17th International Conference on Topics in Astroparticle and Underground Physics IOP Publishing
Journal of Physics: Conference Series **2156** (2022) 012103 doi:10.1088/1742-6596/2156/1/012103

Astrophysical neutrino self-interactions in the high-statistics era

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Abstract. Do neutrinos have sizable self-interactions? They might. Laboratory constraints are weak, so strong effects are possible in astrophysical environments and the early universe. Observations with neutrino telescopes can provide an independent probe of neutrino self ("secret") interactions, as the sources are distant and the cosmic neutrino background intervenes. We define a roadmap for making decisive progress on testing these interactions. This progress will be enabled by IceCube-Gen2 observations of high-energy astrophysical neutrinos. Critical to this is our comprehensive treatment of the theory, taking into account previously neglected or overly approximated effects, as well as including realistic detection physics. We show that IceCube-Gen2 can realize the full potential of neutrino astronomy for testing neutrino self-interactions, being sensitive to cosmologically relevant interaction models.

1. Introduction

Neutrinos, ubiquitous but elusive, remain mysterious. Though many of their properties are known, we still do not know if they might have large self-interactions, also known as neutrino secret interactions (νSI) [1–3]. In that scenario, neutrinos interact with a light boson, increasing the neutrino-neutrino scattering rate with respect to that of the standard model.

Allowed νSI would dramatically affect the evolution of systems with high neutrino densities, such as supernovae [4] and the early universe [5–8]. While cosmological measurements have robustly established the presence of a radiation background compatible with expectations for the cosmic neutrino background (CνB), its dynamics are poorly constrained. In fact, strong neutrino self-interactions could reduce neutrino free-streaming in the early universe, with profound consequences for cosmological parameter extraction [9–14].

Figure 1 shows another essential point about νSI: while the constraints are strong for ν_e, they are incomplete for ν_μ and nearly nonexistent for ν_τ [15] (this figure is explained in detail in Ref. [16]). This is why large cosmological effects from νSI remain allowed.

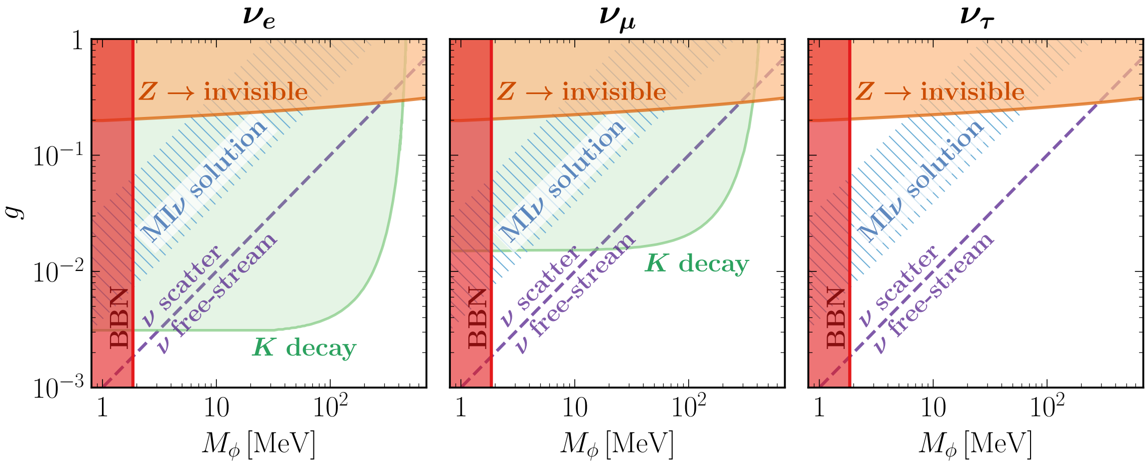


Figure 1: Present constraints on neutrino self-interactions, with coupling strength g and mediator mass M_ϕ, for each of the three neutrino flavors. The hatched region is the "Moderately Interacting neutrino" (MIν) solution [9], argued to affect CMB observables. The dashed purple line is the interaction strength below which cosmic neutrinos free-stream at cosmologically relevant times. Above this line, our understanding of the early universe would be affected. *ν_τ self-interactions are the least explored, leaving room for significant cosmological neutrino effects.*

A new opportunity to probe νSI has arisen [17–19] due to the detection of high-energy neutrinos by IceCube. The basic idea is that scattering of astrophysical neutrinos with the CνB en route to Earth redistributes their energies [20], leading to dips and bumps in the detected spectrum of the diffuse astrophysical neutrino background. However, with the relatively low statistics of IceCube data, it is hard to realize the full potential of this technique.

In this work, we define a roadmap for making decisive progress. The first key to this is the proposed IceCube-Gen2 (Gen2 for brevity) detector [21]. Its principal advantage relative to IceCube, beyond its better statistics, is its much wider energy range. The second key is an improved theoretical treatment. We define the observable signatures of allowed flavor-dependent νSI, correcting errors and omissions in prior work. All calculations are done without any approximation, following careful optimizations. The third key is a realistic treatment of the detector response, using code provided by IceCube. To make future studies easier, we make our code publicly available at this URL .

2. Secret neutrino interactions

We consider νSI parametrized by the Lagrangian $\mathcal{L}_{\rm int} = -\frac{1}{2}\sum_{\alpha,\beta} g_{\alpha\beta}\bar{\nu}_\alpha \nu_\beta \phi$, where ν_α are neutrino flavor eigenstates ($\alpha \in \{e, \mu, \tau\}$), $g_{\alpha\beta}$ is the interaction strength between flavors α and β, and ϕ is the interaction mediator with mass M_ϕ. As the weakest νSI constraints are in the ν_τ sector, we explore how νSI affect astrophysical neutrino propagation assuming that νSI apply only in the ν_τ sector. Nevertheless, our results provide comparable sensitivity to all flavors [16].

Qualitatively, the effects of νSI can be understood through resonant scattering. When $s \equiv 2E_\nu m_j = M_\phi^2$ — with E_ν the neutrino energy and m_j the mass of ν_j—, the neutrino-neutrino cross-section is resonantly enhanced, leading to an enhanced astrophysical neutrino absorption. Since all mass eigenstates have $\mathcal{O}(1)$ mixings with ν_τ, the astrophysical spectrum will feature multiple absorption dips, located at $E_\nu \sim M_\phi^2/(2m_j)$ with $j \in \{1, 2, 3\}$ [22–24]. The separation between these dips, and thus their separate observability, depends on the neutrino mass spectrum. In the last few years, there has been a lot of progress in understanding it: the cosmological bound on neutrino masses, together with the neutrino oscillation preference for the

Normal mass Ordering, implies that νSI in the ν_τ sector should feature *two* absorption dips, separated in energy by an $\mathcal{O}(1)$ factor [16].

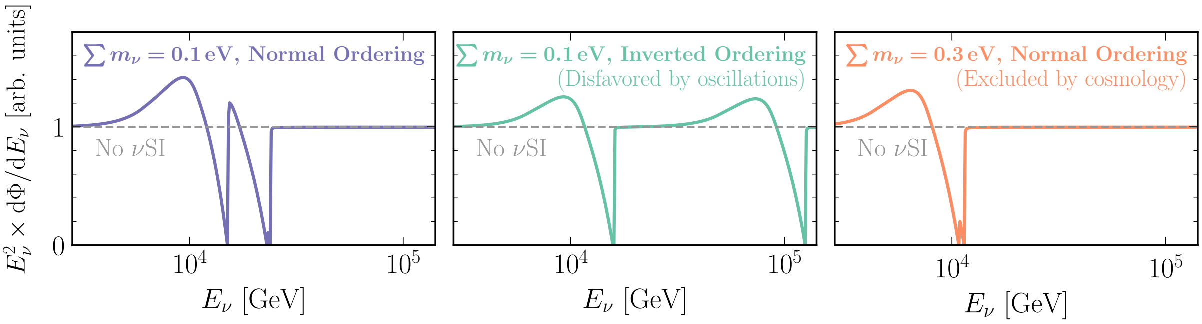


Figure 2: All-flavor neutrino flux at Earth assuming an astrophysical flux $\propto E_\nu^{-2}$ and ν_τ self-interactions ($g = 0.01$ and $M_\phi = 5\,\mathrm{MeV}$), for different neutrino mass scenarios. *The scenario in the left panel, favored at* $\gtrsim 2.5\sigma$ *over the other two scenarios, would produce two close dips in the astrophysical neutrino spectrum.*

Figure 2 shows these features. We display the all-flavor high-energy astrophysical neutrino flux at Earth. We observe the two dips due to neutrino absorption, as well as the two bumps due to the scattering products moving to lower energies.

In addition, as detailed in Ref. [16], approximations made in the literature when computing the neutrino self-interaction cross section were unjustified in some important cases. In our public numerical code they are largely unnecessary, as it has been optimized to carry out the exact calculation with a low computational cost.

3. IceCube-Gen2: the road to precision neutrino astrophysics

The IceCube observatory has firmly established the existence of high-energy astrophysical neutrinos by detecting $\mathcal{O}(100)$ neutrinos with $\mathcal{O}(0.1-1)$ PeV energies. The presence of νSI could leave energy-dependent features in the data.

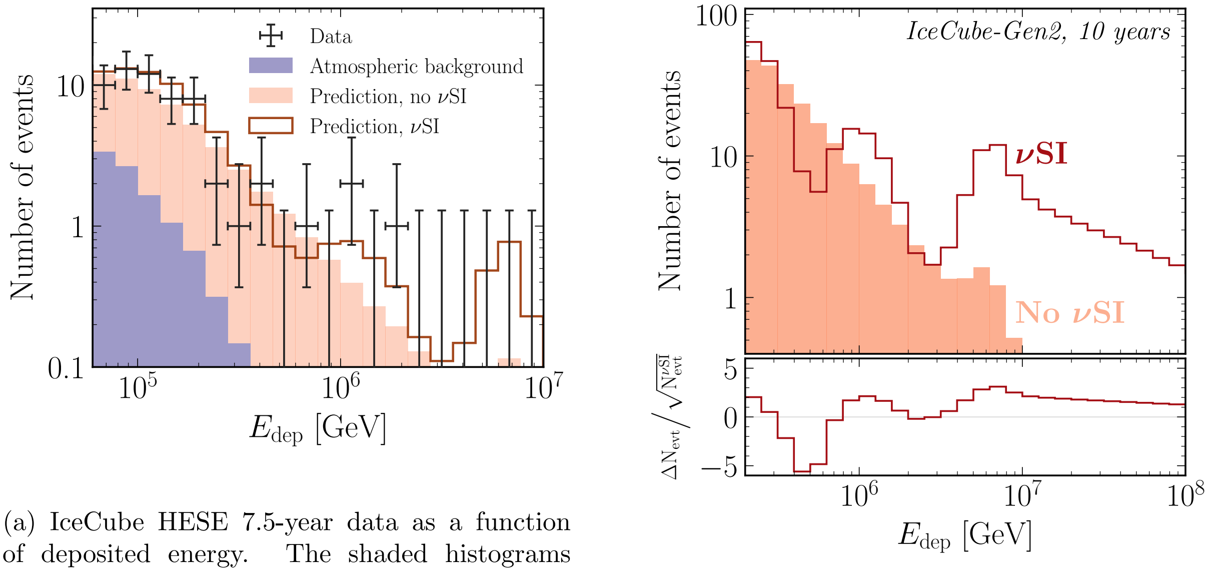
Figure 3a shows that current IceCube data is hardly indistinguishable from νSI with a modified astrophysical spectrum. Presently, IceCube data has two weaknesses to explore νSI: apart from having relatively low statistics, the data only covers about one order of magnitude in neutrino energy. As Fig. 2 shows, νSI-induced spectral features cover a wide energy range. Furthermore, a wider energy coverage also entails a better understanding of the spectral index that to some extent can be degenerate with νSI-induced dips.

Fortunately, Gen2 [21] will have an effective volume about one order of magnitude larger than IceCube, overcoming these issues. To quantify the potential of this future observatory, we carry out a simplified but realistic simulation of Gen2, described in Ref. [16].

Figure 3b shows that Gen2 will indeed be very sensitive to νSI. We show the expected numbers of events after 10 years of data taking using the same physics parameters as in Fig. 3a. There is no longer a degeneracy between νSI and a modified spectral index.

To quantify the future sensitivity of Gen2, along with the νSI presently allowed by IceCube, we carry out a data analysis with the framework sketched above (see Ref. [16] for details).

Figure 4 shows that Gen2 will have superb sensitivity, covering a huge range of cosmologically relevant νSI parameters. For mediator masses between 2 MeV and 20 MeV, Gen2 even competes with the strongest laboratory probes (see meson-decay limits in Fig. 1; we expect the constraints from Fig. 4 to apply with comparable strength to ν_e and ν_μ). The sensitivity there corresponds to a neutrino mean free path $\sim$ Gpc, the typical distance to astrophysical neutrino sources. For lower couplings, the neutrino flux attenuation is hardly different from 1. It will thus be hard to improve upon this sensitivity.



(a) IceCube HESE 7.5-year data as a function of deposited energy. The shaded histograms show the best-fit expectations (with no new physics) for the atmospheric background and the astrophysical neutrino signal ($\propto E_\nu^{-2.9}$ [25]). *The data can also be accommodated by νSI with $g = 0.1$, $M_\phi = 7.5\,\mathrm{MeV}$, $\sum m_\nu = 0.07\,\mathrm{eV}$, the NO, and a modified astrophysical spectrum ($\propto E_\nu^{-2}$) [solid red line].*

(b) Spectra for the same parameters as in Fig. 3a, but now projecting for Gen2, which turns small differences into large ones. *The increased statistics and the wider energy range reduce the degeneracy with the unknown astrophysical flux* (here $\propto E_\nu^{-2}$ for νSI and $\propto E_\nu^{-2.9}$ for no νSI), *dramatically increasing the sensitivity to νSI.*

Figure 3

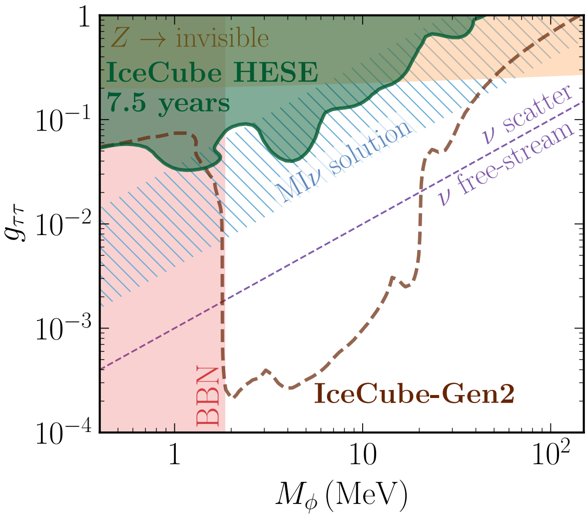


Figure 4: Present and future sensitivity to ν_τ self-interactions, along with present bounds and cosmologically relevant regions (c.f. Fig. 1). The dark green region is excluded by IceCube data, and the dashed brown line shows the Gen2 sensitivity (2σ). *Gen2 will exploit the full potential of testing νSI with high-energy astrophysical neutrino propagation* (see text)*, being sensitive to a large parameter space where neutrinos have a non-trivial cosmological behavior.* The sensitivity to other flavors is comparable.

4. Conclusions and Outlook

A way forward in exploring neutrino self-interactions is to look for signatures of scattering with neutrinos in the CνB, which leads to characteristic features in the spectrum of astrophysical neutrinos at Earth. This has become newly promising now that IceCube has detected $\mathcal{O}(100)$ events at energies larger than 60 TeV.

In this work, we take advantage of the proposed Gen2 detector, develop a comprehensive theoretical treatment, and make predictions that include realistic experimental effects. We benefit from the improved knowledge of the neutrino mass spectrum: measurements of the total neutrino mass and of the neutrino mass ordering shape the signatures that should be looked for.

Our primary result is in Fig. 4: Gen2 will significantly improve the sensitivity to νSI, realizing the full potential of high-energy neutrino astronomy for testing νSI in propagation. At its best sensitivity, Gen2 will overcome laboratory constraints and become the strongest probe of neutrino self-interactions *between any flavors.* The future quest for νSI discovery will not remain bounded to τ neutrinos as it is today. Should a signal appear at Gen2, there will be plenty of opportunities to test it with, for instance, flavor effects or looking for point sources [16].

As neutrino physics enters the precision era, the properties of these ghostly particles will be scrutinized better than ever. In this work, we provide the roadmap to make the most out of neutrino self-interaction measurements in present and next-generation neutrino telescopes. Improvements in understanding high-energy astrophysical sources and further experimental sensitivity studies will enhance this progress. This will open a window into understanding whether neutrinos have sizable self-interactions, providing insight about physics beyond the standard model and the evolution of the early universe.

Acknowledgements J.F.B. is supported by NSF grant No. PHY-2012955.

The text in these proceedings is heavily based on Ref. [16].

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