Neutrino echoes as a probe of secret neutrino interactions

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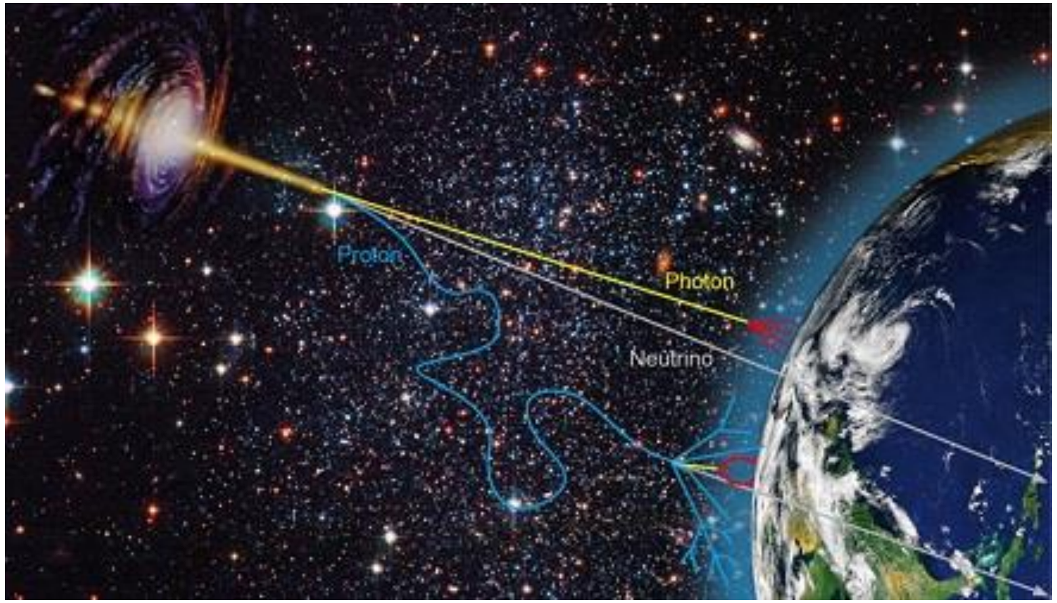
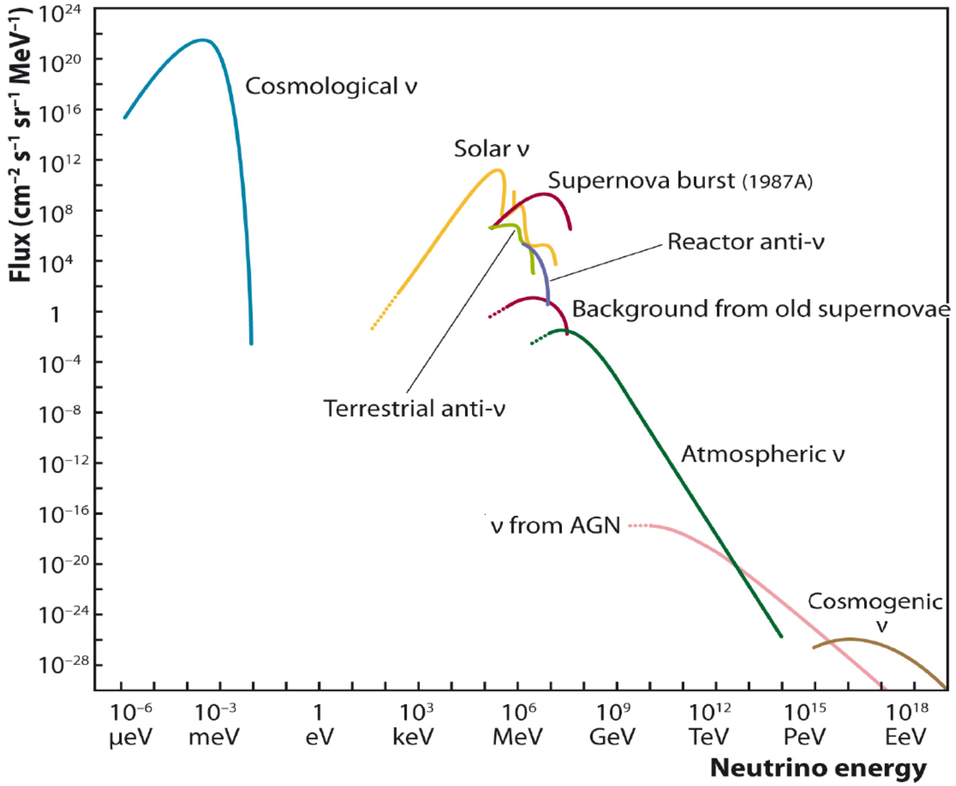
PennState

Why neutrinos?

- Interact only through the weak force in Standard Model (SM).
- Astrophysical neutrinos point towards the source and are also able to escape it
- Neutrinos have mass, which requires Beyond Standard Model (BSM) Physics.

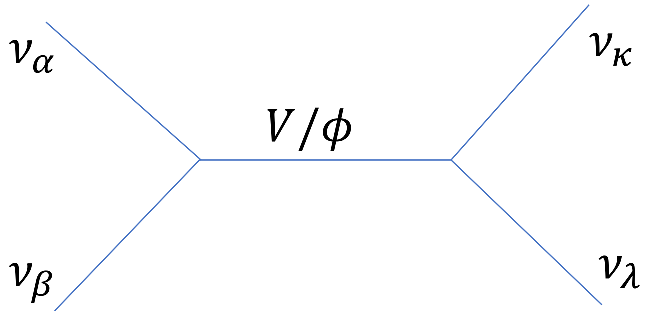
astroparticle-physics.desy.de



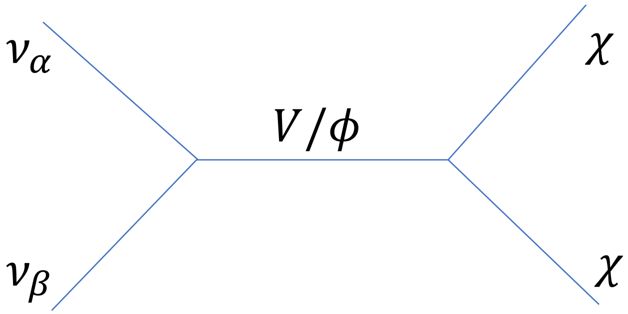


BSM Physics with neutrinos

- Add new interactions, coupling neutrinos to each other or dark matter.
- Interaction types:



$\nu\nu$ interactions

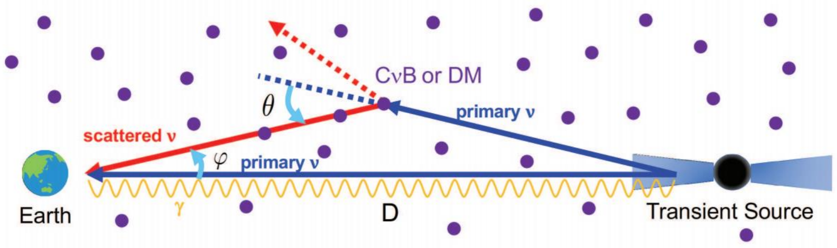


$\nu\chi$ interactions

- Well motivated (Berryman et al. 2022, Snowmass 2021 white paper)
  - Alleviates the Hubble tension
  - A new vector mediator can explain the muon anomalous magnetic moment
  - Secret interactions can also halt supernova explosions by preventing shock revival
  - Allows production of keV sterile neutrino dark matter
  - Allows production of sub-MeV dark matter

Neutrino echoes

- Astrophysical neutrinos propagate through the cosmic ν background and/or dark matter.
- Neutrino scattering → longer trajectory → time delay t with respect to photons/primary ν



Murase & Shoemaker 2019

What increases delay?
- Greater D
- Larger θ
- Lower ν energy (reduced “beaming” effect)
- Multiple scatterings.

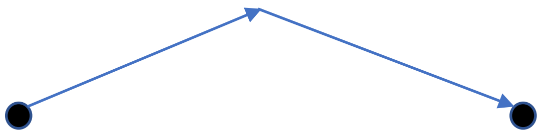
- Need t larger than the duration of the neutrino emission.
- Monte Carlo simulation used to calculate the distribution $P(t)$.
- Propagation uses optical depth

$$\tau_\nu = \int_0^D dx\, n_\nu(x)\sigma_\nu(\varepsilon_\nu)$$

- If $n_\nu\sigma_\nu$ is constant, $\tau_\nu = D/\lambda_\nu$,

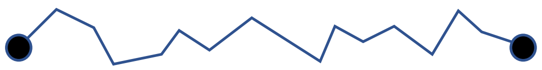
$$\lambda_\nu = \text{mean free path} = 1/n_\nu\sigma_\nu$$

Optically thin $\tau_\nu \ll 1$



One scattering

Optically thick $\tau_\nu \gg 1$



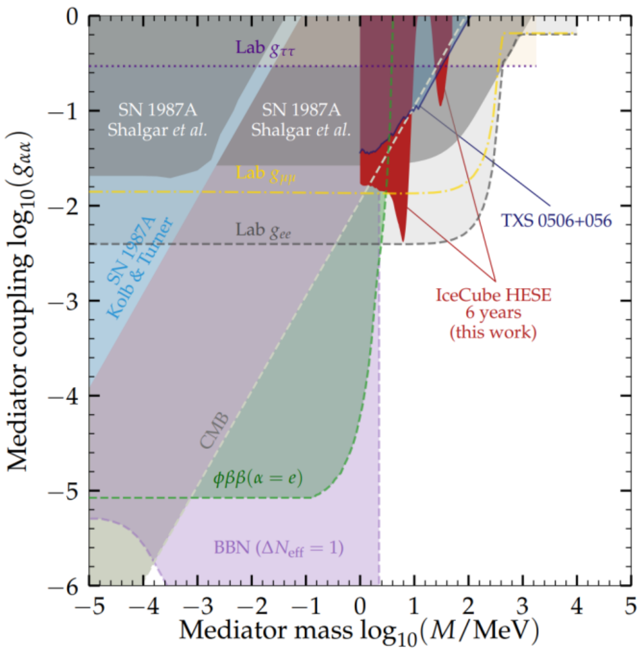
Multiple scatterings

Test model: $\nu\,\nu$ scattering & scalar mediator

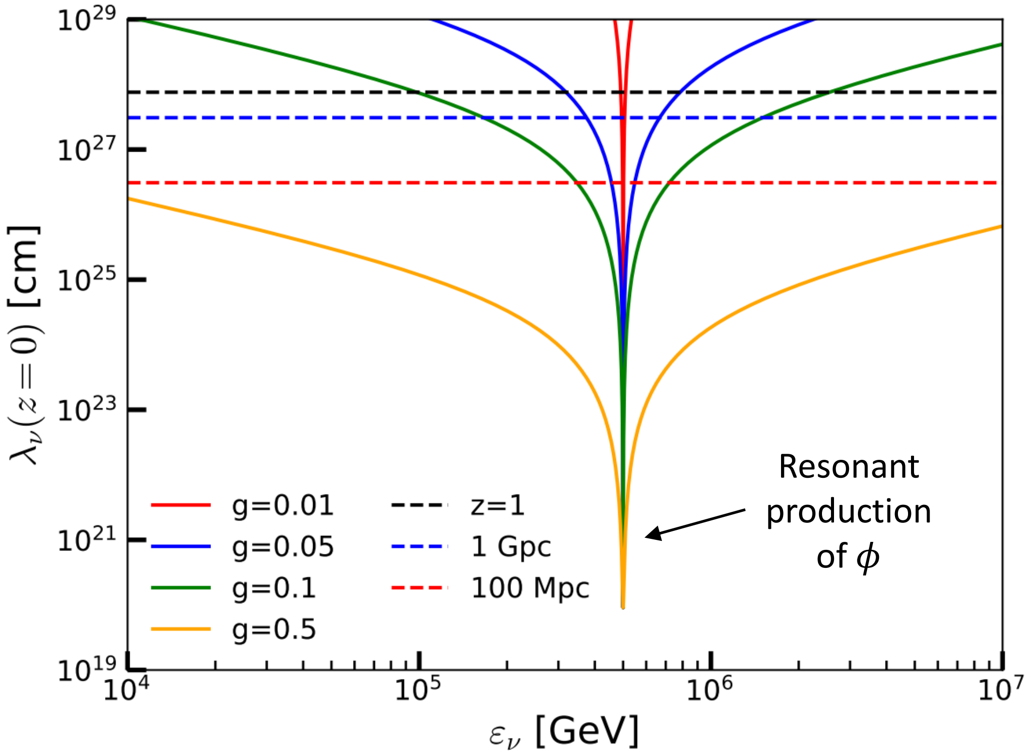
- $\mathcal{L}_{\rm int} \supset \frac{1}{2} g\, \overline{\nu_L^C} \nu_L \phi + \text{c.c.}$ (Majorana neutrinos, 1ν)
- Angular distribution

$$\frac{1}{\sigma_\nu}\frac{d\sigma_\nu}{d\cos\theta} = \frac{\varepsilon_\nu}{m_\nu}\left(1 + \underbrace{\frac{\varepsilon_\nu}{m_\nu}(1-\cos\theta)}_{\text{Strong forward scattering}}\right)^{-2}$$

not Gaussian



Bustamante et al. 2020



- Total cross section

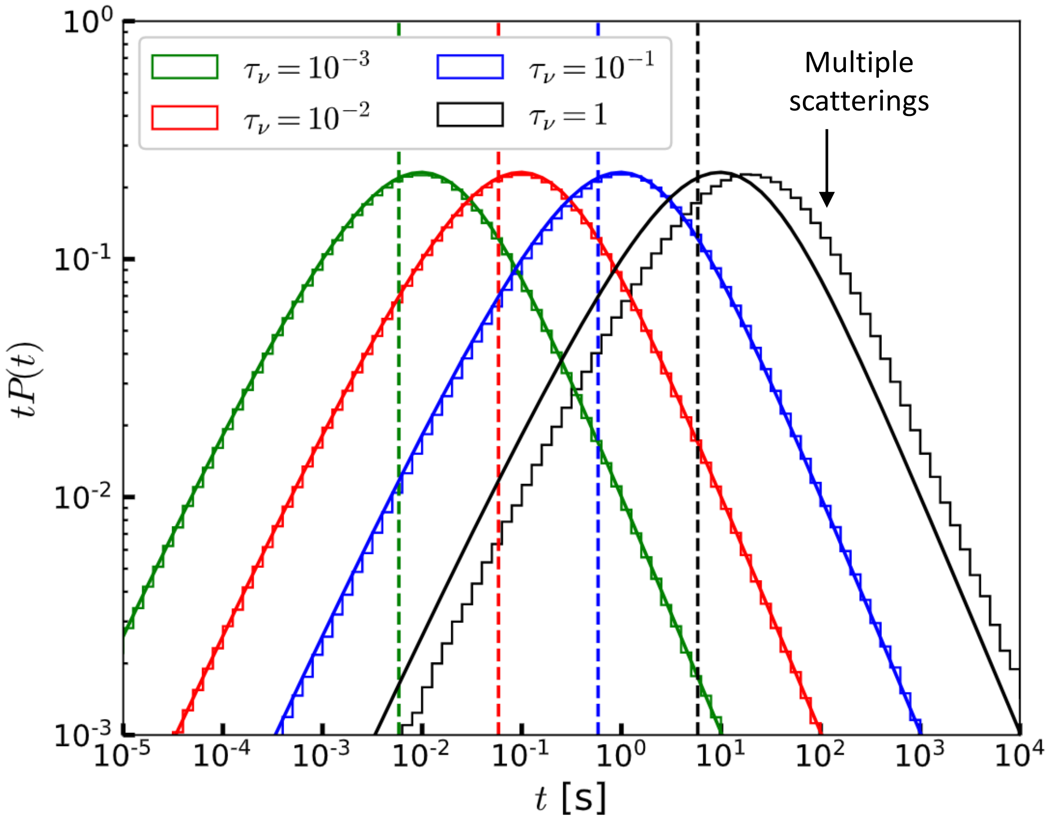
$$\sigma_\nu(\varepsilon_\nu) = \frac{g^4}{32\pi}\frac{s}{(s-m_\phi^2)^2 + m_\phi^2\Gamma_\phi^2}$$

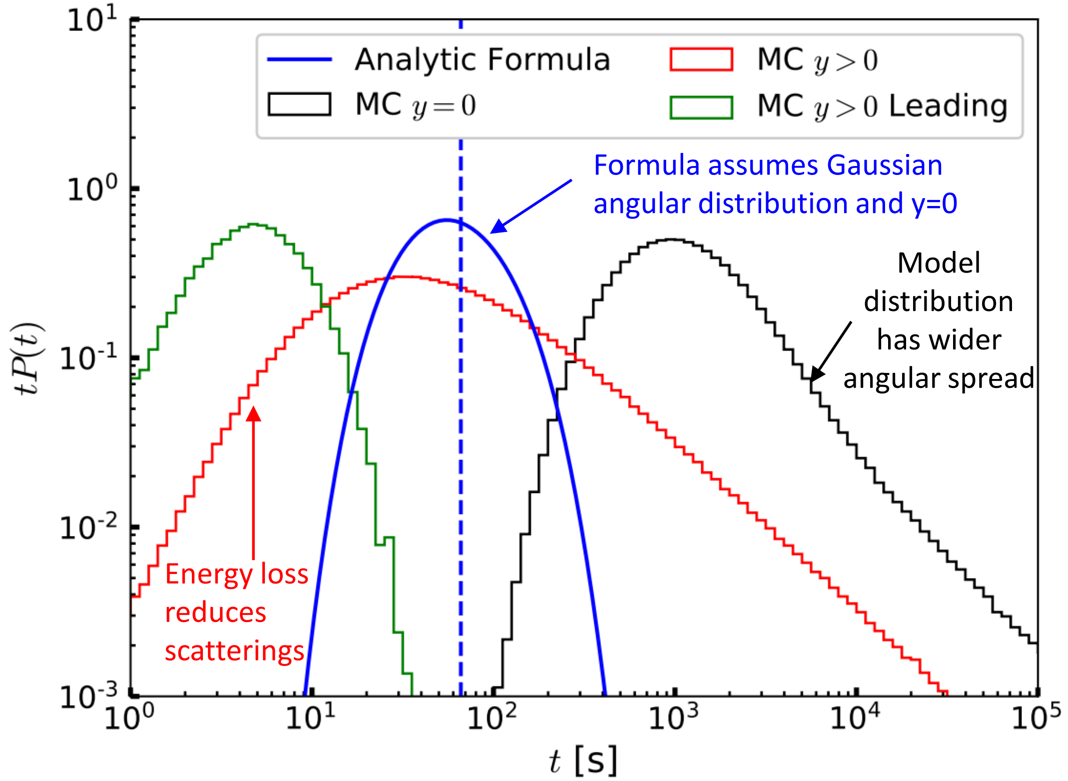
  - $s = 2m_\nu\varepsilon_\nu$
  - $\Gamma = g^2 M_\phi/16\pi$
  - $\lambda_\nu = 1/n_\nu\sigma_\nu,\ n_\nu = 112\ \text{cm}^{-3}$
- Benchmark model
  - m_ν=0.1 eV, M_ϕ=10 MeV (resonance at 500 TeV)

Examples of delay distribution $P(t)$

- 170 TeV neutrinos and $g = 0.1 \longrightarrow \lambda_\nu = 1$ Gpc.
- Great agreement with analytical formula (solid curves).
- $D = \tau_\nu$ Gpc

- Inelasticity parameter $y = \varepsilon'_\nu / \varepsilon_\nu$.
- 300 TeV neutrinos and $g = 0.5 \longrightarrow \lambda_\nu = 10^{24}$cm.
- $D = 100$ Mpc, $\tau_\nu = 310$





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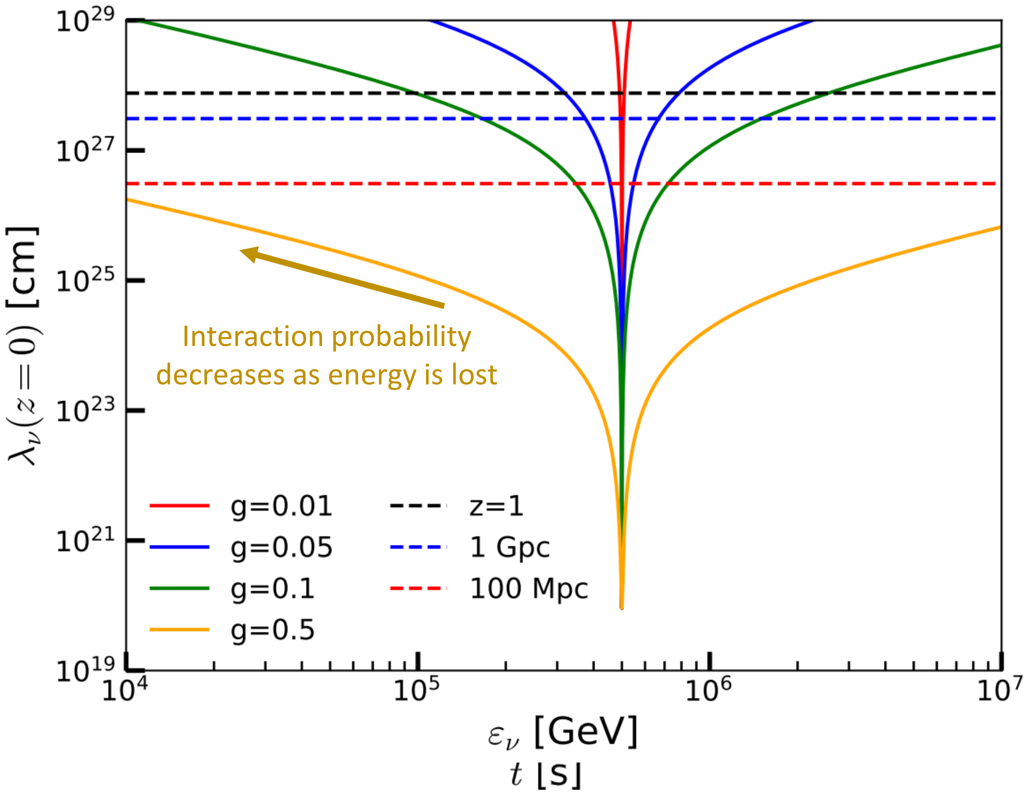

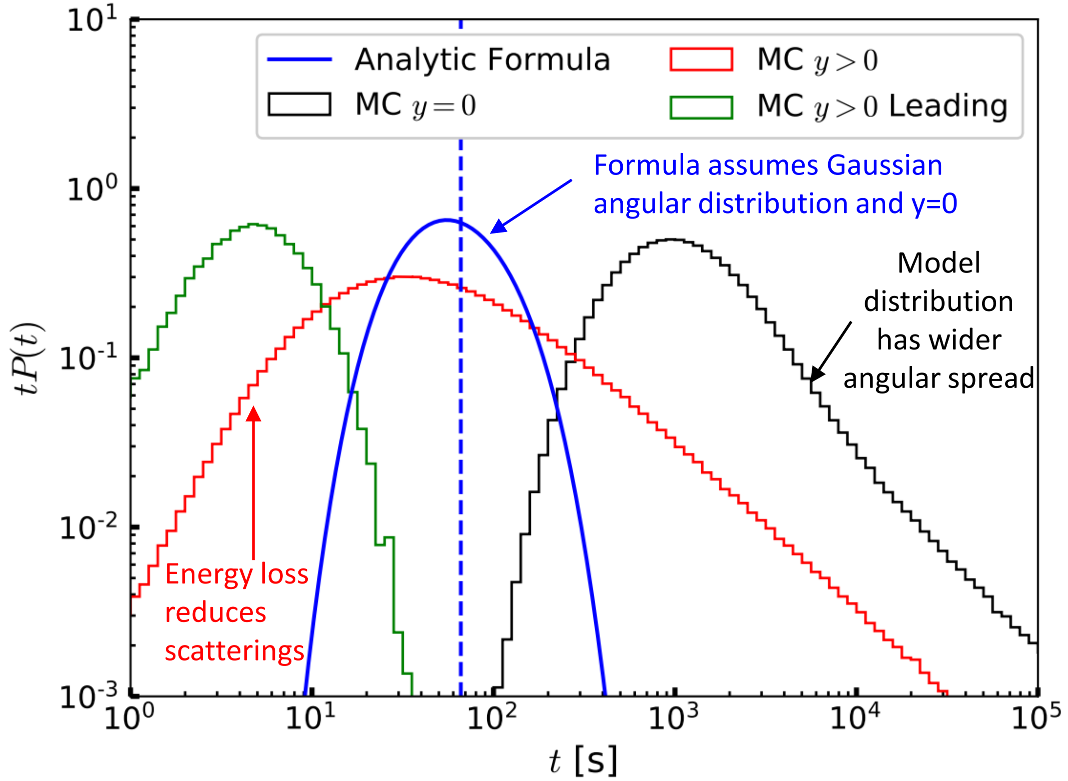

Single source at redshift z=1 and ε_ν^{-2} injection spectrum

- No redshift case included for comparison
- Cutoffs in delay due to threshold effects ($E_\nu > 1$ TeV)

What increases delay?
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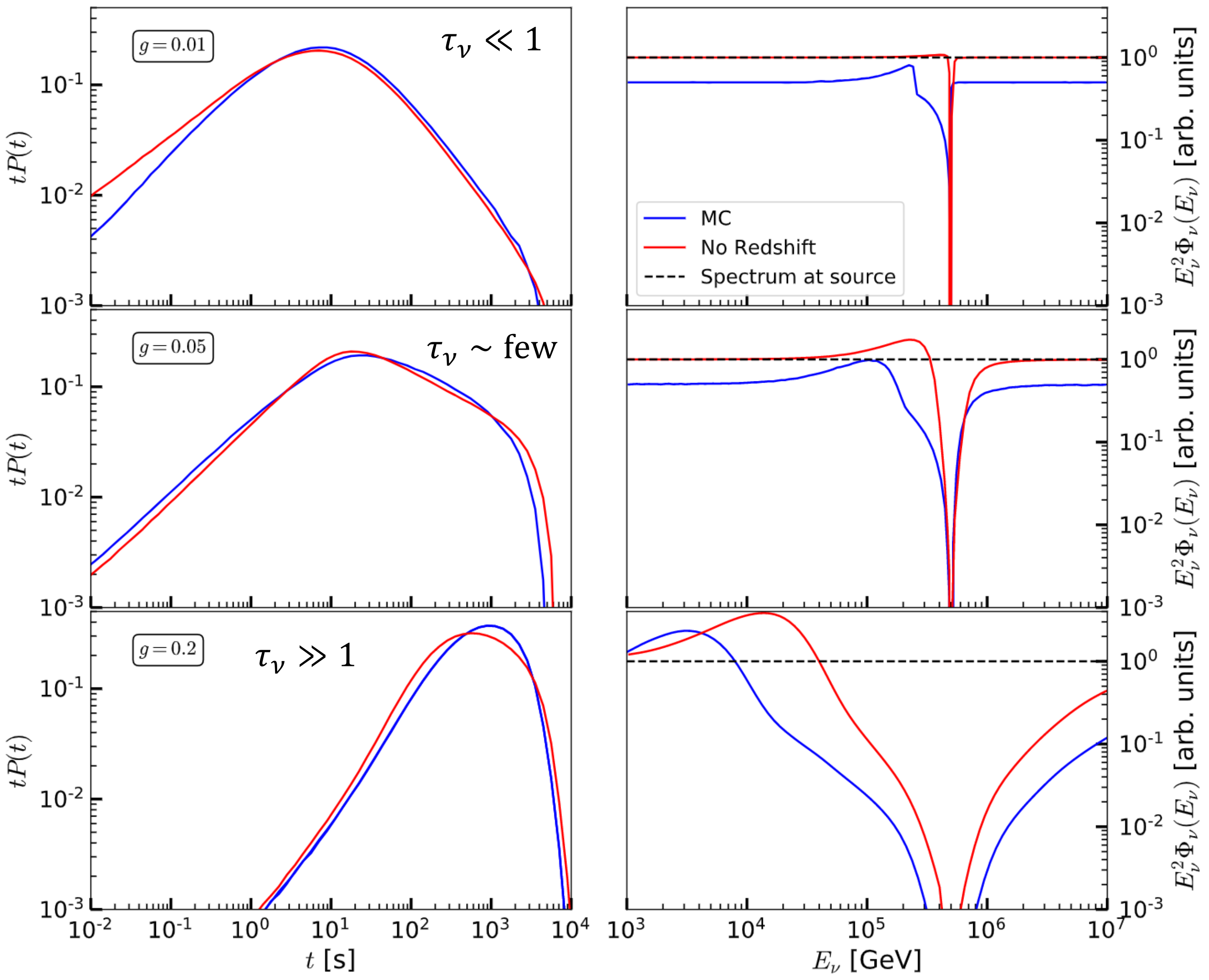
- Lower ν energy (reduced "beaming" effect)
- Multiple scatterings.



Neutrino-dark matter interactions

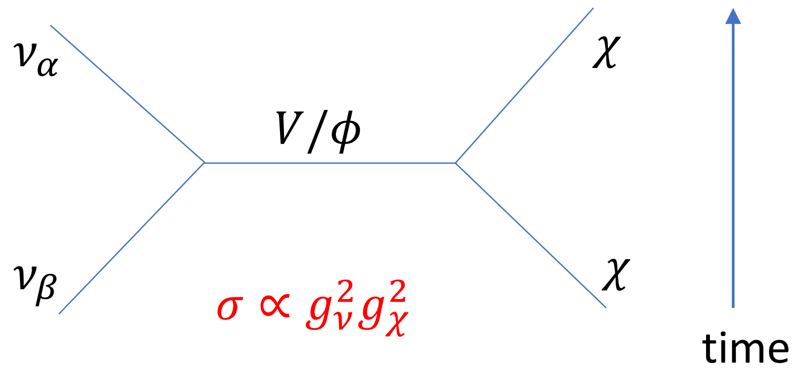
- Consider neutrino – fermionic dark matter (DM) interactions (t −channel, no resonance) with a vector mediator

$$g_\nu \bar{\nu}\gamma^\mu \nu V_\mu + g_\chi \bar{\chi}\gamma^\mu \chi V_\mu$$

- Constraints from neutrino self-interactions AND from DM self interactions

$$\frac{\sigma_{\chi\chi}}{m_\chi} < 0.1\ \mathrm{cm}^2/\mathrm{g}$$

Merging cluster constraints



- Take advantage of high neutrino statistics from Hyper-K for a nearby ($D = 10$ kpc) supernova.
- For supernova models, this gives ~ 40000 events

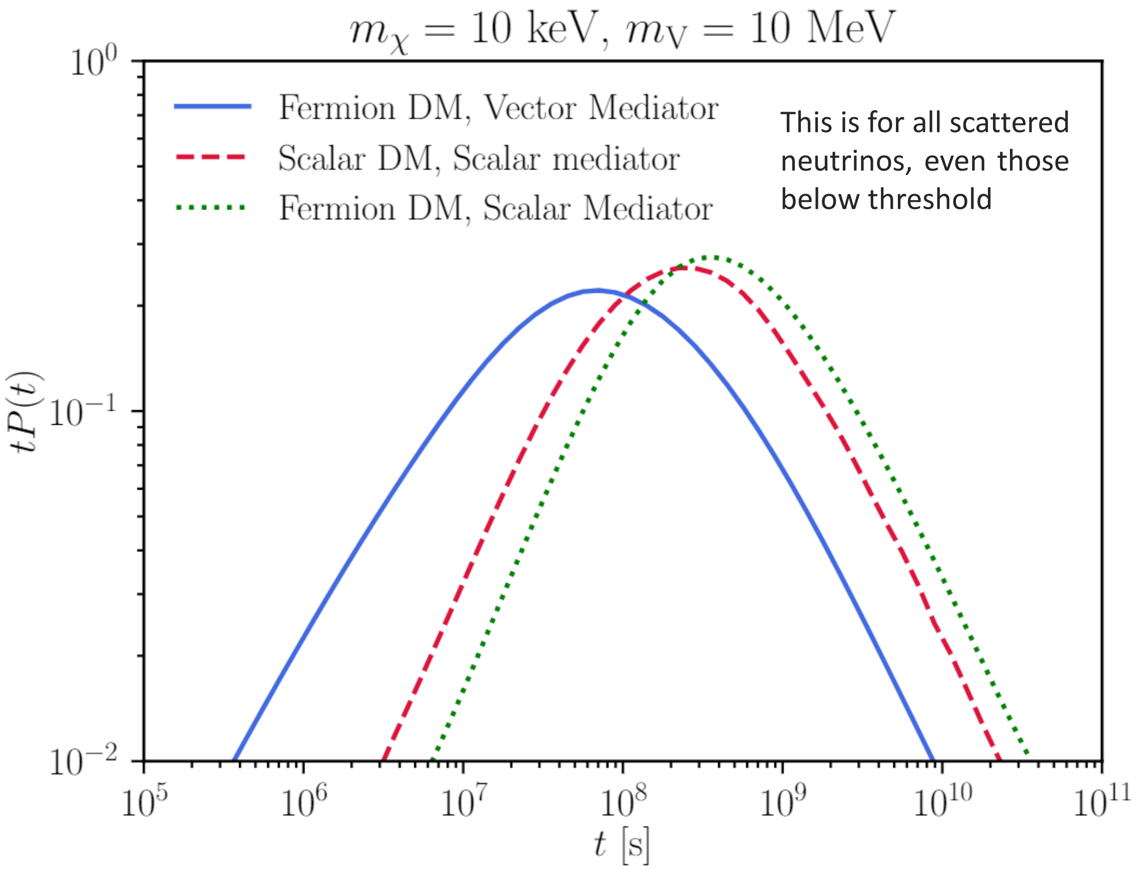
Observed spectrum (ν per energy) — Inverse beta decay

$$N_{\mathrm{events}} = n_{\mathrm{T}} \int_{10\ \mathrm{MeV}}^{100\ \mathrm{MeV}} \frac{dN_\nu}{dE_\nu} \sigma_{\mathrm{IBD}}(E_\nu) dE_\nu$$

Number of targets — Energy threshold

Delayed supernova neutrinos

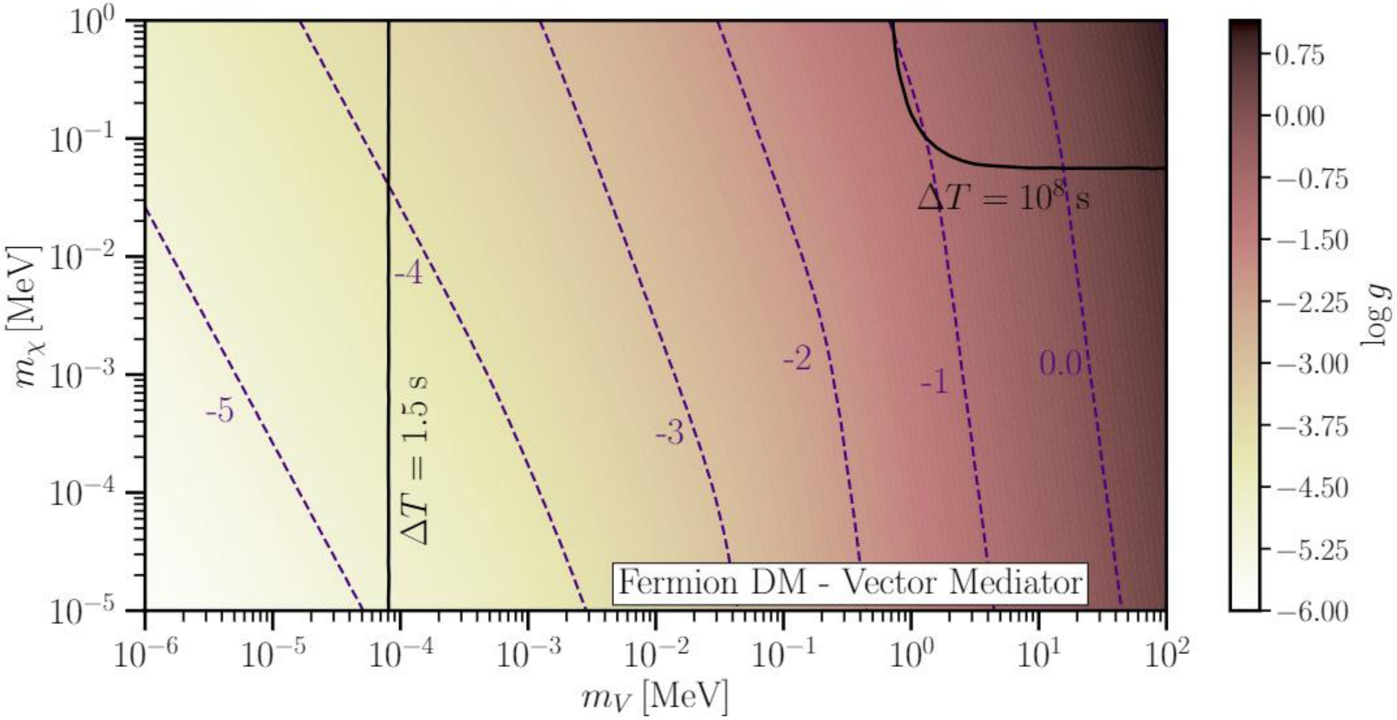
- For $D = 10$ kpc and local dark matter density of 0.3 GeV/cm^3, we have $\tau_\nu \ll 1$
- A fraction τ_ν of the 44000 neutrinos is delayed
- Vector mediator has strong forward scattering

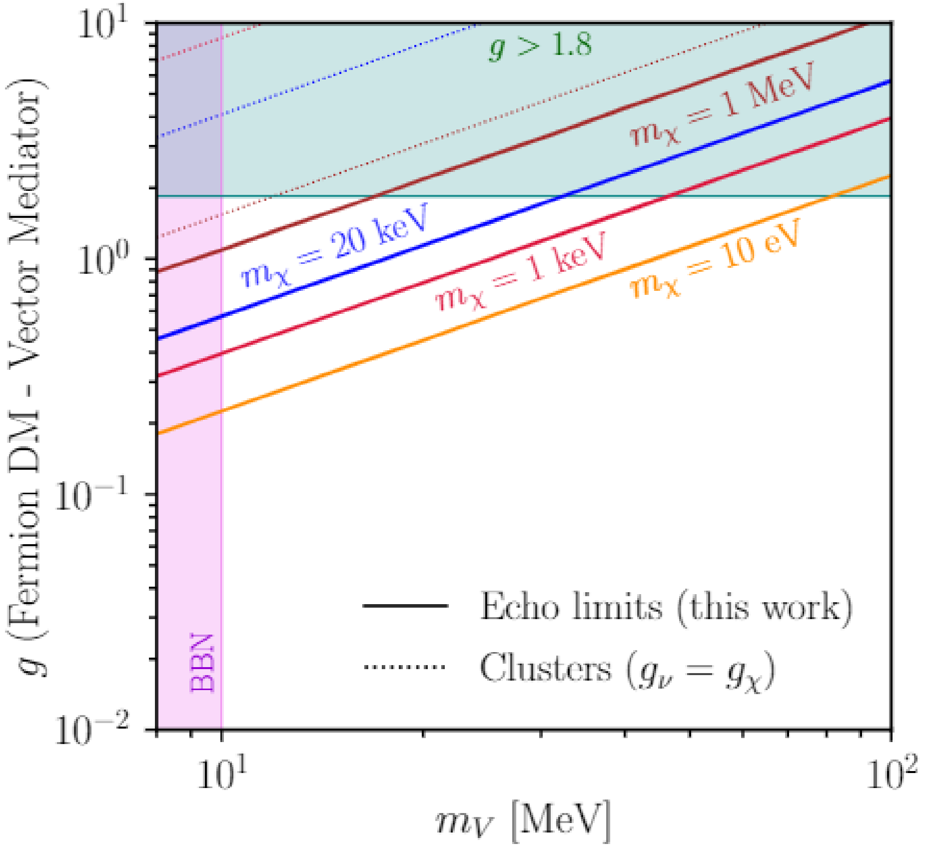


g_ν, g_χ determine τ_ν
Angular distribution determines $P(t)$

Constraints on coupling

Couplings only affect cross section → sensitive to $g = \sqrt{g_\nu g_\chi}$





ΔT = time from initial burst required to enclose 50% of the signal

Concluding remarks

$\nu\nu$ interactions with a scalar mediator

- For elastic scattering, we find significant deviations between the analytical expression and the Monte Carlo result.
- For a single ε_ν^{-2} source at $z = 1$, high energy neutrinos in the 1 TeV- 10 PeV range can be delayed by 1s to 1000s.

Delayed neutrino emission in supernovae from $\nu\chi$ interactions

- Hyper-Kamiokande, DUNE and JUNO provide great opportunities to study secret interactions by observing supernova neutrinos
- Hyper-K provides strong bounds on neutrino-DM coupling which are not excluded by other constraints.

The Monte Carlo code used here can be used for a variety of interaction models and may accommodate pion and muon decays. Code will be publicly available soon.