Dodelson-Widrow mechanism in the presence of neutrino self-interactions

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The sterile neutrino

$\nu_e$  $\nu_\mu$  $\nu_\tau$

Are there more of these?

Four suspects:

1. Theoretical bias.
2. Short baseline anomalies.
3. Reactor anomalies.
4. Cosmology.

$\nu_s$  Are there more of these?
Sterile neutrino: the riddler neutrino

- Provides the SM neutrinos with the ‘right’ partner.

- Can give masses to neutrinos.

- Can be used to answer the baryon-asymmetry of the universe through leptogenesis.

- Possible dark matter candidate. Can also be used to solve small-scale structure problems.

- Hints in terrestrial experiments?

See Abazajian (2017) for a detailed review.
Sterile neutrinos as Dark Matter

- 4th mass eigenstate \( \nu_4 = \cos \theta \nu_s + \sin \theta \nu_a \)

- Can be detected through 1-loop decay into photons: \( \nu_s \rightarrow \nu_a \gamma \).

- Decay rate \( \Gamma \propto m_4^5 \sin^2 2\theta \). Radiative decay detectable.

Pal and Wolfenstein, PRD1982
Abazajian, Fuller and Patel, PRD2001 + many more...

- Non-observation puts bound on \( m_4 - \sin 2 \theta \) plane.

- Radiative decay leads to line at \( E_\gamma = m_4/2 \).

Hints of a line at \( m_4 = 7.1 \text{ keV} \)? — Bulbul et al. Astro. 2014, Boyarski et al., PRL 2014.

- But how do we produce these neutrinos?
Production: the Dodelson-Widrow mechanism

- The $\nu_s$ cannot be in thermal equilibrium with SM particles before BBN.

- Must be produced non-thermally with $\theta \ll 1$.

- $\nu_a$ oscillates into $\nu_s$ before decoupling. Creates a non-thermal population of $\nu_s$.  

Production: the Dodelson-Widrow mechanism

$\nu_a$ oscillates into $\nu_s$ before decoupling. Creates a non-thermal population of $\nu_s$.  

Dodelson and Widrow, PRL1994

\[
T \frac{\partial}{\partial T} f_{\nu_s} \bigg|_{p/T} = \frac{\Gamma_a}{2H} \left\langle P(\nu_a \rightarrow \nu_s) \right\rangle f_{\nu_a},
\]

\[
\left\langle P(\nu_a \rightarrow \nu_s) \right\rangle = \frac{1}{2} \frac{\Delta^2 \sin^2 2 \theta}{\Delta^2 \sin^2 2 \theta + \frac{\Gamma_a^2}{4} + (\Delta \cos 2 \theta - V)^2}
\]

Averaged over one mean free path

$\Delta = \frac{m_s^2}{2E}$

Quantum Zeno damping

Matter potential

$V = V_T + V_D$

Finite temperature: $V_T \propto T$

Finite density: $V_D \propto n_f$
The Dodelson-Widrow mechanism...constrained

- Ruled out by X-ray bounds and phase-space considerations (Tremaine-Gunn, Lyman alpha, etc.).

- A finite lepton asymmetry (Shi-Fuller Mechanism) can help. Required lepton asymmetry difficult to constrain. Shi and Fuller, PRL 1999, Fuller, Abazajian and Patel PRD 2001

- Can we open up parameter space without introducing a lepton asymmetry?
• Active neutrino self-interactions. Can be much stronger than ordinary weak interactions.

Consider \[ \mathcal{L}_\nu = \frac{y}{\Lambda^2} (LH)^2 \phi \quad \overset{EWSB}{\rightarrow} \quad \lambda_{\psi} \nu_a \nu_a \phi \]

• Relic \( \sim \) (rate) \( X \) (mixing angle).

Increasing rate can satisfy same results for smaller \( \theta \). This allows us to shift DW line below X-ray bounds.

• This opens up new production channels for sterile neutrino DM.
What changes in the DW mechanism?

S.M

$M_{W,Z} \geq T_{peak}$

S.M + Self-Interactions

$M_\phi > T_{peak}$  $M_\phi \lesssim T_{peak}$
Numerical estimates

\[
T \frac{\partial}{\partial T} f_{\nu_s} \big|_{p/T} = \frac{\Gamma_a}{4H} \frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + \frac{\Gamma_a}{4} + (\Delta \cos 2\theta - V)^2} f_{\nu_a}
\]

\[
\Omega h^2 = 0.12, \ m_{\nu_s} = 7.1 \text{ keV}, \ \sin^2 2\theta = 7 \times 10^{-11}
\]

Not a monotonic dependence! Why?

de Gouvêa, MS, Tangarife and Zhang PRL 2020
Numerical and analytical estimates

\[ T \frac{\partial}{\partial T} f_{\nu_s} \bigg|_{p/T} = \frac{\Gamma_a}{2H} \frac{1}{2} \frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + \frac{\Gamma_a^2}{4} + (\Delta \cos 2\theta - V)^2} f_{\nu_a} \]

• Two scales in problem:

1. \( t_{\Gamma=H} \): When \( \Gamma/H = 1 \), to determine when interactions are in equilibrium.

2. \( t_{\Delta=V} \): When \( |\Delta| \sim |V| \), mixing angle is unsuppressed, peak production.

3. \( t_{\phi} \): When \( T = m_\phi \), mediator cannot be produced on-shell for lower temperature.

de Gouvêa, MS, Tangarife and Zhang PRL 2020
Cherry, Friedland, Shoemaker 1605.06506
1. **A**: \( t_\phi < t_{\Delta=V} < t_{\Gamma=H} \). Production around \( t_{\Delta=V} \) from scattering via an off-shell \( \phi \). Similar to the usual DW mech.

2. **B**: Intermediate mass, coupling: \( t_\phi < t_{\Gamma=H} < t_{\Delta=V} \). Peak production happens in \((t_\phi < t < t_{\Gamma=H})\) when \( \theta_{\text{eff}} \) is suppressed. Production through scattering via on-shell \( \phi \).

3. **C**: \( t_{\Delta=V} < t_\phi < t_{\Gamma=H} \). DM produced most efficiently through on-shell \( \phi \) exchange between \((t_{\Delta=V} < t < t_\phi)\).
Allowed Relic Density window

Every point in this plane corresponds to a line in the left figure.

de Gouvêa, MS, Tangarife and Zhang PRL 2020
Allowed Relic Density window

Every point in this plane corresponds to a point in left figure

Can be used to satisfy the 3.5 keV X-ray line also ~

\[ m_{\nu_s} = 7.1 \text{ keV}, \quad \sin^2 2\theta = 7 \times 10^{-11} \]

Bulbul et al. Astro. 2014+many more
Experimental tests

The vertex: $\mathcal{L} = \nu_a \nu_a \phi$

- Interested in range $1 \text{ MeV} \leq m_\phi \leq 10 \text{ GeV}$
- $K^- \rightarrow \mu^- \nu_\mu \phi$, $\phi \rightarrow \nu \nu$. Bounds from $\text{Br}(K^- \rightarrow \mu^- 3\nu) < 10^{-6}$.
- BBN bounds on $m_\phi$.
- DUNE can look for “wrong sign muon” in $\nu_\mu N \rightarrow \mu^+ N' \phi$. Parameter space can be probed.

Berryman, de Gouvêa, Kelly and Zhang PRD2018
Blinov, Kelly, Krnjaic and McDermott, PRL2018

de Gouvêa, MS, Tangarife and Zhang PRL 2020
Summary

- A model with the SM appended with sterile neutrinos, and a new interaction among the SM neutrinos, much stronger than weak interactions. Mediator masses can vary from a few keV to GeVs.

- Sterile neutrinos can be produced non-thermally via freeze-in, using new interactions. Stronger interactions helps alleviate tensions with DW mechanism. Can be used as a candidate model for the 3.5 keV line.

- Can be probed using current and upcoming neutrino experiments.

Thank you!