Cooling sterile neutrino dark matter

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based on 1706.02707

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keV dark matter

Largest scale considered here is $\approx$ 100 MeV

Why would you want to make dark matter colder?

Sterile neutrinos

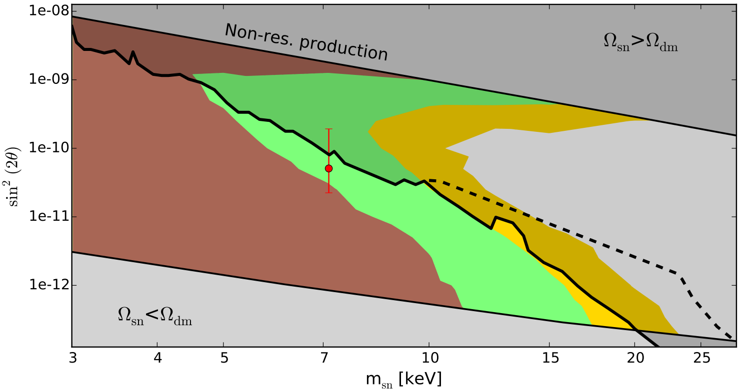
- sterile neutrinos interact with the SM only via mixing with SM neutrinos
- produced non-thermally through oscillations (Dodelson-Widrow/Shi-Fuller mechanism)

  other productions mechanisms exist (production from decays, thermal freeze-out + dilution ..)
- sterile neutrinos are warm dark matter
  - non-negligible kinetic energy/characteristic momentum
  - impact on structure formation

testable with astrophysical observations, i.e subhalo counts, Lyman-alpha forest ...

Too much of a good thing

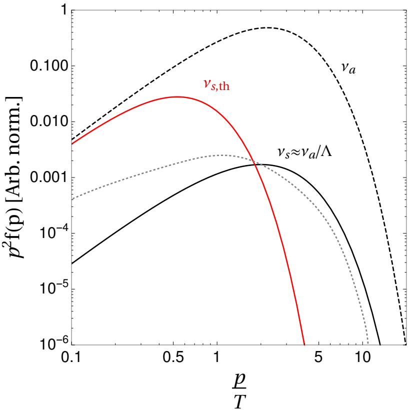
Two parameter: sterile neutrino mass m_{ν_s} and the mixing with active neutrinos $\sin^2(2\theta)$



combination of X-ray and warm dark matter bounds from A. Schneider [1601.07553]

region preferred by tentative 3.5 keV X-ray line (see also talk by Esra Bulbul) seems disfavored

Cooling sterile neutrinos



- distribution is non-thermal
- for DW $f_{\nu_s} \approx \frac{1}{\Lambda} f_{\nu_a}$
- $\langle p \rangle$ set by T_{SM}

$\rightarrow$ reduce $\langle p \rangle$ by turning the distribution in a thermal one

Quantitative estimate

- for illustration $f_{\nu_s} \approx \frac{1}{\Lambda} f_\nu$
  make argument general by using realistic energy density
- energy conservation in an expanding universe $\rho \propto a^{-4}$

$$\rho_i a_i^4 = \rho_\varphi a_\varphi^4 \quad \text{or} \quad C \frac{1}{\Lambda} T_\gamma^4 = C(1 + \frac{4}{7} g_\varphi) T_\varphi^4$$

- once $m_\varphi \approx T$ entropy transfered from φ to ν_s (similar to photon heating by electron decoupling in SM)

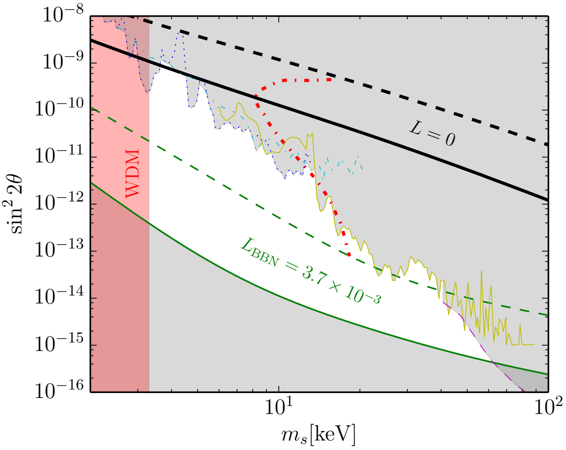
$$s_\varphi a_\varphi^3 = s_f a_f^3 \quad \text{or} \quad K(1 + \frac{4}{7} g_\varphi) T_\varphi^3 = K T_{\nu_s}^3$$

- final expectation:

$$T_{\nu_s} = (1 + \frac{4}{7} g_\varphi)^{1/12} \Lambda^{-1/4} T_\gamma \quad \text{(colder)}$$

$$n_f = (1 + \frac{4}{7} g_\varphi)^{1/4} \Lambda^{1/4} n_i \qquad \text{(more abundant)}$$

Allowed parameter space



X-ray and warm dark matter bounds substantially relaxed

Does this qualitative picture hold?

Brief answer: Yes!
Long answer: Following sildes

Toy model

- starting point: ν_s with a mass m_{ν_s} and mixing $\sin\theta$

New ingredients:

- new scalar φ interacts with sterile neutrinos

$$\mathcal{L}_{\text{int}} = y \bar{\nu}_s \nu_s \varphi$$

- scalar self-interactions

$$\mathcal{L}_{\varphi} = \ldots - \frac{\lambda}{4}\varphi^4$$

$\Rightarrow$ φ decays and number changing $2\varphi \leftrightarrow 4\varphi$ processes

Stages of thermalization

I. $T \sim 100$ MeV: initial abundance of sterile neutrinos produced by oscillations (resonant or non-resonant)

we use the public code sterile-dm by Venumadhav et al. [1507.06655]

II. 100 MeV $\gtrsim T \gtrsim 10$ MeV: φ produced by inverse decays, self-thermalizes due to efficient number changing interactions

III. 10 MeV $\gtrsim T \gtrsim 1$ MeV: once sufficient φ abundance has been built up decays produce ν_s efficiently
$\rightarrow \nu_s$ driven towards thermal equilibrium

IV. $T \lesssim 1$ MeV: φ becomes massive and drops out of thermal bath

$\Rightarrow$ entropy production in sterile sector

Constraints

Don't want an impact on initial production

- contribution of inverse decays to collision rate needs to be small
- potential from sterile neutrino asymmetry V_{ν_s} needs to be small

quantitative:

- $\frac{\Gamma_{new}(T_{new})}{H(T_{new})} < \frac{1}{10} \frac{\Gamma_{DW}(T_{DW})}{H(T_{DW})}$
- $V_{\nu_s} < \frac{1}{10} V_L$

depending on m_{ν_s}, m_φ this implies $\Rightarrow y < 10^{-6} - 10^{-7}$

Momentum averaged Boltzmann equations

Assumptions

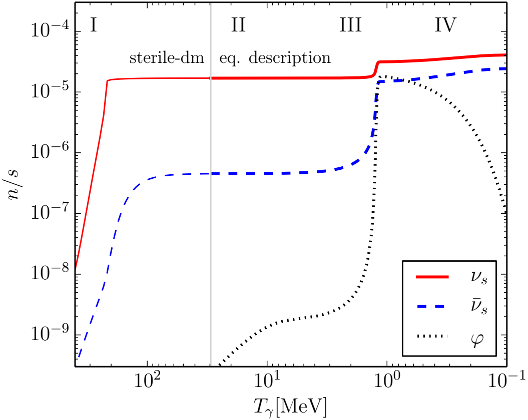
- all particle species (ν, $\bar{\nu}$, φ) in local thermal equilibrium
- $2\varphi \to 4\varphi$ process efficient

$\Rightarrow$ system characterized by 5 quantities (3 energy densities and 2 number densities)

- system of coupled Boltzmann equations:

$$
\begin{aligned}
\dot{\rho}_\varphi + CH\rho_\varphi &= \Gamma_{\rho_{\nu_s}}\rho_{\nu_s} + \Gamma_{\rho_{\bar{\nu}_s}}\rho_{\bar{\nu}_s} - \Gamma_{\rho_\varphi}\rho_\varphi \\
\dot{\rho}_{\nu_s} + 4H\rho_{\nu_s} &= \Gamma_{\rho_\varphi}\rho_\varphi/2 - \Gamma_{\rho_{\nu_s}}\rho_{\nu_s} \\
\dot{\rho}_{\bar{\nu}_s} + 4H\rho_{\bar{\nu}_s} &= \Gamma_{\rho_\varphi}\rho_\varphi/2 - \Gamma_{\rho_{\bar{\nu}_s}}\rho_{\bar{\nu}_s} \\
\dot{n}_{\nu_s} + 3Hn_{\nu_s} &= \Gamma_{n_\varphi}n_\varphi - \Gamma_{n_{\nu_s}}n_{\nu_s} \\
\dot{n}_{\bar{\nu}_s} + 3Hn_{\bar{\nu}_s} &= \Gamma_{n_\varphi}n_\varphi - \Gamma_{n_{\bar{\nu}_s}}n_{\bar{\nu}_s}
\end{aligned}
$$

Thermalization



Here: $m_{\nu_s} = 7$ keV, $m_\varphi = 100$ keV, $y = 7 \times 10^{-9}$, $n_{\bar{\nu}_s}/n_{\nu_s} = 3 \times 10^{-2}$
perfect agreement with analytic result

Conclusion

- keV sterile neutrinos constitute an intriguing warm dark matter candidate
- sterile neutrinos thermalization can be achieved in simple models
- compact description in terms of energy conservation
- parameter space in reach of future observational efforts

Production by oscillations

- Boltzmann equation for sterile neutrinos

$$\frac{\partial}{\partial t} f_{\nu_s}(p,t) - Hp \frac{\partial}{\partial p} f_{\nu_s}(p,t) \approx [f_{\nu_a}(p,t) - f_{\nu_s}(p,t)].$$

- rate given by

$$\frac{1}{4} \frac{\Gamma_a \Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + \frac{\Gamma_a^2}{4} + [\Delta \cos 2\theta - V_T - V_L]^2}$$

  - $\Delta \approx \frac{m_{\nu_s}^2}{2p}$
  - Γ_a collision rate with plasma
  - $V_T \propto \rho_e$ and $V_L \propto n_{\nu_e} - n_{\bar{\nu}_e}$ medium potential