UHE neutrino science with IceCube-Gen2

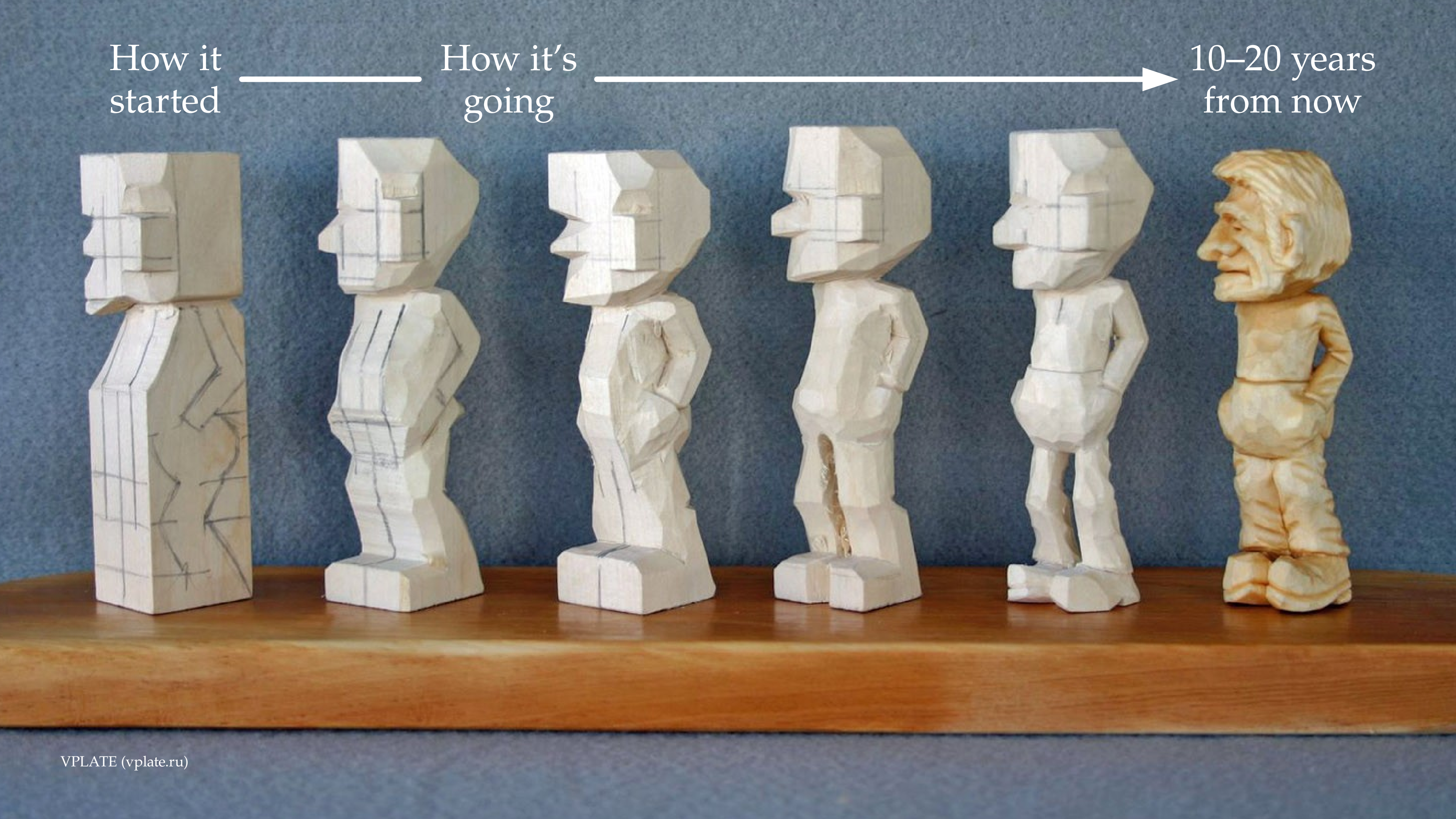
Mauricio Bustamante

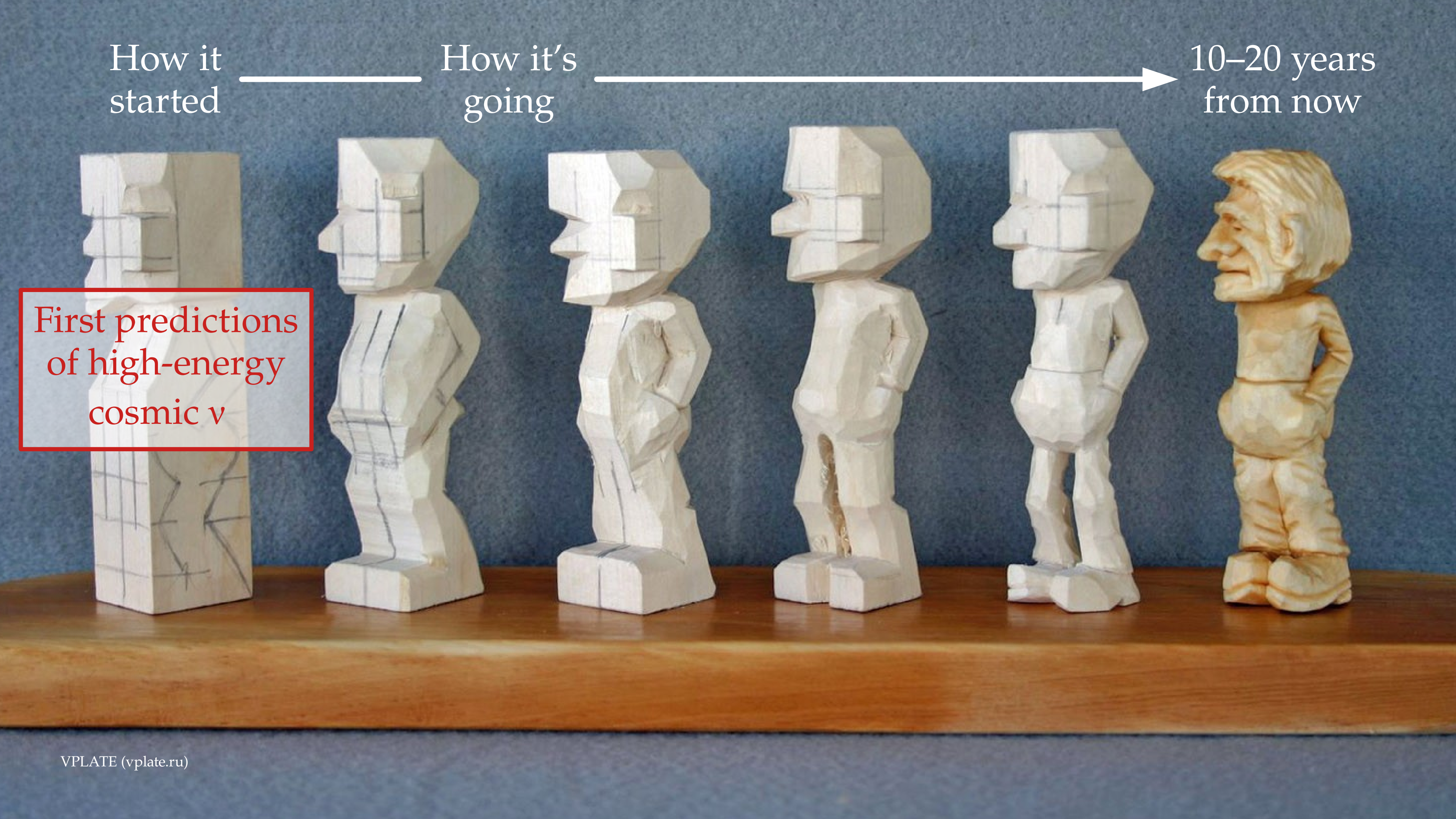
Niels Bohr Institute, University of Copenhagen

IceCube-Gen2 TDR Workshop
October 18, 2021

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN


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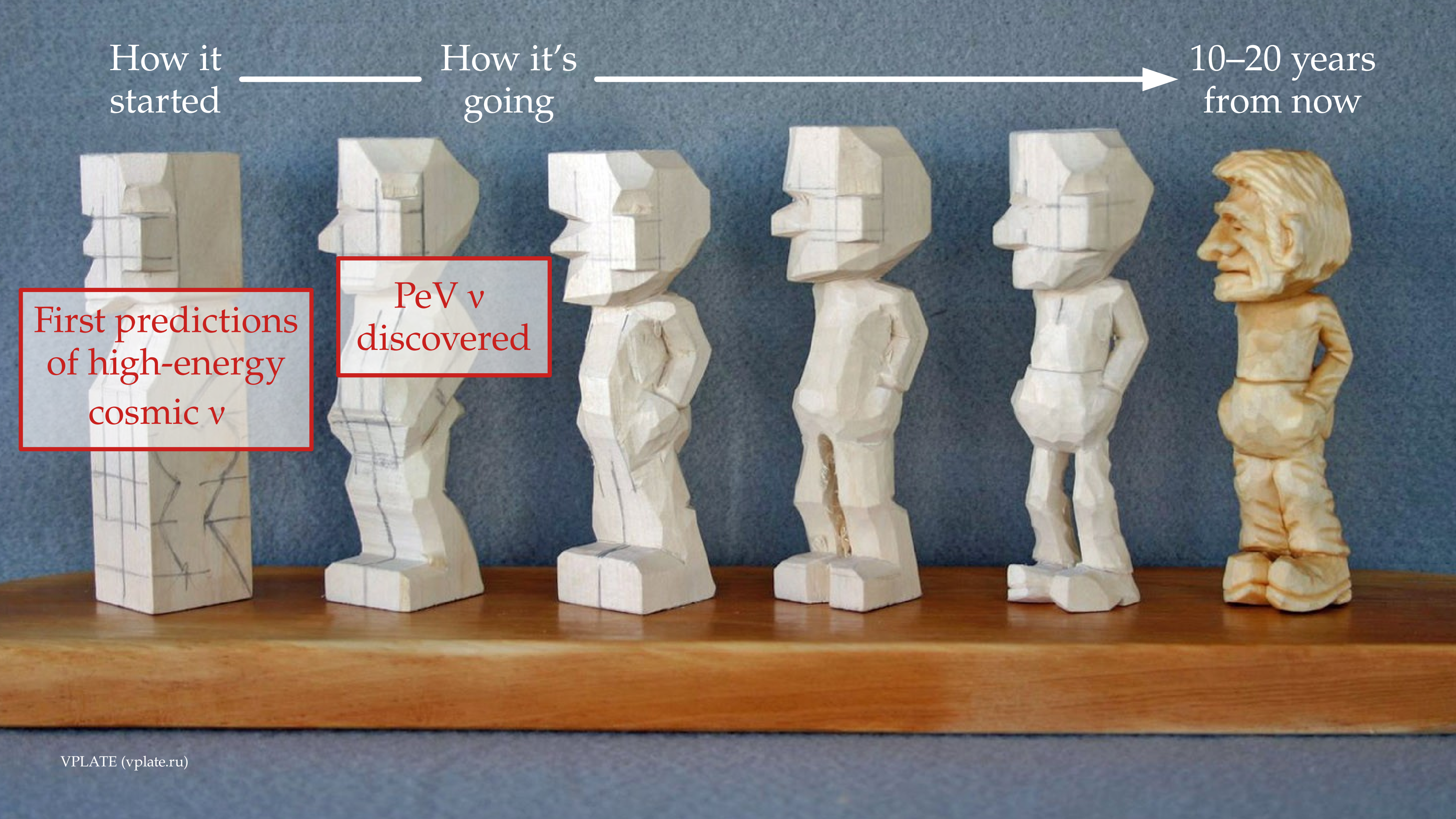
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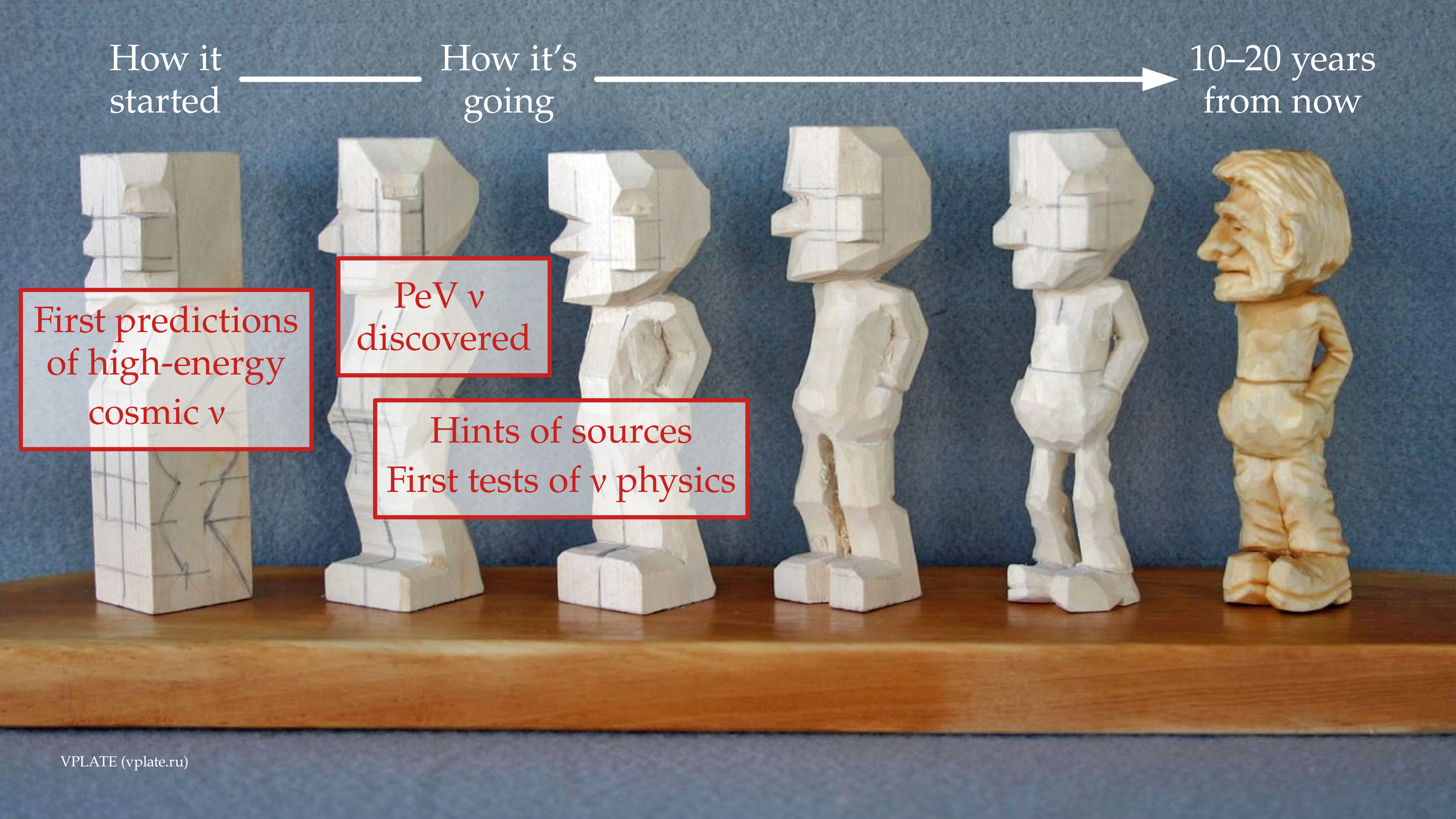
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Hints of sources
First tests of ν physics
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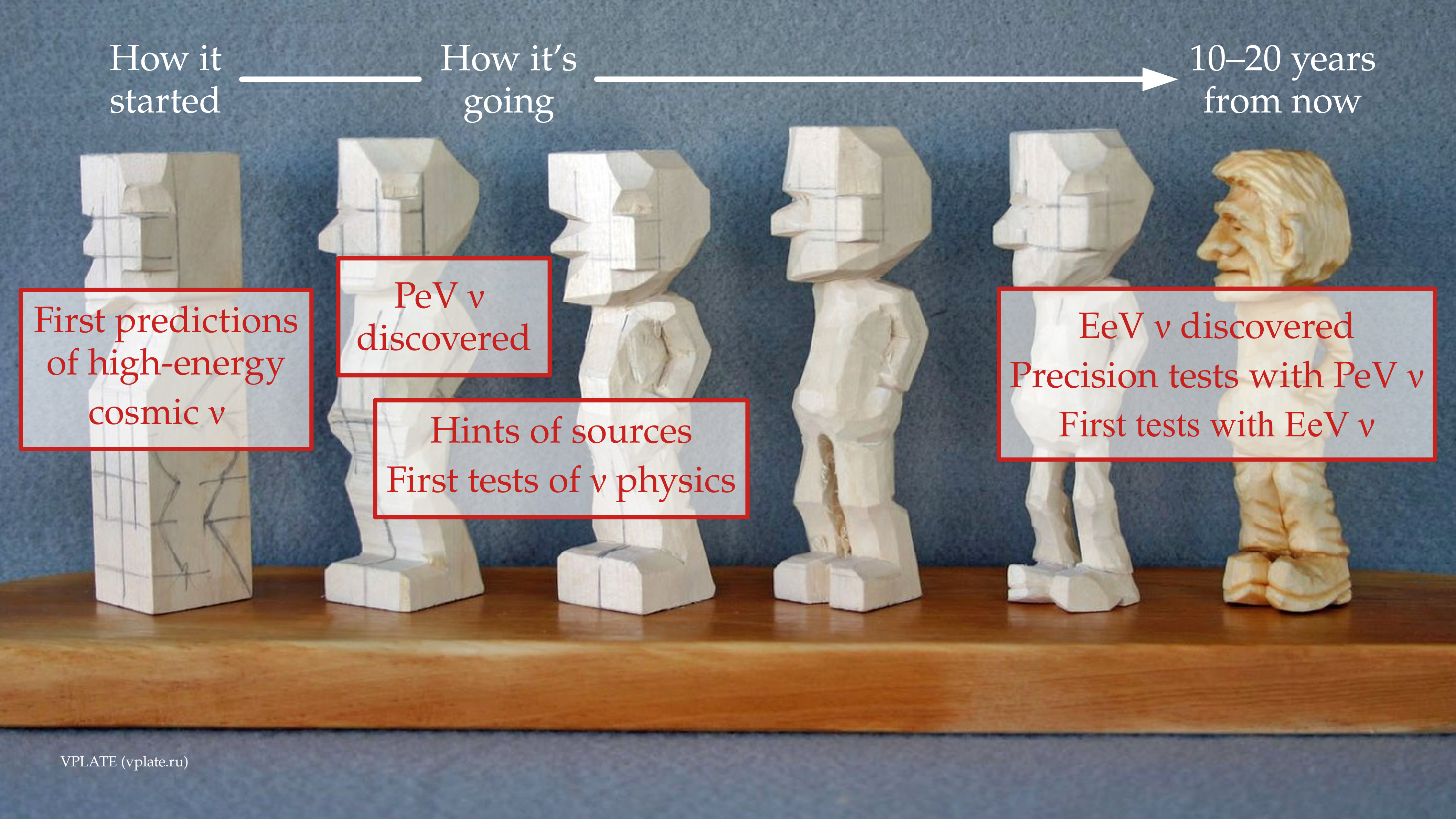
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EeV ν discovered
Precision tests with PeV ν
First tests with EeV ν
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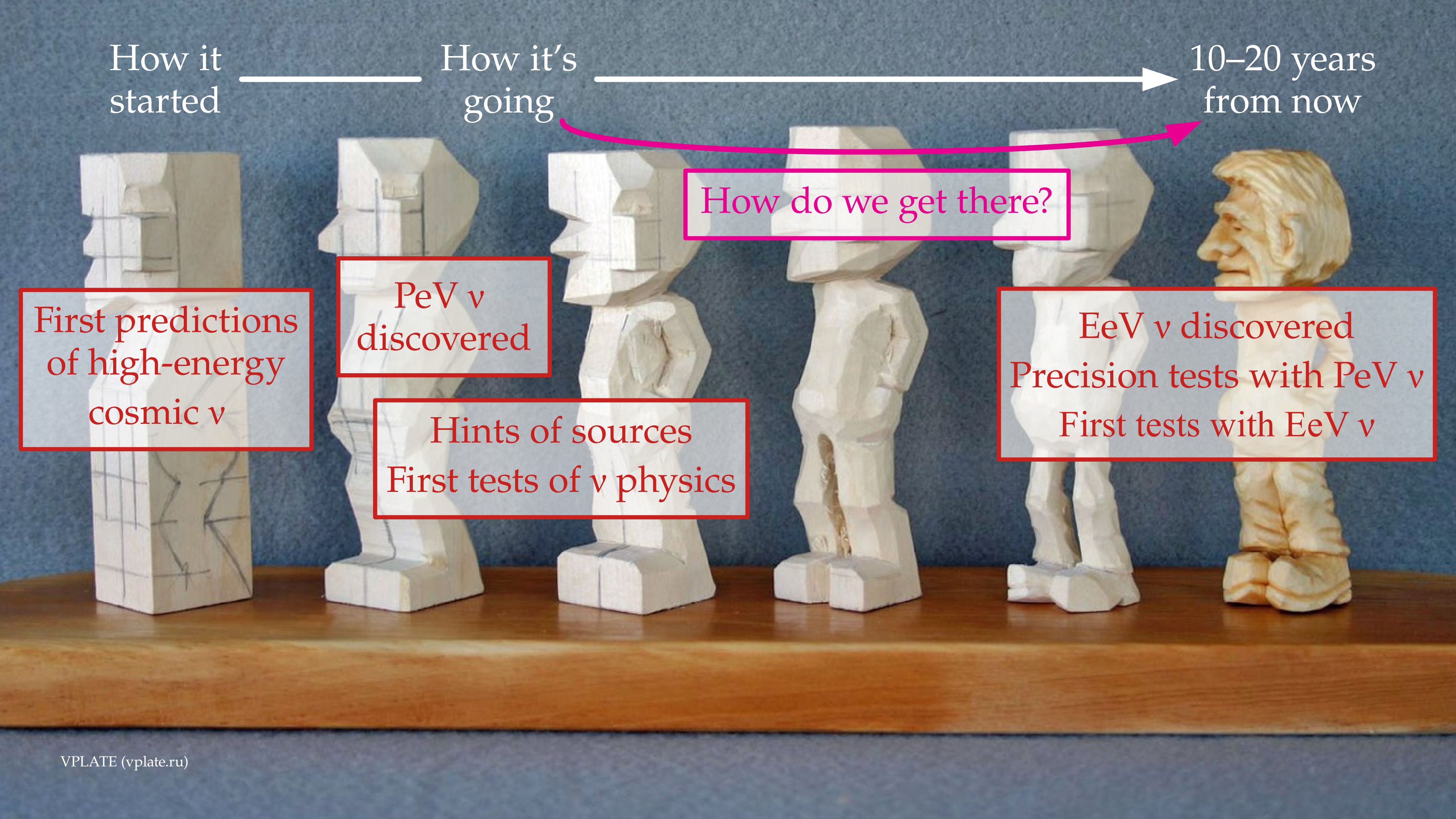
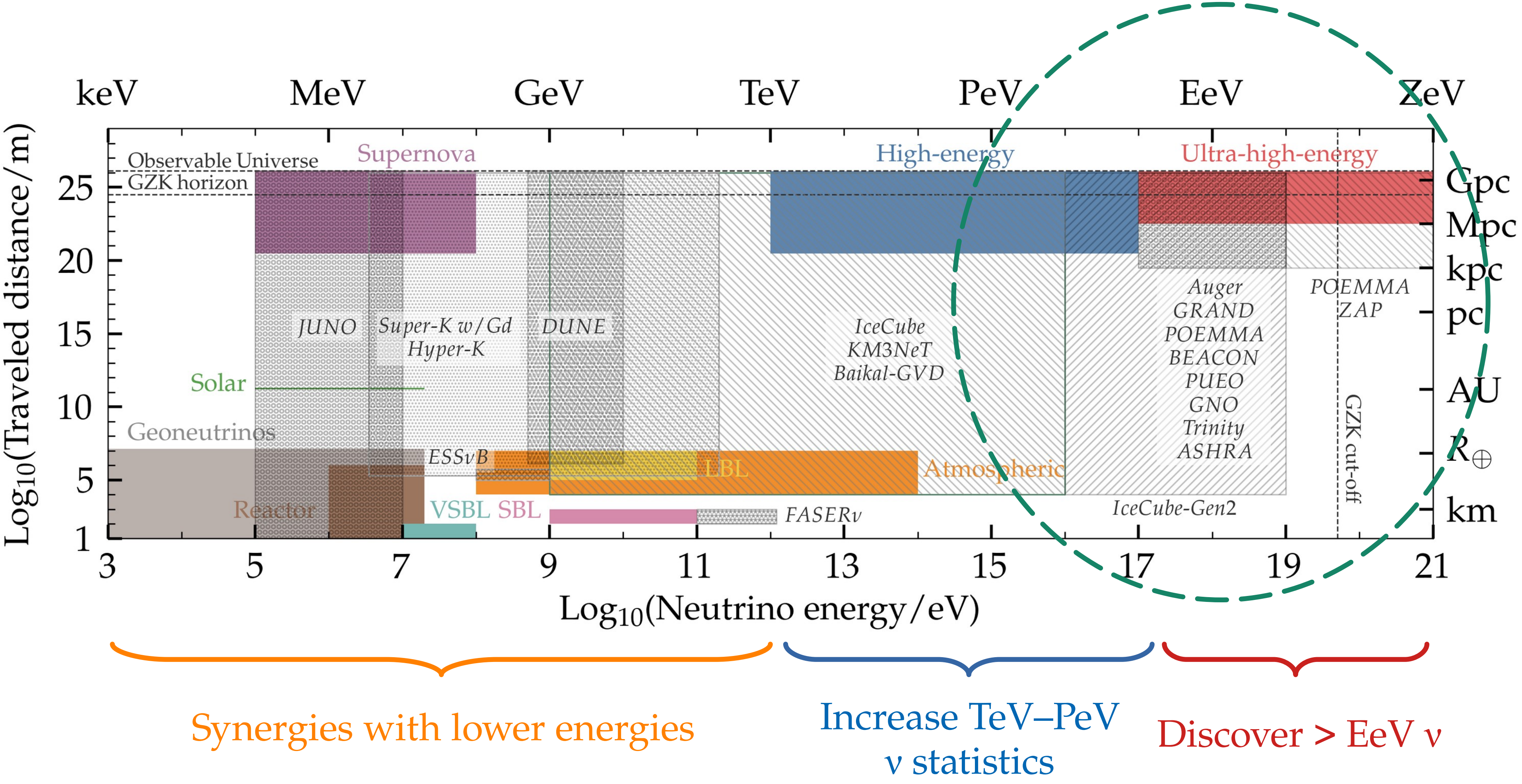


VPLATE (vplate.ru)

Next decade: a host of planned neutrino detectors



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

Five directions

Advanced

Approximate level of progress

(N.B.: All results are preliminary)

Nascent

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. UHE ν physics using flavor ratios

Five directions

Advanced

1 Discovery potential for UHE ν

2 Inferring the spectrum of UHE ν

Approx

level

prog

(N.B.: Al

are prelin

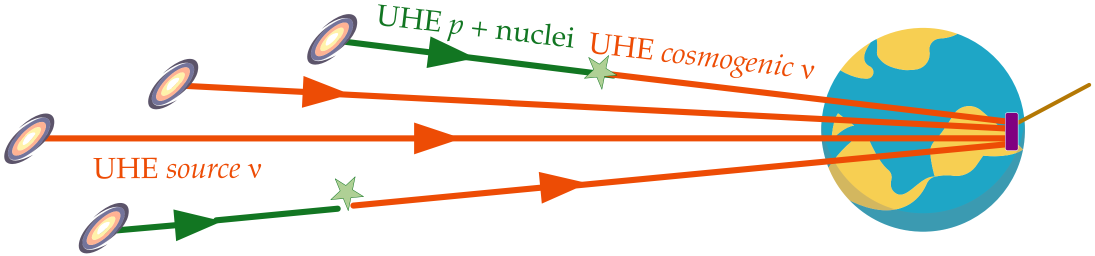
Overall tenet:

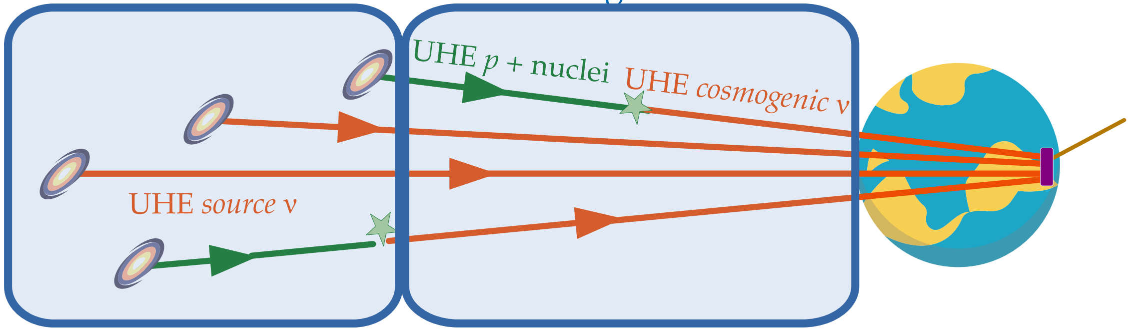
Ground predictions by accounting for all relevant particle and astrophysics unknowns

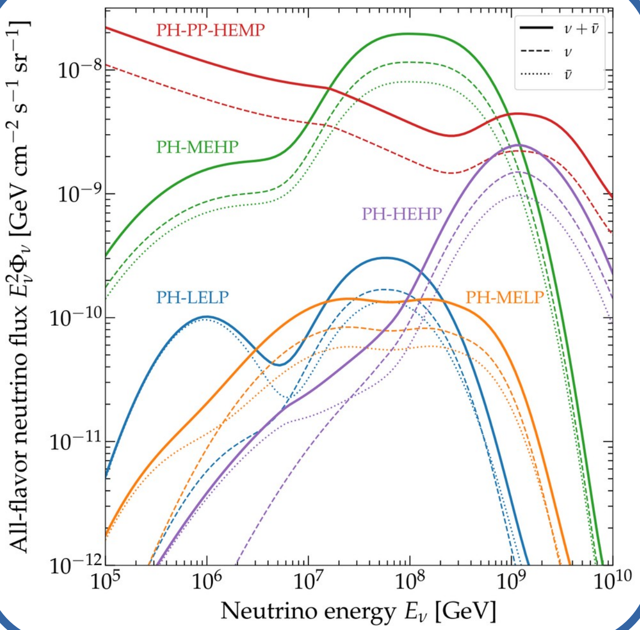
4 Testing other UHE ν BSM models

5 UHE ν physics using flavor ratios

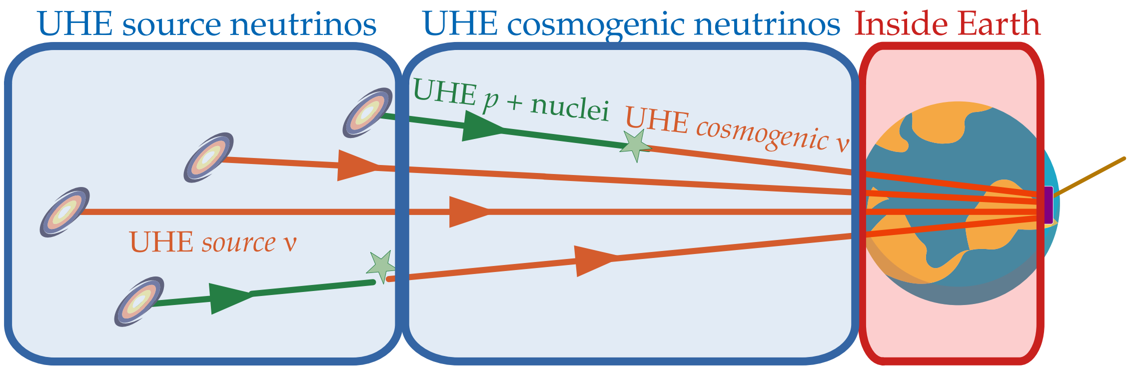
Nascent

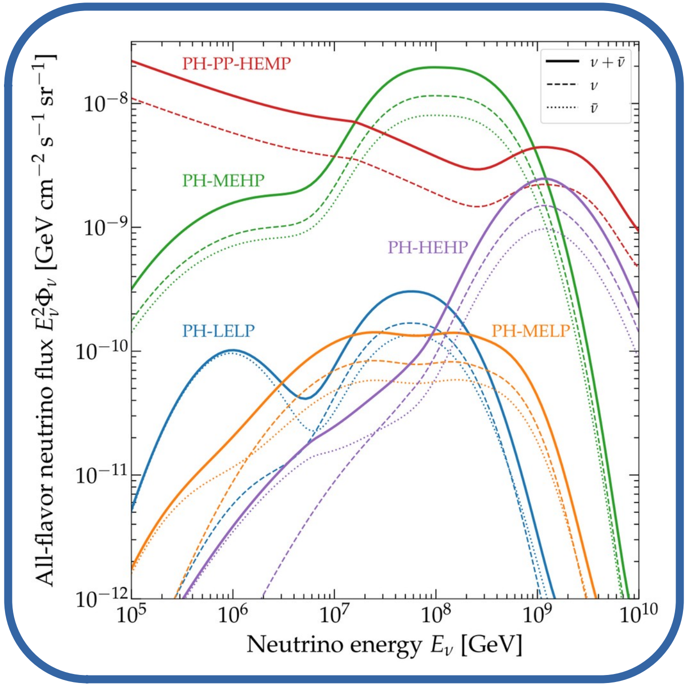

UHE *p* + nuclei
UHE *cosmogenic* ν
UHE *source* ν





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





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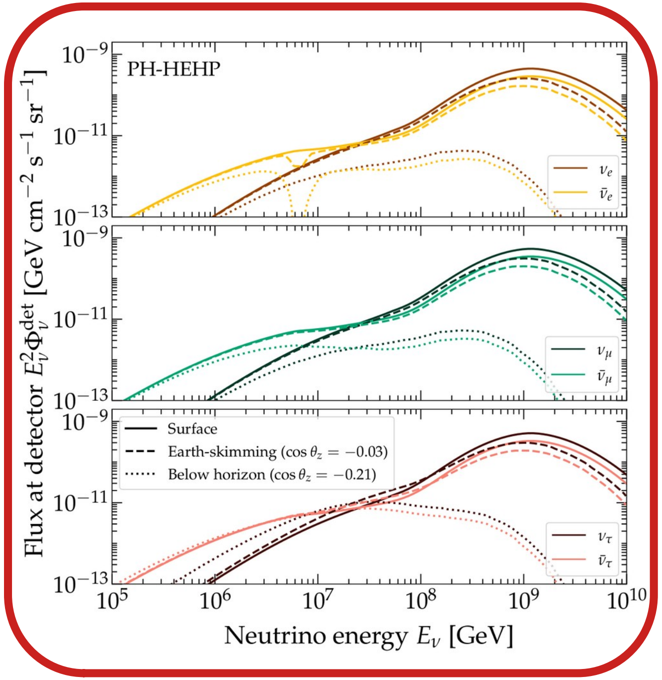
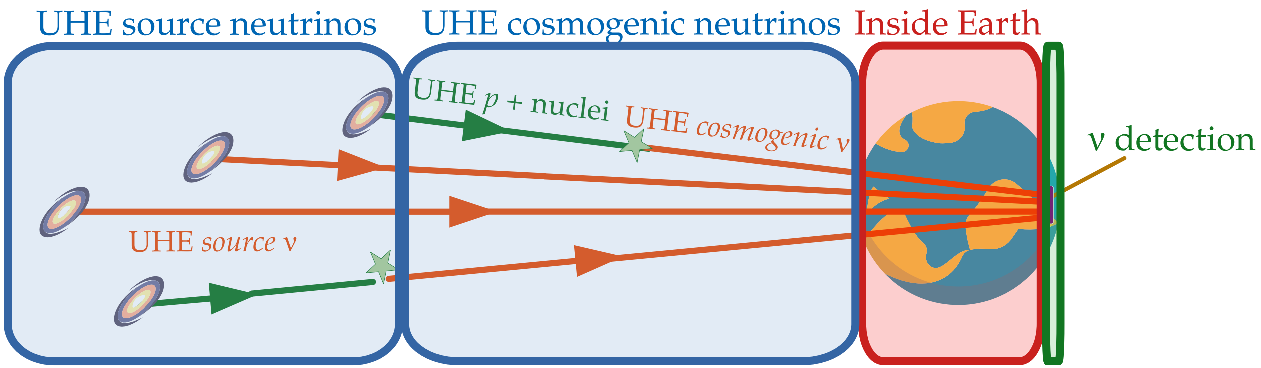
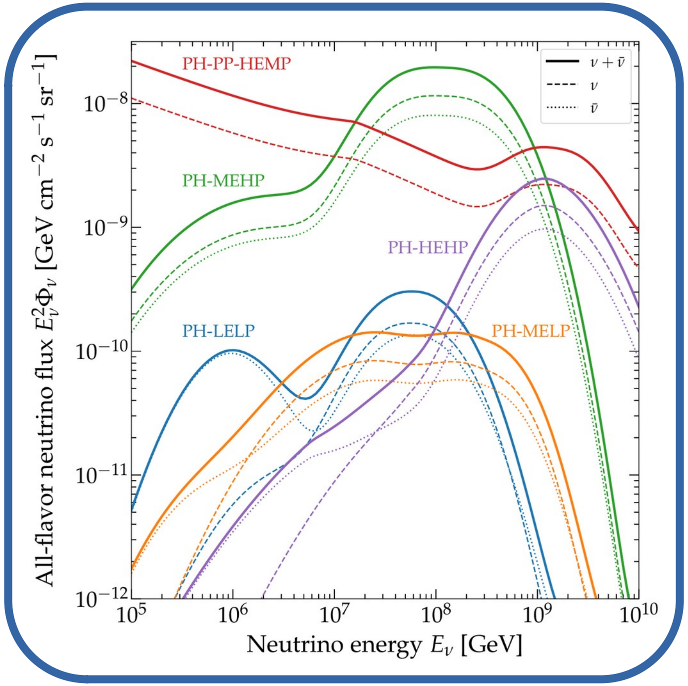


Propagate each flavor of ν and $\bar{\nu}$ separately: deep inelastic scattering, diffractive scattering, ν_τ regeneration





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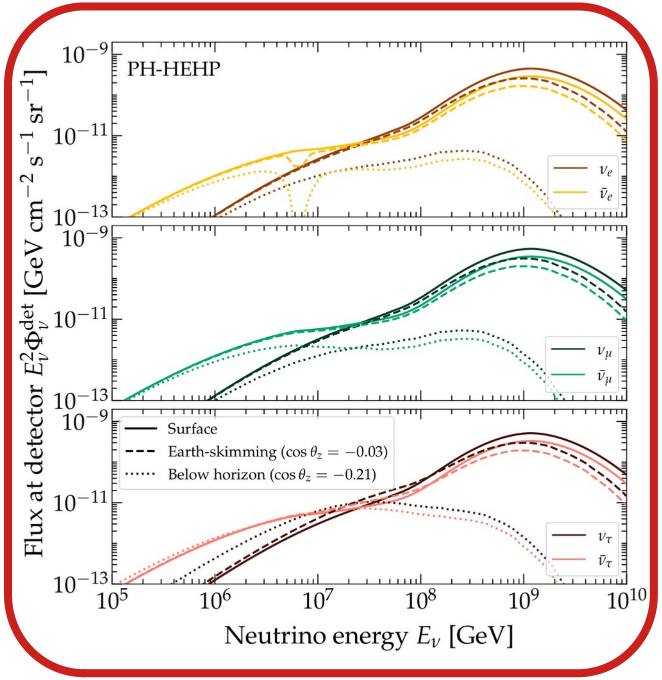

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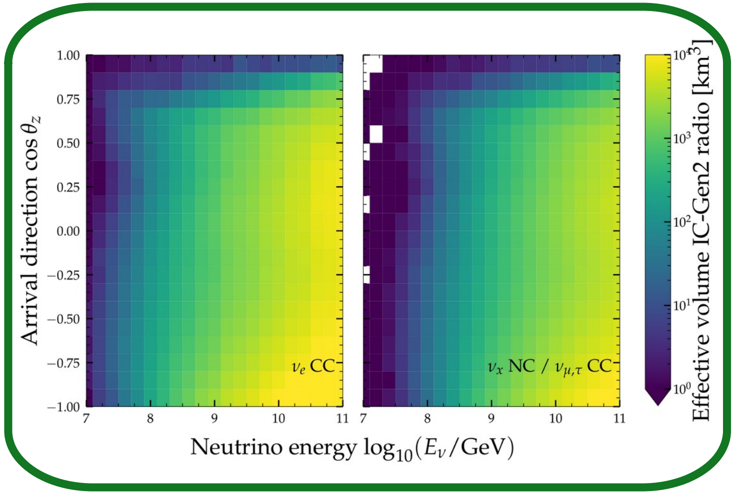
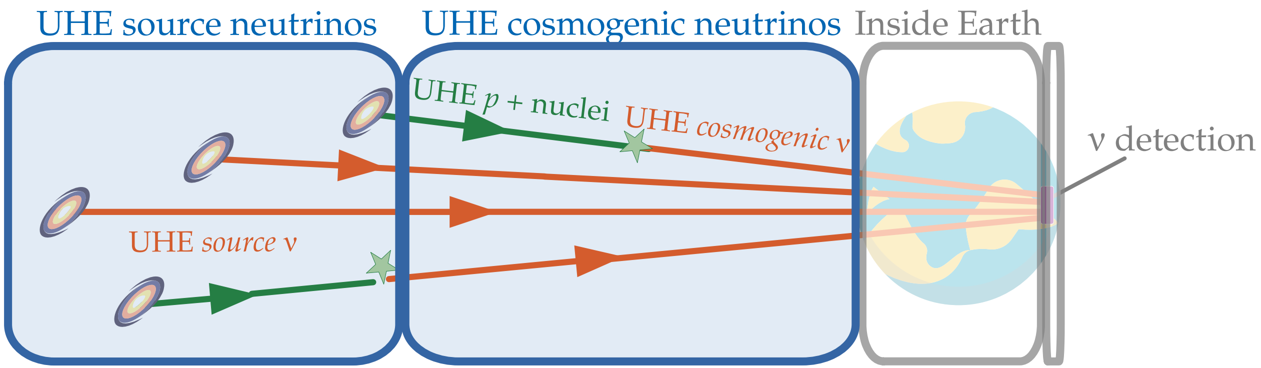
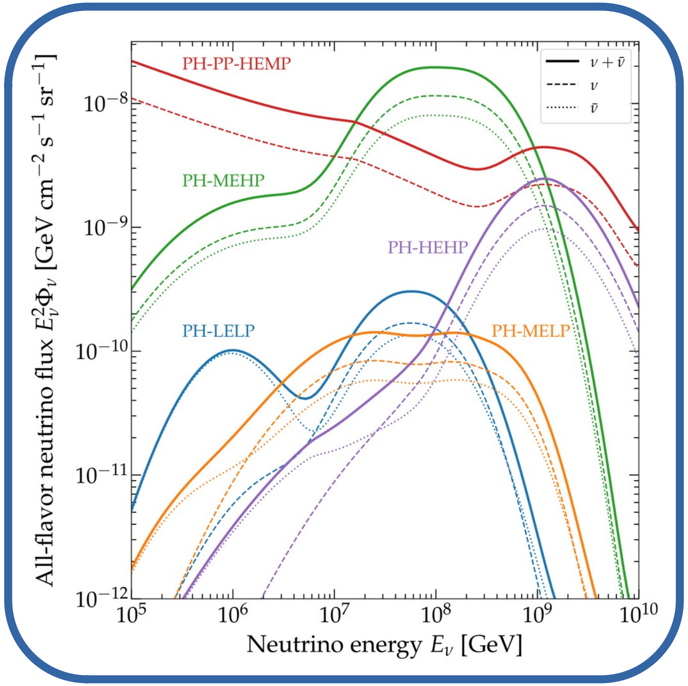


Model radio propagation in ice, antenna response, angular and energy resolution, inelasticity distribution

A general framework for UHE ν physics and astrophysics





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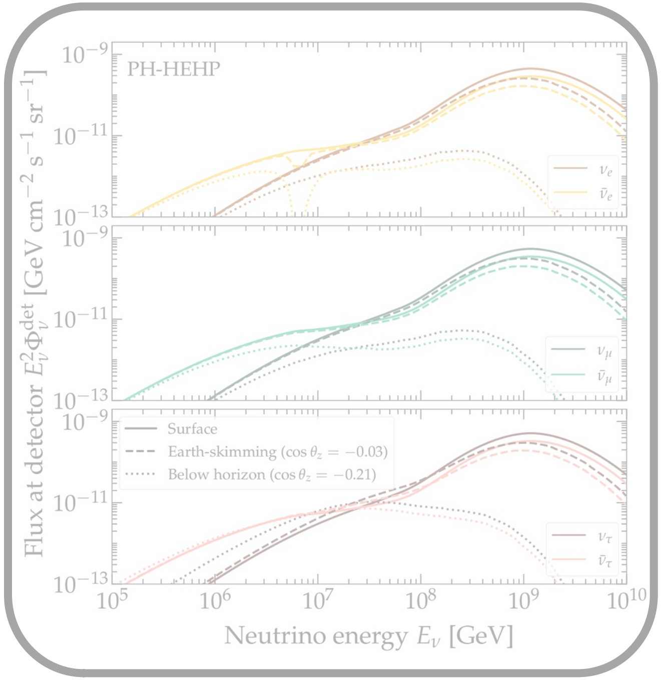

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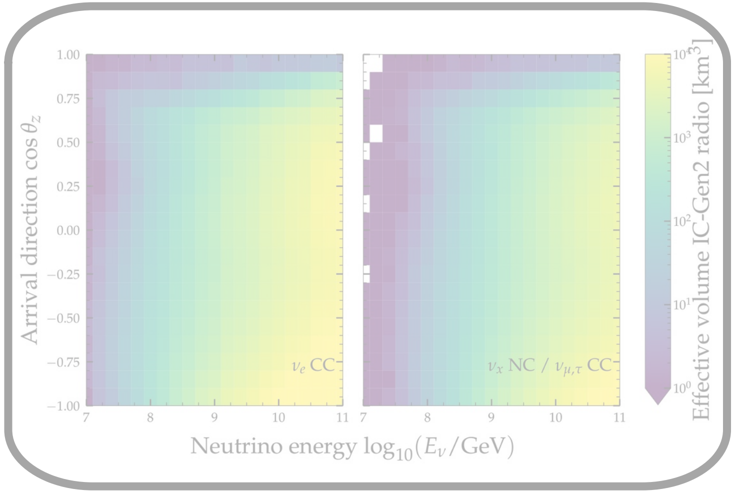

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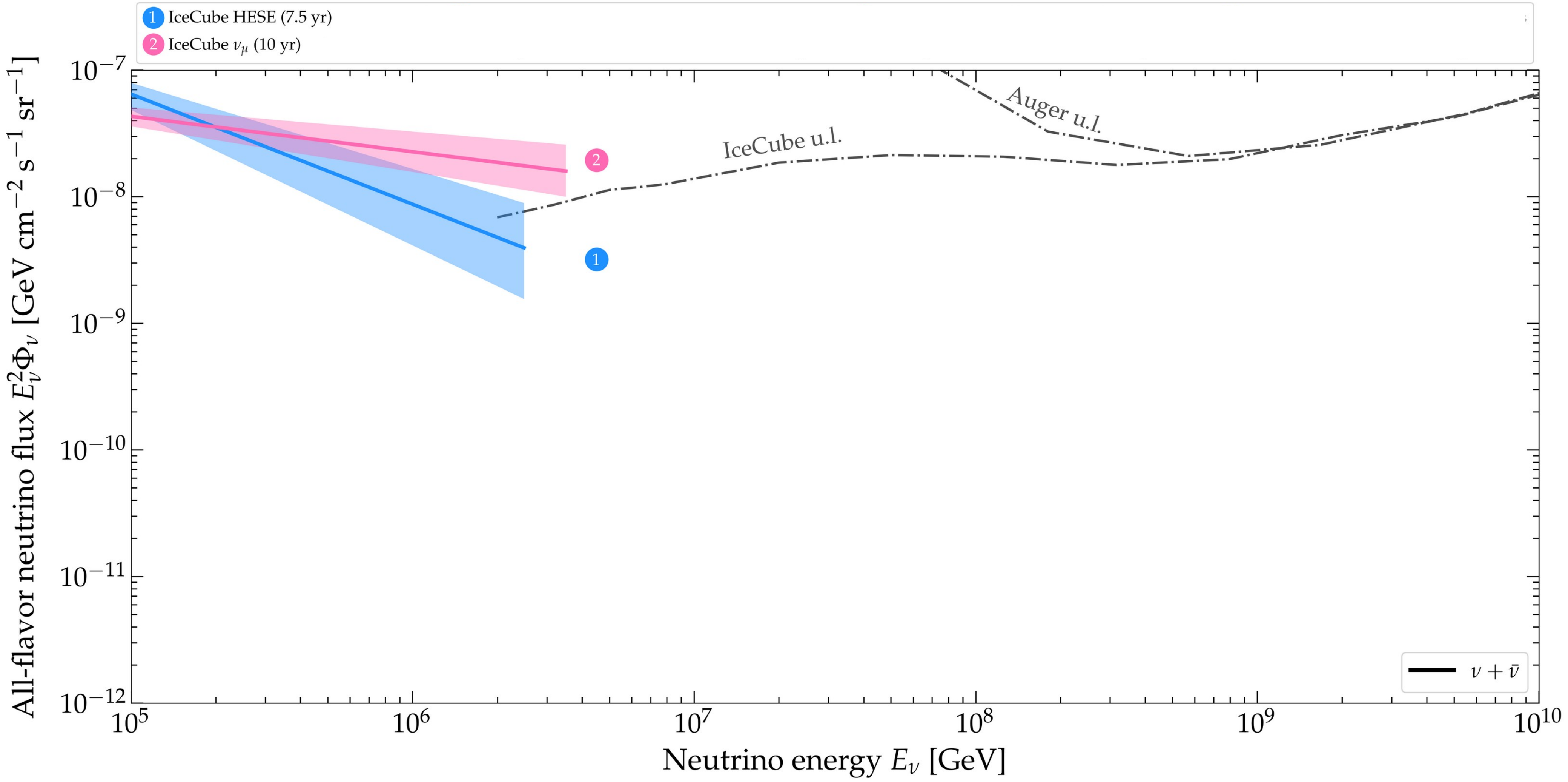
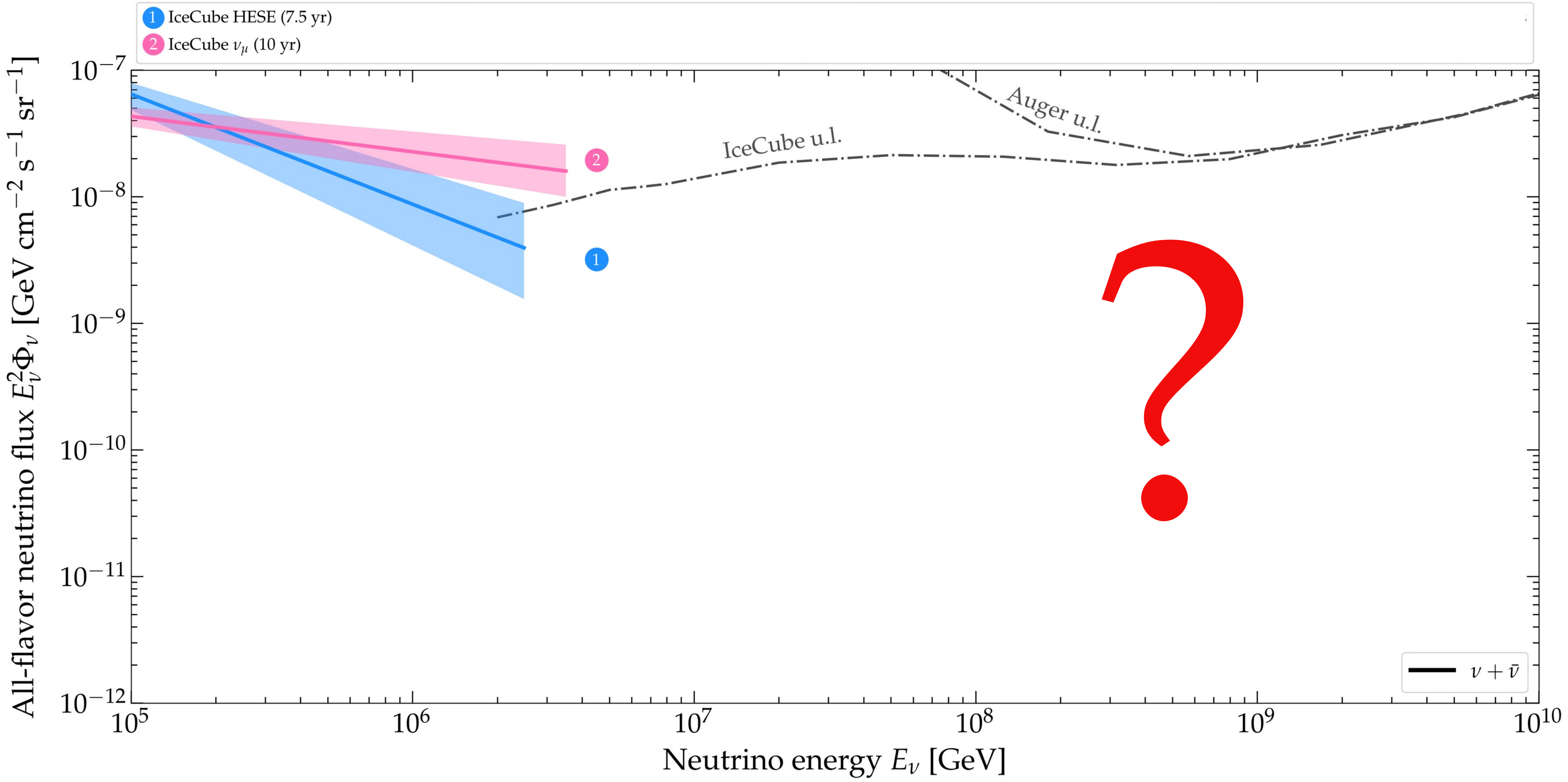


MB, Valera, Glaser, *In preparation*



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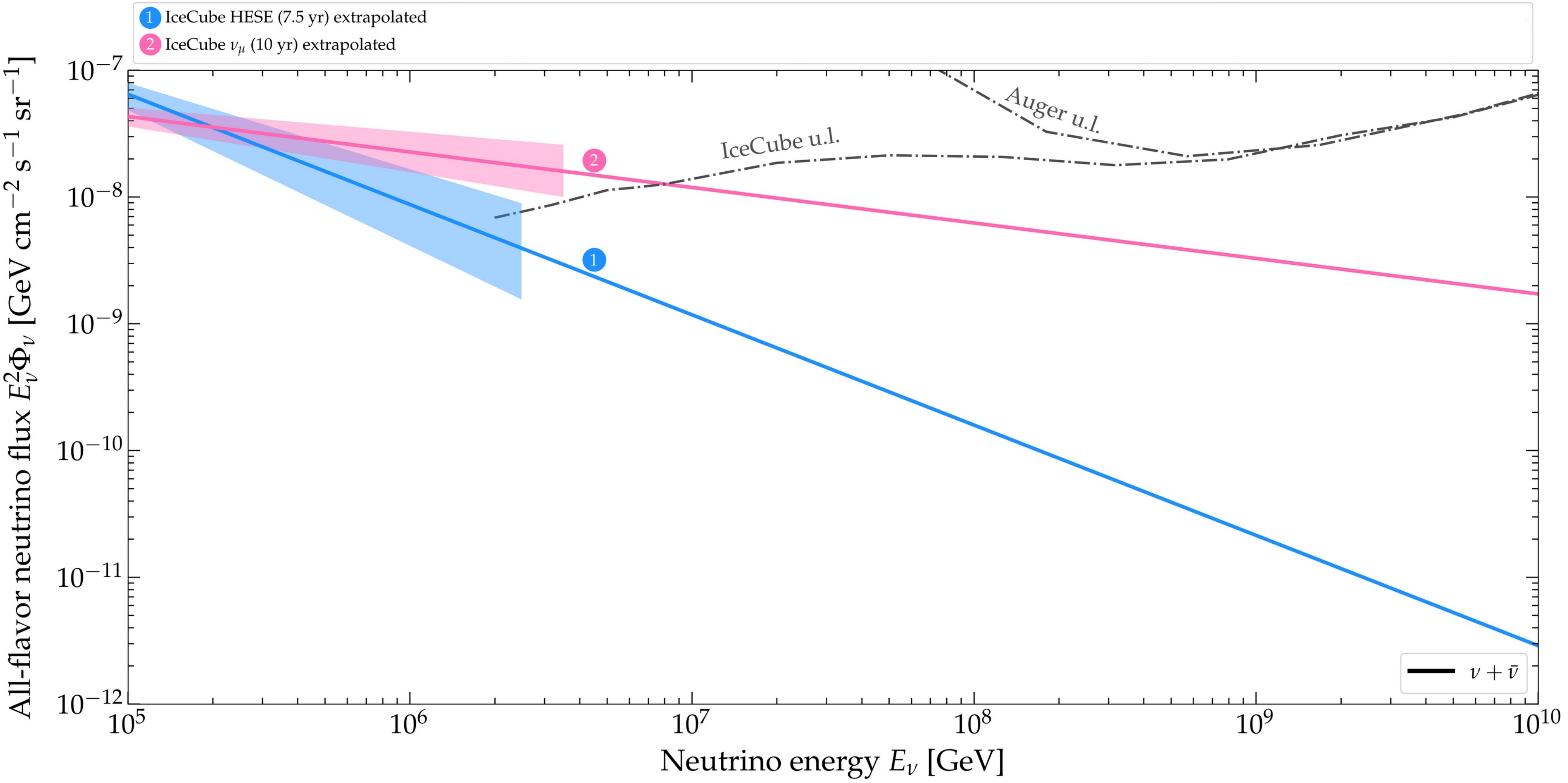

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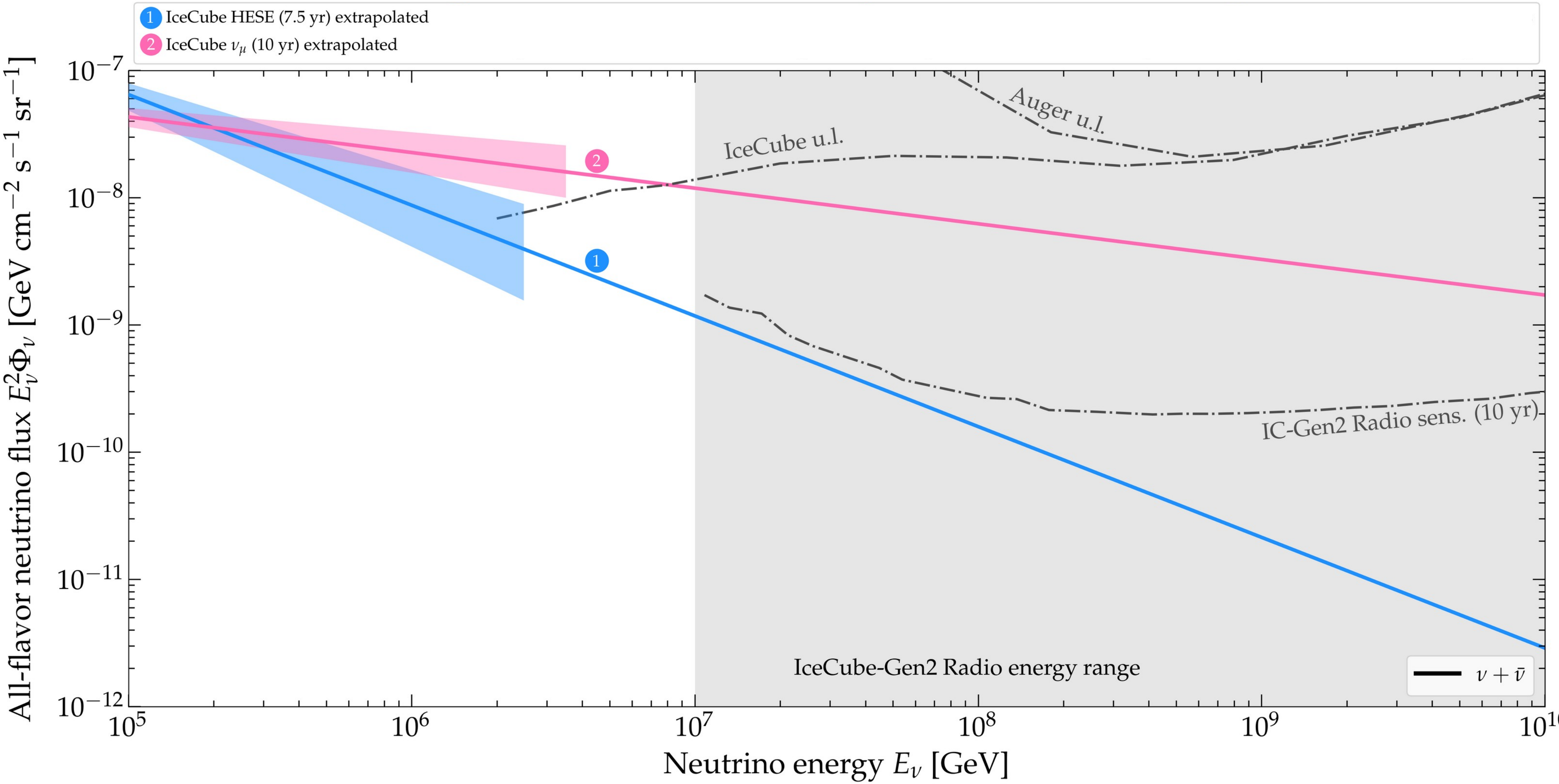

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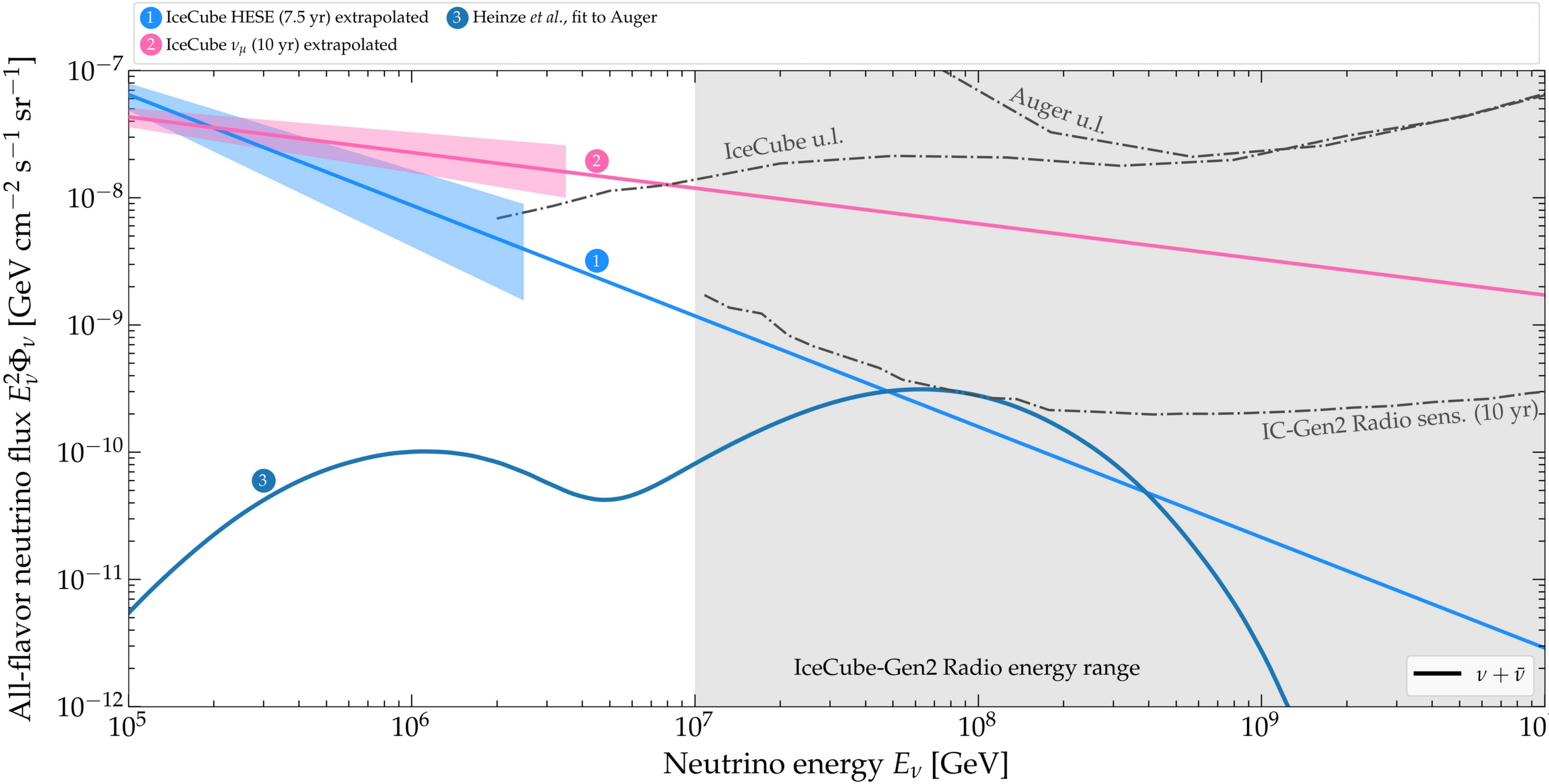

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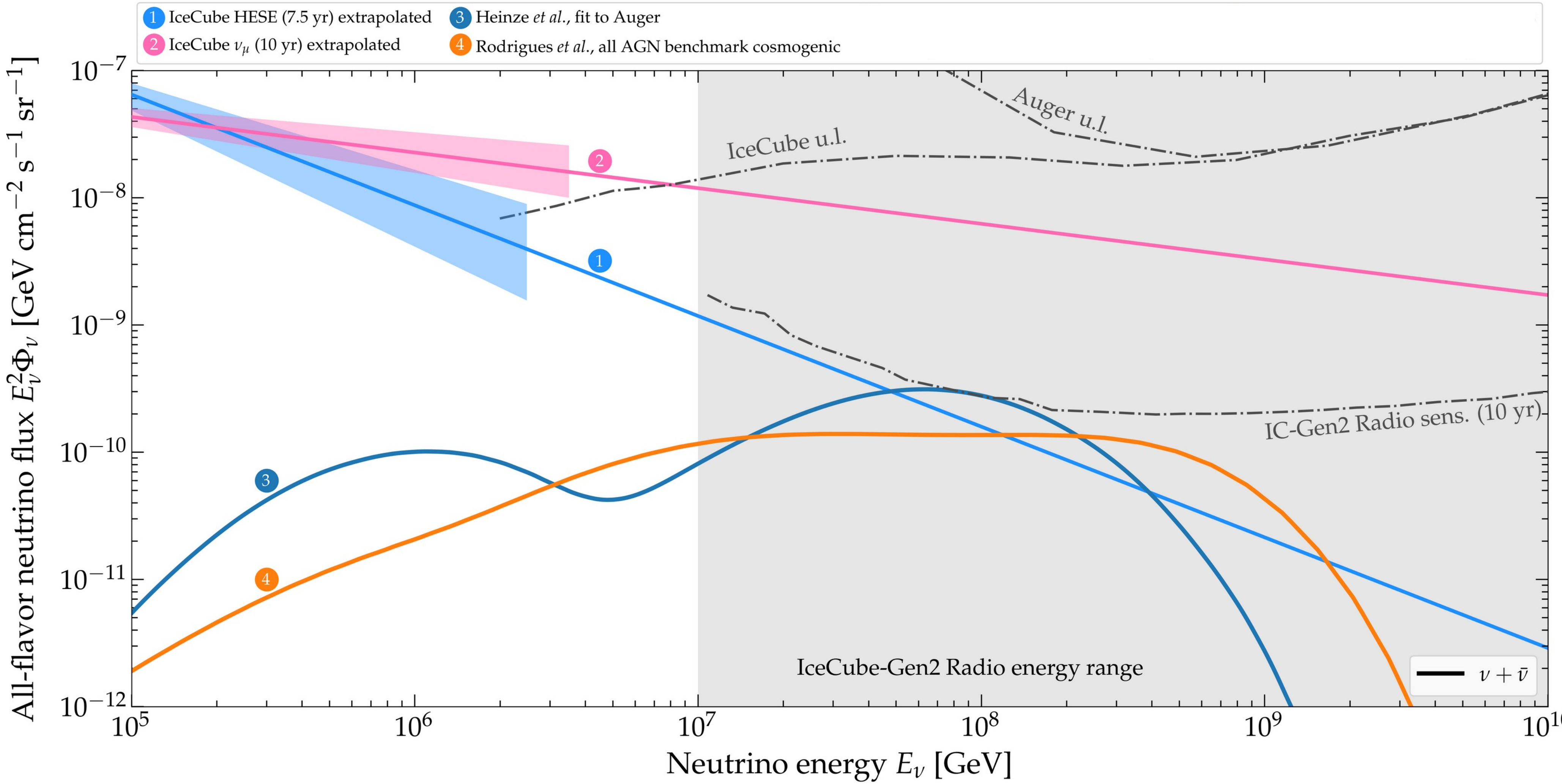

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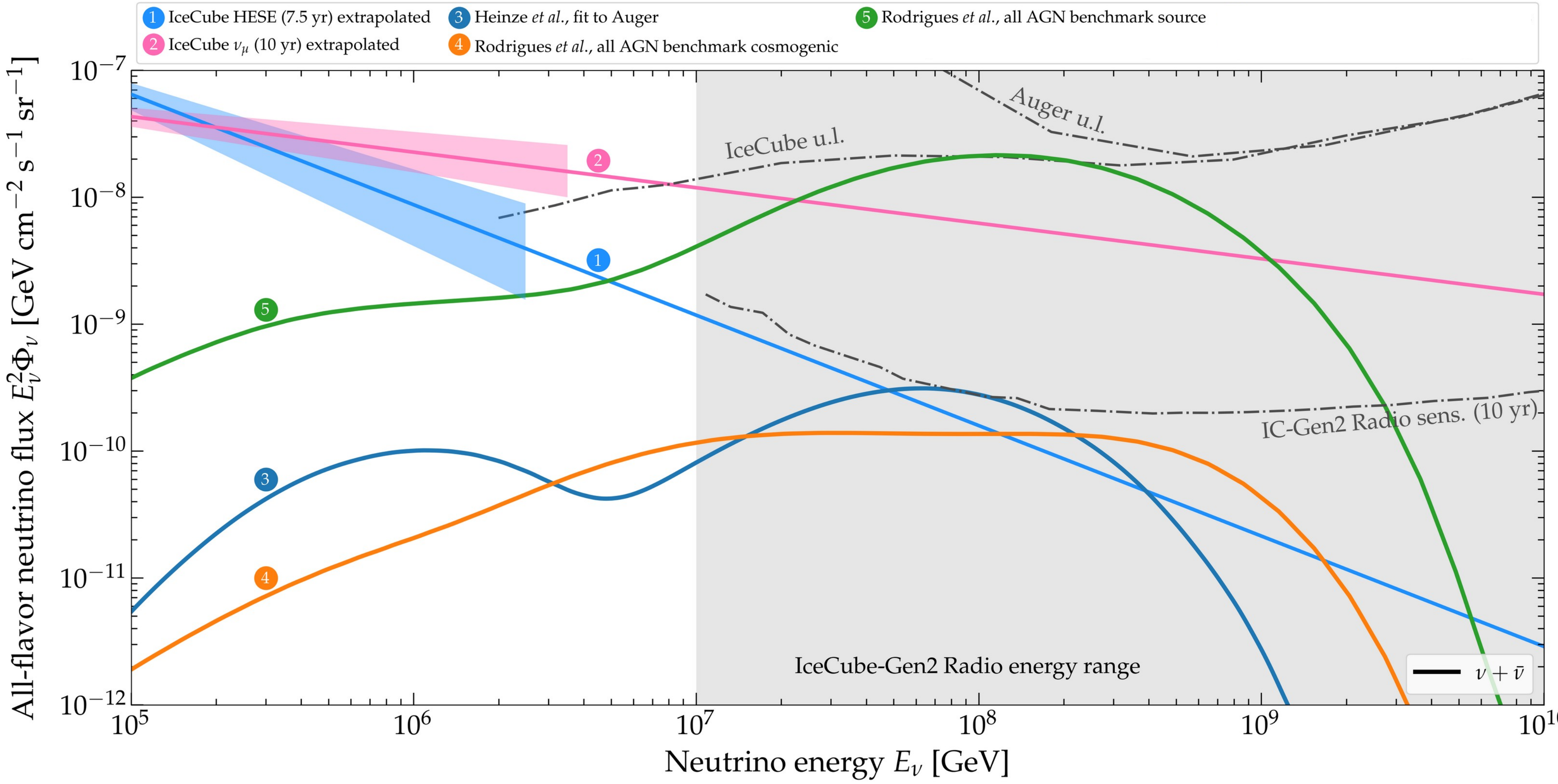

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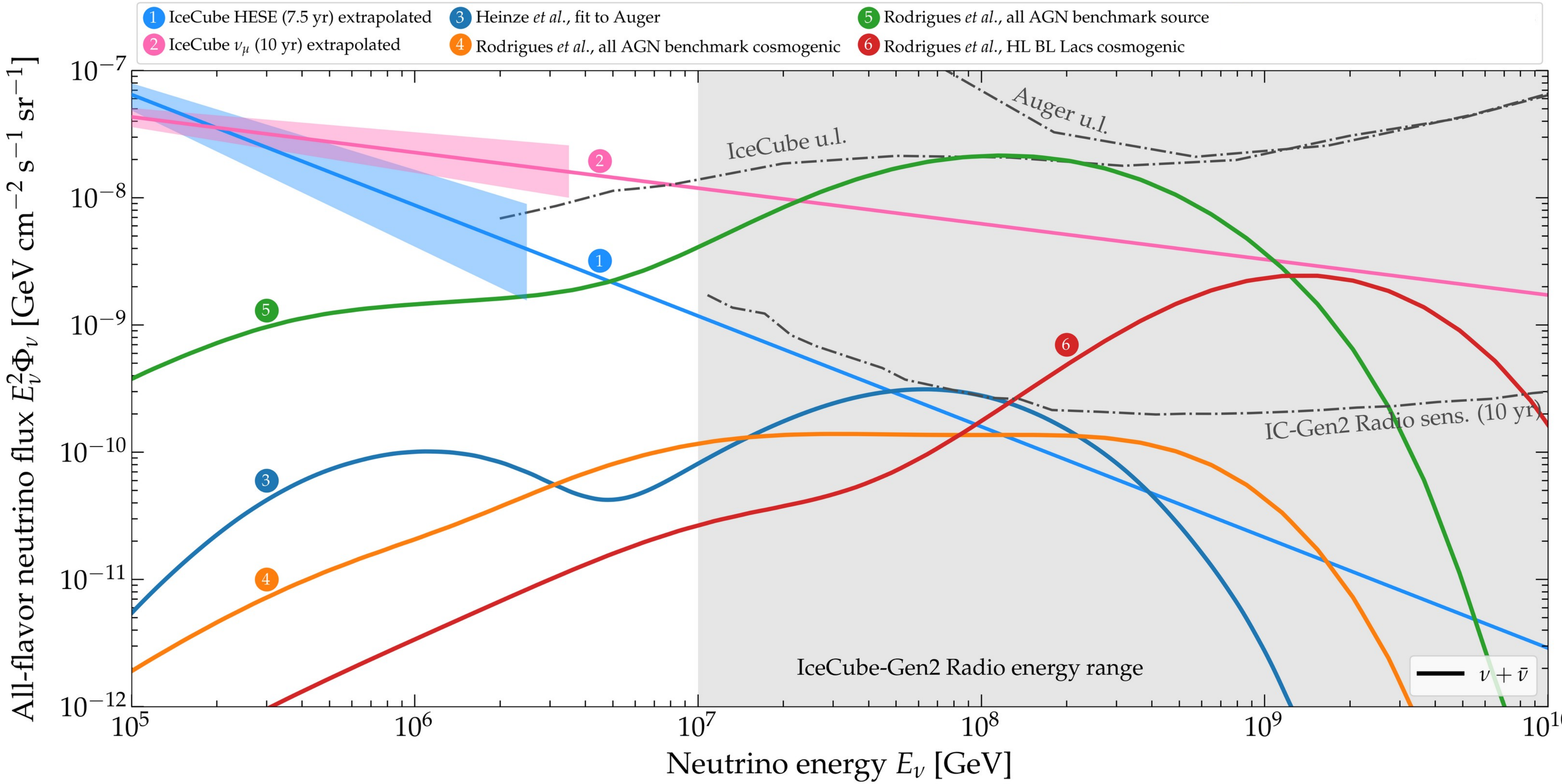

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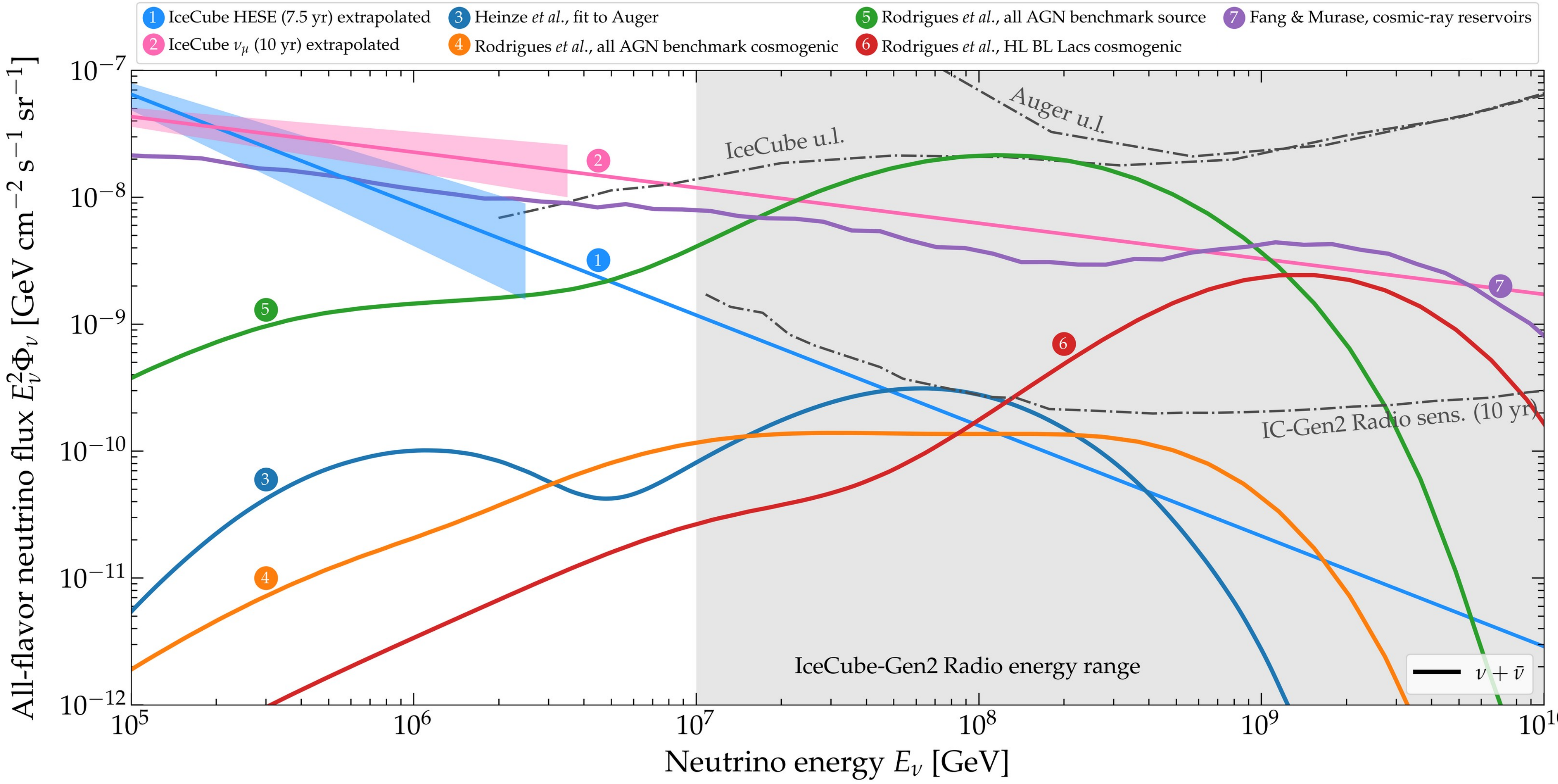

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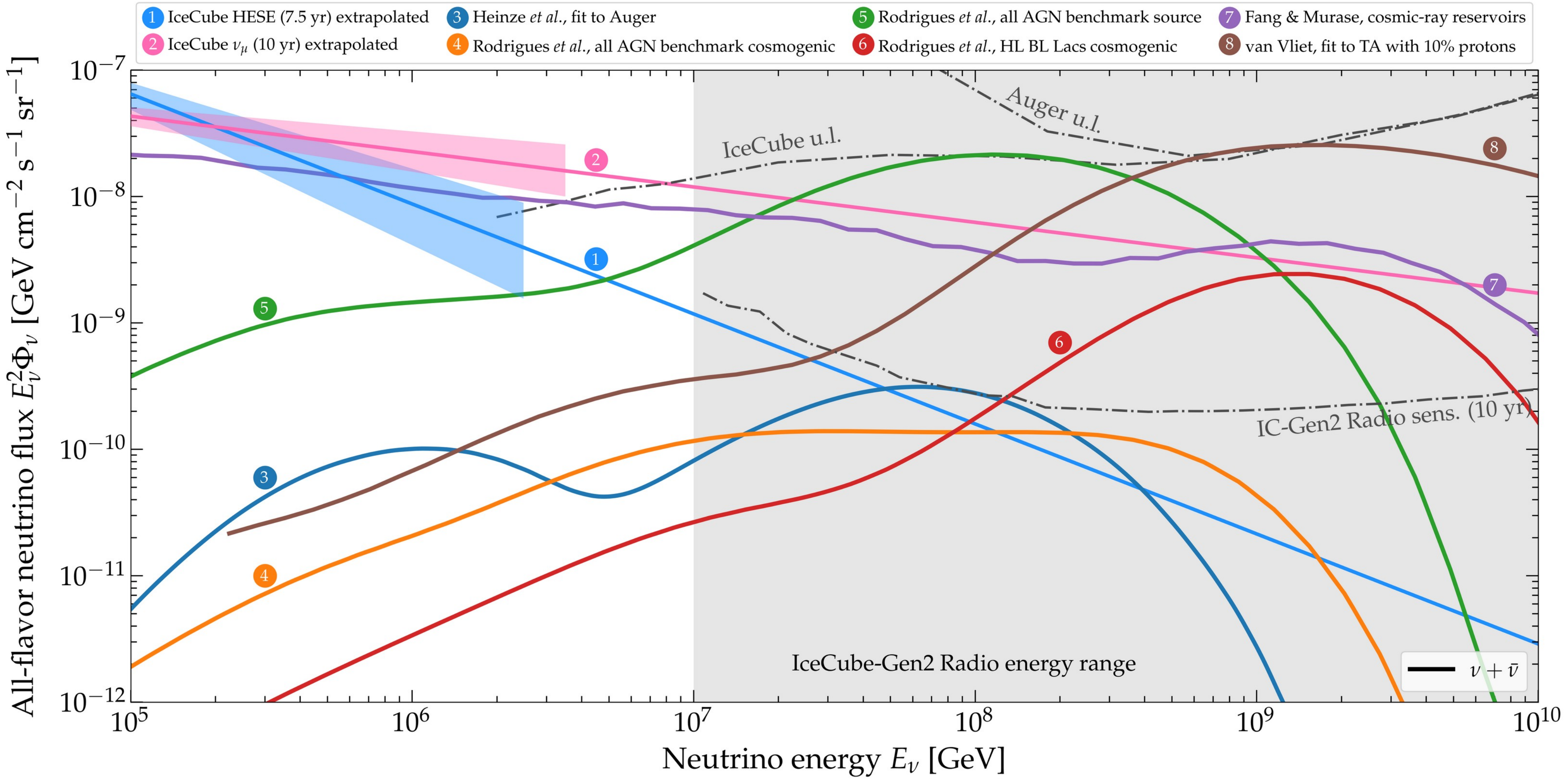

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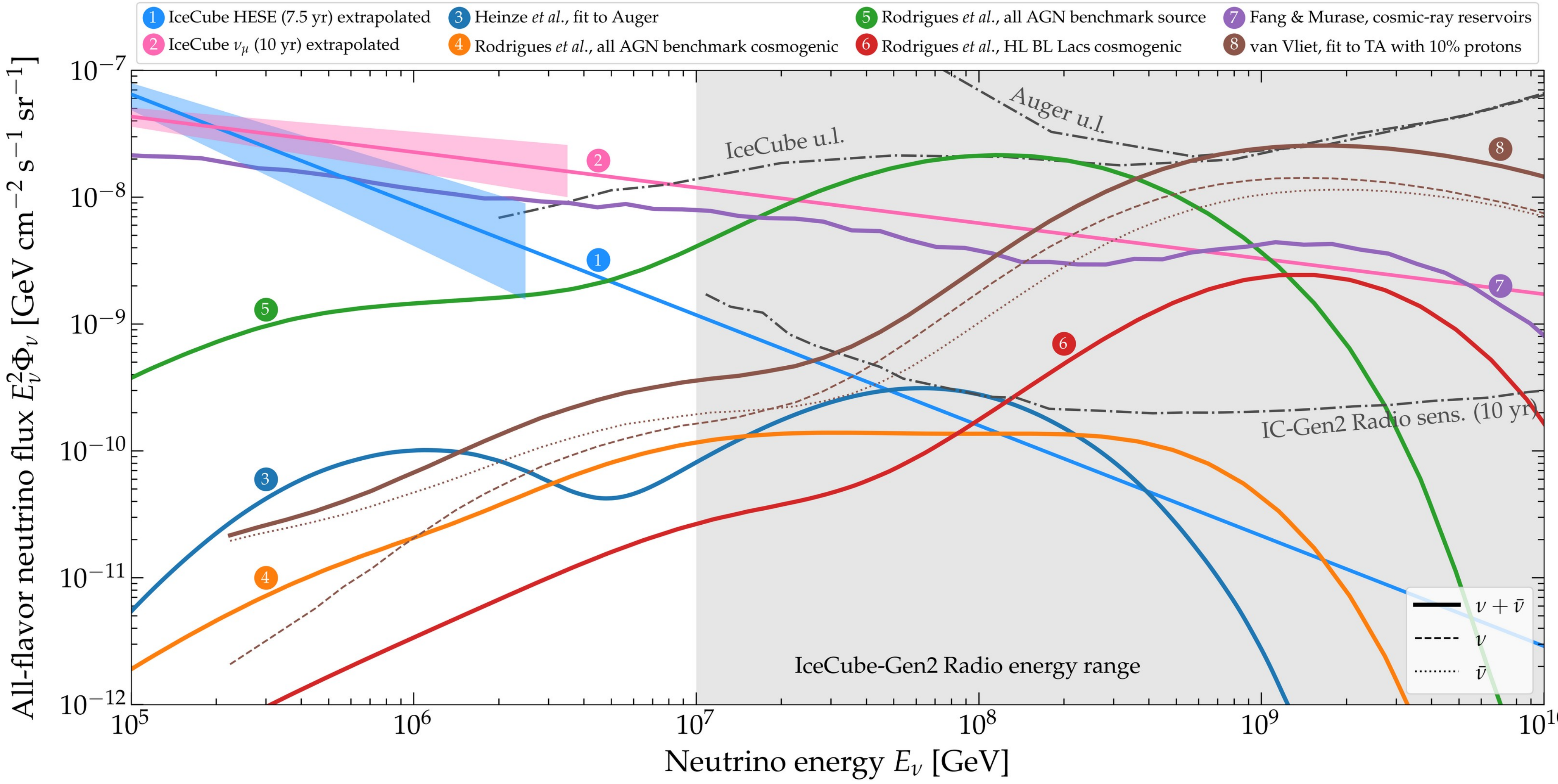

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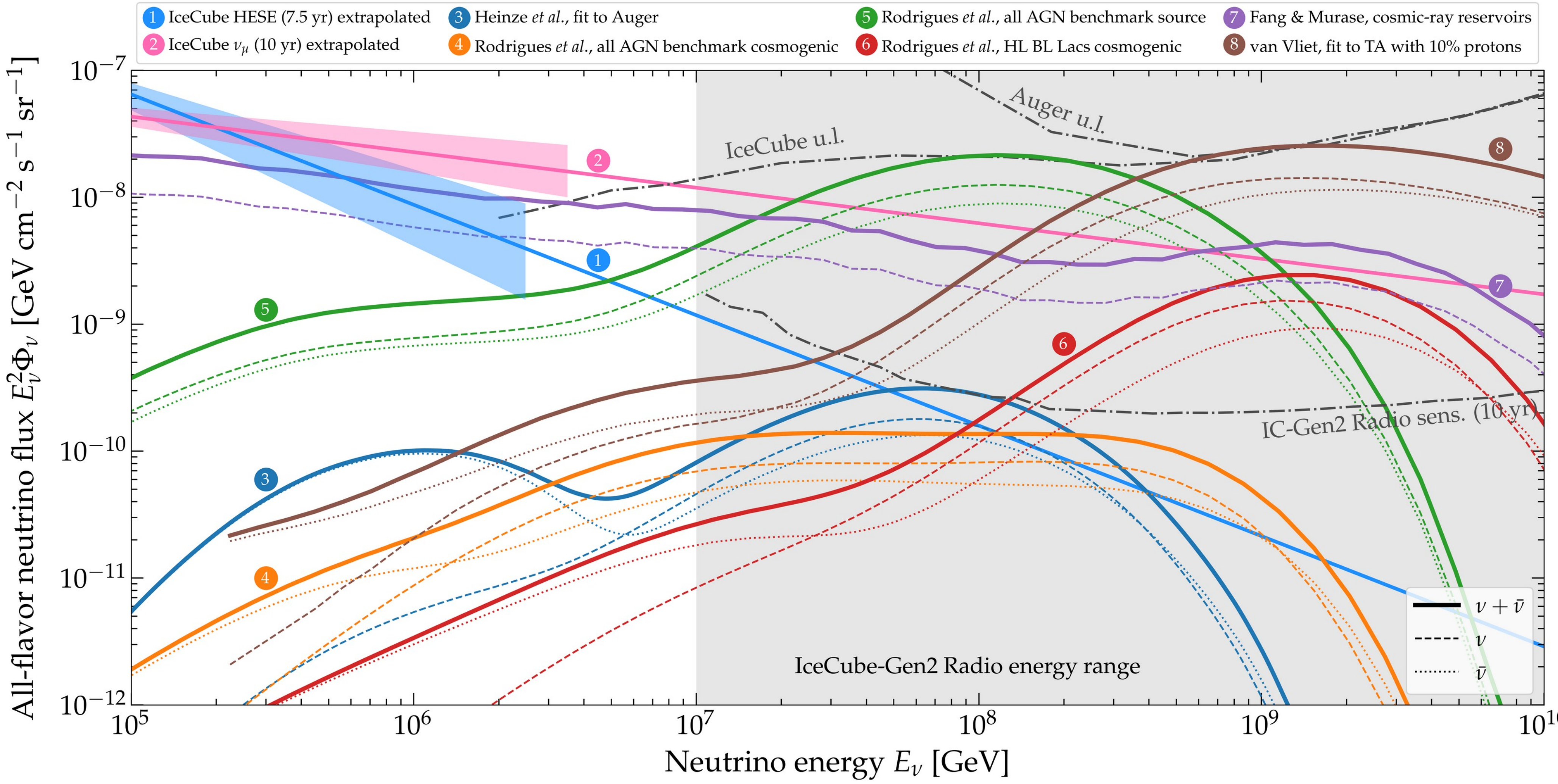

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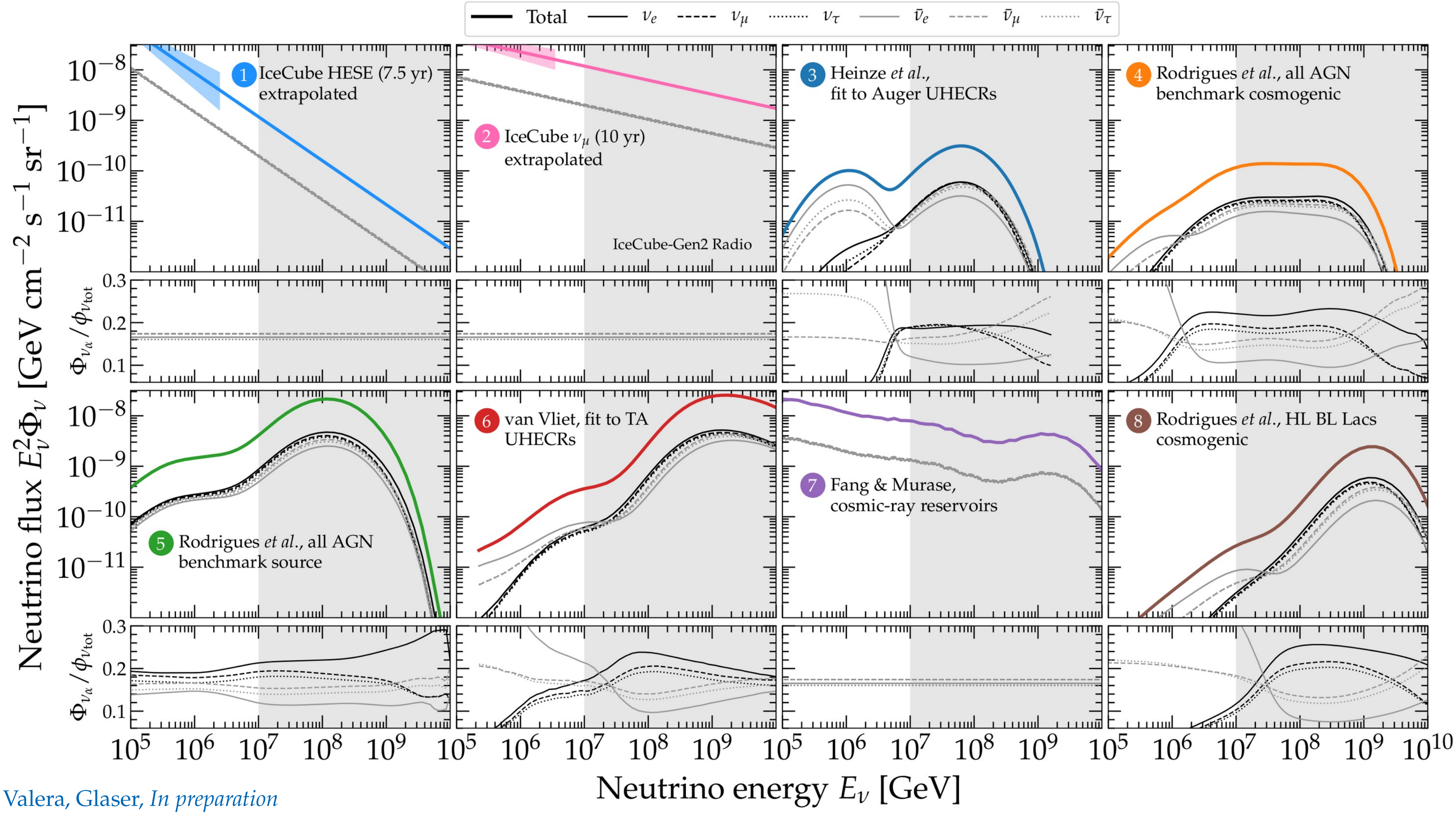
Flavor structure of the UHE ν fluxes



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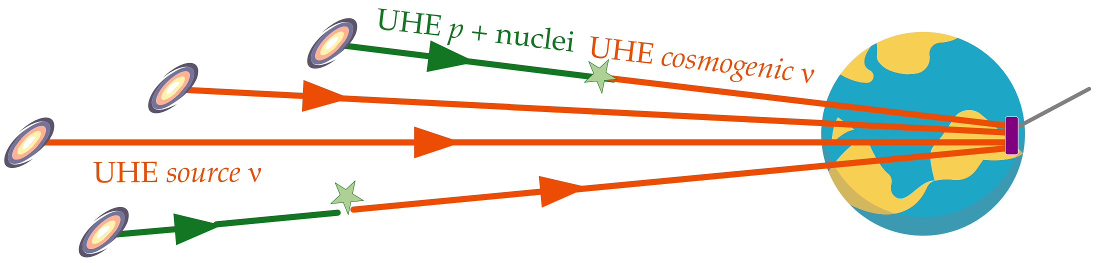
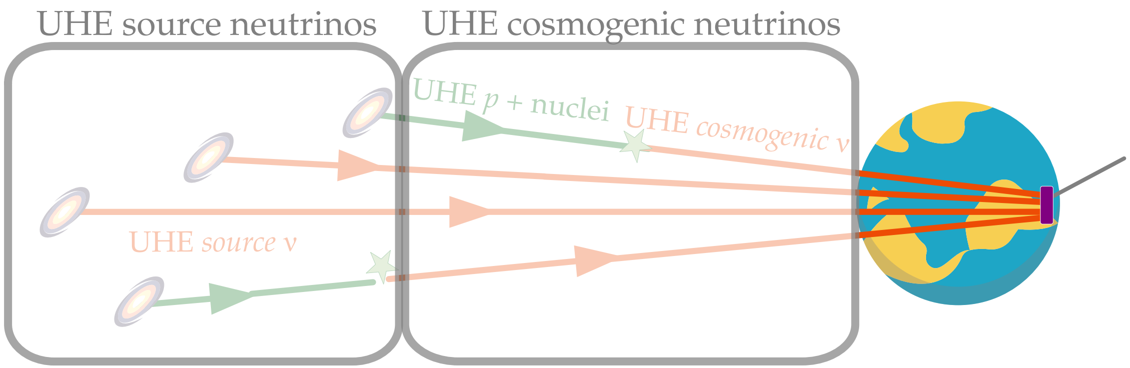
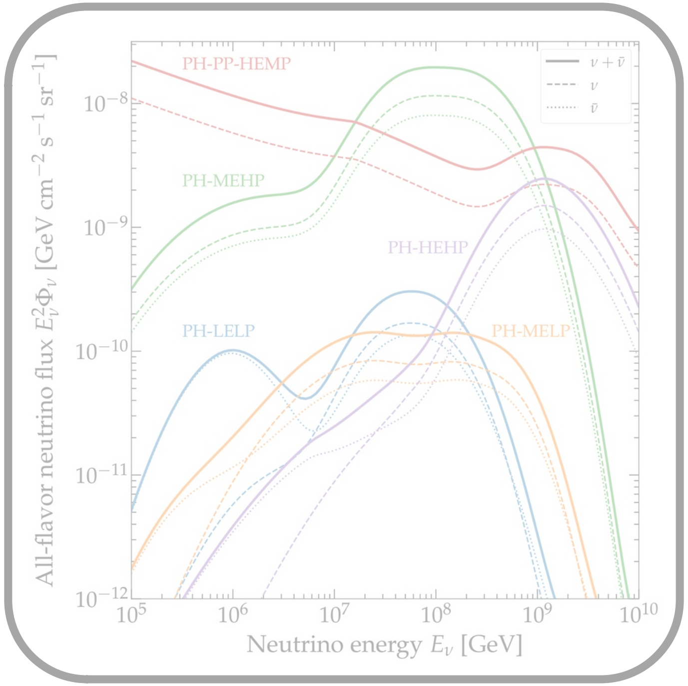
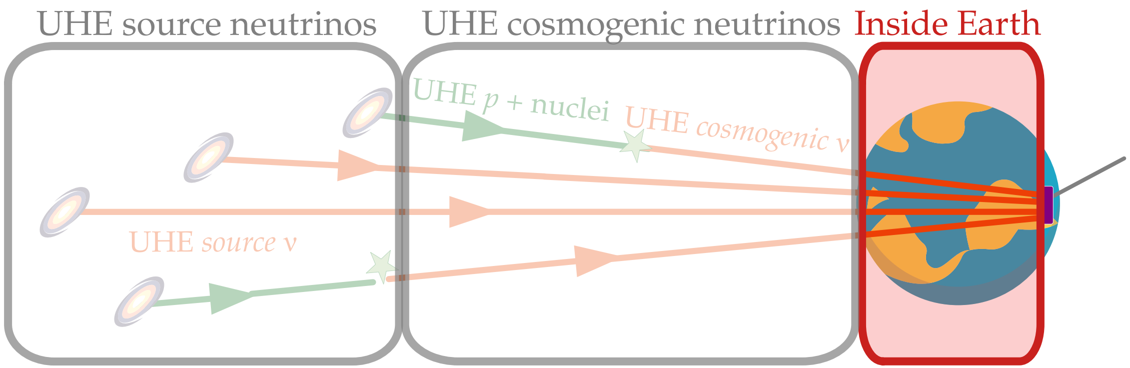
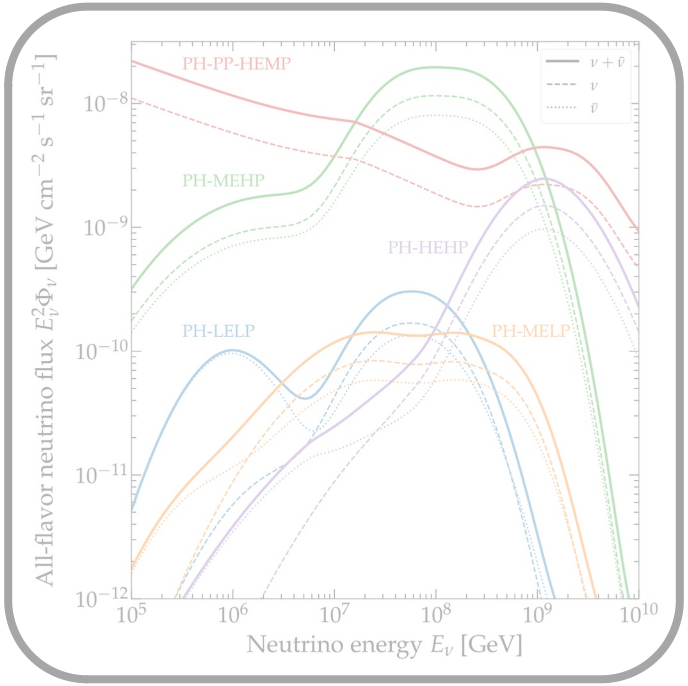

UHE p + nuclei
UHE cosmogenic ν
UHE source ν





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





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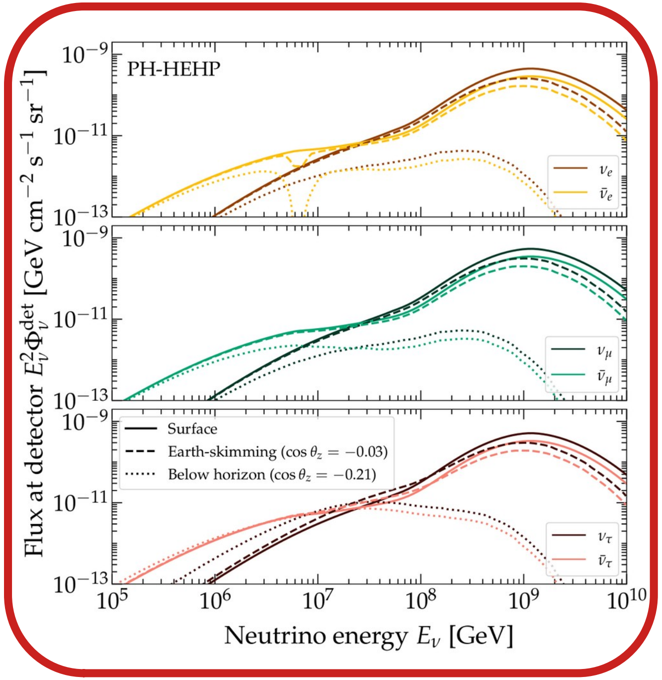

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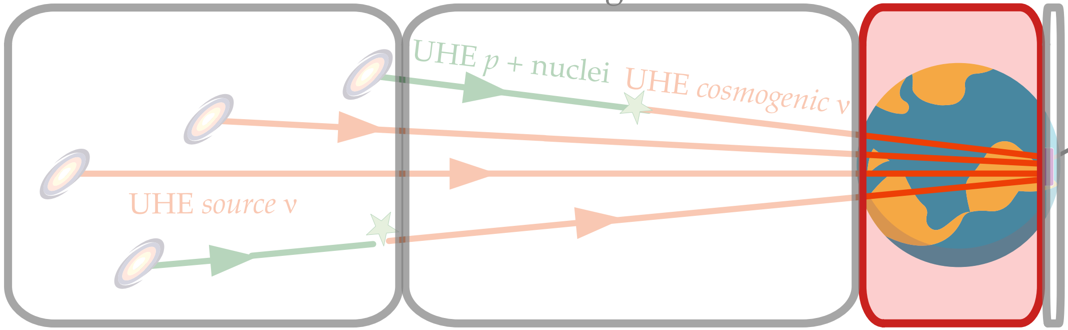

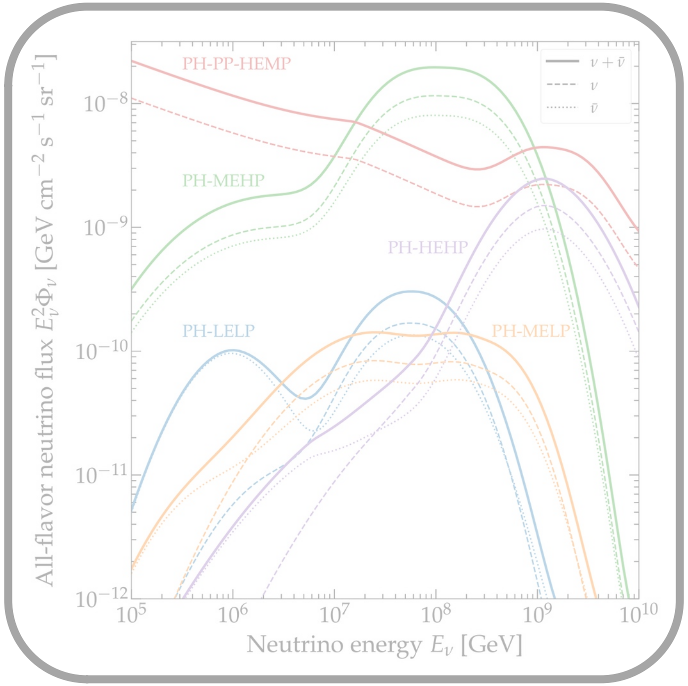

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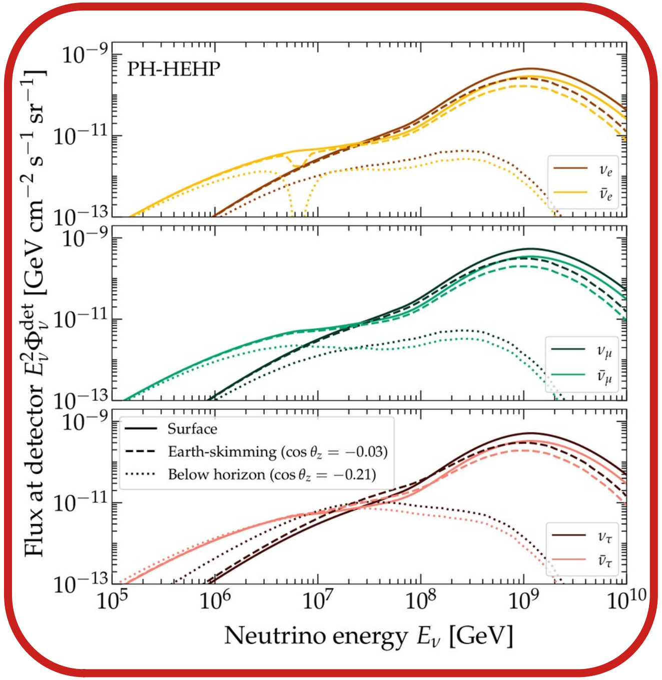

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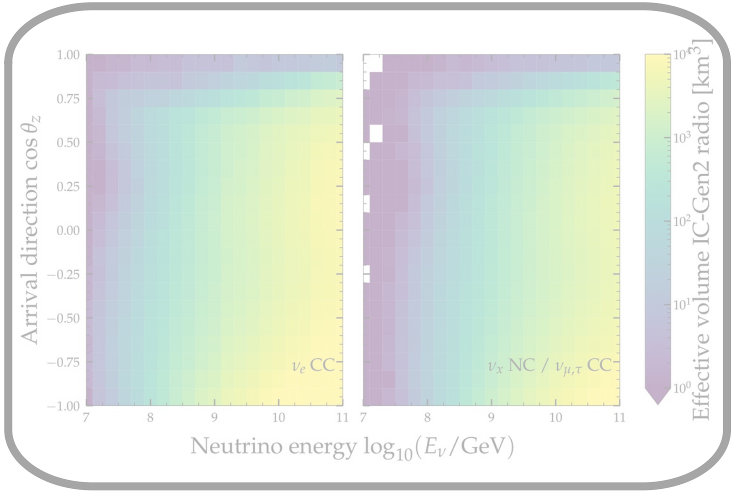
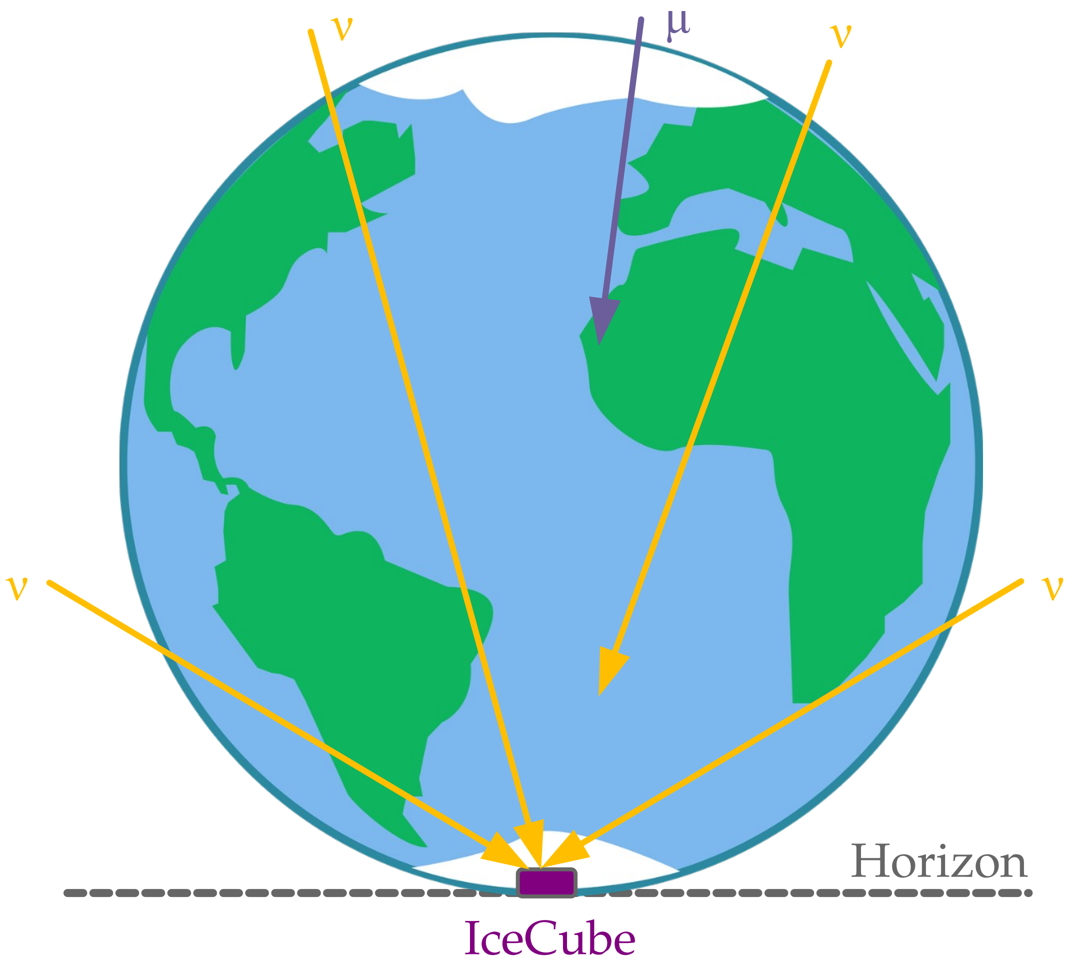
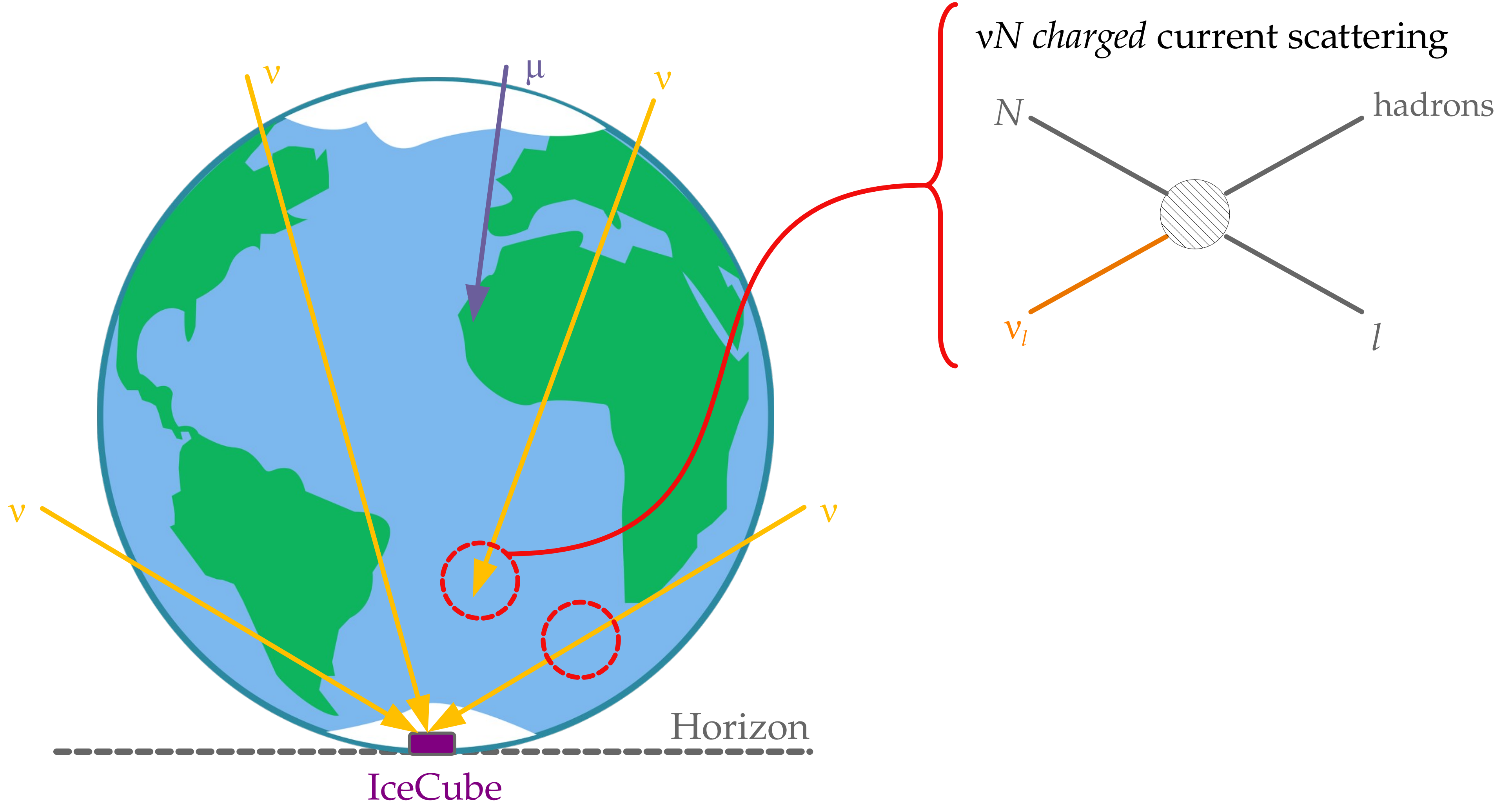


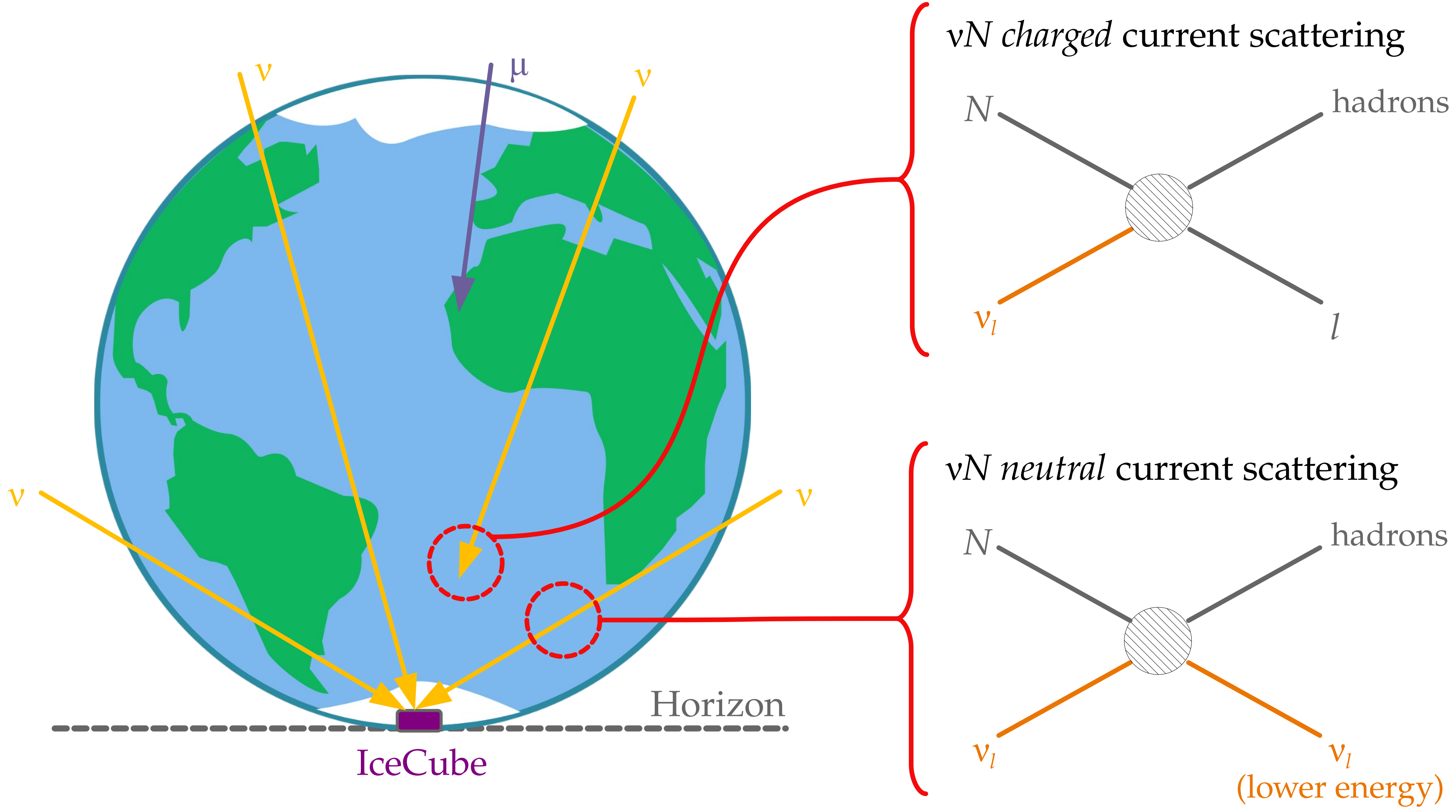
Model radio propagation in ice, antenna response, angular and energy resolution, inelasticity distribution

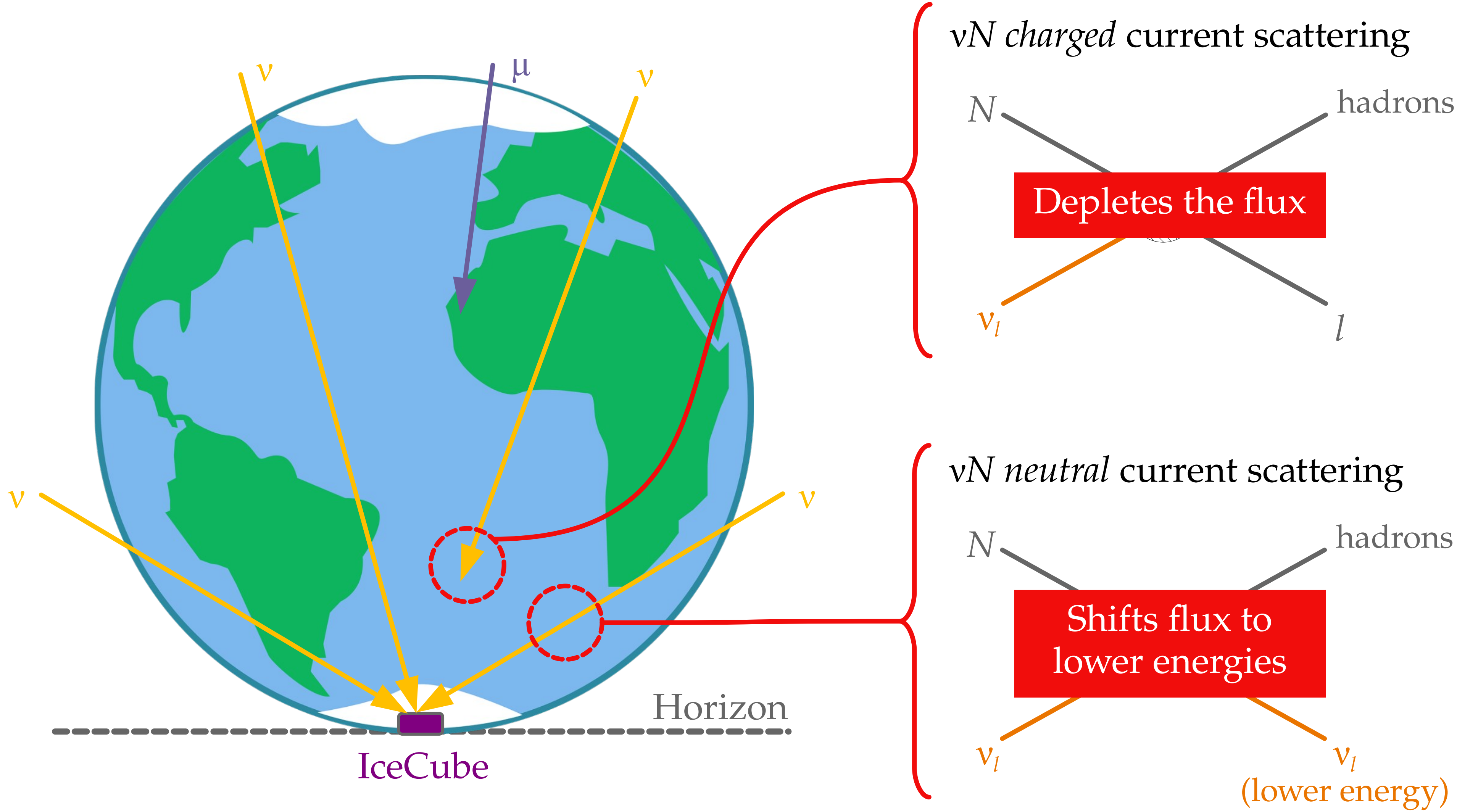
Propagation inside the Earth



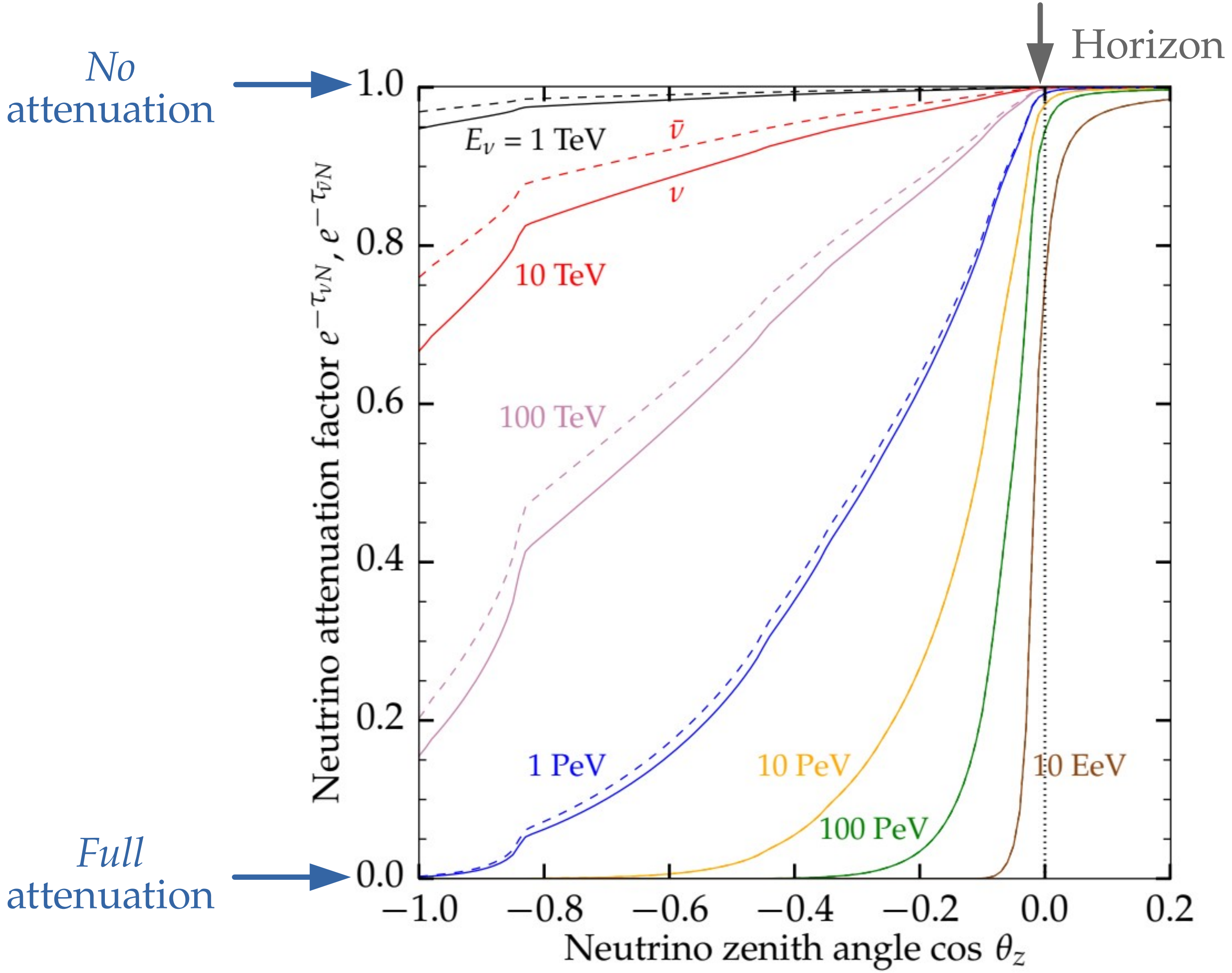


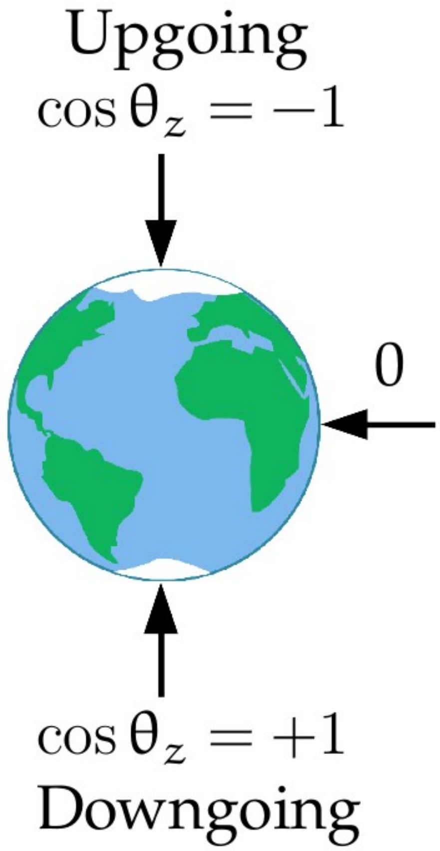
νN *charged* current scattering
N
hadrons
ν_l
l
ν
μ
ν
ν
ν
Horizon
IceCube


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)

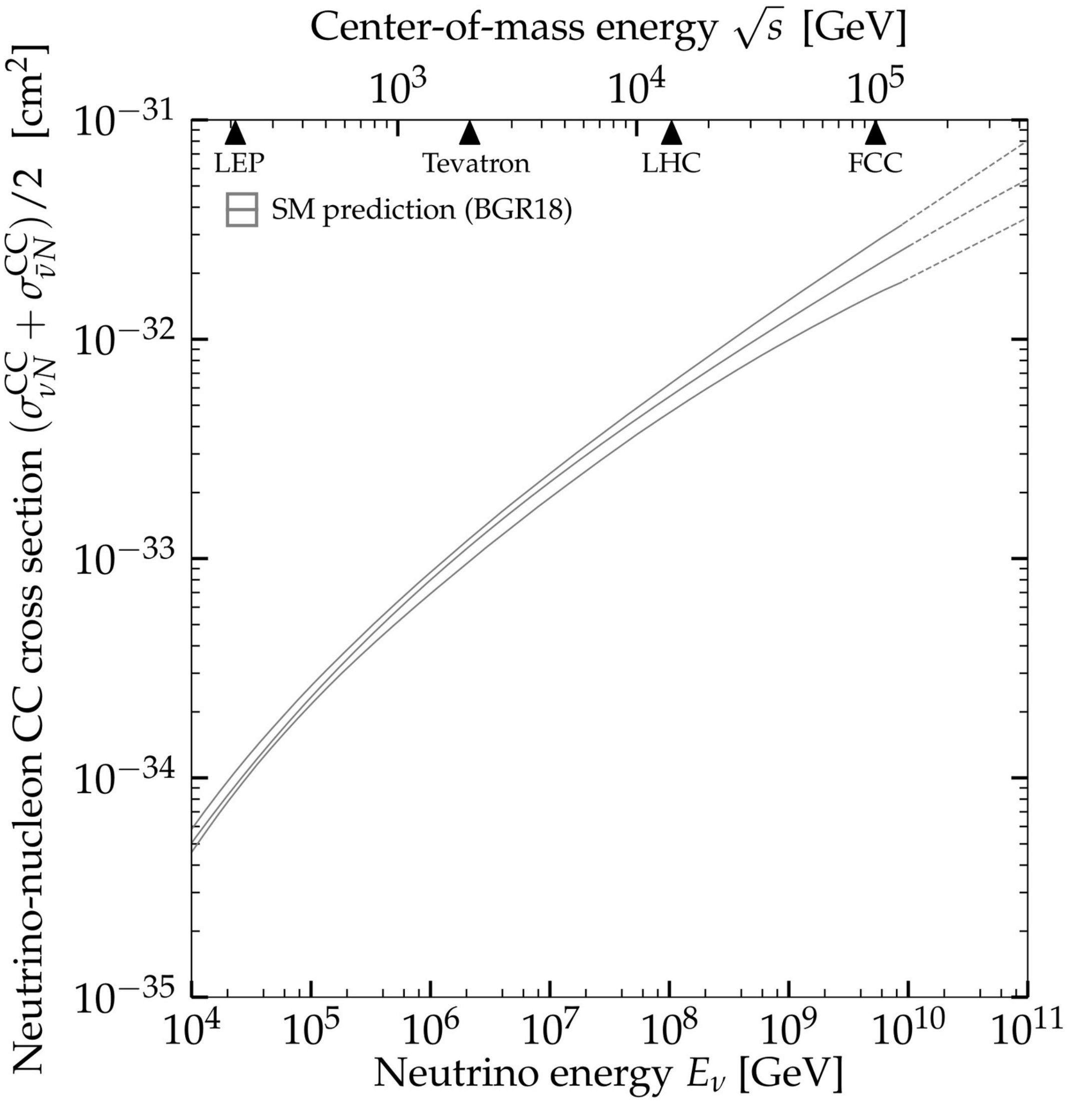


ν
μ
ν
ν
ν
Horizon
IceCube
νN *charged* current scattering
N
hadrons
Depletes the flux
ν_l
l
νN *neutral* current scattering
N
hadrons
Shifts flux to lower energies
ν_l
ν_l
(lower energy)





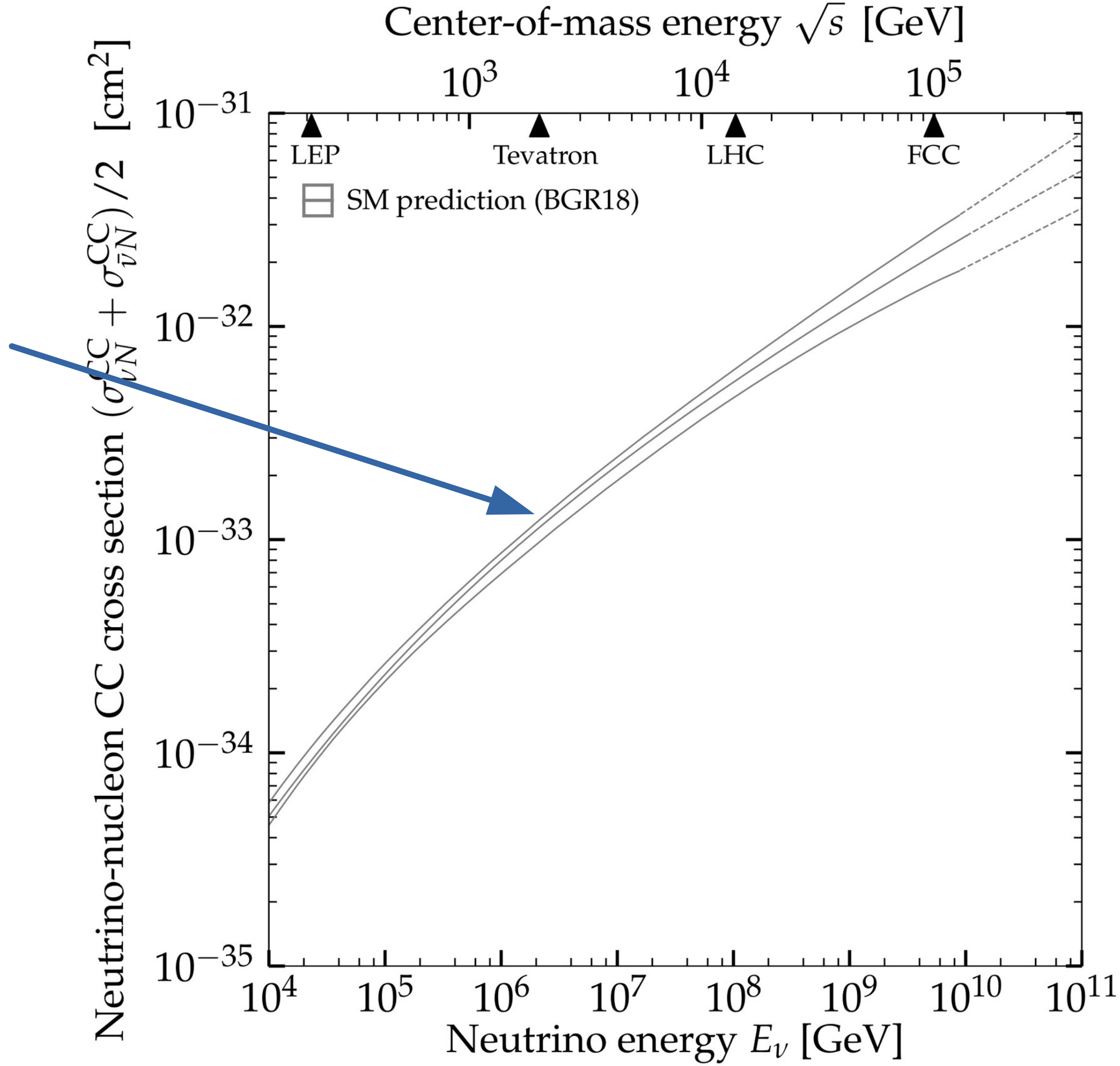
MB & Connolly, *PRL* 2019



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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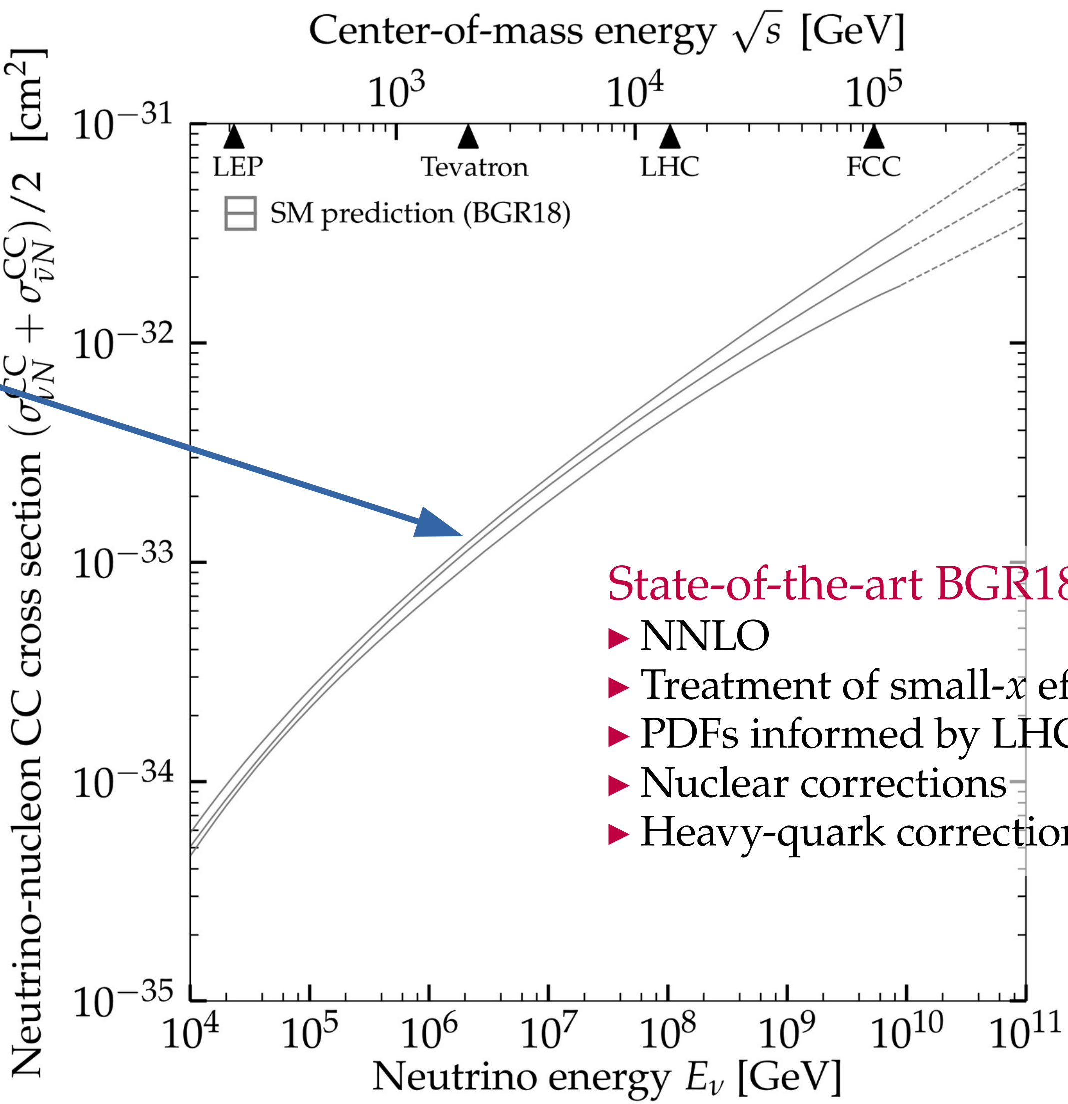


State-of-the-art BGR18 prediction:

- 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

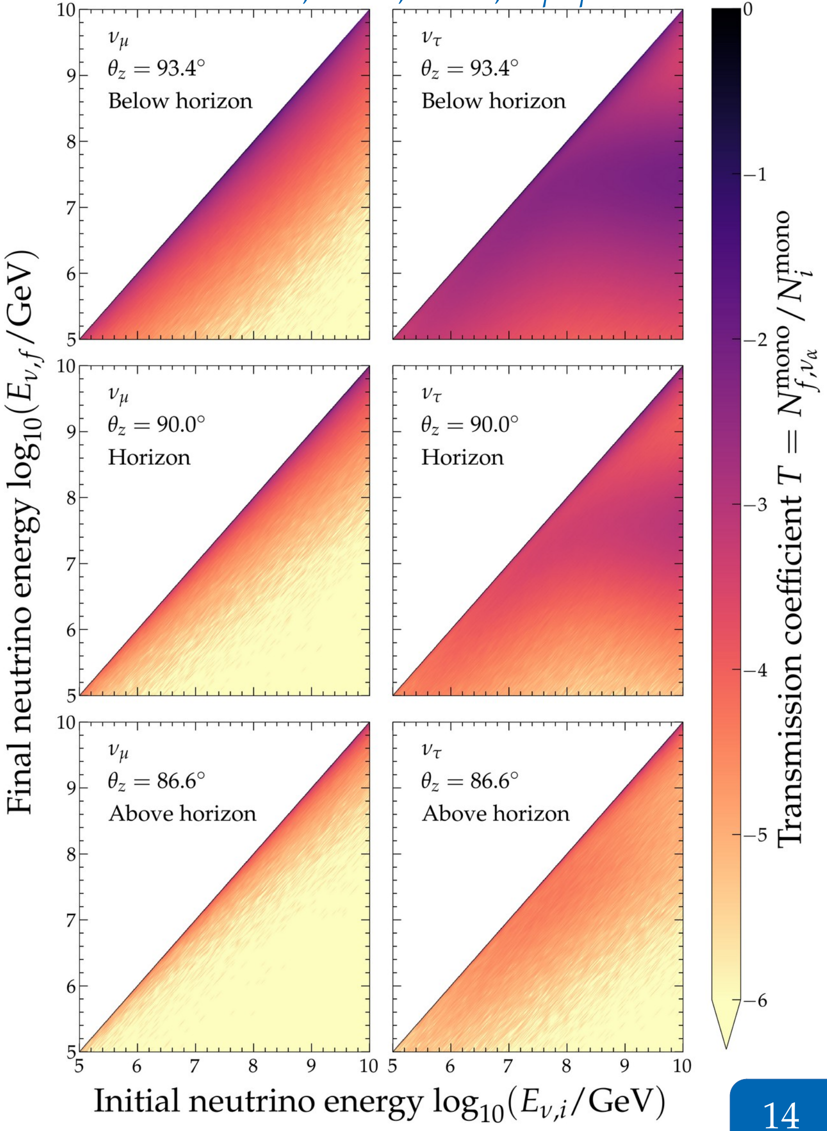
Matter inside Earth:

- 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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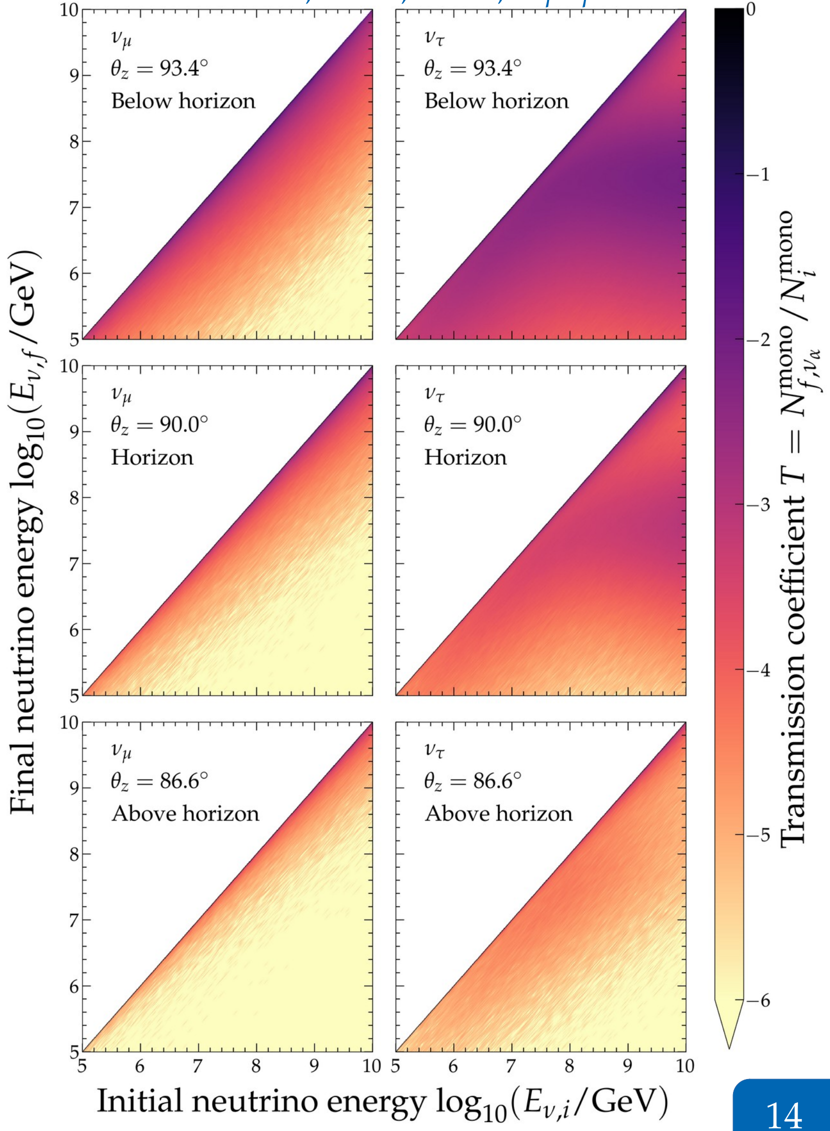
Save look-up tables of propagated ν spectra

MB, Valera, Glaser, *In preparation*



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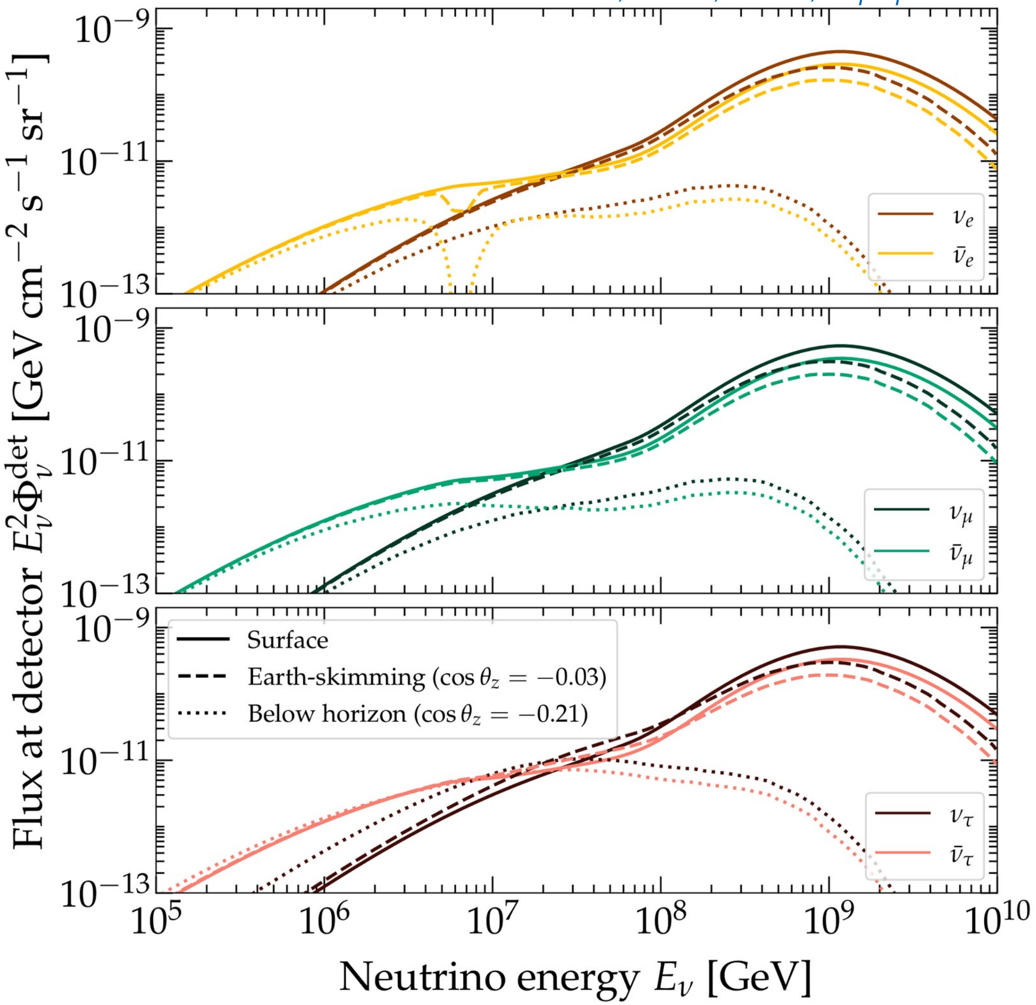
MB, Valera, Glaser, *In preparation*



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

Detector geometry

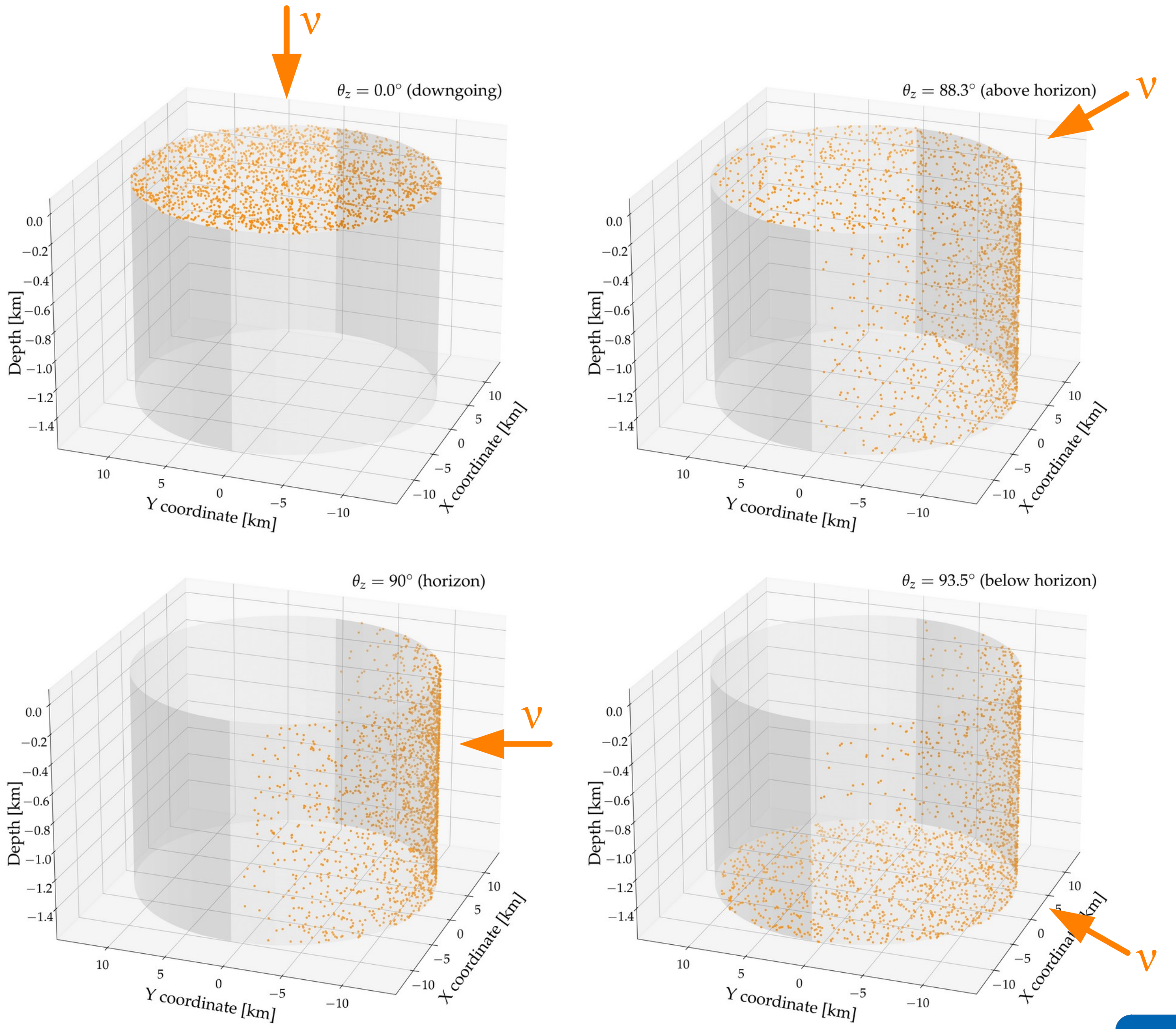
Underground cylinder

Area of lid: 500 km^2

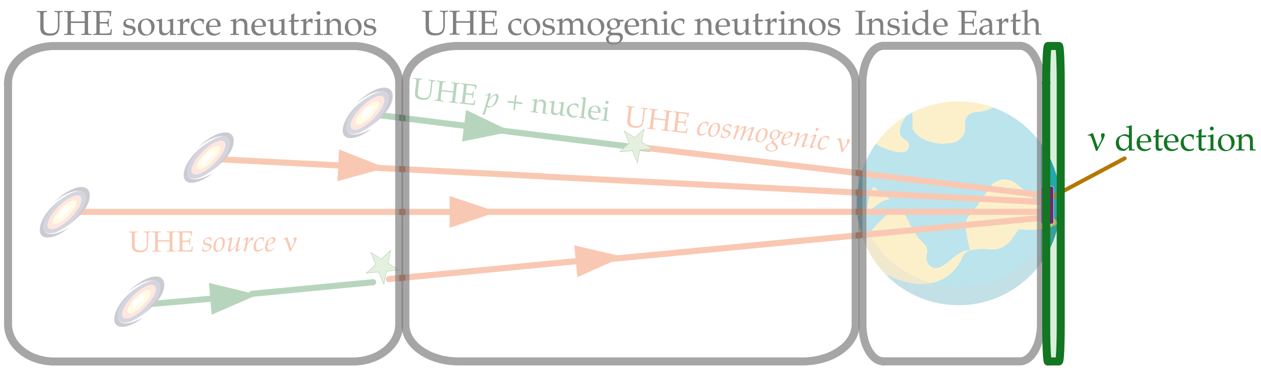
Height: 1.5 km

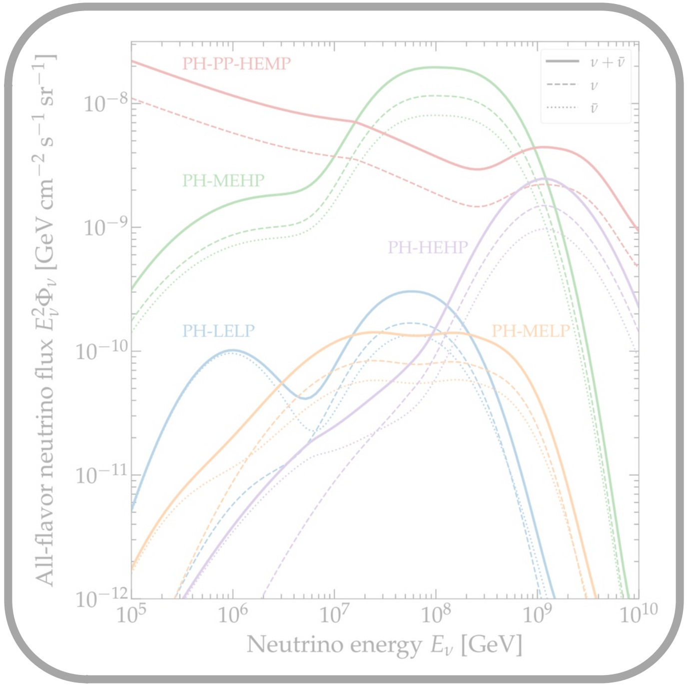
Detector geometry now available in NuPropEarth
[github.com/pochoarus/NuPropEarth]

Work led by Víctor Valera

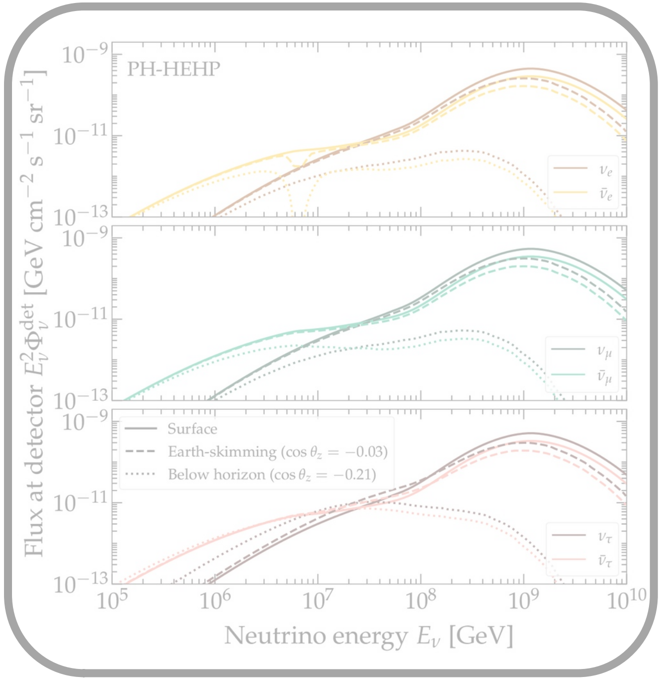


MB, Valera, Glaser, *In preparation*

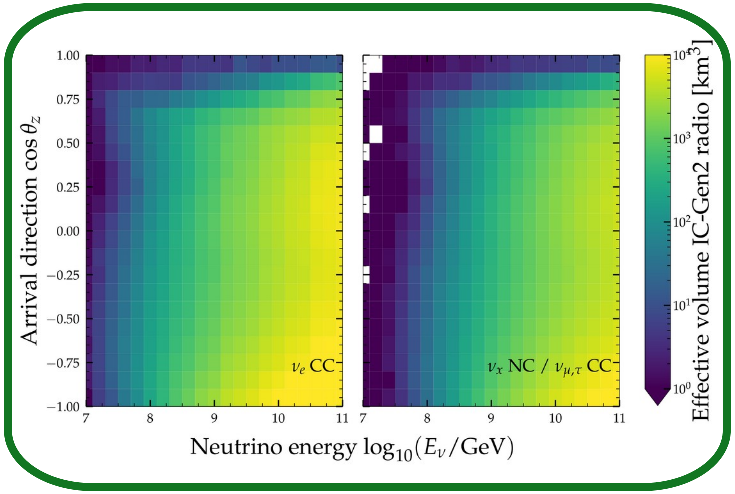




UHE ν from pp and $p\gamma$ interactions, account for cosmic-ray spectrum & mass composition, source properties



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

Detector effective volume

IC-Gen2 has stations containing:

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We simulate the effective volume of with NuRadioMC & NuRadioReco

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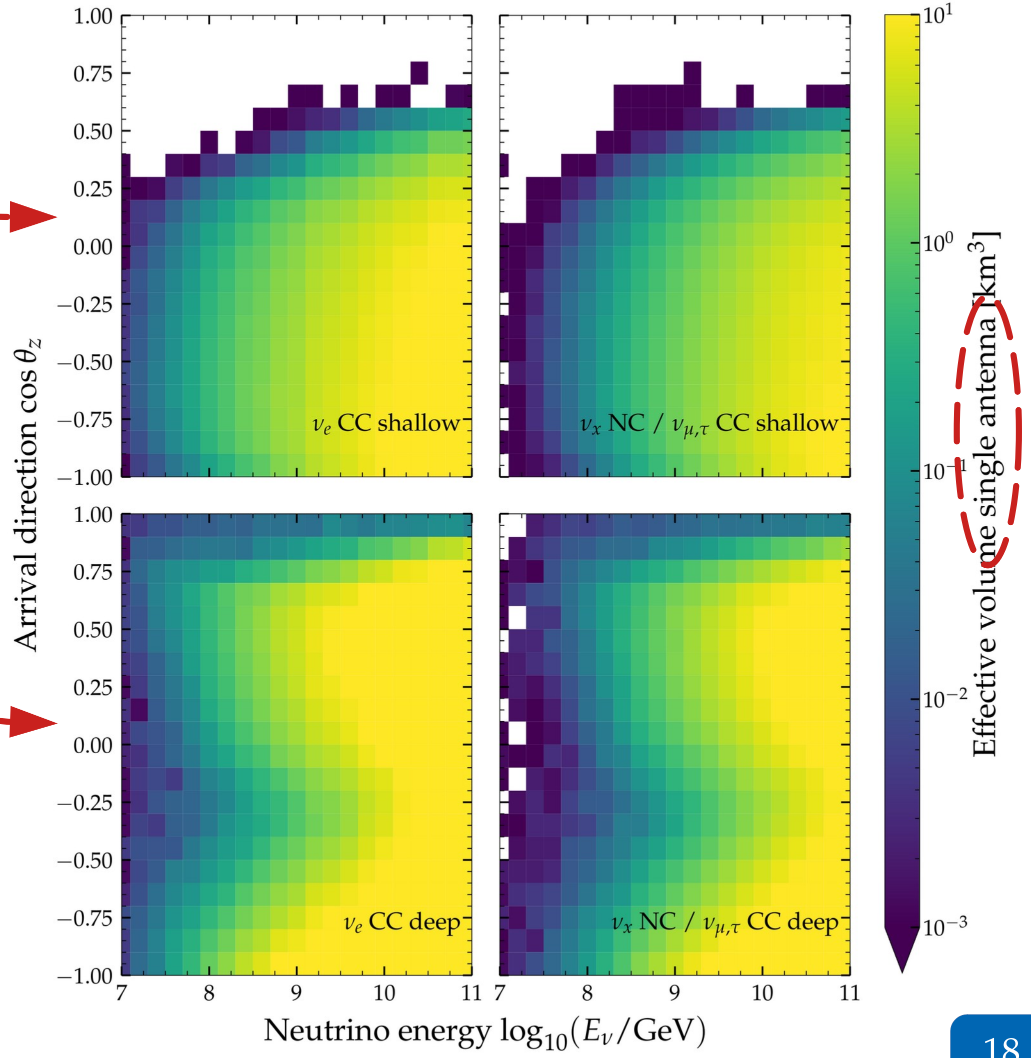

MB, Valera, Glaser, *In preparation*

Detector effective volume

IC-Gen2 has stations containing:

- Shallow antennas
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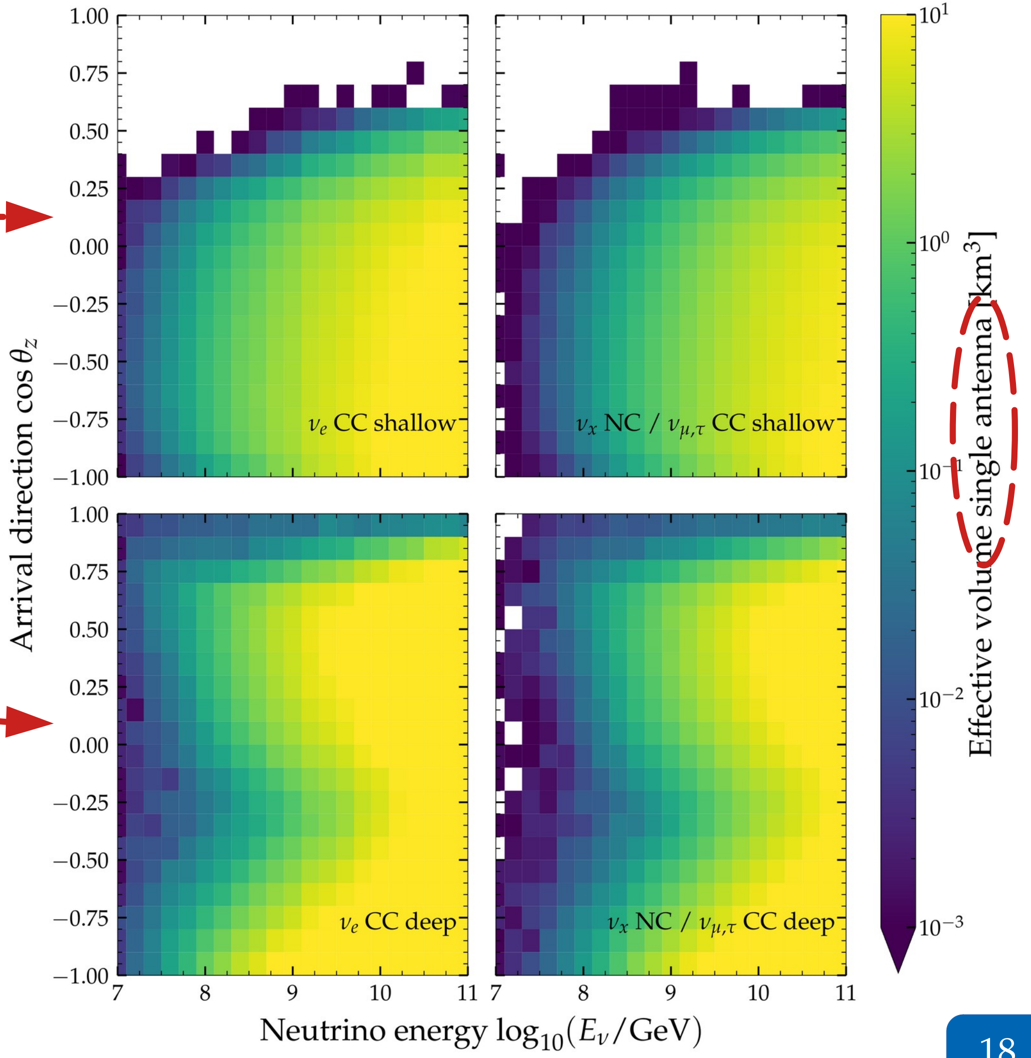
We simulate the effective volume of with NuRadioMC & NuRadioReco

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

For ν_e CC: Use the CC V_{eff}

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



MB, Valera, Glaser, *In preparation*

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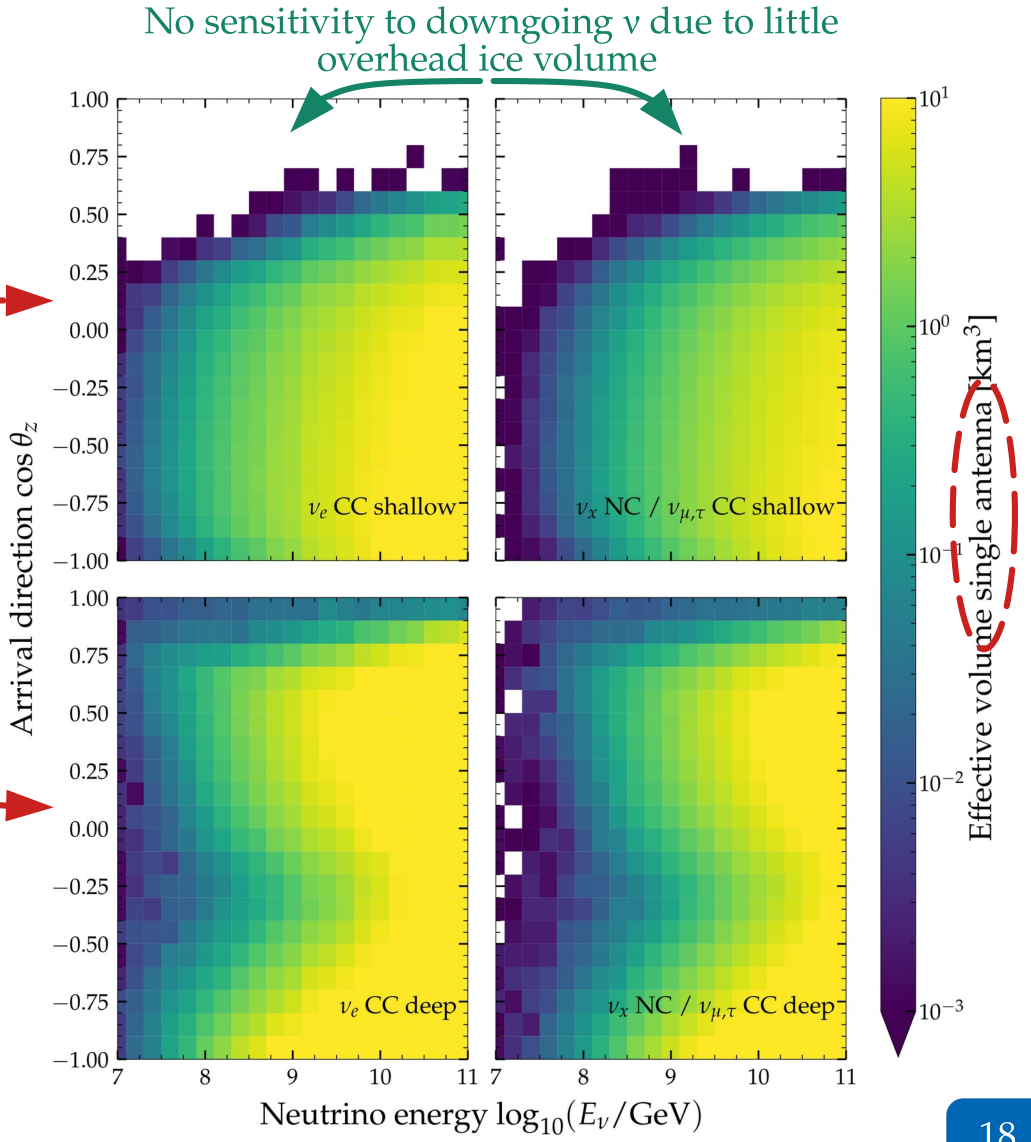
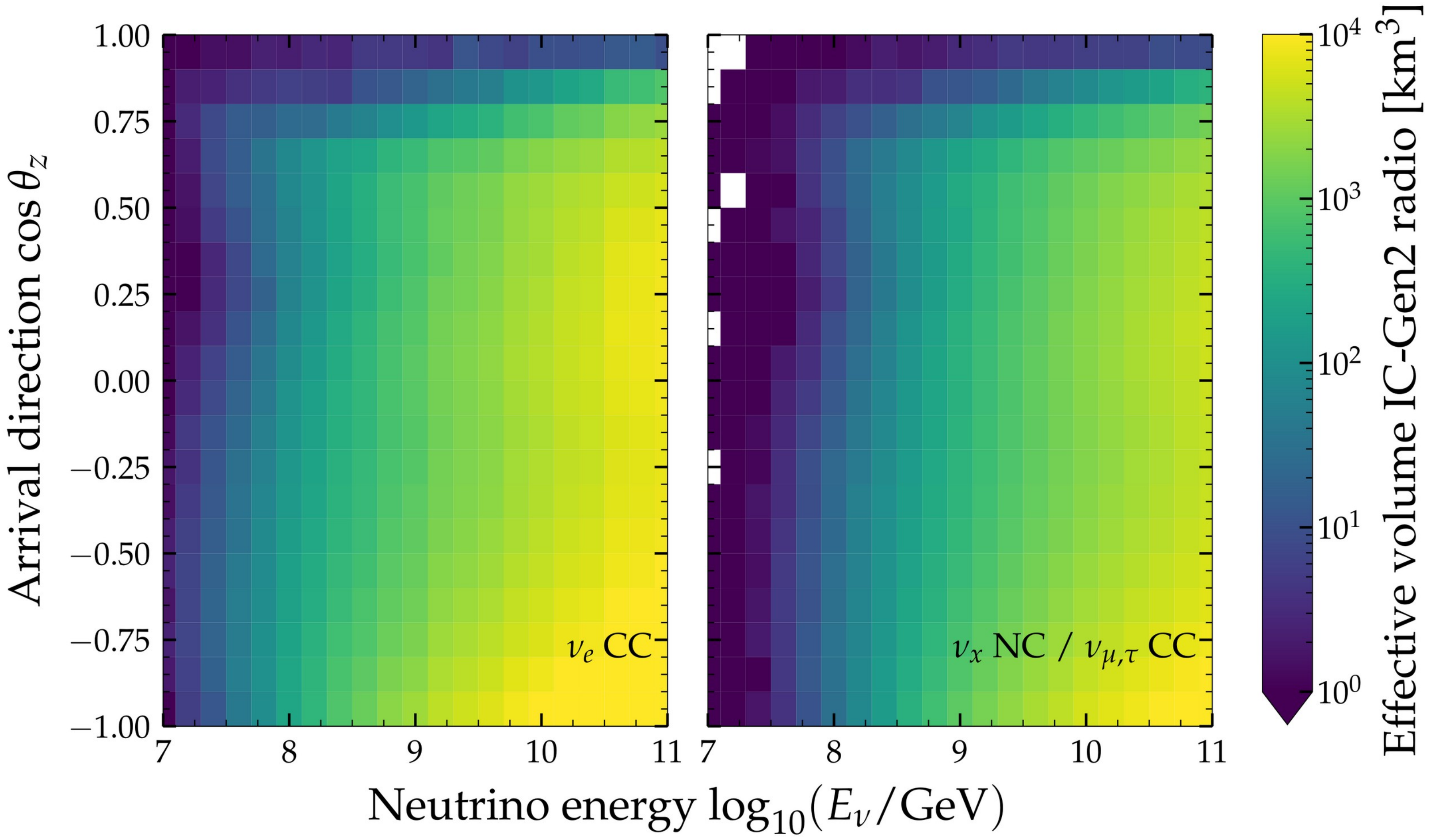
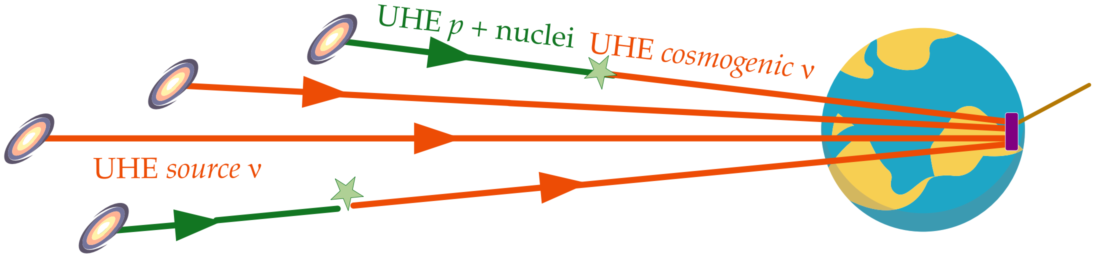


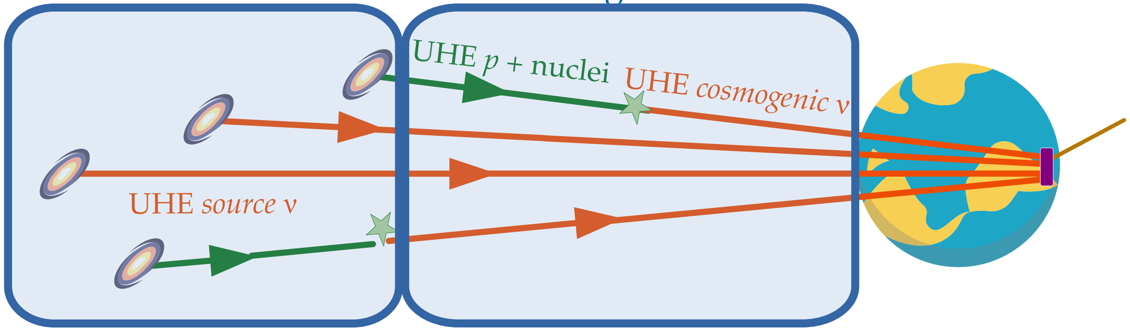
Total volume = 169 shallow-only stations + 144 hybrid (shallow+deep) stations

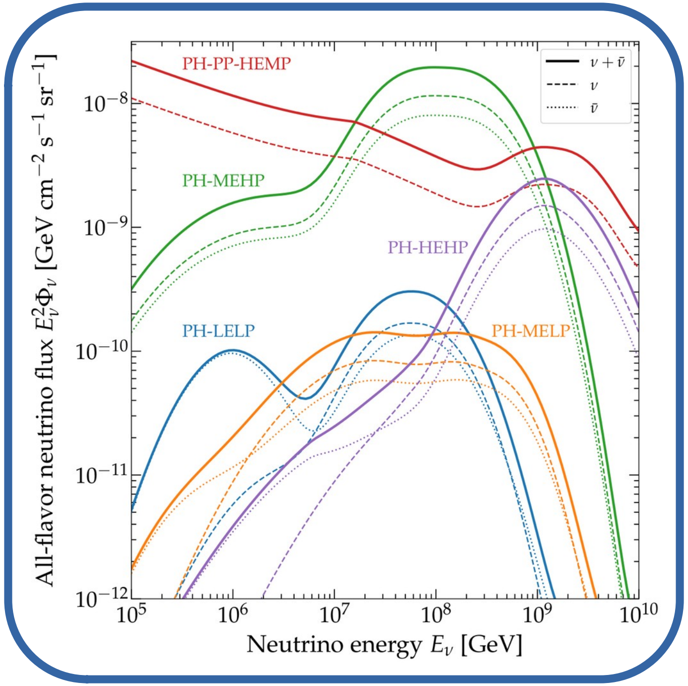


MB, Valera, Glaser, *In preparation*

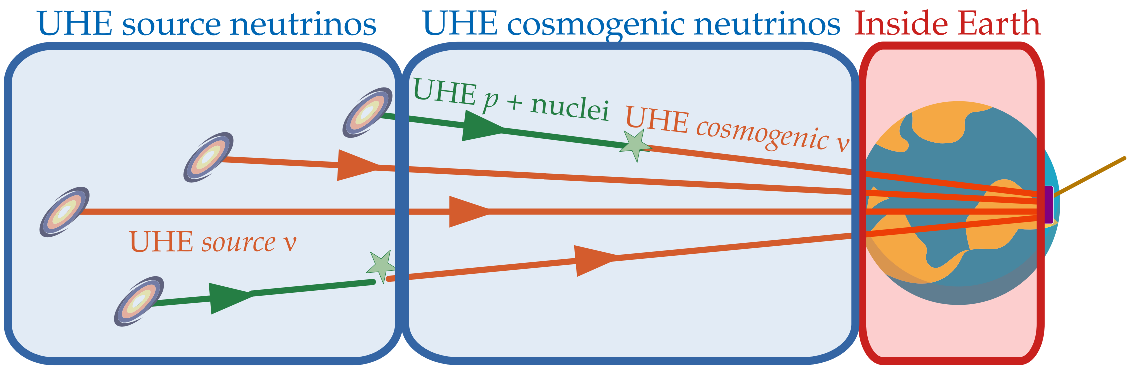

UHE p + nuclei
UHE *cosmogenic* ν
UHE *source* ν

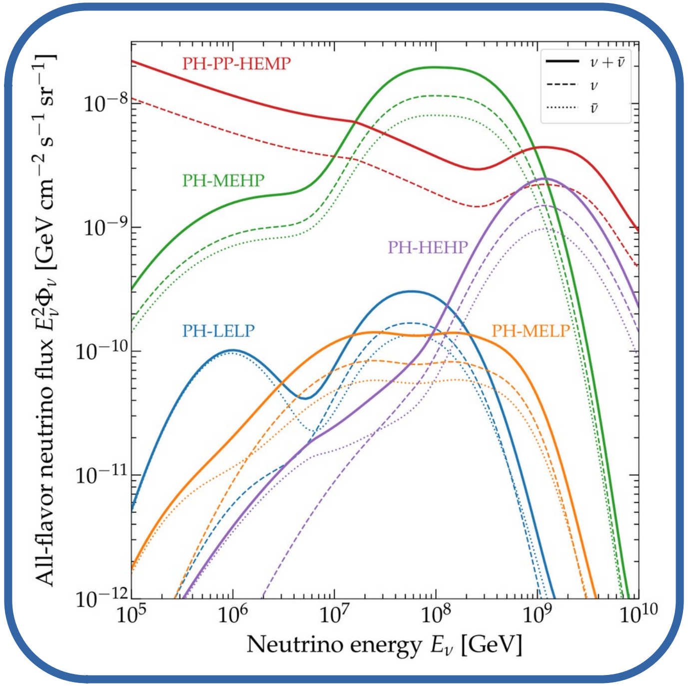
UHE source neutrinos UHE cosmogenic neutrinos





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





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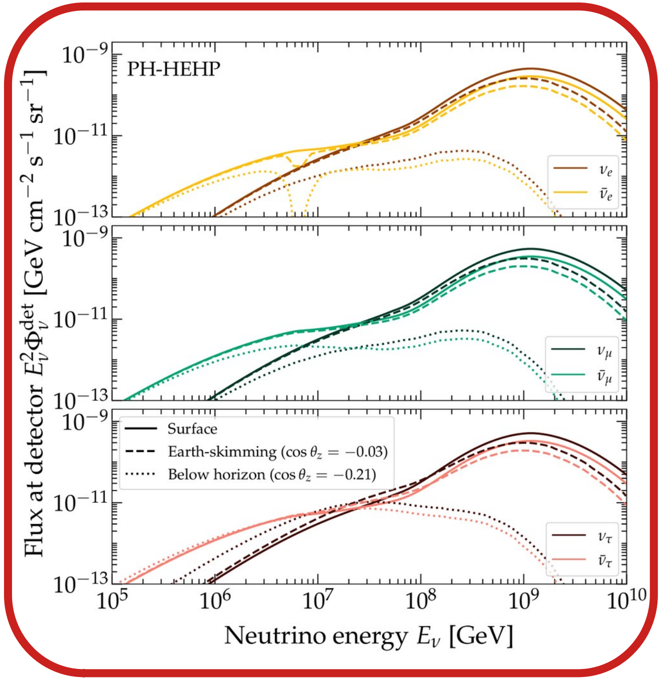
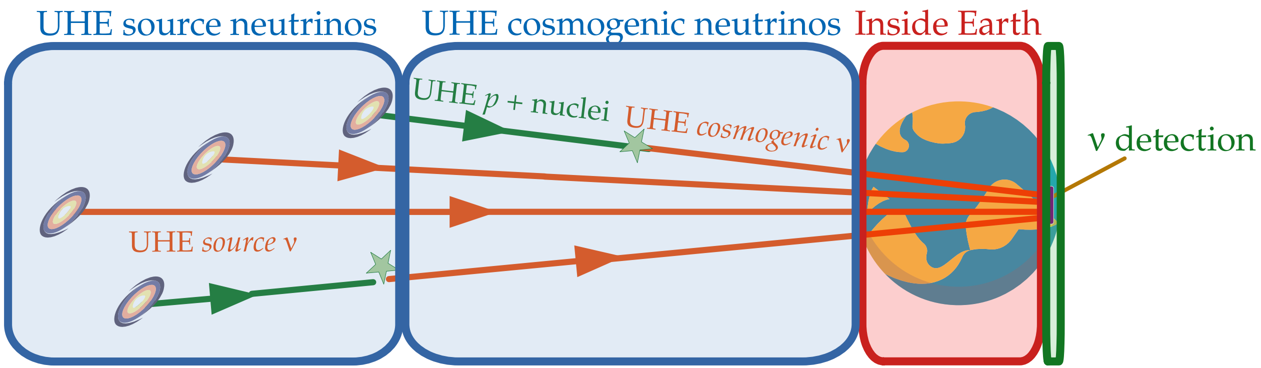
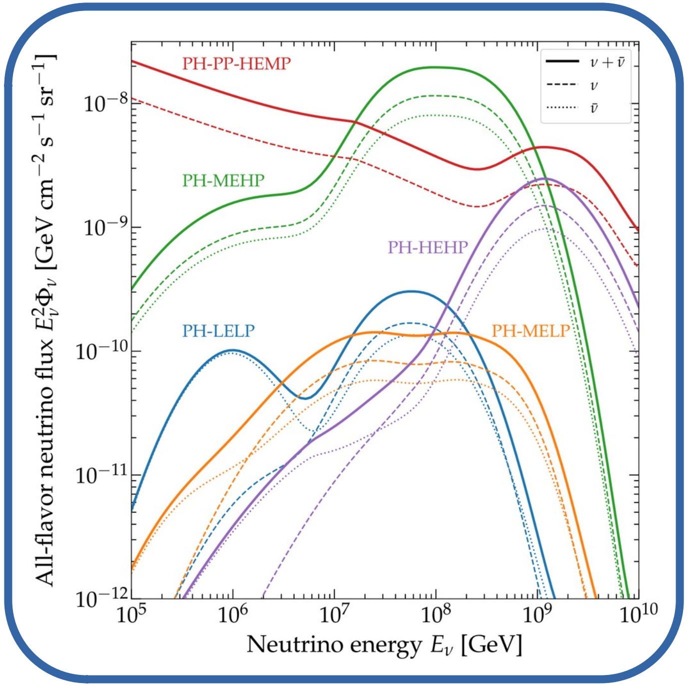


Propagate each flavor of ν and $\bar{\nu}$ separately: deep inelastic scattering, diffractive scattering, ν_τ regeneration





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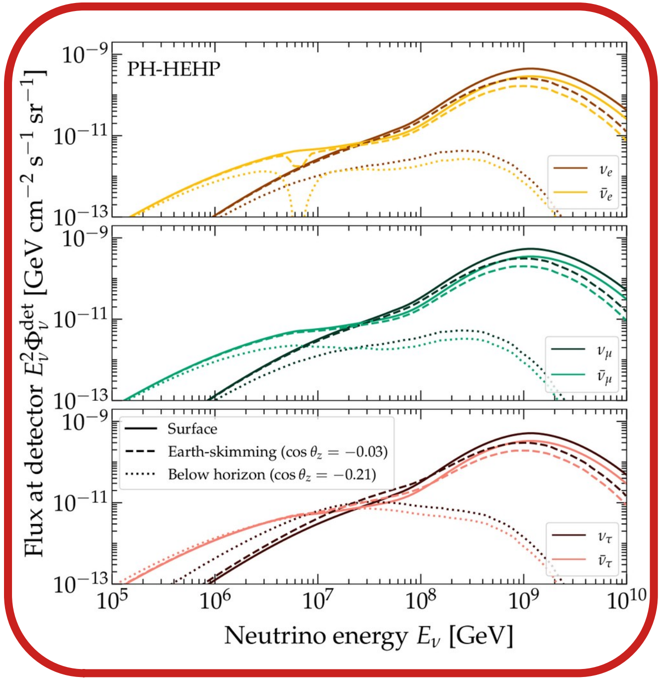

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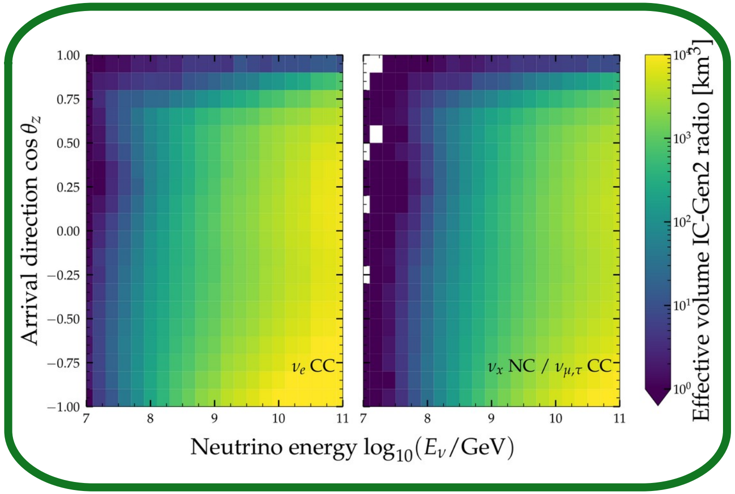

Model radio propagation in ice, antenna response, angular and energy resolution, inelasticity distribution

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
- Effective volume
- Inelasticity distribution

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Detector effects →

Each ν species computed separately

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Includes:

- Flux
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- Inelasticity distribution

Detector effects →

Each ν species computed separately

Detected event rate

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

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

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

E_ν: Neutrino energy

y: Inelasticity

$\cos\theta_z$: Neutrino direction

Includes:

- Flux
- In-Earth propagation
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Detector effects →

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$E_{\rm dep}$: Deposited energy

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

Includes, in addition:

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

Real event rate

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

Real event rate

Number of target nucleons

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

Real event rate

Number of target nucleons

Effective volume

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

Real event rate

Number of target nucleons

Effective volume

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

Flux at detector

Real event rate

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

Real event rate

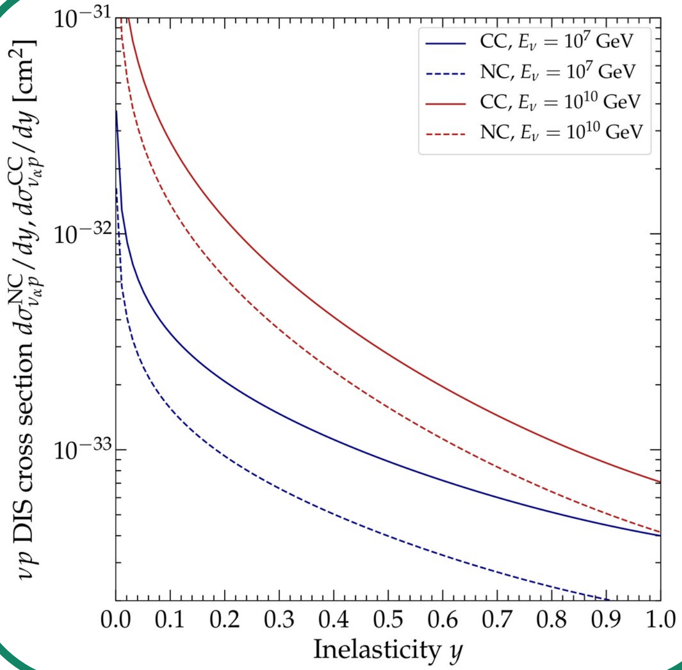
Number of target nucleons

Effective volume

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

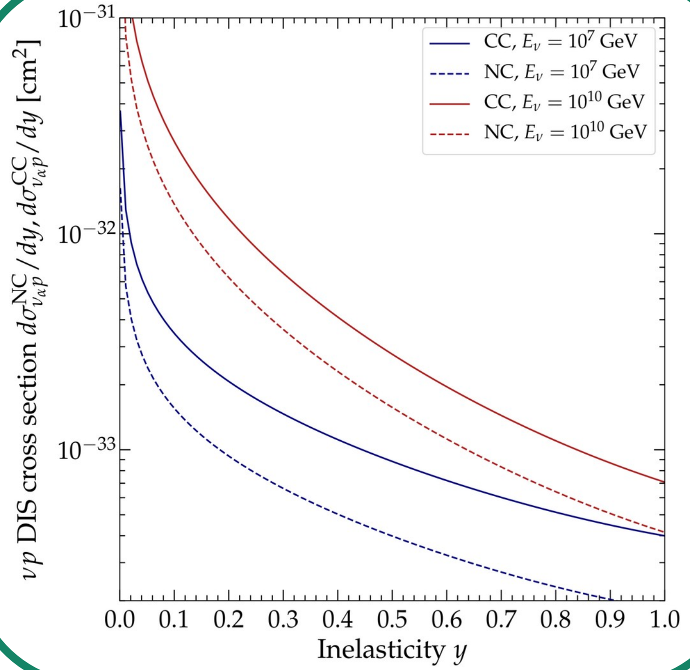
Inelasticity distribution

Flux at detector



Real event rate

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



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

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Deposited energy:

E_{dep}

Real event rate

Detected event rate

Interaction → Shower → Detection

$\nu_l + N \rightarrow l + X$

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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

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

Detected event rate

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

Detected event rate

Real event rate

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

Energy resolution

Detected event rate

Real event rate

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

Energy resolution

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

(Mismatch between shower and deposited energies)

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

Detected event rate

Real event rate

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

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

Angular resolution

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(Mismatch between shower and deposited energies)

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

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

(Mismatch between real and reconstructed directions)

Baseline: $\theta_{z,\mathrm{rec}} = 2^\circ$

Detected event rate

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

Real event rate

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

Energy resolution

Angular resolution

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

(Mismatch between shower and deposited energies)

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: $\theta_{z,\rm rec} = 2°$

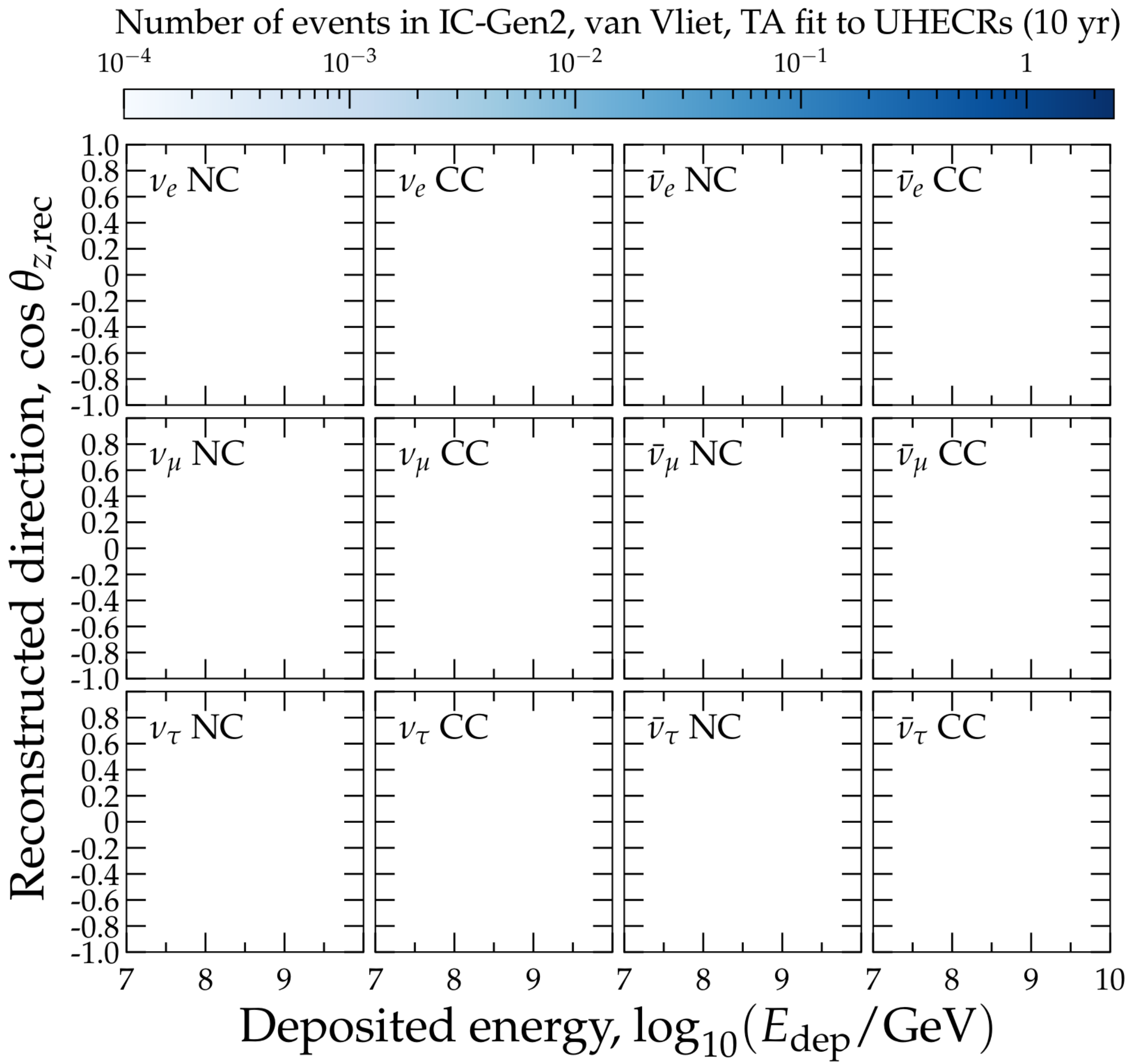
Detected event rate

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

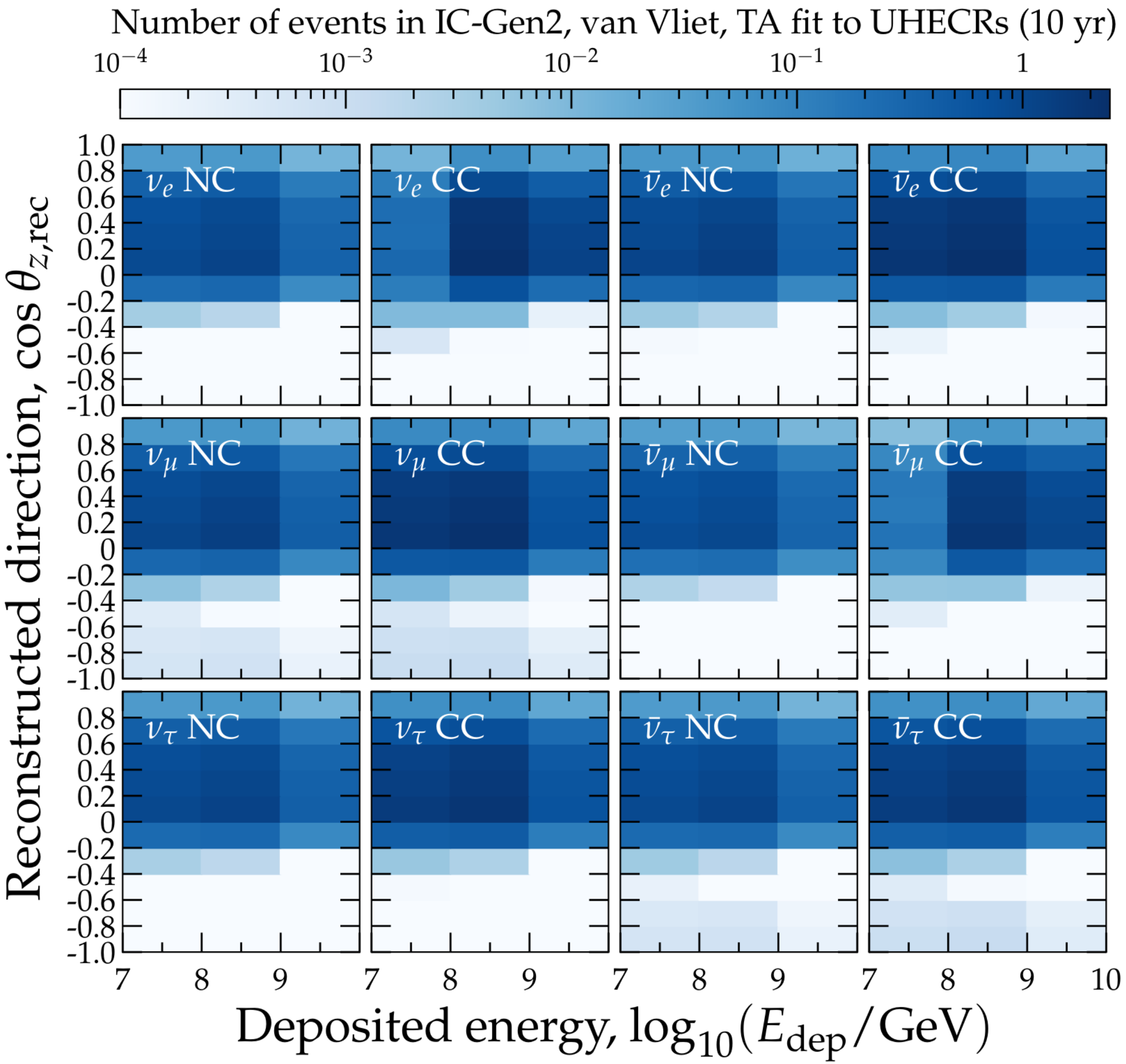
$$\frac{d^2 N_\nu}{dE_{\rm dep} d\theta_{z,\rm rec}} = \sum_i^{\rm NC,CC} \sum_\alpha^{e,\mu,\tau} \left(\frac{d^2 N^i_{\nu_\alpha}}{dE_{\rm dep} d\theta_{z,\rm rec}} + \nu_\alpha \to \bar{\nu}_\alpha \right)$$

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

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

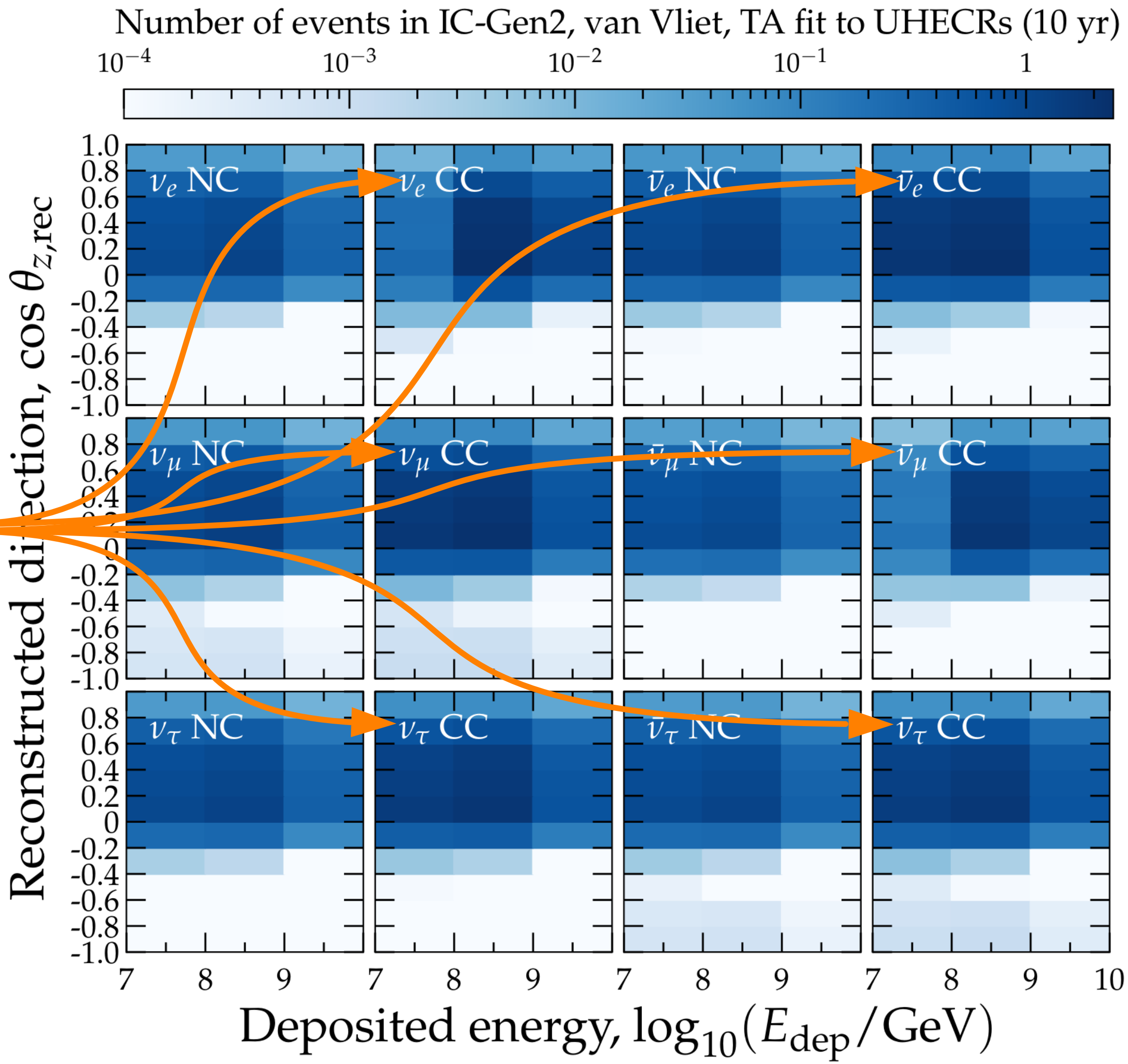


MB, Valera, Glaser, *In preparation*



MB, Valera, Glaser, *In preparation*

CC interactions dominate (mainly ν_e, $\bar{\nu}_e$)



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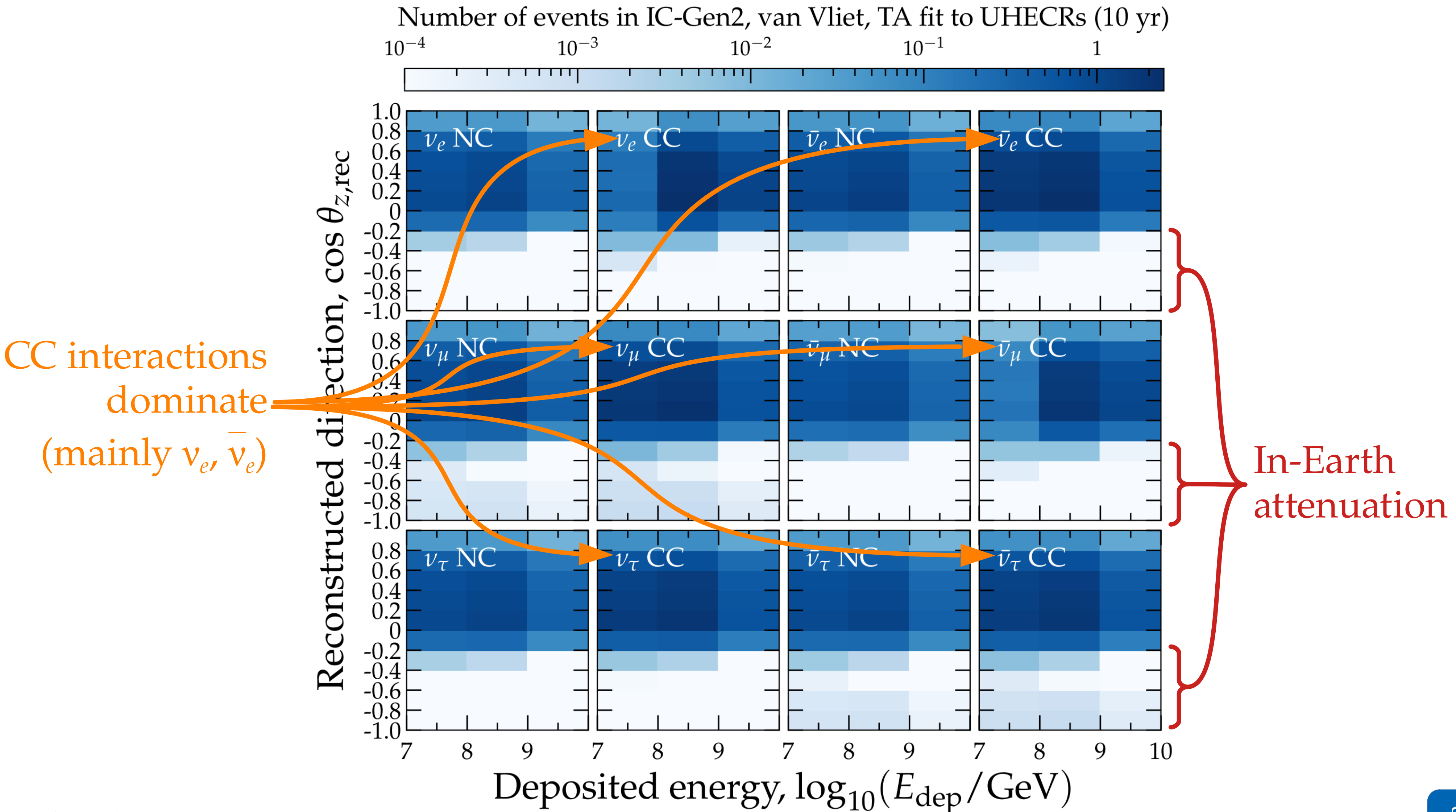
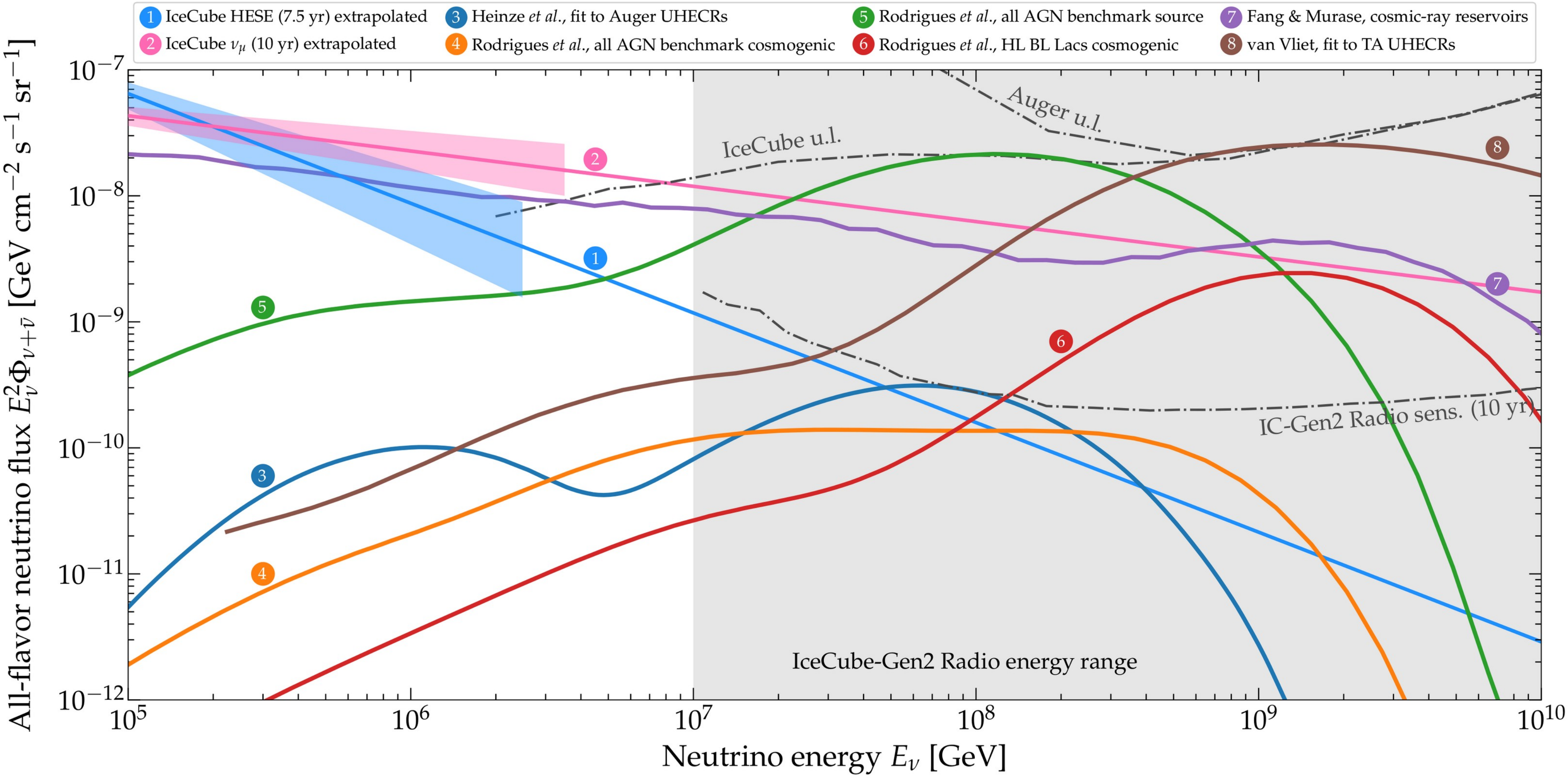


MB, Valera, Glaser, *In preparation*



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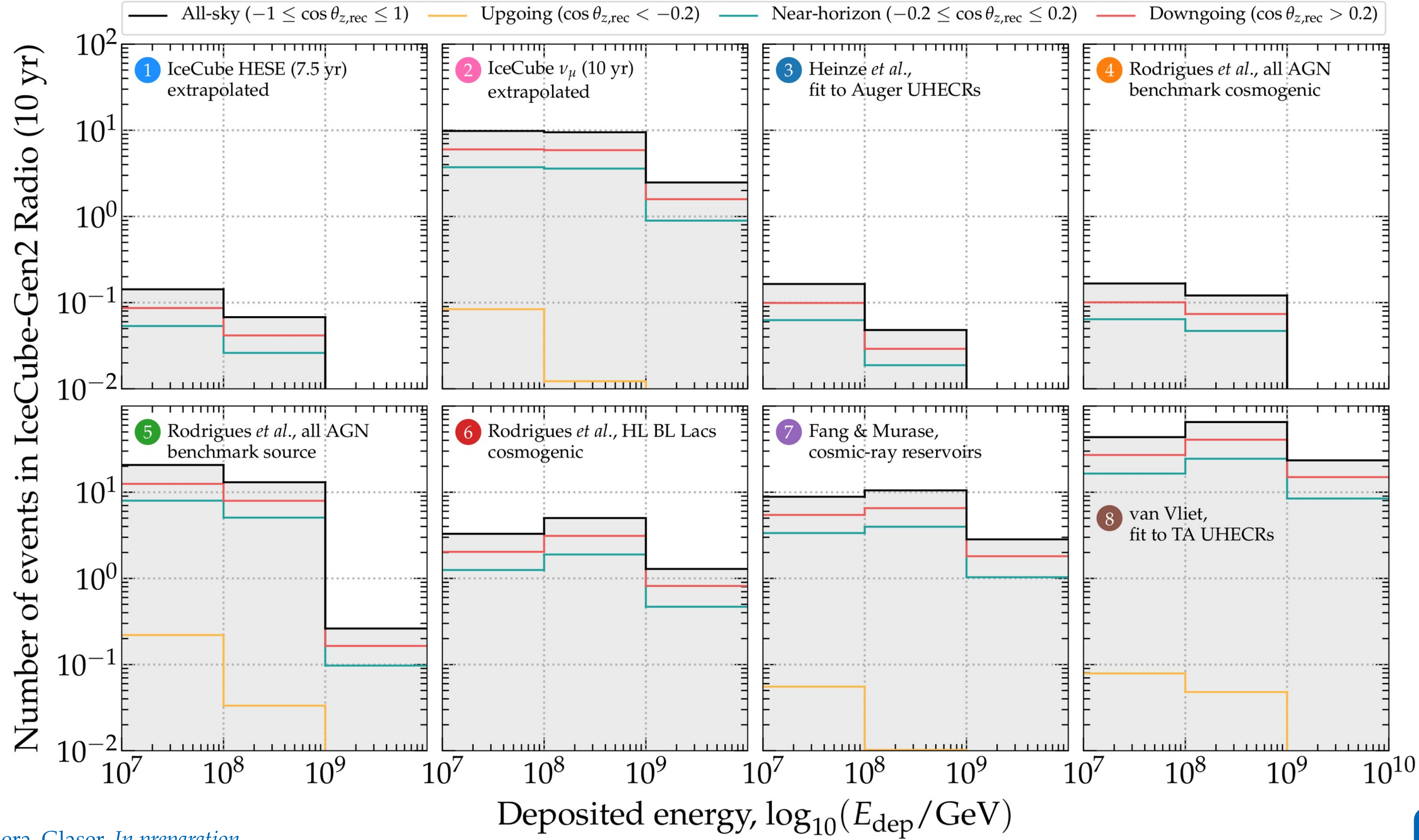

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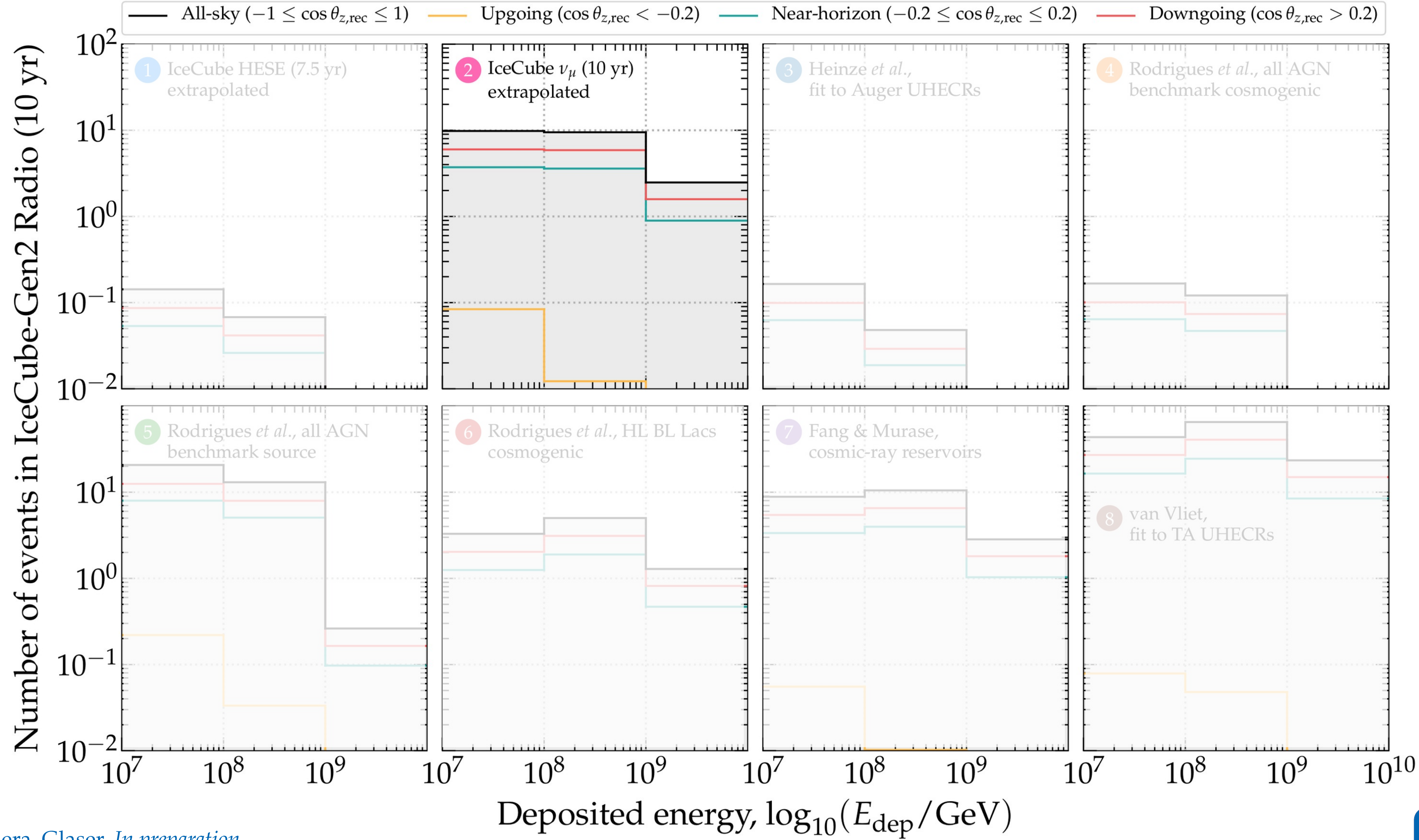

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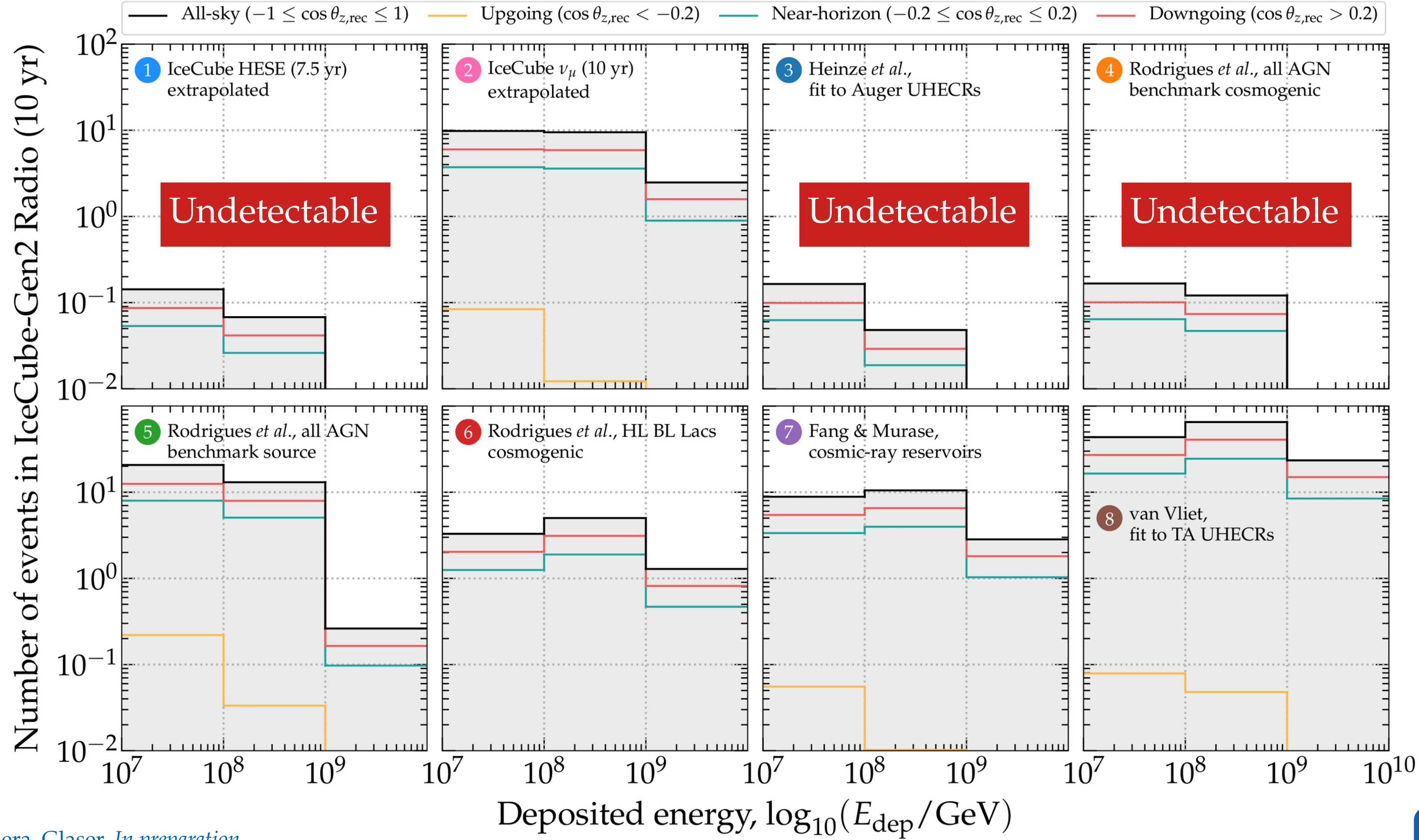

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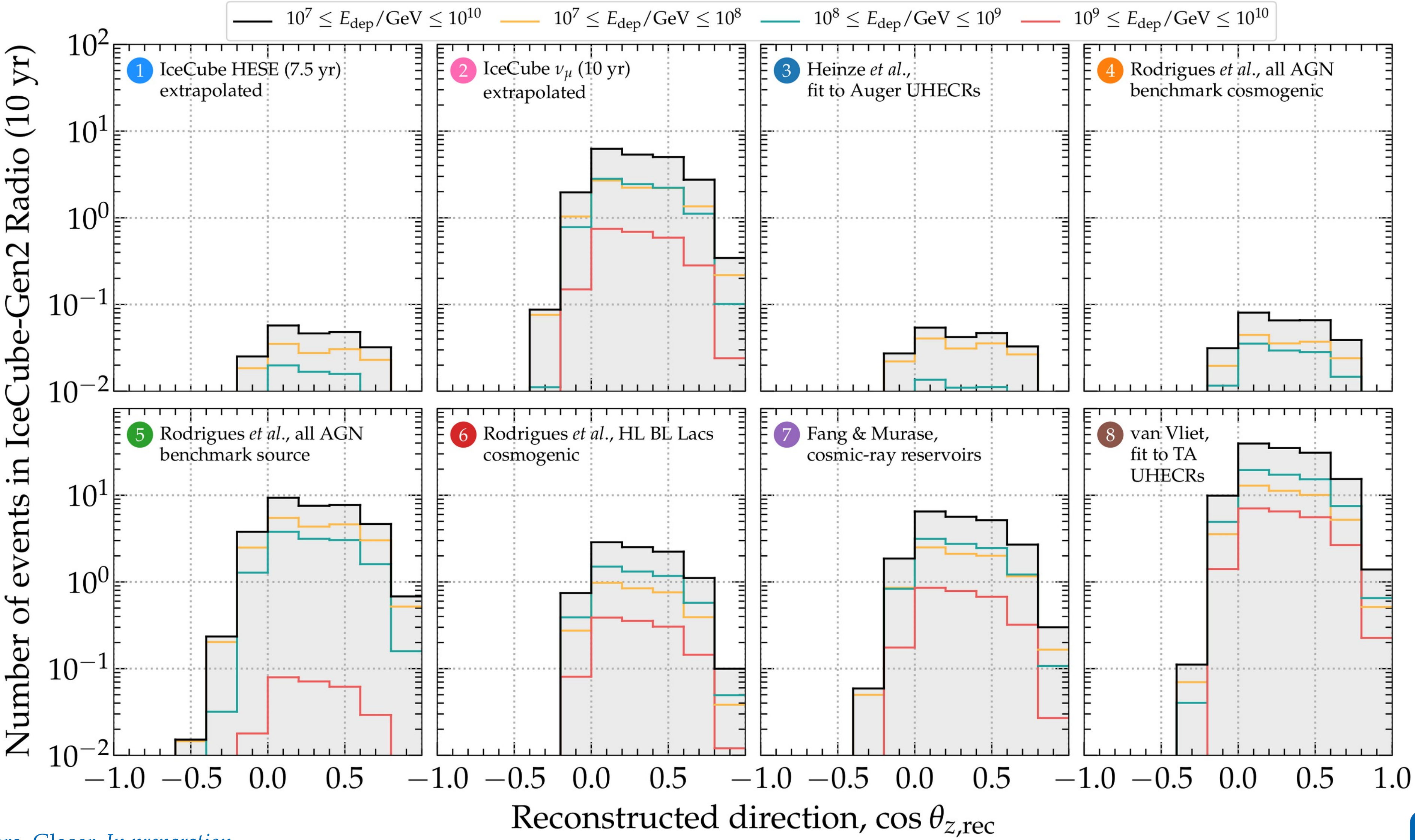

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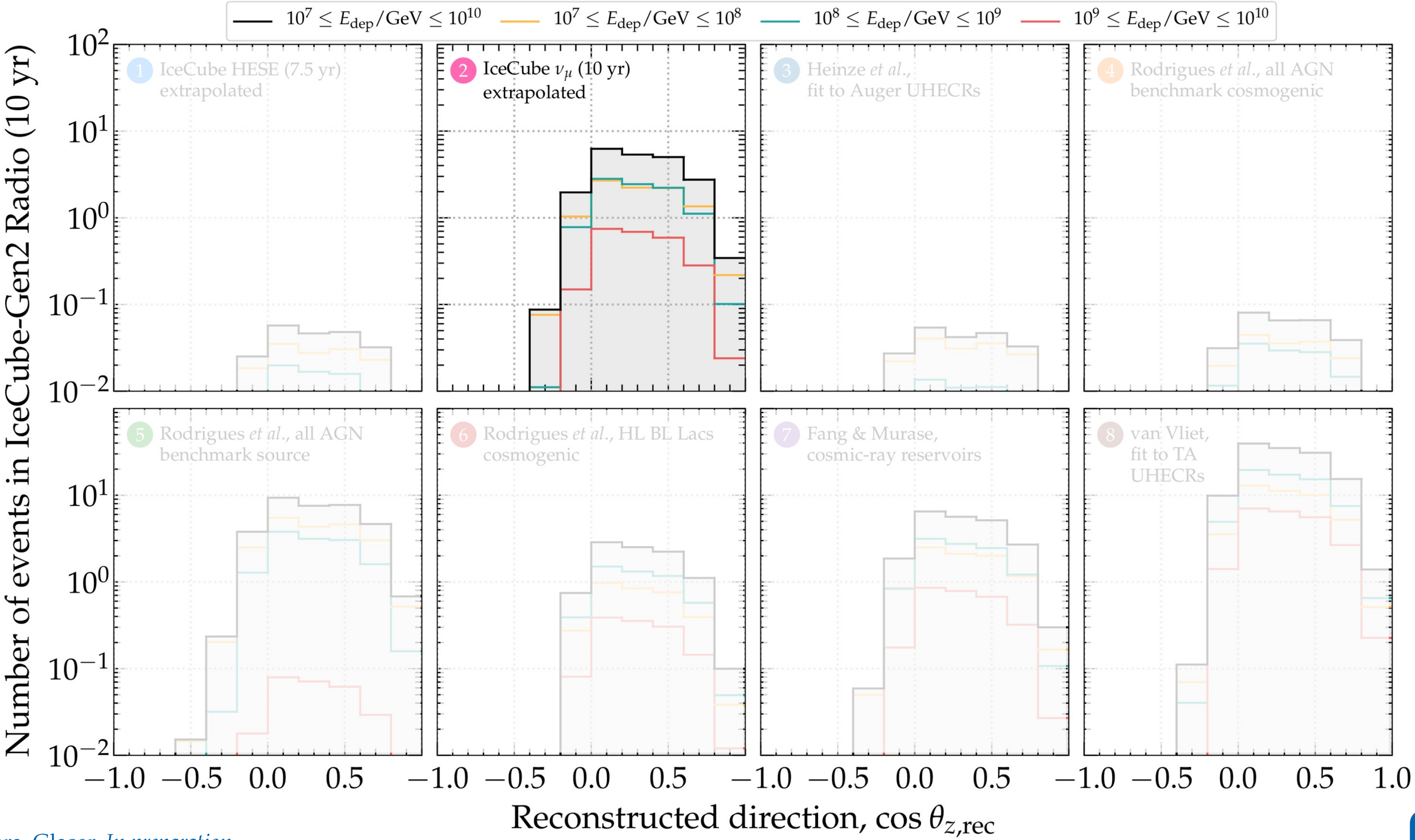

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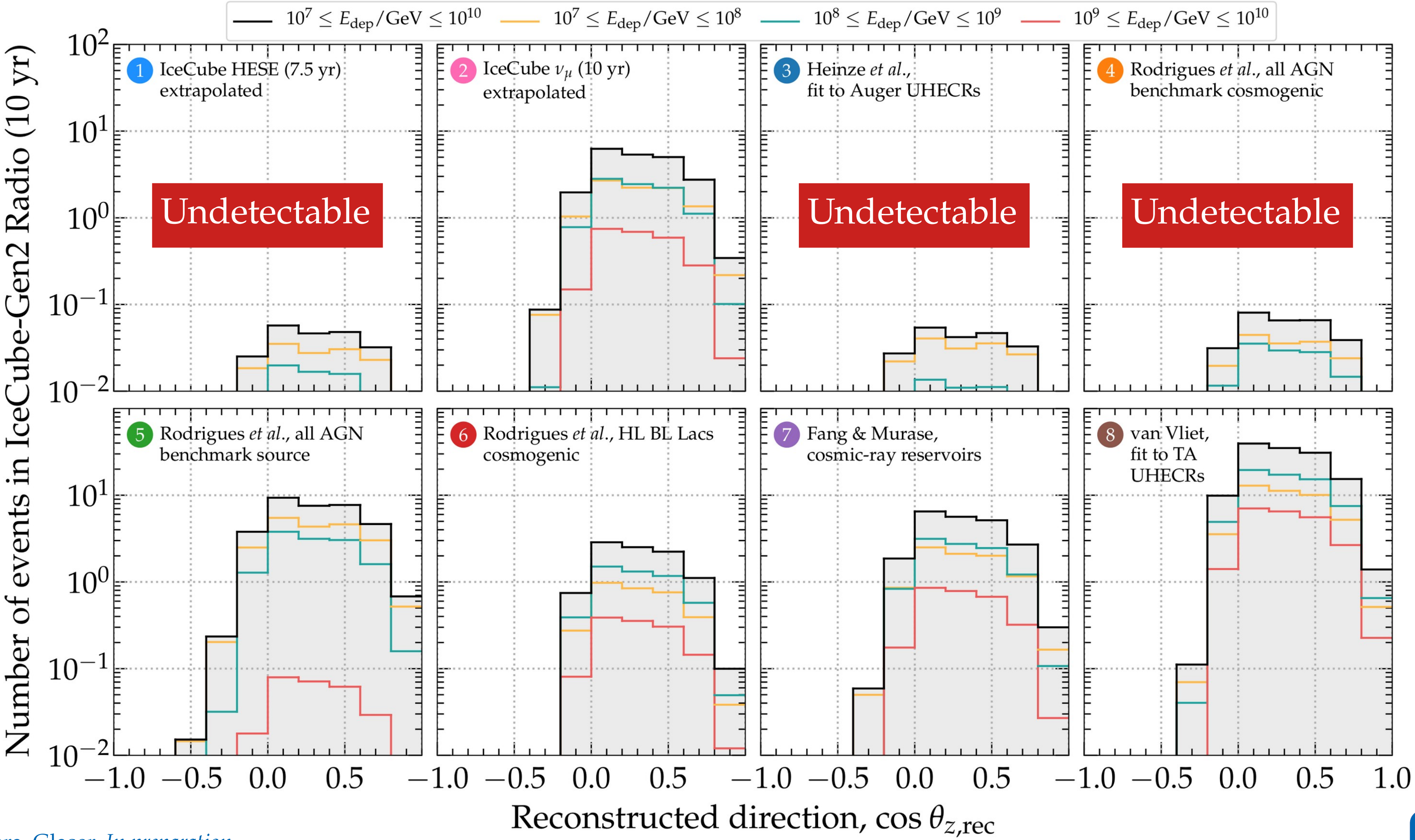
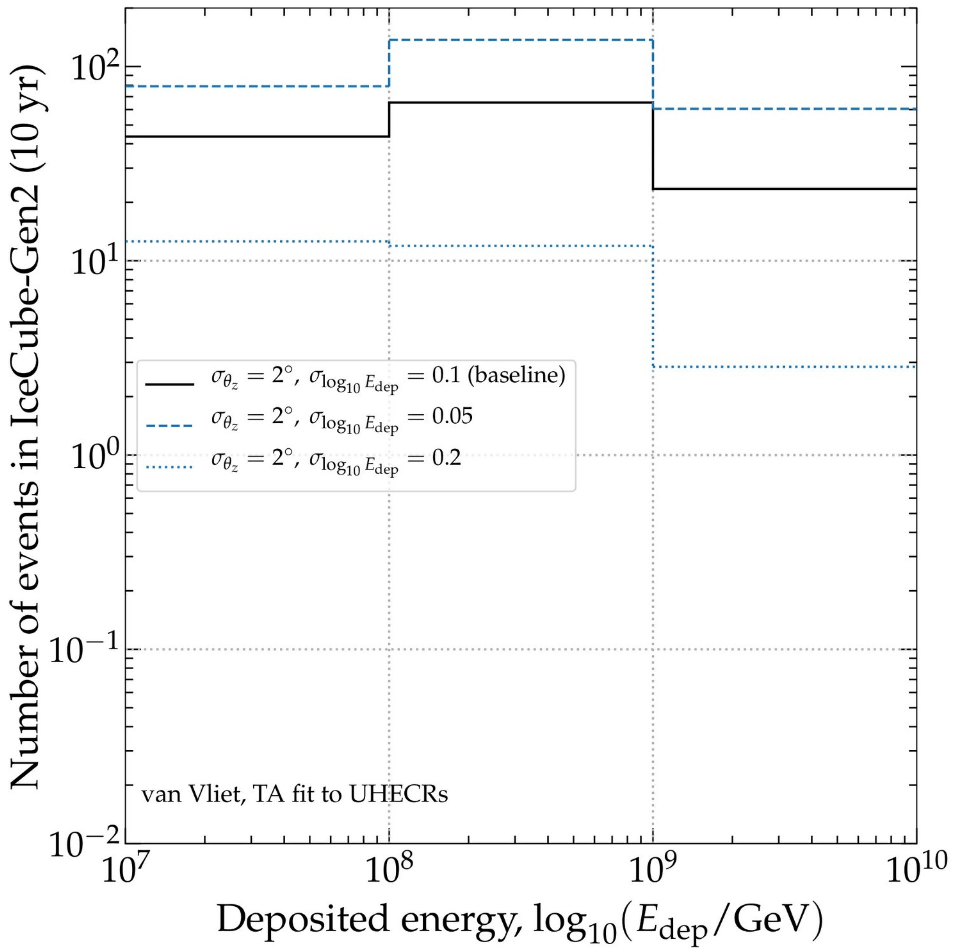


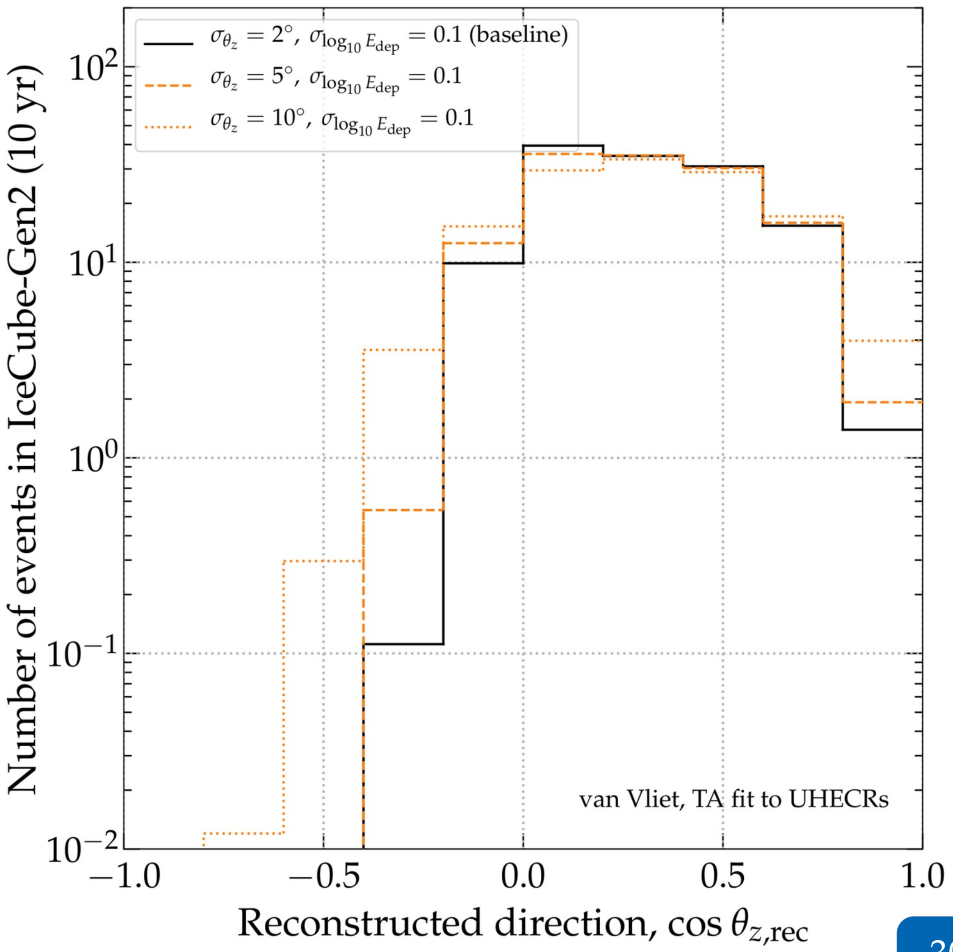
MB, Valera, Glaser, *In preparation*

Effect of energy & angular resolution

Changing resolution in E_{dep}



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



Five directions

Advanced

Approximate level of progress

(N.B.: All results are preliminary)

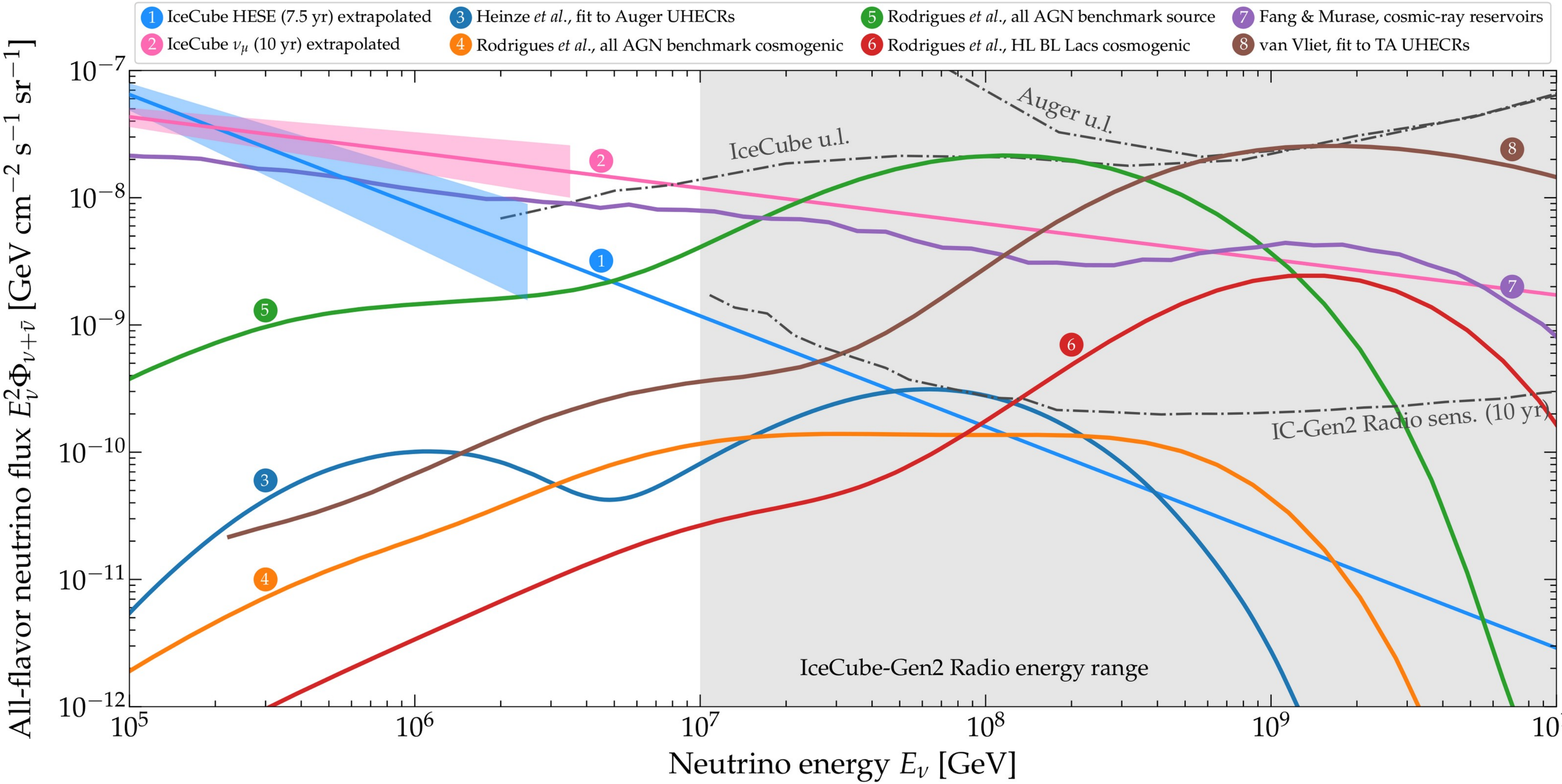
Nascent

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. UHE ν physics using flavor ratios

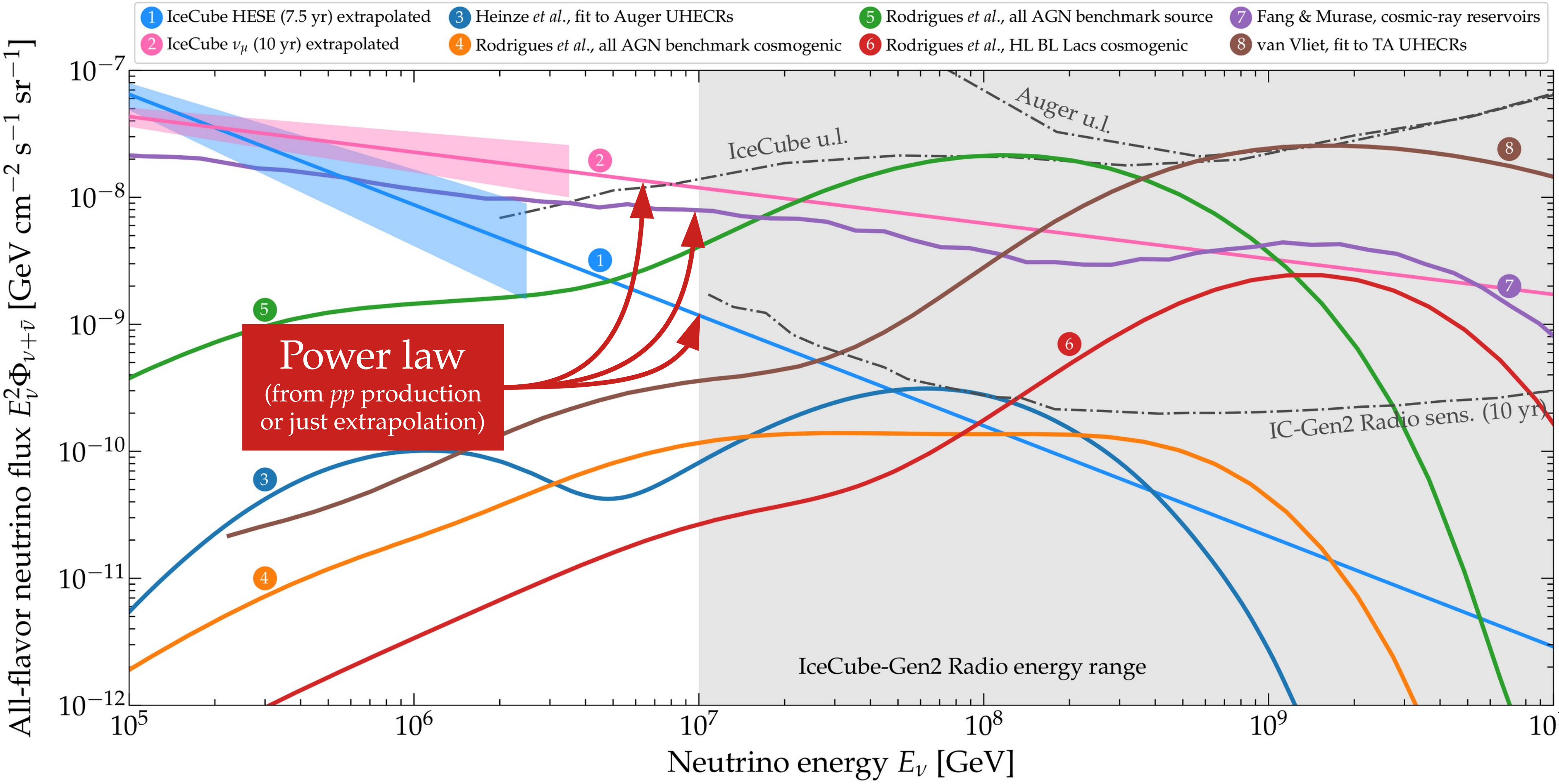
I.
Discovery potential for UHE ν

Work in progress, stay tuned …

II.
Inferring the spectrum of UHE ν



1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
3 Heinze *et al.*, fit to Auger UHECRs
4 Rodrigues *et al.*, all AGN benchmark cosmogenic
5 Rodrigues *et al.*, all AGN benchmark source
6 Rodrigues *et al.*, HL BL Lacs cosmogenic
7 Fang & Murase, cosmic-ray reservoirs
8 van Vliet, fit to TA UHECRs
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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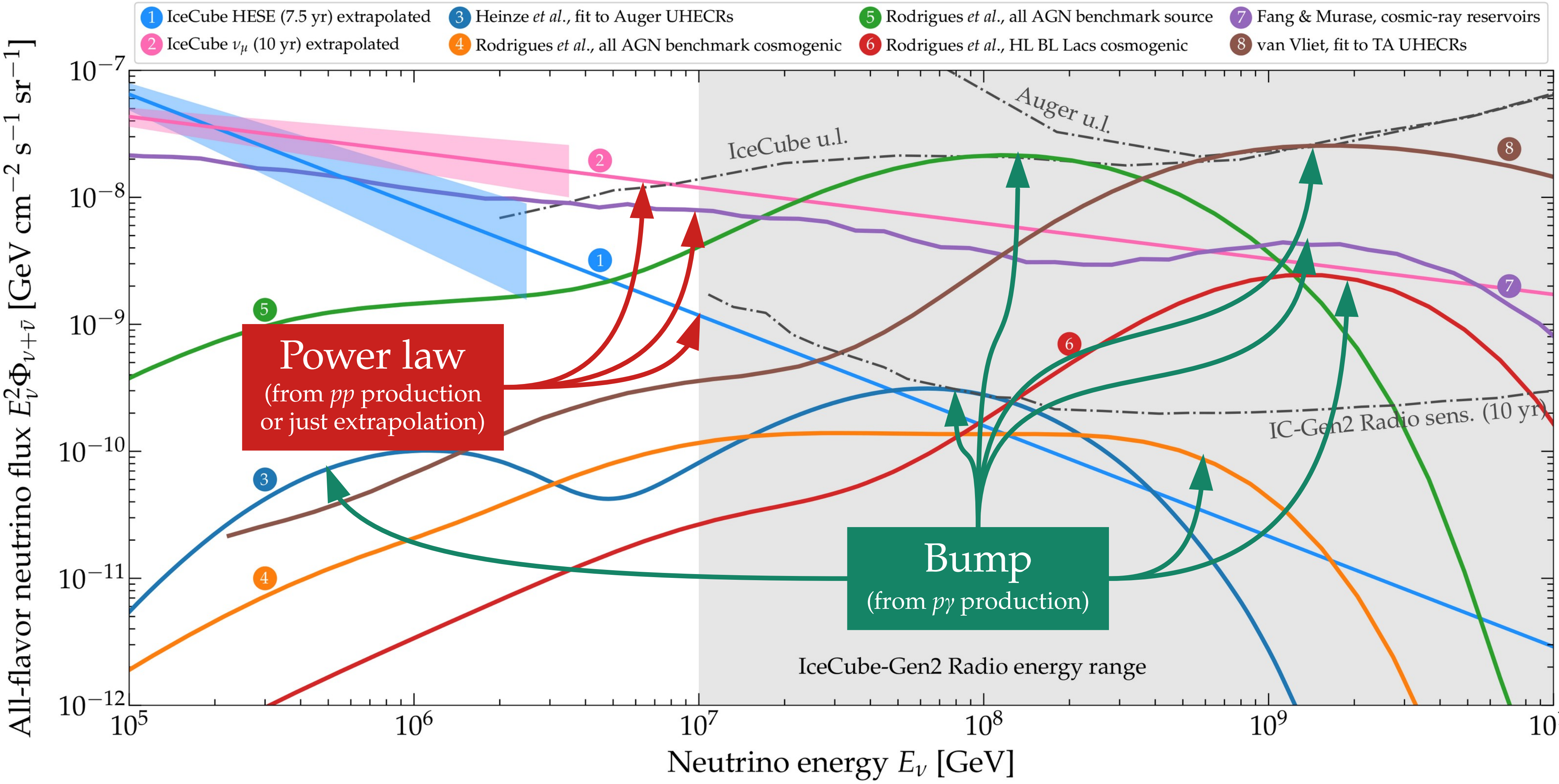
All-flavor neutrino flux $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
Auger u.l.
IceCube u.l.
Power law
(from pp production or just extrapolation)
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
10^5
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy E_ν [GeV]



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

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

Anti-neutrinos:

A generic, empirical model of the UHE ν spectrum

Neutrinos:

Normalization

$$E_\nu^2 \Phi_{\nu_\alpha}(E_\nu) = \underbrace{(E_\nu^2 \Phi_0) f_{\alpha,\oplus} f_\nu}_{\text{Normalization}} \Bigg[\qquad \Bigg]$$

Anti-neutrinos:

A generic, empirical model of the UHE ν spectrum

Neutrinos:

Normalization

Power-law
(from *pp*
or extrapolation)

$$E_\nu^2 \Phi_{\nu_\alpha}(E_\nu) = \underbrace{(E_\nu^2 \Phi_0) f_{\alpha,\oplus} f_\nu}_{\text{Normalization}} \left[\underbrace{\left(\frac{E_\nu}{\mathrm{PeV}} \right)^{-\gamma}}_{\text{Power-law}} \qquad \qquad \right]$$

Anti-neutrinos:

A generic, empirical model of the UHE ν spectrum

Neutrinos:

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

Anti-neutrinos:

A generic, empirical model of the UHE ν spectrum

Neutrinos:

$$\underbrace{}_{}\overbrace{(E_\nu^2\Phi_0) f_{\alpha,\oplus} f_\nu}^{\text{Normalization}}$$

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

Anti-neutrinos:

A generic, empirical model of the UHE ν spectrum

Neutrinos:

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

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Neutrinos:

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Anti-neutrinos:

$$E_\nu^2 \Phi_{\bar{\nu}_\alpha}(E_\nu) = (E_\nu^2 \Phi_0) f_{\alpha,\oplus} (1 - f_\nu)$$

A generic, empirical model of the UHE ν spectrum

Neutrinos:

Normalization

Power-law (from *pp* or extrapolation)

$$E_\nu^2 \Phi_{\nu_\alpha}(E_\nu) = \underbrace{(E_\nu^2 \Phi_0)}_{\text{Normalization}} f_{\alpha,\oplus} f_\nu \left[\left(\frac{E_\nu}{\text{PeV}} \right)^{-\gamma} + \eta_l^\nu \mathcal{G}_l(E_\nu; \alpha_l, \beta_l^\nu, \mu_l) + \eta_h^\nu \mathcal{G}_h(E_\nu; \alpha_h, \beta_h^\nu, \mu_h) \right]$$

Low-energy *pγ* bump (from EBL or in source)

High-energy *pγ* bump (from CMB or in source)

Anti-neutrinos:

$$E_\nu^2 \Phi_{\bar{\nu}_\alpha}(E_\nu) = (E_\nu^2 \Phi_0) f_{\alpha,\oplus} (1 - f_\nu) \left[\qquad \right]$$

A generic, empirical model of the UHE ν spectrum

Neutrinos:

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

Anti-neutrinos:

$$E_\nu^2 \Phi_{\bar{\nu}_\alpha}(E_\nu) = (E_\nu^2 \Phi_0) f_{\alpha,\oplus} (1 - f_\nu) \left[\left(\frac{E_\nu}{\text{PeV}}\right)^{-\gamma} \qquad \right]$$

A generic, empirical model of the UHE ν spectrum

Neutrinos:

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A generic, empirical model of the UHE ν spectrum

Neutrinos:

Normalization

Power-law (from *pp* or extrapolation)

$$E_\nu^2 \Phi_{\nu_\alpha}(E_\nu) = (E_\nu^2 \Phi_0) f_{\alpha,\oplus} f_\nu \left[\left(\frac{E_\nu}{\mathrm{PeV}} \right)^{-\gamma} + \eta_l^\nu \mathcal{G}_l(E_\nu; \alpha_l, \beta_l^\nu, \mu_l) + \eta_h^\nu \mathcal{G}_h(E_\nu; \alpha_h, \beta_h^\nu, \mu_h) \right]$$

Low-energy *pγ* bump (from EBL or in source)

High-energy *pγ* bump (from CMB or in source)

Anti-neutrinos:

$$E_\nu^2 \Phi_{\bar{\nu}_\alpha}(E_\nu) = (E_\nu^2 \Phi_0) f_{\alpha,\oplus} (1 - f_\nu) \left[\left(\frac{E_\nu}{\mathrm{PeV}} \right)^{-\gamma} \quad \eta_l^{\bar{\nu}} \mathcal{G}_l(E_\nu; \alpha_l, \beta_l^{\bar{\nu}}, \mu_l) + \eta_h^{\bar{\nu}} \mathcal{G}_h(E_\nu; \alpha_h, \beta_h^{\bar{\nu}}, \mu_h) \right]$$

Low-energy *pγ* bump (from EBL or in source)

High-energy *pγ* bump (from CMB or in source)

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:

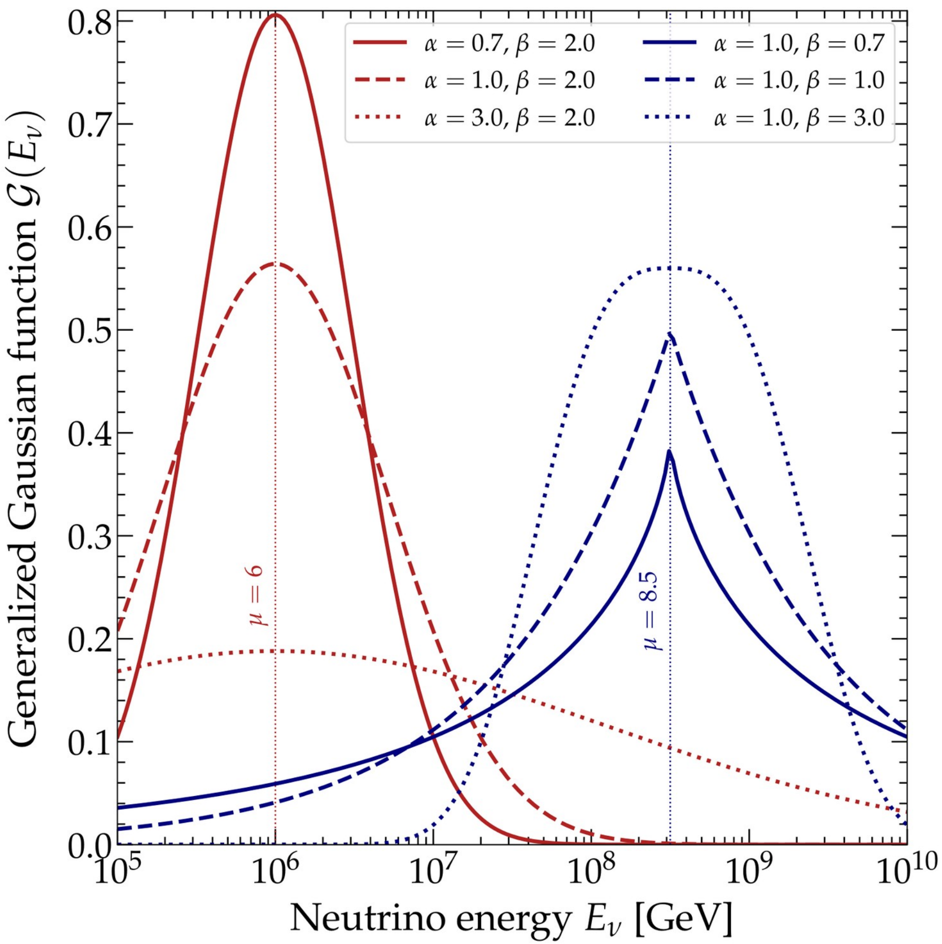
$$E_\nu^2 \Phi_{\bar{\nu}_\alpha}(E_\nu) = (E_\nu^2 \Phi_0) f_{\alpha,\oplus} (1 - f_\nu) \left[\left(\frac{E_\nu}{\mathrm{PeV}} \right)^{-\gamma} + \underbrace{\eta_n^{\bar{\nu}} \mathcal{G}_n(E_\nu; \alpha_n^{\bar{\nu}}, \beta_n^{\bar{\nu}}, \mu_n^{\bar{\nu}})}_{\text{Bump from neutron decay}} + \underbrace{\eta_l^{\bar{\nu}}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

A generic, empirical model of the UHE ν spectrum

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

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

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

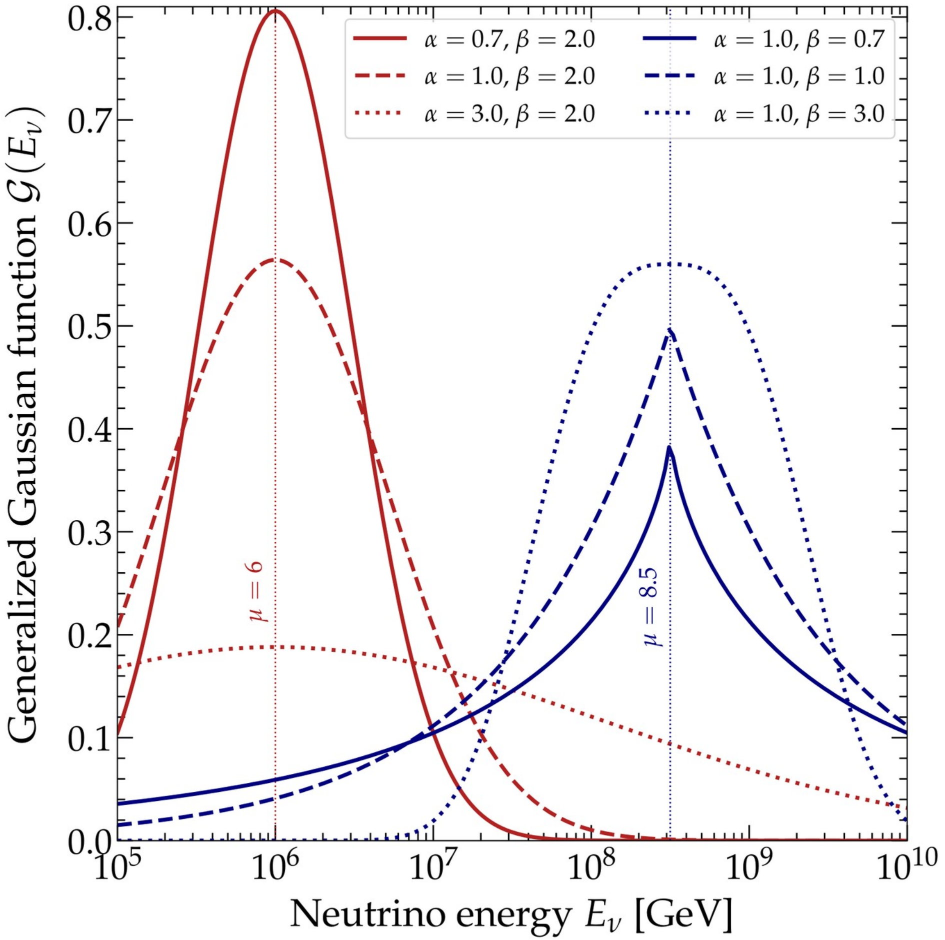


A generic, empirical model of the UHE ν spectrum

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:

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

Anti-neutrinos:

A generic, empirical model of the UHE ν spectrum

Neutrinos:

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

Anti-neutrinos:

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

A generic, empirical model of the UHE ν spectrum

Neutrinos:

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Anti-neutrinos:

$$E_\nu^2 \Phi_{\bar{\nu}_\alpha}(E_\nu) = (E_\nu^2 \Phi_0) f_{\alpha,\oplus} (1 - f_\nu)$$

A generic, empirical model of the UHE ν spectrum

Neutrinos:

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

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A generic, empirical model of the UHE ν spectrum

Neutrinos:

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

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A generic, empirical model of the UHE ν spectrum

Neutrinos:

Normalization

Power-law (from *pp* or extrapolation)

$$E_\nu^2 \Phi_{\nu_\alpha}(E_\nu) = (E_\nu^2 \Phi_0) f_{\alpha,\oplus} f_\nu \left[\left(\frac{E_\nu}{\mathrm{PeV}} \right)^{-\gamma} + \eta_l^\nu \mathcal{G}_l(E_\nu; \alpha_l, \beta_l^\nu, \mu_l) + \eta_h^\nu \mathcal{G}_h(E_\nu; \alpha_h, \beta_h^\nu, \mu_h) \right]$$

Low-energy *pγ* bump (from EBL or in source)

High-energy *pγ* bump (from CMB or in source)

Anti-neutrinos:

$$E_\nu^2 \Phi_{\bar{\nu}_\alpha}(E_\nu) = (E_\nu^2 \Phi_0) f_{\alpha,\oplus} (1 - f_\nu) \left[\left(\frac{E_\nu}{\mathrm{PeV}} \right)^{-\gamma} \qquad \eta_l^{\bar{\nu}} \mathcal{G}_l(E_\nu; \alpha_l, \beta_l^{\bar{\nu}}, \mu_l) \right]$$

Low-energy *pγ* bump (from EBL or in source

A generic, empirical model of the UHE ν spectrum

Neutrinos:

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

A generic, empirical model of the UHE ν spectrum

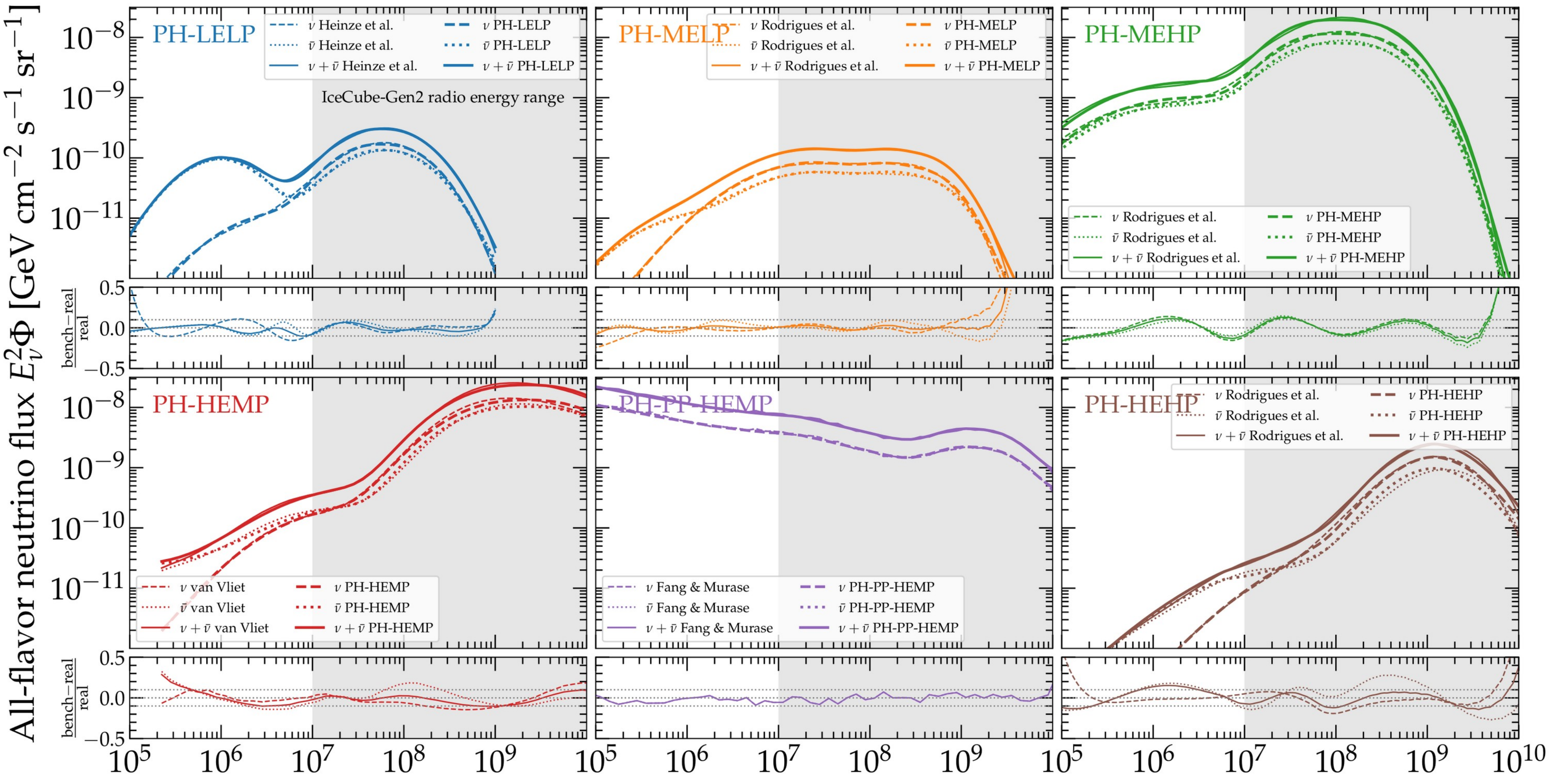
Neutrinos:

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

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.*,

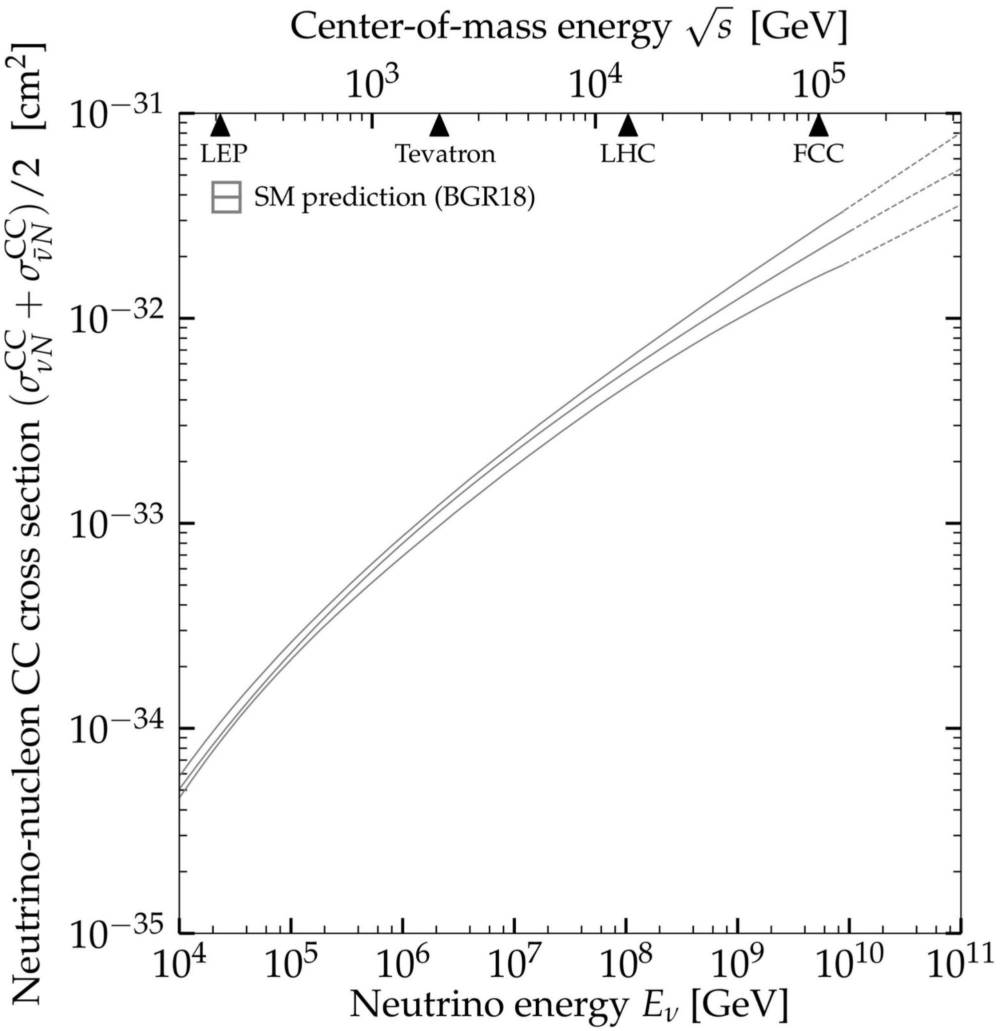


MB, Valera, *In preparation*

Work in progress, stay tuned ...

III.
Measuring the UHE νN cross section

High-energy νN cross section: *prediction*

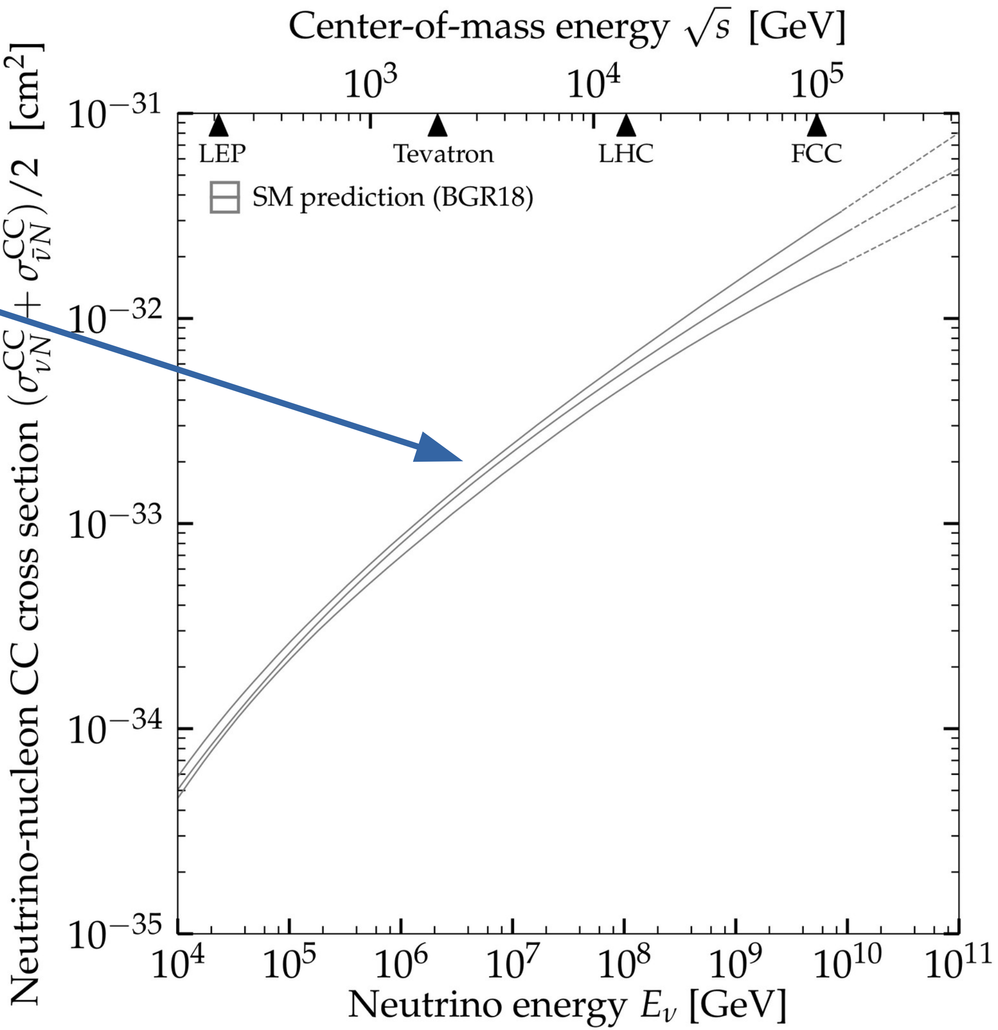


Bertone, Gauld, Rojo, *JHEP* 2019

High-energy νN cross section: *prediction*

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

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

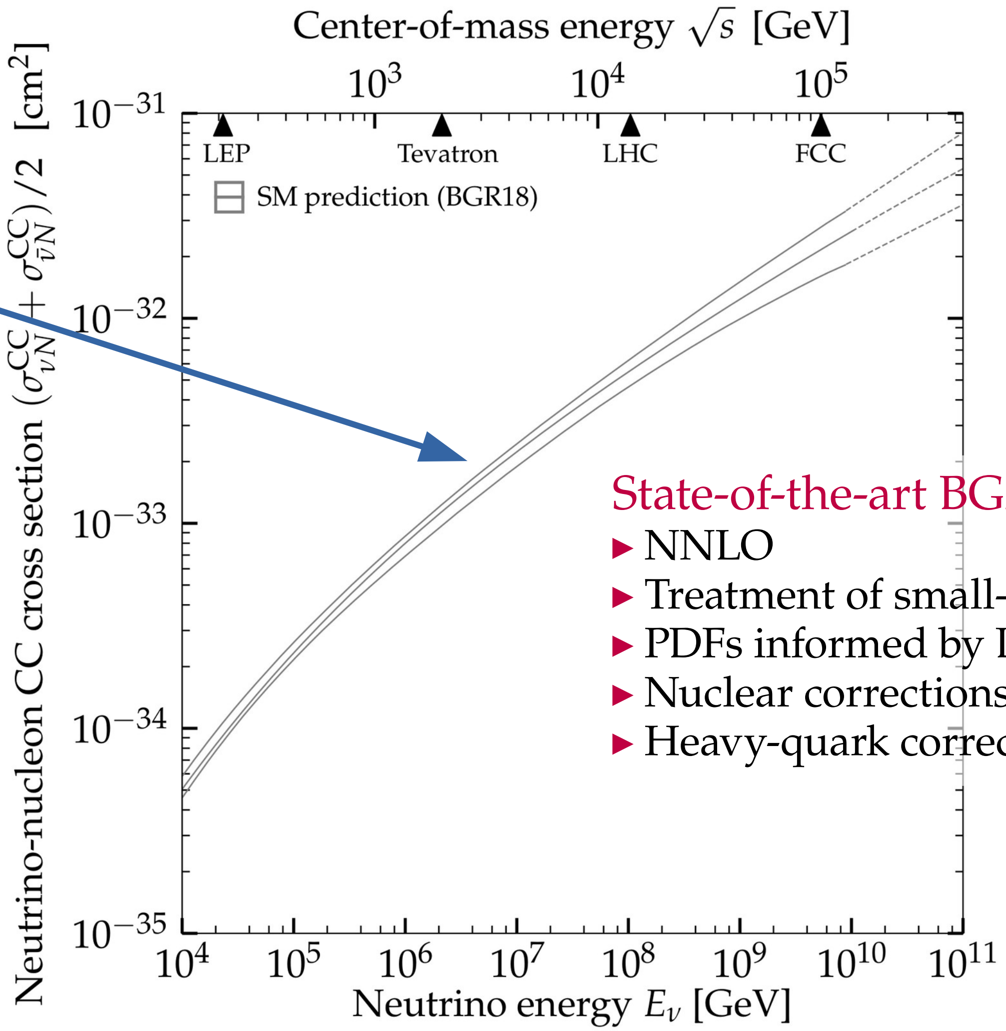


Bertone, Gauld, Rojo, *JHEP* 2019

High-energy νN cross section: *prediction*

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

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



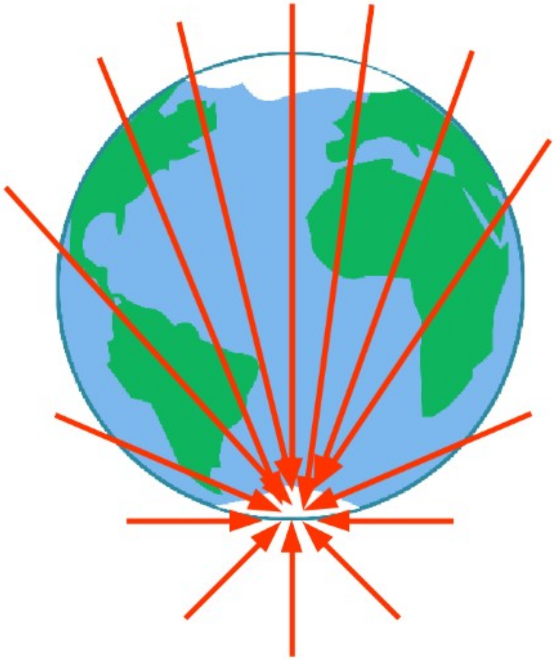
State-of-the-art BGR18 prediction:

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

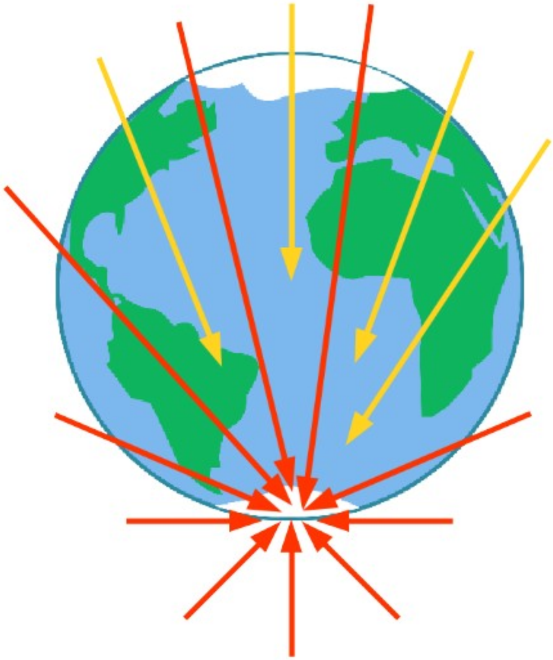
Bertone, Gauld, Rojo, *JHEP* 2019

Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent



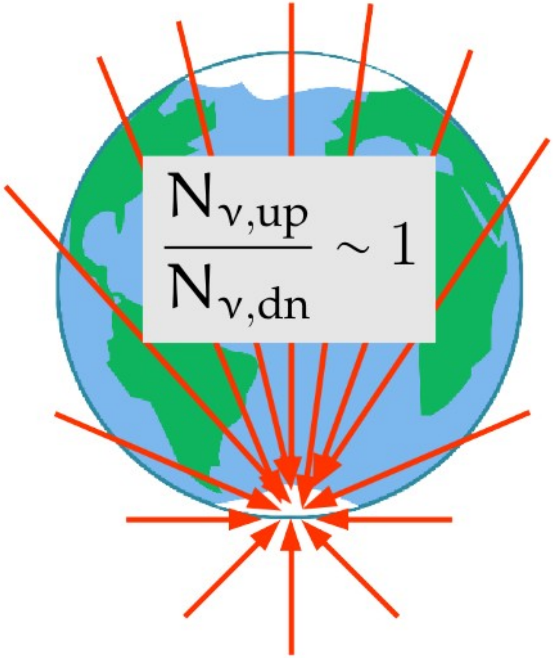
Above ~ 10 TeV: Earth is opaque



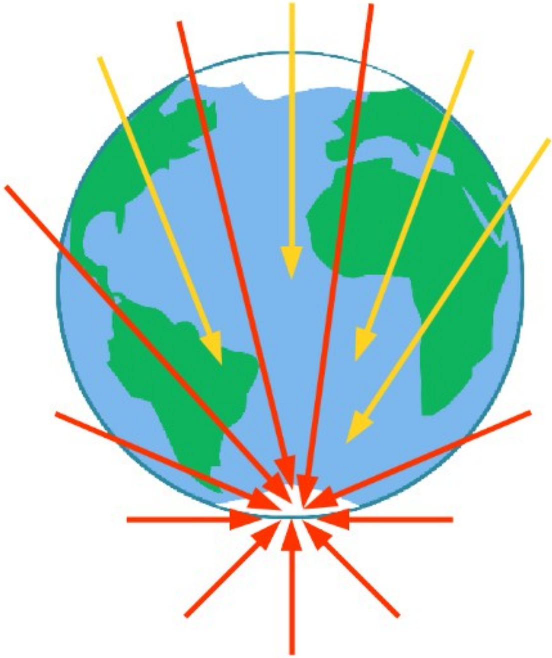
Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008 Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent



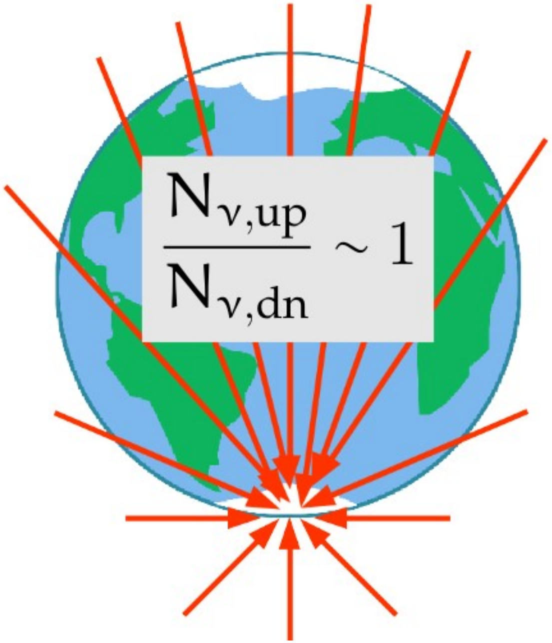
Above ~ 10 TeV: Earth is opaque



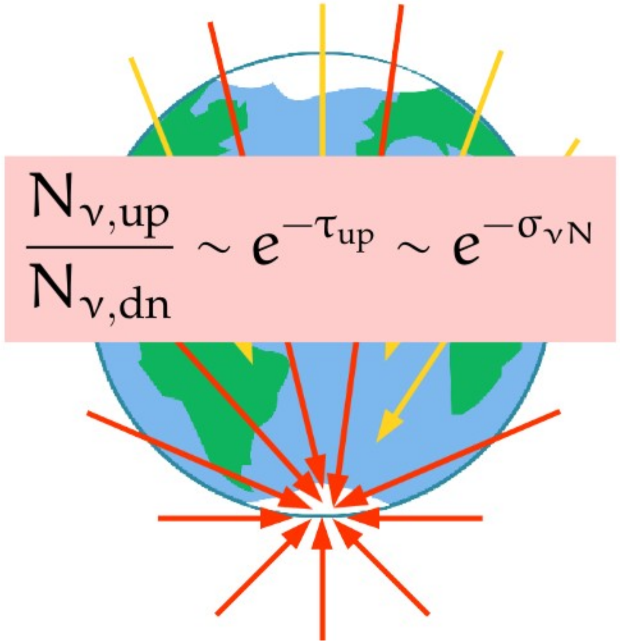
Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008 Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent

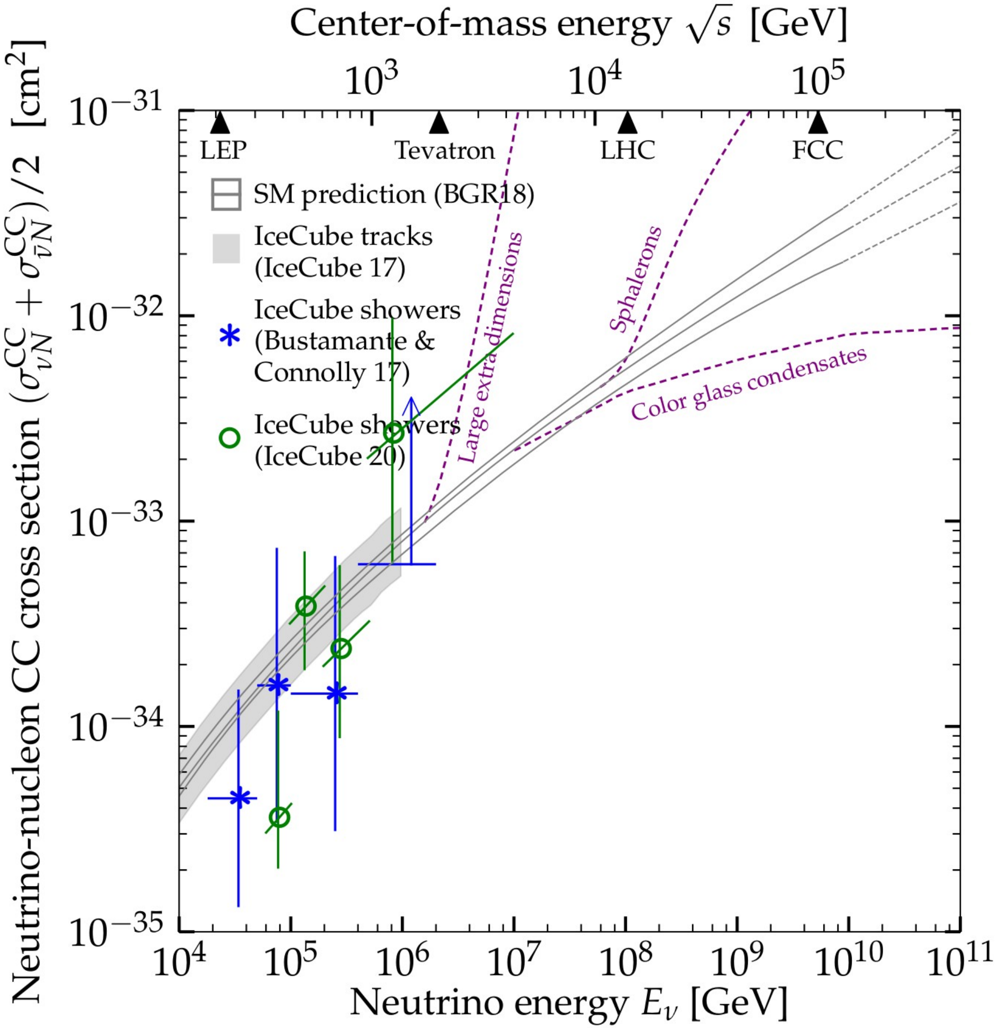


Above ~ 10 TeV: Earth is opaque



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

High-energy νN cross section: *today*

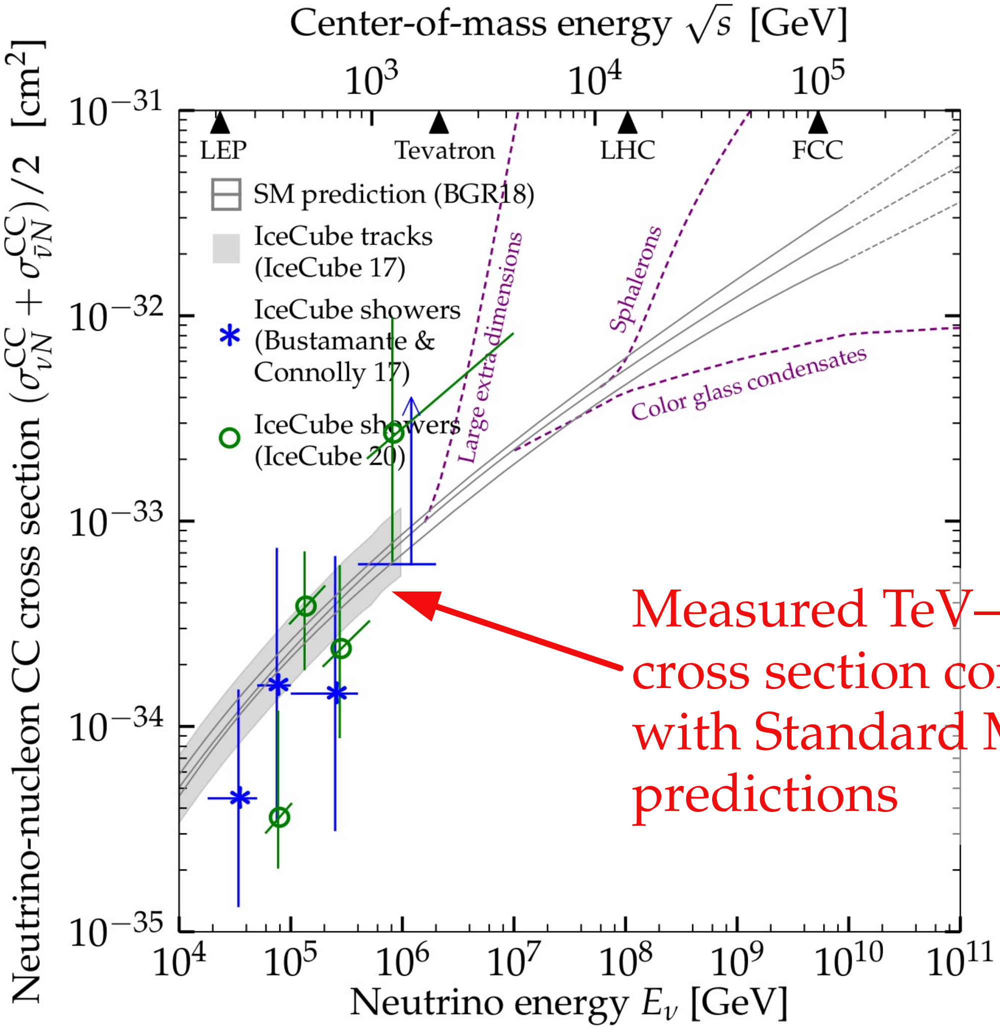


BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019

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

Measurements from:
IceCube, 2011.03560
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

High-energy νN cross section: *today*



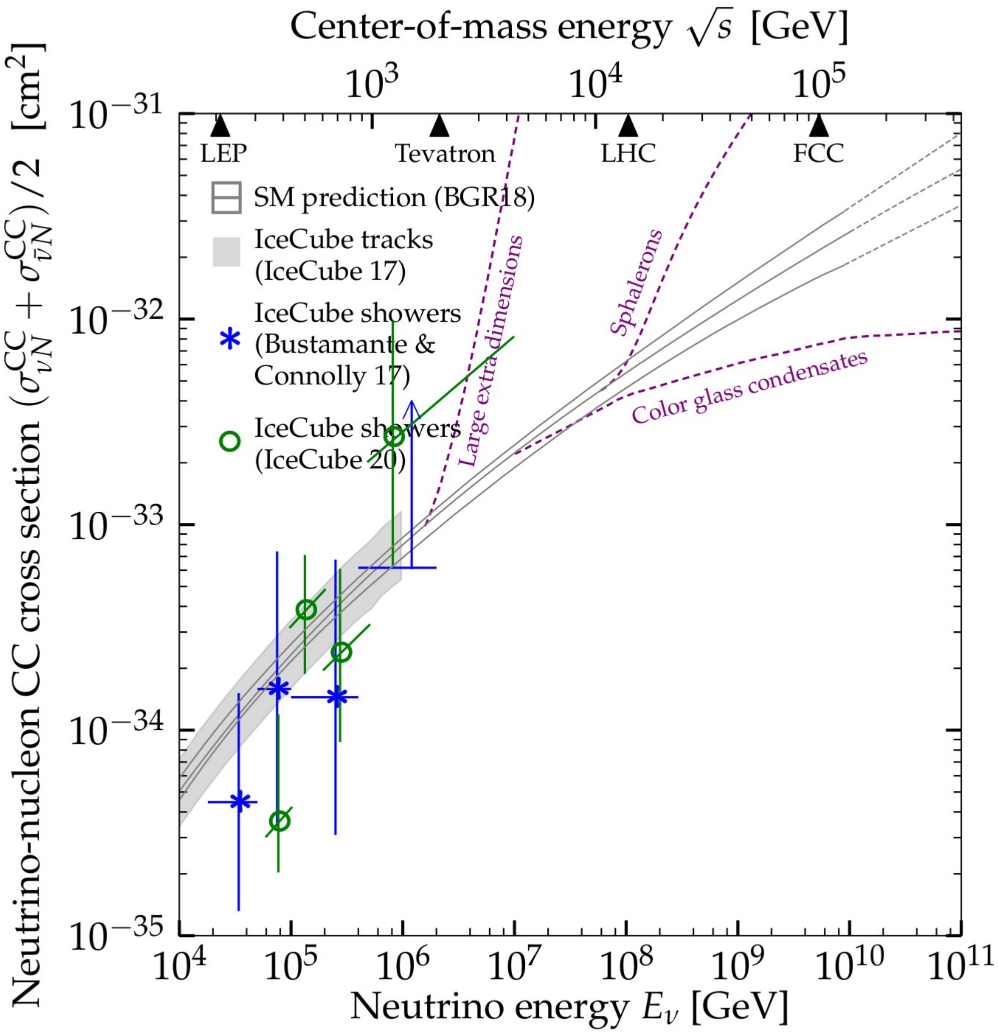
Measured TeV–PeV cross section compatible with Standard Model predictions

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

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

Measurements from:
IceCube, 2011.03560
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

High-energy νN cross section: *today*



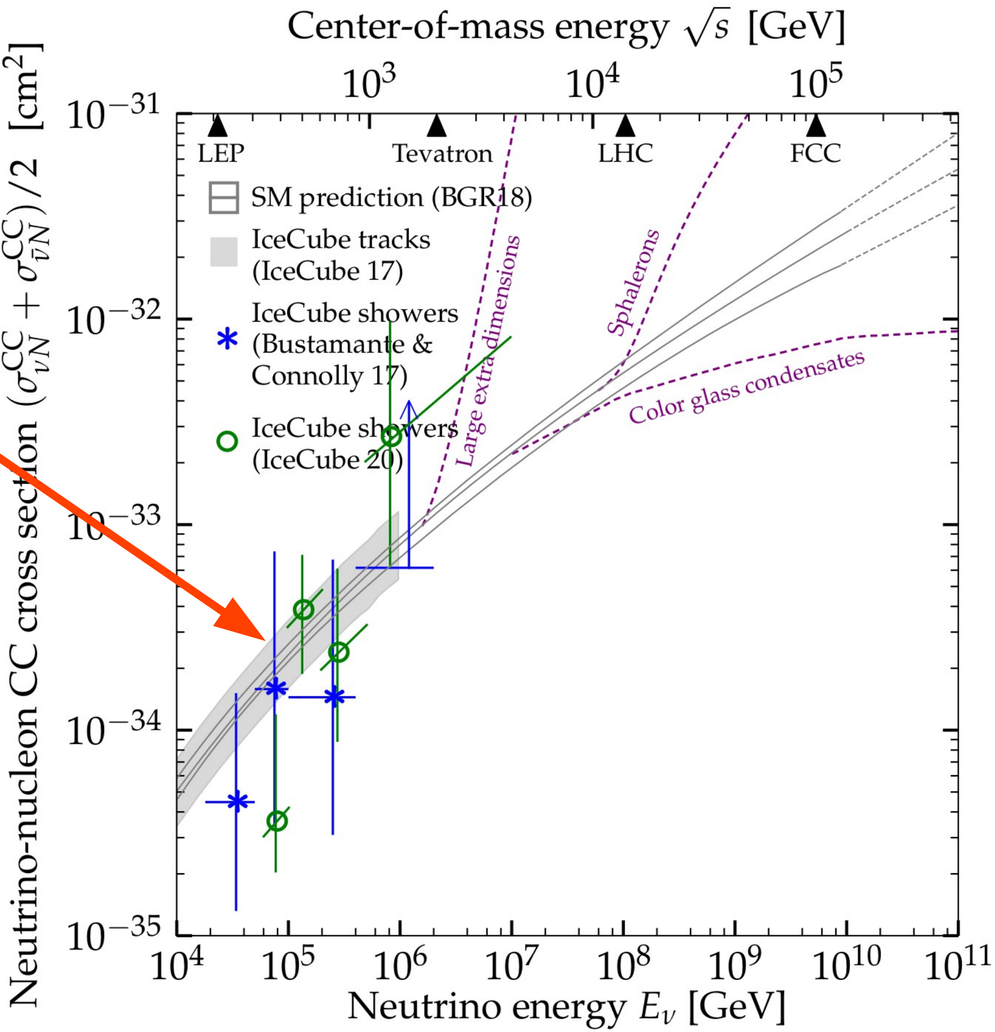
BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019

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

Measurements from:
IceCube, 2011.03560
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

High-energy *νN* cross section: *today*

Measured:
TeV – PeV
cross section



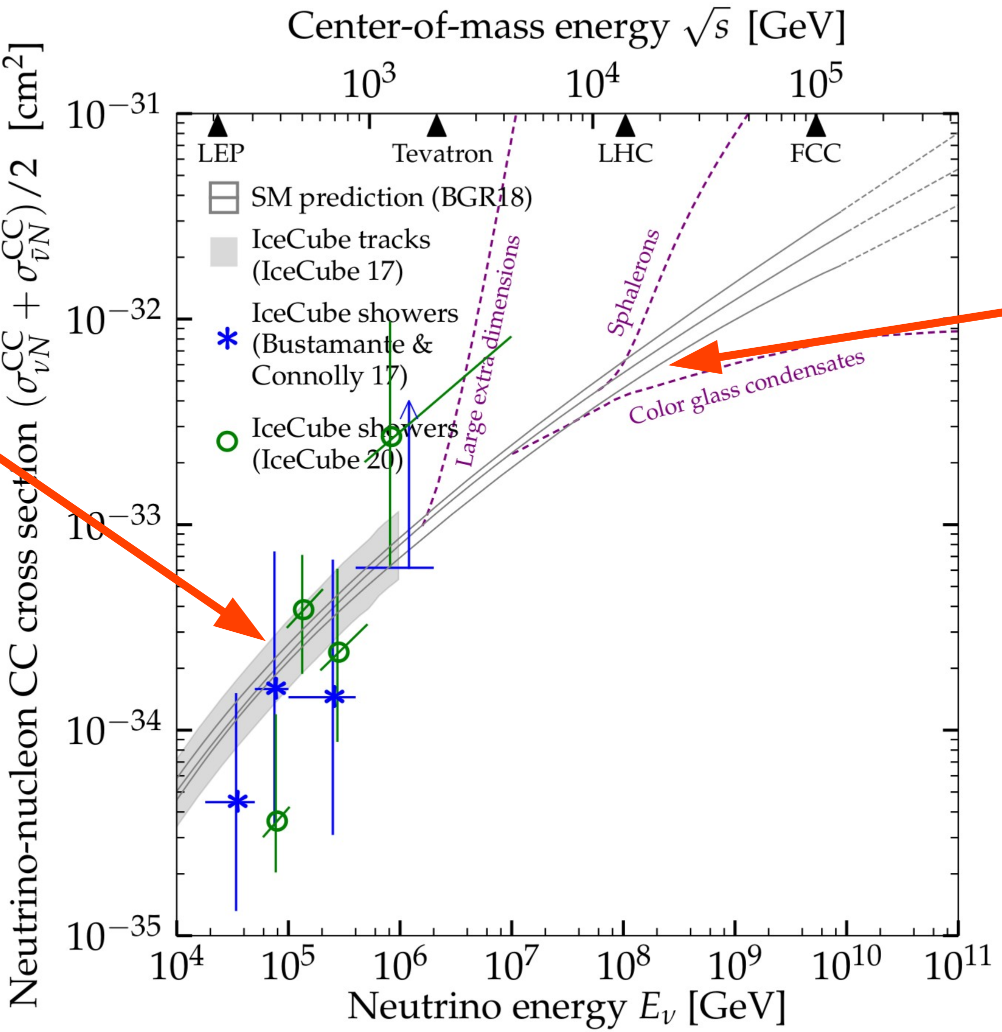
BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019

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

Measurements from:
IceCube, 2011.03560
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

High-energy νN cross section: *today*

Measured:
TeV – PeV
cross section



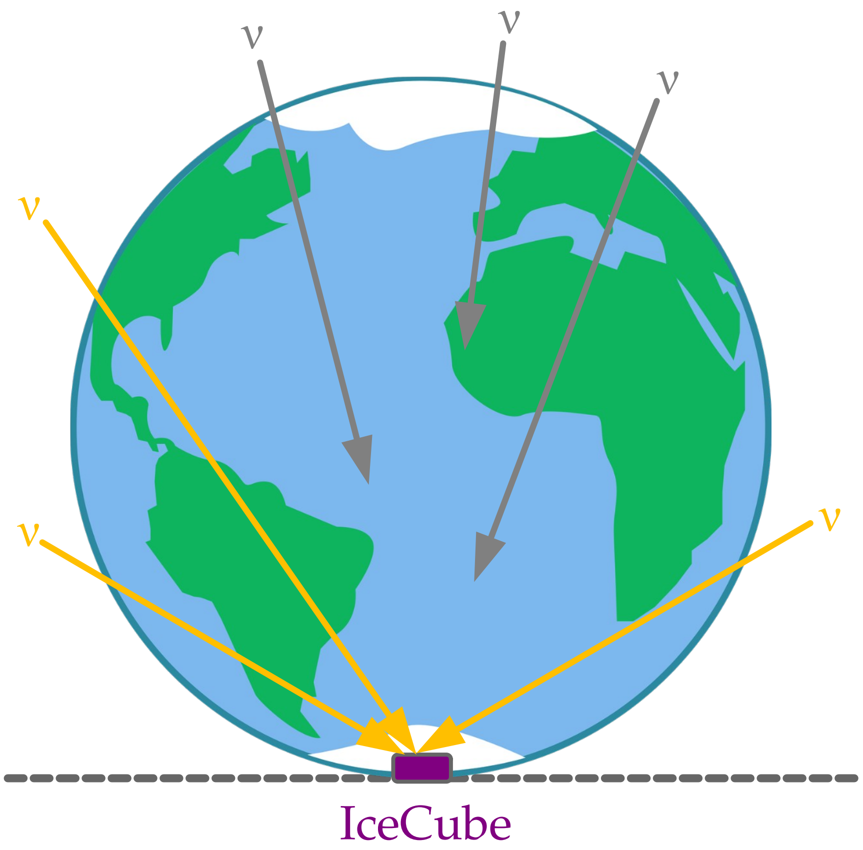
Not measured:
> 10-PeV
cross section

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

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

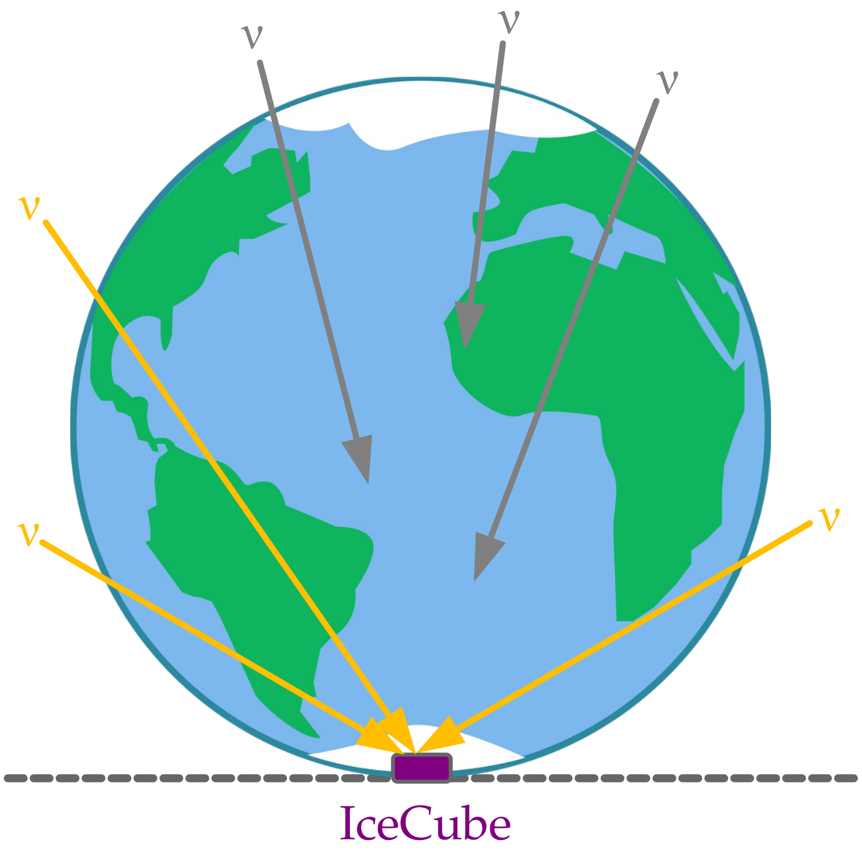
Measurements from:
IceCube, 2011.03560
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

TeV–PeV:



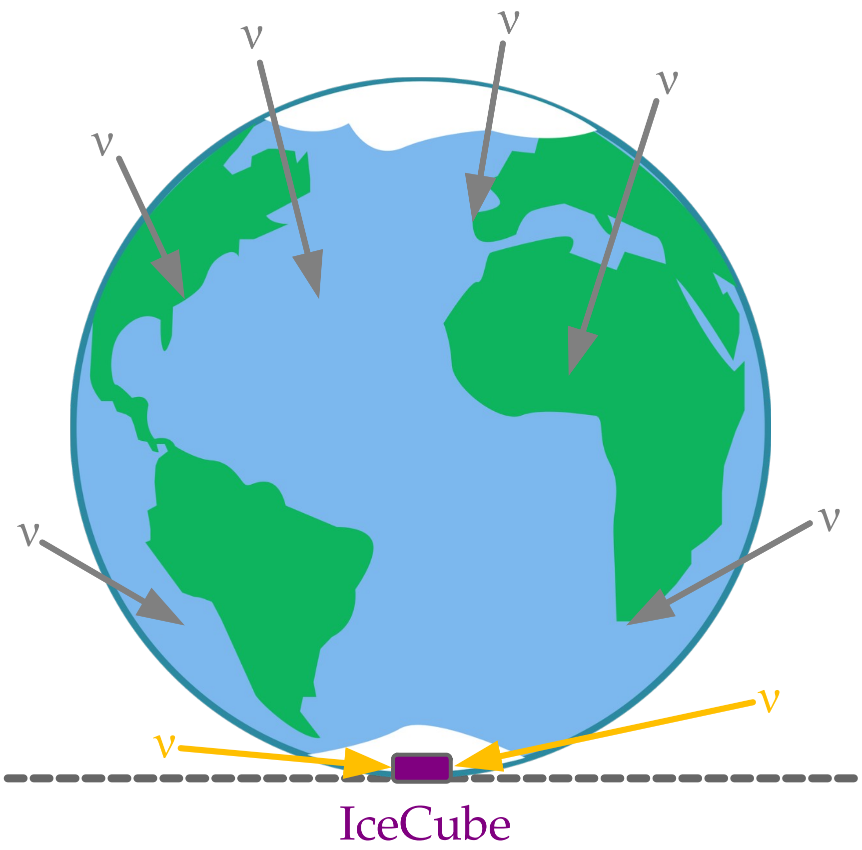
Earth is *almost fully* opaque,
some upgoing ν still make it through

TeV–PeV:



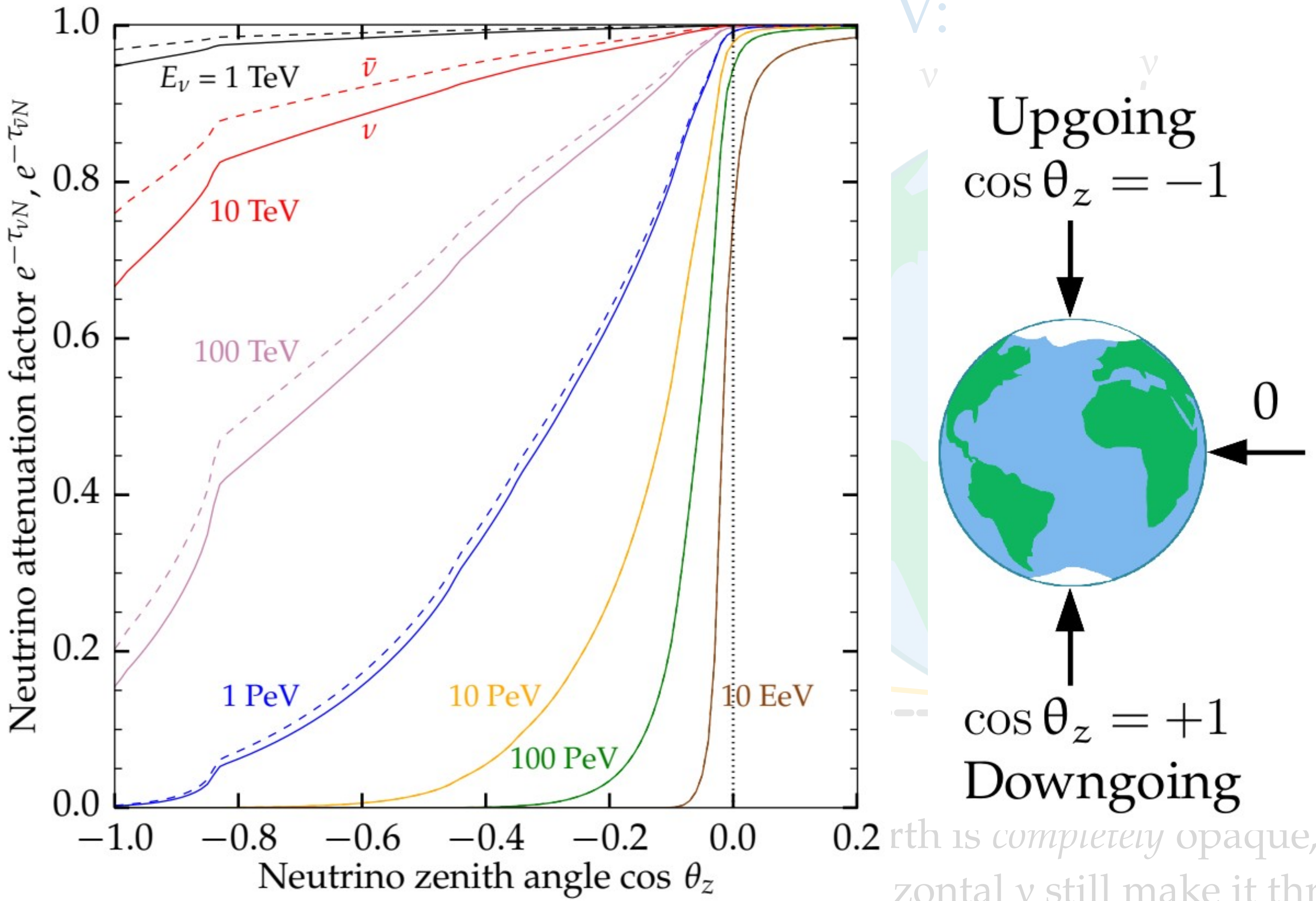
Earth is *almost fully* opaque,
some upgoing ν still make it through

$>$ 100 PeV:



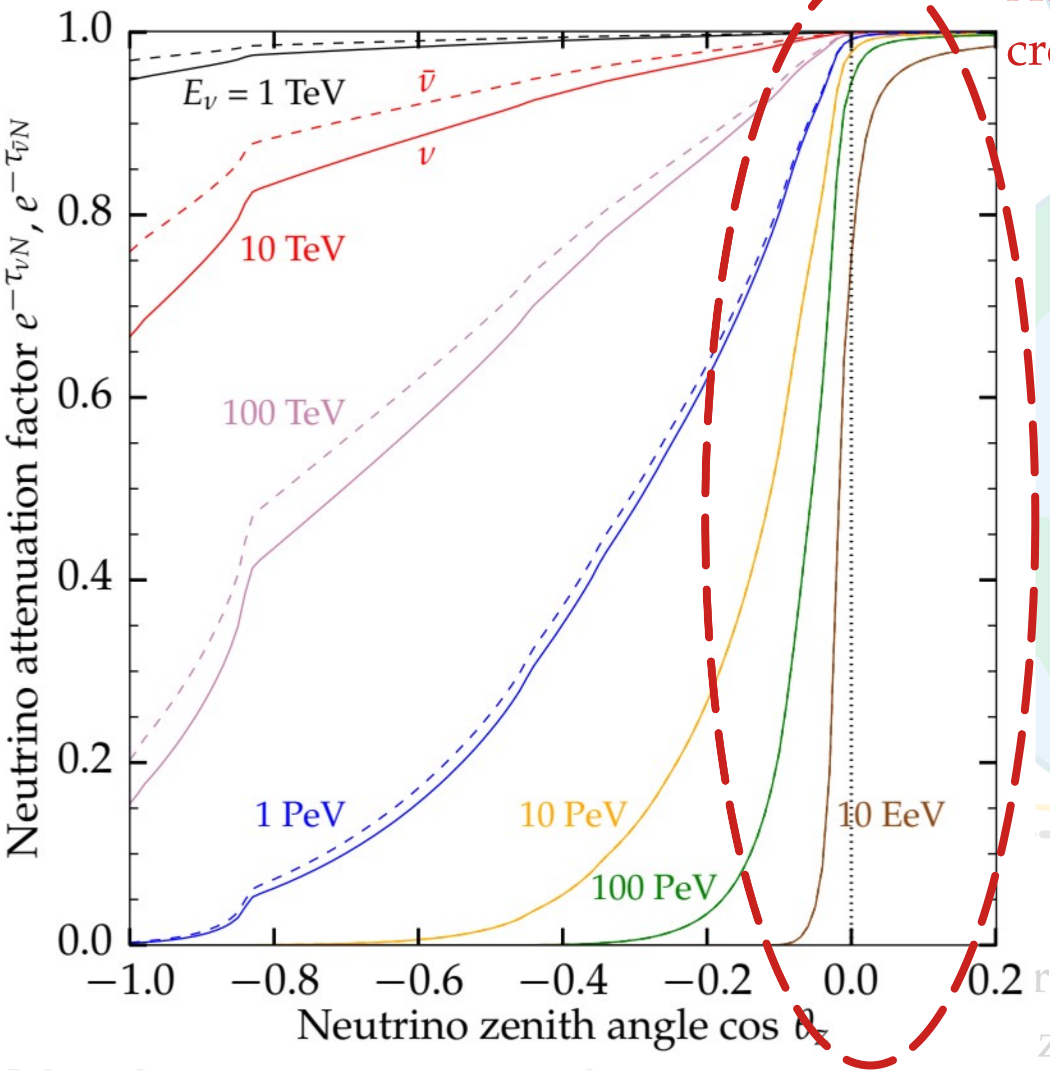
Earth is *completely* opaque,
but horizontal ν still make it through

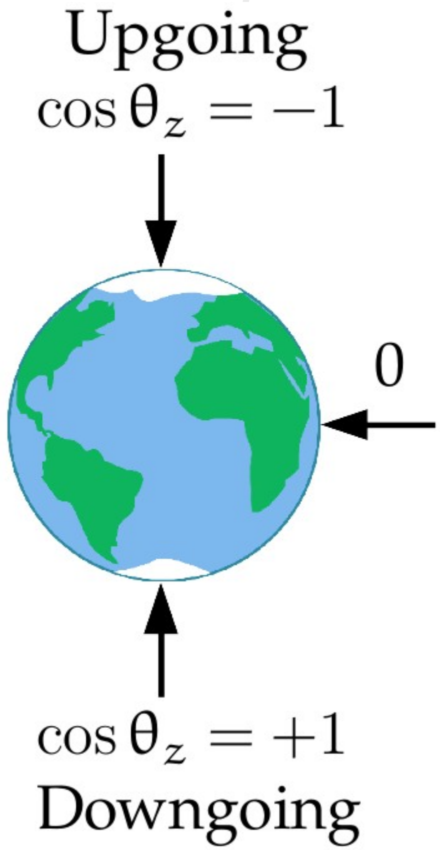
TeV–PeV

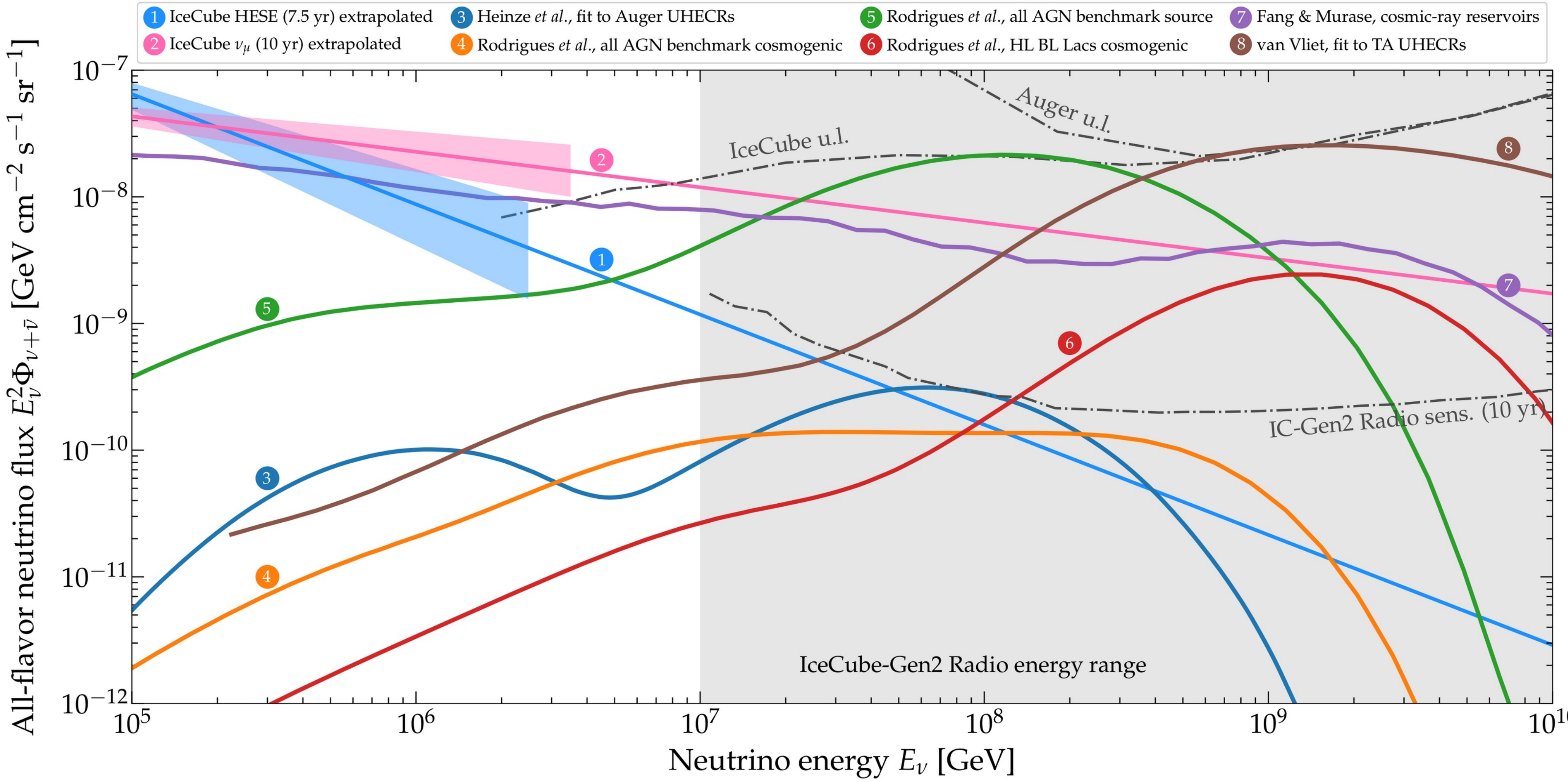


Ea… rth is *completely* opaque,
some … zontal ν still make it through

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





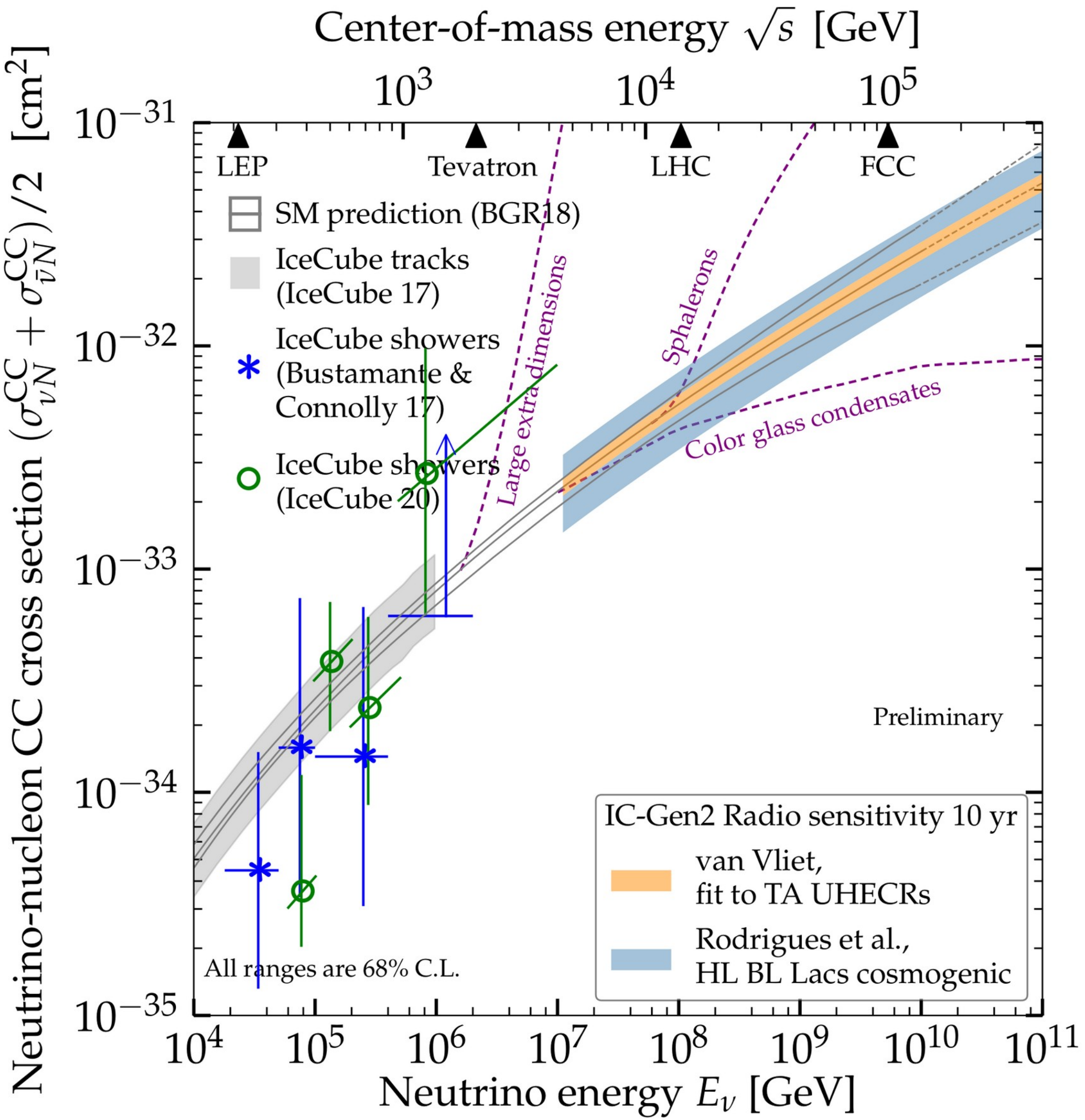


MB, Valera, Glaser, *In preparation*

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

(If the UHE ν fluxes are high)

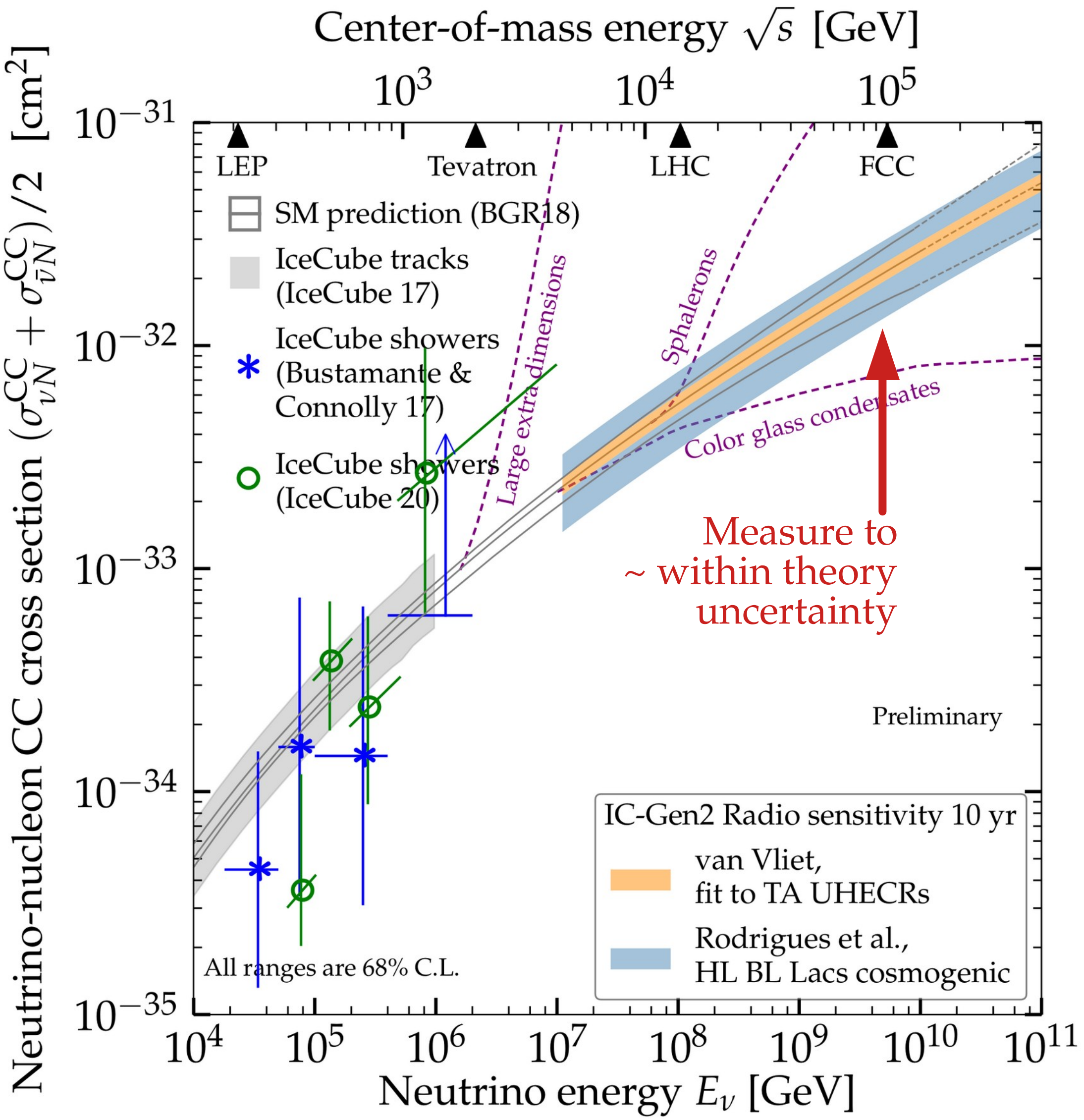
Valera, **MB**, Glaser, *In preparation*



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

(*If the UHE ν fluxes are high*)

Valera, **MB**, Glaser, *In preparation*

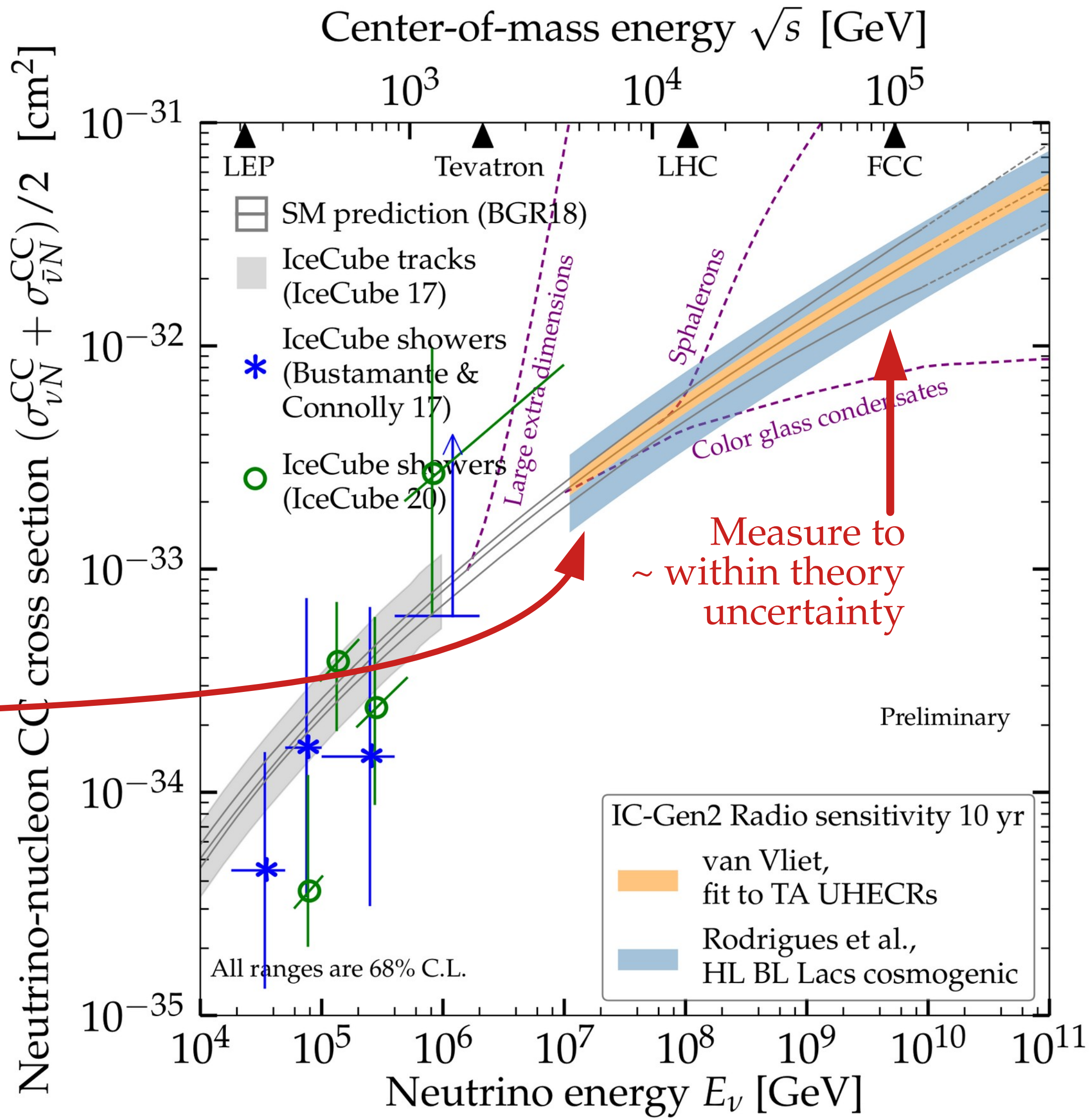


After 10 years of IceCube-Gen2 Radio (~2040):

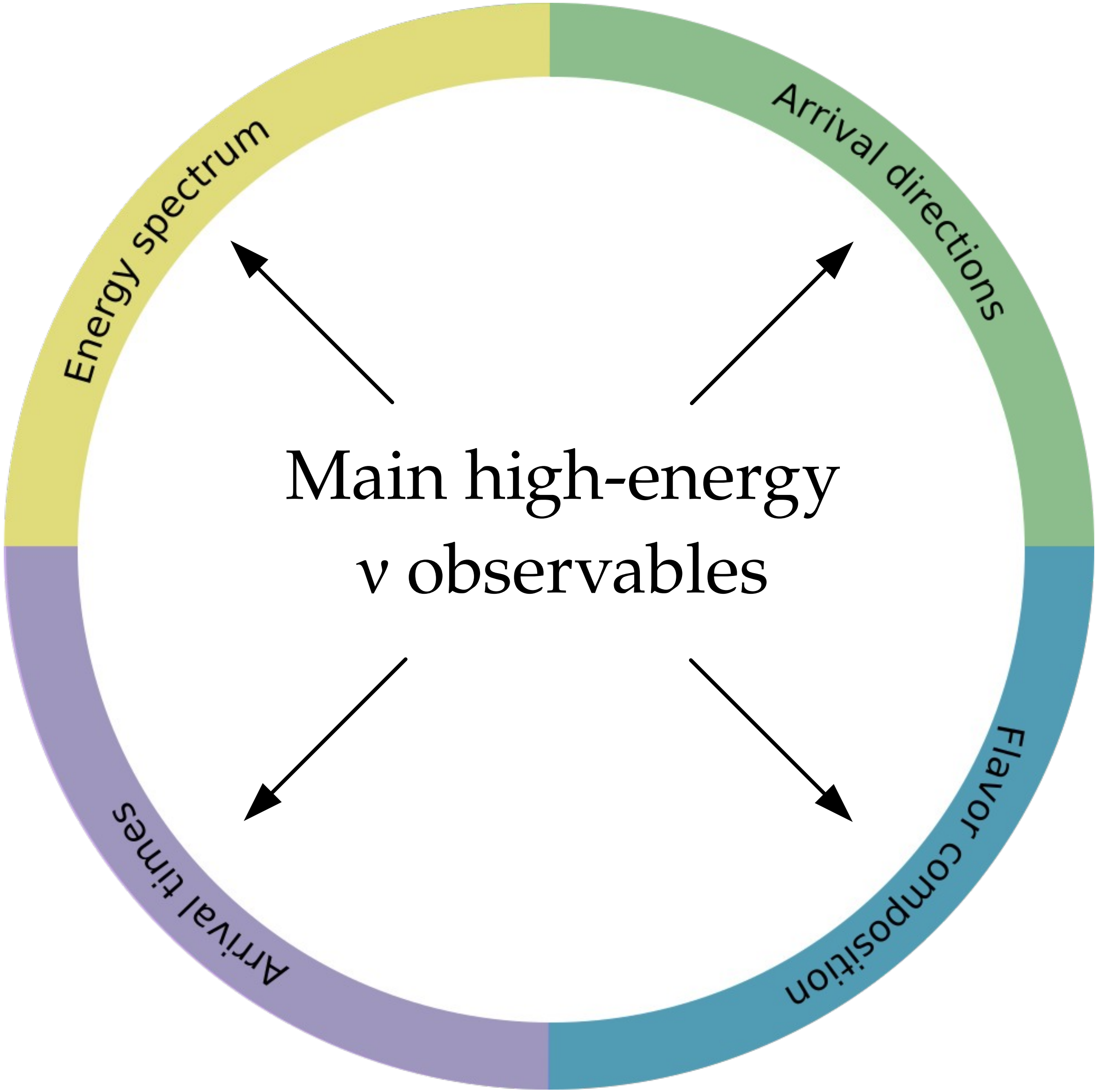
(If the UHE ν fluxes are high)

Valera, **MB**, Glaser, *In preparation*

Work led by
Víctor Valera

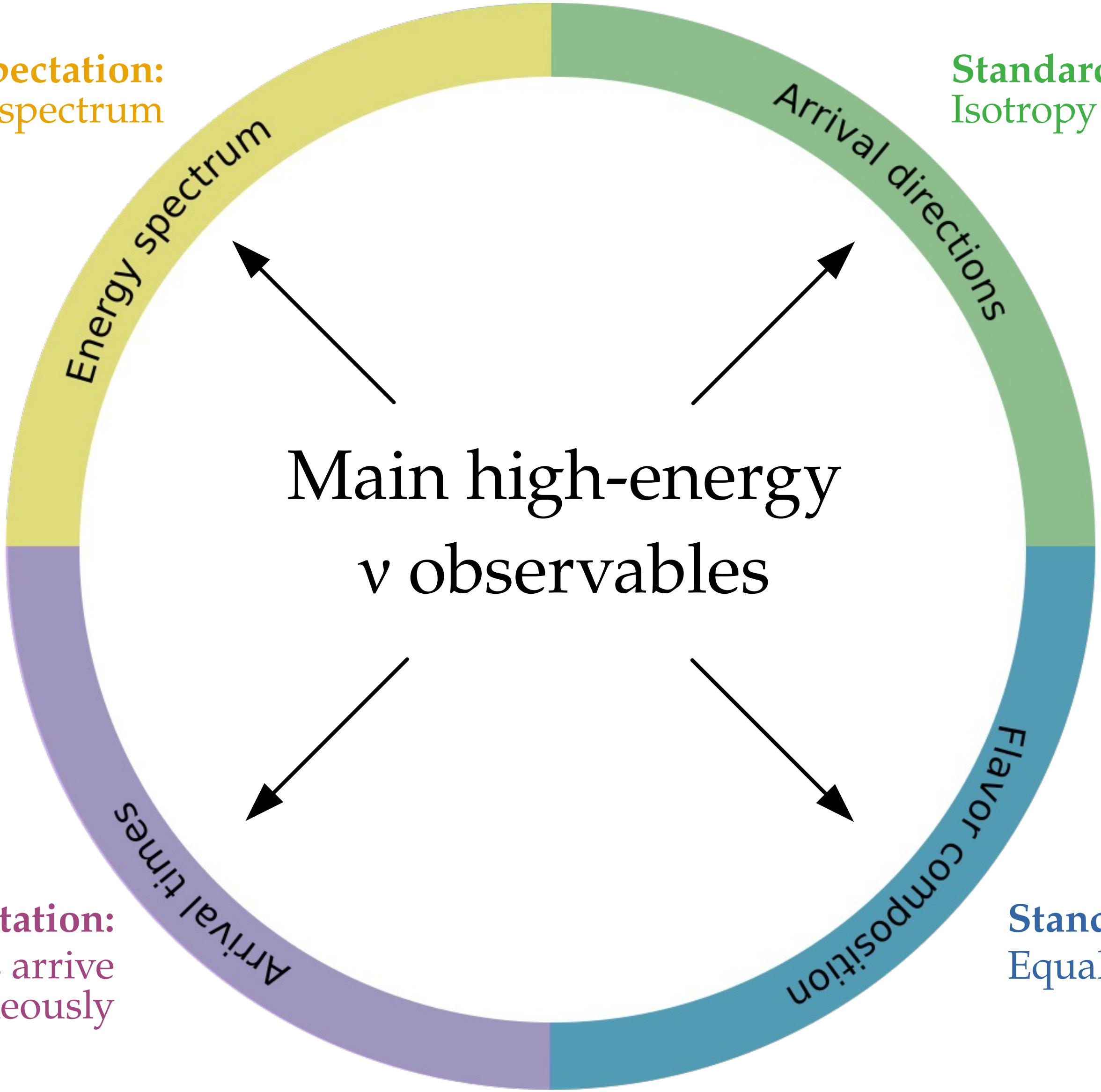


IV.
Testing other
UHE ν BSM models


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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

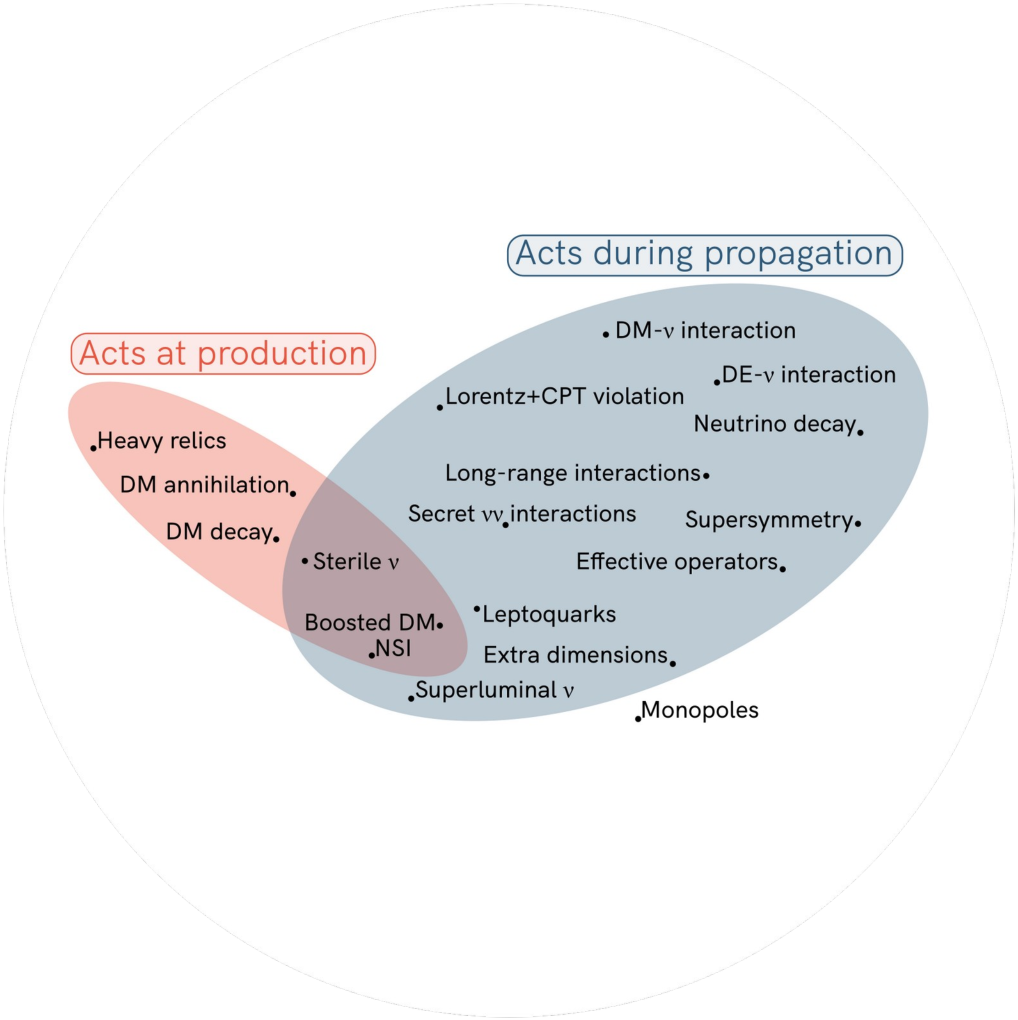


Standard expectation:
ν and γ from transients arrive simultaneously

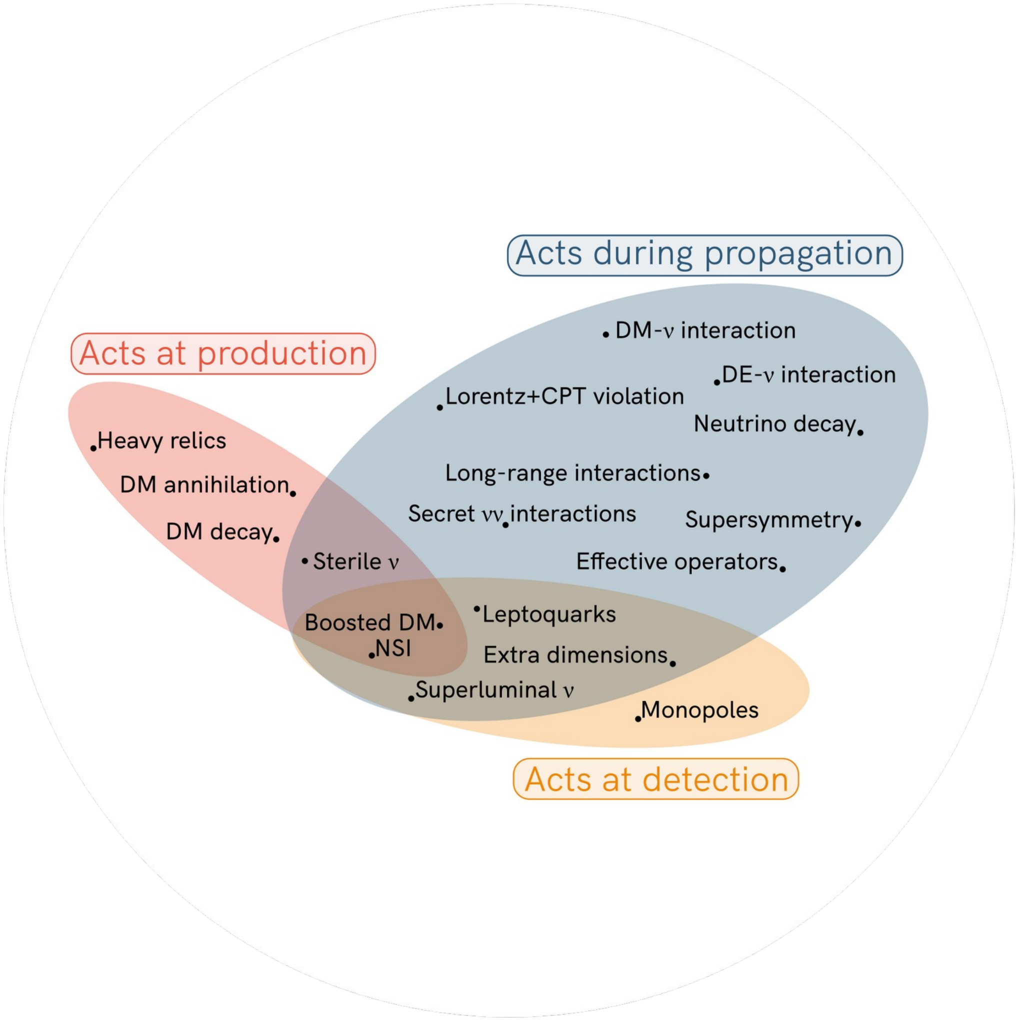
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

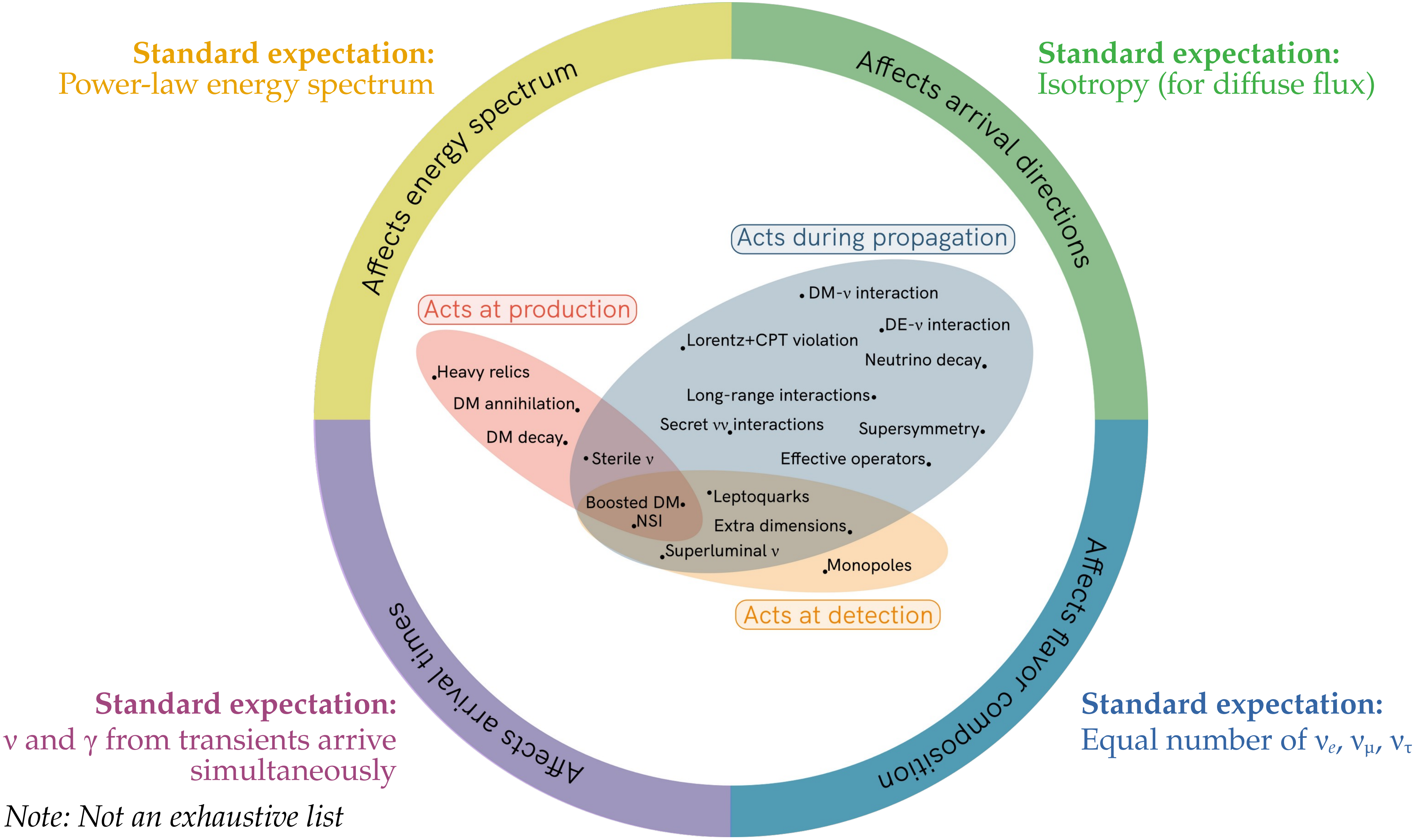
Note: Not an exhaustive list

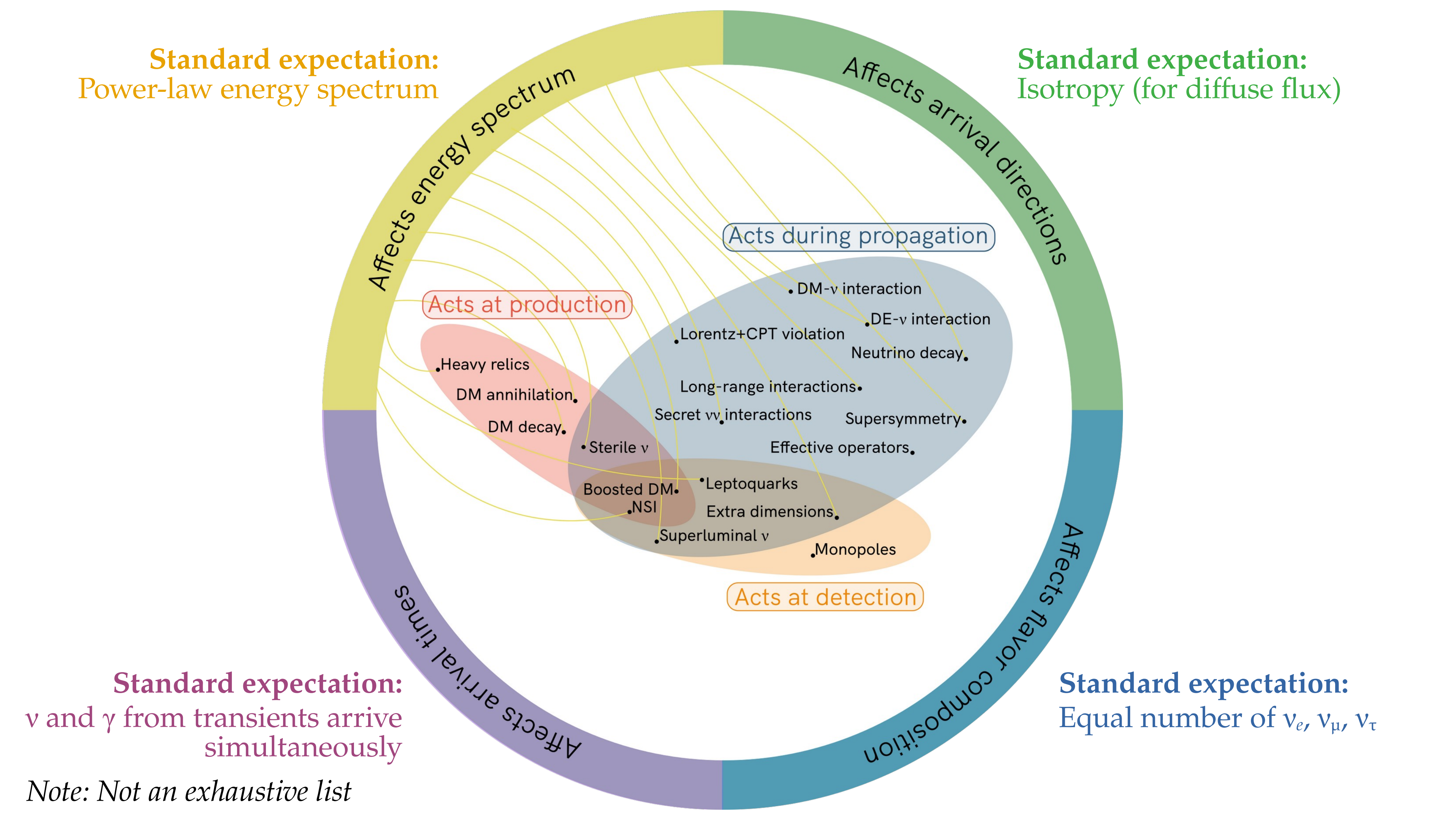


Note: Not an exhaustive list



Note: Not an exhaustive list


Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts during propagation
Acts at production
Acts at detection
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Heavy relics
DM annihilation
DM decay
Long-range interactions
Secret νν interactions
Supersymmetry
Sterile ν
Effective operators
Boosted DM
NSI
Leptoquarks
Extra dimensions
Superluminal ν
Monopoles
Standard expectation:
ν and γ from transients arrive simultaneously
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ
Note: Not an exhaustive list


Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Standard expectation:
ν and γ from transients arrive simultaneously
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ
Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts during propagation
Acts at production
Acts at detection
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Heavy relics
DM annihilation
DM decay
Long-range interactions
Secret νν interactions
Supersymmetry
Sterile ν
Effective operators
Leptoquarks
Boosted DM
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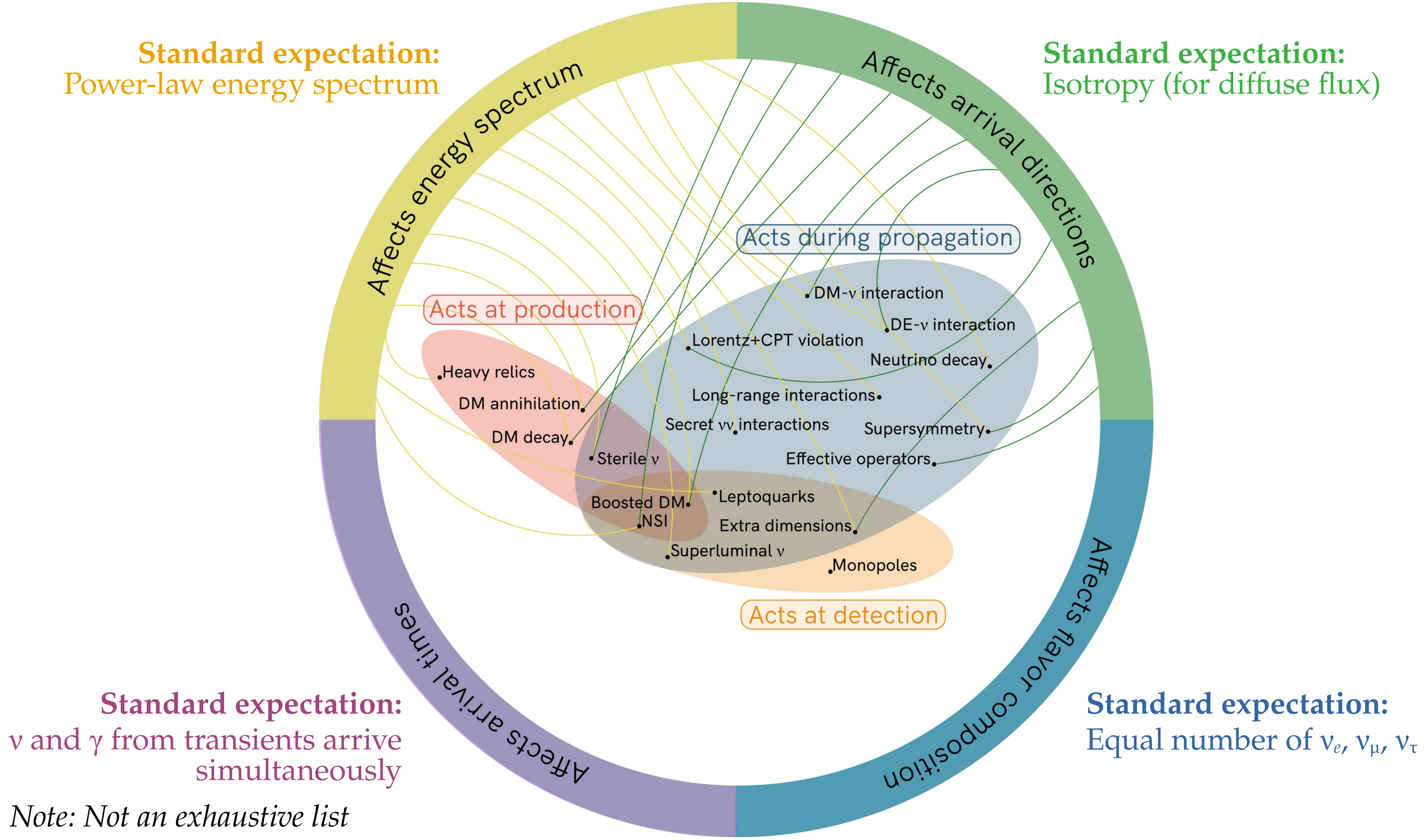
Extra dimensions
Superluminal ν
Monopoles
Note: Not an exhaustive list


Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts during propagation
Acts at production
Acts at detection
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
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Effective operators
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Extra dimensions
Superluminal ν
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Standard expectation:
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Standard expectation:
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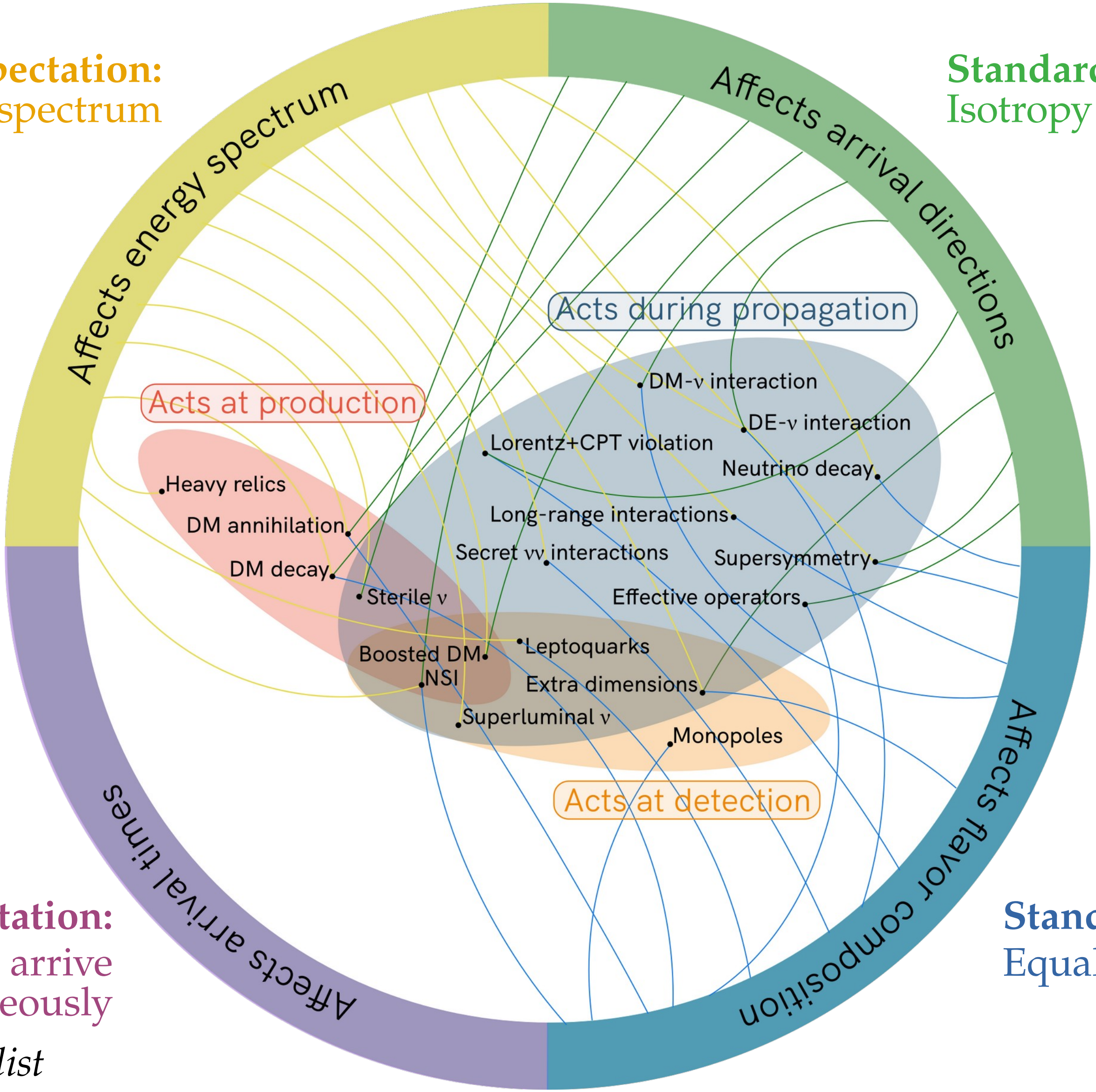
Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



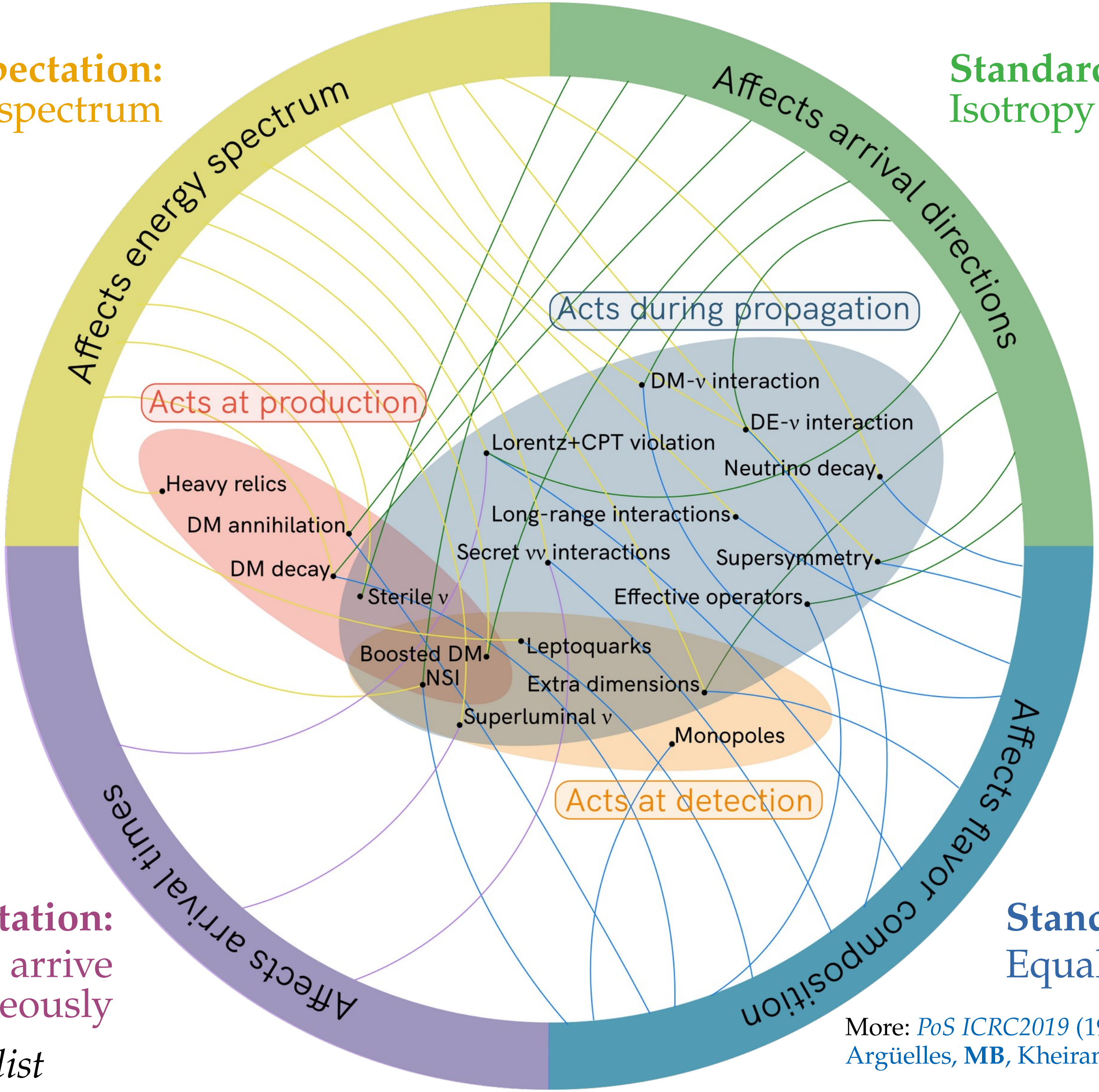
Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

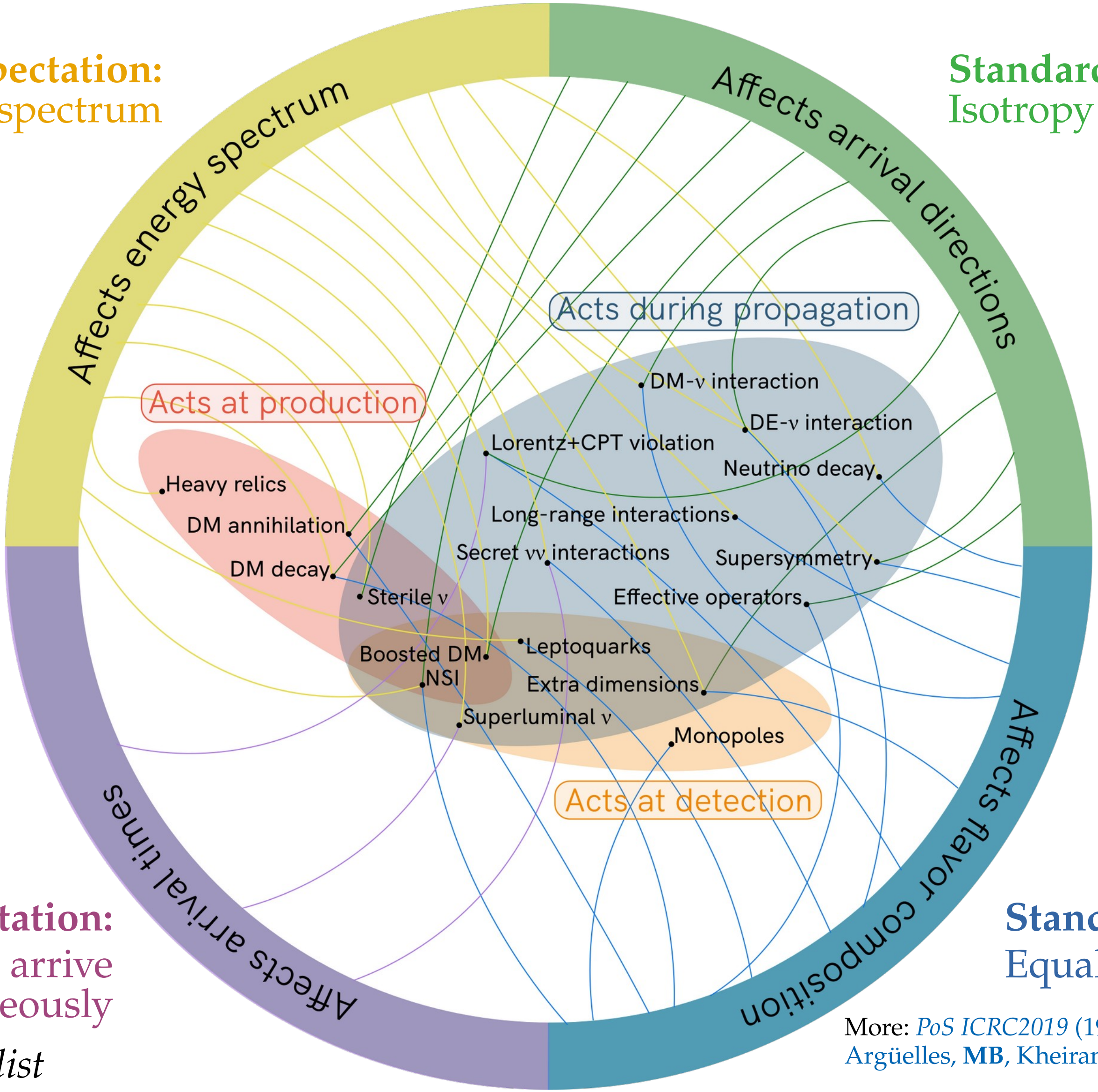
Note: Not an exhaustive list

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

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

Standard expectation:
Power-law energy spectrum

Standard expectation:
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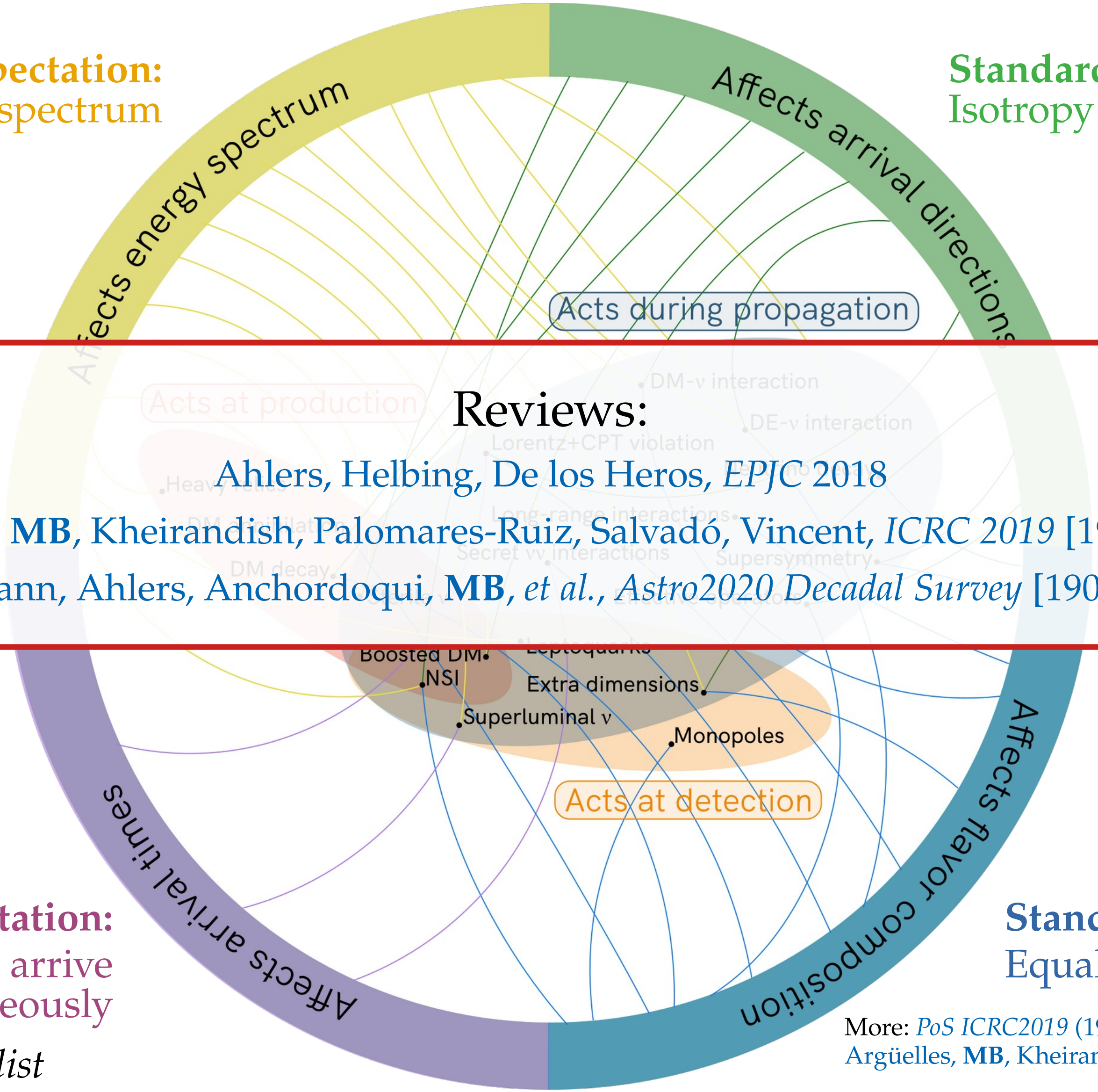


Reviews:

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

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

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

Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

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

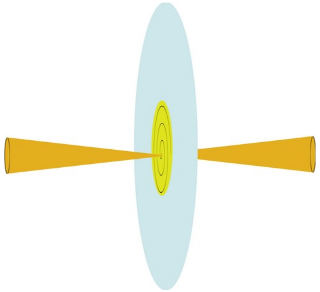
Astrophysical neutrino sources

Earth

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

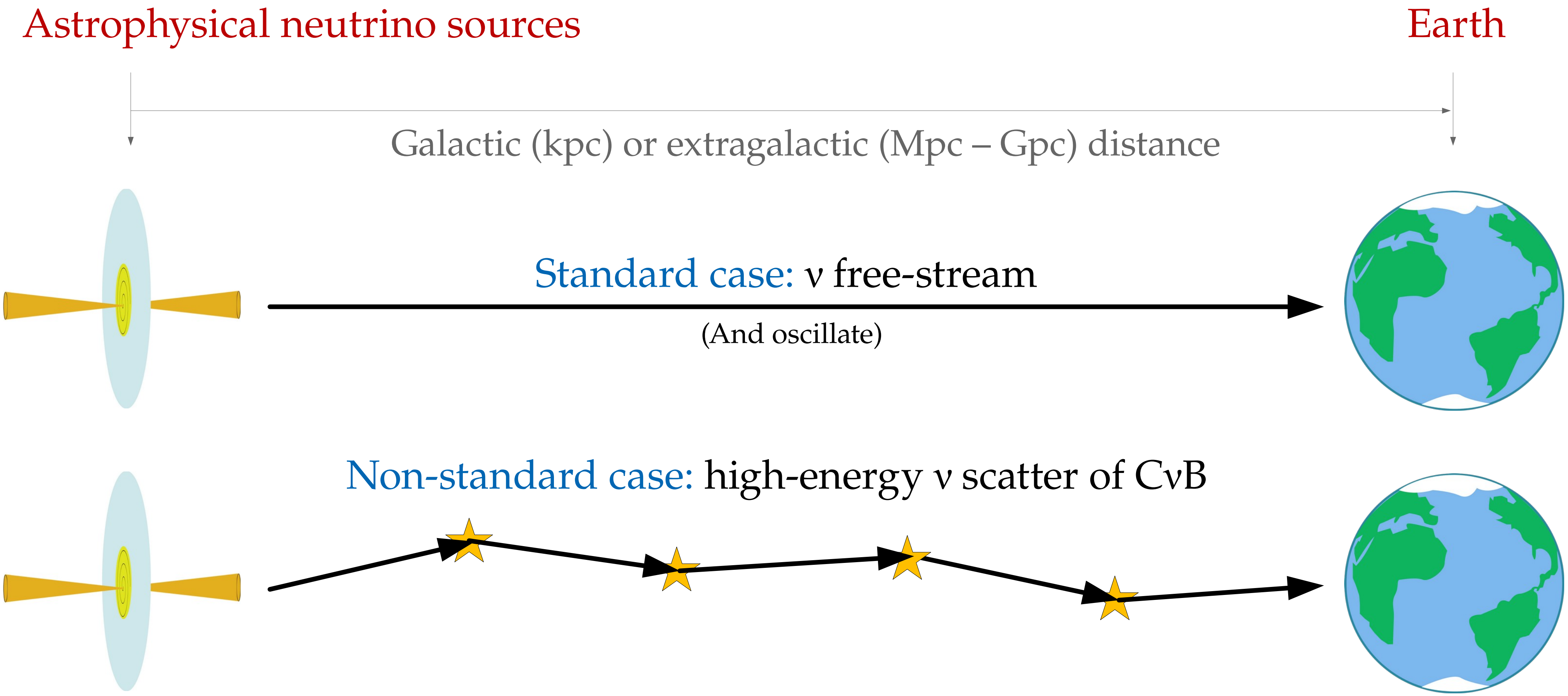
Astrophysical neutrino sources   Earth

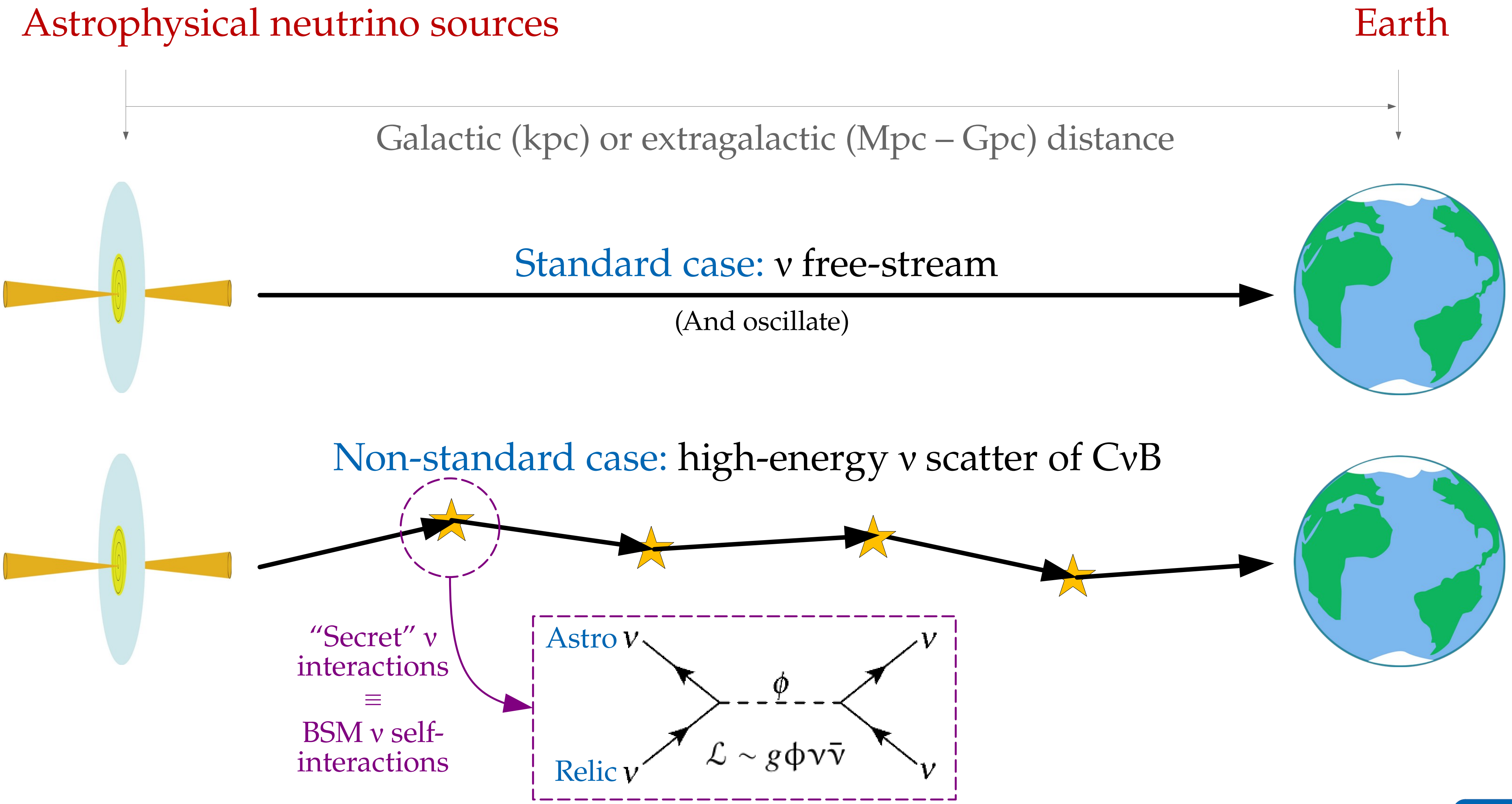
Galactic (kpc) or extragalactic (Mpc – Gpc) distance

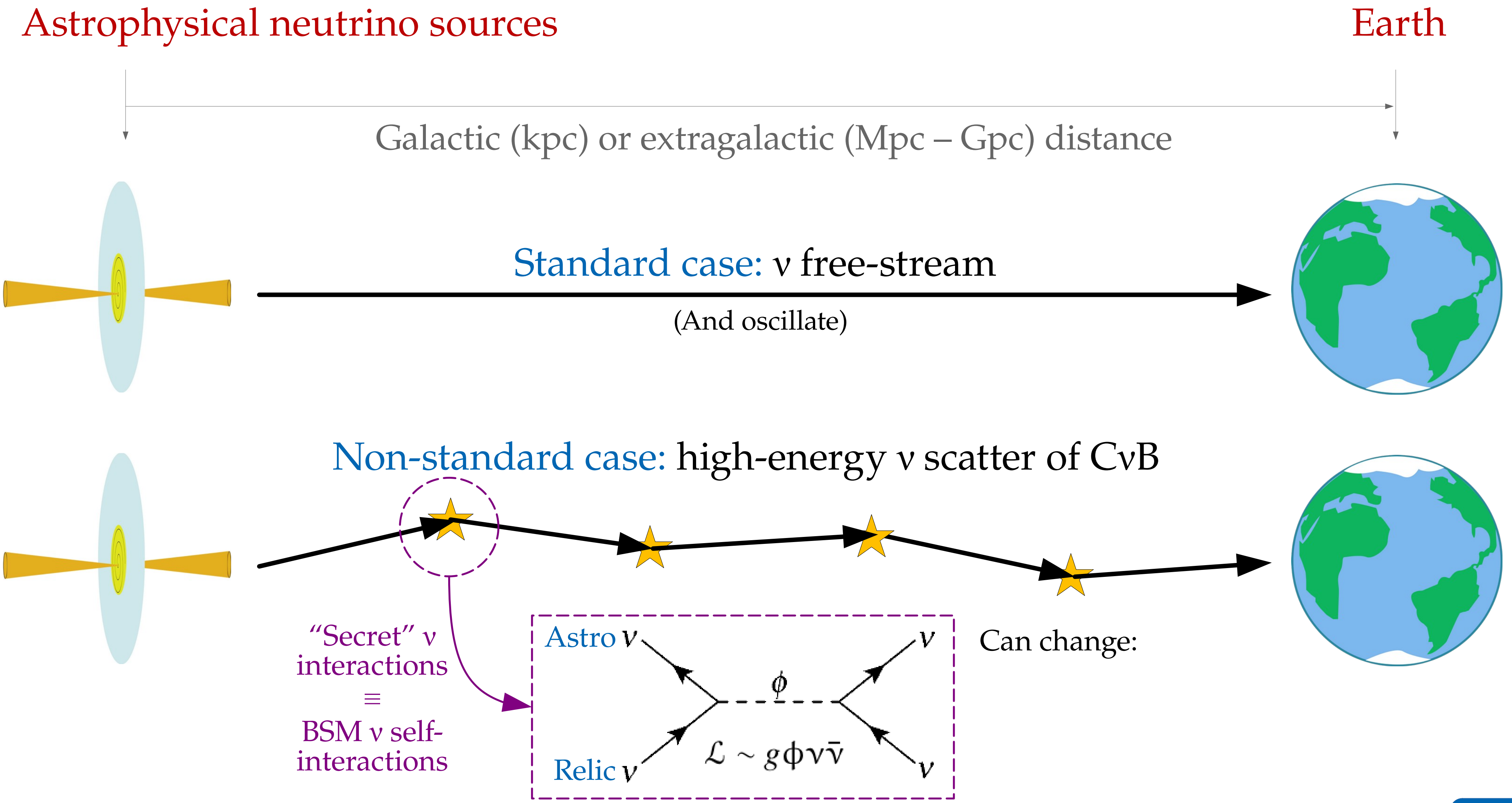


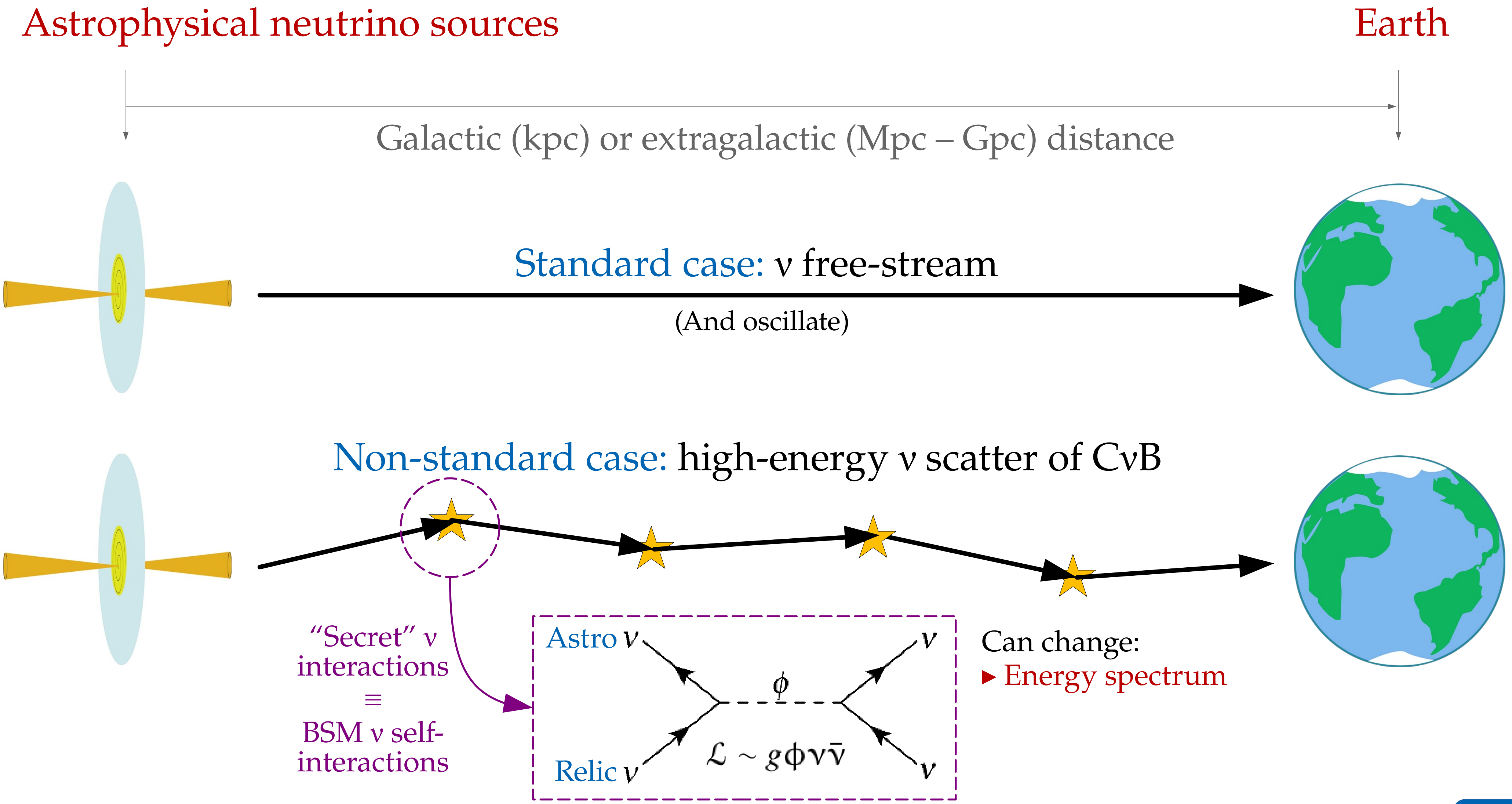
Standard case: ν free-stream

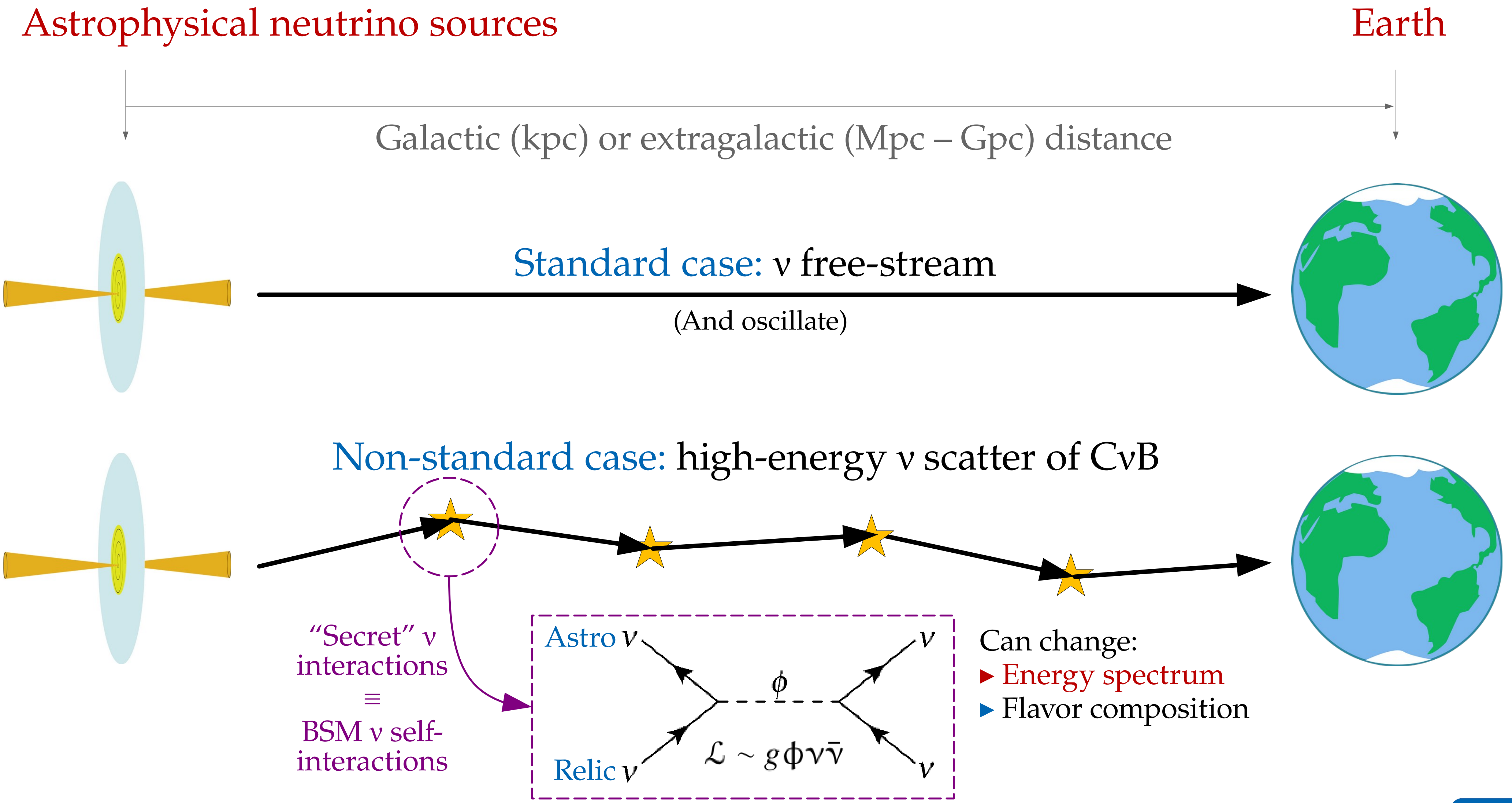
(And oscillate)


Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
(And oscillate)
Non-standard case: high-energy ν scatter of CνB


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
$\mathcal{L} \sim g\phi\nu\bar{\nu}$


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:


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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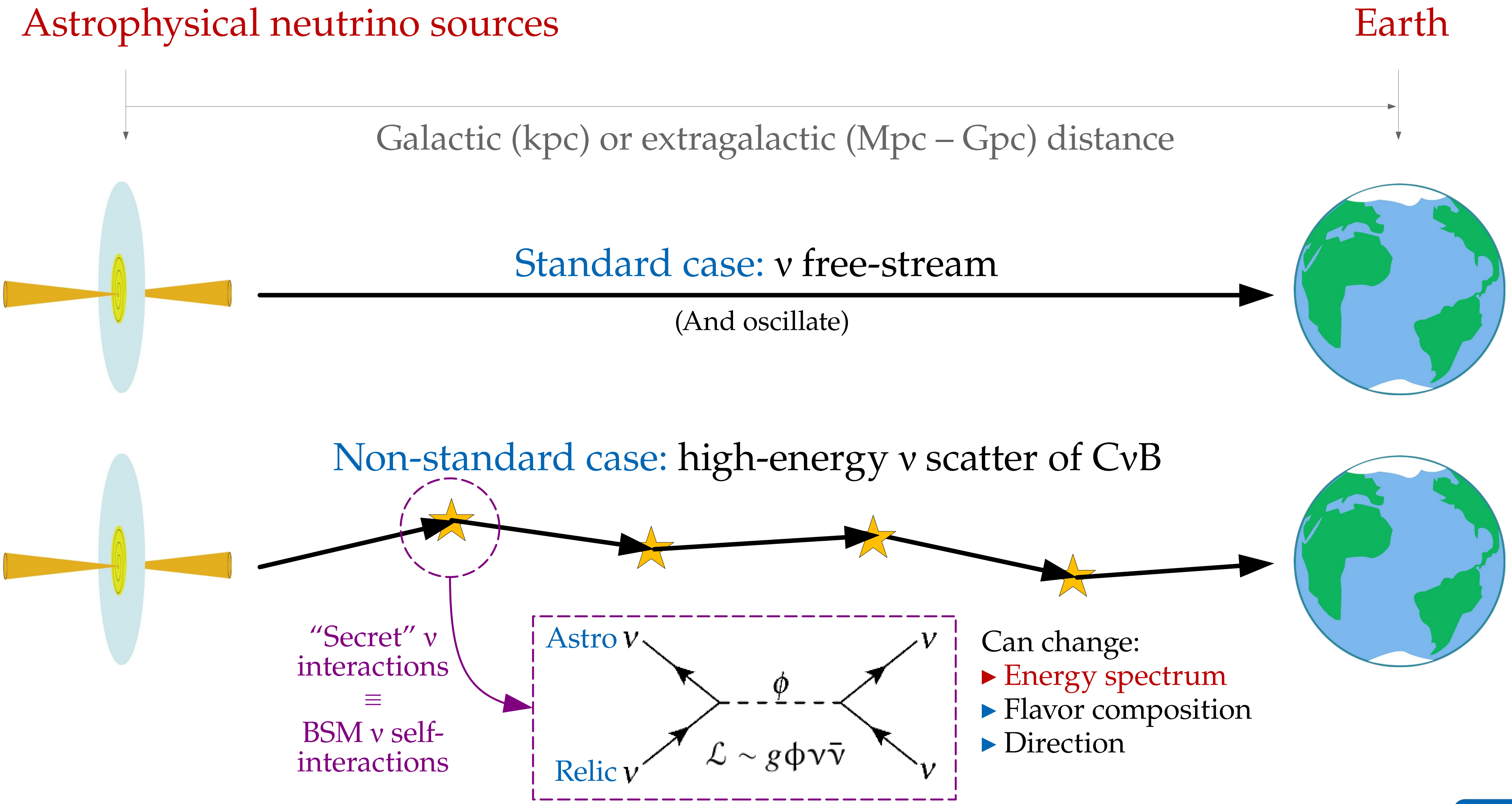
Can change:
▸ Energy spectrum
▸ Flavor composition


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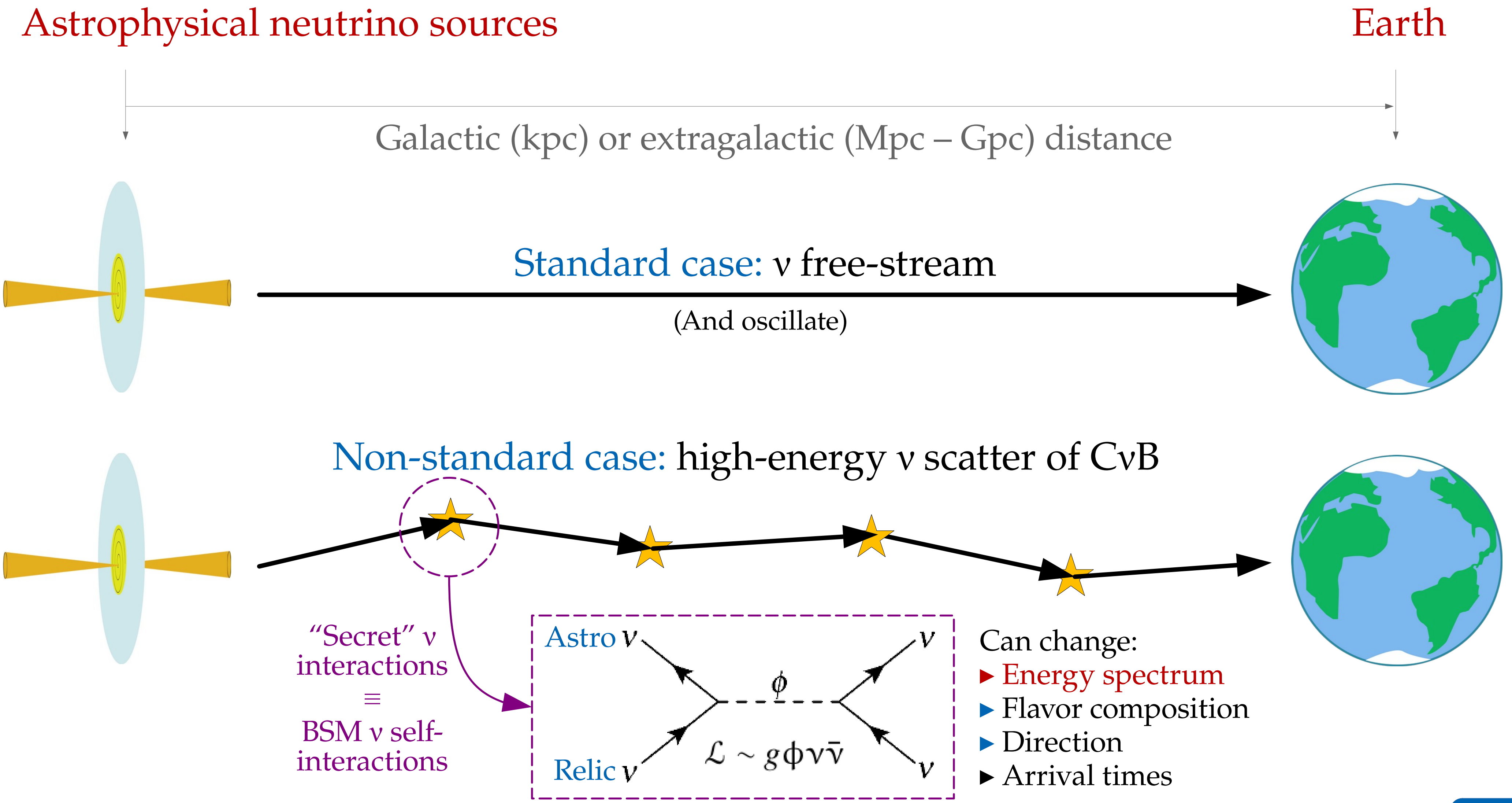
▸ Flavor composition
▸ Direction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$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change:
▸ Energy spectrum
▸ Flavor composition
▸ Direction
▸ Arrival times

νSI with the UHE diffuse flux

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

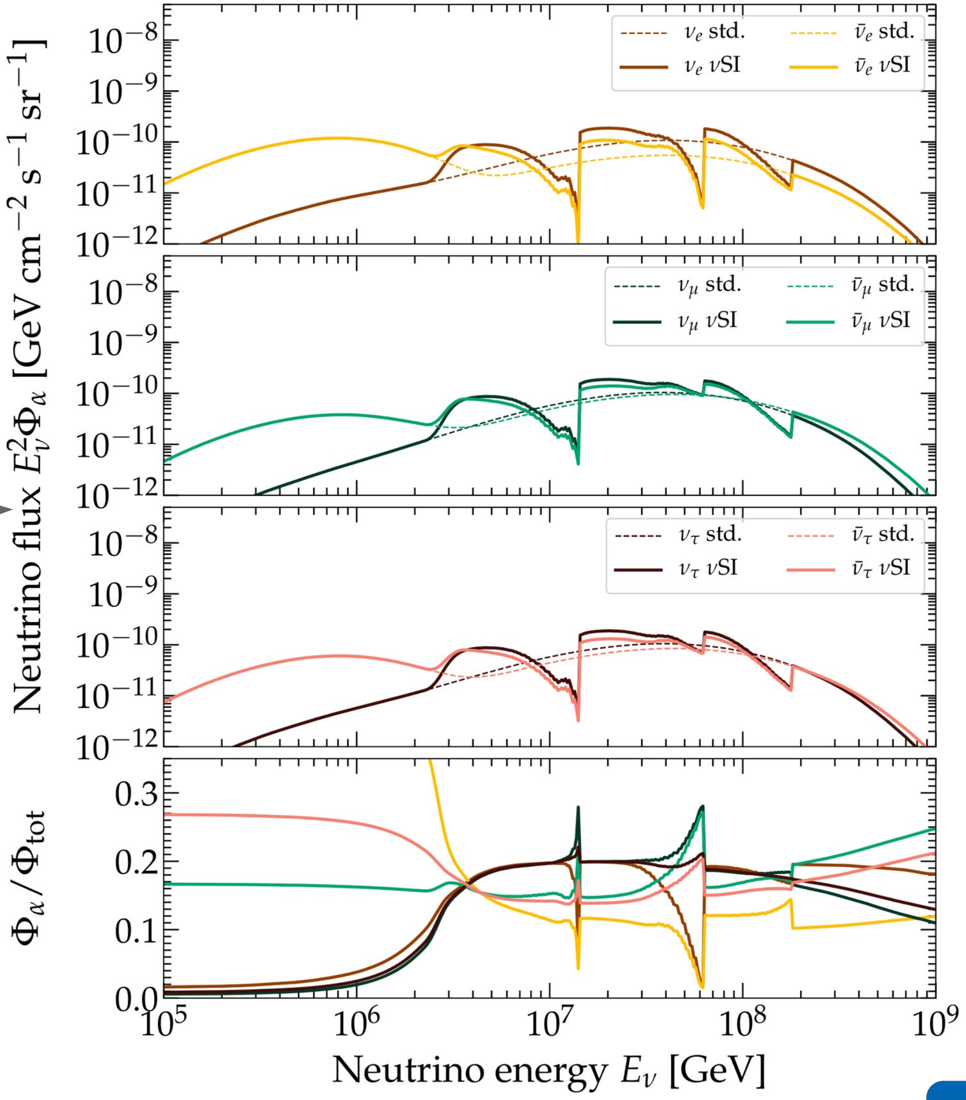
Coupling matrix:

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

Different flavors can have different couplings

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*

V.

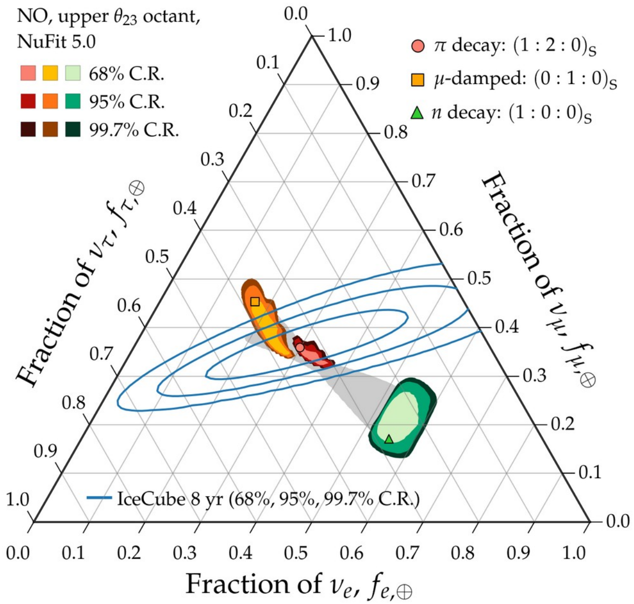
Testing UHE ν physics using flavor ratios

TeV–PeV theoretically palatable regions

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

TeV–PeV theoretically palatable regions

2020



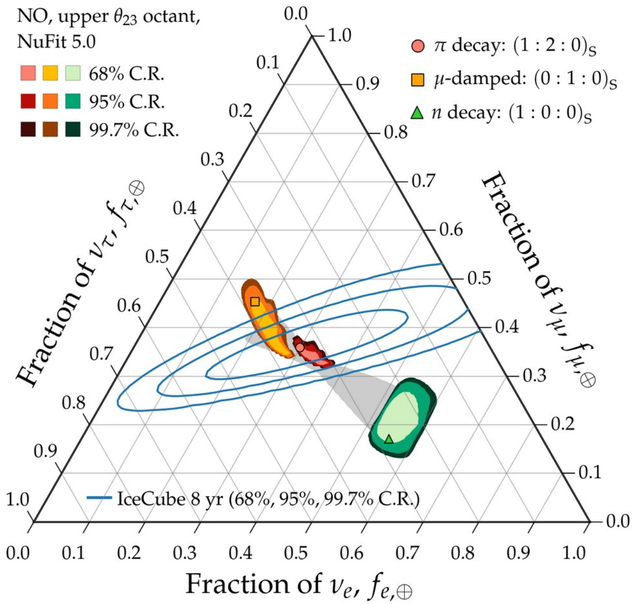
Allowed regions: overlapping

Measurement: imprecise

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

TeV–PeV theoretically palatable regions

2020



Allowed regions: overlapping

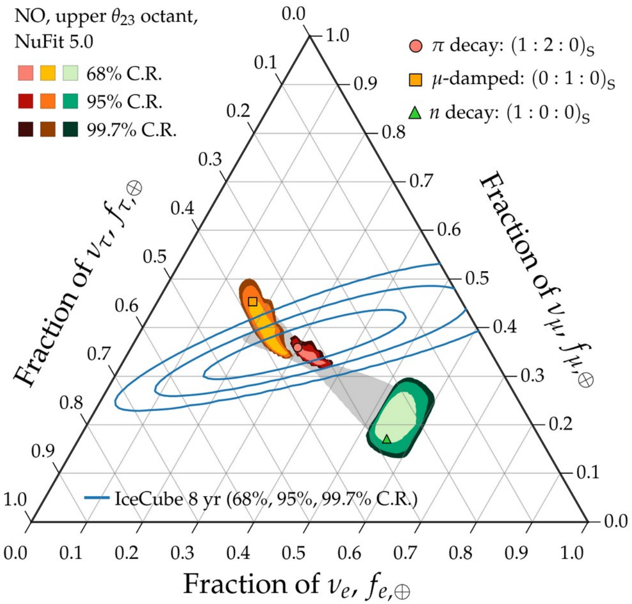
Measurement: imprecise

Not ideal

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

TeV–PeV theoretically palatable regions

2020

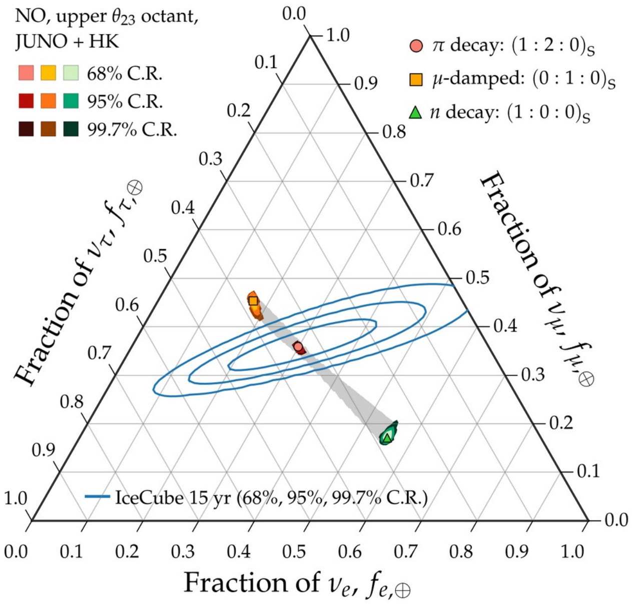


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



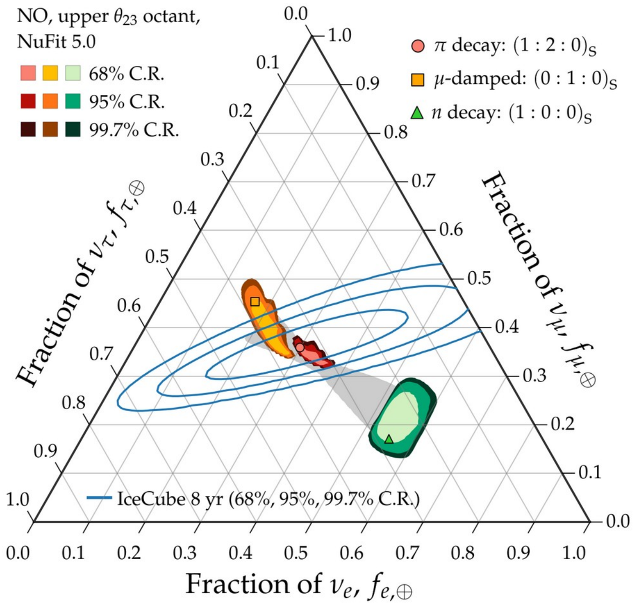
Allowed regions: well separated

Measurement: improving

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

TeV–PeV theoretically palatable regions

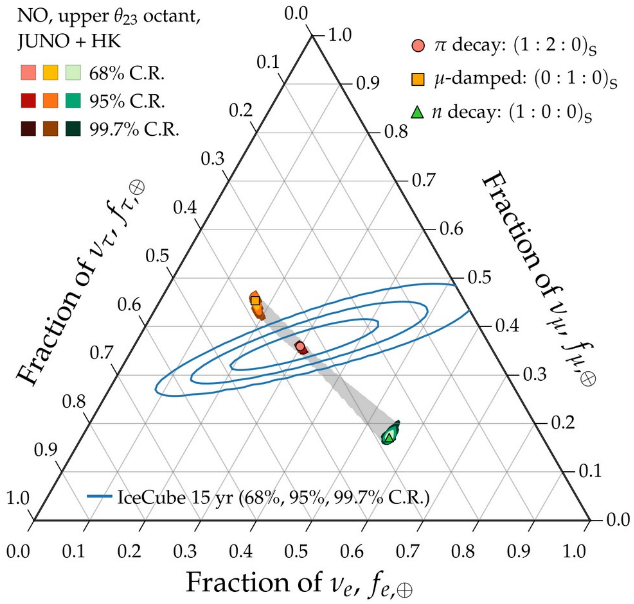
2020



Allowed regions: overlapping
Measurement: imprecise

Not ideal

2030



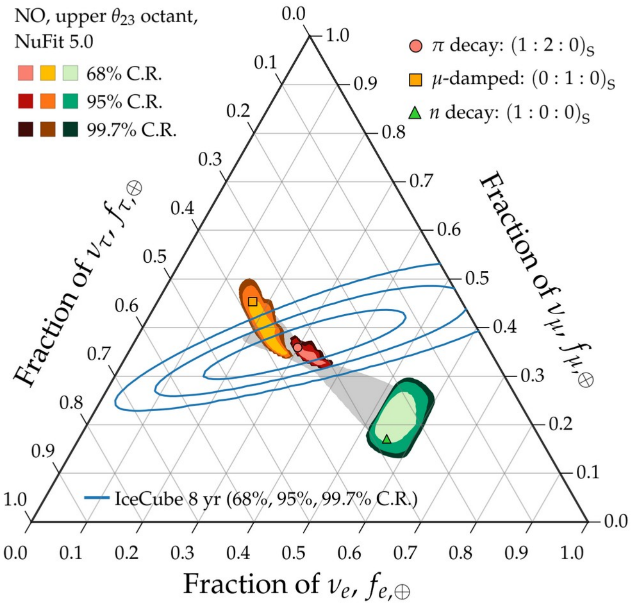
Allowed regions: well separated
Measurement: improving

Nice

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

TeV–PeV theoretically palatable regions

2020



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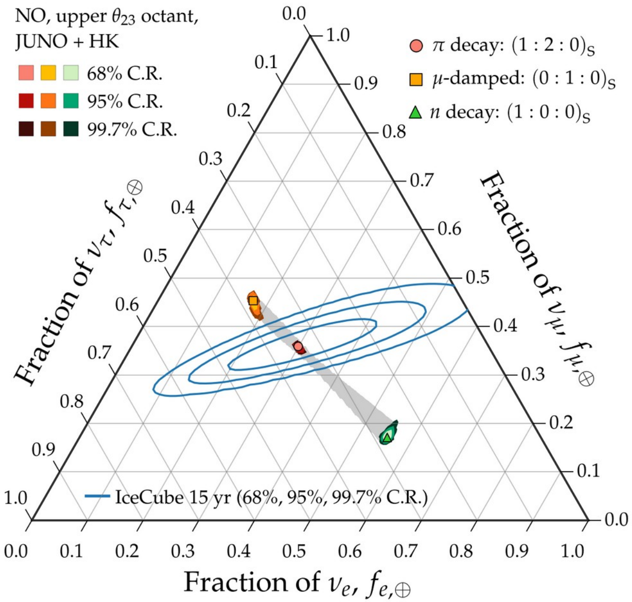
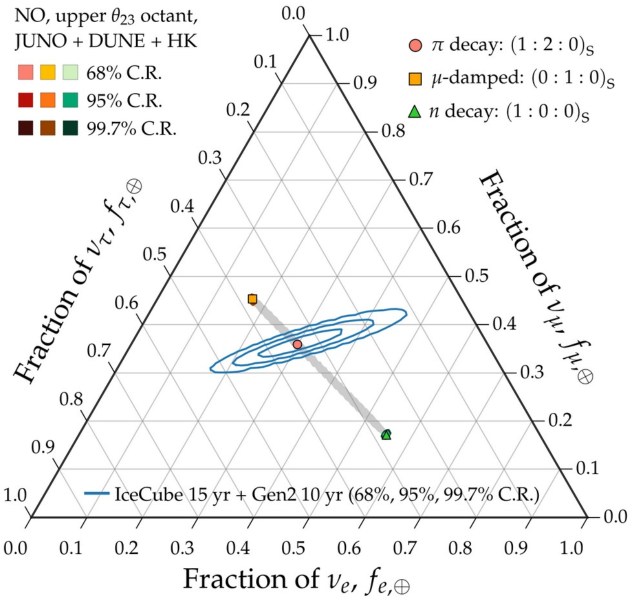


Allowed regions: well separated
Measurement: improving

Nice

2040

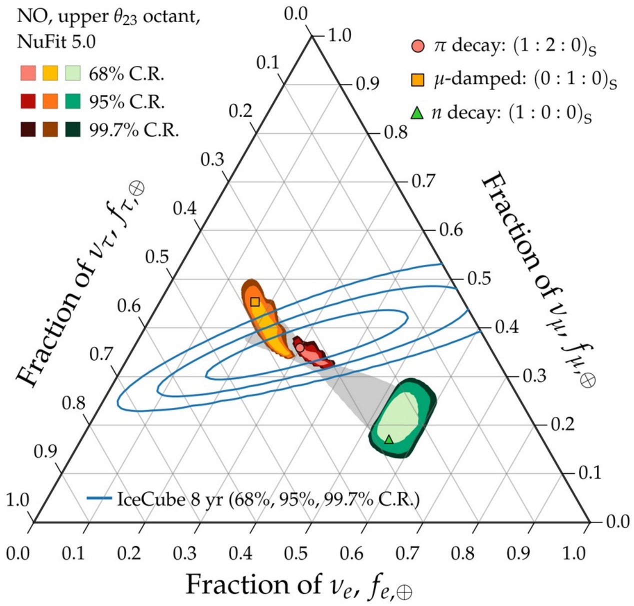


Allowed regions: well separated
Measurement: precise

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

TeV–PeV theoretically palatable regions

2020



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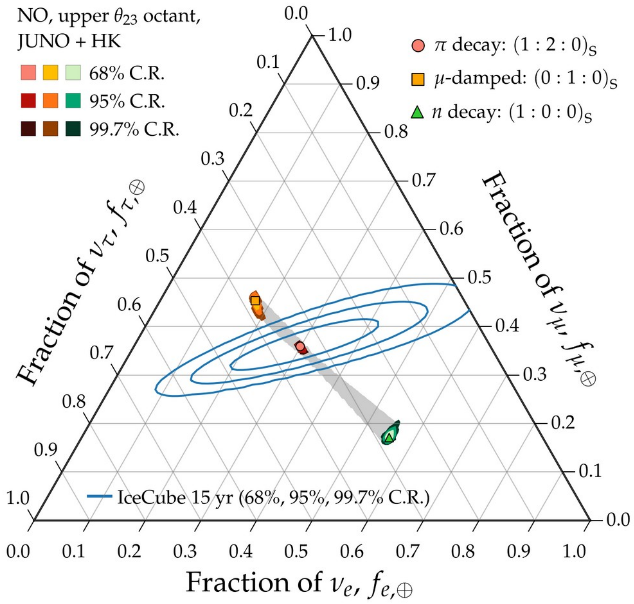

Allowed regions: well separated
Measurement: improving

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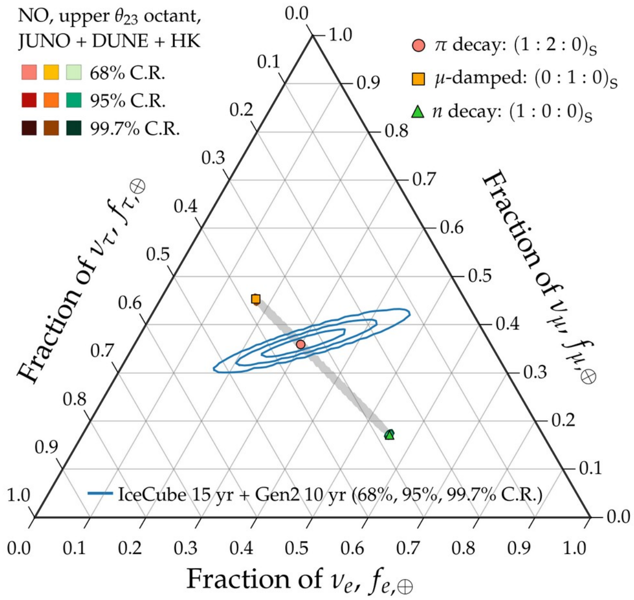
2040



Allowed regions: well separated
Measurement: precise

Success

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

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

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

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

- Neutrino decay
  [Beacom *et al.*, *PRL* 2003; Baerwald, **MB**, Winter, JCAP 2010;
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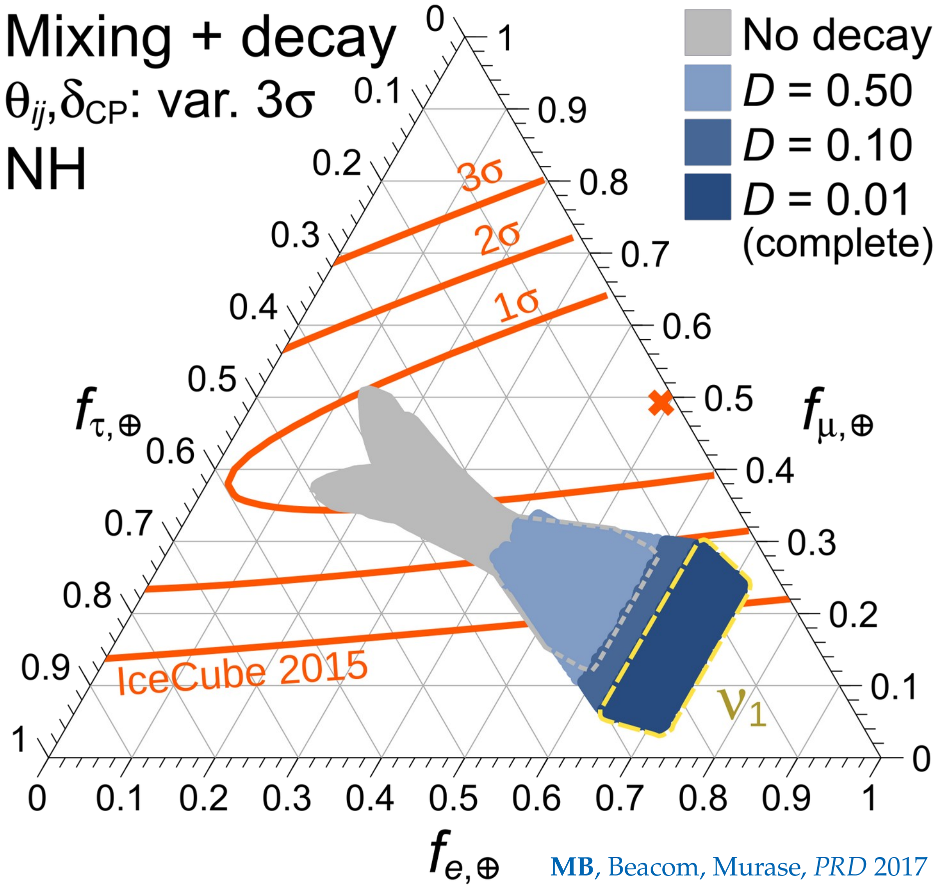

MB, Beacom, Murase, *PRD* 2017

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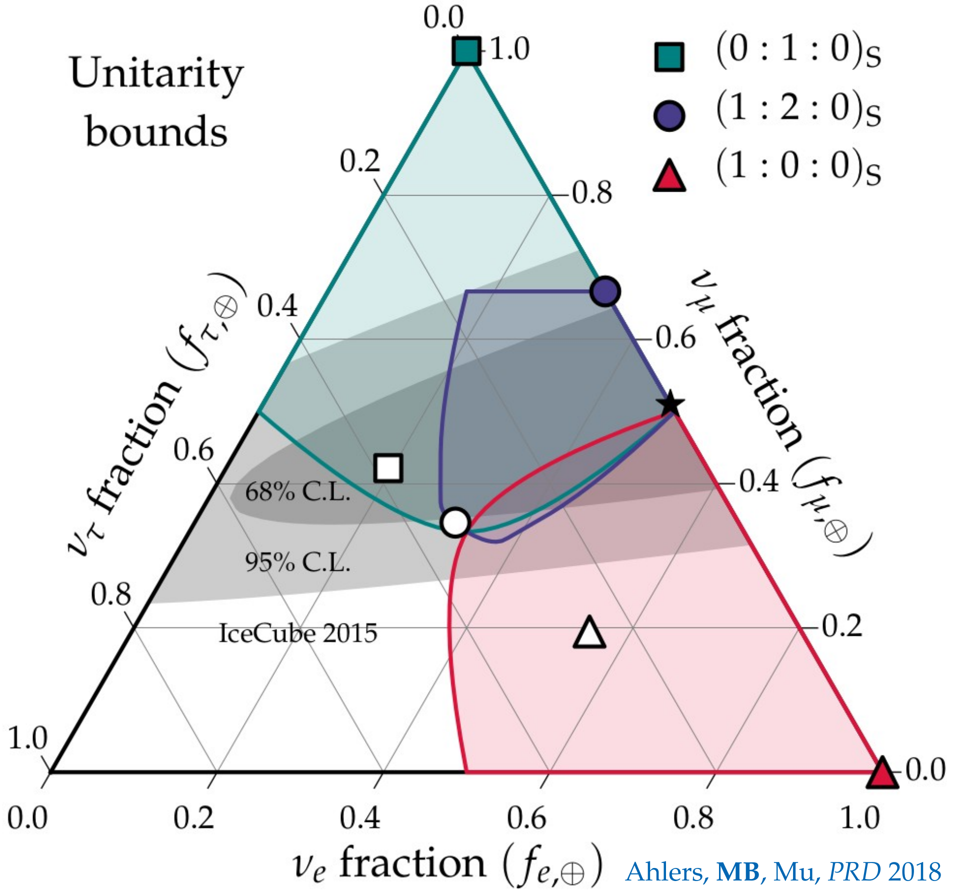
- Tests of unitarity at high energy
  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018; Ahlers, **MB**, Nortvig, *JCAP* 2021]



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

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

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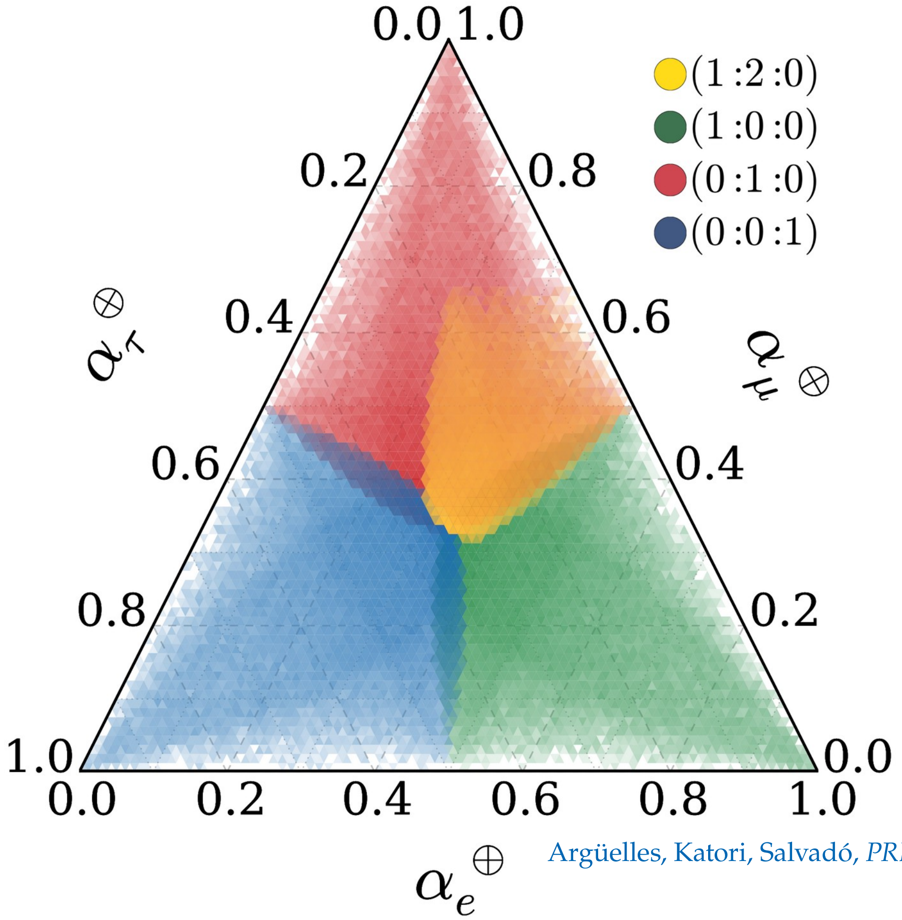

Argüelles, Katori, Salvadó, *PRL* 2015

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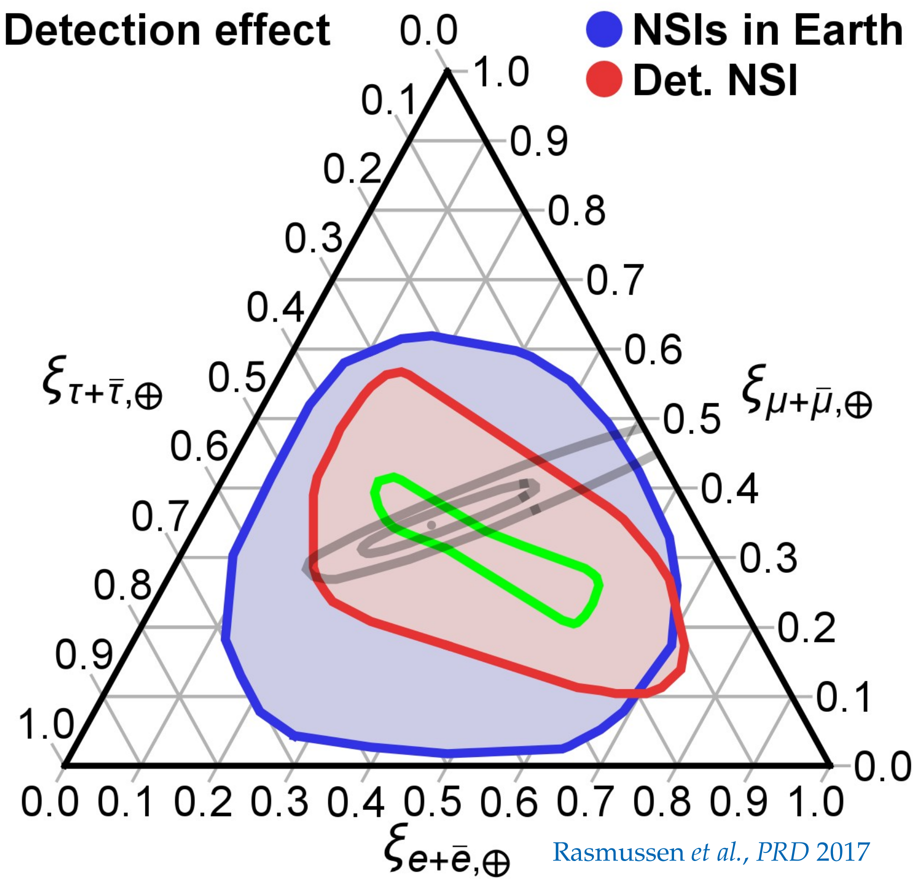

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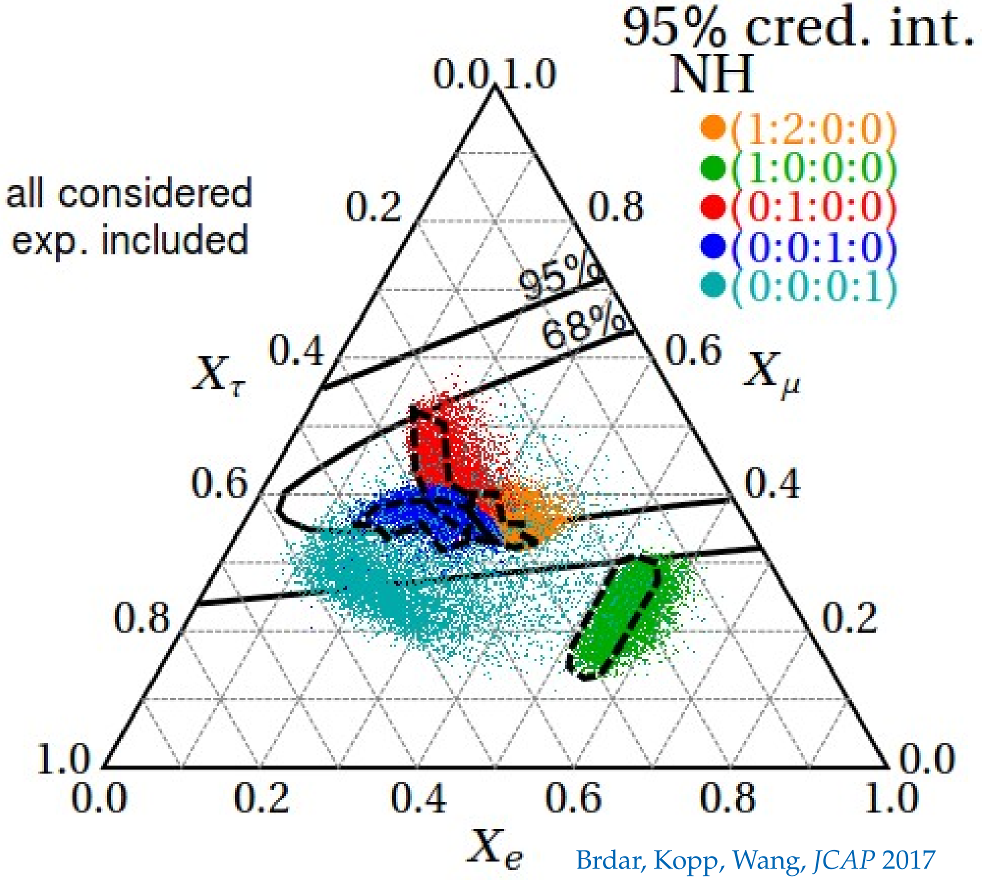

Brdar, Kopp, Wang, *JCAP* 2017

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

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

Reviews:
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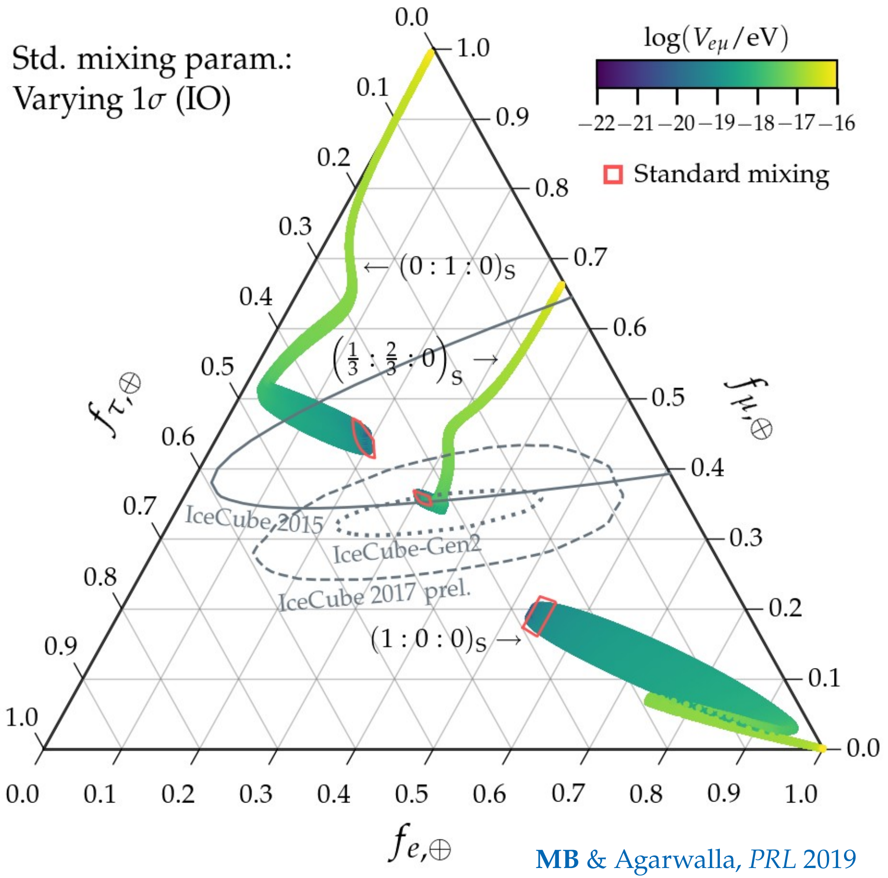

MB & Agarwalla, *PRL* 2019

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- ▶ Tests of unitarity at high energy
  [Xu, He, Rodejo
  Ahlers, **MB**, No
- ▶ Lorentz- a
  [Barenboim & C
  Kostelecky & M
- ▶ Non-stand
  [González-García *et al.*, *Astropart. Phys.* 2016; Rasmussen *et al.*, *PRD* 2017]
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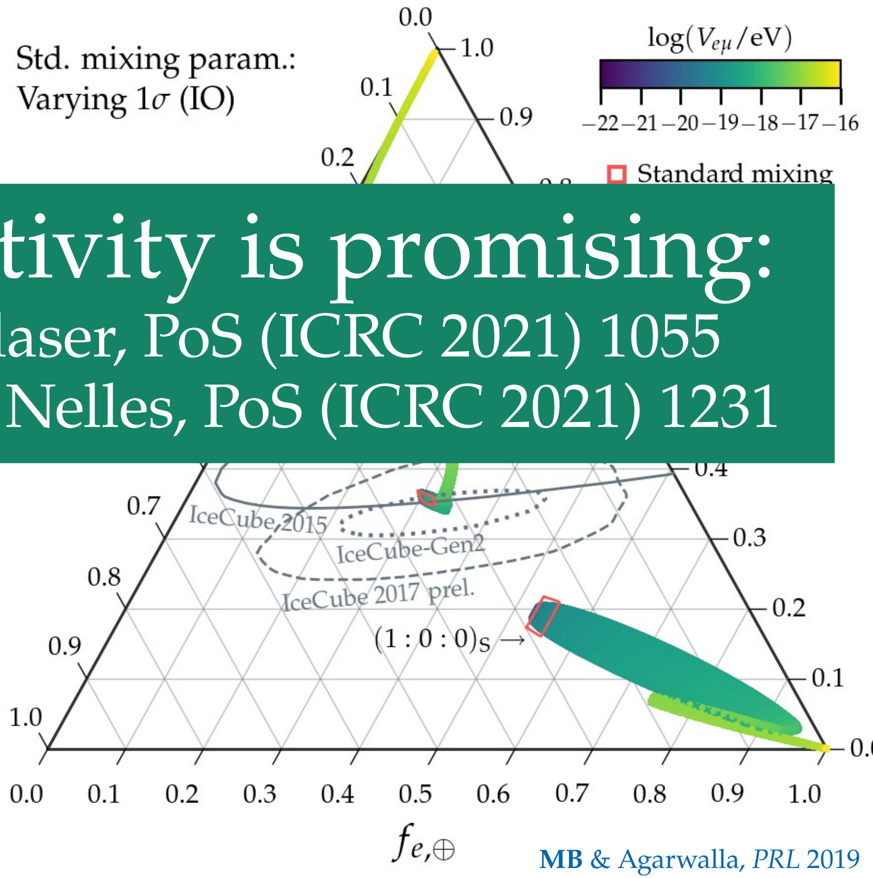


MB & Agarwalla, *PRL* 2019

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

Rough time frames

Five directions

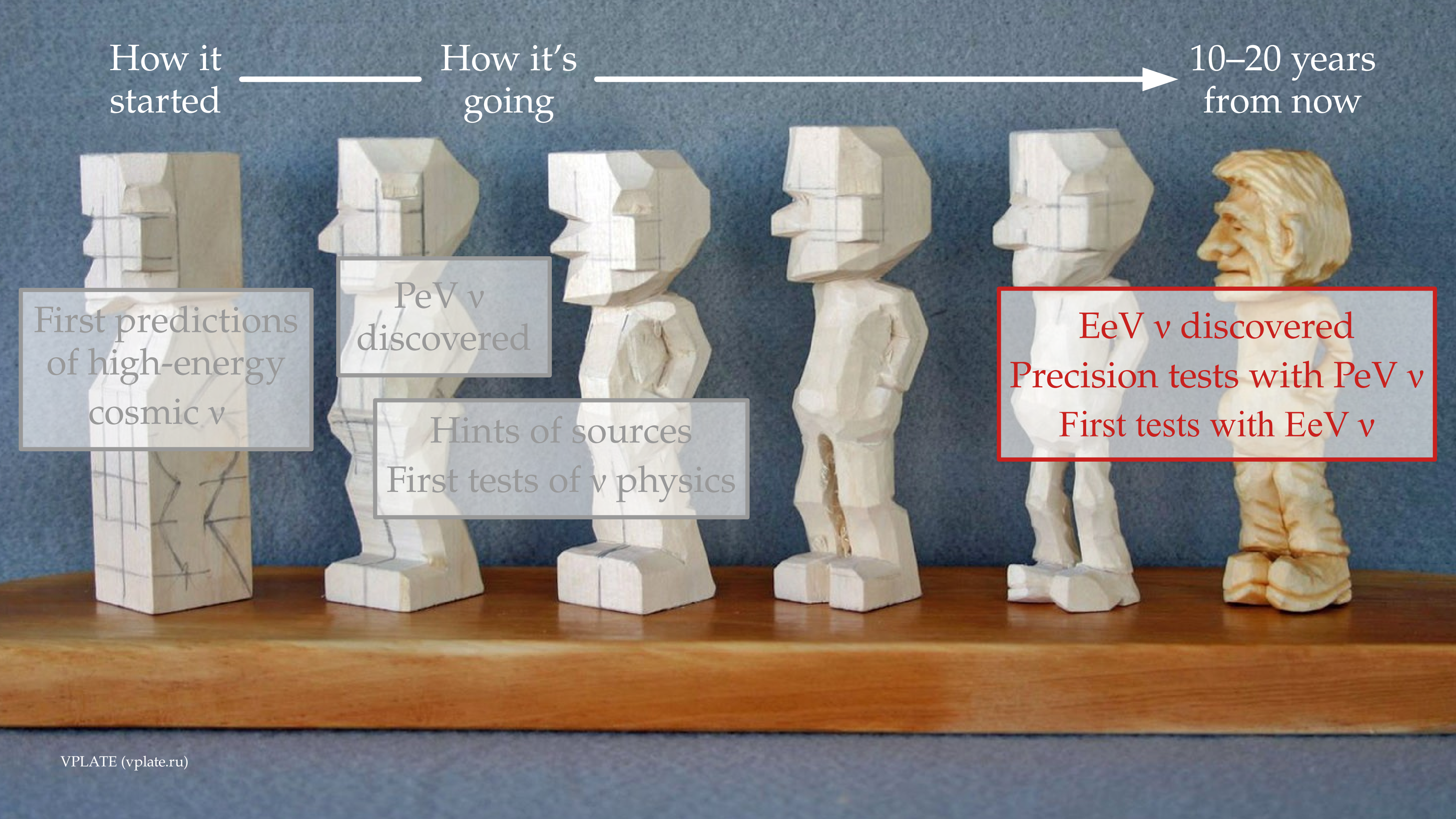
Advanced

Approximate level of progress

(N.B.: All results are preliminary)

Nascent

1. Discovery potential for UHE ν — Late 2021
2. Inferring the spectrum of UHE ν — Late 2021 / Early 2022
3. Measuring the UHE νN cross section — Late 2021
4. Testing other UHE ν BSM models — νSI: Late 2021 / Early 2022
5. UHE ν physics using flavor ratios — ?



VPLATE (vplate.ru)

End

PhD position in high-energy cosmic neutrino physics ← INSPIRE Jobs ad

Bohr Inst. • Europe

astro-ph hep-ph hep-th PhD

Deadline on Oct 31, 2021

Contact:
Mauricio Bustamante (Niels Bohr Institute)
mbustamante@nbi.ku.dk

Job description:
The Niels Bohr International Academy invites applications for a PhD studentship in high-energy neutrino physics with cosmic neutrinos.

The preferred starting date is April 01, 2022 (earlier dates can be discussed).

Applicants are requested to submit their electronic applications including a cover letter, CV, research statement, BSc and MSc academic transcripts, and two reference letters via AcademicJobsOnline. Please see application instructions below.

In order to receive full consideration, complete applications should be received by **October 31, 2021**.

Pushing neutrino physics to the cosmic frontier

What is Nature like at its most fundamental level? What are its building blocks and how do they interact? What are its organizing principles? These questions lie at the core of Physics, science, and human curiosity. During the last century, we steadily found deeper answers, using increasingly powerful particle accelerators that revealed fundamental particles, interactions, and symmetries. Yet, ample territory remains unexplored at higher energies, ripe for discoveries.

Today, accelerators still churn out valuable data, but, so far, fail to guide us in furthering our view of fundamental physics. Observing particle processes at higher energies would provide guidance, but they lie beyond the reach of accelerator technology. Fortunately, Nature itself provides a way forward: we must turn from man-made particle accelerators to naturally occurring cosmic accelerators. These are extreme phenomena---exploding and colliding stars, black holes---that emit particles with energies millions of times higher than man-made accelerators. Among these, neutrinos stand out as incisive probes of particle physics.

During your PhD, you will learn how to harness the vast potential of high-energy cosmic neutrinos to unearth the particle physics that awaits at the highest, unexplored energies. You will look especially for signs of new physics, beyond the Standard Model.

The principal supervisor will be Assistant Prof. Mauricio Bustamante (INSPIRE profile) at the Niels Bohr International Academy. Your PhD will be part of the project “Pushing Neutrino Physics to the Cosmic Frontier”, funded by the Villum Fonden (project no. 29388).