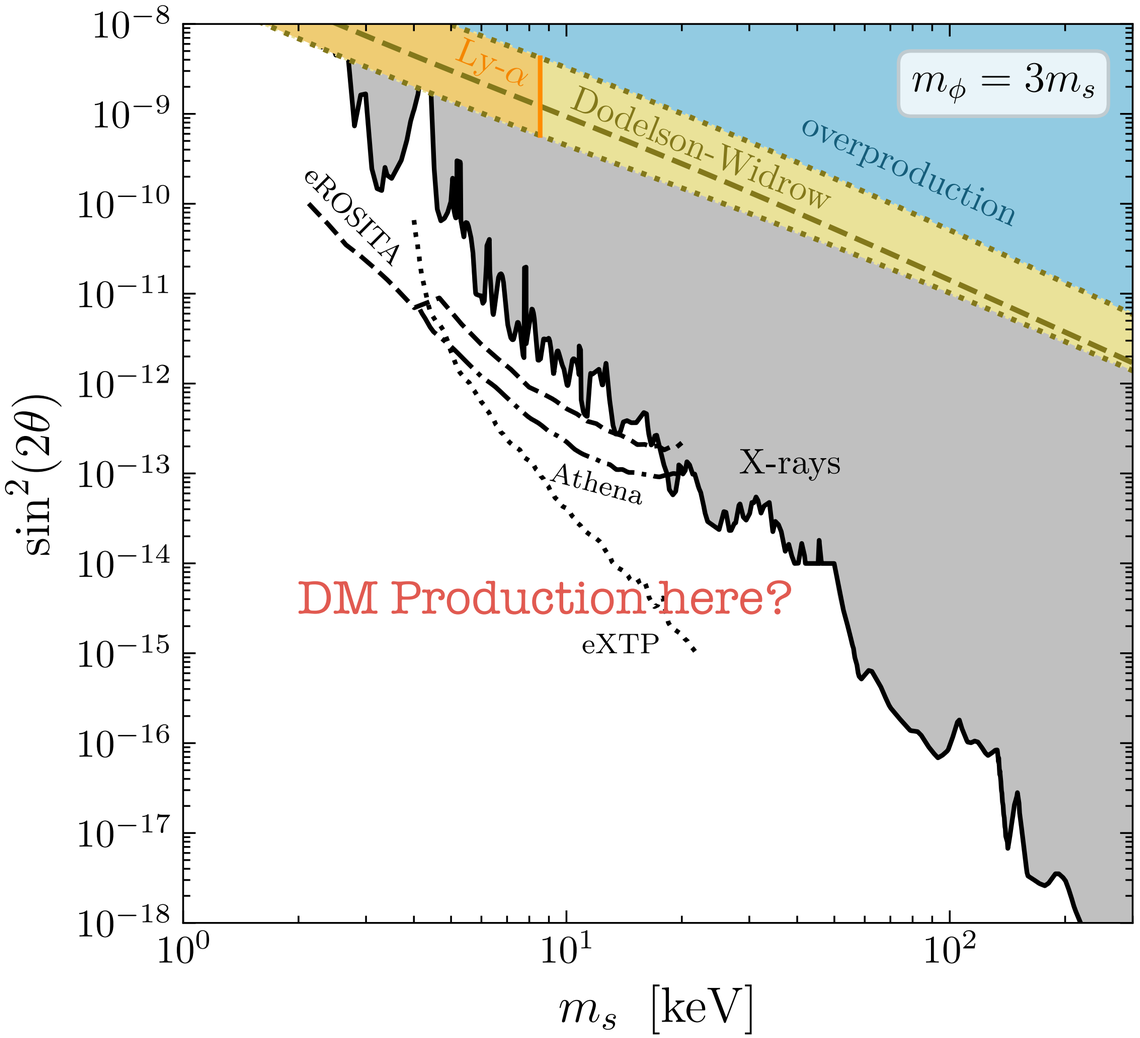
A new life for sterile neutrino dark matter after the pandemic

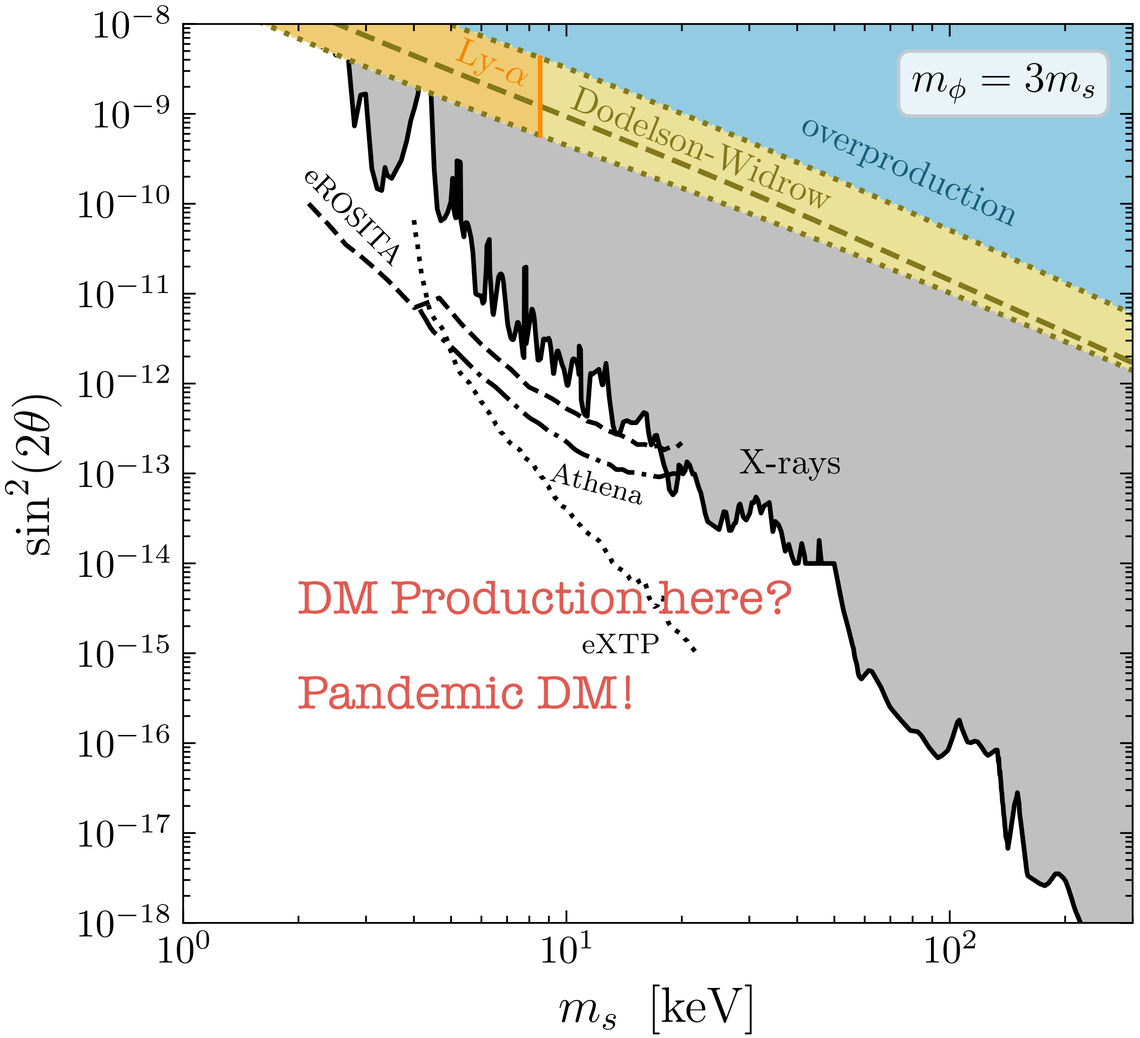
Based on 2206.10630

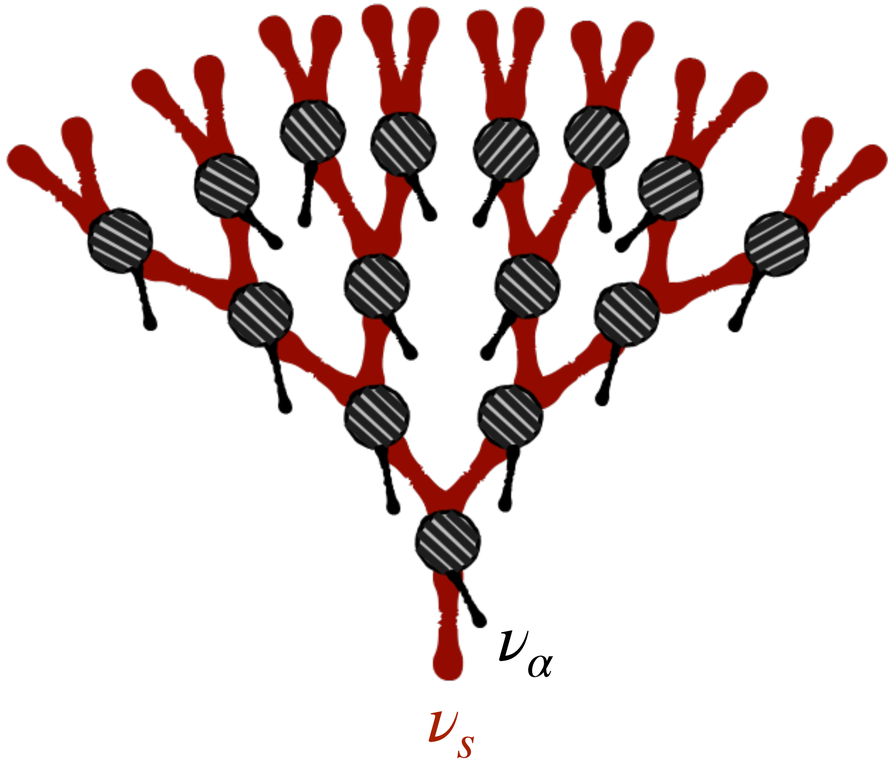
Paul Frederik Depta
Max-Planck-Institut für Kernphysik

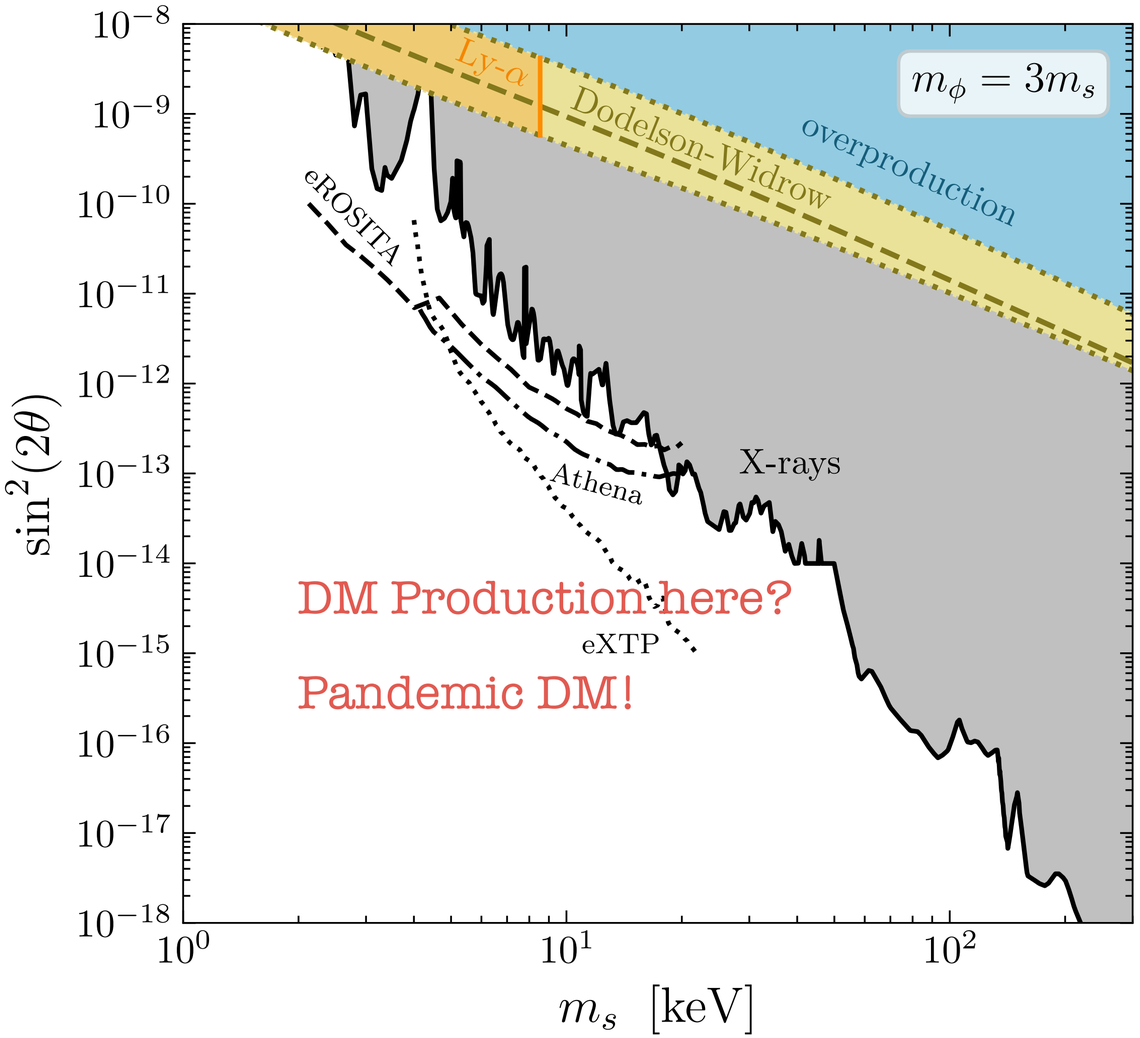
In collaboration with T. Bringmann, M. Hufnagel, J. Kersten, J. T. Ruderman, and K. Schmidt-Hoberg

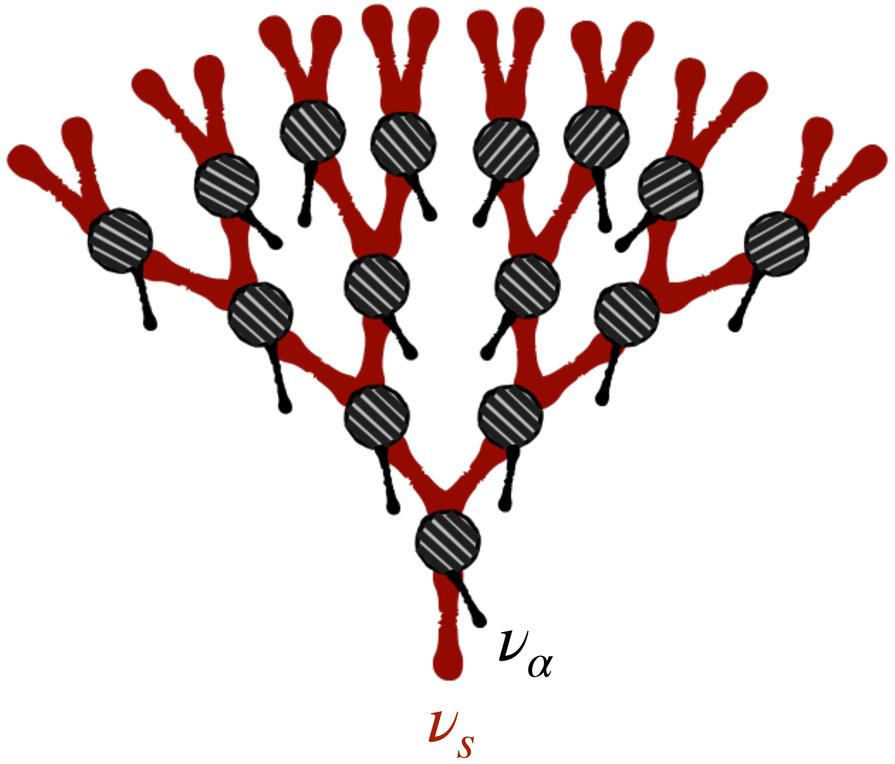
DESY Theory Workshop 2022
29 September 2022


$m_\phi = 3m_s$
Ly-α
Dodelson-Widrow
overproduction
eROSITA
X-rays
Athena
eXTP
DM Production here?
$\sin^2(2\theta)$
m_s [keV]


$m_\phi = 3m_s$
Ly-α
Dodelson-Widrow
overproduction
eROSITA
X-rays
Athena
eXTP
DM Production here?
Pandemic DM!
$\sin^2(2\theta)$
m_s [keV]


ν_α
ν_s



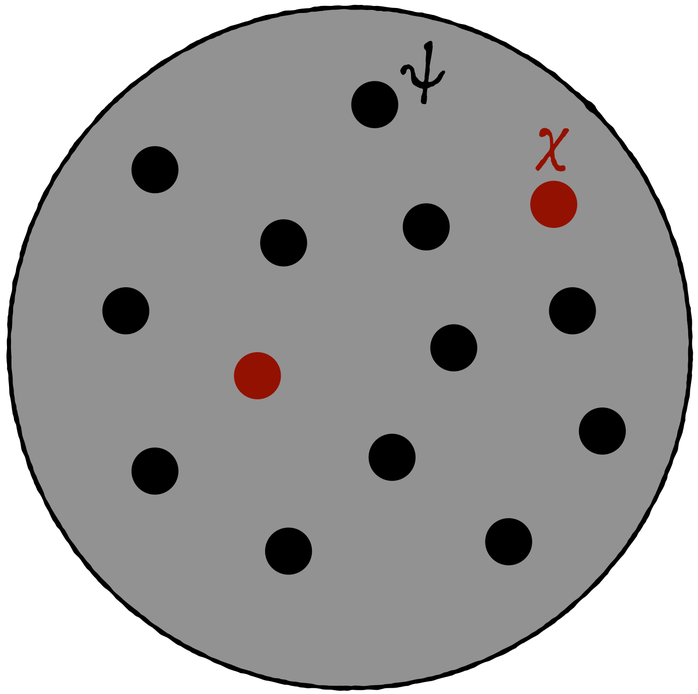


Generally occurs for self-interacting sterile neutrinos!
Simplest model for sterile neutrino DM production as Dodelson-Widrow scenario is excluded!

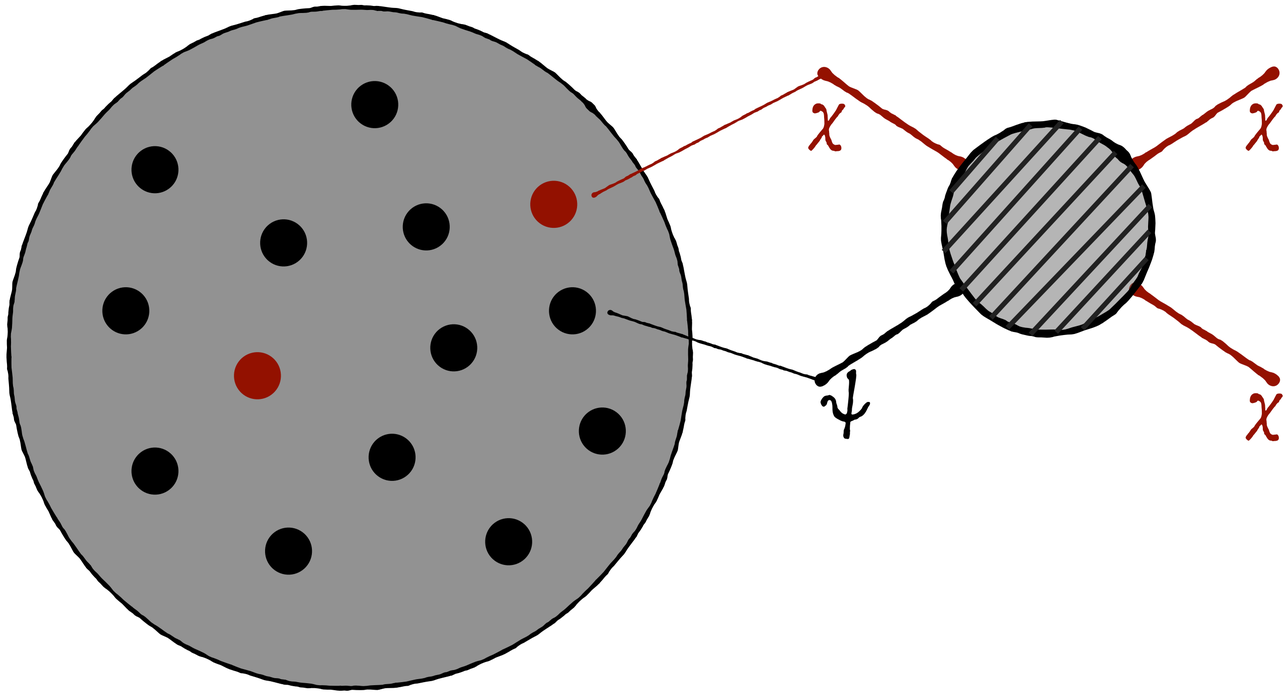
Outline

- Dark matter from exponential growth (Pandemic DM)
- Model setup
- Evolution
- Parameter space

Dark matter from exponential growth



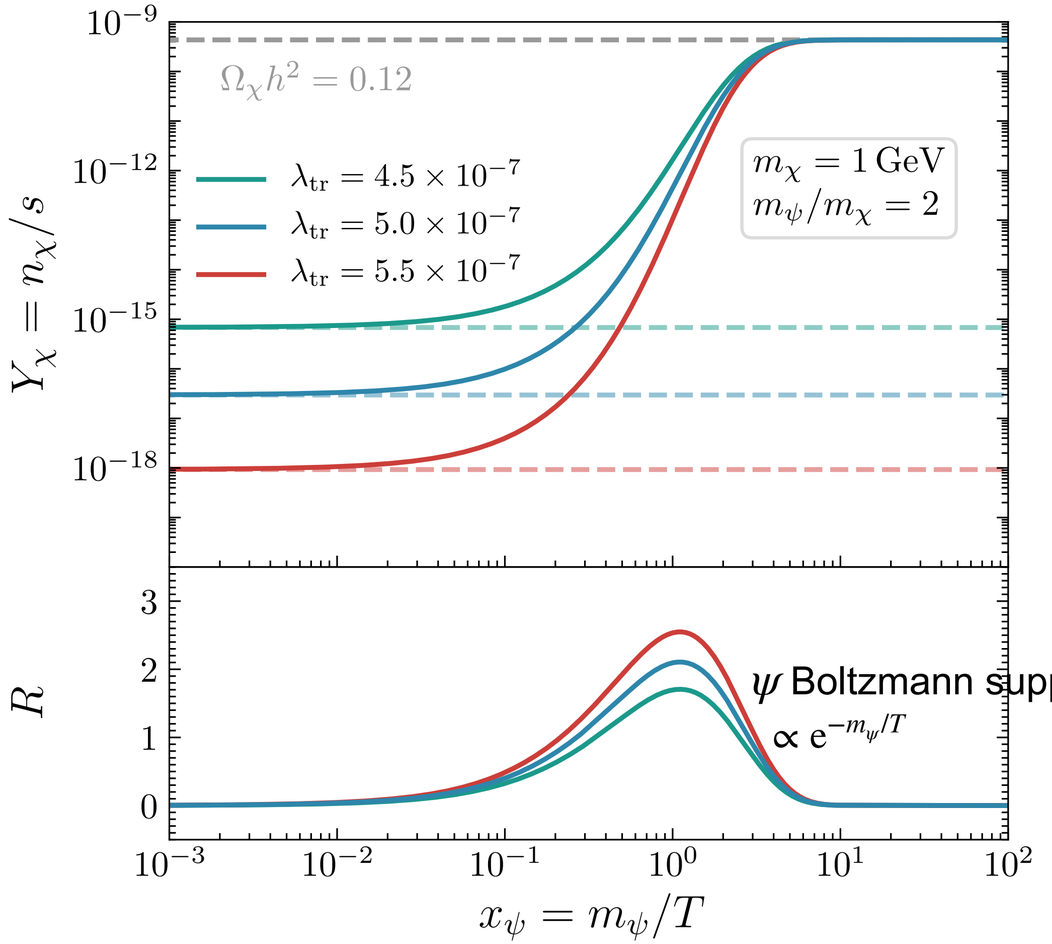
Dark matter from exponential growth



Bringmann, PFD et al. 2103.16572

Dark matter from exponential growth

- $\dot{n}_\chi + 3Hn_\chi = C_{\psi\chi\to\chi\chi} \sim \langle\sigma v\rangle_{\rm tr} n_\psi^{\rm eq} n_\chi$
- $Y_\chi(x_\psi) \equiv n_\chi/s \simeq Y_\chi^0 \exp\left(3\int_{x_\psi^0}^{x_\psi} \frac{{\rm d}x}{x} R(x)\right)$
- $R(x) = \frac{n_\psi^{\rm eq}\langle\sigma v\rangle_{\rm tr}}{3H}$: # of transformations of DM particle per Hubble time
- $\rightarrow$ Phase of exponential production



Bringmann, PFD et al. 2103.16572

Model setup

Necessary conditions

- Generate initial abundance
- Realize hierarchy of (effective) couplings $\lambda_{\text{freeze}-\text{in},\ \psi\psi\to\chi\chi} \ll \lambda_{\text{transformation},\ \psi\chi\to\chi\chi} \ll 1$

Model setup

Necessary conditions

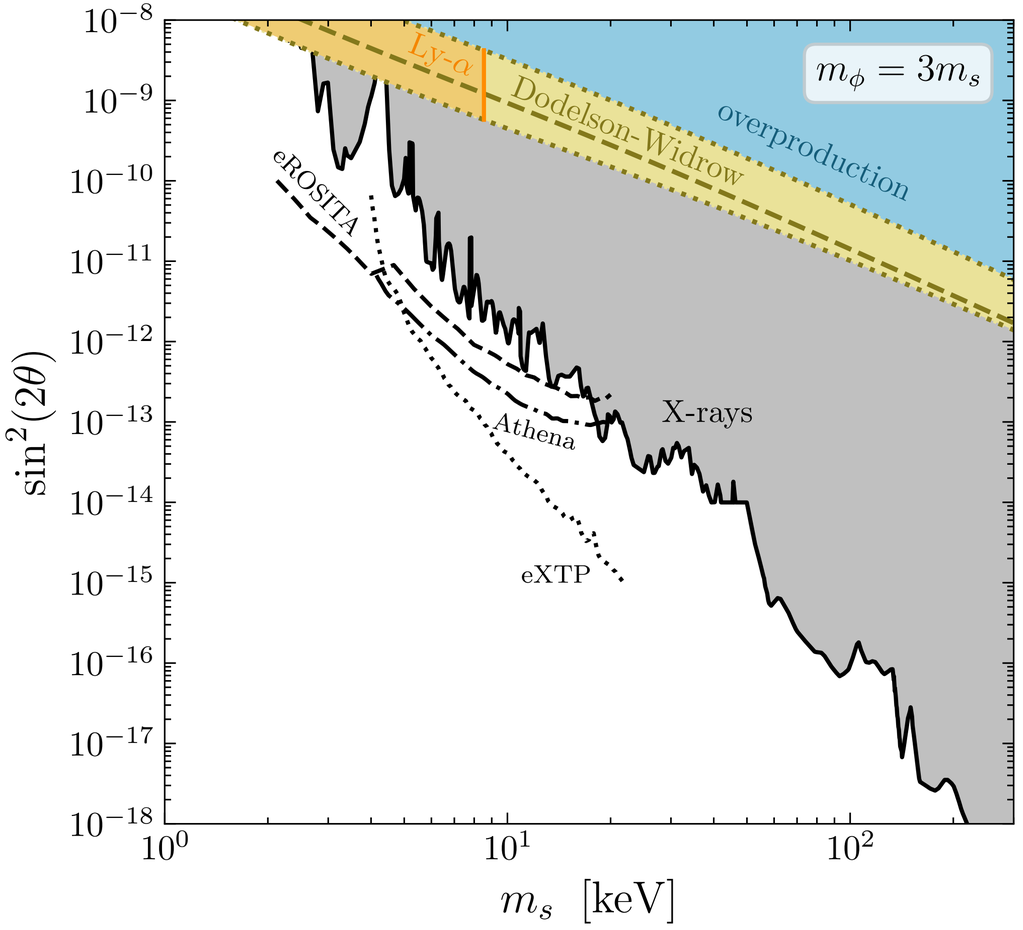
- Generate initial abundance
- Realize hierarchy of (effective) couplings $\lambda_{\text{freeze}-\text{in},\ \psi\psi\to\chi\chi} \ll \lambda_{\text{transformation},\ \psi\chi\to\chi\chi} \ll 1$
  - Two fermions with small mass mixing angle θ, only one (mostly χ) interacts with some mediator ϕ via Yukawa coupling
  - After mass diagonalization:
    - $\bar{\chi}\chi$ vertices $\propto \cos^2\theta \sim 1$
    - $\bar{\psi}\chi$ vertices $\propto \cos\theta \sin\theta \sim \theta$
    - $\bar{\psi}\psi$ vertices $\propto \sin^2\theta \sim \theta^2$
  - Transformation ($\bar{\psi}\chi \to \bar{\chi}\chi$) amplitude $\propto \theta$
  - Freeze-in ($\bar{\psi}\psi \to \bar{\chi}\chi$) amplitude $\propto \theta^2$

Model setup

What if ψ is in the SM?

- Sterile neutrino ($\chi = \nu_s$), mass-mixing with active neutrino ($\psi = \nu_\alpha$)
- Yukawa coupling between mediator ϕ and ν_s in flavor-space generates hierarchy of (eff.) couplings:
- $\mathscr{L}_{\text{int}} \supset \frac{y}{2}\phi\overline{\nu_s^c}\nu_s + \text{h.c.}$

  $\rightarrow \frac{y}{2}\phi\left(\cos^2\theta\,\overline{\nu_s^c}\nu_s - \sin(2\theta)\,\overline{\nu_\alpha}\nu_s + \sin^2\theta\,\overline{\nu_\alpha^c}\nu_\alpha\right) + \text{h.c.}$
- Generally occurs for self-interacting sterile neutrinos

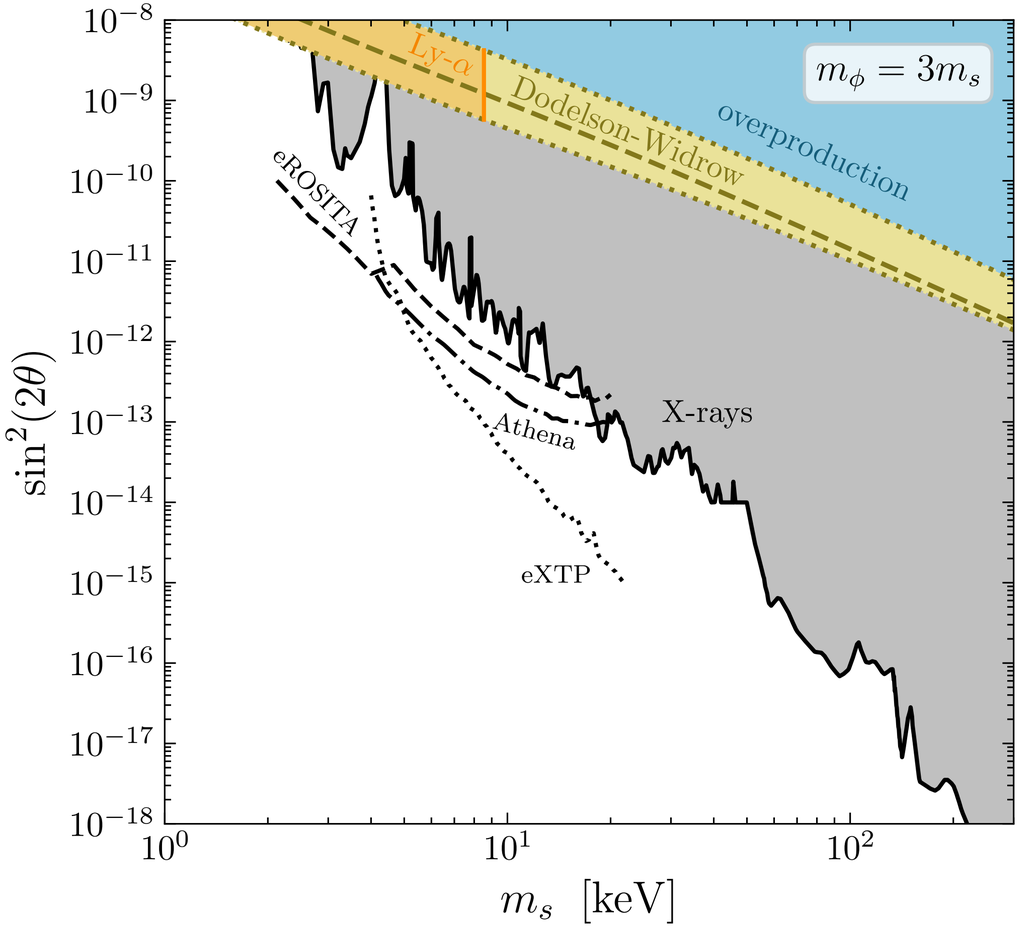


Model setup

What if ψ is in the SM?

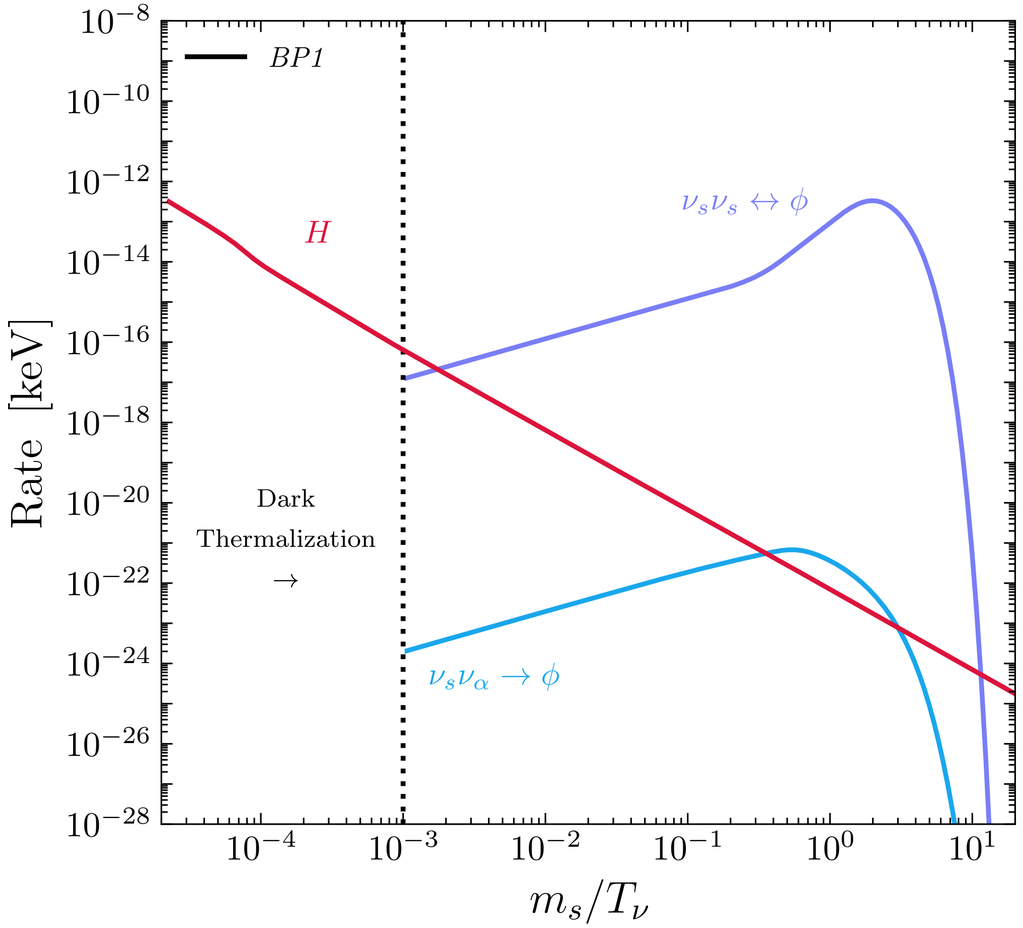
- Sterile neutrino ($\chi = \nu_s$), mass-mixing with active neutrino ($\psi = \nu_\alpha$)
- Yukawa coupling between mediator ϕ and ν_s in flavor-space generates hierarchy of (eff.) couplings:
- $\mathscr{L}_{\text{int}} \supset \frac{y}{2}\phi\overline{\nu_s^c}\nu_s + \text{h.c.}$

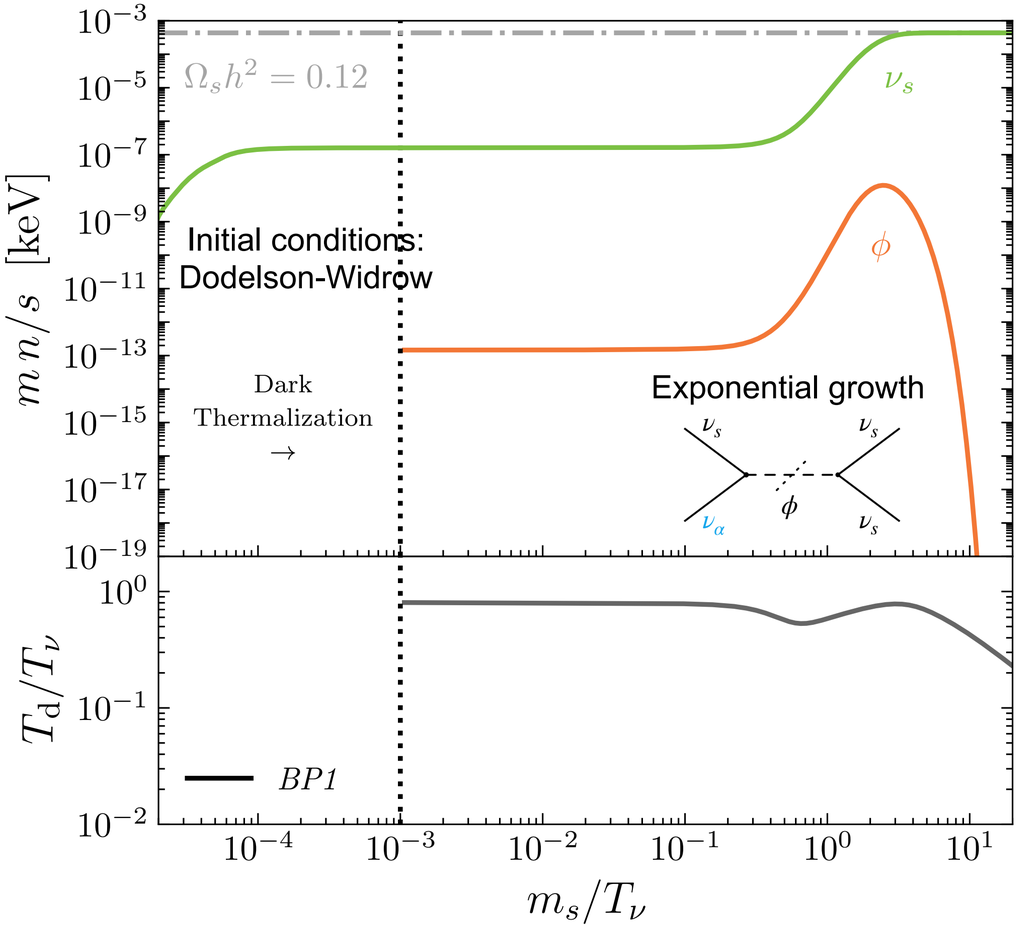
  $\rightarrow \frac{y}{2}\phi\left(\cos^2\theta\,\overline{\nu_s^c}\nu_s - \sin(2\theta)\,\overline{\nu_\alpha}\nu_s + \sin^2\theta\,\overline{\nu_\alpha^c}\nu_\alpha\right) + \text{h.c.}$
- Generally occurs for self-interacting sterile neutrinos
- Initial abundance:
  - Oscillations between active and sterile neutrinos (Dodelson-Widrow mechanism) generates initial abundance of sterile neutrinos!



Evolution

	m_s	m_ϕ	$\sin^2(2\theta)$	y
BP1	12 keV	36 keV	2.5×10^{-13}	1.905×10^{-4}



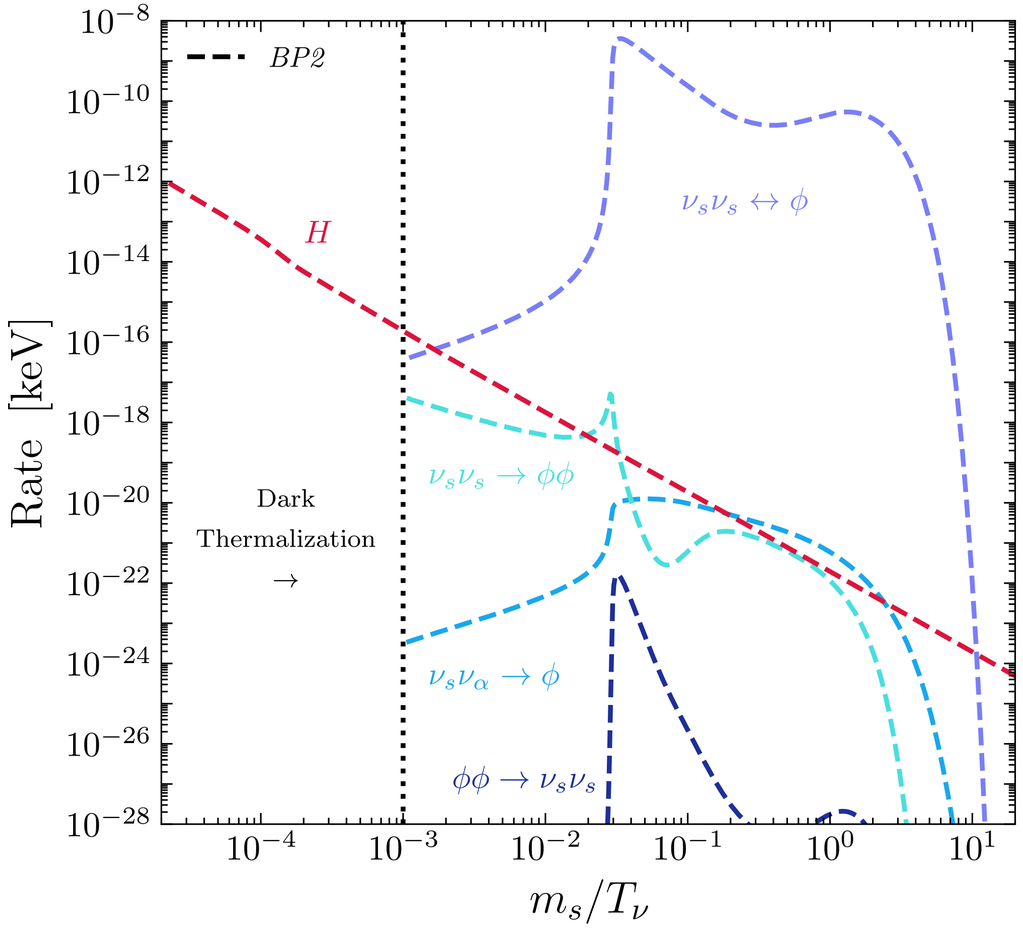


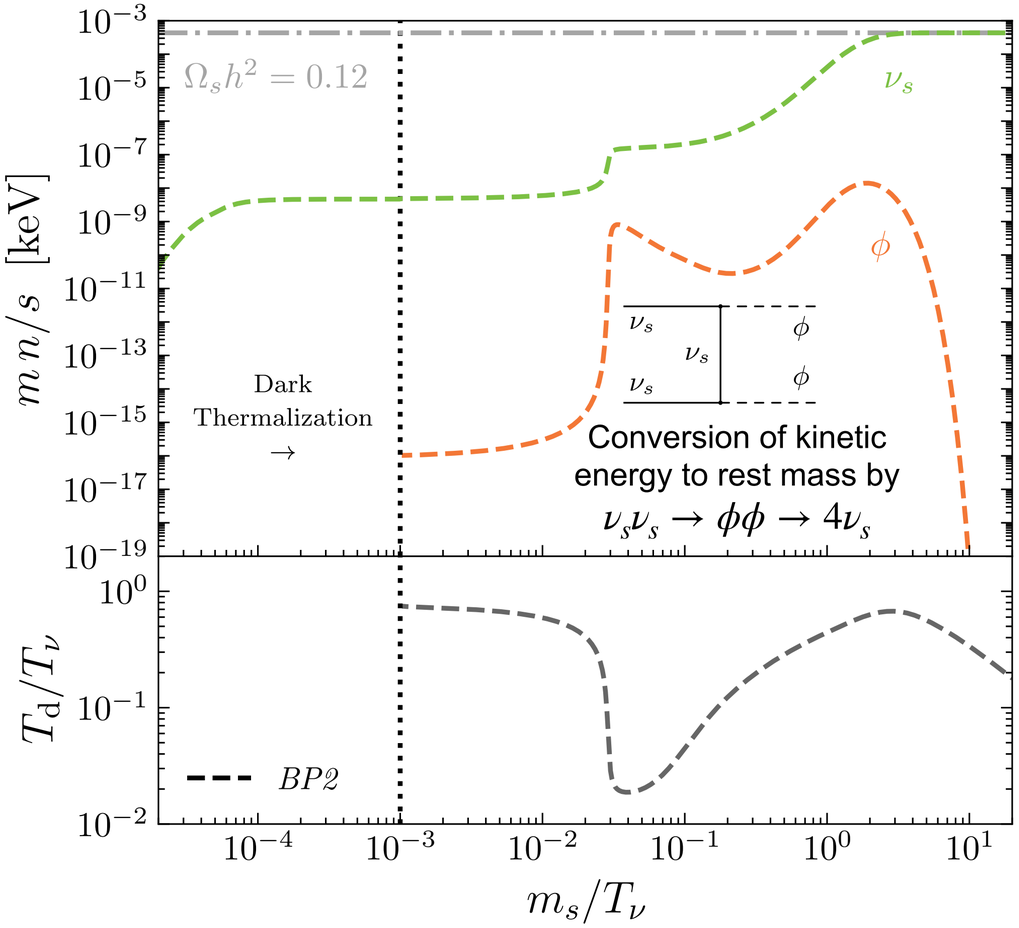
Bringmann, PFD et al. 2206.10630

Evolution

	m_s	m_ϕ	$\sin^2(2\theta)$	y
BP1	12 keV	36 keV	2.5×10^{-13}	1.905×10^{-4}
BP2	20 keV	60 keV	3.0×10^{-15}	1.602×10^{-3}

Smaller $\theta \Rightarrow$ larger $y \Rightarrow$ additional processes



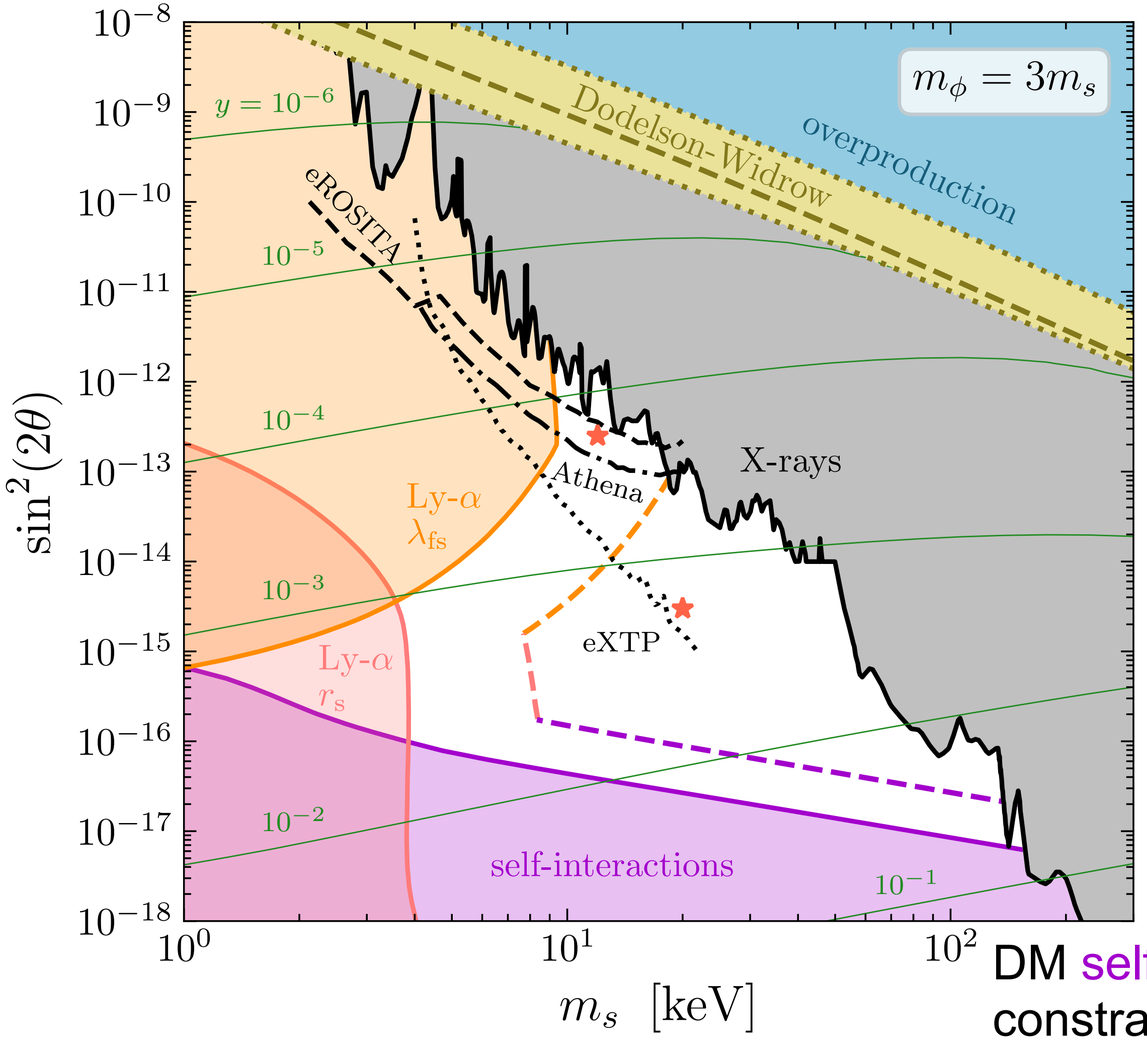


Bringmann, PFD et al. 2206.10630

Parameter space

Lyman-α forest constraints from suppression of small-scale structure:

- DM self-scatterings before kinetic decoupling
  → structures below sound horizon r_s suppressed
- DM free-streaming after kinetic decoupling
  → structures below free-streaming length λ_{fs} suppressed



X-ray constraints from DM decays

DM self-interactions constrained by astrophysical observations at late times

Bringmann, PFD et al. 2206.10630

Conclusions

- Sterile neutrinos excellent DM candidate, but simplest realization excluded
- Endowing sterile neutrinos with self-interactions can lead to exponential growth of abundance
- Allows for DM production at mixing angles much smaller than in Dodelson-Widrow scenario
- Simplest allowed model for sterile neutrino DM production as Dodelson-Widrow is excluded
- Much of parameter space is testable in the foreseeable future

Thank you!