# Boosting sterile neutrino dark matter production

Stefan Vogl

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with M. Dias Astros

universität freiburg

# 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 $\phi$
  (one new parameter: $m_\phi$)
- $\nu_s$ mixing with SM neutrinos remains only connection between DM and SM
- $\phi$ interacts with $\nu_s$
  (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

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

Sterile's distribution function

Hubble's rate

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

Vacuum mixing angle

Total rate

Effective potential

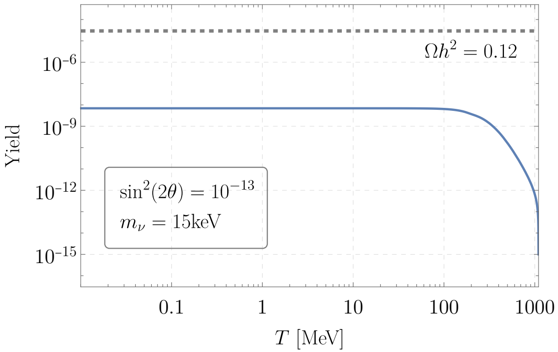
Active's distribution function

Sterile-sterile scattering processes

evolution controlled by

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

# Production from oscillations



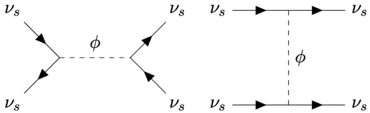

freeze-in type production

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

# Simple modification ...

# ... with rich effects in sterile neutrino production

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

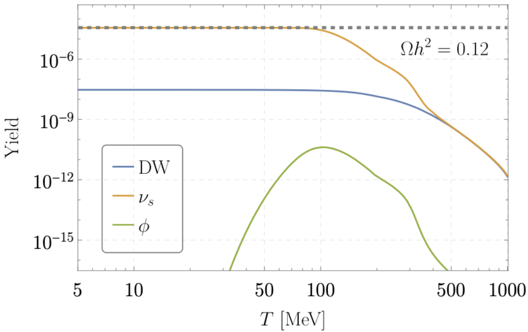



- heuristic: replace one of the inital states with SM neutrino via mixing

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

# Accelerated production

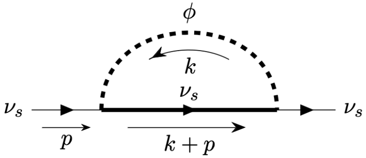
masses: $m_s = 12$ keV, $m_\phi = 1.5$ GeV
mixing $\sin^2(2\theta) = 5 \times 10^{-13}$ and coupling $y \approx 7 \times 10^{-2}$




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

# ... with rich effects in sterile neutrino production

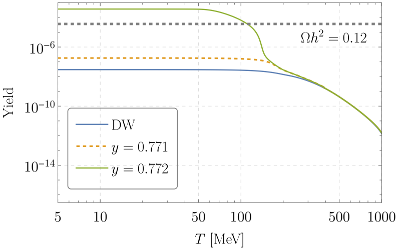
- new physics contribution to thermal potentials

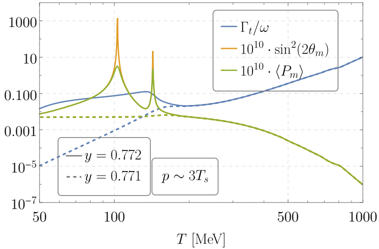



- cancelation in denominator of effective oscillation probability for heavy $\phi$ and large enough *y*

$\Rightarrow$ resonant enhancement of the production rate

# Resonance for large $m_\phi$

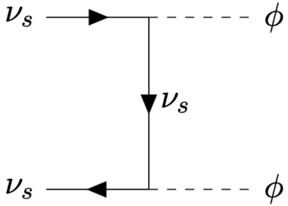



large jump in relic density for very small change in coupling
$\Rightarrow$ highly tuned, typically either too little or too much DM for large $m_\phi$

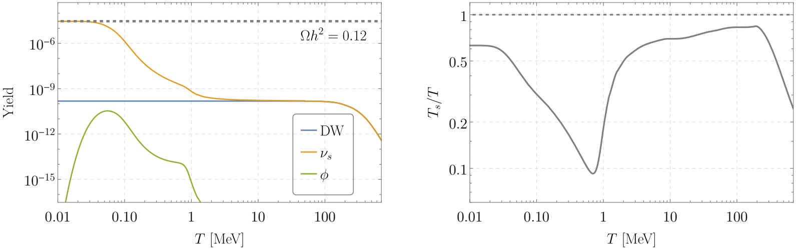
# ... with rich effects in sterile neutrino production

- number changing processes in the sterile neutrino sector




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

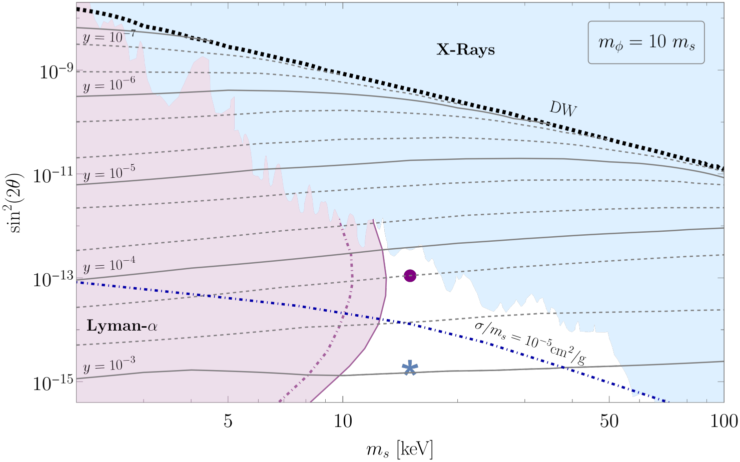
# Thermalization




- 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-$\alpha$ 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