Resonant neutrino self-interactions in astrophysical spectra

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Motivations

- It’s tough to constrain some neutrino properties (e.g. $\nu_\tau$ interactions)

- Neutrino self-interactions are popular to consider: $\mathcal{L}_{int} = g_{ij} \phi \nu_i \nu_j$
  
  e.g. Araki et al. 1409.4180 & 1508.07471, Barenboim et al. 1903.02036, Jones & Spitz 1911.06342, Ng & Beacom 1404.2288, Bustamante et al. 2001.04994, Blinov et al. 1905.02727, Mazumdar et al. 2011.13685, Carpio et al. 2104.15136, Das & Ghosh 2011.12315, Choudhury et al. 2012.07519

- Existing / upcoming neutrino experiments
  
  (Super-K, IceCube, POEMMA, ...)

Flux spectrum at Earth

Source of primary flux → Propagation → Flux spectrum at Earth

https://apod.nasa.gov/apod/ap000312.html

Flux spectrum at Earth

Propagation

Source of primary flux

Possible scattering on CνB

Flux spectrum at Earth
Cosmic background neutrinos (CνB)
Cosmic background neutrinos ($\nu_B$)

Neutrino from some astrophysical source

Cosmic background neutrinos ($\nu_B$)
Cosmic background neutrinos (CνB)

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Two outgoing neutrinos (lowers energy but adds a neutrino to spectrum)

Cosmic background neutrinos (CνB)
Neutrino from some astrophysical source

Also considered in:
Farzan & Palomares-Ruiz 1401.7019, Ibe & Kaneta 1407.2848, Jeong et al. 1803.04541

We generalize to:

- Arbitrary self-coupling matrix
- Closed-form solution (avoids time-intensive numerics).

Two outgoing neutrinos (lowers energy but adds a neutrino to spectrum)

Cosmic background neutrinos (CνB)
Boltzmann equations for evolution of neutrino flux

\[ \frac{\partial \Phi_i}{\partial t} = H \Phi_i + HE \frac{\partial \Phi_i}{\partial E} + S_i(t, E) \]
Boltzmann equations for evolution of neutrino flux

\[ \frac{\partial \Phi_i}{\partial t} = H \Phi_i + H E \frac{\partial \Phi_i}{\partial E} + S_i(t, E) \]

- \( \Phi_i(t, E) \) = specific flux of \( \nu_i \)
  (number per conformal time, per comoving area, per energy)
- Expansion
- Source term for primary flux.

Boltzmann equations for evolution of neutrino flux

\[
\frac{\partial \Phi_i}{\partial t} = H \Phi_i + H E \frac{\partial \Phi_i}{\partial E} + S_i(t, E) - \Gamma_i(t, E)\Phi_i + S_{\text{tert}, i}(t, E)
\]

**Expansion**

\( \Phi_i(t, E) \) = specific flux of \( \nu_i \) (number per conformal time, per comoving area, per energy)

**Source term for primary flux.**

Scattering events remove neutrinos from the primary spectrum. (\( \Gamma \) is rate.)

The tertiary source term represents reinjection of neutrinos after scattering.

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Neutrino self-interactions found here

Resonant $\nu - \nu$ scattering

- Resonant scattering dominant – we take a Breit-Wigner form.

- In many cases, this can be well-approximated as a delta function (e.g. width less than detector energy resolution).
optical depth depends on form of neutrino self-coupling matrix...
Result for multiple flavors, arbitrary self-coupling matrix

\[ \Phi_i(t, E) = \int_{-\infty}^{t} dt' \left( \frac{a(t)}{a(t')} \right) e^{-\tau_i(t', t, E)} S_i \left( t', \frac{a(t)}{a(t')} E \right) \]

Optical depth depends on form of neutrino self-coupling matrix...

\[ \tilde{S}_i = S_i + S_{tertiary}, \]
with tertiary source dep. on self-coupling matrix, and \( \tilde{S}_i \) evaluated at higher resonant energy, ...

Details here are pretty involved for such a short talk... See paper.

Primary source term – depends on physics of source (e.g. supernova neutrinos)

Neutrino self-coupling matrix – depends on new physics model

Inputs: Analytic calculation Result:

Spectrum that arrives at Earth

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Could apply to a wide range of scenarios.

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Analytic calculation

Spectrum that arrives at Earth
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Could apply to a wide range of scenarios.

Not a time-intensive Monte Carlo, etc.

Analytic calculation

Spectrum that arrives at Earth

Is it really a closed-form solution?

Result for multiple flavors, arbitrary self-coupling matrix

Inputs:
- Primary source term – depends on physics of source (e.g. supernova neutrinos)
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Result:
- Not a time-intensive Monte Carlo, etc.
- Analytic calculation
- Spectrum that arrives at Earth
- Is it really a closed-form solution?
  - Yes! But have to be careful with implementation...
Example: Diffuse Supernova Neutrino Background (DSNB)

\[ \Phi_e \text{ [cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}] \]

Neutrino Energy \( E_{\nu} \) [MeV]

- Black line: \( g_{ij} = 0 \)
- Orange line: \( g_{\tau\tau} = 0.01 \)
- Blue line: \( g_{ss} = 0.01 \)
- Green line: \( E_{\nu}^{\text{min}} = 1.806 \text{ MeV} \)

Example: Diffuse Supernova Neutrino Background (DSNB)

Above highest resonant energy, spectrum unaffected by self-interactions.

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Scattering at the highest resonant energy used in (tertiary) source for injection at lower energies.
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Neutrinos removed from spectrum at resonances, injected at lower energies.
Event rates, +/- 1 sigma for 10 years at Super-K w/ gadolinium.

Comparison with expected spectrum at T = 8 MeV in absence of self-interactions.
Forecasted 1-sigma constraints on coupling & scalar mediator, for 10 years at Super-K w/ gadolinium.

Summary

• Efficient way to calculate observed spectra, given a source and model of neutrino self-interactions.

• Observation of the DSNB by Super-K can constrain neutrino self-interactions with ~ keV masses.

• (In paper) High-Energy Astrophysical Neutrinos at IceCube: can constrain ~ MeV mediators.