A New Model for Sterile Neutrino Dark Matter

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Vedran Brdar, Sam Cormack, Dhrubo Jyoti, Joshua Yao-Yu Lin, John Martens, Oleg Popov, Sam Roland

Speaker: Sam Roland

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?

Neutrinos as Dark Matter

Can the active neutrinos compose DM?

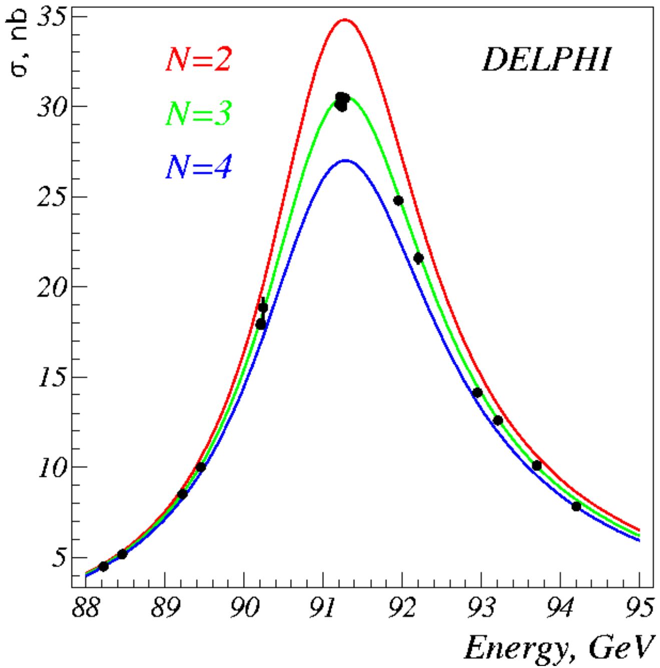
The light active neutrinos are an example of Hot DM

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 measurments 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



Phys.Rept.427:257-454,2006, hep-ex/0509008

Sterile Neutrino Lagrangian

Adding a sterile neutrino N to the SM, the following operators will appear up to dimension 5:

$$\mathcal{L} \supset \underbrace{\lambda_1 M_* N N}_{\text{Majorana mass}} + \underbrace{\lambda_2 L H N}_{\text{Active - sterile mixing}} + \underbrace{\frac{\lambda_3}{M_*} H^\dagger H N N}_{\text{Higgs interaction}}$$

M_* = Cut-off scale

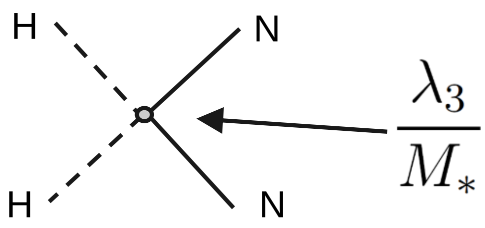
In many models, the sterile neutrino mass is O(keV) and is produced from oscillations with the active neutrinos (see K. Abazajian’s talk)

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



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

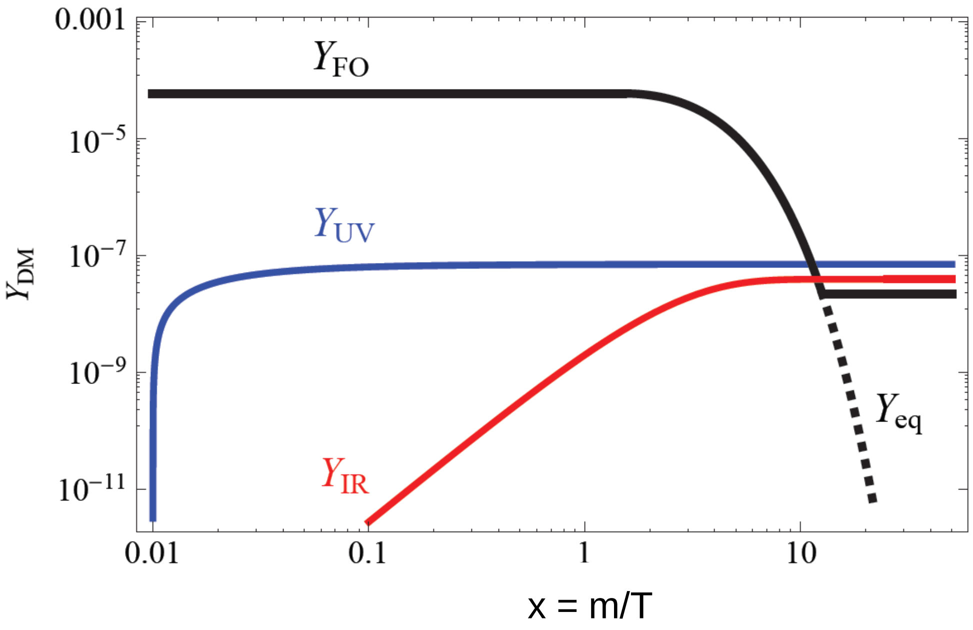
This process only takes place during the very early Universe, when temperatures are high enough to overcome the 1/M suppression

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}

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



Plot from: [1] Elahi, Kolda and Unwin (2014) arXiv:1410.6157v2

Benchmark parameters

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

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

Benchmark point: $\lambda_1 = \lambda_3 = 10^{-5},$

$T_{RH} = 10^4 \text{ GeV}, \quad M_* = 10^6 \text{ GeV}$

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:

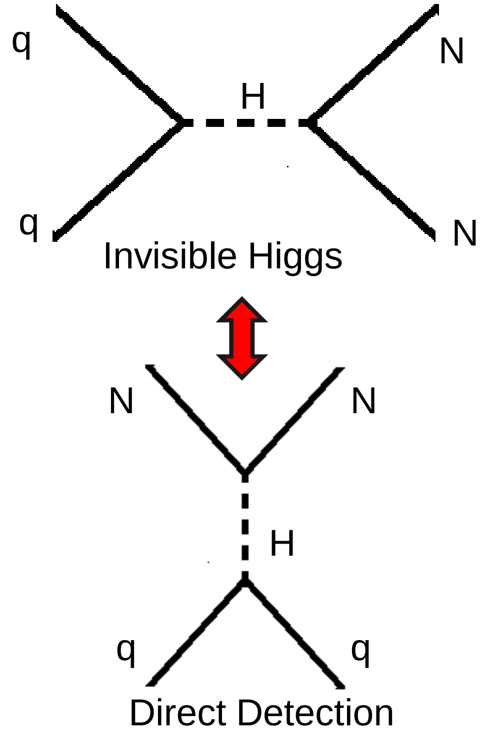
$$\Gamma_{H\to NN} = \frac{1}{16\pi^2}\left(\frac{\lambda_3 \langle h \rangle}{M_*}\right)^2 m_H$$

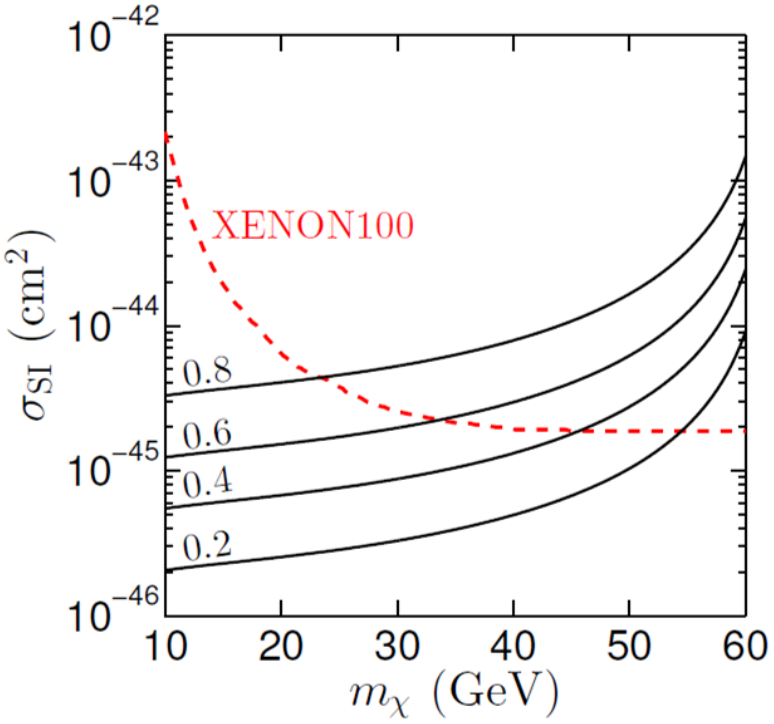
$$\mathcal{BR}(H \to NN) \sim 2 \times 10^{-15}$$

This is well below the limit on LHC invisible Higgs decay of ~ 0.4

N. Zhou, et. al. (2014) Phys. Rev. Lett. **113**, 151801

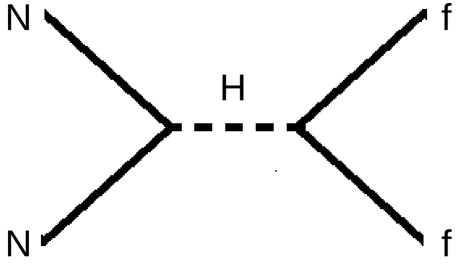
Direct Detection





Plot from: G. Belanger, et. al. (2013) arXiv:1302.5694

Indirect Detection: Annihilation



Annihilation via Higgs to quarks or leptons

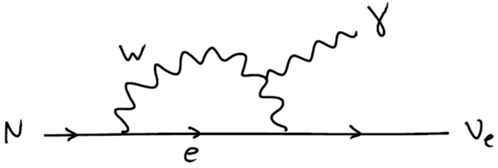
Dimensional analysis:

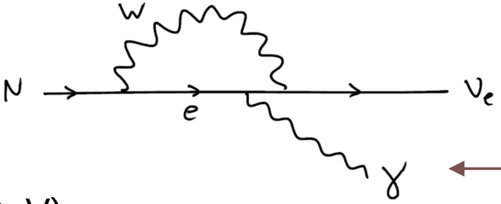
$\langle \sigma v \rangle \sim 10^{-45}\ \mathrm{cm^3 s^{-1}}$

Well below the limits from Fermi-LAT on the annihilation cross section $\sim 10^{-26}\ \mathrm{cm^3 s^{-1}}$

Indirect Detection: Decay

Sterile neutrinos decay to an active neutrino and photon:





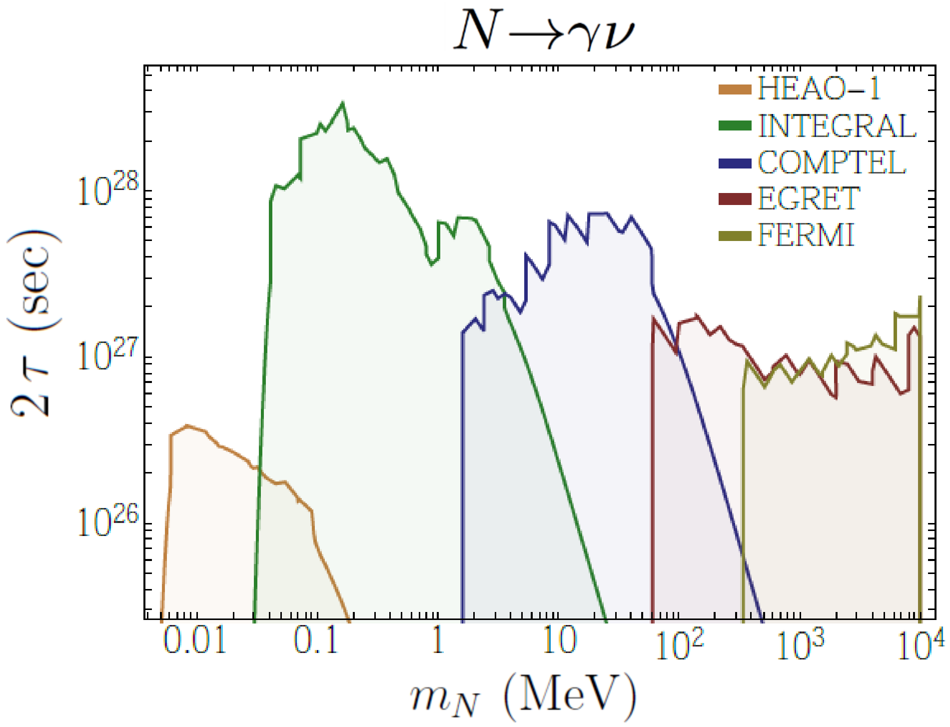
Gamma - Rays

We expect a gamma-ray line at: $E_\gamma = m_N/2$ ~ O(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

Gamma Ray Constraints



Plot adapted from R. Essig et. al. [arXiv: 1309.4091]

$$\tau_{N\to\gamma\nu} = 1.8 \times 10^{27}\ \mathrm{sec}\ \left(\frac{10\ \mathrm{GeV}}{m_N}\right)^5 \left(\frac{10^{-41}}{\sin^2\theta}\right)$$

Consistency with Fermi/EGRET requires:

$$\sin^2\theta \lesssim 10^{-41}$$

Where the mixing is: $\sin\theta = \dfrac{\lambda_2\langle h\rangle}{\lambda_1 M_*}$

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 λ_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 ~ 10 GeV

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

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

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

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

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

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 λ_2 small but non-zero provides a detection mechanism by the Fermi-LAT ($N \to \gamma\nu$)