Galactic Dark Matter Population as the Source of Neutrino Masses

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The Problem of Neutrino Masses

- In the Standard Model, neutrinos are completely massless
- Neutrino oscillation needs mass differences, which means massive neutrinos
- Some new physics is needed to allow for massive neutrinos
- Neutrino masses $m_\nu \lesssim 0.1$ eV are the smallest known non-zero masses, by several orders of magnitude
- All other Standard Model masses for elementary particles are generated by the Higgs mechanism, but neutrino masses might be from something else

The Uncertain Nature of Dark Matter

- Dark matter makes up approximately 80% of matter in the universe by mass
- Dark matter has no explanation in the Standard Model
- Besides having no appreciable electromagnetic interaction, little is known about what dark matter even is
- Dark matter might interact via yet unseen “dark sector” forces, as long as gravity is stronger at large enough distances

Introducing a Long Range Scalar Force

- We assume that both neutrinos, ν and dark matter, X are Dirac fermions
- We posit a repulsive long range scalar force between dark matter and neutrinos, which is mediated by the field ϕ:

$$\mathcal{L}_i = -g_X \phi \bar{X} X - g_\nu \phi \bar{\nu} \nu \tag{1}$$

- We have masses in vacuum for dark matter and the light scalar mediator:

$$\mathcal{L}_m = -m_X \bar{X} X - \frac{1}{2} m_\phi^2 \phi^2 \tag{2}$$

- We do not have any mass term for neutrinos from the Higgs mechanism
- The equation of motion for ϕ is:

$$(\Box + m_\phi^2)\phi = -g_X \bar{X} X - g_\nu \bar{\nu} \nu \tag{3}$$

Getting a Neutrino Mass from the Scalar Potential

- The Lagrangian contains $g_\nu \, \phi \, \bar{\nu} \, \nu$ which looks like a mass term if ϕ is a constant
- If we can get a constant background ϕ, we get an apparent neutrino mass:
$$m_\nu \equiv g_\nu \phi \tag{4}$$
- We'll assume the neutrino and dark matter populations are almost spacially uniform on the typical time and distance scales we'll consider so that we can get a constant background

Finding the Equation for ϕ

- With uniformity in space and time, we can neglect derivatives

$$m_\phi^2 \phi \approx -g_X \bar{X} X - g_\nu \bar{\nu} \nu \tag{5}$$

- The terms like $\bar{f}\, f$ are related to number density n_f:

$$\bar{f}\, f = n_f \langle \sqrt{1 - v_f^2} \rangle = n_f \frac{m_f}{\langle E_f \rangle} \tag{6}$$

- We will assume that dark matter is non-relativistic, and use $\bar{X}\, X = n_X$
- This is almost good, but not quite: m_ν depends on ϕ still

Screening of the Potential by Neutrinos

- Since the effective mass for neutrinos comes from the scalar potential, we find the following equation:

$$g_\nu \, \bar{\nu} \, \nu = g_\nu \, n_\nu \frac{g_\nu \phi}{\langle E_\nu \rangle} = \phi \frac{g_\nu^2 n_\nu}{\langle E_\nu \rangle} \tag{7}$$

- The above term appears in the equation of motion for ϕ and looks like a mass term for ϕ, so we define the screening mass:

$$\omega_\nu^2 \equiv \frac{g_\nu^2 n_\nu}{\langle E_\nu \rangle} \tag{8}$$

The Key Equations

- We finally get the equations we wanted to find:

$$\phi \approx \frac{-g_X n_X}{m_\phi^2 + \omega_\nu^2} \tag{9}$$

$$m_\nu \approx \frac{-g_X g_\nu n_X}{m_\phi^2 + \omega_\nu^2} \tag{10}$$

- When the neutrino number density dominates, ω_ν^2 is large, and the potential and neutrino mass are driven down toward zero
- When the neutrino number density is negligible, we can neglect the screening mass

The Fate of Relic Neutrinos

- In voids with very little dark matter, the neutrino mass is very close to zero
- In regions with abundances of dark matter like our galactic neighborhood, the repulsive Yukawa potential creates masses $\mathcal{O}(0.1 \text{ eV})$
- Relic neutrinos have temperatures $\mathcal{O}(10^{-4} \text{ eV})$
- The neutrino mass near dark matter acts as a potential barrier
- The low energy relic neutrinos are absent from the galaxy and restricted to voids
- This is a prediction of this model that can be tested at future relic neutrino experiments such as PTOLEMY

Choosing Reasonable Parameters

- We choose $m_\phi \sim 10^{-26}$ eV $\sim (0.7\ \mathrm{kpc})^{-1}$ to define the scale of the force
- We choose a dark matter mass $m_X \sim 0.3$ GeV
- We choose the coupling strength to dark matter $g_X \sim 10^{-20}$
  - The scalar force between dark matter is constrained from tidal stream bounds so that $g_X/m_X \lesssim 10^{-19}$ GeV^{-1}
- We choose the coupling stregth to neutrinos $g_\nu \sim 10^{-19}$
  - The most important bound seems to be free streaming in the early universe, leading to $g_\nu \lesssim 10^{-7}$

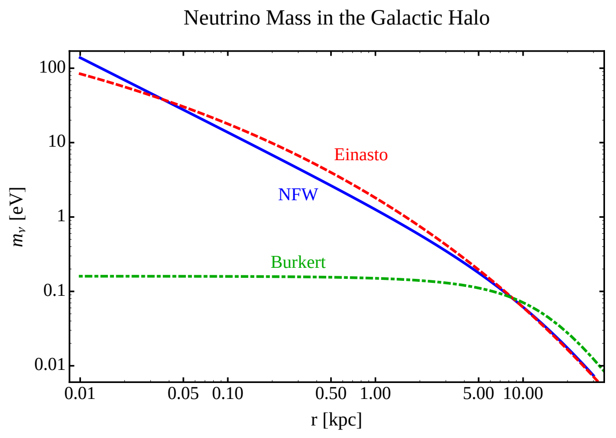
An Extremely Abridged History of the Universe

- Extremely early in the universe, horizon size, which has been neglected, is dominant
- At the time of Big Bang Nucleosynthesis, the screening mass from neutrinos dominates, and thus neutrinos are driven to be nearly massless
- As dark matter starts to clump, areas where neutrinos would be massive start to arise
- As relic neutrinos cool and dark matter continues to clump, relic neutrinos are repelled from galaxies and eventually are not energetic enough to return

The Universe Now

- Relic neutrinos are massless and only outside galaxies
- Neutrios in galaxies would mostly be from stellar production, and the expected density should not be large enough for the screening mass to be important

Neutrino Masses in the Milky Way



- All the profiles have $\rho_X(r_\odot) = 0.3\ \mathrm{GeV.cm}^{-3}$ and $m_X = 0.3$ GeV, where $r_\odot = 8.5$ kpc
- We get $m_\nu \sim 0.1$ eV around our solar system

Summary

- Our ignorance of dark matter and neutrino masses allows us to be creative
- In our model, dark matter can source a scalar potential which gives neutrinos a location dependent mass
- Our model predicts that future experiments such as PTOLEMY won't find any relic neutrinos, because they have been repelled away from the galaxy

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Backup

Is The Force Between Neutrinos Attractive or Repulsive?

- The Yukawa potential between a dark matter particle and neutrino would have the textbook form:

$$V_\phi(r) = -\frac{g_X g_\nu}{4\pi\ r} e^{-m_\phi\ r} \tag{11}$$

- In the usual approach, the force is attractive if $g_X g_\nu$ is positive and repulsive otherwise
- It looks like we can choose our couplings arbitrarily to get an attractive or repulsive potential...
- But the sign of the neutrino mass $m_\nu \approx \frac{-g_X g_\nu n_X}{m_\phi^2 + \omega_\nu^2}$ also depends on the product $g_X g_\nu$
- By performing a chiral transformation of ν, we can change the sign of the mass term so that it is positive
  - This is just a convention, but it is also a very good convention, and one that is implicitly assumed usually (like in discussions about attractive or repulsive forces!)
- This leads us to conclude that dark matter repels neutrinos

Why is the Neutrino Yukawa Term Absent?

- With a right handed neutrino, one would expect a term like $H\bar{L}\nu_R$ to be present, and neutrinos would get a mass from the Higgs mechanism
- We can forbid by introducing a Z_2 symmetry under which $\nu_R \to -\nu_R$ and SM fields are unchanged
- To allow the neutrinos to couple to ϕ, we also require $\phi \to -\phi$ under this Z_2
- Now to allow dark matter to couple to ϕ, we will have $X_R \to -X_R$ and $X_L \to X_L$ under this Z_2
- We get neutrino coupling to ϕ from a dimension 5 operator $\phi H\bar{L}\nu_R/M$

How Does X Get Its Mass?

- Unfortunately the symmetries we introduced forbids a mass term for the dark matter X, but we can introduce a dark Higgs Φ with a vev on the order of GeV that also transforms as $\Phi \to -\Phi$ and include the term $\Phi \bar{X}_L X_R$
- A similar dimension 5 operator $\Phi H \bar{L} \nu_R / M$ should exist with a similar scale, but for our parameter values this would be $m_\nu \lesssim 10^{-8}$ eV and wouldn't be the main source of mass