# Sterile Neutrino Dark Matter from the PeV Scale

Sam Roland
University of Michigan

Pheno 2015 - March, 10th 2015

Based on work with James Wells and Bibhushan Shakya
[arXiv:1412.4791]

# Extending the Standard Model: Neutrino Masses

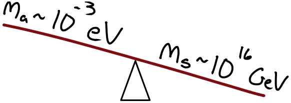
The three neutrinos in the standard model are massless, left-handed chiral states.

Neutrino oscillation experiments indicates that these neutrinos do have a non-zero mass.

The traditional explanation of neutrino masses is an extension of the SM by right-handed, sterile (SM singlet) neutrinos $N_i$:

$$\mathcal{L} \supset \underbrace{y_{\alpha i}\bar{L}_\alpha H^\dagger N_i}_{\text{Dirac Mass}} + \underbrace{M_i \bar{N}_i^c N_i}_{\text{Majorana Mass}} .$$

# What is the scale of the right-handed Majorana mass?



A good choice might be the GUT scale. Then the see-saw mechanism can explain the small LH neutrino masses with $y \sim \mathcal{O}(1)$.

However, such heavy RH neutrinos are essentially unobservable.

RH neutrinos masses below the electroweak scale are phenomenologically interesting and can provide a viable dark matter candidate.

This possibility has been well studied ($\nu$MSM), but no explanation for why the RH masses are below EW scale, and requires $y^2 \lesssim 10^{-13}$.

We want to explore the possibility of new degrees of freedom interacting with $N_i$ that naturally leads to lighter RH neutrions.

# Looking to the PeV ($= 10^6$ GeV) scale

What is the scale of new physics that interacts with RH neutrinos?

In particular, we are interested in interactions with the SUSY sector.

The measured mass of the Higgs boson at 125 GeV can give insight to the scale of SUSY.

In the MSSM, with no sfermion mixing, the Higgs mass at one loop is

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2} \log \frac{m_{\tilde{t}}^2}{m_t^2} \, .$$

With $\tan\beta \sim \mathcal{O}(1)$, the measured Higgs mass is obtained from sfermion masses at 1-100 PeV.

# Goal and Outline

We examine the consequences of sterile neutrino interactions with new degrees of freedom at the PeV scale.

Particularly, I will demonstrate how the active neutrino masses and a sterile neutrino dark matter candidate can arise naturally from the PeV scale.

In this talk I will:

- Describe a model of RH neutrinos that couple to a new scalar field,
- Examine the productions mechanisms for the DM candidate, and the associated constraints,
- Give explicit choices of parameters that yield DM and the measured active mass splittings.

# New Interactions for RH Neutrinos

Add 3 right-handed, SM-singlet, neutrinos $N_i$ to the Standard Model.

$N_i$ uncharged under SM gauge group, but charged under a new $U(1)'$ symmetry.

This forbids the terms in the traditional see-saw mechanism.

Adding a new scalar $\phi$ charged under $U(1)'$ we may include new higher-dimensional operator in the superpotential:

$$W \supset \frac{y}{M_*} L H_u N^c \phi + \frac{x}{M_*} N^c N^c \phi\, \phi.$$

$x$ and $y$ are dimensionless $\mathcal{O}(1)$ couplings, $M_*$ is the cutoff scale.

# Modified See-Saw Mechanism

We suppose that the same mechanism breaking SUSY causes $\phi$ to obtain a vev at the PeV scale.

This breaks $U(1)'$ and after EW symmetry breaking yields Dirac and Majorana neutrino masses:

$$m_D = \frac{y\langle\phi\rangle\langle H_u^0\rangle}{M_*}, \qquad m_M = \frac{x\langle\phi\rangle^2}{M_*}.$$

$m_D \ll m_M$ causes a modified see-saw mechanism with active and sterile mass scales:

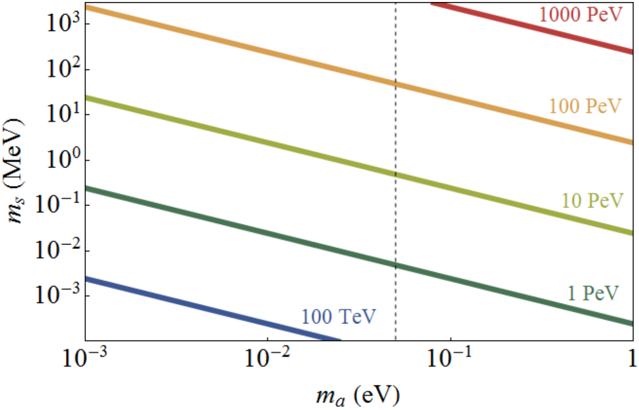
$$m_s = m_M = \frac{x\langle\phi\rangle^2}{M_*}, \qquad m_a = \frac{m_D^2}{m_M} = \frac{y^2\langle H_u^0\rangle^2}{xM_*},$$

and active-sterile mixing angle:

$$\theta \simeq \sqrt{\frac{m_a}{m_s}} = \frac{y\langle H_u^0\rangle}{x\langle\phi\rangle}$$

# Modified See-Saw Mechanism

Active and sterile mass scales for
several values of $y\langle\phi\rangle$



Dashed line:
$\Delta m^2_{atm} =$
$2.3 \times 10^{-3}$ eV$^2$

$M_* = M_{GUT}$
$\tan\beta = 2$
$\langle H_u^0 \rangle = 155.6$ GeV
$0.001 < x < 2$

# Sterile Neutrino Dark Matter

With $\langle\phi\rangle \sim 1 - 100$ PeV, we expect sterile neutrinos of masses in the keV-GeV range with $\mathcal{O}(1)$ couplings.

We want to choose the masses of $N_i$ and their mixing with active neutrinos so that we

- produce the correct active neutrino mass splittings, and
- have a DM candidate.

Call the lightest sterile neutrino $N_1$ - this is our DM candidate.

# Active-Sterile Mixing

How can we produce enough DM? For the small mixing angles relevant here, $N_i$ has always been out of equilibrium - no freeze-out.

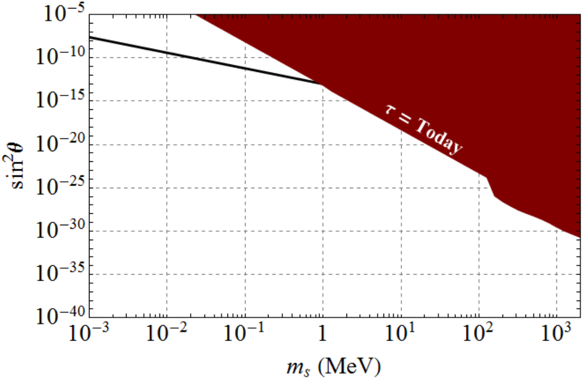
Because of active-sterile mixing, sterile neutrinos will always be produced by active-sterile oscillations (the Dodelson-Widrow mechanism).

Taking into account the temperature dependent mixing angle, the DW mechanism produces a relic abundance:

$$\Omega_{N_1} \sim 0.2 \left( \frac{\sin^2\theta}{3 \times 10^{-9}} \right) \left( \frac{m_s}{3 \text{ keV}} \right)^{1.8} .$$

# Relic Abundance from Active-Sterile Mixing

The black line is where $\Omega_{N_1} = \Omega_{DM}$ in the DW scenario, lifetime constraints are in red:



$N_1$ stable and has correct abundance in keV - MeV range.

# Constrains on Sterile Neutrino DM

The combination of gamma-ray constraints ($N \to \nu\,\gamma$) and structure formation constraints (Lyman-$\alpha$ data) rule out $N_1$ composing all of dark matter in the DW scenario.

There are several alternative production mechanisms that can save keV sterile neutrino DM (resonant production, particle decays).

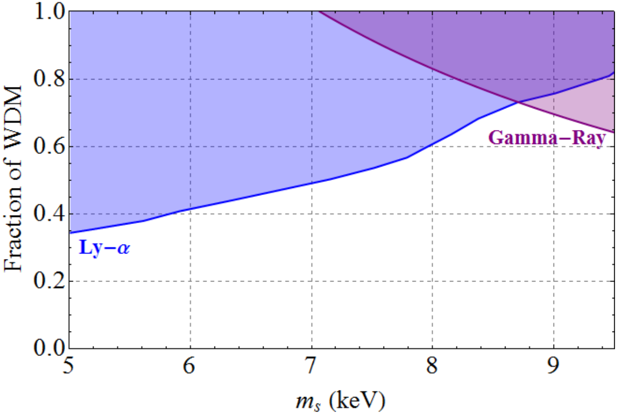
Here, we will consider $\Omega_{N_1} < \Omega_{DM}$.

The remaining fraction of DM can come from the LSP in the SUSY sector or axions. So we have a mix of warm and cold DM.

Compared to pure cold DM, a warm component might be beneficial in resolving some small-scale cosmology problems (core vs cusp, "too big to fail").

# Fraction of DM

Reducing $\Omega_{N_1}$ alleviates both gamma-ray and Lyman-$\alpha$ bounds:



An $\mathcal{O}(10)$ keV sterile neutrino can constitute a significant fraction of DM, consistent with all existing constraints.

Lyman-$\alpha$ bounds from: A. Boyarsky, J. Lesgourgues, O. Ruchayskiy, M. Viel (2009)
Gamma-ray constraints from R. Essig, E. Kuflik, S. McDermott, T. Volansky, K. Zurek (2013)

# Production of DM from Scalar Decays

The are production mechanisms for $N_1$ beyond the active-sterile oscillation, coming from the interactions between $N_1$ and scalars.

$$W \supset \frac{y}{M_*} L H_u N^c \phi + \frac{x}{M_*} N^c N^c \phi \, \phi .$$

Once $\phi$ obtains a vev, two decay channels open

$$H_u \to N_1 \nu \quad \text{and} \quad \phi \to N_1 N_1 .$$

We suppose that $\phi$ has additional interactions that keep it in equilibrium with the thermal bath at high temperatures.

As $\phi$ decays, the abundance of $N_1$ increases until the temperature drops below $m_\phi$ - abundance is frozen in.

For simplicity, we assume that $x > y$ so that $\phi \to N_1 N_1$ is the dominant contribution to $\Omega_{N_1}$.

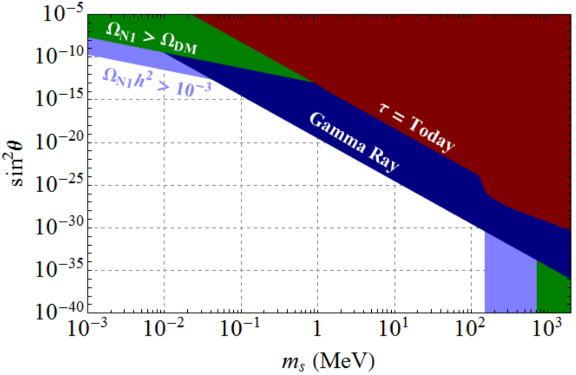
# Production of DM from Scalar Decays

The case of freeze-in by heavy scalar decays has been well studied. The abundance due to $\phi \to N_1 N_1$ is approximately

$$\Omega_{N_1} h^2 \simeq 0.3 \left(\frac{m_s}{\text{GeV}}\right)^3 \left(\frac{100\ \text{PeV}}{\langle\phi\rangle}\right)^3 \left(\frac{\langle\phi\rangle}{m_\phi}\right).$$

Note that this is independent of the mixing angle $\theta$.

If we consider both scalar decays and active-sterile mixing, we find two regions of parameter space:



Note that the Gamma-Ray bounds here assume $\Omega_{N_1} = \Omega_{DM}$

Here we have set $m_\phi = \langle\phi\rangle = 100$ PeV

# Two DM Candidates

$\mathcal{O}(10)$ keV sterile neutrino

- Produced by active-sterile mixing (DW mechanism)
- Warm DM
- $\lesssim 60\%$ of DM

$\mathcal{O}(1)$ GeV sterile neutrino

- Produced by $\phi$ decay (freeze-in mechanism)
- Cold DM
- $100\%$ of DM
- No mixing with active neutrinos ($\sin^2\theta \lesssim 10^{-35}$)

The two heavier sterile neutrinos, $N_2, N_3$, set the mass of the active neutrinos via the see-saw mechanism.

Constrains from cosmological observables (ex: $H$, $\Delta N_{\text{eff}}$, CMB,...) require $N_2$, $N_3$ to decay before BBN

# Benchmark Scenarios

Now we will look at two benchmark points that yield the active neutrino masses and a DM candidate.

Restoring the full flavor structure, the couplings $x$ and $y$, become $3 \times 3$ matrices $\mathbf{X}$ and $\mathbf{Y}$.

The full $6 \times 6$ neutrino mass matrix is

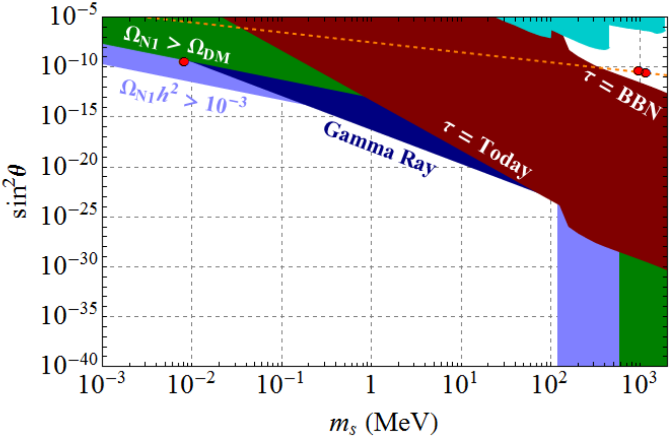
$$M_\nu = \begin{pmatrix} 0 & \frac{\langle\phi\rangle\langle H_u^0\rangle}{M_*}\mathbf{Y} \\ \frac{\langle\phi\rangle\langle H_u^0\rangle}{M_*}\mathbf{Y}^\dagger & \frac{\langle\phi\rangle^2}{M_*}\mathbf{X} \end{pmatrix}.$$

The $N_i$ basis can be chosen such that $\mathbf{X}$ is diagonal.

For concreteness, we choose $M_* = M_{GUT} = 10^{16}$ GeV and $\tan\beta = 2$.

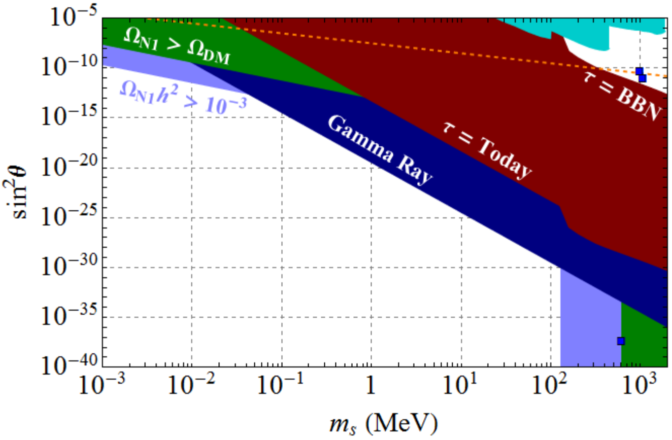
# Benchmark 1: keV scale DM

| $\langle\phi\rangle$ | $\mathbf{Y}$ | diag ( $\mathbf{X}$ ) | $m_a$ (eV) | $\Omega_s h^2$ |
|---|---|---|---|---|
| 79.4 PeV | $\begin{pmatrix} -1.70 & -0.20 & 9\times10^{-5} \\ 1.49 & -3.96 & -3\times10^{-5} \\ 3.91 & -2.21 & 5\times10^{-5} \end{pmatrix}$ | $1.91$<br>$1.58$<br>$0.000013$ | $0.049$<br>$0.0087$<br>$2.4\times10^{-6}$ | 0.058 |



# Benchmark 2: GeV scale DM

| $\langle\phi\rangle$ | $\mathbf{Y}$ | diag ( $\mathbf{X}$ ) | $m_a$ (eV) | $\Omega_s h^2$ |
|---|---|---|---|---|
| 85.1 PeV | $\begin{pmatrix} -1.31 & 0.73 & \sim 0 \\ -1.25 & -3.71 & \sim 0 \\ 1.45 & -3.65 & \sim 0 \end{pmatrix}$ | 1.46<br>1.38<br>0.85 | 0.049<br>0.0087<br>$\sim 0$ | 0.11 |



# Summary and Future Directions

Connecting sterile neutrinos to the PeV scale can yield sterile masses below the electroweak scale with predominantly $\mathcal{O}(1)$ couplings.

In this model, there are two regions where $N_1$ is a DM candidate consistent with all existing constraints:

- $\mathcal{O}(10)$ keV, $\lesssim 60\%$ warm DM, produced be active-sterile mixing,
- $\mathcal{O}(1)$ GeV cold DM, produced by $\phi$ decays,

while the two heavier neutrinos decay before BBN and set the active neutrino masses.

The two recent observations

- 3.5 keV line in X-ray spectrum of galactic clusters,
- PeV energy neutrinos detected at IceCube

give further support for this model of sterile neutrino physics.

Thanks for listening!

Questions?