Boosting sterile neutrino dark matter production

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Sterile neutrino dark matter

- sterile neutrino $\rightarrow$ gauge singlet fermion
- interacts with SM via mixing with regular neutrinos

interesting since

- one of the most minimal SM extensions
- DM candidate since it is naturally dark

with oscillations alone (Dodelson-Widrow mechanism)

- right amount of DM for $\mathcal{O}(keV)$ masses
- decays to photon and SM neutrino (X-ray lines)
- tends to be warm (i.e. affect structure formation)
- current status: excluded

Self-interacting sterile neutrinos

Minimal setup for a more complex dark sector:

- add one scalar singlet ϕ
  (one new parameter: m_ϕ)
- ν_s mixing with SM neutrinos remains only connection between DM and SM
- ϕ interacts with ν_s
  (one parameter: Yukawa coupling y)

see also Hansen and SV '17, Fuller and Johns '19, Bringmann et al '22

Production in early Universe

sterile neutrinos are produced by “freeze-in" with some extra hoops
Master equation for production

$$\frac{\partial f_s}{\partial t} - Hp\frac{\partial f_s}{\partial p} = \frac{\Gamma_t}{4}\left(\frac{\omega^2 \sin^2(2\theta)}{\omega^2 \sin^2(2\theta) + \frac{\Gamma_t^2}{4} + [\omega\cos(2\theta) - V_{\rm eff}]^2}\right)[f_a - f_s] + \mathcal{C}_s$$

Sterile’s distribution function

Hubble’s rate

Vacuum oscillation frequency $\sim \frac{m_s{}^2}{2p}$

Vacuum mixing angle

Total rate

Effective potential

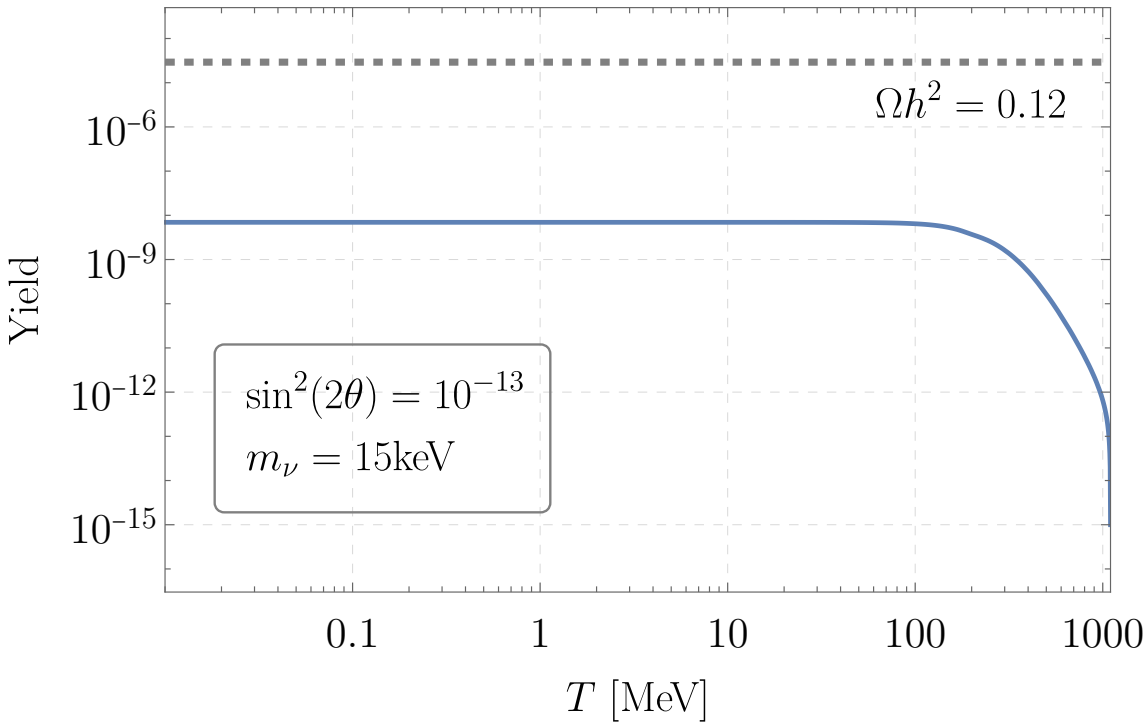
Active’s distribution function

Sterile-sterile scattering processes

evolution controlled by

- effective in medium oscillation probabilities, i.e. term in brackets
- total interaction rate of neutrinos, Γ_t
- dark sector thermalization rate, C_s

Production from oscillations



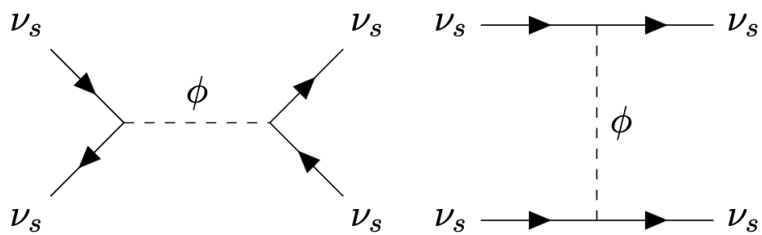
freeze-in type production

- no sterile neutrinos at high T
- most relevant production at $T \sim 200$ to 300 MeV
- yield constant below ~ 100 MeV

Simple modification ...

... with rich effects in sterile neutrino production

- large self scattering rate for non-vanishing sterile neutrino population

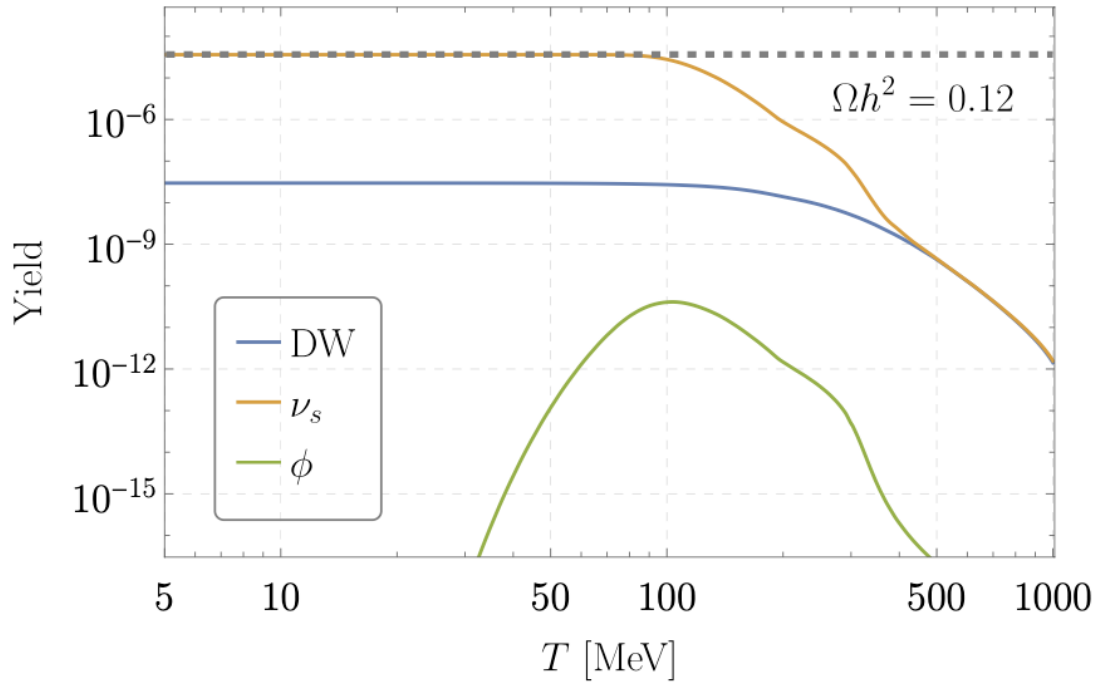


- heuristic: replace one of the inital states with SM neutrino via mixing

the more sterile there are the more they scatter
$\Rightarrow$ self-accelerating production rate

Accelerated production

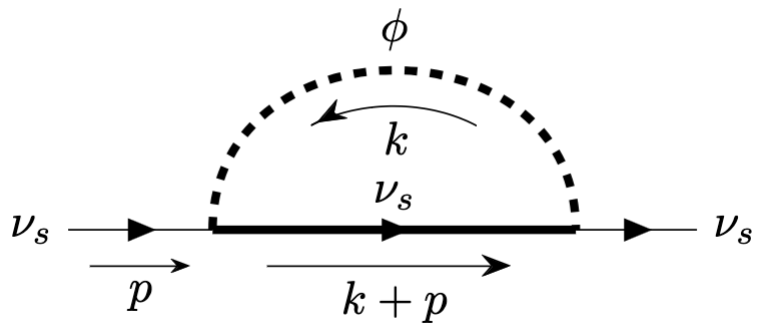
masses: $m_s = 12$ keV, $m_\phi = 1.5$ GeV
mixing $\sin^2(2\theta) = 5 \times 10^{-13}$ and coupling $y \approx 7 \times 10^{-2}$



- high T: DW production
- intermediate T: self-interaction pick up and pull in more stuff
- low T: production shuts of when ϕ becomes massive

... with rich effects in sterile neutrino production

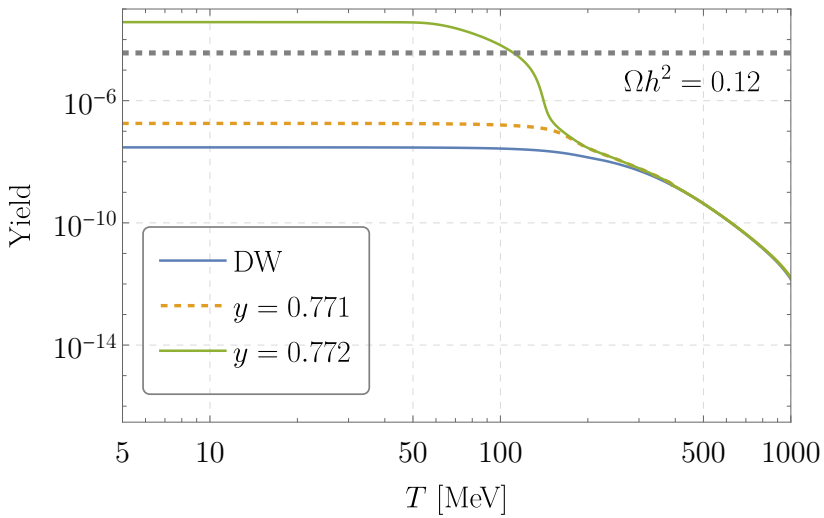
- new physics contribution to thermal potentials

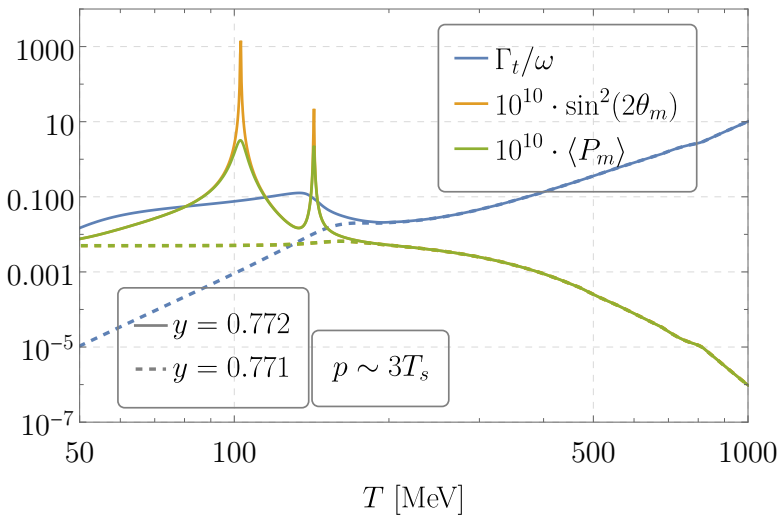


- cancelation in denominator of effective oscillation probability for heavy ϕ and large enough y

  $\Rightarrow$ resonant enhancement of the production rate

Resonance for large m_ϕ

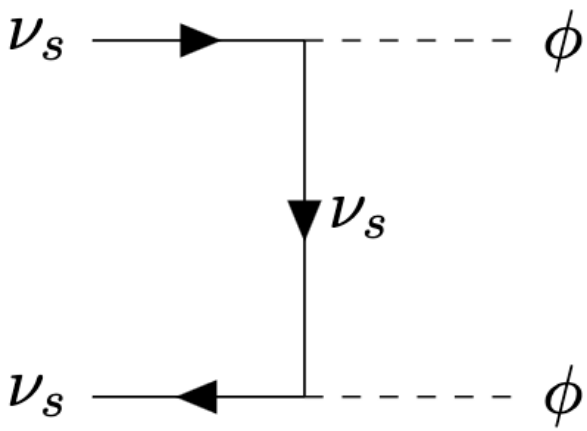




large jump in relic density for very small change in coupling
$\Rightarrow$ highly tuned, typically either too little or too much DM for large m_ϕ

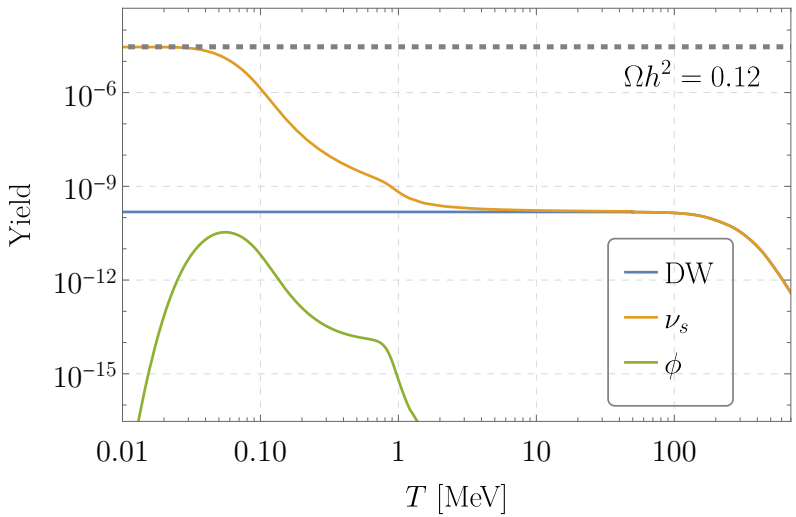
... with rich effects in sterile neutrino production

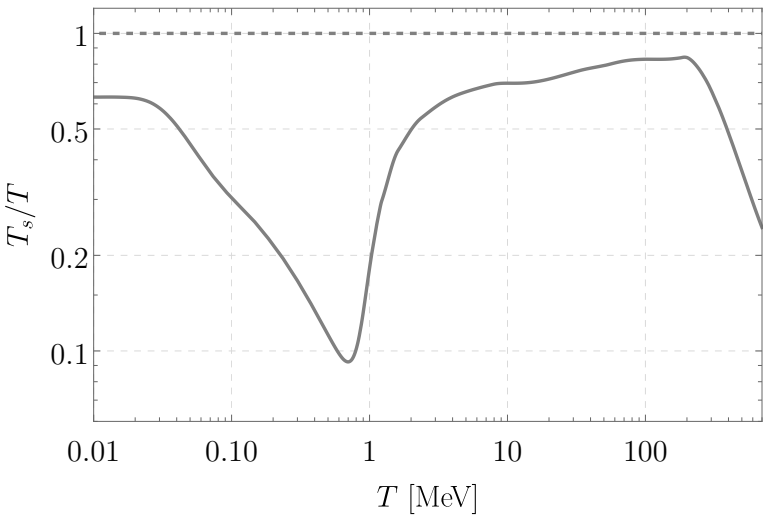
- number changing processes in the sterile neutrino sector



$\Rightarrow$ allows for additional DM production and independent evolution of dark sector temperature

Thermalization

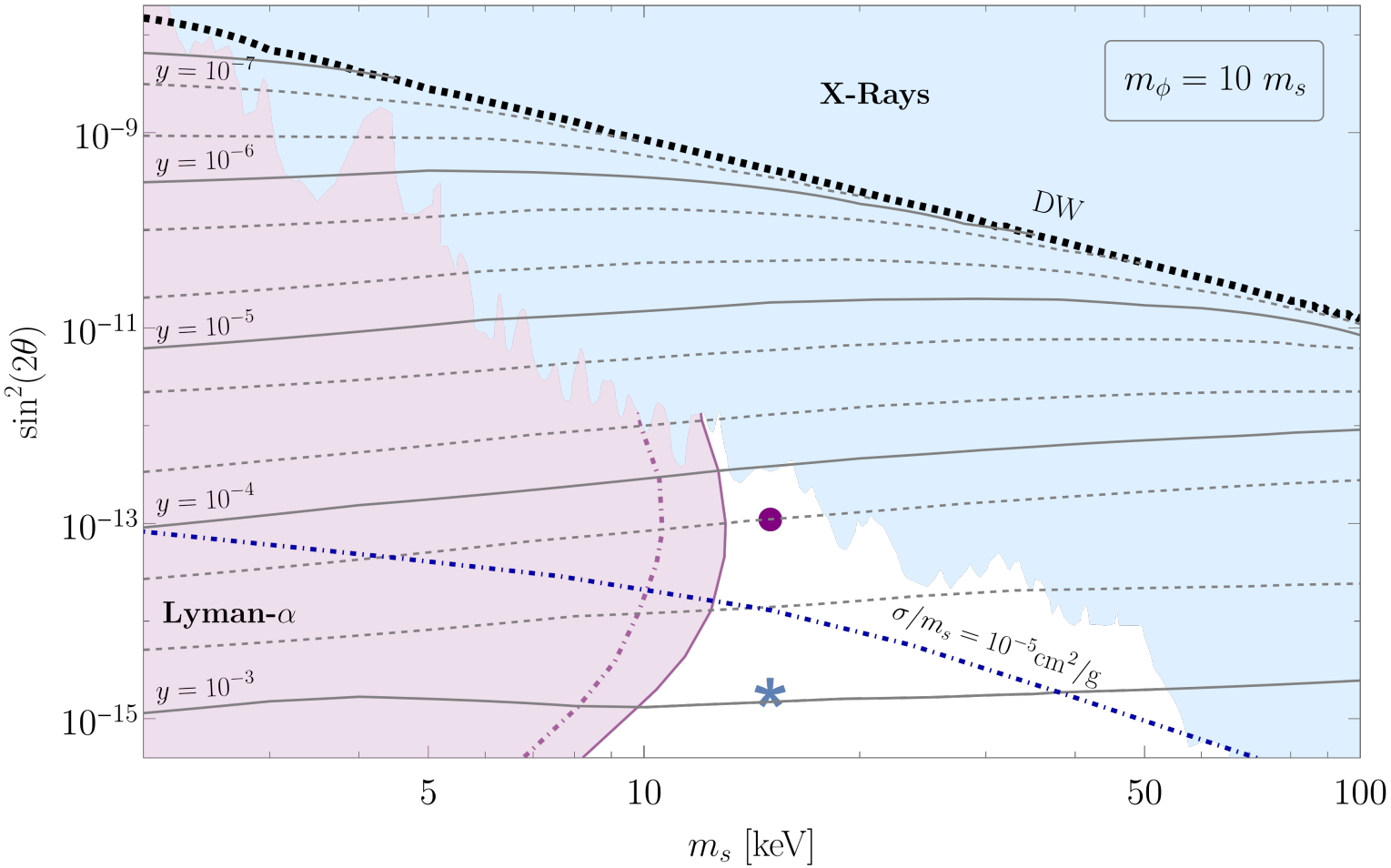




- thermalization leads to a significant decrease in the dark sector temperature early on
- more neutrinos pulled in via self-scattering later

Can this be tested?

Parameter space of sterile neutrino dark matter



constraints from

- structure formation (Lyman-α forest)
- X-ray satellites

Conclusions

- keV sterile neutrinos are an attractive dark matter candidate
- large enhancement of production from interactions in dark sector
- impact on phenomenology mixed
  - X-ray bounds less constraining
  - structure formation bounds similar or stronger