Neutrinos and dark matter

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Abstract.
Neutrino mass and dark matter may be closely connected. I briefly review the status of neutrino oscillations along with neutrino mass generation schemes which suggest dark matter candidates, briefly discussing their properties and relevant direct/indirect/collider detection prospects.

1. Introduction
The mounting evidence in favor of the existence of some sort of non-baryonic dark matter [1], together with the historic discovery of neutrino oscillations [2] and their profound implications for neutrino properties [3, 4, 5], both indicate the need for new physics, beyond the Standard Model. In other words, the simplest Standard Model picture of matter in terms of three generations of fermions interacting by SU(3)⊗SU(2)⊗U(1) gauge boson exchange certainly requires amendment.

Underpinning the origin of neutrino masses and mixing and the elusive nature of dark matter constitute two of the most important challenges of elementary particle physics and modern cosmology. As already mentioned in preceding talks, in the framework of supersymmetry, for example in the Minimal Supersymmetric Standard Model (MSSM), there is a popular dark matter candidate, namely the lightest supersymmetric particle, typically a neutralino. Its stability [6] follows from assuming an ad hoc symmetry associated to R-parity conservation.

Here I show how, irrespective of the existence of supersymmetry in nature, the problem of neutrino mass and the explanation of dark matter may have a common origin [7]. As we illustrate, some of the the associated dark matter candidates are potentially detectable through nuclear recoil, while others require indirect methods.

2. Status of neutrino oscillations
The basic tool in terms of which to describe oscillations is the lepton mixing matrix, whose general structure has been characterized long ago [8]. This matrix has new phases with no counterpart in the quark sector. These are intrinsic to the Majorana nature of neutrinos and do not affect (standard) oscillations. However they play a crucial role in the description of lepton-number-violating processes like neutrinoless double beta decay. The latter also highlights the conceptual advantage of the original [8] symmetric parametrization [9] over its equivalent PDG
Neutrino oscillation data come from a variety of solar (Homestake, SAGE, GALLEX/GNO, Super-K and SNO), atmospheric (mainly Super-K), reactor (mainly Chooz and short-baseline experiments) and accelerator experiments (mainly MINOS and recently T2K) [2]. To describe them one assumes the simplest unitary form for the lepton mixing matrix and uses state-of-the-art solar and atmospheric flux calculations.

Figs. 1, 2 show the regions of oscillation parameters allowed by current neutrino oscillation data. The curves in Fig. 1 delimit the regions in the $\sin^2 \theta_{23} - \Delta m^2_{31}$ plane consistent with Super-K I, II and III atmospheric data and long-baseline neutrino oscillation appearance data, while the shaded area gives the region allowed by all global data. On the other hand the regions in $\sin^2 \theta_{12} - \Delta m^2_{21}$ allowed by solar + KamLAND data, after minimizing over $\theta_{13}$, are shown in Fig. 2. These depend upon reactor flux assumptions, the results displayed here correspond to our recommended analysis of solar + KamLAND data including short-baseline reactor results [3]. Other alternative choices are also given in Ref. [3], and also the comparison with the previous solar + KamLAND data analysis [11].

Fig. 3 shows the regions in $\sin^2 \theta_{13} - \delta$ allowed by latest global neutrino oscillation data, after minimizing over all undisplayed oscillation parameters. The left (right) panels correspond to normal (inverted) neutrino mass hierarchy types. The triangle (star) corresponds to the best fit point of the global long-baseline neutrino oscillation appearance analysis [4]. Marginalizing over the CP phase $\delta$ and remaining oscillation parameters we find that [4]

$$
\begin{align*}
\sin^2 \theta_{13} &= 0.013_{-0.005}^{+0.007}, \\
\Delta \chi^2 &= 10.1 (3.2\sigma) \\
\sin^2 \theta_{13} &= 0.016_{-0.006}^{+0.008}, \\
\Delta \chi^2 &= 10.1 (3.2\sigma)
\end{align*}
$$

where we display the best fit, one-sigma errors, and the significance for $\theta_{13} > 0$.

1 In seesaw-type schemes lepton mixing has a rectangular form, which leads to lepton-flavour violation and non-standard neutrino interactions [10].
Figure 3. Shaded regions in $\sin^2 \theta_{13} - \delta$ are allowed by latest global neutrino oscillation data. Curves delimit regions consistent with long-baseline appearance data. The left (right) panels are for normal (inverted) neutrino mass hierarchy. The triangle (star) corresponds to the best fit point of the LBL app (global) analysis, see Ref. [4] for more details.

As expected the upper bound on $\sin^2 \theta_{13}$ is dominated by global data without long-baseline appearance data, whereas the lower bound comes mainly from T2K. We eagerly wait for more data in order to settle the situation and to strengthen the prospects for CP violation studies in the next generation of neutrino oscillation experiments [12, 13].

3. Origin of neutrino mass

The origin of neutrino mass remains as elusive as ever. The simplest way it can arise is from Weinberg’s dimension-five operator in the left panel of Fig. 4.

Figure 4. Weinberg operator and type-1/type-2 seesaw schemes.

The seesaw remains an attractive mechanism to ascribe the observed smallness of neutrino mass relative to other standard model fermions to the presence of a large mass scale [8, 14, 15, 16, 17, 18, 19, 20] characterizing the violation of lepton number. Effective neutrino masses arise from the exchange of a heavy $SU(3) \otimes SU(2) \otimes U(1)$ singlet “right”-handed neutrino or a heavy scalar triplet scalar boson, or both, as indicated in the two middle panels in Fig. 4.

Thanks to the arbitrary number of gauge singlets that may be added in the seesaw [8] it can be realized also at low-scale. Examples of low-scale seesaw schemes are the inverse [21, 22] and linear seesaw schemes [23, 24, 25]. In this case, in the presence of supersymmetry the role of dark matter may be played by a sneutrino-like state, instead of the standard neutralino [26, 27].

If the breaking of lepton number is spontaneous there is additional dynamics associated to neutrino mass generation. For example in gauged lepton number schemes [23, 24, 25] [28] there is an additional neutral gauge boson coupled to neutrinos. In contrast, if lepton number is not a gauge symmetry, like the $SU(2) \otimes U(1)$ seesaw scheme, there is a remnant physical Goldstone
boson, generically called majoron [29, 18]. As we will see below in the presence of gravitational interactions this may act as dark matter [7, 30].

![Figure 5. Neutrino mass generation diagrams from spontaneous R-parity violation.](image)

On the other hand there are alternative schemes based on weak-scale physics, such as supersymmetry without a conserved R-parity [31], where one may naturally arrange for the breaking of R-parity to be spontaneous [32, 33]. This leads to a very predictive scheme called bilinear R-parity violation (BRpV) with the atmospheric neutrino mass scale generated by tree seesaw-like diagrams such as the one in the left plot in Fig. 5 involving supersymmetric fermion exchange, and the solar scale induced radiatively (right plot) [34]. This accounts naturally for the smallness of solar with respect to atmospheric squared mass splittings. In this case the neutralino can not be dark matter, as it decays typically inside collider experiments detectors, such as those at the Large Hadron Collider (LHC). However one can show that the gravitino can play the role of dark matter [35].

4. Neutrino mass dark matter connection

It has been suggested that these two apparently unrelated issues may be closely inter-linked [7]. I now scan over a few examples of “neutrino-motivated” dark matter candidates. While they are all cold insofar as the properties of the Cosmic microwave background (CMB) are concerned, some, like the majoron, may behave as warm dark matter regarding structure formation. When it comes to detection, some are ideal for direct detection, while others require indirect, like the majoron and the gravitino.

4.1. Sneutrino-like dark matter in inverse seesaw

As a first example we consider the case of supersymmetric dark matter in a model where neutrinos acquire mass through a low-scale seesaw mechanism. For definiteness we take the simplest SU(3) ⊗ SU(2) ⊗ U(1) inverse seesaw mechanism [21, 22] within the constrained Minimal Supersymmetric Standard Model (CMSSM) inspired by minimal supergravity [26]. The low-scale breaking of lepton number may arise dynamically as discussed in Ref. [27].

One can show that when neutrino masses are generated this way it is more likely to have a sneutrino-like state as the lightest superparticle than the conventional neutralino [26], as illustrated in the left plot in Fig. 6. In this region the neutralino behaves as LSP in both standard and modified mSUGRA within the white region (plotted for a given choice for tan β = 35, A₀ = 0 and μ > 0). However in the shaded (red) and light (yellow) areas one finds that, for a suitable choice of parameters associated to the inverse seesaw scheme a sneutrino-like state is the LSP [26]. Note also that the light (yellow) region includes all the region where the τ is the LSP in the standard mSUGRA case. On the other hand the dark (blue) region is excluded by experimental and theoretical constraints. This region is now substantially larger thanks to the recent results from the ATLAS and CMS collaborations [36], as illustrated by the extended region in dark at the left part of the left plot in Fig. 6.
One can demonstrate that such schemes also naturally reconcile the small neutrino masses with the correct relic sneutrino dark matter abundance, as shown in the mid panel in Fig. 6, which gives the sneutrino-like LSP relic abundance $\Omega h^2$ as a function of the LSP sneutrino mass $m_1$, when the supersymmetric parameters are scanned within the ranges $100\,\text{GeV} < m_0 < 3\,\text{TeV}$, $100\,\text{GeV} < m_{1/2} < 3\,\text{TeV}$, $A_0 = 0$, $3 < \tan\beta < 50$, and similarly for the inverse seesaw parameters (see Ref. [26] for details). Finally, the right panel in Fig. 6 illustrates how one can obtain an accessible direct detection rates in nuclear recoil experiments.

**Figure 6.** The blue points in the left panel give the LSP relic abundance $\Omega h^2$ as a function of the “sneutrino” LSP mass. The right panel gives the “sneutrino”–nucleon scattering cross section vs. its relic abundance, for the same scan of parameters as in the left panel. The horizontal (light blue) band denotes the current sensitivity of direct detection experiments. The yellow bands delimit the WMAP cold dark matter $3\,\sigma$ range [37].

### 4.2. Dark matter stabilized by flavour symmetry

A remarkable feature of current neutrino oscillation data described in Sec. 2 is that they imply a pattern of mixing angles radically different from that which characterizes the quark sector, with one maximal mixing angle, one large but non-maximal and one small [3, 4]. Attempts to understand this in terms of basic flavour symmetries have brought in the idea that perhaps the symmetry explaining flavour may also account for the required stability of dark matter. This opens an attractive link between neutrino physics and dark matter; two sectors that show a clear need for physics beyond the Standard Model.

A mechanism realizing the idea of stabilizing dark matter through a discrete unbroken subgroup of a non-abelian flavour symmetry has been recently proposed in Ref. [38]. The model is based on an A4 symmetry extending the Higgs sector of the Standard Model with three scalar doublets. After electroweak symmetry breaking two of the scalars of the model acquire vacuum expectation values (vevs) which spontaneously break A4, leaving a residual parity symmetry. The lightest neutral odd scalar is then protected to be stable and can play the role of dark matter candidate. The phenomenology of this model has been studied in [39].

The dark matter particle is thermally produced via a Higgs portal (left plot in Fig. 7) and is therefore a typical WIMP. All constraints from current laboratory experiments and astrophysical observations are satisfied and direct detection prospects are promising for the near future as many collaborations are closing in on the low mass region of the WIMP parameter space (right plot in Fig. 7).

Fig. 7 gives the spin-independent dark matter scattering cross section off-protons as a function of the dark matter mass. The orange regions delimited by the dashed (solid) line show the DAMA/LIBRA annual modulation regions including (neglecting) the channeling effect [40]. The green region corresponds to the COGENT data [41]. Dashed and dotted lines correspond
to the upper bound from CDMS (respectively from [42] and [43]). XENON100 bounds [44] are shown as a solid black line.

Coming to indirect detection, one may also compute the annihilation cross section times velocity as a function of the dark matter mass [39]. One finds that the sensitivity of current Fermi-LAT observations are starting to probe the model for low-intermediate dark matter masses (see e.g. [45, 46]).

From the neutrino side one finds an inverted neutrino mass hierarchy, hence a neutrinoless double beta decay rate accessible to upcoming searches, while \( \theta_{13} = 0 \) giving no CP violation in neutrino oscillations. This scheme is just an example of a possibly deeper connection between neutrino and dark matter physics, the details of which are highly model dependent.

![Figure 7](image)

**Figure 7.** Higgs portal (left plot), and spin-independent dark matter scattering cross section off-protons as a function of the dark matter mass versus current experimental sensitivities (right plot).

### 4.3. Majoron as decaying dark matter

In a large class of models neutrino masses may arise from spontaneous breaking of ungauged lepton number [29, 18]. Due to quantum gravity effects [47] the associated Goldstone boson - the majoron - will pick up a mass.

By construction, the majoron couples to, and hence will decay to, a pair of neutrinos [48]. The lifetime and mass required by cosmic microwave background observations can be determined so that the massive majoron provides the observed dark matter of the Universe [30]. This scenario fits nicely in models where neutrino masses arise \textit{a la seesaw}, and may lead to other possible cosmological implications associated to structure formation. Indeed, even though the majoron in this mass range behaves as cold dark matter particle as far as the CMB is concerned, its small thermal velocities might play a role in structure formation.

In a number of schemes the decaying majoron has also a sub-leading decay mode into two photons see, e.g. Refs. [7] and [49, 50]. Upper limits exist on the decay rate arising from NGC3227 (red), the Milky Way halo observed with a prototype cryogenic spectrometer (salmon), XMM observations of the Milky Way (sand), Chandra observations of the Bullet Cluster and M31 (orange), HEAO-1 observations of the diffuse X-ray background (aquamarine), INTEGRAL SPI line search in the Milky Way halo (blue). Shaded regions are excluded. These have been compiled and extended in Ref. [49] where details and original experimental references can be found. For a specific decaying dark matter seesaw model see Ref. [50]. Improved sensitivities are expected by the proposed XENIA mission [51].
4.4. Decaying gravitino as dark matter in BRPV

An attractive way to induce the dimension-five operator responsible for neutrino mass generation and lepton mixing angles is to assume the weak-scale supersymmetry without R-parity [31], i.e. to assume that the origin of neutrino mass is intrinsically supersymmetric, as indicated in Fig. 5. In the presence of $SU(3) \otimes SU(2) \otimes U(1)$ singlet “right” neutrino superfields one can indeed induce the spontaneous arrange for the breaking of R-parity in agreement with LEP measurements of the invisible $Z$ width [32, 33].

This leads to effective bilinear R-parity violation, or BRpV [34], the simplest extension of the minimal supersymmetric standard model (MSSM) which includes lepton number violation and which can successfully reproduce the present neutrino oscillation parameters [52, 53].

We describe how it leads to a successful phenomenological model for neutrino masses, but one in which the lightest neutralino can not be dark matter, as it decays typically inside collider detectors, as illustrated in Fig. 10.

An alternative way to relate dark matter with neutrino properties in a scenario where supersymmetry is the origin of neutrino mass is to assume that the LSP is the gravitino [35]. In this picture the same lepton number violating superpotential terms that generate neutrino masses and mixing also induce gravitino decays, into a gamma plus a neutrino, which also breaks R parity. The latter is doubly suppressed, first by the smallness of the R-parity violating couplings, and in addition by the Planck scale. The allowed gravitino mass-lifetime region consistent with neutrino oscillation data and astrophysical bounds from searches for gamma-ray
Figure 10. Neutralino NLSP decay length as a function of its mass. For illustration we show the results of a scan with $A_0=100$ GeV, $\text{sign}(\mu)=+1$, $\tan\beta=10$, $200 \leq M_0 \leq 1000$ GeV and $240 \leq m_{1/2} \leq 1000$ GeV.

lines from dark matter decay is indicated in the left plot in Fig. 11. The yellow region is excluded by gamma-ray line searches at Fermi and EGRET. The lower and upper black lines correspond to $m_{1/2}=240$ and 3000 GeV respectively. The right plot shows the parameters in terms of reheat temperature and gravitino mass [35]. In the orange area a consistent gravitino relic abundance would require gluino masses already excluded by present collider searches. In contrast, the blue area is viable but requires too large gluino masses, $M_3 > 6000$ GeV, while the yellow region is excluded by astrophysical gamma-ray line searches.

In contrast to seesaw models, the BRpV gravitino dark matter model can be probed at future collider experiments, like the LHC or the Next Linear Collider, since the decay pattern of the next-to-lightest supersymmetric particle provides a direct connection with the lepton mixing angles determined by neutrino experiments [54, 55, 56, 57].

Figure 11. Allowed gravitino mass-lifetime region (grey color) consistent with neutrino oscillation data and astrophysical bounds on gamma-ray lines from dark matter decay (left plot). The white region in the right plot is consistent with neutrino oscillations, gravitino dark matter, gamma-ray line searches, and gluino searches at the LHC.

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