Dark Matter from Exponential Growth: Pandemic Dark Matter

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

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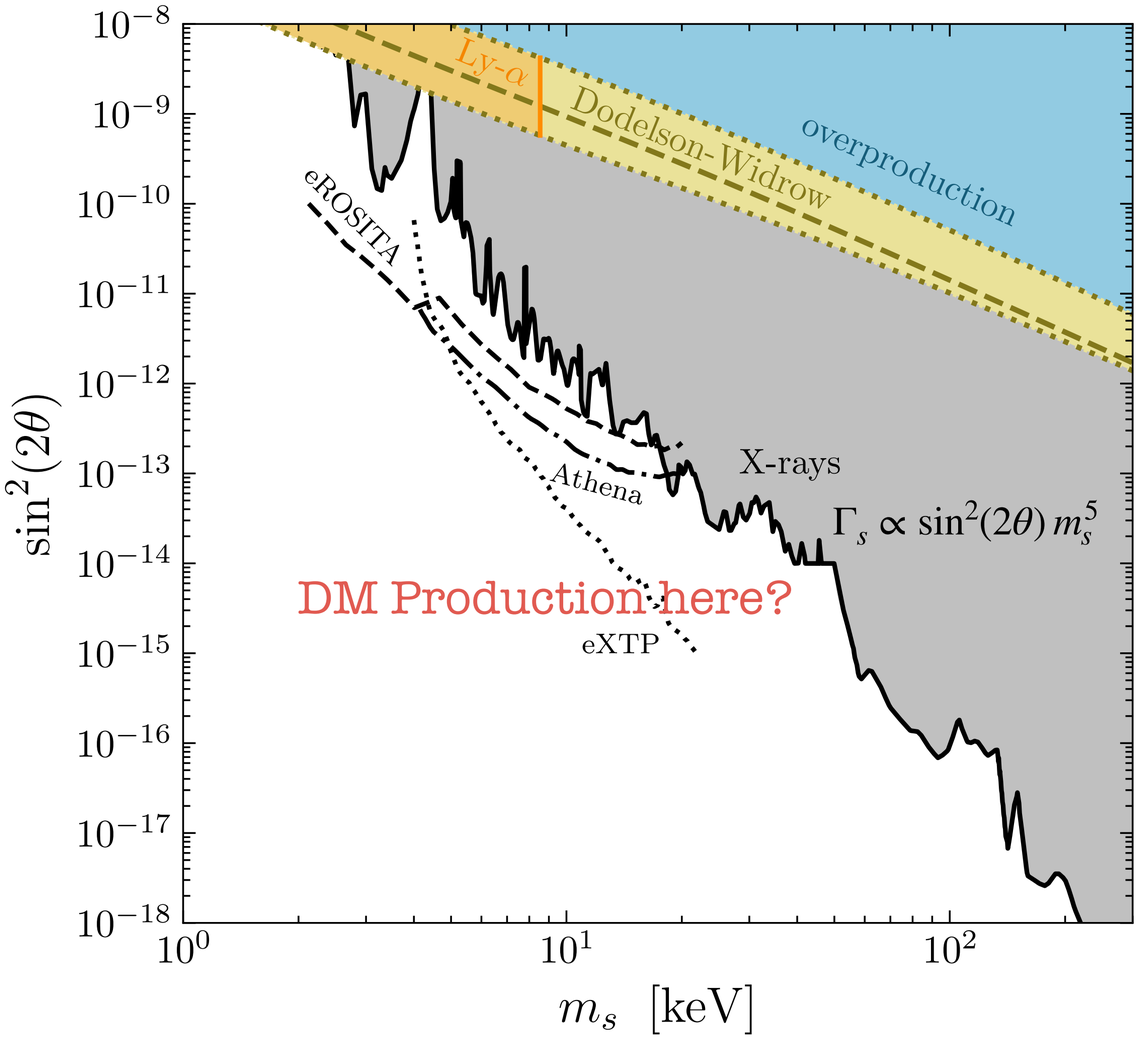
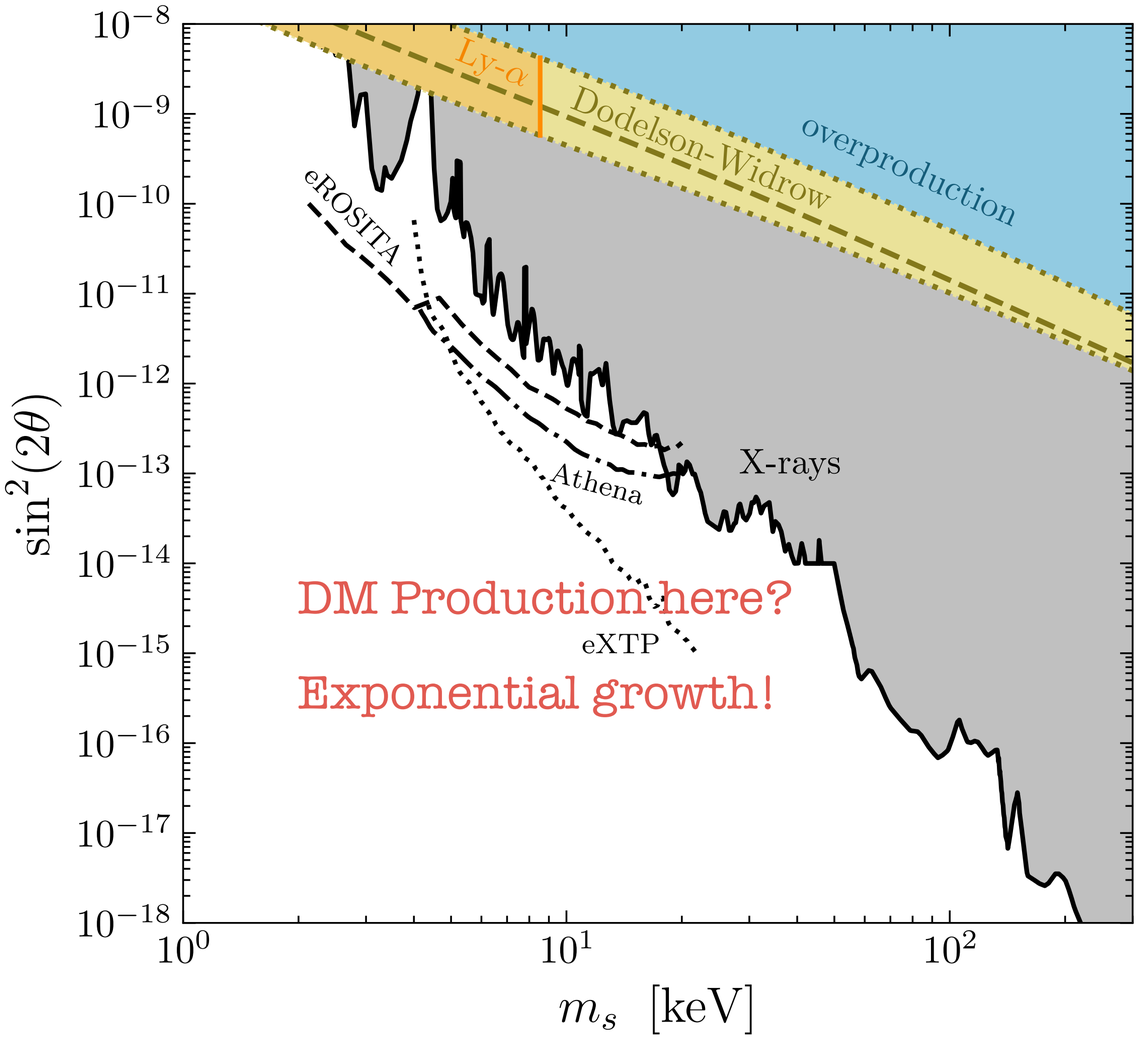
In collaboration with T. Bringmann, M. Hufnagel, J. Kersten, J. T. Ruderman, and K. Schmidt-Hoberg

DISCRETE 2022
11 November 2022


Ly-α
Dodelson-Widrow
overproduction
eROSITA
Athena
X-rays
$\Gamma_s \propto \sin^2(2\theta)\, m_s^5$
DM Production here?
eXTP
$\sin^2(2\theta)$
m_s [keV]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Exponential growth!
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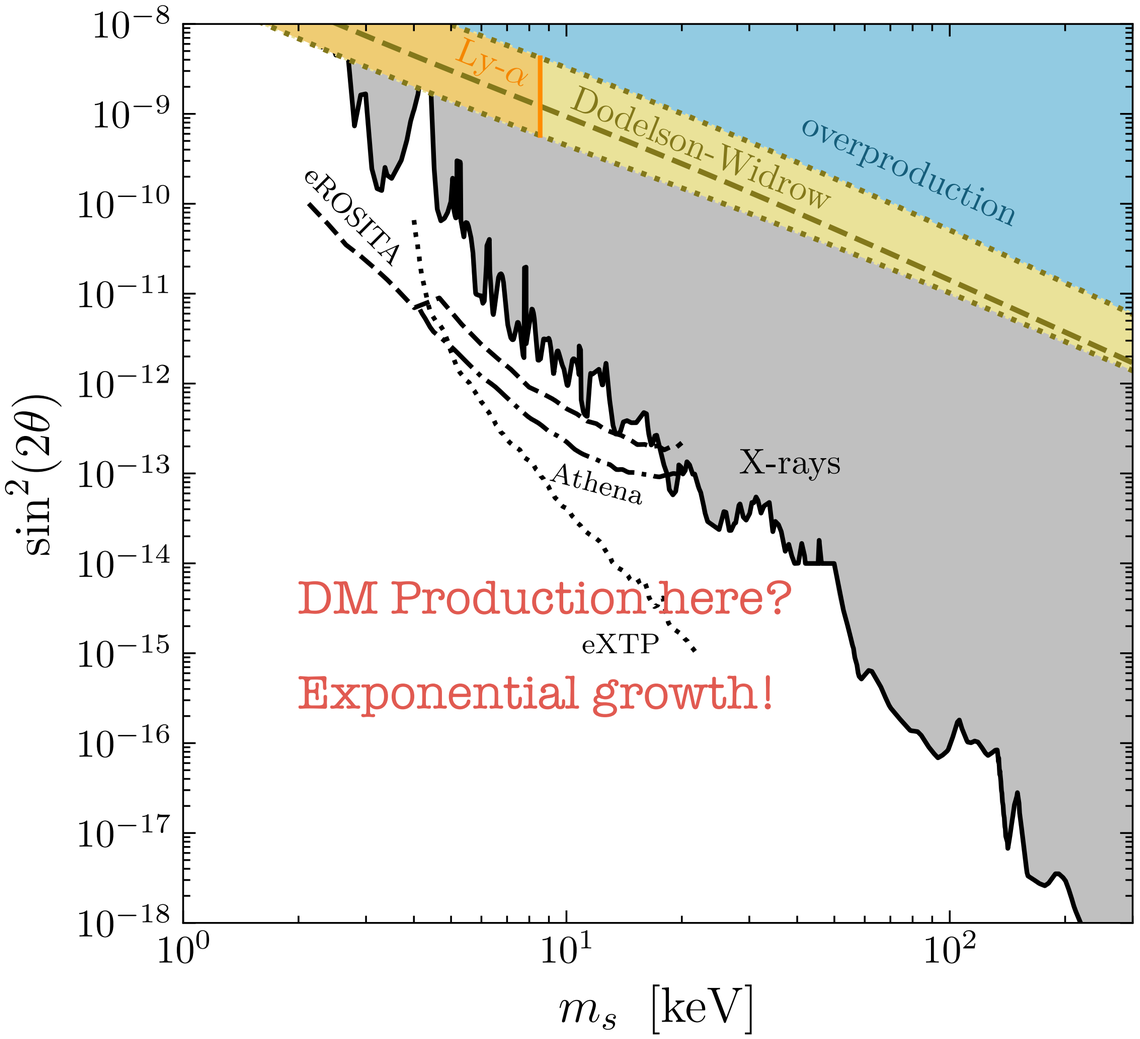
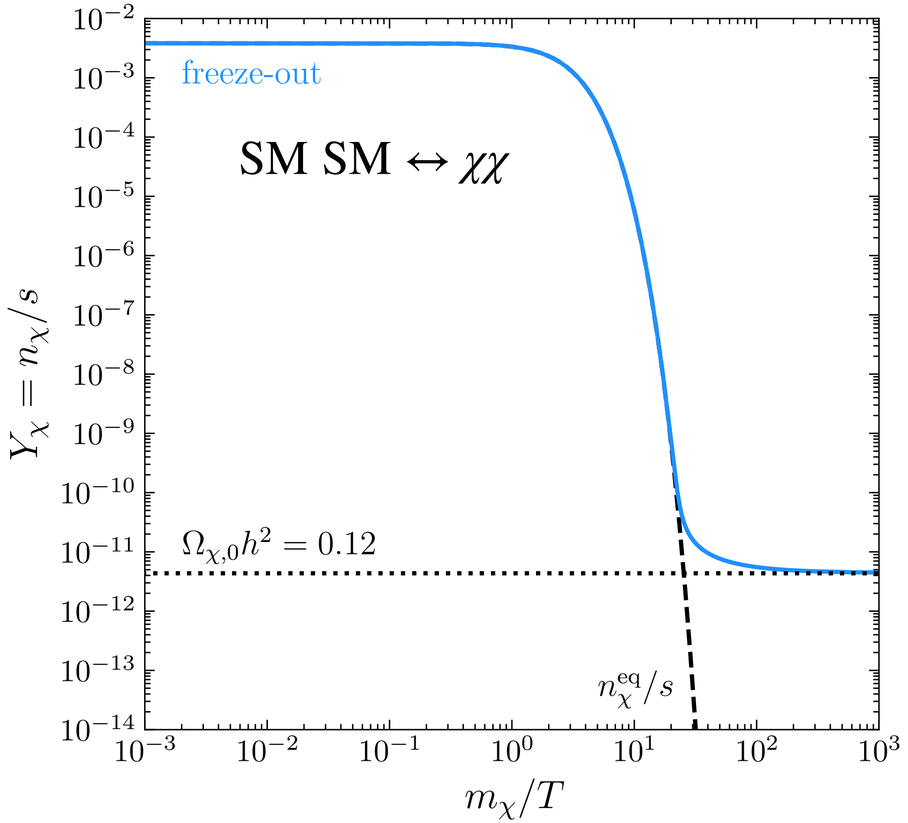


Generally occurs for self-interacting sterile neutrinos!
Simplest allowed model for sterile neutrino DM production!

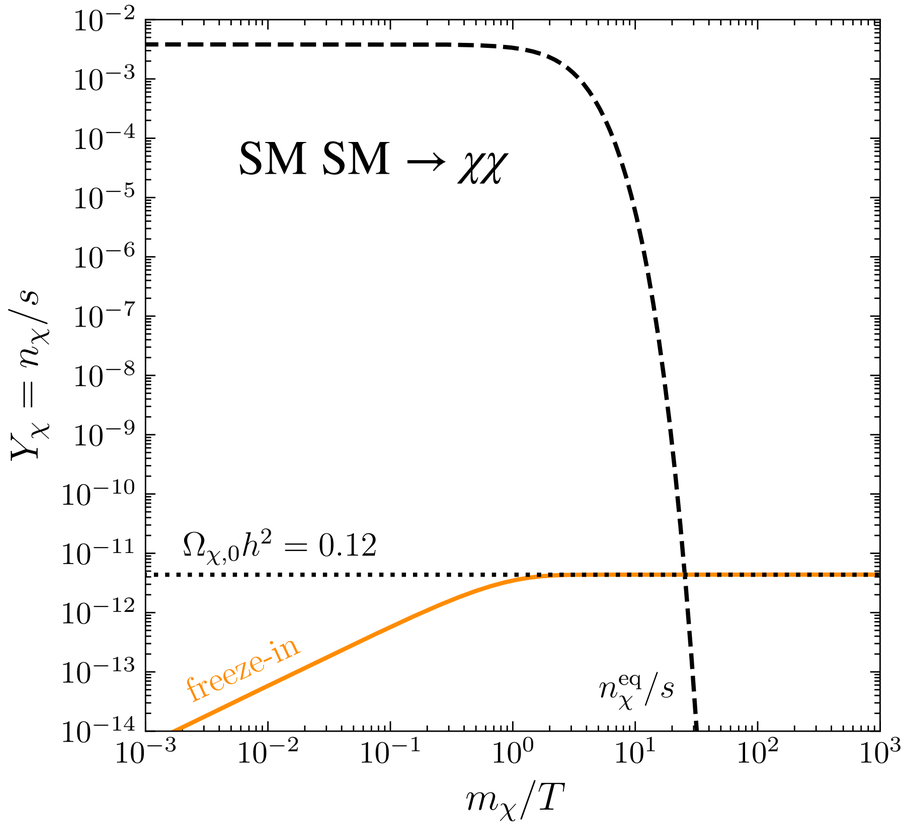
Outline

- General mechanism
- Higgs portal model
- Sterile neutrino model

Thermal



Non-Thermal



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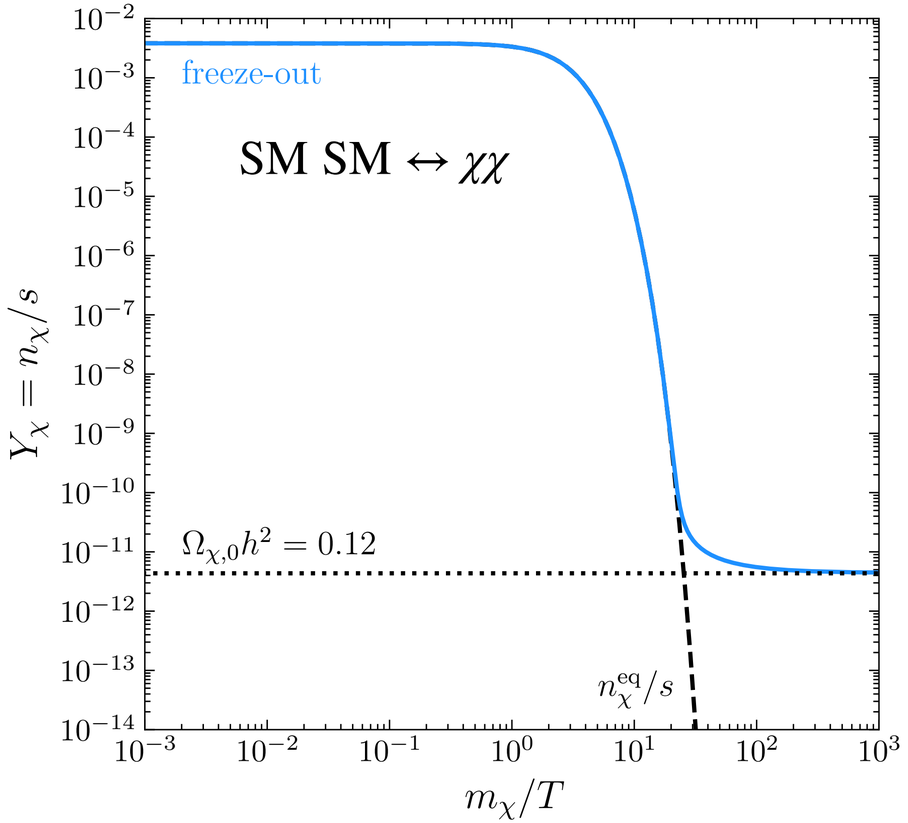
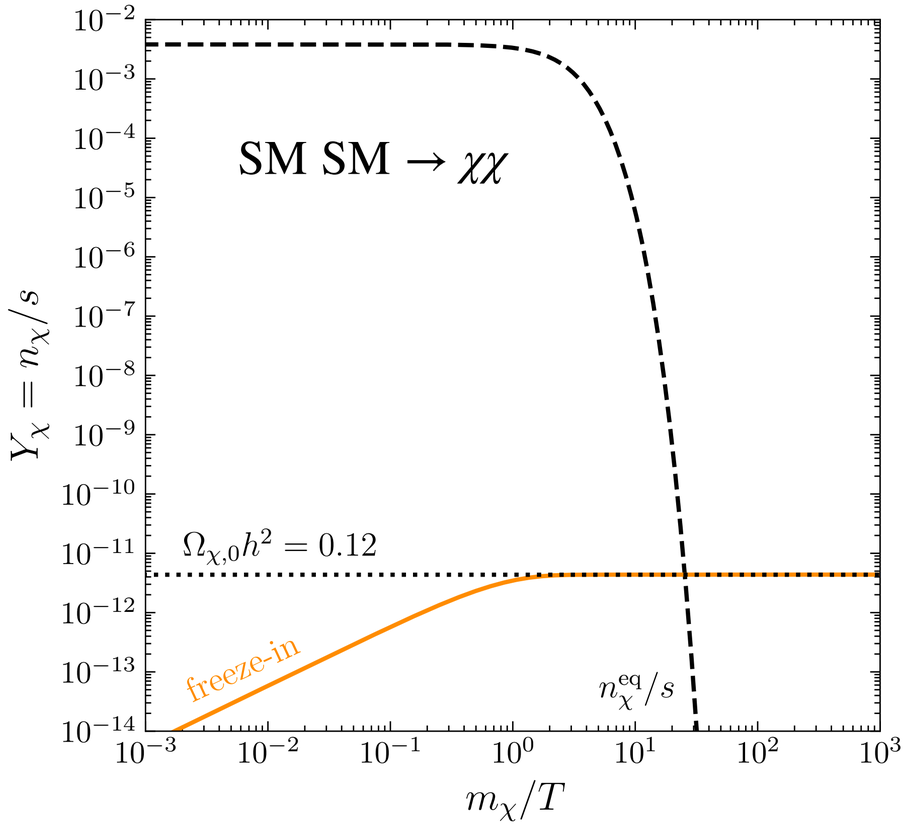


Many variants of freeze-out:

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

Non-Thermal



Less variants for freeze-in

Dark Matter from Exponential Growth

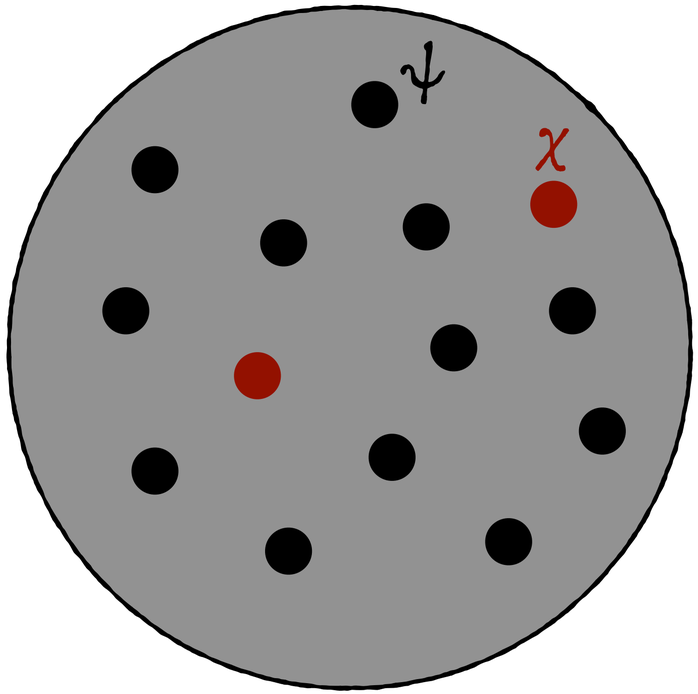
Bringmann, PFD et al. 2103.16572

Hryczuk and Laletin 2104.05684

Very interesting application to sterile neutrinos

Bringmann, PFD et al. 2206.10630

Production by transformation



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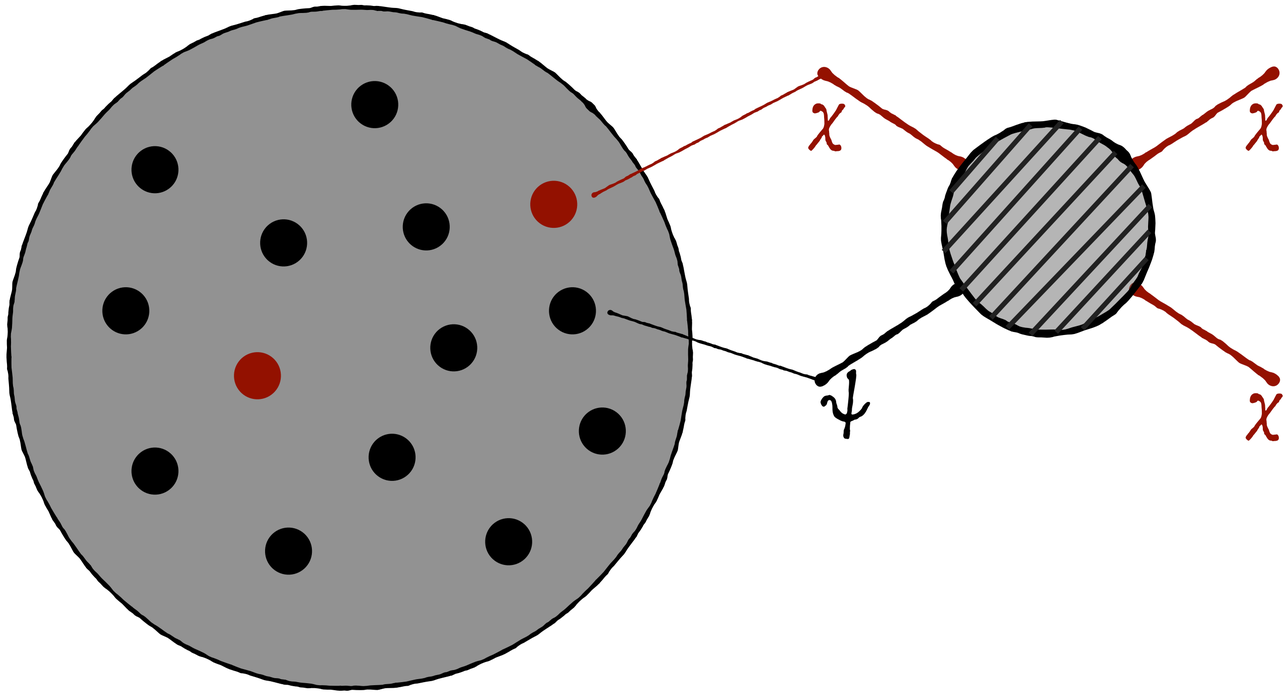
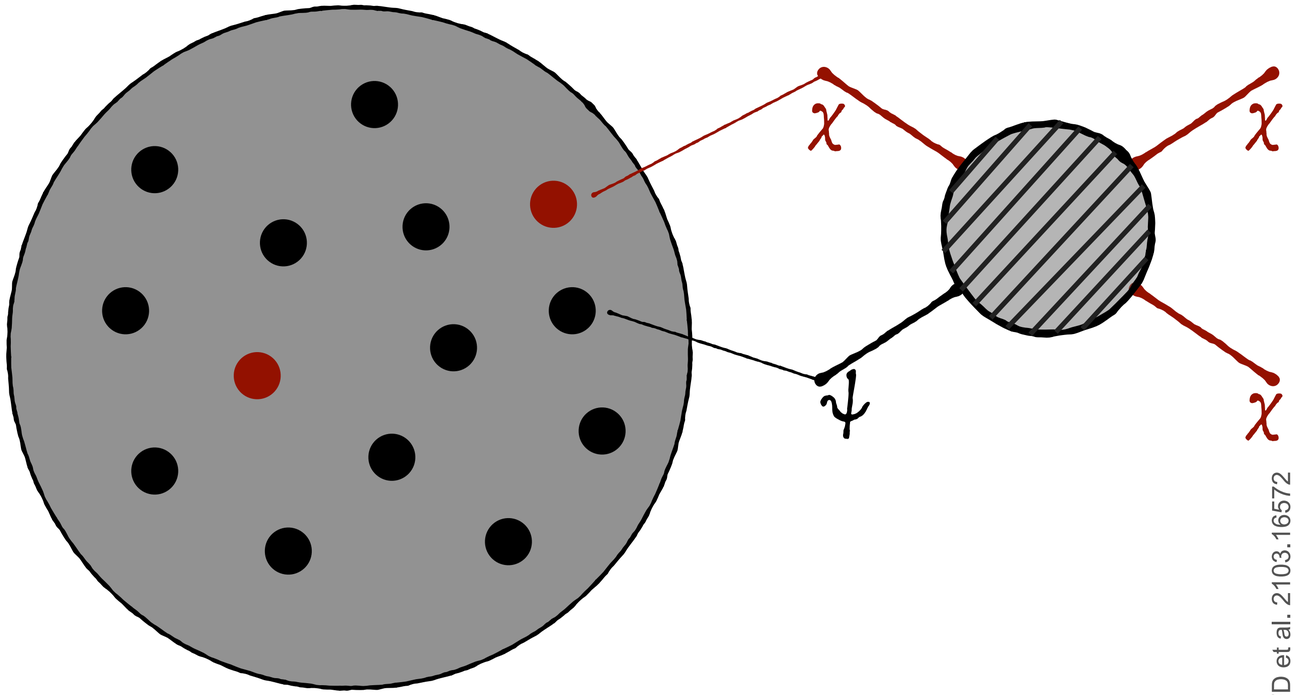


Bringmann, PFD et al. 2103.16572

Production by transformation

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



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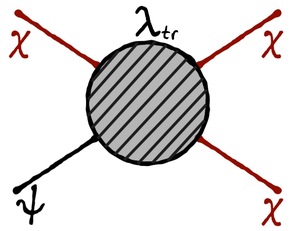
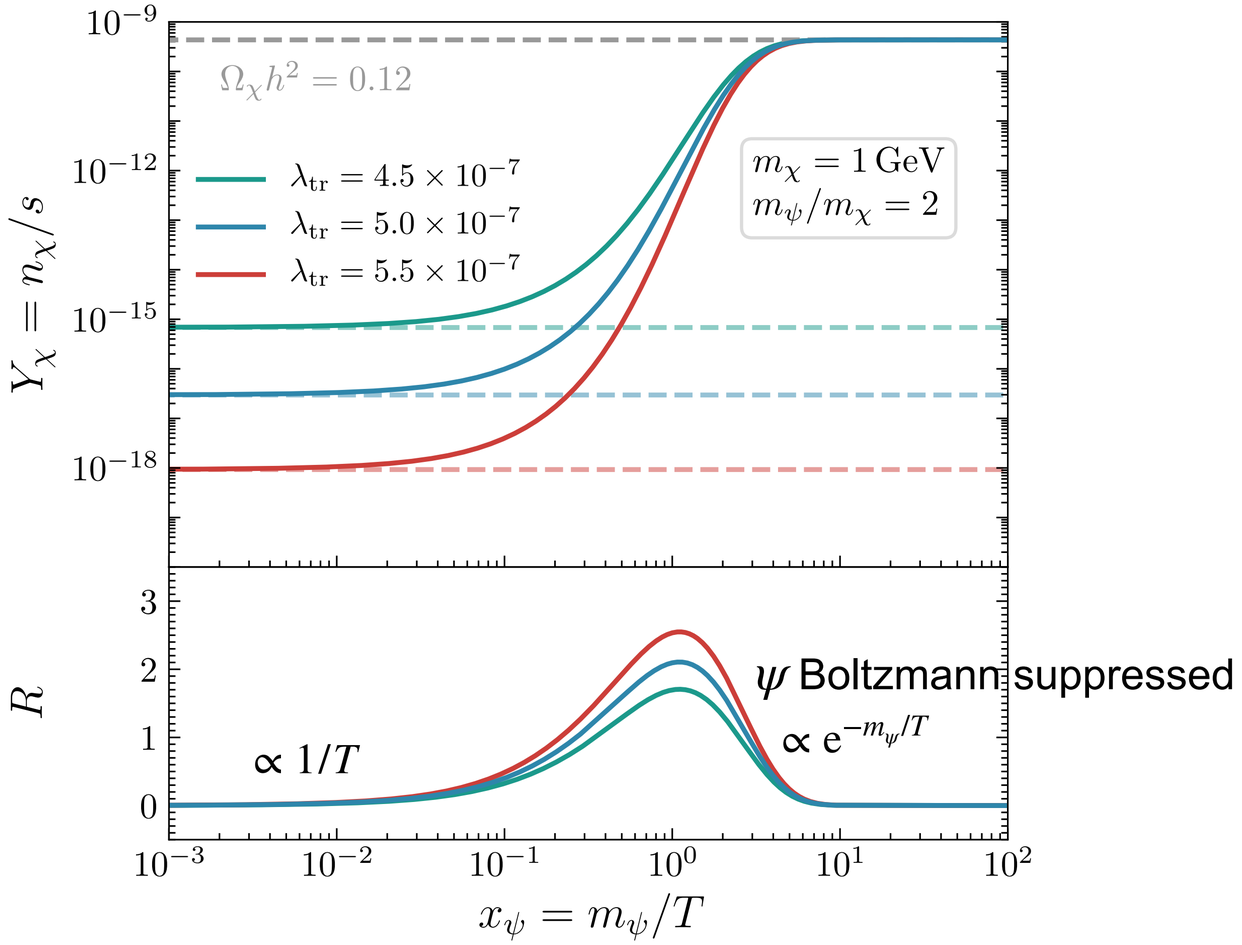
Evolution of DM abundance

Fixed initial abundance



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



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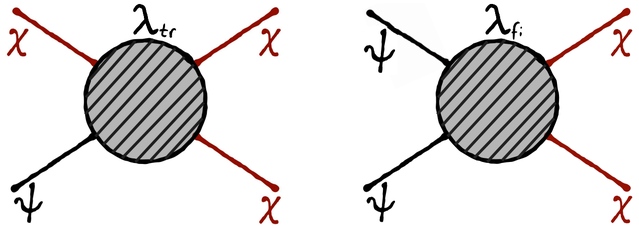
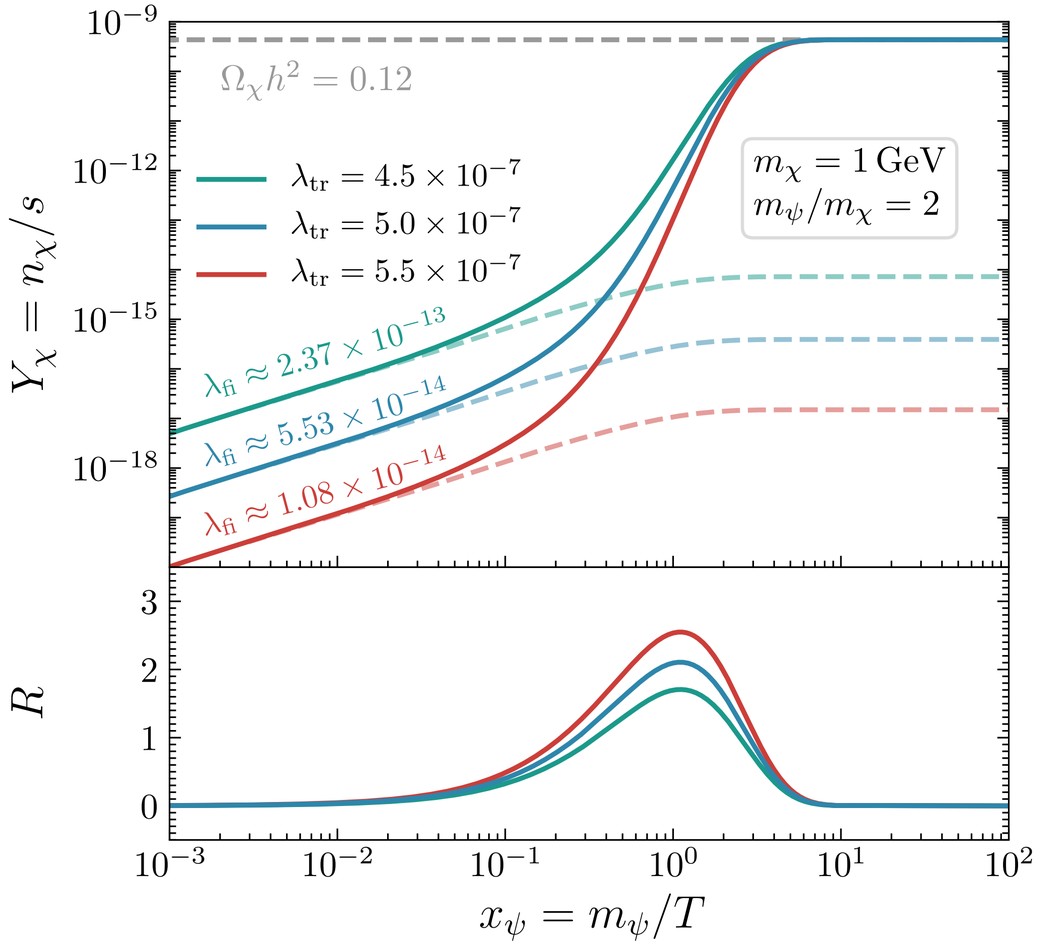
Evolution of DM abundance

Initial abundance from freeze-in



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



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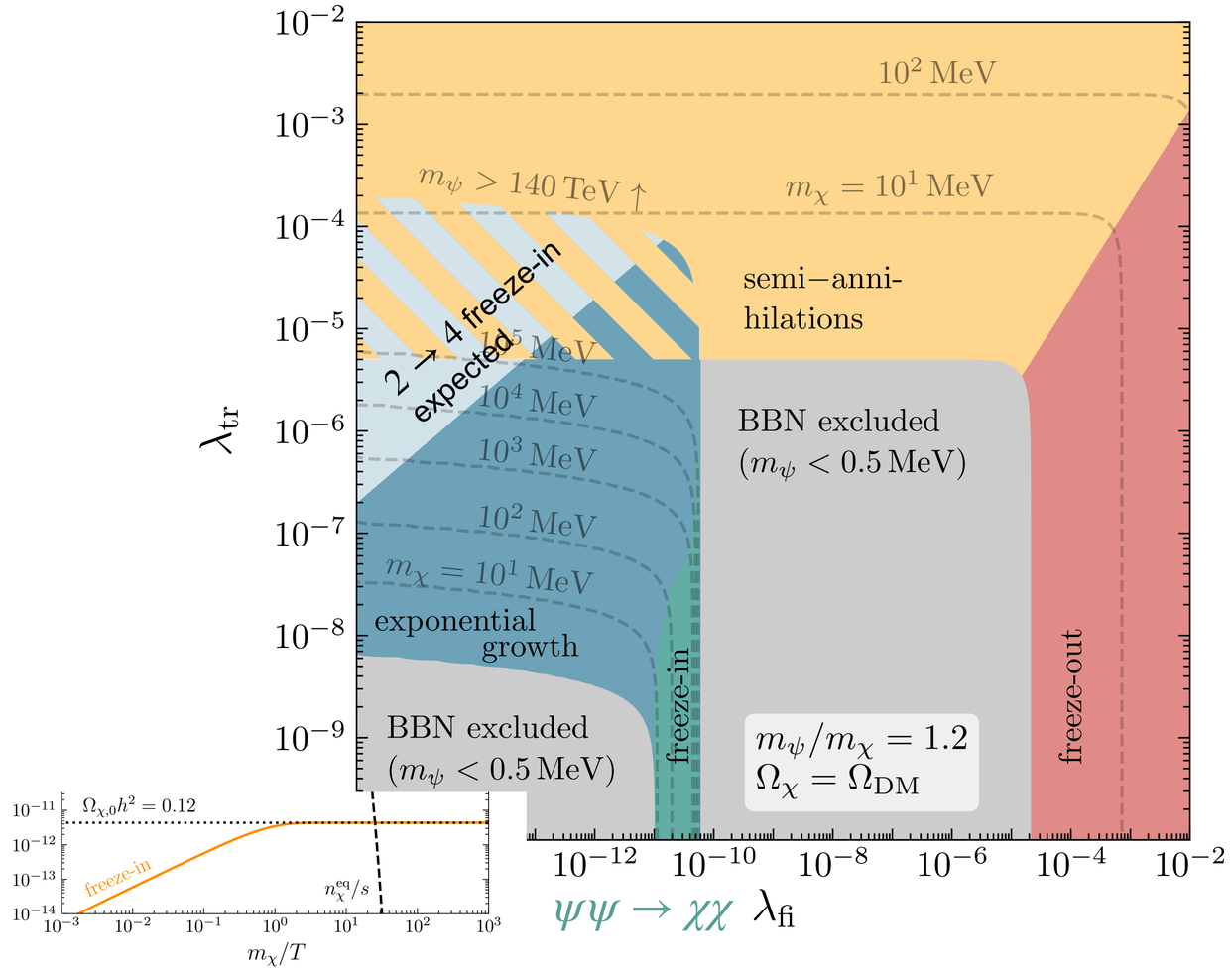
Phase diagram

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



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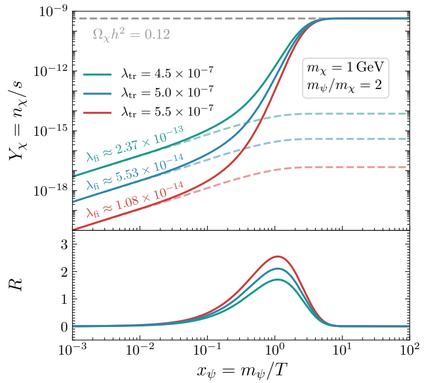
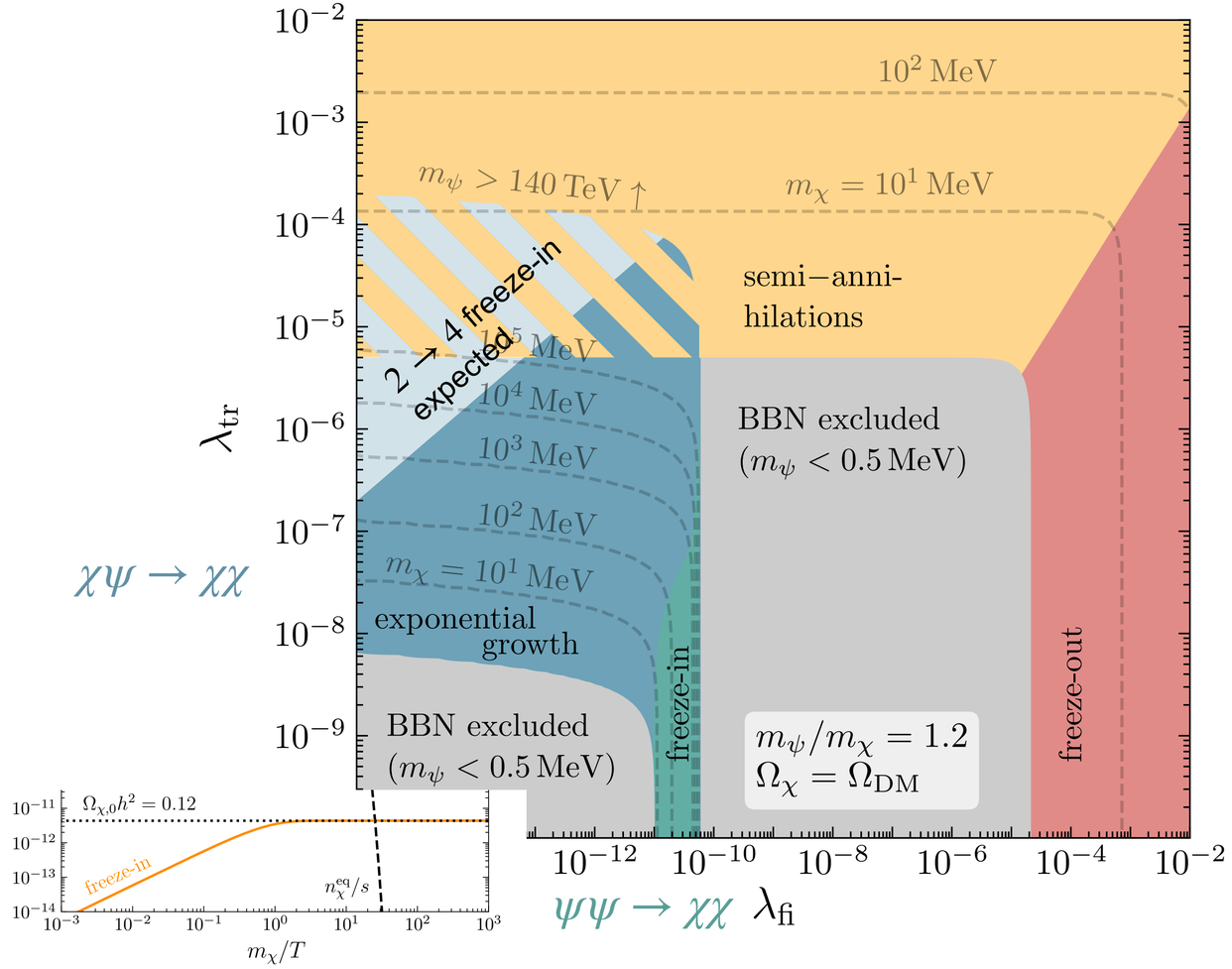


Generally: $\lambda_{\rm fi} \ll \lambda_{\rm tr}$



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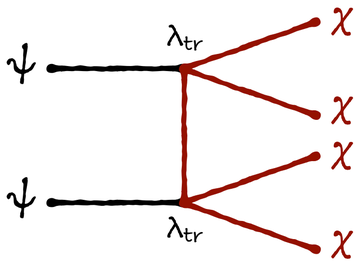

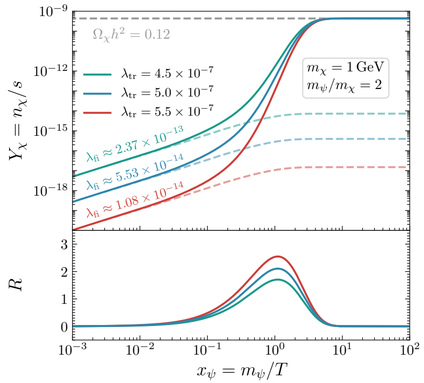

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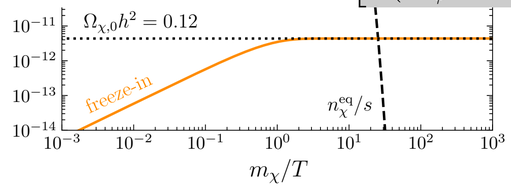
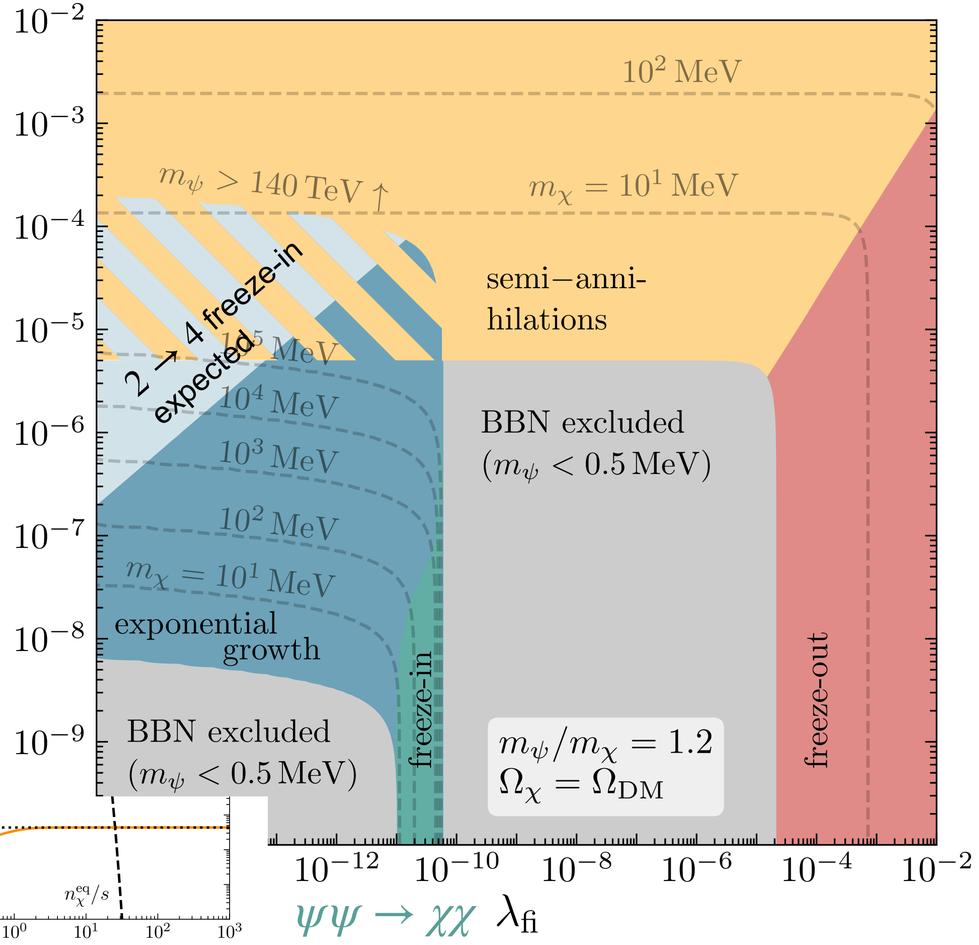
$\chi\psi \to \chi\chi$





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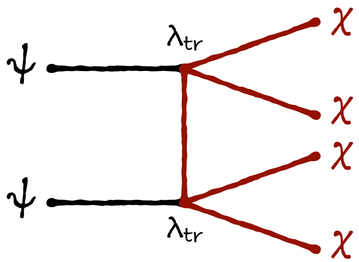
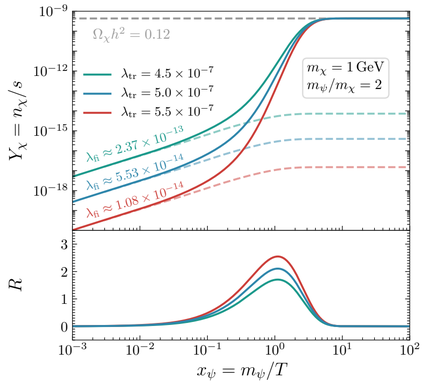
Phase diagram

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

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





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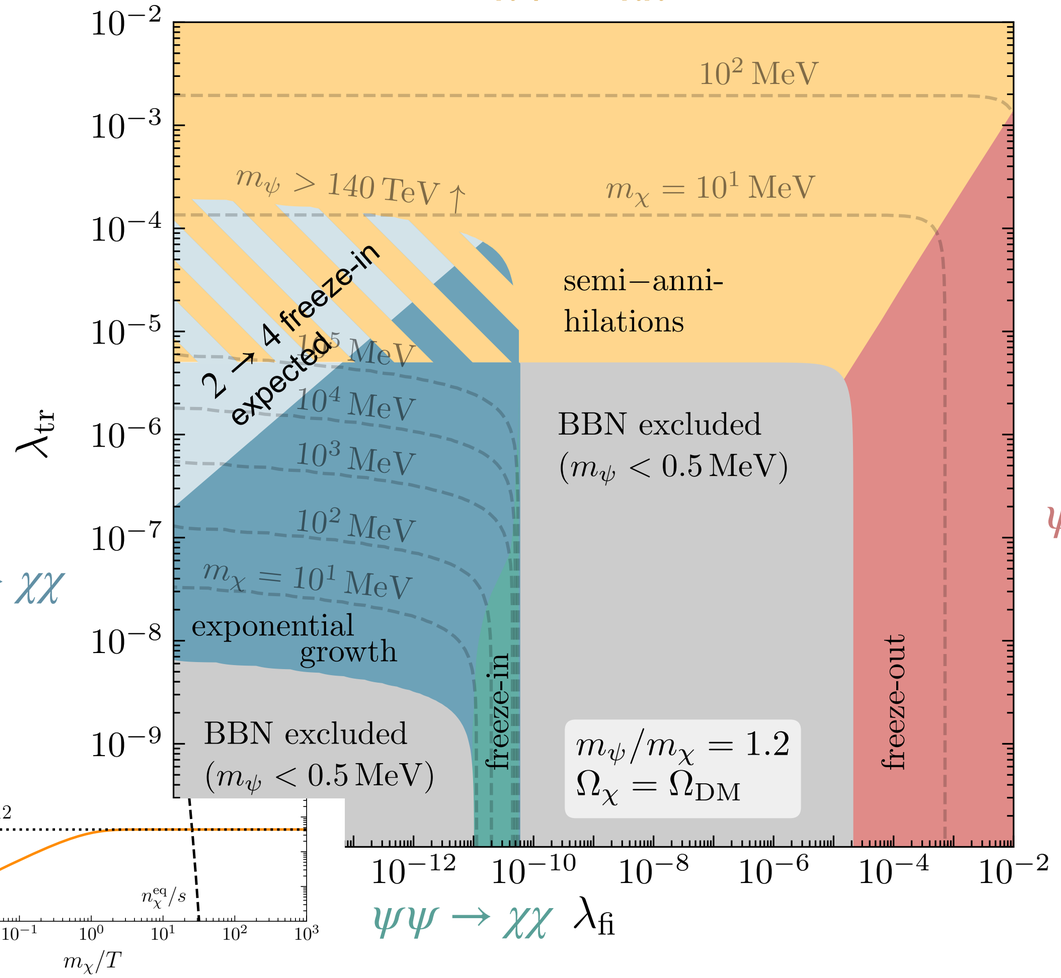

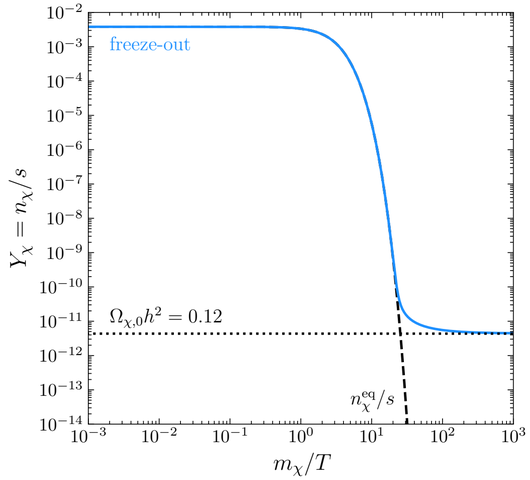

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Towards concrete models

Necessary conditions

- Generate abundance of ψ
- Generate initial abundance of χ

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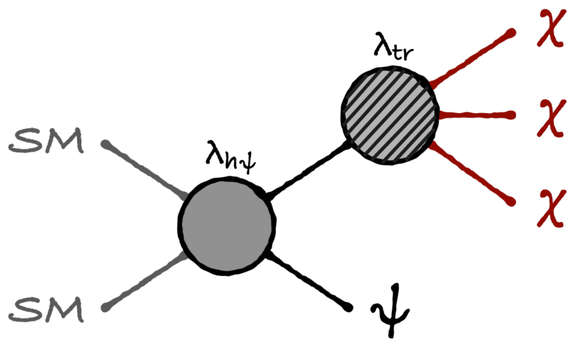
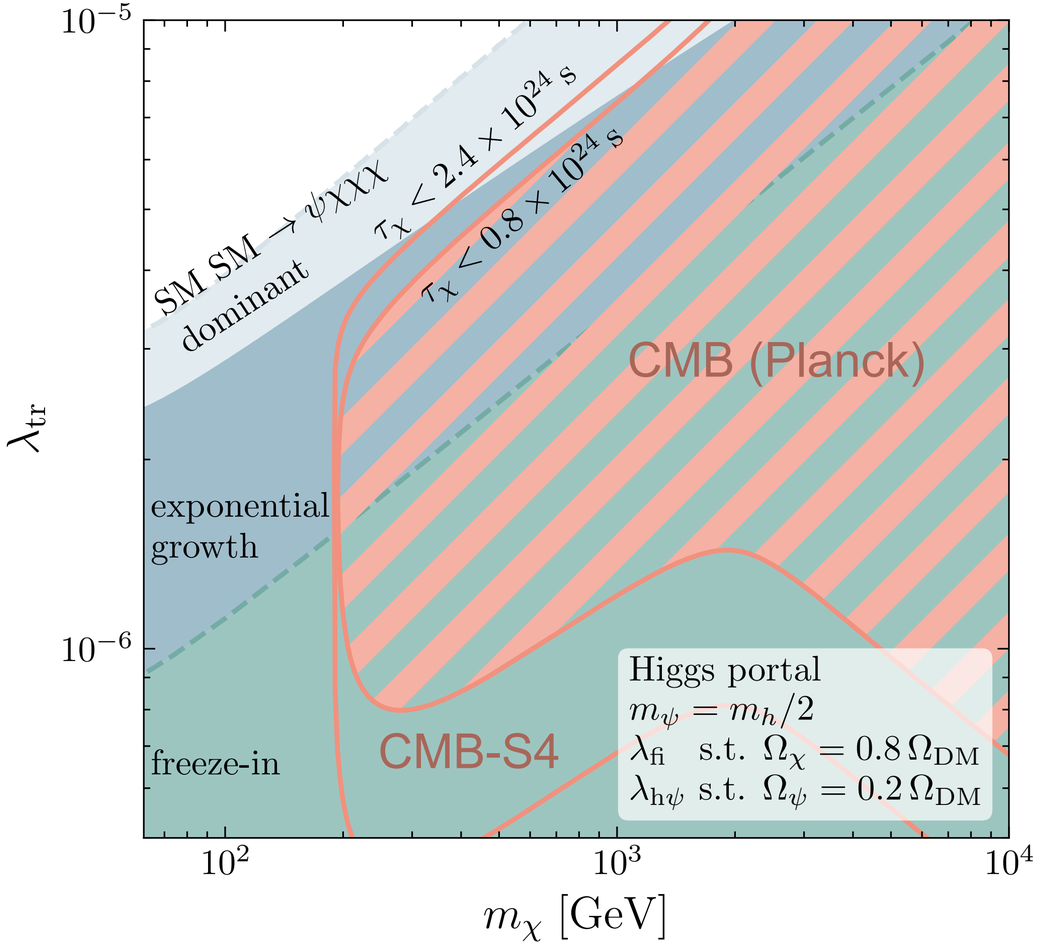
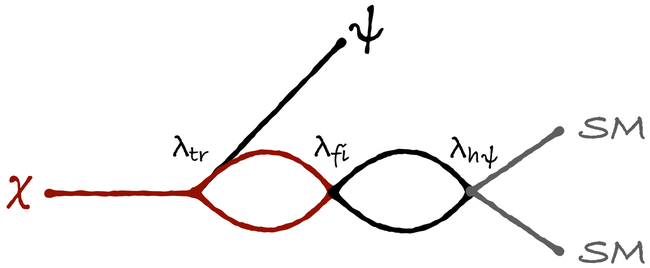
- Generate abundance of ψ $\rightarrow$ Higgs portal $\lambda_{h\psi}|H|^2\psi^2/2$
- Generate initial abundance of χ $\rightarrow$ freeze-in $\lambda_{\mathrm{fi}}\psi^2\chi^2$

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







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Interlude: Discrete symmetries

- Problem: DM may not be stable
- Possible fix:
  - Assume χ to be complex scalar charged under $\mathbb{Z}_3$ symmetry, other particles (in particular scalar ψ) not charged
  - Still allows for terms $\psi\chi^3$, $\psi(\chi^*)^3$, $\psi^2\chi^*\chi$ in Lagrangian
  - DM decays forbidden

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  - DM decays forbidden
- Concrete model realization in Hryczuk and Laletin 2104.05684
  - Assume ψ to couple to SM Higgs
  - Consider small coupling to Higgs (Higgs-to-invisibles searches), ψ is only produced by freeze-in
  - Possible indirect detection signatures as $\langle\sigma v\rangle_{\mathrm{tr}}$ is larger than for freeze-in, ψ decays to SM

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Necessary conditions

- Generate abundance of ψ
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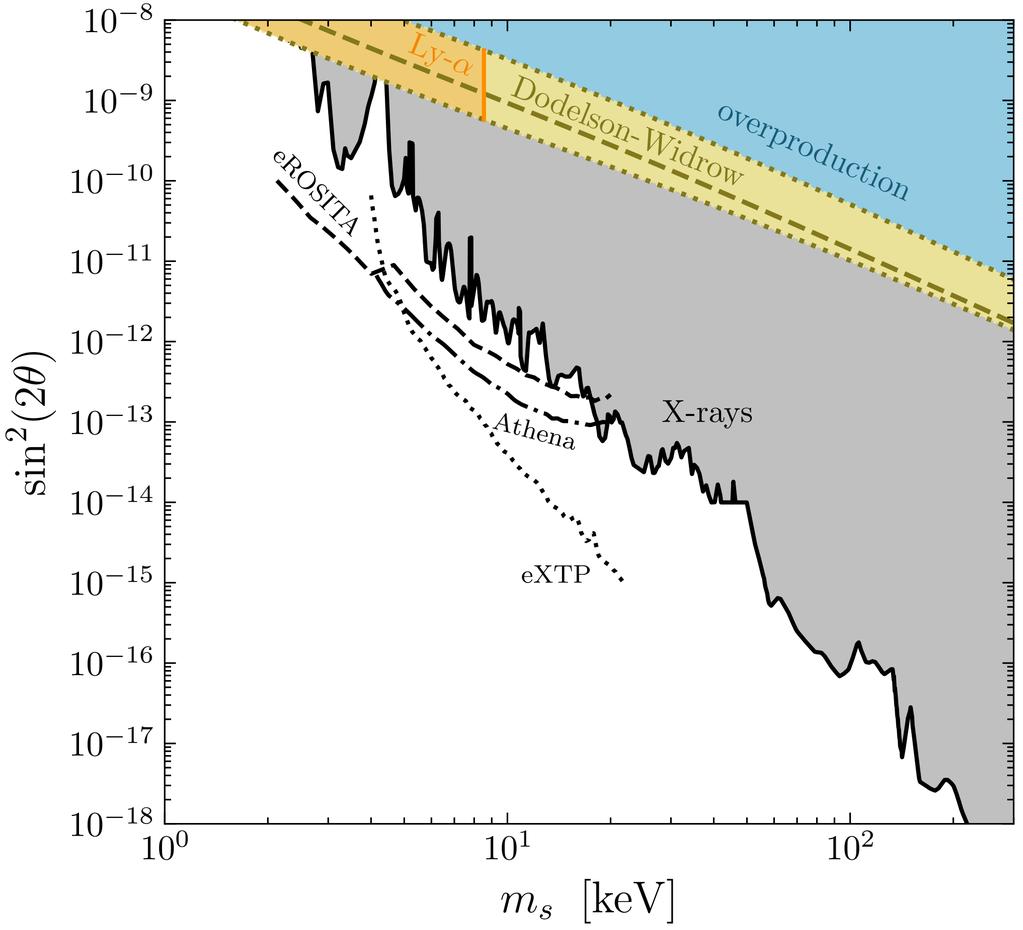
- Realize hierarchy of (effective) couplings $\lambda_{\mathrm{fi}} \ll \lambda_{\mathrm{tr}} \ll 1$
  - Two fermions with small mass mixing angle θ, only one (mostly χ) interacts with mediator ϕ via Yukawa coupling:
    - $\bar{\chi}\chi$ vertices $\propto \cos^2\theta \sim 1$
    - $\bar{\psi}\chi$ 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 for sterile neutrinos

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

  $\rightarrow \frac{y}{2}\phi\left(\cos^2\theta\,\overline{\nu_s^c}\nu_s - \sin(2\theta)\,\overline{\nu_\alpha}\nu_s + \sin^2\theta\,\overline{\nu_\alpha^c}\nu_\alpha\right) + \text{h.c.}$
- Initial abundance of sterile neutrinos from oscillations between active and sterile neutrinos (Dodelson-Widrow mechanism)



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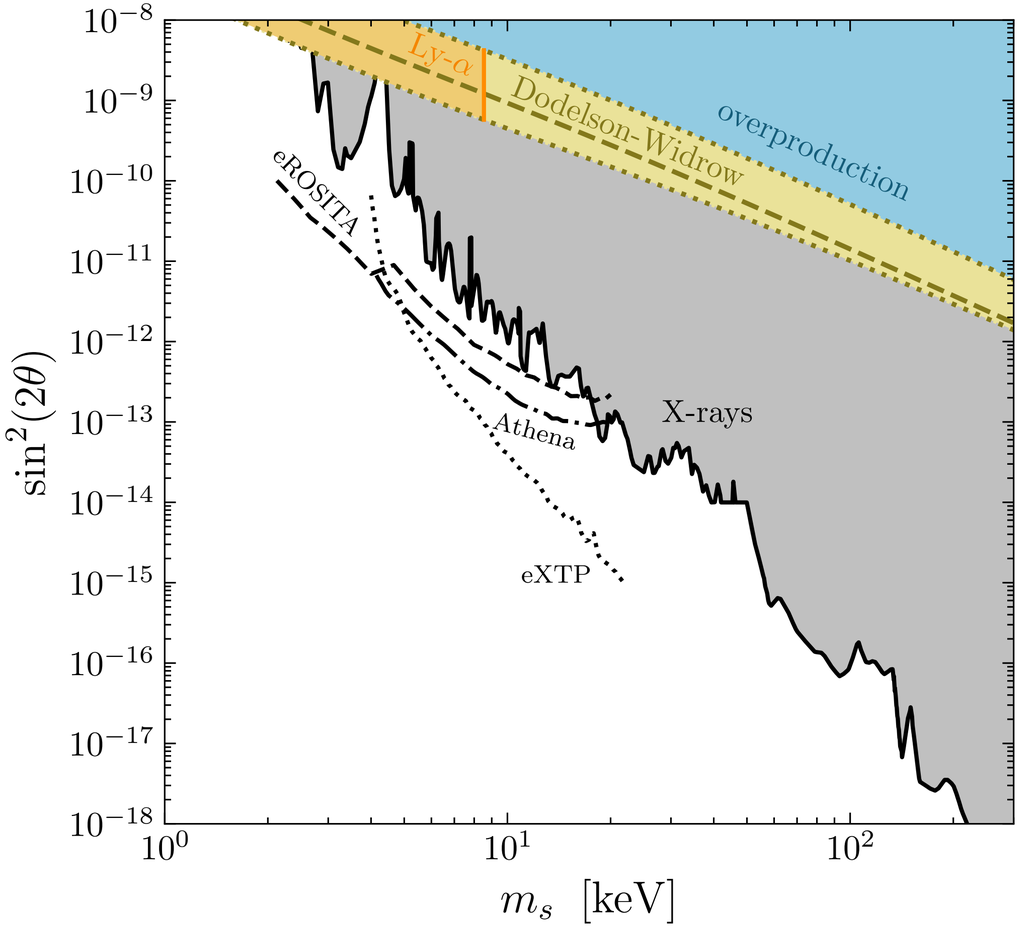
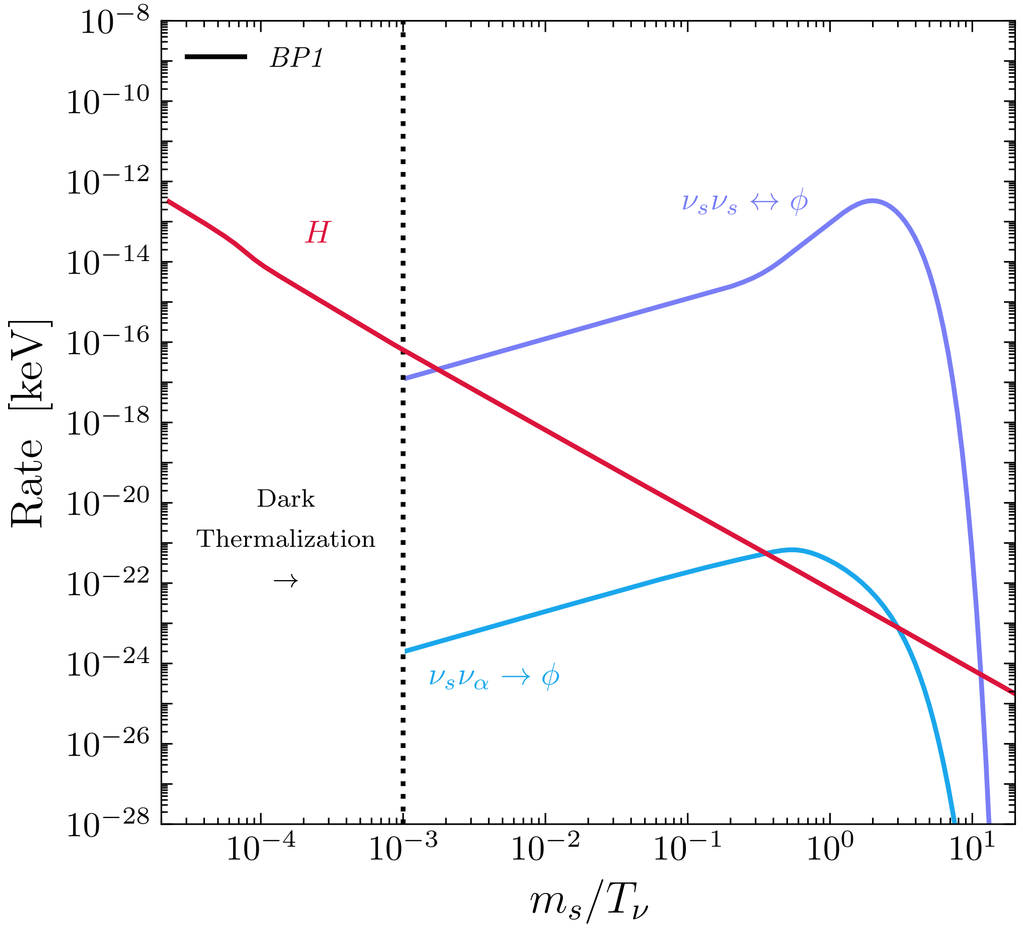
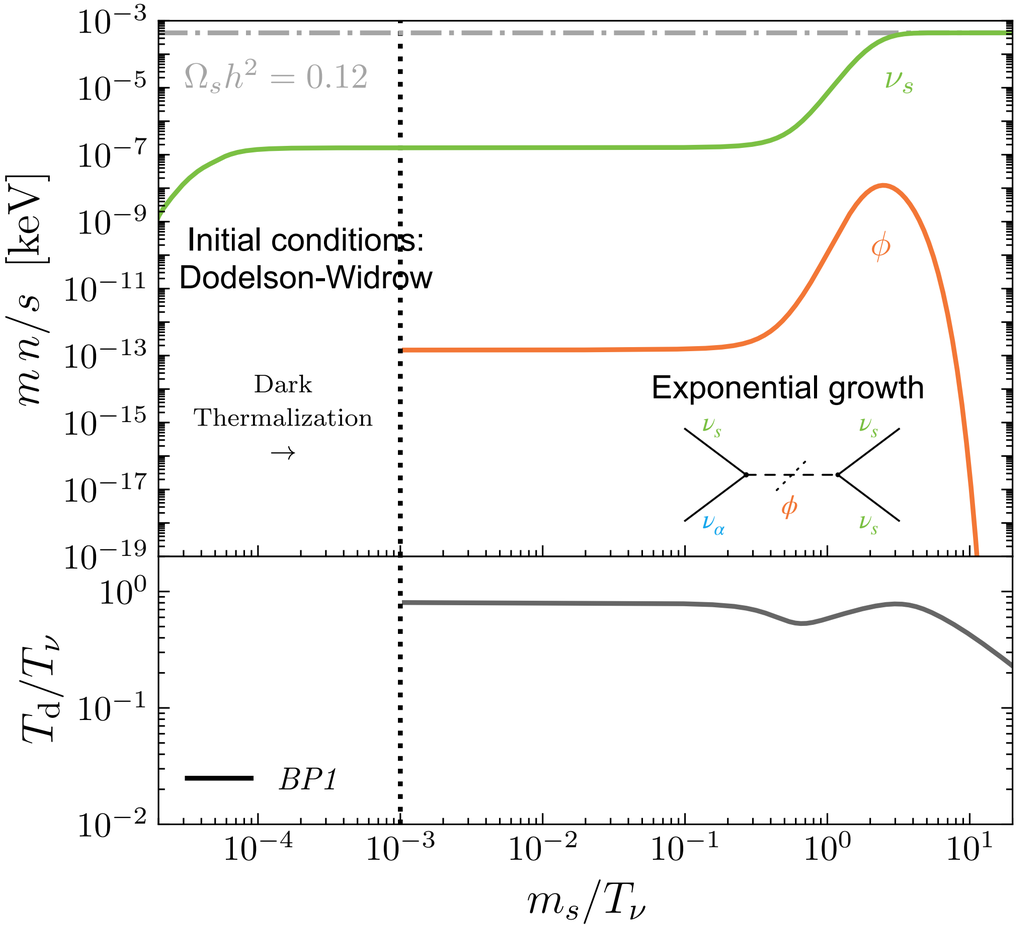
- Generally occurs for self-interacting sterile neutrinos
- Simplest allowed model for sterile neutrino DM production



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}





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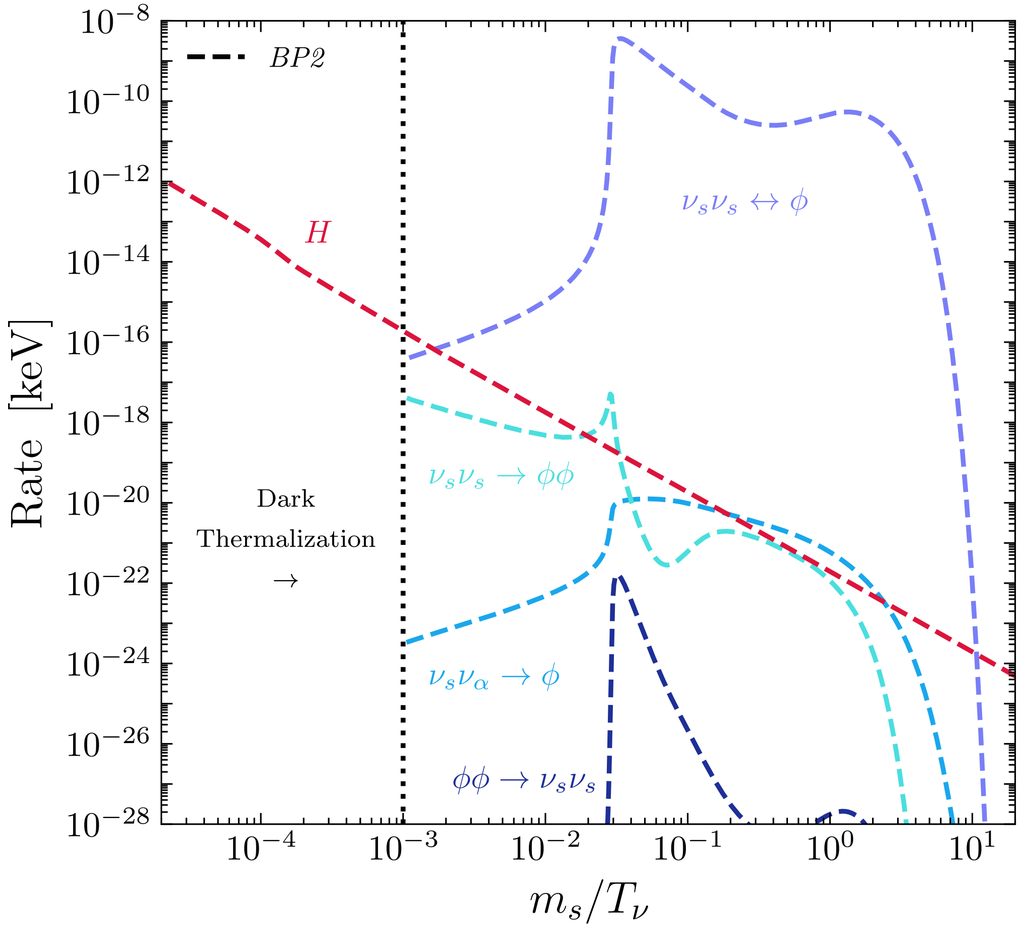
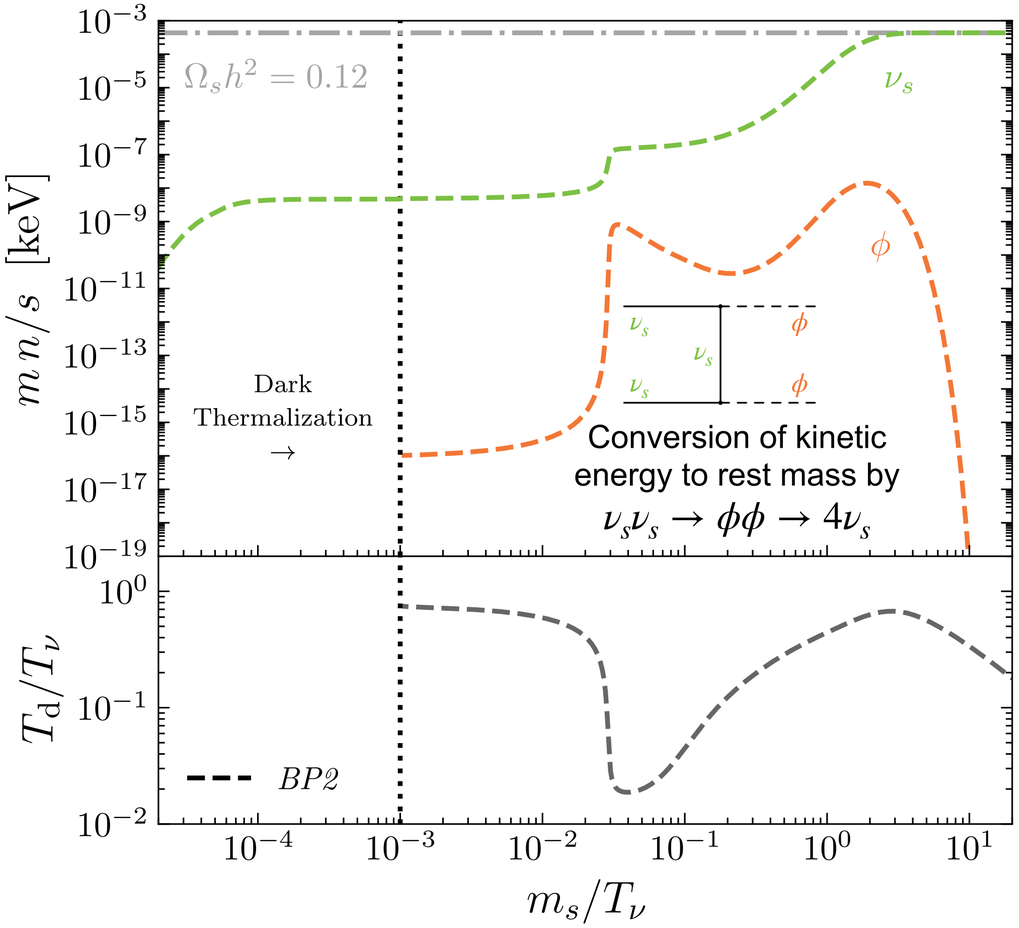
Evolution

	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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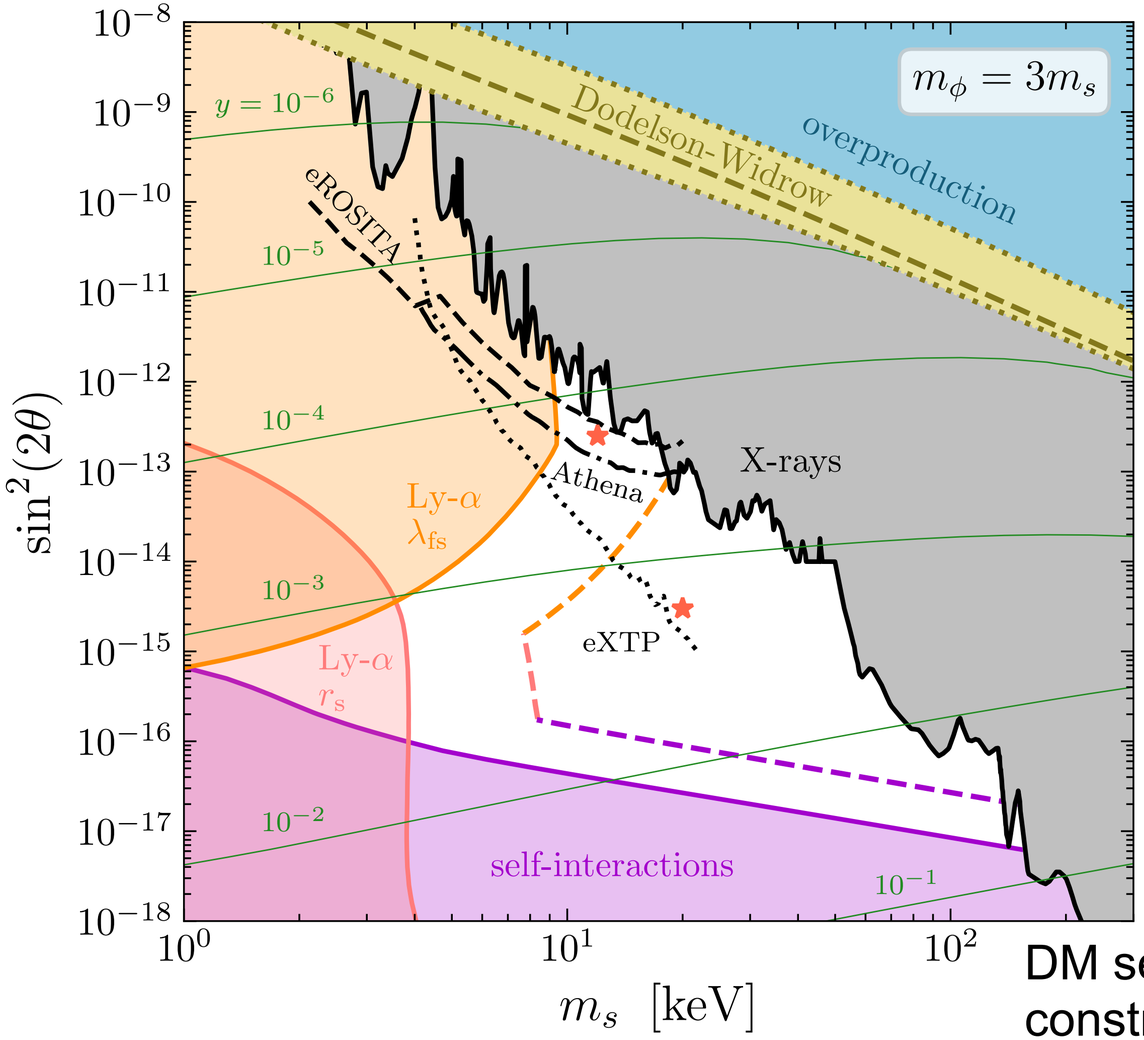
Parameter space

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

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
- Discrete symmetries can be interesting and useful
- Sterile neutrino DM after the pandemic:
  - 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!