Neutrino time delay as a probe of secret neutrino interactions

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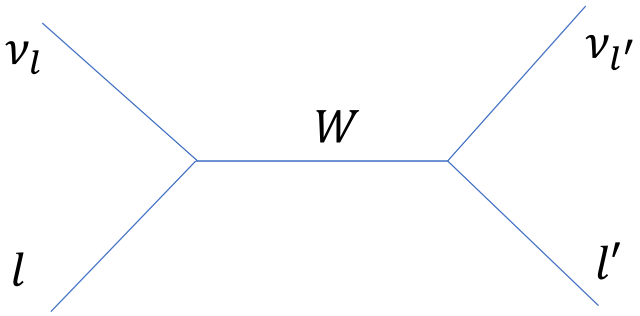
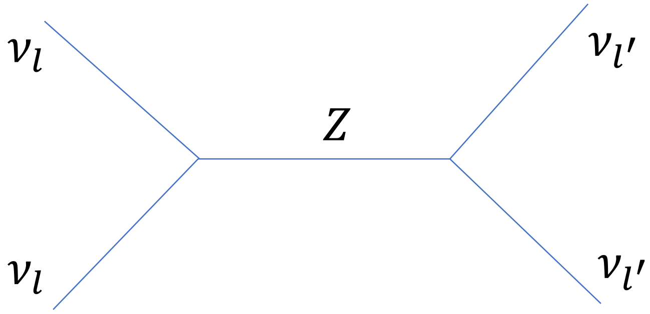
Massless neutrinos in the Standard Model

- Three lepton generations, each separated as a charged lepton and neutrinos. Each has an antiparticle.
- Two types of weak interactions involving leptons only

e	μ	τ
ν_e	ν_μ	ν_τ



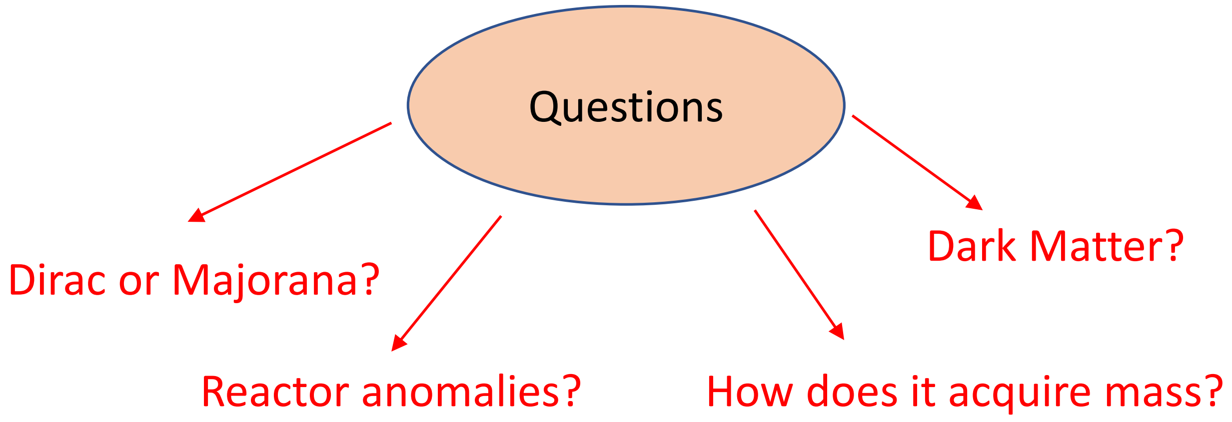
Charged-current



Neutral-current

- Neutrinos can be either Dirac (ν and $\bar{\nu}$ are different) or Majorana (the neutrino is its own antiparticle).
- Same coupling for all flavors, no generation mixing at vertex.
- Standard Model neutrinos are massless by construction.

Unanswered questions



Are neutrinos Dirac or Majorana? → Neutrinoless double beta decay

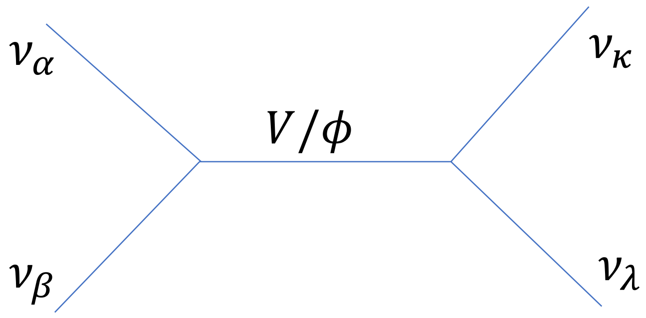
How do neutrinos acquire mass? → Seesaw mechanism

Reactor anomalies? → Sterile neutrinos

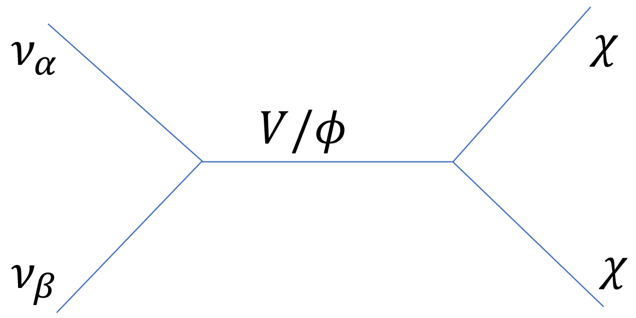
Can sterile neutrinos contribute to dark matter? → Maybe

Introducing new physics

- Add new interactions, coupling neutrinos to each other or dark matter.
- This class of models avoids many lab constraints.
- Interaction types:



$\nu\nu$ interactions

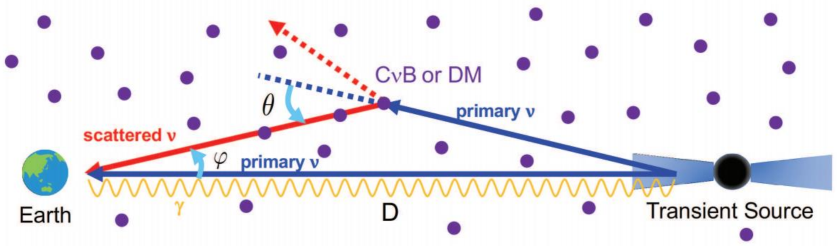


$\nu\chi$ interactions

- Well motivated
  - Alleviates the Hubble tension
  - A new vector mediator can explain the muon anomalous magnetic moment
  - Allows production of keV sterile neutrino dark matter
  - Secret interactions can also halt supernova explosions by preventing shock revival
  - Allows production of sub-MeV dark matter

Neutrino echoes

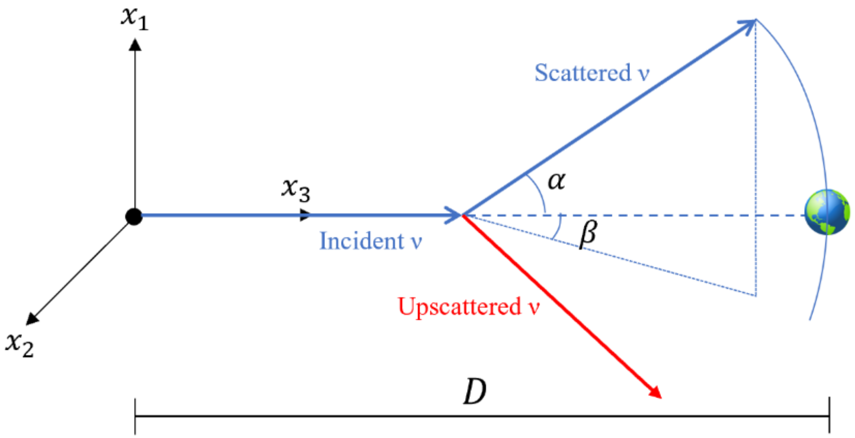
- Astrophysical neutrinos propagate through the cosmic ν background and/or dark matter.
- Neutrino scattering → longer trajectory → time delay t with respect to photons/primary ν



Murase & Shoemaker 2019

- For small angle scattering (Williamson 72, Alcock & Hatchett 78)

$$t = \frac{1}{2}\int_0^D (\alpha^2 + \beta^2) dx_3 - \frac{1}{2D}\left[\left(\int_0^D \alpha dx_3\right)^2 + \left(\int_0^D \beta dx_3\right)^2\right]$$



- Easy to implement in Monte Carlo simulations
- The alternative is to solve the transport equation

Neutrino propagation – when do scatterings occur?

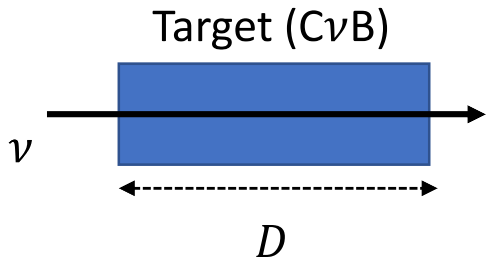
- Convert cross sections to interaction probability via optical depth

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

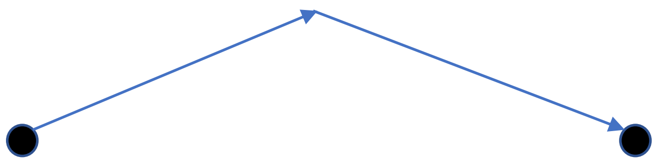
- Interaction probability $P = 1 - e^{-\tau_\nu}$
- For uniform density and constant σ

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

- For constant λ_ν, average number of scatterings in medium is equal to τ_ν

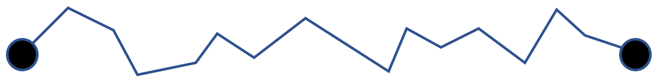


Optically thin $\tau_\nu \ll 1$



One scattering

Optically thick $\tau_\nu \gg 1$



Multiple scatterings

Test model: $\nu\ \nu$ scattering with a scalar mediator

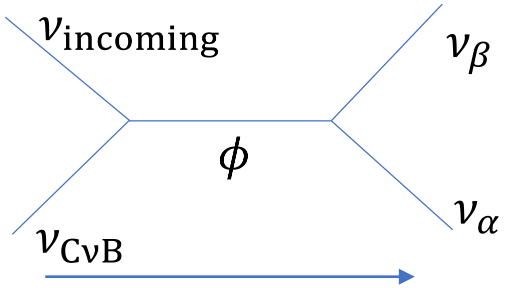
- $\mathcal{L}_{\rm int} \supset \frac{1}{2} g\, \overline{\nu_L^C} \nu_L \phi + \text{c.c.}$ (Majorana neutrinos, 1ν)
- Angular distribution

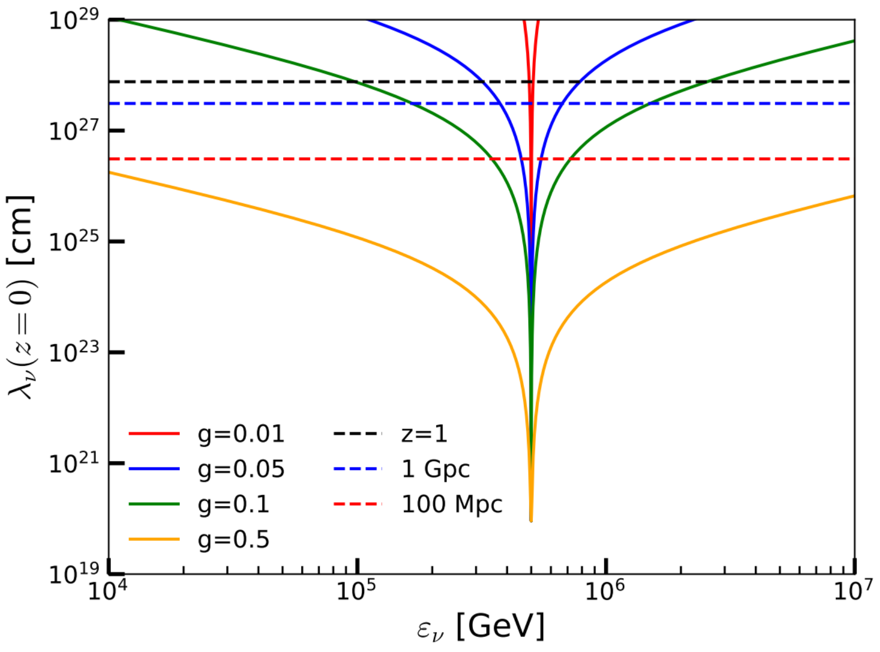
$$\frac{1}{\sigma_\nu}\frac{d\sigma_\nu}{d\cos\theta} = \frac{\varepsilon_\nu}{m_\nu}\left(1 + \underbrace{\frac{\varepsilon_\nu}{m_\nu}(1-\cos\theta)}_{\text{Strong forward scattering}}\right)^{-2}$$

- Total cross section

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

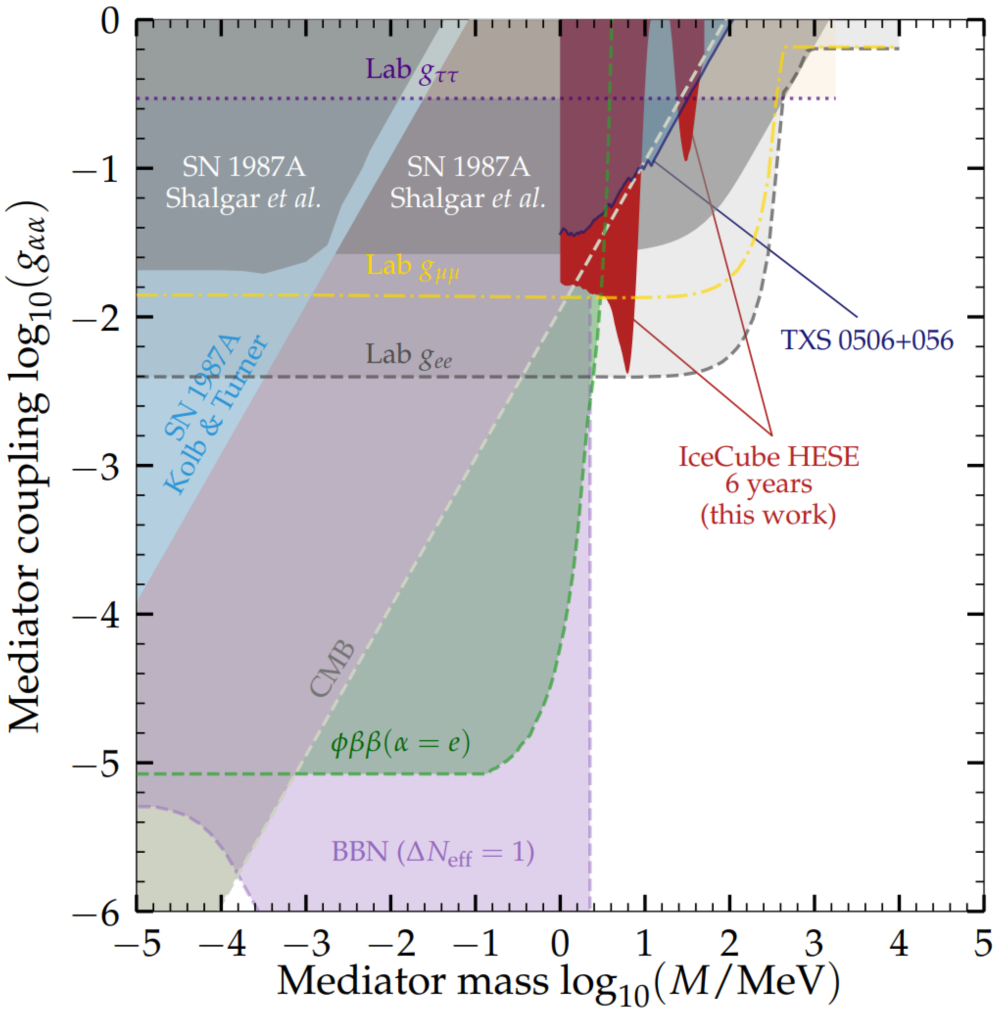
  - $s = 2m_\nu\varepsilon_\nu$
  - $\Gamma = g^2 M_\phi/16\pi$
  - $\lambda_\nu = 1/n_\nu\sigma_\nu,\ n_\nu = 112\ \text{cm}^{-3}$
- Benchmark model
  - m_ν=0.1 eV, M_ϕ=10 MeV (resonance at 500 TeV)





Why 10 MeV scalar mediators?

- Mediator mass has a lower bound from BBN.
- IceCube has good sensitivity to 10 MeV mediators
- $g_{\tau\tau}$ is not well-constrained



Bustamante et al (2020)

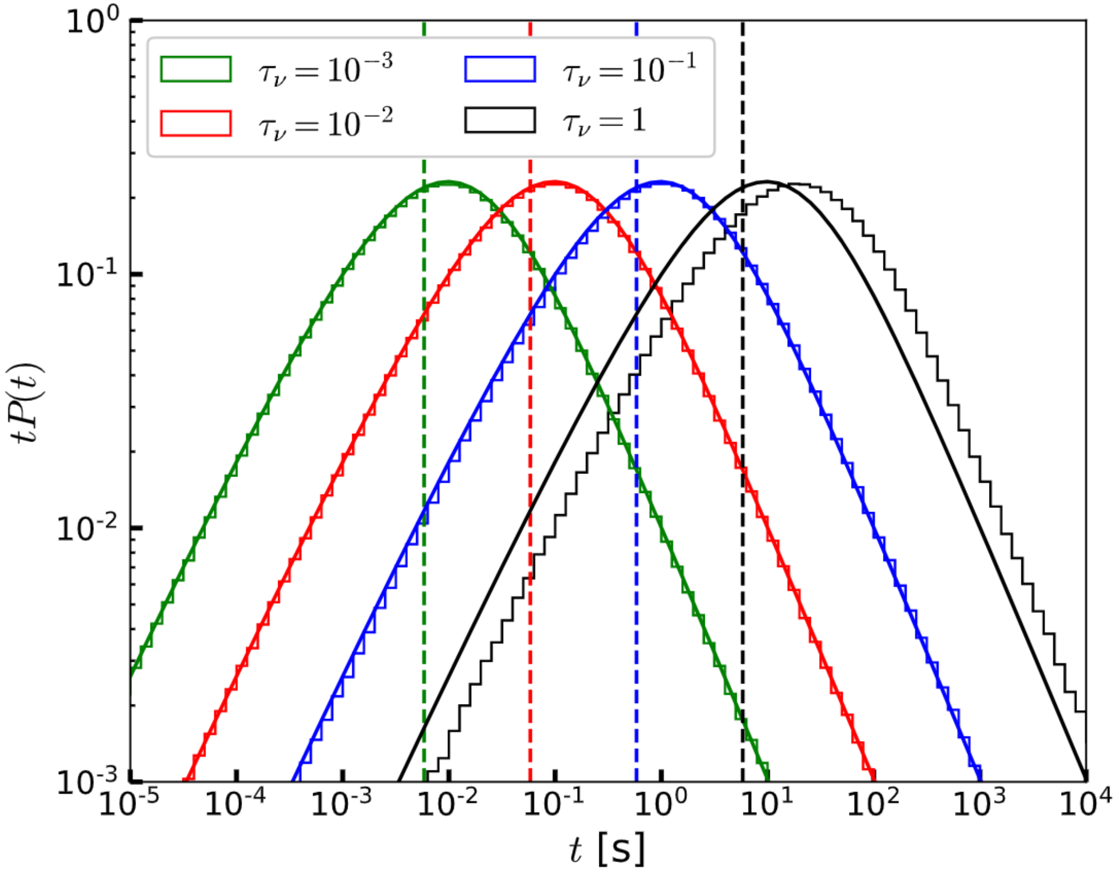
Example 1: Scattering in the $\tau_\nu \ll 1$ limit

- Use 170 TeV neutrinos and $g = 0.1 \longrightarrow \lambda_\nu = 1$ Gpc
- Great agreement with analytical formula (solid curves)
- Characteristic time delay

$$\Delta t \approx \frac{1}{2}\frac{\langle\theta^2\rangle}{4} D \simeq 77 \text{ s } C^2 \left(\frac{D}{3 \text{ Gpc}}\right)\left(\frac{m_\nu}{0.1 \text{ eV}}\right)\left(\frac{100 \text{ TeV}}{E_\nu}\right)$$

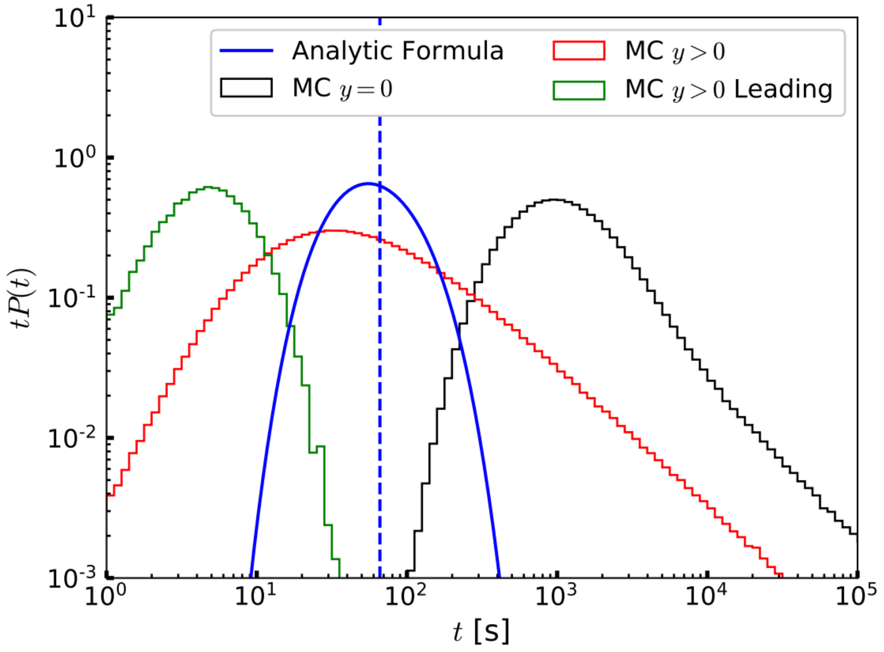
with $C = 0.62$ for leading neutrinos.

- At $\tau_\nu = 1$, multiple scatterings shift the distribution to larger t



Example 2: Scattering in the $\tau \gg 1$ limit - zero inelasticity

- Inelasticity parameter $y = \varepsilon_\nu'/\varepsilon_\nu$. $y = 0$ $\rightarrow$ no upscattered neutrinos.
- 300 TeV neutrinos and $g = 0.5 \longrightarrow \lambda_\nu = 10^{24}\text{cm}$.
- The $\tau \gg 1$ limit has an analytical solution, with an exponential decay at large t.



For $D = 100$ Mpc $(\tau = 310)$

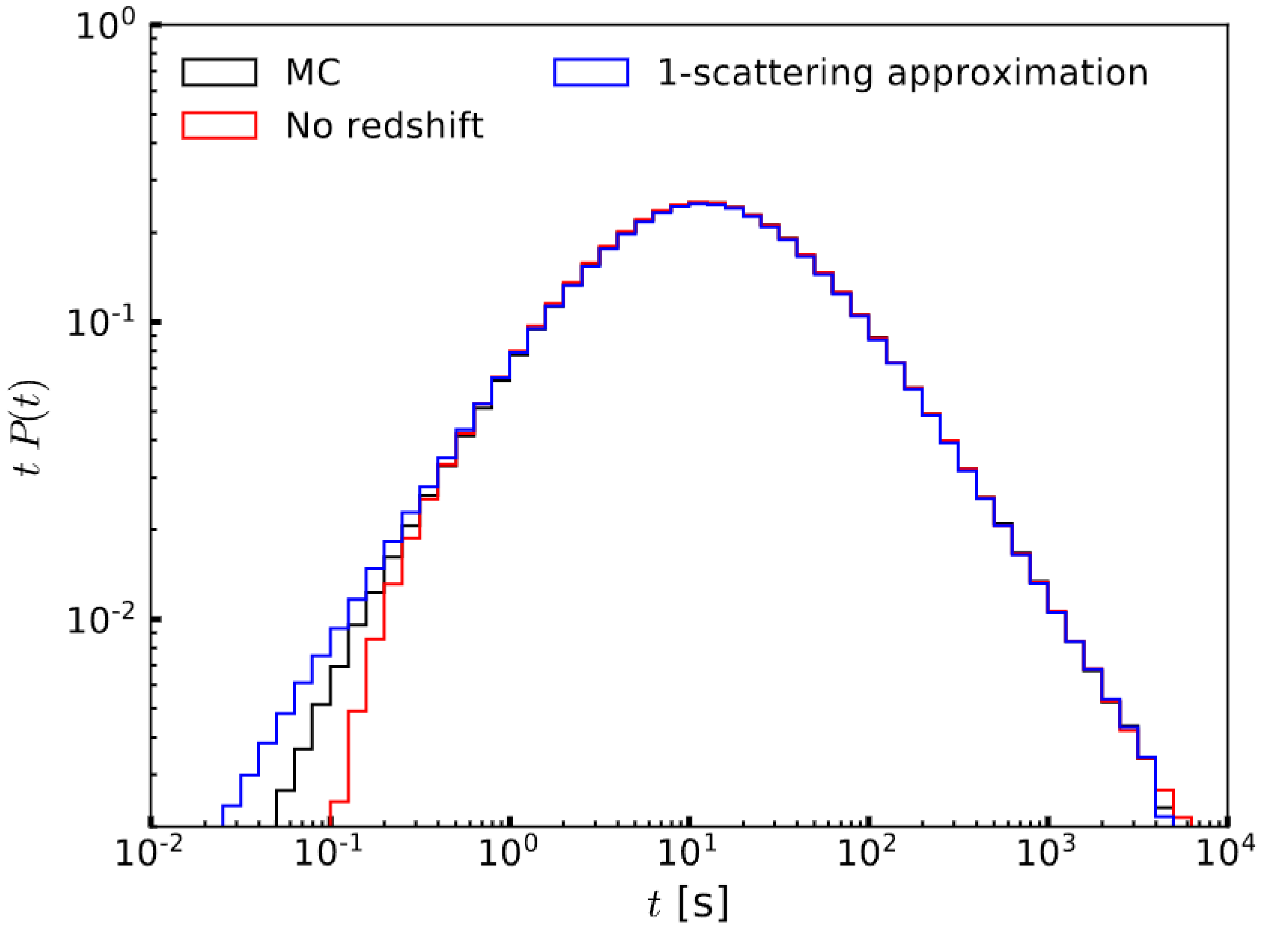
- ❑ MC simulation suggests $P(\Delta t) \propto t^{-2}$.
- ❑ MC predicts peak at 1000s.
- ❑ Analytical expression underestimates the peak's location.

Example 3: Monoenergetic source at $z = 1$

- 800 TeV neutrinos and g=0.01
- Resonance occurs at $z = 0.25$.
- Compare against

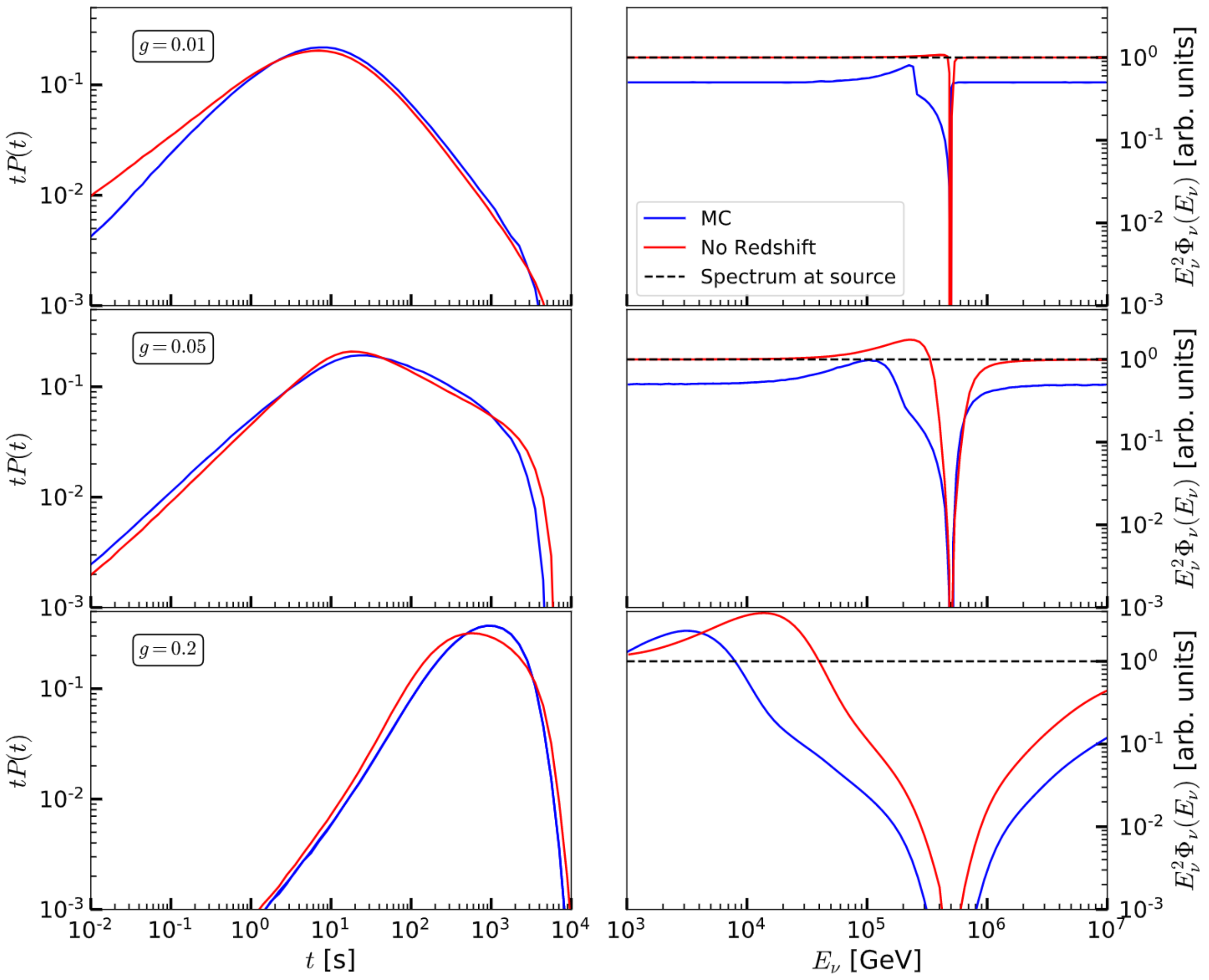
"No redshift": Ignore adiabatic energy loss, but force 800 TeV neutrino to become a 500 TeV neutrino at $z = 0.25$.

One-scattering approximation: Allow adiabatic loss, but forbid more than 1 scattering.



Example 4: Single source at redshift z=1 and ε_ν^{-2} injection spectrum

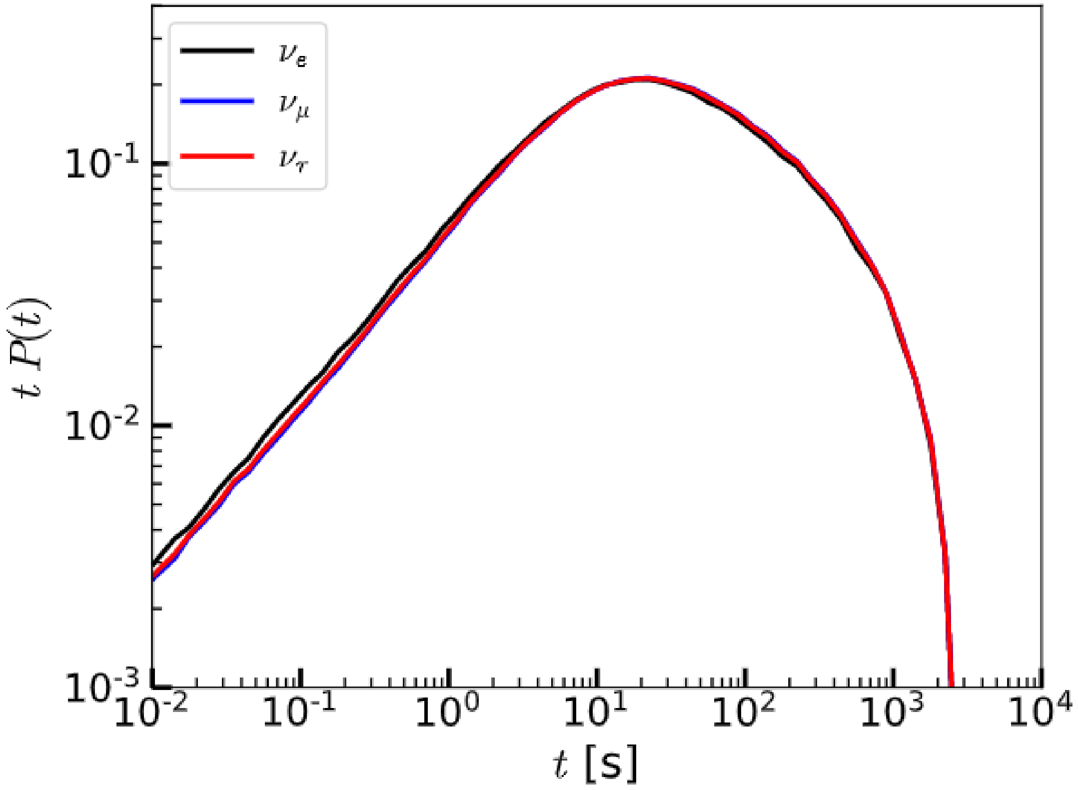
- Cutoffs in delay due to threshold effects
- For g=0.2, the cascade effect is strong enough to overcome the flux decrease due to redshift.
- Comparing against the no redshift case, there are no major differences in time delay.

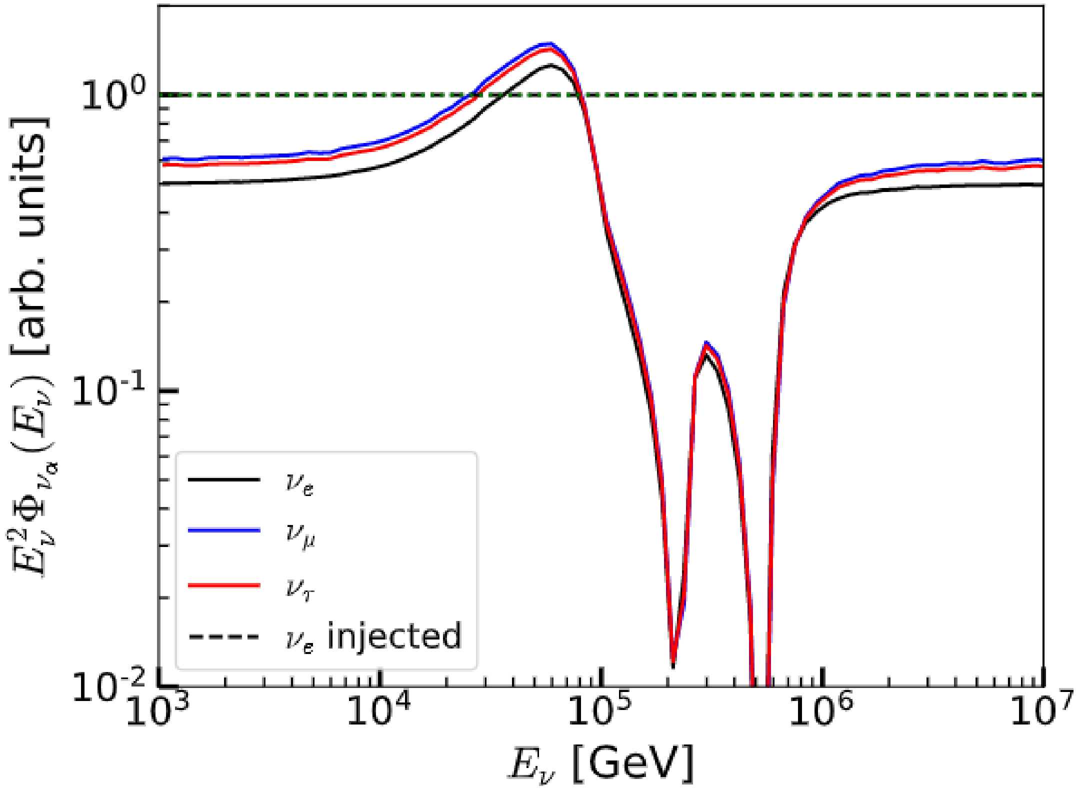


Example 5: Source at redshift z=1 and ε_ν^{-2} injection spectrum, 3ν

Consider a coupling only to ν_τ via $g_{\alpha\beta} = \mathrm{Diag}(0{,}0, g_{\tau\tau})$ and assume $g_{\tau\tau} = 0.05$.
$m_1 = 0.022\ \mathrm{eV}, m_2 = 0.024\ \mathrm{eV}, m_3 = 0.055\ \mathrm{eV}, m_\phi = 5\ \mathrm{MeV}$

Time delay distribution is quite similar among all neutrino flavors.





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 small coupling/optical depth, redshift energy loss only affects the shortest time delays
- 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.
- Time delay distribution for three flavors look similar

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.

More on this work, see 220.409029 (JC & Murase)

For an application of time delay to neutrino-dark matter interactions, see 2204.09650 (JC, Kheirandish & Murase)

Considerations for inelastic scattering and cosmological distances

- Measure lengths as light travel distance

$$l = c\int_{z_1}^{z_2} \frac{dz'}{H_0(1+z')\sqrt{\Omega_M(1+z')^3+\Omega_\Lambda}}$$

Benchmark Model
$\Omega_M = 0.7, \Omega_\Lambda$=0.3, $H_0 = 67 \text{ km s}^{-1} \text{ Mpc}^{-1}$

- If source is at non-negligible redshift

$$\varepsilon_\nu(z_2 < z_1) = \varepsilon_\nu(z_1)\frac{1+z_2}{1+z_1}$$

Expansion losses

$$n_\nu(z) = 112(1+z)^3 \text{cm}^{-3}$$

CνB density

- After each scattering, we have an additional neutrino to track
- Neutrinos above 500 TeV can enter the resonance region due to redshift losses.