Dark Matter from Exponential Growth

Originally proposed as Pandemic Dark Matter

Based on Phys. Rev. Lett. 127 (2021) 191802 and 2206.10630

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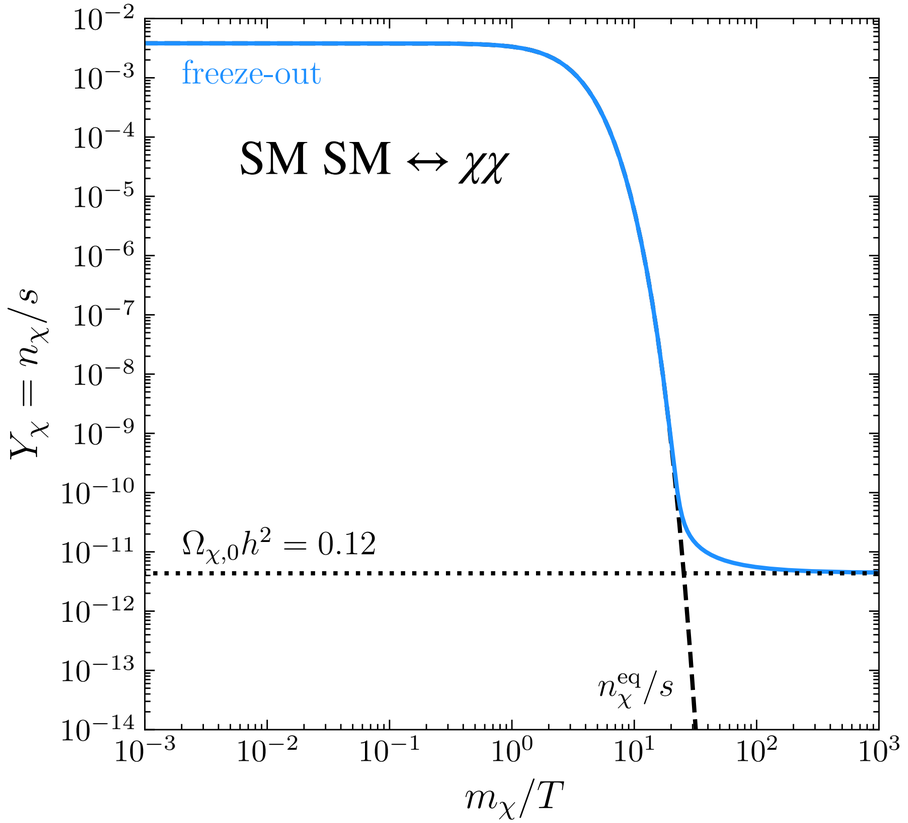
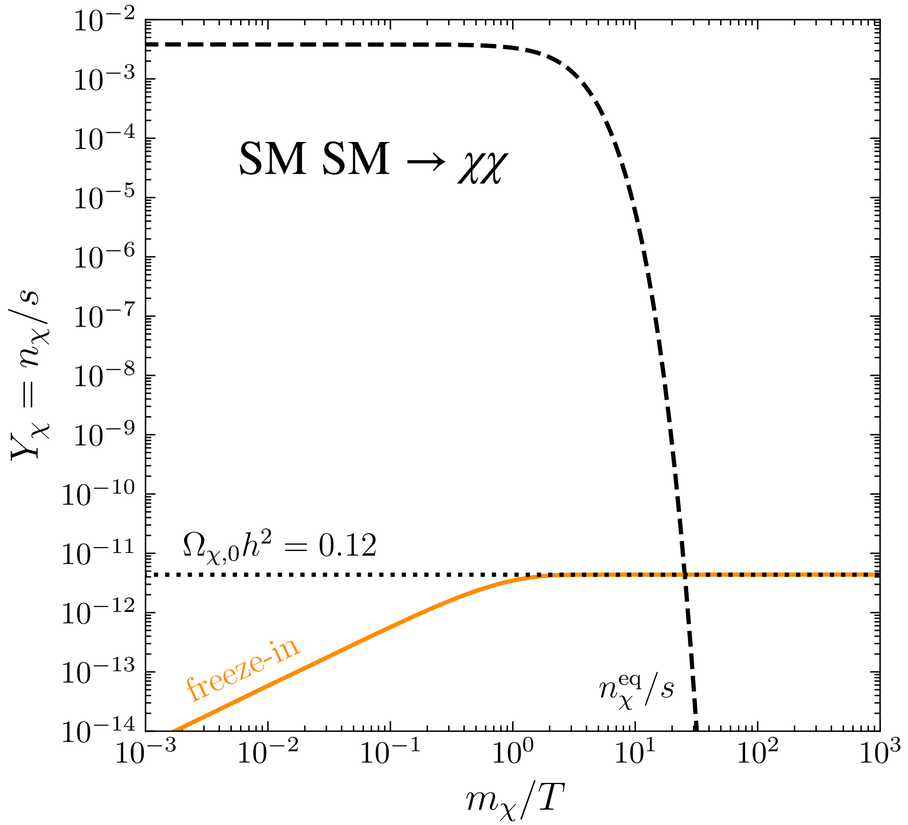
In collaboration with T. Bringmann, M. Hufnagel, J. Kersten, J. T. Ruderman, and K. Schmidt-Hoberg

IDM 2022
18 July 2022

Thermal



Non-Thermal



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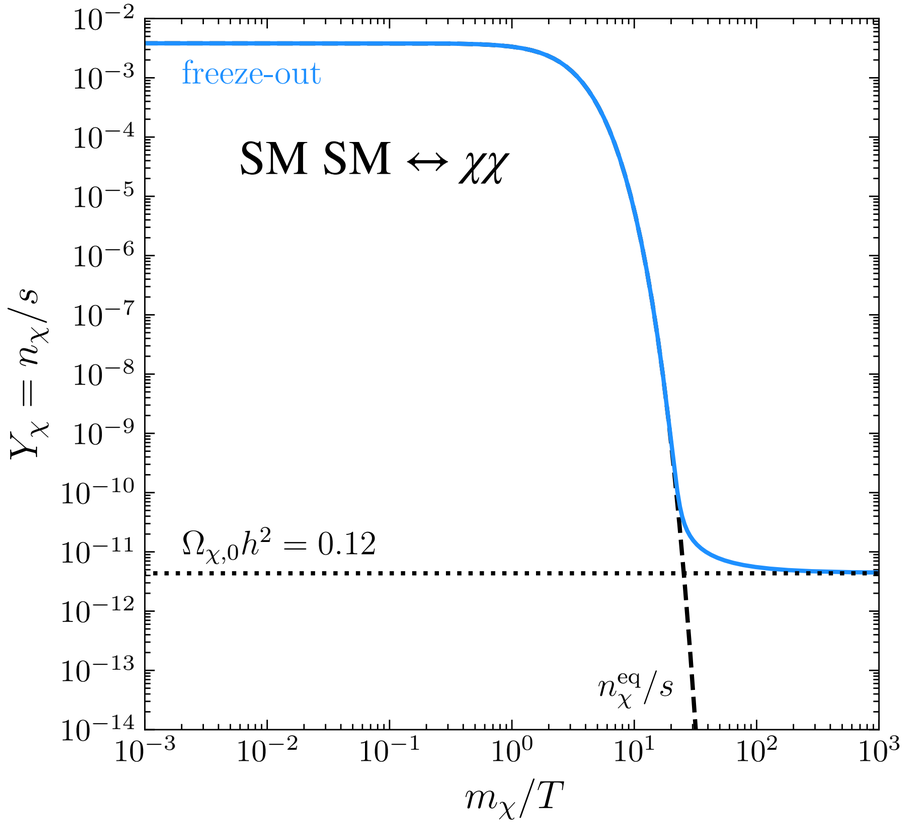
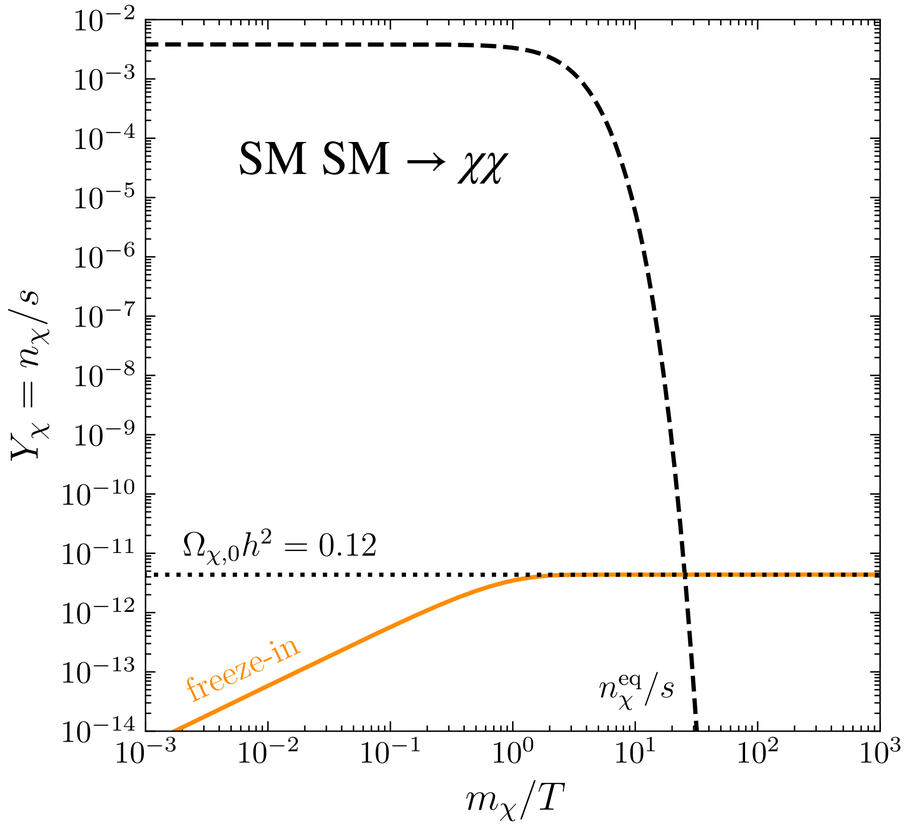


Many variants of freeze-out:

- Semi-annihilations
- Hidden sector
- Cannibal DM
- Forbidden DM
- …

Non-Thermal



Less variants for freeze-in

Dark Matter from Exponential Growth

Bringmann, PFD et al. 2103.16572

Hryczuk, Laletin 2104.05684

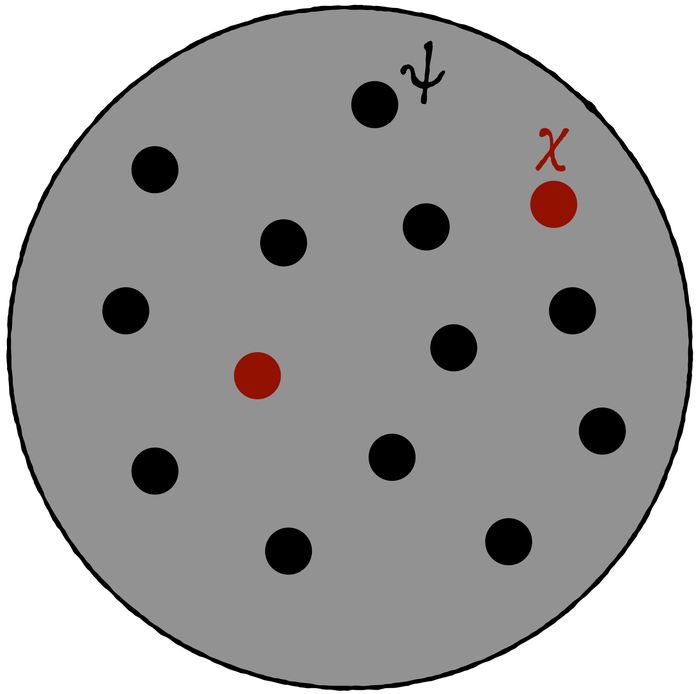
Very interesting application to sterile neutrinos

Bringmann, PFD et al. 2206.10630

Outline

- Production by transformation
- Evolution of the DM abundance
- Phase diagram
- A new life for sterile neutrino DM after the pandemic (exponential growth)

Production by transformation



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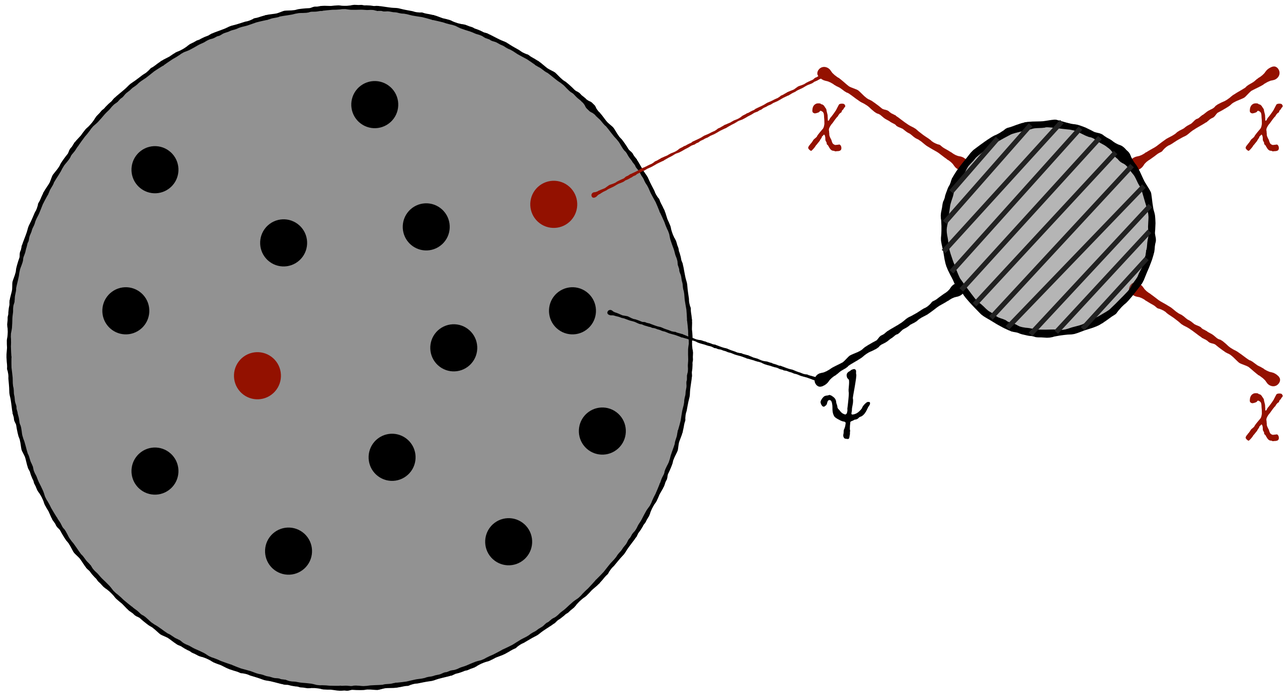
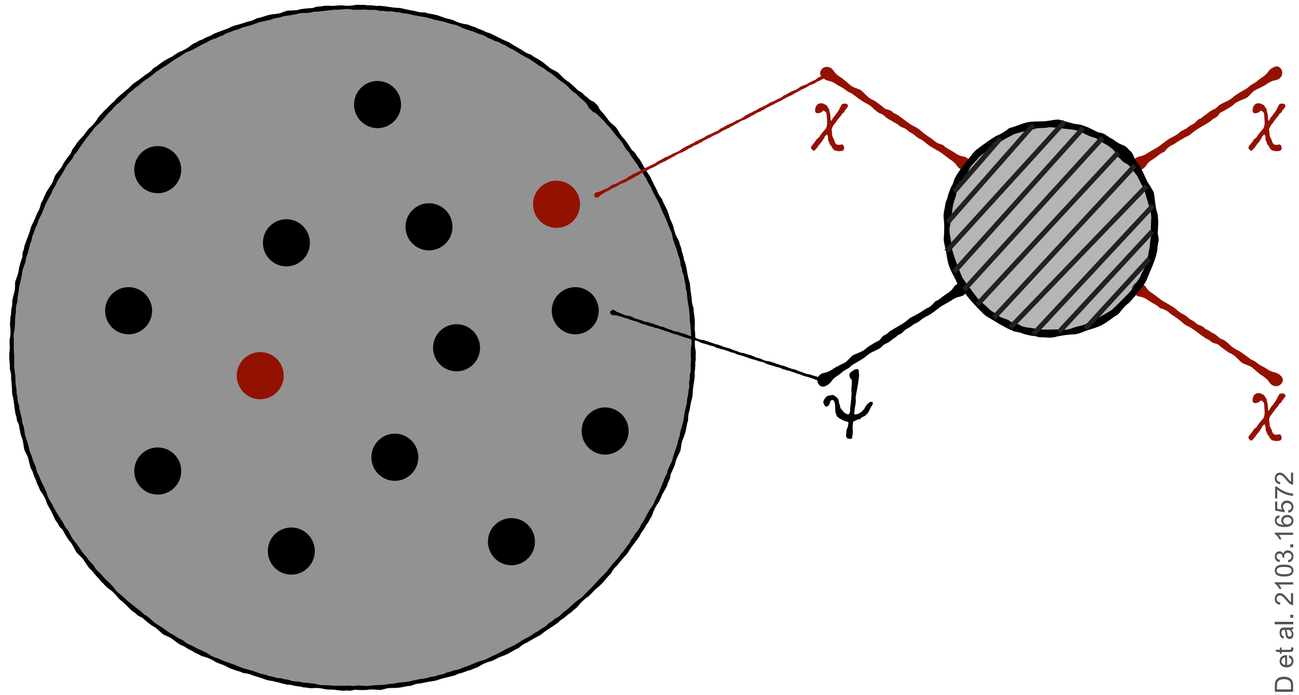


Bringmann, PFD et al. 2103.16572

Production by transformation

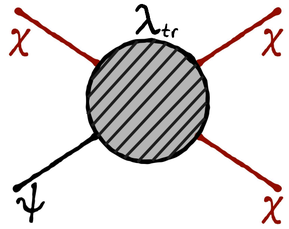
- $\dot{n}_\chi + 3Hn_\chi = \langle\sigma v\rangle_{\rm tr}\, n_\psi^{\rm eq} n_\chi$
- $Y_\chi(x_\psi) \equiv n_\chi/s \simeq Y_\chi^0 \exp\left(3\int_{x_\psi^0}^{x_\psi} \frac{{\rm d}x}{x} R(x)\right)$
- $R(x) = \frac{n_\psi^{\rm eq}\langle\sigma v\rangle_{\rm tr}}{3H}$: # of transformations of DM particle per Hubble time
- $\rightarrow$ Phase of exponential production
- Shutoff by kinematical or Boltzmann suppression
- First: constant matrix element for simplicity



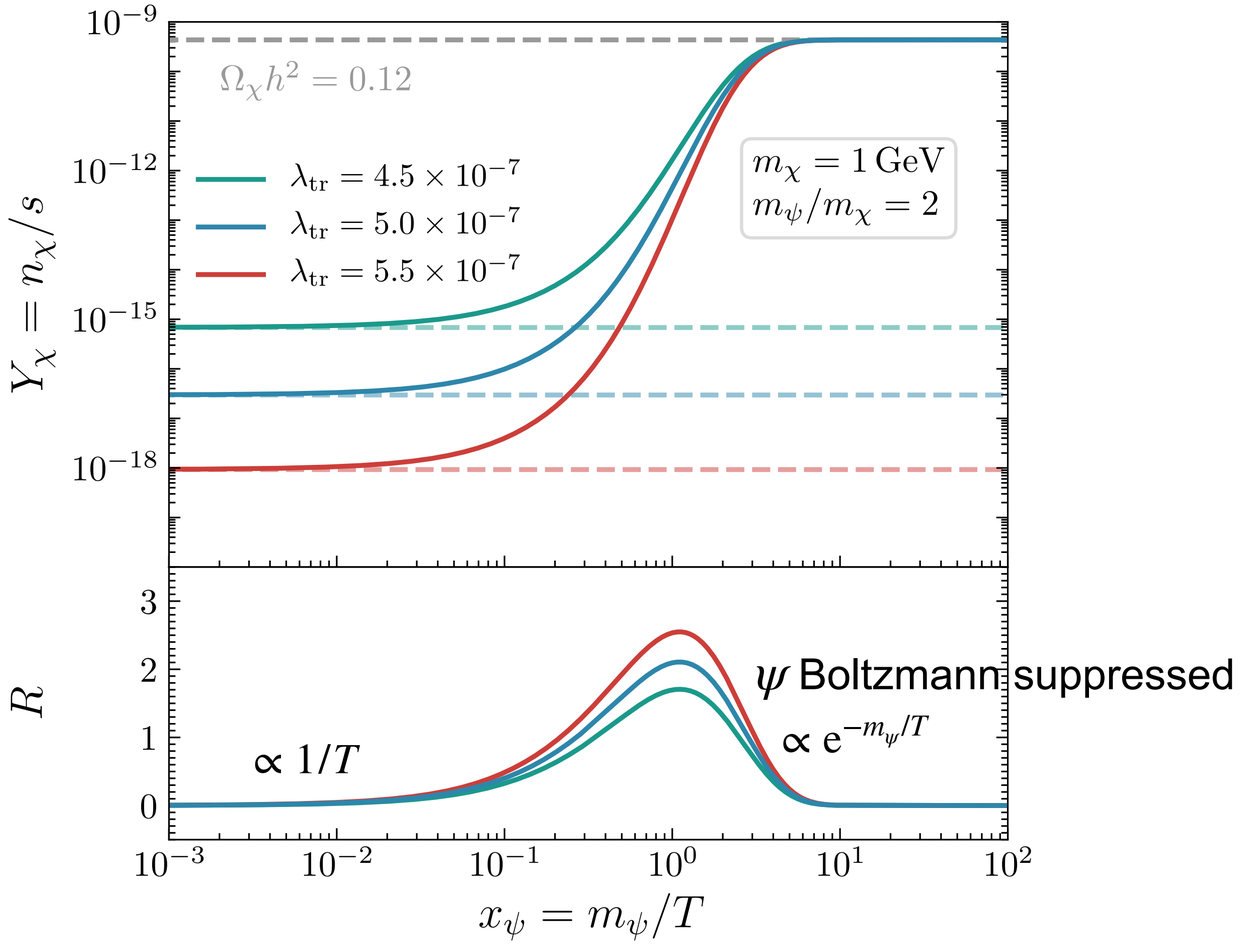
Bringmann, PFD et al. 2103.16572

Evolution of DM abundance

Fixed initial abundance



$$\dot{n}_\chi + 3Hn_\chi = \langle\sigma v\rangle_{\rm tr}\, n_\psi^{\rm eq} n_\chi$$



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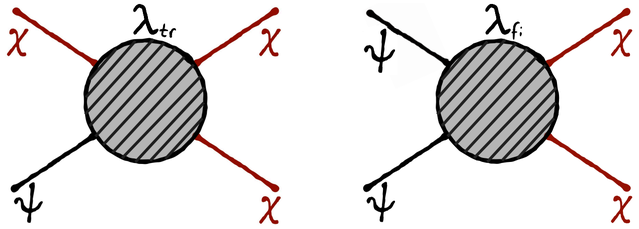
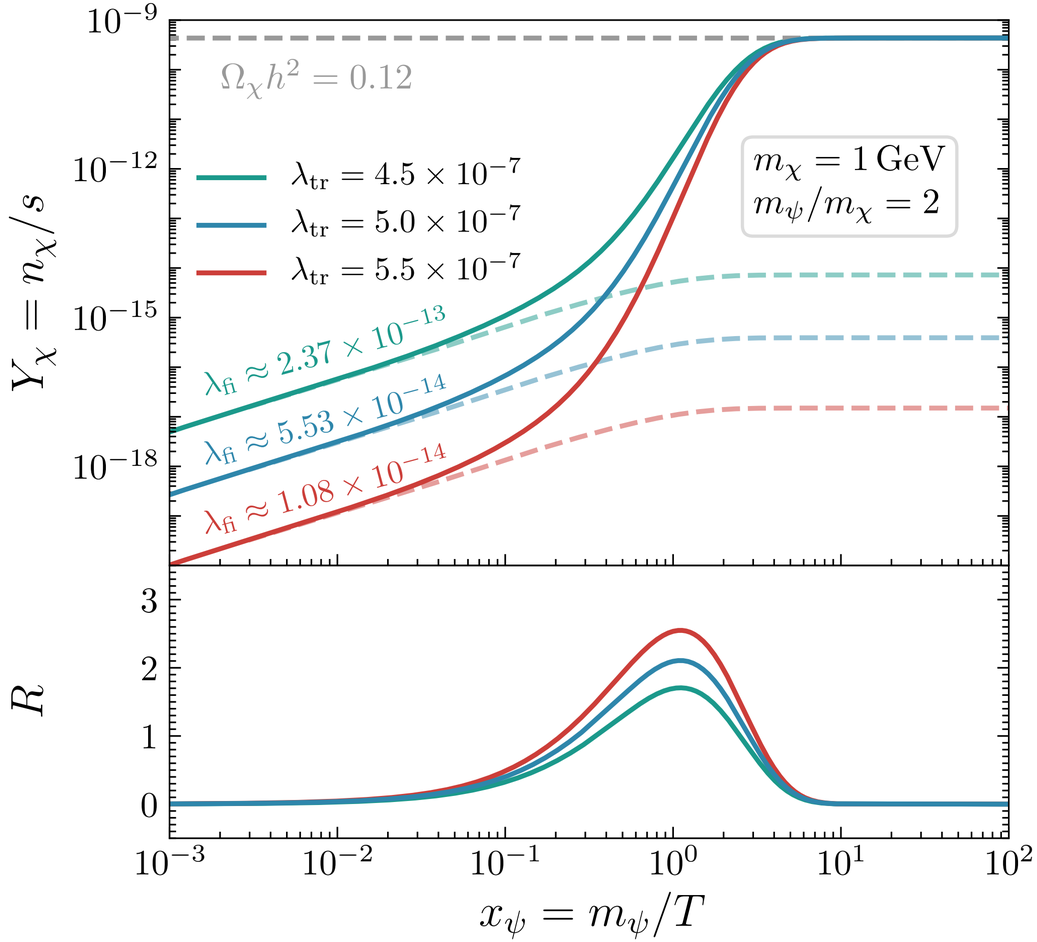
Evolution of DM abundance

Initial abundance from freeze-in



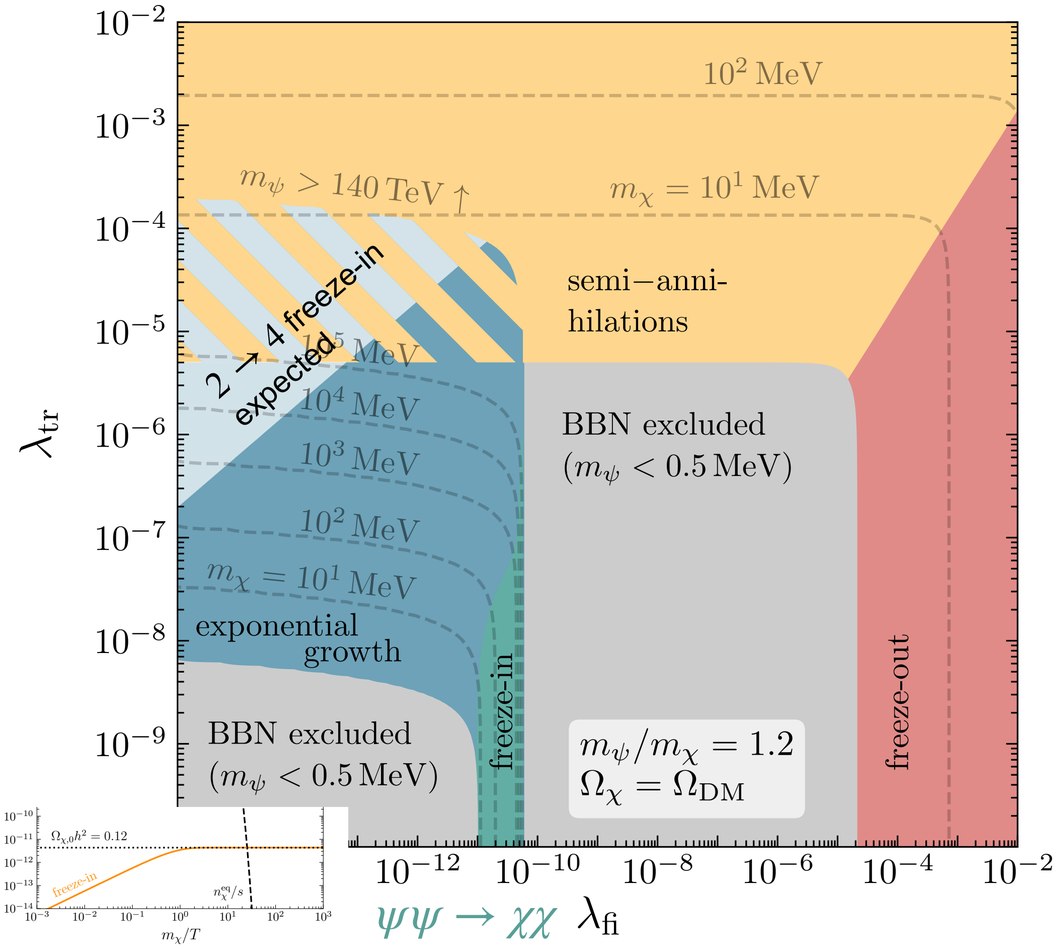
$$\dot{n}_\chi + 3Hn_\chi = \langle\sigma v\rangle_{\rm tr}\, n_\psi^{\rm eq} n_\chi + \langle\sigma v\rangle_{\rm fi}\, (n_\psi^{\rm eq})^2$$



Bringmann, PFD et al. 2103.16572

Phase diagram

$$\dot{n}_\chi + 3Hn_\chi = \langle\sigma v\rangle_{\rm fi}\,[(n_\psi^{\rm eq})^2 \quad]$$



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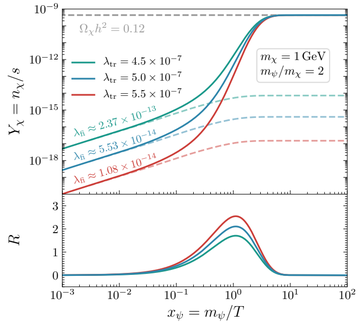
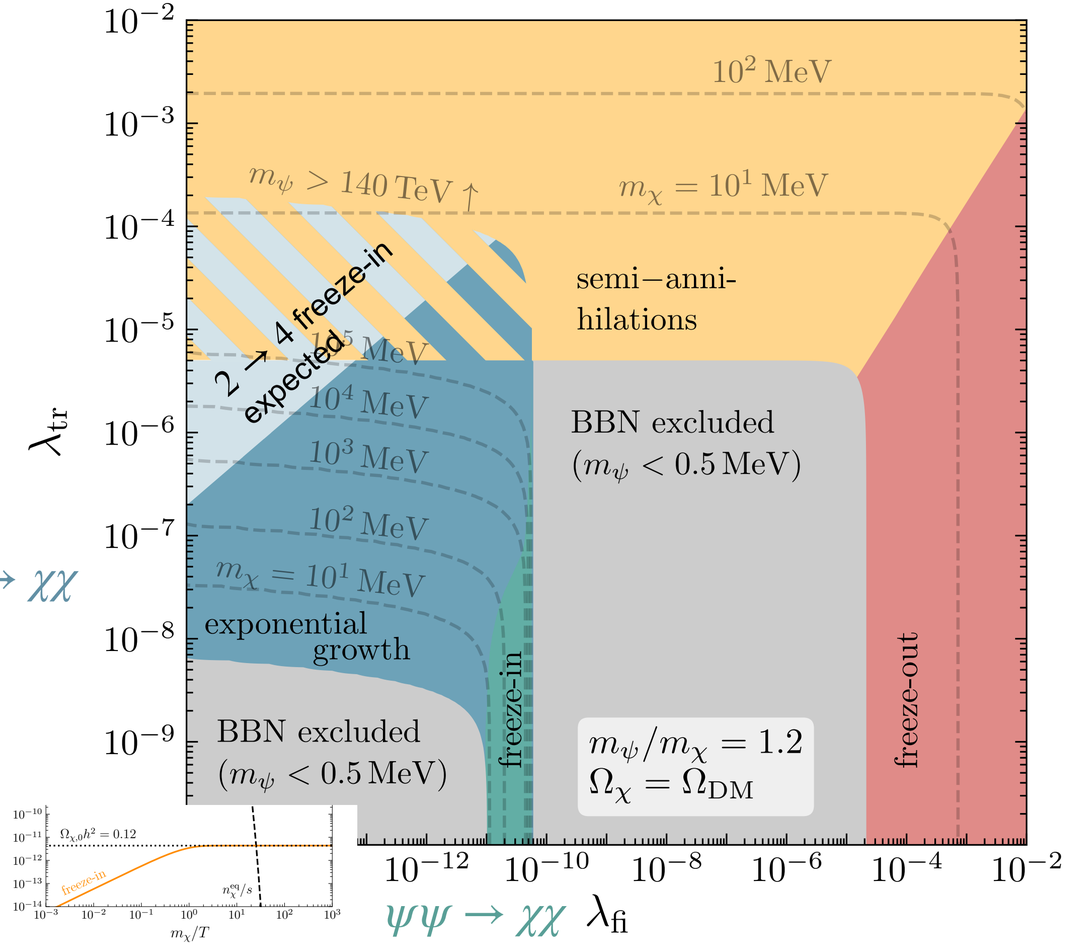


$\chi\psi \to \chi\chi$

Generally: $\lambda_{\rm fi} \ll \lambda_{\rm tr}$



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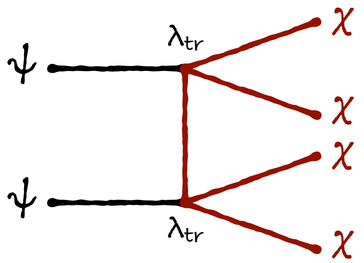

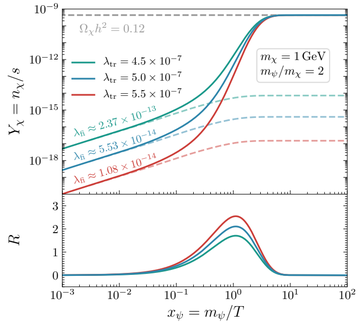

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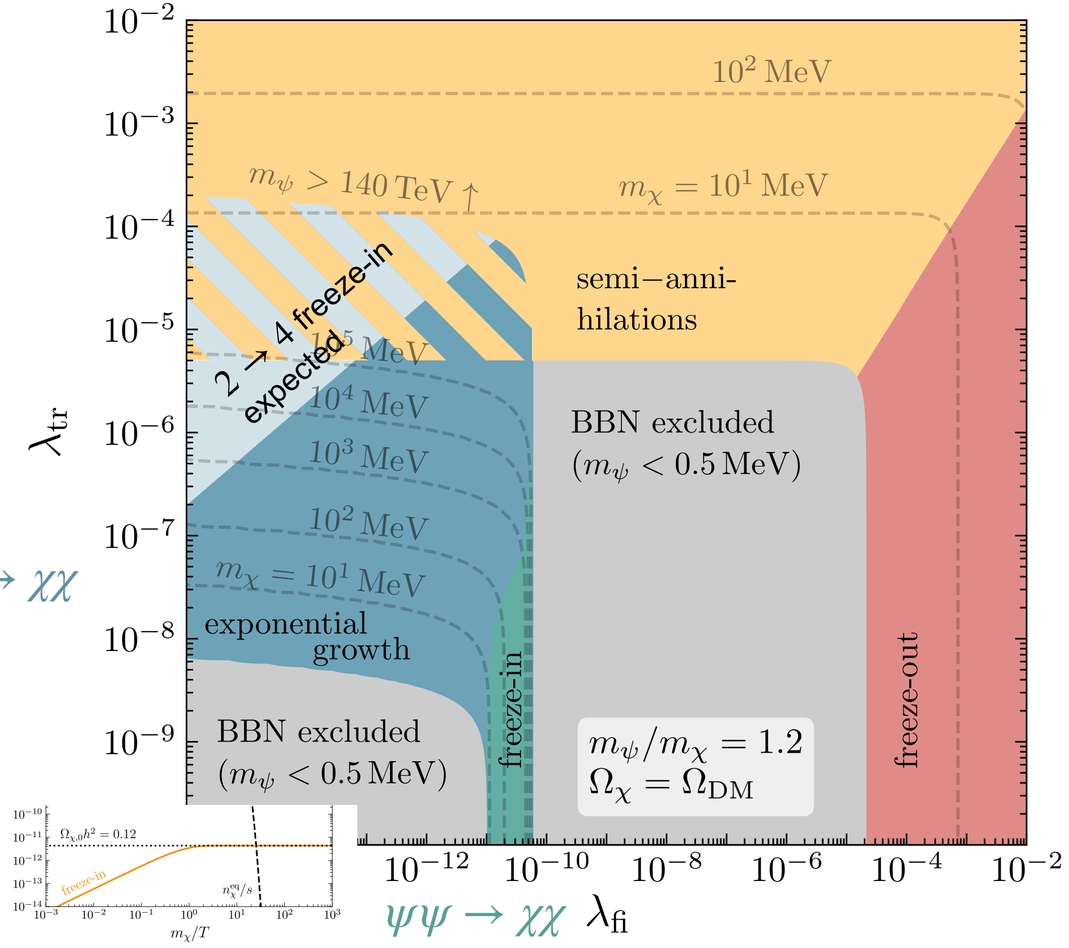
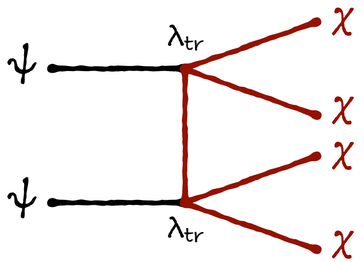


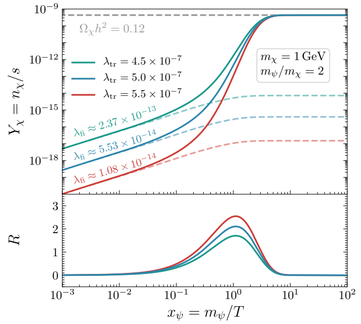
Bringmann, PFD et al. 2103.16572

Phase diagram

$$\dot{n}_\chi + 3Hn_\chi = \langle\sigma v\rangle_{\rm tr}\,[n_\psi^{\rm eq} n_\chi - n_\chi^2 n_\psi^{\rm eq}/n_\chi^{\rm eq}] + \langle\sigma v\rangle_{\rm fi}\,[(n_\psi^{\rm eq})^2 - (n_\chi n_\psi^{\rm eq}/n_\chi^{\rm eq})^2]$$

$\chi\psi \leftrightarrow \chi\chi$





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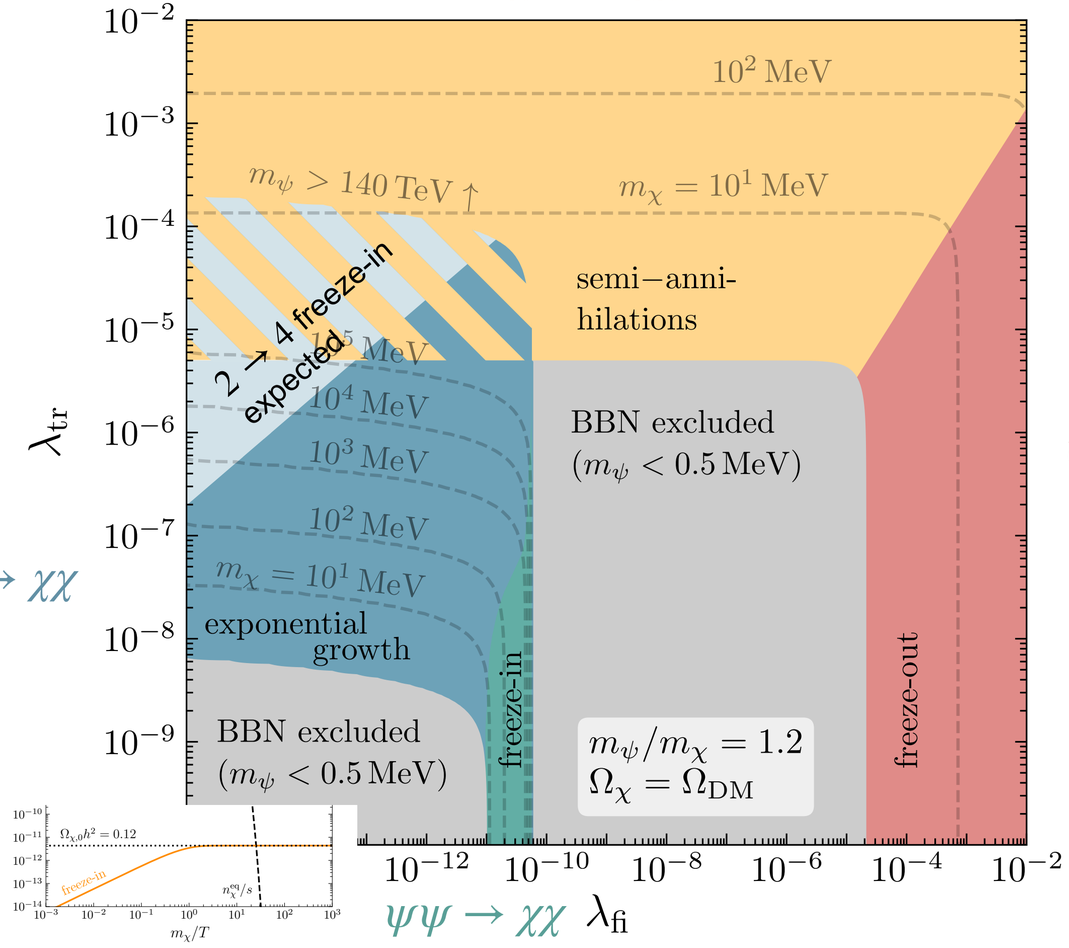

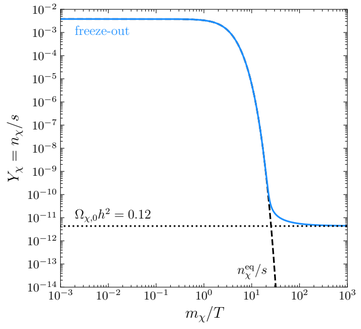

$\psi\psi \leftrightarrow \chi\chi$

Generally: $\lambda_{\rm fi} \ll \lambda_{\rm tr}$

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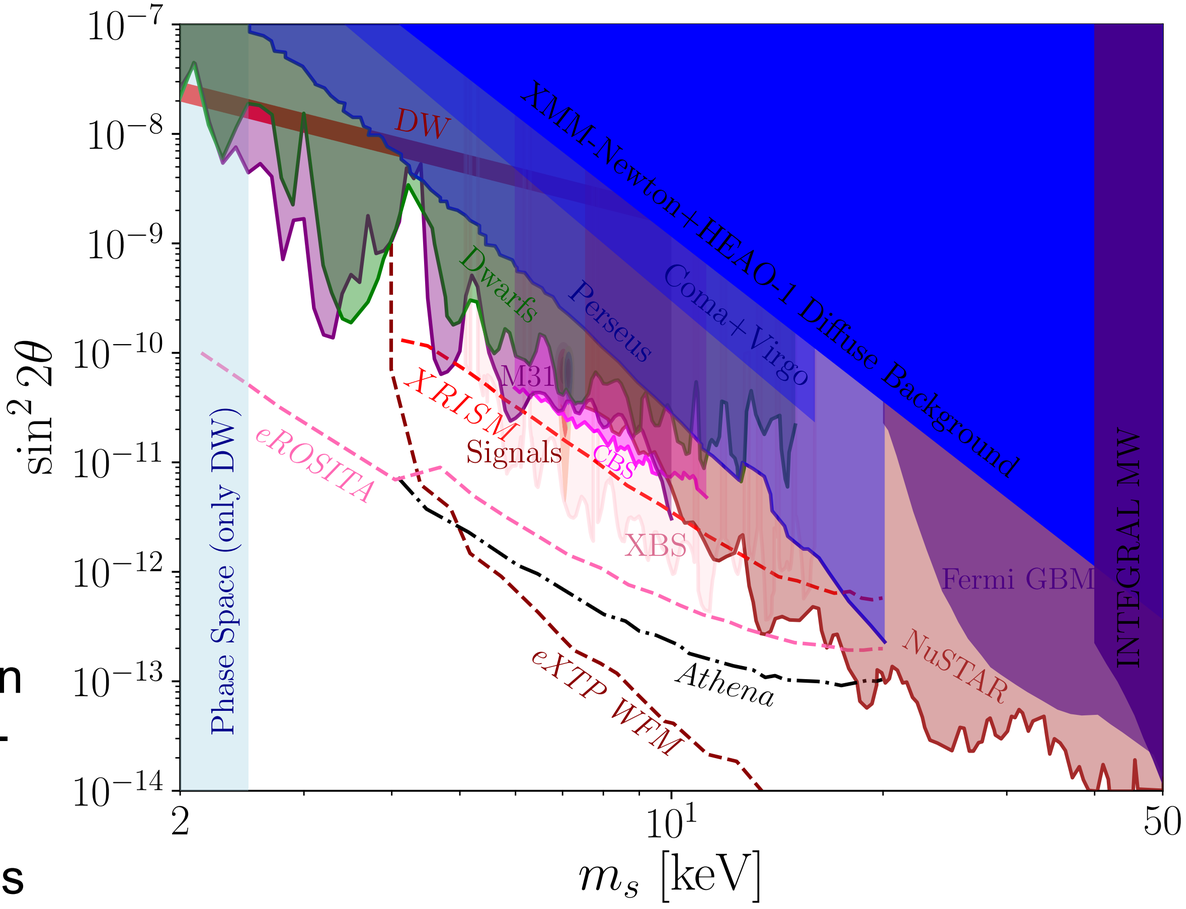
Coupling hierarchy through mass mixing

- Convenient way to realize $\lambda_{\mathrm{fi}} \ll \lambda_{\mathrm{tr}}$: Two fermions with tiny 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 amplitude $\propto \theta$
- Freeze-in amplitude $\propto \theta^2$

A new life for sterile neutrino DM after exp. growth

- What if ψ further 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:
- $\mathscr{L}_{\text{int}} \supset \frac{y}{2}\phi\overline{\nu_s^c}\nu_s + \text{h.c.}$

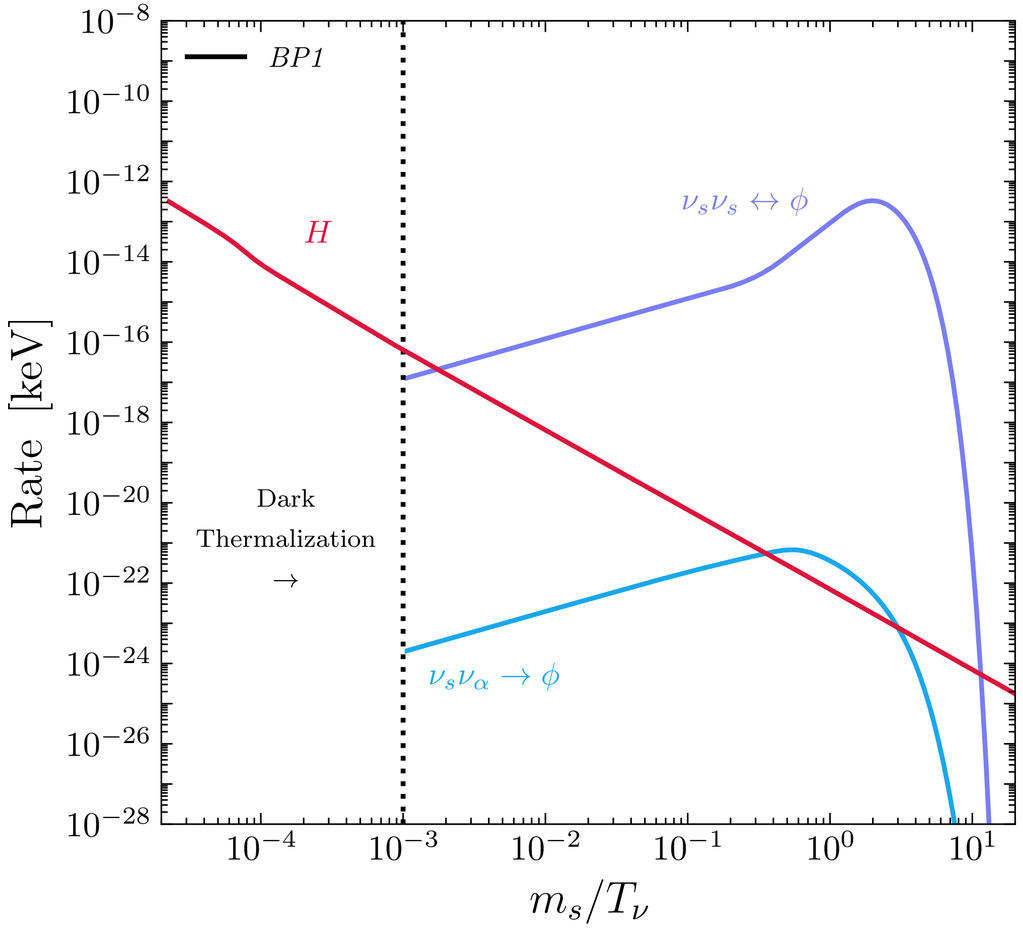
  $\rightarrow \frac{y}{2}\phi\left(\cos^2\theta\overline{\nu_s^c}\nu_s - \sin(2\theta)\overline{\nu_\alpha}\nu_s + \sin^2\theta\overline{\nu_\alpha^c}\nu_\alpha\right) + \text{h.c.}$
- Allows for sterile neutrino DM at θ much smaller than Dodelson-Widrow mechanism (production by active-sterile oscillations) in a very simple model
- Generally present for self-interacting sterile neutrinos

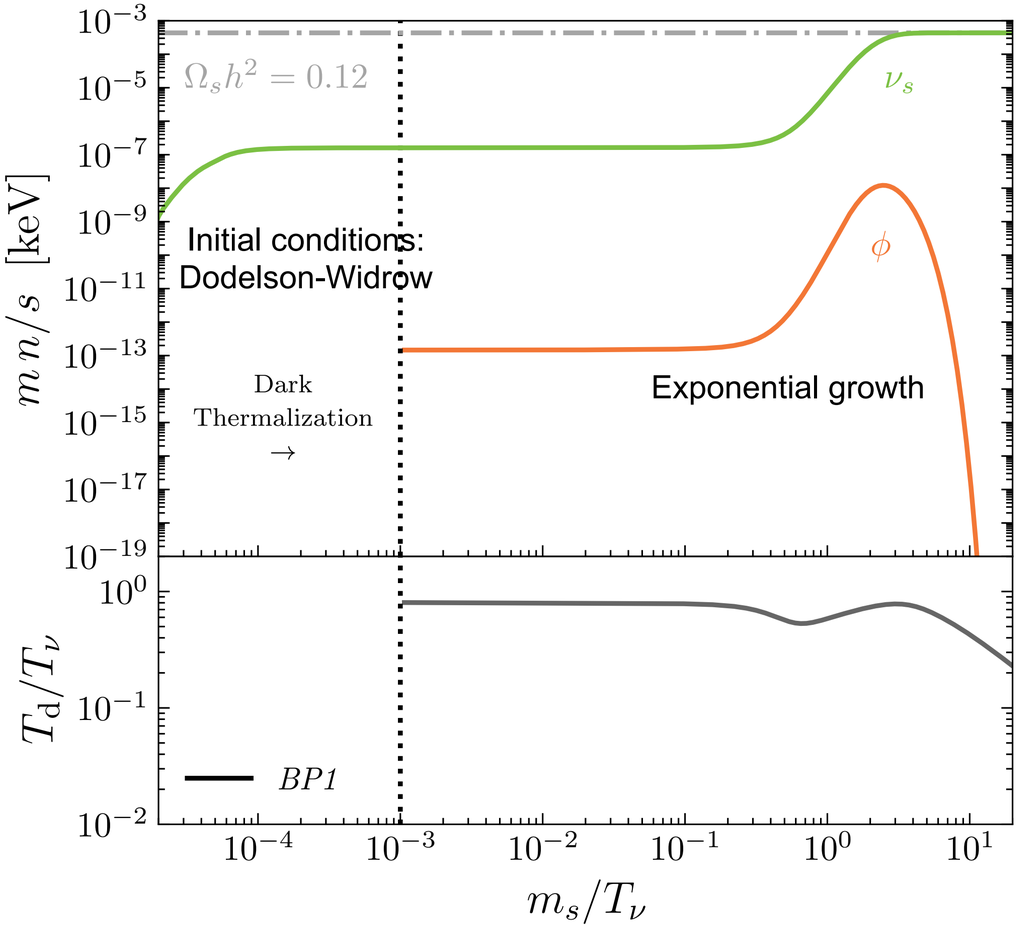


Abazajian al. 2203.07377

Evolution

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



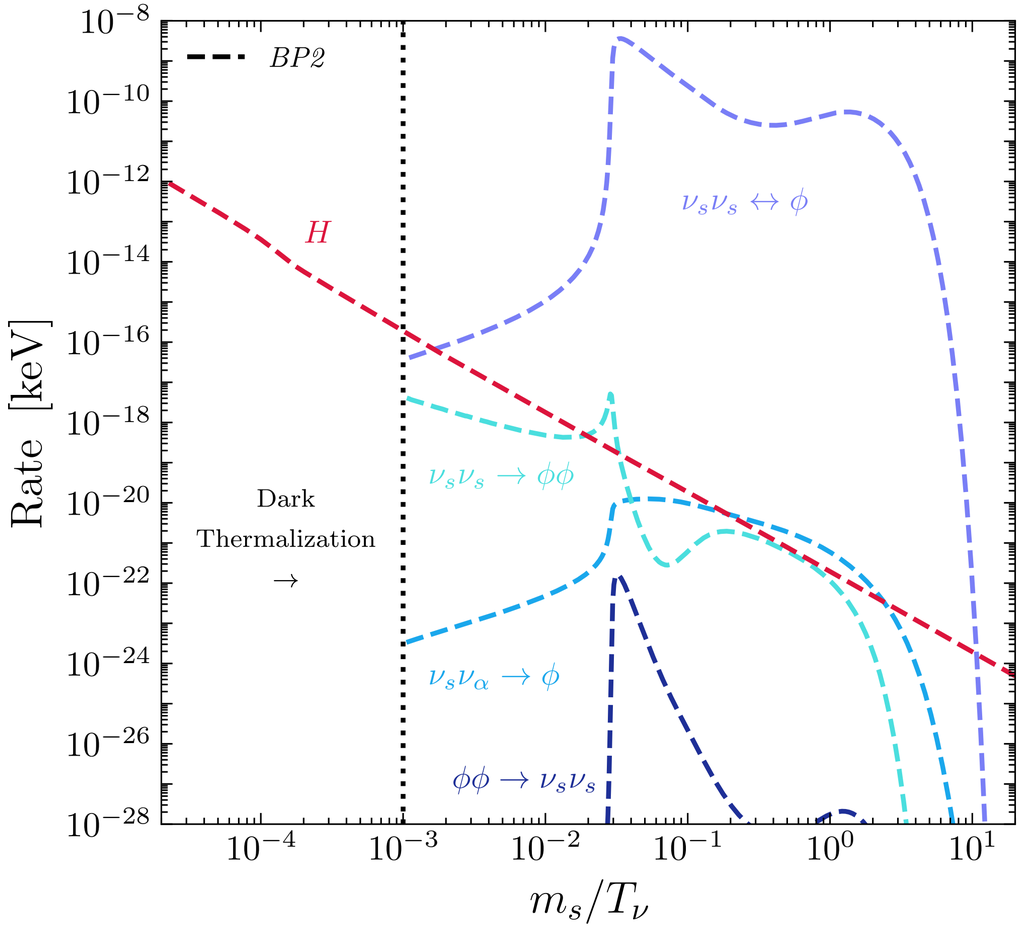


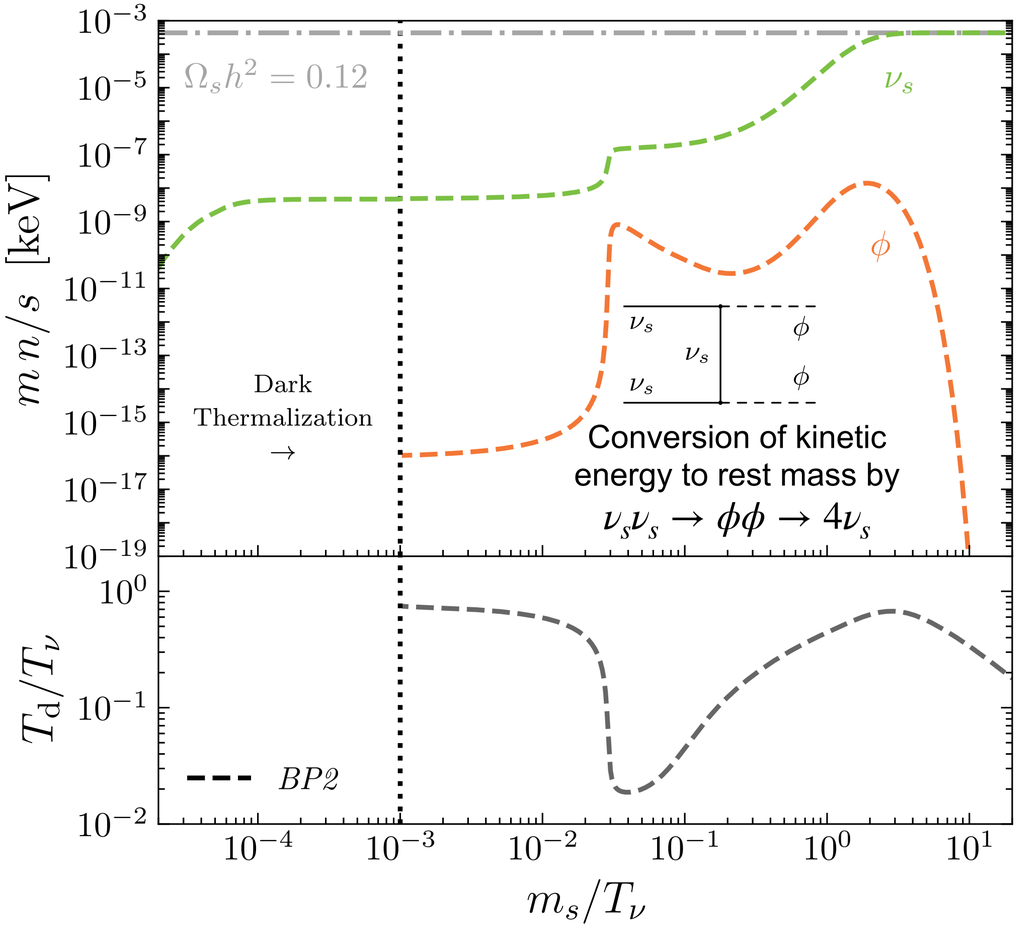
Bringmann, PFD et al. 2206.10630

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





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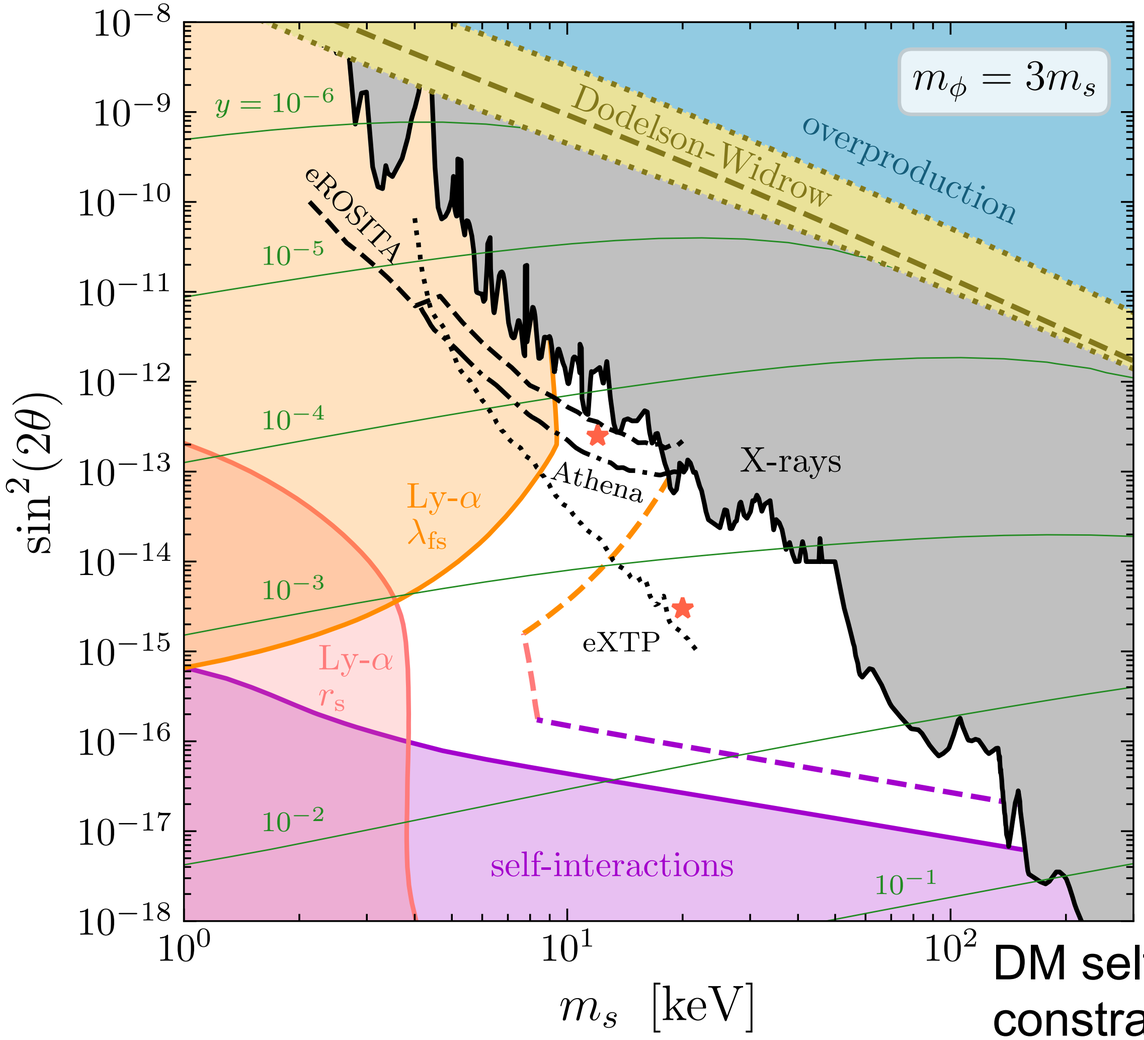
Parameter space

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

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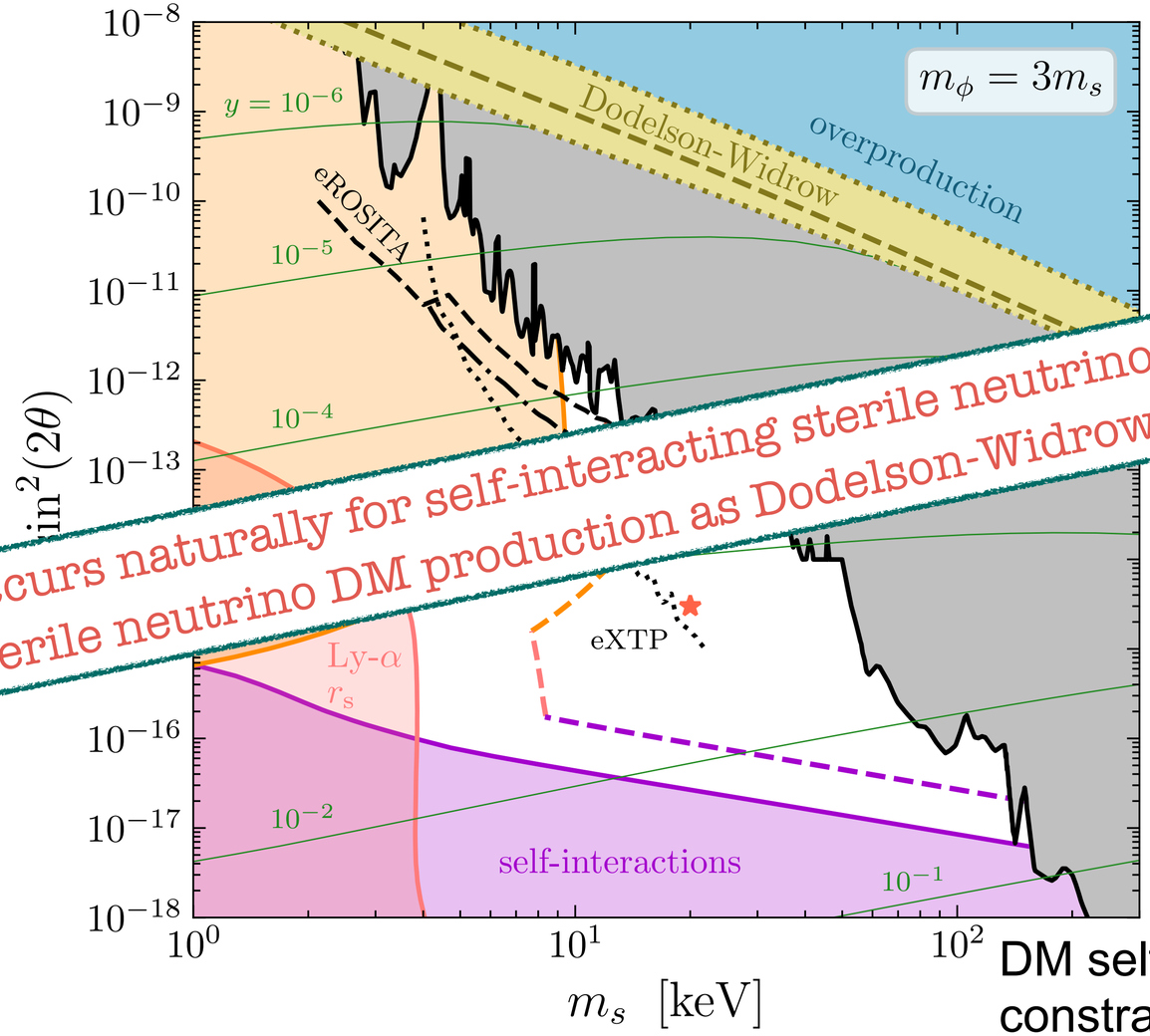


Simplest model for sterile neutrino DM production as Dodelson-Widrow scenario is excluded!

Occurs naturally for self-interacting sterile neutrinos!

X-ray constraints from DM decays

DM self-interactions constrained by astrophysical observations at late times

Bringmann, PFD et al. 2206.10630

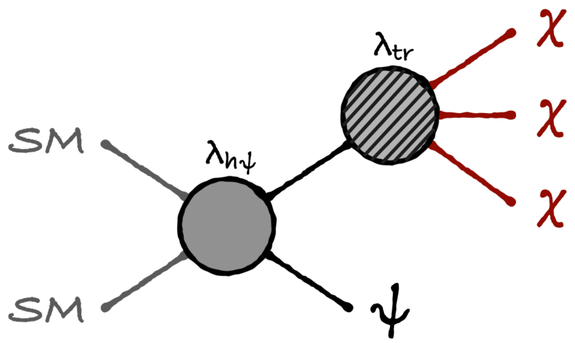
Conclusions

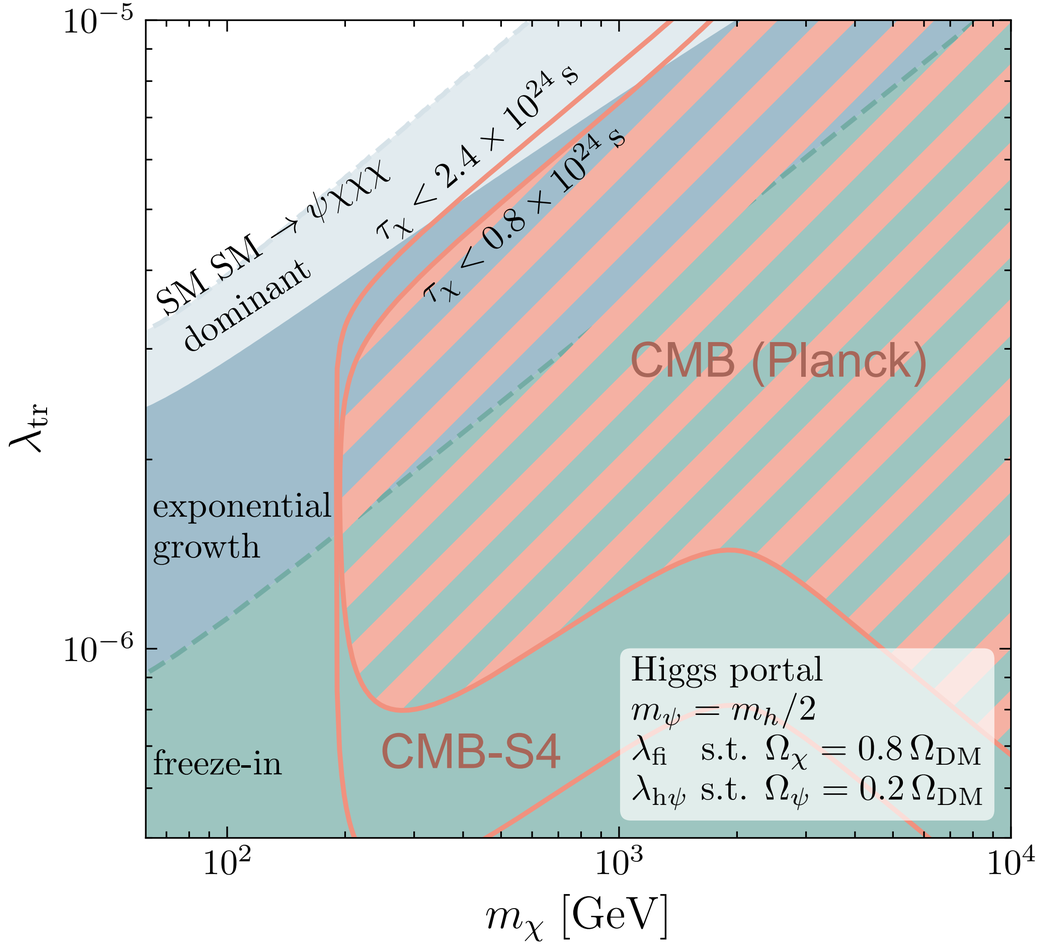
- New non-thermal DM production mechanism involving exponential growth
- Complements freeze-in and freeze-out scenarios
- Interesting phenomenological consequences
- A new life for sterile neutrino DM after exponential growth
  - Exponential growth regime occurs naturally for self-interacting sterile neutrinos
  - Allows for mixing angle 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

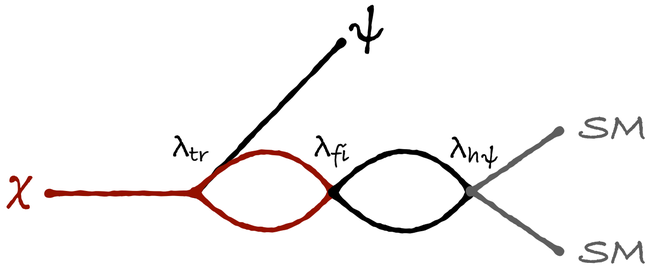
Thank you!

Phenomenological consequences

Higgs portal $\lambda_{h\psi}|H|^2\psi^2/2$







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