Secret interactions of UHE neutrinos with POEMMA

Mauricio Bustamante

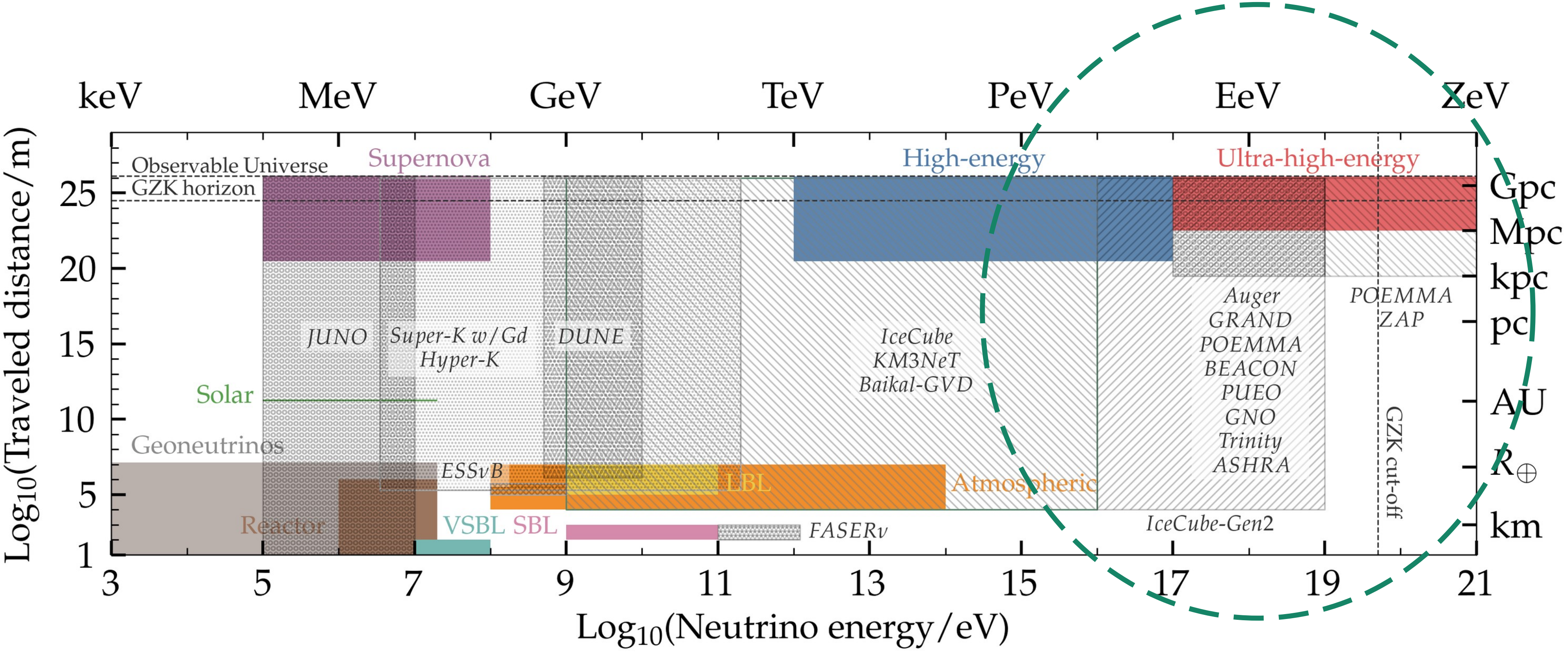
Niels Bohr Institute, University of Copenhagen

UNIVERSITY OF COPENHAGEN

29th JEM-EUSO International Collab. Meeting
June 10, 2021

VILLUM FONDEN

Next decade: a host of planned neutrino detectors



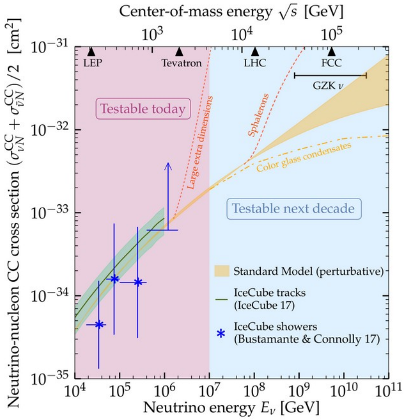
Synergies with lower energies

Increase TeV–PeV
ν statistics

Discover > EeV ν

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

TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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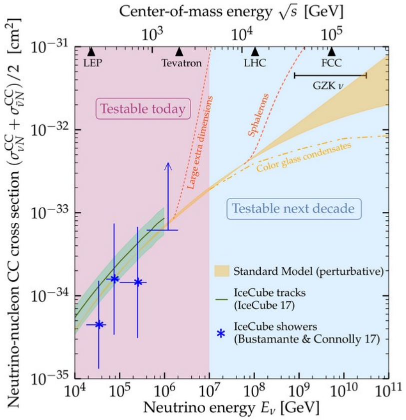
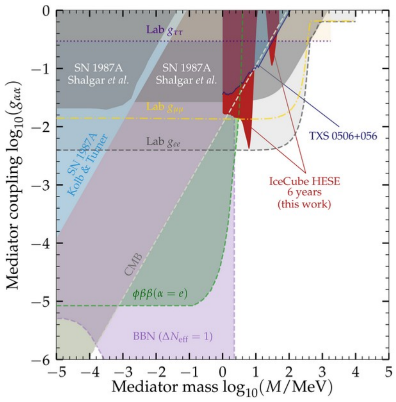


MB & Connolly, *PRL* 2019

ν self-interactions



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

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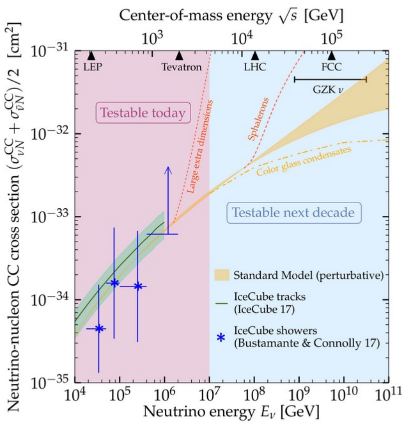

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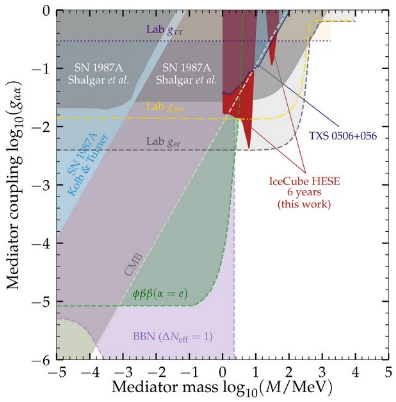
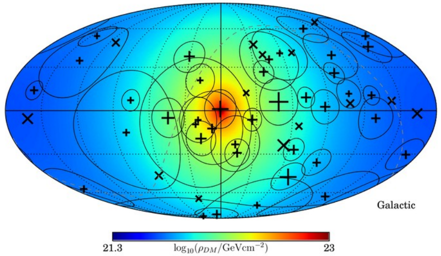


MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



Argüelles, Kheirandish, Vincent, *PRL* 2017

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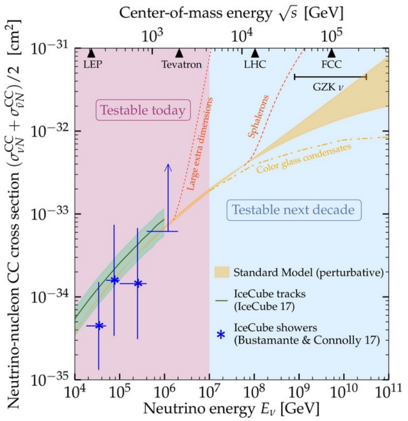

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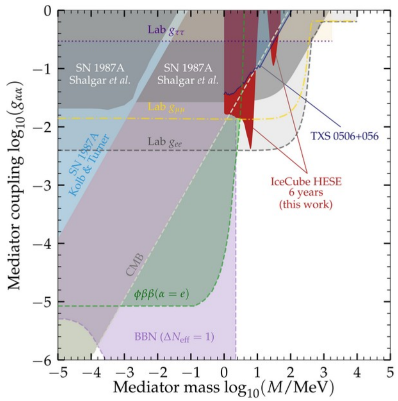

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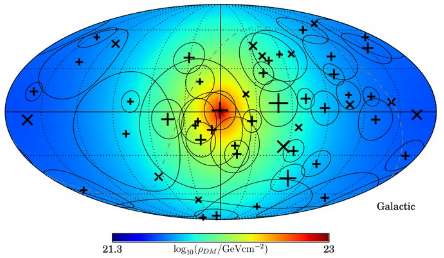

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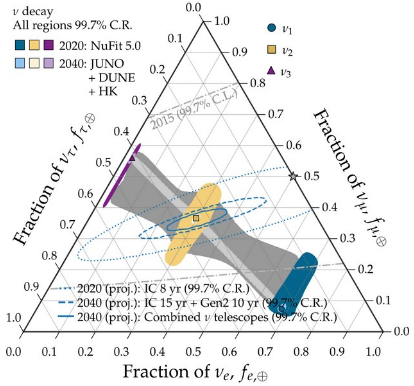
ν decay



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

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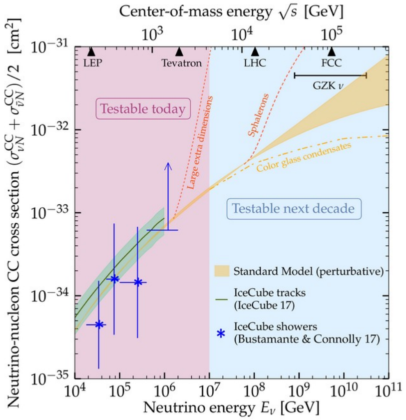

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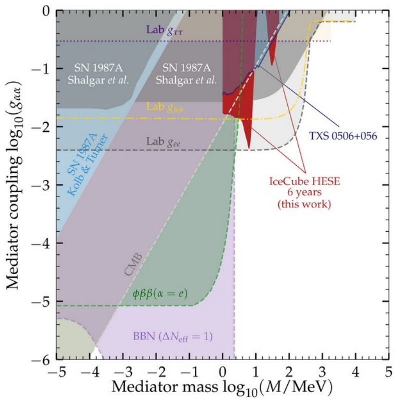

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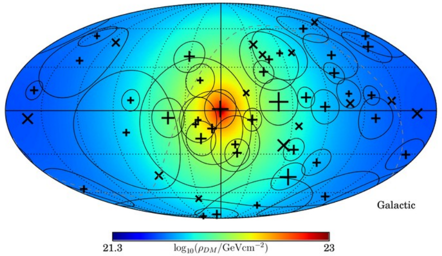

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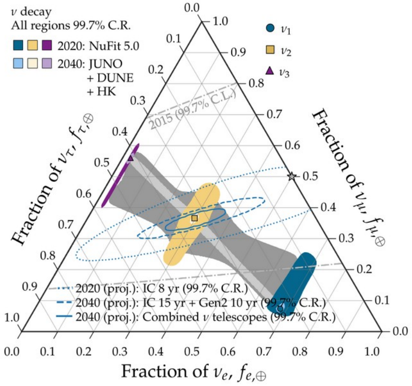

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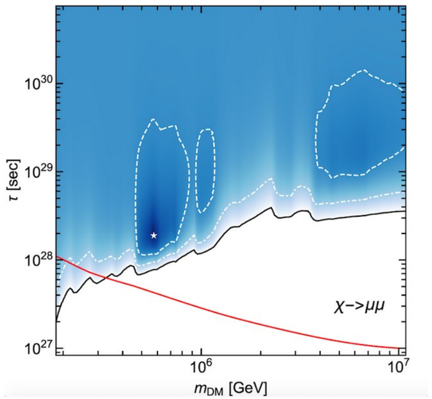
Dark matter decay



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

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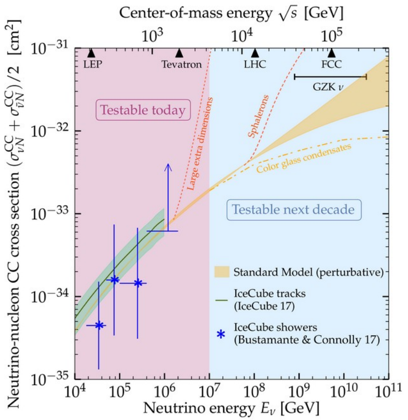

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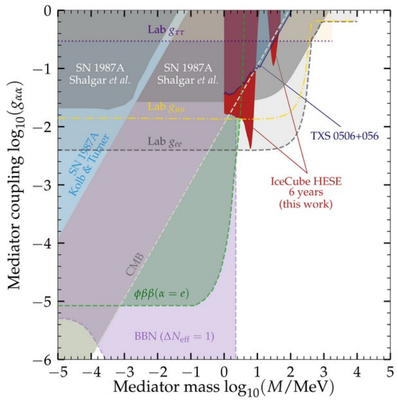

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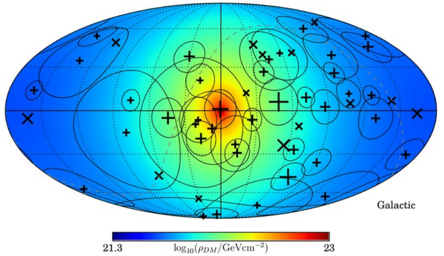

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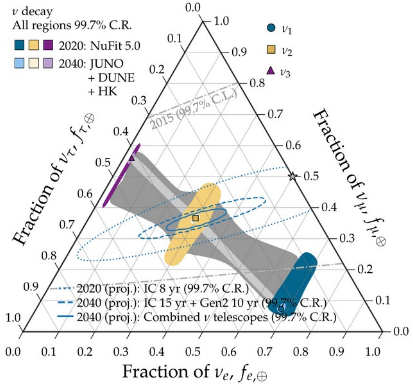

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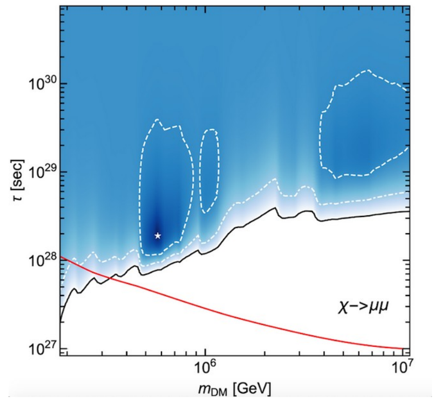

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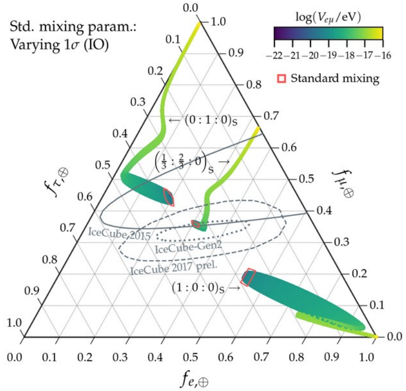

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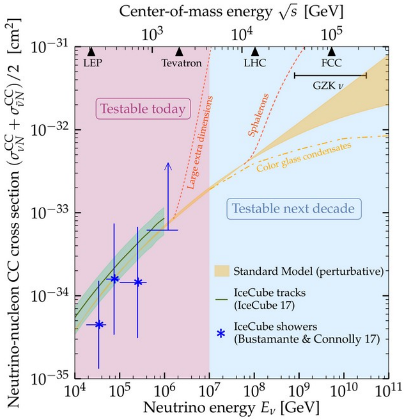

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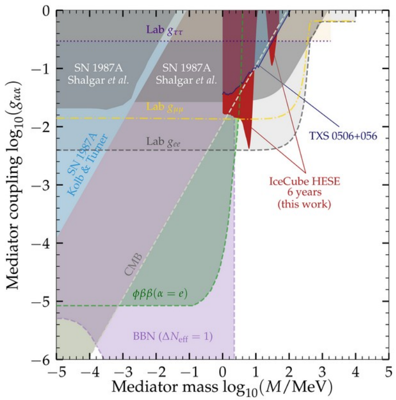

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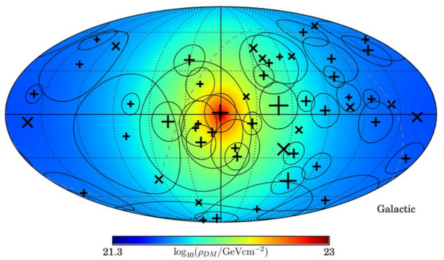

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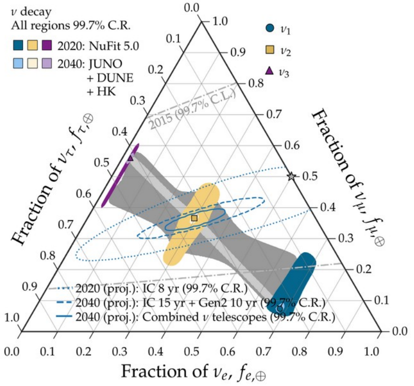

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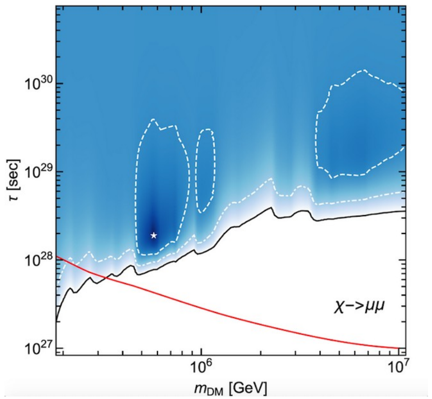

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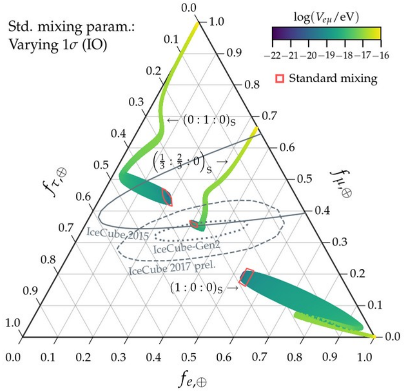

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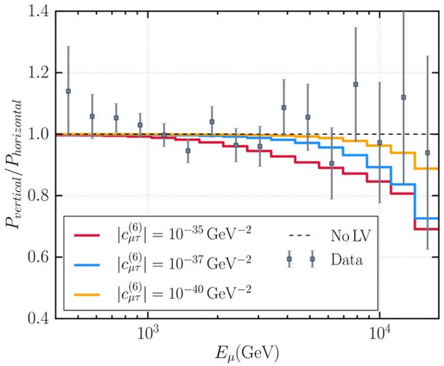
Lorentz-invariance violation



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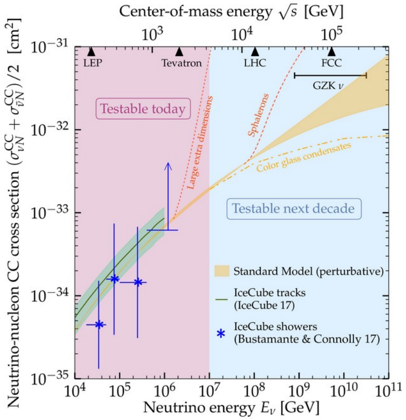

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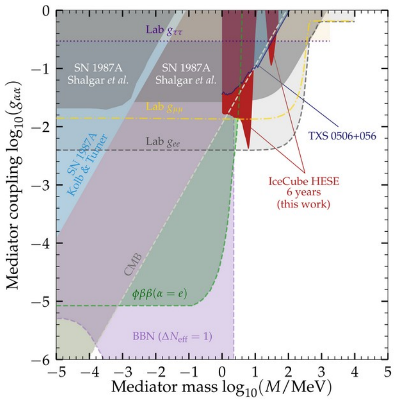

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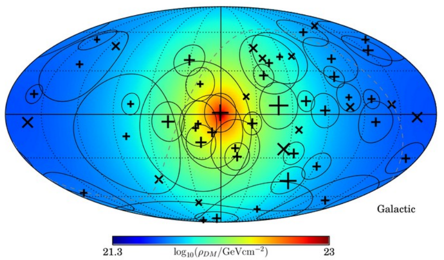

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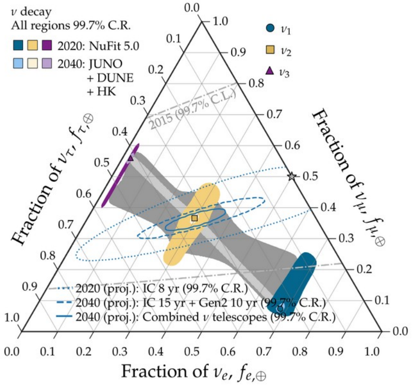

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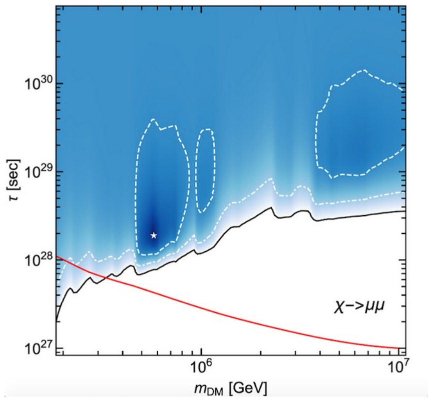

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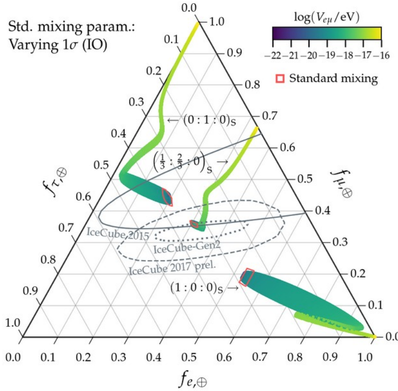

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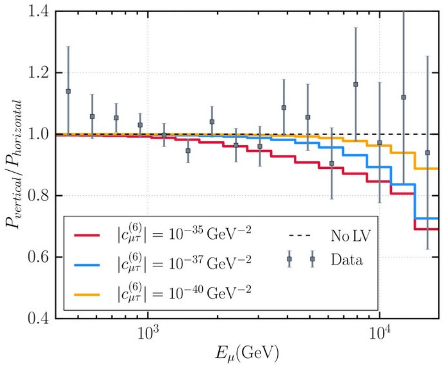

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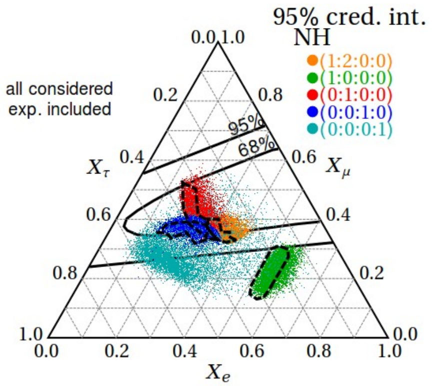
Sterile neutrinos



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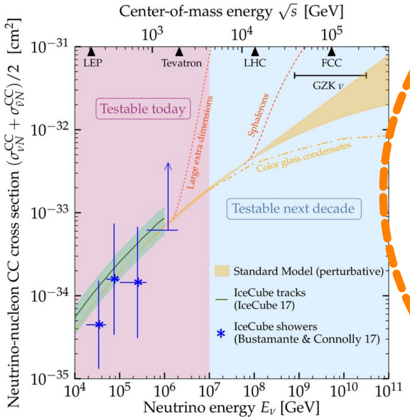

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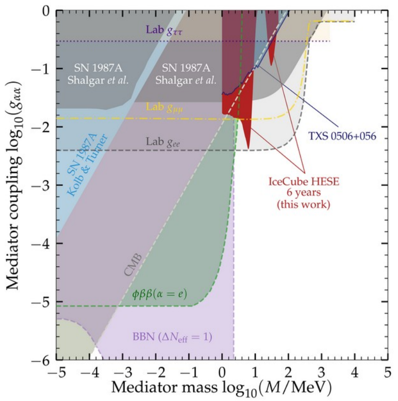

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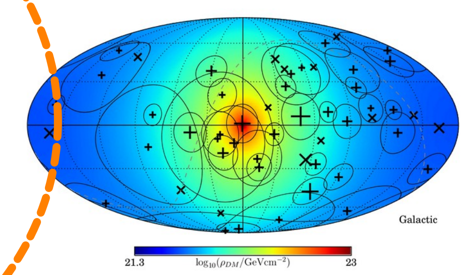

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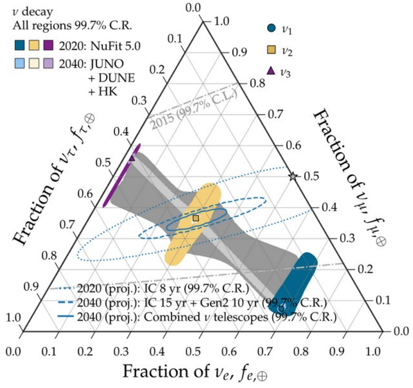

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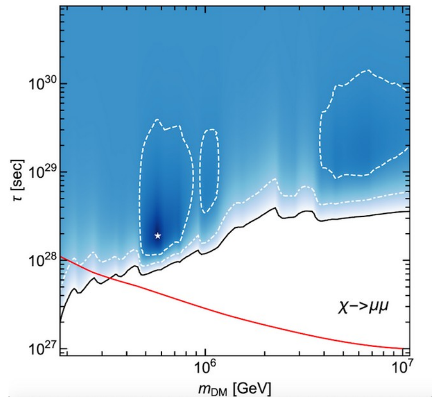

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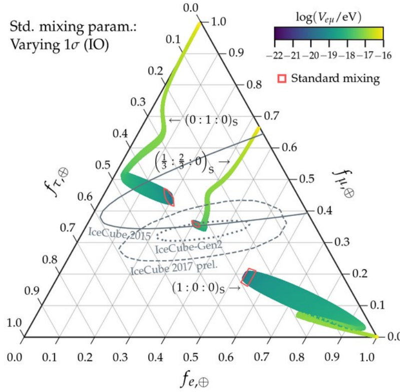

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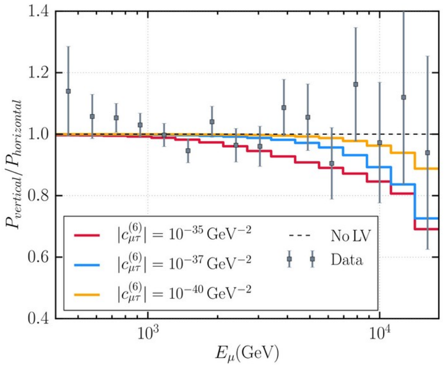

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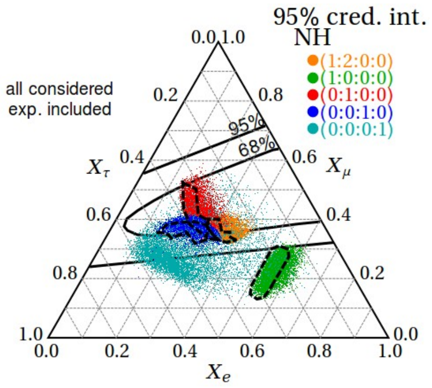

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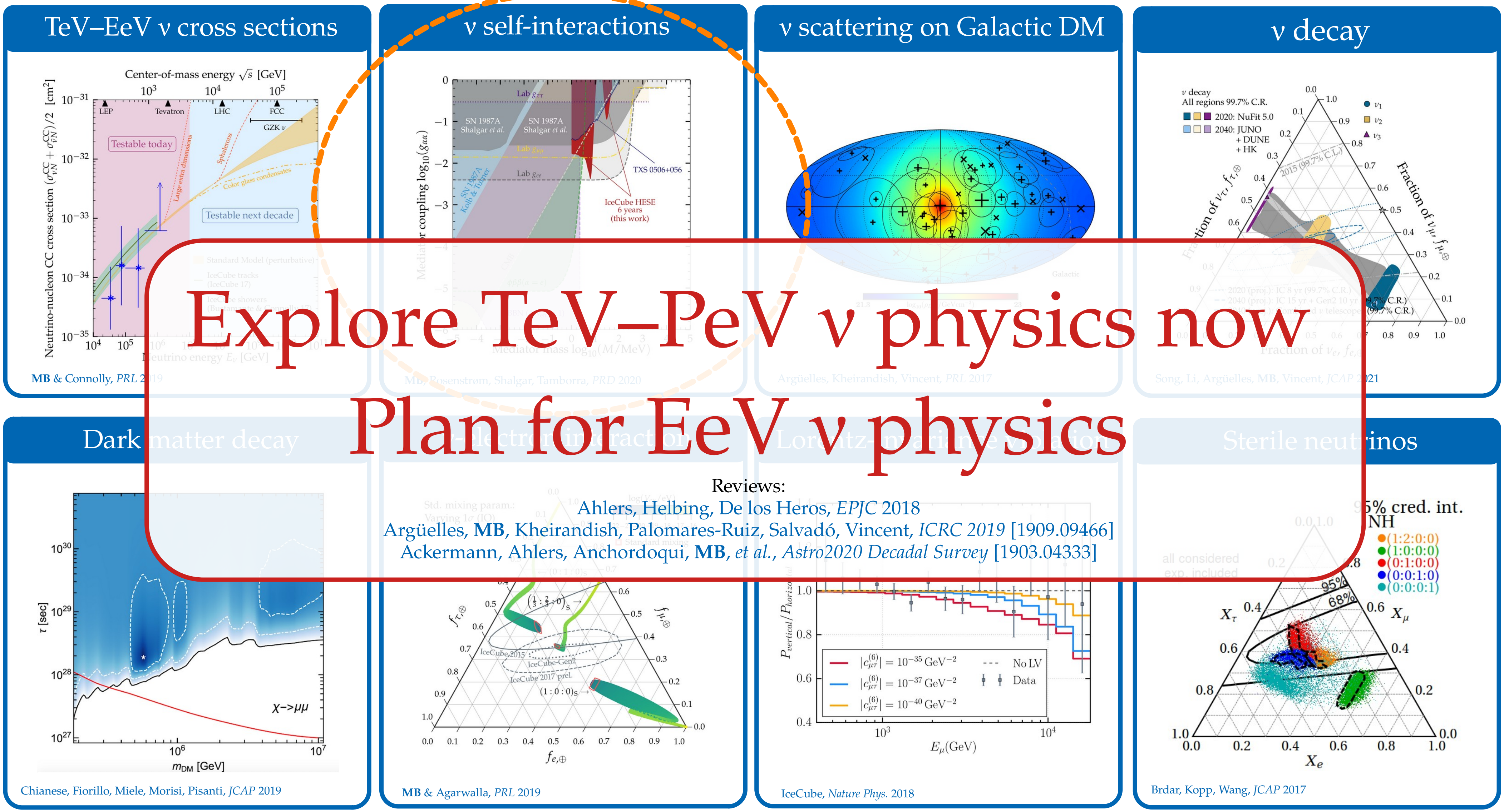


Explore TeV–PeV ν physics now
Plan for EeV ν physics

Reviews:
Ahlers, Helbing, De los Heros, *EPJC* 2018
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, *ICRC 2019* [1909.09466]
Ackermann, Ahlers, Anchordoqui, **MB**, *et al.*, *Astro2020 Decadal Survey* [1903.04333]

Astrophysical neutrino sources

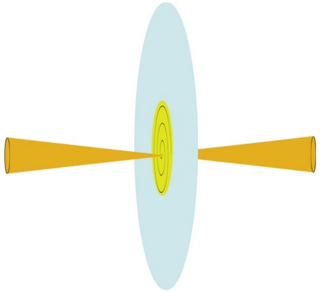
Earth

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

Astrophysical neutrino sources

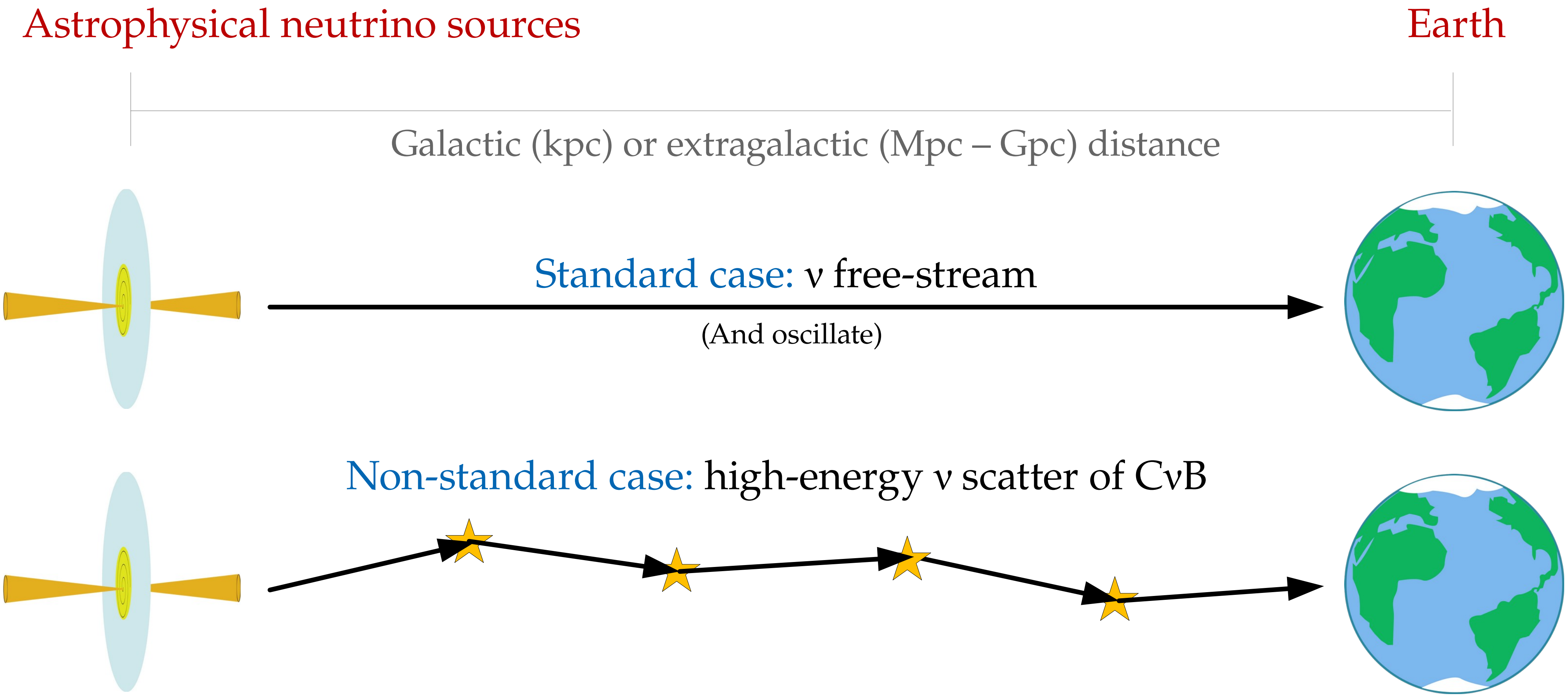
Earth

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



Standard case: ν free-stream

(And oscillate)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Astrophysical neutrino sources — Earth

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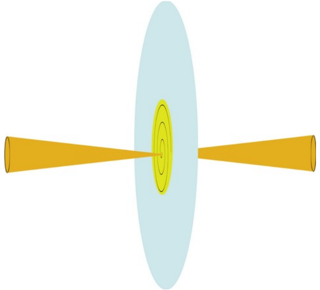

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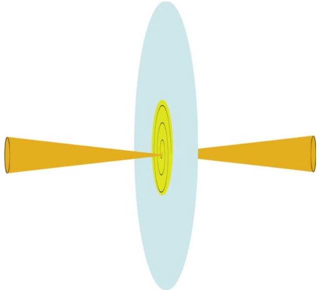
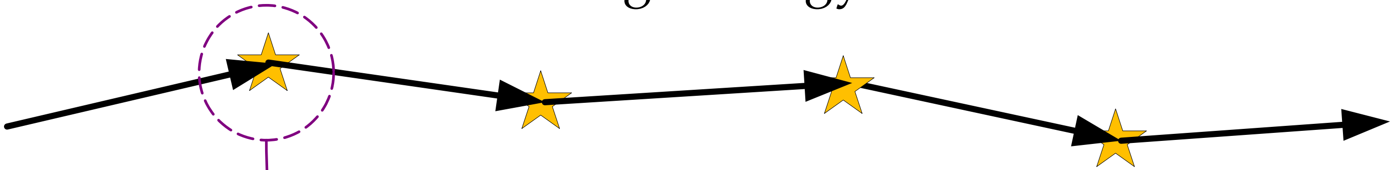
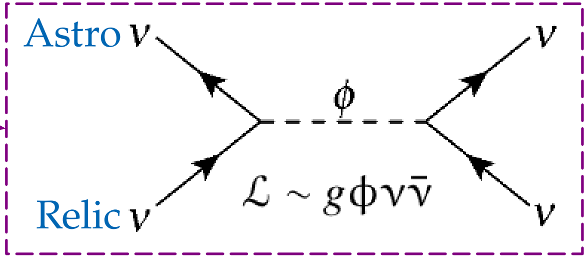
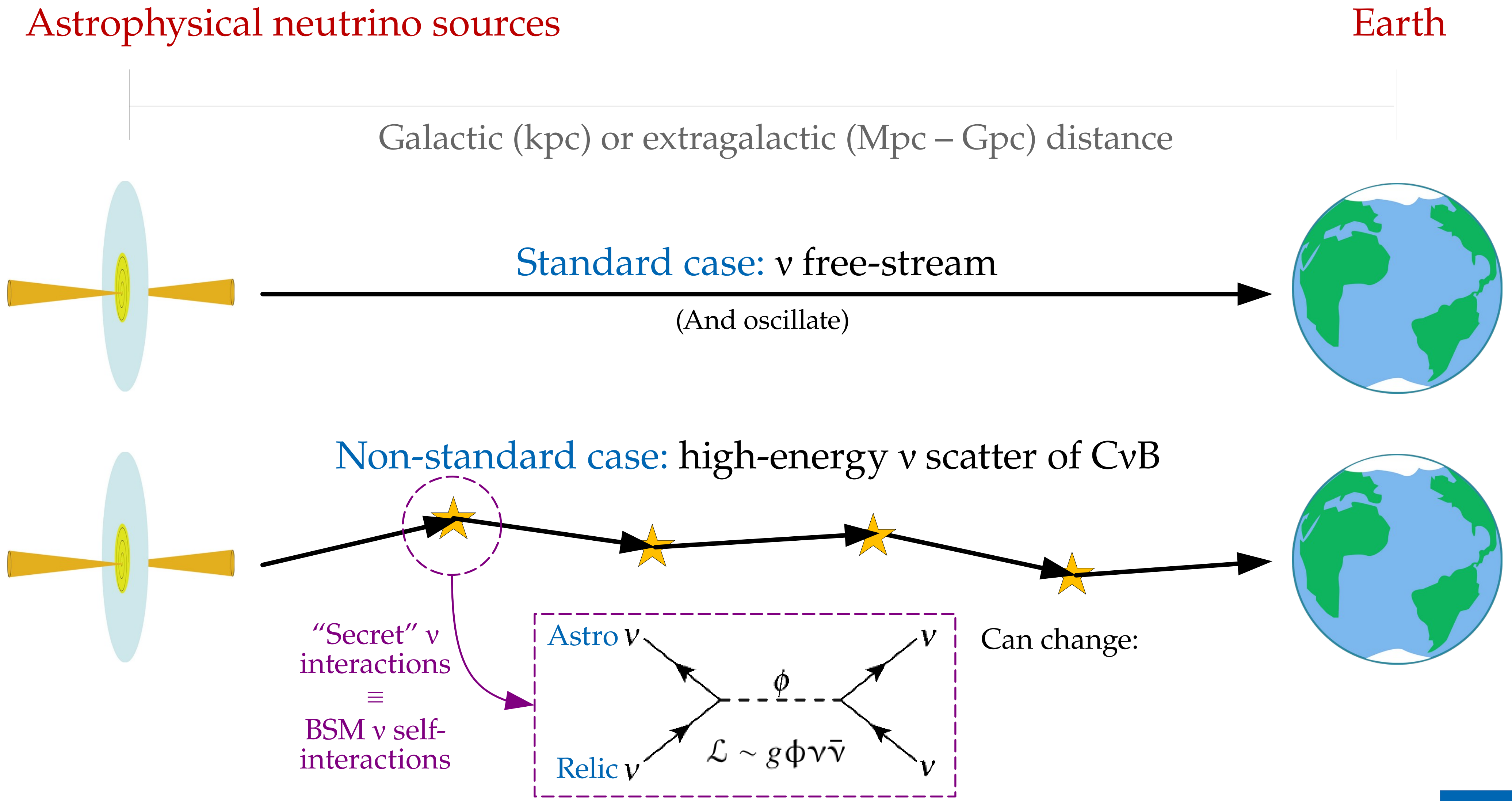




"Secret" ν interactions ≡ BSM ν self-interactions

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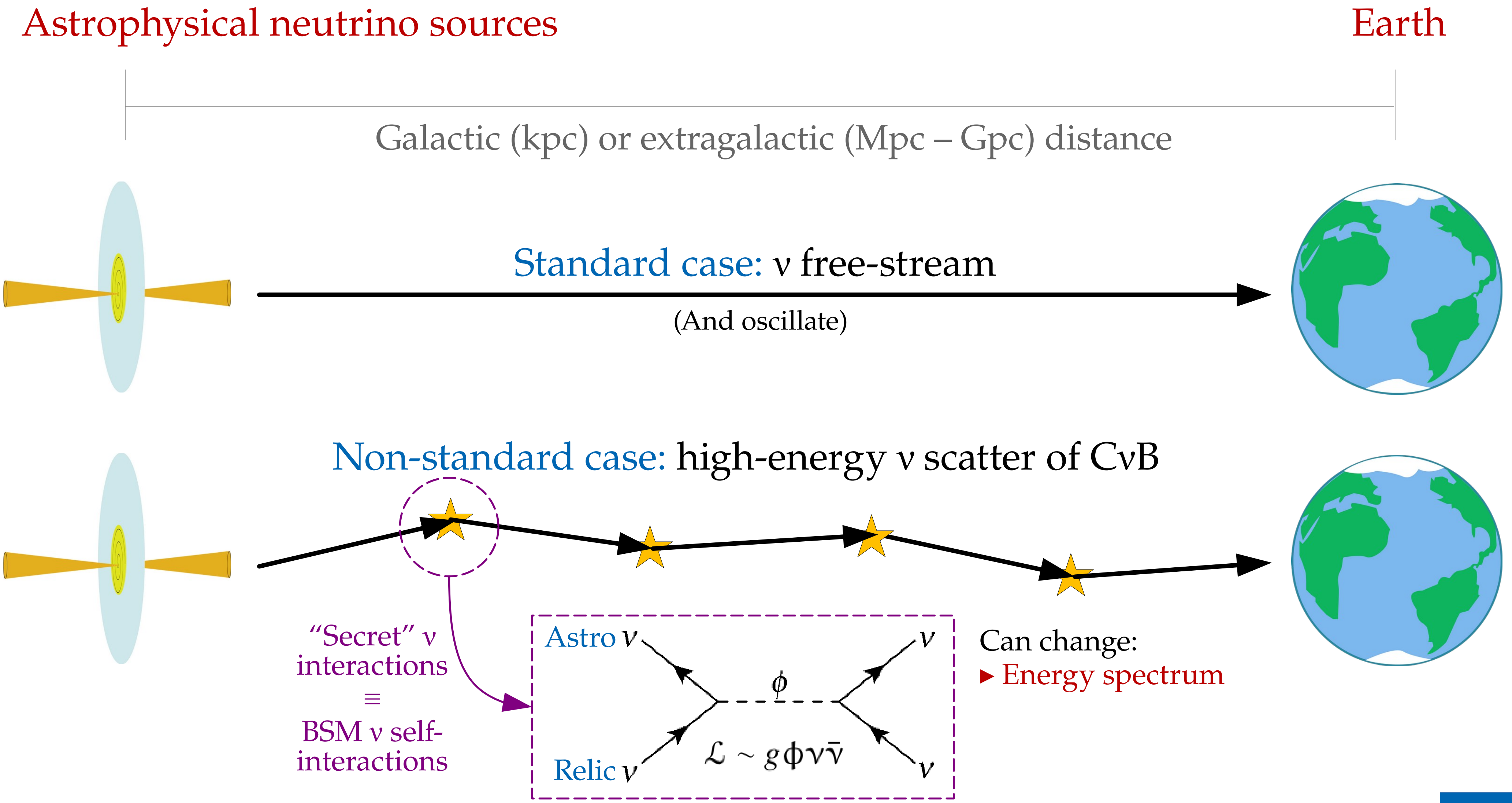
≡
BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change: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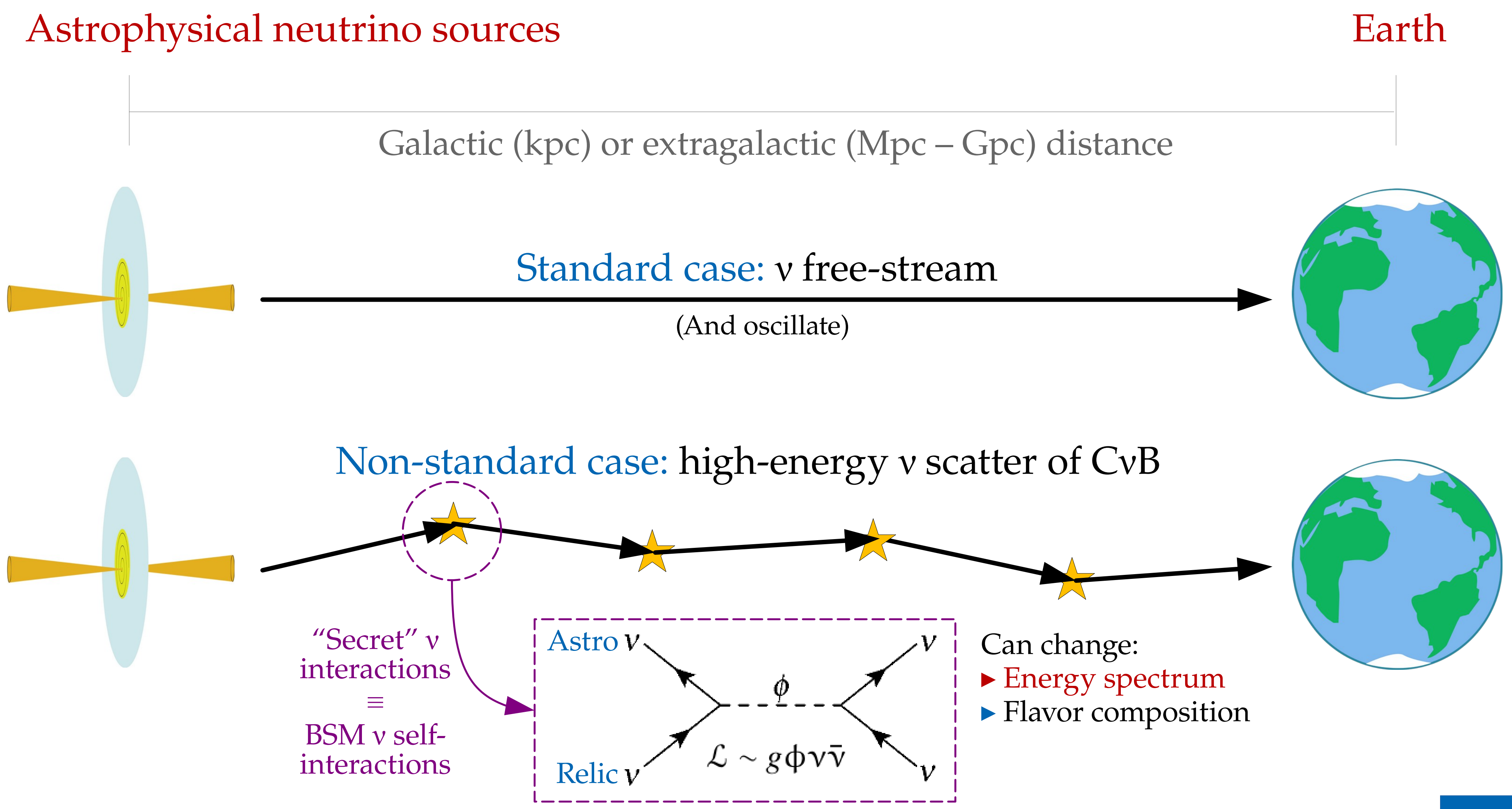
Can change:
▸ Energy spectrum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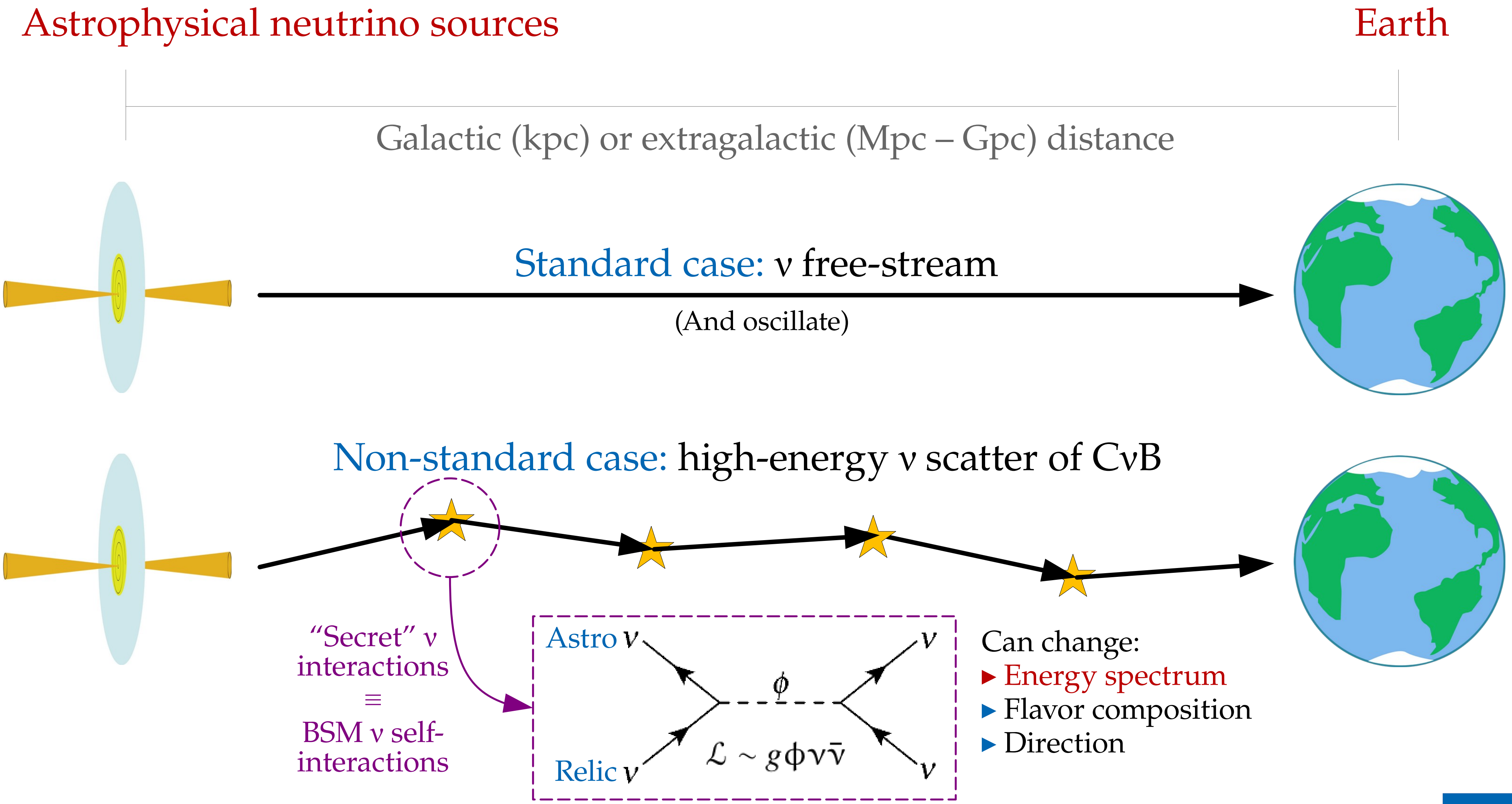
Can change:
▸ Energy spectrum
▸ Flavor composition



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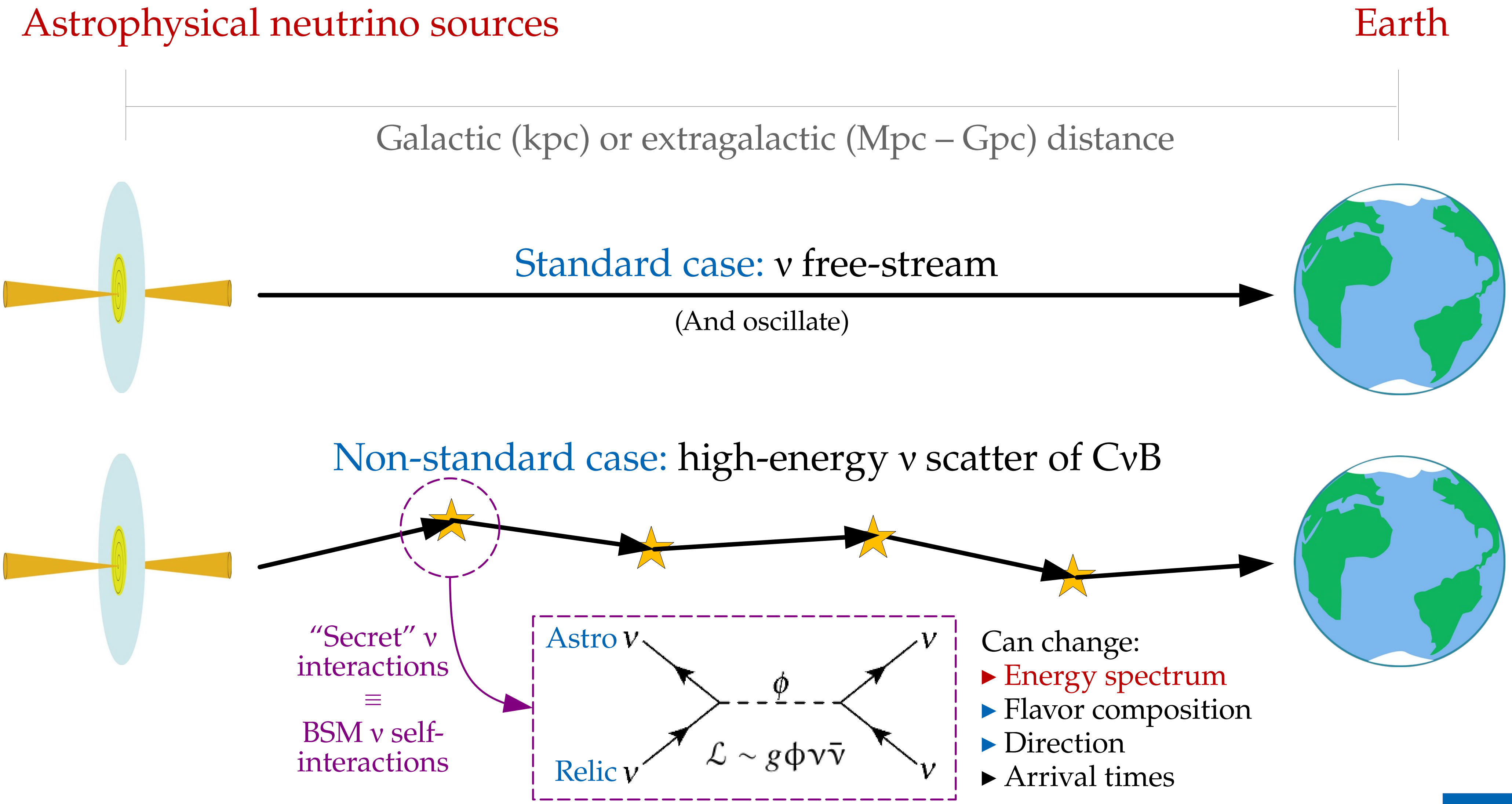
Can change:
Energy spectrum
Flavor composition
Direction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Relic ν
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ϕ
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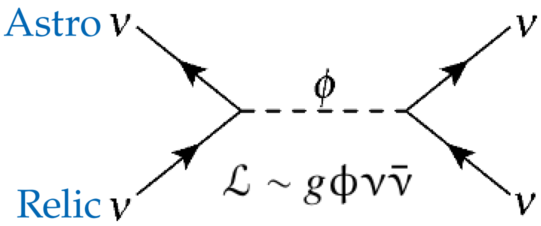
Can change:
Energy spectrum
Flavor composition
Direction
Arrival times

Secret interactions of high-energy neutrinos

“Secret” neutrino interactions between UHE ν (EeV) and relic ν (0.1 meV):



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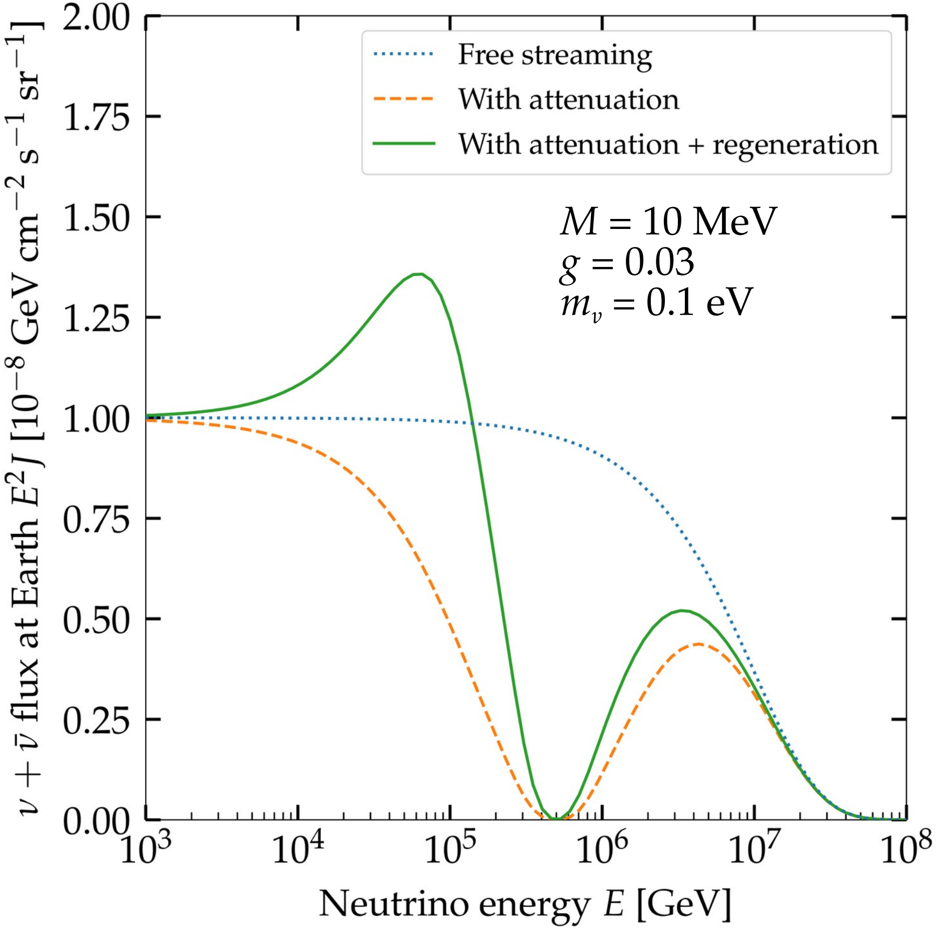

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
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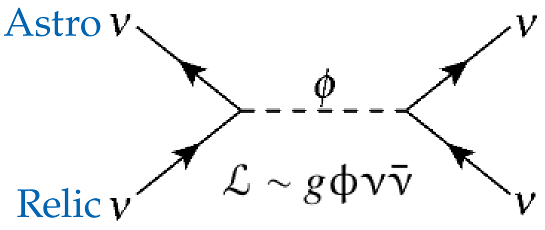

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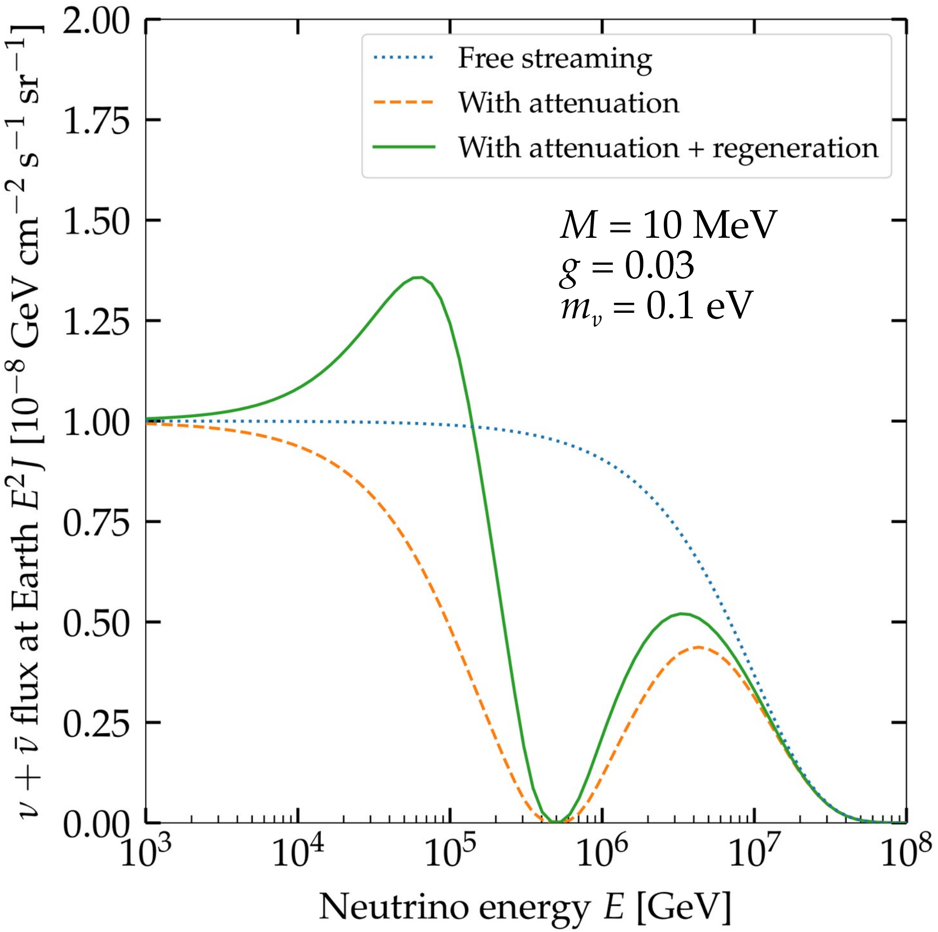

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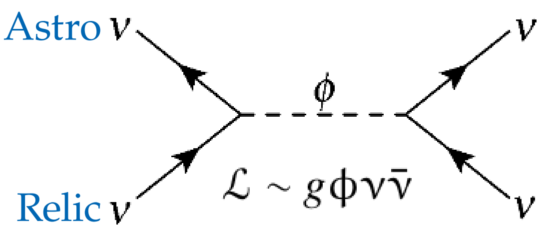

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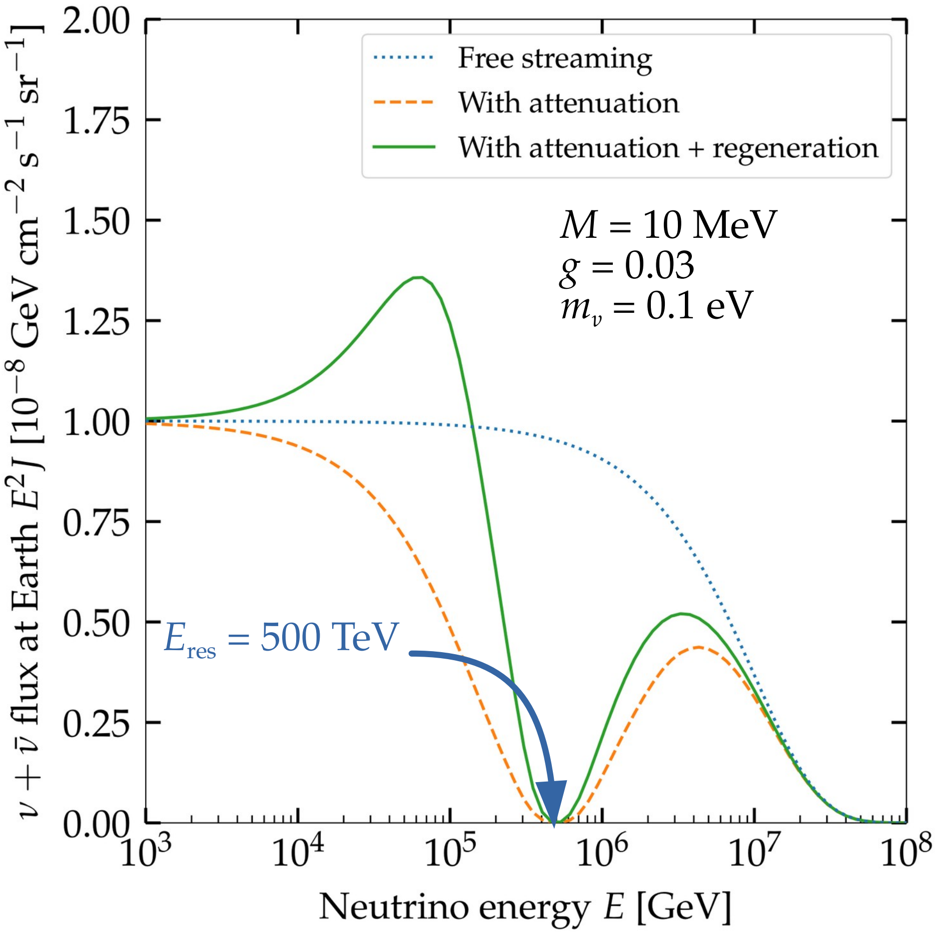

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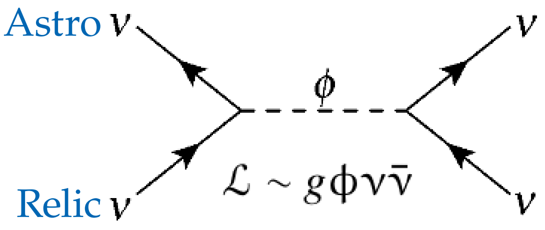

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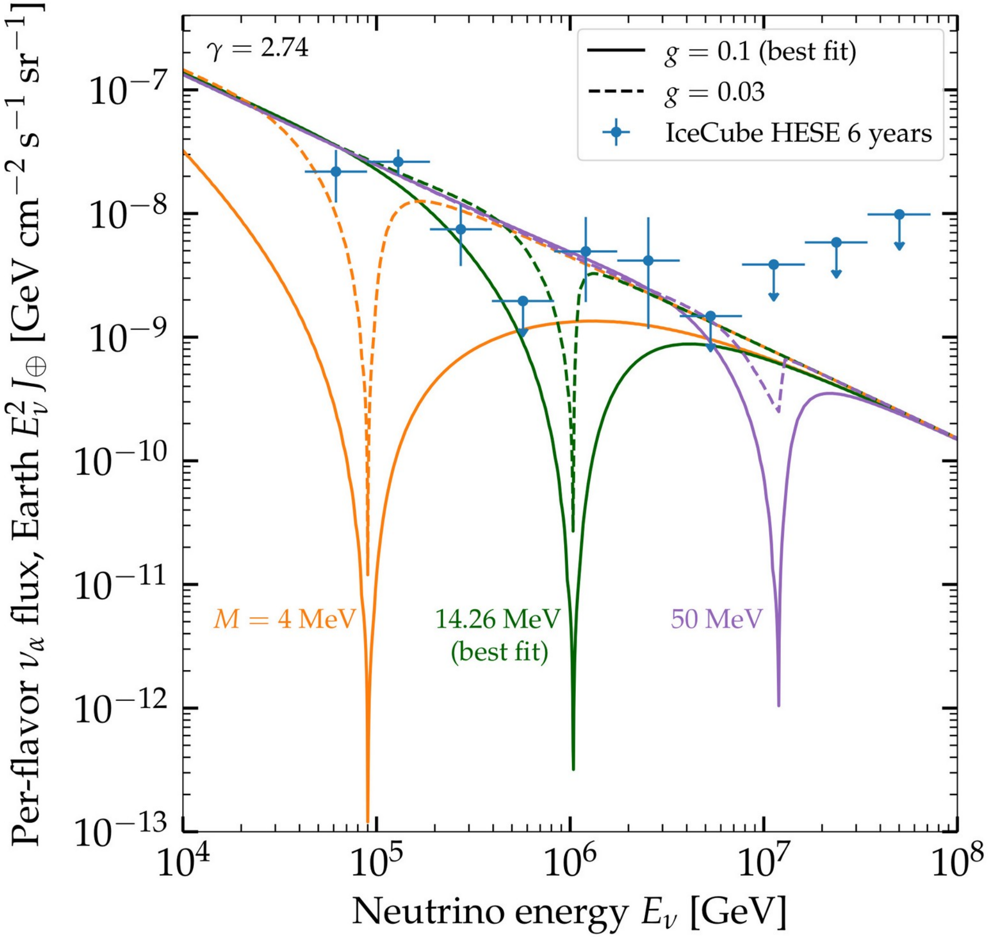

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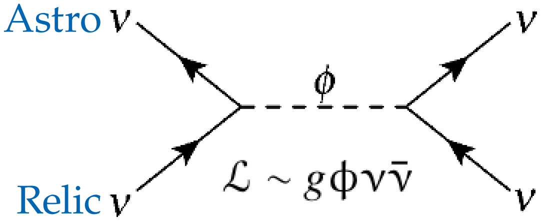

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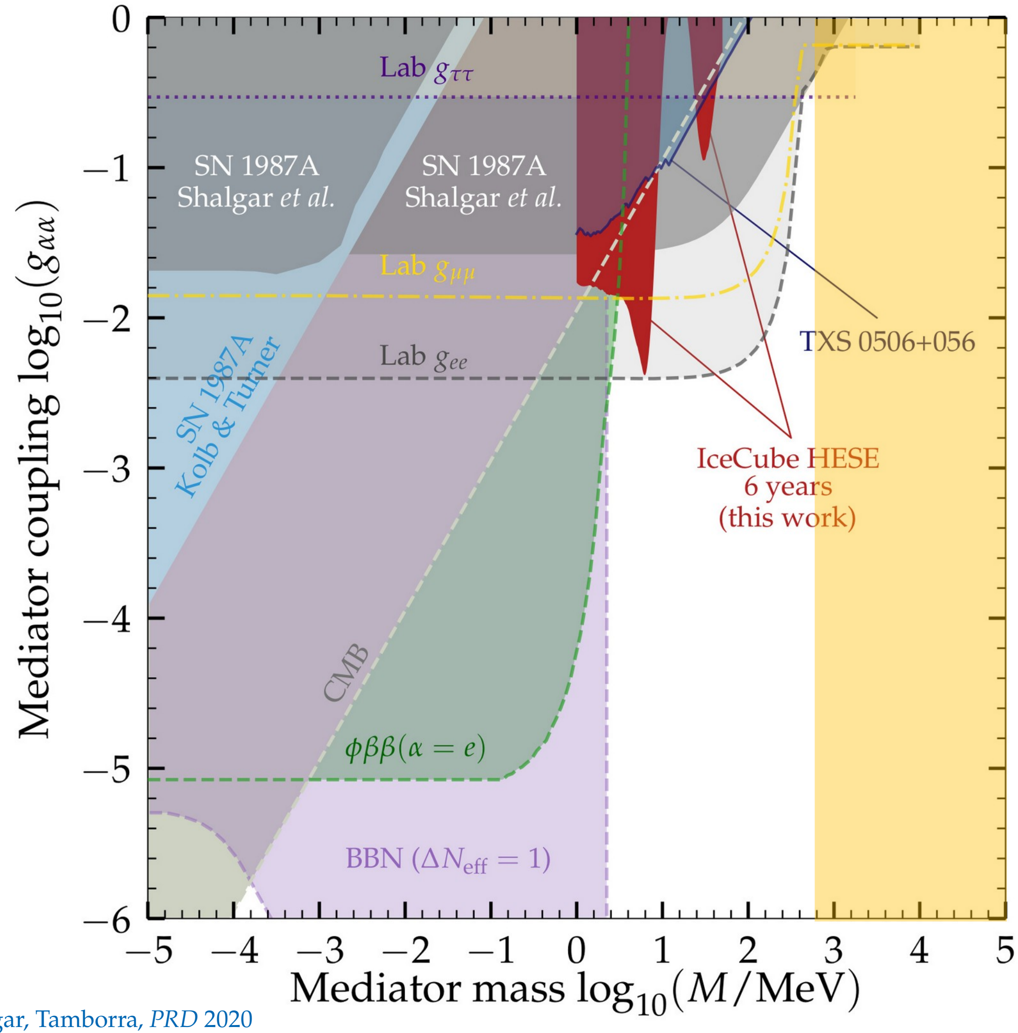

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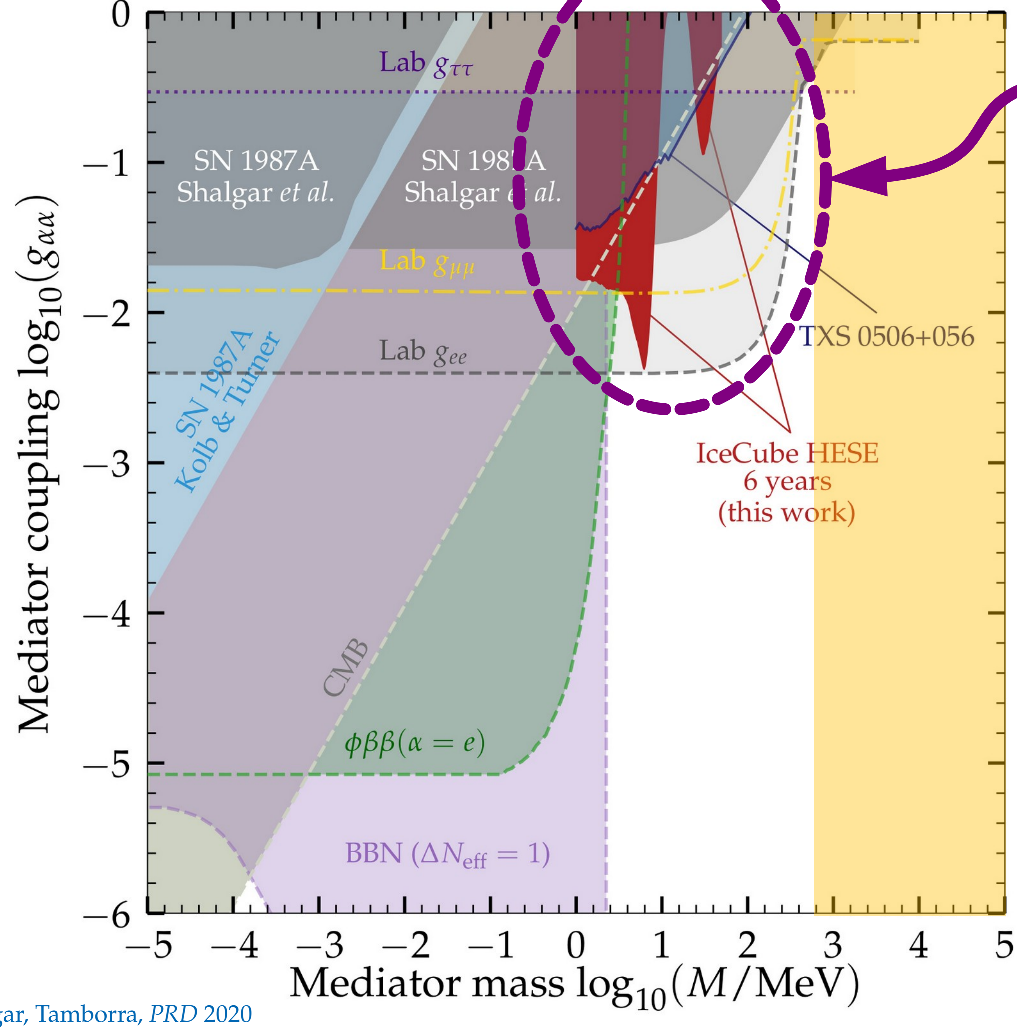

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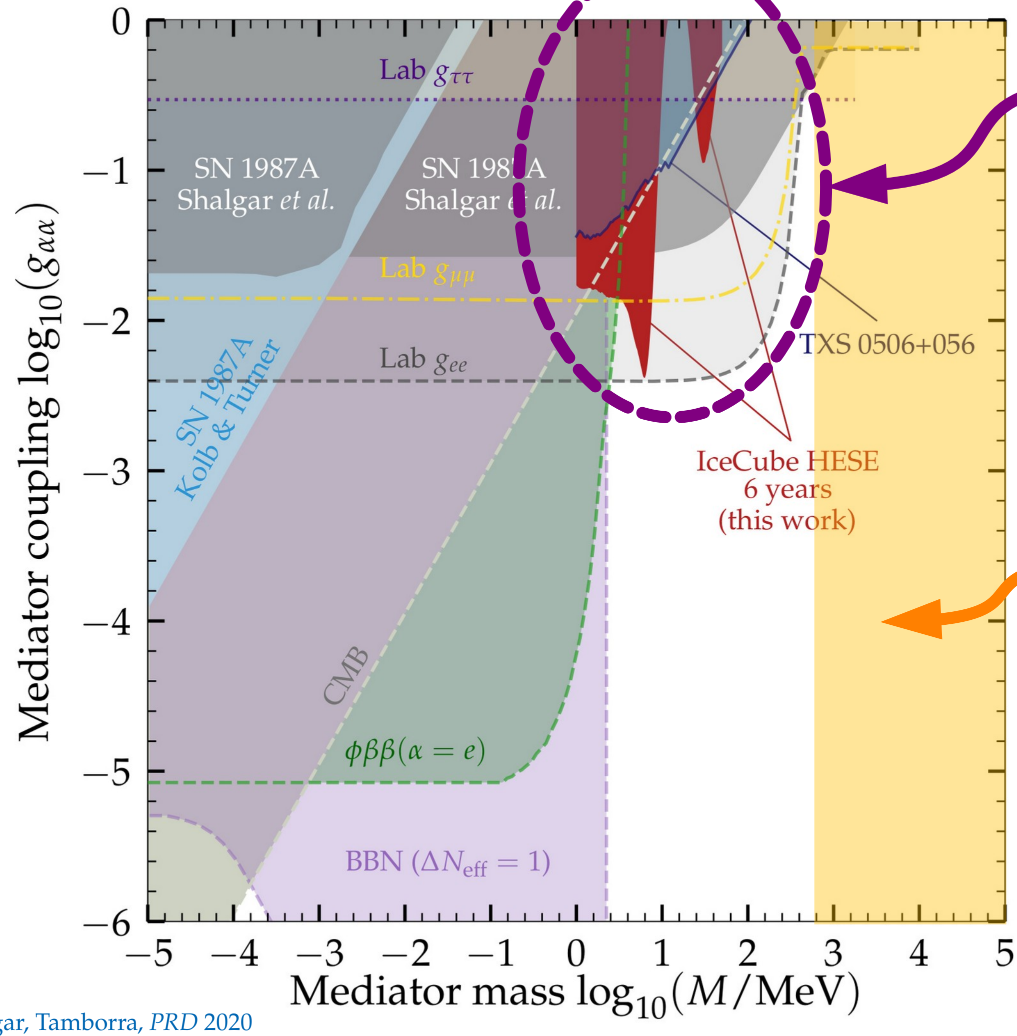

Constraints from IceCube TeV–PeV ν observations

UHE ν could place first constraints on GeV-scale mediators

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POEMMA, *JCAP* 2021
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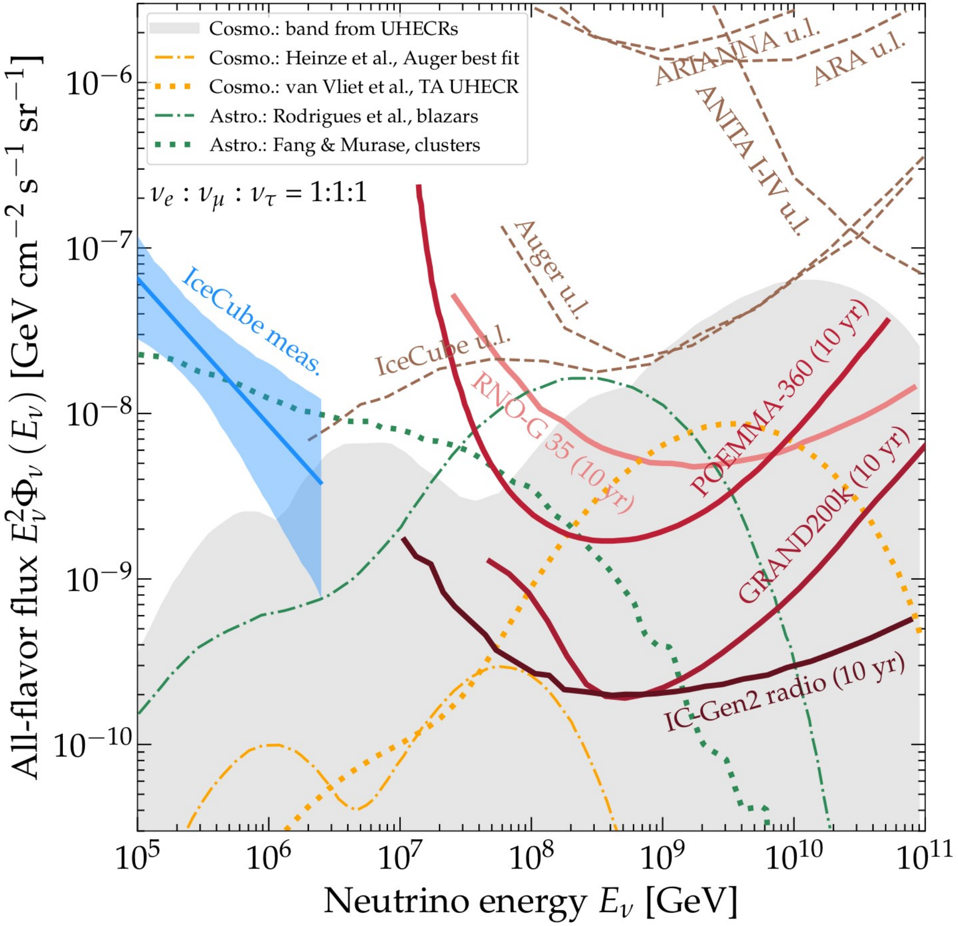
Steady-state UHE ν flux



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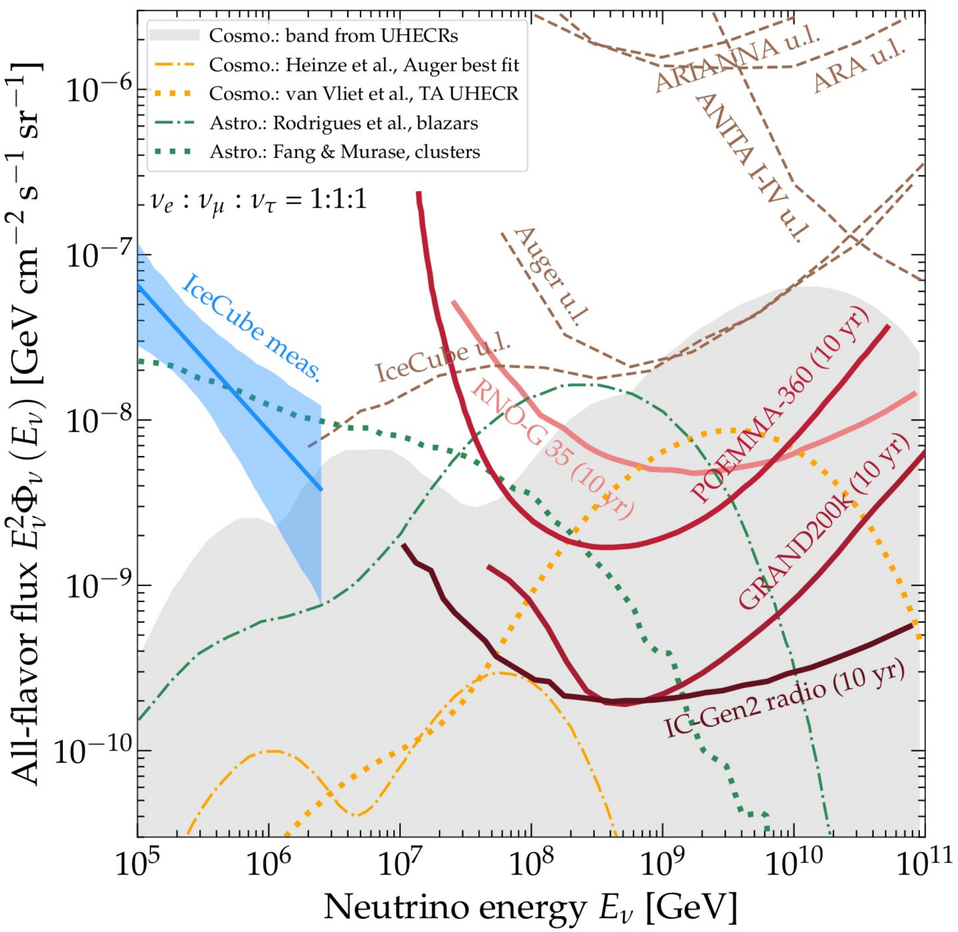
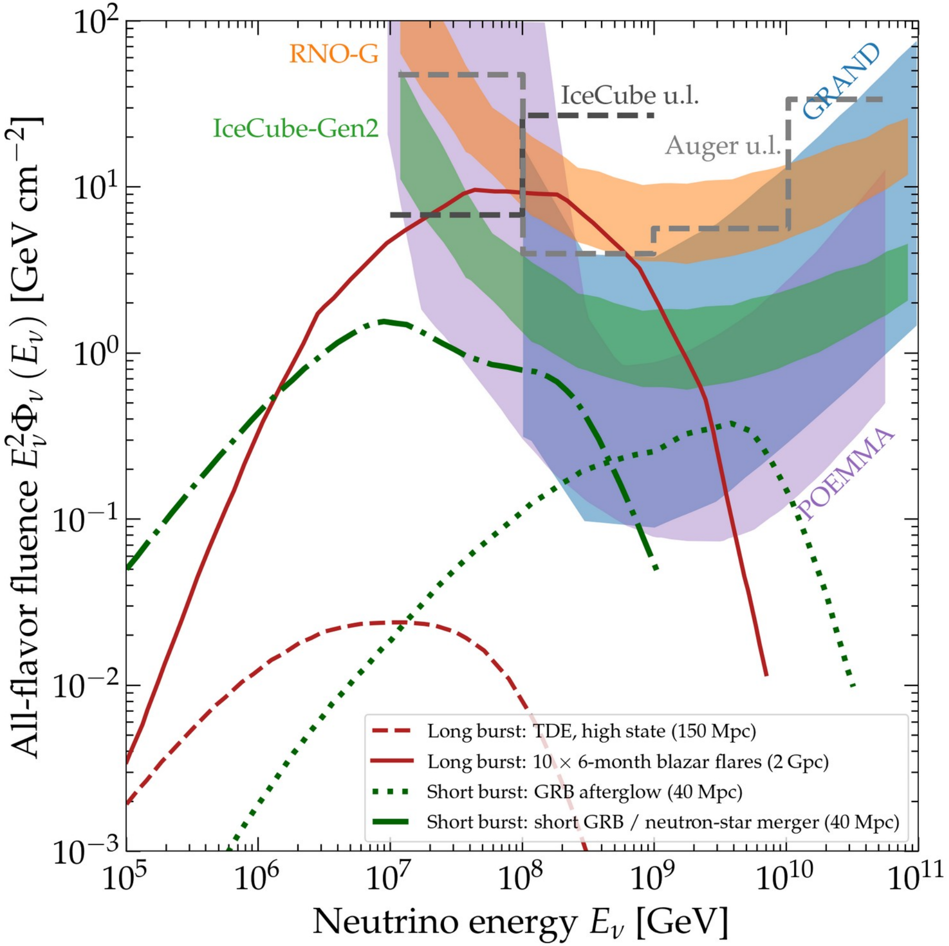


Transient UHE ν flux



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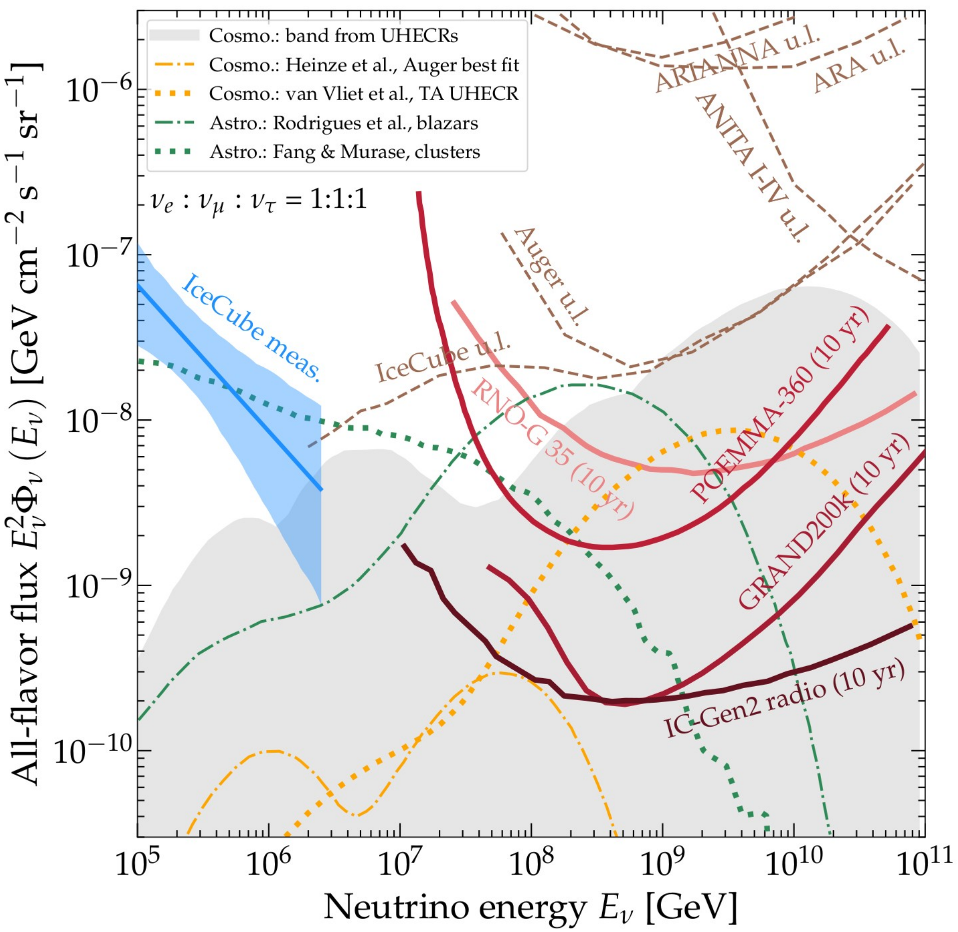

Test νSI with POEMMA-360

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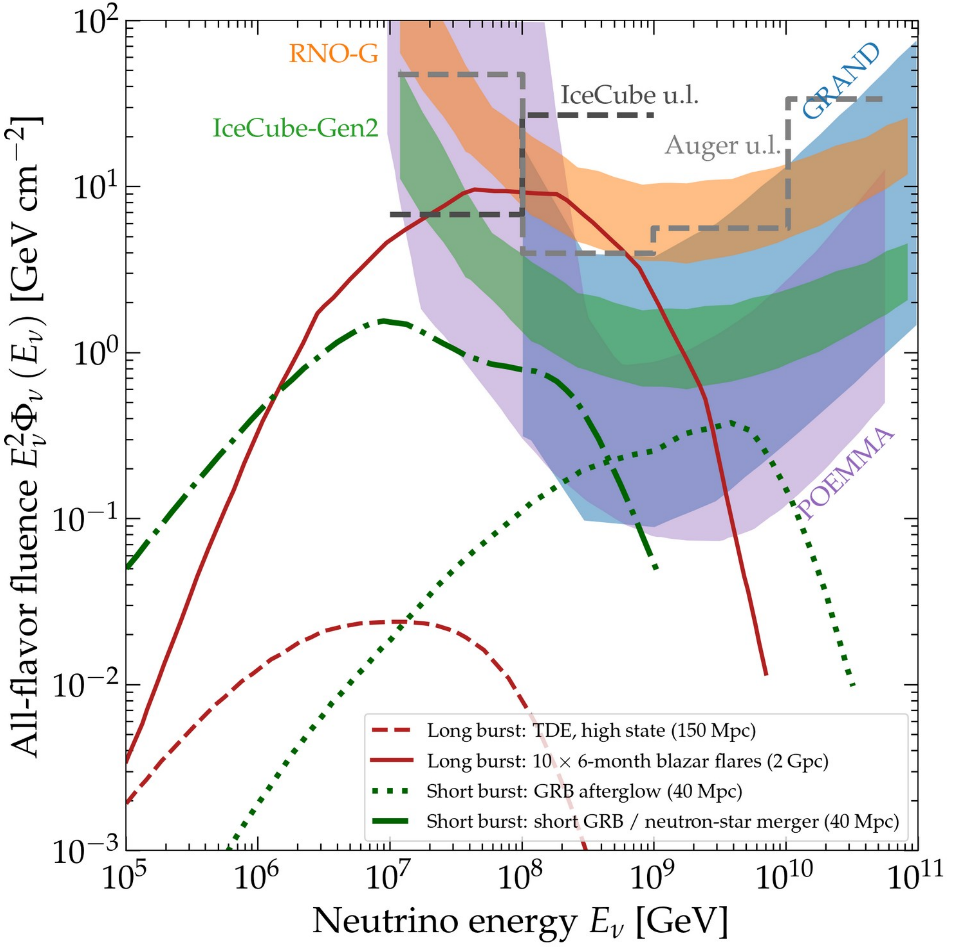


Test νSI with POEMMA

νSI with the UHE diffuse flux

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

Coupling matrix:

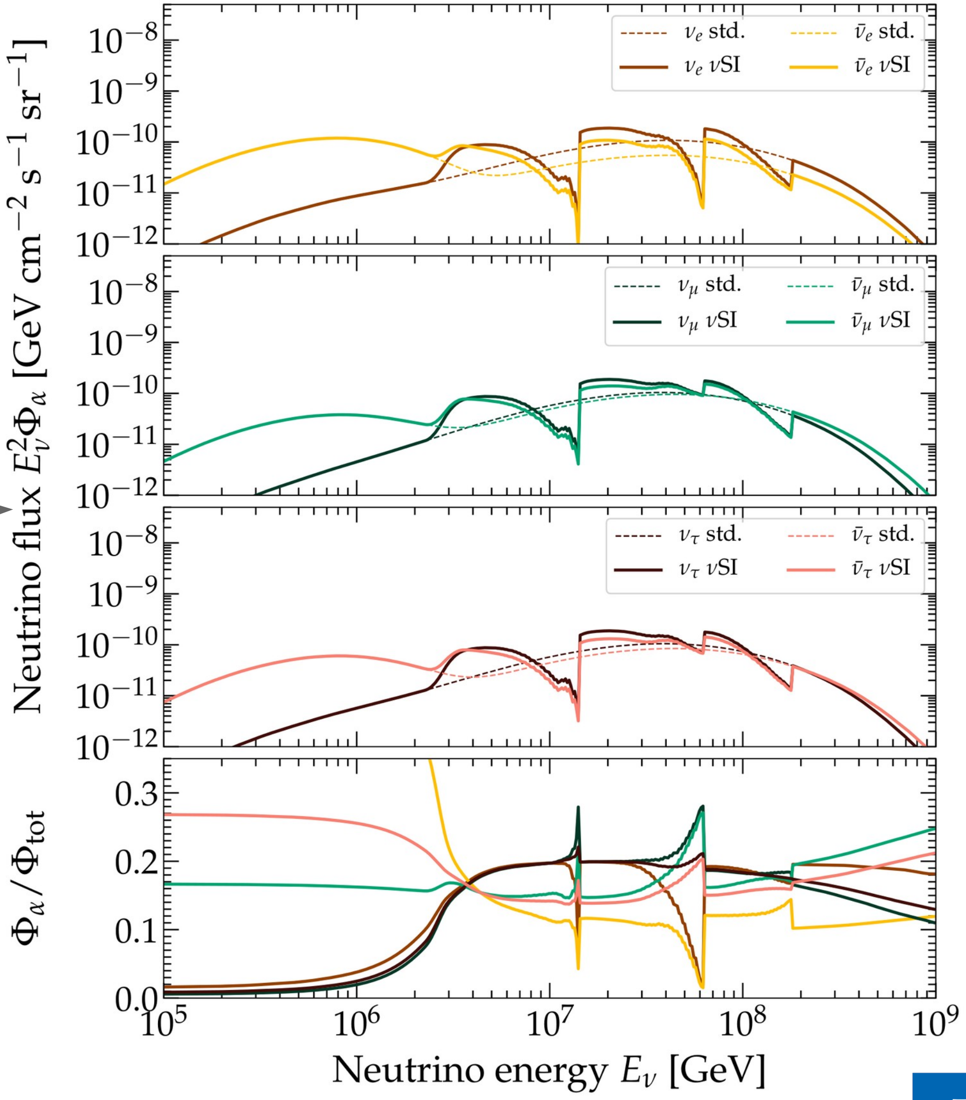
$$\mathbf{G} \equiv \begin{pmatrix} g_{ee} & g_{e\mu} & g_{e\tau} \\ g_{e\mu} & g_{\mu\mu} & g_{\mu\tau} \\ g_{e\tau} & g_{\mu\tau} & g_{\tau\tau} \end{pmatrix}$$

Different flavors can have different couplings

νSI dips and bumps in the diffuse UHE ν flux:

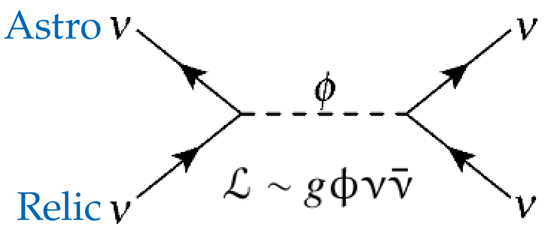
- In the cosmogenic flux
- In the flux from sources

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



MB, Másson, Valera, In prep.

νSI with the UHE transient flux



If this happens repeatedly, high-energy neutrinos disappear

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

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

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

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

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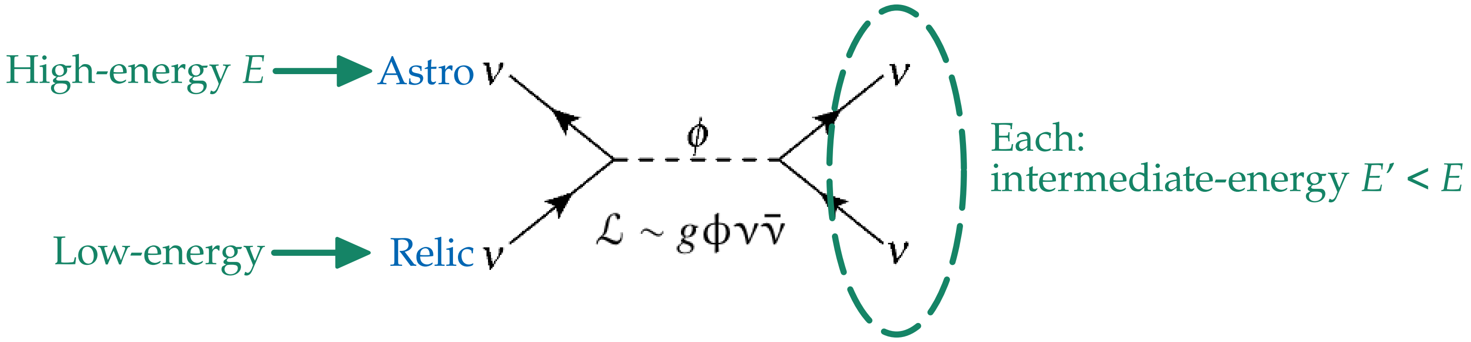

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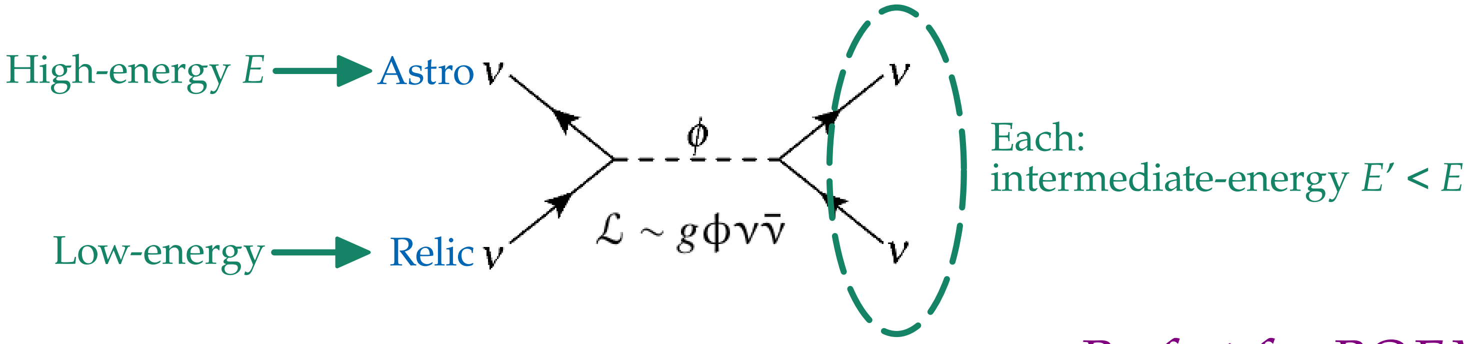

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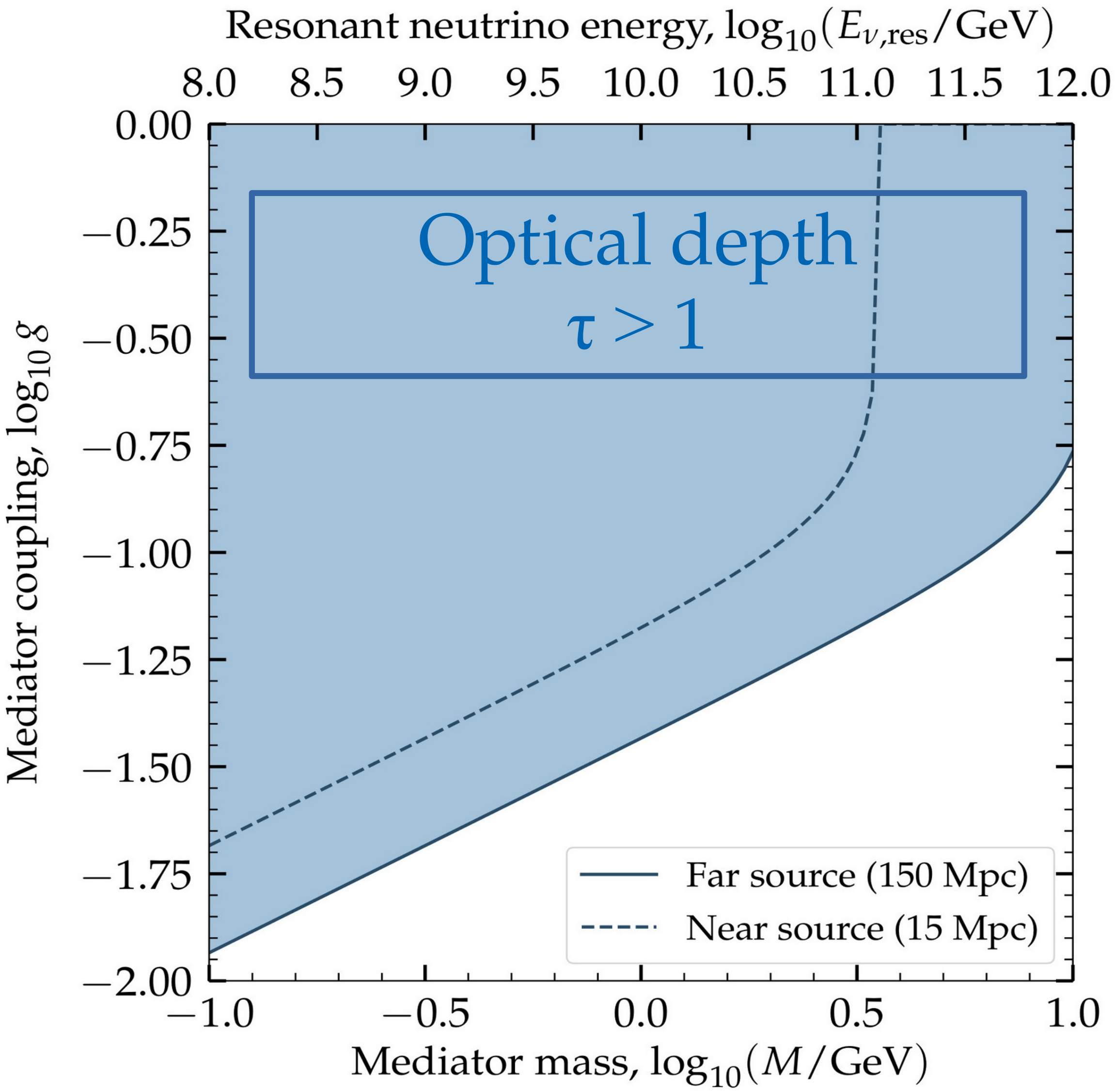
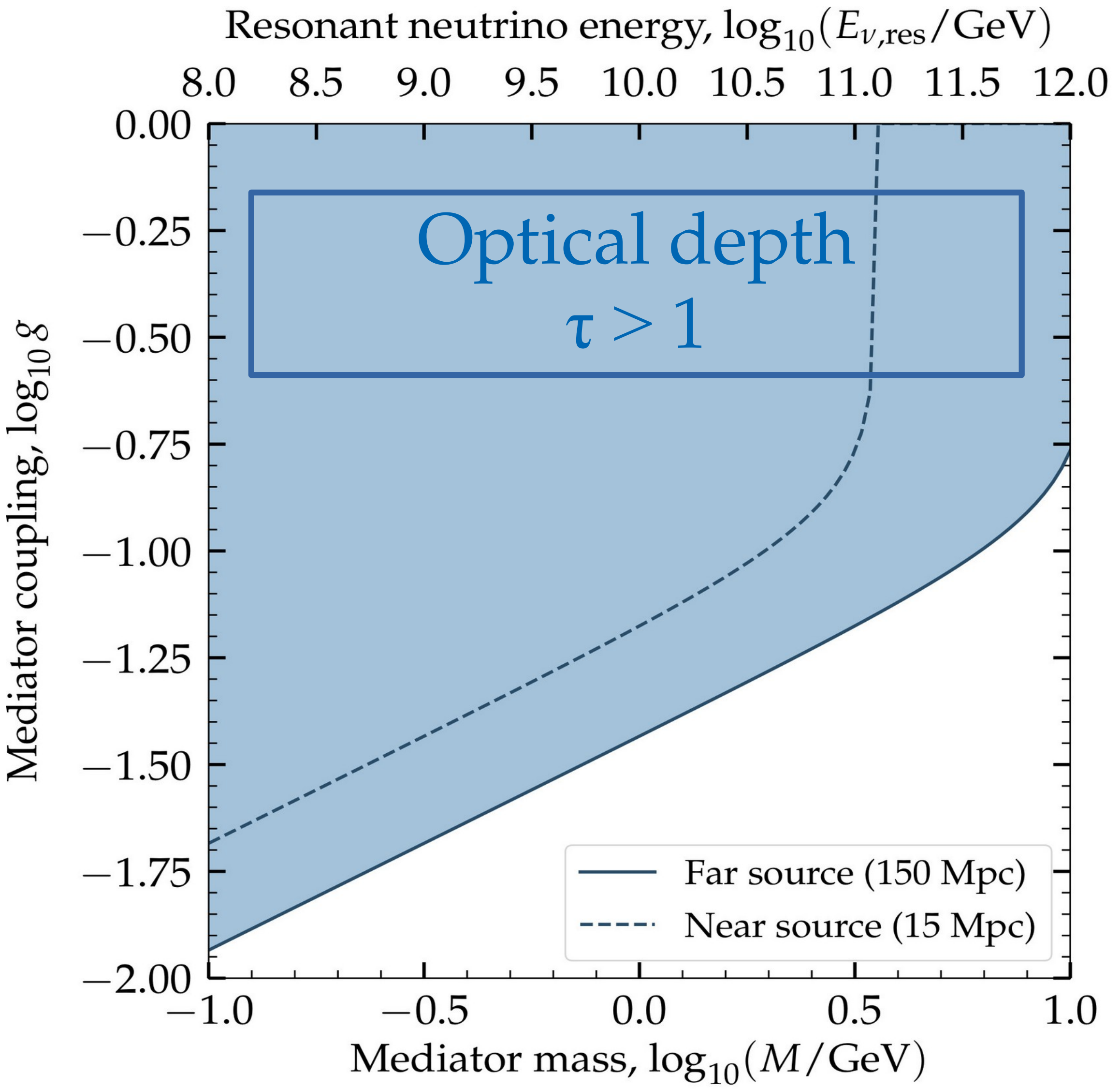


POEMMA Collab., *JCAP* 2021



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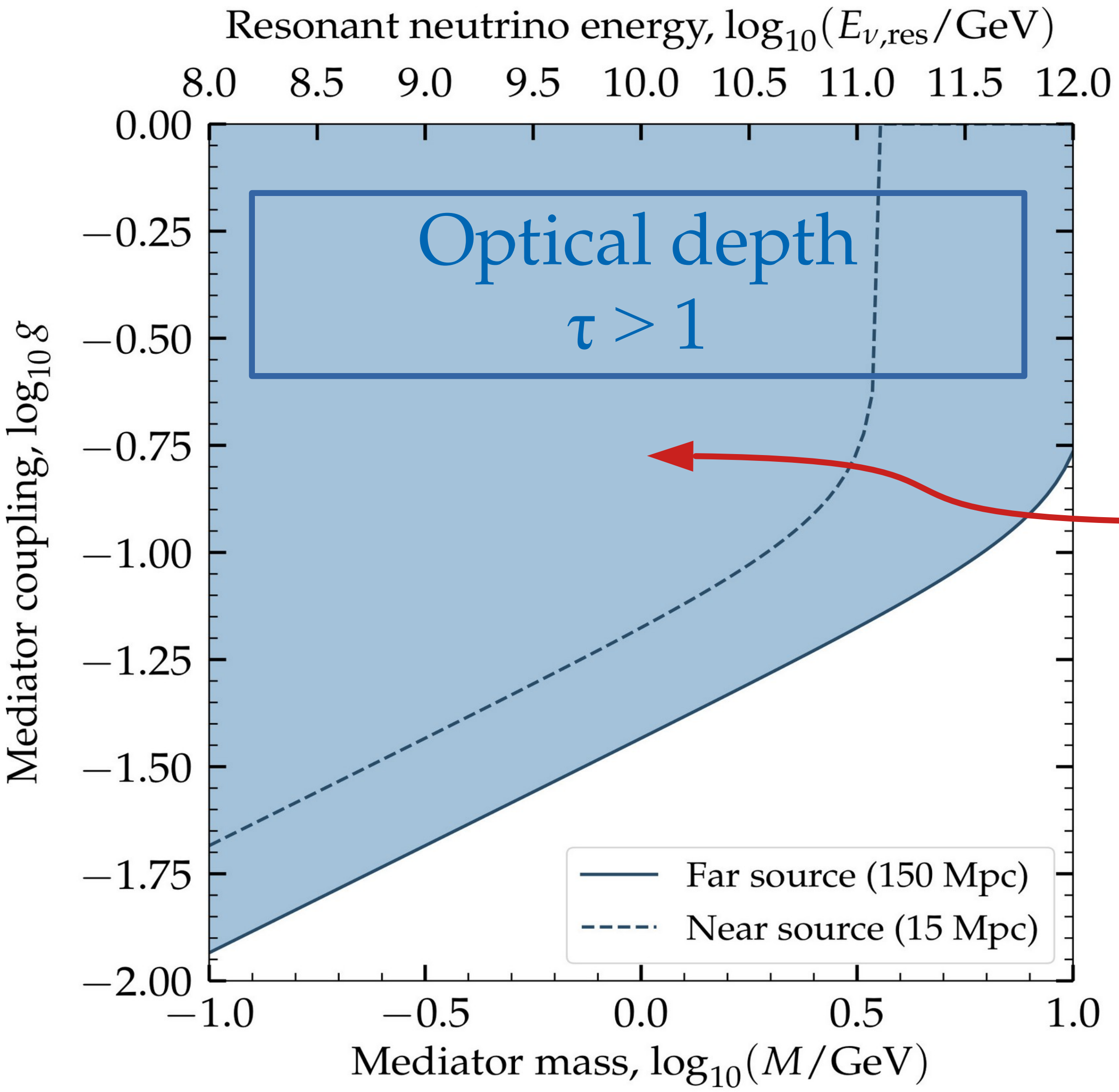

If POEMMA sees UHE ν from a flare, we can kill part of this parameter space

POEMMA Collab., *JCAP* 2021

What's next?

- For POEMMA — discover a UHE ν flare:
  - Full propagation of UHE ν from sources to Earth?
  - Include detector effects (energy resolution)?

- For POEMMA360 — look for spectral features in the diffuse UHE ν flux:
  - Can re-use the fluxes we have obtained already in MB, Másson, Valera (*In prep.*)
  - Need effective area
  - Include detector effects

Backup slides

What makes high-energy cosmic ν exciting?

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4. Neutrinos have a unique quantum number: flavor

   Particle: Versatile probe of flavor-sensitive new physics

   Astro: Can reveal the neutrino production mechanism

Fundamental physics with UHE cosmic neutrinos

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

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

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

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

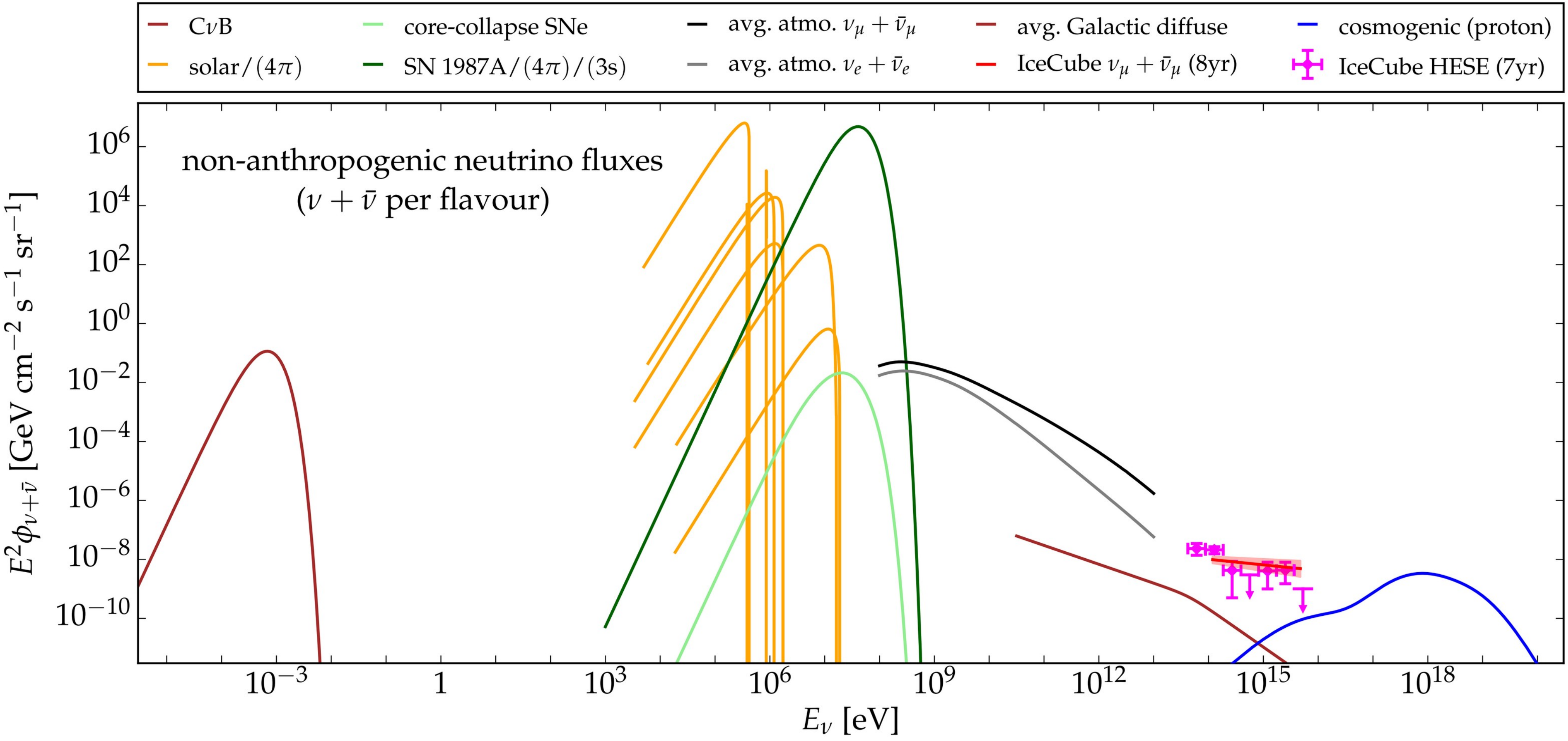
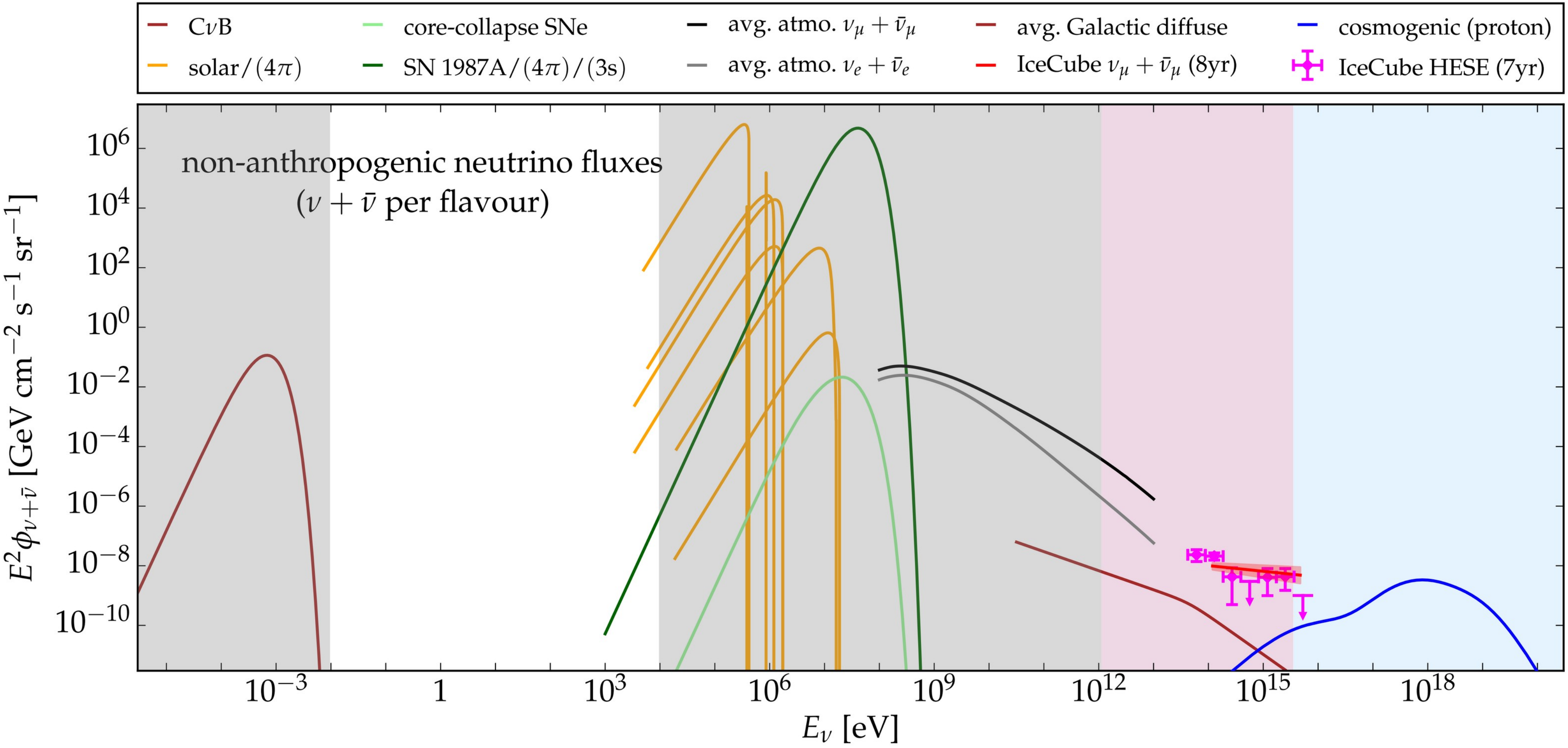


Figure courtesy of Markus Ahlers
Also in: Van Elewyck *et al.*, PoS(ICRC2019), 1023



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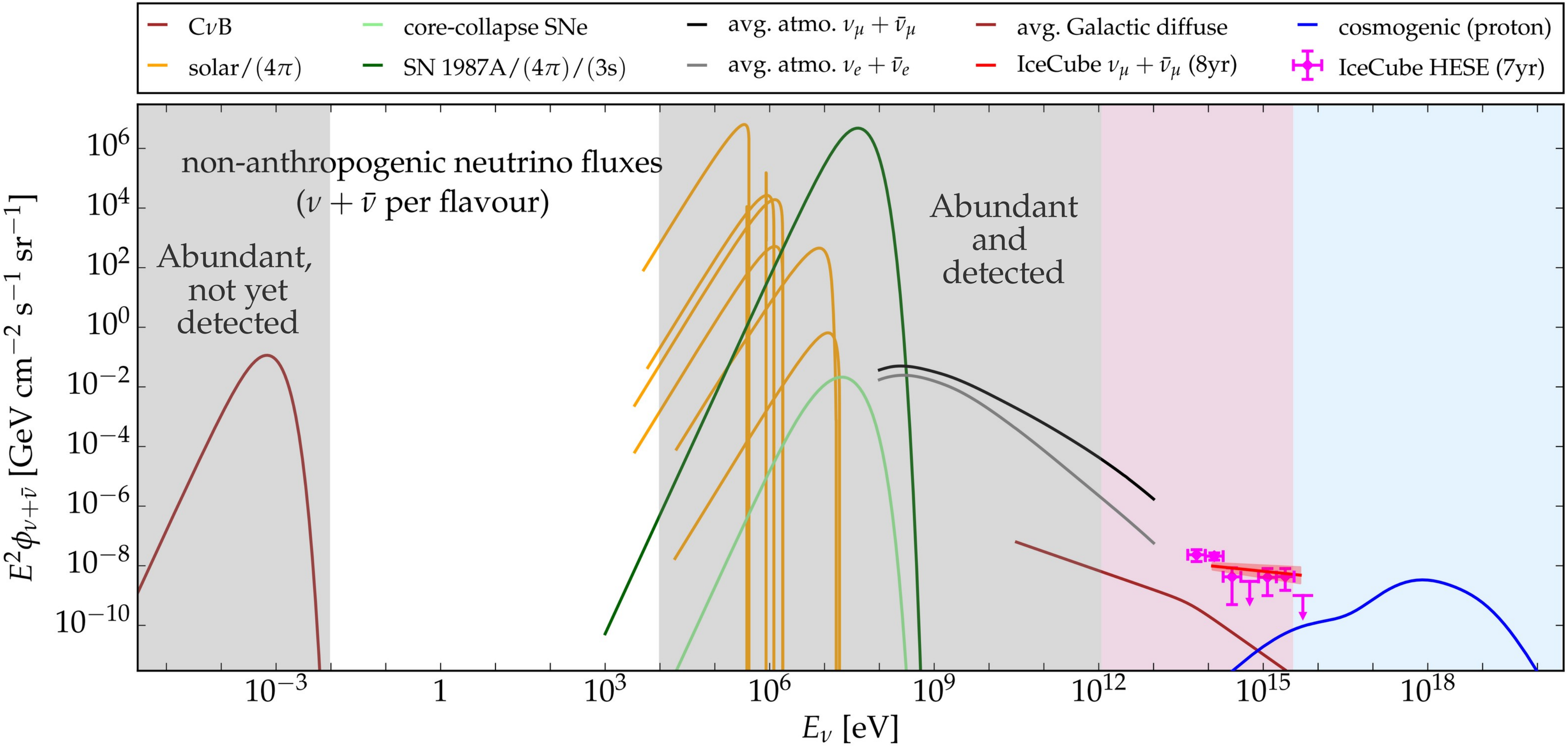

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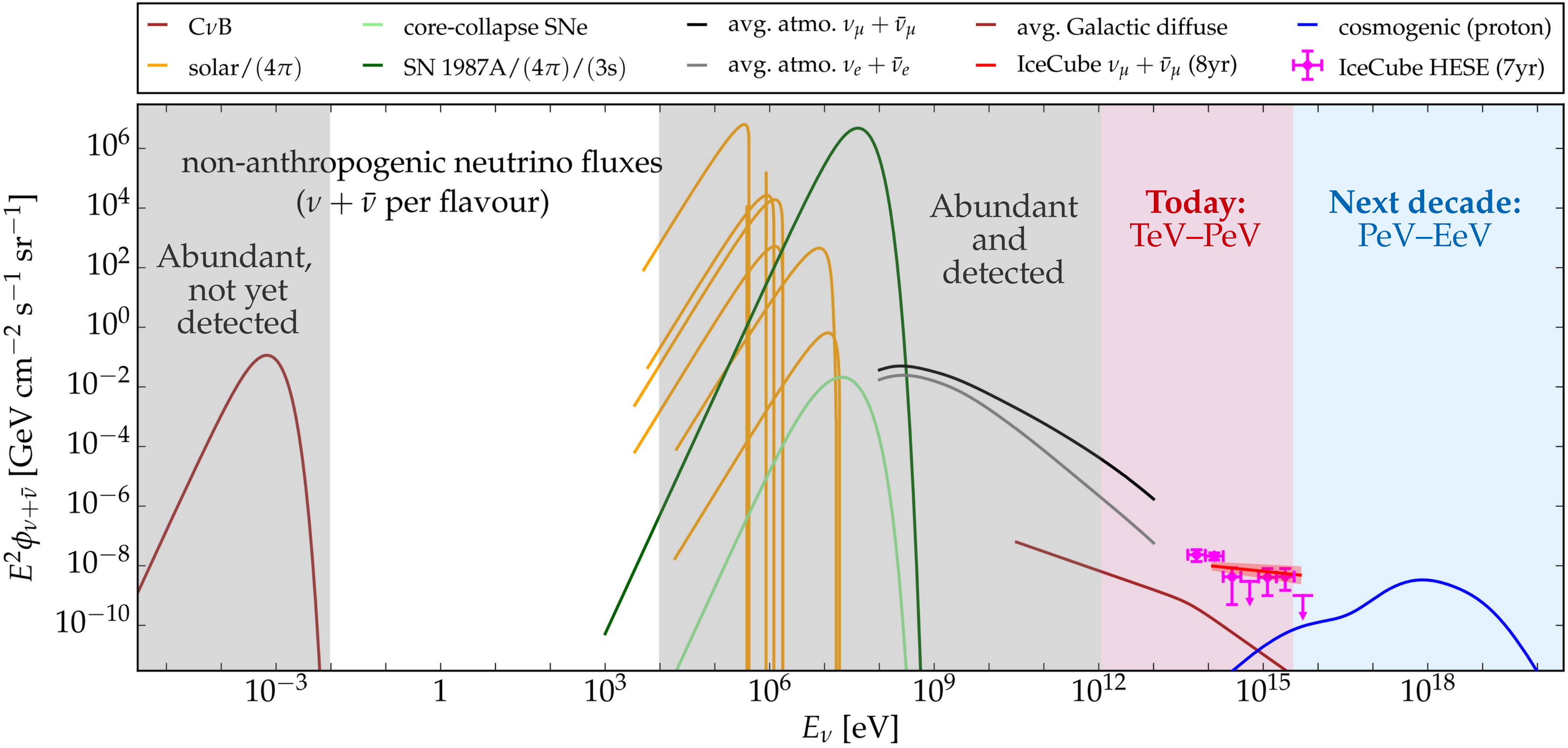

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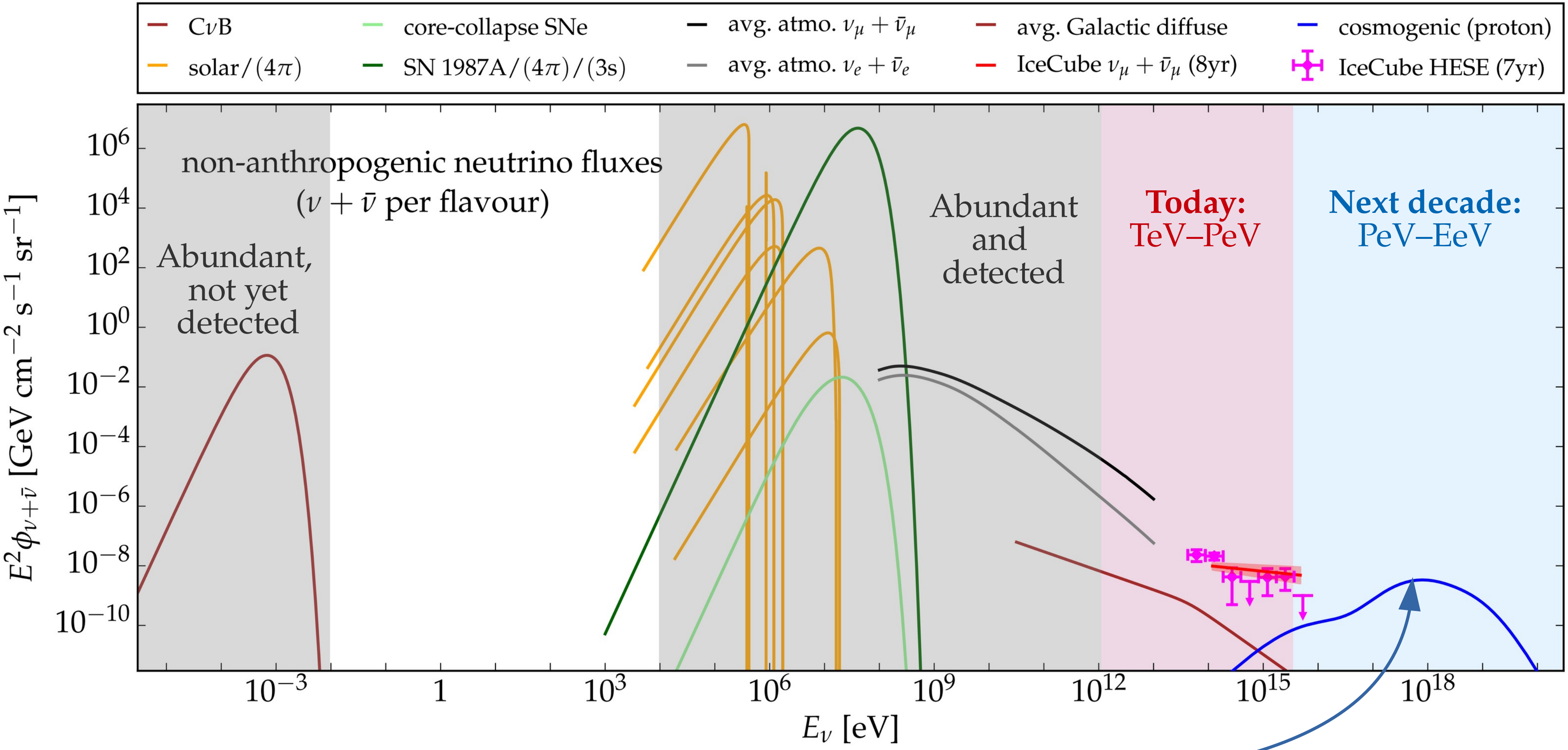
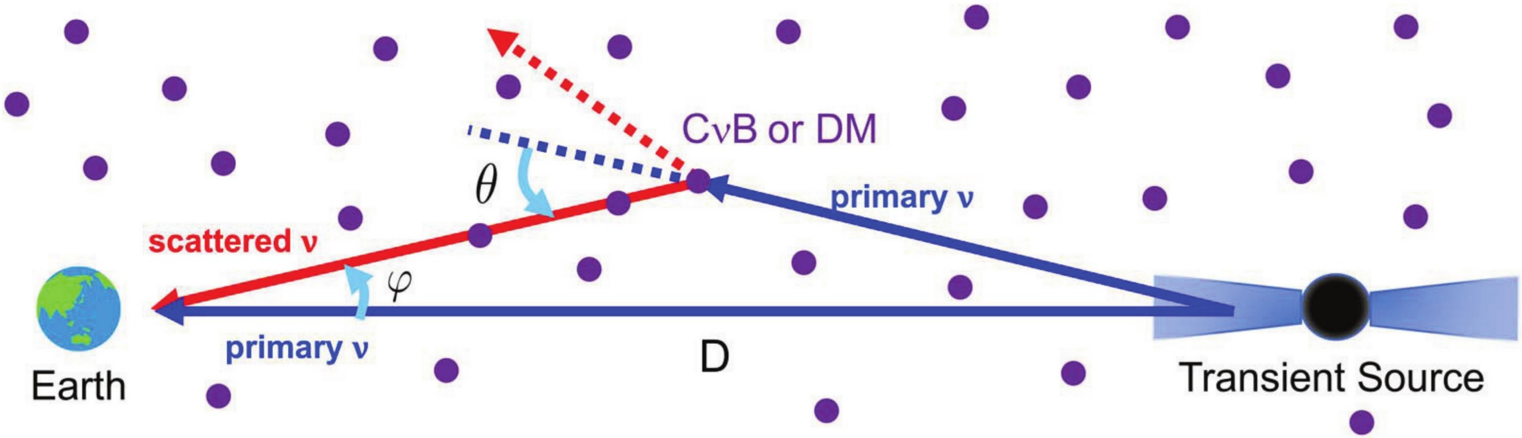


N.B.: POEMMA is *not* sensitive to cosmogenic ν

Figure courtesy of Markus Ahlers
Also in: Van Elewyck *et al.*, PoS(ICRC2019), 1023

Delays from secret interactions

Multiple secret νν scatterings may delay the arrival of neutrinos from a transient



Shoemaker & Murase, *PRL* 2019

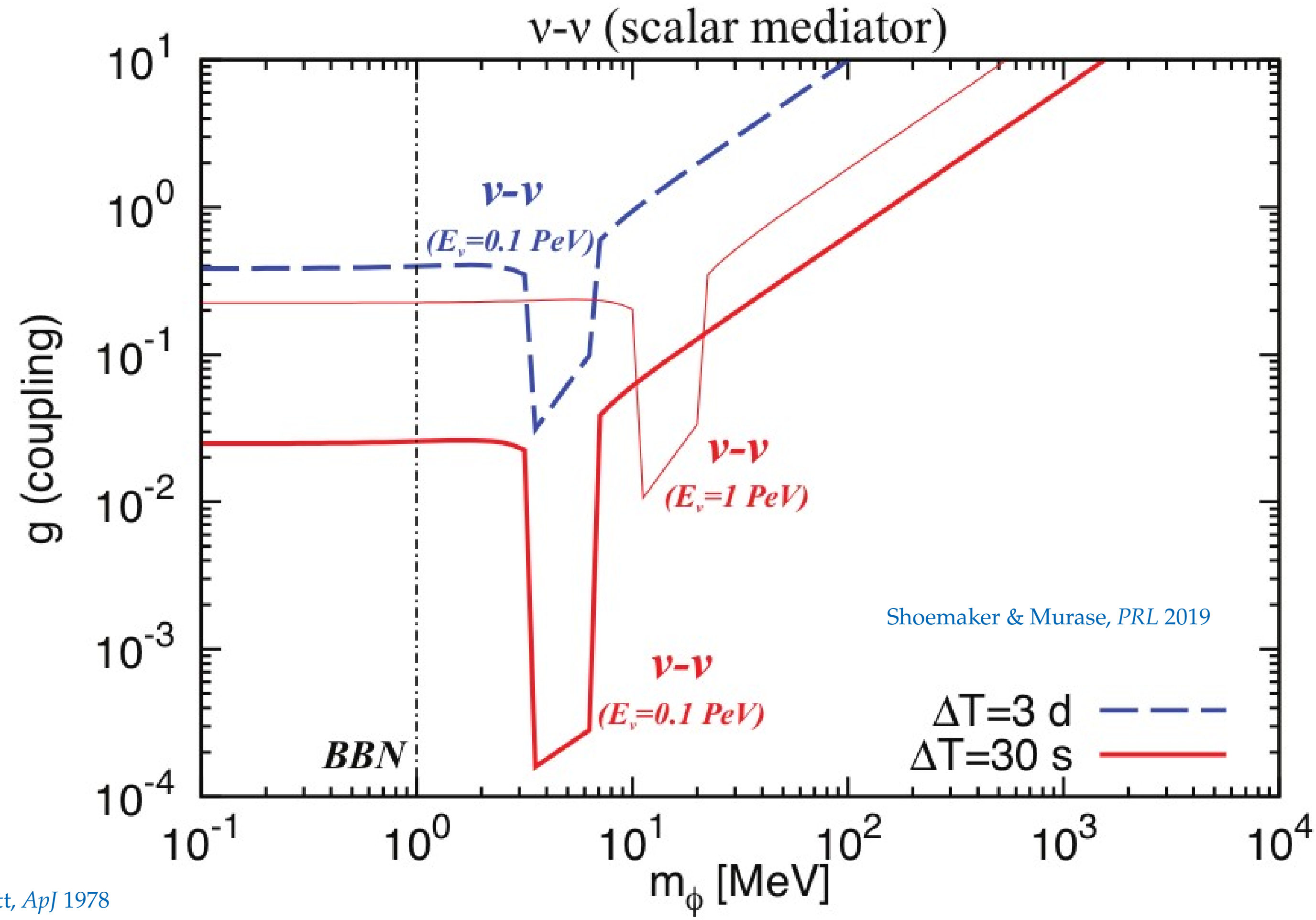
Characteristic time delay —

Optical depth to νν: $\tau_{\nu\nu} = n_\nu \, \sigma_{\nu\nu} \, D$

$$\Delta t \approx 1500\,\mathrm{s} \left(\frac{\tau_{\nu\nu}}{30}\right) \left(\frac{D}{3\ \mathrm{Gpc}}\right) \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right) \left(\frac{0.1\ \mathrm{PeV}}{E_\nu}\right)$$

See also: Alcock & Hatchett, *ApJ* 1978

Delays from secret interactions



Shoemaker & Murase, *PRL* 2019

See also: Alcock & Hatchett, *ApJ* 1978

The multi-messenger connection: a simple picture

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

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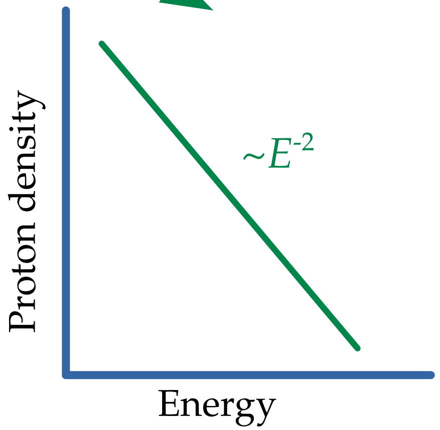

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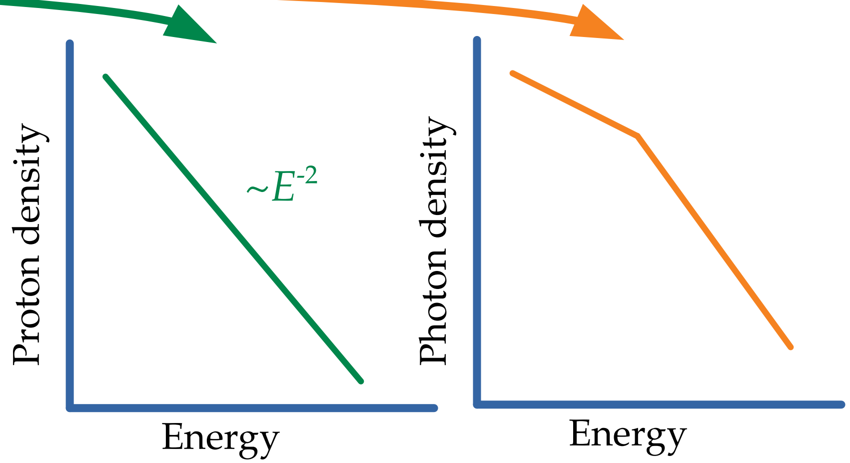

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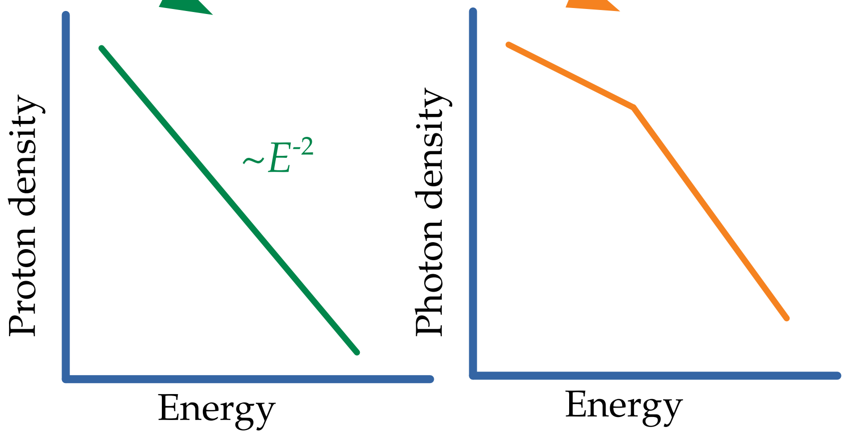
$$\pi^0 \rightarrow \gamma + \gamma$$

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

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



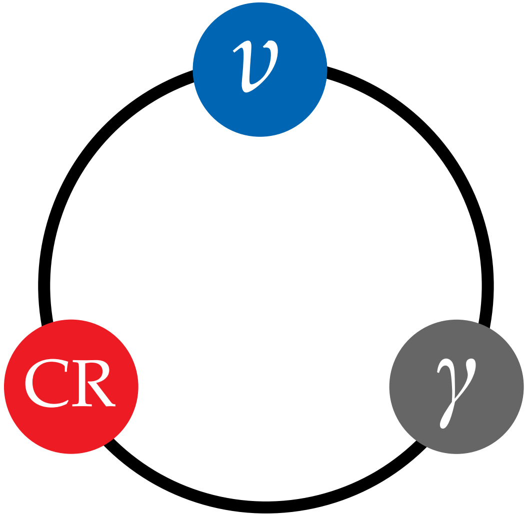
The multi-messenger connection: a simple picture

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

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

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

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



Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

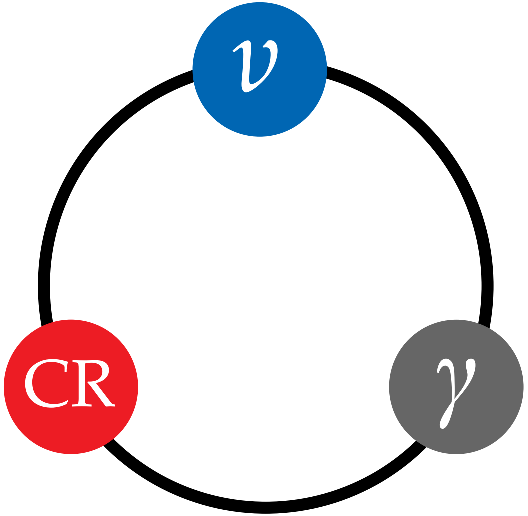
The multi-messenger connection: a simple picture

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

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

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

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



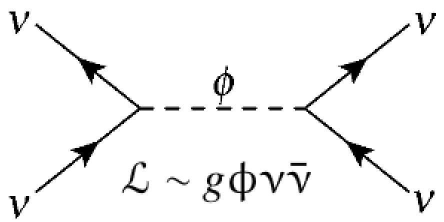
1 PeV 20 PeV

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

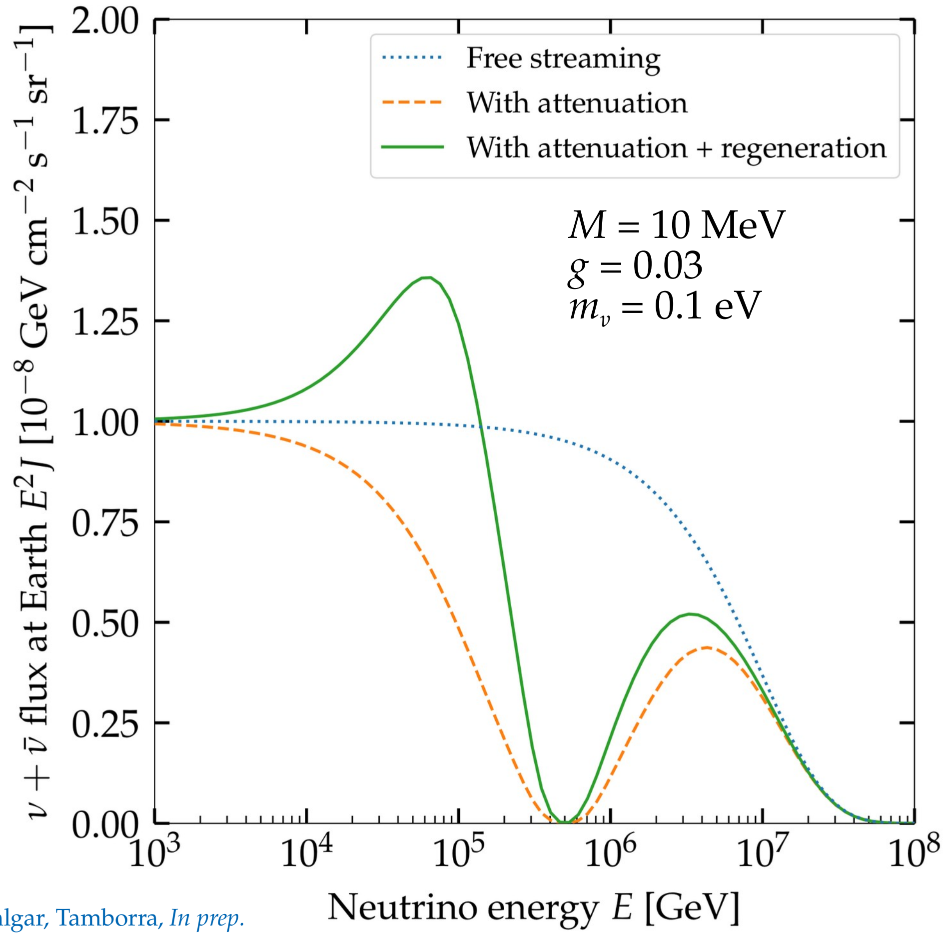
New physics in the spectral shape: νν interactions

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



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

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



MB, Rosenstroem, Shalgar, Tamborra, *In prep.*
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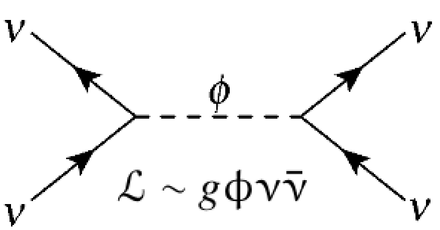

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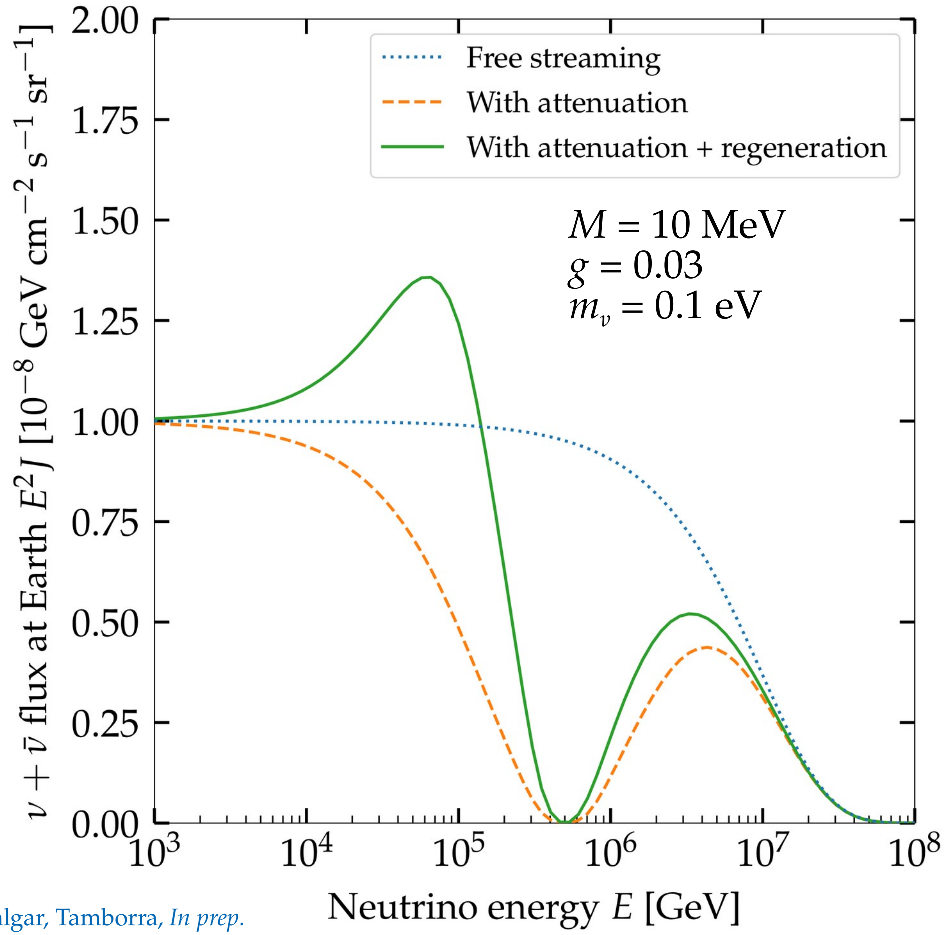

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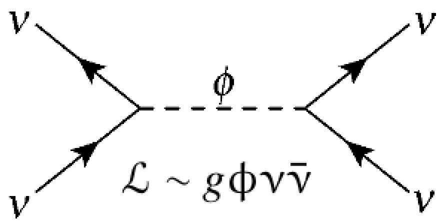

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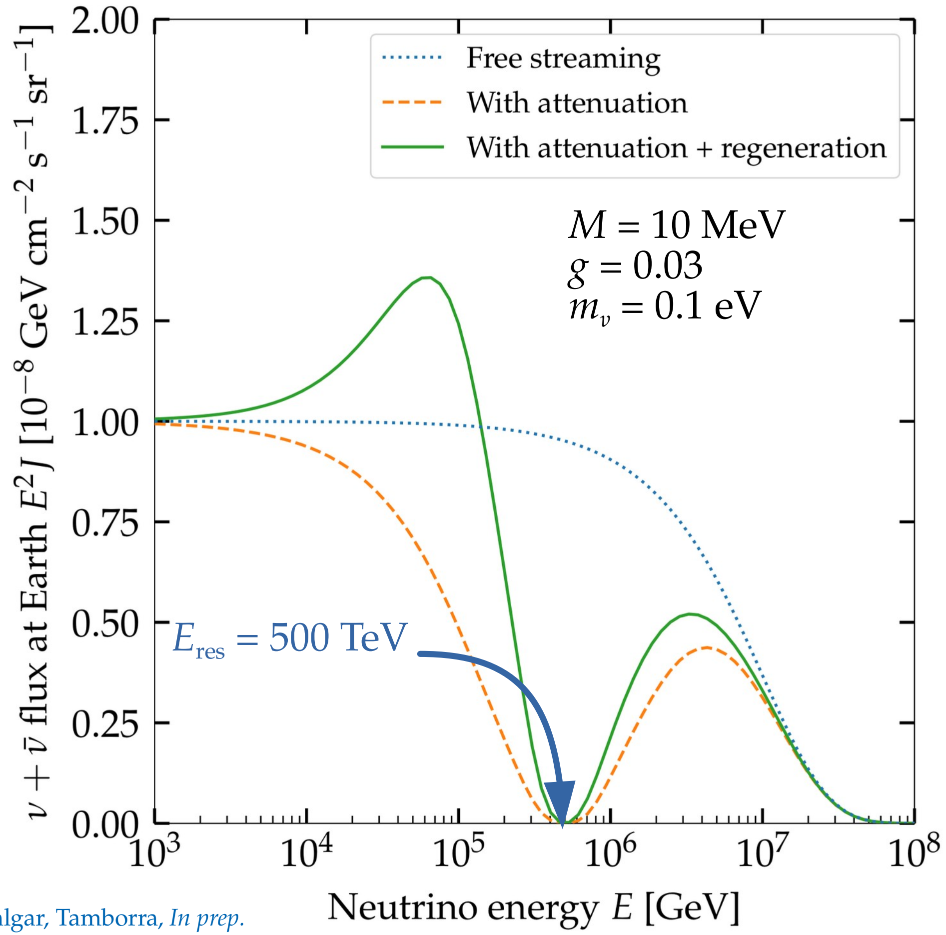

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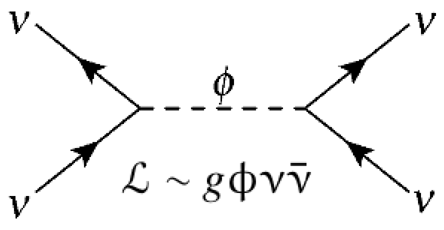

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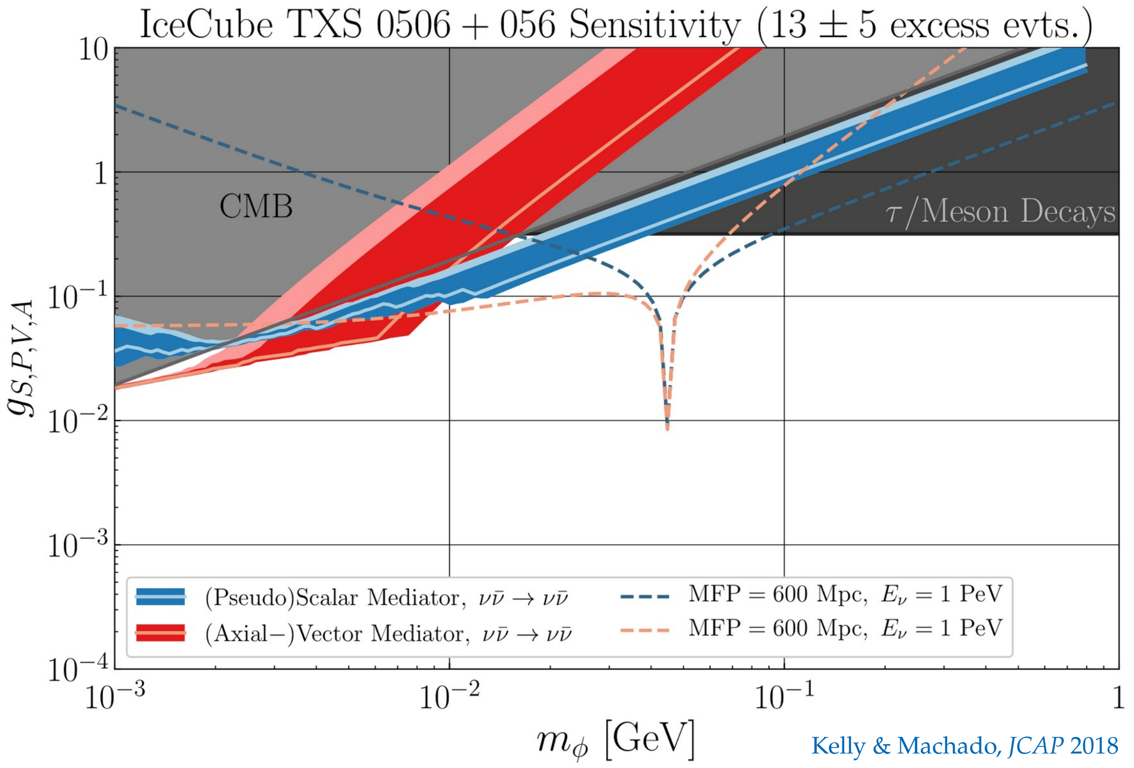
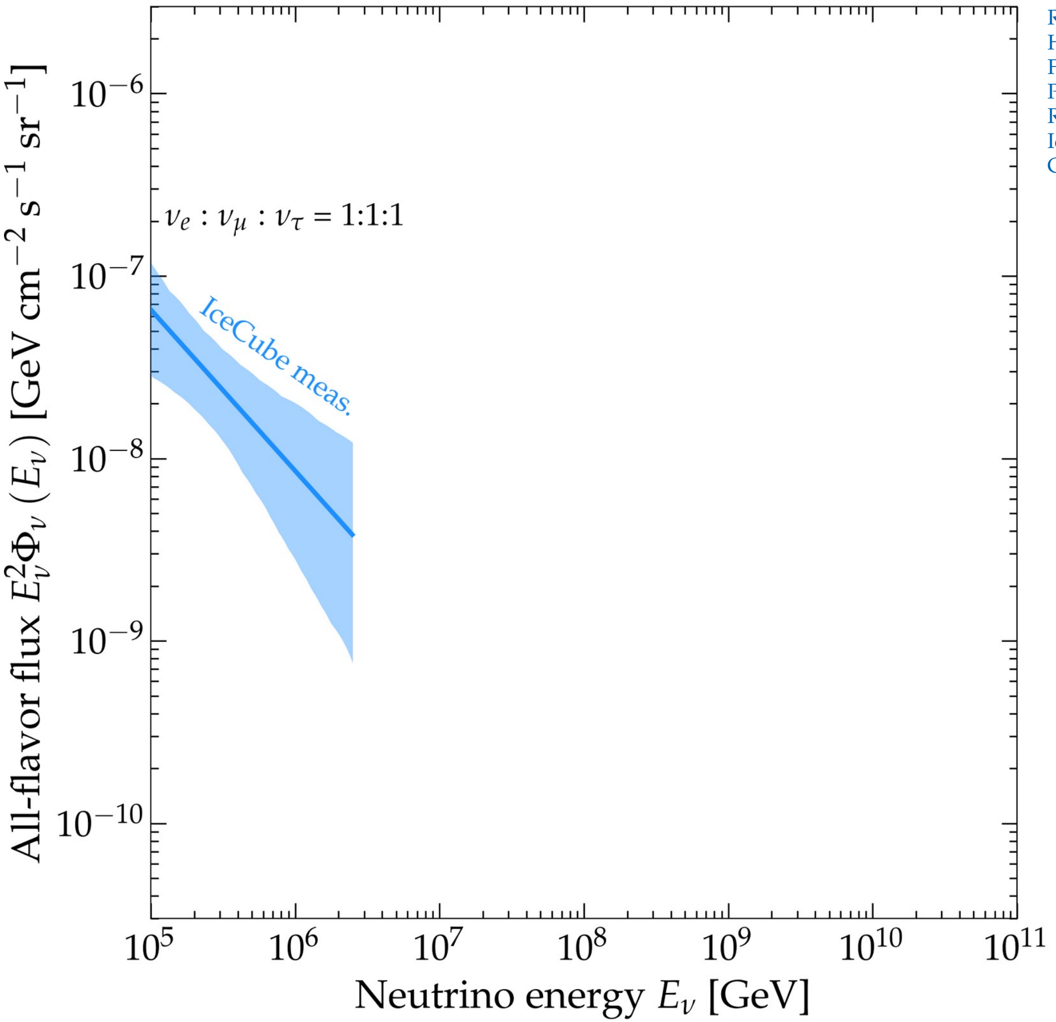


Kelly & Machado, *JCAP* 2018

UHE neutrinos: *steady-state sources*



Rodrigues, Heinze, Palladino, van Vliet, Winter, 2003.08392
Heinze, Fedynitch, Boncioli, Winter *ApJ* 2019
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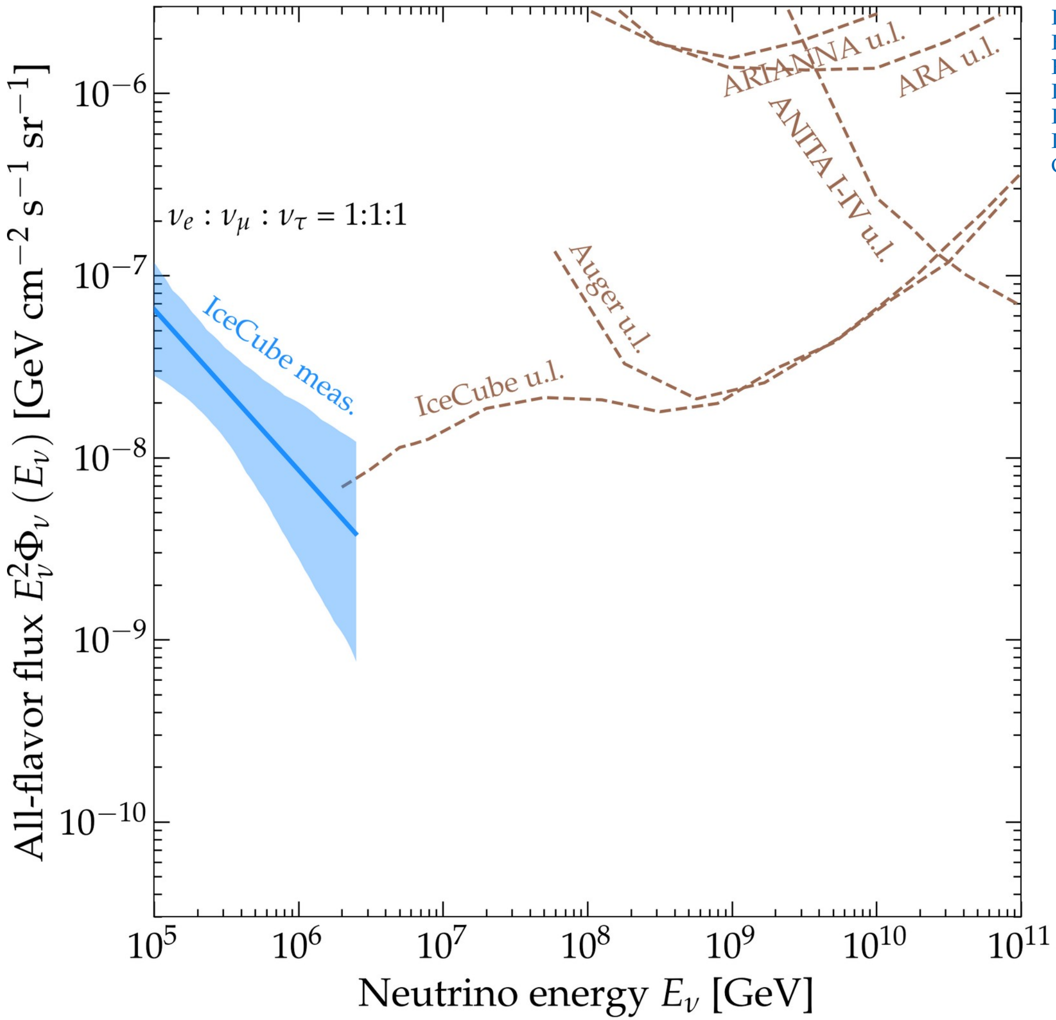

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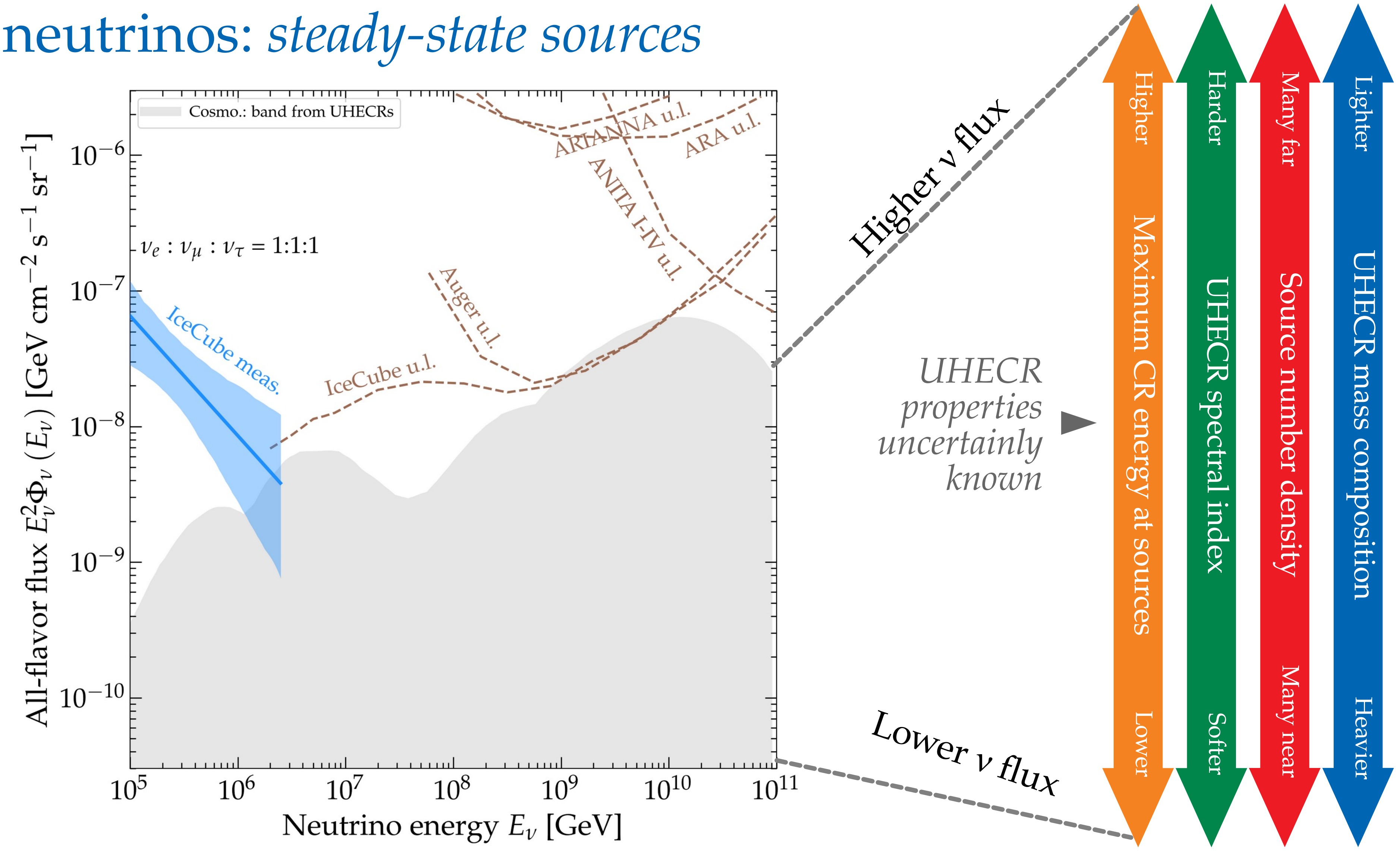

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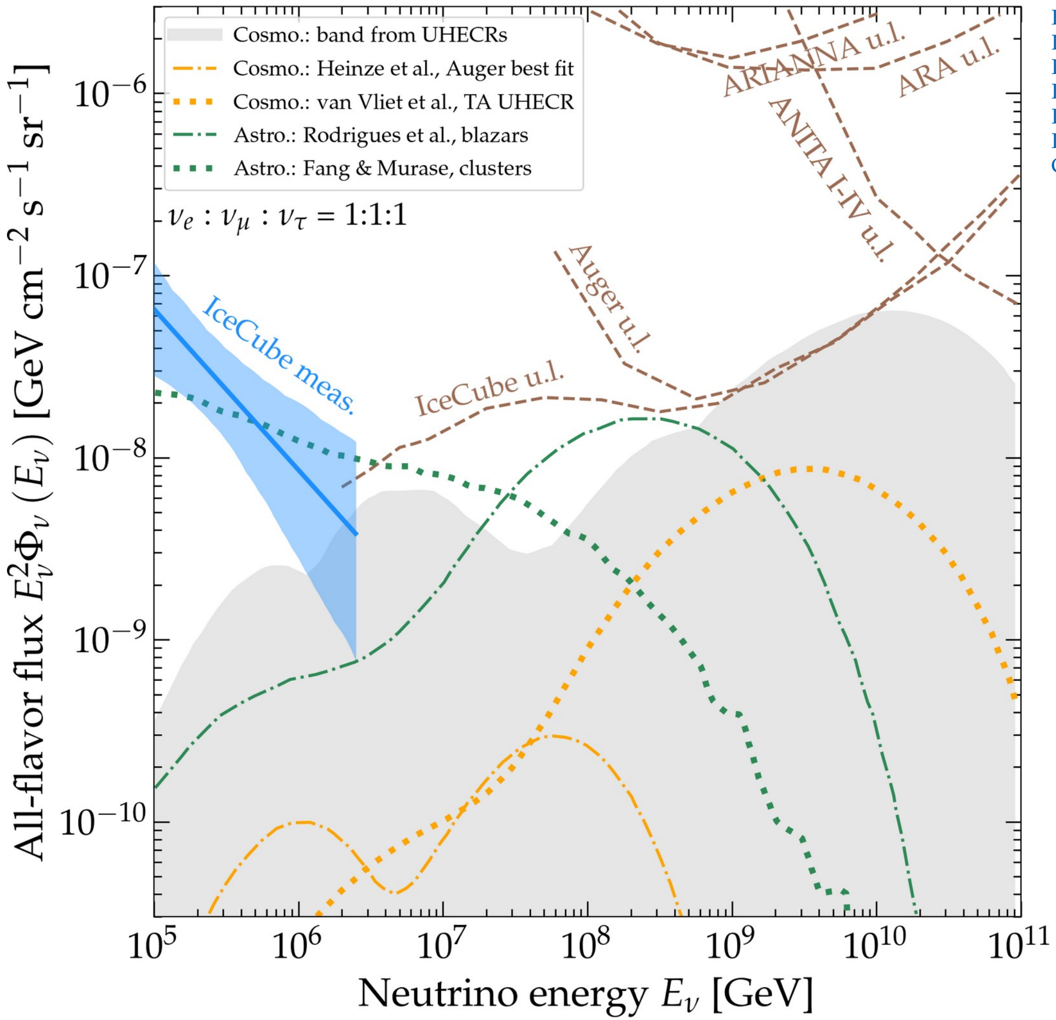

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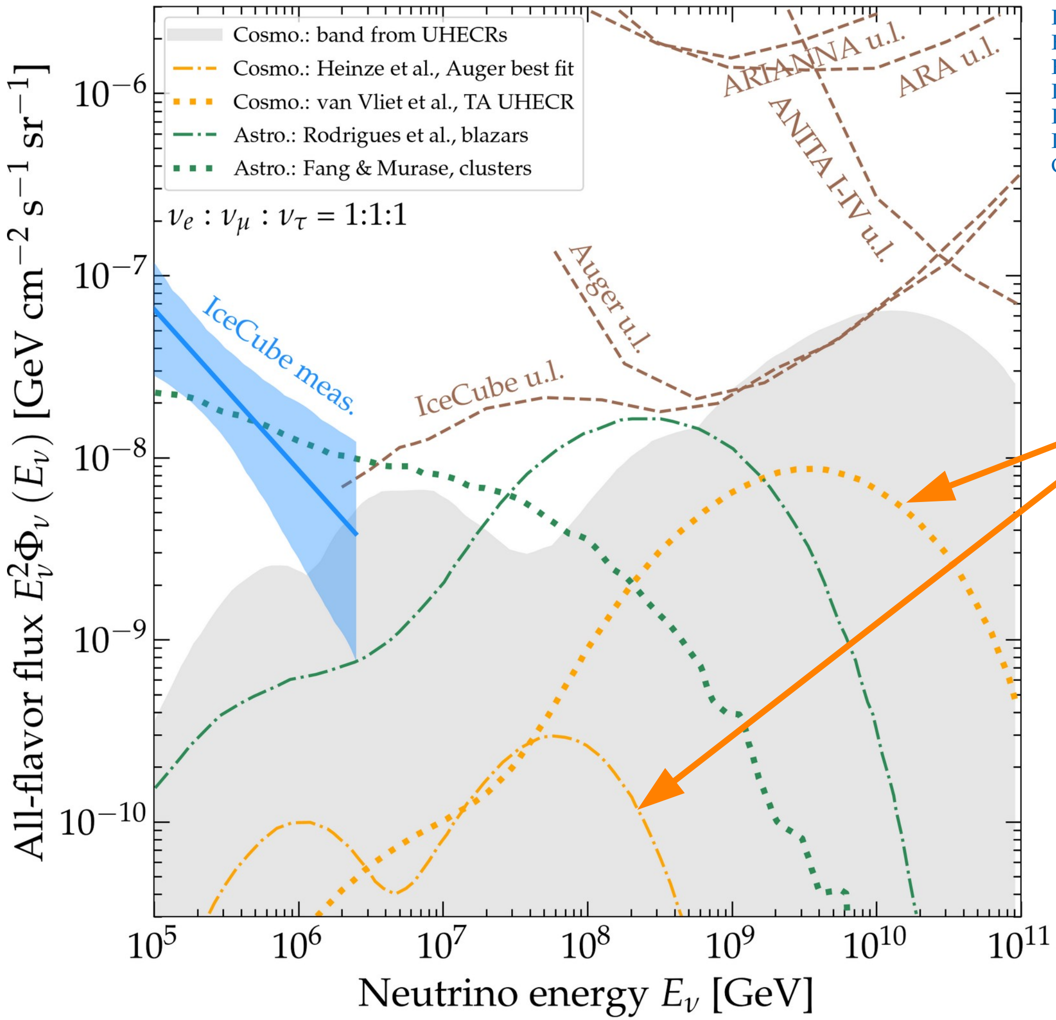

Cosmogenic neutrinos

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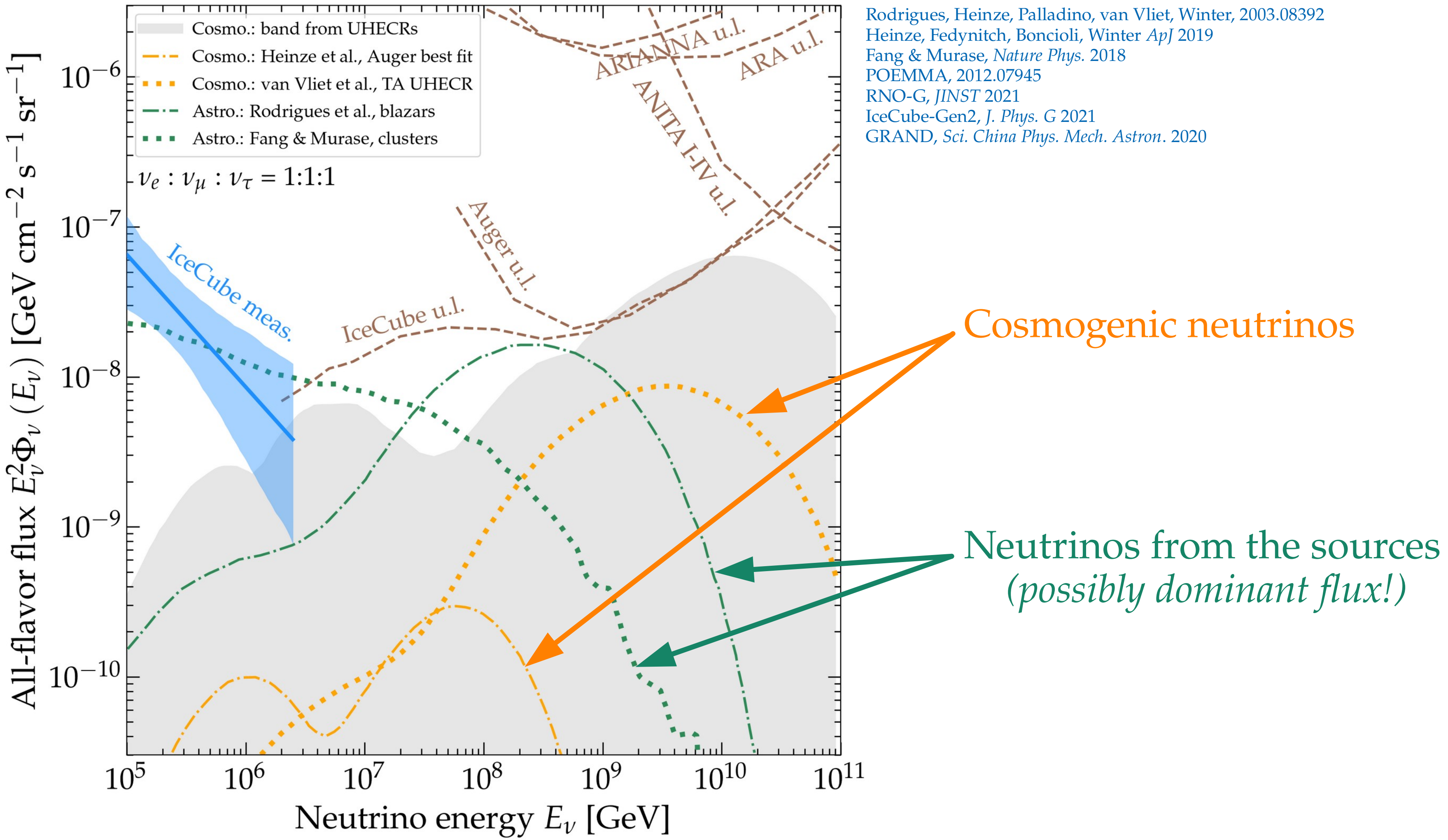

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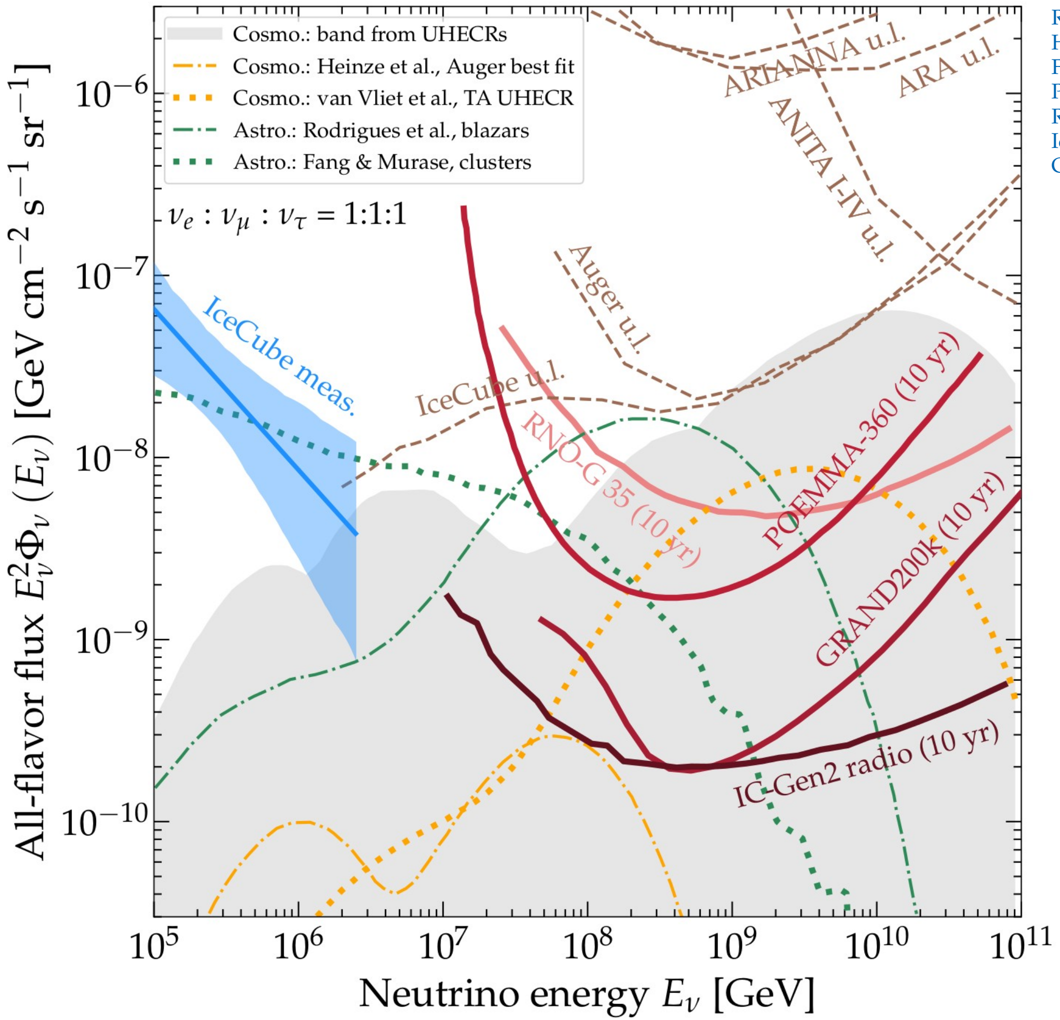

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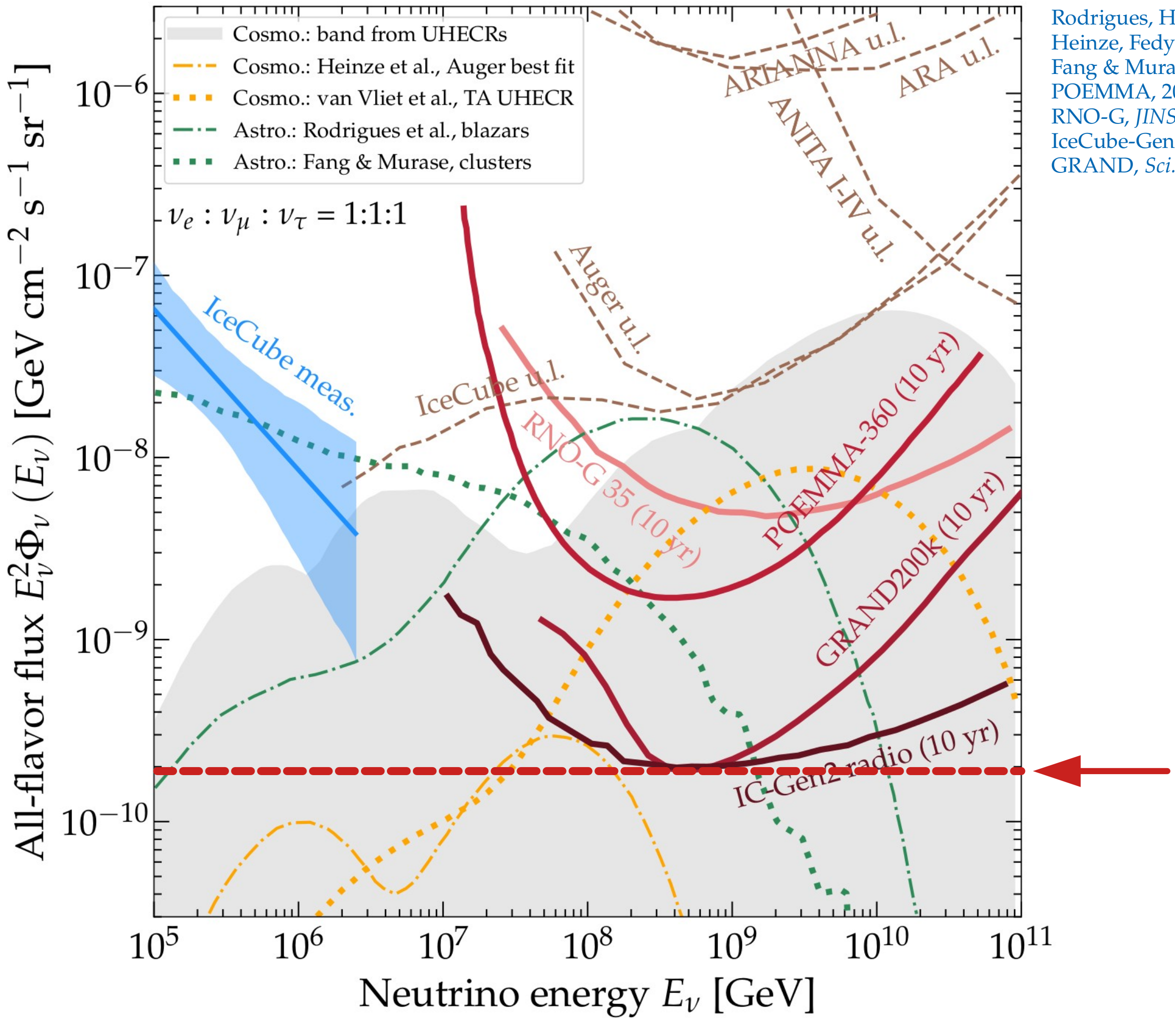

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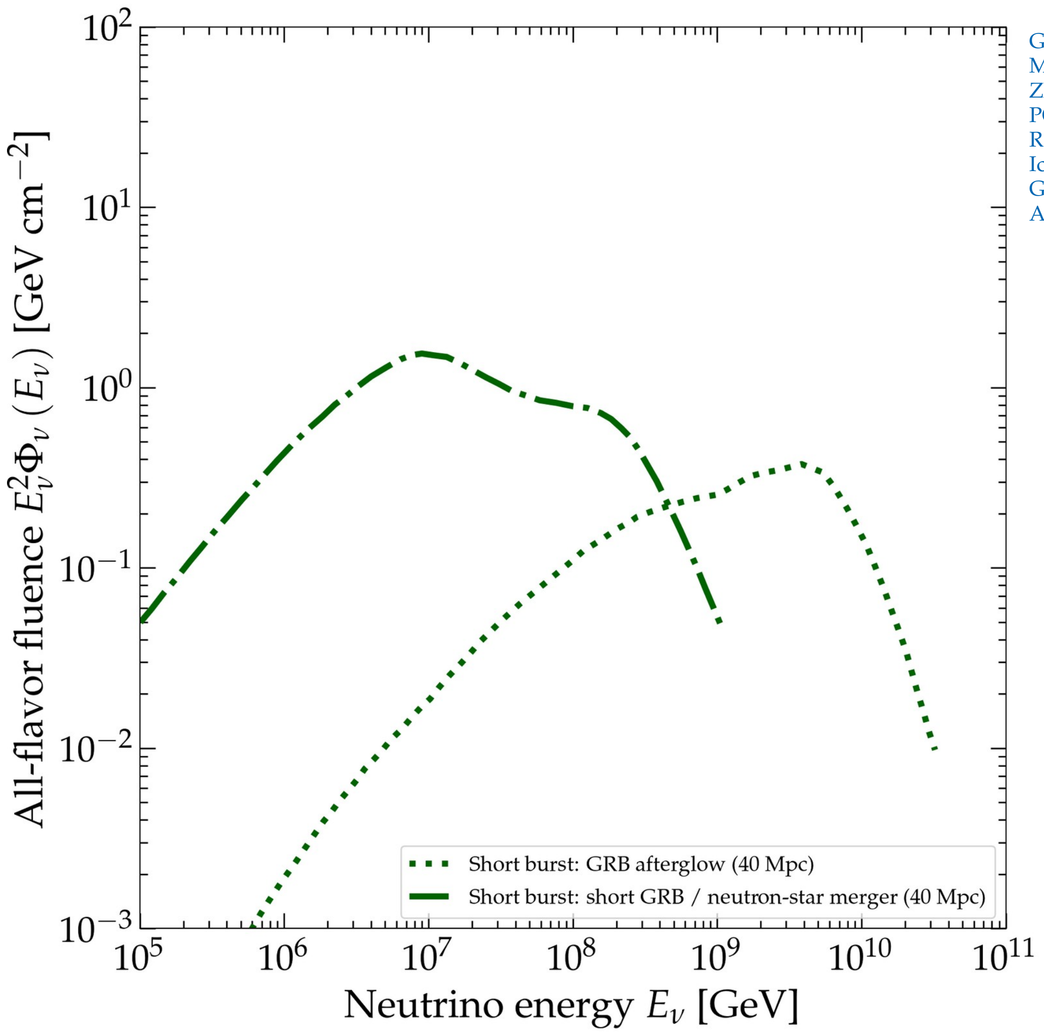
Ultimate target sensitivity for next-gen detectors

(if protons are ~10% of the highest-energy UHECRs)

UHE neutrinos: *transient sources*



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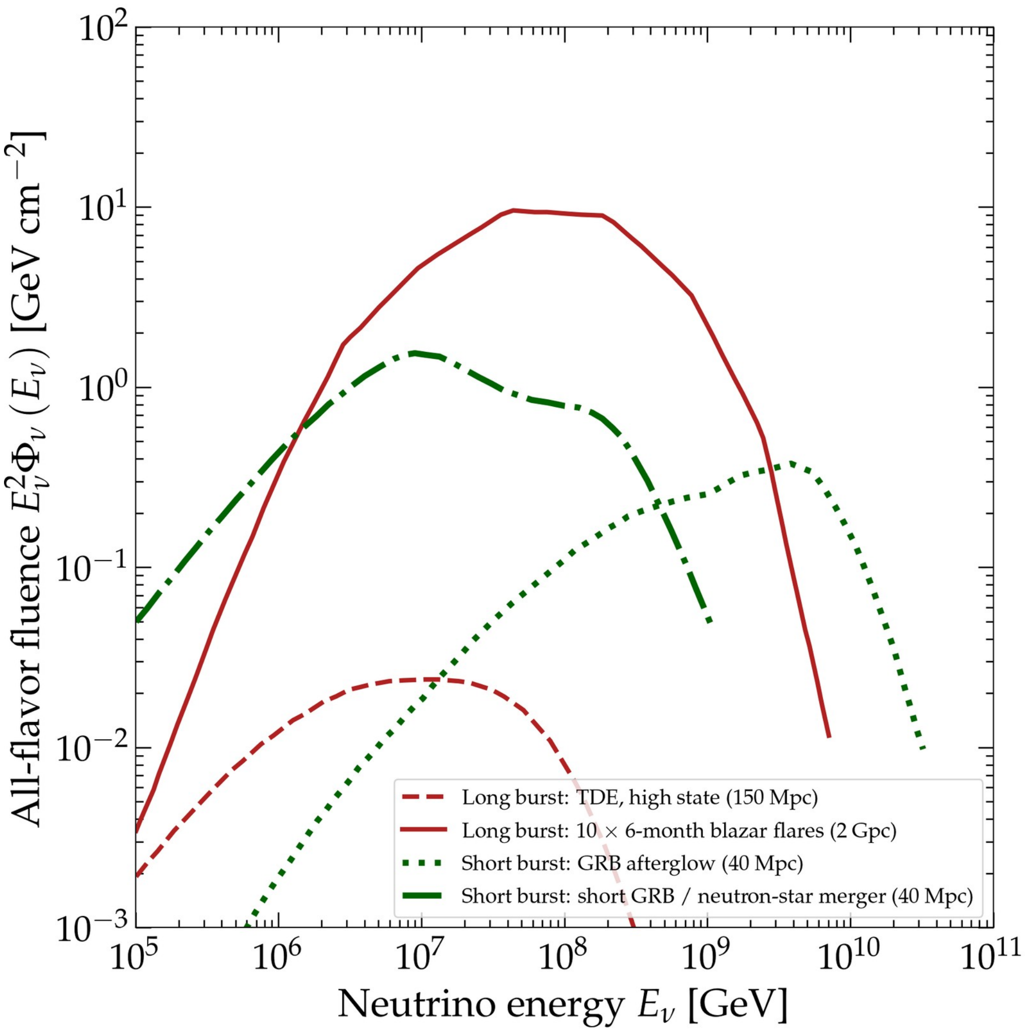

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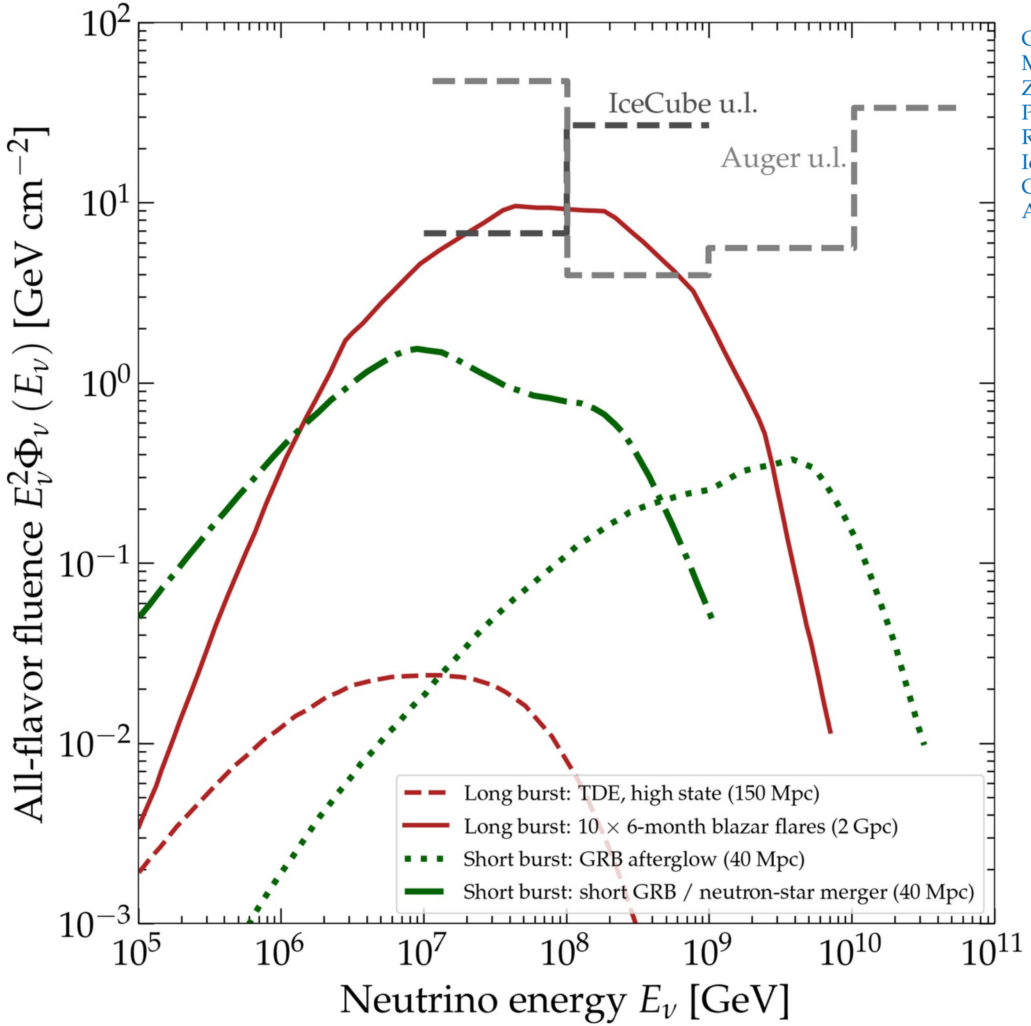

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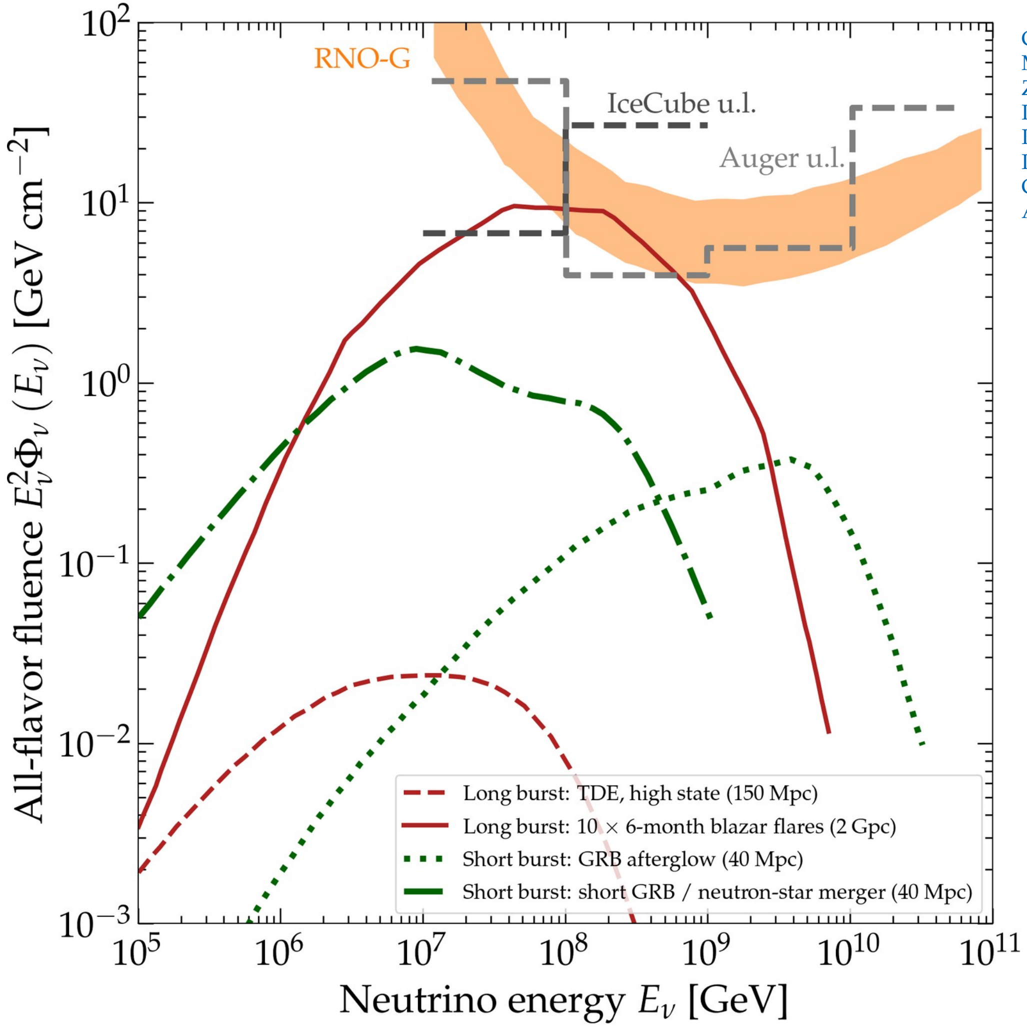

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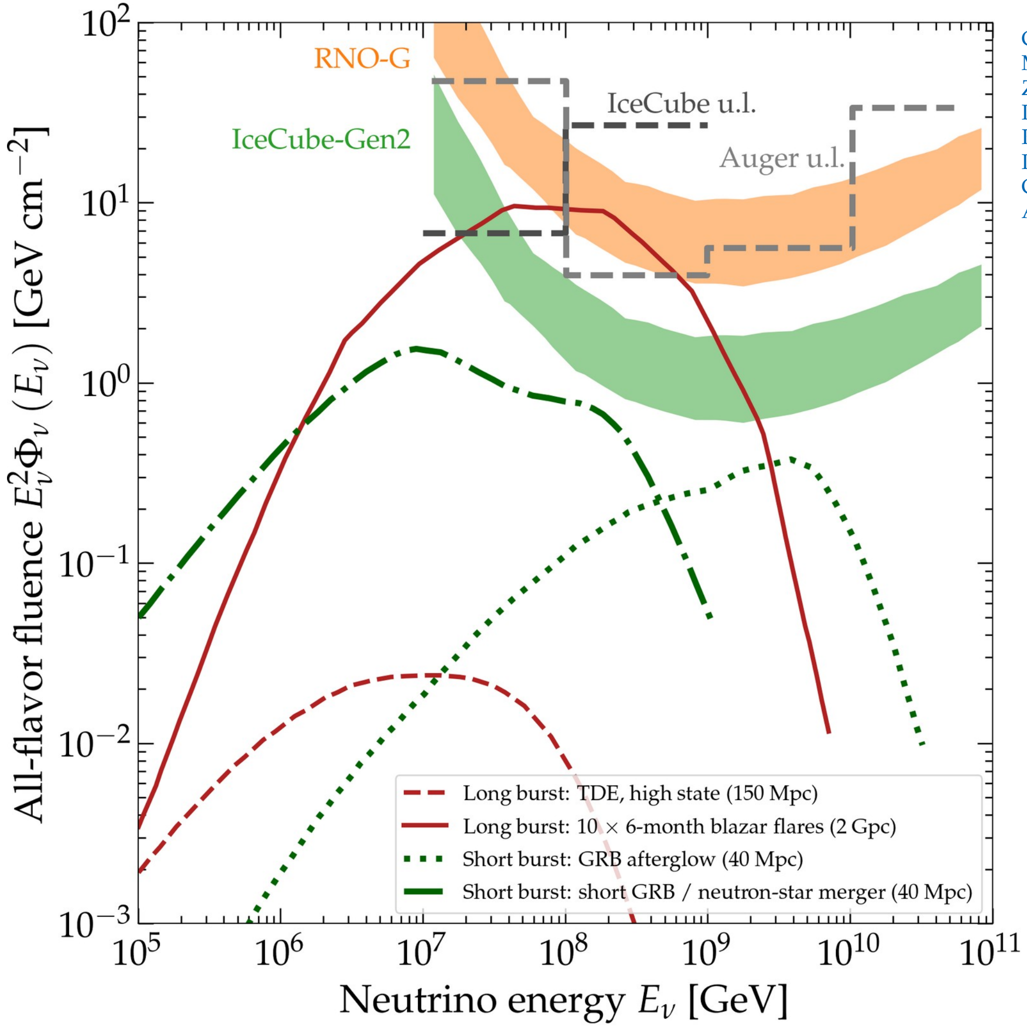

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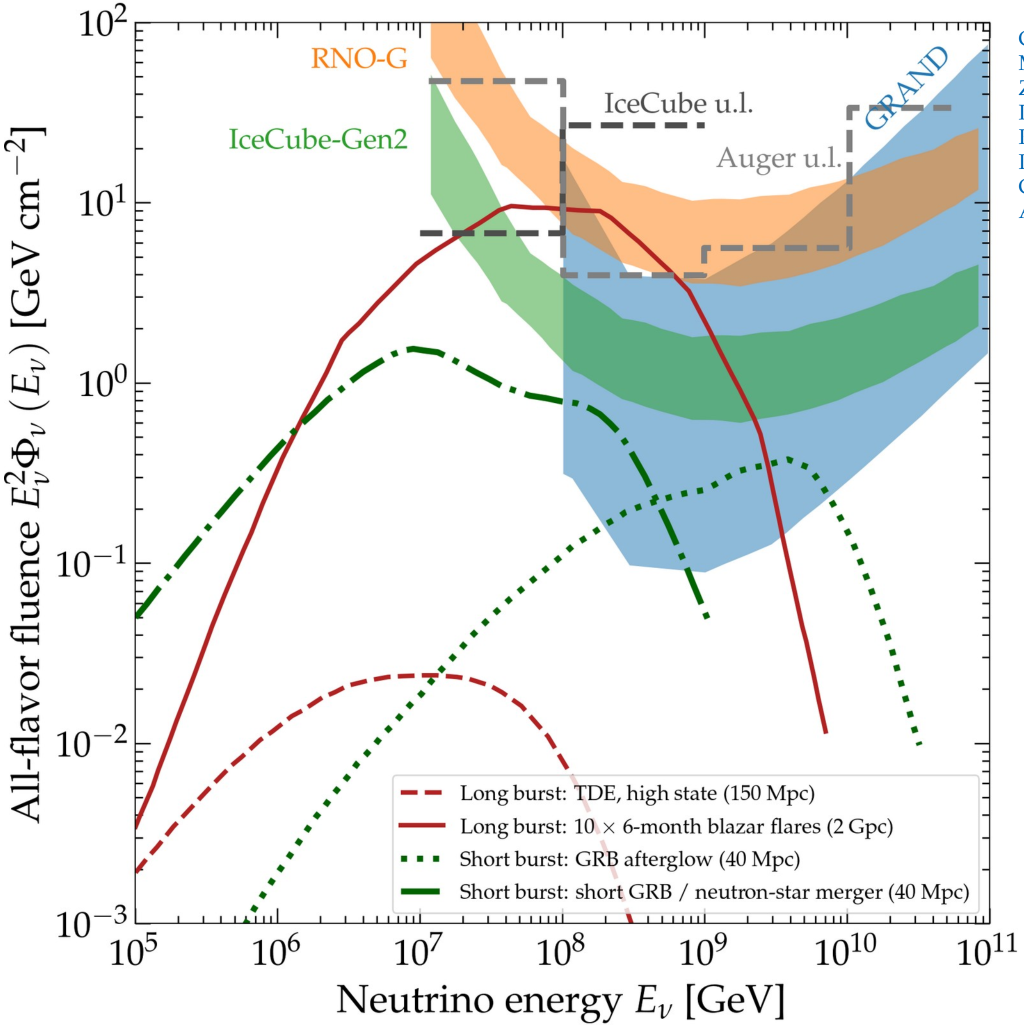

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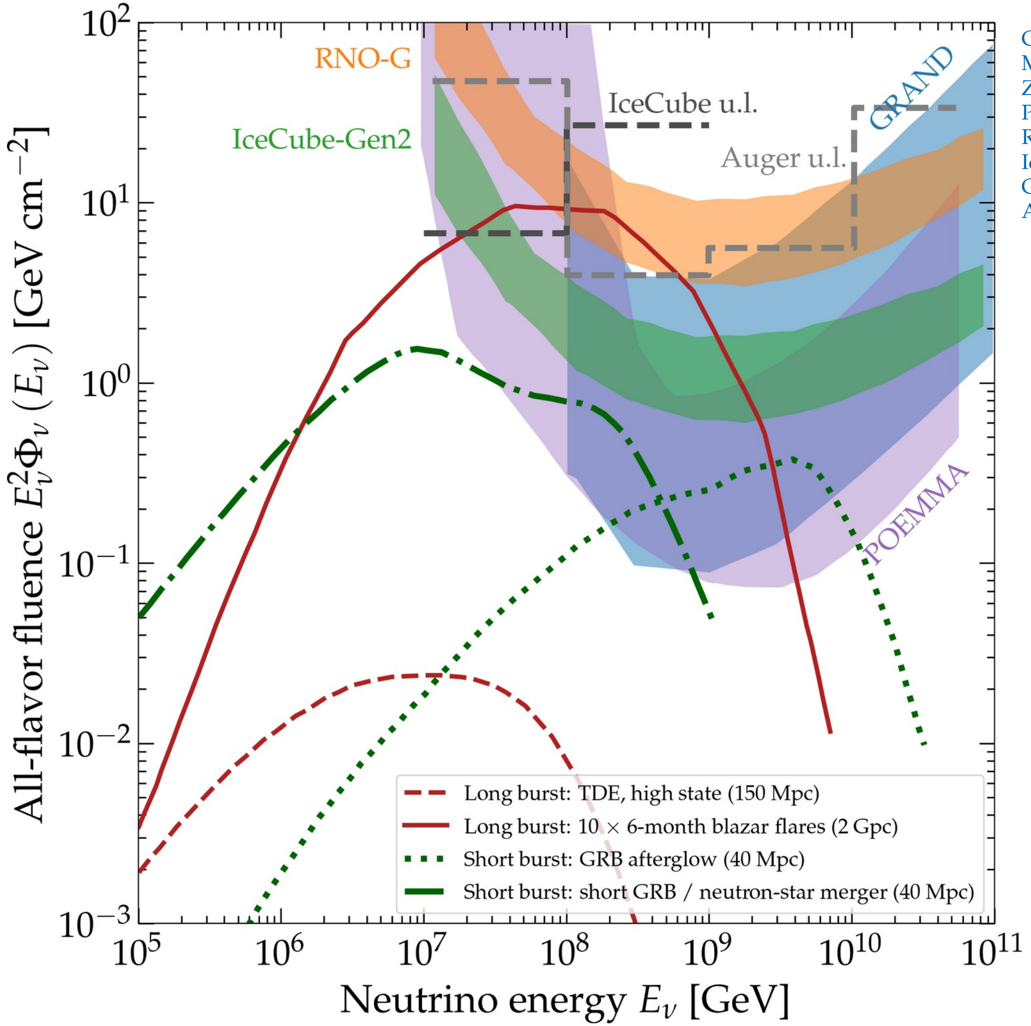

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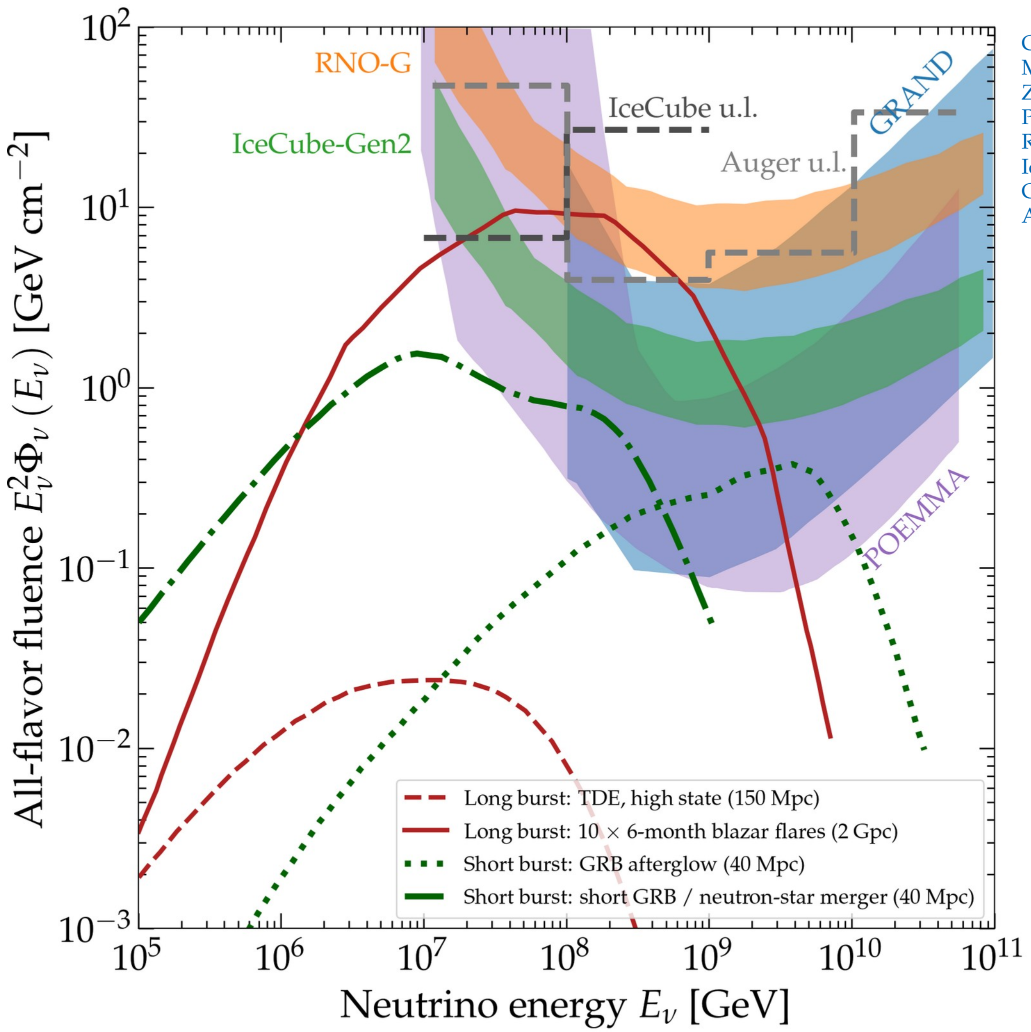

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Take-home message

We might see an UHE ν burst before we see a diffuse flux