Cool Warm Sterile Neutrino Dark Matter

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Based on upcoming work with Lukas Graf, Amol Partwardahan, George Fuller

Sterile Neutrinos

$$\delta\mathcal{L} = \bar{N}_I i\partial_\mu\gamma^\mu N_I - F_{\alpha I}\,\bar{L}_\alpha N_I \Phi - \frac{M_I}{2}\,\bar{N}_I^c N_I + h.c.$$

Standard model gauge group singlets N_I, I=(1,2,...)

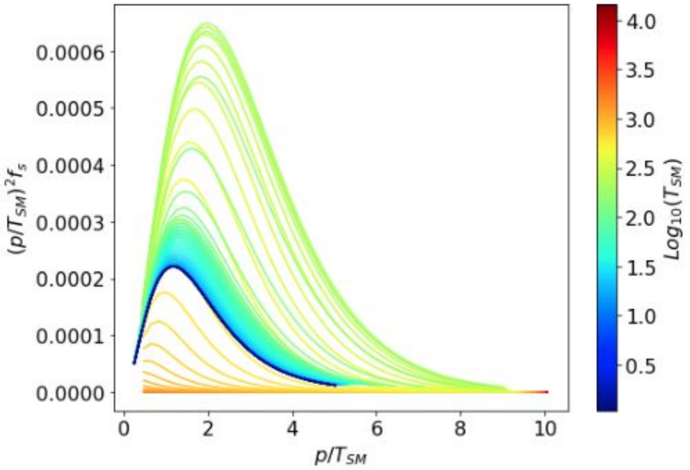
Can explain:

1. Neutrino masses
    a. Require ≥2 sterile neutrinos to explain 2 mass squared splittings
2. Smallness of neutrino masses (seesaw mechanism)
3. Baryogenesis (νMSM) Asaka & Shaposhnikov PLB 2005

keV mass range: dark matter candidate

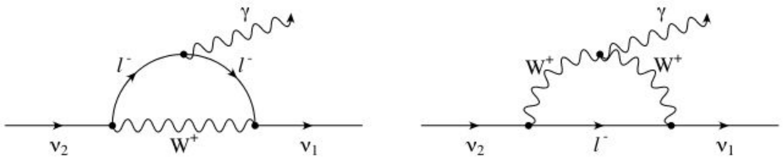
Sterile Neutrinos as Freeze-in Dark Matter

- Sterile neutrino(s) imply additional ‘mostly sterile’ mass state(s)
  - mass/flavor mixing
- Scattering-induced decoherence production in early universe:
  - Negligible initial abundance
  - SM neutrinos acquire small sterile component via oscillations
  - ‘measurement’ → collapse to sterile state



Sterile neutrino distribution function f(p,T) generated by scattering-induced decoherence for m_N = 50 keV, $\sin^2(2\theta) = 10^{-10}$

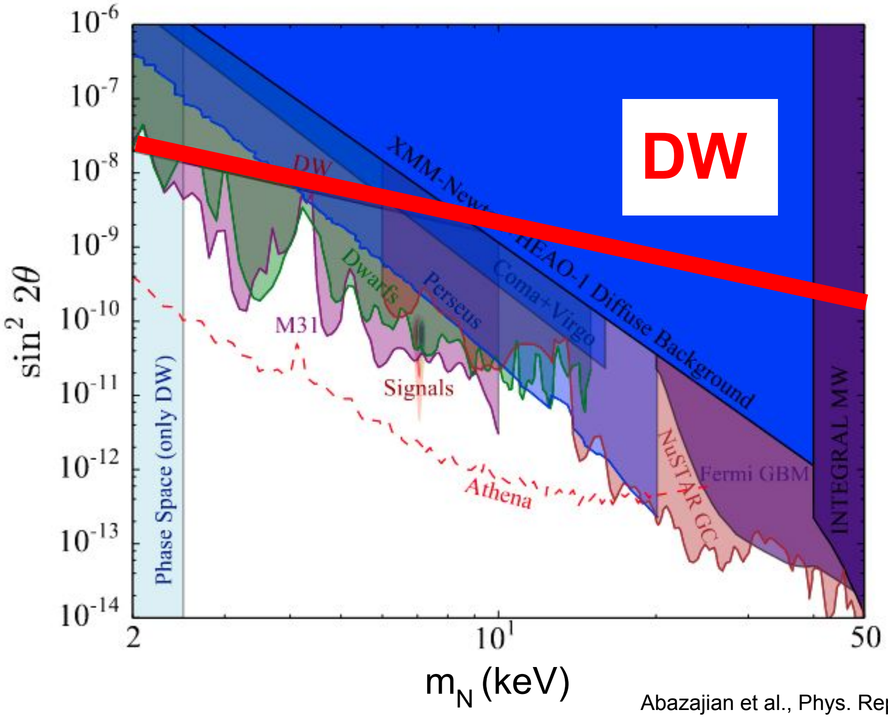
Dodelson-Widrow Mechanism



Abazajian, Fuller, Tucker APJ 2001

- Dodelson-Widrow (DW) mechanism: scattering-induced decoherence makes all the dark matter (Dodelson and Widrow, PRL 1994)
- X-ray constraints **rule this out**
- Structure formation constraints:
  - Warm dark matter
  - Current bound: m_N>92 keV Zelko et al. PRL 2022

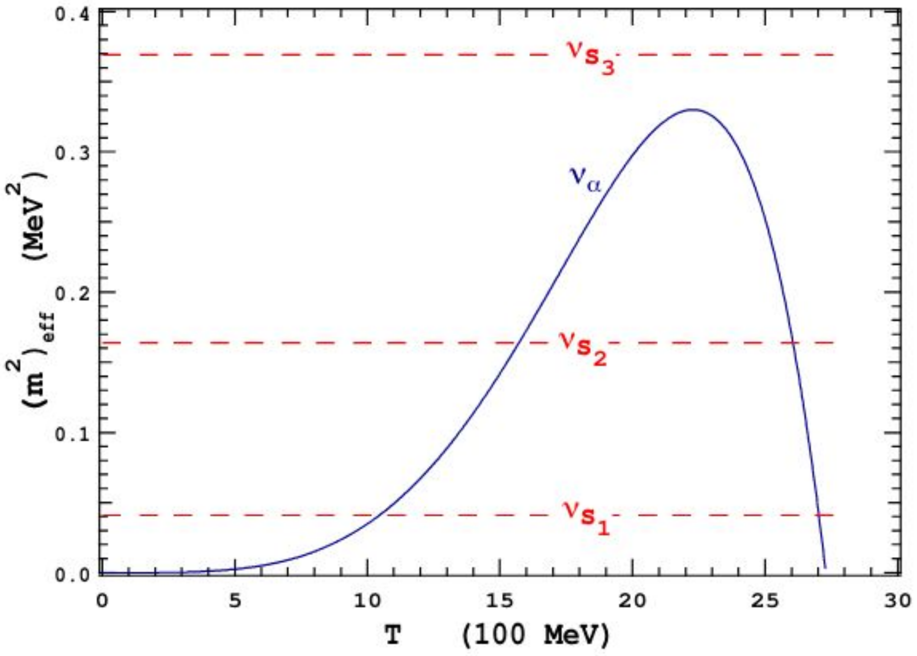
Radiative decay mode



Abazajian et al., Phys. Reports 2017

Resonant Production (Shi-Fuller Mechanism)

- Non-zero lepton number implies additional matter potential
- Resonance in mixing angle: production boost Shi & Fuller PRL 1999
  - Advantage: cooler spectrum
  - Current bound: m_N>16 keV Zelko et al. PRL 2022
- **Narrowing parameter space** allowed by x-ray constraints



Abazajian, Fuller, Patel PRD 2001

Other Models of Sterile Neutrino Dark Matter

- Non-oscillation based production:
  - e.g. Higgs singlet decay Kusenko PRL 2006
- Self-interactions among SM neutrinos de Gouvea PRL 2019
- **All require additional degrees of freedom**

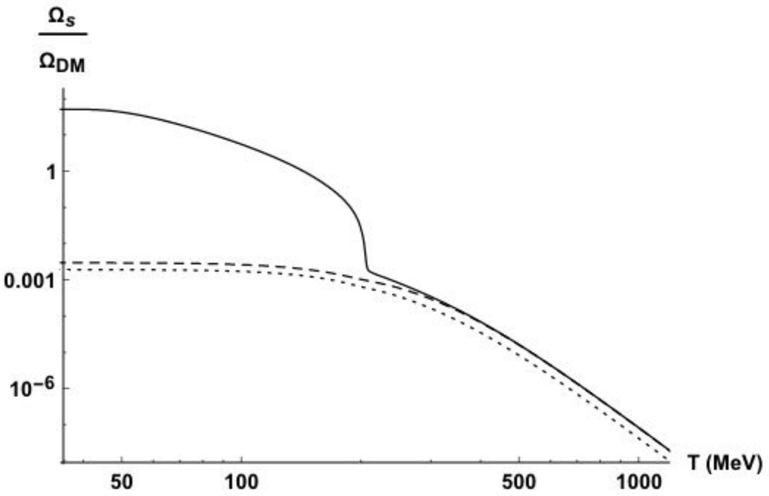
Multiple Sterile Neutrinos

$$\delta\mathcal{L} = \bar{N}_I i\partial_\mu\gamma^\mu N_I - F_{\alpha I}\,\bar{L}_\alpha N_I \Phi - \frac{M_I}{2}\,\bar{N}_I^c N_I + h.c.$$

- Previously outlined mechanisms: one sterile neutrino + its mixing
  - But require ≥2 sterile neutrinos to explain 2 mass squared splittings
- Do multiple sterile neutrinos allow for new interplay in production?
  - **No in minimal model**
- **Yes if sterile neutrinos have self-interactions**

Self-interacting Sterile Neutrino: One Sterile Only

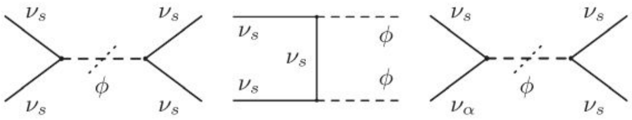
Heavy mediator: new resonance → difficult to produce correct abundance

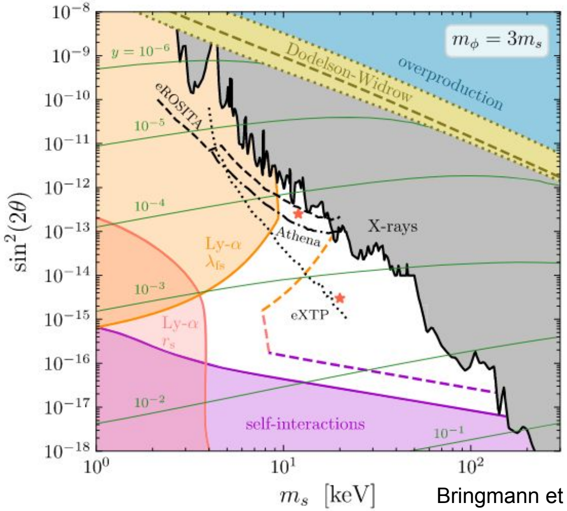


Johns & Fuller PRD 2019

Relic abundance when resonance is triggered (solid) vs not (dashed)

Lighter mediators: Possible to produce correct abundance





Bringmann et al. PRD 2023

Self-interactions Among Multiple Sterile Neutrinos

Our model: two sterile neutrinos and heavy scalar mediator ϕ

$$\mathcal{L} \supset \frac{g_\phi^{ij}}{2} \overline{N_j^C} N_i \phi$$

Idea:

- **Produce heavy N_1** through scattering-induced decoherence
- **Transfer energy** (via self-interaction) **to light N_2 (DM)**
- **Only N_1 mixing is relevant**

Self-interactions:

$$\Gamma_{s,2\to2} \propto \alpha G_\phi^2 p T^4$$

$$\Gamma_{s,2\to4} \propto \alpha G_\phi^4 p T^8$$

$$\Gamma_{s,1\to3} \propto \alpha G_\phi^2 m_N^5$$

Hubble rate:

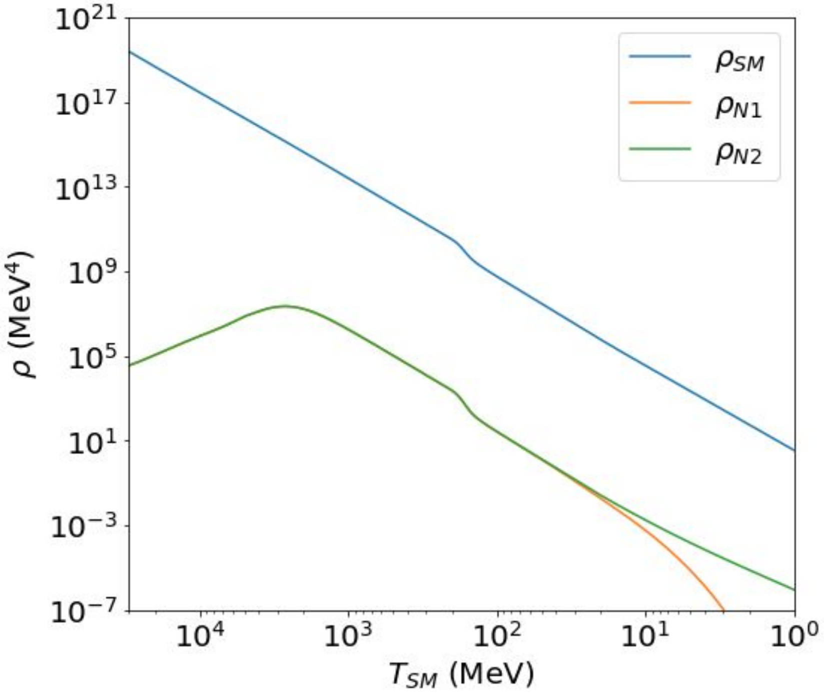
$$H \propto \sqrt{g^\star(T)} \frac{T^2}{m_{pl}}$$

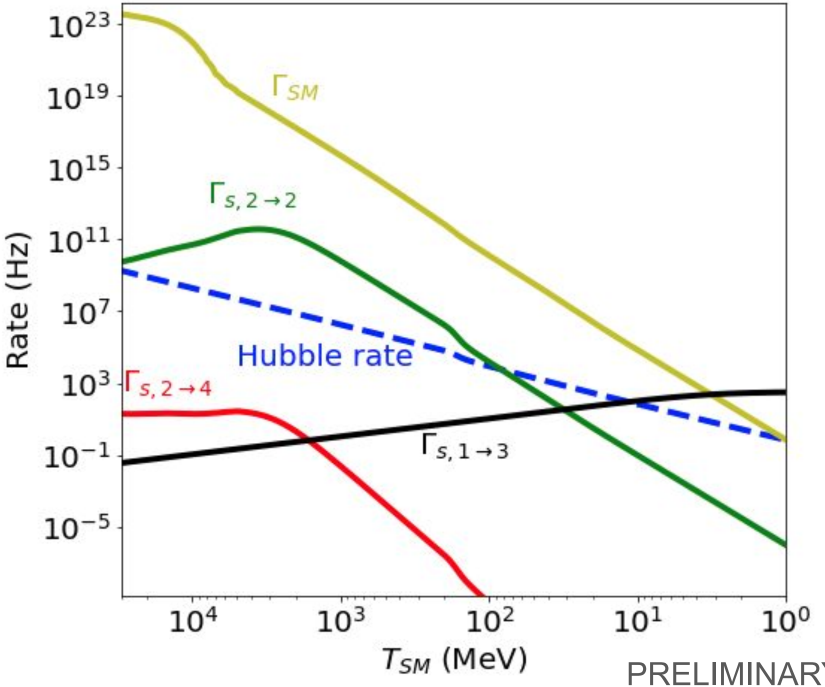
SM neutrino scattering:

$$\Gamma_{\rm SM} = C(p,T) G_F^2 p T^4$$

Small Coupling: 2→2 Thermalization and Decay

N_1(heavy): Populated through scattering-induced decoherence
N_2 (light): Populated through self-interactions with N_1, becomes dark matter



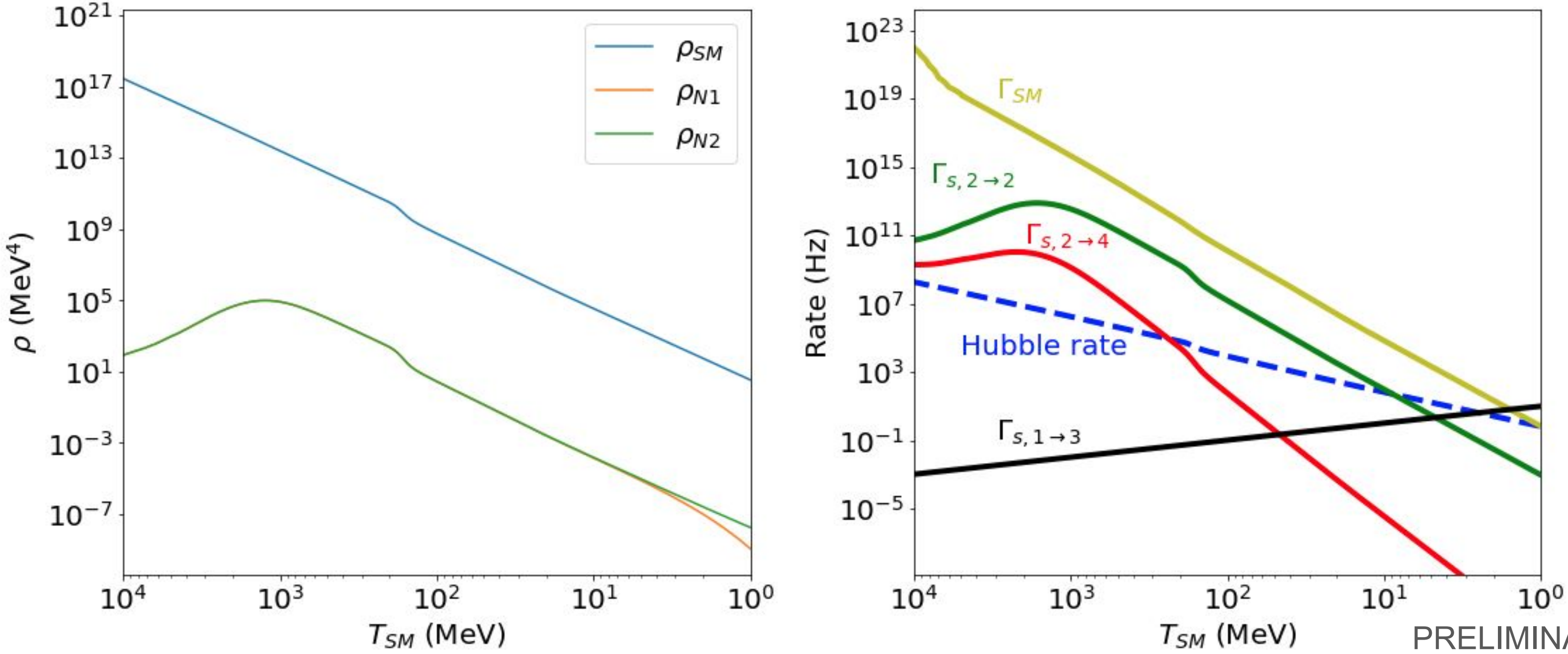


PRELIMINARY

G_ϕ/G_F=10, m_{N1}=10 MeV, $\sin^2(2\theta)=10^{-15}$. Rates at fixed p/T=3.

Large Coupling: Full Thermalization

N_1(heavy): Populated through scattering-induced decoherence
N_2 (light): Populated through self-interactions with N_1, becomes dark matter

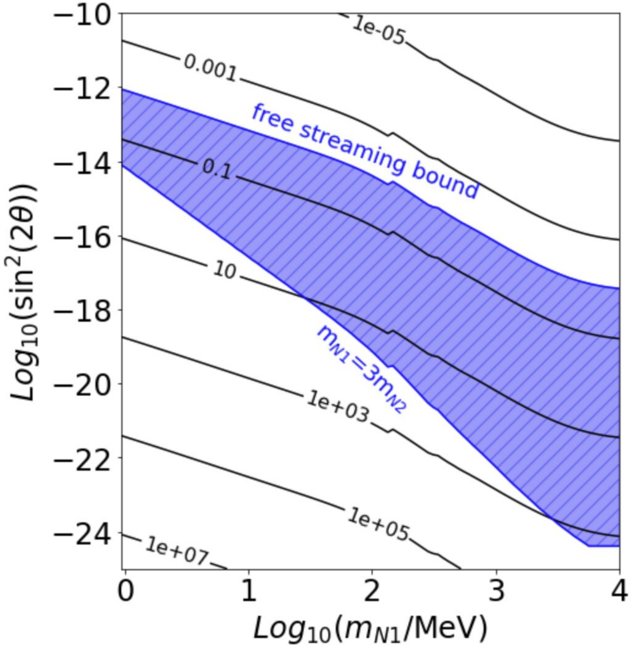


PRELIMINARY

G_ϕ/G_F=1000, m_{N1}=1 MeV, $\sin^2(2\theta)=10^{-15}$. Rates at fixed p/T=3.

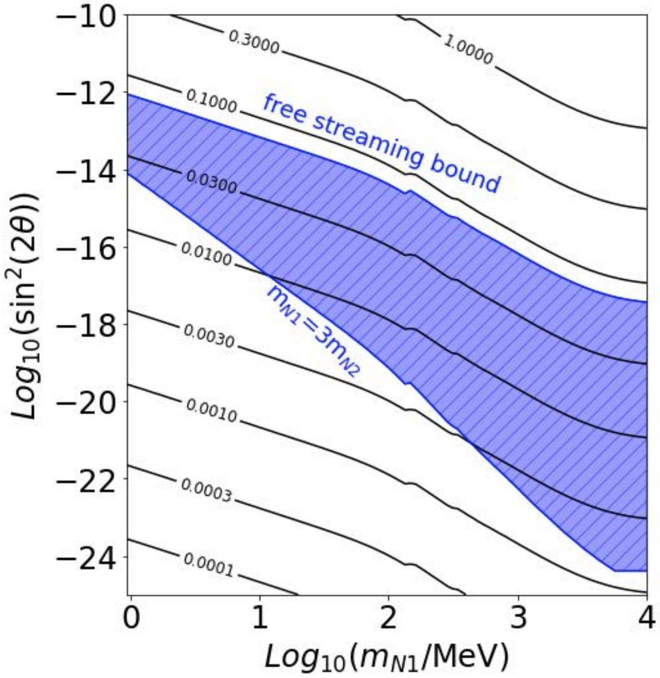
Full Thermalization: Parameter Space

Light Sterile Neutrino Mass



Contours: m_{N2} (MeV) so that $\Omega h^2 = 0.12$

Dark Sector Temperature



PRELIMINARY

Contours: T_{DS}/T_{SM}

Discussion and Conclusion

Key features:

- Not excluded by x-rays
  - Production is NOT based on DM sterile's mixing with SM
  - Could show up in x-ray searches at smaller mixing angles: Athena, XRISM, eROSITA
- Cooler spectrum = relaxed free streaming bounds (smaller allowed masses)
- Other constraints and observational handles
  - Lab experiments: heavy sterile mixing
  - Bullet cluster: bounds on self-interacting dark matter strength
- Multiple light steriles: could decrease temperature further

Backup

Production

$$\Gamma_{sa}(\nu_\alpha \to \nu_s : p,t) \approx \frac{\Gamma_\alpha(p)}{2} \langle P_m(\nu_\alpha \to \nu_s : p,t) \rangle,$$

where

$$\langle P_m(\nu_\alpha \to \nu_s : p,t) \rangle = \frac{1}{2} \frac{\Delta^2(p)\sin^2(2\theta_\alpha)}{(\Delta^2(p)\sin^2(2\theta_\alpha) + \left(\frac{\Gamma_\alpha(p)}{2}\right)^2 + (\Delta(p)\cos(2\theta_\alpha) - V_\alpha)^2}$$

and

$$\Delta(p) = \frac{m_s^2}{2p}.$$

$$V_\alpha(p,T) = \pm\sqrt{2} G_F n_\gamma \frac{\eta_B}{4}(2\delta_{\alpha e}-1) - \frac{8\sqrt{2}G_F p}{3M_Z^2}(n_{\nu_\alpha}\langle E_{\nu_\alpha}\rangle + n_{\overline{\nu}_\alpha}\langle E_{\overline{\nu}_\alpha}\rangle) - \frac{8\sqrt{2}G_F p}{3M_W^2}(n_\alpha\langle E_\alpha\rangle + n_{\bar{l}_\alpha}\langle E_{\bar{l}_\alpha}\rangle)$$