Population Transfer Mechanism for Sterile Neutrino Dark Matter

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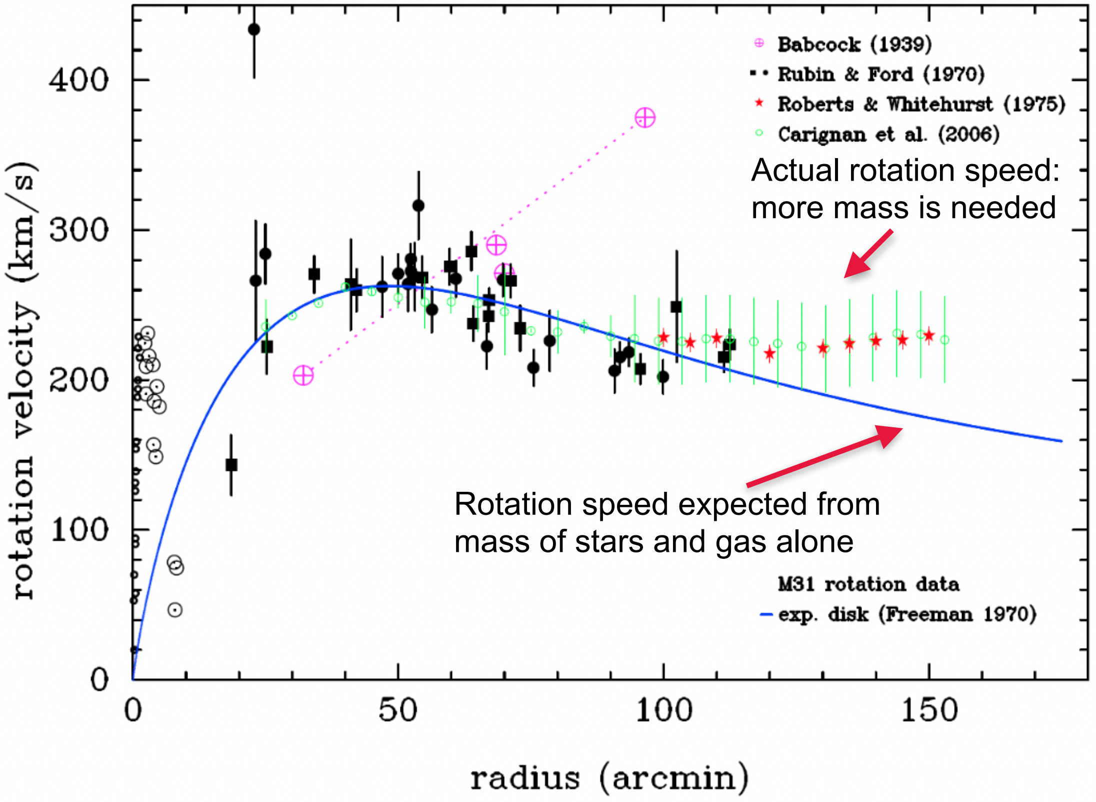
Galaxy Rotation Curves

Bertone: Rev. Mod. Phys. (2016)

- What is dark matter?
- requirements:
  - 5x as abundant as normal matter
  - exists from early universe until today
  - clumps to form halos
  - no more than tiny interactions with visible matter



Active Neutrinos

- neutrinos – left-handed, neutral and massive fermions – evidence from oscillations (at least 2 of them must have mass)

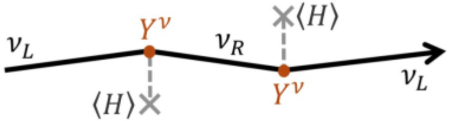
$$\sqrt{\Delta m^2_{21}} \simeq 8\ \mathrm{meV}$$

$$\sqrt{|\Delta m^2_{31}|} \simeq 50\ \mathrm{meV}$$

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

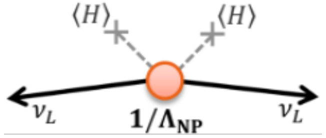
- Dirac mass – as other fermions, but tiny couplings to Higgs

$$m_D \nu_L \nu_R^c \subset y_\nu L H \nu_R^c$$



- Majorana mass – only left-handed neutrino → lepton number violation

$$m_M \overline{\nu}_L \nu_L^c$$



Sterile Neutrinos

- singlet fermions under the Standard Model *N*

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

- can explain:
  - neutrino masses — require ≥ 2 sterile neutrinos to explain 2 mass squared splittings
  - smallness of neutrino masses (seesaw mechanism)
  - baryon asymmetry of Universe
  - dark matter candidate

Mixing-in the Sterile Neutrino(s)

- consider a simplified model with one active and one sterile neutrino:

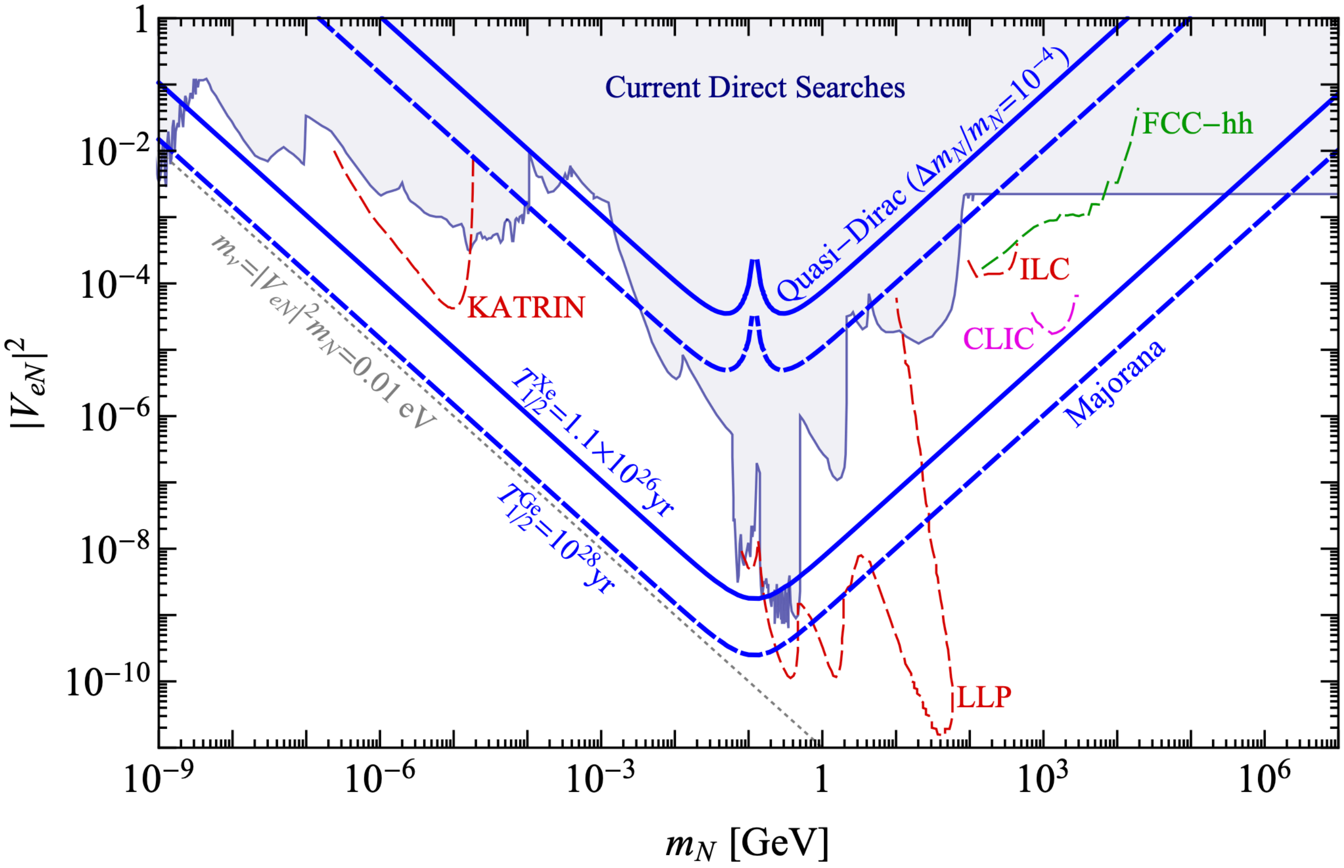
$$\begin{pmatrix} \nu_e \\ N \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

  → active-sterile mixing; sterile not entirely sterile, mass state receives contribution from the active neutrino, but suppressed

- for theta << 1 the second mass state, v_2, can be treated also as "sterile"
- multiple steriles - mixing among them can be removed, not a physical parameter → mass matrix diagonal, unless additional interaction(s)

Lab Constraints

F. F. Deppisch, LG, F. Iachello, J. Kotila: PRD 102 [2009.10119]



Sterile Neutrinos as Dark Matter?

Production in the Early Universe

- via scattering-induced decoherence:

$$\left(\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right) f_N = \frac{1}{2}\Gamma_\alpha P(\nu_\alpha \to N)(f_{\nu_\alpha} - f_N)$$

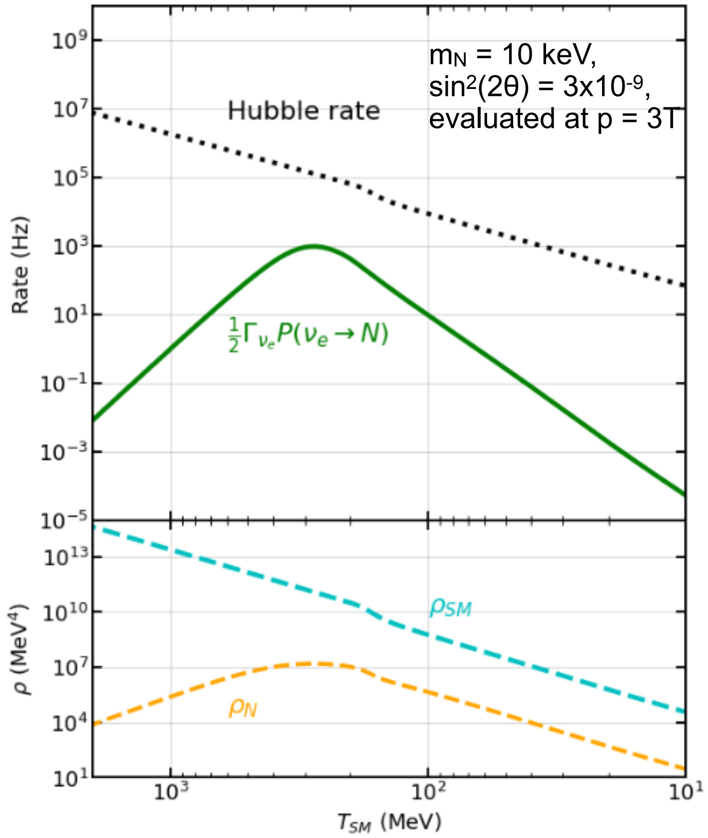
- conversion probability:

$$P(\nu_\alpha \to N) = \frac{1}{2}\frac{\Delta^2 \sin^2(2\theta)}{\Delta^2 \sin^2(2\theta) + \left(\frac{\Gamma_\alpha}{2}\right)^2 + (\Delta\cos(2\theta) - V_\alpha)^2}$$

$$\Delta \approx \frac{m_N^2}{2p}$$

- Dodelson-Widrow (DW) mechanism: this makes all the dark matter

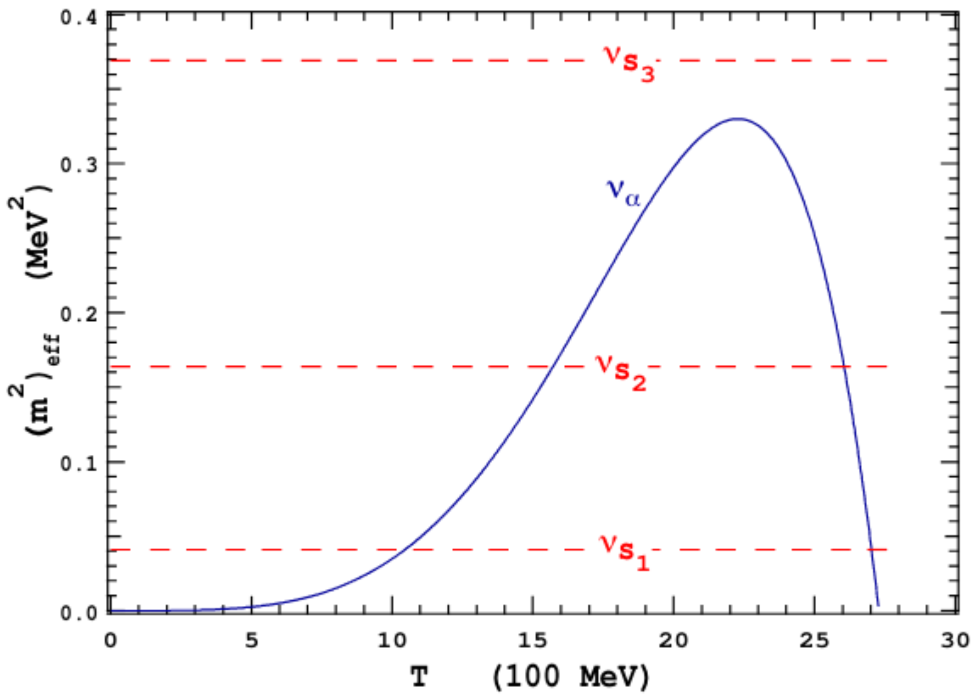
Dodelson and Widrow: PRL (1994)



Resonant Production

- non-zero lepton asymmetry yields additional matter potential
- resonance in conversion probability gives production boost: “Shi-Fuller” mechanism
- advantages: smaller mixing angles and cooler spectrum

Shi and Fuller: PRL (1999)

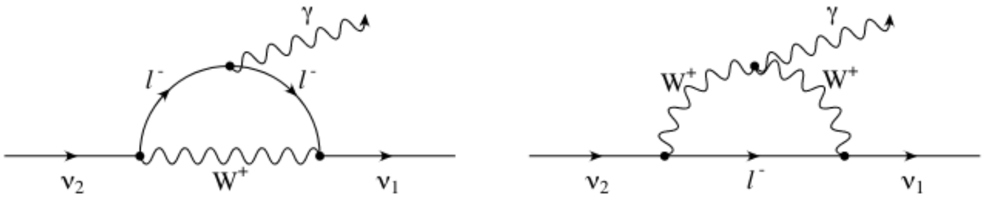


Abazajian, Fuller, Patel PRD 2001

Astrophysical Implications

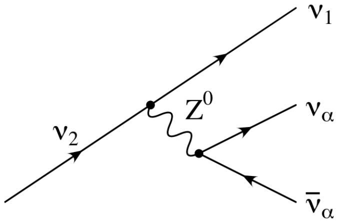
- electromagnetic line signature:

$$\Gamma_{\nu\gamma} = 6.8 \times 10^{-33} \left(\frac{m_N^5}{1\mathrm{keV}} \right) \left(\frac{\sin^2(2\theta)}{10^{-10}} \right)$$



Abazajian, Fuller, Tucker: APJ (2001)

- principle decay mode (upper mass bound):



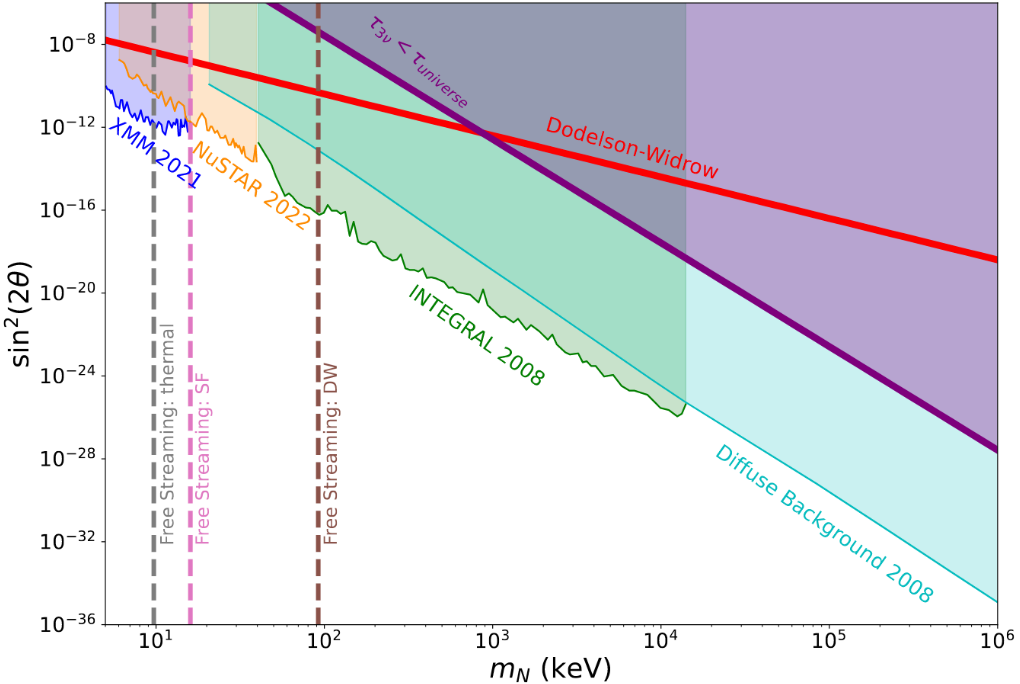
$$\Gamma_{3\nu} = \frac{1}{192\pi^3} G_F^2 m_N^5 \sin^2(\theta)$$

Abazajian, Fuller, Tucker: APJ (2001)

- free streaming: bound on energy spectrum (lower mass bound)

Constraints on Sterile Neutrino DM

- red line: realizes the Dodelson-Widrow mechanism (all DM)
- green, yellow, blue regions: ruled out from non-observation of EM lines
- purple region: lifetime for 3 active neutrino decay is shorter than age of the Universe

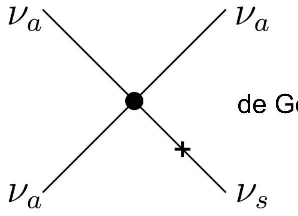


- dashed lines: most stringent lower mass limits from free streaming constraints derived from strong lenses and Milky Way satellite galaxies

Other Possibilities

- non-scattering-induced-decoherence based production, e.g. Higgs singlet decay, etc. Kusenko: PRL (2006), …

- self-interactions among SM neutrinos



de Gouvea, Sen, Tangarife, Zhang: PRL 124 (2019)

- self-interaction in the sterile neutrino sector
  - heavy mediator vs. light mediator

    Johns, Fuller: PRD 100 (2019)

    Bringmann et al.: PRD (2023)

    Astros, Vogl: JHEP 03 (2024)

- all require additional degrees of freedom

Dark Population Transfer Mechanism

- incorporating more sterile neutrinos?
- produce heavy sterile neutrino (N_1) through scattering-induced decoherence
- transfer energy to lighter sterile neutrino (N_2)
- lighter sterile persists as dark matter

LG, A. Patwardhan, G. Fuller, J. Spisak: 2402.13878

- key parameters: both masses m_{N1} and m_{N2}, and mixing angle θ of the heavy sterile, which is relevant for production
- light sterile mixing is irrelevant, but can be searched for

Evolution of the Dark Sector

- Standard Model (SM) and dark sector (DS) evolution

$$\frac{\mathrm{d}\rho_{\mathrm{SM}}}{\mathrm{d}t} = -3H(\rho_{\mathrm{SM}} + P_{\mathrm{SM}}) - \frac{\mathrm{d}\rho_{\mathrm{inj}}}{\mathrm{d}t}$$

$$\frac{\mathrm{d}\rho_{\mathrm{DS}}}{\mathrm{d}t} = -3H(\rho_{\mathrm{DS}} + P_{\mathrm{DS}}) + \frac{\mathrm{d}\rho_{\mathrm{inj}}}{\mathrm{d}t}$$

$$H^2 = \frac{8\pi G}{3}(\rho_{\mathrm{SM}} + \rho_{\mathrm{DS}})$$

energy injection into the dark sector

$$\frac{\mathrm{d}\rho_{\mathrm{inj}}}{\mathrm{d}t} = \int \frac{\mathrm{d}^3 p}{(2\pi)^3} E f_{\nu_\alpha}^{(\mathrm{eq})} \frac{\Gamma_\alpha}{2} P(\nu_\alpha \to N_1)$$

Mechanism Realization

- e.g. self-interaction with a heavy scalar:

$$\mathcal{L} \supset \frac{g_\phi^{ij}}{2} \overline{N}_j^C N_i \phi \qquad G_\phi \equiv g_\phi^2 / m_\phi^2$$

- interaction rates:

$$\Gamma_{\phi,2\to2} \propto \beta G_\phi^2 p T^4$$
$$\Gamma_{\phi,1\to3} \propto G_\phi^2 m_N^5 / \gamma(p)$$
$$\Gamma_{\phi,2\to4} \propto G_\phi^2 T^4 \Gamma_{\phi,2\to2}$$

$$f(E,T) \simeq \beta / (e^{E/T} + 1)$$

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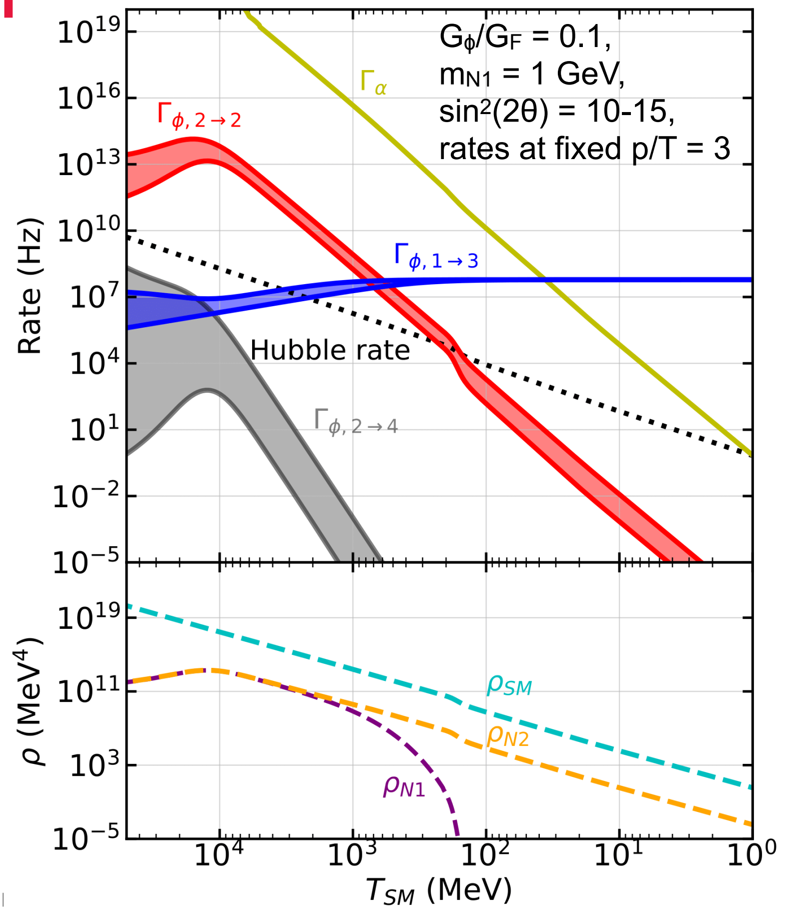


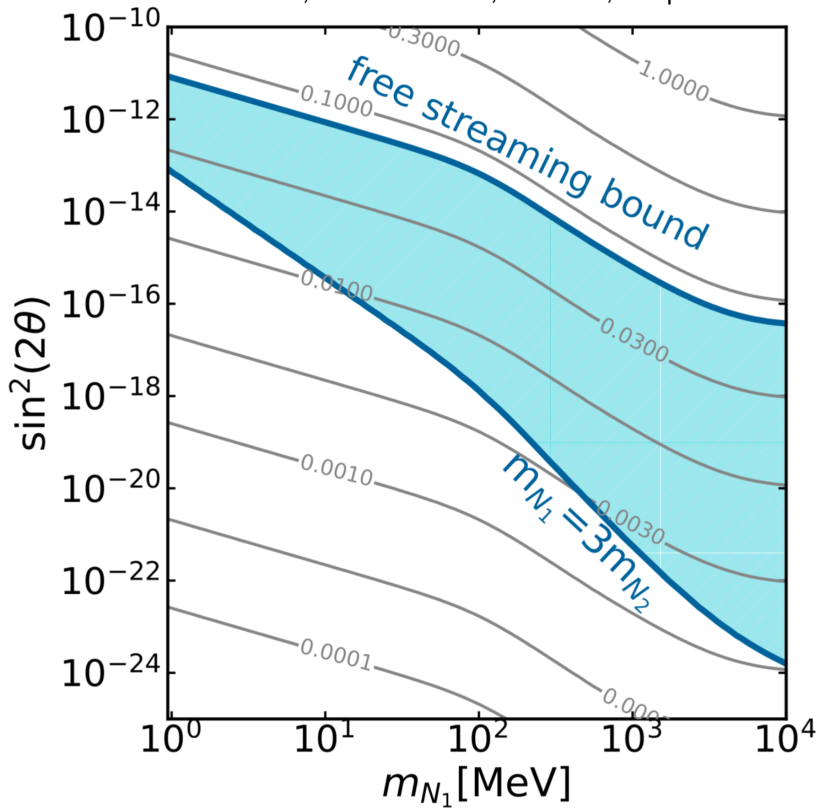
Dark Sector Temperature

- contours: T_{DS}/T_{SM} today
- DS temperature suppressed relative to SM
- free streaming bound
  - assumes thermalized dark matter, for which energy spectrum is fixed by:

$$\rho_{\rm DM} \sim g^{\star} m T_{\rm DS}^3$$

  - bound is 10x lower than in Dodelson-Widrow mechanism

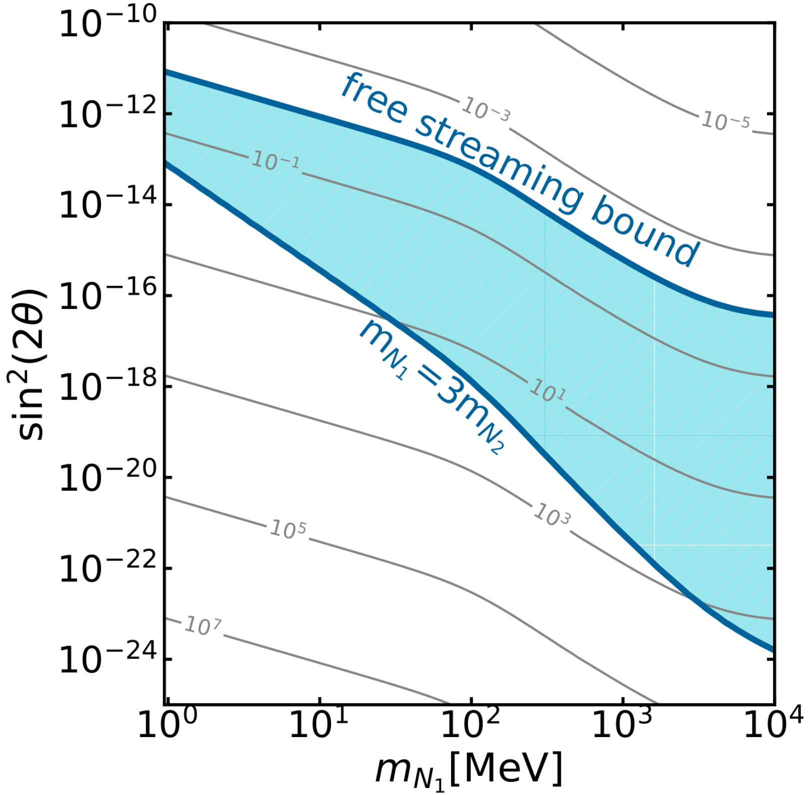
LG, A. Patwardhan, G. Fuller, J. Spisak: 2402.13878



Dark Matter Sterile Neutrino Mass (N_2)

LG. A. Patwardhan, G. Fuller, J. Spisak: 2402.13878

- contours: m_{N2} (MeV) so that $\Omega h^2 = 0.12$
- allowed mass range:
  10 keV to 1 GeV
  → much broader than typical sterile neutrino dark matter
- can evade traditional upper limits by setting the mixing of the light sterile to be small



Discussion and Conclusion

- lighter sterile neutrino is dark matter, produced from decays of heavier sterile
- possible lab constraints on the the heavy sterile mixing, but too small for current experiments
- not excluded by X-rays
  - lighter sterile’s mixing can be arbitrarily small
  - if signal seen at higher energies, could be a sterile: NuSTAR, HEX-P, Fermi GRB
  - bullet cluster: bounds on strength of dark matter self-interaction
- cooler spectrum = smaller allowed masses
  - multiple light sterile neutrinos: could decrease temperature further

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Thank you!