Sterile neutrino dark matter
Dodelson-Widrow and beyond

Amol V. Patwardhan
SLAC National Accelerator Laboratory

INT program 22-2b: Dark Matter in Compact Objects, Stars, and in Low Energy Experiments

August 29, 2022
Outline

1 Introduction

2 Sterile neutrino dark matter: production and constraints

3 Diluted equilibrium sterile neutrino dark matter (DESNDM)

4 Conclusions
What we know (and don’t know) about dark matter

- $\Omega_{DM} h^2 \approx 0.12$ at $z = 0 \rightarrow$ Evidence purely gravitational
  - Cosmic microwave background
  - Baryon acoustic oscillations
  - Galactic rotation curves and velocity dispersion
  - Gravitational lensing

- Stable over cosmological timescales

- No strong or electromagnetic interactions with visible matter

- Non-relativistic kinematics at $z = 0$, probably also at $z = 3000$ (matter-radiation equality) — DM not “hot”

- What we don’t know: identity and interactions of DM
Dark matter candidates

- Often a byproduct of beyond-standard-model theories that also solve another problem (e.g., hierarchy problem, strong CP, neutrino mass, etc.)

- Hot, cold or warm dark matter (collisionless damping scale)
  - Baryonic DM
  - (Active) Neutrinos
  - Primordial black holes
  - Weakly interacting massive particles (WIMPs)
  - Axions
  - Sterile neutrinos
  - Asymmetric dark matter
  - ... and many more

- $\text{DM} \in \text{Dark sector}$
What we know (and don’t know) about neutrinos

What we know:

- Electrically neutral
- Interact with $W$ and $Z$ bosons (3 flavors)
- Exhibit flavor oscillations $\implies$ propagating neutrinos have mass differences and are not weak interaction eigenstates
- *Nearly* massless (at least 2 states with $0 < m_\nu \lesssim eV$)

What we do not know:

- Absolute neutrino masses and their hierarchy (sign of $\Delta m_{32}^2$)
- Origin of neutrino mass and mixing
- Dirac or Majorana nature
- Electromagnetic properties, non-standard interactions, etc.
Sterile neutrinos

- Neutrino oscillations $\Rightarrow$ non-zero rest masses

- Suggests possible right-handed, or “sterile”, neutrino states, with no interactions with SM gauge bosons

- For example, neutrino masses can be generated via the (Seesaw) Lagrangian

$$\mathcal{L} \supset -\lambda_{\alpha i} L^\alpha H N^i - \sum_{i,j}^3 \frac{M_{ij}}{2} N_i N_j,$$

where $N_i = 1, \ldots, n$ are new fermions with no SM gauge interactions.
Mass and mixing angle generation

- After electroweak symmetry breaking, the above Lagrangian diagonalizes into $n + 3$ mass eigenstates, $\nu_i$. If $M \gg \lambda \langle H \rangle$:
  - $m_i \sim \lambda^2 \langle H \rangle^2 / M$, for $i = 1, \ldots, 3$
  - $m_i \sim M$ for $i = 4, \ldots, n$

- Two of the masses $M_i$ required to be $\gtrsim 100$ GeV to account for solar and atmospheric $\Delta m^2$. Rest of the $M_i$ unconstrained — anywhere from $\mathcal{O}(\text{eV})$ – GUT scale

- Mixing angles: $\theta_{\alpha i}^2 \sim \lambda_{\alpha i}^2 \langle H \rangle^2 / M^2$
Sterile neutrinos

- **Caveat:** Seesaw Lagrangian can also give rise to sterile $\nu$ mixing with active $\nu$

$$|\nu_\alpha\rangle = \cos \theta_{14} |\nu_1\rangle + \sin \theta_{14} |\nu_4\rangle$$

$$|\nu_s\rangle = - \sin \theta_{14} |\nu_1\rangle + \cos \theta_{14} |\nu_4\rangle$$

- Sterile neutrino can oscillate into an active neutrino as it propagates, giving it an effective sub-weak interaction

$$\sigma \sim G_F^2 E_\nu^2 \sin^2 2\theta$$

- In the simplest scenario, the active-sterile mixing angle $\theta$ is responsible for production in the early universe, as well as decay in the late universe
Introduction

Sterile neutrino dark matter: production and constraints

Diluted equilibrium sterile neutrino dark matter (DESNDM)

Conclusions
Sterile neutrino dark matter: various models

- Neutrino-neutrino scattering induced decoherence
Sterile neutrino dark matter: various models

- Neutrino-neutrino scattering induced decoherence

- Resonant production (lepton-number enhanced decoherence)
  - Abazajian, Fuller and Patel, Phys. Rev. D 64, 023501 (2001)
Sterile neutrino dark matter: various models

- Neutrino-neutrino scattering induced decoherence

- Resonant production (lepton-number enhanced decoherence)
  - Abazajian, Fuller and Patel, Phys. Rev. D 64, 023501 (2001)

- $\nu$MSM: minimal standard model with right-handed neutrinos
Sterile neutrino dark matter: various models

- Neutrino-neutrino scattering induced decoherence

- Resonant production (lepton-number enhanced decoherence)
  - Abazajian, Fuller and Patel, Phys. Rev. D 64, 023501 (2001)

- $\nu$MSM: minimal standard model with right-handed neutrinos

- Scalar decay
  - König et al., JCAP11(2016)038
... and some more!

- Additional gauge symmetry

- Dodelson-Widrow with nonstandard $\nu$-$\nu$ interactions
  - Johns and Fuller, Phys. Rev. D 100, 023533 (2019)

- $\nu$MSM + light scalar
Dodelson-Widrow: scattering-induced decoherence

- Proposed as mechanism for producing sterile neutrino DM with $m_s \sim \text{keV}$ in the early universe

- In the very early universe, sterile-$\nu$ production blocked by quantum Zeno effect, and in-medium suppression of active-sterile mixing. Therefore, zero initial abundance (if mixing angle small enough)

- As temperature drops to $\mathcal{O}(100-1000)\,\text{MeV}$, production can begin through scattering-induced decoherence

- Active neutrinos $\nu_\alpha$ in thermal and chemical equilibrium. $\nu_\alpha$ partly oscillates into $\nu_s$ in-between scattering events. Small chance to collapse into $\nu_s$ at each event
Dodelson-Widrow: scattering-induced decoherence

- Boltzmann equation:

\[ T \frac{df_{\nu_s}}{dT} = \frac{\Gamma_\alpha}{2H} \langle P_{\alpha s} \rangle f_{\nu_\alpha}, \]

where

\[ \langle P_{\alpha s} \rangle = \frac{1}{2} \frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + (\Delta \cos 2\theta - V)^2 + (\Gamma_\alpha/2)^2} \]

- \( V = V_T(T) + V_L(T, L_{\nu_\alpha}) \). In the early universe, \( V_T < 0 \), and \( V_L \propto L_{\nu_\alpha} \)

- Dodelson-Widrow assumed no lepton asymmetry (\( V_L = 0 \))
Sterile neutrino dark matter: constraints

Main constraints come from electromagnetic decay (X-ray/γ-ray observations), small-scale structure, phase space considerations

- $\nu_s \to \nu + \gamma$ decay through effective electromagnetic vertex

\[ \Gamma_{\nu_s \to \nu \gamma} \approx 6.8 \times 10^{-33} \text{ s}^{-1} \left( \frac{\sin^2 2\theta_{12}}{10^{-10}} \right) \left( \frac{m_s}{\text{keV}} \right)^5 \]

- Monochromatic photon emission at $E_\gamma = m_s/2$

- Constraints on mass-mixing parameter space using X-ray/γ-ray telescopes, e.g., HEAO, Chandra, XMM, Suzaku, NuSTAR, Fermi-GBM, INTEGRAL

- Improved bounds likely from current and future experiments: eROSITA, XRISM, eXTP, ATHENA, etc.
Sterile neutrino dark matter: constraints

- Sterile neutrinos ‘warmer’ than WIMPs $\implies$ damping of structure at scales smaller than their free-streaming scale

- Free-streaming scale and $m_s$ related by production mechanism, therefore careful interpretation of constraints is needed

- Analysis of DM phase space distribution in dwarf spheroidal galaxies rules out $m_s \lesssim 1–2$ keV [Tremaine and Gunn (1979), Boyarsky et al. (2008)]

- Other bounds from Lyman-α forest, Milky-way satellites, lensing substructure, impose lower limits of $m_s \sim 5–20$ keV for various viable models of interest [see Zelko et al., arXiv:2205.09777]
Sterile neutrino dark matter: constraints

- Constraints on parameter space of sterile neutrino mass $m_s$ vs mixing $\sin^2 2\theta$

![Graph showing constraints on sterile neutrino mass and mixing](image)

**Figure:** K. Abazajian, arxiv:2102.01083. Does not include the latest bounds from arXiv:2205.09777 using Lensing + Ly-α + MW satellites.
Beyond Dodelson-Widrow

- Dodelson-Widrow mechanism ruled out by a combination of X-ray and structure/phase-space constraints

- If production can be enhanced in the early-universe, then one can make same amount of DM with smaller value of $\theta_s$

- Some mechanisms enhance the scattering-induced decoherence rate (e.g., resonant production, nonstandard neutrino self-interactions), whereas other mechanisms provide an alternate pathway for production (e.g., scalar decay, additional gauge symmetry)

- The idea is to alter the relationship between how the mixing angle governs early universe production and how it causes electromagnetic decay in the late universe. In some cases, the relationship is severed entirely.
Resonant production

- A nontrivial cosmological lepton number in the neutrino sector can lead to a Mikheyev-Smirnov-Wolfenstein (MSW) resonant enhancement of sterile-$\nu$ production at a certain temperature

$$\langle P_{\alpha s} \rangle = \frac{1}{2} \frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + (\Delta \cos 2\theta - V)^2 + (\Gamma_{\alpha}/2)^2},$$

where $V = V_T(T) + V_L(T, L_{\nu_\alpha})$, and $V_L$ can be $> 0$. Then, resonant enhancement happens when $\Delta \cos 2\theta - V = 0$.

- Resonantly produced $\nu_s$ tend to have a “colder” distribution

- The cosmological lepton number is constrained through observations of primordial light element abundances ($^2$D and $^4$He). A large lepton number ($L_\nu \sim 10^{-2} - 10^{-1}$) can affect the outcome of big-bang nucleosynthesis
Resonant production: constraints

Figure: Adopted from slides by K. Abazajian. Latest constraints from arXiv:2205.09777 appear likely to rule out entire parameter space for resonant production of sterile neutrino DM.
Enhanced neutrino self-interactions

- Non-standard self-interactions (e.g., $\mathcal{L} \supset \lambda_{\phi} \nu_{\alpha} \nu_{\alpha} \phi$) among neutrinos that are much stronger than the weak interaction can enhance the $\nu_s$ production rate relative to Dodelson-Widrow, allowing for smaller $\theta_s$ values to produce the correct DM density, and therefore evading the X-ray bounds.

**Figure:** A. de Gouvêa et al. (2020)
Outline

1. Introduction
2. Sterile neutrino dark matter: production and constraints
3. Diluted equilibrium sterile neutrino dark matter (DESNDM)
4. Conclusions
“Diluted equilibrium” sterile neutrino dark matter

- Dark matter candidate sterile neutrino freezes out from an initial equilibrium distribution
  - Problem: overclosure for $m_s \gtrsim 100$ eV. Unless . . .

- Relic density subsequently lowered by an epoch of entropy generation (“dilution”)

- Entropy dilution from out-of-equilibrium decay of a heavier particle is a component of several sterile neutrino models (e.g., $\nu$MSM, or models with additional gauge symmetry). Although in some of these models (e.g., $\nu$MSM), the $\nu_s$ does not start from an equilibrium abundance
DESNDM: ingredients


Sterile neutrino ($m_s \sim \text{keV–MeV}$) in thermal/chemical equilibrium in the very early universe
  - Requires additional interactions (e.g., left-right symmetry)

- Entropy generation from out-of-equilibrium particle decay
  - Dilution generator, i.e., “diluton” with $m_H \sim \text{TeV–EeV}$, also in equilibrium initially
  - Examples: heavier sterile neutrino, LSP with broken $R$-parity
DESNDM model: mechanism

- Both particles decouple at $T > T_{\text{electroweak}} \sim 100$ GeV

- Diluton decays prior to weak decoupling (preferably prior to EW transition), injecting entropy into the plasma

- Diluton mass and lifetime can be chosen to give the appropriate amount of dilution

- Can dilute the sterile neutrino to the right relic density to constitute dark matter
Ingredients/handles

- **X-ray + Ly-α**
- **Age of universe**
- **New physics?**
- **Colliders**

### ν_σ (DM candidate)
- mass (m_σ)
- vacuum mixing (θ_σ)
- lifetime (τ_σ)

### Laboratory tests
(must decouple before diluton decay)

### Decoupling

### D_H (diluton)
- mass (m_H)
- lifetime (τ_H)
- couplings (G_H)

### Baryogenesis
(Diluton must decay before EW scale?)

### Cosmic rays

Amol V. Patwardhan, SLAC
Sterile-ν DM: Dodelson-Widrow & beyond 25/38
INT program 22-2b
Diluton should decay prior to weak decoupling to preserve BBN/$N_{\text{eff}}$

Diluton decay prior to electroweak scale more baryogenesis-friendly
Sterile neutrino cooling

- Co-moving entropy $S \propto g_s a^3 T^3$

- $\Delta_x S = 0$ by symmetry
  - But $\Delta_t S \neq 0$, e.g., if particles decaying out-of-equilibrium!

- $g_s a^3 T^3 = g_{s,i} a_i^3 T_i^3 F$, where $F$ = “diution factor”

- For sterile neutrinos (decoupled), $a T_{\nu_s} = a_i T_{\nu_s,i}$

- Ratio of sterile neutrino to photon temperature at late times given by

$$
\frac{T_{\nu_s}}{T_\gamma} = \left[ \frac{4}{11} \cdot \frac{g_{s,wd}}{g_{s,i}} \cdot \frac{1}{F} \right]^{1/3}
$$
Dark matter mass and relic density

- For relativistic F-D spectral shape w/ temp parameter $T_{\nu_s}$,

$$\rho_{\nu_s} = \left[ \frac{3 \zeta(3) T_{\nu_s}^3}{(2\pi^2)} \right] \cdot m_s$$

- Sterile neutrino rest-mass for closure parameter $\Omega_s h^2$ is

$$m_s \approx 2.26 \text{ keV} \left( \frac{g_{s,i}/g_{s,wd}}{10} \right) \left( \frac{F}{20} \right) \left( \frac{\Omega_s h^2}{0.12} \right)$$

- Relic density set by entropy injection from out-of-equilibrium decay of a different particle (the diluton)

- Key feature: relic density not a function of active-sterile mixing angle!
Dilution event “cools” the energy spectrum of the lighter sterile neutrino, making it a lot colder than its rest mass would suggest!

- $m_H = 1.6$ TeV,
- $\tau_H = 0.07406$ s,
- $F = S_{\text{final}}/S_{\text{initial}} = 1981.8,$
- $m_s = 219.6$ keV

- $m_H = 0.498$ TeV,
- $\tau_H = 0.7406 \times 10^{-3}$ s,
- $F = S_{\text{final}}/S_{\text{initial}} = 64.07,$
- $m_s = 7.1$ keV
Dilution event “cools” the energy spectrum of the lighter sterile neutrino, making it a lot colder than its rest mass would suggest!

Temperature [MeV]

$m_H = 29.1 \text{ PeV},$
$\tau_H = 0.7406 \times 10^{-11} \text{ s},$
$F = S_{\text{final}}/S_{\text{initial}} = 637.3,$
$m_s = 70.6 \text{ keV}$

$m_H = 2.91 \text{ PeV},$
$\tau_H = 0.7406 \times 10^{-11} \text{ s},$
$F = S_{\text{final}}/S_{\text{initial}} = 64.10,$
$m_s = 7.1 \text{ keV}$
Contours of sterile neutrino rest-mass in keV that gives the appropriate relic density $\Omega_s = 0.26$, plotted across a parameter space of diluton rest-mass and decay lifetime.
DESNDM: Parametric plots

Contours of sterile neutrino rest-mass in keV that gives the appropriate relic density $\Omega_s = 0.26$, plotted across a parameter space of diluton rest-mass and decay lifetime.
Dark matter collisionless damping

- Fluctuations damped by dark-matter particle free-streaming

- Collisionless damping scale estimated as

\[ M_{FS} \approx 4 \times 10^5 M_\odot \left( \frac{2 \text{ keV}}{m_s} \right)^3 \left( \frac{T_{\nu_s}/T_\gamma}{0.1} \right)^3 \left( \frac{\Omega_m h^2}{0.14} \right) \]

\[ \times \left[ 10 + \ln \left( \frac{m_s}{2 \text{ keV}} \cdot \frac{0.1}{T_{\nu_s}/T_\gamma} \cdot \frac{0.14}{\Omega_m h^2} \right) \right]^3, \]

- Smaller \( M_{FS} \Rightarrow \) “colder” dark matter
Collisionless damping scale

Dark matter collisionless damping scale in our model, as a function of sterile neutrino rest-mass. Can be probed down to $10^9 - 10^{10} M_\odot$ with Ly-$\alpha$ forest observations, possibly lower ($10^6 M_\odot$?) with future 21-cm observations. $M_{FS} \sim 10^6 - 10^9 M_\odot$ could influence small-scale structure.
DESNDM: constraints
**Bonus: early matter-dominated epochs**

- Epoch of early matter domination prior to dilution decay
  - Jeans mass drops below horizon mass
  - Sub-horizon fluctuations ($10^{-7} - 10^{-5} \, M_\odot$) can begin to grow
  - Damped by radiative diffusion, scales too small in any case

---

**Figure:** (left) Matter-to-radiation ratio; (right) Jeans and horizon mass

(Matter-to-radiation ratio vs. Temperature [MeV])

(Mass-energy in $M_\odot$ vs. Temperature [MeV])

(Ratio of Jeans mass to horizon mass vs. Temperature [MeV])
Other constraints

- Core-collapse supernova cooling bound: can be evaded if $\theta_s$ small enough, or if $m_s$ heavy enough to avoid MSW resonance

- Feedback from changing matter potential as a result of $\nu_\alpha \rightarrow \nu_s$ conversion inhibits further production of $\nu_s$. This weakens existing constraints on the DM parameter space from CCSN [Suliga et al., JCAP 08 (2020) 018].

- Laboratory constraints: beta-decay (or electron capture) endpoint experiments can constrain $|m_{\nu_e}|$, and therefore the contribution of the sterile state
  - KATRIN, TRISTAN: Tritium beta decay - $m_s < 17.5$ keV
  - ECHo, HOLMES: $^{163}$Ho electron capture - $m_s < 2.5$ keV
  - HUNTER: $^{131}$Cs electron capture - $m_s < 350$ keV
  - BeEST: $^7$Be electron capture - $m_s < 860$ keV
Handles on the diluton

- Current and future colliders could probe diluton rest-masses $m_H \sim \text{TeV}$, through observing decays or constraining lifetime.

- Dilutons that are heavy sterile neutrinos could influence electroweak precision variables, e.g., $W$-boson mass, invisible $Z$-decay width, CC-to-NC ratio for neutrino scattering. Likely influence on $0\nu\beta\beta$ in certain parameter regimes.

- Higher-mass dilutons produced in cosmic rays?
Recent hints?

- Unidentified X-ray line found at 3.55 keV in Chandra and XMM-Newton data, from various sources
  - Various galaxy clusters, M31 (Andromeda), Milky way GC

- Initial detection and analysis by two independent groups (Bulbul et. al. 1402.2301, Boyarsky et. al. 1401.4119, 1408.2503). Several follow-up observations since then.

- Possible interpretation as byproduct of sterile neutrino decay
  - $m_s \approx 7.1$ keV, $\sin^2 2\theta_v \sim 10^{-10}$

- But could also be atomic physics
Outline

1. Introduction
2. Sterile neutrino dark matter: production and constraints
3. Diluted equilibrium sterile neutrino dark matter (DESNDM)
4. Conclusions
Summary

- Sterile neutrinos are a naturally well-motivated and viable dark matter candidate, although the parameter space for producing the correct DM relic density continues to become increasingly endangered in the face of improving observational data.

- Some of the production mechanisms directly depend on the active-sterile mixing angle, but others do not — these are much harder to get a handle on, although not impossible.

- Recent results reporting an unidentified X-ray line have sparked some additional interest in this DM candidate over the last several years.
Bonus slides