Probing New Physics with Astrophysical Neutrinos

Nicole F. Bell

School of Physics, The University of Melbourne, Victoria 3010, Australia

E-mail: `n.bell@unimelb.edu.au`

Abstract. We review the prospects for probing new physics with neutrino astrophysics. High energy neutrinos provide an important means of accessing physics beyond the electroweak scale. Neutrinos have a number of advantages over conventional astronomy and, in particular, carry information encoded in their flavor degree of freedom which could reveal a variety of exotic neutrino properties. We also outline ways in which neutrino astrophysics can be used to constrain dark matter properties, and explain how neutrino-based limits lead to a strong general bound on the dark matter total annihilation cross-section.

1. Introduction

Neutrino astronomy is in its infancy. To date, the only neutrinos we have observed from beyond our solar system are those from SN1987A. Together with solar neutrinos, and those produced by cosmic ray interactions in the atmosphere, these form the complete inventory of astrophysical neutrinos that have been detected. For distant astrophysical objects, we currently have only upper limits on the neutrino fluxes. However, a plethora of exciting new experiments are now coming on line with excellent prospects of detecting a signal. The eagerly awaited era of neutrino astronomy is likely to prove extremely revealing, both in terms of the properties of astrophysical neutrino sources, and the properties of neutrinos themselves. In this article I concentrate on the later.

Studying the astrophysical neutrino flux produced by sources beyond the solar system, may eventually be as revealing as the solar neutrino flux has proven to be. From an astrophysics point of view, neutrinos have the advantage that (unlike cosmic ray protons) they are not deflected by magnetic fields and thus their arrival direction points back to the source. In addition, they are not attenuated by intervening matter. Neutrino astrophysics will thus allow us to see further in the cosmos and deeper into astrophysical sources. In addition, the flavor composition of astrophysical neutrino fluxes may encode important information about neutrino properties.

There are many interesting sources of high energy astrophysical neutrinos, including cosmic accelerators such as gamma ray bursts, supernovae remnants or active galactic nuclei. Interactions of accelerated nucleons in the vicinity of these sources lead to the production of charged pions, and hence neutrinos via their decays. If the sources are optically thin, the neutrino fluxes may be related to the fluxes of cosmic rays and gamma rays [1, 2], while for optically thick sources these constraints do not apply [2]. There may even be "hidden sources" for which the density of matter is such that only neutrinos escape; see, for example, Ref. [3, 4]. In addition, "cosmogenic" neutrinos are generated via the interaction of high energy cosmic rays with the cosmic microwave background. Finally, dark matter annihilation or decay may contribute a source of high energy neutrinos that are detected in neutrino telescope experiments.

2. Above the electroweak scale

One of the most exciting prospects of neutrino astronomy is ability to access physics beyond the electroweak scale. For neutrinos with PeV energies, the center of mass energy in a neutrino-nucleon interaction is at the TeV scale. At such high energies, the neutrino-nucleon cross sections have not been measured and must be extrapolated from lower energy data [5, 6, 7]. Cross-sections either smaller or larger than the standard model extrapolation could signal new physics contributions. Possible effect that could enhance neutrino cross-sections include the exchange of towers of Kaluza-Klein gravitons [8, 9] or the production of black holes [10, 11, 12].

Event rates in neutrino telescopes obviously depend on both the neutrino fluxes and cross-sections. However, it is possible to disentangle flux and cross-section, since event rates in the up-going, down-going, and earth-skimming directions have a different dependence on neutrino cross-sections, due to absorption of neutrinos which traverse the Earth [13, 10]. Current Amanda data place weak flux and cross-section constraints at center of mass energies of order ~ 1 TeV [14], while IceCube and other experiments have potential to make a measurement of these parameters.

Many example of physics beyond the Standard Model may also show up in neutrino telescopes. For instance, in some supersymmetric models a very distinctive process would be the production of long-lived NLSP pairs, for which the signature in IceCube would be a pair of two parallel charged tracks [15, 16, 17].

3. Flavor Composition

Neutrinos from astrophysical sources are expected to arise dominantly from the decays of pions, which result in initial flavor ratios of $\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} = 1 : 2 : 0$. The fluxes of each mass eigenstate are given by $\phi_{\nu_i} = \sum_\alpha \phi_{\nu_\alpha}^{\rm source} |U_{\alpha i}|^2$, where $U_{\alpha i}$ are elements of the neutrino mixing matrix. If we assume exact ν_μ–ν_τ symmetry ($\theta_{23} = 45^\circ$ and $\theta_{13} = 0$) this implies that neutrinos are produced in the ratios $\phi_{\nu_1} : \phi_{\nu_2} : \phi_{\nu_3} = 1 : 1 : 1$ in the mass eigenstate basis, independent of the solar mixing angle. Oscillations do not change these ratios, only the relative phases between mass eigenstates, which will be washed out by uncertainties in the energy or distance since $\delta m^2 \times L/E \gg 1$. An incoherent mixture with the ratios $1 : 1 : 1$ in the mass basis implies an equal mixture in any basis (since $\mathcal{U} I \mathcal{U}^\dagger \equiv I$) and in particular in the flavor basis in which the neutrinos are detected [18, 19].

Variation from the assumed ν_μ–ν_τ symmetry lead to only small deviations of the flavor ratios. However, such deviations could be used to measure neutrino mixing parameters, if sufficiently high precision measurements of the astrophysical flux were to be made [20, 21, 22]. On the other hand, the flavor composition of astrophysical neutrino fluxes may encode important information about exotic neutrino properties. Variations to the expected flavor ratios may reveal new physics such as neutrino decay [23], CPT violation [24], oscillation to sterile neutrinos [25, 26, 27], and various other exotic scenarios [28, 29, 30].

Neutrino decay can result in particularly large deviations to the expected flavor ratios [23]. For non-radiative decays such as $\nu_i \to \nu_j + X$ and $\nu_i \to \bar{\nu}_j + X$, where X is a massless particle (e.g. a Majoron) existing limits are quite weak. If neutrinos are unstable, the cosmic neutrinos detected may all be in the lightest mass eigenstate. The flavor composition of this lightest eigenstate is $\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} = 5 : 1 : 1$ in the case of the normal hierarchy, and $0 : 1 : 1$ in the case of the inverted hierarchy. For either hierarchy, this represents a large and distinctive deviation to the expected flavor equality.

Another feature of astrophysical neutrino experiments is the enormous distance scales at our disposal. With neutrino from distant astrophysical sources, we may do oscillation experiments with baselines comparable to the size of observable Universe. Given a neutrino oscillation length scale of $\sim 2E/\delta m^2$, cosmological scale baselines provide sensitivity to oscillations with extremely small mass splittings [25, 26, 27]. In Fig. 1 we show the δm^2 sensitivity of various

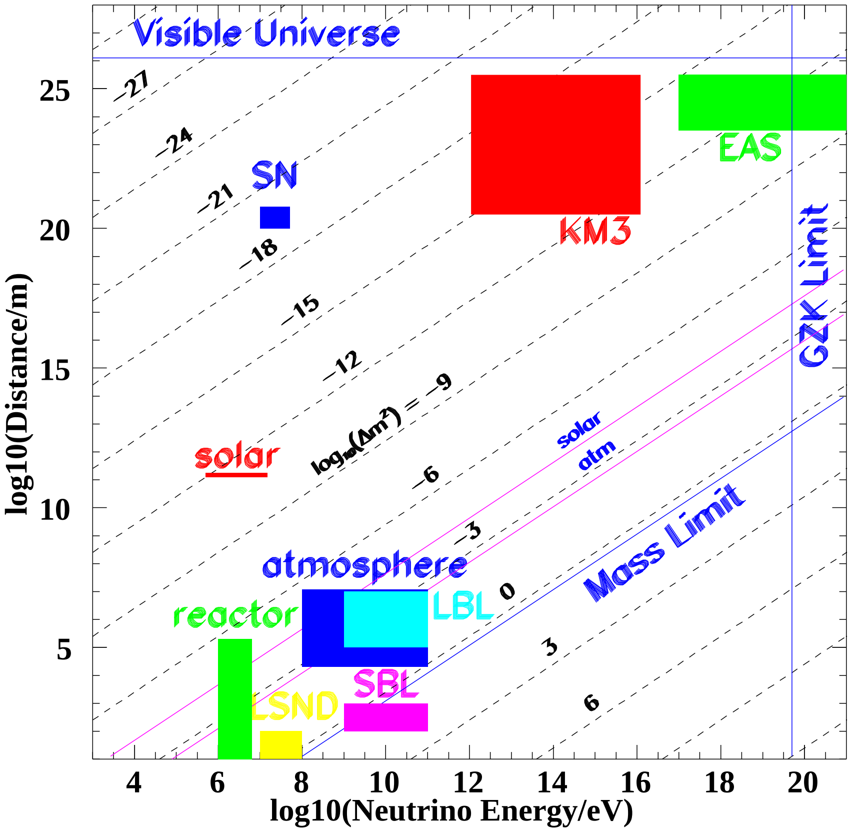

Figure 1. The energy and distance ranges covered in various neutrino experiments. The diagonal lines indicate the mass-squared differences (in eV^2) that can be probed with vacuum oscillations; at a given L/E, larger δm^2 values can be probed by averaged oscillations. The shaded regions display the sensitivity of solar, atmospheric, reactor, supernova (SN), short-baseline (SBL), long-baseline (LBL), LSND, and extensive air shower (EAS) experiments. The KM3 region describes the parameter space that would be accessible to a 1-km^3 scale neutrino telescope, given sufficient flux. Figure taken from Ref. [25].

neutrino experiments. An example in which such tiny mass splittings occur is the case of pseudo-Dirac neutrinos, in which a Dirac neutrino is split into a pair of almost degenerate Majorana neutrinos by the presence of tiny, sub-dominant, Majorana mass terms. In this scenario the active neutrinos are each maximally mixed with a sterile partner with very tiny δm^2. The deviations to the astrophysical neutrino flavor ratios due to oscillations driven by these tiny mass splittings would be milder than those predicted for neutrino decay. However, it is a potential probe of tiny Majorana mass terms (and thus lepton number violation) not discernible via any other means.

If neutrinos are produced via some mechanism other than conventional pion decay, there will also be departures from the canonical flavor ratios 1 : 1 : 1. One scenario is that where neutrons, produced in the Galaxy by photo-disintegration of heavy nuclei, decay to a pure $\bar{\nu}_e$ flux [31, 32]. After oscillations wash out phase information, this flux is transformed to the ratios $\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} = 5 : 2 : 2$. Another possibility is a muon damped source in which charged pions decay to muons and neutrinos, but the muon daughters loose energy before decaying further [33]. The pure ν_μ flux produced is transformed by oscillations to $\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} = 1 : 2 : 2$.

The flavor degree of freedom clearly carries important information about both the astrophysical neutrino production mechanism, and exotic physics in the neutrino sector. An important question is whether a given flavor signature is unique to a particular scenario. However, a number of the scenarios discussed above have large and distinctive effect on the flavor ratios. For example, it is difficult to see how the neutrino decay of prediction $\phi_{\nu_e} : \phi_{\nu_\mu} = 5 : 1$ could be replicated by another mechanism.

Neutrino flavor ratios will not be directly measured at neutrino telescope experiments, but can be inferred from the ratios of different types of events. In an experiment like IceCube, the ratio of muon tracks to shower events is likely to be most useful, and would permit the ν_e fraction of the flux to be calculated. In Ref. [34], it was found that a ν_e fraction of 1/3 (the default prediction) could be measured to a range of approximately 0.2–0.4, provided the neutrino spectrum was also measured.

Double-bang and lollipop events, which are unique to ν_τ, would provide important direct information on the size of the tau neutrino flux [18, 35]. A double-bang event consists of a shower initiated by a charged current interaction of ν_τ, followed by a second shower initiated by the decay of the resulting tau lepton. (Lollipop events consists of the second of these two showers, along with a reconstructed tau lepton track.) The detection threshold for these ν_τ events is a few PeV, and thus expected events rates will be small. However, given that the some exotic physics scenario can lead to large deviations from the expected flavor equality, even small numbers of events can provide important information.

4. Dark matter annihilation to neutrinos

Dark matter (DM) may well be a source of high energy neutrinos that are detected in neutrino telescope experiments, and there are a number of techniques that use neutrinos to constrain dark matter cross sections.

WIMPS captured by the gravitational field of the Sun (and also the Earth) accumulate in the center of the body and annihilate with a rate proportional to the square of the DM number density [36]. All products of such DM annihilation would be absorbed in the Sun, with the exception of neutrinos. Therefore, since neutrinos produced via solar fusion processes have typical energies of ~ 10 MeV, an observation of neutrinos with GeV energies or above emanating from the solar core would be strong evidence for dark matter. Such techniques enable Super-Kamiokande [37], Amanda [38] and other experiments to place competitive constraints on the WIMP-nucleon scattering cross-section.

High energy neutrinos may also be produced via DM annihilation or decay in galactic halos. In this case, we look for fluxes produced in the Milky Way, in other galaxies, or for a diffuse flux arising from annihilation or decay in all halos throughout the Universe. Neutrinos, despite being generally harder to detect than, e.g., gamma rays, in fact provide important information and surprisingly strong bounds on the *total* dark matter annihilation rate [39].

Let us assume that the DM is the lightest particle beyond those in the Standard Model (SM). It then follows that all dark matter annihilation products must be Standard Model particles, as any other (new) particles must be kinematically inaccessible. Among SM final states, it is clear that all but neutrinos will inevitably produce gamma rays. Quarks and gluons hadronize, producing pions, where $\pi^0 \to \gamma\gamma$, and the decays of weak bosons and tau leptons also produce π^0. The stable final state e^+e^- is not invisible, since it produces gamma rays either through electromagnetic radiative corrections or energy loss processes, while the final state $\mu^+\mu^-$ produces e^+e^- via decays. Given that limits on the $\bar{\nu}\nu$ final state will be weaker than the limits on all other final states, we can set a conservative upper limit on the *total* annihilation cross-section by setting the branching ratio to the $\bar{\nu}\nu$ final state at $Br(\bar{\nu}\nu) = 100\%$.

The most straightforward approach to bound the DM + DM $\to \bar{\nu}\nu$ cross section is to use the cosmic diffuse neutrino flux arising from dark matter annihilation in all halos throughout the Universe [39]. The neutrino annihilation rate depends on the average of n^2_{DM} (where n_{DM}

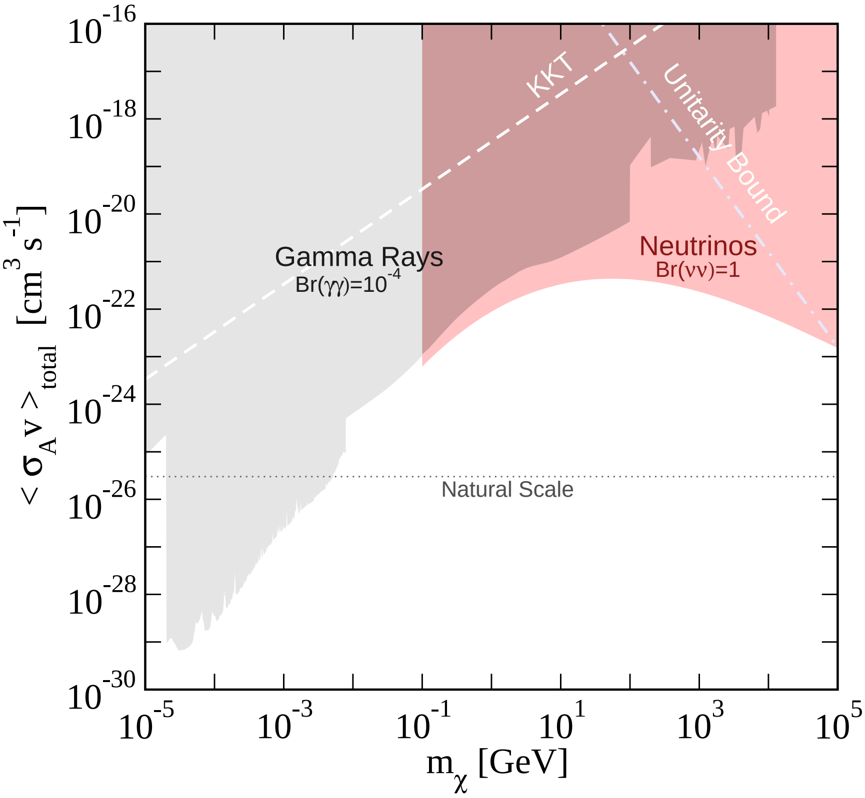

Figure 2. Neutrino and gamma-ray limits on the dark matter total annihilation cross section in galaxy halos, selecting $Br(\gamma\gamma) = 10^{-4}$ as a conservative value. The general unitarity bound is shown for comparison, while the KKT limit denotes the point at which annihilations would significantly modify dark matter halo density profiles [44]. The overall bound on the total cross section at a given mass is determined by the strongest of the various upper limits. Figure taken from Ref. [42].

is the DM number density) which is enhanced by the clustering of dark matter in halos, while the monochromatic neutrino energy is smeared by redshift to form a broader spectrum. A complementary approach, with comparable or slightly better sensitivity, is to consider the signal from annihilations within our Galactic halo [40]. In order for the annihilation flux to be detectable, it must be larger than the atmospheric neutrino background. We may adopt the conservative criteria that the signal be as large as the angle averaged atmospheric neutrino background, and use the Super-Kamiokande atmospheric neutrino measurements [41] to bound the possible neutrino flux arising from dark matter annihilation.

In Fig. 2 , we show the constraints on the *total* dark matter annihilation cross-section, obtained by conservatively setting the branching ratio to neutrinos at 100% (the figure displays the Milky Way constraints derived in Ref [40]). Also shown are constrains on the annihilation cross-section obtained by assuming a 10^{-4} branching ratio to the state $\gamma\gamma$ [42]. The neutrino results are surprisingly strong, particularly for large dark matter mass. In particular, they are more stringent than the general unitarity bound [43] over a large range of masses, and strongly rule out proposals in which annihilation rates are large enough to modify dark matter halos (denoted by KKT [44] in Fig. 2).

The technique to constrain the dark matter total annihilation cross-section can be applied to MeV energies using the Super-Kamiokande data [45], and analogous bounds on the DM decay rate can also be derived [46]. Note that although we have set the branching ratio to neutrinos at 100% (in order to derive a conservative and model independent bound) final state neutrinos will inevitably by accompanied by gamma rays due to electroweak radiative corrections. However, these gamma ray constraints on the annihilation cross-section are weaker than or comparable to those obtained directly with neutrinos [47, 48, 49].

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