A New Model for Sterile Neutrino Dark Matter

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Project 3:

Construct a model where the properties of a new neutrino would make it a possible DM candidate while evading the current experimental constraints.

How could such a model be experimentally tested?
Can the active neutrinos compose DM?

The light active neutrinos are an example of Hot DM.

If they composed all of DM, their free-streaming effect would wash out most structures we observe in the Universe.

Can we add a heavier 4th generation neutrino?

LEP measurements on the Z resonance rules out the existence of a 4th neutrino with electroweak charge.

We add a new “sterile neutrino”, $N$, that is uncharged under the SM gauge group.

Adding a sterile neutrino $\tilde{N}$ to the SM, the following operators will appear up to dimension 5:

$$\mathcal{L} \supset \lambda_1 M_* NN + \lambda_2 LHN + \frac{\lambda_3}{M_*} H^+ HNN$$

- Majorana mass
- Active - sterile mixing
- Higgs interaction

In many models, the sterile neutrino mass is $O(\text{keV})$ and is produced from oscillations with the active neutrinos (see K. Abazajian’s talk)

Here, we will consider a different production mechanism via the Higgs interaction and see if we can obtain the correct DM abundance
Production mechanism: “Freeze-in”

Our sterile neutrino will never be in thermal equilibrium - their abundance is not set by usual “freeze-out”

Instead, in the early Universe while Higgses are in thermal equilibrium, they will annihilate to N’s

\[
\text{H} \rightarrow \frac{\lambda_3}{M_*} \text{N} \quad \text{H} \rightarrow \frac{\lambda_3}{M_*} \text{N}
\]

The abundance of N will “freeze-in” over time

This process only takes place during the very early Universe, when temperatures are high enough to overcome the $1/M$ suppression
Production mechanism: “Freeze-in”

The process of freeze-in by higher dimensional operators has been studied in [1].

Because this process primarily takes place in the very early Universe, it is sensitive to the reheat temperature $T_{RH}$.

$$\Omega_N \sim 0.2 \left( \frac{m_N}{10 \text{ GeV}} \right) \lambda_3^2 \frac{T_{RH} M_P}{M_*^2}$$

Benchmark parameters

\[ \mathcal{L} \supset \lambda_1 M_* NN + \lambda_2 LHN + \frac{\lambda_3}{M_*} H^\dagger H NN \]

We require: \( M_* > T_{RH} > m_{Higgs} > m_N = \lambda_1 M_* \)

Benchmark point: \( \lambda_1 = \lambda_3 = 10^{-5}, \quad T_{RH} = 10^4 \text{ GeV}, \quad M_* = 10^6 \text{ GeV} \)

This fixes: \( m_N = \lambda_1 M_* = 10 \text{ GeV} \) and \( \Omega_N \simeq \Omega_{DM} \)
Higgs Decay

The Higgs will decay into sterile neutrinos due to the Lagrangian term:

\[ \frac{\lambda_3}{M_*} H^{\dagger} H N N \]

With our choices of parameters, we find the following decay width and branching ratio:

\[ \Gamma_{H \to NN} = \frac{1}{16\pi^2} \left( \frac{\lambda_3 \langle h \rangle}{M_*} \right)^2 m_H \]

\[ \mathcal{BR}(H \to NN) \sim 2 \times 10^{-15} \]

This is well below the limit on LHC invisible Higgs decay of \( \sim 0.4 \)

**Direct Detection**

Invisible Higgs

Indirect Detection: Annihilation via Higgs to quarks or leptons

Dimensional analysis:
\[ \langle \sigma v \rangle \sim 10^{-45} \text{ cm}^3\text{s}^{-1} \]

Well below the limits from Fermi-LAT on the annihilation cross section \( \sim 10^{-26} \text{ cm}^3\text{s}^{-1} \)
We expect a gamma-ray line at: $E_\gamma = m_N/2 \sim O(\text{GeV})$

The diffuse photon spectrum has been well studied by several experiments (HEAO-1, INTEGRAL, COMPTEL, EGRET, and Fermi-LAT) in the keV - GeV range

The non-observation of such a photon line places upper limits on $m_N$ and active-sterile mixing
\[ \tau_{N \rightarrow \gamma \nu} = 1.8 \times 10^{27} \text{ sec} \left( \frac{10 \text{ GeV}}{m_N} \right)^5 \left( \frac{10^{-41}}{\sin^2 \theta} \right) \]

Consistency with Fermi/EGRET requires:
\[ \sin^2 \theta \lesssim 10^{-41} \]

Where the mixing is:
\[ \sin \theta = \frac{\lambda_2 \langle h \rangle}{\lambda_1 M_*} \]

Using our choices for \( \lambda_1, M_* \) this bound translates to:
\[ \lambda_2 \lesssim 10^{-22} \]

Charging \( N \) under a \( \mathbb{Z}_2 \) symmetry would set \( \lambda_2 \) exactly to zero, but letting this decay happen provides a possible detection mechanism.
Conclusions

We have presented a model for sterile neutrino DM, with mass $\sim 10$ GeV

$$\mathcal{L} \supset \lambda_1 M_* N N + \lambda_2 L H N + \frac{\lambda_3}{M_*} H^\dagger H N N$$

$\lambda_1 \sim 10^{-5}$

Active - sterile mixing $\lambda_2 \lesssim 10^{-22}$

Higgs interaction $\lambda_3 \sim 10^{-5}$

$T_{RH} = 10^4$ GeV
$M_* = 10^6$ GeV

The DM abundance is obtained through freeze-in via a higher dimensional Higgs portal

This DM is well below limits from direct detection and annihilation to SM

Keeping $\lambda_2$ small but non-zero provides a detection mechanism by the Fermi-LAT ($N \rightarrow \gamma \nu$)