SHEDDING NEW LIGHT ON STERILE NEUTRINOS

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1401.2549 and 1403.2727

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Motivation for sterile neutrinos

- No experimental evidence seen in favour of new physics responsible for:
  - Observed dark matter abundance
  - Origin of the baryon-antibaryon asymmetry
- Would like **well-motivated, testable** models to guide pheno. study
- There is strong evidence for new physics from neutrino oscillations: at least two massive SM neutrinos
  - Simplest explanation: there is a partner gauge-singlet neutrino $N$ for each SM neutrino
    - Standard lore is that $F \sim 1$, $M_N \sim M_{GUT}$, but the $N$ could be much lighter
      - If $N$ are at/below weak scale, then they and associated physics are accessible at current experiments

\[
\mathcal{L}_{\text{see-saw}} = F L \Phi N + \frac{M_N}{2} N^2
\]

\[
m_{\text{SM } \nu} \approx \frac{F^2 \langle \Phi \rangle^2}{M_N}
\]

\[
F \sim 10^{-7} \left( \frac{m_{\text{SM } \nu}}{0.1 \text{ eV}} \right)^{1/2} \left( \frac{M_N}{\text{GeV}} \right)^{1/2} \left( \frac{100 \text{ GeV}}{\langle \Phi \rangle} \right)
\]
Motivation for sterile neutrinos

- In the sub-weak-scale mass range, $N$ are called sterile neutrinos

- Could these new states resolve the questions of DM & baryogenesis?
  - New singlets: possible dark matter candidate if at least one stable
  - $N$ break global $B-L$ number symmetry $\rightarrow$ can lead to baryon-antibaryon asymmetry
  - Unified framework called the neutrino minimal SM (vMSM)

- For generic choices of parameters, sterile neutrinos satisfying see-saw and DM stability constraints are actually too sterile:
  - Dark matter production is too inefficient to explain observed abundance
  - Yukawa couplings are too feeble to generate observed baryon asymmetry
  - $N$ can be hard to produce/observe in experiments
New interactions

• The minimal model is only viable if there is some kind of resonant enhancement of certain rates
  • Typically arise as mass degeneracies and/or relative tuning of the Yukawa matrix entries

• **Our motivation:** Do we need to live in tuned parameter space? Can moving “beyond minimality” enhance DM/baryon asymmetry prod?
  • We find that each of DM/baryogenesis can be achieved for completely generic parameters with one additional field coupled to the **visible sector**
  • Can look for these new particles/interactions; cosmological implications for particle physics searches

• In the interest of time, I’ll focus on the DM question in this talk
Sterile neutrino DM

- Is $N$ a viable dark matter candidate?
  - Does it have the correct abundance?
  - Is it sufficiently long-lived?

- $N$ talk to SM fields through its mixing with the SM neutrino

$$\mathcal{M} = \begin{pmatrix} 0 & F\langle \Phi \rangle \\ F\langle \Phi \rangle & MN \end{pmatrix}$$

$$\sin \theta_\alpha (T = 0) \approx \frac{F_\alpha \langle \Phi \rangle}{m_N}$$

- $N$ is slowly created through SM electroweak processes (Dodelson, Widrow, 1993)

$$\Gamma_N \sim \sum_\alpha \sin^2 2\theta_\alpha (T) G_F^2 T^5$$
Sterile neutrino DM

- At finite temperature, the thermal mass of the SM neutrinos in the plasma further suppresses the mixing

$$\sin^2 2\theta_\alpha(T) \approx \frac{\sin^2 2\theta_\alpha(T = 0)}{\left[1 + 0.27 \left(\frac{T}{100 \text{ MeV}}\right)^6 \left(\frac{\text{keV}}{M_N}\right)^2\right]^2}$$

$$\Gamma_N \approx \frac{\sin^2 2\theta_\alpha(T = 0) T^5}{\left[1 + 0.27 \left(\frac{T}{100 \text{ MeV}}\right)^6 \left(\frac{\text{keV}}{M_N}\right)^2\right]^2}$$

- DM is predominantly created at $T \sim$ few hundred MeV
- Abundance is completely determined by mass and mixing angle
Sterile neutrino DM

- DM abundance (√)
  \[ \Omega_N \approx 0.27 \left( \frac{\sin^2 2\theta}{2 \times 10^{-9}} \right) \left( \frac{M_N}{9 \text{ keV}} \right)^{1.8} \]

- Is it sufficiently long-lived?
  The same mixing for production leads to DM decay:

- Together with small-scale structure constraints completely exclude the possibility of electroweak \( N \) production for DM
- Stable DM -> effective \( N \) interactions too weak for \( \Omega_{DM} \)

Taken from Horiuchi et al., 1311.0282
New lepton forces & $N$ DM

- **Our approach:** See that if *any* new interactions couple to SM leptons, they also produce $N$ through the same mixing
  - Example: new gauge interaction
  - Anomaly-free choices include: $U(1)_{\mu-\tau}$, $U(1)_{B-L}$, ...
  - If the new $Z'$ is in the thermal bath during dominant epoch of $N$ prod. (~few hundred MeV), then rapid 1->2 processes give large $N$ rate

- We focused on currents that only couple to leptons
  - Constraints from muon $g-2$, $N$ lifetime, meson/SM gauge boson widths, neutrino-electron scattering constraints (if couples to $e$)
  - Shown: largest mixing angle $\theta$ allowed by X-ray constraints for given $N$ mass

BS, Yavin, 1403.2727
see also Altmannshofer *et al.*, 1406.2332
New lepton forces & N DM

- Constraints change depending on U(1) charges
  - Ex: U(1)\textsubscript{B-L} (adapted from Williams et al., 1103.4556)
  - Much of remaining B-L space to be probed by APEX and HPS, improved \(N_{\text{eff}}\)

- Possible detection of 3.57 keV X-ray line in stacked galaxy clusters!

- 7.15 keV \(N\) is below small-scale structure bounds for thermal production
- Our mechanism produces somewhat colder \(N\) than thermal (✓)

Taken from Boyarsky et al., 1402.4119
Conclusions

- Sterile neutrinos are well-motivated extensions of the SM
  - Can account for neutrino oscillations, dark matter, baryogenesis
  - Related physics kinematically accessible for masses < weak scale

- Minimal models typically produce insufficient DM and baryon asymmetry unless there are severe mass degeneracies, tunings in the Yukawa couplings

- We have shown that models with one new degree of freedom can:
  - Obviate the need for any tuning
  - Give phenomenological probes of physics connected to sterile neutrino cosmology (often complementary to existing strategies)

- Similar story for enhancing baryogenesis through modifications of Yukawa couplings in a 2-Higgs-doublet model (see BS, Yavin, 1401.2459)

- Further development of these ideas, unifying the DM and baryogenesis pictures, are work in progress
Back-up slides
Quick peek: Baryogenesis

- Baryogenesis proceeds via “leptogenesis through neutrino oscillations”
  - Baryon asymmetry requires small sterile neutrino mass splittings and large scattering rates (Yukawa couplings)
  - Looking at see-saw relation, these conditions are in conflict! \[ M_N \approx \frac{F^2 \langle \Phi \rangle^2}{m_{SM} \nu} \]

- Once again, the Yukawa couplings are too small for fixed \( N \) mass

- **Our approach**: With non-standard interactions, the Yukawa couplings can naturally be much larger
  - Example: If \( \Phi \) is a non-SM Higgs coupling to leptons, its VEV can be smaller, giving larger \( F \)
  - Much larger asymmetries possible than even the tuned minimal model
  - No degeneracy or alignment of parameters needed

BS, Yavin, 1401.2459
Resonant production

- The minimal model can still work with **non-thermal production**

\[ V_\nu \approx 2\sqrt{2}G_F(N_\nu - N_{\bar{\nu}}) - \frac{7\pi}{90\alpha} \sin^2(2\theta_W) G_F^2 T^4 E_\nu \]

\[
\sin^2(2\theta_{m,\alpha}) = \frac{\sin^2(2\theta_{\alpha 1})}{\sin^2(2\theta_{\alpha 1}) + \left(\cos 2\theta_{\alpha 1} - \frac{2V_{\nu,\alpha} E}{M_{N_1}^2}\right)^2}
\]

- MSW resonant enhancement of mixing angle when \( V_\nu \approx \frac{M_{N_1}^2}{2E} \cos 2\theta \) (Shi, Fuller 1999)

- Need a large, late-time lepton asymmetry

- Spectrum is typically **colder** than thermal

\[ \frac{E_{\nu,\text{res}}}{T} \approx 0.1245 \left(\frac{M_N^2 \cos 2\theta}{\text{keV}^2}\right) \left(\frac{10^{-2}}{\mathcal{L}}\right) \left(\frac{100 \text{ MeV}}{T}\right)^4 \]

taken from Abazajian, Fuller, Patel 2001
Resonant production

• Can occur for lepton asymmetries $\gtrsim 10^{-5}$
  - Need large asymmetry from leptogenesis below weak scale
  - Achieved in the minimal model through resonant leptogenesis from the decay of the heavier sterile neutrinos; highly degenerate spectrum needed
  - Shown at right: $N_2$ and $N_3$ are 10 GeV, from Canetti et al. 2012

• Other sources of asymmetry possible with new beyond-SM physics
**Results**

- Show dependence on mixing angle (7 keV sterile neutrino shown here)
- Complementarity between direct and astrophysical probes
Results

- Sterile neutrinos can be **hot**, **warm**, or **cold** (Abazajian, Fuller, Patel 2001)
- Sterile neutrino spectrum from $Z'$ is often **colder** than thermal
- Sensitivity to QCD phase transition and thermal effects
  - We show spectrum relative to photon bath at $T = 1$ MeV

![Graph](image)

(solid) $M_N = 7.1$ keV, $M_{Z'} = 300$ MeV
(dashed) thermal distribution