

Neutrino physics at the highest energies *today and in the future*

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UNIVERSITY OF
COPENHAGEN



VILLUM FONDEN



How it
started

How it's
going

10–20 years
from now



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First predictions
of high-energy
cosmic ν



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PeV ν
discovered



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Hints of sources
First tests of ν physics

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

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How do we get there?

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

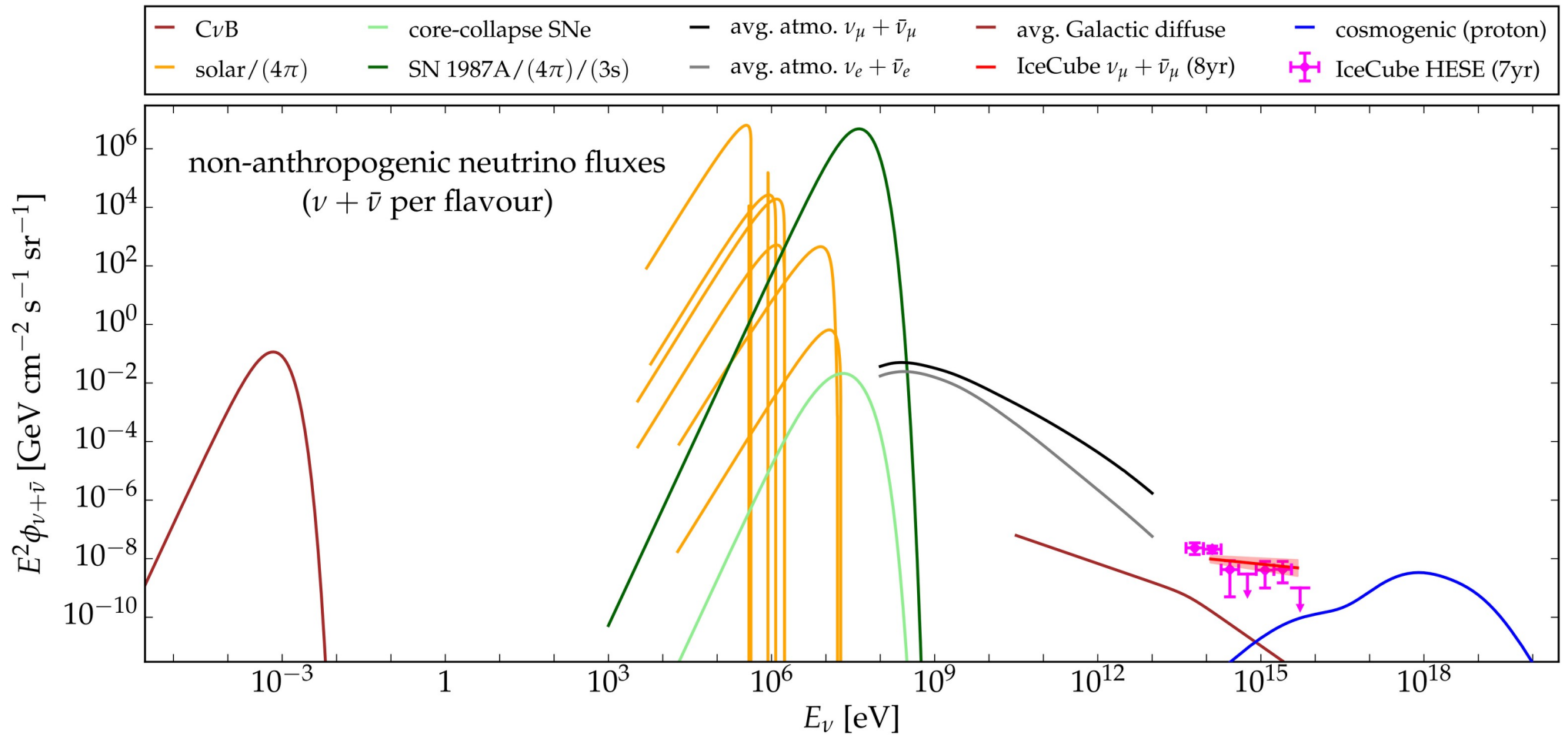


Figure courtesy of Markus Ahlers
 Maoloud, De Wasseige, Ahlers, MB, Van Elewyck, PoS(ICRC2019), 1023

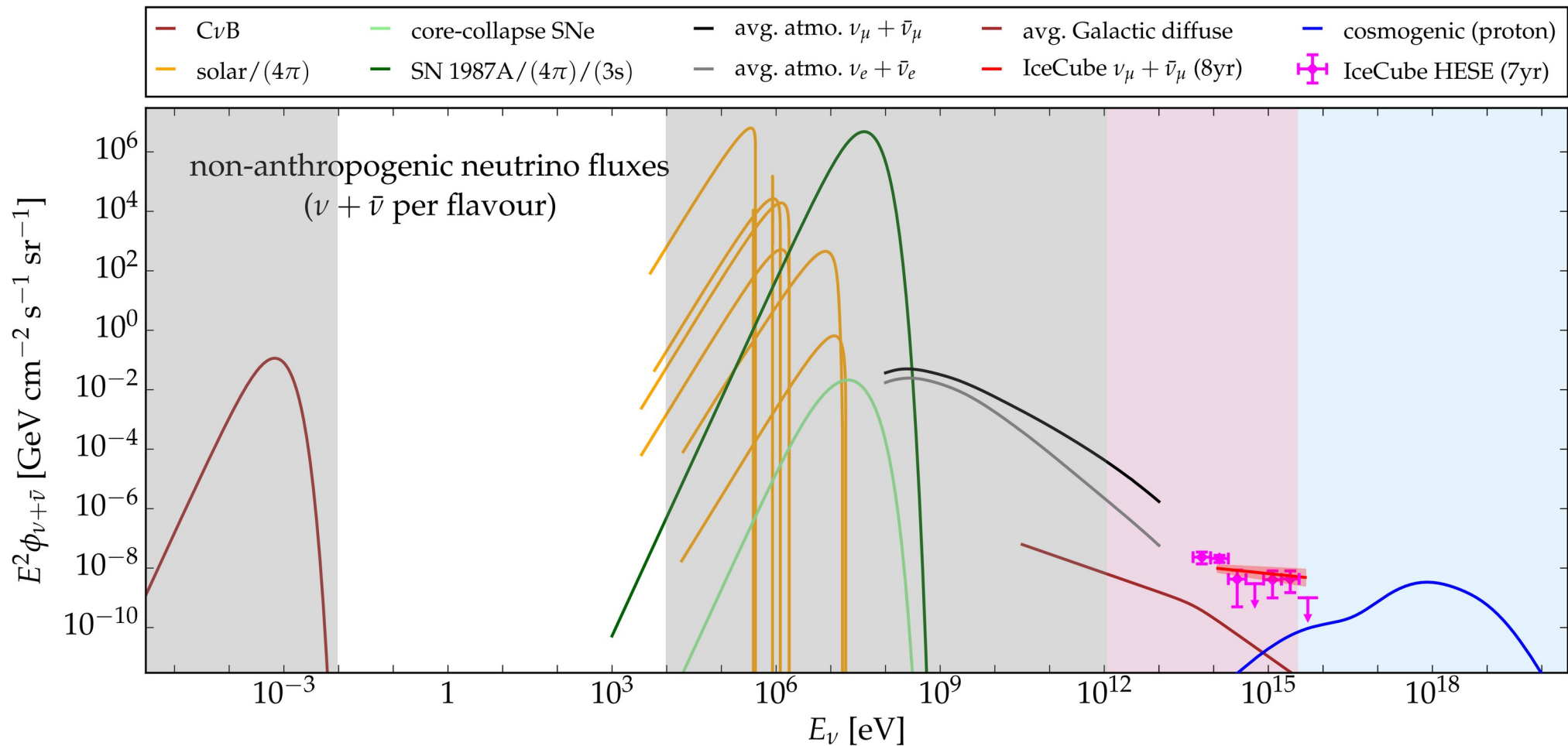


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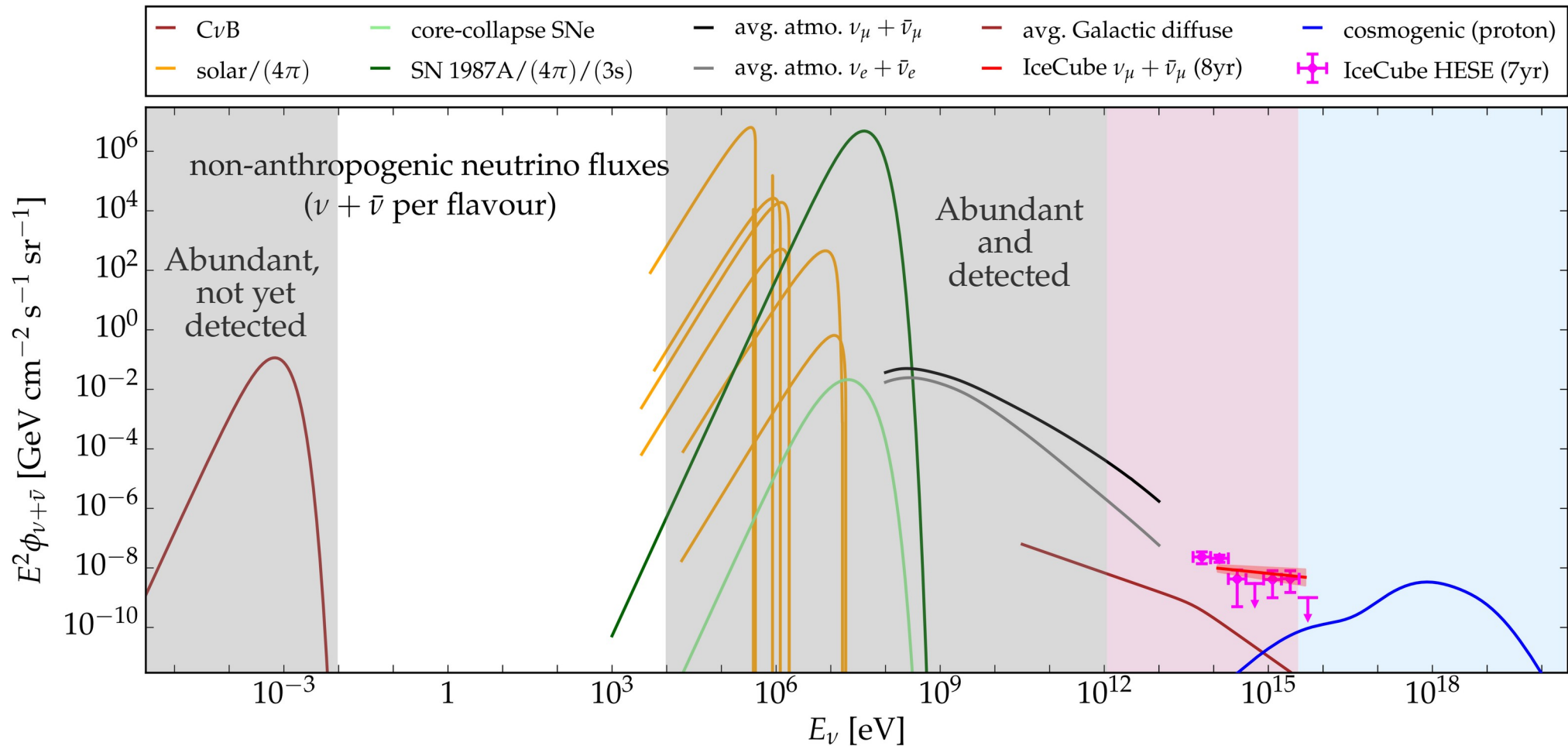


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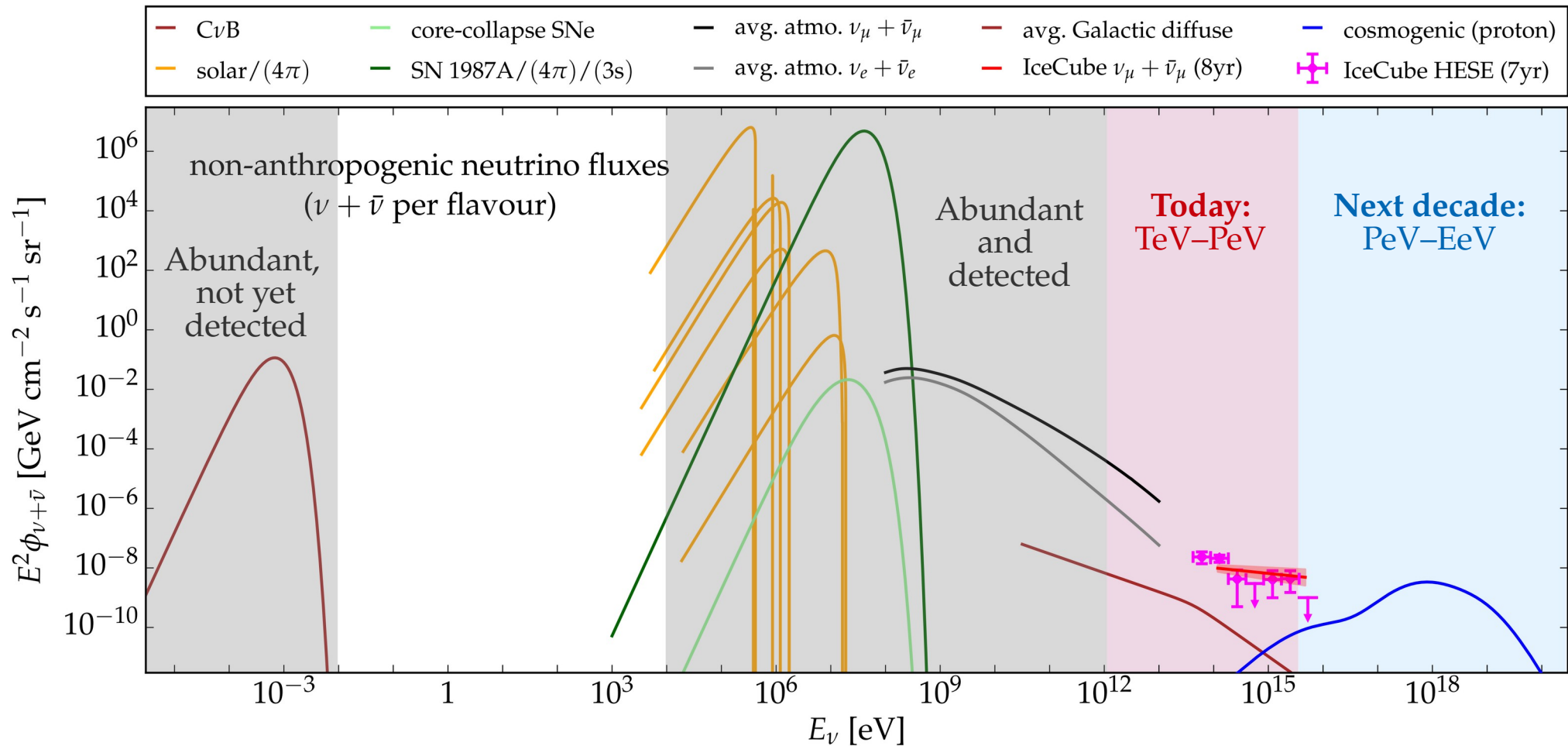


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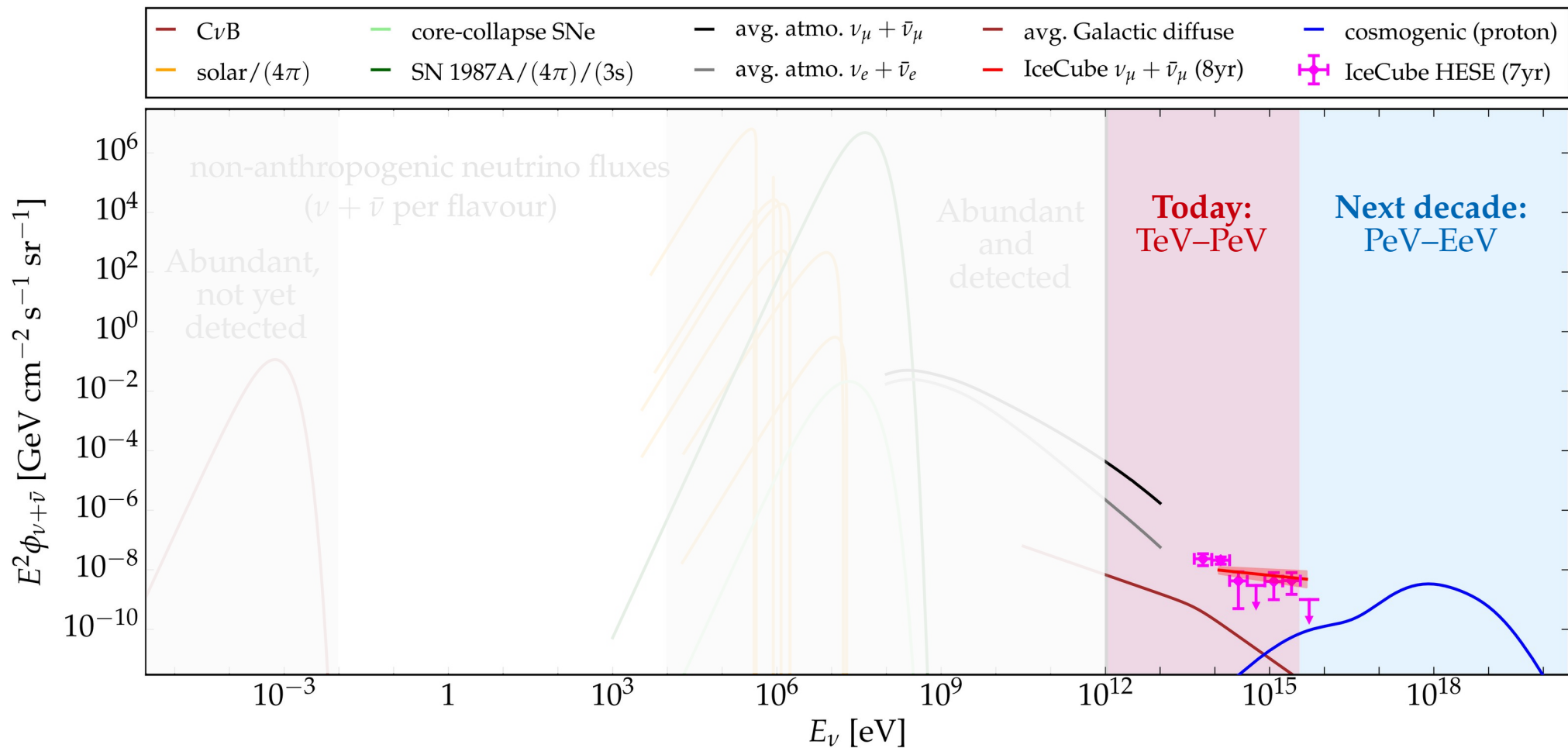
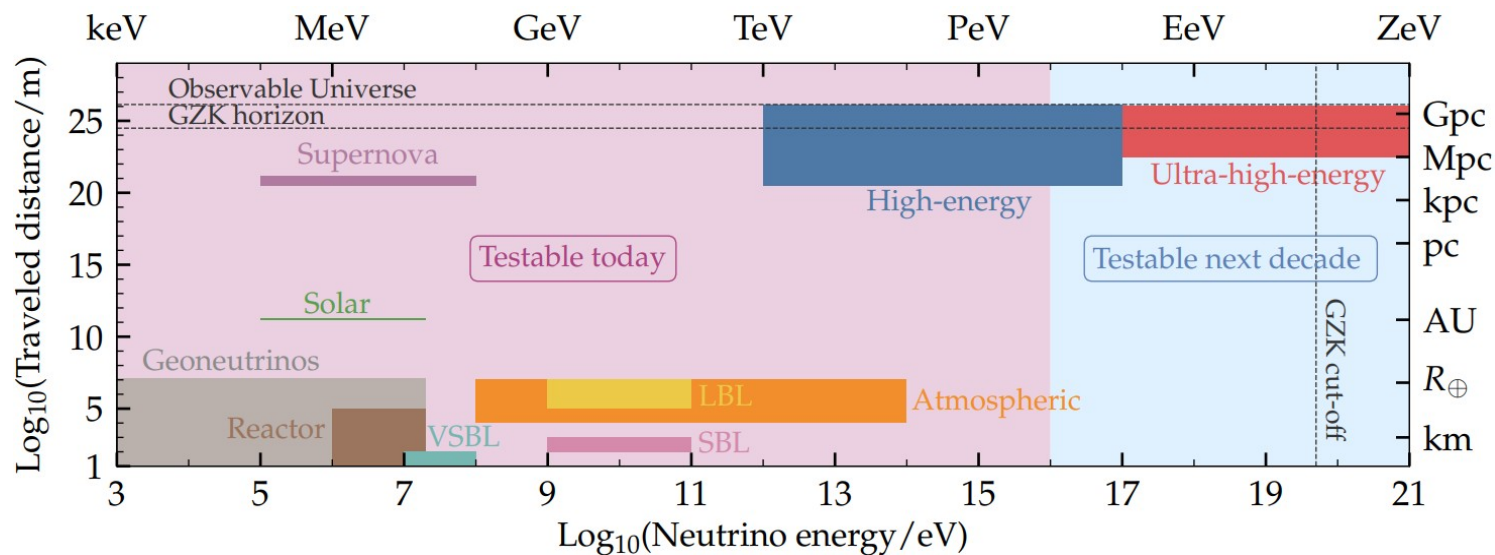


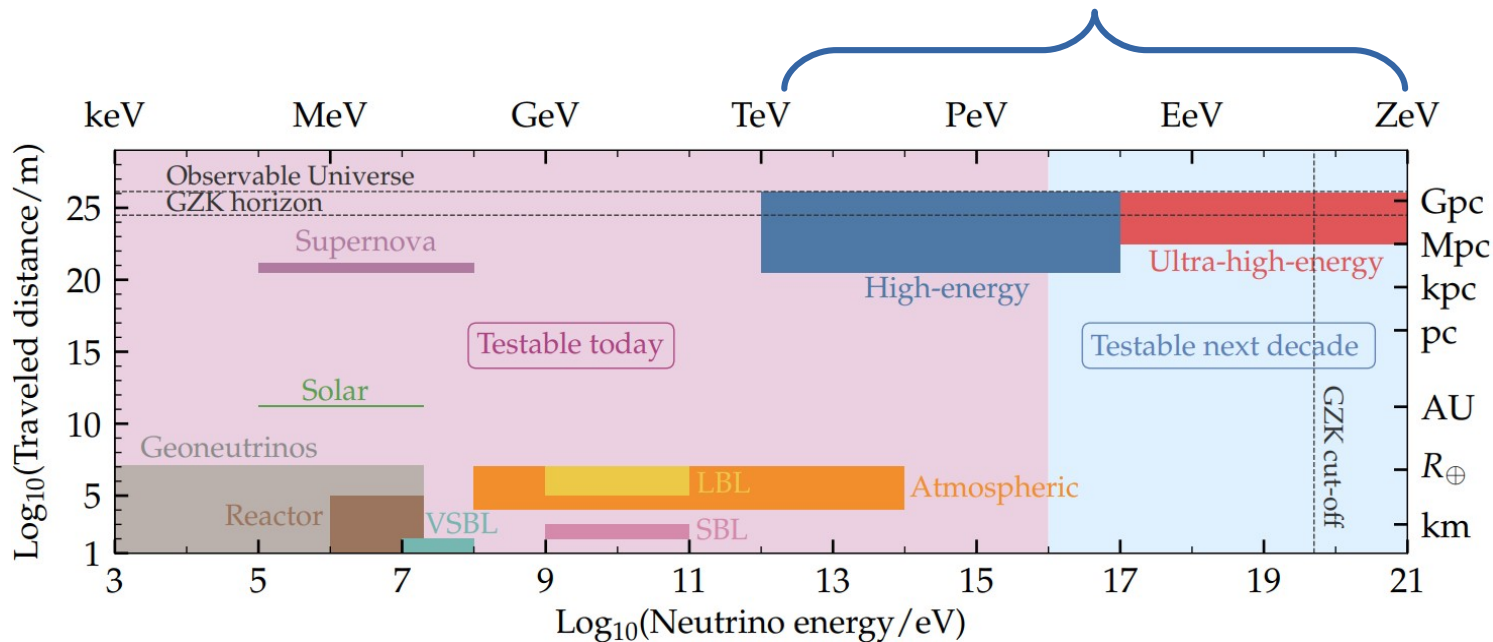
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What makes high-energy cosmic ν exciting?



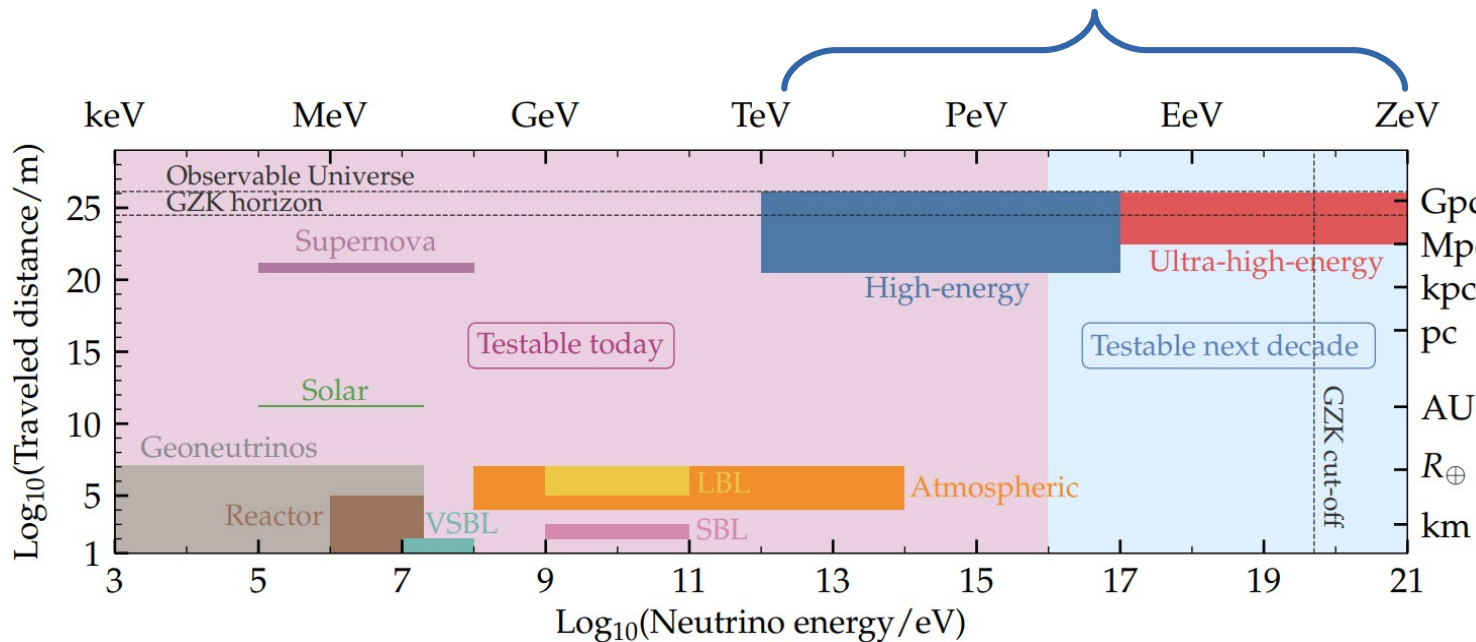
What makes high-energy cosmic ν exciting?

They have the **highest energies**



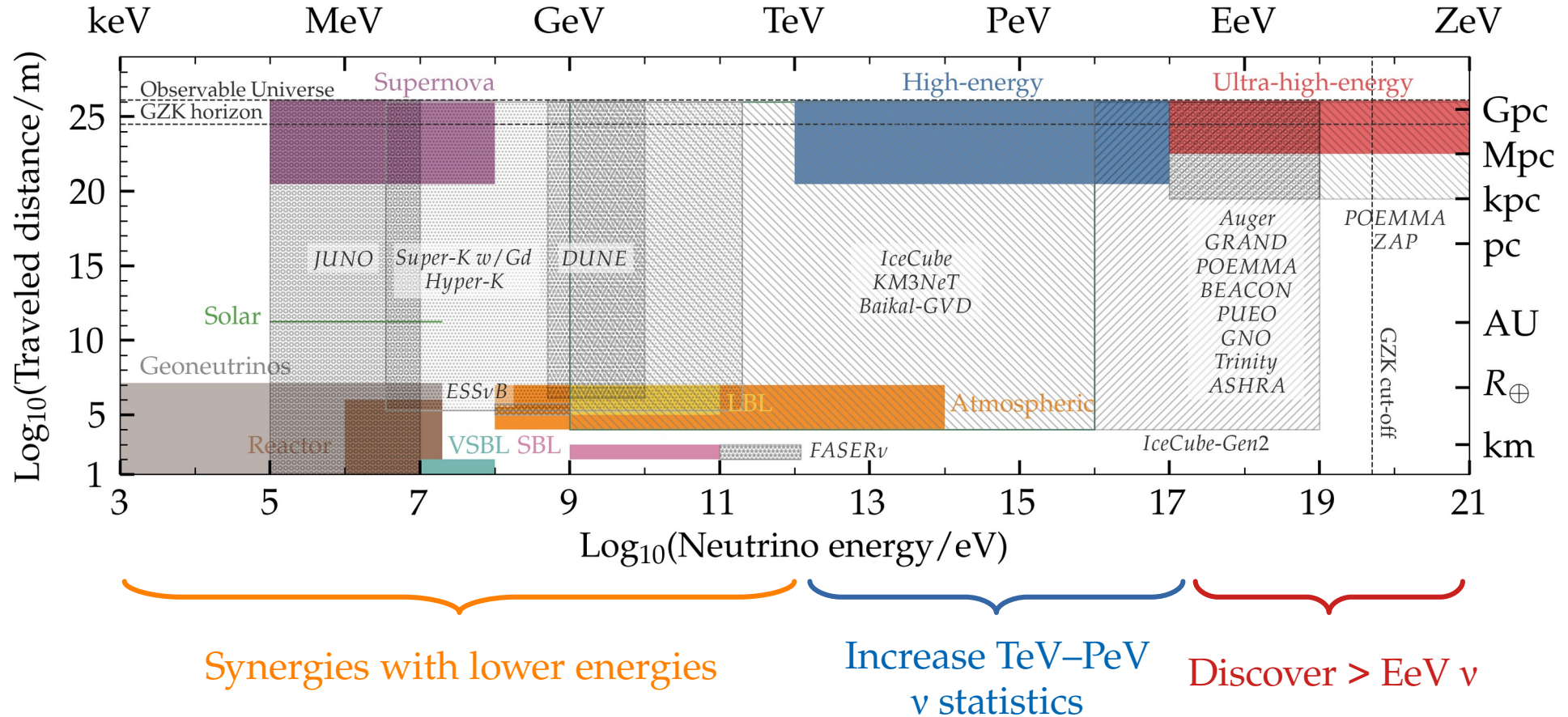
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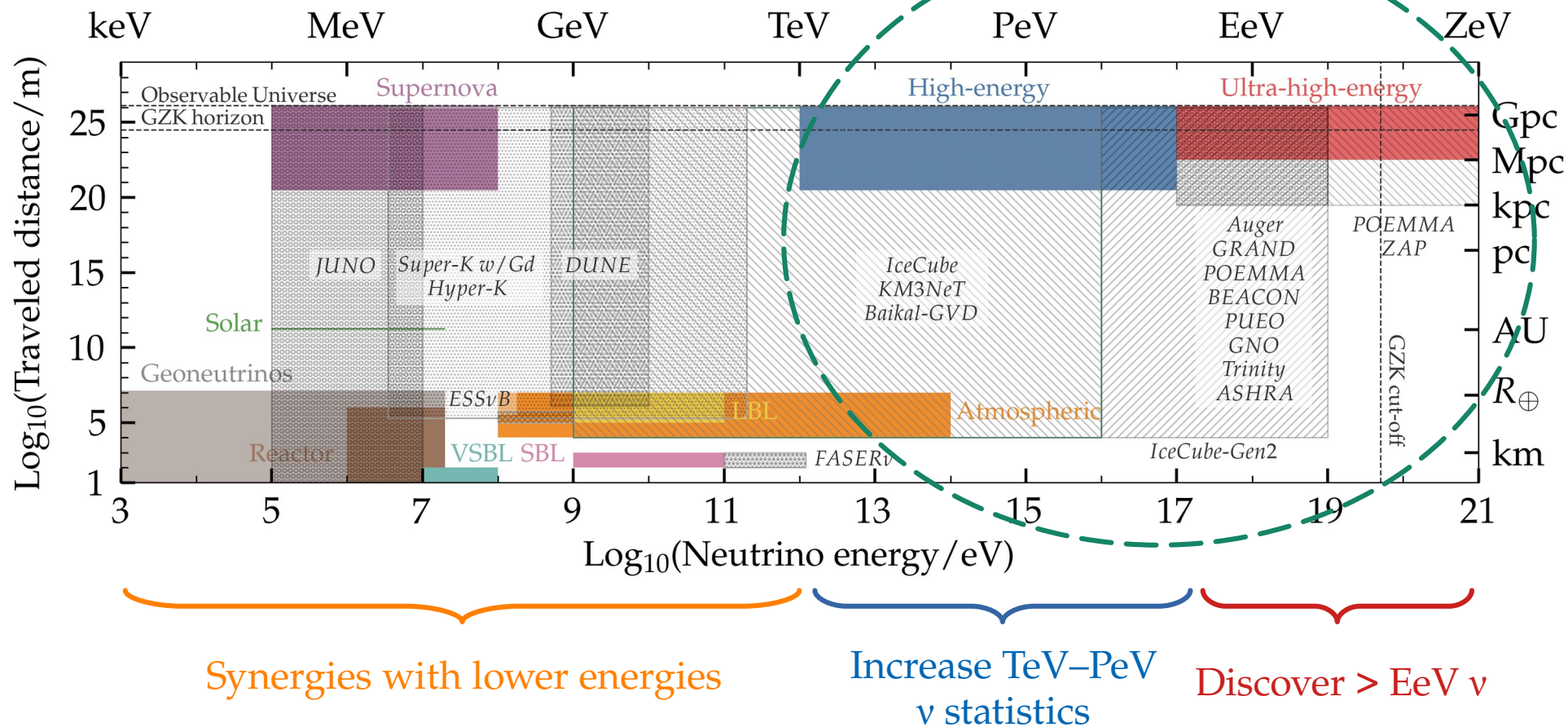


They travel the **longest distances**

Next decade: a host of planned neutrino detectors



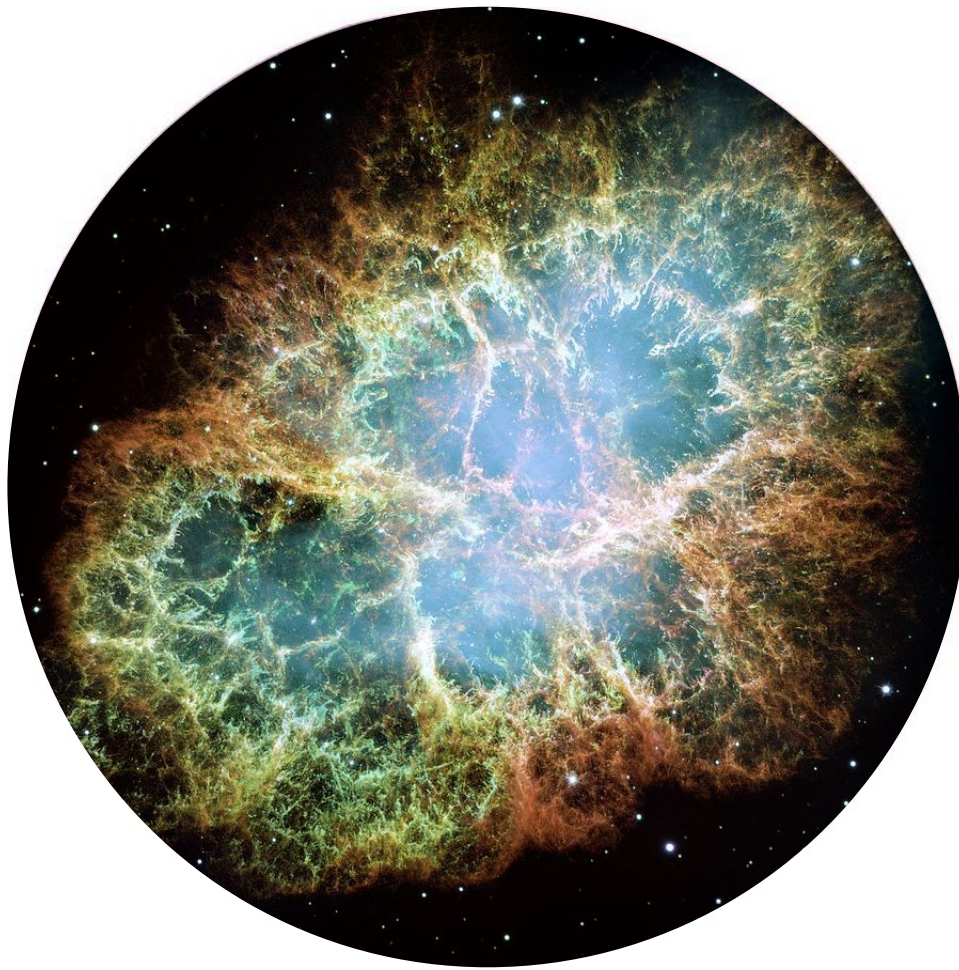
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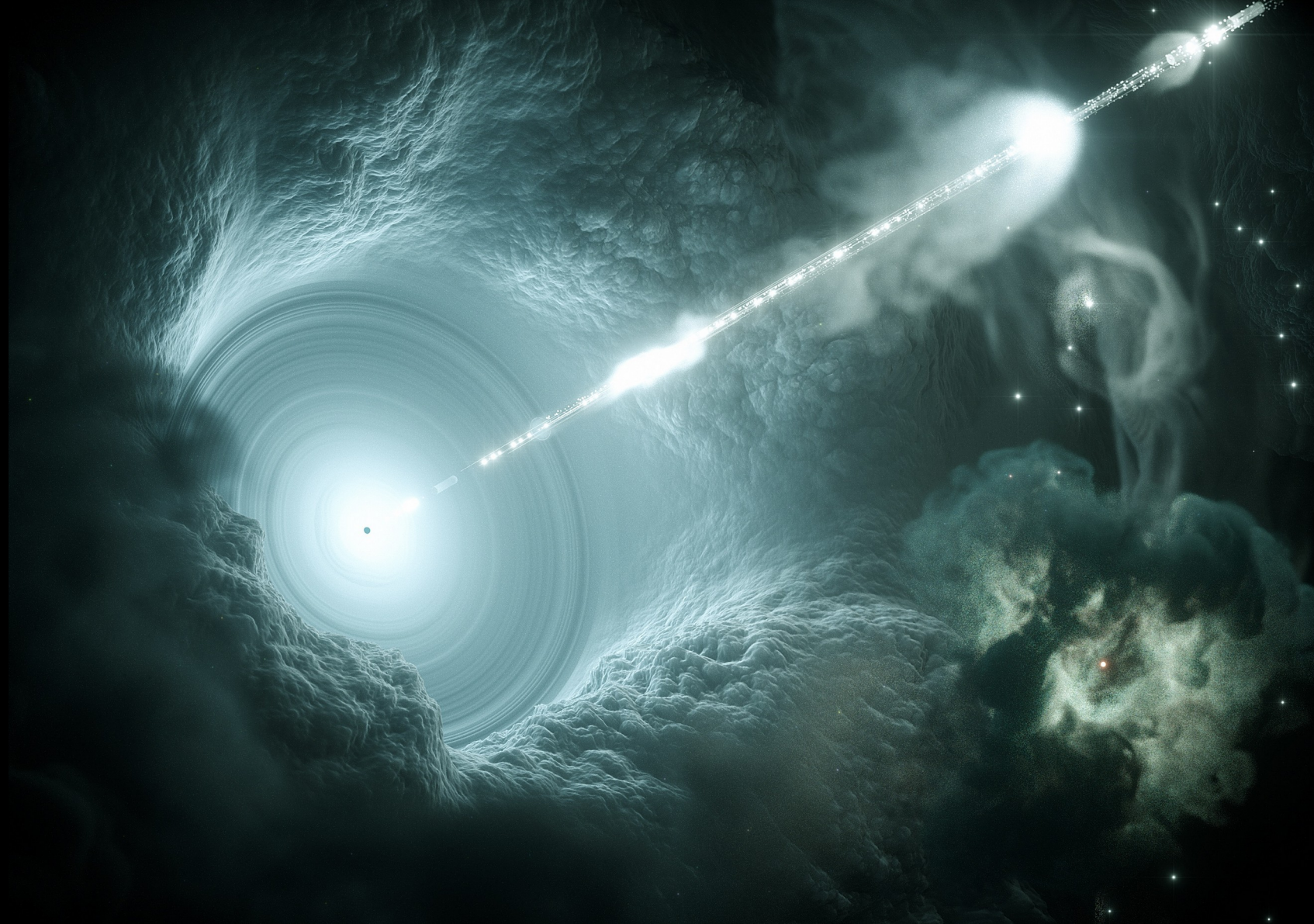


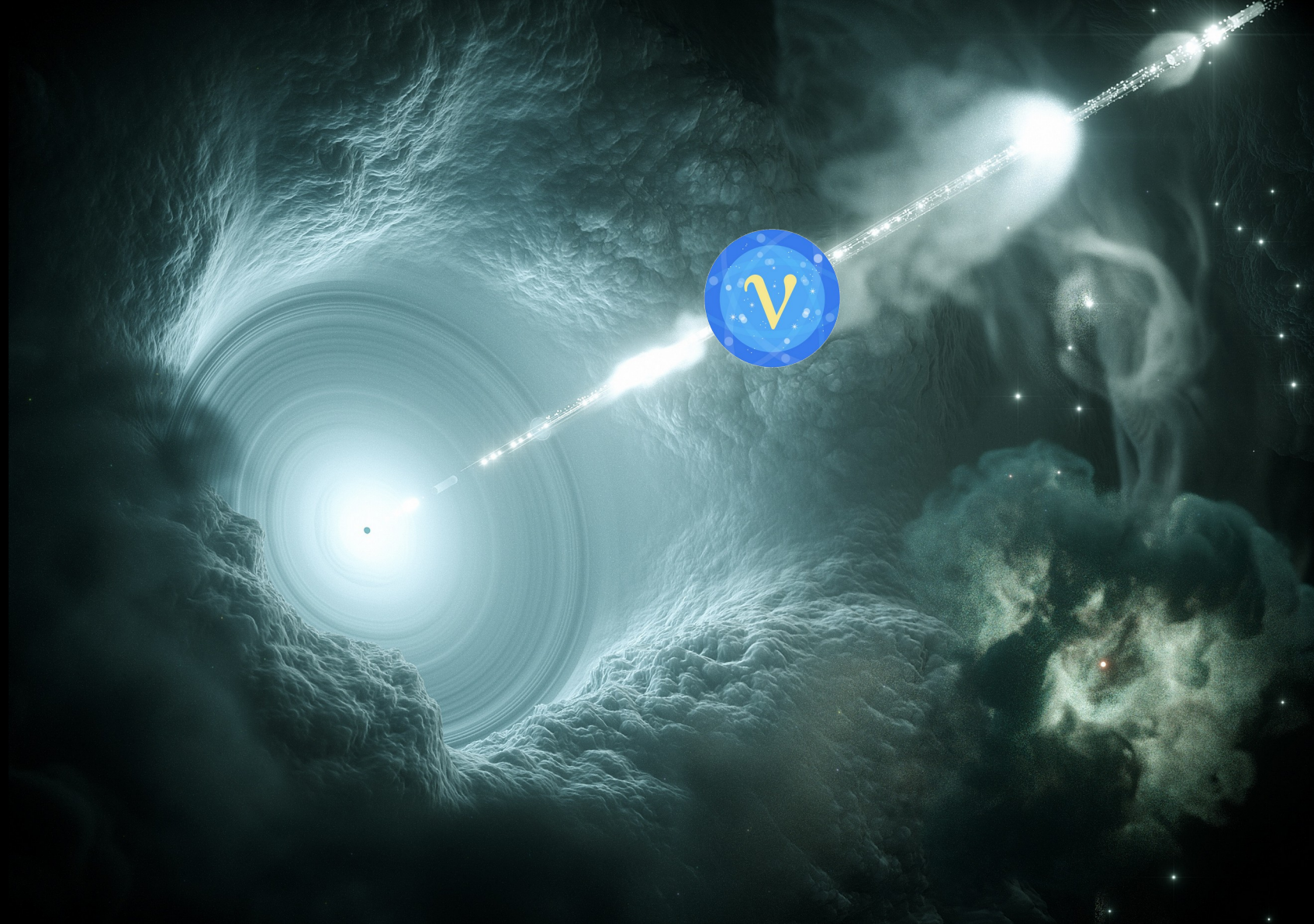
High-energy neutrinos: TeV–PeV
(*Discovered*)

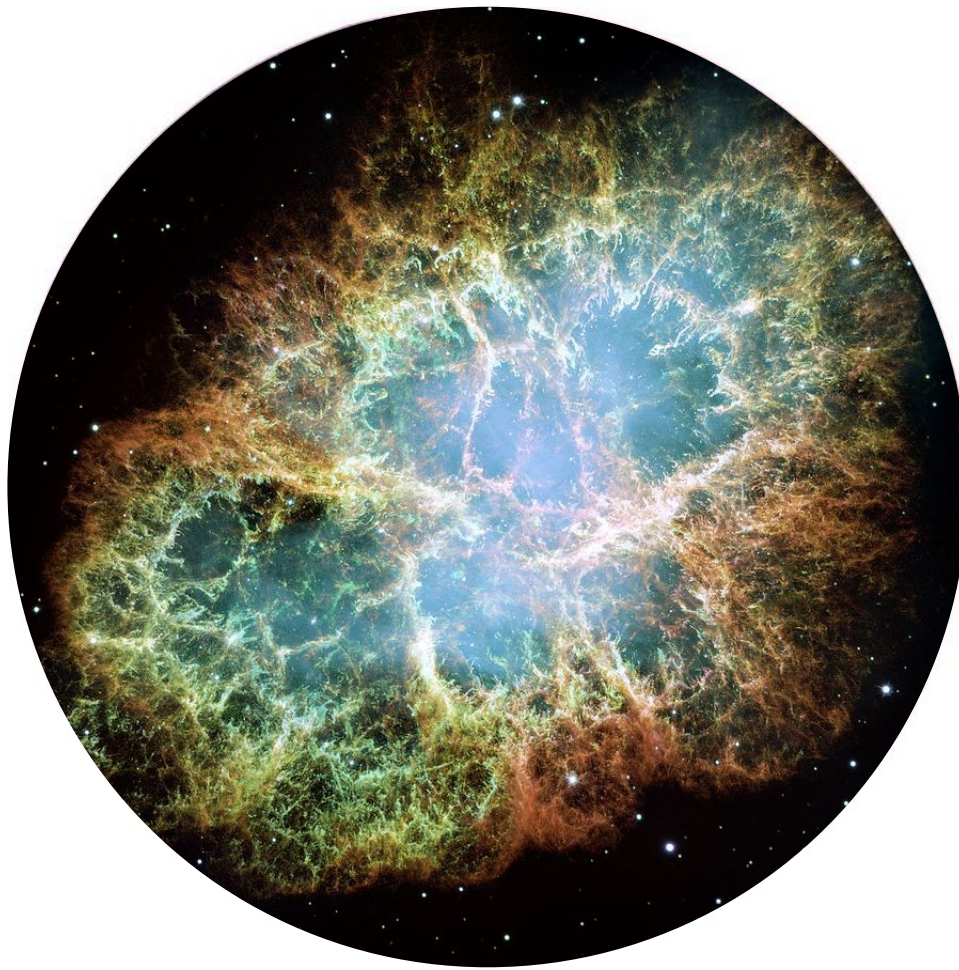
Ultra-high-energy neutrinos: > 100 PeV
(*Predicted but undiscovered*)

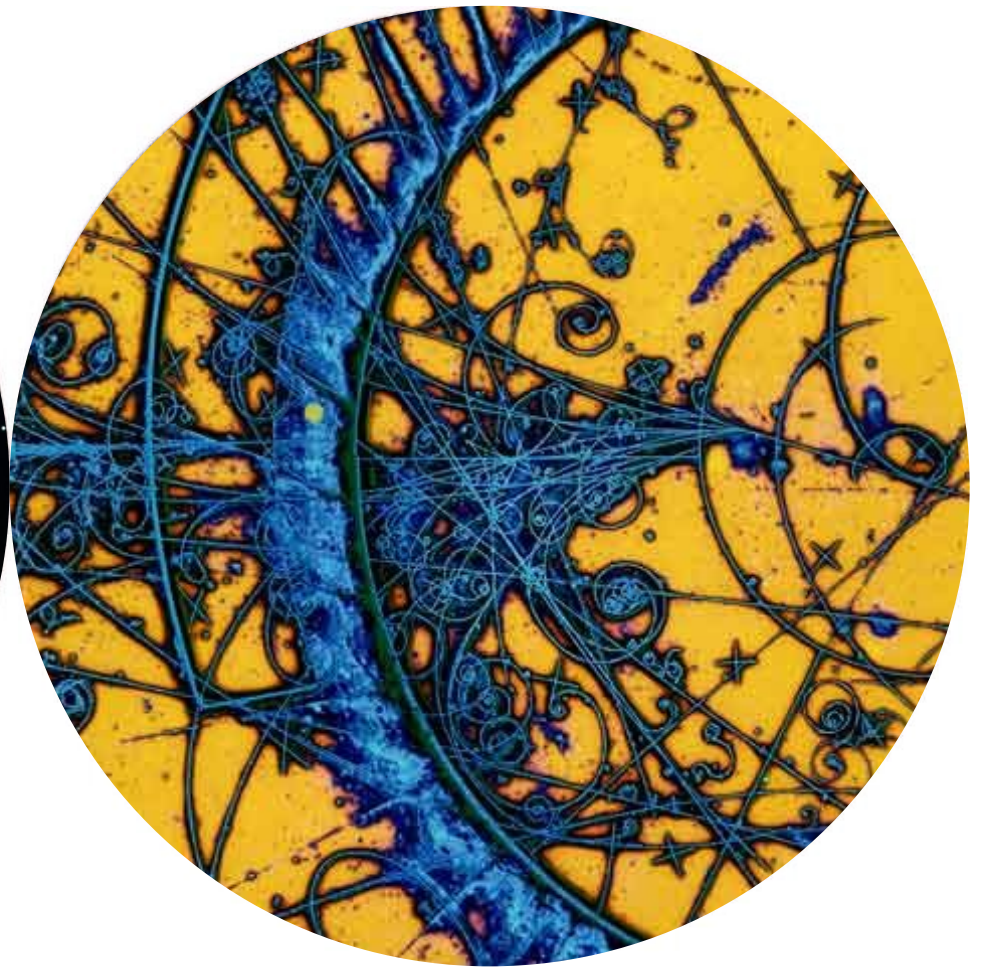
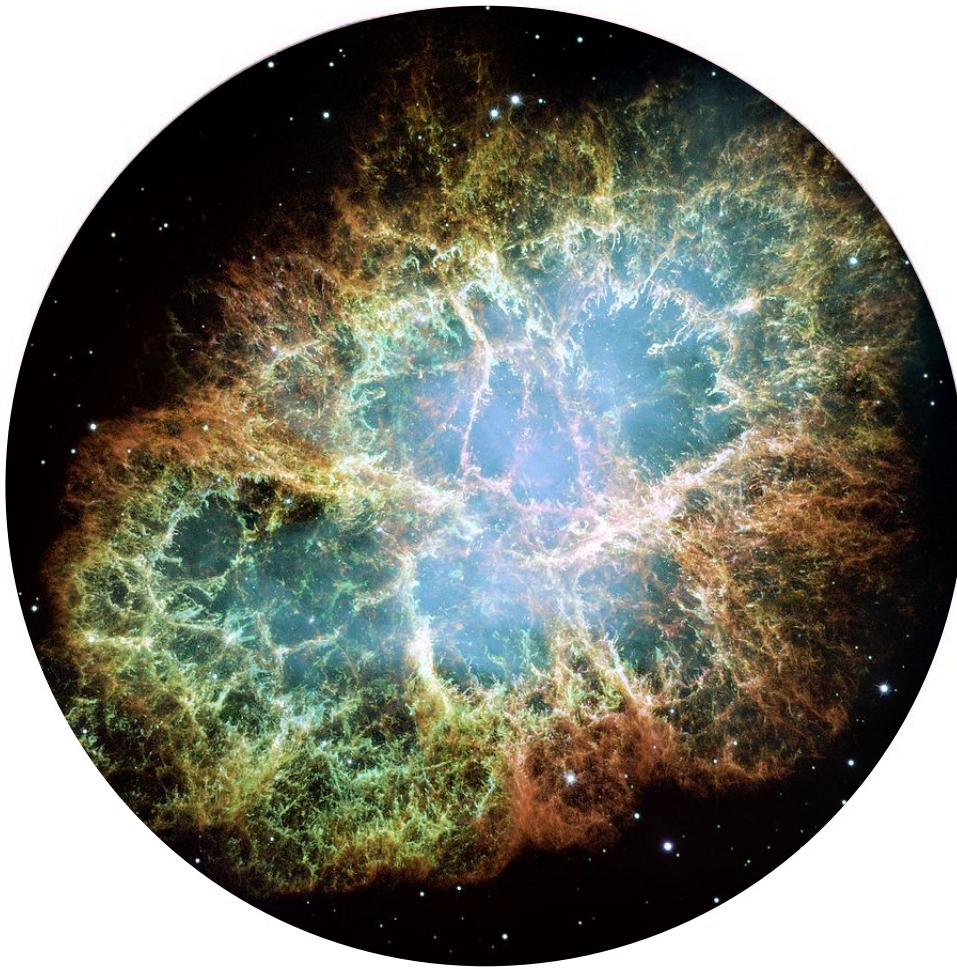




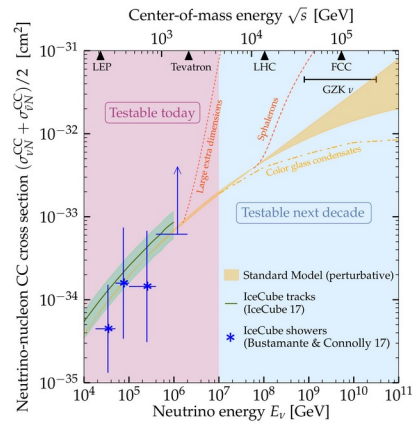






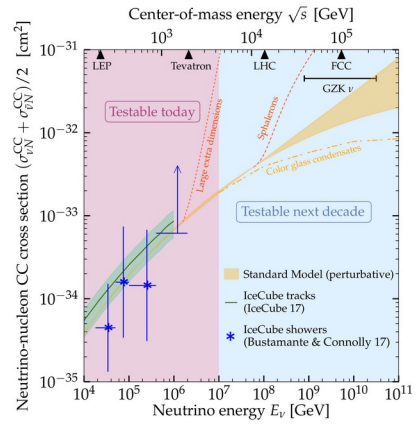


TeV–EeV ν cross sections



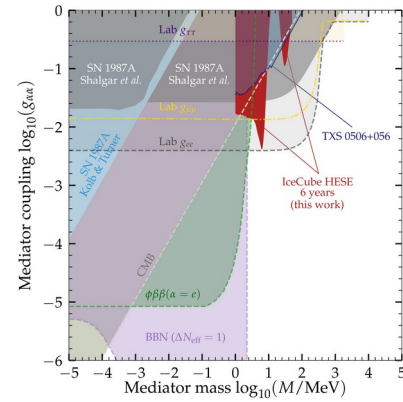
MB & Connolly, *PRL* 2019

TeV–EeV ν cross sections



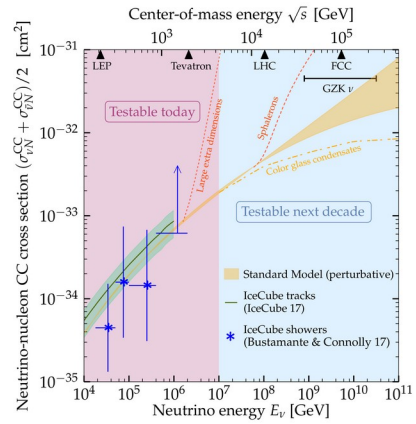
MB & Connolly, *PRL* 2019

ν self-interactions



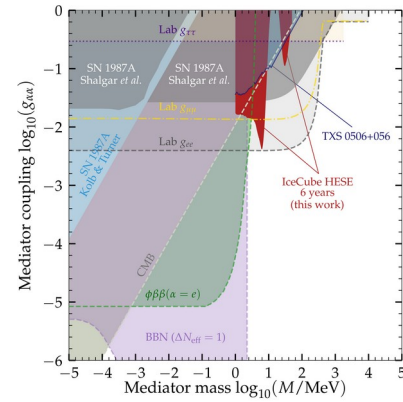
MB, Rosenström, Shalgar, Tamborra, *PRD* 2020

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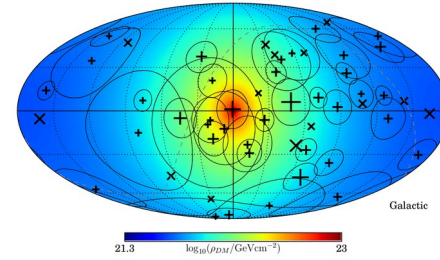
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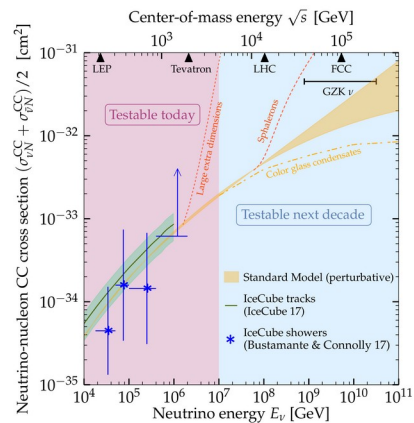
MB, Rosenström, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



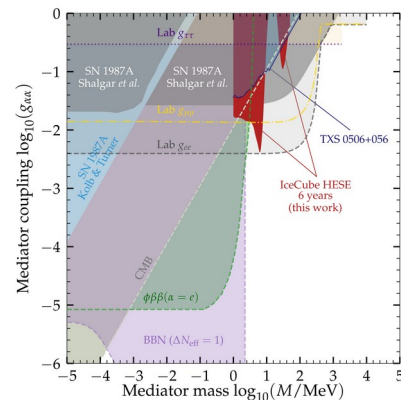
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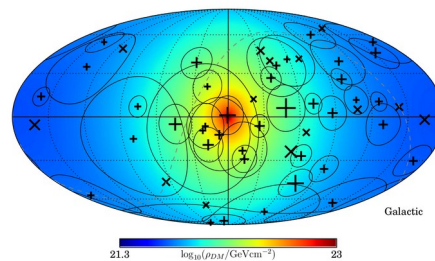
MB & Connolly, PRL 2019

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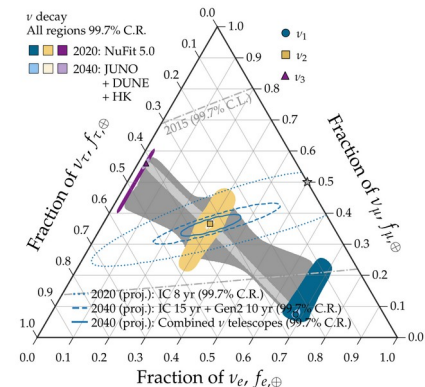
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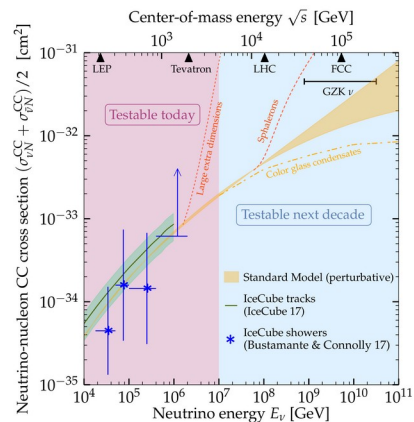
Argüelles, Kheirandish, Vincent, PRL 2017

ν decay



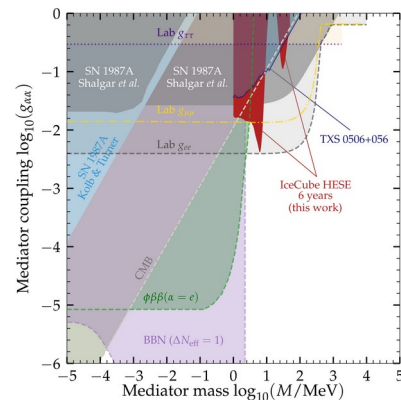
Song, Li, Argüelles, MB, Vincent, JCAP 2021

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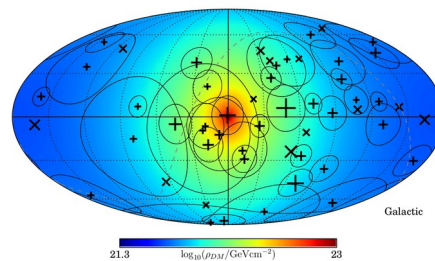
MB & Connolly, PRL 2019

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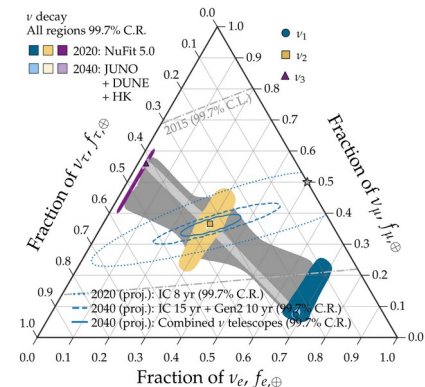
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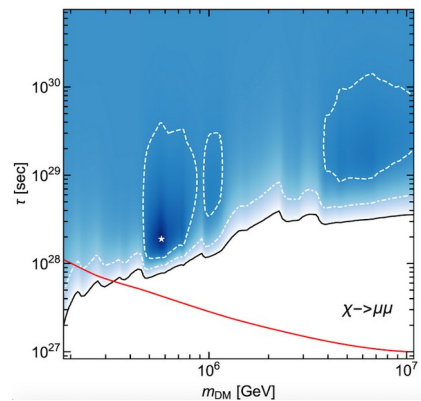
Argüelles, Kheirandish, Vincent, PRL 2017

ν decay



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

Dark matter decay



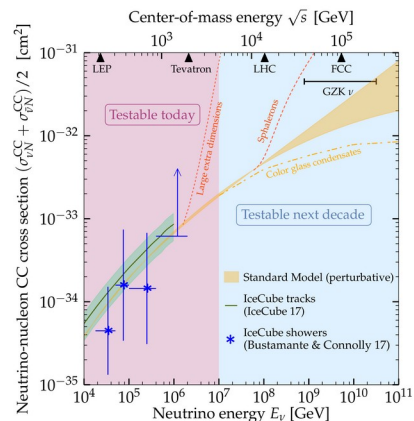
Chianese, Fiorillo, Miele, Morisi, Pisanti, JCAP 2019

Figure 1 is a log-log plot showing the neutrino-nucleon CC cross section $(\sigma_{\nu N}^{CC} + \sigma_{\bar{\nu} N}^{CC})/2$ [cm²] versus Neutrino energy E_ν [GeV]. The plot is divided into regions for different physical processes: Standard Model (perturbative) in yellow, IceCube tracks (IceCube 17) in green, and IceCube showers (Bustamante & Connolly 17) in blue. The plot also shows the center-of-mass energy $\sqrt{s}$ [GeV] on the top x-axis, ranging from 10^3 to 10^5 GeV. Key features include the 'Testable today' region (pink) and the 'Testable next decade' region (blue). The plot includes data points from LEP, Tevatron, LHC, FCC, and GZK, as well as theoretical predictions for sphalerons and color glass condensates.

Figure 1 is a ternary plot showing the fraction of neutrino flavors ν_e , ν_μ , and ν_τ . The plot is bounded by three axes: the left axis is 'Fraction of $\nu_\tau, f_{\tau,\odot}$ ' (0.0 to 1.0), the right axis is 'Fraction of $\nu_\mu, f_{\mu,\odot}$ ' (0.0 to 1.0), and the bottom axis is 'Fraction of $\nu_e, f_{e,\odot}$ ' (0.0 to 1.0). The plot shows the 2015 99.7% C.L. region for ν_1 (blue circle), ν_2 (orange square), and ν_3 (purple triangle). It also shows the 2020 (proj.) IC 15 yr (99.7% C.R.) region (blue dashed line), the 2040 (proj.) IC 15 yr Gen2 10 yr (99.7% C.R.) region (orange dashed line), and the 2040 (proj.) Combined ν telescopes (99.7% C.R.) region (blue solid line). The plot is labeled 'ν decay' and 'All regions 99.7% C.R.'

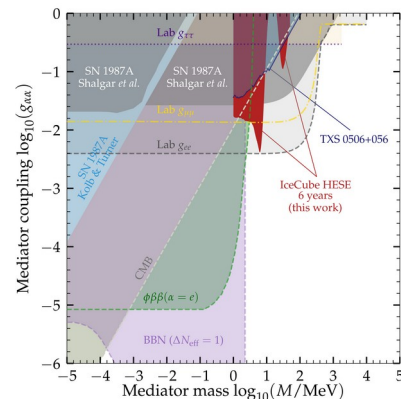
MB & Agarwalla, PRL 2019

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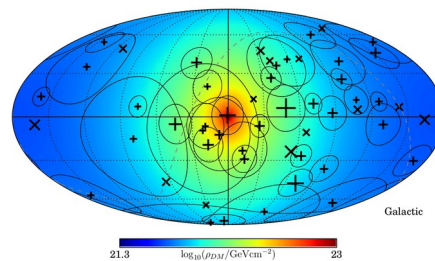
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ν self-interactions



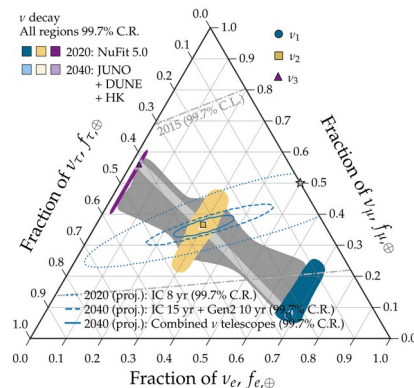
MB, Rosenström, Shalgar, Tamborra, PRD 2020

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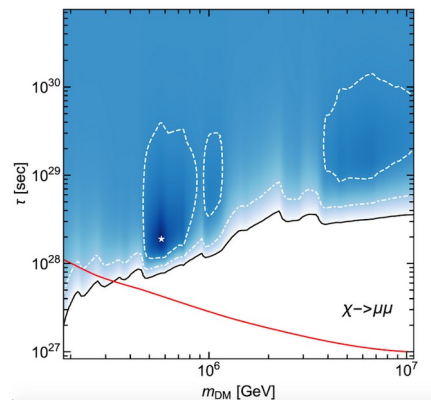
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ν decay



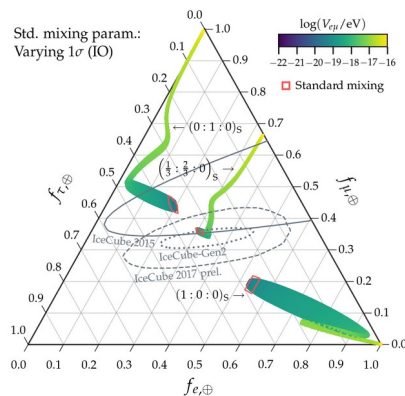
Song, Li, Argüelles, MB, Vincent, JCAP 2021

Dark matter decay



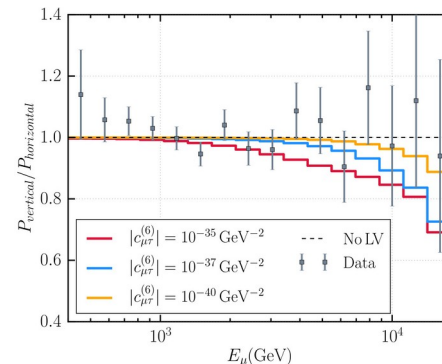
Chianese, Fiorillo, Miele, Morisi, Pisanti, JCAP 2019

ν -electron interaction



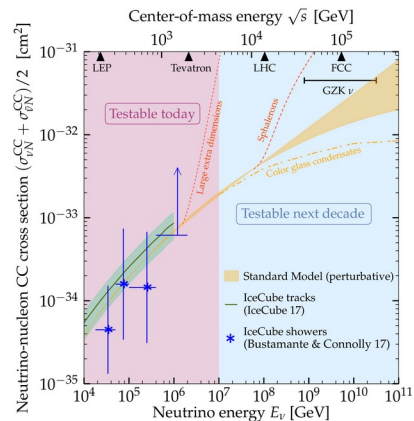
MB & Agarwalla, PRL 2019

Lorentz-invariance violation



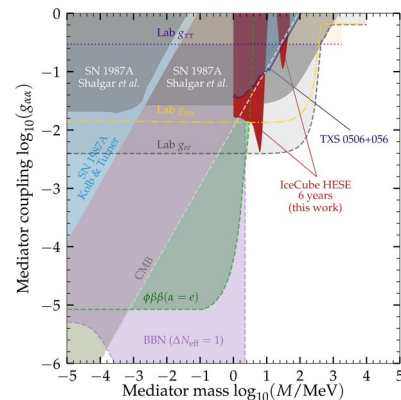
IceCube, Nature Phys. 2018

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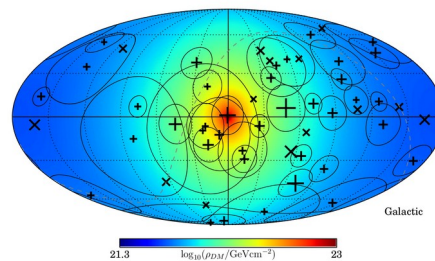
MB & Connolly, PRL 2019

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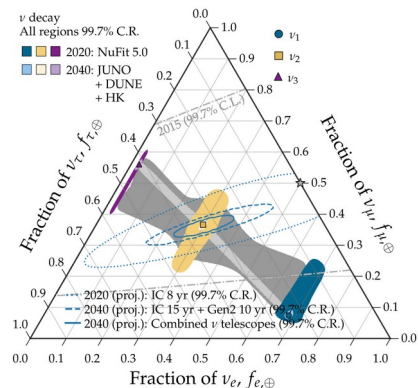
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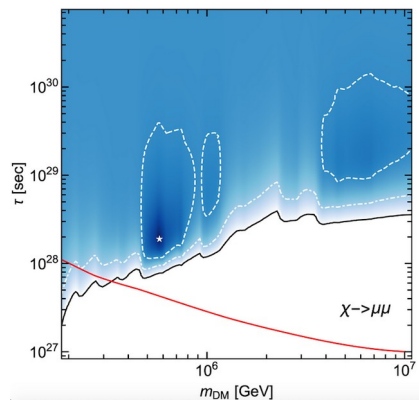
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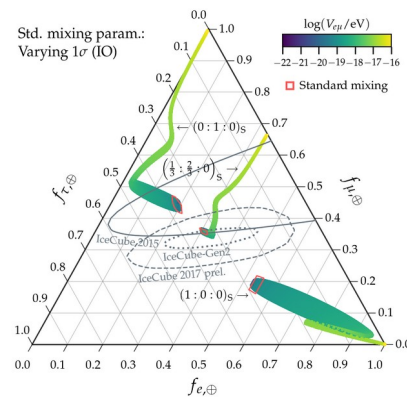
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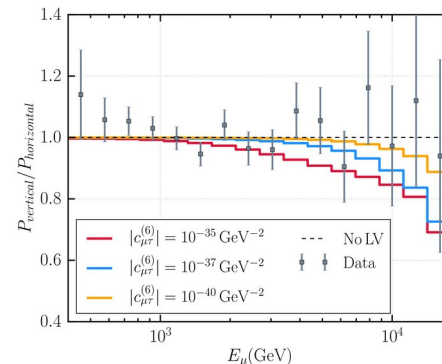
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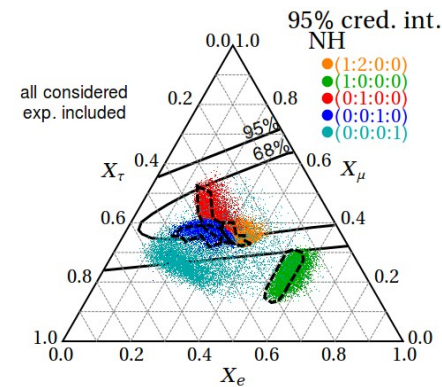
MB & Agarwalla, PRL 2019

Lorentz-invariance violation



IceCube, Nature Phys. 2018

Sterile neutrinos



Brdar, Kopp, Wang, JCAP 2017

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

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- ▶ Fundamental physics can be extracted from four neutrino observables:
 - ▶ Spectral shape
 - ▶ Angular distribution
 - ▶ Flavor composition
 - ▶ Timing $\left. \begin{array}{l} \text{In spite of} \\ \text{poor energy, angular, flavor reconstruction} \\ \text{\& astrophysical unknowns} \end{array} \right\}$

Today

TeV–PeV ν

Turn predictions
into data-driven tests

Next decade

> 100 -PeV ν

Make predictions for
a new energy regime

I.

The story so far

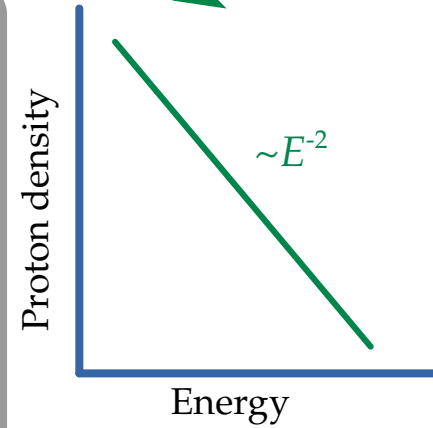
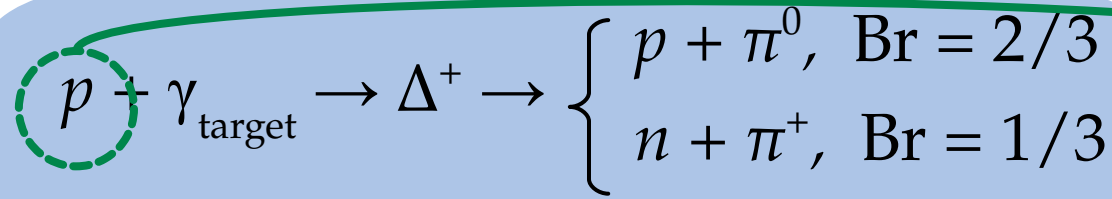
Making high-energy astrophysical neutrinos

(or $p + p$)

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

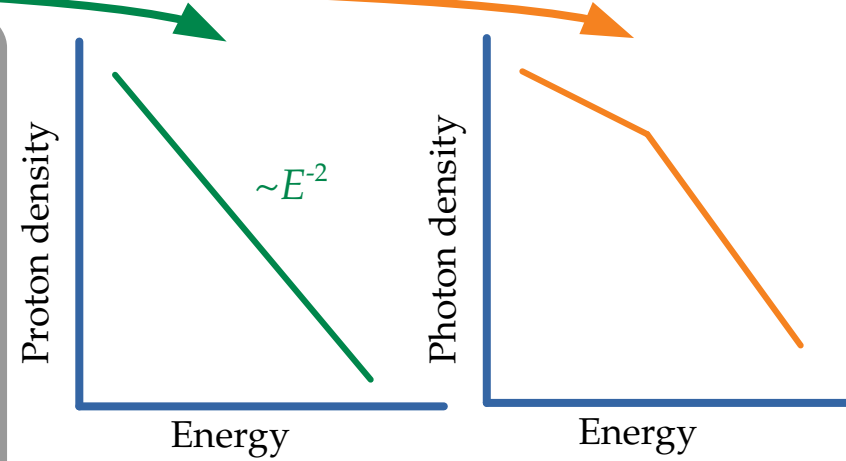
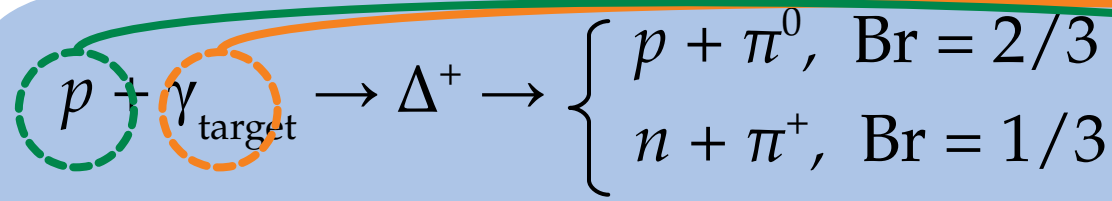
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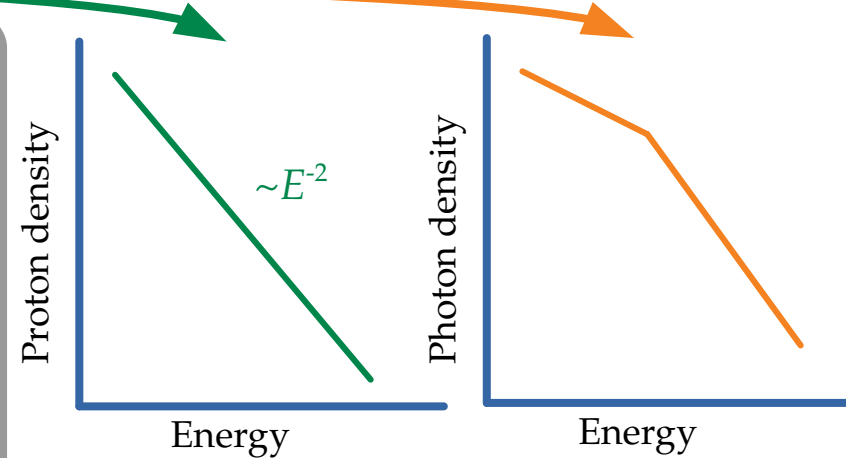
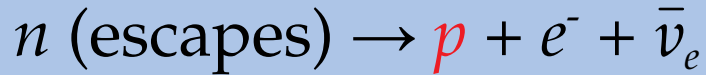
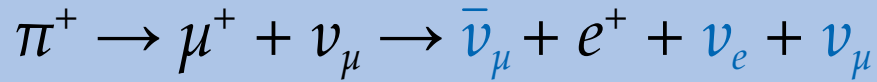
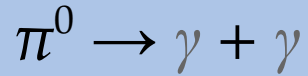
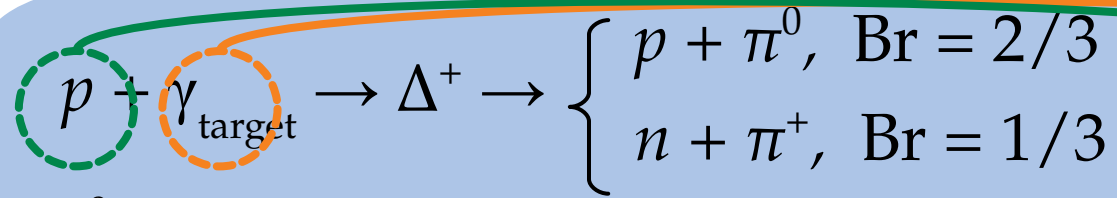
Making high-energy astrophysical neutrinos

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Making high-energy astrophysical neutrinos

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Making high-energy astrophysical neutrinos

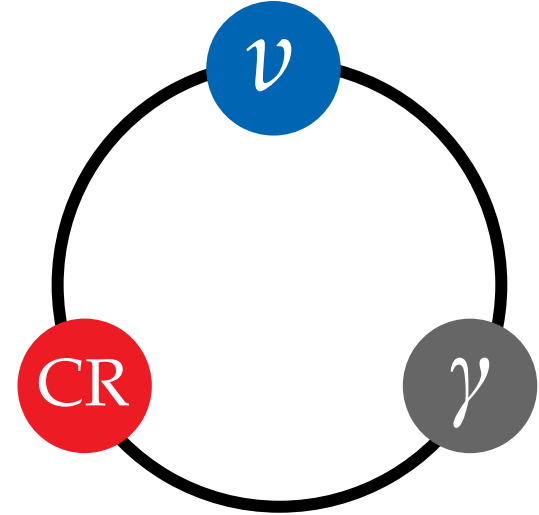
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$$p + \gamma_{\text{target}} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0, & \text{Br} = 2/3 \\ n + \pi^+, & \text{Br} = 1/3 \end{cases}$$

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

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

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



Neutrino energy = Proton energy / 20

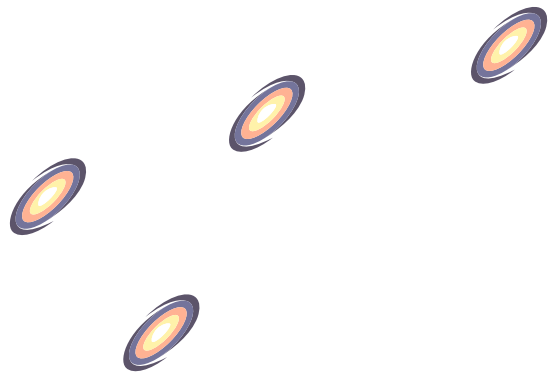
Gamma-ray energy = Proton energy / 10

Redshift



$z = 0$

Note: v sources can be steady-state or transient



Redshift

$z = 0$

Discovered

MeV γ

PeV p

TeV–PeV ν

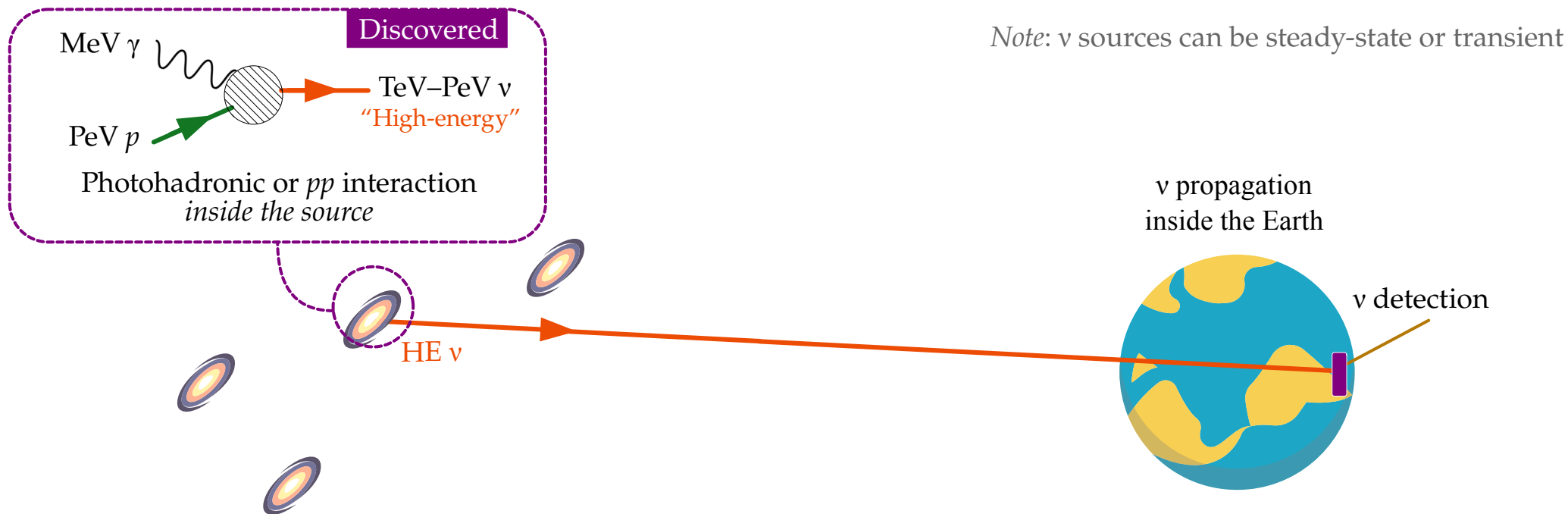
“High-energy”

Photohadronic or pp interaction
inside the source

Note: ν sources can be steady-state or transient

ν propagation
inside the Earth

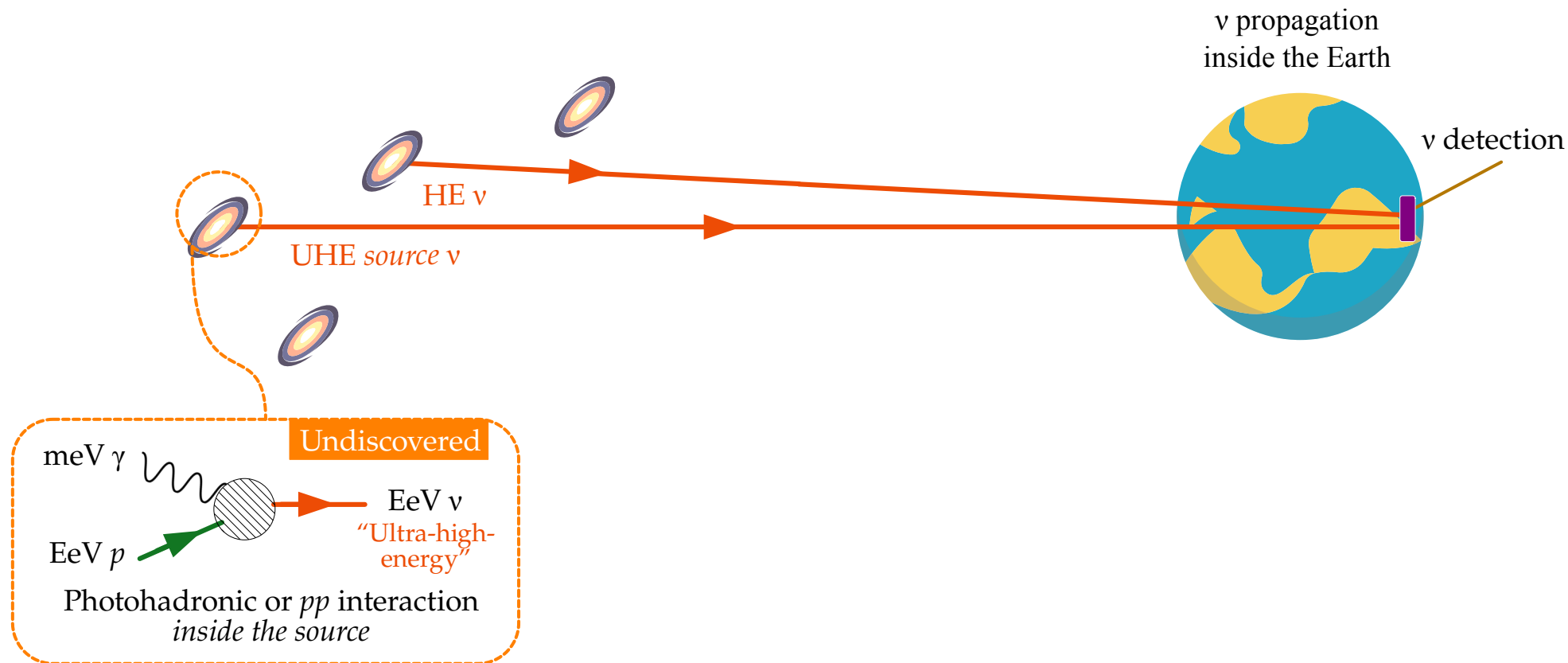
ν detection



Redshift

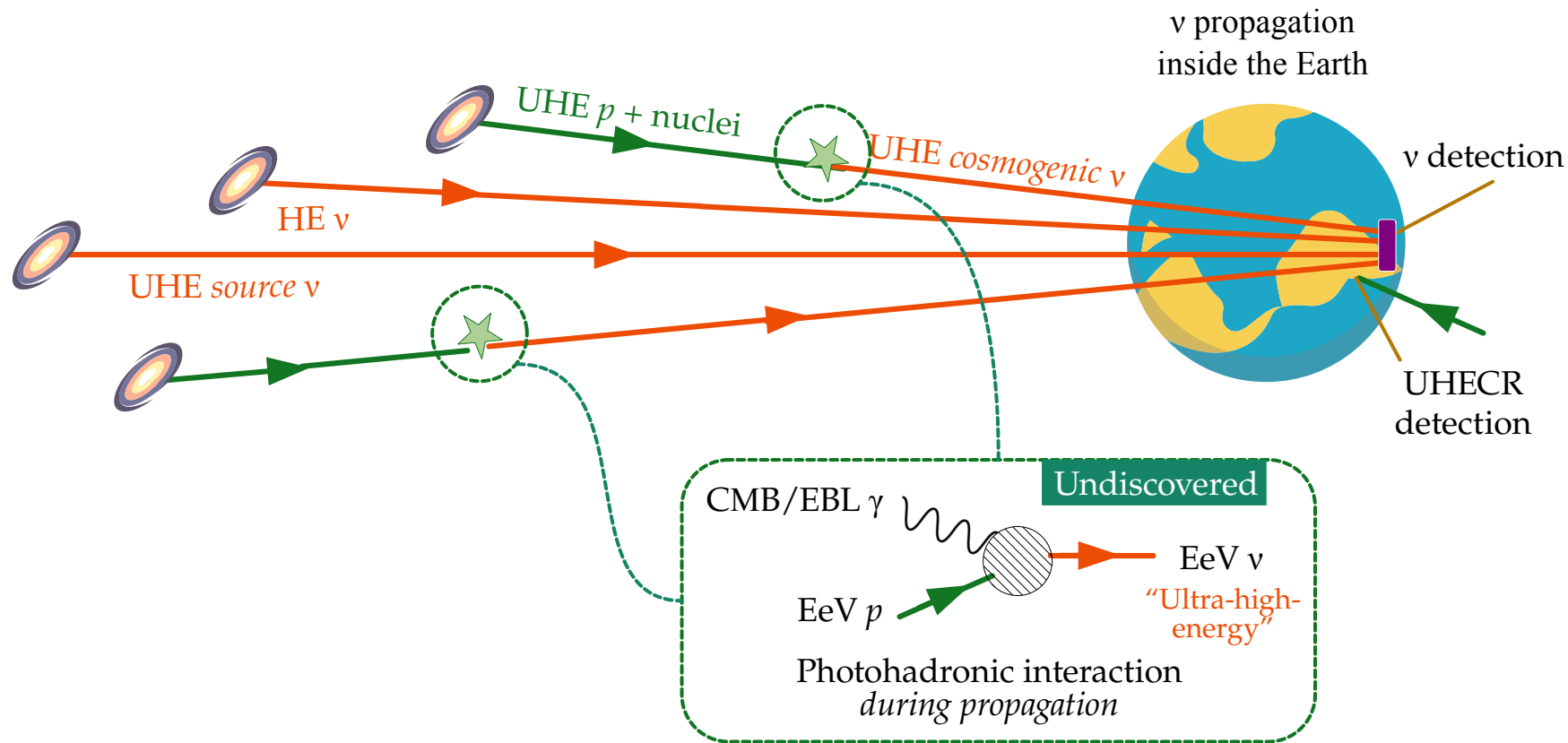
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Note: ν sources can be steady-state or transient



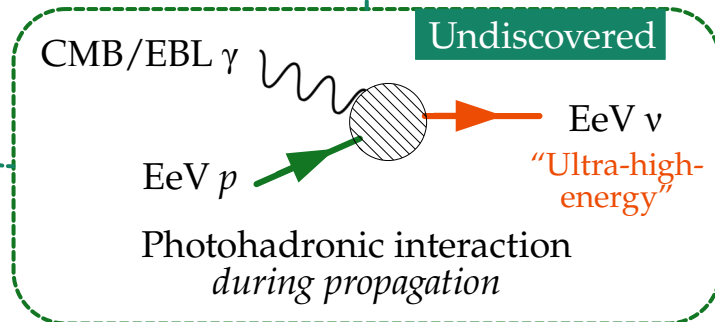
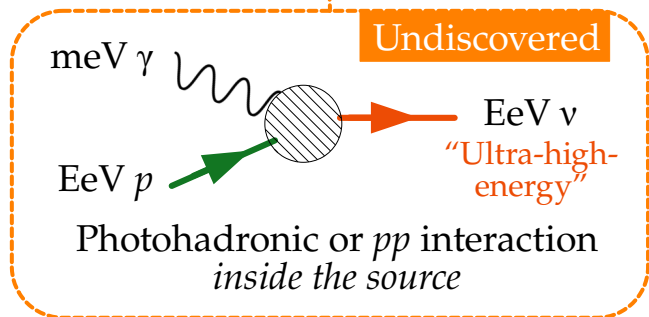
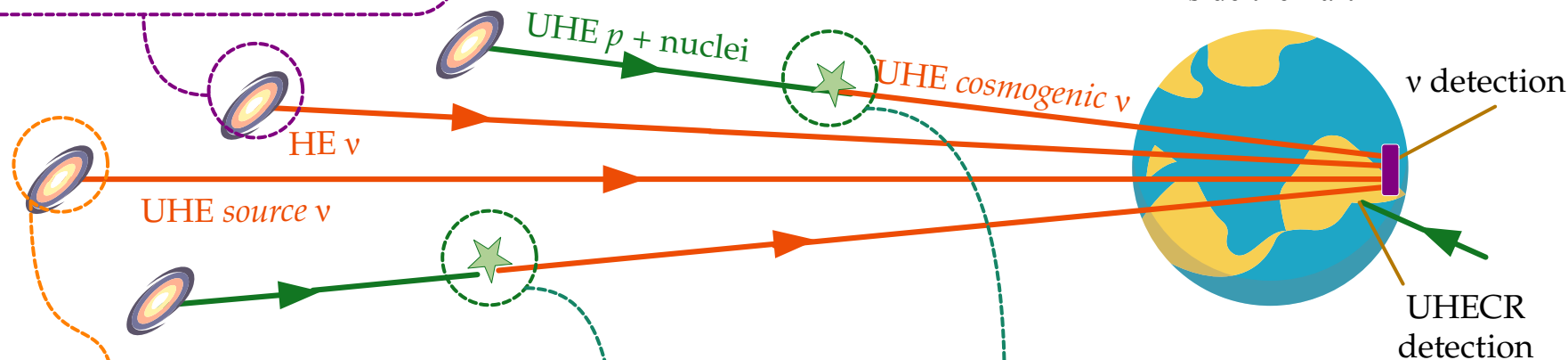
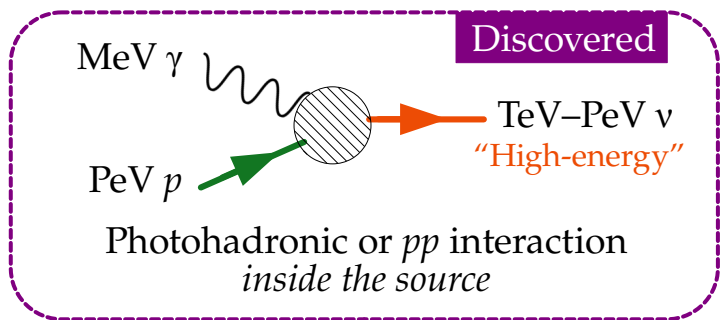
Redshift ← $z = 0$

Note: ν sources can be steady-state or transient



Redshift ← z = 0

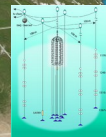
Note: ν sources can be steady-state or transient



TeV–PeV ν
telescopes, 2021

ANTARES

- ▶ Mediterranean Sea
- ▶ Completed 2008
- ▶ $V_{\text{eff}} \sim 0.2 \text{ km}^3$ (10 TeV)
- ▶ $V_{\text{eff}} \sim 1 \text{ km}^3$ (10 PeV)
- ▶ 12 strings, 900 OMs
- ▶ Sensitive to ν from the Southern sky



Baikal NT200+

- ▶ Lake Baikal
- ▶ Completed 1998 (upgraded 2005)
- ▶ $V_{\text{eff}} \sim 10^{-4} \text{ km}^3$ (10 TeV)
- ▶ $V_{\text{eff}} \sim 0.01 \text{ km}^3$ (10 PeV)
- ▶ 8 strings, 192+ OMs

IceCube

- ▶ South Pole
- ▶ Completed 2011
- ▶ $V_{\text{eff}} \sim 0.01 \text{ km}^3$ (10 TeV)
- ▶ $V_{\text{eff}} \sim 1 \text{ km}^3$ ($> 1 \text{ PeV}$)
- ▶ 86 strings, 5000+ OMs
- ▶ Sees high-energy astrophysical ν

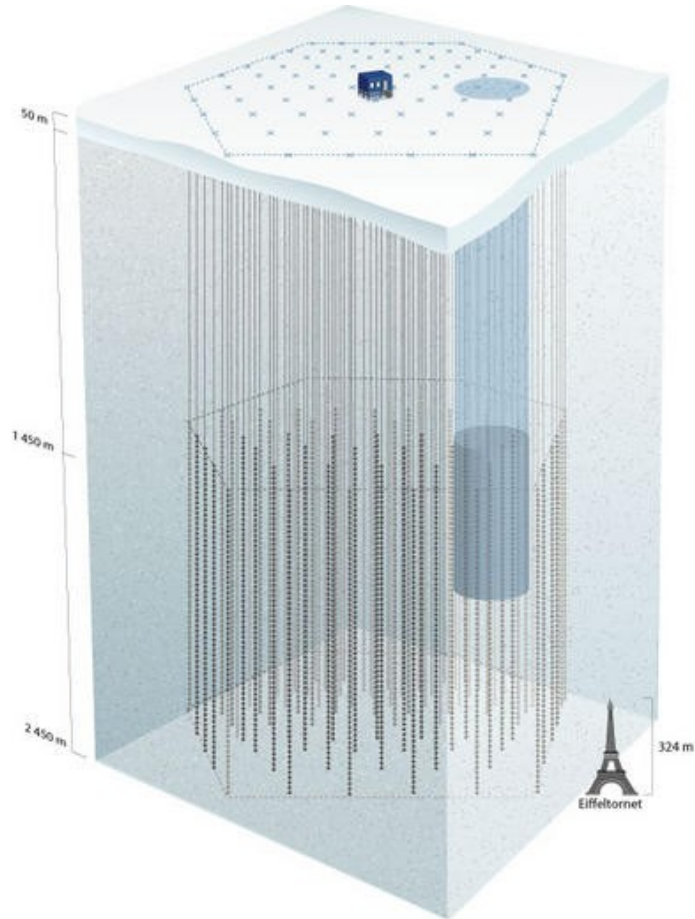


OM: optical module



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



How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering

Neutral current (NC)

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

Charged current (CC)

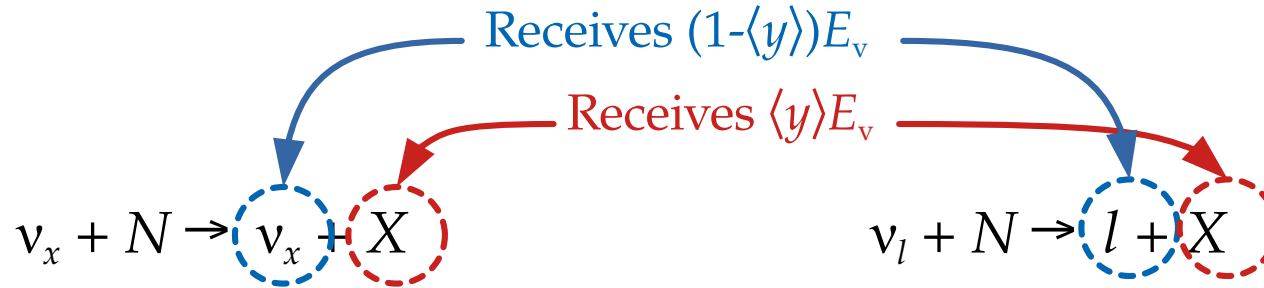
$$\nu_l + N \rightarrow l + X$$

How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering

Neutral current (NC)

Charged current (CC)



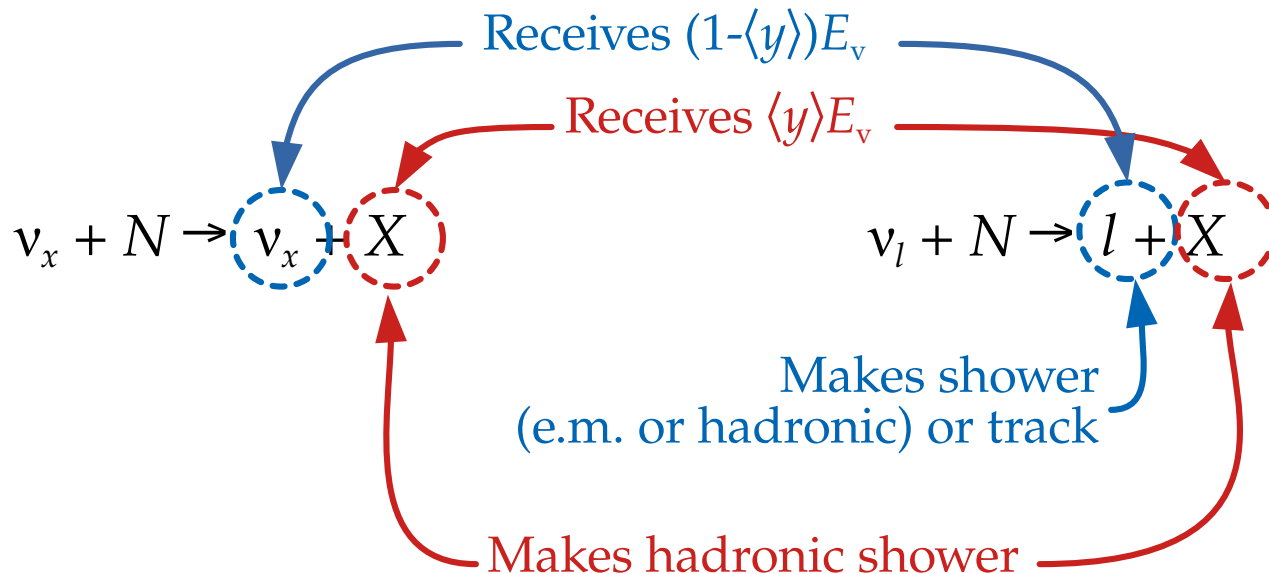
At TeV–PeV, the average inelasticity $\langle y \rangle = 0.25\text{--}0.30$

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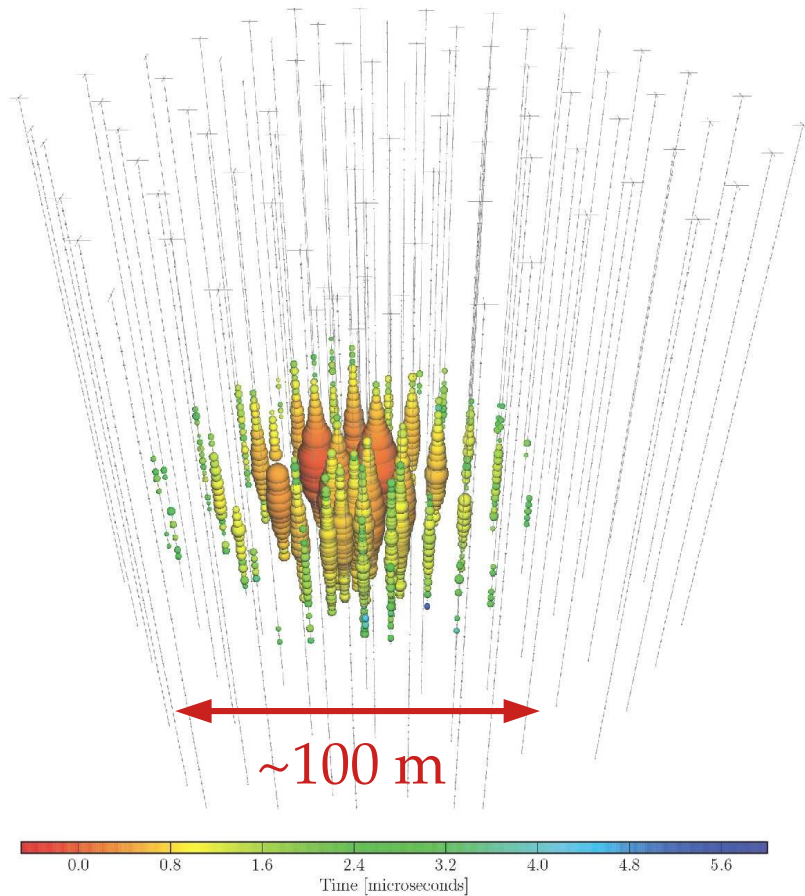
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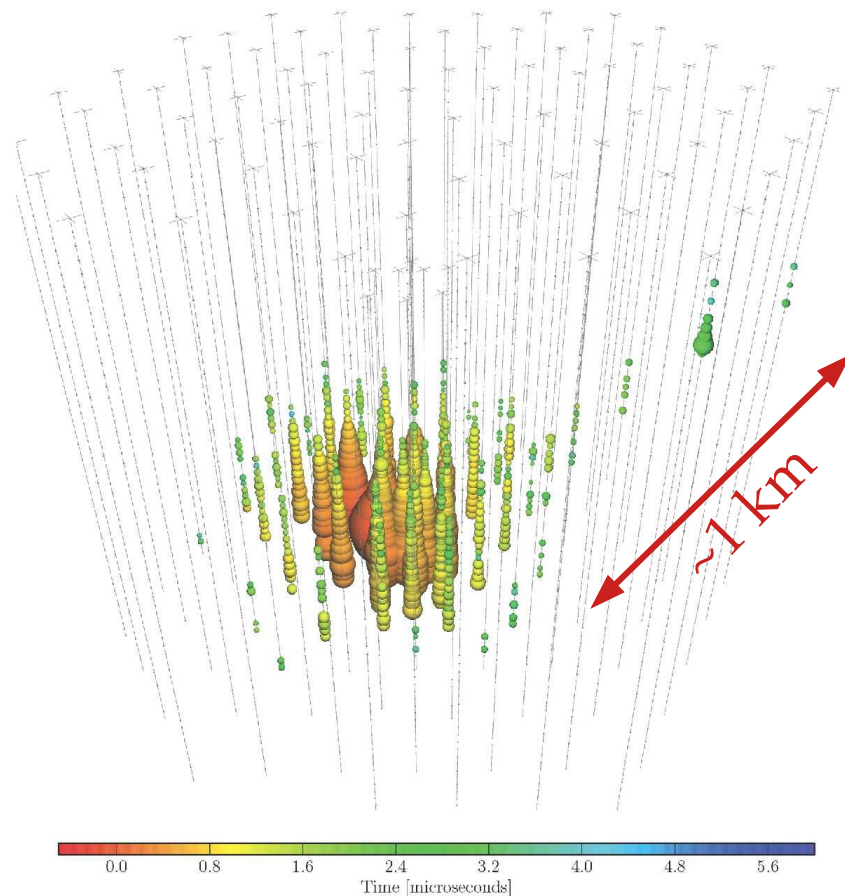
At TeV–PeV, the average inelasticity $\langle y \rangle = 0.25\text{--}0.30$

Shower
(mainly from ν_e and ν_τ)

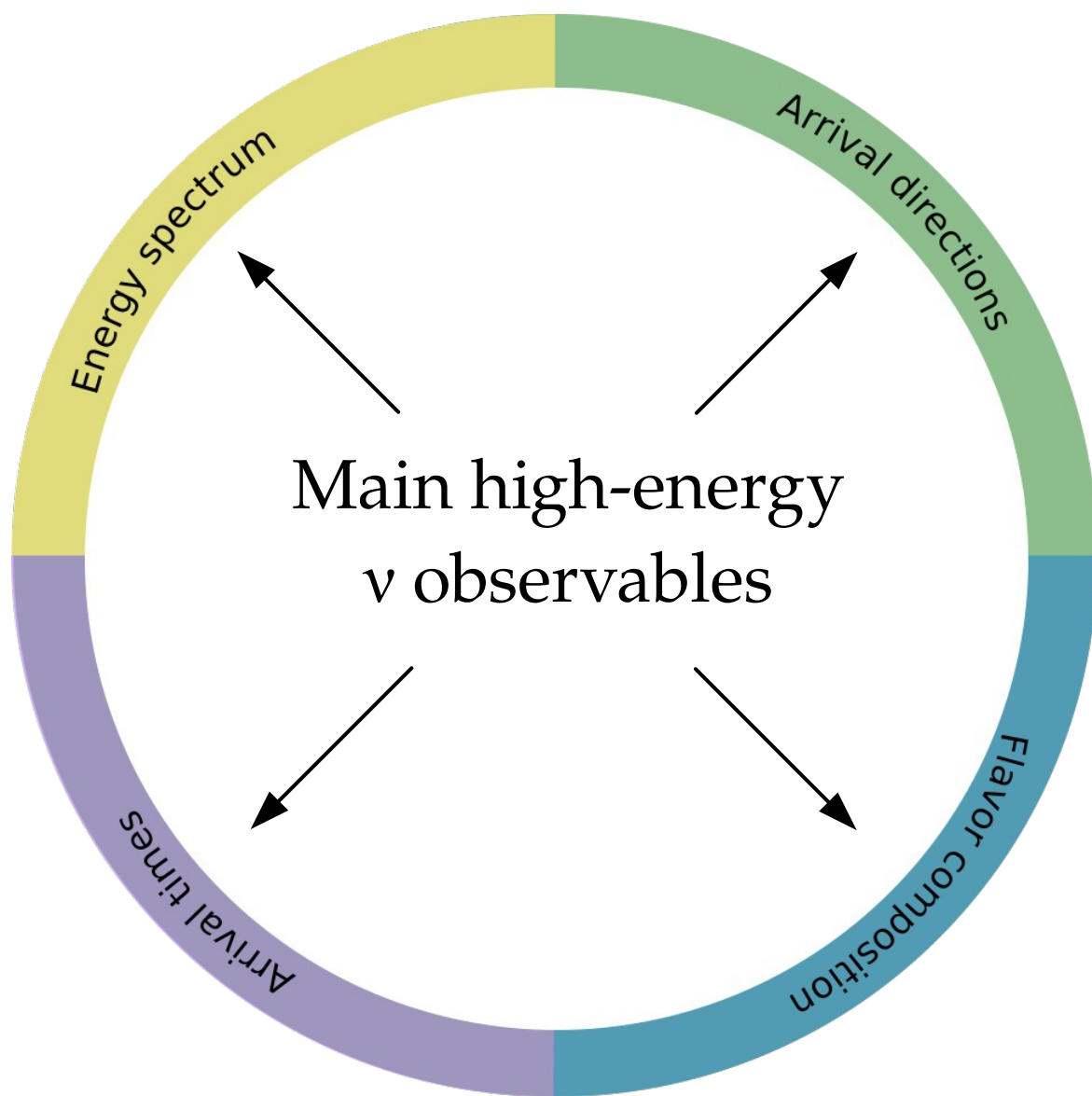


Poor angular resolution: $\sim 10^\circ$

Track
(mainly from ν_μ)



Angular resolution: $< 1^\circ$

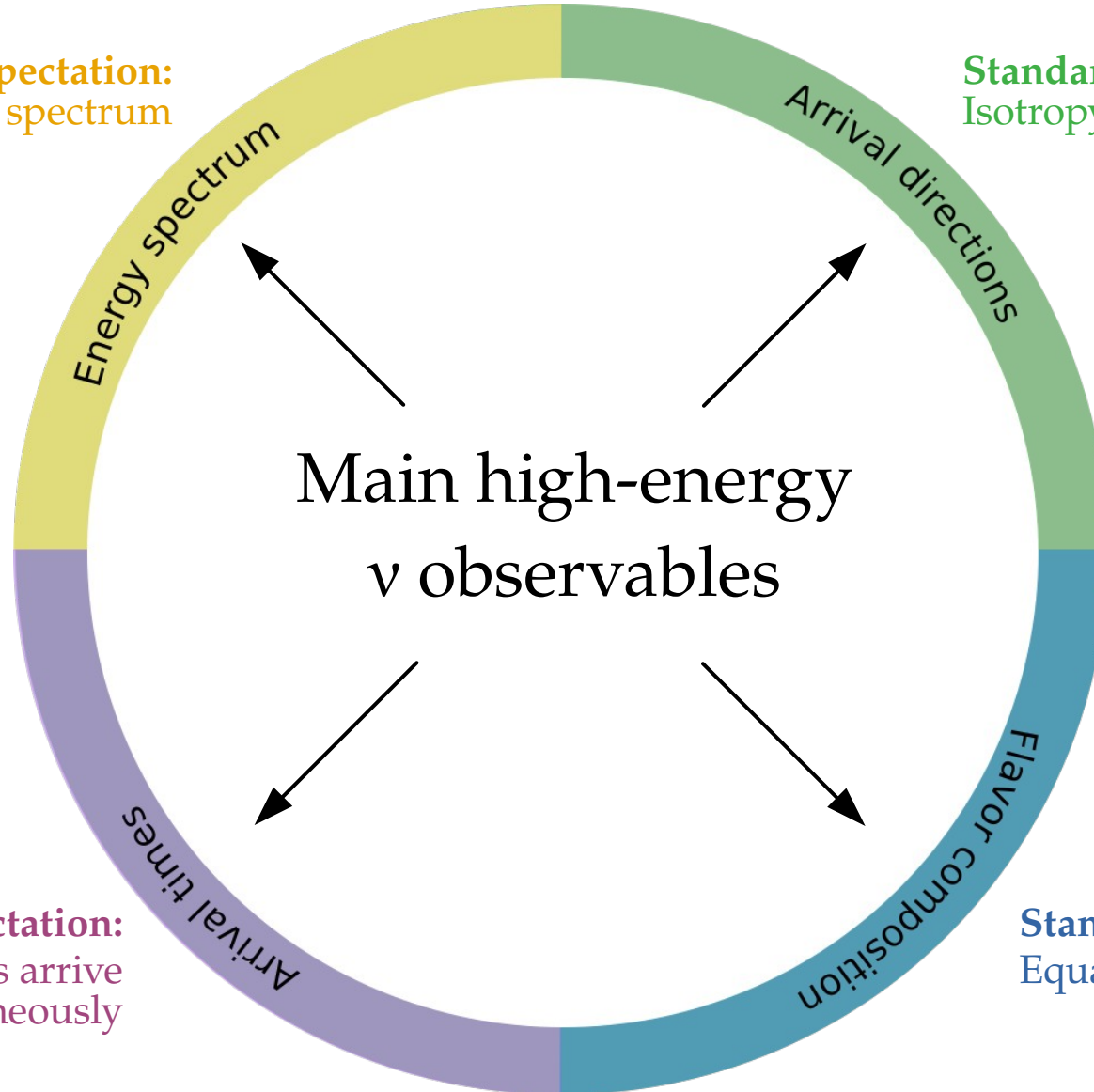


Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

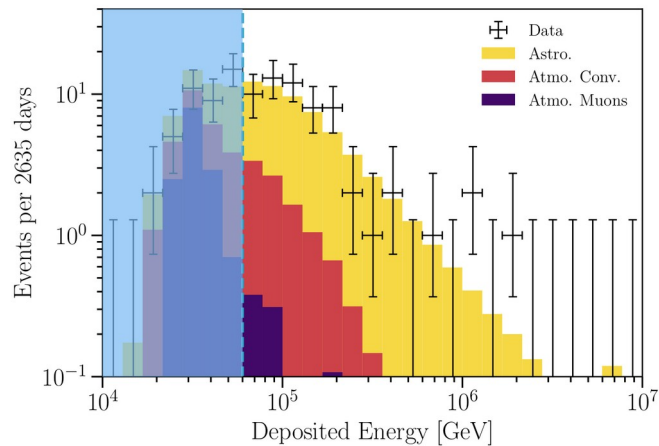
Standard expectation:
 ν and γ from transients arrive
simultaneously

Standard expectation:
Equal number of ν_e , ν_μ , ν_τ

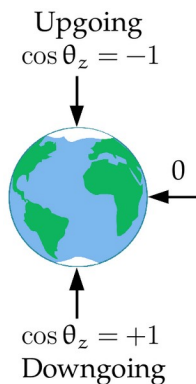
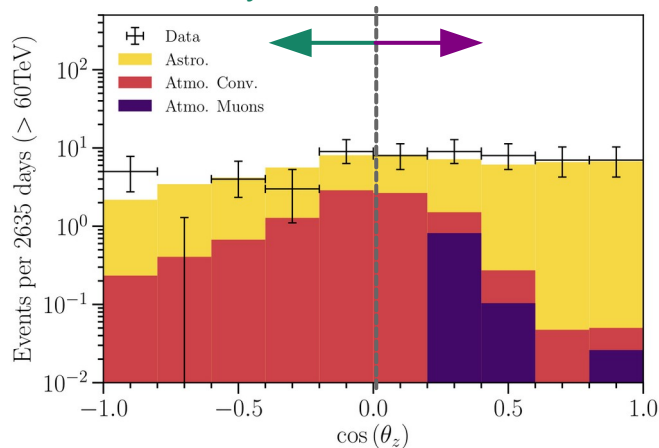


Energy spectrum (7.5 yr)

100+ contained events above 60 TeV:

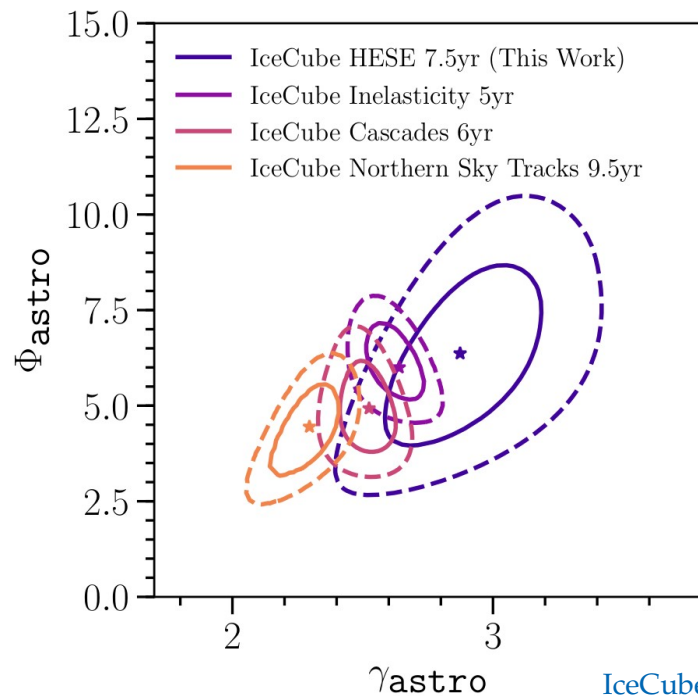


ν attenuated by Earth Atm. ν and μ vetoed



Data is fit well by a single power law:

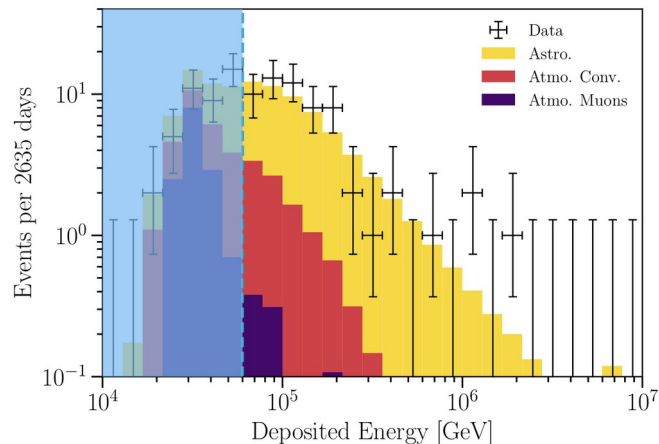
$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\text{astro}} \left(\frac{E_\nu}{100 \text{ TeV}} \right)^{-\gamma_{\text{astro}}} \cdot 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$



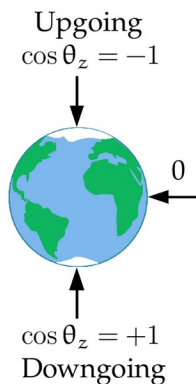
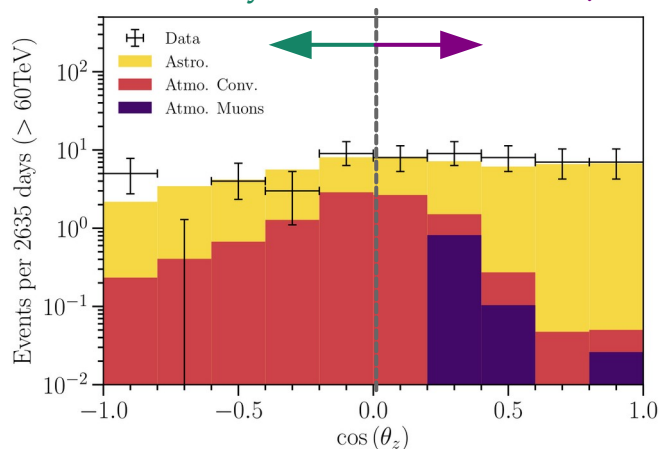
IceCube, 2011.03545

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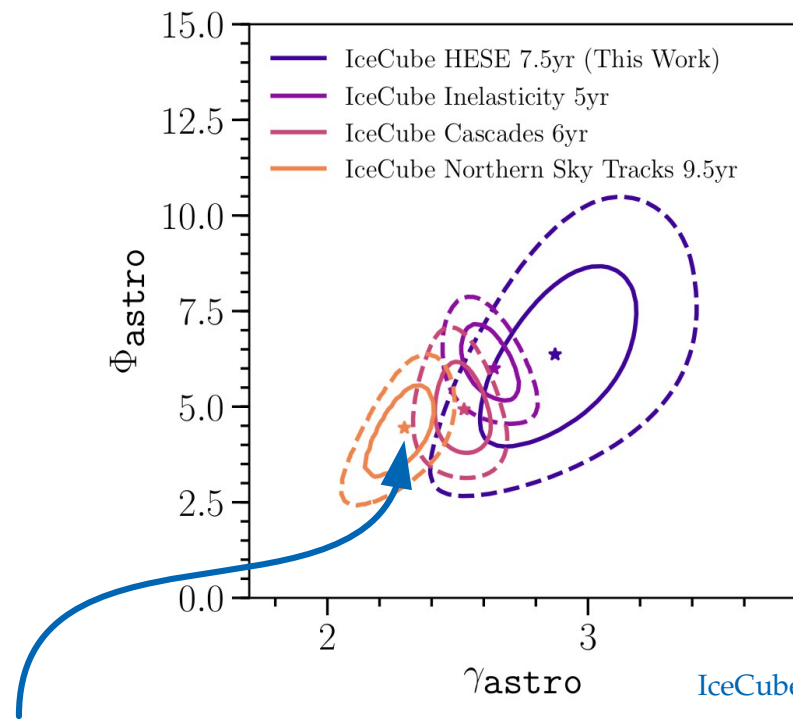


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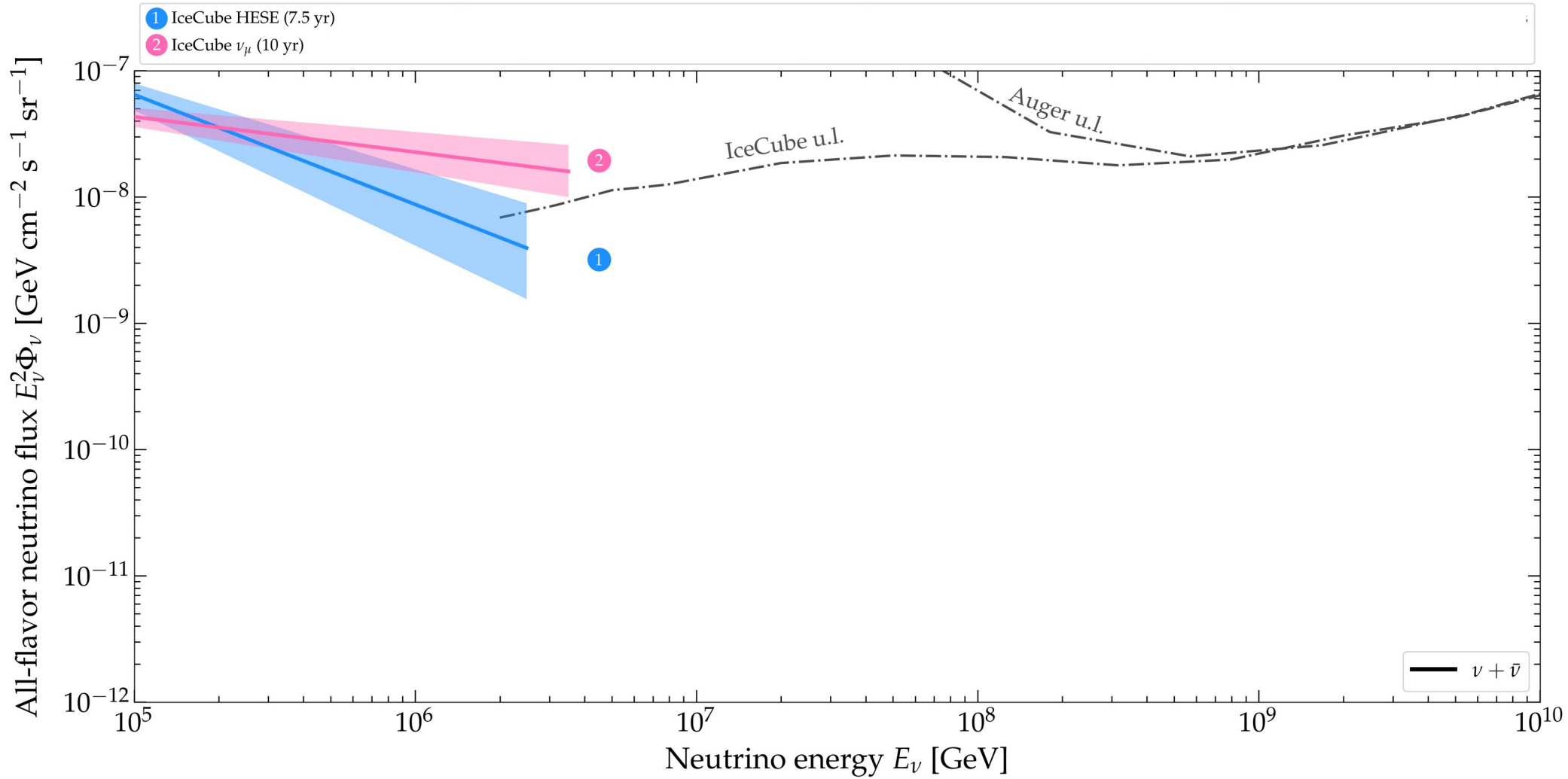
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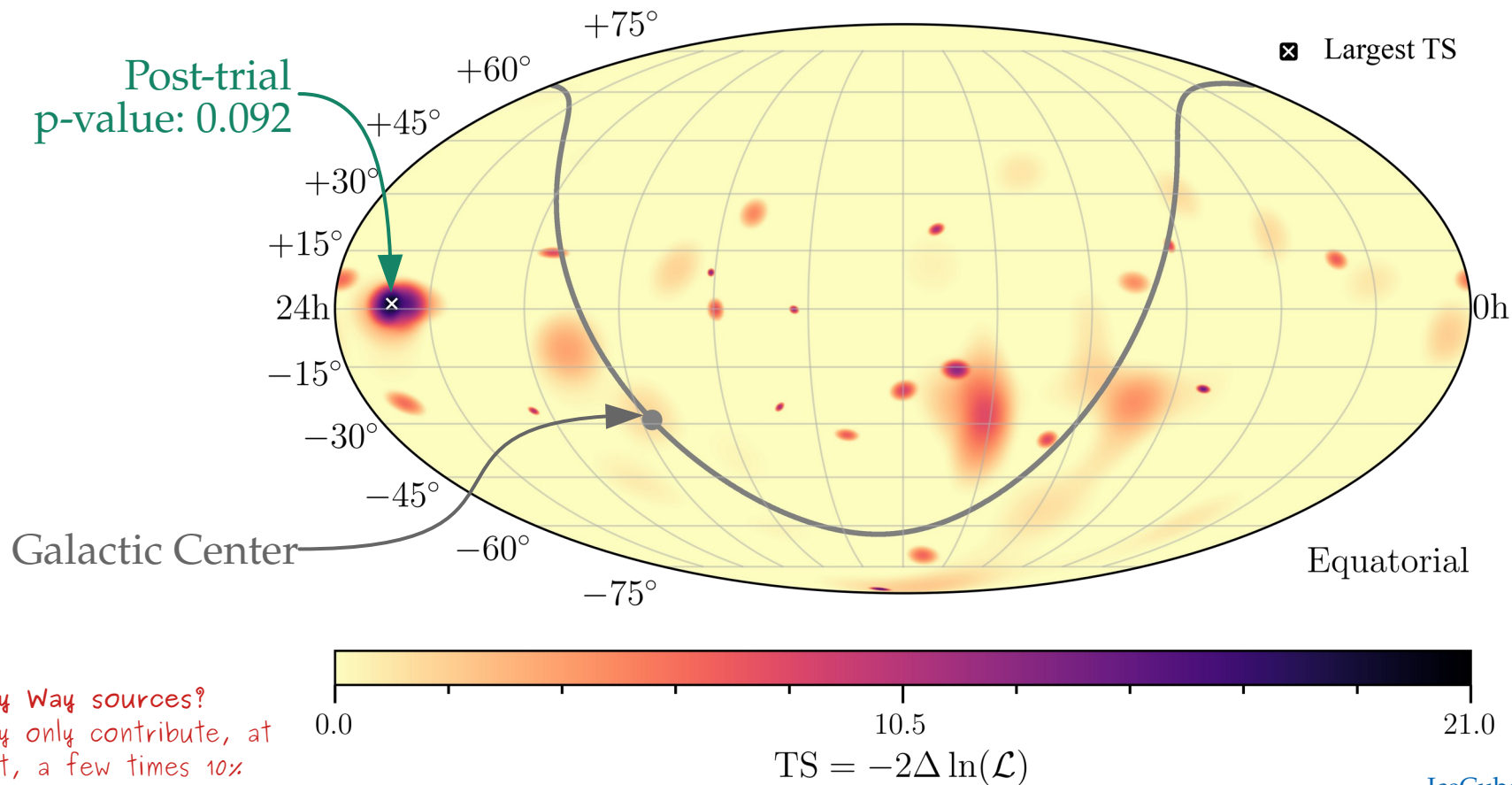
IceCube, 2011.03545

Spectrum looks harder for through-going ν_μ



Arrival directions (7.5 yr)

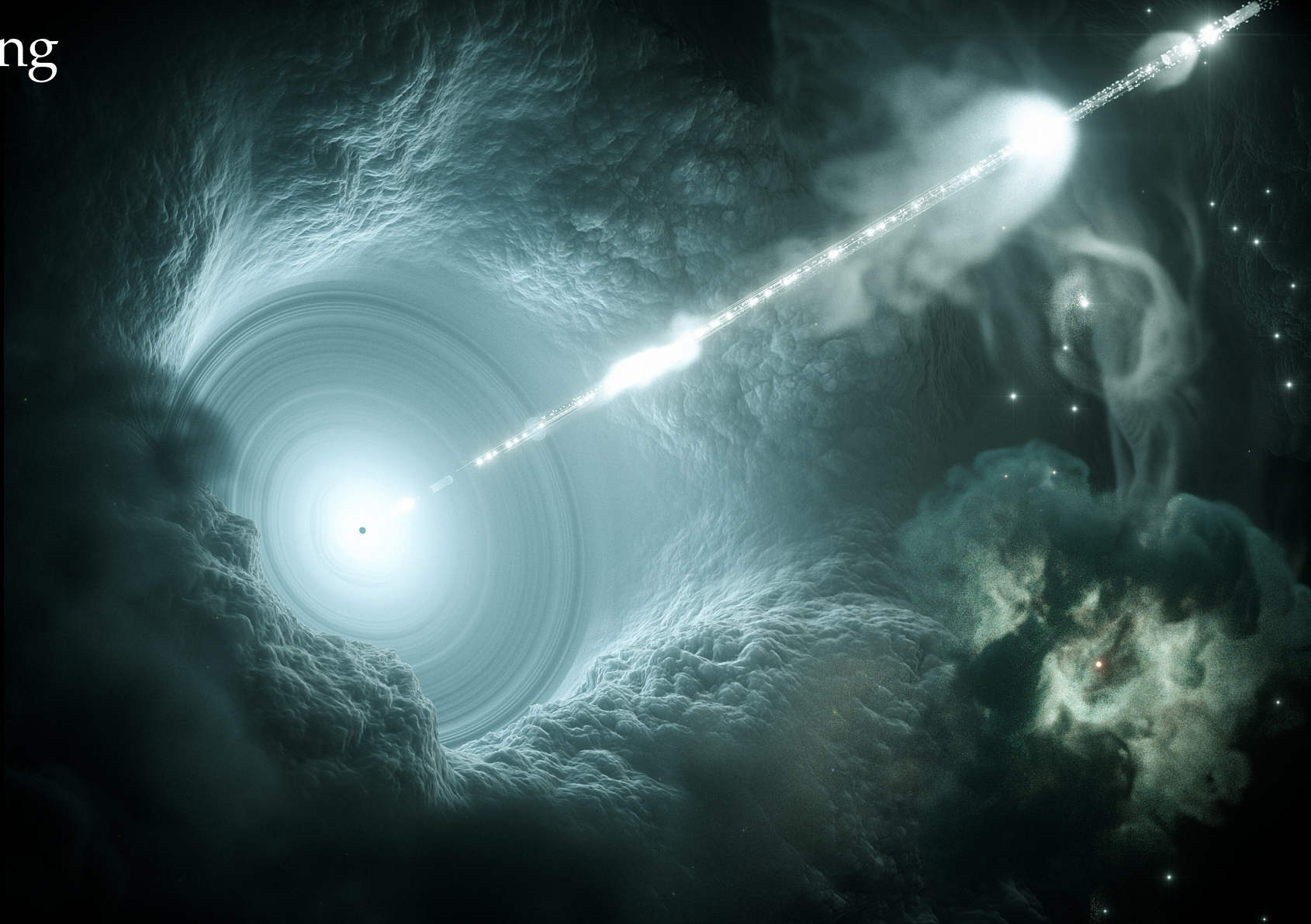
No significant excess in the neutrino sky map:



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

IceCube, 2011.03545

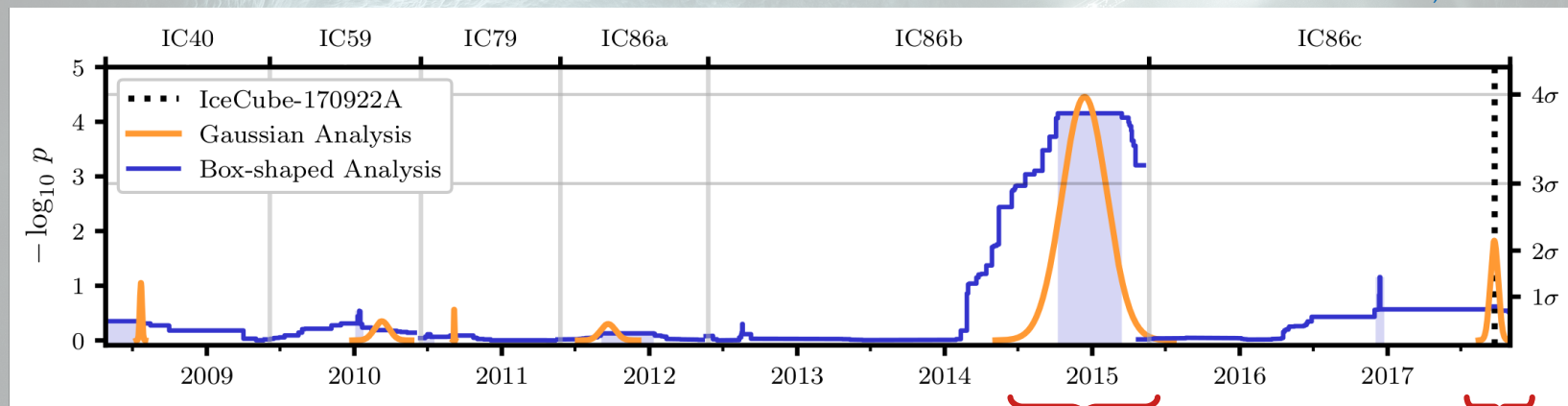
Timing



Timing

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
3.5 σ significance of correlation (post-trial)

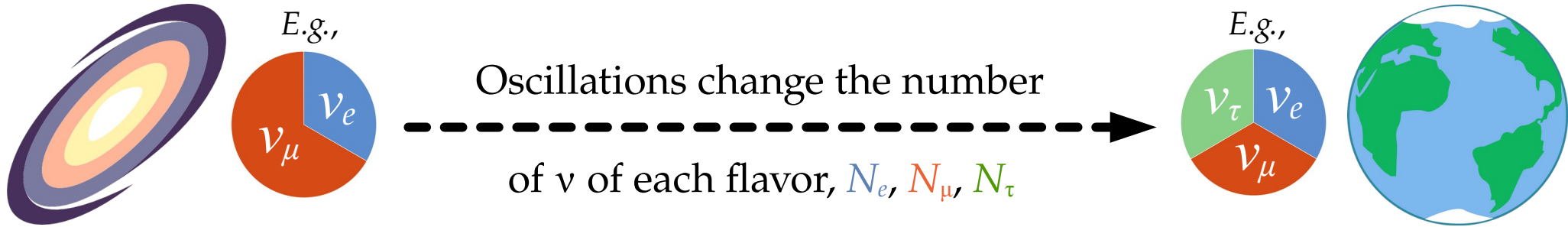
2017: one 290-TeV ν + X-ray flare
1.4 σ significance of correlation

Combined (pre-trial): 4.1 σ

Astrophysical sources

Earth

Up to a few Gpc



Different production mechanisms yield different flavor ratios:

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

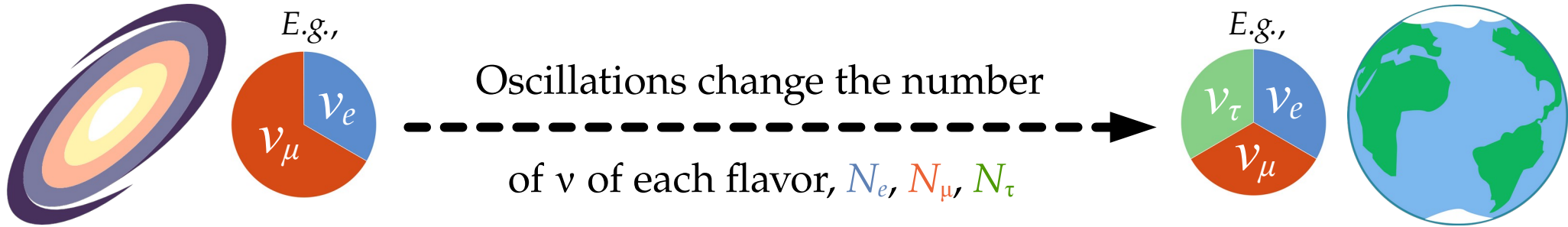
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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

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Standard oscillations
or
new physics

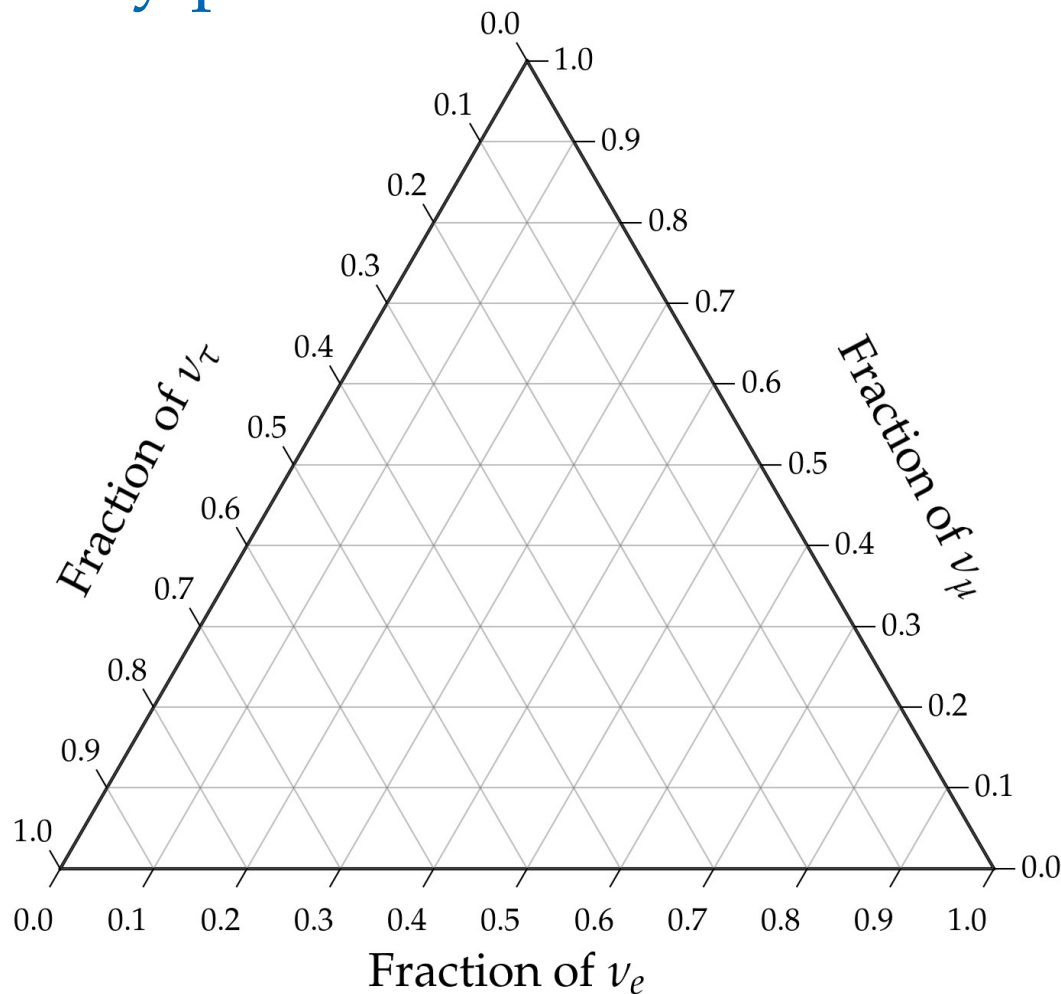
Quick aside: how to read a ternary plot

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)



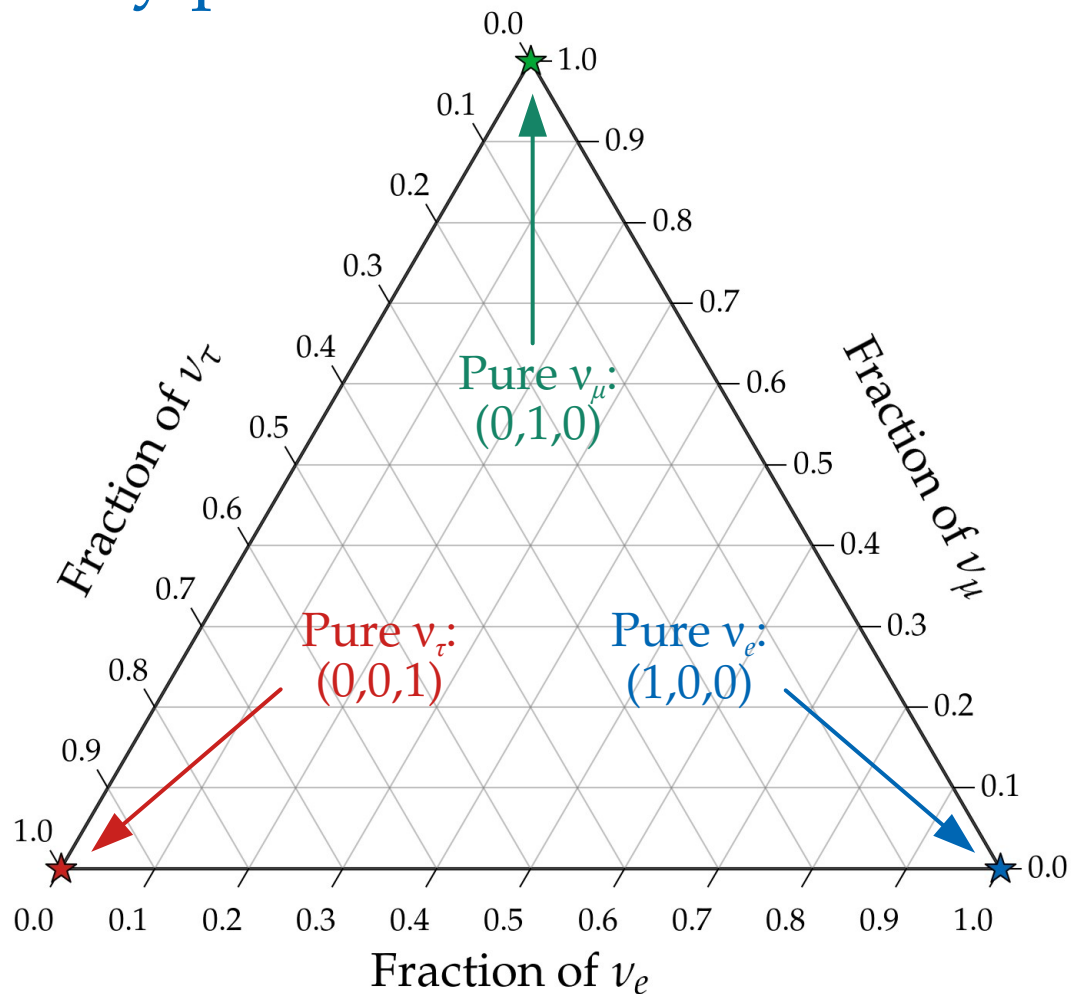
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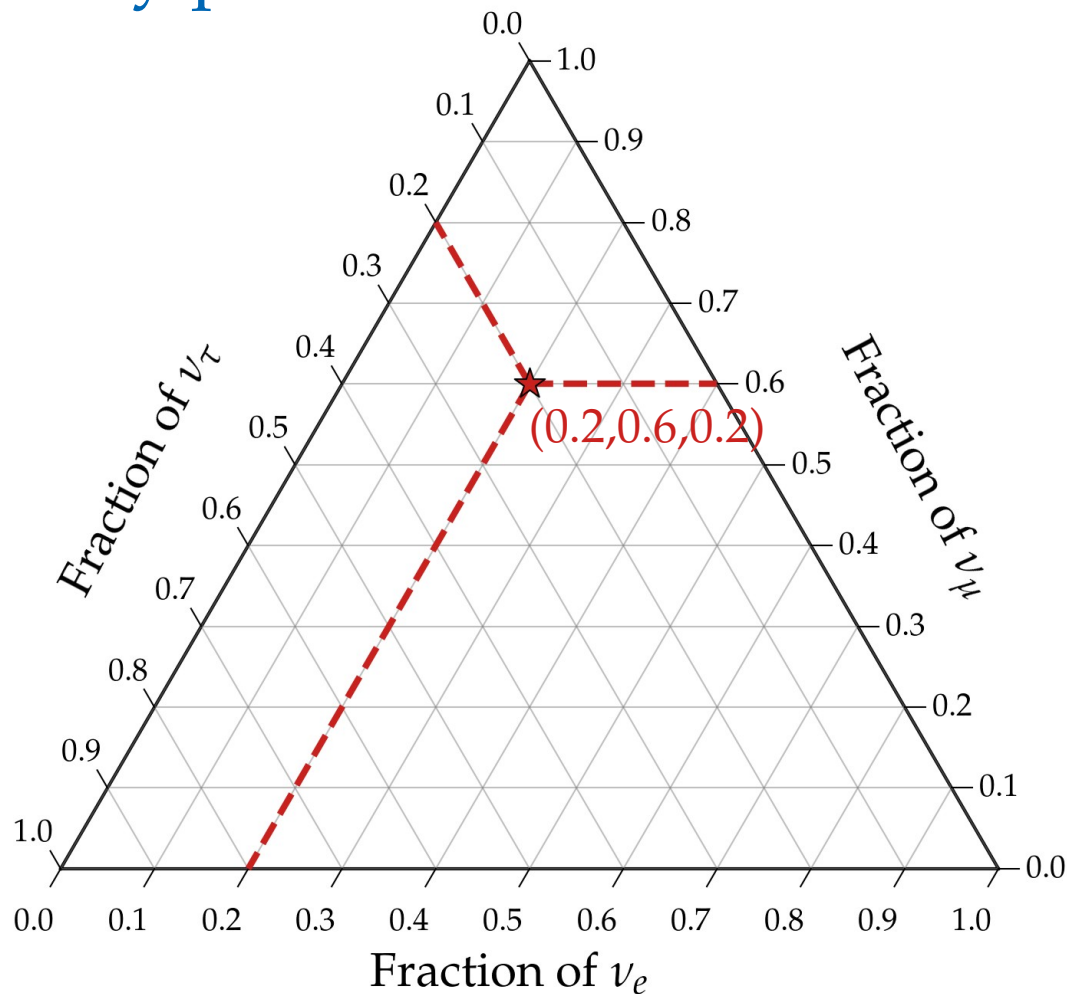
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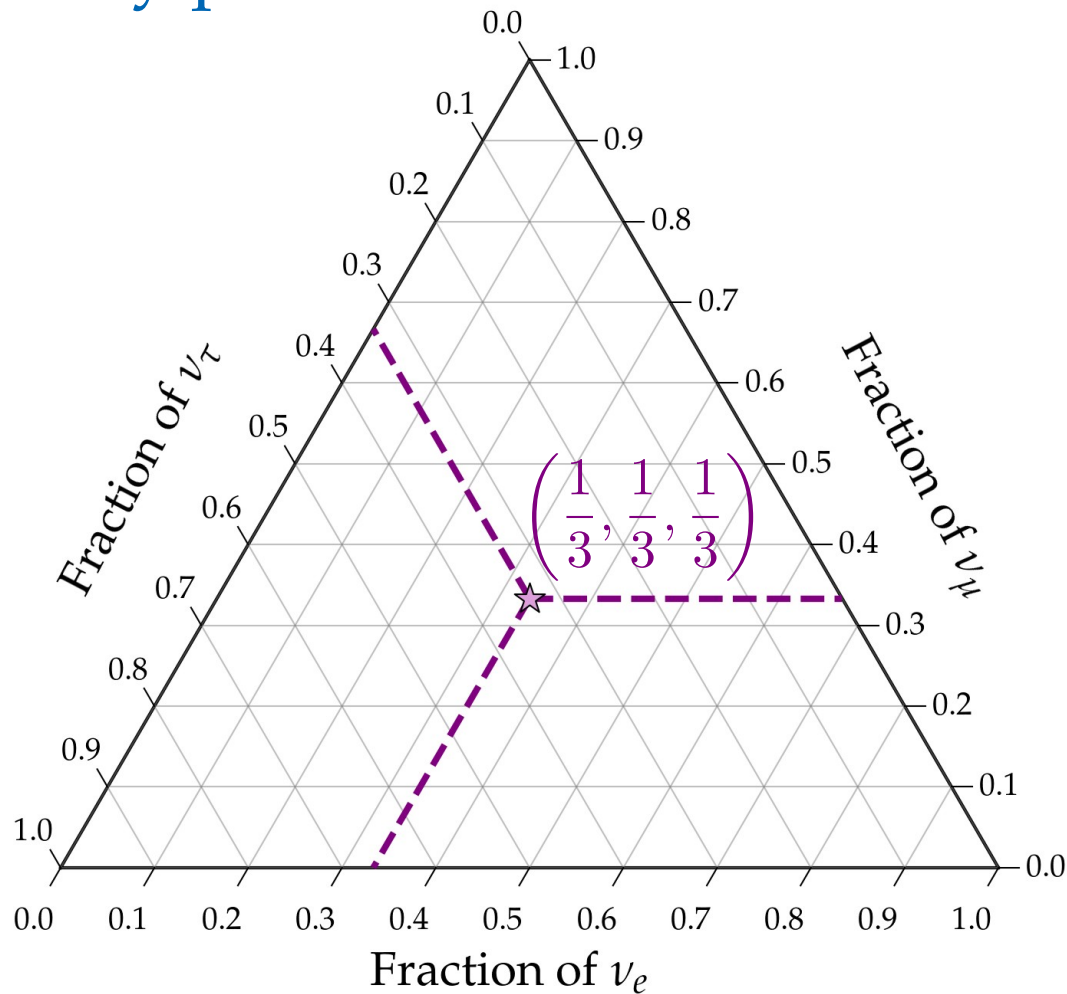
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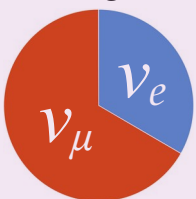


From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$

Sources



E.g.,



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

Oscillations

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

Earth



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

One likely TeV–PeV ν production scenario:

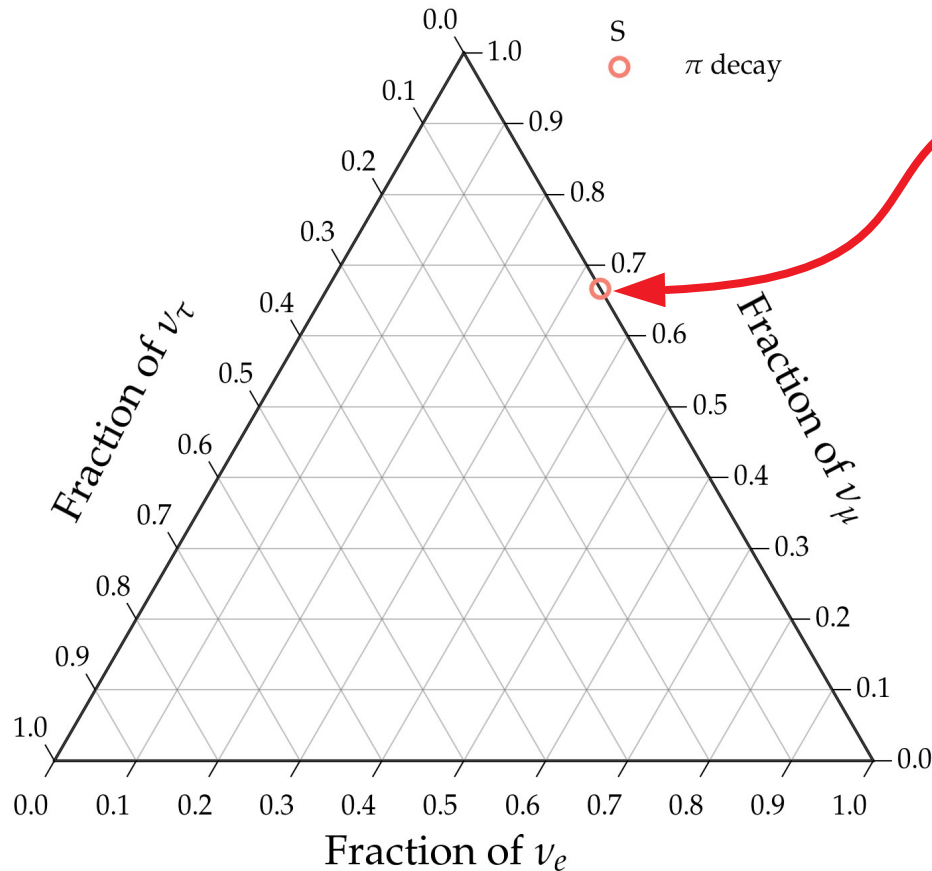
$$p + \gamma \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu \text{ followed by } \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

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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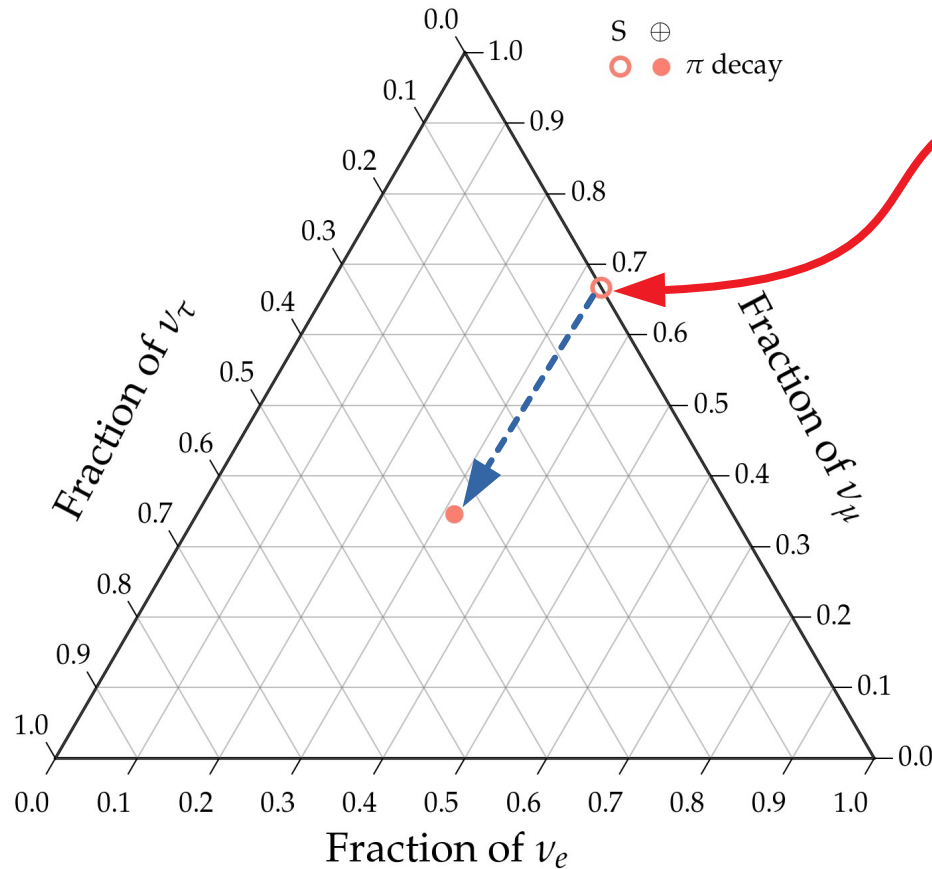


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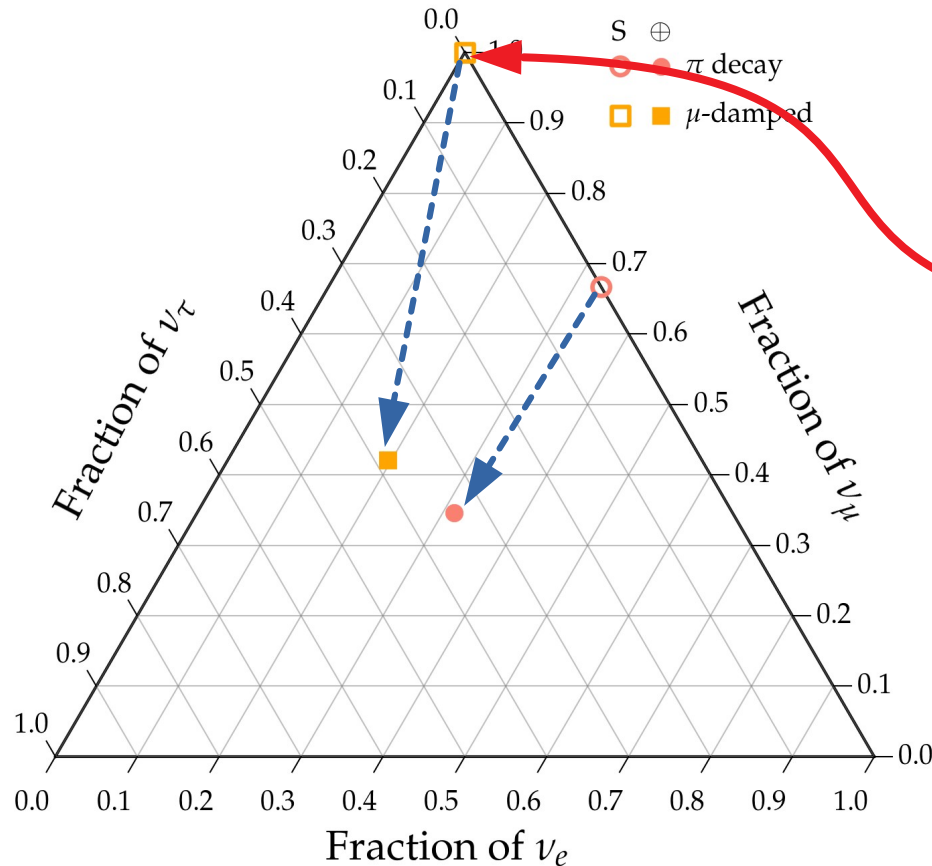


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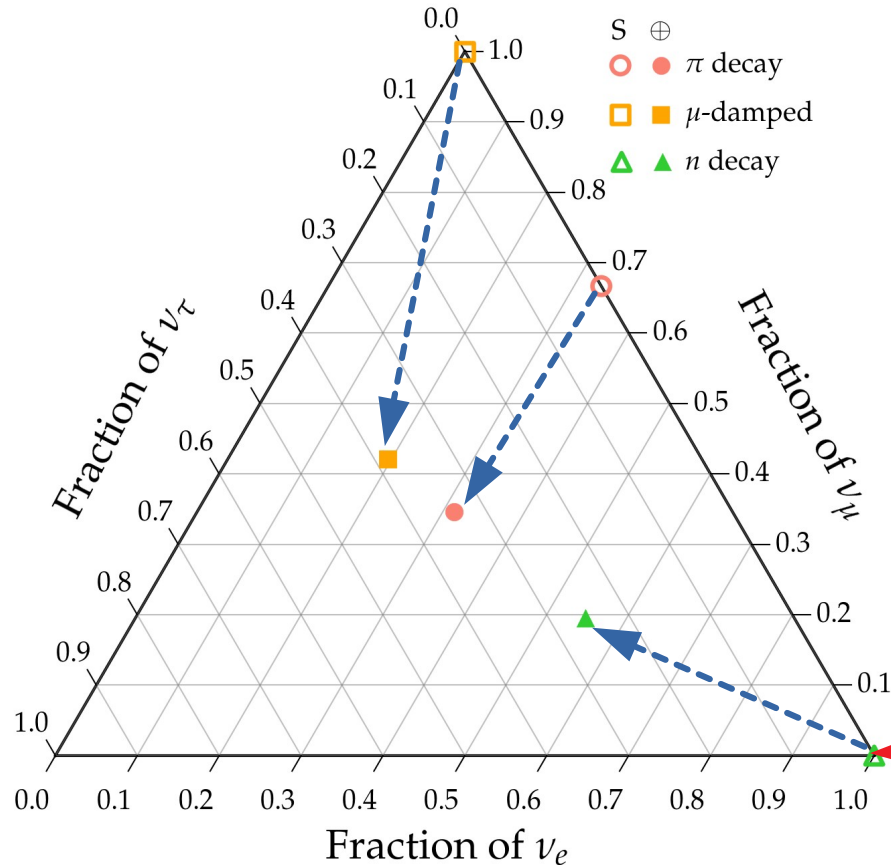
$(1/3:2/3:0)_S$

Muon damped

$(0:1:0)_S$

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One likely TeV–PeV ν production scenario:



Full π decay chain

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

Muon damped

$(0:1:0)_S$

Neutron decay

$(1:0:0)_S$

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

II.

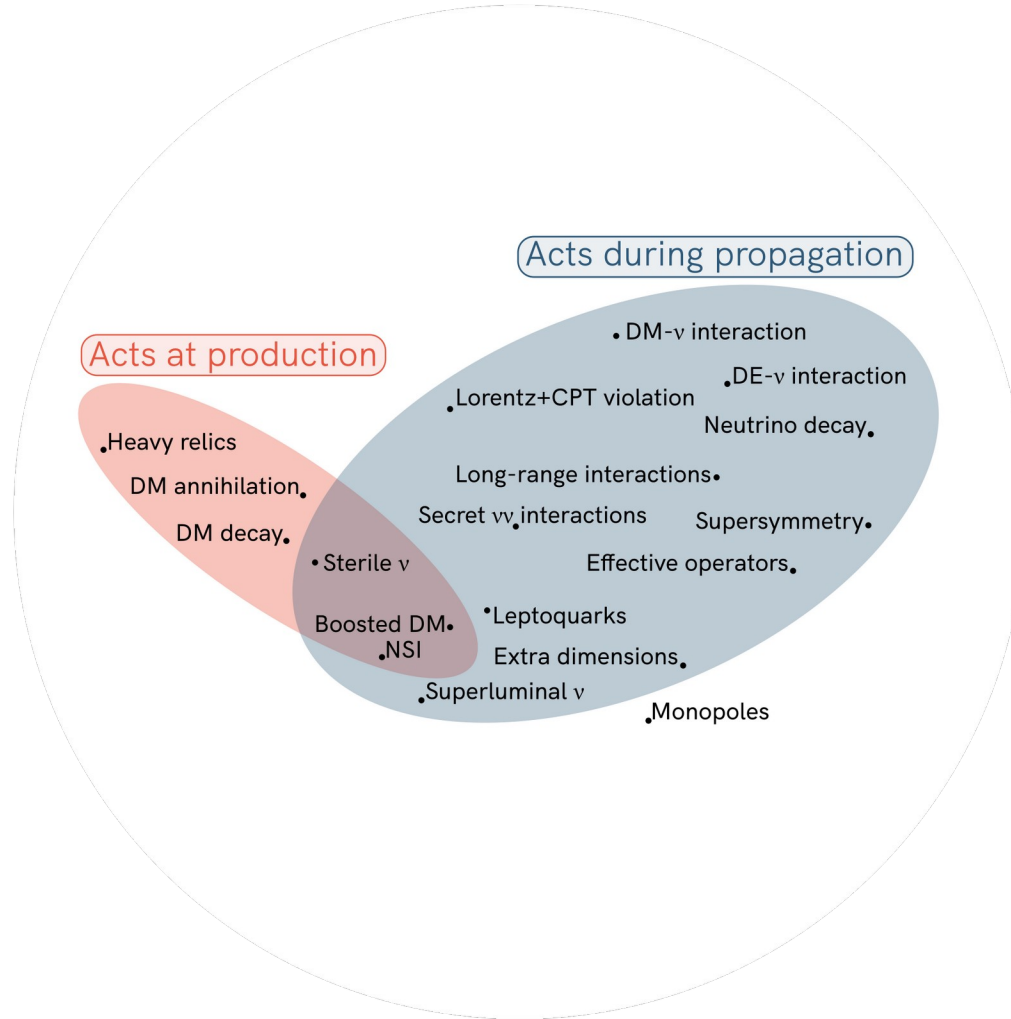
High-energy and ultra-high-energy neutrino physics



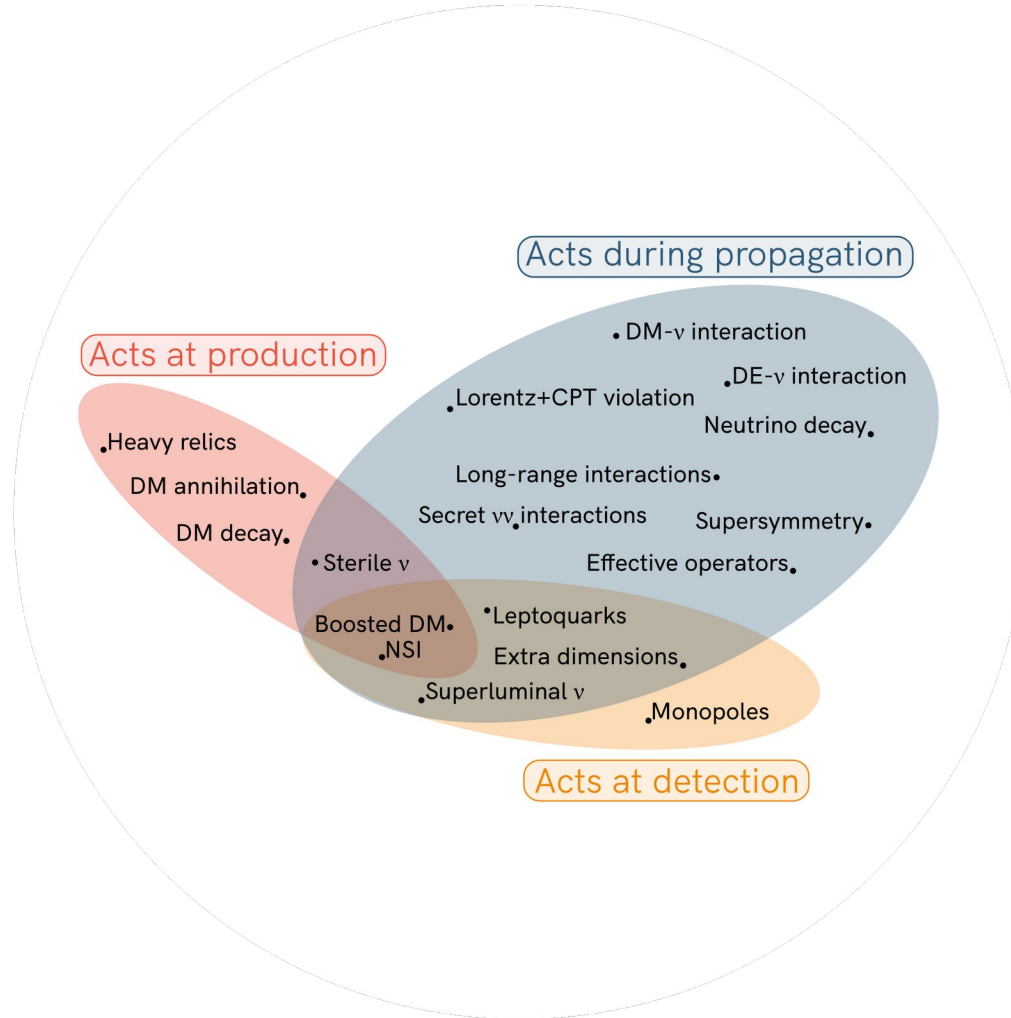
Note: Not an exhaustive list



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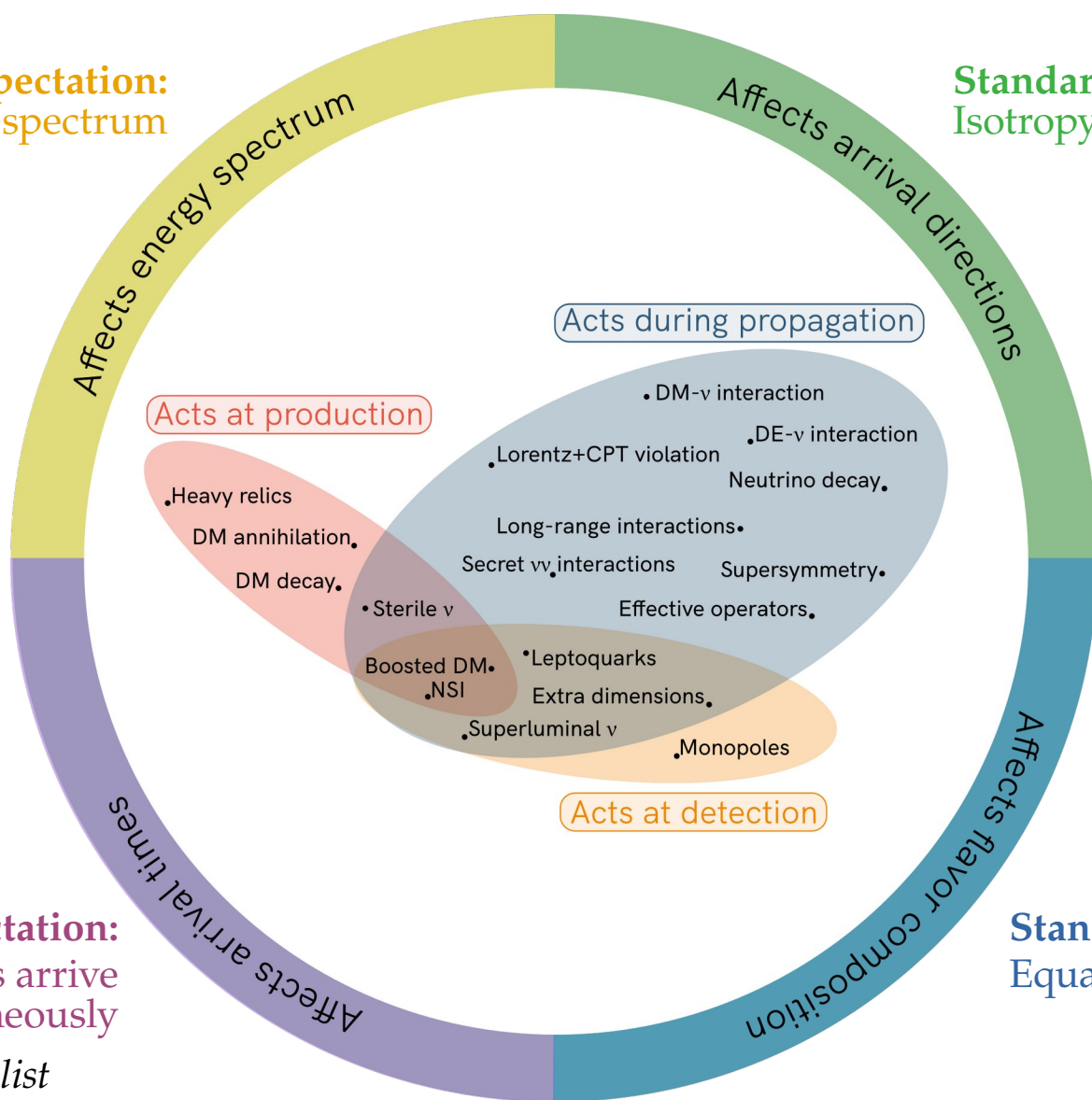
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Standard expectation:
 ν and γ from transients arrive
simultaneously

Standard expectation:
Equal number of ν_e , ν_μ , ν_τ

Note: Not an exhaustive list



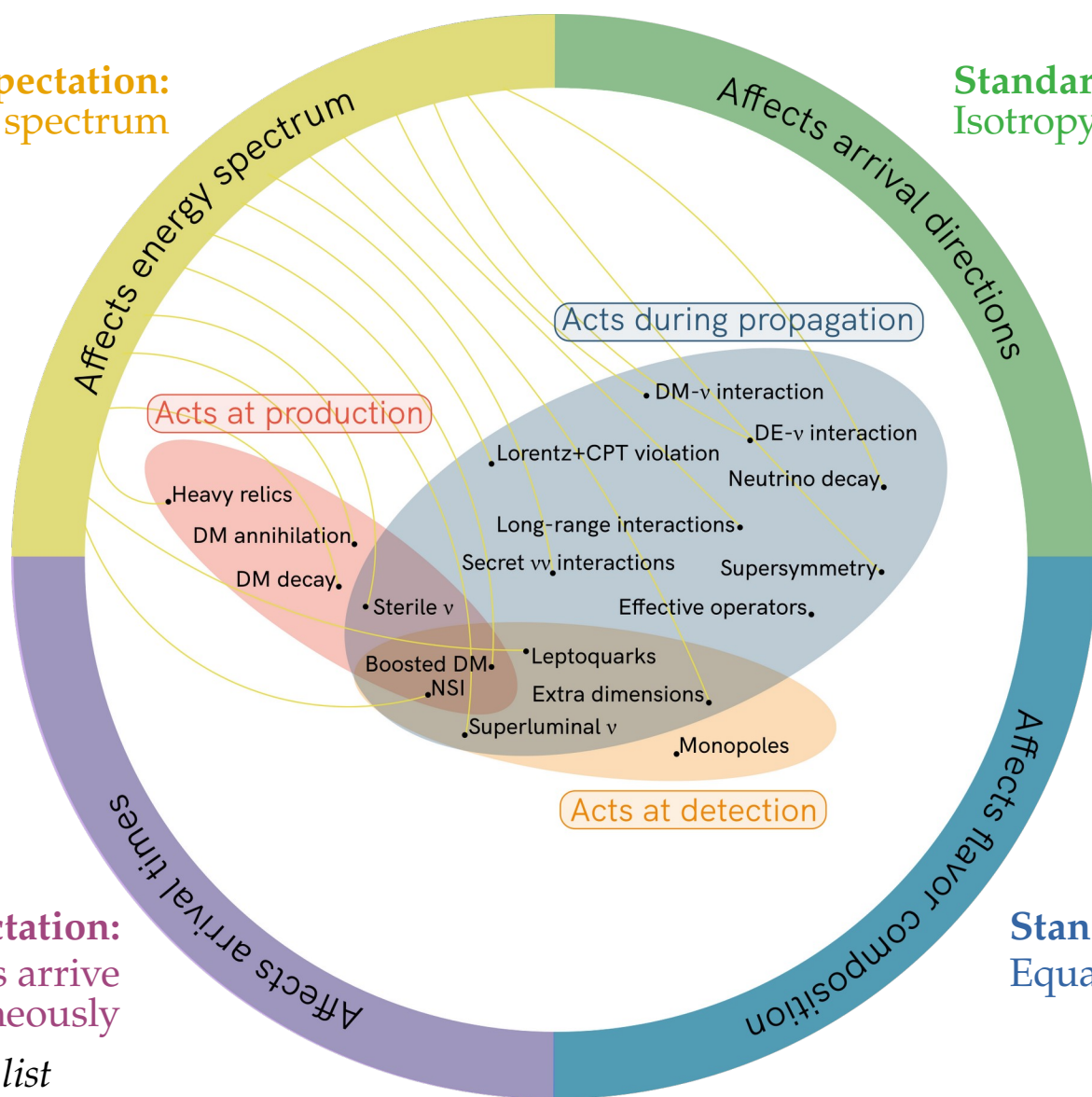
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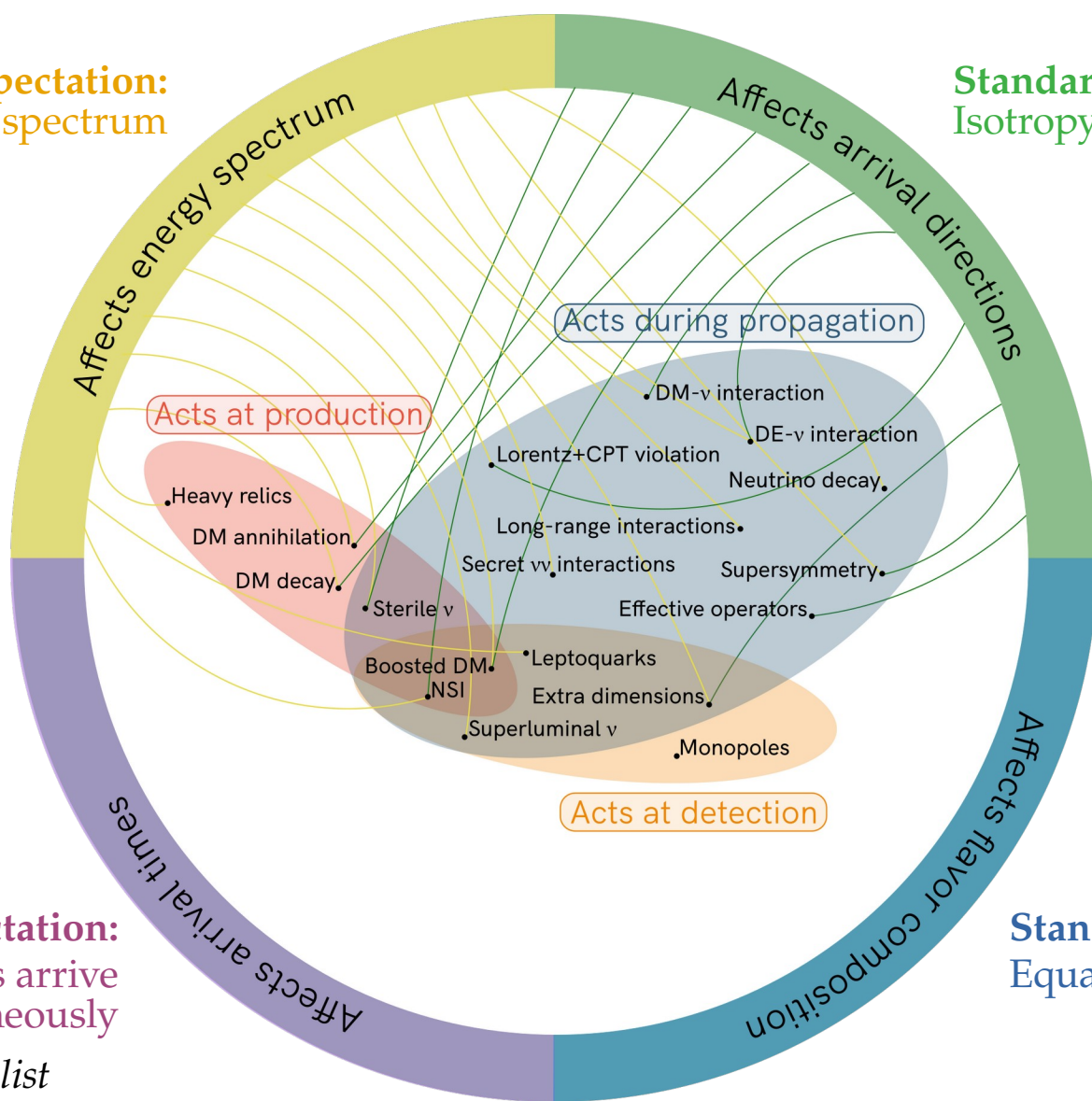
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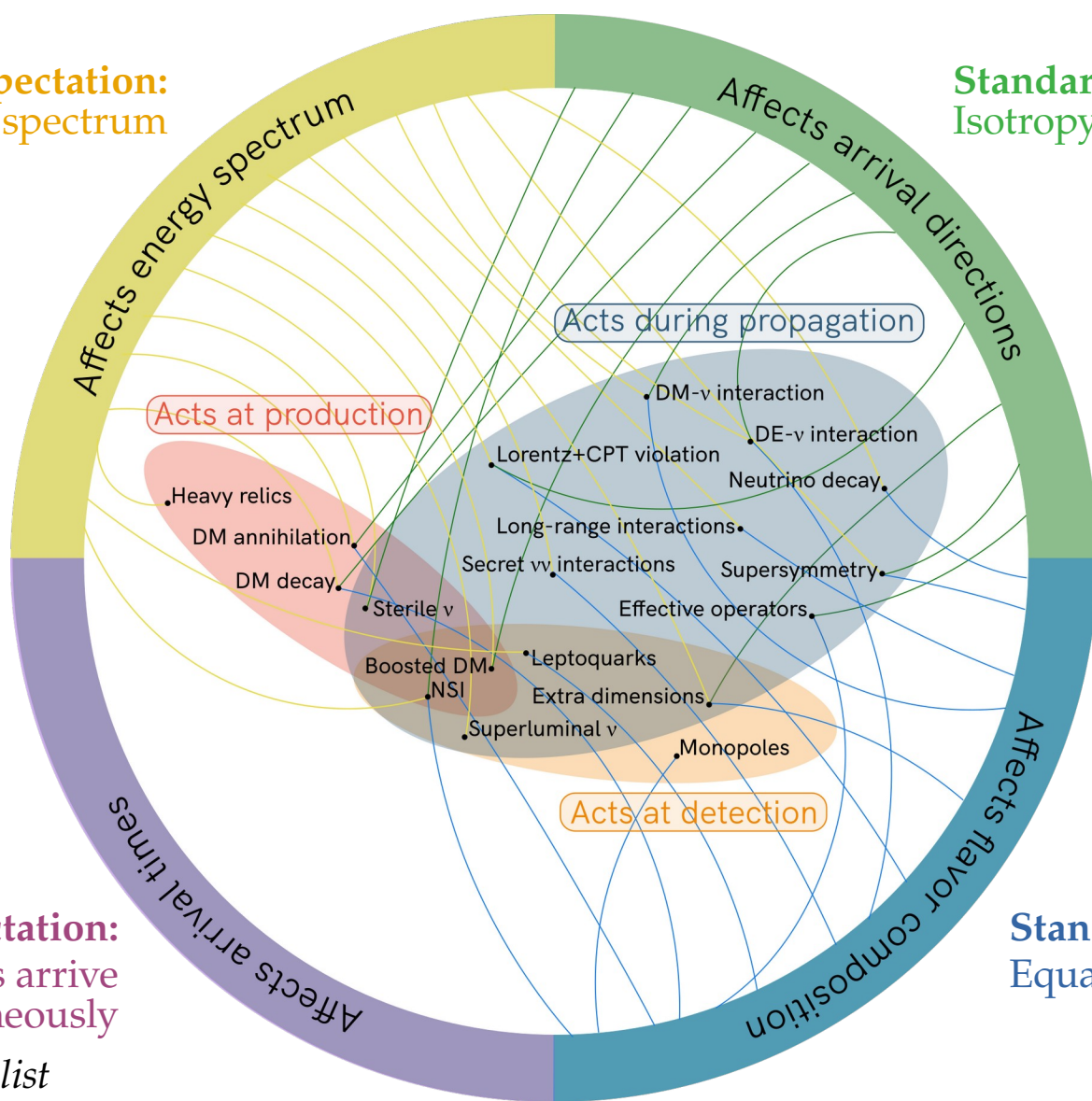
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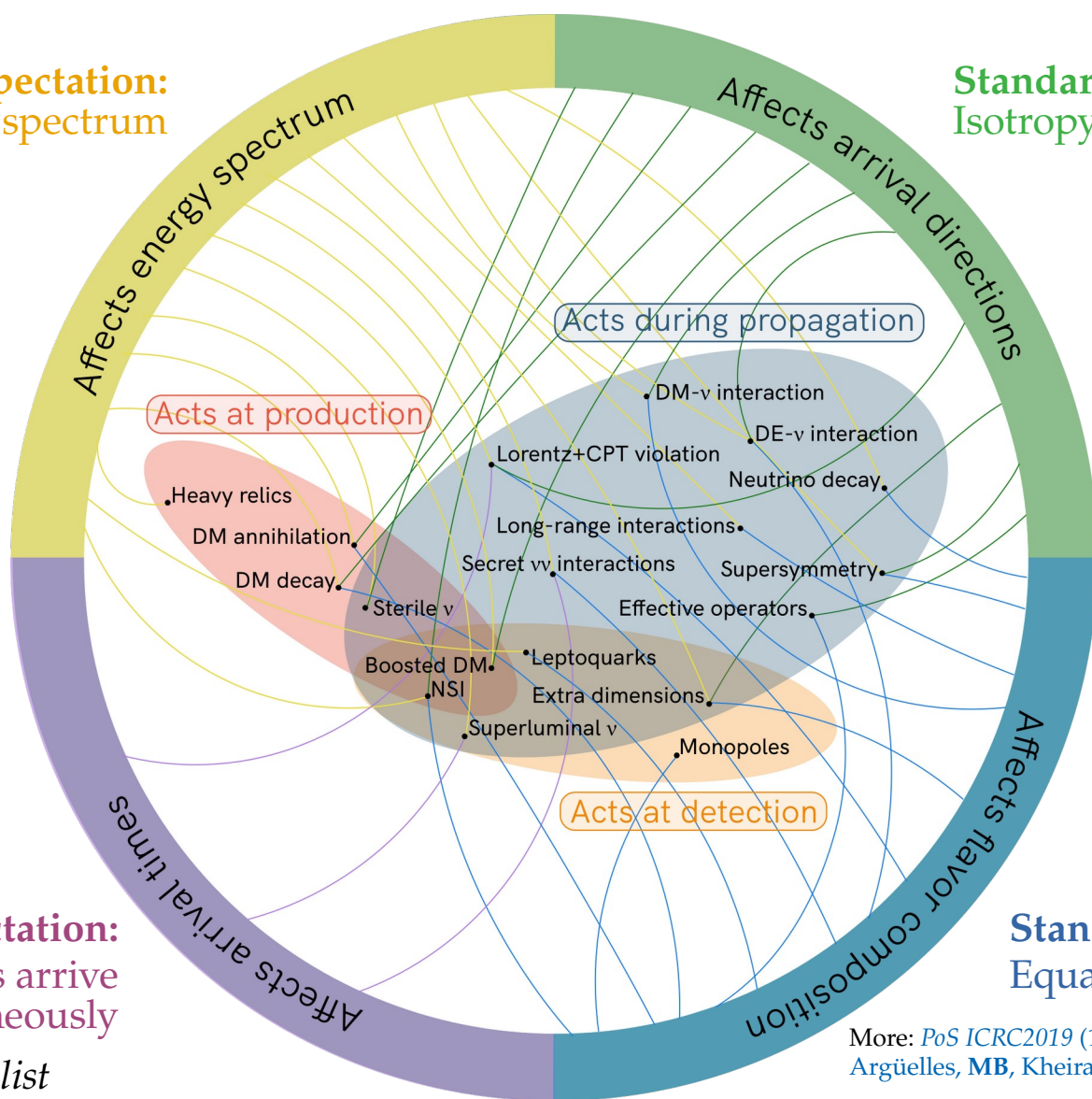
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More: *PoS ICRC2019* (1907.08690)

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

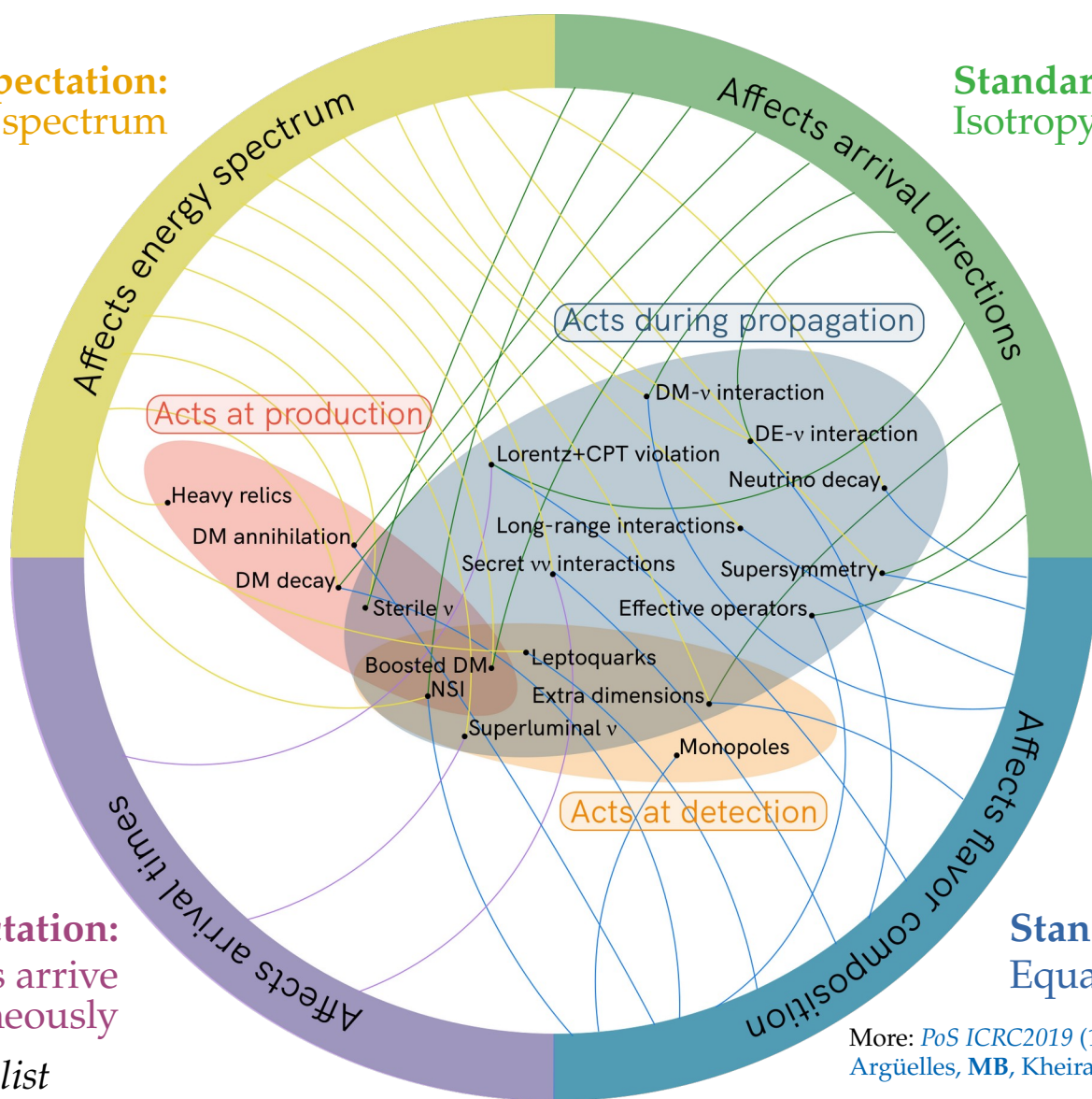
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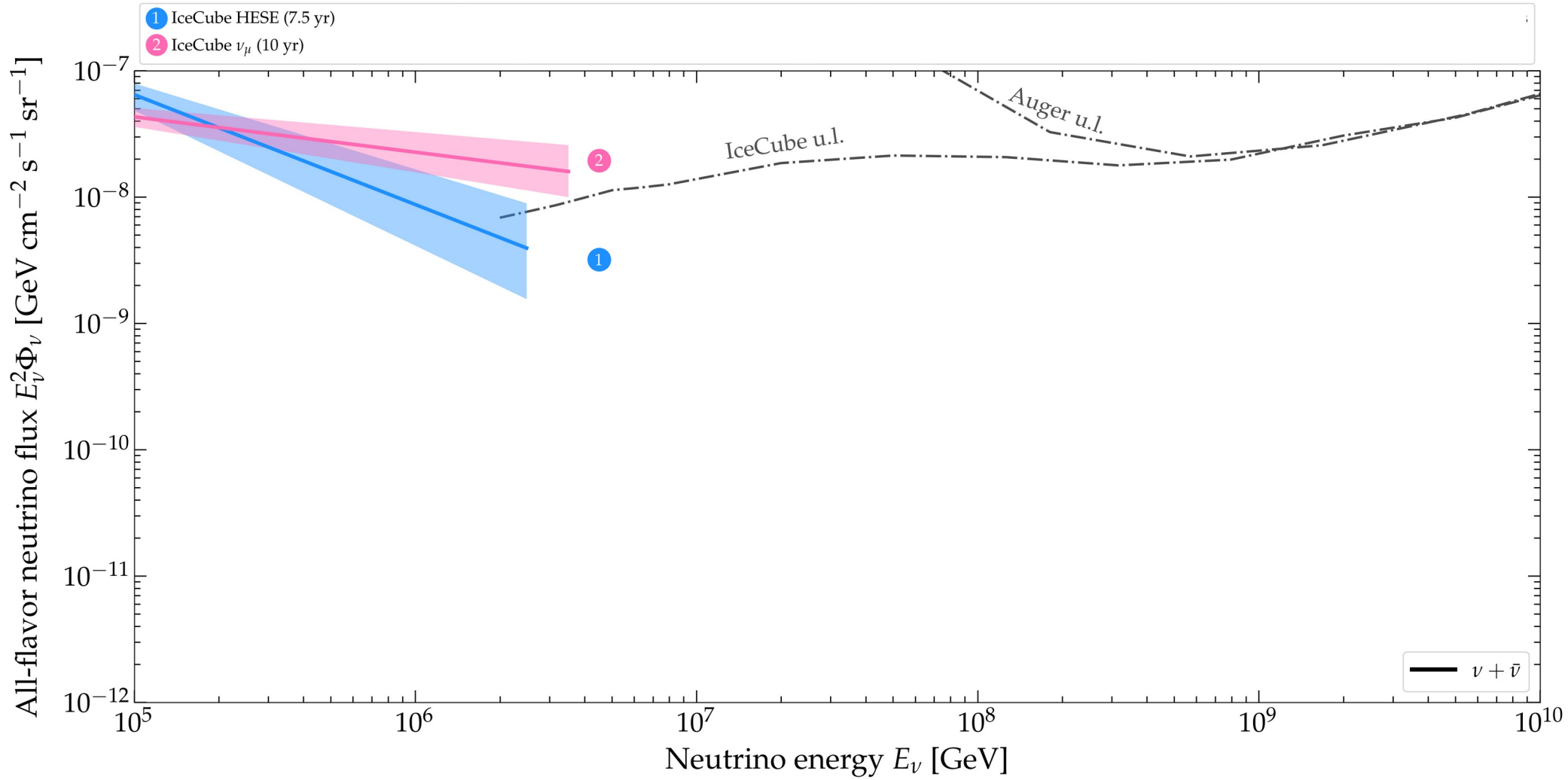
Reviews:
Ahlers, Helbing, De los Heros, *EPJC* 2018
Argüelles, MB, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, *ICRC* 2019 [1907.08690]
Ackermann, Ahlers, Anchordoqui, MB, et al., *Astro2020 Decadal Survey* [1903.04333]

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Today
TeV–PeV ν

Today
TeV–PeV ν

Turn predictions
into data-driven tests

Today

TeV–PeV ν

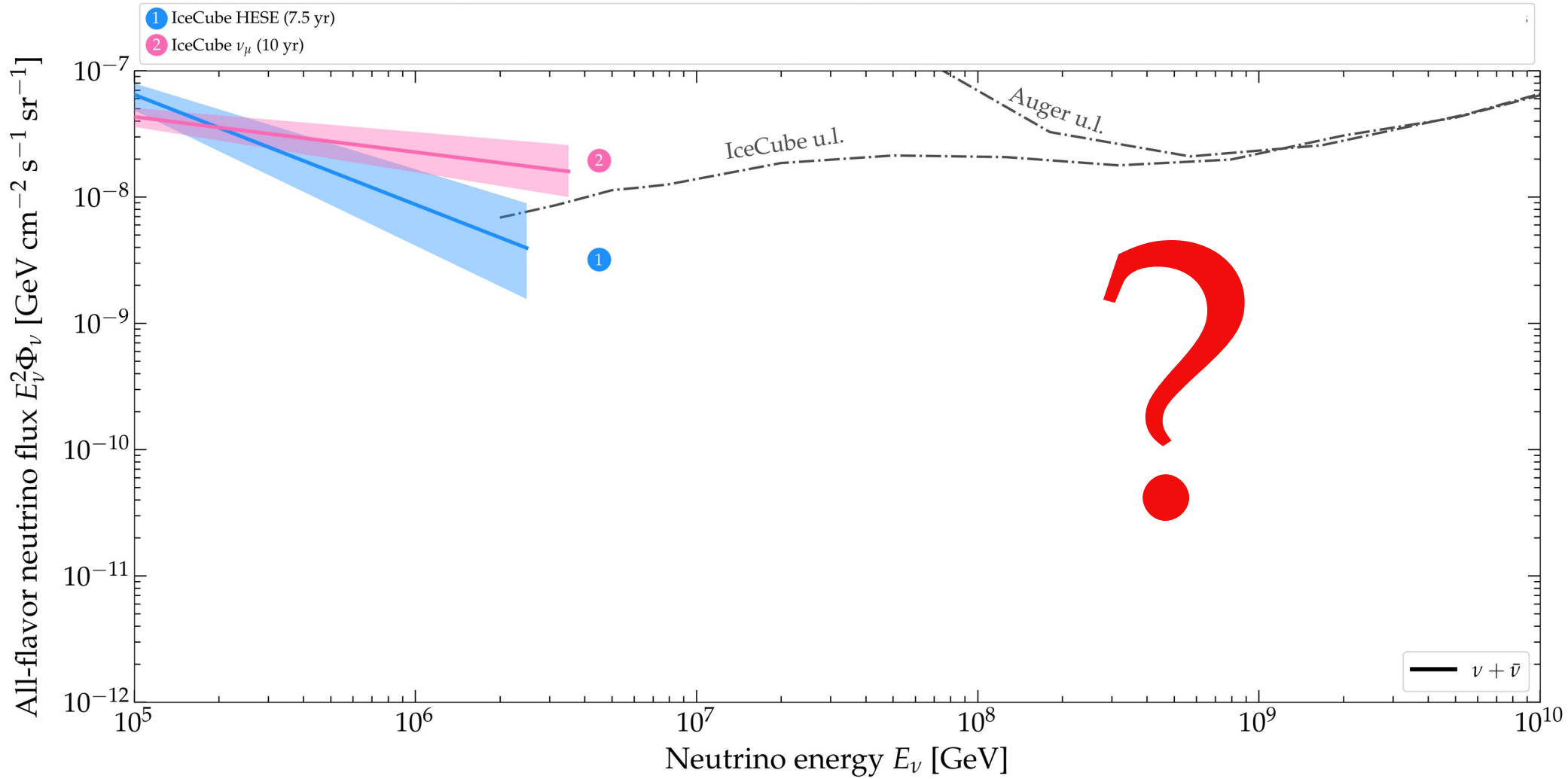
Turn predictions
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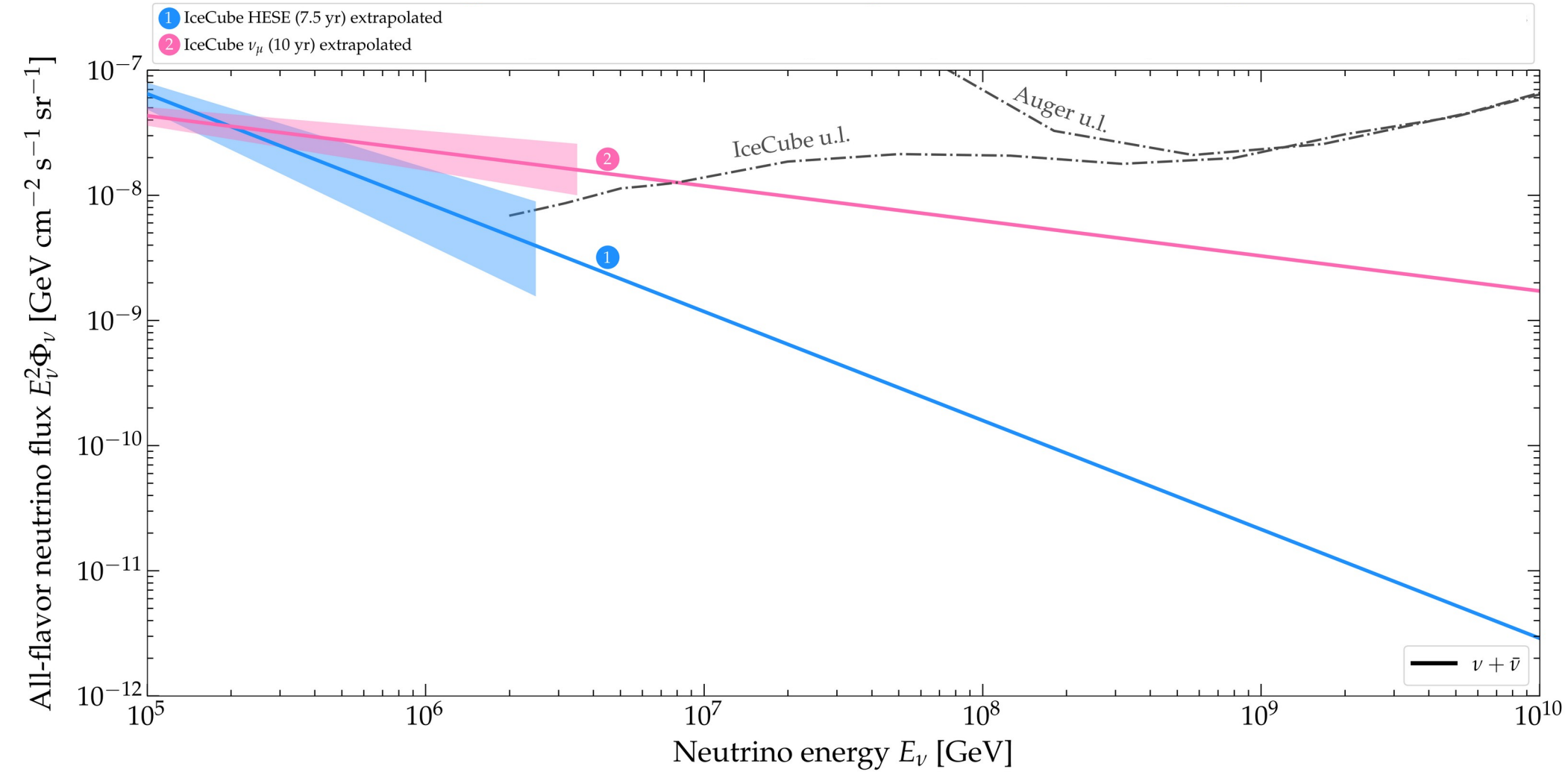
Key developments:

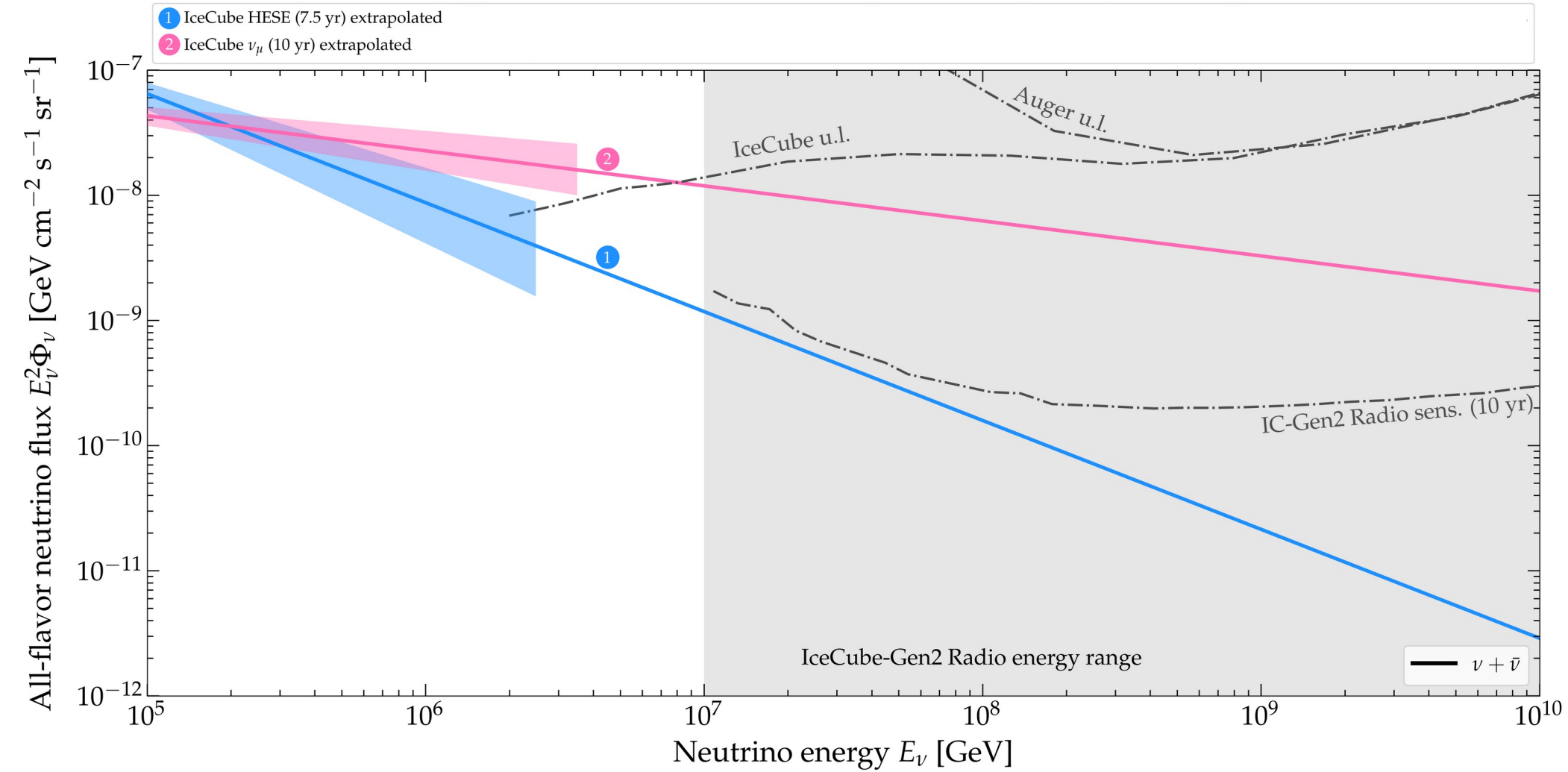
Bigger detectors $\rightarrow$ larger statistics

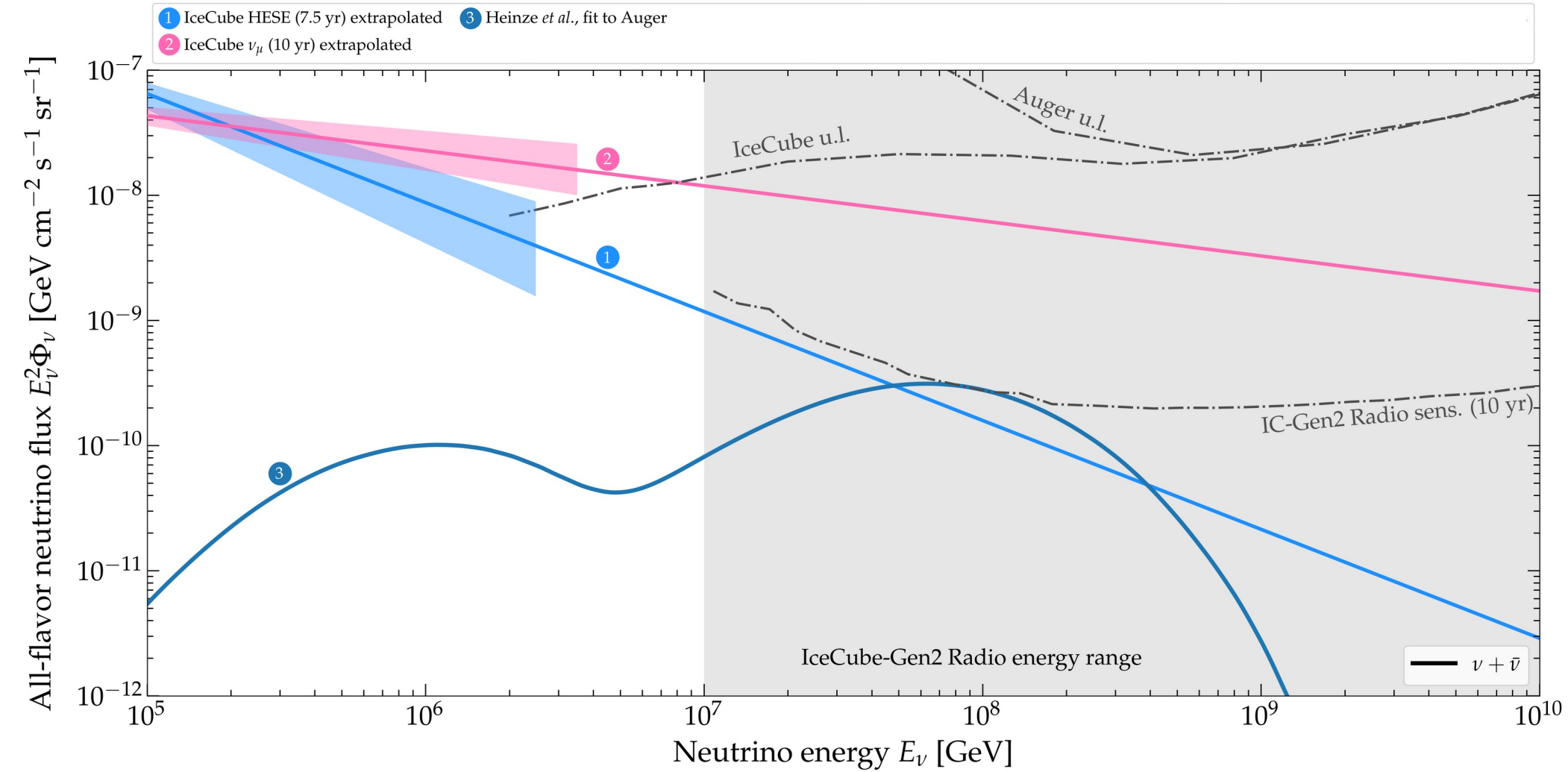
Better reconstruction

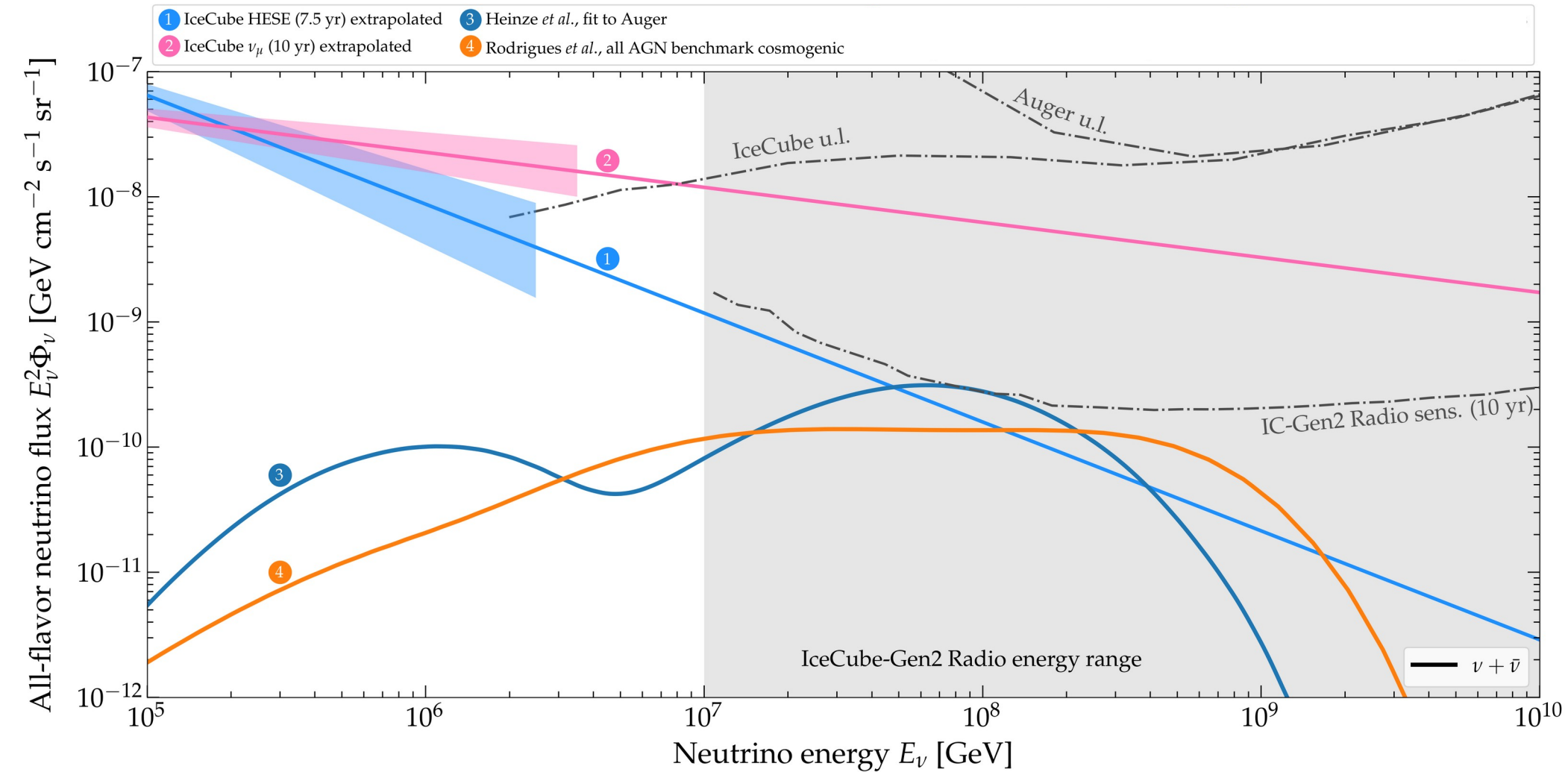
Smaller astrophysical uncertainties

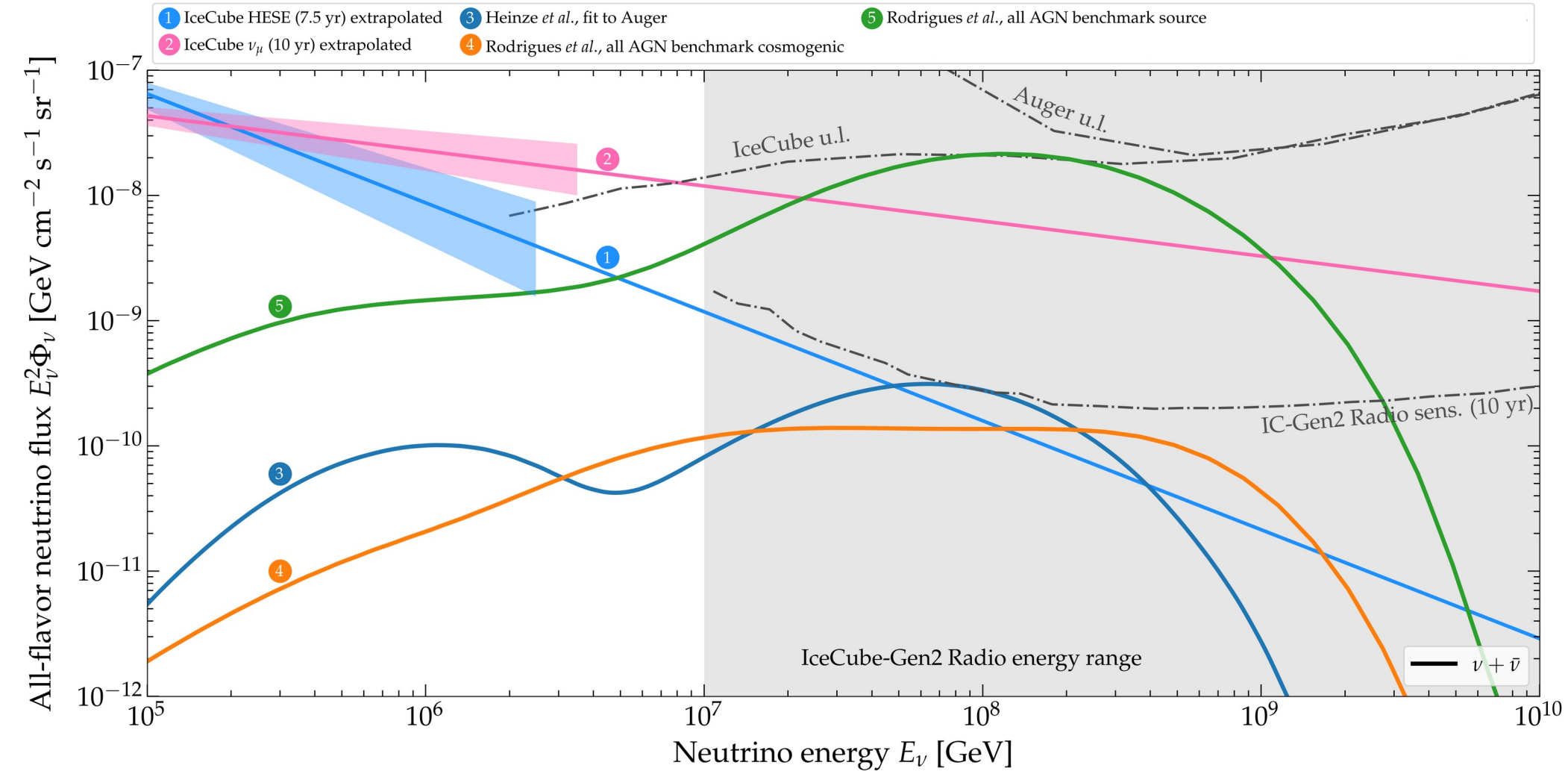


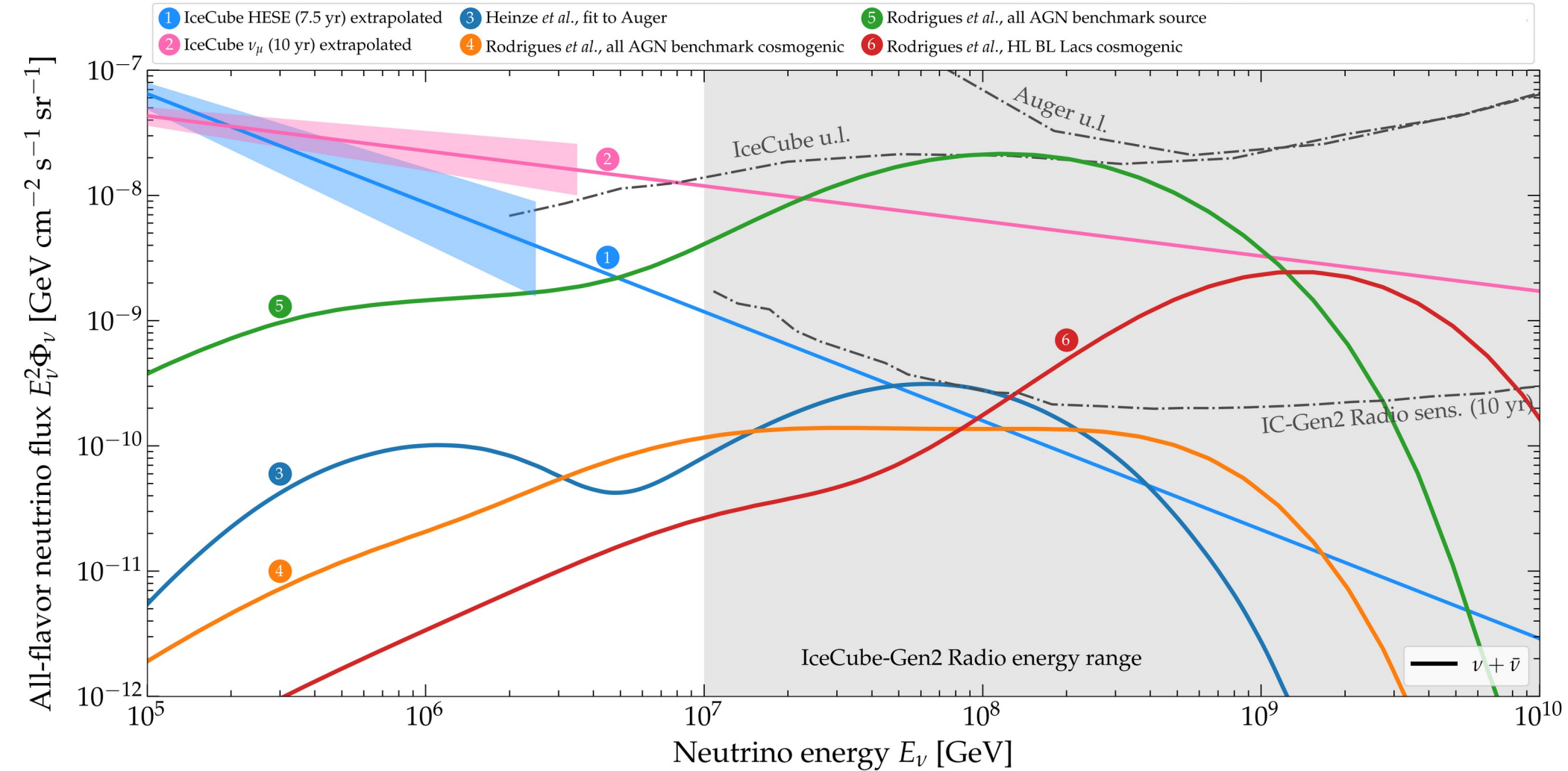


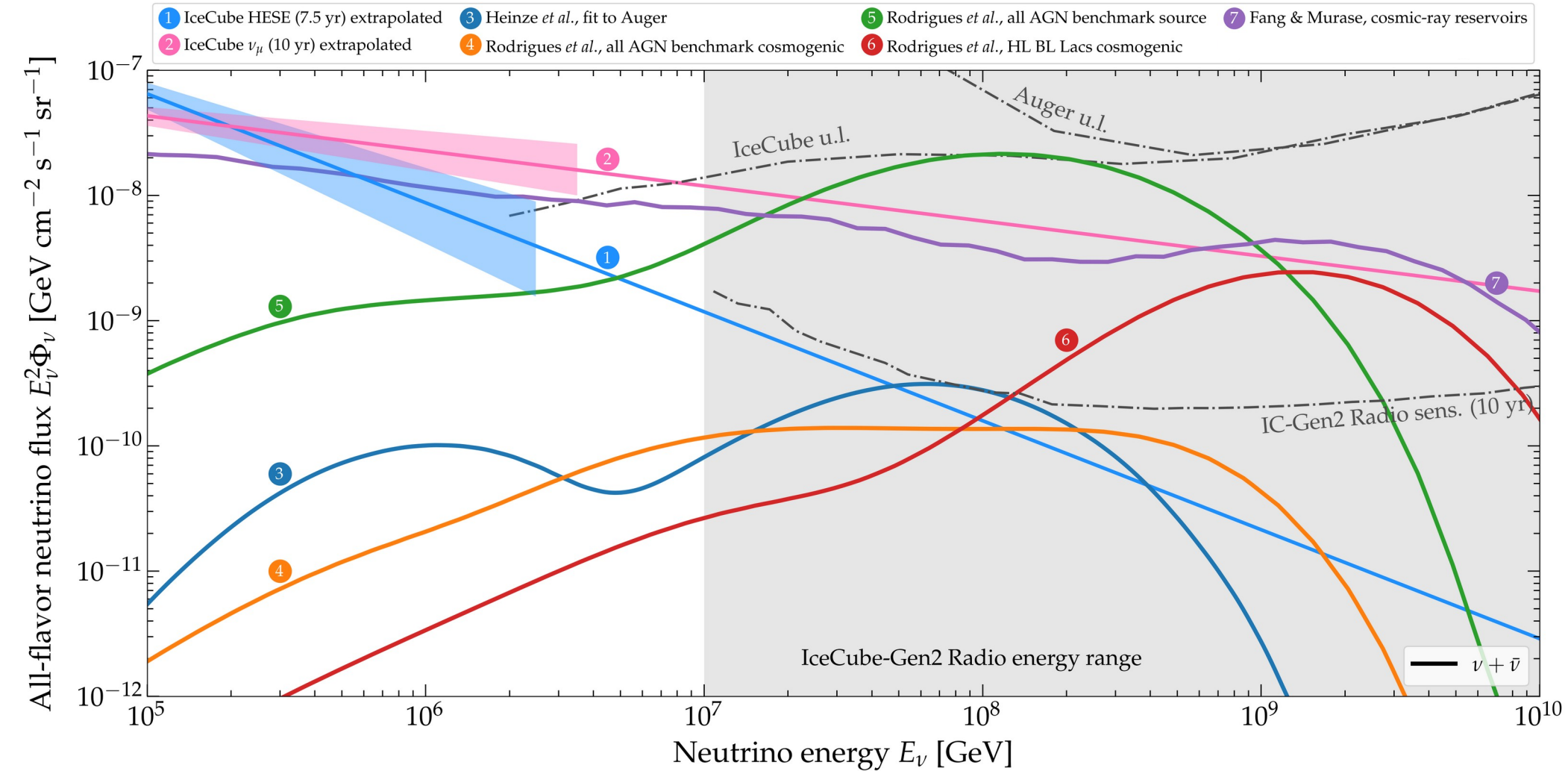


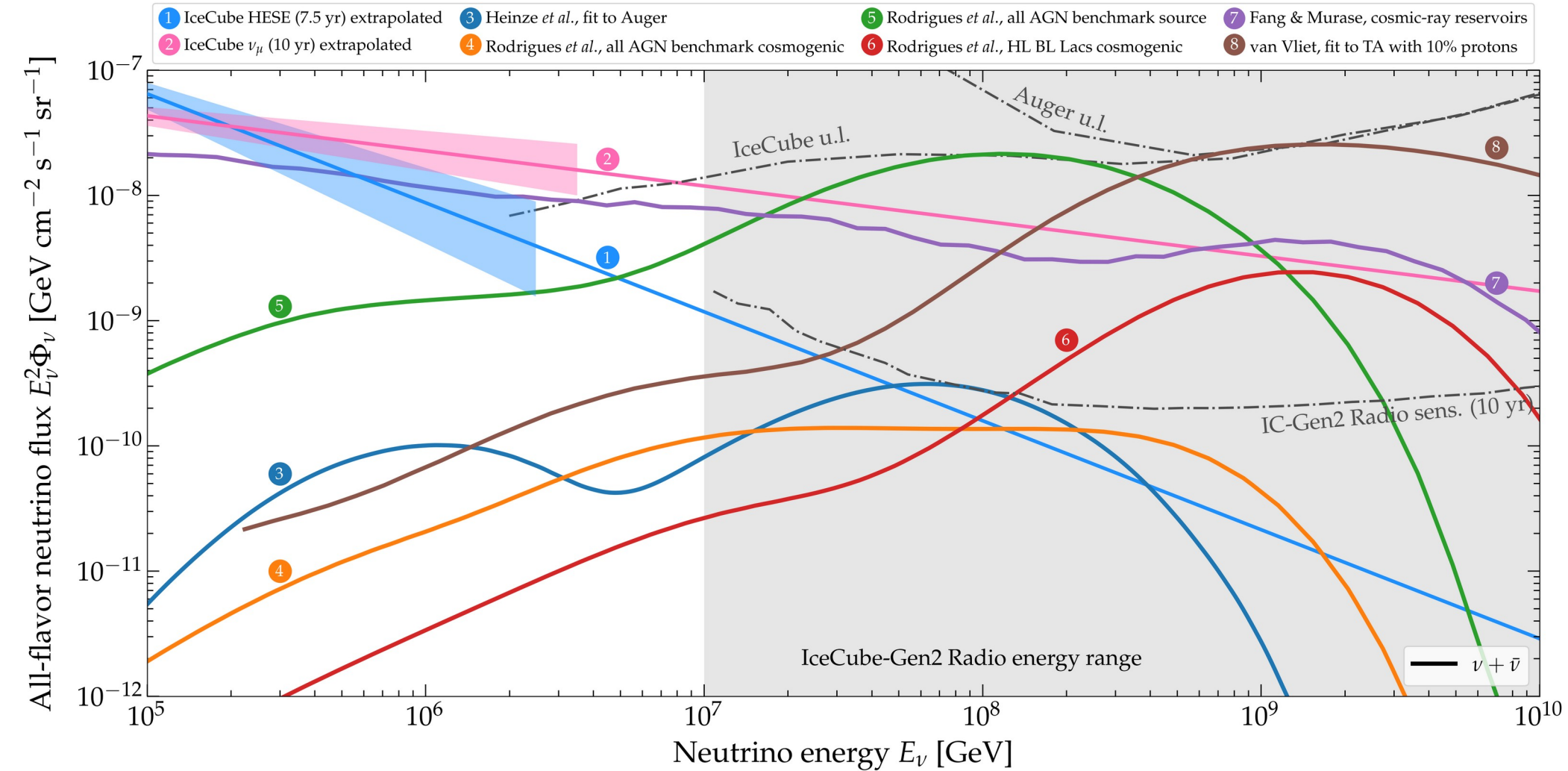


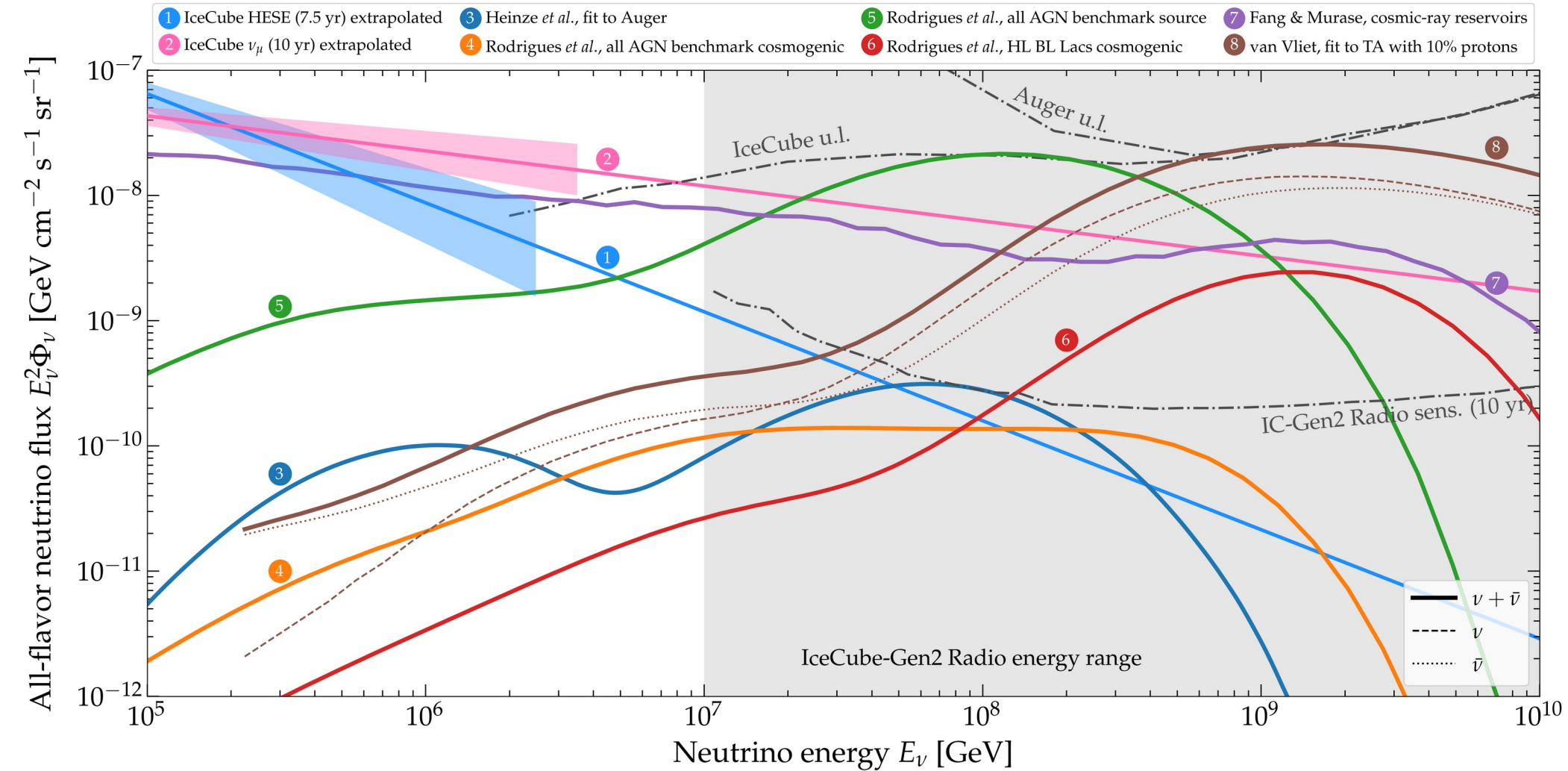


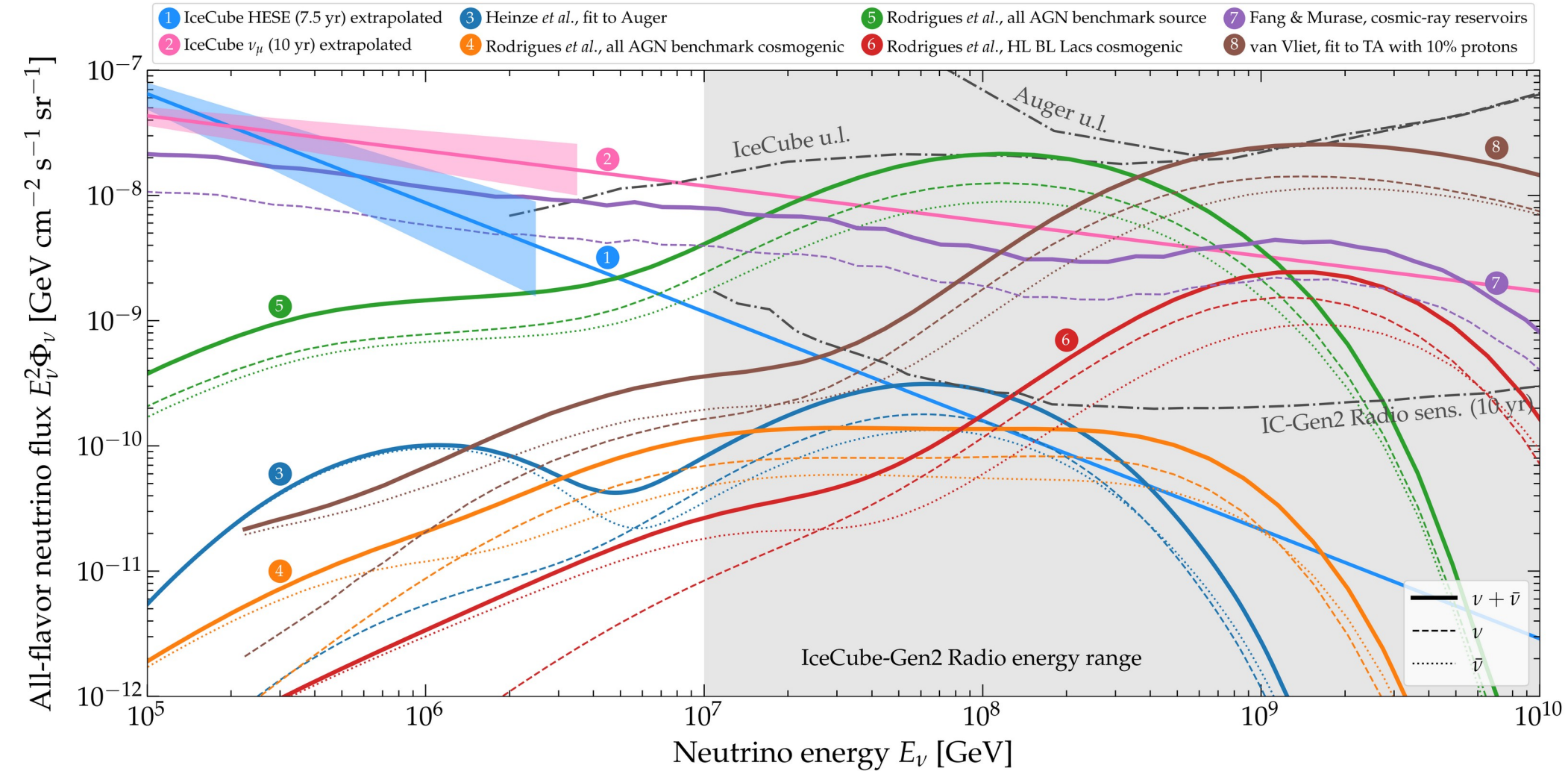












Today

TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:

Bigger detectors $\rightarrow$ larger statistics

Better reconstruction

Smaller astrophysical uncertainties

Today
TeV–PeV ν

Turn predictions
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Next decade
 > 100 -PeV ν

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Turn predictions
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Key developments:

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Next decade
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Make predictions for
a new energy regime

Today
TeV–PeV ν

Turn predictions
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Key developments:

Bigger detectors $\rightarrow$ larger statistics

Better reconstruction

Smaller astrophysical uncertainties

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Key developments:

Discovery

New detection techniques

Better UHE ν flux predictions

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Turn predictions
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Smaller astrophysical uncertainties

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

Turn predictions
into data-driven tests

Key developments:

Bigger detectors $\rightarrow$ 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

Two examples

1 Flavor stuff

2 Cross-section stuff

Good chances of discovery
or setting strong bounds

*Keep ourselves grounded by accounting for all
relevant particle and astrophysics unknowns*

Flavor:

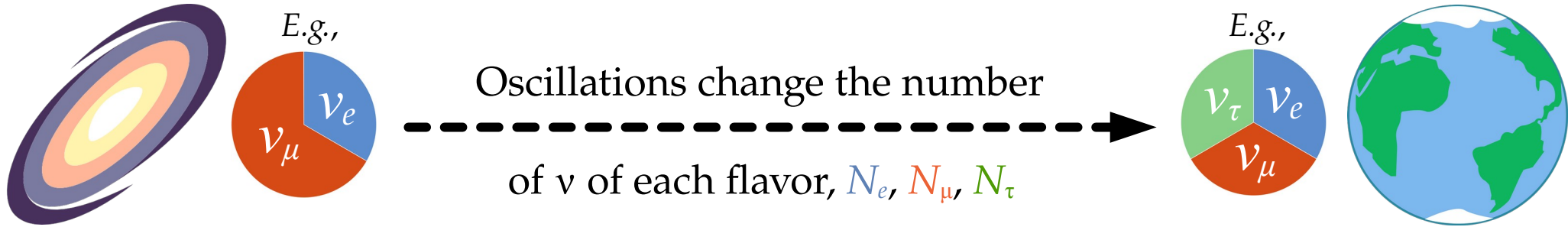
Towards precision, finally

(with the help of lower-energy experiments)

Astrophysical sources

Earth

Up to a few Gpc



Different production mechanisms yield different flavor ratios:

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

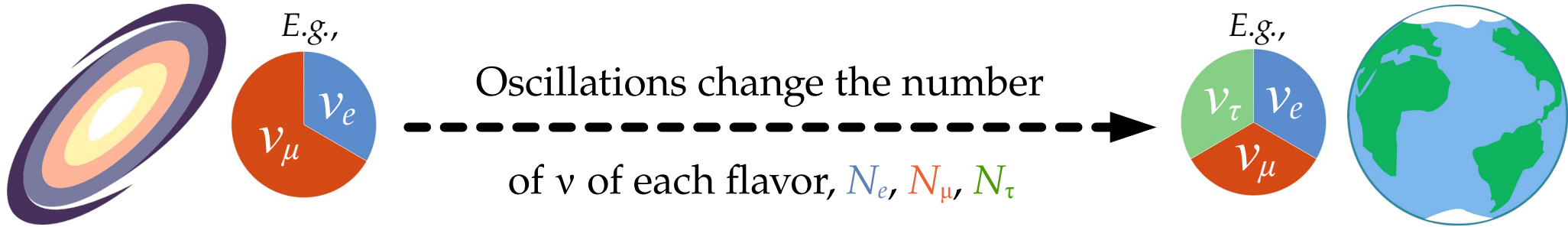
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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

Astrophysical sources

Earth

Up to a few Gpc



Different production mechanisms yield different flavor ratios:

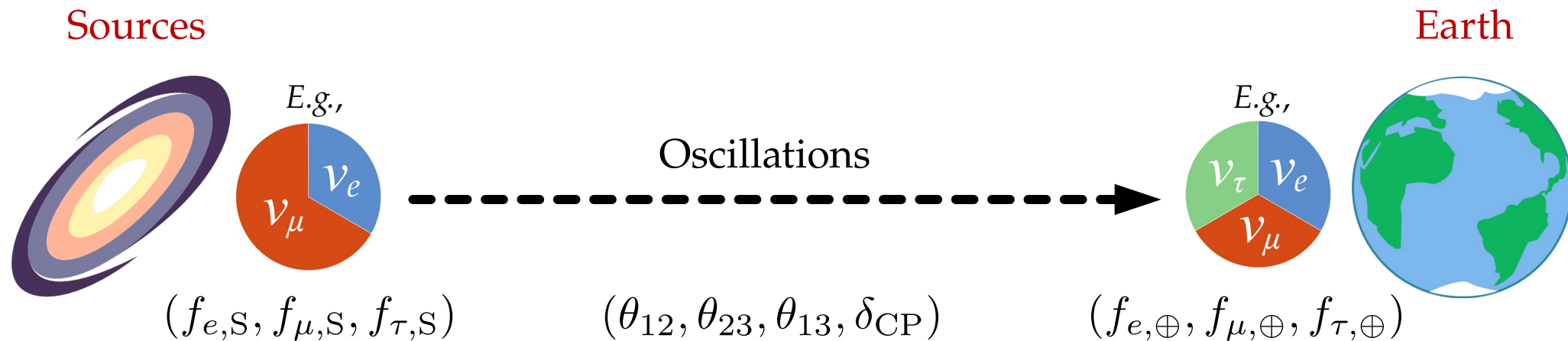
$$(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S}) / N_{\text{tot}}$$

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

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

Standard oscillations
or
new physics

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



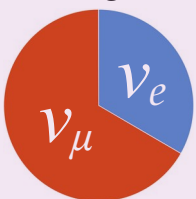
From Earth to sources: we let the data teach us about $f_{\alpha,S}$

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

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

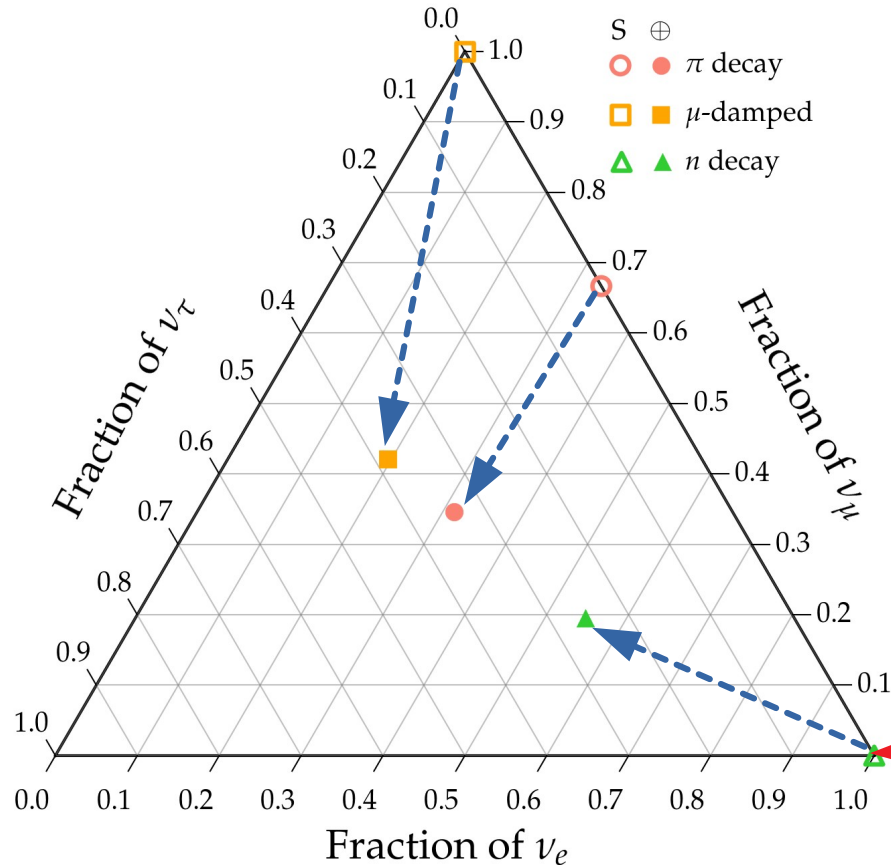
Earth



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

One likely TeV–PeV ν production scenario:

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



Full π decay chain

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

Muon damped

$(0:1:0)_S$

Neutron decay

$(1:0:0)_S$

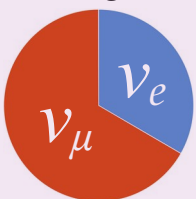
Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

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

Sources



E.g.,



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

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

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

MB, Beacom, Winter, PRL 2015

Allowed regions of flavor ratios at Earth derived from oscillations

Note:

The original palatable regions were
frequentist [MB, Beacom, Winter, PRL 2015];
the new ones are Bayesian

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

MB, Beacom, Winter, PRL 2015

Allowed regions of flavor ratios at Earth derived from oscillations

Ingredient #1:

Flavor ratios at the source,

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

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

or

Explore all possible combinations

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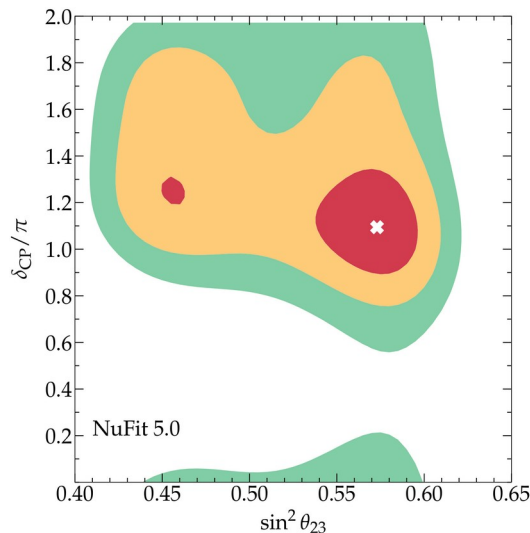
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2020: Use χ^2 profiles from
the NuFit 5.0 global fit
(solar + atmospheric
+ reactor + accelerator)

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



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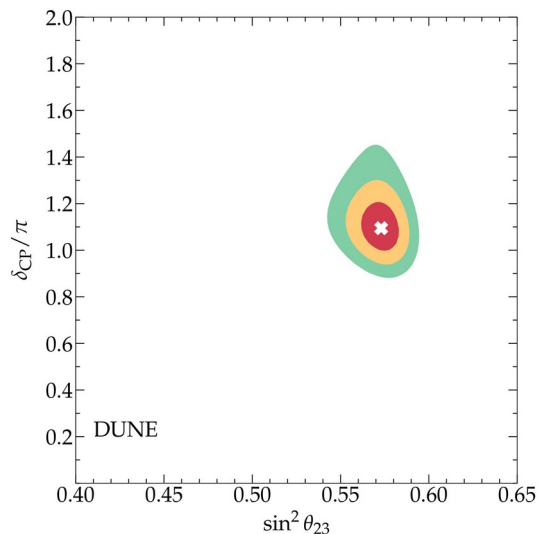
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

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

Post-2020: Build our own profiles using simulations of JUNO, DUNE, Hyper-K

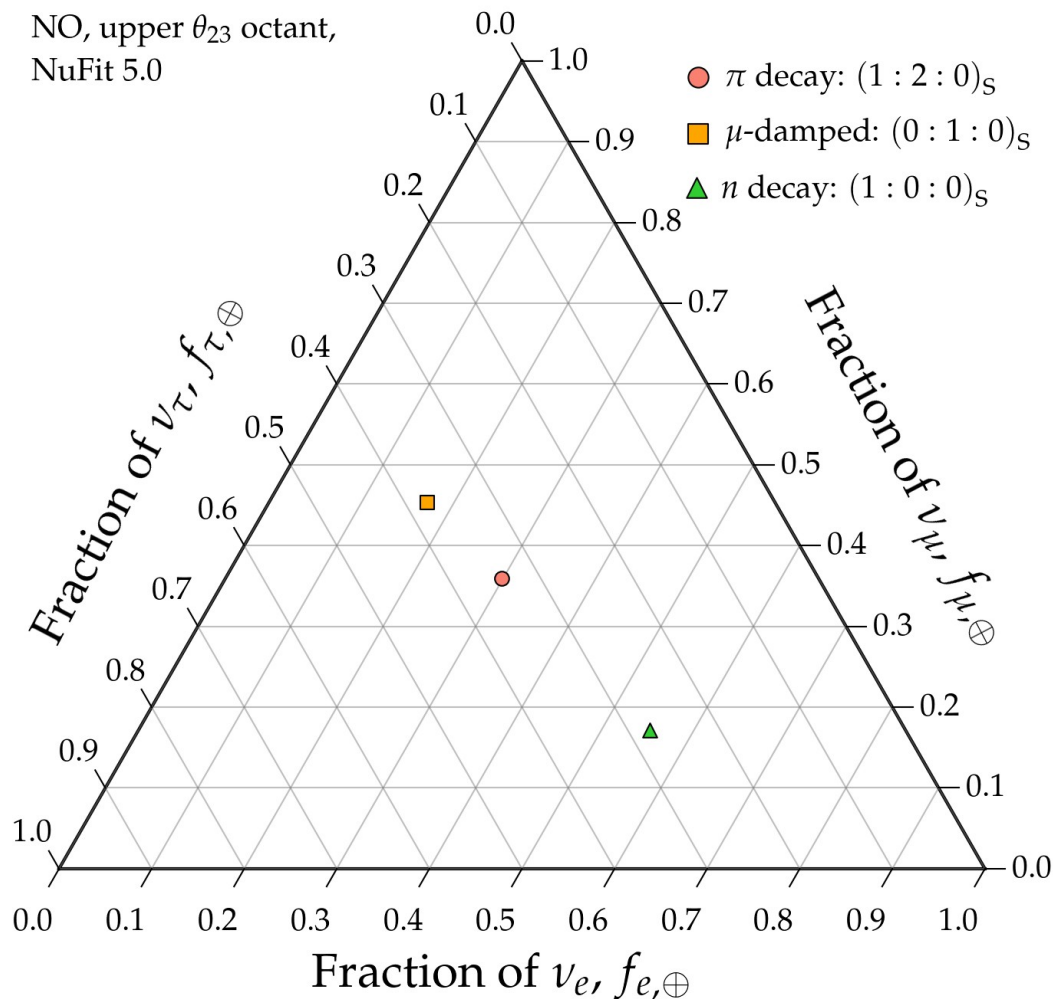
An *et al.*, *J. Phys. G* 2016
DUNE, 2002.03005

Huber, Lindner, Winter, *Nucl. Phys. B* 2002



Theoretically palatable regions: today (2021)

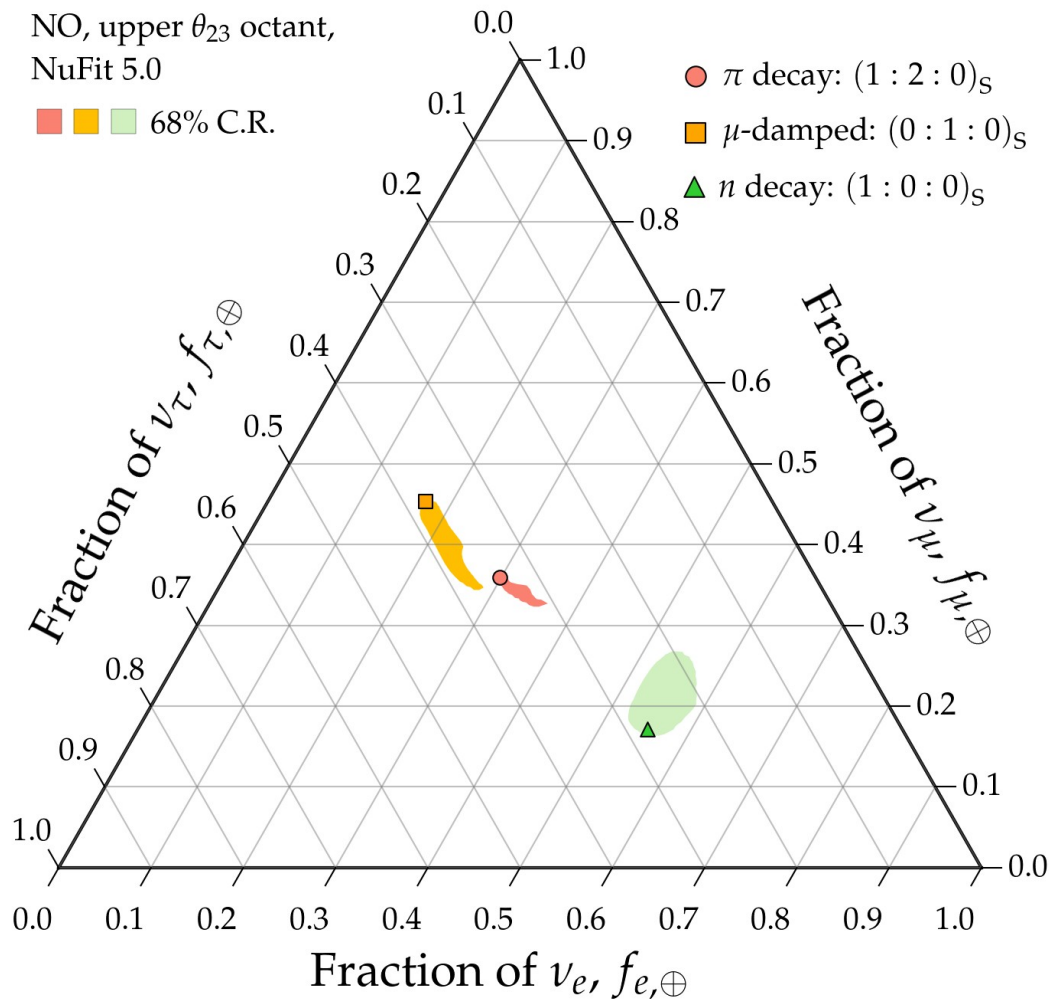
NO, upper θ_{23} octant,
NuFit 5.0



Note:

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

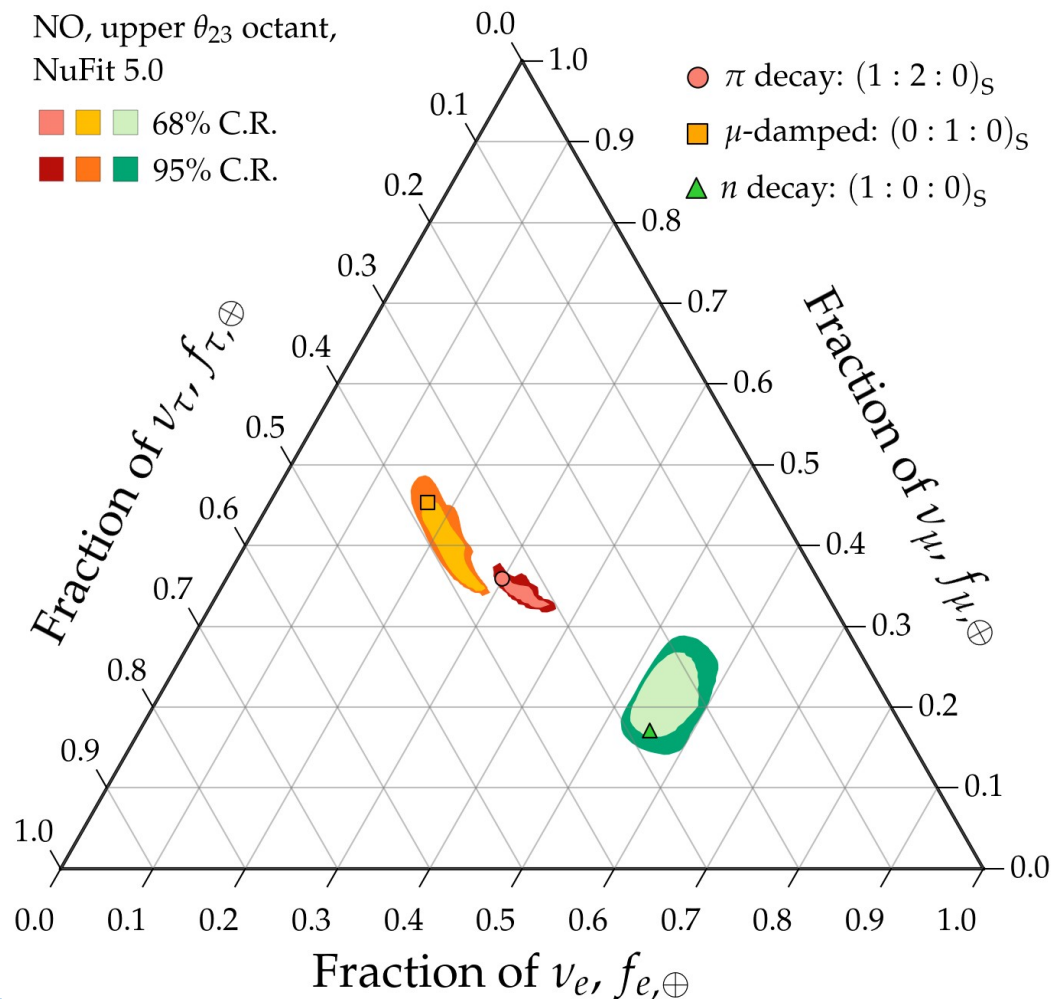
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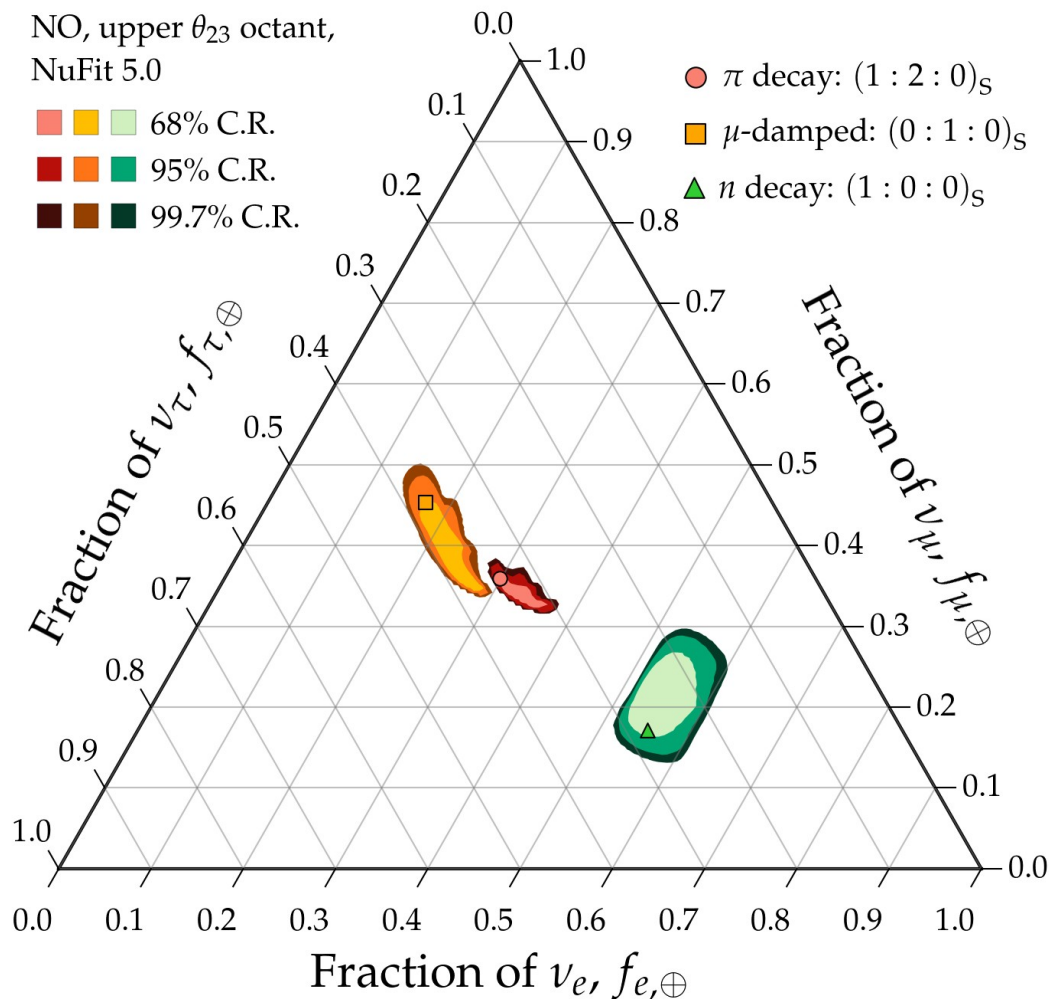
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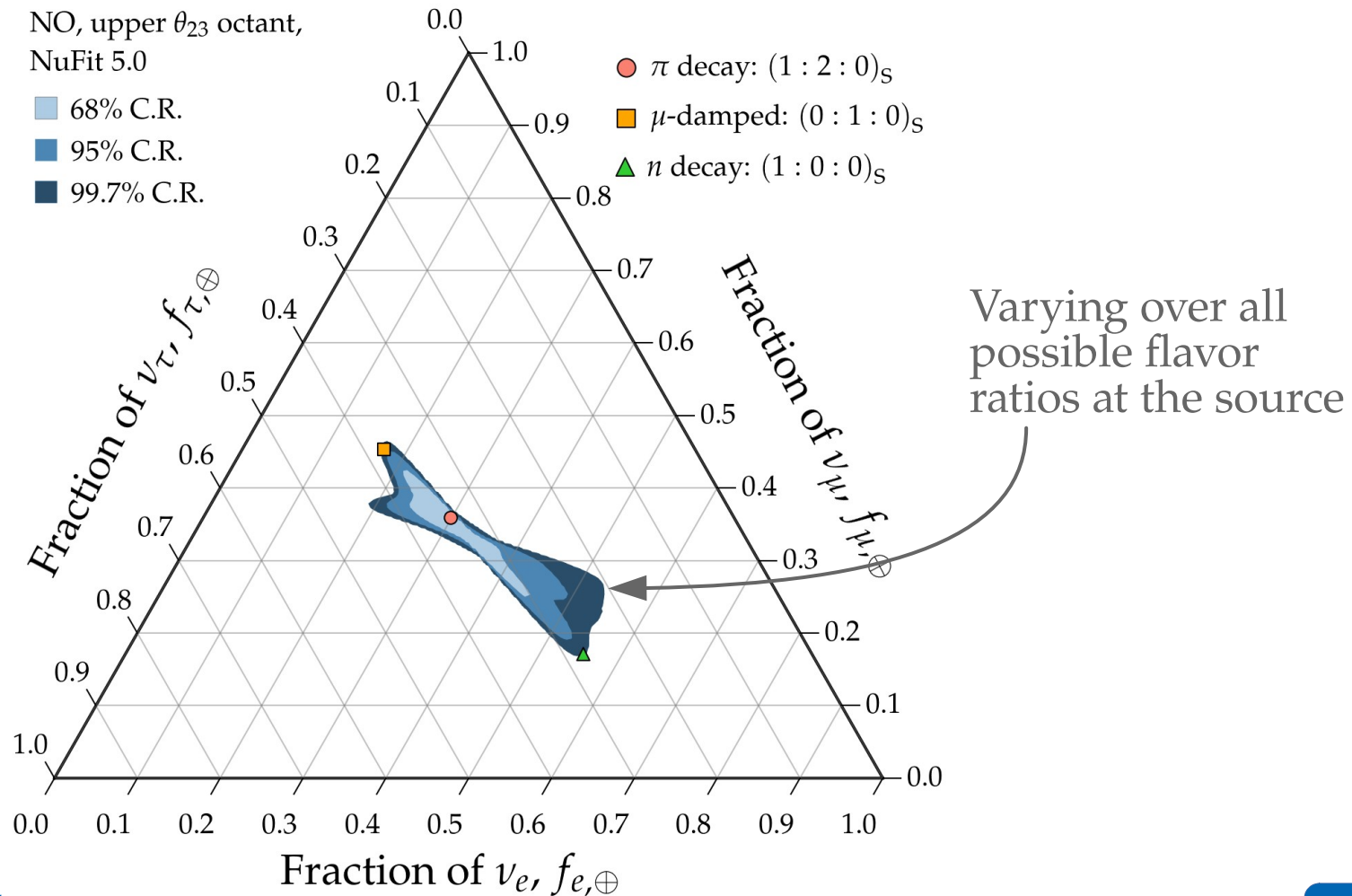
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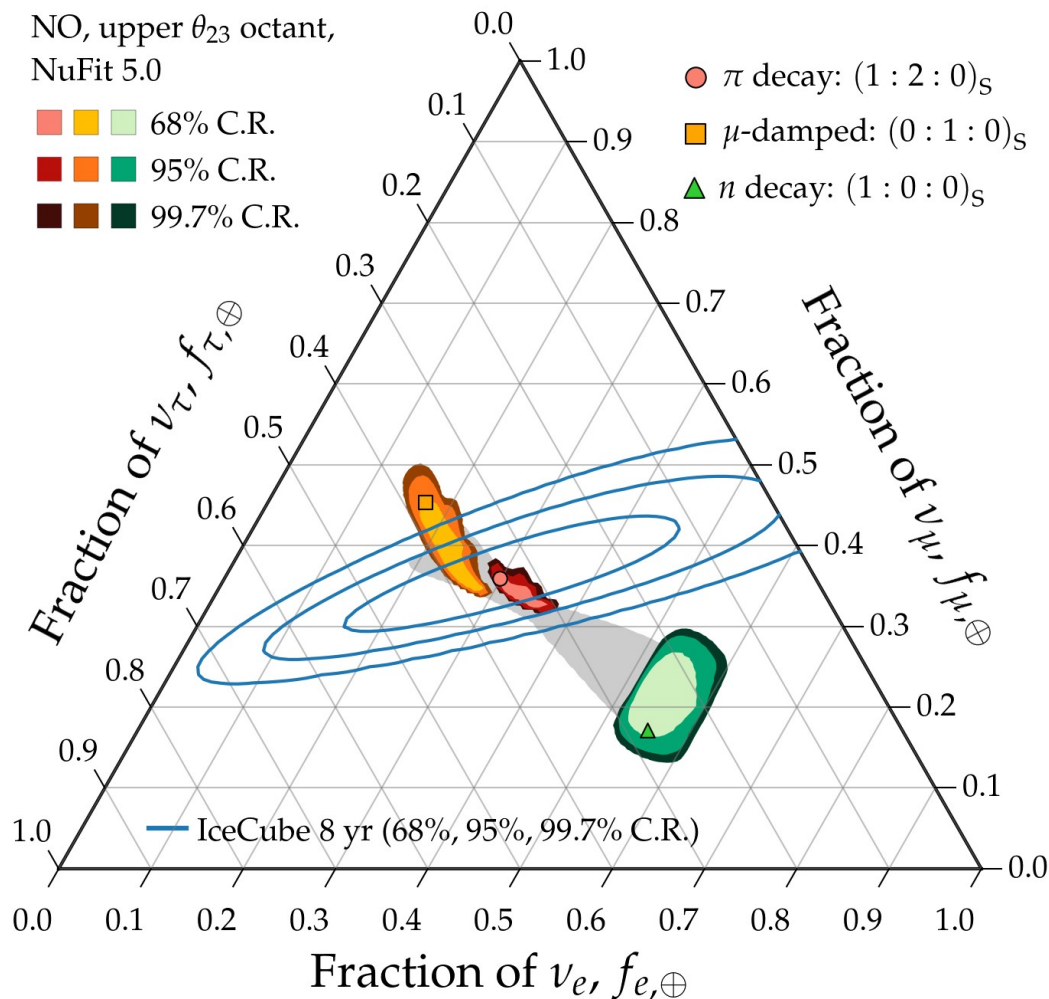
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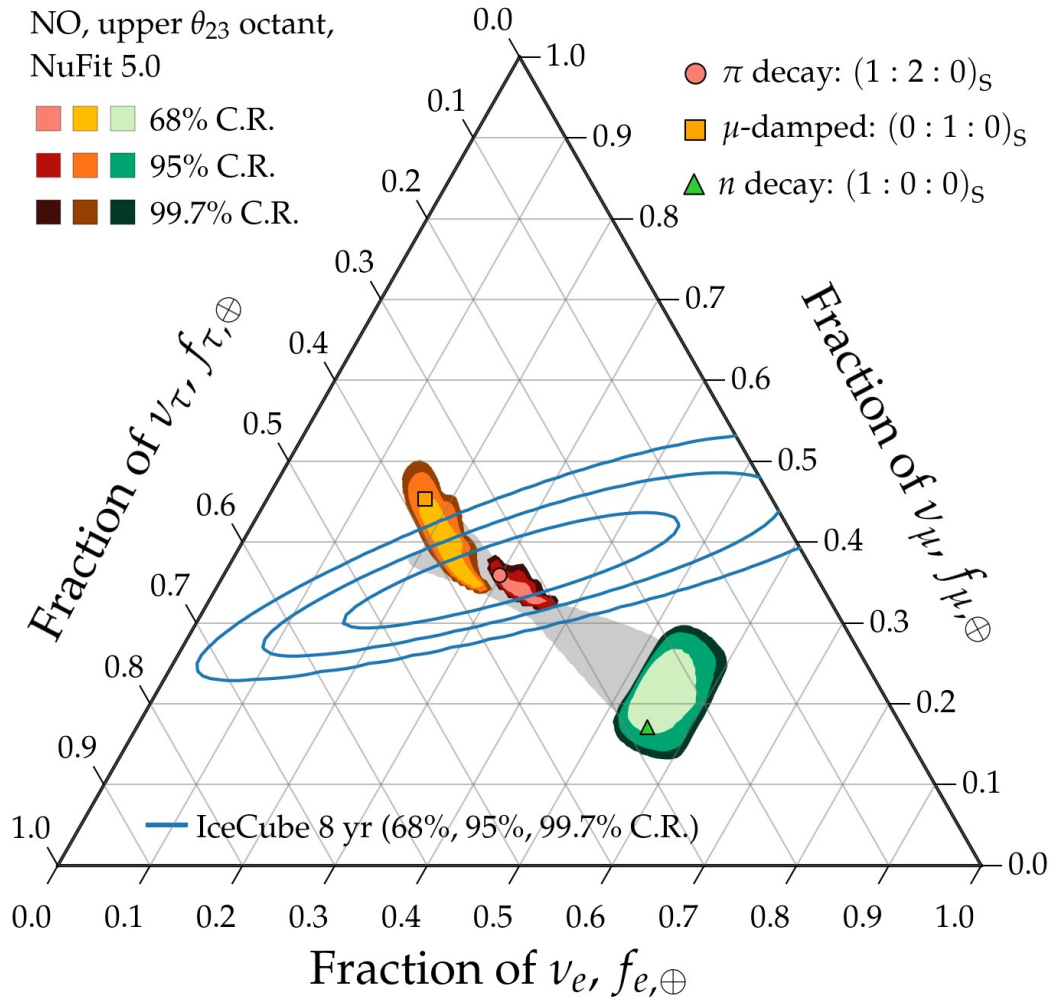
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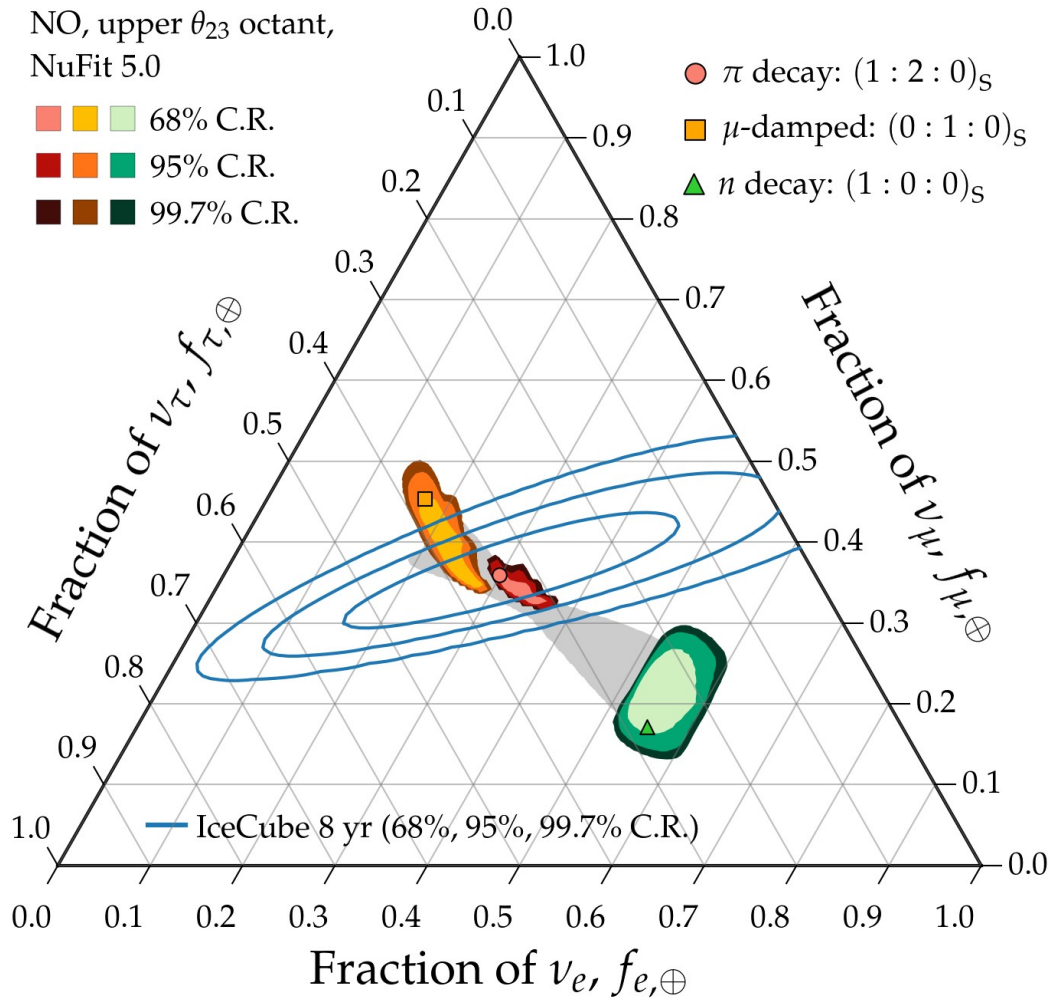


Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the
mixing parameters

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

Theoretically palatable regions: today (2021)



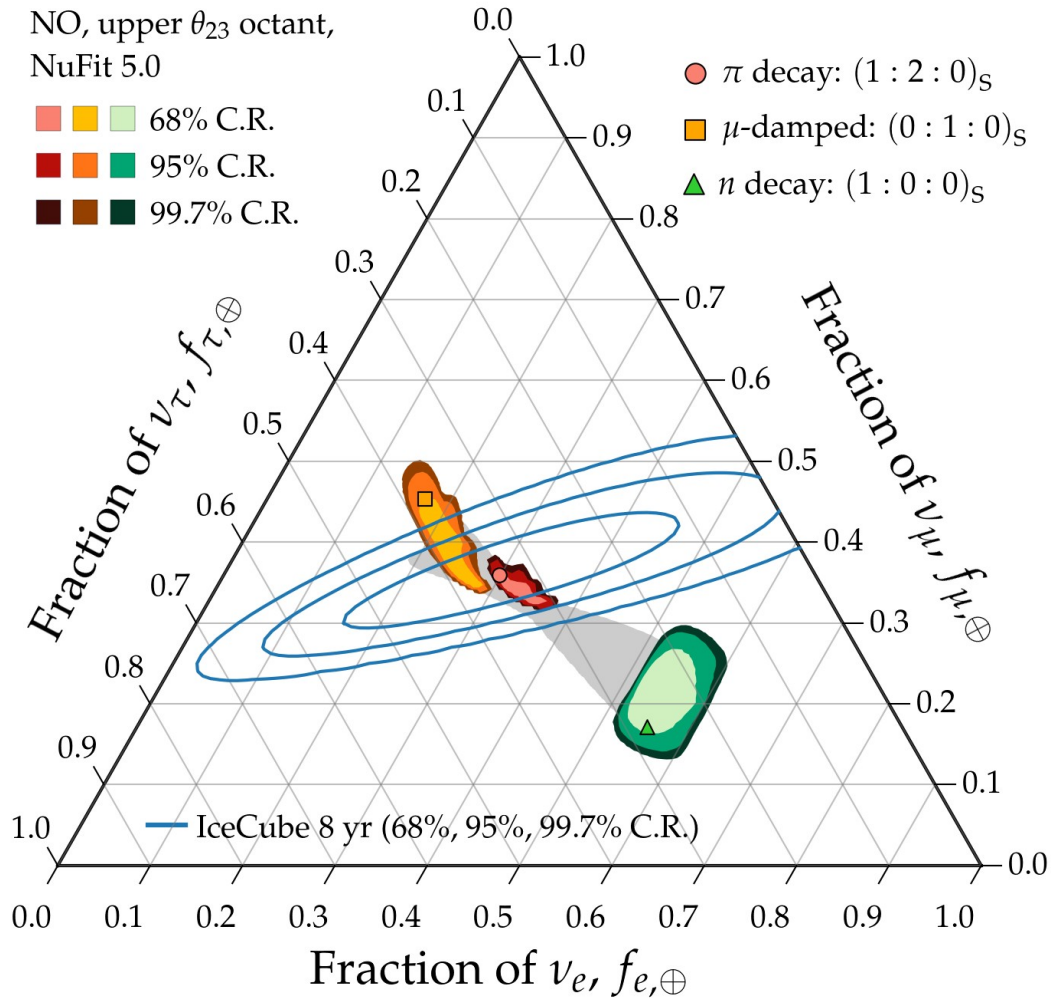
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Will be overcome by 2030

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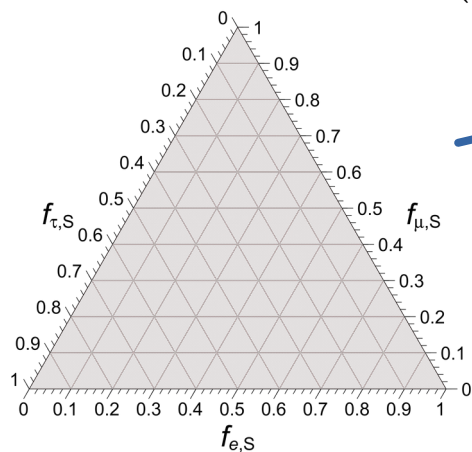
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Will be overcome by 2040

Measuring the neutrino lifetime

Sources

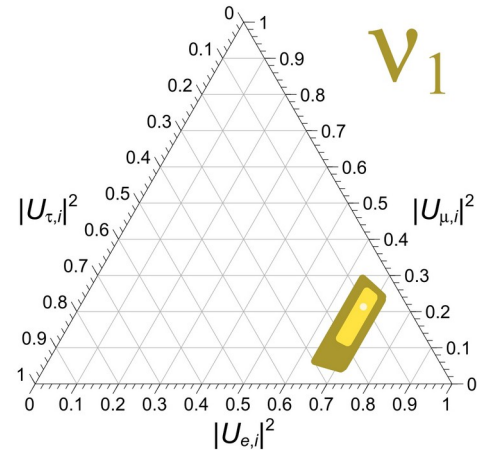


$\underbrace{\nu_{2'}, \nu_3 \rightarrow \nu_1}_{\nu_1 \text{ lightest and stable (normal mass ordering)}}$

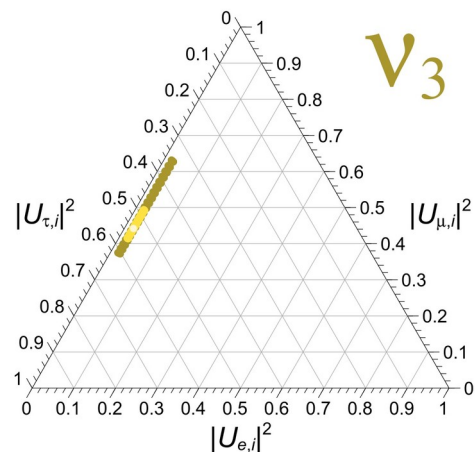
If all unstable neutrinos decay

$\underbrace{\nu_{1'}, \nu_2 \rightarrow \nu_3}_{\nu_3 \text{ lightest and stable (inverted mass ordering)}}$

Earth



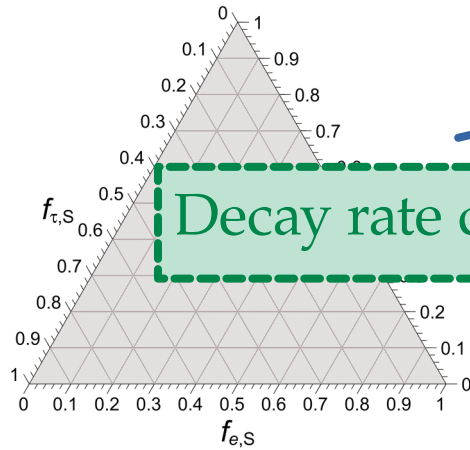
$$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$$



$$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$$

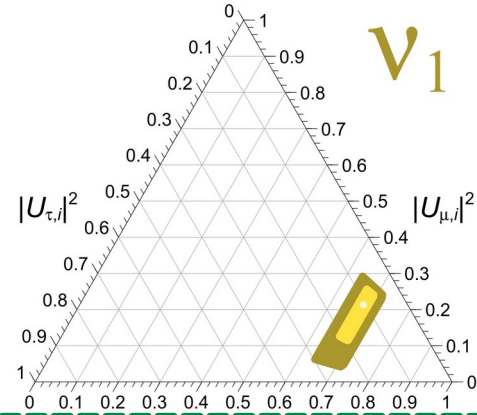
Measuring the neutrino lifetime

Sources



$\nu_{2'}, \nu_3 \rightarrow \nu_1$
 ν_1 lightest and stable
 (normal mass ordering)

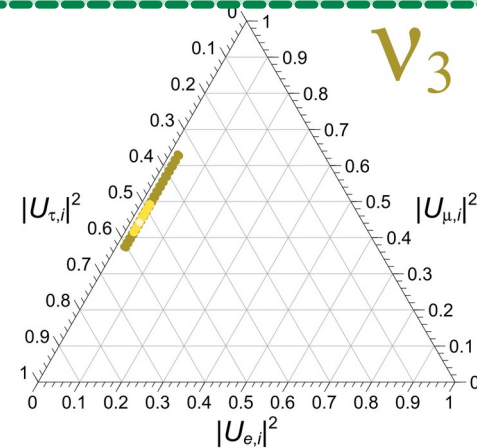
Earth



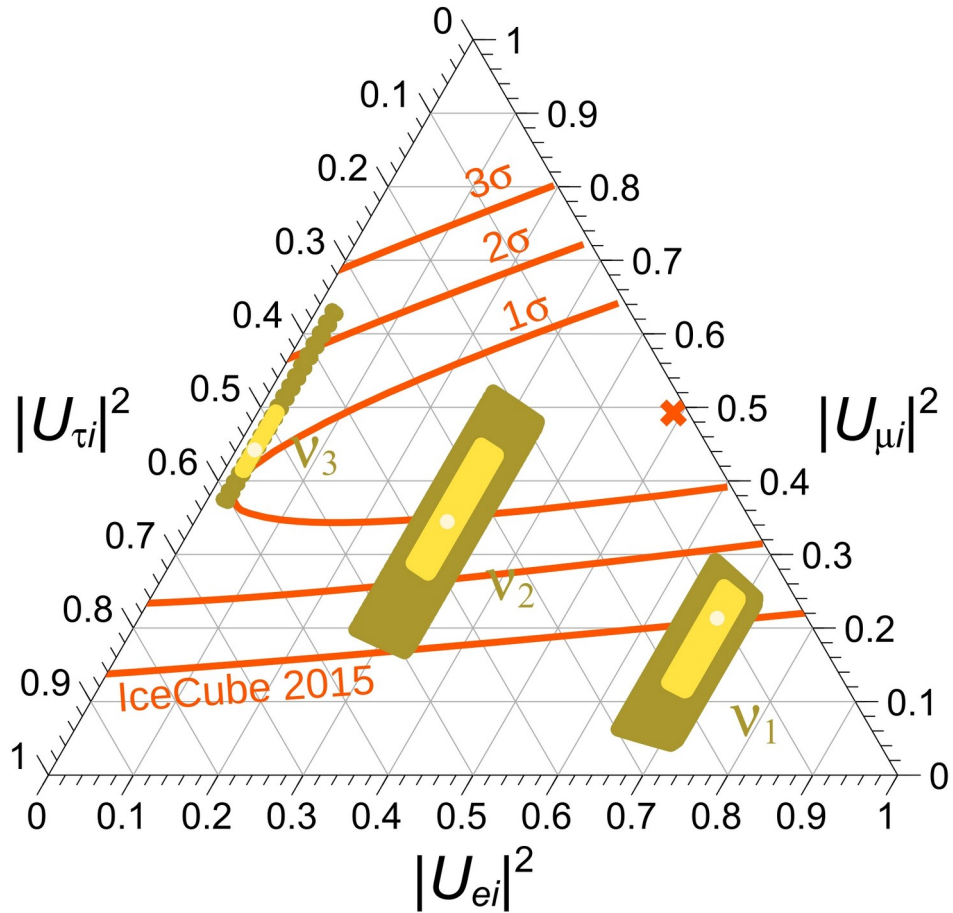
$$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$$

Decay rate depends on $\exp[-t / (\gamma \tau_i)] = \exp[-(L/E) \cdot (m_i/\tau_i)]$

$\nu_{1'}, \nu_2 \rightarrow \nu_3$
 ν_3 lightest and stable
 (inverted mass ordering)

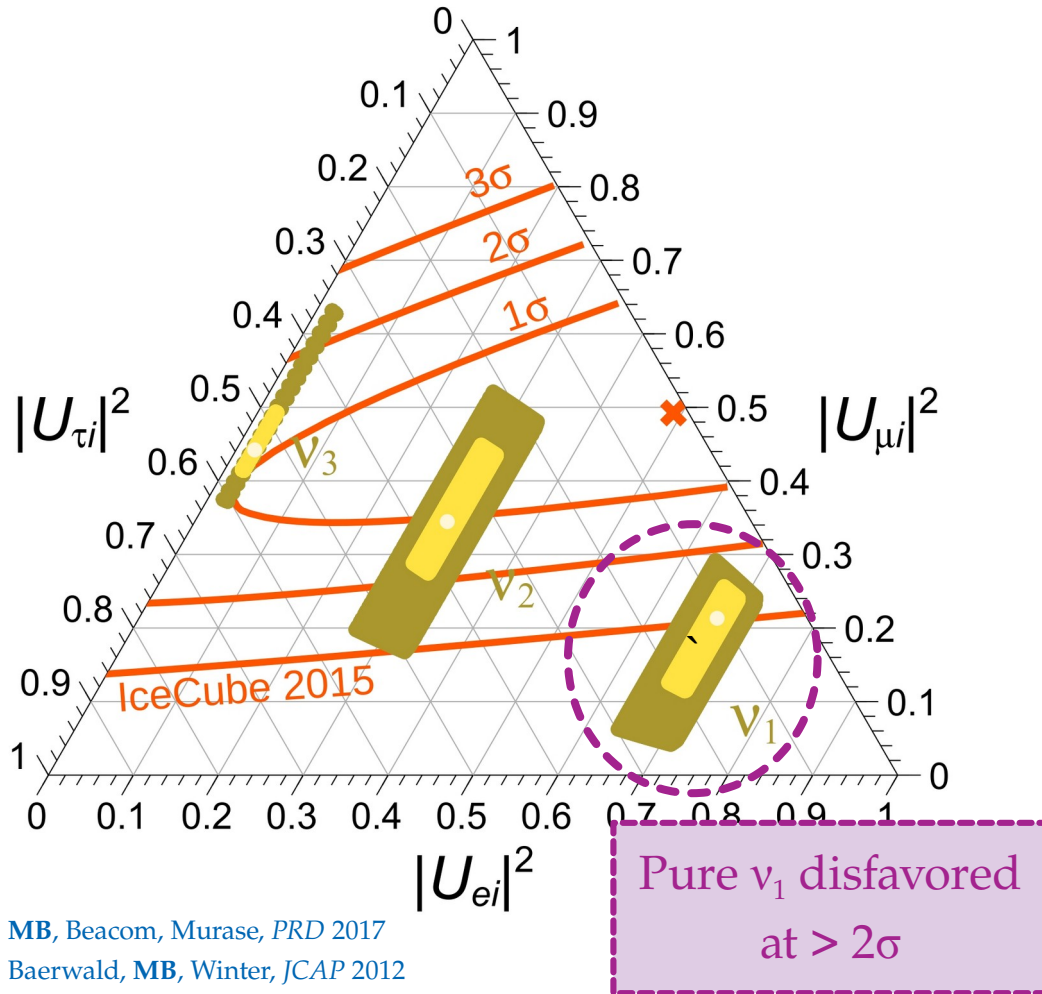


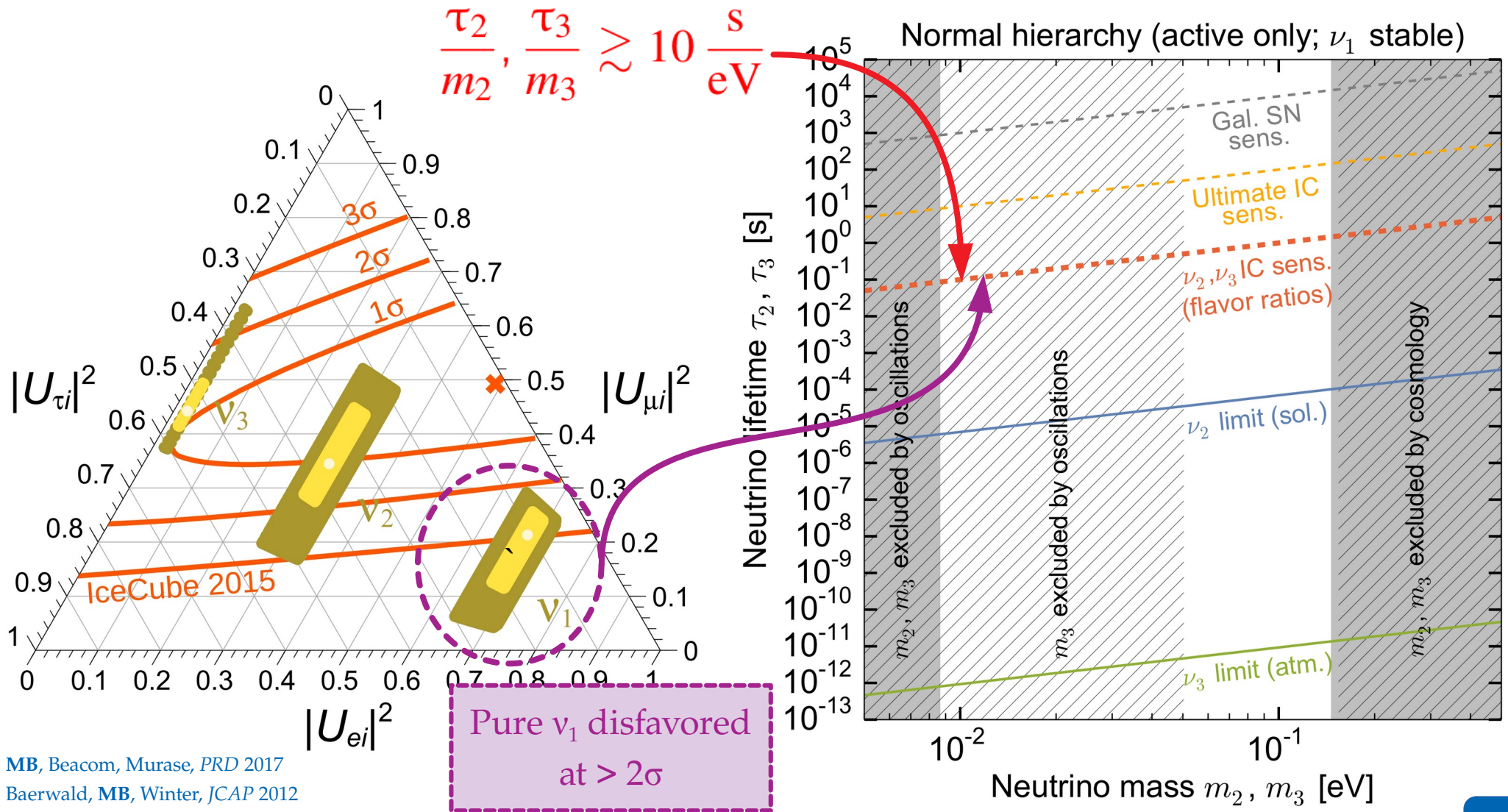
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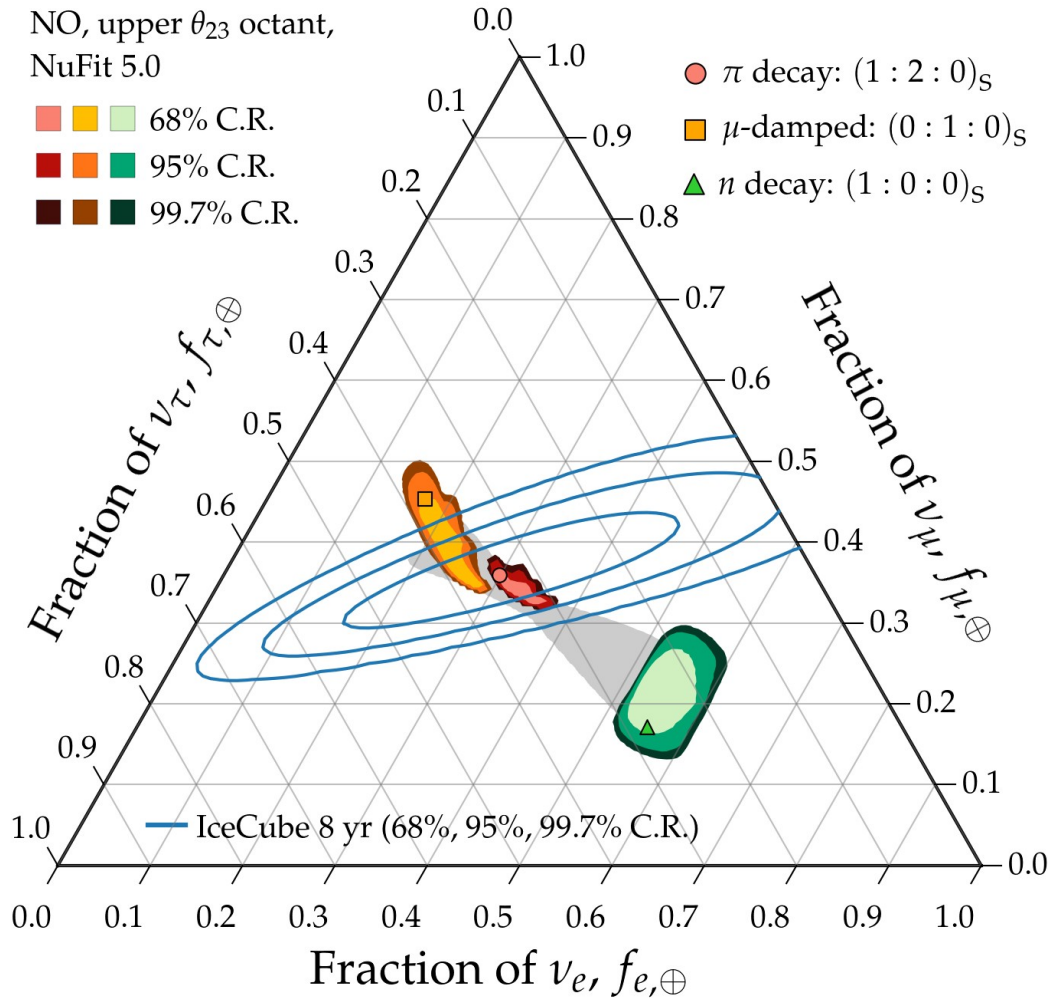
MB, Beacom, Murase, *PRD* 2017

Baerwald, MB, Winter, *JCAP* 2012





Theoretically palatable regions: today (2021)



Two limitations:

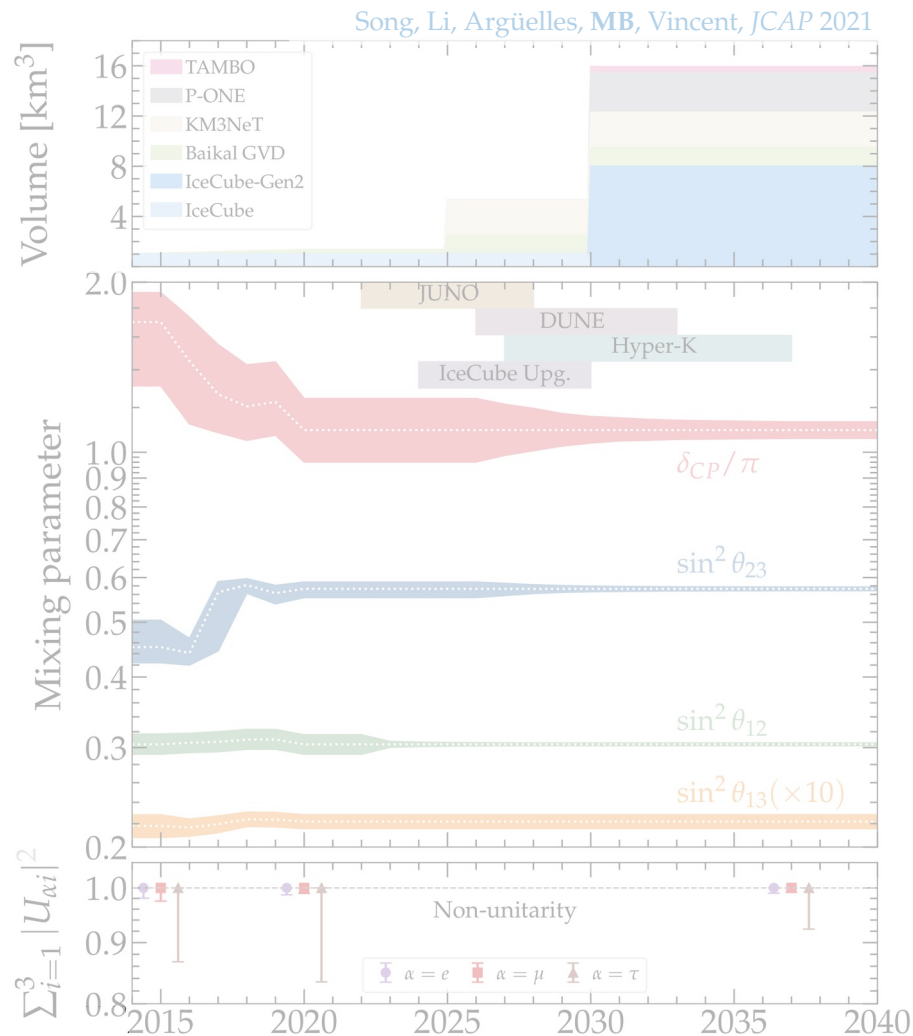
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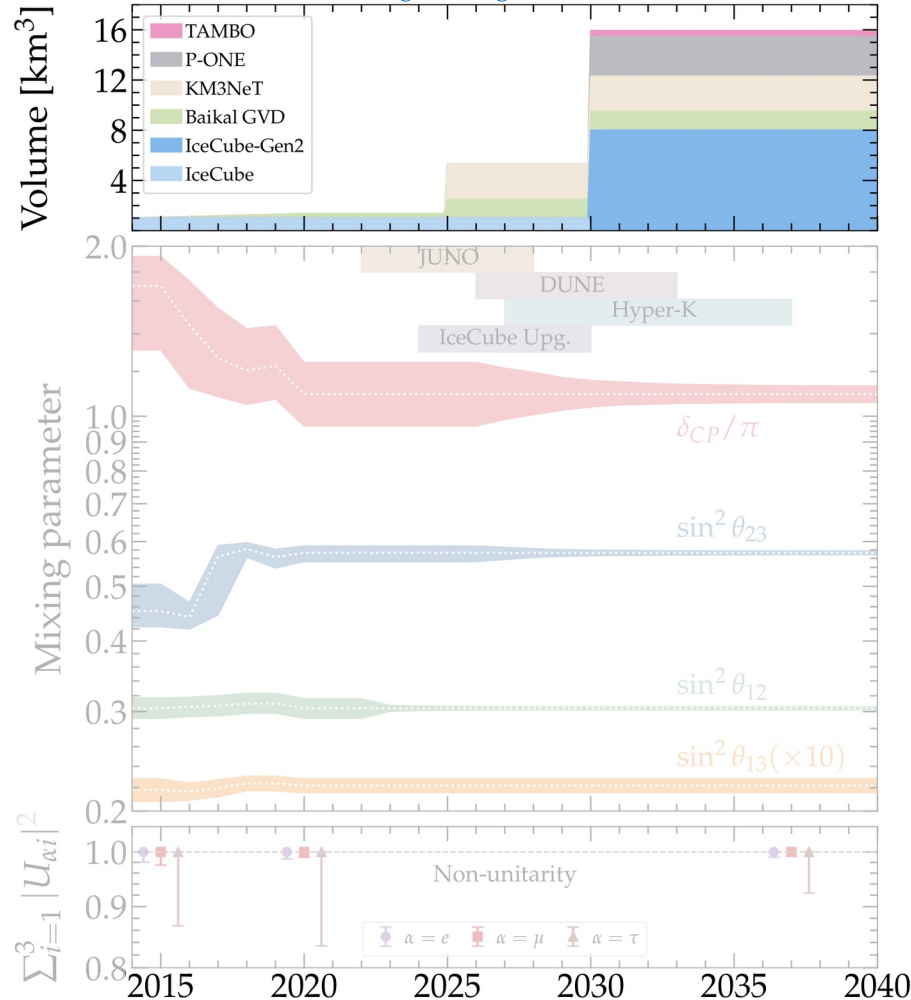
Will be overcome by 2040

Three reasons to be excited



Three reasons to be excited

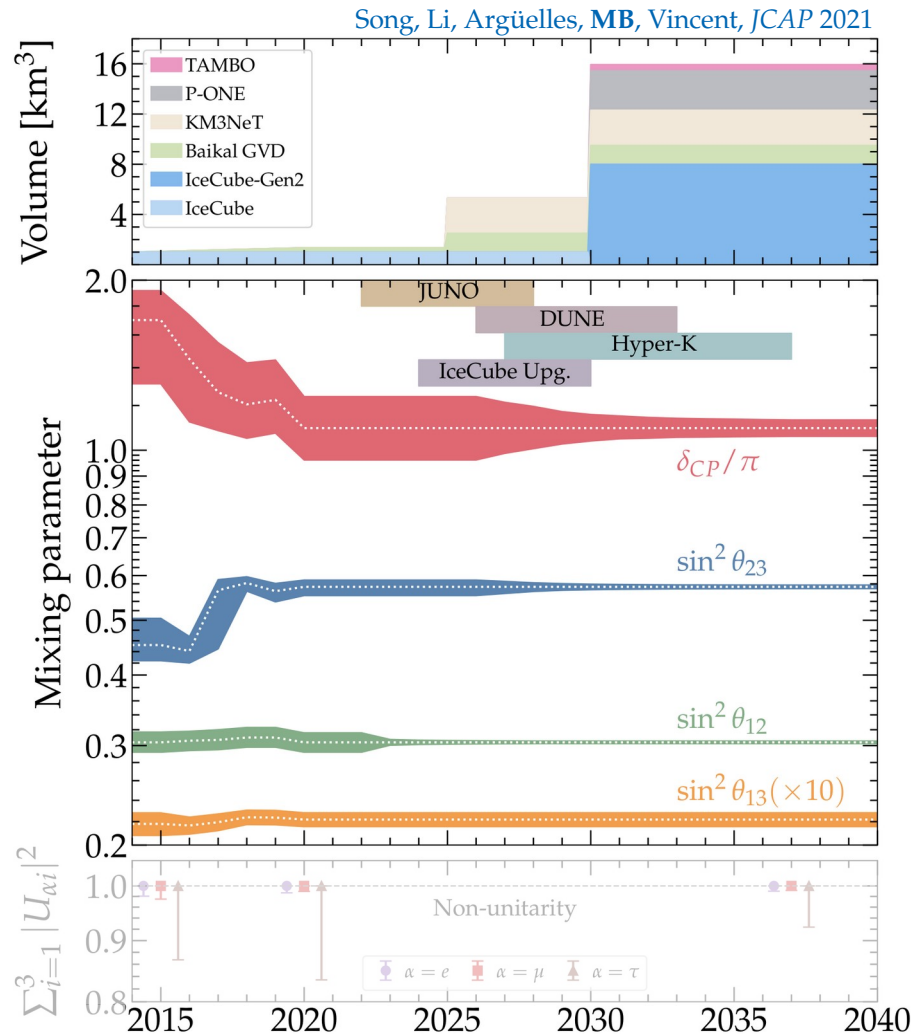
Song, Li, Argüelles, MB, Vincent, JCAP 2021



Flavor measurements:

New neutrino telescopes = more events, better flavor measurement

Three reasons to be excited



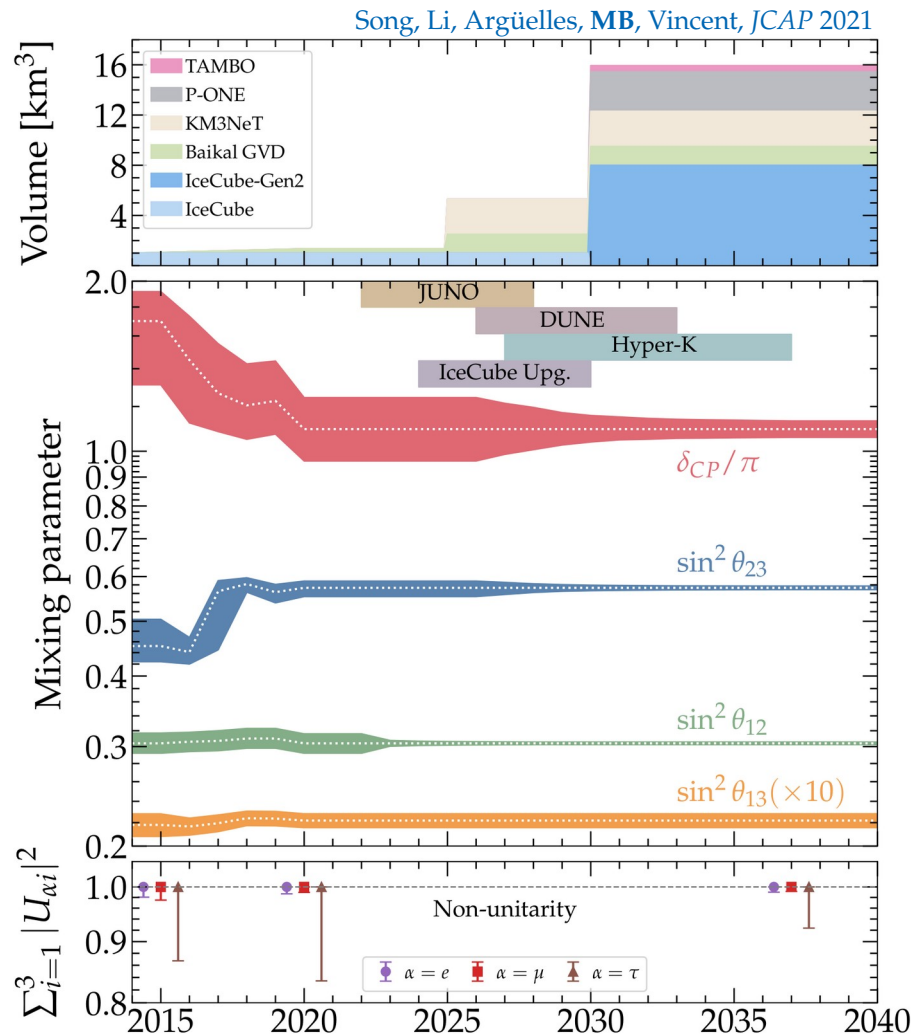
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We will know the mixing parameters better (JUNO, DUNE, Hyper-K, IceCube Upgrade)

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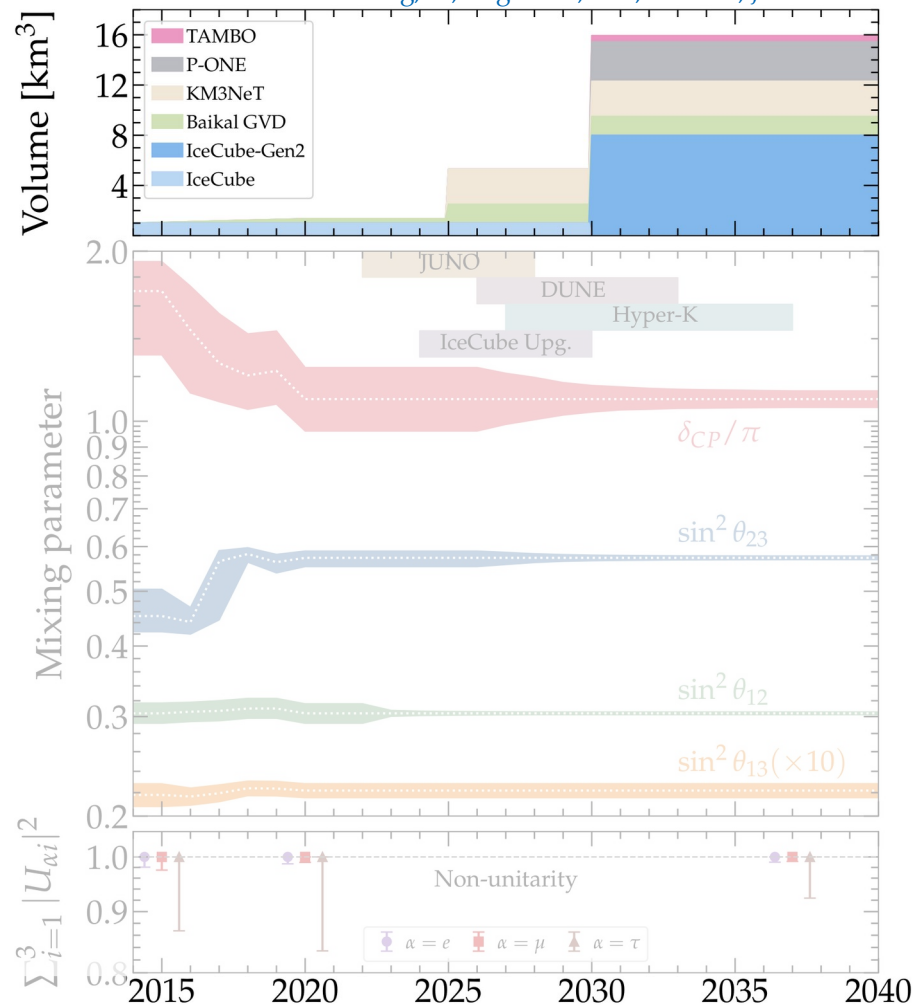
We will know the mixing parameters better (JUNO, DUNE, Hyper-K, IceCube Upgrade)

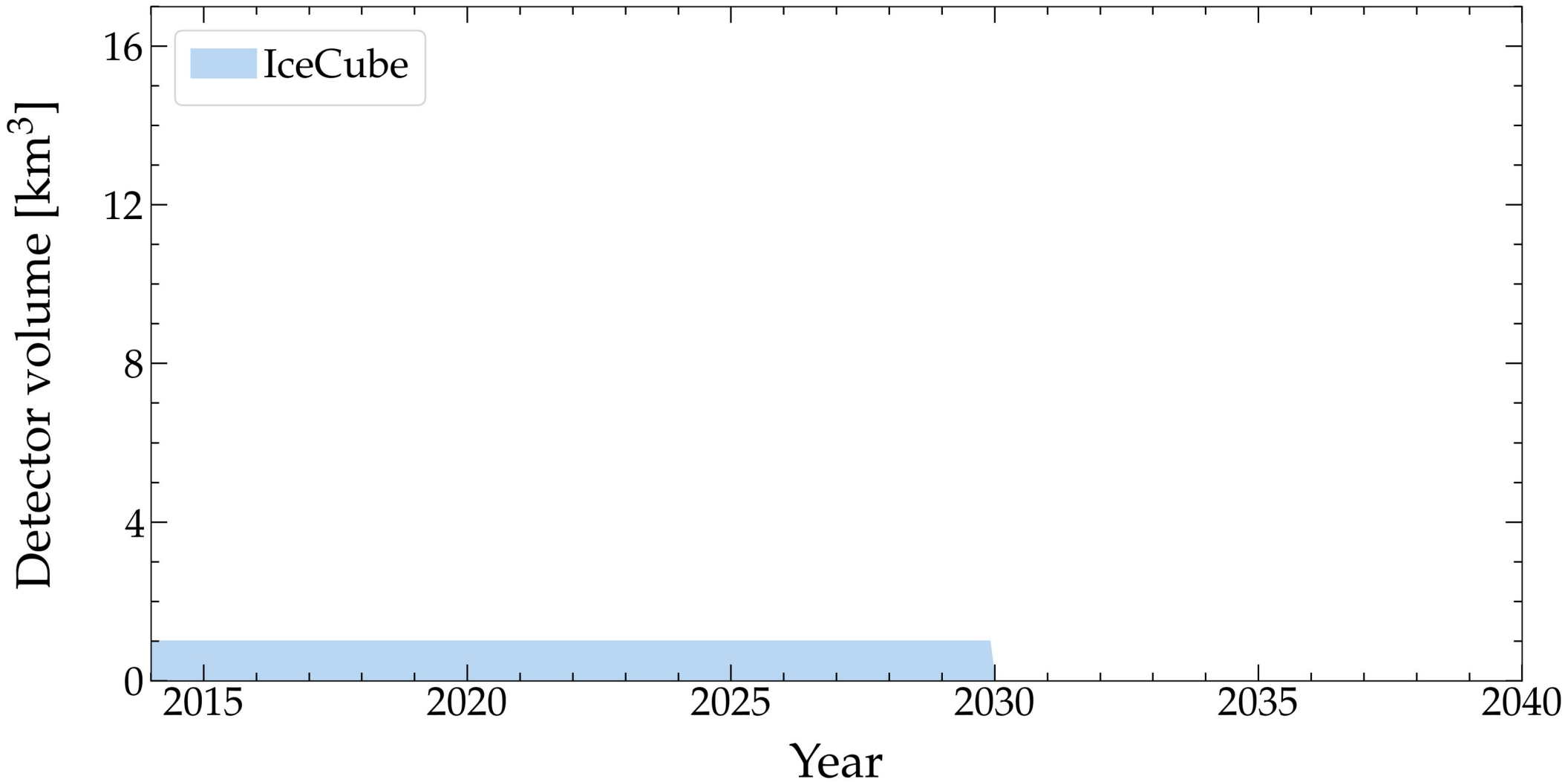
Test of the oscillation framework:

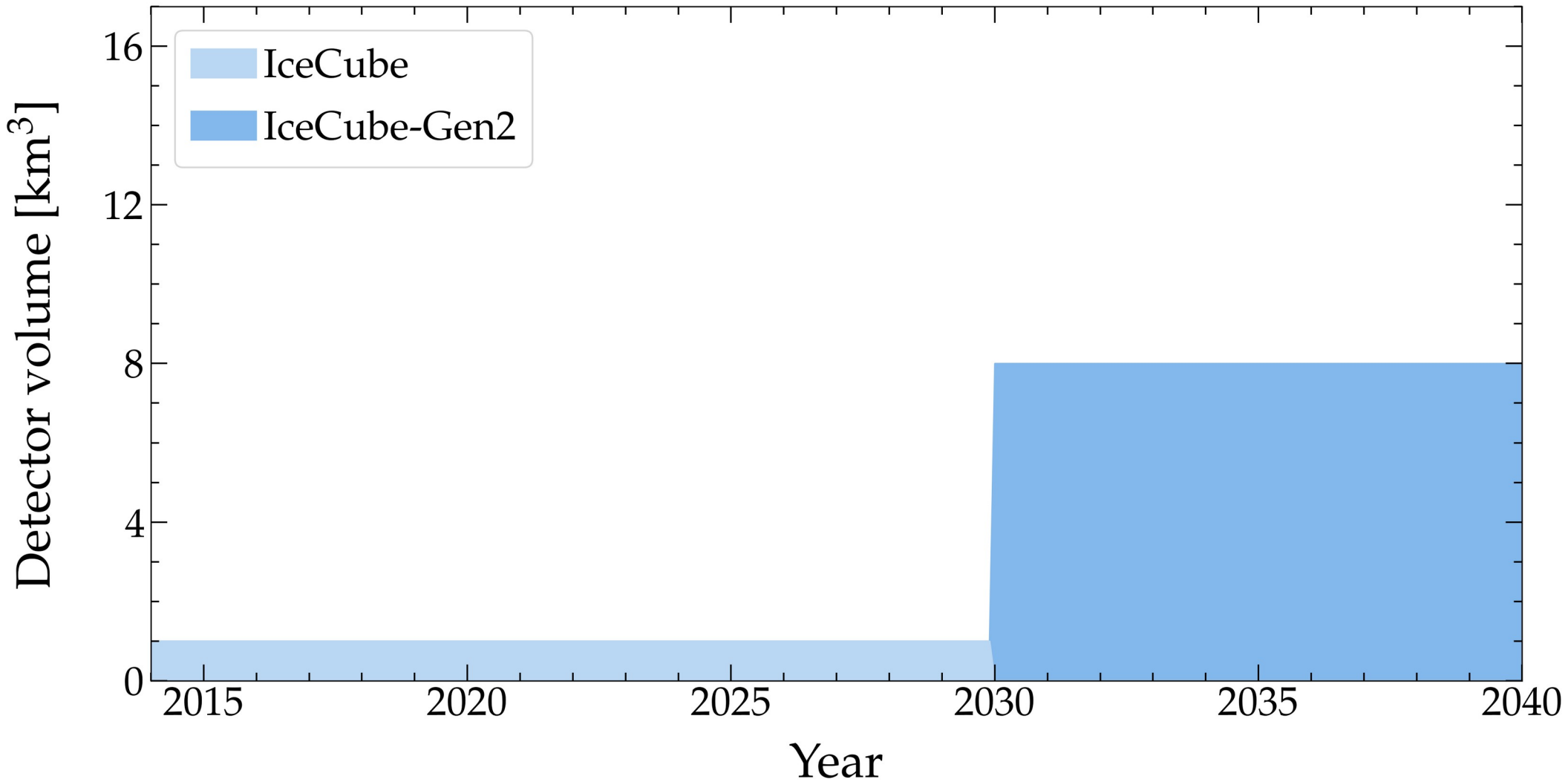
We will be able to do what we want even if oscillations are non-unitary

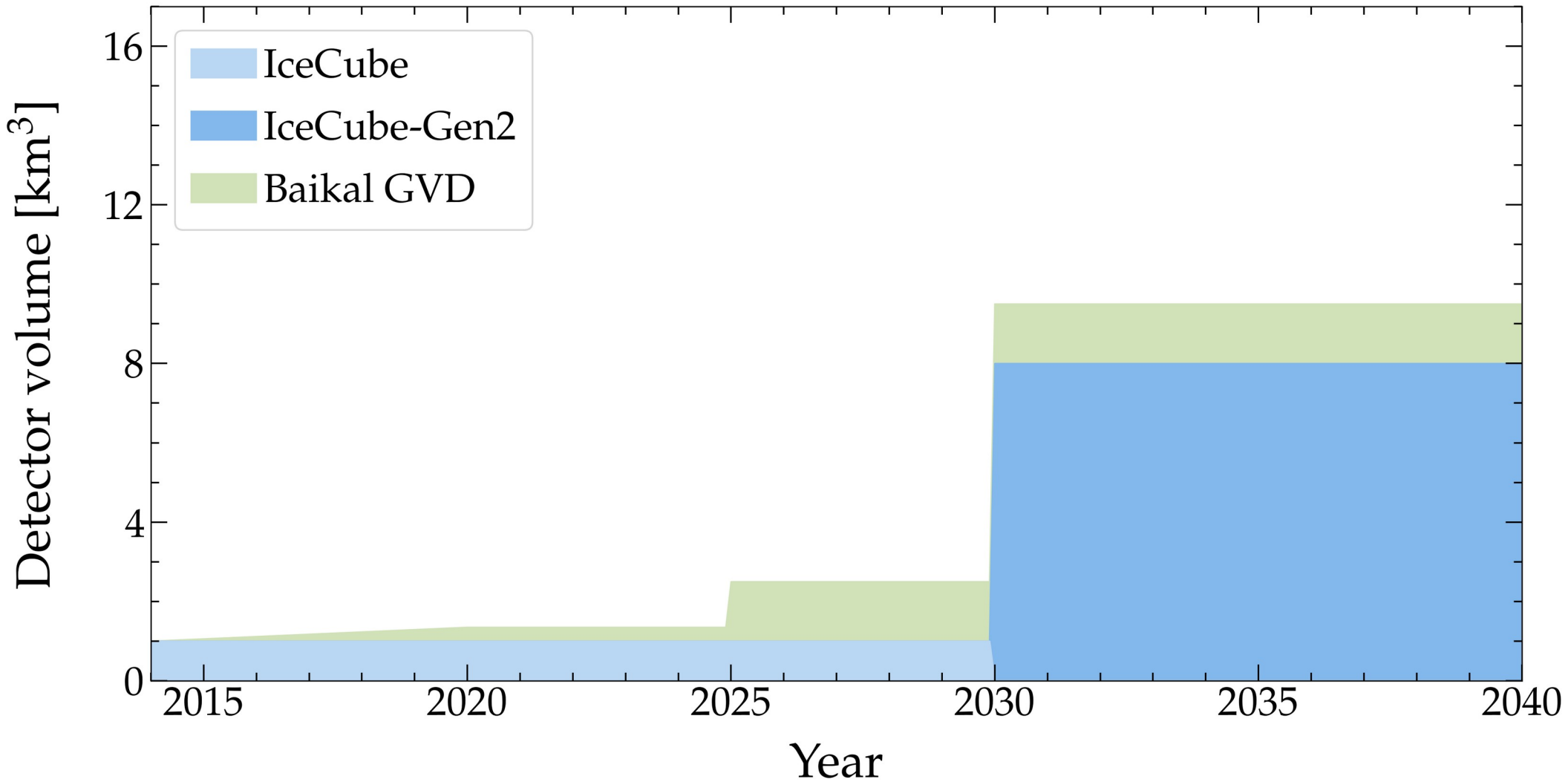
Measuring flavor composition: 2015–2040

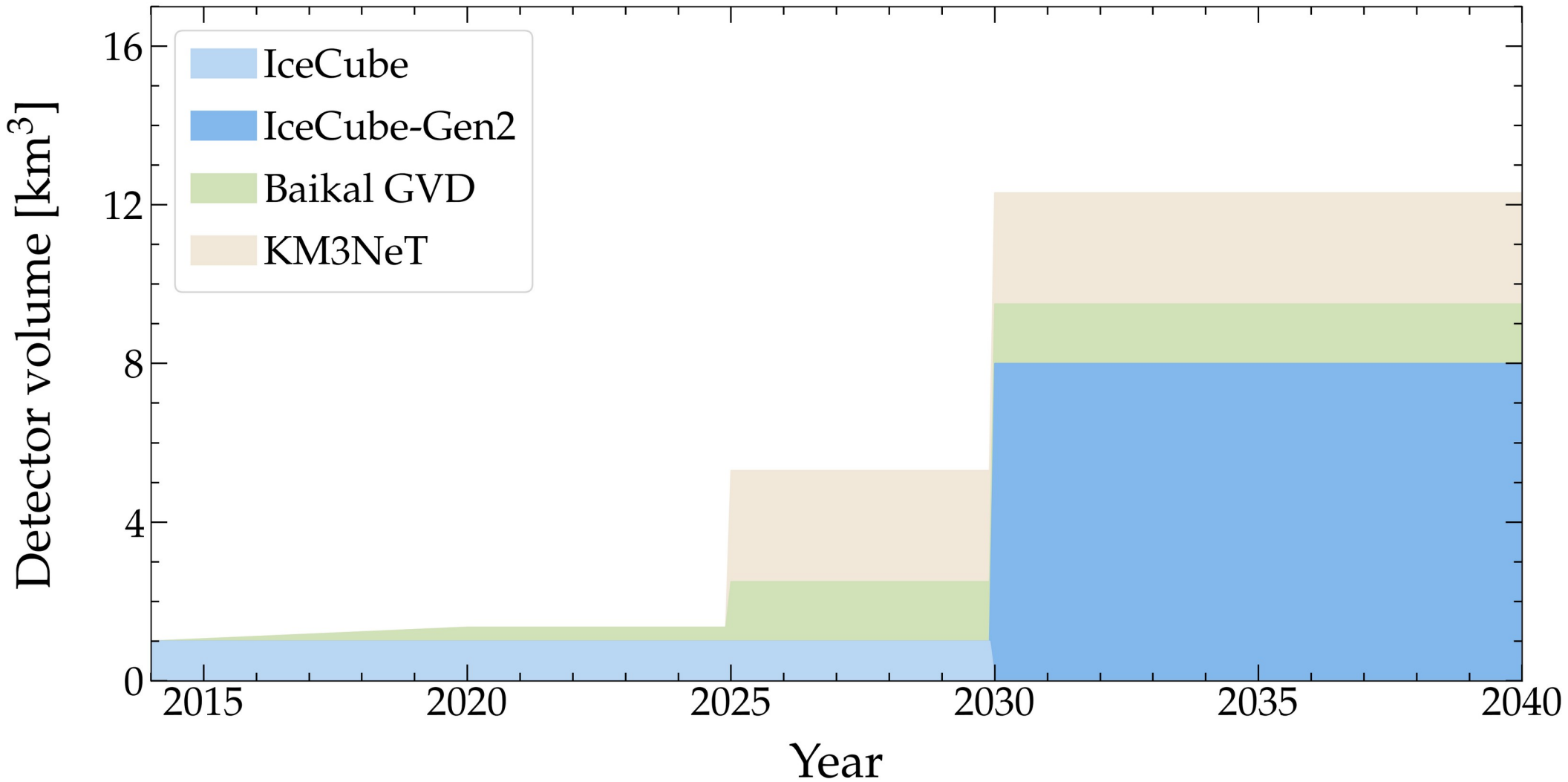
Song, Li, Argüelles, MB, Vincent, JCAP 2021

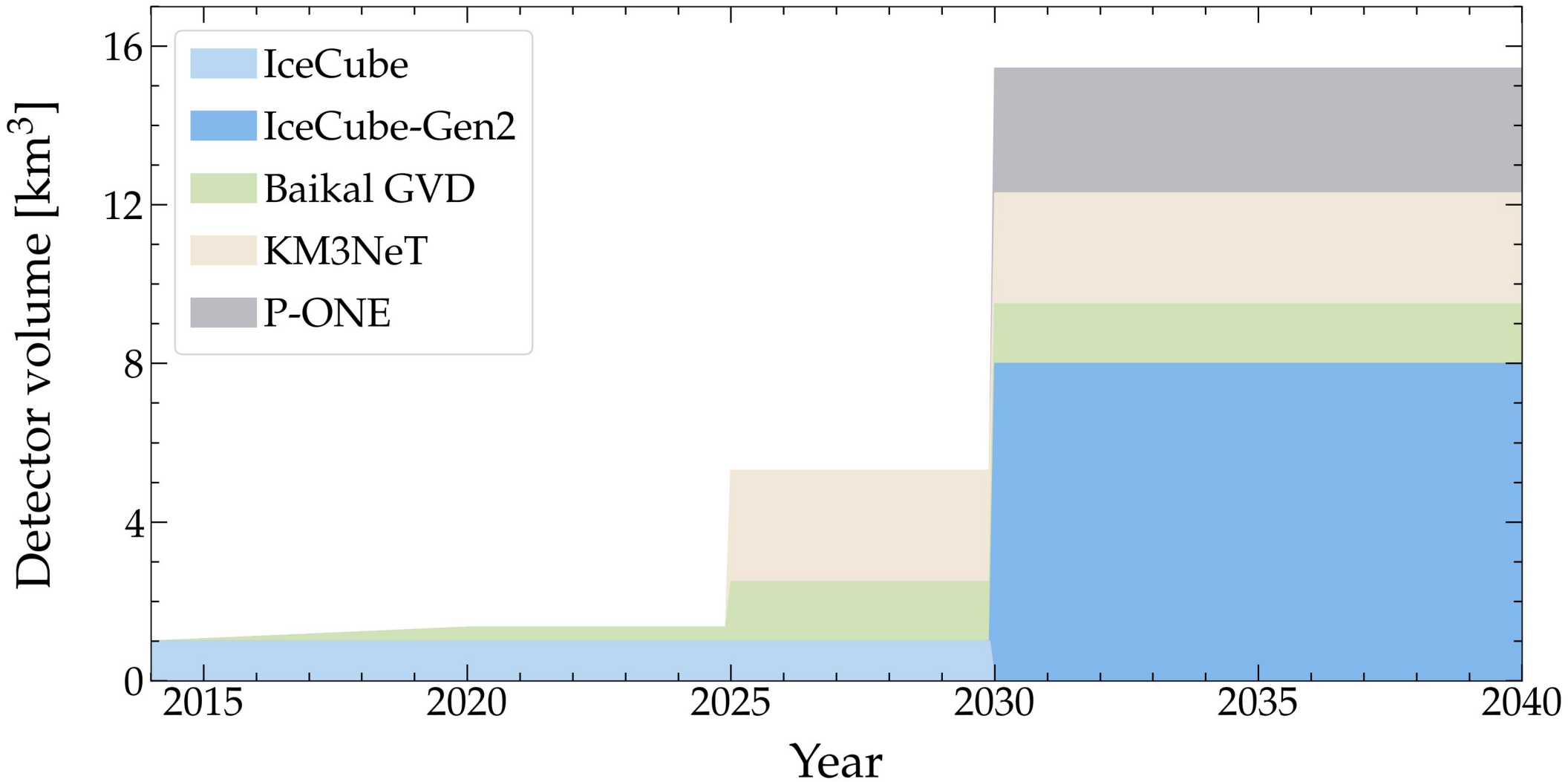


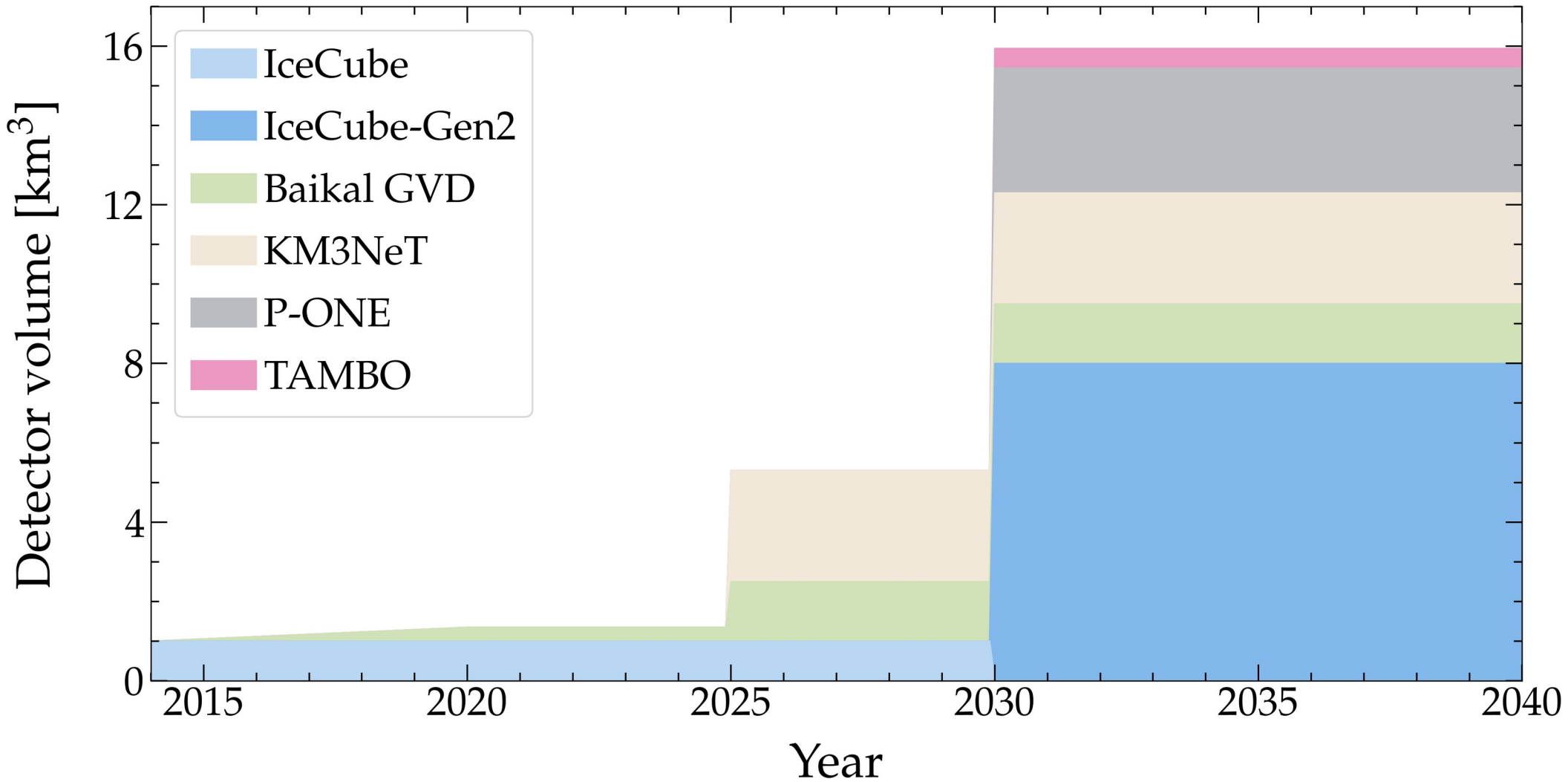


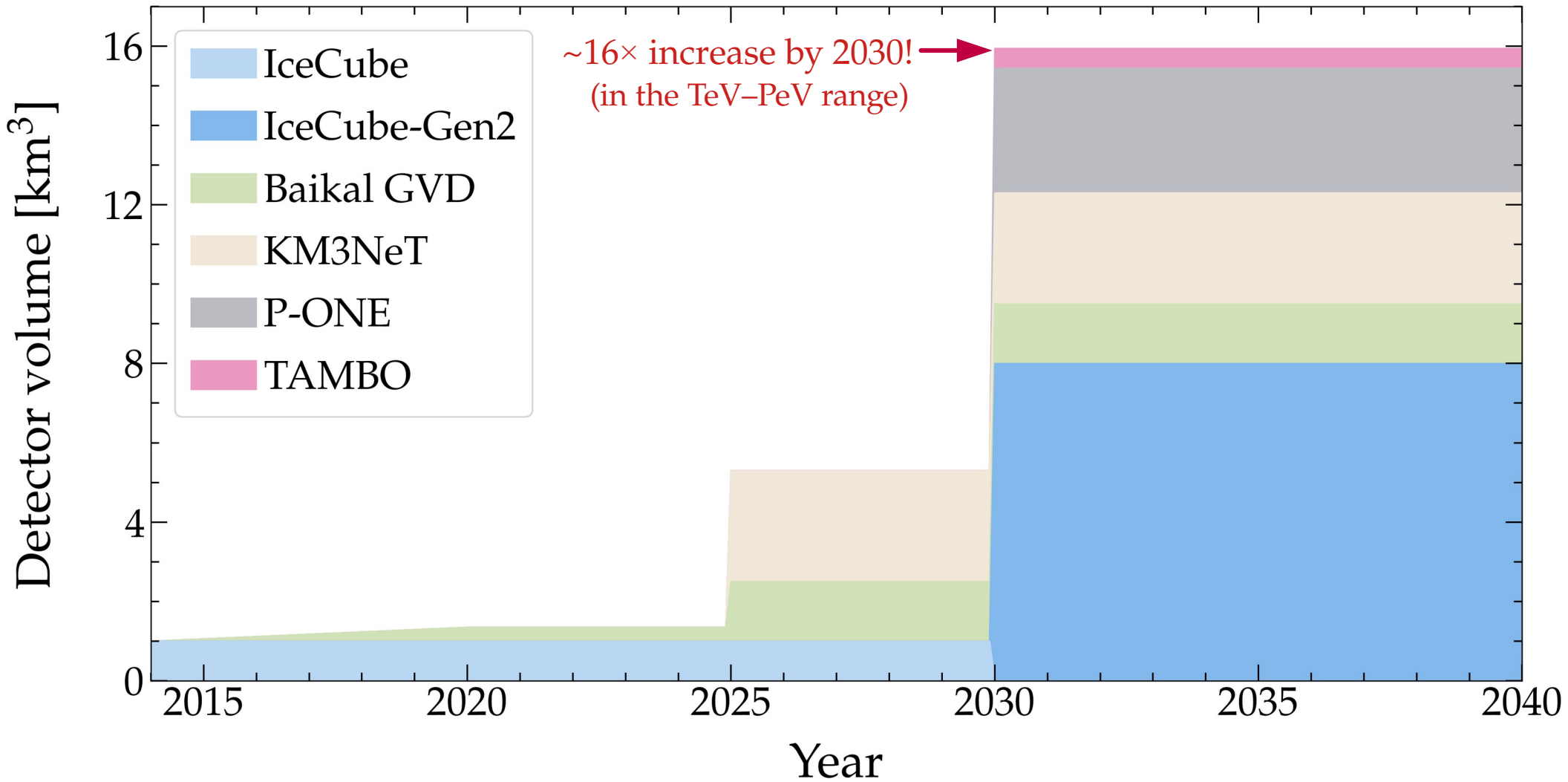






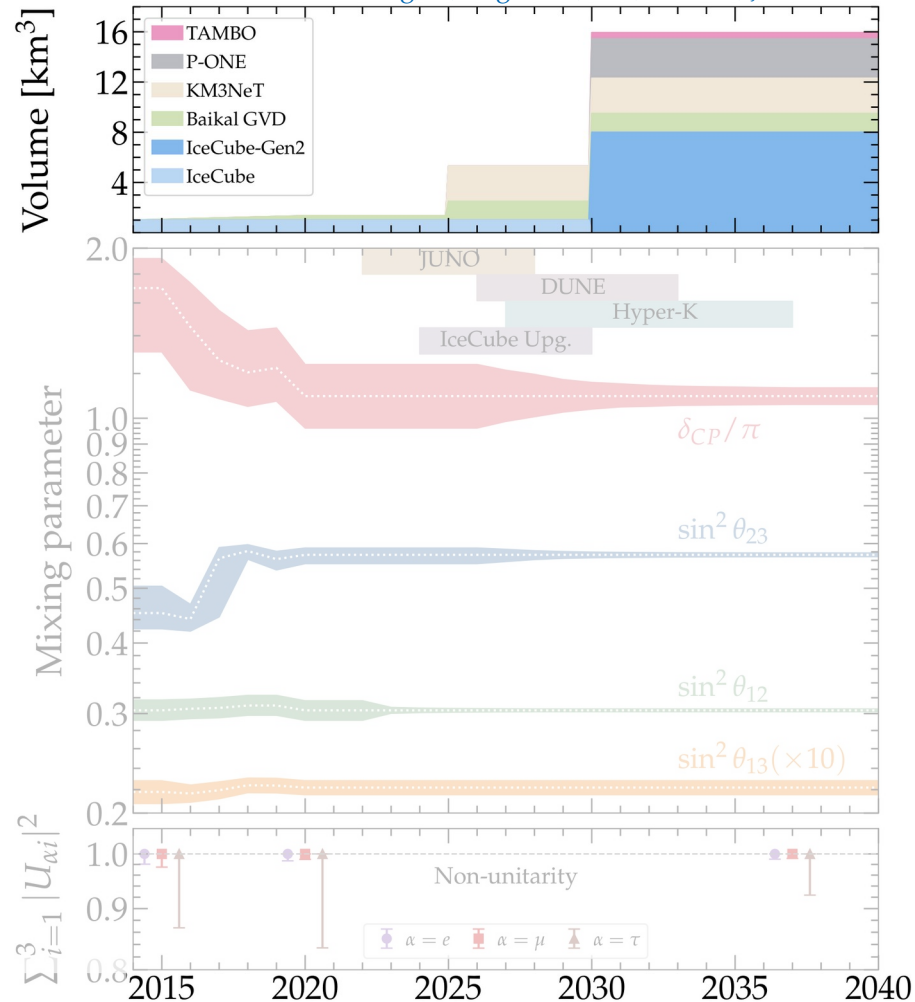






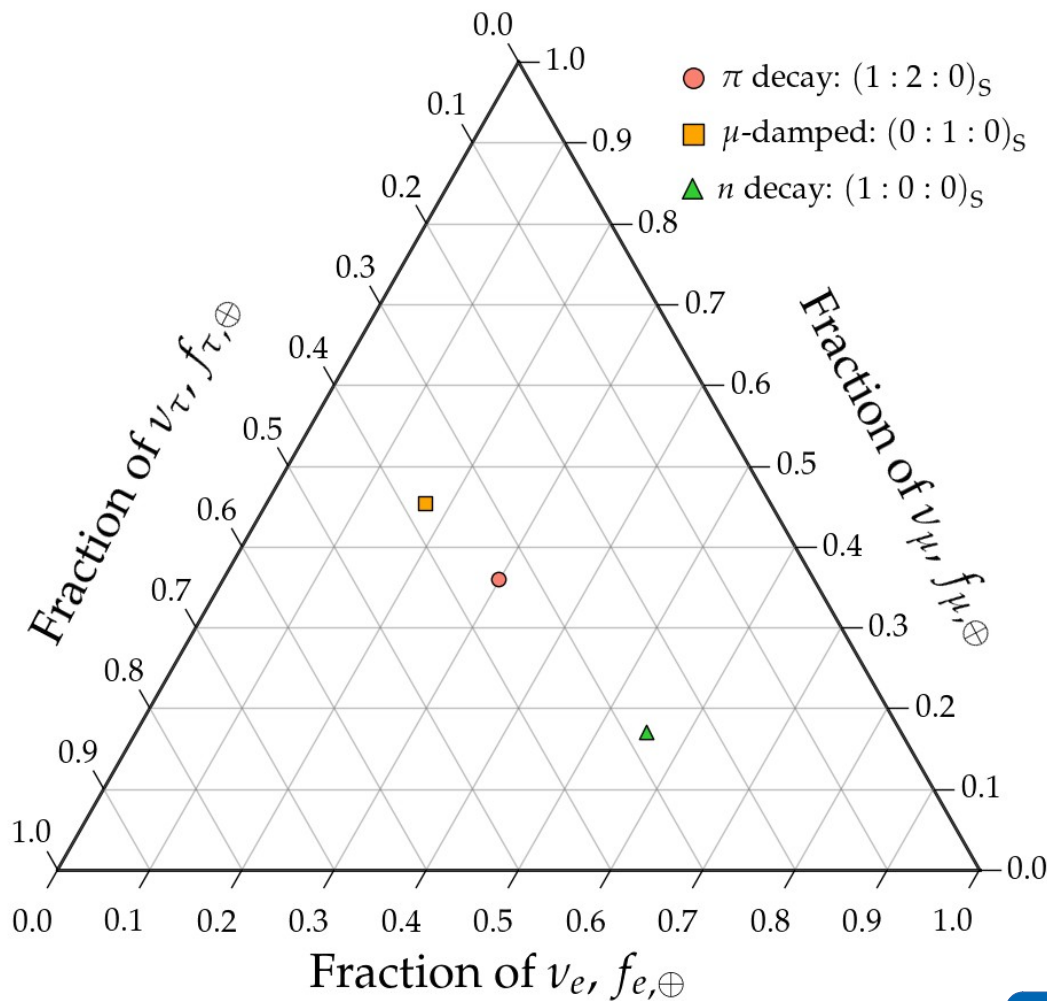
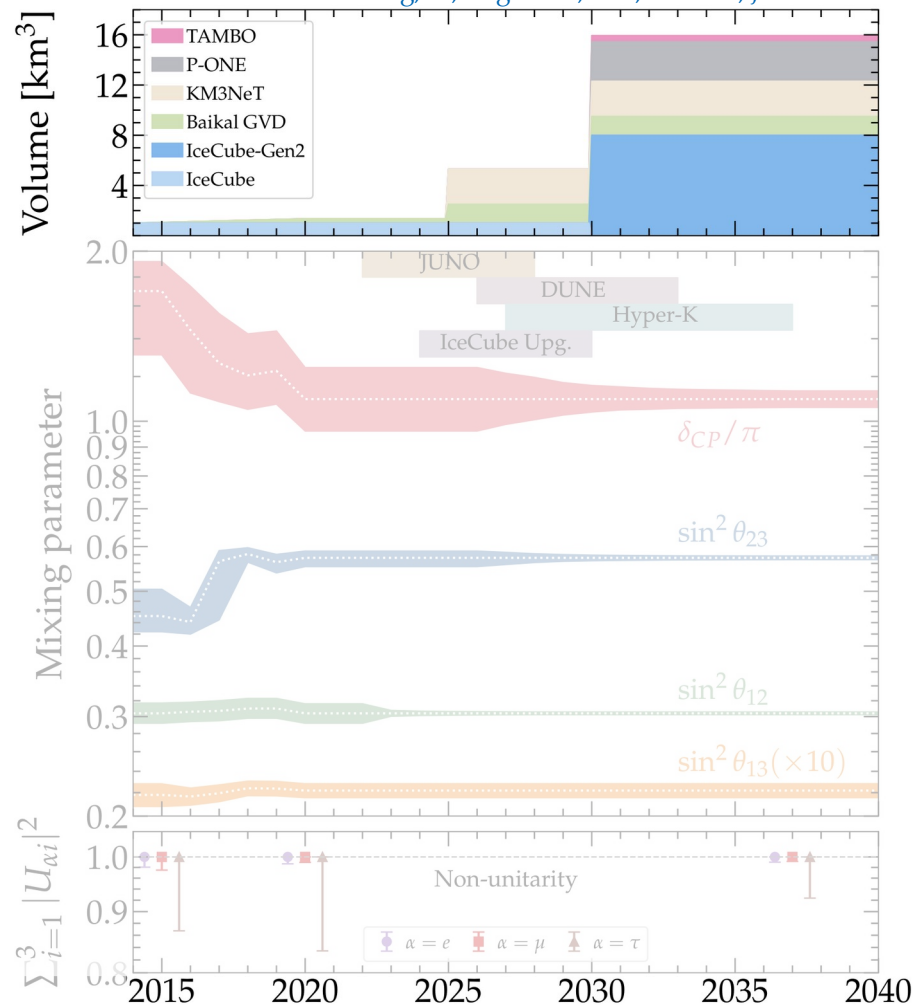
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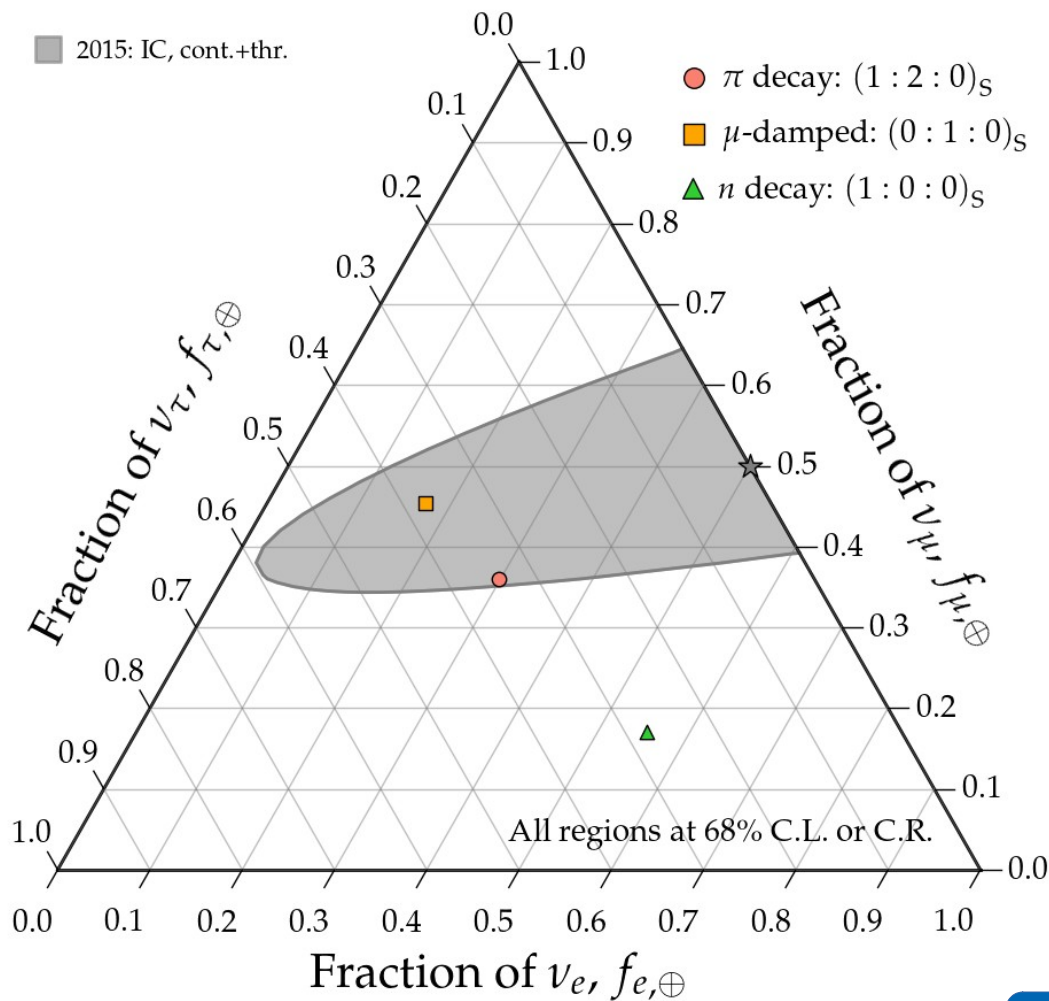
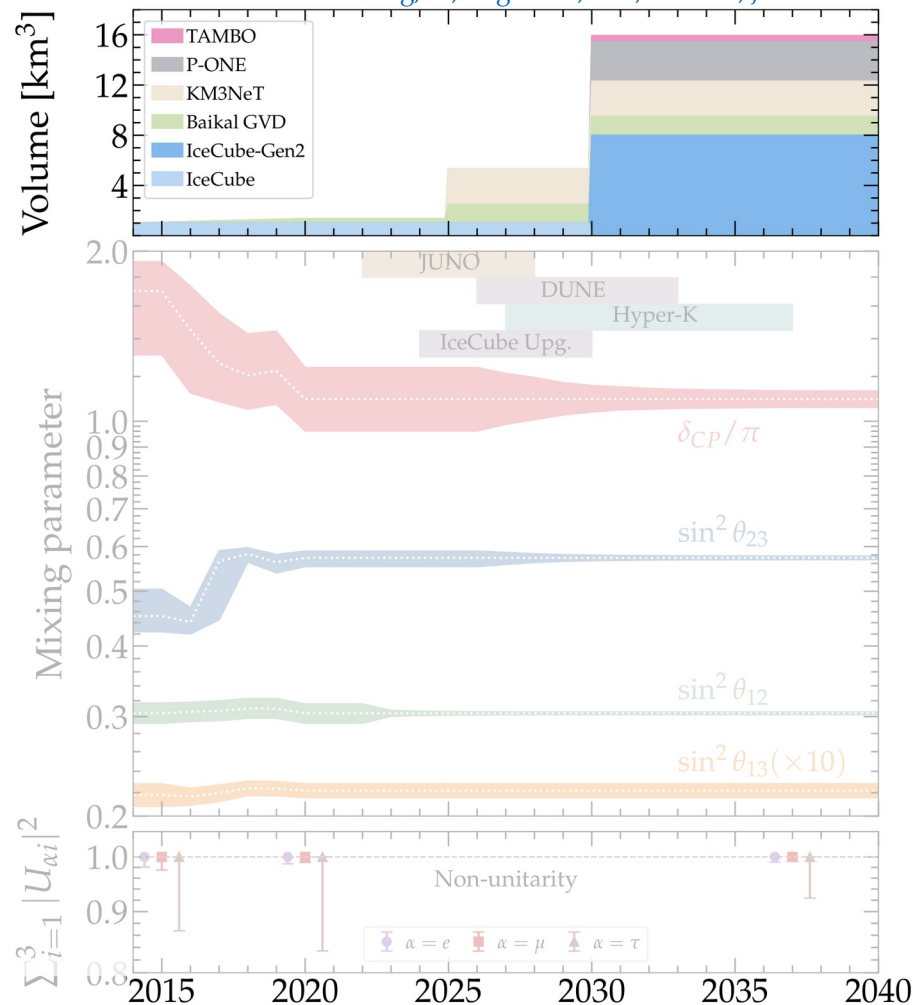
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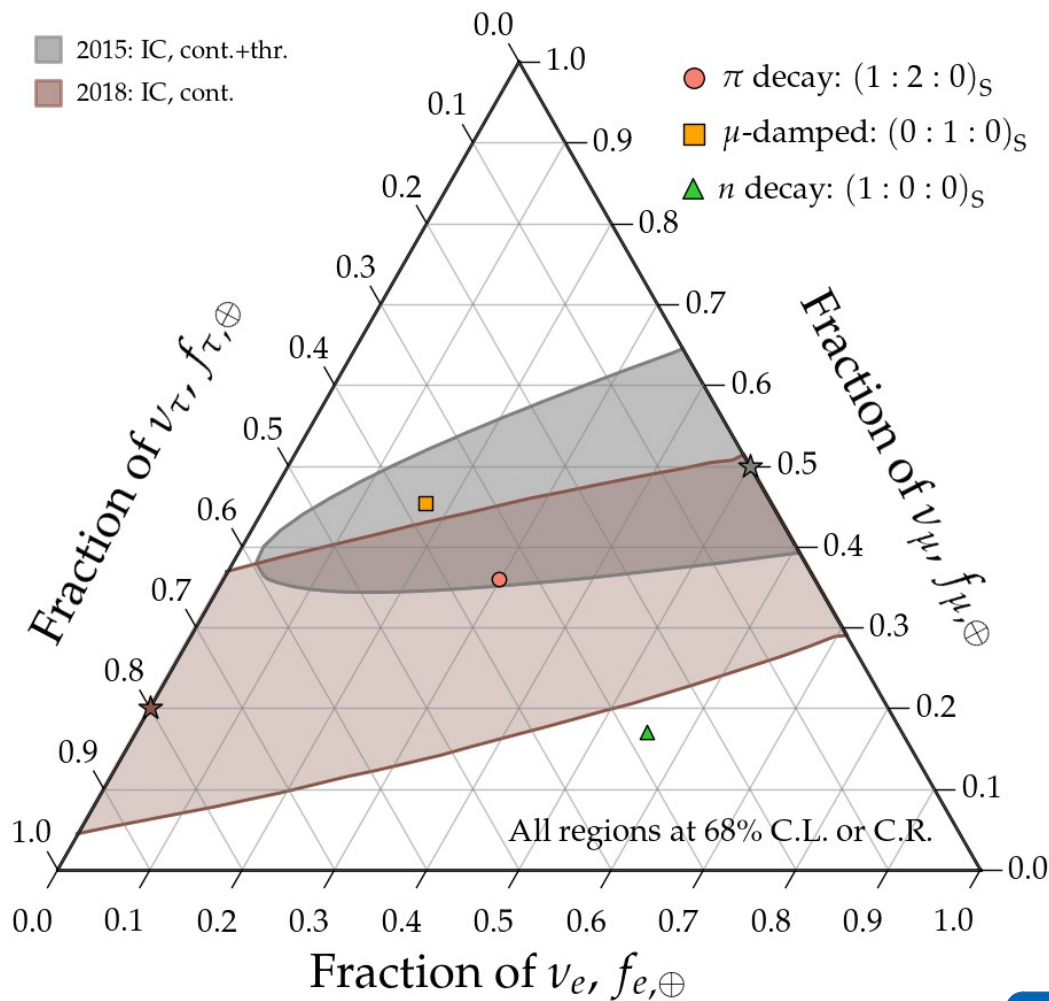
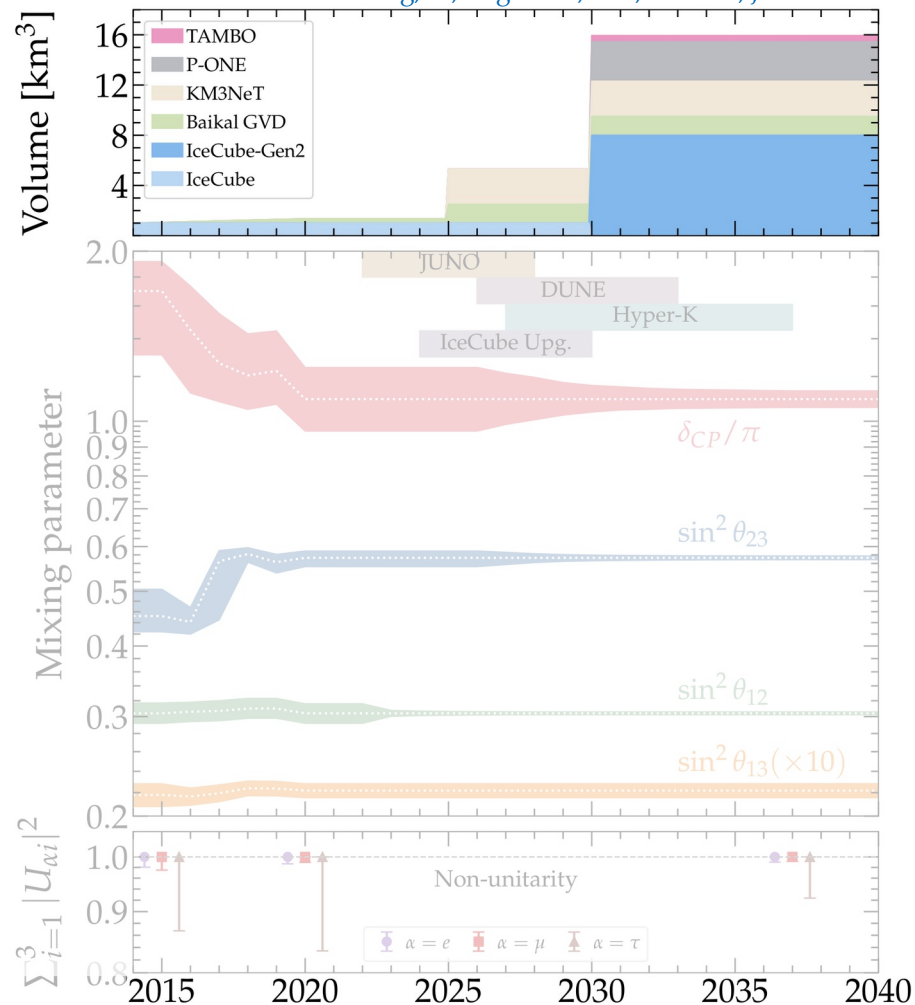
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Song, Li, Argüelles, MB, Vincent, JCAP 2021



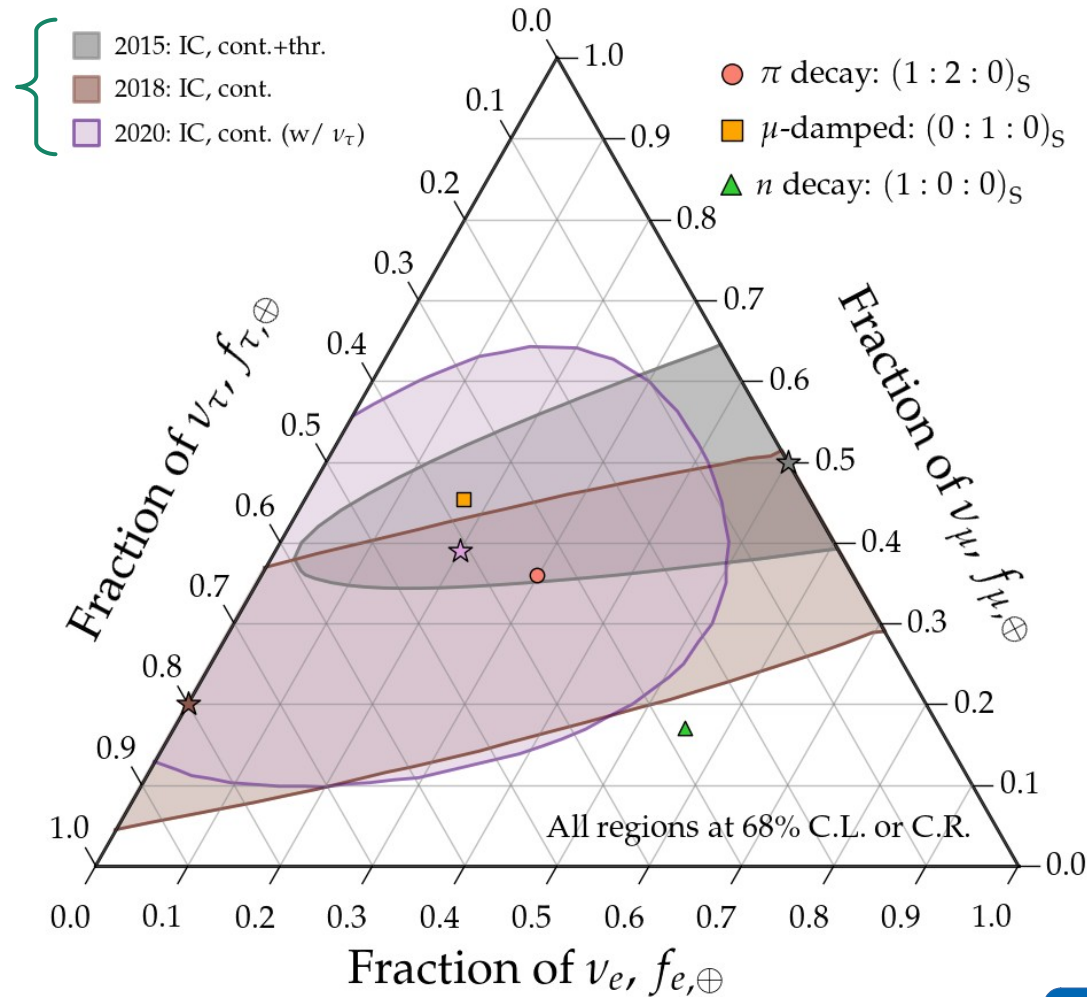
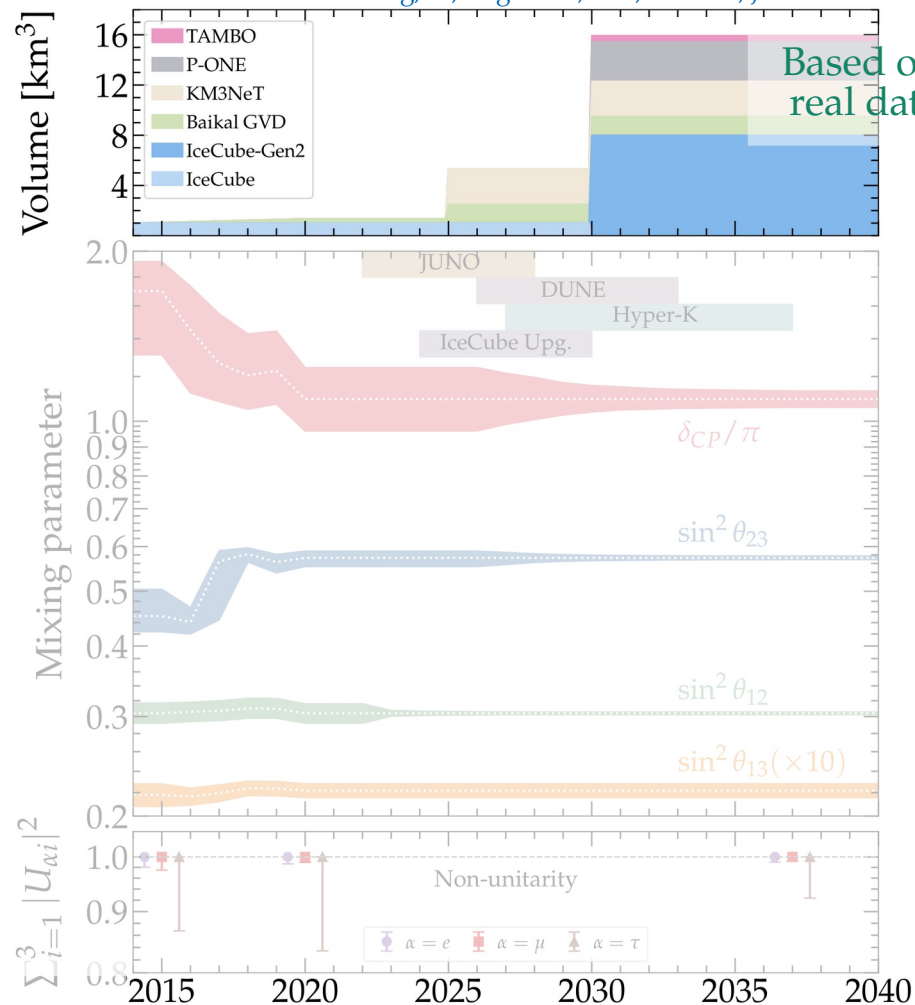
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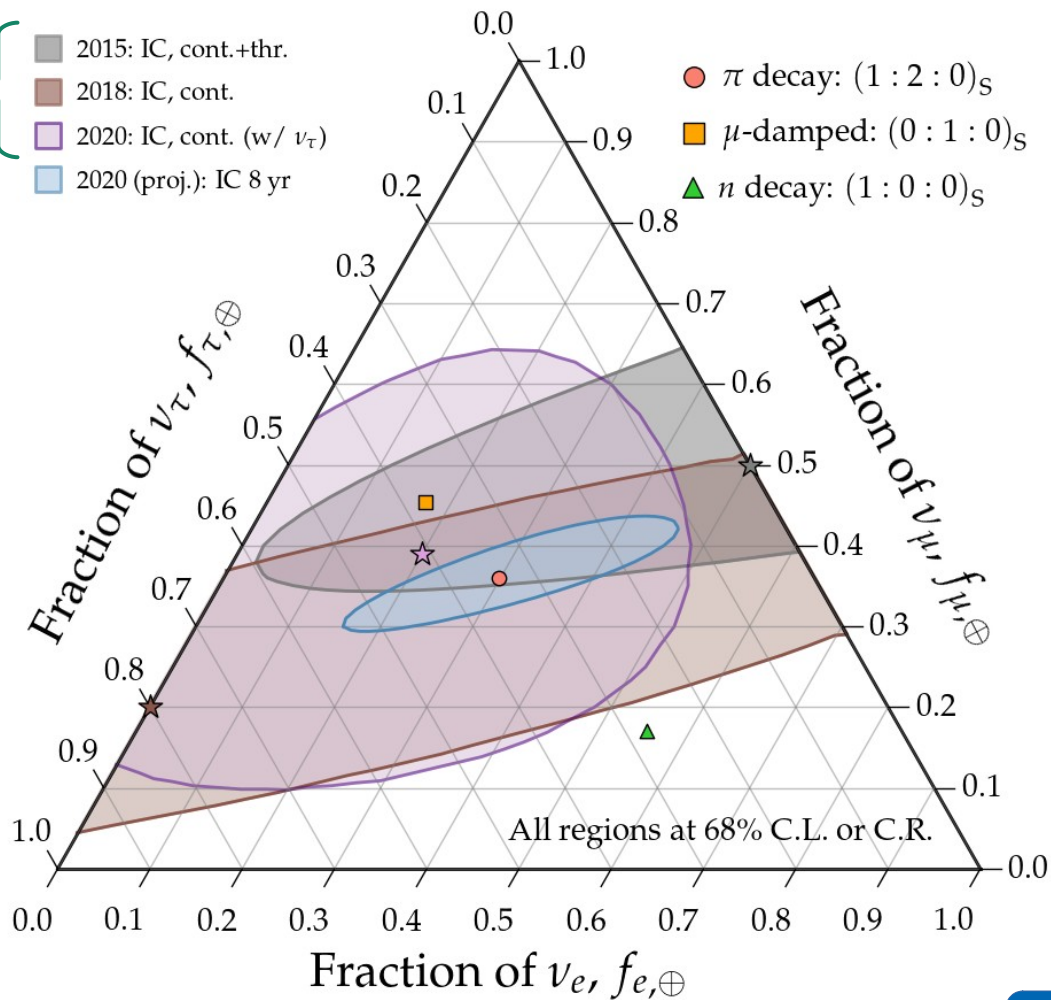
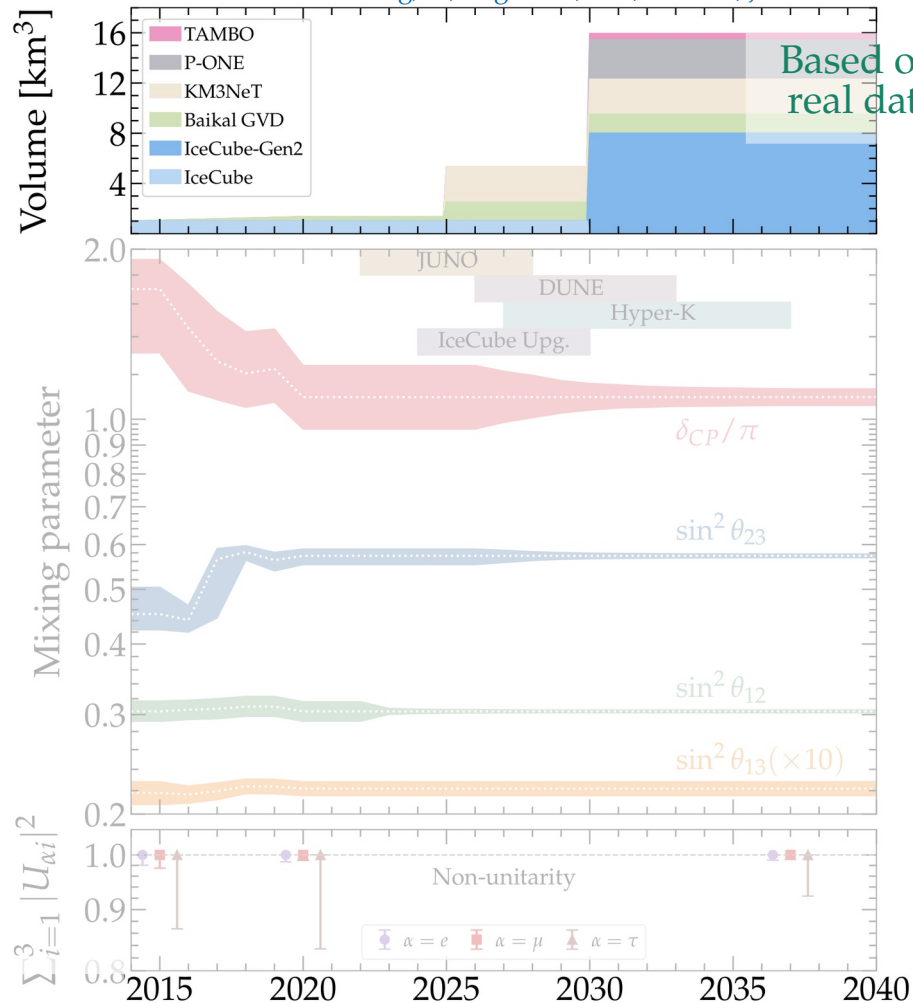
Measuring flavor composition: 2015–2040

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



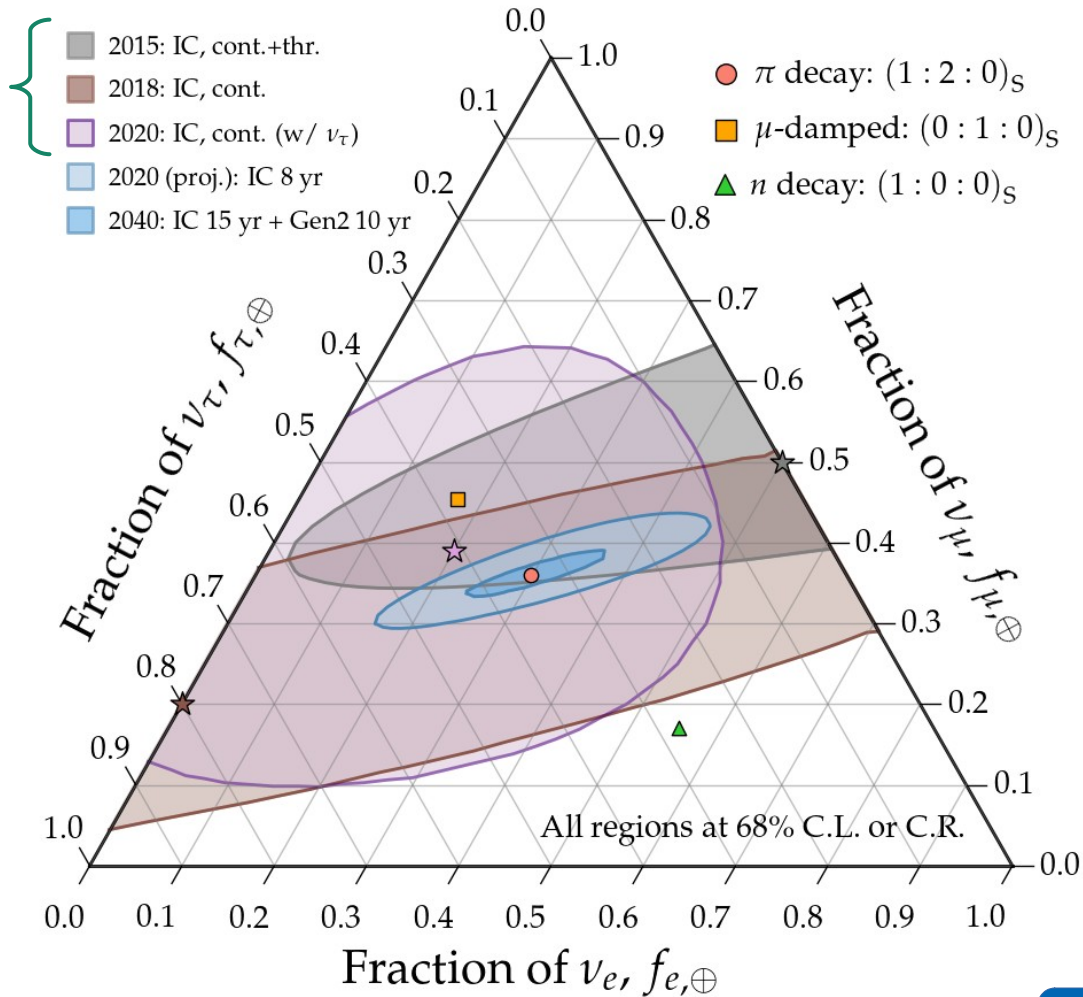
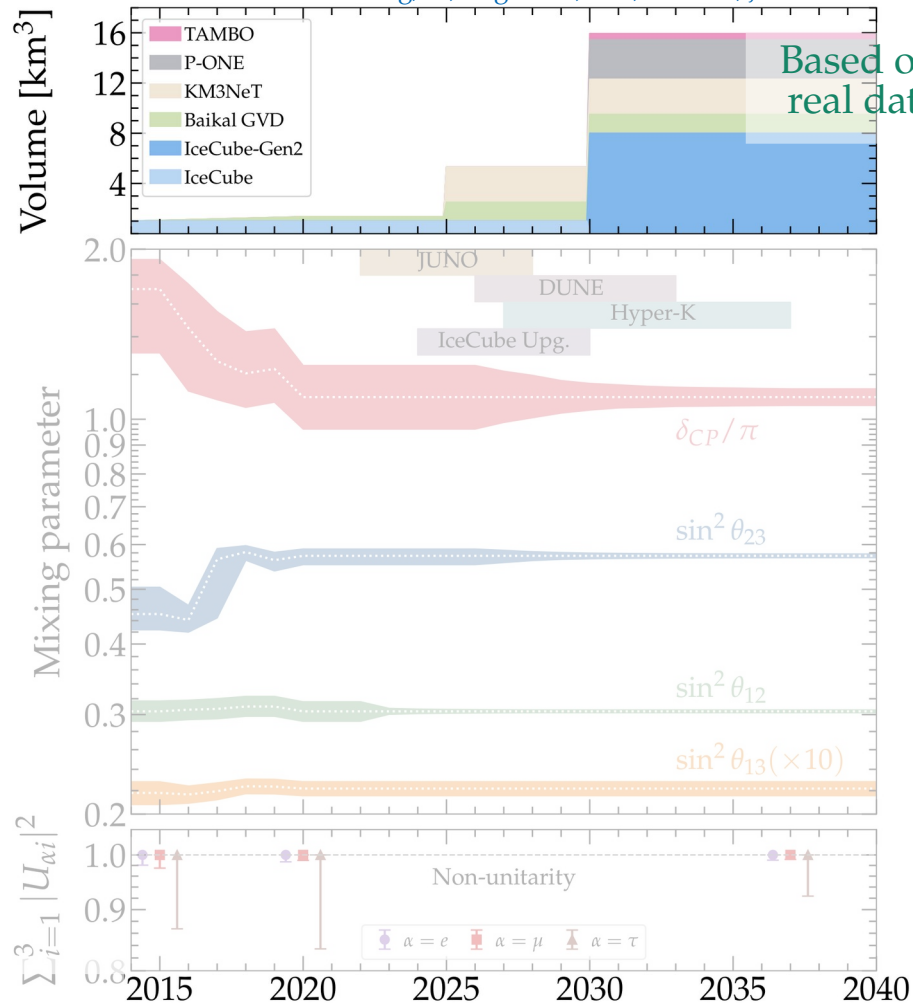
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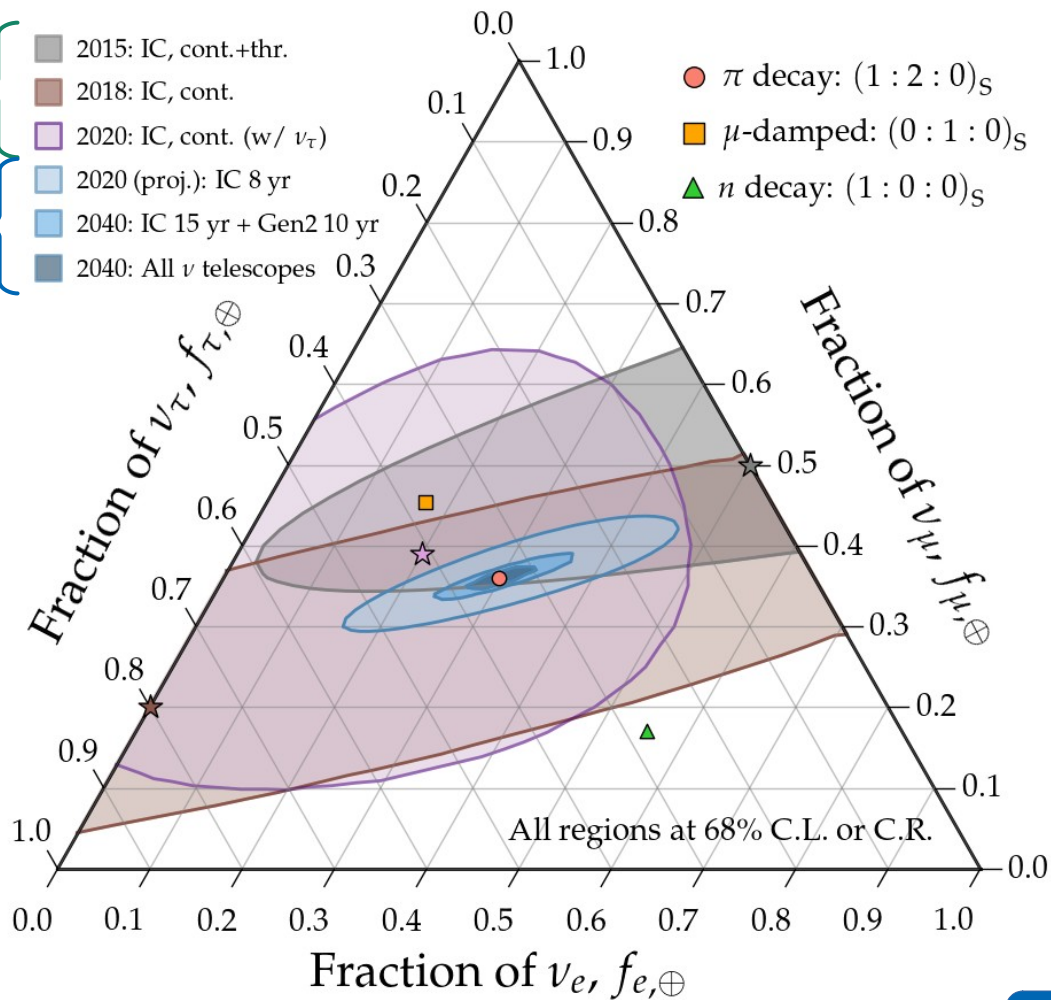
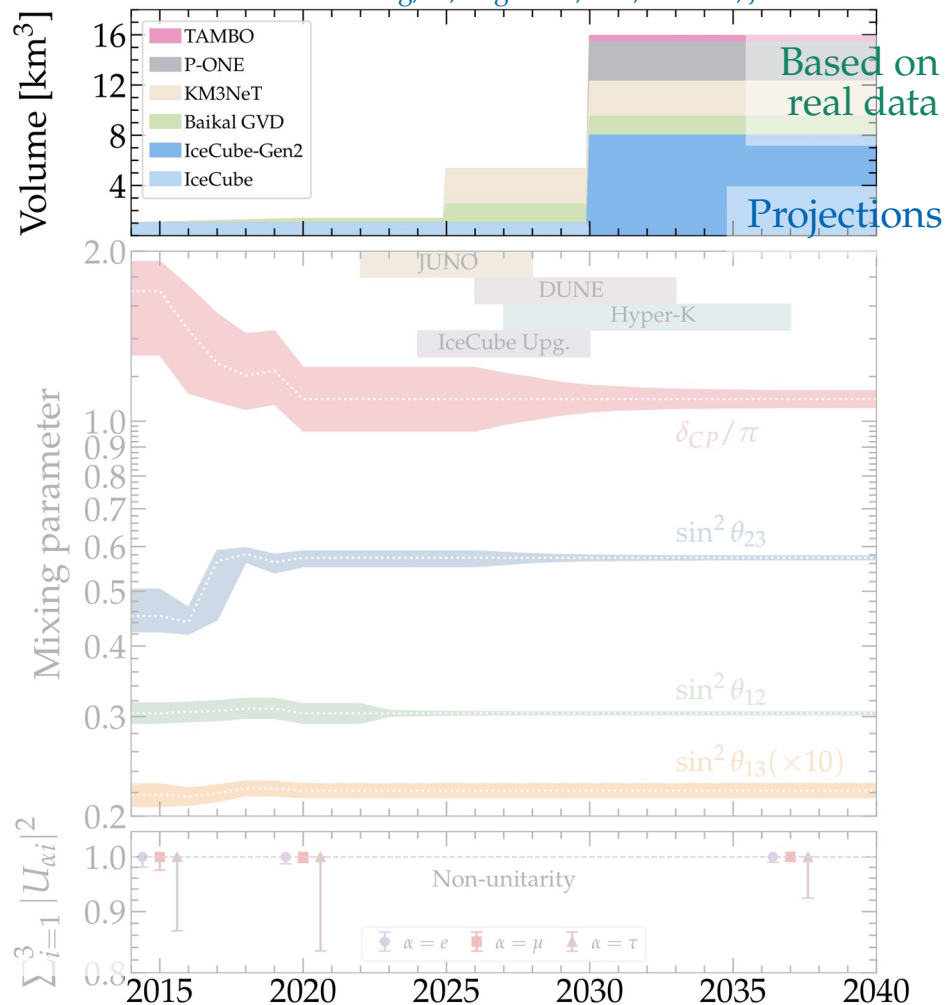
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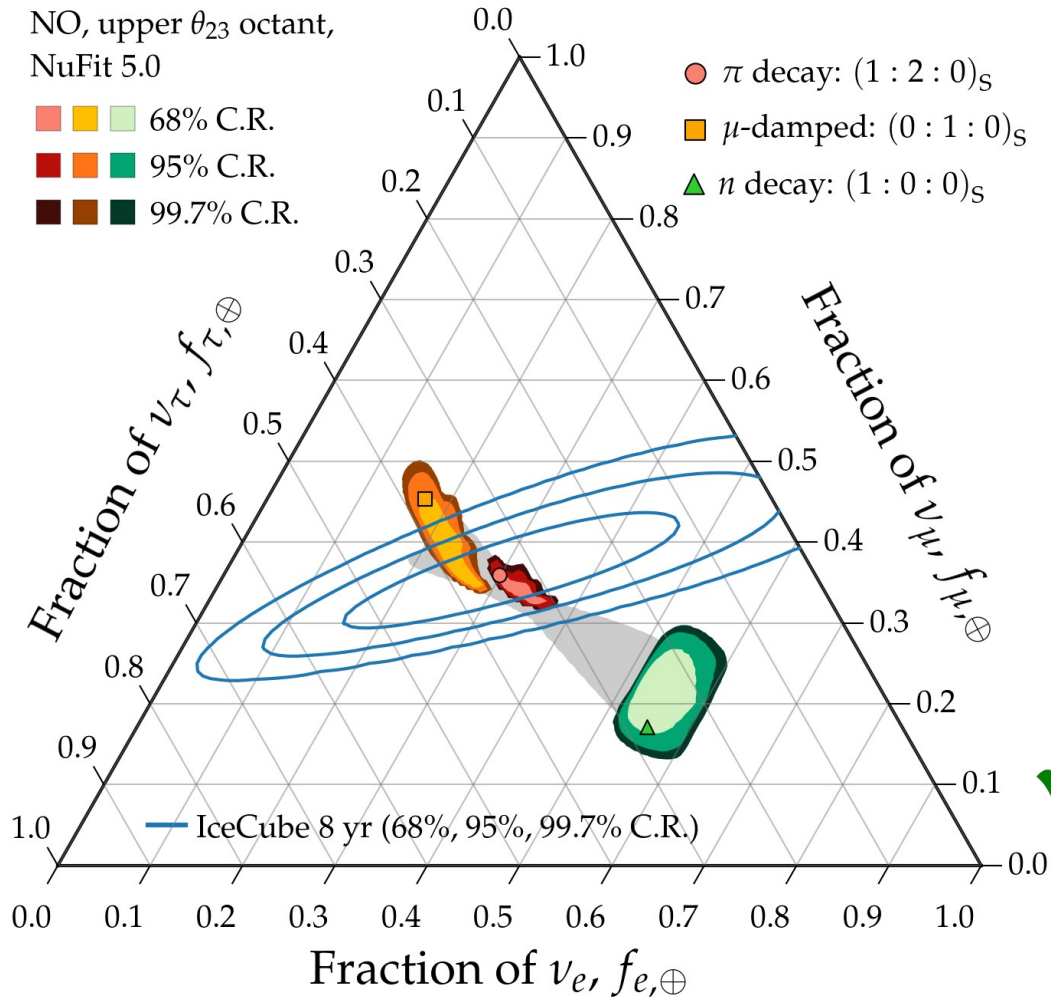


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Theoretically palatable regions: today (2021)



Two limitations:

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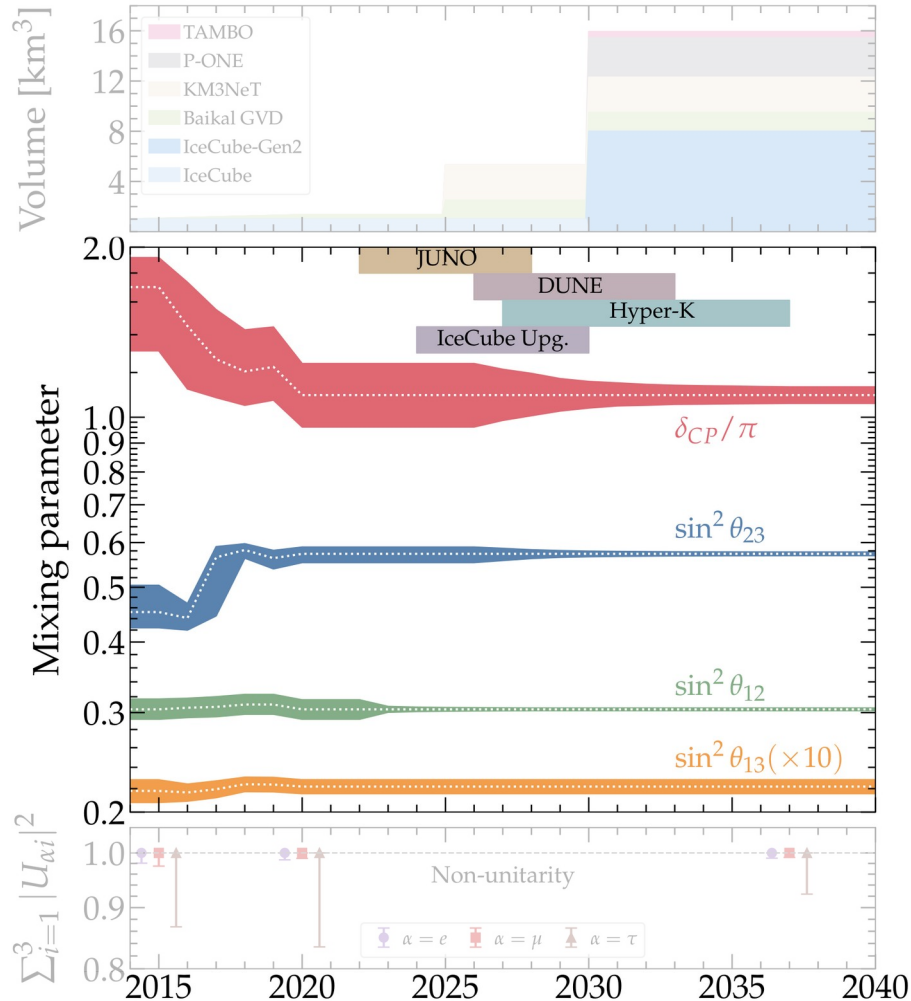
Will be overcome by 2030

Measurement of flavor ratios –
~~Cannot distinguish between
pion-decay and muon-damped
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Will be overcome by 2040

How knowing the mixing parameters better helps

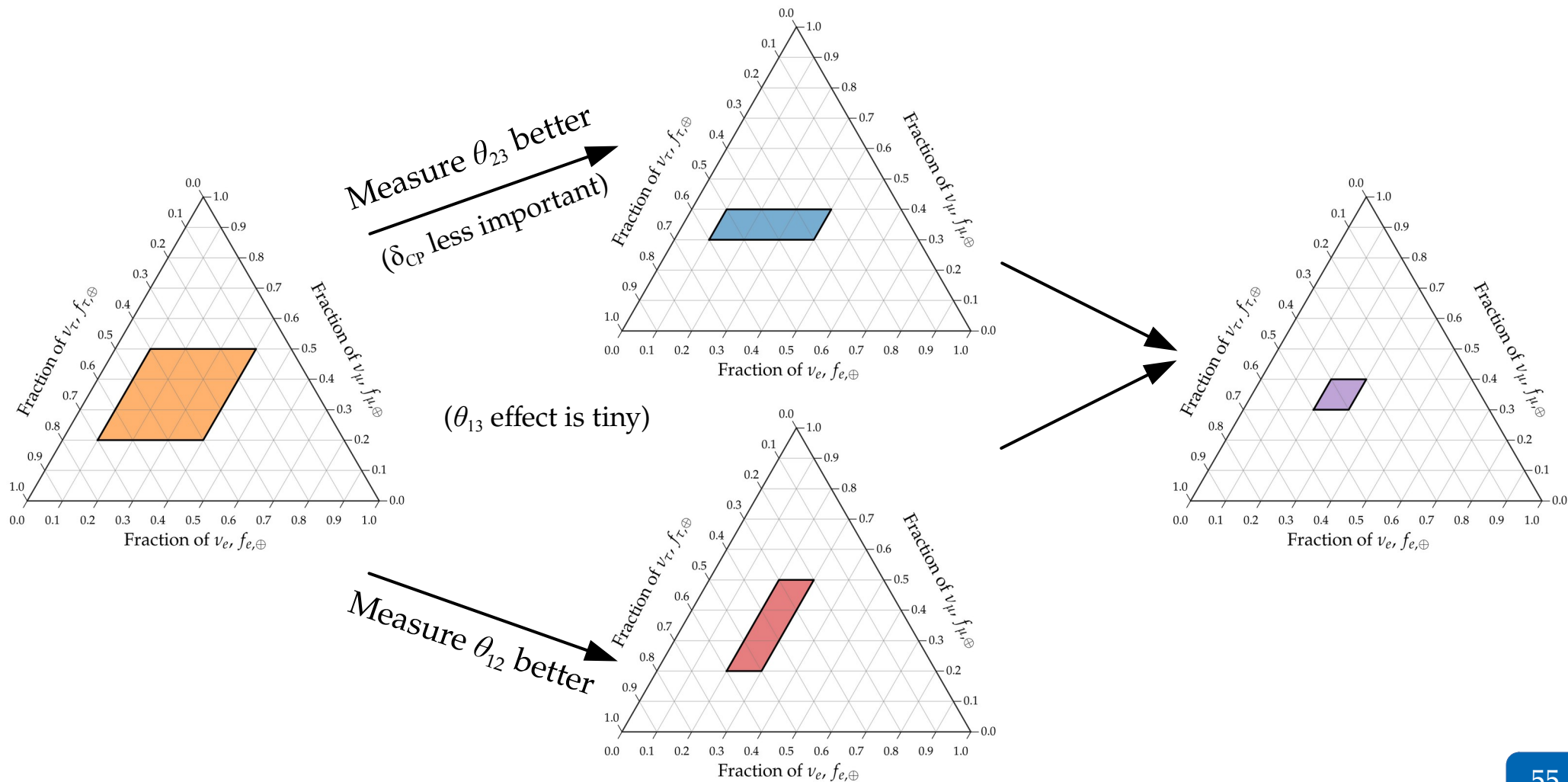


We can compute the oscillation probability more precisely:

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

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

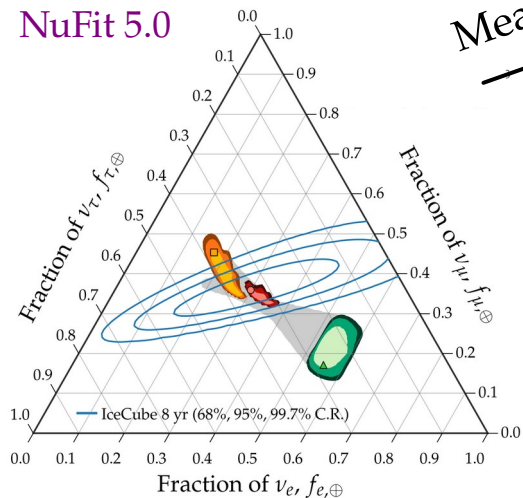
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

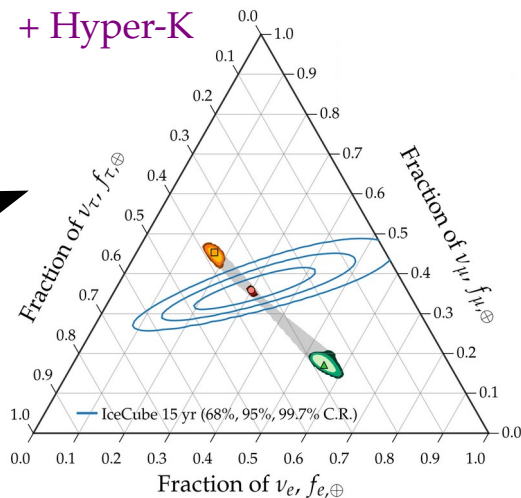
2020

NuFit 5.0

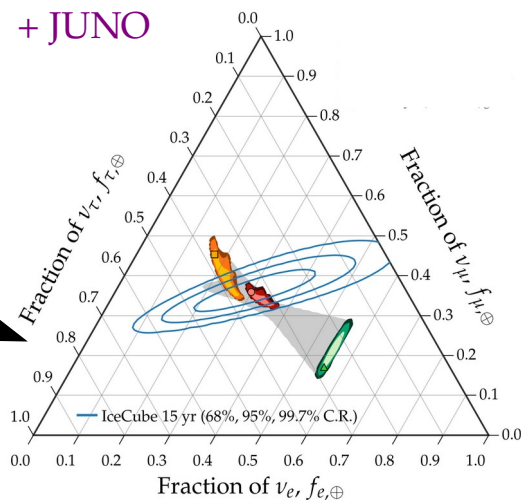


Measure θ_{23} better

+ Hyper-K



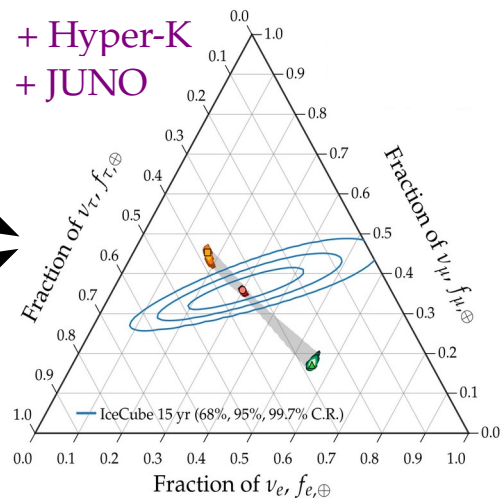
+ JUNO



Measure θ_{12} better

~2030

+ Hyper-K
+ JUNO



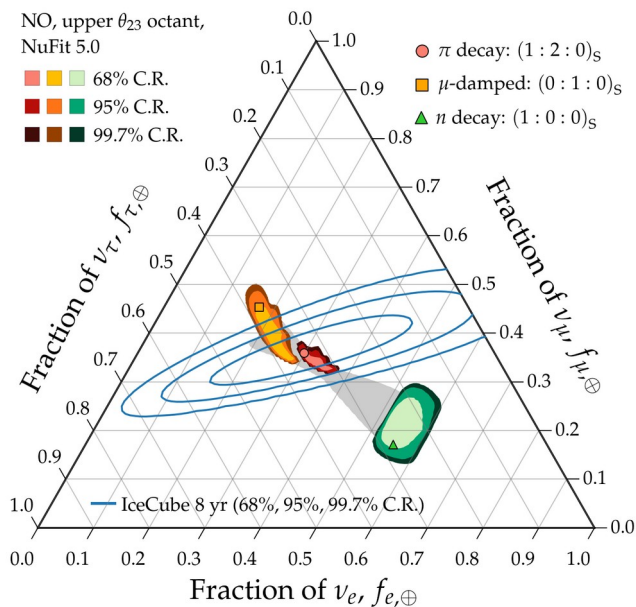
In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

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

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

2020

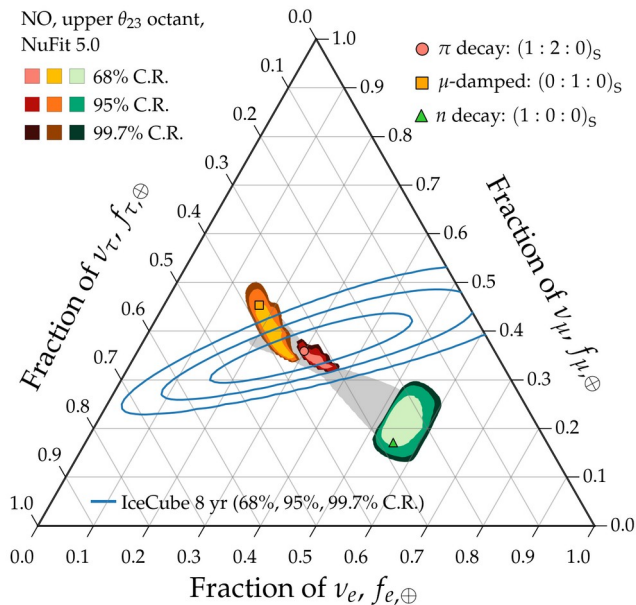


Allowed regions: overlapping

Measurement: imprecise

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

2020



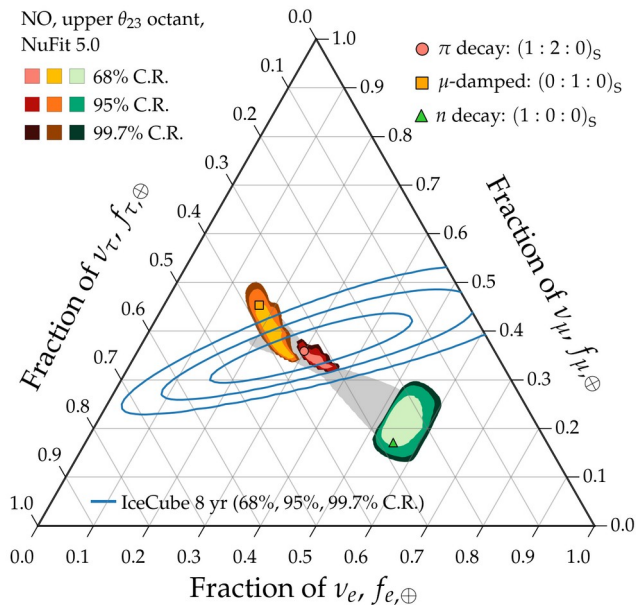
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Not ideal

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

2020

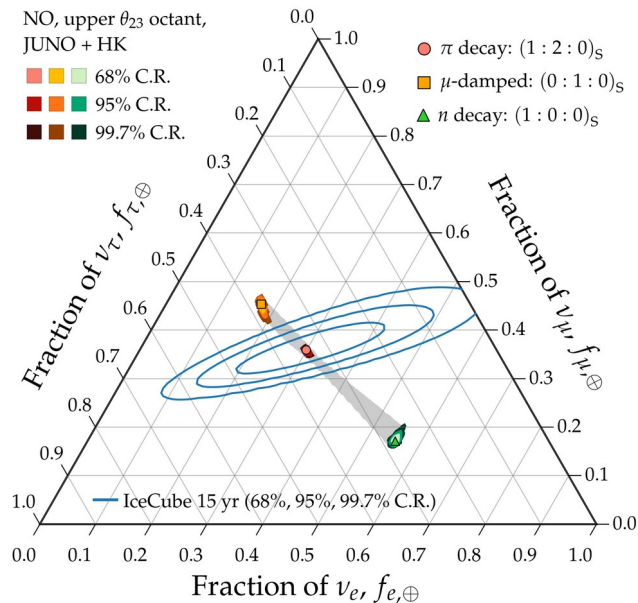


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Measurement: imprecise

Not ideal

2030

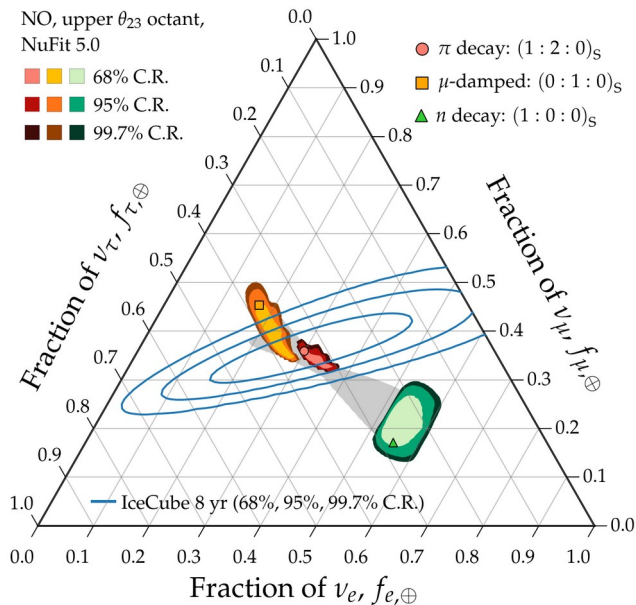


Allowed regions: well separated

Measurement: improving

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

2020

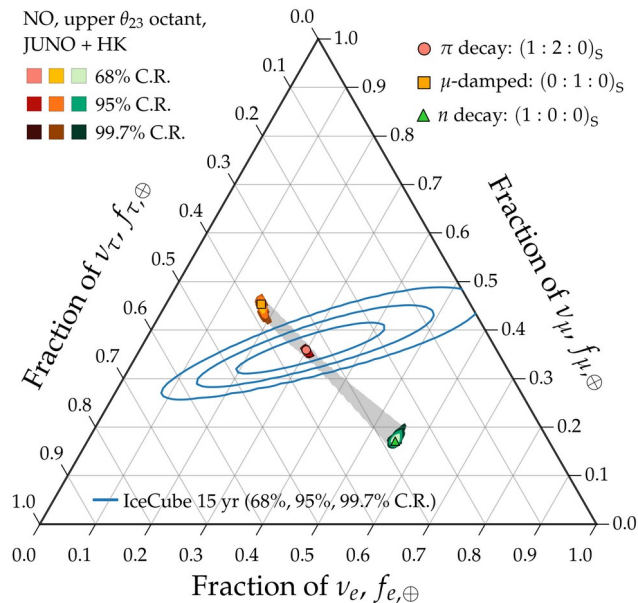


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Measurement: imprecise

Not ideal

2030



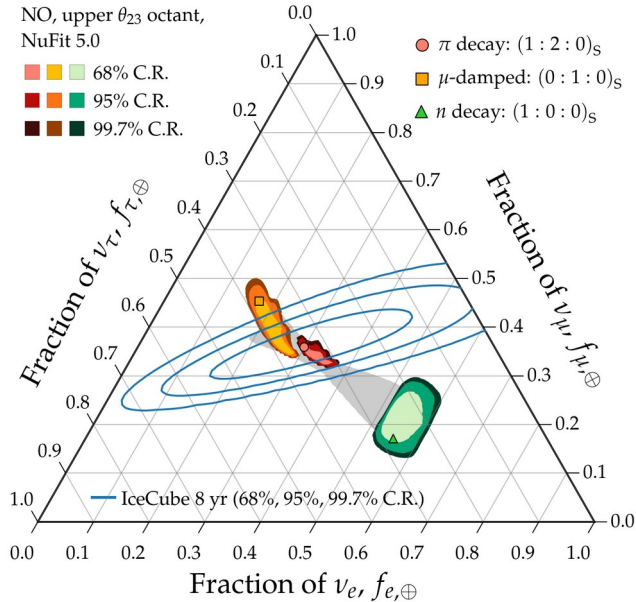
Allowed regions: well separated

Measurement: improving

Nice

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

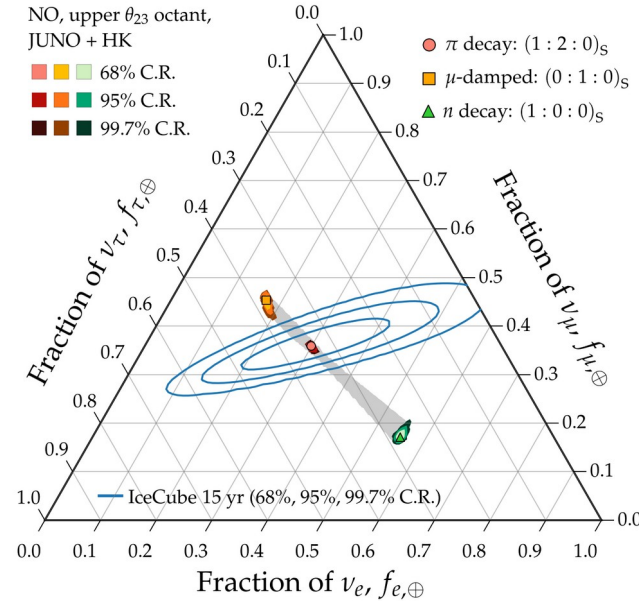
2020



Allowed regions: overlapping
Measurement: imprecise

Not ideal

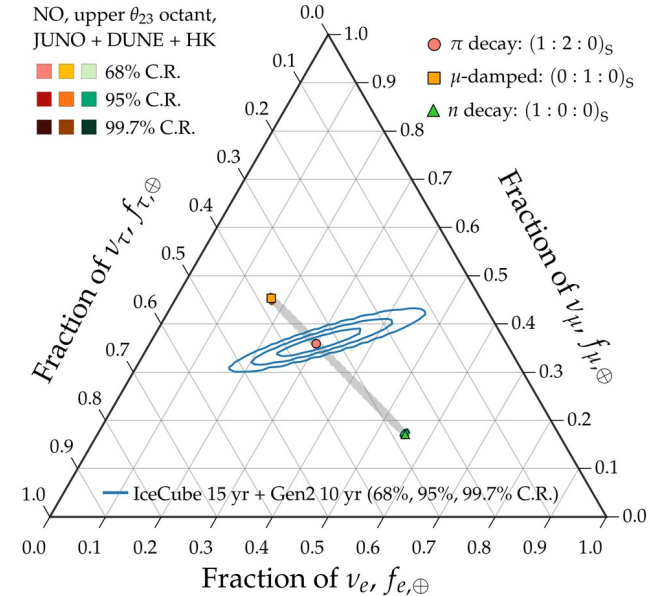
2030



Allowed regions: well separated
Measurement: improving

Nice

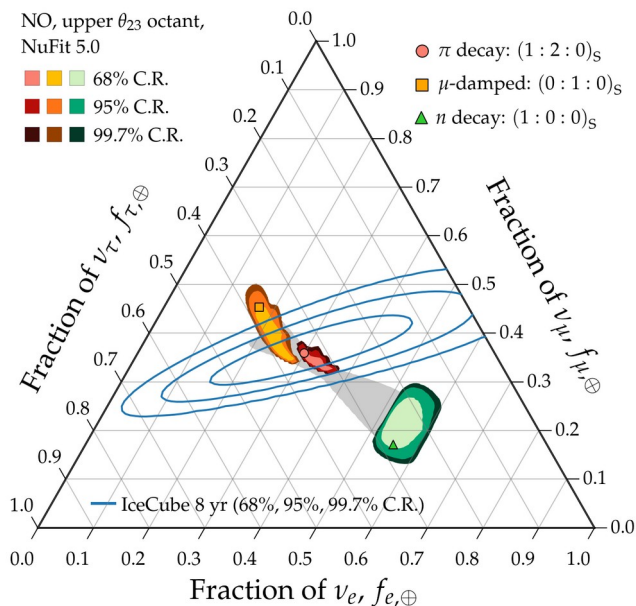
2040



Allowed regions: well separated
Measurement: precise

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

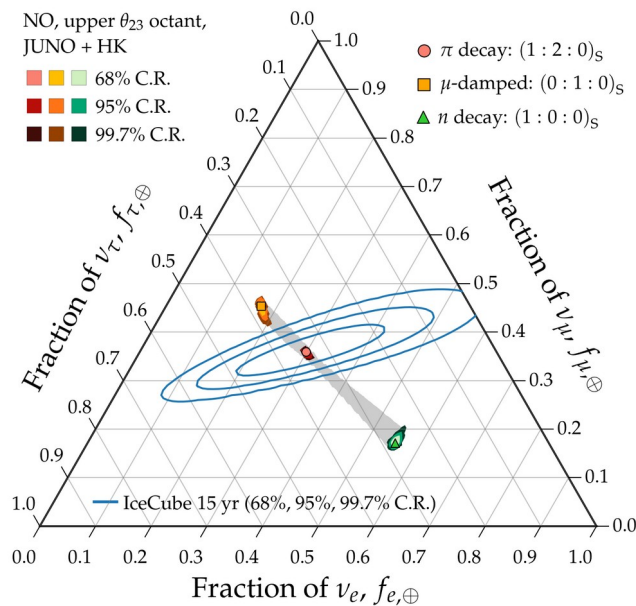
2020



Allowed regions: overlapping
Measurement: imprecise

Not ideal

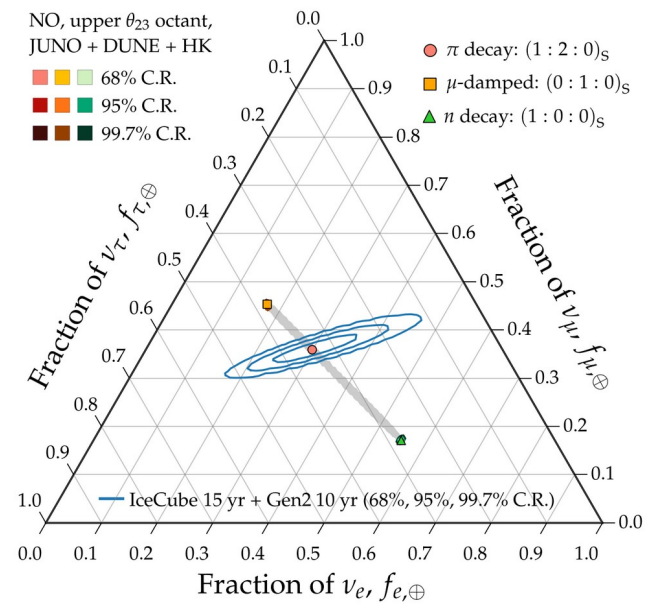
2030



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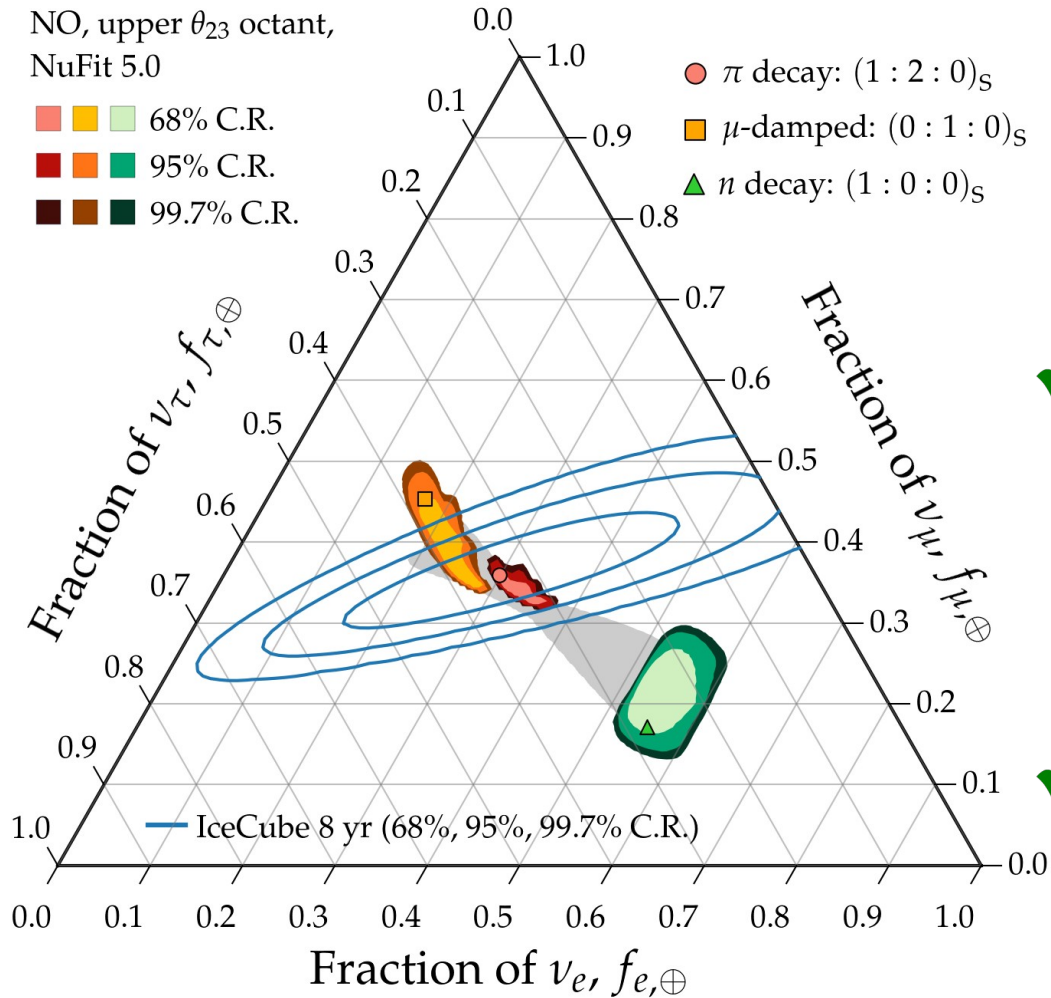
2040



Allowed regions: well separated
Measurement: precise

Success

Theoretically palatable regions: today (2021)



Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

✓ *Will be overcome by 2030*

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

✓ *Will be overcome by 2040*

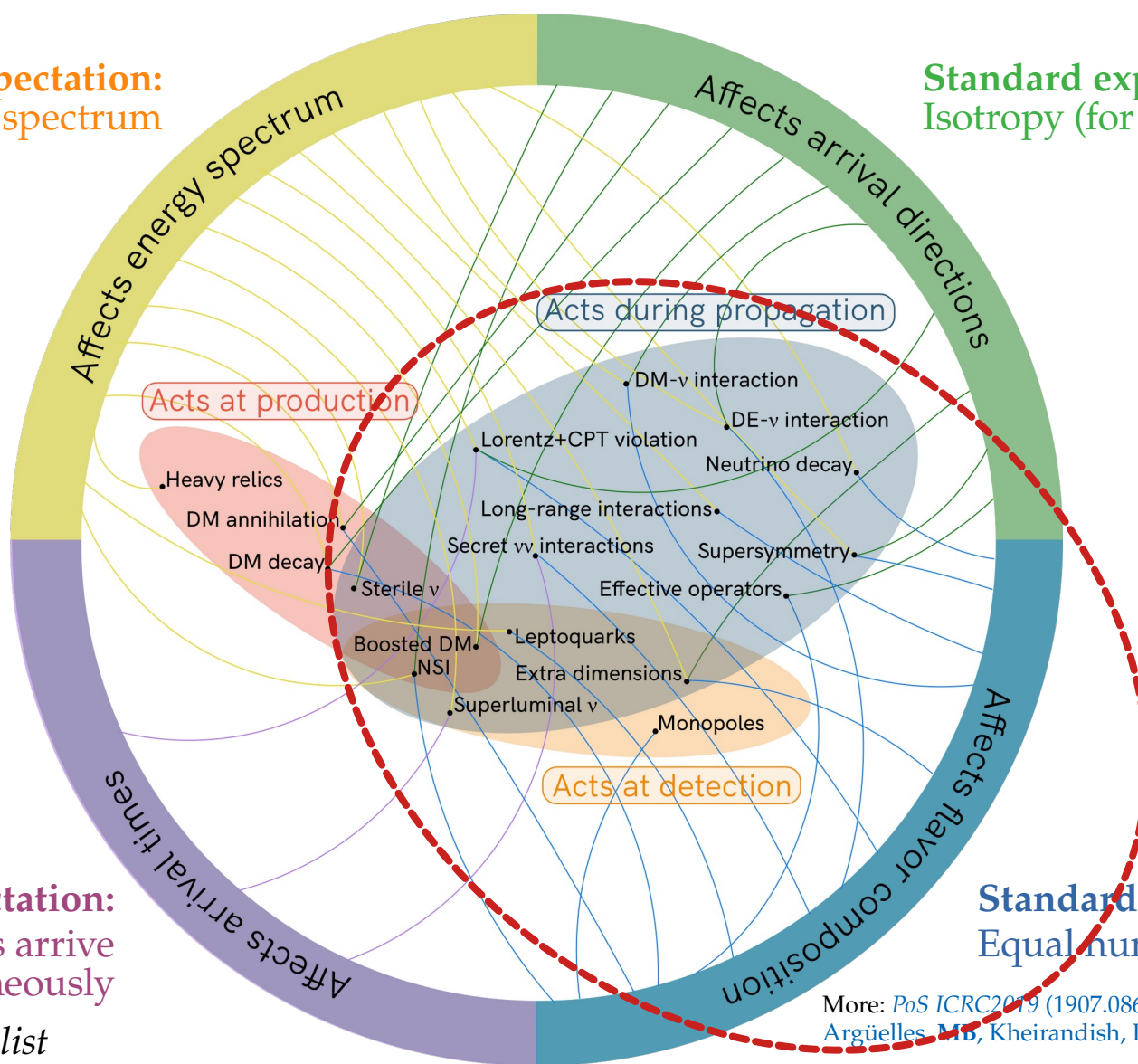
Standard expectation:
Power-law energy spectrum

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, M.B., Kheirandish, Palomares-Ruiz, Salvadó, Vincent

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

Reviews:

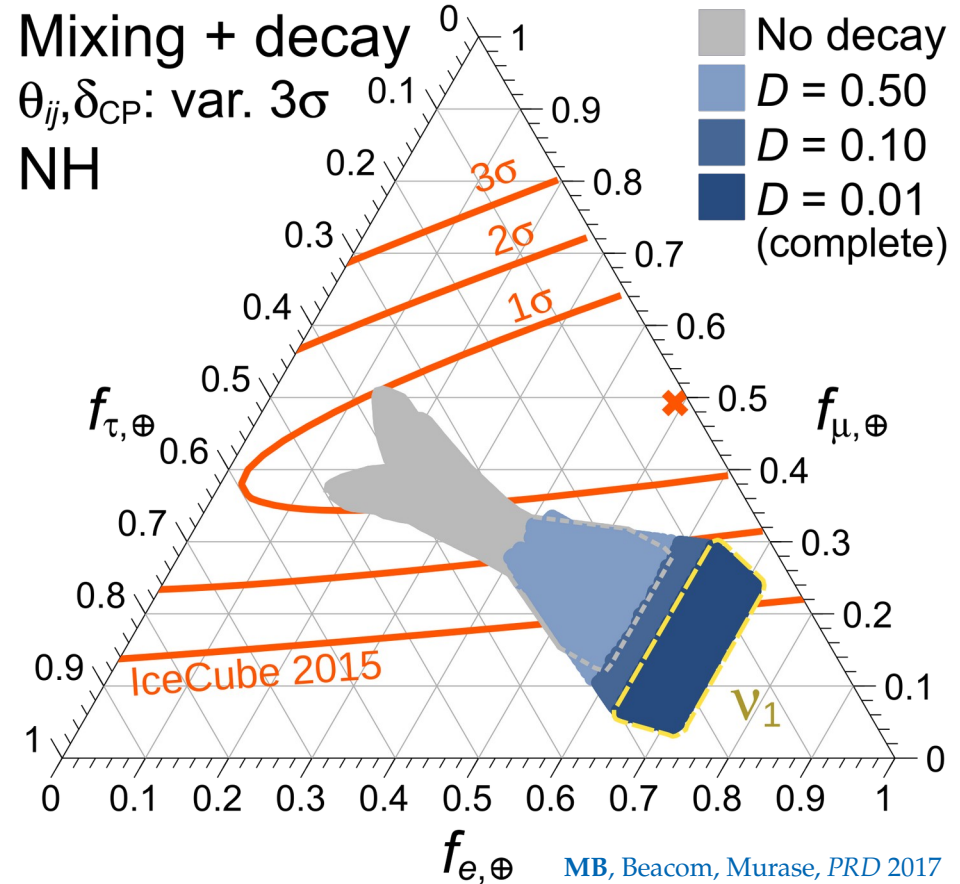
Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

► Neutrino decay

[Beacom *et al.*, *PRL* 2003; Baerwald, MB, Winter, *JCAP* 2010;
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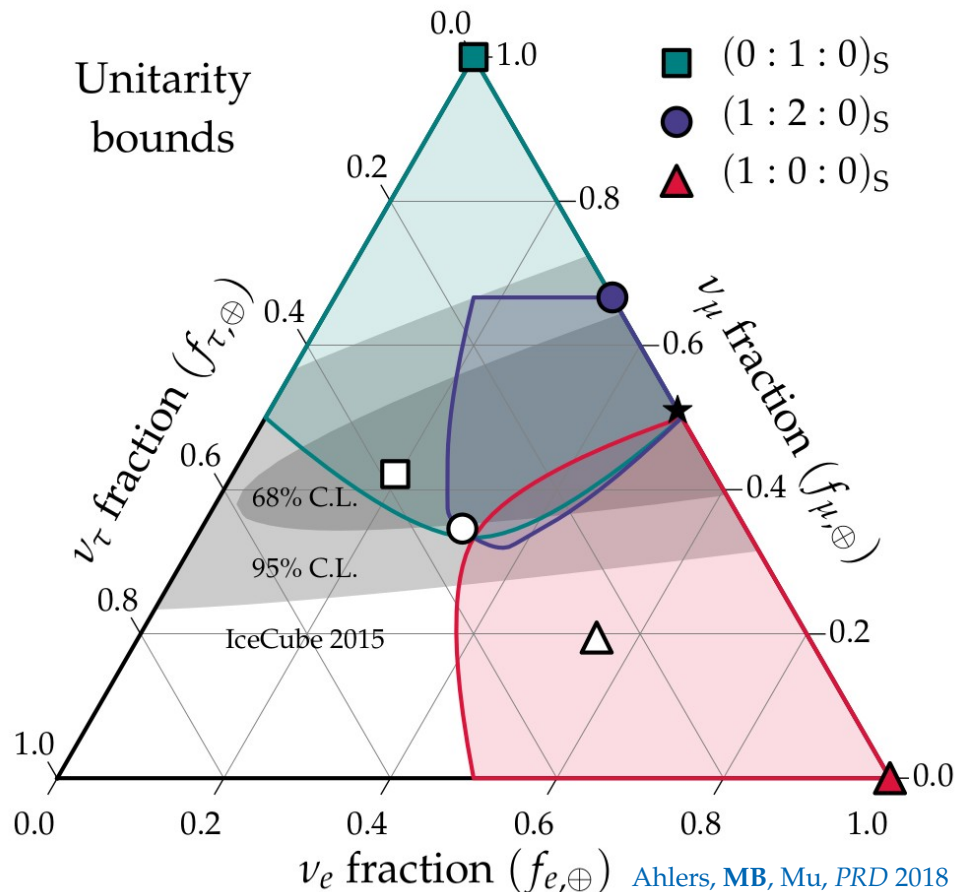
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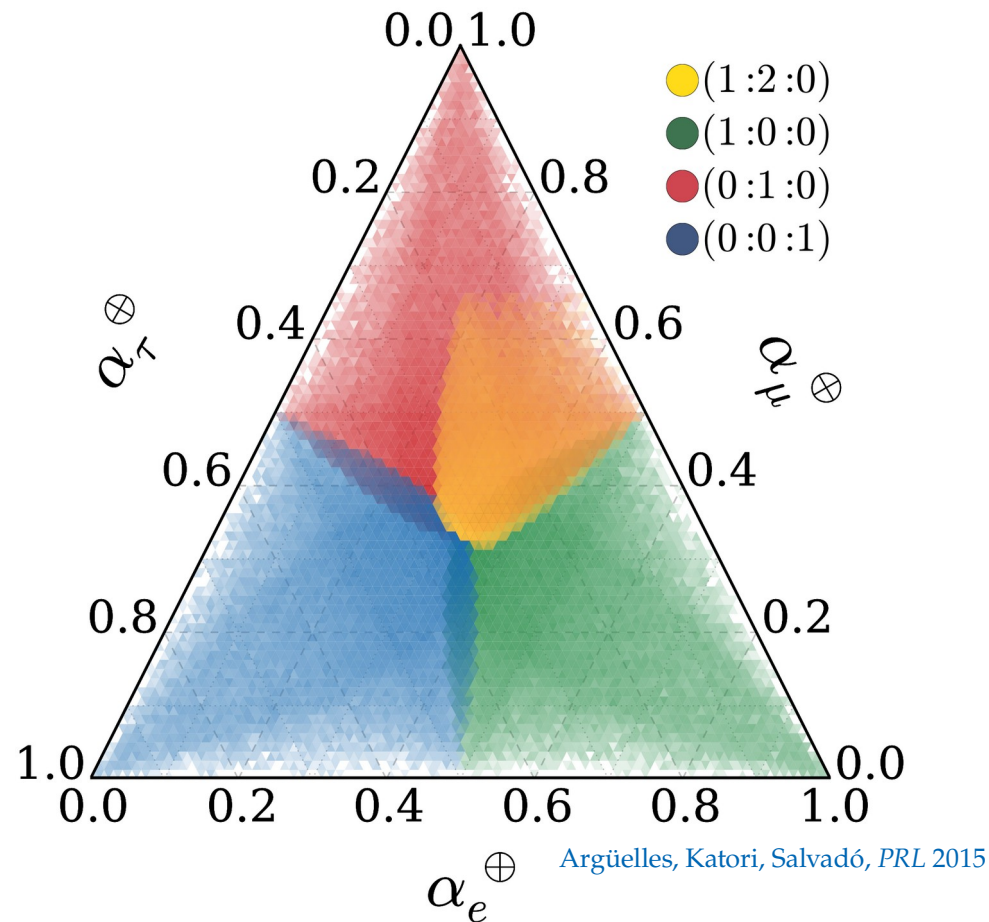
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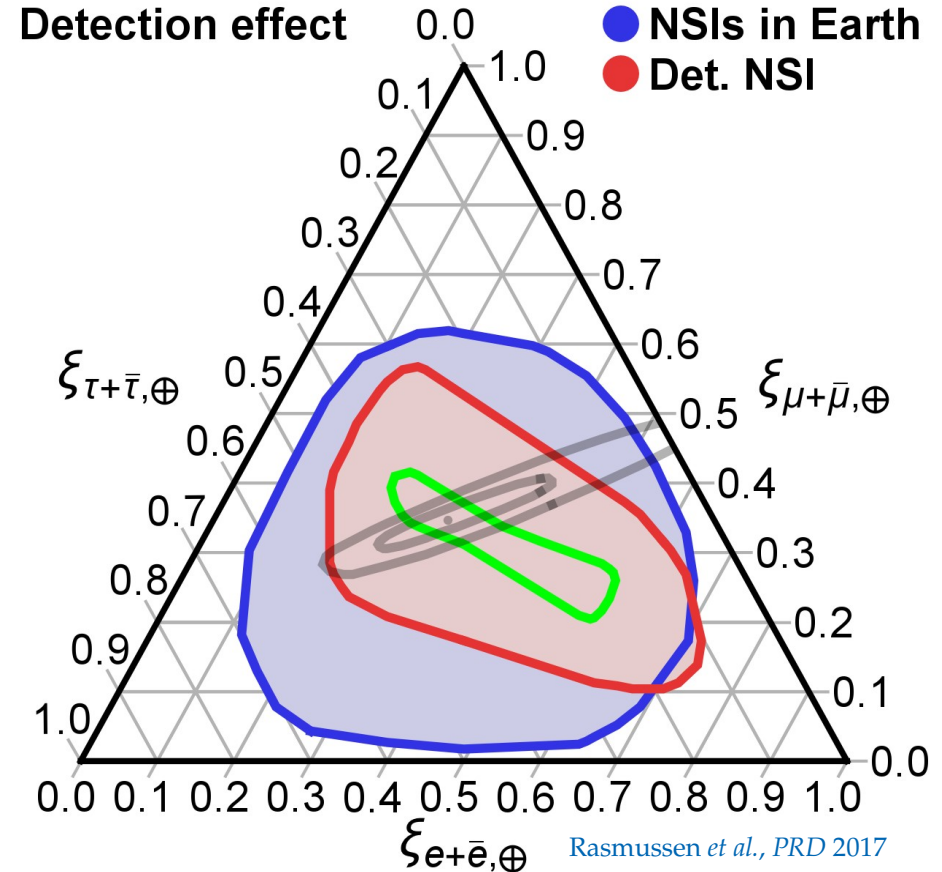
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- ▶ Non-standard interactions

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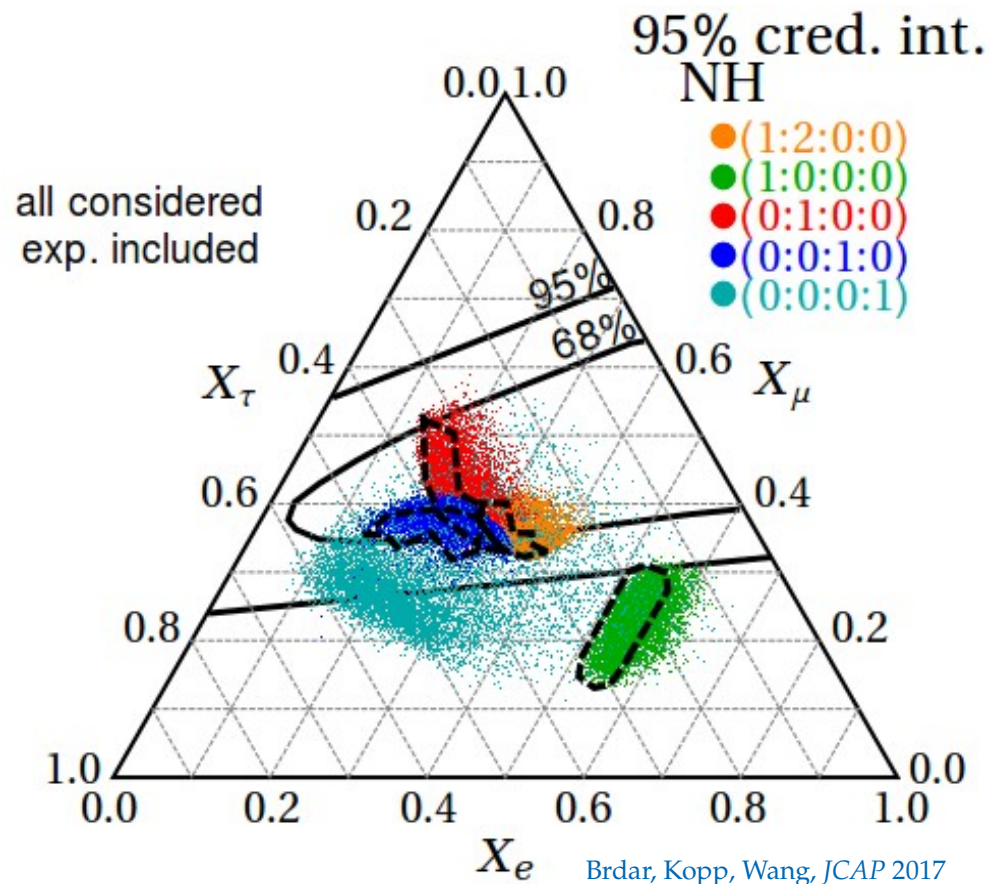
[González-García *et al.*, *Astropart. Phys.* 2016;
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- Active-sterile ν mixing

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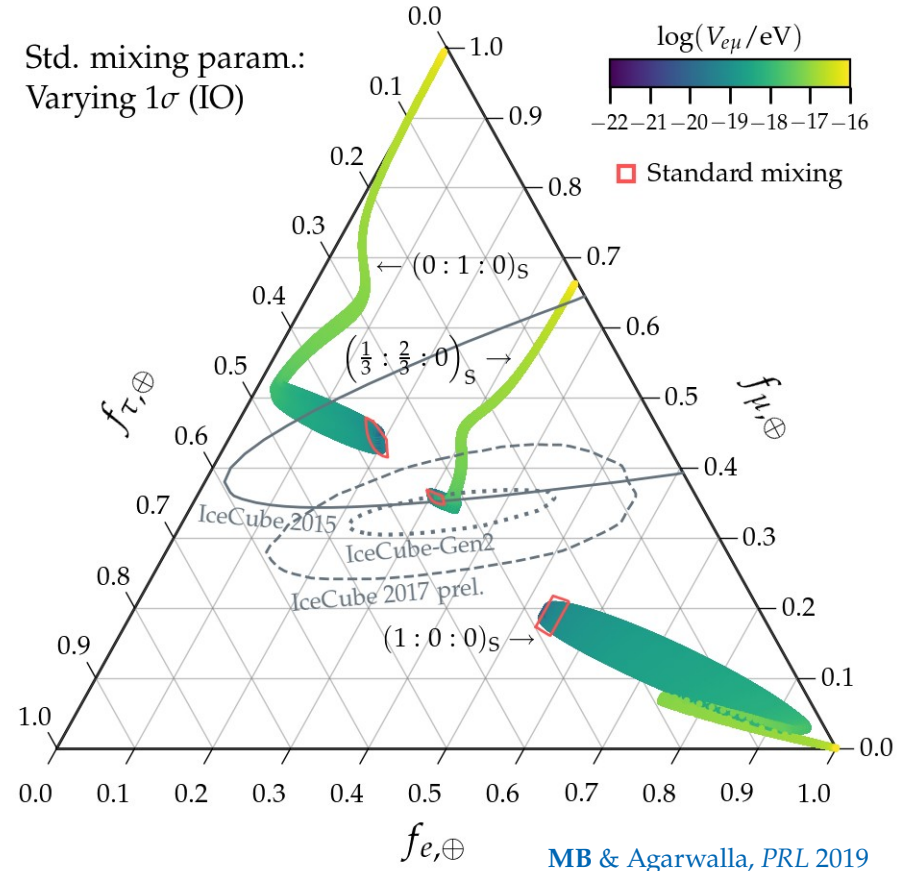
[Aeikens *et al.*, *JCAP* 2015; Brdar, Kopp, Wang, *JCAP* 2017;
Argüelles *et al.*, *JCAP* 2020; Ahlers, **MB**, *JCAP* 2021]

- ▶ Long-range $e\nu$ interactions

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

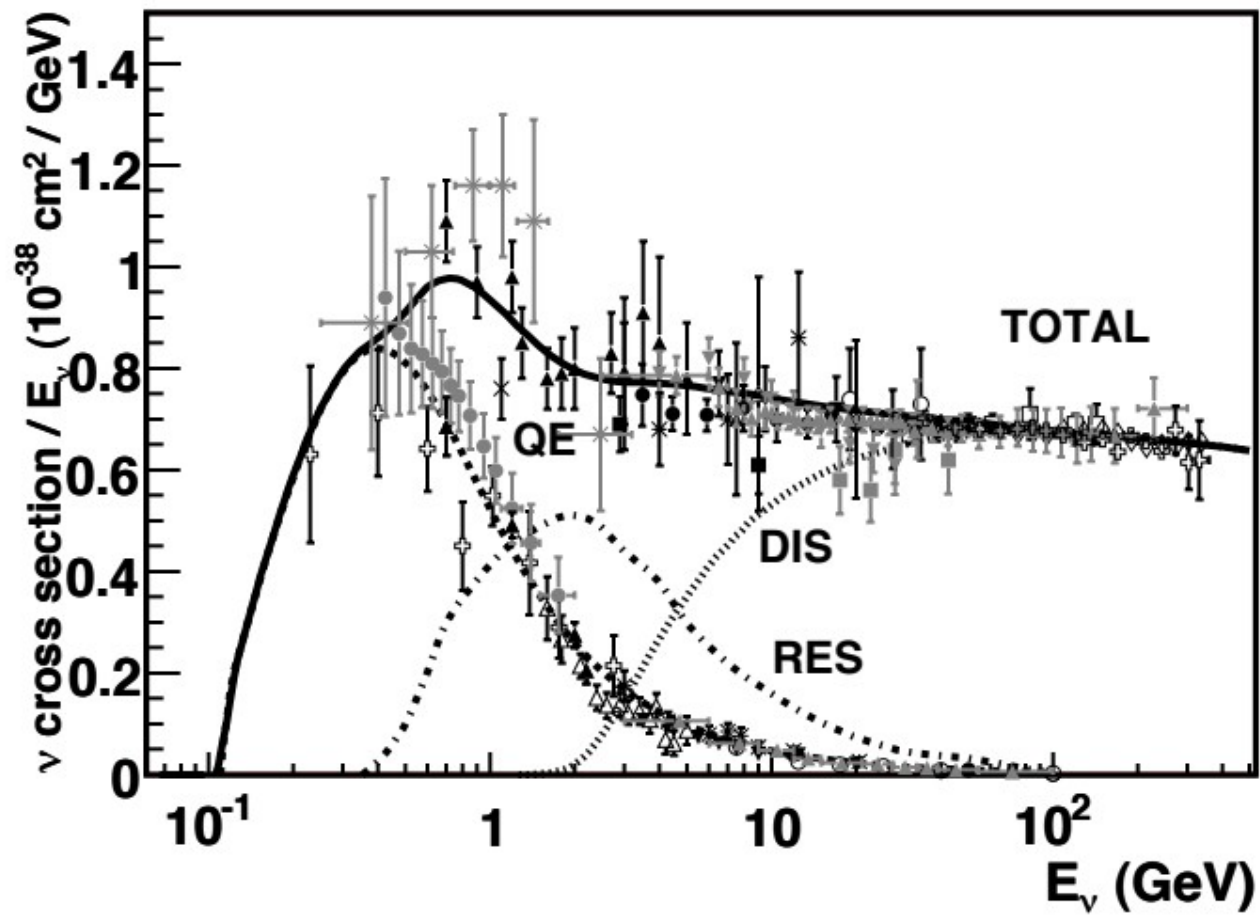
Reviews:

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



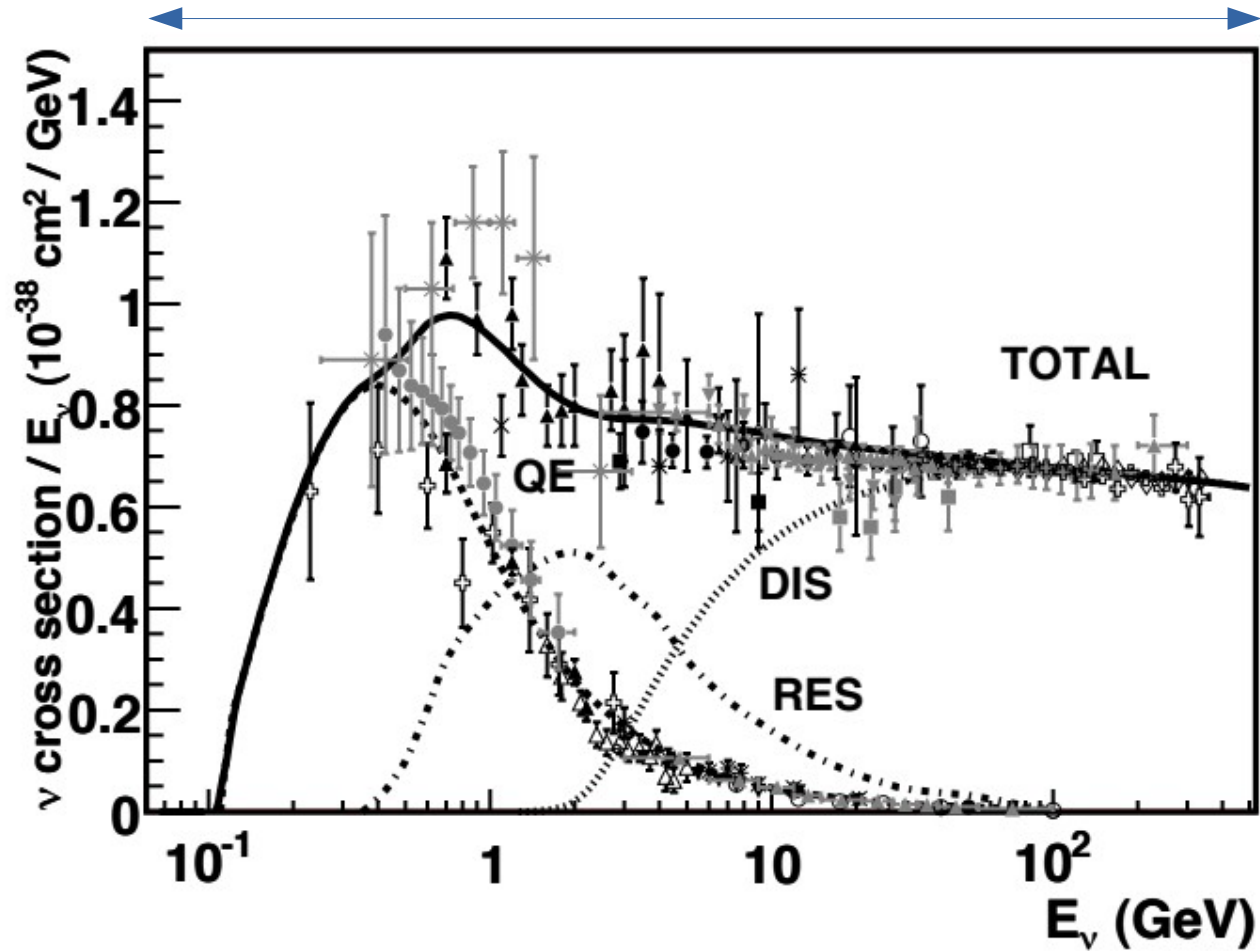
Neutrino-nucleon cross section:

From high to ultra-high energies



Particle Data Group

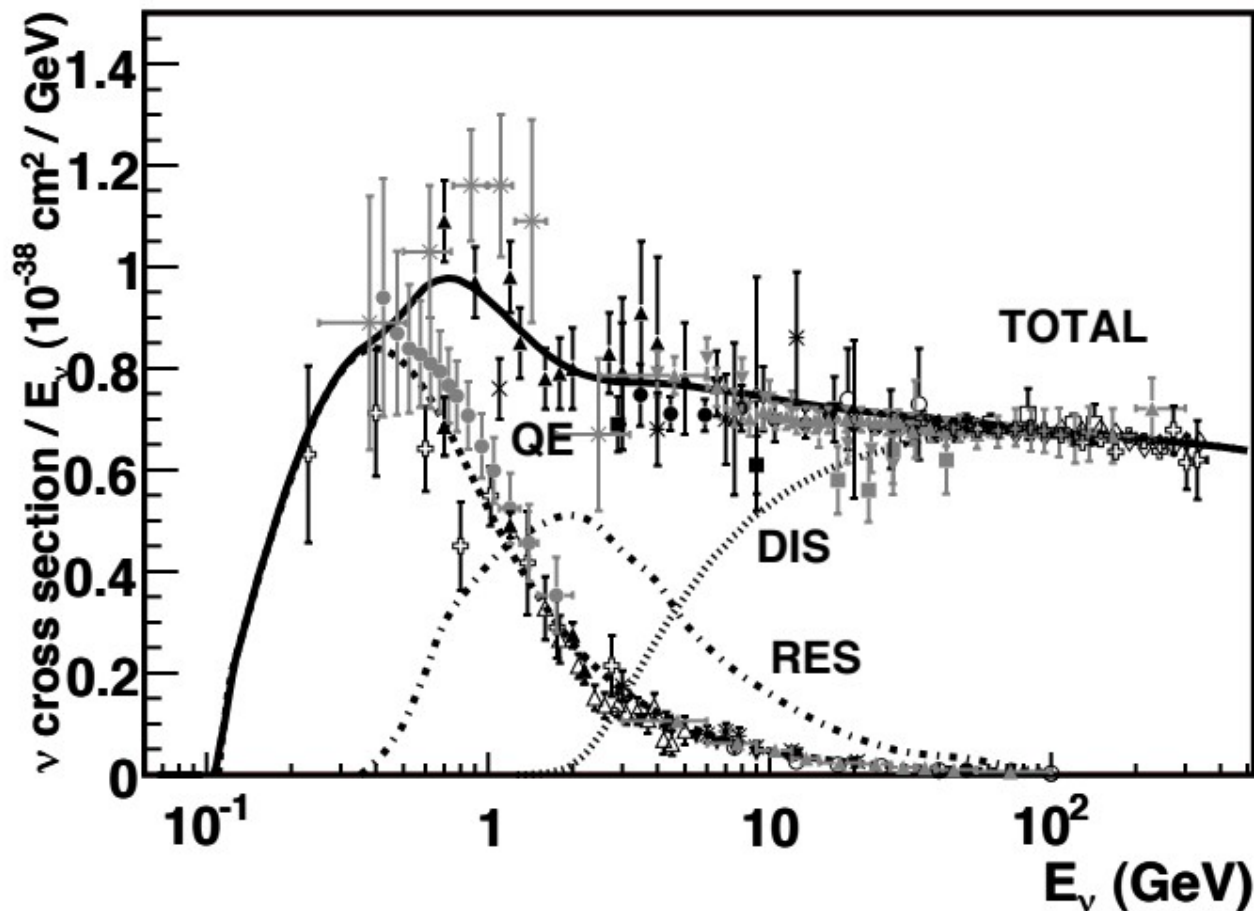
Accelerator experiments



Particle Data Group

Accelerator experiments

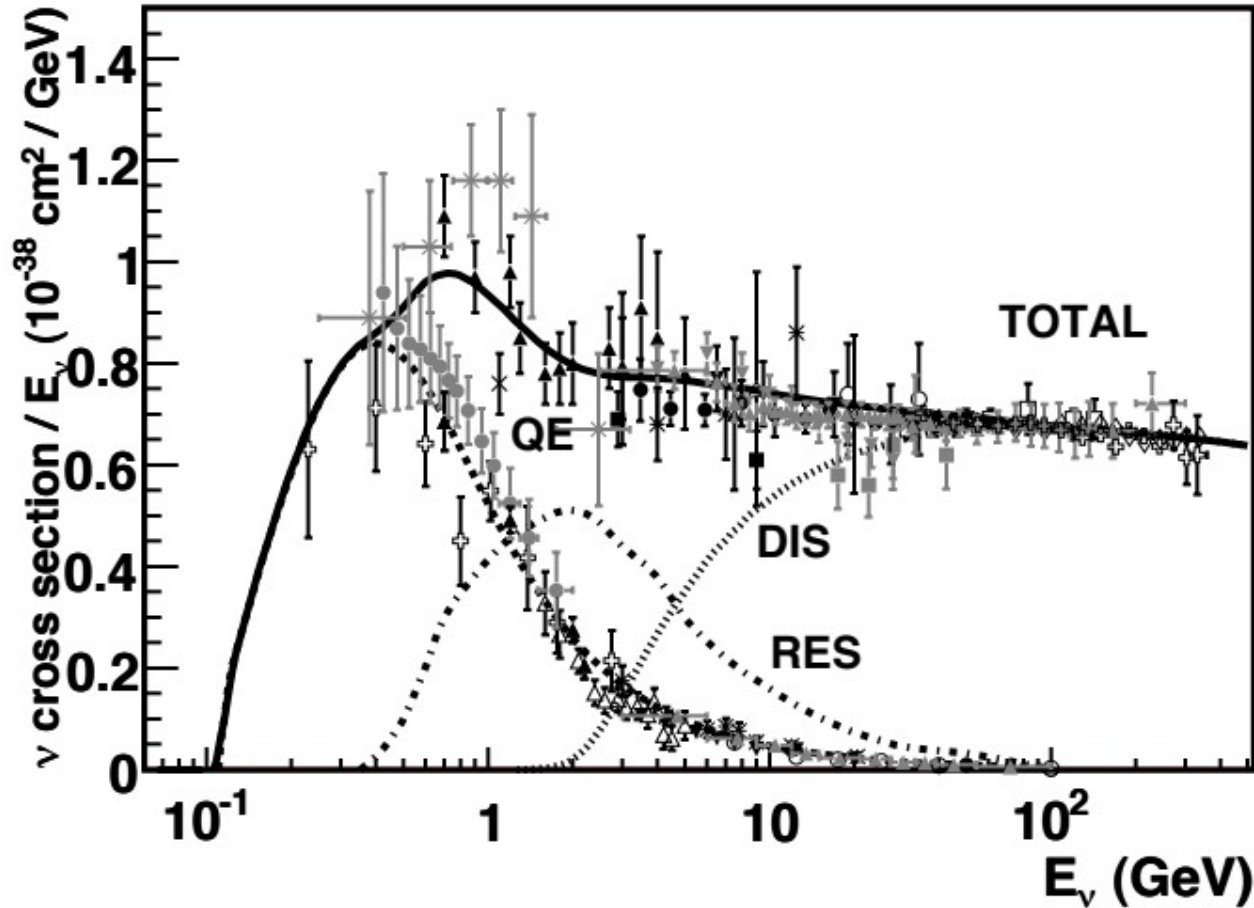
One recent
measurement
(COHERENT)



Particle Data Group

Accelerator experiments

One recent
measurement
(COHERENT)

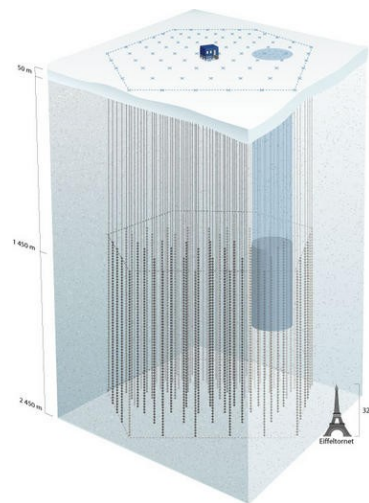
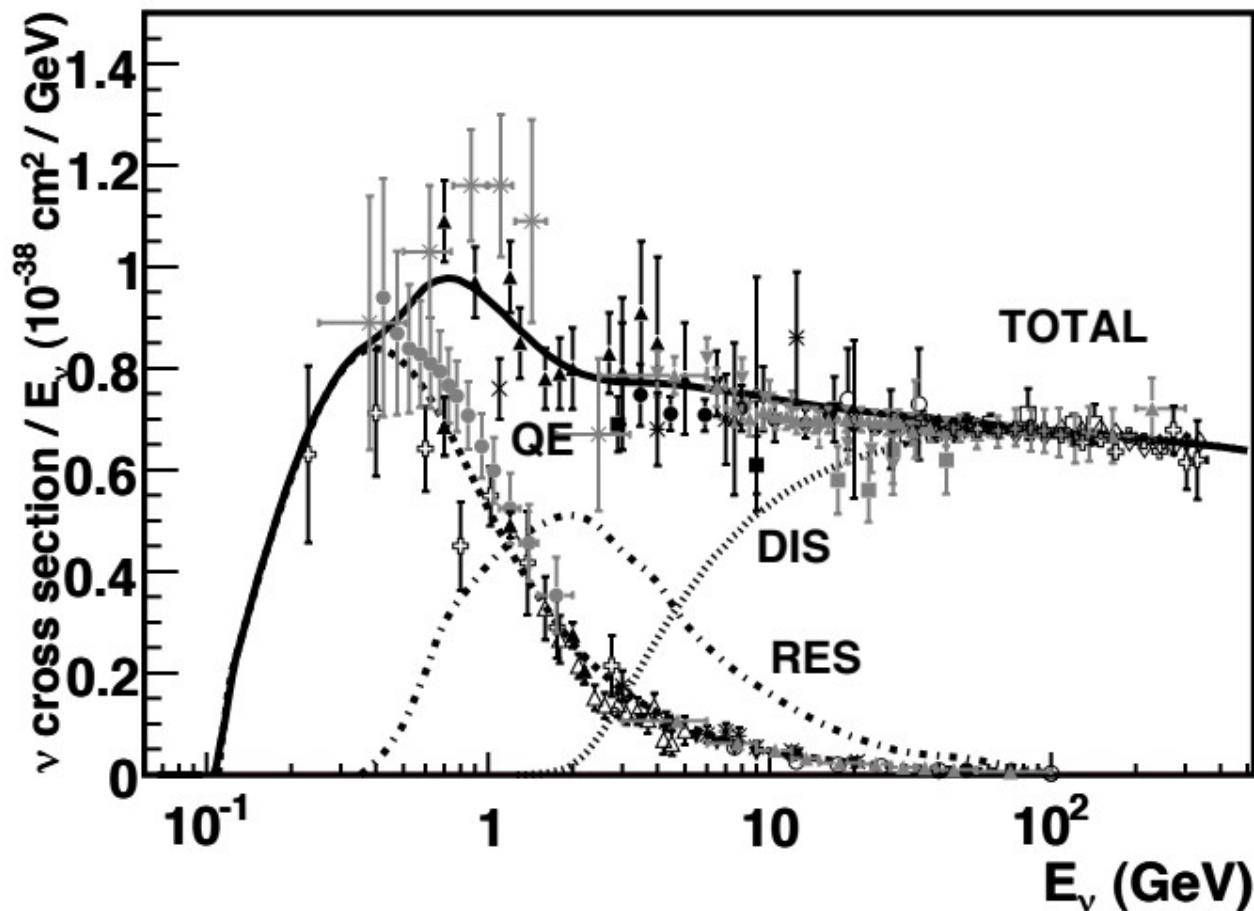


No
measurements
... until recently!

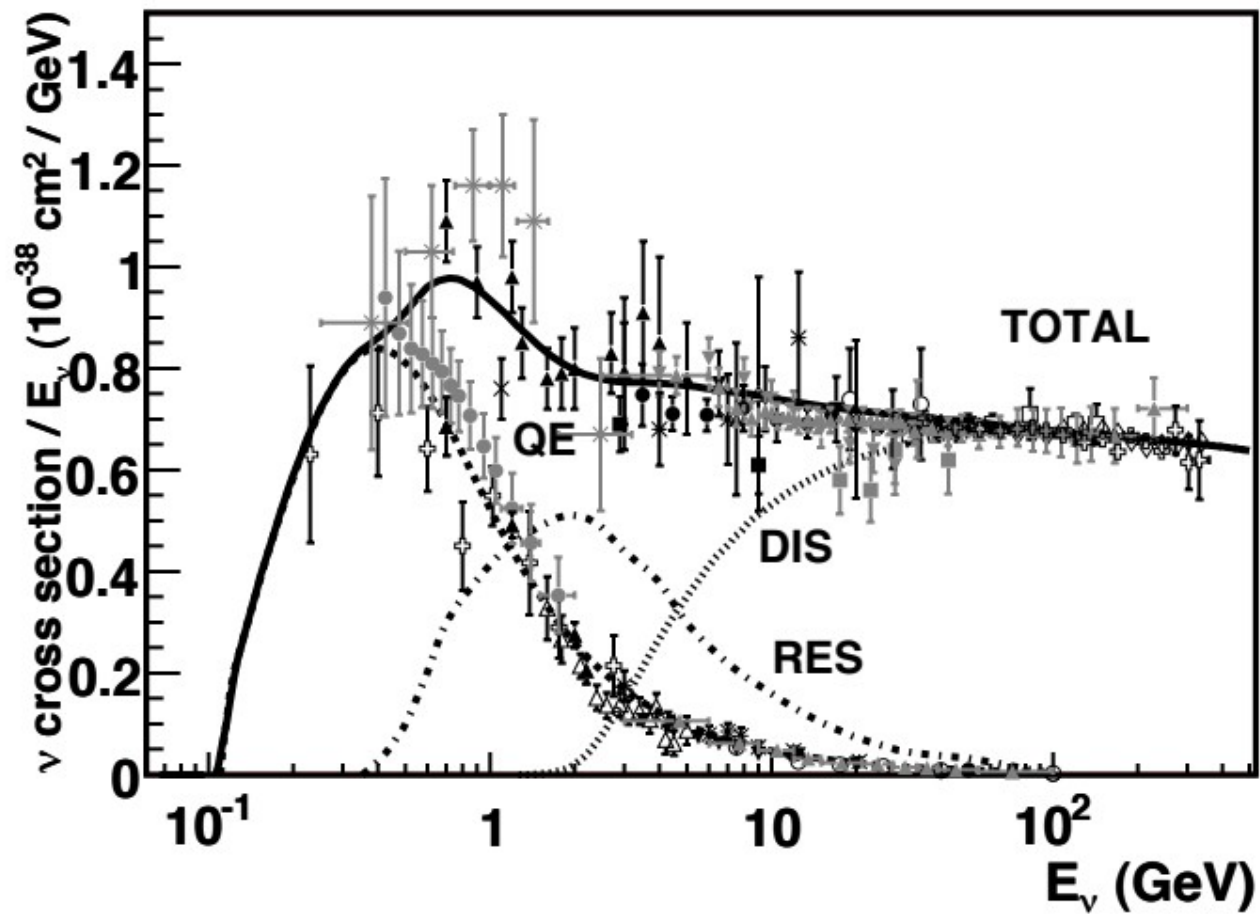
Particle Data Group

Accelerator experiments

One recent
measurement
(COHERENT)



Particle Data Group

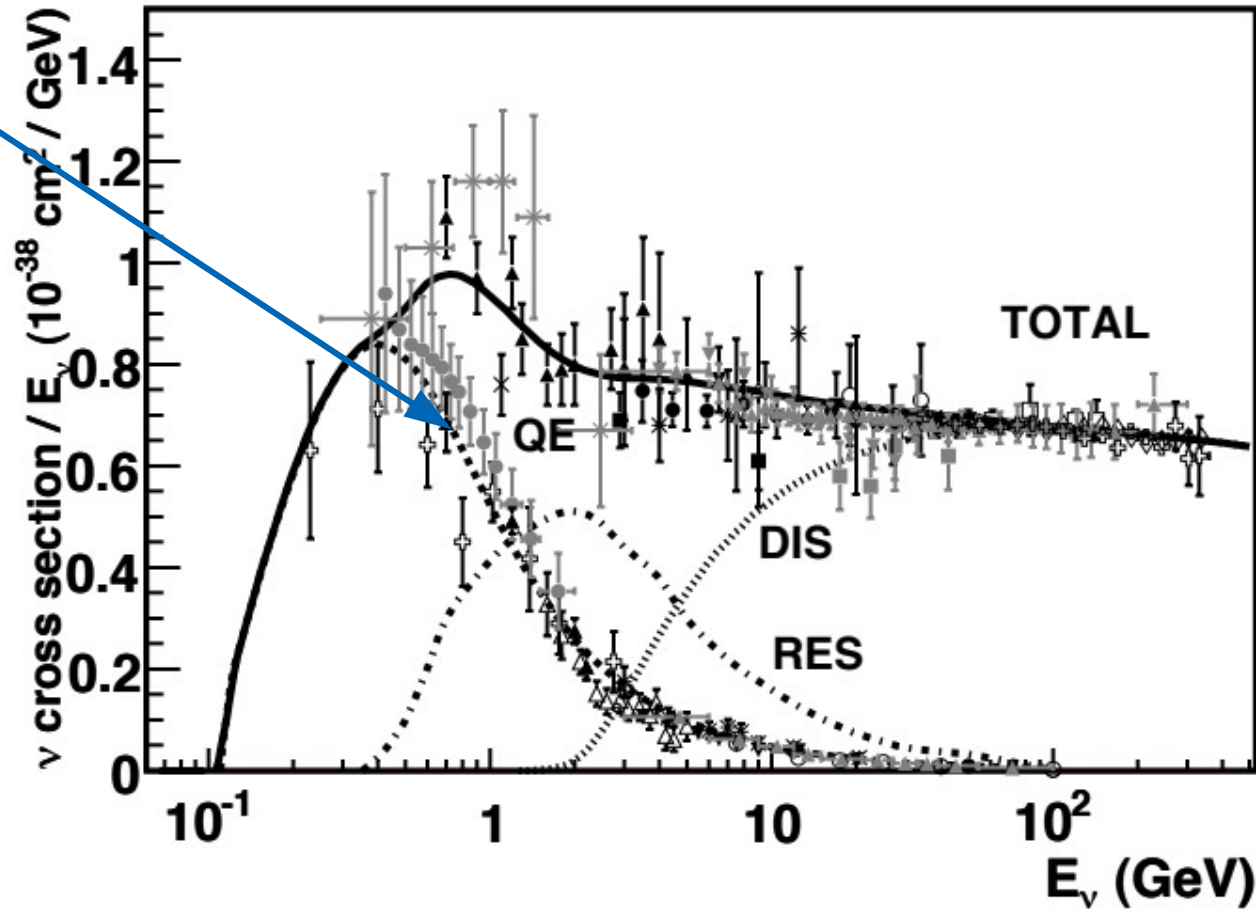


Particle Data Group

Quasi-elastic
scattering:

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

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

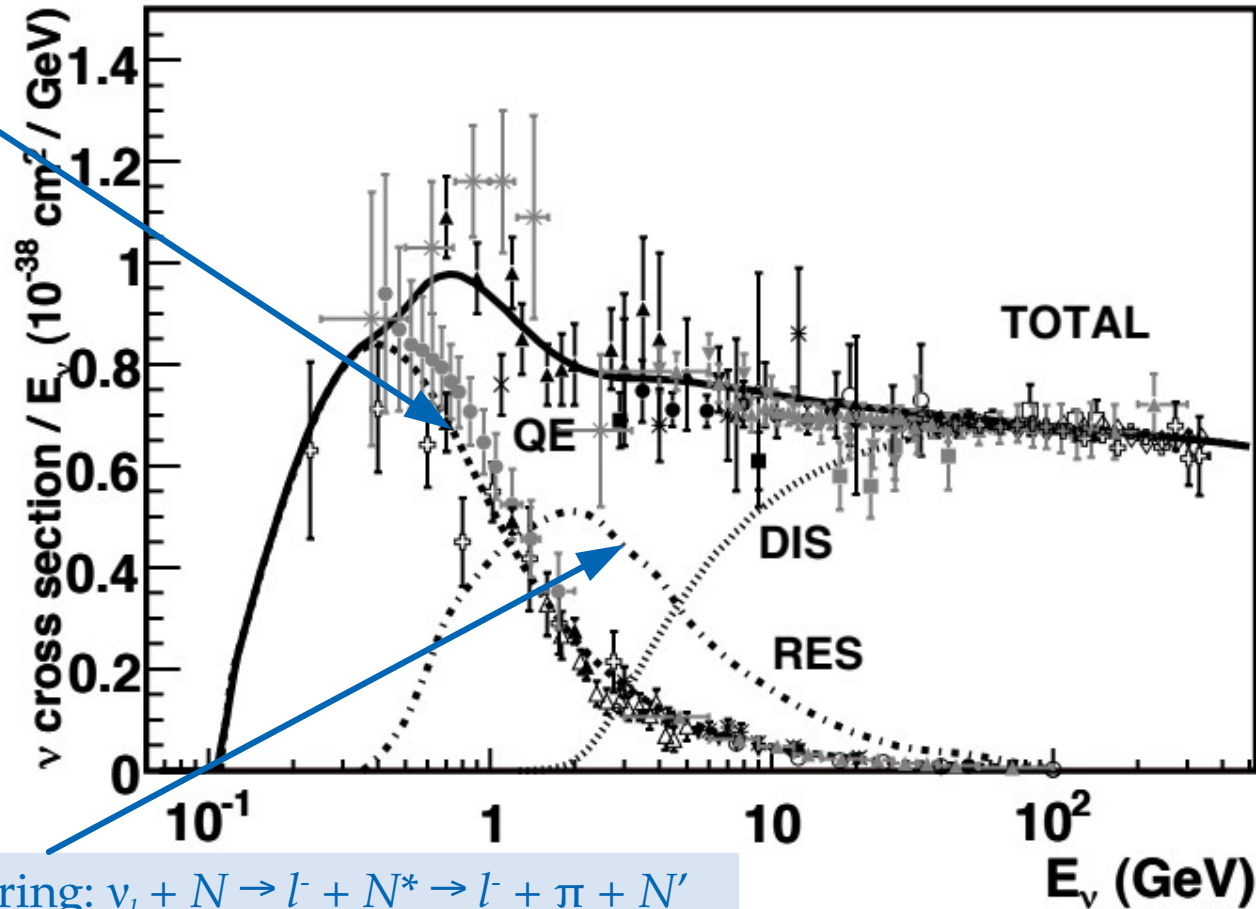


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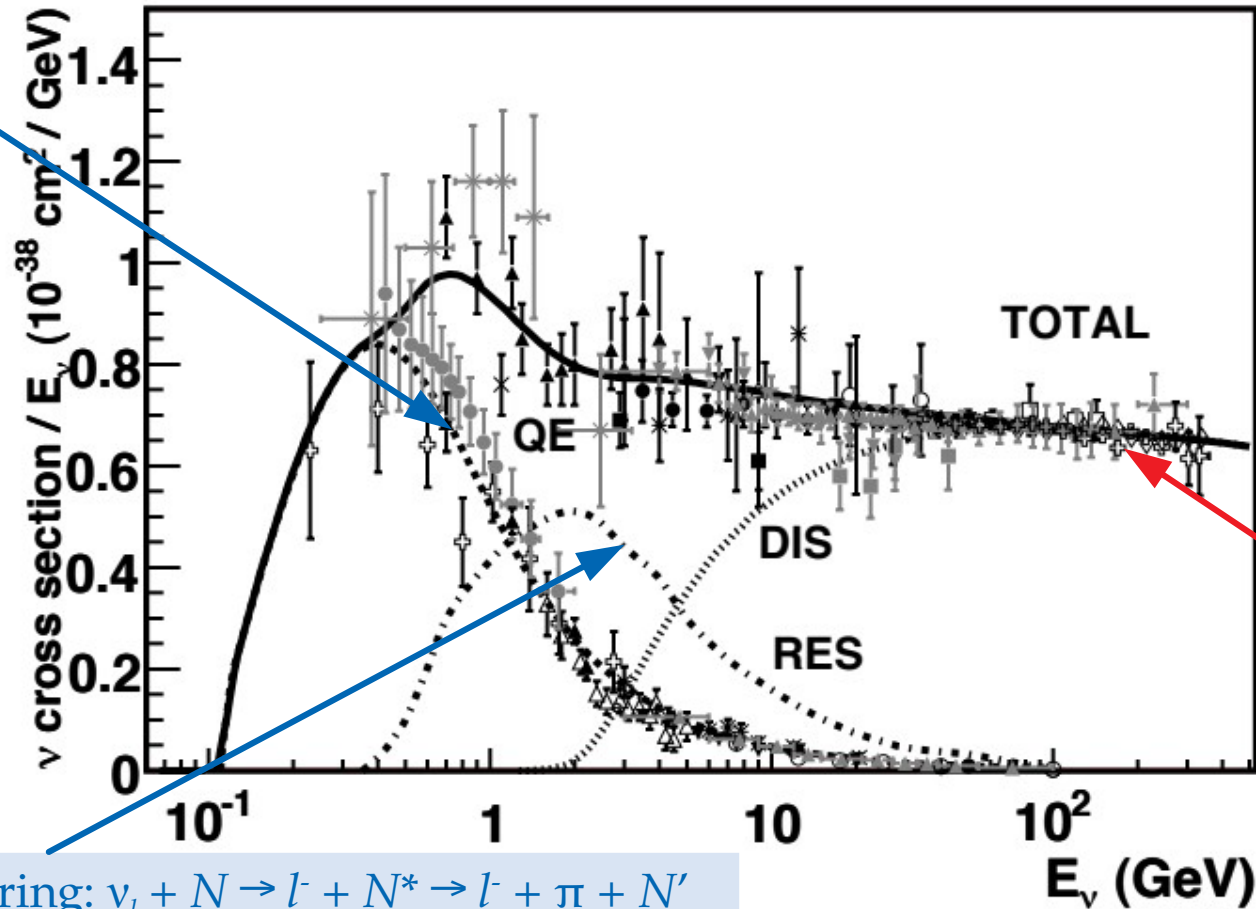
Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

Quasi-elastic
scattering:

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

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



Deep inelastic
scattering:

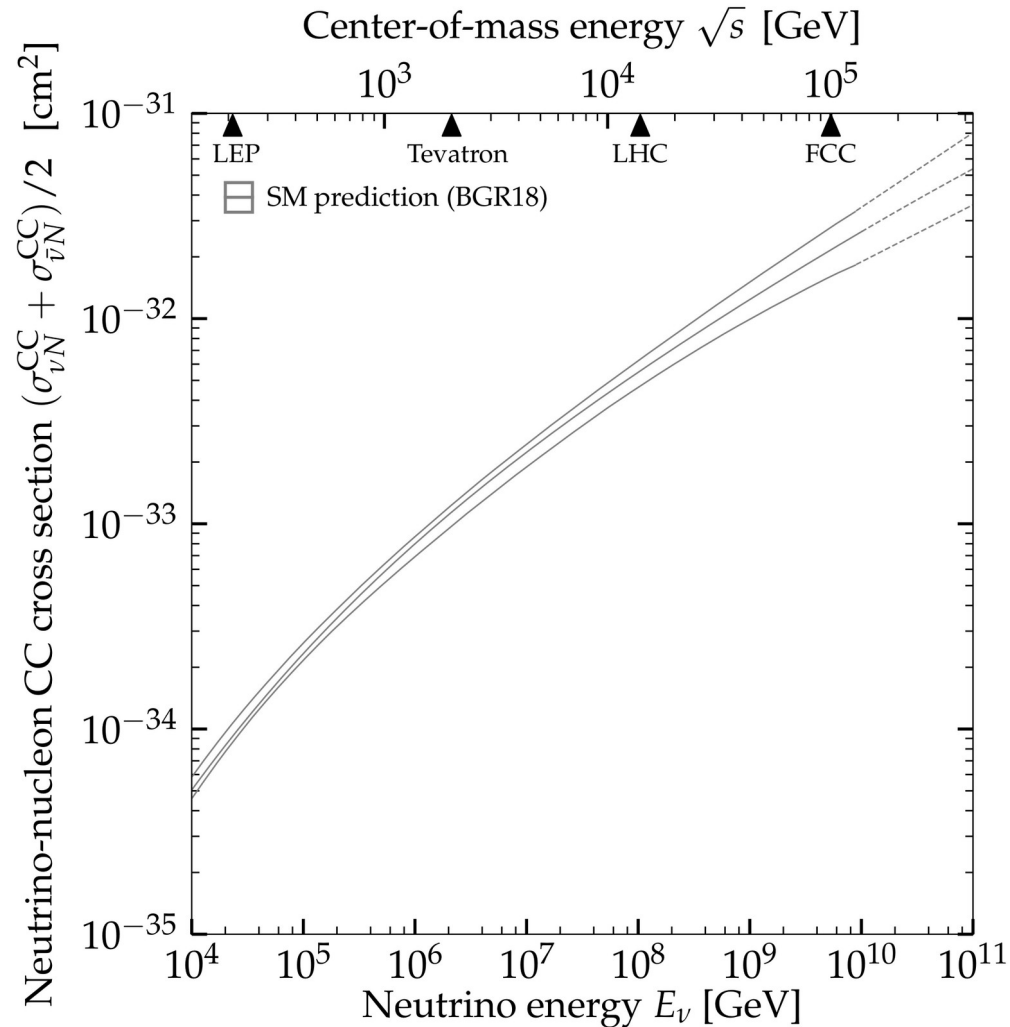
$$\nu_l + N \rightarrow l^- + X$$

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

Particle Data Group

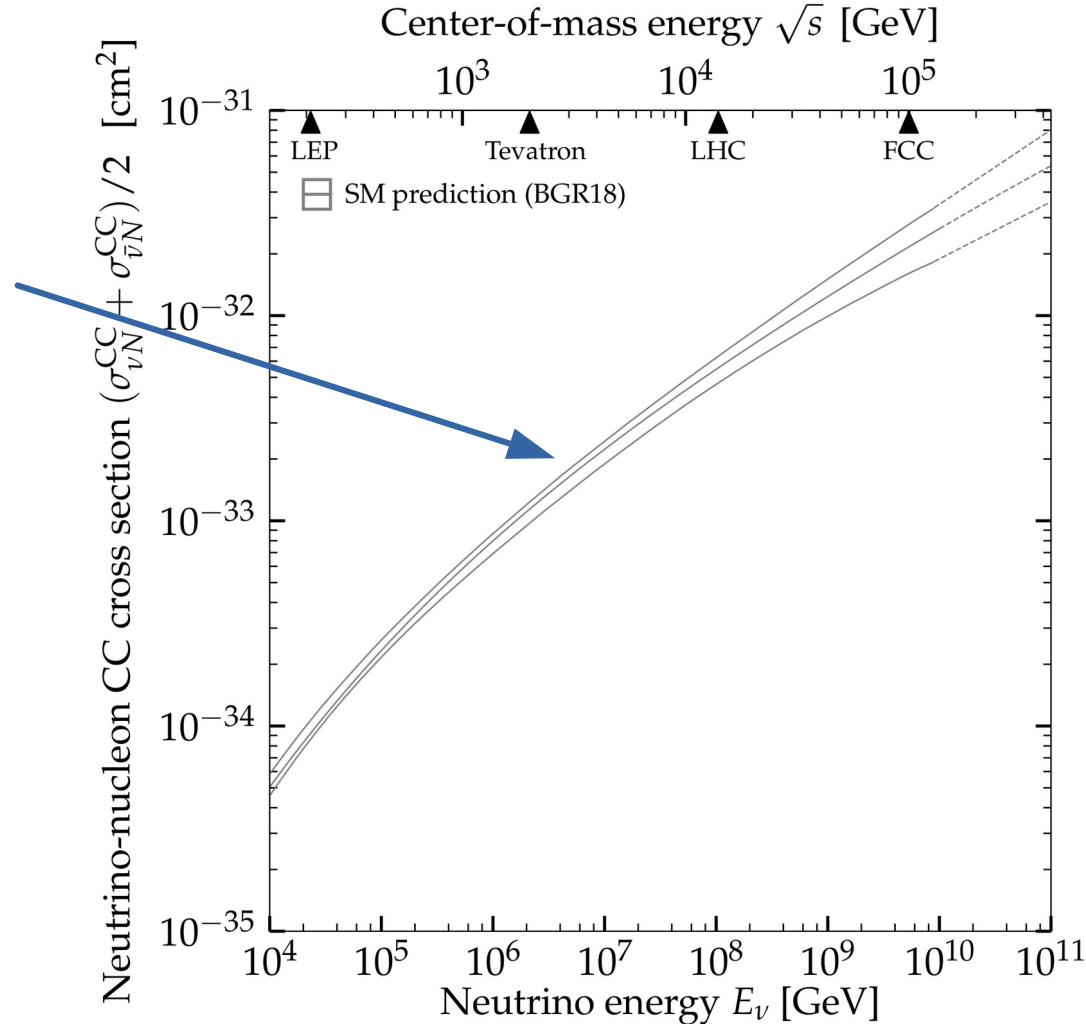
High-energy νN cross section: *prediction*



High-energy νN cross section: *prediction*

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

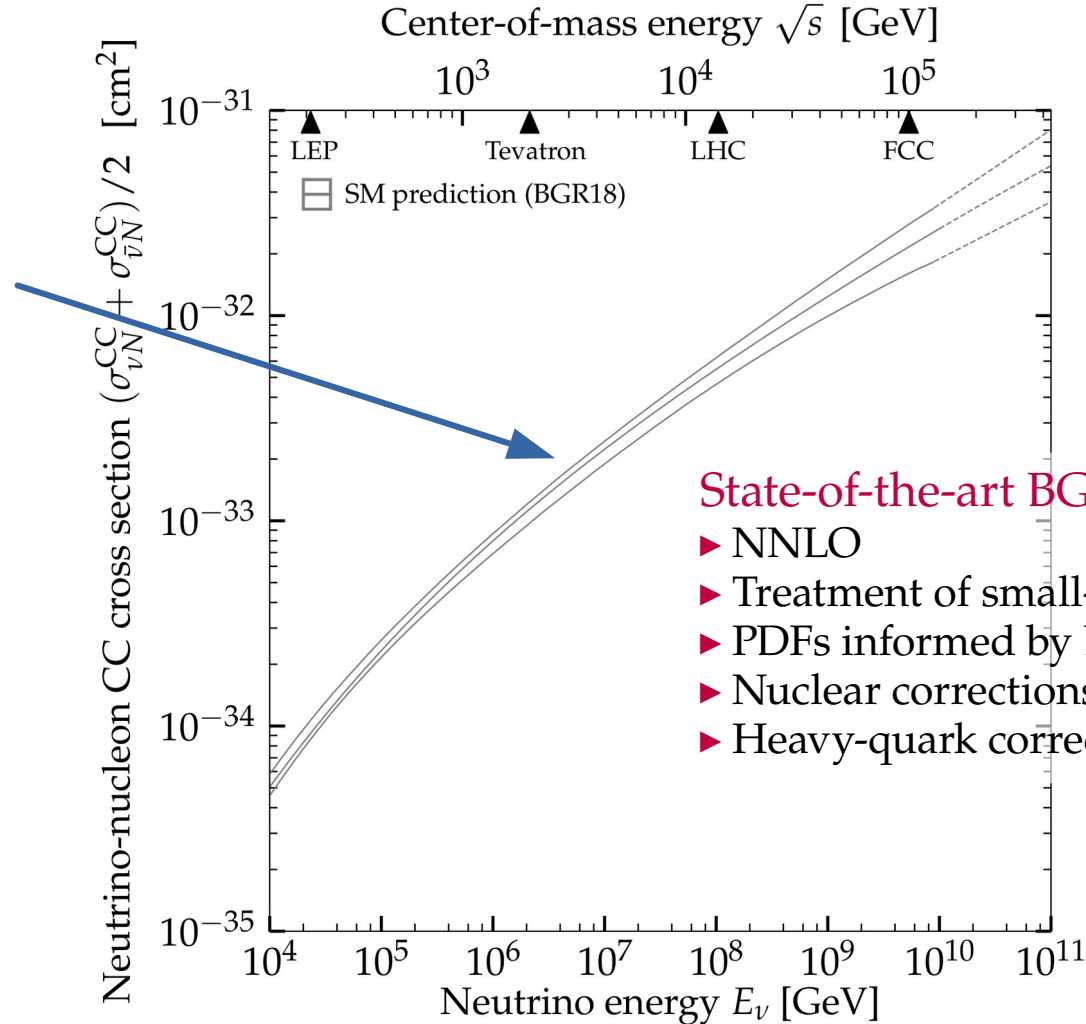
Uncertainty from
extrapolating parton
distribution functions
(PDFs) to Bjorken
 $x \sim m_W/E_\nu \sim 10^{-6}$



High-energy νN cross section: *prediction*

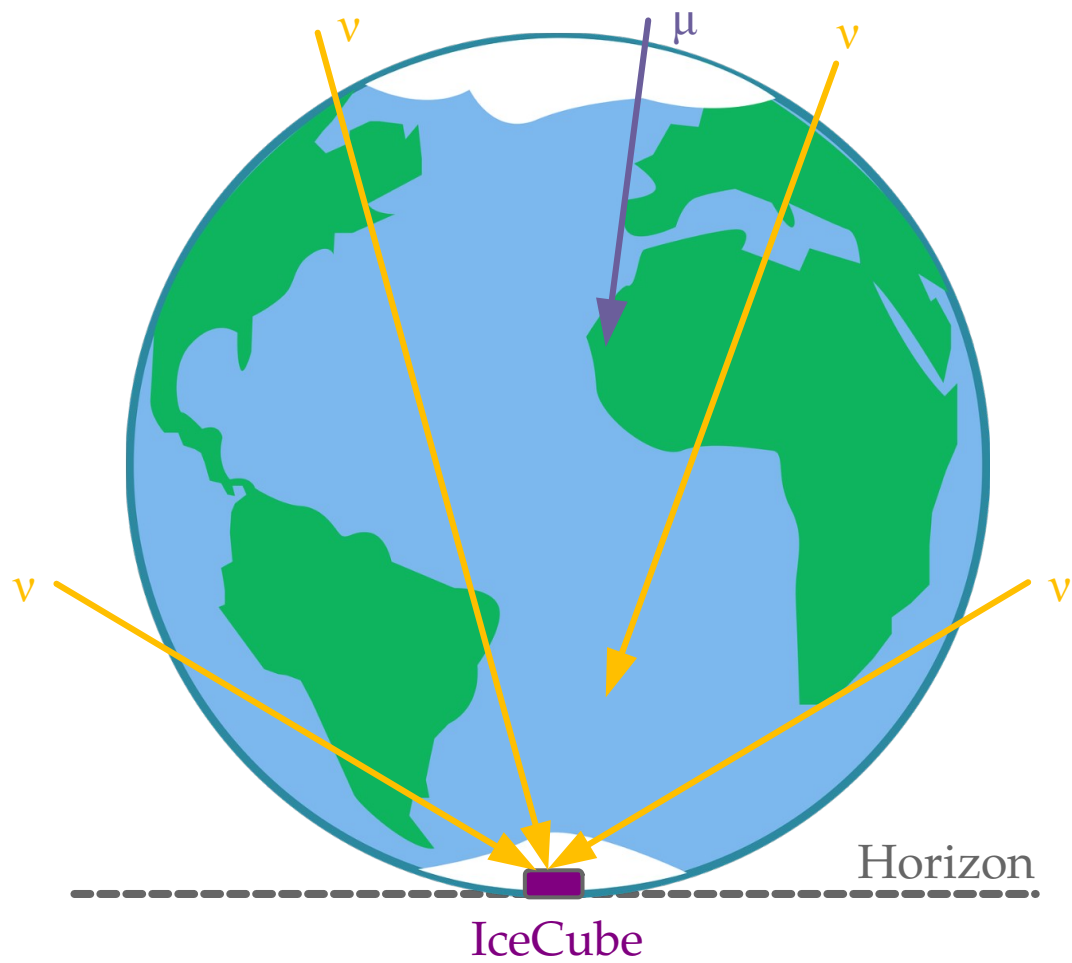
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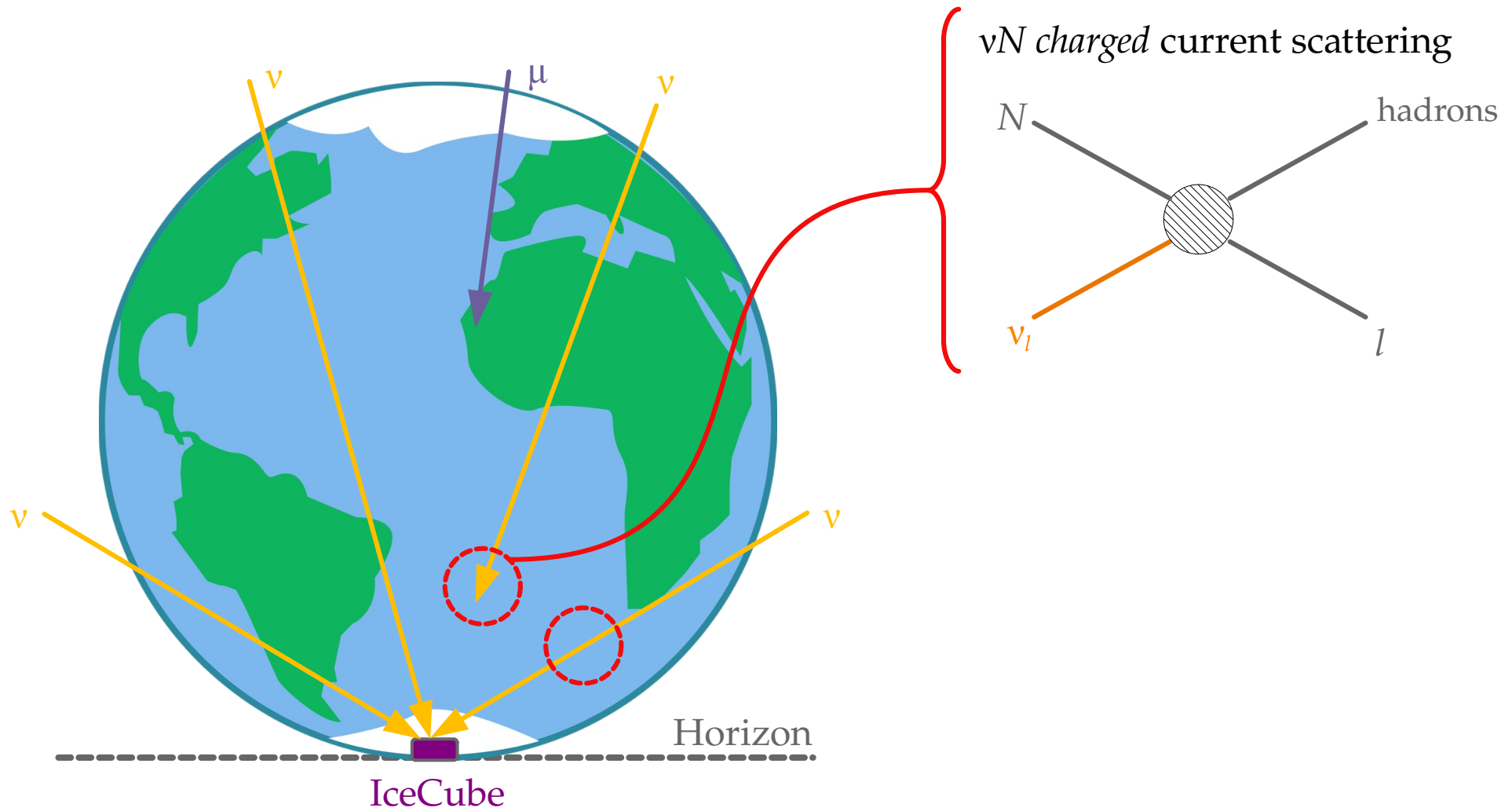
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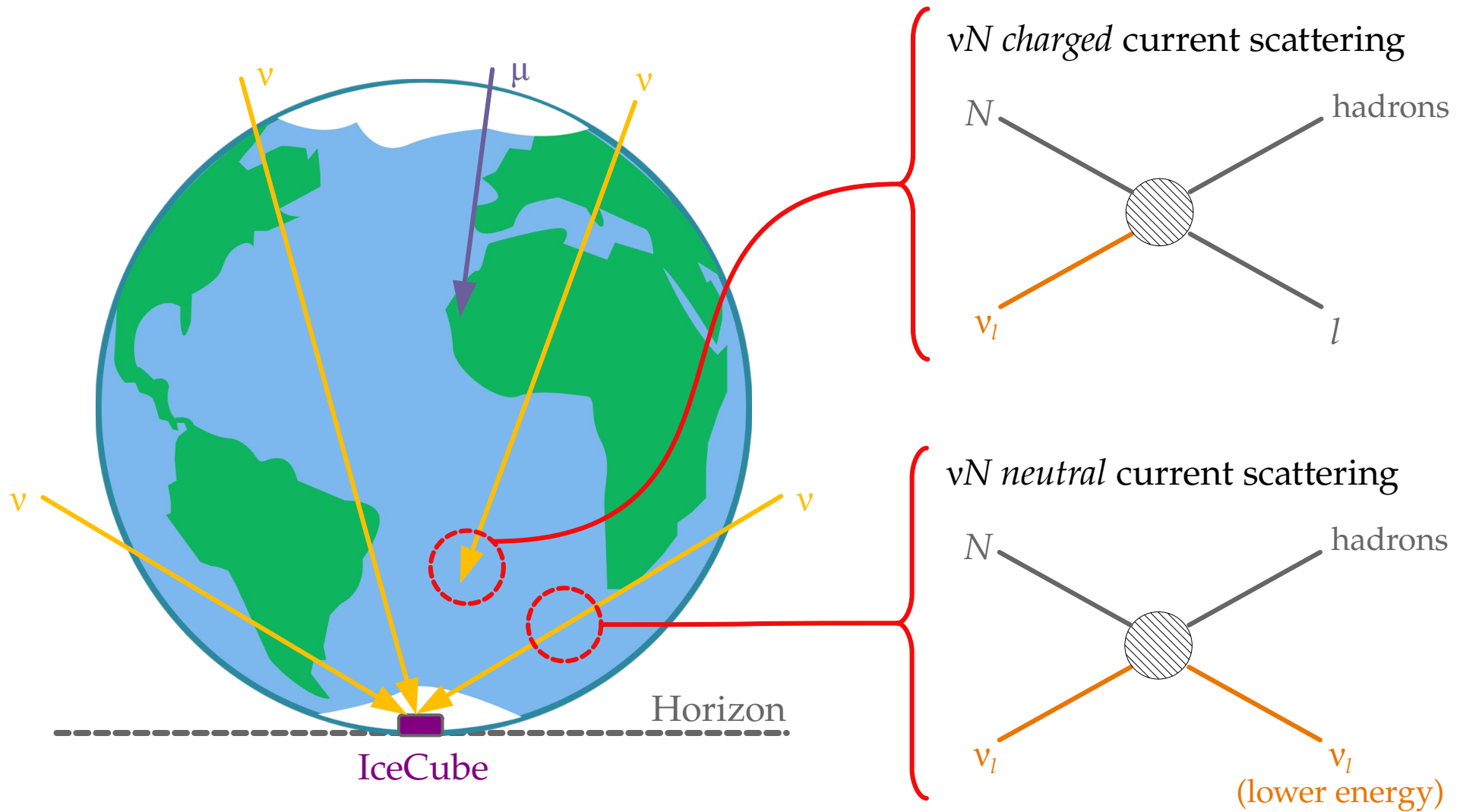


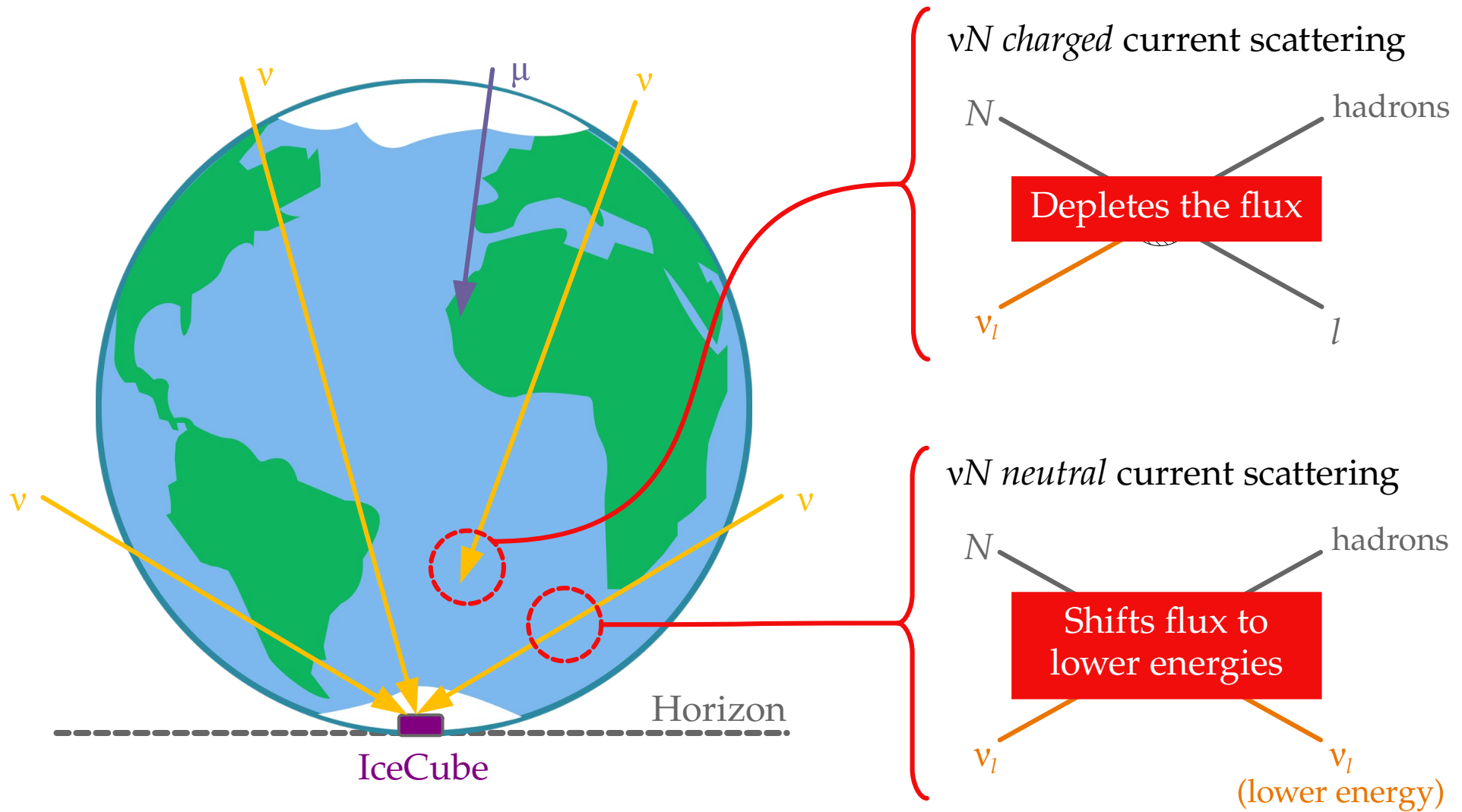
State-of-the-art BGR18 prediction:

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

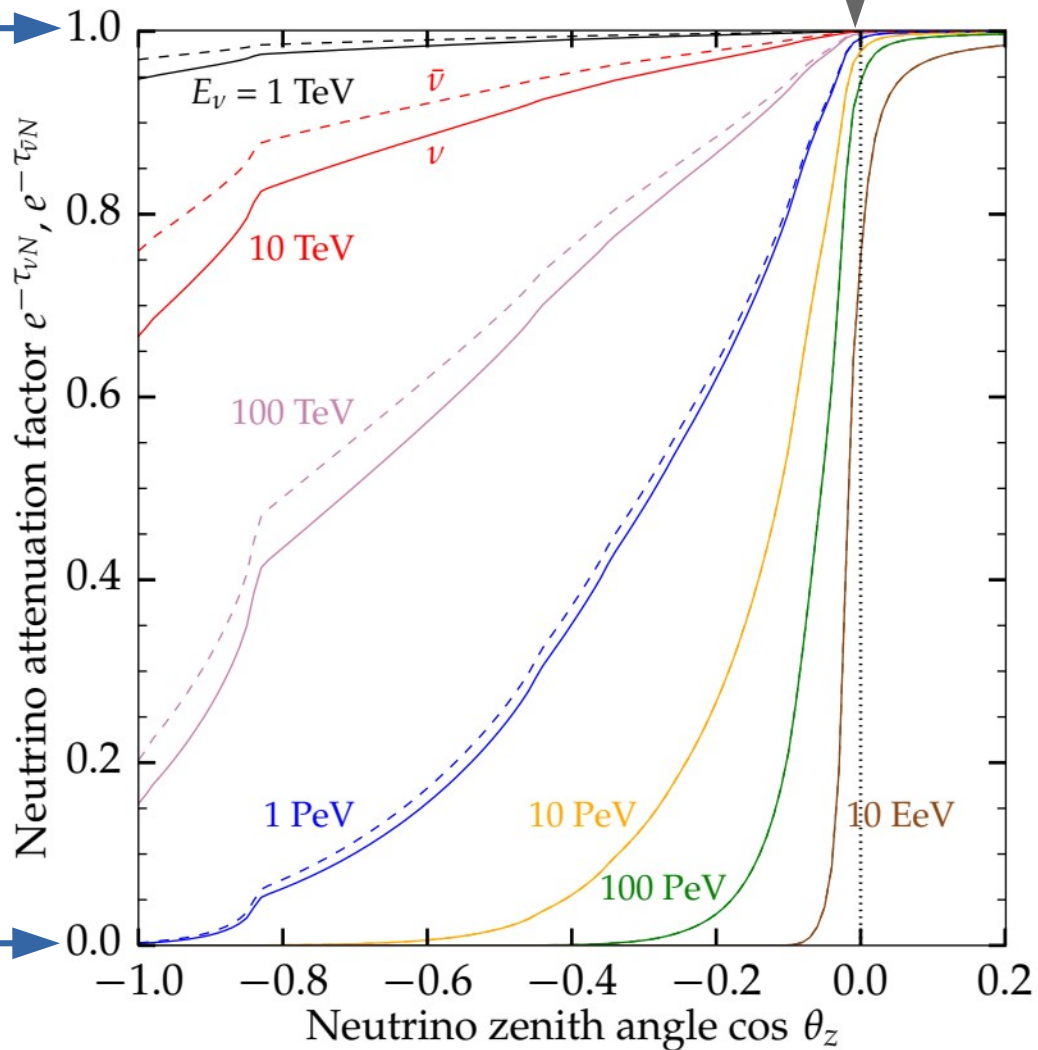




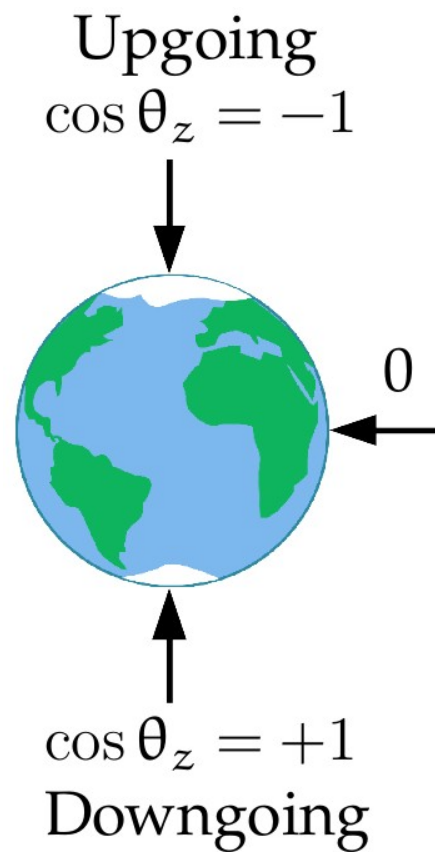




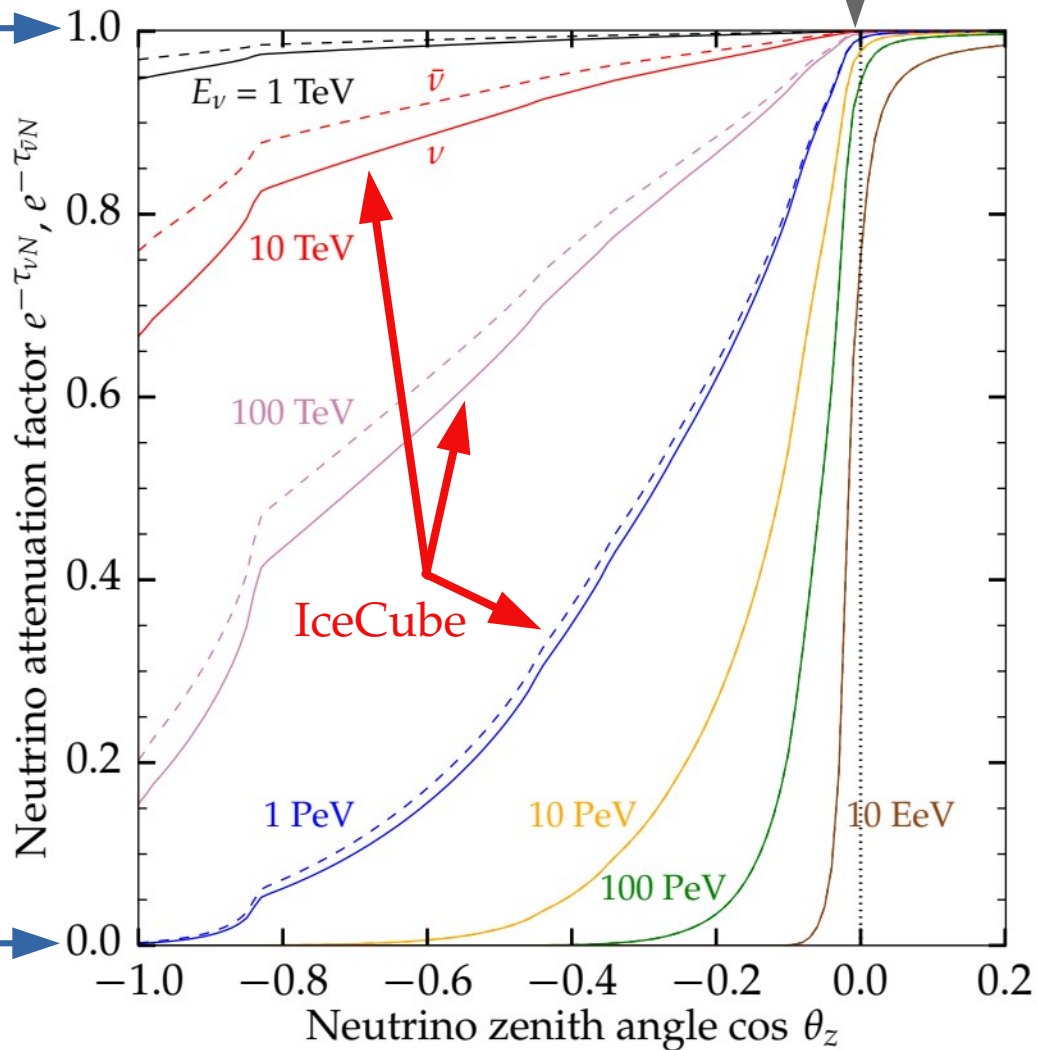
No
attenuation



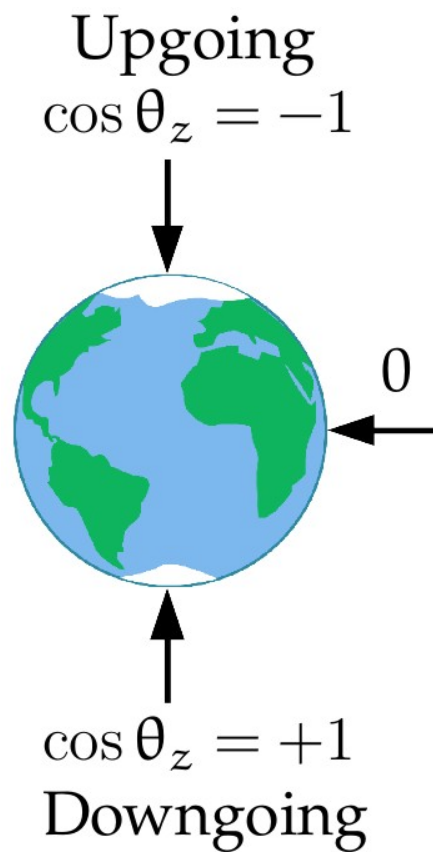
Full
attenuation



No
attenuation

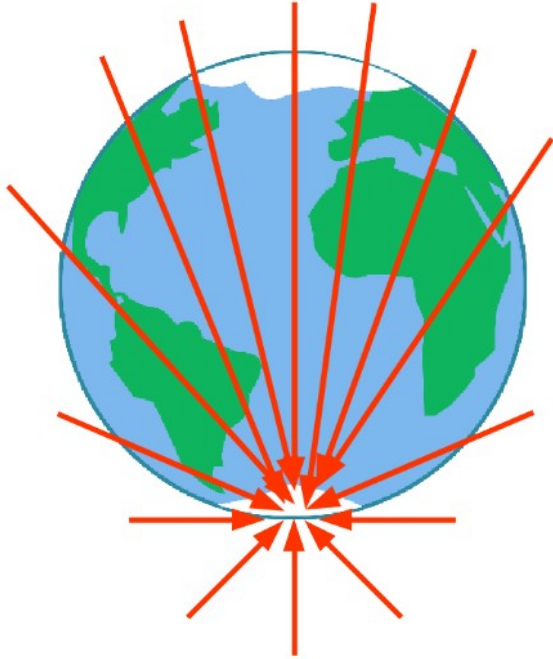


Full
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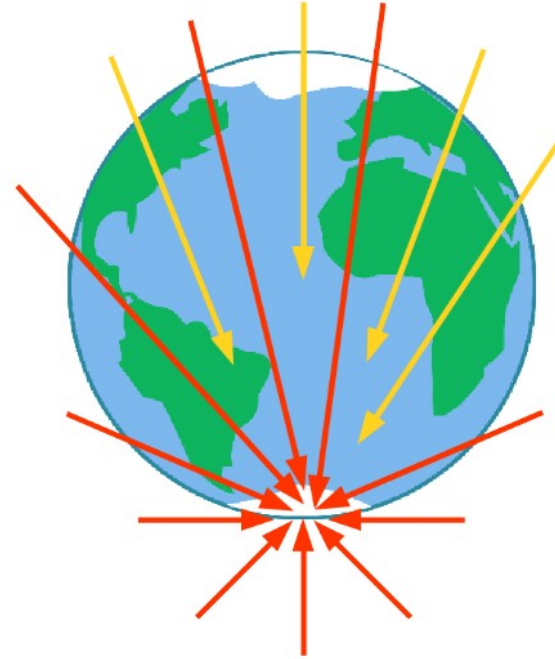


Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent

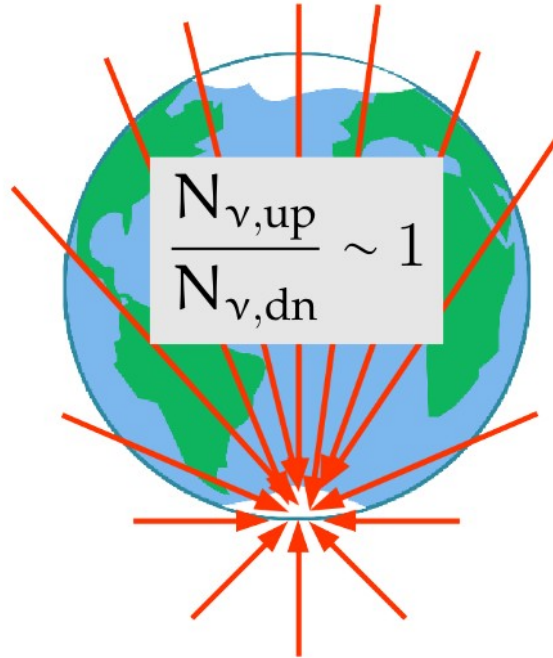


Above ~ 10 TeV: Earth is opaque

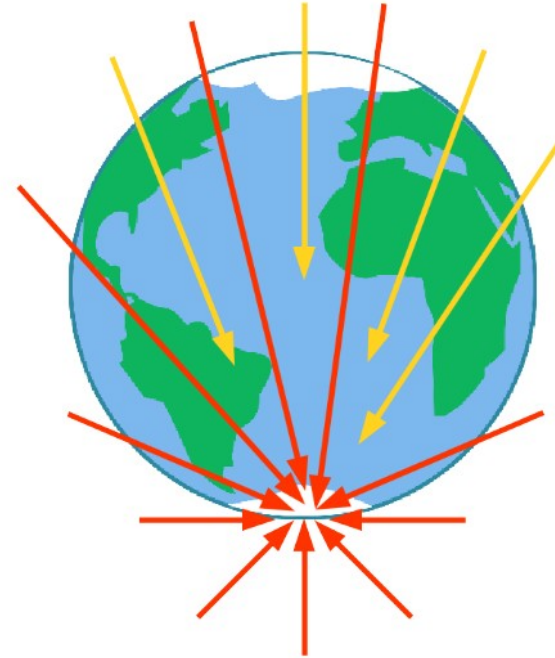


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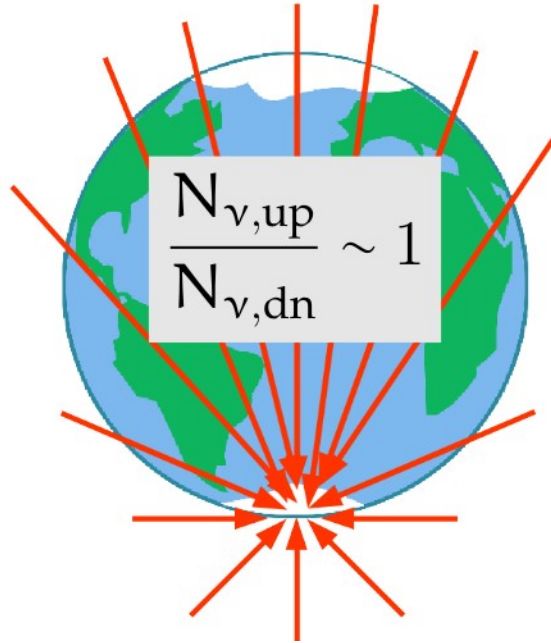


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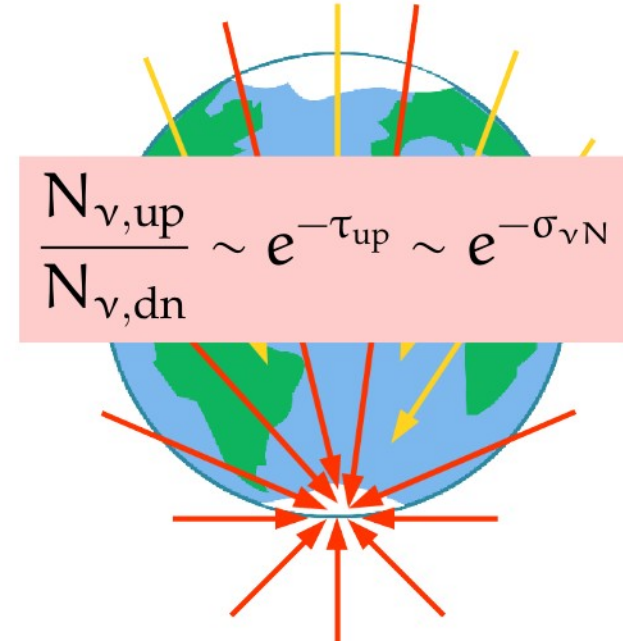


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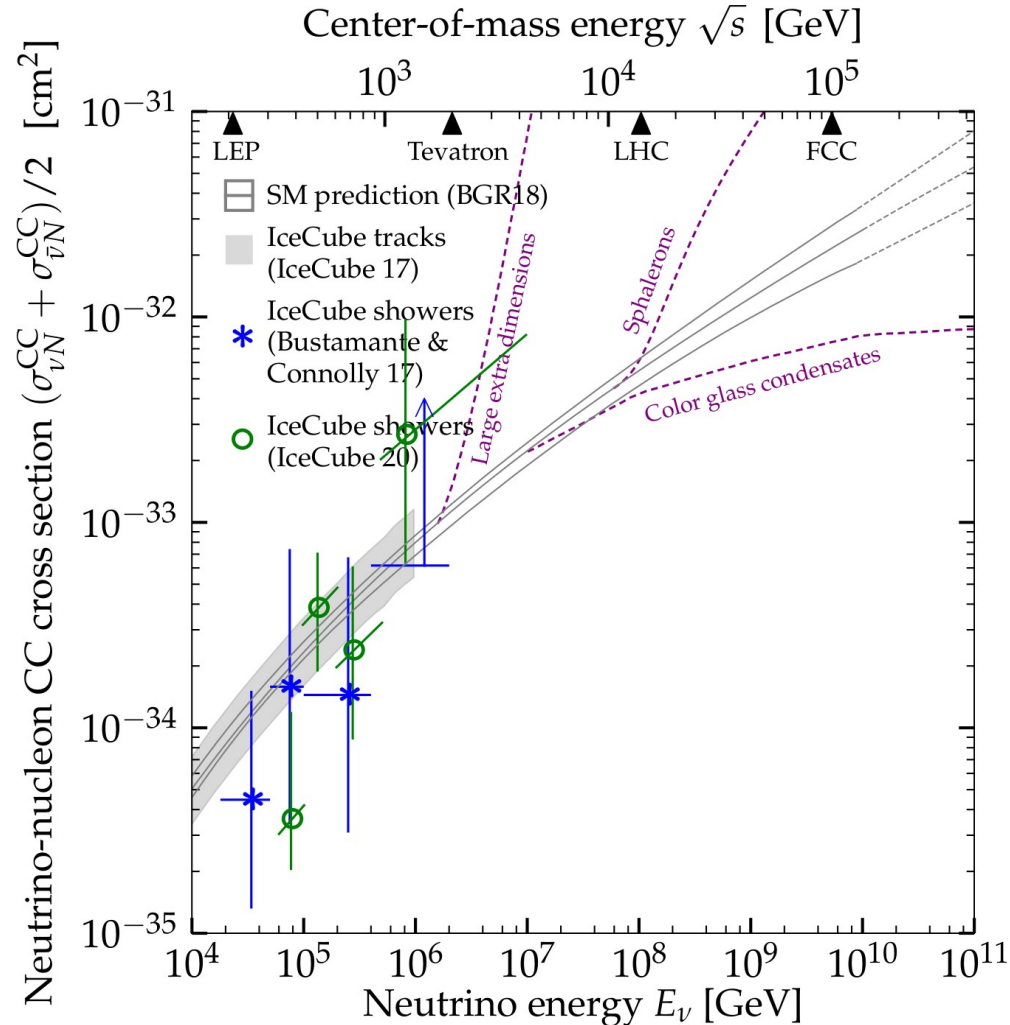
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Above ~ 10 TeV: Earth is opaque



High-energy νN cross section: *today*

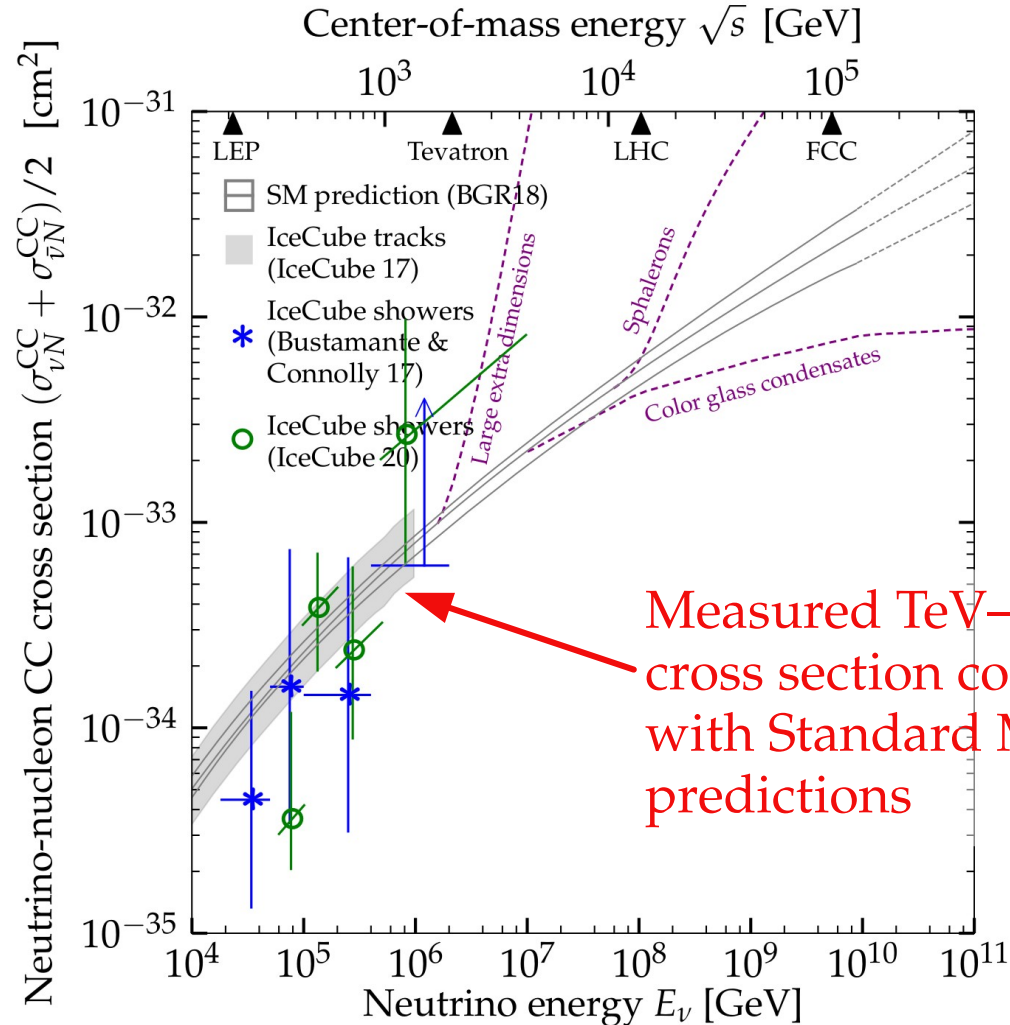


BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019

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

Measurements from:
IceCube, 2011.03560
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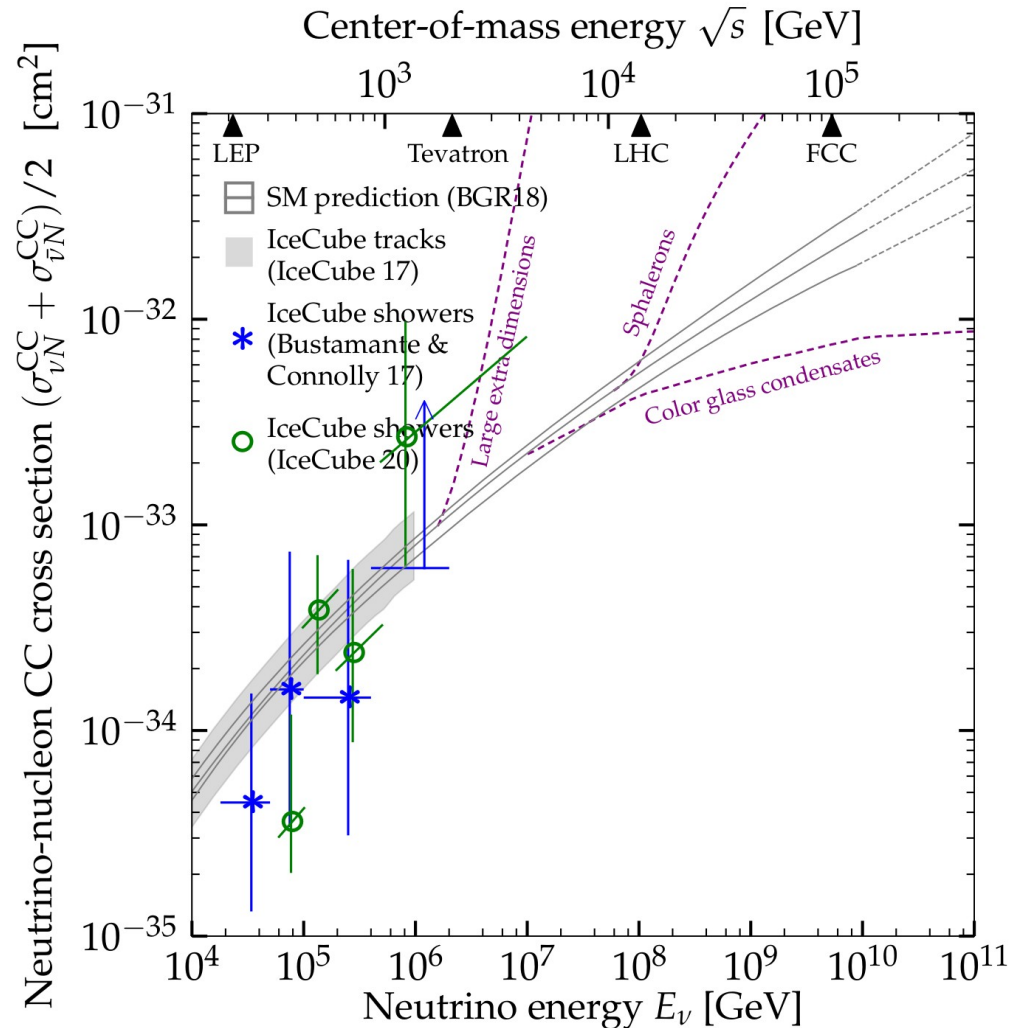


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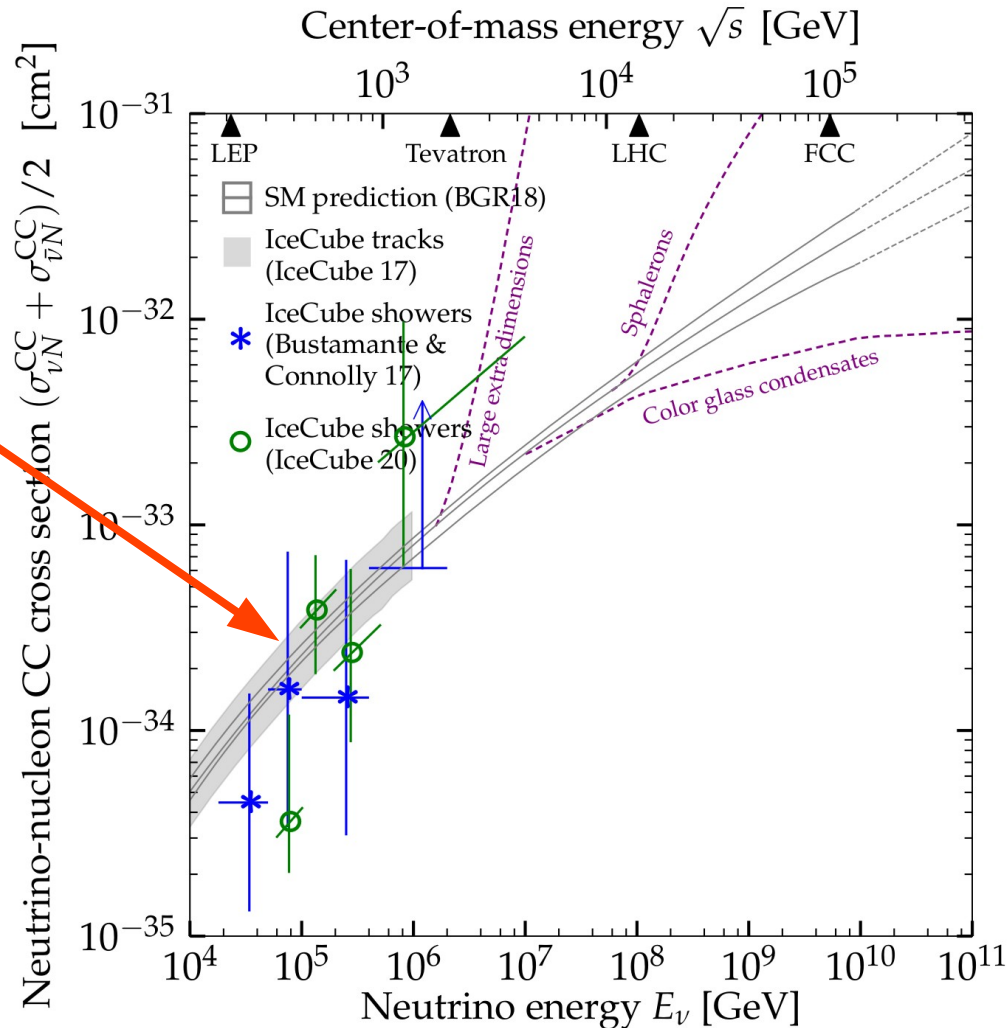
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Measured:
TeV – PeV
cross section



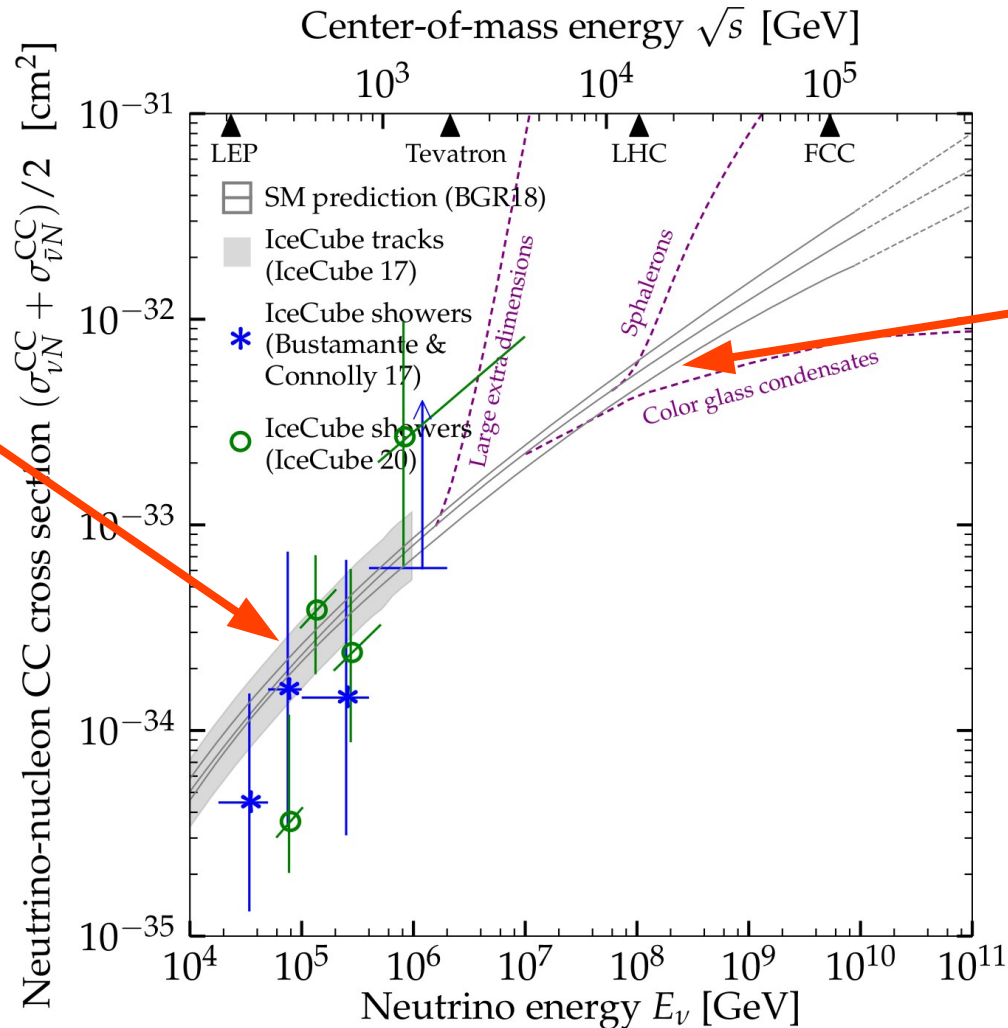
BGR18 prediction from:
[Bertone, Gauld, Rojo, JHEP 2019](#)

See also:
[García, Gauld, Heijboer, Rojo, JCAP 2020](#)

Measurements from:
[IceCube, 2011.03560](#)
[MB & Connolly, PRL 2019](#)
[IceCube, Nature 2017](#)

High-energy νN cross section: *today*

Measured:
TeV – PeV
cross section

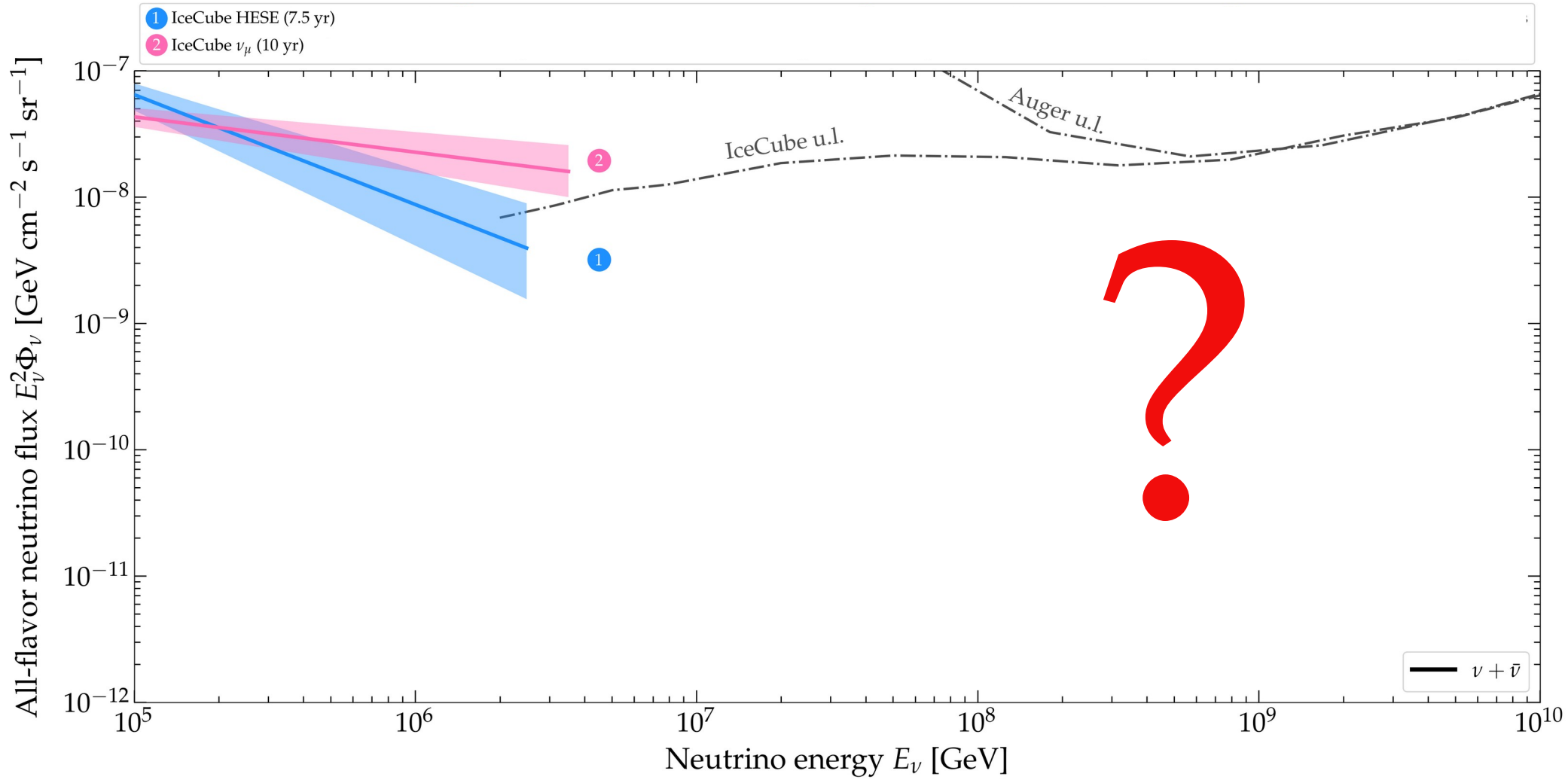


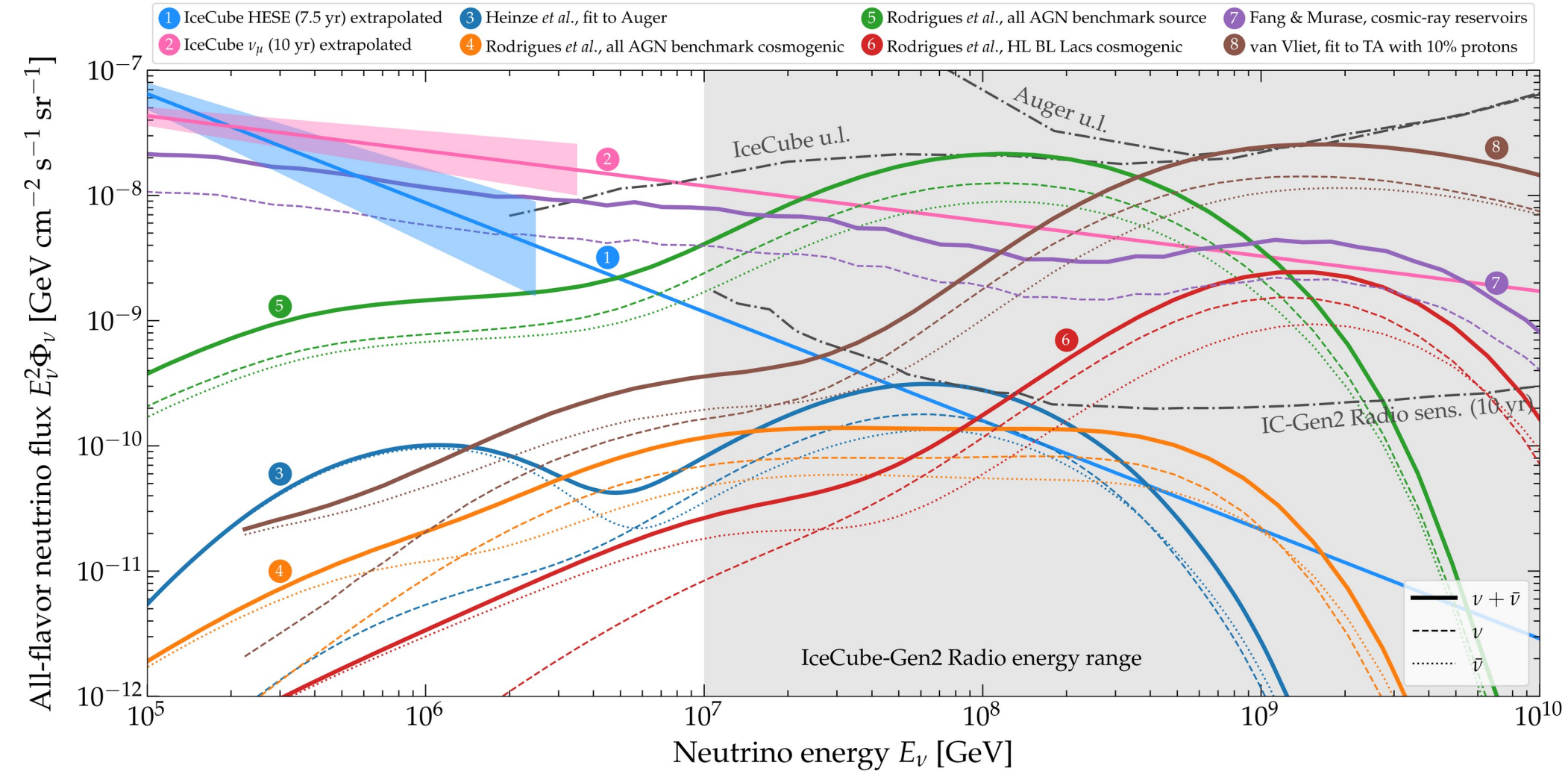
Not measured:
> 10-PeV
cross section

BGR18 prediction from:
[Bertone, Gauld, Rojo, JHEP 2019](#)

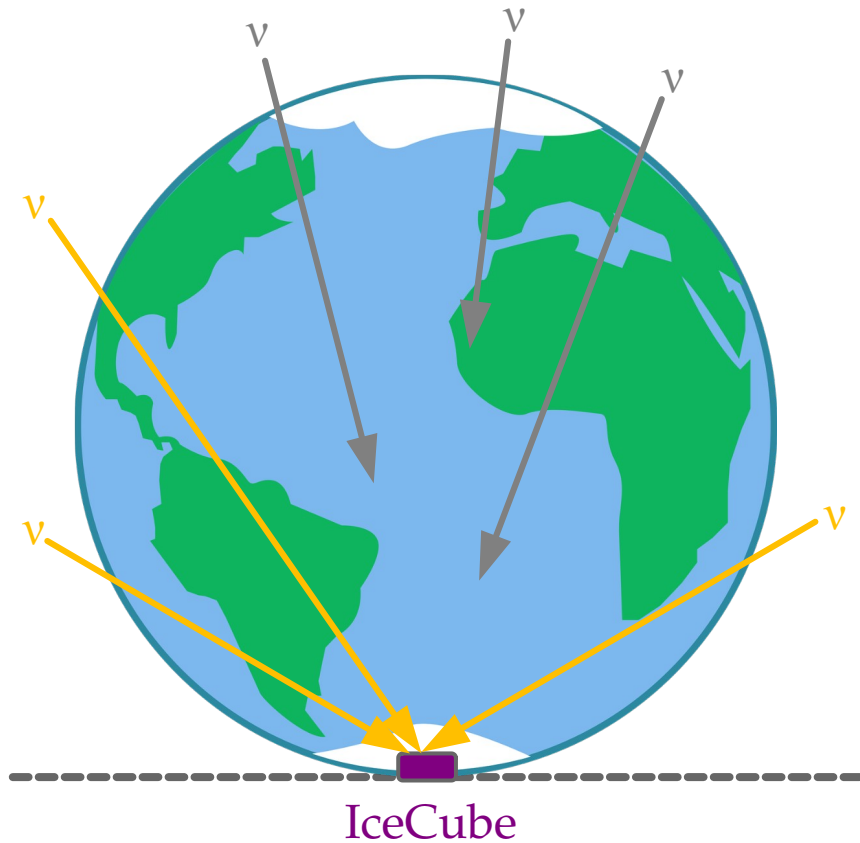
See also:
[García, Gauld, Heijboer, Rojo, JCAP 2020](#)

Measurements from:
[IceCube, 2011.03560](#)
[MB & Connolly, PRL 2019](#)
[IceCube, Nature 2017](#)



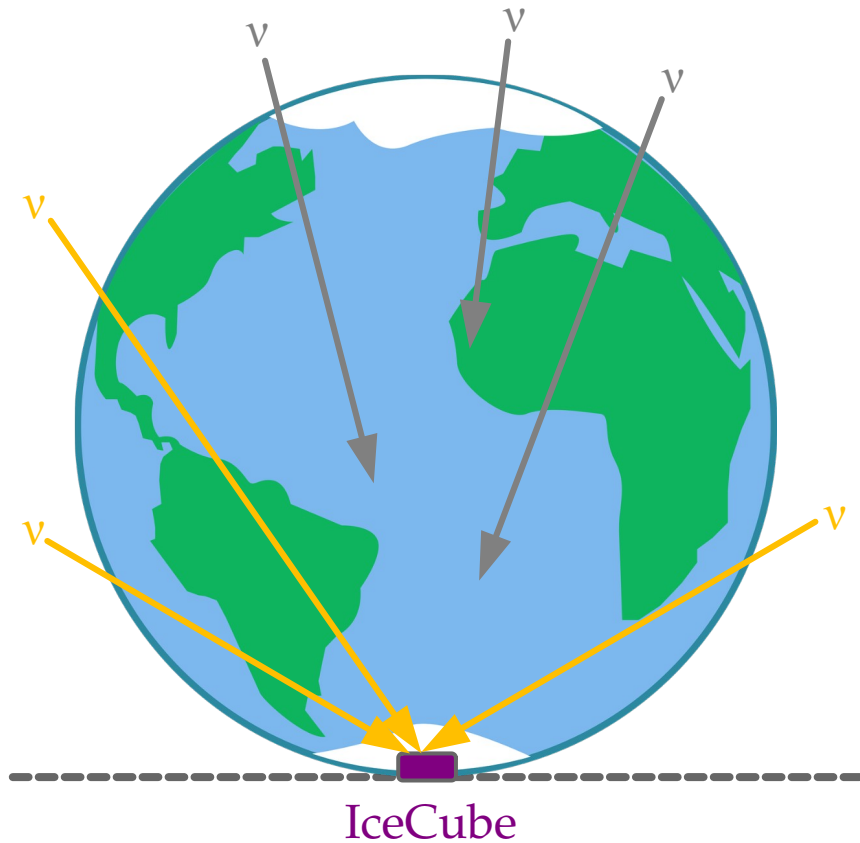


TeV–PeV:



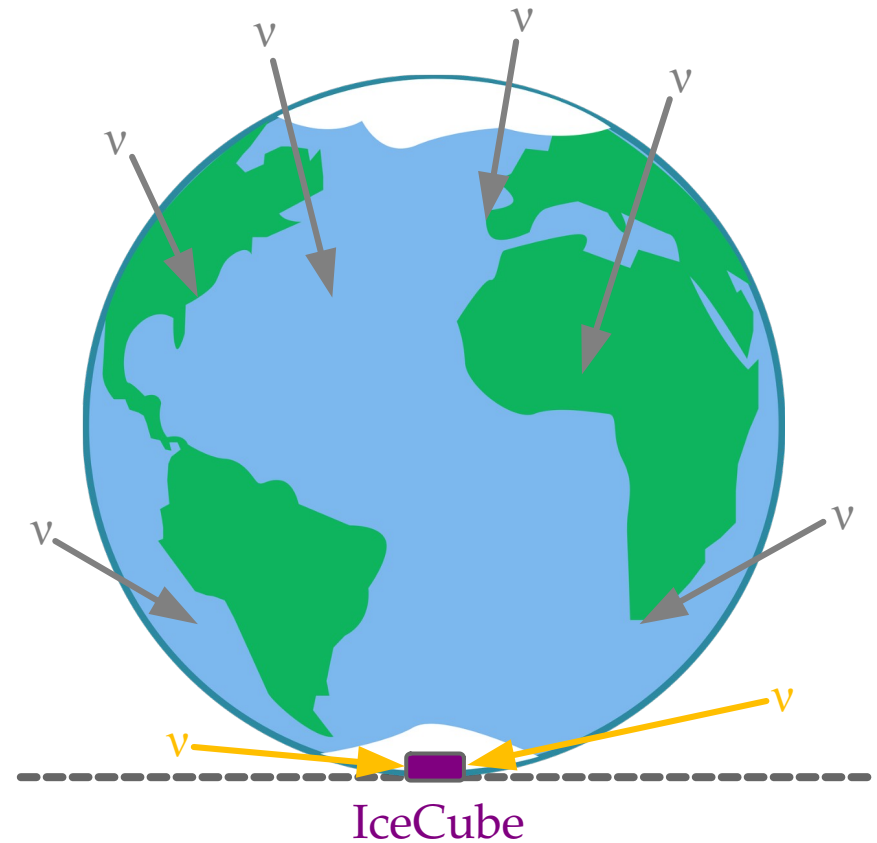
Earth is *almost fully* opaque,
some upgoing ν still make it through

TeV–PeV:



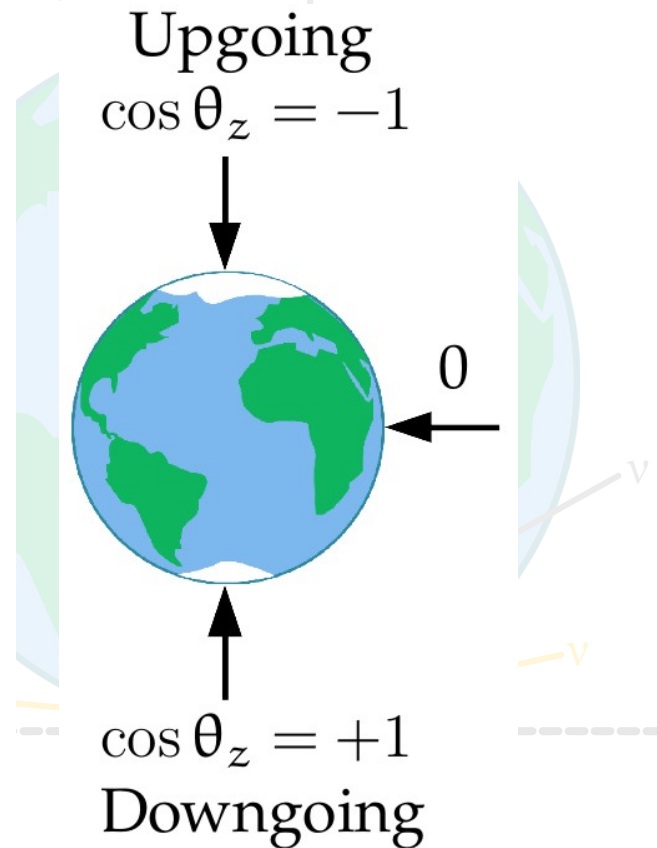
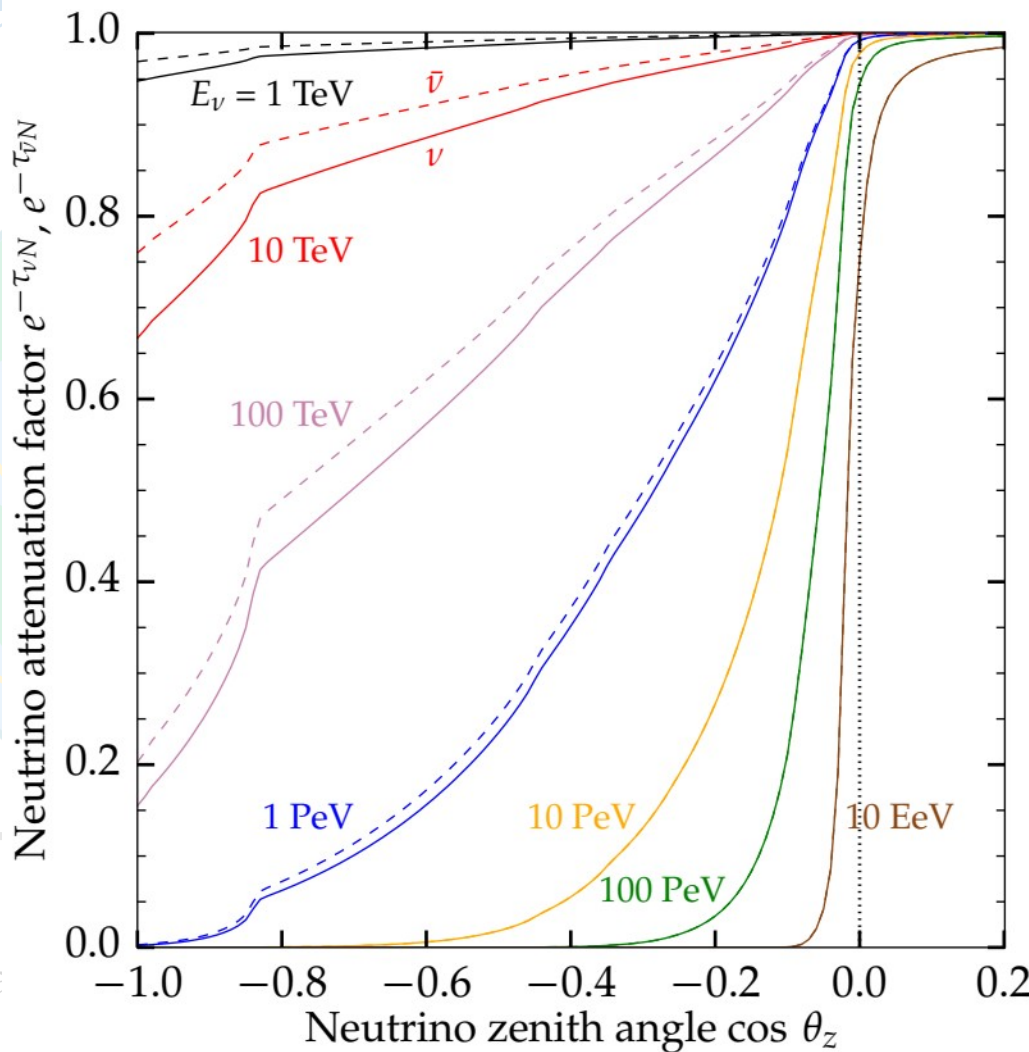
Earth is *almost fully* opaque,
some upgoing ν still make it through

> 100 PeV:

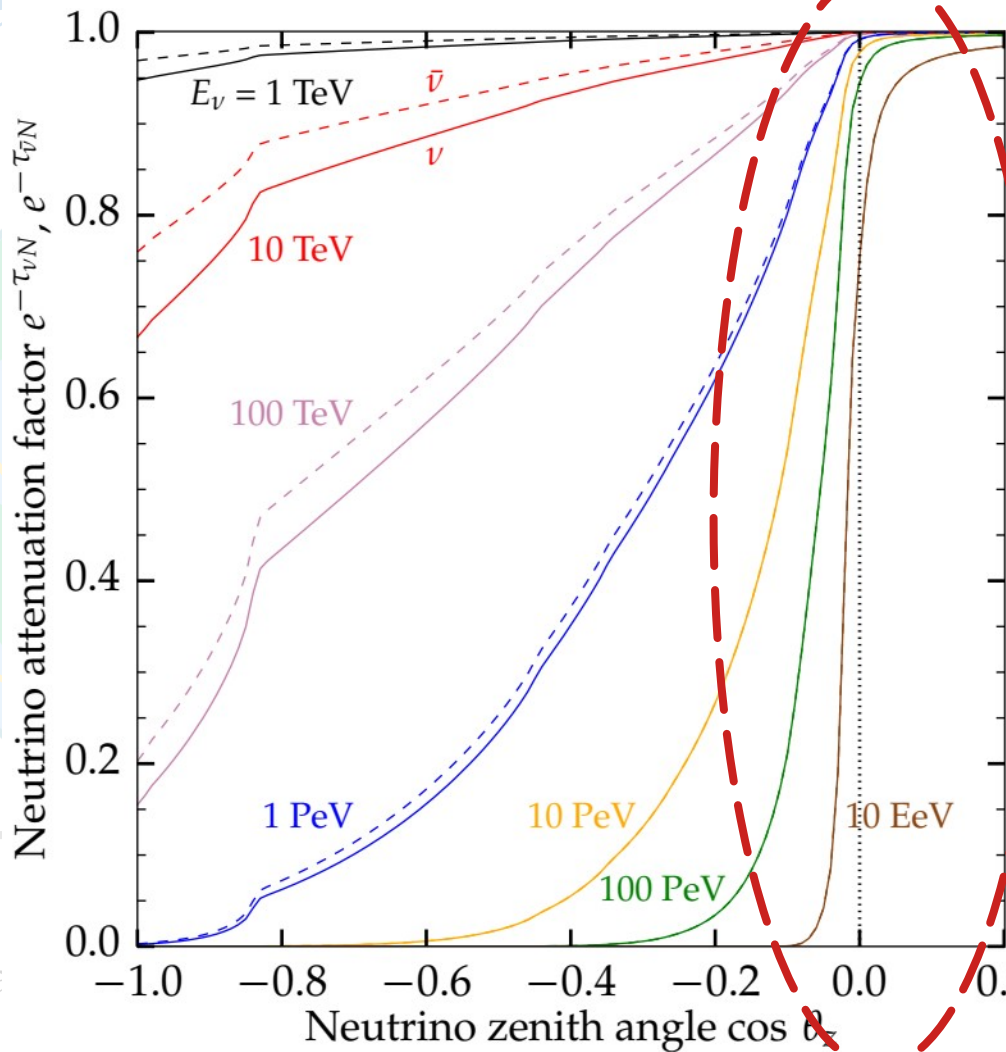


Earth is *completely* opaque,
but horizontal ν still make it through

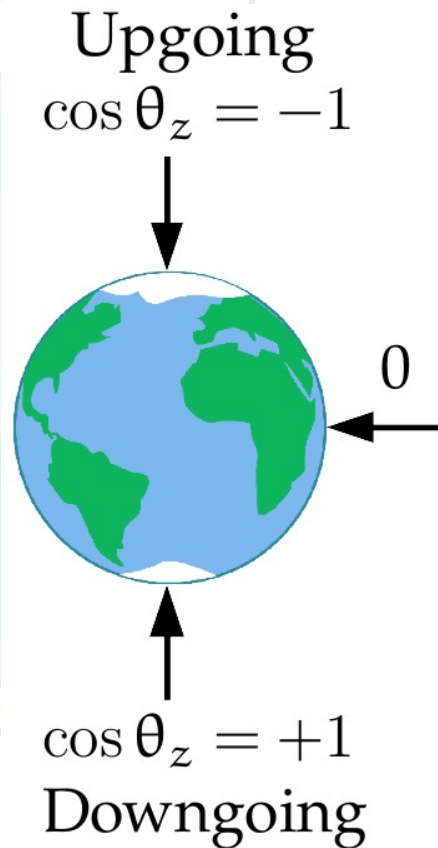
TeV–PeV



Earth is completely opaque,
horizontal ν still make it through

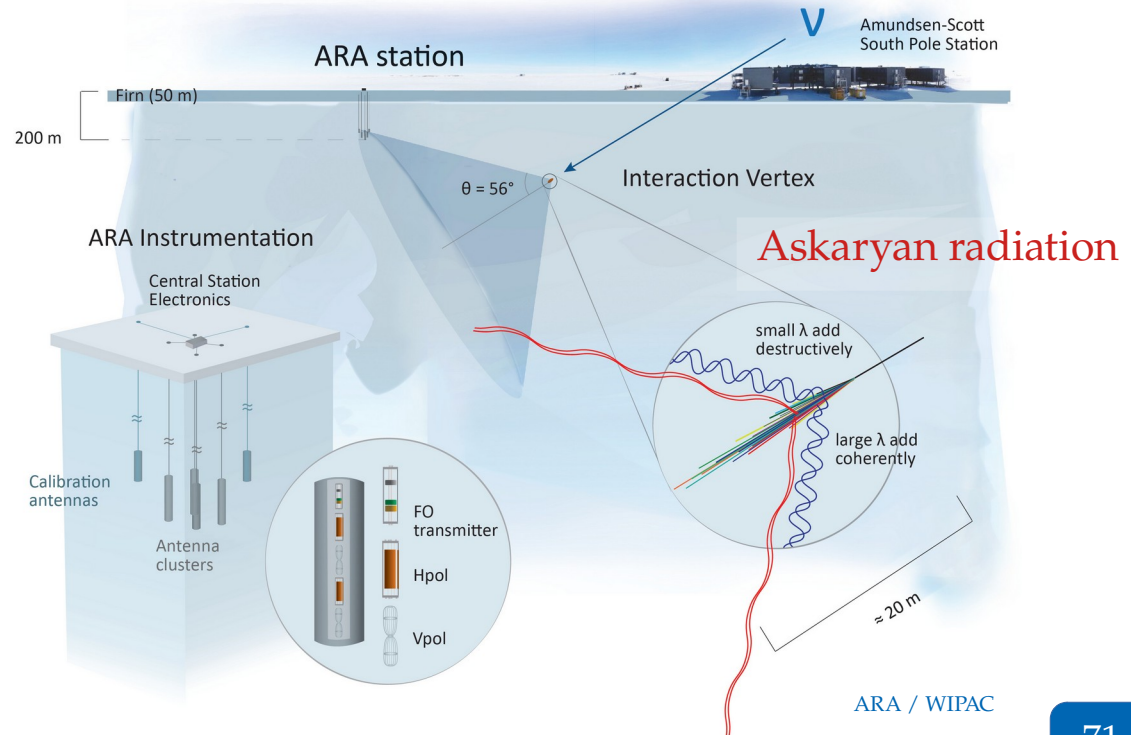
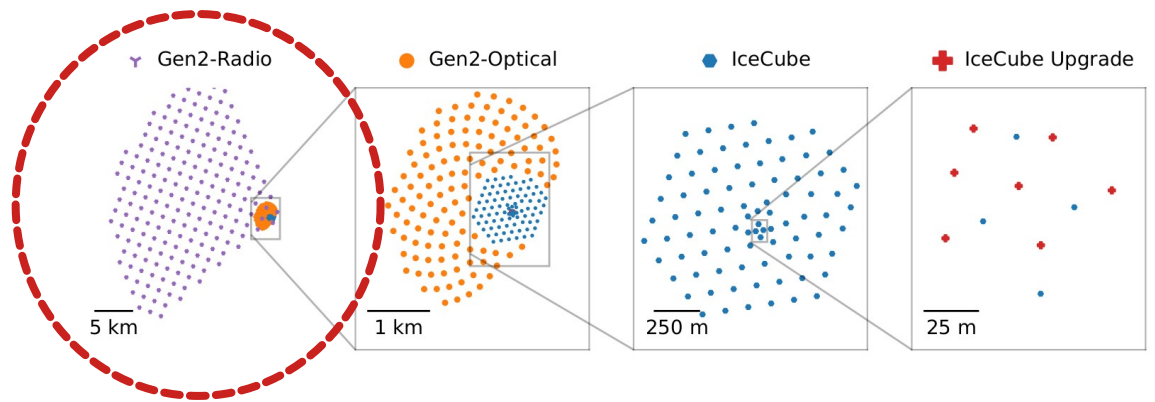
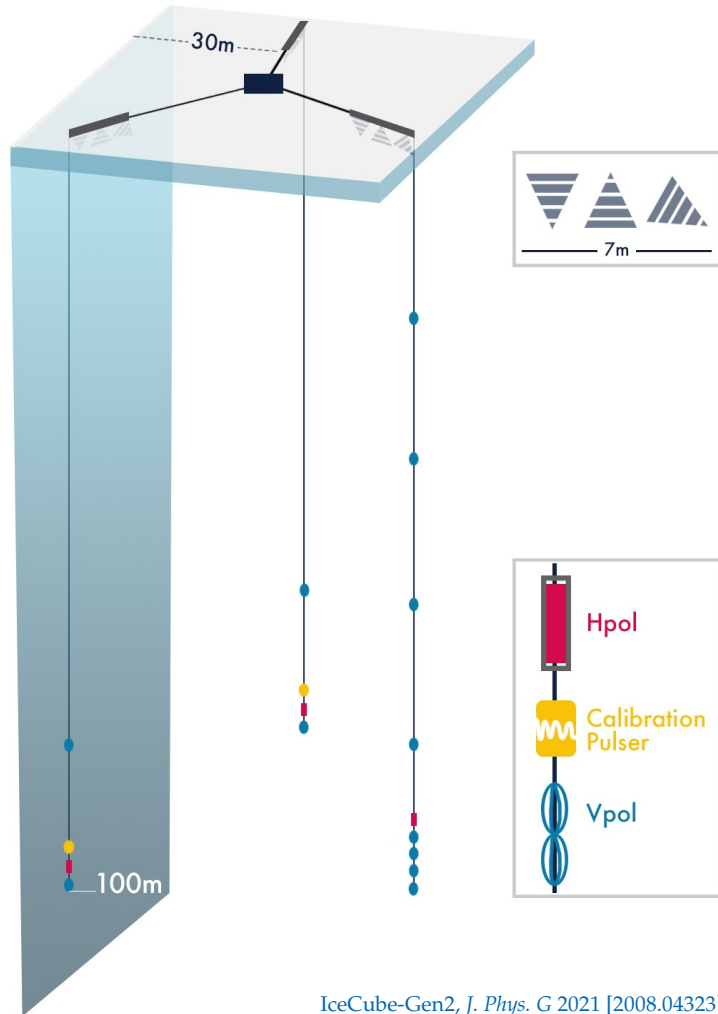


At UHE, we can only extract the cross section using horizontal ν



Earth is completely opaque,
horizontal ν still make it through

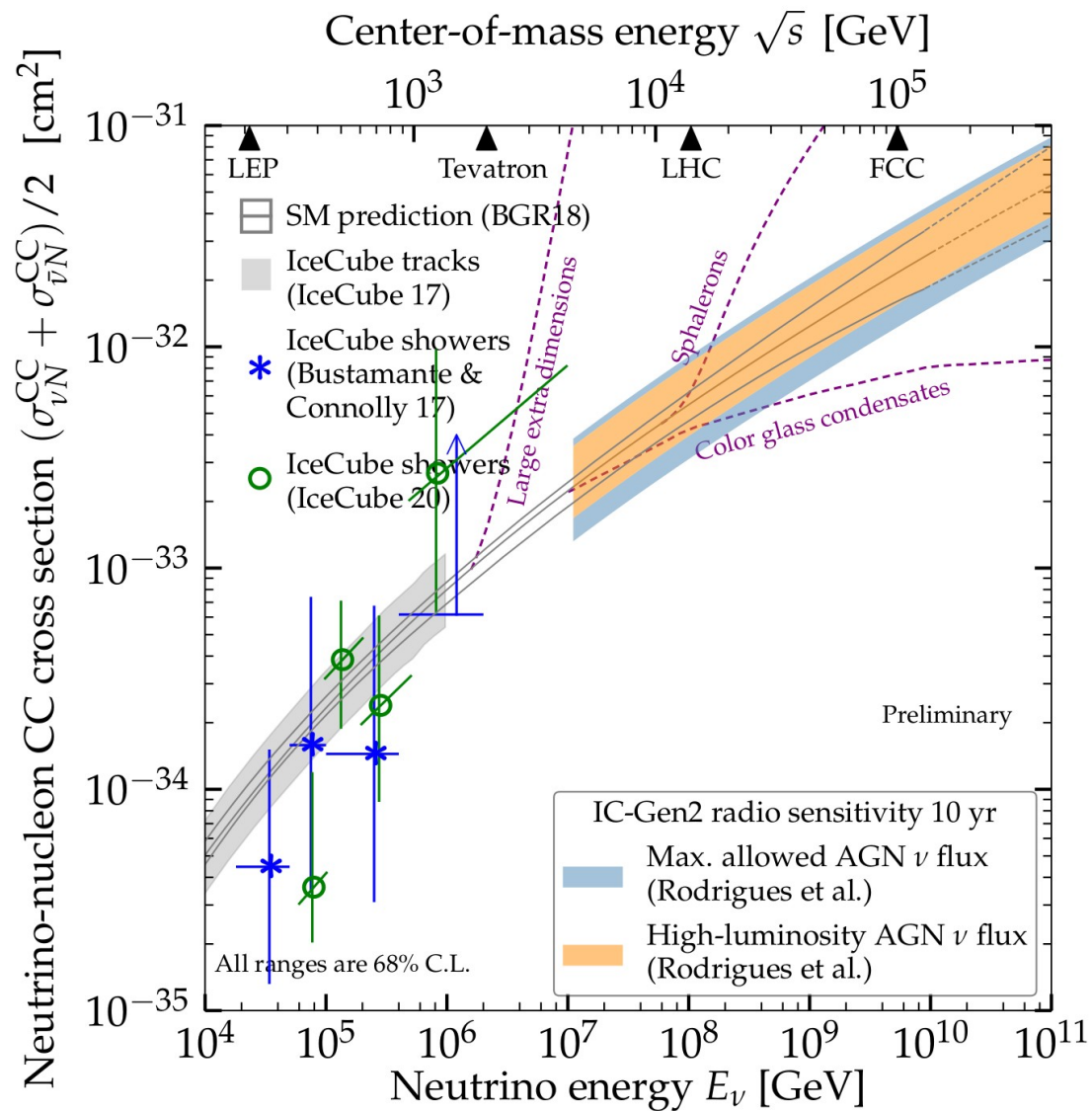
IceCube-Gen2 Radio



After 10 years of IceCube-Gen2 Radio (~2040):

(If the UHE ν fluxes are high)

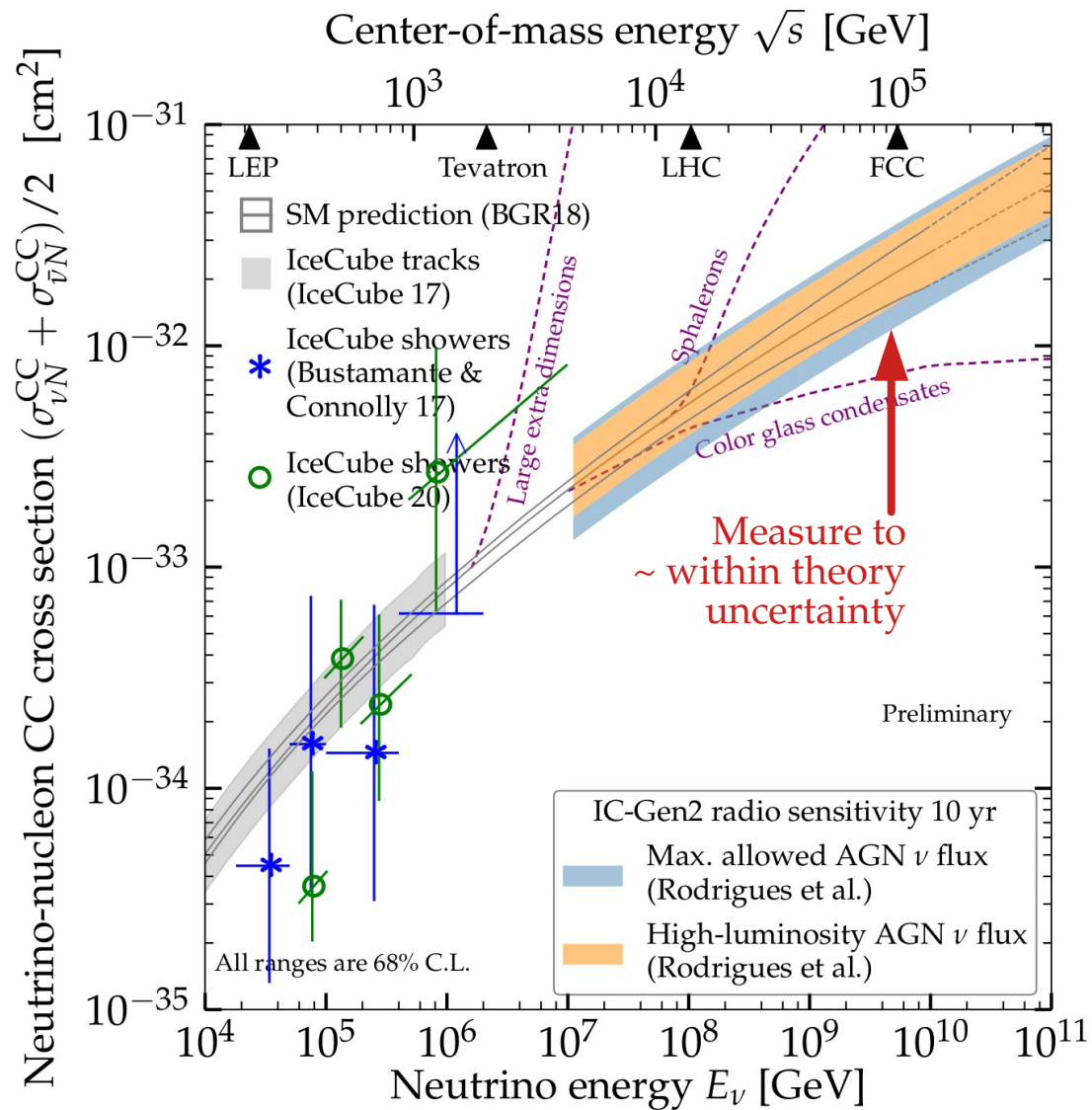
Valera, MB, Glaser, *In preparation*



After 10 years of IceCube-Gen2 Radio (~2040):

(If the UHE ν fluxes are high)

Valera, MB, Glaser, *In preparation*



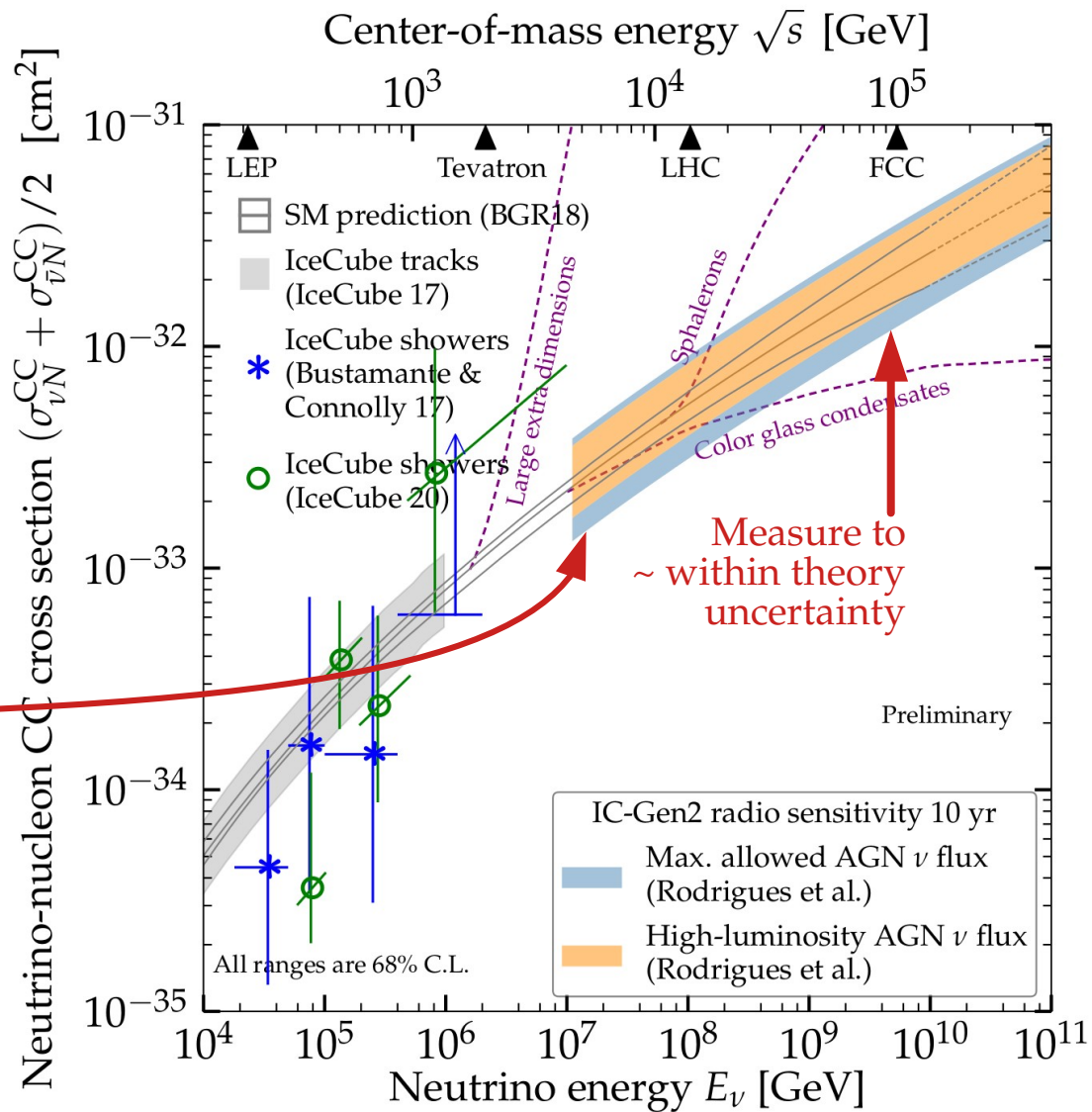
After 10 years of IceCube-Gen2 Radio (~2040):

(If the UHE ν fluxes are high)

Valera, MB, Glaser, In preparation



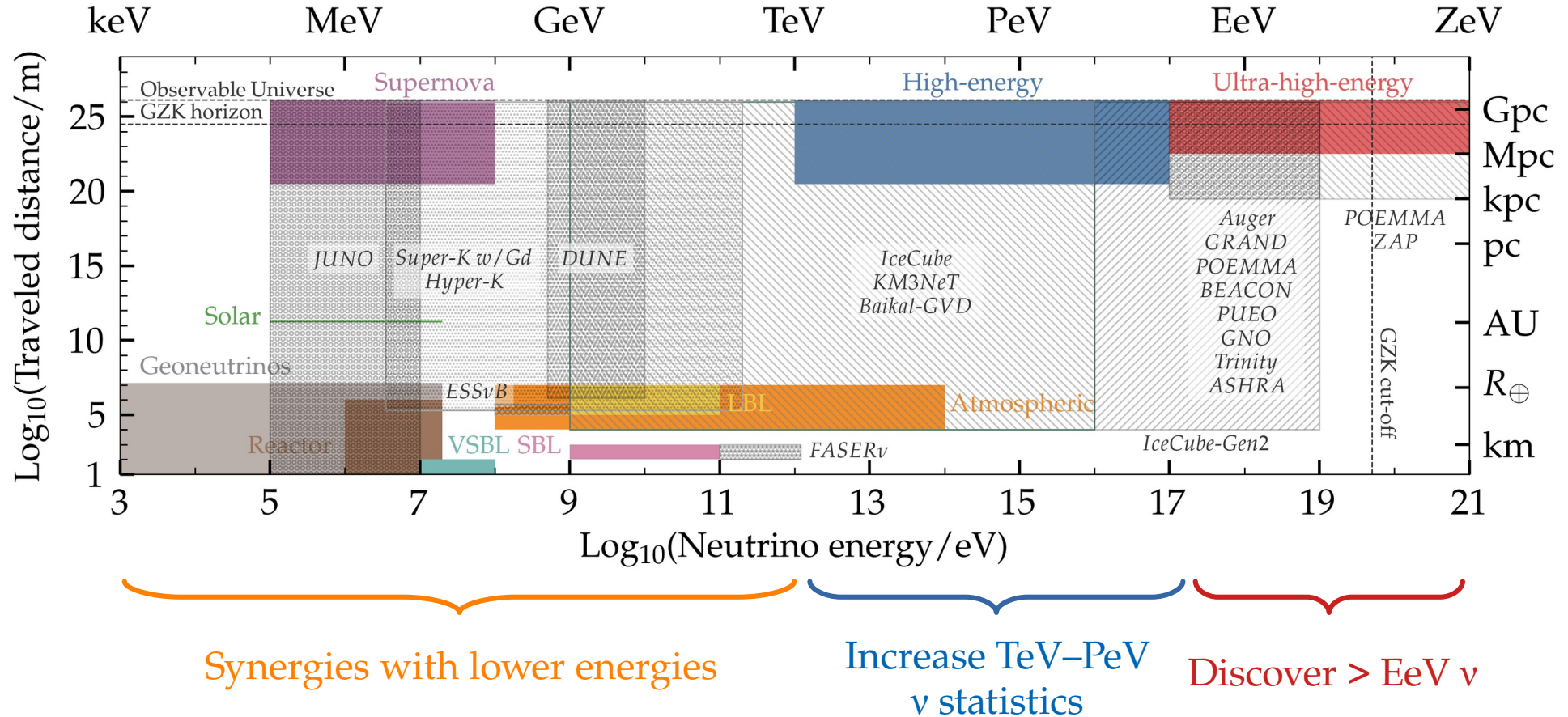
Work led by
Víctor Valera



III.

The future

Next decade: a host of planned neutrino detectors



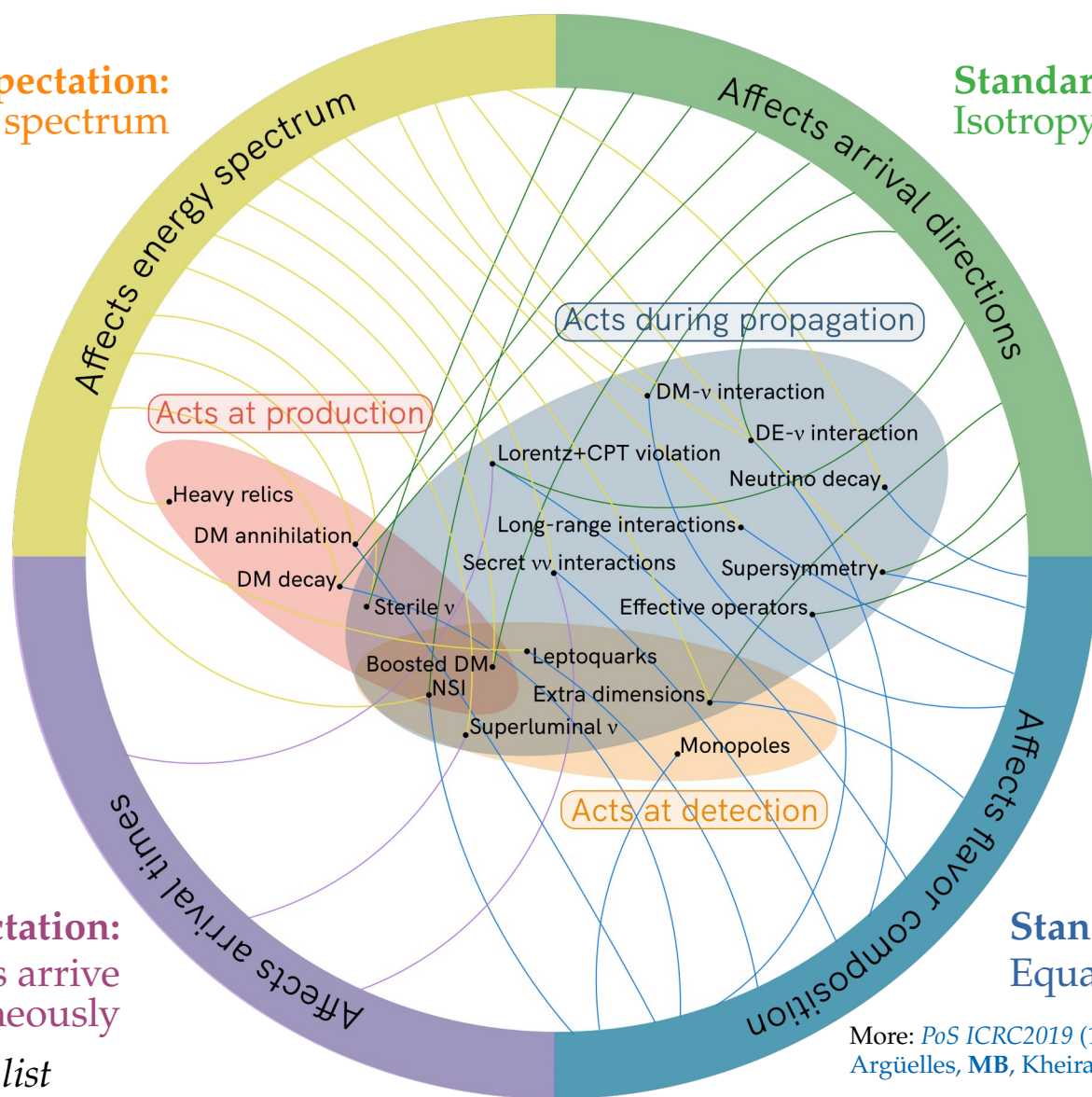
Standard expectation:
Power-law energy spectrum

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

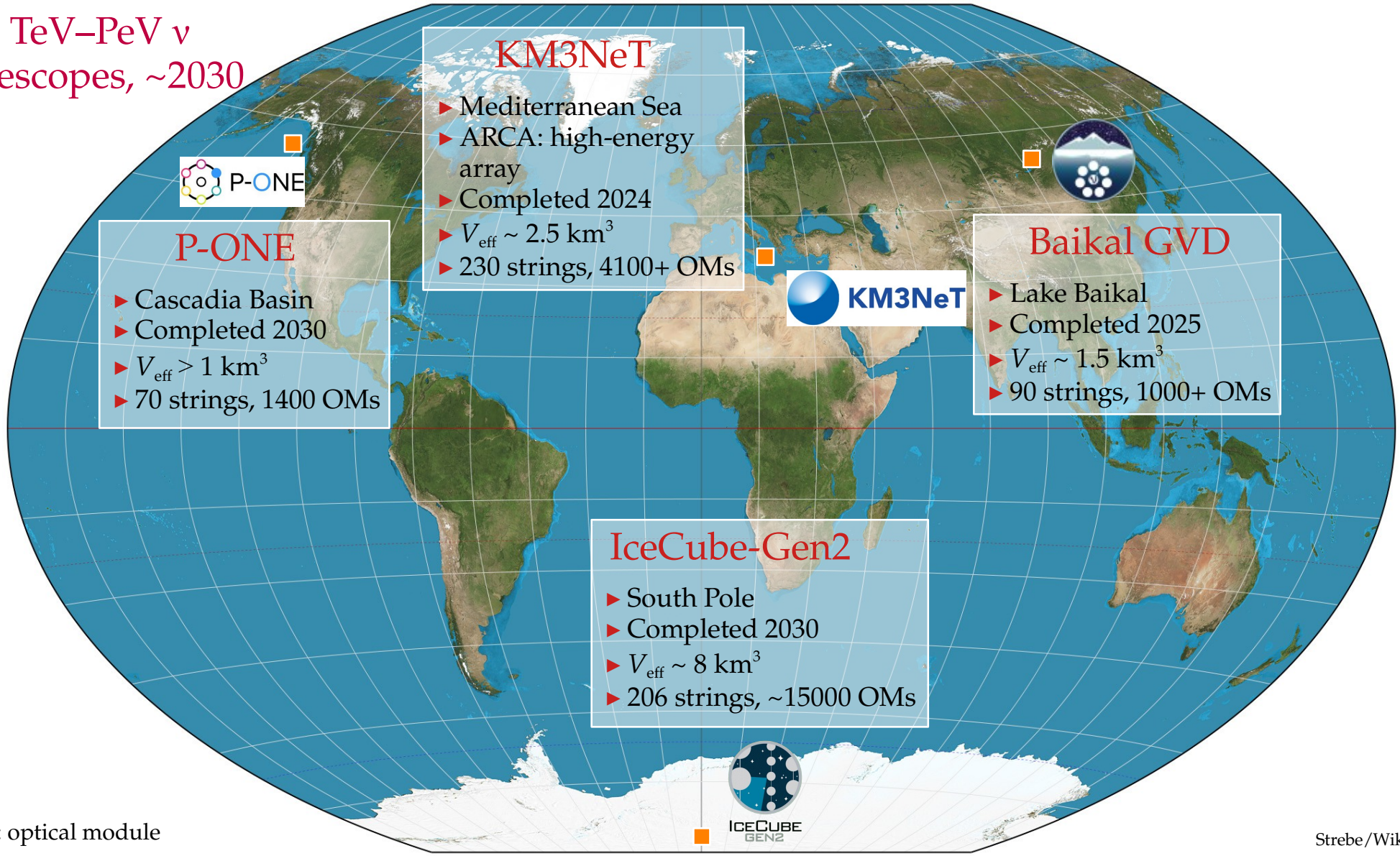
Note: Not an exhaustive list



More: *PoS ICRC2019* (1907.08690)

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

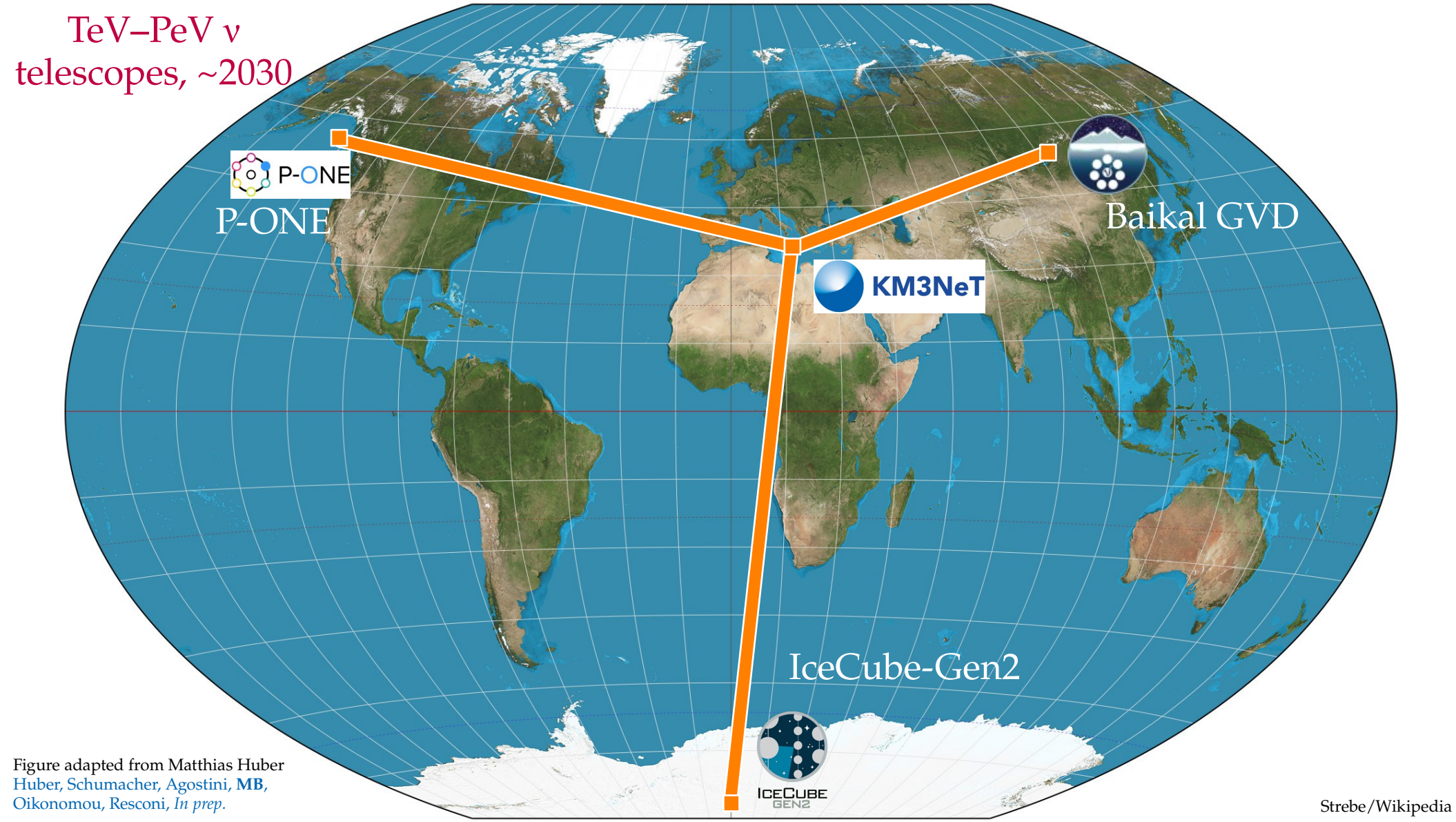
TeV–PeV ν
telescopes, ~2030



TeV–PeV ν
telescopes, ~2030



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



TeV–PeV ν
telescopes, ~2030

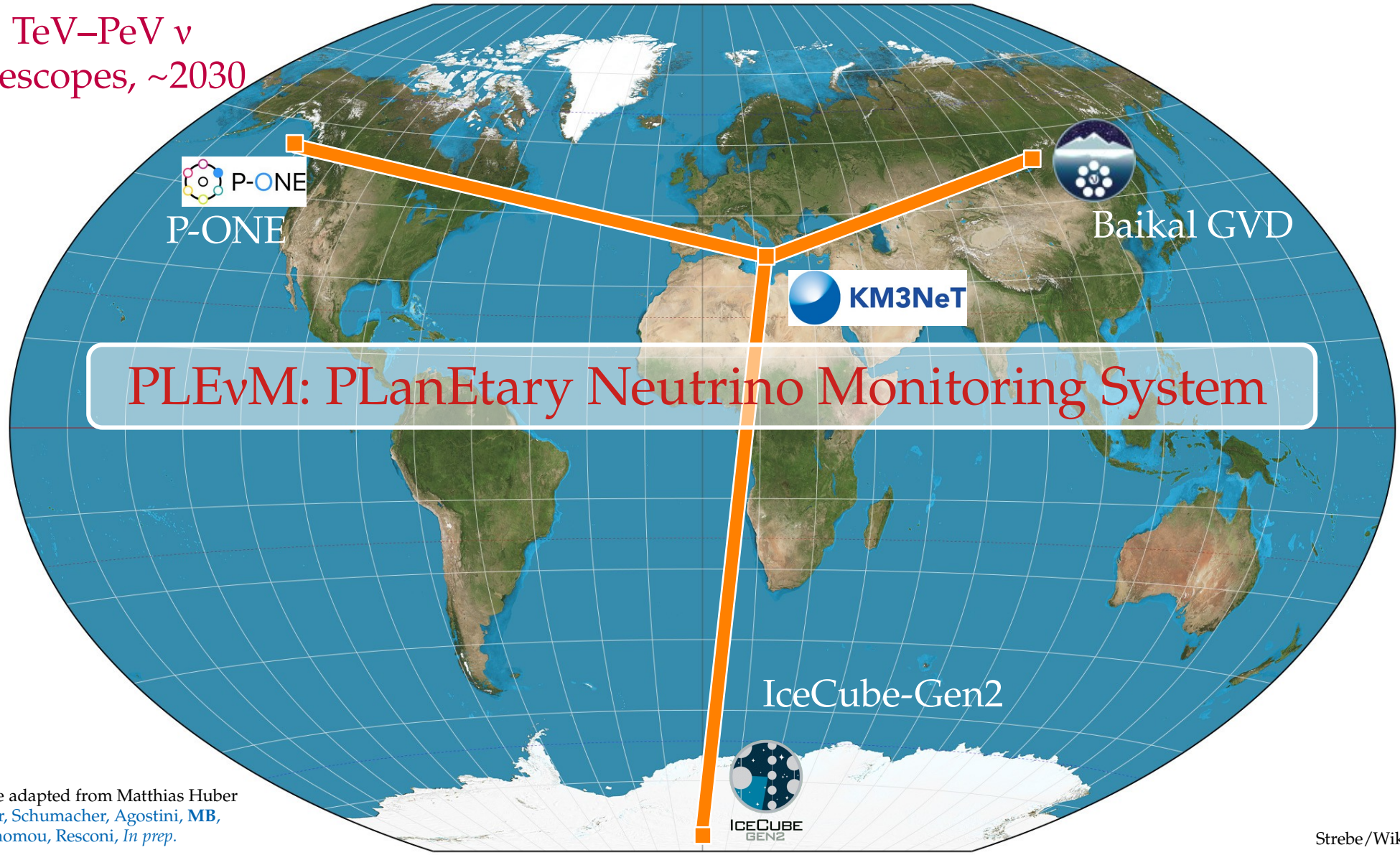
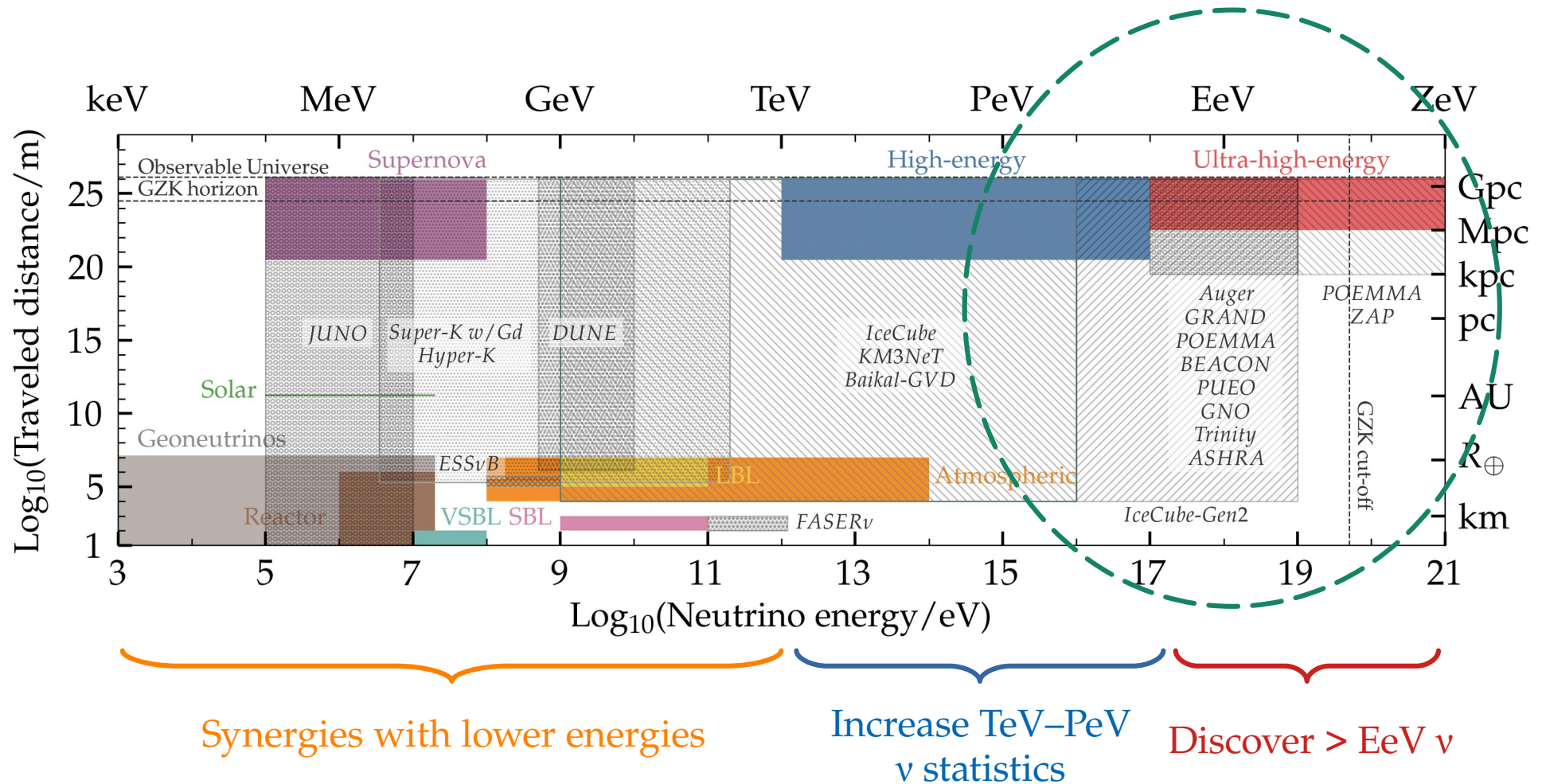


Figure adapted from Matthias Huber
Huber, Schumacher, Agostini, MB,
Oikonomou, Resconi, *In prep.*

Next decade: a host of planned neutrino detectors



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

End

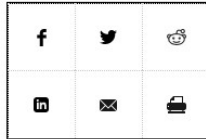
Backup slides

PHYSICS

Searching for the Universe's Most Energetic Particles, Astronomers Turn on the Radio

New radio-based observatories could soon detect ultrahigh-energy neutrinos, opening a new window on extreme cosmic physics

By Katrina Miller on April 27, 2021



Artist's composite of the IceCube Neutrino Observatory in Antarctica, accompanied by a distant astrophysical source emitting neutrinos that are detected in IceCube's subsurface sensors. Credit: IceCube and NSF

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SPACE

South Pole Experiment Traps Neutrinos from Beyond the Galaxy

December 1, 2015 — Francis Halzen

SPACE

Neutrinos on Ice: Astronomers' Long Hunt for Source of Extragalactic "Ghost Particles" Pays Off

July 12, 2018 — Mark Bowen

SPACE

Didn't Scientists Already Know Where Cosmic Rays Come from?

September 22, 2017 — Yvette Cendes

Katrina Miller for *Scientific American*,
April 27, 2021 [\[link\]](#)

Ever since their discovery in the 1960s, ultrahigh-energy cosmic rays have

Basics

Status quo of high-energy cosmic neutrinos

What we know

- ▶ Isotropic distribution of sources
- ▶ Spectrum is a power law $\propto E^{-p}$
- ▶ At least some sources are gamma-ray transients
- ▶ No correlation between directions of cosmic rays and neutrinos
- ▶ Flavor composition: compatible with equal number of ν_e , ν_μ , ν_τ
- ▶ No evident new physics

What we don't know

- ▶ The sources of the diffuse ν flux
- ▶ The ν production mechanism
- ▶ The spectral index of the spectrum
- ▶ A spectral cut-off at a few PeV?
- ▶ Are there Galactic ν sources?
- ▶ The precise flavor composition
- ▶ Is there new physics?

Status quo of high-energy cosmic neutrinos

But we have solid theory expectations
+ fast experimental progress

What we know

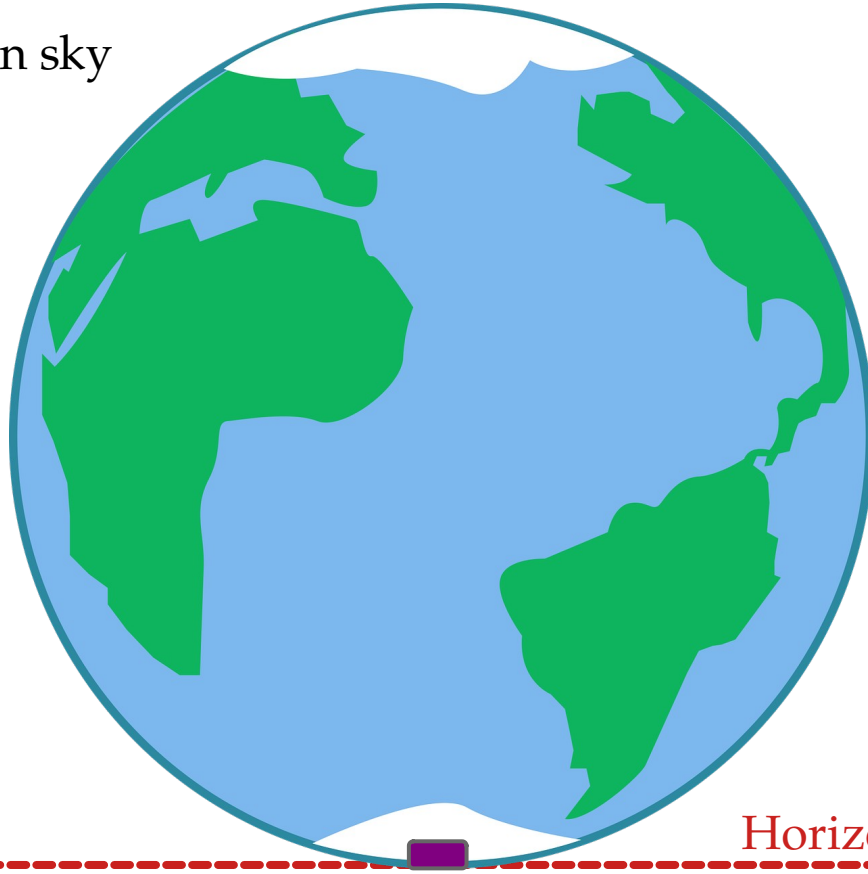
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- ▶ Are there Galactic ν sources?
- ▶ The precise flavor composition
- ▶ Is there new physics?

Upgoing *vs.* downgoing neutrinos

Northern sky



Horizon

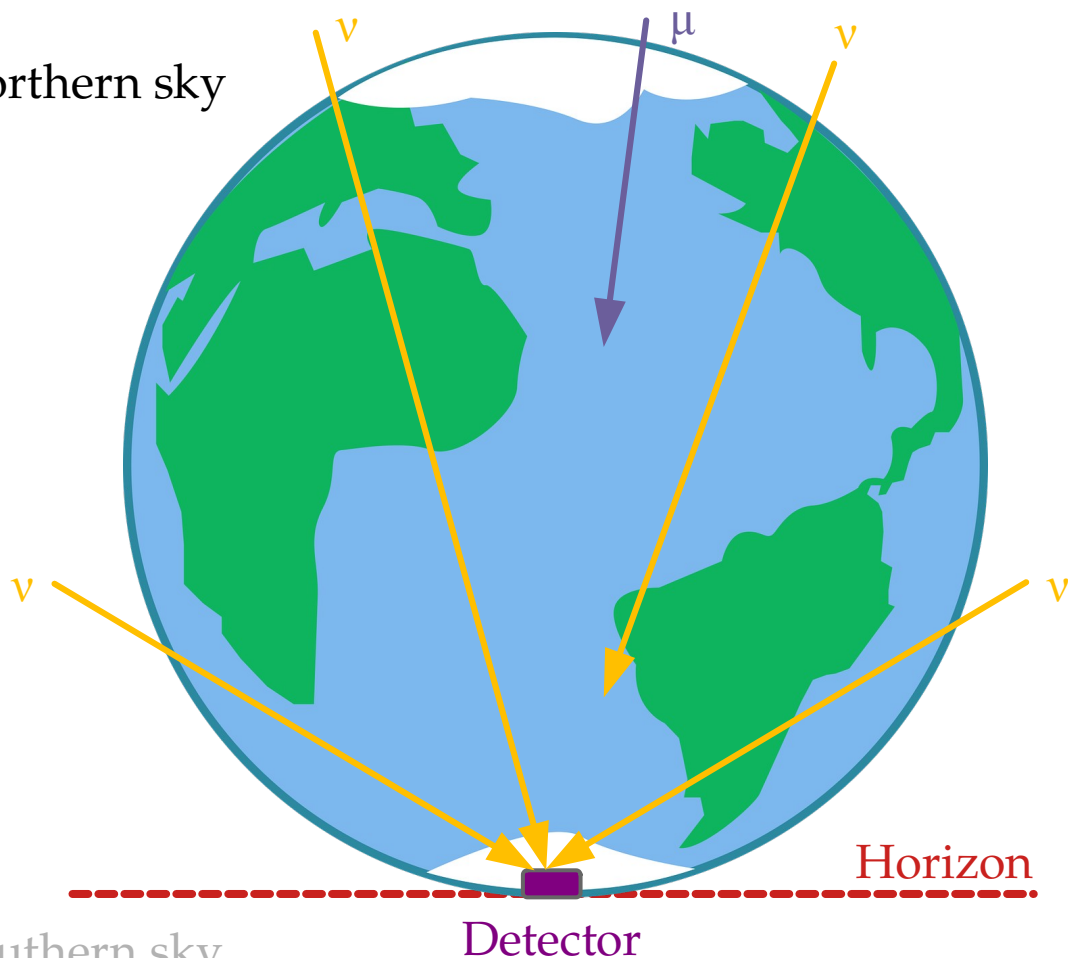
Detector

Southern sky

(Galactic Center is here)

Upgoing vs. downgoing neutrinos

Northern sky



Detector

Southern sky

(Galactic Center is here)

Neutrinos from the Northern sky

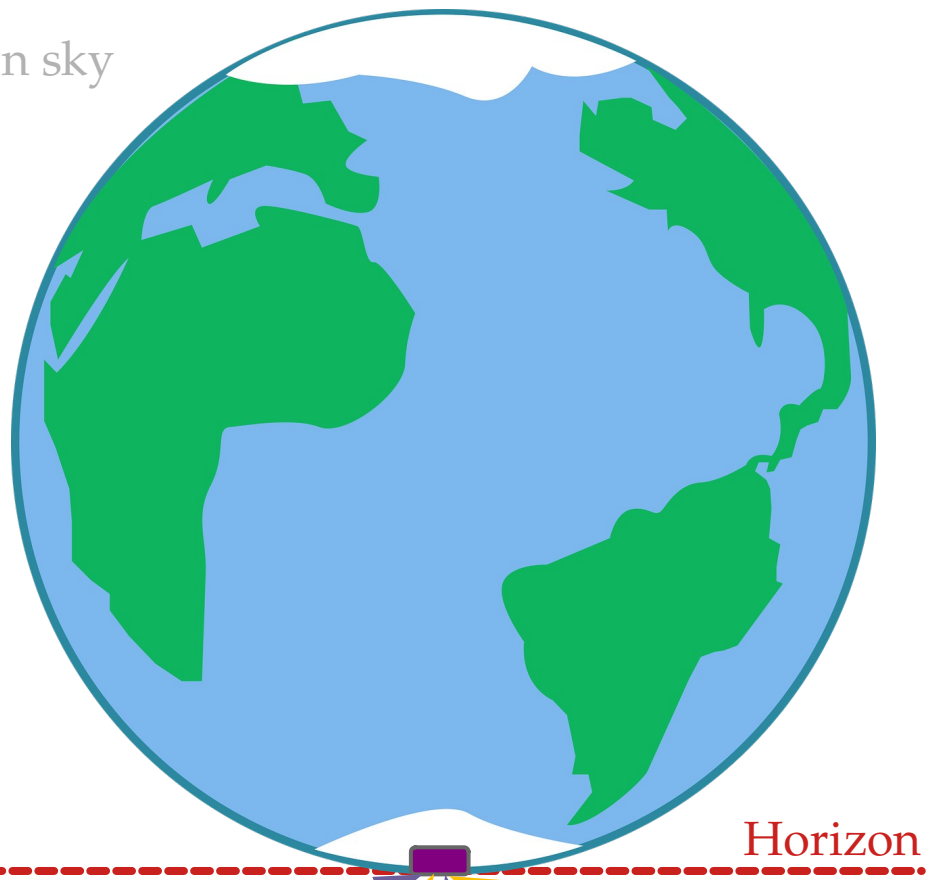
≡

Upgoing neutrinos

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

Downgoing vs. upgoing neutrinos

Northern sky



Southern sky
(Galactic Center is here)

Neutrinos from the Southern sky

≡

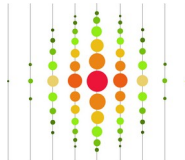
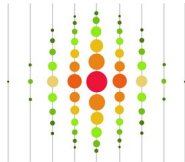
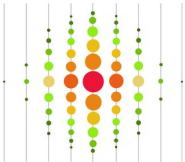
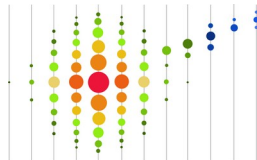
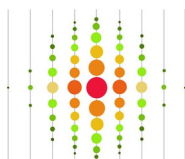
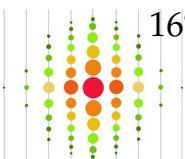
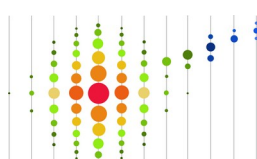
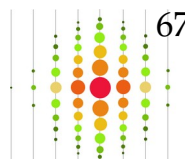
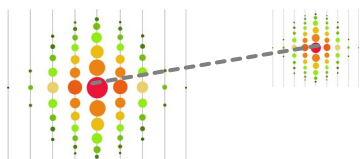
Downgoing neutrinos

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

IceCube

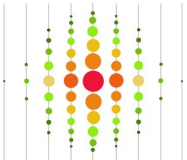
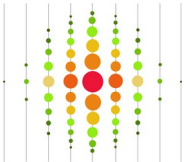
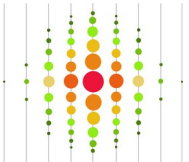
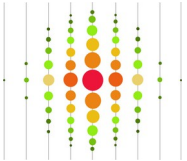
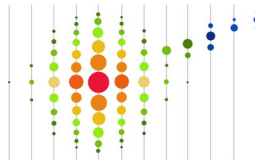
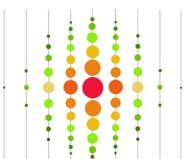
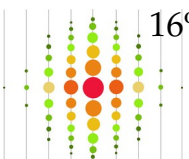
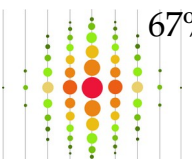
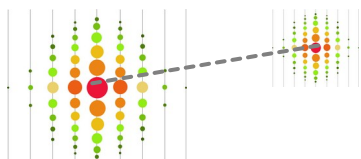
Detected

To be confirmed

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

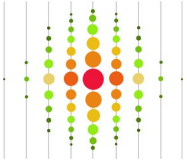
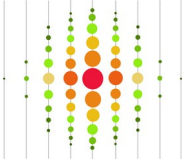
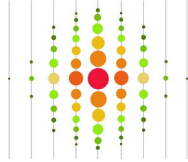
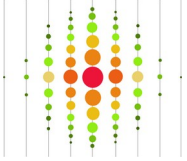
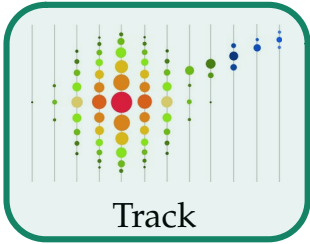
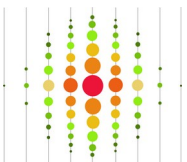
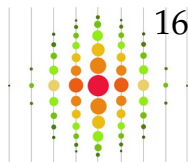
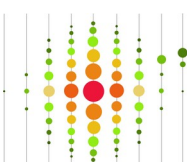
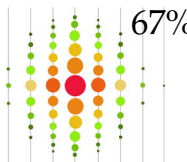
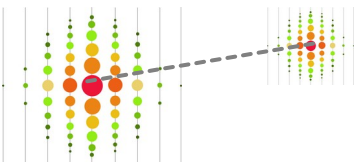
Detected

~~To be confirmed~~

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

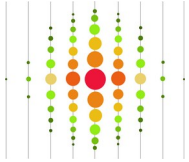
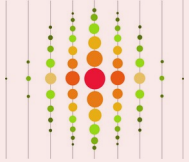
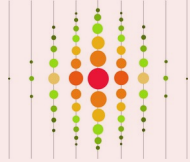
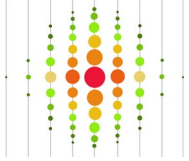
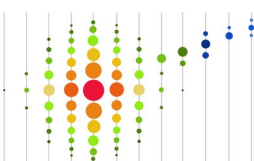
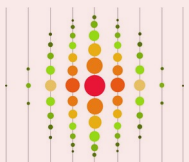
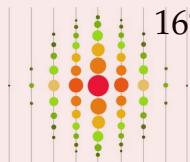
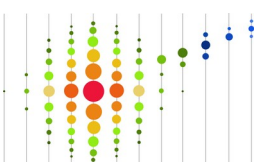
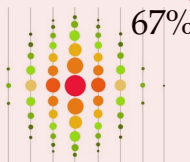
Detected

~~To be confirmed~~

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

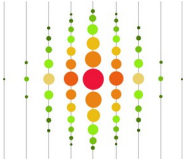
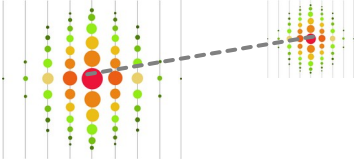
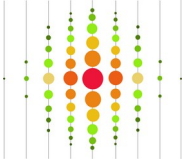
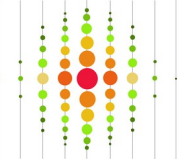
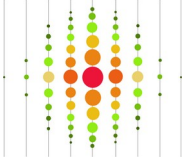
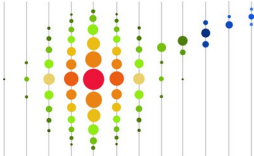
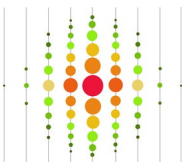
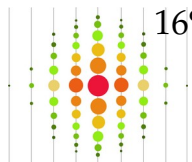
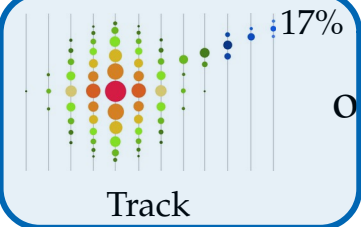
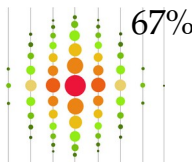
Detected

~~To be confirmed~~

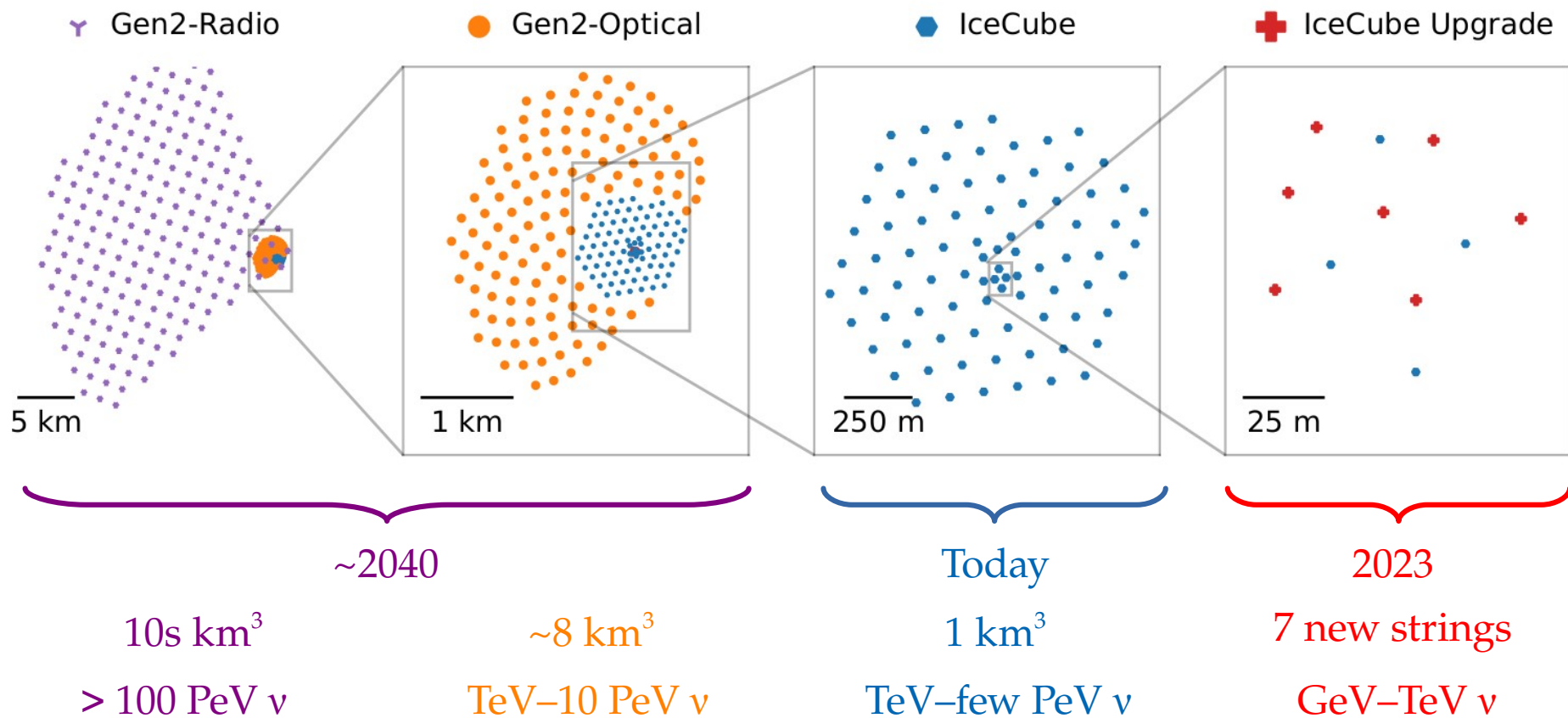
$\nu_x + \bar{\nu}_x$ NC	 Hadronic X shower	Confirmed (more later)
$\nu_e + \bar{\nu}_e$ CC	  ν_e and ν_τ: difficult to distinguish, both make showers	
$\nu_\mu + \bar{\nu}_\mu$ CC	 	
$\nu_\tau + \bar{\nu}_\tau$ CC	    Double pulse/bang	

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~~To be confirmed~~

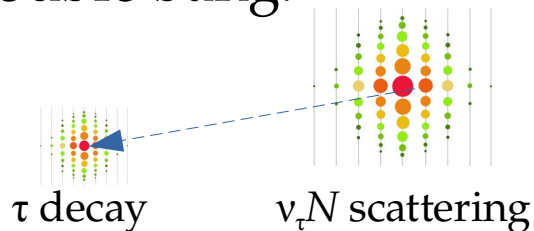
$\nu_x + \bar{\nu}_x$ NC	 Hadronic X shower				Confirmed (more later)  Double pulse/bang
$\nu_e + \bar{\nu}_e$ CC	 Hadronic X shower	+	 E.m. shower	The occasional track (weakly) breaks the ν_e / ν_τ degeneracy	
$\nu_\mu + \bar{\nu}_\mu$ CC	 Hadronic X shower	+	 Track		
$\nu_\tau + \bar{\nu}_\tau$ CC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

IceCube-Gen2

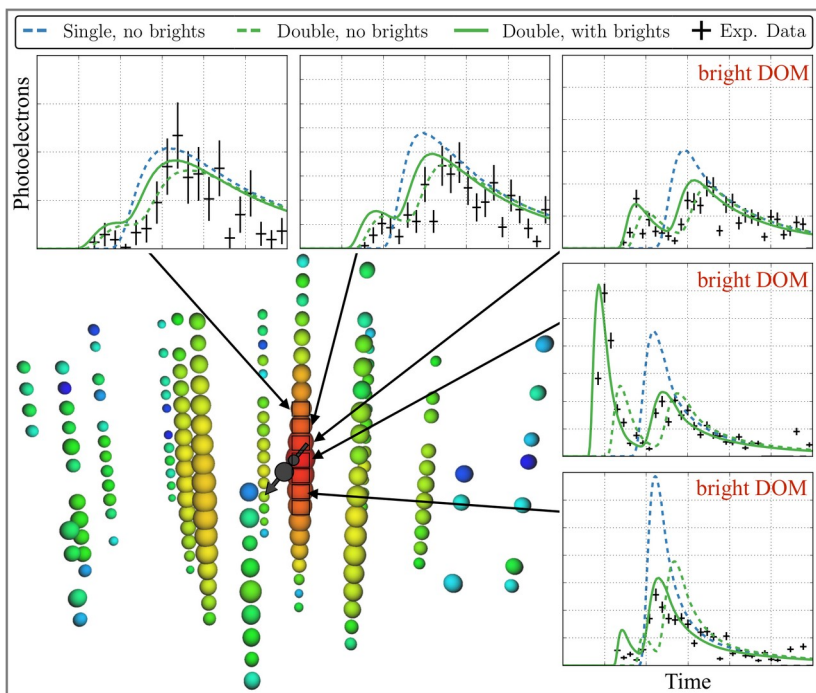
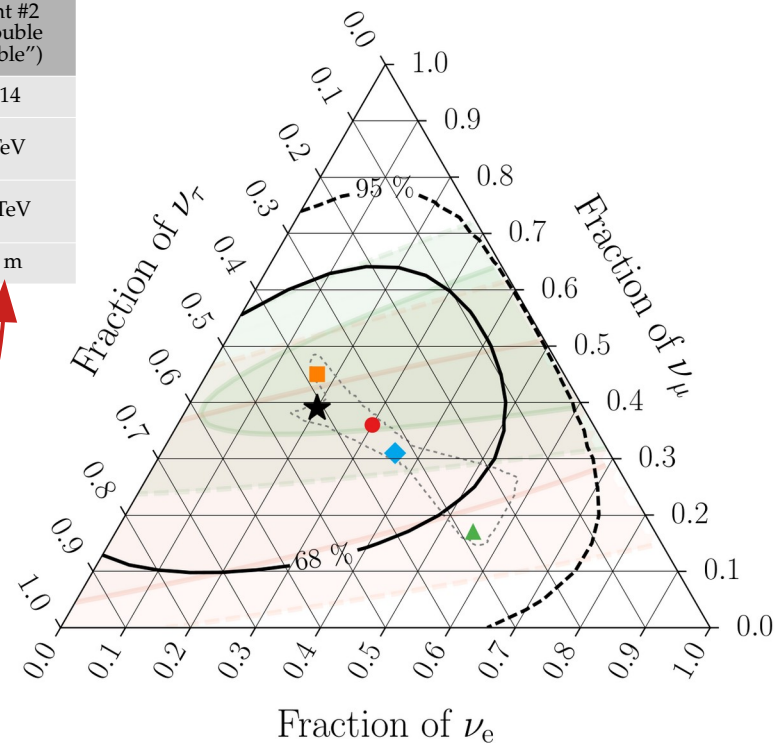


First identified high-energy astrophysical ν_τ

Double bang:



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

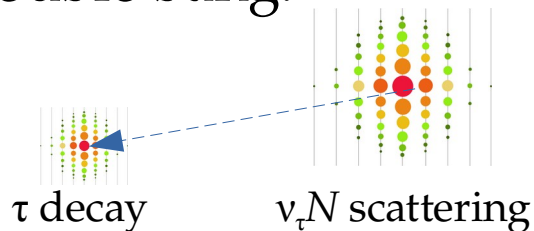


- HESE with ternary topology ID
- ★ Best fit: 0.20 : 0.39 : 0.42
- Global Fit (IceCube, APJ 2015)
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- 3ν -mixing 3σ allowed region

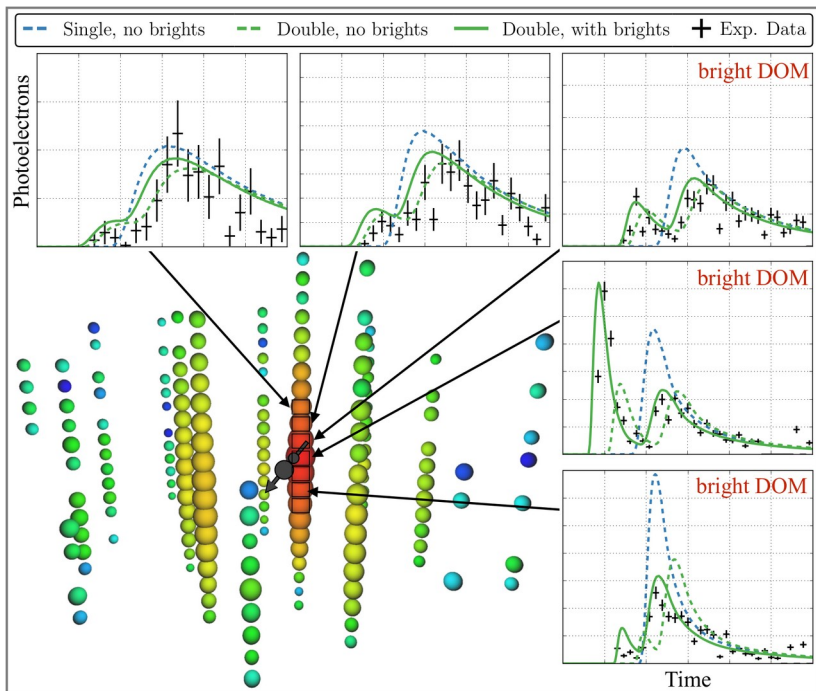
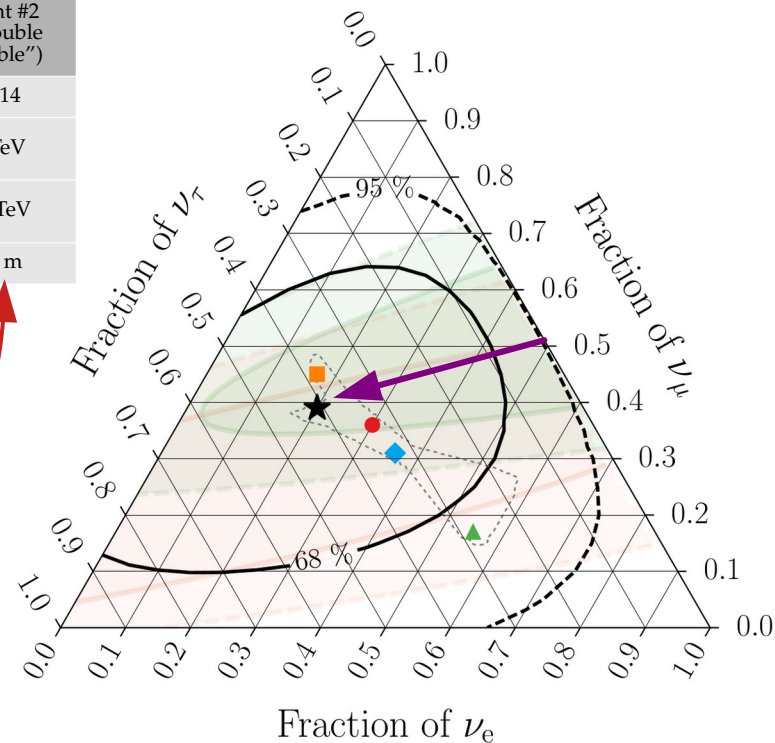
- $\nu_e : \nu_\mu : \nu_\tau$ at source $\rightarrow$ on Earth:
- 0:1:0 $\rightarrow$ 0.17 : 0.45 : 0.37
 - 1:2:0 $\rightarrow$ 0.30 : 0.36 : 0.34
 - ▲ 1:0:0 $\rightarrow$ 0.55 : 0.17 : 0.28
 - ◆ 1:1:0 $\rightarrow$ 0.36 : 0.31 : 0.33

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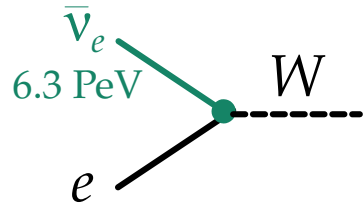
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First observation of a Glashow resonance

Predicted in 1960:

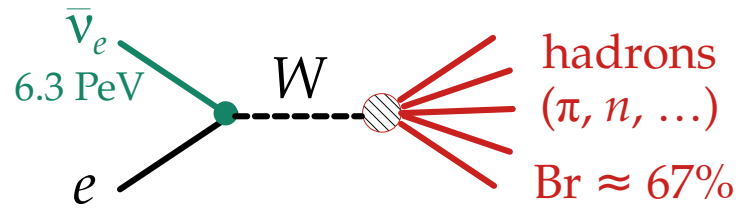
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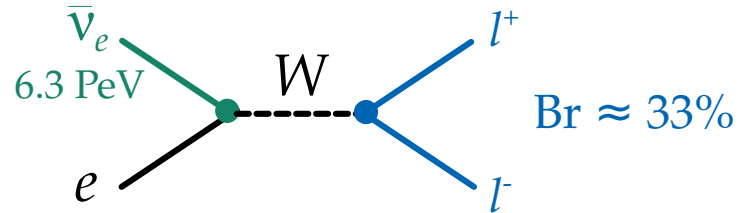
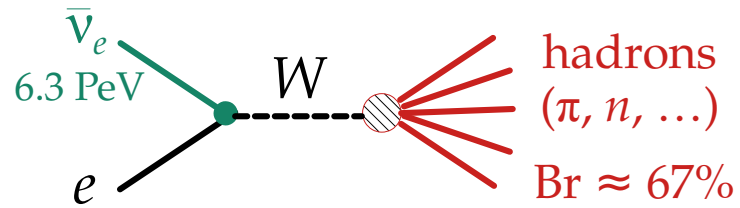
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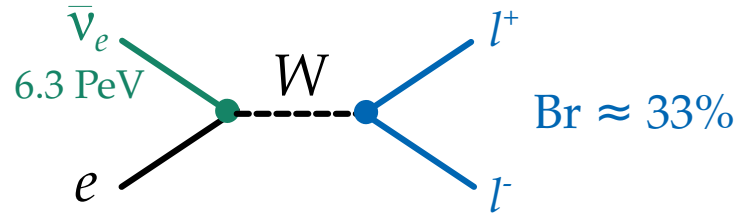
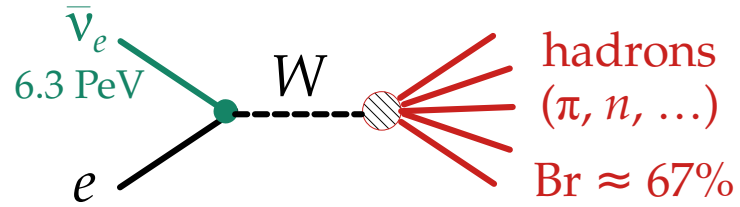
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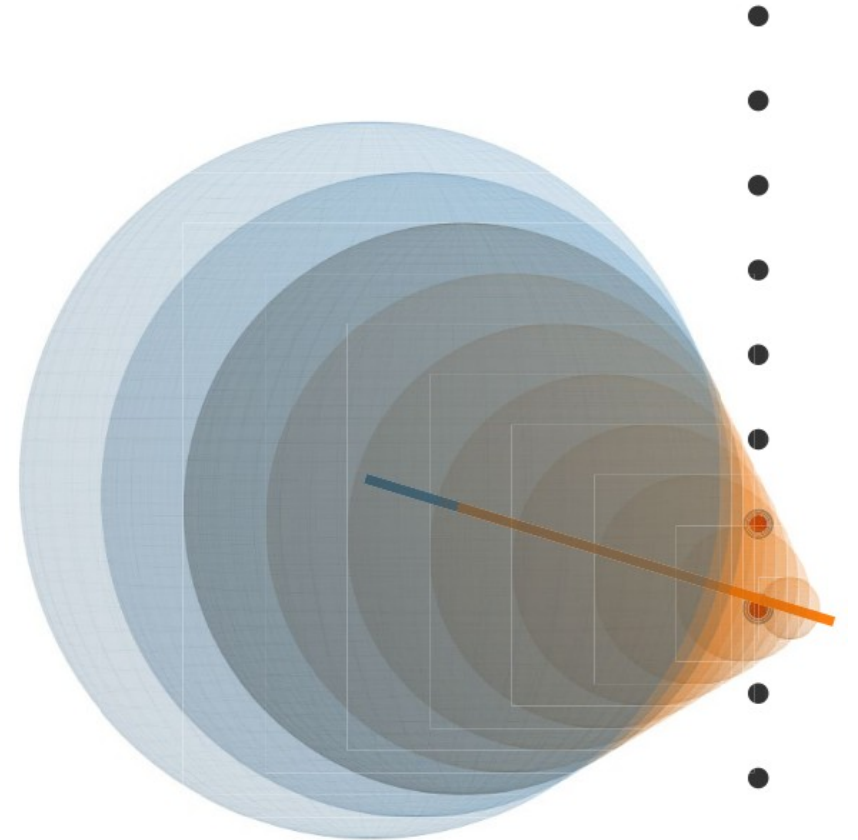


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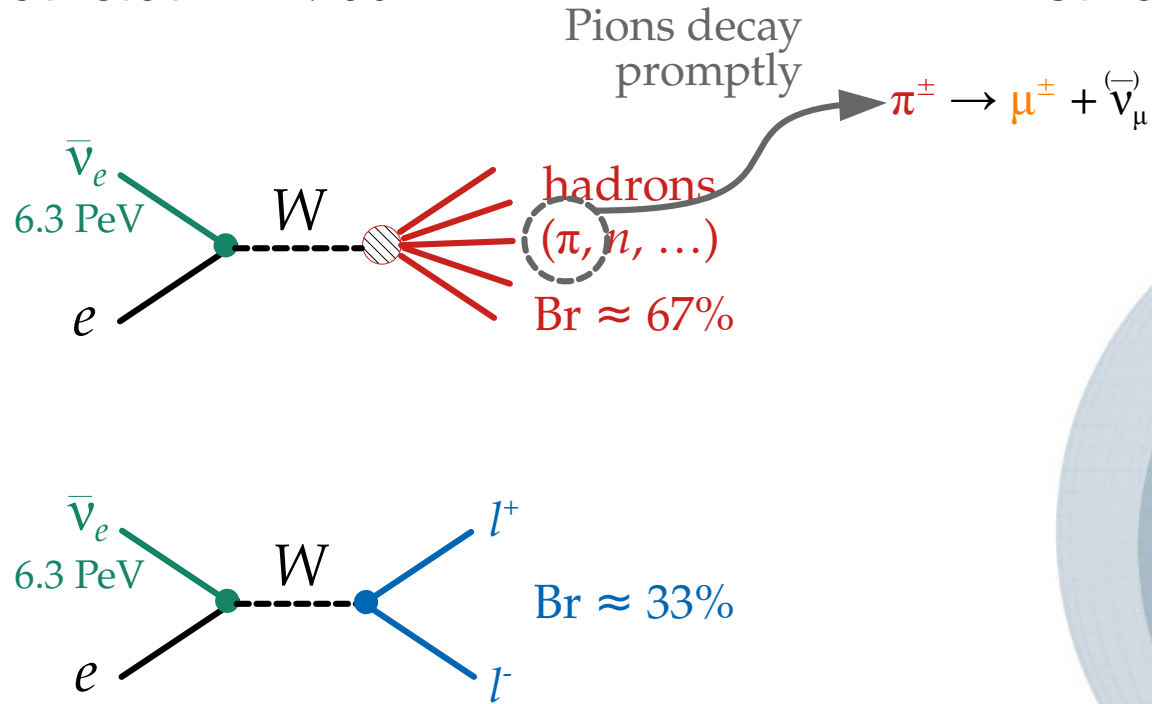


First reported by IceCube in 2021:

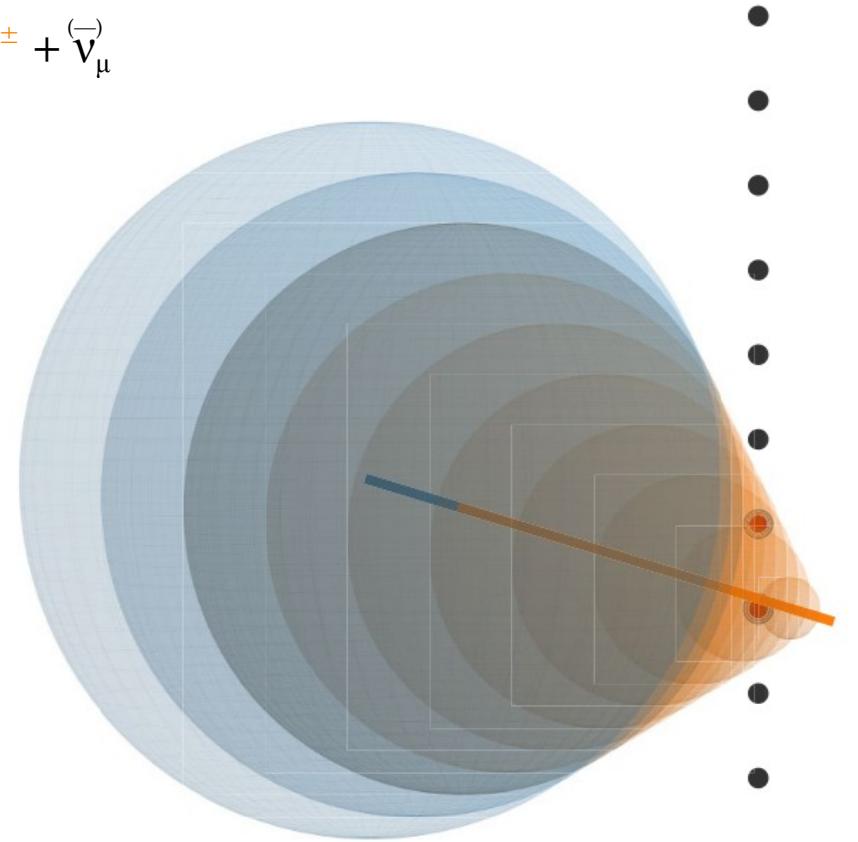


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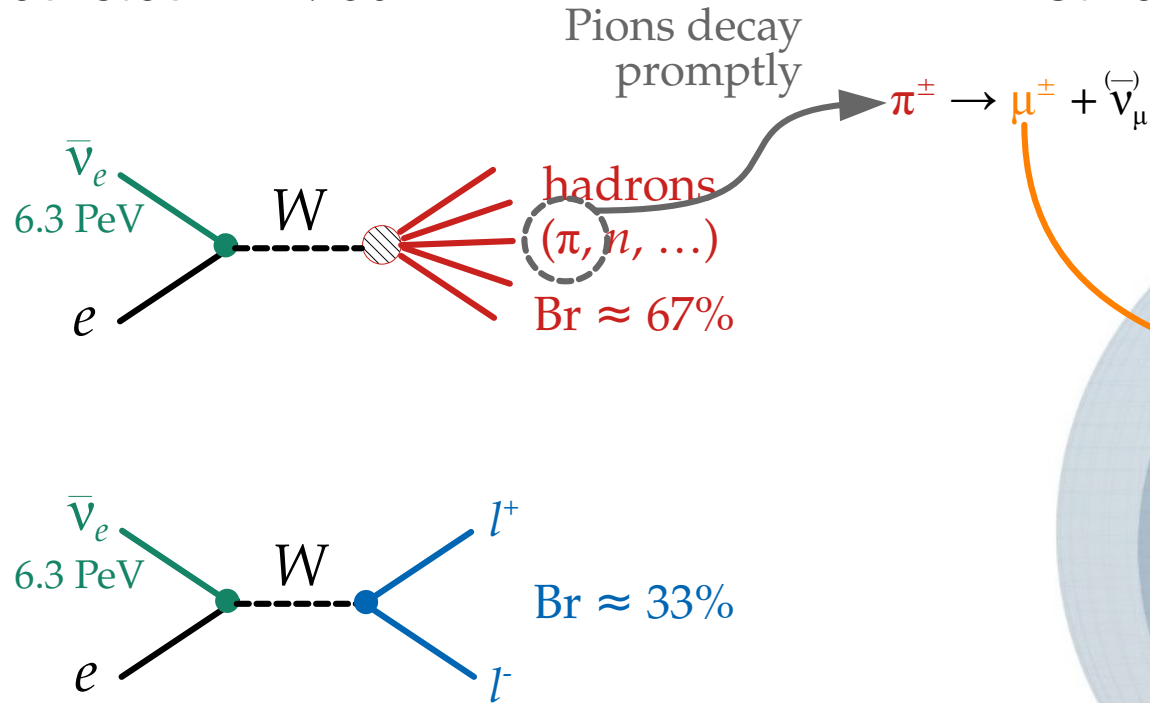


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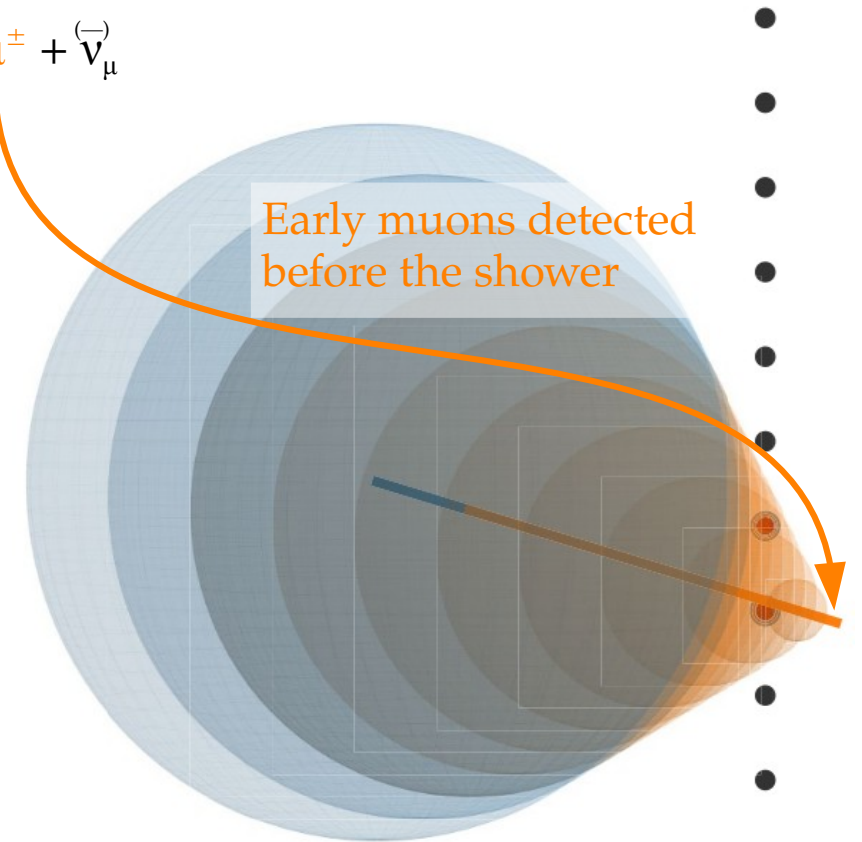


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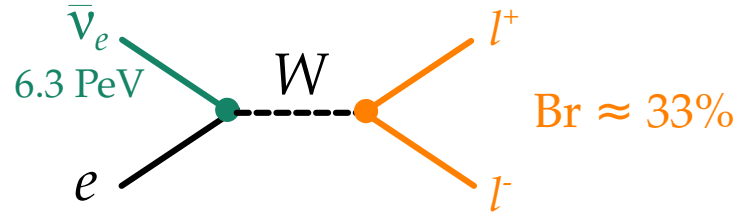
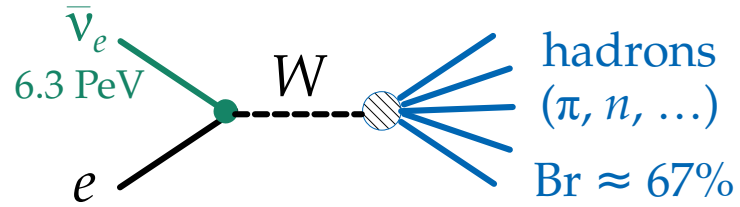


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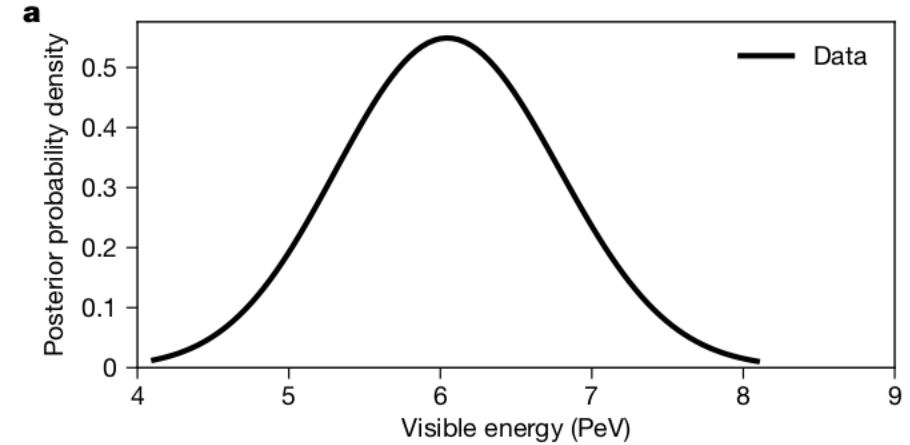


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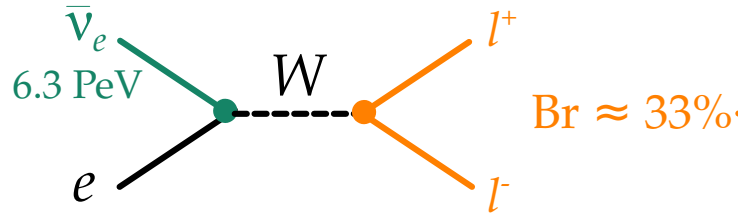
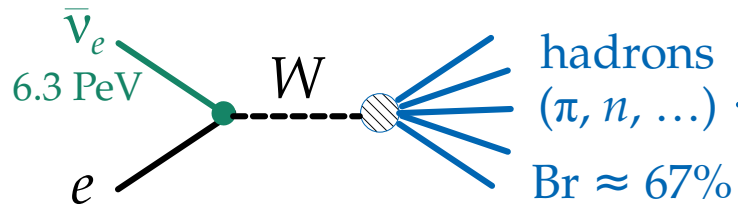


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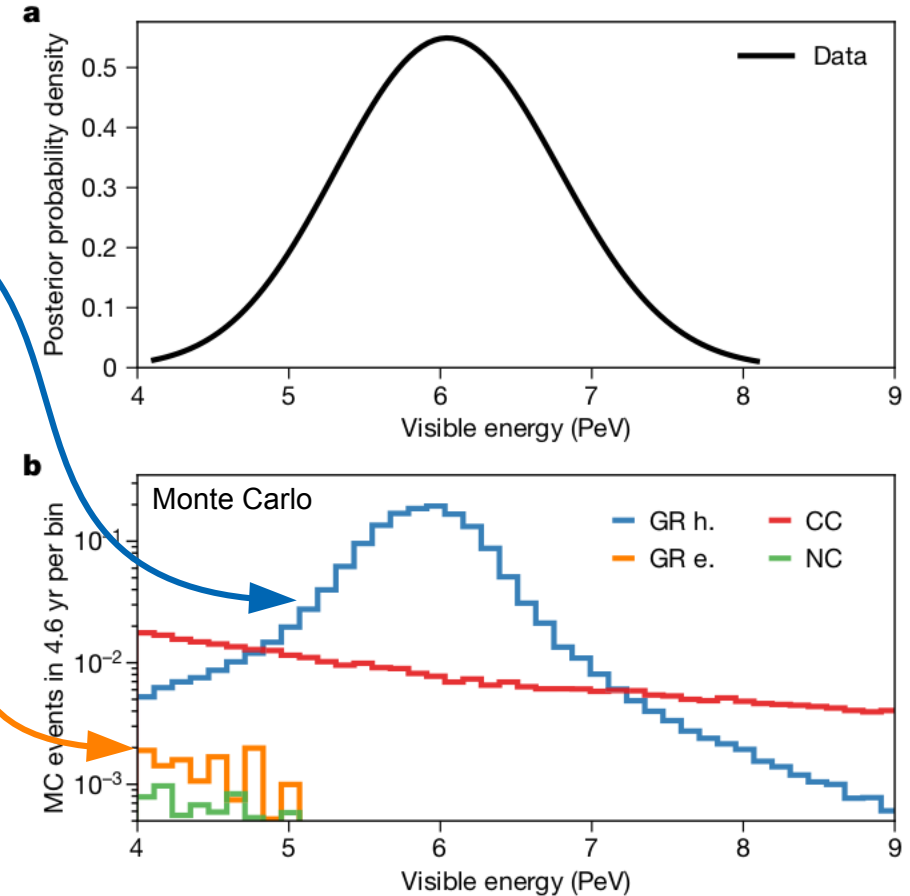


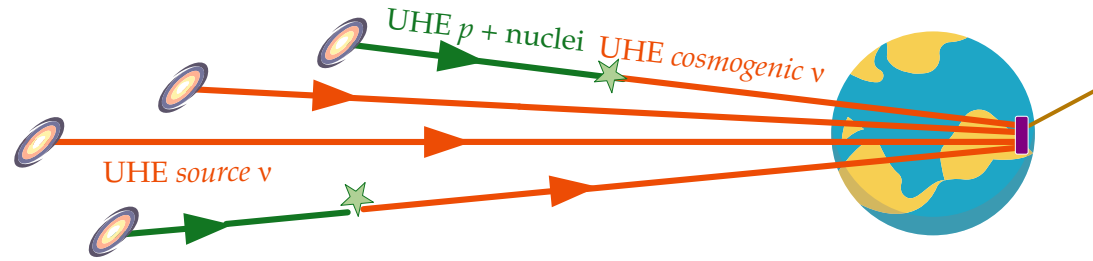
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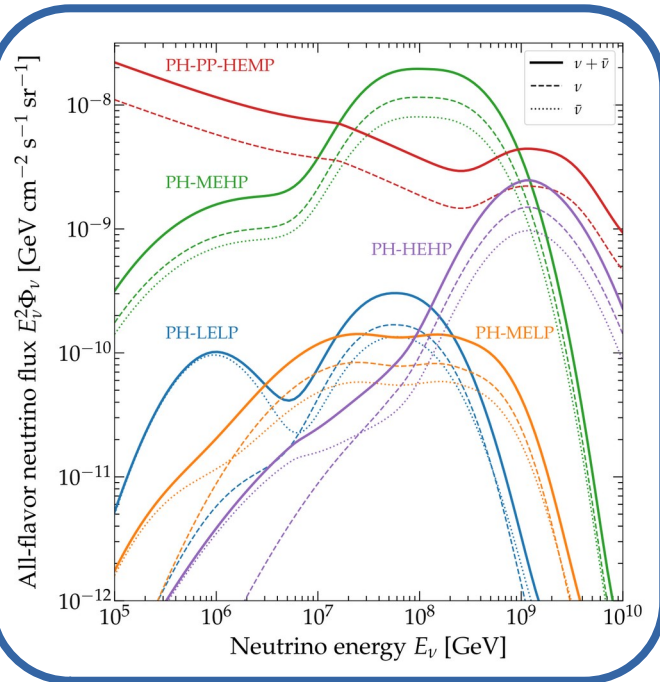
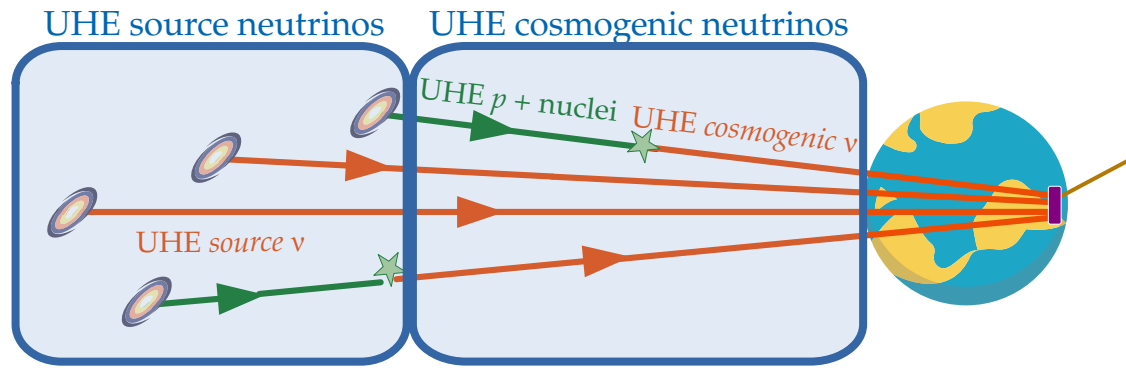
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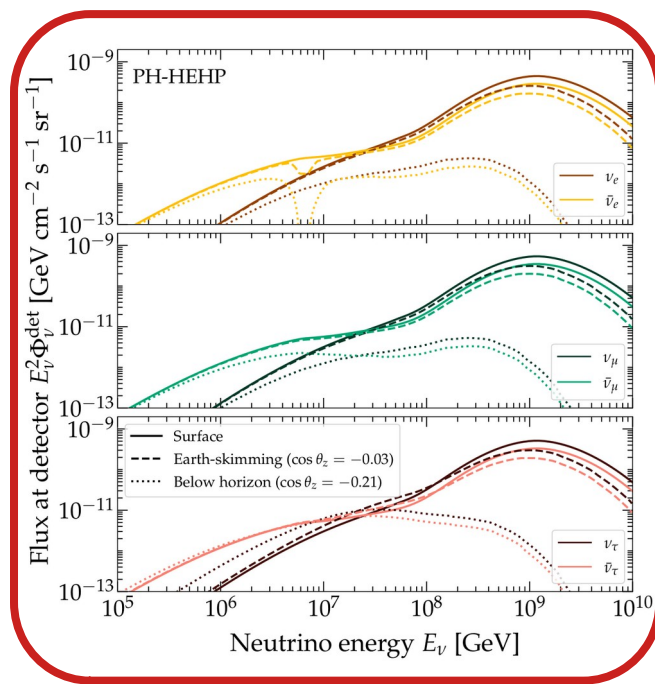
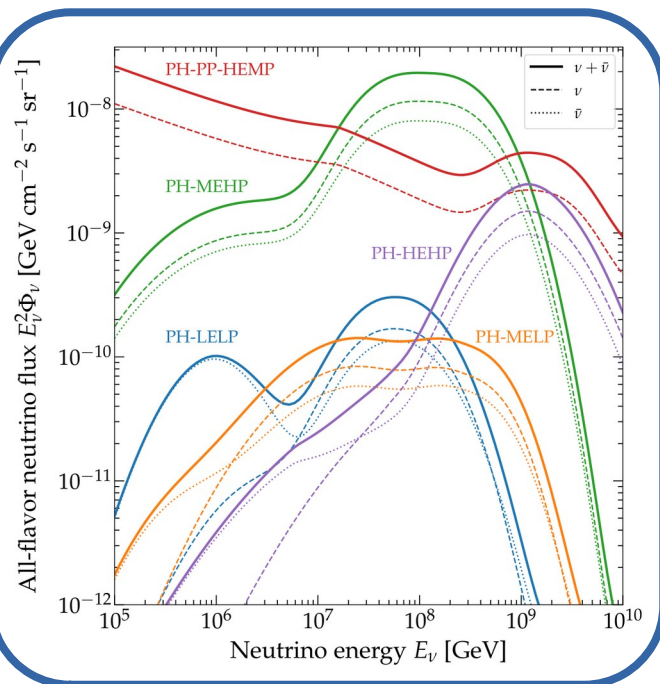
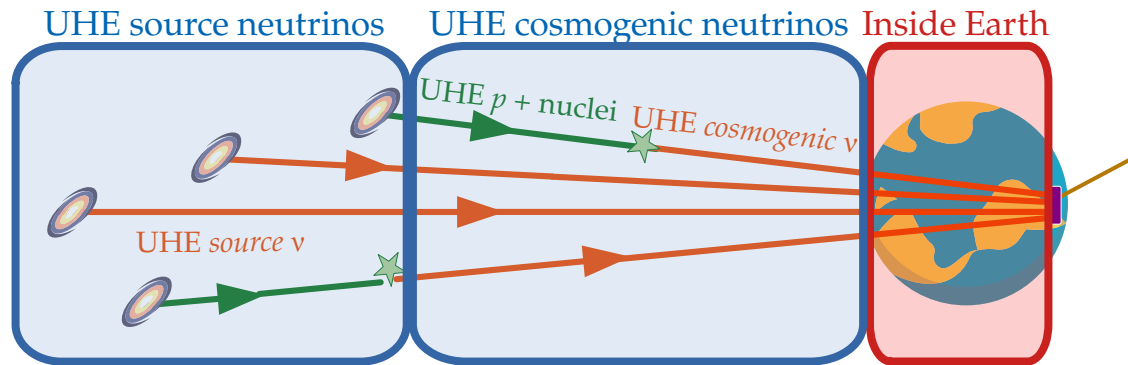
First reported by IceCube in 2021:





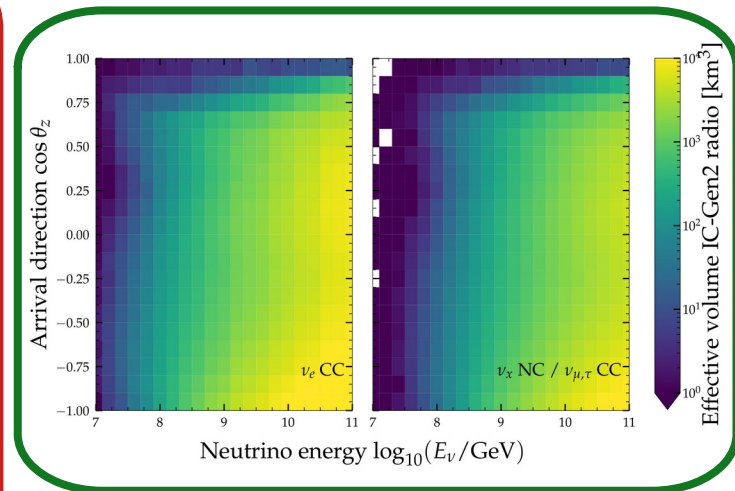
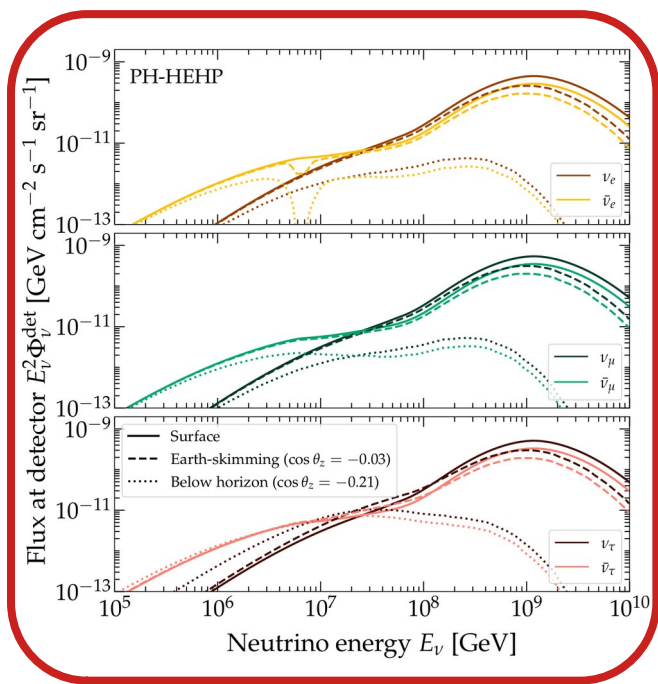
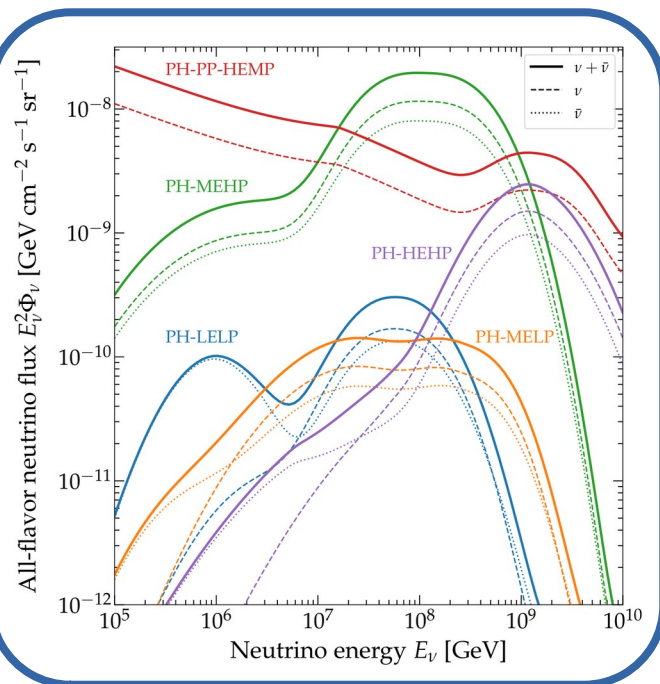
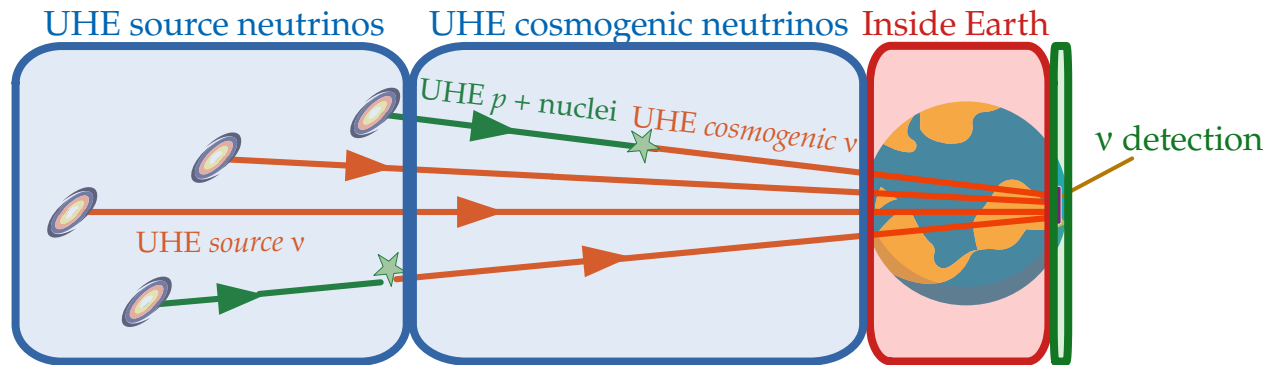


UHE ν from pp and $p\gamma$ interactions, account for
 cosmic-ray spectrum & mass composition,
 source properties



UHE ν from pp and $p\gamma$ interactions, account for
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Propagate each flavor of ν and $\bar{\nu}$ separately:
deep inelastic scattering, diffractive
scattering, ν_τ regeneration



Model radio propagation in ice, antenna response, angular and energy resolution, inelasticity distribution

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Fundamental physics

Fundamental physics with HE cosmic neutrinos

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

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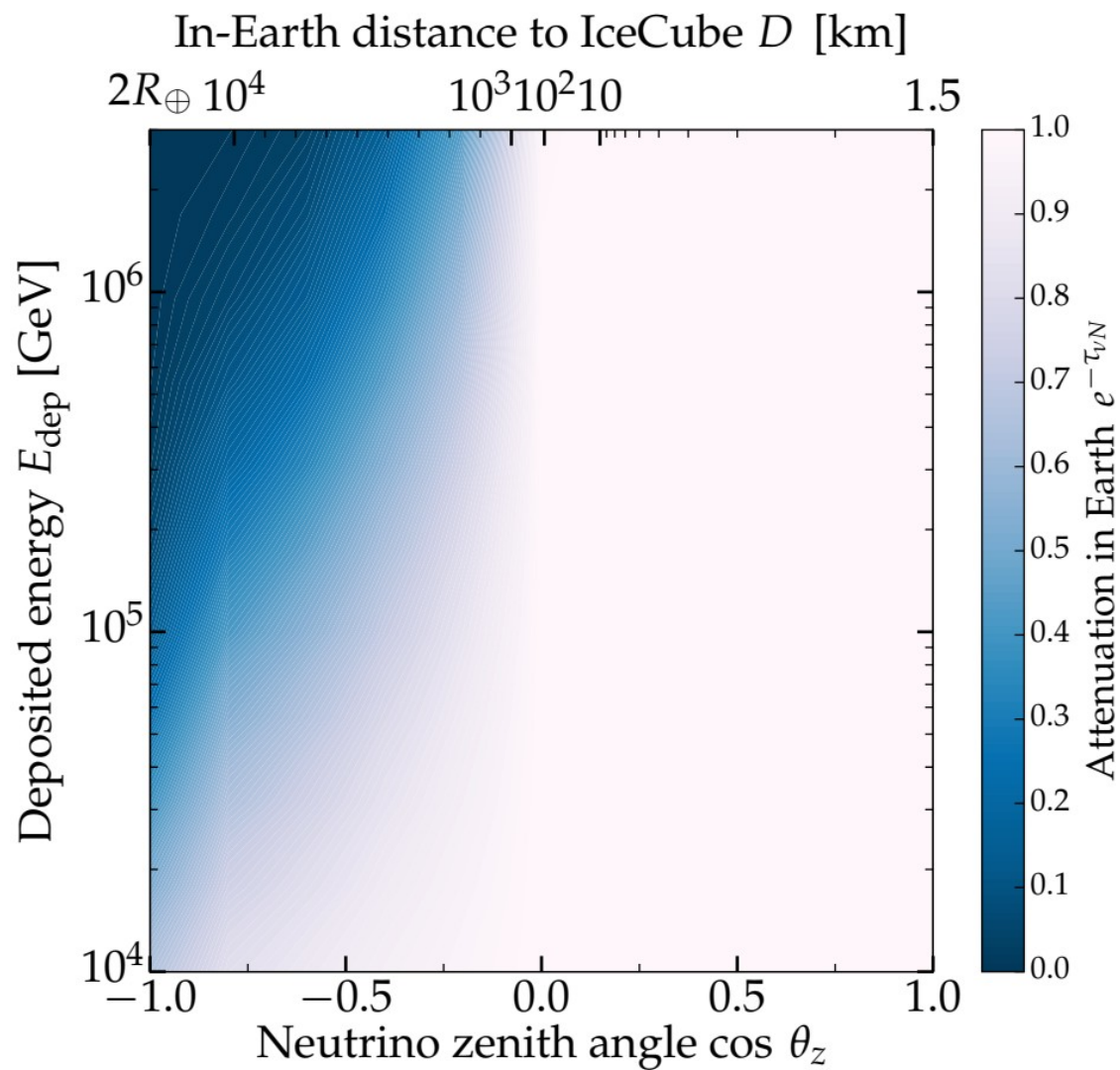
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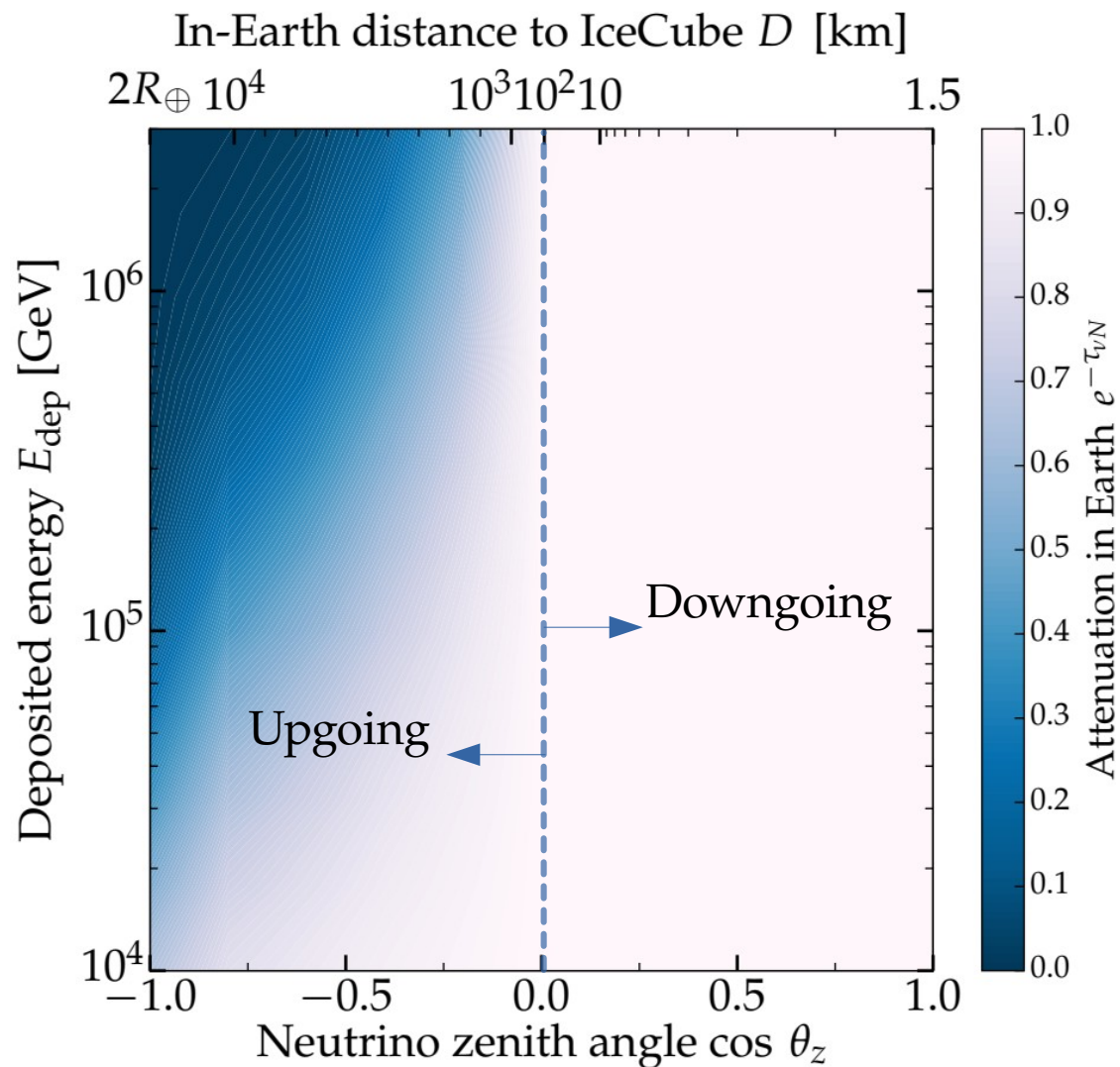
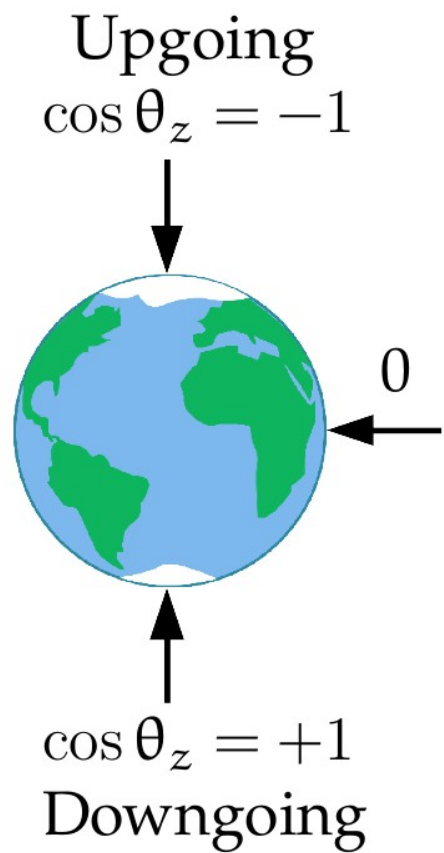
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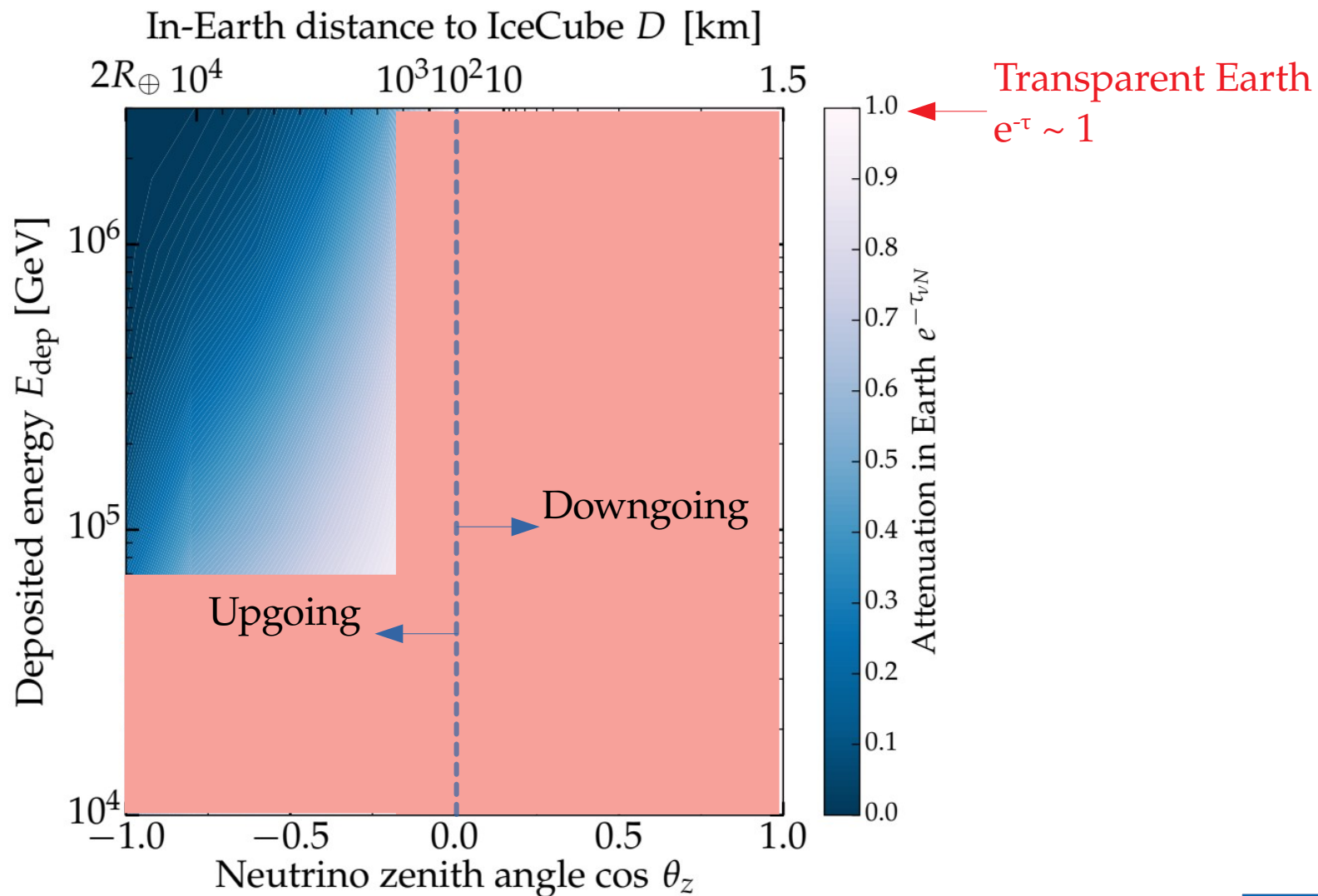
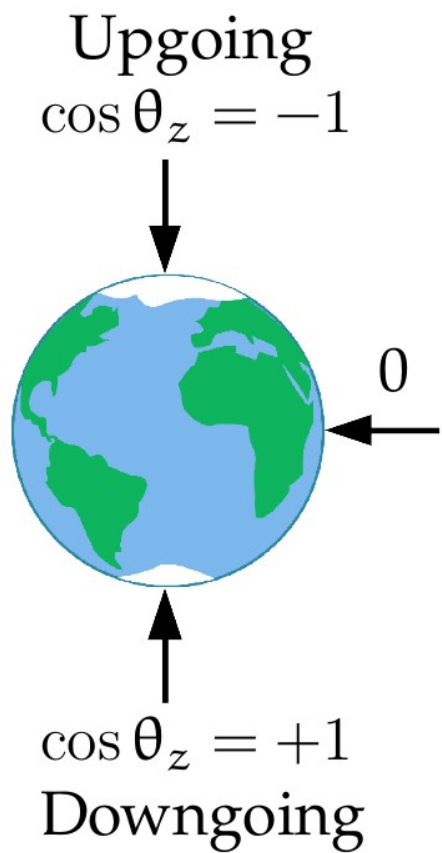
*In spite of
poor energy, angular, flavor reconstruction
& astrophysical unknowns*

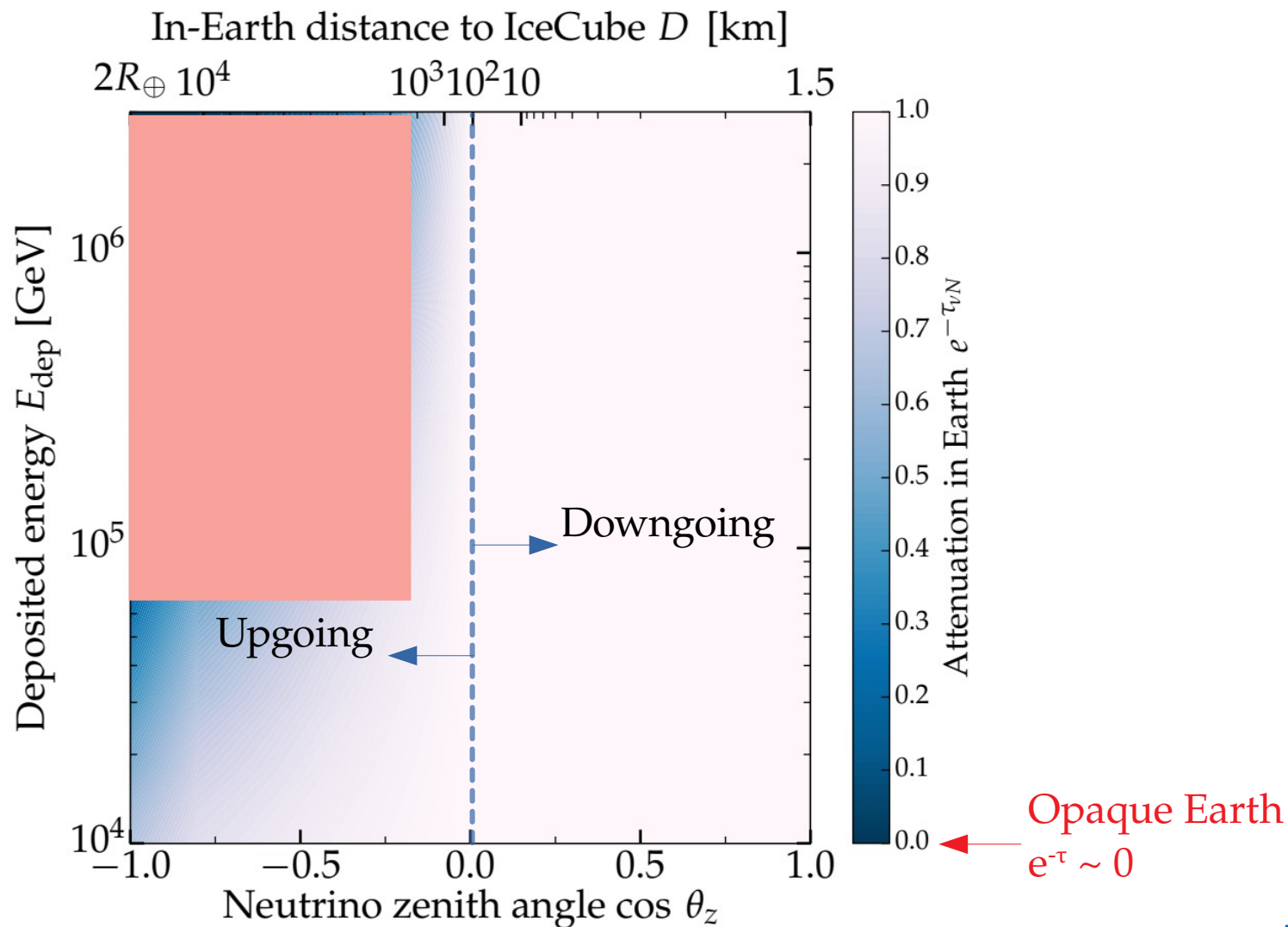
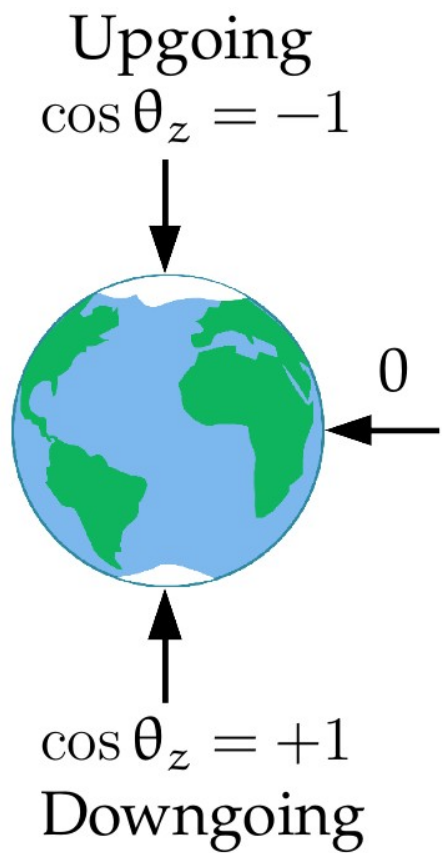
Example 1:

Measuring TeV–PeV ν cross sections





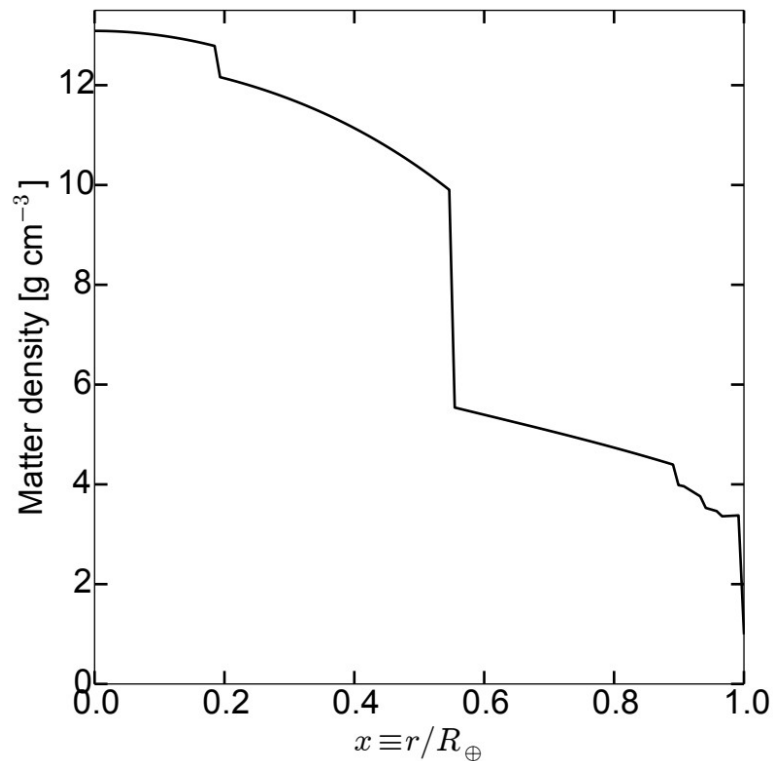




A feel for the in-Earth attenuation

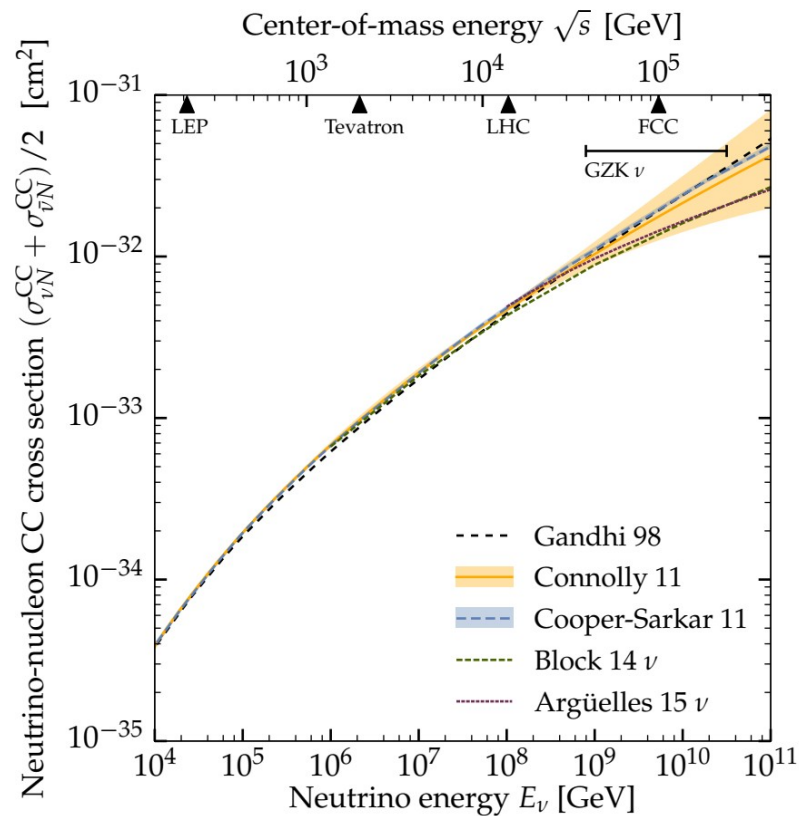
Earth matter density

(Preliminary Reference Earth Model)

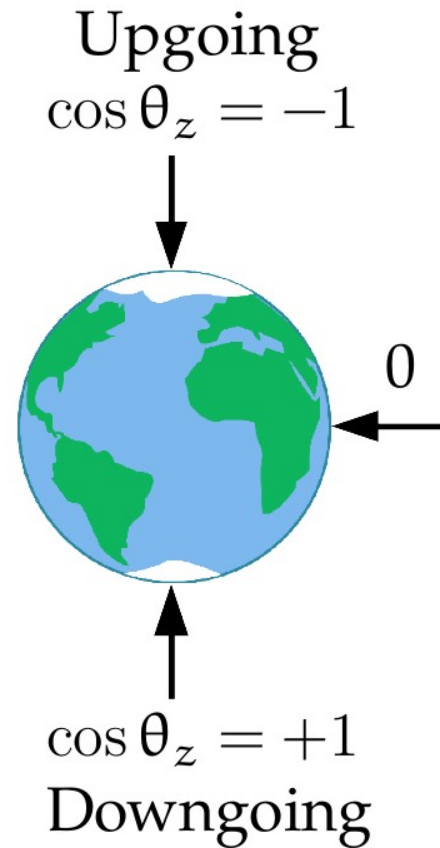
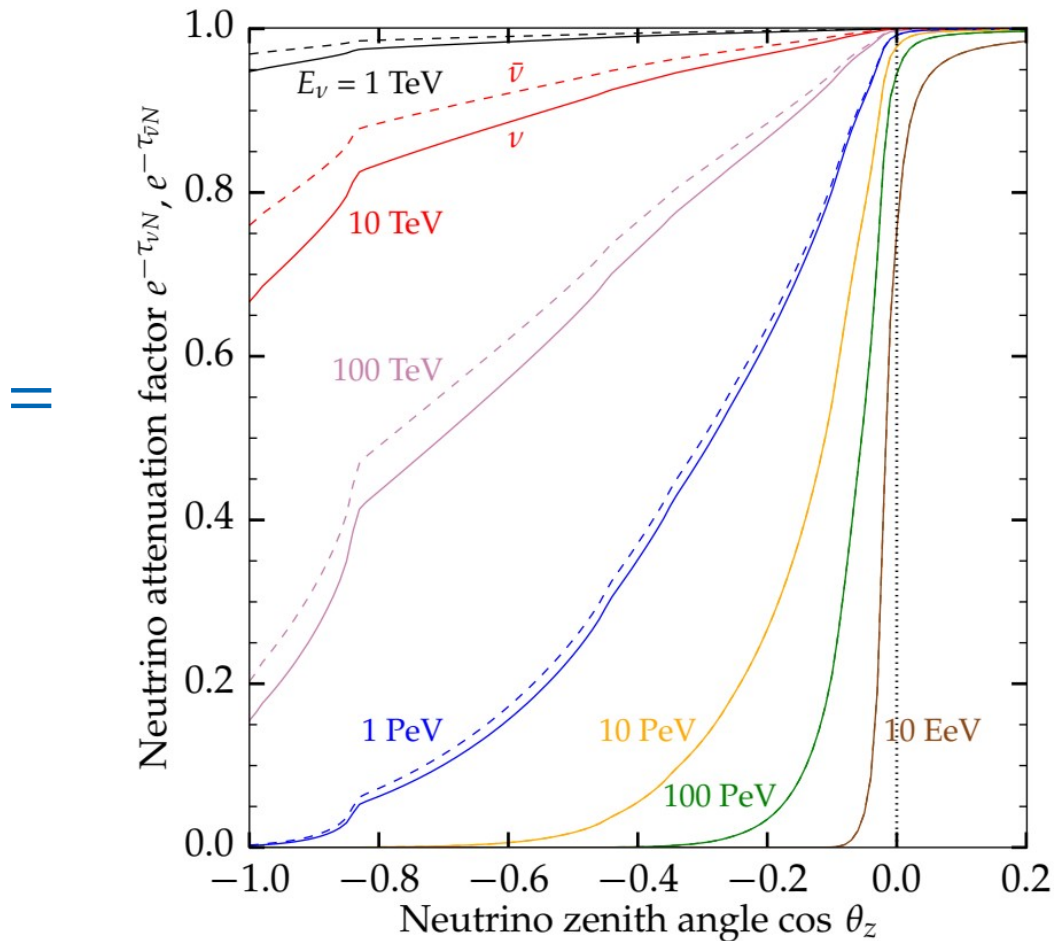


+

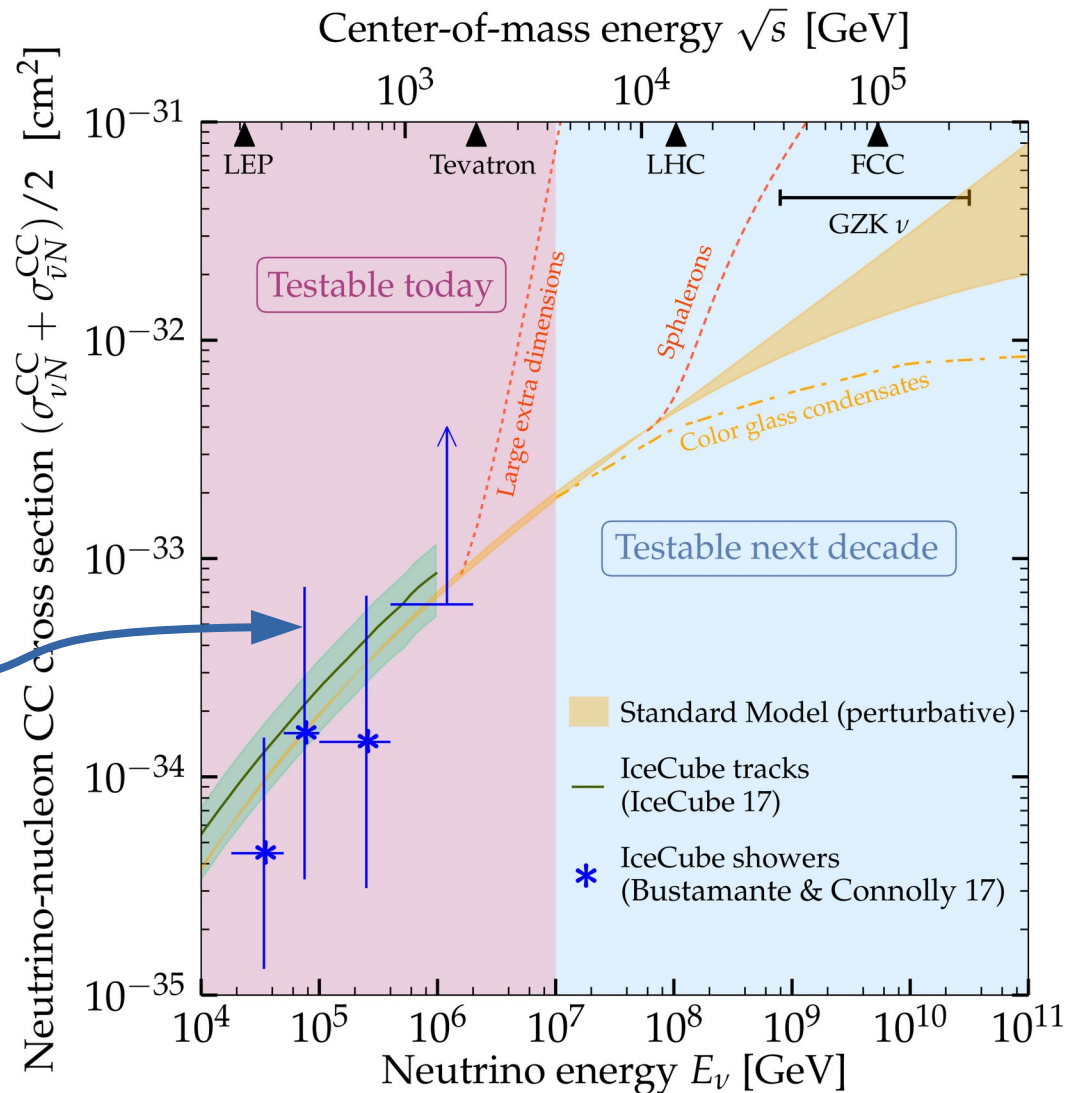
Neutrino-nucleon cross section

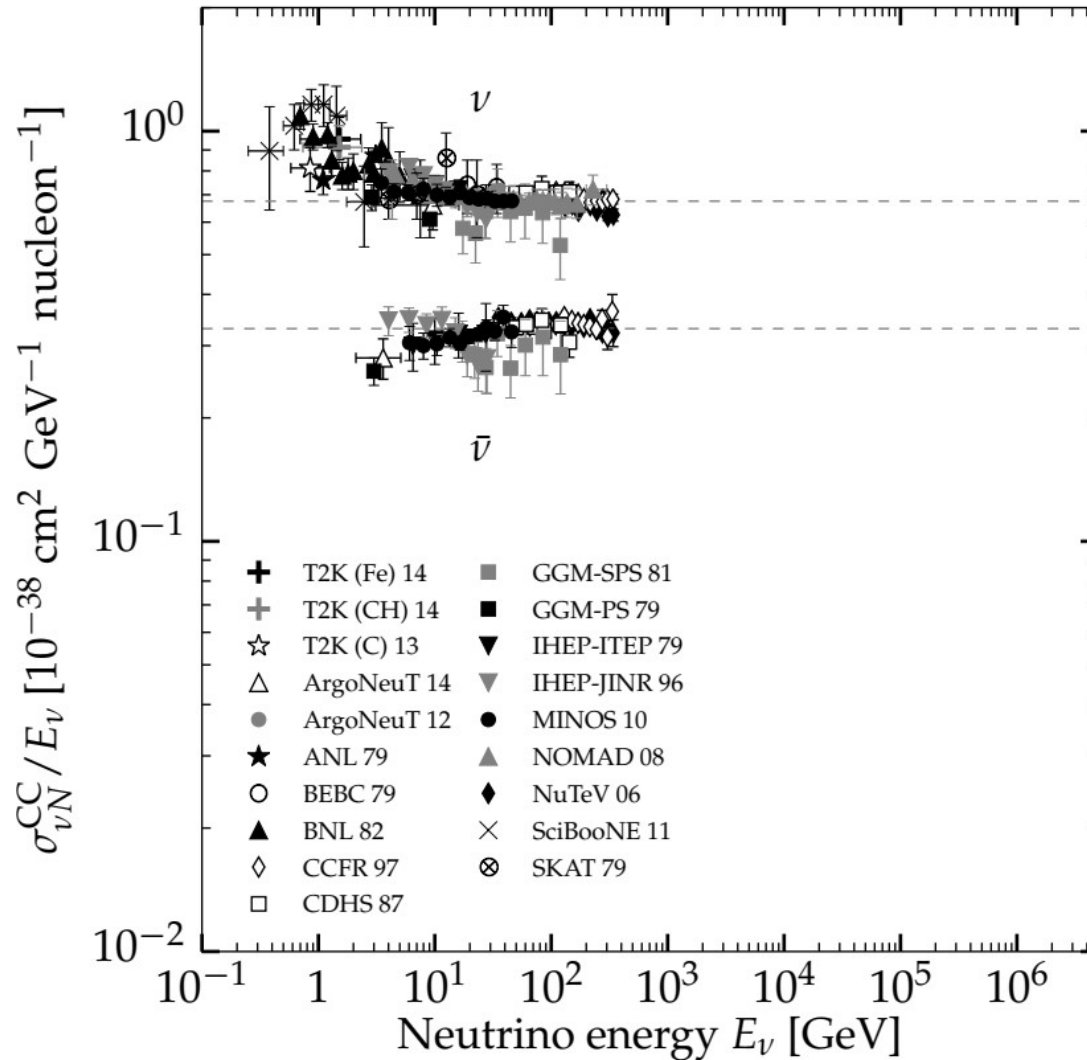


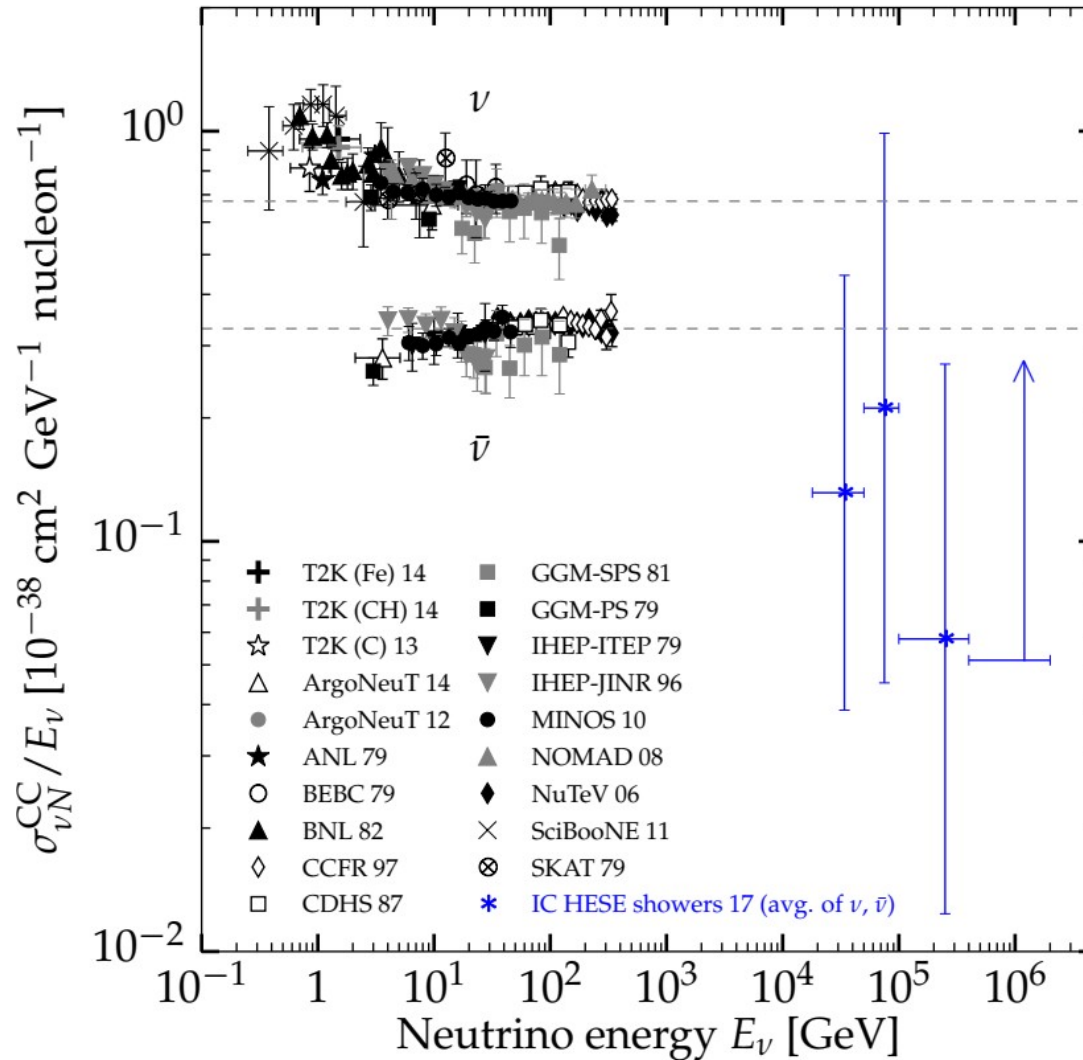
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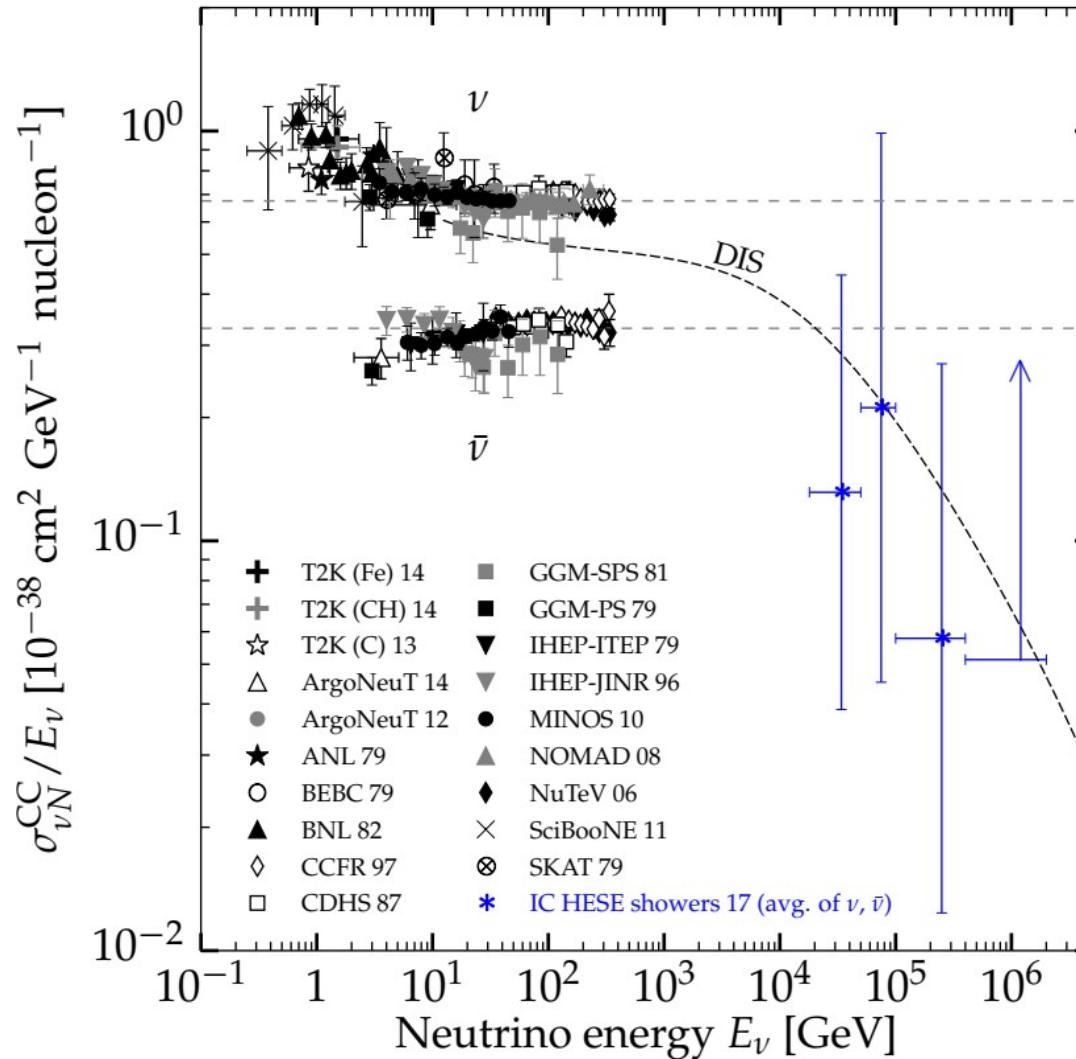


- ▶ Fold in astrophysical unknowns (spectral index, normalization)
- ▶ Compatible with SM predictions
- ▶ Still room for new physics
- ▶ Today, using IceCube:
 - ▶ Extracted from ~60 showers in 6 yr
 - ▶ Limited by statistics
- ▶ Future, using IceCube-Gen2:
 - ▶ $\times 5$ volume $\Rightarrow$ 300 showers in 6 yr
 - ▶ Reduce statistical error by 40%

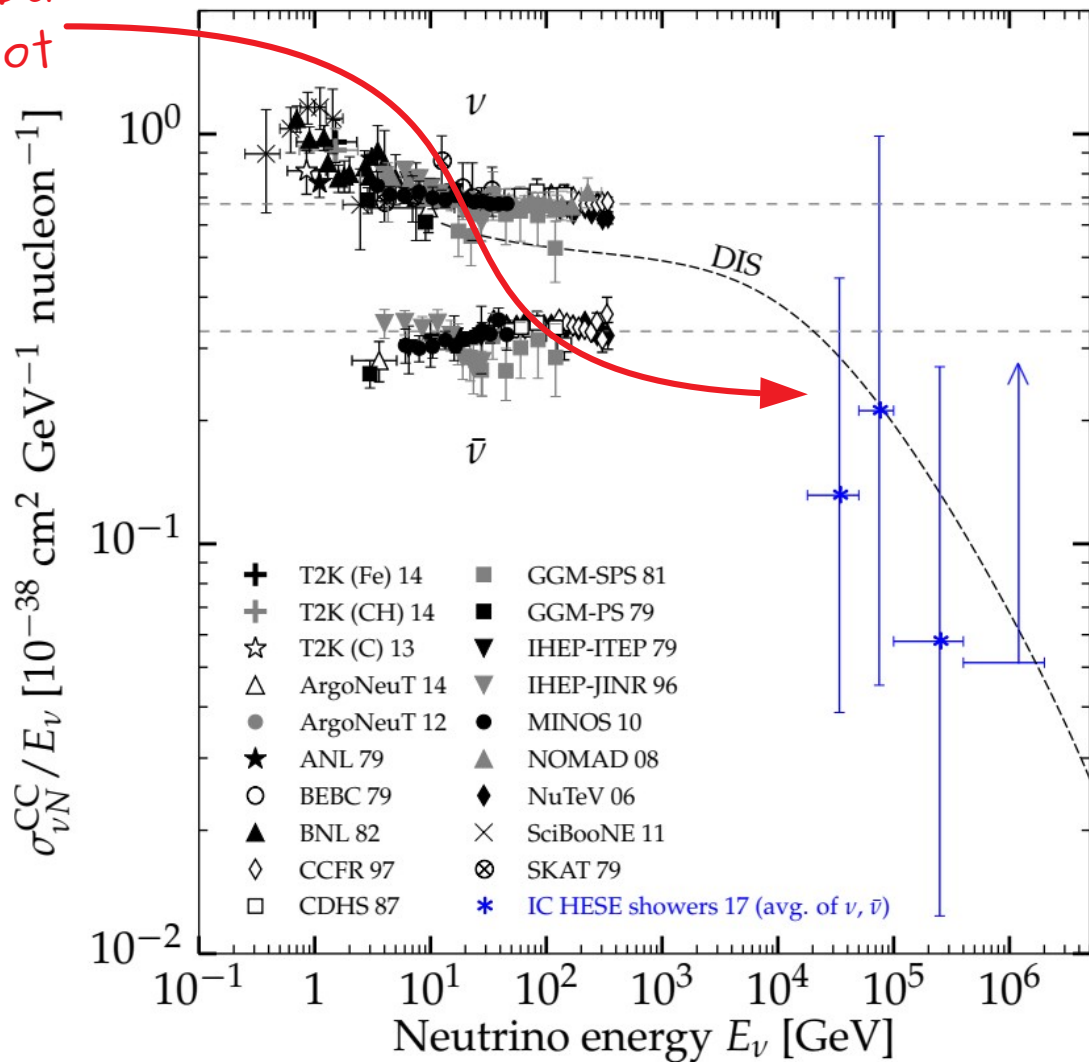








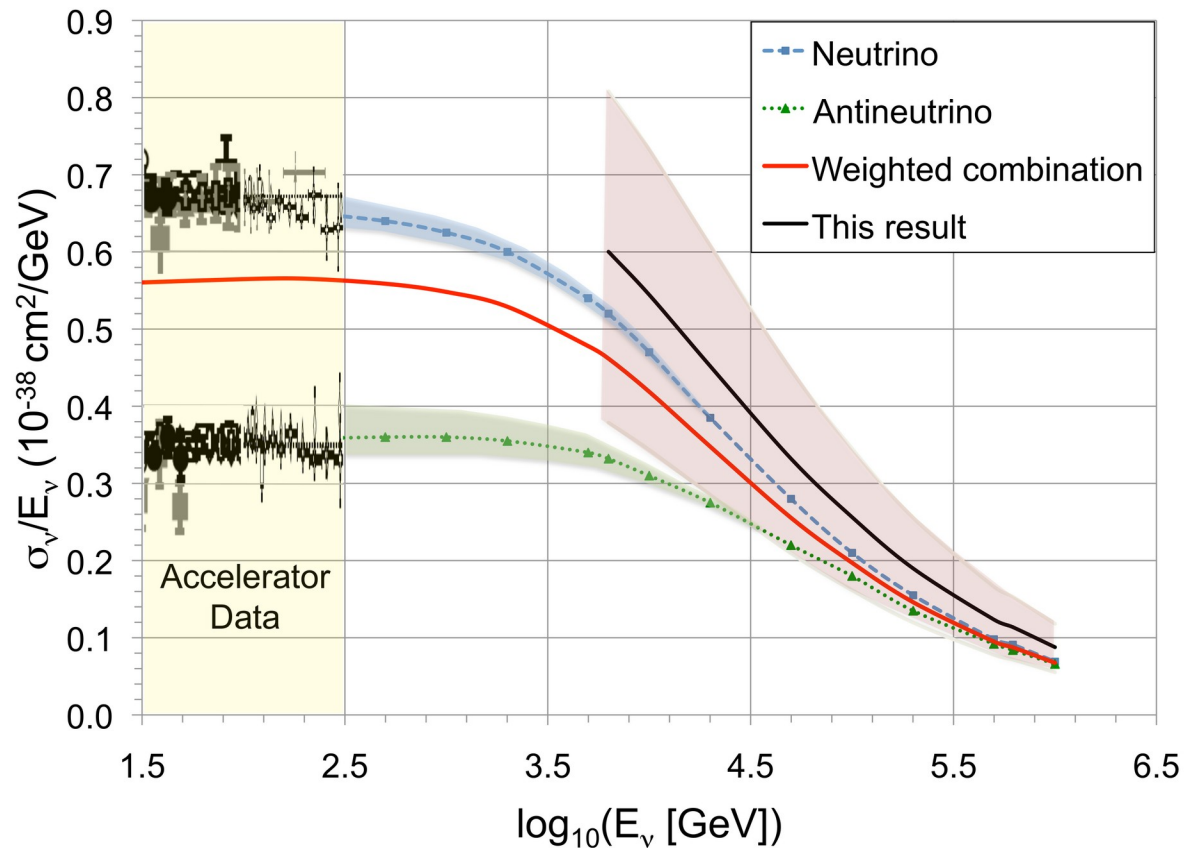
Extending the PDG
cross-section plot



MB & Connolly PRL 2019
See also: IceCube, Nature 2017

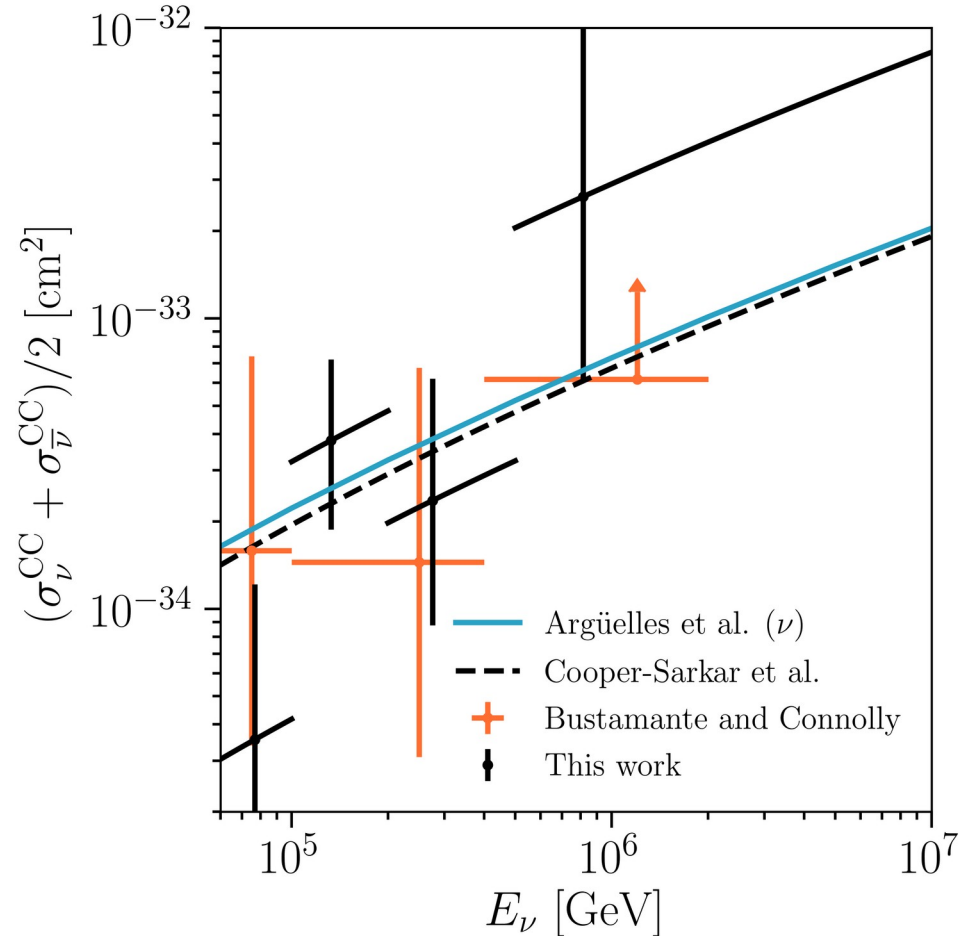
Using through-going muons instead

- ▶ Use $\sim 10^4$ through-going muons
- ▶ Measured: dE_μ/dx
- ▶ Inferred: $E_\mu \approx dE_\mu/dx$
- ▶ From simulations (uncertain):
most likely E_ν given E_μ
- ▶ Fit the ratio $\sigma_{\text{obs}}/\sigma_{\text{SM}}$
 $1.30^{+0.21}_{-0.19}(\text{stat.})^{+0.39}_{-0.43}(\text{syst.})$
- ▶ All events grouped in a single
energy bin 6–980 TeV



Updated cross section measurement

- ▶ Uses 7.5 years of IceCube data
- ▶ Uses starting showers + tracks
 - ▶ Vs. starting showers only in Bustamante & Connolly 2017
 - ▶ Vs. throughgoing muons in IceCube 2017
- ▶ Extends measurement to 10 PeV
- ▶ Still compatible with Standard Model predictions
- ▶ Higher energies? Work in progress by Valera & MB



Bonus: Measuring the inelasticity $\langle y \rangle$

- ▶ Inelasticity in CC ν_μ interaction $\nu_\mu + N \rightarrow \mu + X$:

$$E_X = y E_\nu \quad \text{and} \quad E_\mu = (1-y) E_\nu \Rightarrow y = (1 + E_\mu/E_X)^{-1}$$

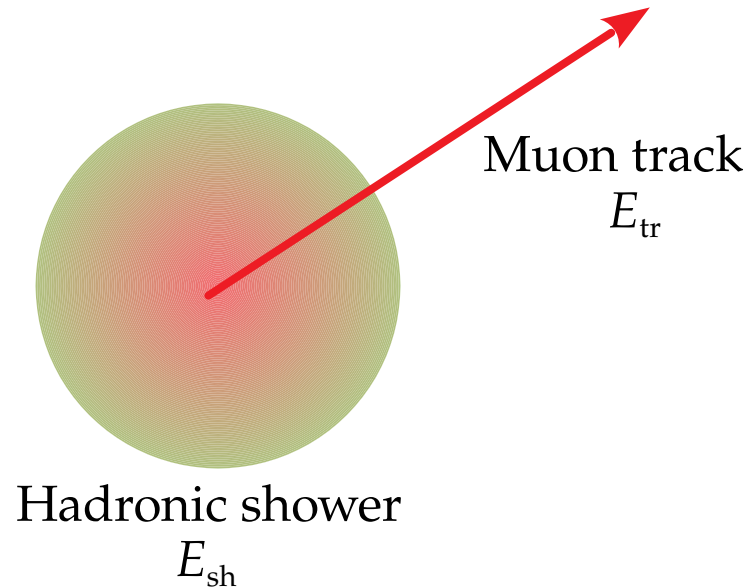
- ▶ The value of y follows a distribution $d\sigma/dy$

- ▶ In a HESE starting track:

$$\left. \begin{array}{l} E_X = E_{\text{sh}} \text{ (energy of shower)} \\ E_\mu = E_{\text{tr}} \text{ (energy of track)} \end{array} \right\} y = (1 + E_{\text{tr}}/E_{\text{sh}})^{-1}$$

- ▶ New IceCube analysis:

- ▶ 5 years of starting-track data (2650 tracks)
- ▶ Machine learning separates shower from track
- ▶ Different y distributions for ν and $\bar{\nu}$



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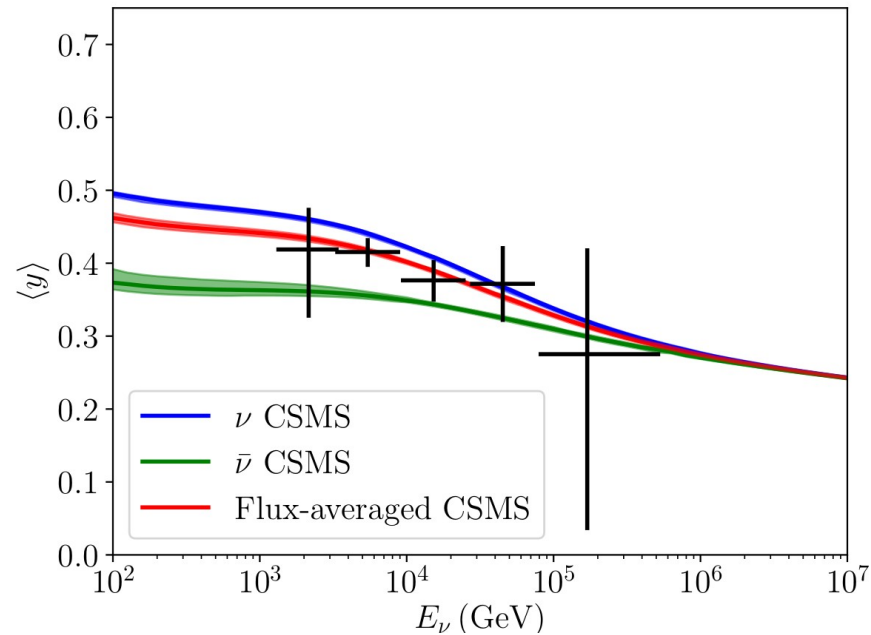
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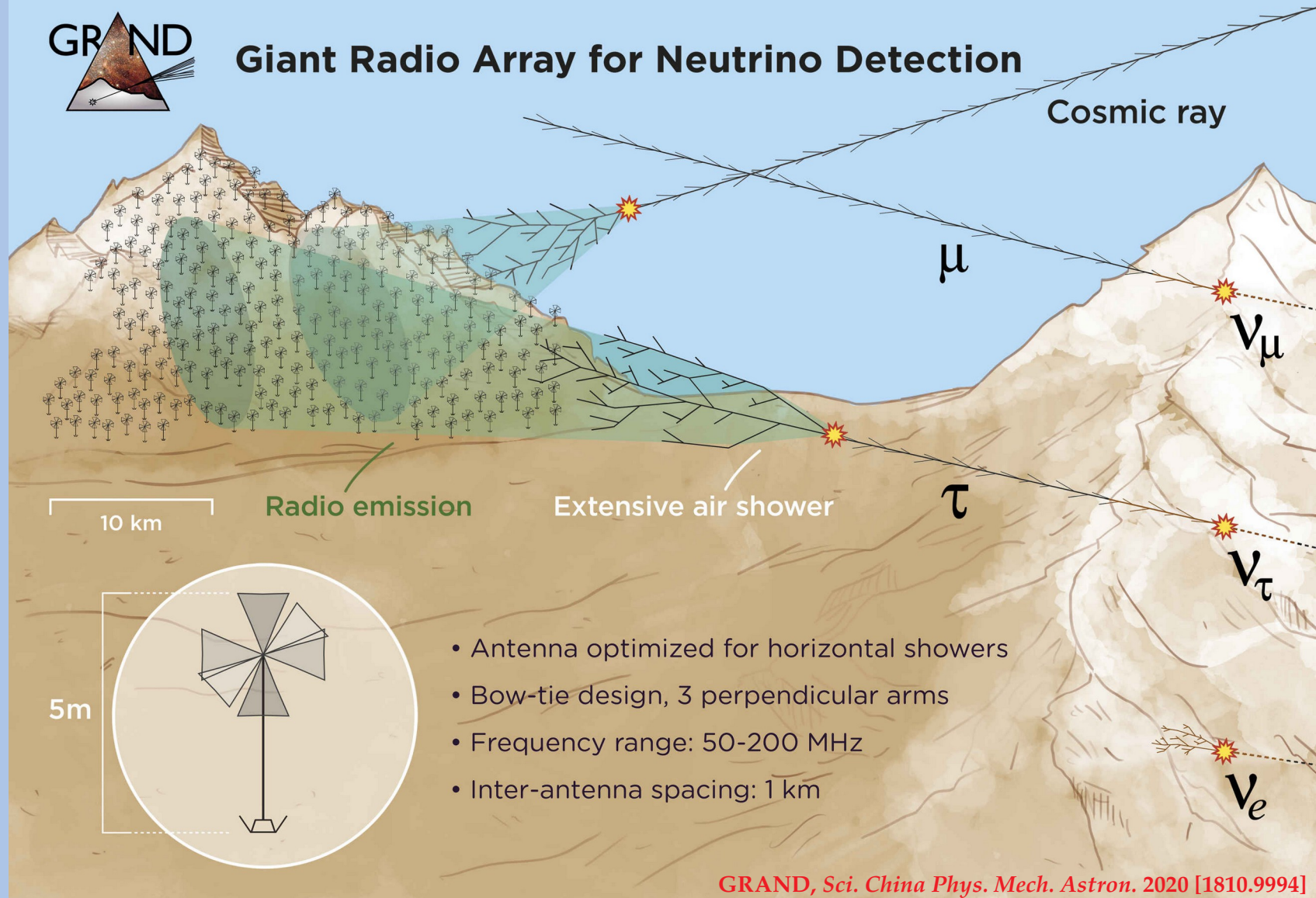
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IceCube, PRD 2019

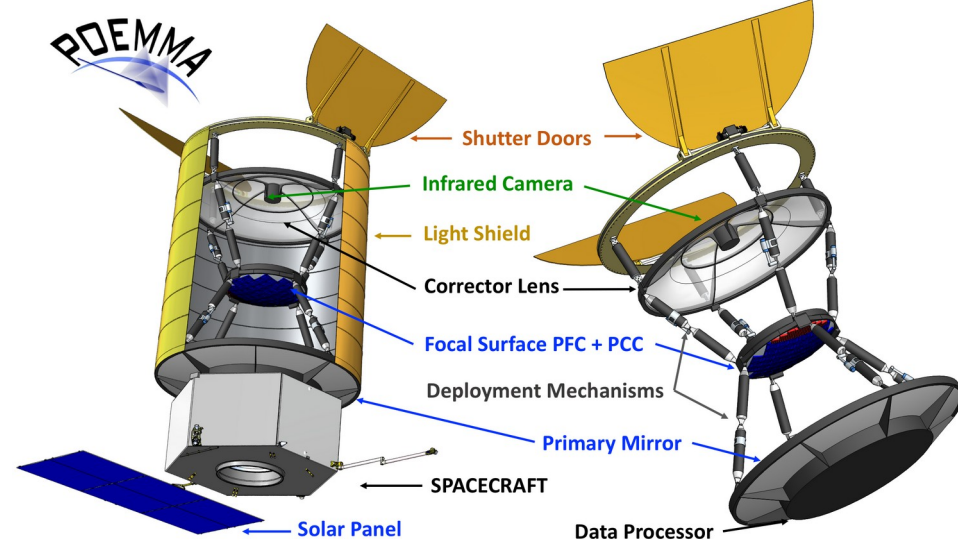


Giant Radio Array for Neutrino Detection



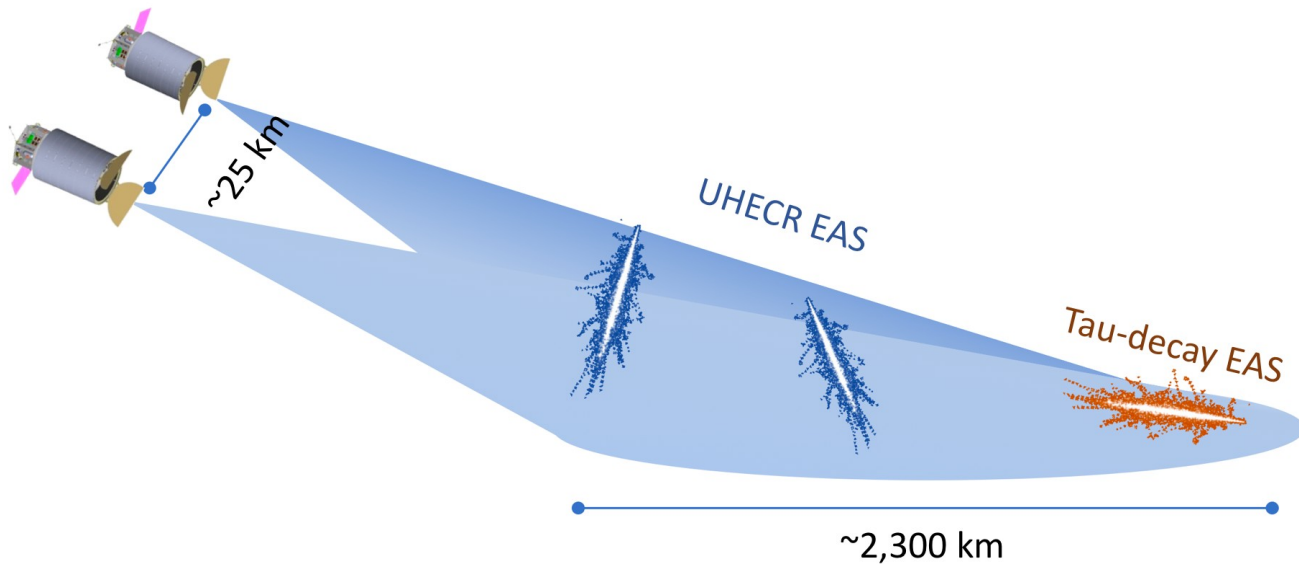
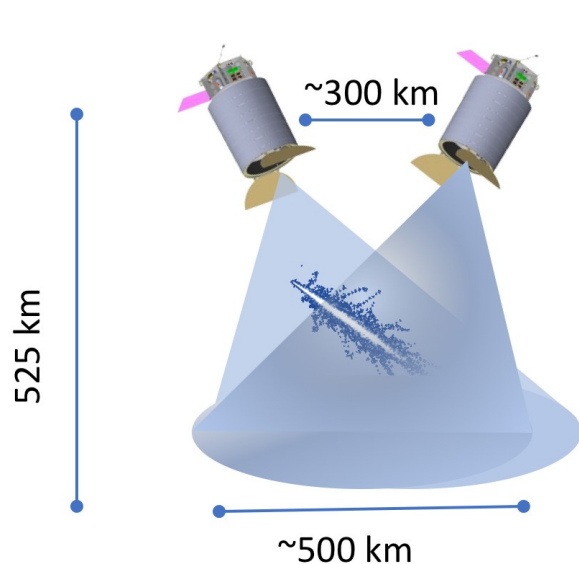
POEMMA: Probe of Extreme Multi-Messenger Astrophysics

POEMMA, JCAP 2021 (1012.07945)



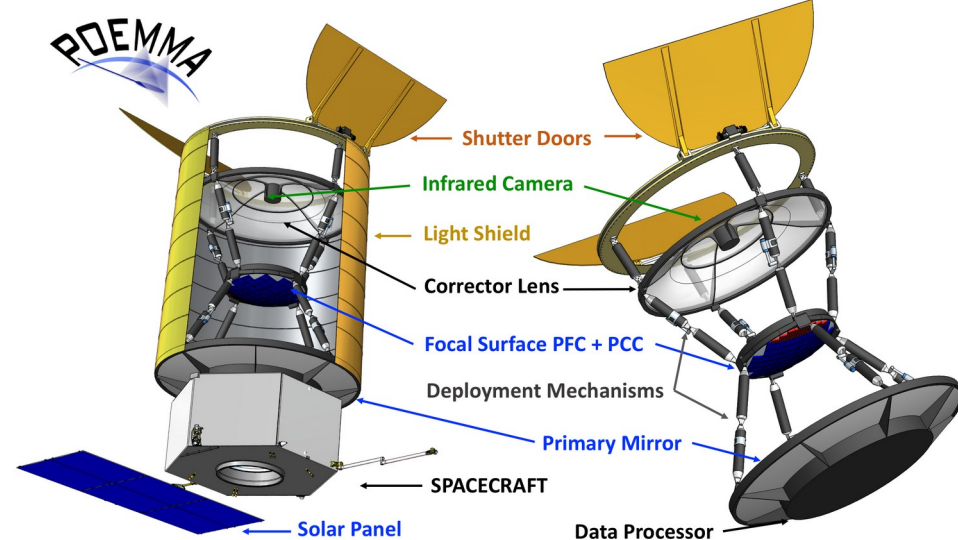
POEMMA=Limb

POEMMA=Stereo

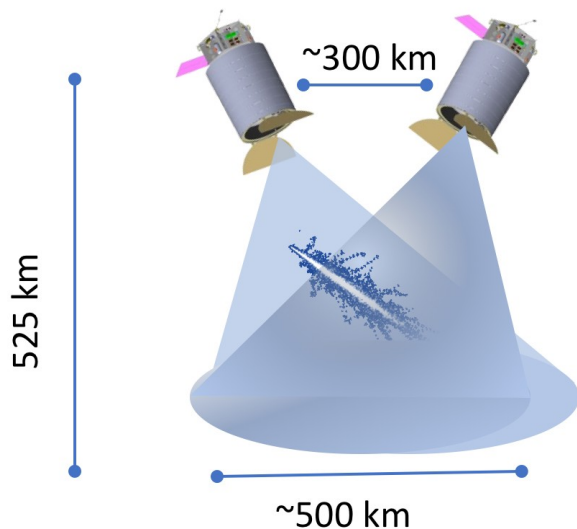


POEMMA: Probe of Extreme Multi-Messenger Astrophysics

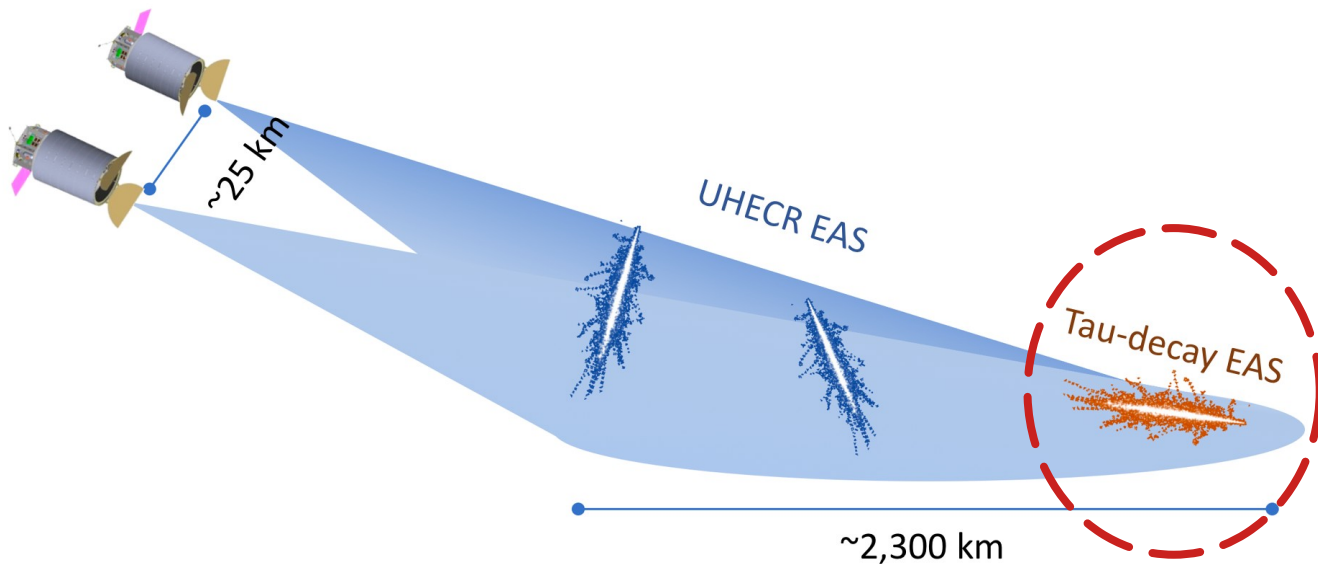
POEMMA, *JCAP* 2021 (2012.07945)



POEMMA-Stereo

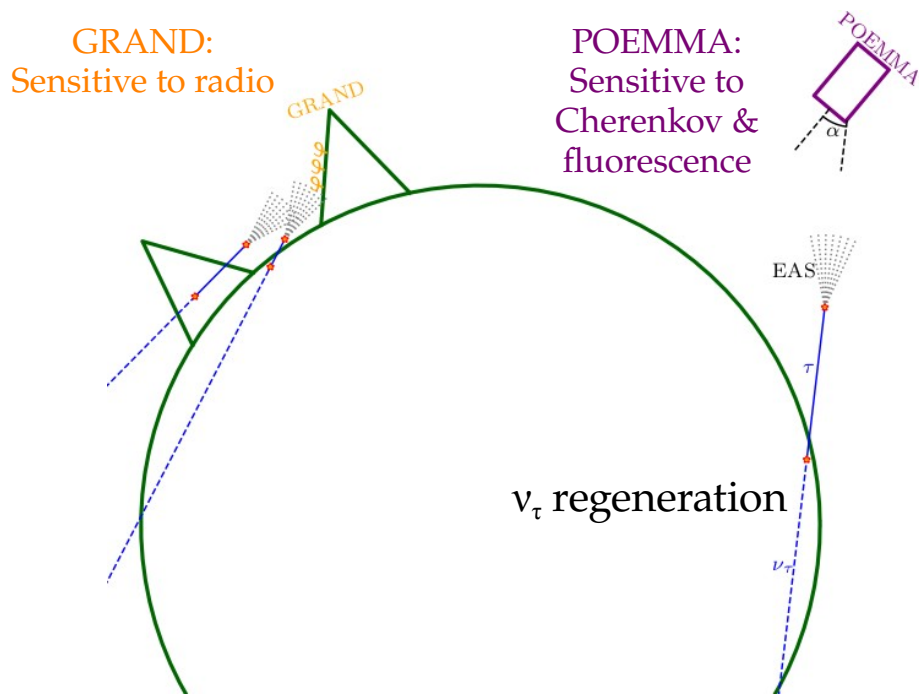


POEMMA-Limb

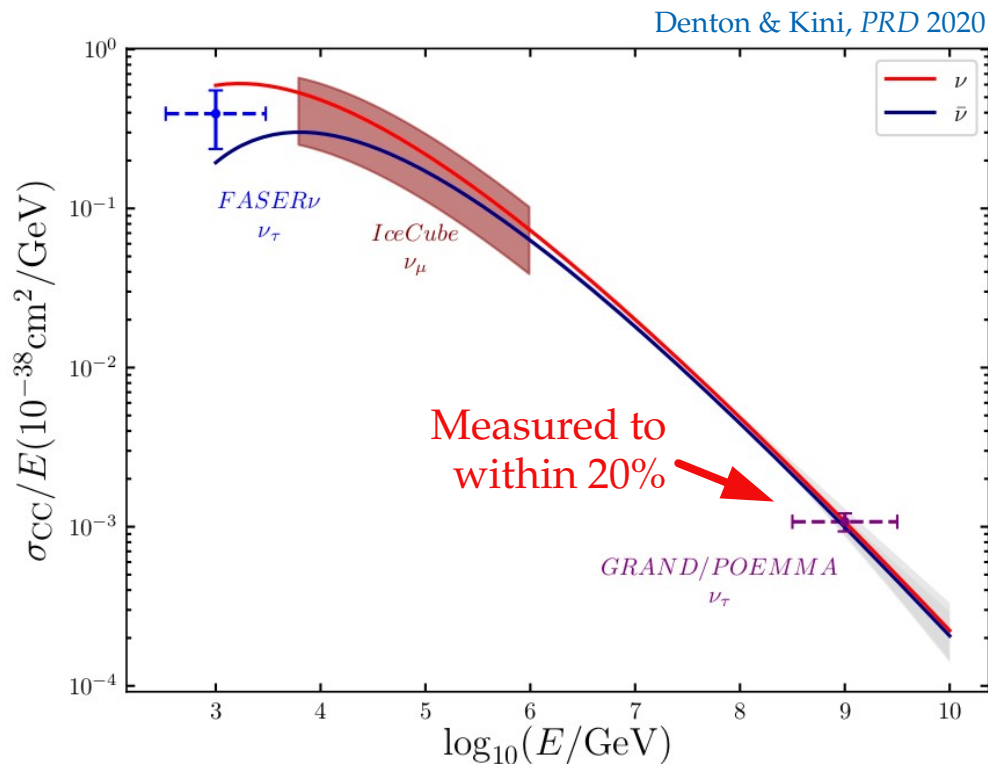


GRAND & POEMMA

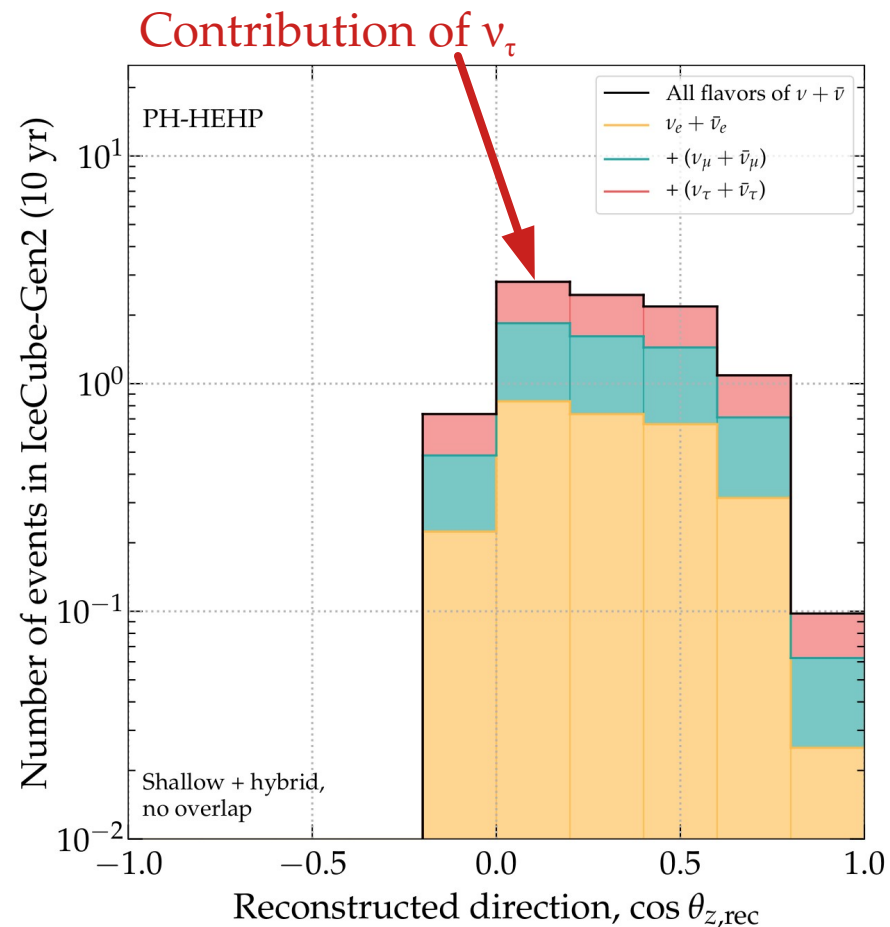
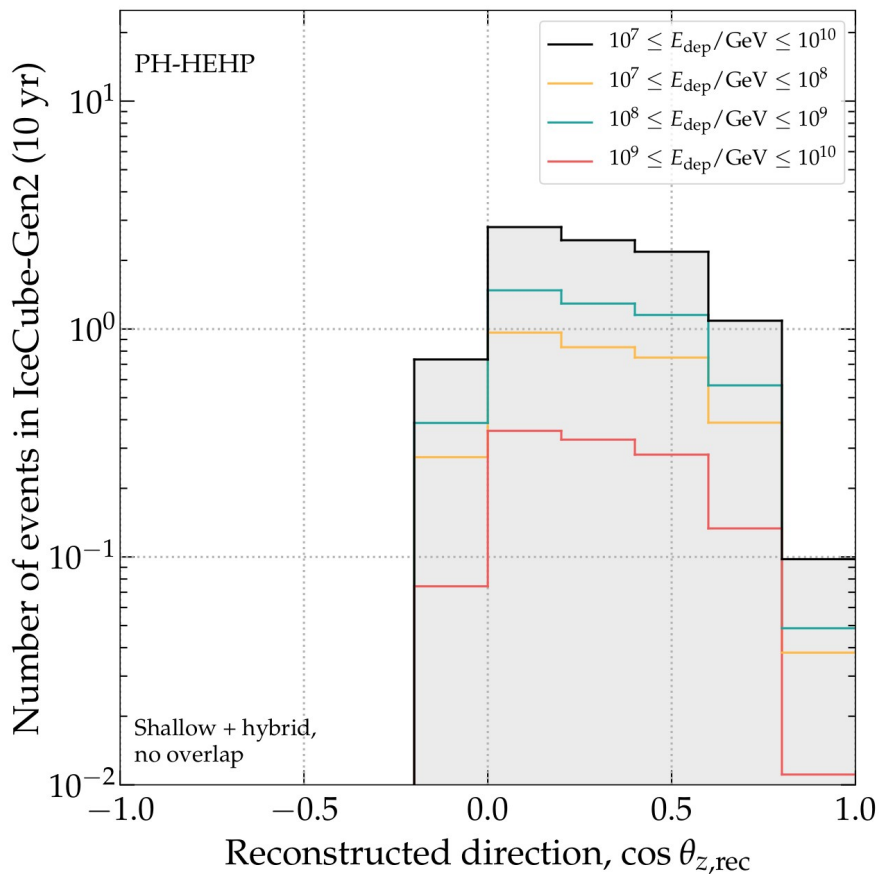
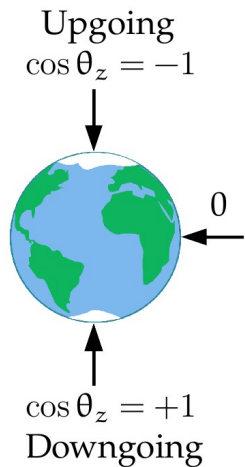
Both sensitive to extensive air showers induced by Earth-skimming UHE ν_τ



If they see 100 events from ν_τ with initial energy of 10^9 GeV (pre-attenuation):



IceCube-Gen2 Radio



Angular resolution in $\theta_{z,\text{rec}}$: 2°
Energy resolution in $\log_{10}(E_{\text{dep}}/\text{GeV})$: 0.1

Example 2:
Secret neutrino interactions

ν SI with the UHE diffuse flux

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

Coupling matrix:

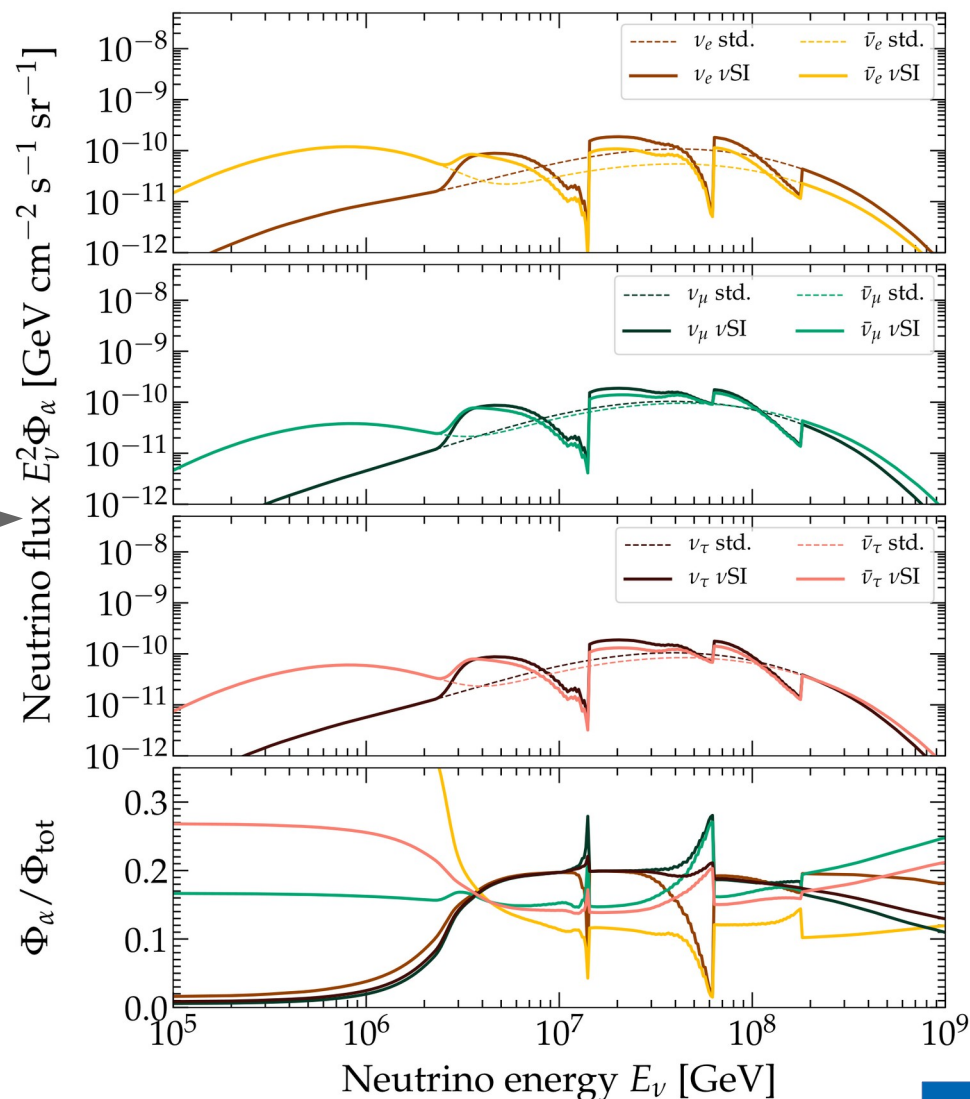
$$\mathbf{G} \equiv \begin{pmatrix} g_{ee} & g_{e\mu} & g_{e\tau} \\ g_{e\mu} & g_{\mu\mu} & g_{\mu\tau} \\ g_{e\tau} & g_{\mu\tau} & g_{\tau\tau} \end{pmatrix}$$

Different flavors can have different couplings

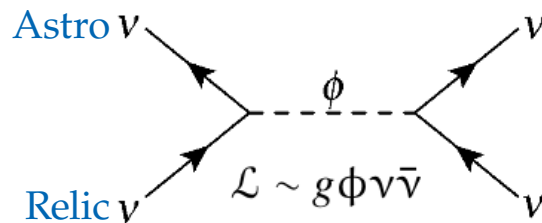
ν SI dips and bumps in the diffuse UHE ν flux:

- ▶ In the cosmogenic flux
- ▶ In the flux from sources

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



ν SI with the UHE transient flux



If this happens repeatedly, high-energy neutrinos disappear

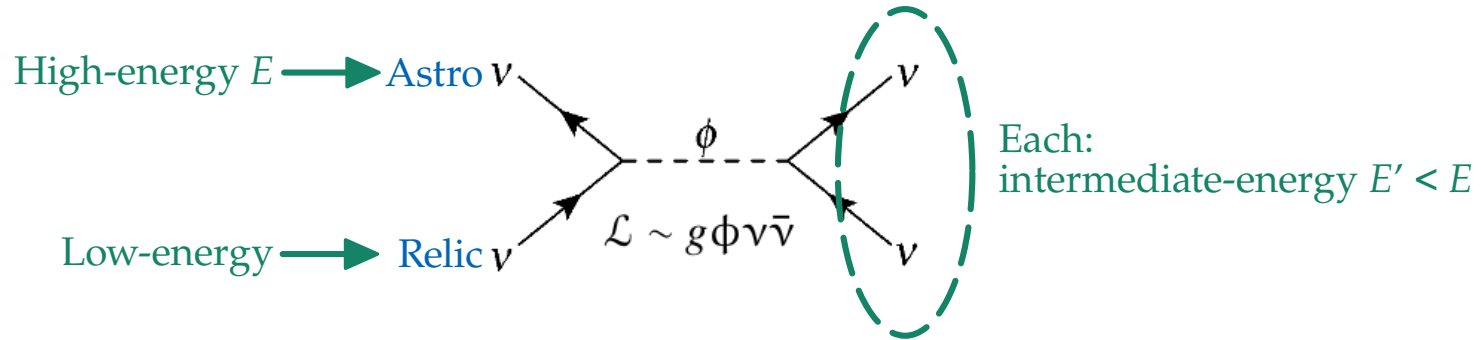
So, if we see high-energy neutrinos, we can set an upper limit on the ν SI strength

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

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

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

ν SI with the UHE transient flux



If this happens repeatedly, high-energy neutrinos disappear

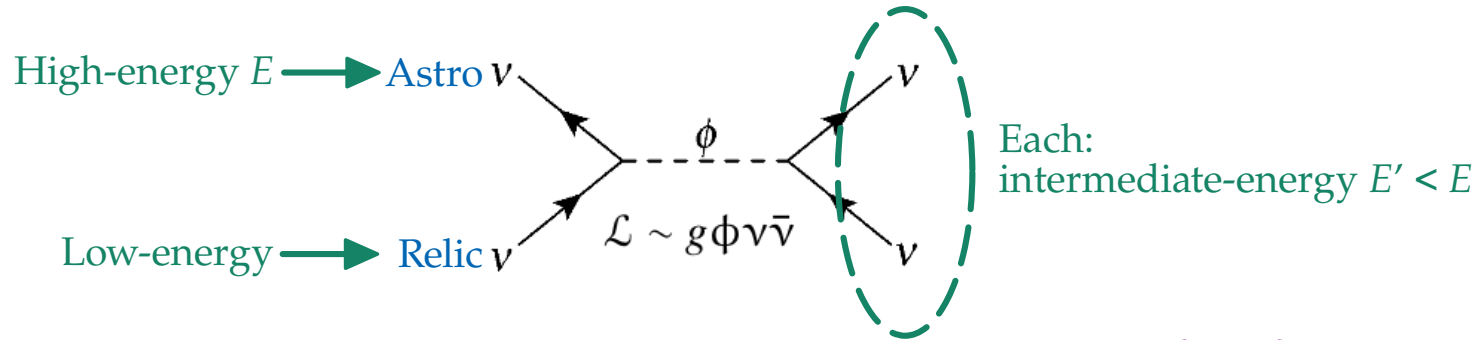
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ν SI with the UHE transient flux



Perfect for POEMMA!

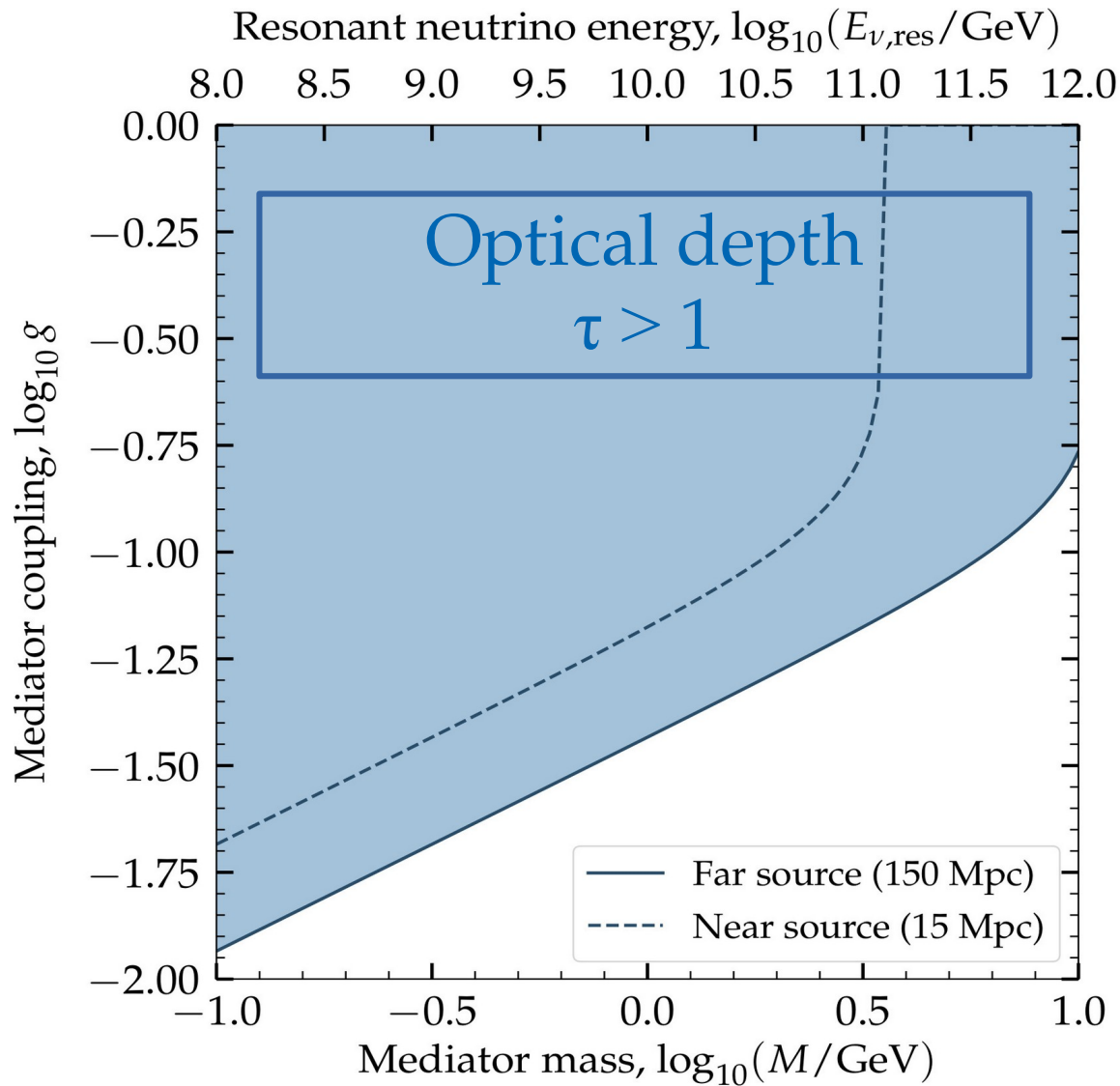
If this happens repeatedly, high-energy neutrinos disappear

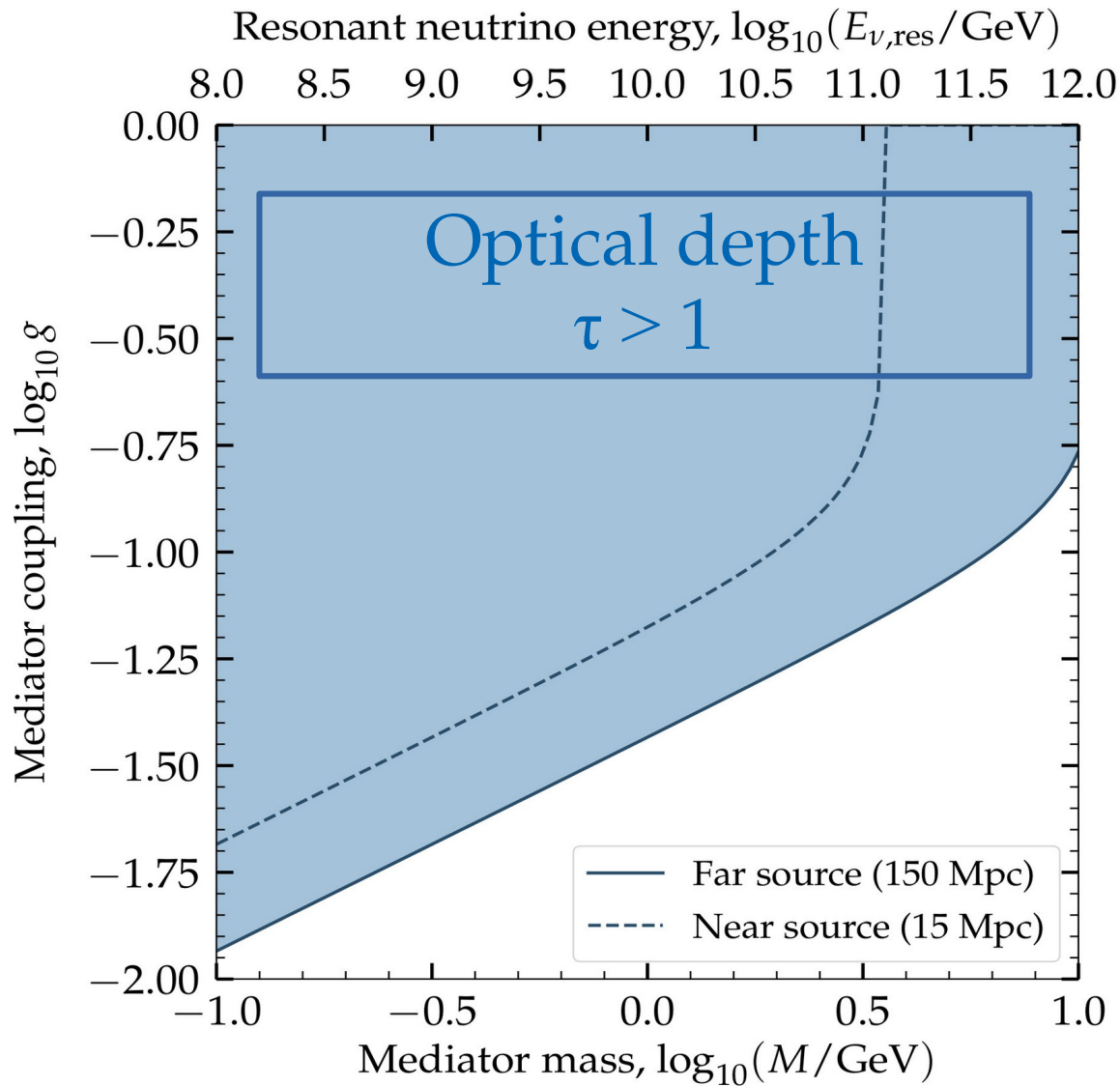
So, if we see high-energy neutrinos, we can set an upper limit on the ν SI strength

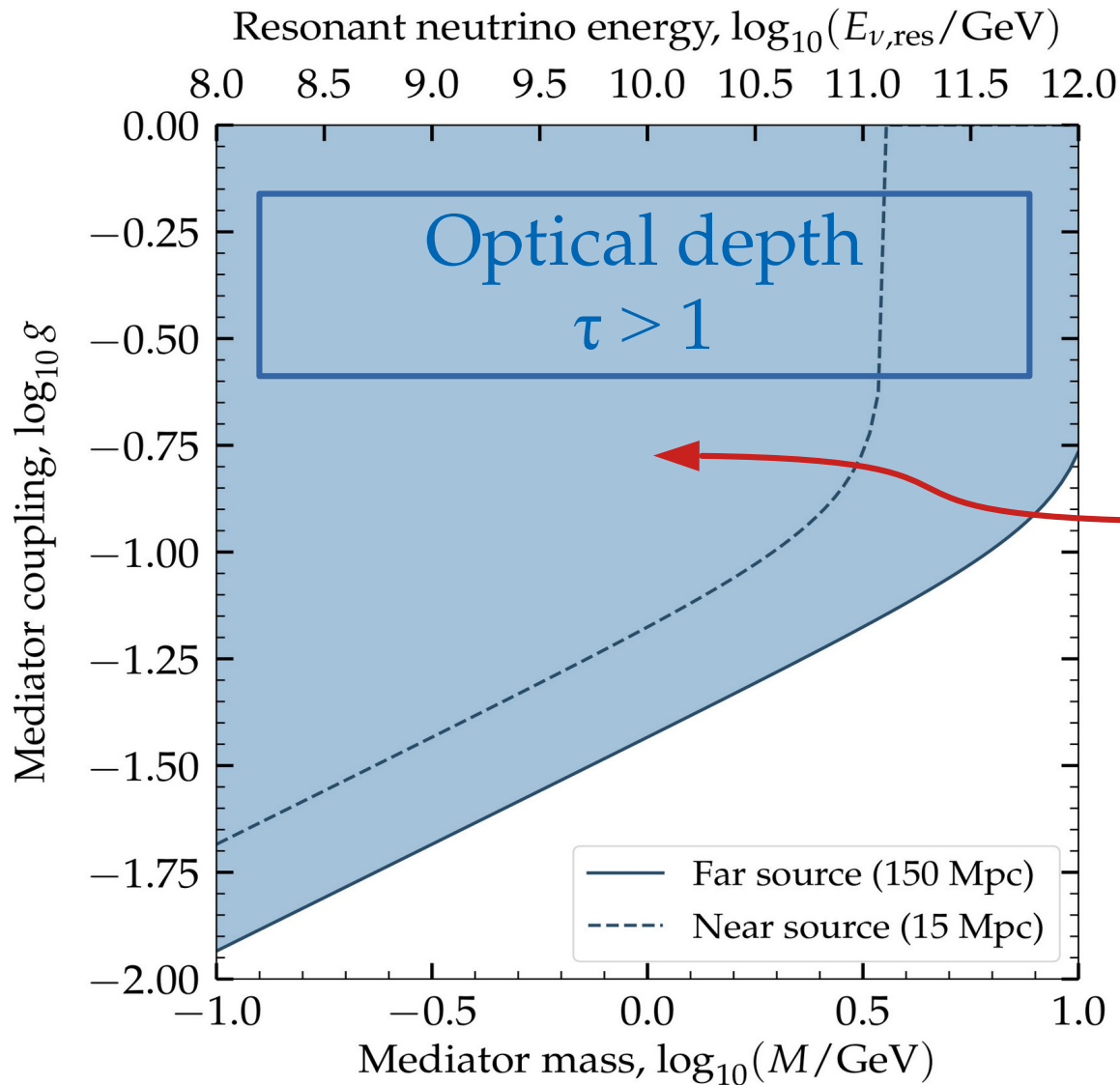
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Estimated optical depth if emitted by a source at a distance L : $\tau(E) = \frac{l_{\text{int}}(E)}{L}$







If POEMMA
sees UHE ν from
a flare, we can
kill part of this
parameter space

Example 4:
Neutrino decay

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: $\nu_i \rightarrow \nu_j + \phi$
- ▶ ϕ : Nambu-Goldstone boson of a broken symmetry (e.g., Majoron)
- ▶ We work in a model-independent way:
the nature of ϕ is unimportant if it is invisible to neutrino detectors

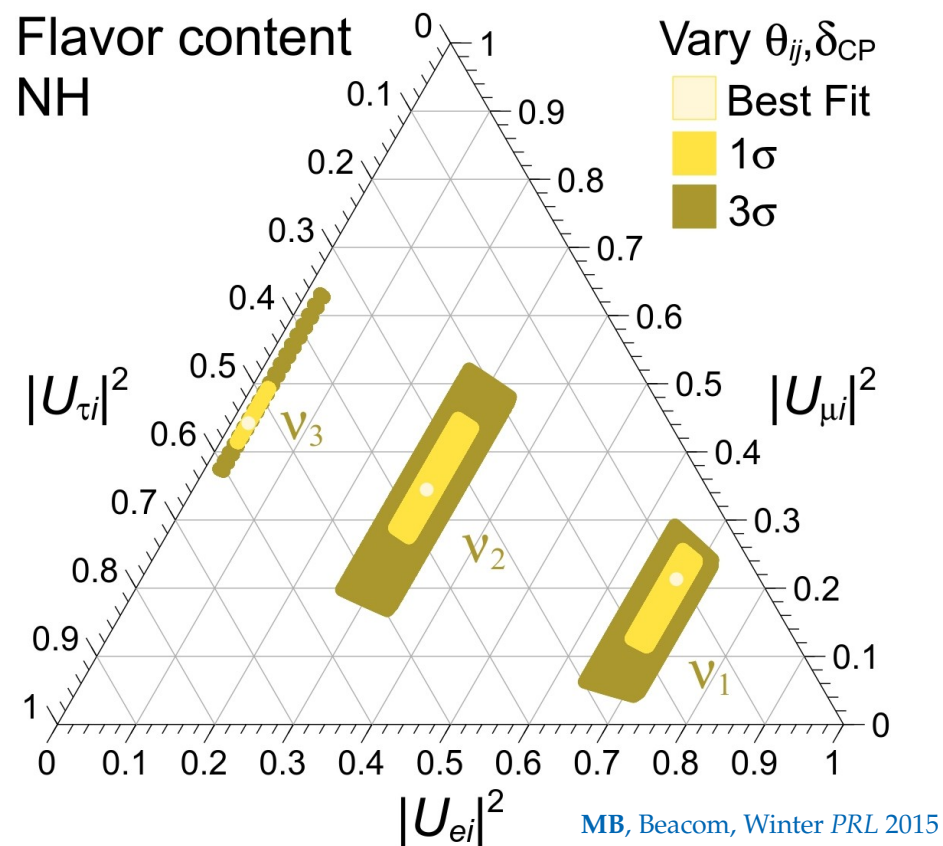
Flavor content of neutrino mass eigenstates

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

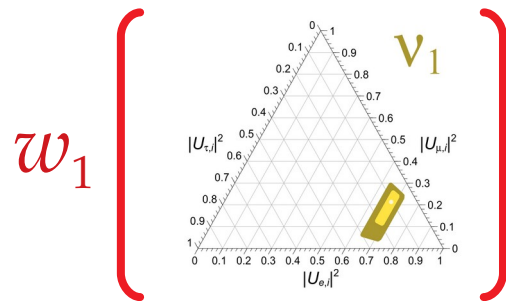
Known to within 2%

Known to within 8%

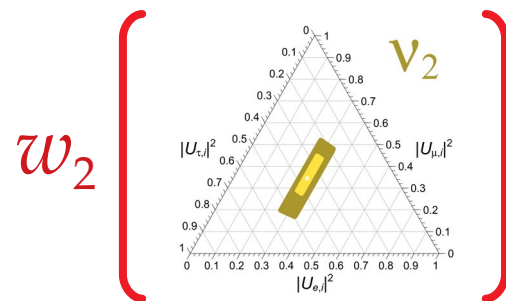
Known to within 20% (or worse)



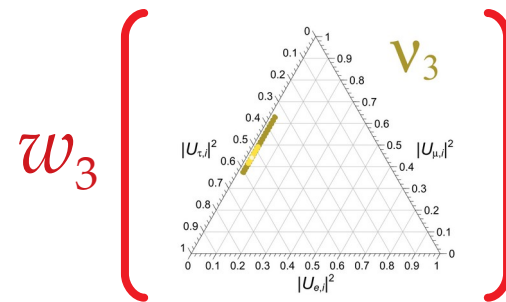
Neutrinos propagate as an incoherent mix of ν_1, ν_2, ν_3 —



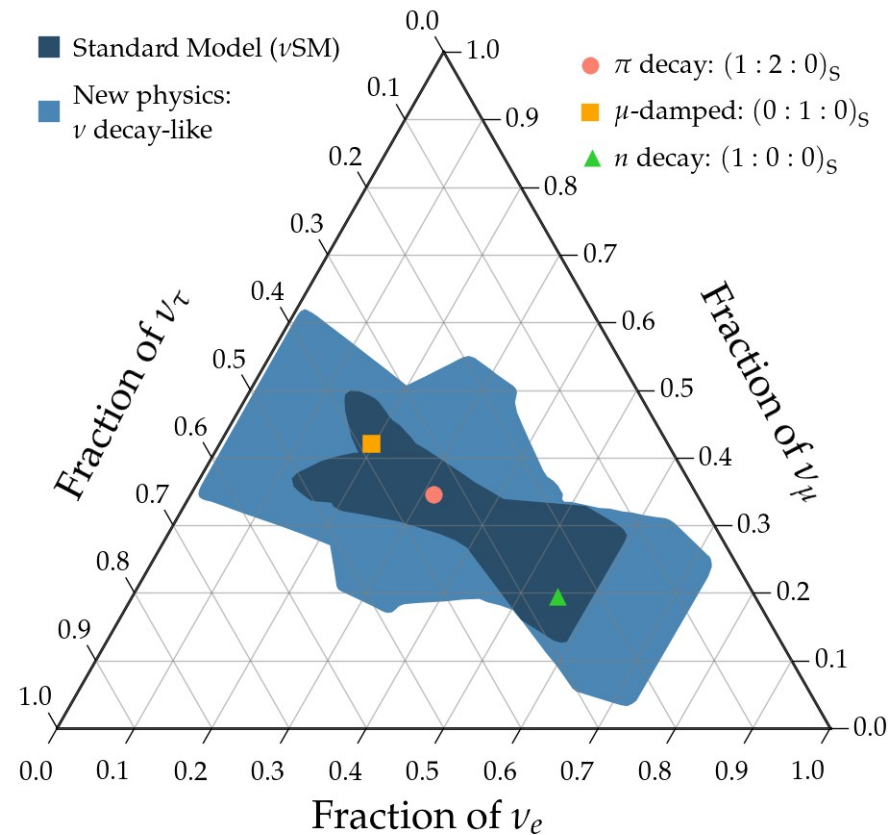
+



+



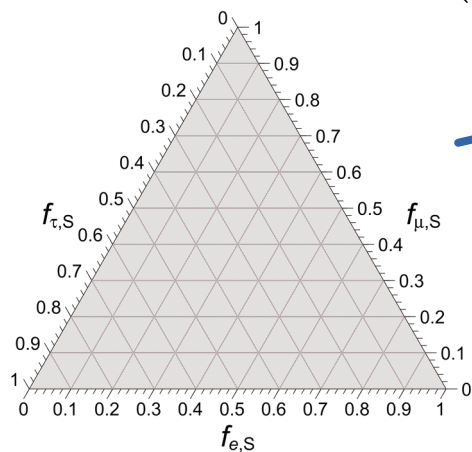
Varying all possible combinations of weights w_i and mixing parameters



Complete decay selects particular weights ►
with striking consequences for flavor

Measuring the neutrino lifetime

Sources

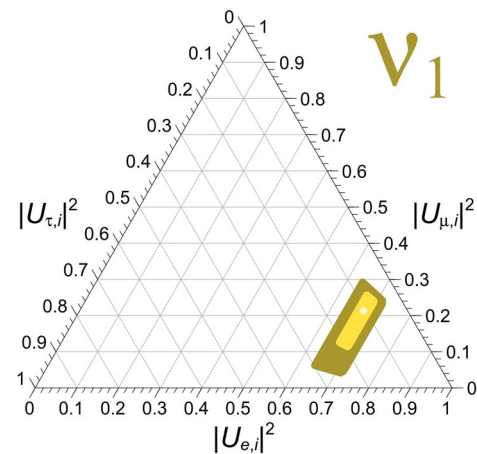


$\underbrace{\nu_{2'}, \nu_3 \rightarrow \nu_1}_{\nu_1 \text{ lightest and stable (normal mass ordering)}}$

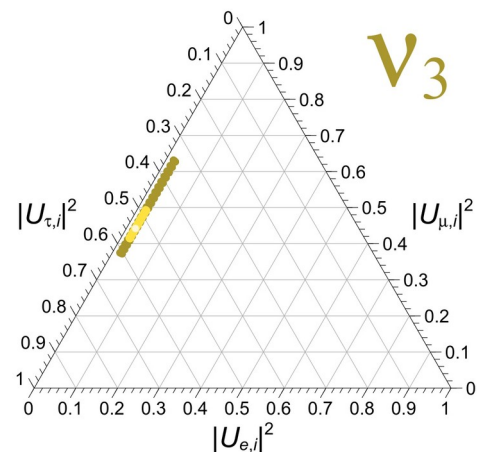
If all unstable neutrinos decay

$\underbrace{\nu_{1'}, \nu_2 \rightarrow \nu_3}_{\nu_3 \text{ lightest and stable (inverted mass ordering)}}$

Earth



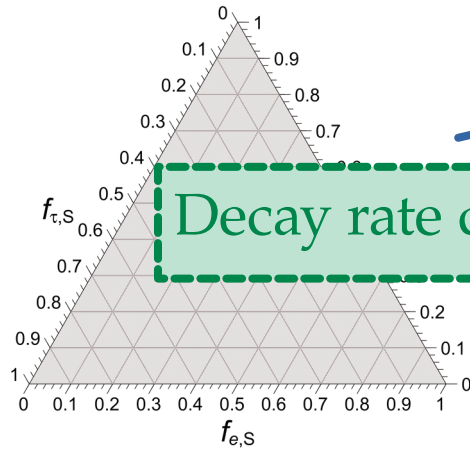
$$f_{\alpha,\oplus} = |U_{\alpha 1}|^2 \quad (w_1 \sim 1; w_2, w_3 \sim 0)$$



$$f_{\alpha,\oplus} = |U_{\alpha 3}|^2 \quad (w_3 \sim 1; w_1, w_2 \sim 0)$$

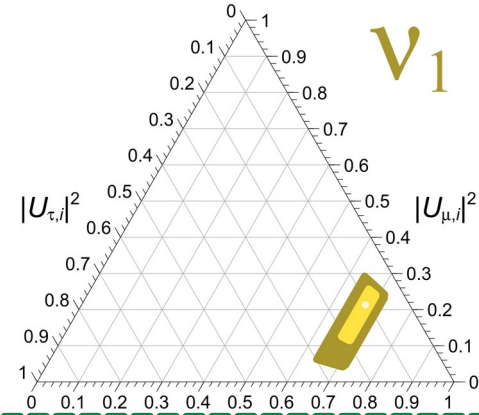
Measuring the neutrino lifetime

Sources



$\nu_{2'}, \nu_3 \rightarrow \nu_1$
 ν_1 lightest and stable
 (normal mass ordering)

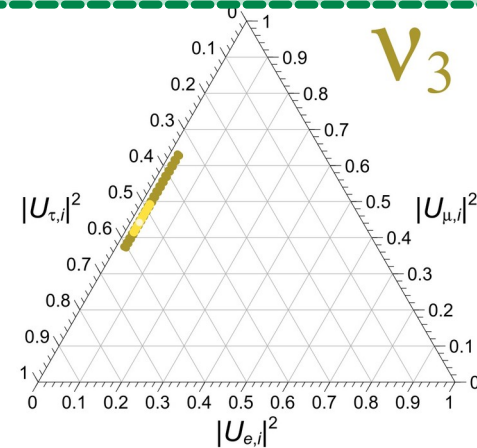
Earth



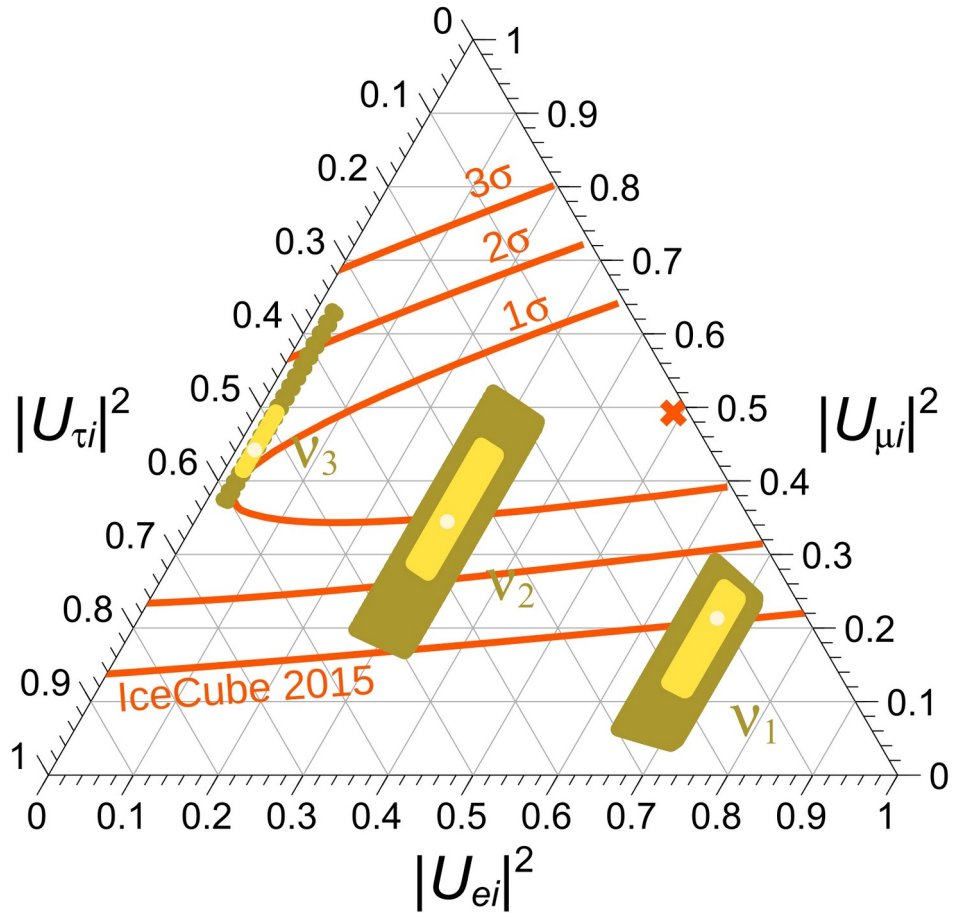
$$f_{\alpha,\oplus} = |U_{\alpha 1}|^2 \quad (w_1 \sim 1; w_2, w_3 \sim 0)$$

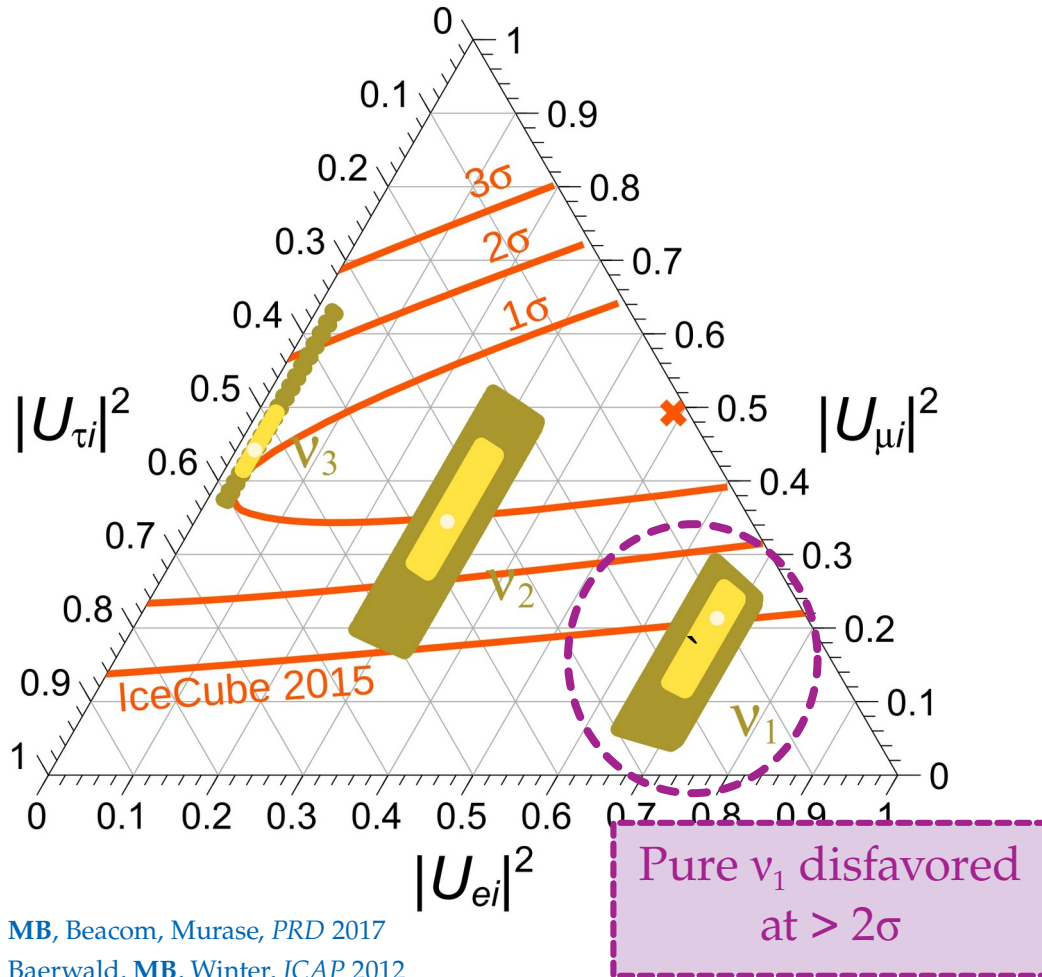
Decay rate depends on $\exp[-t / (\gamma \tau_i)] = \exp[-(L/E) \cdot (m_i/\tau_i)]$

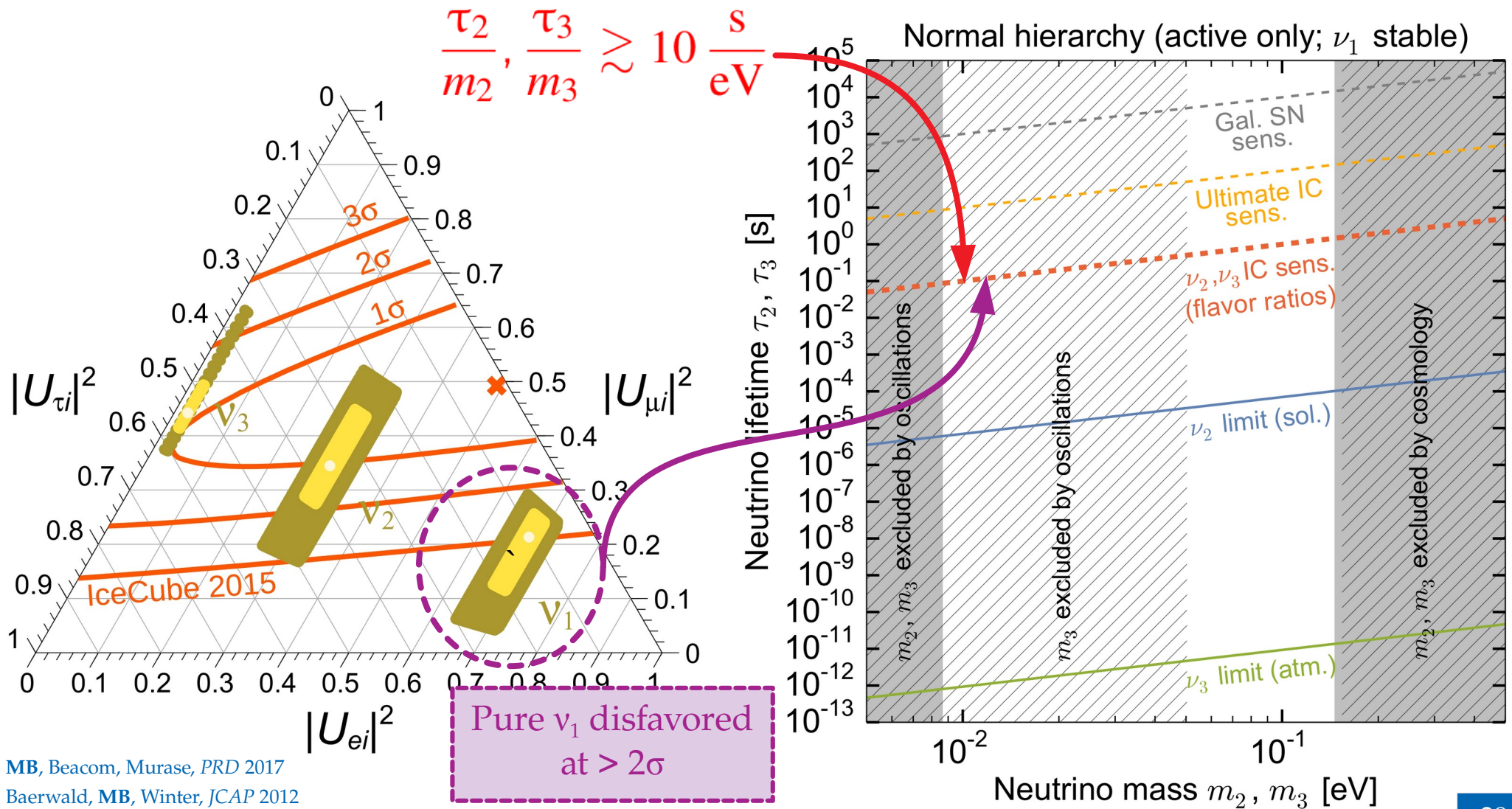
$\nu_{1'}, \nu_2 \rightarrow \nu_3$
 ν_3 lightest and stable
 (inverted mass ordering)



$$f_{\alpha,\oplus} = |U_{\alpha 3}|^2 \quad (w_3 \sim 1; w_1, w_2 \sim 0)$$

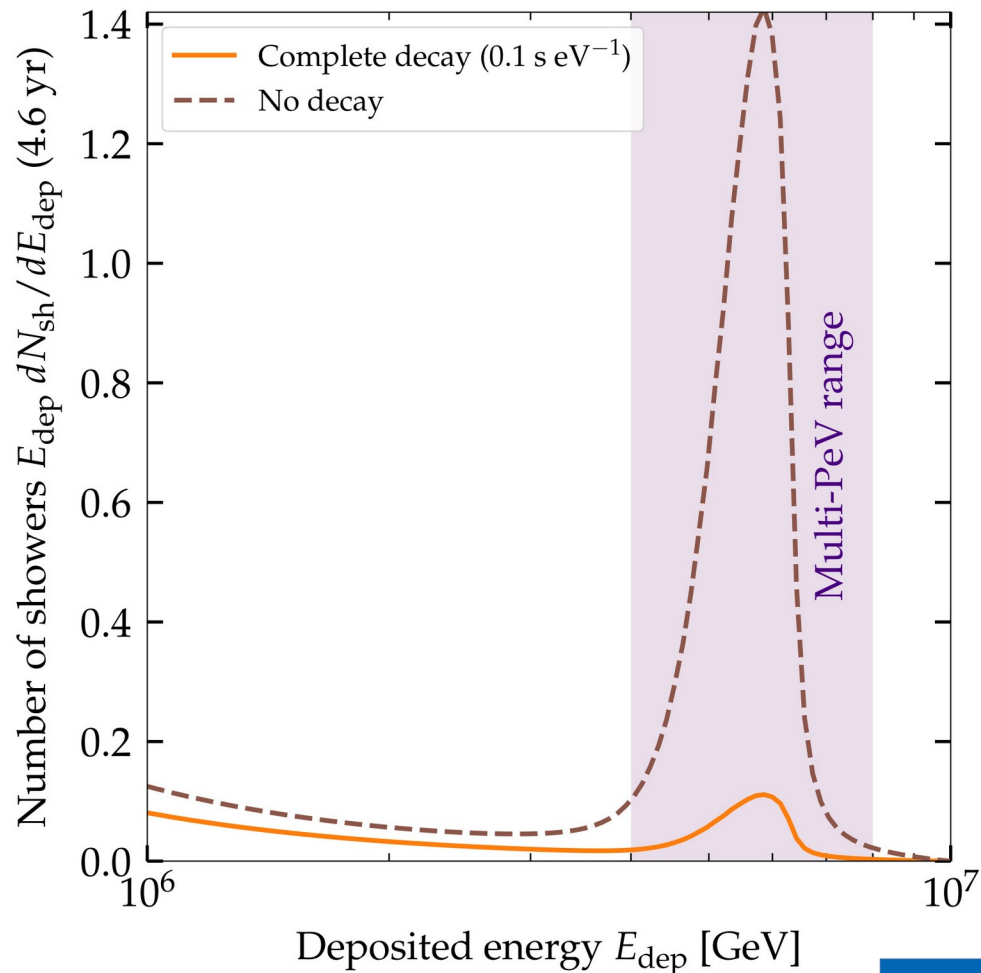






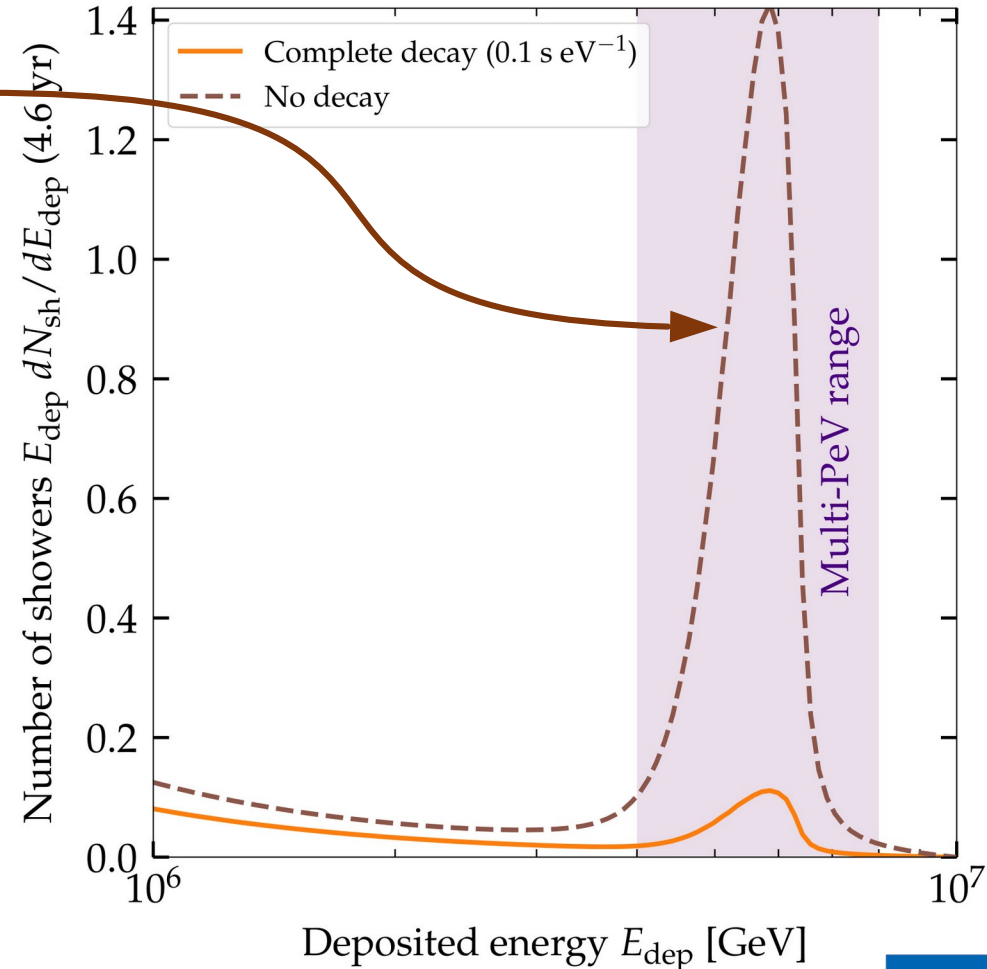
Using the Glashow resonance to test decay

- ▶ At 6.3 PeV, the Glashow resonance ($\bar{\nu}_e + e \rightarrow W$) should trigger showers in IceCube
- ▶ ... unless ν_1, ν_2 decay to ν_3 en route to Earth (the surviving ν_3 have little electron content)
- ▶ IceCube has seen 1 shower in the 4–8 PeV range, so ν_1, ν_2 *must* make it to Earth
- ▶ So we set *lower* limits on their lifetimes (in the inverted mass ordering)
- ▶ Translated into *upper* limits on coupling



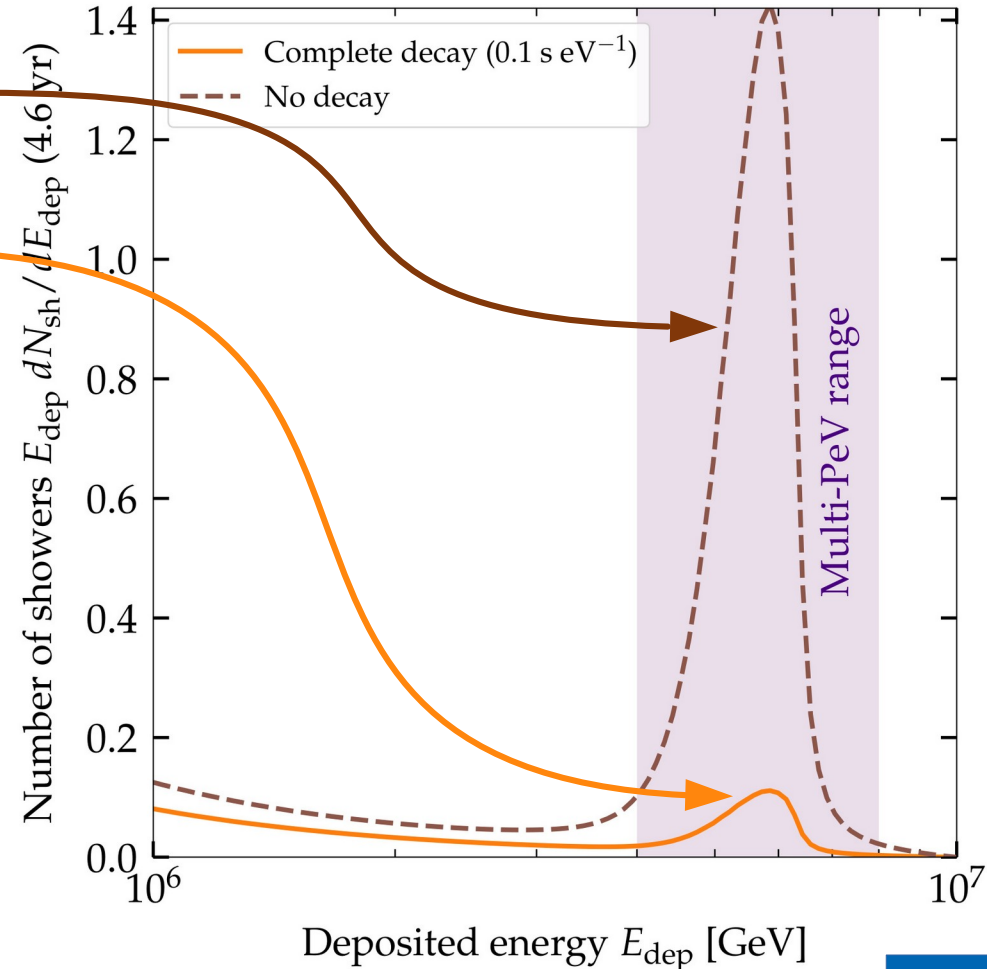
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Using the Glashow resonance to test decay

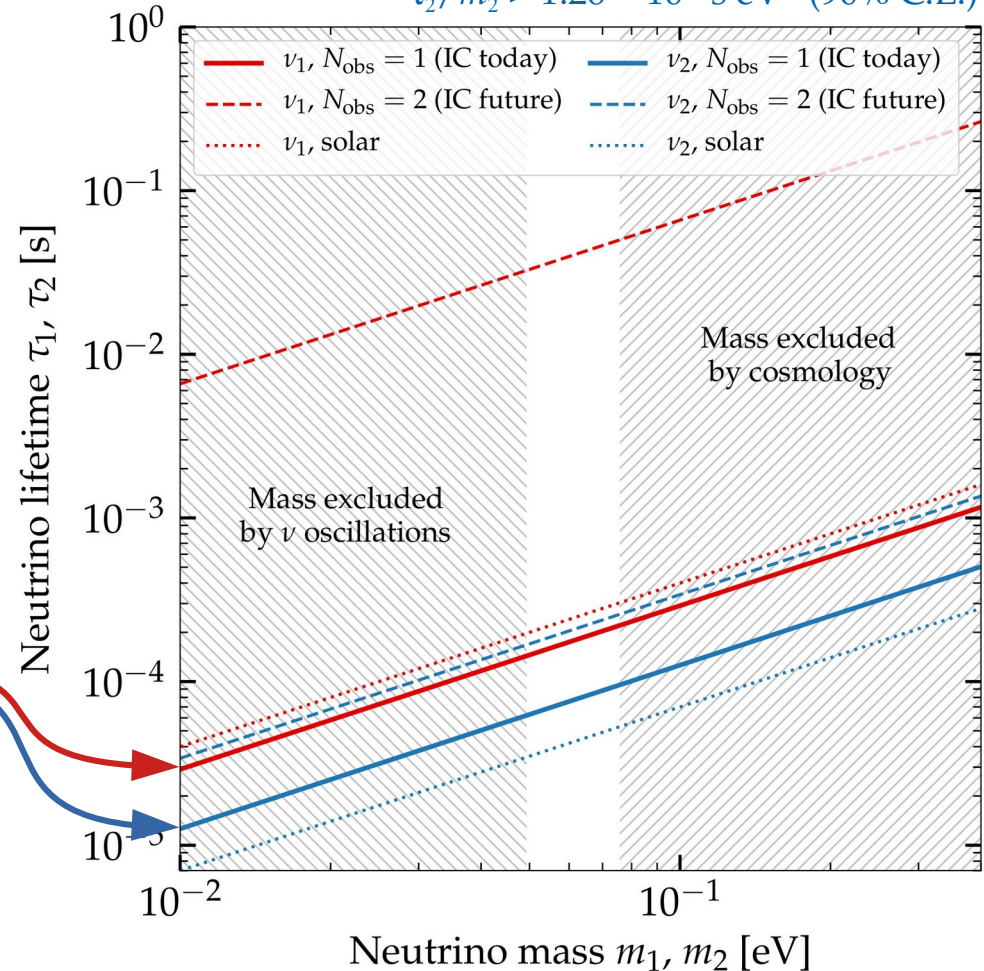
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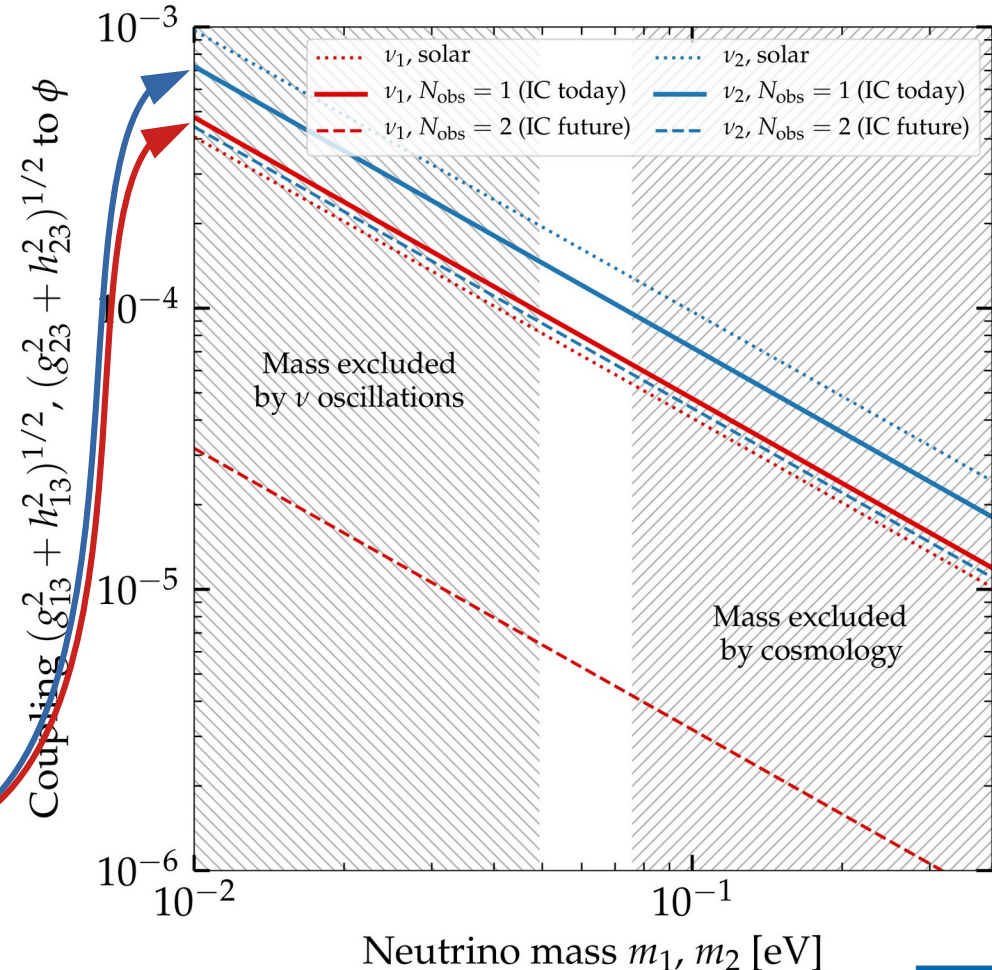
$$\tau_1/m_1 > 2.91 \times 10^{-3} \text{ s eV}^{-1} \text{ (90\% C.L.)}$$
$$\tau_2/m_2 > 1.26 \times 10^{-3} \text{ s eV}^{-1} \text{ (90\% C.L.)}$$



Using the Glashow resonance to test decay

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- ▶ So we set *lower* limits on their lifetimes (in the inverted mass ordering)
- ▶ Translated into *upper* limits on coupling

$$\mathcal{L} = g_{ij} \bar{\nu}_i \nu_j \phi + h_{ij} \bar{\nu}_i \gamma_5 \nu_j \phi + \text{h.c.}$$

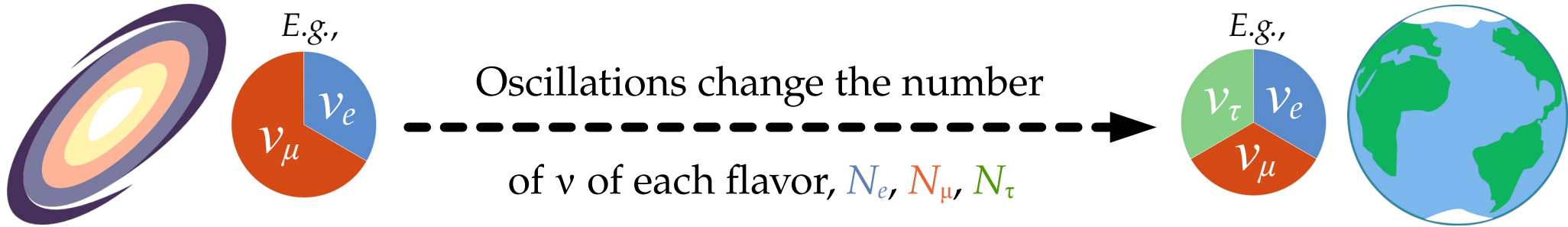


Flavor composition

Astrophysical sources

Earth

Up to a few Gpc



Different production mechanisms yield different flavor ratios:

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

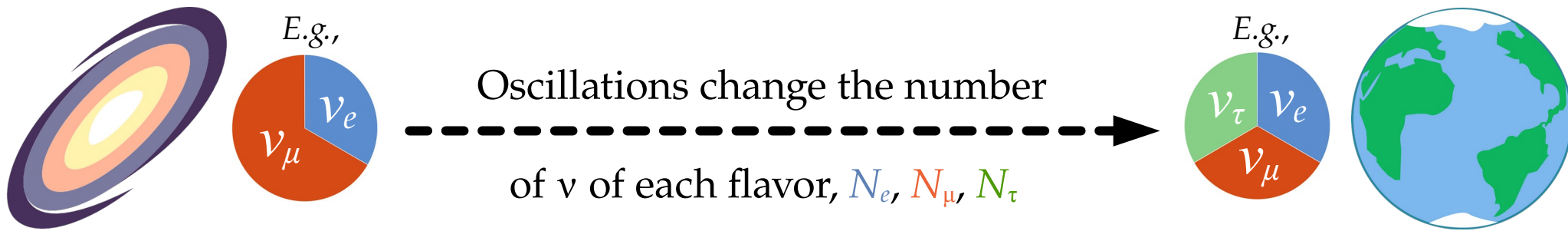
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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

Astrophysical sources

Earth

Up to a few Gpc



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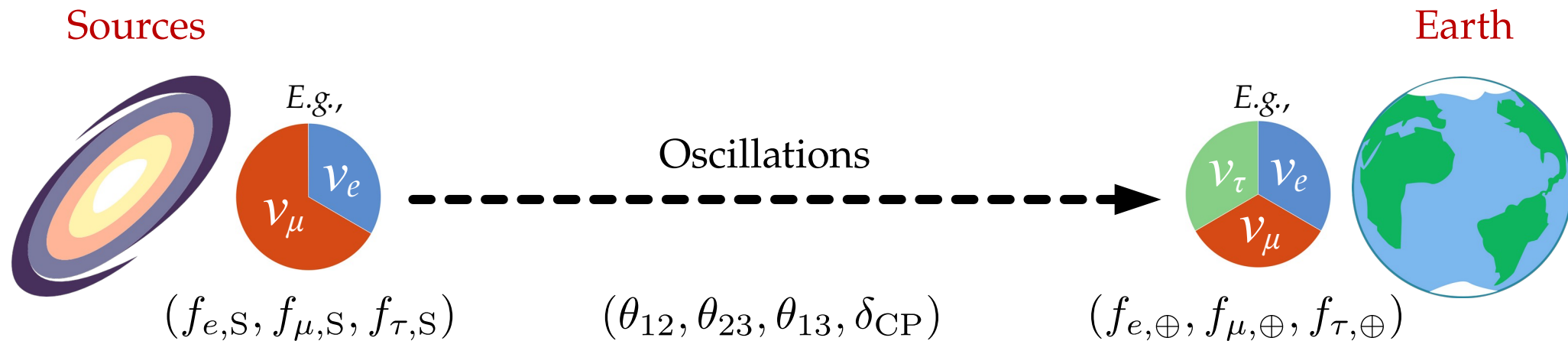
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Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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

Standard oscillations
or
new physics

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



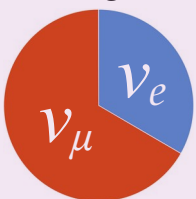
From Earth to sources: we let the data teach us about $f_{\alpha,S}$

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

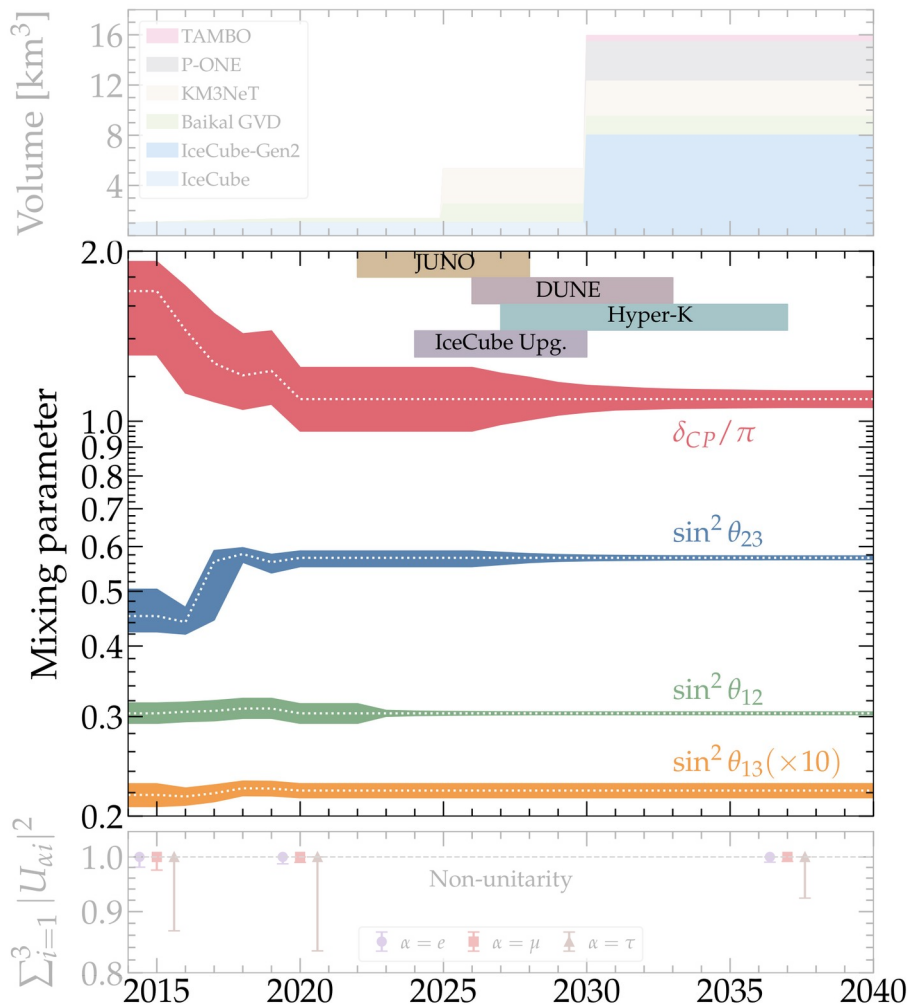
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$

Earth



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

How knowing the mixing parameters better helps



For a future experiment
 $\varepsilon = \text{JUNO, DUNE, Hyper-K:}$

Best fit from NuFit 5.0

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

From our simulations

We combine experiments in
 a likelihood:

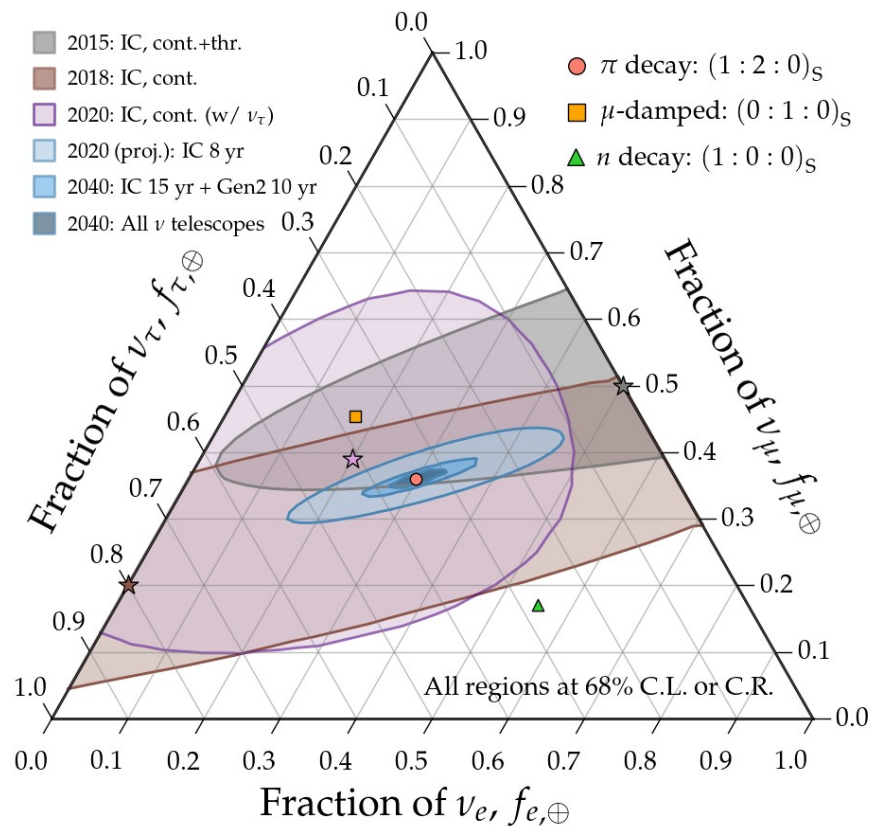
$$-2 \log \mathcal{L}(\boldsymbol{\theta}) = \sum_{\varepsilon} \chi_{\varepsilon}^2(\boldsymbol{\vartheta})$$

Inferring the flavor composition at the sources

Ingredient #1:

Flavor ratios measured at Earth,

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

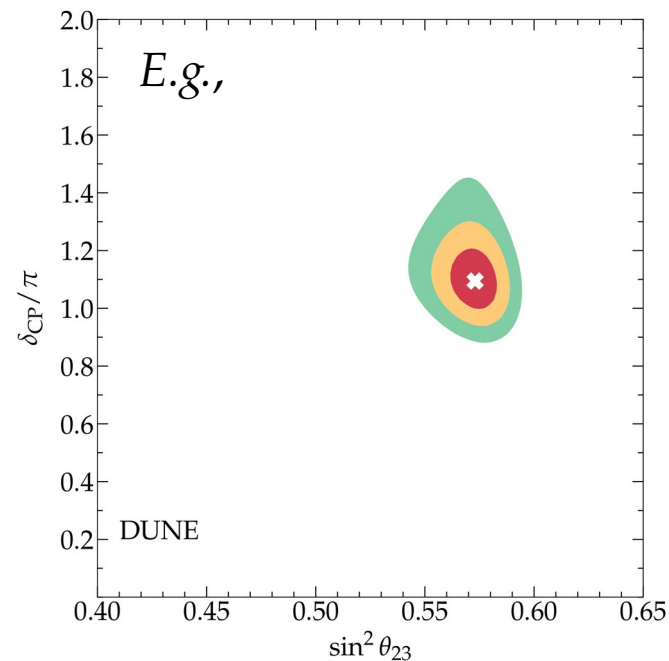


Ingredient #2:

Probability density of mixing

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

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



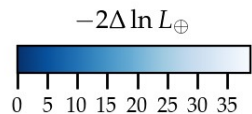
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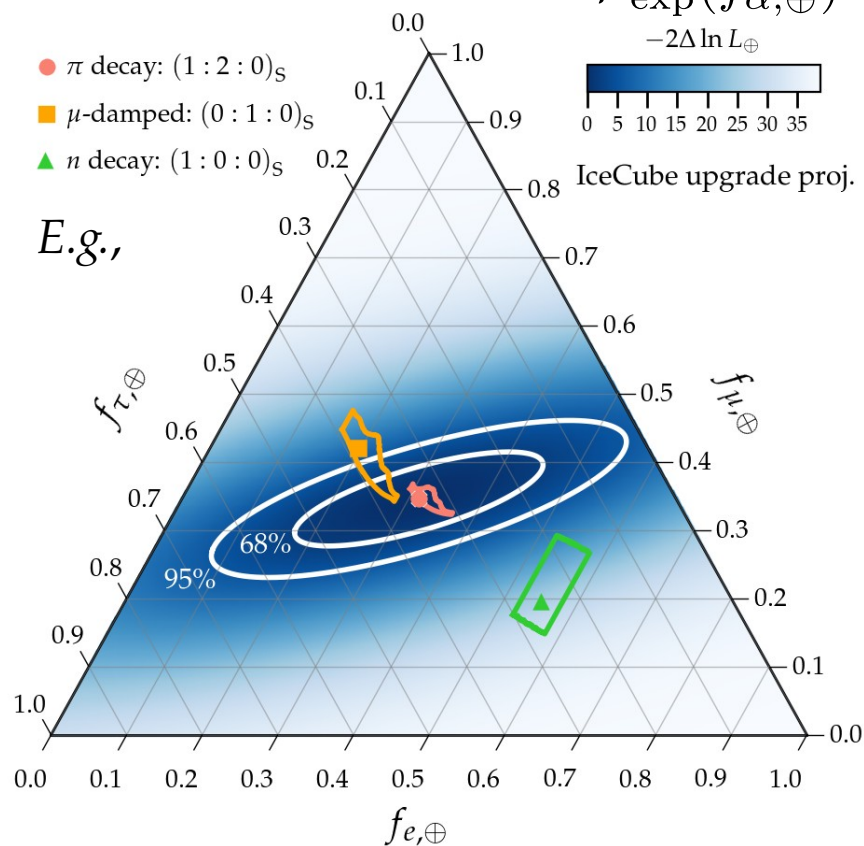
$$\mathcal{P}_{\text{exp}}(f_{\alpha,\oplus})$$



IceCube upgrade proj.

- π decay: $(1:2:0)_S$
- μ -damped: $(0:1:0)_S$
- ▲ n decay: $(1:0:0)_S$

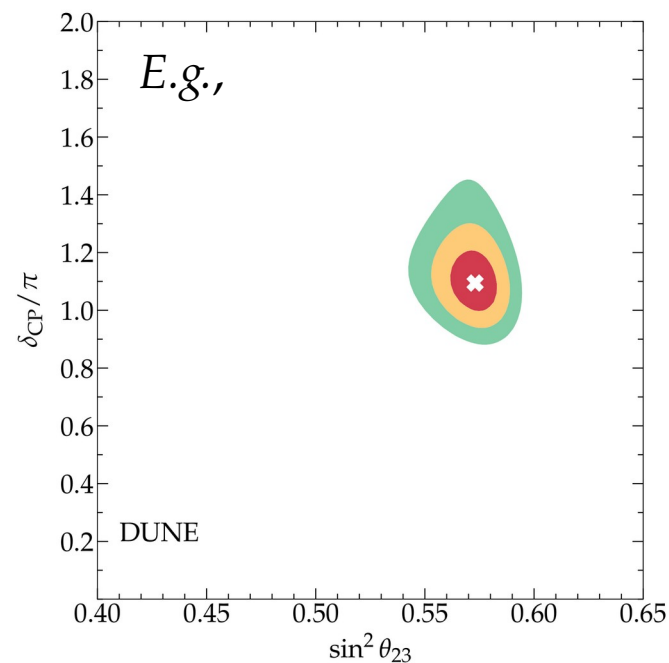
E.g.,



Ingredient #2:

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

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



Inferring the flavor composition at the sources

Ingredient #1:

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

Ingredient #2:

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

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

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

Inferring the flavor composition at the sources

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

$$\mathcal{P}(\mathbf{f}_s) = \int d\mathbf{\vartheta} \underbrace{\mathcal{L}(\mathbf{\vartheta})}_{\text{Oscillation experiments}} \underbrace{\mathcal{P}_{\text{exp}}(\mathbf{f}_{\oplus}(\mathbf{f}_S, \mathbf{\vartheta}))}_{\text{Neutrino telescopes}}$$

Oscillation experiments Neutrino telescopes

Inferring the flavor composition at the sources

Ingredient #1:

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

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Probability density of mixing
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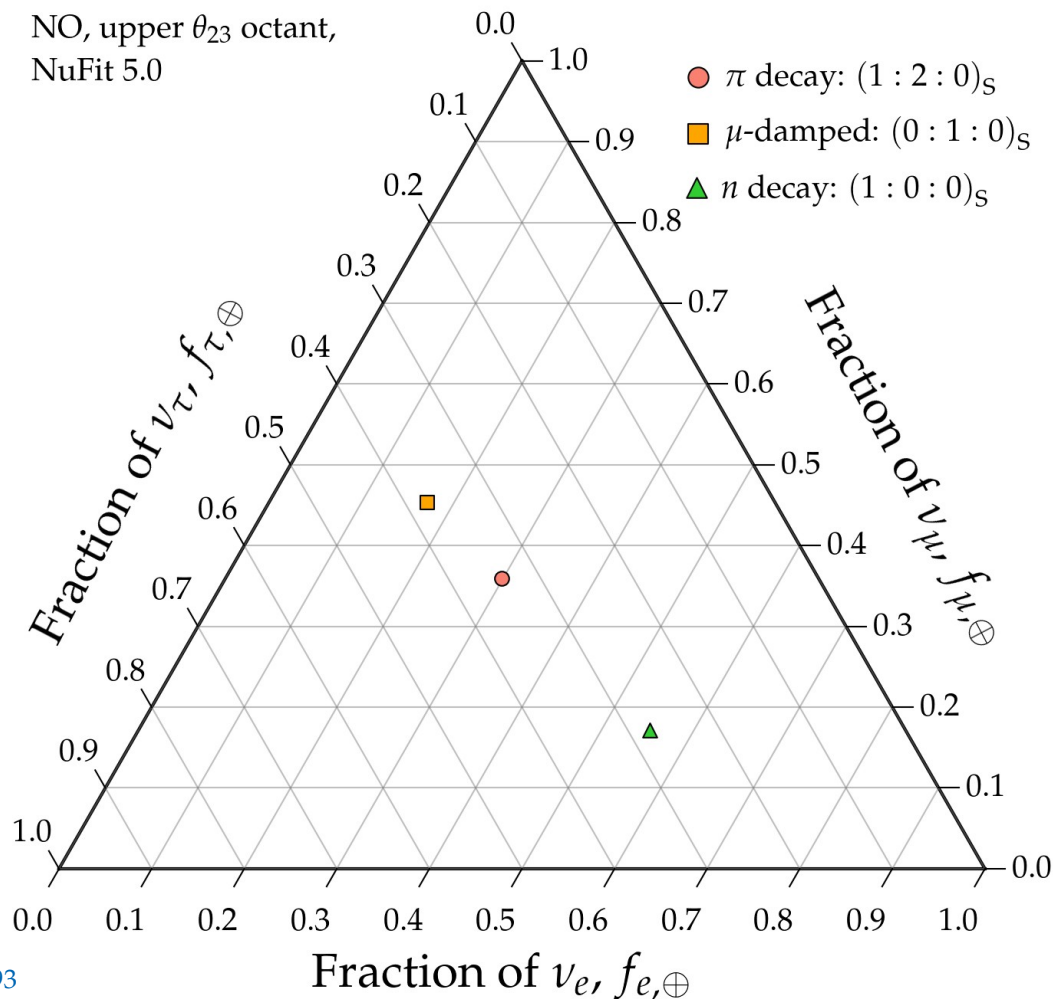
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$$\mathcal{P}(\mathbf{f}_s) = \int \underbrace{d\boldsymbol{\vartheta} \mathcal{L}(\boldsymbol{\vartheta})}_{\text{Oscillation experiments}} \underbrace{\mathcal{P}_{\text{exp}}(\mathbf{f}_{\oplus}(\mathbf{f}_S, \boldsymbol{\vartheta}))}_{\text{Neutrino telescopes}}$$

Oscillation experiments Neutrino telescopes

Theoretically palatable regions: today (2020)

NO, upper θ_{23} octant,
NuFit 5.0

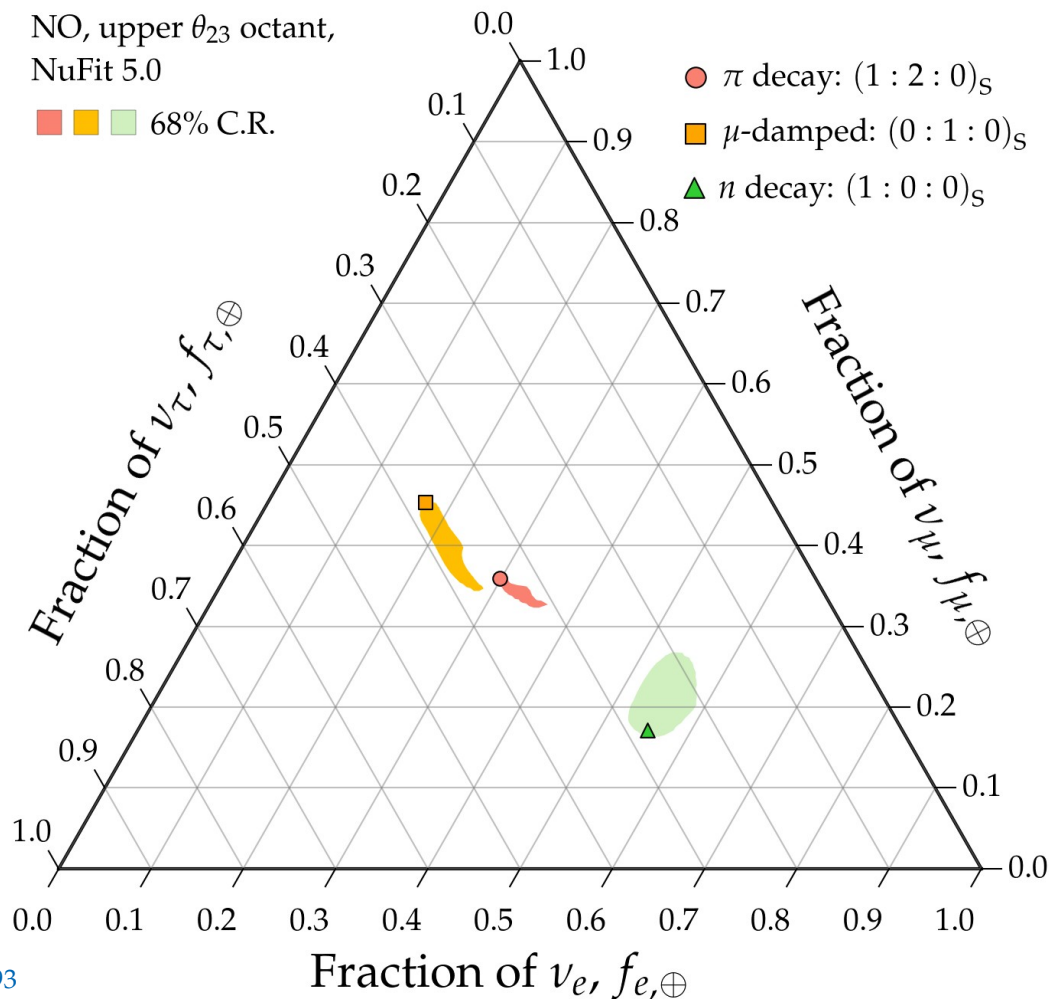


Note:

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

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

Theoretically palatable regions: today (2020)

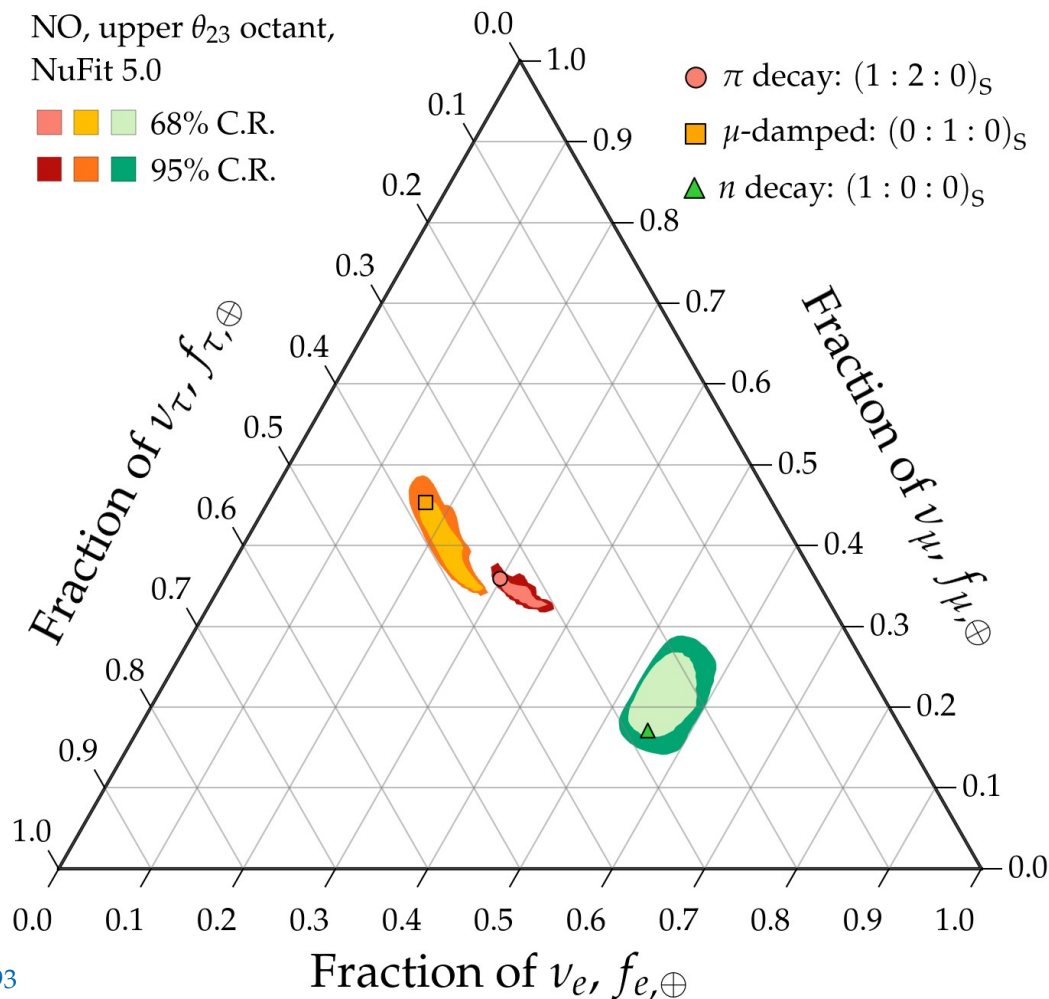


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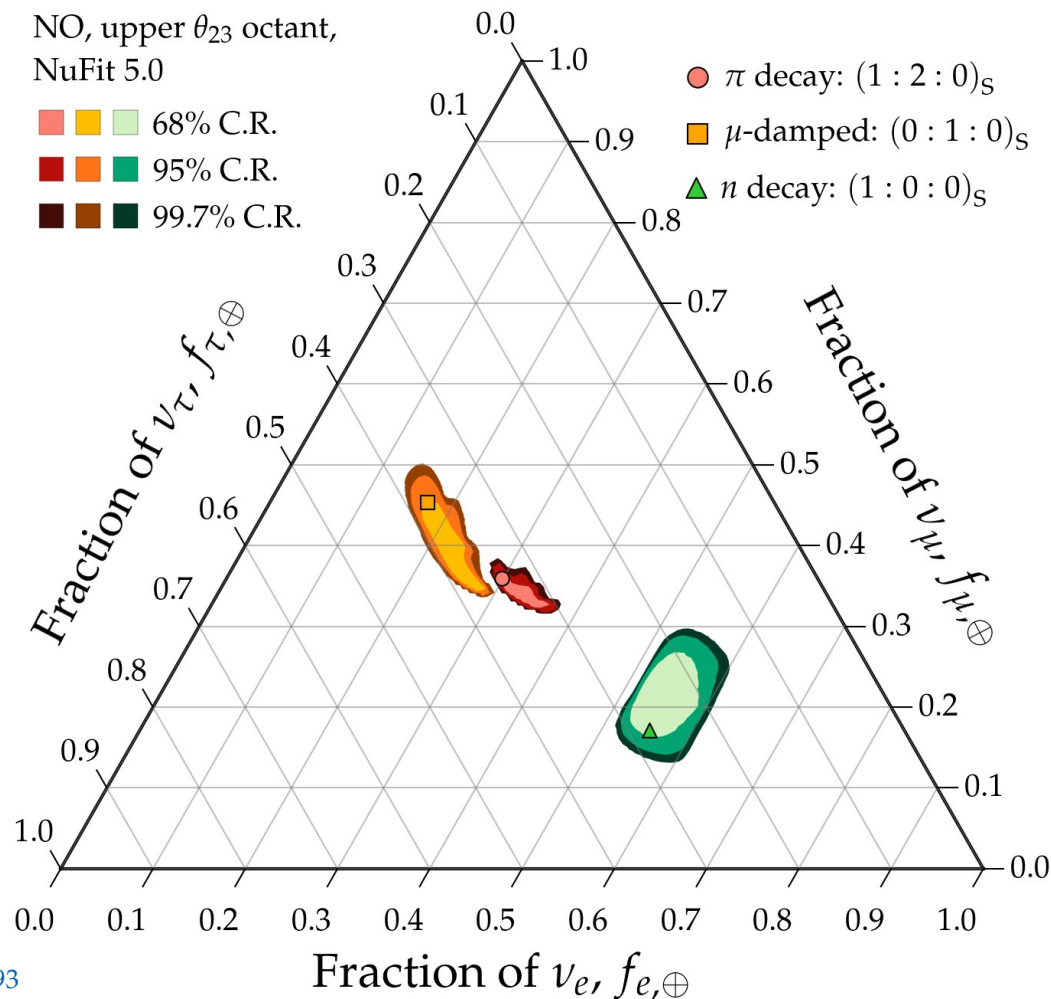


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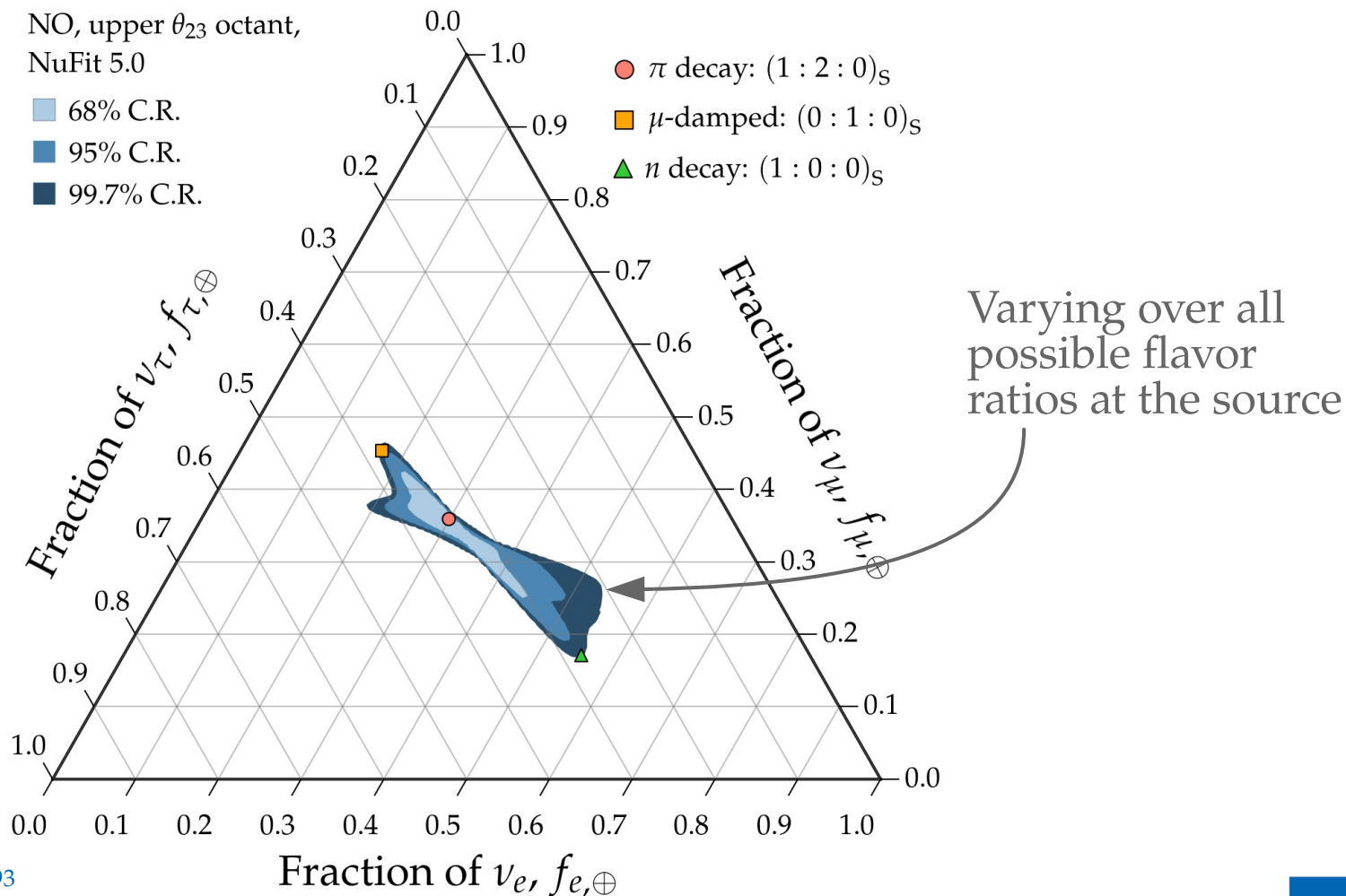
Theoretically palatable regions: today (2020)



Note:

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inverted ordering looks similar

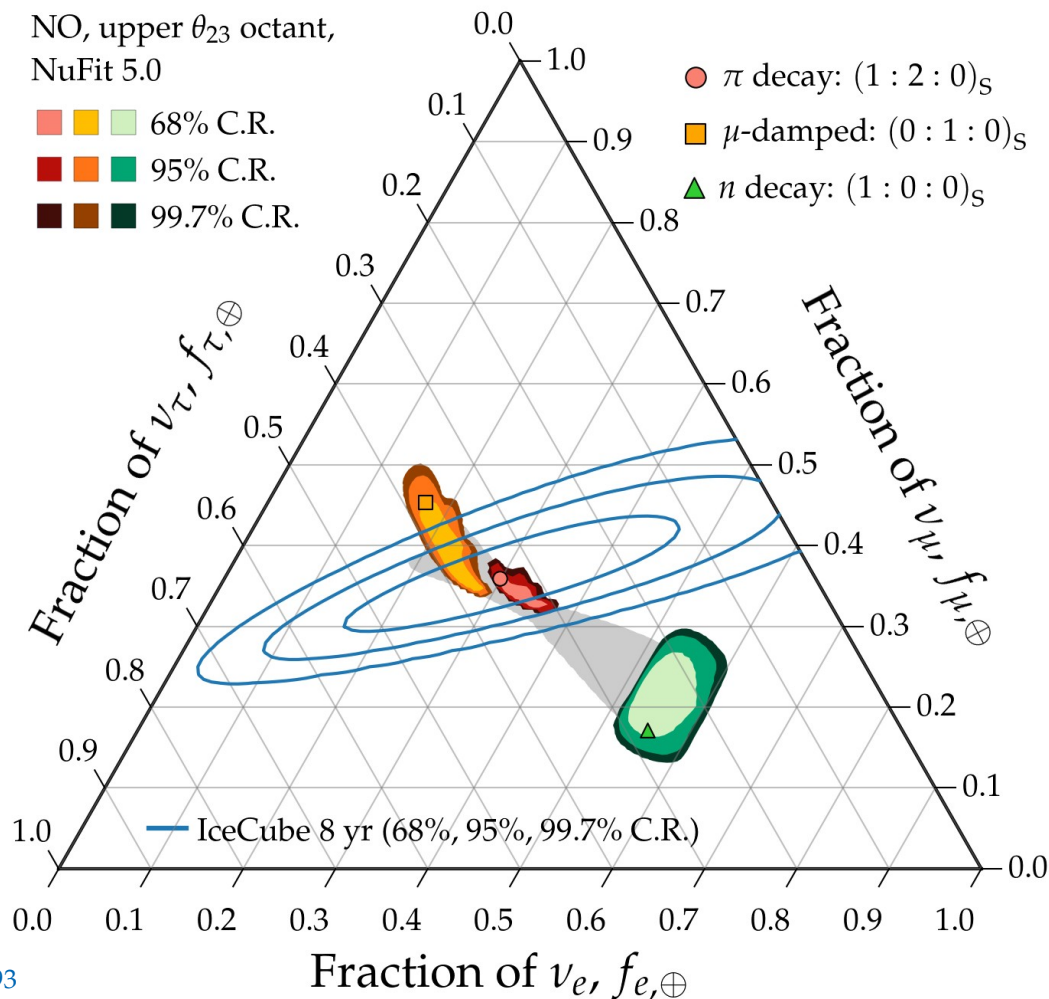
Theoretically palatable regions: today (2020)



Note:

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Theoretically palatable regions: today (2020)

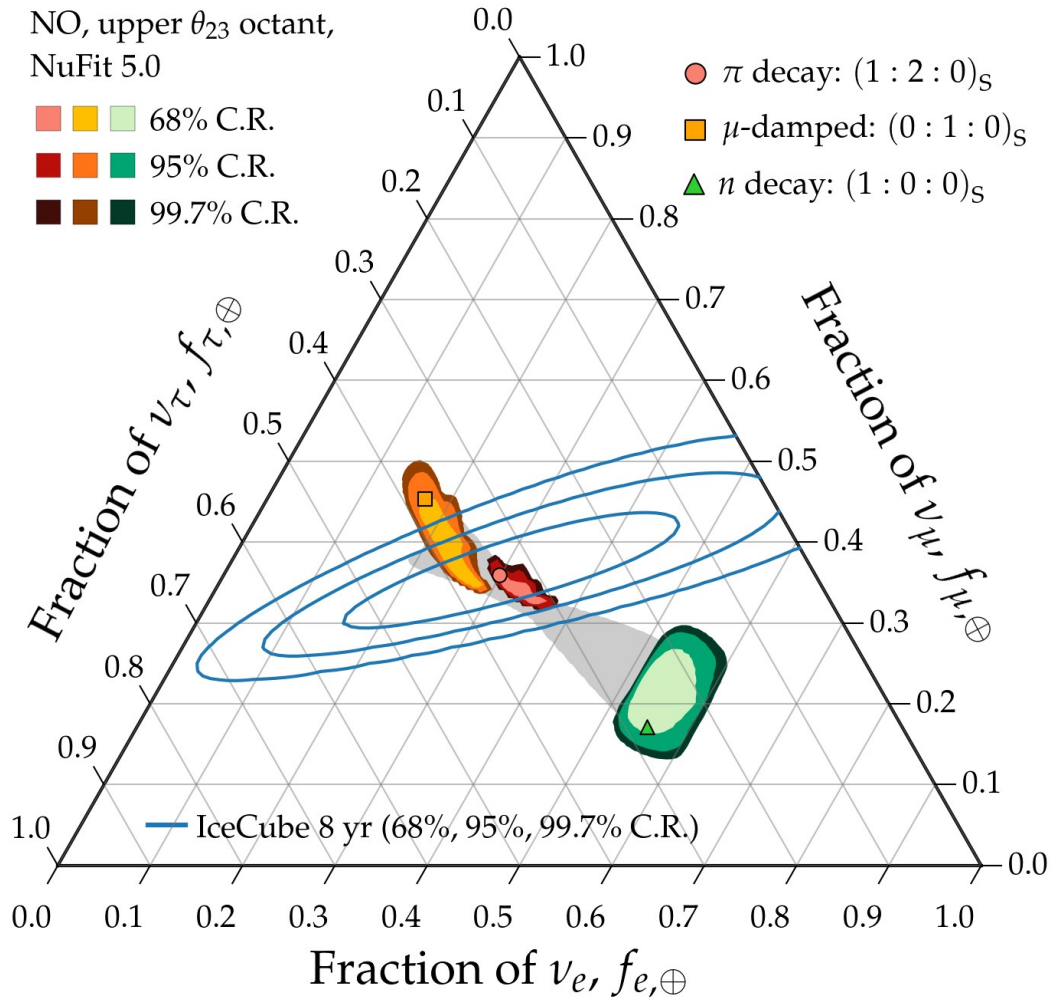


Note:

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inverted ordering looks similar

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

Theoretically palatable regions: today (2020)



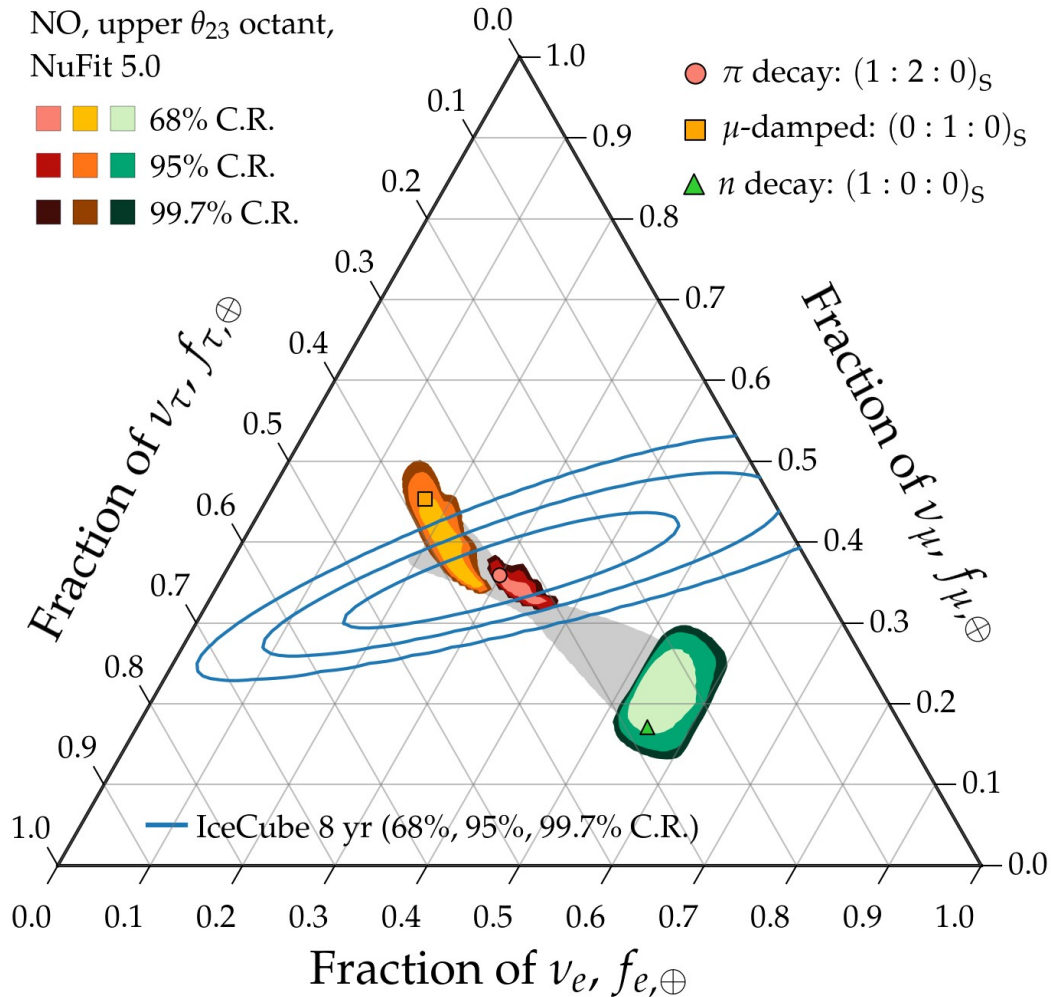
Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the
mixing parameters

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

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

Theoretically palatable regions: today (2020)



Two limitations:

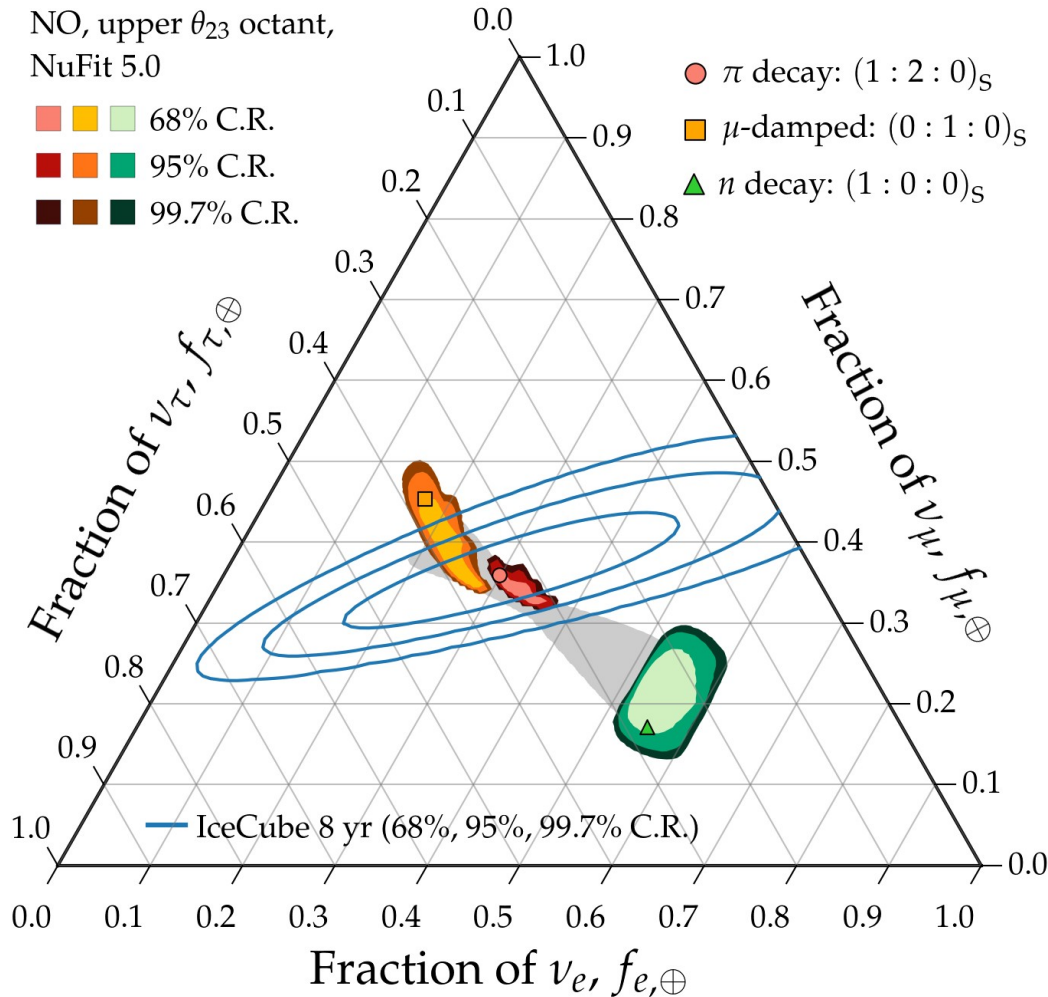
Allowed flavor regions overlap –
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Will be overcome by 2030

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

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

MB, Beacom, Winter, PRL 2015

Allowed regions of flavor ratios at Earth derived from oscillations

Note:

The original palatable regions were
frequentist [MB, Beacom, Winter, PRL 2015];
the new ones are Bayesian

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

MB, Beacom, Winter, PRL 2015

Allowed regions of flavor ratios at Earth derived from oscillations

Ingredient #1:

Flavor ratios at the source,

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

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

or

Explore all possible combinations

Note:

The original palatable regions were
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Flavor at the Earth: *theoretically palatable regions*

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Flavor at the Earth: *theoretically palatable regions*

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

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Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

MB, Beacom, Winter, *PRL* 2015

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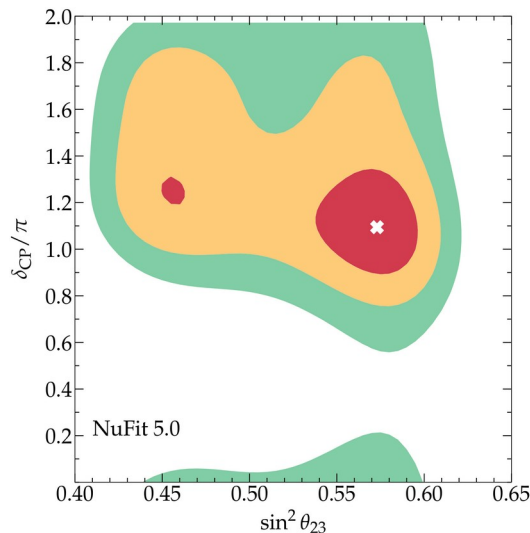
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or

Explore all possible combinations

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

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



Note:

The original palatable regions were
frequentist [MB, Beacom, Winter, *PRL* 2015];
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Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

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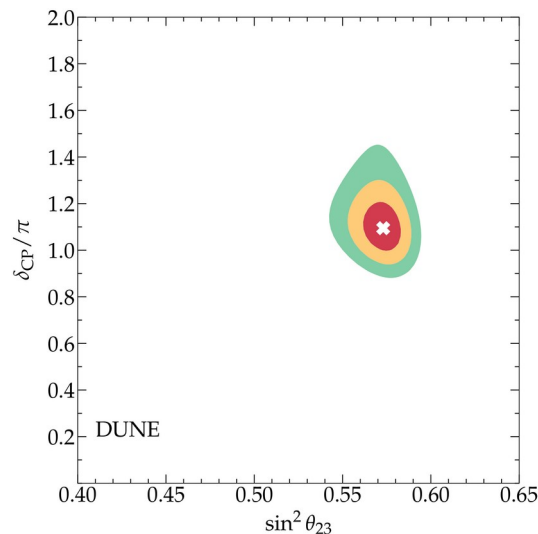
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

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

Post-2020: Build our own profiles using simulations of JUNO, DUNE, Hyper-K

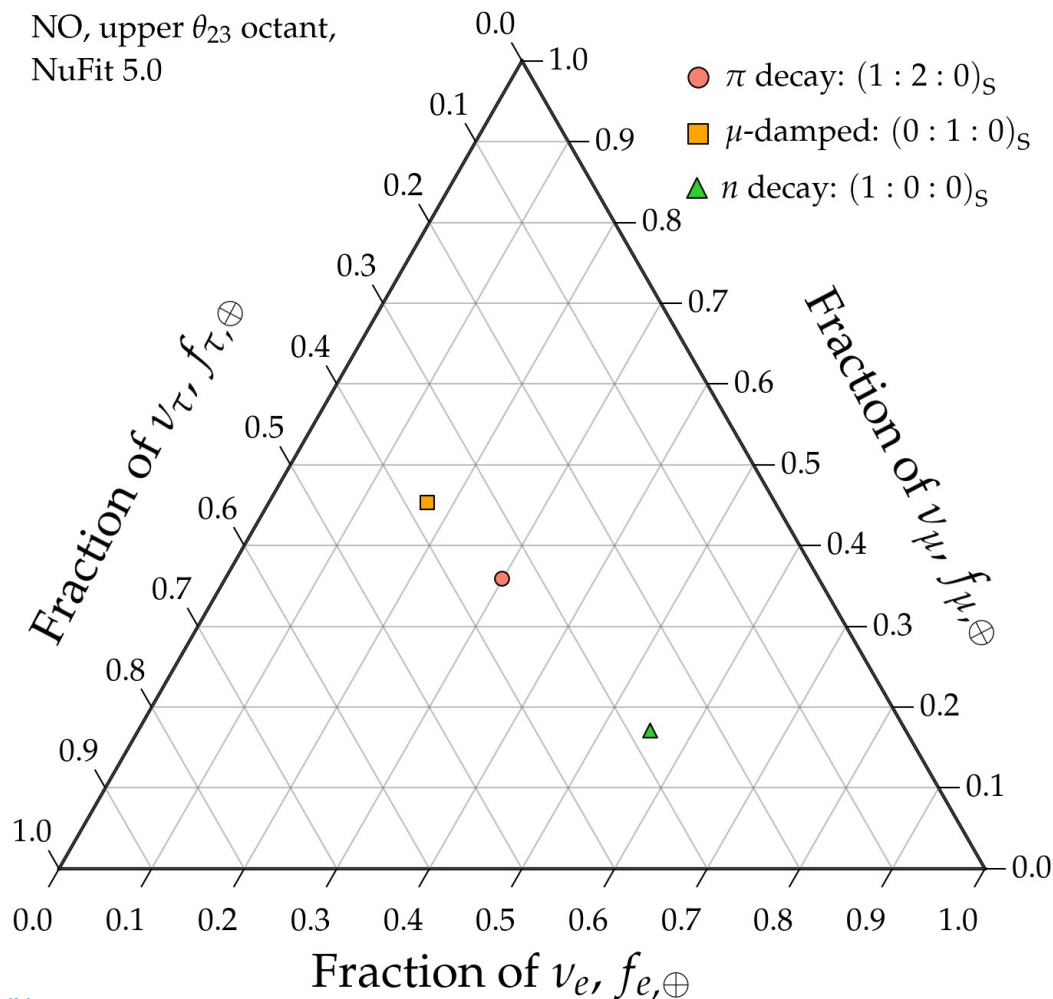
An *et al.*, *J. Phys. G* 2016
DUNE, 2002.03005

Huber, Lindner, Winter, *Nucl. Phys. B* 2002



Theoretically palatable regions: today (2020)

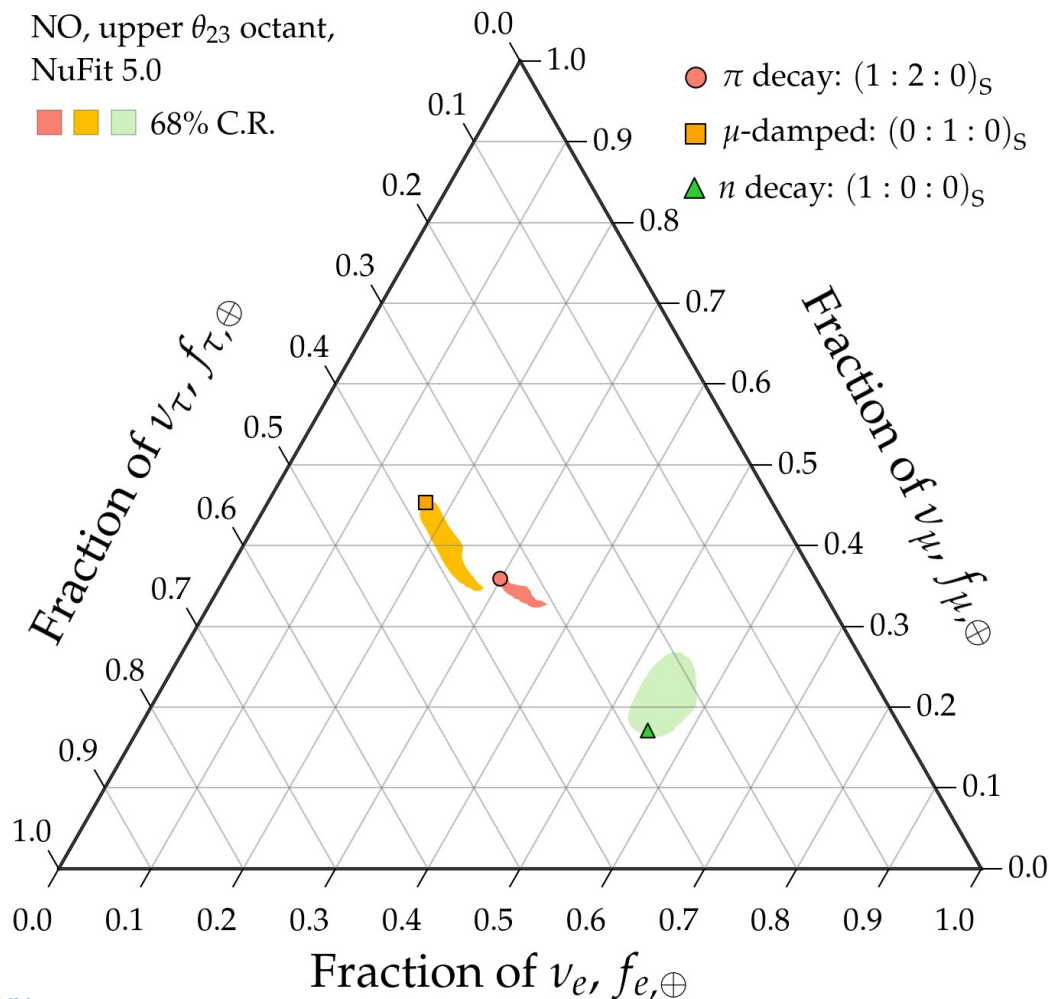
NO, upper θ_{23} octant,
NuFit 5.0



Note:

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

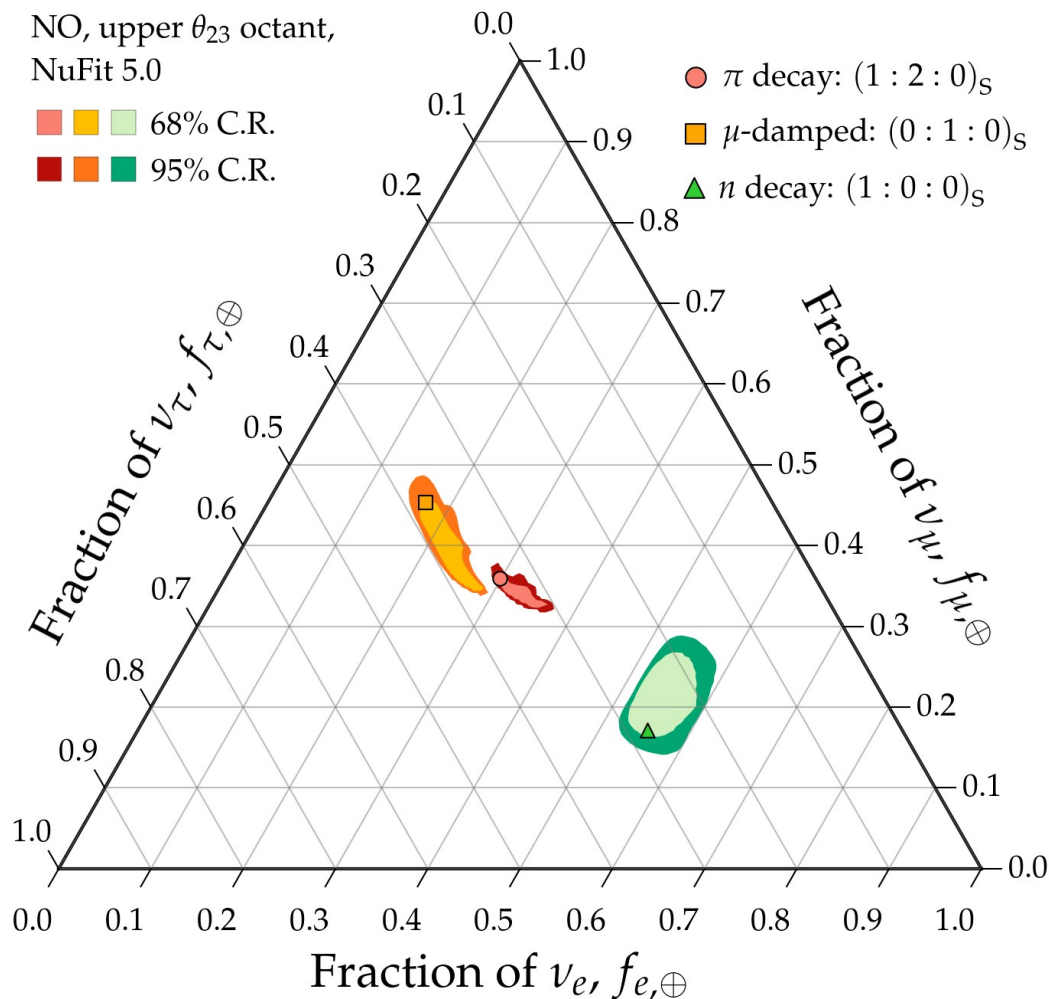
Theoretically palatable regions: today (2020)



Note:

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neutrino mass ordering (NO);
inverted ordering looks similar

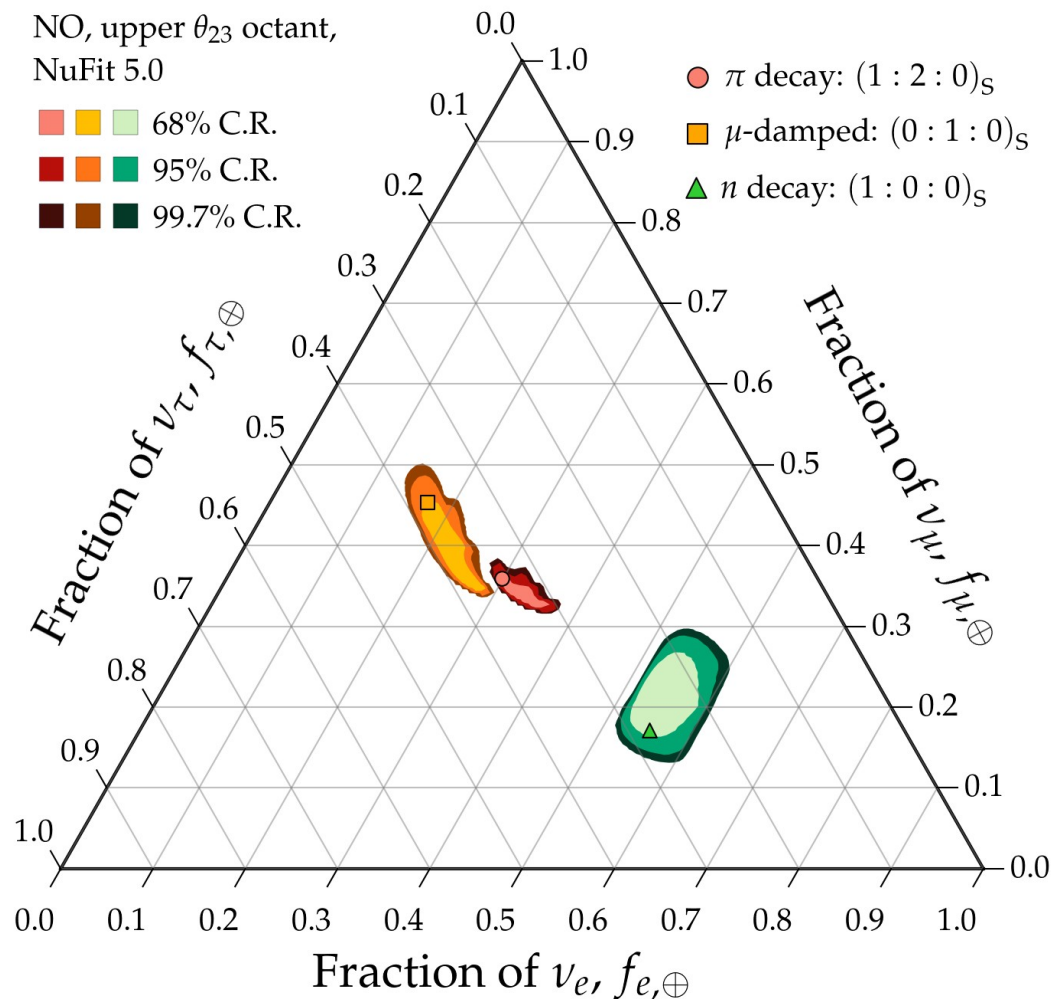
Theoretically palatable regions: today (2020)



Note:

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inverted ordering looks similar

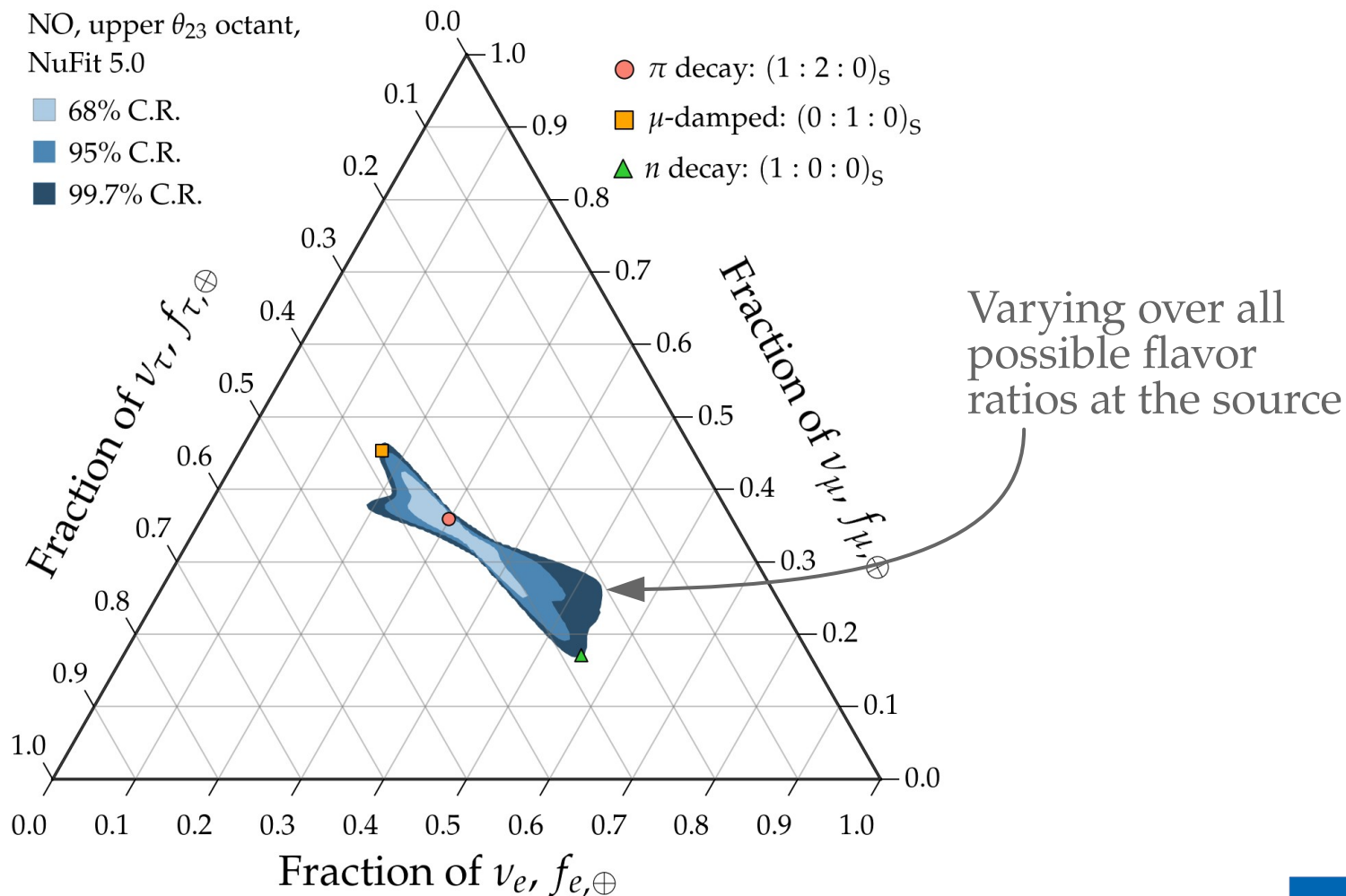
Theoretically palatable regions: today (2020)



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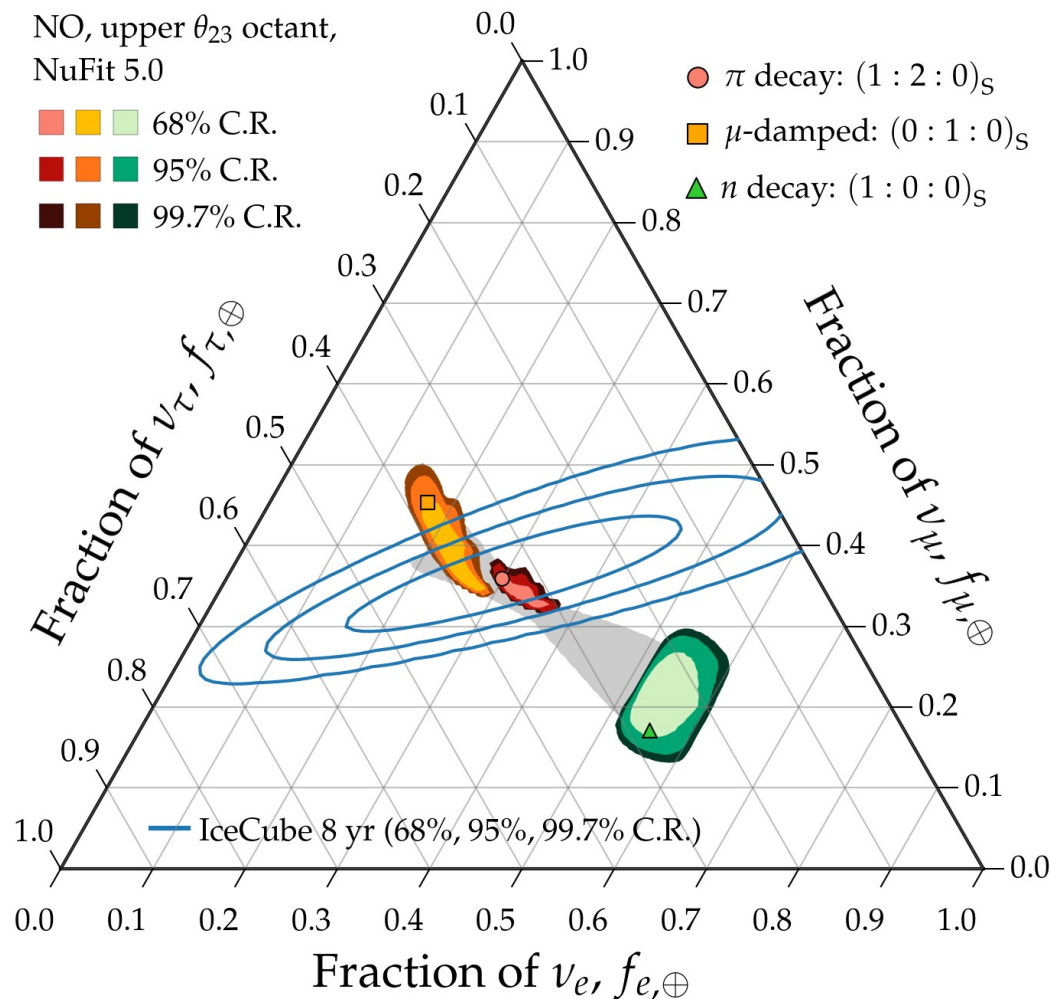
Theoretically palatable regions: today (2020)



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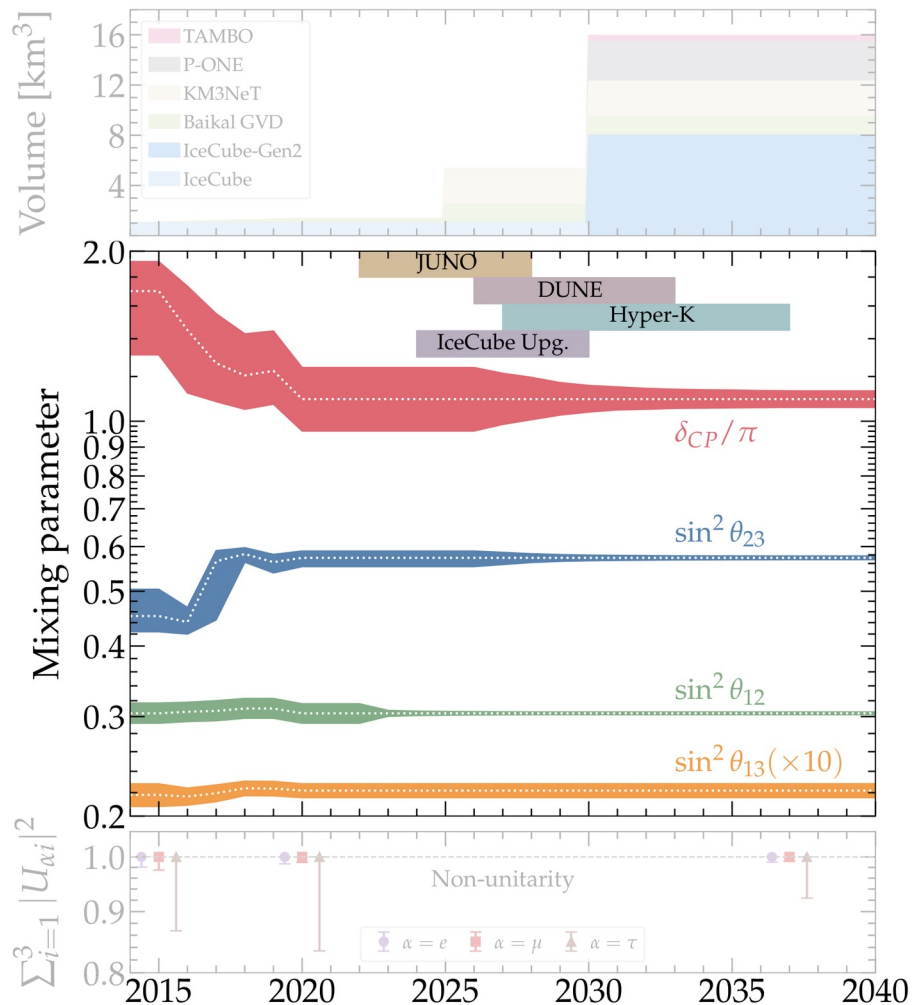
Theoretically palatable regions: today (2020)



Note:

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neutrino mass ordering (NO);
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How knowing the mixing parameters better helps

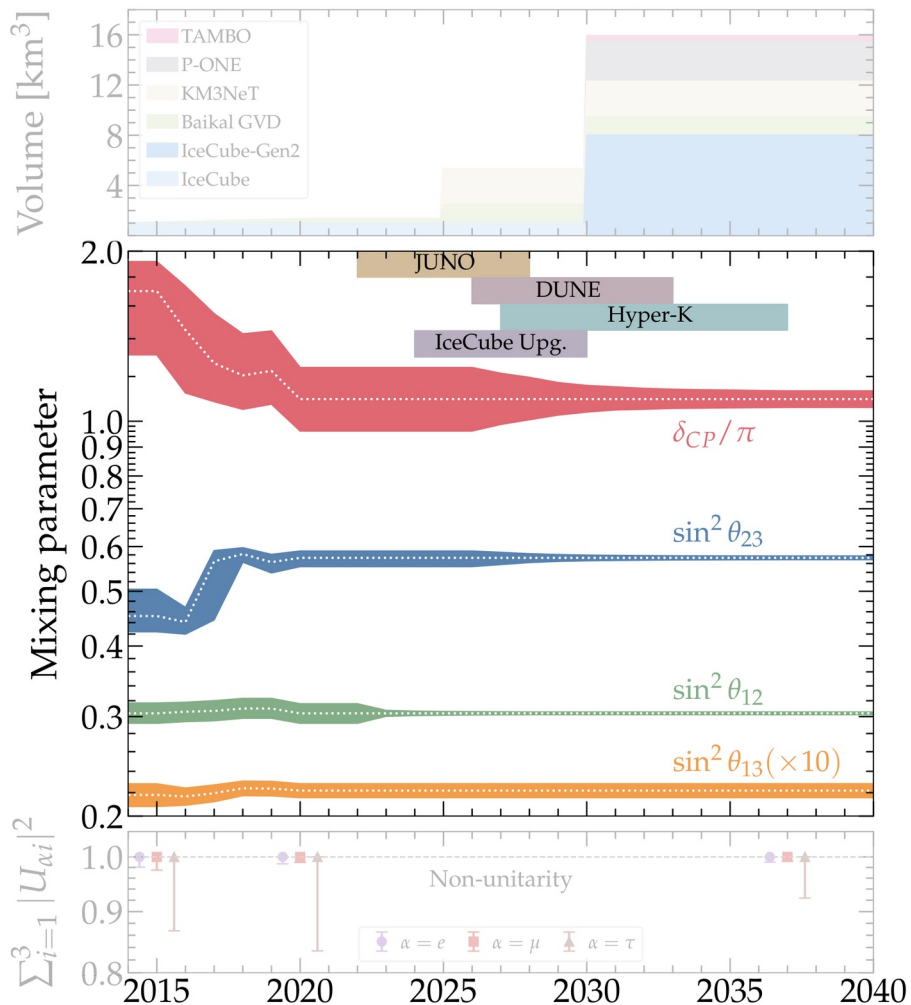


We can compute the oscillation probability more precisely:

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

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

How knowing the mixing parameters better helps



For a future experiment
 $\varepsilon = \text{JUNO, DUNE, Hyper-K}$:

Best fit from NuFit 5.0

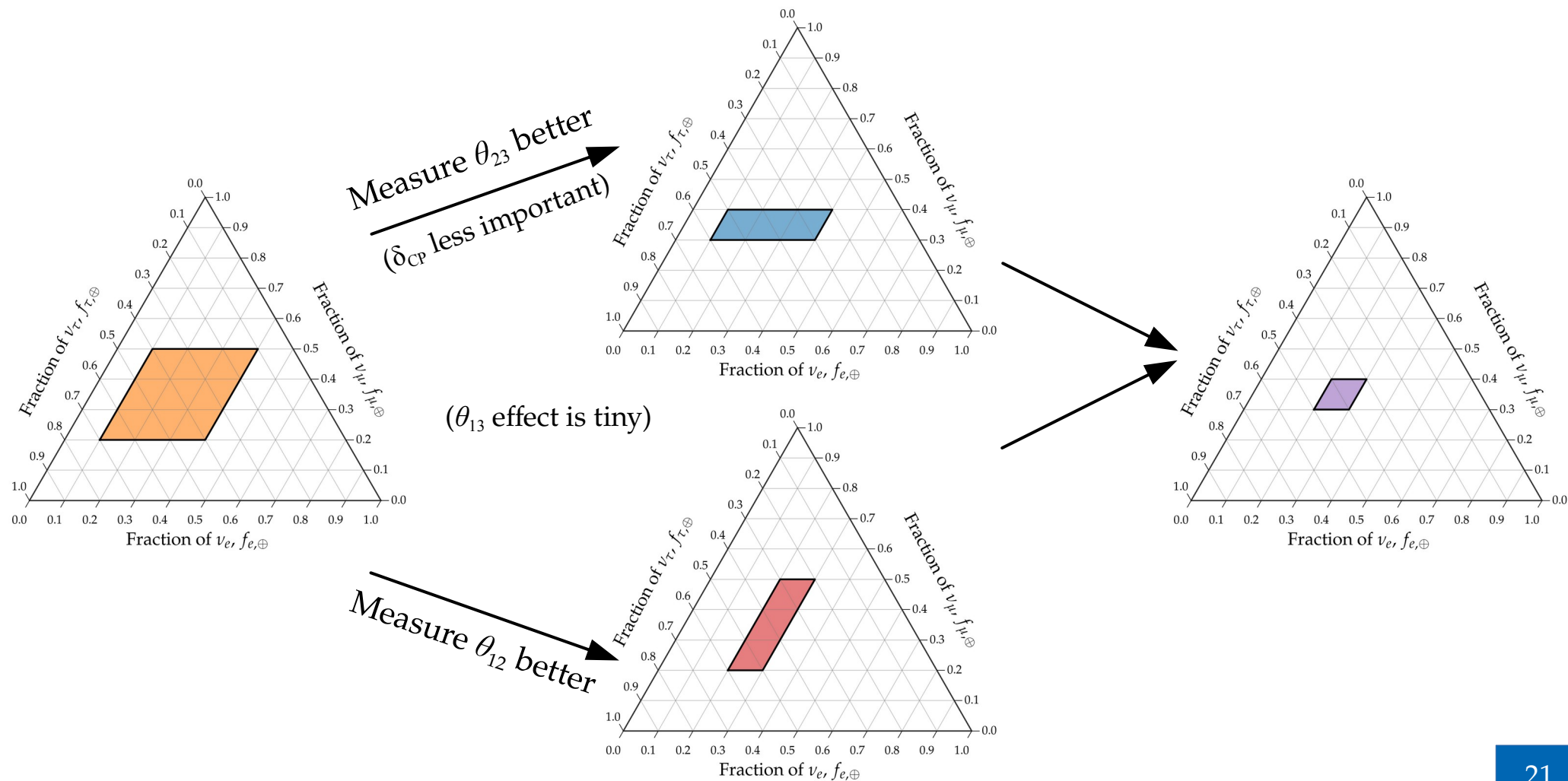
$$\chi_{\varepsilon}^2(\boldsymbol{\vartheta}) = \sum_i \frac{(\vartheta_i - \bar{\vartheta}_i)^2}{\sigma_{i,\varepsilon}^2}$$

From our simulations

We combine experiments in
 a likelihood:

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

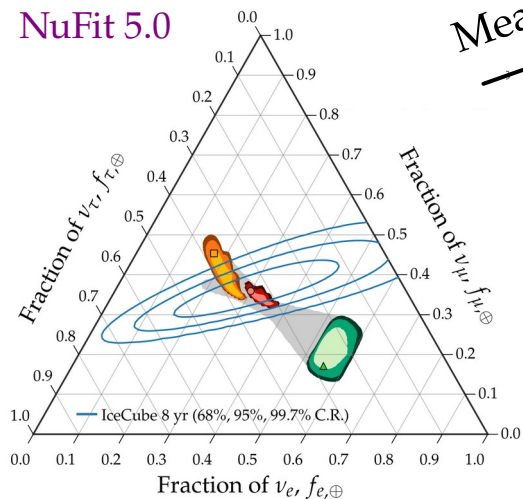
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

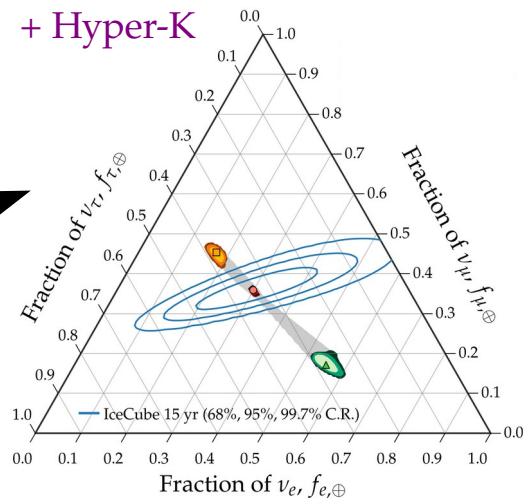
2020

NuFit 5.0

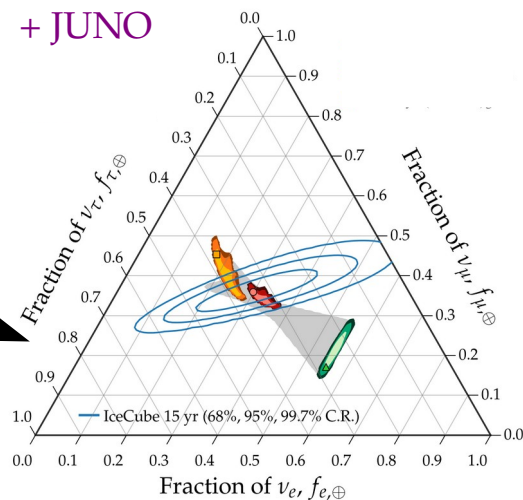


Measure θ_{23} better

+ Hyper-K



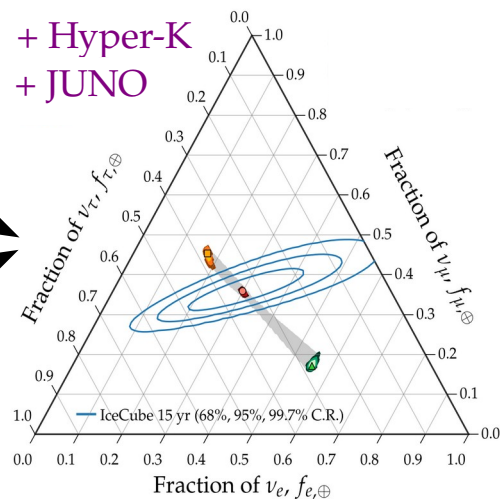
+ JUNO



Measure θ_{12} better

~2030

+ Hyper-K
+ JUNO



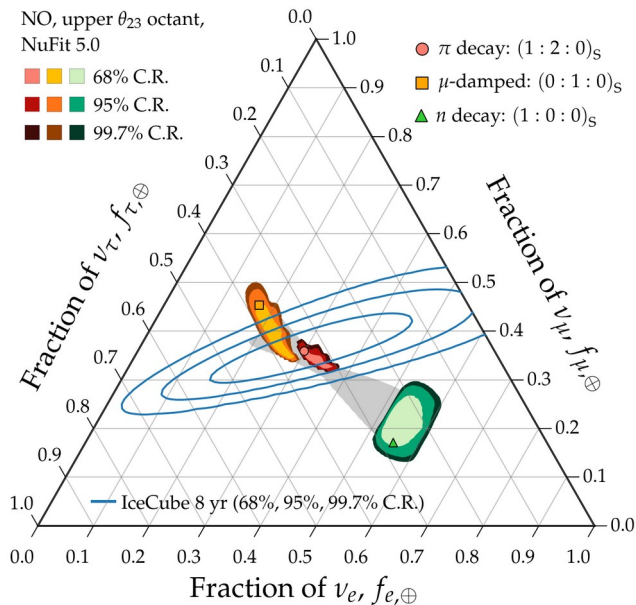
In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

Theoretically palatable regions: 2020 → 2030 → 2040

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

2020

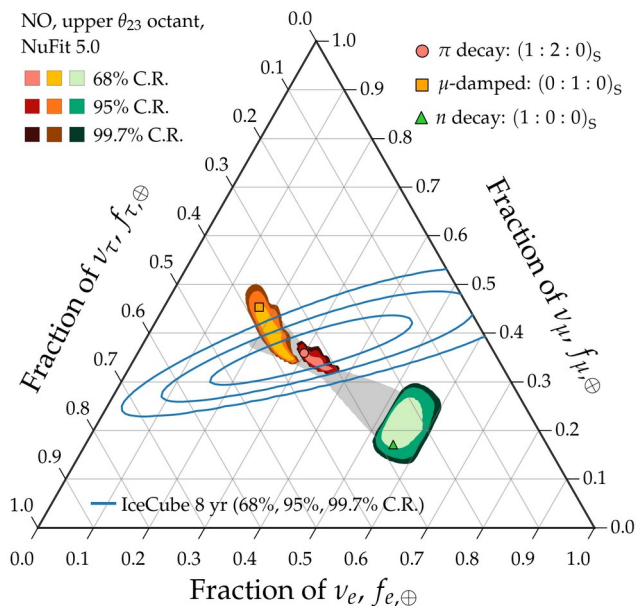


Allowed regions: overlapping

Measurement: imprecise

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

2020



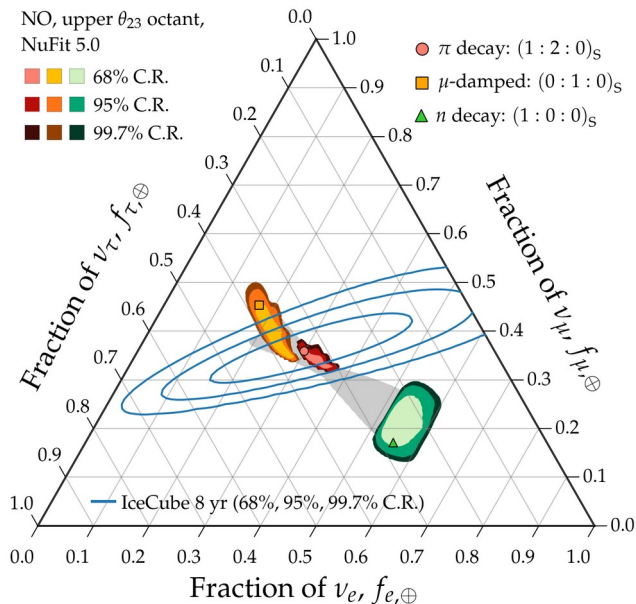
Allowed regions: overlapping

Measurement: imprecise

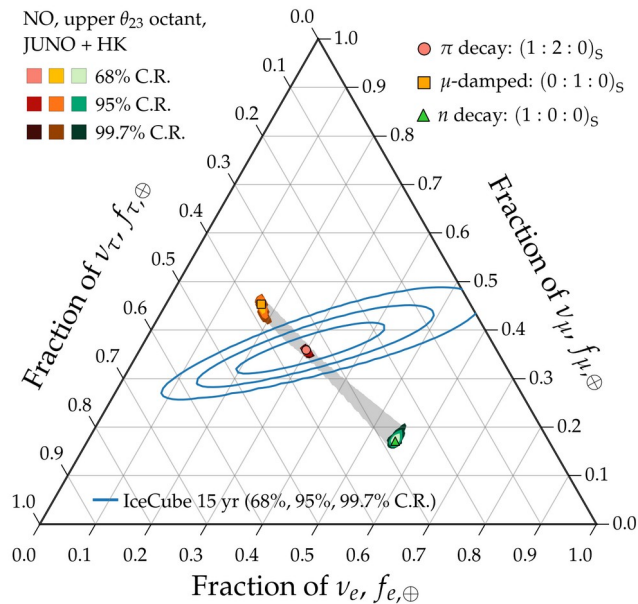
Not ideal

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

2020



2030



Allowed regions: overlapping

Measurement: imprecise

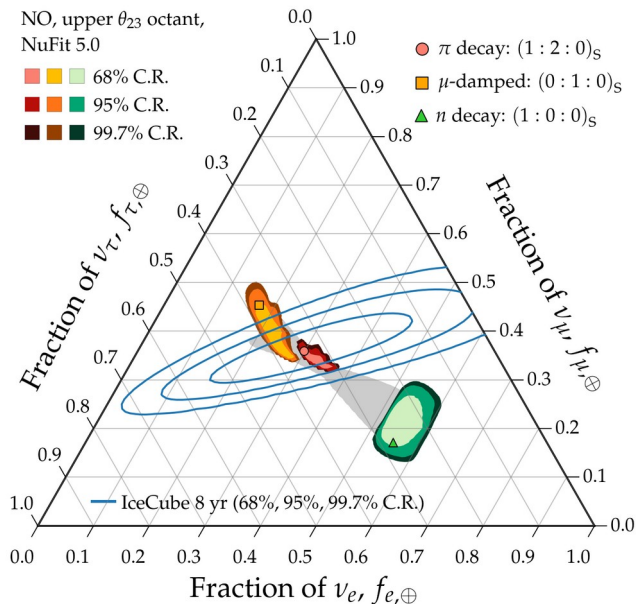
Not ideal

Allowed regions: well separated

Measurement: improving

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

2020

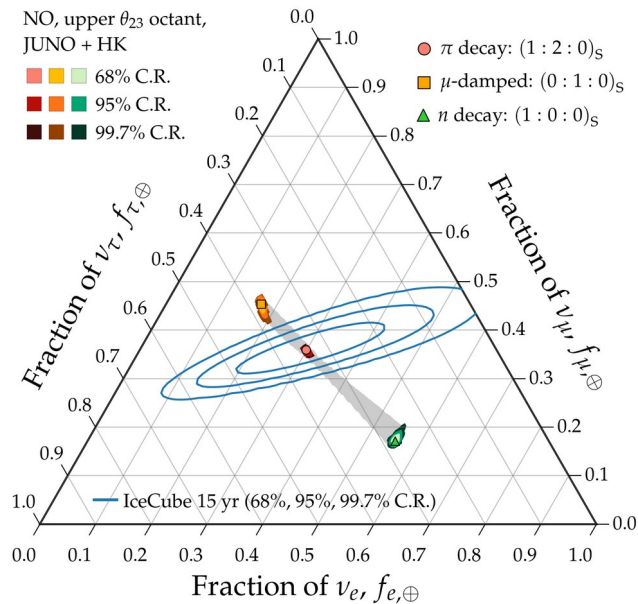


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



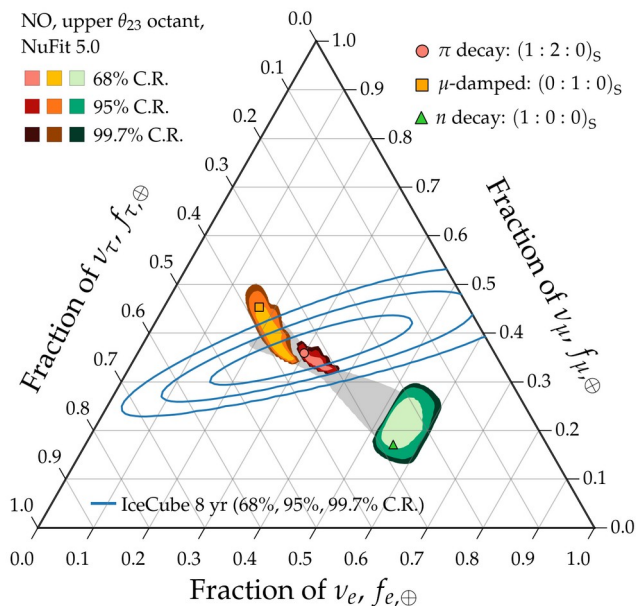
Allowed regions: well separated

Measurement: improving

Nice

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

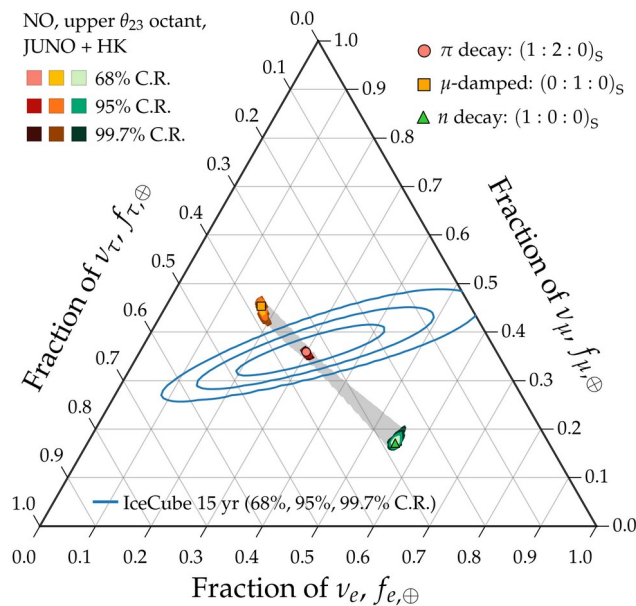
2020



Allowed regions: overlapping
Measurement: imprecise

Not ideal

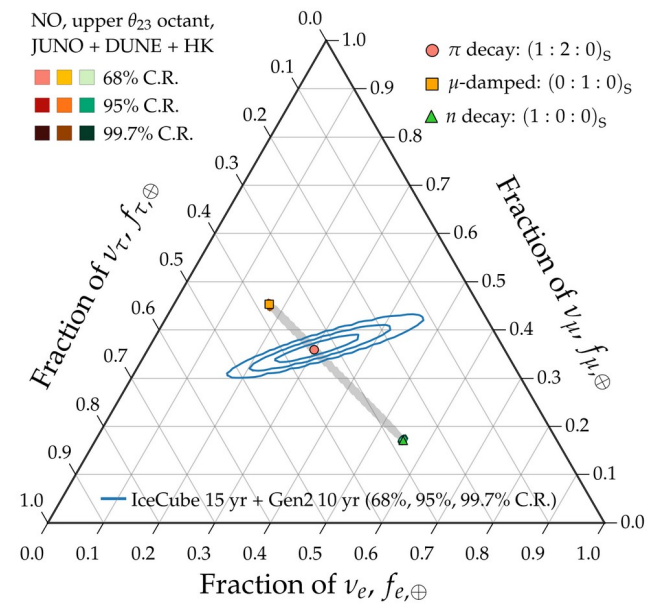
2030



Allowed regions: well separated
Measurement: improving

Nice

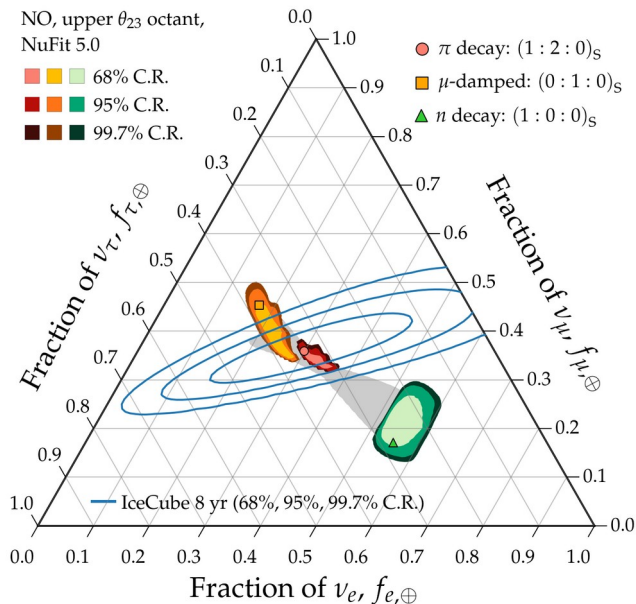
2040



Allowed regions: well separated
Measurement: precise

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

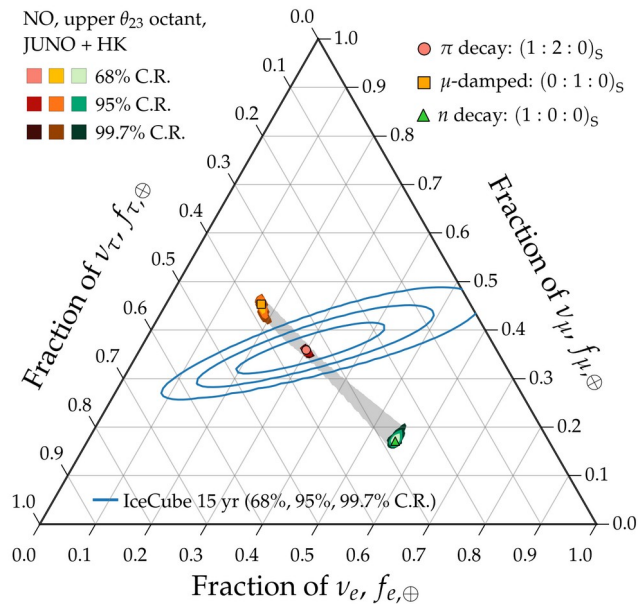
2020



Allowed regions: overlapping
Measurement: imprecise

Not ideal

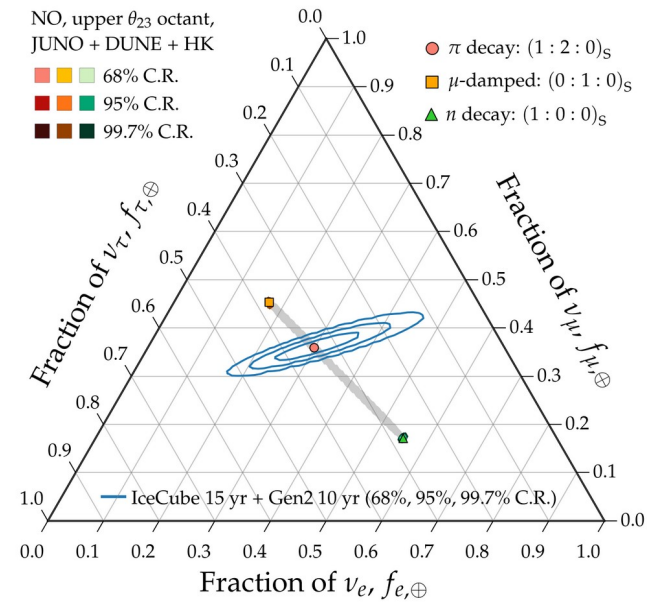
2030



Allowed regions: well separated
Measurement: improving

Nice

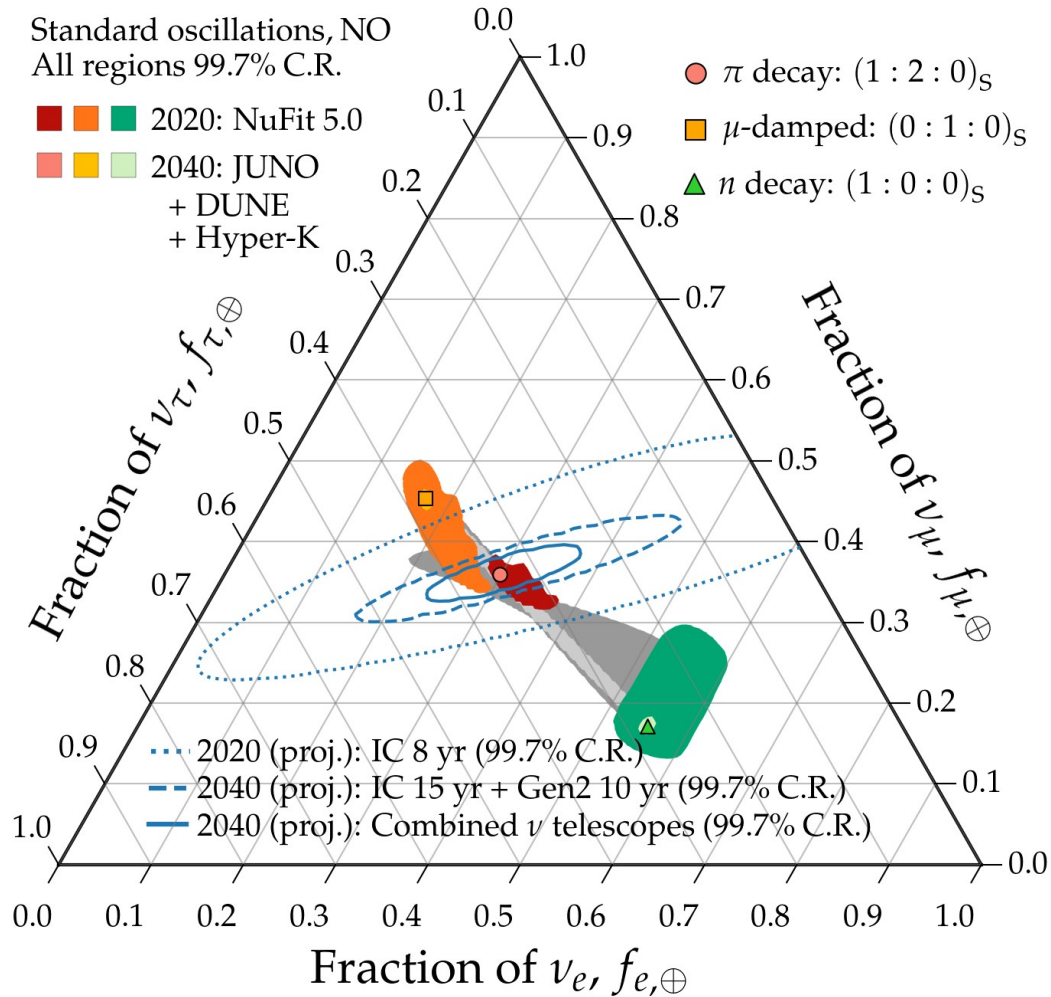
2040



Allowed regions: well separated
Measurement: precise

Success

Theoretically palatable regions: 2020 *vs.* 2040



By 2040:

Theory –

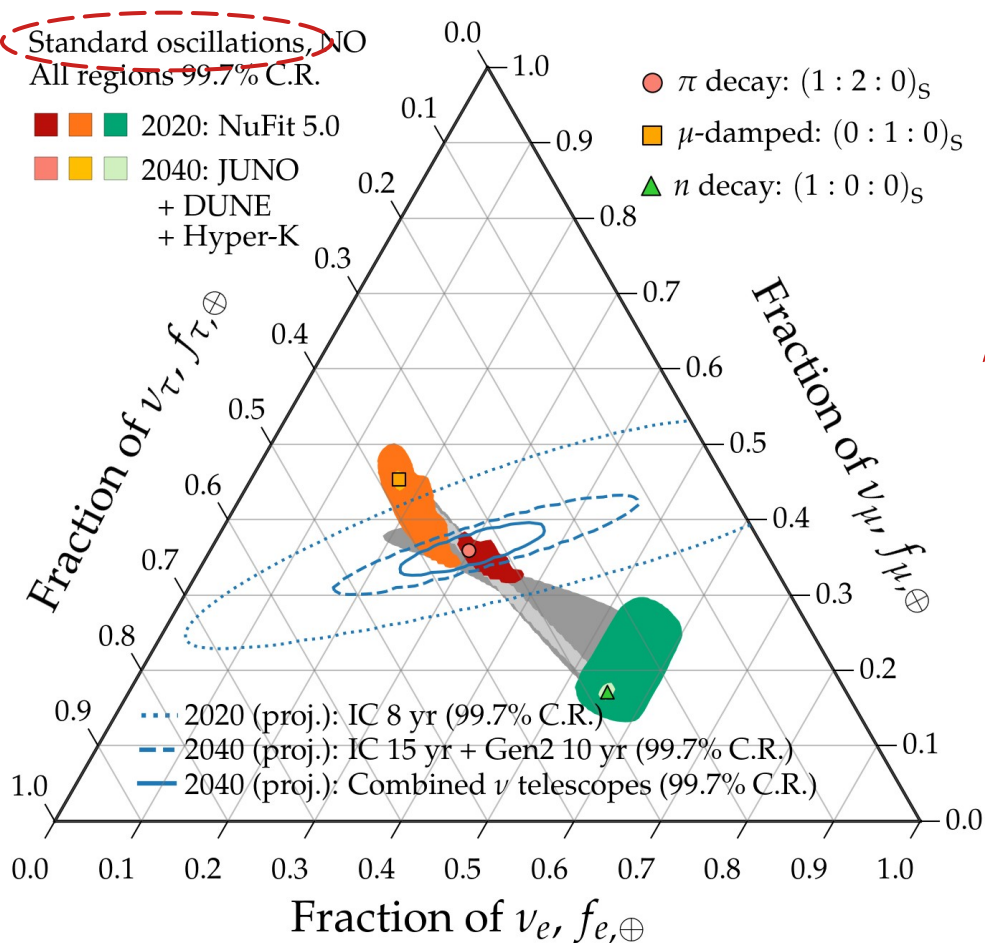
Mixing parameters known precisely: allowed flavor regions are *almost* points (already by 2030)

Measurement of flavor ratios –

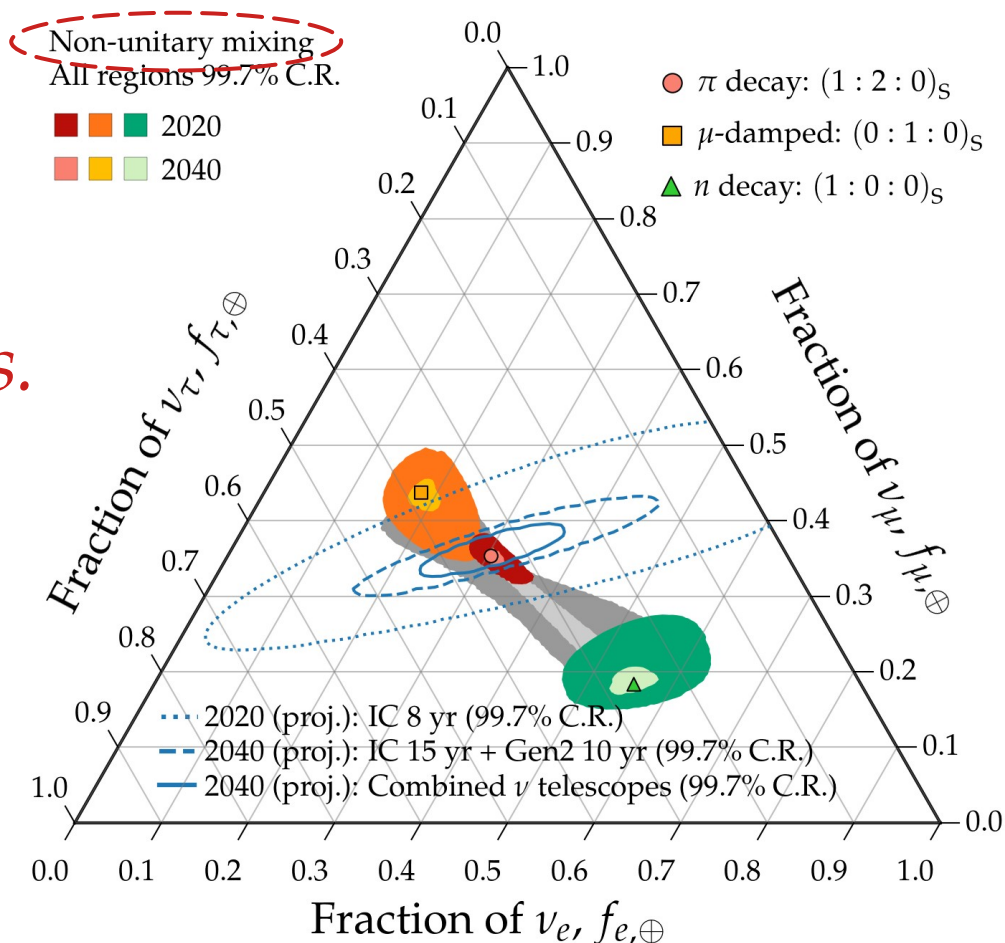
Can distinguish between similar predictions at 99.7% C.R. (3σ)

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

No unitarity? No problem

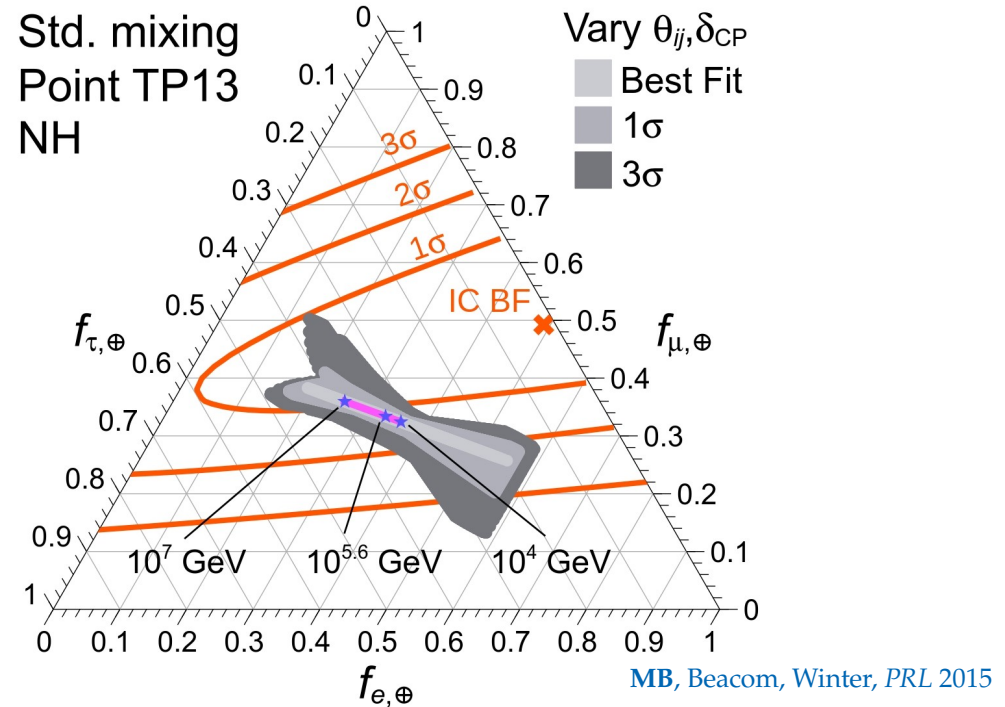
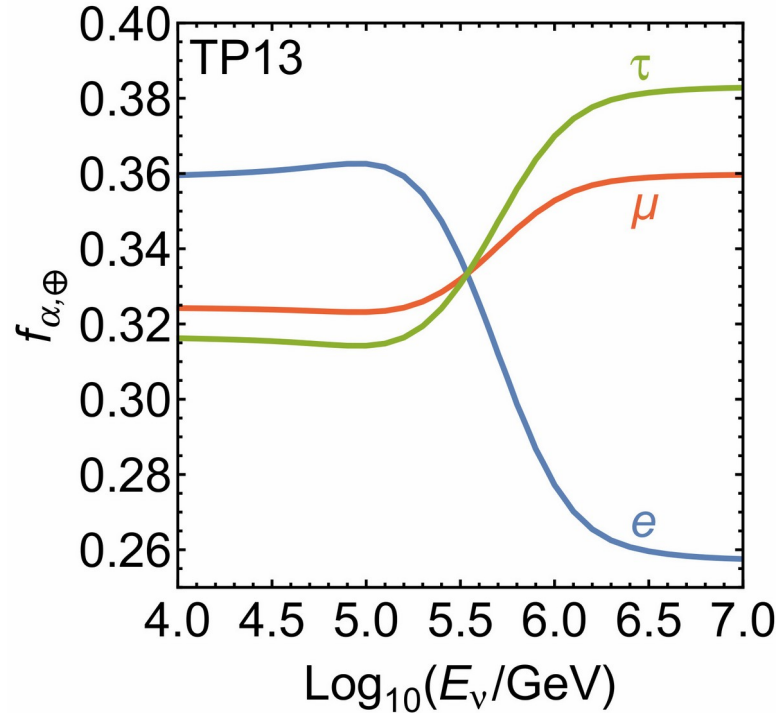


vs.



Energy dependence of the flavor composition?

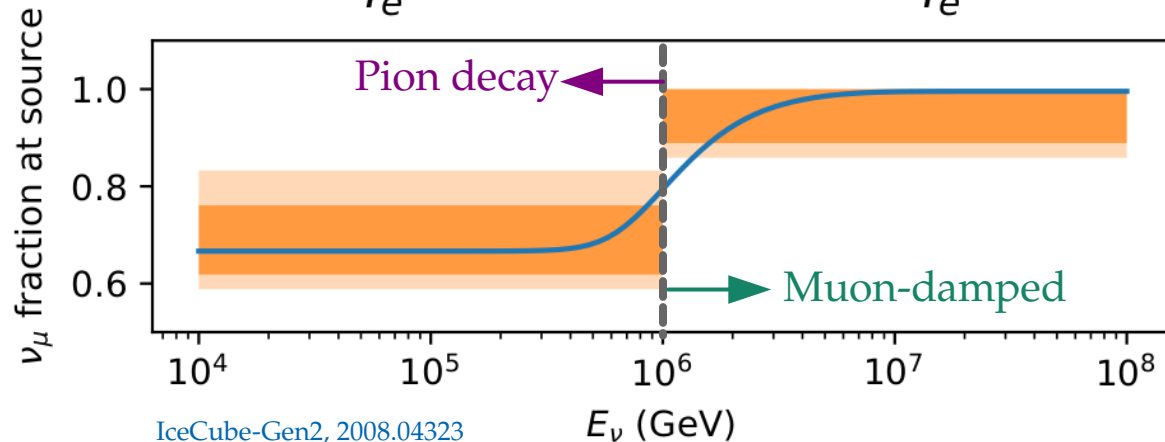
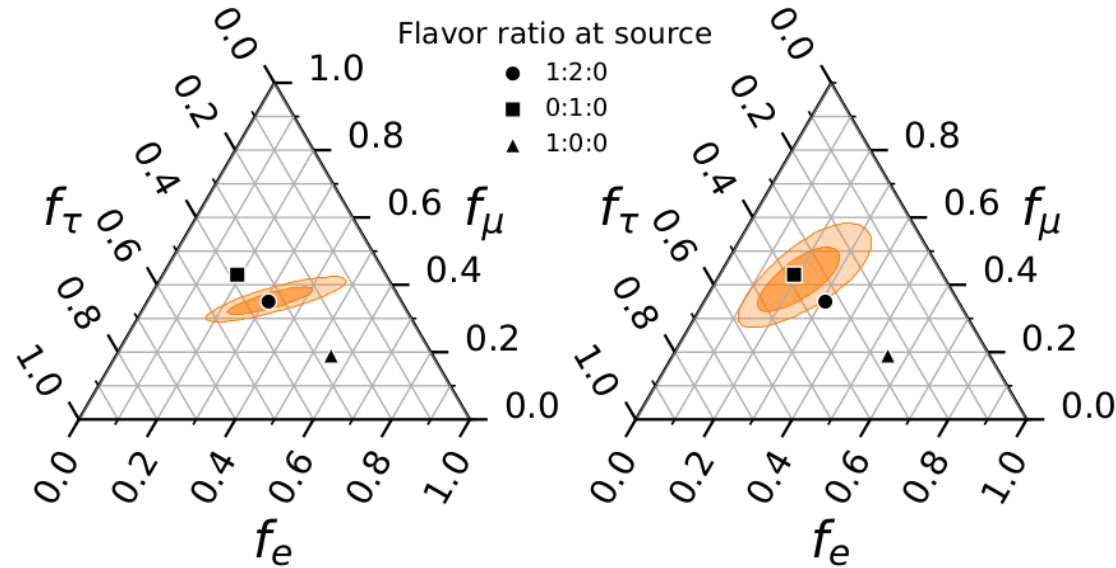
Different neutrino production channels accessible at different energies –



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

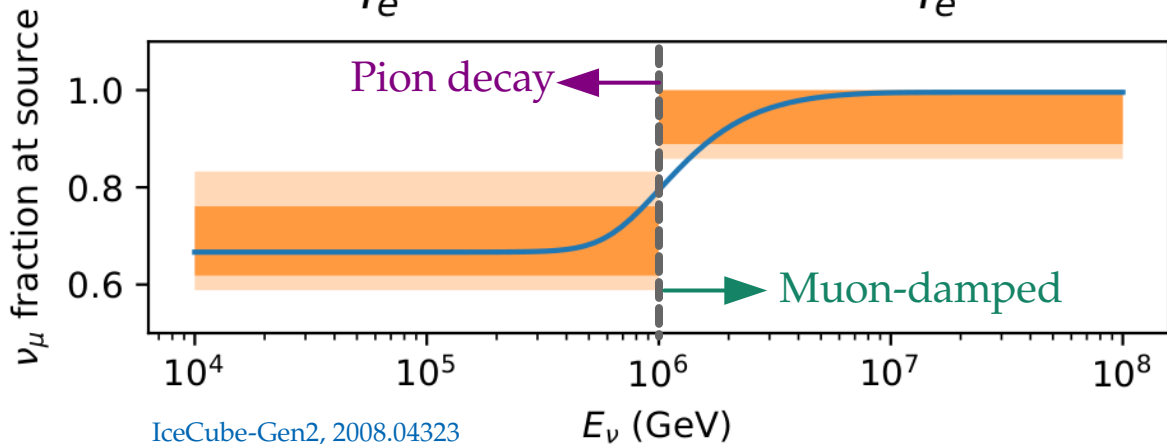
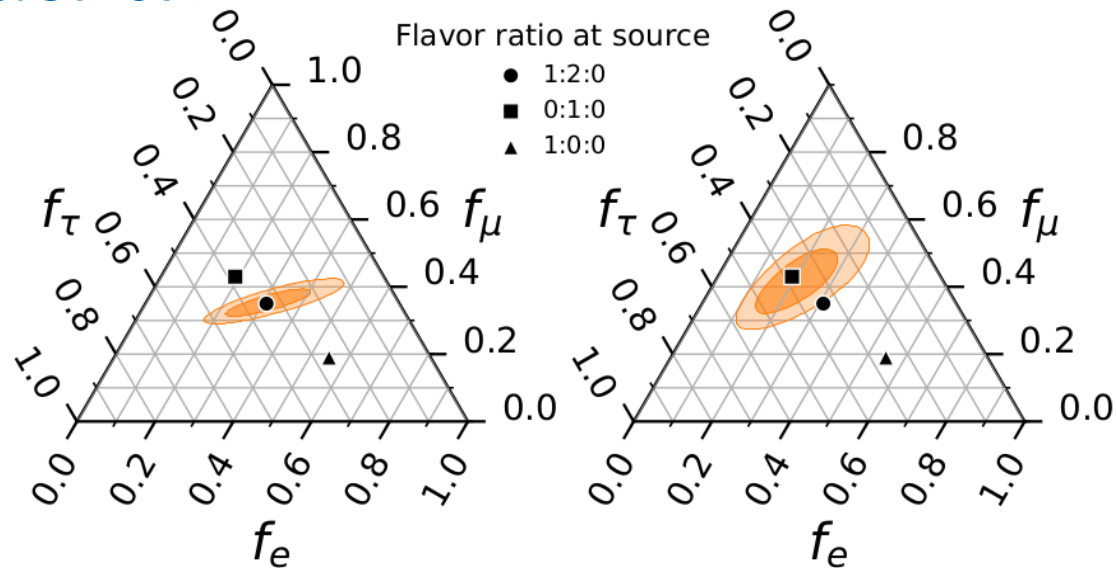
Energy dependence of flavor ratios – in IceCube-Gen2

Measured:



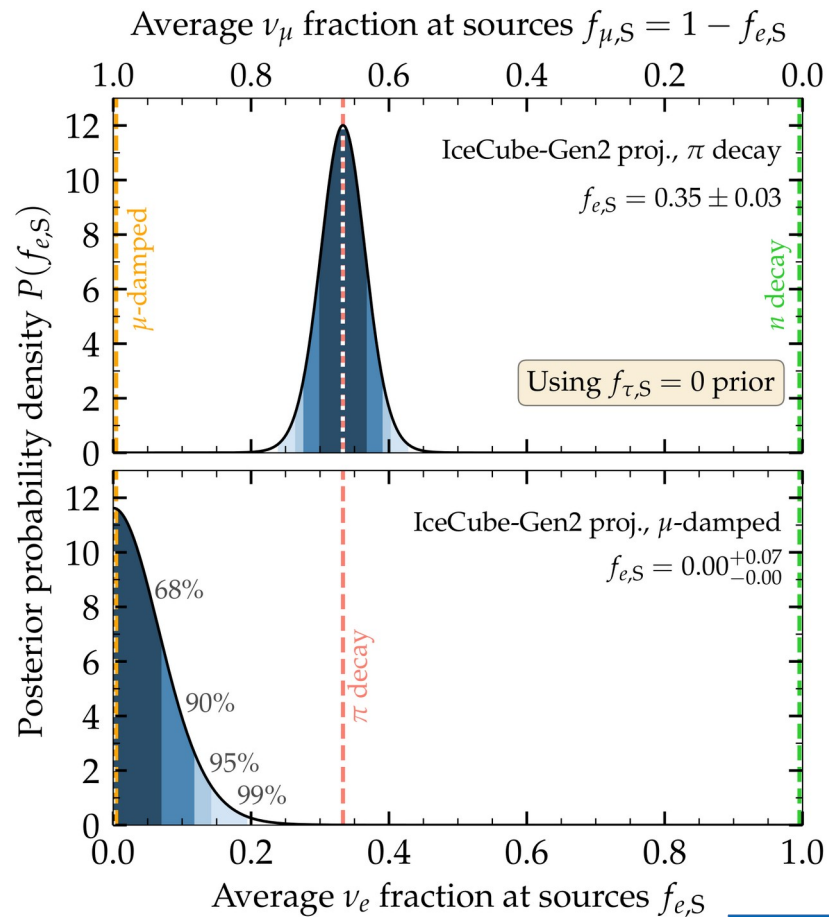
Energy dependence of flavor ratios – in IceCube-Gen2

Measured:



IceCube-Gen2, 2008.04323

Inferred (at sources):

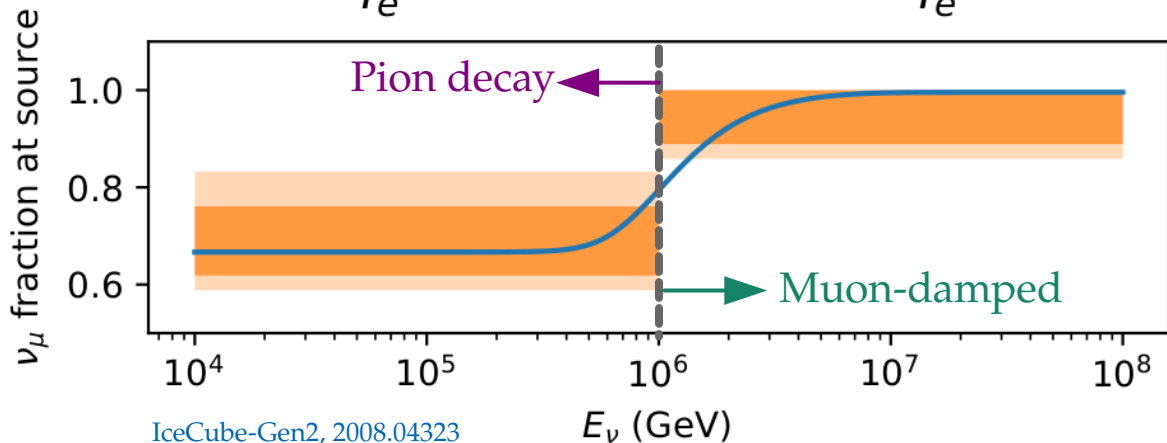
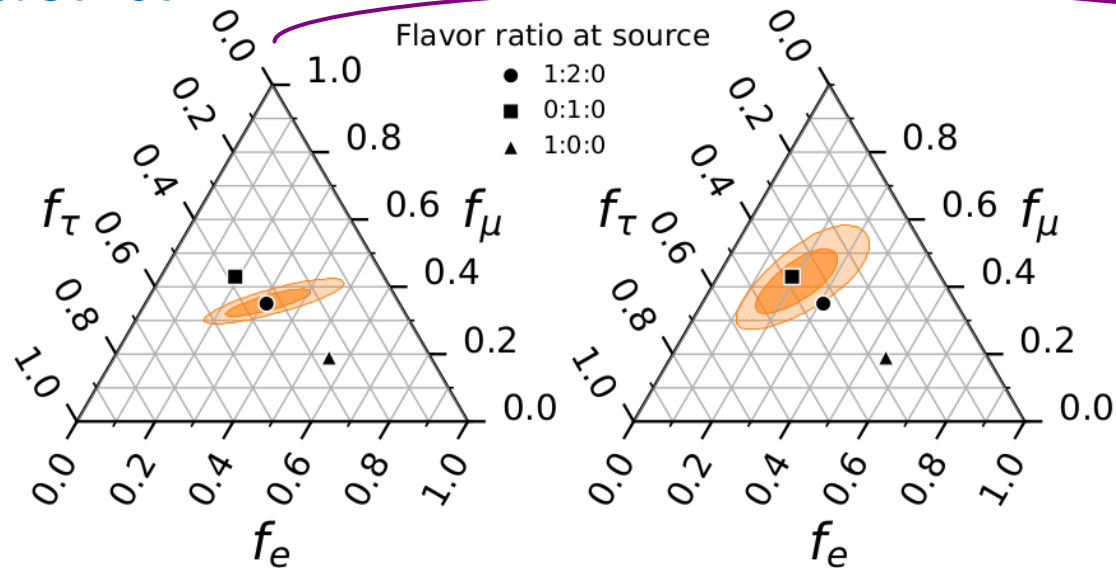


MB & Ahlers, PRL 2019

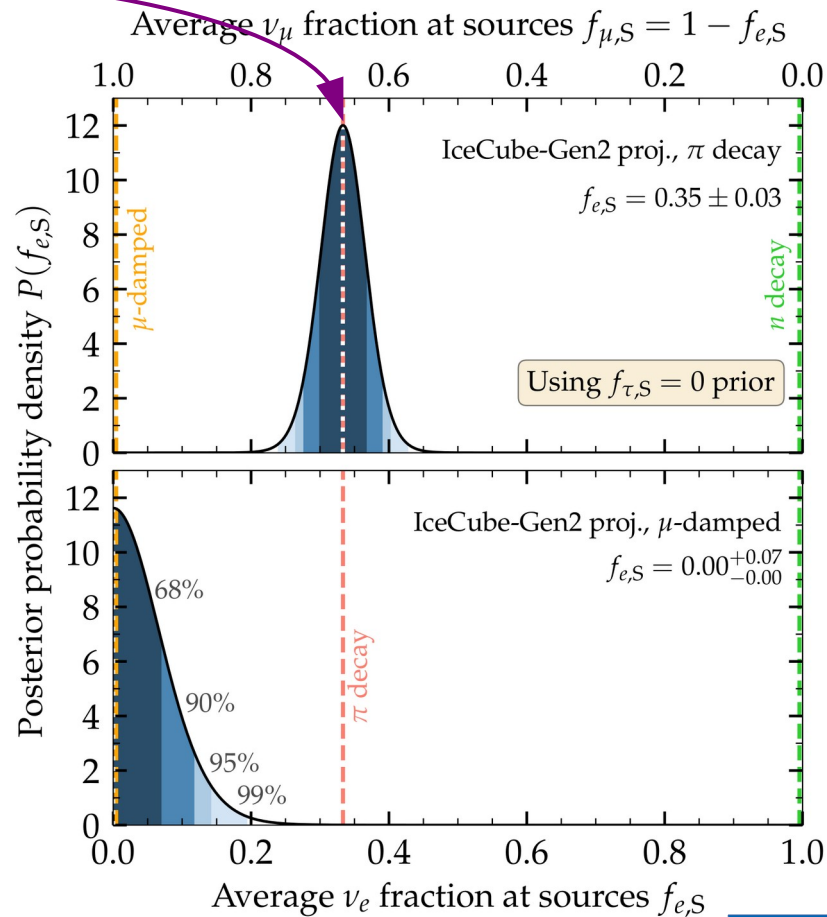
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IceCube-Gen2, 2008.04323

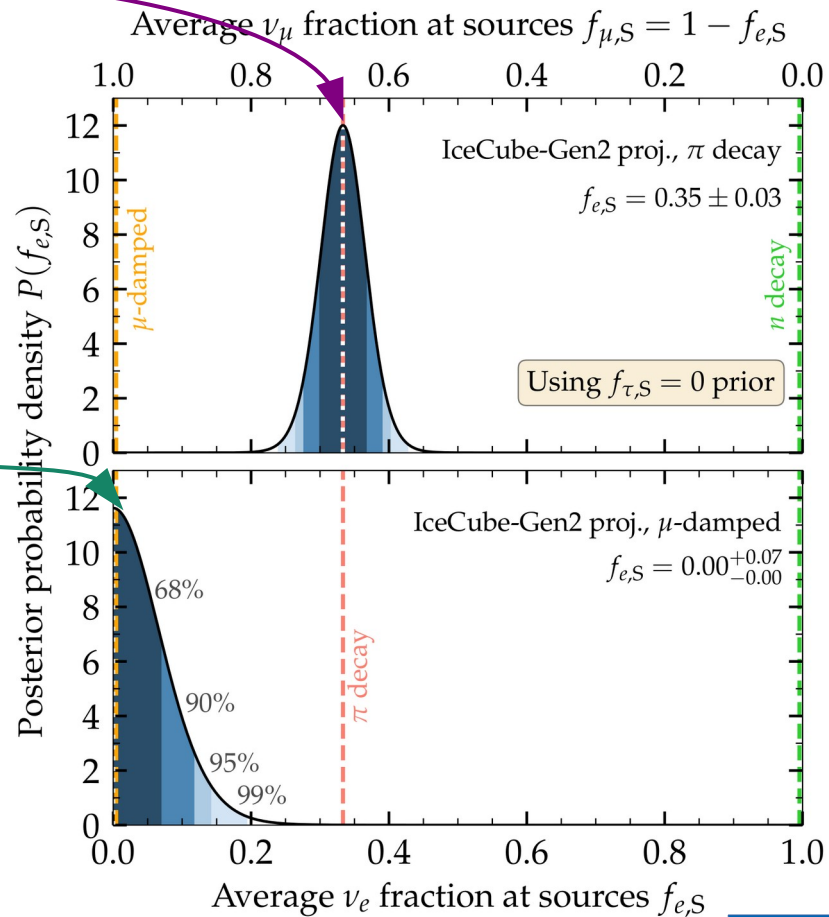
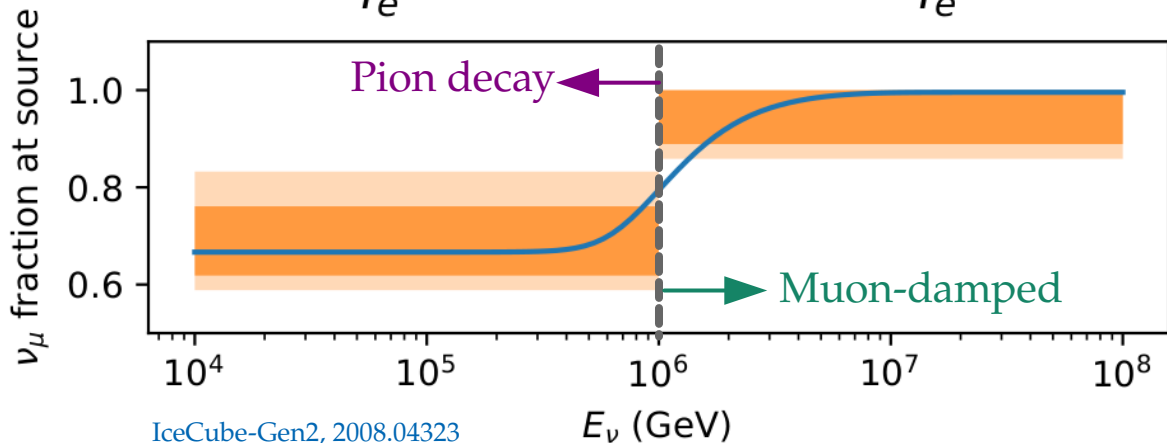
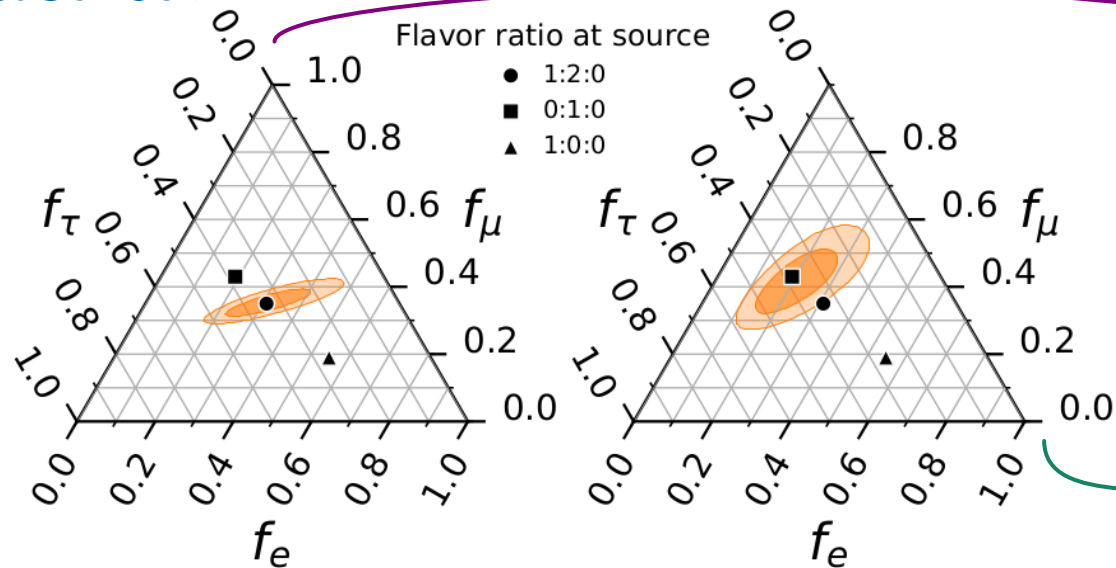


MB & Ahlers, PRL 2019

Energy dependence of flavor ratios – in IceCube-Gen2

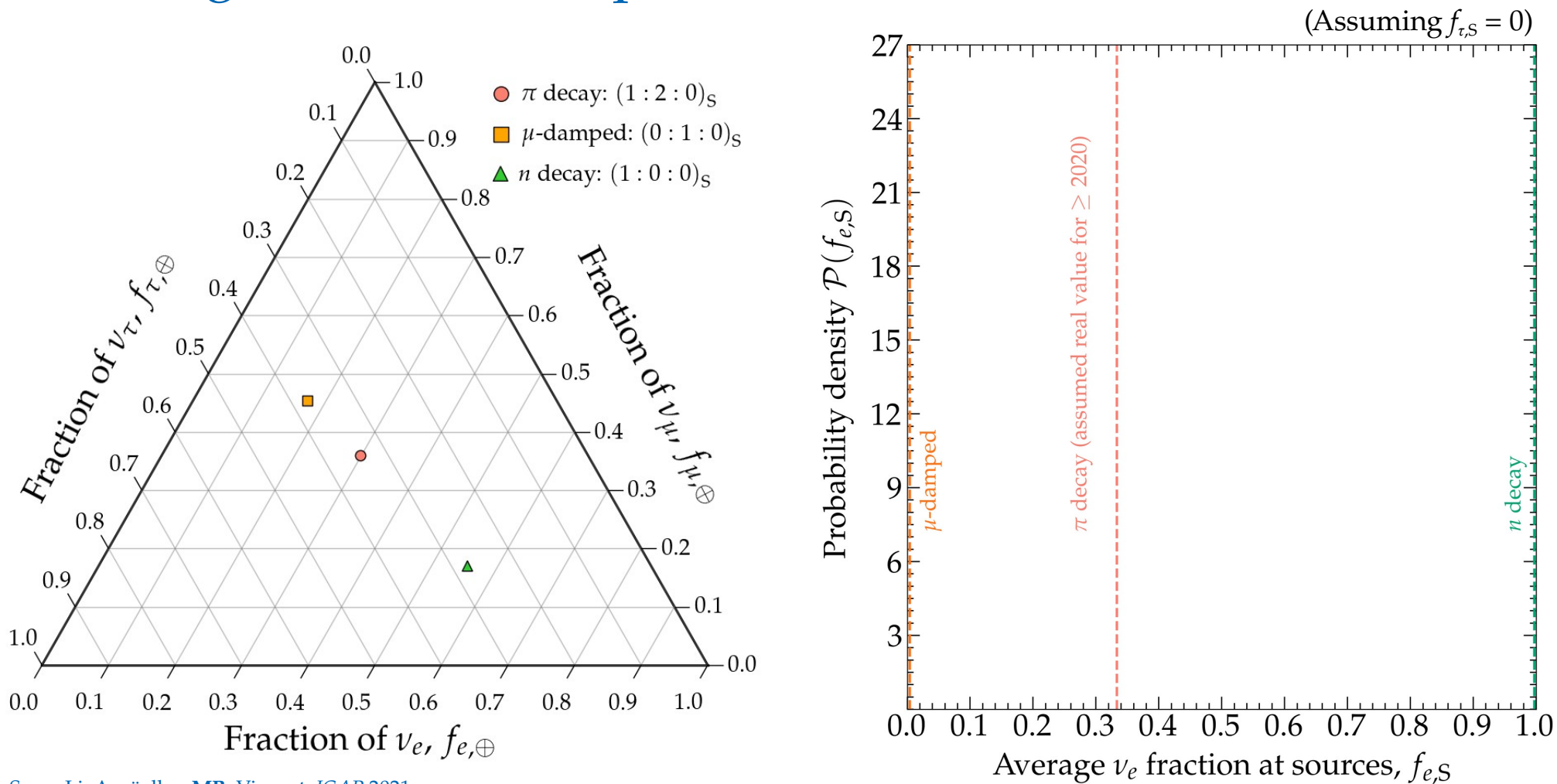
Measured:

Inferred (at sources):

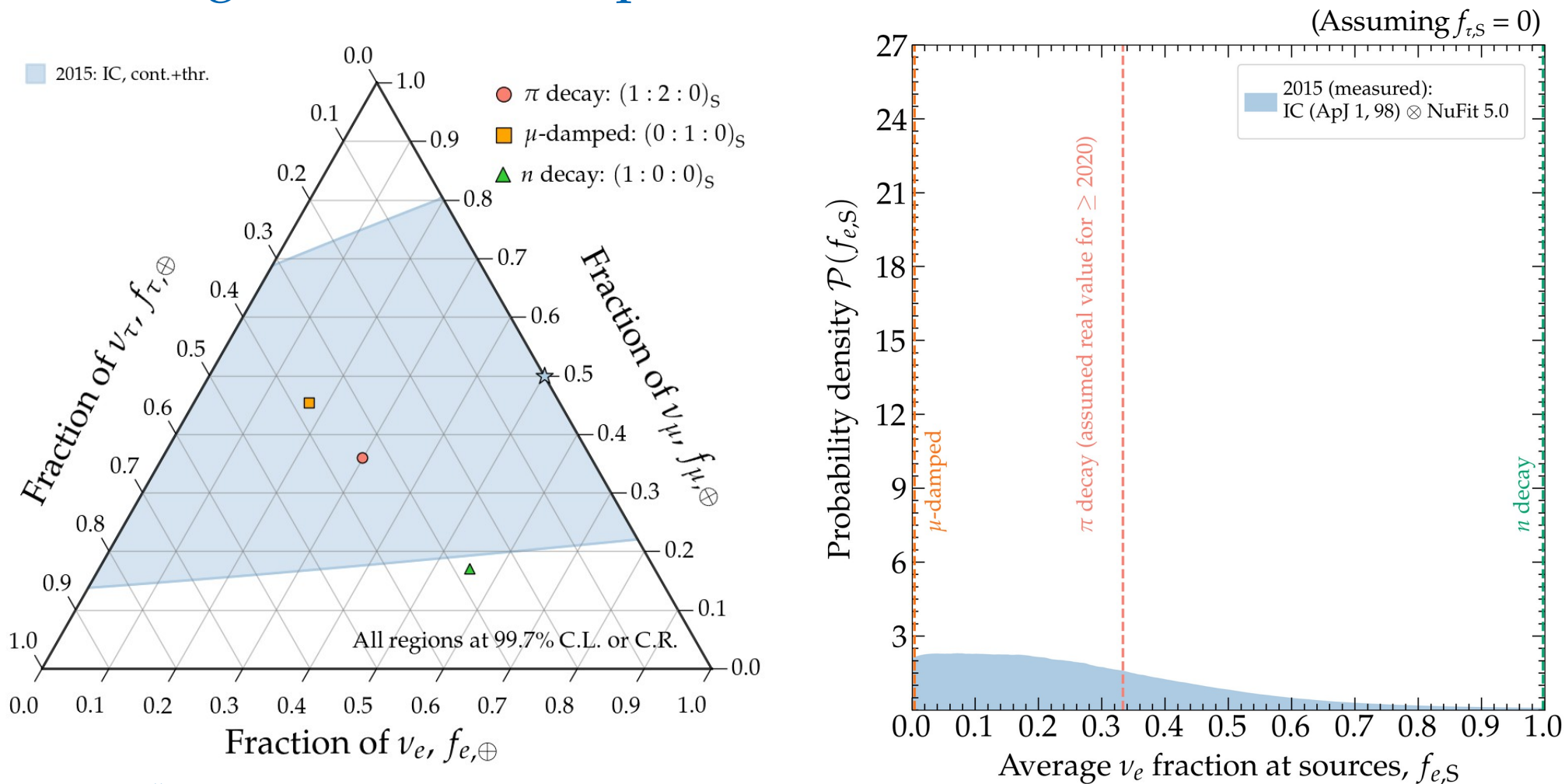


Inferring the flavor composition at the sources

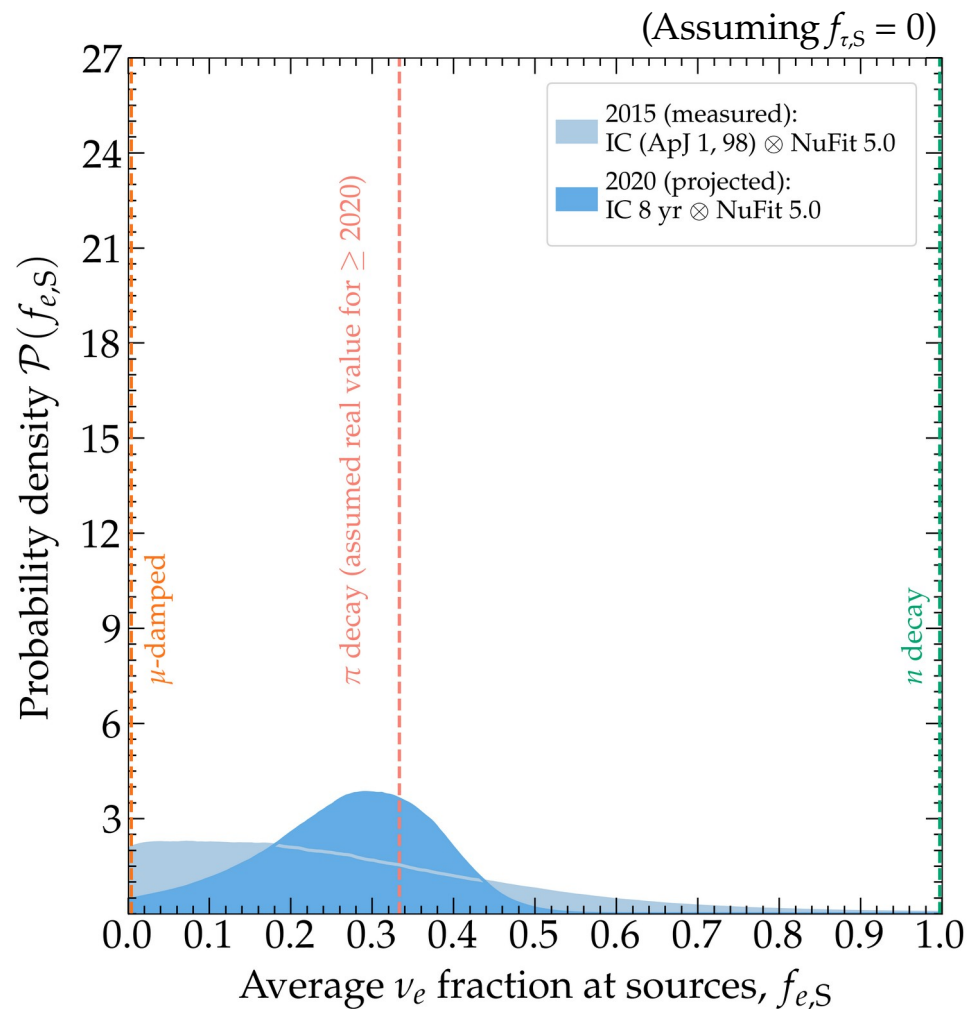
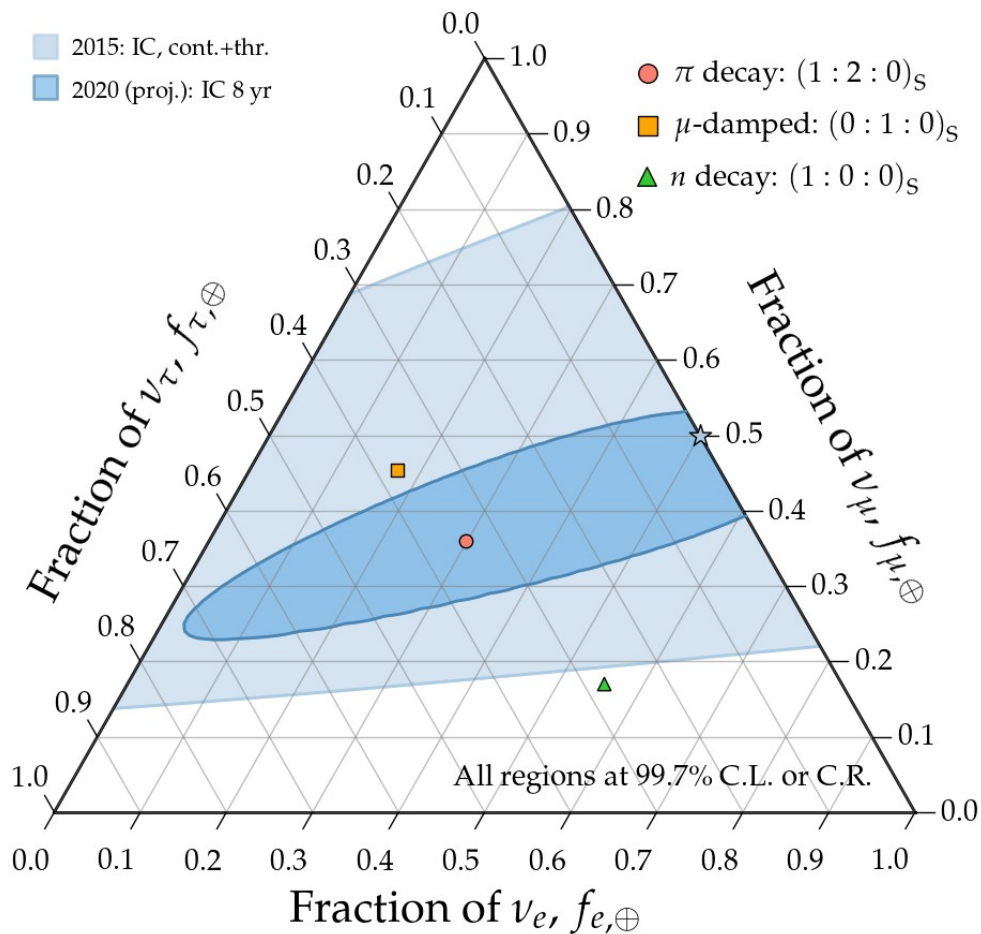
Inferring the flavor composition at the sources



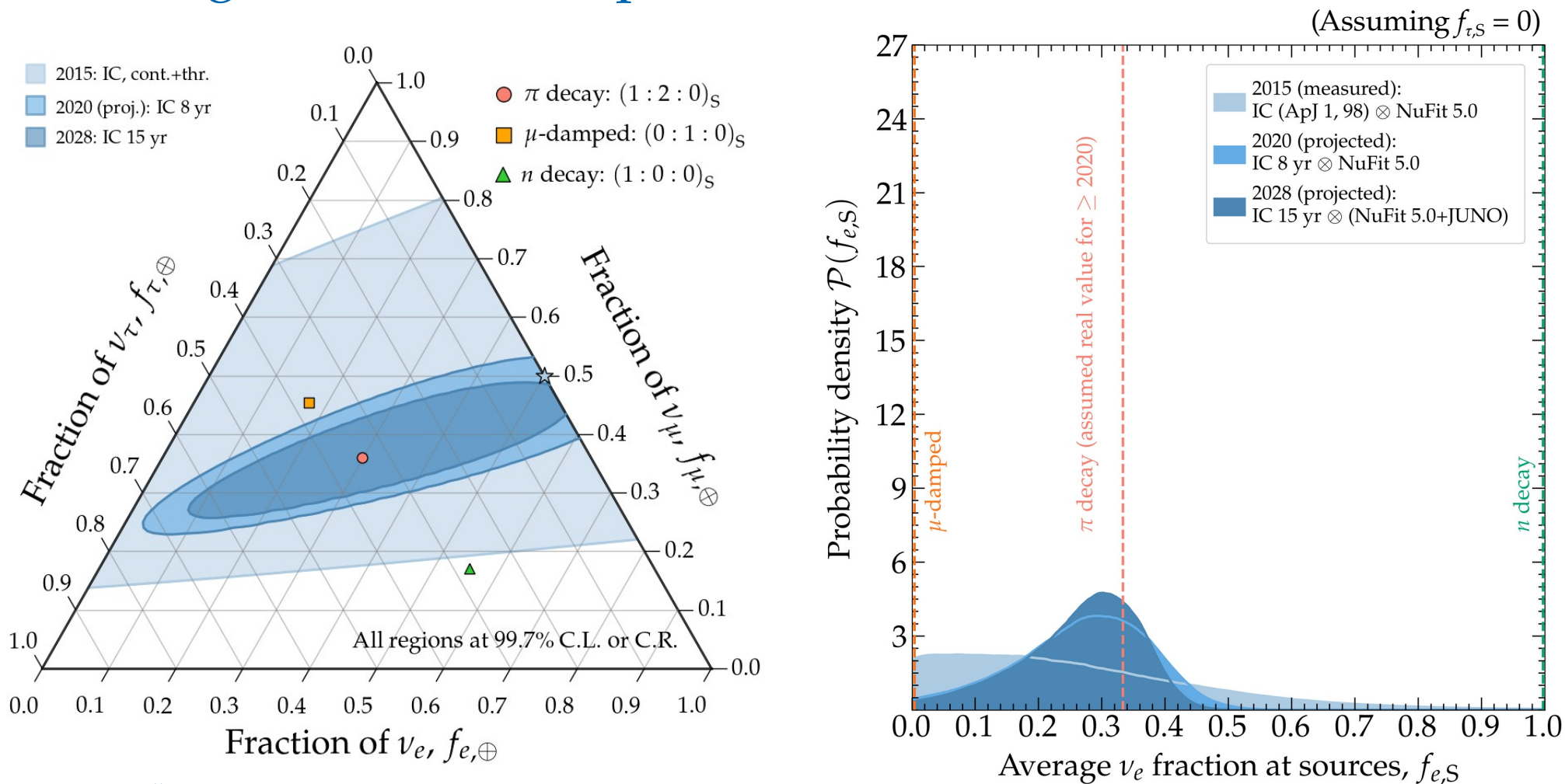
Inferring the flavor composition at the sources



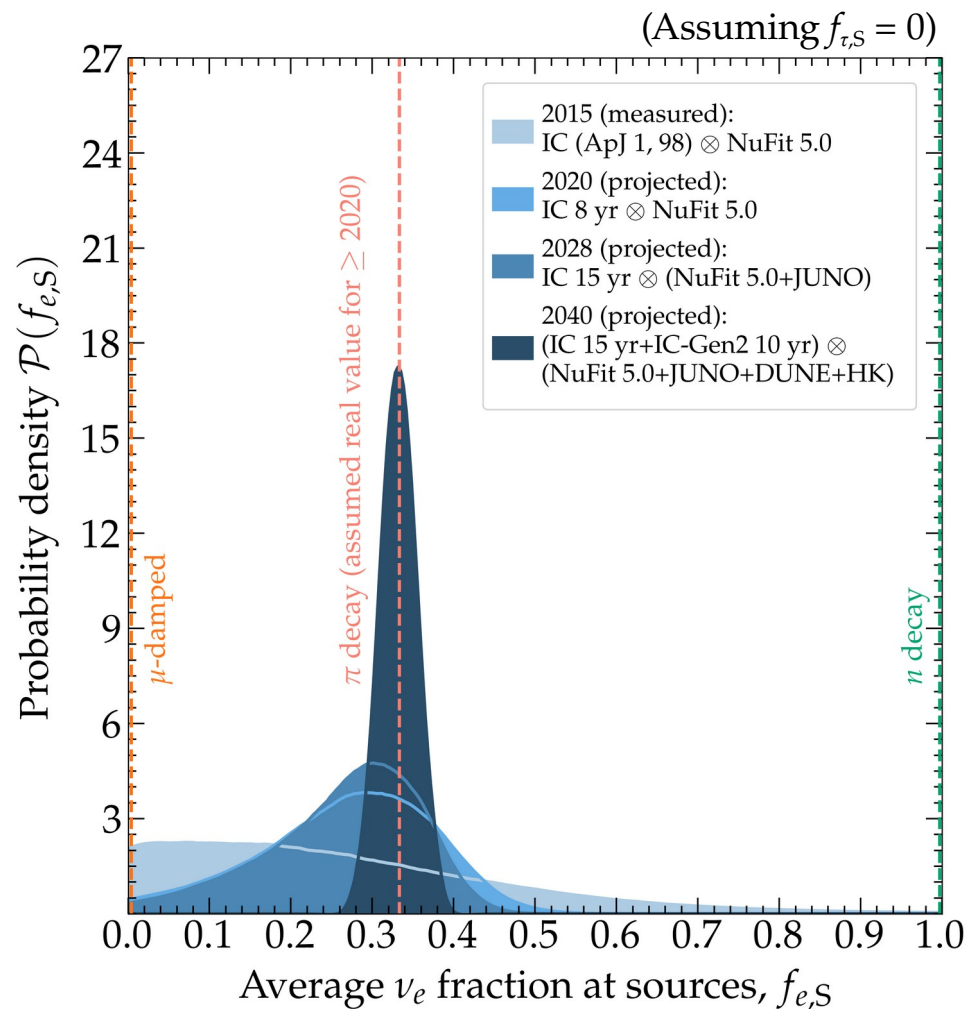
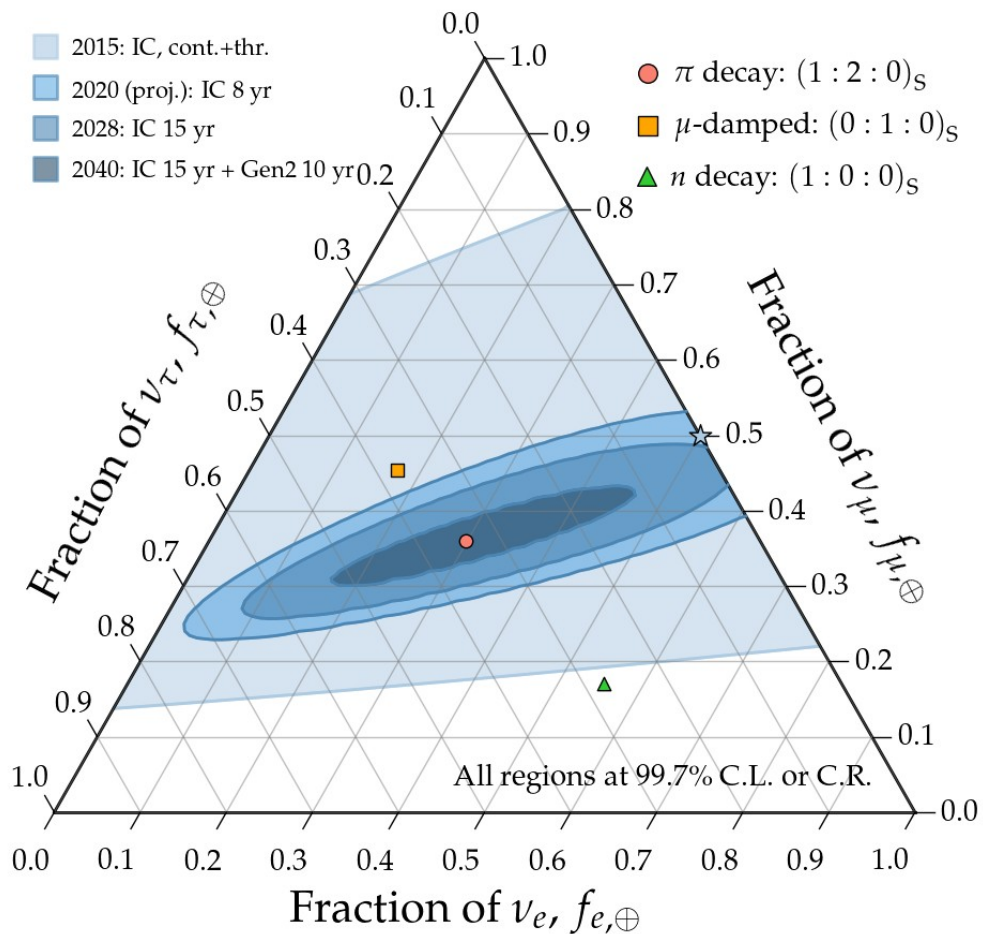
Inferring the flavor composition at the sources



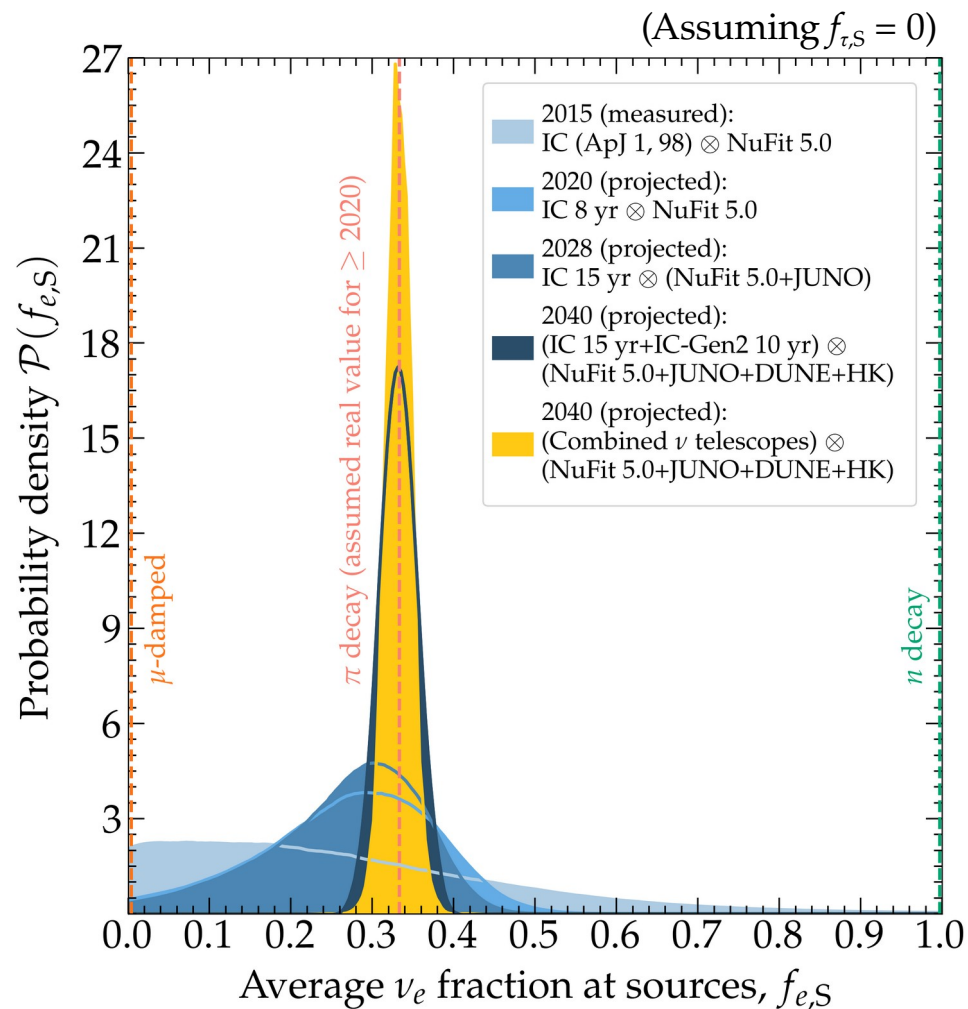
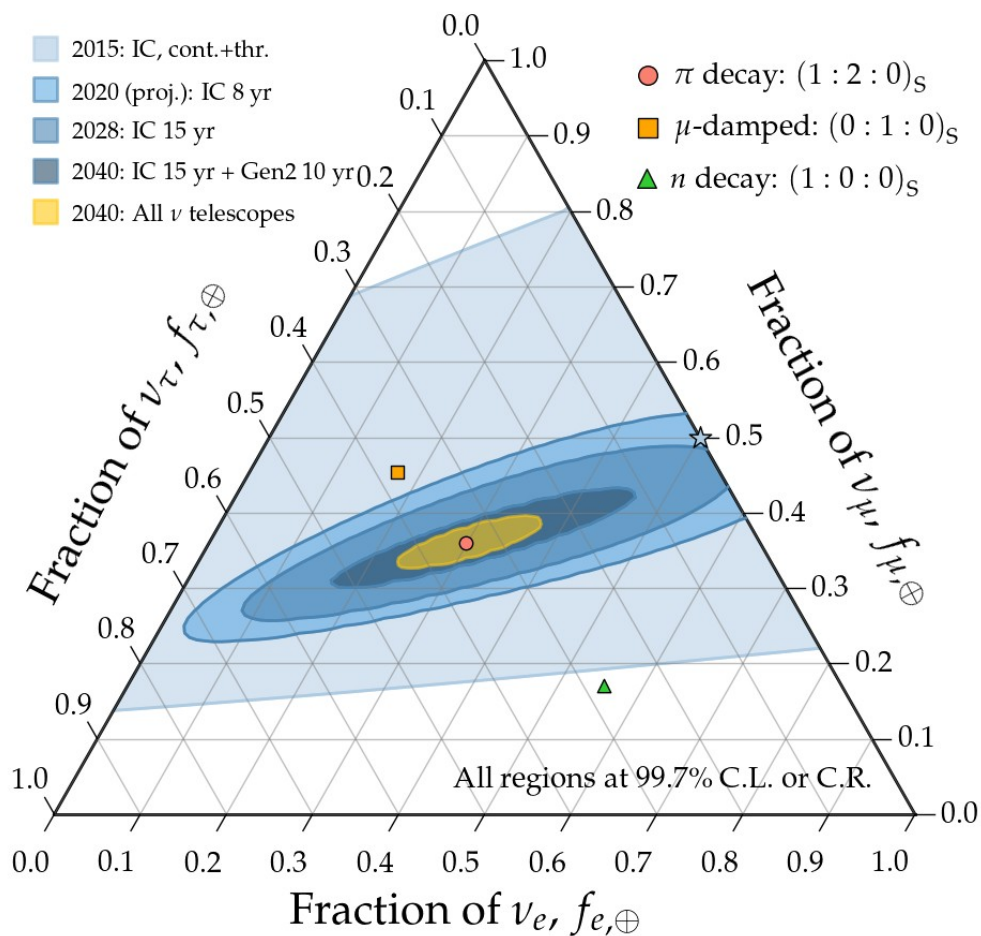
Inferring the flavor composition at the sources



Inferring the flavor composition at the sources



Inferring the flavor composition at the sources



More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

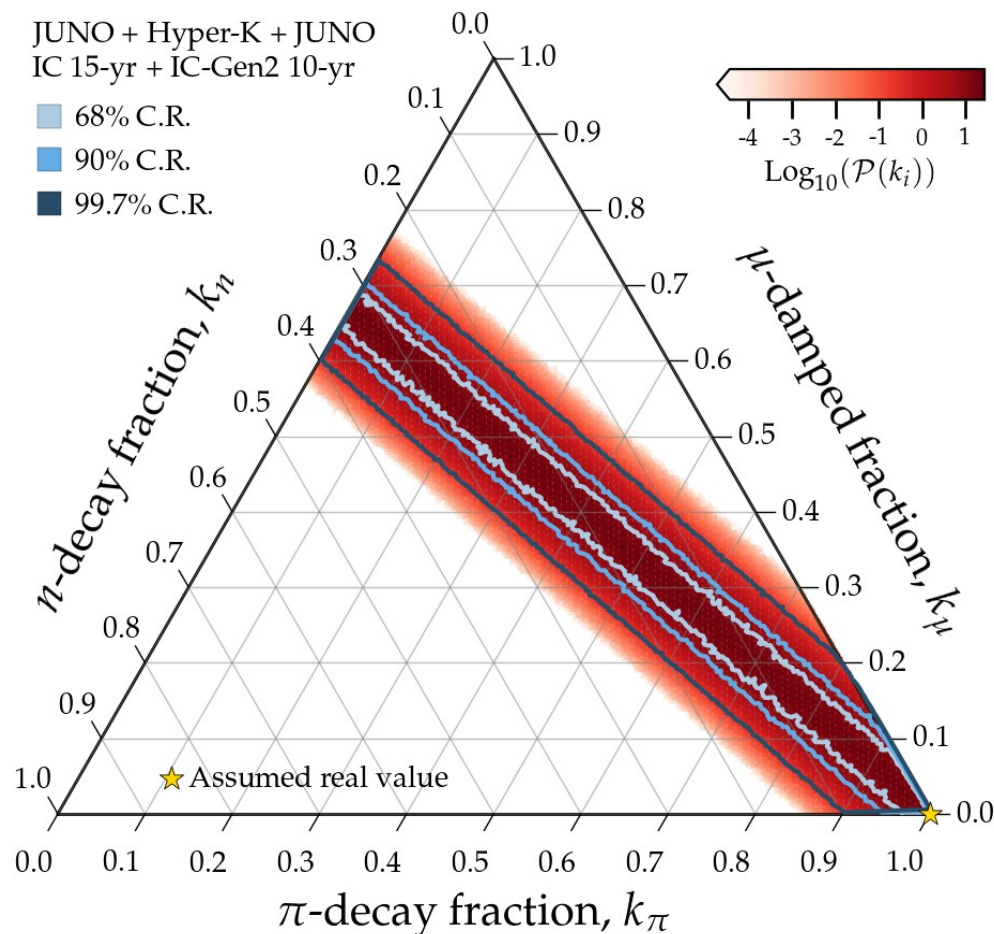
$$\mathbf{f}_S = k_\pi \underbrace{\mathbf{f}_S^\pi}_{\text{\color{red}\pi decay: (1/3, 2/3, 0)}} + k_\mu \underbrace{\mathbf{f}_S^\mu}_{\text{\color{brown}\mu damped: (0, 1, 0)}} + k_n \underbrace{\mathbf{f}_S^n}_{\text{\color{teal}n decay: (1, 0, 0)}}$$

Propagate to Earth
 $\downarrow$
 $\mathbf{f}_\oplus$

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

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

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



More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

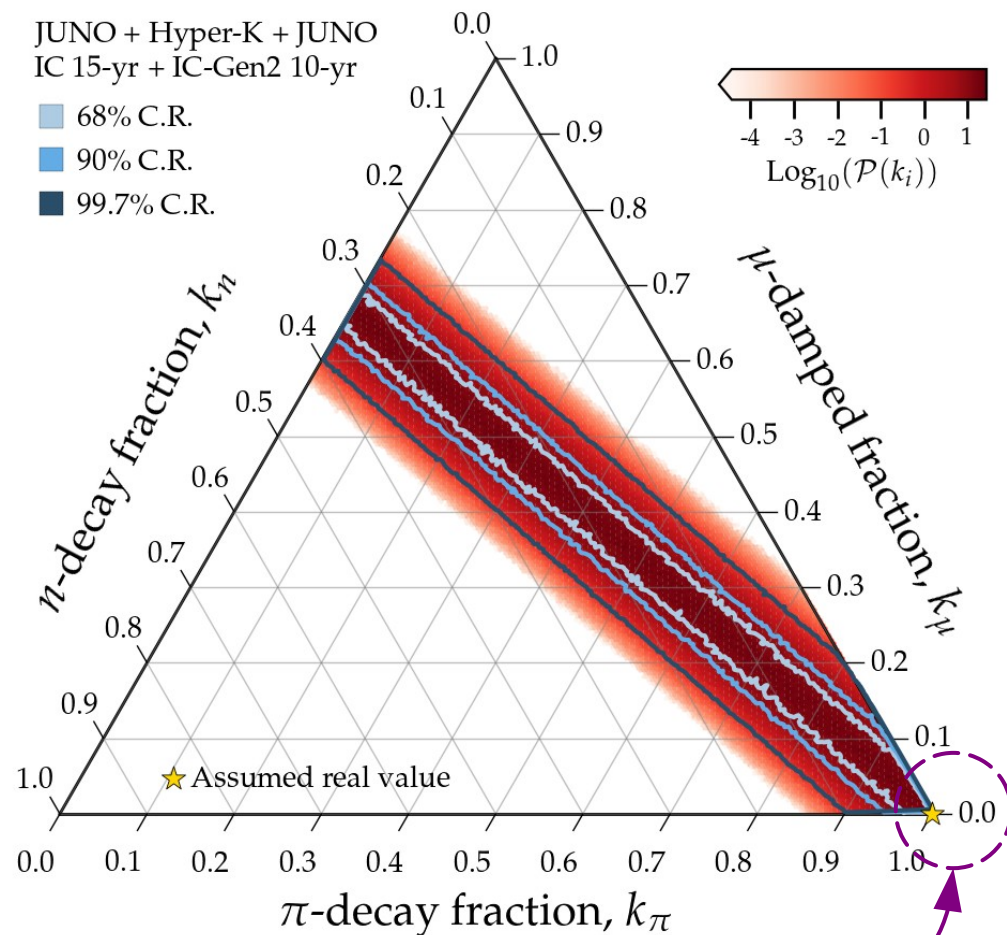
$$\mathbf{f}_S = k_\pi \underbrace{\mathbf{f}_S^\pi}_{\text{\color{red}\pi decay: (1/3, 2/3, 0)}} + k_\mu \underbrace{\mathbf{f}_S^\mu}_{\text{\color{brown}\mu damped: (0, 1, 0)}} + k_n \underbrace{\mathbf{f}_S^n}_{\text{\color{teal}n decay: (1, 0, 0)}}$$

Propagate to Earth
 $\downarrow$
 $\mathbf{f}_\oplus$

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

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

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



We do recover the real value

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

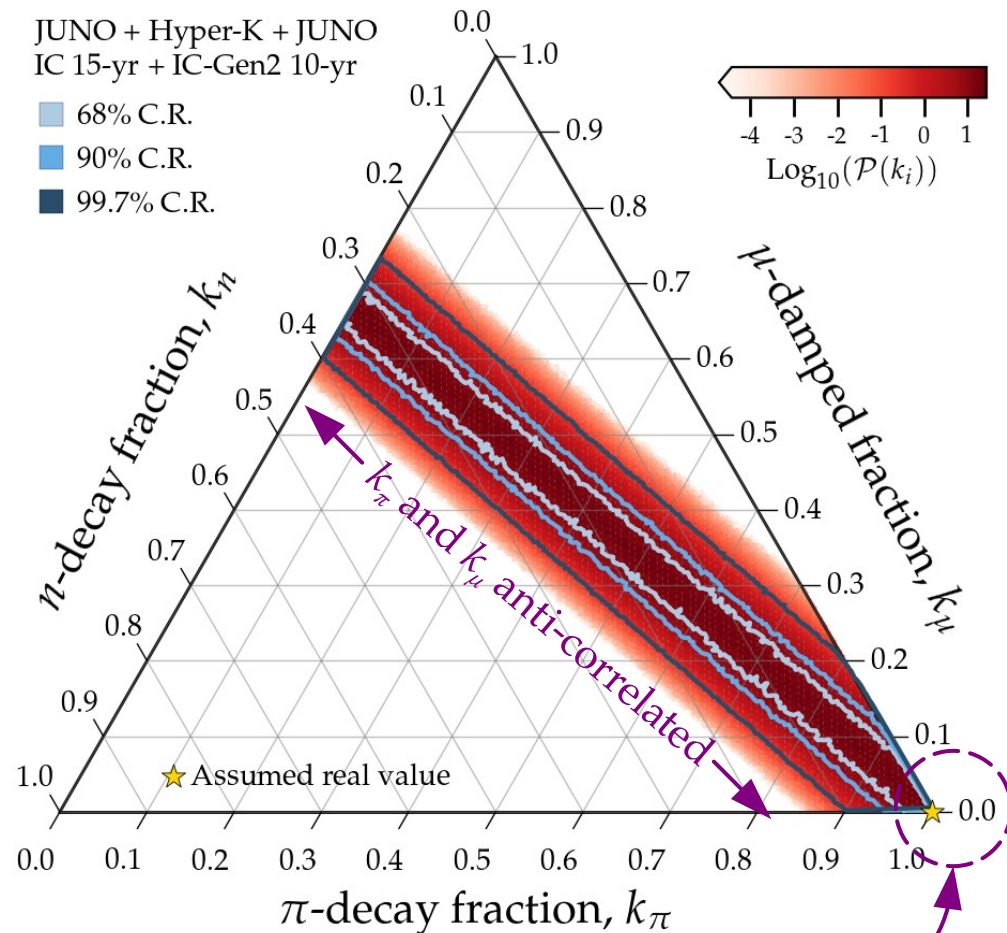
$$\mathbf{f}_S = k_\pi \underbrace{\mathbf{f}_S^\pi}_{\text{\color{red}\pi decay: (1/3, 2/3, 0)}} + k_\mu \underbrace{\mathbf{f}_S^\mu}_{\text{\color{orange}\mu damped: (0, 1, 0)}} + k_n \underbrace{\mathbf{f}_S^n}_{\text{\color{teal}n decay: (1, 0, 0)}}$$

Propagate to Earth
 $\downarrow$
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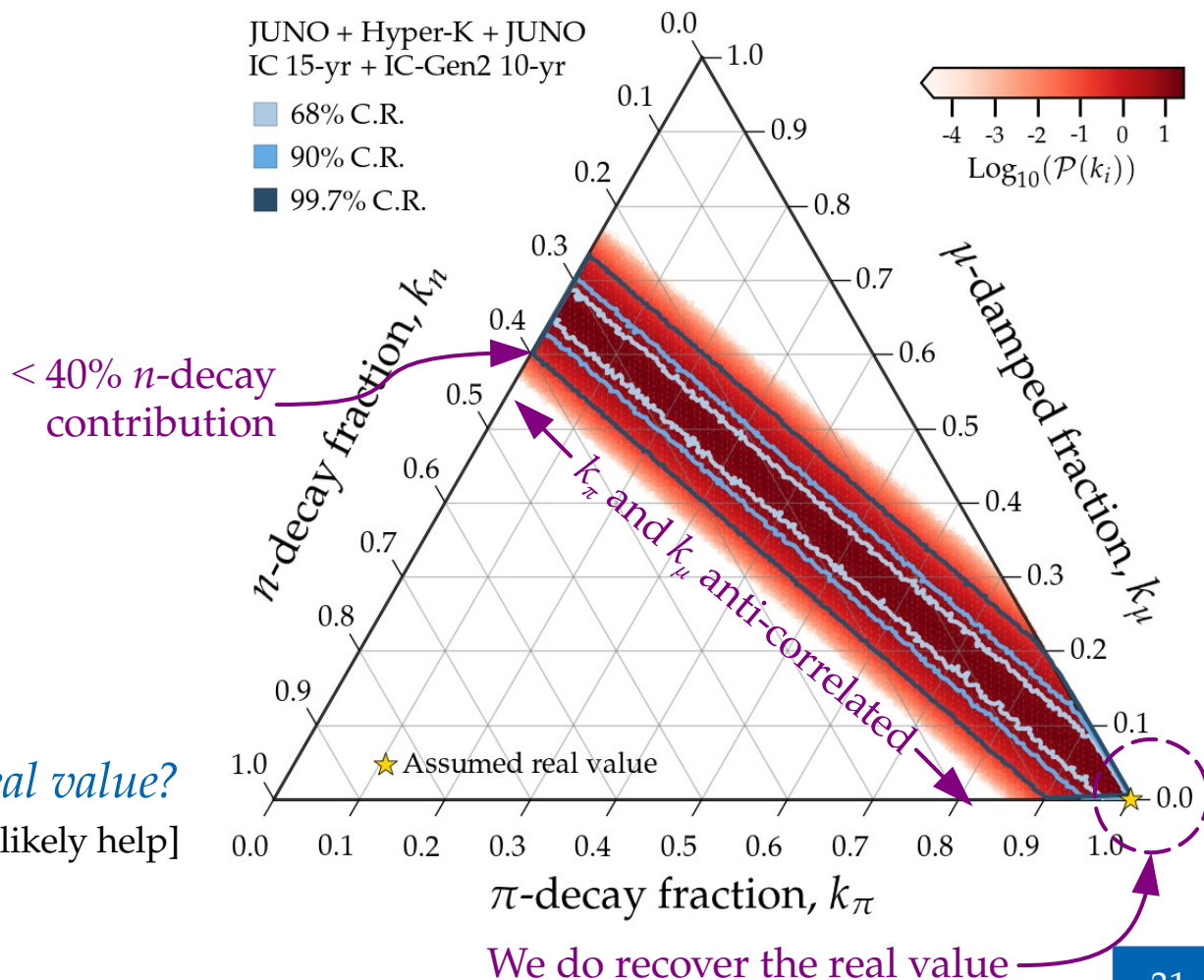
$$\mathbf{f}_S = k_\pi \underbrace{\mathbf{f}_S^\pi}_{\text{\color{red}\pi decay: (1/3, 2/3, 0)}} + k_\mu \underbrace{\mathbf{f}_S^\mu}_{\text{\color{orange}\mu damped: (0, 1, 0)}} + k_n \underbrace{\mathbf{f}_S^n}_{\text{\color{teal}n decay: (1, 0, 0)}}$$

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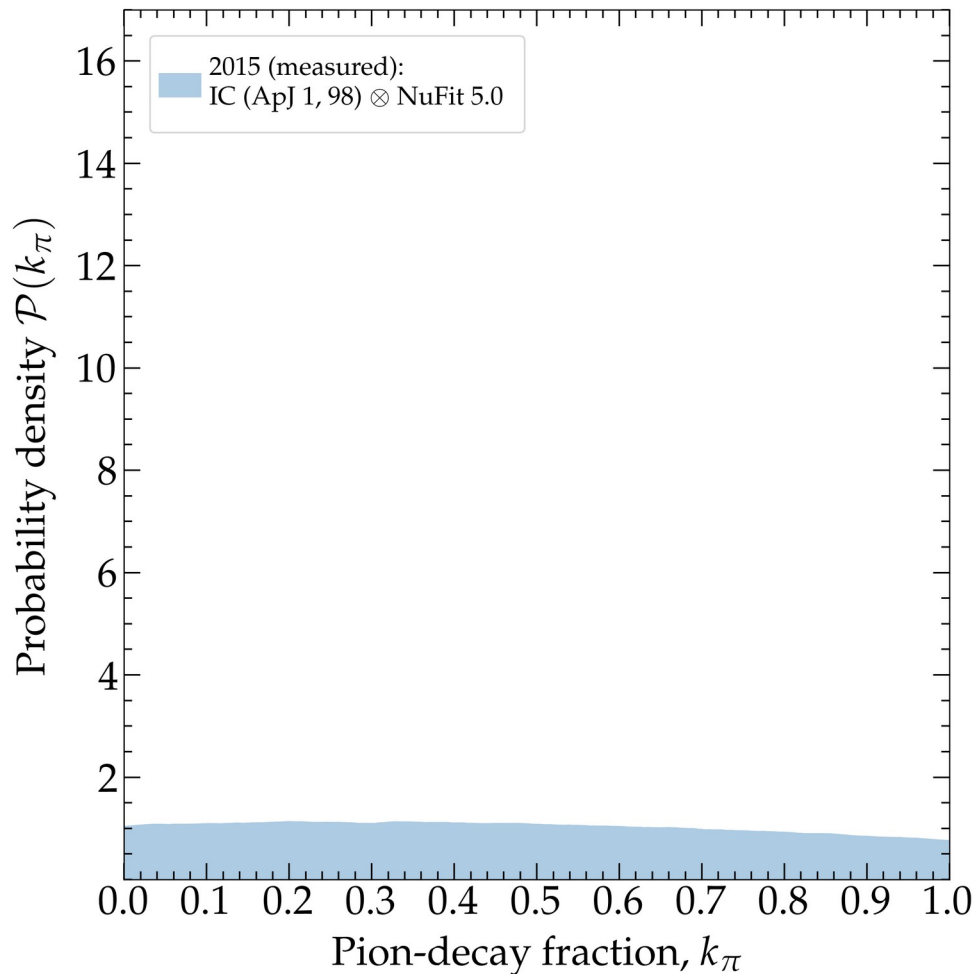
Propagate to Earth

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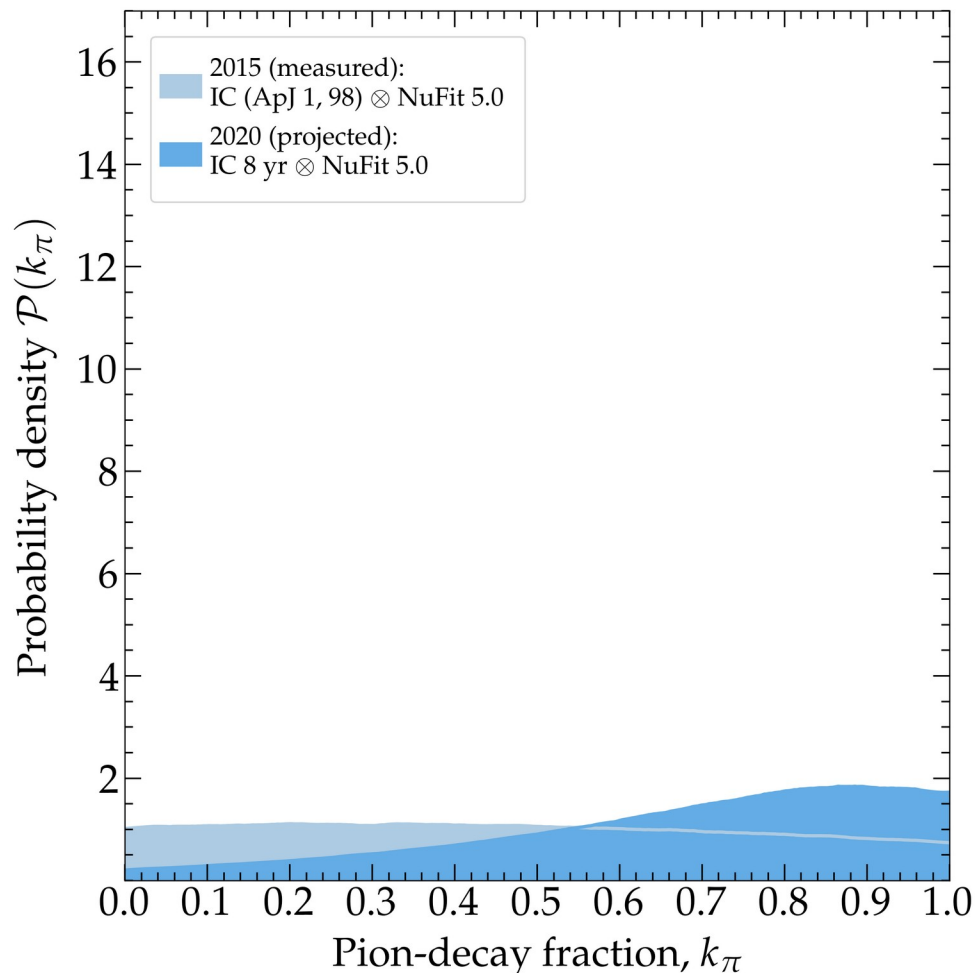
Propagate to Earth

$$\downarrow$$
$$f_\oplus$$

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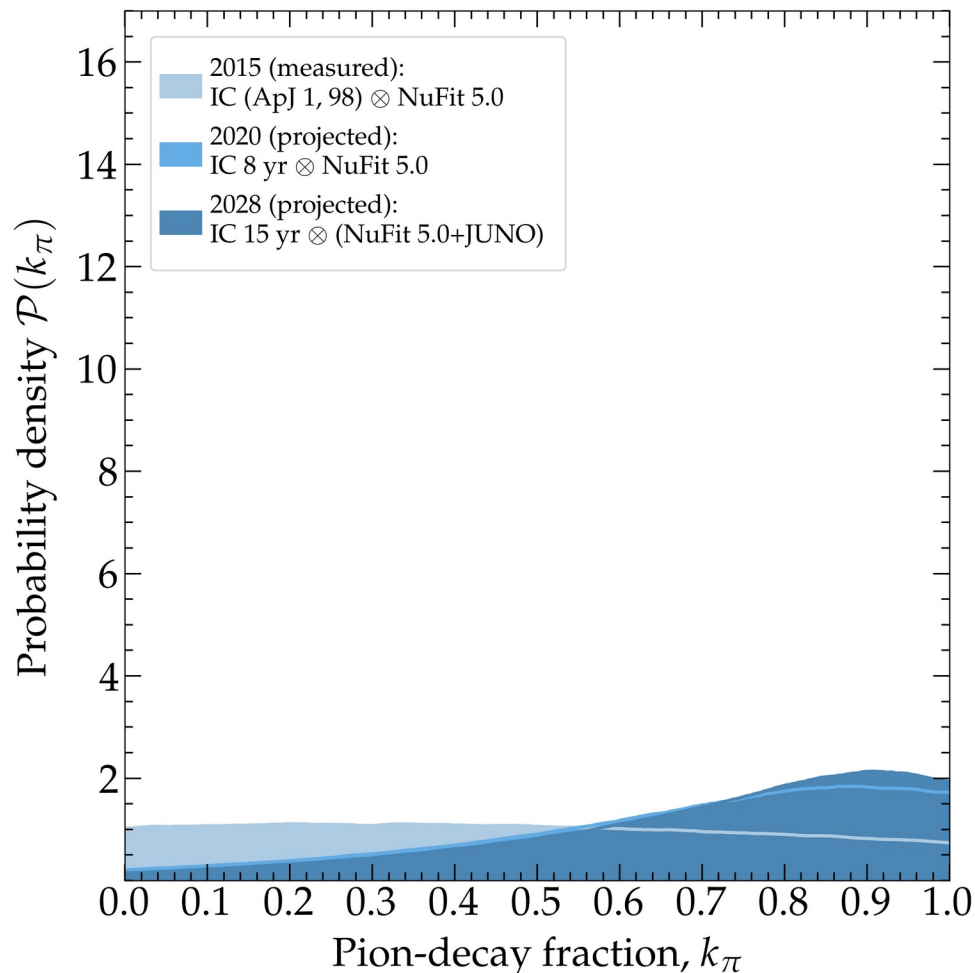
Propagate to Earth

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$$f_\oplus$$

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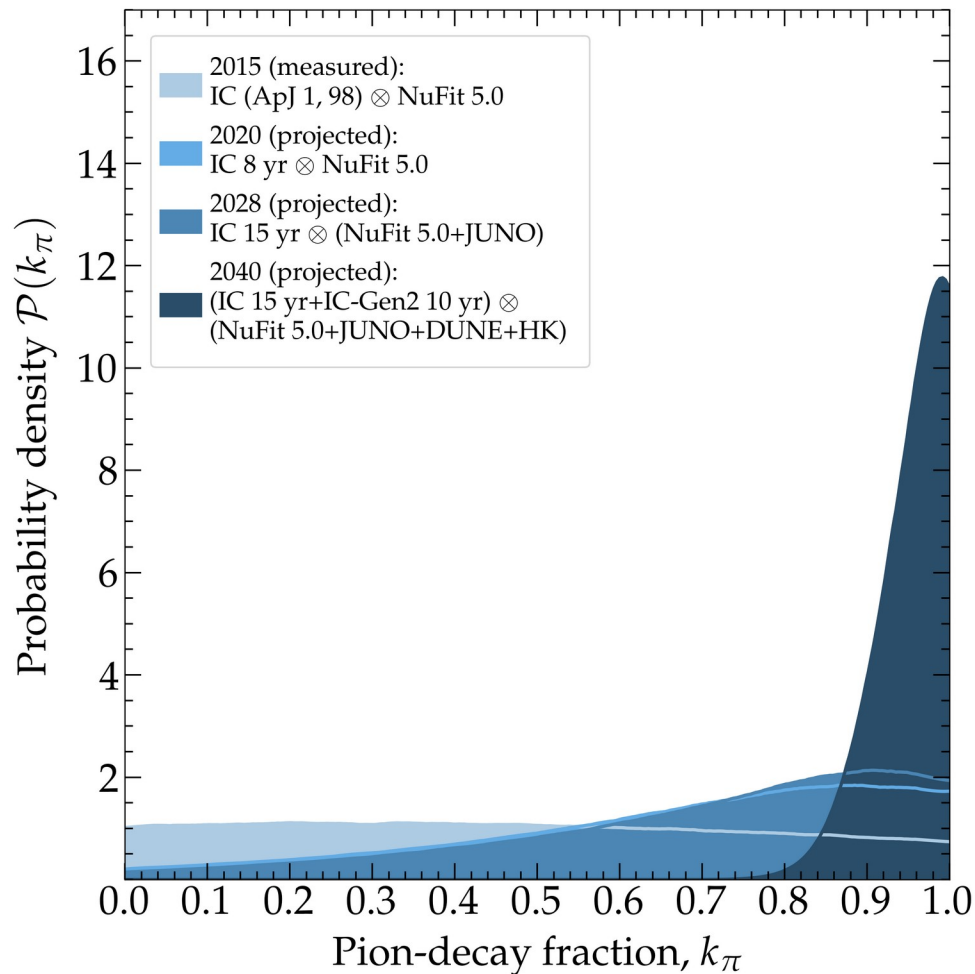
Propagate to Earth

$f_\oplus$

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



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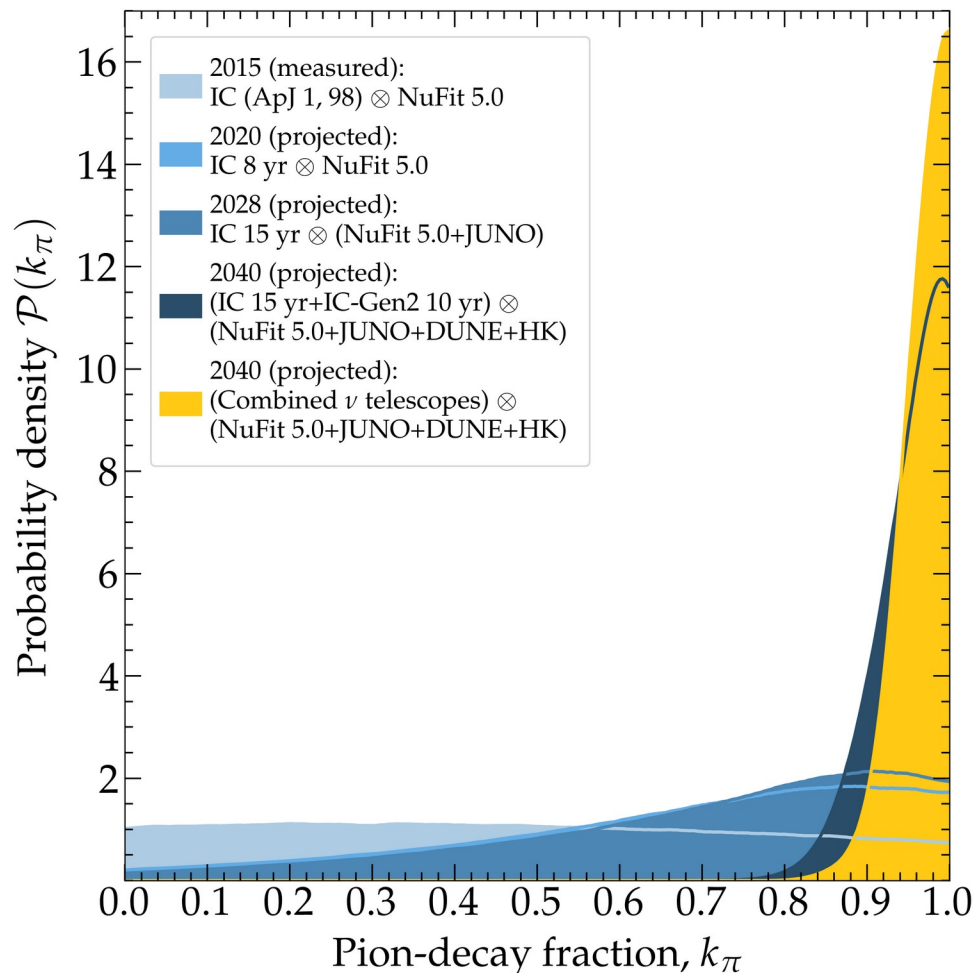
$$f_S = k_\pi \underbrace{f_S^\pi}_{\text{\color{red}\pi decay: (1/3, 2/3, 0)}} + k_\mu \underbrace{f_S^\mu}_{\text{\color{brown}\mu damped: (0, 1, 0)}} + k_n \underbrace{f_S^n}_{\text{\color{teal}n decay: (1, 0, 0)}}$$

Propagate to Earth
↓
 $f_\oplus$

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

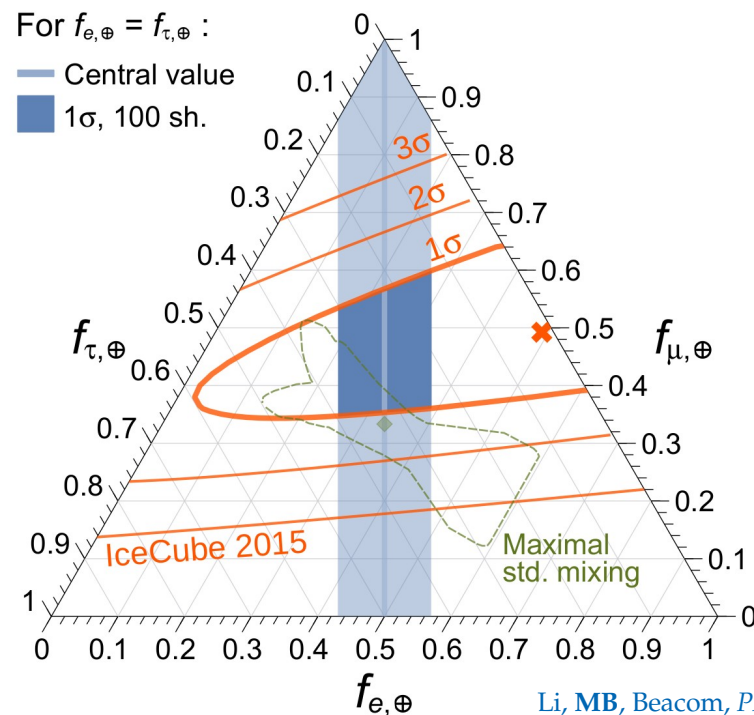
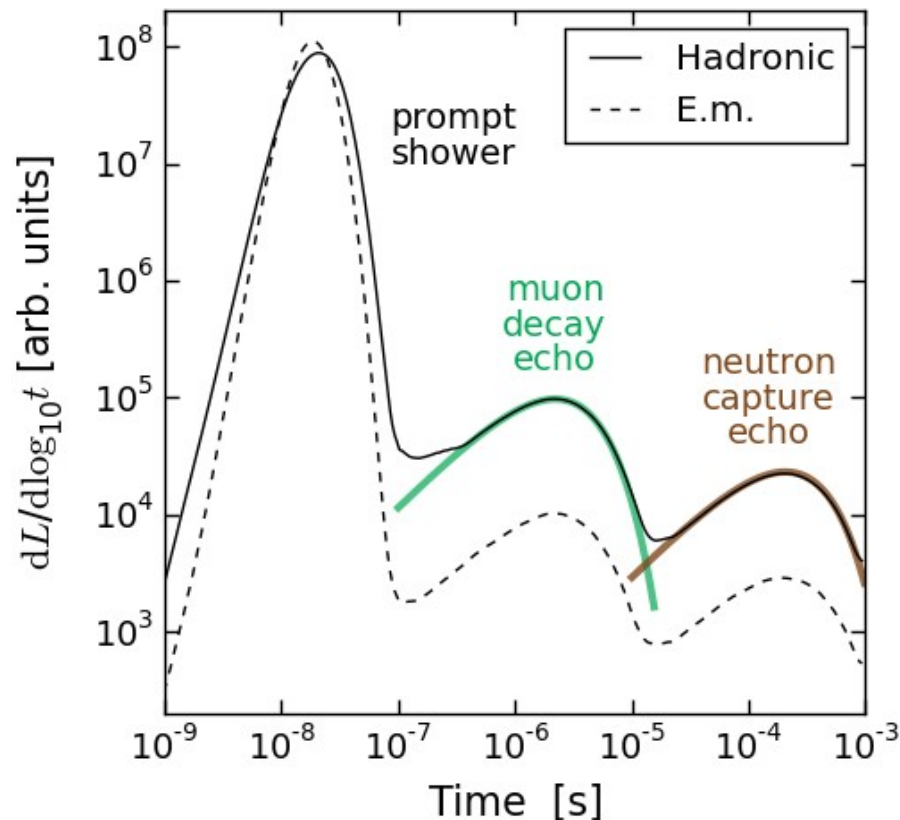
By 2040, how well will we recover the real value?

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



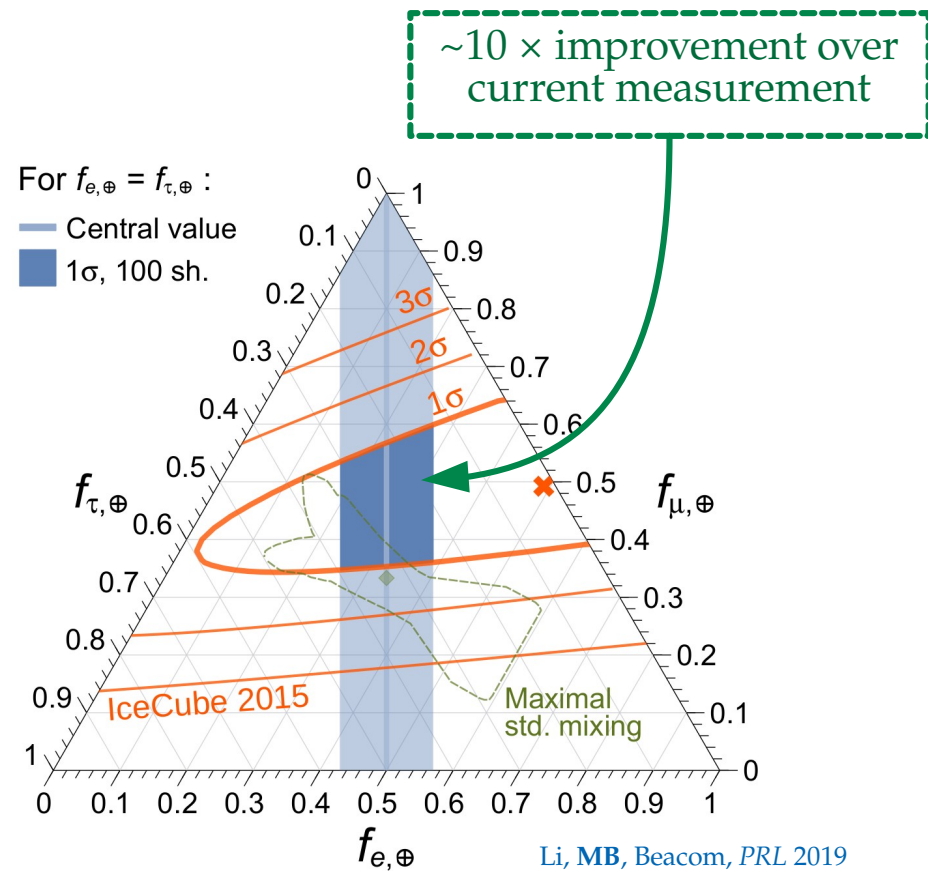
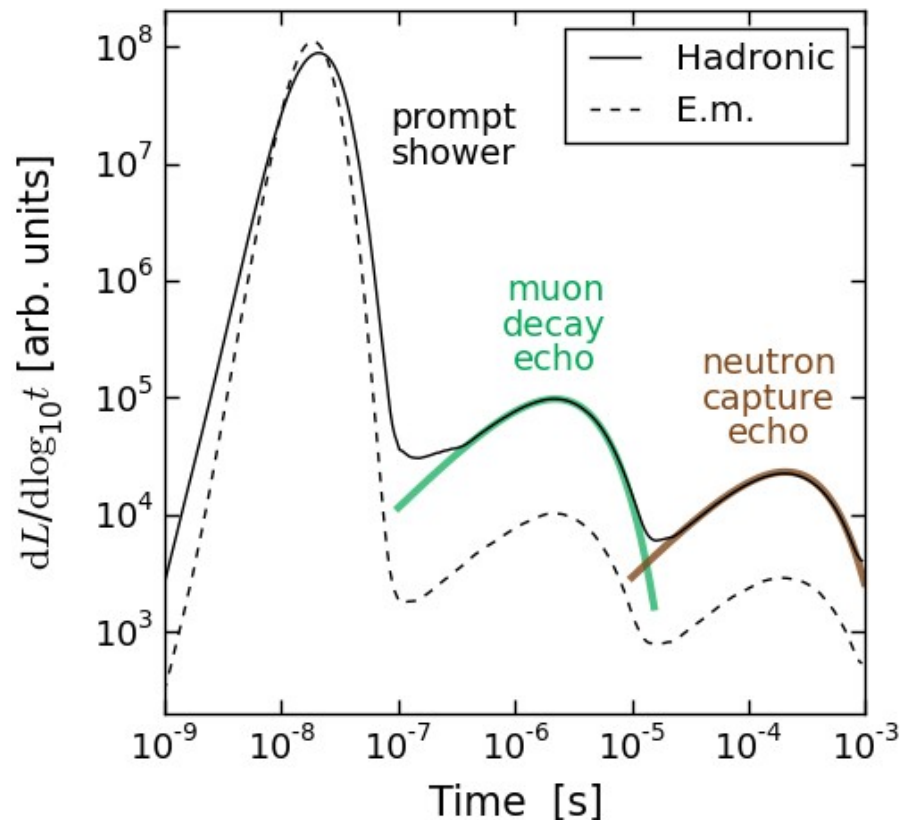
Side note: Improving flavor-tagging using *echoes*

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



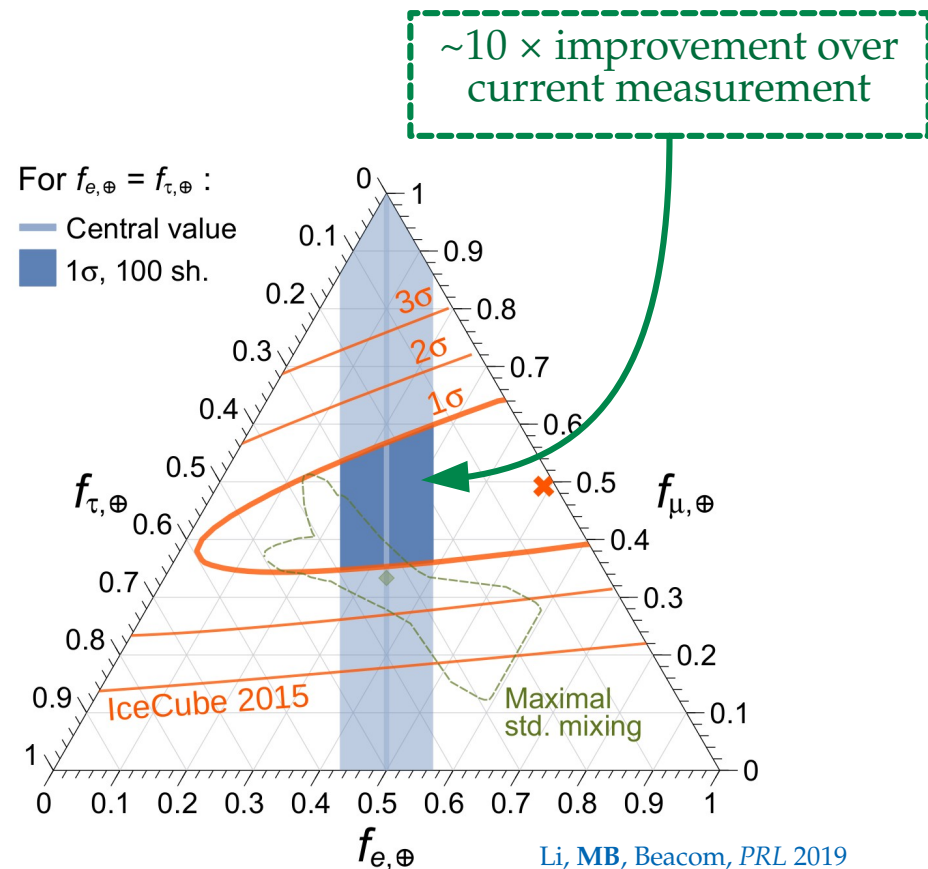
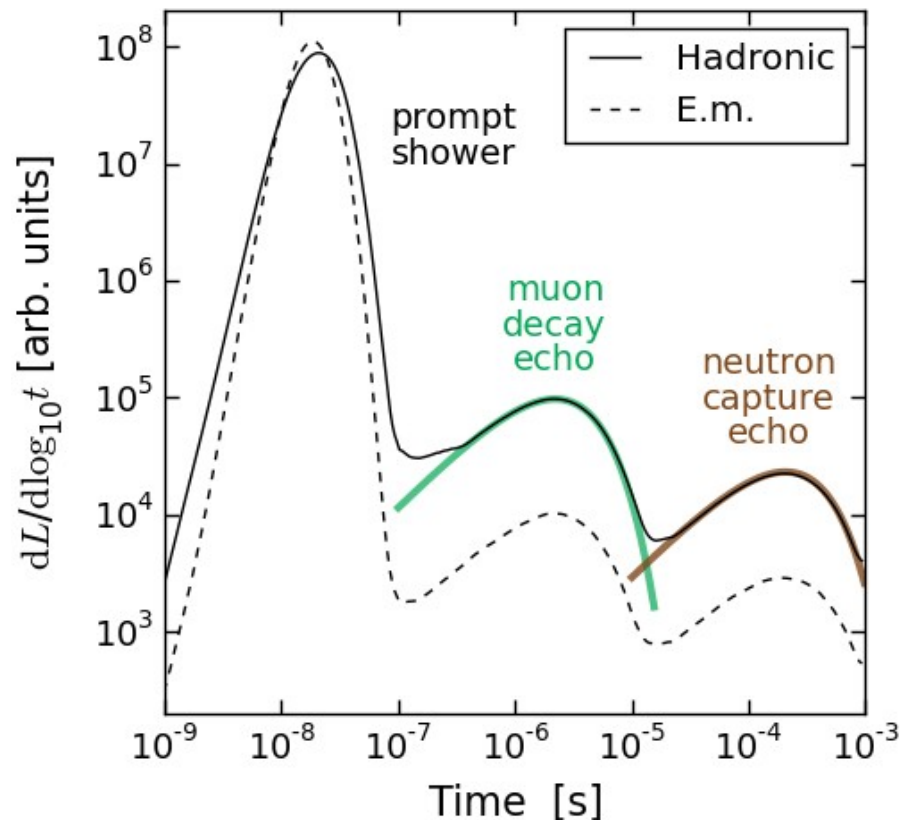
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Side note: Improving flavor-tagging using *echoes*

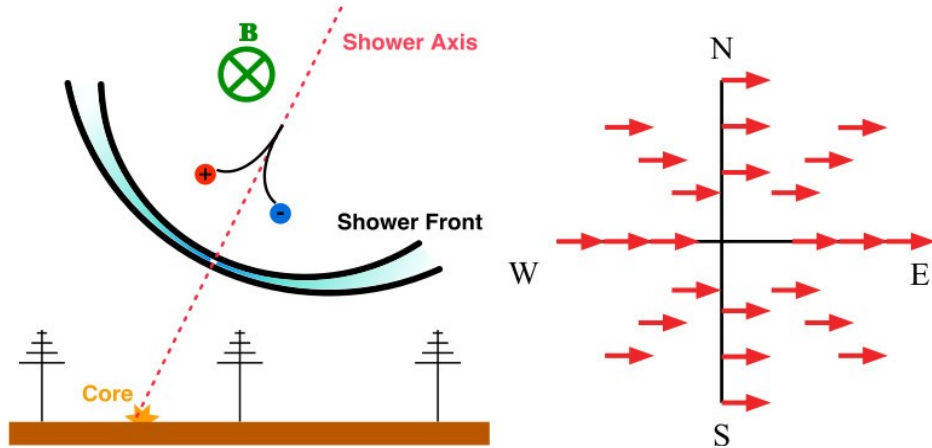
Late-time light (*echoes*) from muon decays and neutron captures can separate showers made by ν_e and ν_τ –



Detectors

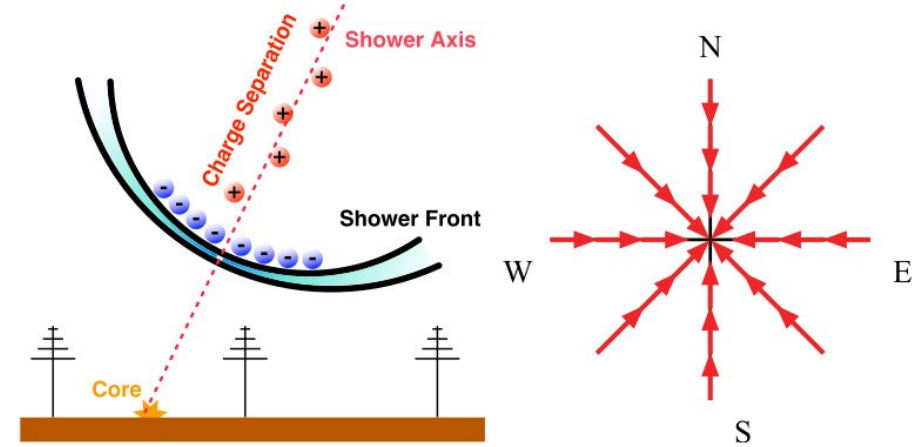
Radio emission: geomagnetic and Askaryan

Geomagnetic



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

Askaryan



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

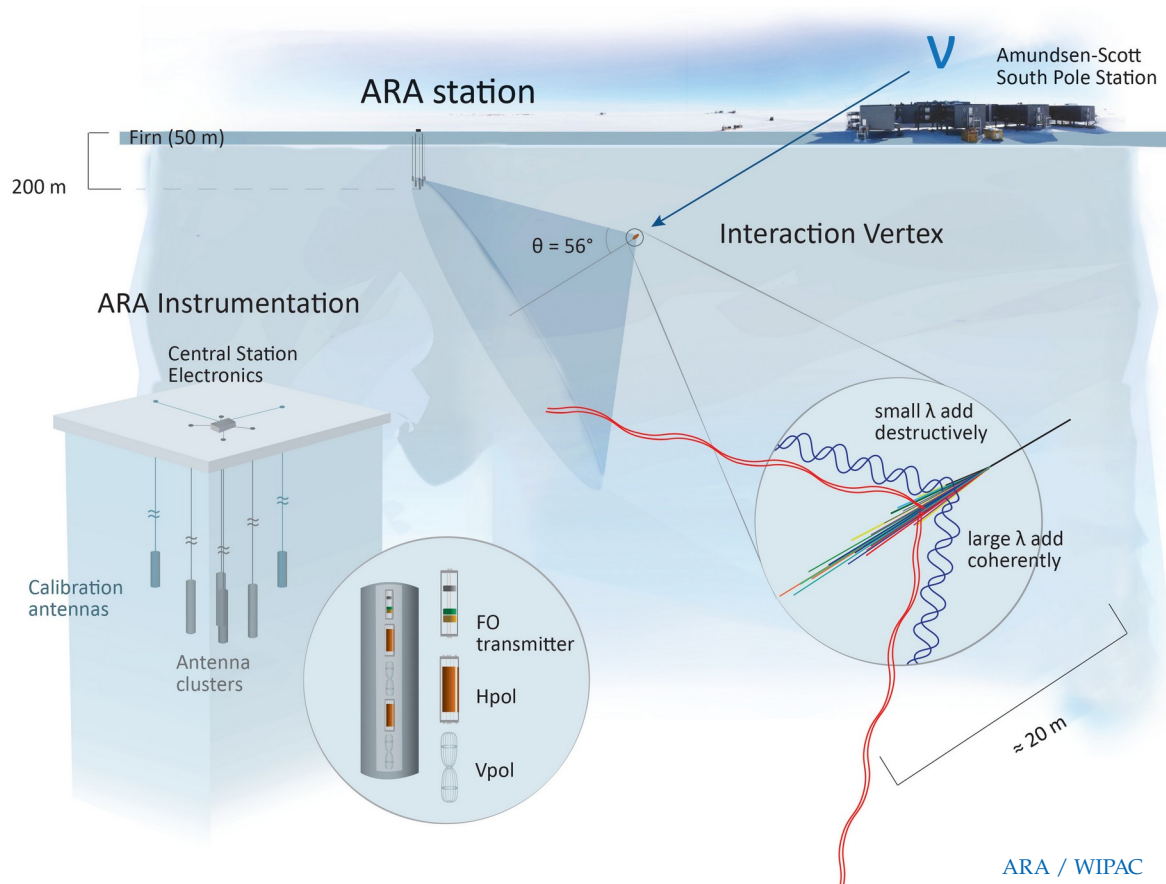
Radio emission: geomagnetic and Askaryan

Radio-detection of UHE neutrinos in ice

- ▶ Radio attenuation length in ice: **few km** (*vs.* 100 m for light)
- ▶ Larger monitored volume than IceCube
- ▶ **ARA, ARIANNA**: antennas buried in ice
- ▶ **ANITA**: antennas mounted on a balloon

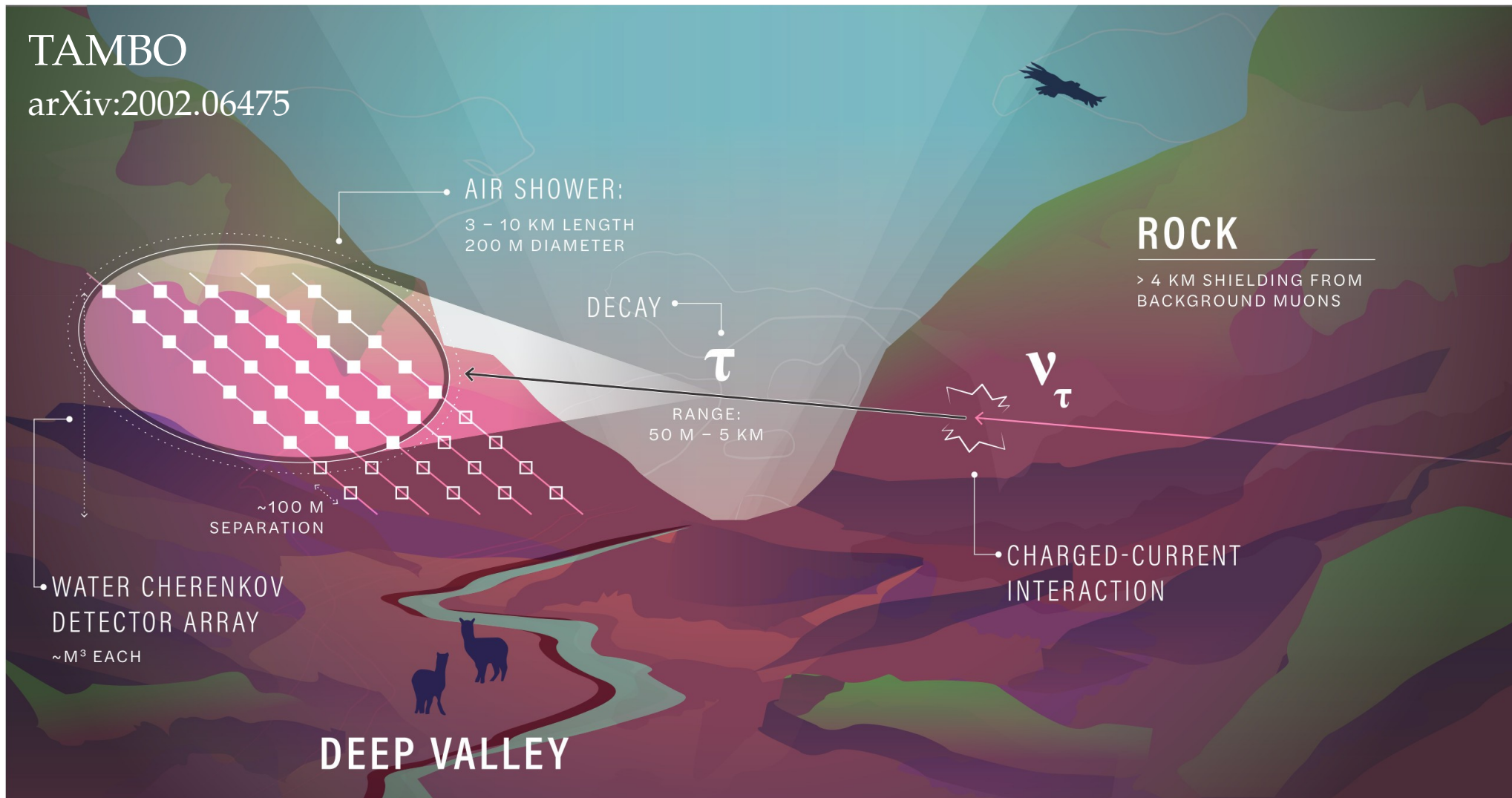
No ν detected yet

(But UHECRs detected regularly!)



TAMBO

arXiv:2002.06475



Detection of UHE ν in ice and water

Optical detection in ice or water

 IceCube $\rightarrow$ IceCube-Gen2 
 ANTARES $\rightarrow$ KM3NeT 
 NT200+ $\rightarrow$ Baikal GVD 
 P-ONE 

Radio detection in ice

ARA 
 ARIANNA 
 RNO-G 
 IceCube-Gen2 

Radio detection from the air or space

✓ ANITA $\rightarrow$ PUEO 
 NuMoon ✓

Detection of air showers from UHE ν_τ

Surface particle detection

 Auger $\rightarrow$ AugerPrime 
 TA $\rightarrow$ TA $\times$ 4 
 HAWC 
 TAMBO 

Radio detection in the atmosphere

✓ ANITA $\rightarrow$ PUEO 
 BEACON 
 GRAND 
 TAROGE & TAROGE-M 

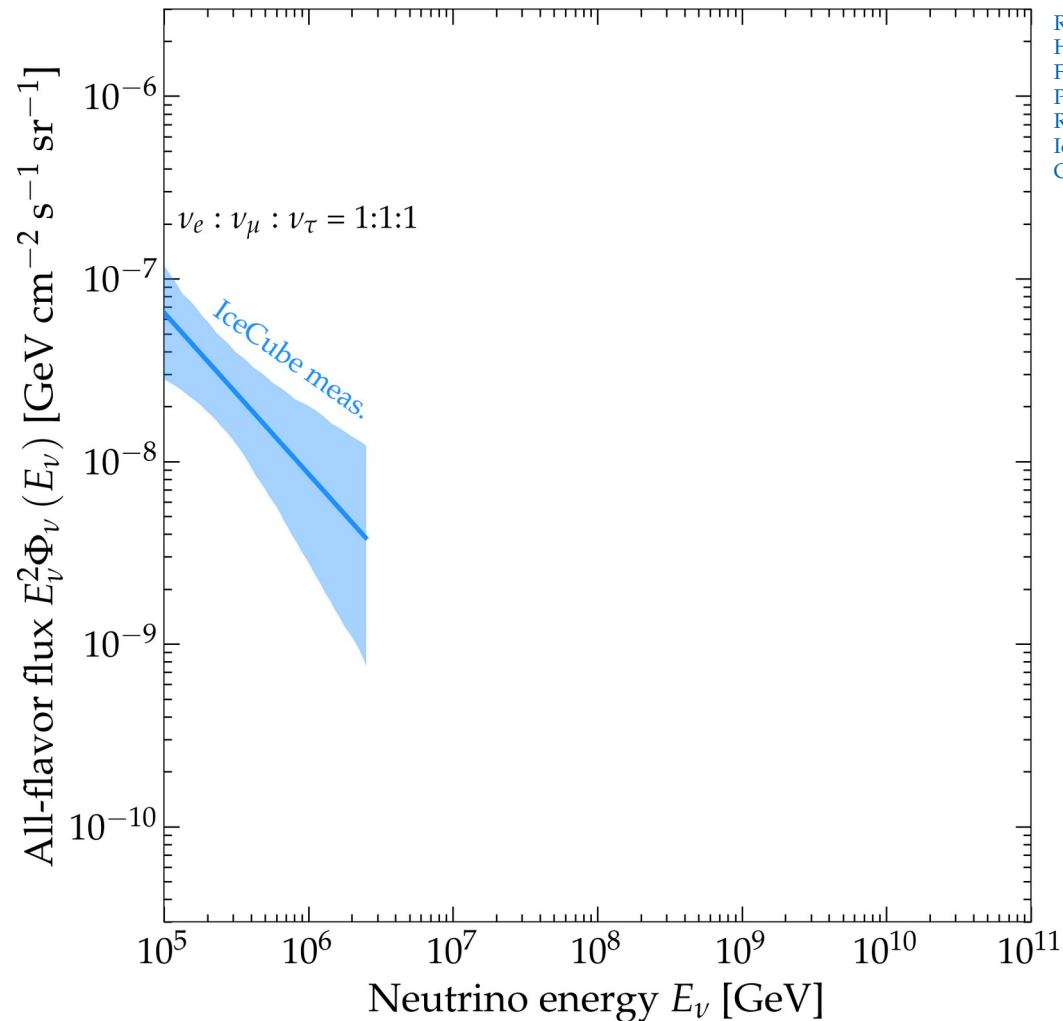
Air-shower imaging from the ground

Trinity 
 MAGIC 
 CTA 
 ASHRA NTA 

Cherenkov/fluorescence from air or space

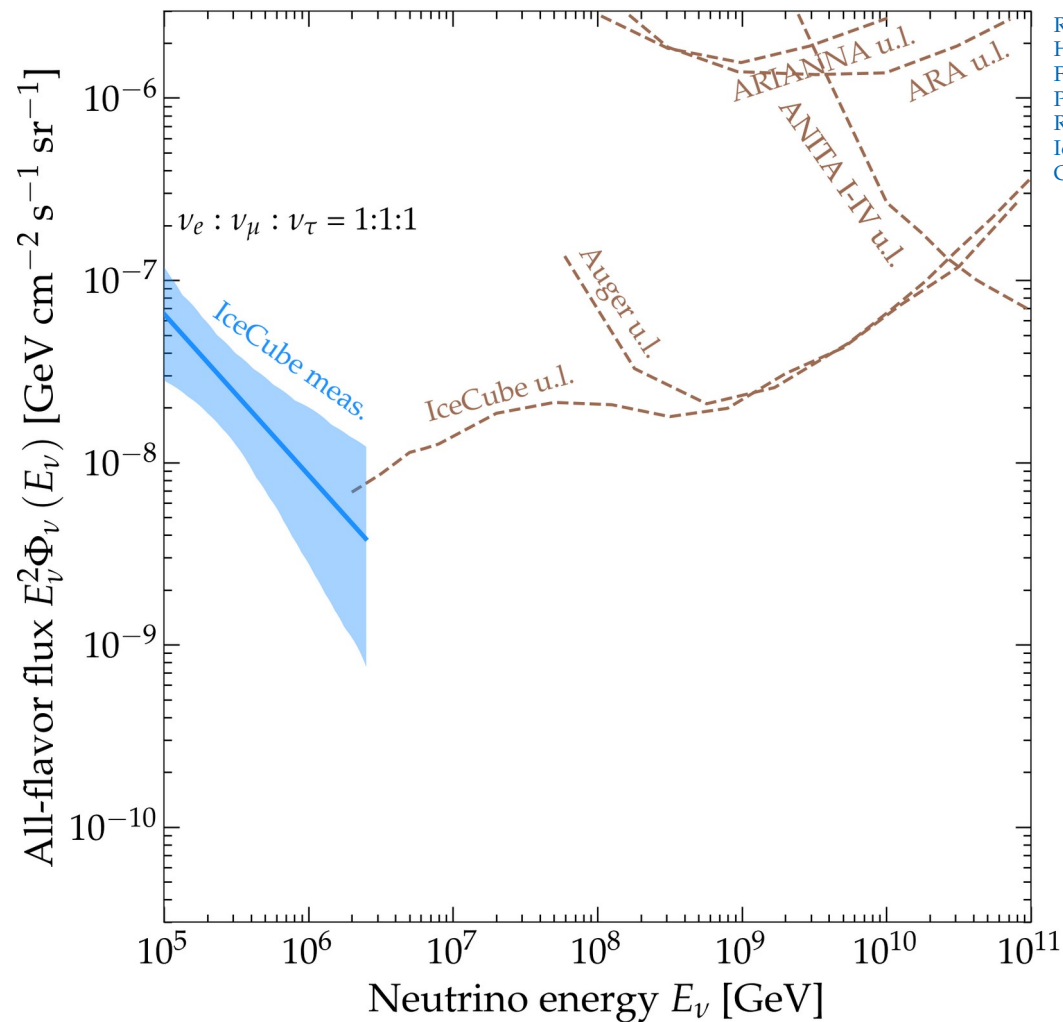
EUISO-SPB2 
 POEMMA 

UHE neutrinos: *steady-state sources*



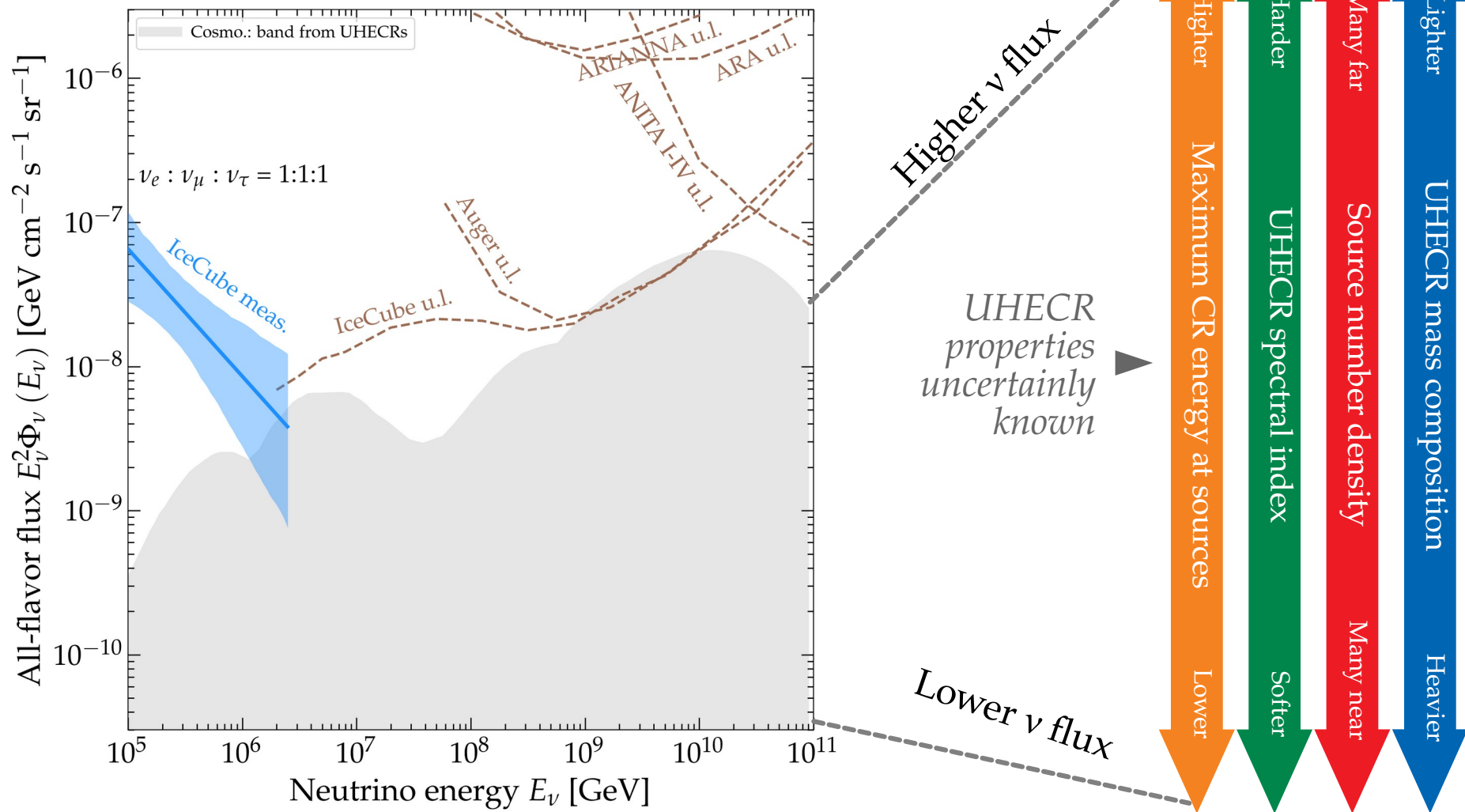
Rodrigues, Heinze, Palladino, van Vliet, Winter, 2003.08392
Heinze, Fedynitch, Boncioli, Winter *ApJ* 2019
Fang & Murase, *Nature Phys.* 2018
POEMMA, 2012.07945
RNO-G, *JINST* 2021
IceCube-Gen2, *J. Phys. G* 2021
GRAND, *Sci. China Phys. Mech. Astron.* 2020

UHE neutrinos: *steady-state sources*

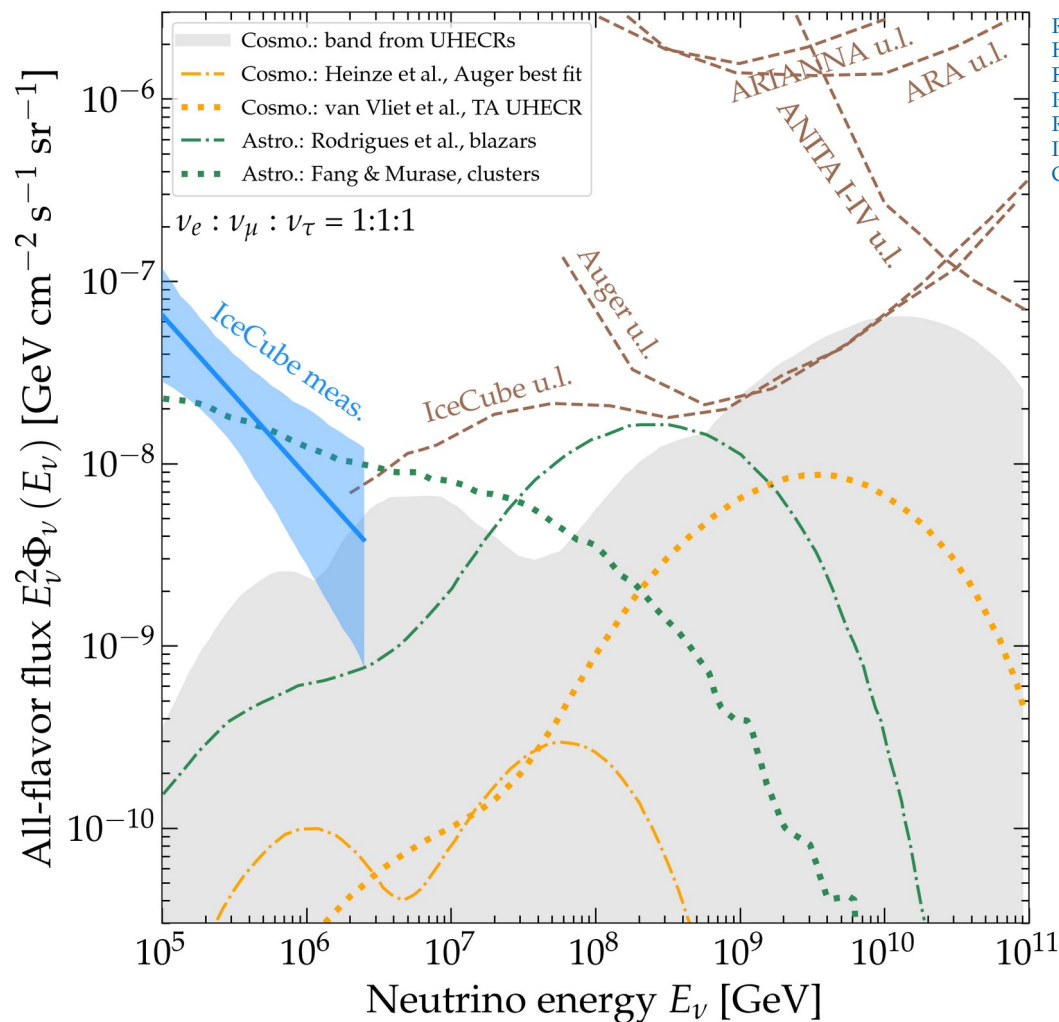


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Heinze, Fedynitch, Boncioli, Winter *ApJ* 2019
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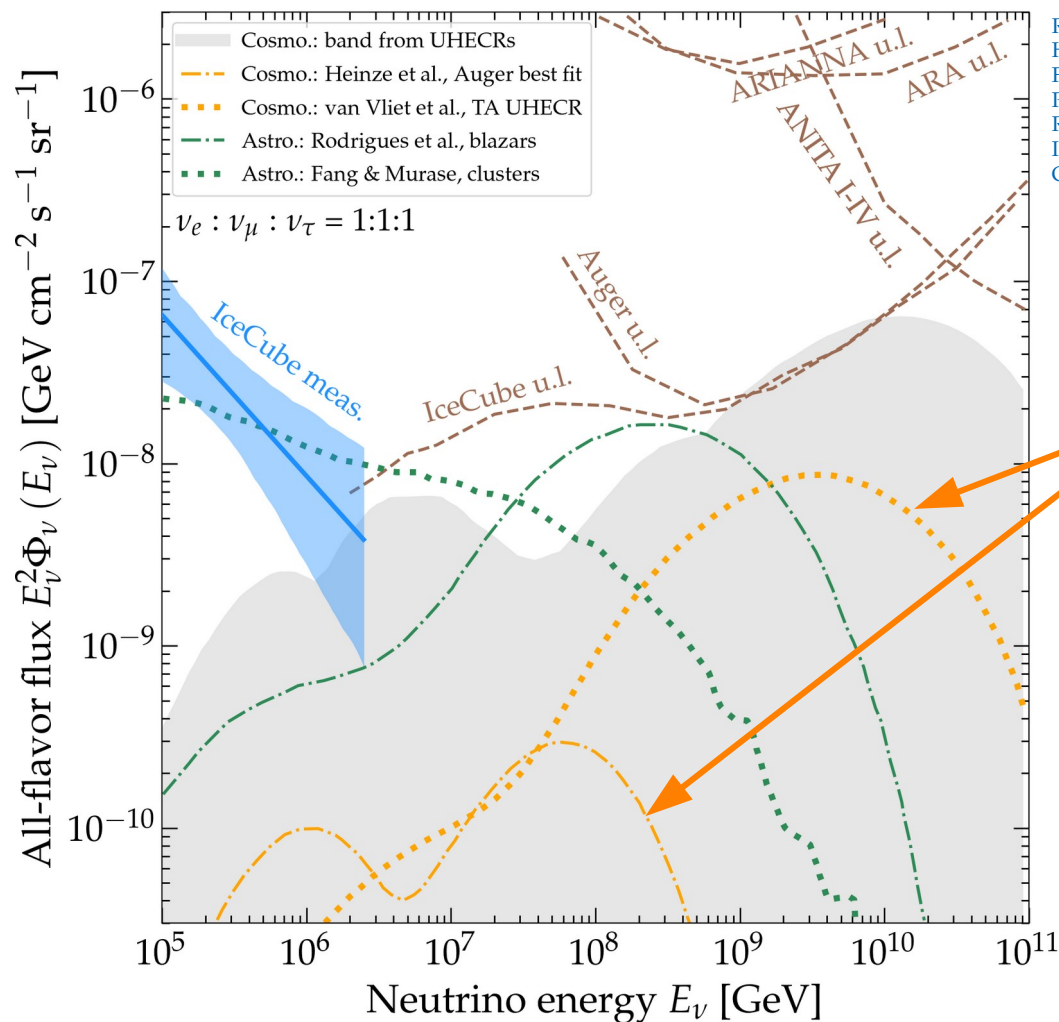


UHE neutrinos: *steady-state sources*



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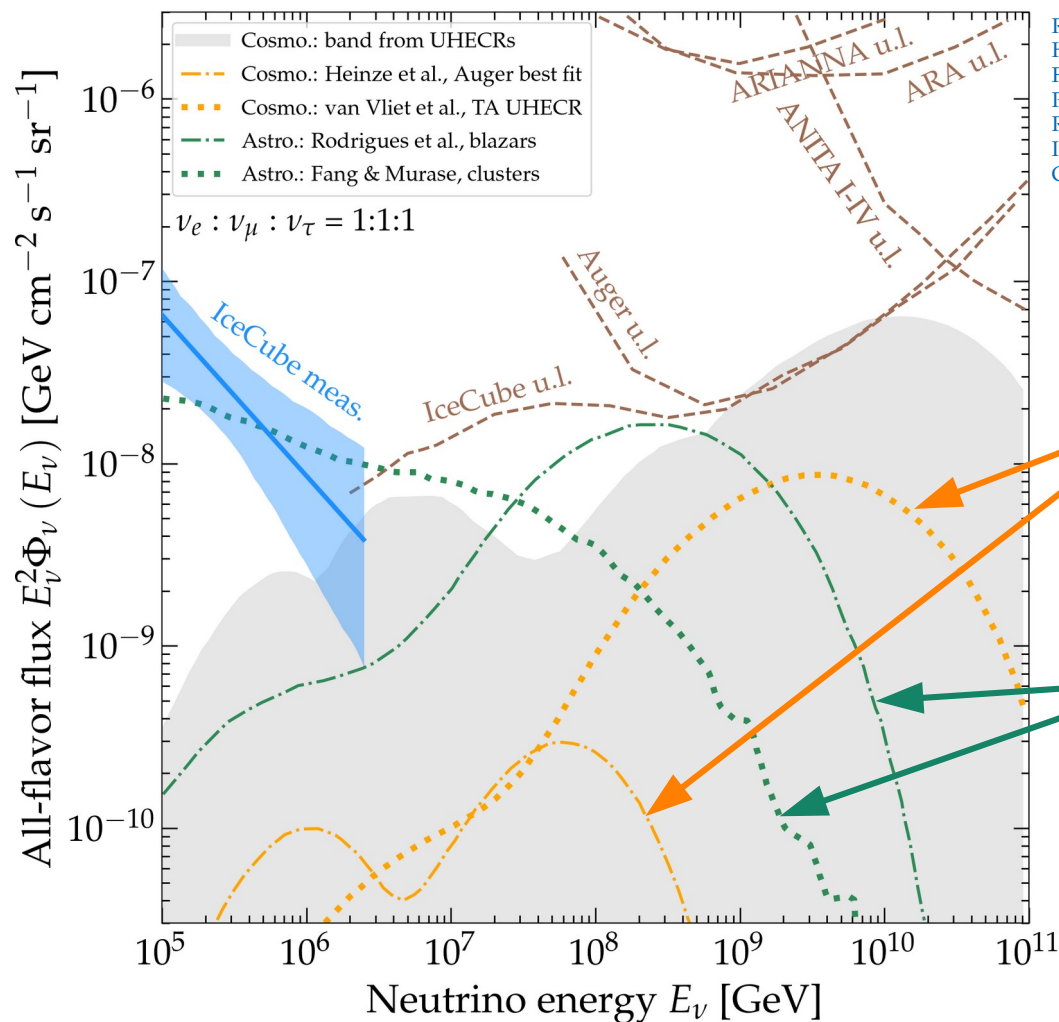
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Cosmogenic neutrinos

UHE neutrinos: *steady-state sources*

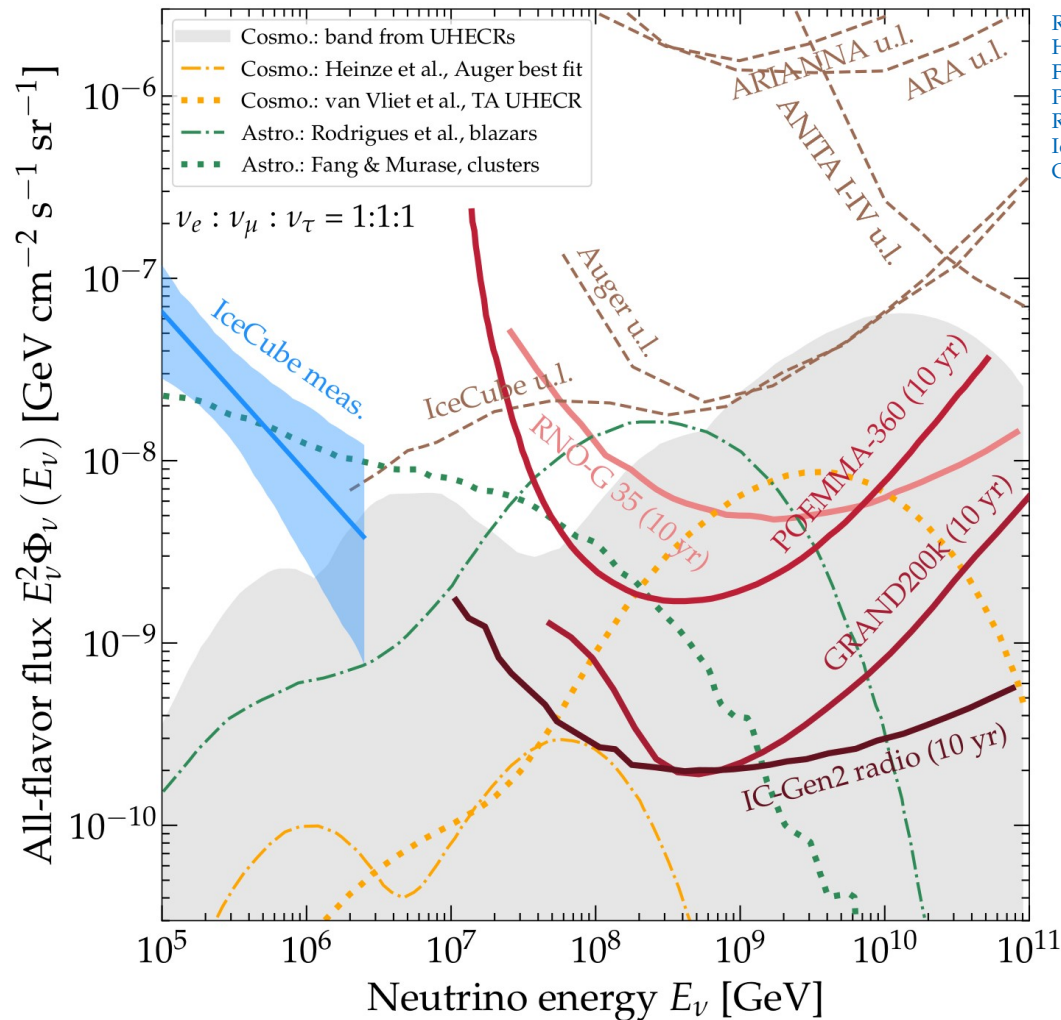


Rodrigues, Heinze, Palladino, van Vliet, Winter, 2003.08392
Heinze, Fedynitch, Boncioli, Winter *ApJ* 2019
Fang & Murase, *Nature Phys.* 2018
POEMMA, 2012.07945
RNO-G, *JINST* 2021
IceCube-Gen2, *J. Phys. G* 2021
GRAND, *Sci. China Phys. Mech. Astron.* 2020

Cosmogenic neutrinos

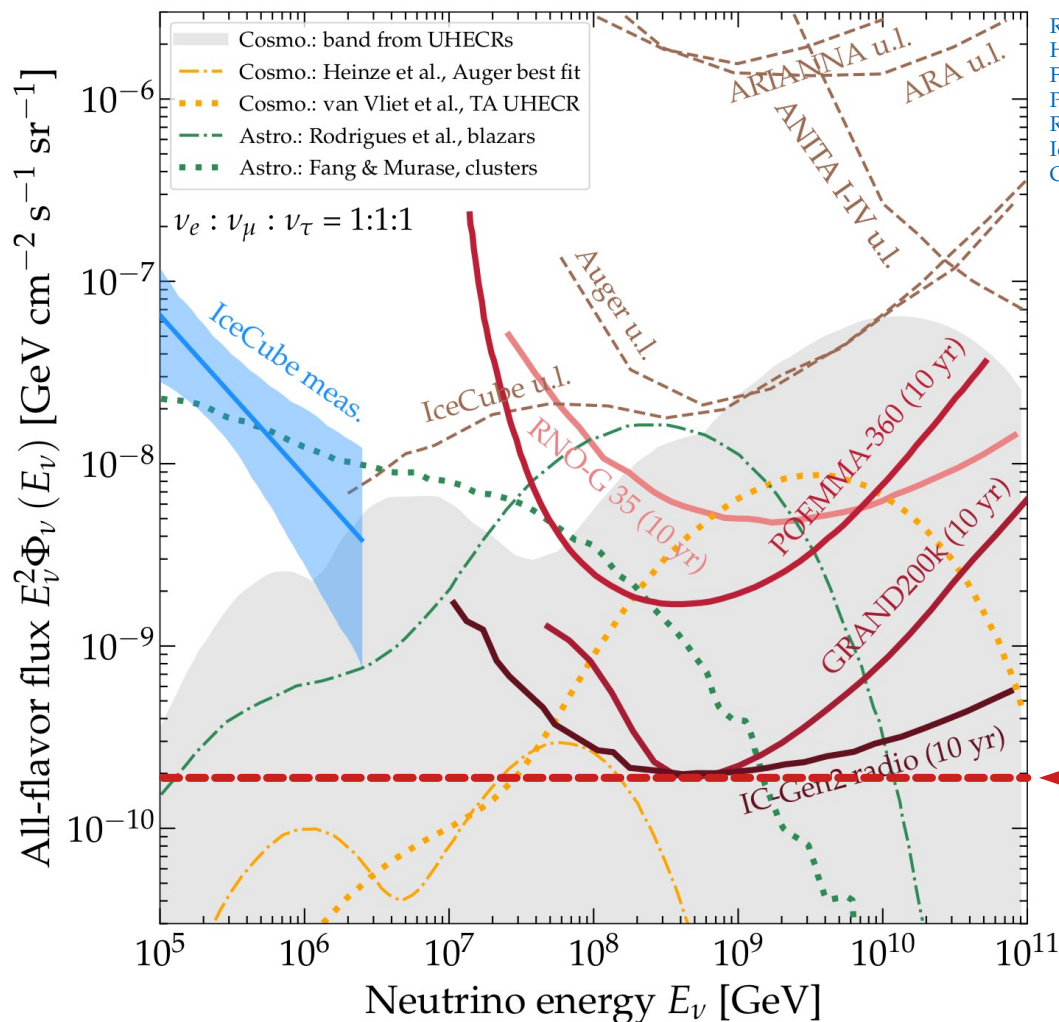
Neutrinos from the sources
(possibly dominant flux!)

UHE neutrinos: *steady-state sources*



Rodrigues, Heinze, Palladino, van Vliet, Winter, 2003.08392
 Heinze, Fedynitch, Boncioli, Winter *ApJ* 2019
 Fang & Murase, *Nature Phys.* 2018
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 RNO-G, *JINST* 2021
 IceCube-Gen2, *J. Phys. G* 2021
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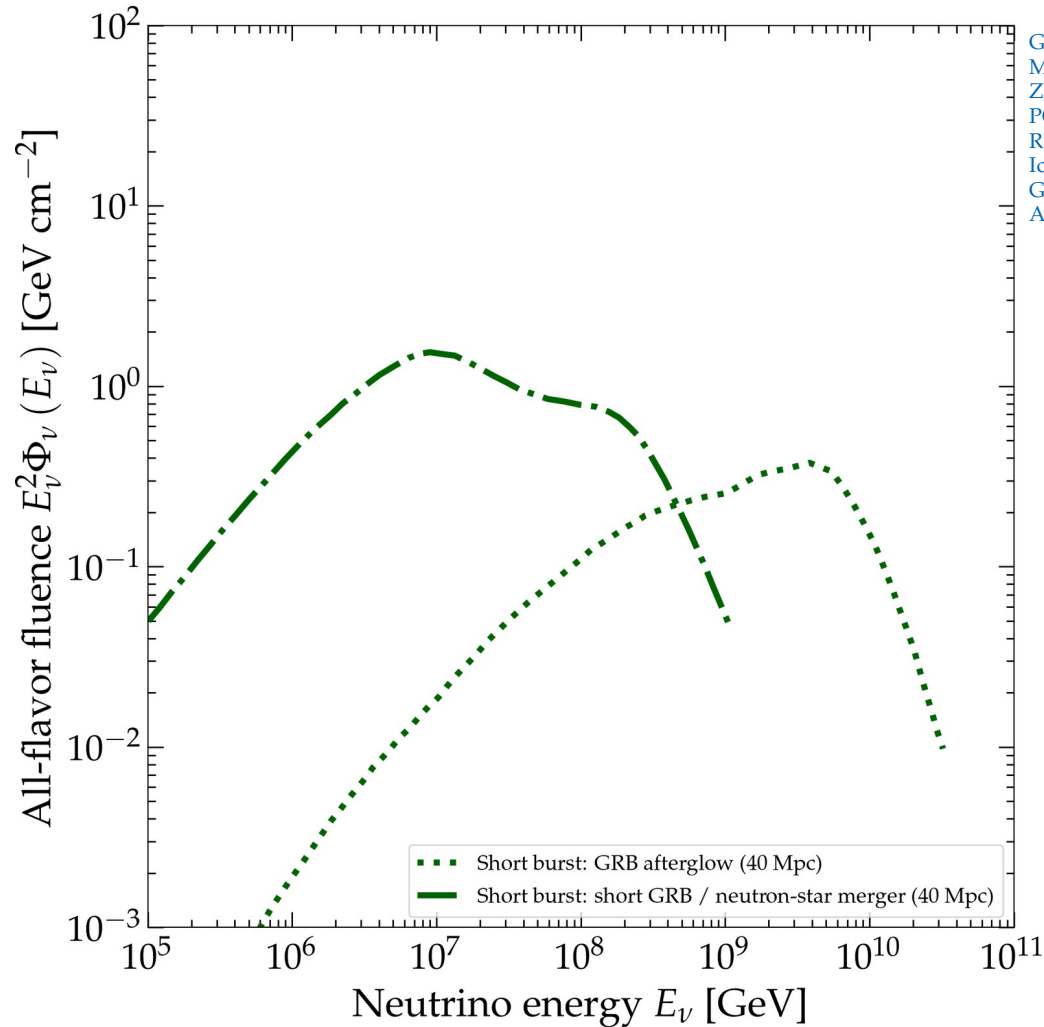
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IceCube-Gen2, *J. Phys. G* 2021
GRAND, *Sci. China Phys. Mech. Astron.* 2020

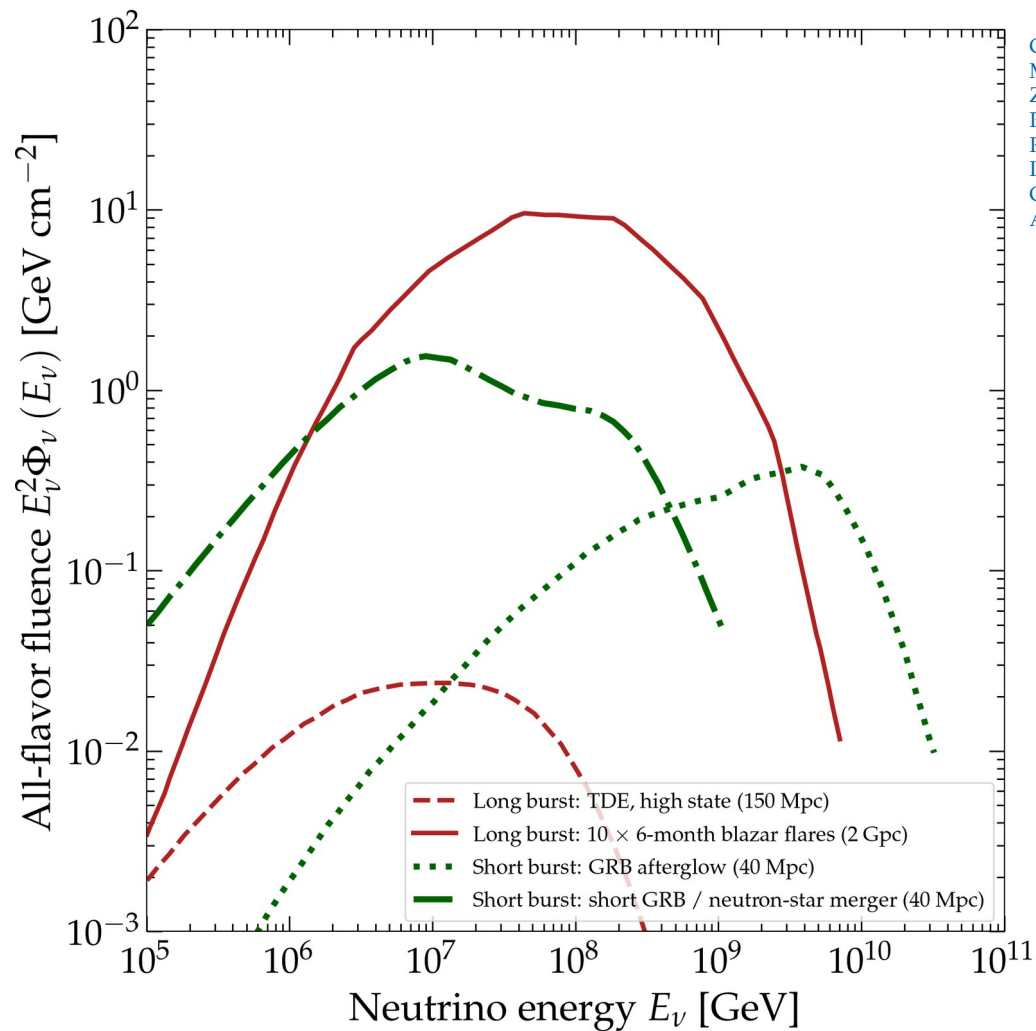
Ultimate target sensitivity
for next-gen detectors
(if protons are ~10% of the
highest-energy UHECRs)

UHE neutrinos: *transient sources*



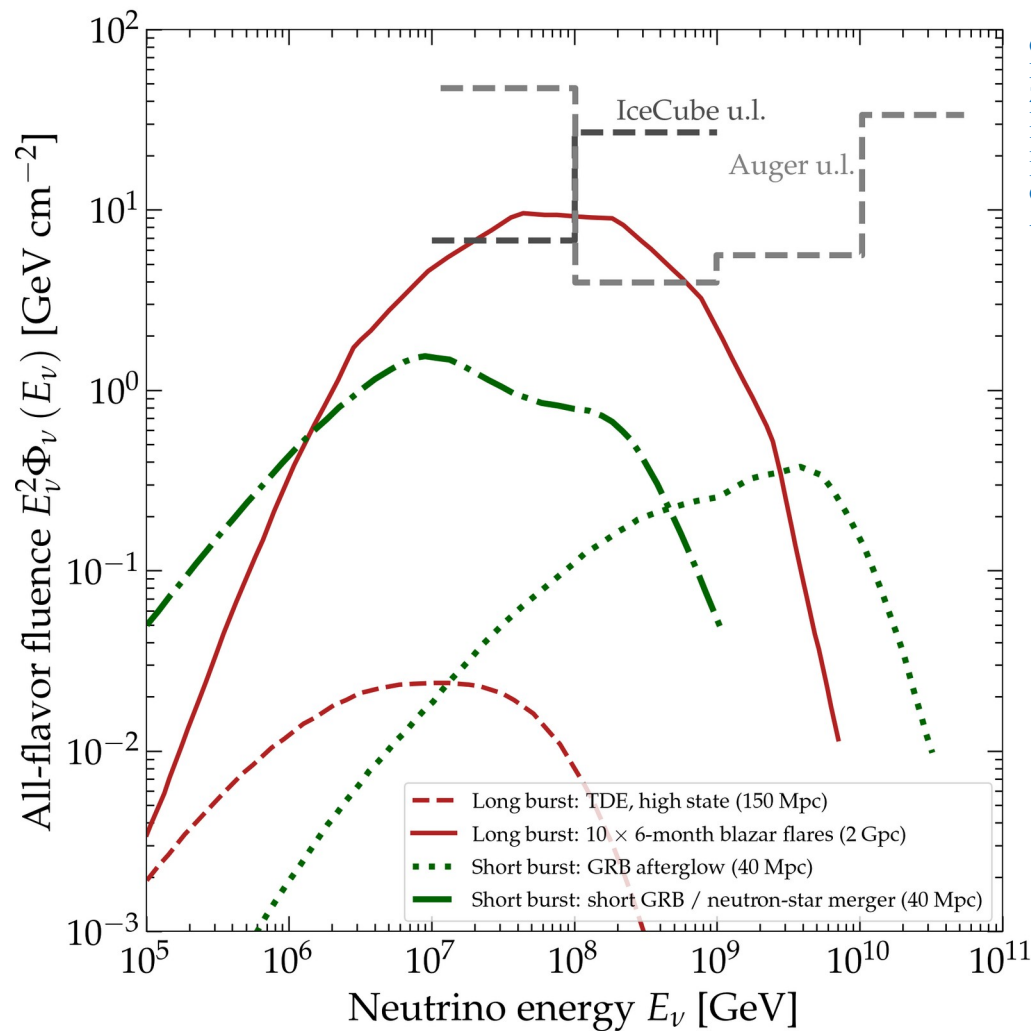
Guépin, Kotera, Barausse, Fang, Murase, *A&A* 2018
Murase, *PRD* 2017
Zhang *et al.*, *Nature Commun.* 2018
POEMMA, 2012.07945
RNO-G, *JINST* 2021
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GRAND, *Sci. China Phys. Mech. Astron.* 2020
ANTARES, IceCube, Auger, LIGO, Virgo, *ApJ* 2017

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IceCube-Gen2, *J. Phys. G* 2021
GRAND, *Sci. China Phys. Mech. Astron.* 2020
ANTARES, IceCube, Auger, LIGO, Virgo, *ApJ* 2017

PLEnuM

Characterizing the diffuse power-law flux in PLEvM

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

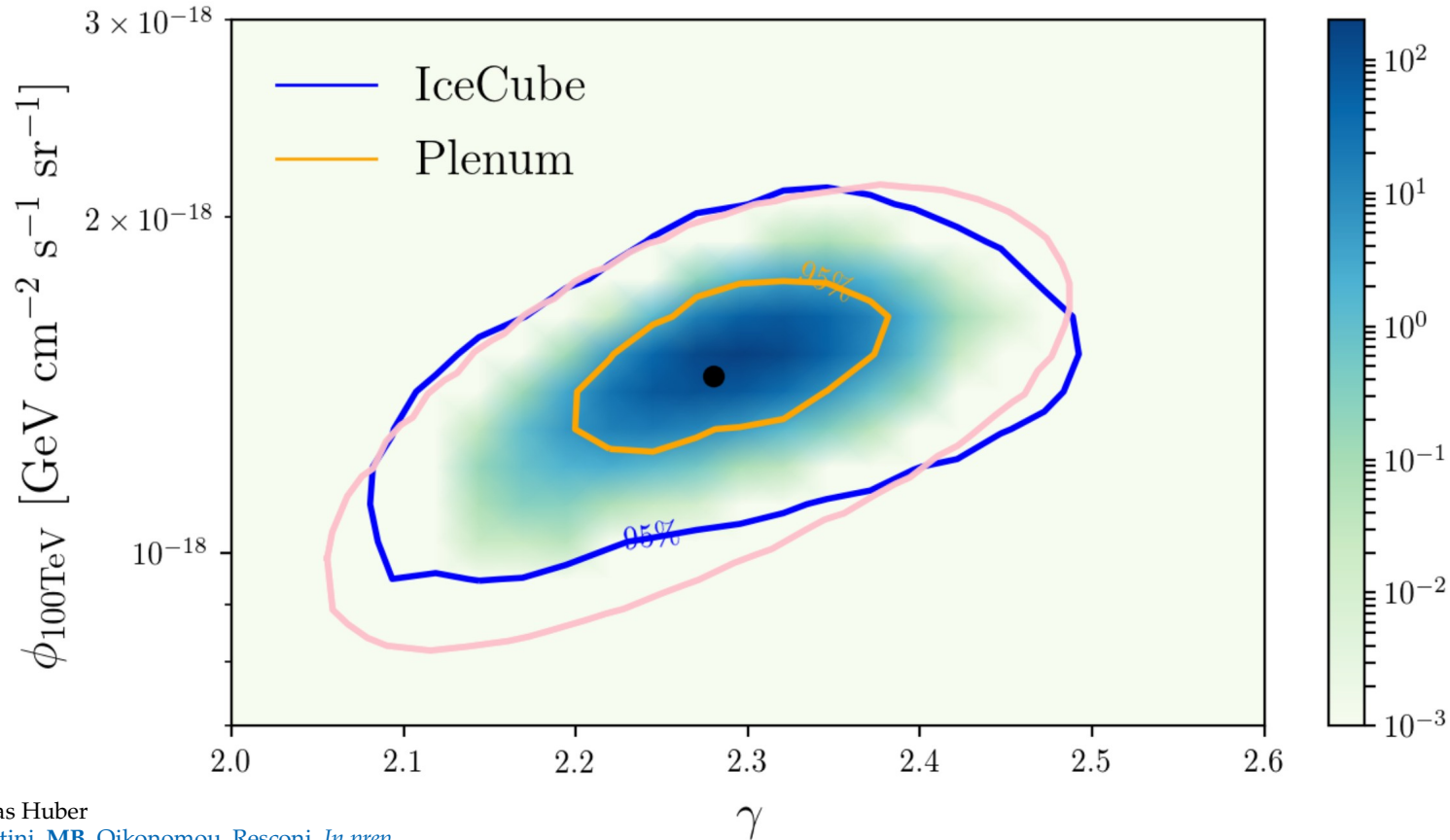
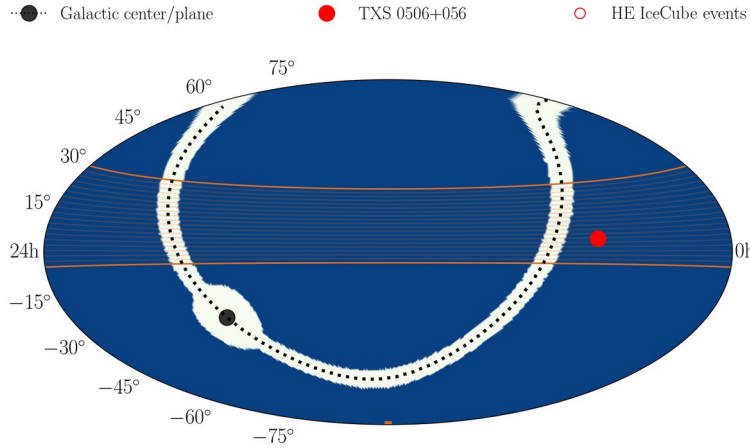


Figure courtesy of Matthias Huber
Huber, Schumacher, Agostini, MB, Oikonomou, Resconi, *In prep.*

Discovering a Galactic ν flux in PLEvM

Galactic emission template:



Flux uniformly distributed:

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

5 σ discovery potential (GC only)

