Widen the Resonance: Probing a New Regime of Neutrino Self-Interactions with Astrophysical Neutrinos

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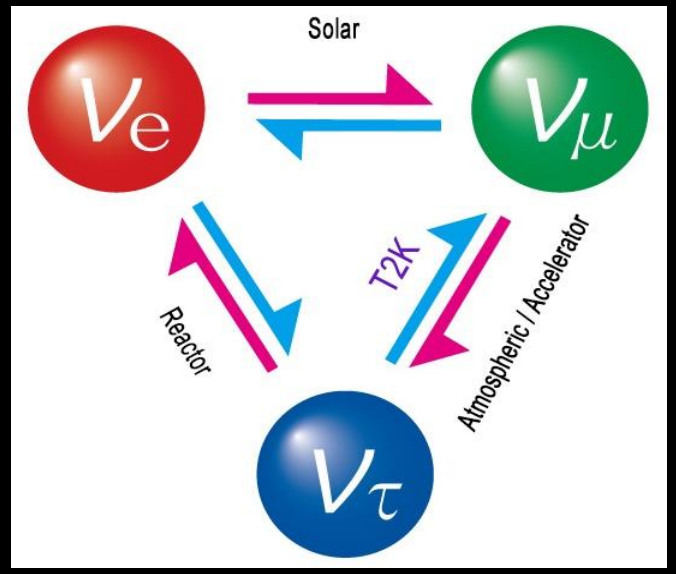
Isaac Wang (Fermilab), Xun-Jie Xu (IHEP), Bei Zhou (Fermilab & KICP), arXiv: 2501.07624 & PRL

Pedro A. N. Machado (Fermilab), Isaac R. Wang, Xun-Jie Xu, Bei Zhou, arXiv: 2512.00165

Neutrinos have new physics

Neutrino oscillation indicates neutrinos have masses



$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\,\sin^2\left(1.27\,\frac{\Delta m^2\,[\mathrm{eV}^2]\cdot L\,[\mathrm{km}]}{E\,[\mathrm{GeV}]}\right)$$

Nonzero neutrino masses guarantee new physics

$$\mathcal{L}_{\mathrm{Dirac}} = -y_\nu\,\bar{L}\tilde{H}\nu_R + \mathrm{h.c.}$$

$$\Rightarrow \quad m_\nu^{\mathrm{Dirac}} = y_\nu\,\frac{v}{\sqrt{2}}$$

$$\mathcal{L}_{\mathrm{Majorana}} = \frac{c}{\Lambda}\left(\bar{L}\tilde{H}\right)\left(\tilde{H}^T L^c\right) + \mathrm{h.c.}$$

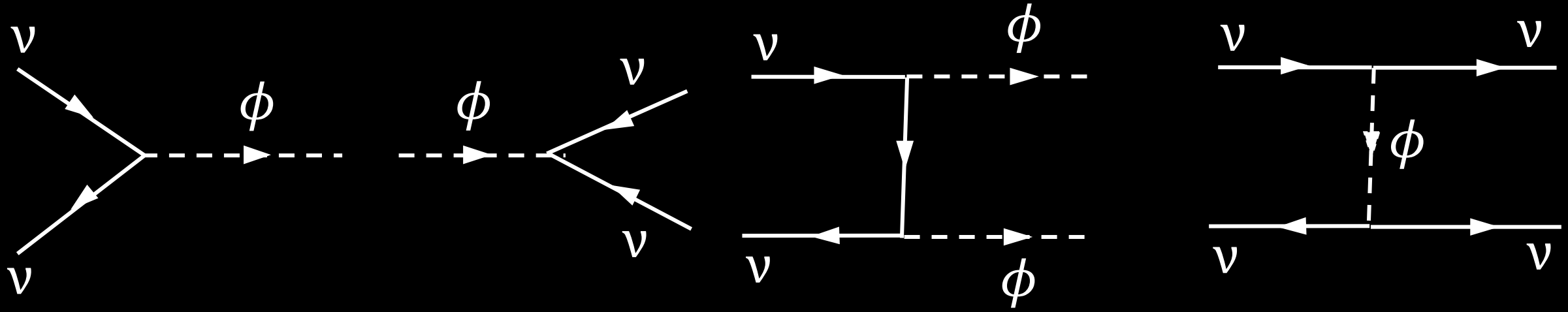
$$\Rightarrow \quad m_\nu^{\mathrm{Majorana}} \sim \frac{c\,v^2}{\Lambda}$$

Neutrino masses motivate neutrino self-interactions (NuSI)

$$\mathcal{L} \supset \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 + g_\nu\phi(\nu\nu + \nu^\dagger\nu^\dagger)$$

NuSI (flavor universal)

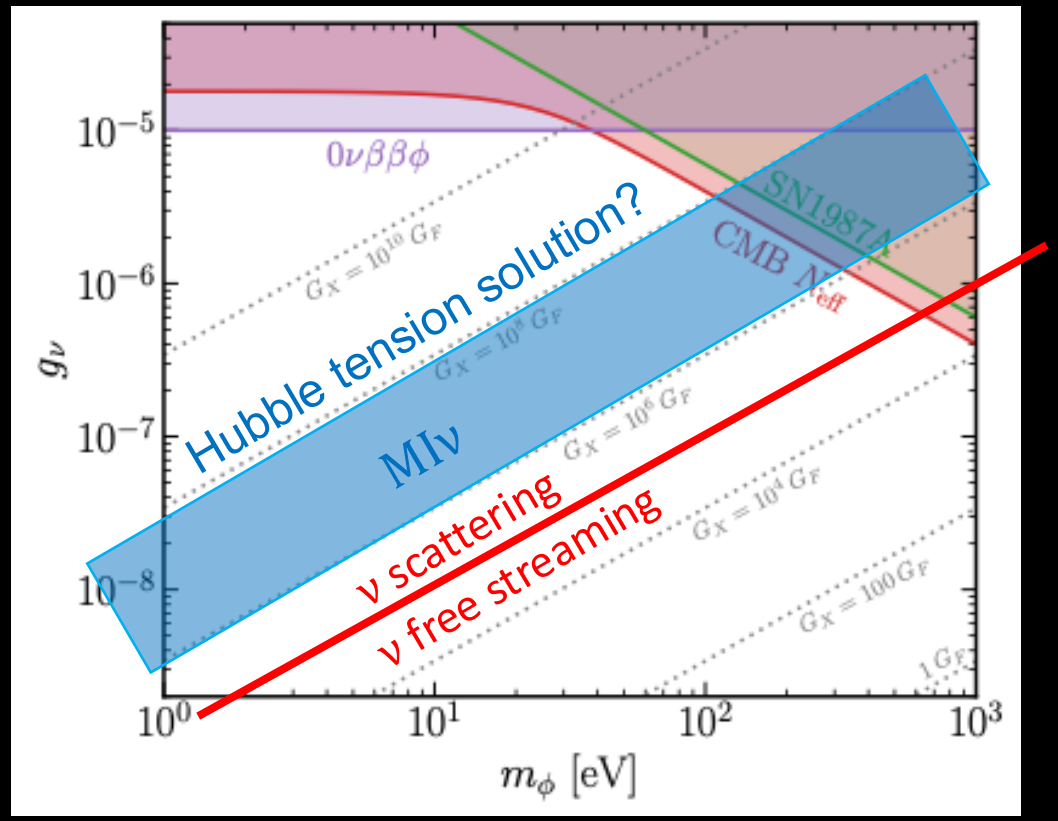
NuSI processes → rich phenomena in particle physics, cosmology, astrophysics



Strong constraints on NuSI from the rich phenomena

$$\mathcal{L} \supset \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 + g_\nu\phi(\nu\nu + \nu^\dagger\nu^\dagger)$$

NuSI (flavor universal)



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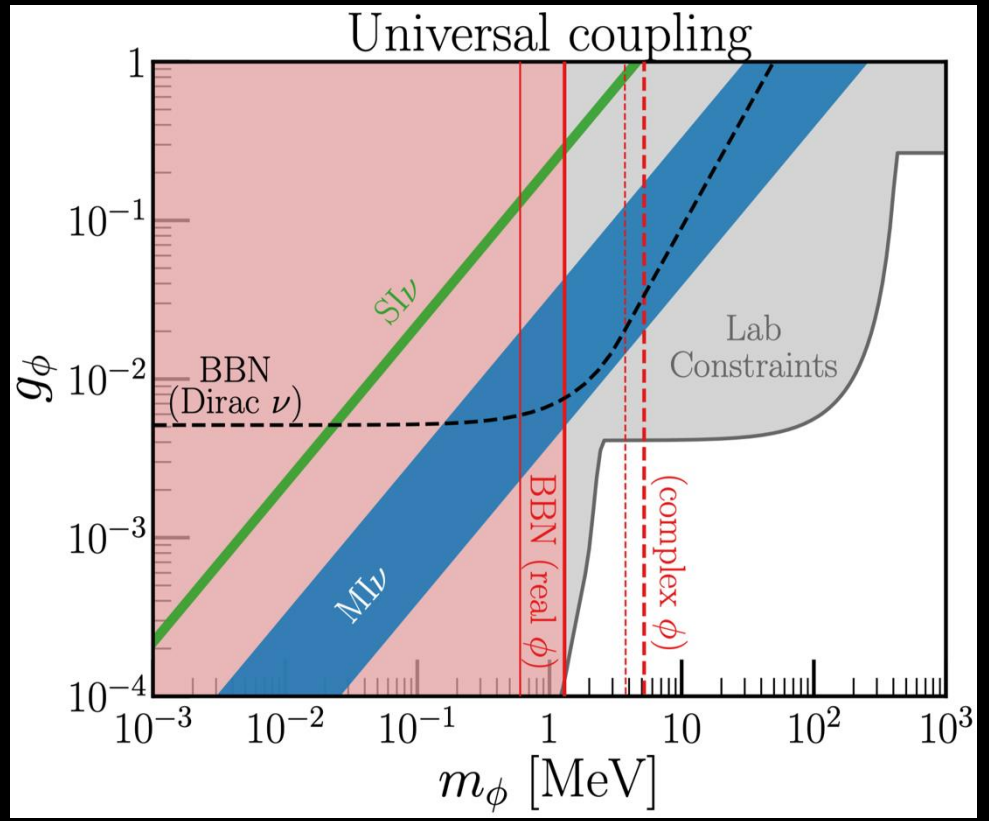
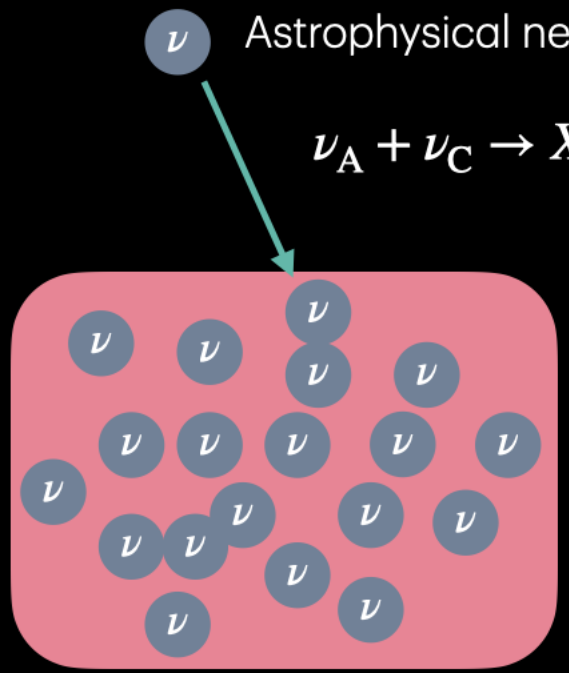


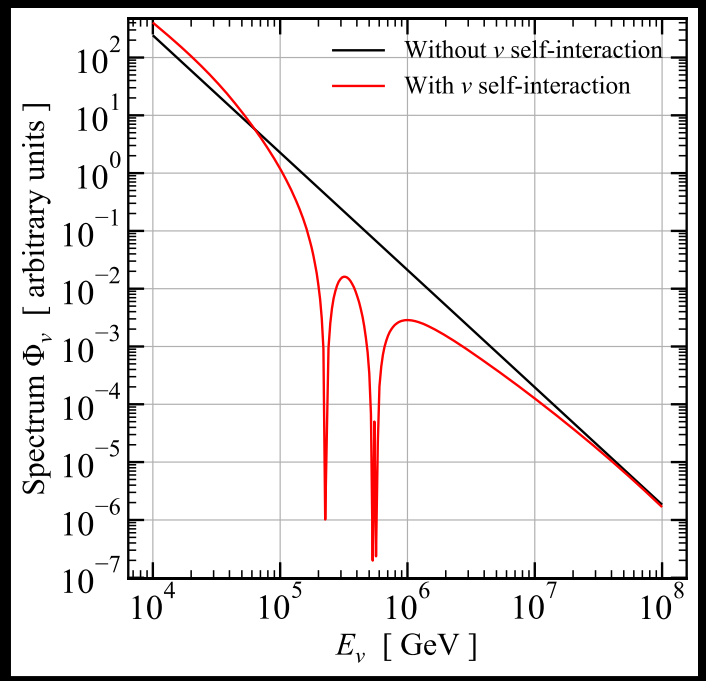
Blinov, Kelly, Krnjaic, McDermott 1905.02727

Astrophysical ν from cosmological distances probing NuSI

$$\mathscr{L} \supset \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 + g_\nu\phi(\nu\nu + \nu^\dagger\nu^\dagger)$$



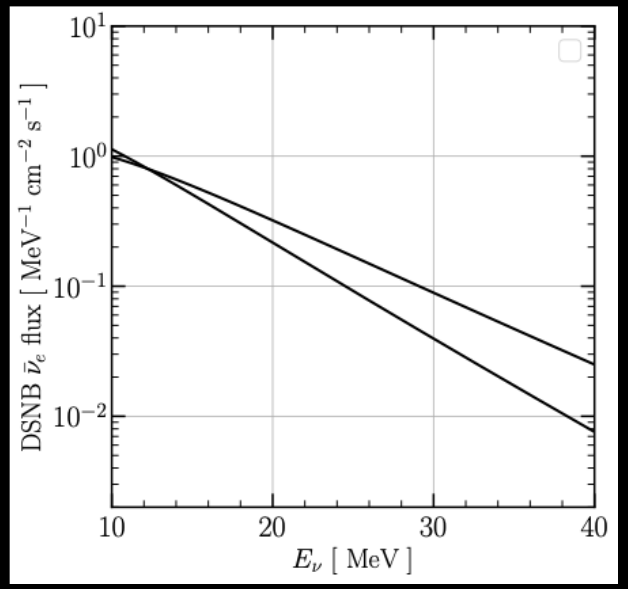
Cosmic neutrino background (CnuB)



Astrophysical neutrinos from cosmological distances

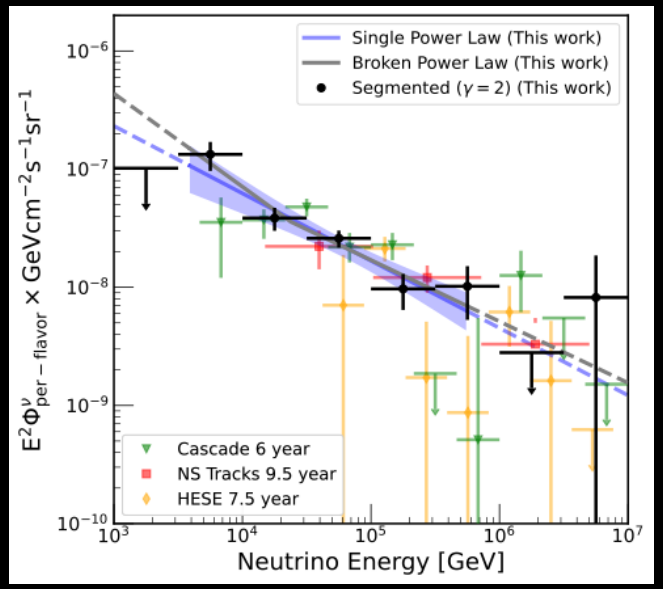
MeV

- Diffuse supernova neutrino background



TeV—PeV (HE)

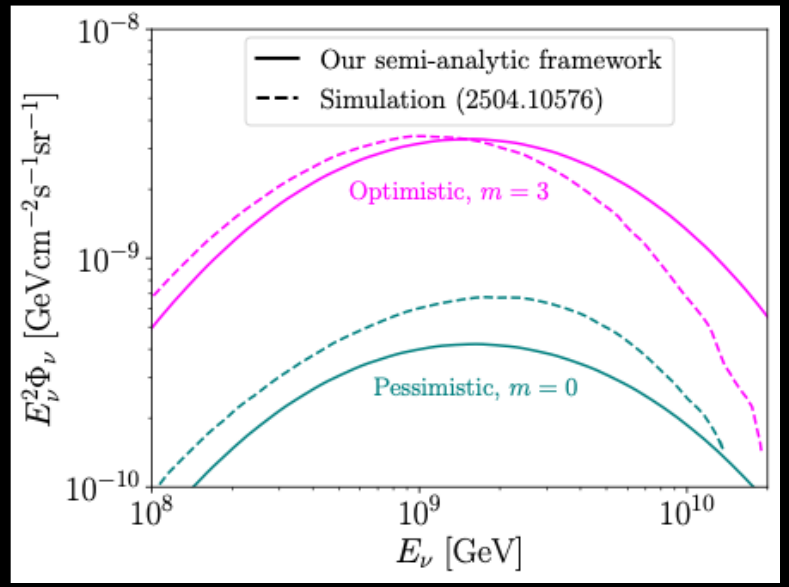
- TeV—PeV astrophysical neutrinos
  - First detected by IceCube
    Later by other detectors



2402.18026 IceCube Collaboration

EeV (UHE)

- UHE cosmogenic neutrinos



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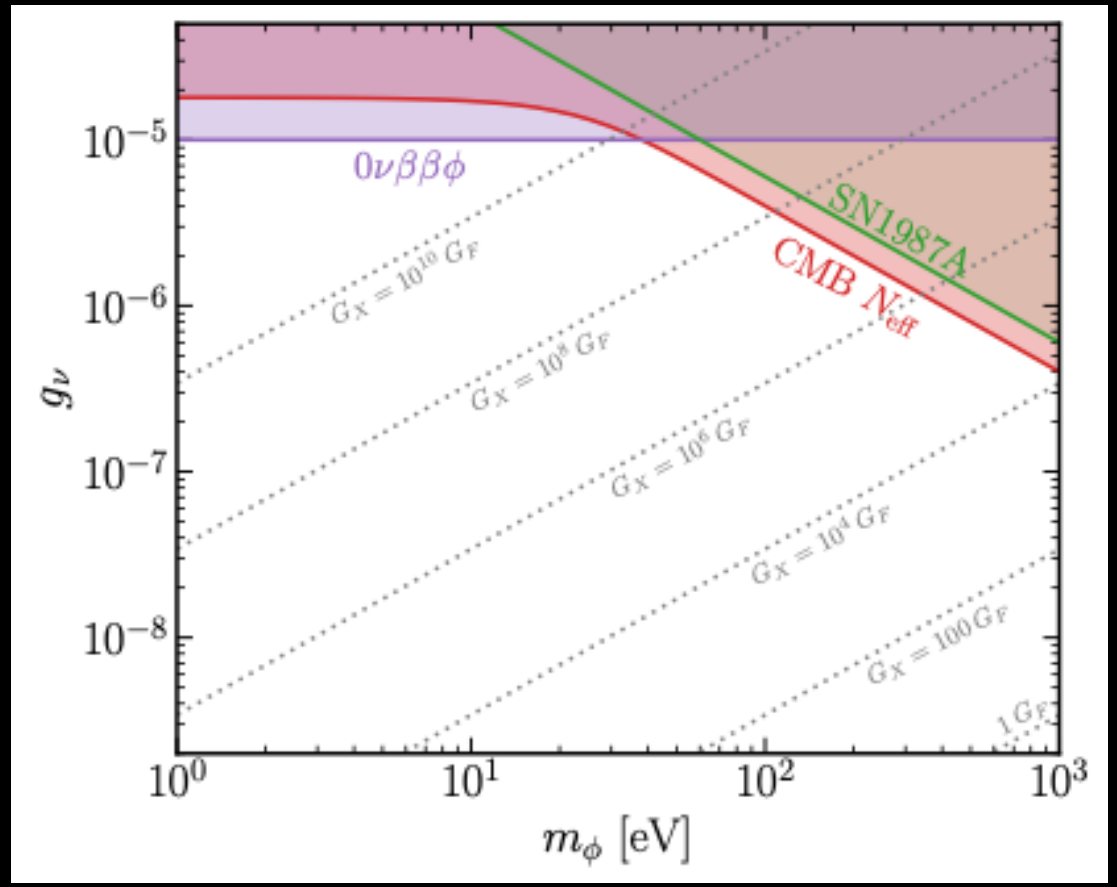
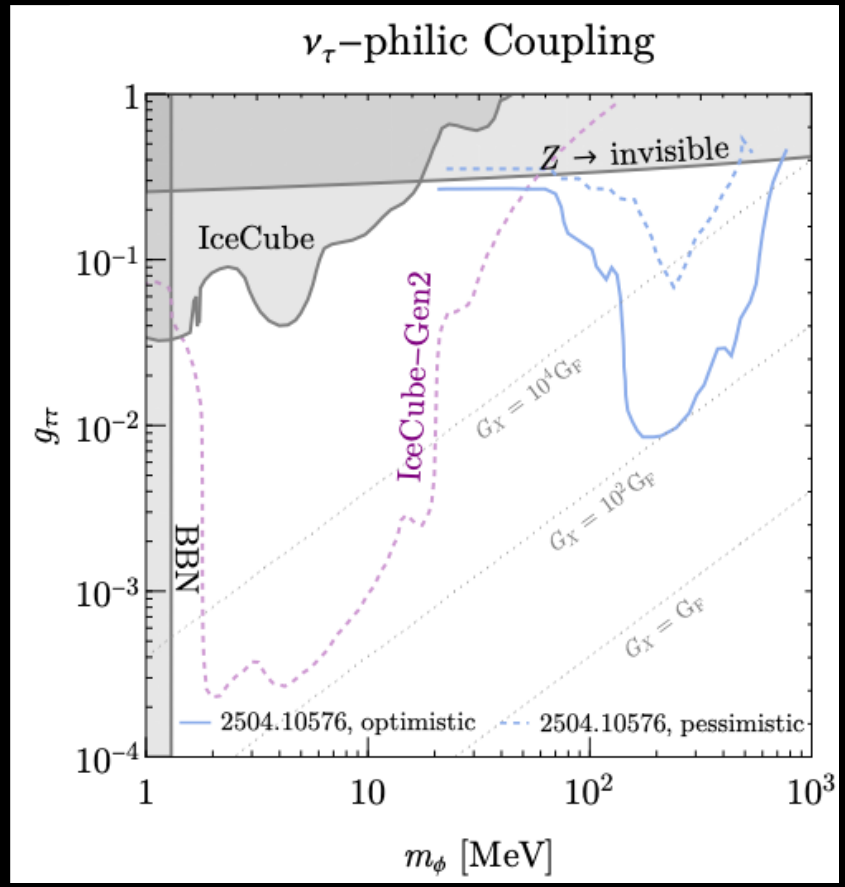
Astrophysical ν from cosmological distances probing NuSI





2107.13568 Esteban, Pandey, Brdar, Beacom
2504.10576 Leal, Naredo-Tuero, Funchal
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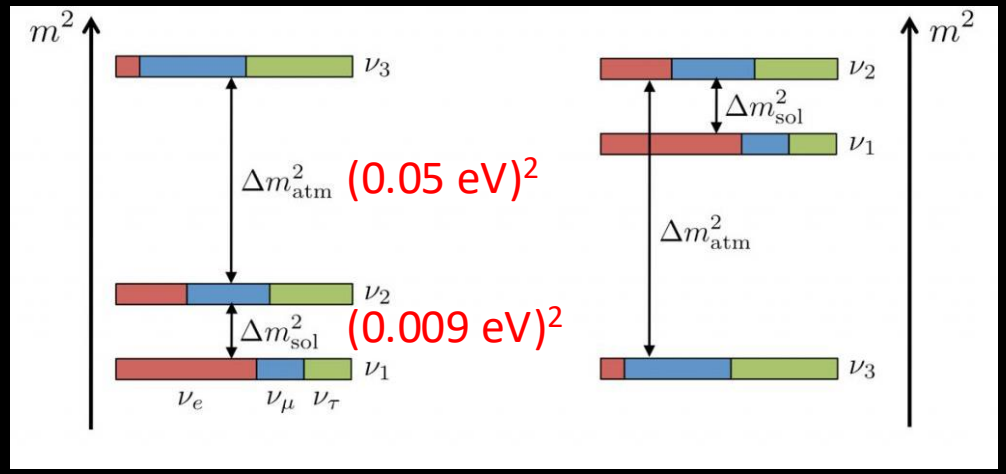
Novel regime of NuSI

Normal ordering Inverted ordering

(Previous studies all assumed $\sum m_\nu = 0.1$ eV)

Conventional:



$$m_\phi \simeq \sqrt{2E_\nu m_\nu} \simeq 1.5\ \text{keV} \left(\frac{E_\nu}{10\ \text{MeV}}\right)^{\frac{1}{2}} \left(\frac{m_\nu}{0.1\ \text{eV}}\right)^{\frac{1}{2}}$$

Nonrelativistic nuSI

Our idea:

What if the lowest mass state has

$m_\nu \ll T_{\rm CnuB} \simeq 1.95\ \text{K} \simeq 1.7\text{e-}4\ \text{eV}$?

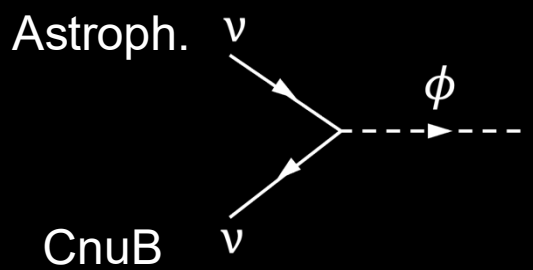
1. Allowed by oscillation measurements
2. Highly favored by recent DESI results

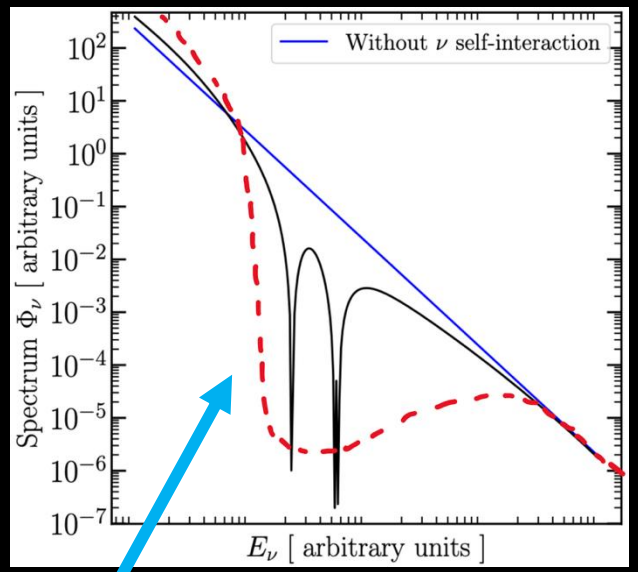
$$m_\phi \simeq \sqrt{4E_\nu T_{C\nu B}} \simeq 80\ \text{eV} \left(\frac{E_\nu}{10\ \text{MeV}}\right)^{\frac{1}{2}} \left(\frac{T_{C\nu B}}{1.7\times10^{-4}\ \text{eV}}\right)^{\frac{1}{2}}$$

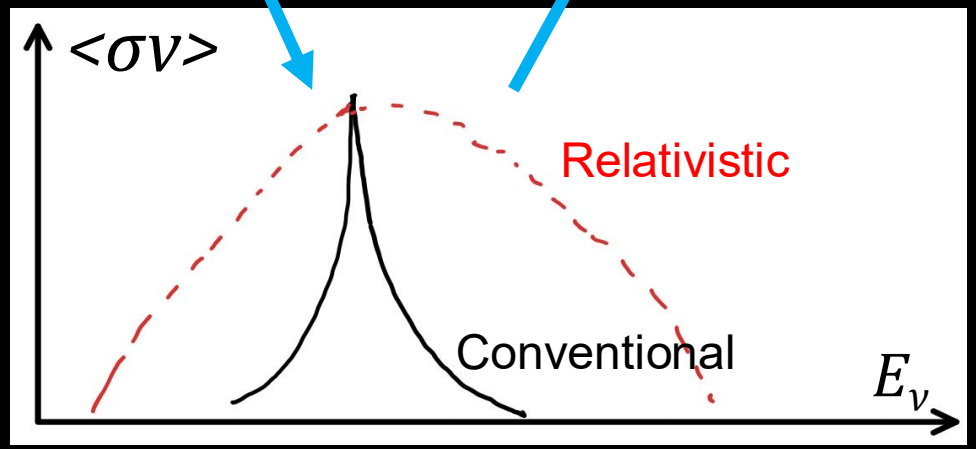
Relativistic nuSI

Novel regime of NuSI

Widened xsec resonance → widened absorption







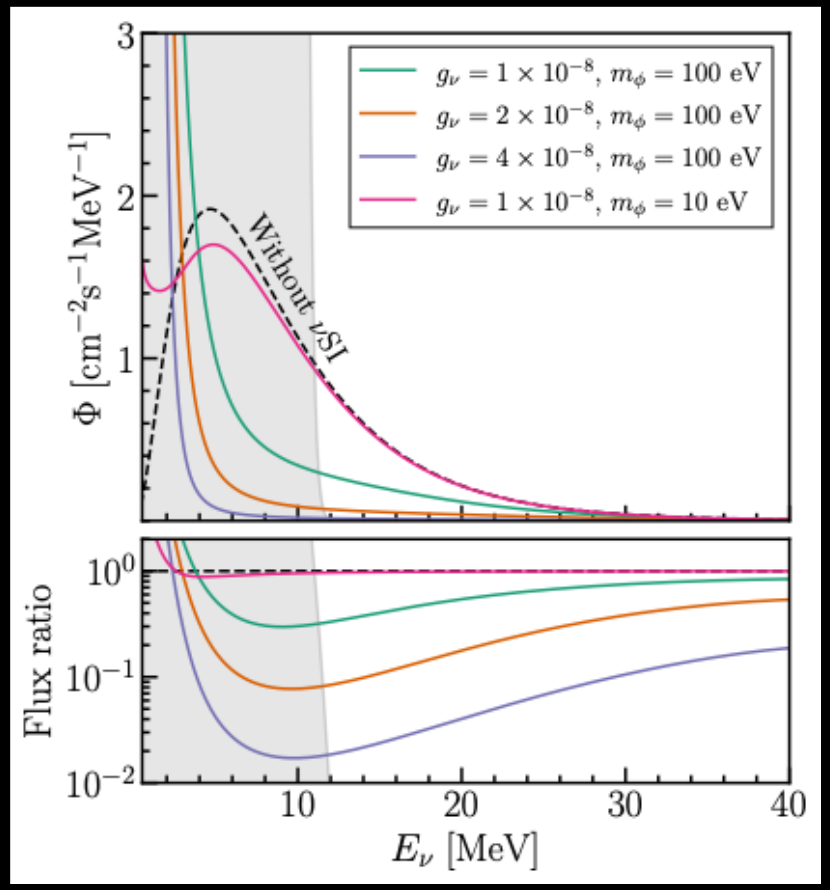
Probing very small couplings

$$\sigma \propto \frac{g^2}{m_\phi^2}$$

Relativistic and nonrelativistic NuSI

Neutrino spectra: without and with relativistic NuSI

MeV DSNB



To be measured at Hyper-Kamiokande, water Cherenkov neutrino detector in Japan

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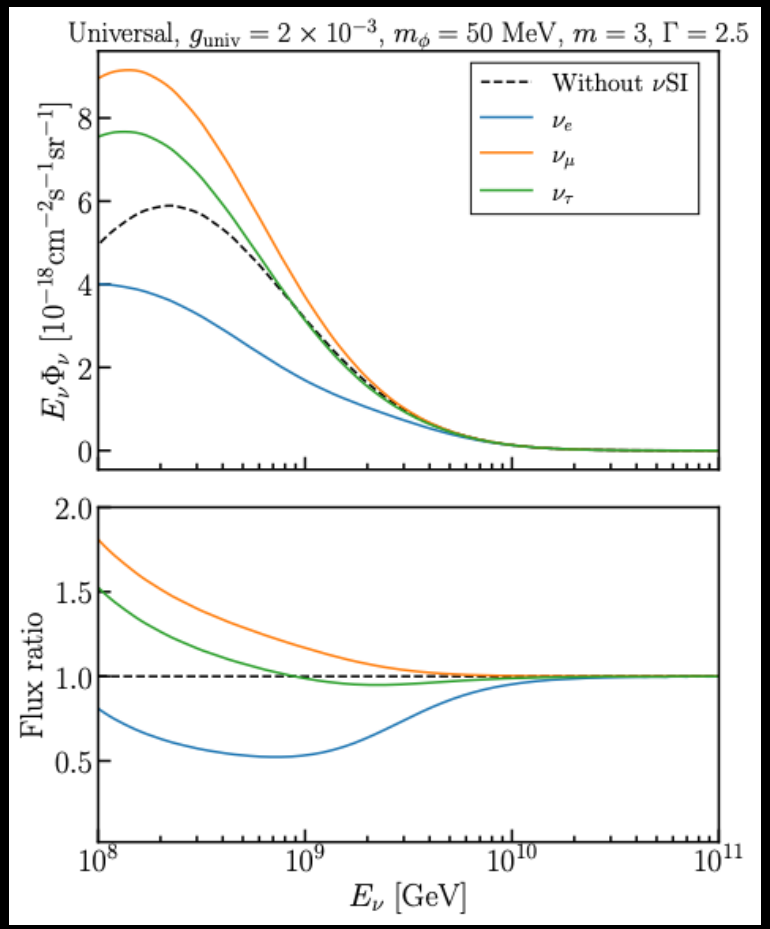
UHE cosmogenic neutrinos



To be measured at GRAND, earth emergent tau detector

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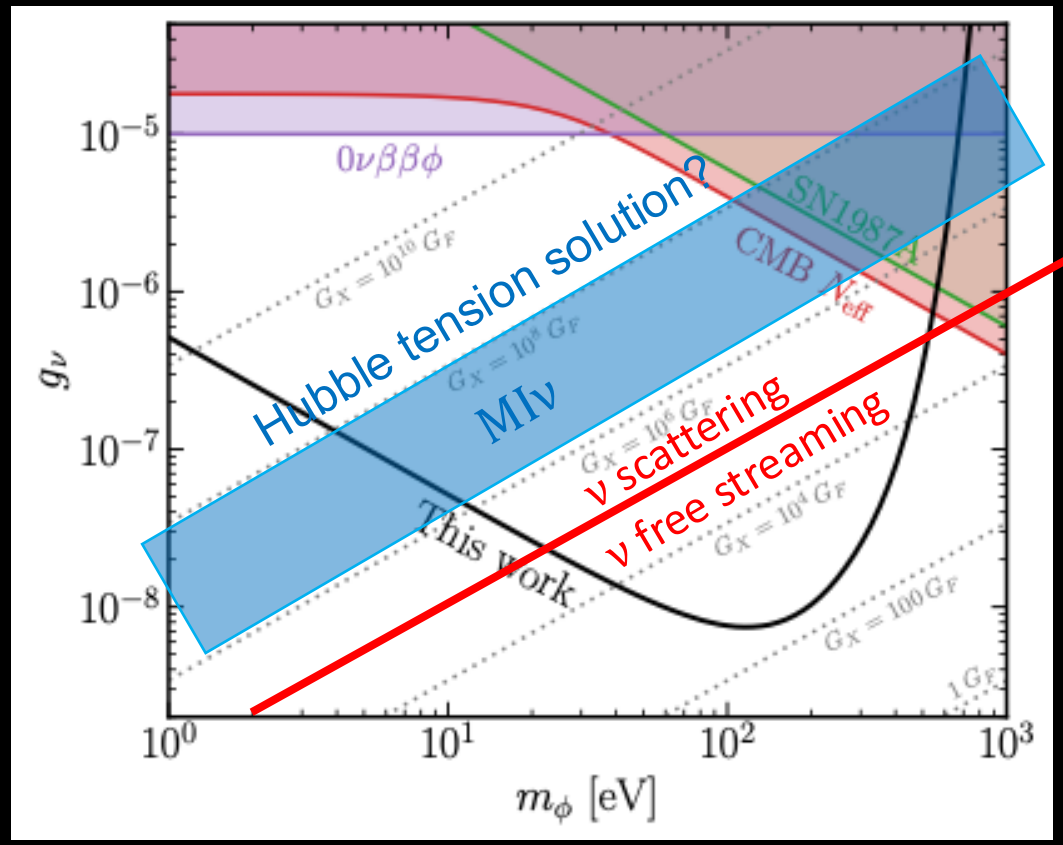
Results: using MeV diffuse supernova neutrino background

$$\mathcal{L} \supset \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 + g_\nu\phi(\nu\nu + \nu^\dagger\nu^\dagger)$$

NuSI



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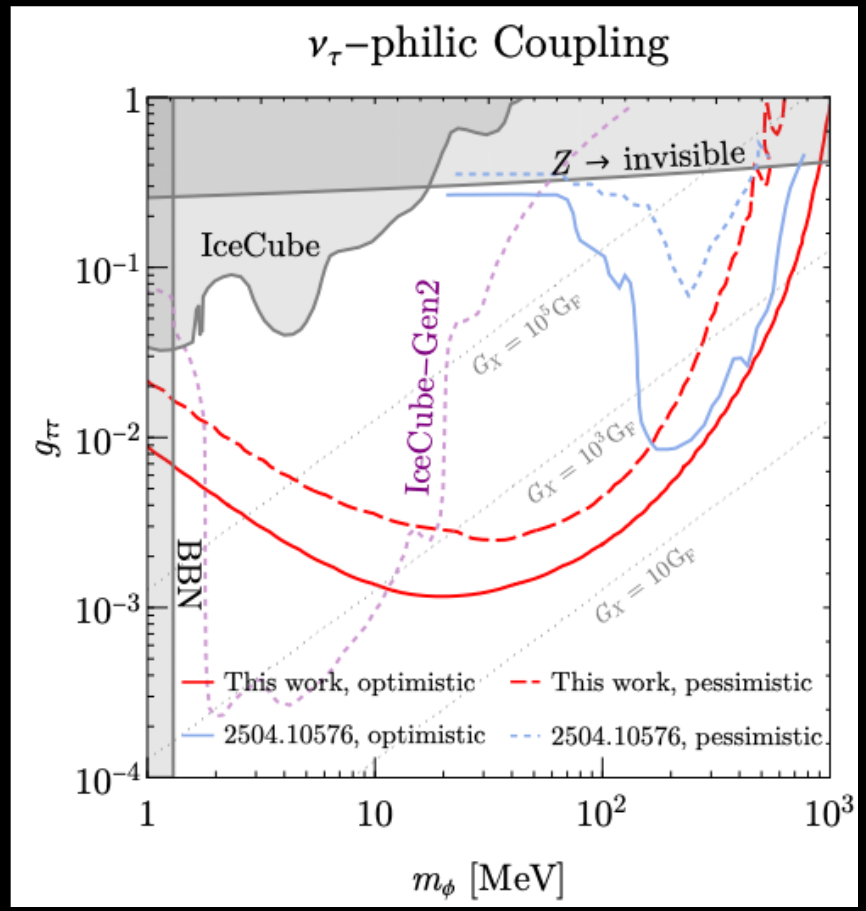
Relativistic NuSI + DSNB can probe NuSI with sub-keV mediator mass and couplings down to 1e-8

Results: using UHE cosmogenic neutrino background

$$\mathcal{L} \supset \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 + g_\nu\phi(\nu\nu + \nu^\dagger\nu^\dagger)$$

NuSI



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Thanks for your attention!