Grounded tests of neutrino physics with high- and ultra-high energy cosmic neutrinos

Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

Paris-Saclay Astroparticle Symposium
October 26, 2021

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

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& astrophysics
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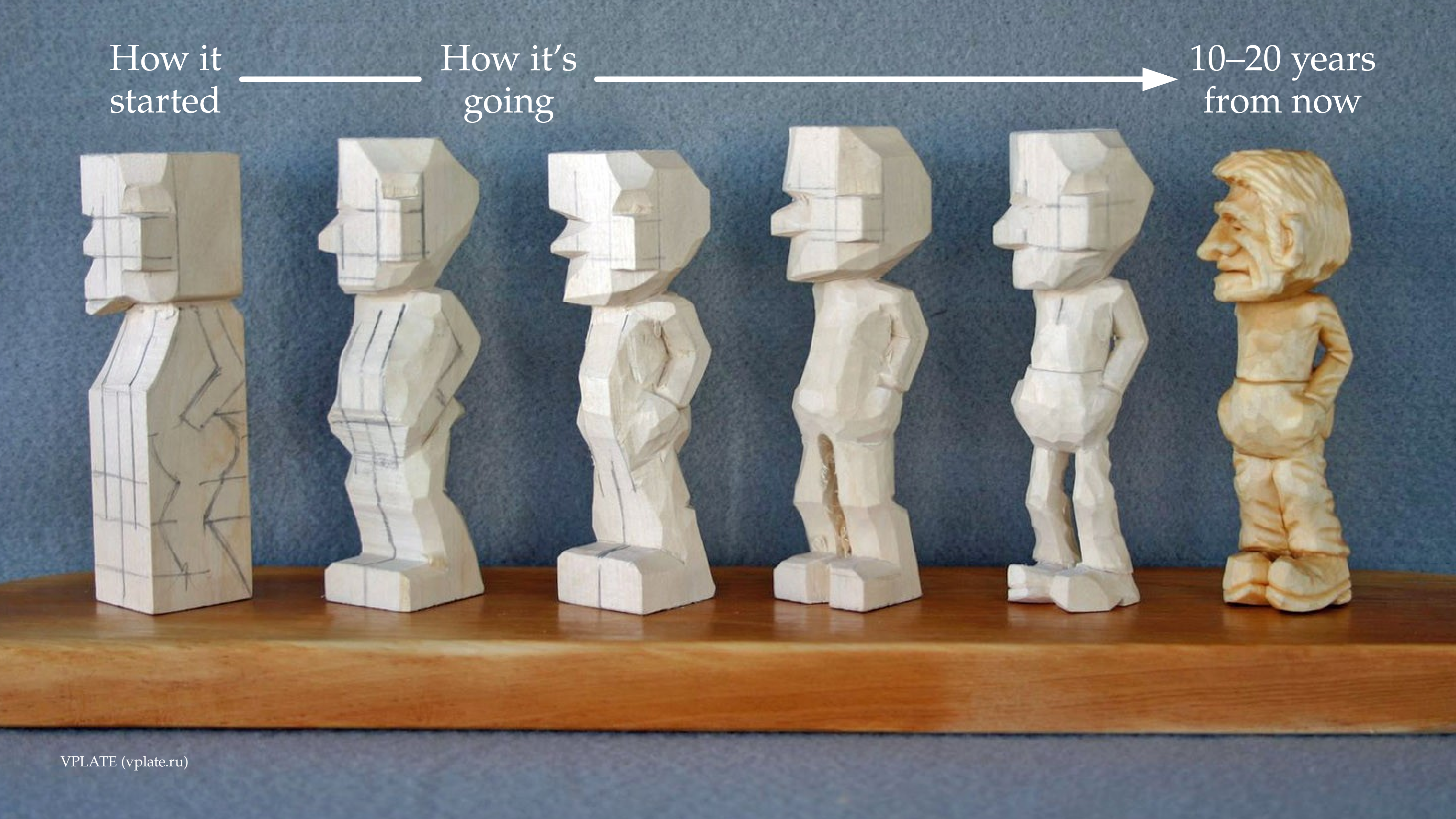
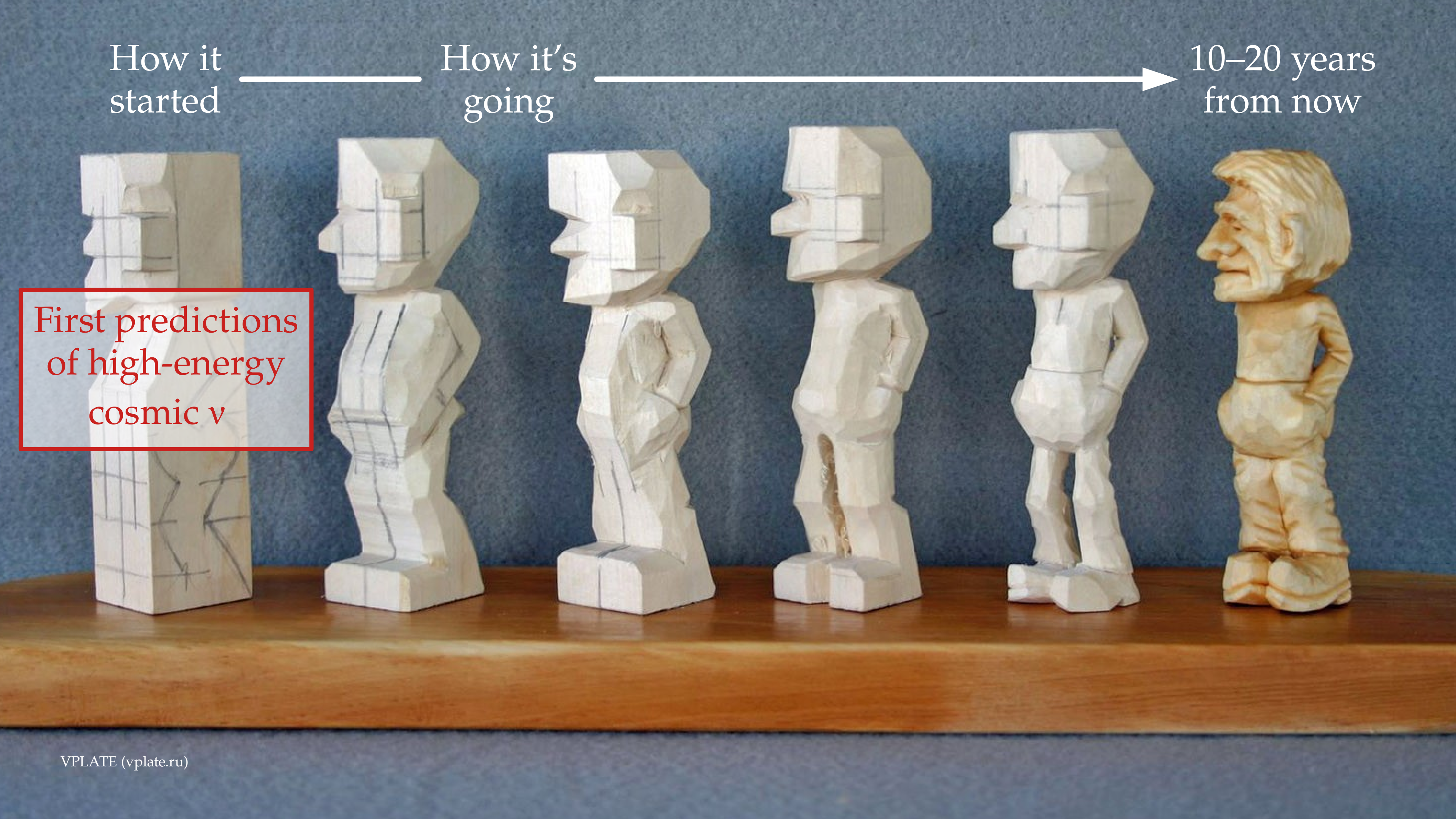

How it started
How it's going
10–20 years from now
VPLATE (vplate.ru)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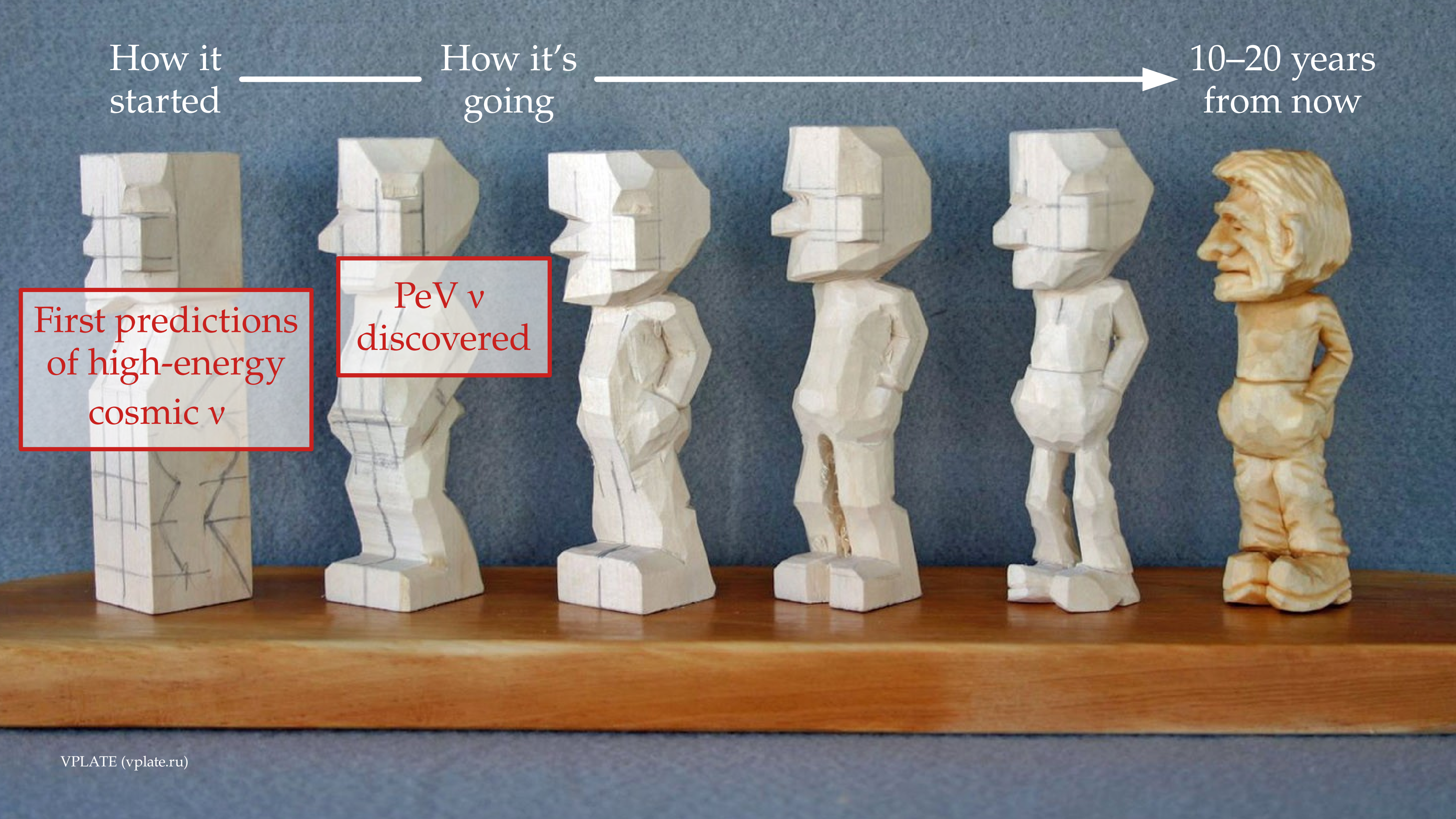
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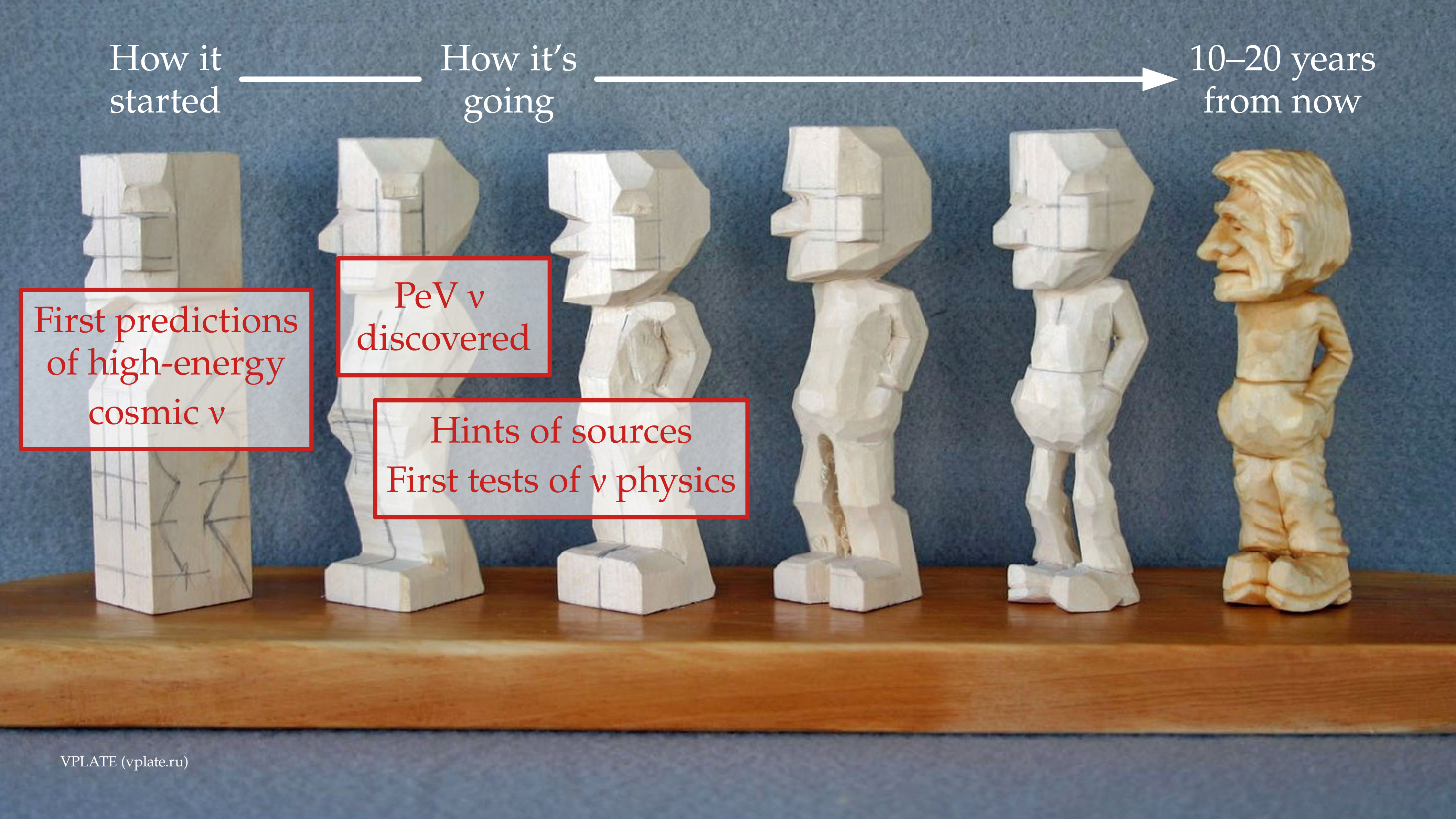
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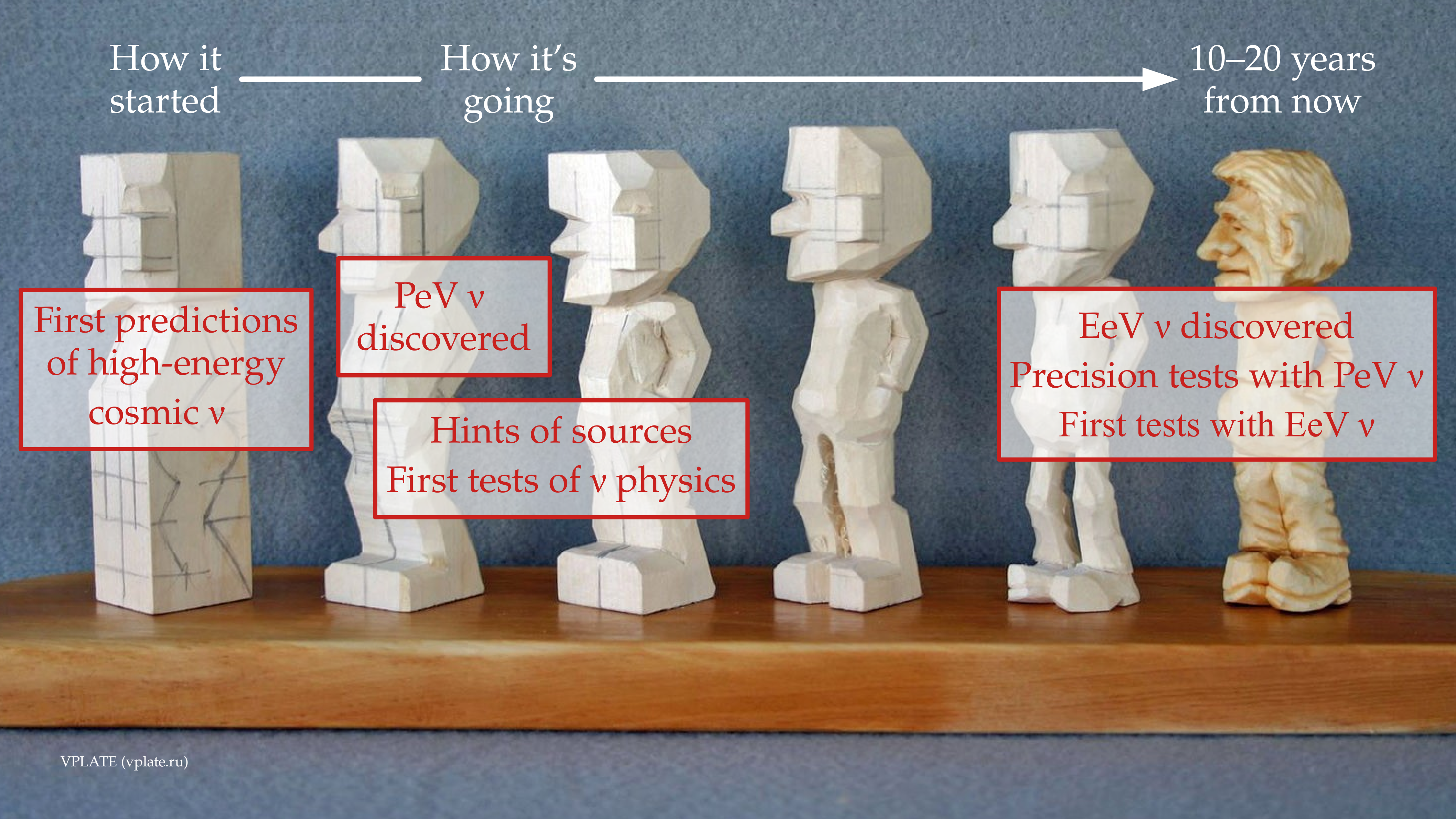
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First tests with EeV ν
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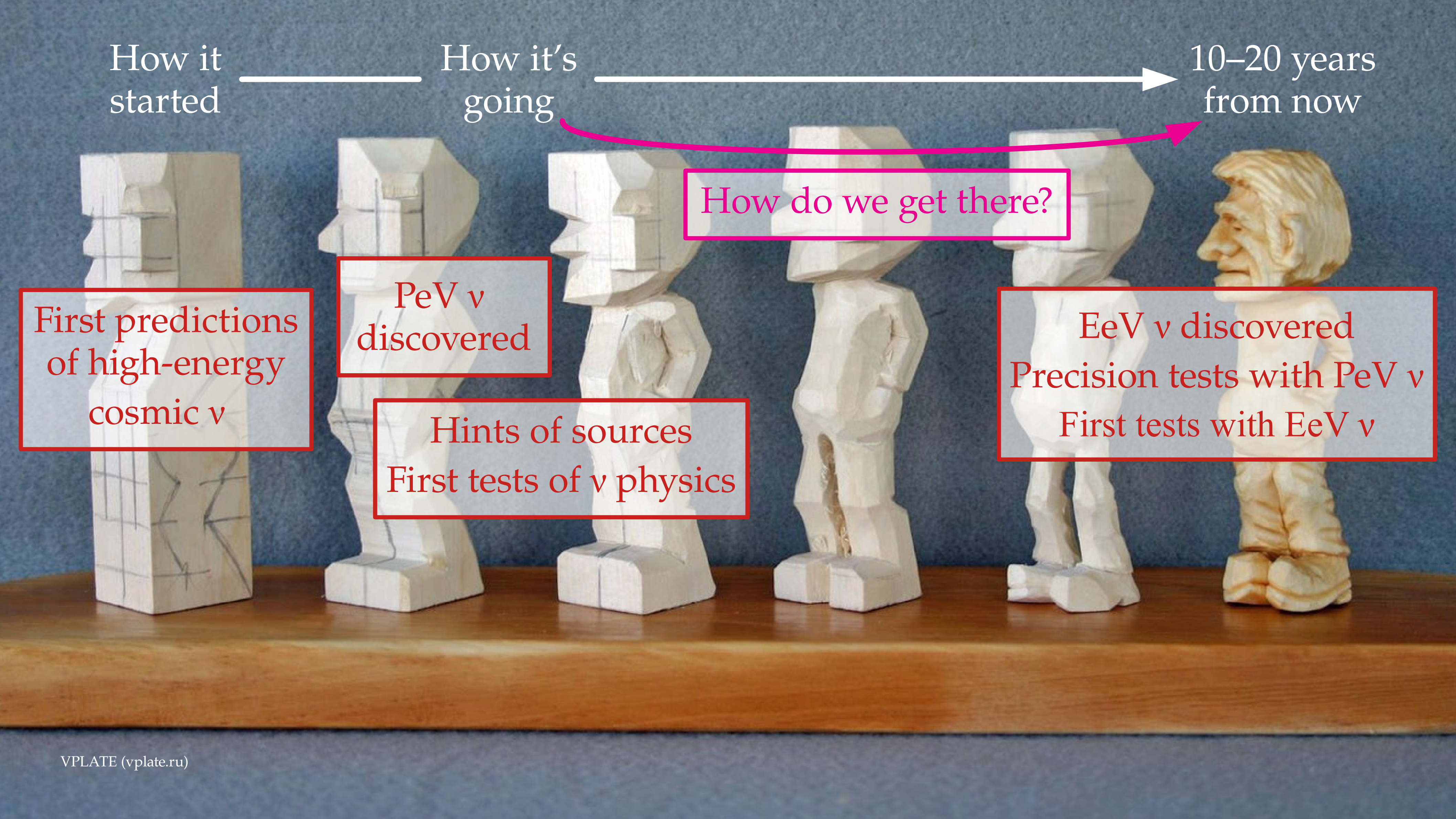
How it started
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10–20 years from now
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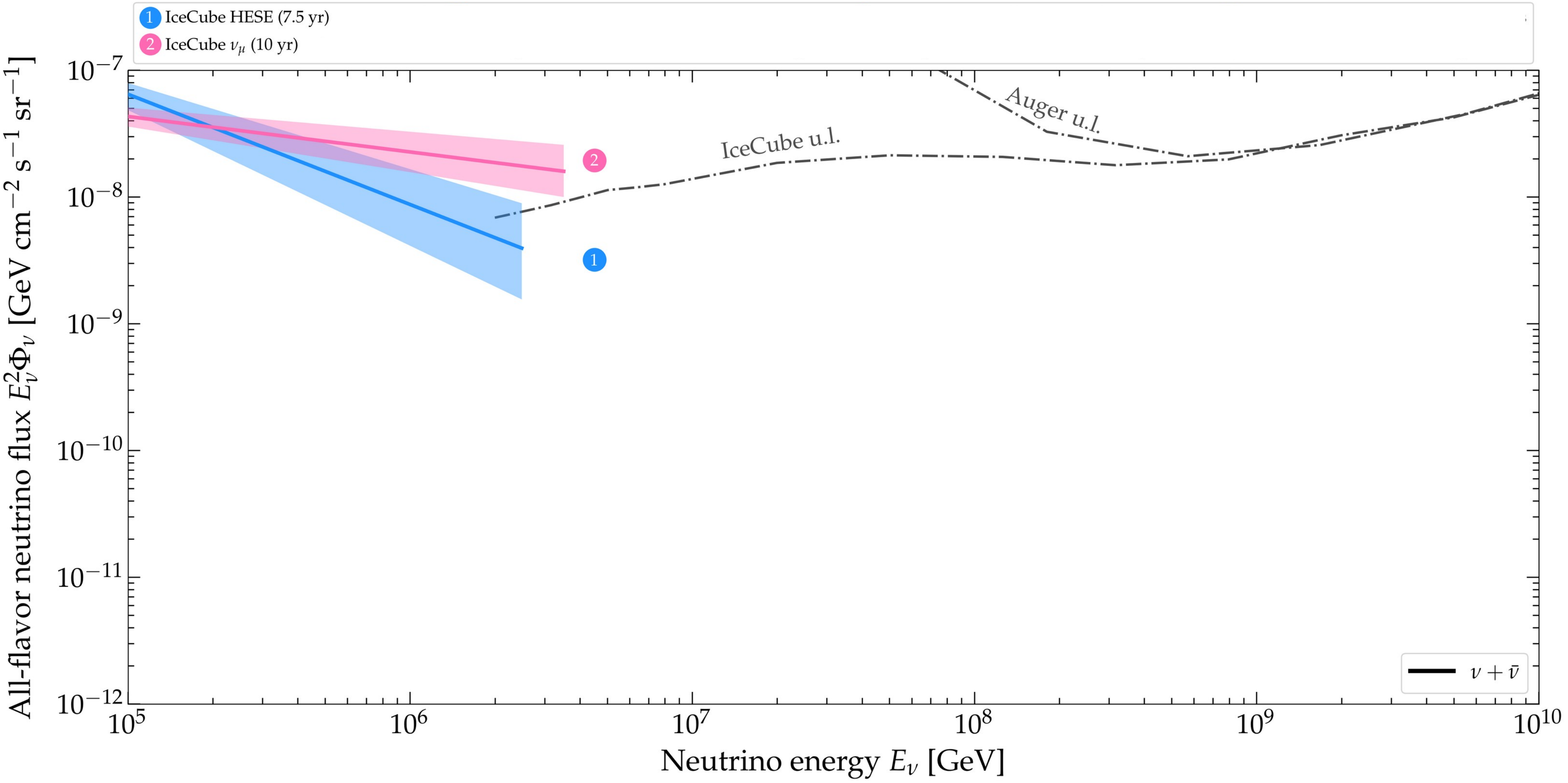


MB, Valera, Glaser, *In preparation*

Today

TeV–PeV ν

Today

TeV–PeV ν

Turn predictions
into data-driven tests

Today

TeV–PeV ν

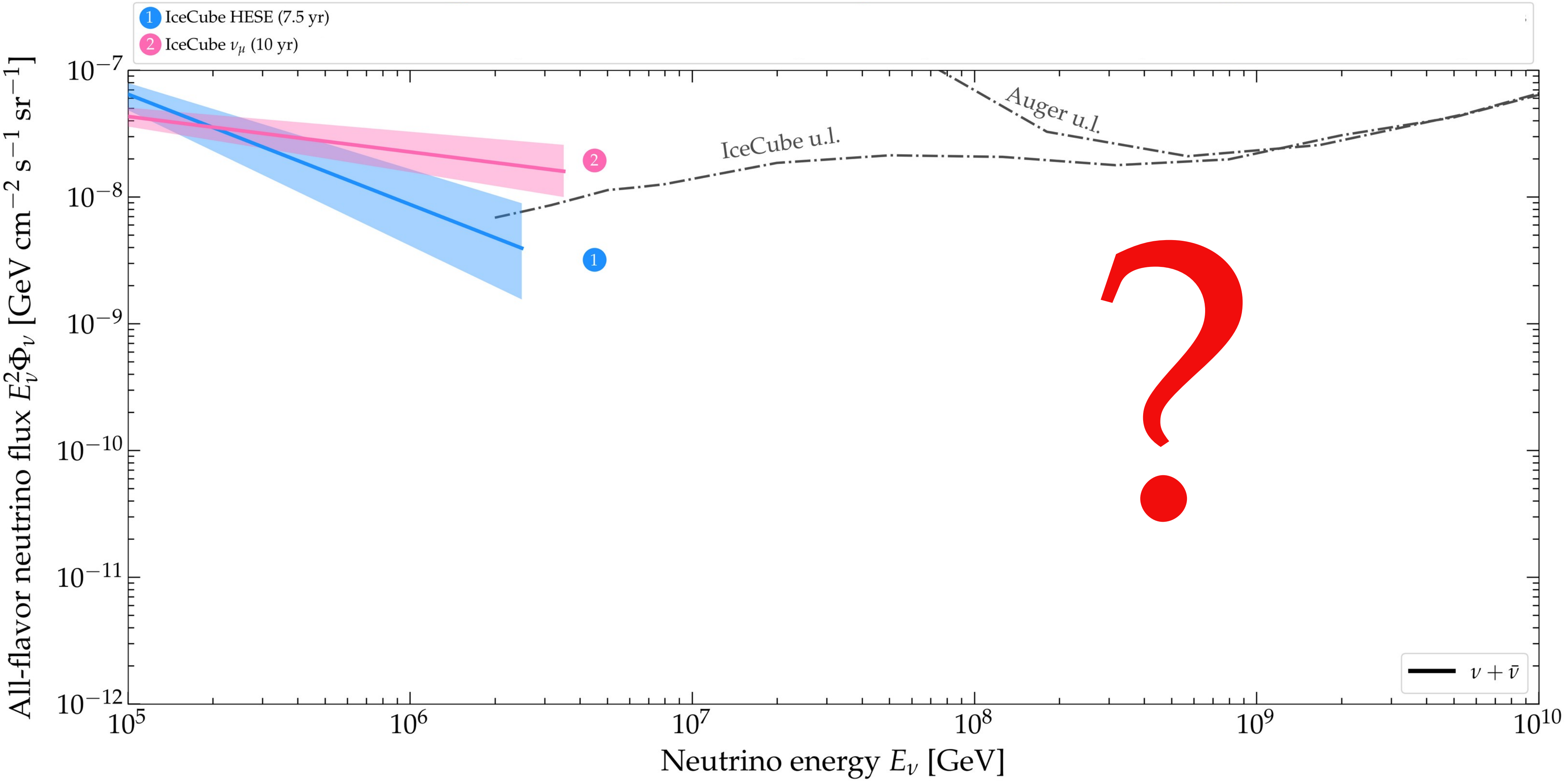
Turn predictions
into data-driven tests

<u>Key developments</u>:

Bigger detectors → larger statistics

Better reconstruction

Smaller astrophysical uncertainties



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Next decade

> 100-PeV ν

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Make predictions for
a new energy regime

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Make predictions for a new energy regime

Key developments:

Discovery

New detection techniques

Better UHE ν flux predictions

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<u>Key developments</u>:
Discovery
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Made robust and meaningful by accounting
for all relevant particle and astrophysics uncertainties

Today

TeV–PeV ν

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

Next decade

> 100-PeV ν

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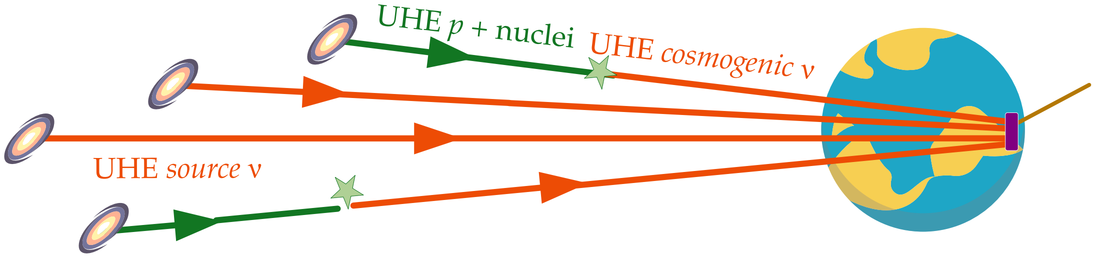
Key developments:
Discovery
New detection techniques
Better UHE ν flux predictions

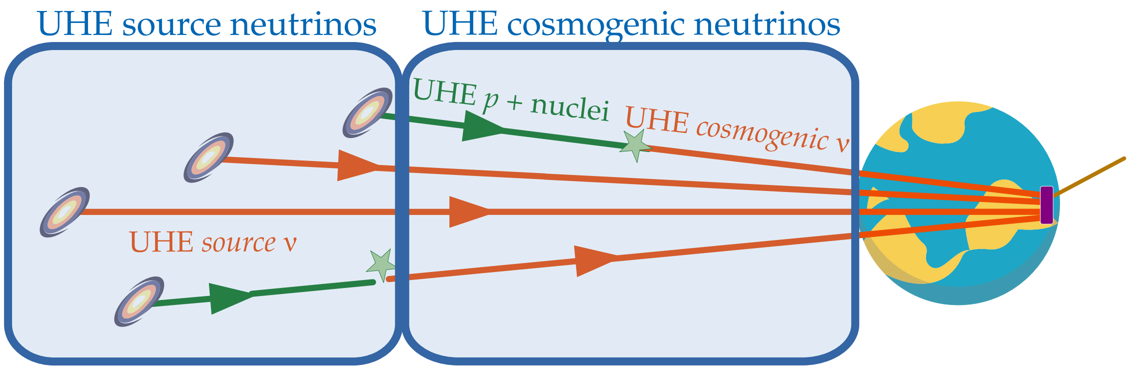
Similar to the evolution of cosmology to a high-precision field in the 1990s

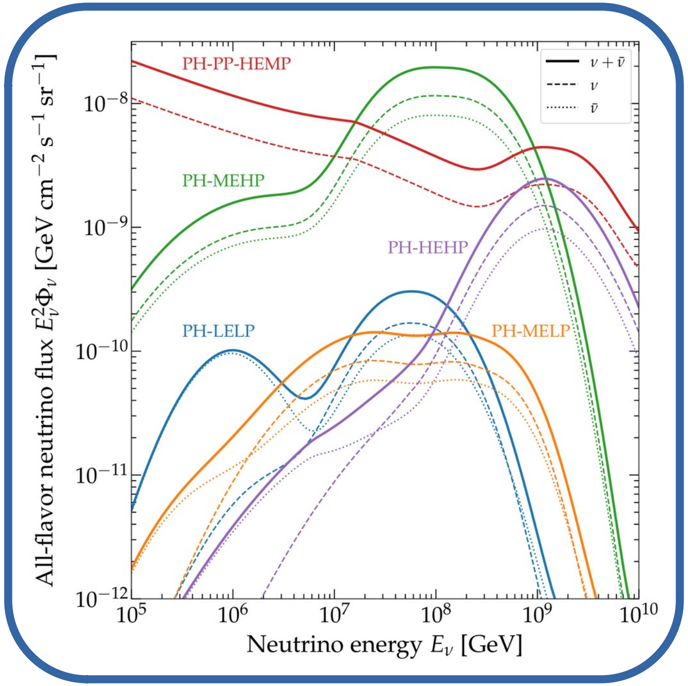
Made robust and meaningful by accounting
for all relevant particle and astrophysics uncertainties

A general framework

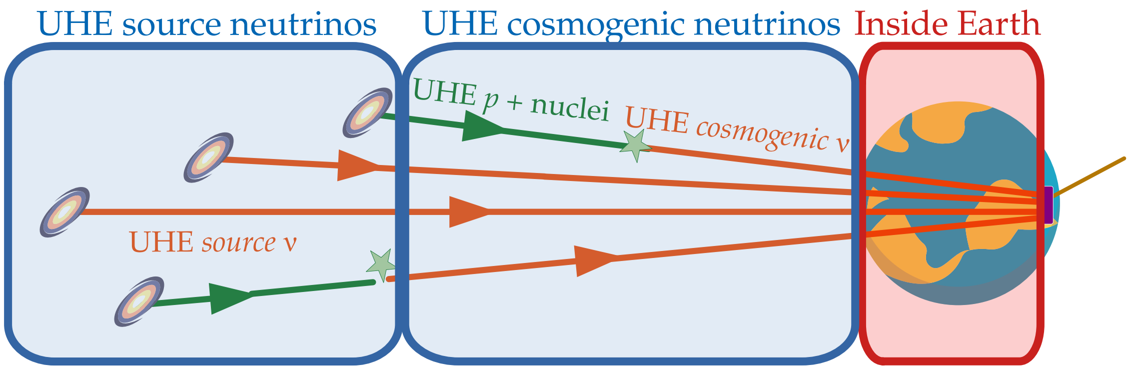
(Focused on UHE ν and IC-Gen2 Radio)

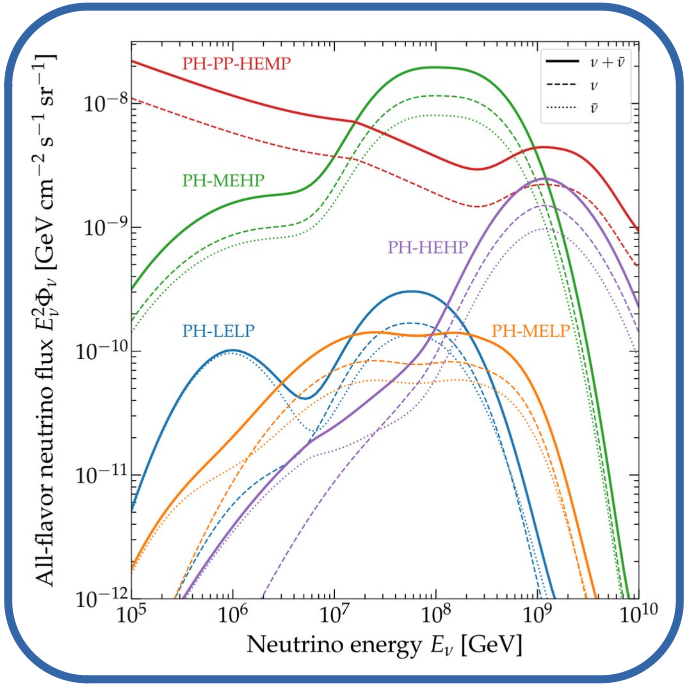

UHE p + nuclei
UHE cosmogenic ν
UHE source ν





UHE ν from *pp* and *pγ* interactions, account for cosmic-ray spectrum & mass composition, source properties





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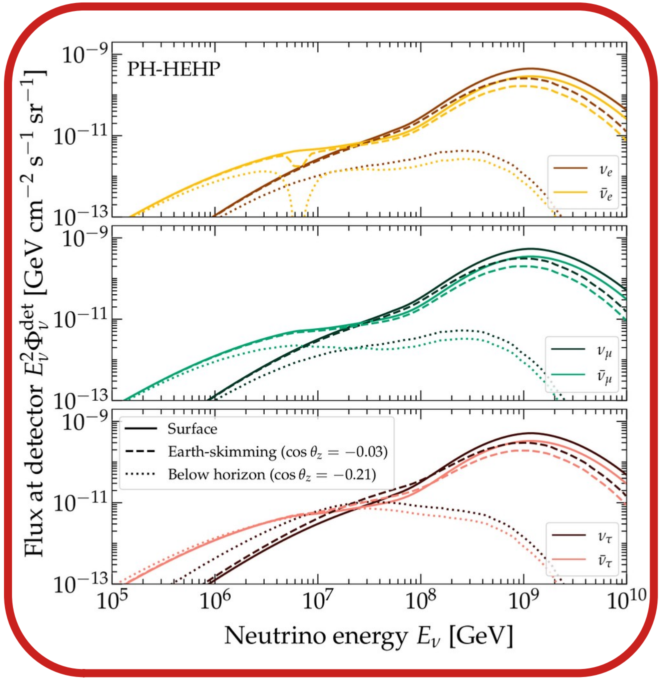

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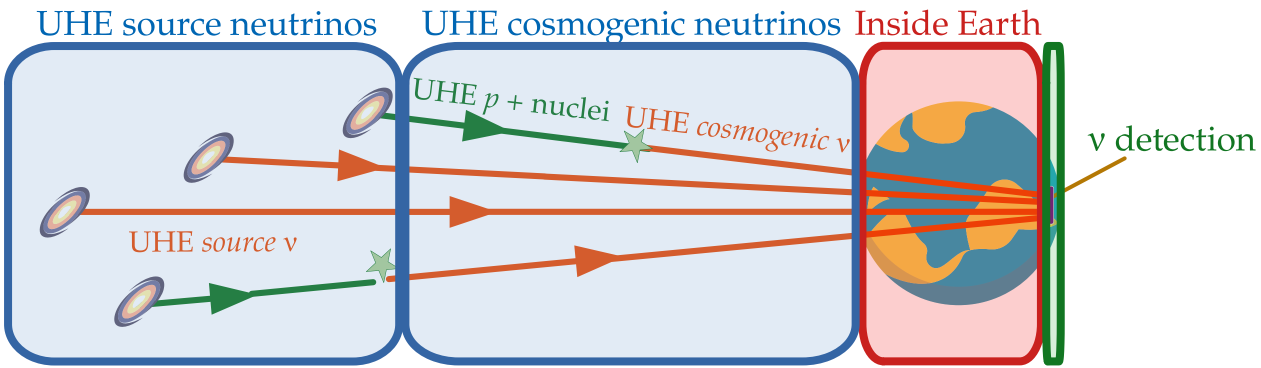

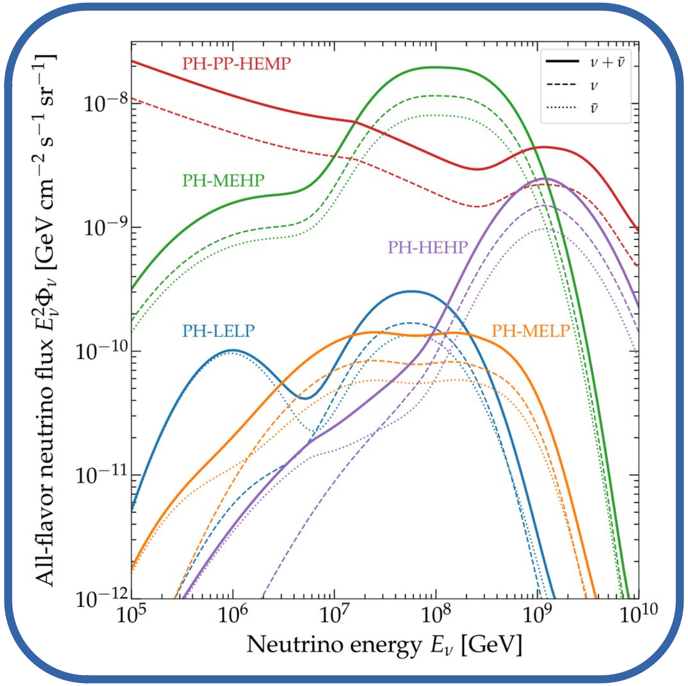

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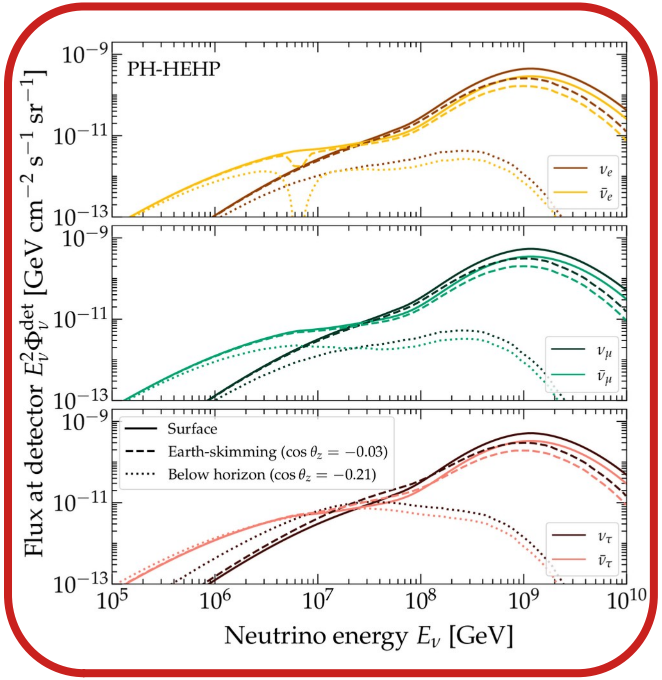

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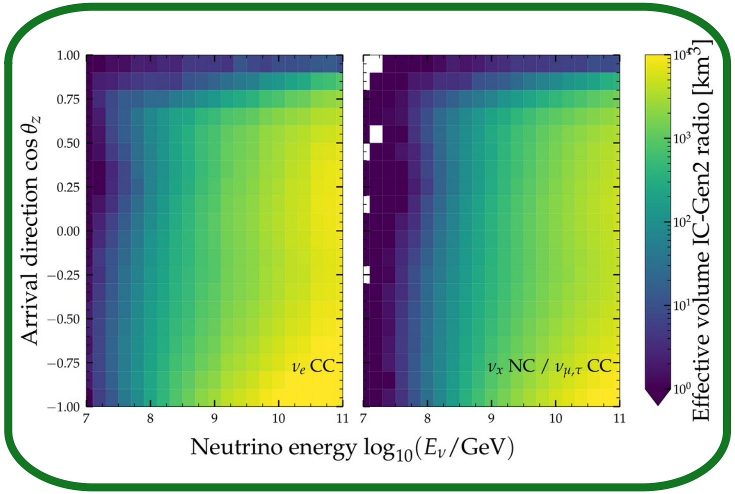
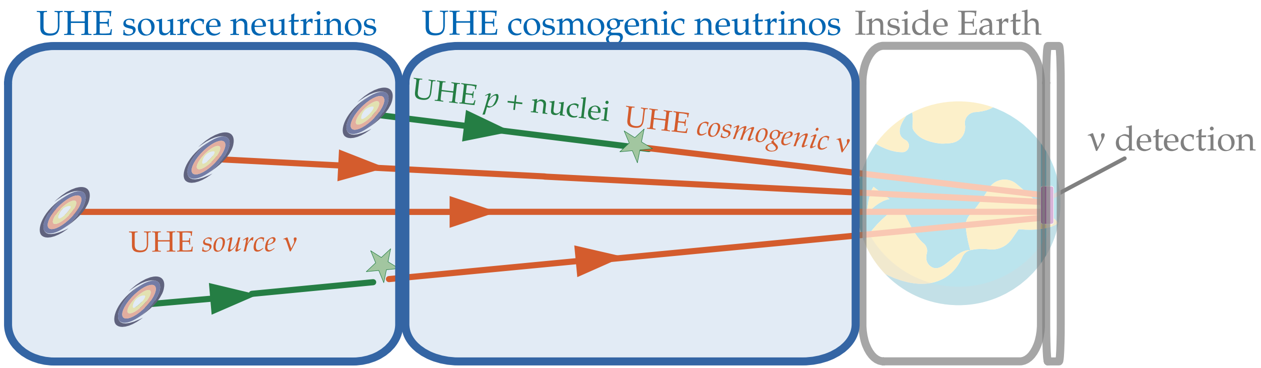
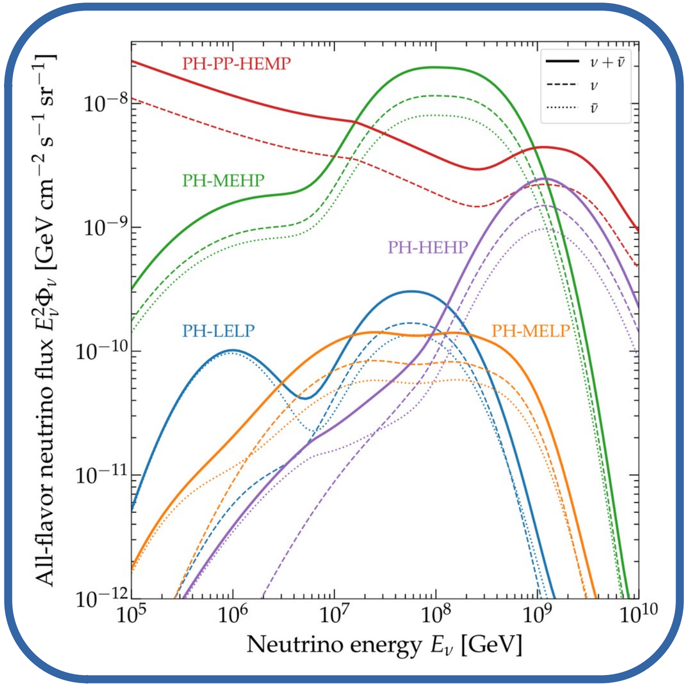


Model radio propagation in ice, antenna response, angular and energy resolution, inelasticity distribution





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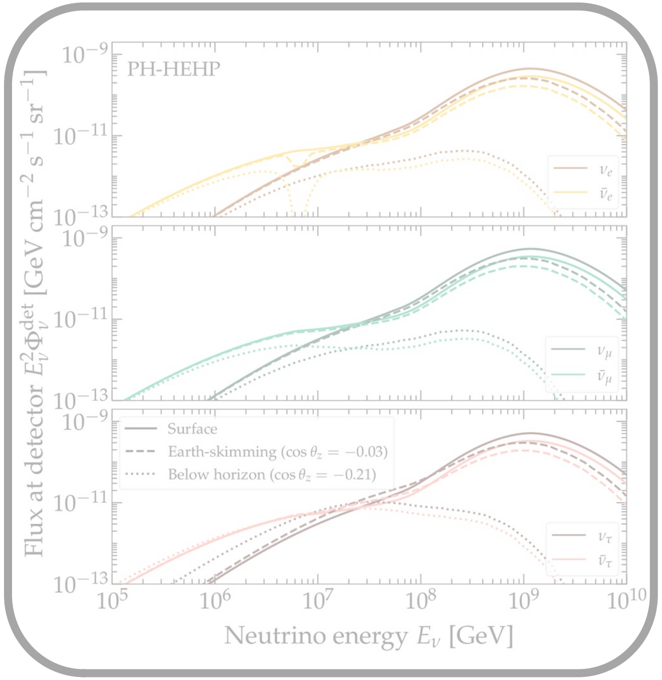

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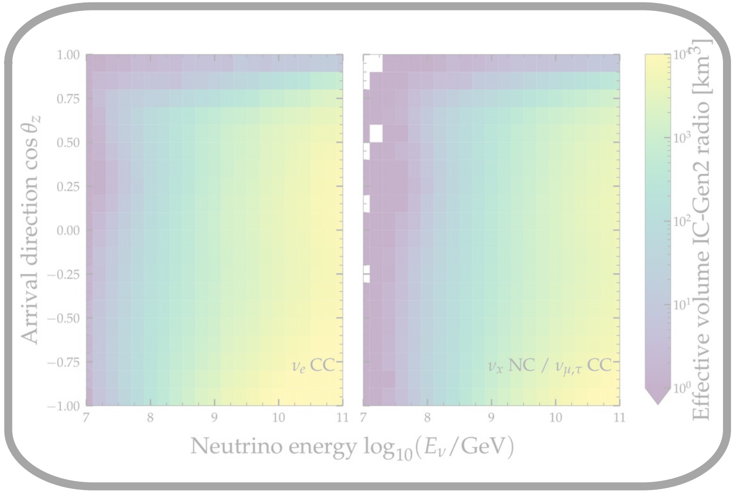

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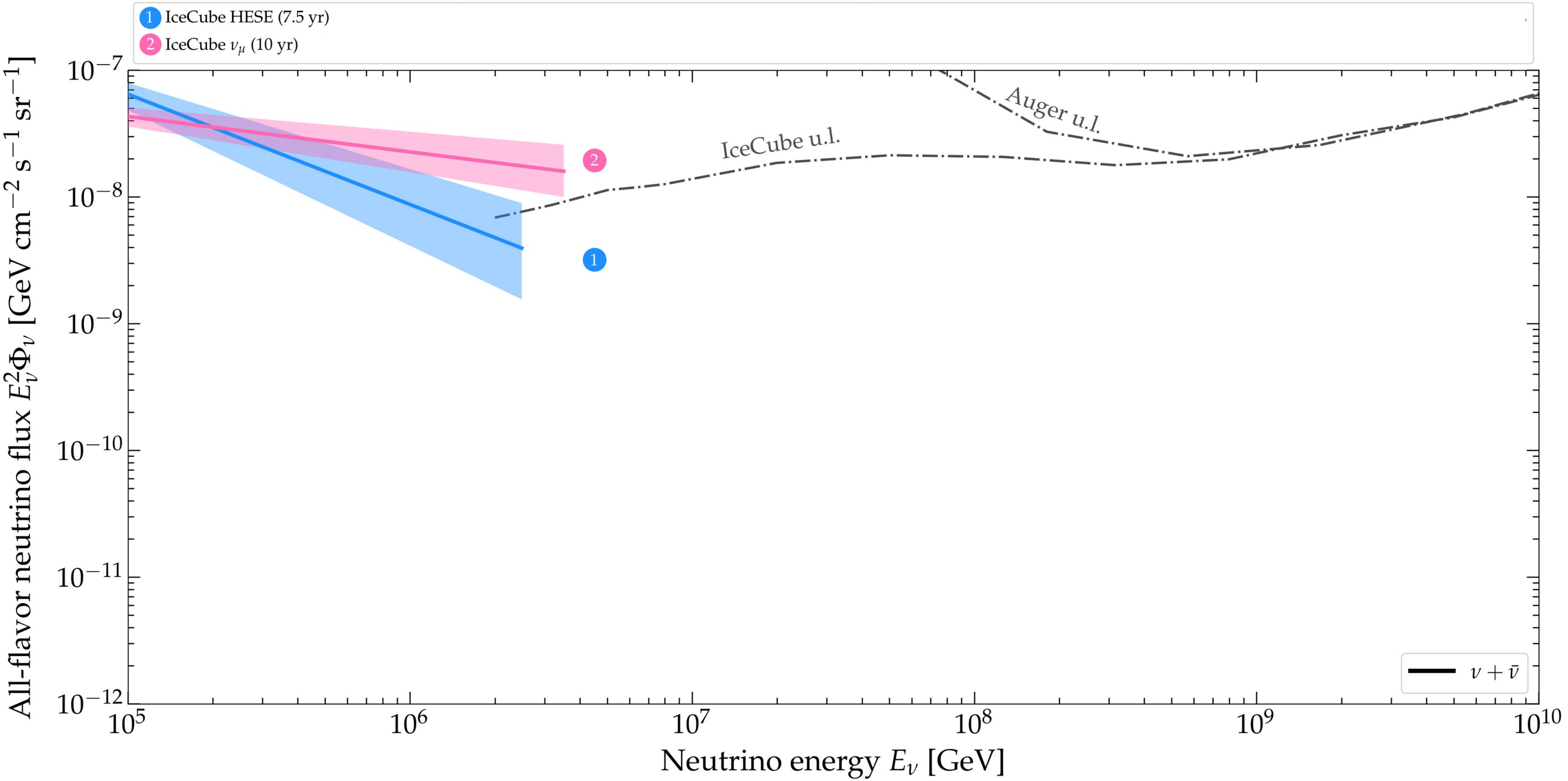
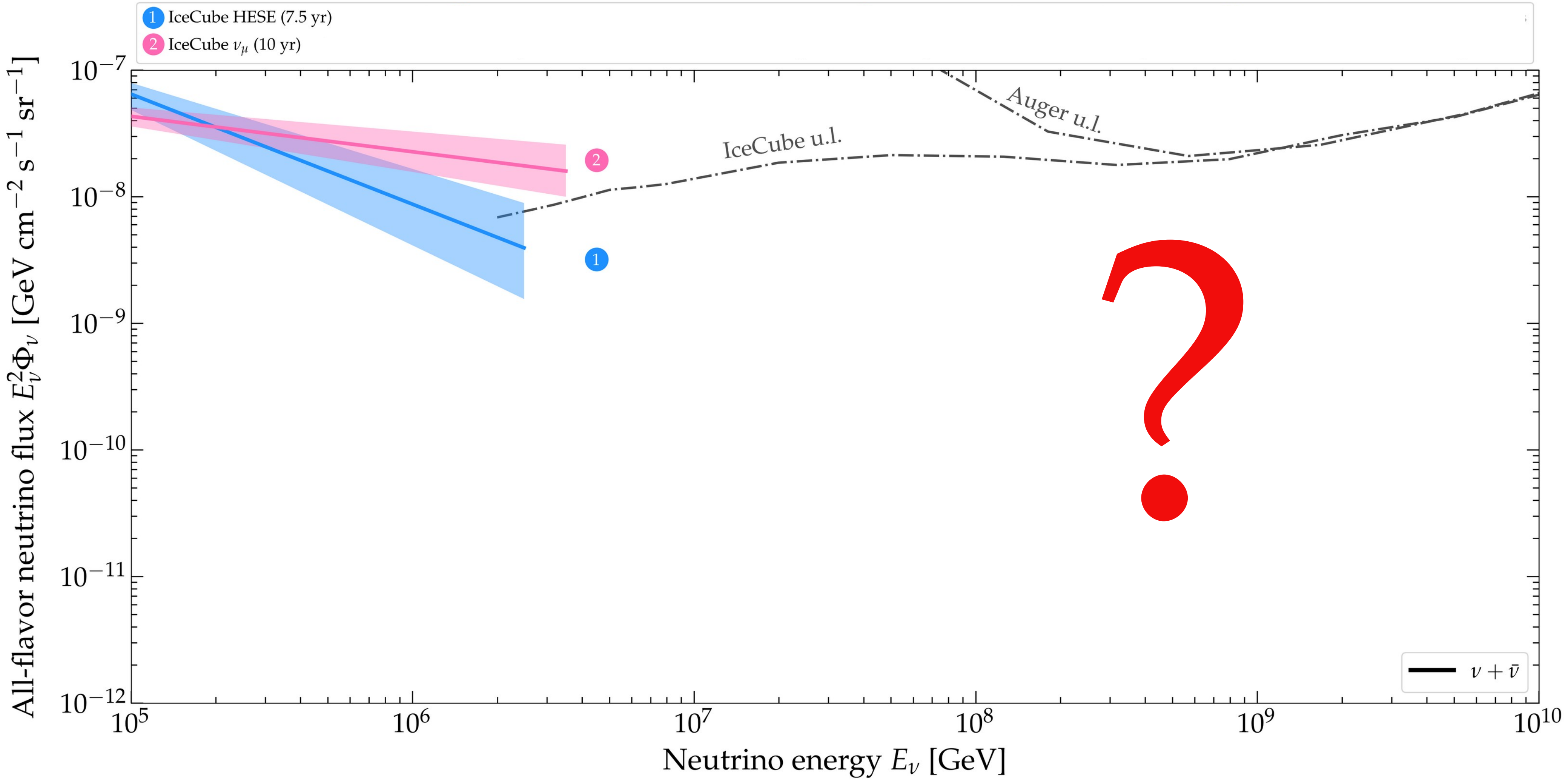


MB, Valera, Glaser, *In preparation*



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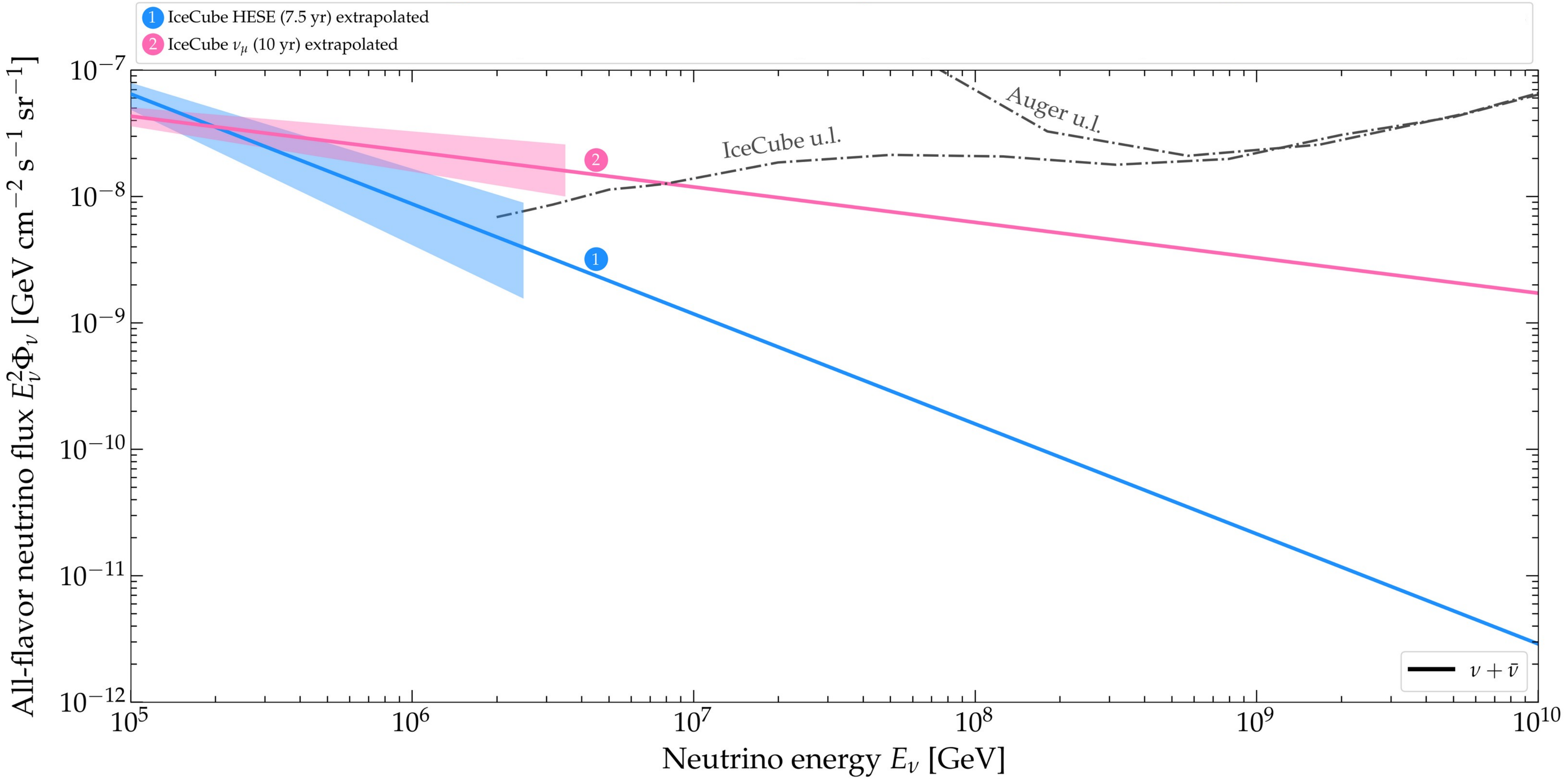

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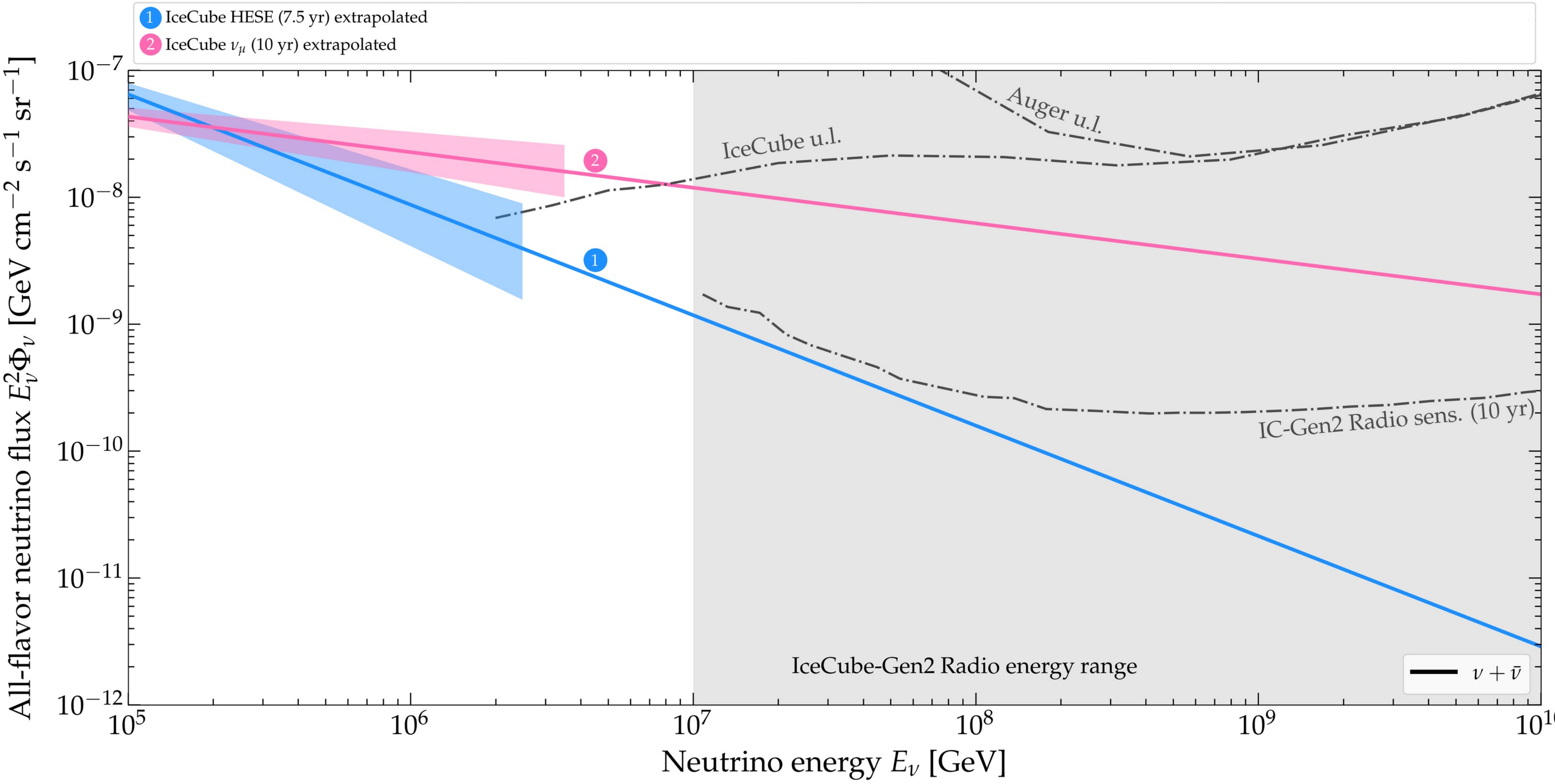

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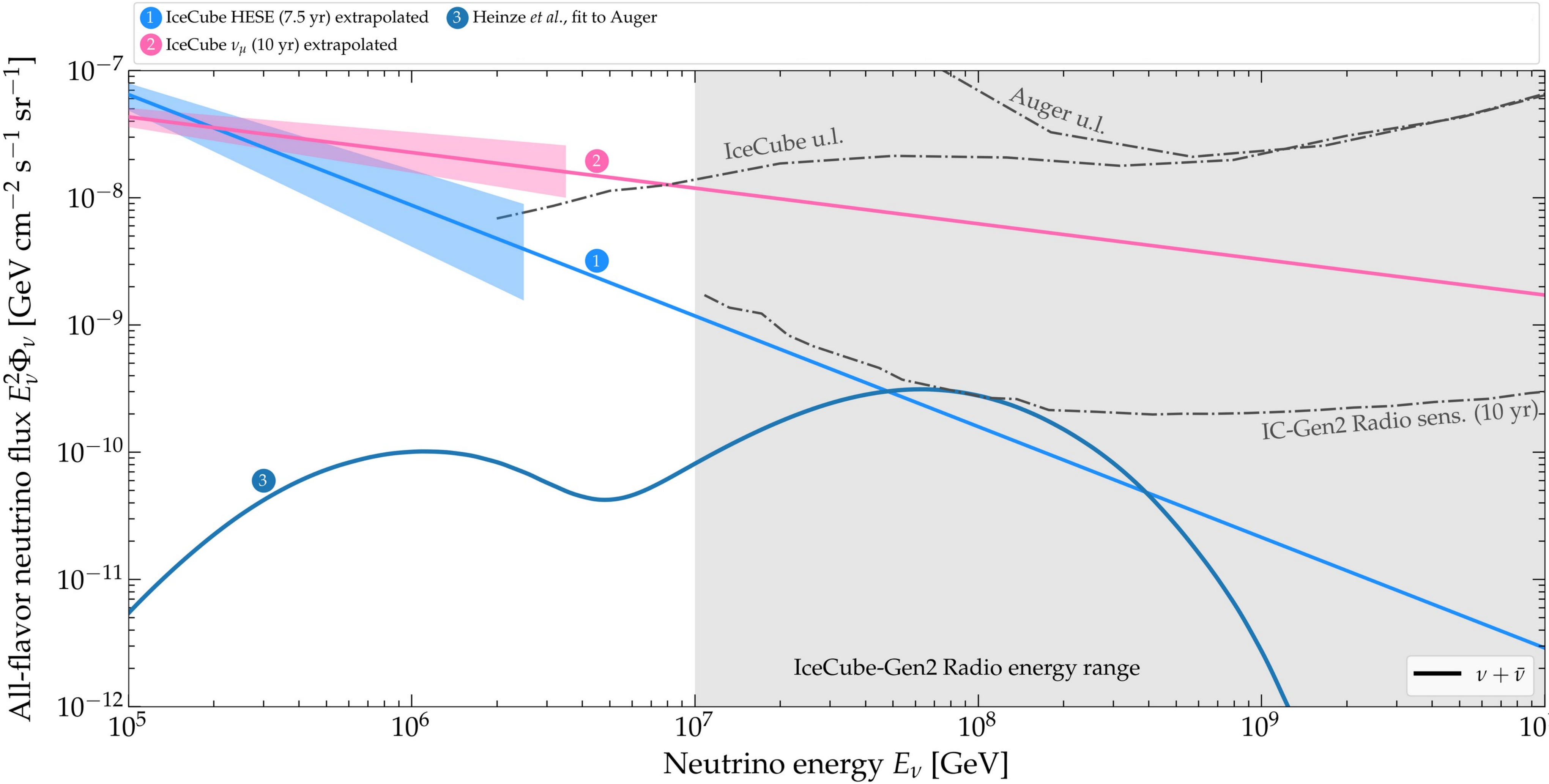

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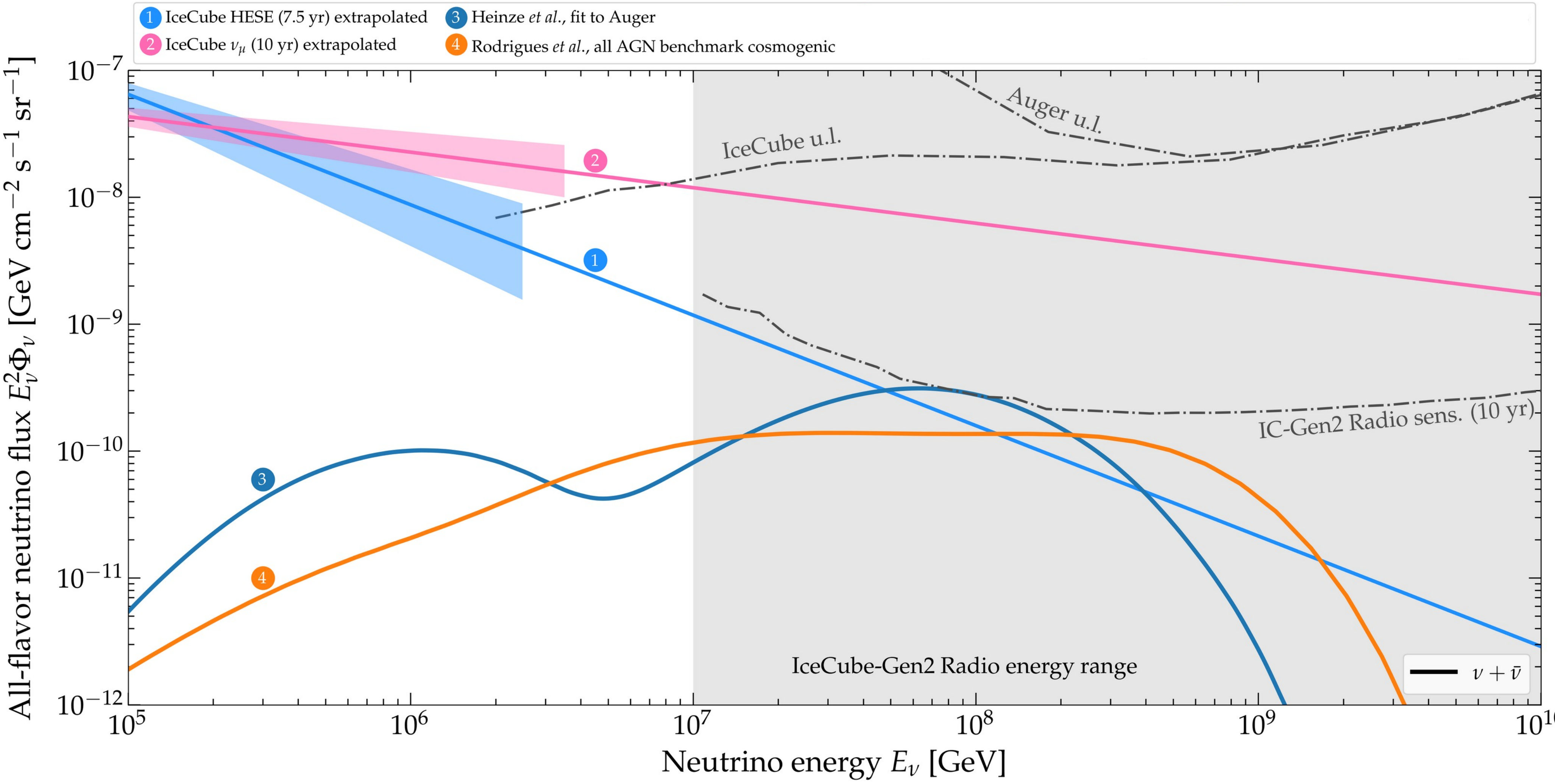
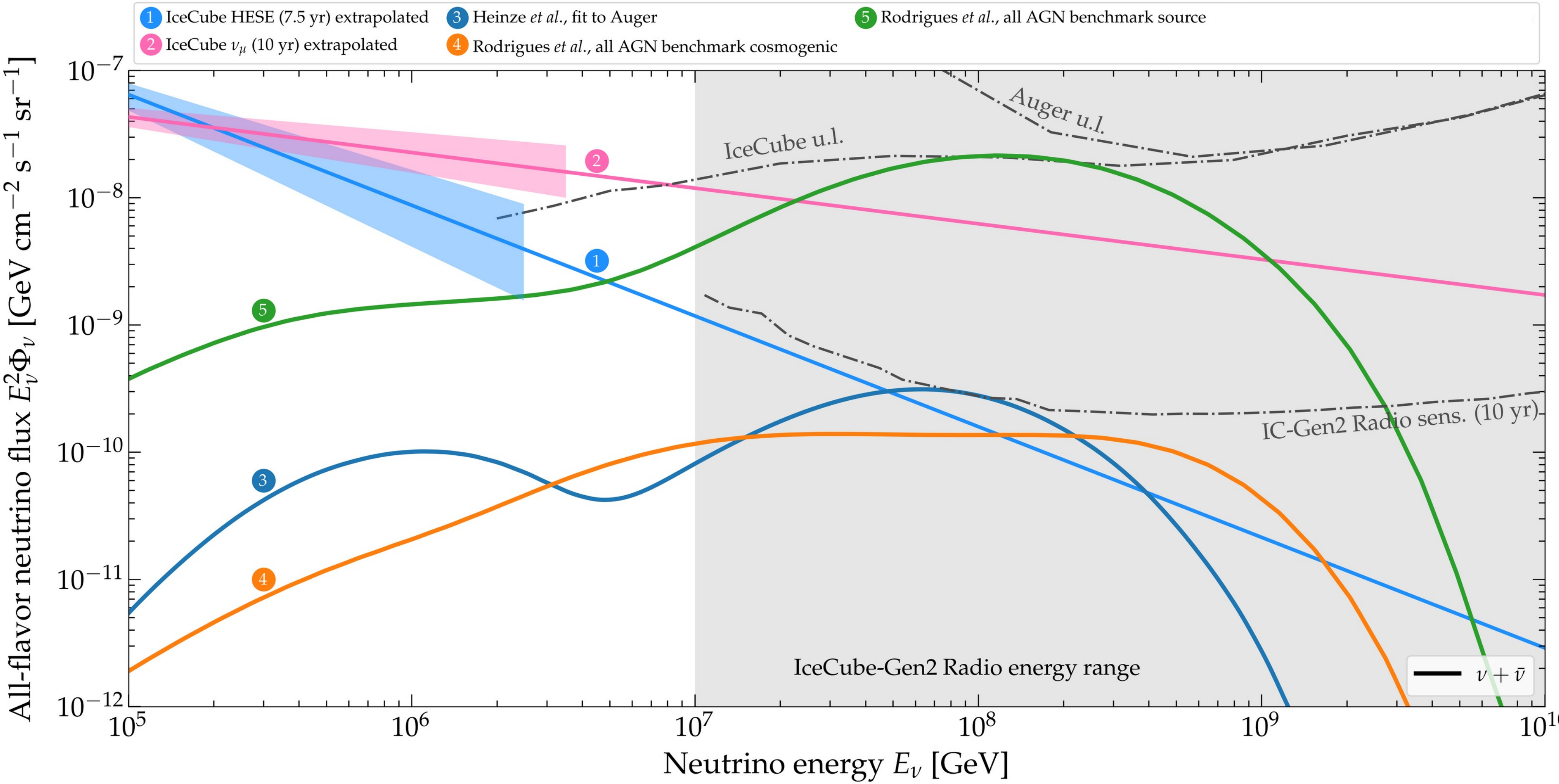


1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
3 Heinze *et al.*, fit to Auger
4 Rodrigues *et al.*, all AGN benchmark cosmogenic
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}



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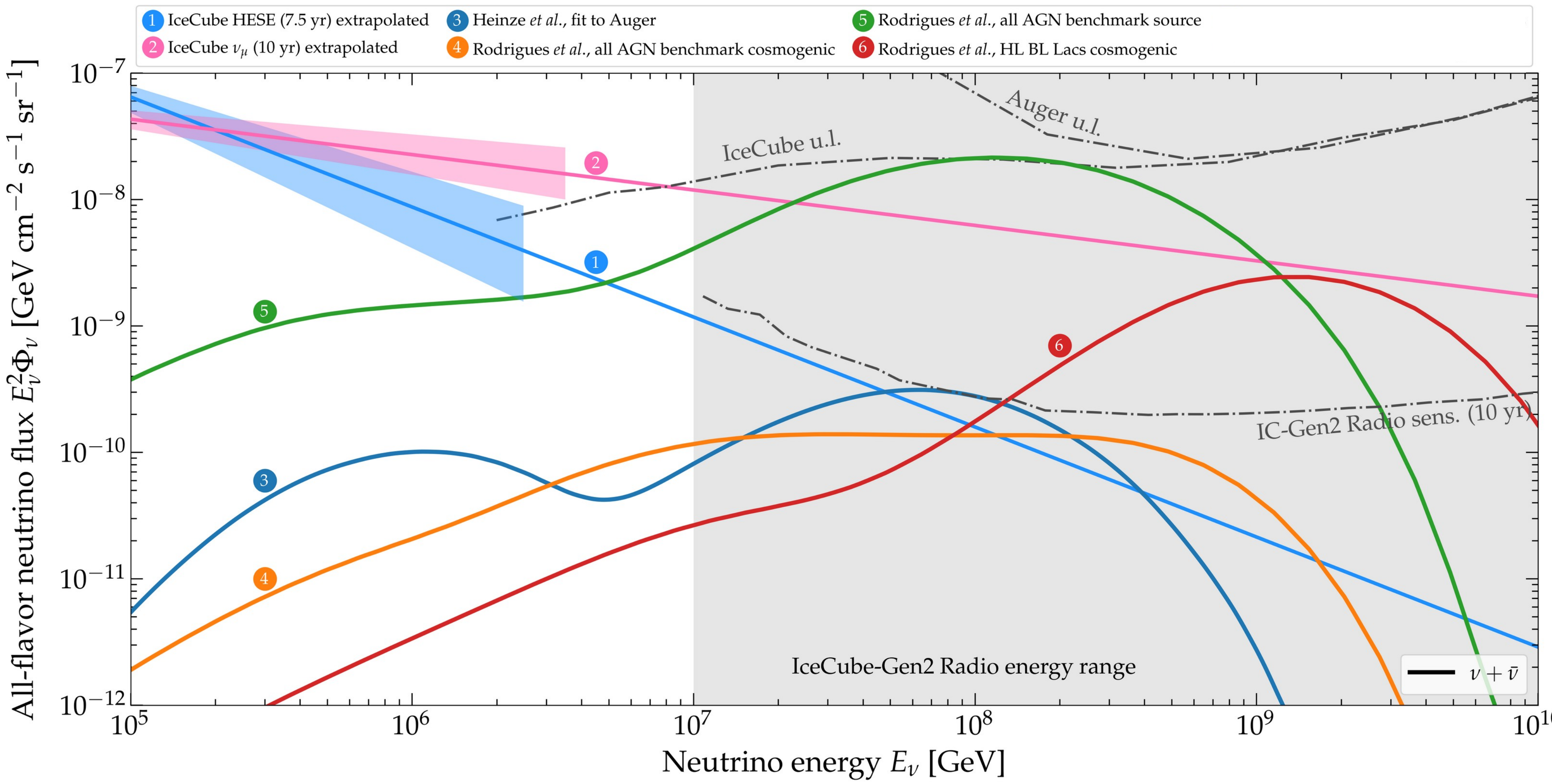

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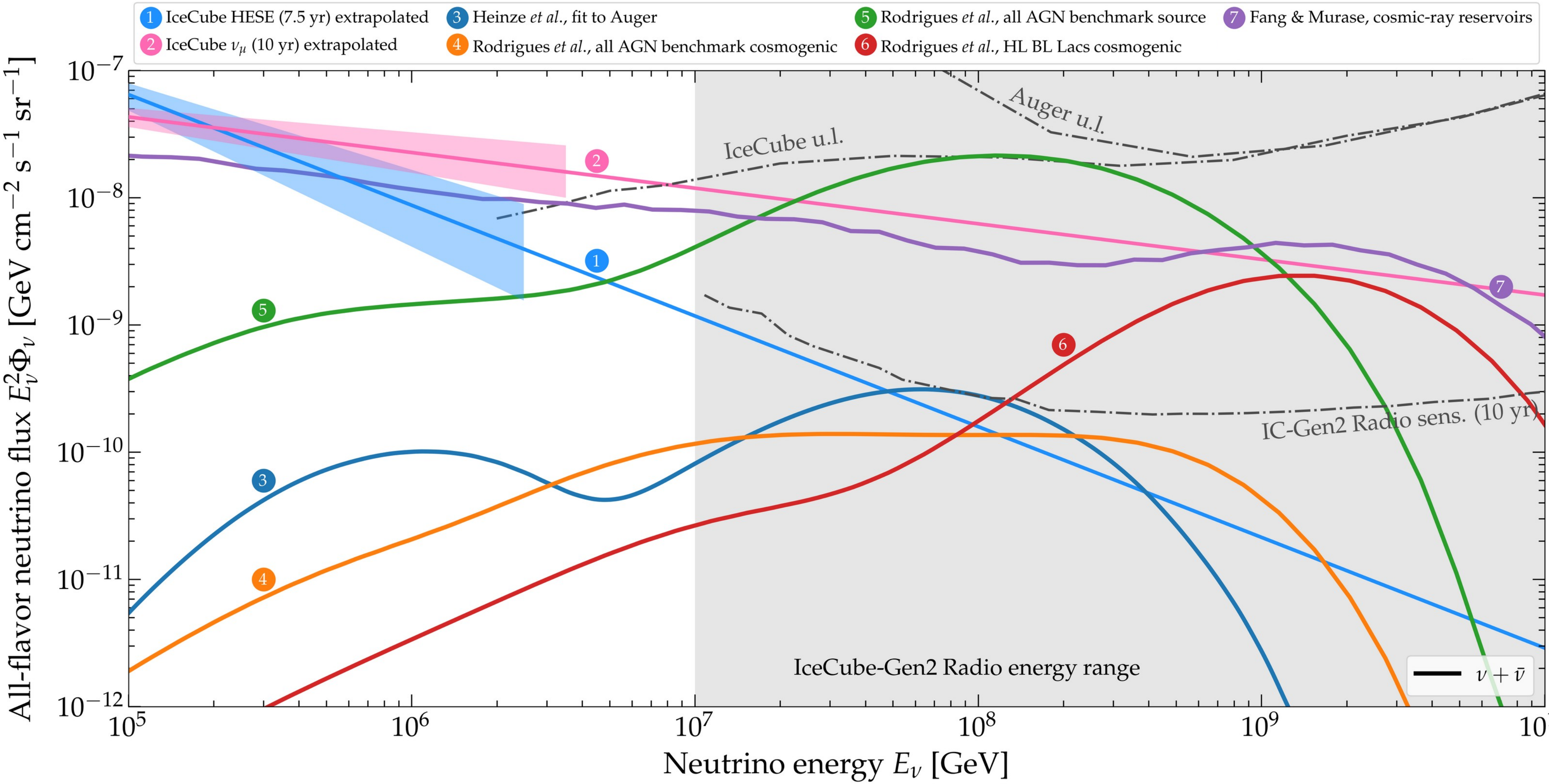

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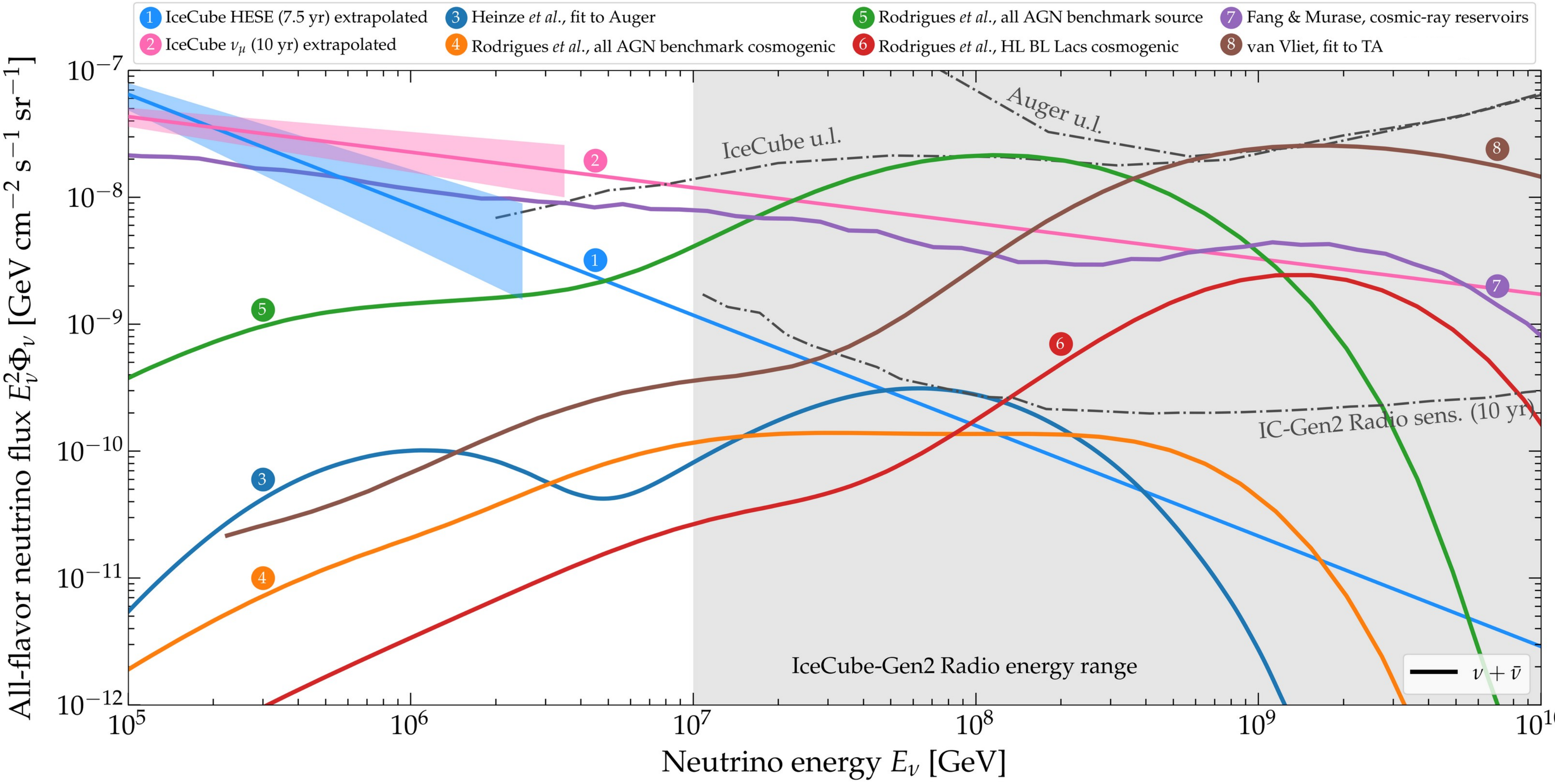

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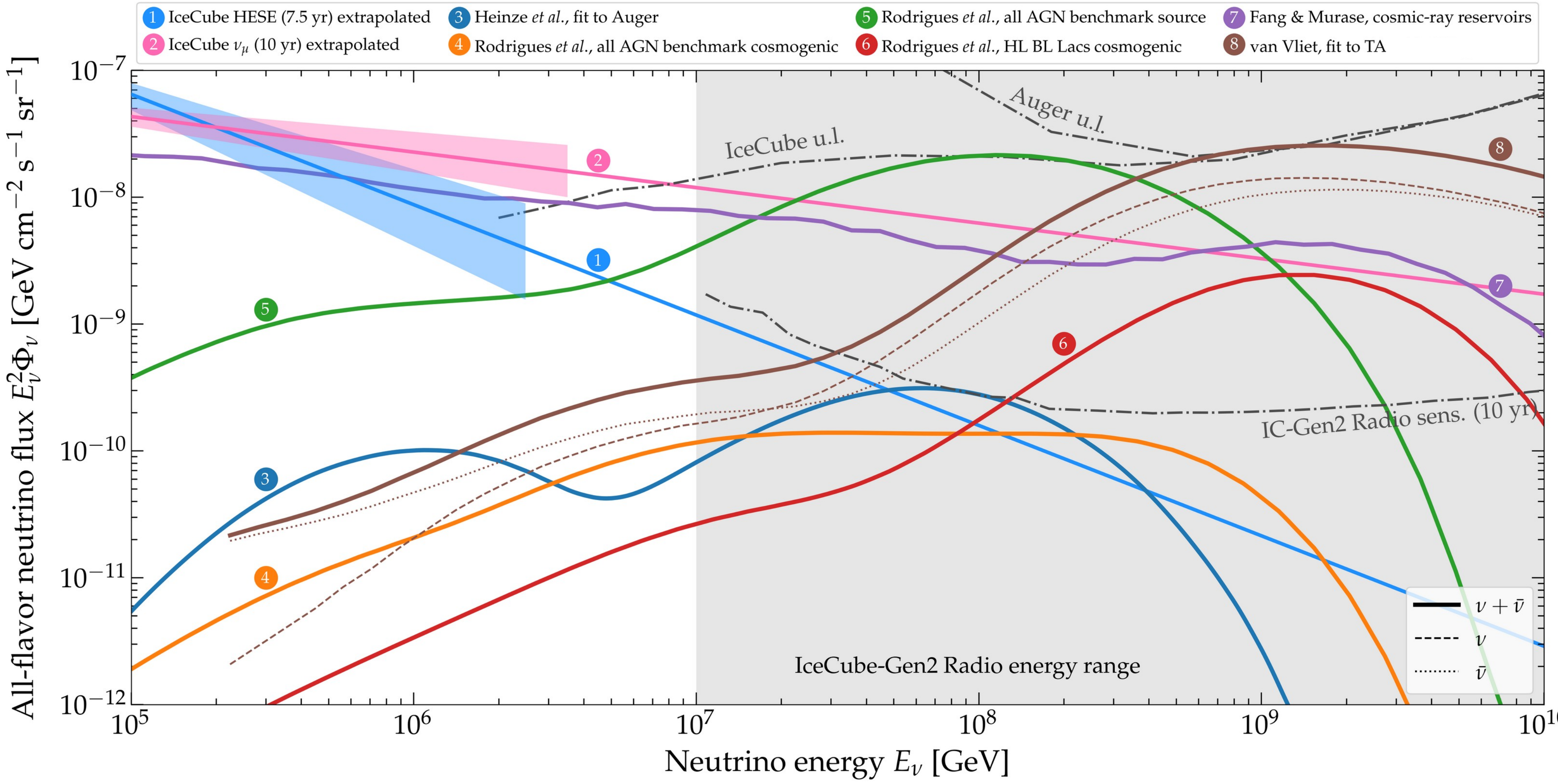

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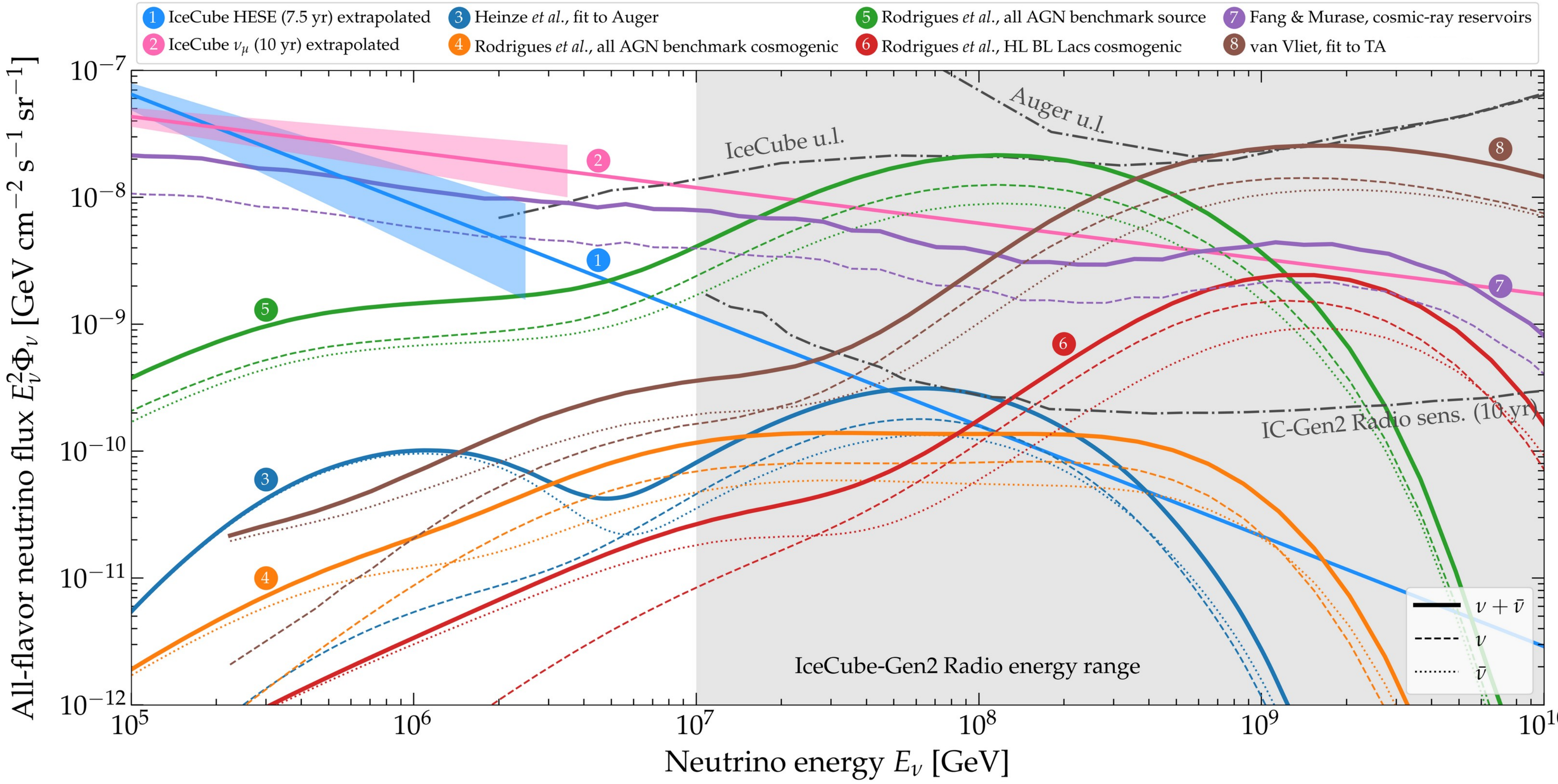
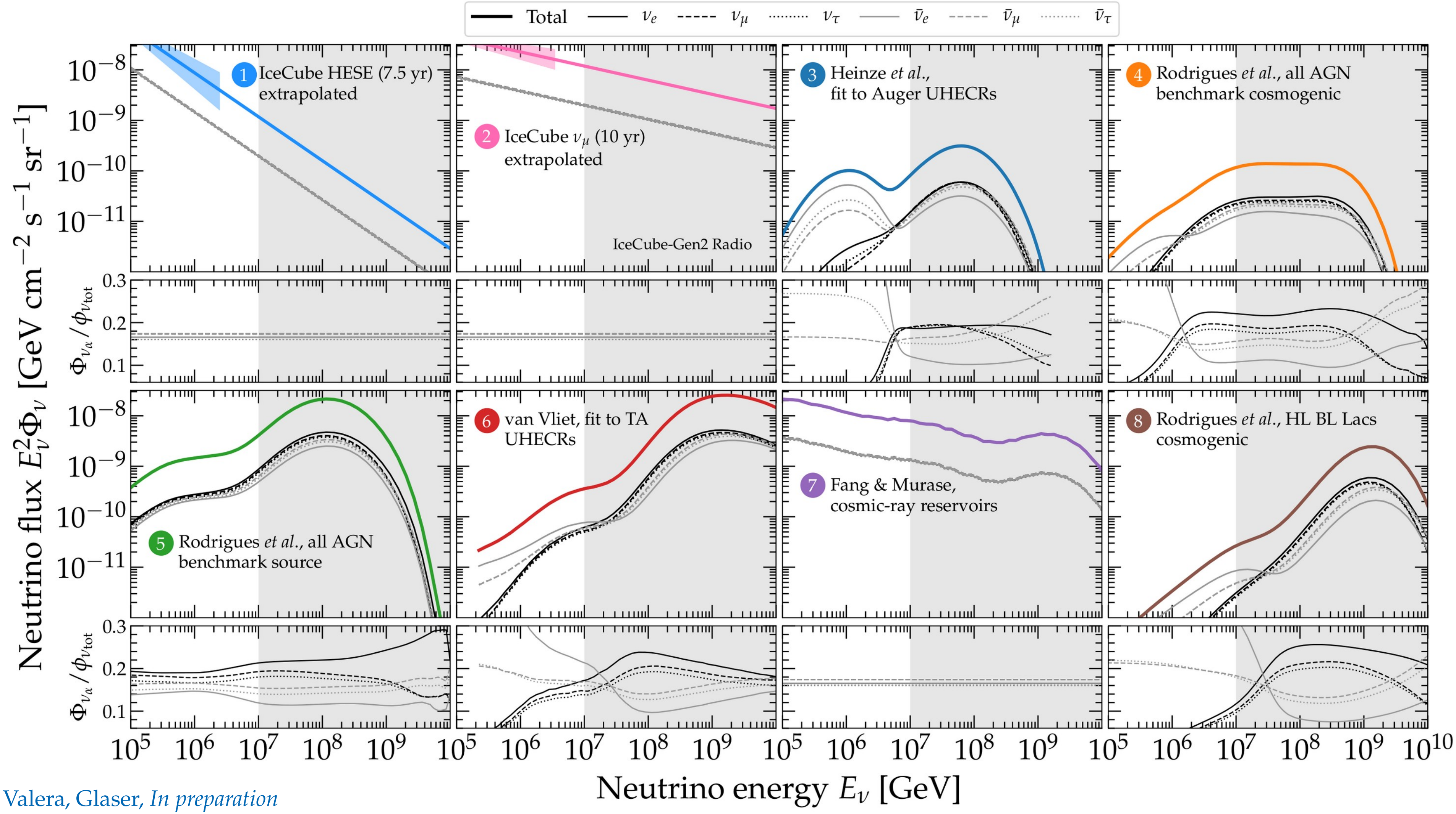


MB, Valera, Glaser, *In preparation*

Flavor structure of the UHE ν fluxes



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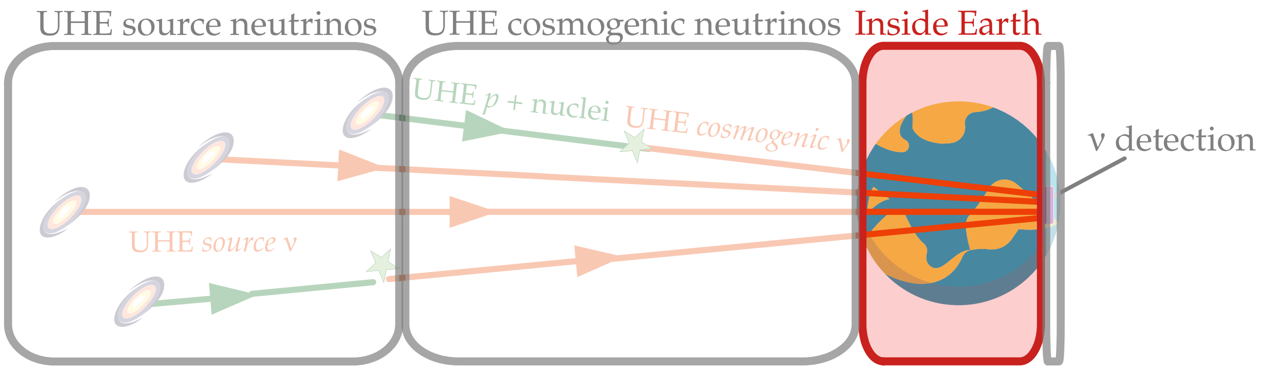

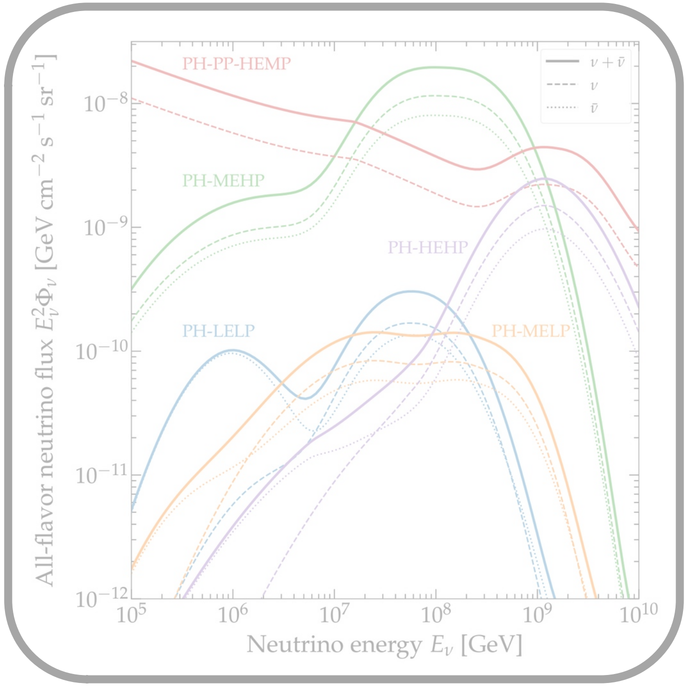

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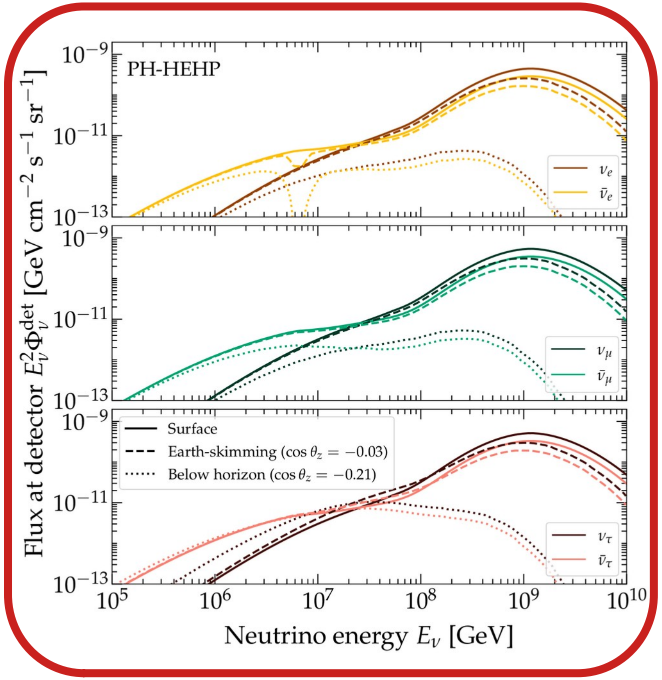

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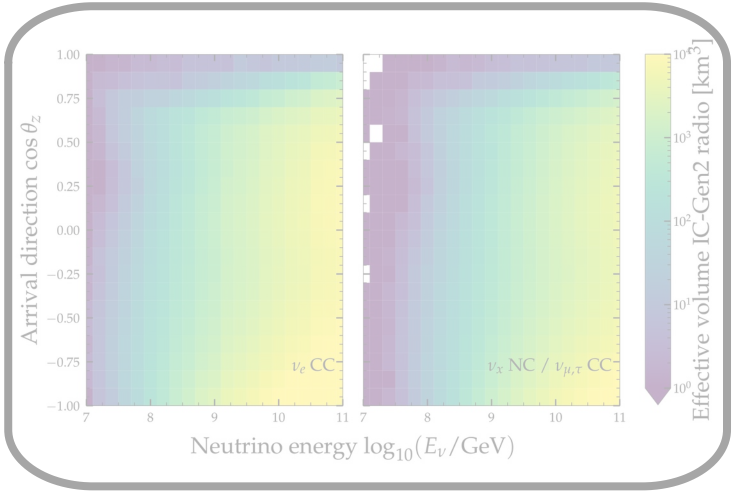
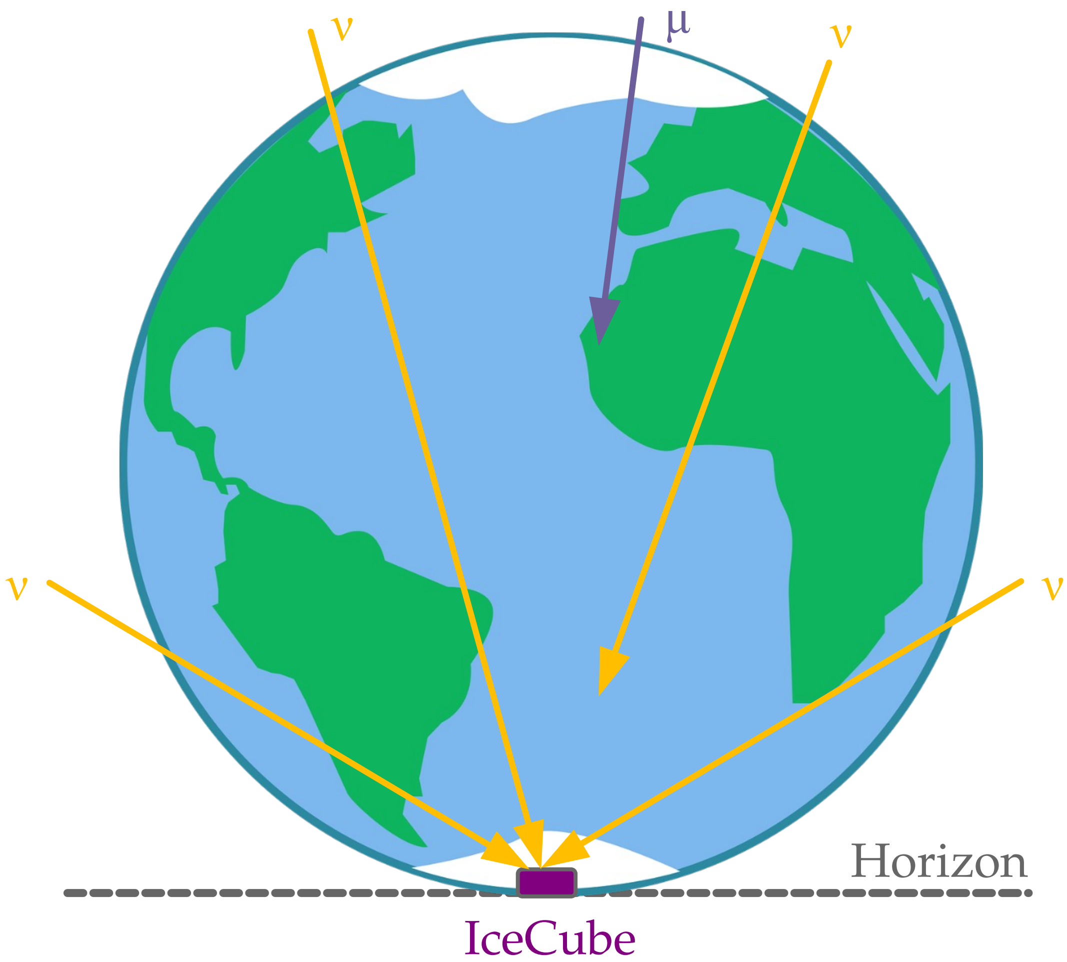
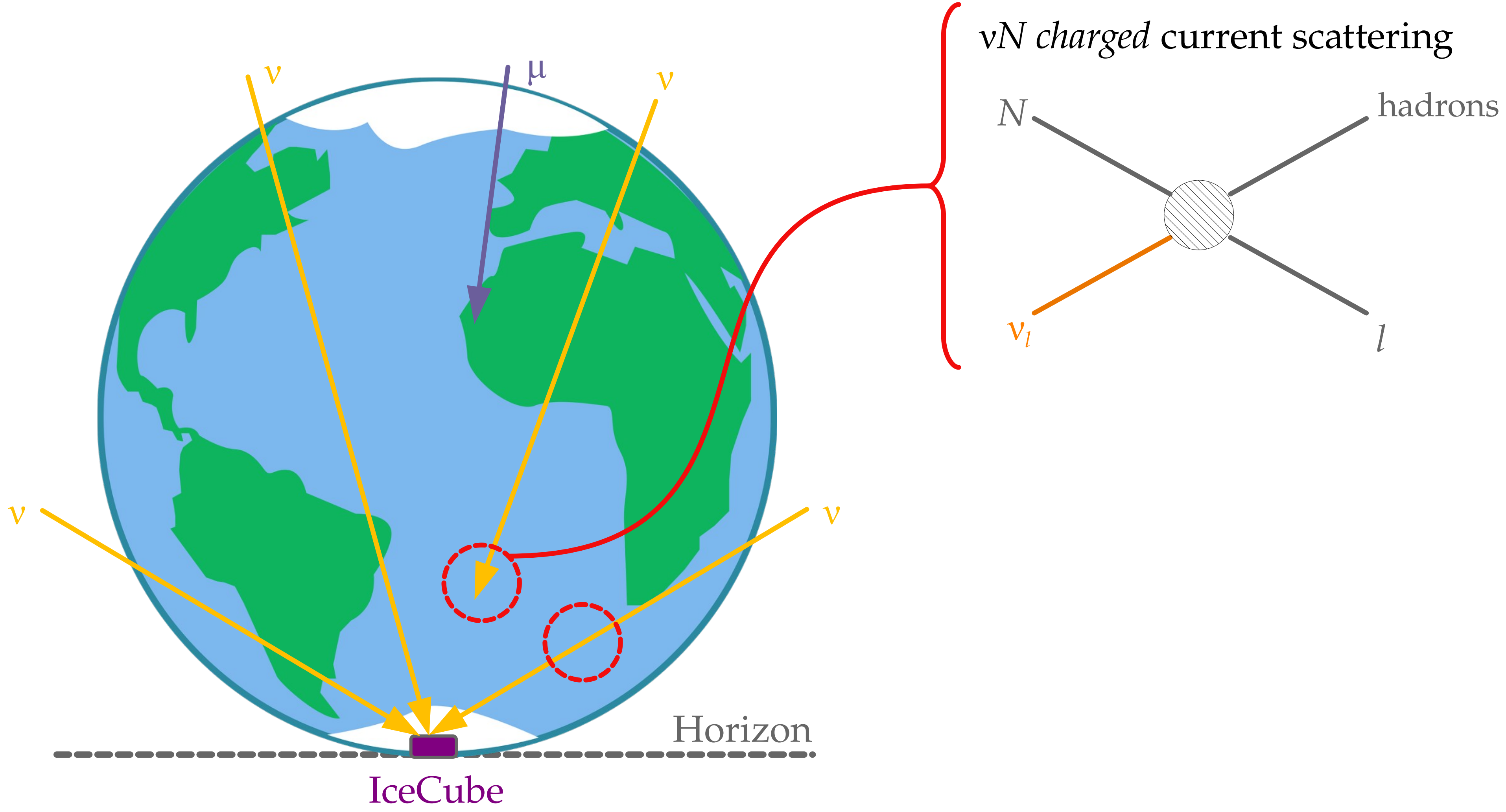
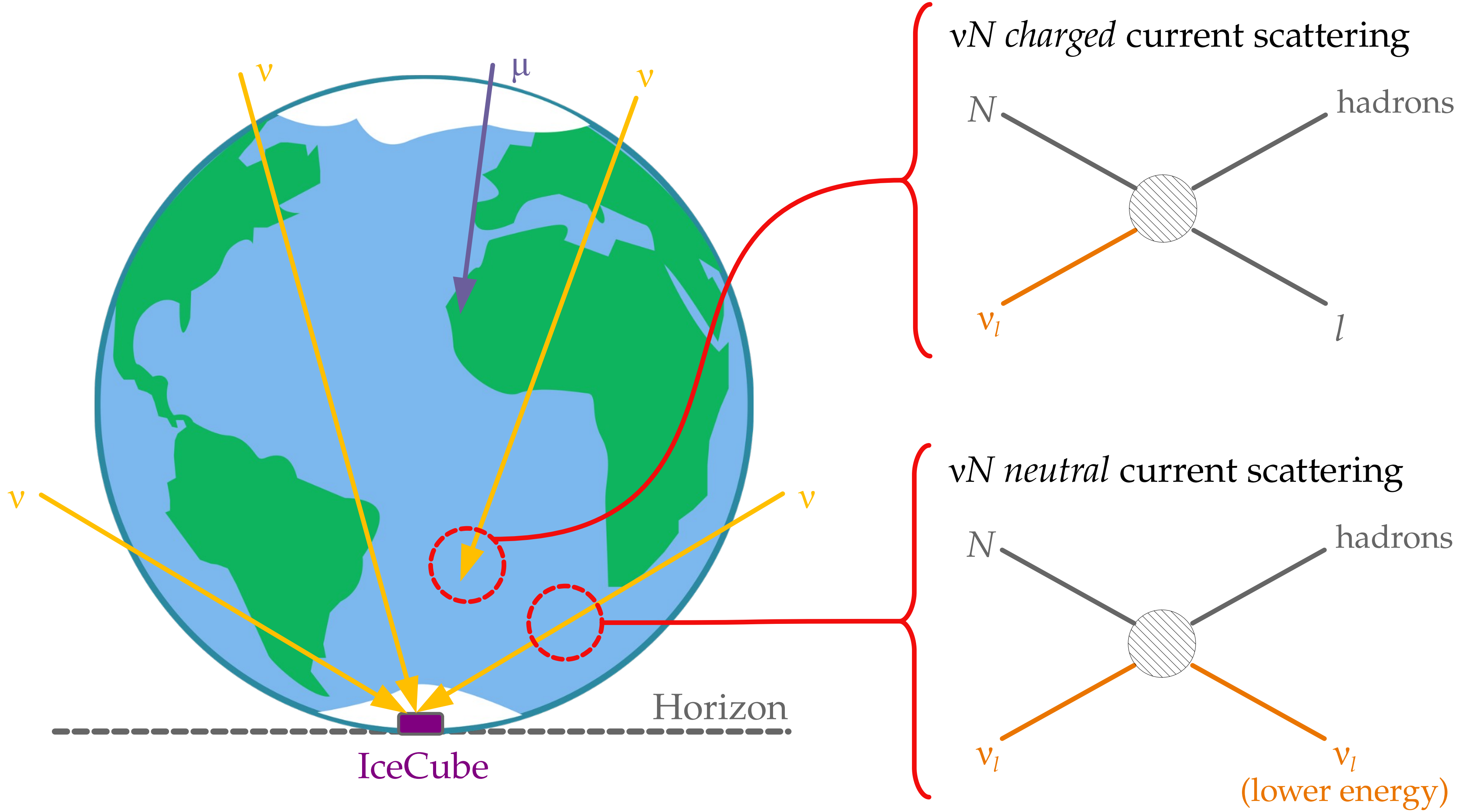


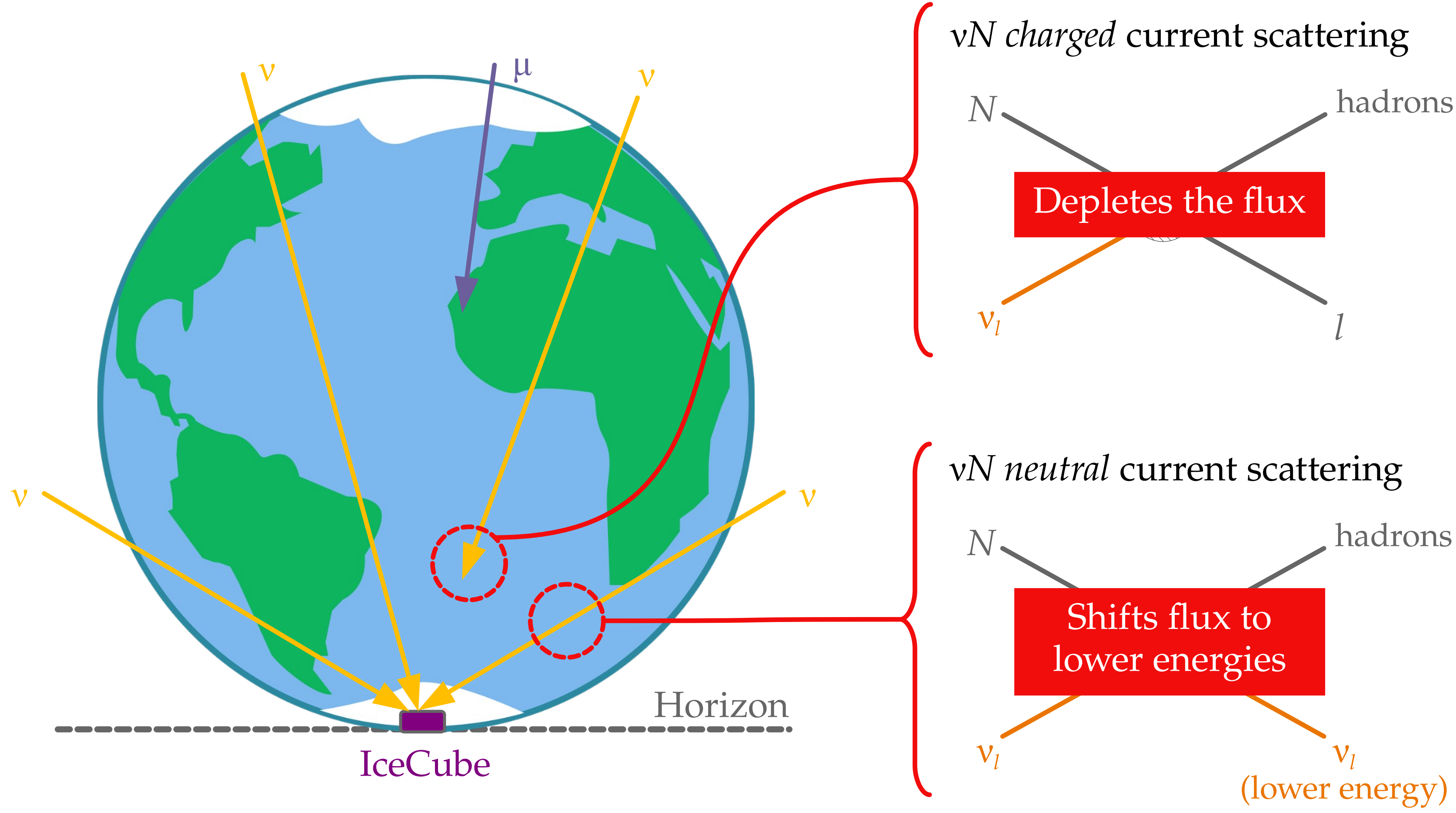
Model radio propagation in ice, antenna response, angular and energy resolution, inelasticity distribution

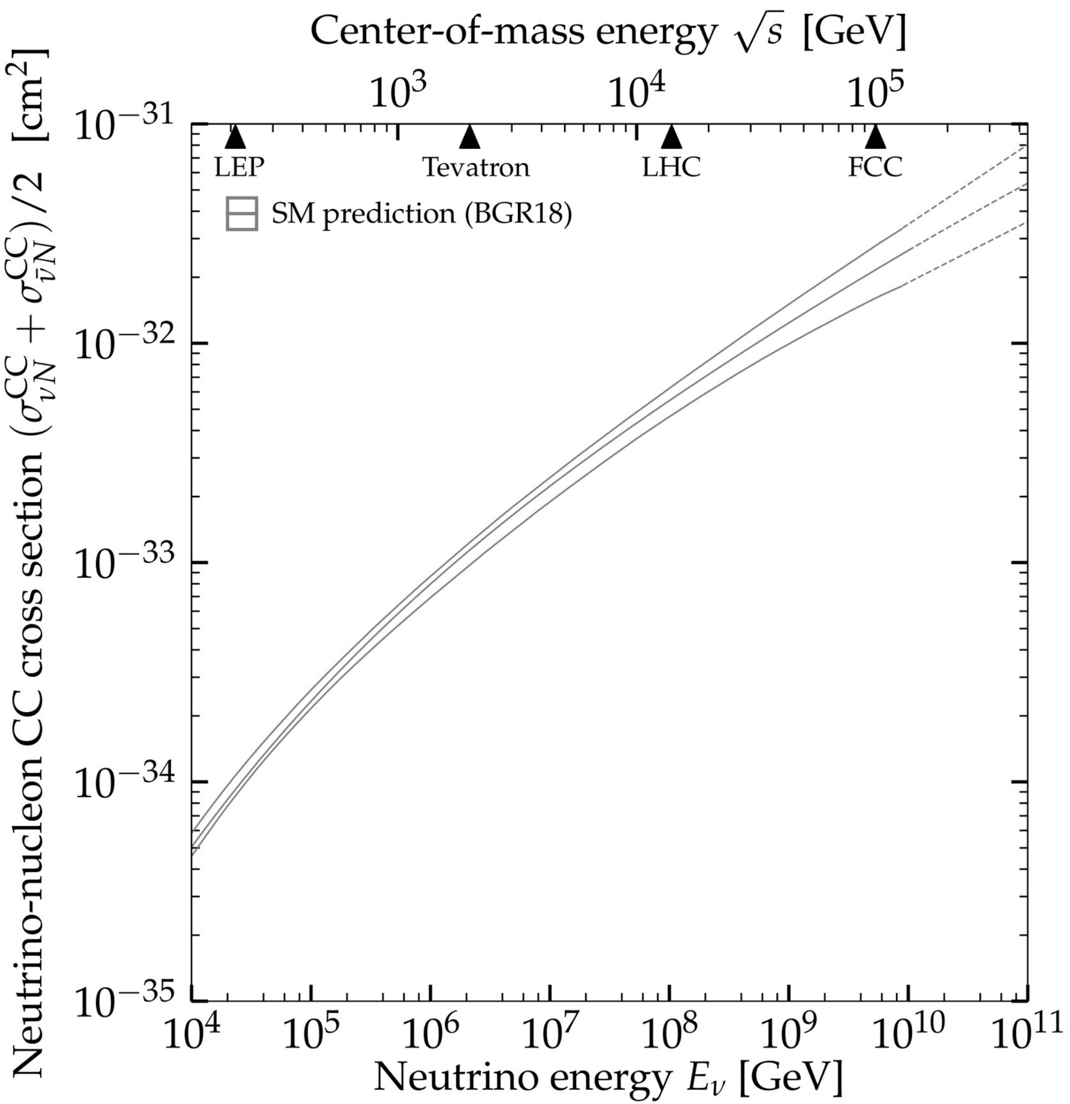
Propagation inside the Earth




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


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

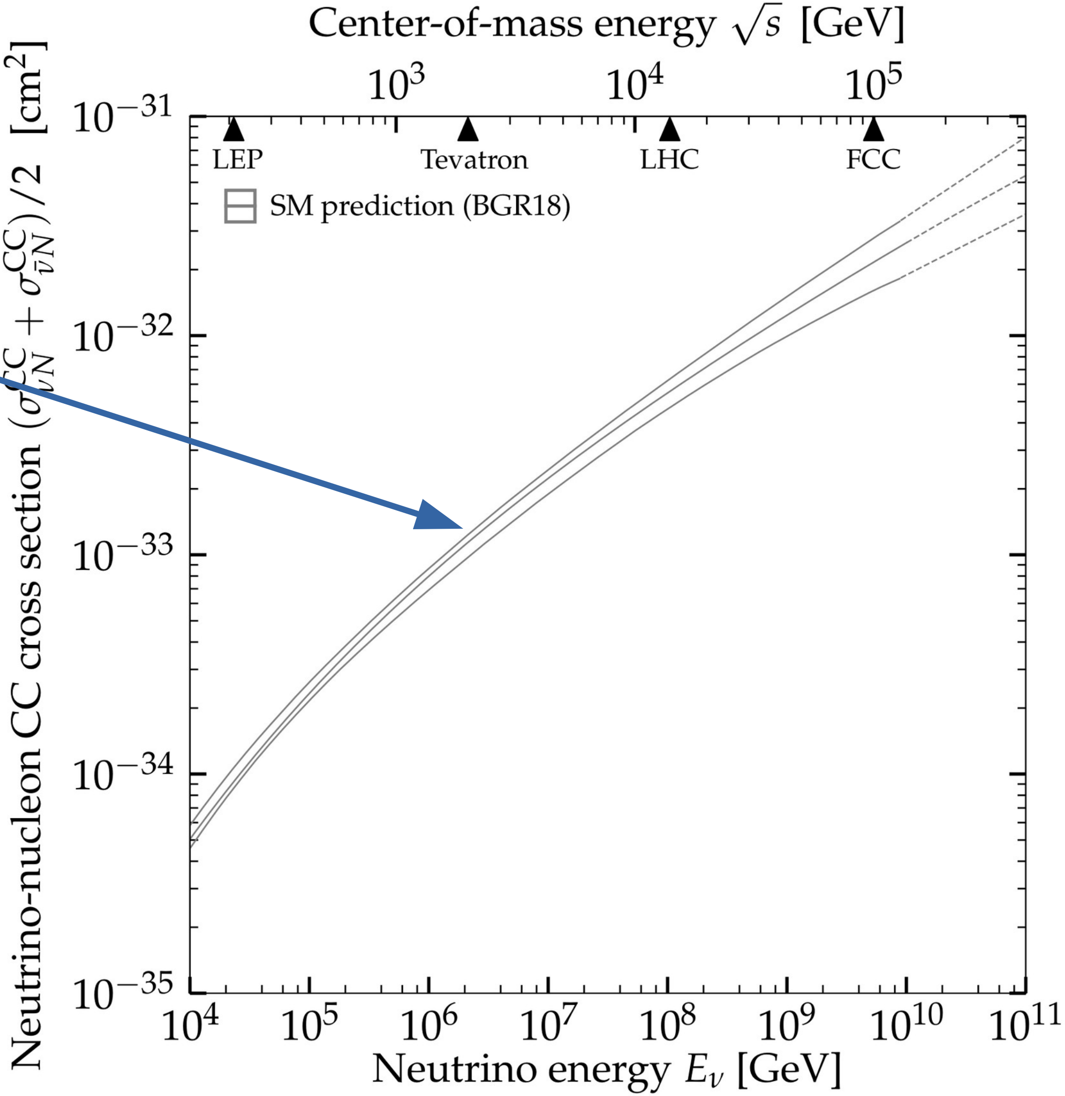

ν
μ
ν
ν
ν
IceCube
Horizon
νN *charged* current scattering
N
hadrons
Depletes the flux
ν_l
l
νN *neutral* current scattering
N
hadrons
Shifts flux to lower energies
ν_l
ν_l
(lower energy)



Bertone, Gauld, Rojo, *JHEP* 2019

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

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



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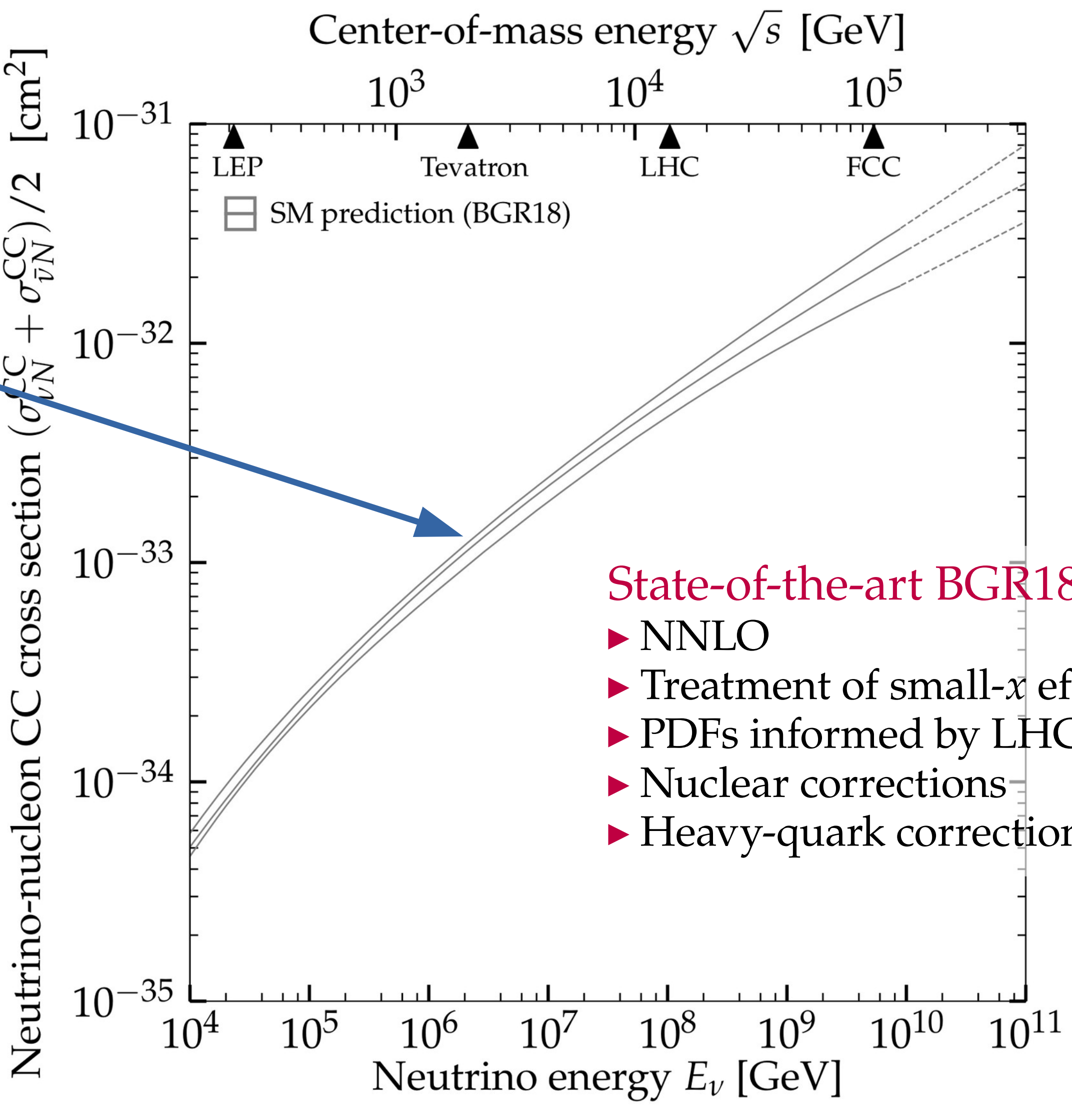


State-of-the-art BGR18 prediction:

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

Bertone, Gauld, Rojo, *JHEP* 2019

Use NuPropEarth for in-Earth propagation

[github.com/pochoarus/NuPropEarth]

Interactions:

- BGR18 νN deep inelastic scattering (DIS) on partons (dominant)
- DIS on photon field of nucleons
- Coherent νA scattering
- Elastic & diffractive νN scattering
- ν scattering on atomic electrons

Sub-dominant: increase attenuation by ~10%

Includes ν_τ regeneration:

- TAUSIC: Energy losses of intermediate τ
- TAUOLA: Distribution of τ decay products

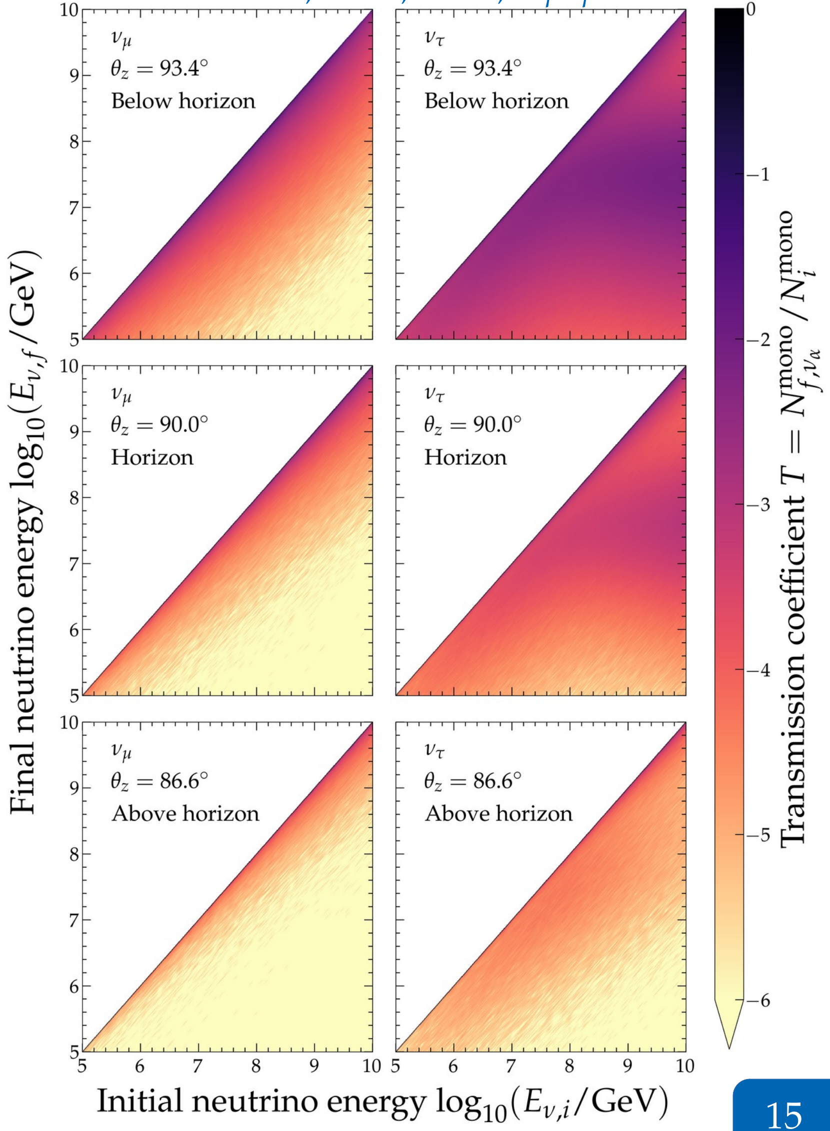
Matter inside Earth:

- Density: Preliminary Reference Earth Model
- Top layer of ice
- Varying element composition (non-isoscalar)

We propagate ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$, ν_τ, $\bar{\nu}_\tau$ separately

García, Gauld, Heijboer, Rojo, *JCAP* 2020

MB, Valera, Glaser, *In preparation*



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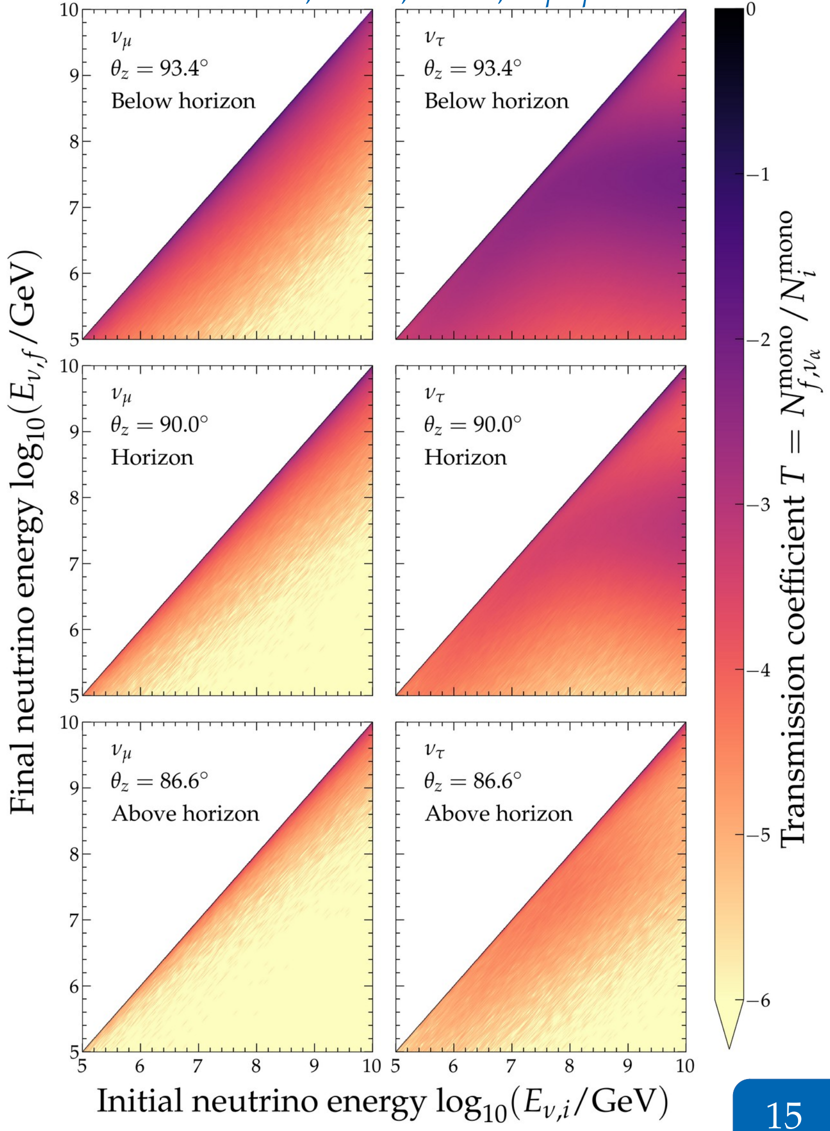
Save look-up tables of propagated ν spectra

MB, Valera, Glaser, *In preparation*



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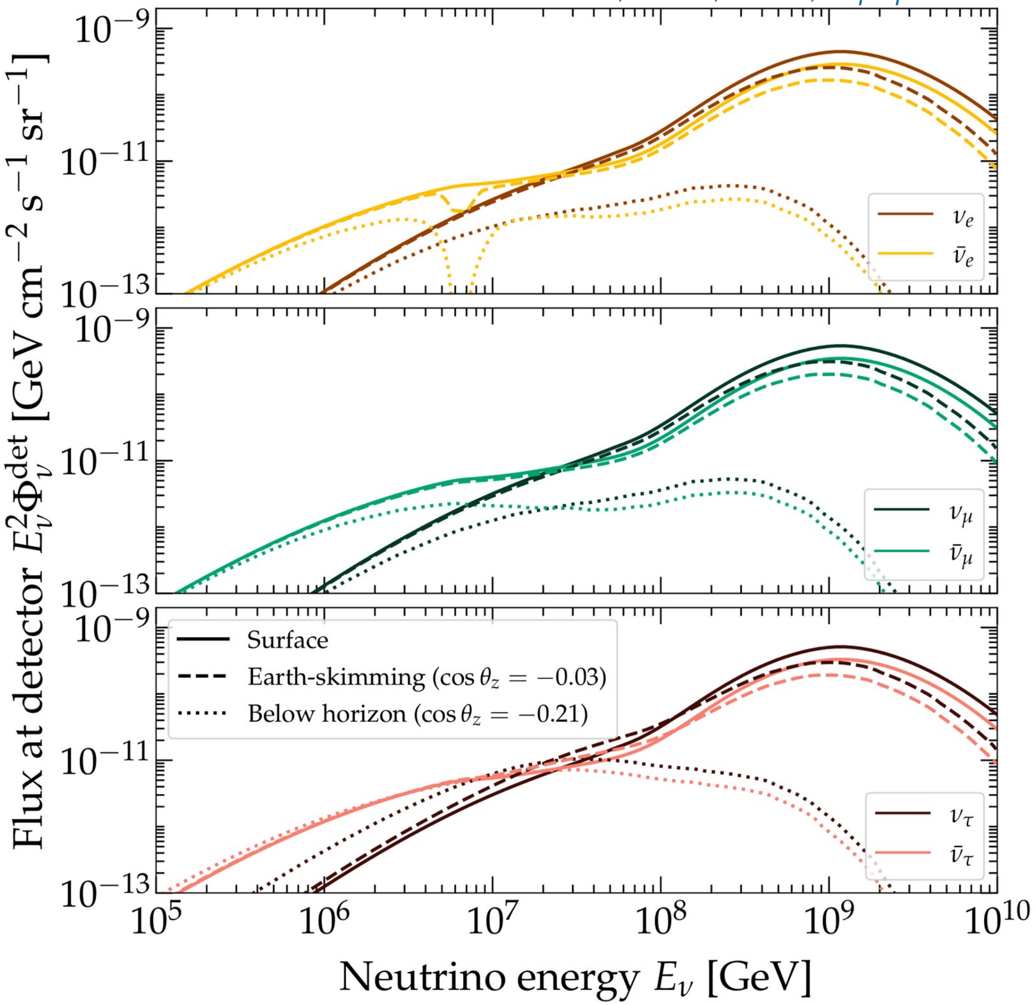
MB, Valera, Glaser, *In preparation*



García, Gauld, Heijboer, Rojo, *JCAP* 2020

Detector geometry

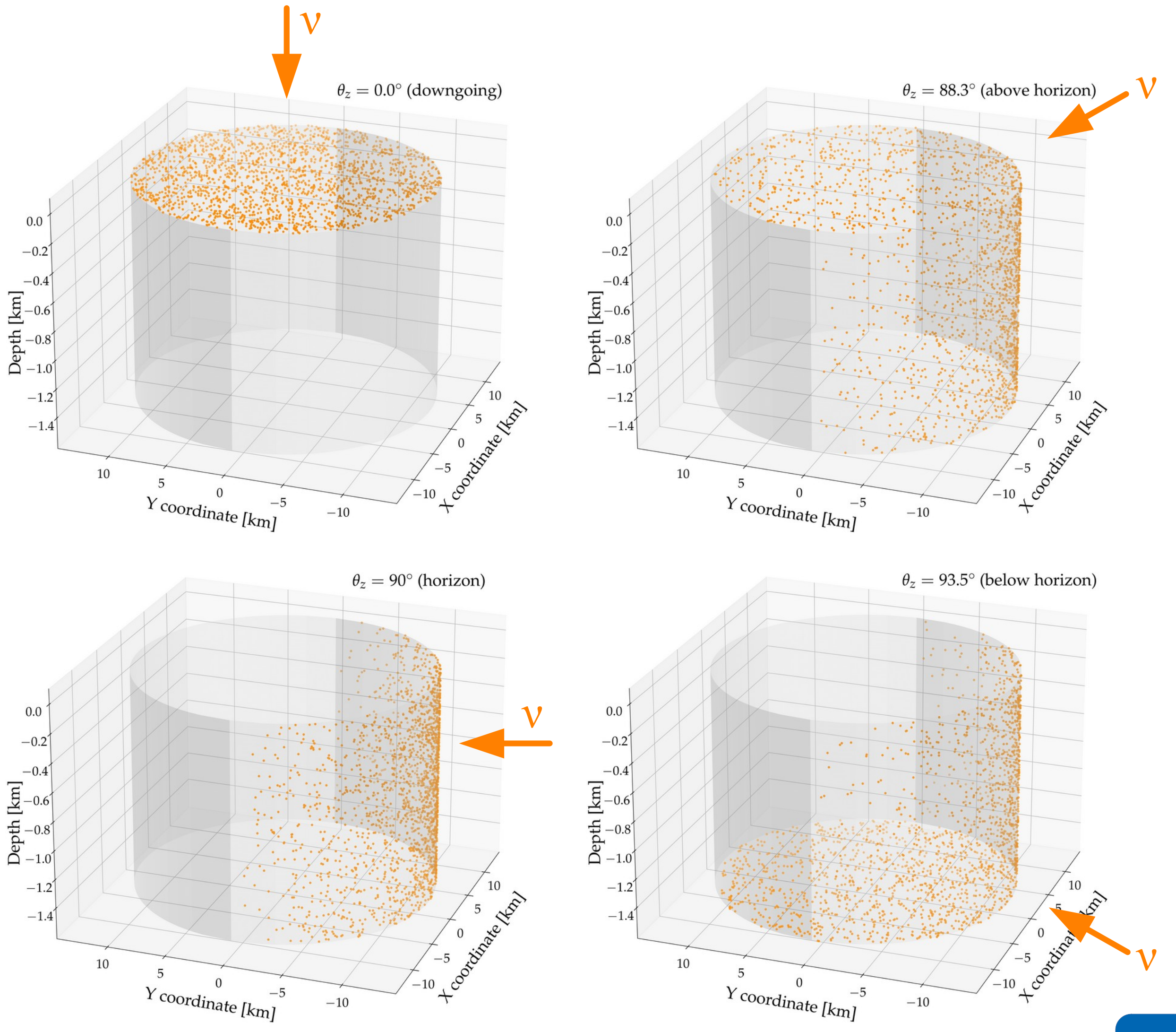
Underground cylinder

Area of lid: 500 km^2

Height: 1.5 km

Detector geometry now available in NuPropEarth
[github.com/pochoarus/NuPropEarth]

Work led by Víctor Valera



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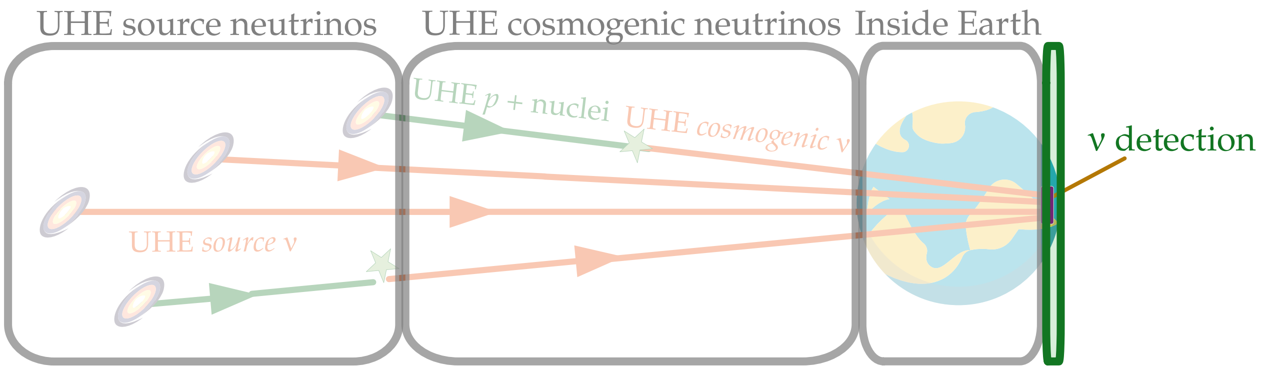
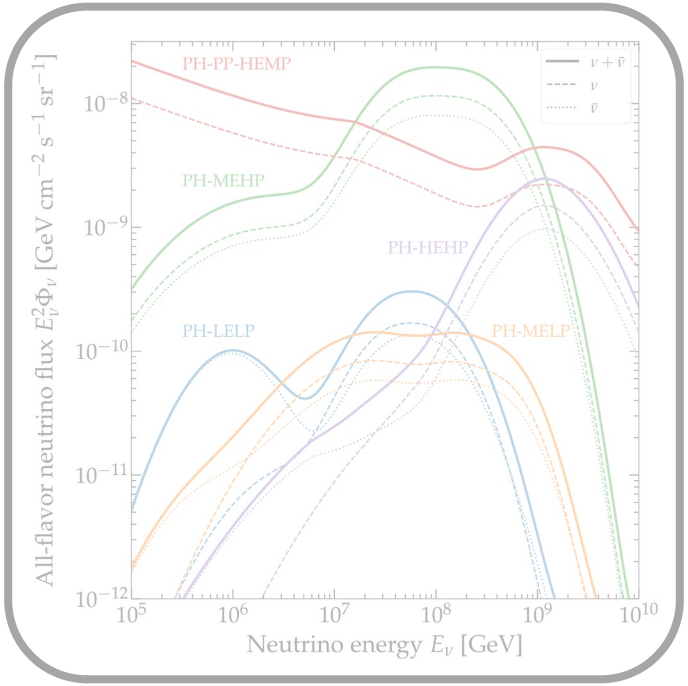
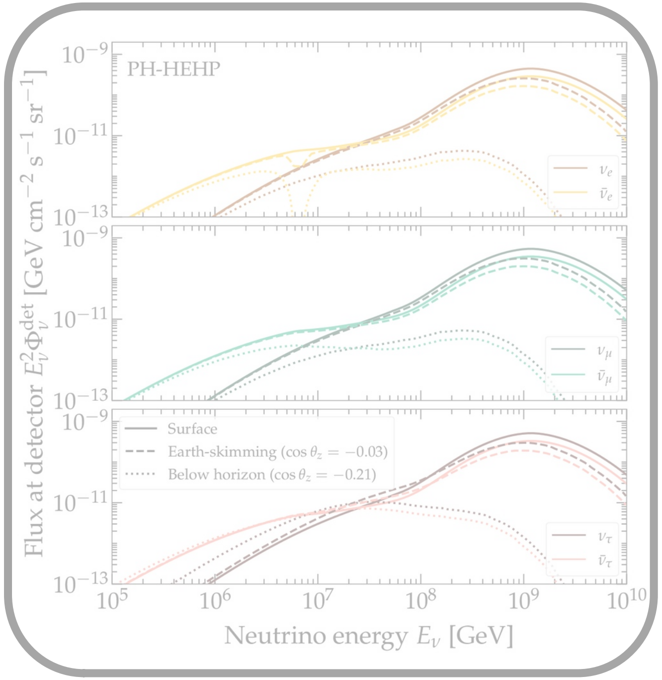
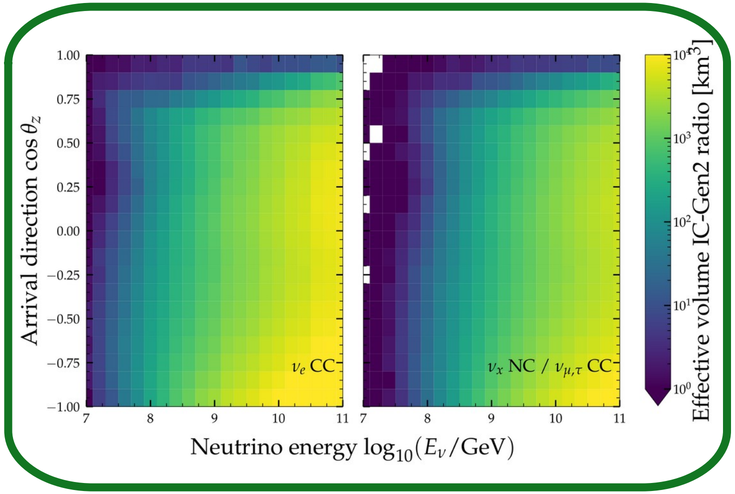




UHE ν from *pp* and *p*γ interactions, account for cosmic-ray spectrum & mass composition, source properties



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

Detector effective volume

IC-Gen2 has stations containing:

- Shallow antennas
- Deep antennas

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We simulate the effective volume of
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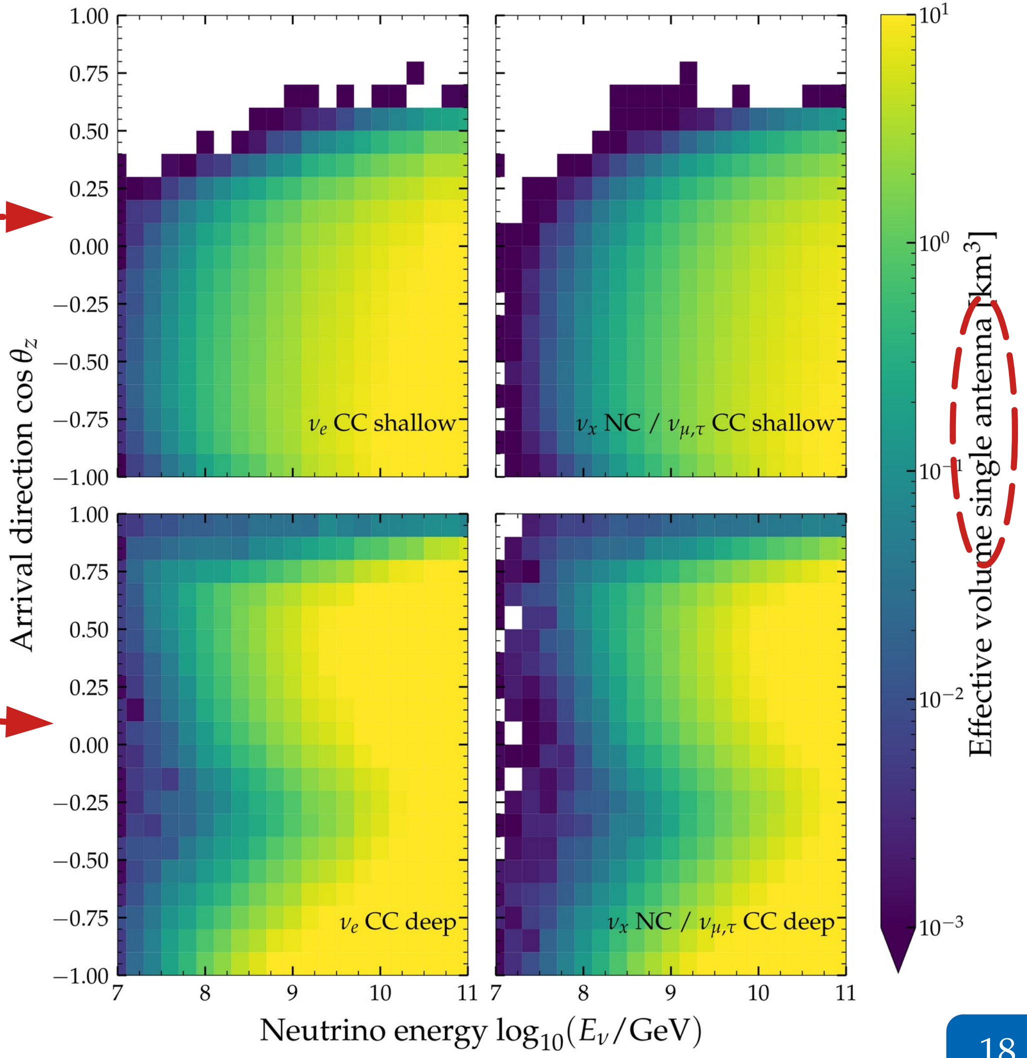

MB, Valera, Glaser, *In preparation*

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Note: For now, we turned off the contribution of secondary leptons

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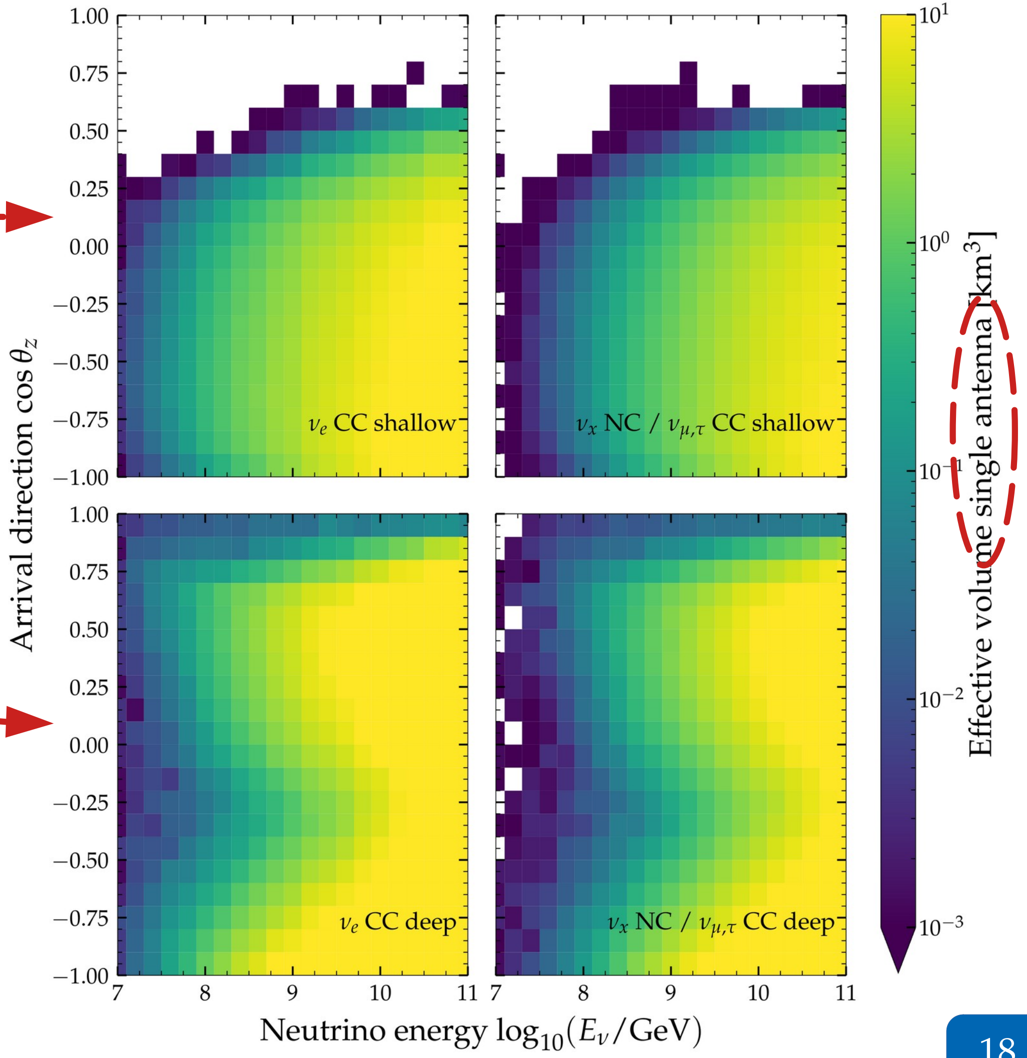
For ν_μ CC, ν_τ CC, ν_l NC: Use the NC V_{eff}



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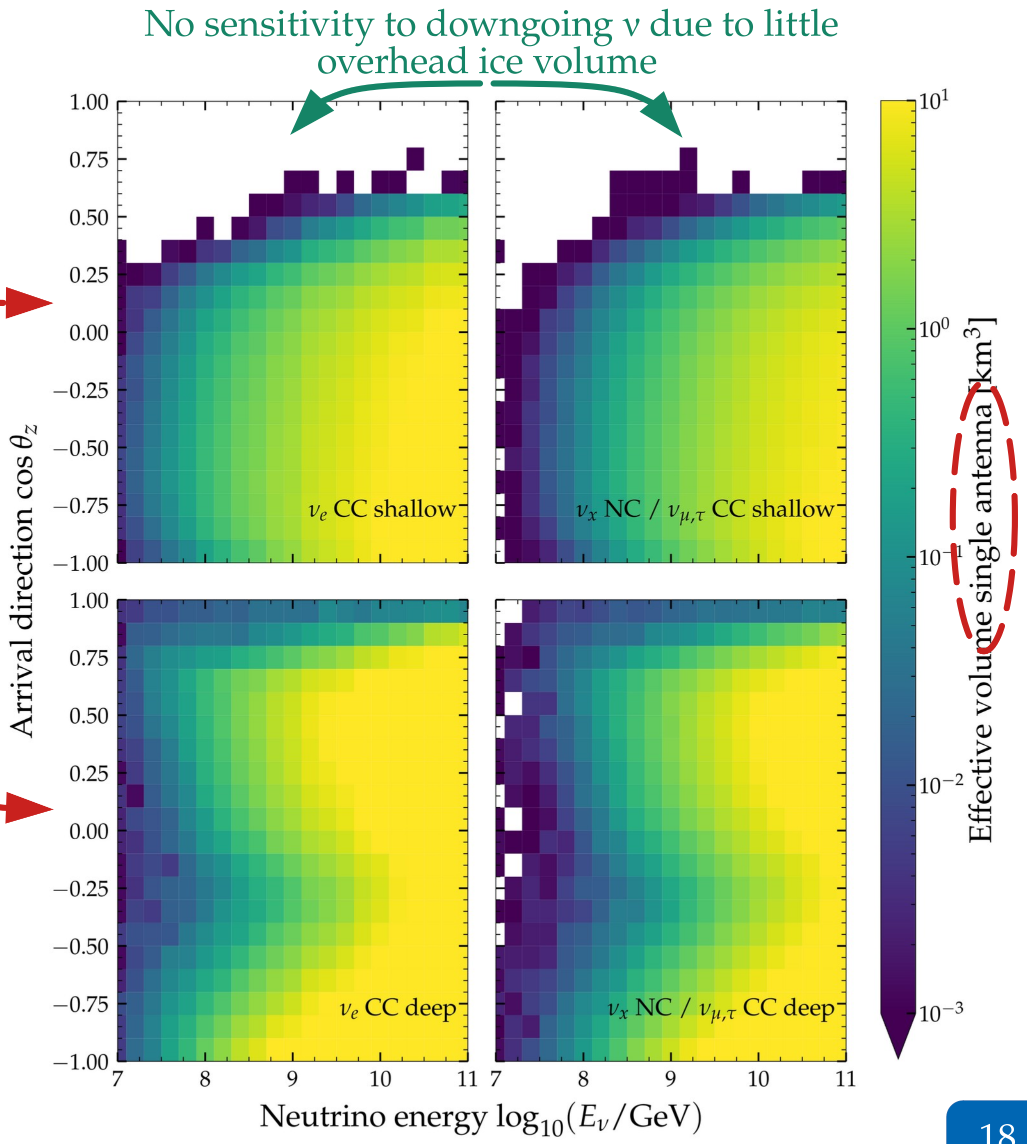
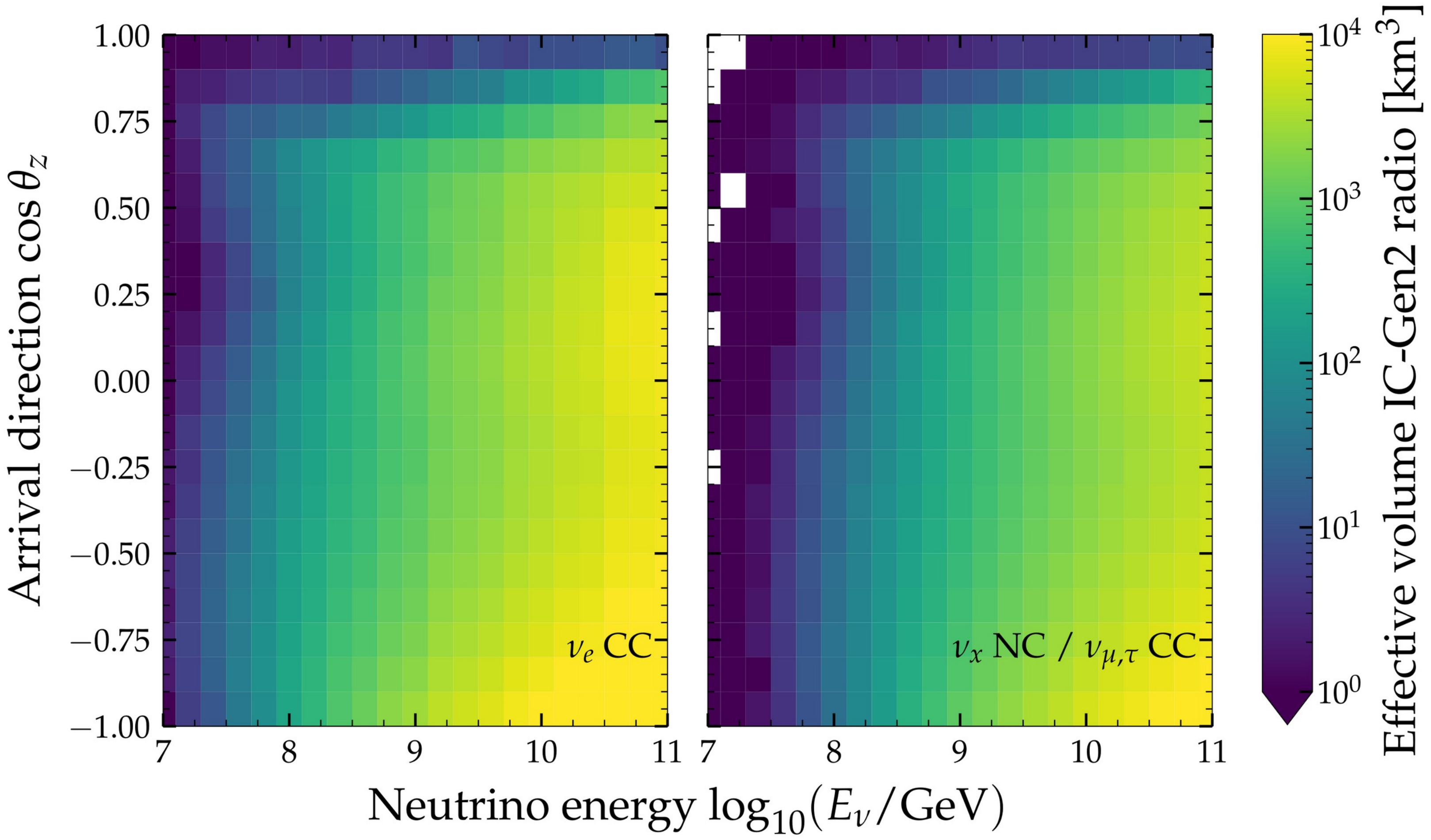


Total volume = 169 shallow-only stations + 144 hybrid (shallow+deep) stations



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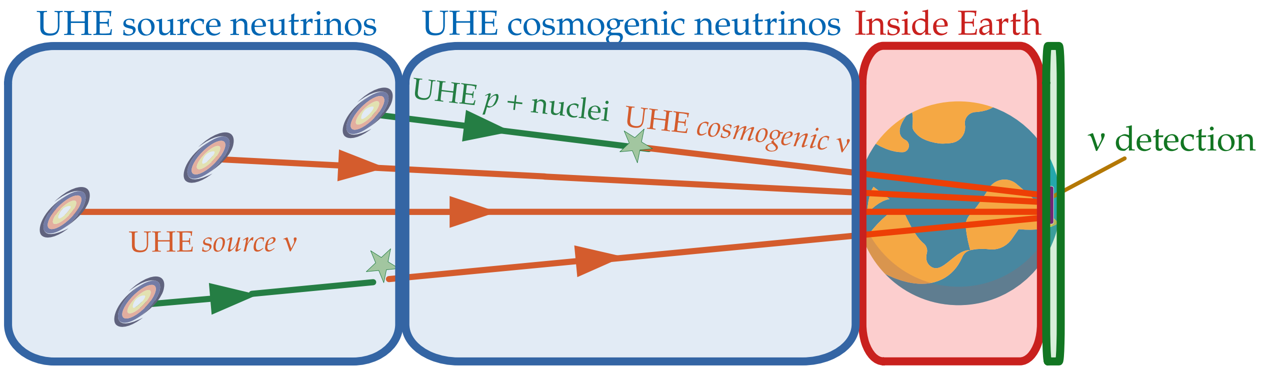

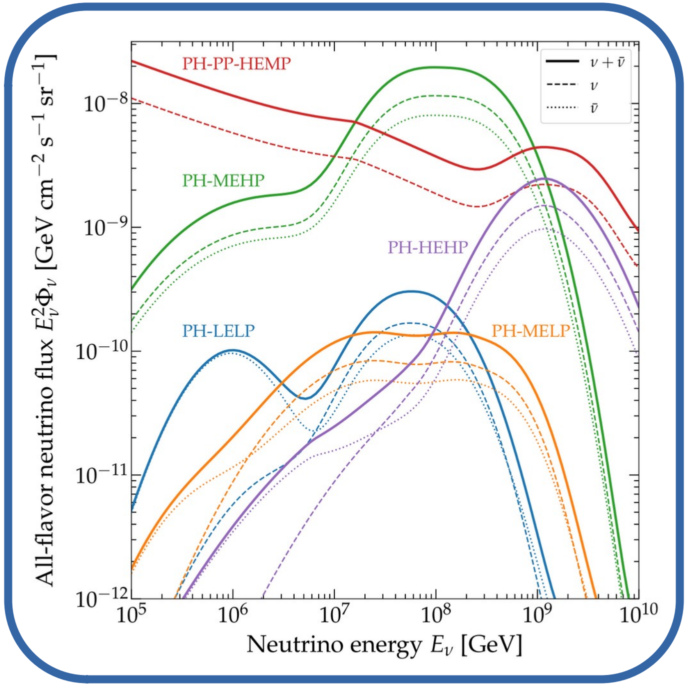

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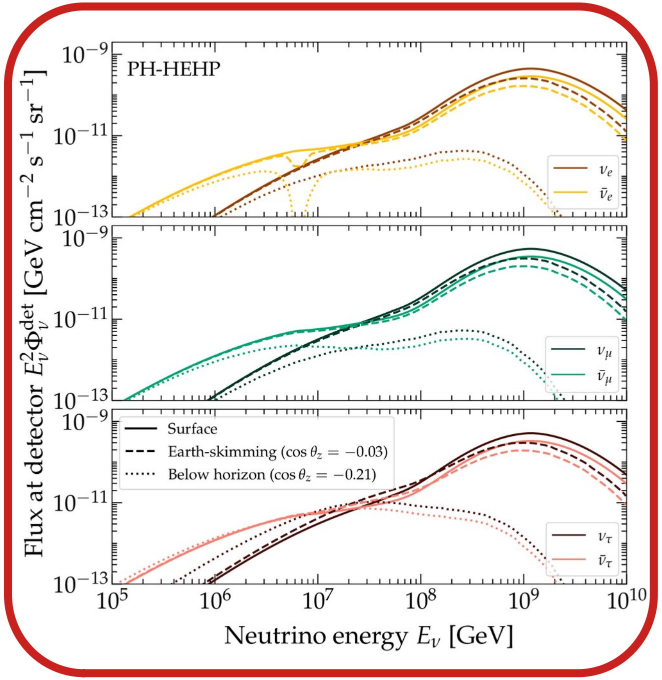

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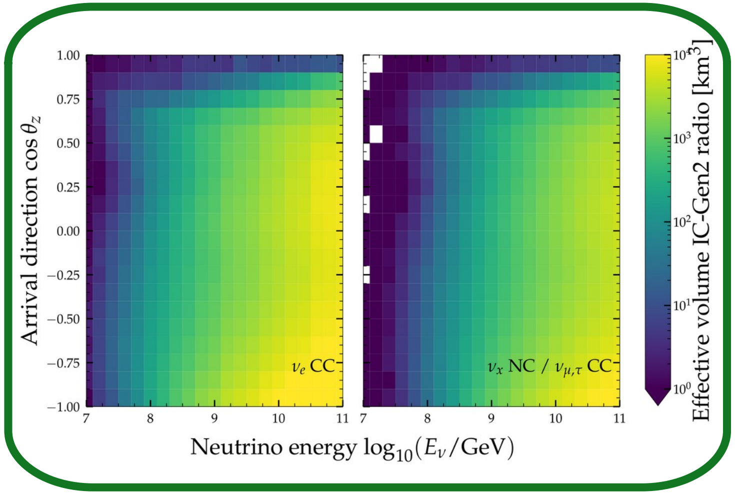

Model radio propagation in ice, antenna response, angular and energy resolution, inelasticity distribution

Event rate at IC-Gen2 Radio

Event rate at IC-Gen2 Radio

Real event rate

$$\frac{d^3 N_{\nu_\alpha}^{\mathrm{CC}}}{dE_\nu dy d\cos\theta_z}$$

E_ν: Neutrino energy

y: Inelasticity

$\cos\theta_z$: Neutrino direction

Includes:

- Flux
- In-Earth propagation
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Detector effects →

Each ν species computed separately

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Detector effects →

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Detected event rate

$$\frac{d^2 N_{\nu_\alpha}^{\mathrm{CC}}}{dE_{\mathrm{dep}} d\theta_{z,\mathrm{rec}}}$$

E_{dep}: Deposited energy

$\cos\theta_{z,\mathrm{rec}}$: Reconstructed direction

Includes, in addition:

- Connection between ν energy and shower energy
- Energy resolution
- Angular resolution

Event rate at IC-Gen2 Radio

Note: Calculations are similar for CC and NC

Real event rate

$$\frac{d^3 N_{\nu_\alpha}^{\mathrm{CC}}}{dE_\nu dy d\cos\theta_z}$$

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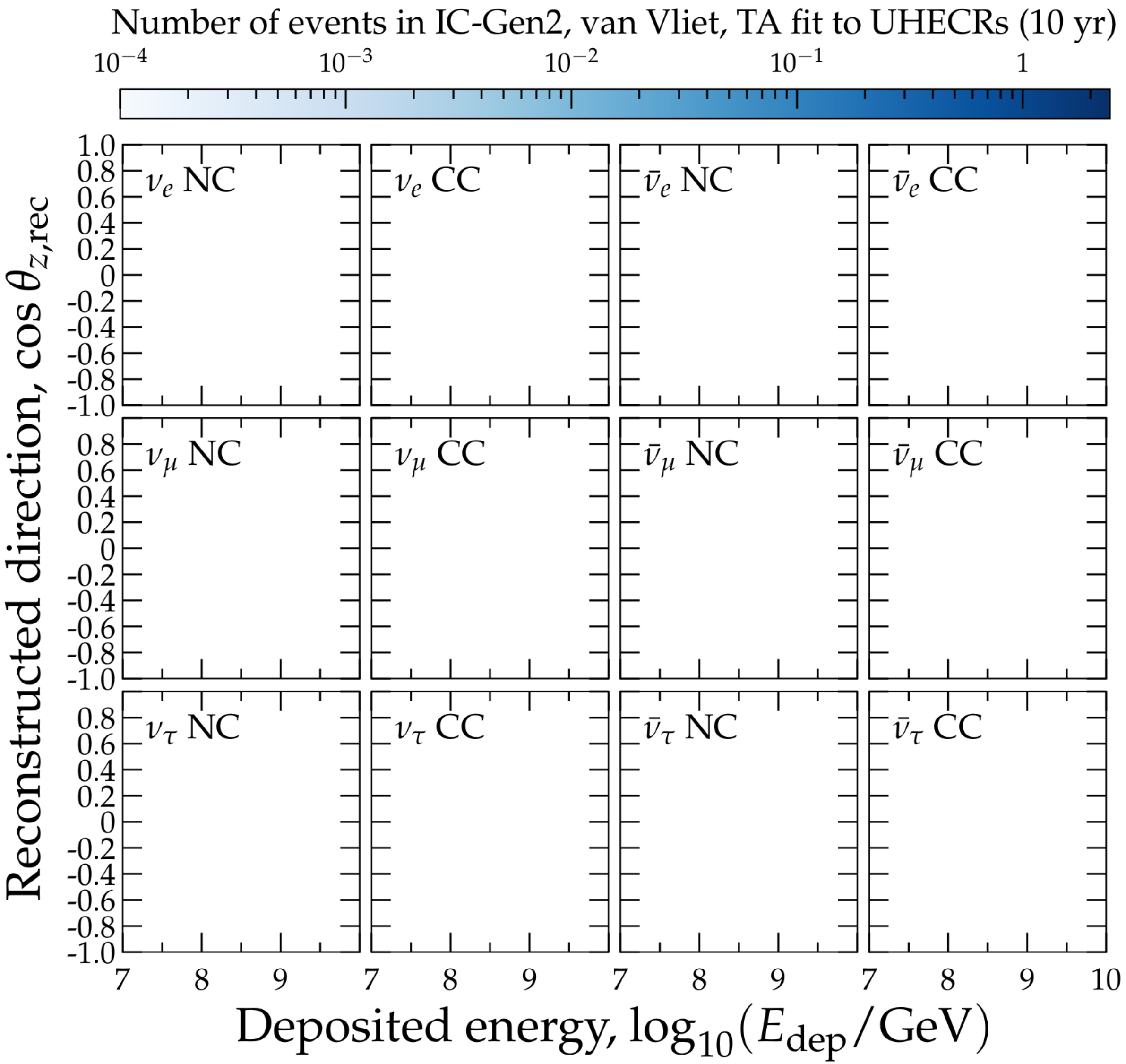
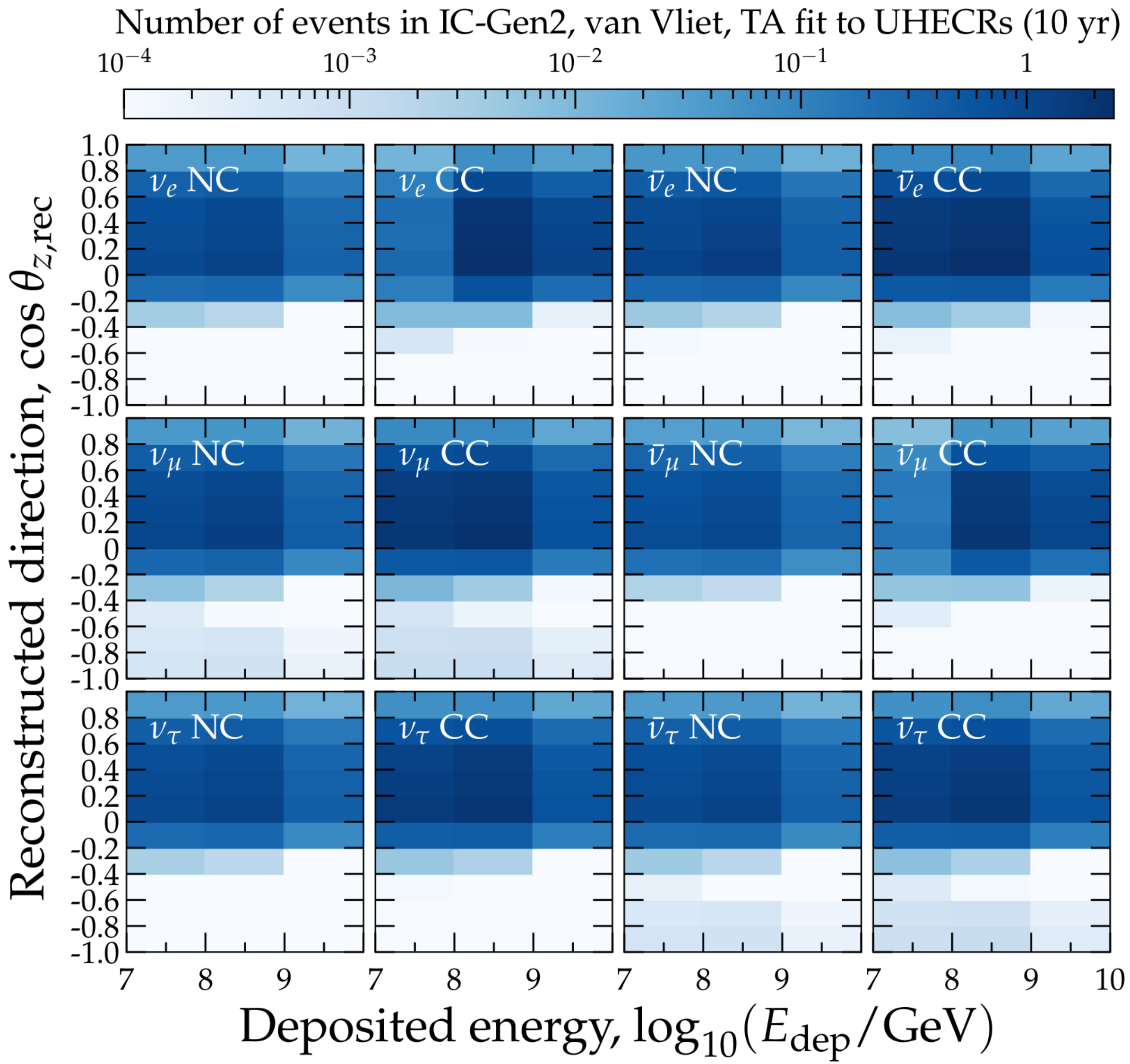
Benchmark event rates

(Focused on UHE ν and IC-Gen2 Radio)



MB, Valera, Glaser, *In preparation*



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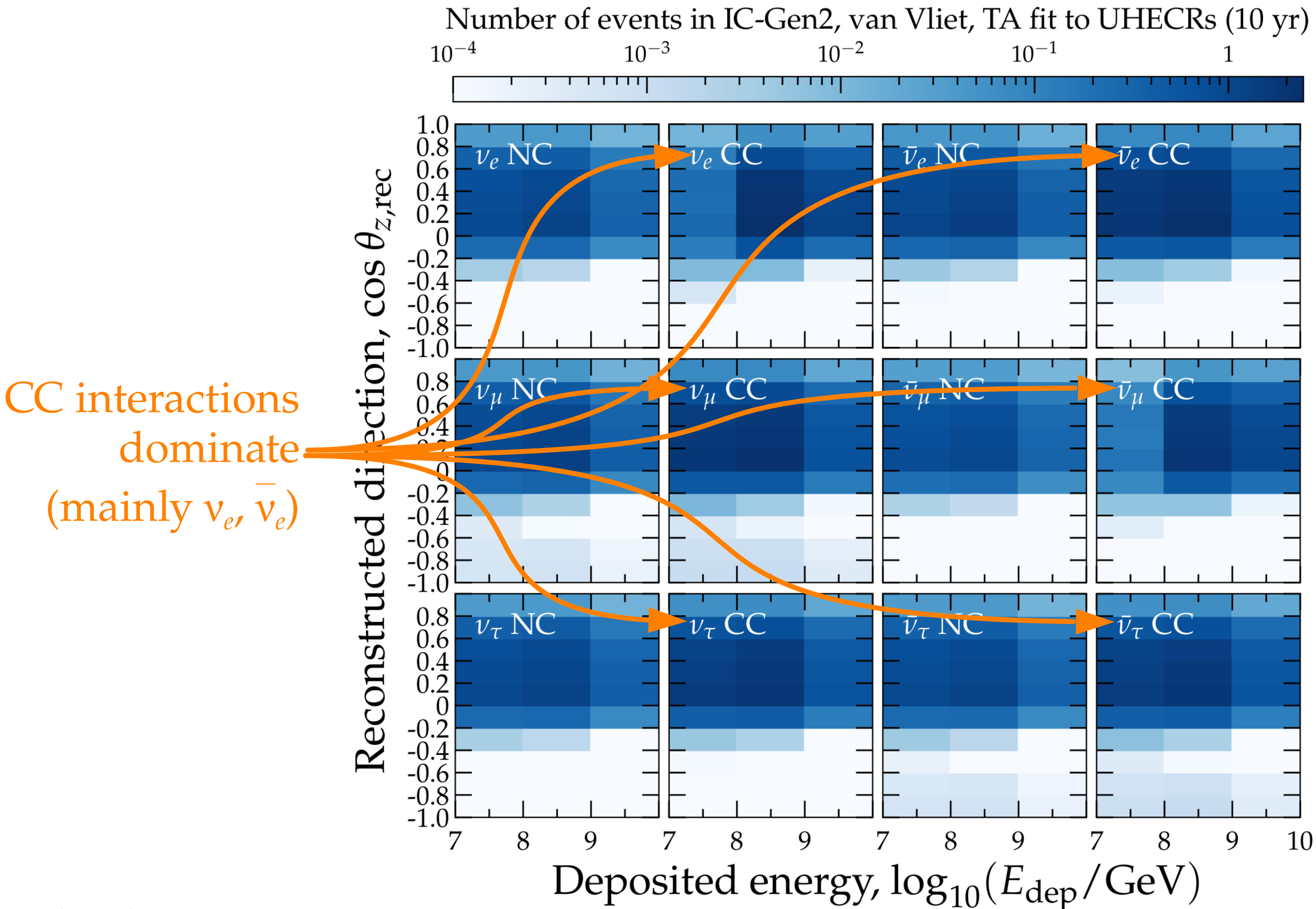

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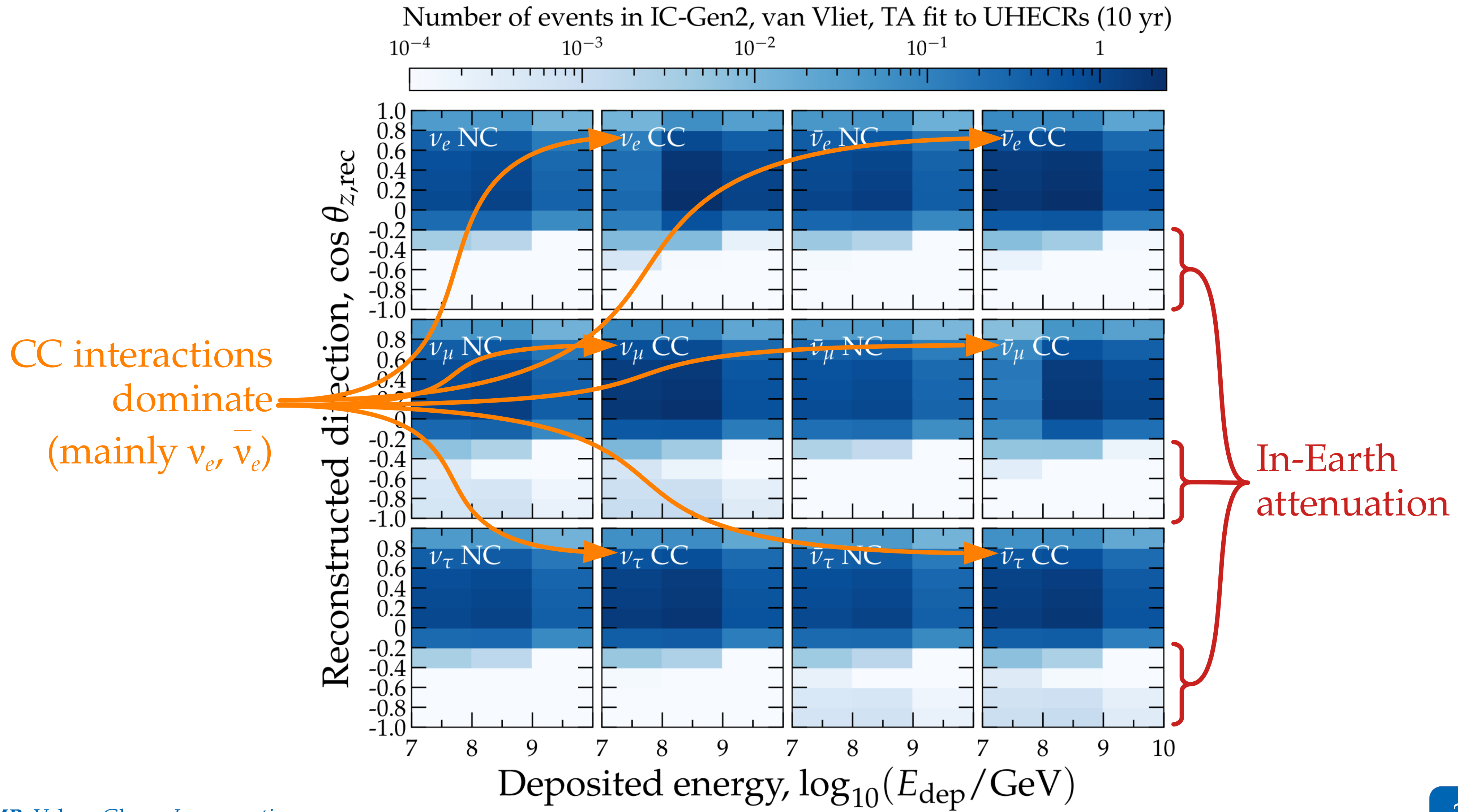

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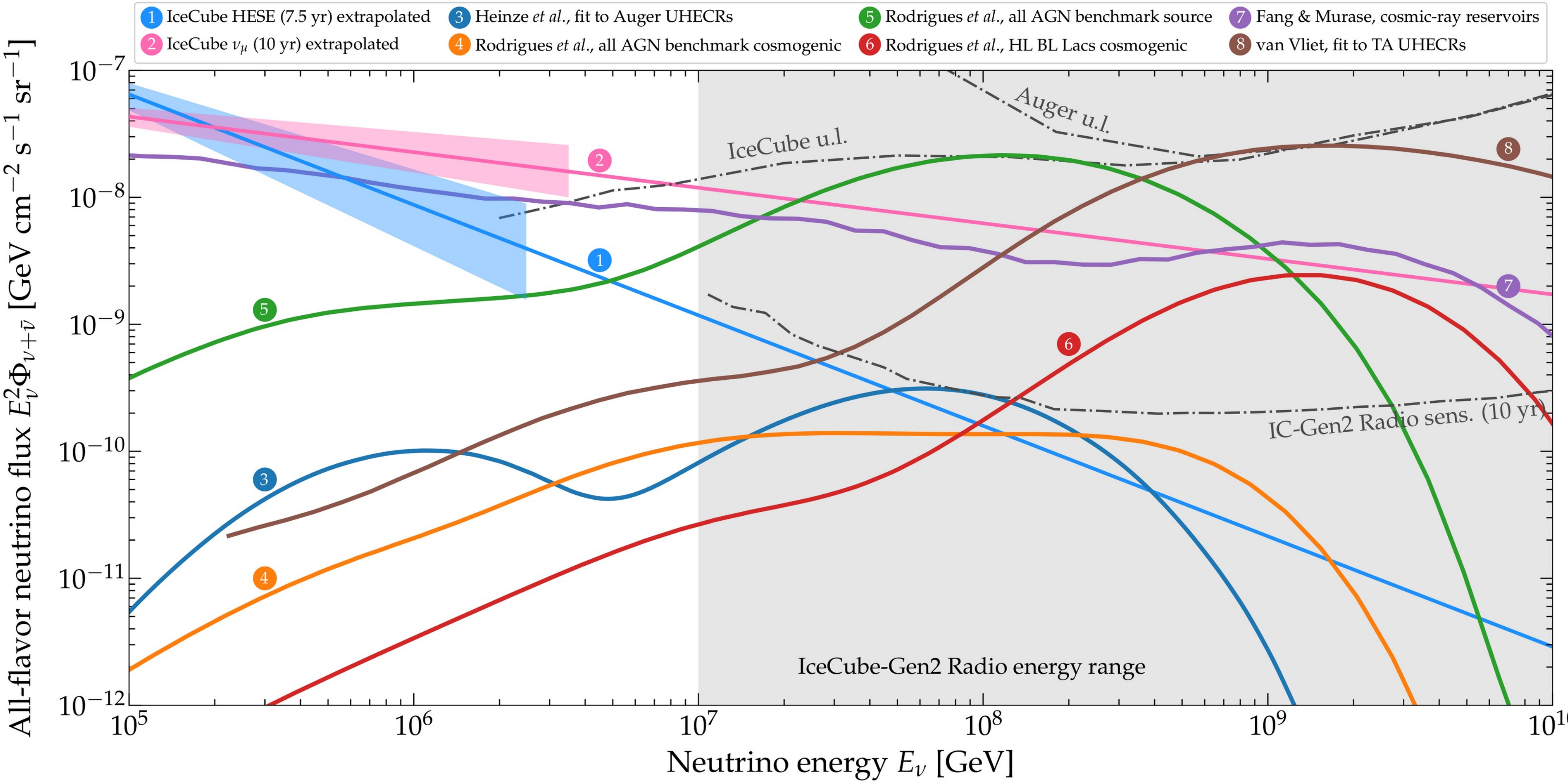

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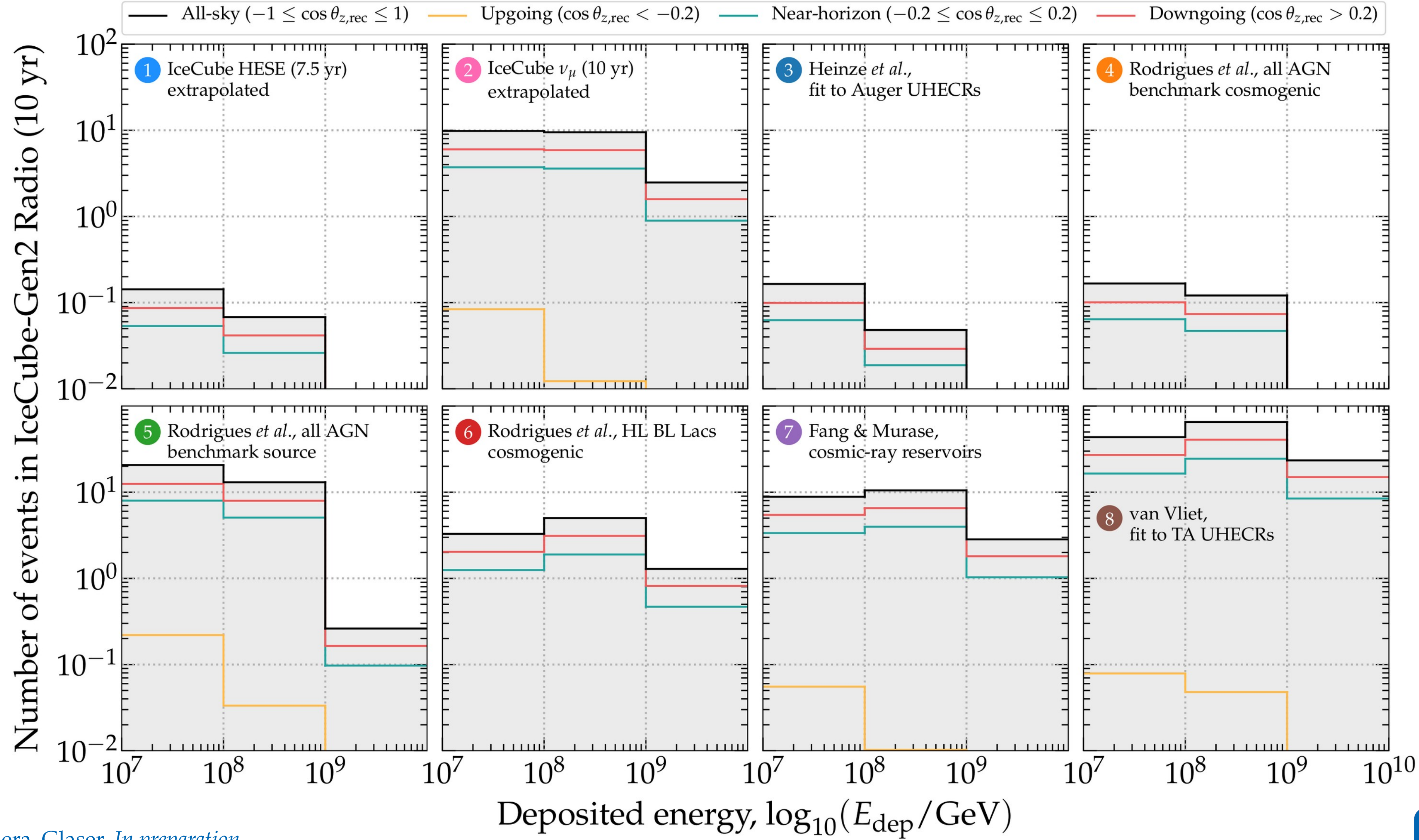

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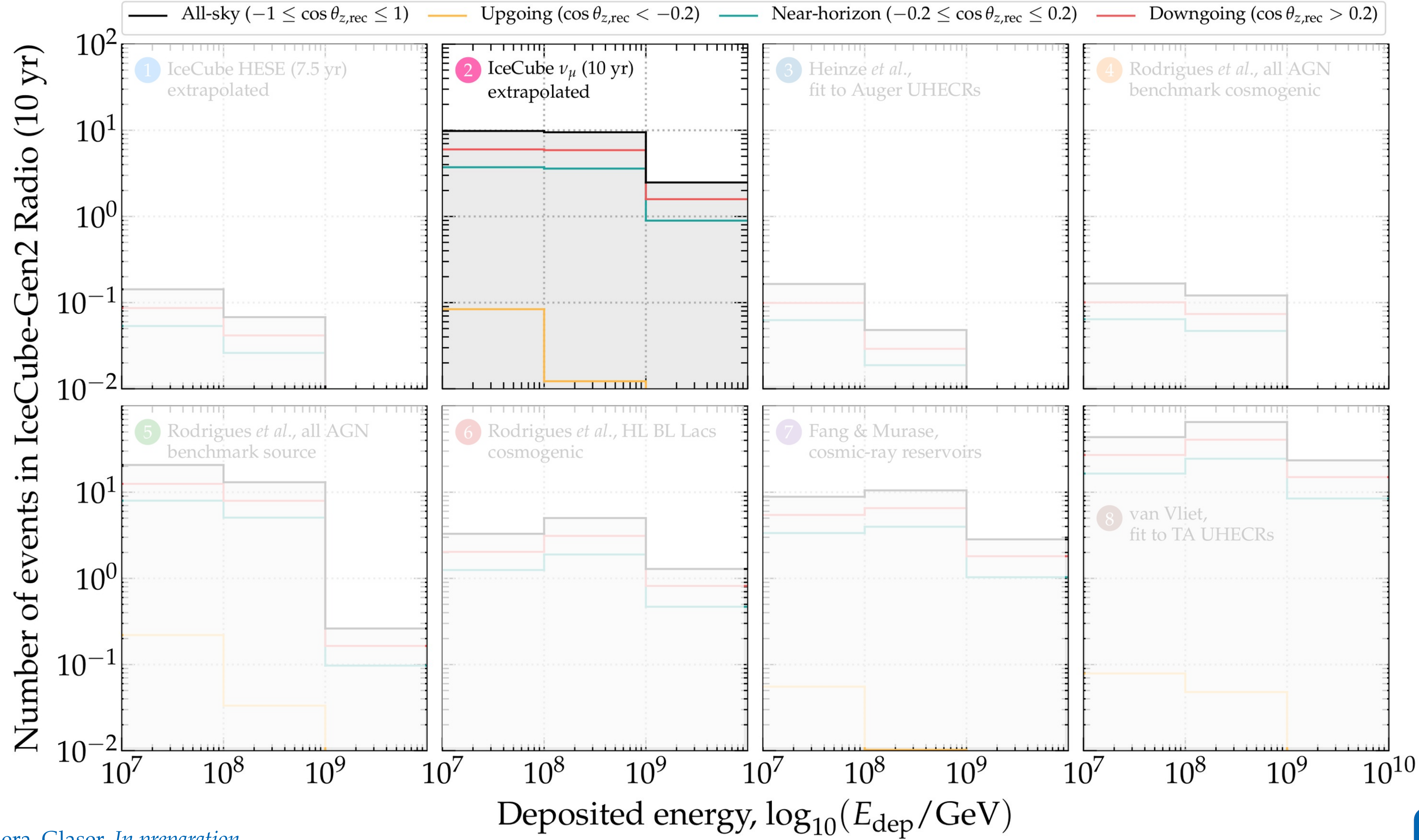

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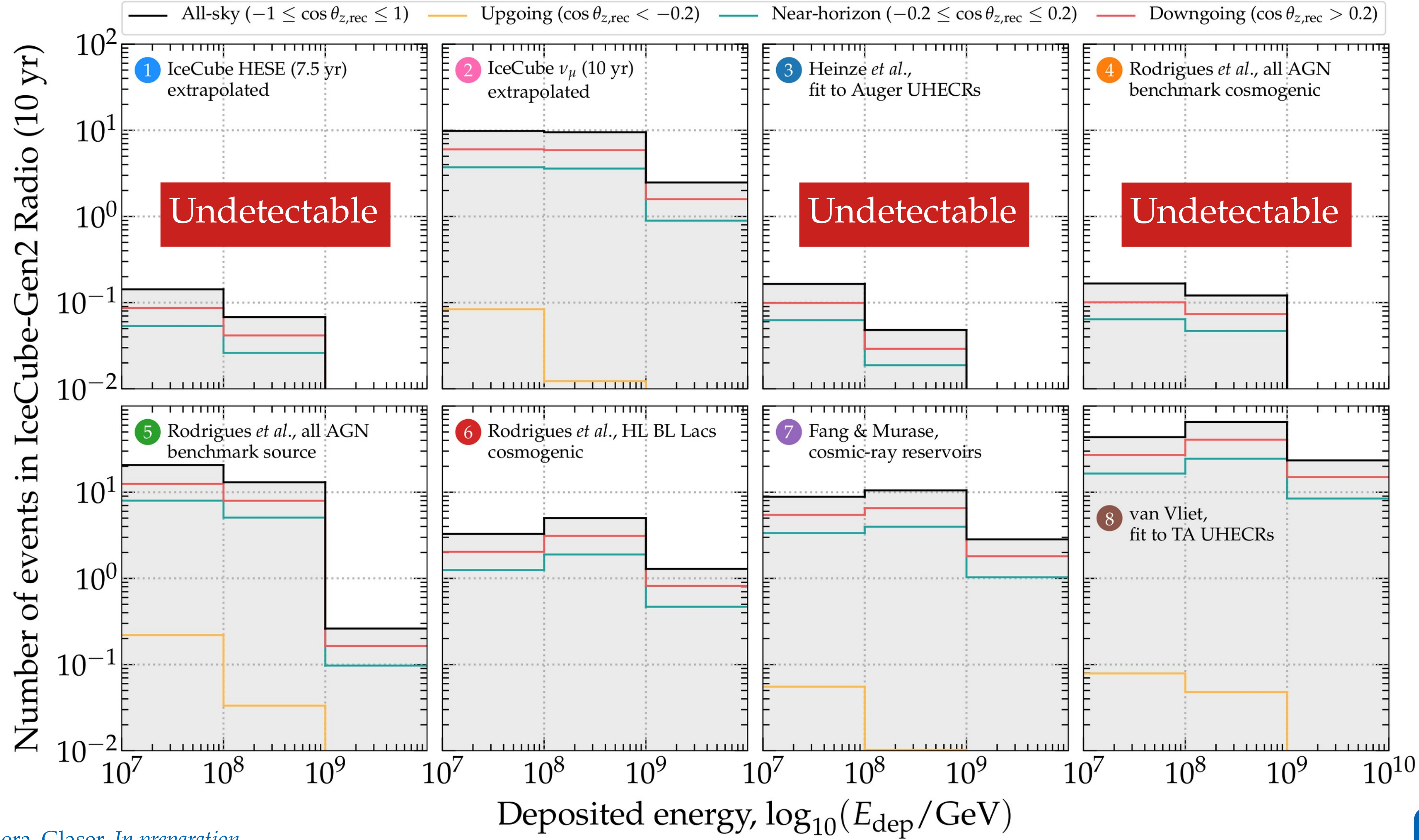

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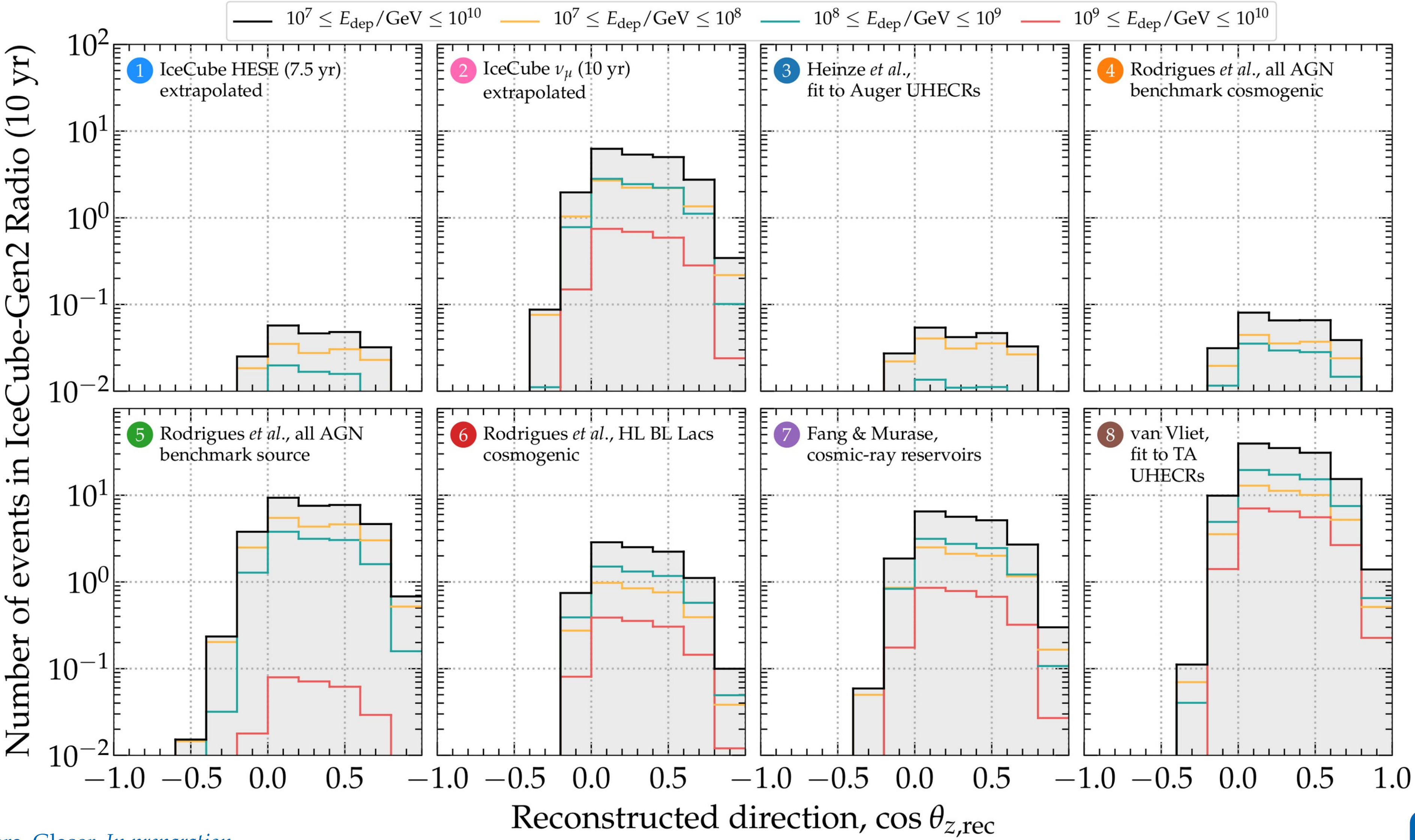

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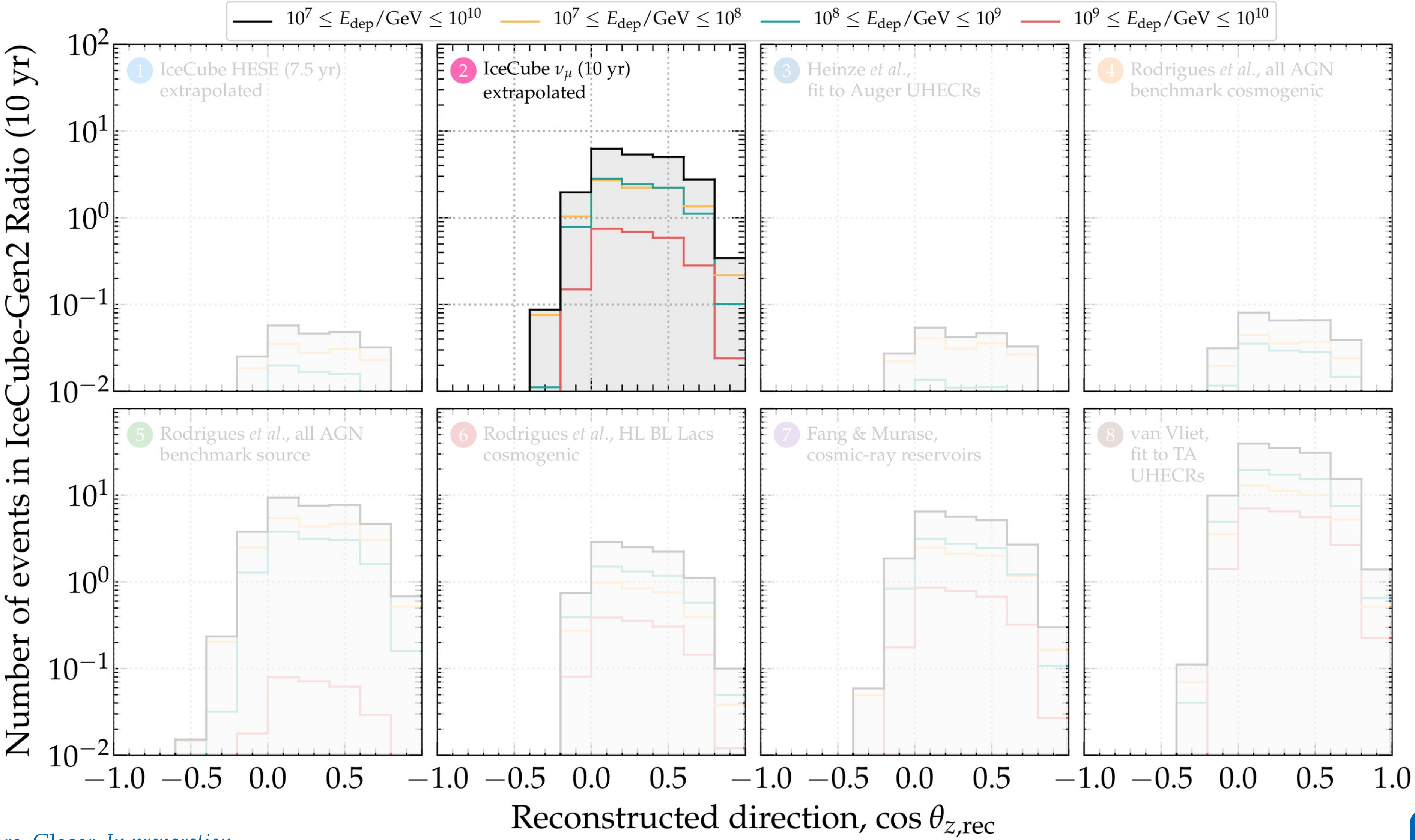

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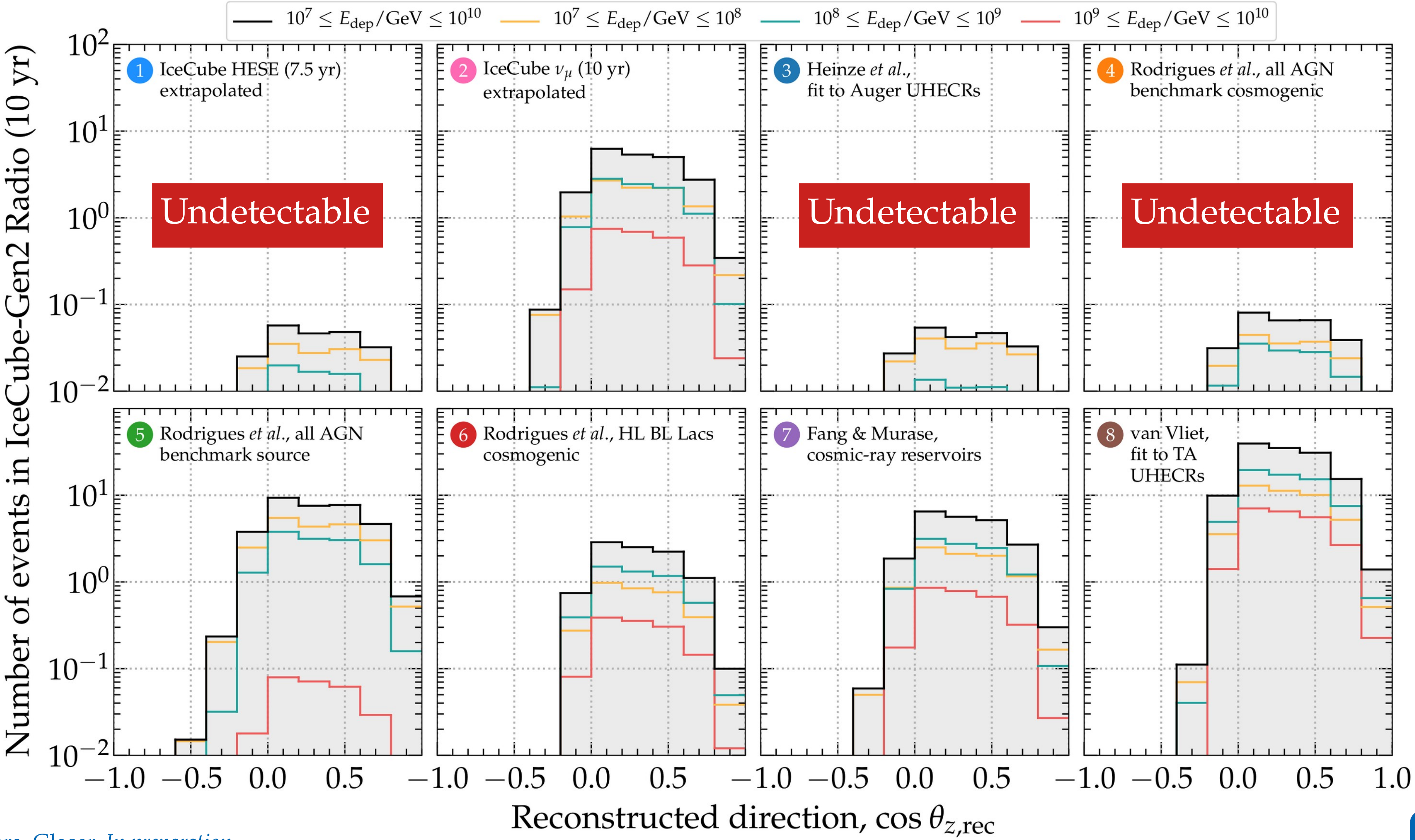

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Applications:
Physics and astrophysics

Work in progress

1. Discovery potential for UHE ν
2. Inferring the spectrum of UHE ν
3. Measuring the UHE νN cross section
4. Testing other UHE ν BSM models
5. Testing ν physics using flavor ratios

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Work in progress, stay tuned ...

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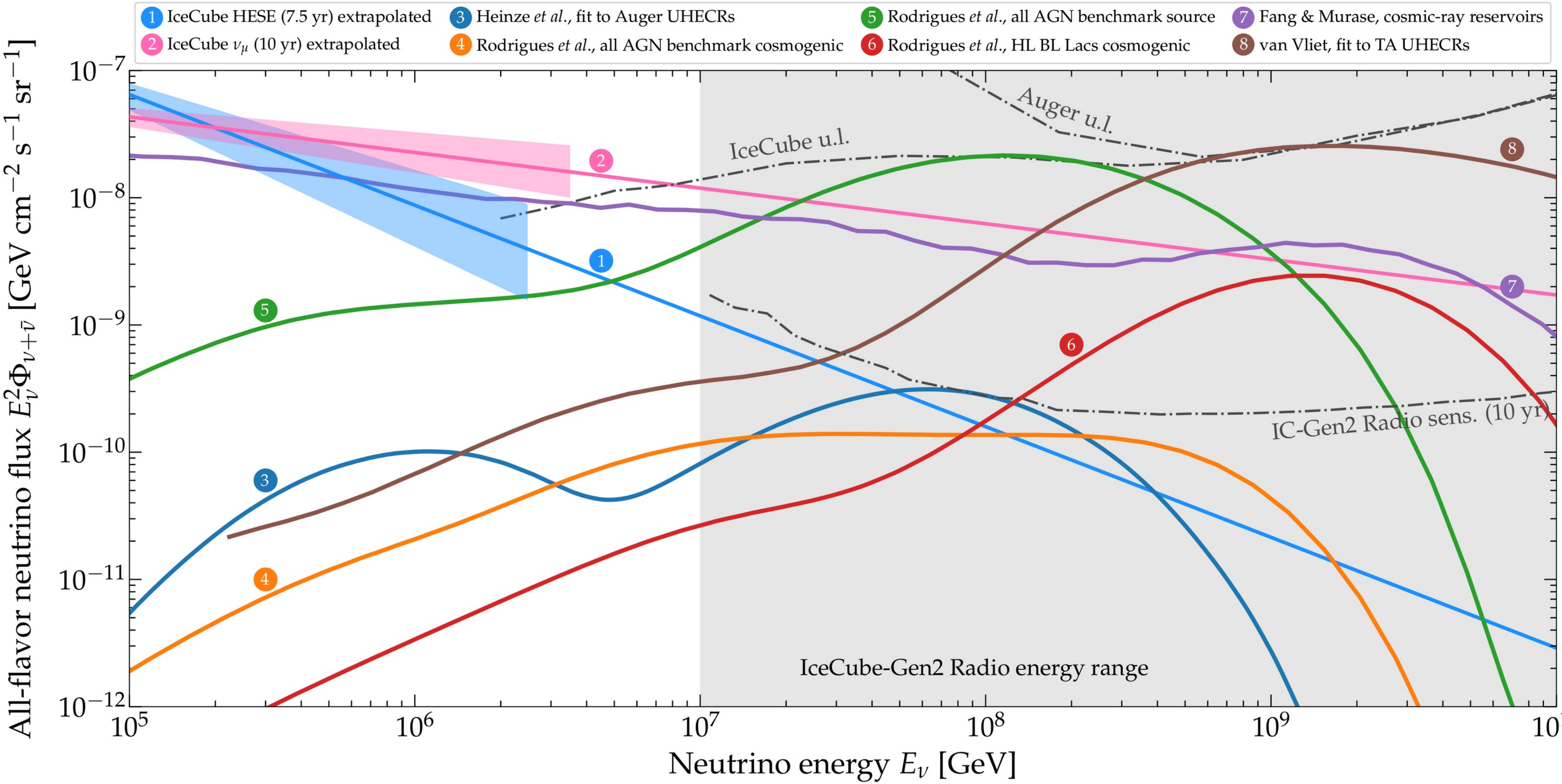

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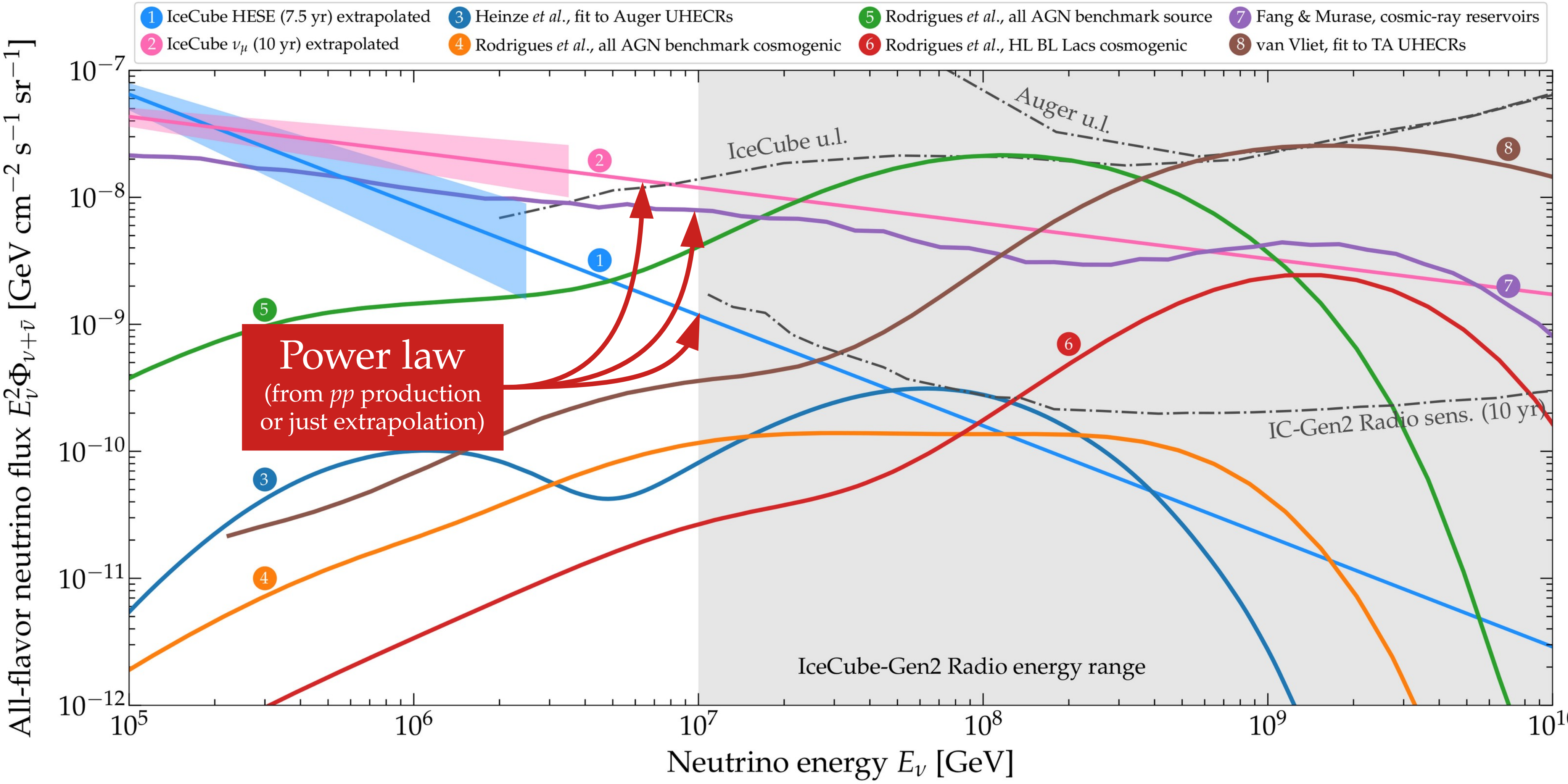
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
All-flavor neutrino flux $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}



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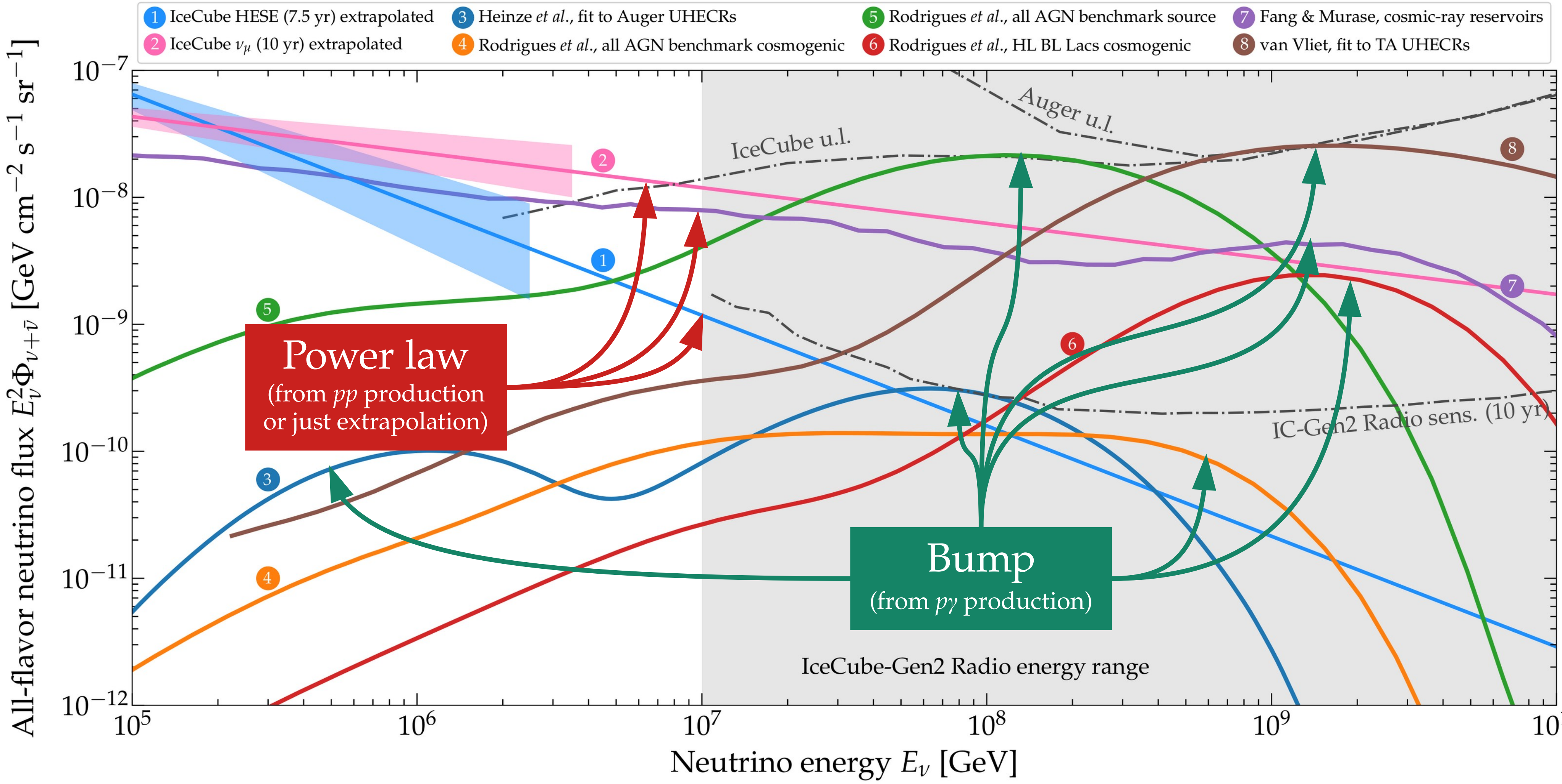

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Bump
(from *pγ* production)

A generic, empirical model of the UHE ν spectrum

Neutrinos:

$$E_\nu^2 \Phi_{\nu_\alpha}(E_\nu) =$$

Anti-neutrinos:

A generic, empirical model of the UHE ν spectrum

Neutrinos:

$$E_\nu^2 \Phi_{\nu_\alpha}(E_\nu) = \overbrace{(E_\nu^2 \Phi_0)}^{\text{Normalization}} f_{\alpha,\oplus} f_\nu$$

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Normalization

Power-law
(from *pp*
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Low-energy *pγ* bump (from EBL or in source) — High-energy *pγ* bump (from CMB or in source)

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A generic, empirical model of the UHE ν spectrum

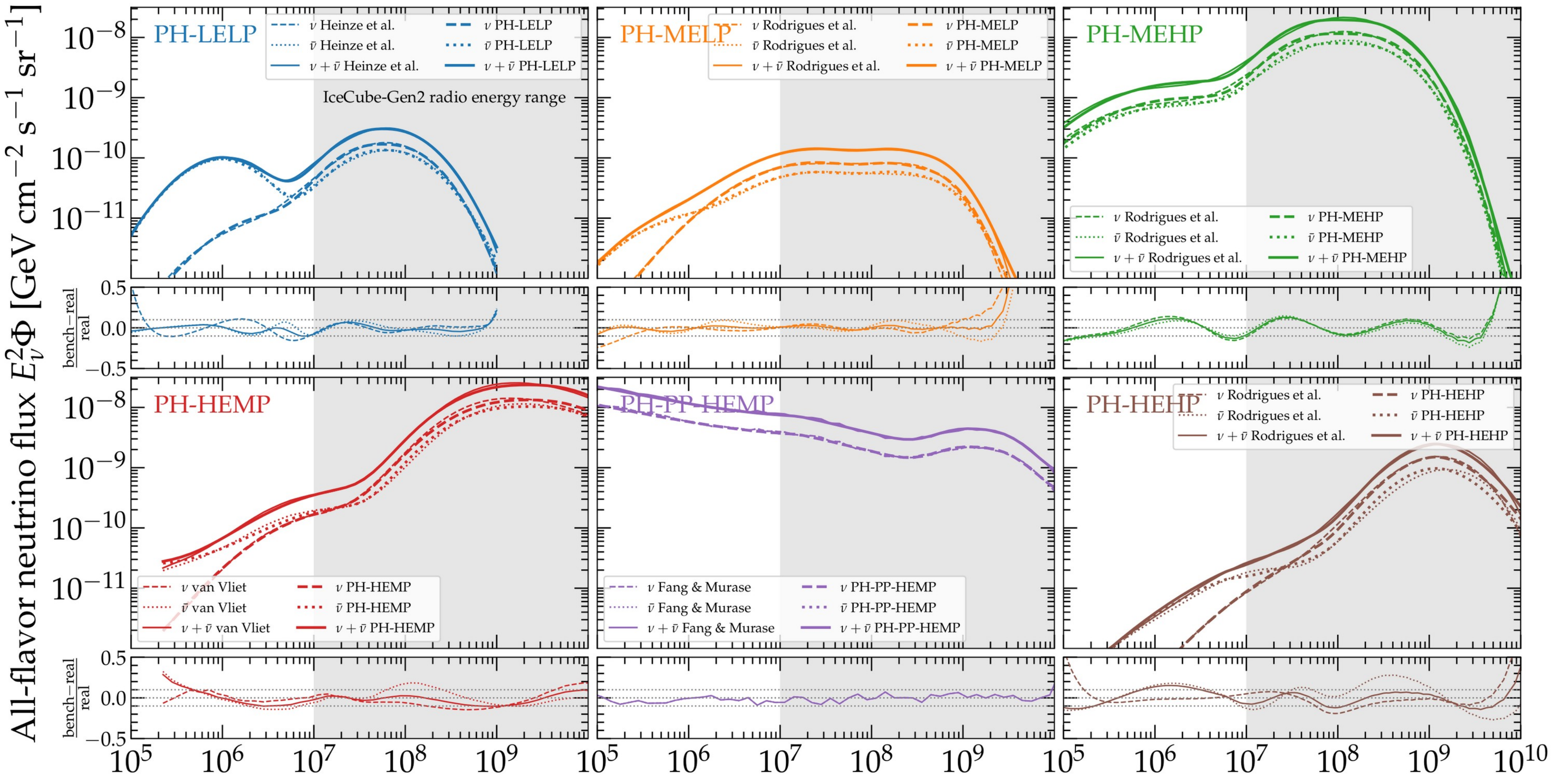
Neutrinos:

$$E_\nu^2 \Phi_{\nu_\alpha}(E_\nu) = \underbrace{(E_\nu^2 \Phi_0) f_{\alpha,\oplus} f_\nu}_{\text{Normalization}} \left[\underbrace{\left(\frac{E_\nu}{\text{PeV}}\right)^{-\gamma}}_{\text{Power-law (from } pp \text{ or extrapolation)}} + \underbrace{\eta_l^\nu \mathcal{G}_l(E_\nu; \alpha_l, \beta_l^\nu, \mu_l)}_{\text{Low-energy } p\gamma \text{ bump (from EBL or in source)}} + \underbrace{\eta_h^\nu \mathcal{G}_h(E_\nu; \alpha_h, \beta_h^\nu, \mu_h)}_{\text{High-energy } p\gamma \text{ bump (from CMB or in source)}} \right]$$

Anti-neutrinos:

$$E_\nu^2 \Phi_{\bar{\nu}_\alpha}(E_\nu) = (E_\nu^2 \Phi_0) f_{\alpha,\oplus} (1 - f_\nu) \left[\left(\frac{E_\nu}{\text{PeV}}\right)^{-\gamma} + \underbrace{\eta_n^{\bar{\nu}} \mathcal{G}_n(E_\nu; \alpha_n^{\bar{\nu}}, \beta_n^{\bar{\nu}}, \mu_n^{\bar{\nu}})}_{\text{Bump from neutron decay}} + \underbrace{\eta_l^{\bar{\nu}} \mathcal{G}_l(E_\nu; \alpha_l, \beta_l^{\bar{\nu}}, \mu_l)}_{\text{Low-energy } p\gamma \text{ bump (from EBL or in source)}} + \underbrace{\eta_h^{\bar{\nu}} \mathcal{G}_h(E_\nu; \alpha_h, \beta_h^{\bar{\nu}}, \mu_h)}_{\text{High-energy } p\gamma \text{ bump (from CMB or in source)}} \right]$$

The empirical model fits all benchmark fluxes to within 10%, *i.e.*,



MB, Valera, *In preparation*

Work in progress, stay tuned ...

Work in progress

1. Discovery potential for UHE ν
2. Inferring the spectrum of UHE ν
3. Measuring the UHE νN cross section
4. Testing other UHE ν BSM models
5. Testing ν physics using flavor ratios

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See talk by Víctor Valera

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Work in progress

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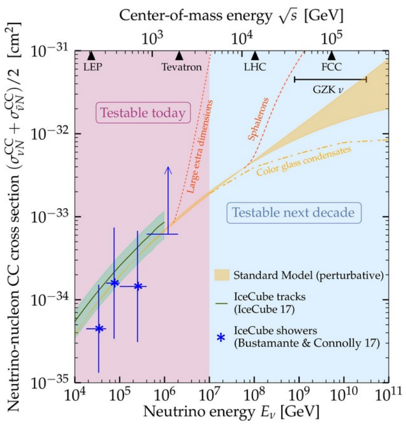
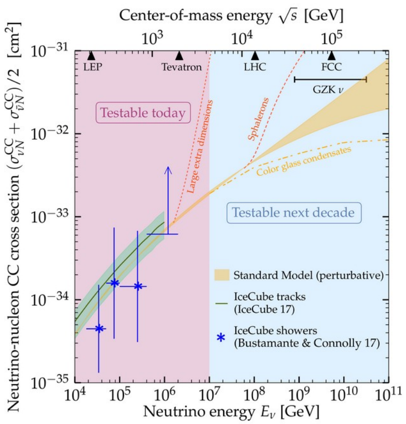
TeV–EeV ν cross sections



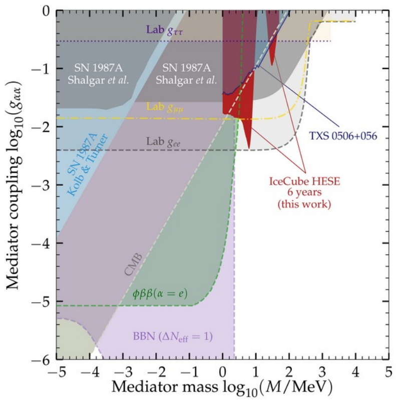
MB & Connolly, *PRL* 2019

TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

ν self-interactions



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

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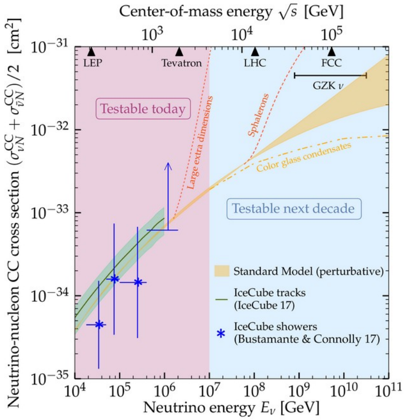

MB & Connolly, *PRL* 2019

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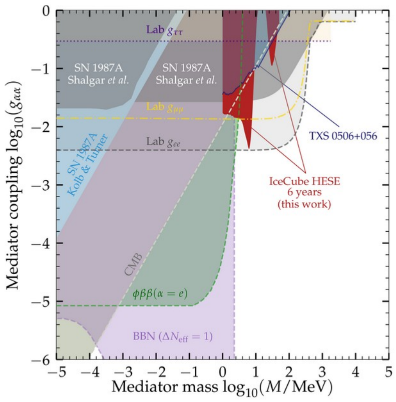
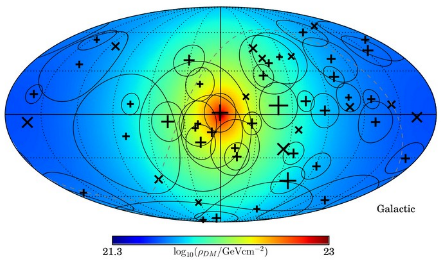


MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



Argüelles, Kheirandish, Vincent, *PRL* 2017

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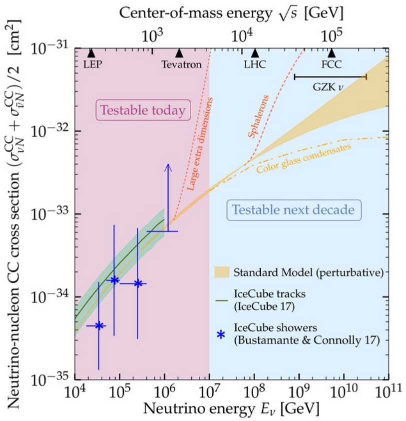

MB & Connolly, *PRL* 2019

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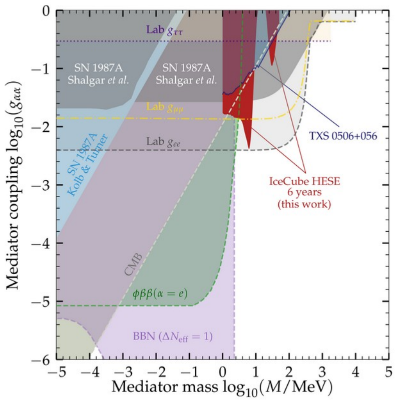

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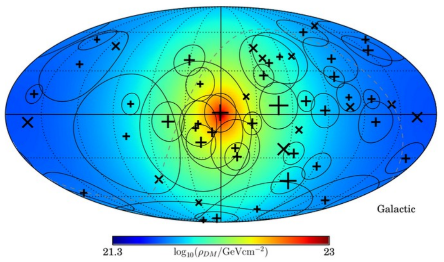

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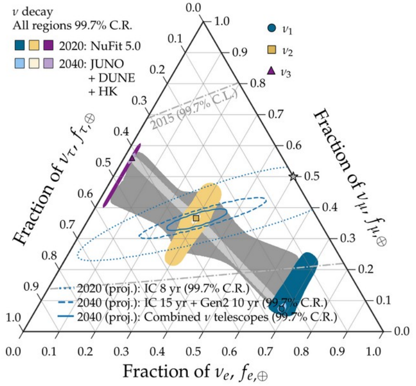
ν decay



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

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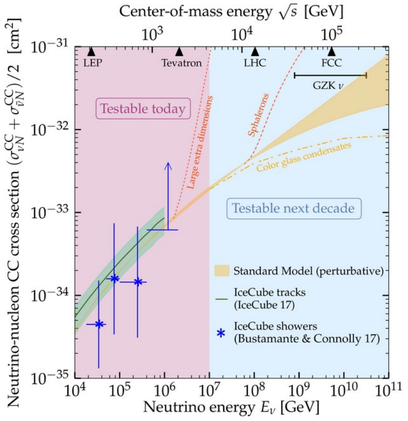

MB & Connolly, *PRL* 2019

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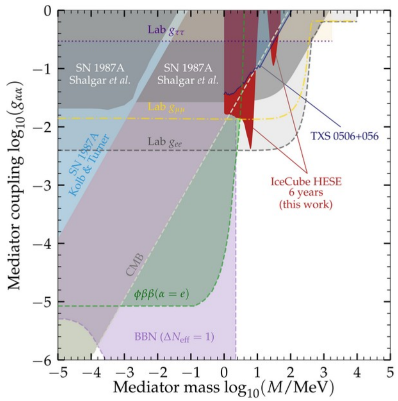

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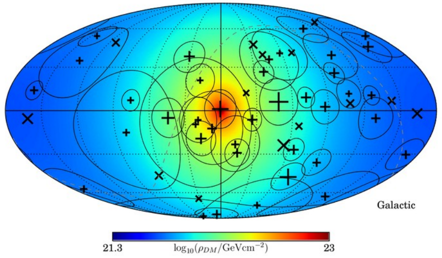

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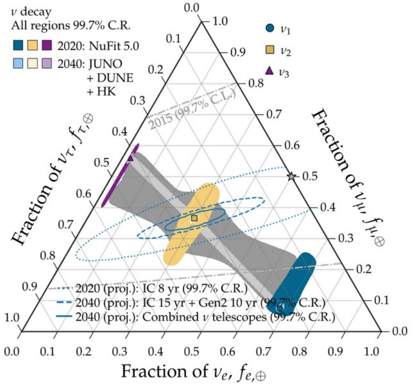
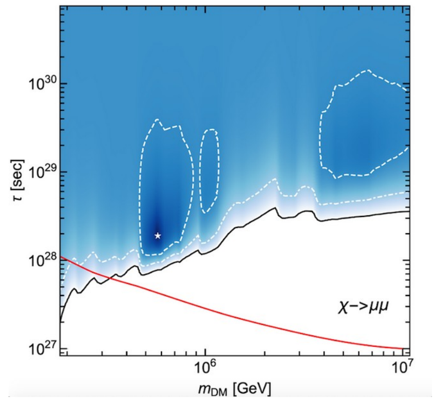


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



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

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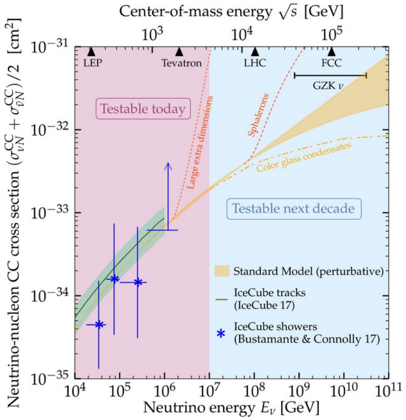

MB & Connolly, *PRL* 2019

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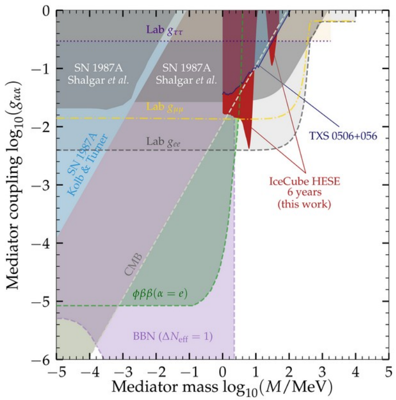

MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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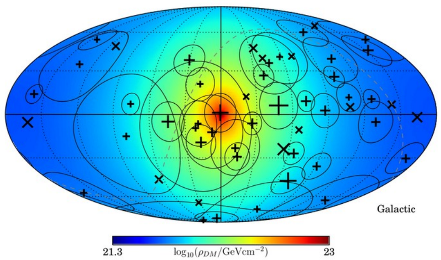

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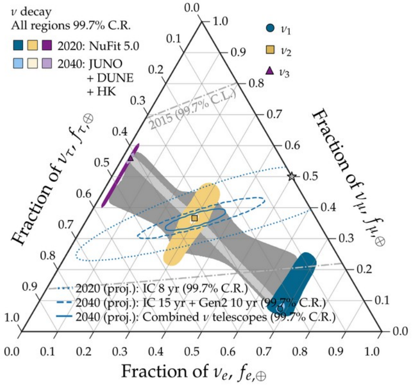

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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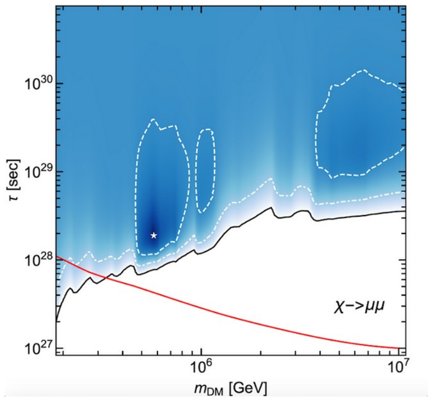
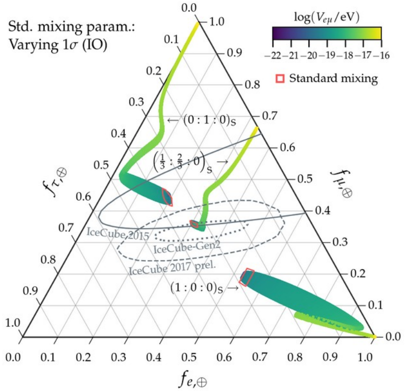


Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



MB & Agarwalla, *PRL* 2019

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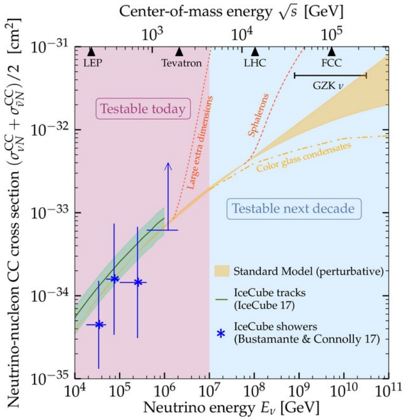

MB & Connolly, *PRL* 2019

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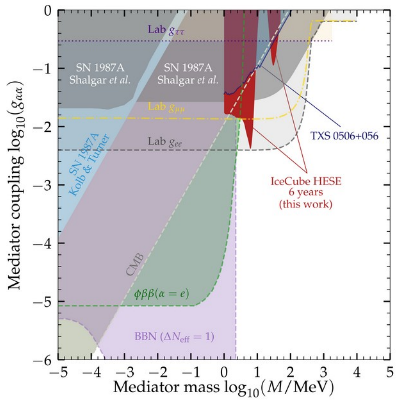

MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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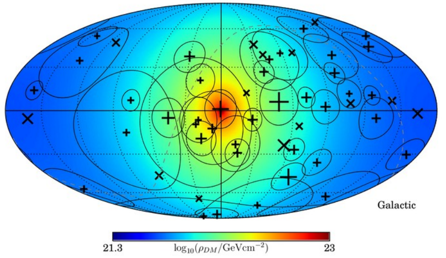

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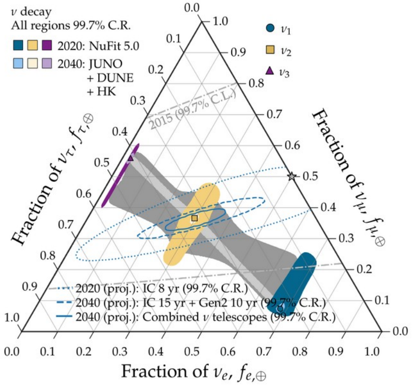
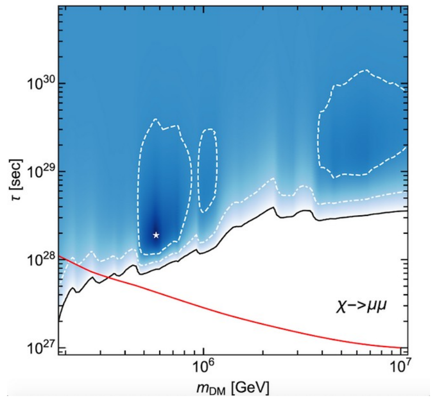


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



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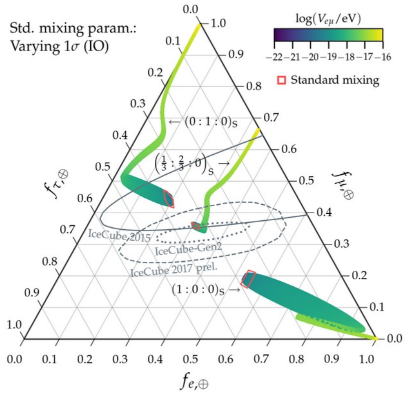
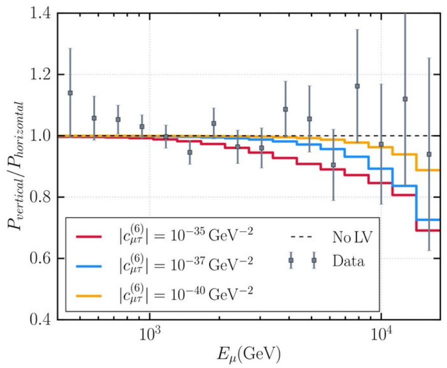


MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



IceCube, *Nature Phys.* 2018

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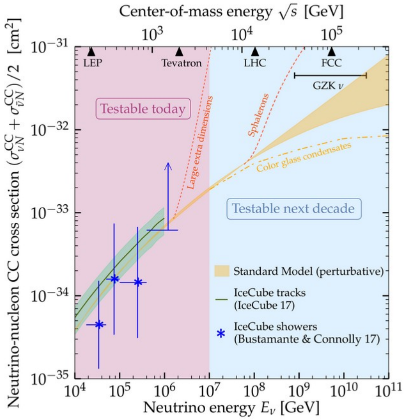

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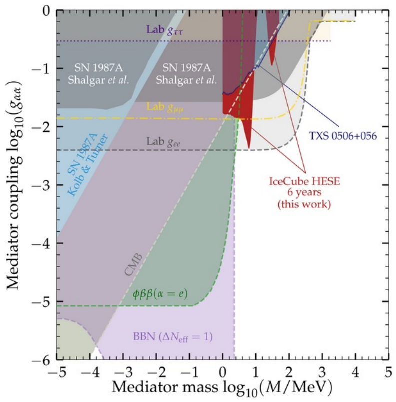

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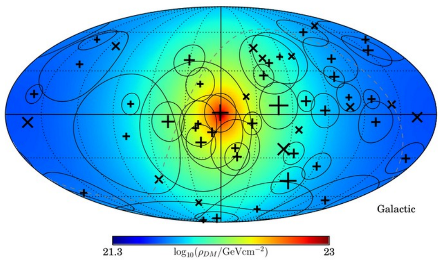

Argüelles, Kheirandish, Vincent, *PRL* 2017

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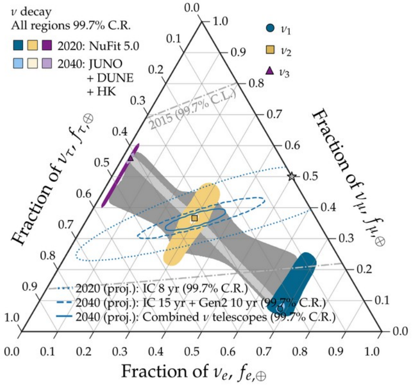
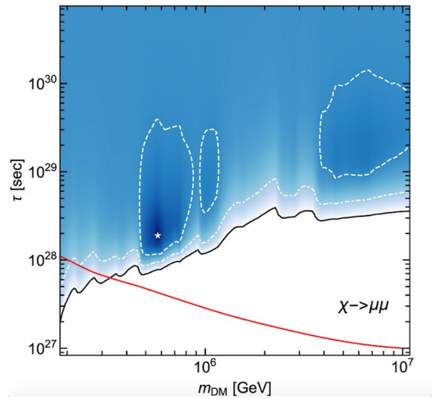


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



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

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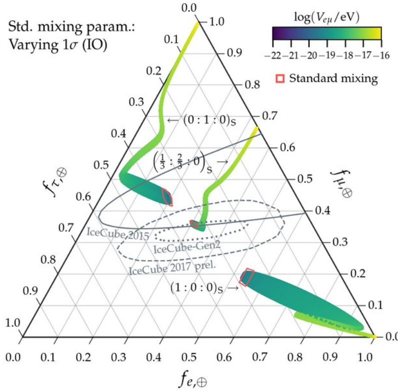

MB & Agarwalla, *PRL* 2019

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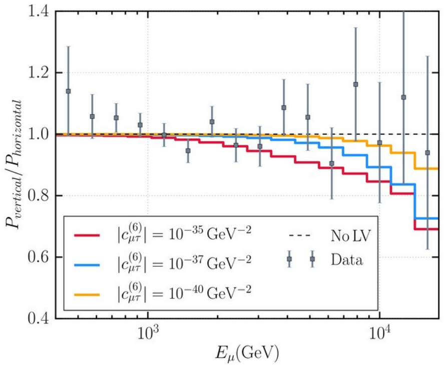
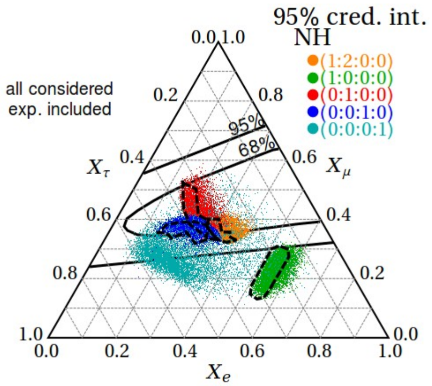


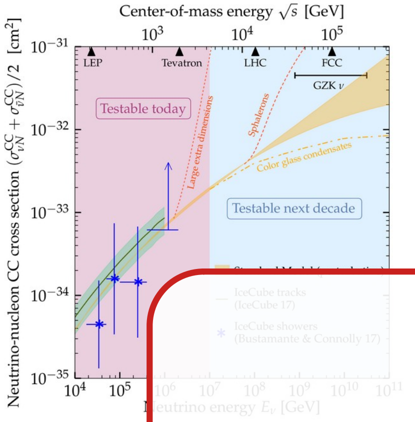
IceCube, *Nature Phys.* 2018

Sterile neutrinos



Brdar, Kopp, Wang, *JCAP* 2017

TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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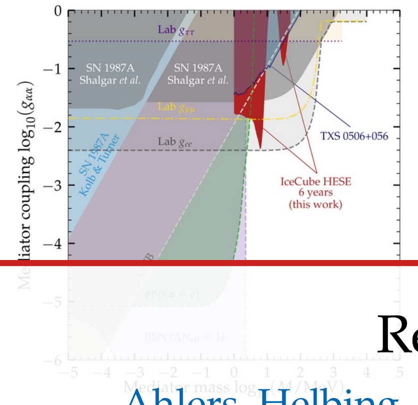
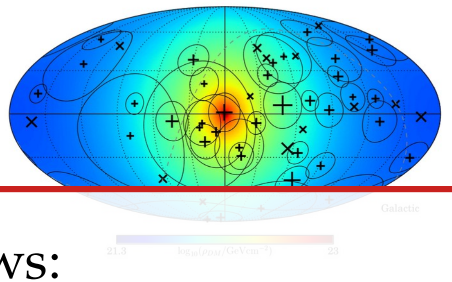


MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



Argüelles, Kheirandish, Vincent, *PRL* 2017

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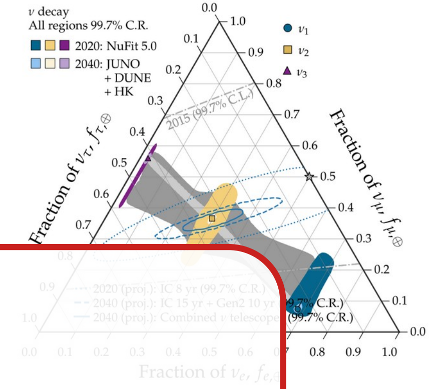
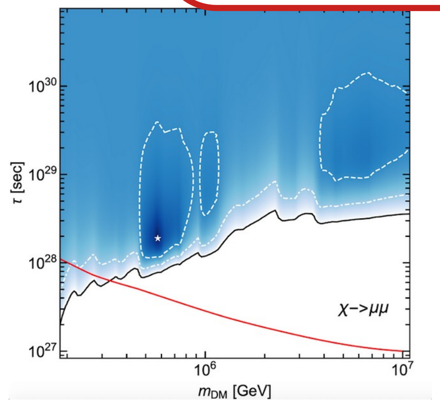


Song, Li, Argüelles, MB, Vincent, *JCAP* 2021

Dark matter decay



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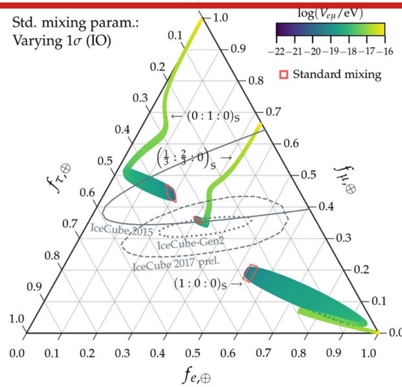
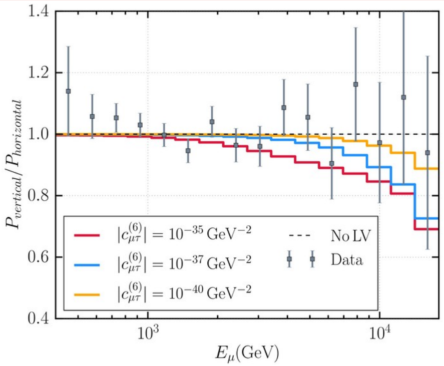


MB & Agarwalla, *PRL* 2019

Lorentz invariance violation



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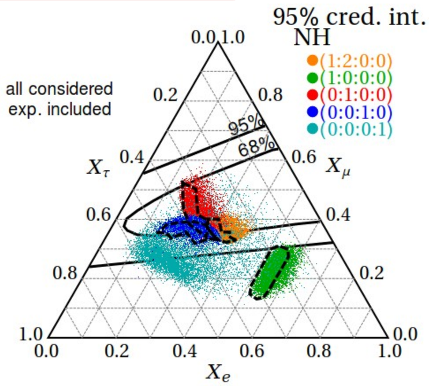


Brdar, Kopp, Wang, *JCAP* 2017

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]

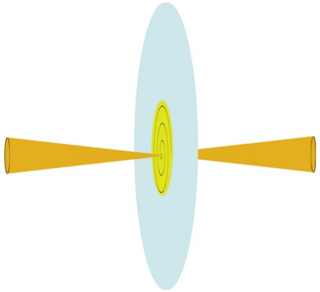
Astrophysical neutrino sources

Earth

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

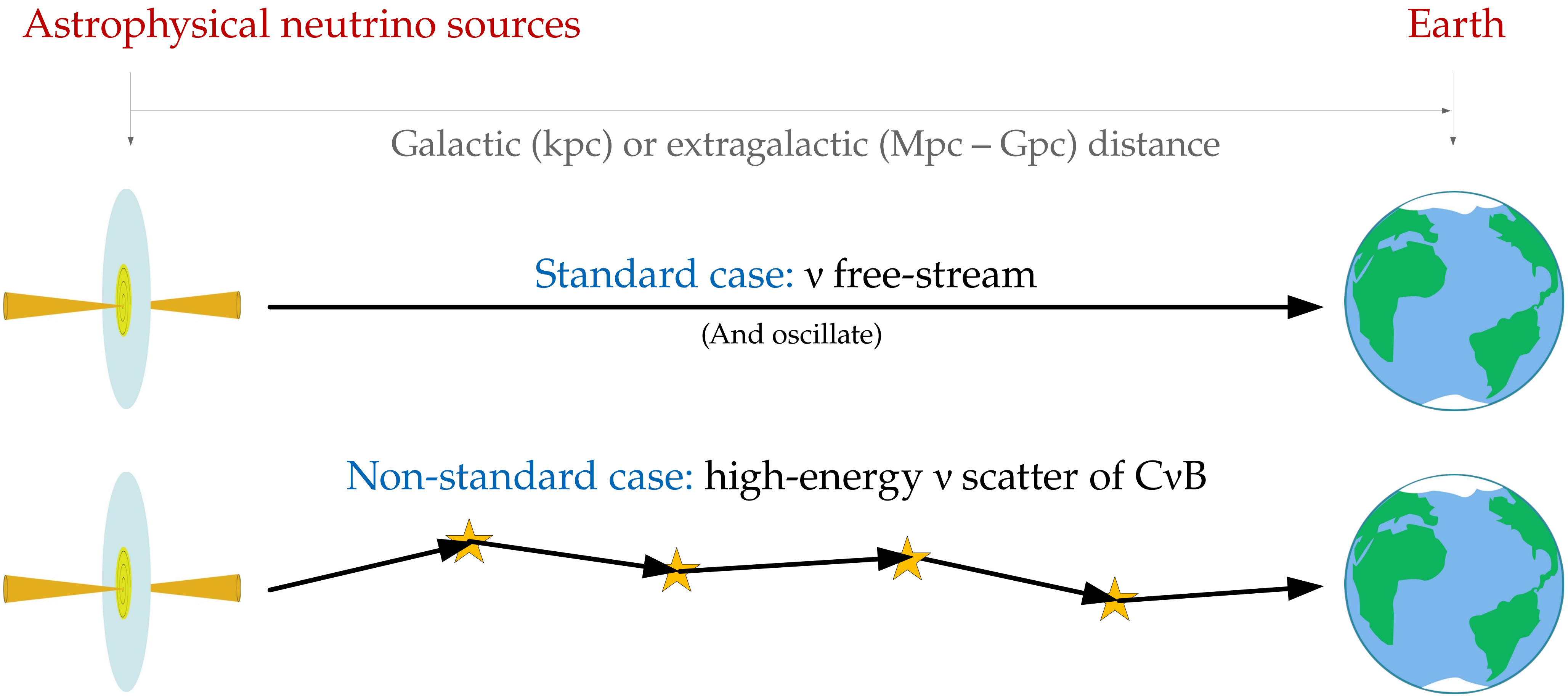
Astrophysical neutrino sources — Earth

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



Standard case: ν free-stream

(And oscillate)


Astrophysical neutrino sources
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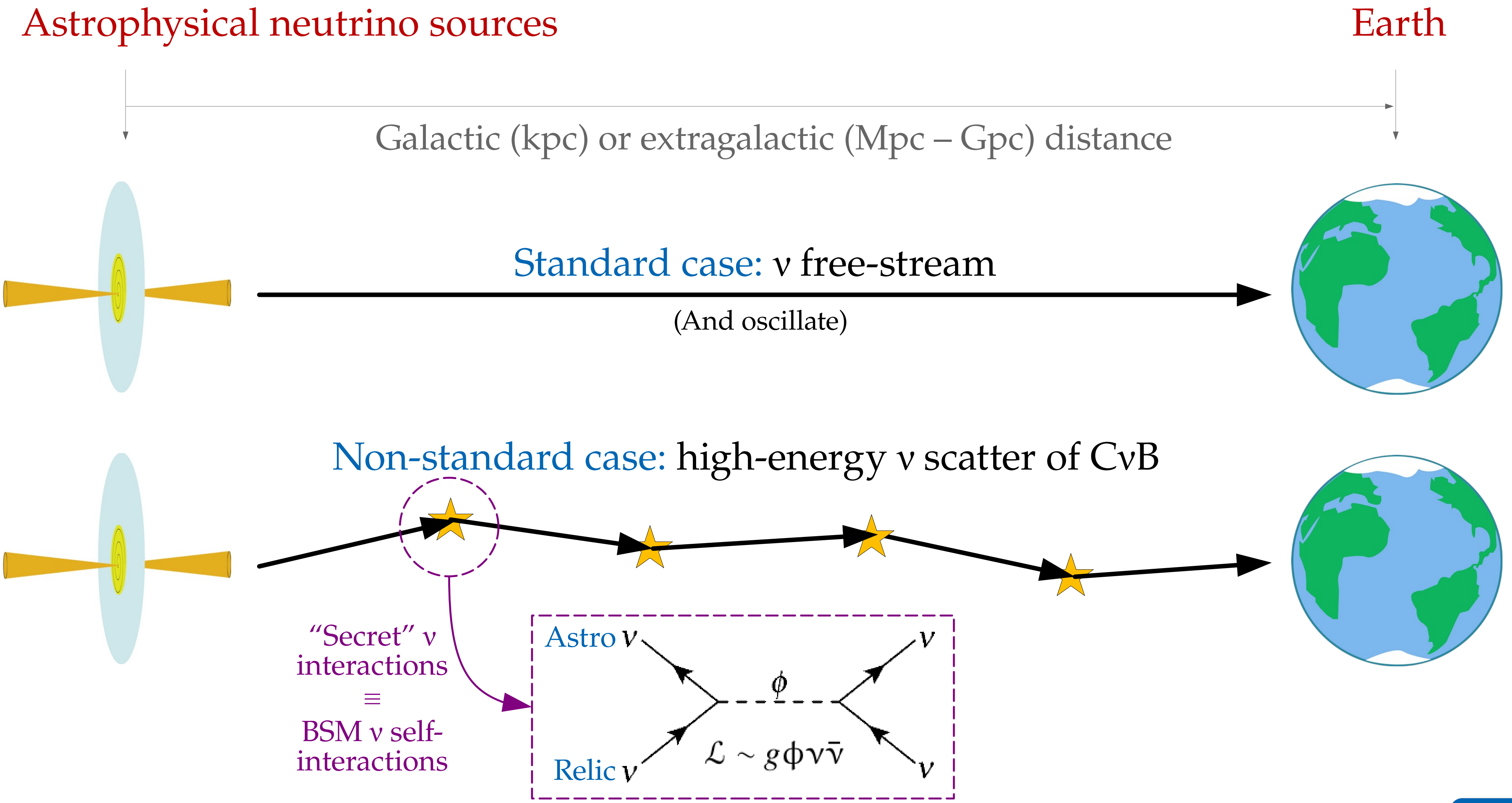
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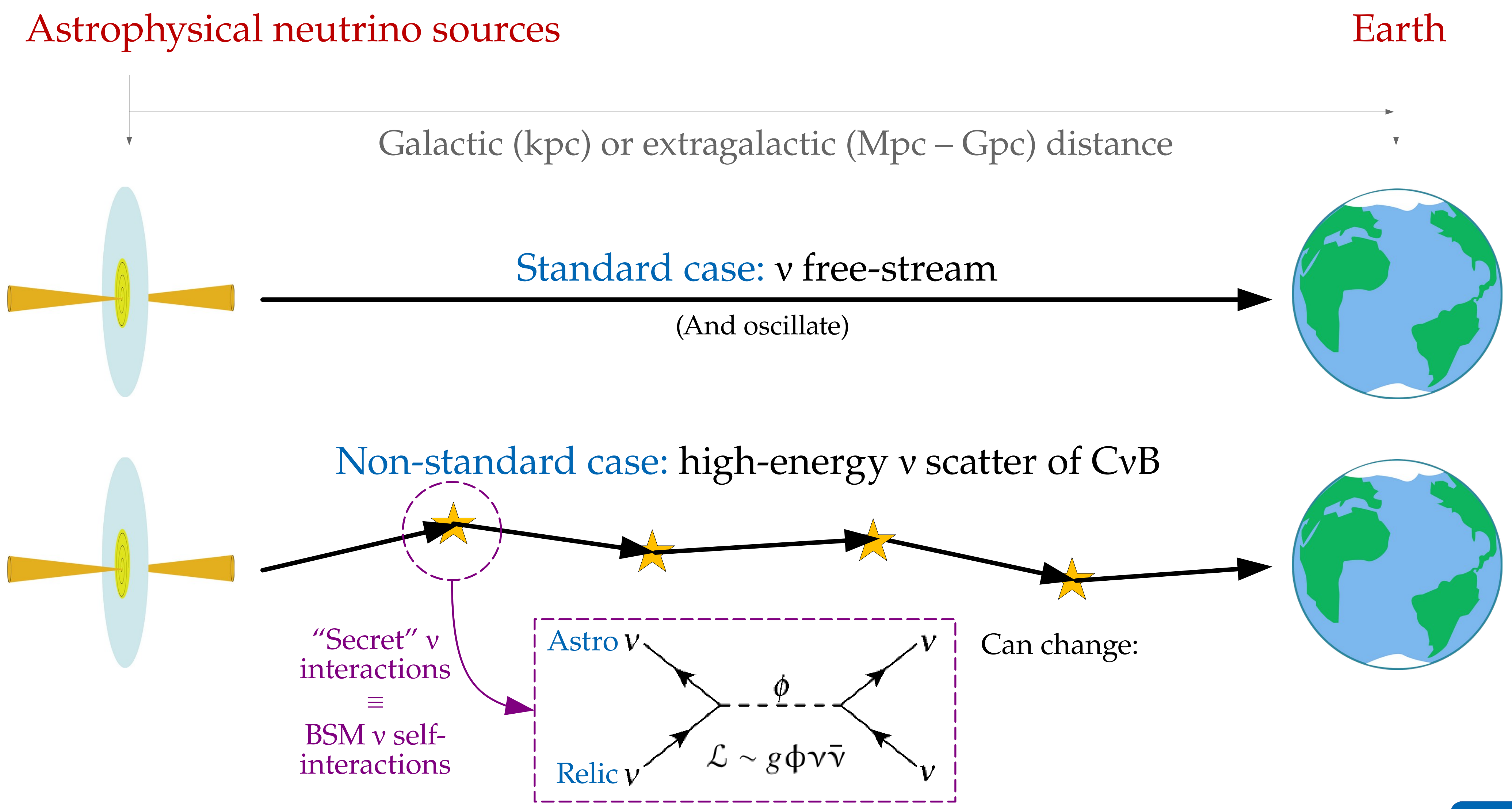
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$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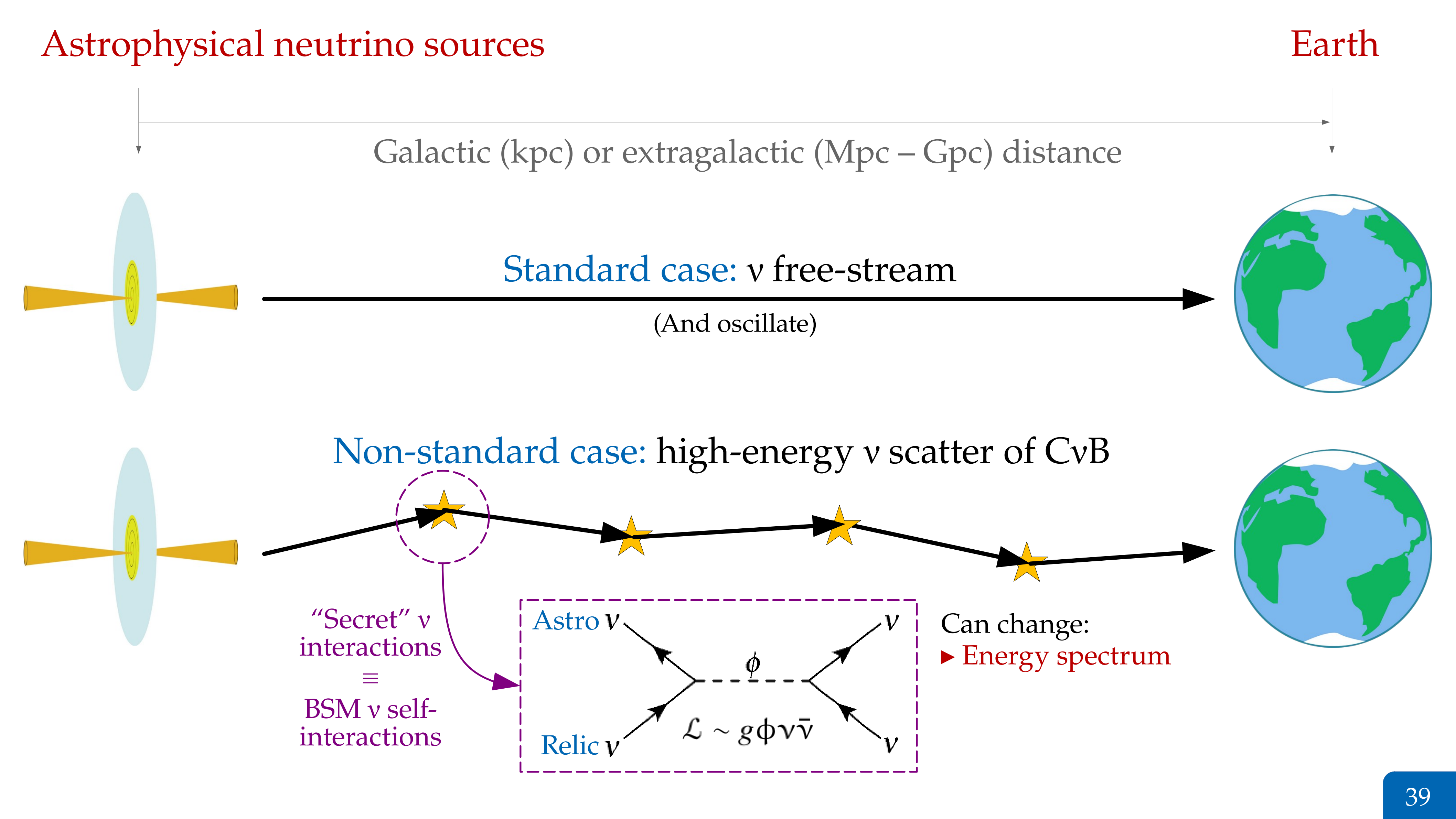
Can change:



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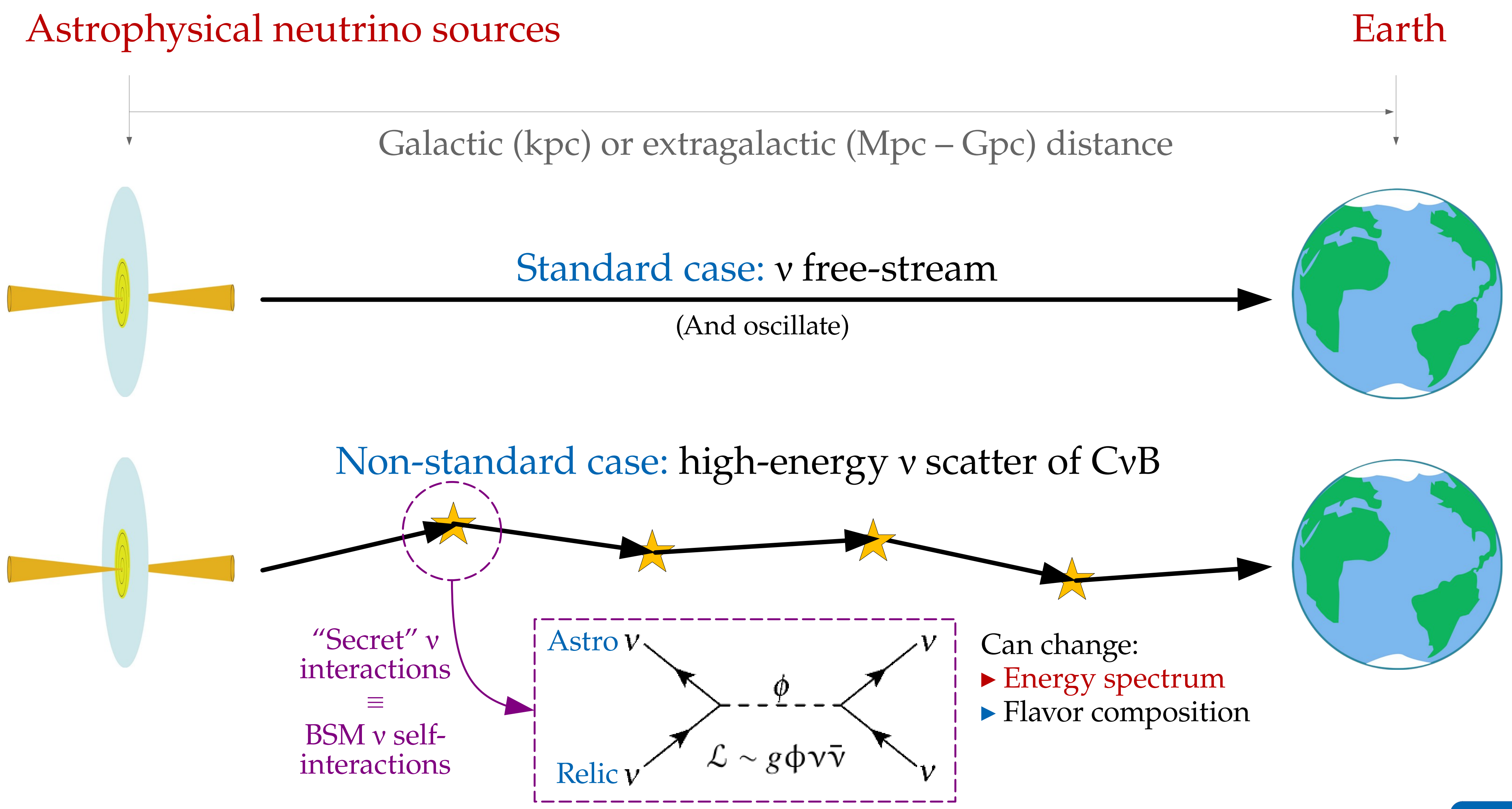
Can change:
▸ Energy spectrum



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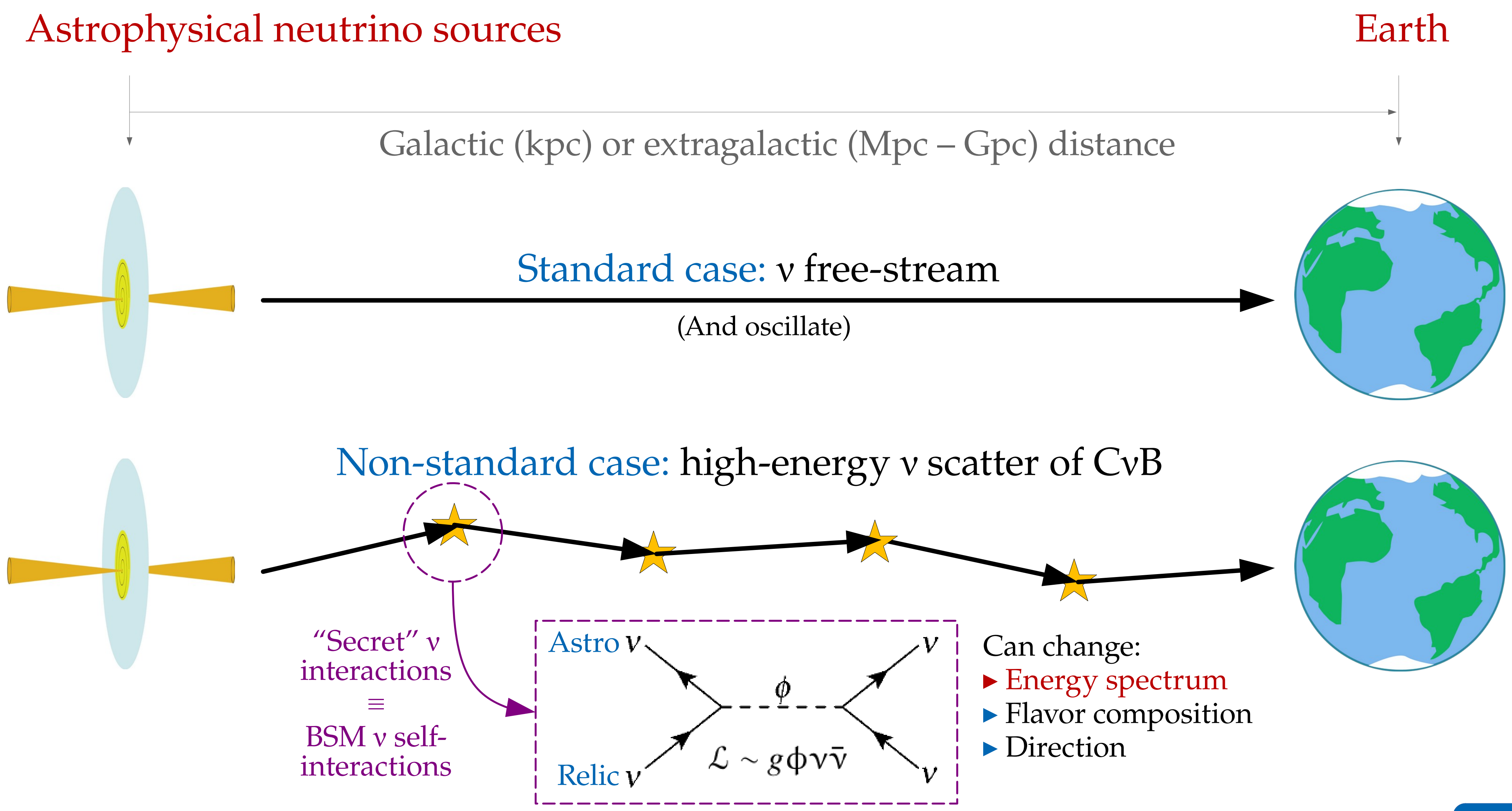
Astro ν
Relic ν
ν
ν
ϕ
ℒ ~ gϕνν̄
Can change:
Energy spectrum
Flavor composition



Astrophysical neutrino sources
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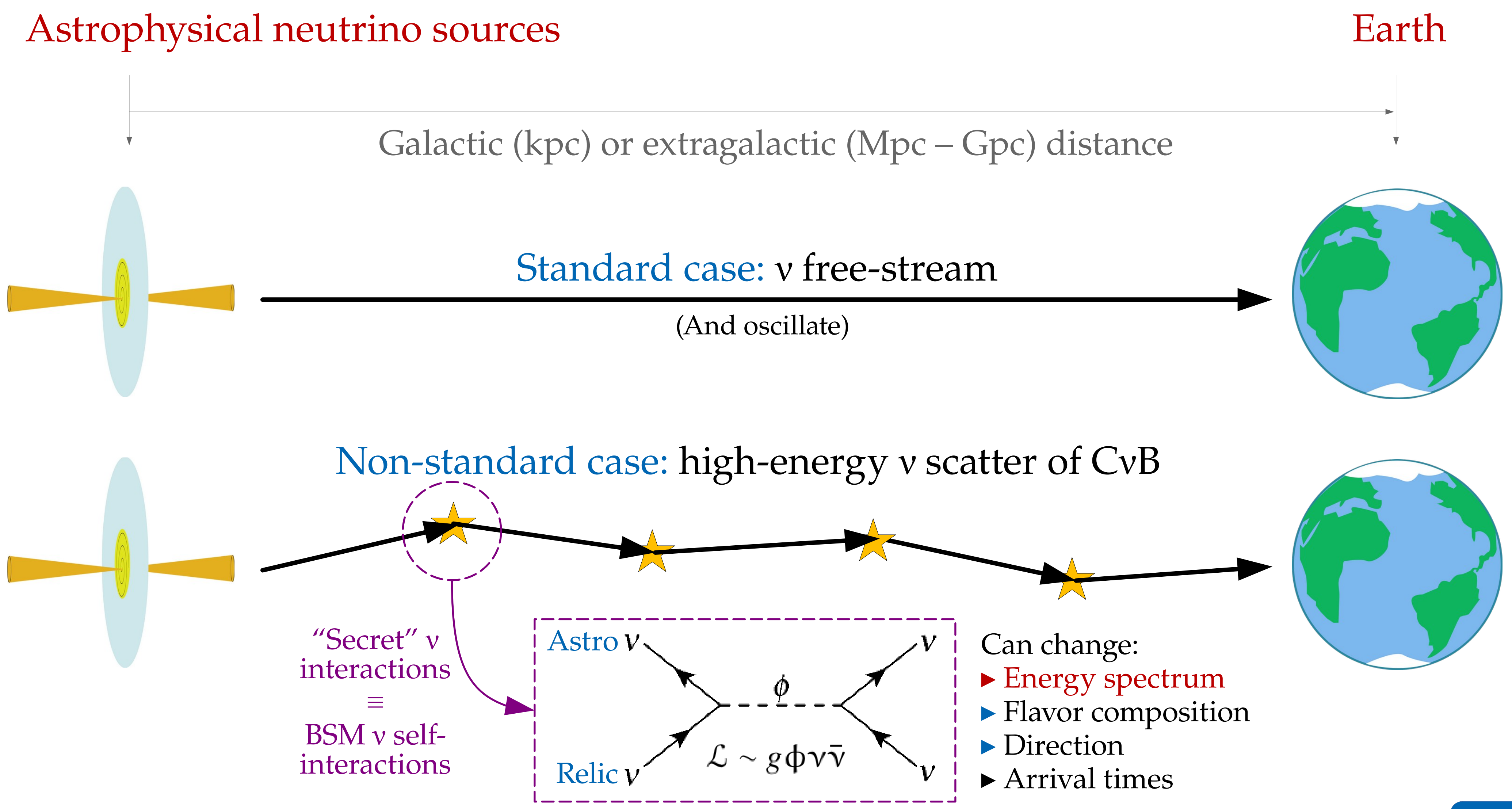
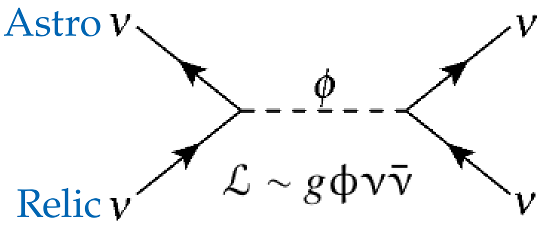
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change:
▸ Energy spectrum
▸ Flavor composition
▸ Direction


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

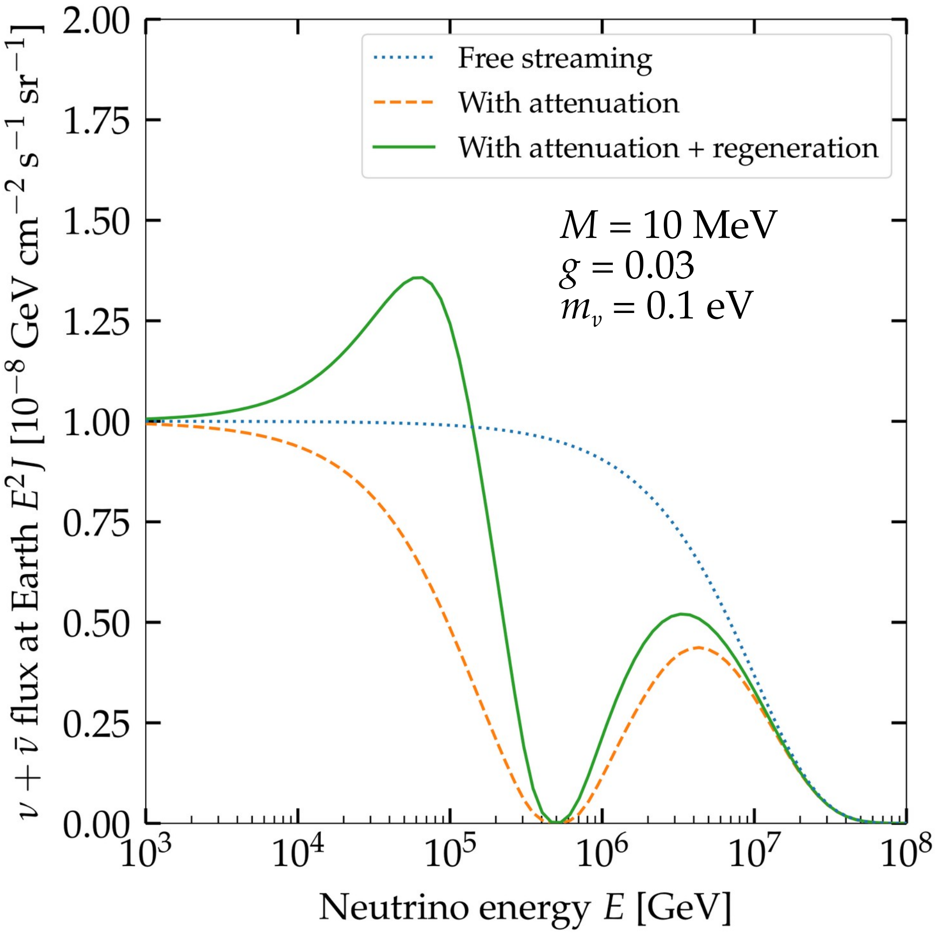
Secret interactions of high-energy astrophysical neutrinos

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



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

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



MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Ng & Beacom, *PRD* 2014
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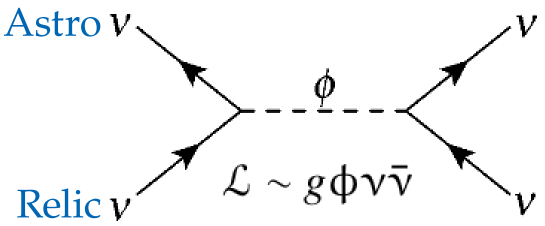

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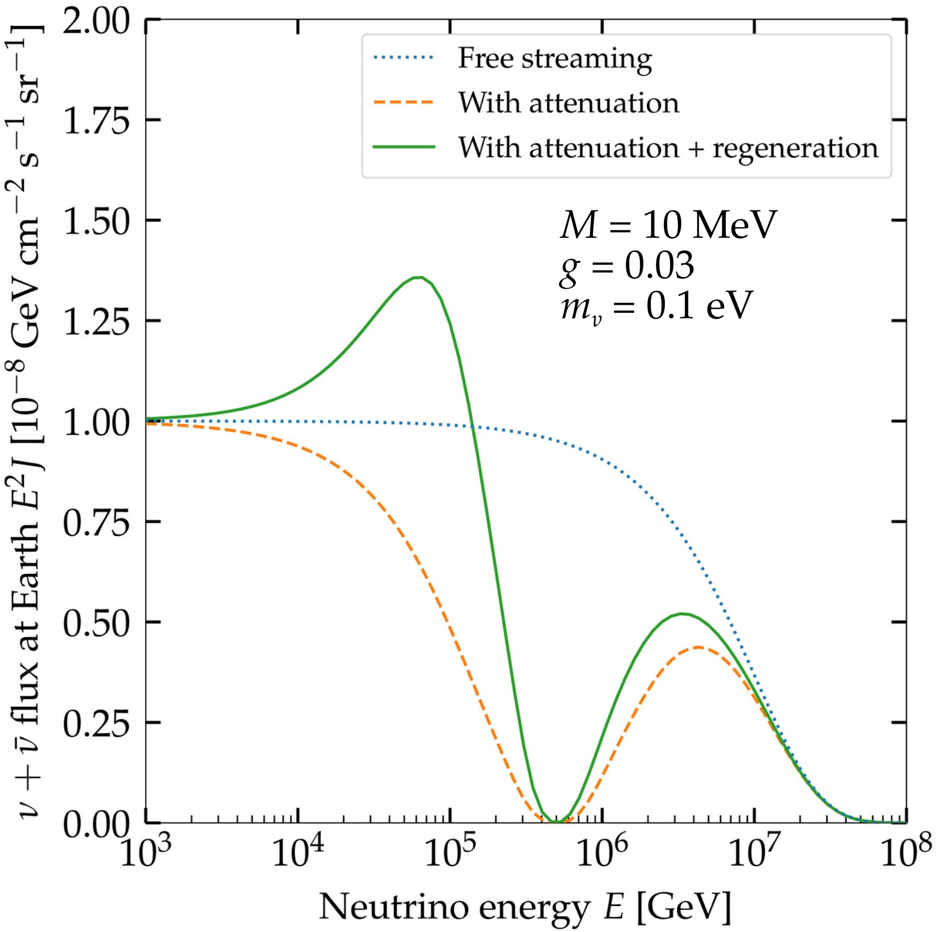

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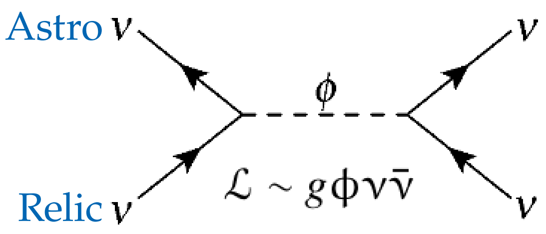

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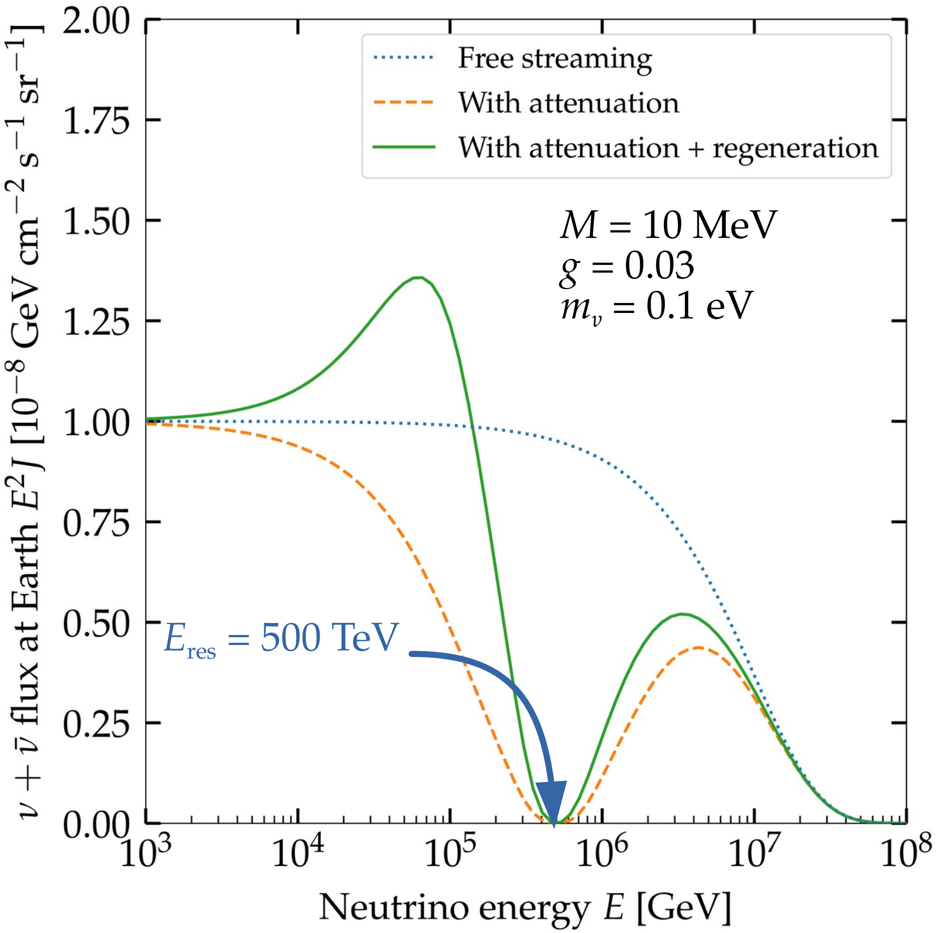

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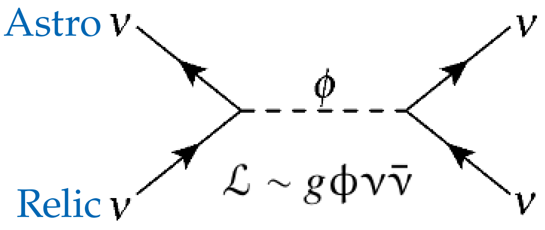

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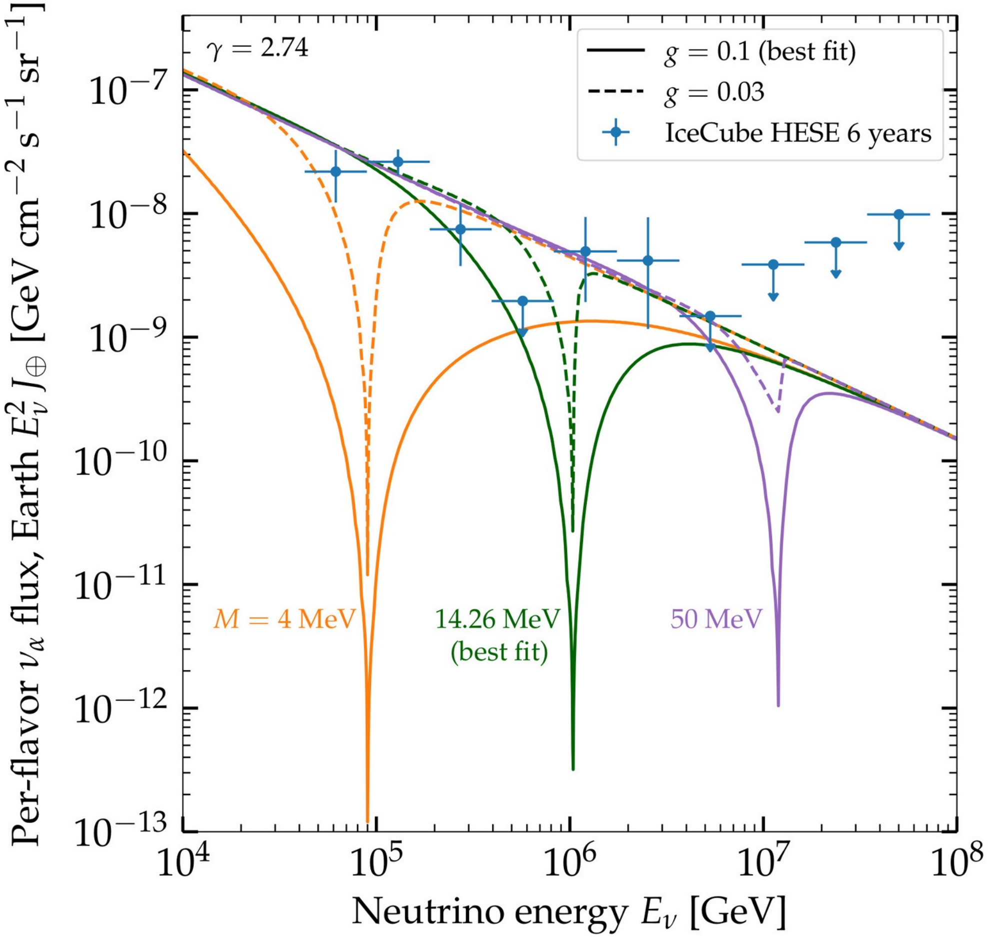

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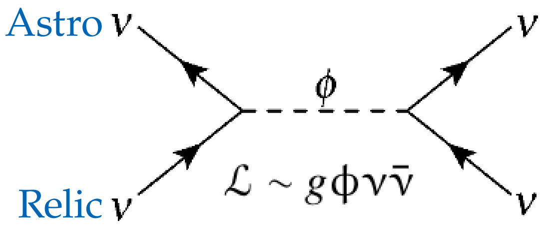

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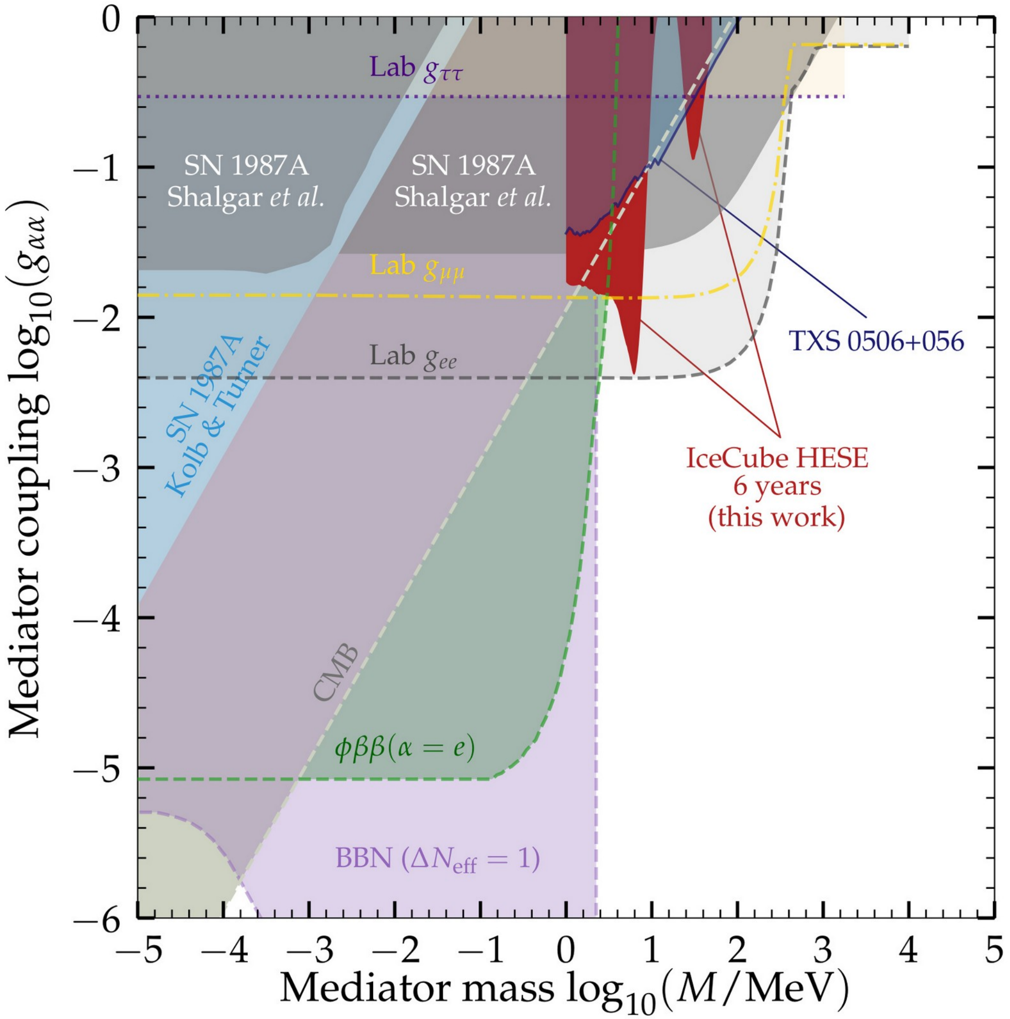
Looking for evidence of νSI

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



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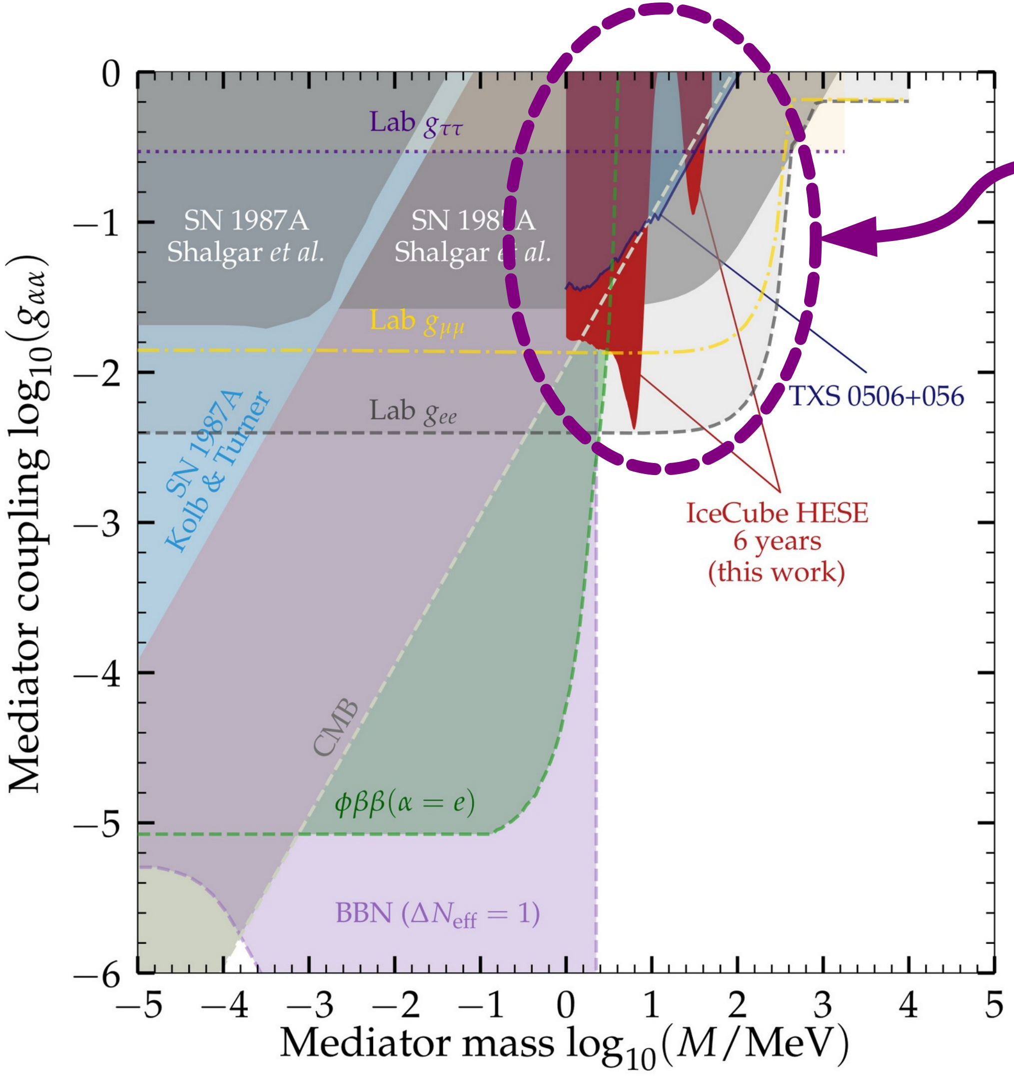

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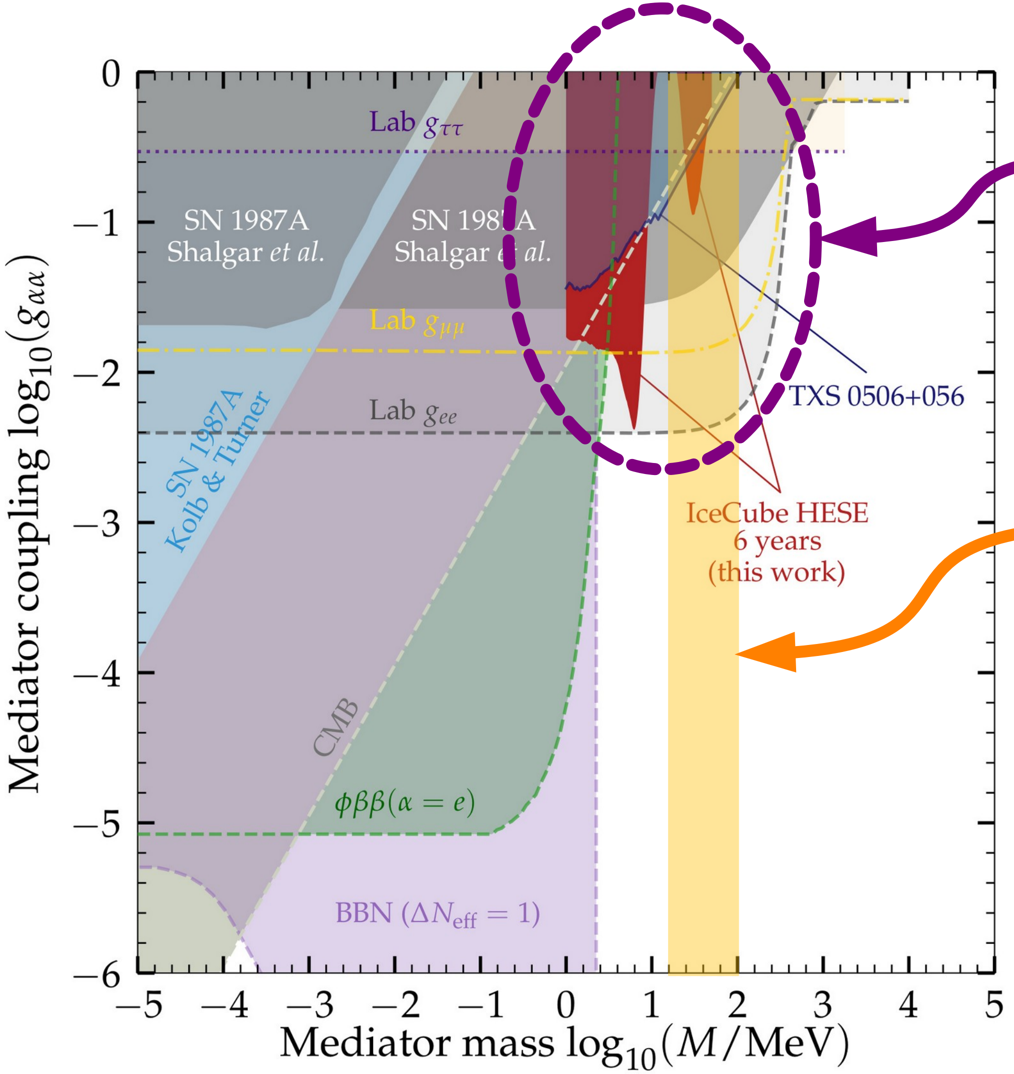

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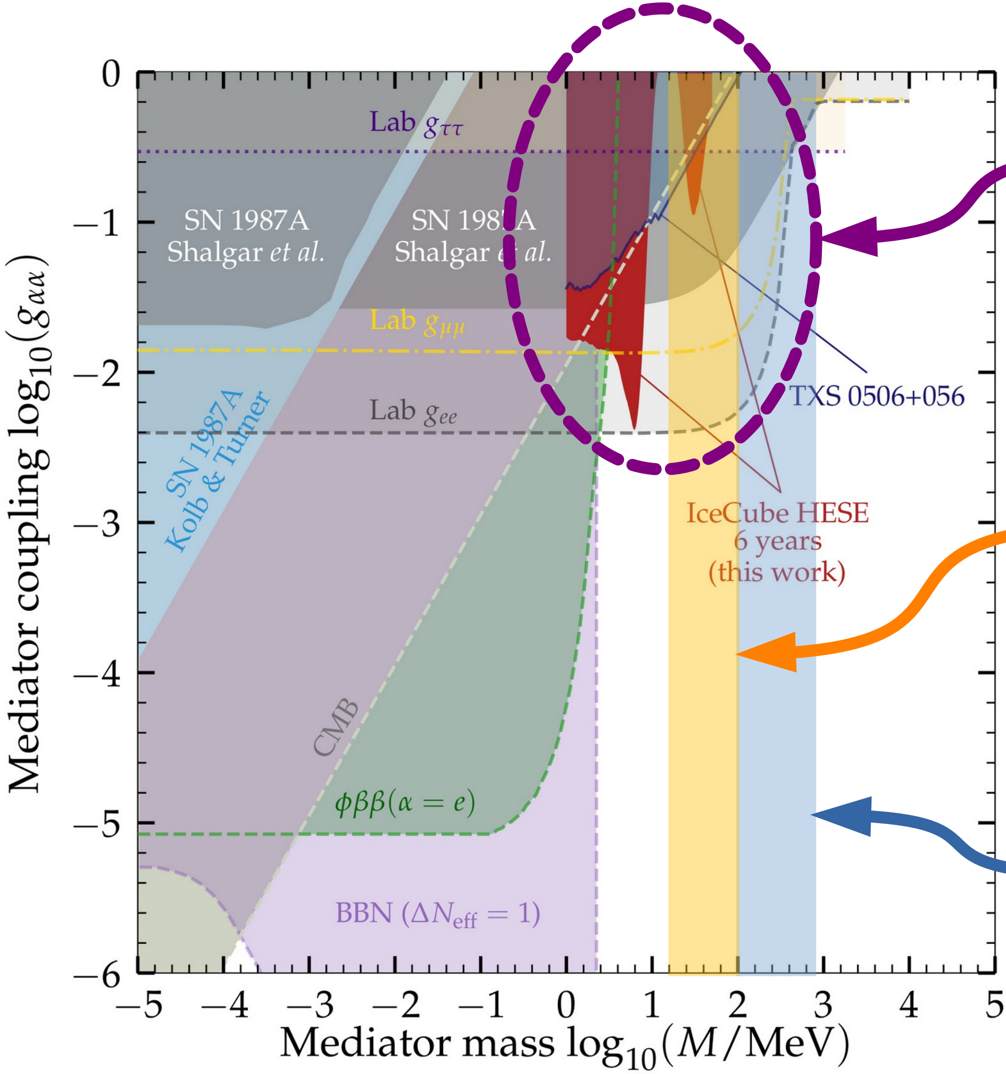
Future: High-statistics TeV–PeV ν in IceCube-Gen2 (optical)

Esteban, Pandey, Brdar, Beacom, 2107.13568

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



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Esteban, Pandey, Brdar, Beacom, 2107.13568

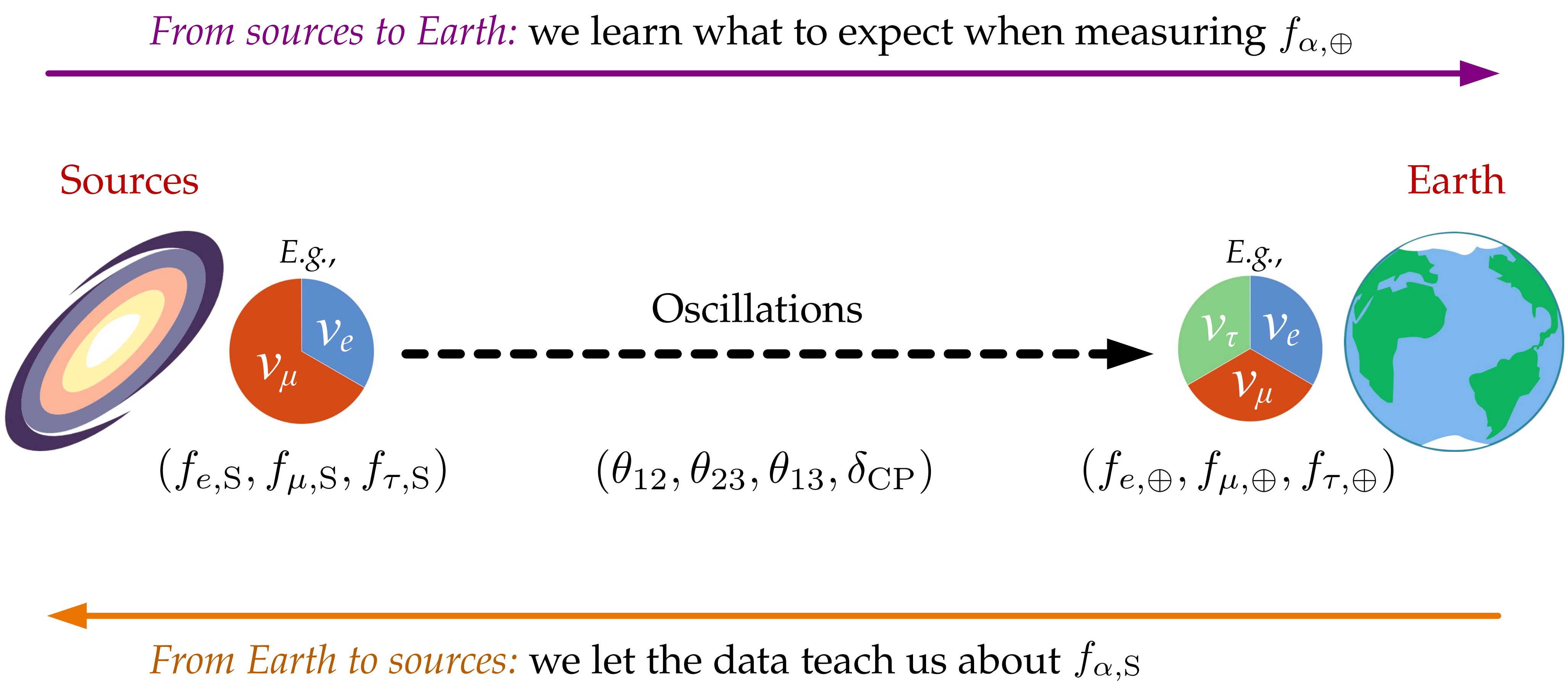
Future: UHE ν in IceCube-Gen2 (radio)

MB, Másson, Valera, *In preparation*

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

Work in progress

1. Discovery potential for UHE ν
2. Inferring the spectrum of UHE ν
3. Measuring the UHE νN cross section
4. Testing other UHE ν BSM models
5. Testing ν physics using flavor ratios



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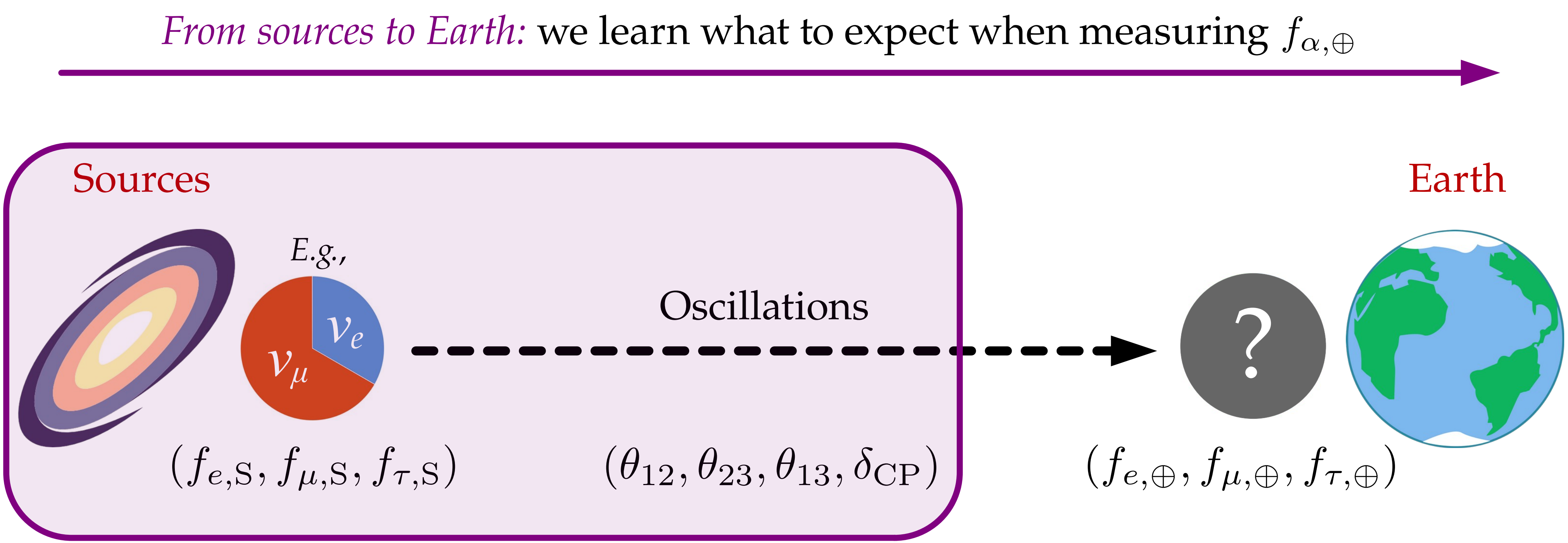

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One likely TeV–PeV ν production scenario:

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

Full π decay chain

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

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

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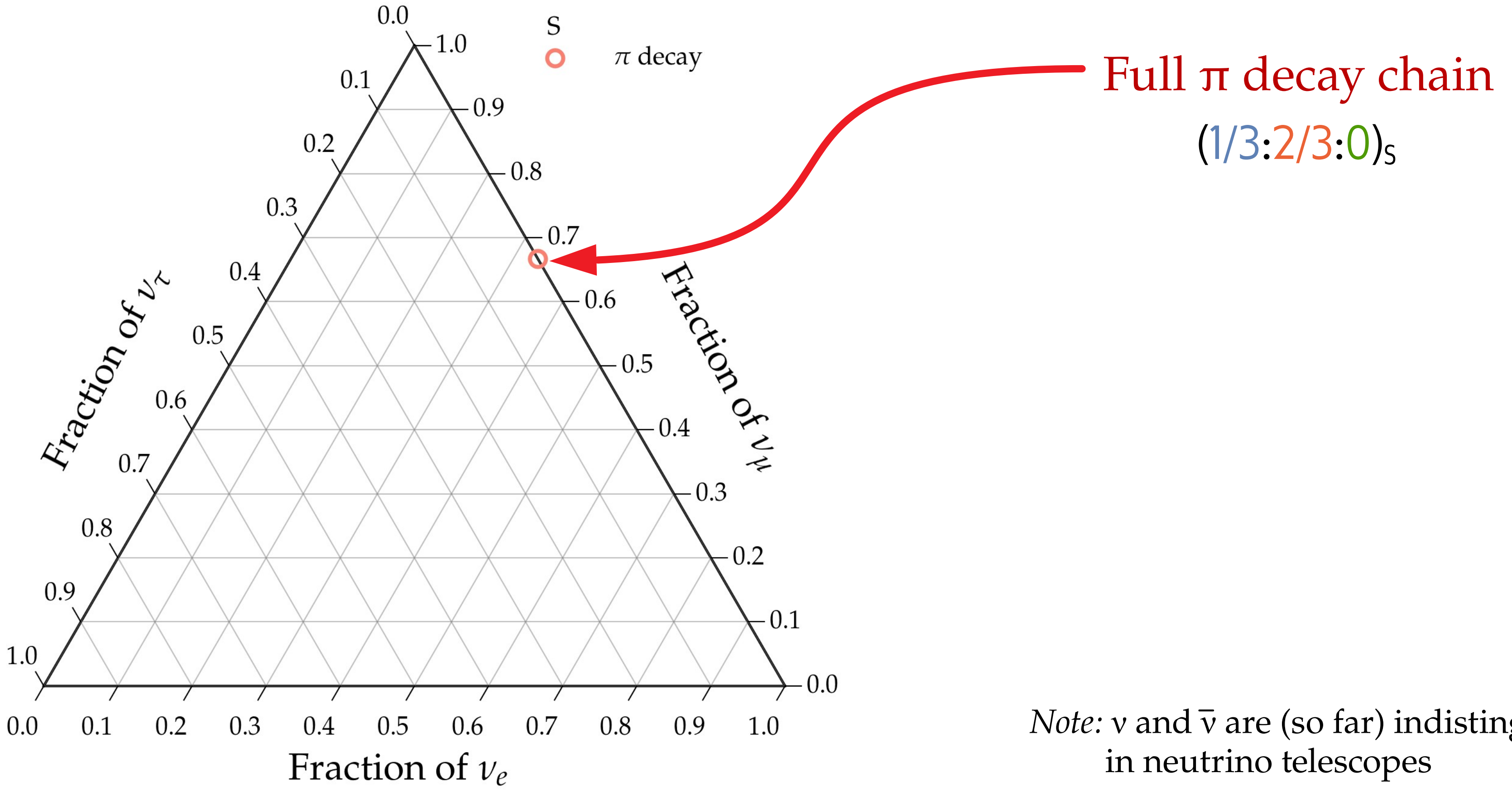

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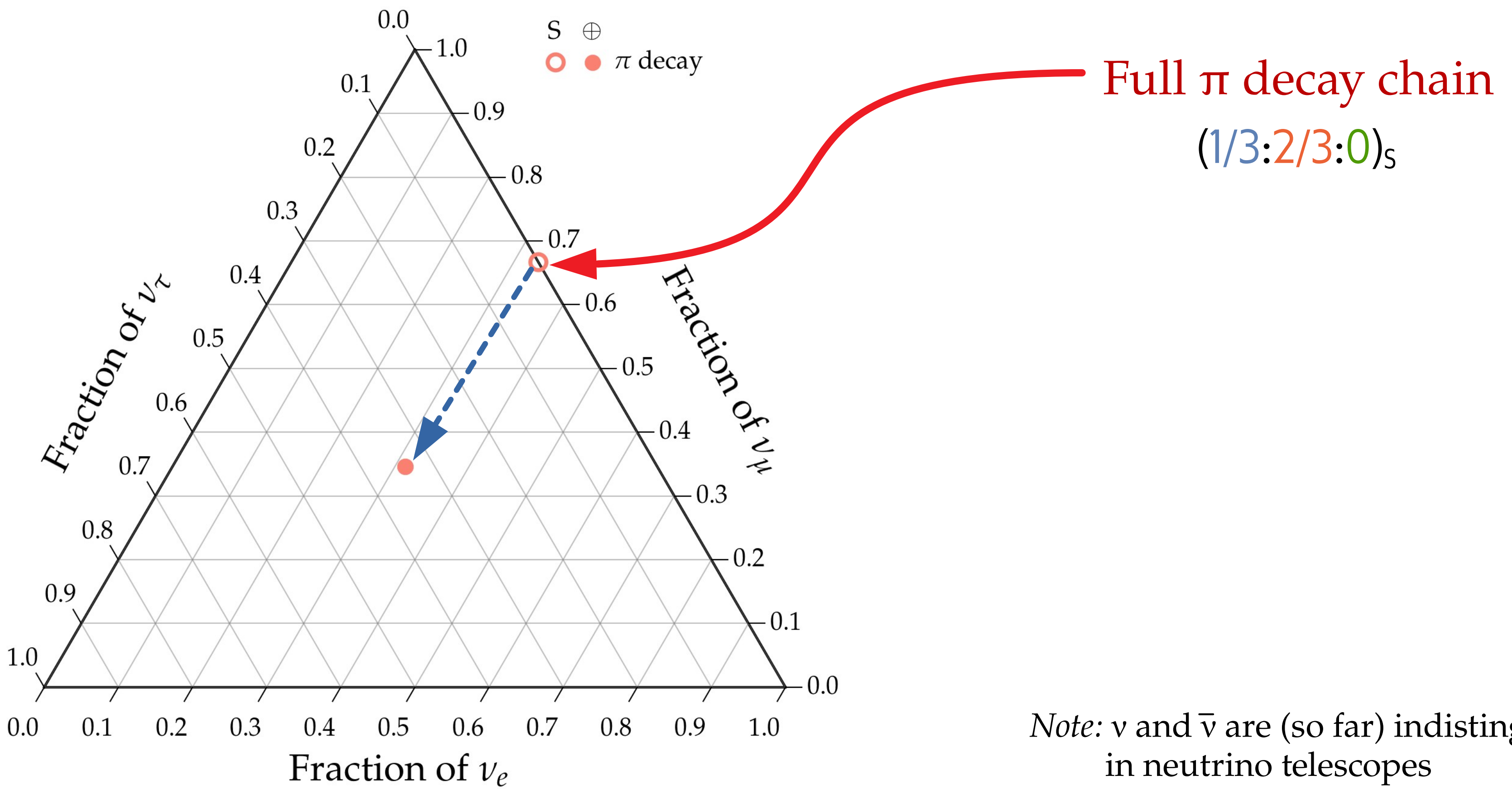

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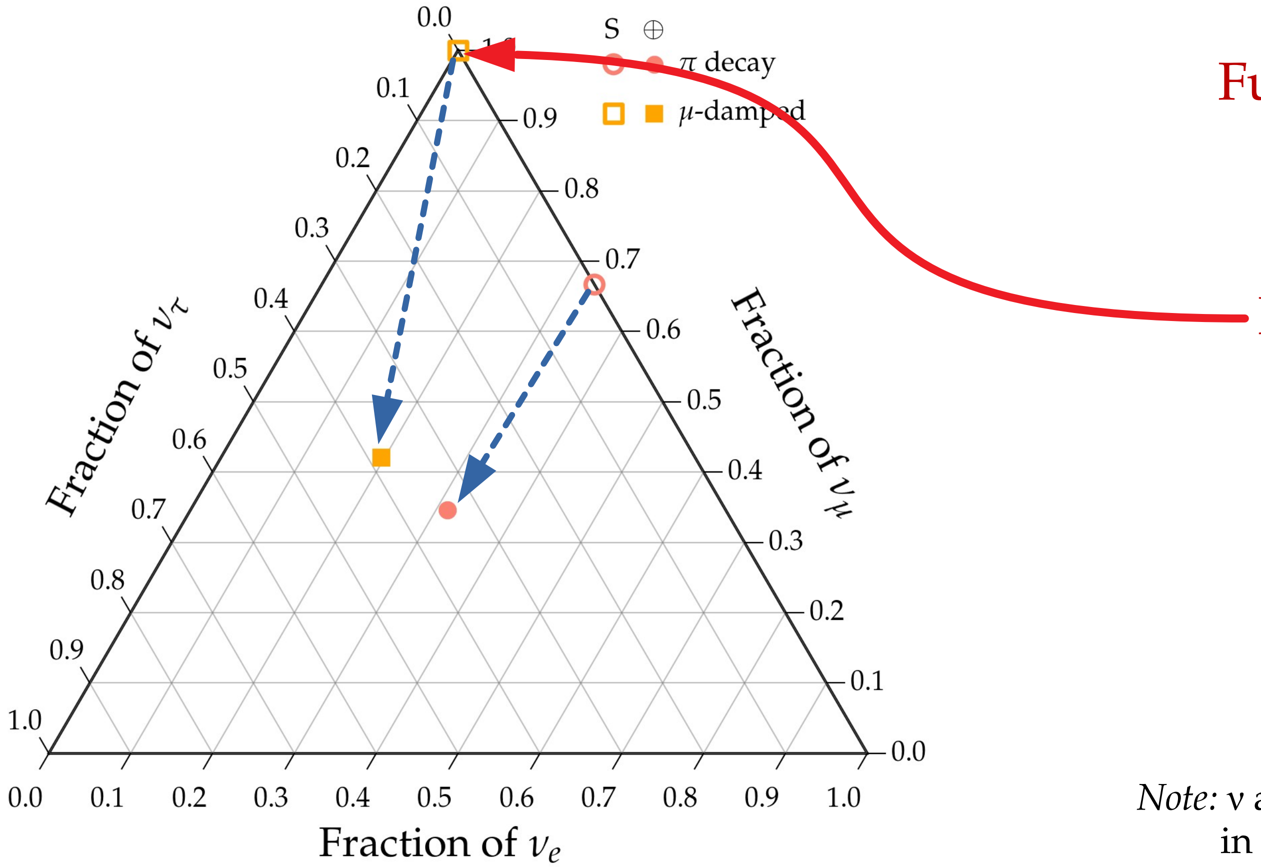

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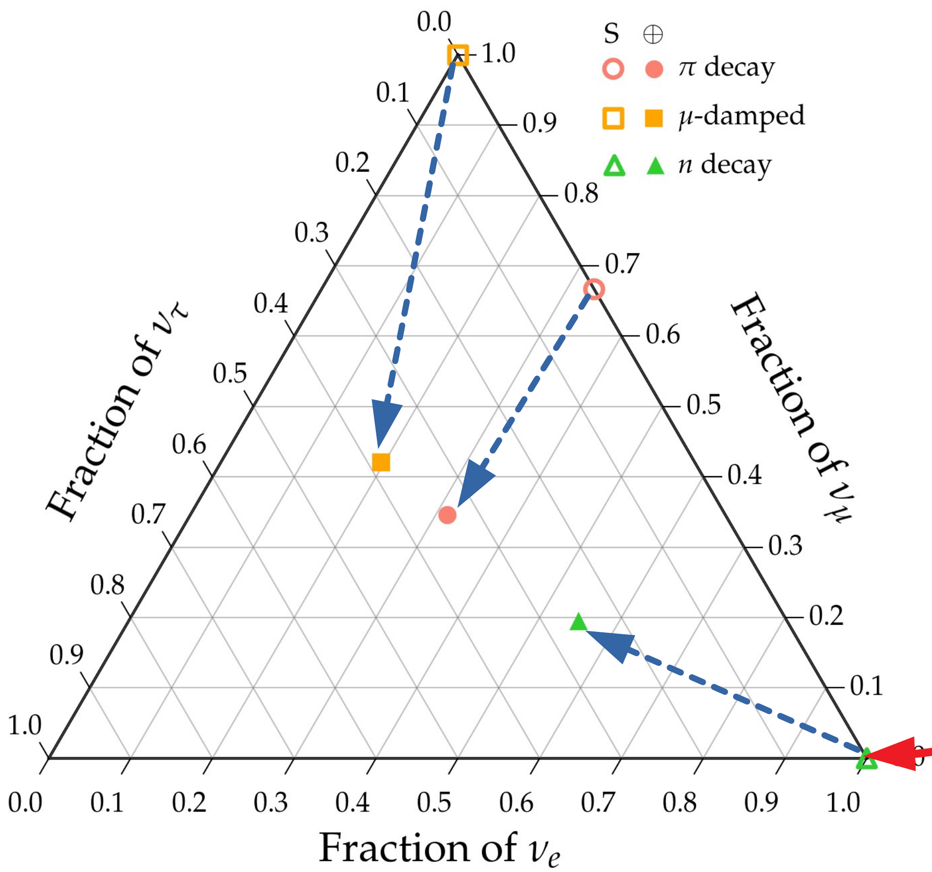

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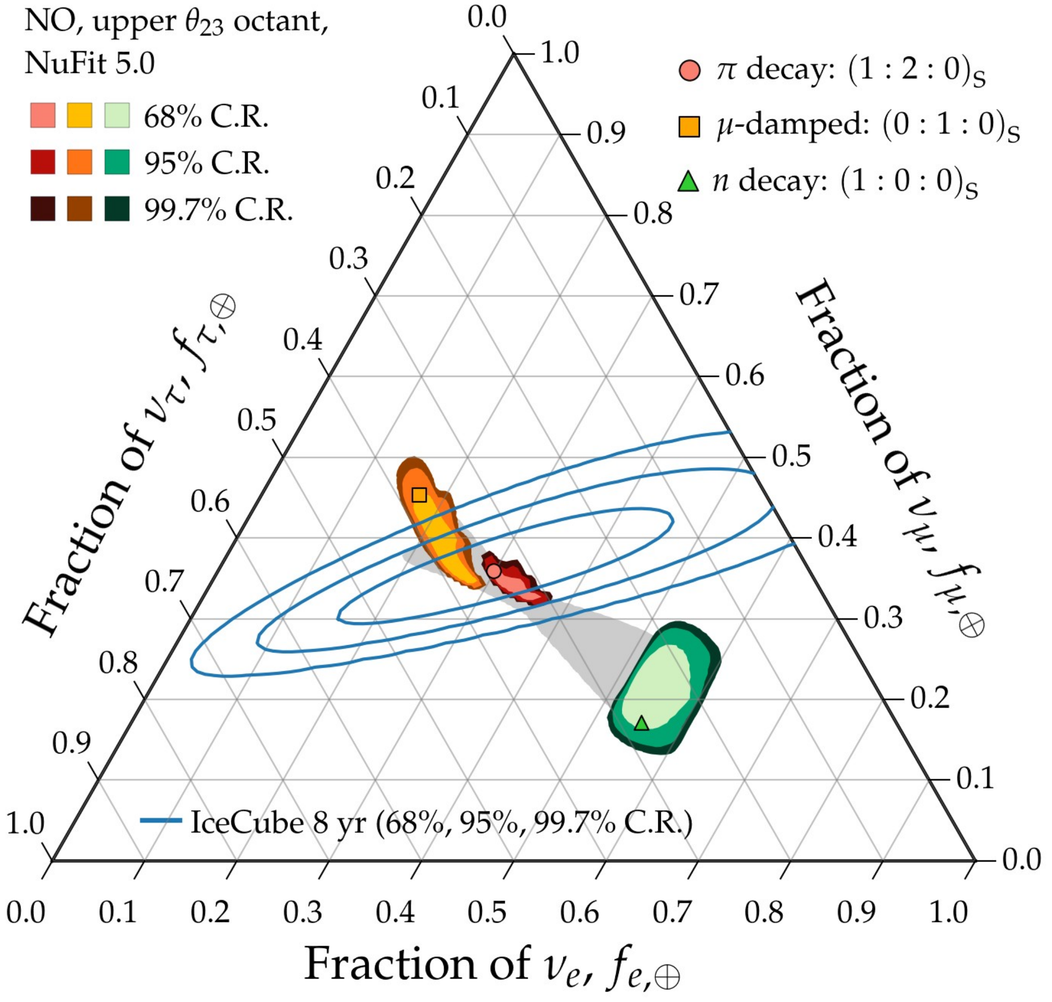
Theoretically palatable regions: today (2021)



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, *JCAP* 2021
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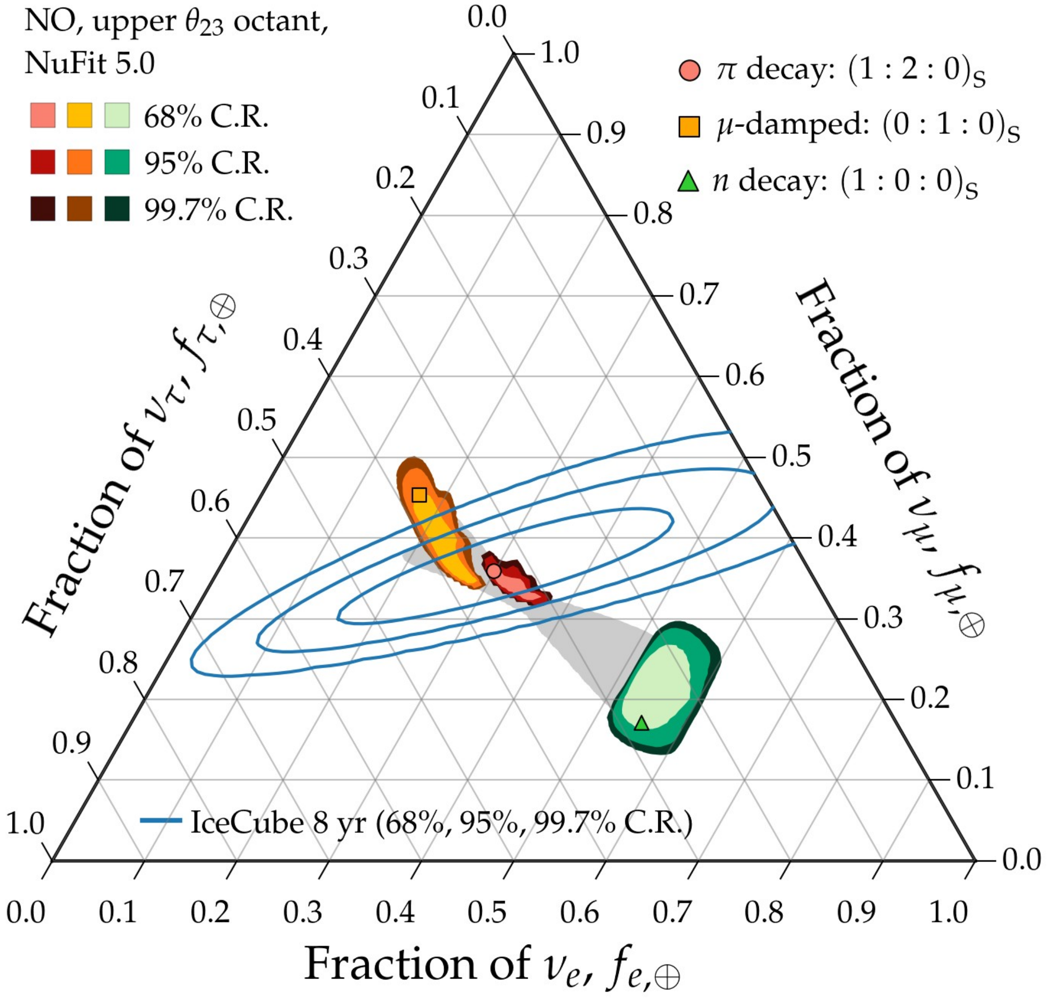

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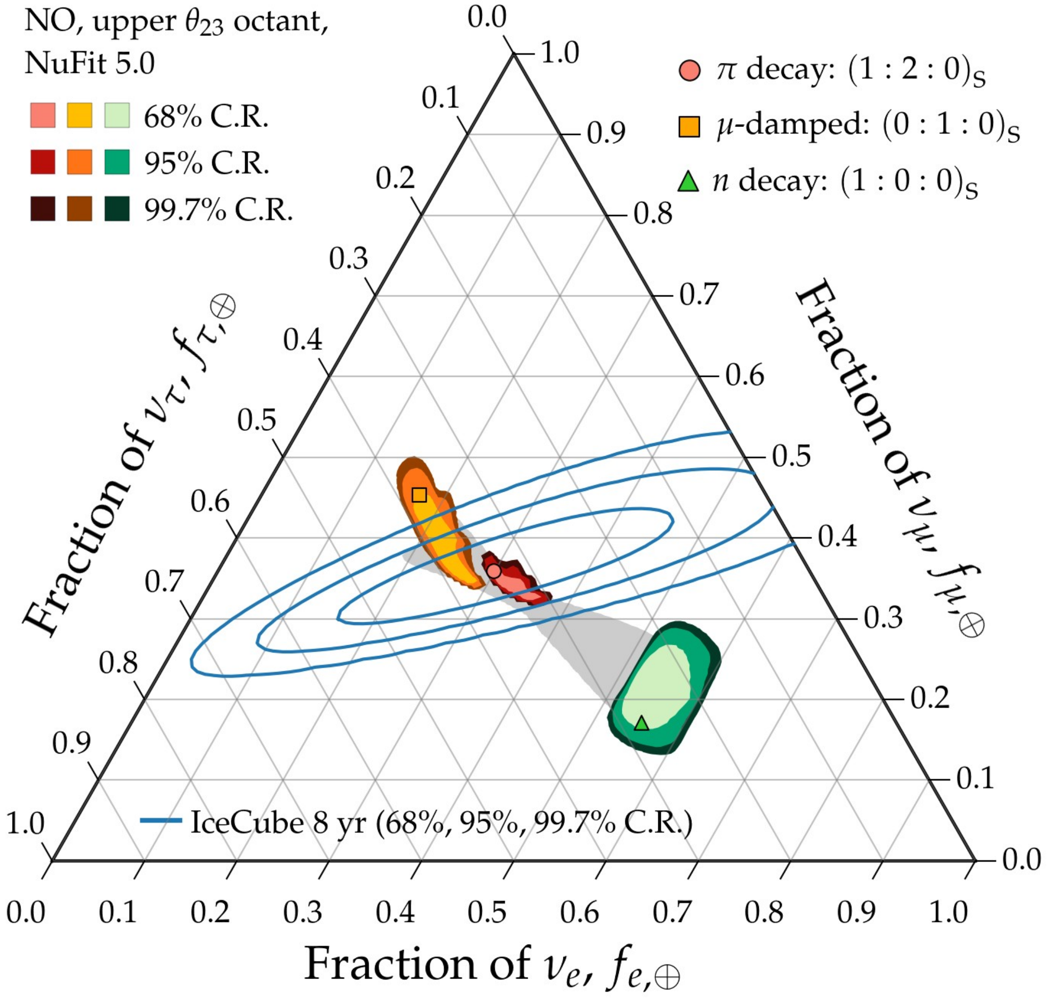

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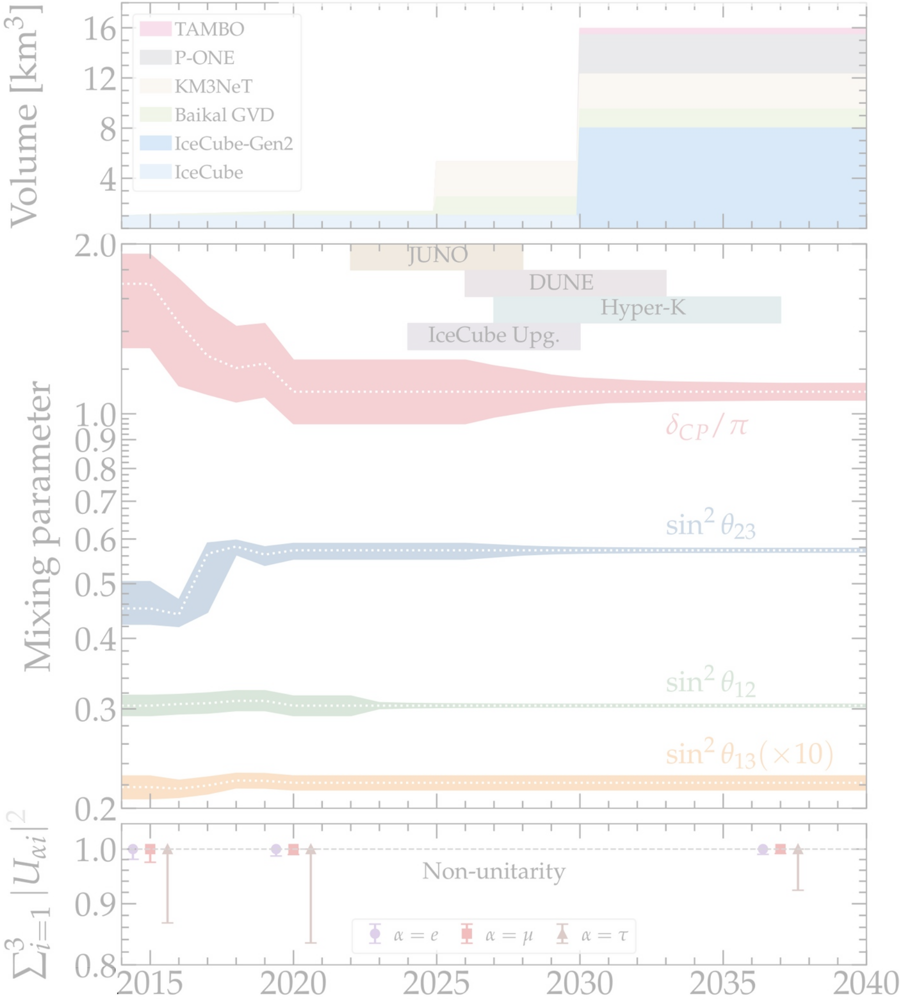
Three reasons to be excited

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



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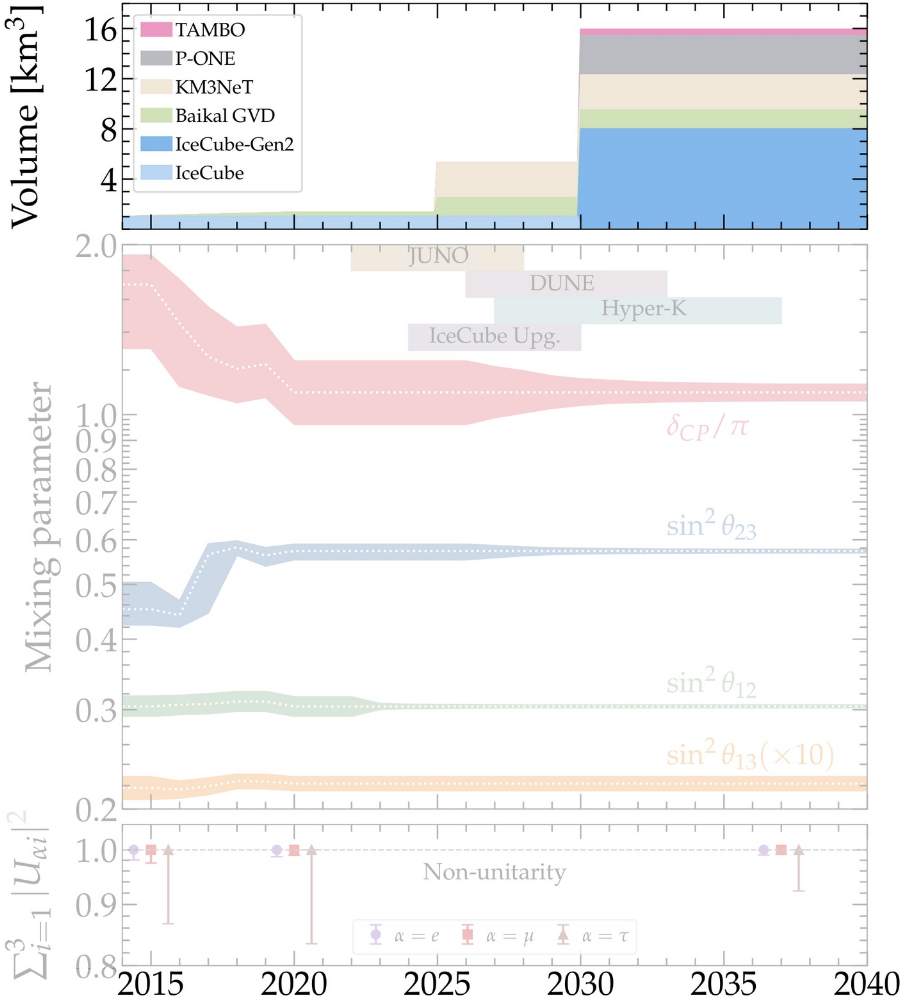

Flavor measurements:

New neutrino telescopes = more events, better flavor measurement

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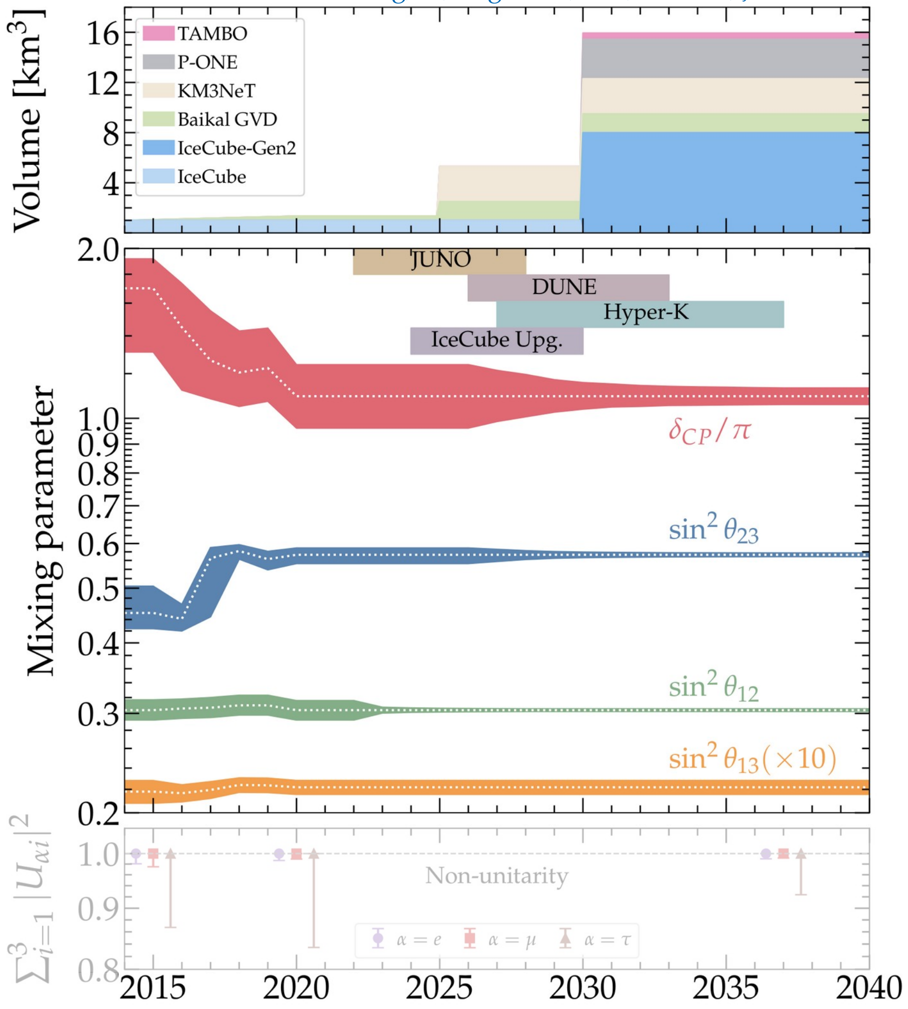

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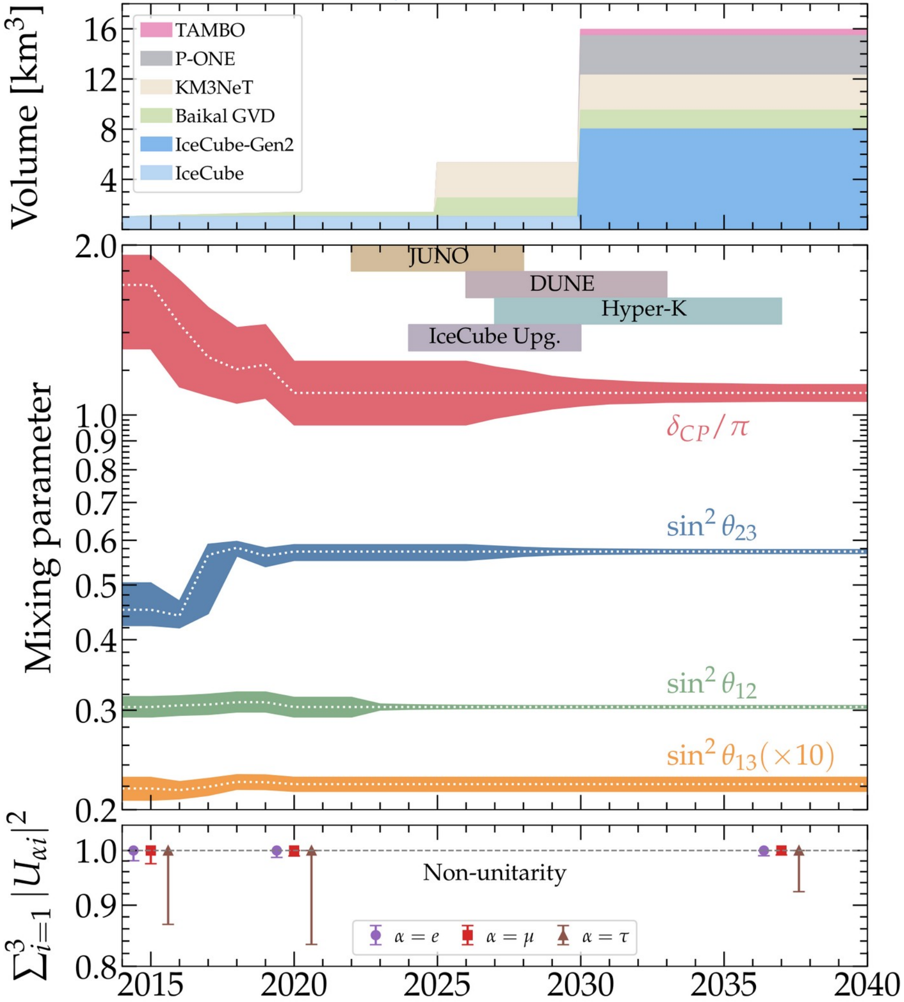

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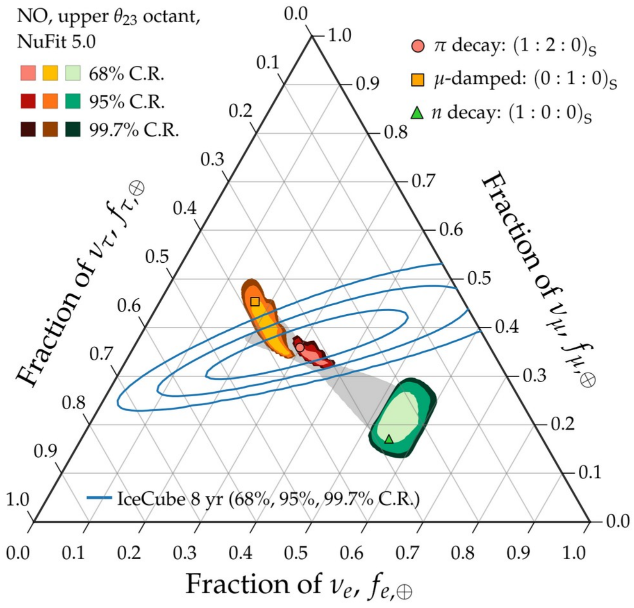
Test of the oscillation framework:
We will be able to do what we want even if oscillations are non-unitary

TeV–PeV theoretically palatable regions

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

TeV–PeV theoretically palatable regions

2020



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Measurement: imprecise

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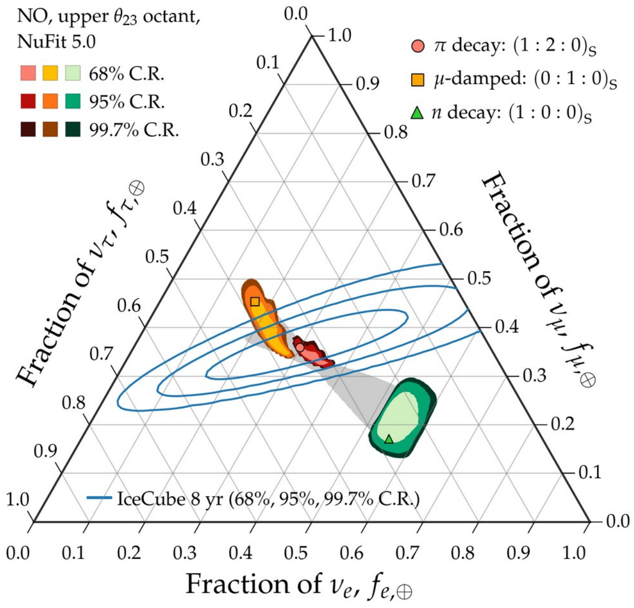

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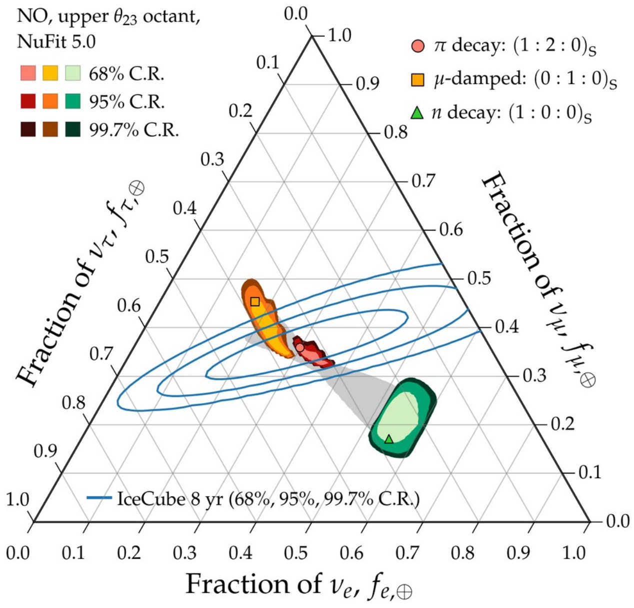
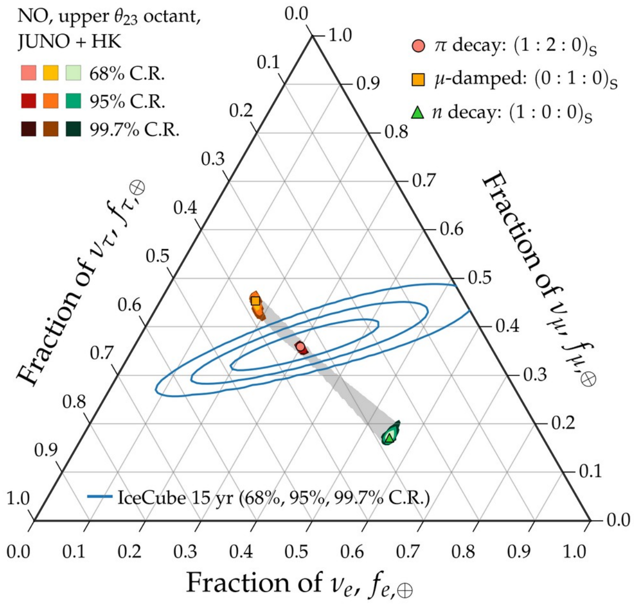


2030



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Allowed regions: well separated
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Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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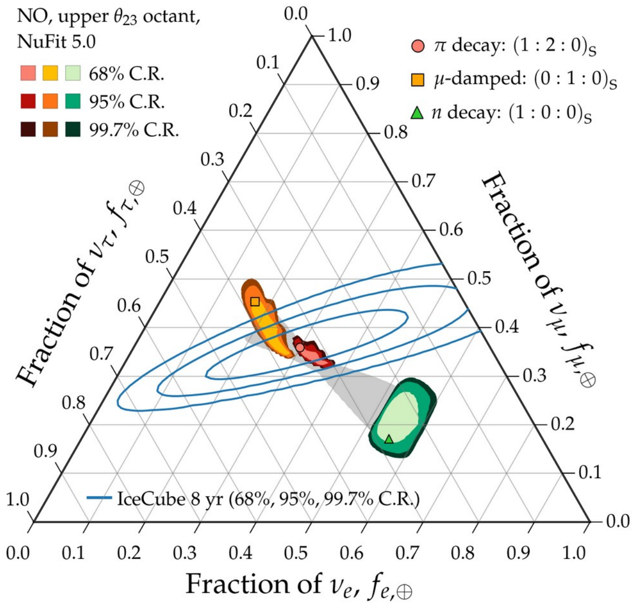

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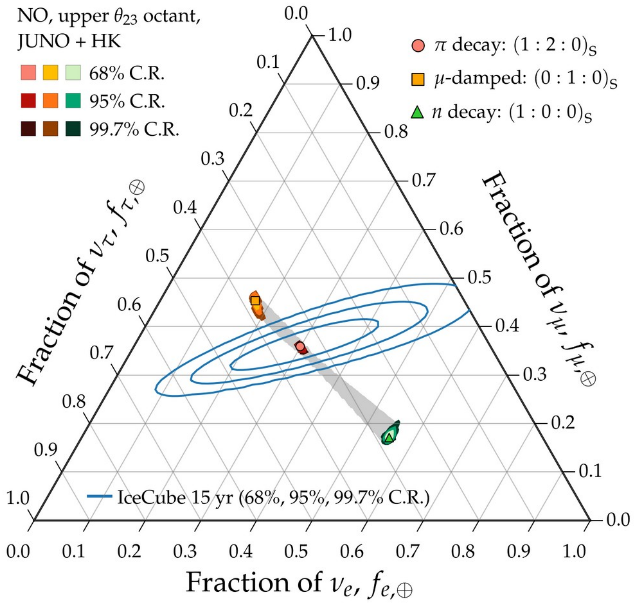

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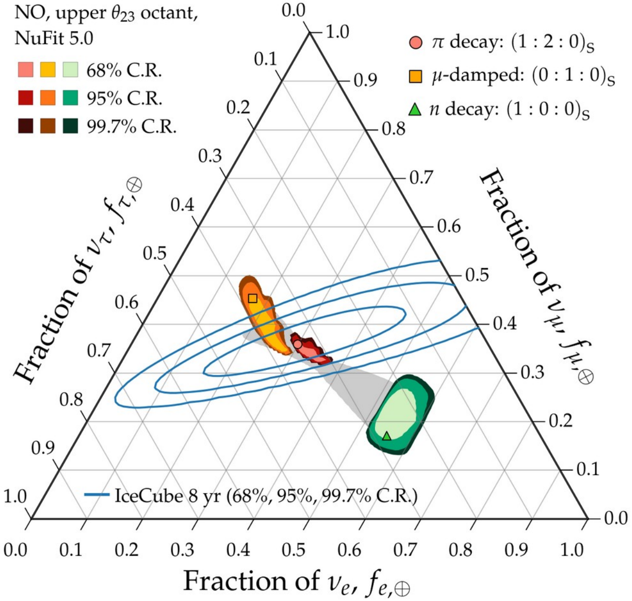

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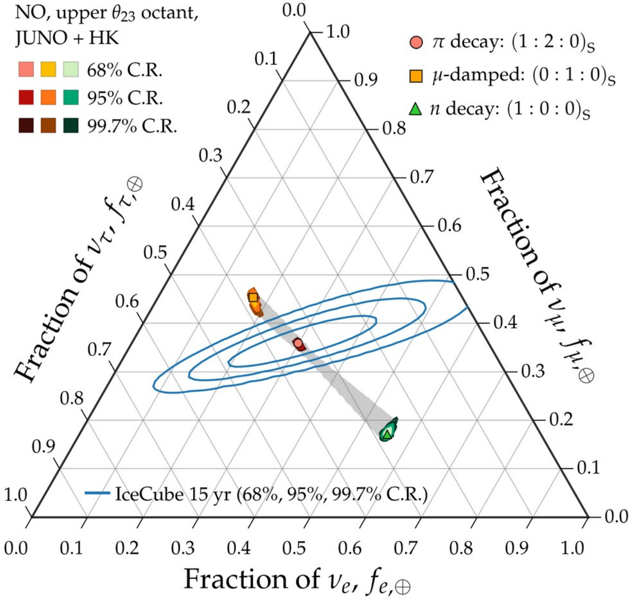

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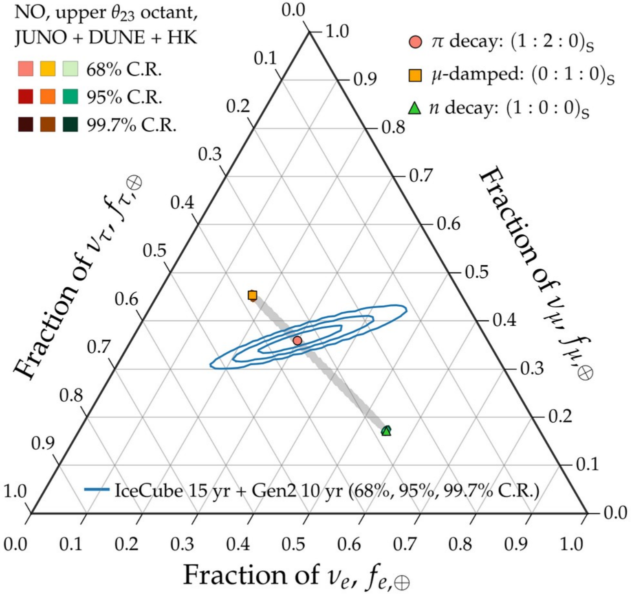

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Measurement: precise

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

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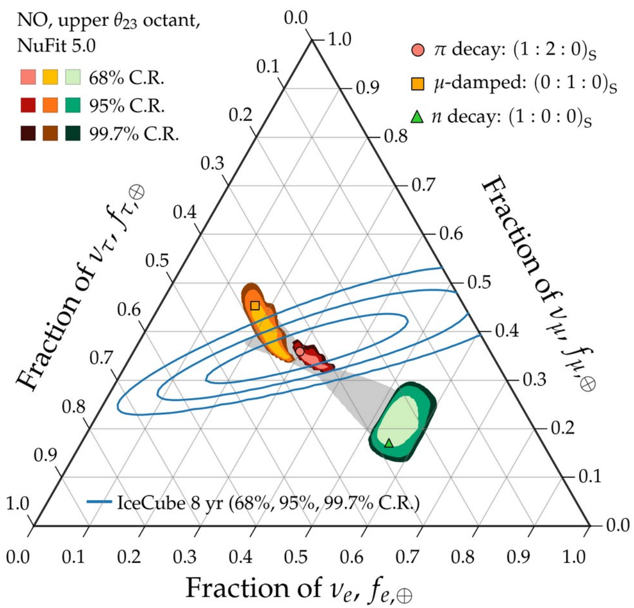

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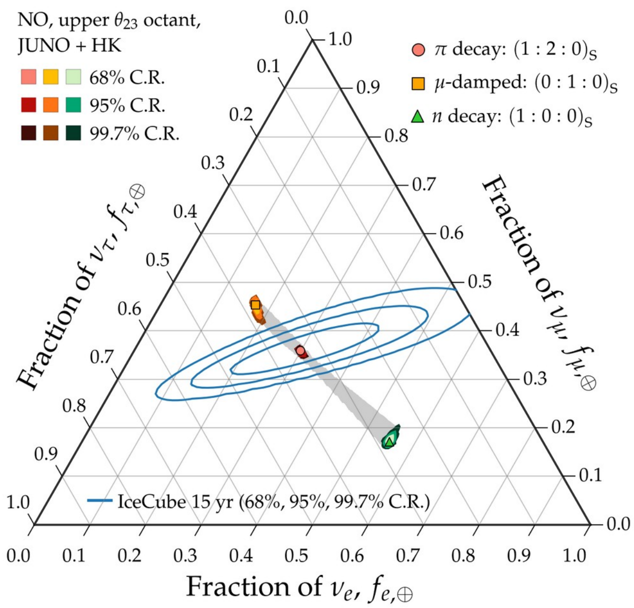

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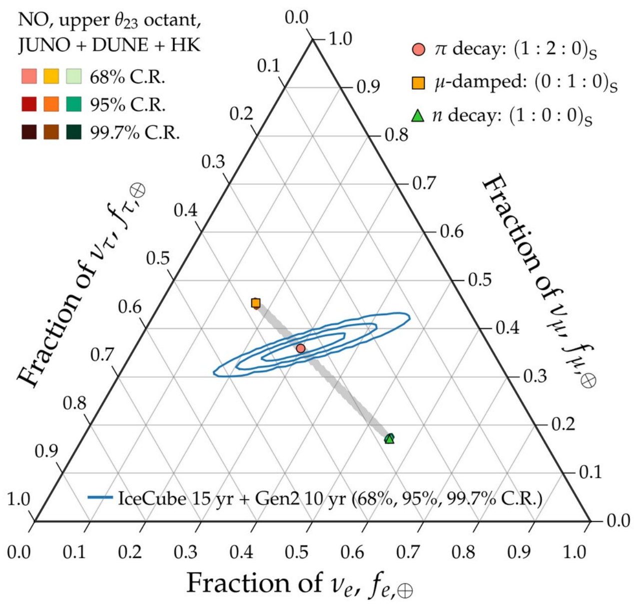

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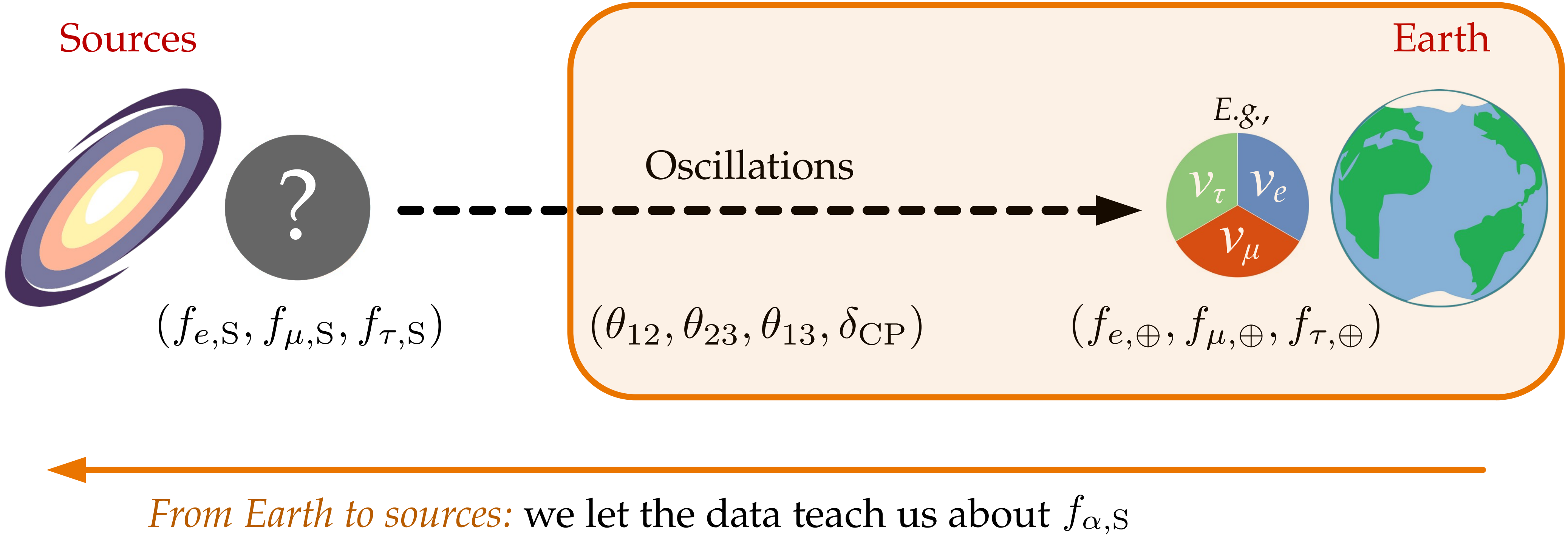
Success

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021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From Earth to sources: we let the data teach us about $f_{\alpha,\mathrm{S}}$

Inferring the flavor composition at the sources

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

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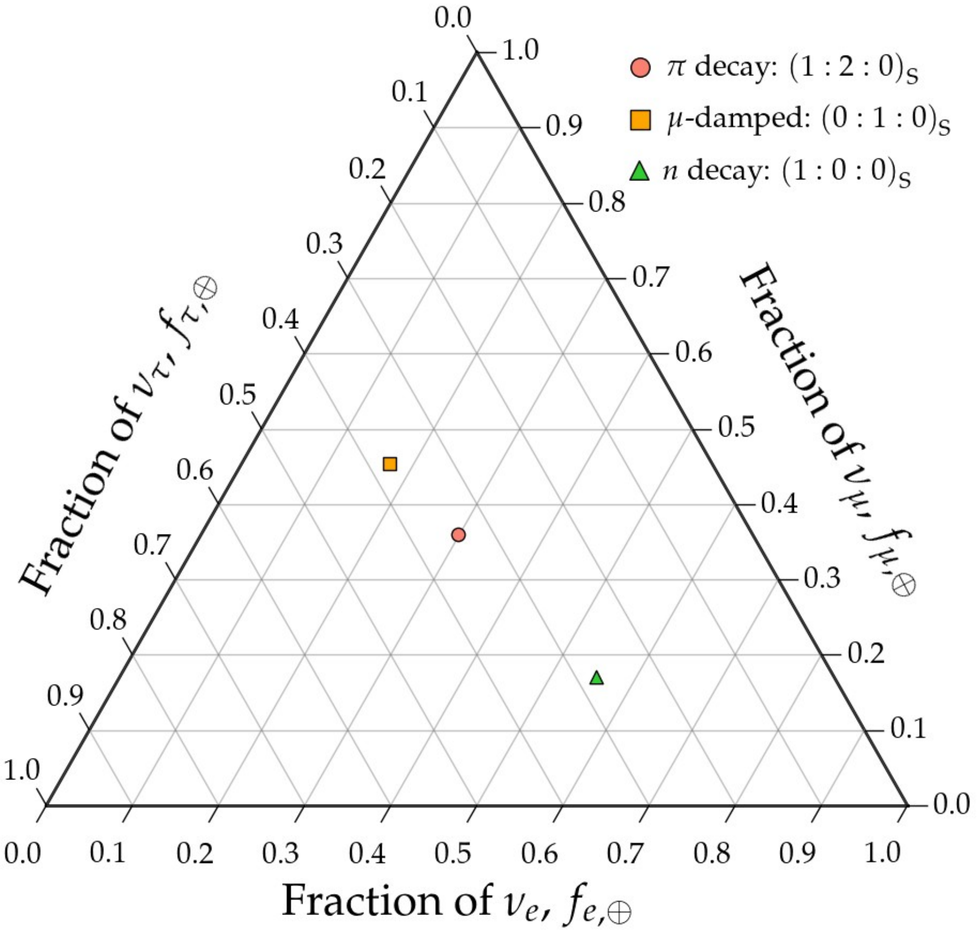
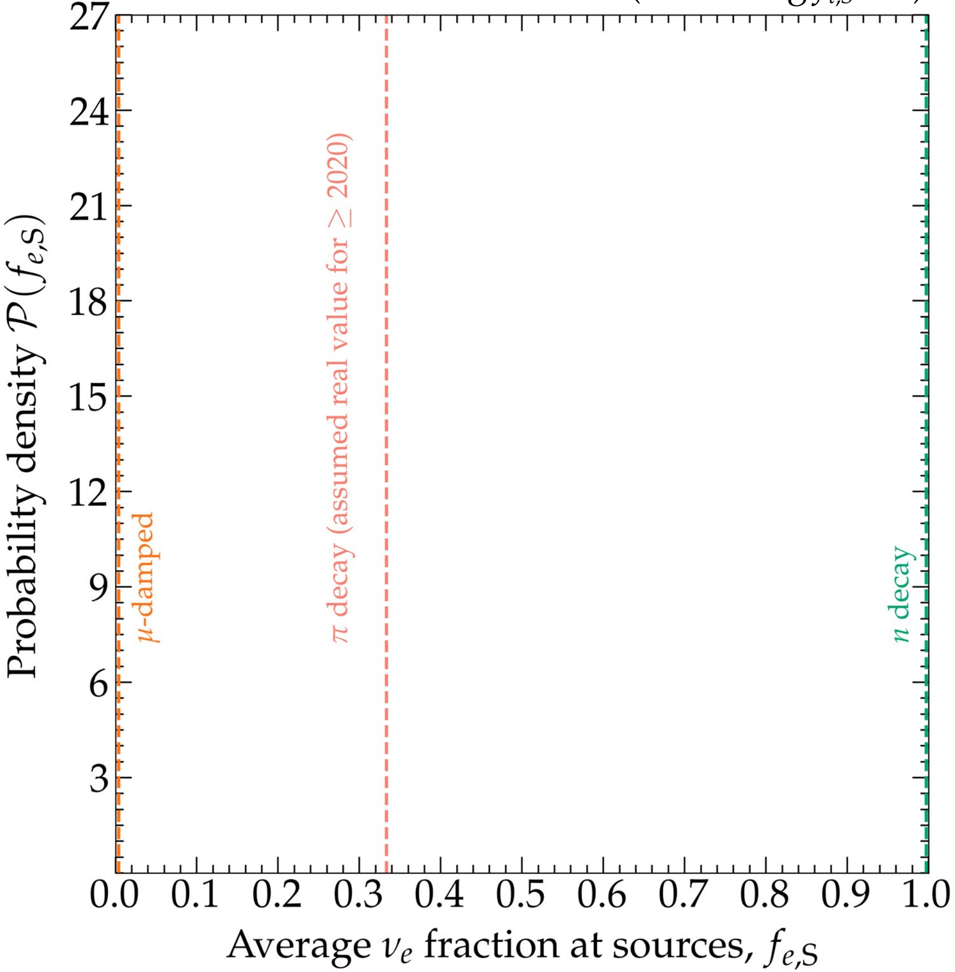


(Assuming $f_{\tau,S} = 0$)



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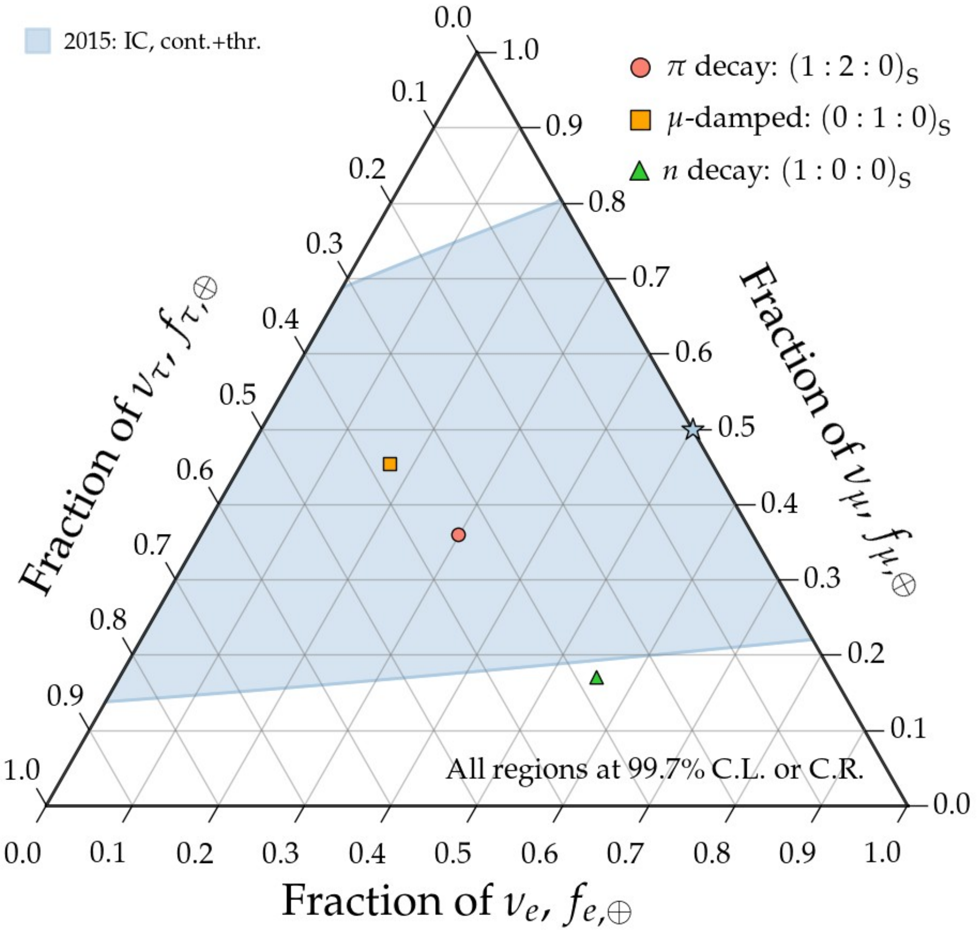

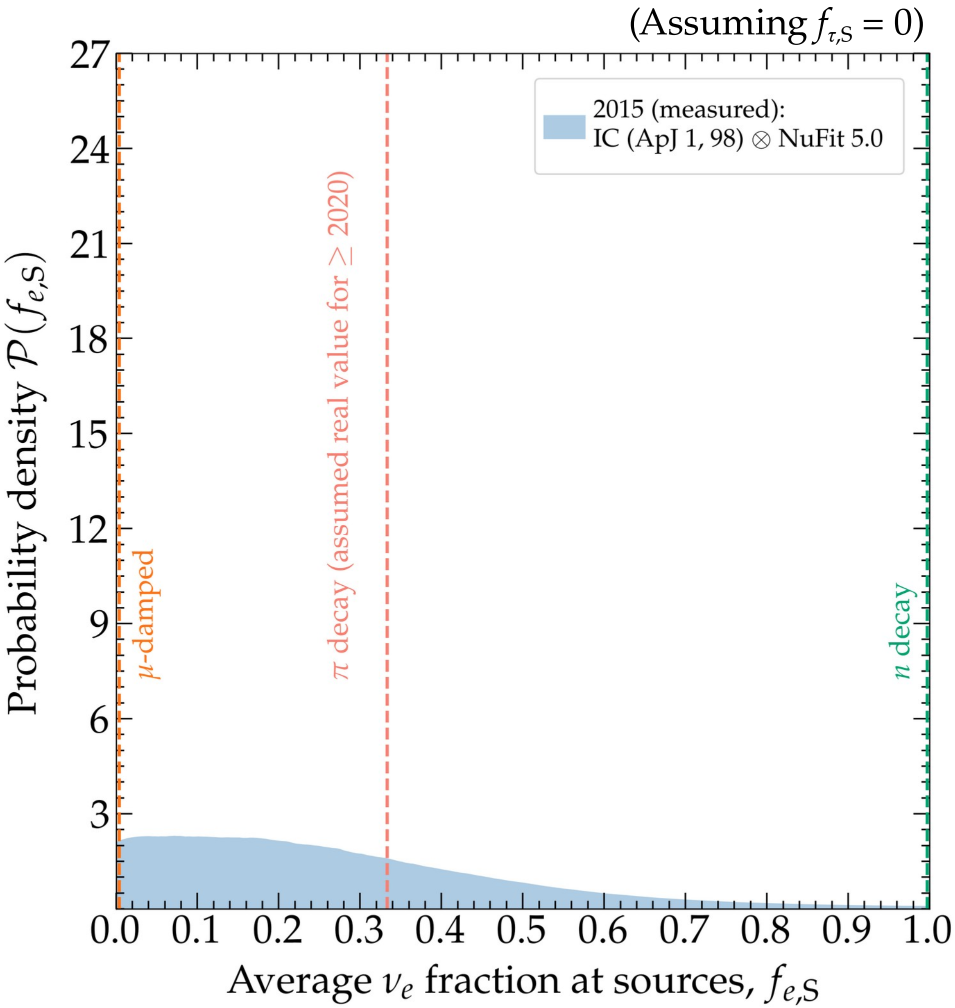

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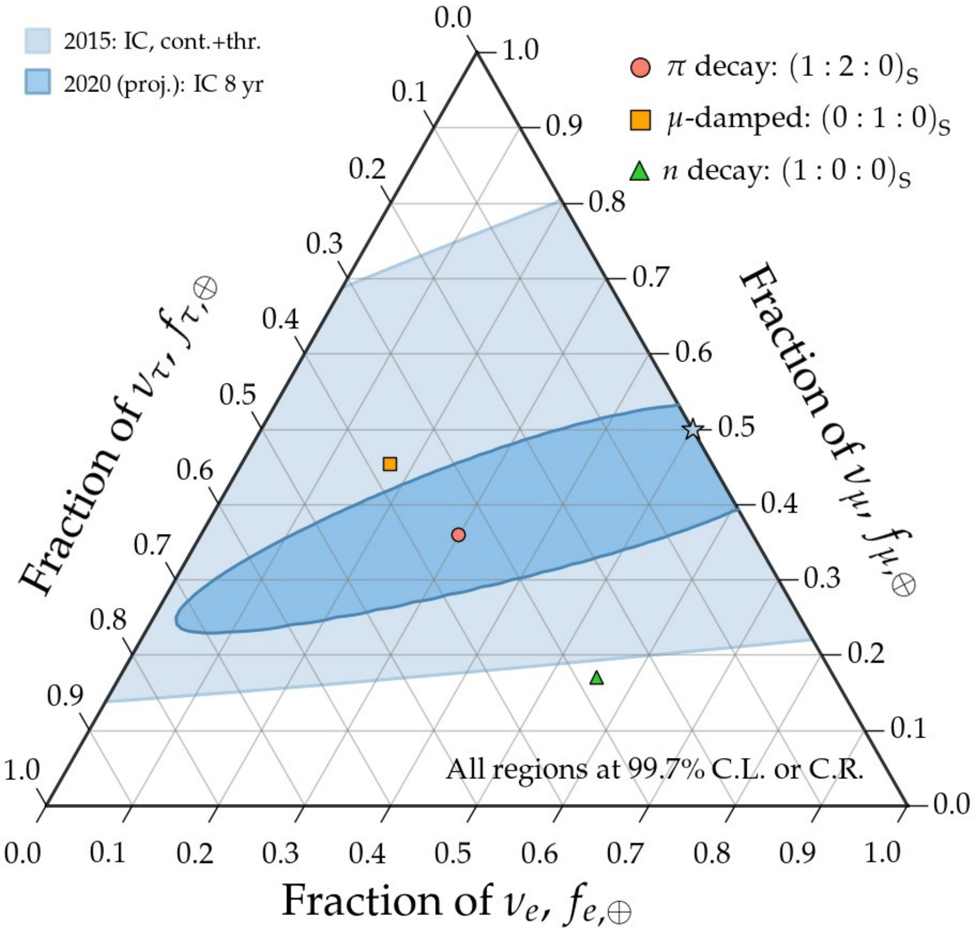

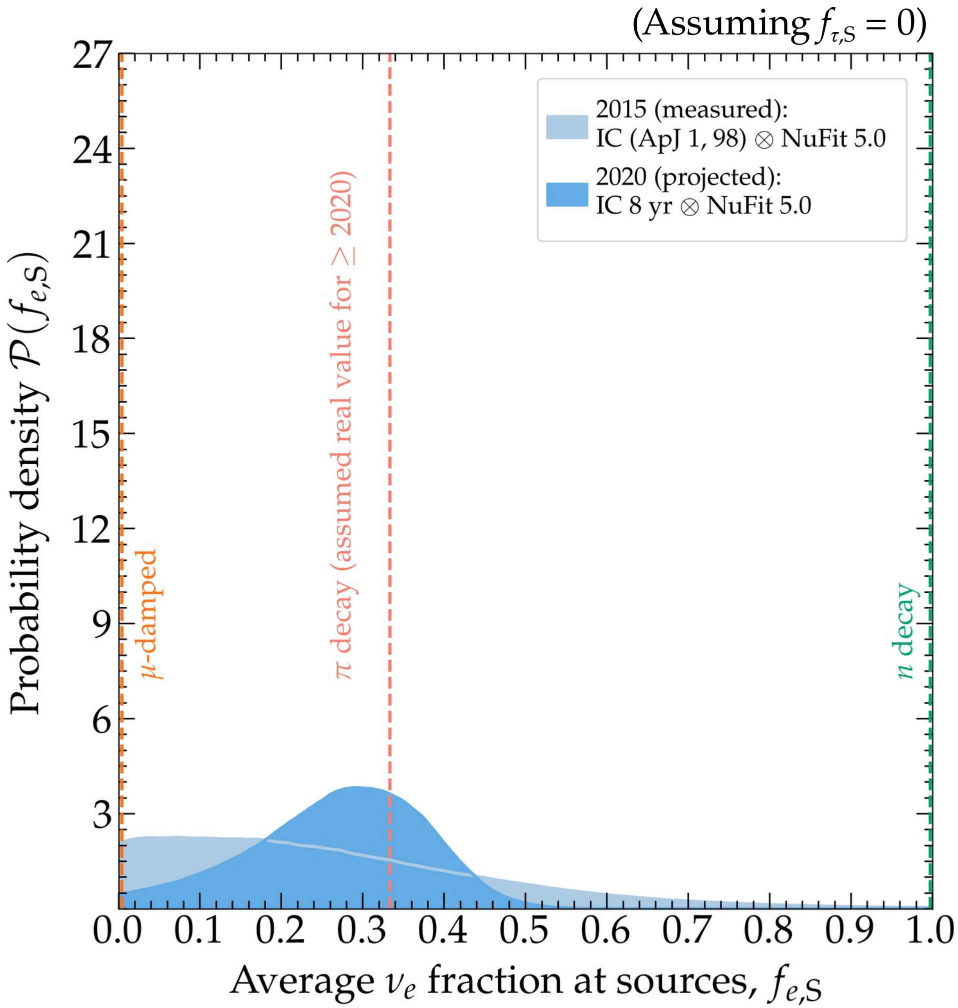

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
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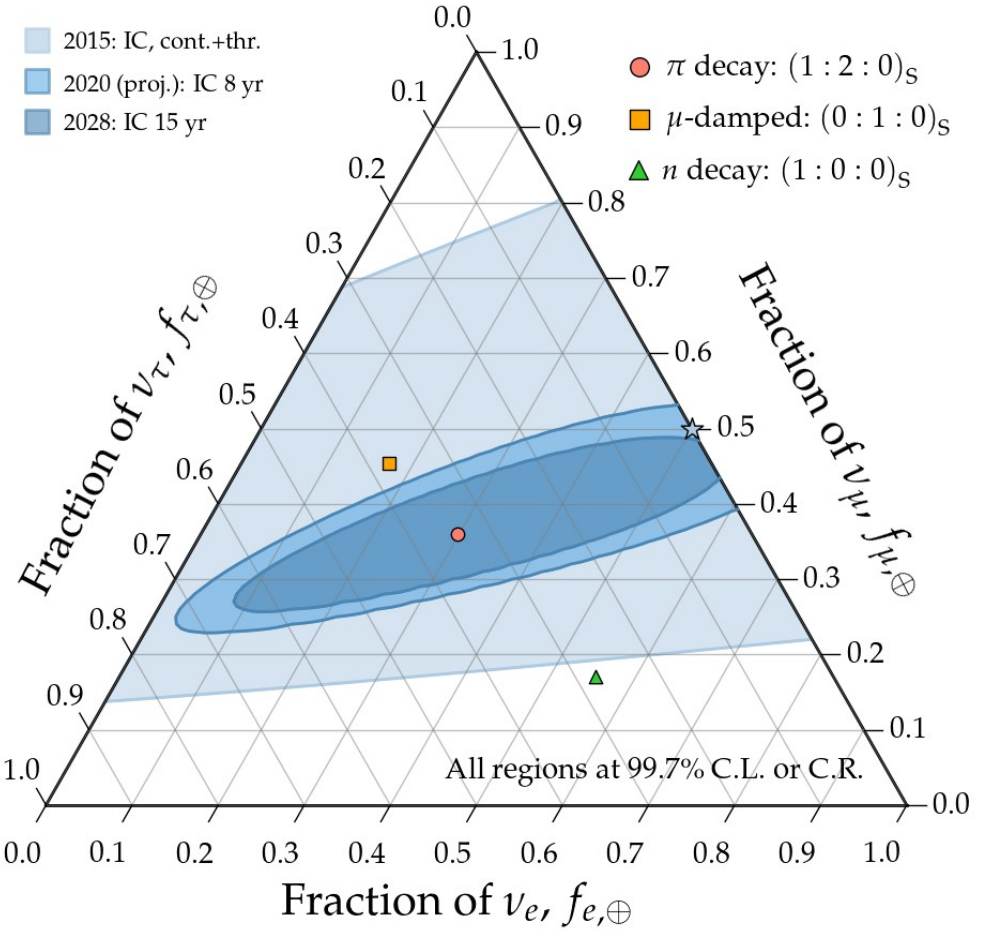

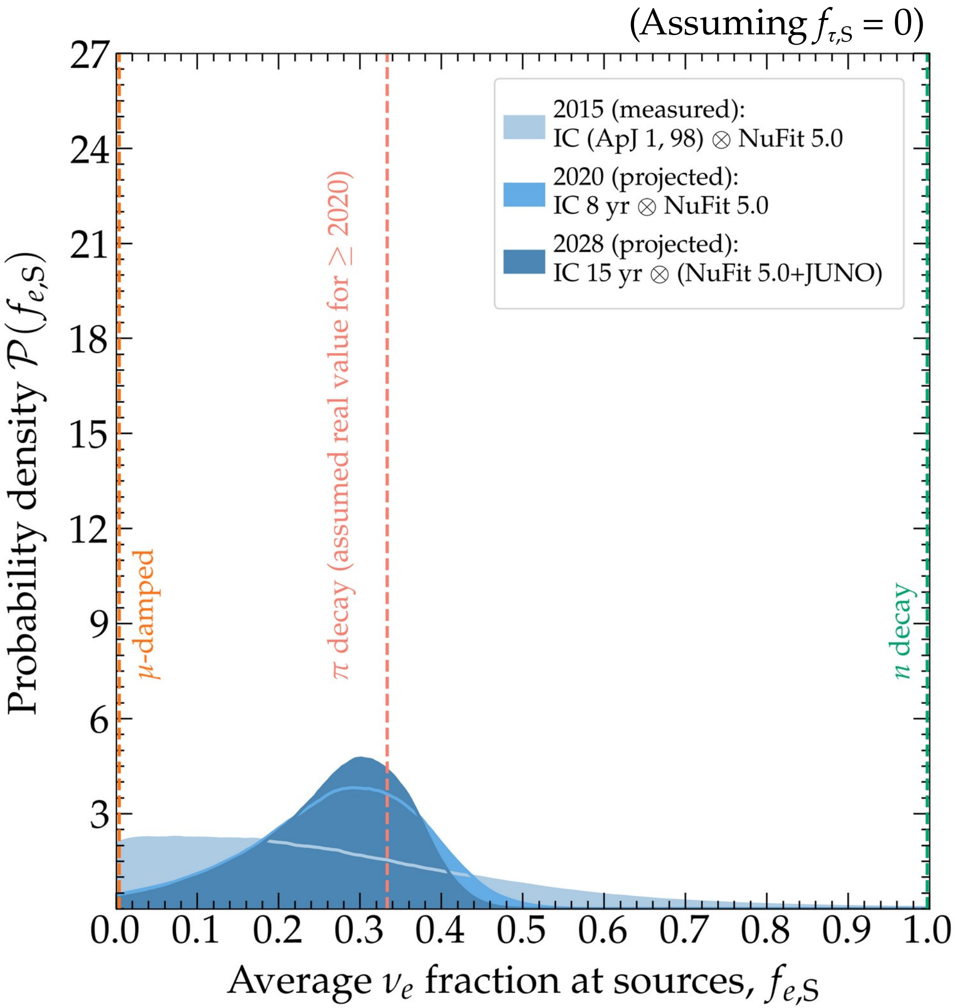

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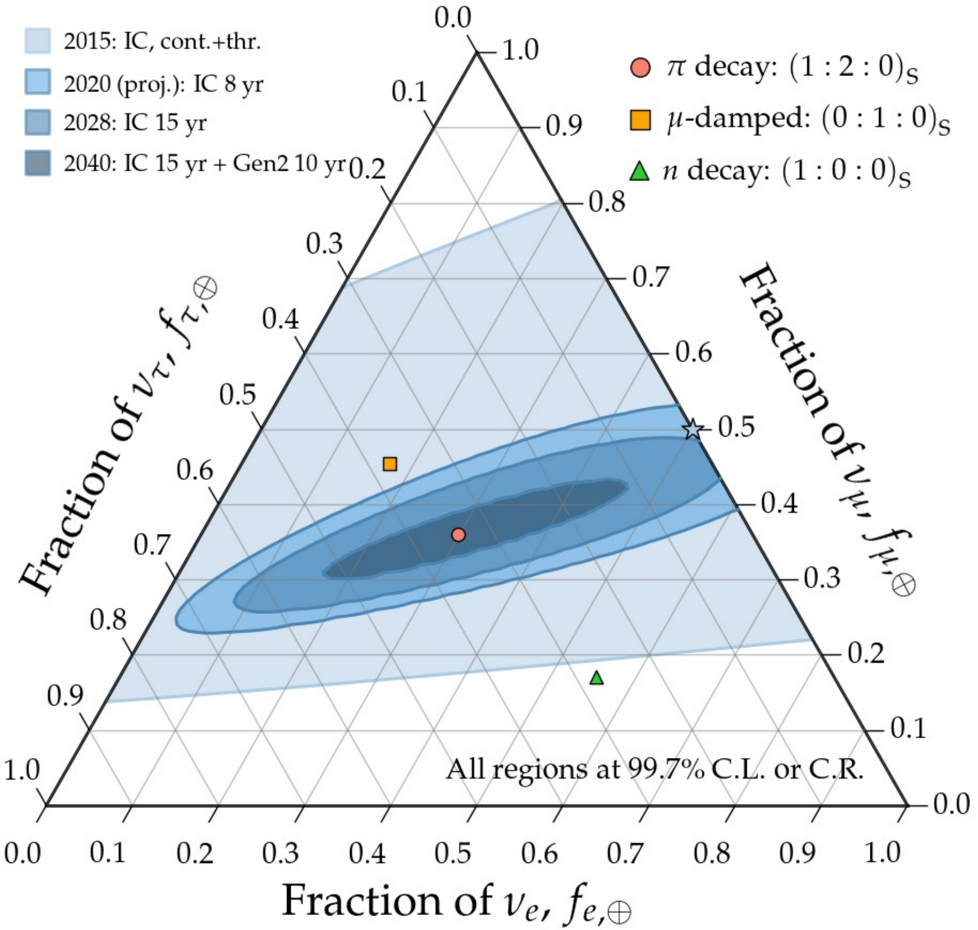
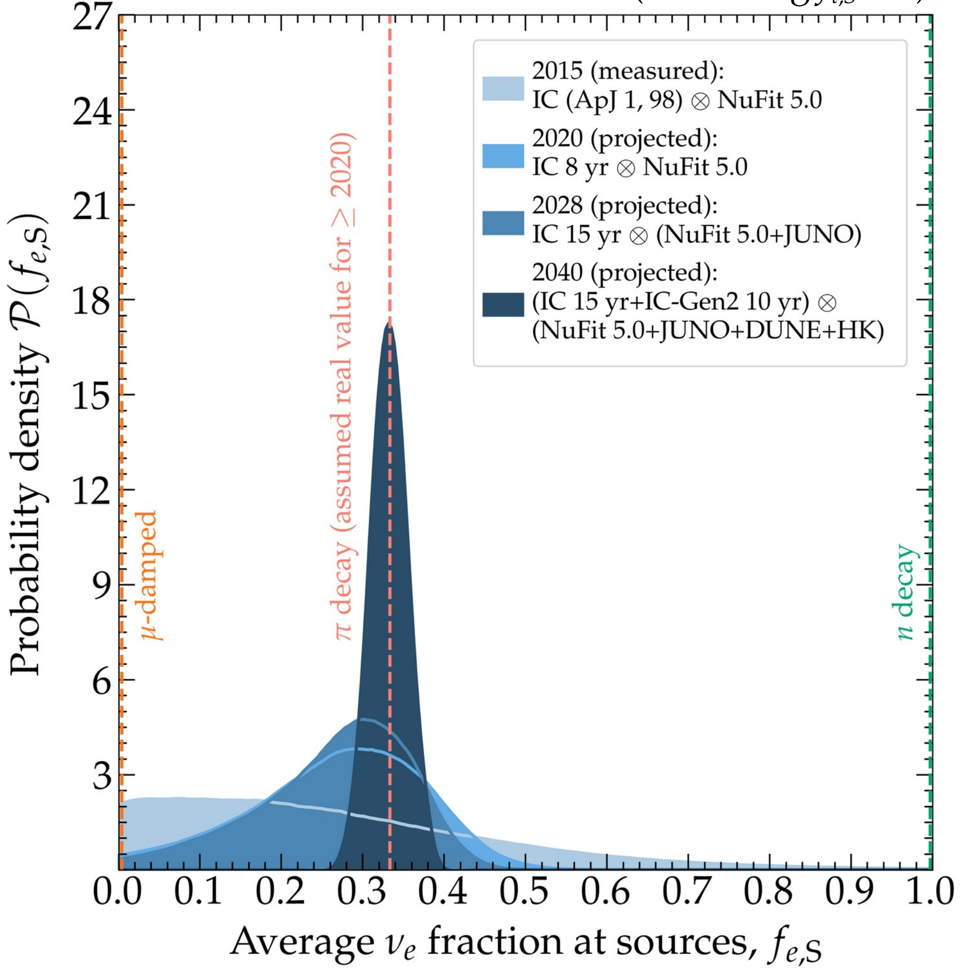


(Assuming $f_{\tau,S} = 0$)



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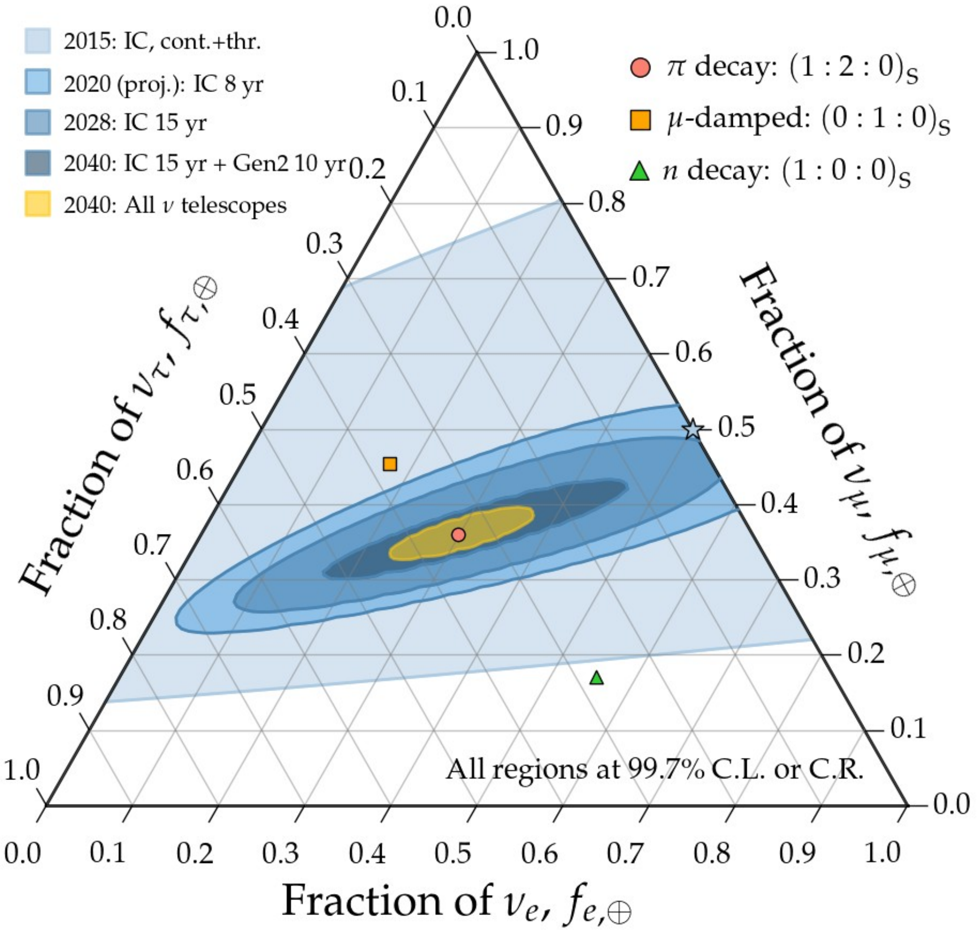

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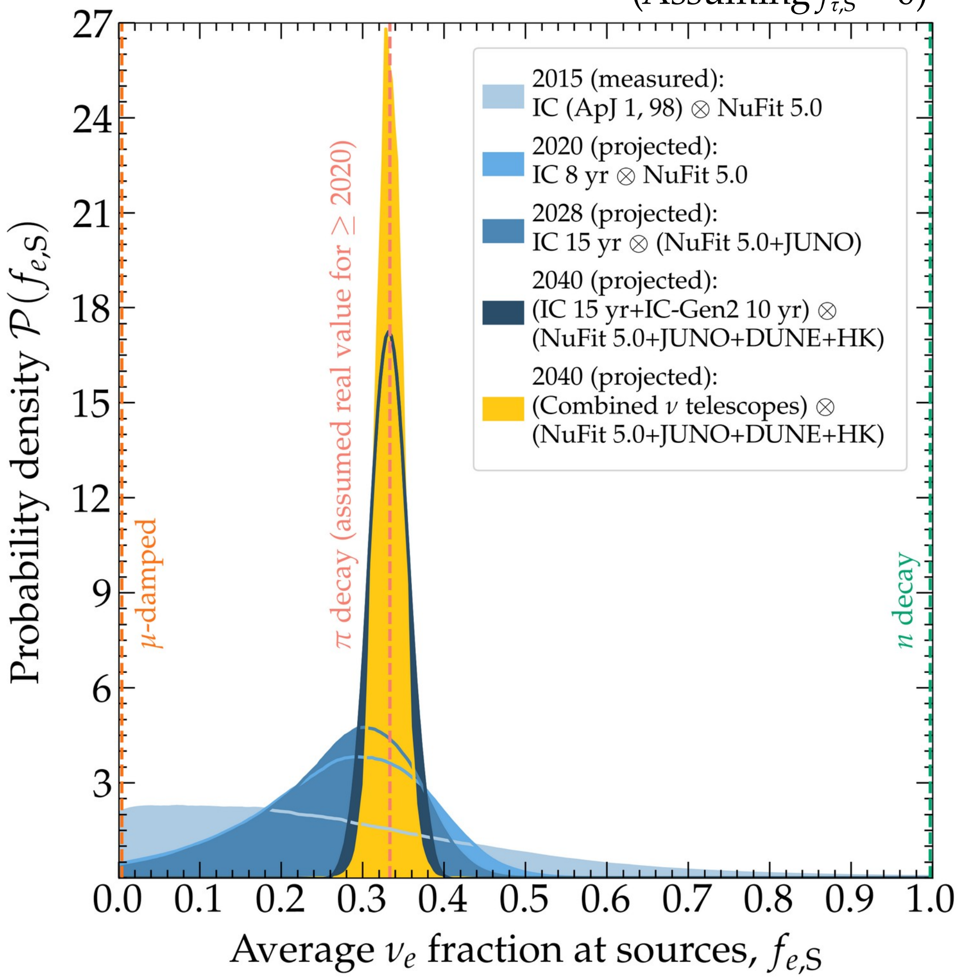

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New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

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Reviews:
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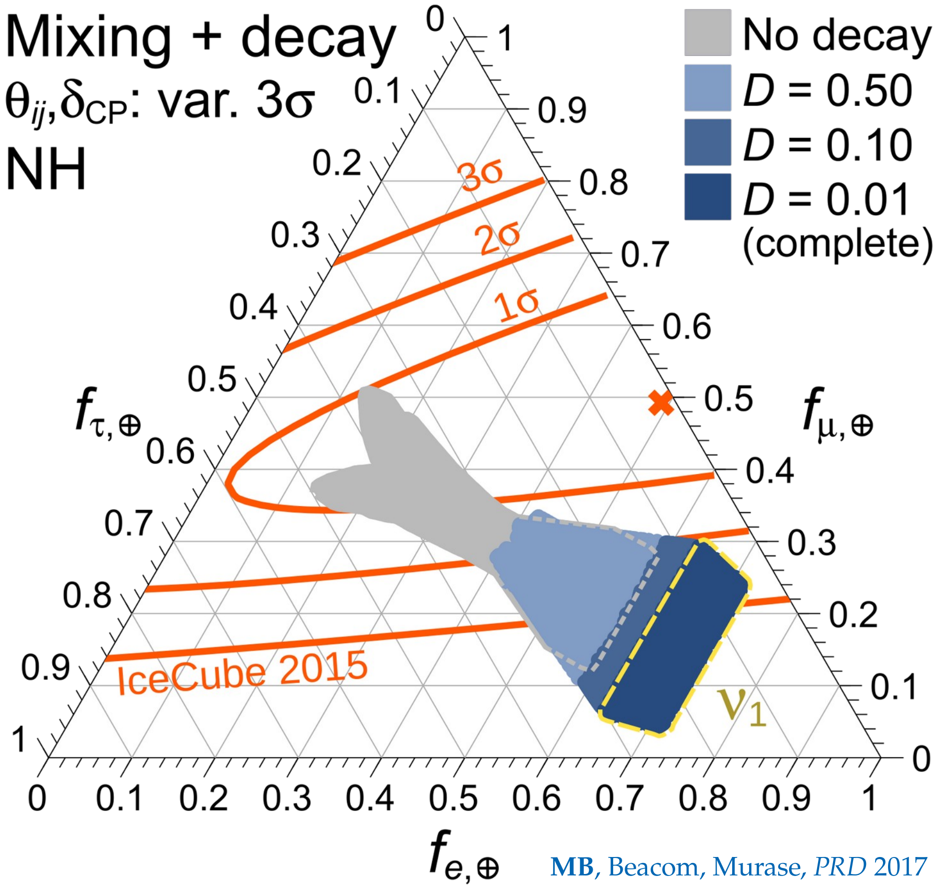

MB, Beacom, Murase, *PRD* 2017

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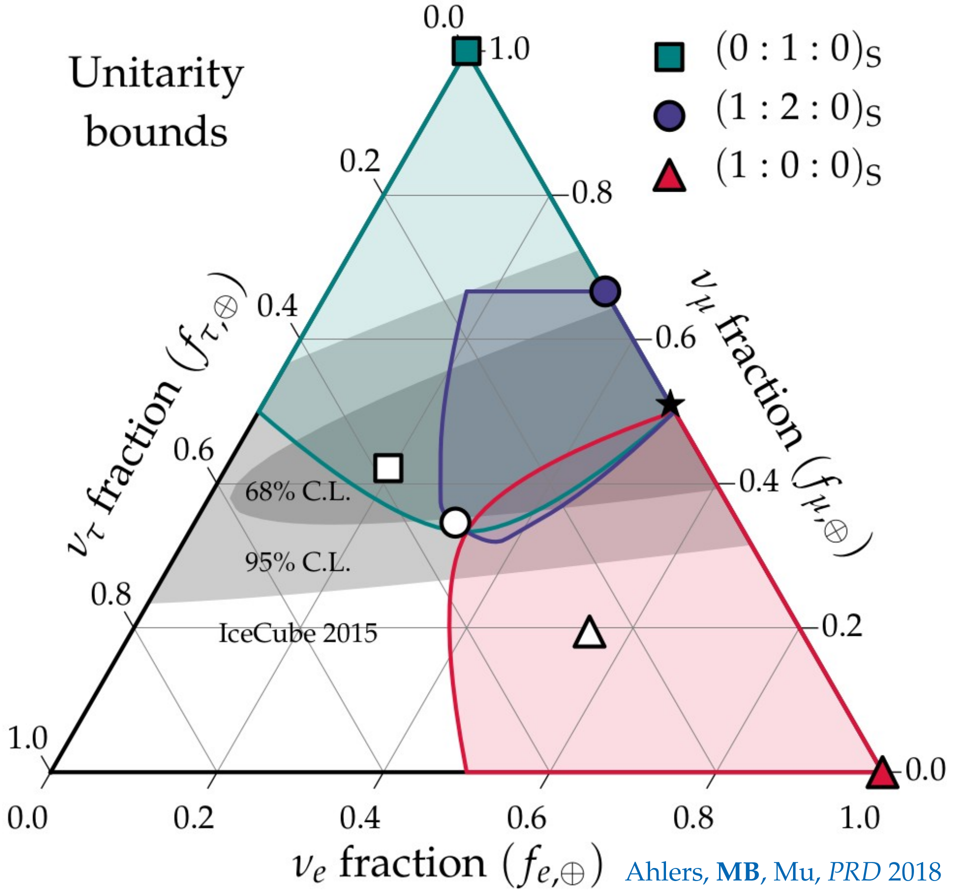

Ahlers, **MB**, Mu, *PRD* 2018

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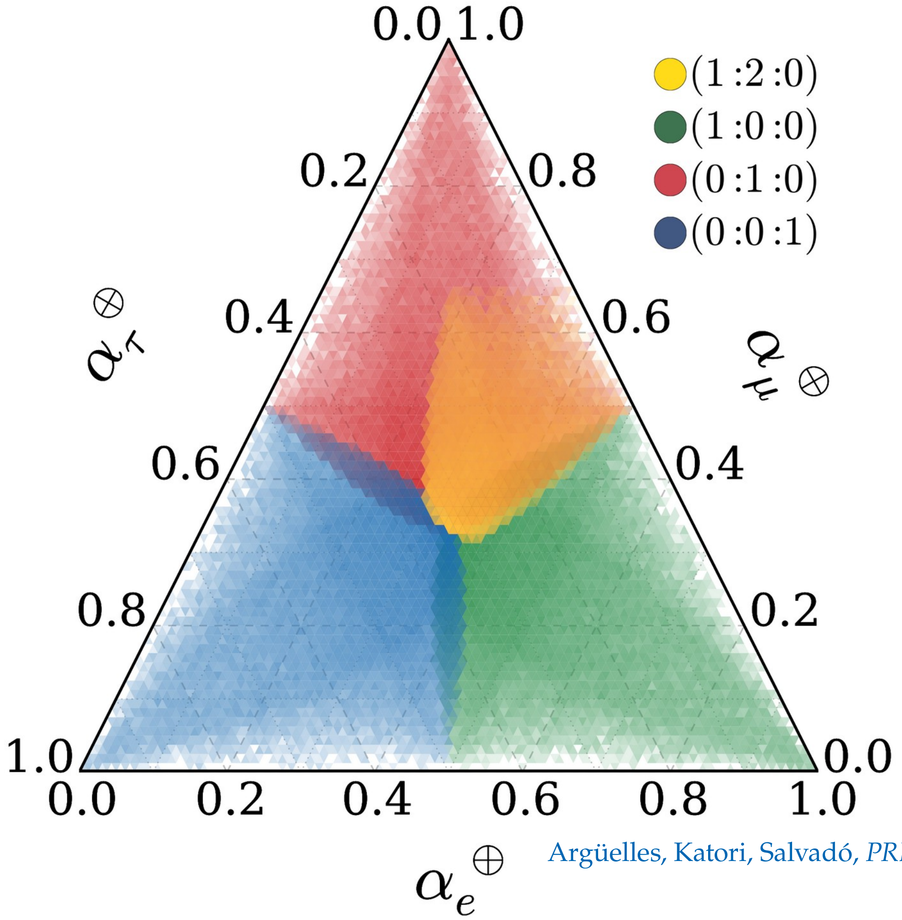

Argüelles, Katori, Salvadó, *PRL* 2015

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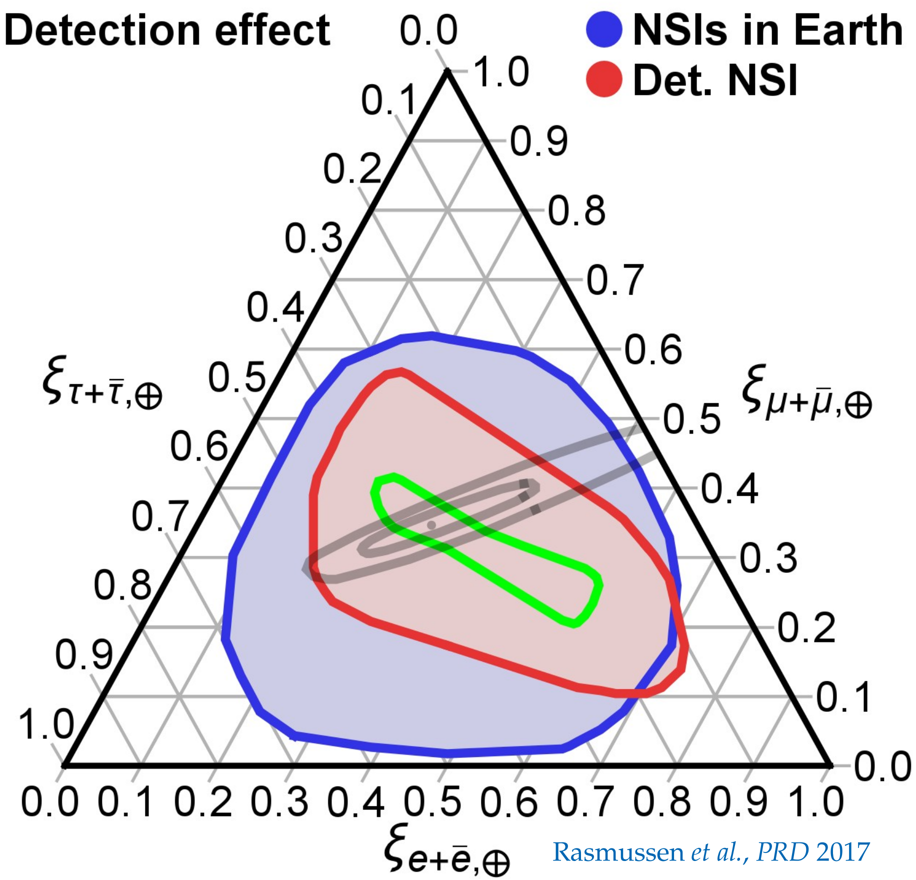

Rasmussen *et al.*, *PRD* 2017

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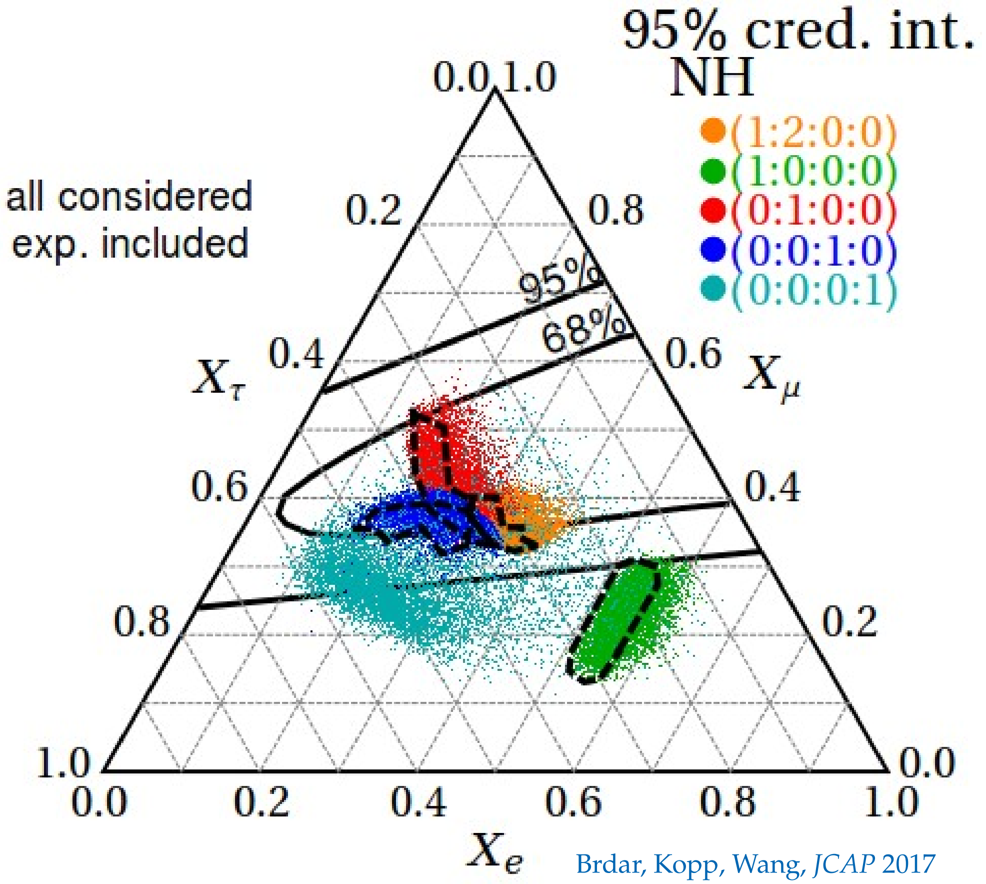

Brdar, Kopp, Wang, *JCAP* 2017

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

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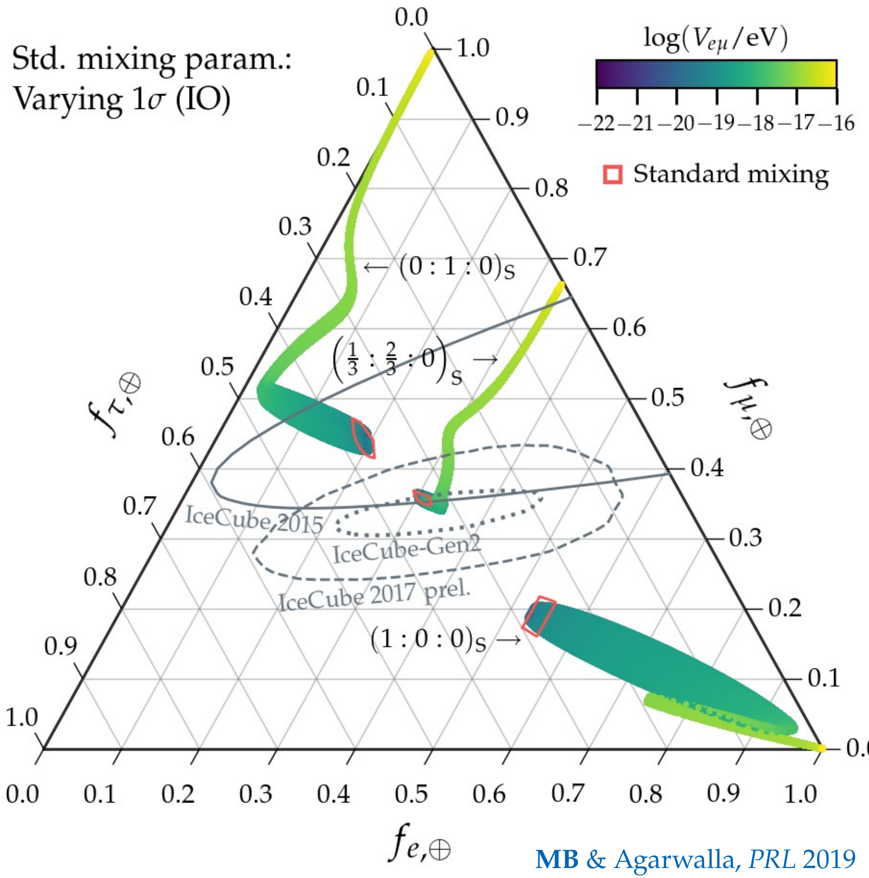

MB & Agarwalla, *PRL* 2019

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  Ahlers, **MB**, No
- Lorentz- a
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  Kostelecky & M
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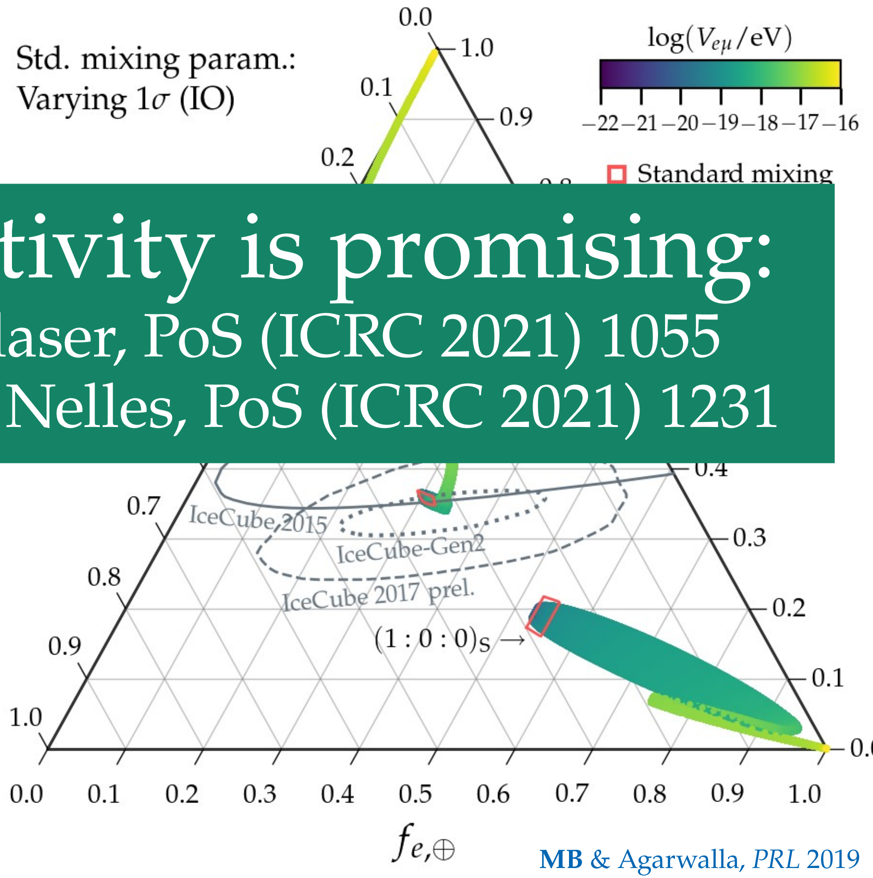


MB & Agarwalla, *PRL* 2019

UHE flavor sensitivity is promising:
Stjärnholm, Ericsson, Glaser, PoS (ICRC 2021) 1055
Glaser, García-Fernández, Nelles, PoS (ICRC 2021) 1231

Open questions / to-do

Event-rate predictions for other detectors of UHE ν?

Just need the effective volumes

Event rates from transient emission of UHE ν?

What should we expect for benchmark fluences?

BSM studies using transient emission of UHE ν?

Severely underdeveloped forecasts

Can we tell apart cosmogenic vs. source UHE ν diffuse fluxes?

Can we use the spectral shape? Flavor composition? Both seem unlikely

Realistic prospects for flavor studies at UHE?

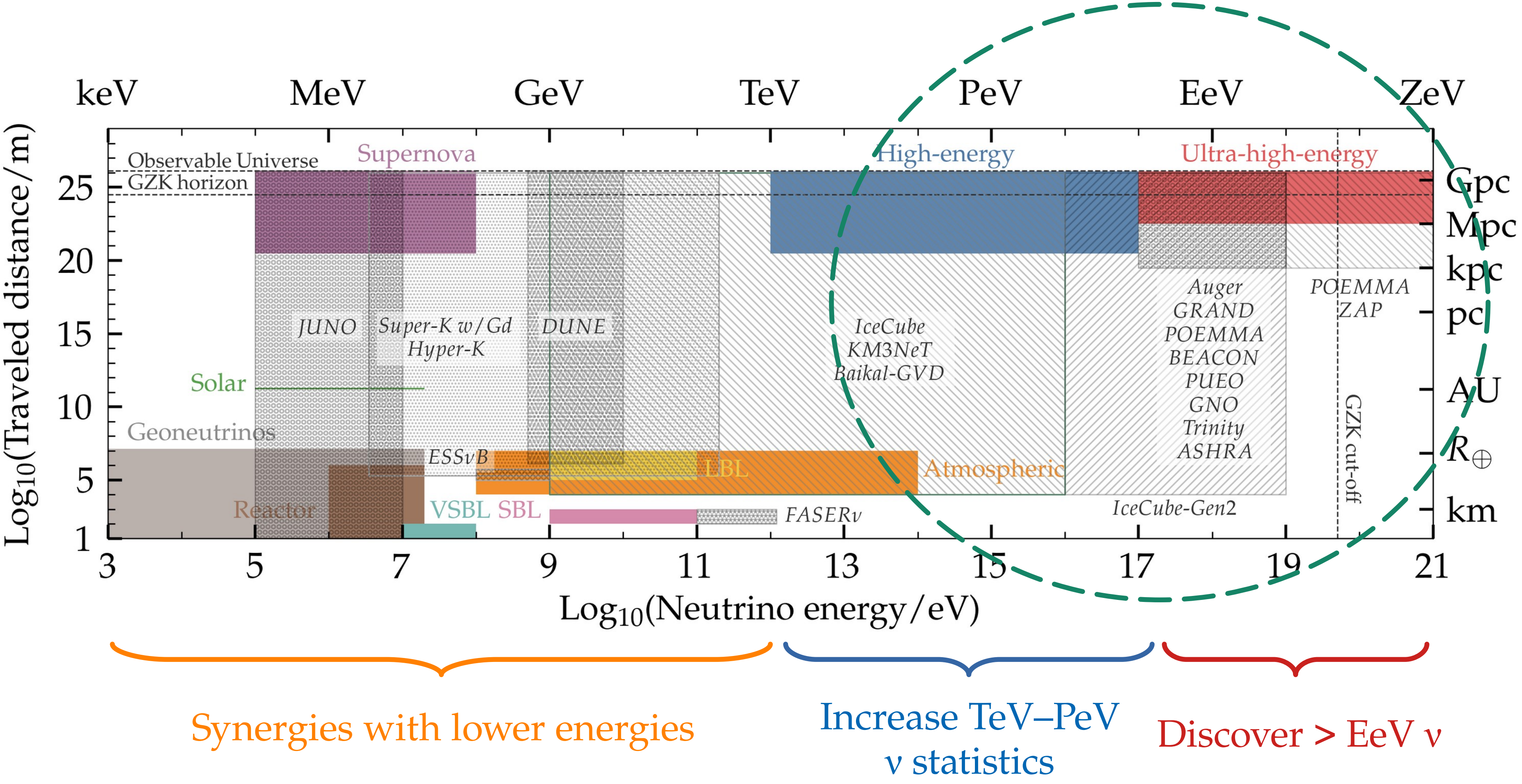
Can we measure the UHE flavor ratios? With what precision? What do we learn from them?

What would you like to test?

End

Backup slides

Next decade: a host of planned neutrino detectors



MB *et al.*, Snowmass 20201 Letter of interest

Real event rate

$$\frac{d^3 N_{\nu_\alpha}^{\mathrm{CC}}}{dE_\nu dy d\cos\theta_z} = 2\pi T N_{\mathrm{Av}} \frac{\rho_{\mathrm{ice}}}{M_{\mathrm{ice}}} V_{\mathrm{eff},\nu_\alpha}^{\mathrm{CC}}(E_\nu, \cos\theta_z) \frac{d\sigma_{\nu N}^{\mathrm{CC}}(E_\nu, y)}{dy} \Phi_{\nu_\alpha}^{\mathrm{det}}(E_\nu, \cos\theta_z)$$

Real event rate

Number of target nucleons

$$\frac{d^3 N_{\nu_\alpha}^{\rm CC}}{dE_\nu \, dy \, d\cos\theta_z} = 2\pi T \overbrace{N_{\rm Av} \frac{\rho_{\rm ice}}{M_{\rm ice}}}^{\text{Number of target nucleons}} V_{\text{eff},\nu_\alpha}^{\rm CC}(E_\nu, \cos\theta_z) \frac{d\sigma_{\nu N}^{\rm CC}(E_\nu, y)}{dy} \Phi_{\nu_\alpha}^{\rm det}(E_\nu, \cos\theta_z)$$

Real event rate

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Real event rate

$$\frac{d^3 N_{\nu_\alpha}^{\mathrm{CC}}}{dE_\nu\, dy\, d\cos\theta_z} = 2\pi T \underbrace{N_{\mathrm{Av}} \frac{\rho_{\mathrm{ice}}}{M_{\mathrm{ice}}}}_{\text{Number of target nucleons}} \underbrace{V_{\mathrm{eff},\nu_\alpha}^{\mathrm{CC}}(E_\nu, \cos\theta_z)}_{\text{Effective volume}} \frac{d\sigma_{\nu N}^{\mathrm{CC}}(E_\nu, y)}{dy} \underbrace{\Phi_{\nu_\alpha}^{\mathrm{det}}(E_\nu, \cos\theta_z)}_{\text{Flux at detector}}$$

Real event rate

$$\frac{d^3 N^{CC}_{\nu_\alpha}}{dE_\nu dy d\cos\theta_z} = 2\pi T \underbrace{N_{Av} \frac{\rho_{ice}}{M_{ice}}}_{\text{Number of target nucleons}} \underbrace{V^{CC}_{\text{eff},\nu_\alpha}(E_\nu, \cos\theta_z)}_{\text{Effective volume}} \underbrace{\frac{d\sigma^{CC}_{\nu N}(E_\nu, y)}{dy}}_{\text{Inelasticity distribution}} \underbrace{\Phi^{det}_{\nu_\alpha}(E_\nu, \cos\theta_z)}_{\text{Flux at detector}}$$

Real event rate

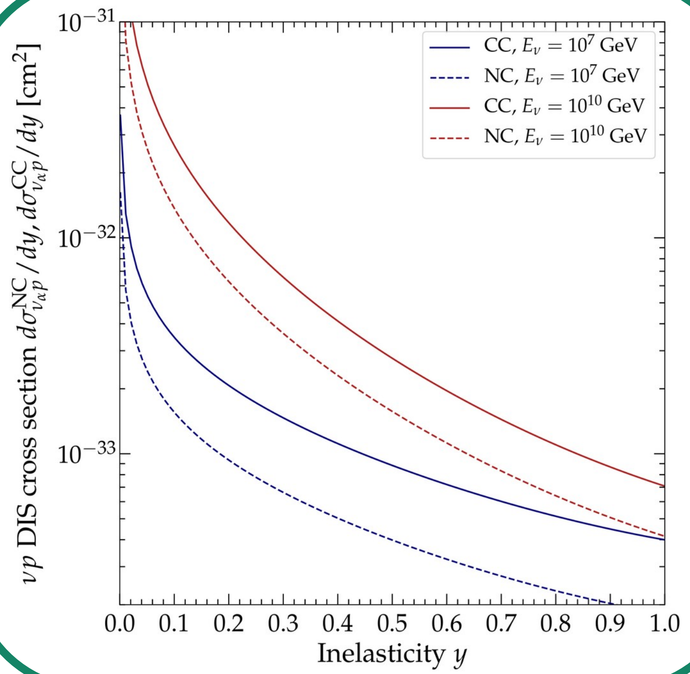
Number of target nucleons

Effective volume

$$\frac{d^3 N^{\mathrm{CC}}_{\nu_\alpha}}{dE_\nu dy d\cos\theta_z} = 2\pi T N_{\mathrm{Av}} \frac{\rho_{\mathrm{ice}}}{M_{\mathrm{ice}}} V^{\mathrm{CC}}_{\mathrm{eff},\nu_\alpha}(E_\nu, \cos\theta_z) \frac{d\sigma^{\mathrm{CC}}_{\nu N}(E_\nu, y)}{dy} \Phi^{\mathrm{det}}_{\nu_\alpha}(E_\nu, \cos\theta_z)$$

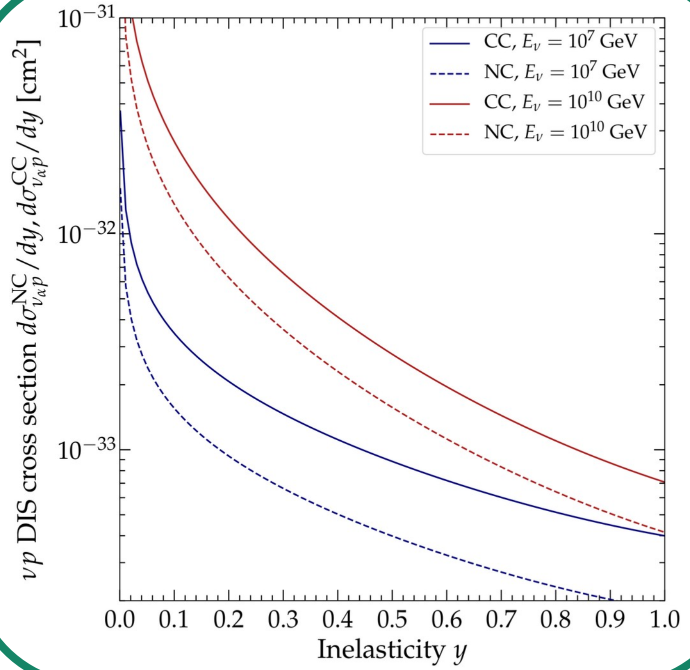
Inelasticity distribution

Flux at detector



Real event rate

$$\frac{d^3 N_{\nu_\alpha}^{\mathrm{CC}}}{dE_\nu dy d\cos\theta_z} = 2\pi T \underbrace{N_{\mathrm{Av}} \frac{\rho_{\mathrm{ice}}}{M_{\mathrm{ice}}}}_{\text{Number of target nucleons}} \underbrace{V_{\mathrm{eff},\nu_\alpha}^{\mathrm{CC}}(E_\nu, \cos\theta_z)}_{\text{Effective volume}} \underbrace{\frac{d\sigma_{\nu N}^{\mathrm{CC}}(E_\nu, y)}{dy}}_{\text{Inelasticity distribution}} \underbrace{\Phi_{\nu_\alpha}^{\mathrm{det}}(E_\nu, \cos\theta_z)}_{\text{Flux at detector}}$$



Use the BGR18 νN cross section during propagation and at detection

Detected event rate

Interaction → Shower → Detection

$\nu_l + N \to l + X$

Final-state particles (l, X) shower & emit radio

Shower energy is deposited in the detector

Real event rate

Detected event rate

Interaction → Shower → Detection

$$\nu_l + N \to l + X$$

Final-state particles (l, X) shower & emit radio

Shower energy is deposited in the detector

Neutrino energy:

E_ν

Real event rate

Detected event rate

Interaction → Shower → Detection

$\nu_l + N \to l + X$

Final-state particles (l, X) shower & emit radio

Shower energy is deposited in the detector

Neutrino energy:

E_ν

Shower energy:

$$E^i_{\mathrm{sh},\nu_\alpha}(E_\nu, y) = \begin{cases} yE_\nu, & \text{for } \nu_\alpha \text{ NC} \\ E_\nu, & \text{for } \nu_e \text{ CC} \\ yE_\nu, & \text{for } \nu_\mu \text{ and } \nu_\tau \text{ CC} \end{cases}$$

Real event rate

Detected event rate

Interaction → Shower → Detection

$\nu_l + N \to l + X$

Final-state particles (l, X) shower & emit radio

Shower energy is deposited in the detector

Neutrino energy:

Shower energy:

Deposited energy:

E_ν

$$E^i_{\mathrm{sh},\nu_\alpha}(E_\nu, y) = \begin{cases} yE_\nu, & \text{for } \nu_\alpha \text{ NC} \\ E_\nu, & \text{for } \nu_e \text{ CC} \\ yE_\nu, & \text{for } \nu_\mu \text{ and } \nu_\tau \text{ CC} \end{cases}$$

E_{dep}

Real event rate

Detected event rate

Interaction → Shower → Detection

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Final-state particles (l, X) shower & emit radio

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Neutrino energy:

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Deposited energy:

E_{dep}

$$\frac{d^3 N^{\mathrm{CC}}_{\nu_\alpha}}{dE_\nu dy d\cos\theta_z} \longrightarrow \frac{d^2 N^{\mathrm{CC}}_{\nu_\alpha}}{dE_{\mathrm{dep}} d\theta_{z,\mathrm{rec}}}$$

Real event rate → *Detected* event rate

Detected event rate

$$\frac{d^2 N_{\nu_\alpha}^{\rm CC}}{dE_{\rm dep} d\theta_{z,\rm rec}} = \int_{-1}^{+1} d\cos\theta_z \int_{E_{\rm dep}}^{\infty} dE_\nu \int_0^1 dy \frac{d^3 N_{\nu_\alpha}^{\rm CC}}{dE_\nu dy d\cos\theta_z} R_E[E_{\rm dep}, E_{{\rm sh},\nu_\alpha}^{\rm CC}(E_\nu, y)] R_{\theta_z}(\theta_{z,\rm rec}, \theta_z)$$

Detected event rate

Real
event rate

$$\frac{d^2 N_{\nu_\alpha}^{\rm CC}}{dE_{\rm dep} d\theta_{z,{\rm rec}}} = \int_{-1}^{+1} d\cos\theta_z \int_{E_{\rm dep}}^{\infty} dE_\nu \int_0^1 dy \underbrace{\frac{d^3 N_{\nu_\alpha}^{\rm CC}}{dE_\nu dy d\cos\theta_z}}_{\text{Real event rate}} R_E[E_{\rm dep}, E_{{\rm sh},\nu_\alpha}^{\rm CC}(E_\nu, y)] R_{\theta_z}(\theta_{z,{\rm rec}}, \theta_z)$$

Detected event rate

Real event rate

$$\frac{d^2 N_{\nu_\alpha}^{\rm CC}}{dE_{\rm dep} d\theta_{z,\rm rec}} = \int_{-1}^{+1} d\cos\theta_z \int_{E_{\rm dep}}^{\infty} dE_\nu \int_0^1 dy \underbrace{\overbrace{\frac{d^3 N_{\nu_\alpha}^{\rm CC}}{dE_\nu dy d\cos\theta_z}}^{\text{Real event rate}} R_E[E_{\rm dep}, E_{{\rm sh},\nu_\alpha}^{\rm CC}(E_\nu, y)]}_{\text{Energy resolution}} R_{\theta_z}(\theta_{z,\rm rec}, \theta_z)$$

Energy resolution

Detected event rate

Real
event rate

$$\frac{d^2 N^{CC}_{\nu_\alpha}}{dE_{dep} d\theta_{z,rec}} = \int_{-1}^{+1} d\cos\theta_z \int_{E_{dep}}^{\infty} dE_\nu \int_0^1 dy \frac{d^3 N^{CC}_{\nu_\alpha}}{dE_\nu dy d\cos\theta_z} R_E[E_{dep}, E^{CC}_{sh,\nu_\alpha}(E_\nu, y)] R_{\theta_z}(\theta_{z,rec}, \theta_z)$$

Energy
resolution

$$R_E(E_{dep}, E_{sh}) = \frac{2}{\sqrt{2\pi}\sigma_{E_{dep}}} e^{-\frac{(E_{dep}-E_{sh})^2}{2\sigma^2_{E_{dep}}}}$$

(Mismatch between shower and deposited energies)
Baseline: $\sigma_{\log_{10} E_{dep}} = 0.1$

Detected event rate

Real event rate

$$\frac{d^2 N^{\rm CC}_{\nu_\alpha}}{dE_{\rm dep} d\theta_{z,\rm rec}} = \int_{-1}^{+1} d\cos\theta_z \int_{E_{\rm dep}}^{\infty} dE_\nu \int_0^1 dy \underbrace{\frac{d^3 N^{\rm CC}_{\nu_\alpha}}{dE_\nu dy d\cos\theta_z}}_{\text{Real event rate}} \underbrace{R_E[E_{\rm dep}, E^{\rm CC}_{{\rm sh},\nu_\alpha}(E_\nu, y)]}_{\text{Energy resolution}} \underbrace{R_{\theta_z}(\theta_{z,\rm rec}, \theta_z)}_{\text{Angular resolution}}$$

Energy resolution

Angular resolution

$$R_E(E_{\rm dep}, E_{\rm sh}) = \frac{2}{\sqrt{2\pi}\sigma_{E_{\rm dep}}} e^{-\frac{(E_{\rm dep}-E_{\rm sh})^2}{2\sigma^2_{E_{\rm dep}}}}$$

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Energy resolution

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Baseline: $\sigma_{\log_{10} E_{\rm dep}} = 0.1$

$$R_{\theta_z}(\theta_{z,\rm rec}, \theta_z) = \frac{1}{\sqrt{2\pi}\sigma_{\theta_z}} e^{-\frac{(\theta_{z,\rm rec}-\theta_z)^2}{2\sigma^2_{\theta_z}}}$$

(Mismatch between real and reconstructed directions)

Baseline: $\theta_{z,\rm rec} = 2°$

Detected event rate

Contribution from all values of real direction & energy, and inelasticity

Real event rate

$$\frac{d^2 N^{CC}_{\nu_\alpha}}{dE_{dep} d\theta_{z,rec}} = \int_{-1}^{+1} d\cos\theta_z \int_{E_{dep}}^{\infty} dE_\nu \int_0^1 dy \frac{d^3 N^{CC}_{\nu_\alpha}}{dE_\nu dy d\cos\theta_z} R_E[E_{dep}, E^{CC}_{sh,\nu_\alpha}(E_\nu, y)] R_{\theta_z}(\theta_{z,rec}, \theta_z)$$

Energy resolution

Angular resolution

$$R_E(E_{dep}, E_{sh}) = \frac{2}{\sqrt{2\pi}\sigma_{E_{dep}}} e^{-\frac{(E_{dep}-E_{sh})^2}{2\sigma^2_{E_{dep}}}}$$

(Mismatch between shower and deposited energies)

Baseline: $\sigma_{\log_{10} E_{dep}} = 0.1$

$$R_{\theta_z}(\theta_{z,rec}, \theta_z) = \frac{1}{\sqrt{2\pi}\sigma_{\theta_z}} e^{-\frac{(\theta_{z,rec}-\theta_z)^2}{2\sigma^2_{\theta_z}}}$$

(Mismatch between real and reconstructed directions)

Baseline: $\theta_{z,rec} = 2°$

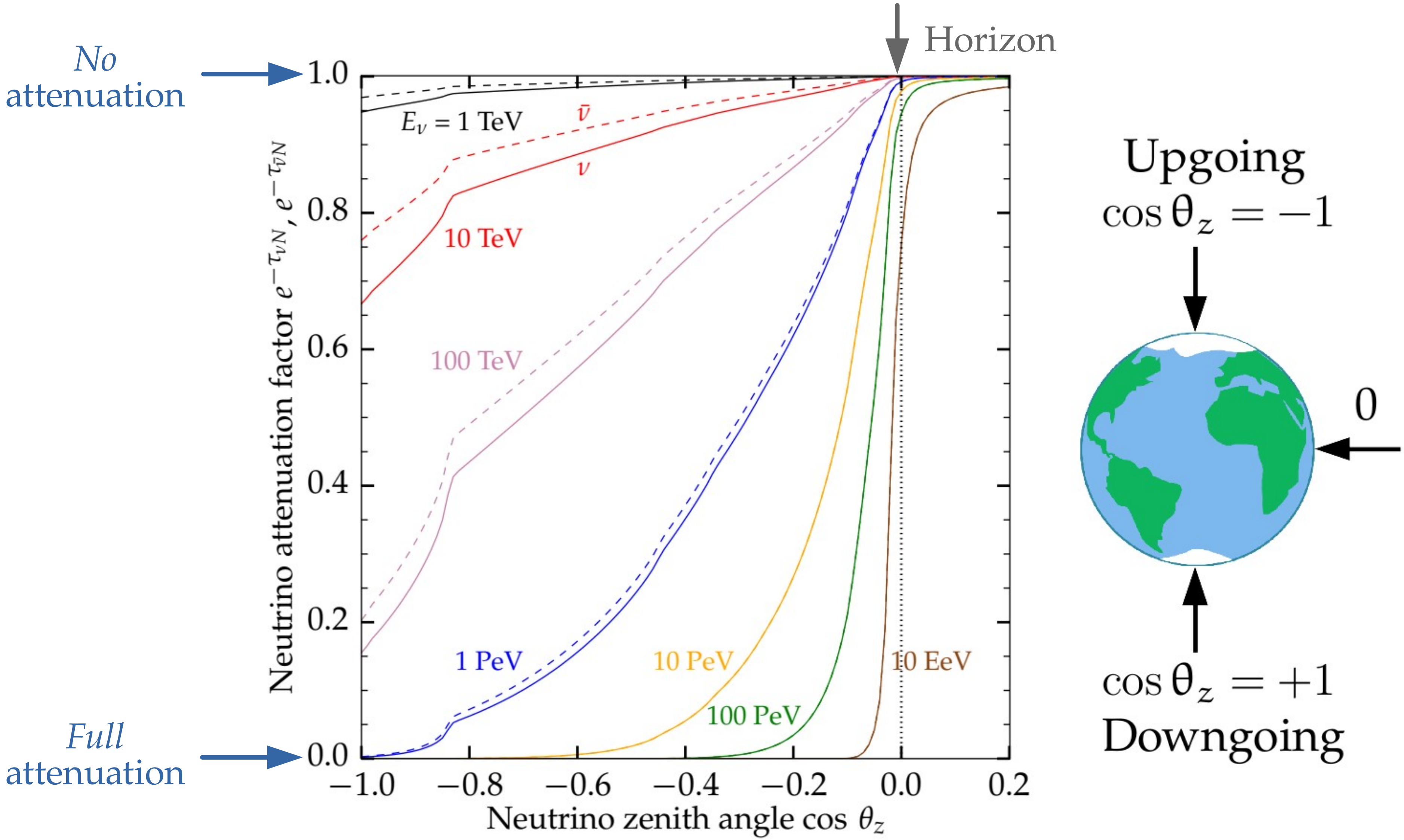
Detected event rate

Sum over NC & CC, and all flavors of ν and $\bar{\nu}$:

$$\frac{d^2N_\nu}{dE_{\rm dep}d\theta_{z,\rm rec}} = \sum_i^{\rm NC,CC} \sum_\alpha^{e,\mu,\tau} \left(\frac{d^2N^i_{\nu_\alpha}}{dE_{\rm dep}d\theta_{z,\rm rec}} + \nu_\alpha \to \bar{\nu}_\alpha \right)$$

Total number of events in energy bin $[E_{\rm dep}^{\rm min}, E_{\rm dep}^{\rm max}]$ and direction bin $[\cos^{\rm min}_{z,\rm rec}, \cos^{\rm max}_{z,\rm rec}]$:

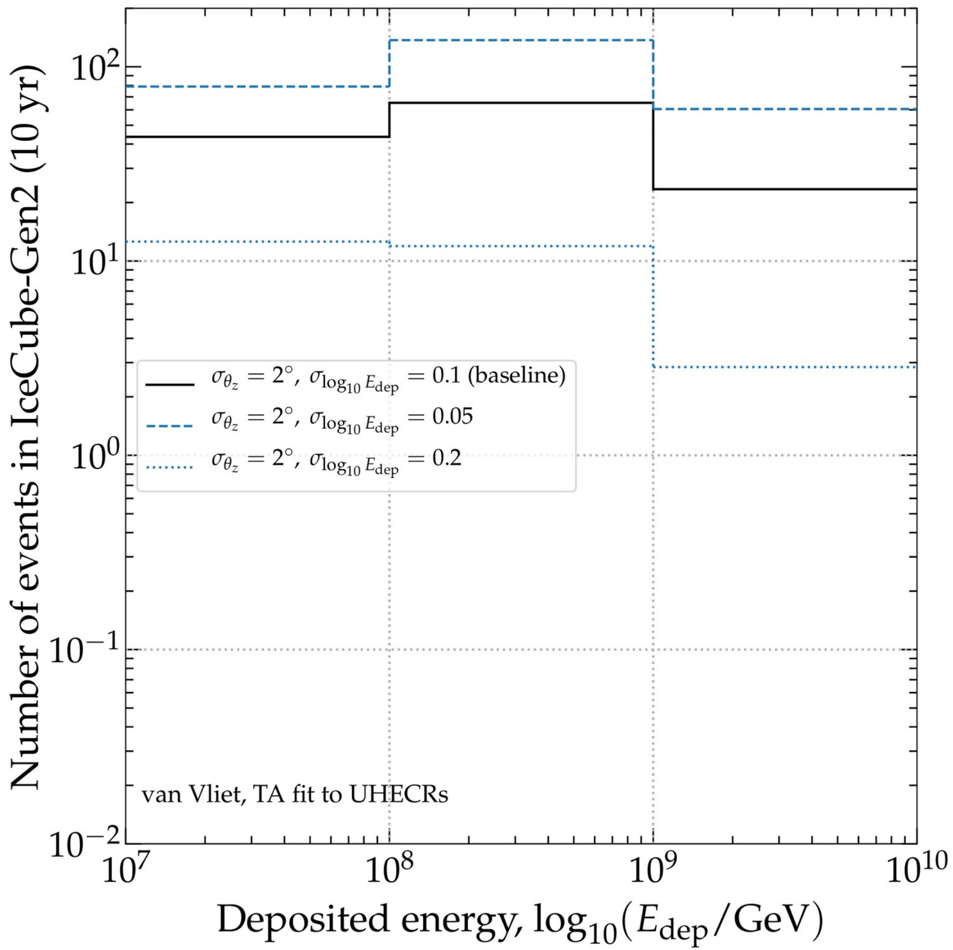
$$N_\nu = \int_{E_{\rm dep}^{\rm min}}^{E_{\rm dep}^{\rm max}} dE_{\rm dep} \int_{\theta_{z,\rm rec}^{\rm min}}^{\theta_{z,\rm rec}^{\rm max}} d\theta_{z,\rm rec} \frac{d^2N_\nu}{dE_{\rm dep}d\theta_{z,\rm rec}}$$



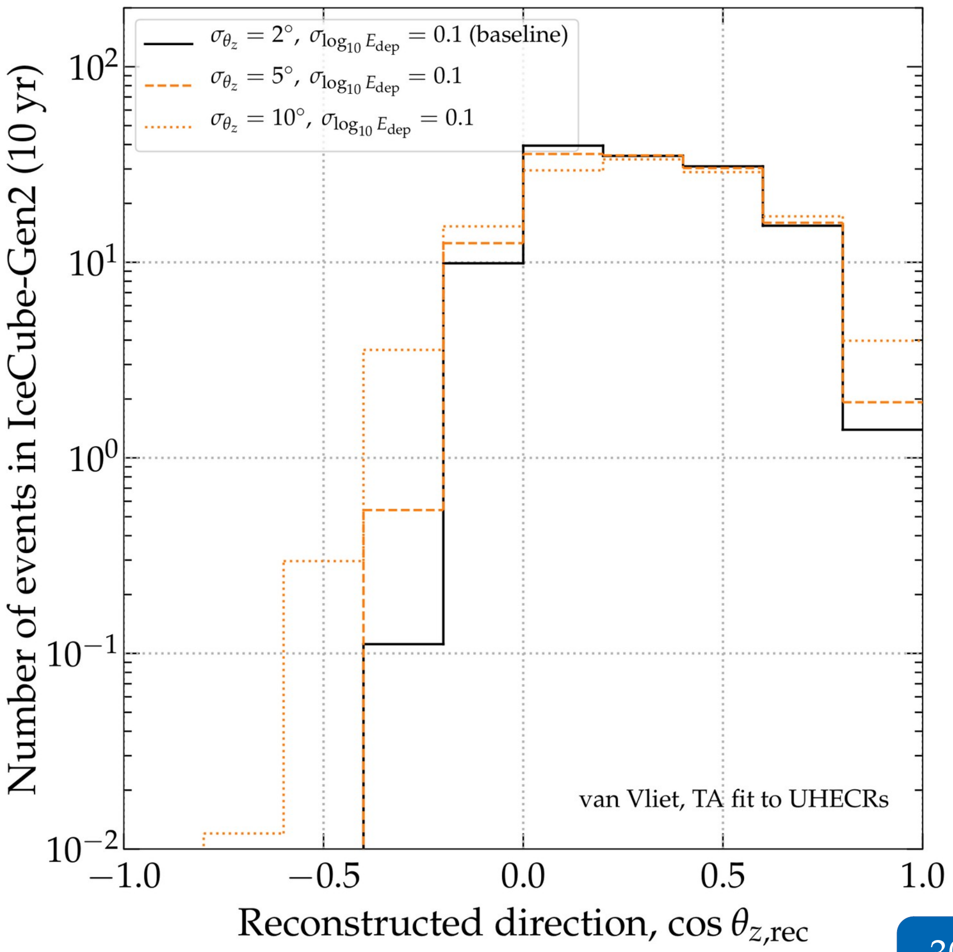
MB & Connolly, *PRL* 2019

Effect of energy & angular resolution

Changing resolution in E_{dep}



Changing resolution in $\theta_{z,rec}$



A generic, empirical model of the UHE ν spectrum

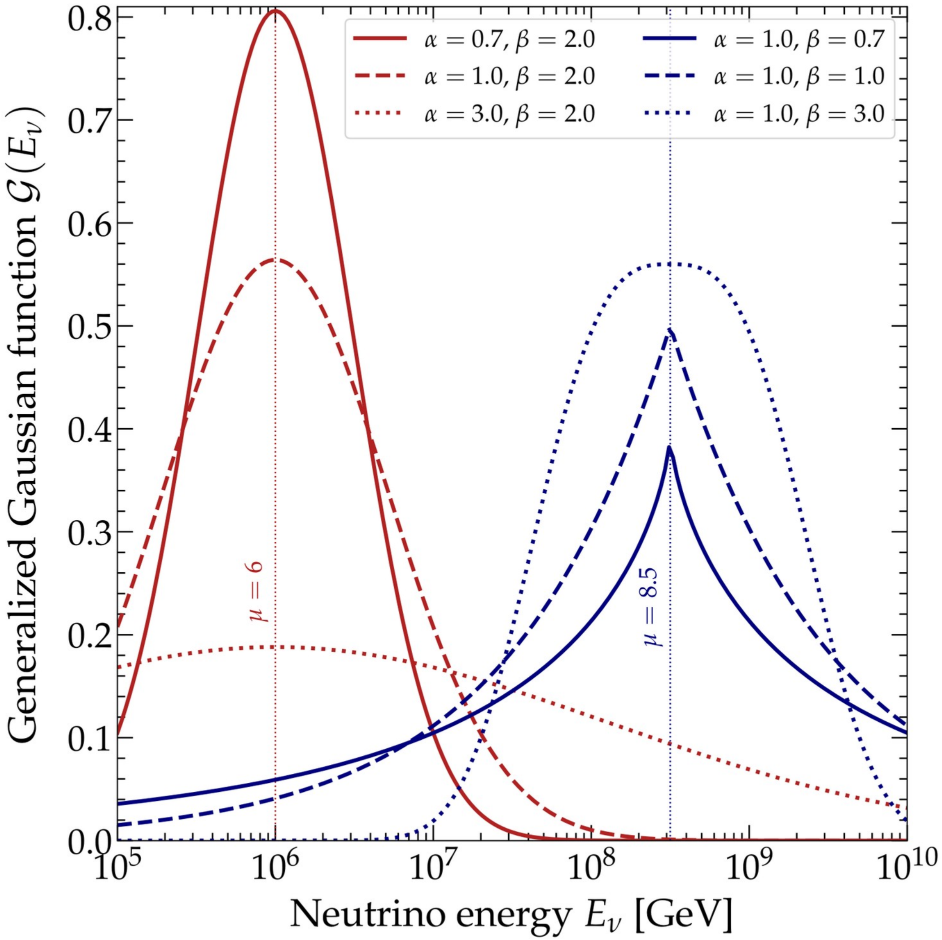
Each bump $\mathcal{G}$ is a generalized Gaussian, *e.g.*,

Center

$$\mathcal{G}(E_\nu; \alpha, \beta, \mu)$$

Scale Shape

Has non-zero kurtosis
(for more accurate fits to known spectra)

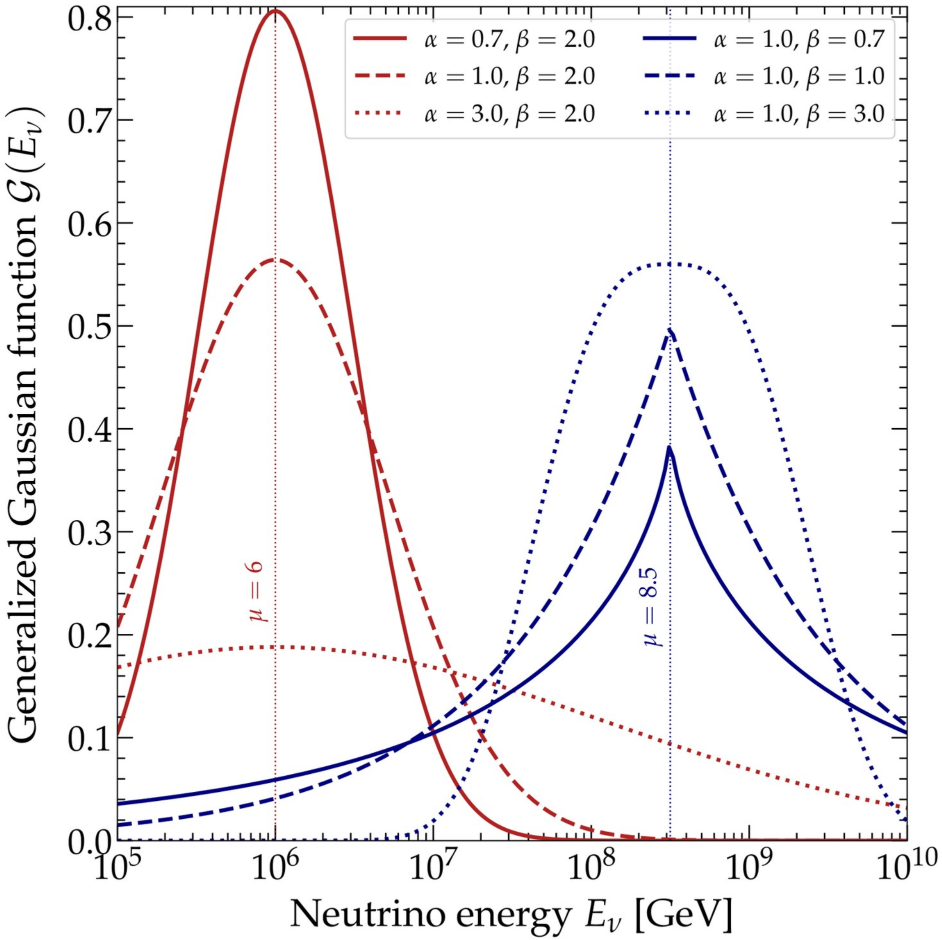


A generic, empirical model of the UHE ν spectrum

Each bump $\mathcal{G}$ is a generalized Gaussian, *e.g.*,

$$\underbrace{\eta}_{\text{Height}}\, \mathcal{G}(E_\nu; \underbrace{\alpha}_{\text{Scale}}, \underbrace{\beta}_{\text{Shape}}, \underbrace{\mu}_{\text{Center}})$$

Has non-zero kurtosis
(for more accurate fits to known spectra)



A generic, empirical model of the UHE ν spectrum

Neutrinos:

$$E_\nu^2 \Phi_{\nu_\alpha}(E_\nu) = \underbrace{(E_\nu^2 \Phi_0) f_{\alpha,\oplus} f_\nu}_{\text{Normalization}} \left[\underbrace{\left(\frac{E_\nu}{\mathrm{PeV}} \right)^{-\gamma}}_{\text{Power-law (from } pp \text{ or extrapolation)}} + \underbrace{\eta_l^\nu \mathcal{G}_l(E_\nu; \alpha_l, \beta_l^\nu, \mu_l)}_{\text{Low-energy } p\gamma \text{ bump (from EBL or in source)}} + \underbrace{\eta_h^\nu \mathcal{G}_h(E_\nu; \alpha_h, \beta_h^\nu, \mu_h)}_{\text{High-energy } p\gamma \text{ bump (from CMB or in source)}} \right]$$

Anti-neutrinos:

$$E_\nu^2 \Phi_{\bar{\nu}_\alpha}(E_\nu) = (E_\nu^2 \Phi_0) f_{\alpha,\oplus} (1 - f_\nu) \left[\left(\frac{E_\nu}{\mathrm{PeV}} \right)^{-\gamma} + \underbrace{\eta_n^{\bar{\nu}} \mathcal{G}_n(E_\nu; \alpha_n^{\bar{\nu}}, \beta_n^{\bar{\nu}}, \mu_n^{\bar{\nu}})}_{\text{Bump from neutron decay}} + \underbrace{\eta_l^{\bar{\nu}} \mathcal{G}_l(E_\nu; \alpha_l, \beta_l^{\bar{\nu}}, \mu_l)}_{\text{Low-energy } p\gamma \text{ bump (from EBL or in source)}} + \underbrace{\eta_h^{\bar{\nu}} \mathcal{G}_h(E_\nu; \alpha_h, \beta_h^{\bar{\nu}}, \mu_h)}_{\text{High-energy } p\gamma \text{ bump (from CMB or in source)}} \right]$$

νSI with the UHE diffuse flux

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

Coupling matrix:

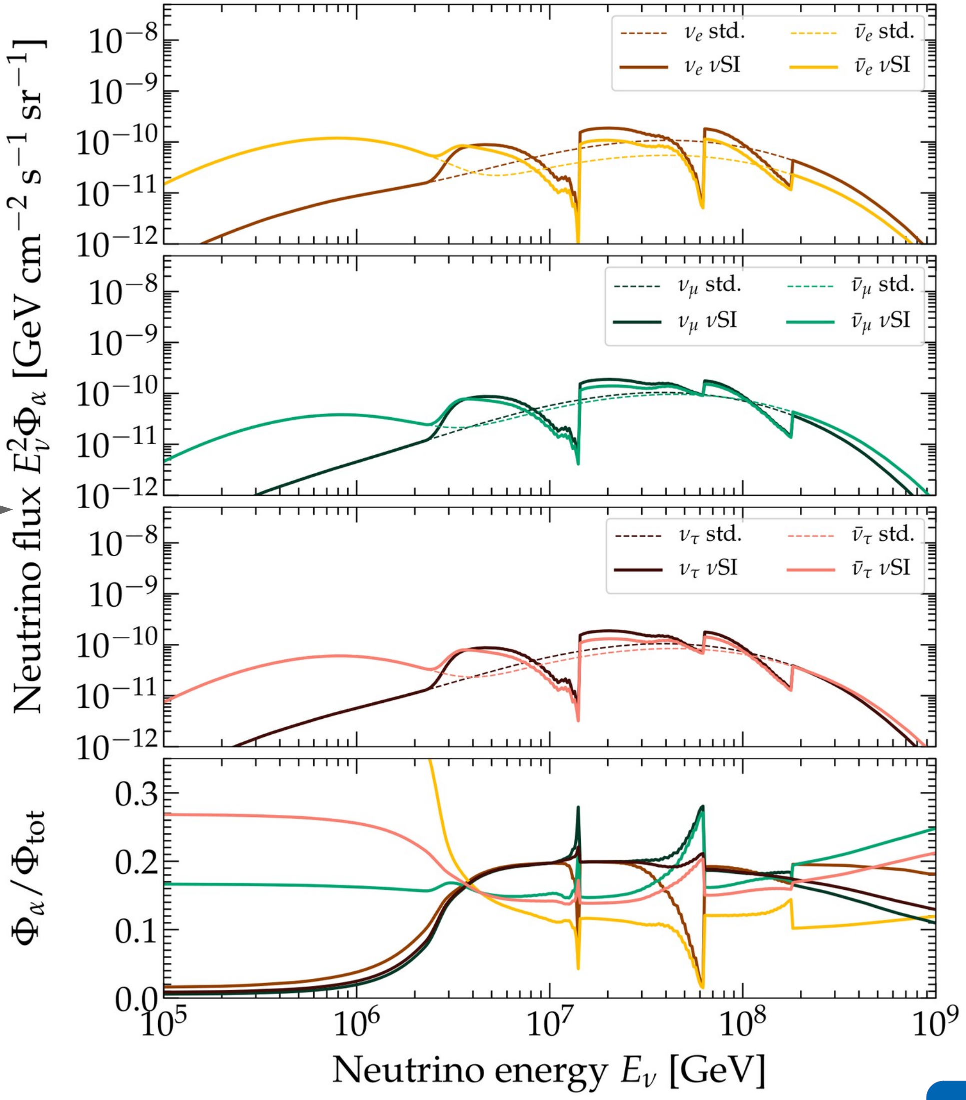
Different flavors can have different couplings

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

νSI dips and bumps in the diffuse UHE ν flux:

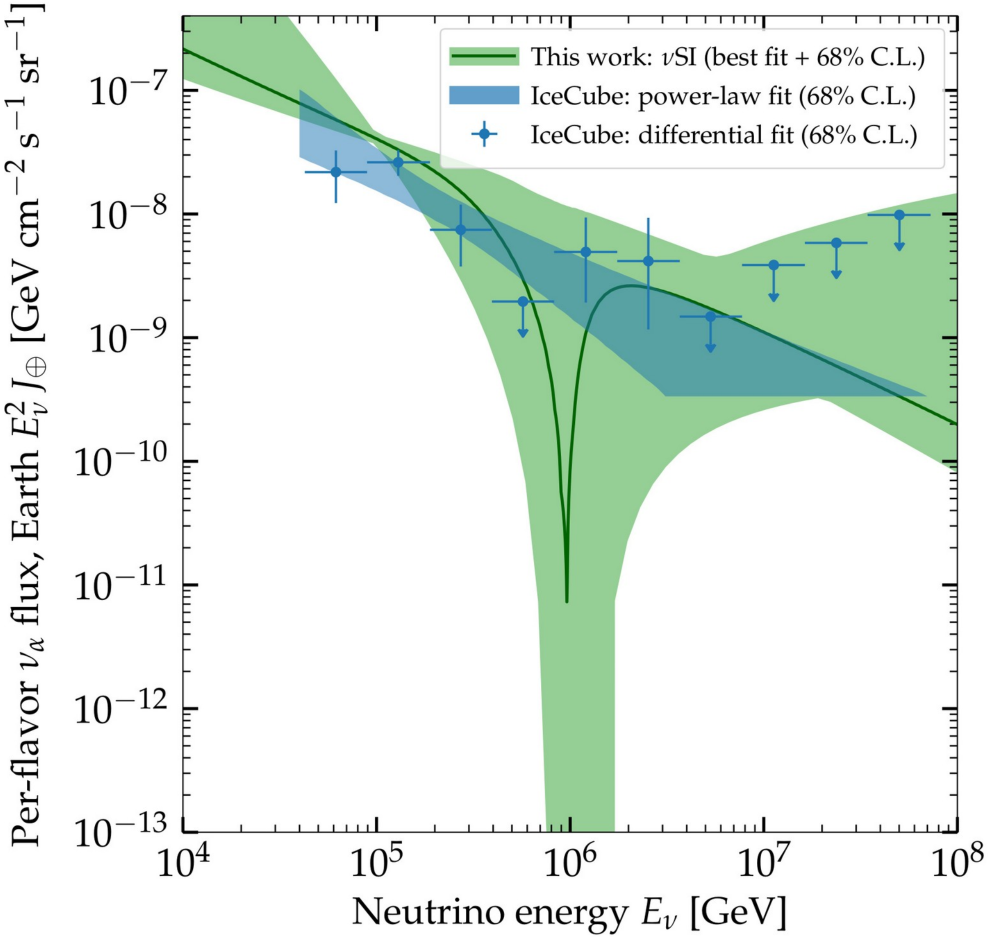
- In the cosmogenic flux
- In the flux from sources

Work in progress, stay tuned...



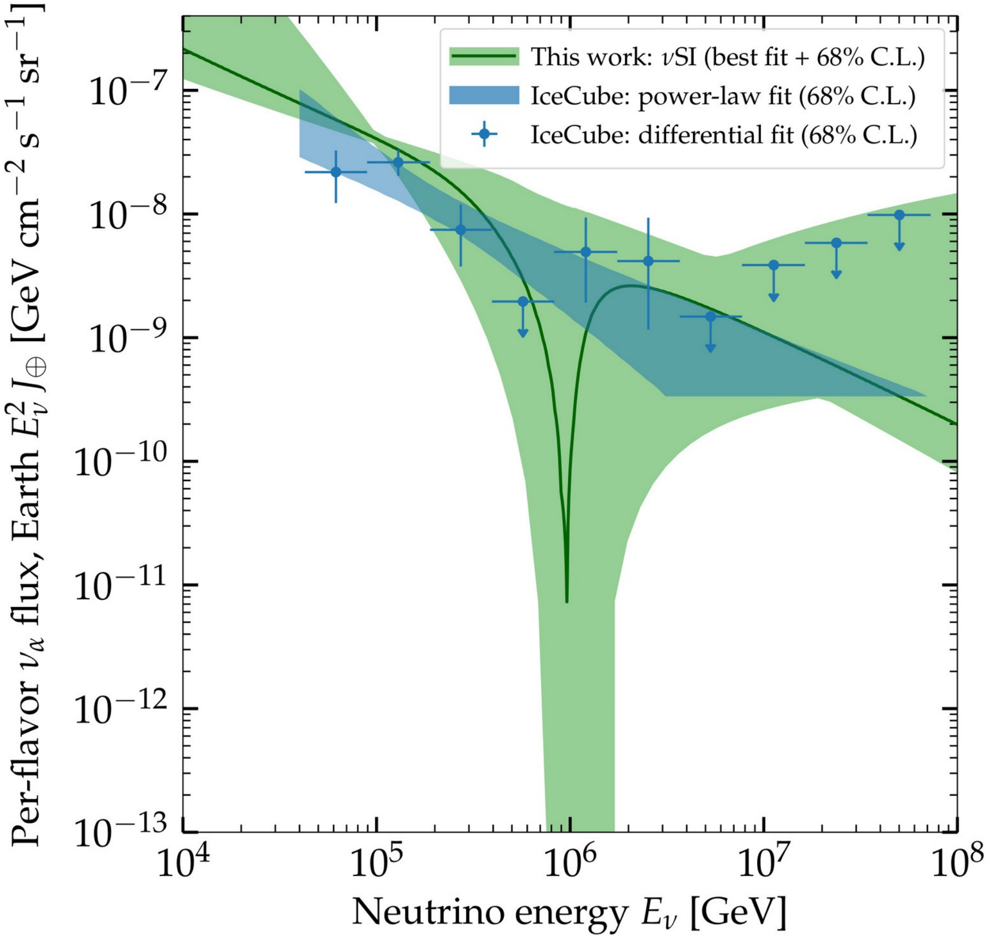
MB, Másson, Valera, *In preparation*

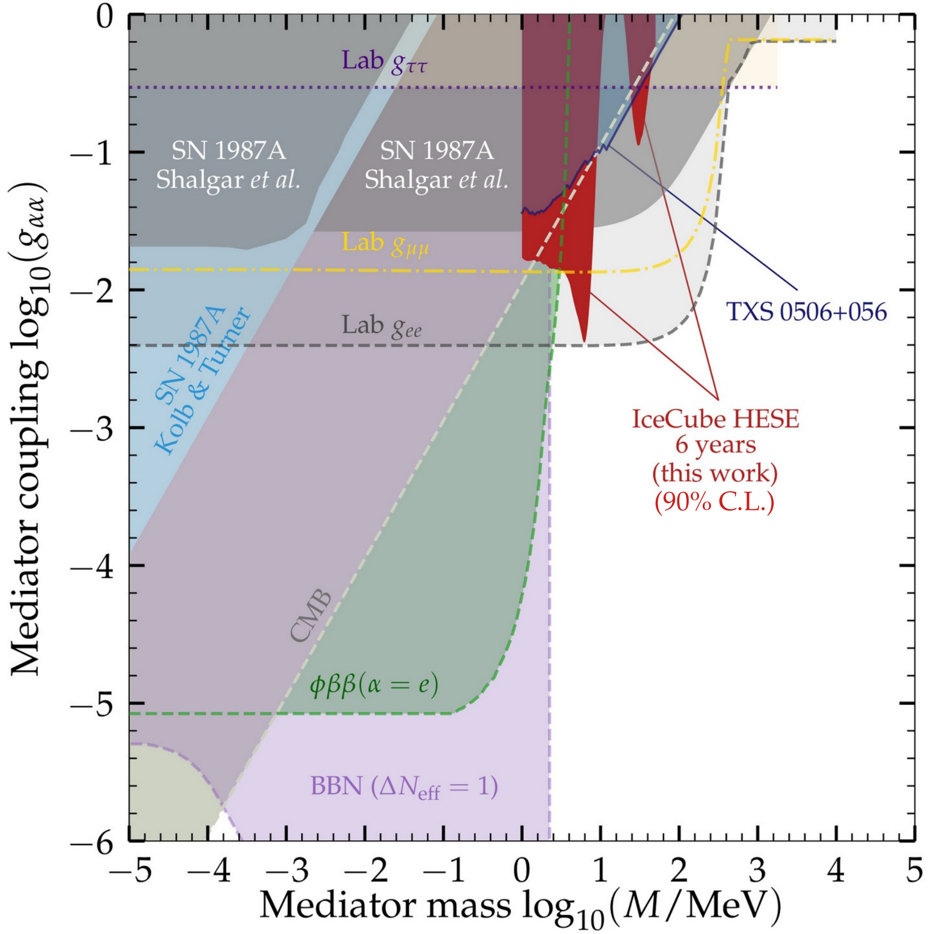
No significant (> 3σ) evidence for a spectral dip …



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

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





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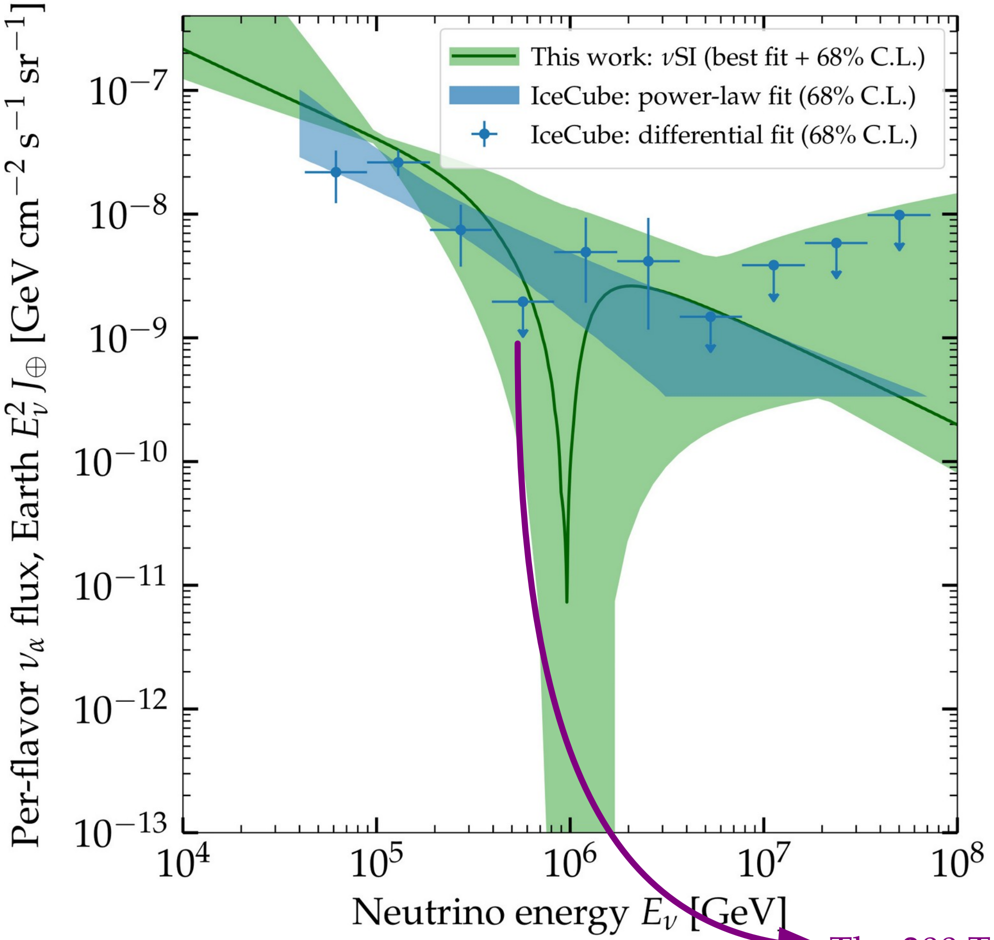
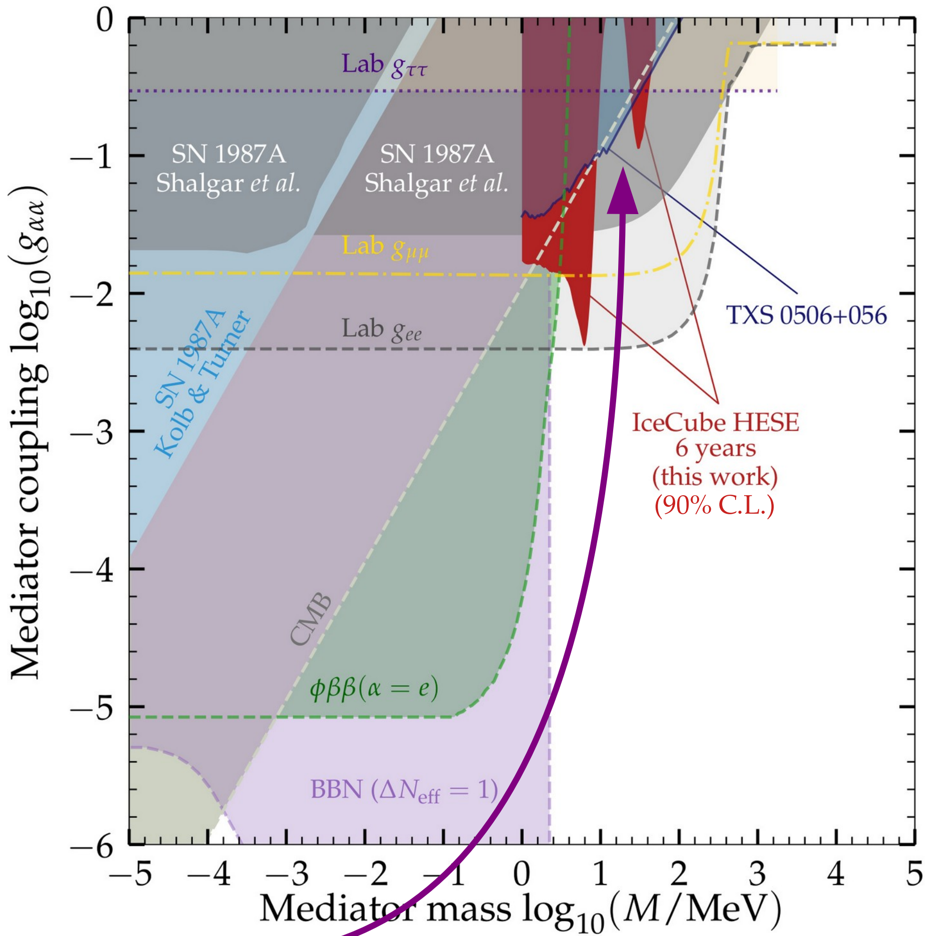




The 300 TeV–1 PeV "gap" degrades the limit at ~10 MeV

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

Are neutrinos forever?

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

  » Age of Universe (~ 14.5 Gyr)

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

- 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

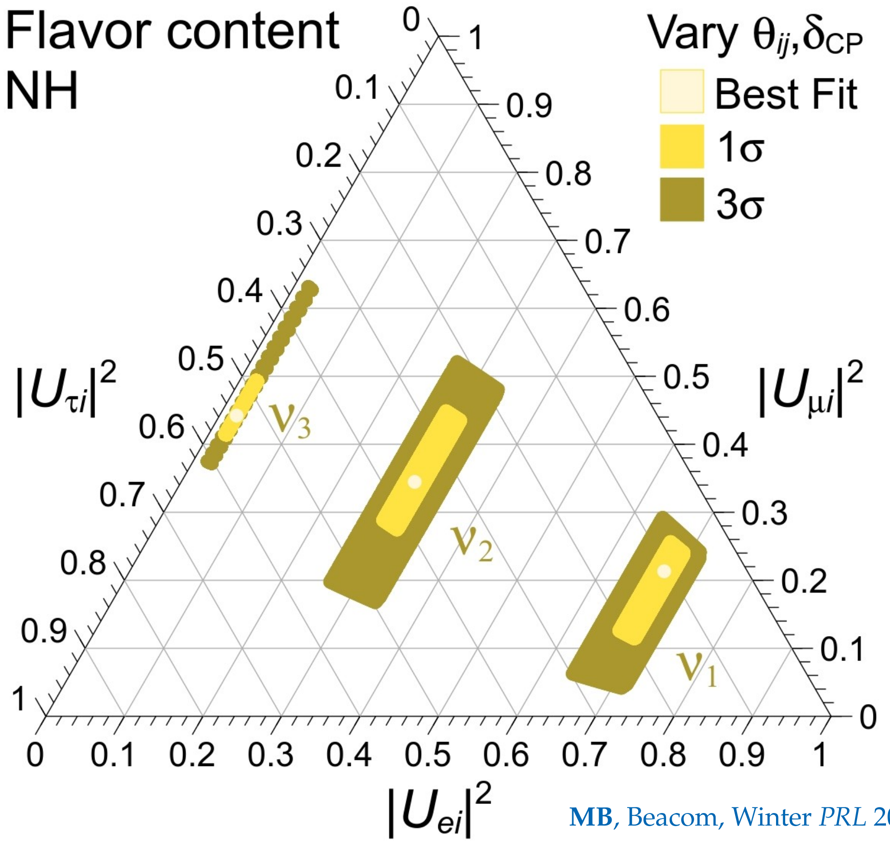
Flavor content of neutrino mass eigenstates

Known to within 2%

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

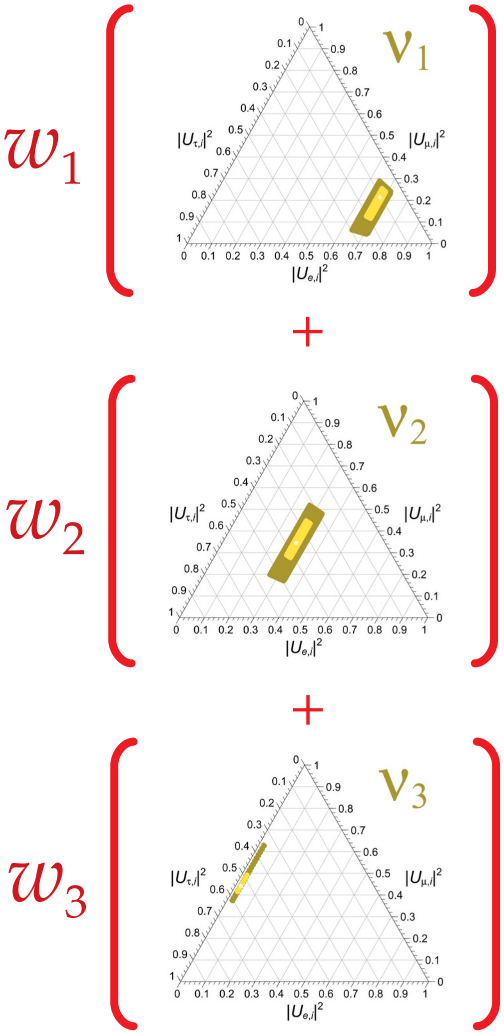
Known to within 8%

Known to within 20%
(or worse)

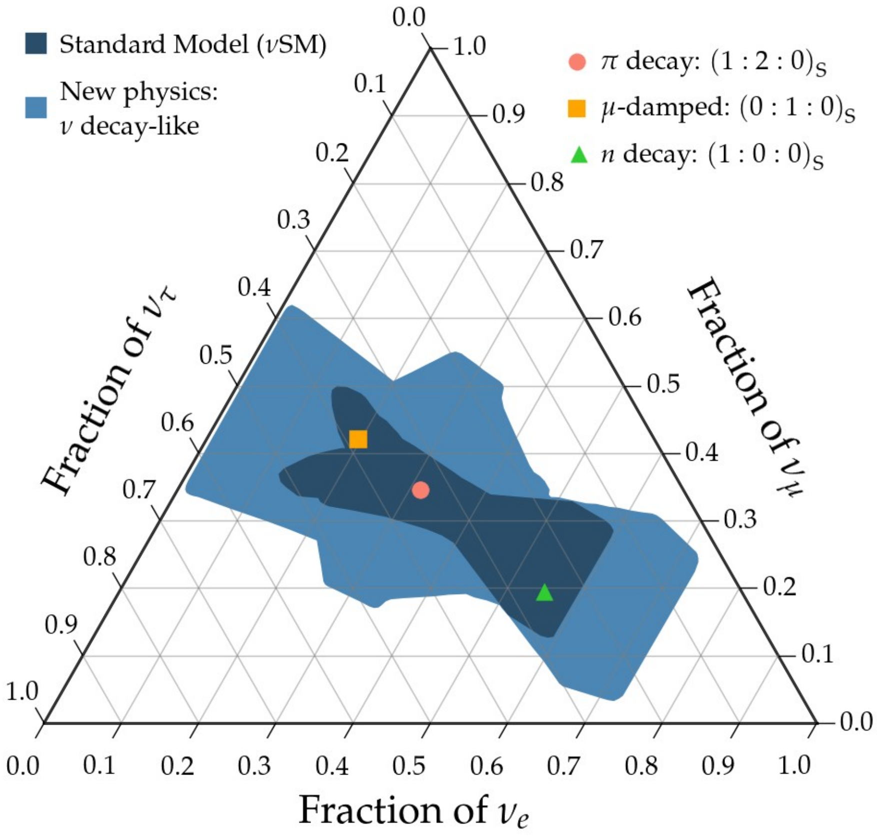


MB, Beacom, Winter *PRL* 2015

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



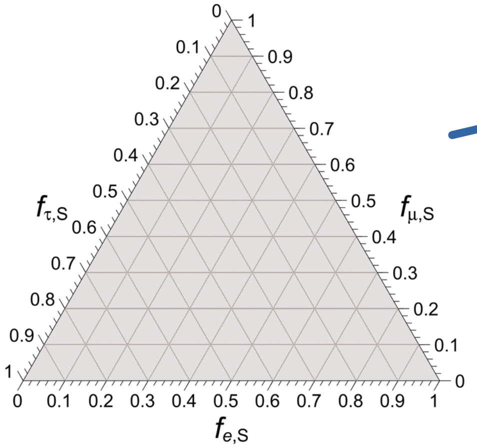
Varying all possible combinations of weights w_i and mixing parameters



Complete decay selects particular weights with striking consequences for flavor ▸

Measuring the neutrino lifetime

Sources



$\nu_2, \nu_3 \to \nu_1$

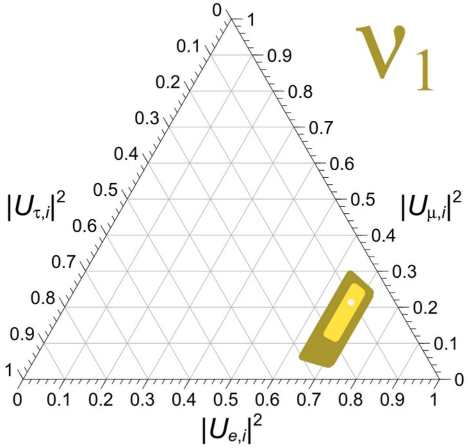
ν_1 lightest and stable
(normal mass ordering)

If all unstable neutrinos decay

$\nu_1, \nu_2 \to \nu_3$

ν_3 lightest and stable
(inverted mass ordering)

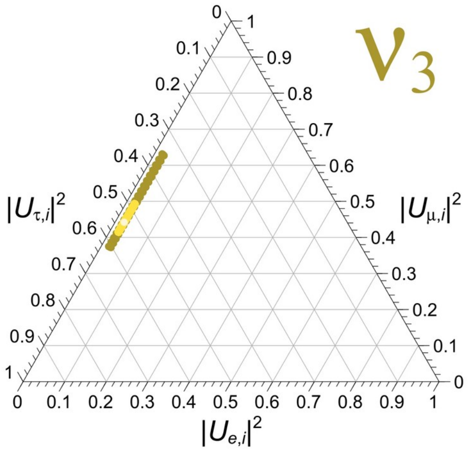
Earth



ν_1

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

$(w_1 \sim 1; w_2, w_3 \sim 0)$



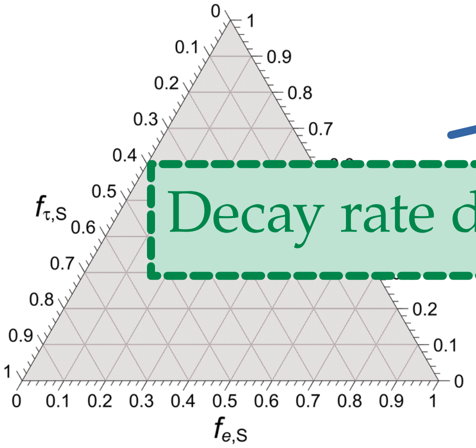
ν_3

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

$(w_3 \sim 1; w_1, w_2 \sim 0)$

Measuring the neutrino lifetime

Sources



$\nu_2, \nu_3 \rightarrow \nu_1$

ν_1 lightest and stable
(normal mass ordering)

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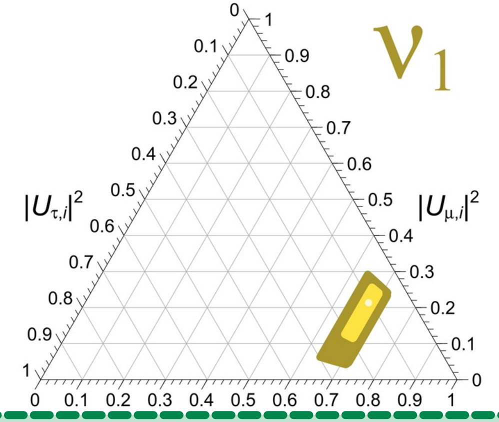

$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$

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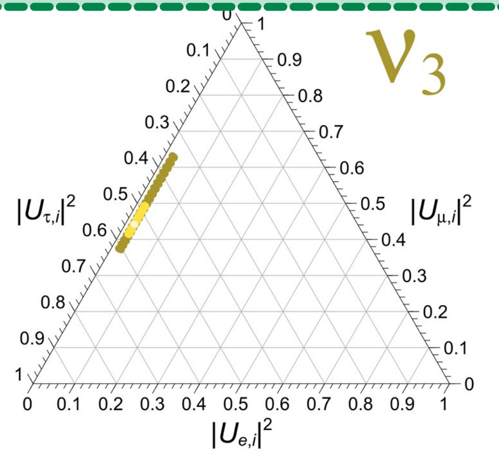
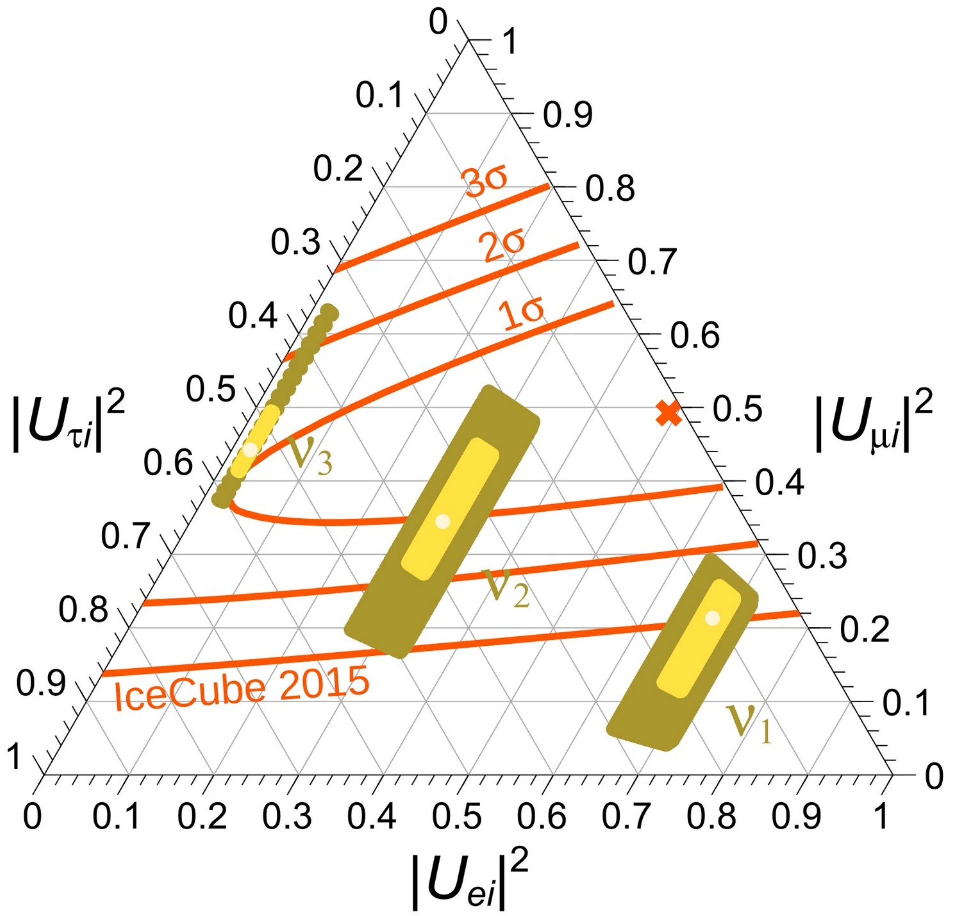


$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$

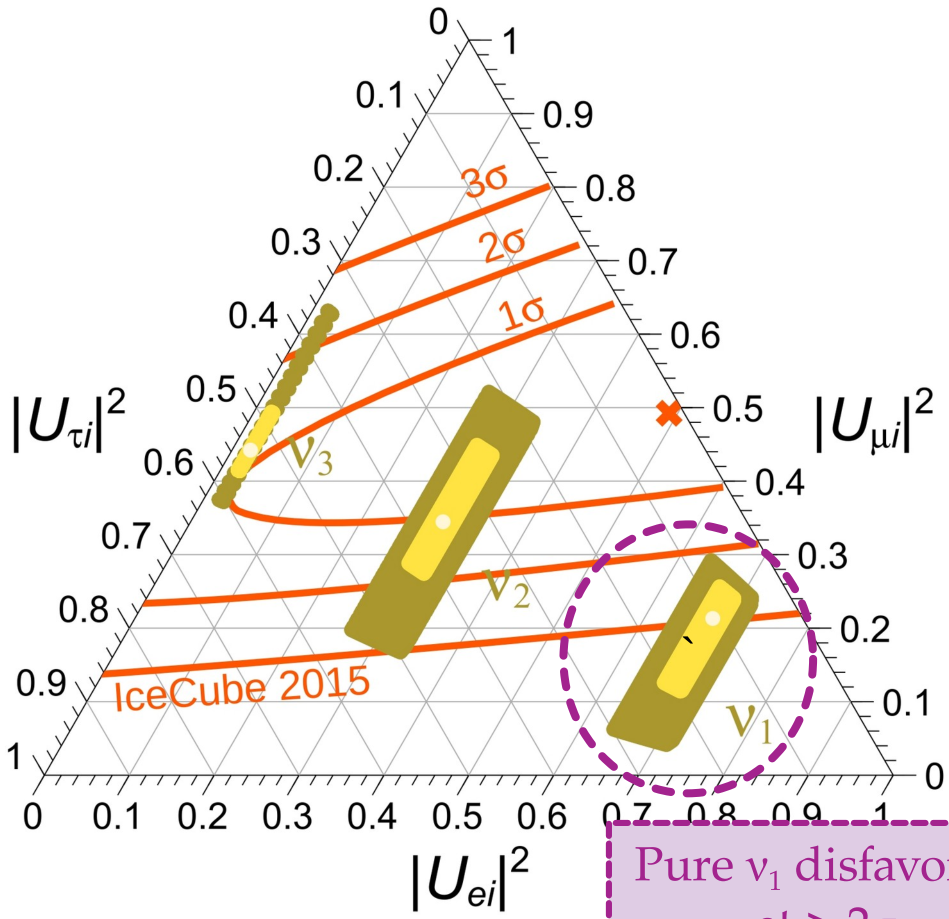
$(w_3 \sim 1;\, w_1, w_2 \sim 0)$

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



MB, Beacom, Murase, *PRD* 2017

Baerwald, **MB**, Winter, *JCAP* 2012

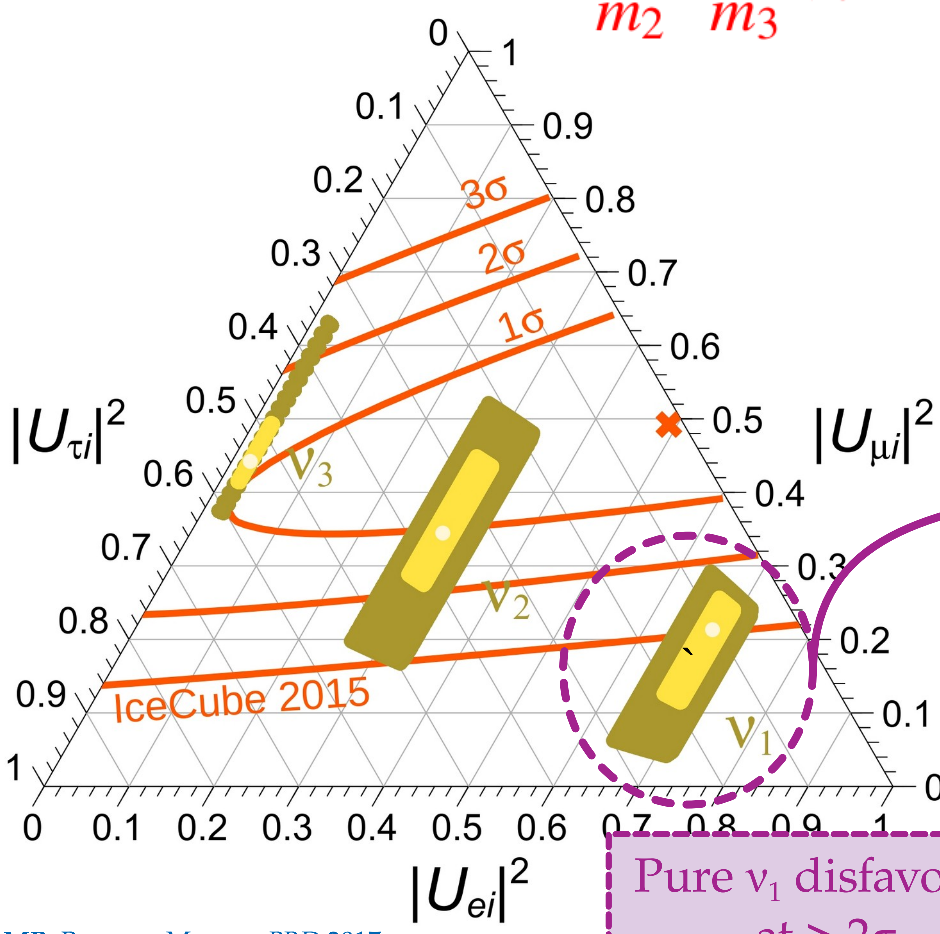


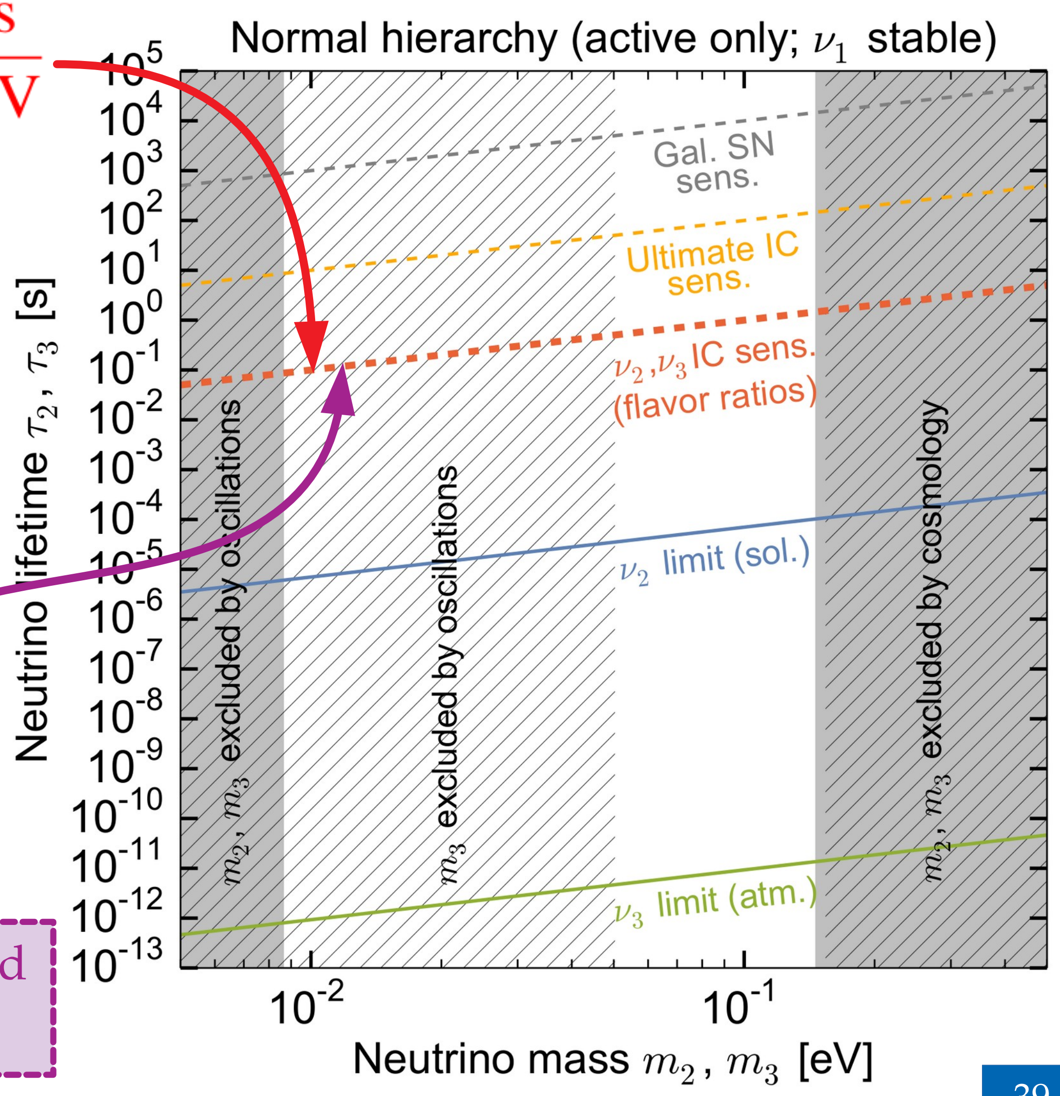
Pure ν_1 disfavored at > 2σ

MB, Beacom, Murase, *PRD* 2017

Baerwald, **MB**, Winter, *JCAP* 2012

$$\frac{\tau_2}{m_2}, \frac{\tau_3}{m_3} \gtrsim 10 \frac{\mathrm{s}}{\mathrm{eV}}$$





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Using the Glashow resonance to test decay

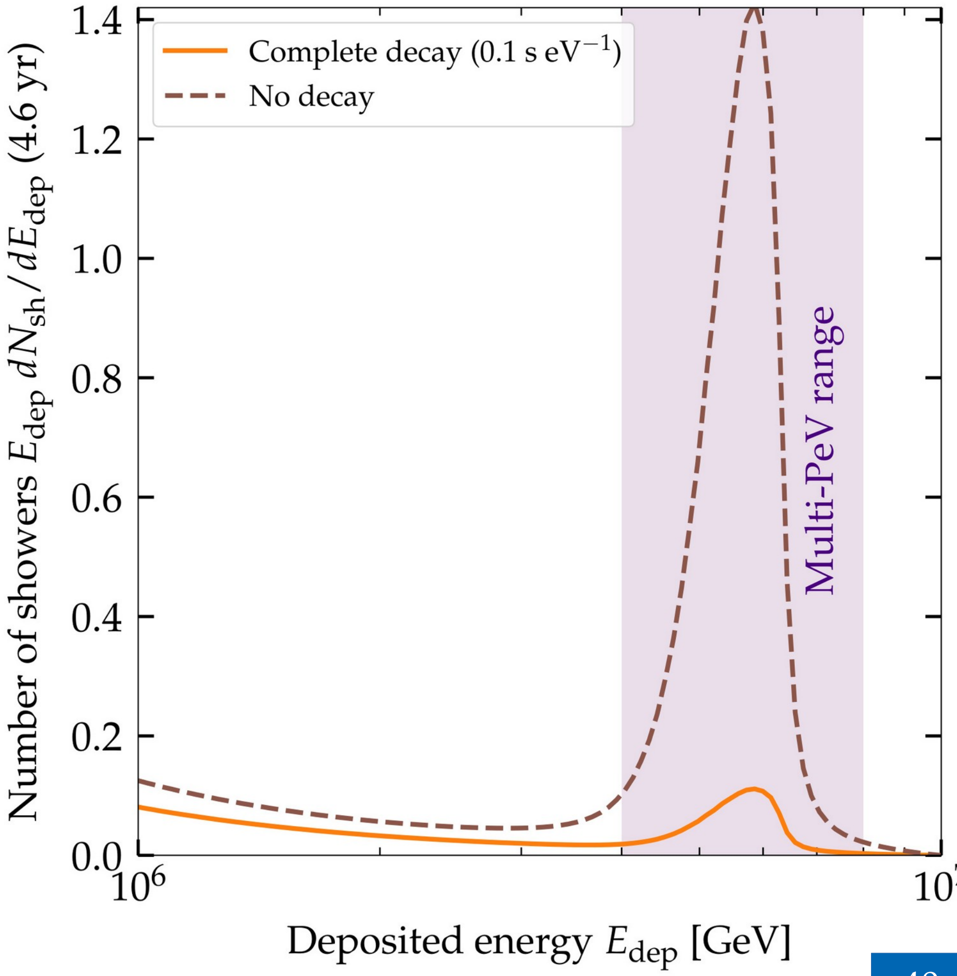
- At 6.3 PeV, the Glashow resonance ($\bar{\nu}_e + e \rightarrow W$) should trigger showers in IceCube

- … 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



MB, 2004.06844
See also: **MB**, Beacom, Murase, *PRD* 2017

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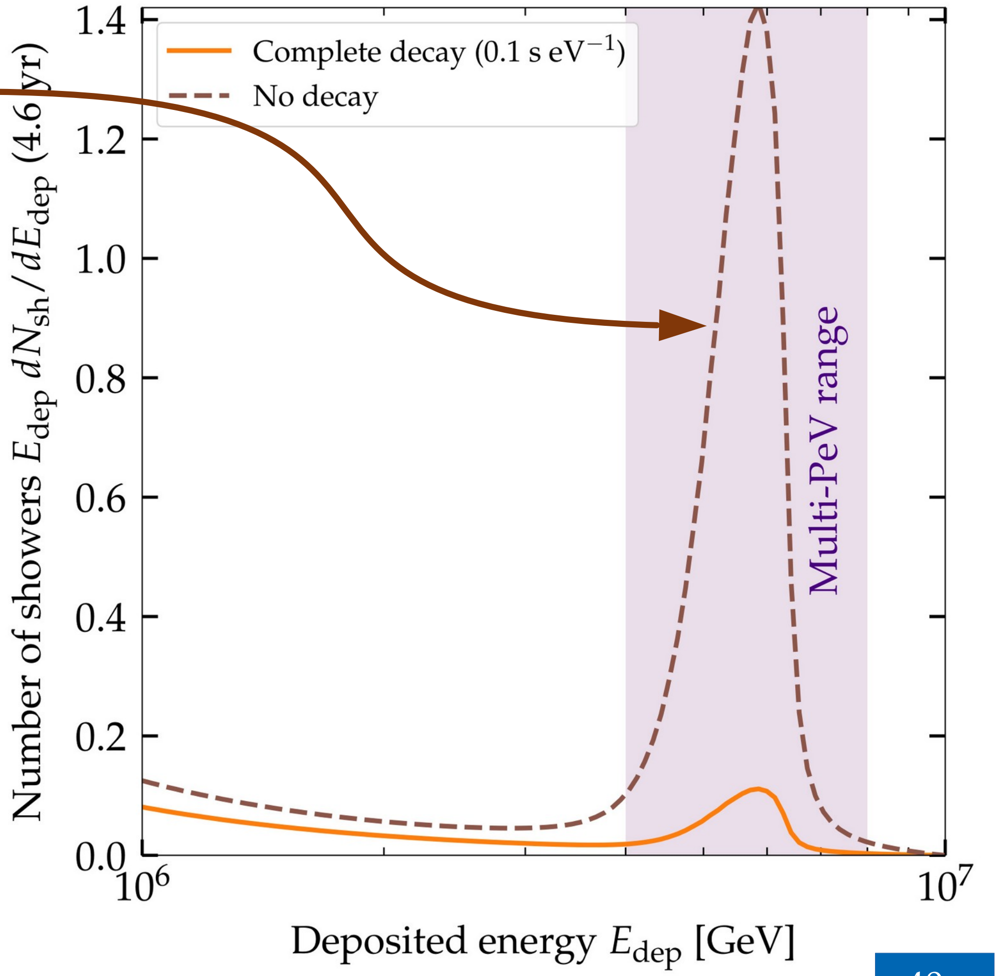

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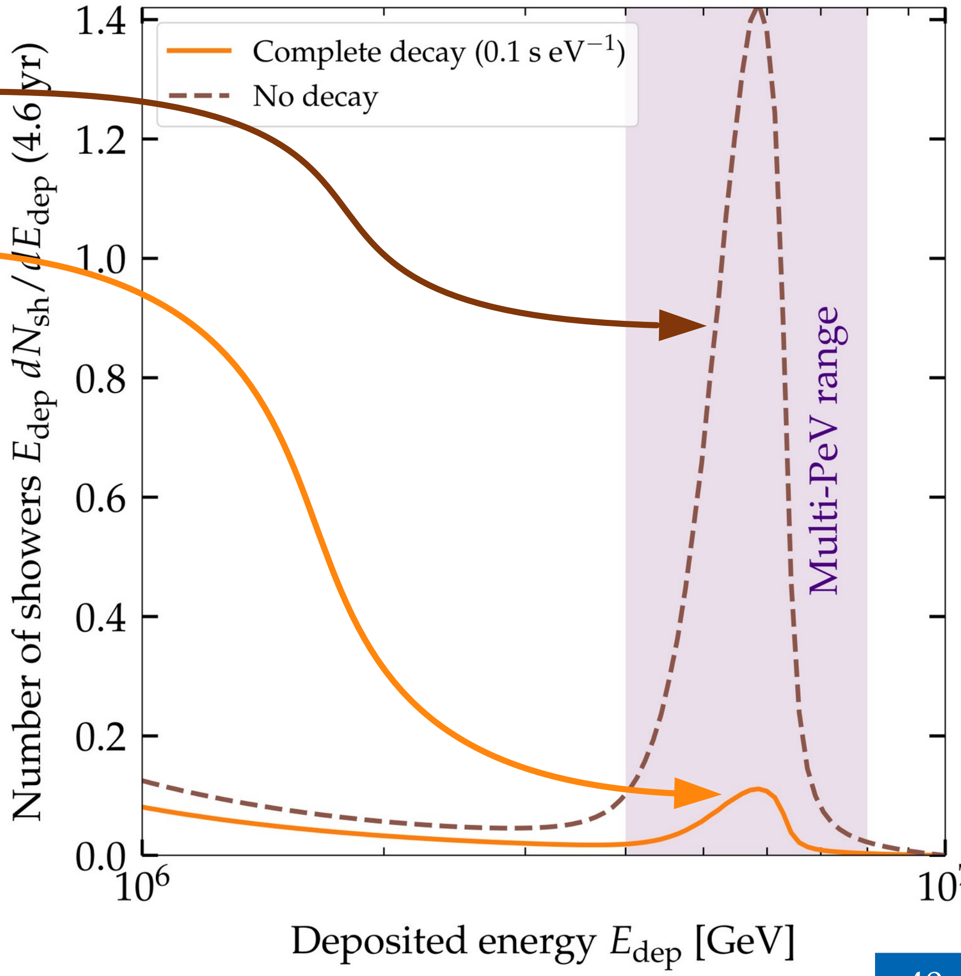

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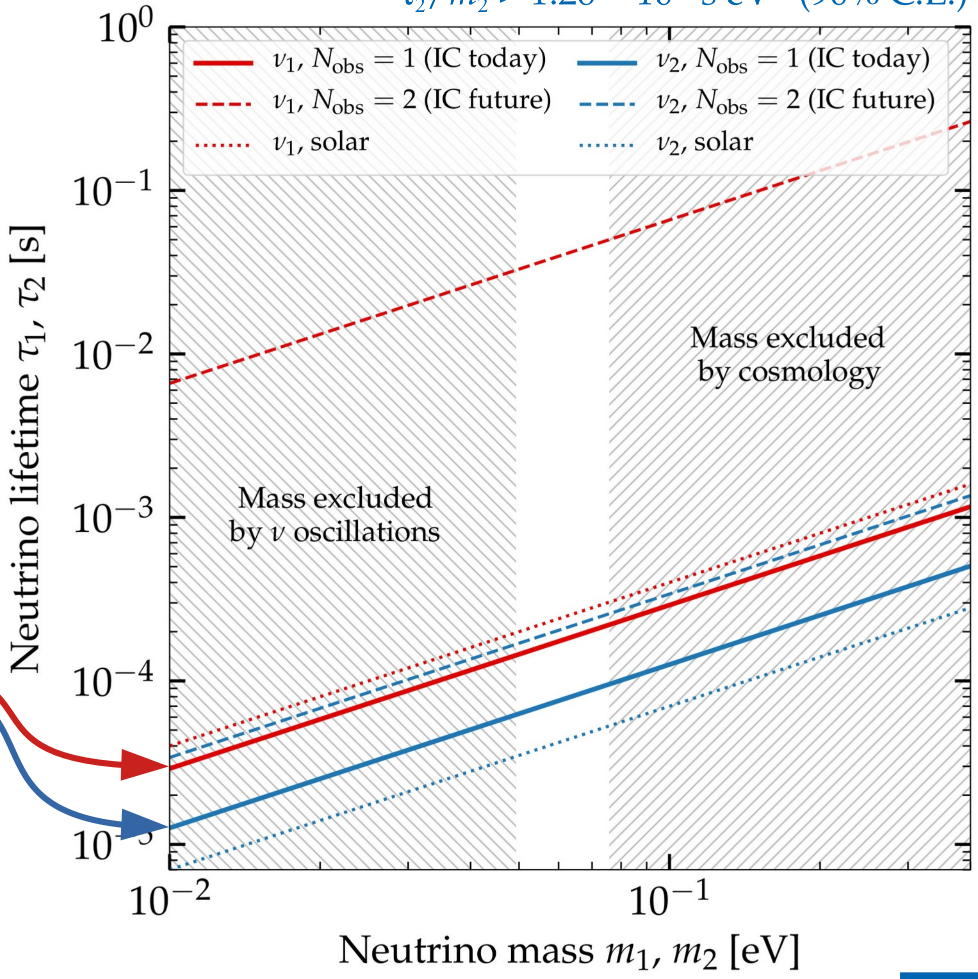
$\tau_1/m_1 > 2.91 \times 10^{-3}$ s eV^{-1} (90% C.L.)
$\tau_2/m_2 > 1.26 \times 10^{-3}$ s eV^{-1} (90% C.L.)



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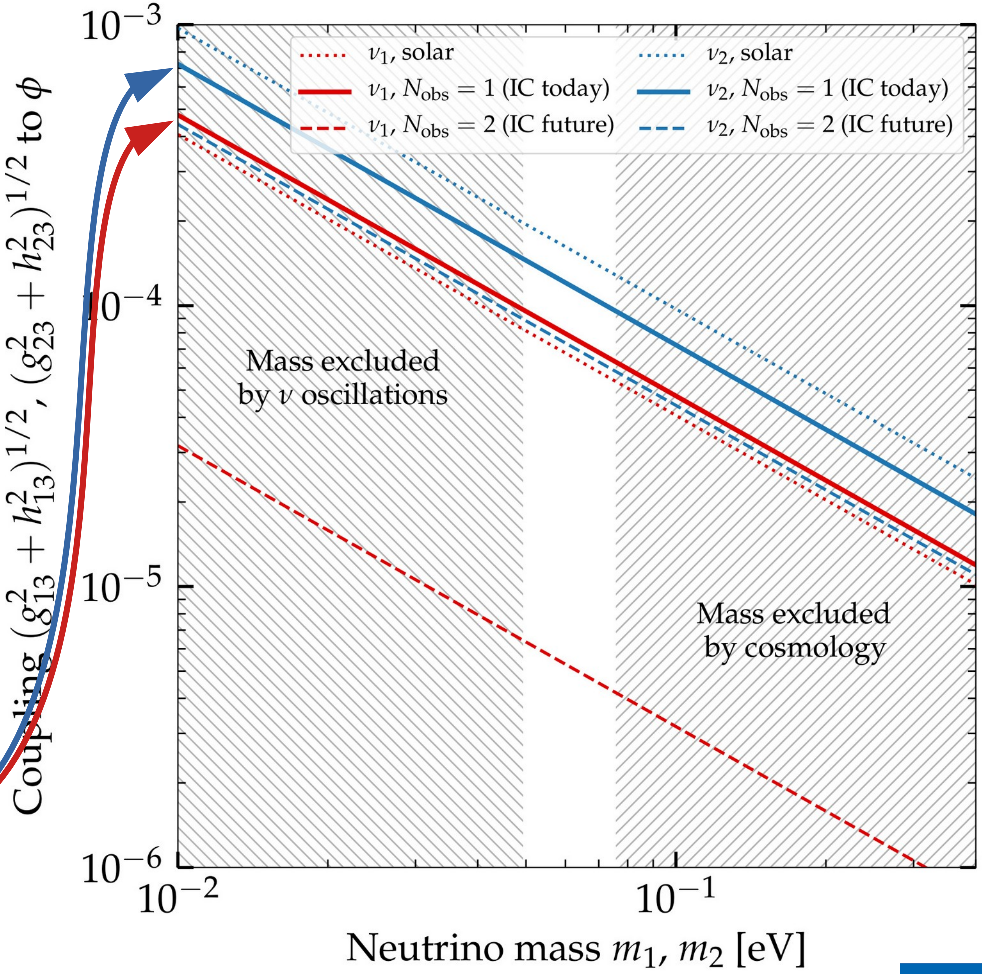
- Translated into *upper* limits on coupling

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



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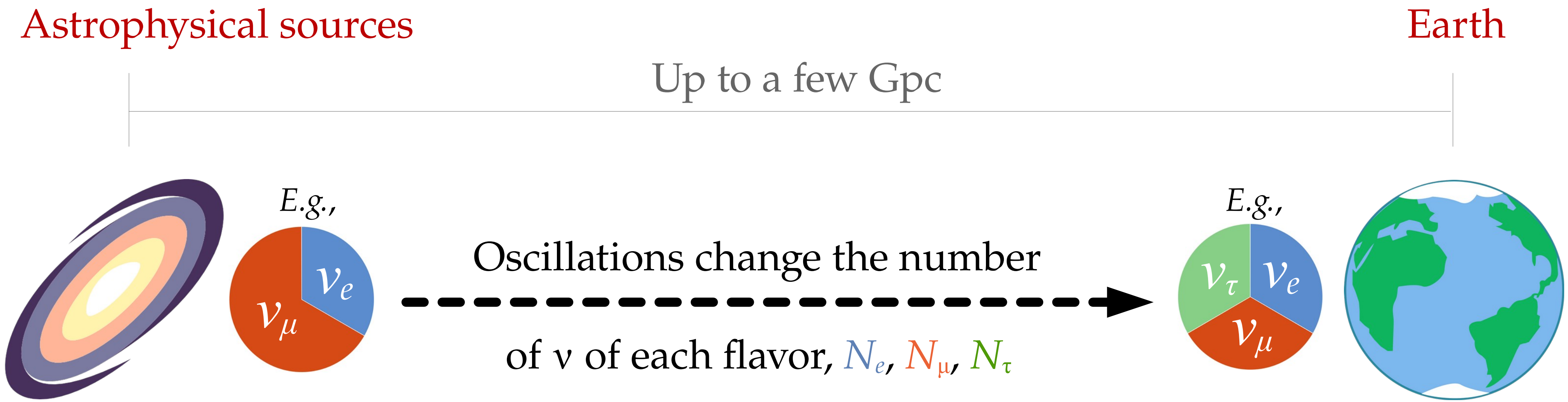
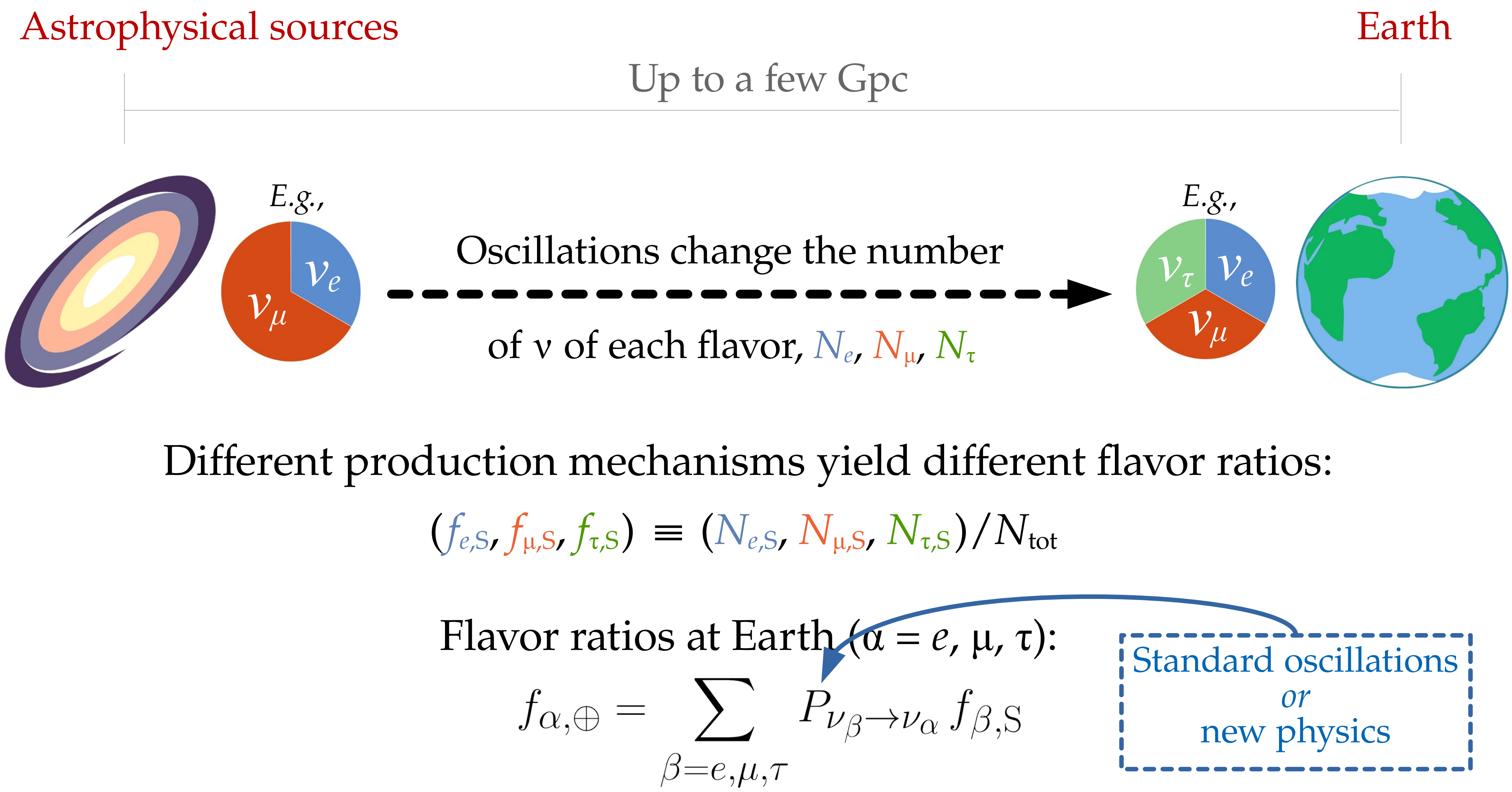


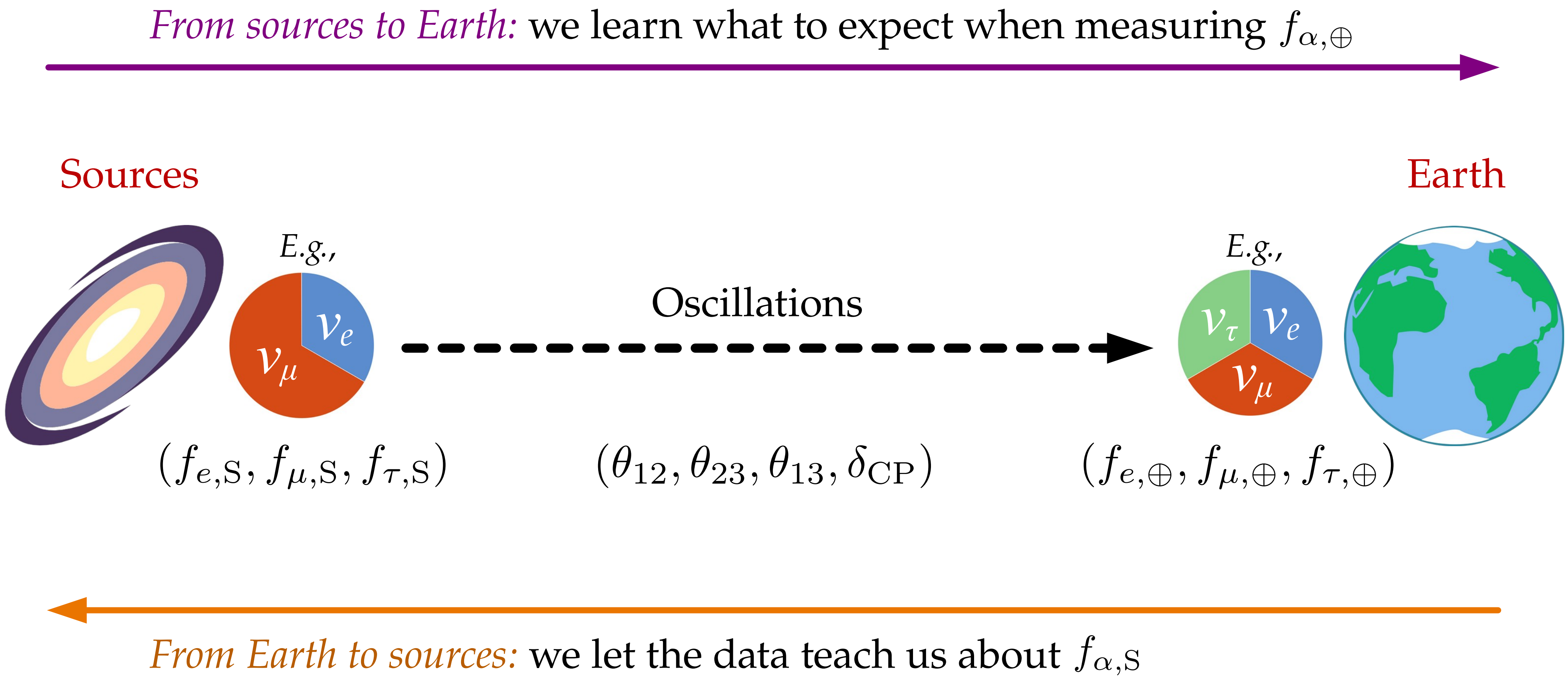
Different production mechanisms yield different flavor ratios:

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

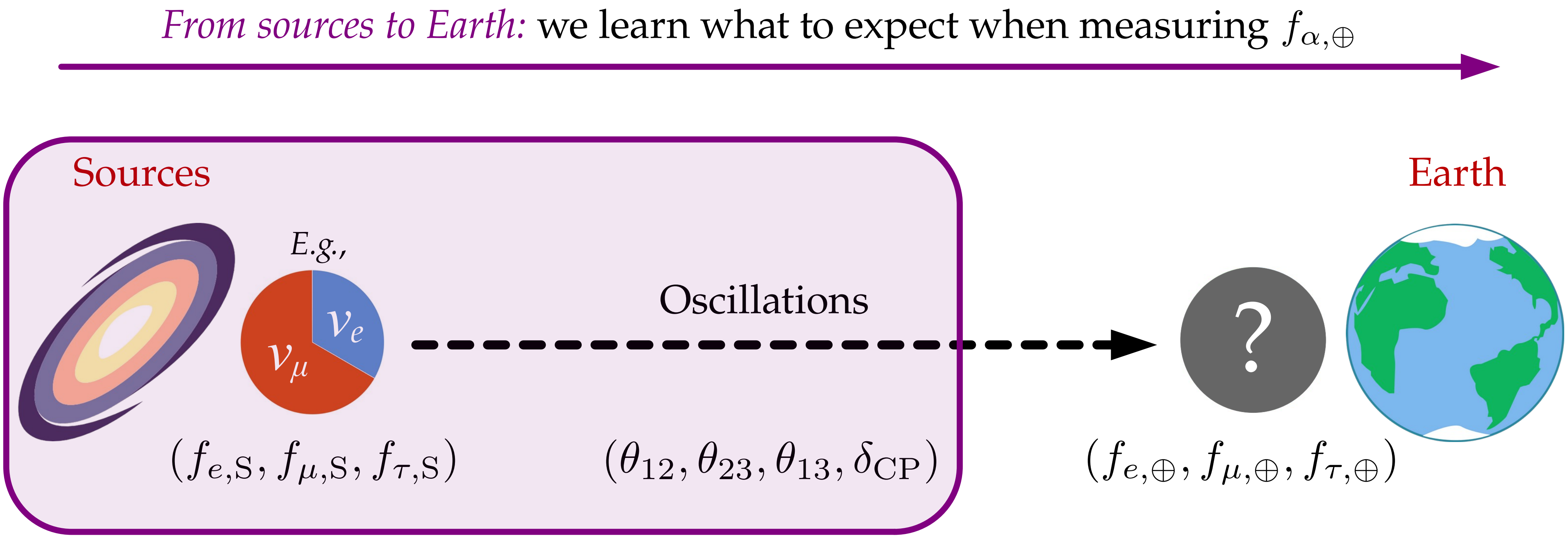
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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


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

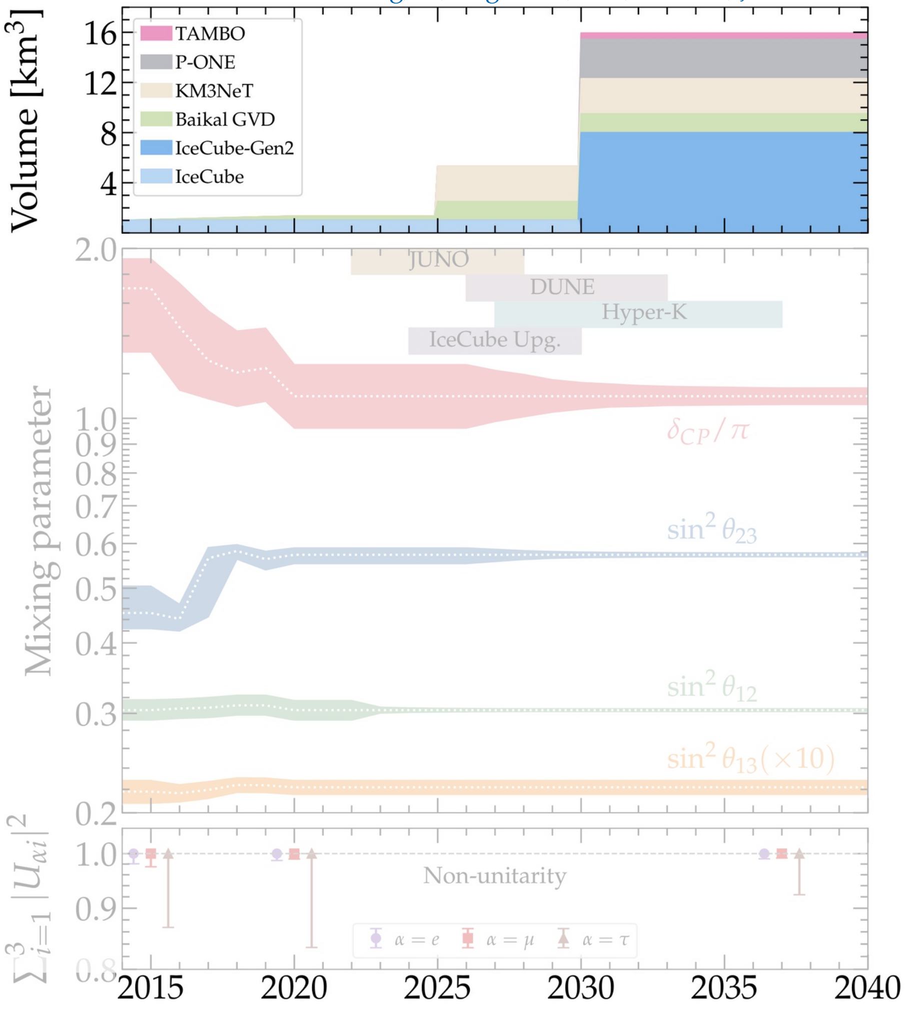


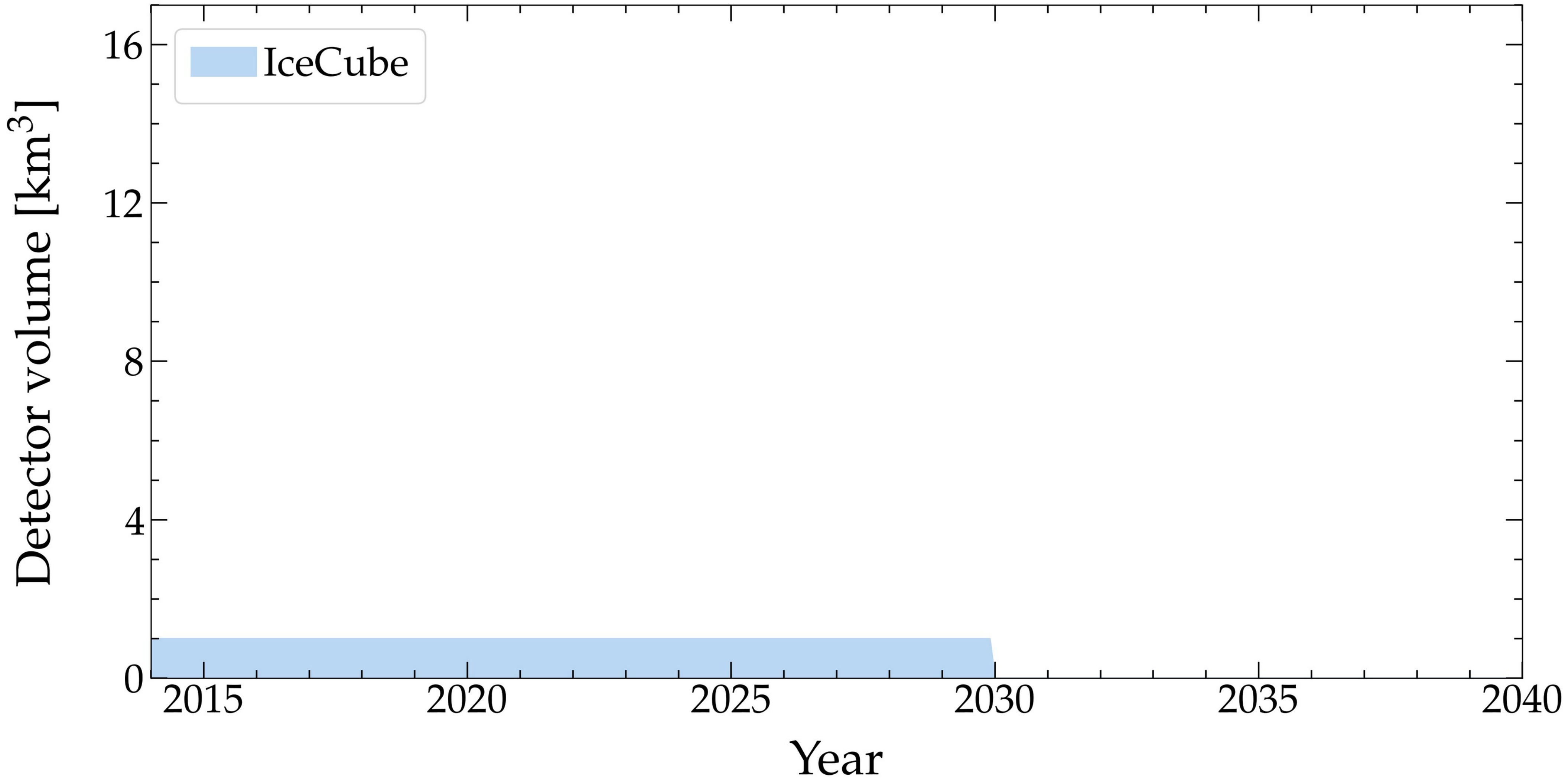
From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$
Sources
Earth
E.g.,
ν_e
ν_μ
Oscillations
E.g.,
ν_τ
ν_e
ν_μ
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$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


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

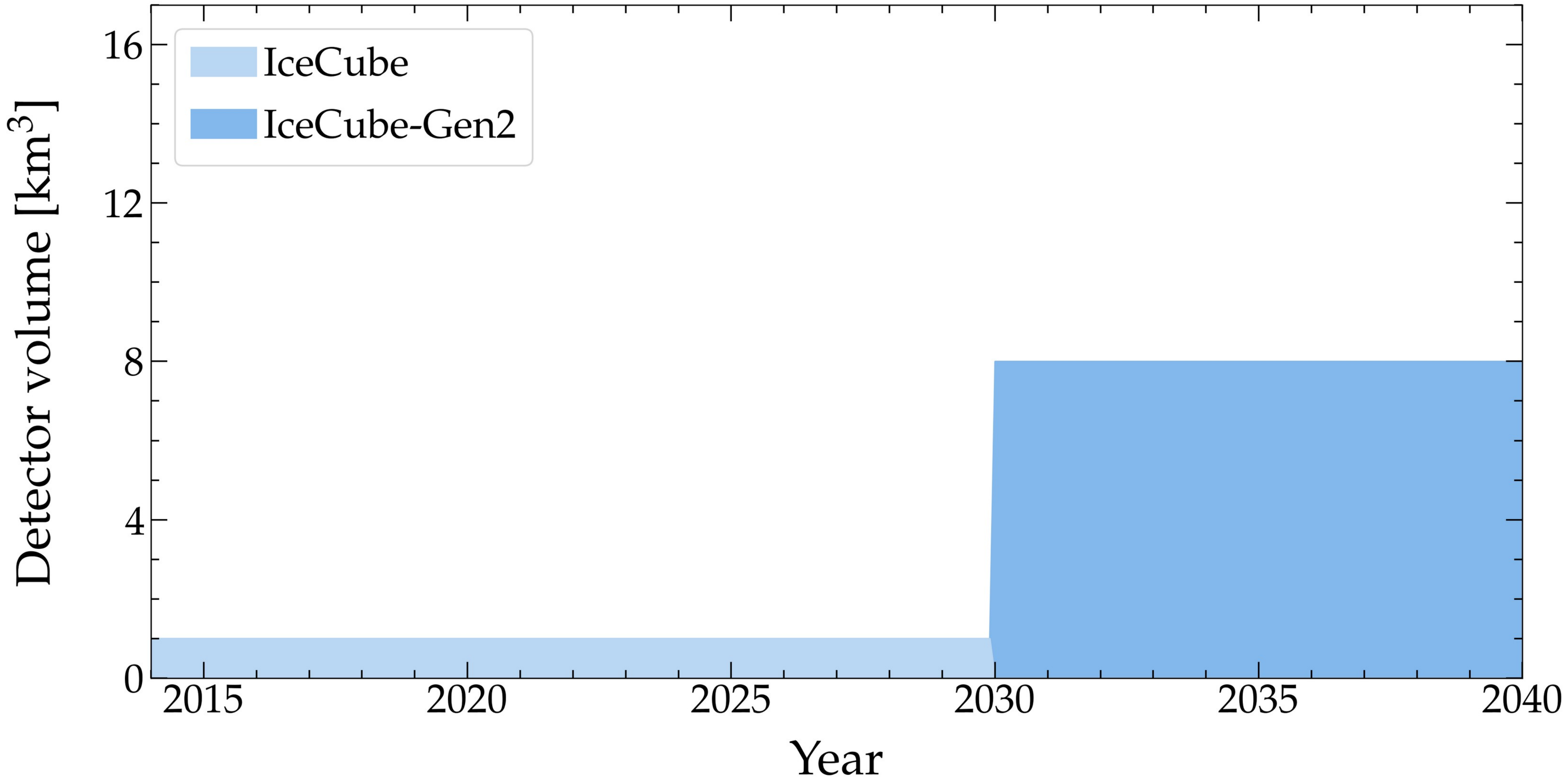
Measuring flavor composition: 2015–2040

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

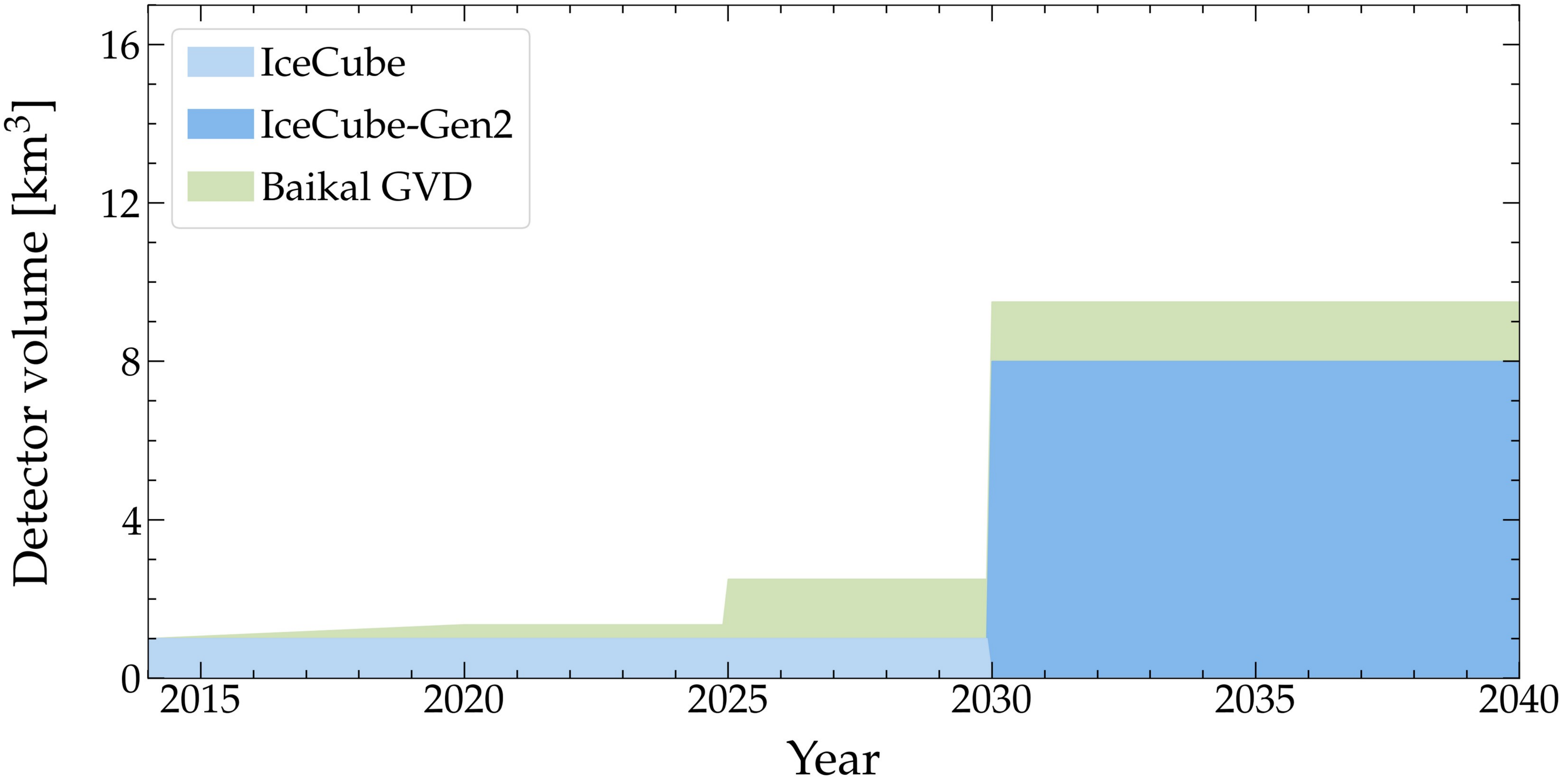




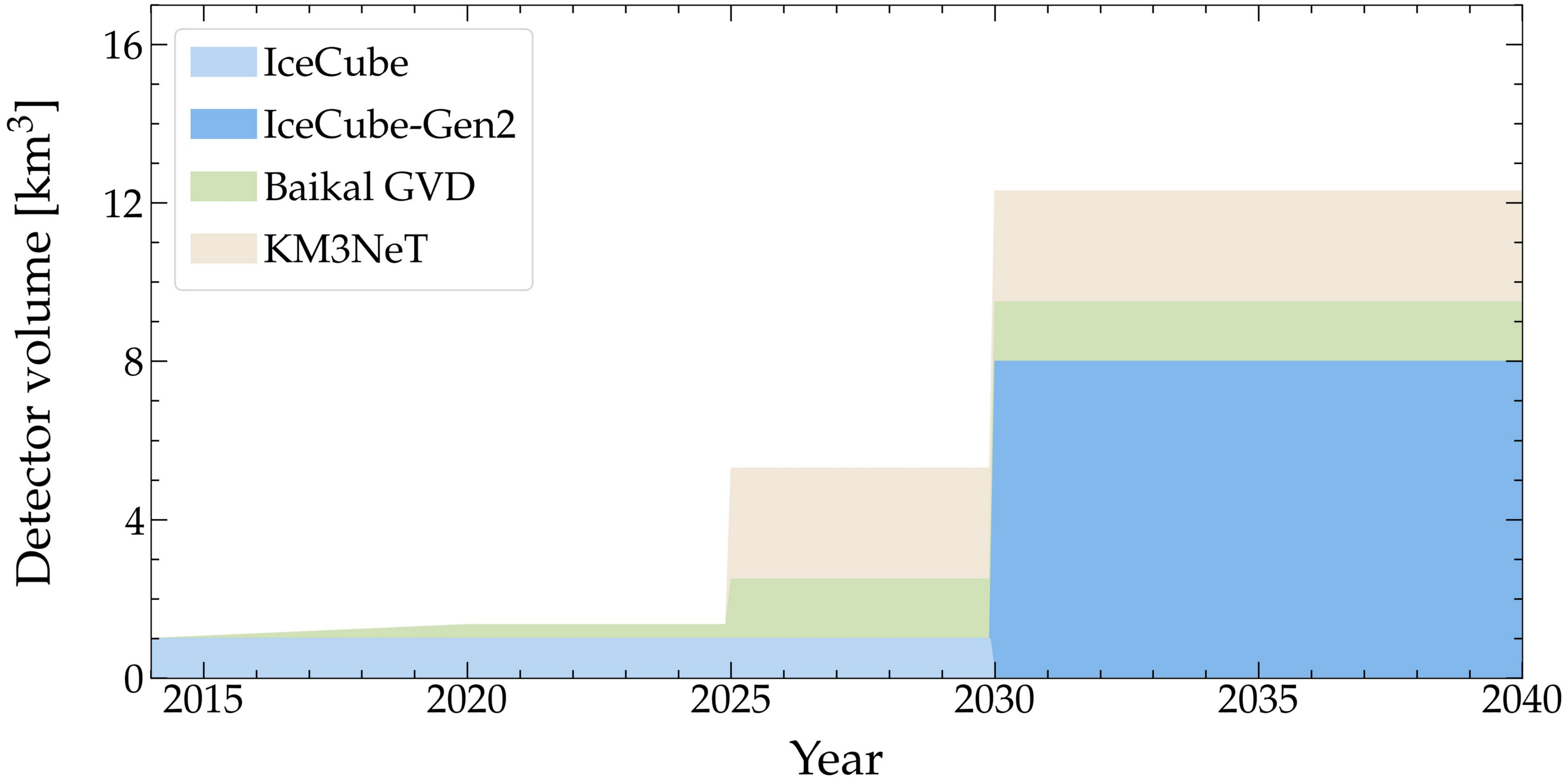
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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



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



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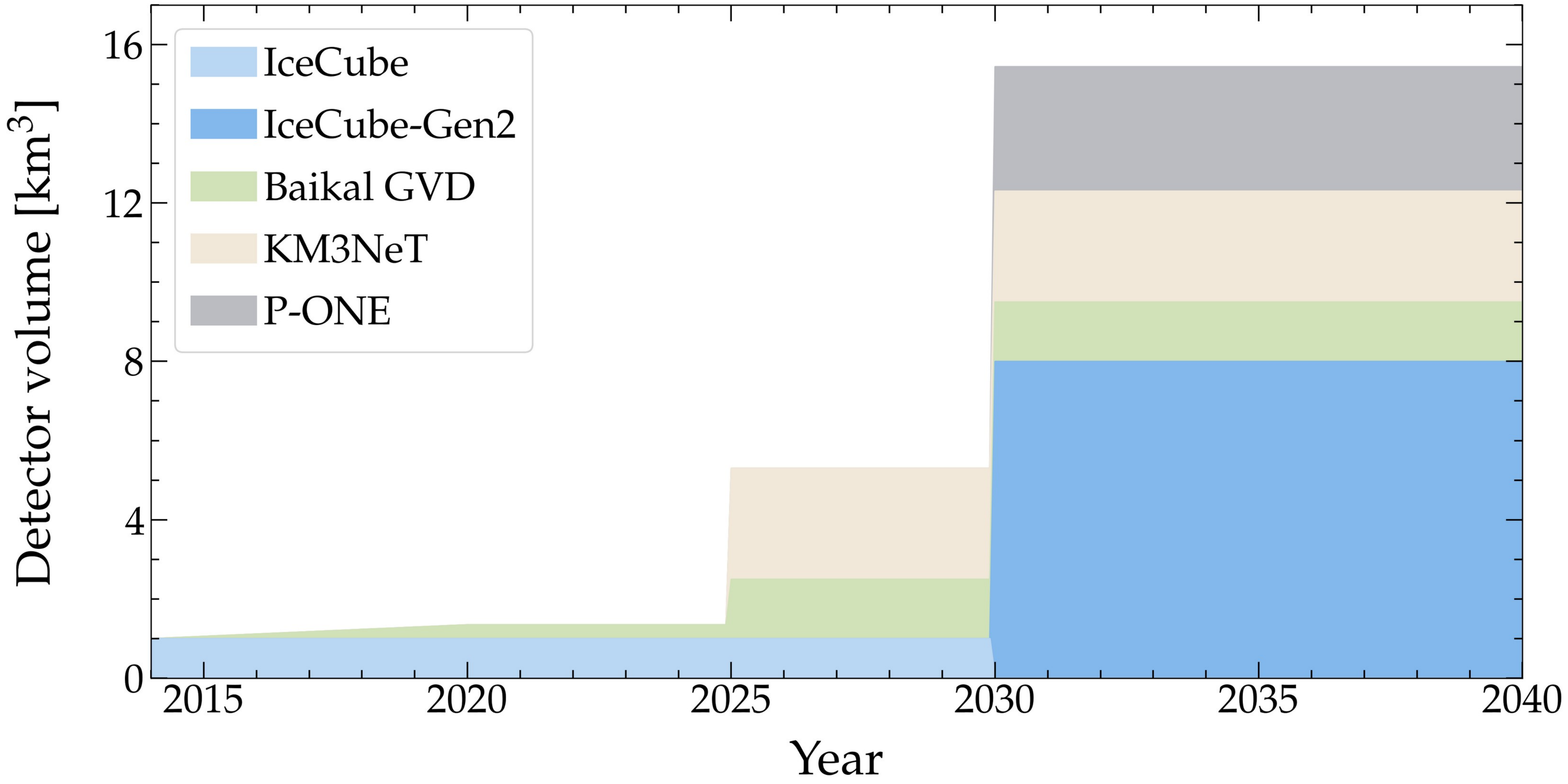
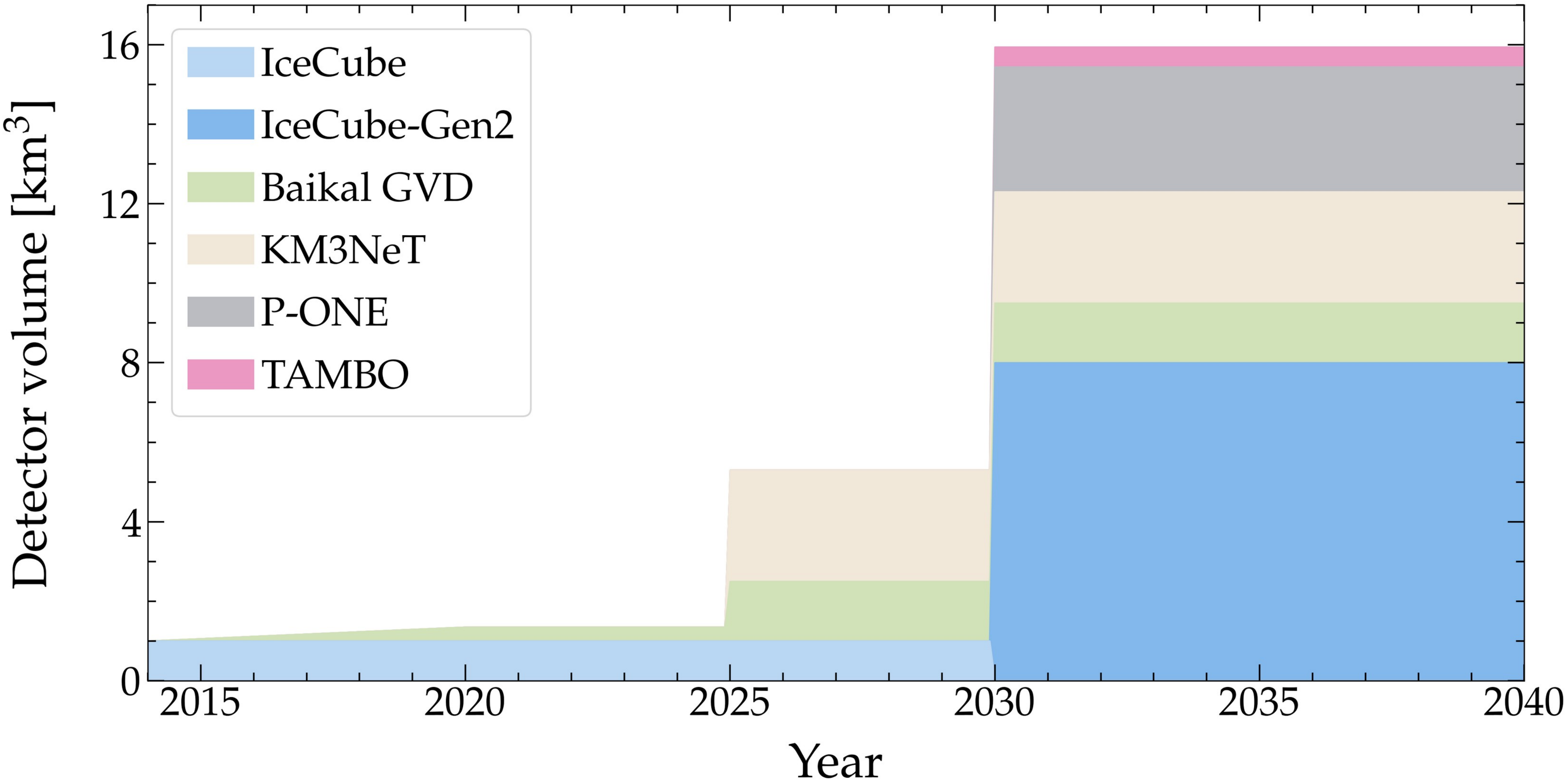
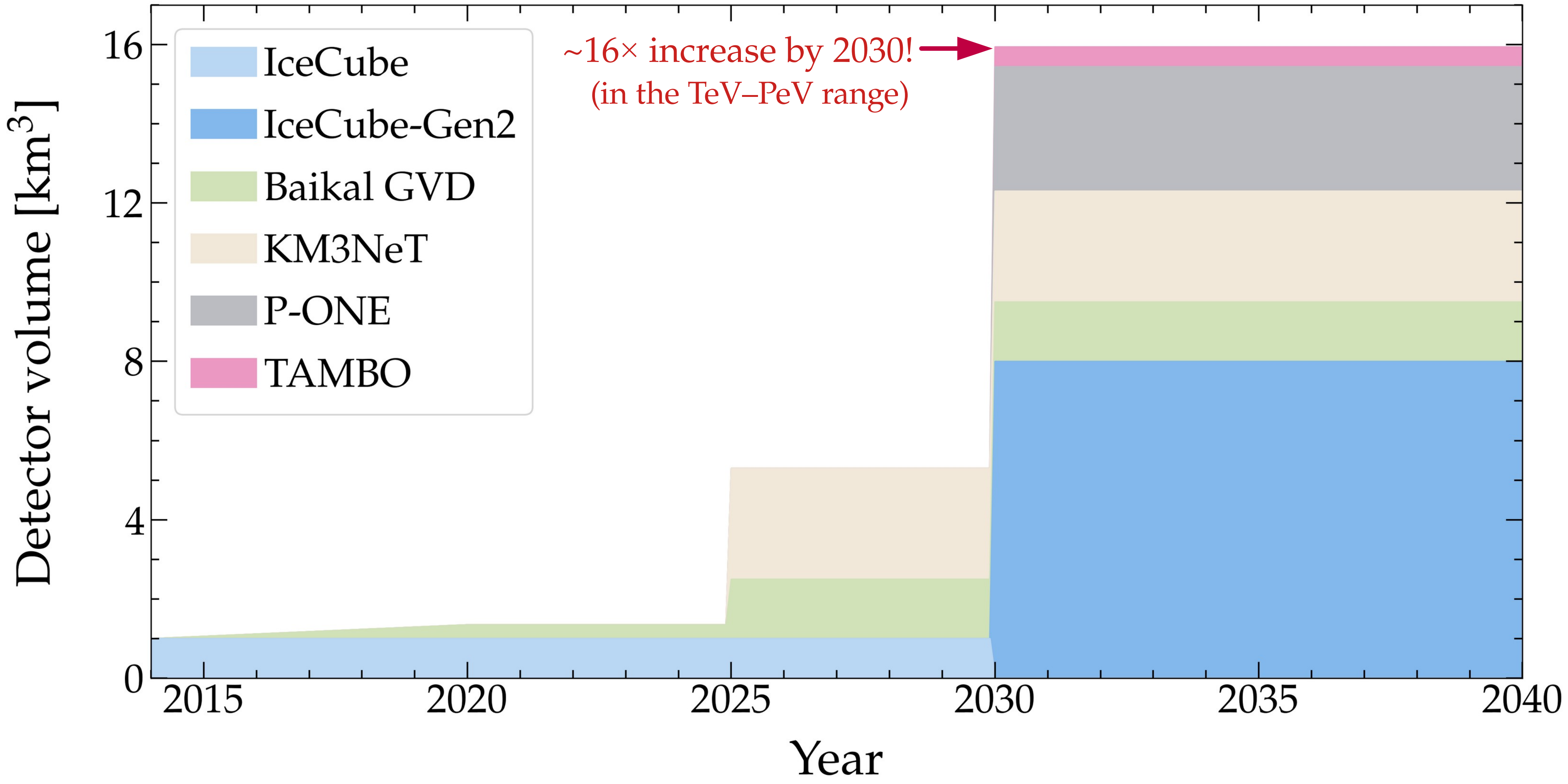


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



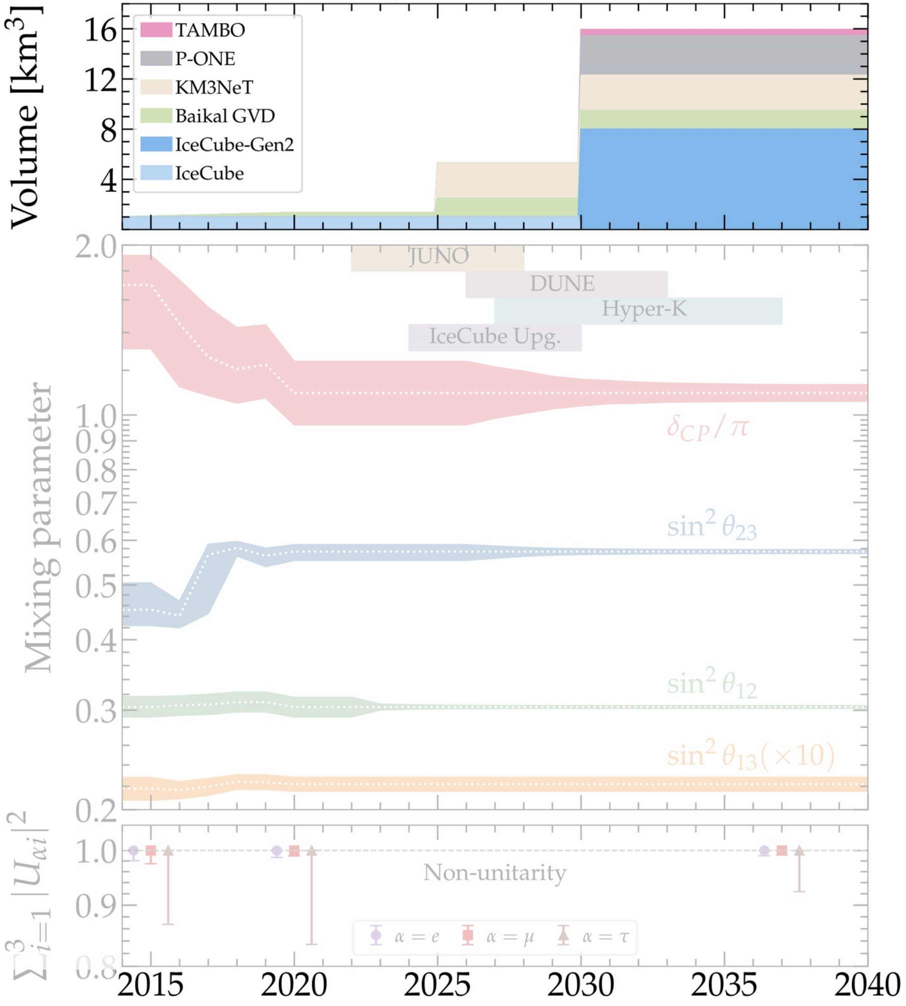
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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

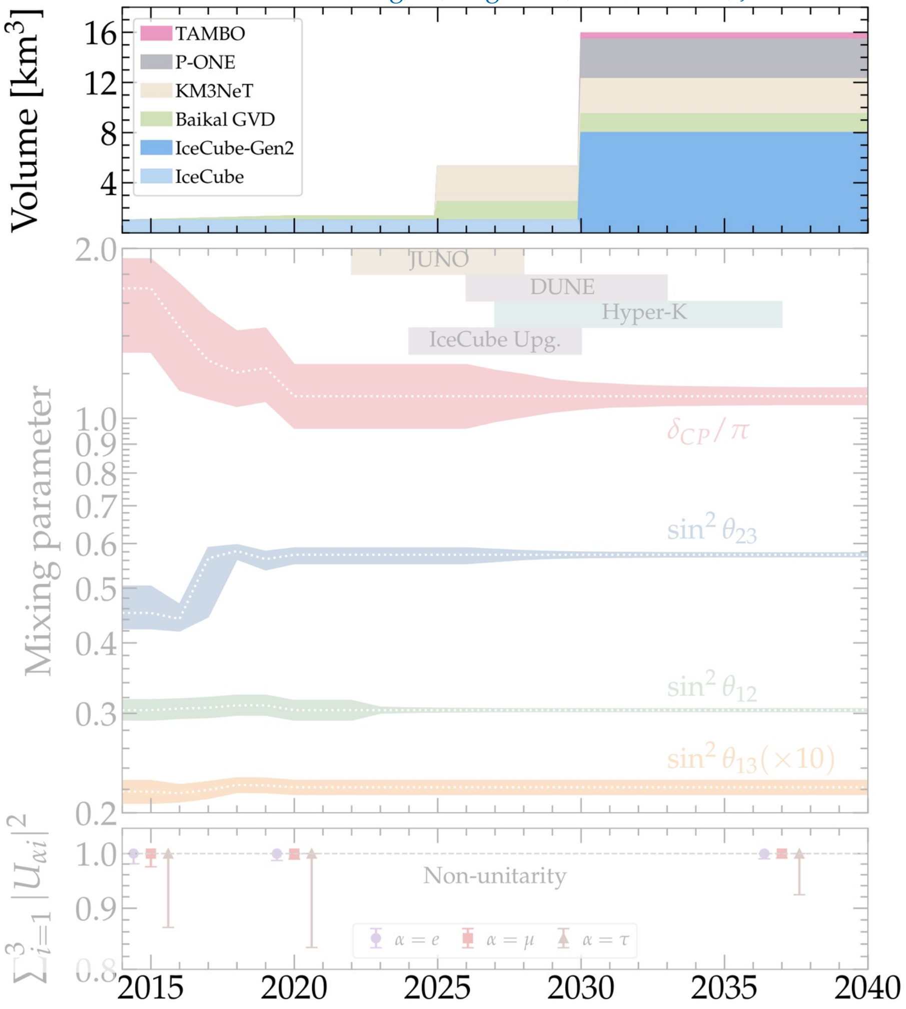
Measuring flavor composition: 2015–2040

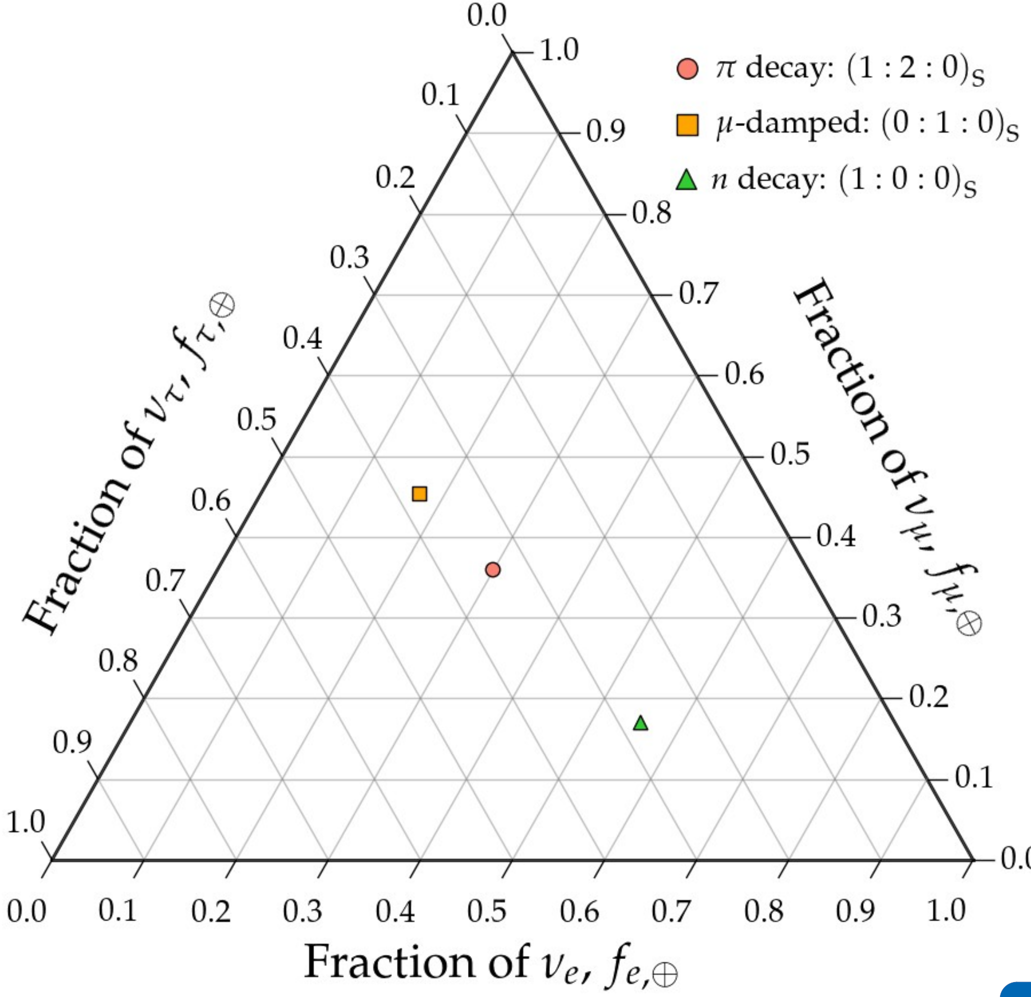
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



Measuring flavor composition: 2015–2040

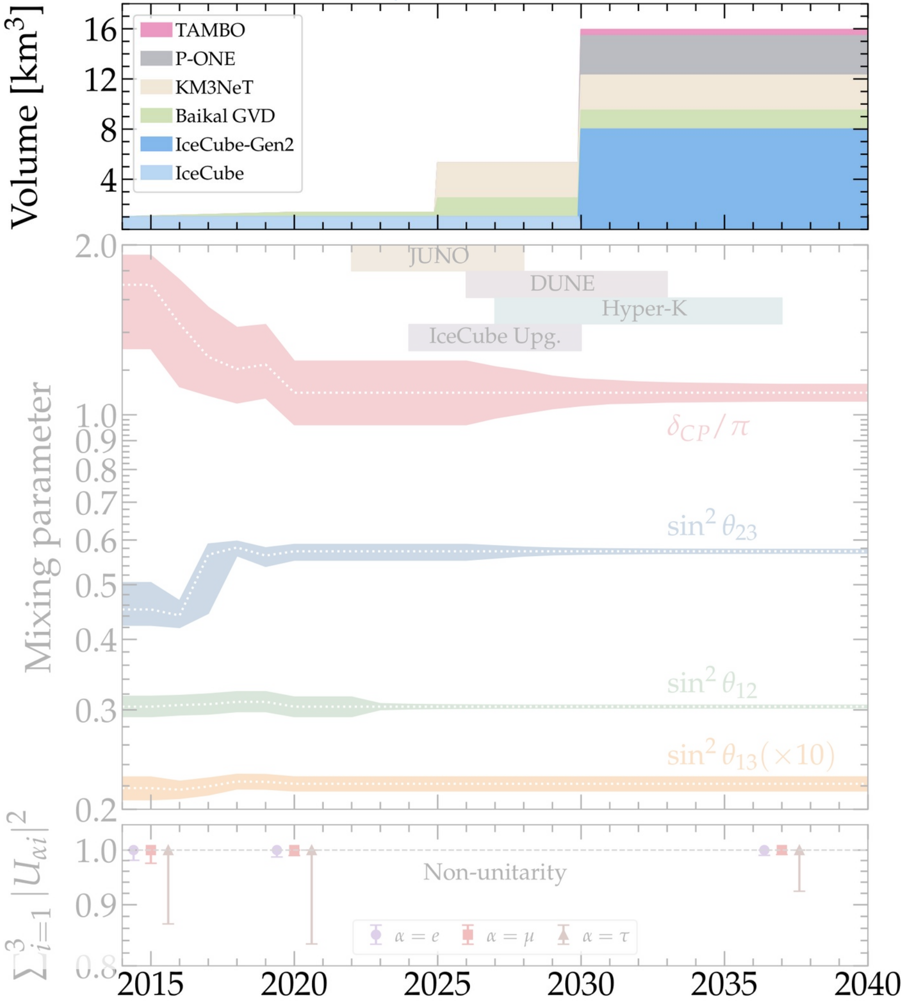
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

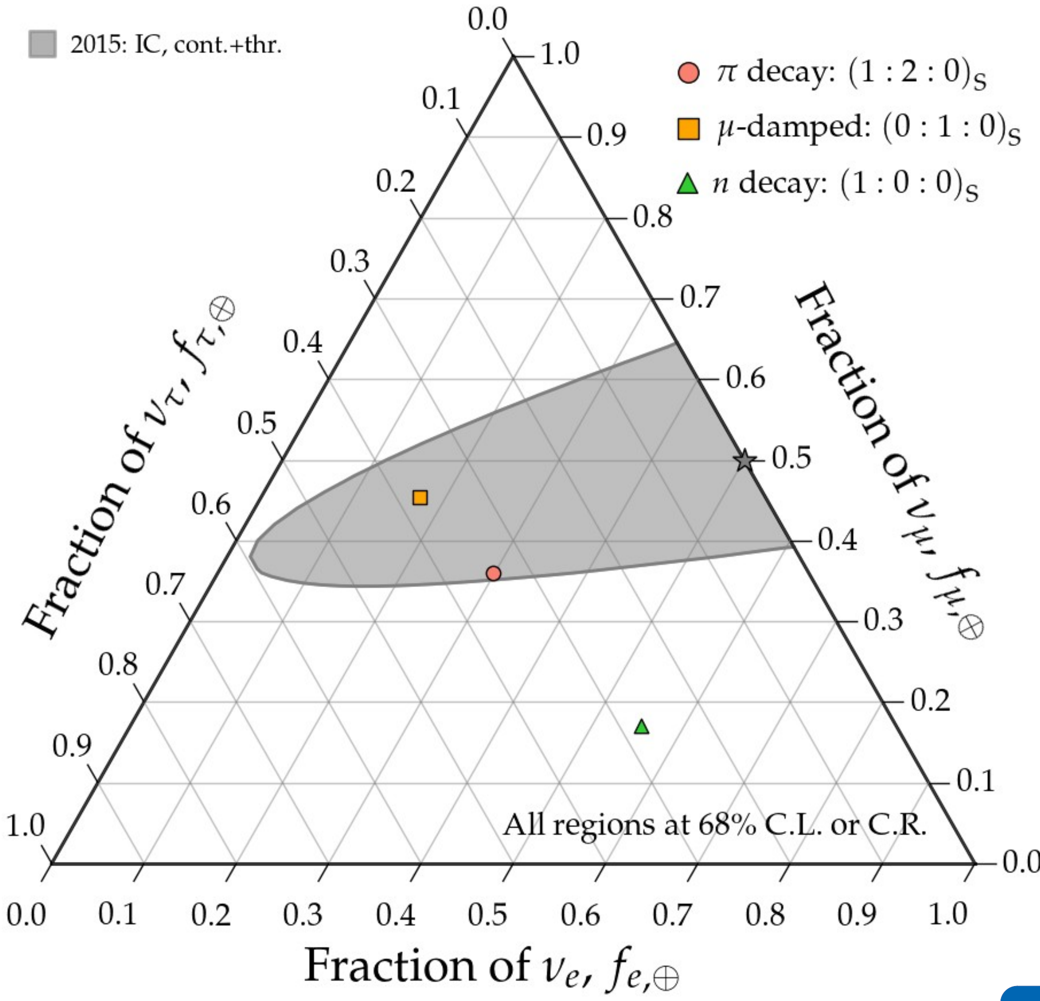




Measuring flavor composition: 2015–2040

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





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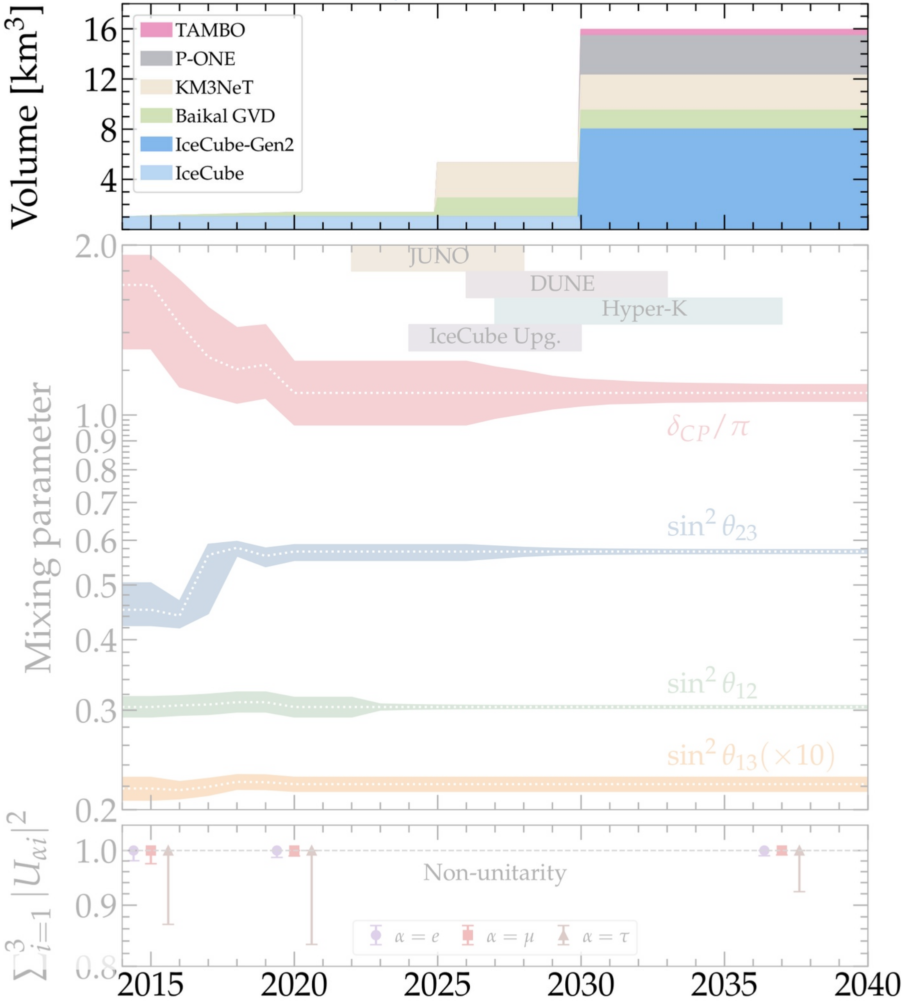
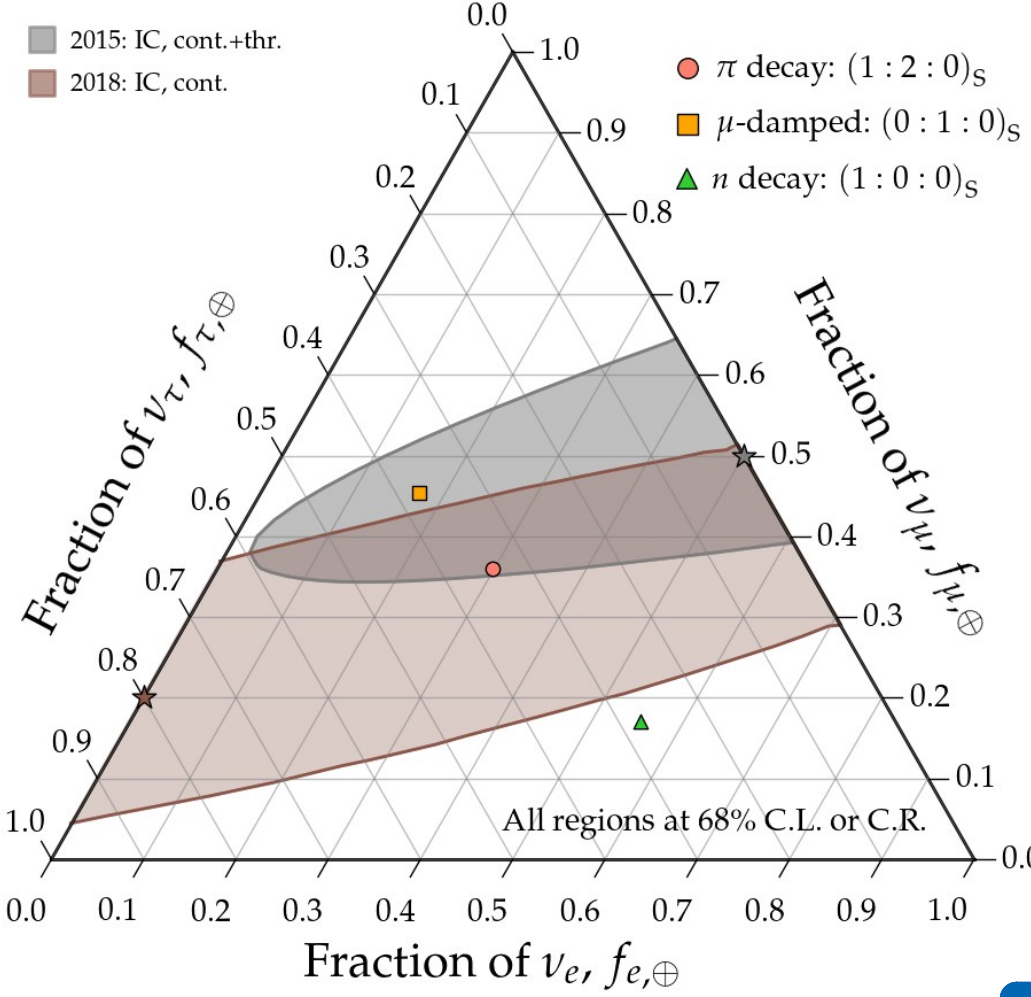
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021





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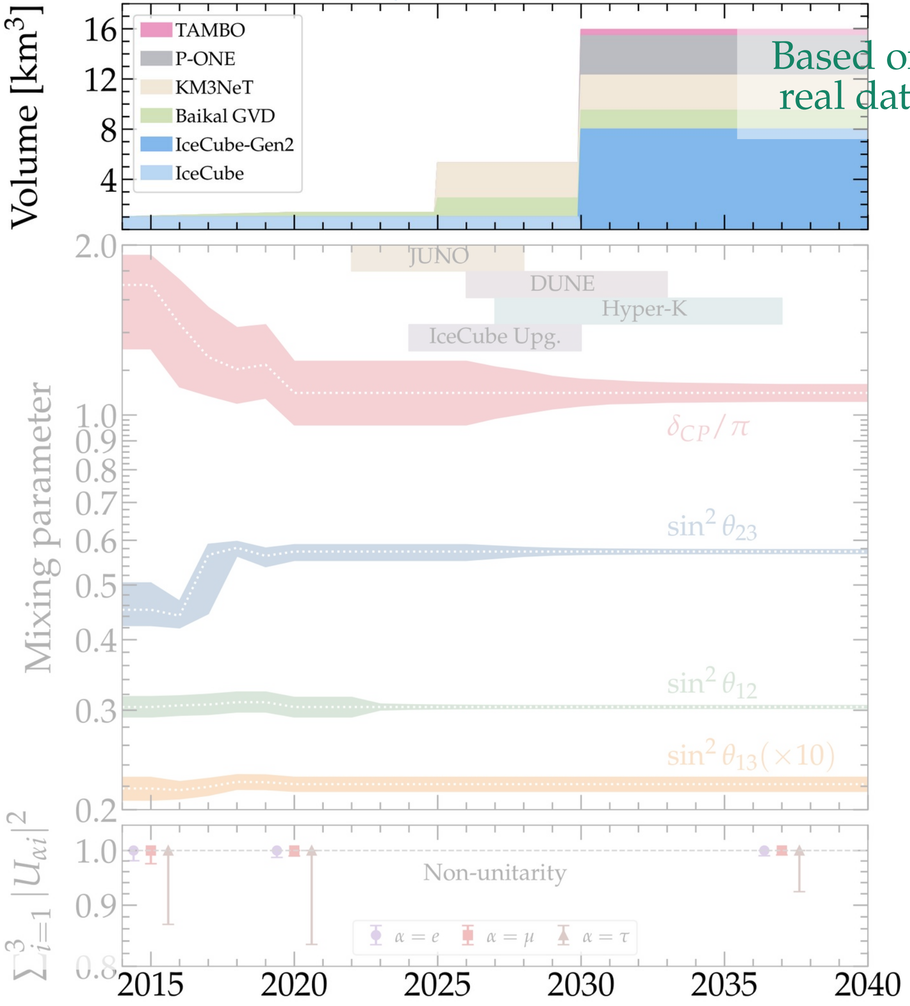
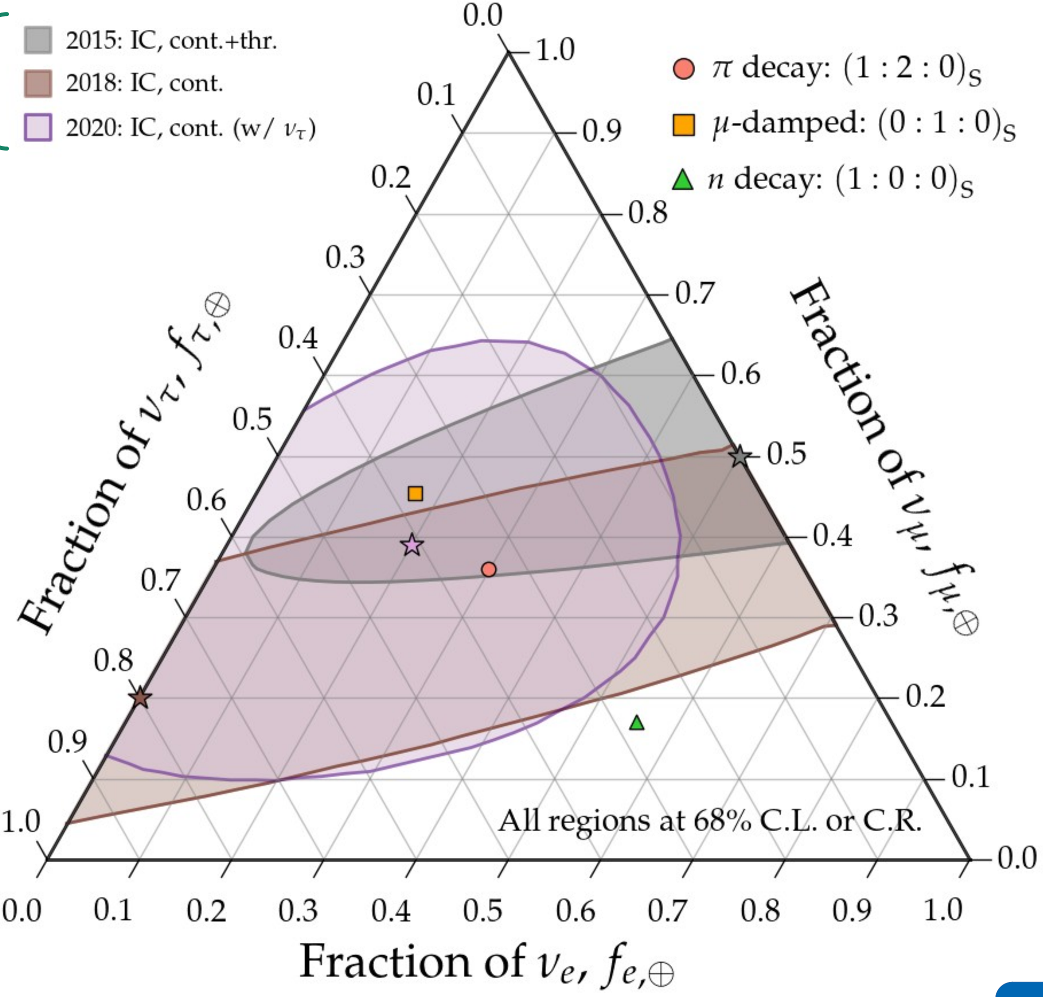


Based on real data



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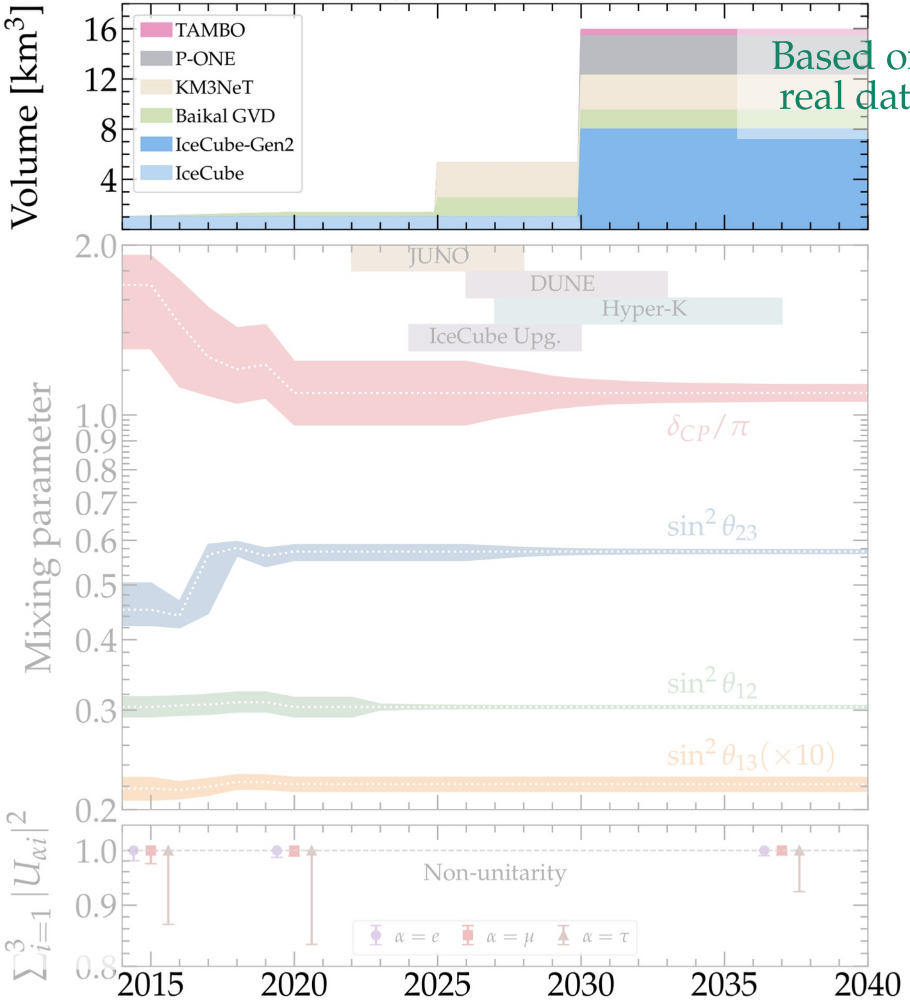
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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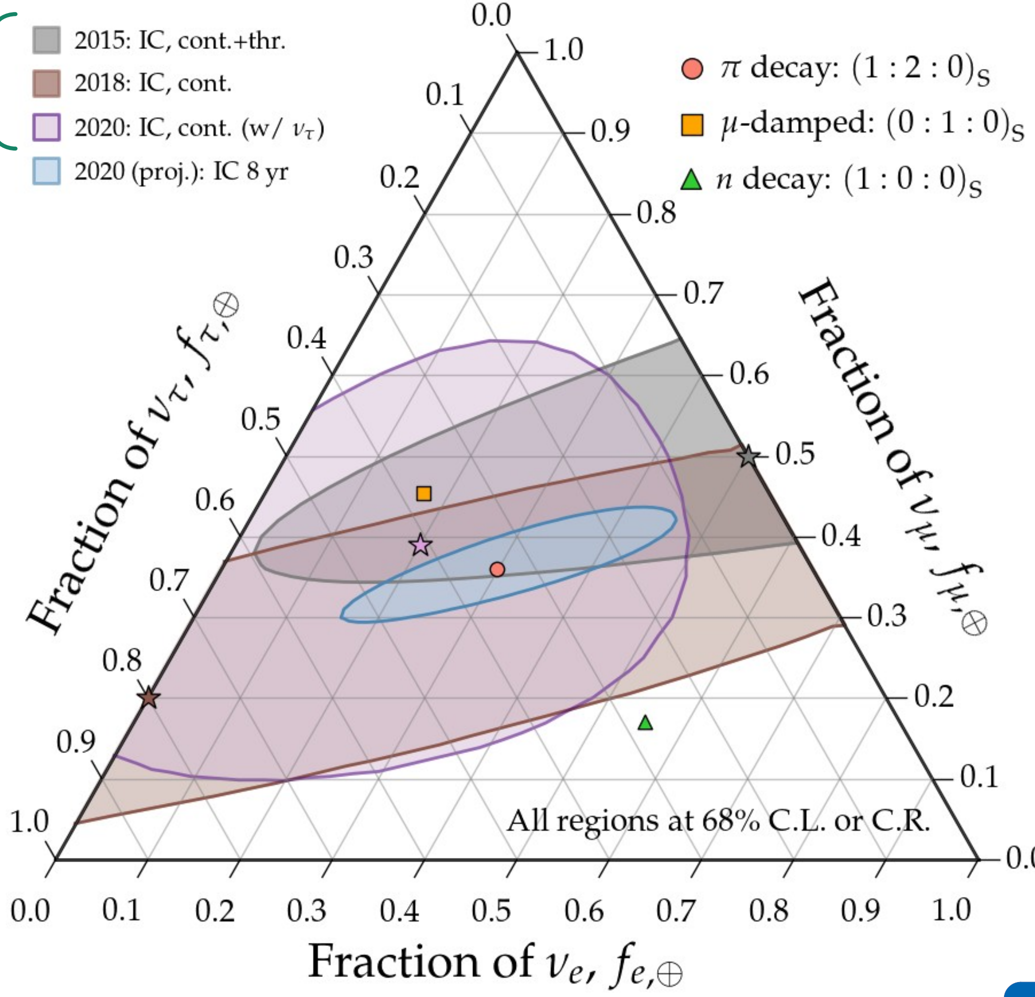

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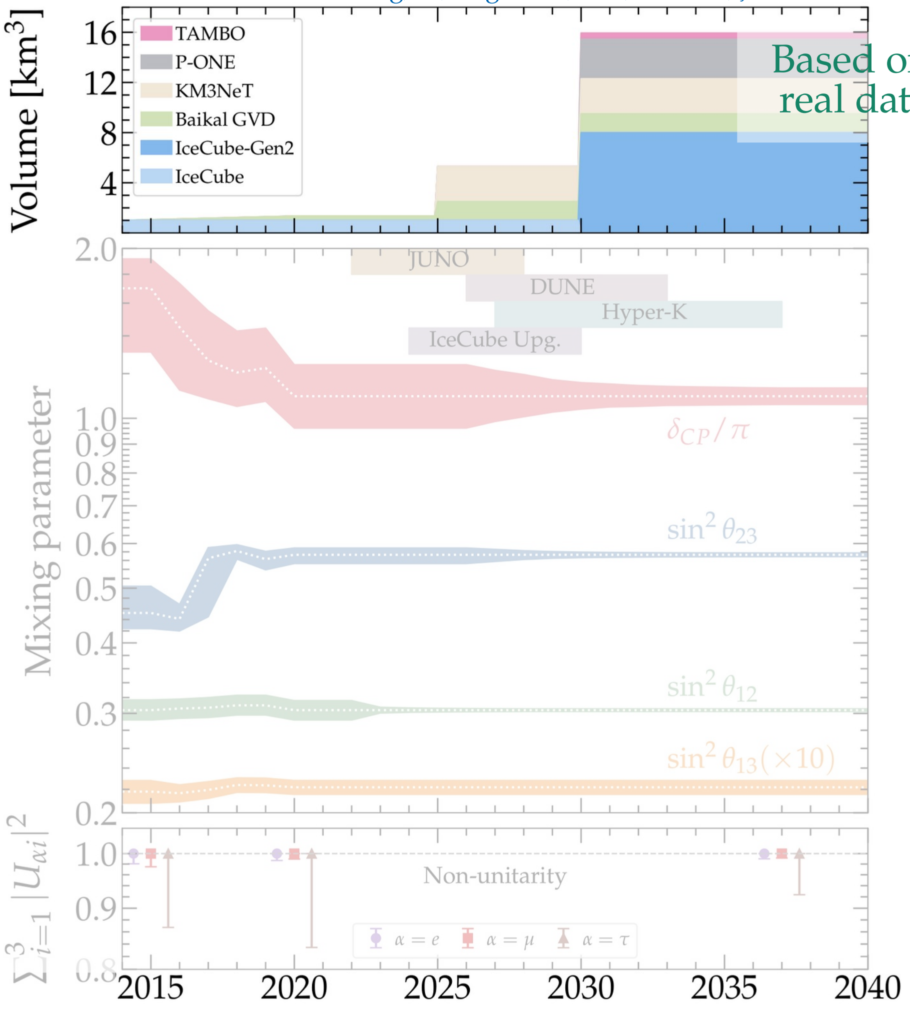

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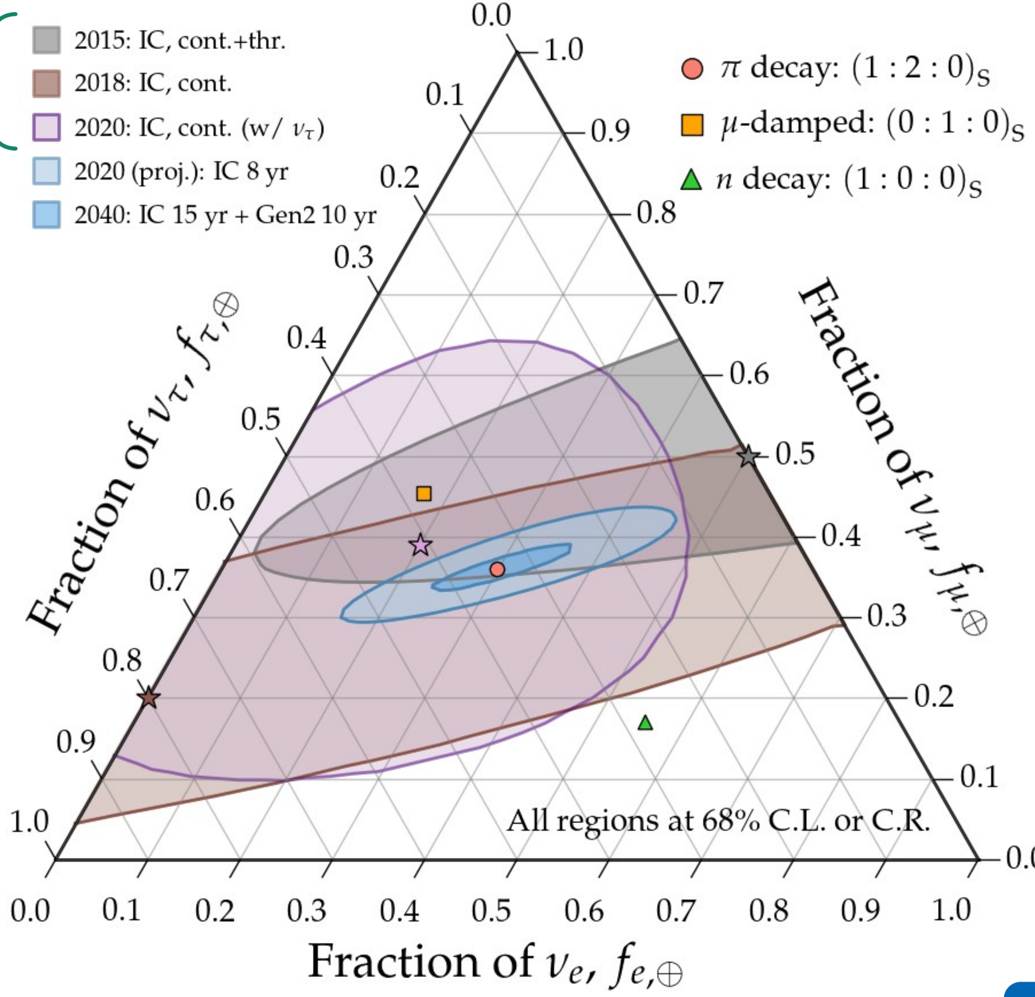
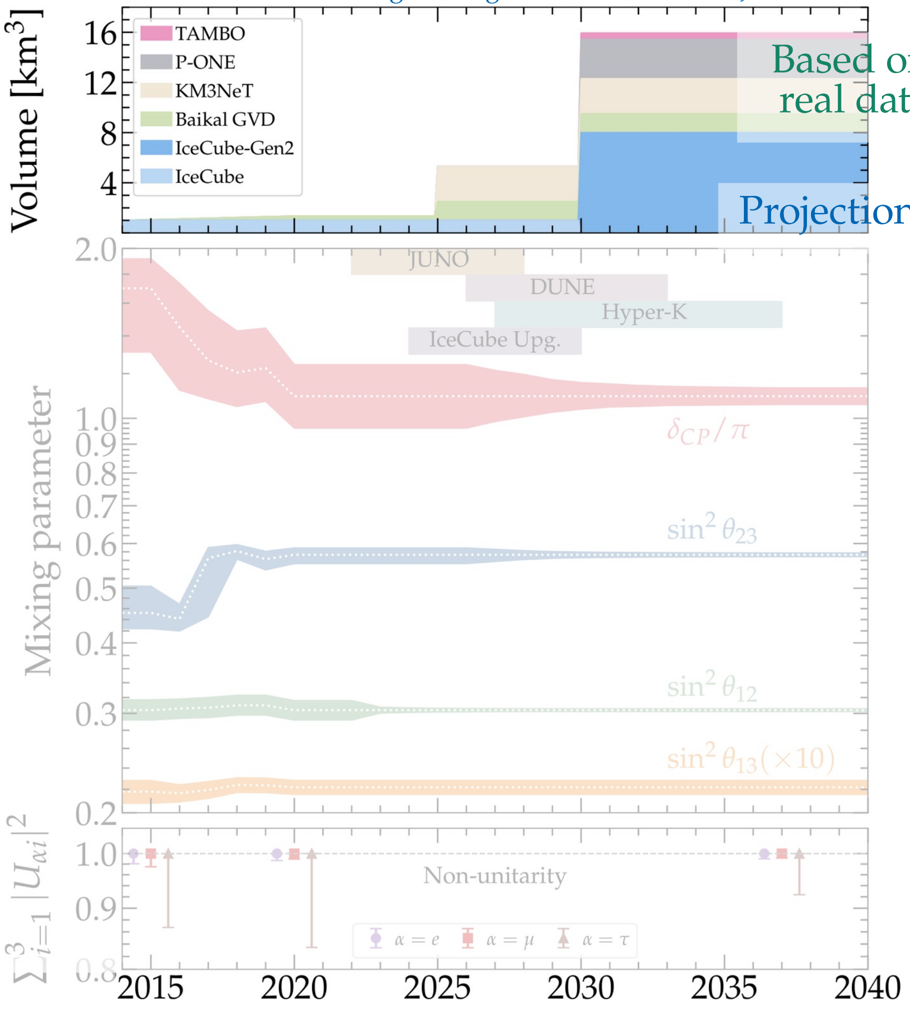
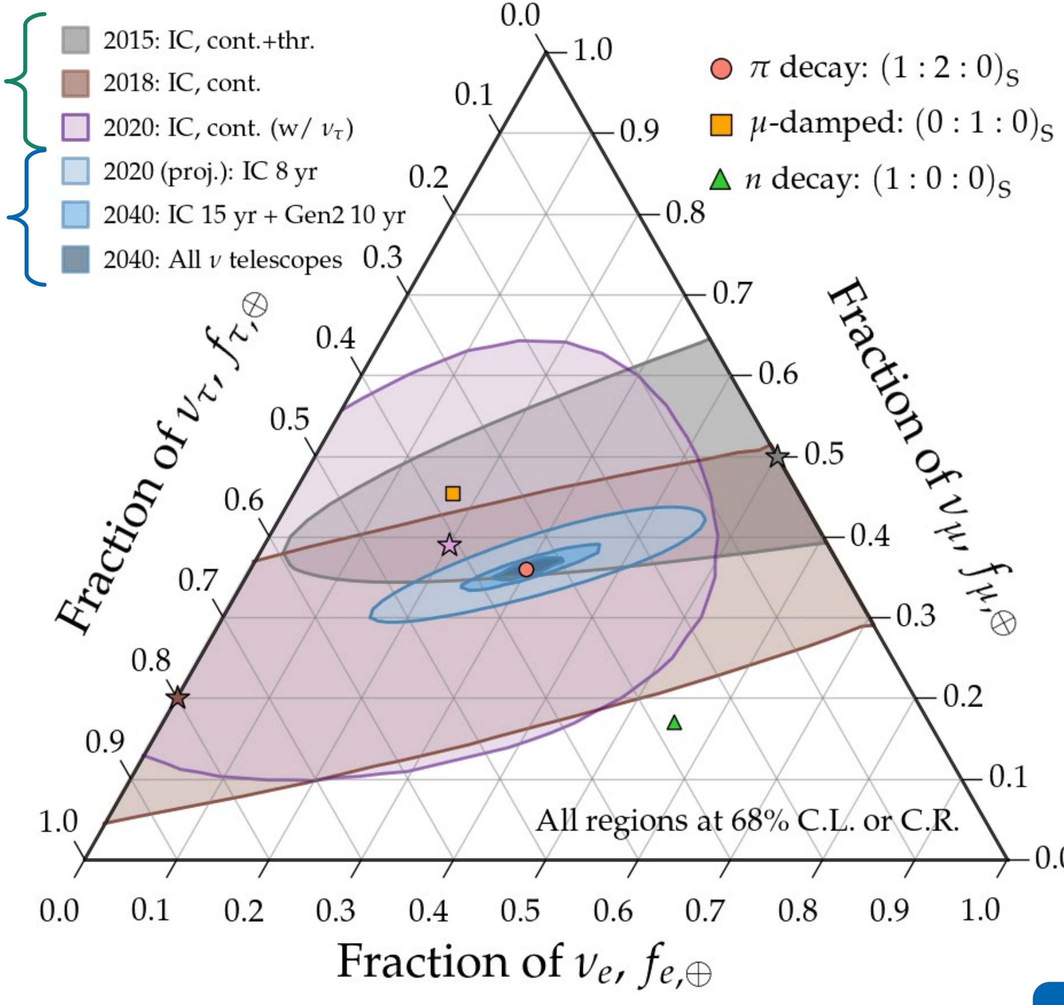


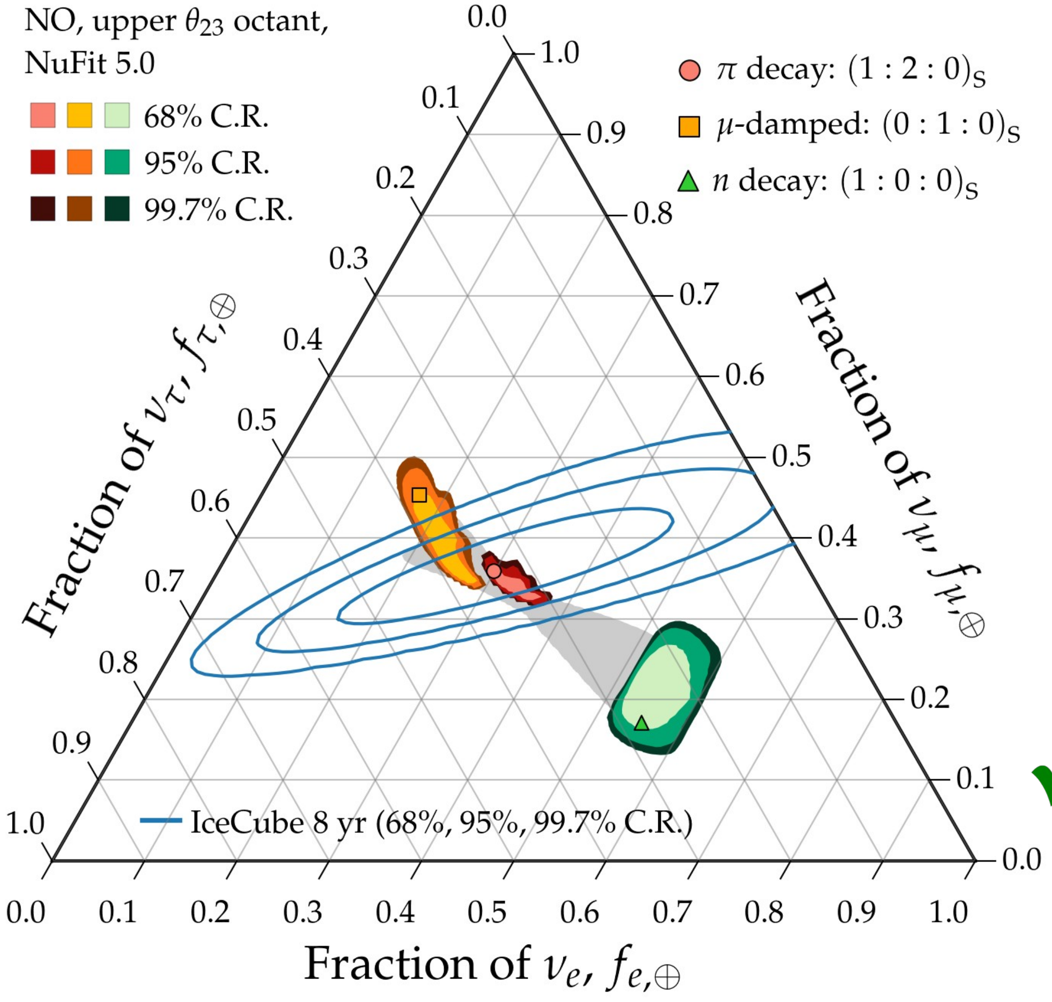
Measuring flavor composition: 2015–2040

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





Theoretically palatable regions: today (2021)



Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

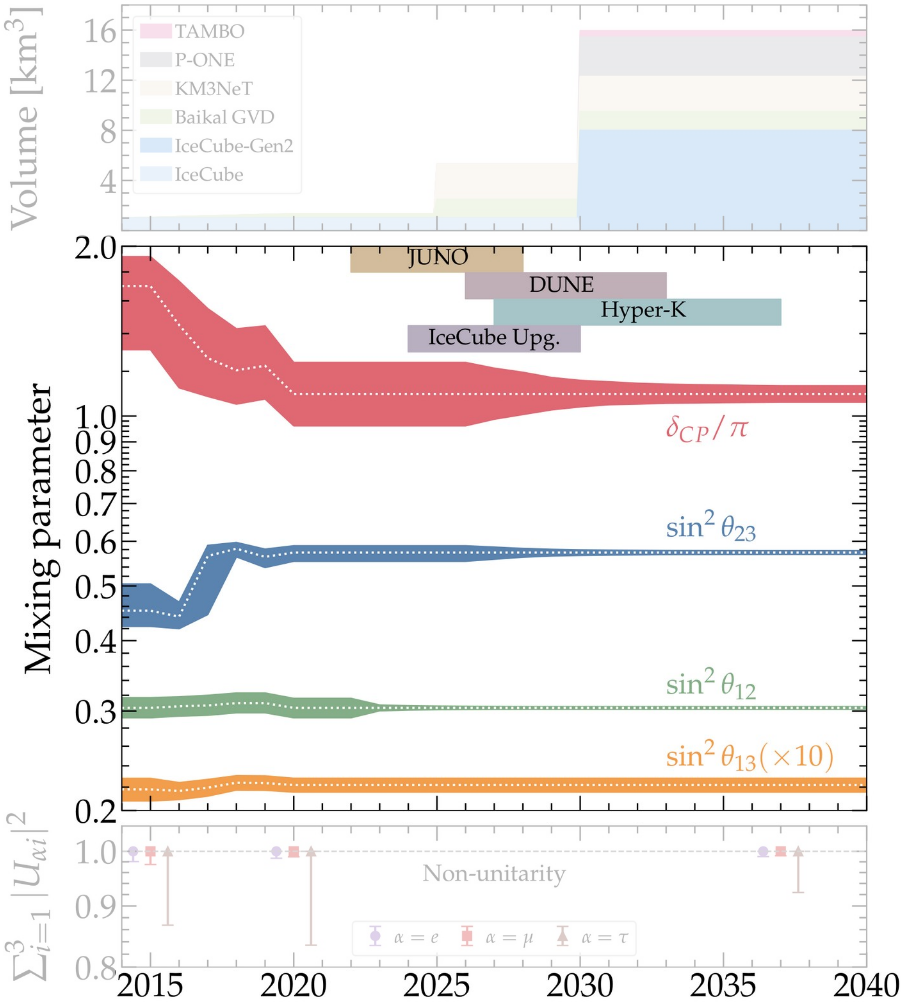
Will be overcome by 2030

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

✓ *Will be overcome by 2040*

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

How knowing the mixing parameters better helps

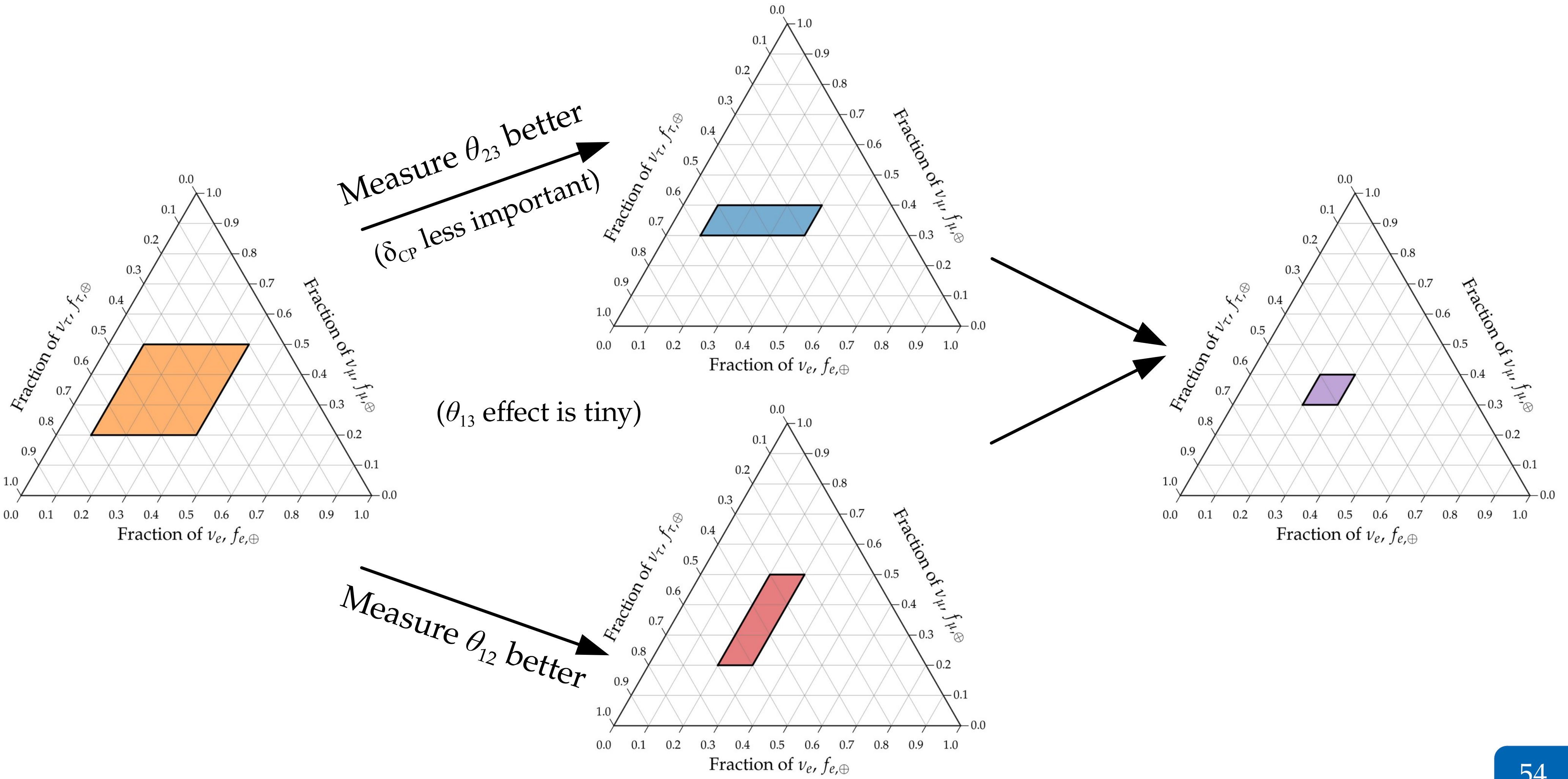


We can compute the oscillation probability more precisely:

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

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

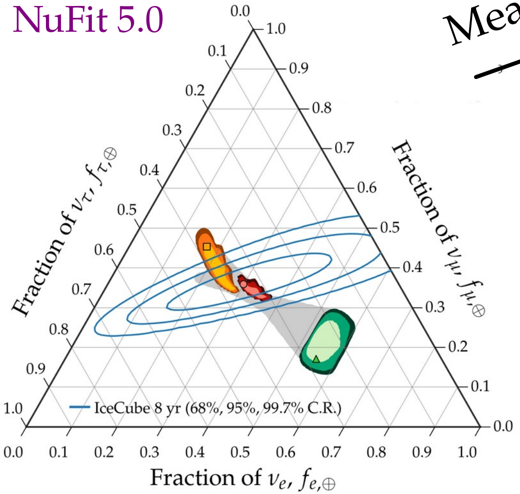
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

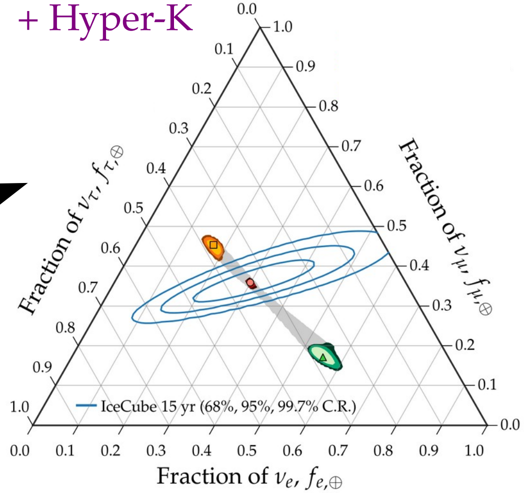
2020

NuFit 5.0



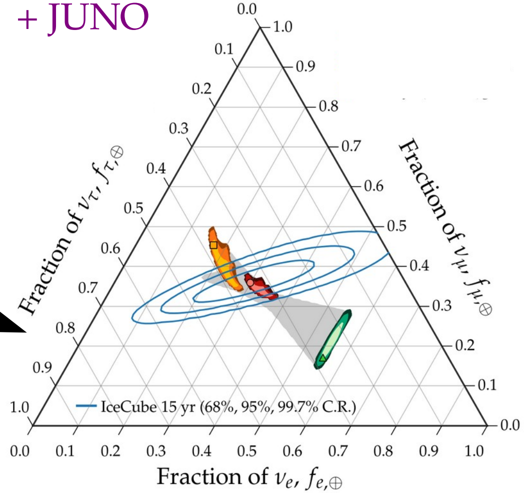
Measure θ_{23} better

+ Hyper-K



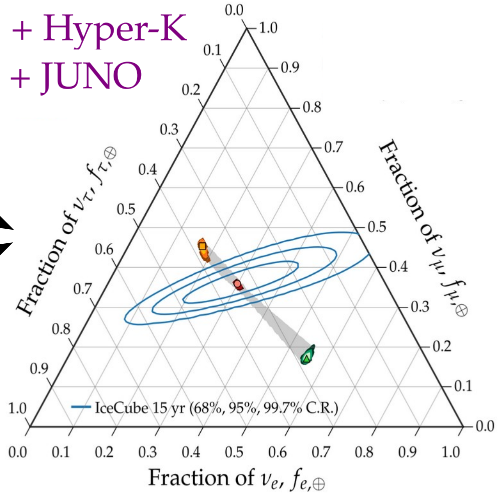
Measure θ_{12} better

+ JUNO



~2030

+ Hyper-K
+ JUNO

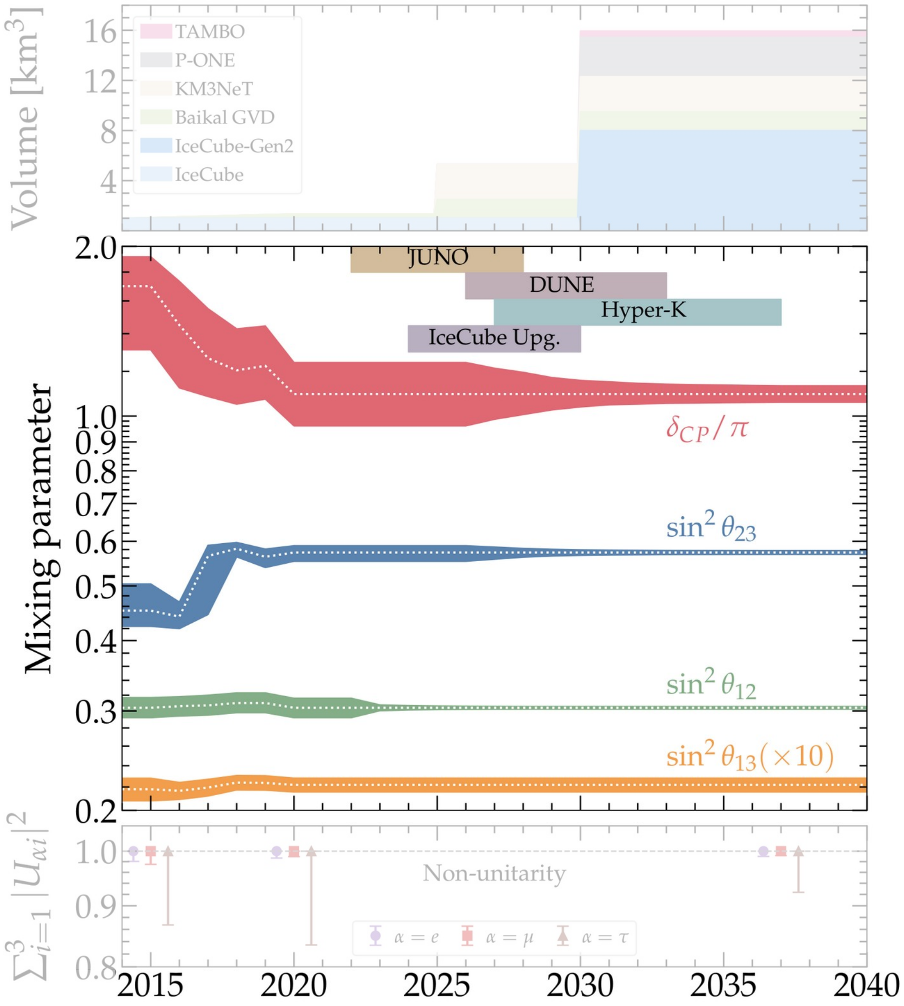


In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

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

How knowing the mixing parameters better helps



For a future experiment
ε = JUNO, DUNE, Hyper-K:

Best fit from NuFit 5.0

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

From our simulations

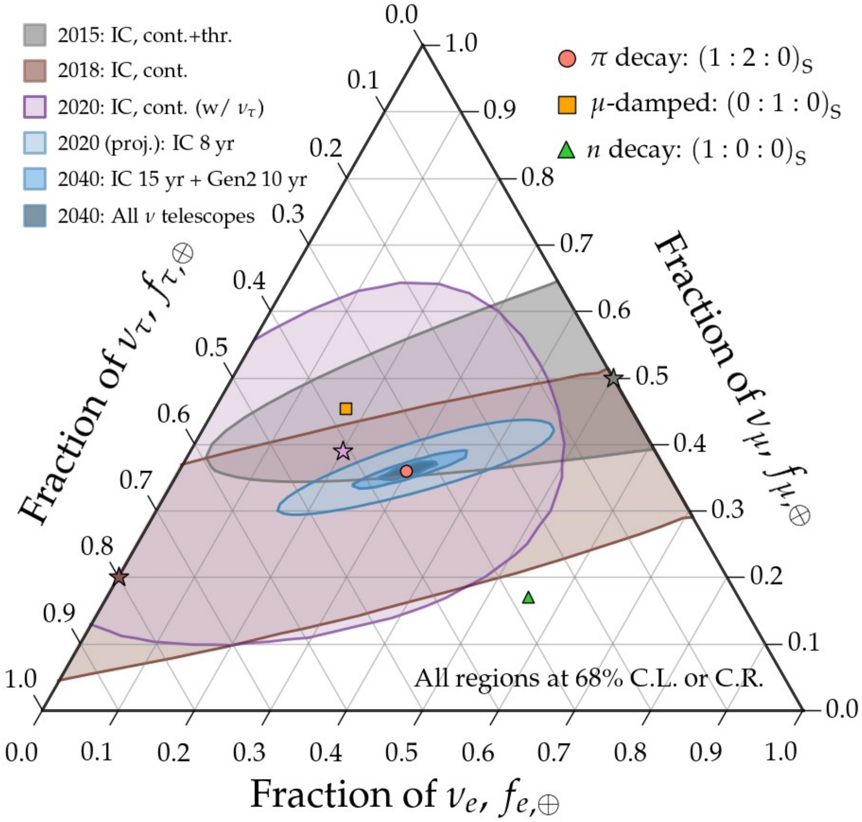
We combine experiments in a likelihood:

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

Inferring the flavor composition at the sources

Ingredient #1:

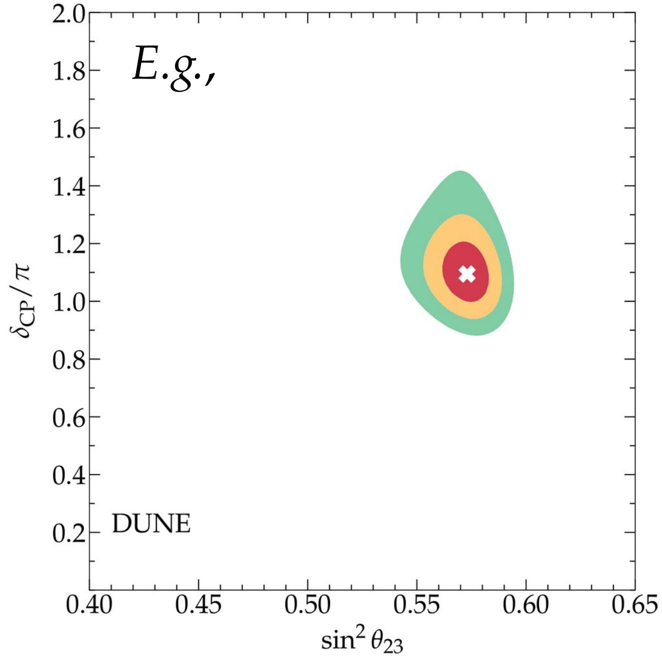
Flavor ratios measured at Earth,
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$



Ingredient #2:

Probability density of mixing parameters (θ_{12}, θ_{23}, θ_{13}, δ_{CP})

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



Song, Li, Argüelles, **MB**, Vincent, 2012.12893
MB & Ahlers, *PRL* 2019

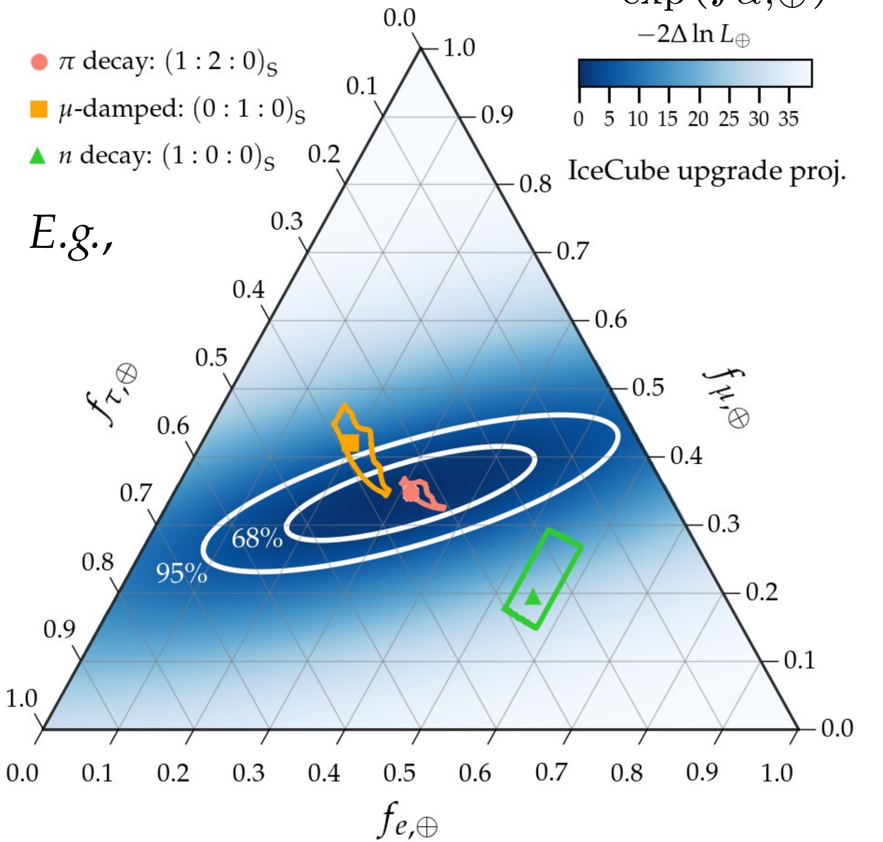
Inferring the flavor composition at the sources

Ingredient #1:

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

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

E.g.,



Ingredient #2:

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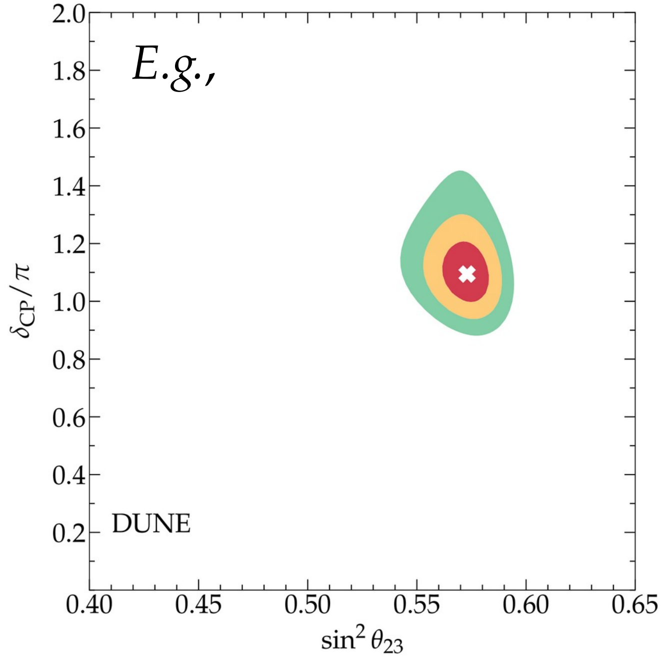
$\mathcal{L}(\boldsymbol{\vartheta})$

E.g.,



Song, Li, Argüelles, **MB**, Vincent, 2012.12893
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Posterior probability of $f_{\alpha,\rm S}$ [**MB** & Ahlers, *PRL* 2019]:

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

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
MB & Ahlers, *PRL* 2019

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

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Song, Li, Argüelles, **MB**, Vincent, 2012.12893
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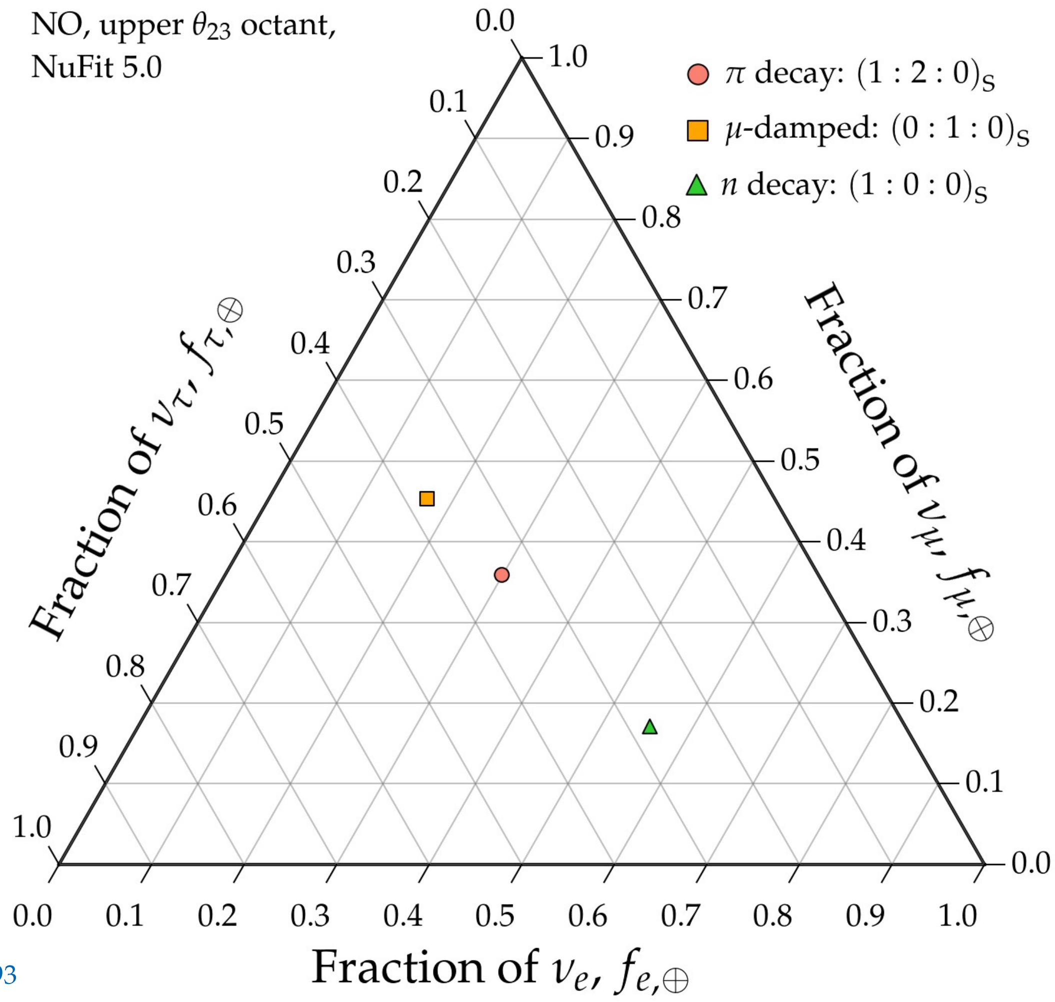
Theoretically palatable regions: today (2020)



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

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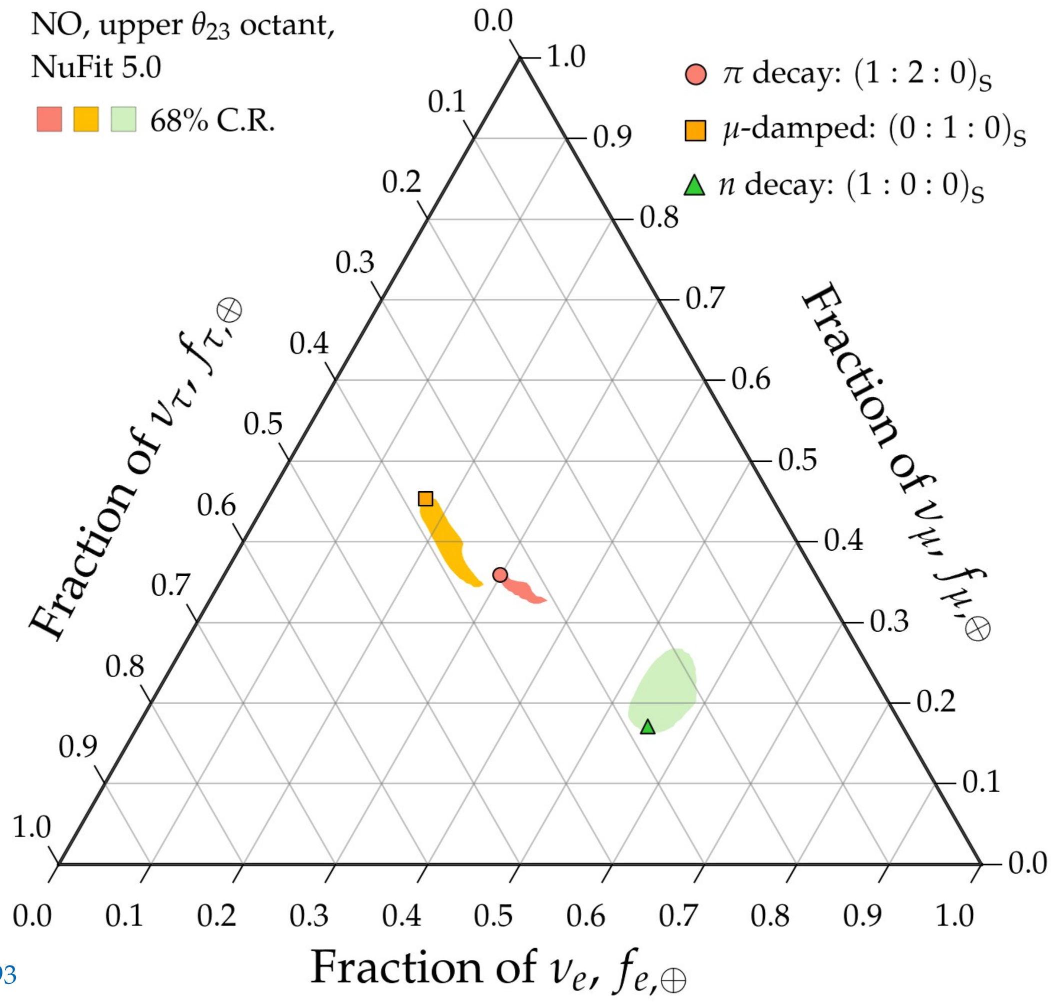

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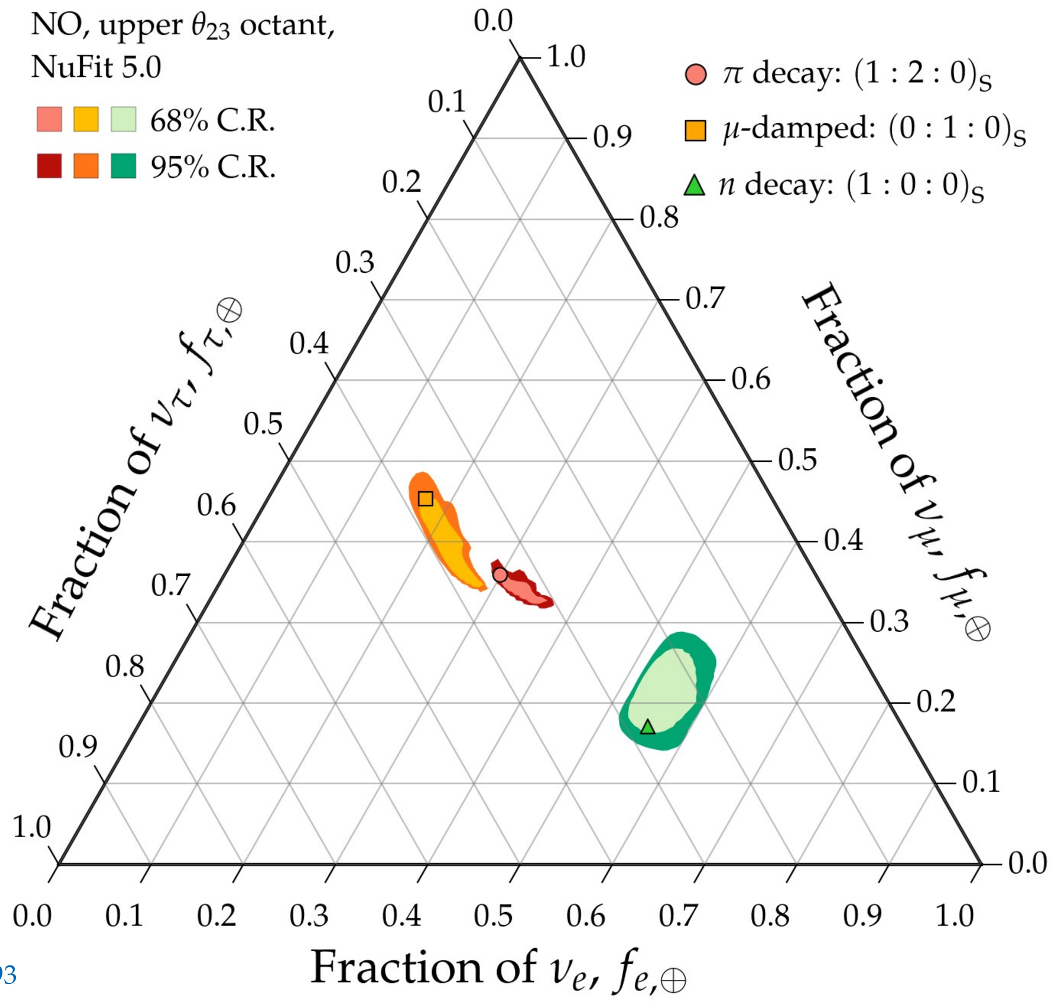

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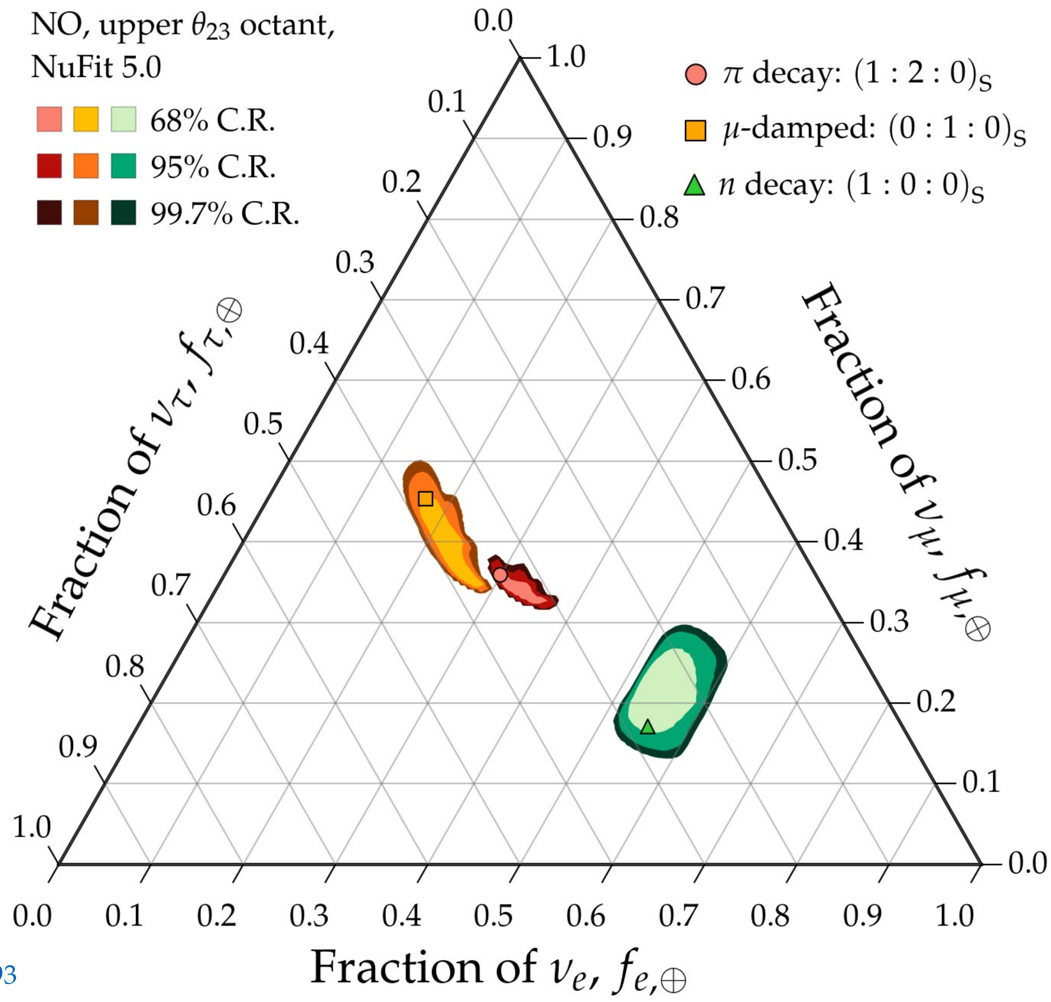

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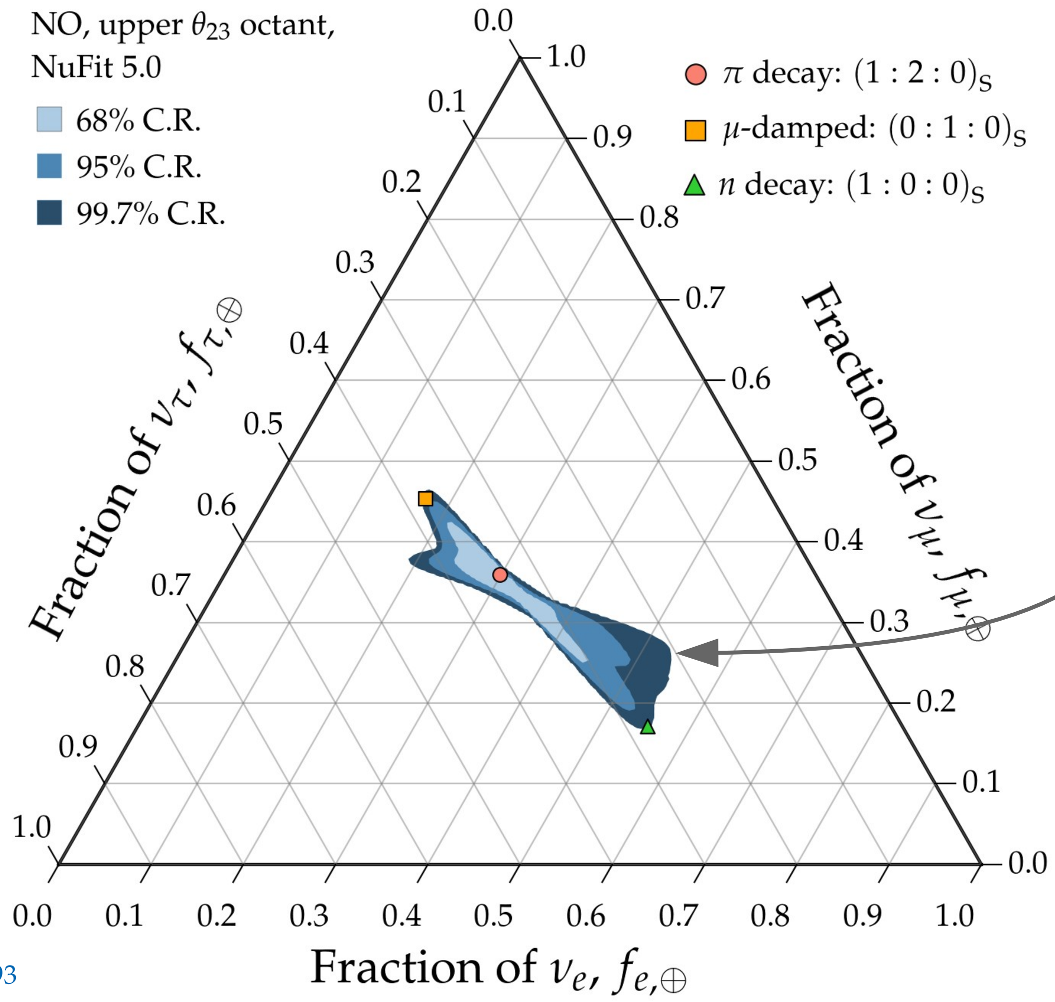

Varying over all possible flavor ratios at the source

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Song, Li, Argüelles, **MB**, Vincent, 2012.12893
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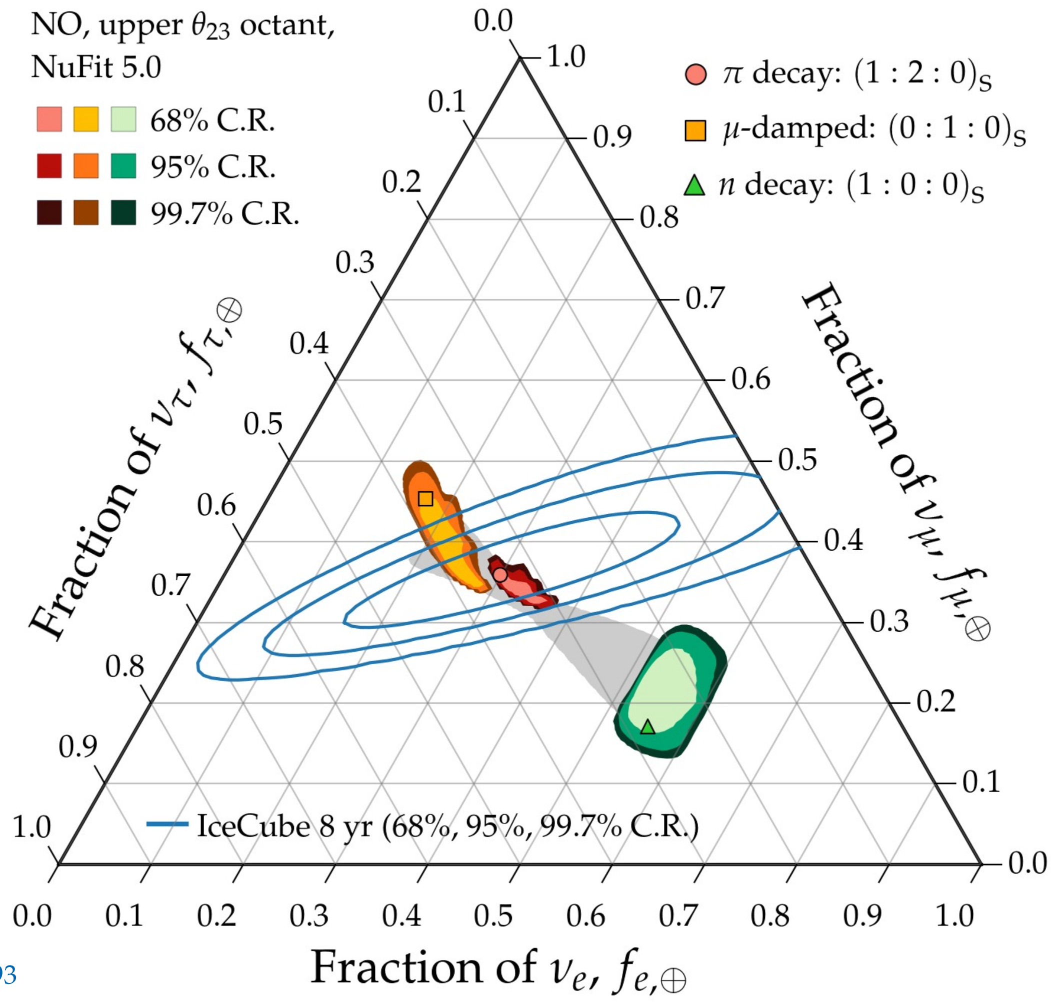
Theoretically palatable regions: today (2020)



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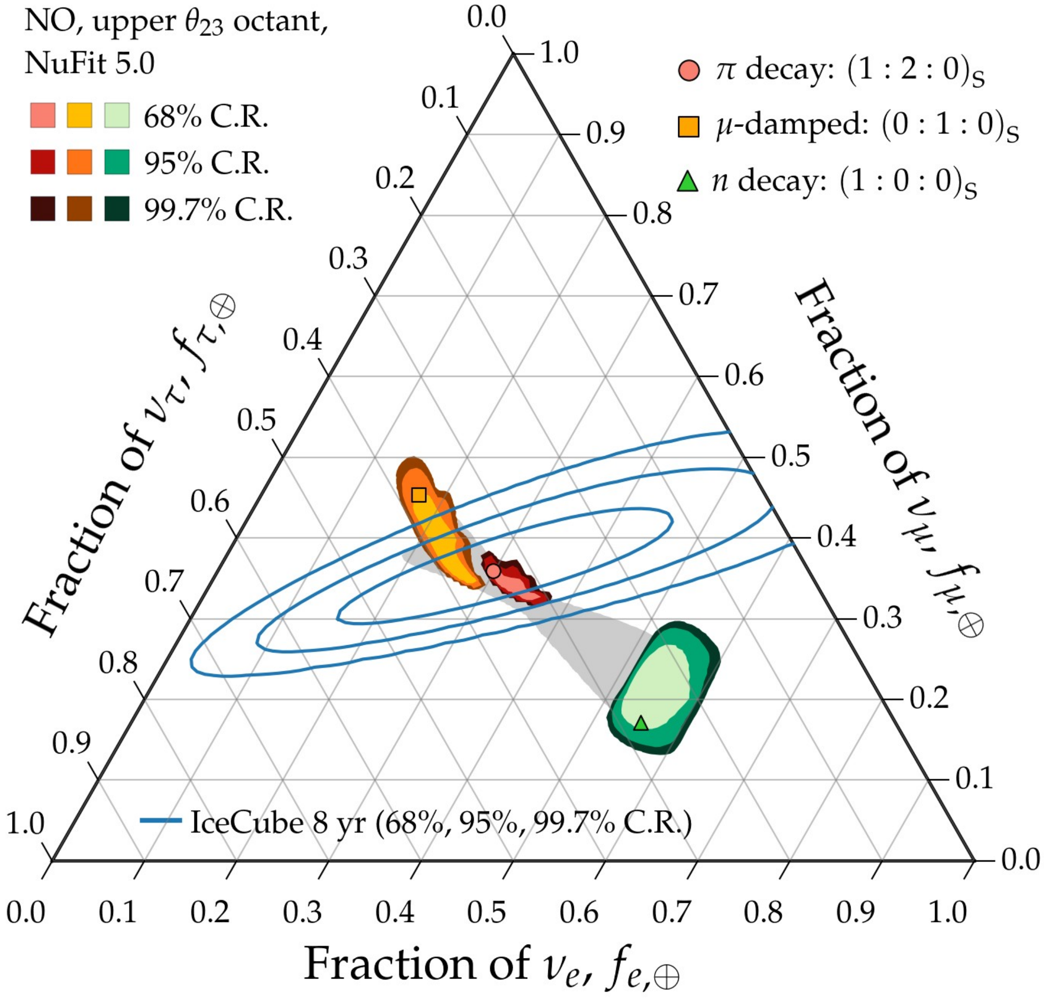

Two limitations:

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)

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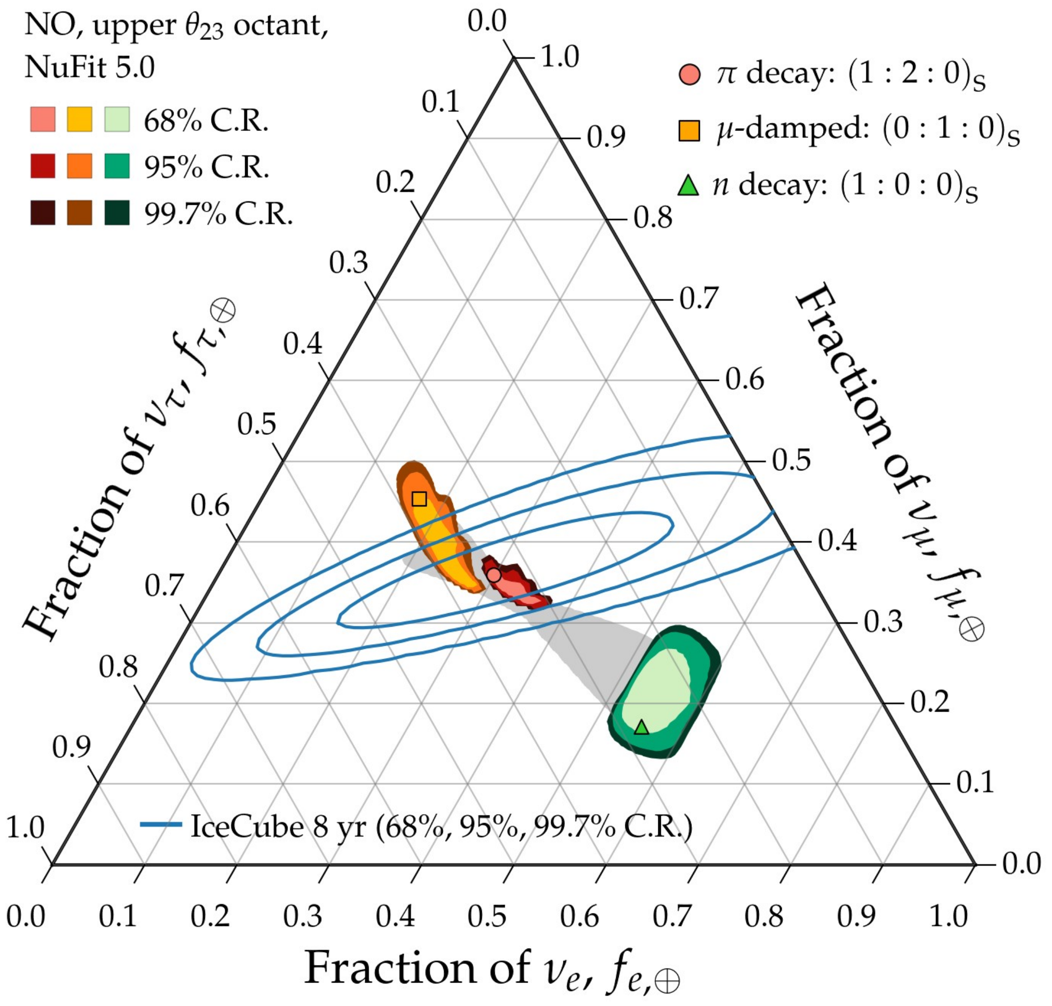

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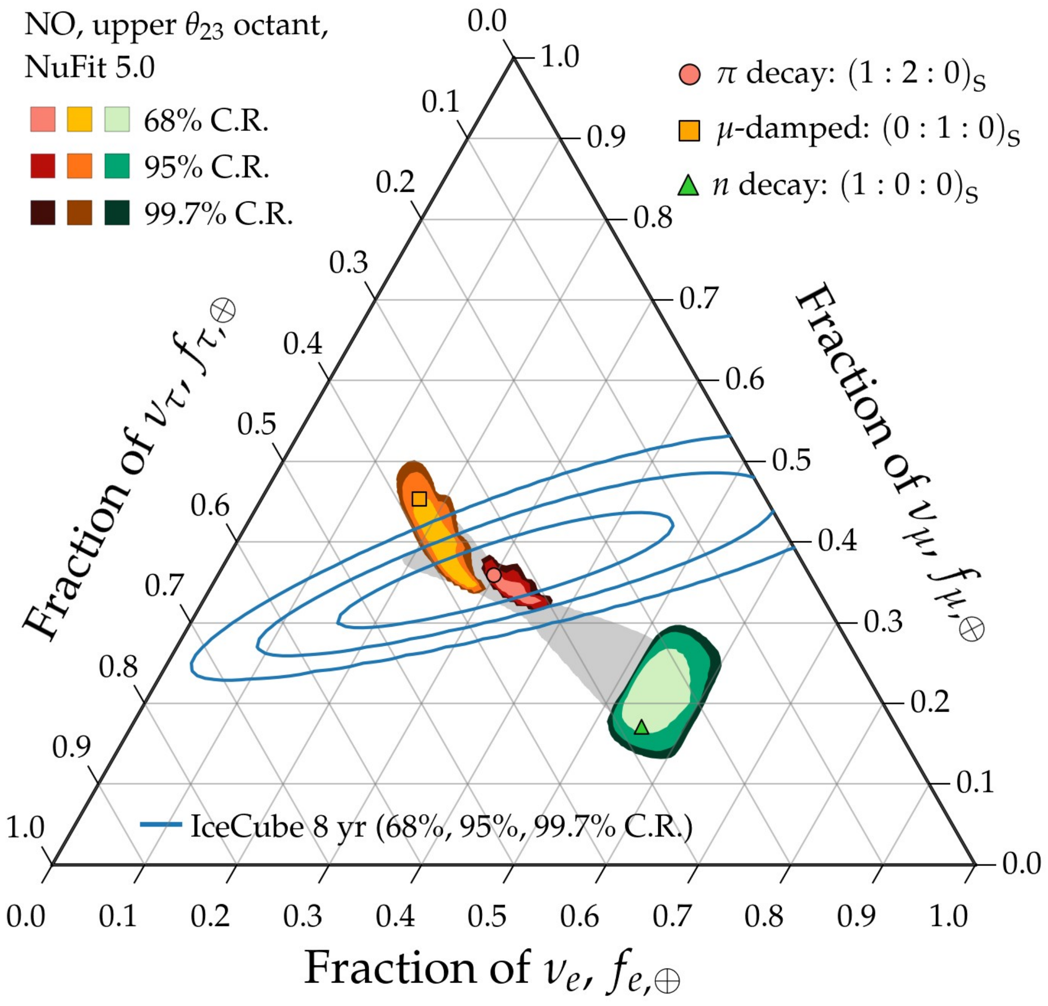

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Song, Li, Argüelles, **MB**, Vincent, 2012.12893
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Flavor at the Earth: *theoretically palatable regions*

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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$\equiv$

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$\equiv$

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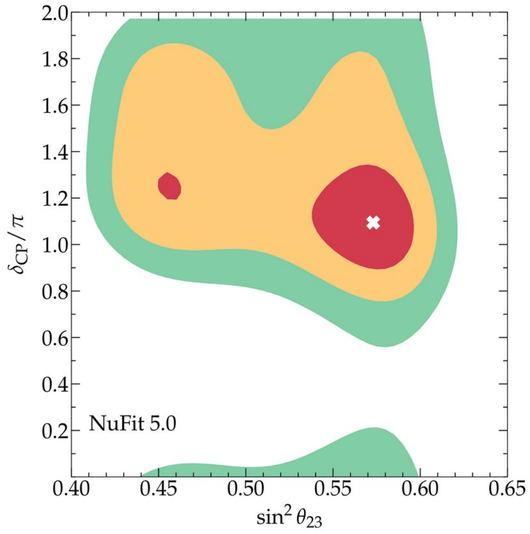
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

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



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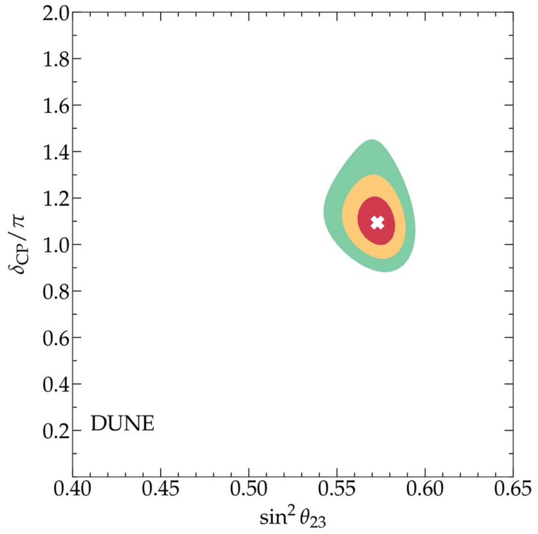
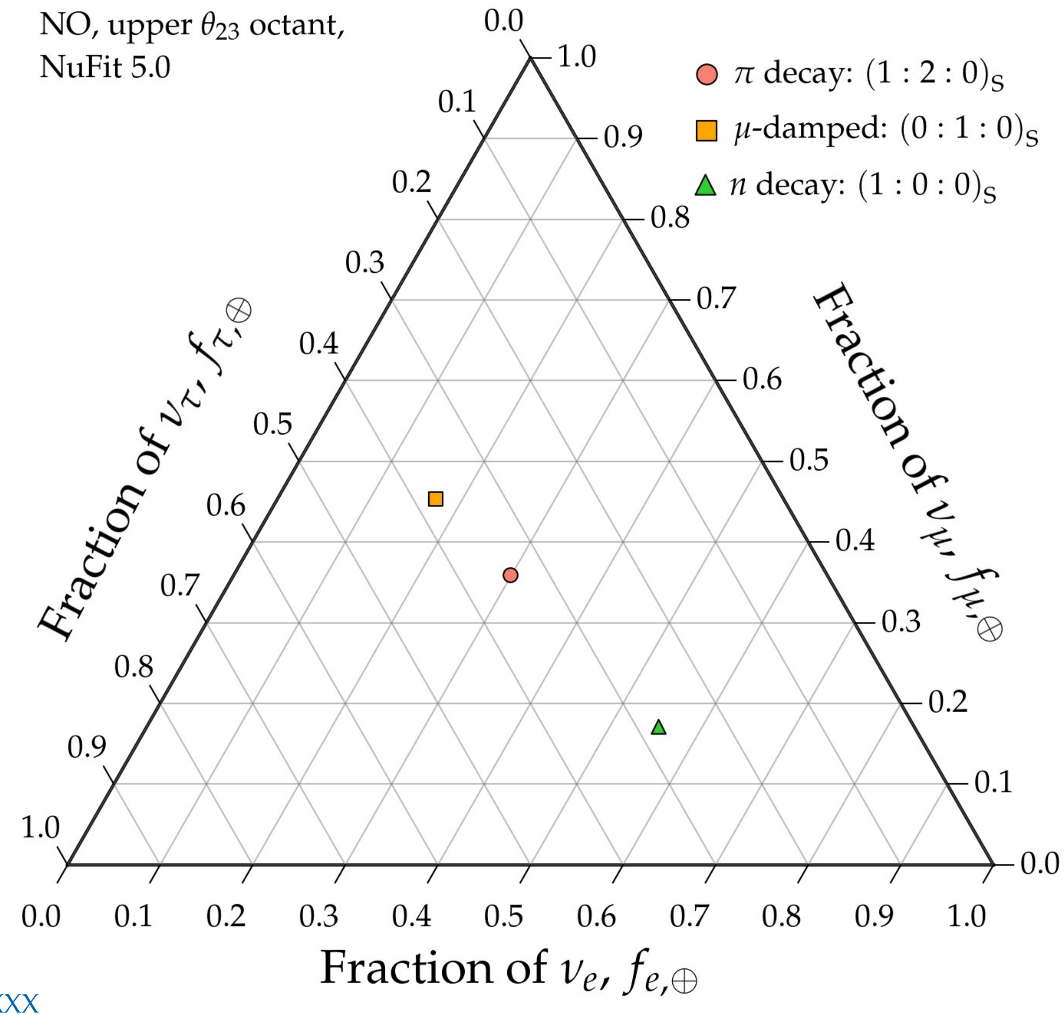
Esteban *et al.*, *JHEP* 2020
www.nu-fit.org

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)



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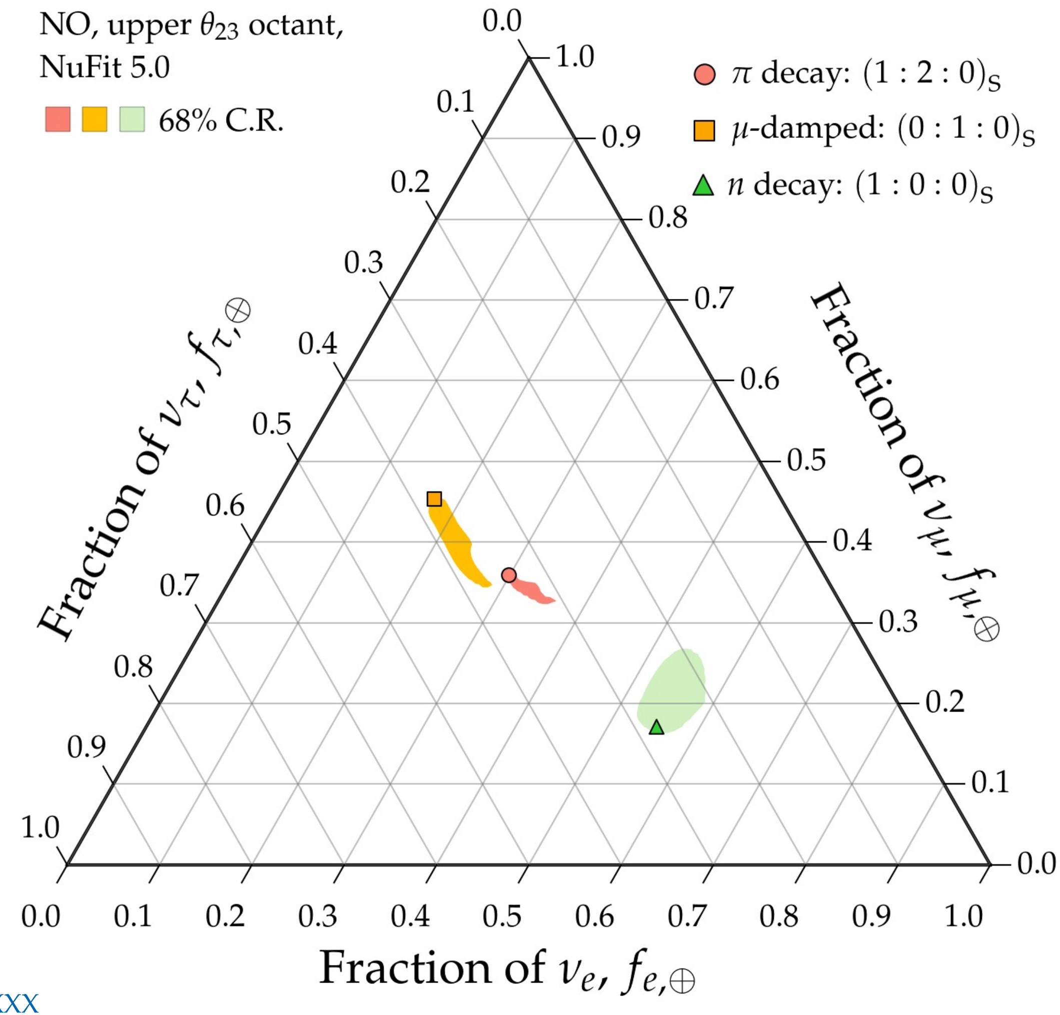
Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: today (2020)



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

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

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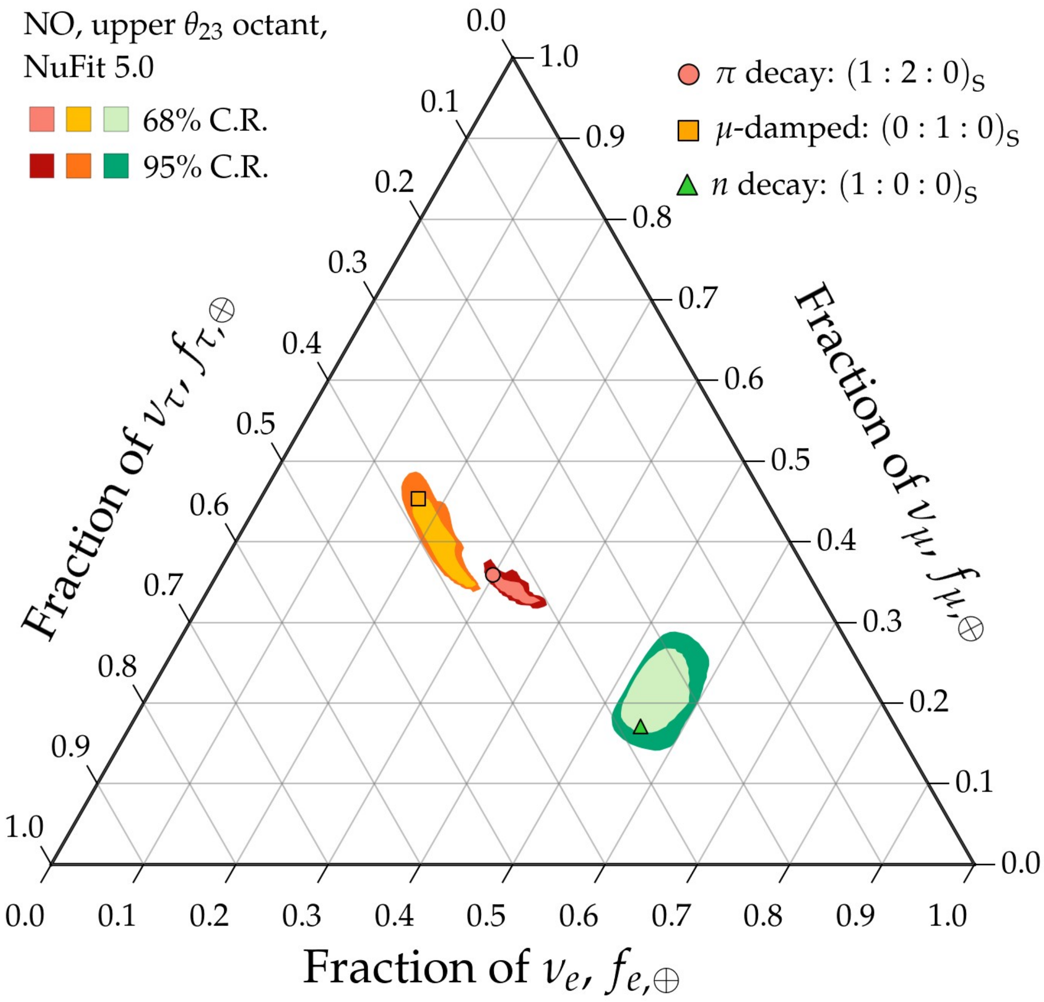

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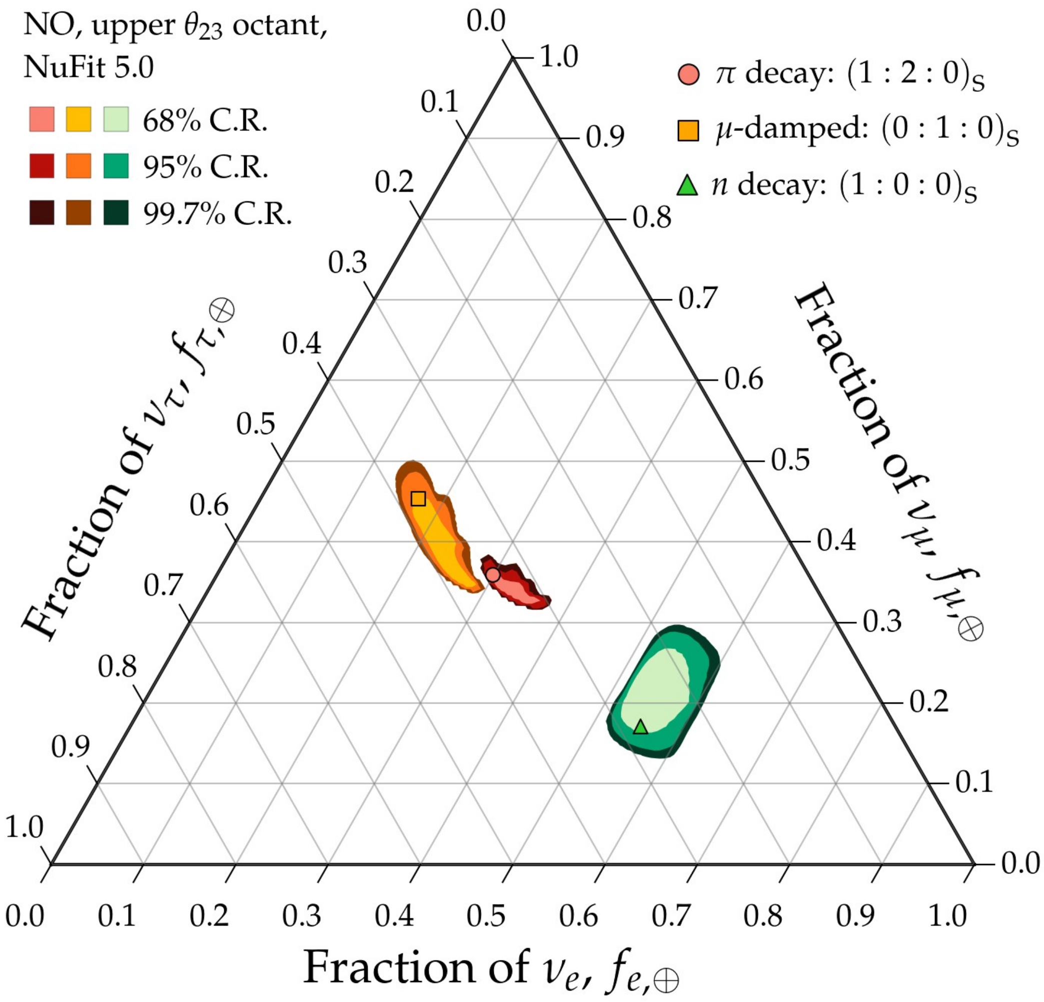

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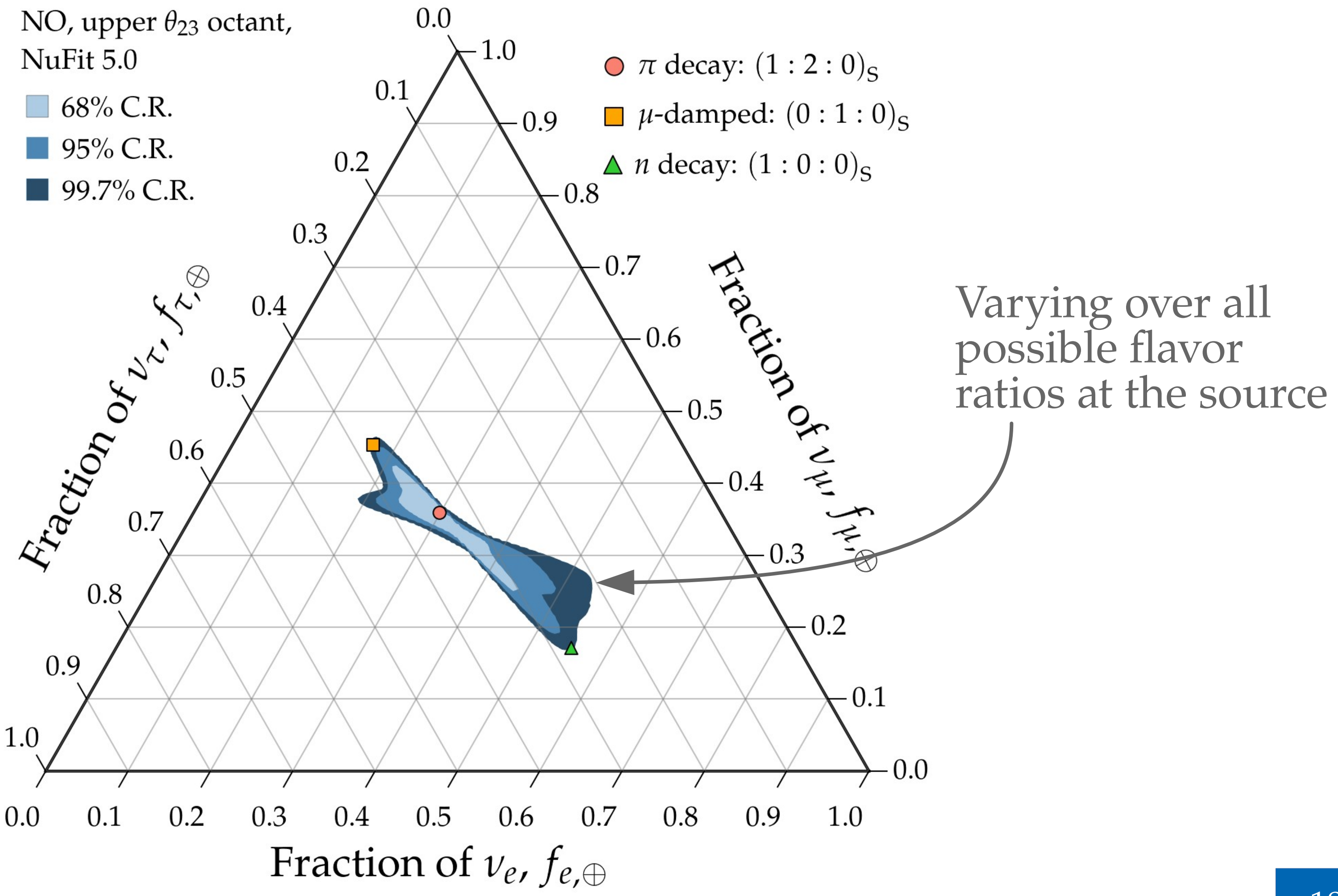

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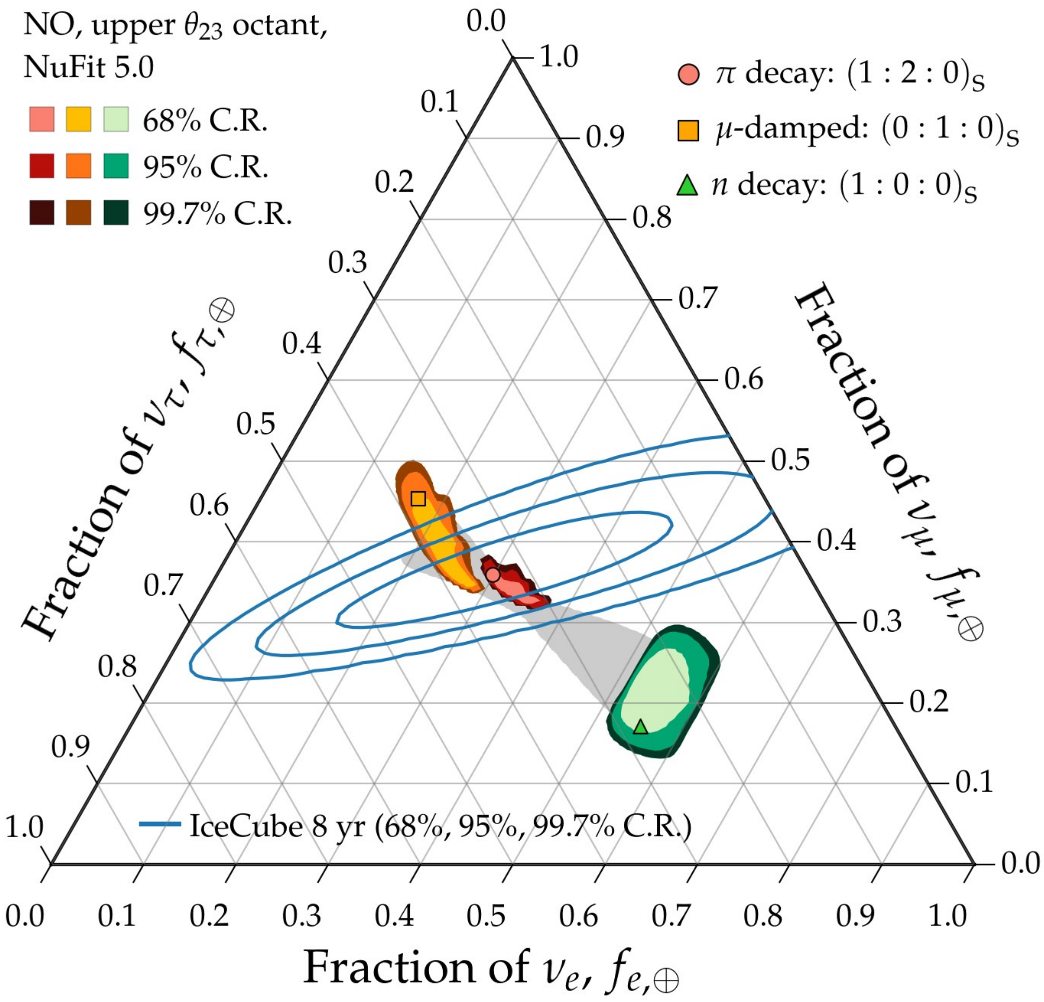

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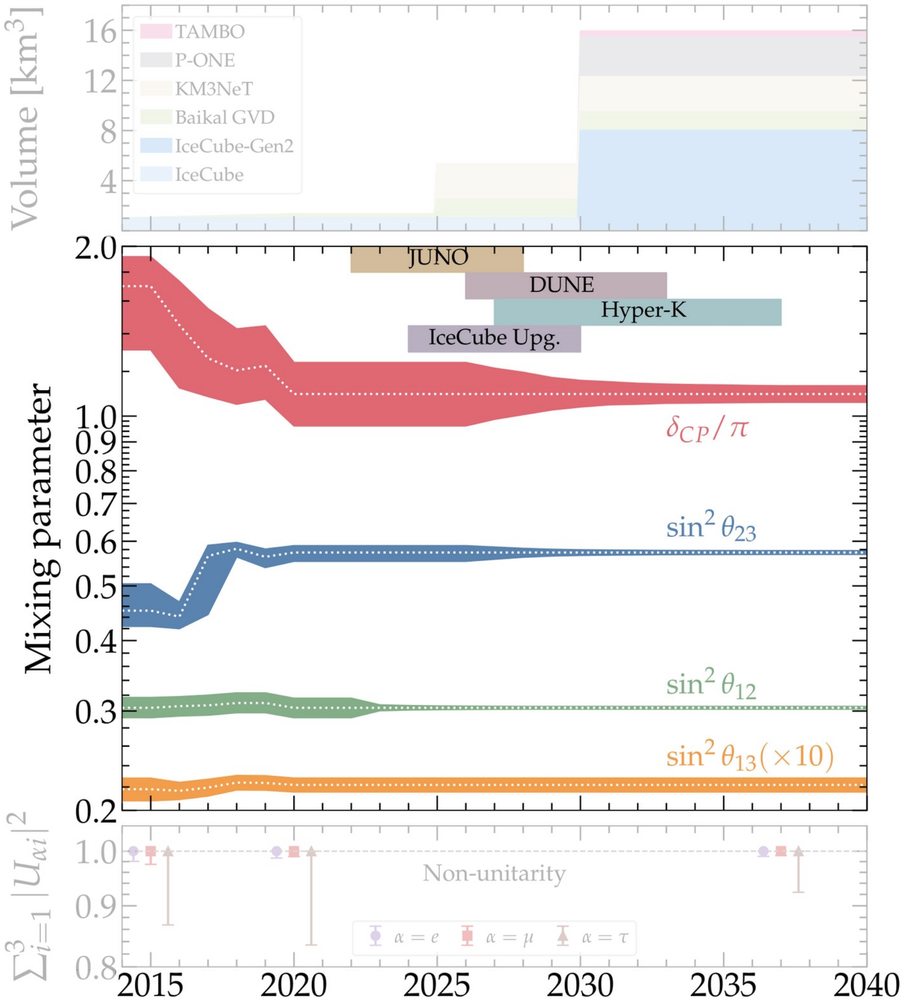
How knowing the mixing parameters better helps

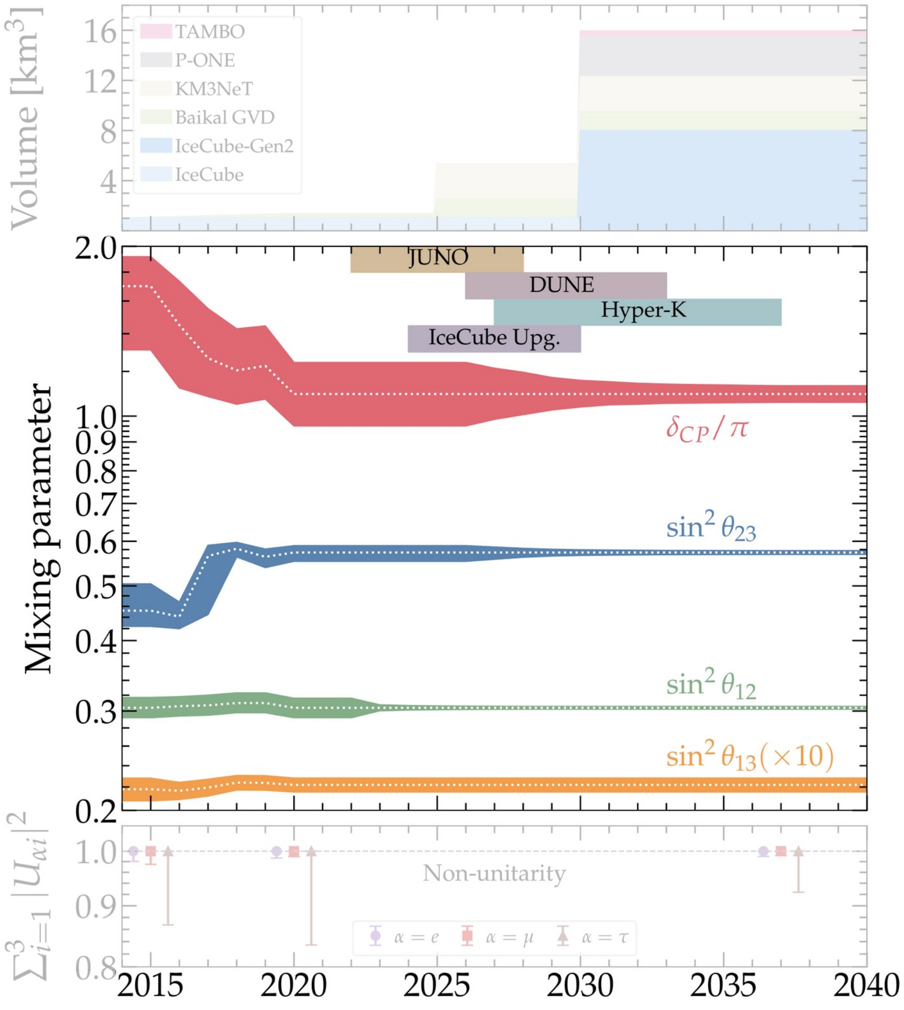


We can compute the oscillation probability more precisely:

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

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

How knowing the mixing parameters better helps



For a future experiment
ε = JUNO, DUNE, Hyper-K:

Best fit from NuFit 5.0

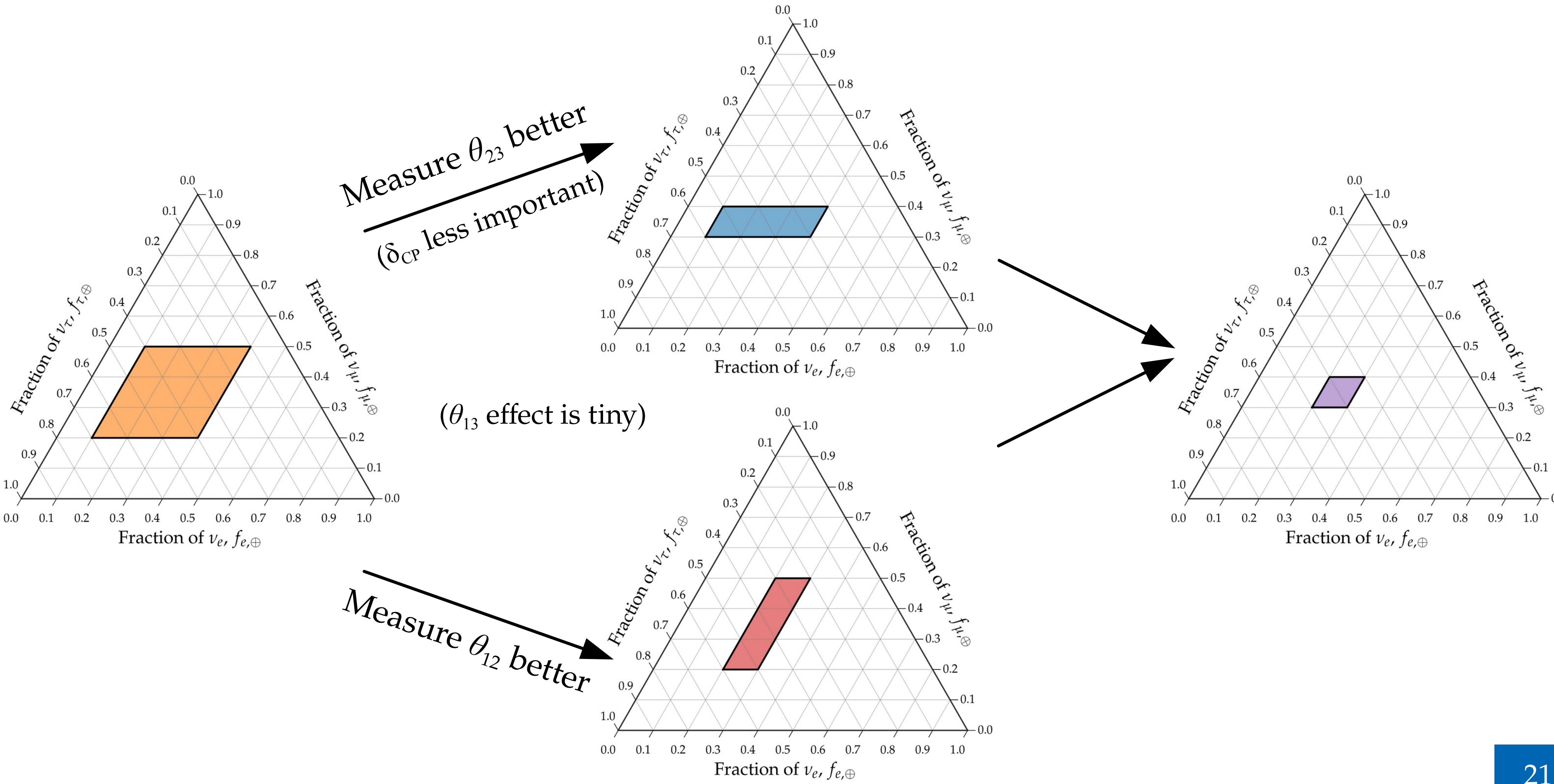
$$\chi^2_\varepsilon(\boldsymbol{\vartheta}) = \sum_i \frac{(\vartheta_i - \bar{\vartheta}_i)^2}{\sigma^2_{i,\varepsilon}}$$

From our simulations

We combine experiments in a likelihood:

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

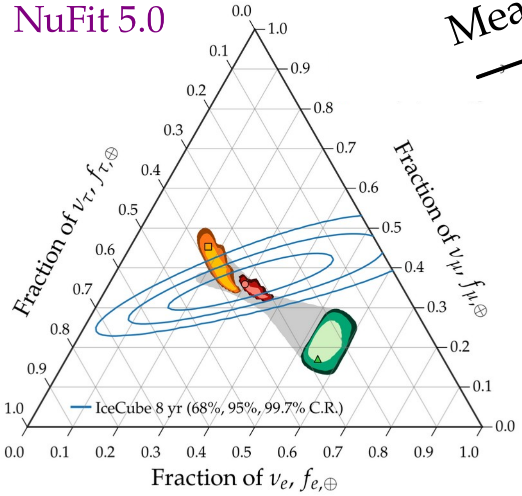
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

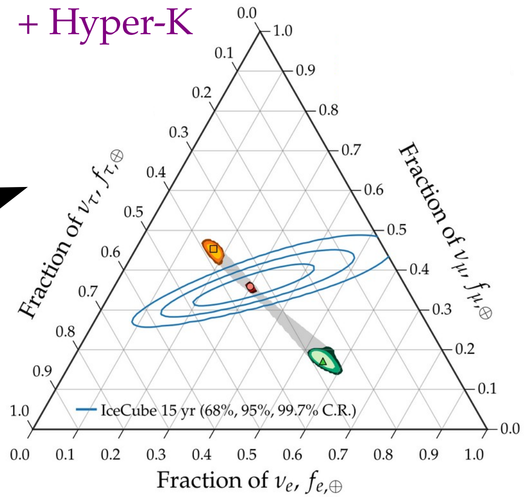
2020

NuFit 5.0



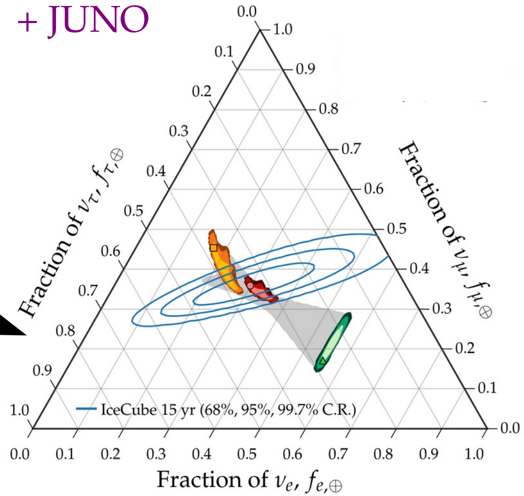
Measure θ_{23} better

+ Hyper-K



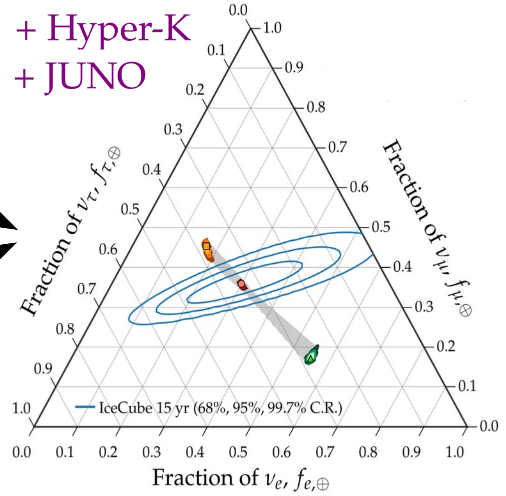
Measure θ_{12} better

+ JUNO



~2030

+ Hyper-K
+ JUNO



In our results:
JUNO + Hyper-K + DUNE

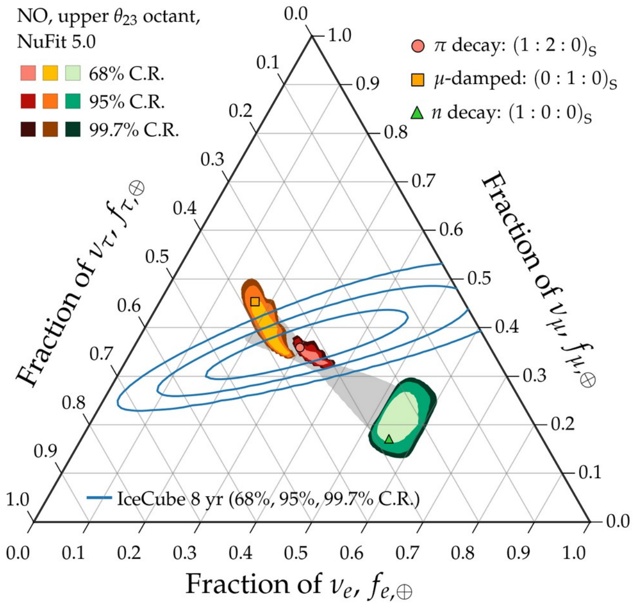
Marginal improvement til 2040

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



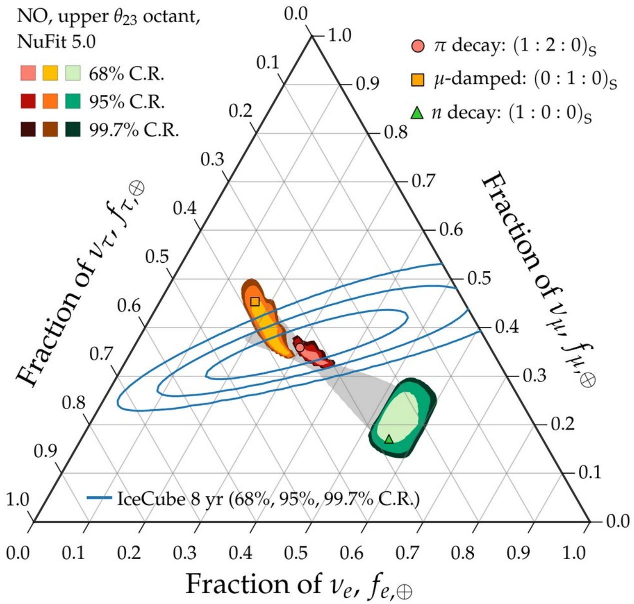
Allowed regions: overlapping

Measurement: imprecise

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020



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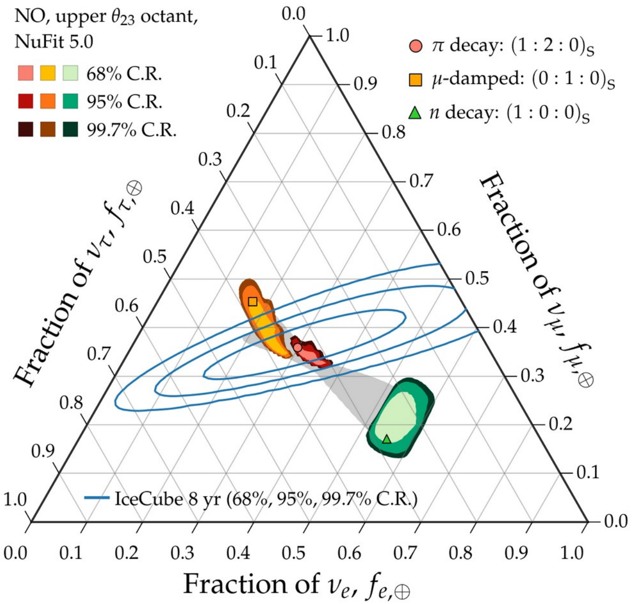
Measurement: imprecise

Not ideal

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020



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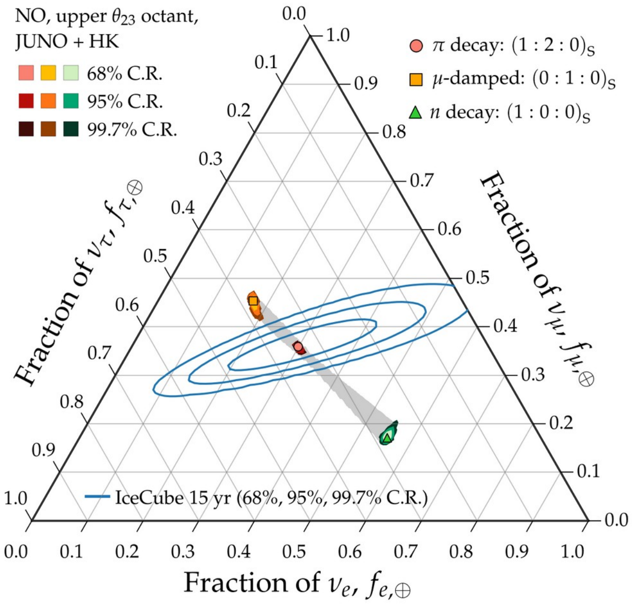
Measurement: imprecise

Not ideal

2030



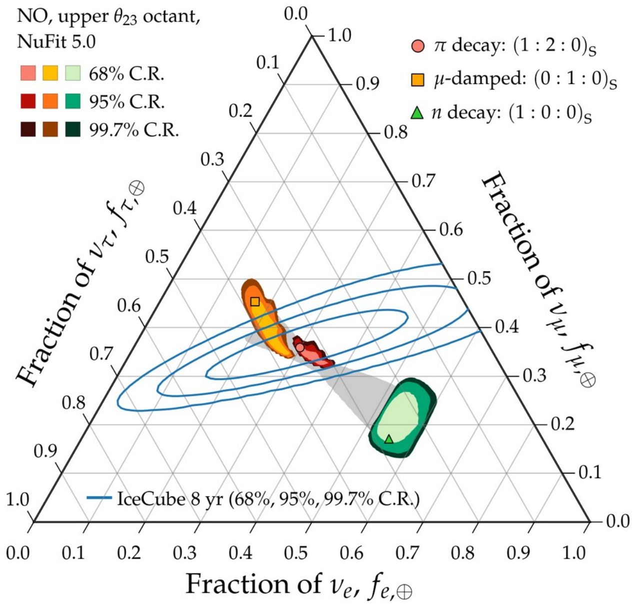
Allowed regions: well separated

Measurement: improving

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020



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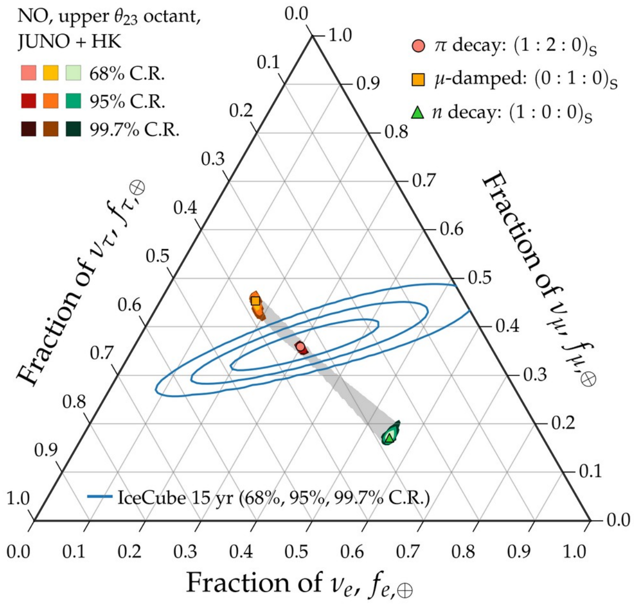
2030



Allowed regions: well separated

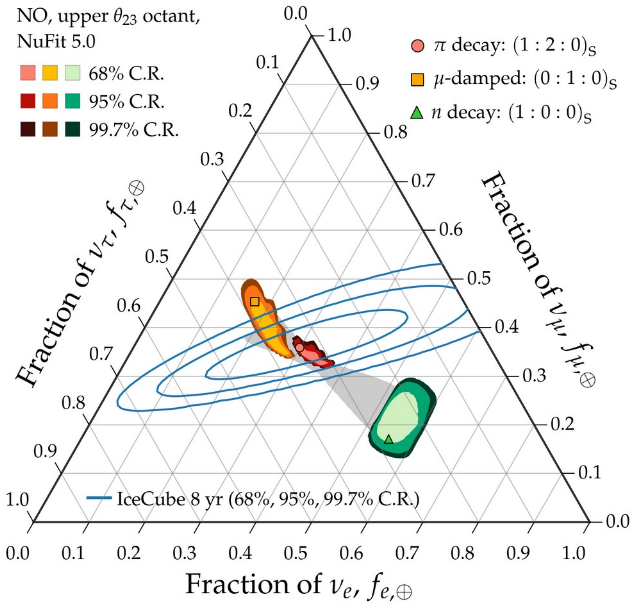
Measurement: improving

Nice

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020



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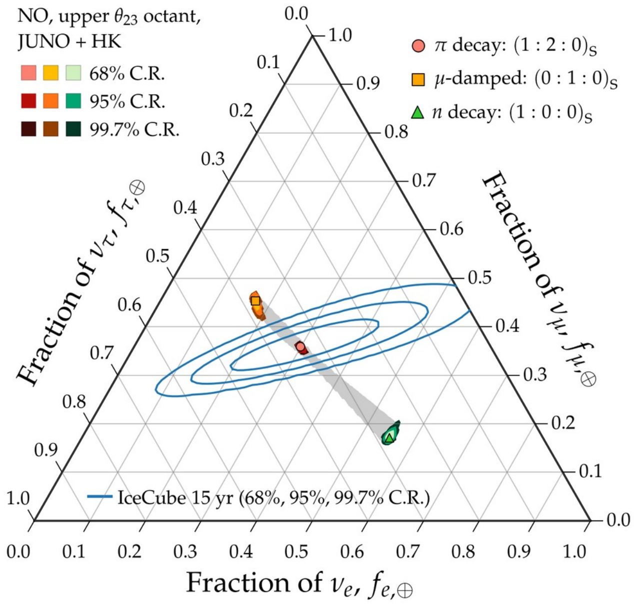
Measurement: imprecise

Not ideal

2030

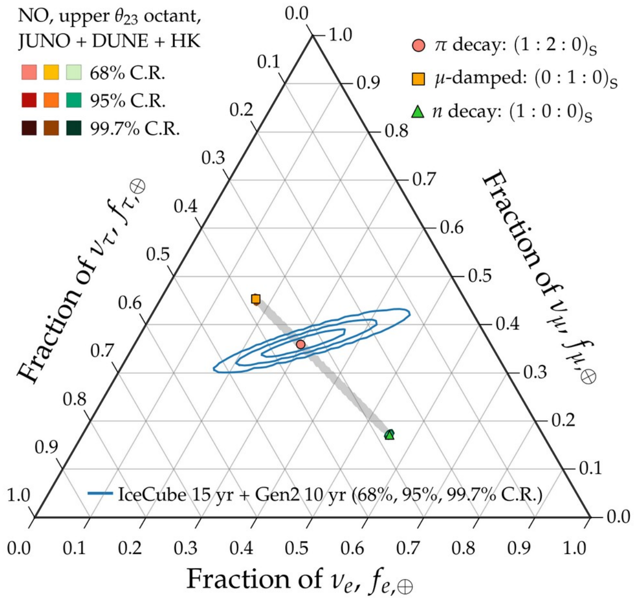


Allowed regions: well separated

Measurement: improving

Nice

2040



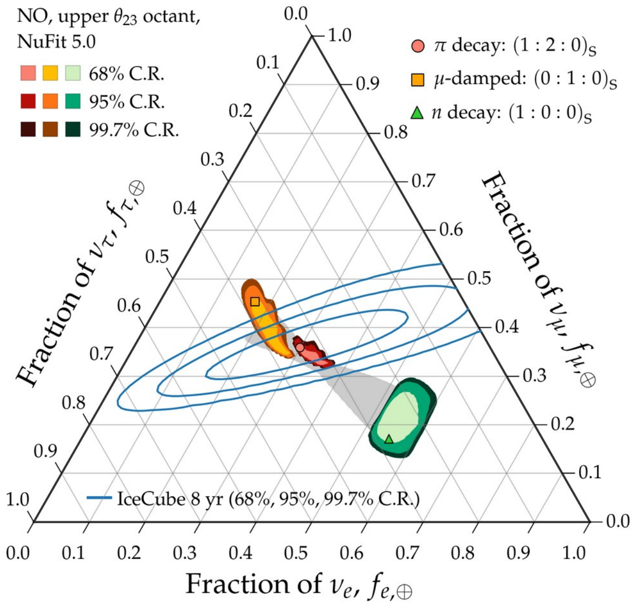
Allowed regions: well separated

Measurement: precise

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

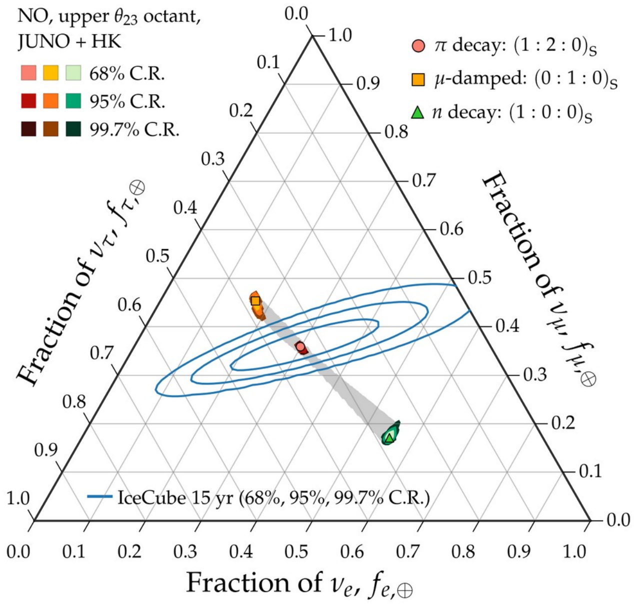
2020



Allowed regions: overlapping
Measurement: imprecise

Not ideal

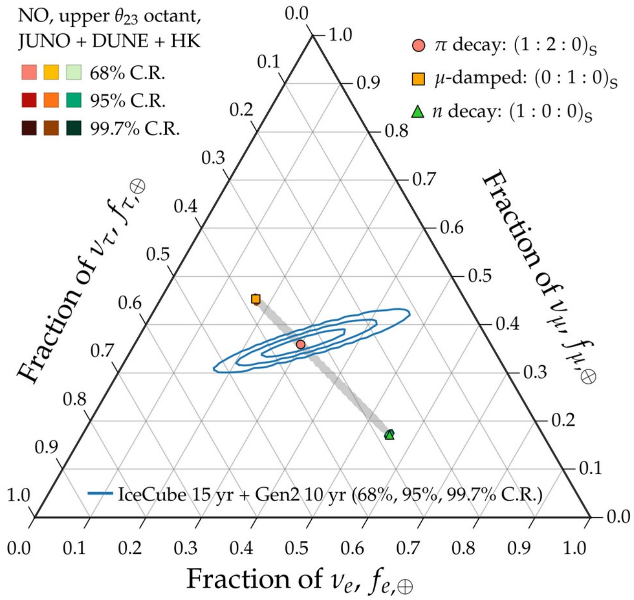
2030



Allowed regions: well separated
Measurement: improving

Nice

2040

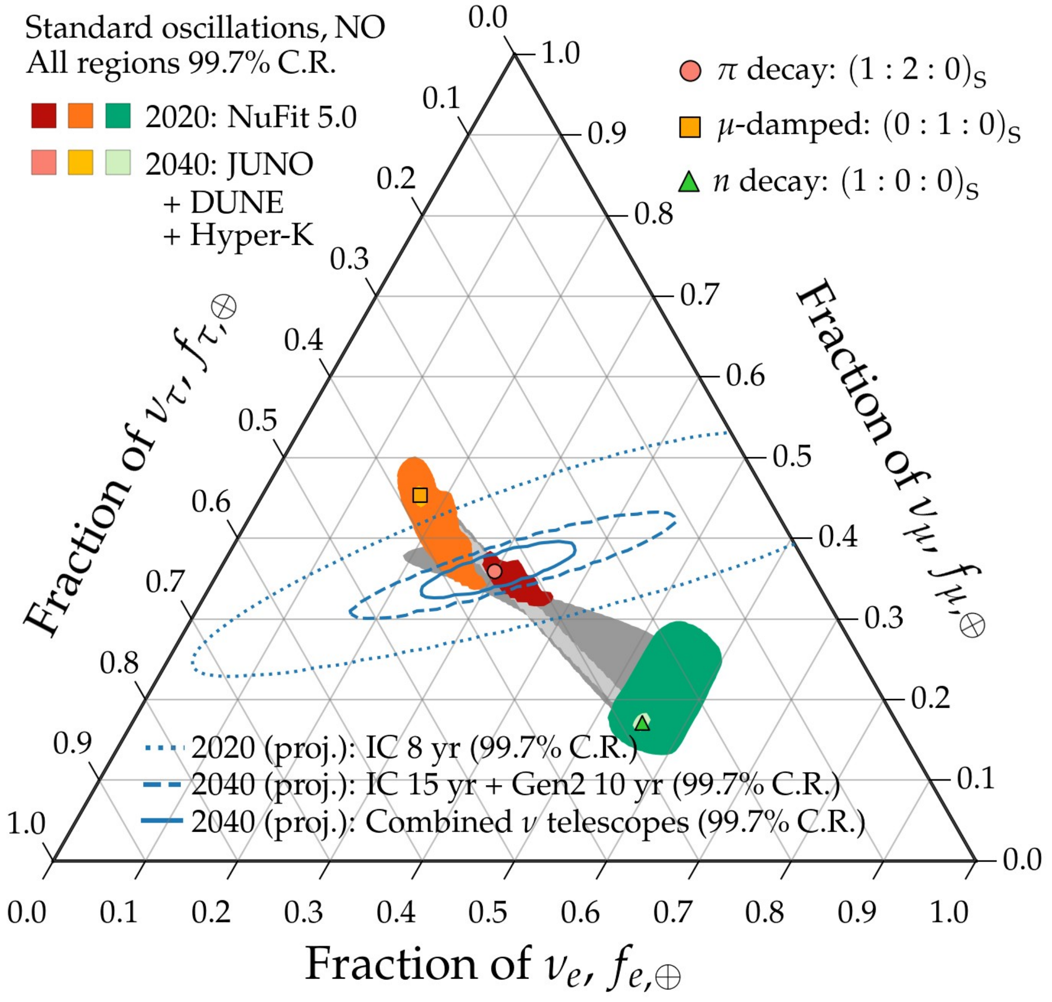


Allowed regions: well separated
Measurement: precise

Success

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 *vs.* 2040



By 2040:

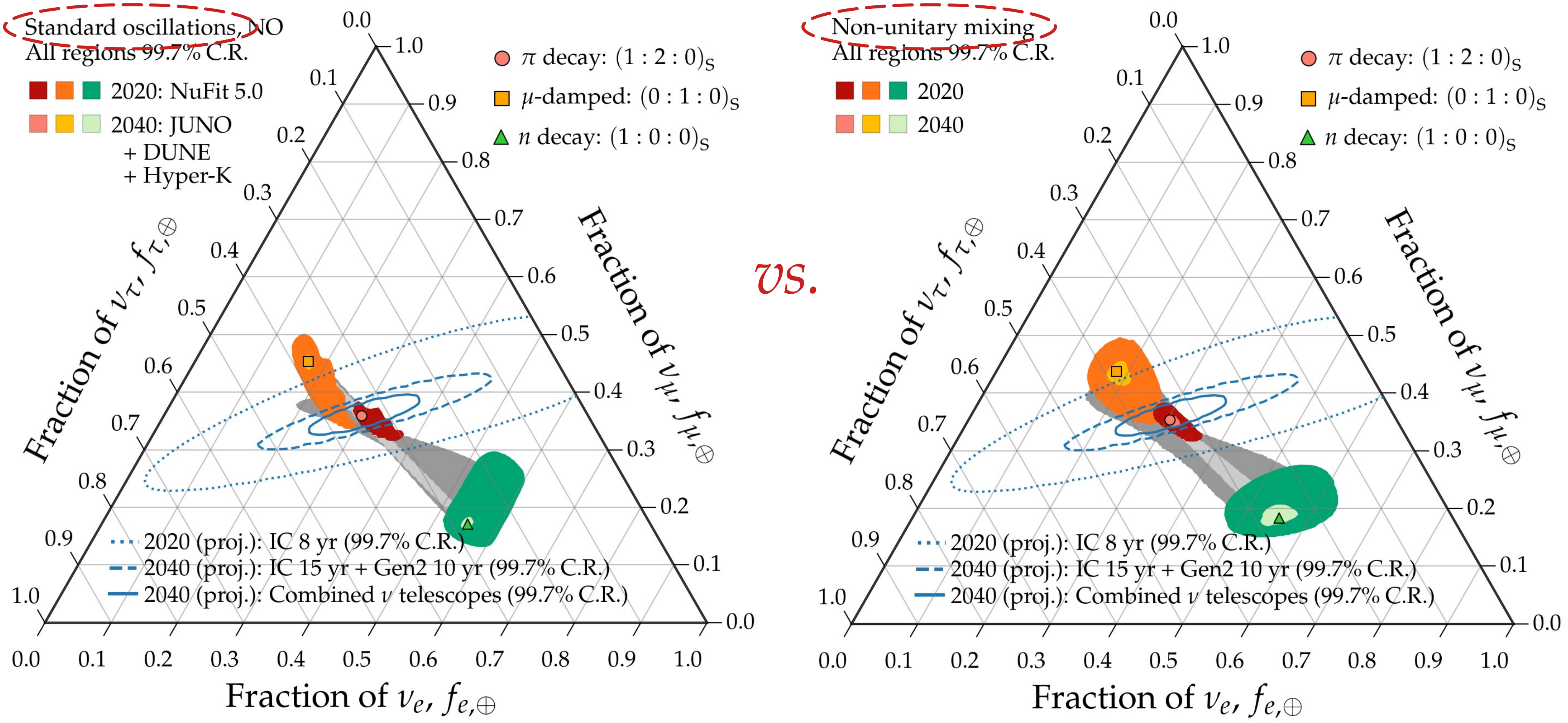
Theory –
Mixing parameters known precisely: allowed flavor regions are *almost* points (already by 2030)

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

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

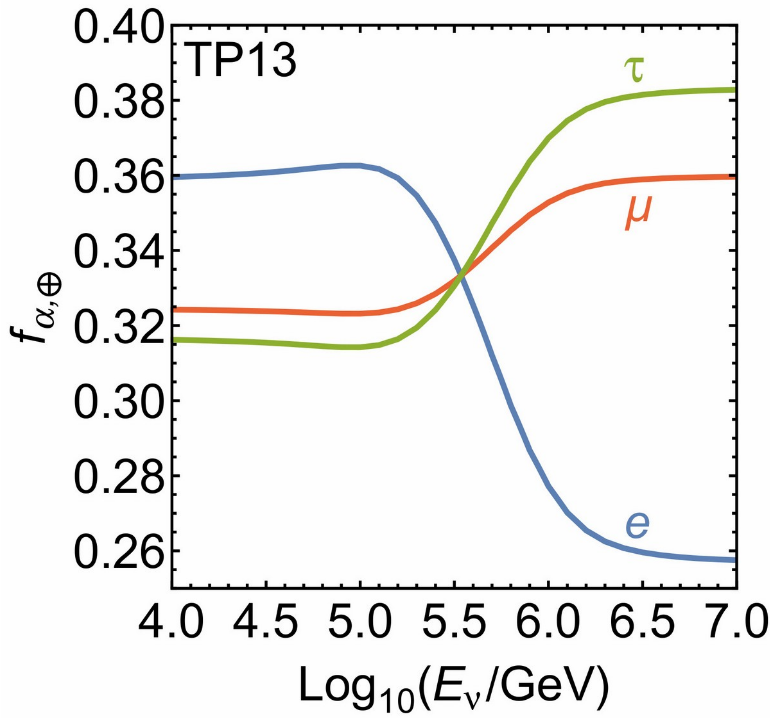
No unitarity? *No problem*

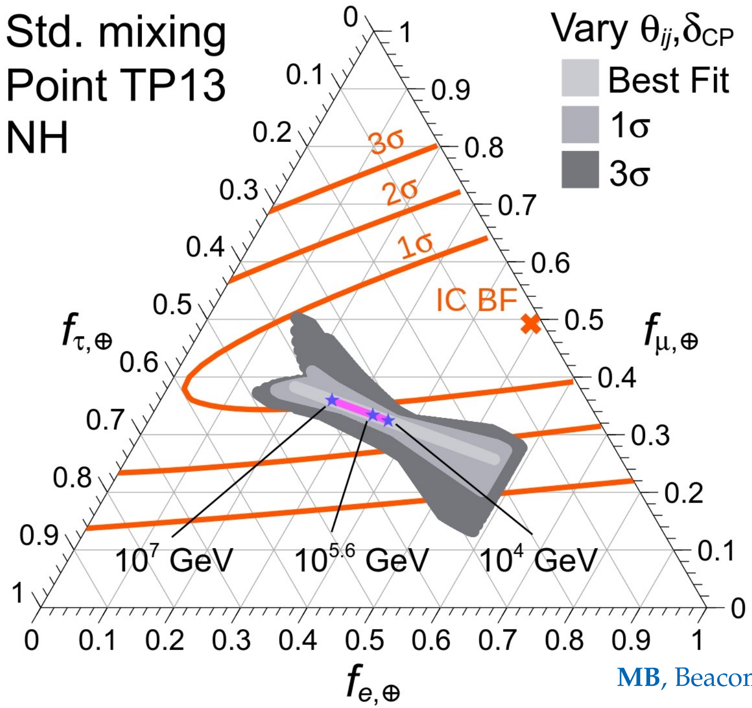


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –



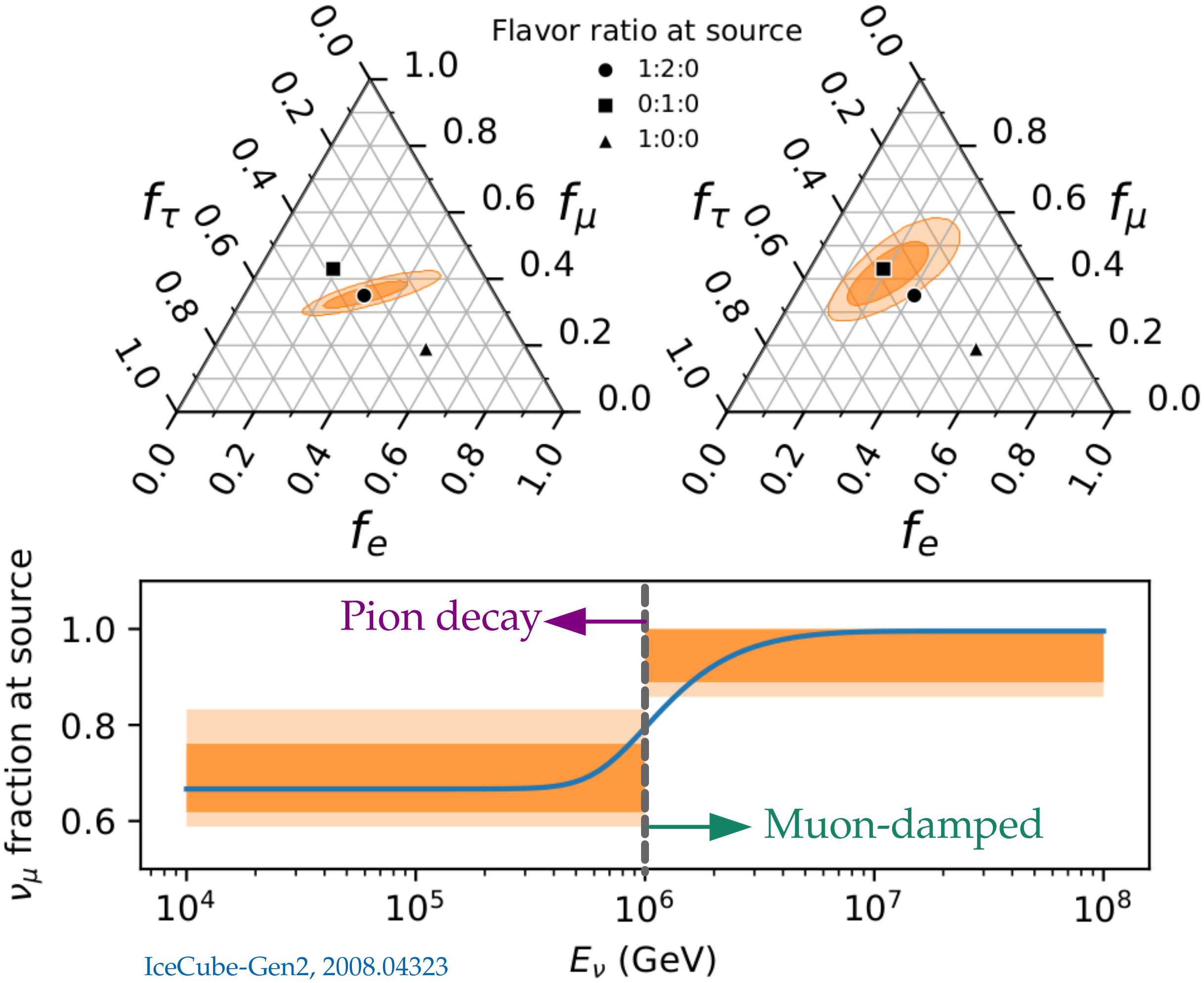


MB, Beacom, Winter, *PRL* 2015

- 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:



IceCube-Gen2, 2008.04323

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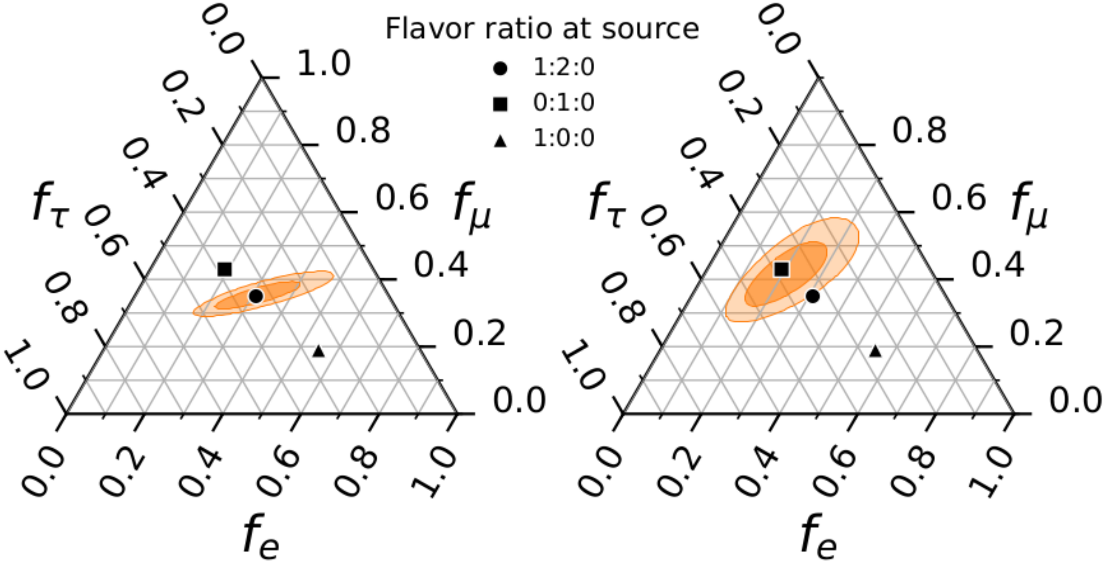
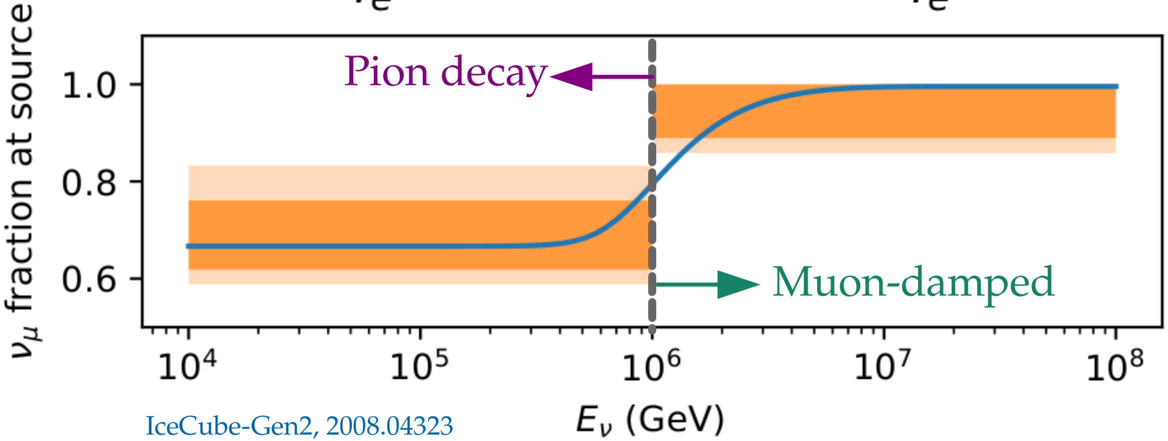
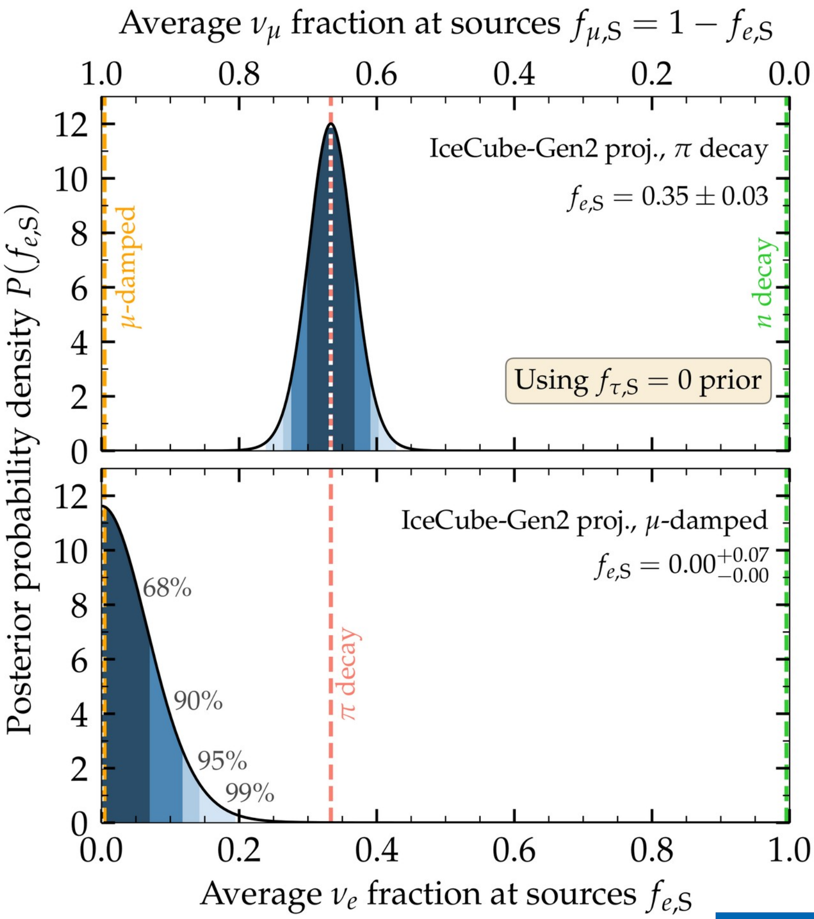




Inferred (at sources):



IceCube-Gen2, 2008.04323

MB & Ahlers, *PRL* 2019

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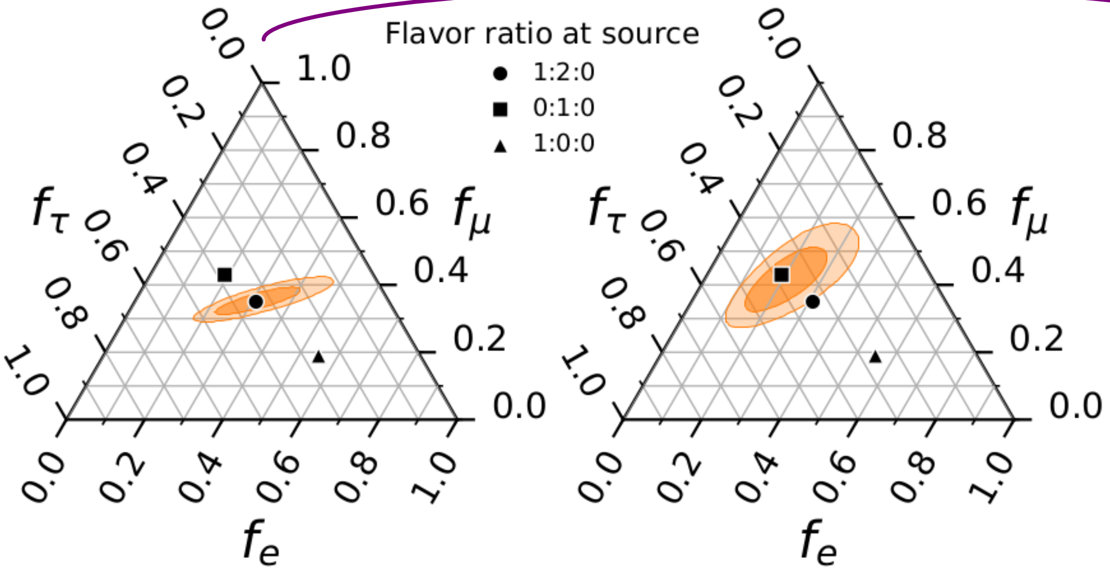

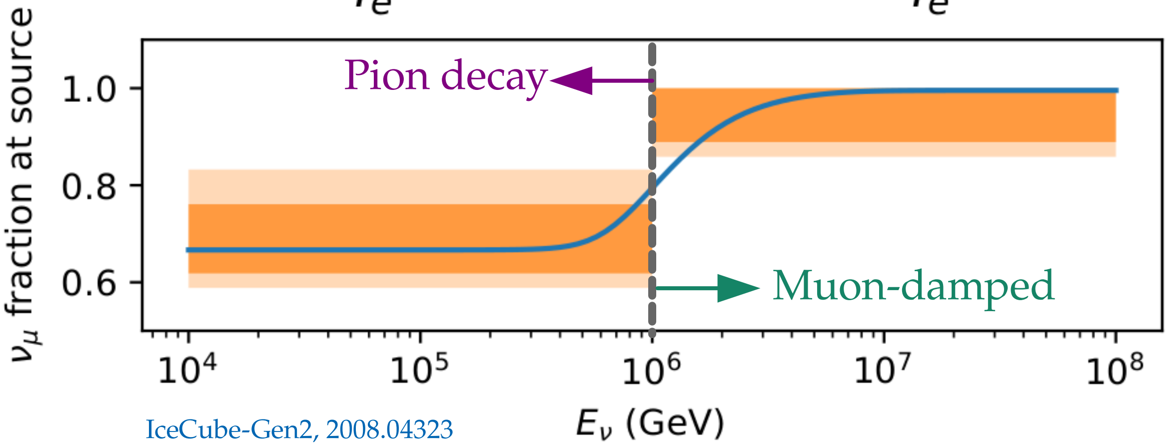

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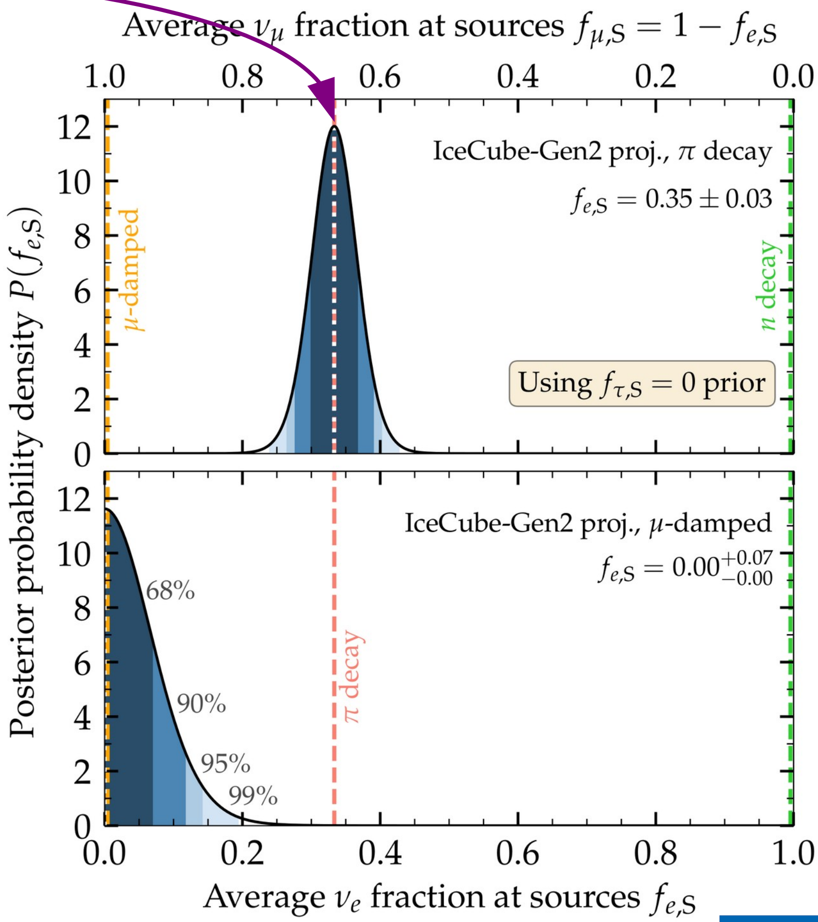

MB & Ahlers, *PRL* 2019

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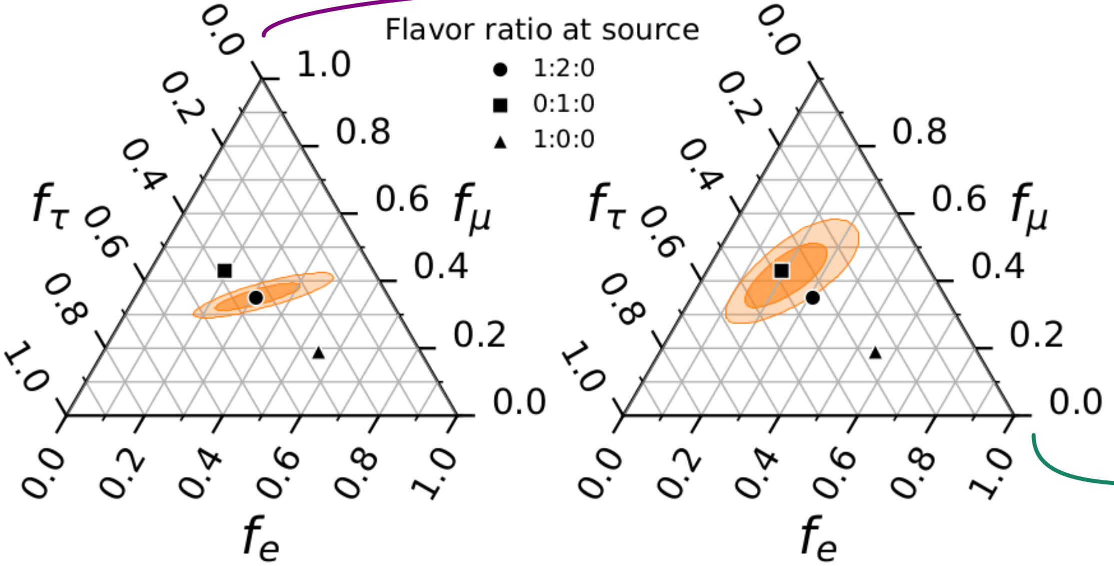

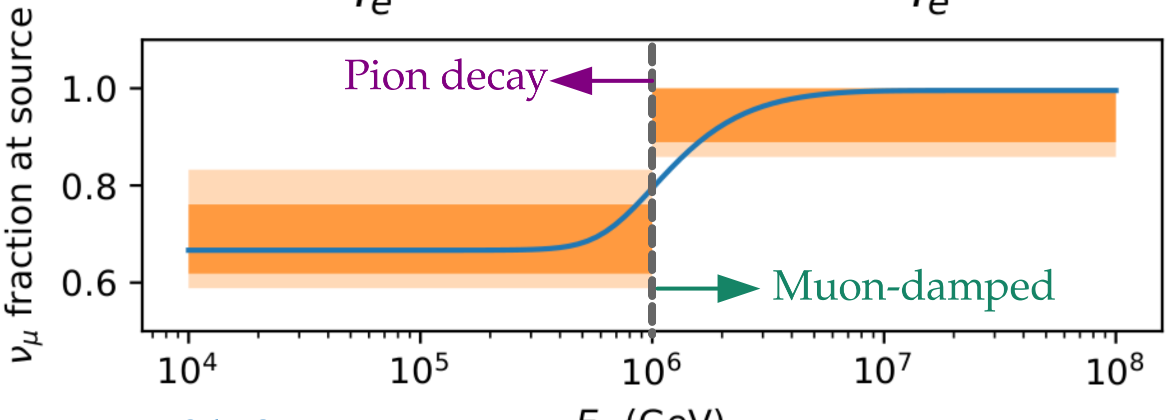

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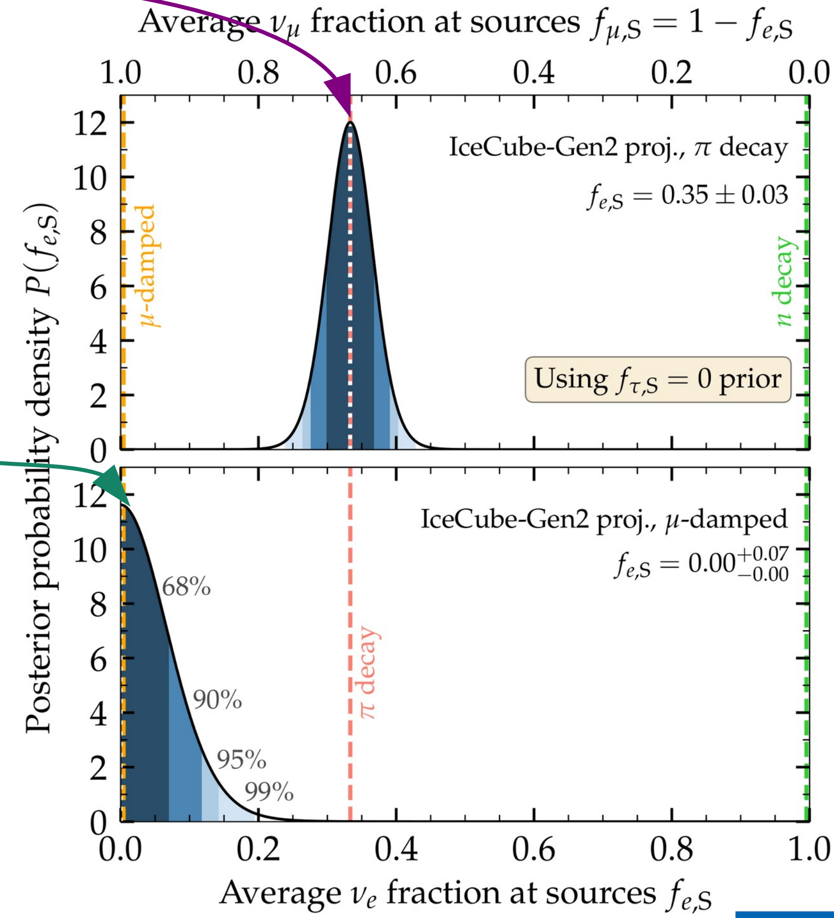

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More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

$$\boldsymbol{f}_{\rm S} = \underbrace{k_\pi \boldsymbol{f}_{\rm S}^\pi}_{} + \underbrace{k_\mu \boldsymbol{f}_{\rm S}^\mu}_{} + \underbrace{k_n \boldsymbol{f}_{\rm S}^n}_{}$$

π decay: (1/3, 2/3, 0) μ damped: (0, 1, 0) *n* decay: (1, 0, 0)

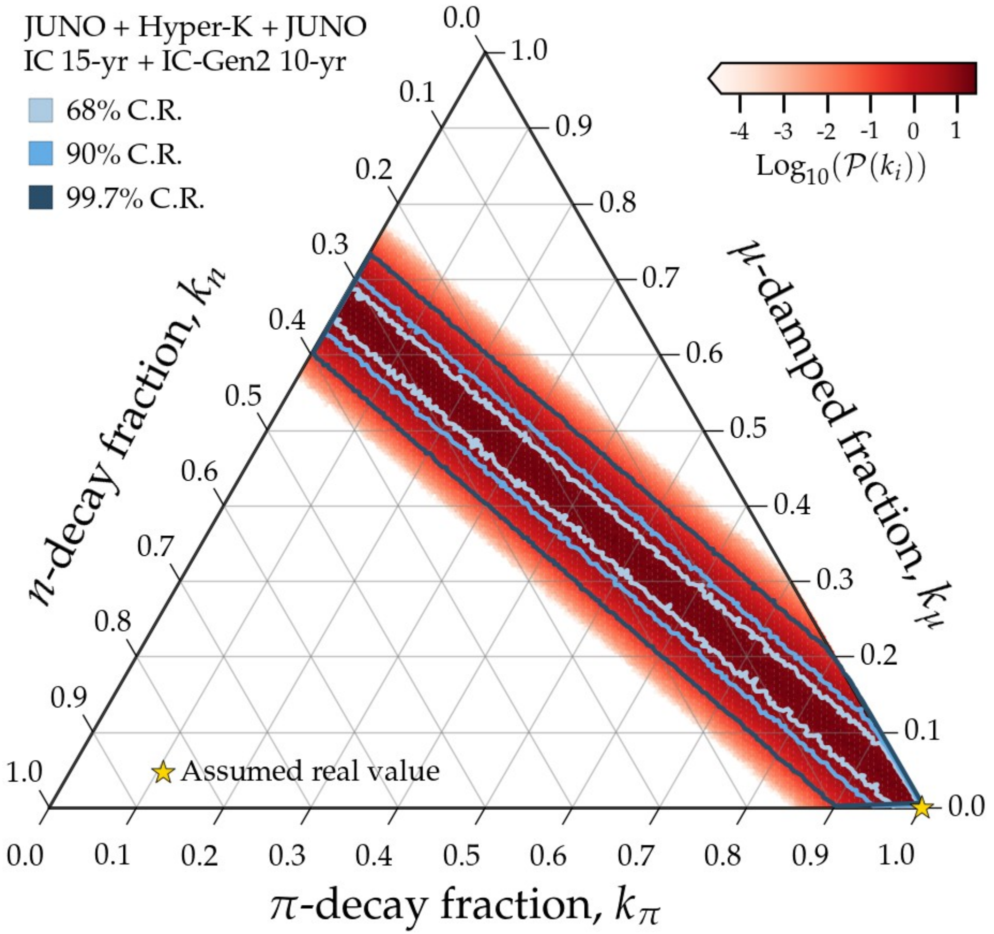
Propagate to Earth ↓

$\boldsymbol{f}_\oplus$

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]



Song, Li, Argüelles, **MB**, Vincent, 2012.12893

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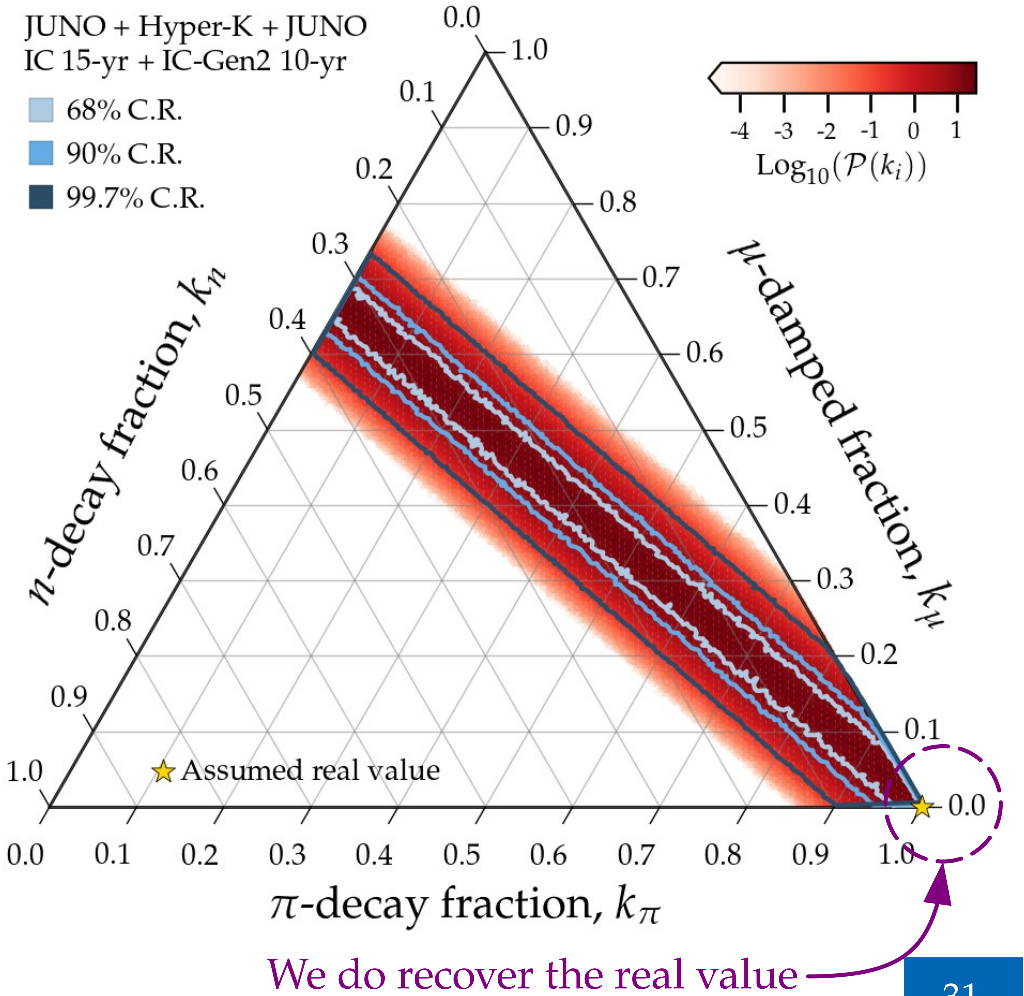

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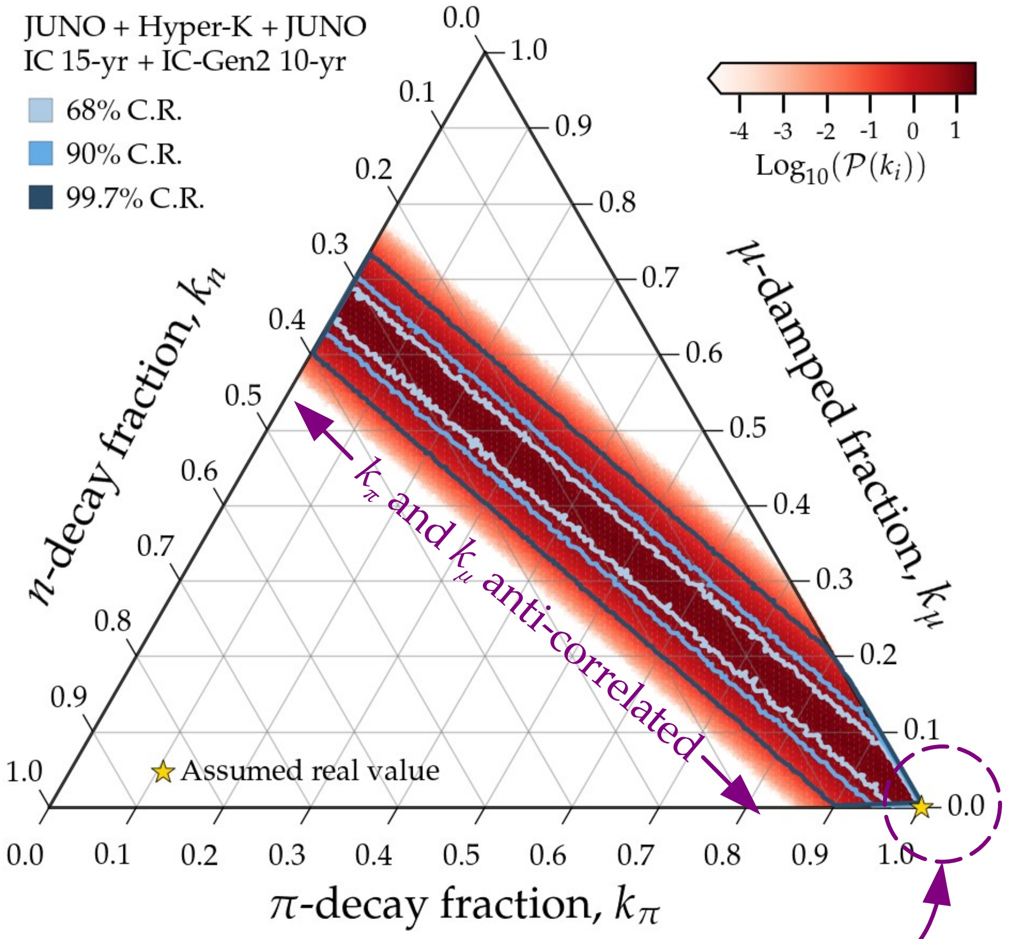

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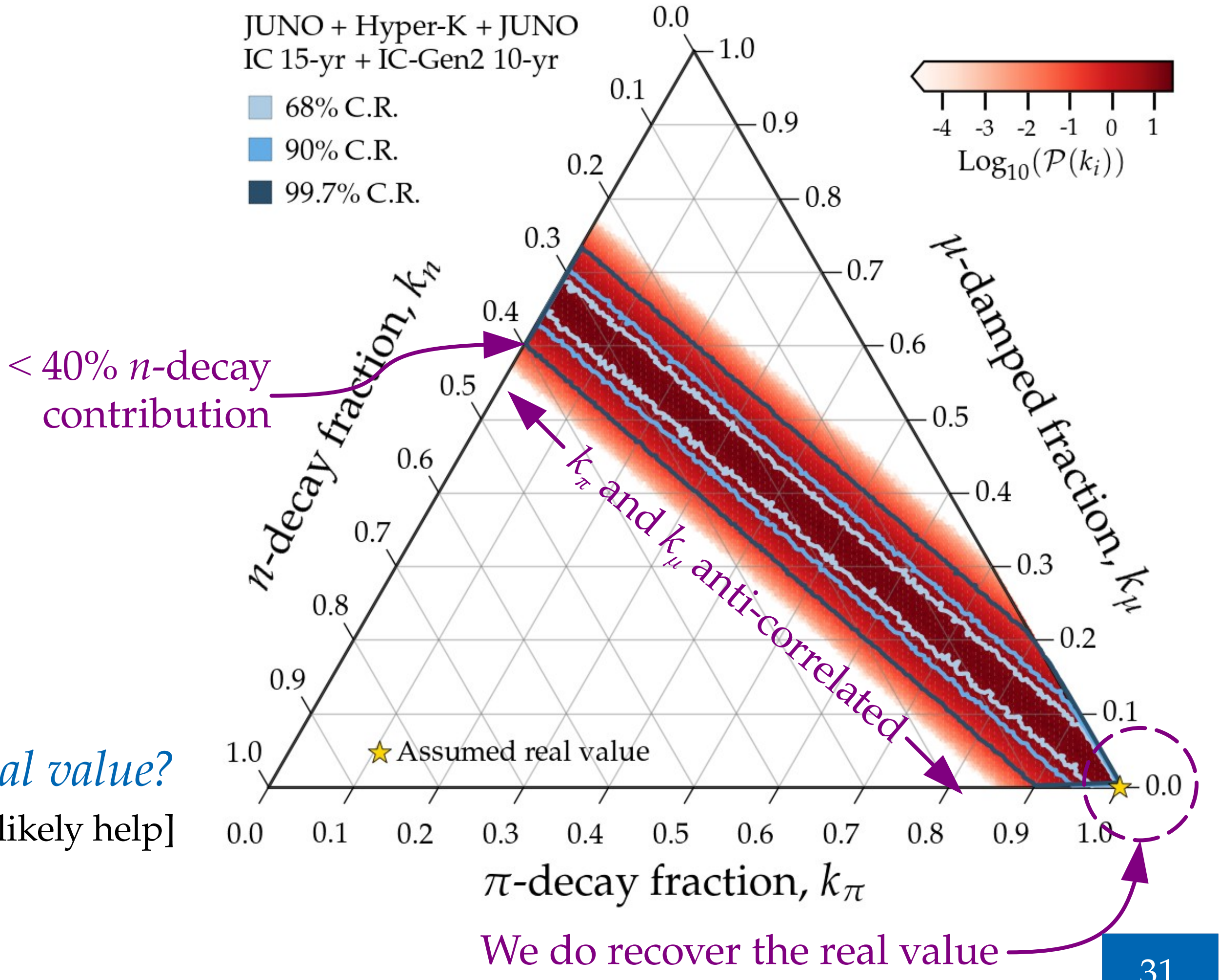

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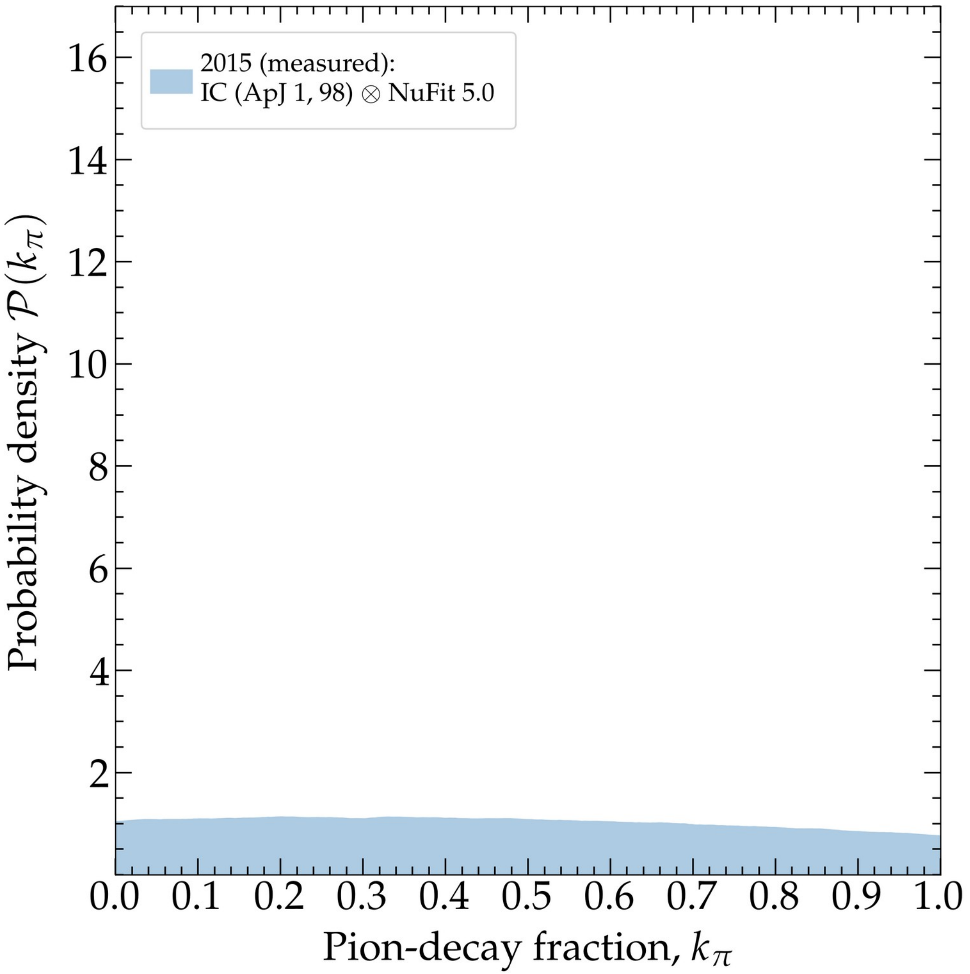

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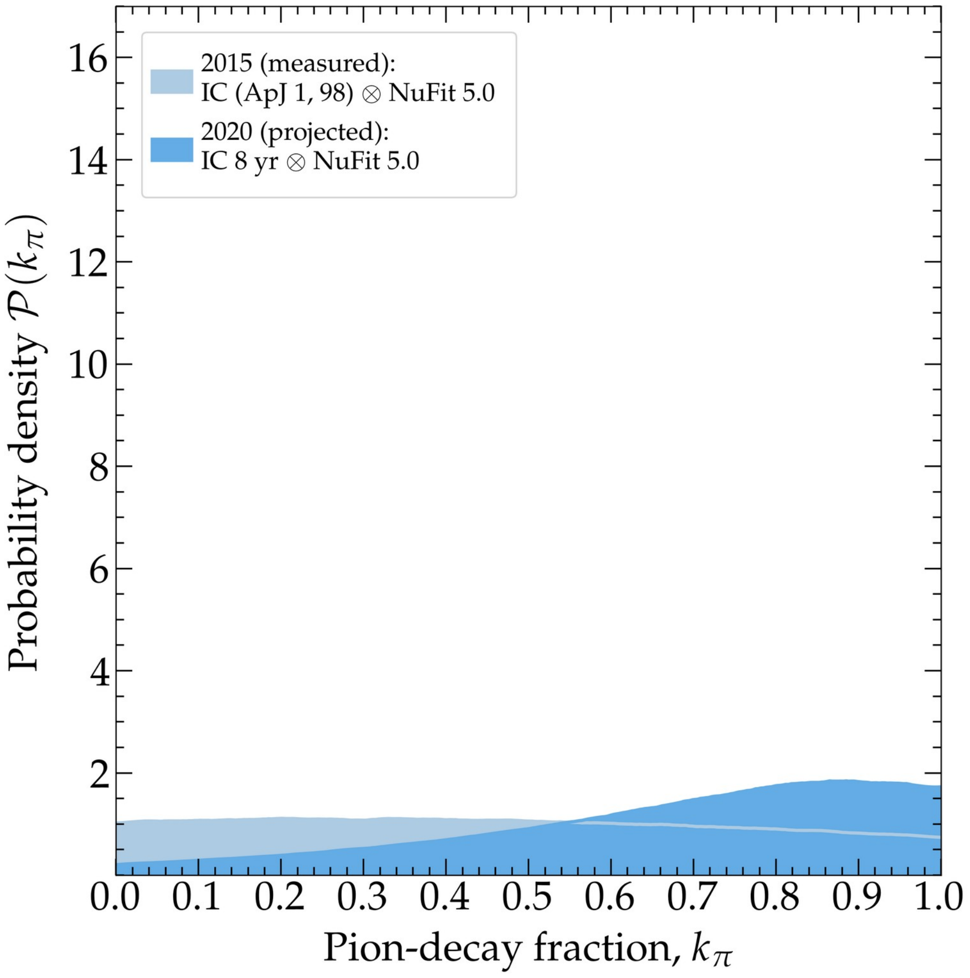

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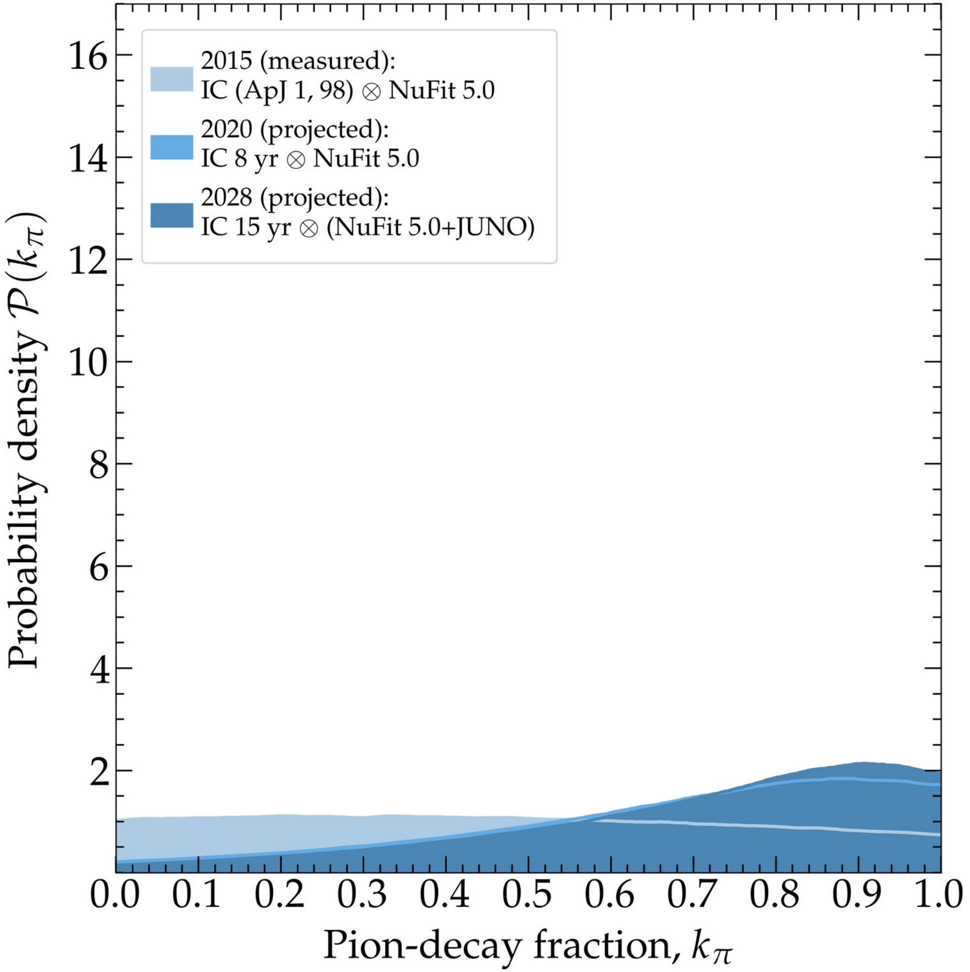

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μ damped: (0, 1, 0)

n decay: (1, 0, 0)

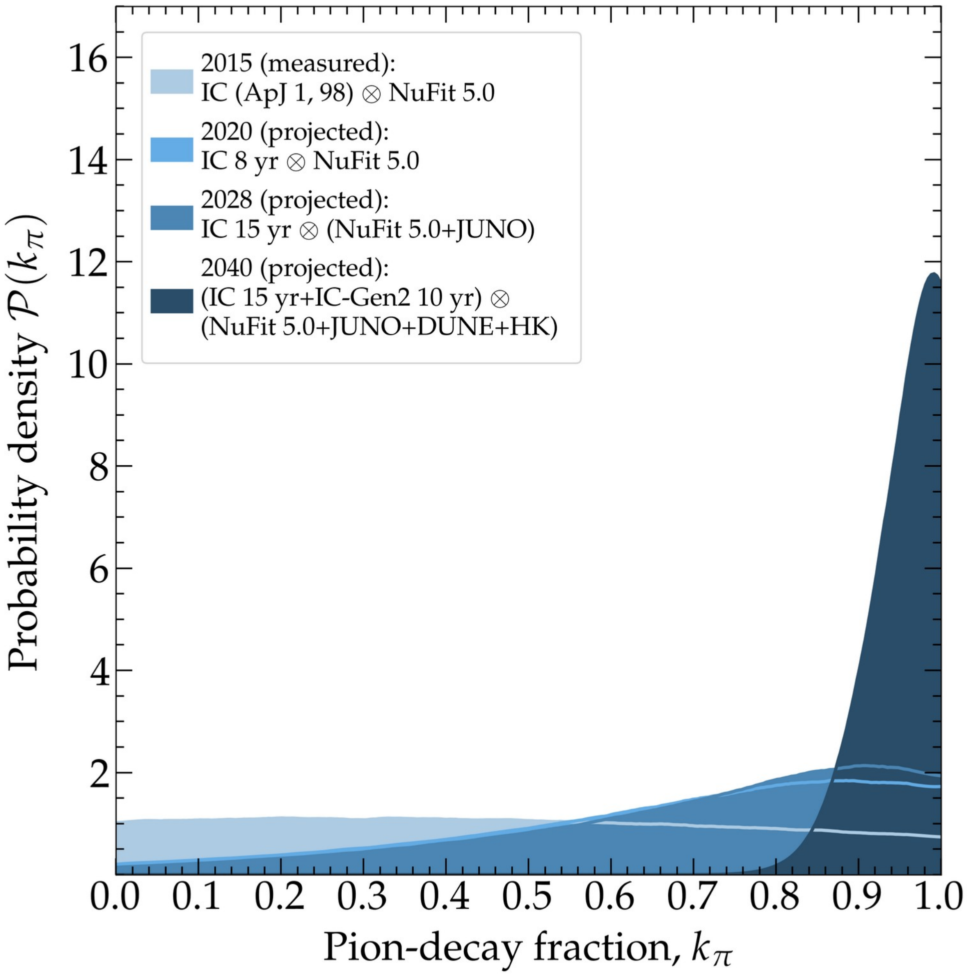
Propagate to Earth

$$\boldsymbol{f}_{\oplus}$$

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]



Song, Li, Argüelles, **MB**, Vincent, 2012.12893

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

$$\boldsymbol{f}_{\rm S} = k_\pi \boldsymbol{f}_{\rm S}^\pi + k_\mu \boldsymbol{f}_{\rm S}^\mu + k_n \boldsymbol{f}_{\rm S}^n$$

π decay: (1/3, 2/3, 0) μ damped: (0, 1, 0) n decay: (1, 0, 0)

Propagate to Earth

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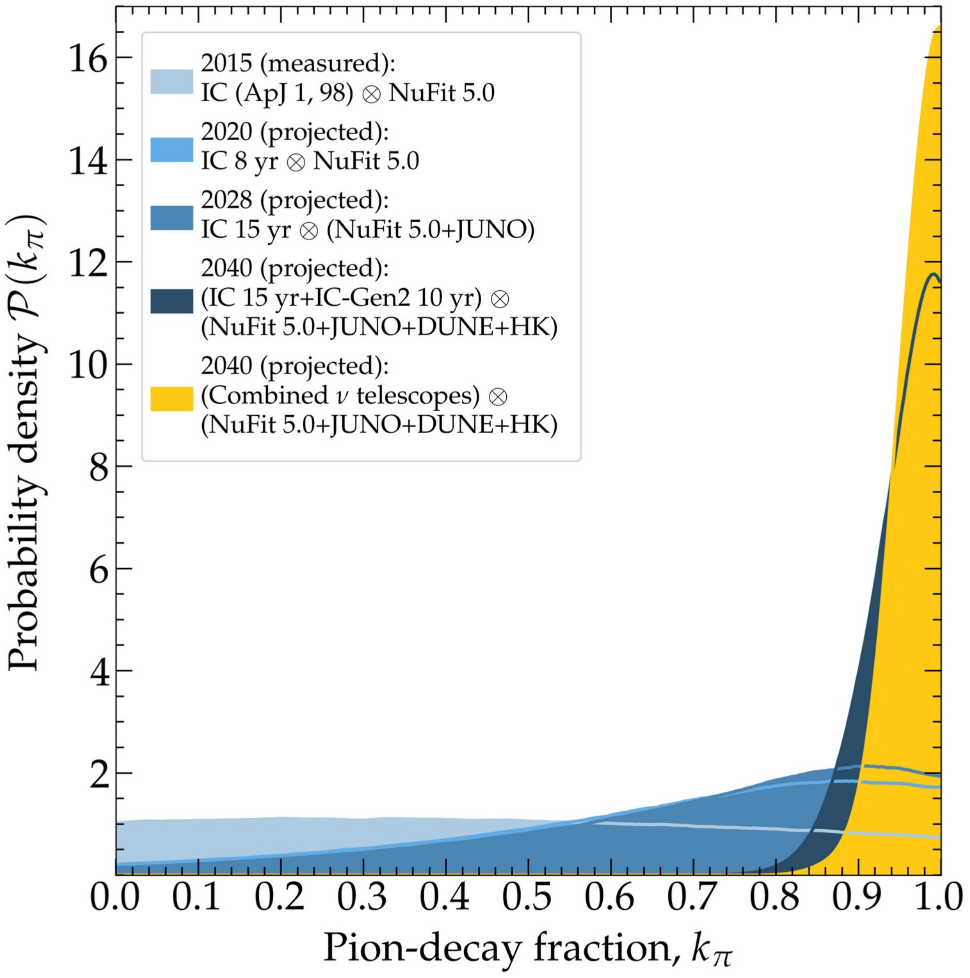

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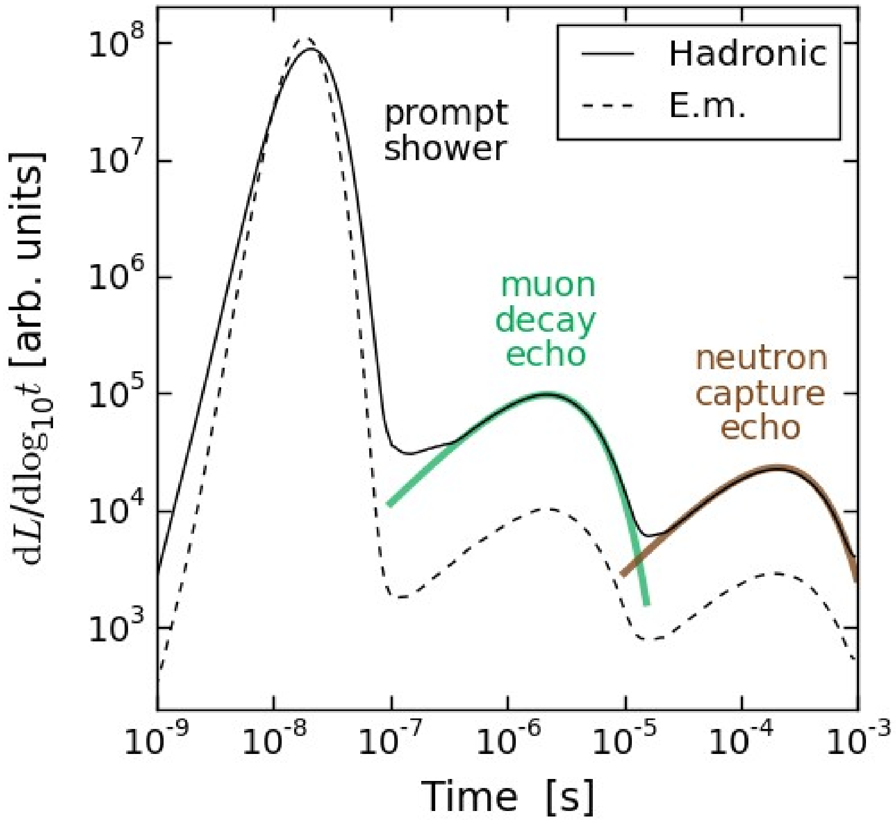
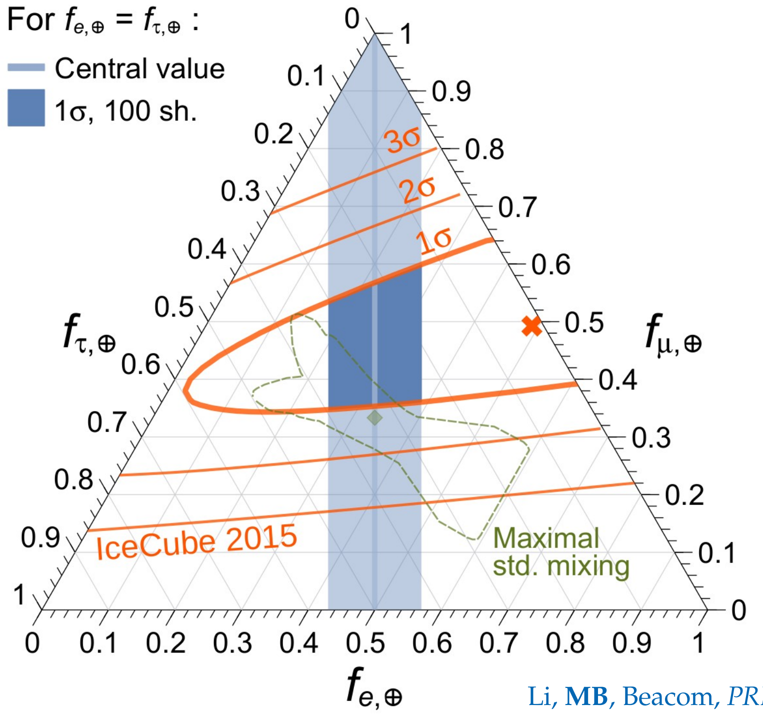
Side note: Improving flavor-tagging using *echoes*

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





Li, **MB**, Beacom, *PRL* 2019

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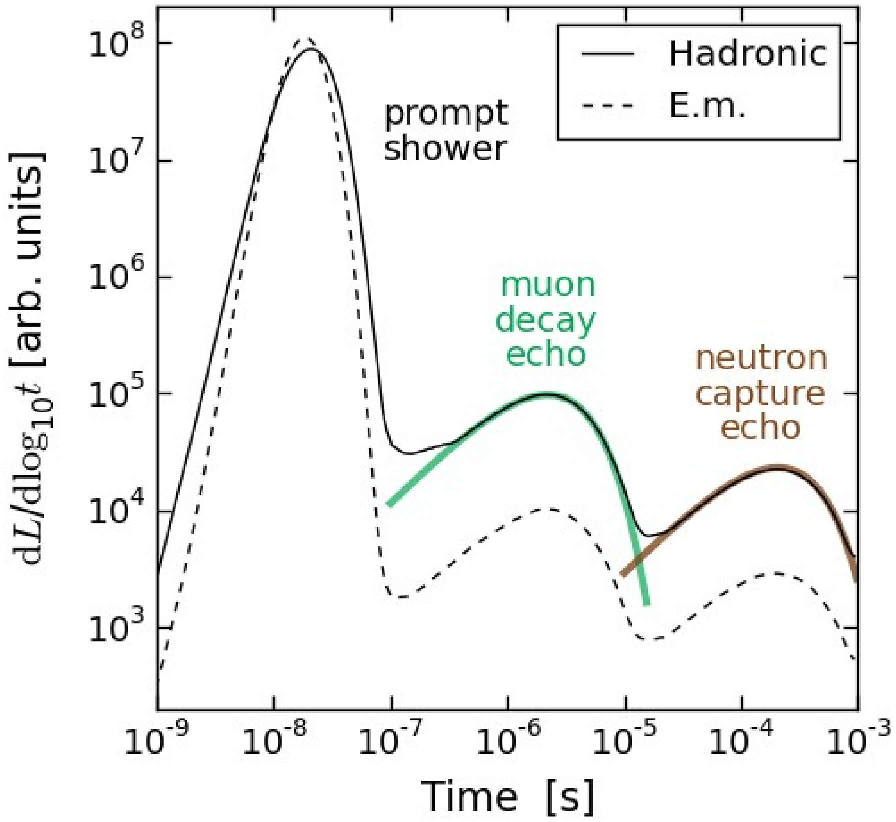

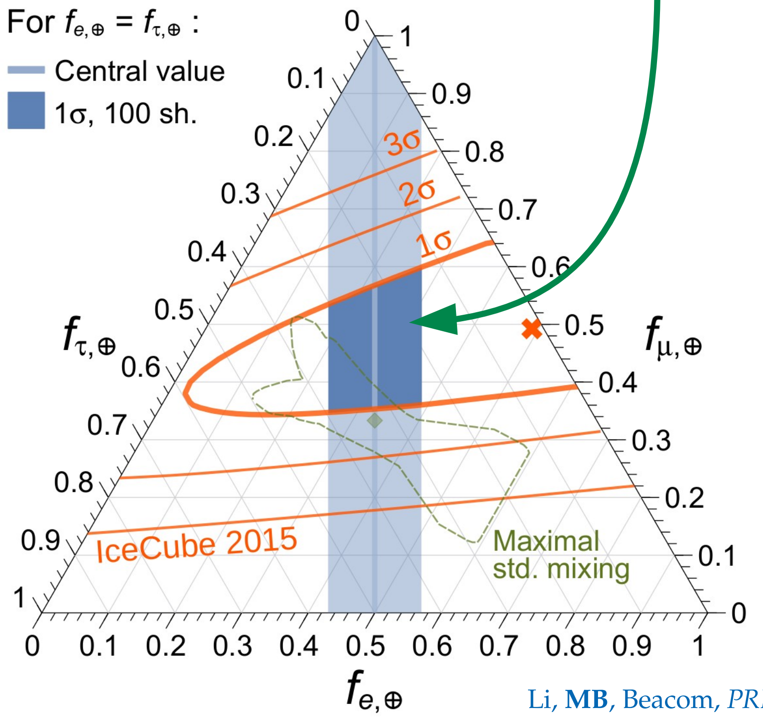

Li, **MB**, Beacom, *PRL* 2019

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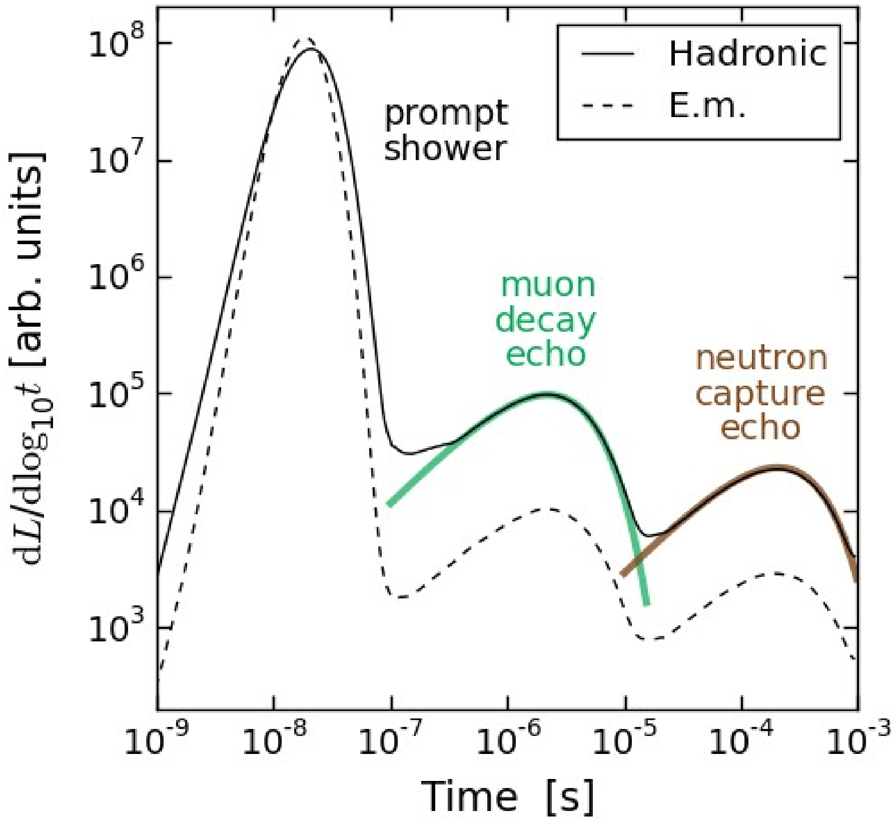

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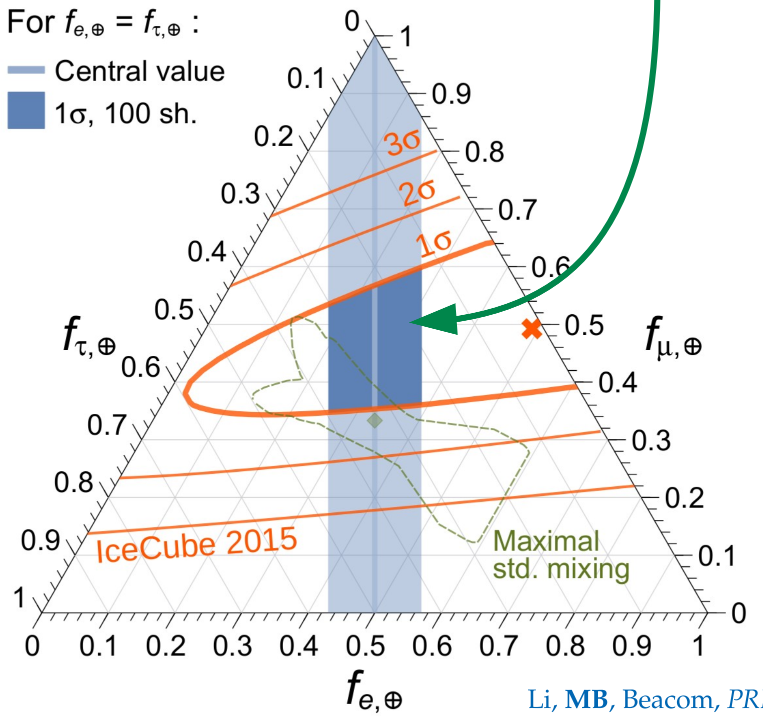

Li, **MB**, Beacom, *PRL* 2019