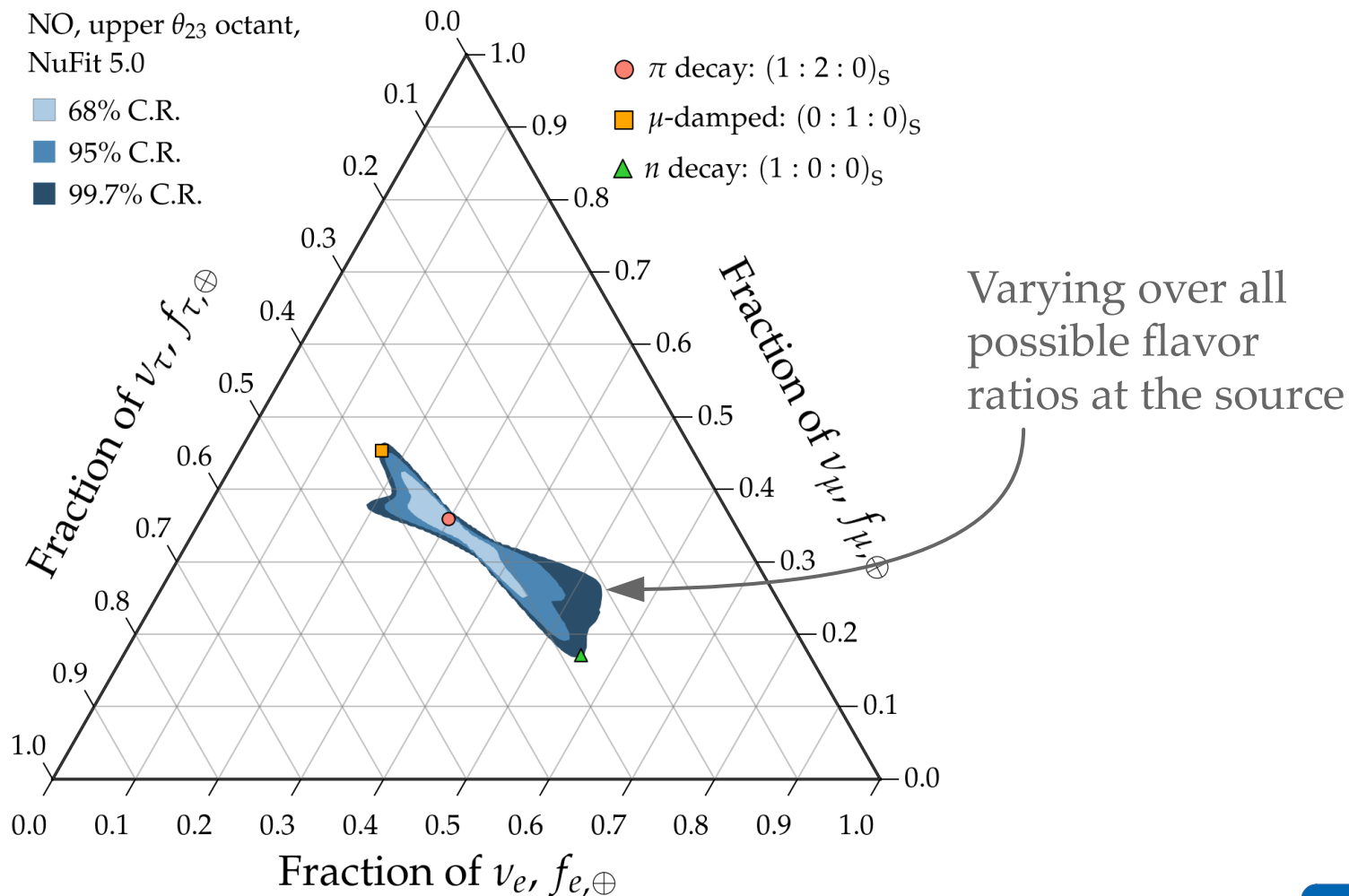
Theoretically palatable regions: today



Note:

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Theoretically palatable regions: today



Note:

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inverted ordering looks similar

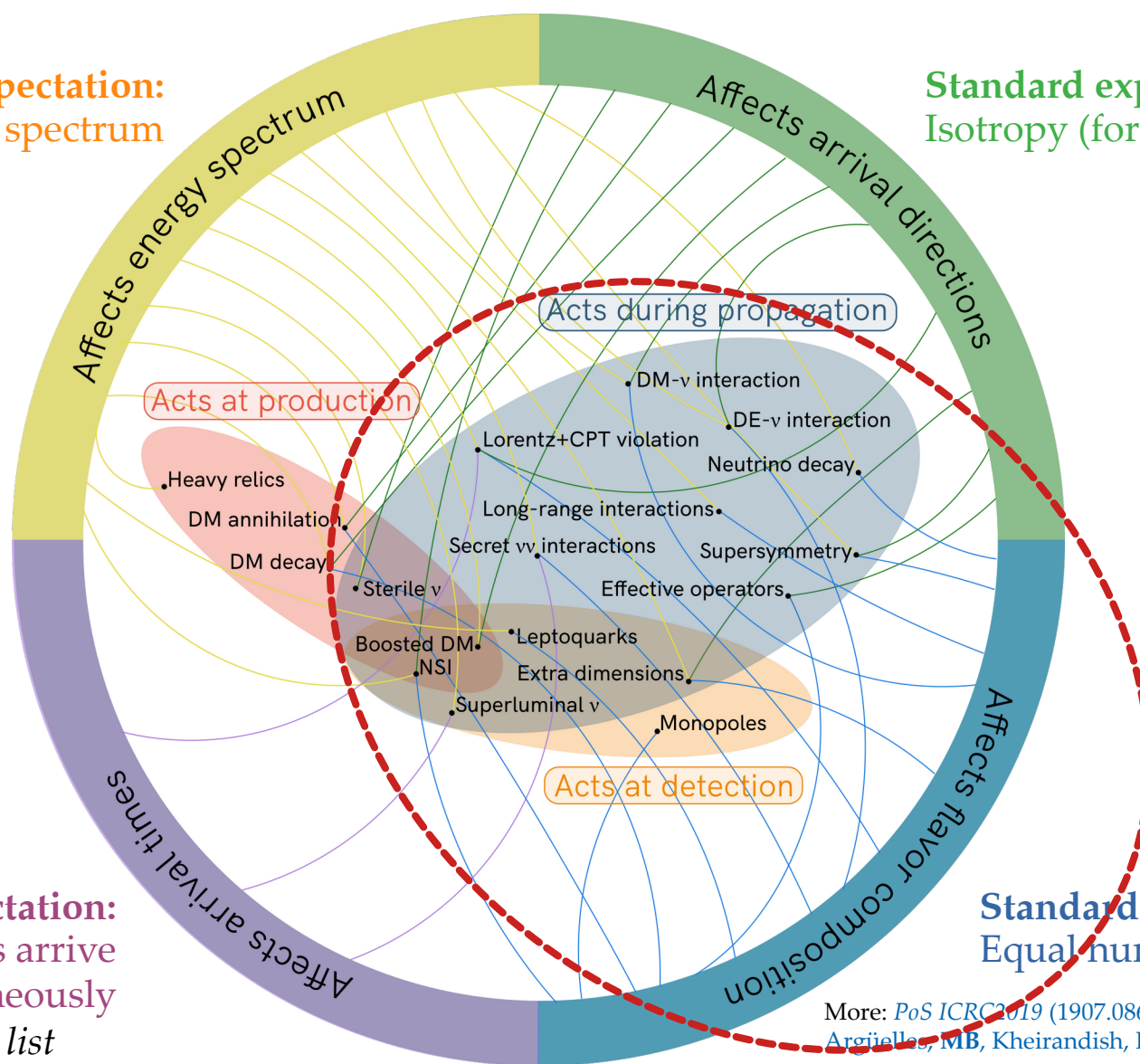
Theoretically palatable regions: today

Note:

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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
 ν and γ from transients arrive
simultaneously

Standard expectation:
Equal number of ν_e , ν_μ , ν_τ

Note: Not an exhaustive list

More: *PoS ICRC2019* (1907.08690)

Argüelles, MB, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

New physics in flavor composition

Use the flavor sensitivity to test new physics:

Reviews:

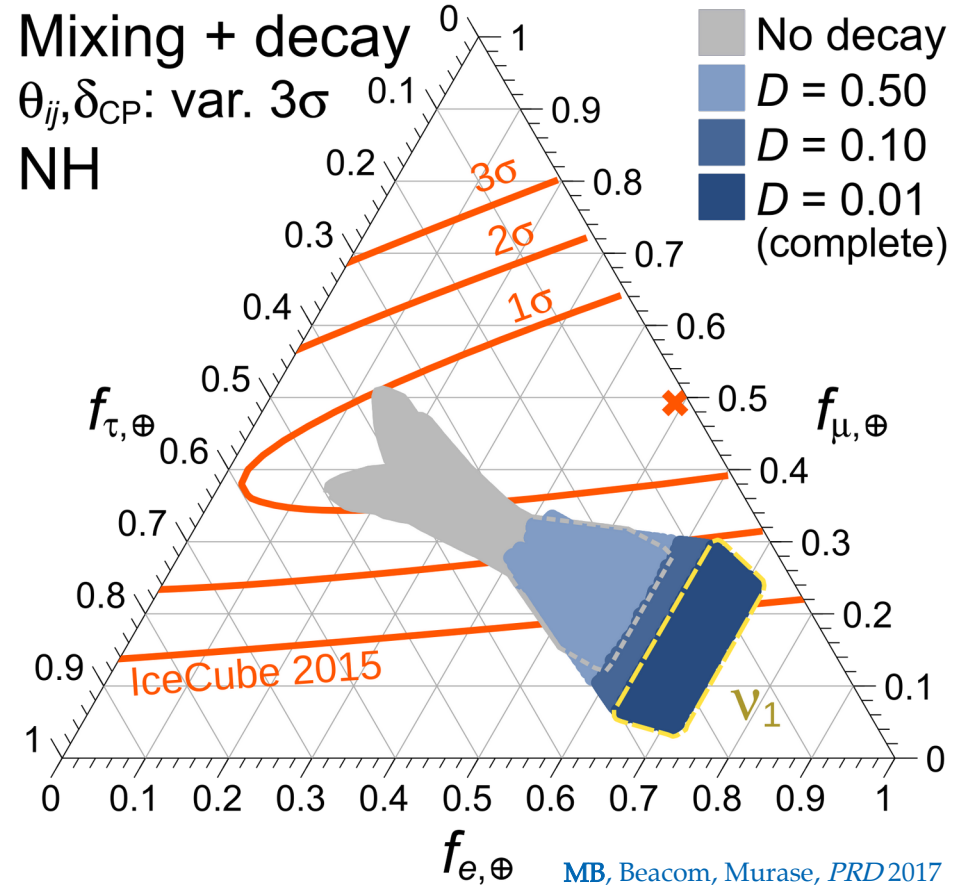
Argüelles *et al.* (inc. *MB*), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

Use the flavor sensitivity to test new physics:

► Neutrino decay

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



Reviews:

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

New physics in flavor composition

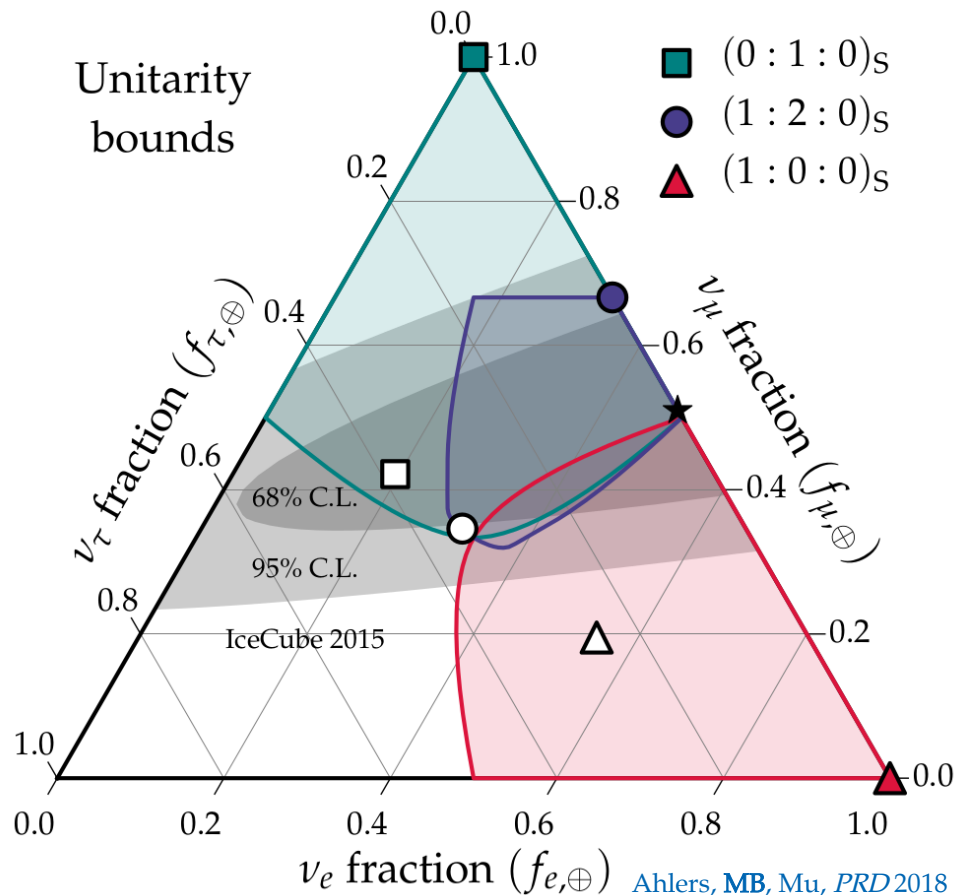
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[Beacom *et al.*, *PRL* 2003; Baerwald, *MB*, Winter, *JCAP* 2010;
MB, Beacom, Winter, *PRL* 2015; *MB*, Beacom, Murase, *PRD* 2017]

- ▶ Tests of unitarity at high energy

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



Reviews:

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

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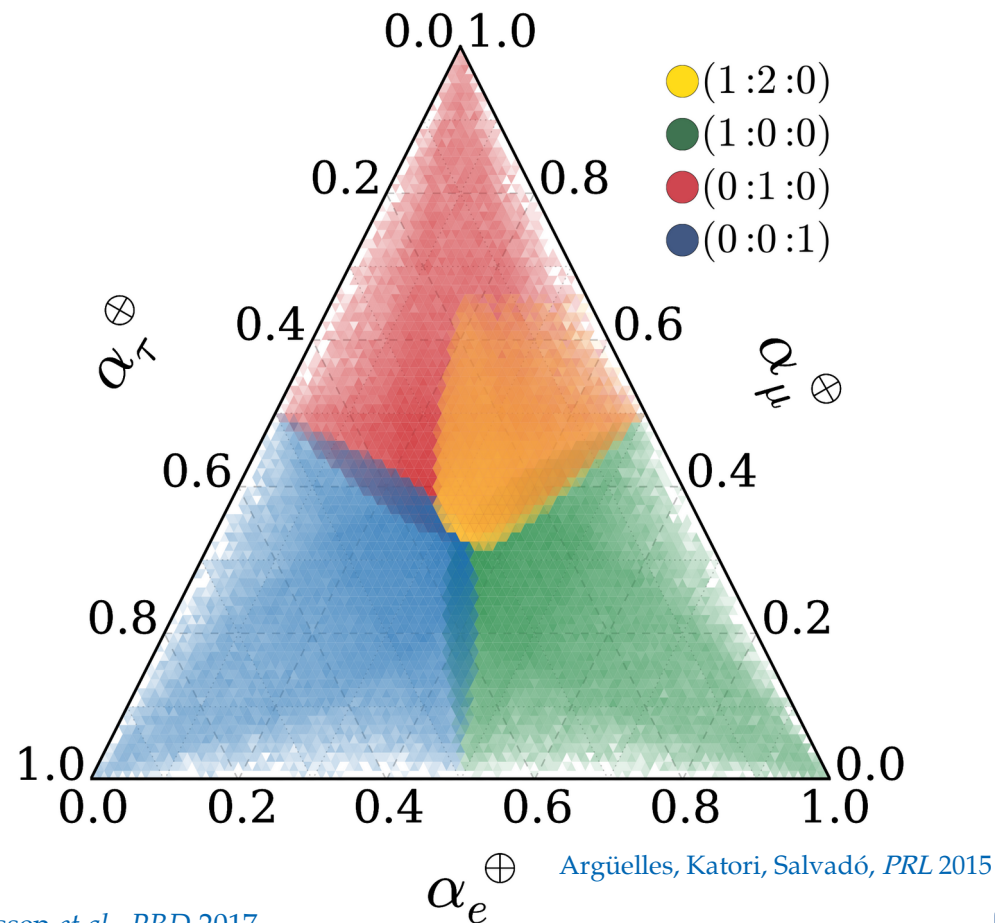
[Beacom *et al.*, *PRL* 2003; Baerwald, *MB*, Winter, *JCAP* 2010;
MB, Beacom, Winter, *PRL* 2015; *MB*, Beacom, Murase, *PRD* 2017]

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- Lorentz- and CPT-invariance violation

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



Reviews:

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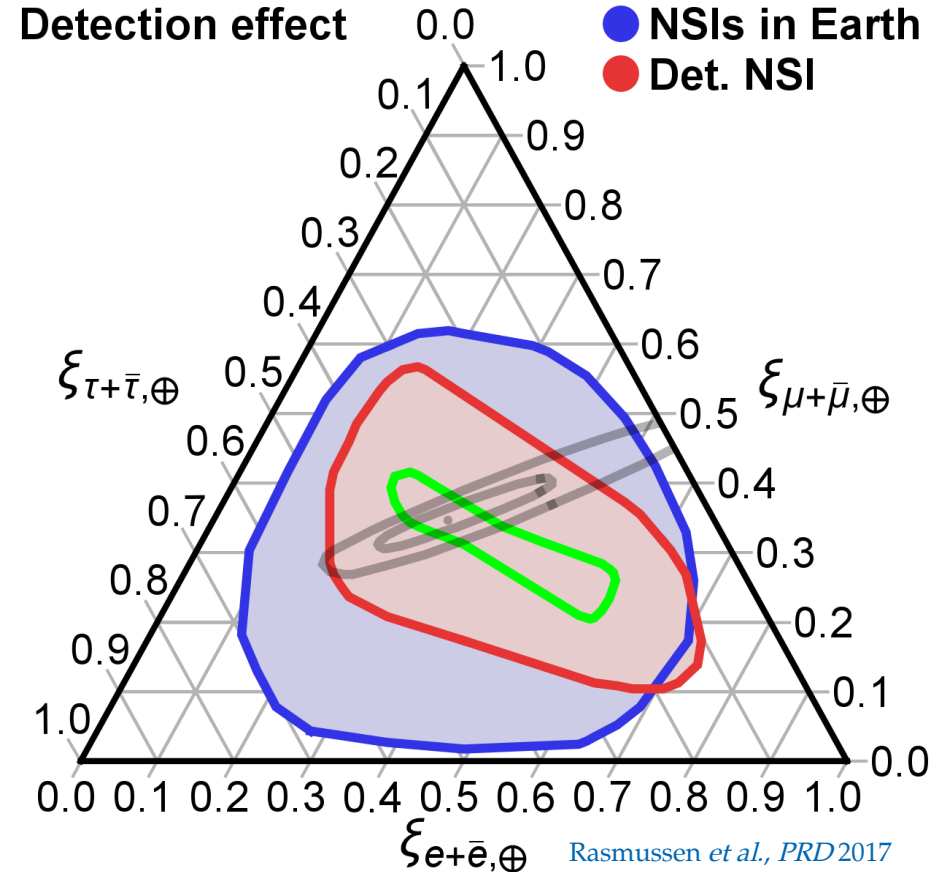
[Barenboim & Quigg, *PRD* 2003; *MB*, Gago, Peña-Garay, *JHEP* 2010;
Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]

- ▶ Non-standard interactions

[González-García *et al.*, *Astropart. Phys.* 2016;
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Reviews:

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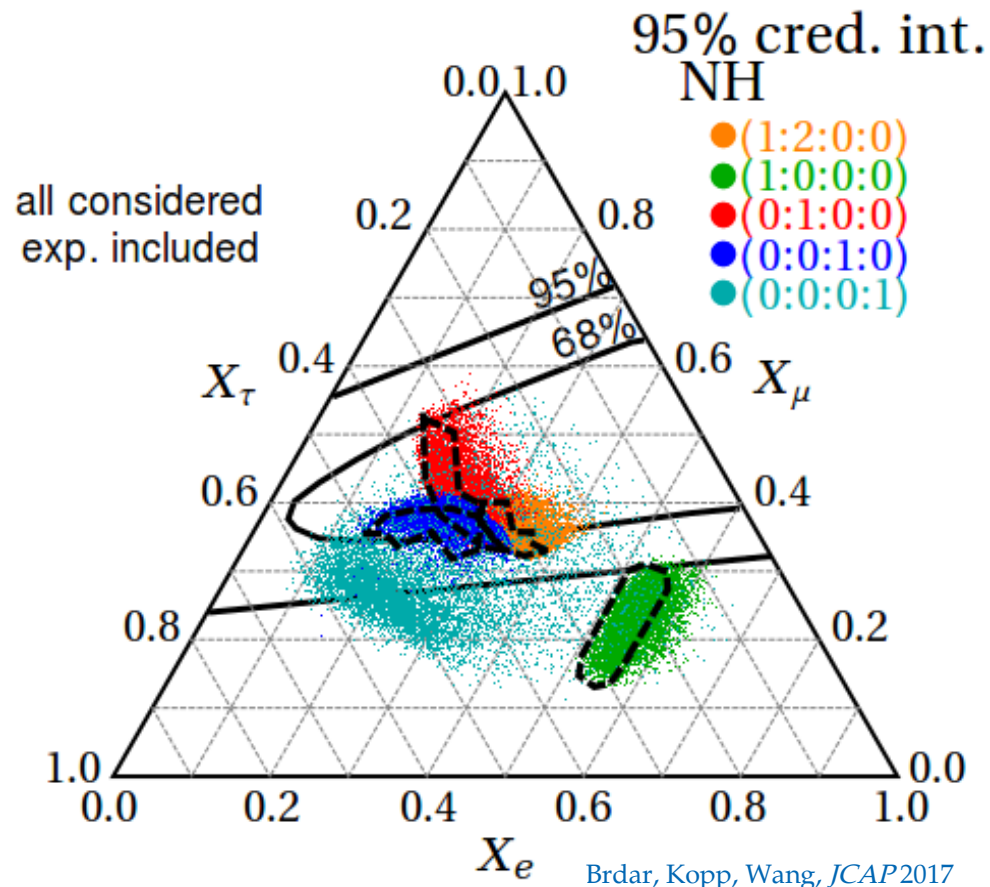
[Barenboim & Quigg, *PRD* 2003; *MB*, Gago, Peña-Garay, *JHEP* 2010; Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]

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

► Active-sterile ν mixing

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



Reviews:

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Rasmussen *et al.*, *PRD* 2017]

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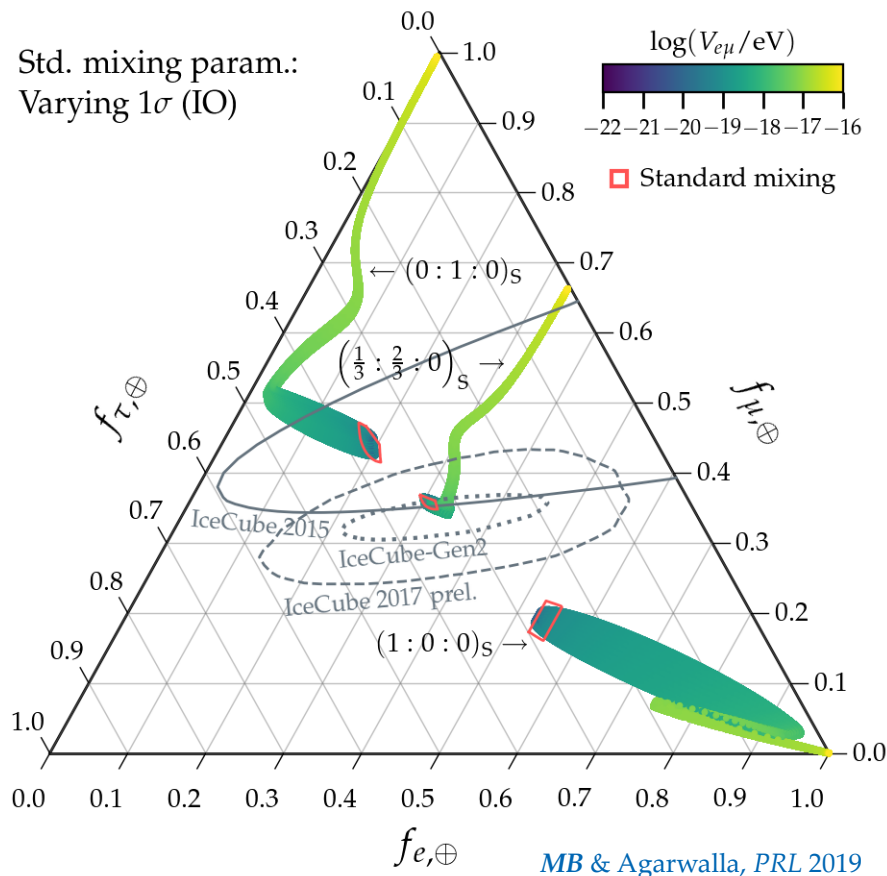
[Aeikens *et al.*, *JCAP* 2015; Brdar, Kopp, Wang, *JCAP* 2017;
Argüelles *et al.*, *JCAP* 2020; Ahlers, *MB*, *JCAP* 2021]

- Long-range $e\nu$ interactions

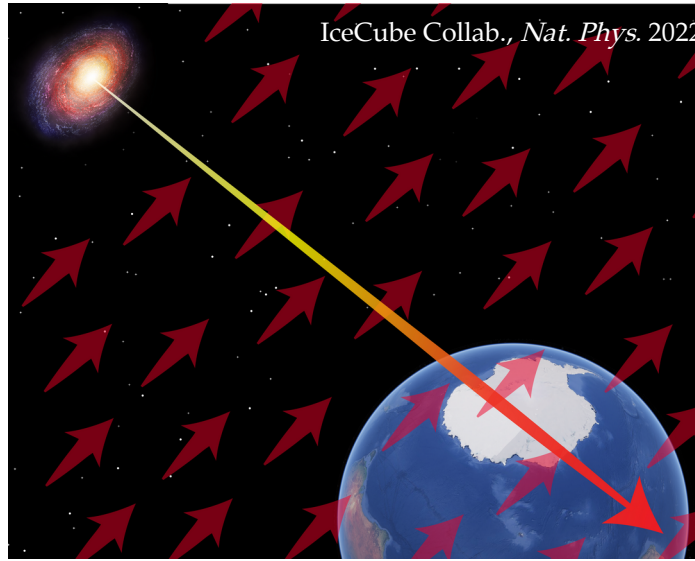
[*MB* & Agarwalla, *PRL* 2019]

Reviews:

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



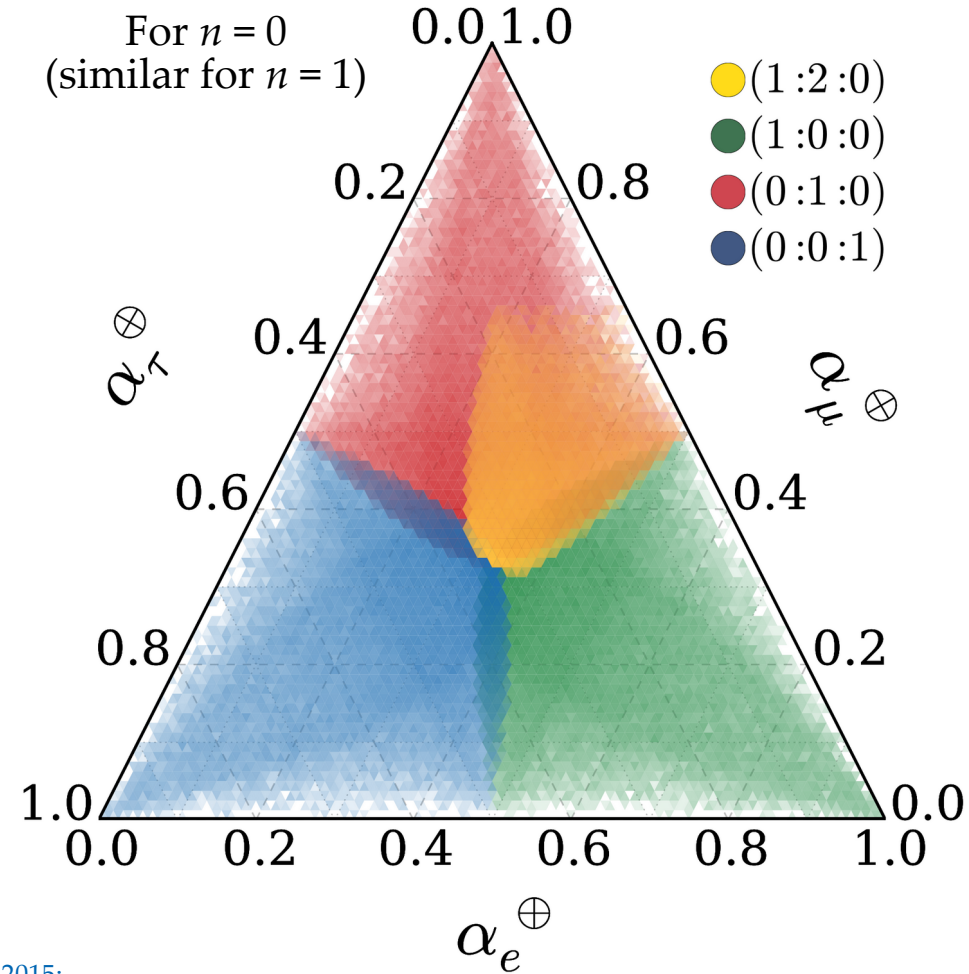
Lorentz-invariance violation can fill up the flavor triangle



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

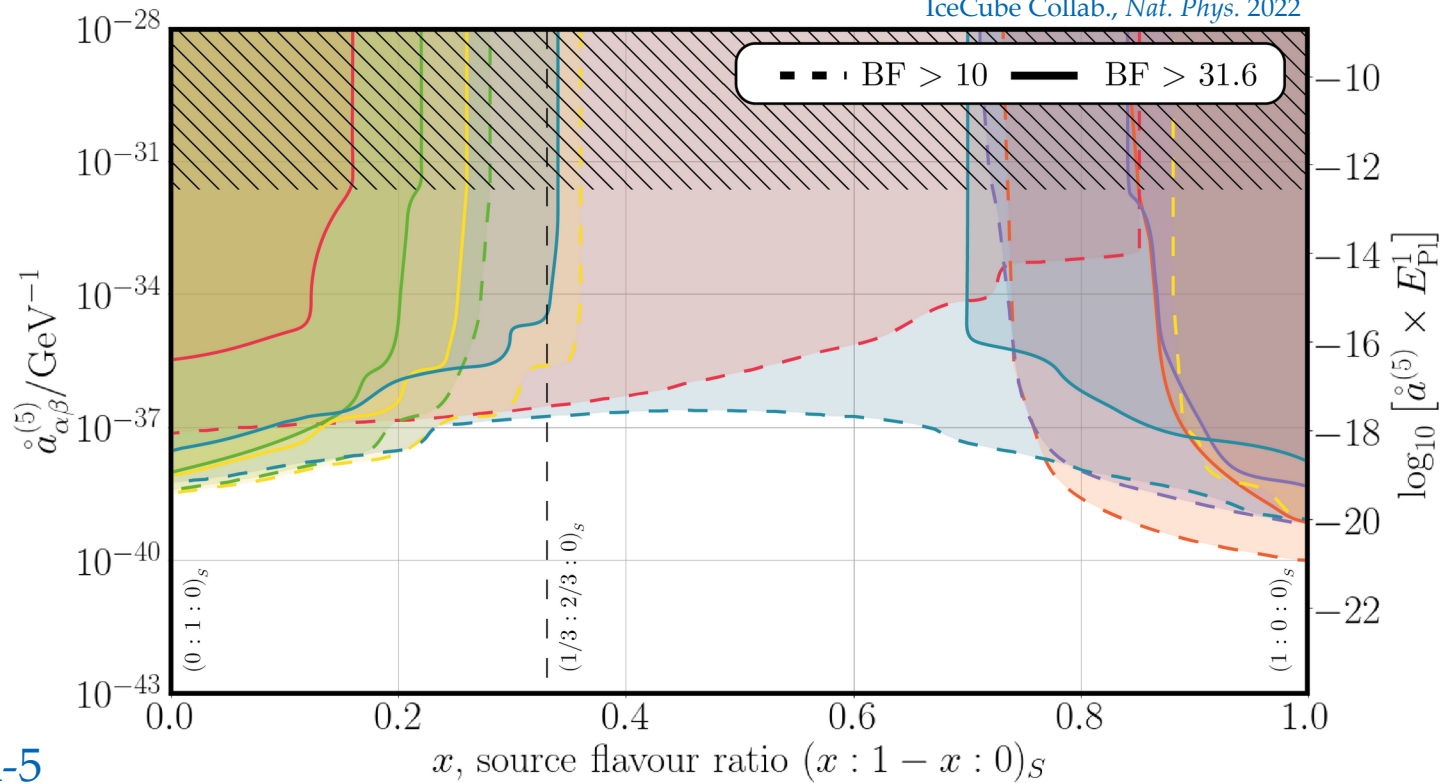
$$H_{\text{std}} = \frac{1}{2E} U_{\text{PMNS}}^\dagger \text{diag} (0, \Delta m_{21}^2, \Delta m_{31}^2) U_{\text{PMNS}}$$

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

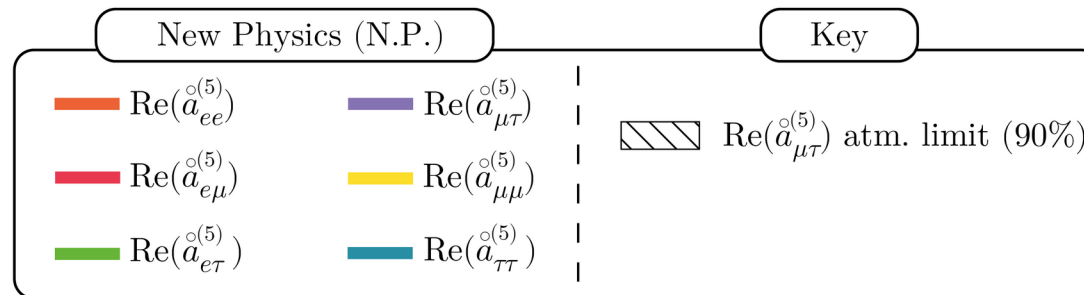


See also: Ahlers, MB, Mu, *PRD* 2018; Rasmusen *et al.*, *PRD* 2017; **MB**, Beacom, Winter *PRL* 2015; MB, Gago, Peña-Garay *JCAP* 2010; Bazo, **MB**, Gago, Miranda *IJMPA* 2009; + many others

Argüelles, Katori, Salvadó, *PRL* 2015



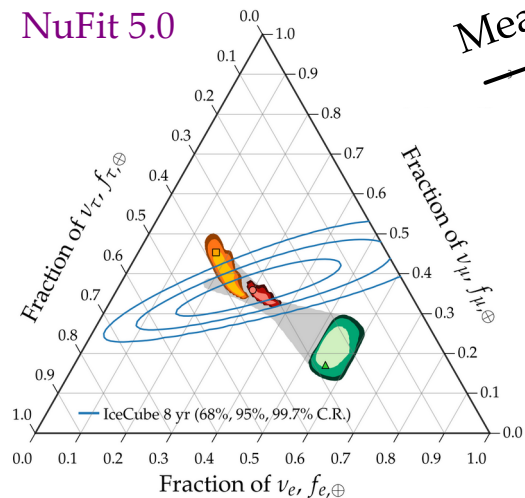
Dimension-5
CPT-odd
isotropic
Lorentz-invariance
-violating
coefficient



How knowing the mixing parameters better helps

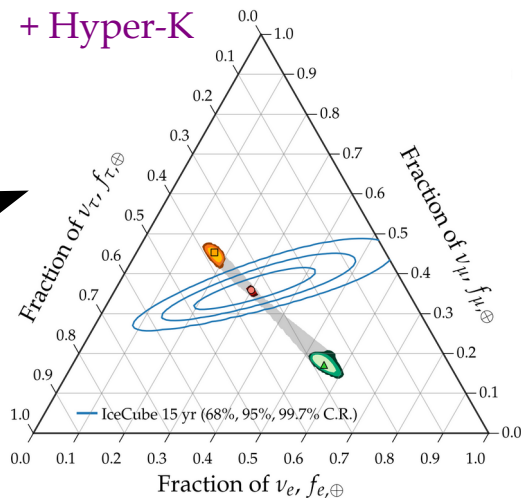
2020

NuFit 5.0

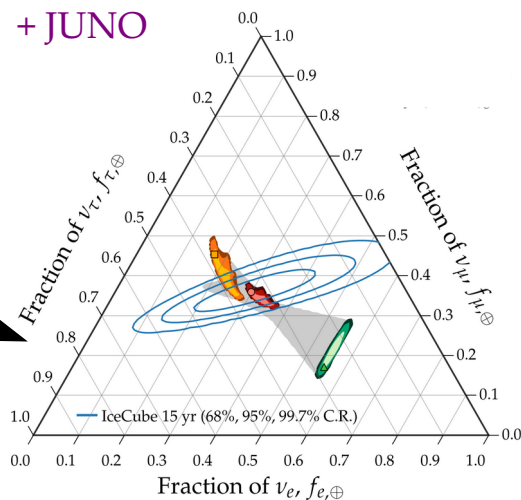


Measure θ_{23} better

+ Hyper-K



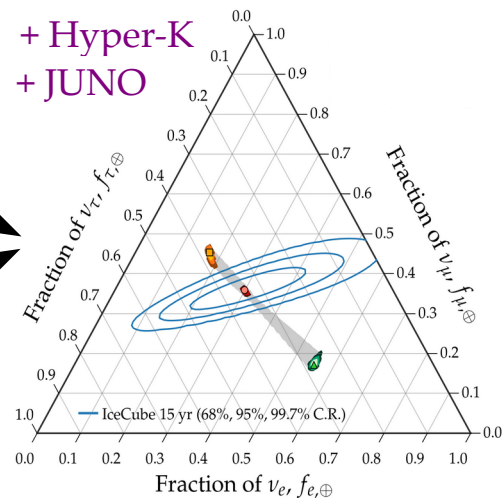
+ JUNO



Measure θ_{12} better

~2030

+ Hyper-K
+ JUNO

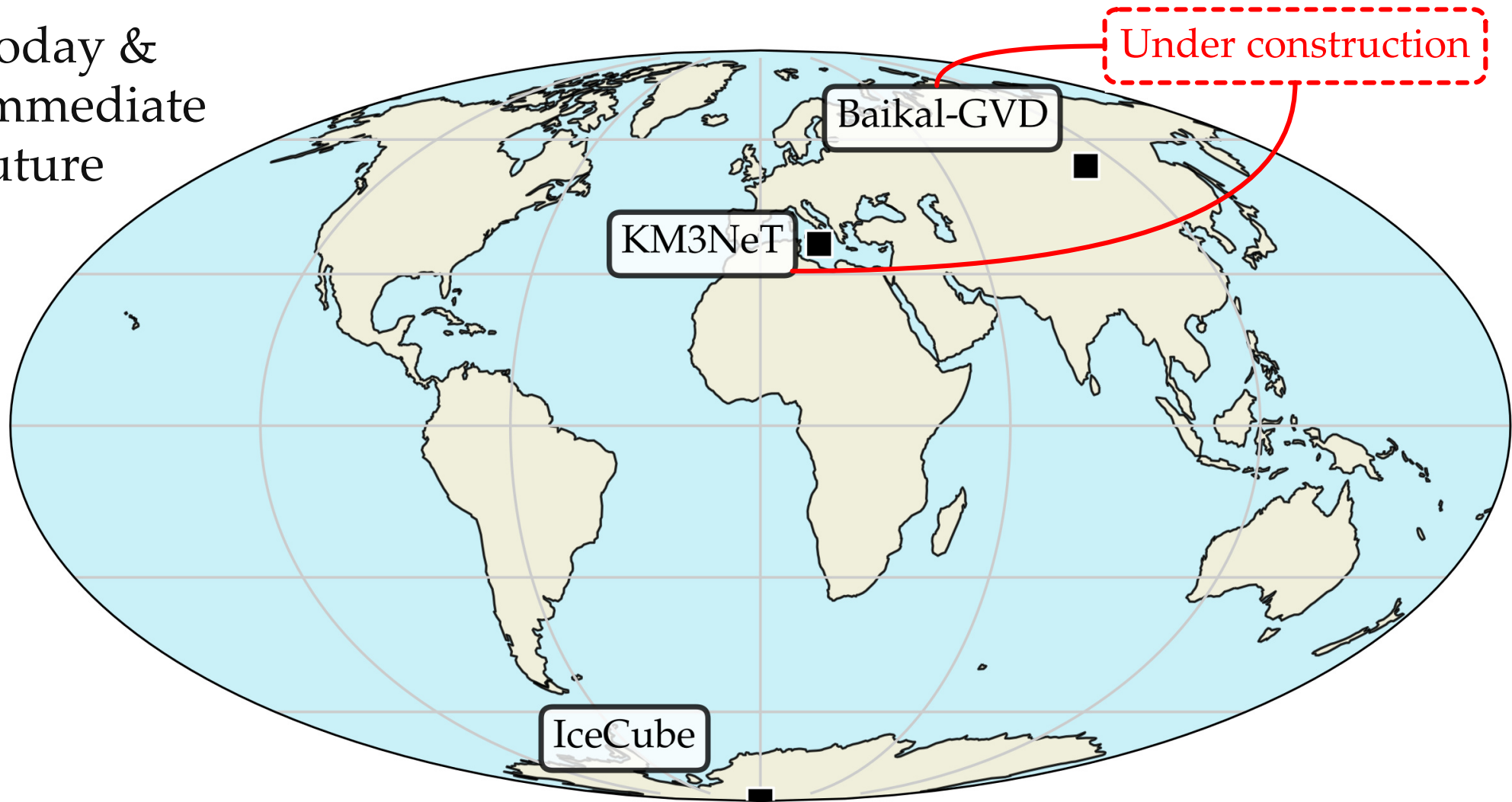


In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

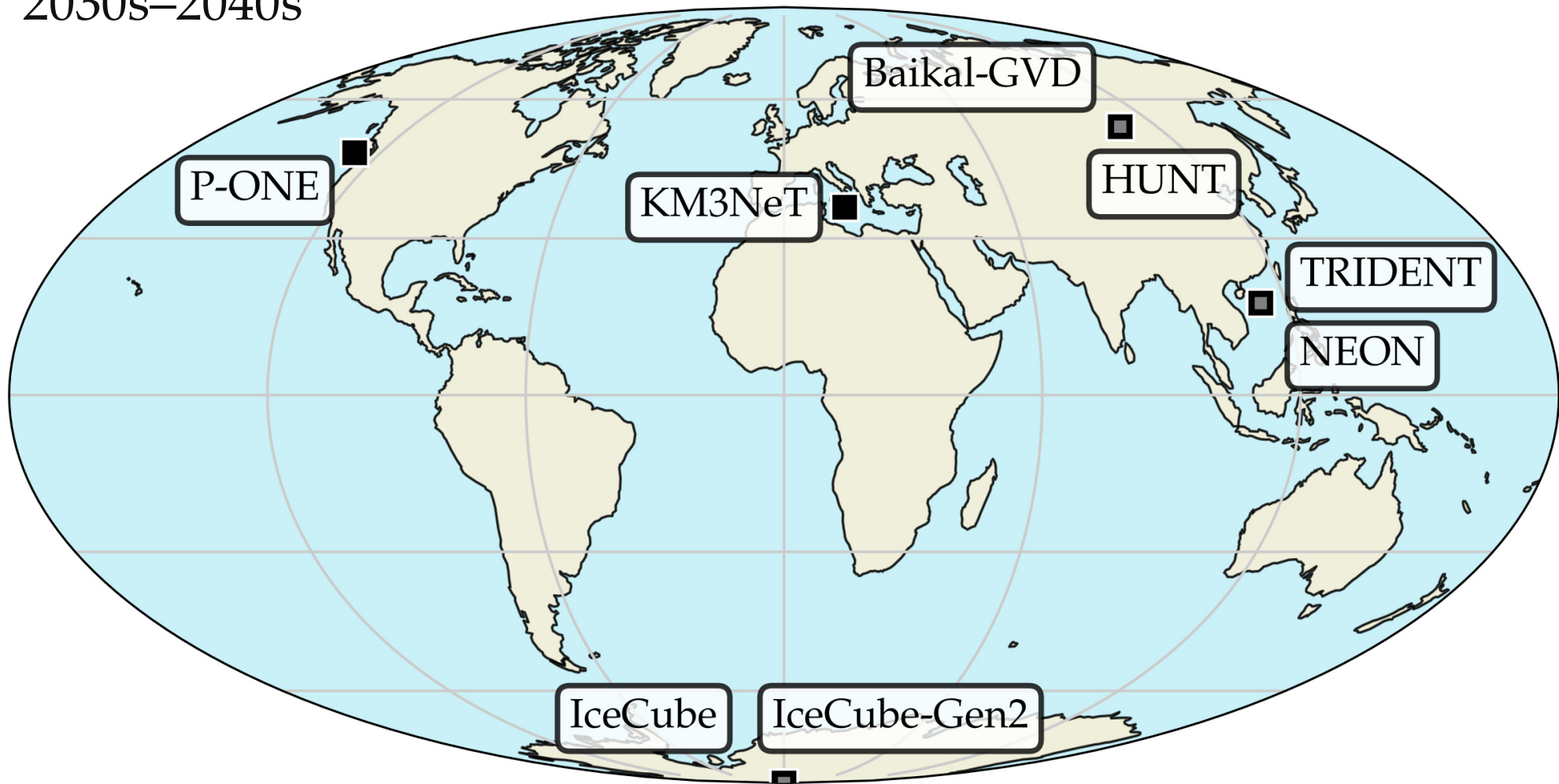
Quo vadis?

Today &
immediate
future

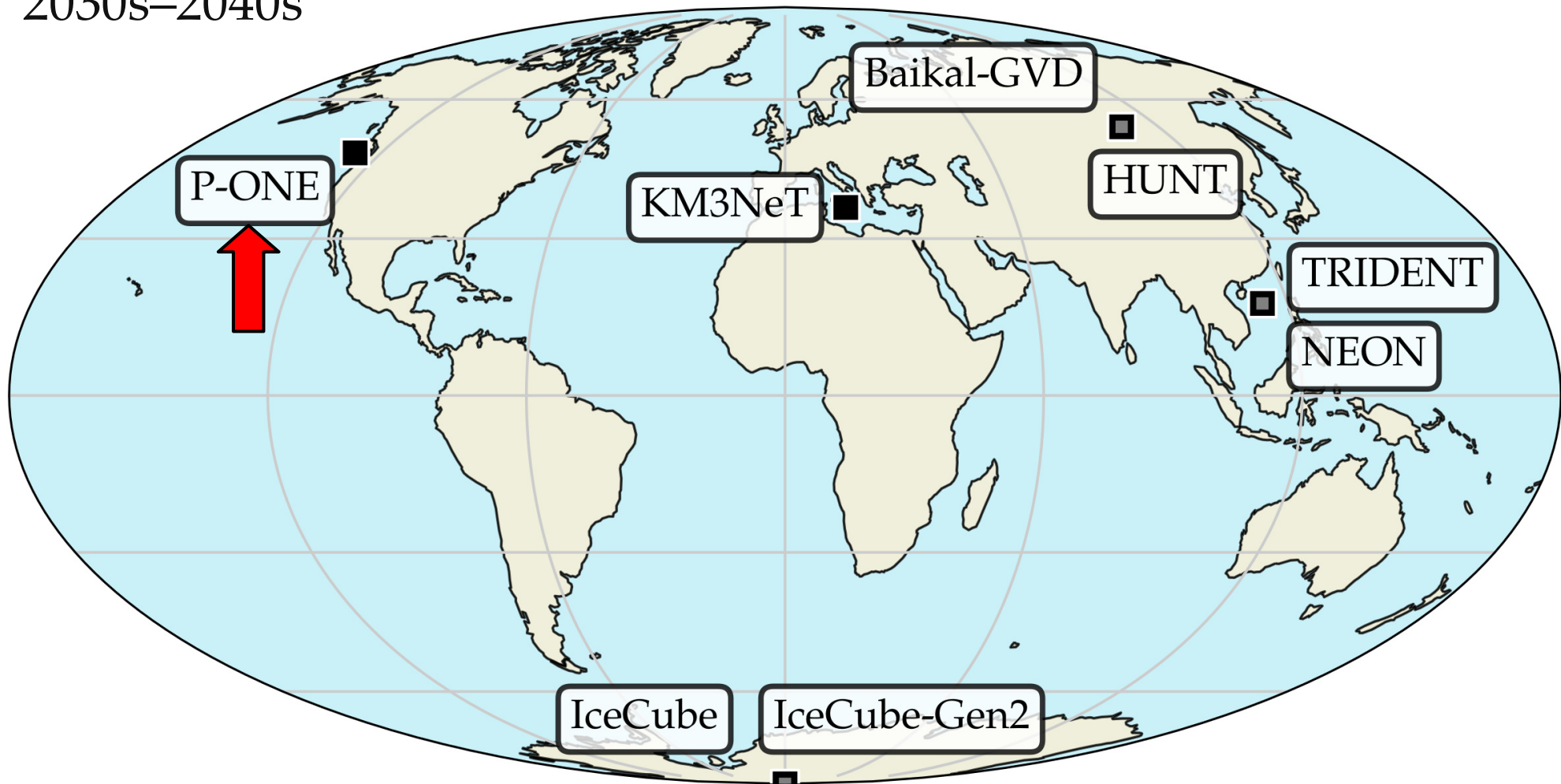


Under construction

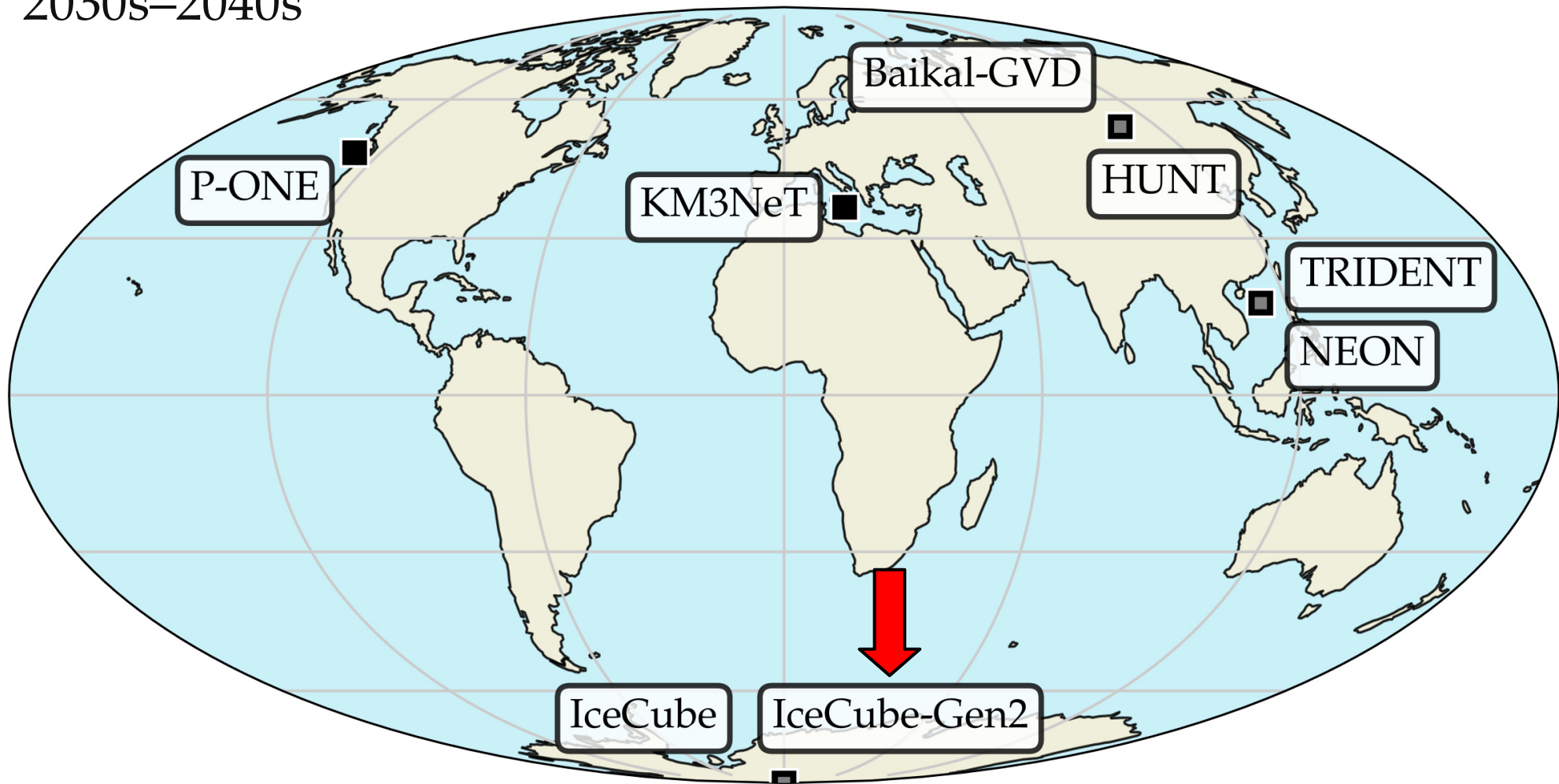
2030s–2040s



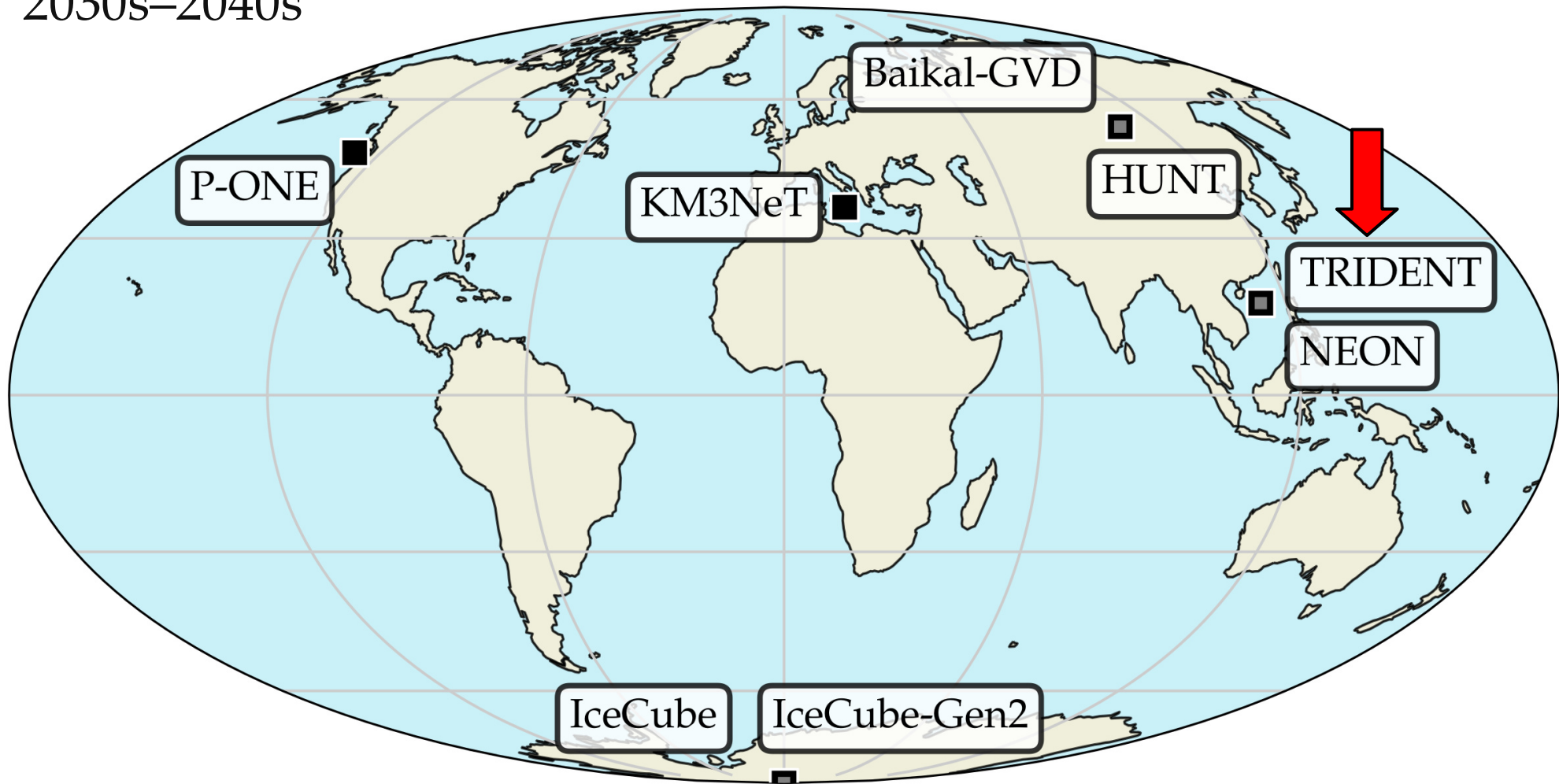
2030s–2040s



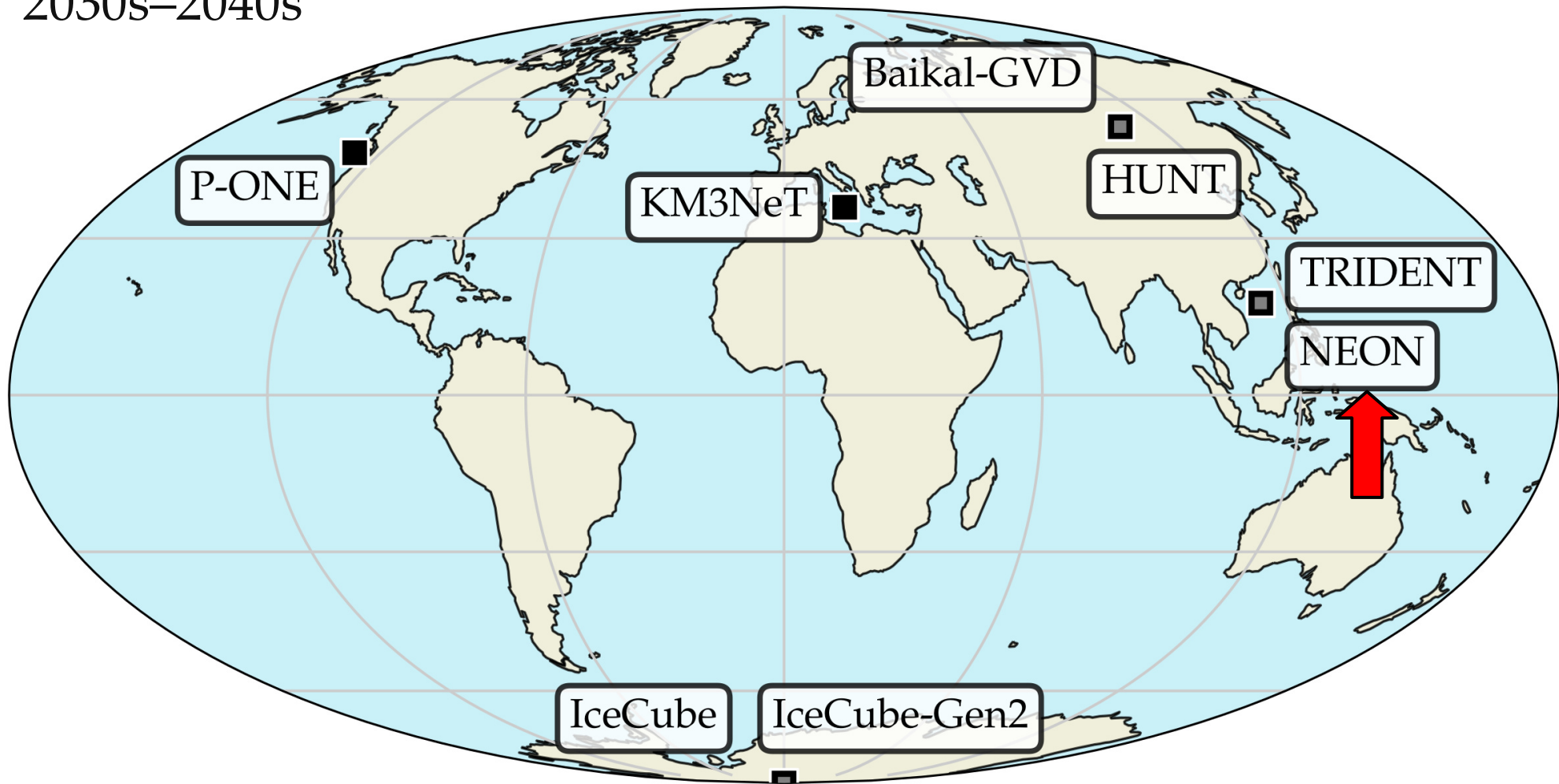
2030s–2040s



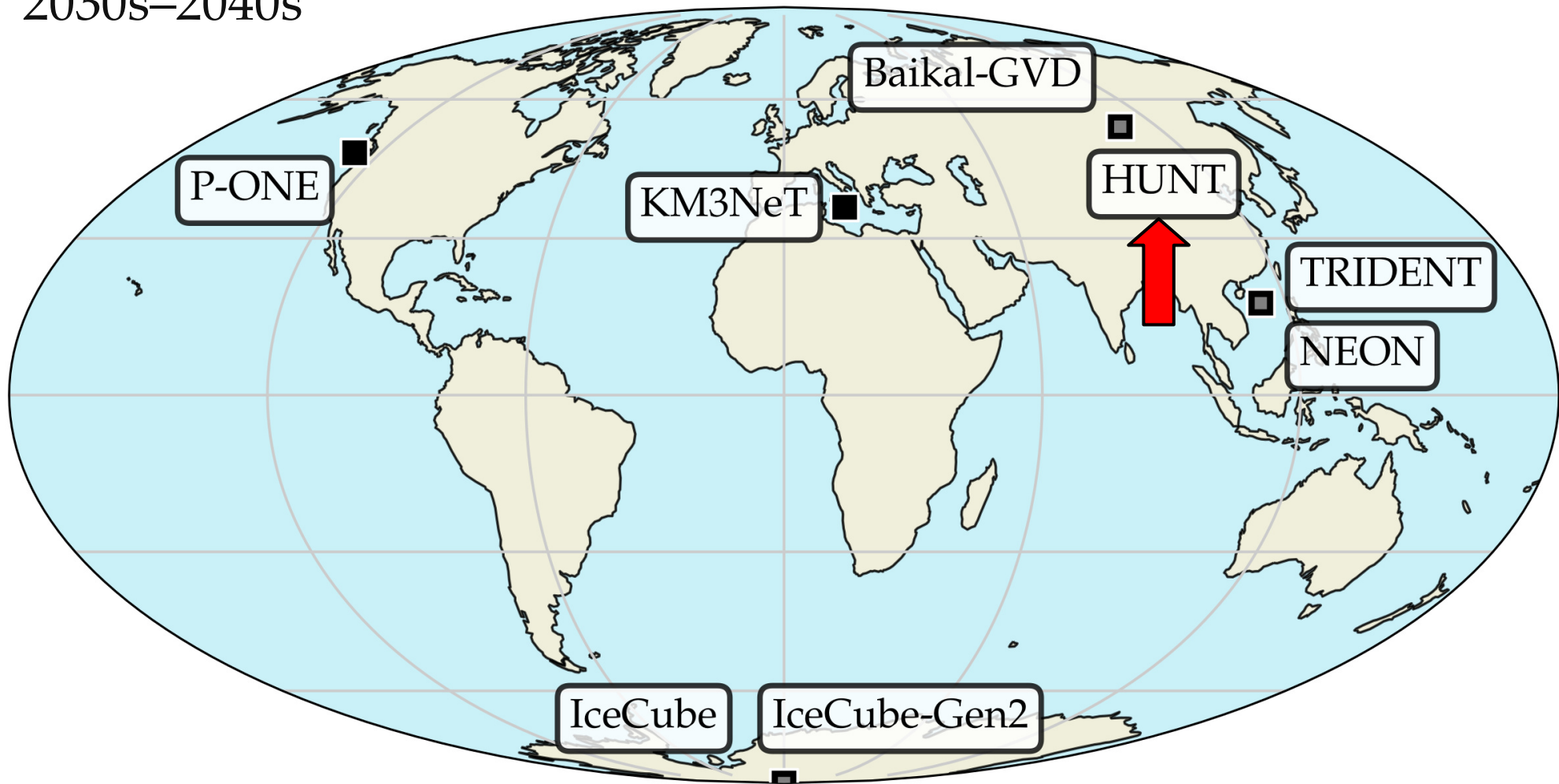
2030s–2040s

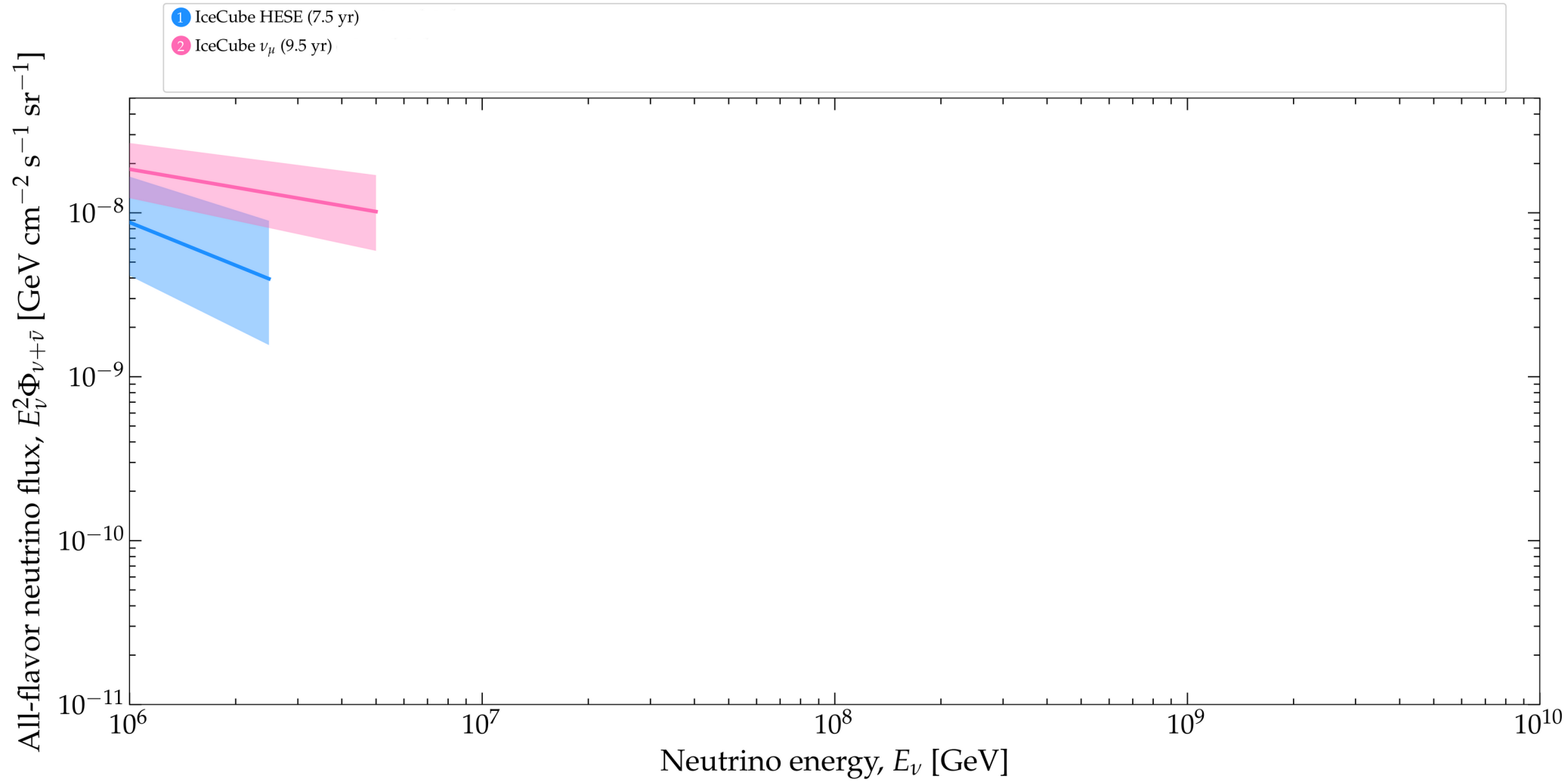


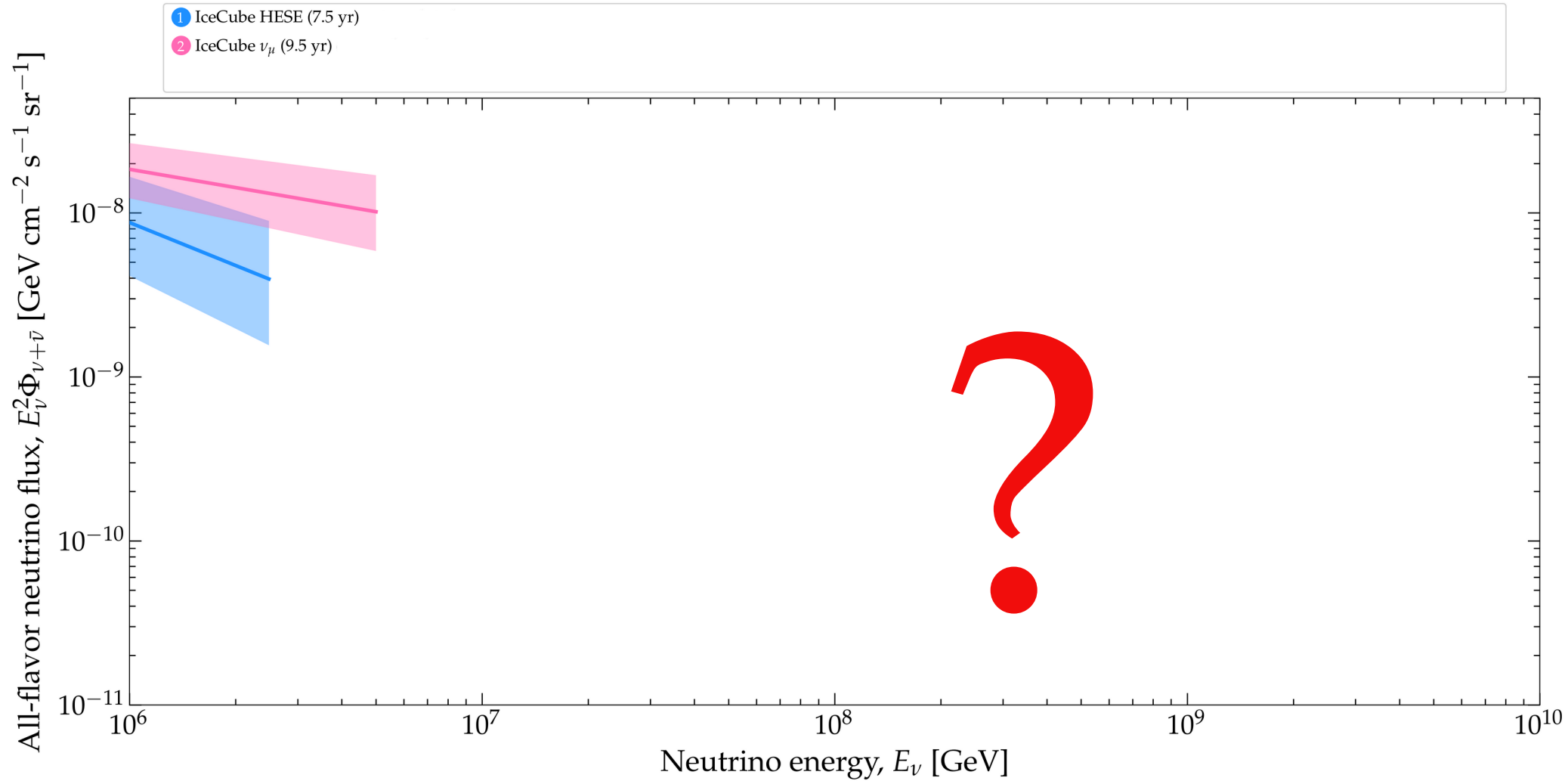
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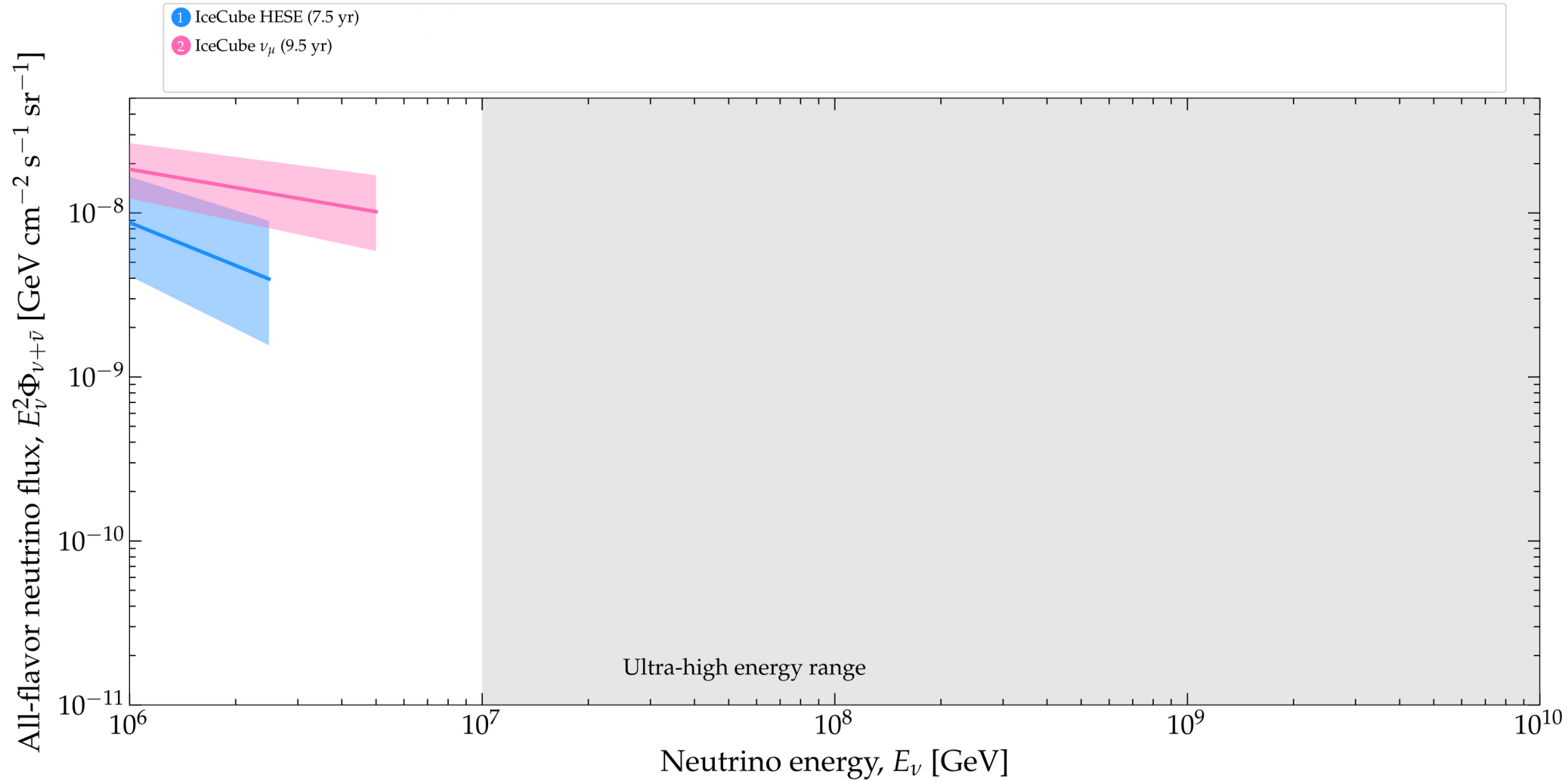


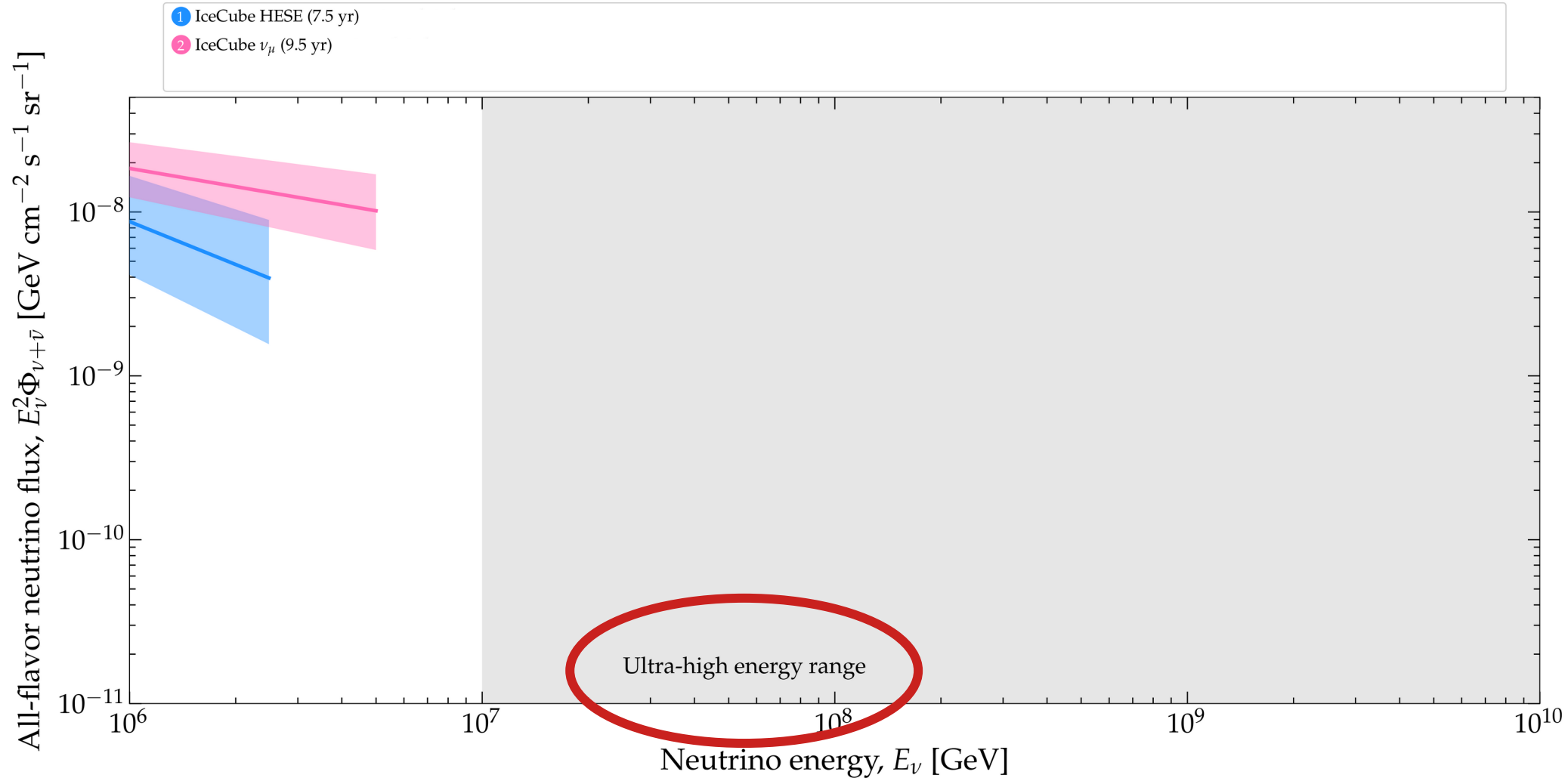
2030s–2040s





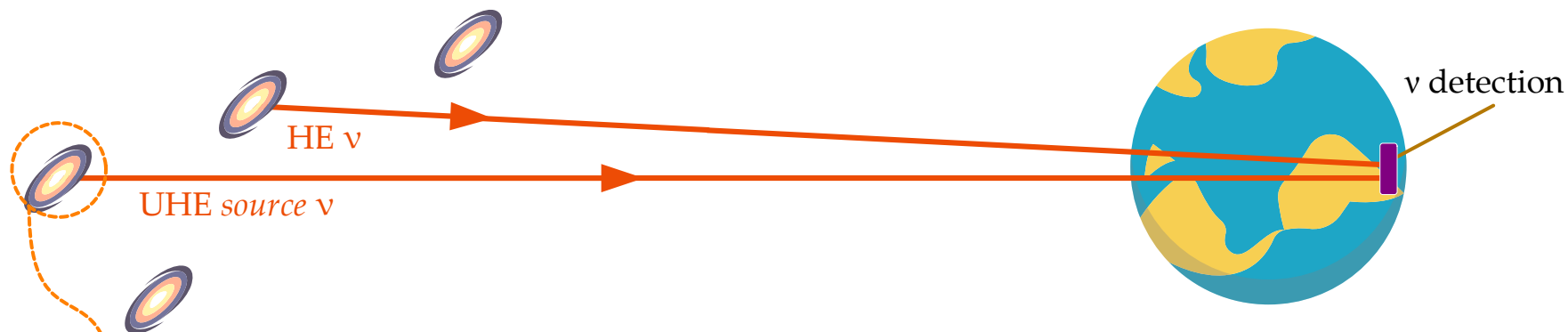






Redshift

$z = 0$



meV γ

Undiscovered

EeV p

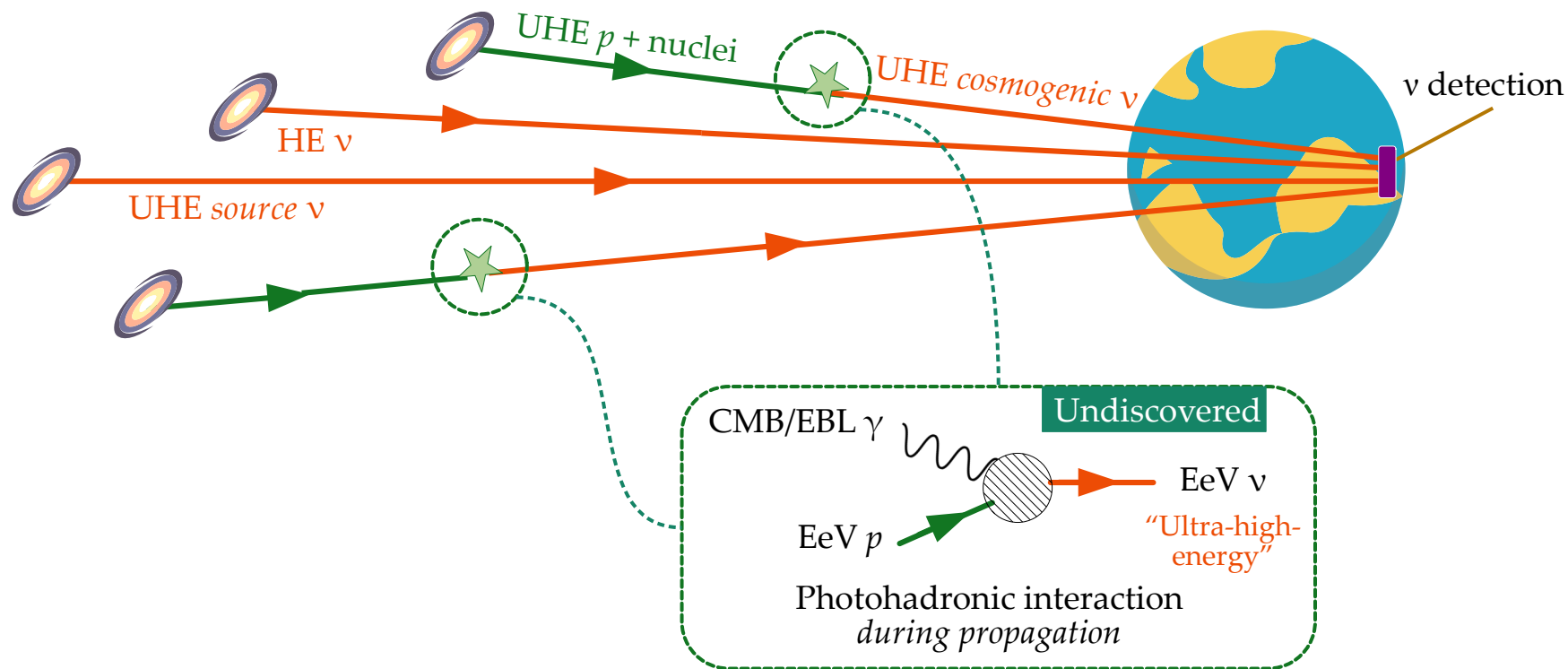
EeV ν

"Ultra-high-energy"

Photohadronic or pp interaction
inside the source

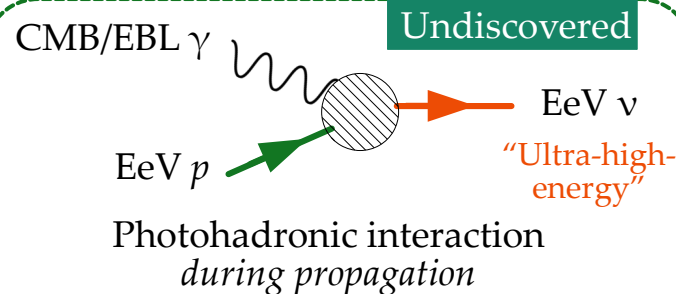
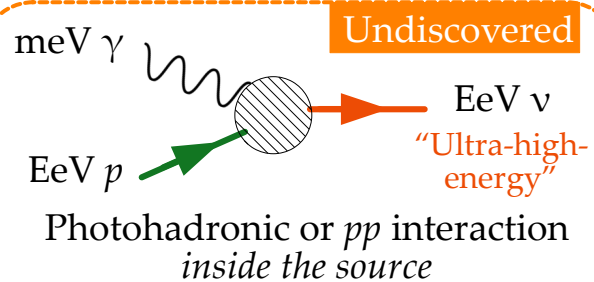
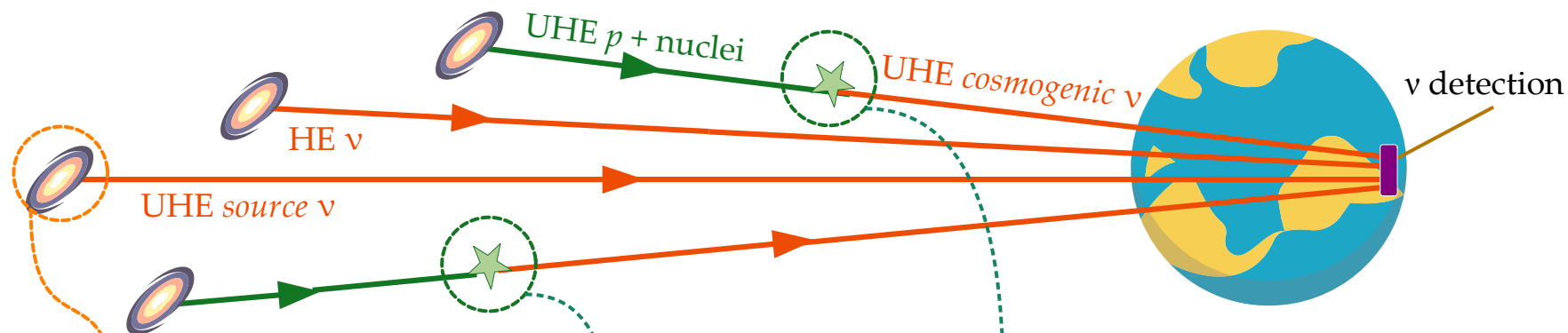
Redshift

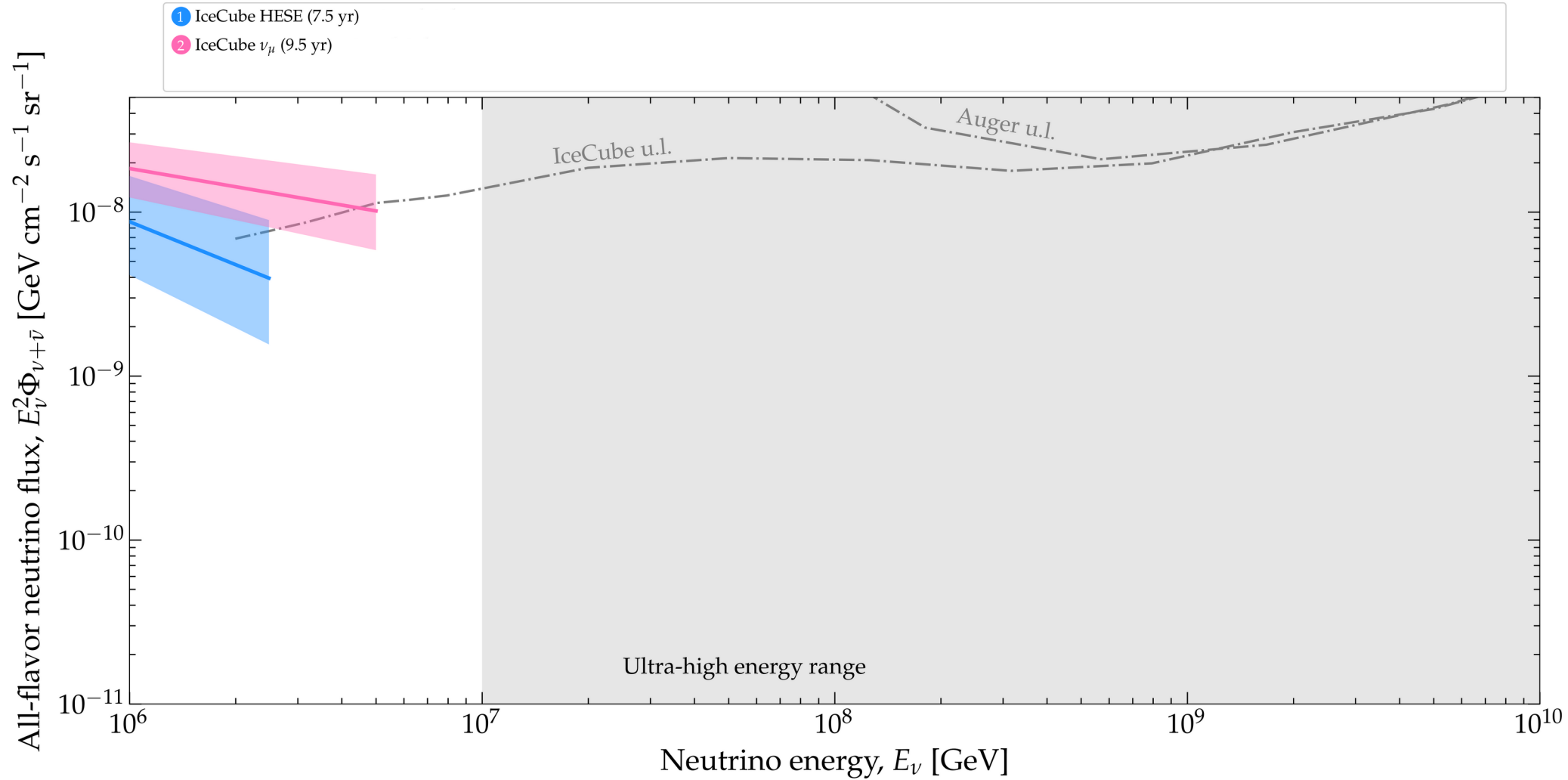
$z = 0$



Redshift

$z = 0$





The international journal of science / 13 February 2025

nature

COSMIC CATCHER

Deep-sea telescope detects
neutrino with highest
energy ever recorded

Article

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

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

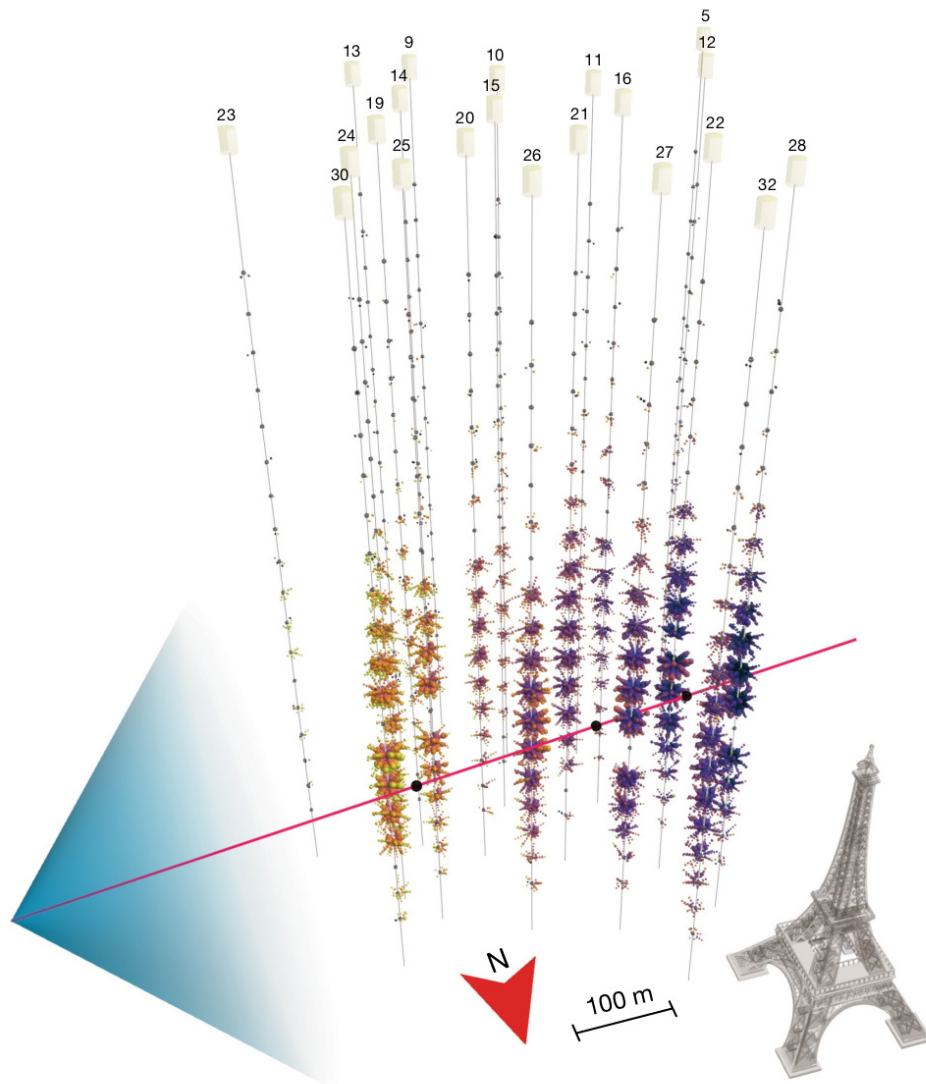
One muon detected with 120^{+110}_{-60} PeV

The international journal of science / 13 February 2025

nature

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But is it due to a neutrino?

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

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

nature

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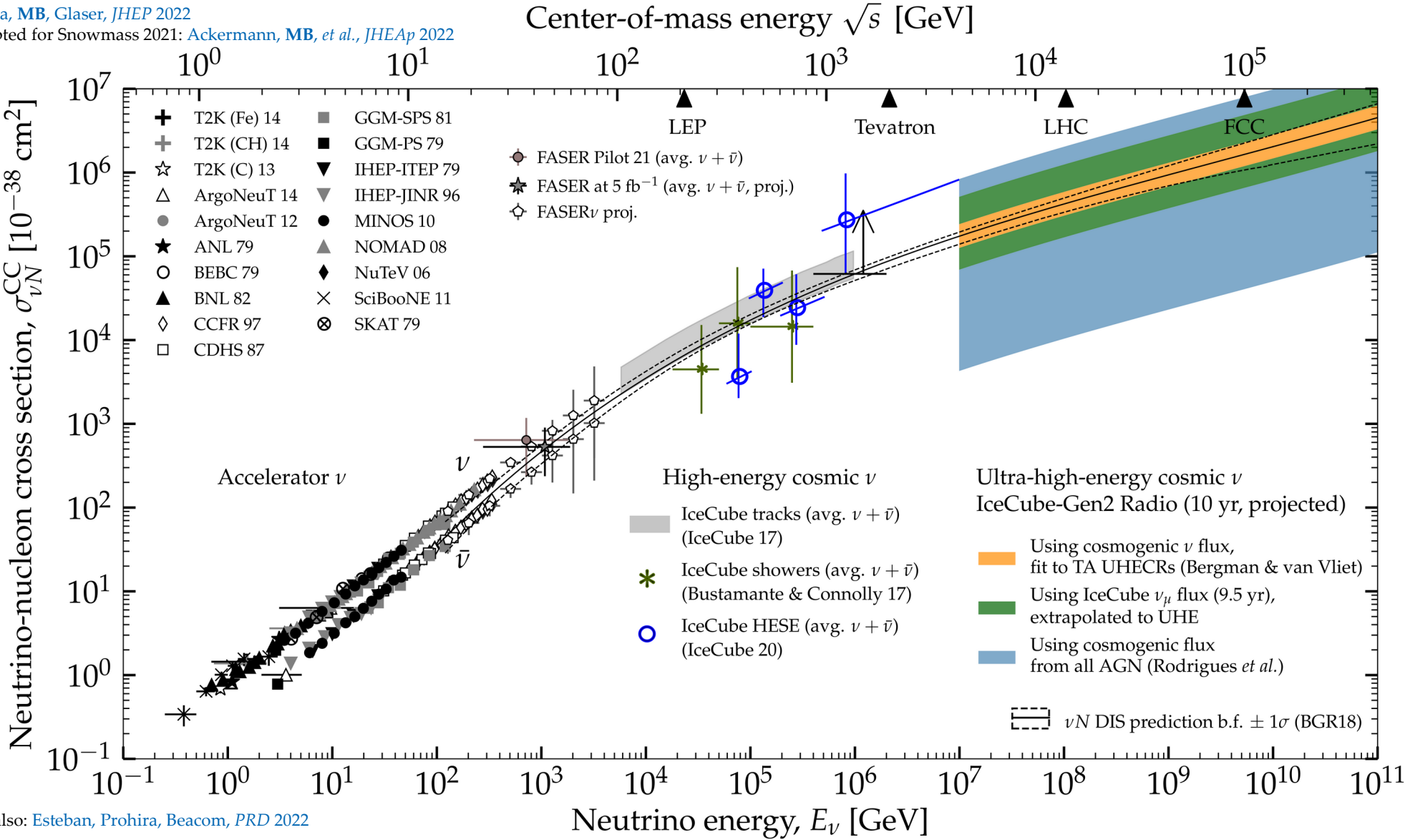
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Yes! Direction points underground,
after traveling 150 km through Earth

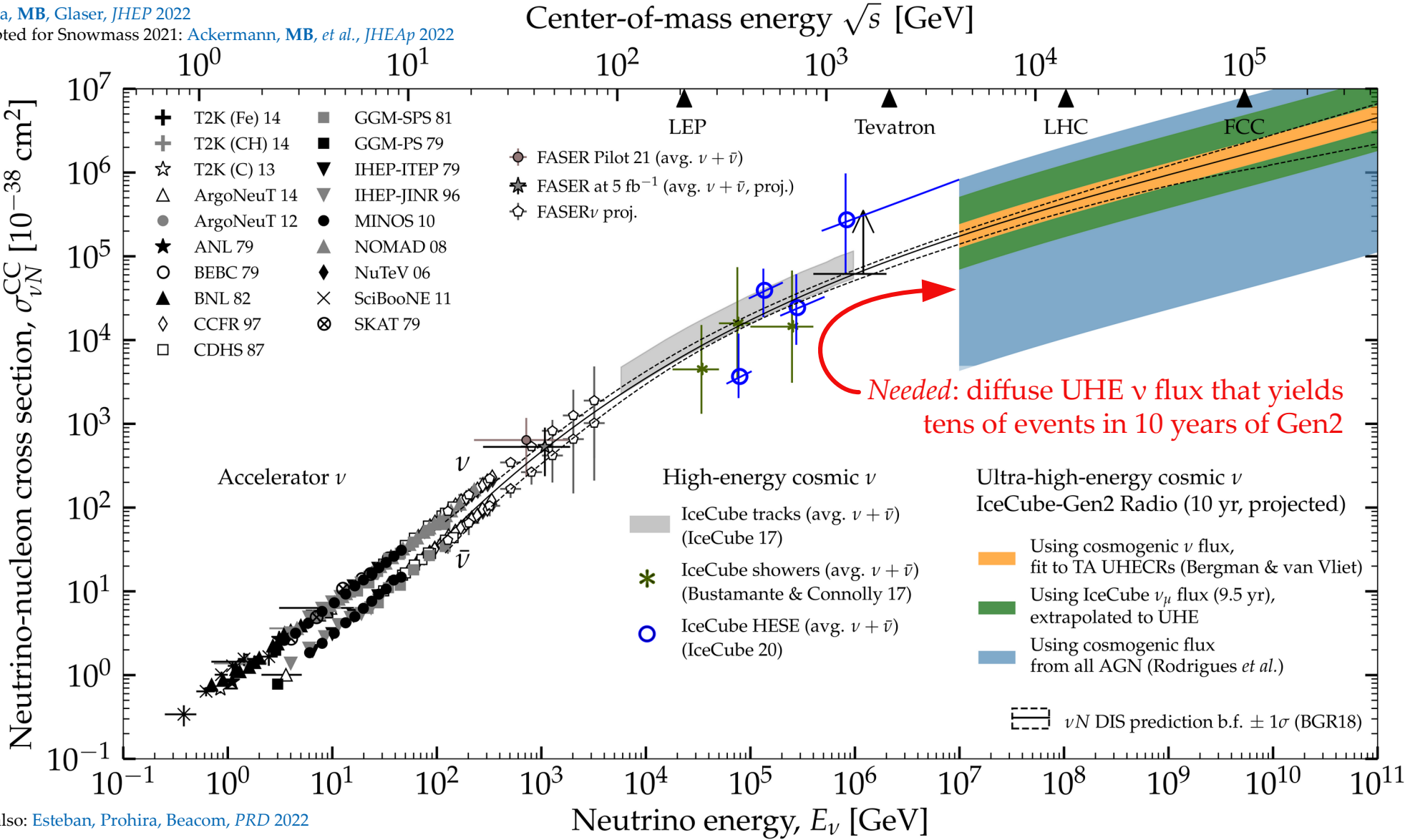
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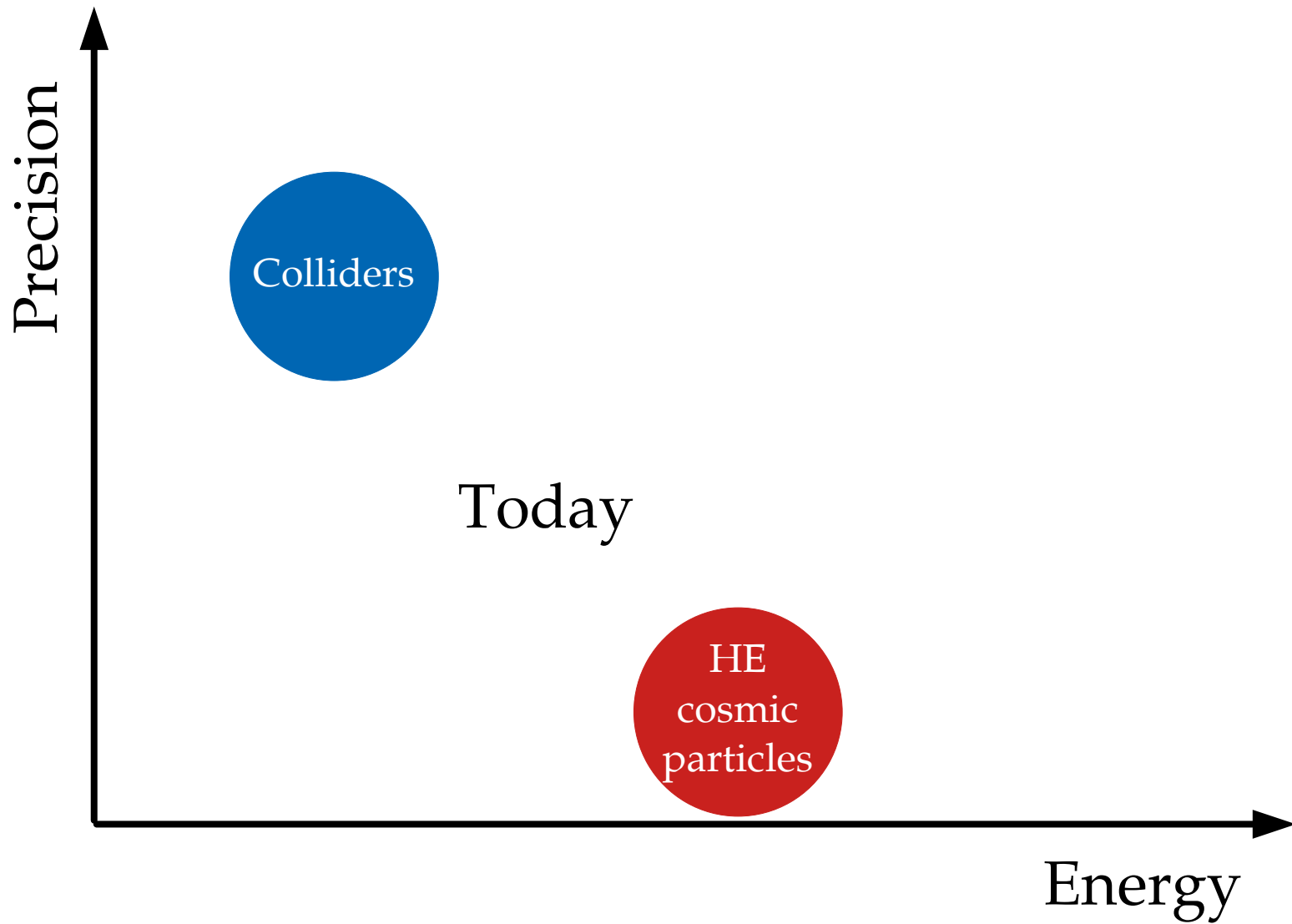
**RECORD
BREAKER**

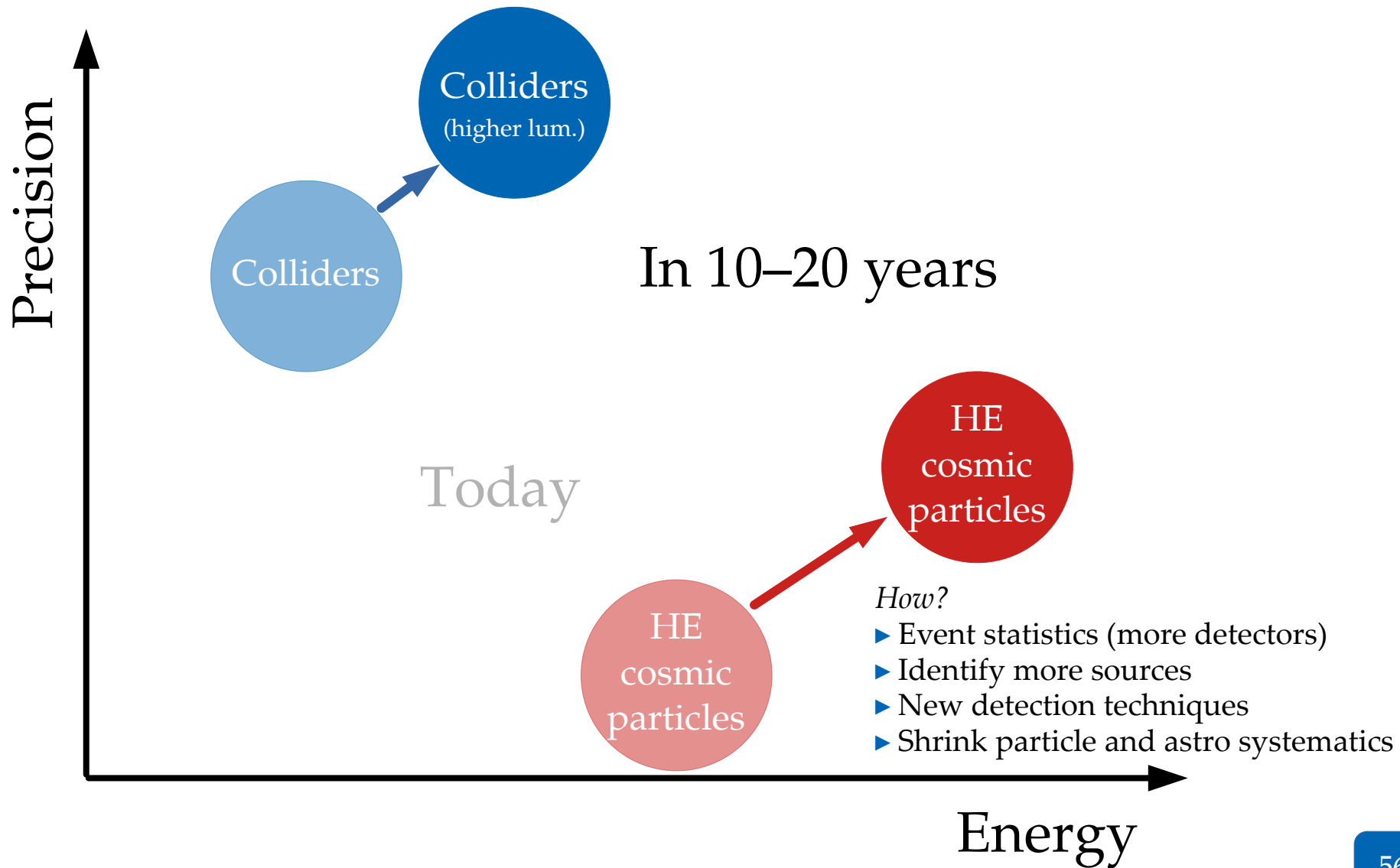
Center-of-mass energy $\sqrt{s}$ [GeV]



Center-of-mass energy $\sqrt{s}$ [GeV]







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

How do we get there?

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

Thanks!

IV PHD SUMMER SCHOOL ON NEUTRINOS HERE, THERE & EVERYWHERE

Lectures:

Mariam Tórtola (U. Valencia) • Neutrino phenomenology
Maria Petropoulou (U. Athens) • Neutrino astrophysics
Vivian Poulin (U. Montpellier) • Neutrino cosmology

Registration:

nbia.dk/neutrino2025

Deadline:

March 31, 2025

NIELS BOHR INSTITUTE

COPENHAGEN • JULY 7–11, 2025



For PhD and advanced MSc students • Organizers: Markus Ahlers & Mauricio Bustamante

UNIVERSITY OF
COPENHAGEN



The Niels Bohr
International Academy

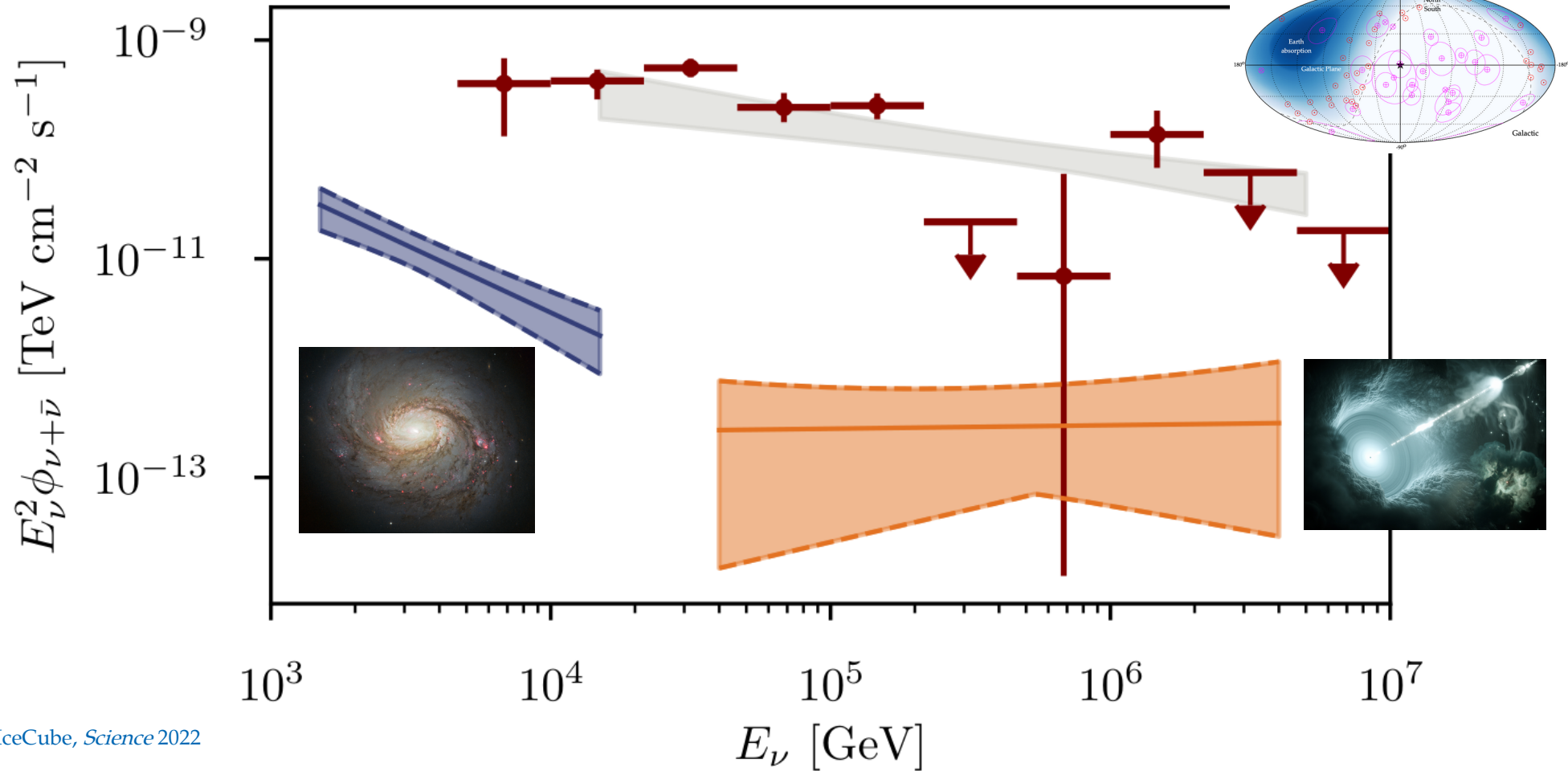
VILLUM FONDEN



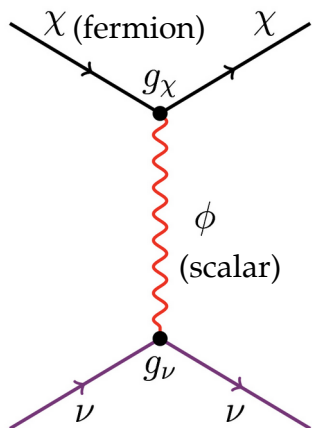
- ▶ Three tracks:
 - ▶ Neutrino **phenomenology**:
Mariam Tórtola (Valencia)
 - ▶ Neutrino **astrophysics**:
Maria Petropoulou (Athens)
 - ▶ Neutrino **cosmology**:
Vivian Poulin (Montpellier)
- ▶ Plus topical seminars & student talks
- ▶ Registration remains open for
remote participation (no charge!)

nbia.dk/neutrino2025

Backup slides

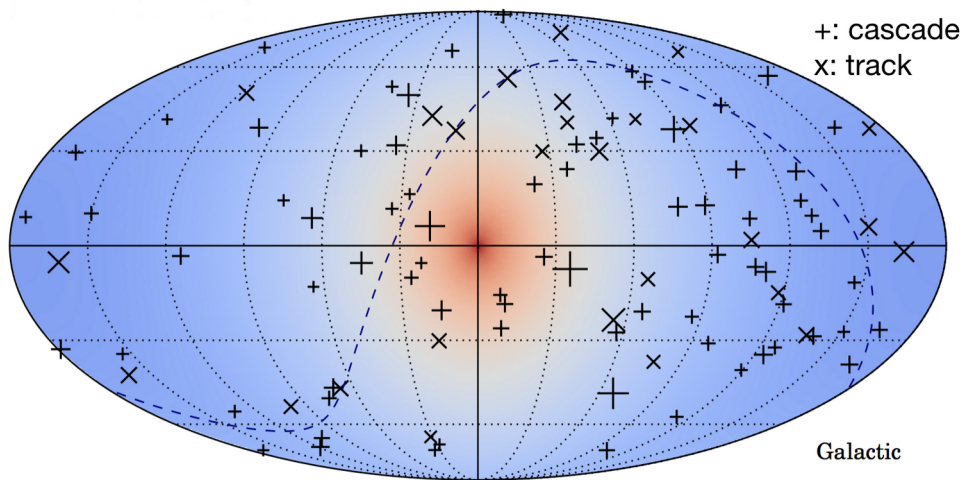


Neutrino-dark matter scattering



Signature:

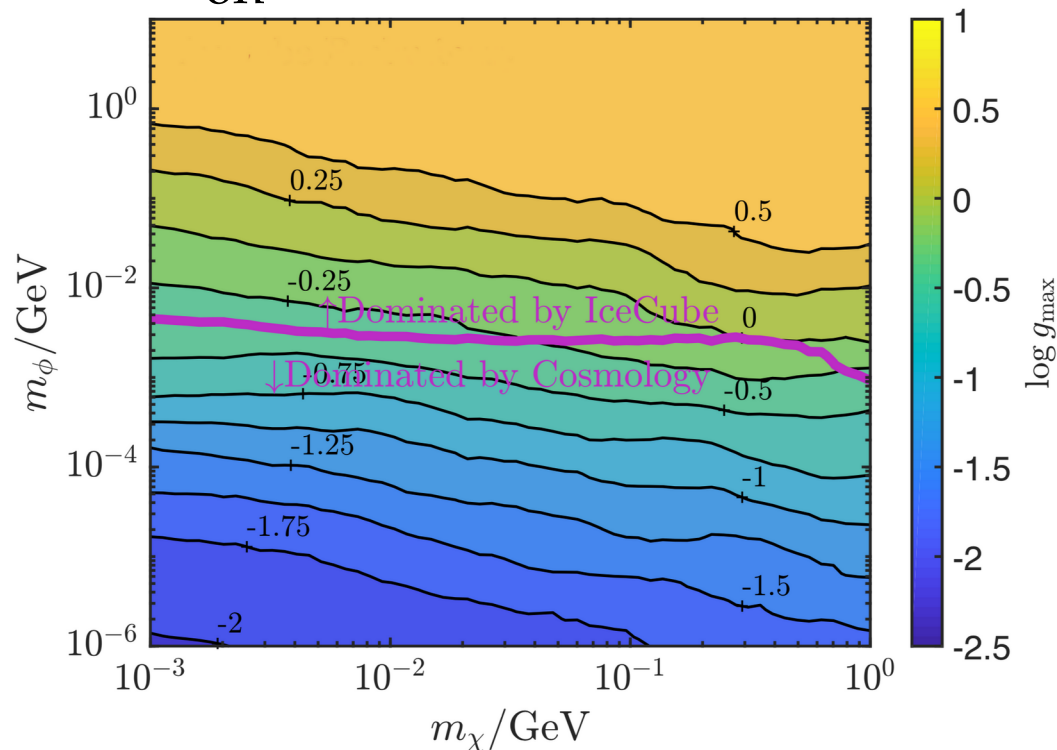
Deficit of high-energy ν
from the Galactic Center



21.3 $\log_{10}(\rho_{DM}/\text{GeV cm}^{-2})$ 23

7.5 years of
IceCube HESE data

Upper limits (90% C.L.)
on $g_{\text{max}} = \sqrt{g_\chi g_\nu}$



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

Measuring the high-energy νN cross section

Number of detected neutrinos (simplified for presentation):

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

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

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(L long $\rightarrow$ lots of matter)

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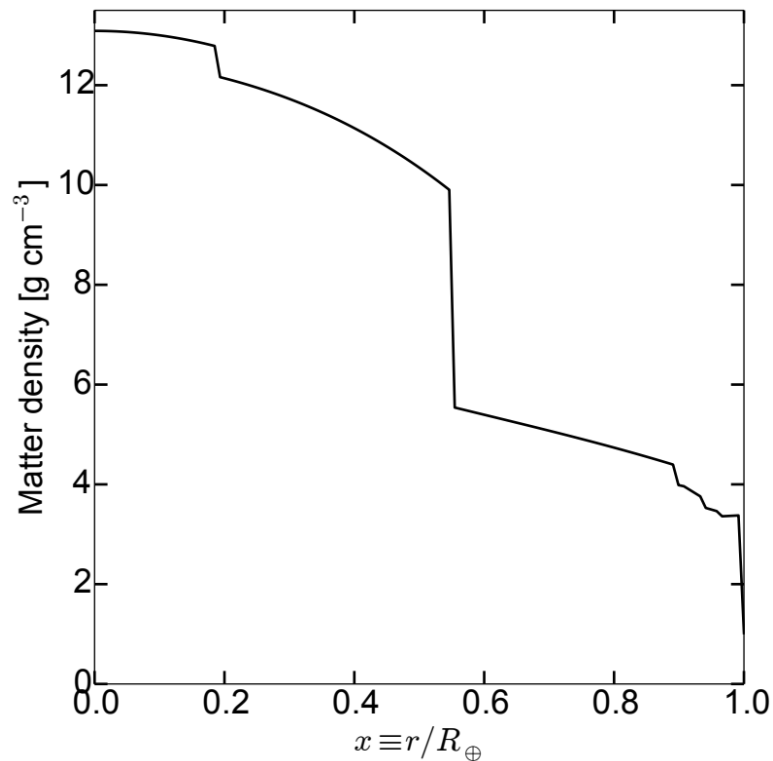
Upgoing neutrinos
(L long $\rightarrow$ lots of matter)

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

A feel for the in-Earth attenuation

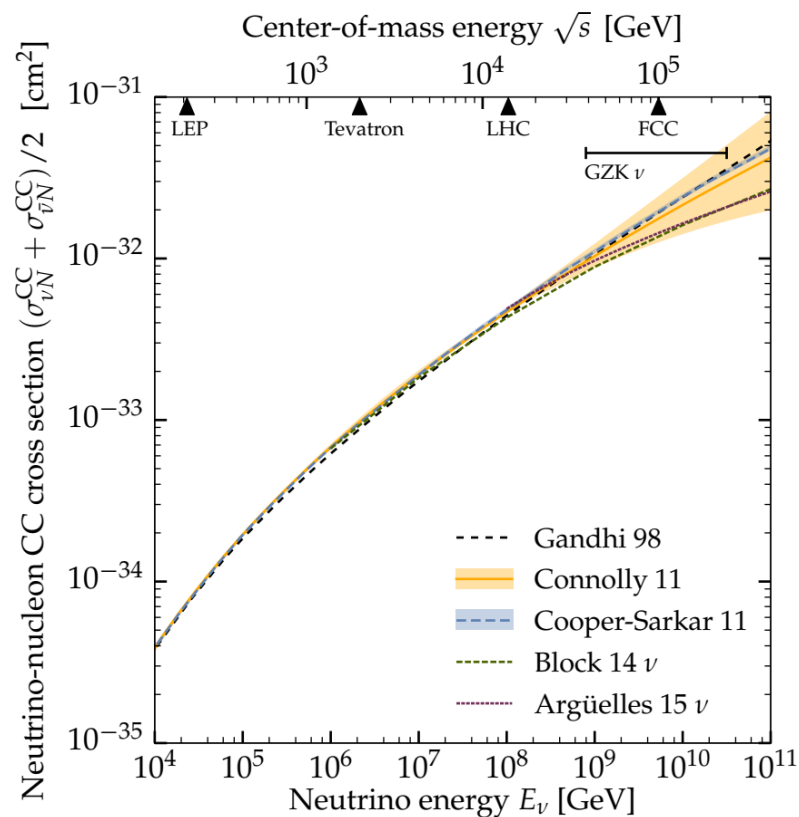
Earth matter density

(Preliminary Reference Earth Model)

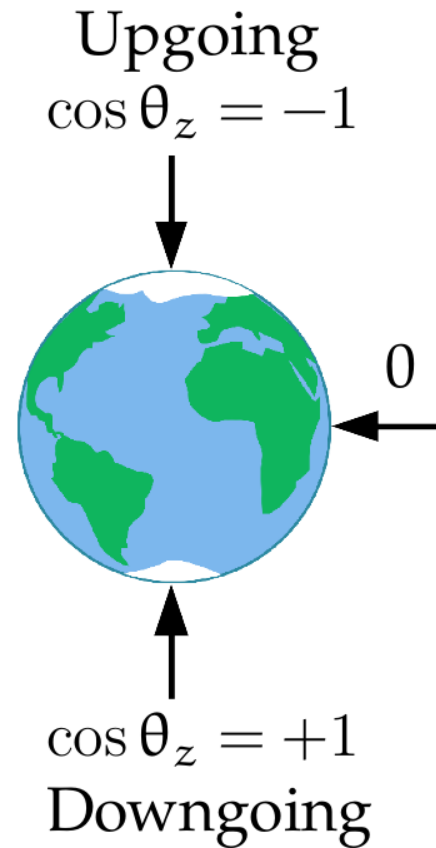
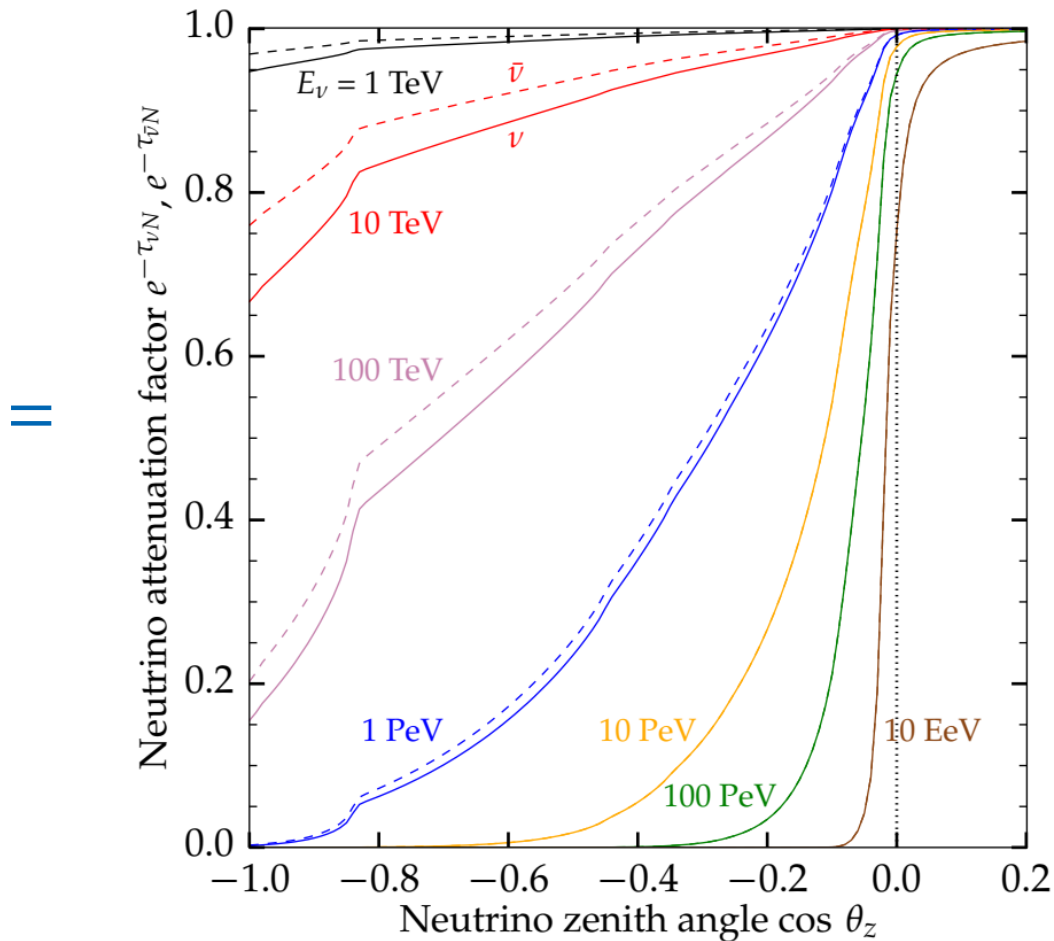


+

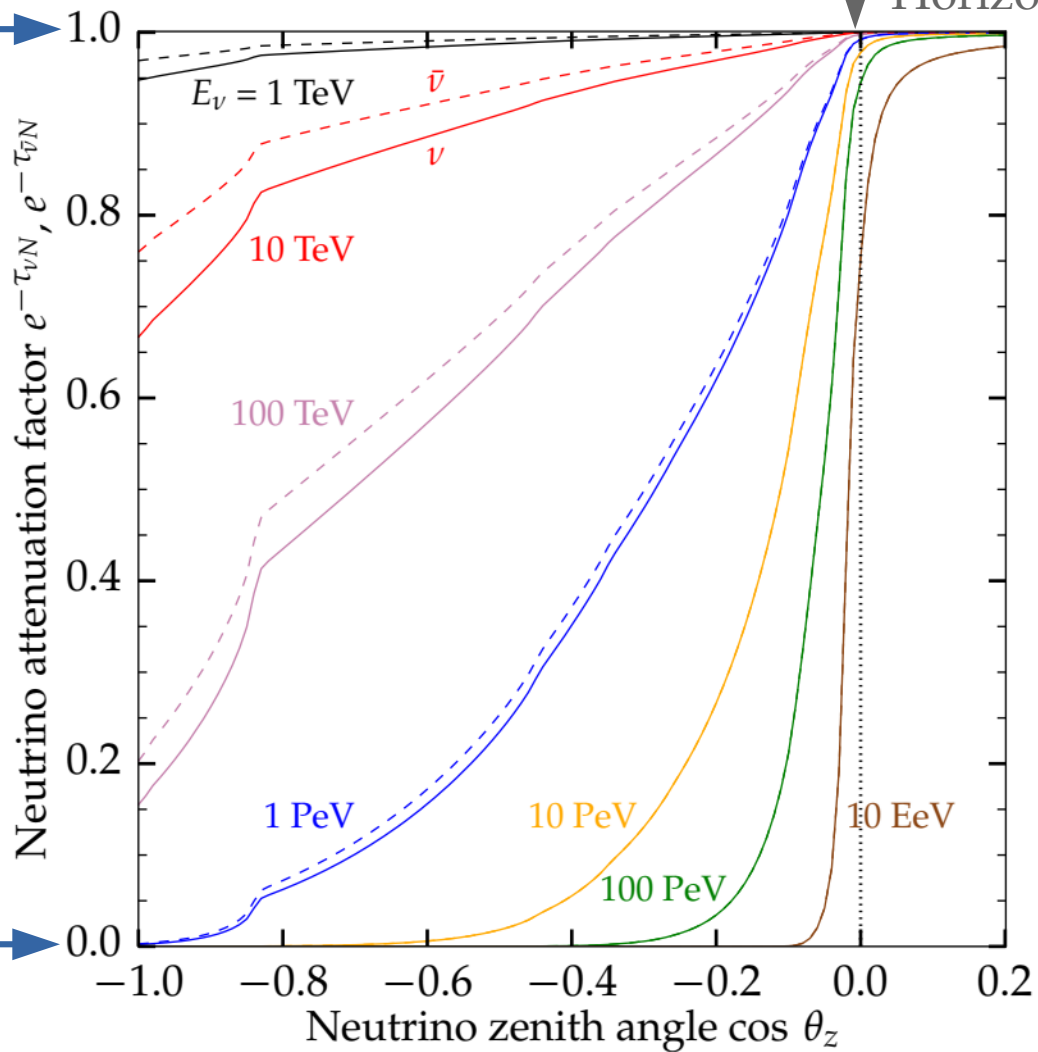
Neutrino-nucleon cross section



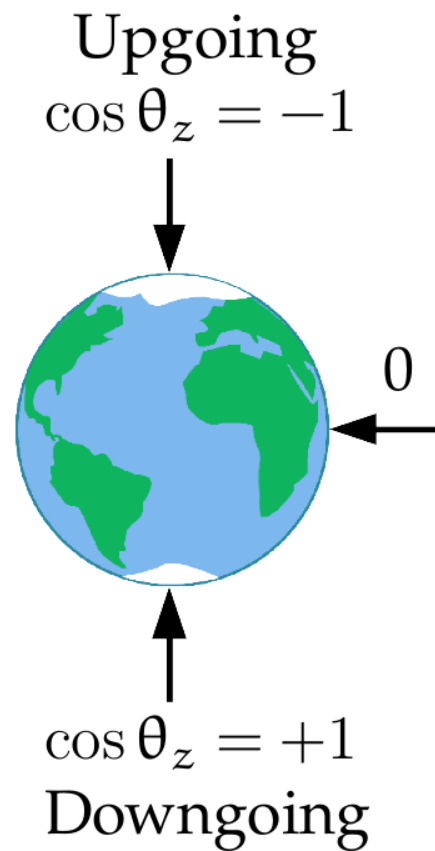
A feel for the in-Earth attenuation



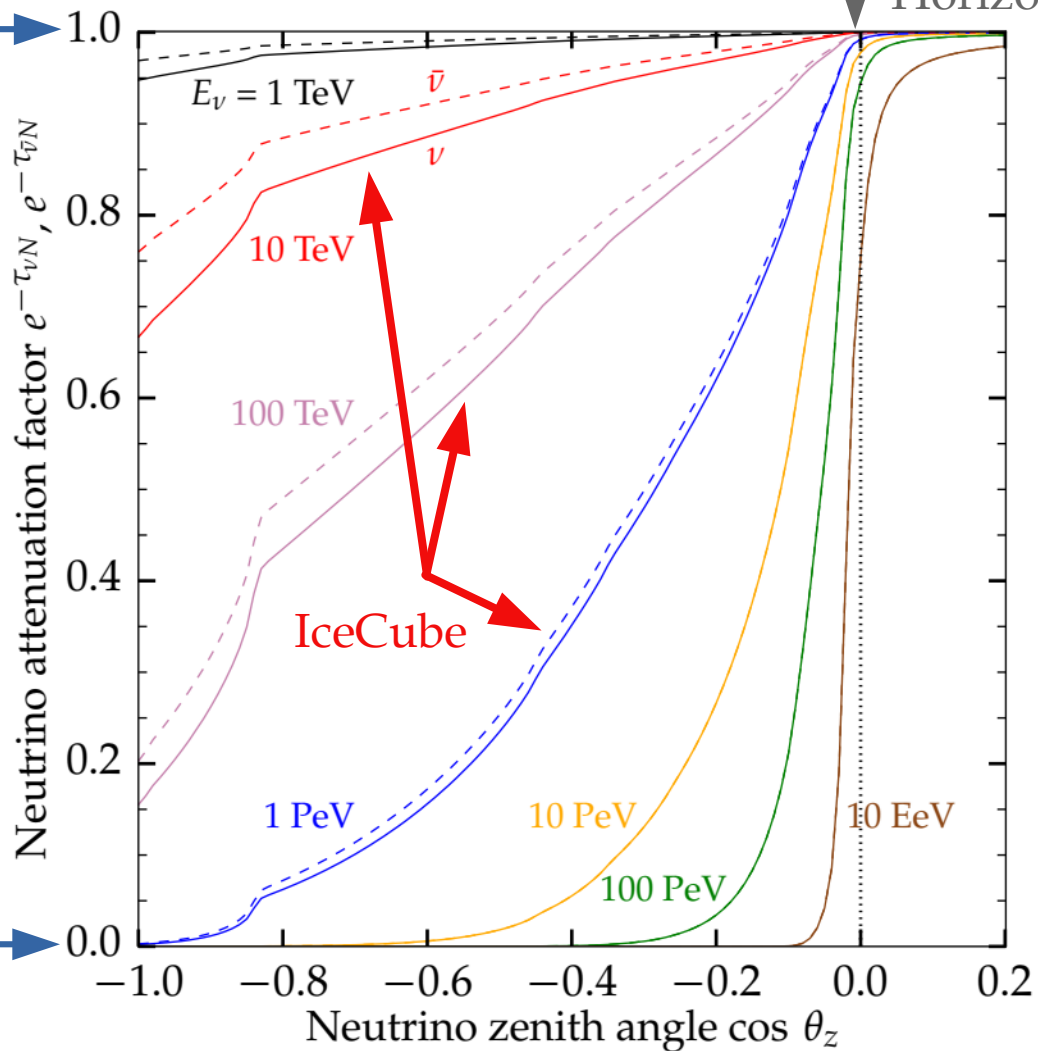
No
attenuation



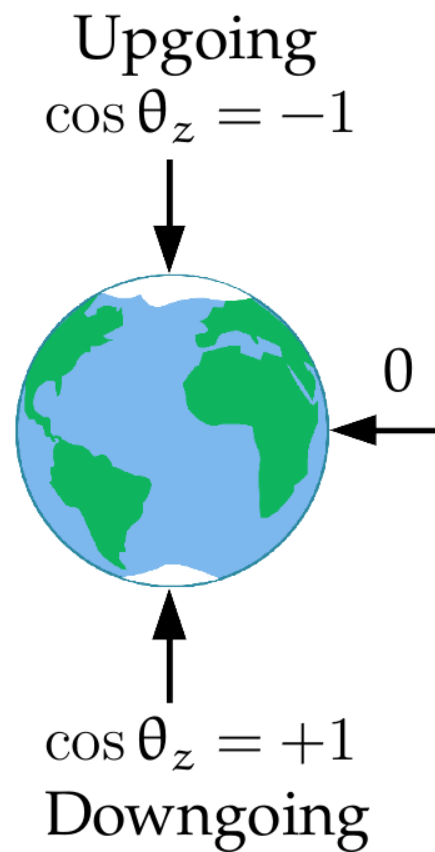
Full
attenuation

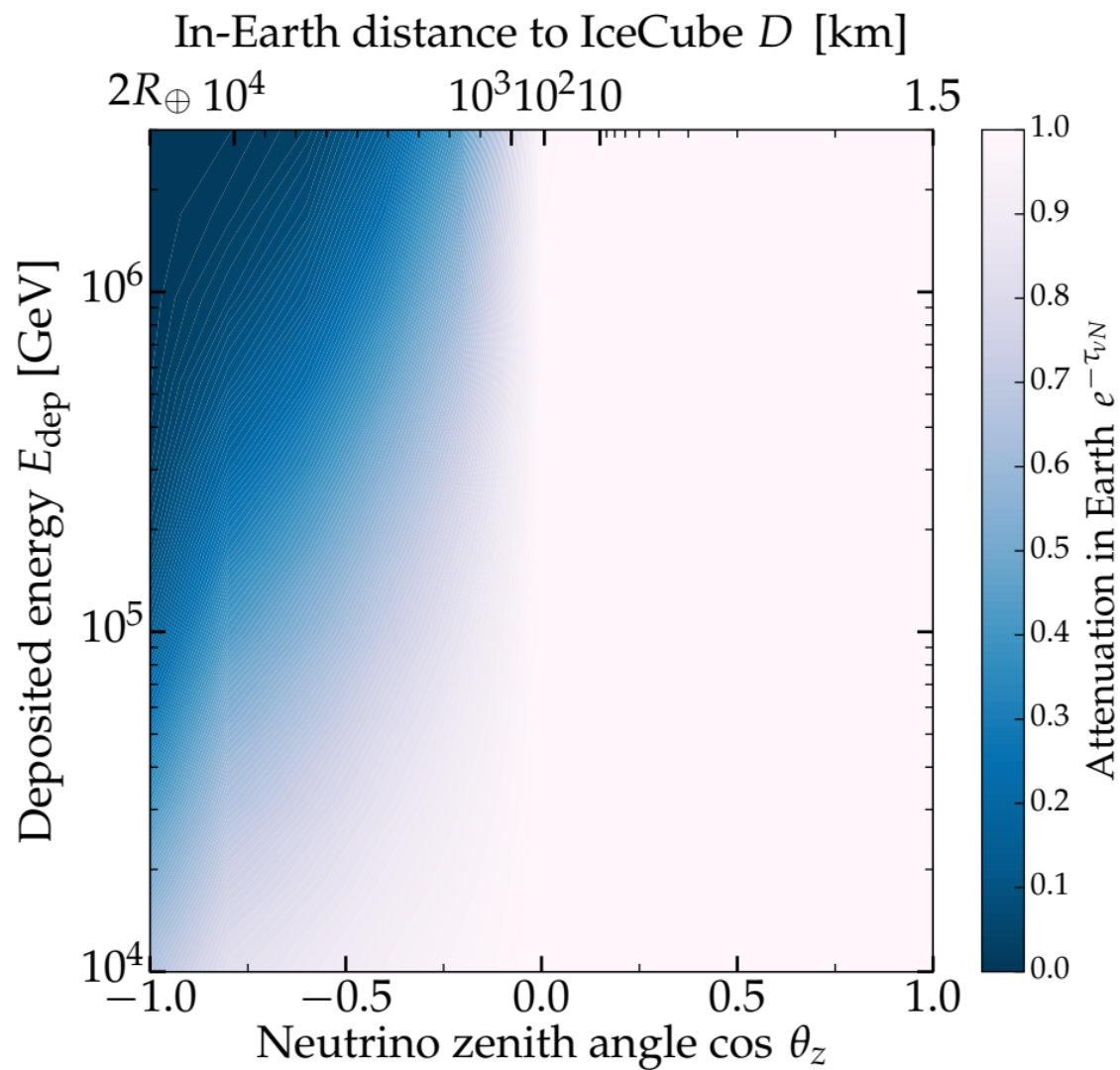


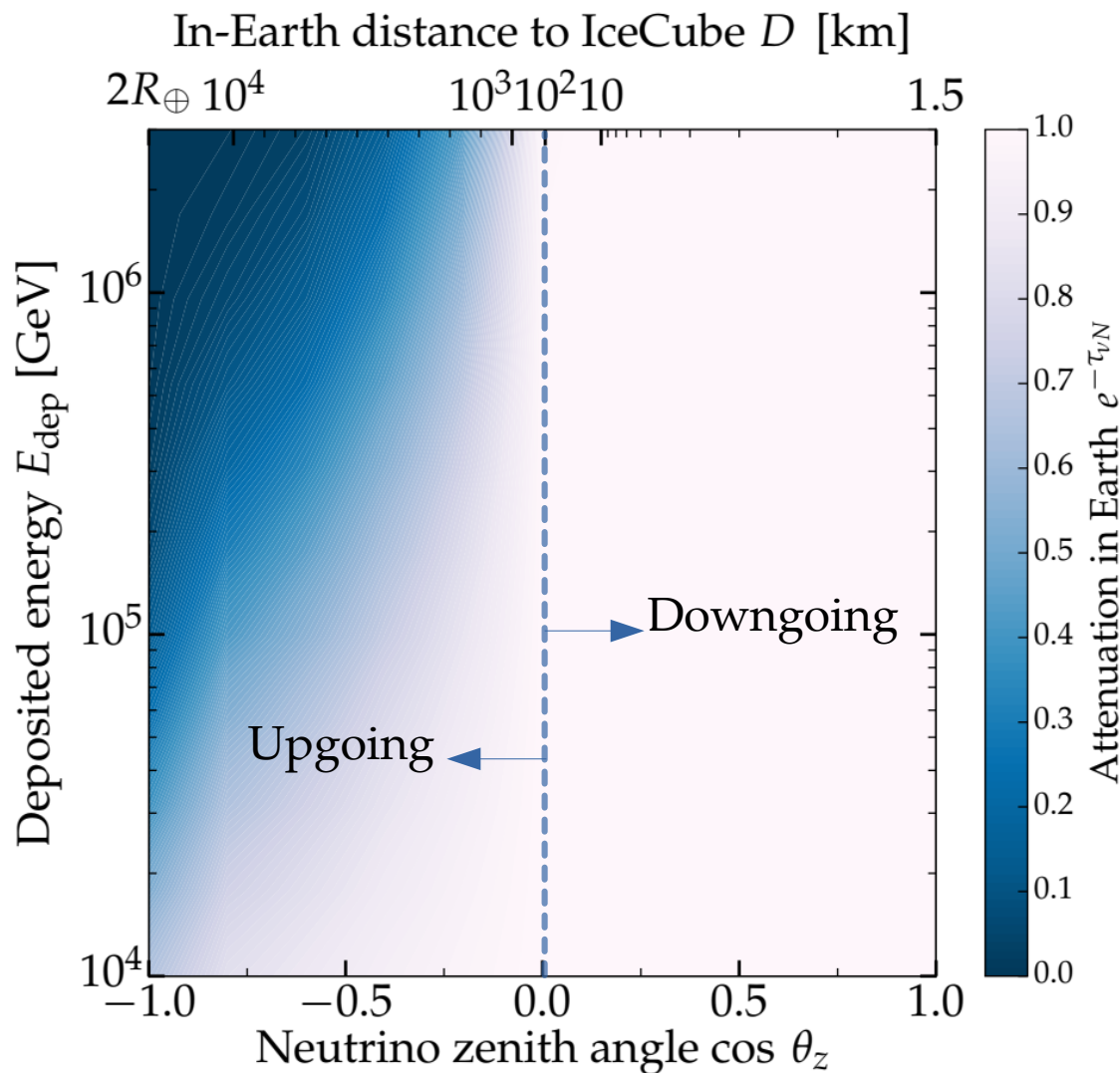
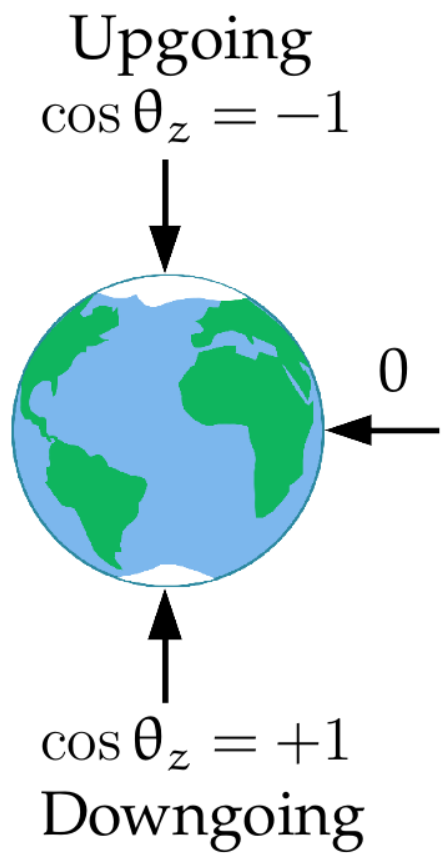
No
attenuation

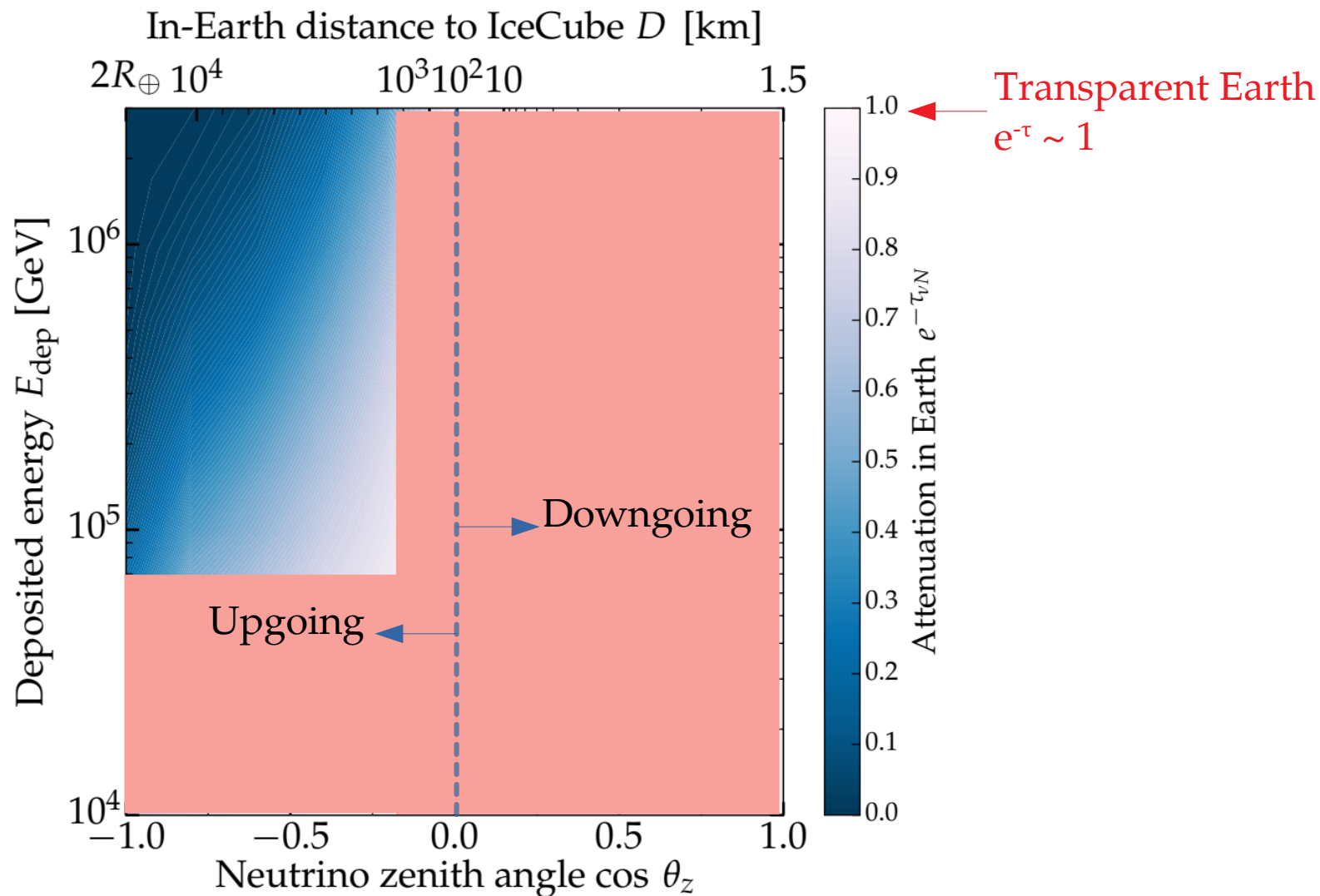
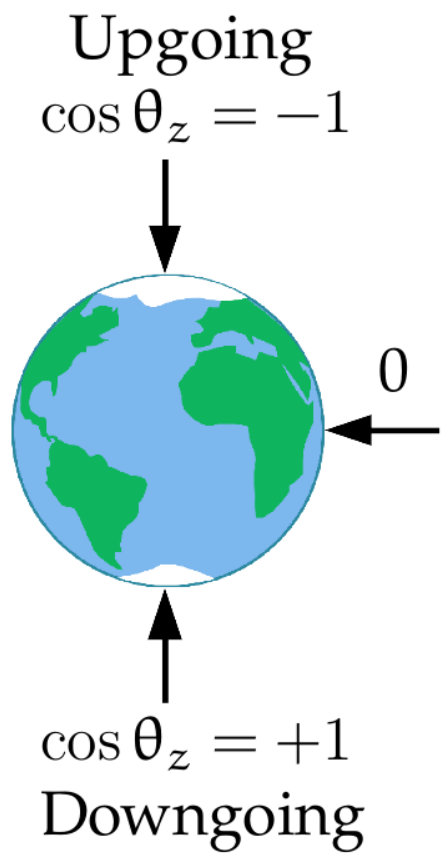


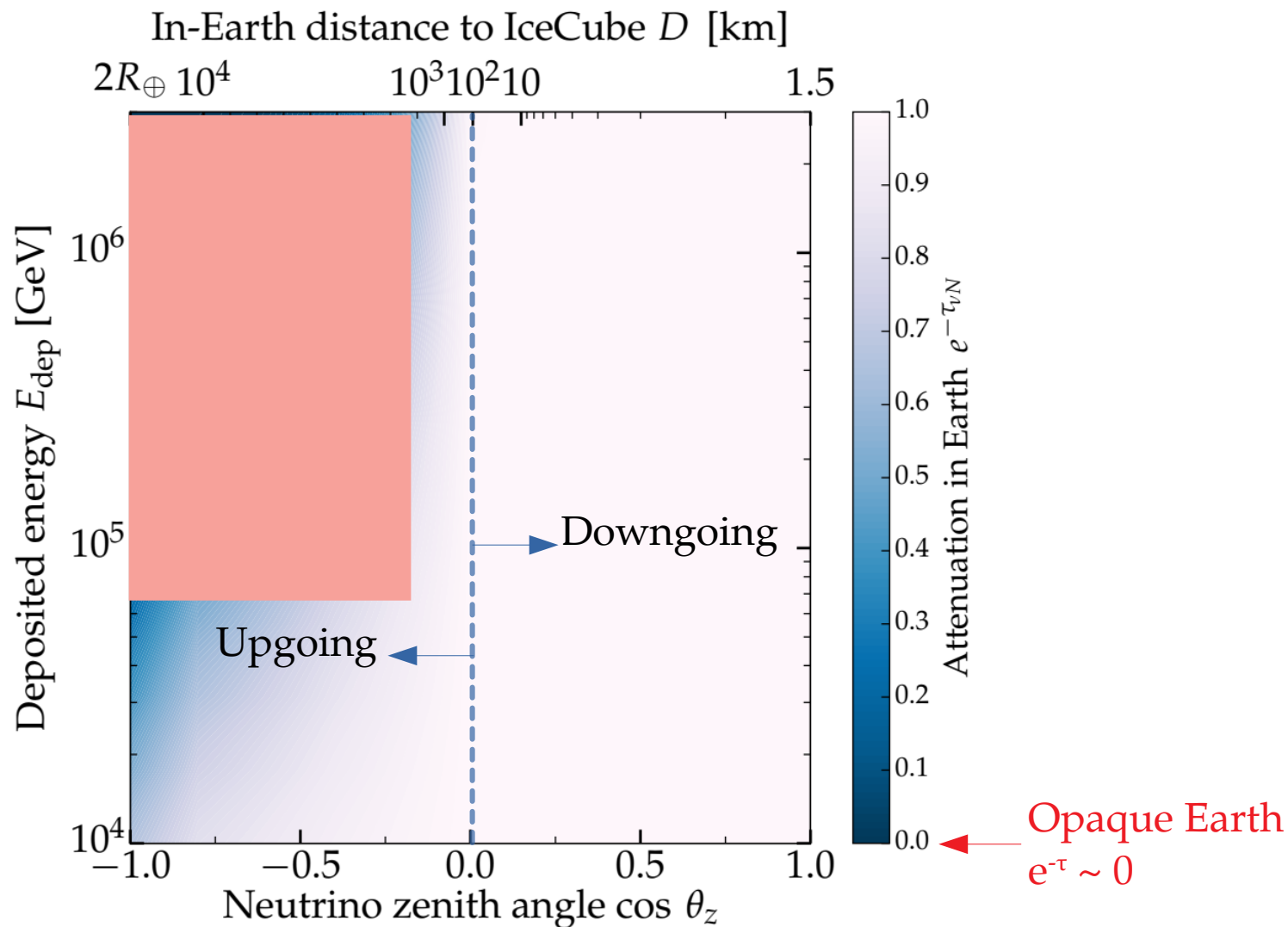
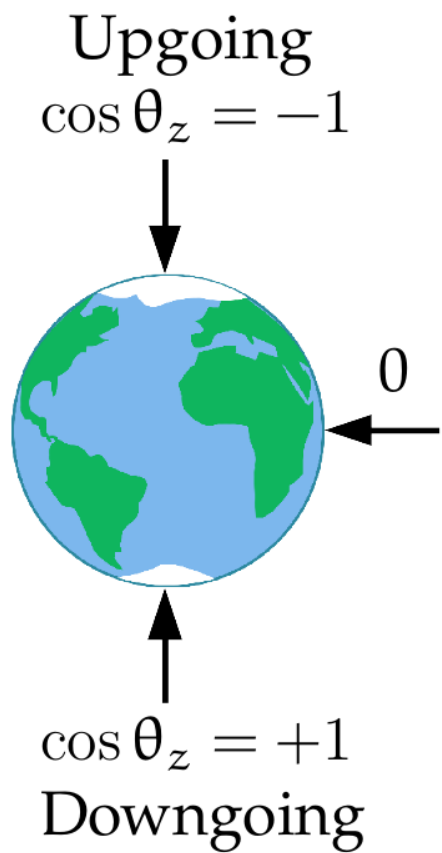
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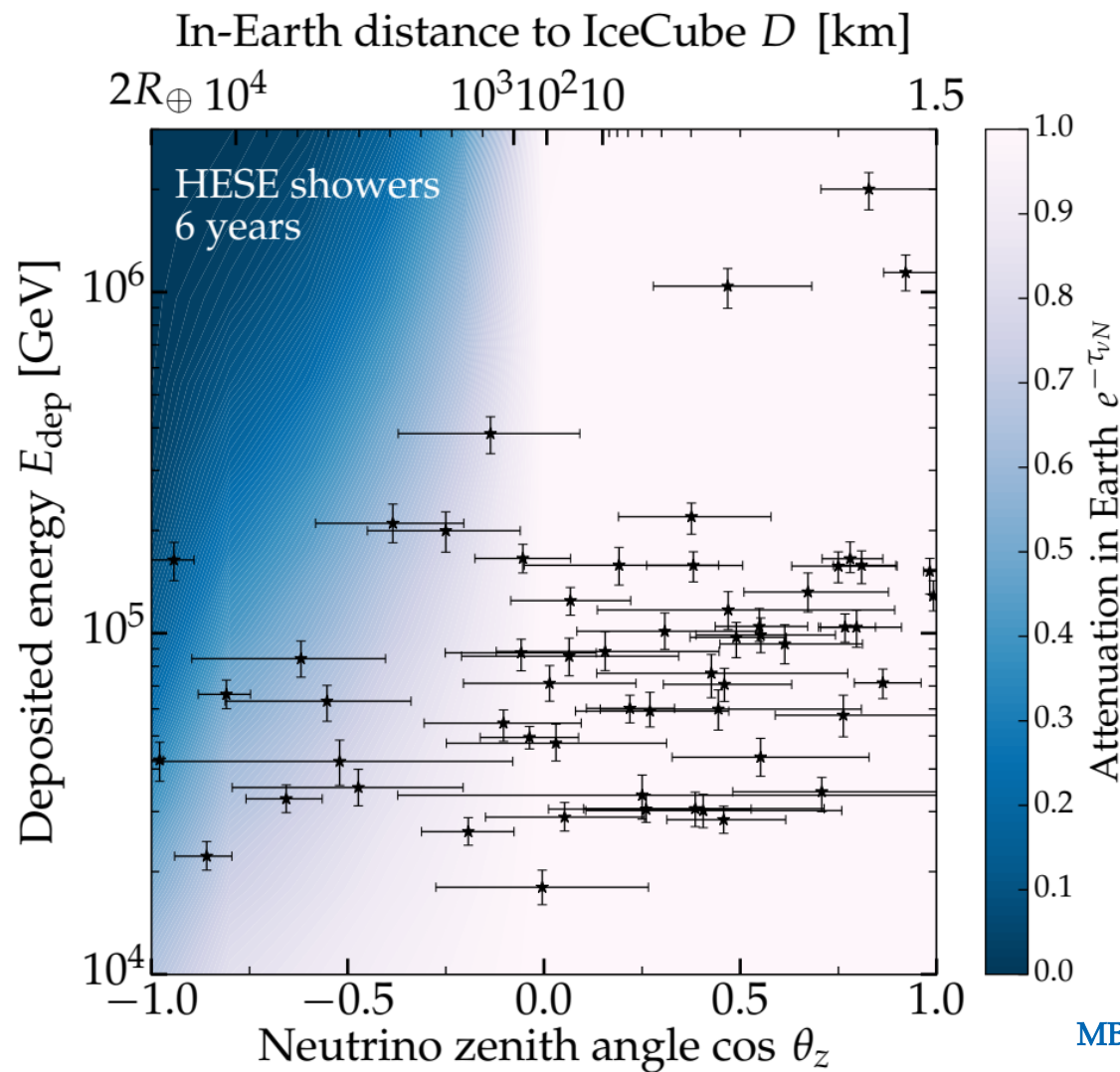




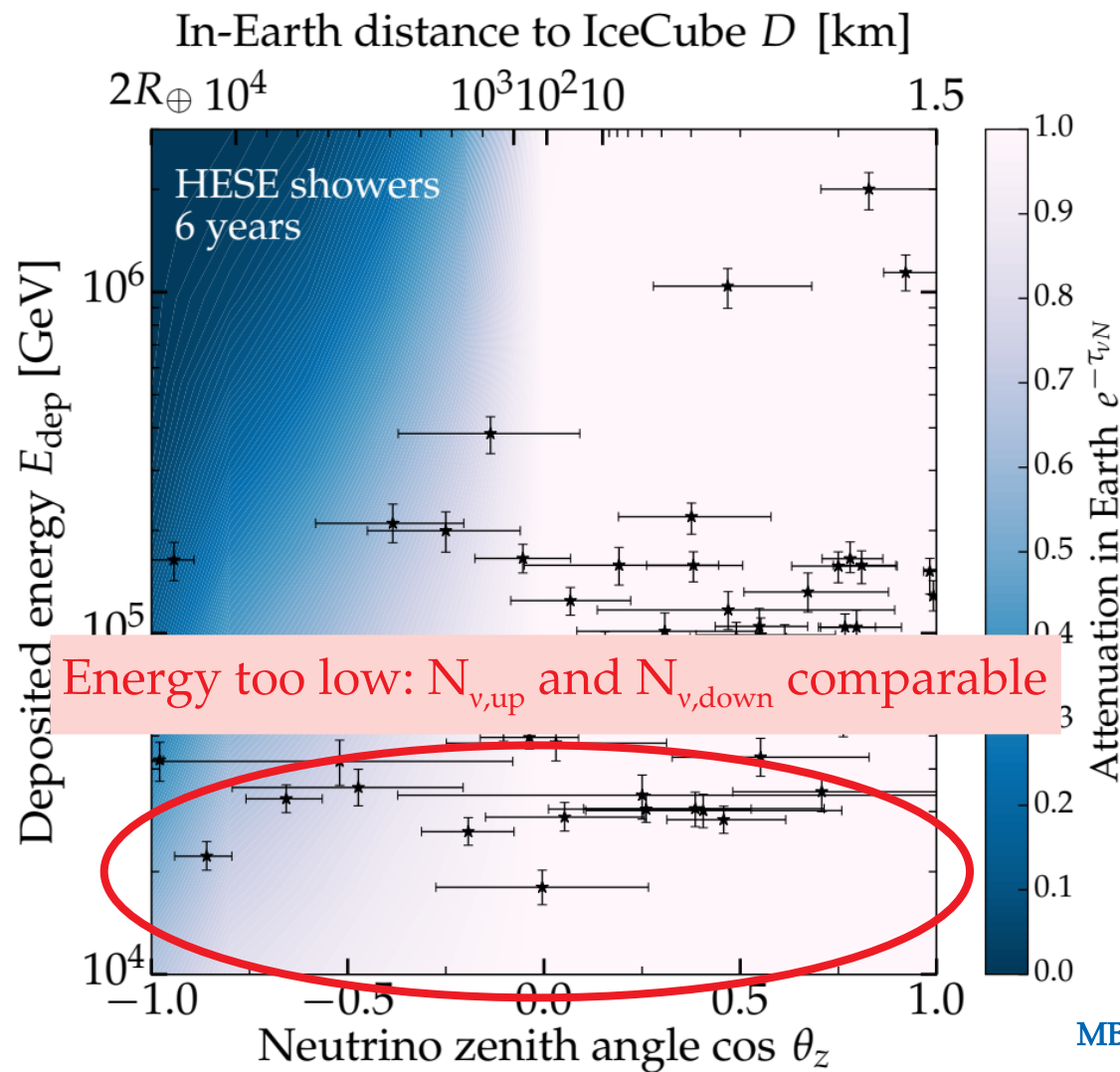




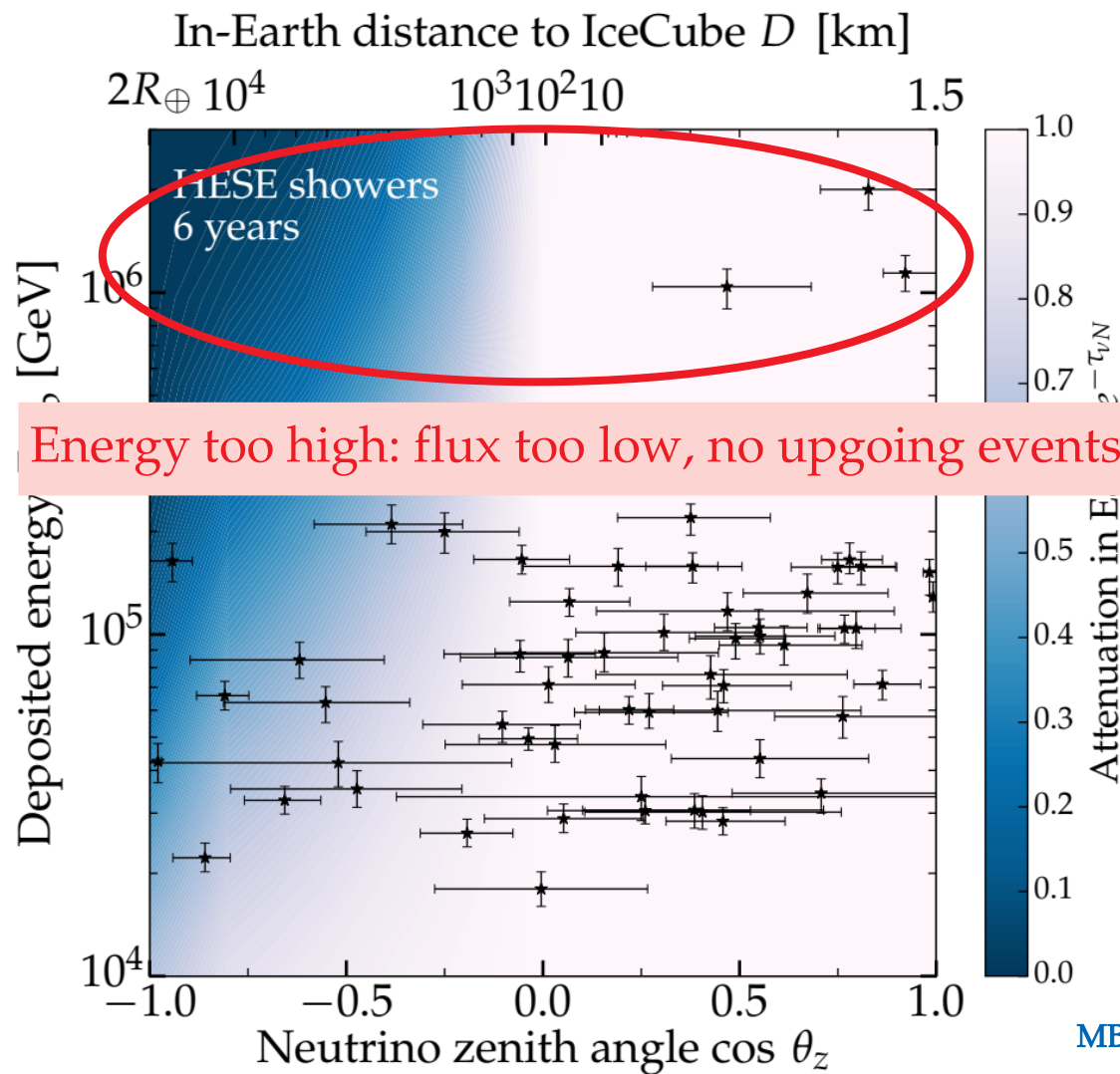




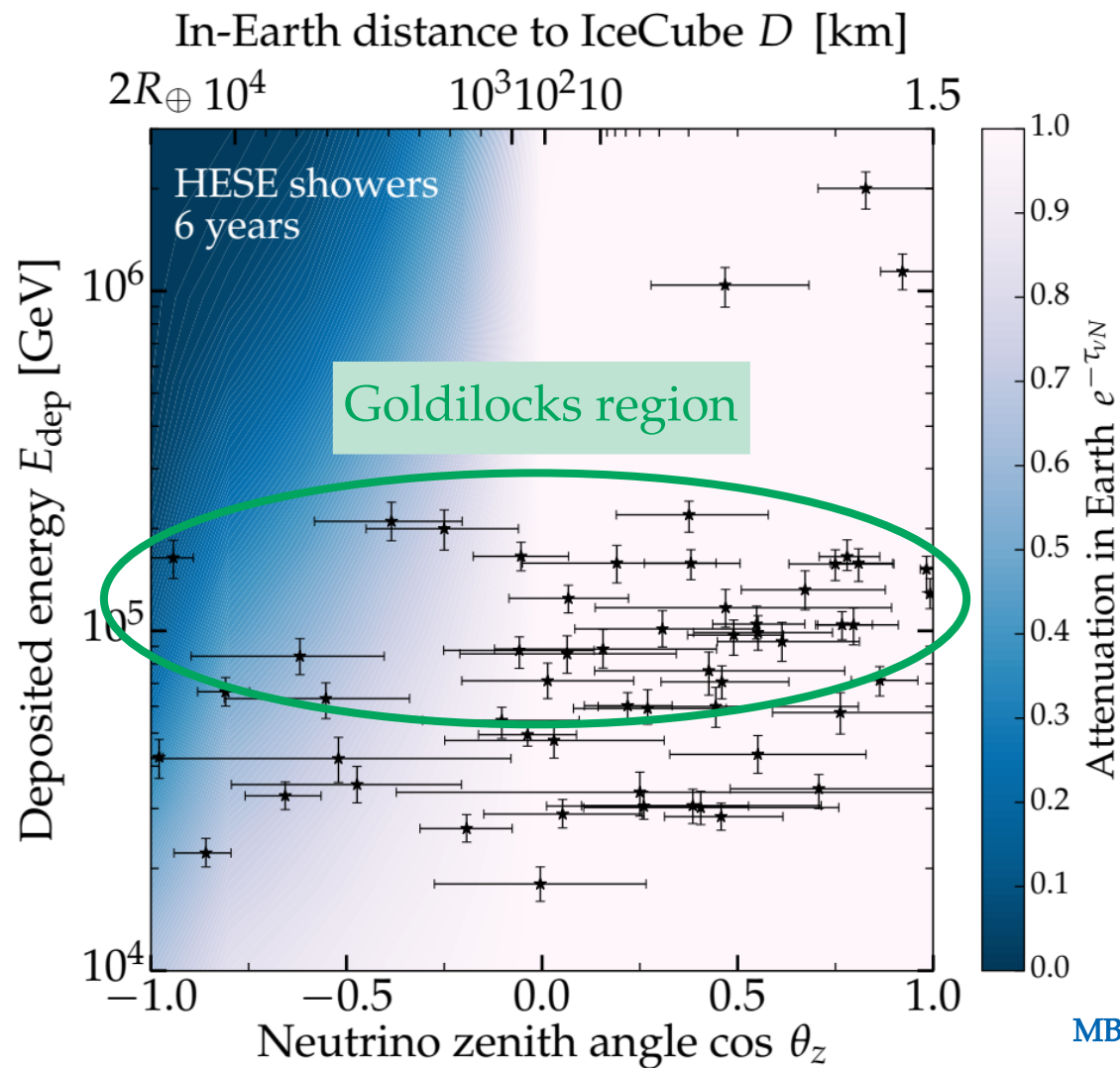
MB & Connolly, *PRL* 2019



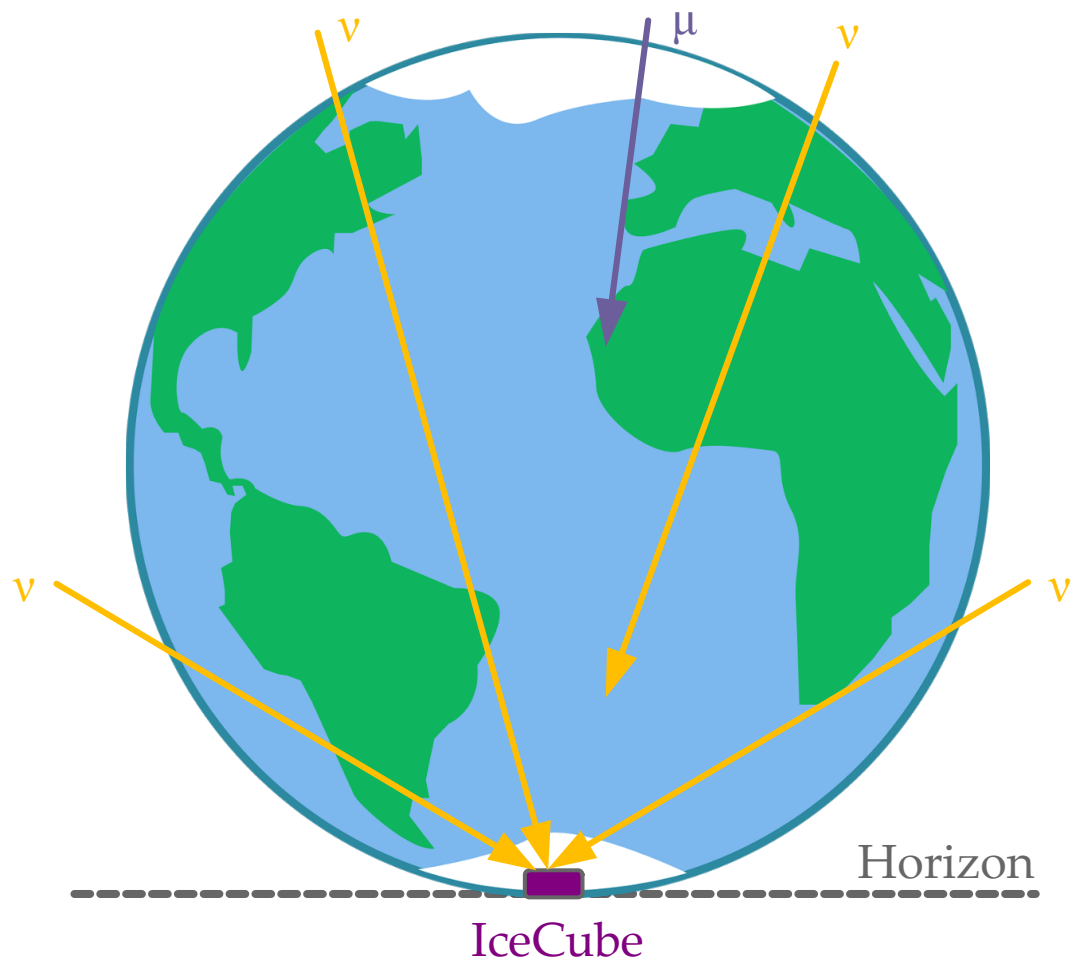
MB & Connolly, *PRL* 2019

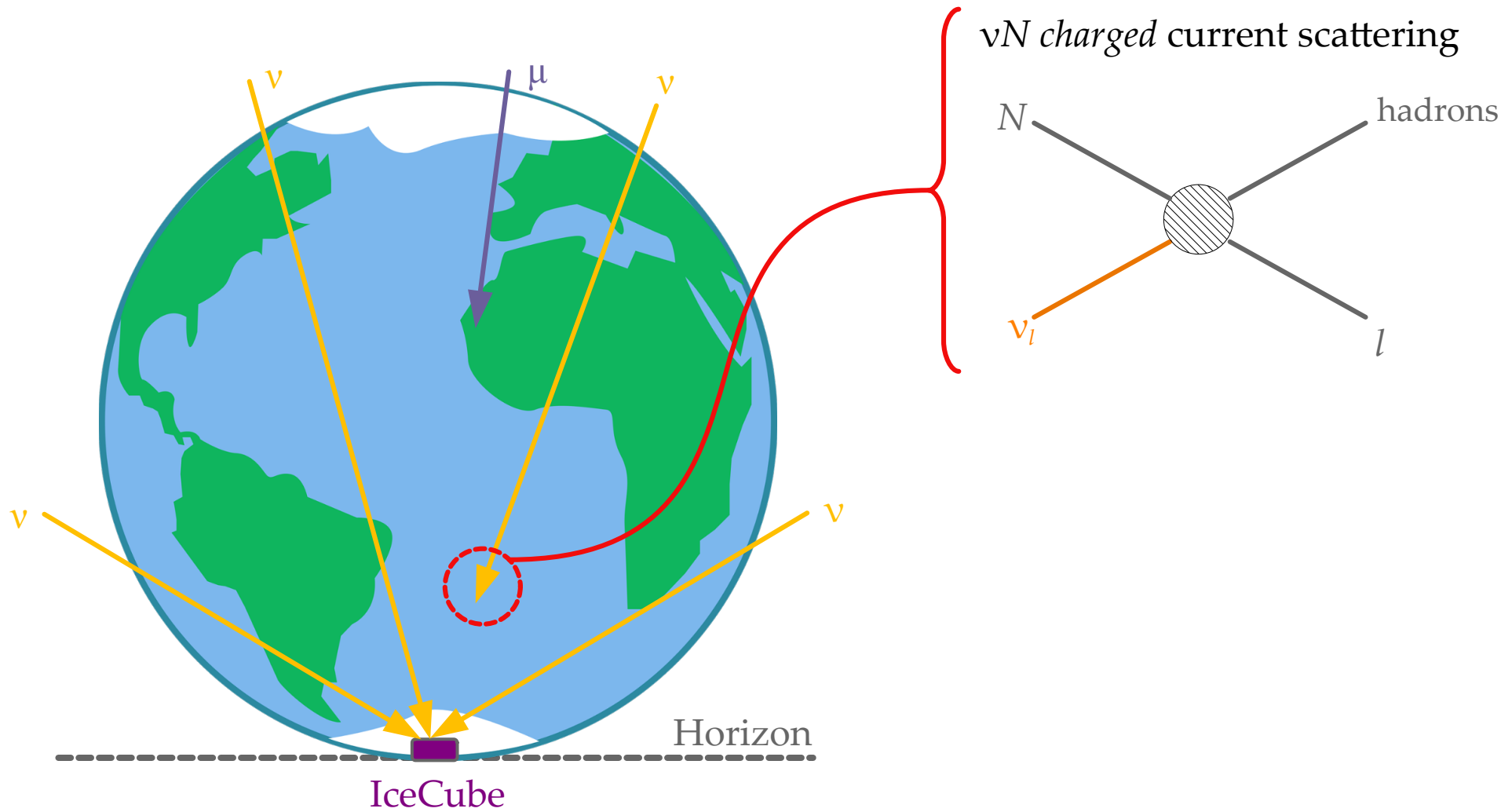


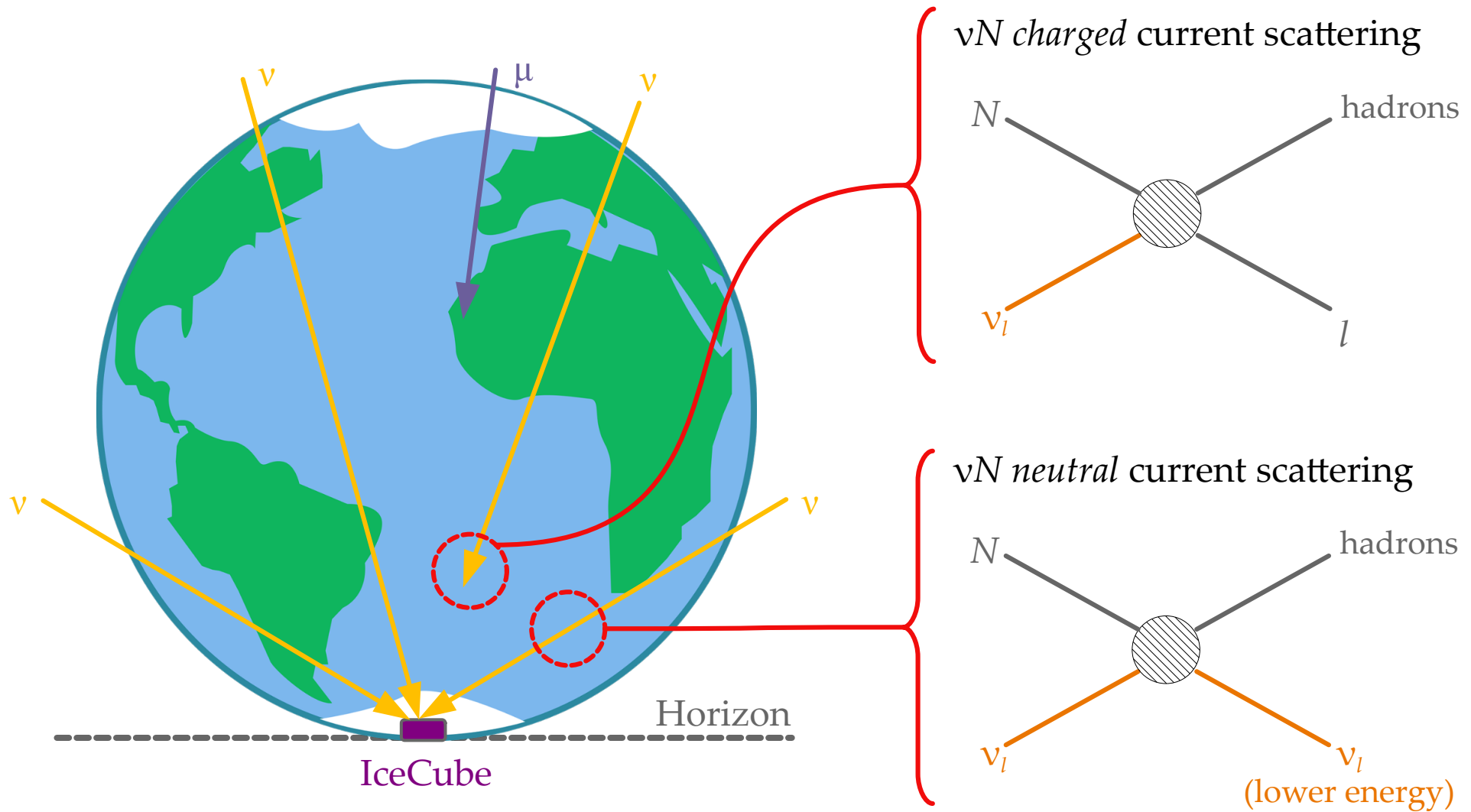
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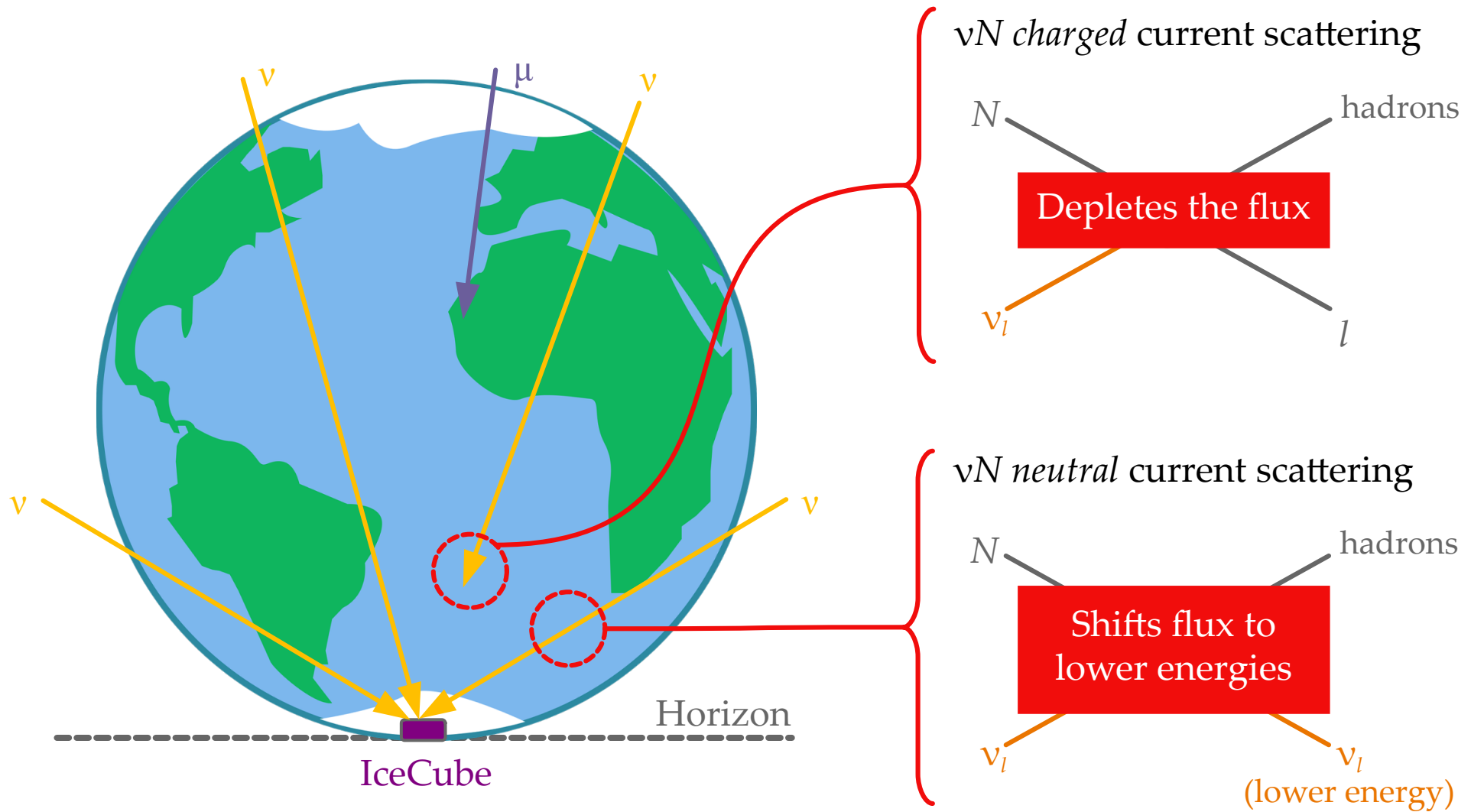


MB & Connolly, *PRL* 2019



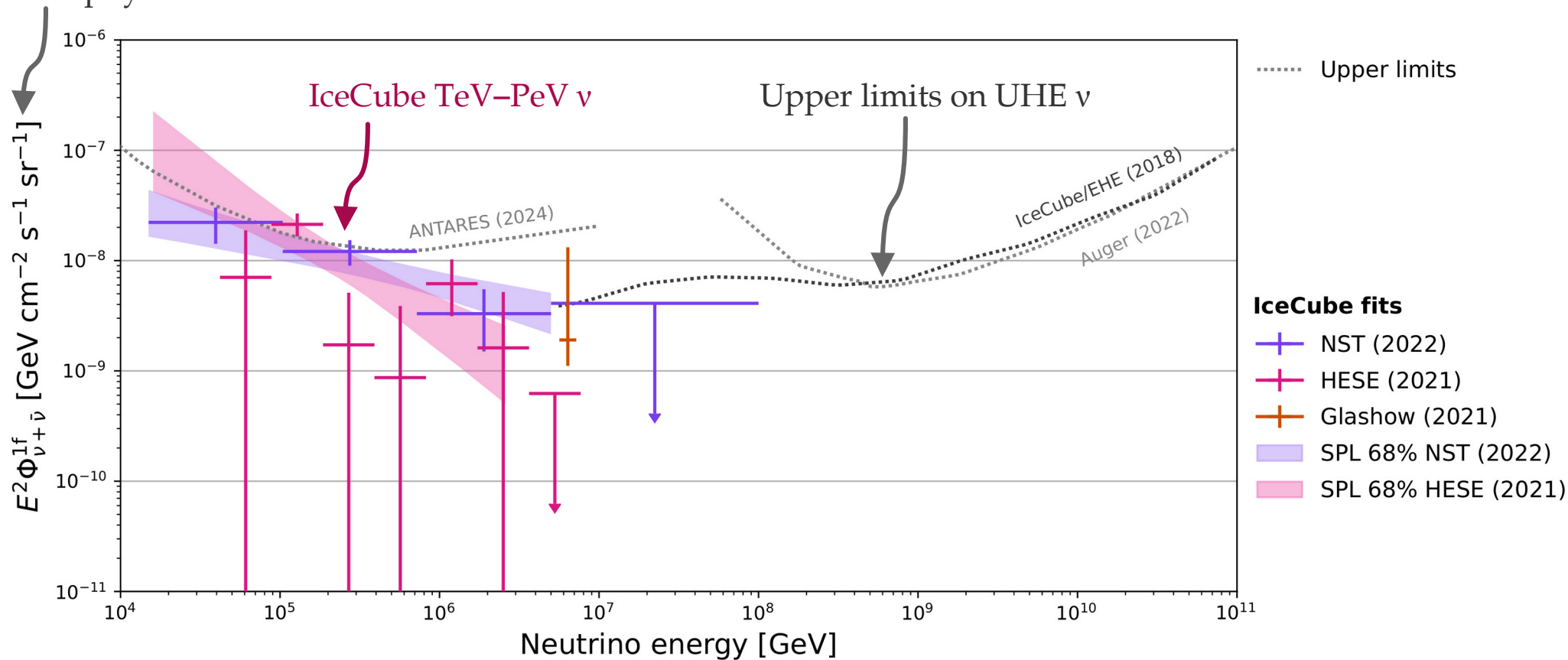






Was it a *cosmogenic* neutrino? KM3NeT vs. IceCube

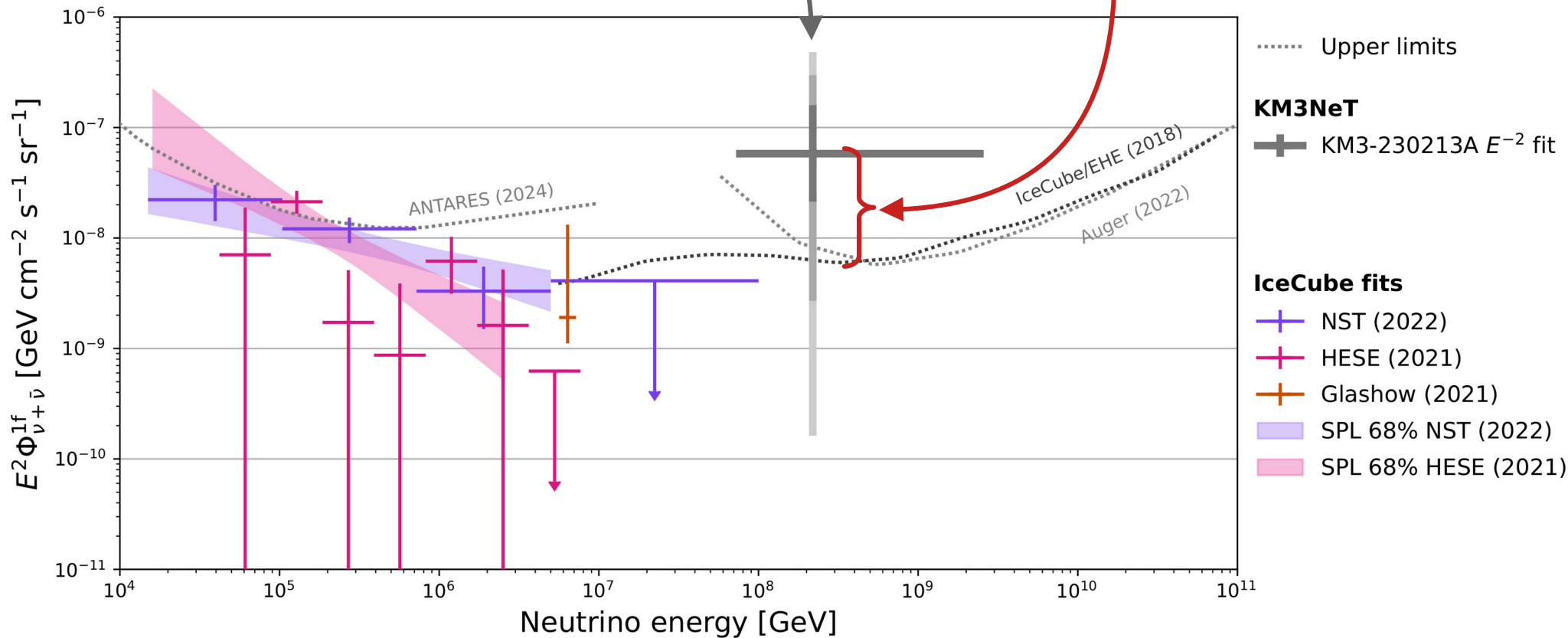
Diffuse flux of high-energy
astrophysical ν



Was it a *cosmogenic* neutrino? KM3NeT vs. IceCube

UHE ν flux inferred from KM3NeT event

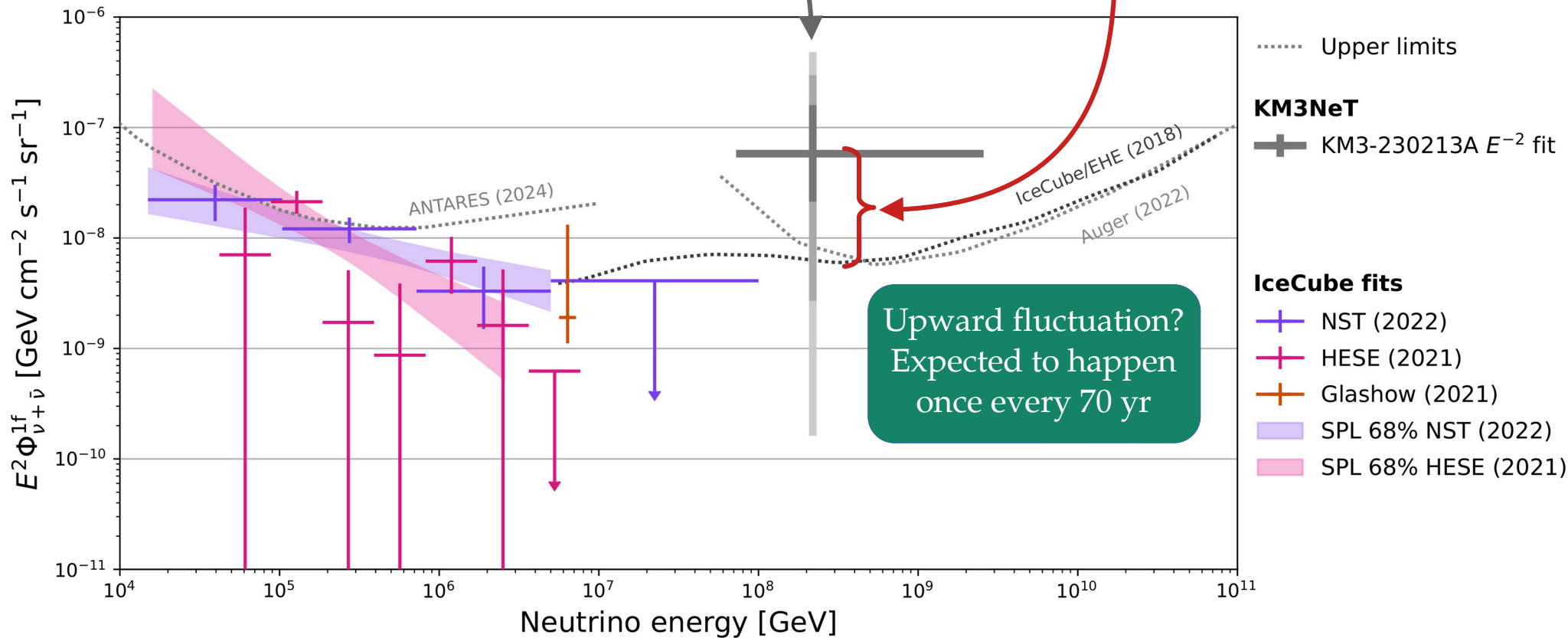
Flux is above upper limits! 2.5σ – 3σ tension



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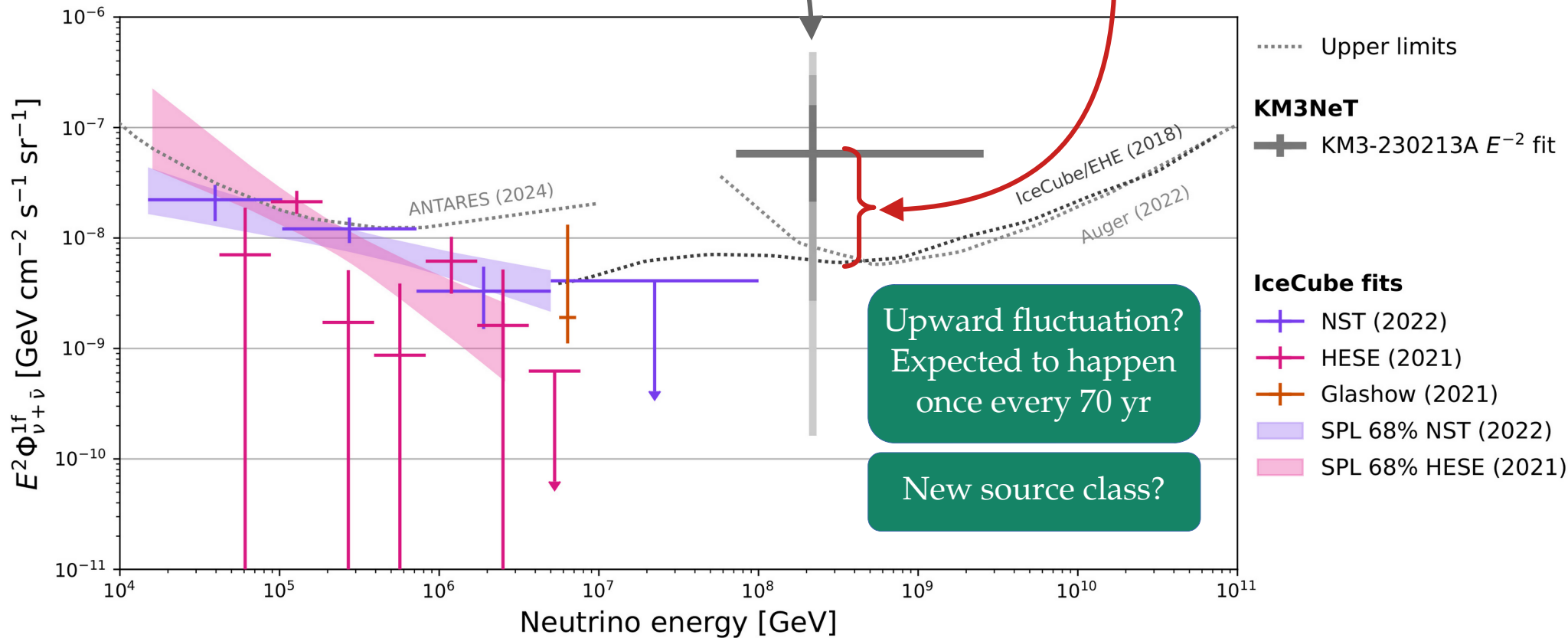
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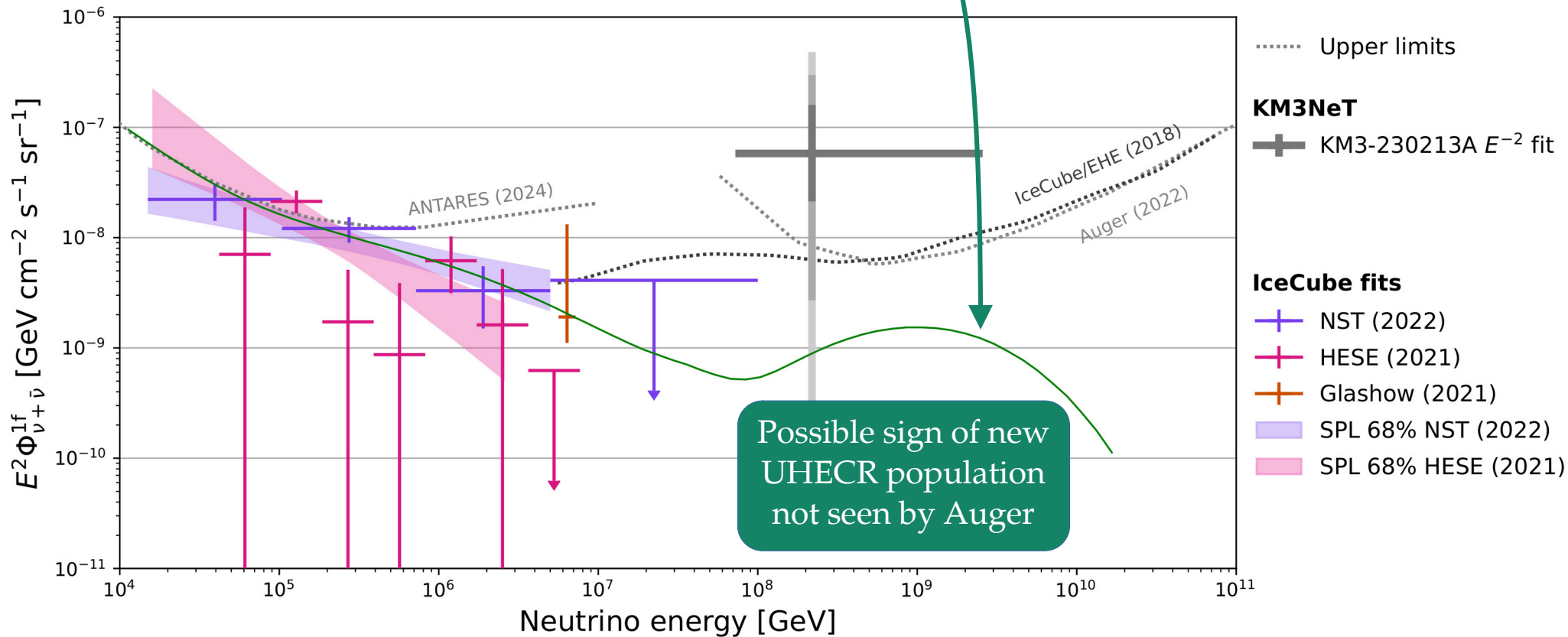
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Was it a *cosmogenic* neutrino? KM3NeT vs. IceCube

Joint fit to IceCube and KM3NeT ν data + Auger UHECR data

Muzio, Yuan, Lu, arXiv:2502.06944



5. Dark matter:

Annihilation and decay into ν

High-energy neutrinos from dark matter

Dark matter co-annihilation:

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

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

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

Dark matter decay:

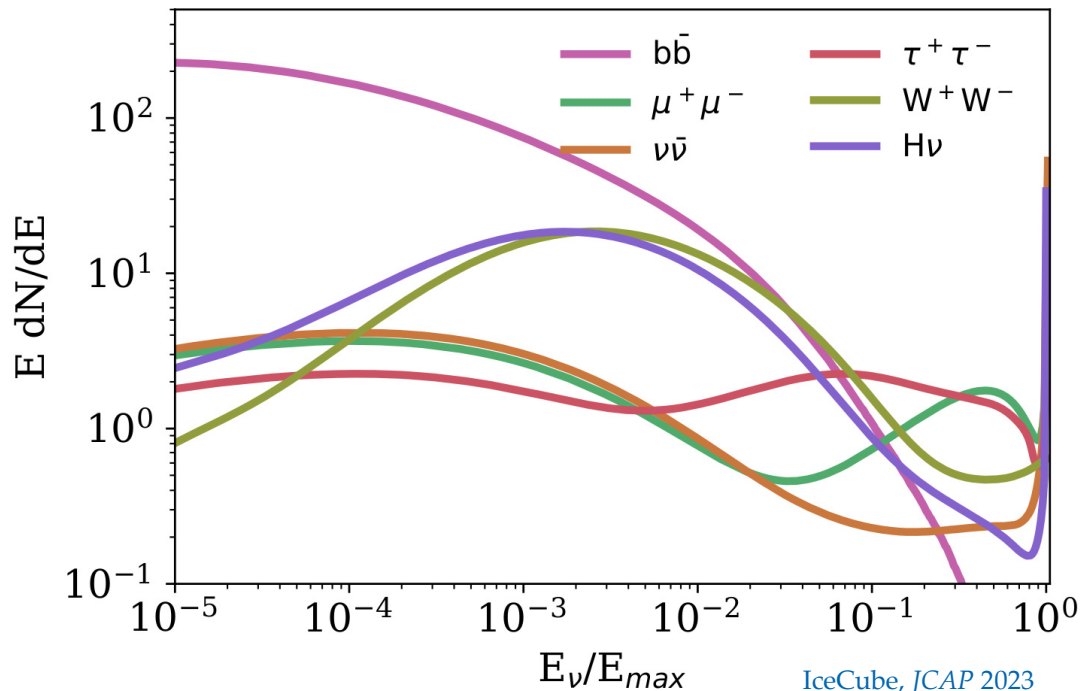
$$\chi \rightarrow \nu + \bar{\nu}$$

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

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

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

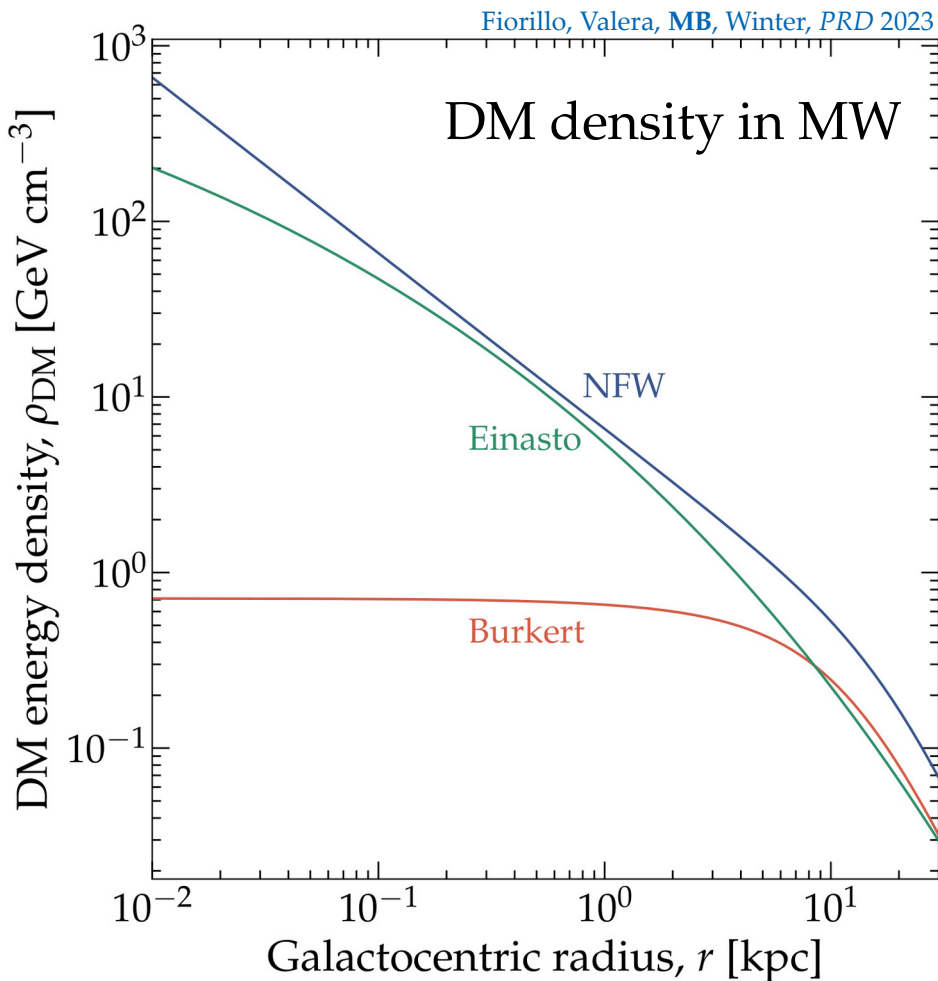
$\nu + \nu$ yield from DM (at source)



IceCube, JCAP 2023

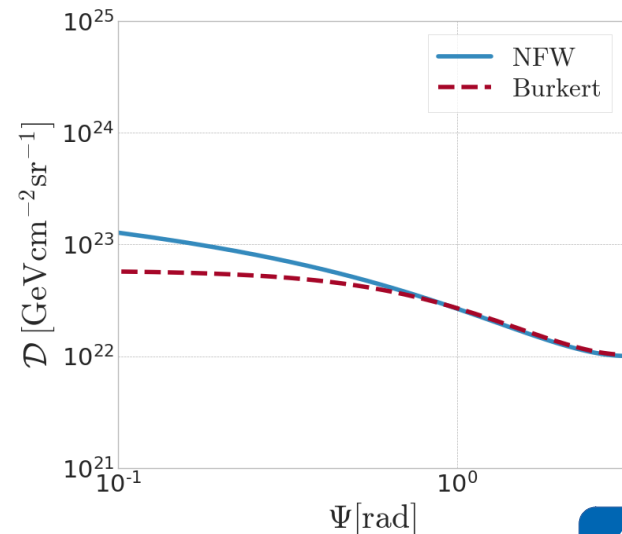
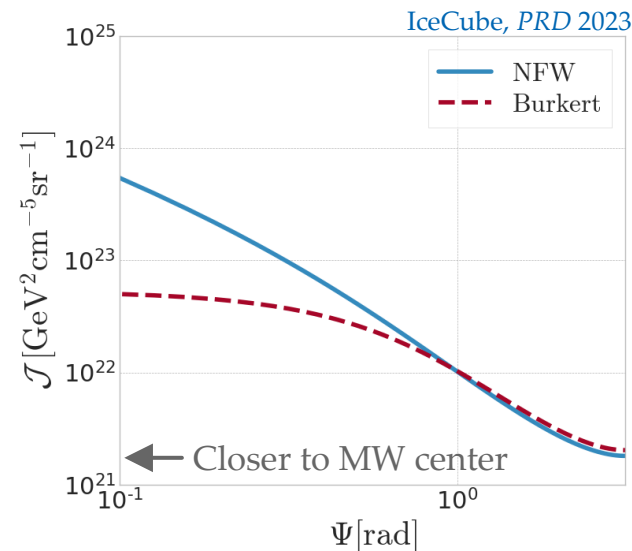
Approximate independence on m_{χ}
valid for $m_{\chi} \approx 100 \text{ TeV} - 10 \text{ PeV}$

Dark matter in the Milky Way



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

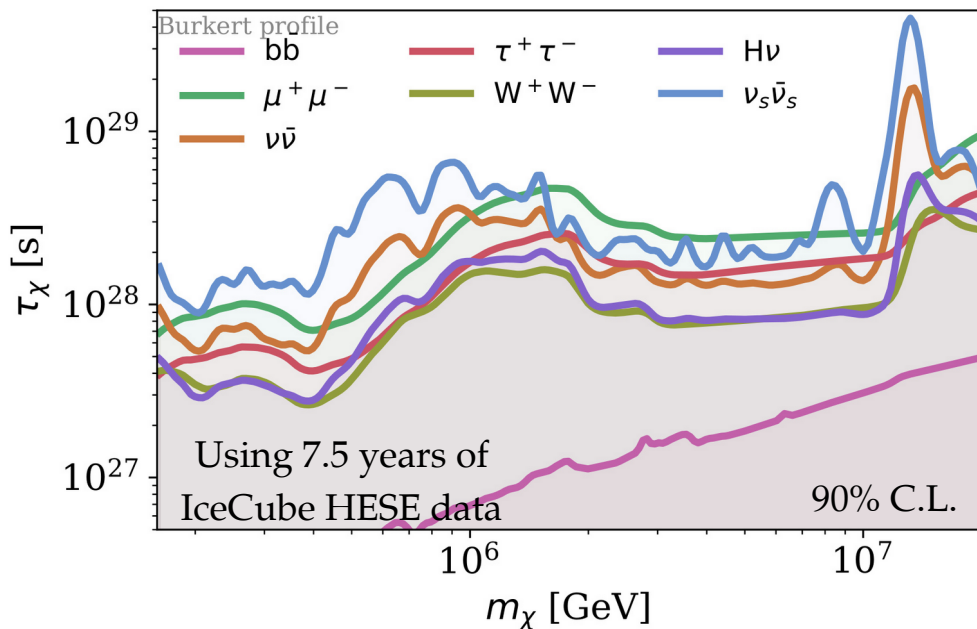
DM decay
 $\Phi_\nu \propto \mathcal{D} \propto \rho_{\text{DM}}$



Limits on dark matter decay

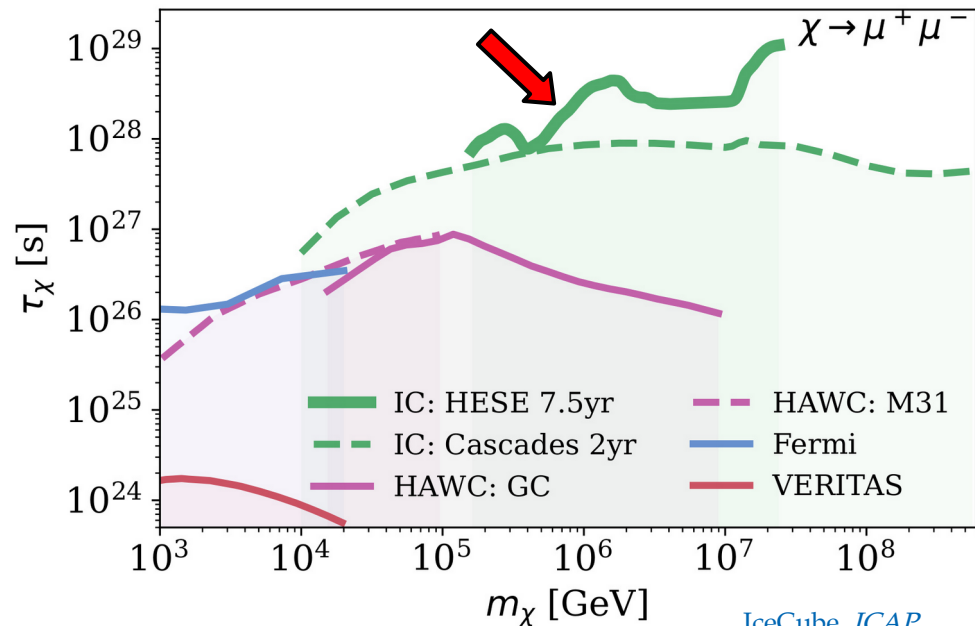
Per annihilation channel

(assuming 100% branching ratio)



Compared to other limits

(assuming decay into muons)



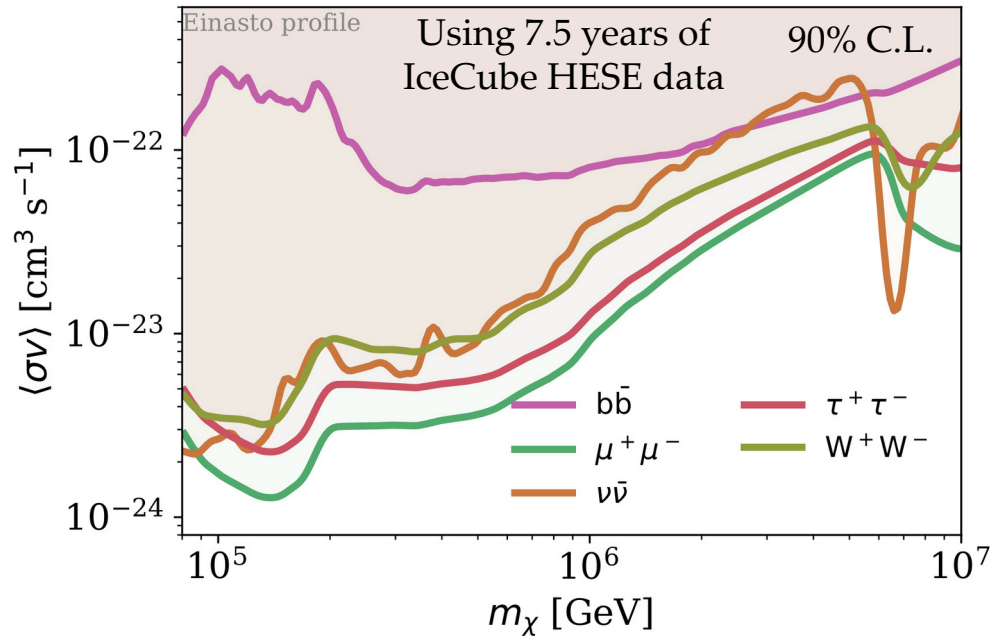
IceCube, JCAP
2023

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

Plus background of atmospheric neutrinos (anisotropic, but different)

Limits on dark matter annihilation

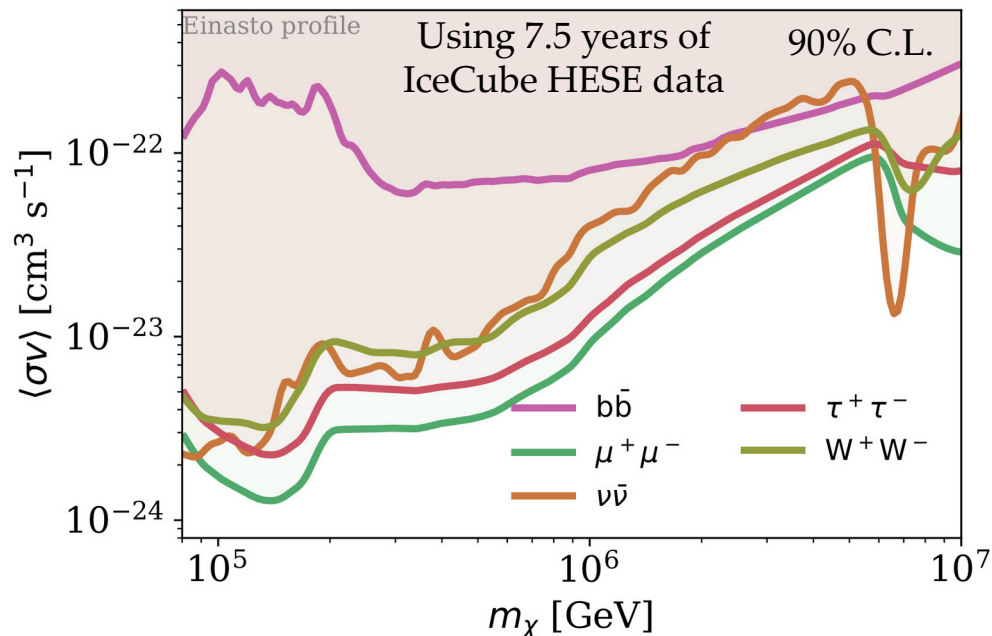
Per annihilation channel
(assuming 100% branching ratio)



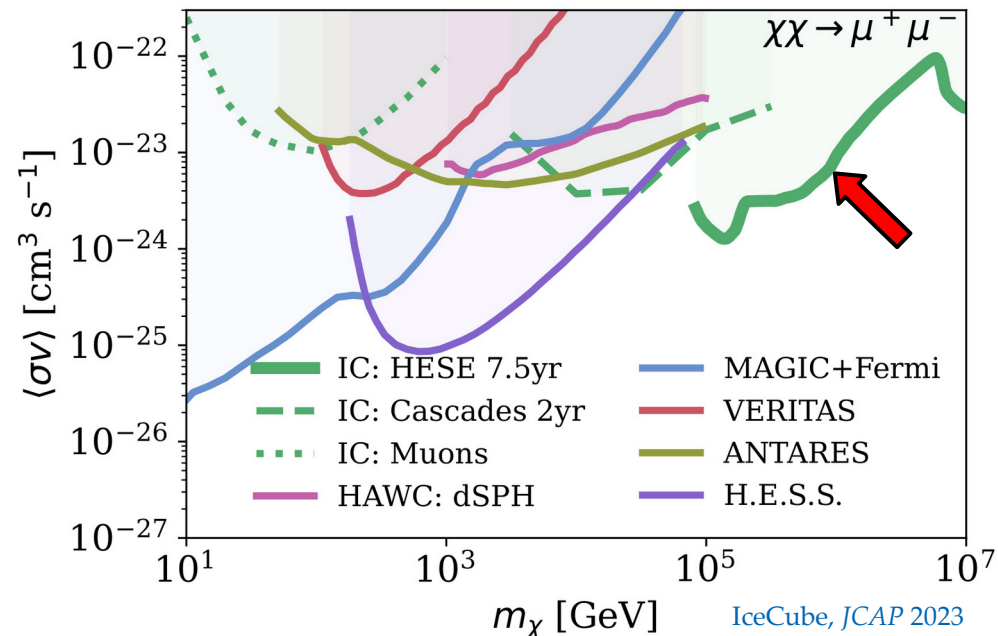
Two DM contributions: **Galactic** (anisotropic) + **extragalactic** (isotropic)
Plus background of **atmospheric** neutrinos (anisotropic, but different)

Limits on dark matter annihilation

Per annihilation channel
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Compared to other limits
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IceCube, JCAP 2023

Two DM contributions: Galactic (anisotropic) + extragalactic (isotropic)
Plus background of atmospheric neutrinos (anisotropic, but different)

6. Unstable neutrinos: *Are neutrinos for ever?*

Are neutrinos forever?

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

» Age of Universe (~ 14.5 Gyr)
- ▶ BSM decays may have significantly higher rates: $\nu_i \rightarrow \nu_j + \varphi$
- ▶ We work in a model-independent way:
the nature of φ is unimportant if it is invisible to neutrino detectors

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Nambu-Goldstone
boson of a broken
symmetry

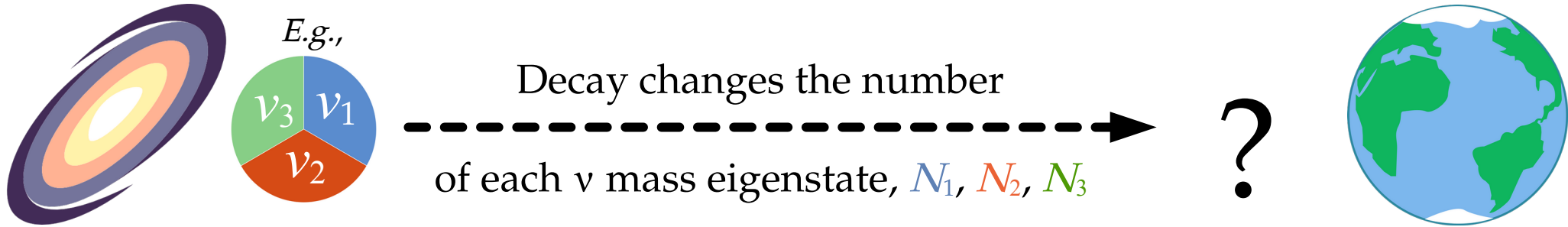
- ▶ We work in a model-independent way:

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

Astrophysical sources

Earth

$L \sim$ up to a few Gpc



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

Mass of ν_i Lifetime of ν_i

Astrophysical sources

Earth

$L \sim$ up to a few Gpc



Decay changes the number
of each ν mass eigenstate, N_1, N_2, N_3

?



Only sensitive to their ratio

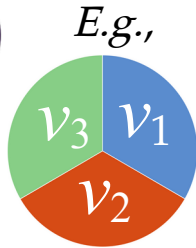
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Mass of ν_i Lifetime of ν_i

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Decay changes the number
of each ν mass eigenstate, N_1, N_2, N_3

?



Lower- E ν are longer-lived...

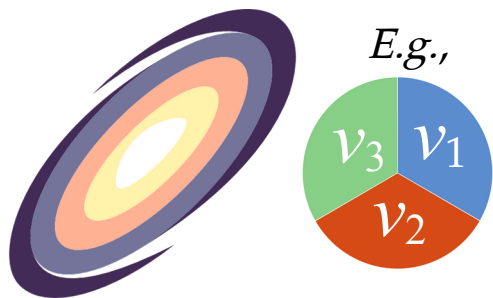
The flux of ν_i is attenuated by $\exp[-(L/E) \cdot (m_i/\tau_i)]$

... but ν that travel longer L are more attenuated!

Astrophysical sources

Earth

$L \sim$ up to a few Gpc



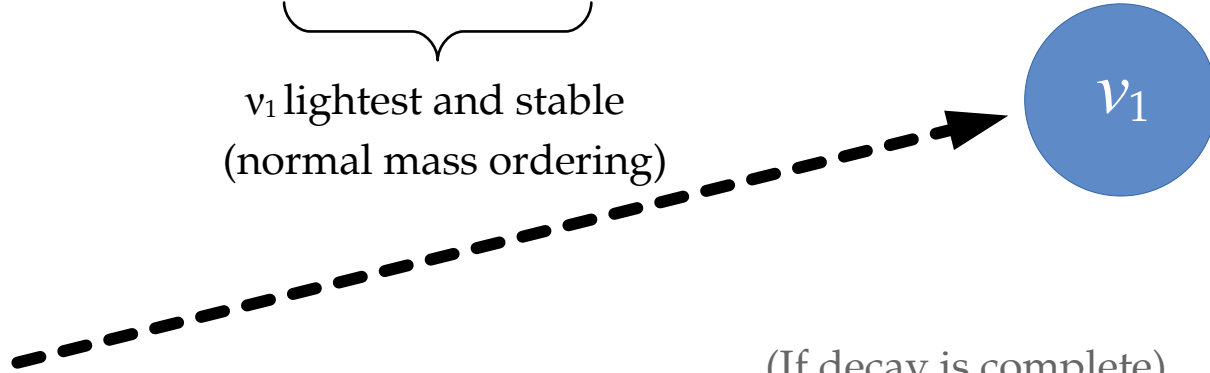
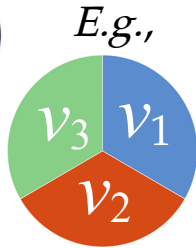
Astrophysical sources

Earth

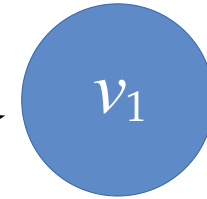
$L \sim$ up to a few Gpc

$$\nu_2, \nu_3 \rightarrow \nu_1$$

ν_1 lightest and stable
(normal mass ordering)



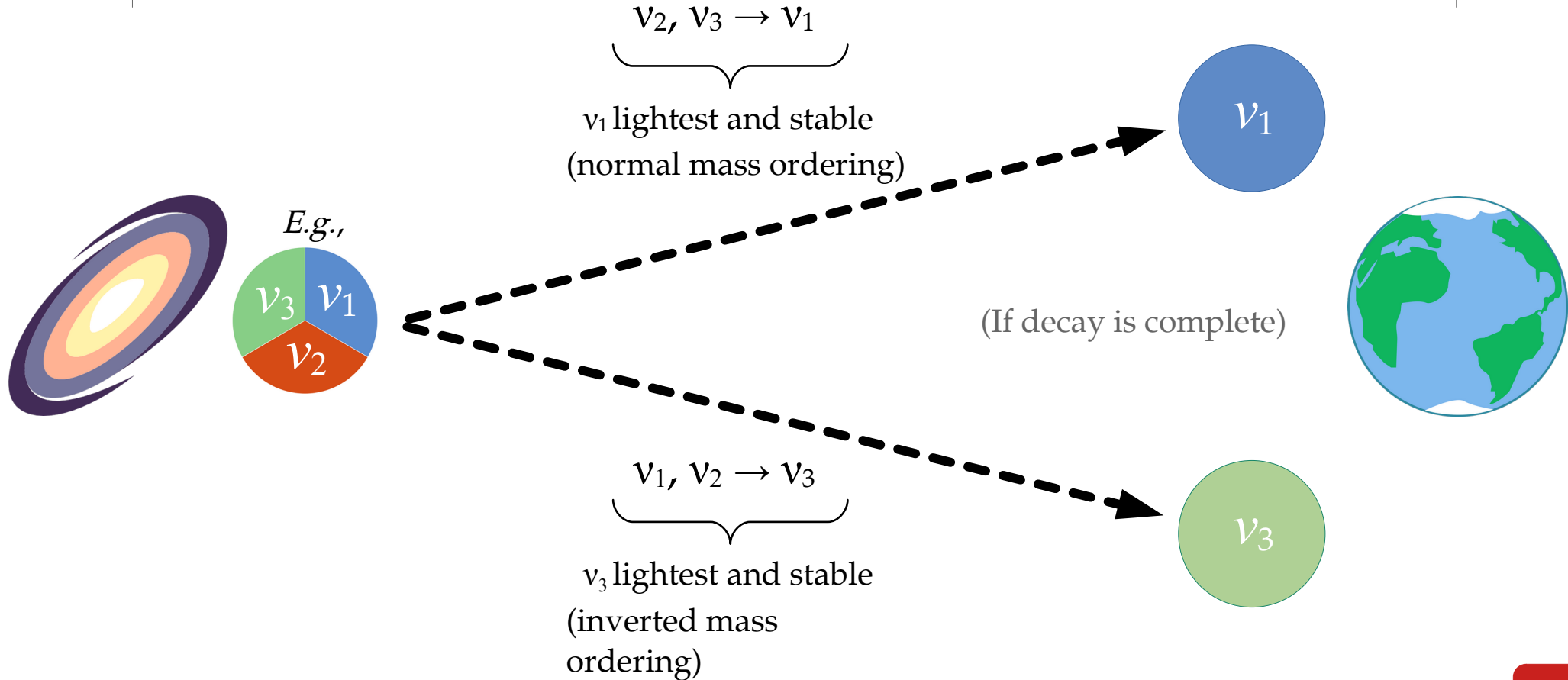
(If decay is complete)

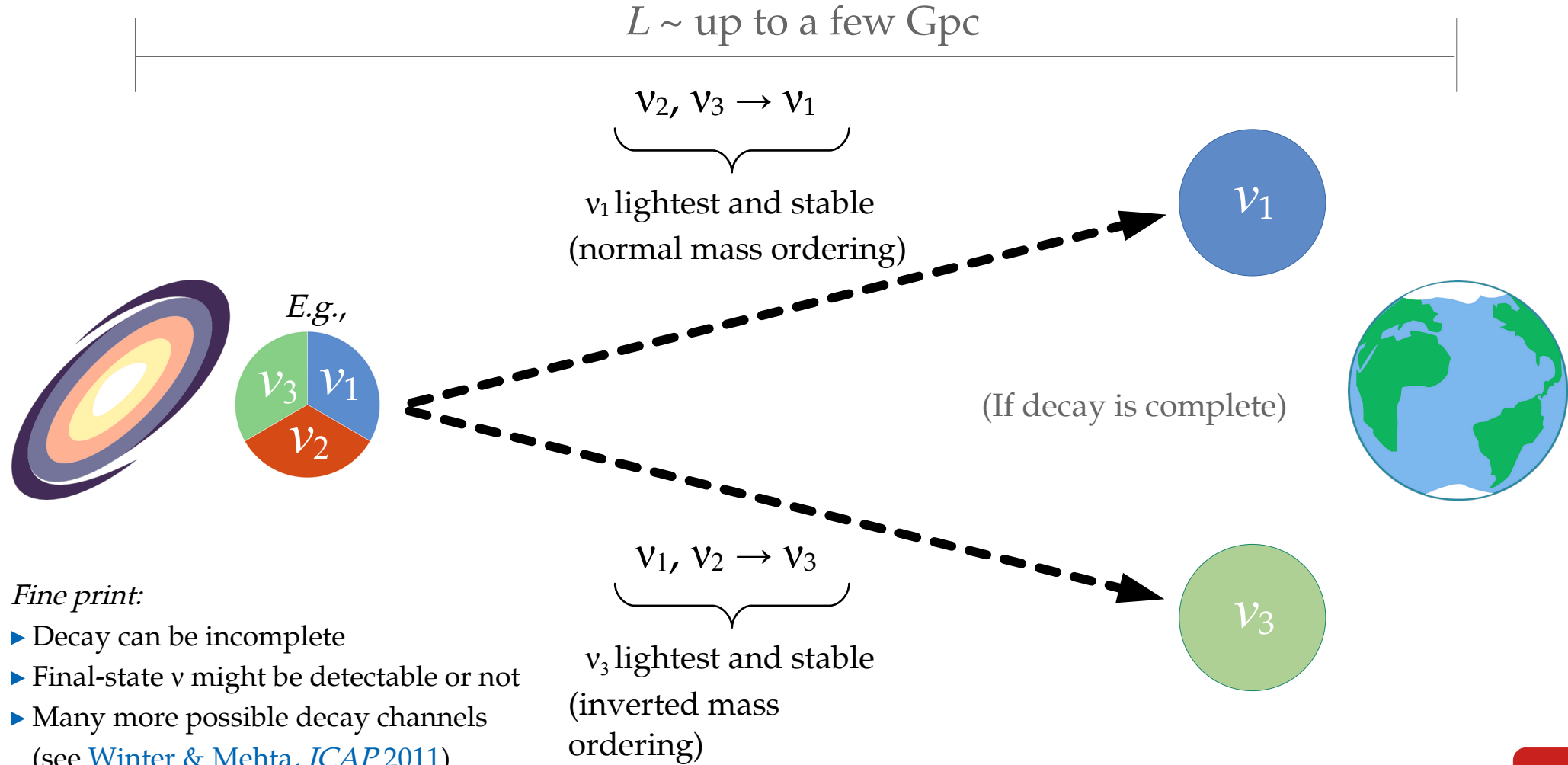


Astrophysical sources

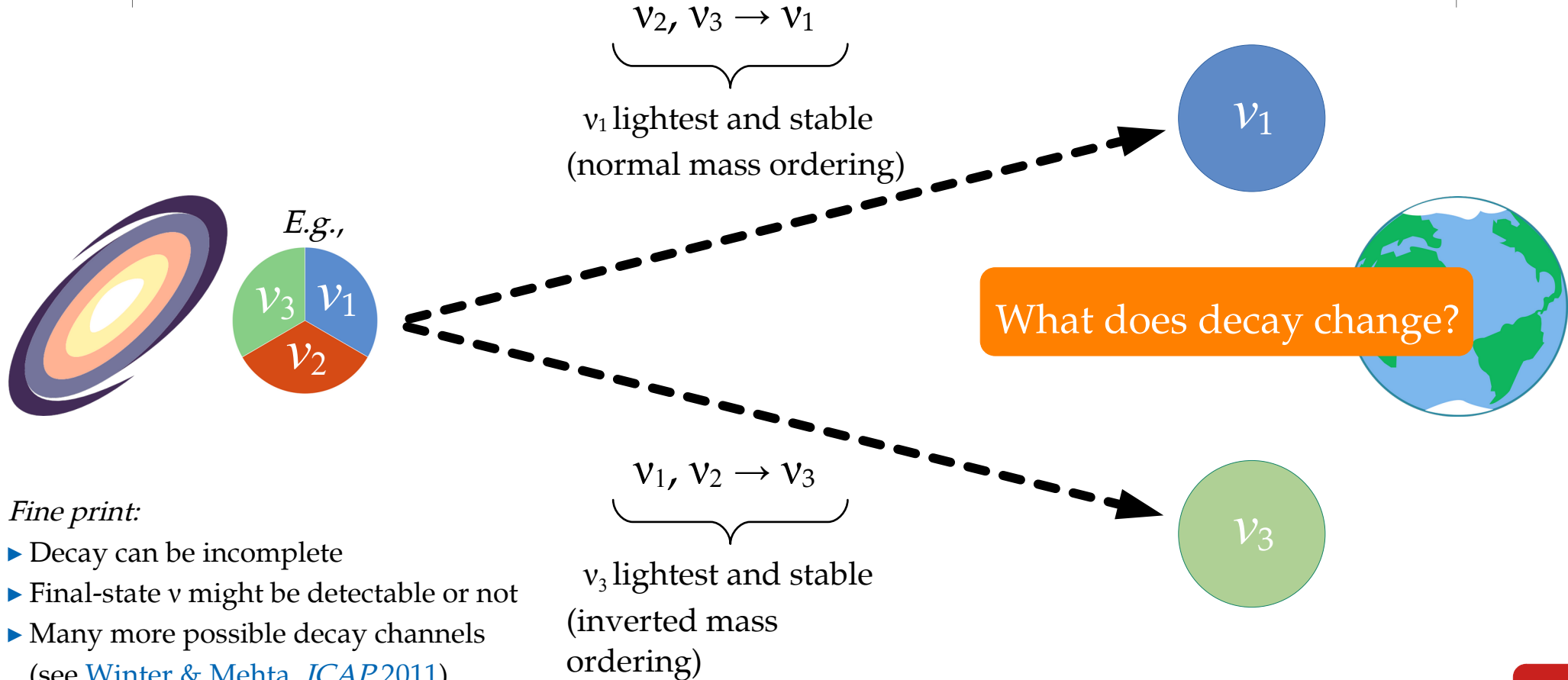
Earth

$L \sim$ up to a few Gpc





$L \sim \text{up to a few Gpc}$



Fine print:

- Decay can be incomplete
- Final-state ν might be detectable or not
- Many more possible decay channels
(see [Winter & Mehta, JCAP2011](#))

What does neutrino decay change?

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

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

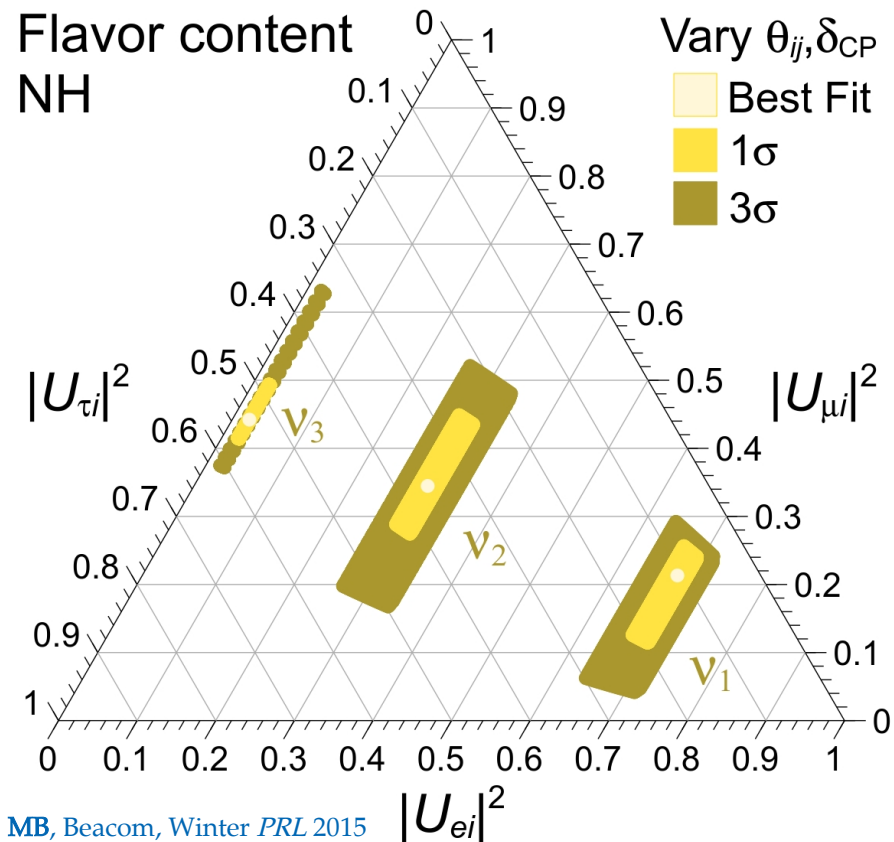
Flavor content of mass eigenstates:

Known to within 2%

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

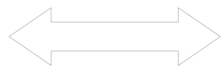
Known to within 8%

Known to within 20% (or worse)

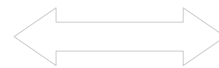


What does neutrino decay change?

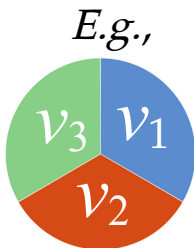
Flavor composition



Spectrum shape

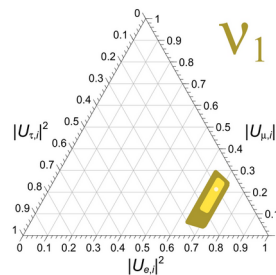


Event rate



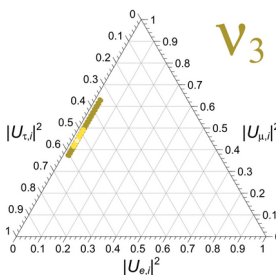
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ν_1 lightest and stable
(normal mass ordering)



$$\nu_1, \nu_2 \rightarrow \nu_3$$

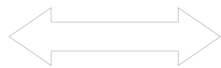
ν_3 lightest and stable
(inverted mass ordering)



What does neutrino decay change?

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

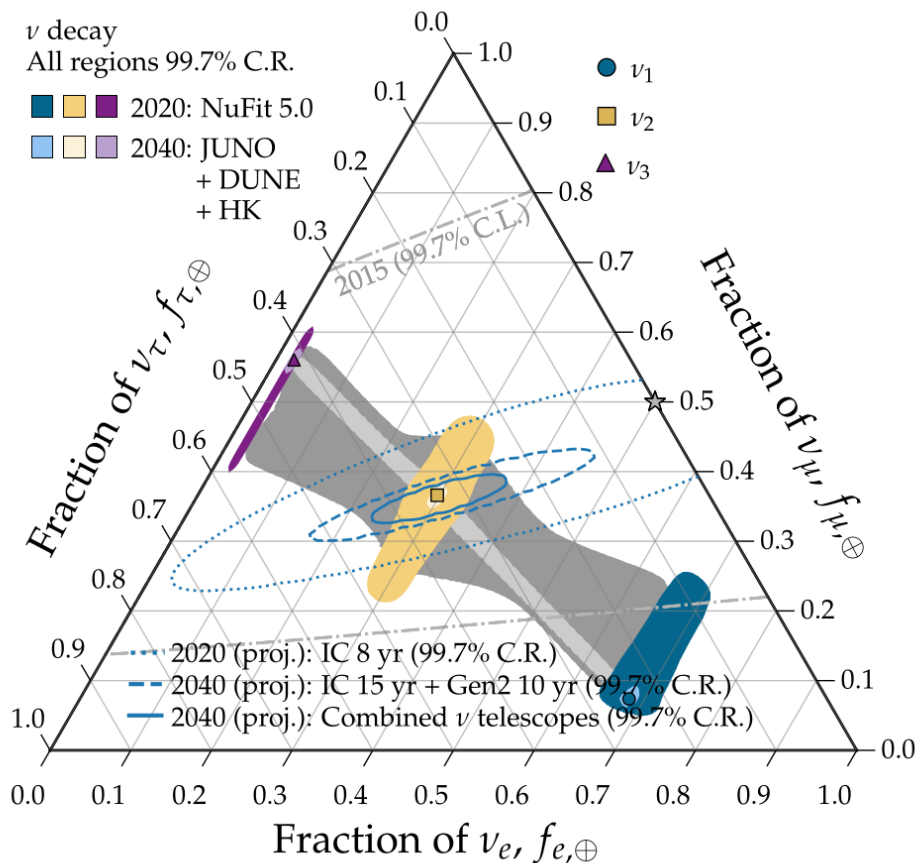
Flavor composition



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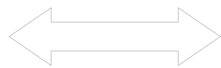
Event rate



What does neutrino decay change?

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

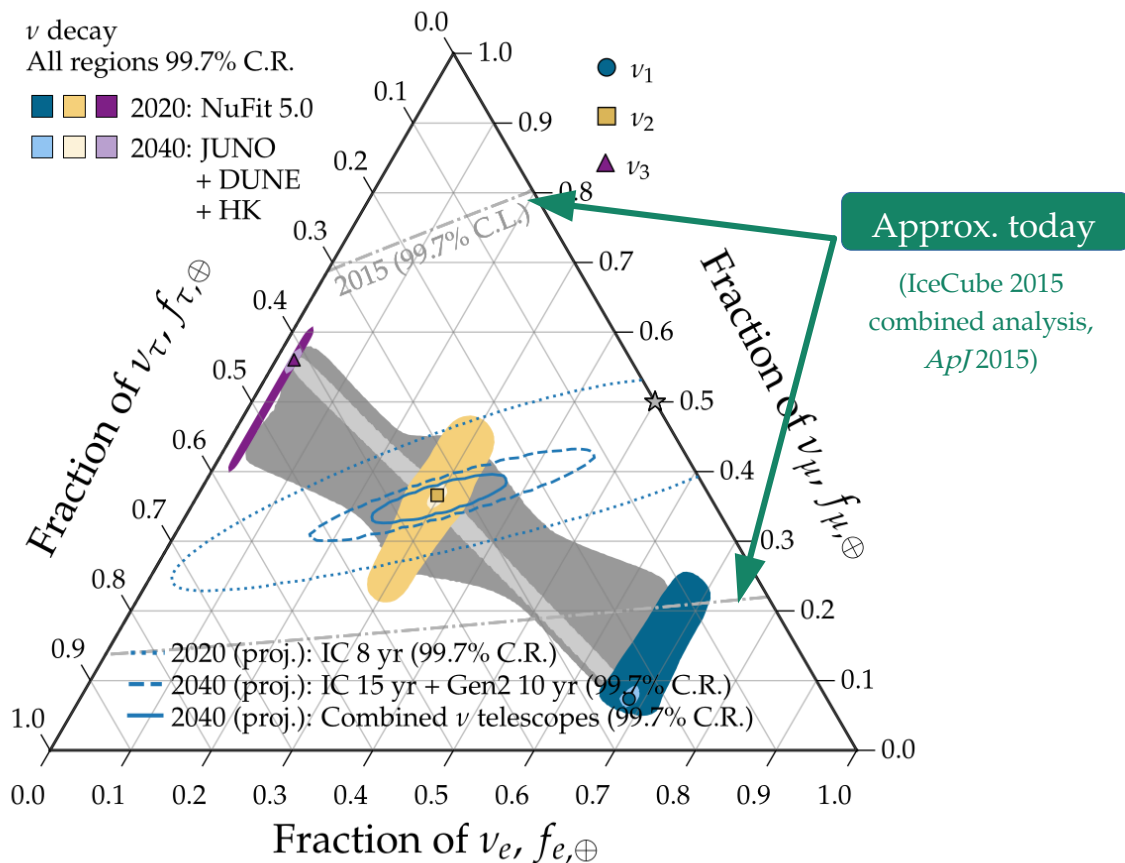
Flavor composition



Spectrum shape



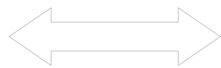
Event rate



What does neutrino decay change?

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

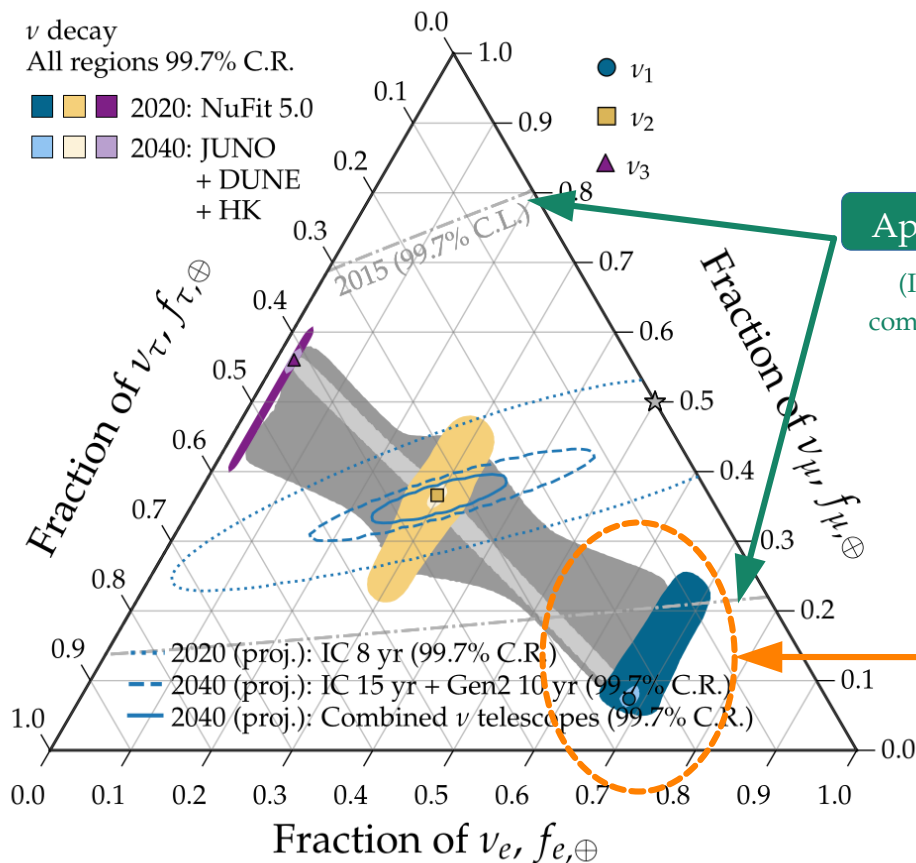
Flavor composition



Spectrum shape



Event rate



Approx. today

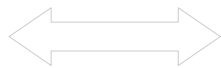
(IceCube 2015
combined analysis,
ApJ 2015)

Complete decay into
 ν_1 disfavored by 2015
IceCube flavor measurement

What does neutrino decay change?

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

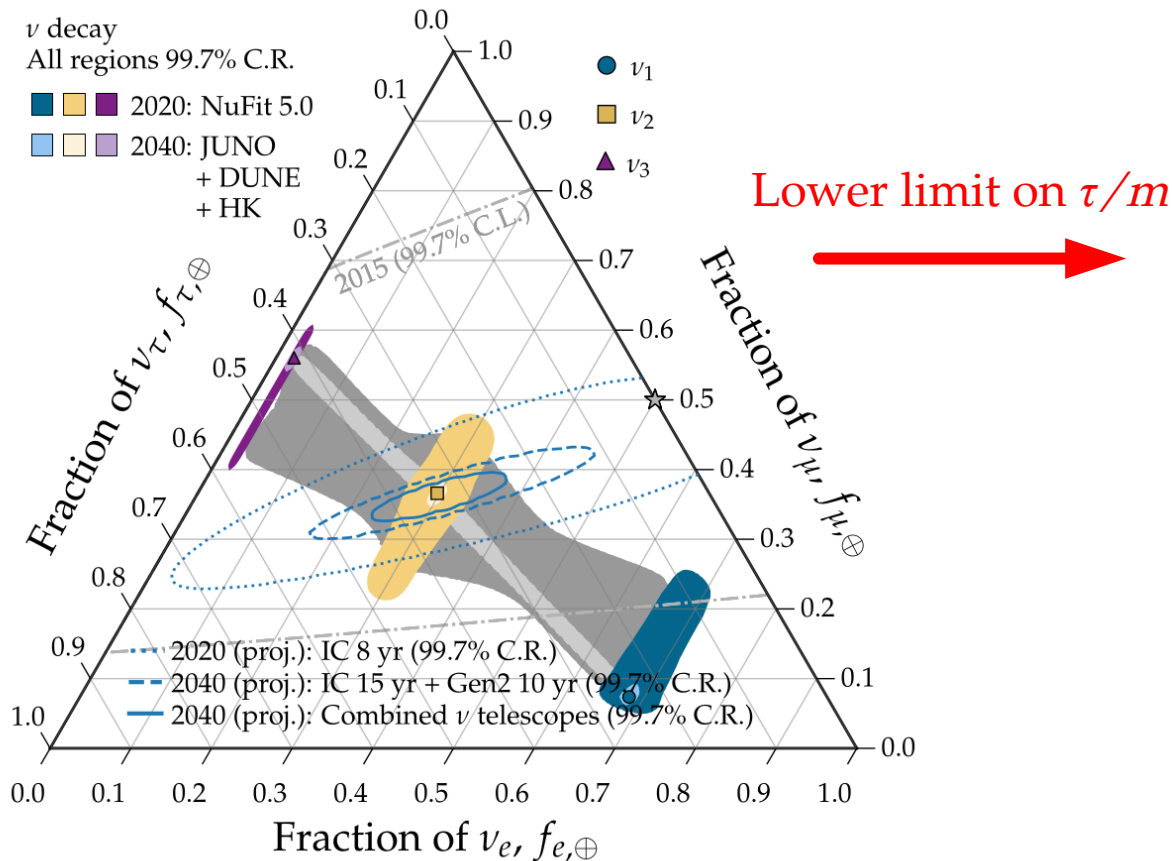
Flavor composition



Spectrum shape



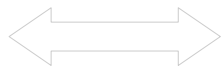
Event rate



What does neutrino decay change?

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

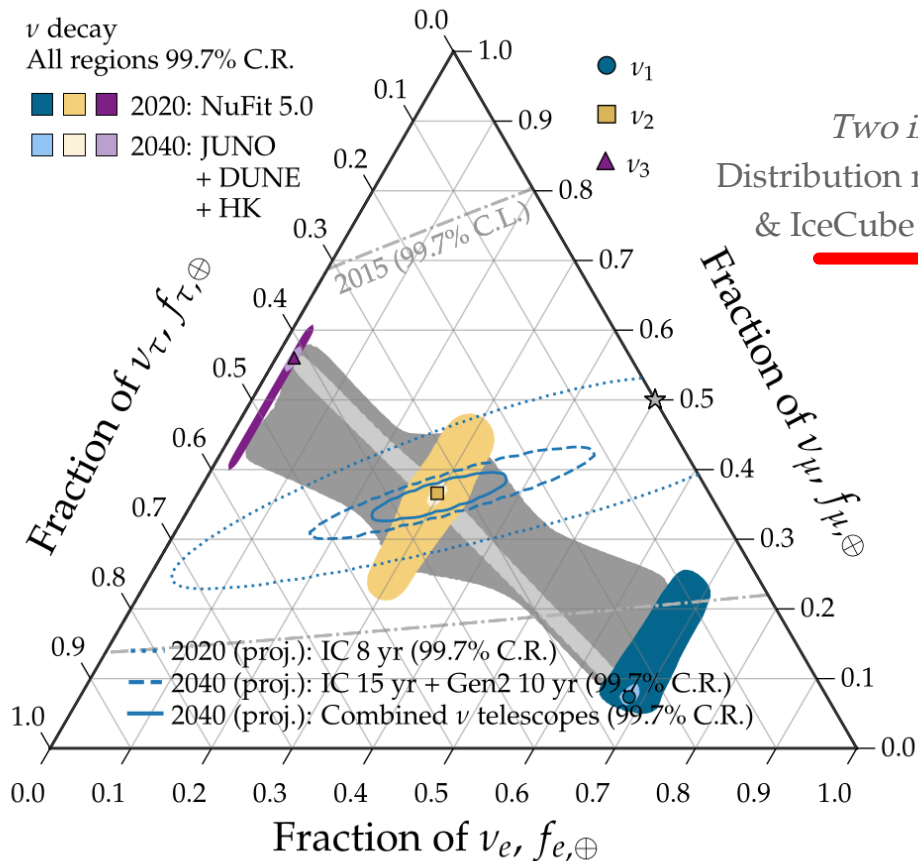
Flavor composition



Spectrum shape



Event rate



Two ingredients:

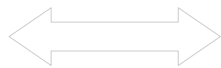
Distribution mixing parameters
& IceCube flavor posterior



What does neutrino decay change?

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

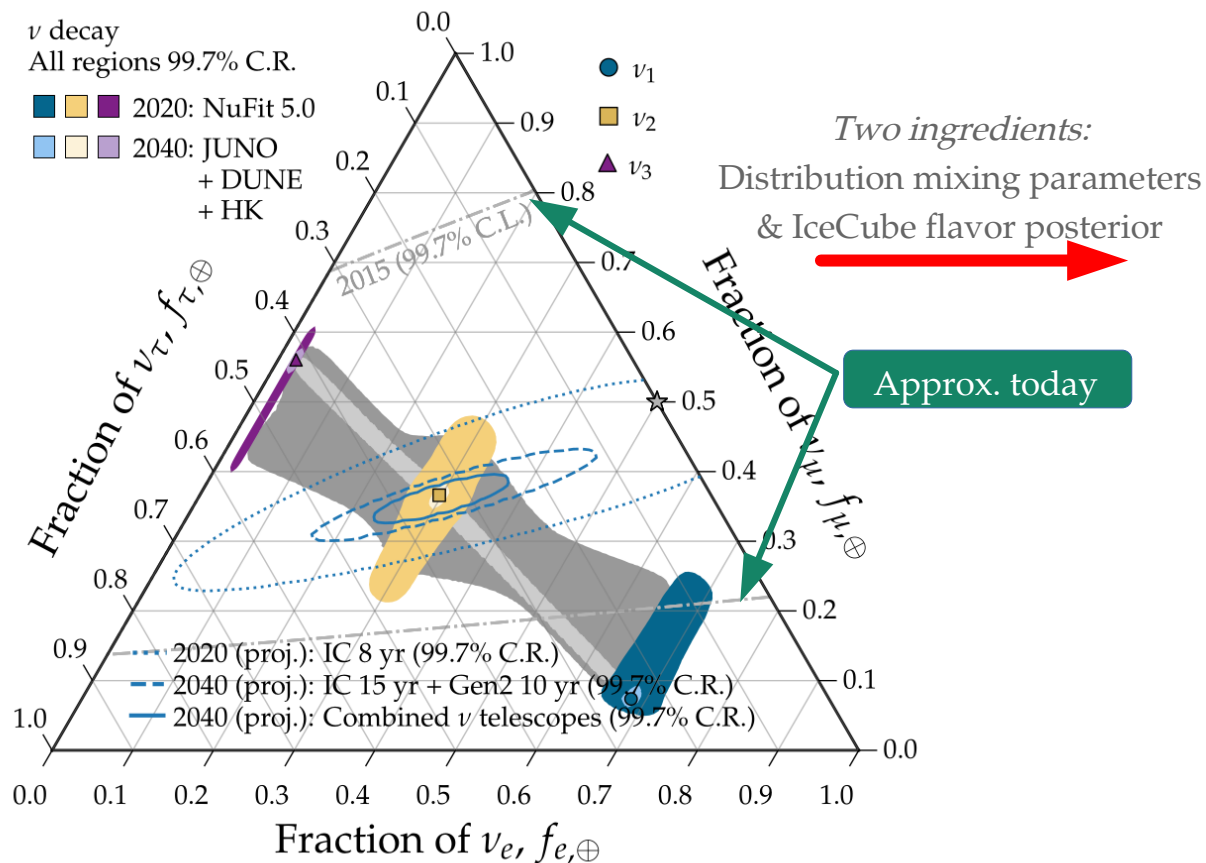
Flavor composition



Spectrum shape



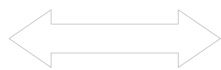
Event rate



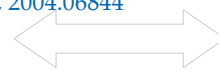
What does neutrino decay change?

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

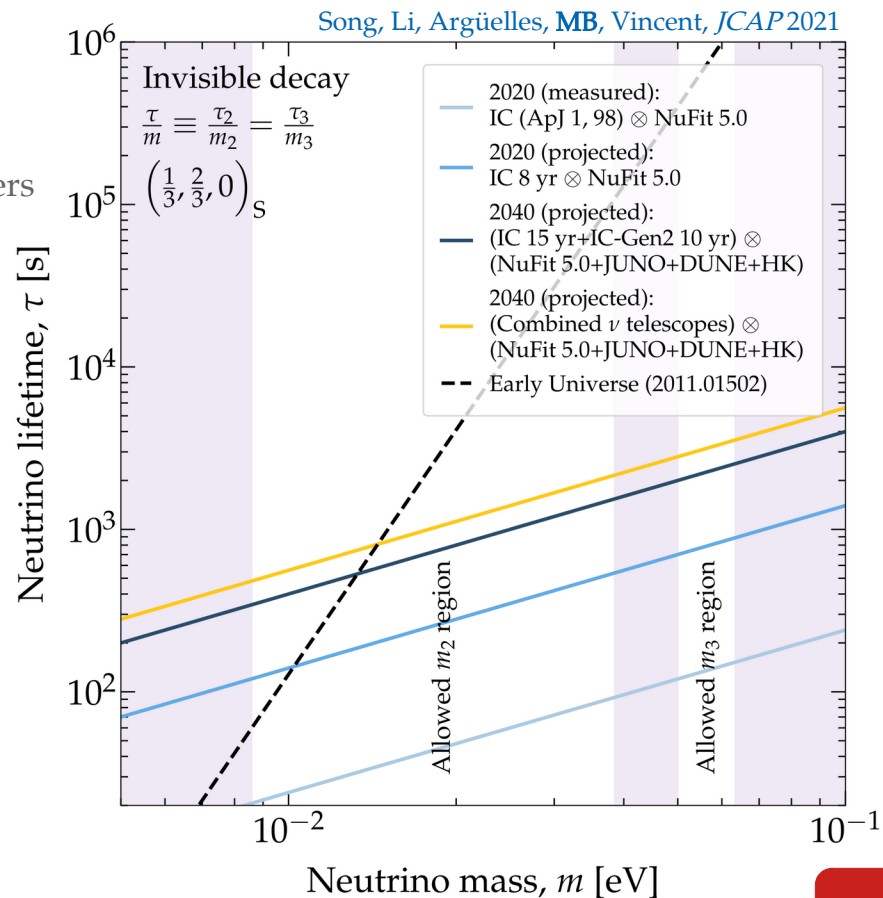
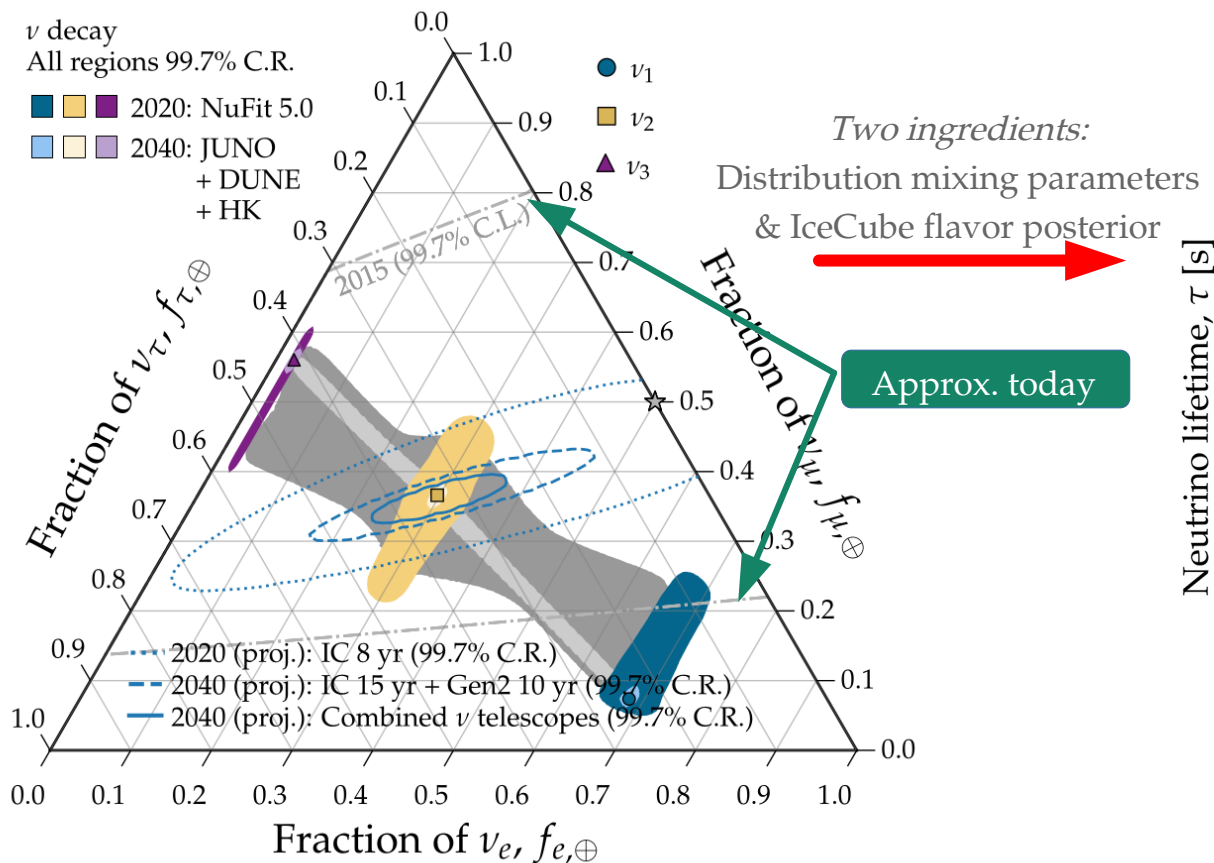
Flavor composition



Spectrum shape



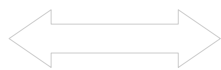
Event rate



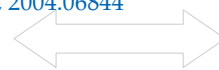
What does neutrino decay change?

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

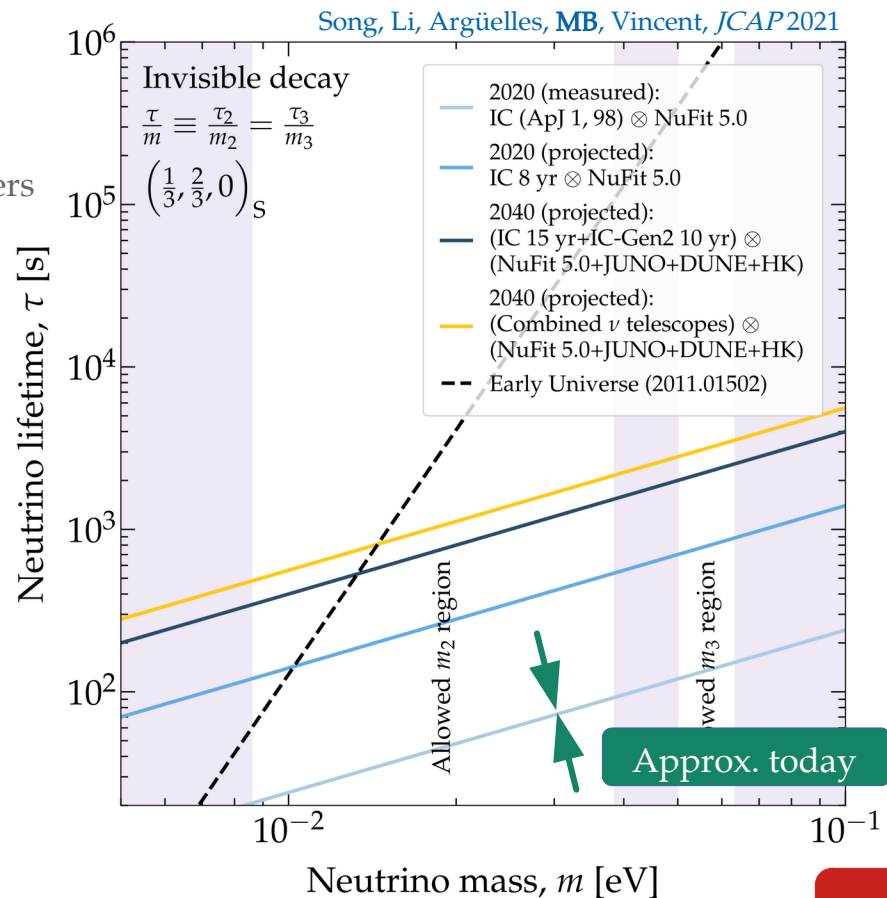
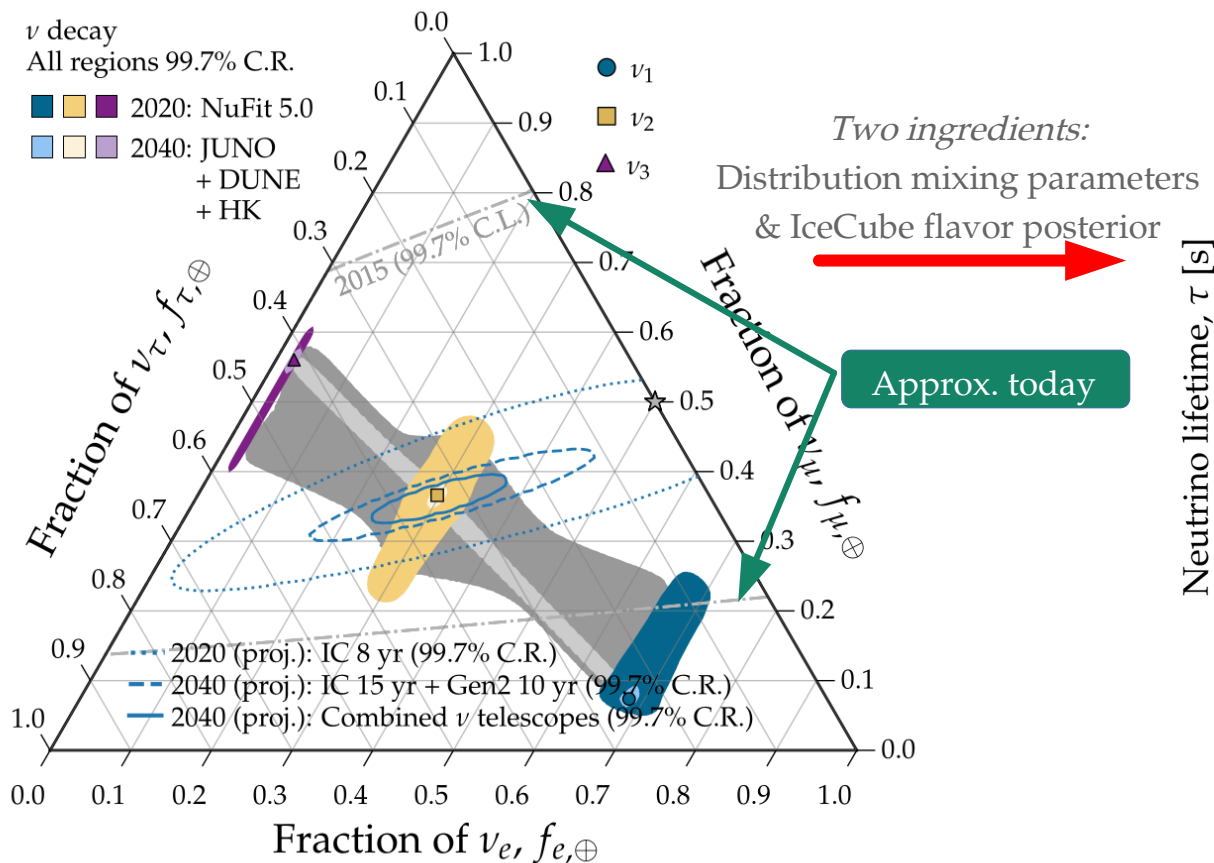
Flavor composition



Spectrum shape



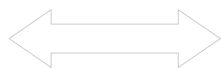
Event rate



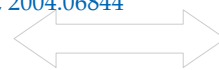
What does neutrino decay change?

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

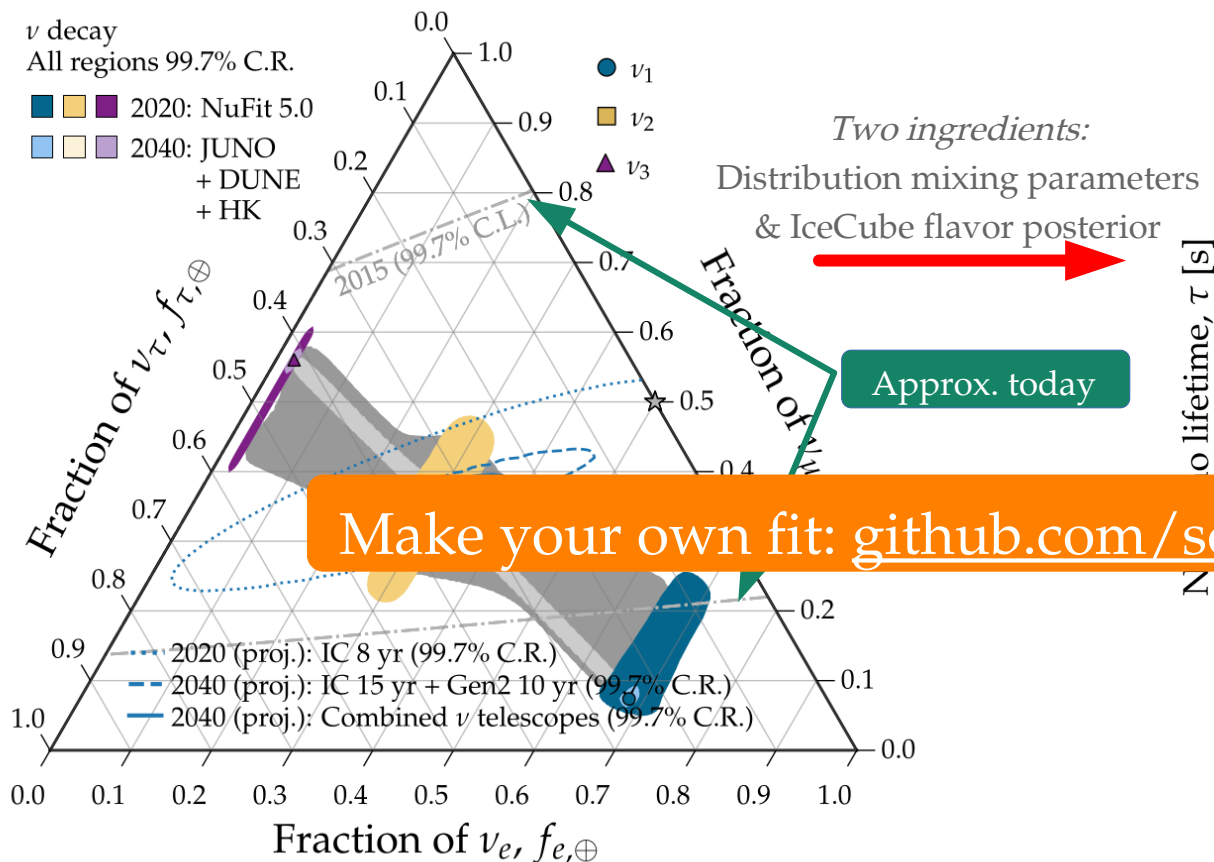
Flavor composition



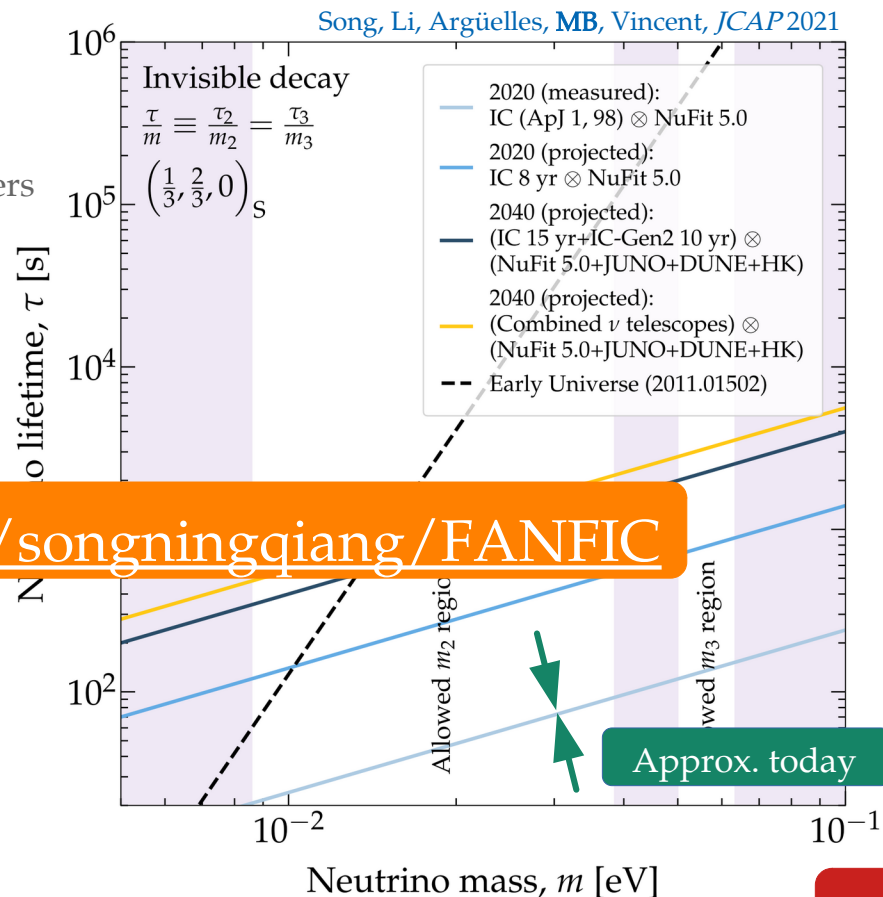
Spectrum shape



Event rate



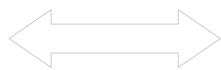
Make your own fit: github.com/songningqiang/FANFIC



What does neutrino decay change?

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

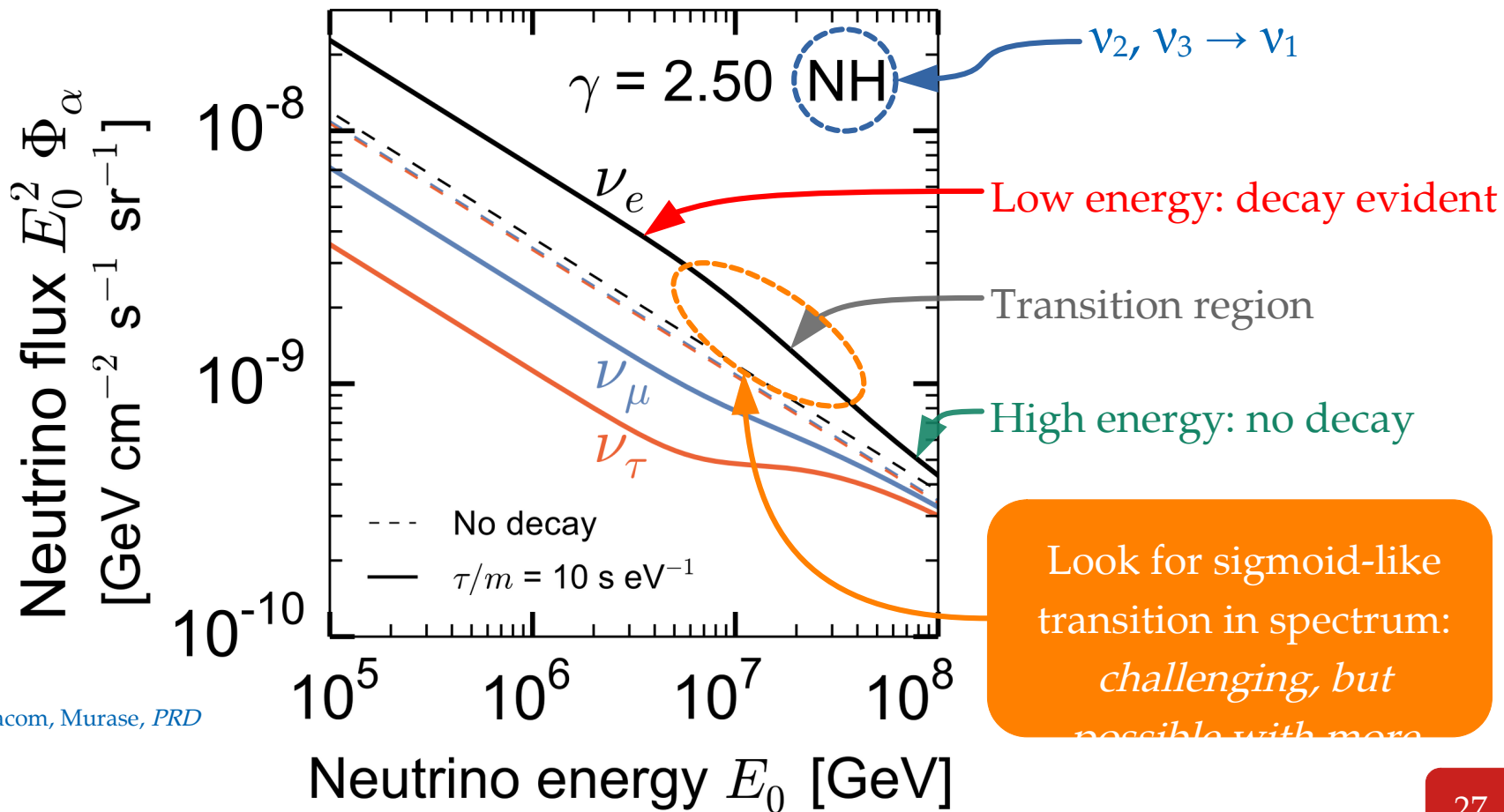
Flavor composition



Spectrum shape



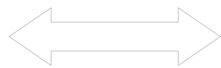
Event rate



What does neutrino decay change?

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

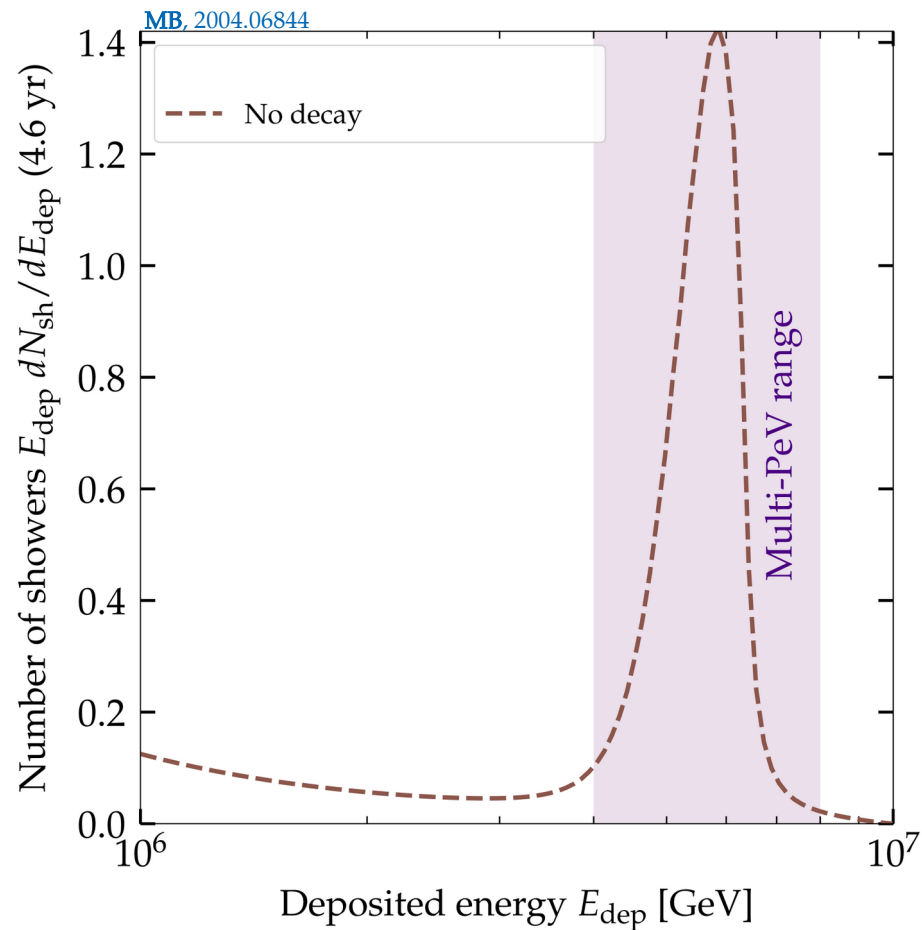
Flavor composition



Spectrum shape



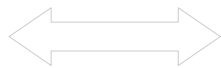
Event rate



What does neutrino decay change?

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

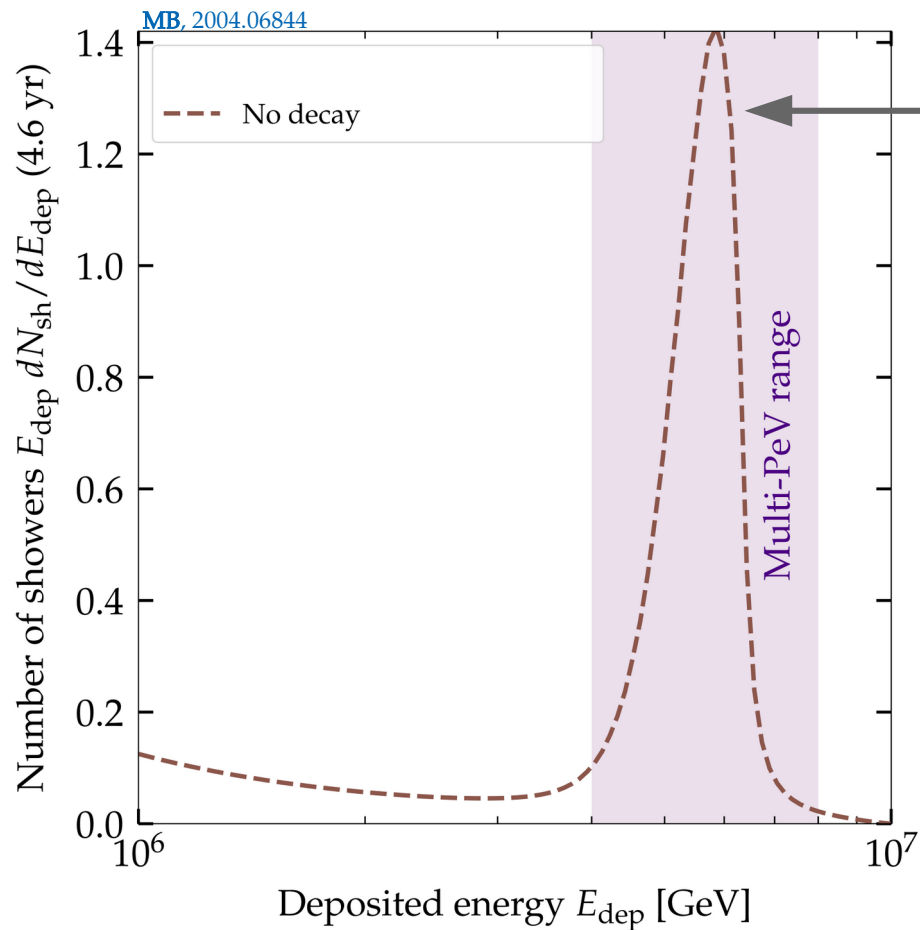
Flavor composition



Spectrum shape



Event rate



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

What does neutrino decay change?

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

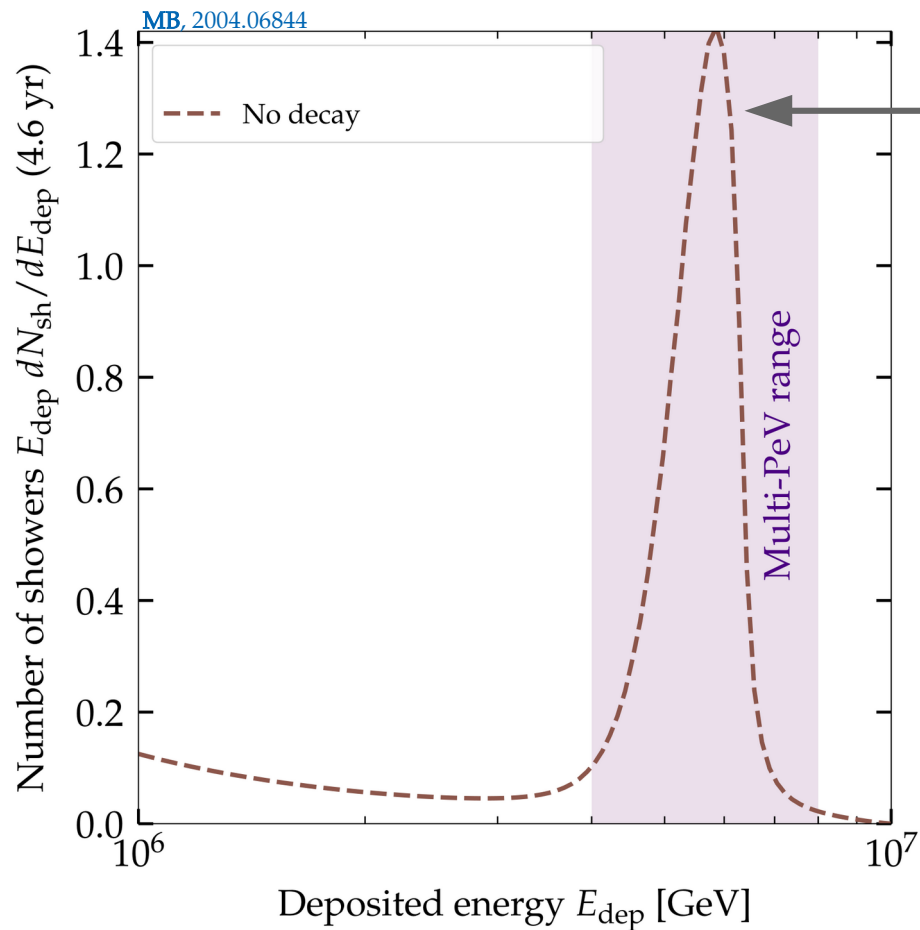
Flavor composition



Spectrum shape

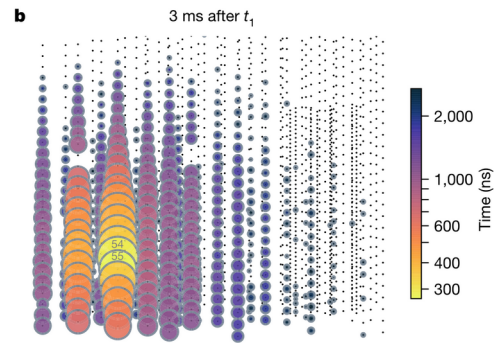
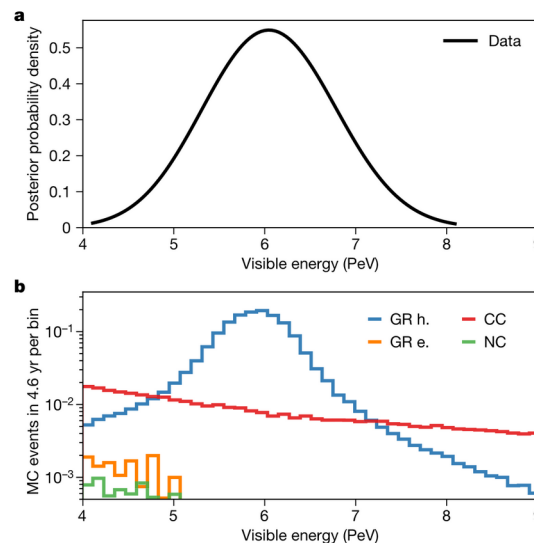


Event rate



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

IceCube has seen one GR candidate in 4.6 years:

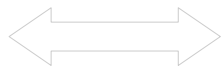


IceCube Collab., *Nature* 2021

What does neutrino decay change?

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

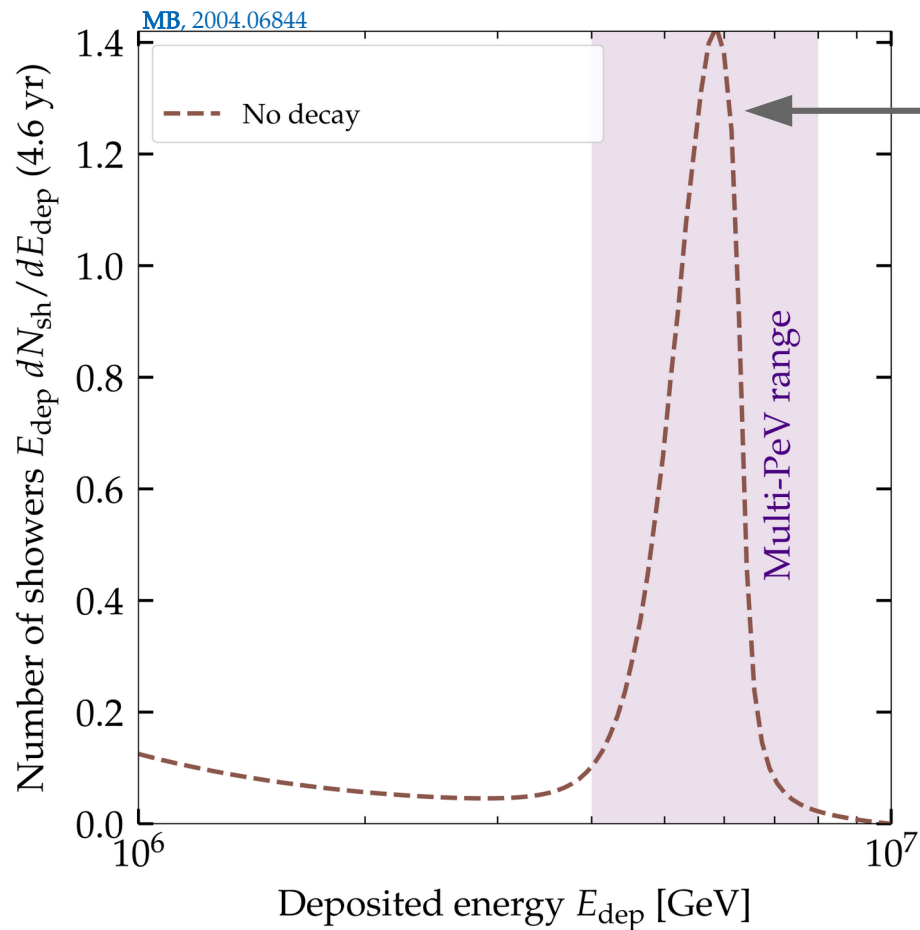
Flavor composition



Spectrum shape



Event rate

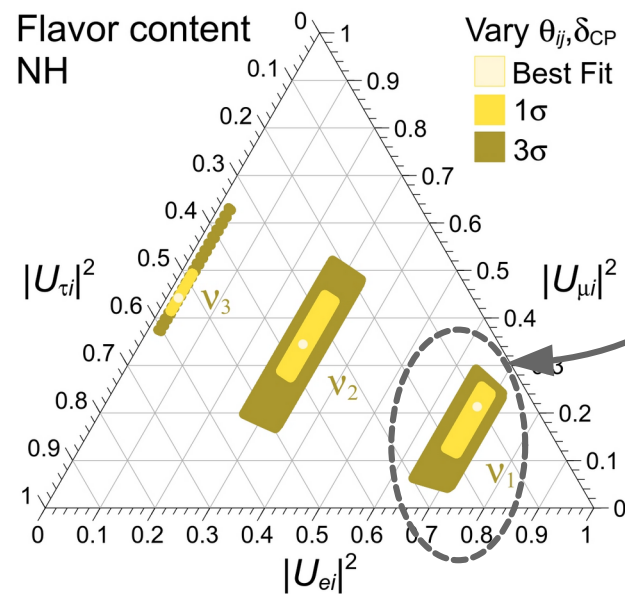


Glashow resonance (GR):

$\bar{\nu}_e + e \rightarrow W \rightarrow \text{hadrons} \rightarrow$

shower

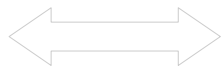
ν_1 is the mass eigenstate with the most e flavor



What does neutrino decay change?

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

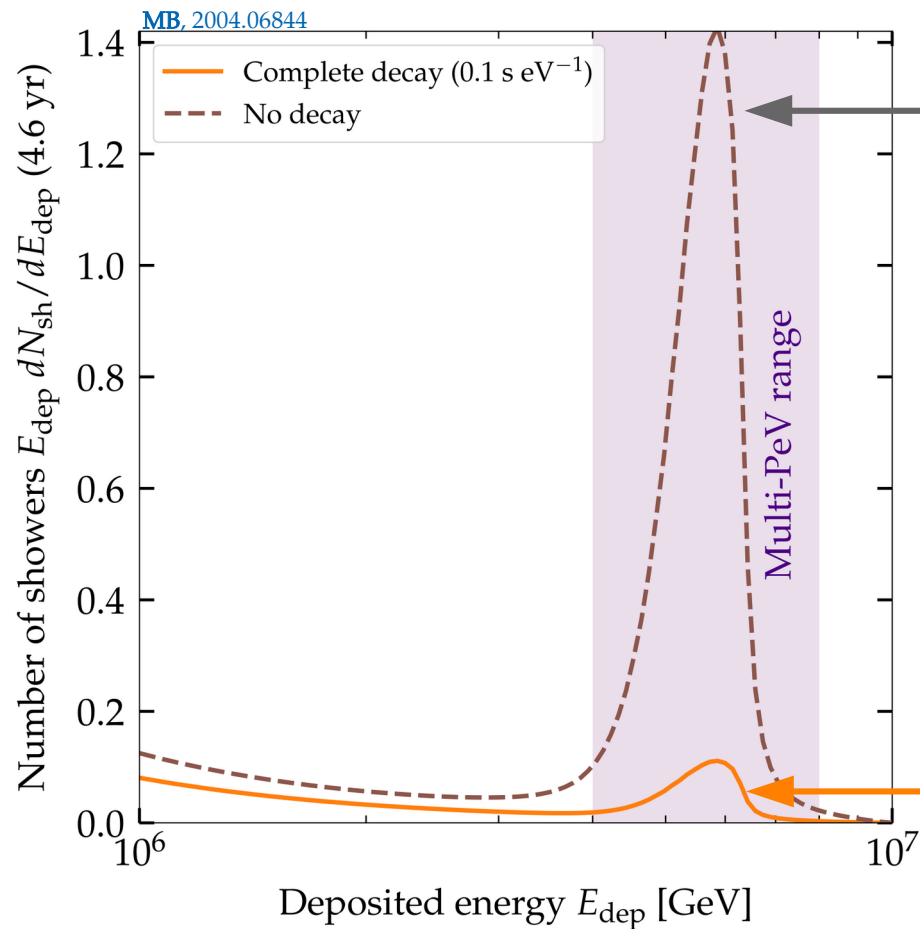
Flavor composition



Spectrum shape



Event rate



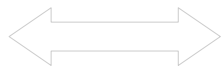
Glashow resonance (GR):
 $\bar{\nu}_e + e \rightarrow W \rightarrow \text{hadrons} \rightarrow \text{shower}$

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

What does neutrino decay change?

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

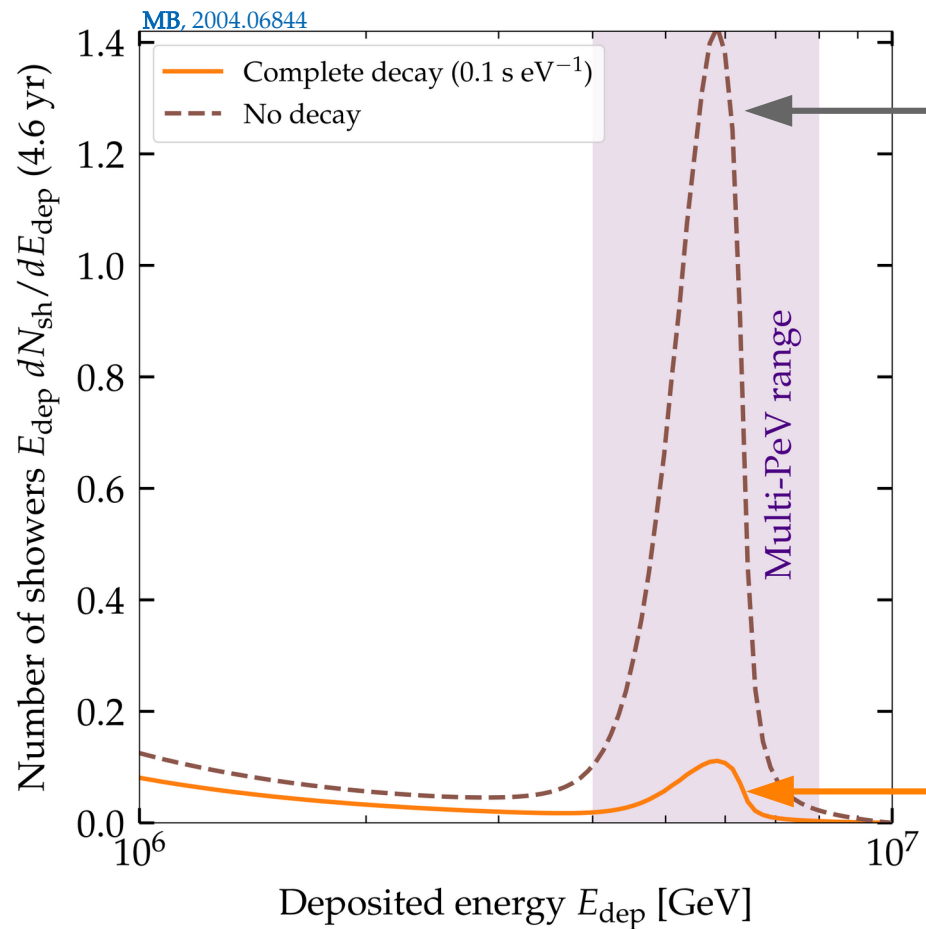
Flavor composition



Spectrum shape



Event rate



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

So by having observed 1 GR event we can
 place a *lower* limit on the lifetime of $\bar{\nu}_1$ ($= \nu_1$)

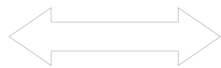


If $\bar{\nu}_1$ had decayed en route to Earth,
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What does neutrino decay change?

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

Flavor composition

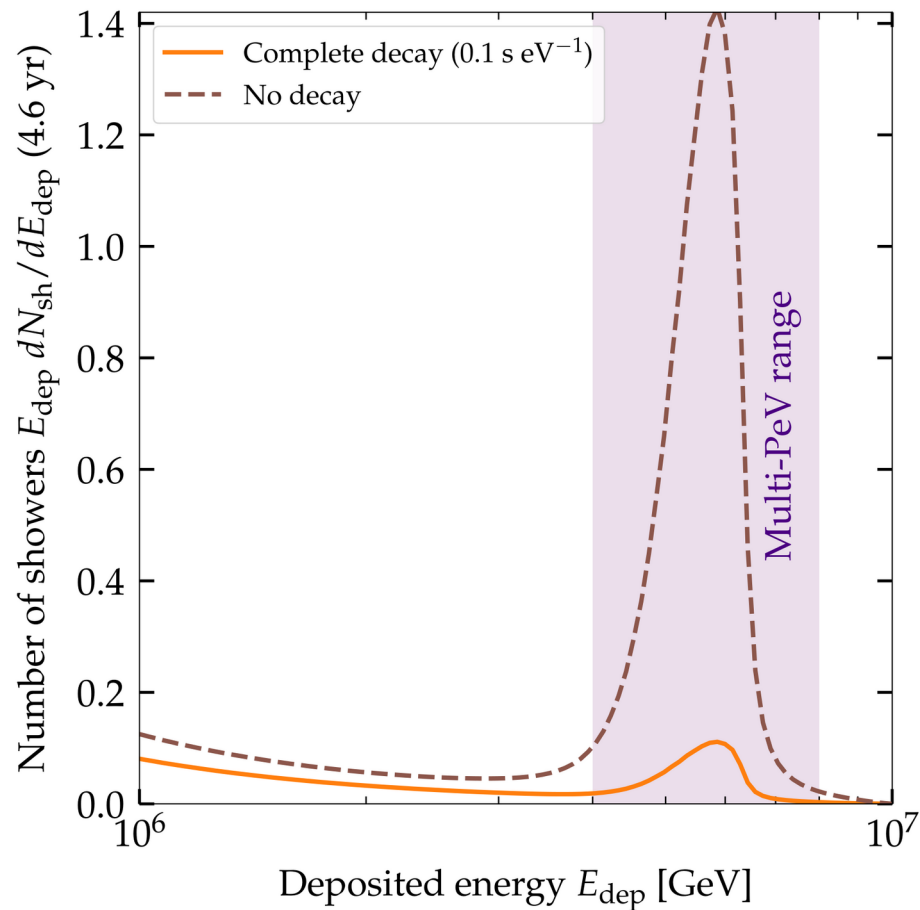


Spectrum shape



Event rate

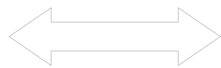
MB, 2004.06844



What does neutrino decay change?

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

Flavor composition

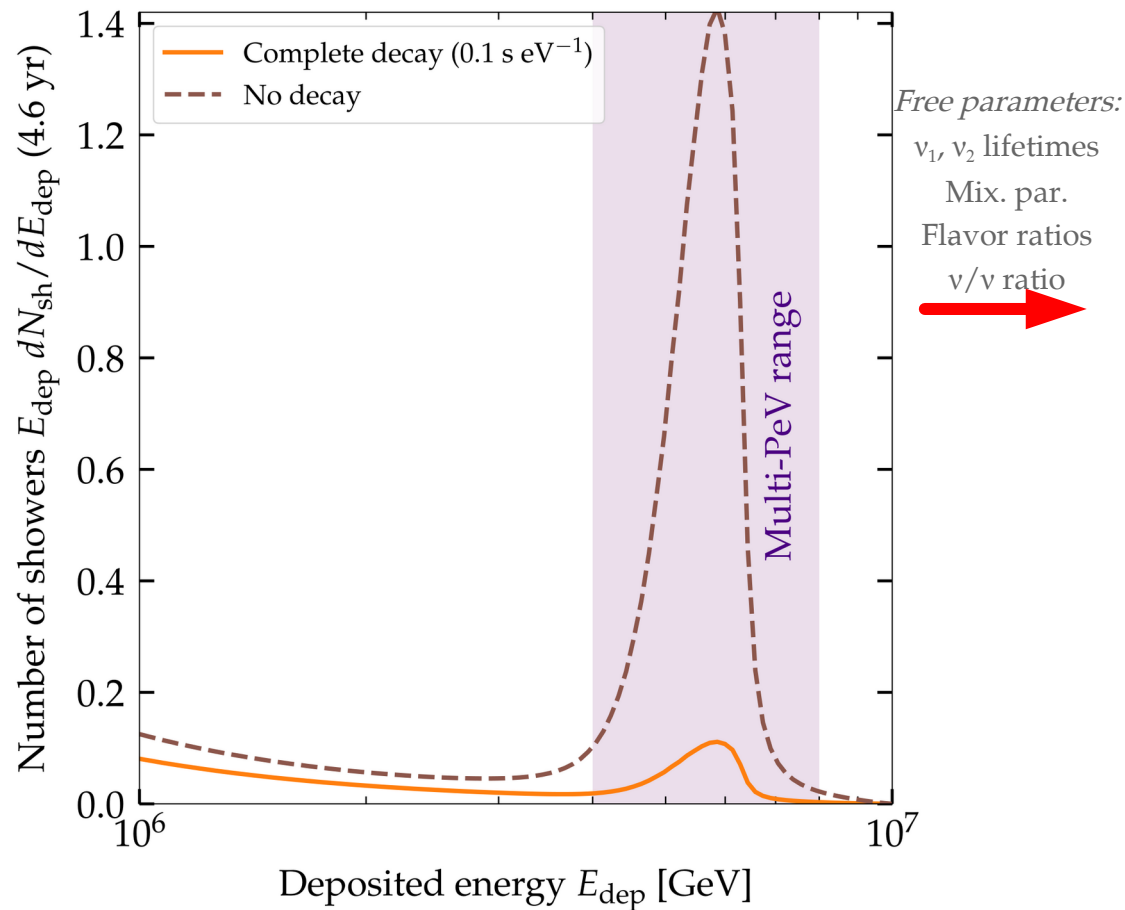


Spectrum shape



Event rate

MB, 2004.06844



What does neutrino decay change?

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

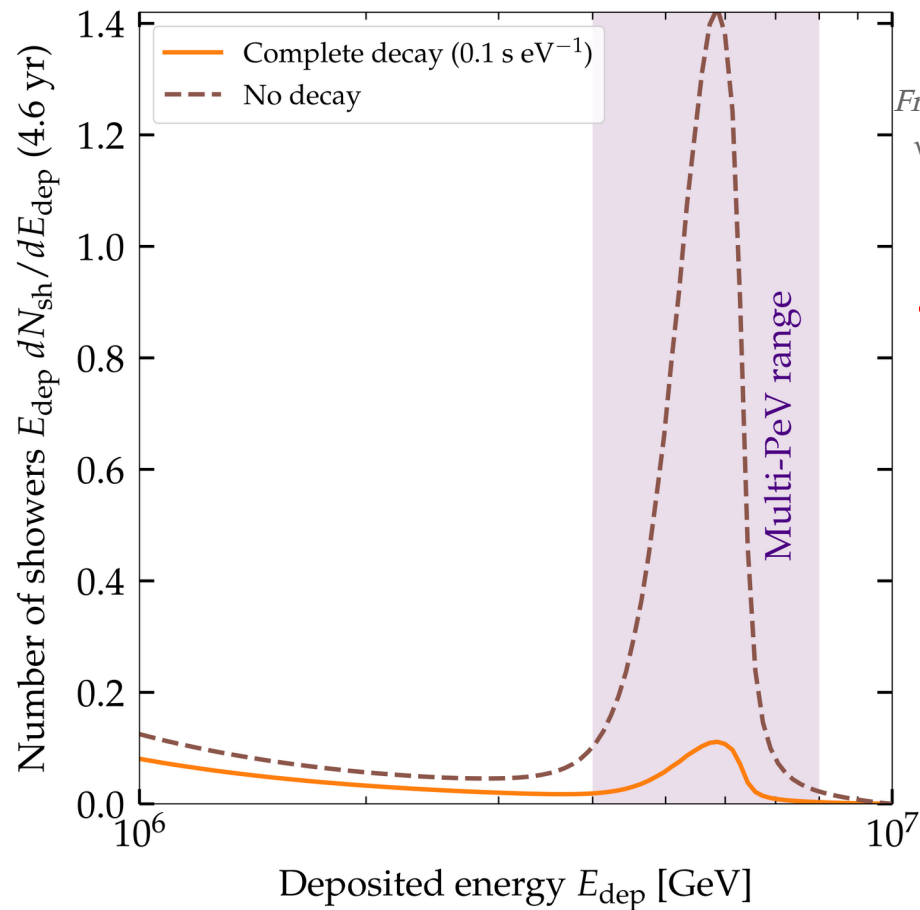
Flavor composition



Spectrum shape



Event rate



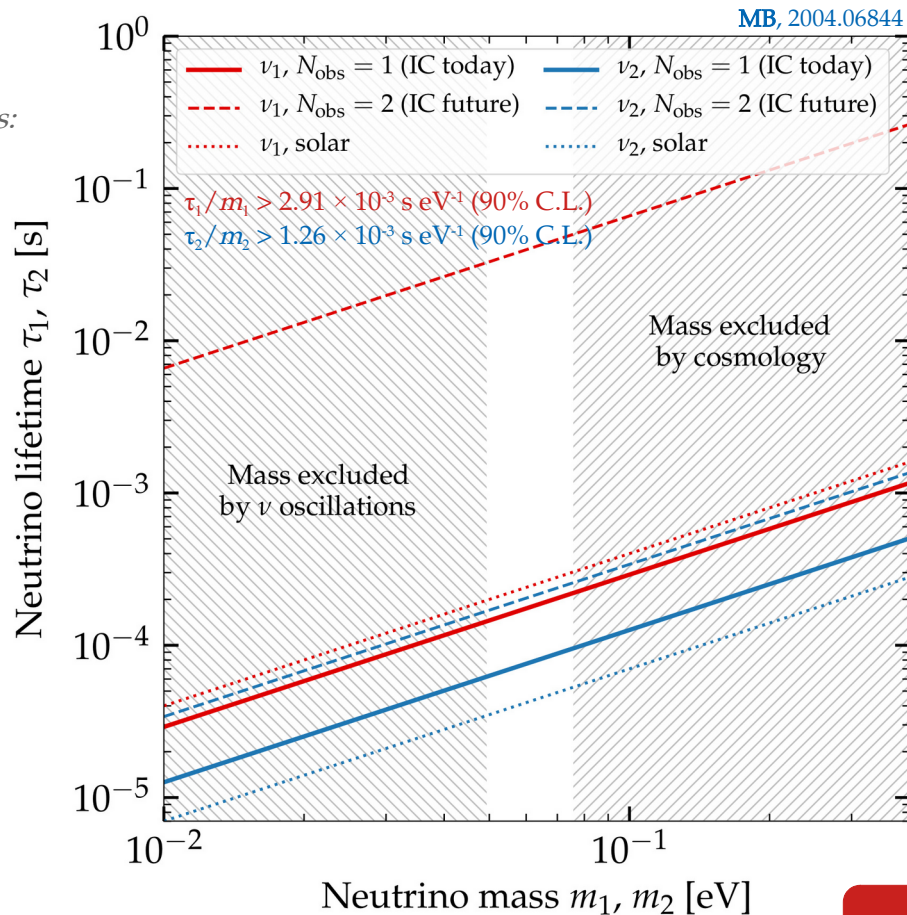
Free parameters:

ν_1, ν_2 lifetimes

Mix. par.

Flavor ratios

ν/ν ratio



What does neutrino decay change?

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

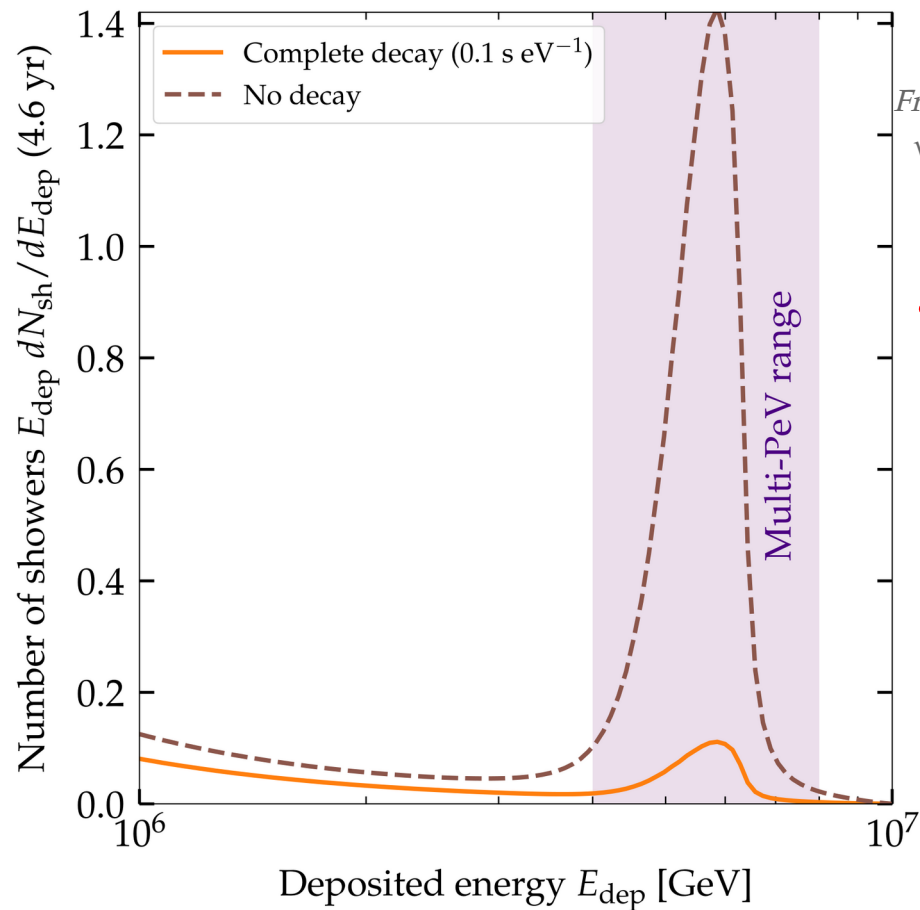
Flavor composition



Spectrum shape



Event rate



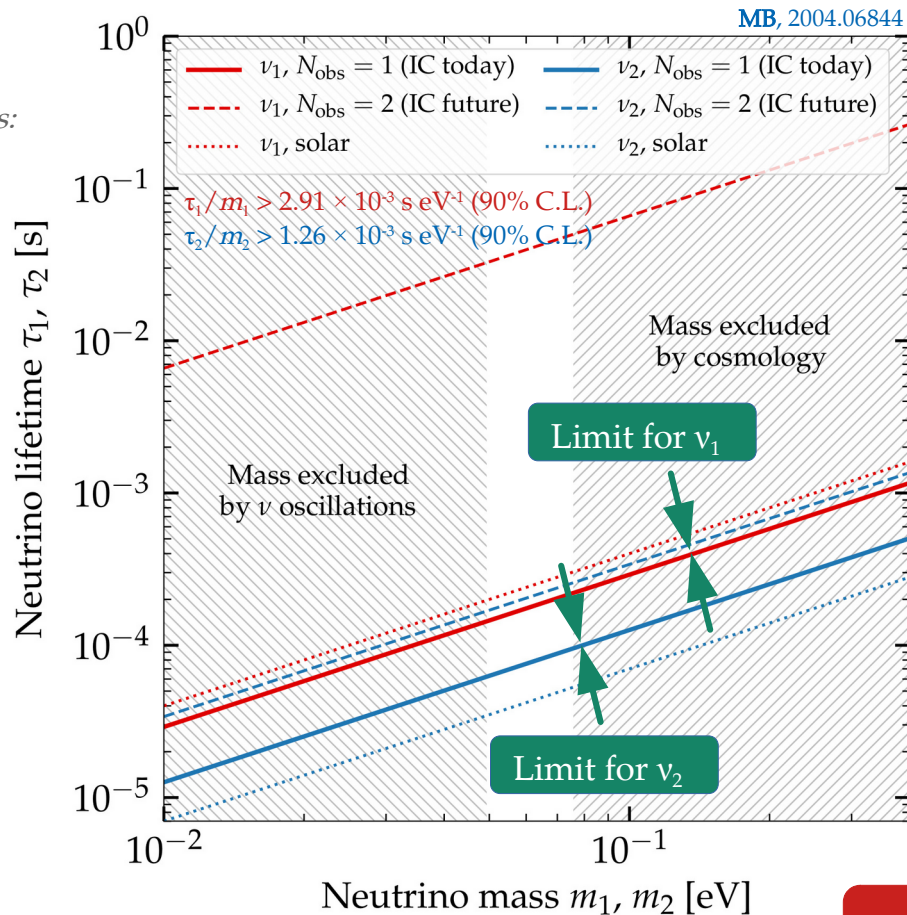
Free parameters:

ν_1, ν_2 lifetimes

Mix. par.

Flavor ratios

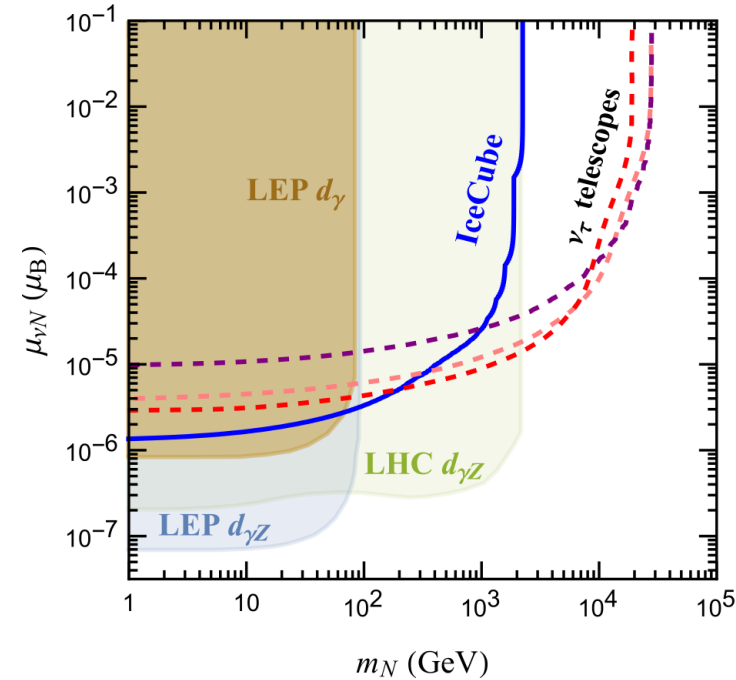
ν/ν ratio



New physics in the UHE νN cross section

New physics in the UHE νN cross section

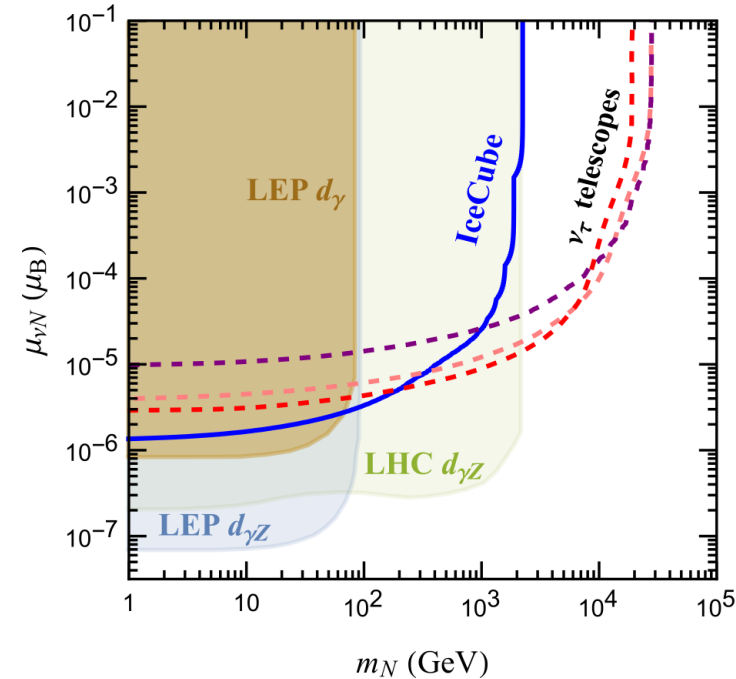
Heavy sterile neutrinos
via the dipole portal



Huang, Jana, Lindner, Rodejohann, 2204.10347

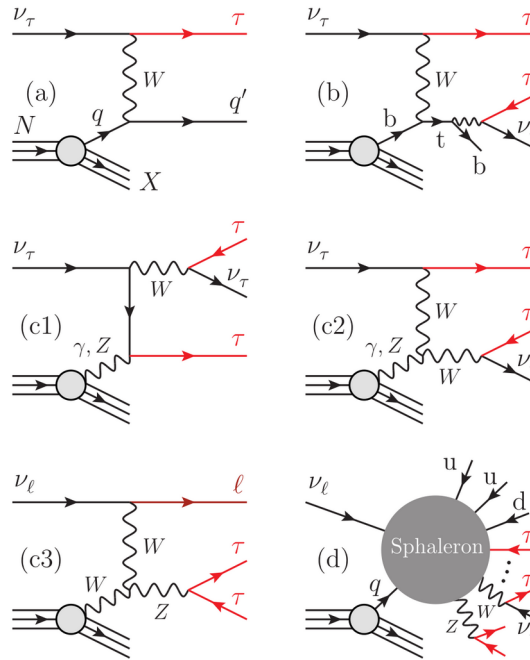
New physics in the UHE νN cross section

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Huang, Jana, Lindner, Rodejohann, 2204.10347

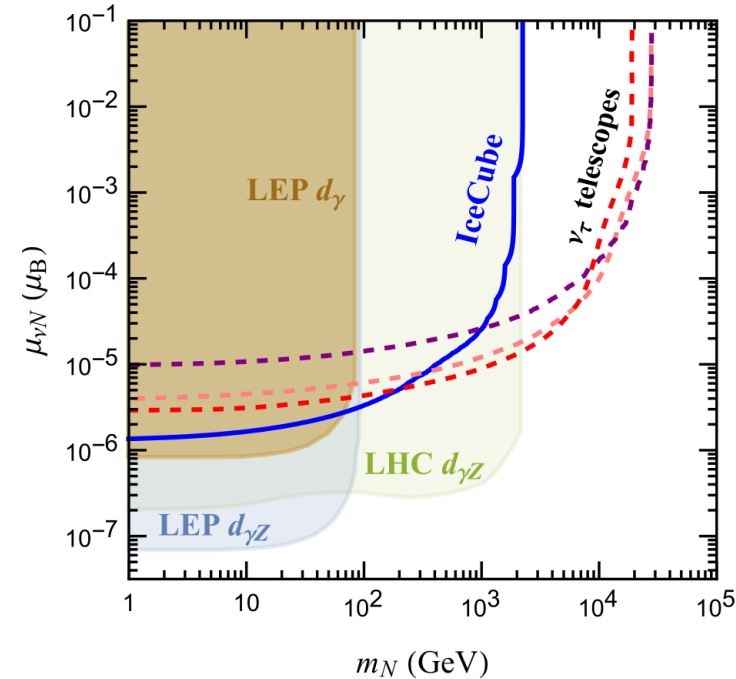
Multiple ν_τ -induced
bangs



Huang, EPJC 2022
[2207.02222]

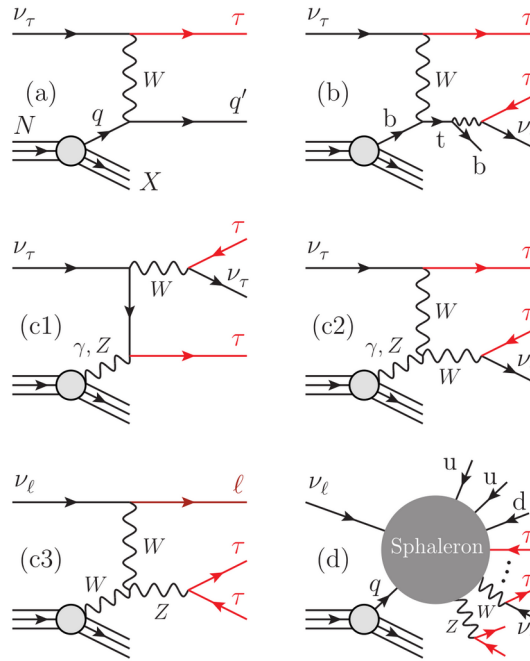
New physics in the UHE νN cross section

Heavy sterile neutrinos
via the dipole portal



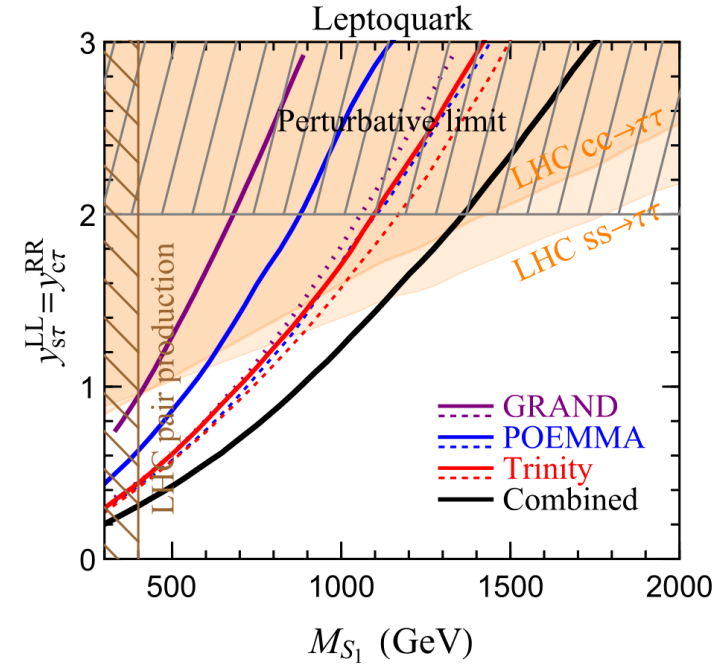
Huang, Jana, Lindner, Rodejohann, 2204.10347

Multiple ν_τ -induced
bangs



Huang, EPJC 2022
[2207.02222]

Leptoquarks,
charged Higgs, etc.



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