A new life for sterile neutrino dark matter after the pandemic

Based on 2206.10630

Frederik Depta
Max-Planck-Institut für Kernphysik

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

MPIK Particle and Astroparticle Theory Seminar
17 October 2022

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HEIDELBERG

A new life for sterile neutrino dark matter after the pandemic (at $t \sim 1000\,\mathrm{s}$, not $t \sim 13.8\,\mathrm{Gyr}$)

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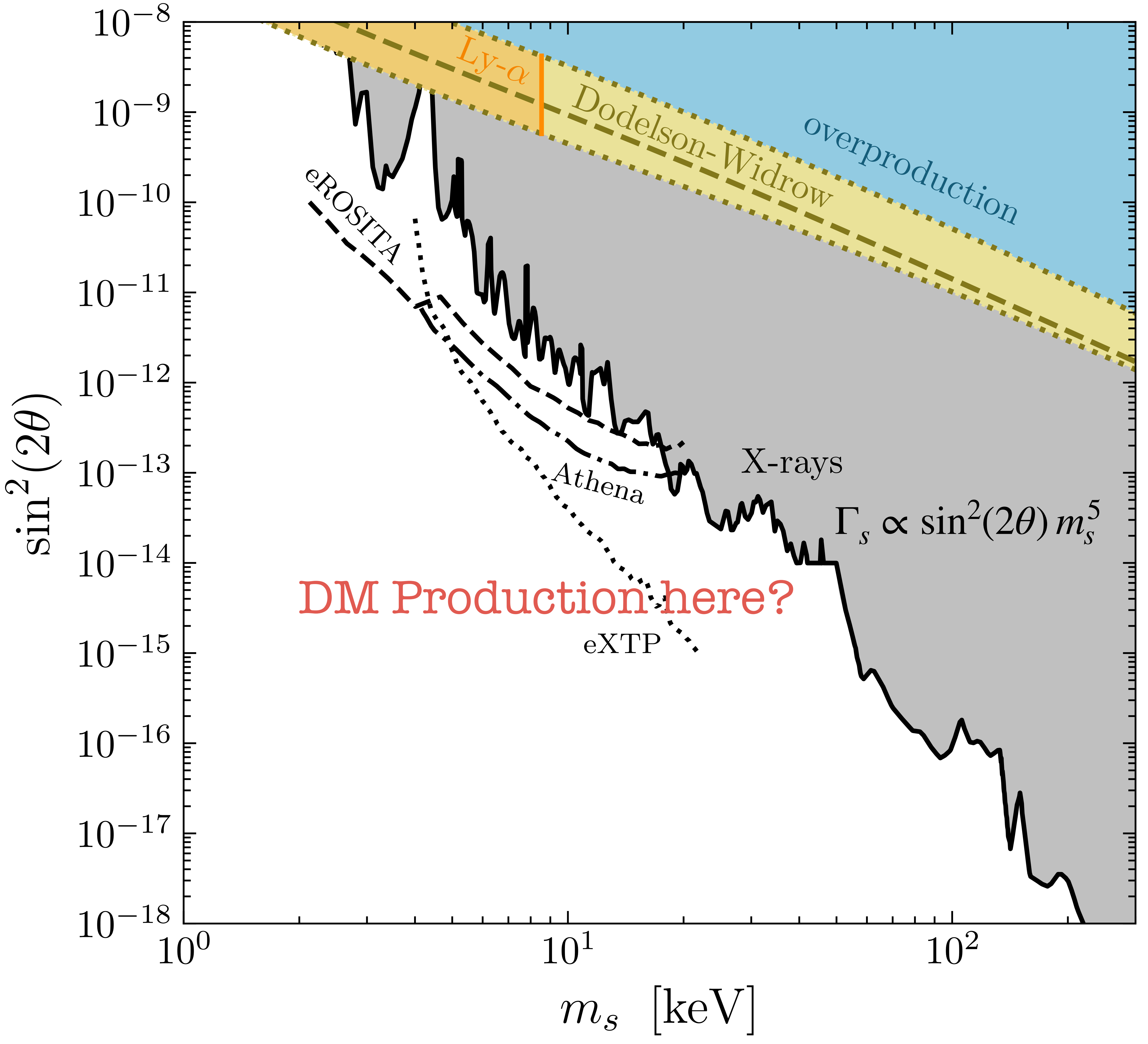
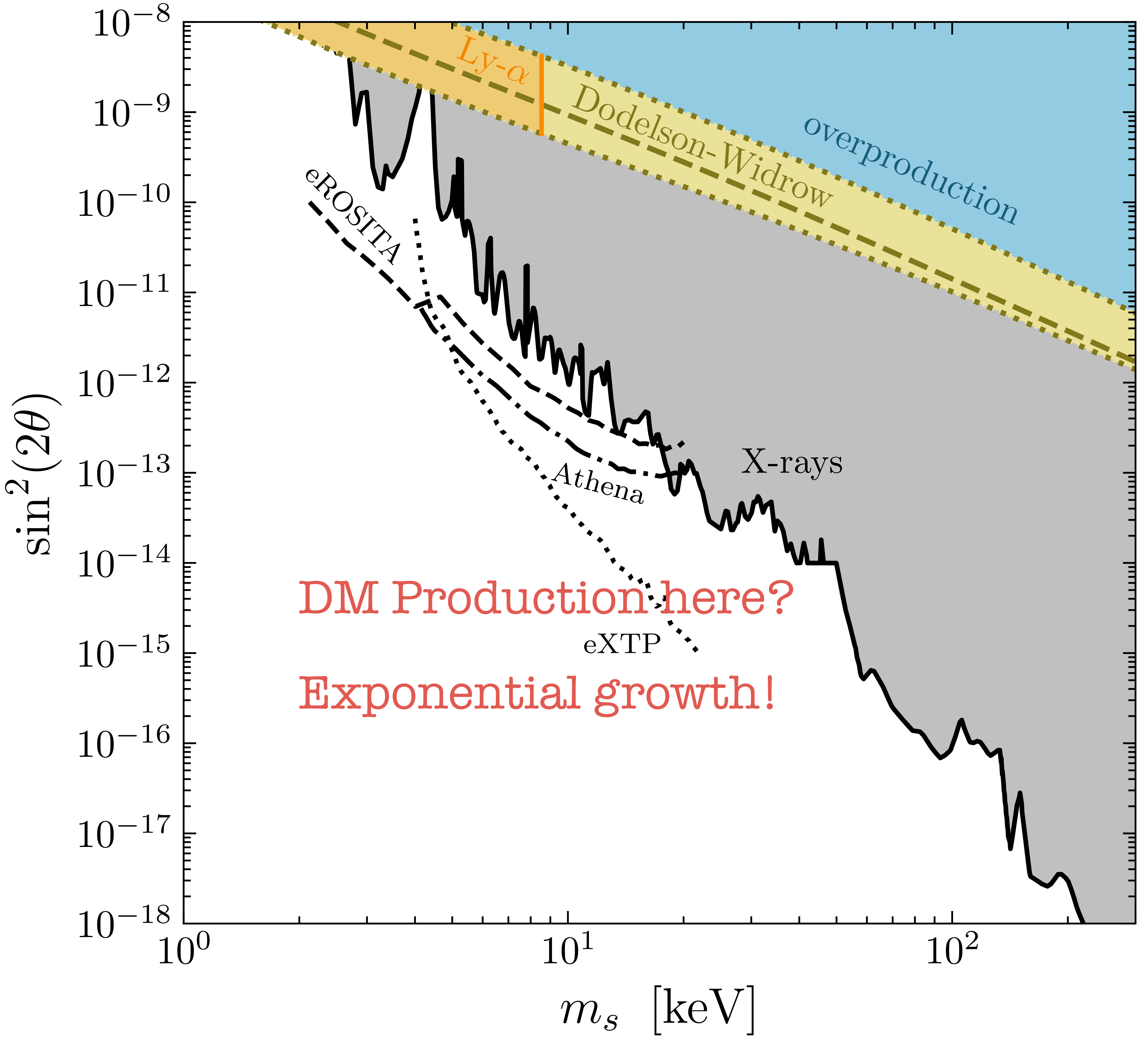


Ly-α
Dodelson-Widrow
overproduction
eROSITA
X-rays
$\Gamma_s \propto \sin^2(2\theta)\, m_s^5$
Athena
DM Production here?
eXTP
$\sin^2(2\theta)$
m_s [keV]



10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
$\sin^2(2\theta)$
10^0
10^1
10^2
m_s [keV]
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DM Production here?
Exponential growth!

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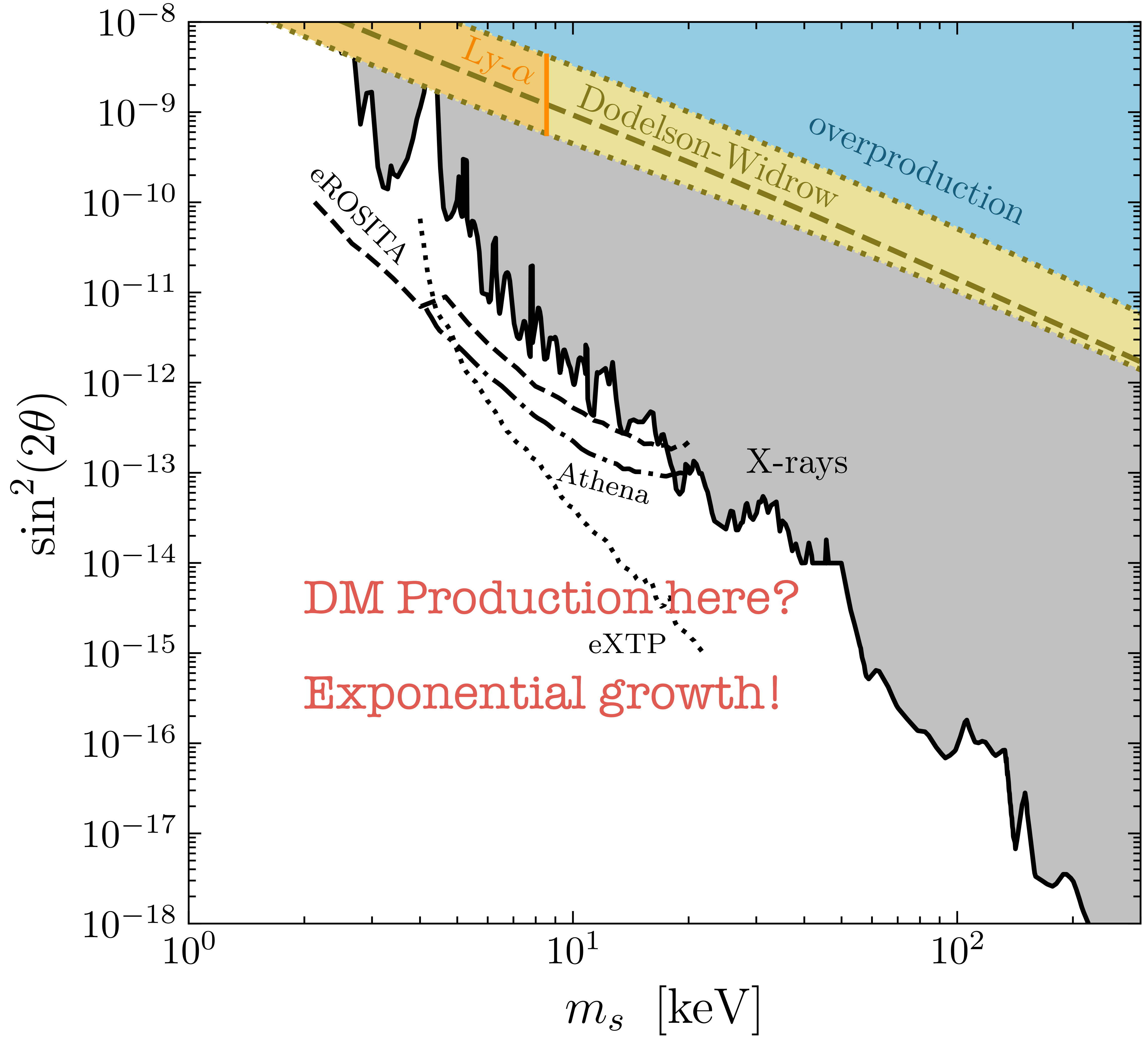
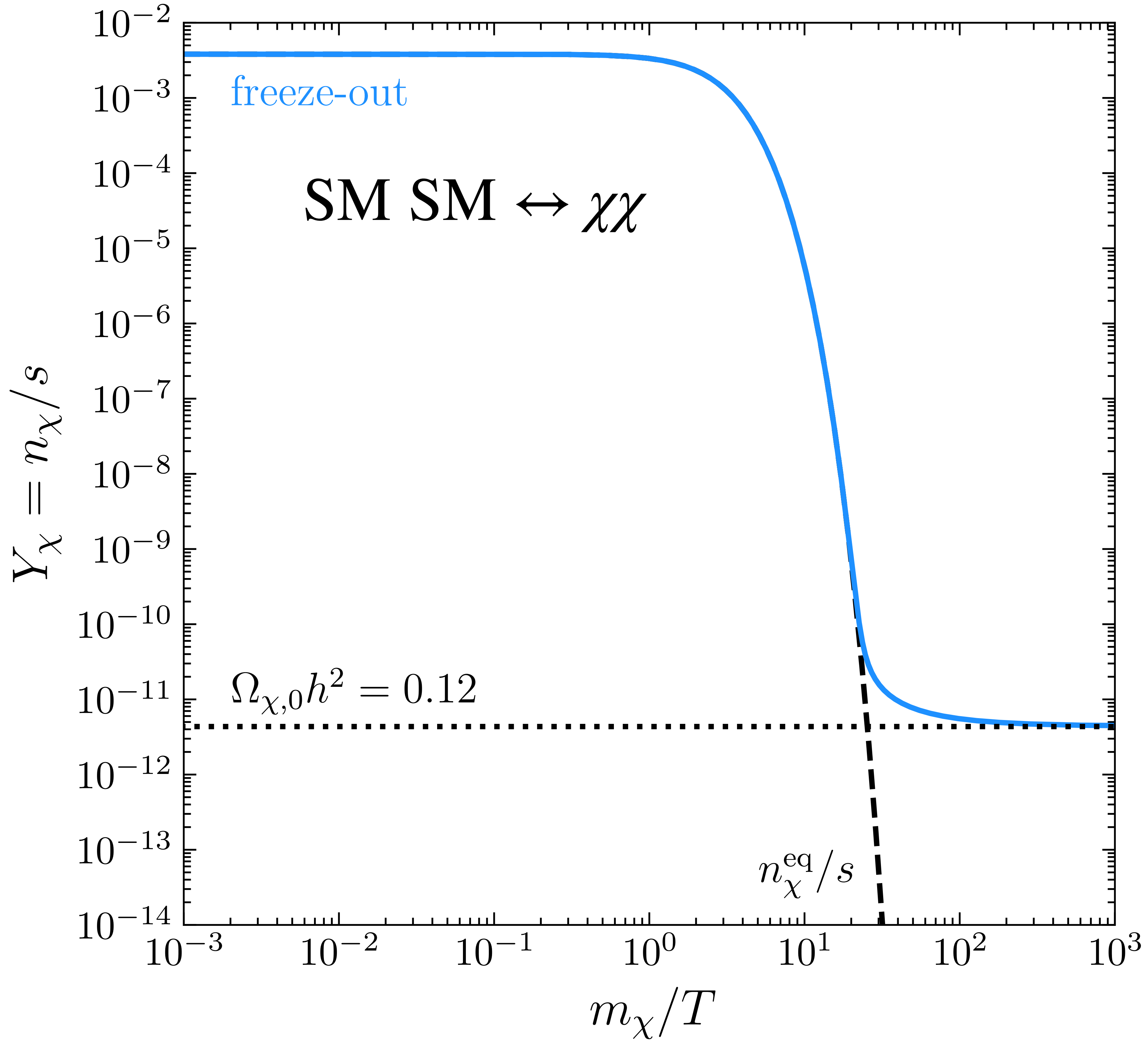


Generally occurs for self-interacting sterile neutrinos!
Simplest allowed model for sterile neutrino DM production!

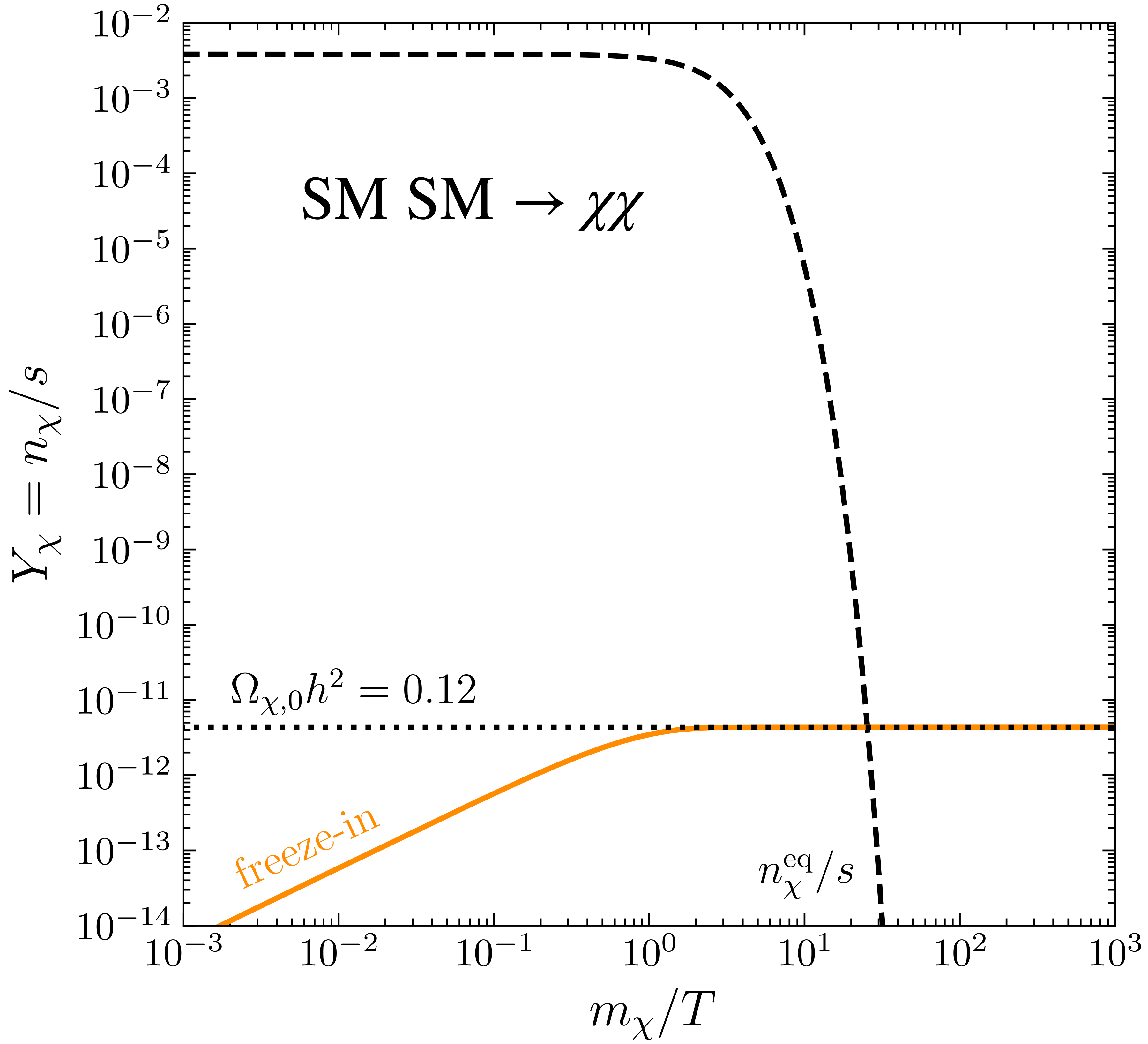
Outline

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

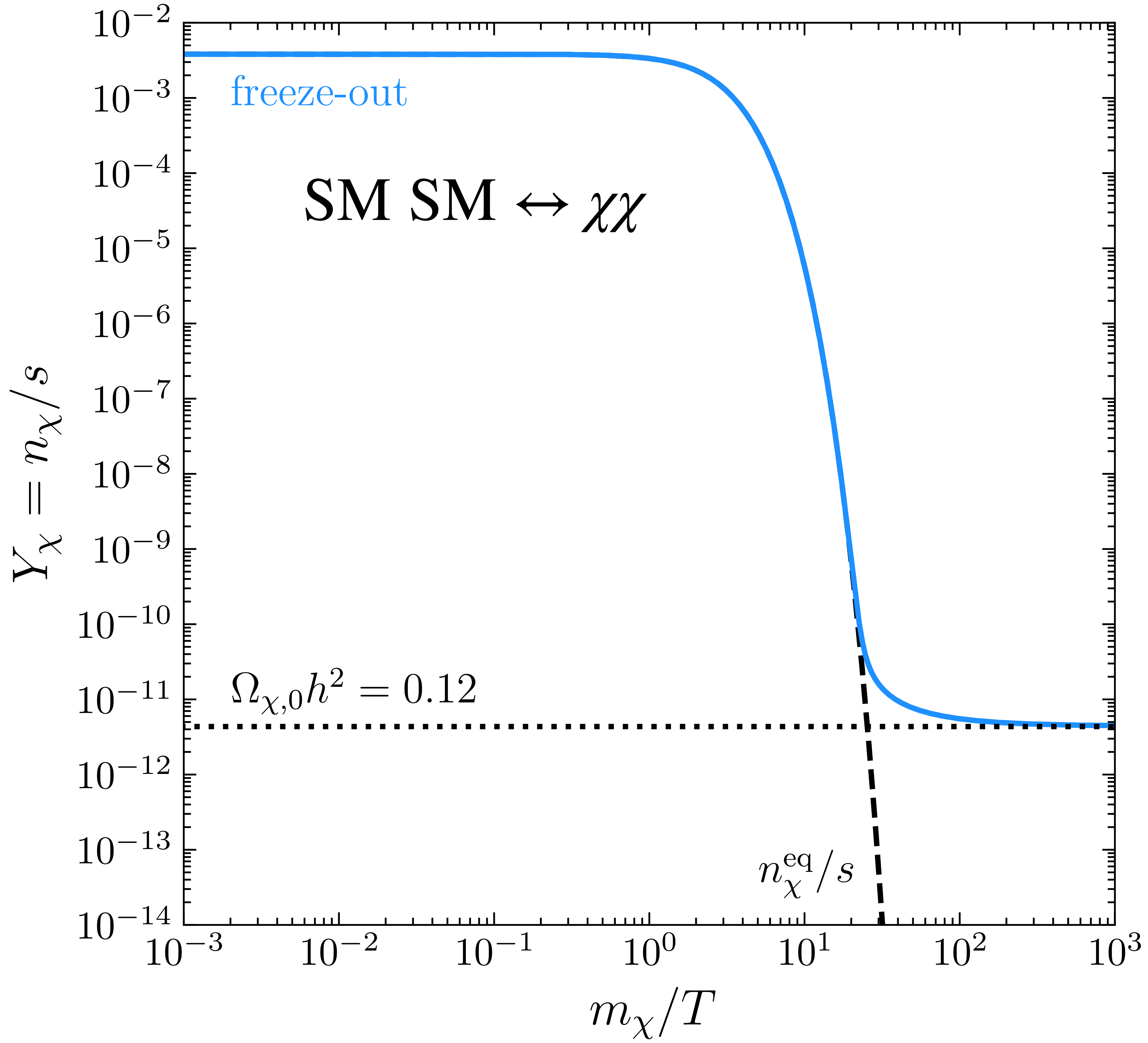
Thermal



Non-Thermal



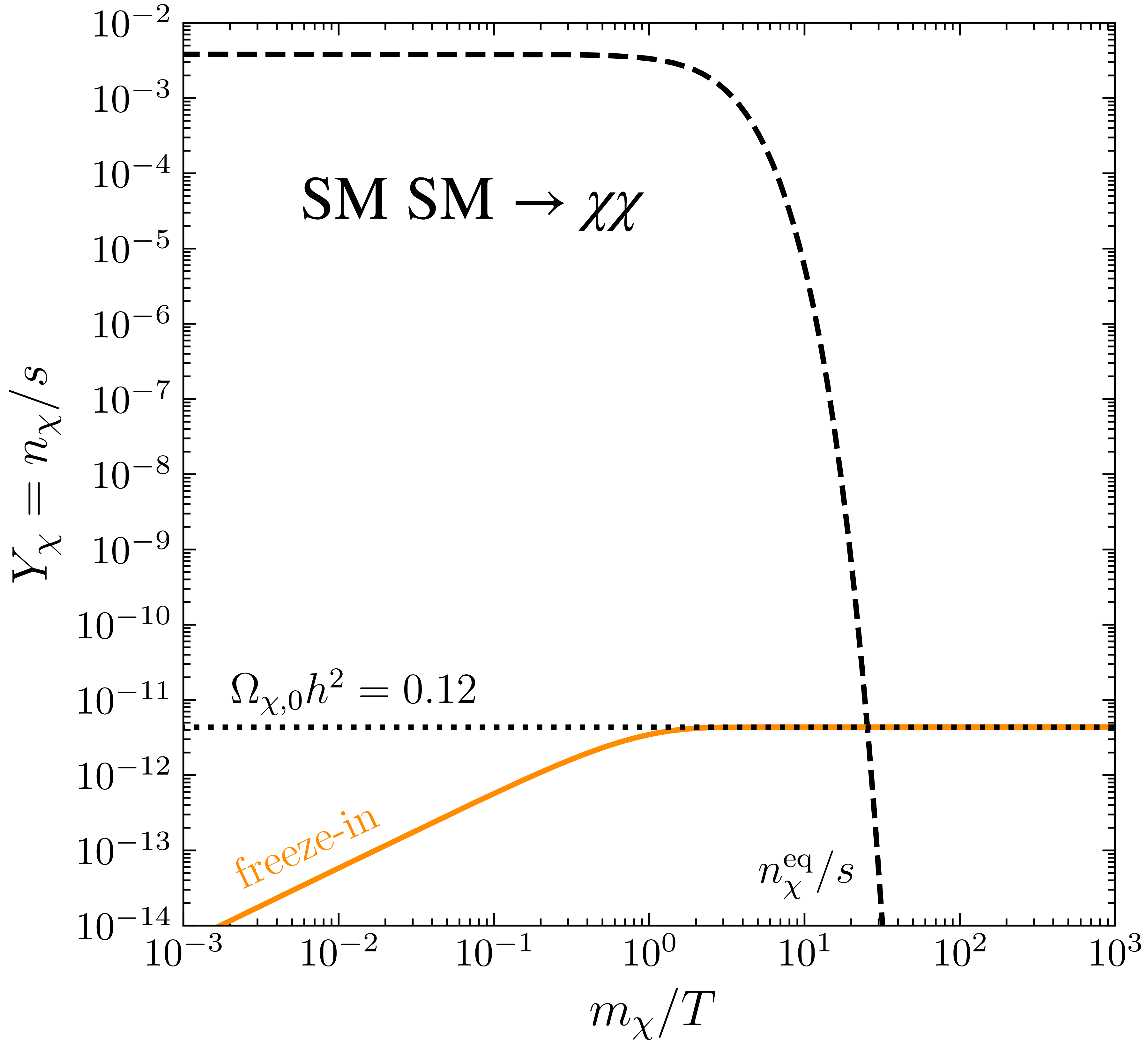
Thermal



Many variants of freeze-out:

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

Non-Thermal



Less variants for freeze-in

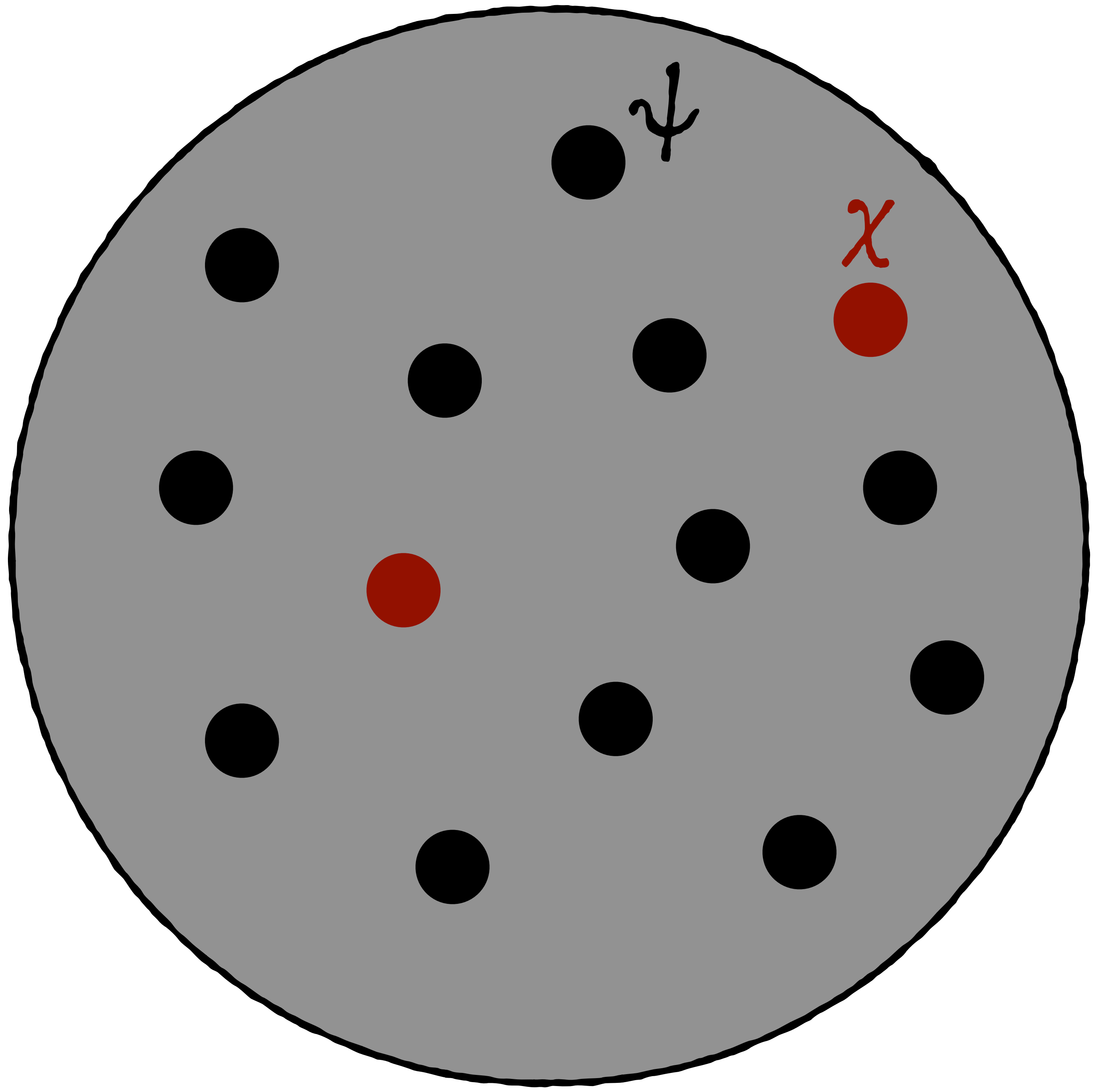
Dark Matter from Exponential Growth

Bringmann, PFD et al. 2103.16572

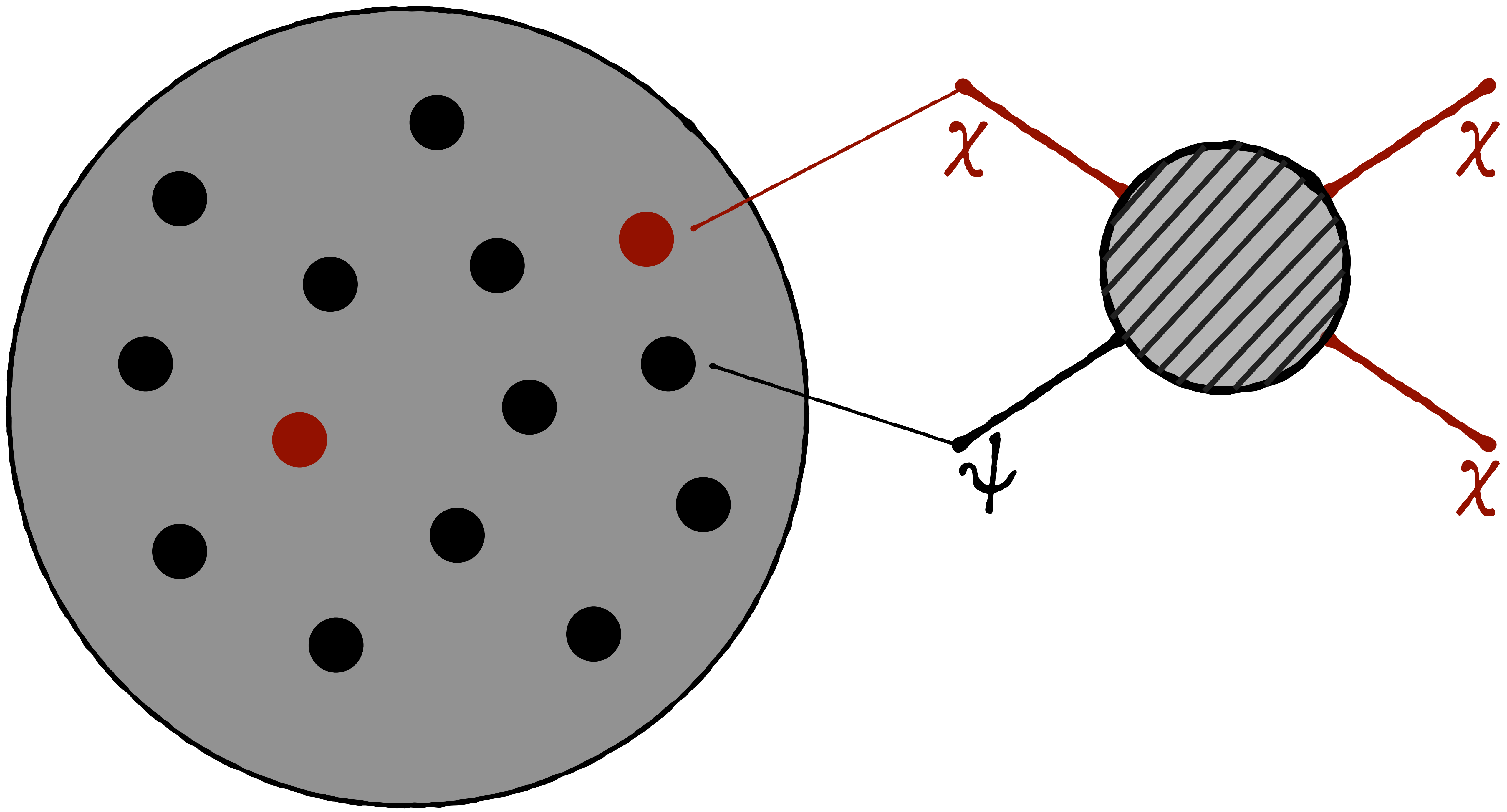
Hryczuk and Laletin 2104.05684

(First DM production mechanism w/ exponential growth!)

Dark matter from exponential growth



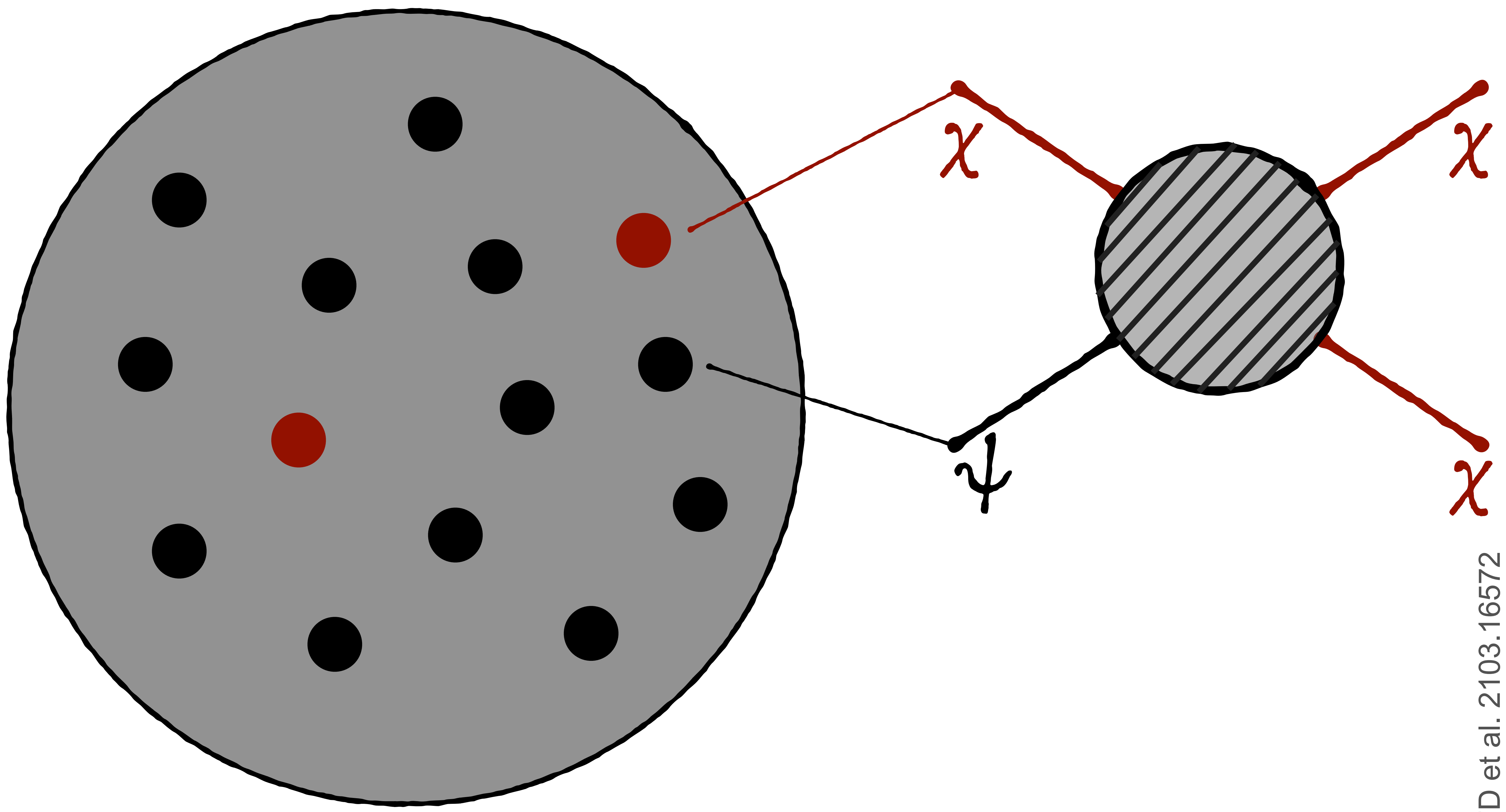
Dark matter from exponential growth



Bringmann, PFD et al. 2103.16572

Dark matter from exponential growth

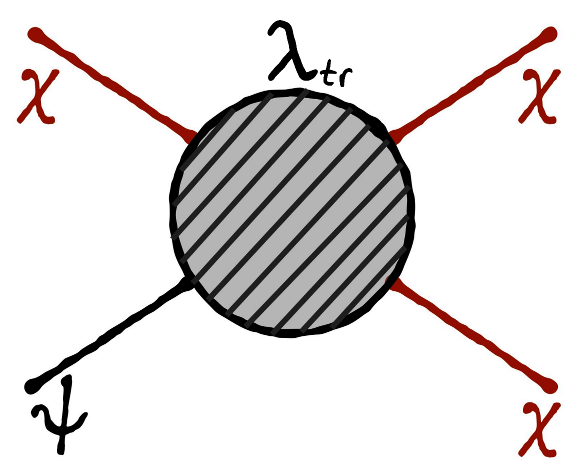
- $\dot{n}_\chi + 3Hn_\chi = C_{\psi\chi\to\chi\chi} \sim \langle\sigma v\rangle_{\rm tr}\, n_\psi^{\rm eq} n_\chi$
- $Y_\chi(x_\psi) \equiv n_\chi/s \simeq Y_\chi^0 \exp\left(3\int_{x_\psi^0}^{x_\psi} \frac{\mathrm{d}x}{x} R(x)\right)$
- $R(x) = \frac{n_\psi^{\rm eq}\langle\sigma v\rangle_{\rm tr}}{3H}$: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



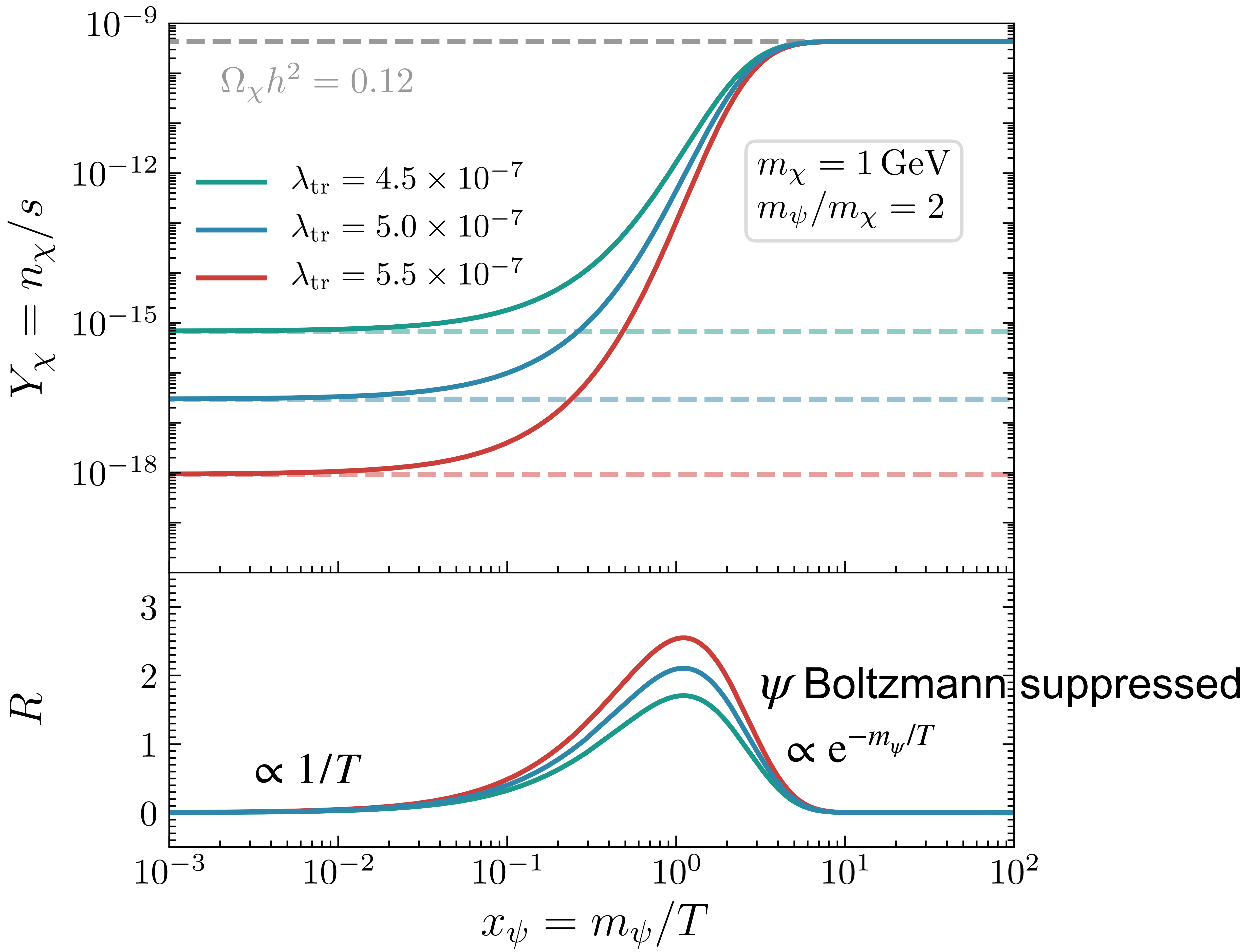
Bringmann, PFD et al. 2103.16572

Evolution of DM abundance

Fixed initial abundance



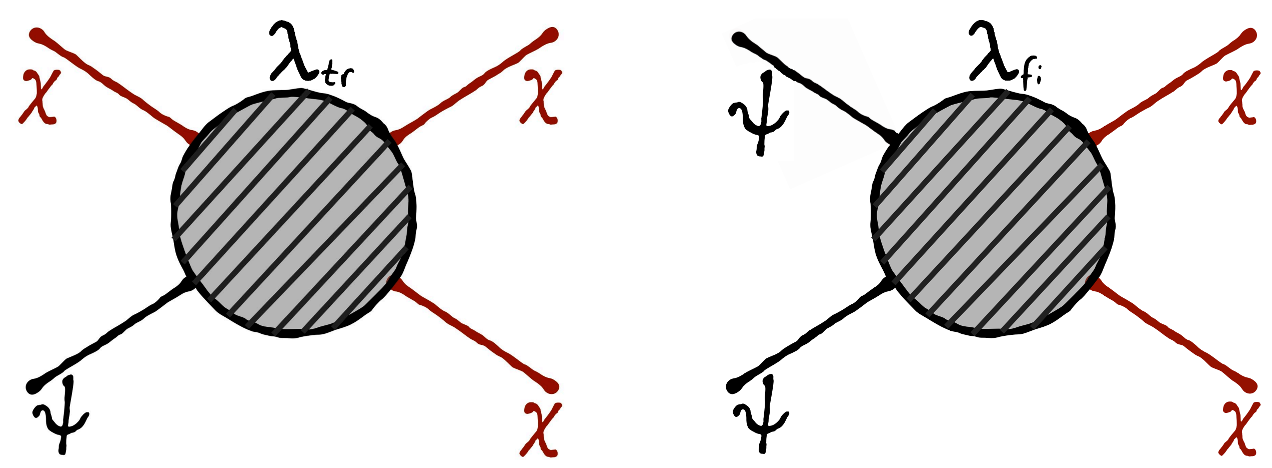
$$\dot{n}_\chi + 3Hn_\chi = \langle\sigma v\rangle_{\rm tr}\, n_\psi^{\rm eq} n_\chi$$



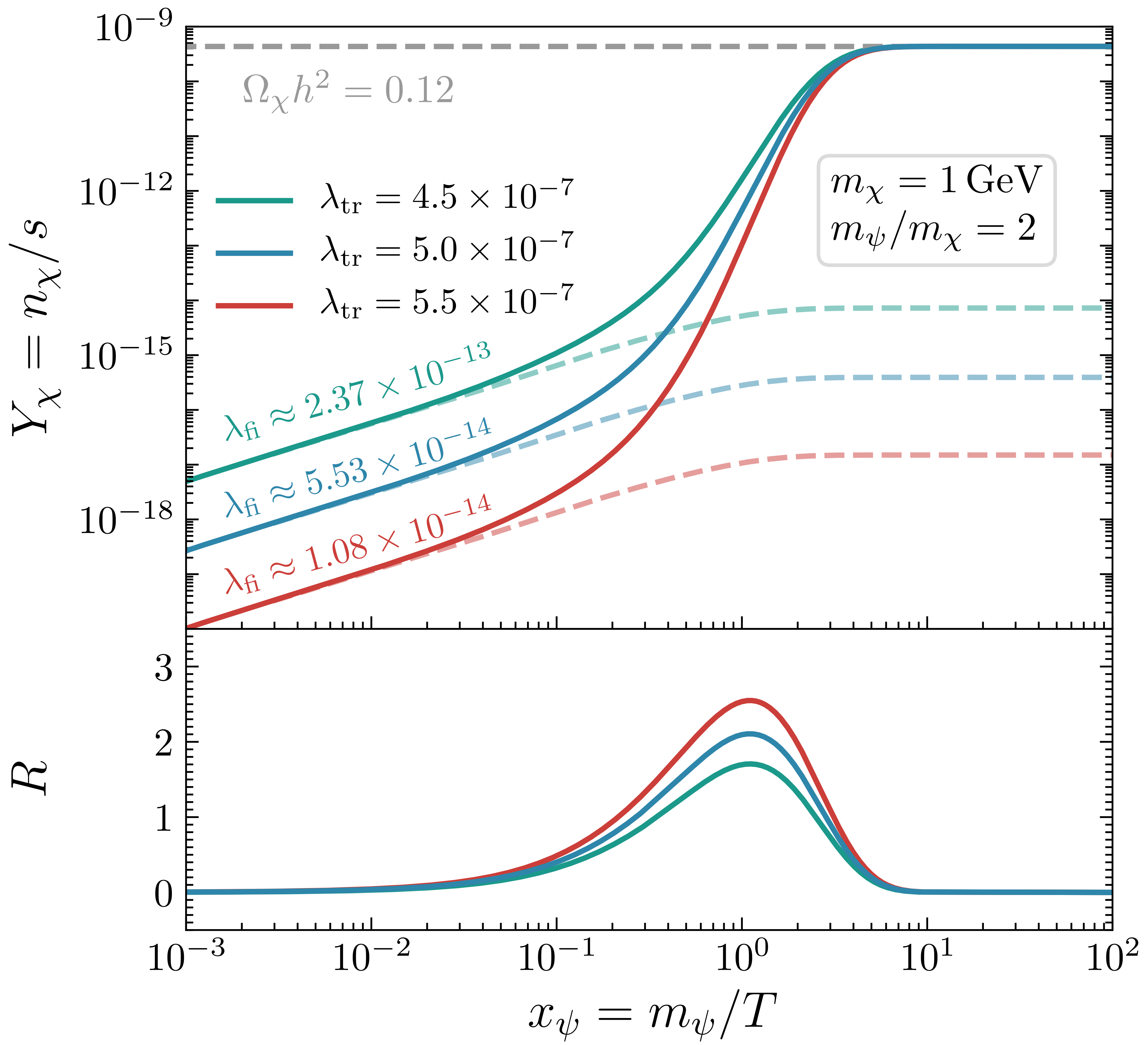
Bringmann, PFD et al. 2103.16572

Evolution of DM abundance

Initial abundance from freeze-in



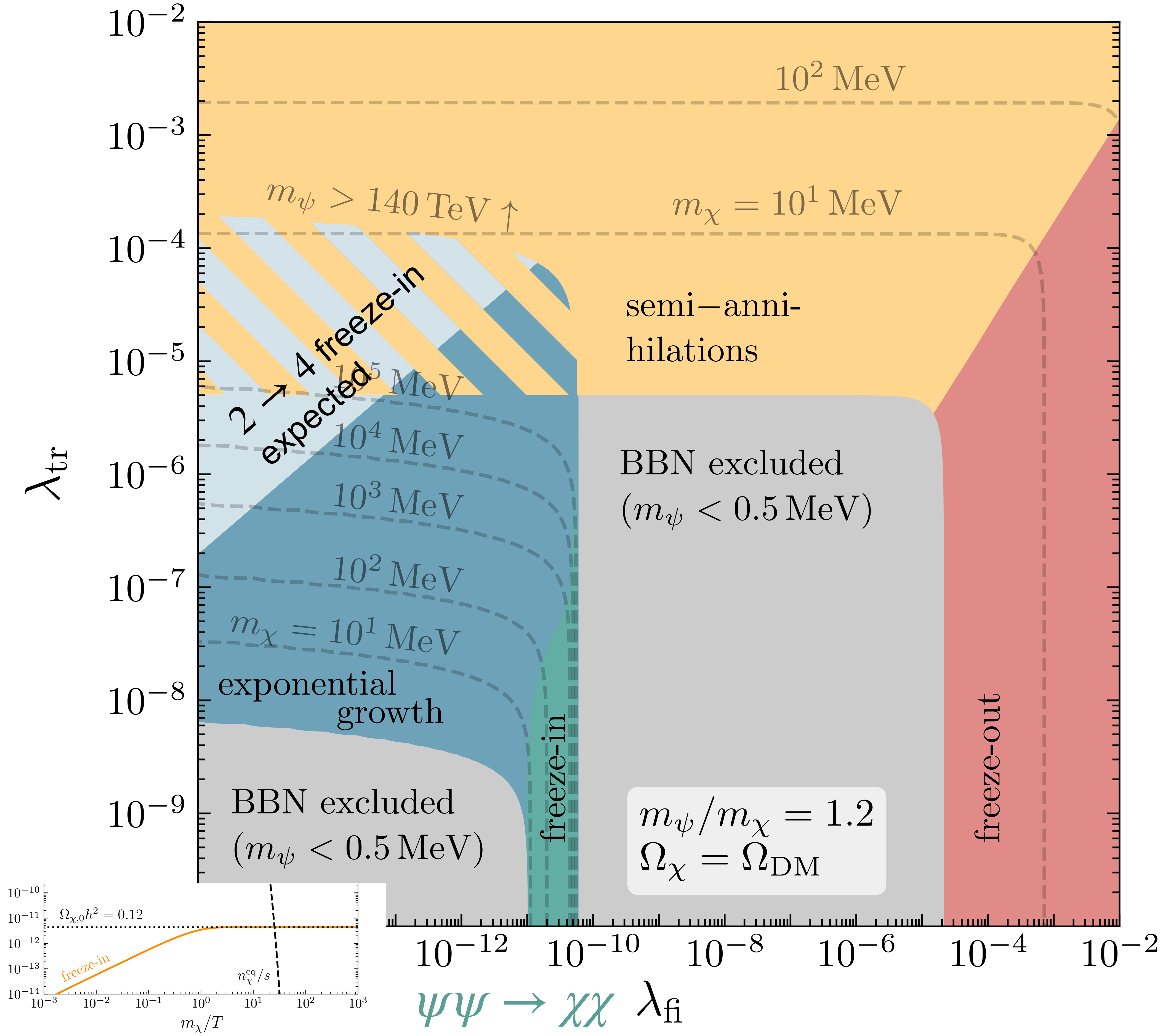
$$\dot{n}_\chi + 3Hn_\chi = \langle\sigma v\rangle_{\rm tr}\, n_\psi^{\rm eq} n_\chi + \langle\sigma v\rangle_{\rm fi}\, (n_\psi^{\rm eq})^2$$



Bringmann, PFD et al. 2103.16572

Phase diagram

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



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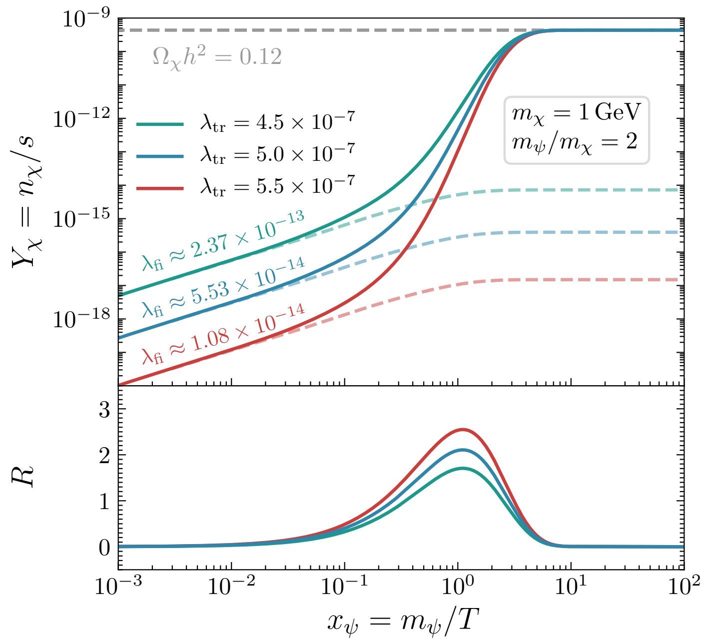
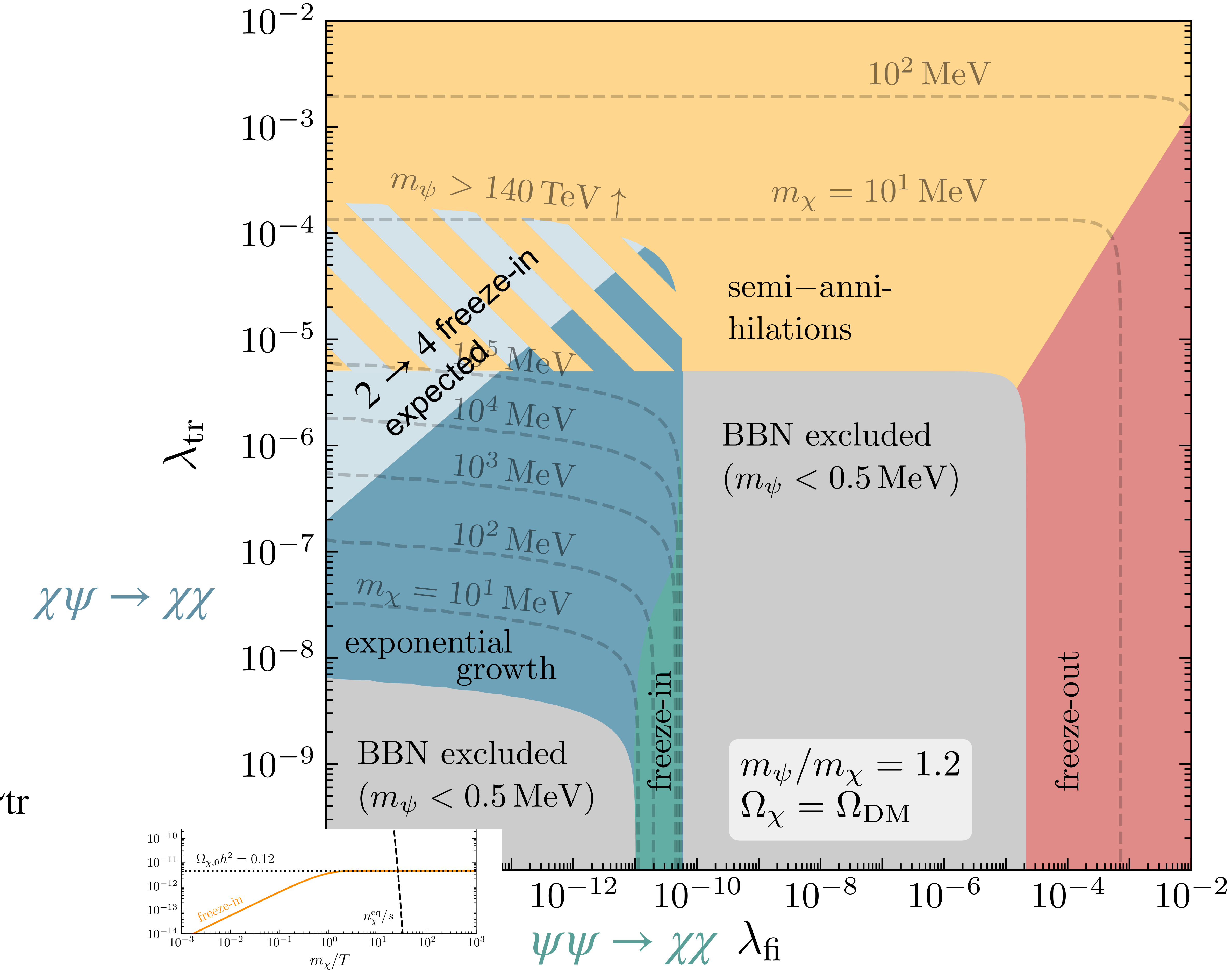


Generally: $\lambda_{\text{fi}} \ll \lambda_{\text{tr}}$



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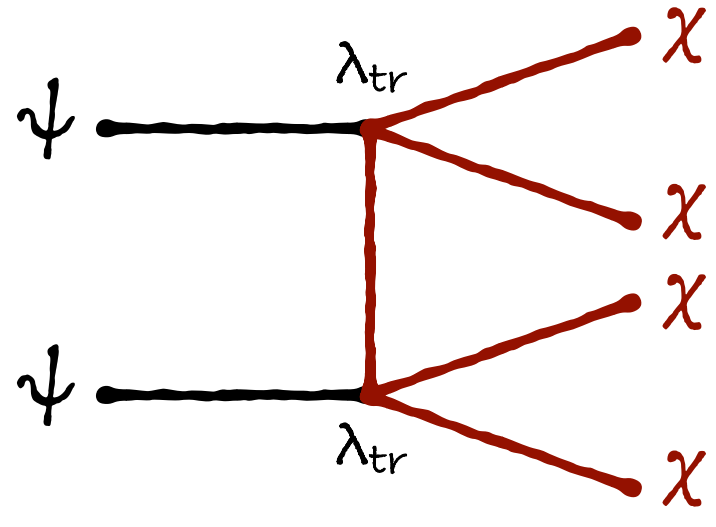
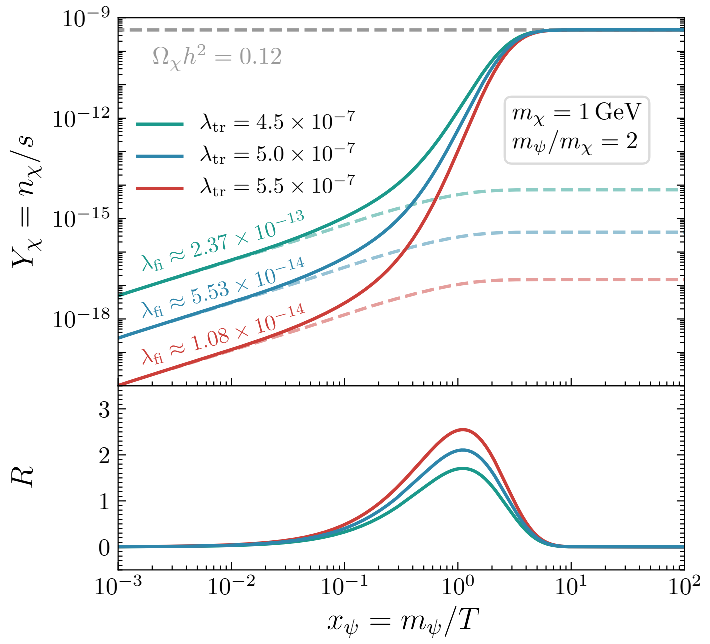
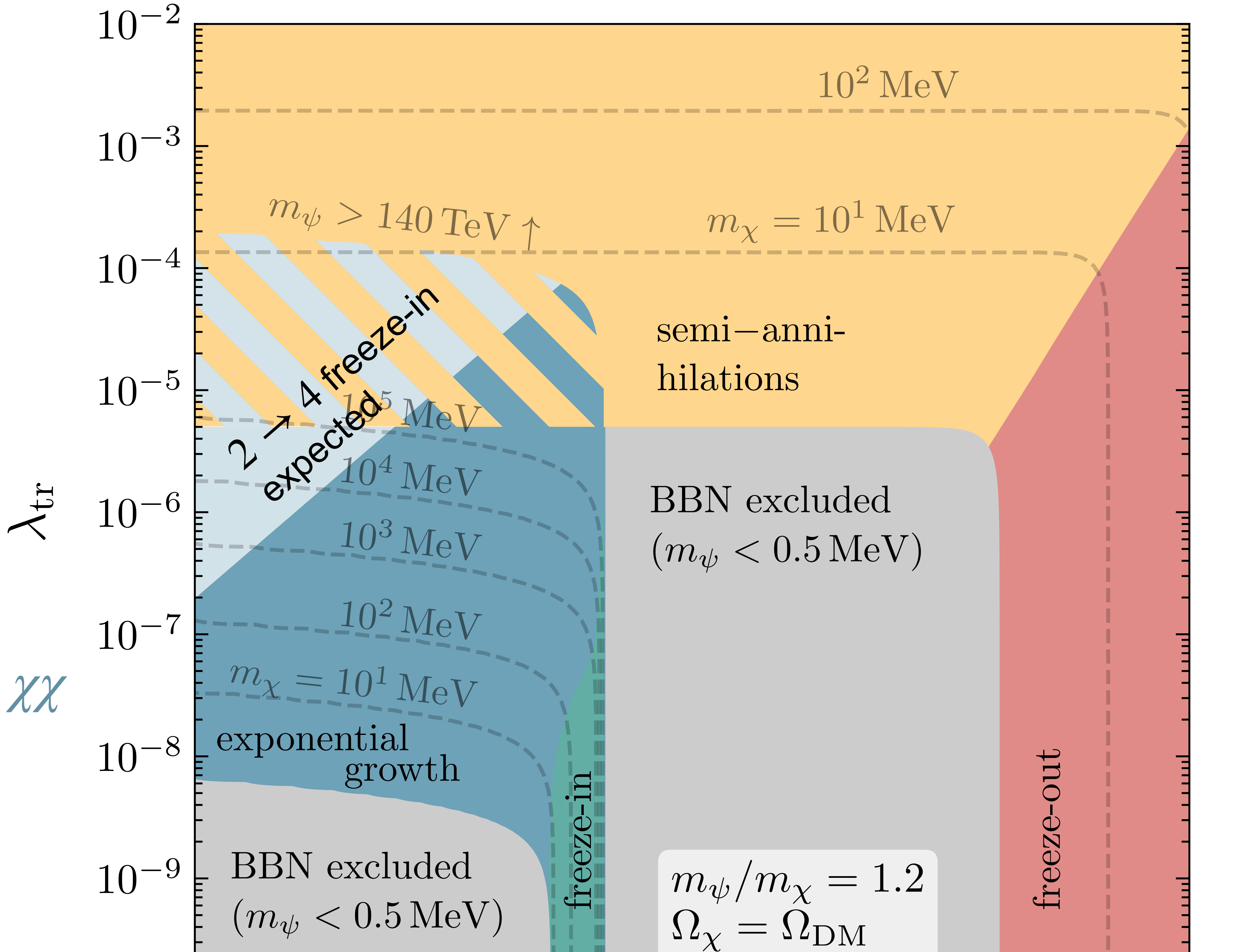
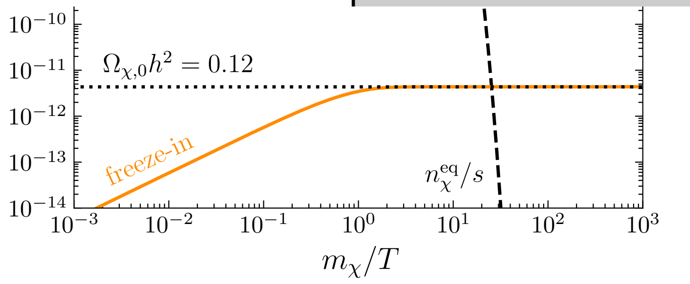






$\chi\psi \to \chi\chi$



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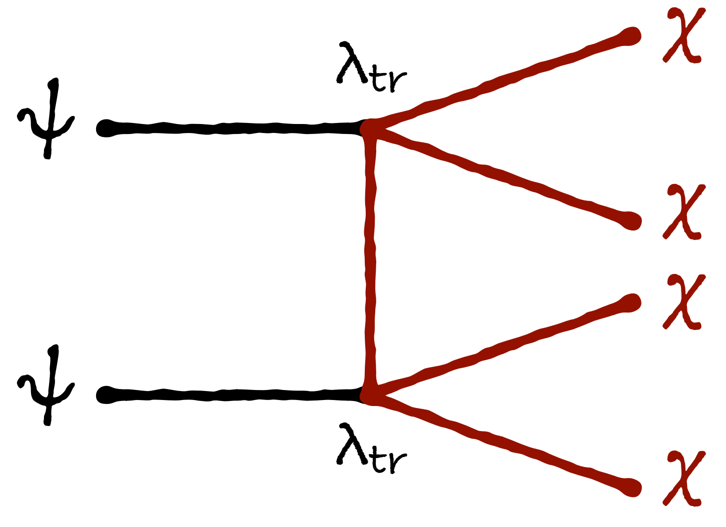
Generally: $\lambda_{\rm fi} \ll \lambda_{\rm tr}$

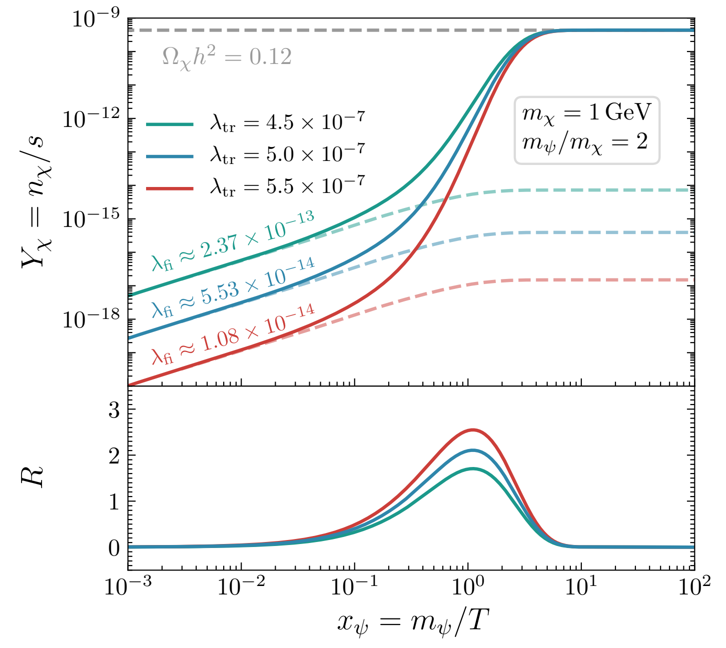
Bringmann, PFD et al. 2103.16572

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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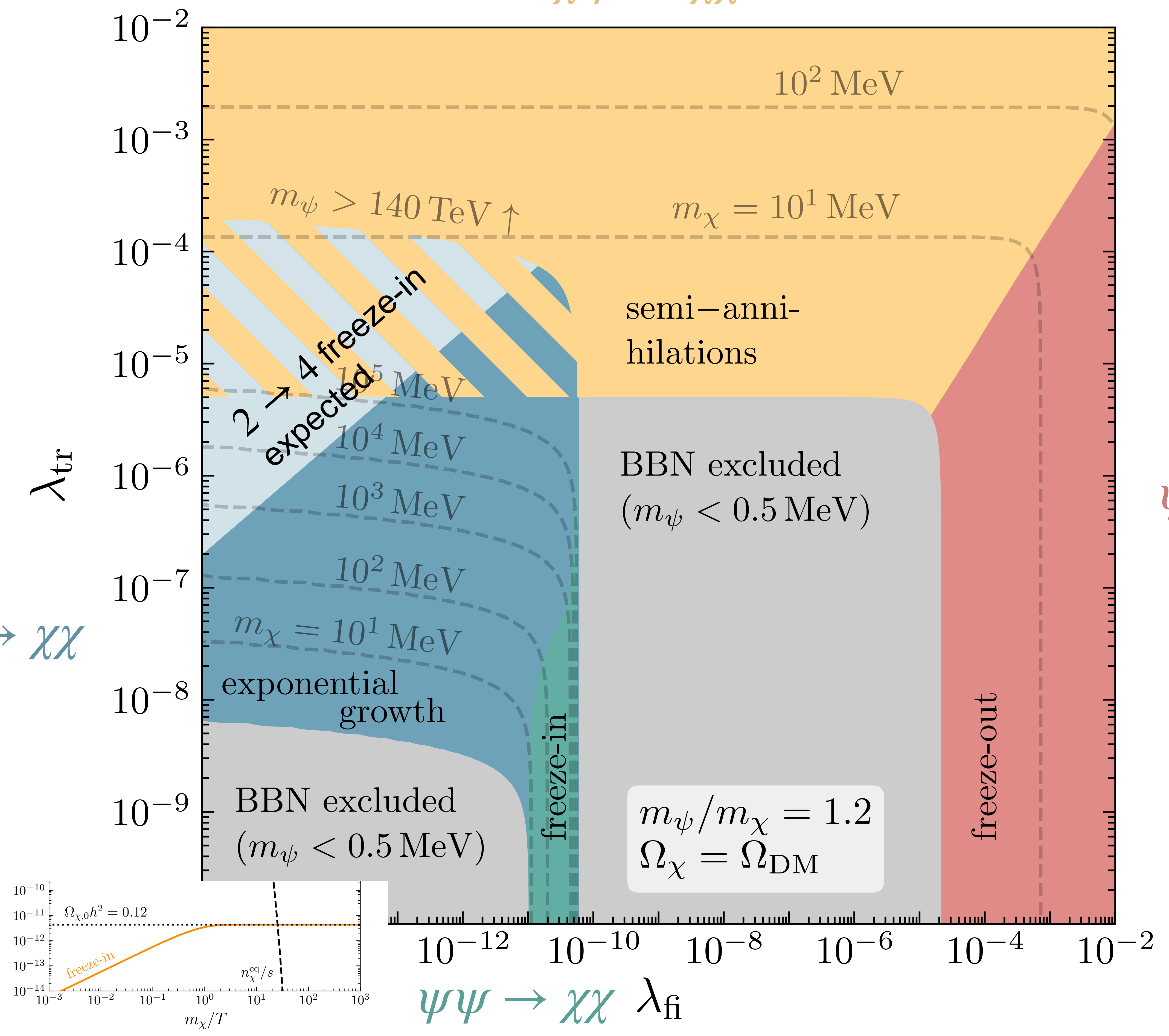

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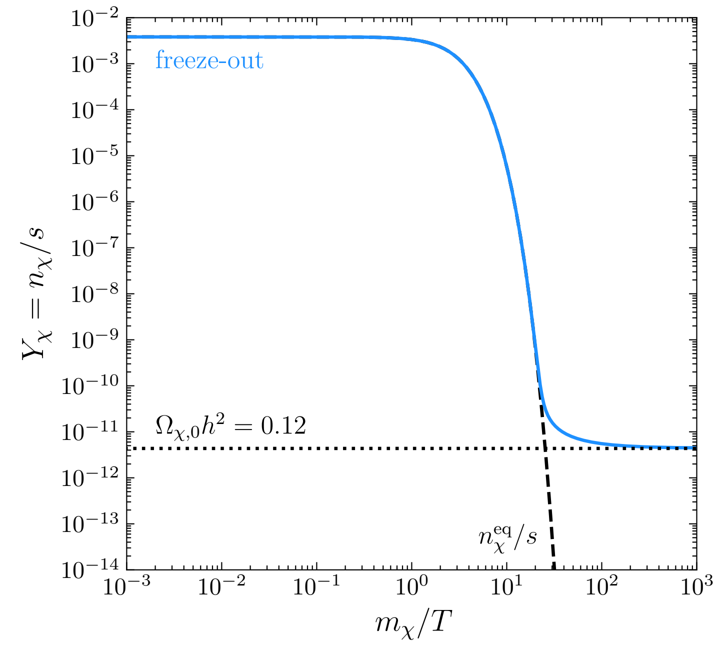

$\psi\psi \leftrightarrow \chi\chi$

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

Bringmann, PFD et al. 2103.16572

Model setup

Necessary conditions

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

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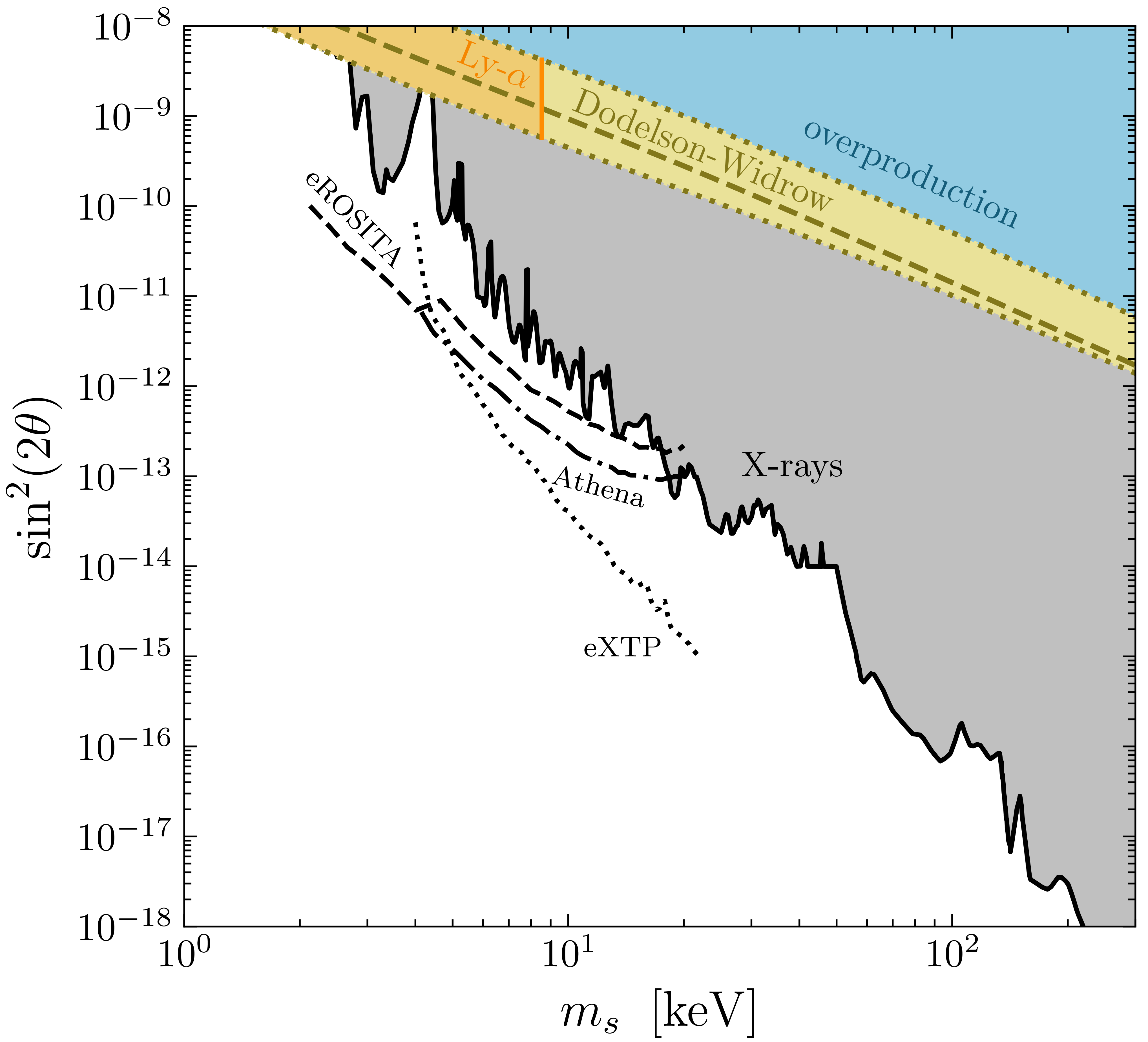
- Generate initial abundance
- Realize hierarchy of (effective) couplings $\lambda_{\text{freeze-in},\, \psi\psi\to\chi\chi} \ll \lambda_{\text{transformation},\, \psi\chi\to\chi\chi} \ll 1$
  - Two fermions with small mass mixing angle θ, only one (mostly χ) interacts with some mediator ϕ via Yukawa 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 ($\chi = \nu_s$, right-handed), mass-mixing with active neutrino ($\psi = \nu_\alpha$, left-handed)
- $\mathscr{L}_m = -\frac{1}{2}\overline{\nu_s^c} m_s \nu_s - \overline{\nu_\alpha} m_{\alpha s} \nu_s - \frac{1}{2}\overline{\nu_\alpha^c} m_\alpha \nu_\alpha$ + h.c.
- $m_\alpha \ll m_s \Rightarrow \theta \simeq m_{\alpha s}/m_s$



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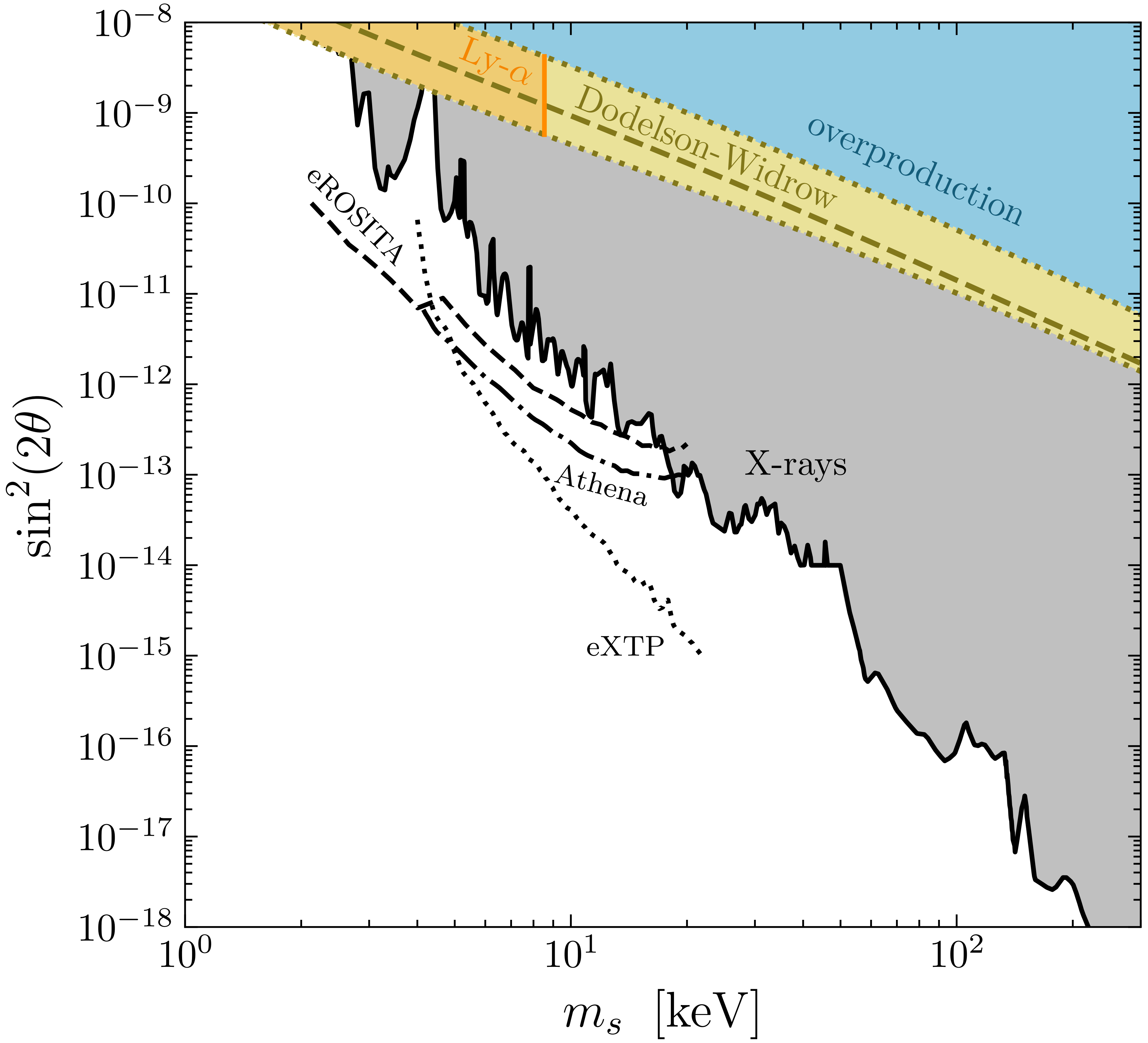
- $m_\alpha \ll m_s \Rightarrow \theta \simeq m_{\alpha s}/m_s$
- Yukawa coupling between mediator ϕ and ν_s in flavor-space generates hierarchy of couplings:
- $\mathscr{L}_{\phi,\mathrm{int}} = \frac{y}{2}\phi\overline{\nu_s^c}\nu_s$ + h.c.

$\rightarrow \frac{y}{2}\phi\left(\cos^2\theta\,\overline{\nu_s^c}\nu_s - \sin(2\theta)\,\overline{\nu_\alpha}\nu_s + \sin^2\theta\,\overline{\nu_\alpha^c}\nu_\alpha\right)$ + h.c.



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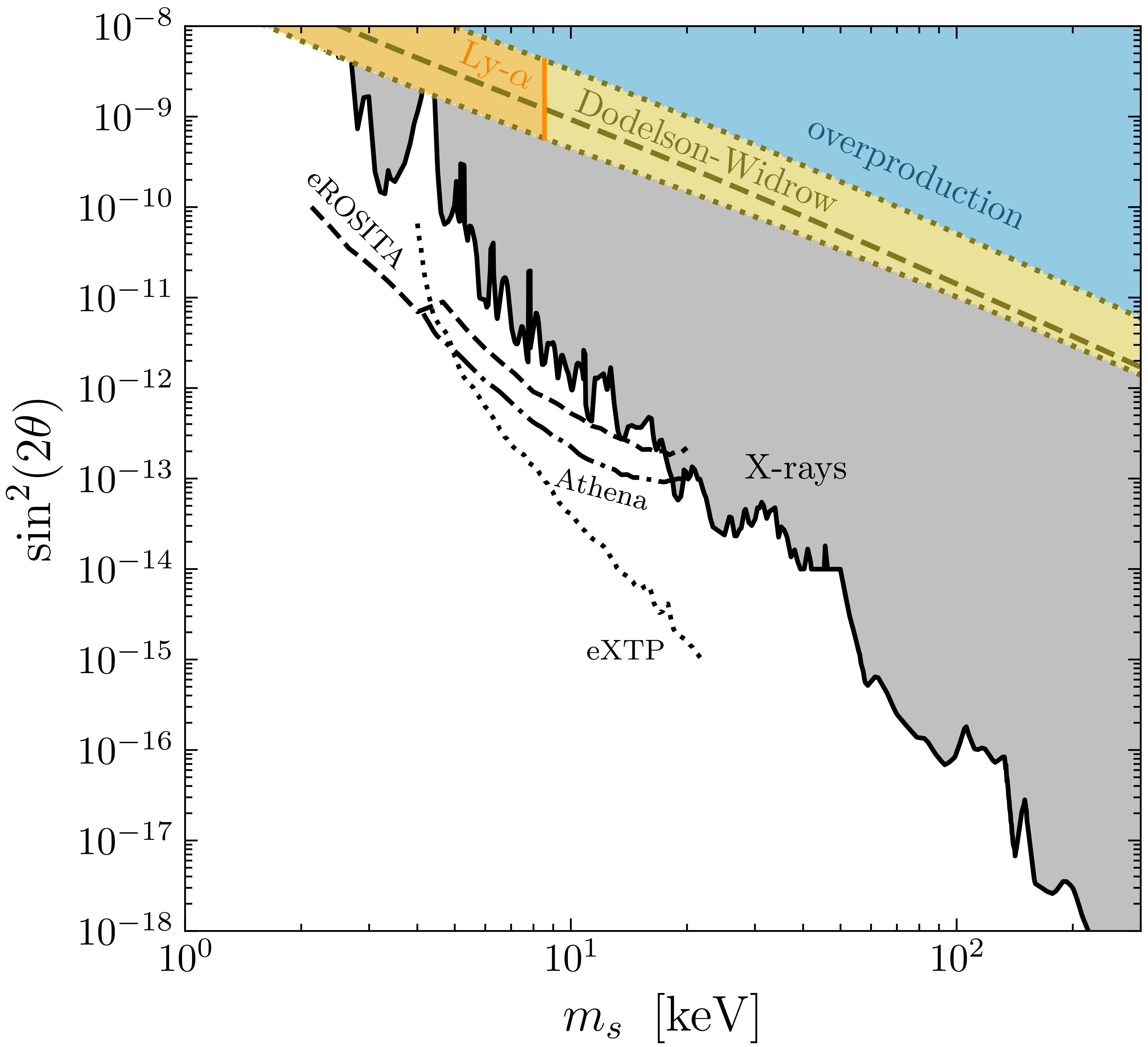
  $\rightarrow \frac{y}{2}\phi\left(\cos^2\theta\,\overline{\nu_s^c}\nu_s - \sin(2\theta)\,\overline{\nu_\alpha}\nu_s + \sin^2\theta\,\overline{\nu_\alpha^c}\nu_\alpha\right) +$ h.c.
- Consider $m_\phi > 2m_s$
- Use Majorana spinors from now on



Comparison to other works

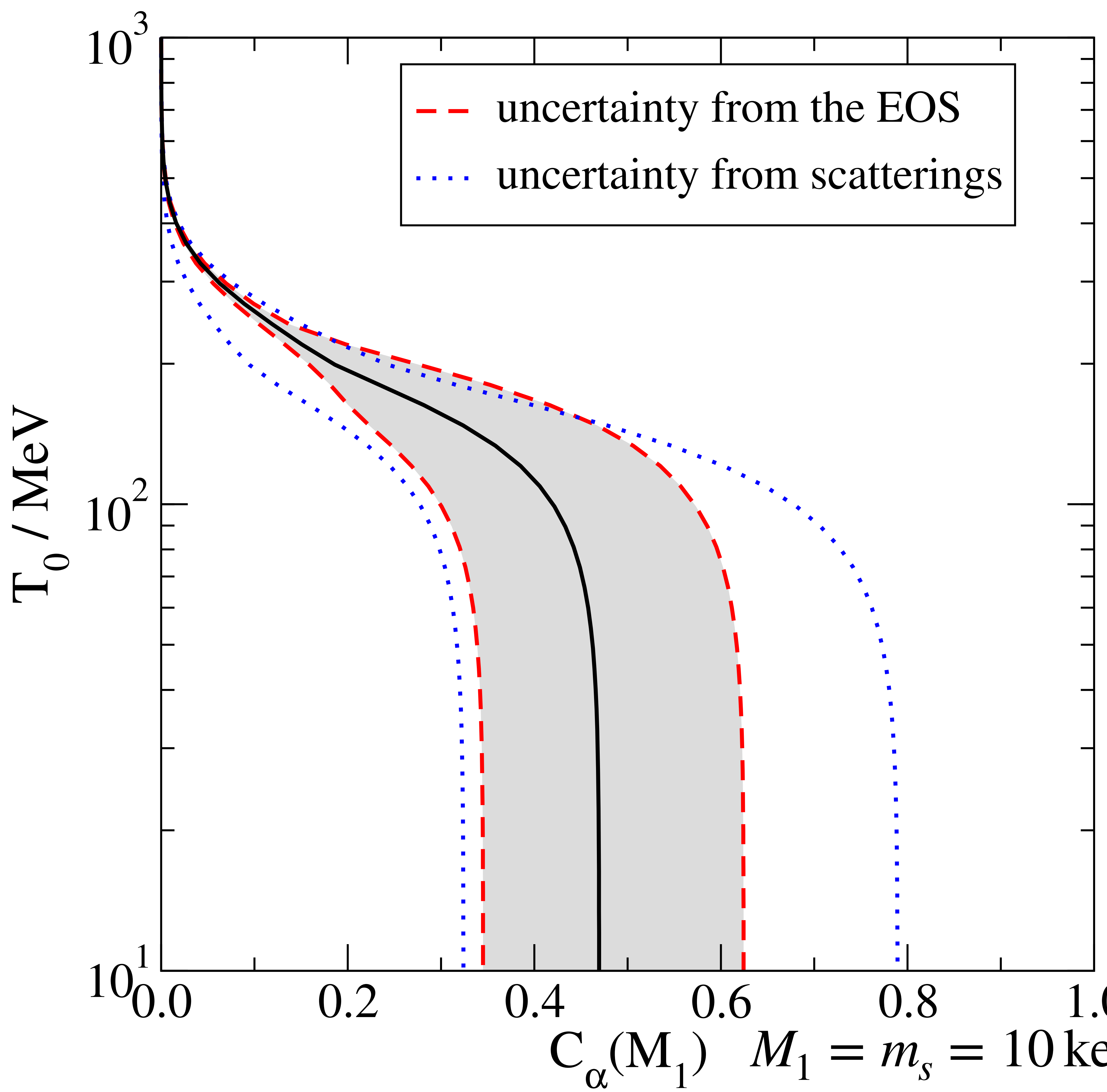
- Dodelson-Widrow scenario (Dodelson and Widrow hep-ph/9303287): excluded
- Shi-Fuller mechanism (Shi and Fuller astro-ph/9810076): production by resonant oscillations due to large lepton asymmetry (origin?), bounds from X-rays, Lyman-α, and BBN already very strong
- Decay of scalar
- New interactions of active neutrinos
- Extended gauge sector
- New interactions of sterile neutrinos

Comparison to other works

- New interactions of sterile neutrinos
- Particularly simple as only a scalar and Yukawa couplings are needed, no issues with SU(2) invariance
- $m_\phi > 1\,\mathrm{GeV}$ (Johns and Fuller 1903.08296)
    - Interactions affect in-medium neutrino potential
    - Either no impact or runaway production $\rightarrow$ does not work
- $m_\phi \sim 100\,\mathrm{keV}$ (Hansen and Vogl 1706.02707)
    - Thermalization of dark sector with zero chemical potential (number-changing interactions e.g. in scalar potential)
    - Viable for $m_s \simeq 4\,\mathrm{keV}$ (but Lyman-α very close) or lepton asymmetry
- $m_\phi > 2m_s$ (Bringmann, PFD et al. 2206.10630) $\leftarrow$ this work
    - Viable due to exponential growth of abundance!

Initial abundance

- Dodelson-Widrow mechanism still present, but only produces small initial abundance
  - Exactly what we need!
- Boltzmann equation:
- $\frac{\partial f_s}{\partial t} - Hp\frac{\partial f_s}{\partial t} = \frac{\Gamma_\alpha}{2}\sin^2(2\theta_M) f_\alpha$
- Mostly active around $T \sim 130\,\mathrm{MeV}(m_s/1\,\mathrm{keV})^{1/3}$
- We use results for number and energy density from Asaka, Laine, and Shaposhnikov hep-ph/0612182
  - Most precise calculation on the market, derived from first principles

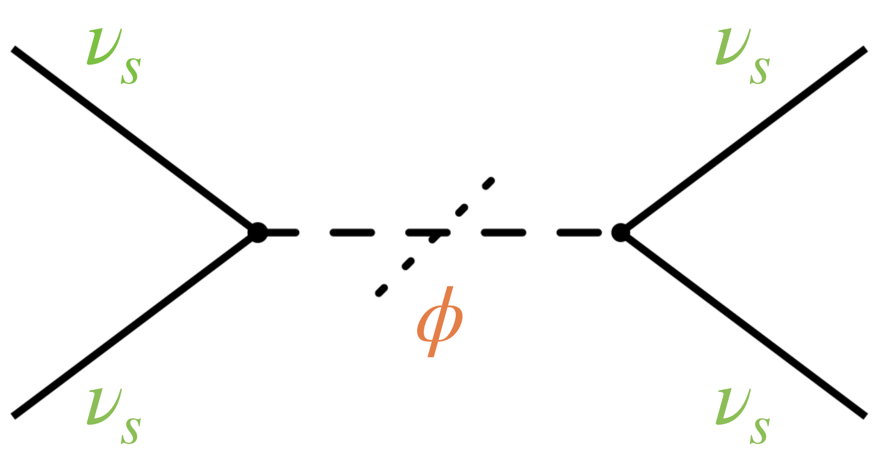


$M_1 = m_s = 10\,\mathrm{keV}$

$\Omega_s h^2 = 0.11\,(\theta m_s/0.1\,\mathrm{eV})^2\,C_\alpha(m_s)$

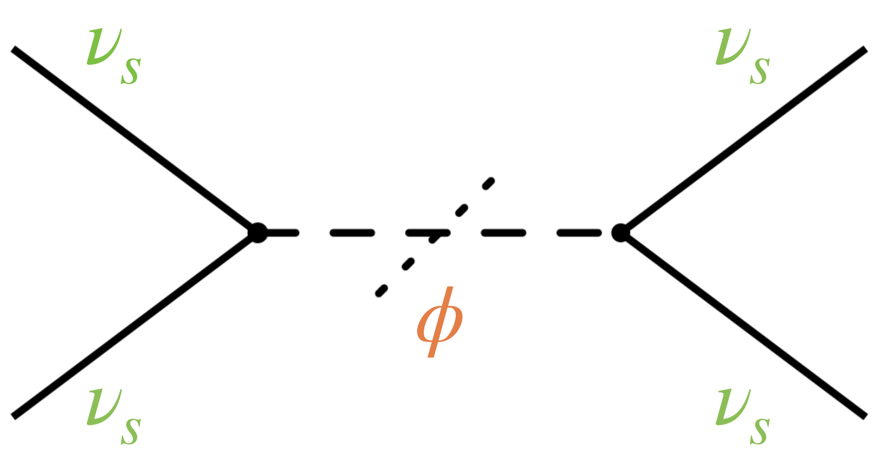
Asaka, Laine, and Shaposhnikov hep-ph/0612182

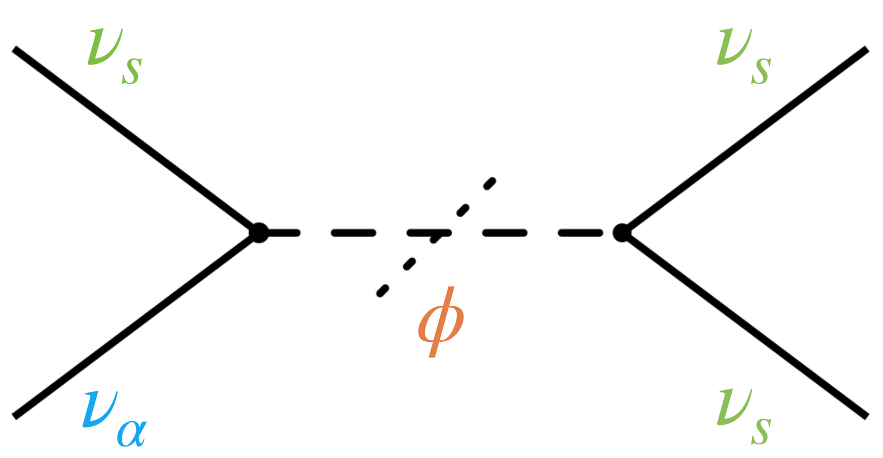
Relevant processes



- Thermalizes dark sector
- Common temperature T_d
- Chemical potentials
  $2\mu_s = \mu_\phi$

Relevant processes





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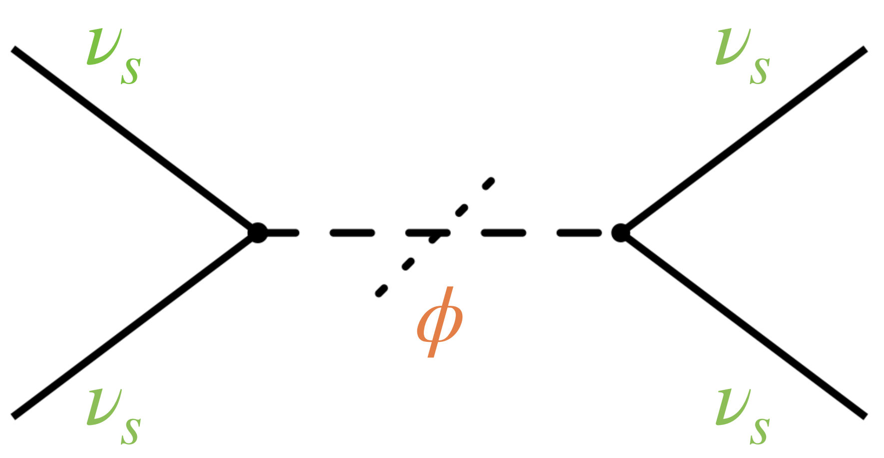
- Responsible for exponential growth

Relevant processes



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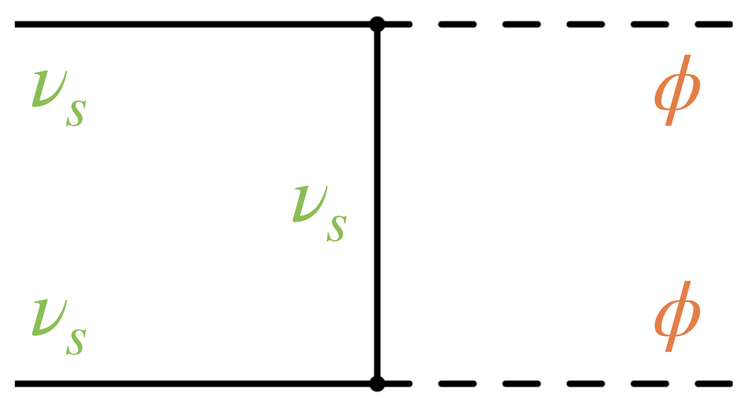
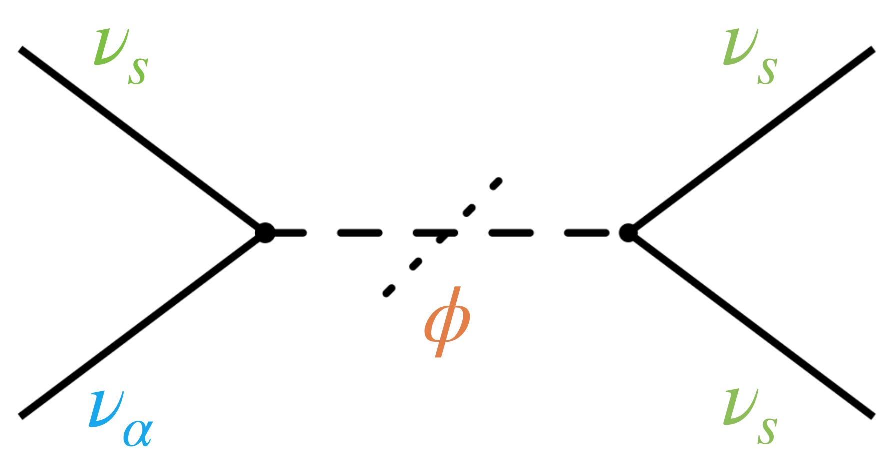


- Effectively turns $2\nu_s$ into $4\nu_s$
- Leads to additional growth in abundance between Dodelson-Widrow production and exponential growth



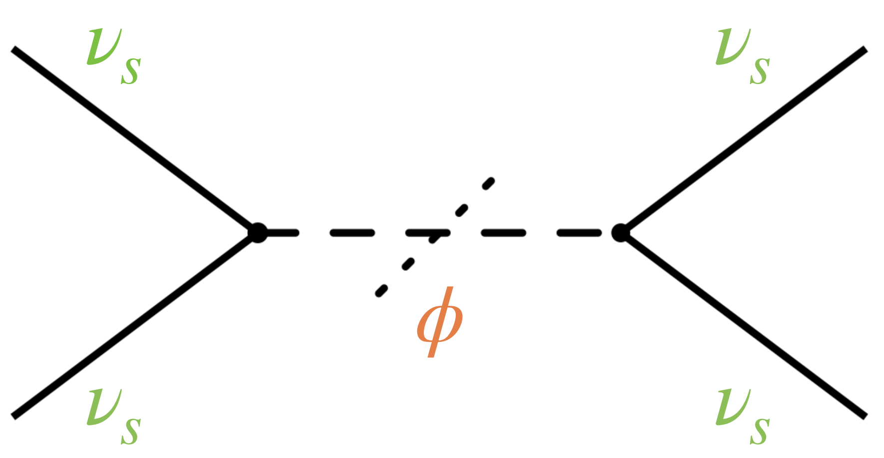
- Responsible for exponential growth

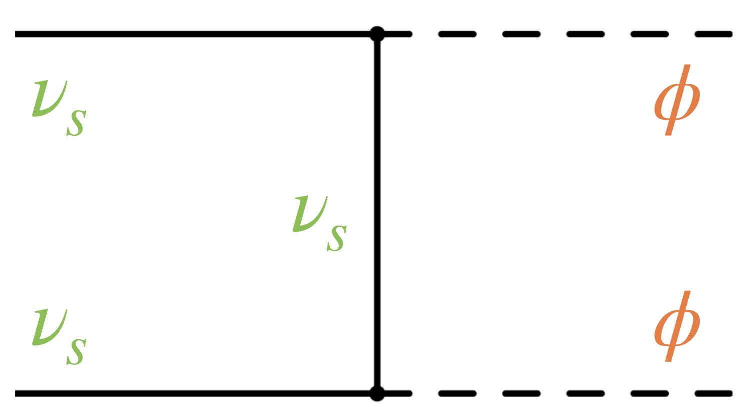
Evolution equations

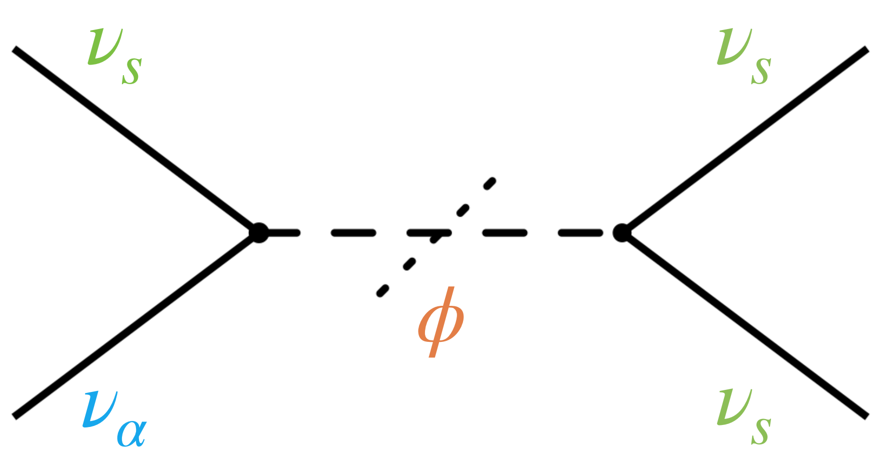
- Thermalization leads to Fermi-Dirac/Bose-Einstein distribution functions
- Can consider integrated Boltzmann equations ($\rho = \rho_s + \rho_\phi$)
- $\dot{n}_s + 3Hn_s = C_{n_s}$
- $\dot{n}_\phi + 3Hn_\phi = C_{n_\phi}$
- $\rho + 3H(\rho + P) = C_\rho$
- Fully take into account spin-statistical factors in collision operators
  - By-product: General formulas, even for 2-to-2 processes
- (Inverse) decays $\nu_s \nu_s \leftrightarrow \phi$ enforce $2\mu_s = \mu_\phi$ $\rightarrow$ replace first two equations with single one for $\tilde{n} = n_s + 2n_\phi$
  - Cancels (inverse) decay terms, leads to more stable numerical implementation

Relevant processes

Contributions to collision operators







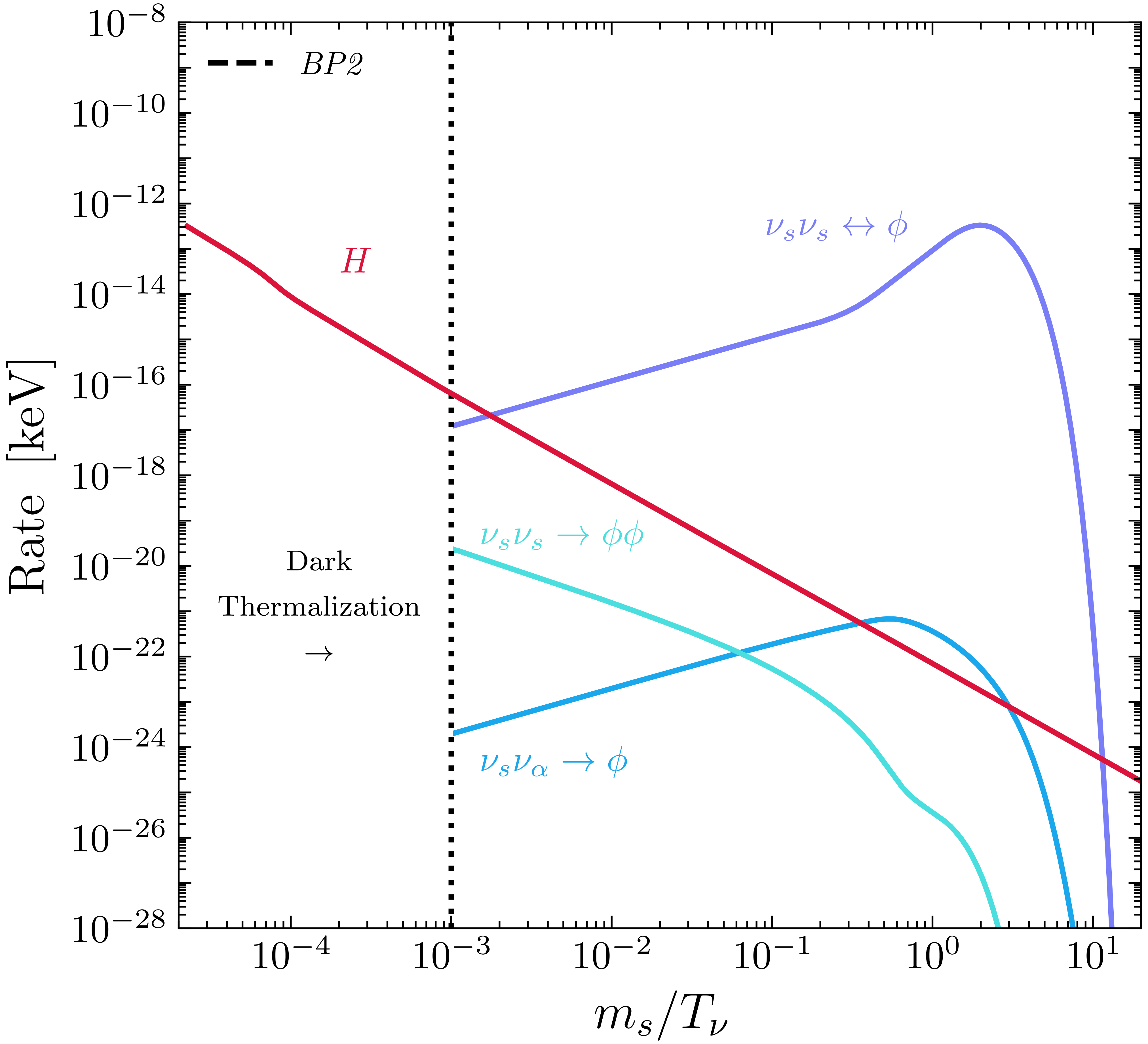
- s-channel resonance dominates (on-shell contribution $\propto y^2$ vs. off-shell $\propto y^4$)
- No contribution to C_ρ or $C_{\tilde{n}}$ (in equilibrium)
- Only needs to be calculated for kinetic decoupling

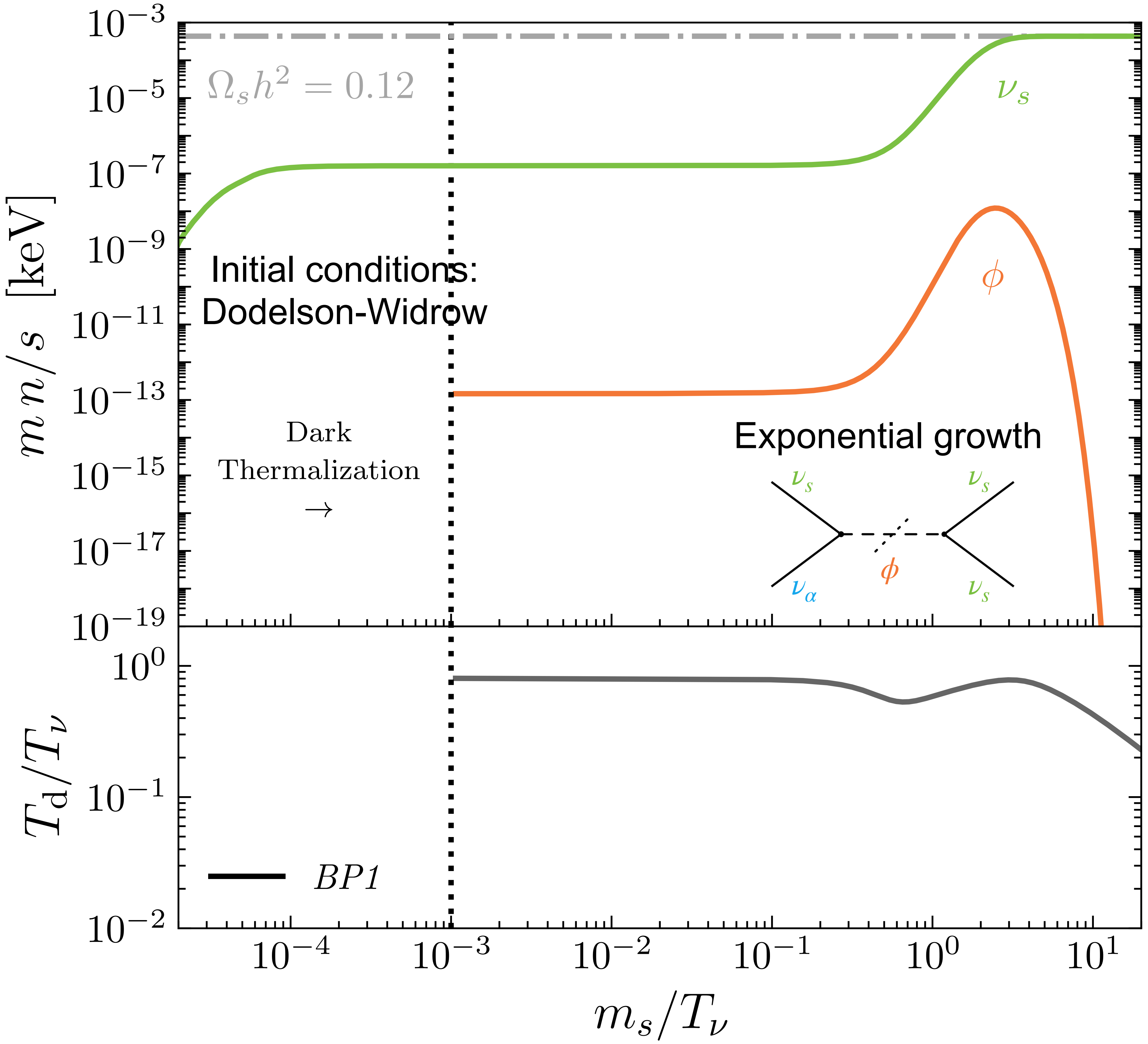
- Still need to calculate full 2-to-2 process
- Always $\propto y^4$, but not suppressed by mixing angle
- No contribution to C_ρ

- s-channel resonance dominates ($\propto y^2$ vs. $\propto y^4$)
- Sufficient to include $\nu_s \nu_\alpha \rightarrow \phi$
- Contribution to C_ρ and $C_{\tilde{n}}$

Evolution

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



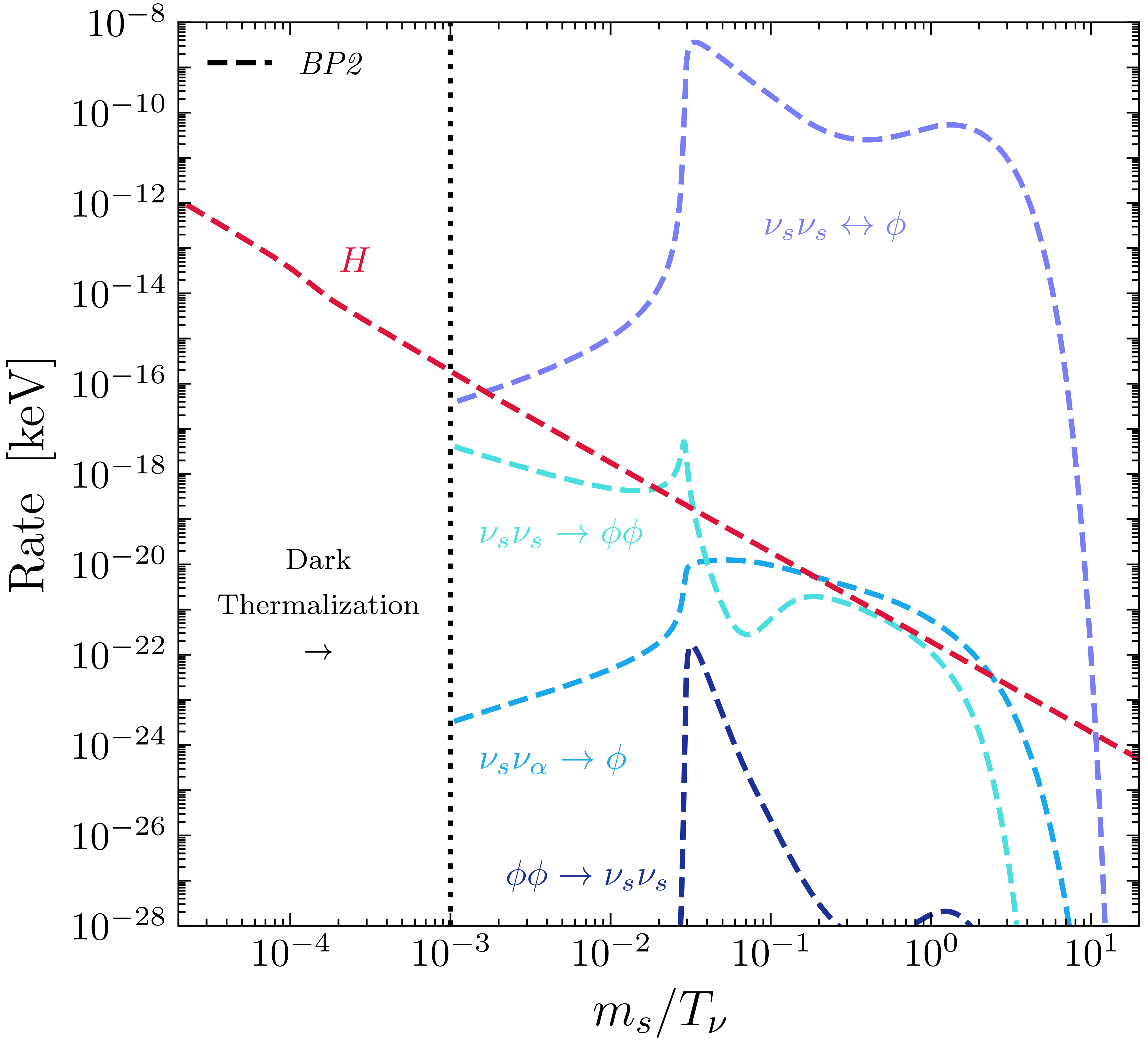


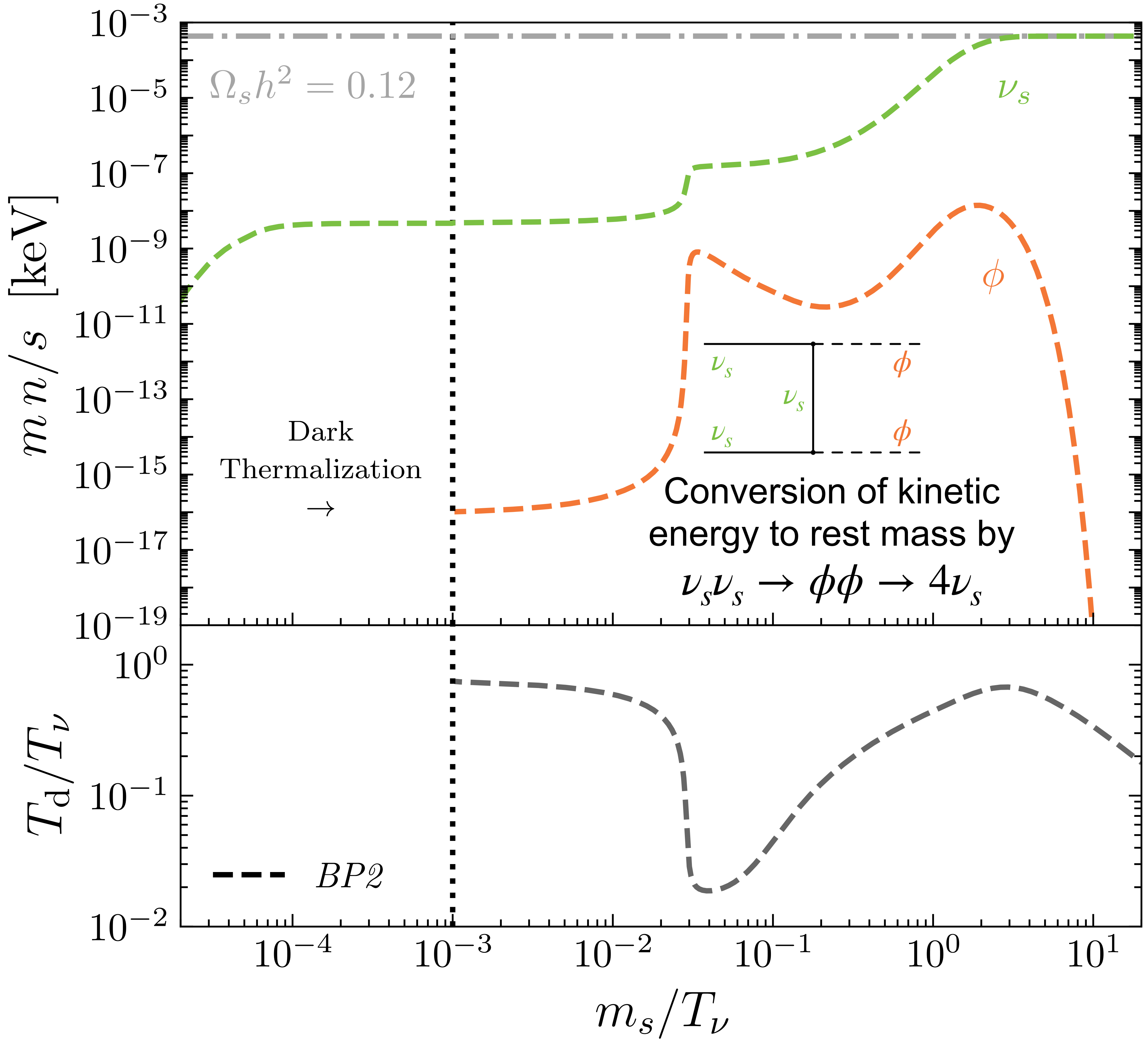
Bringmann, PFD et al. 2206.10630

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





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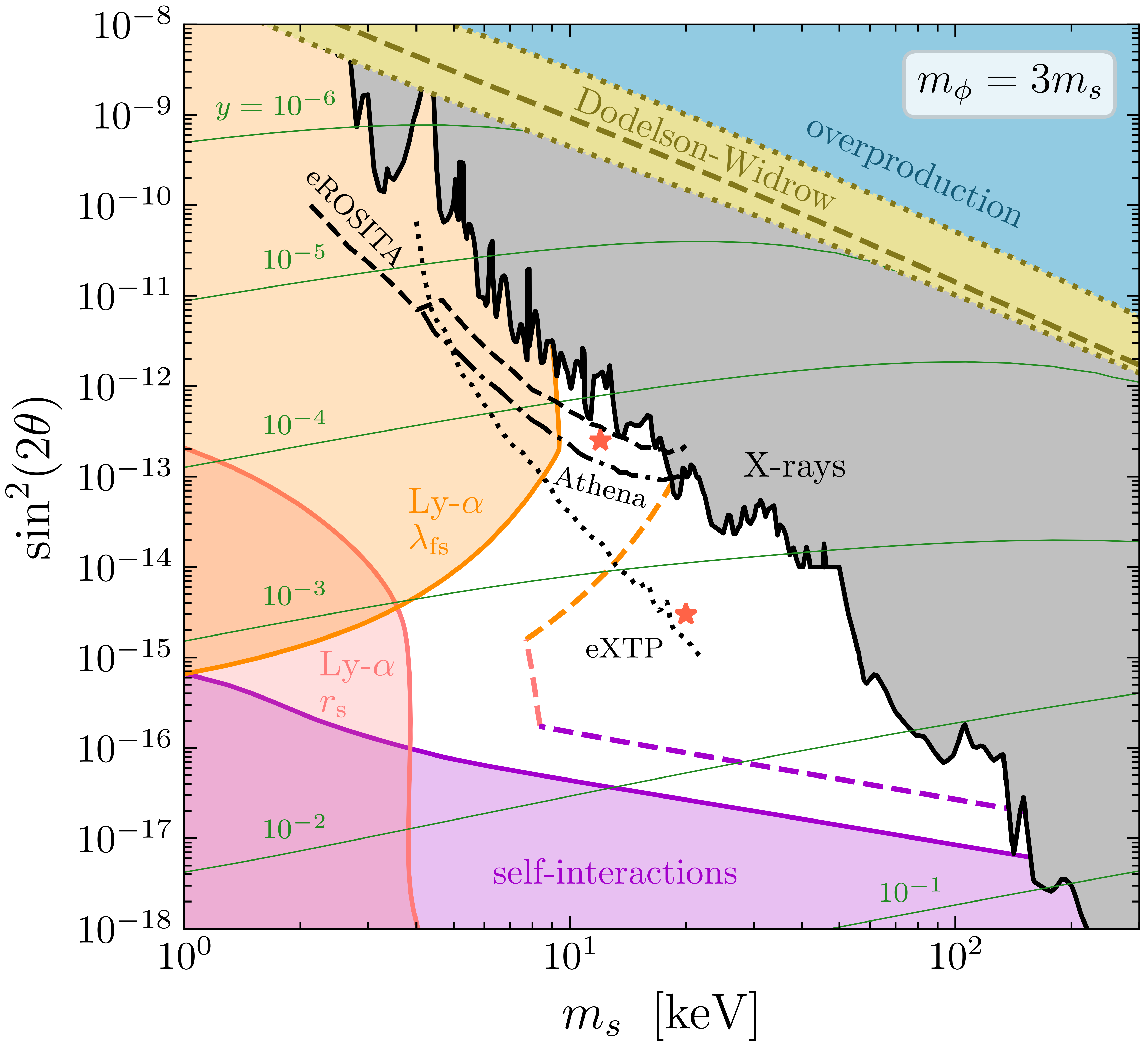
Parameter space



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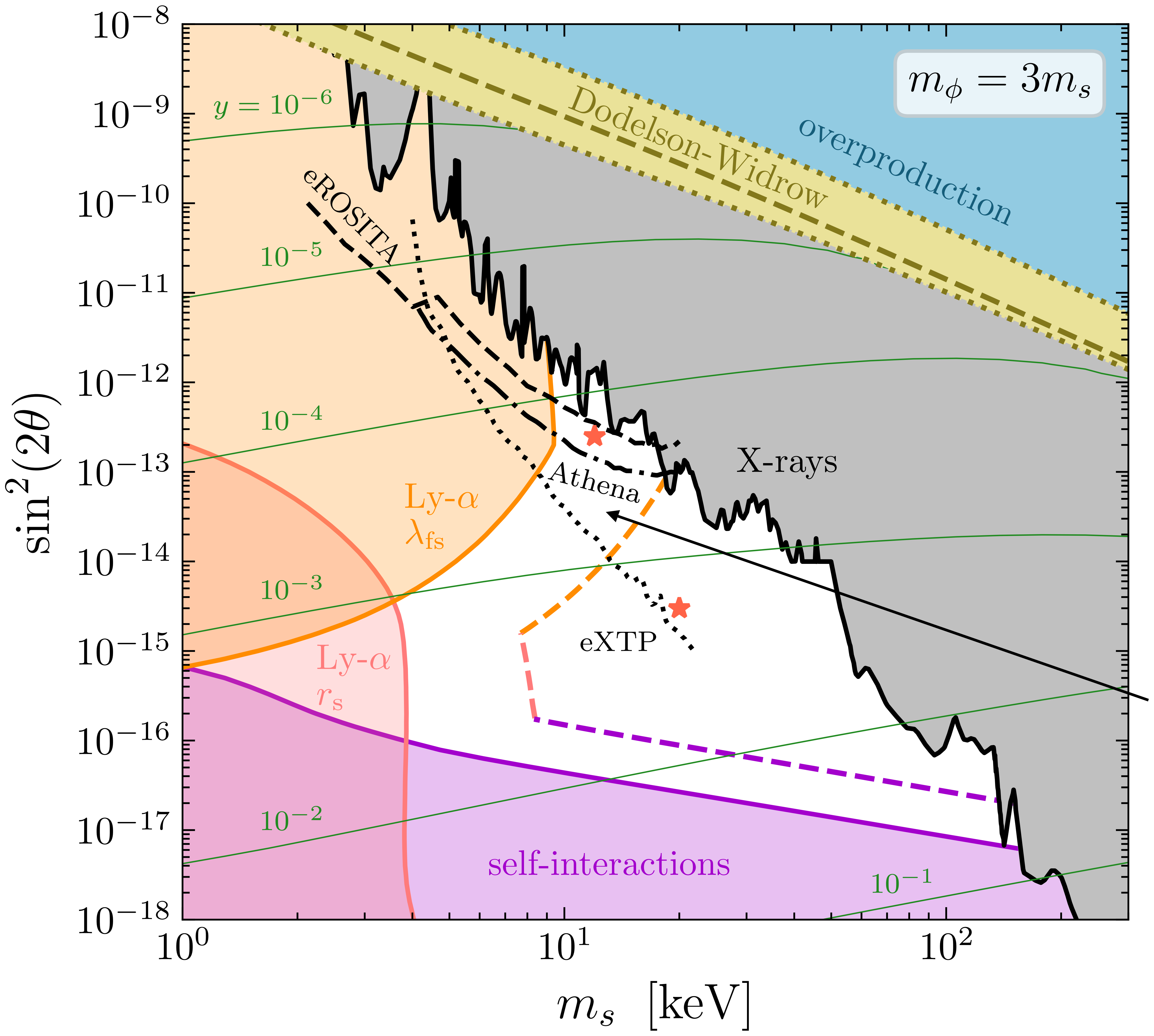

X-ray constraints from DM decays $\Gamma_s \propto \sin^2(2\theta)\, m_s^5$

Future Experiments

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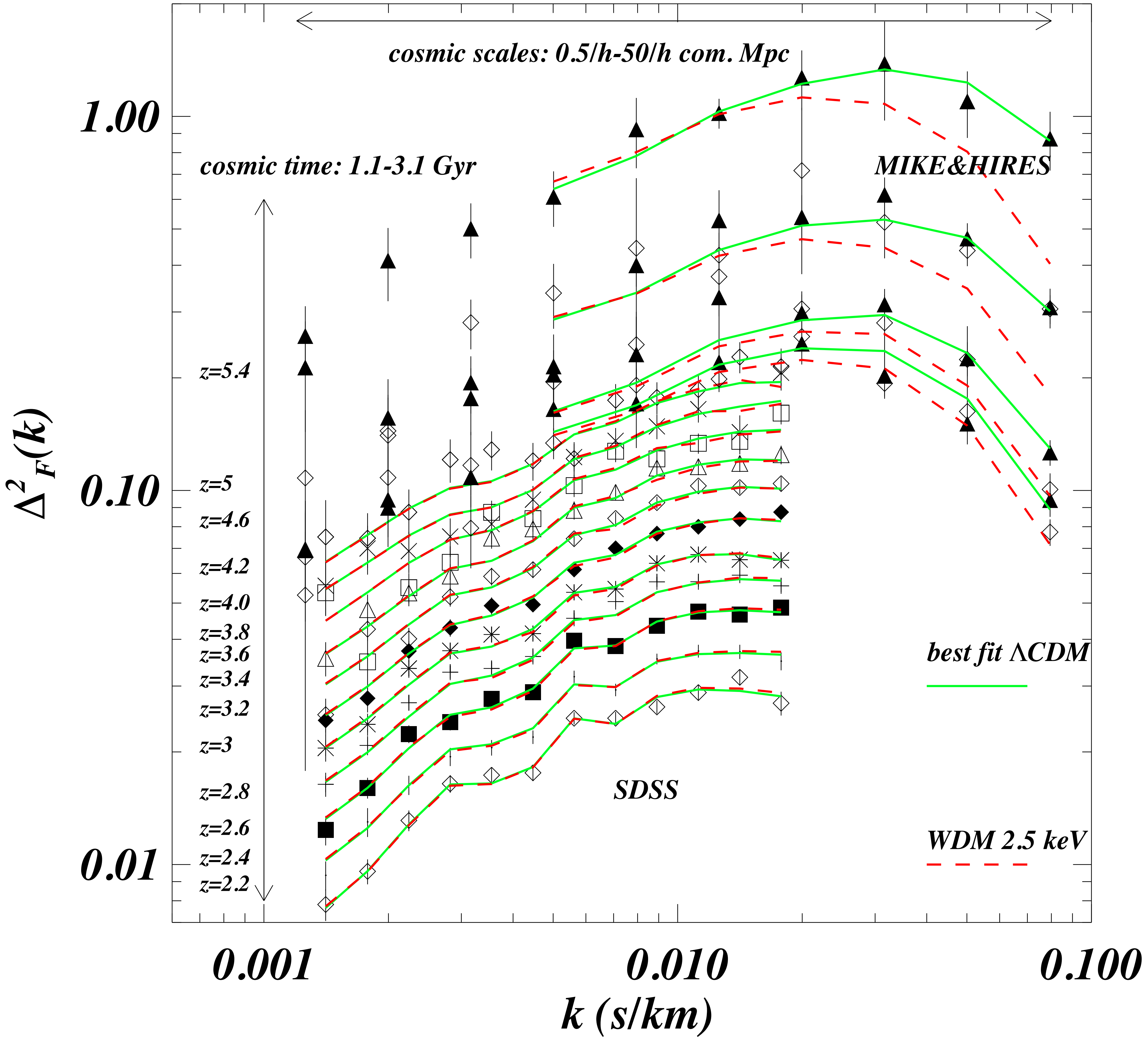
Lyman-α constraints

Basics

- Distant quasars shine light on neutral hydrogen gas clouds → absorption lines → Lyman-α forest
- Can be used to probe matter power spectrum at small scales
- Stringent limits on possible suppression!
- Limits often given in terms of warm dark matter mass
- Fermion with 2 degrees of freedom, Fermi-Dirac distribution with $\mu = 0$ and T to give DM relic abundance
- How to translate to our setup?

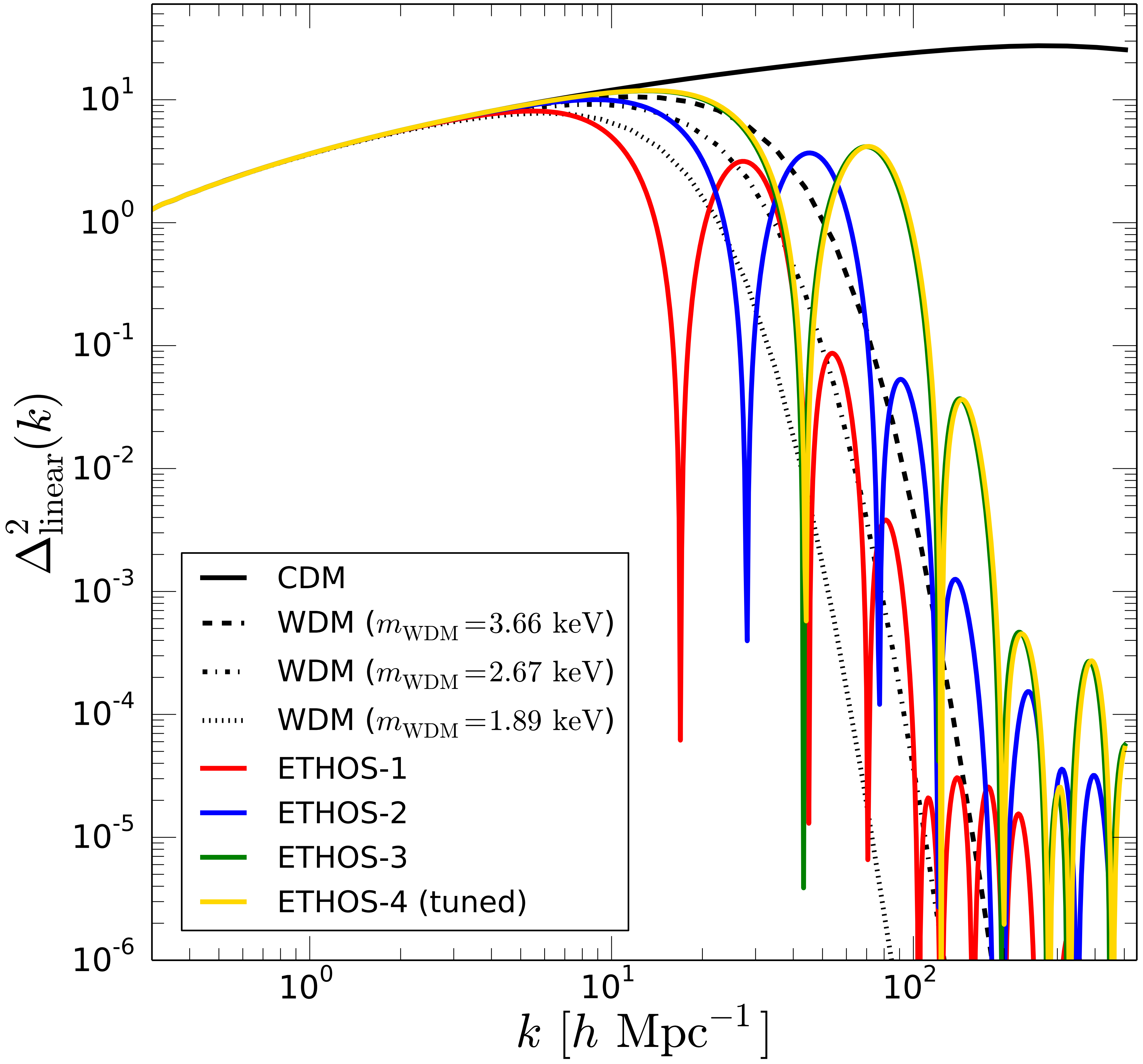


Viel et al. 1306.2314

Lyman-α constraints

Recast

- WDM: structures below free-streaming length $\lambda_{\rm fs} = \int_{t_i}^{t_{\rm nl}} {\rm d}t \, \langle v \rangle / a \propto m_{\rm WDM}^{-4/3}$ suppressed
- $m_{\rm WDM} > 1.9\,{\rm keV}$ (Garzilli et al. 1912.09397)



Vogelsberger et al. 1512.05349

Lyman-α constraints

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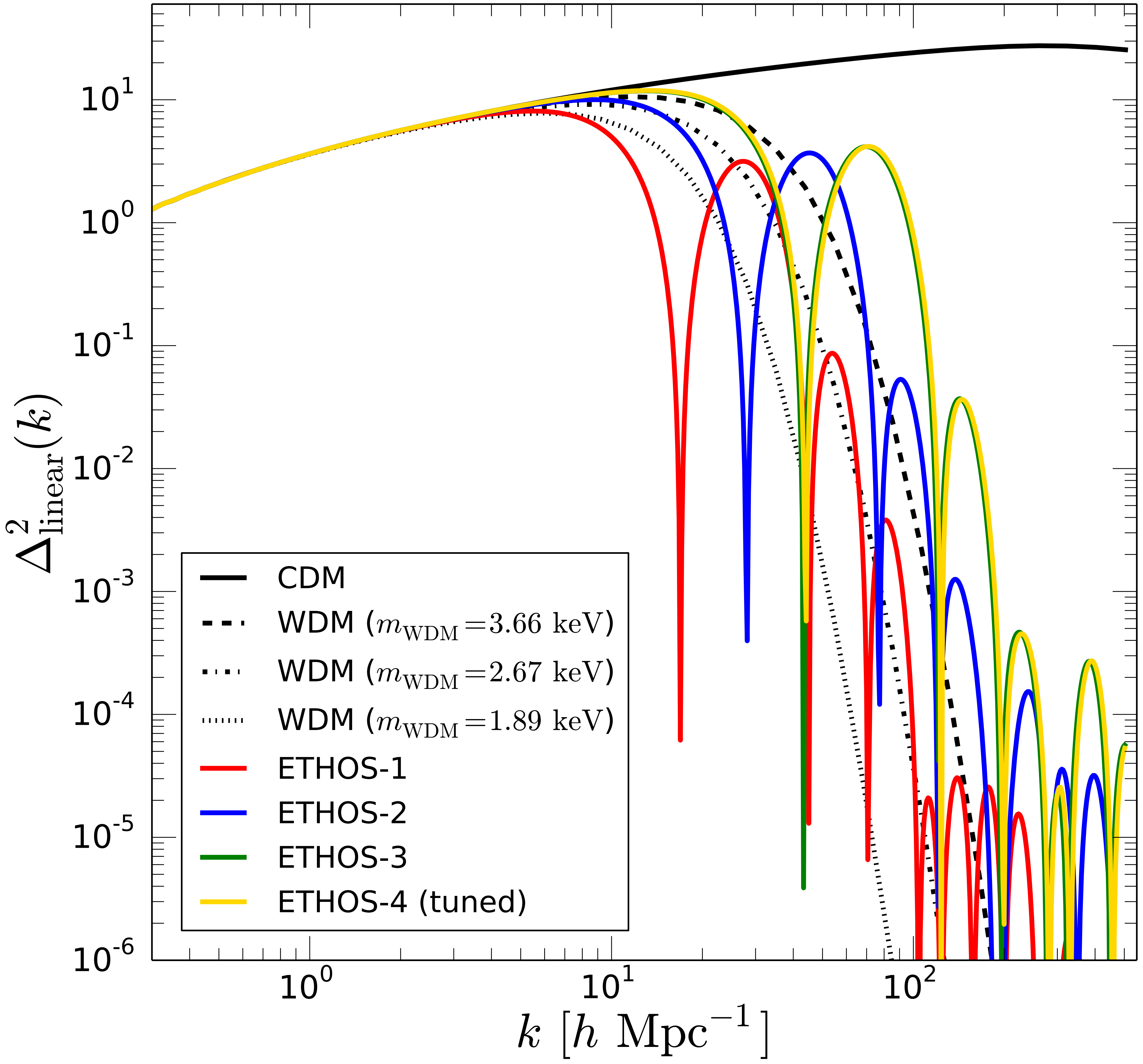
- $t < t_{\rm kd}$: DM self-scatterings prevent growth of structures below sound-horizon $r_{\rm s} = \int_0^{t_{\rm kd}} {\rm d}t\, c_{\rm s}/a$, $c_s = \sqrt{{\rm d}P/{\rm d}\rho}$ (Egana-Ugrinovic et al. 2102.06215)
    - WDM bound from Lyman-α can be recast (Vogelsberger et al. 1512.05349) to $r_{\rm s} < 0.34\,{\rm Mpc}$
- $t > t_{\rm kd}$: free-streaming, $\lambda_{\rm fs} = \int_{t_{\rm kd}}^{t_{\rm nl}} {\rm d}t\, \langle v \rangle / a < 0.24\,{\rm Mpc}$



Vogelsberger et al. 1512.05349

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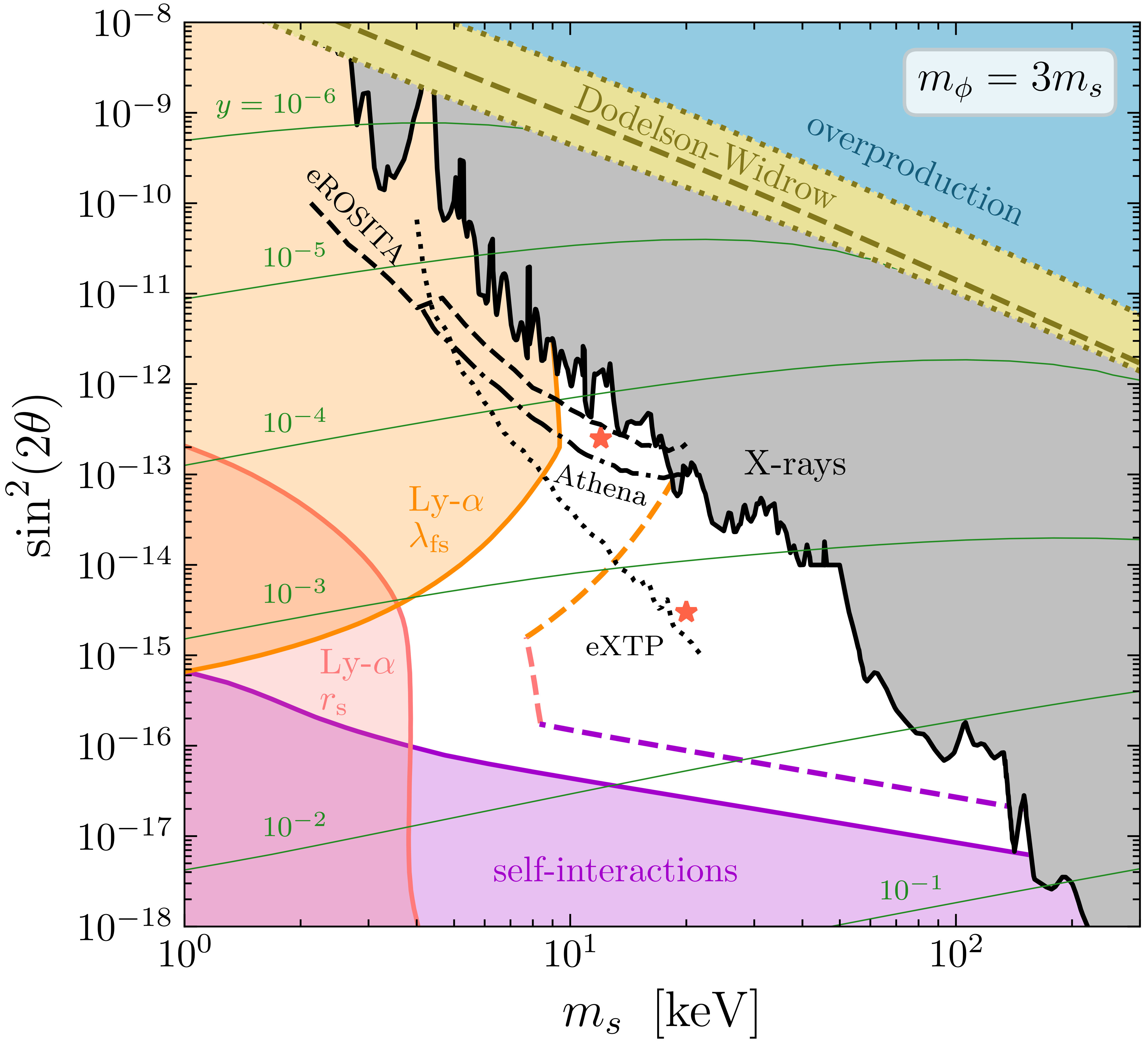
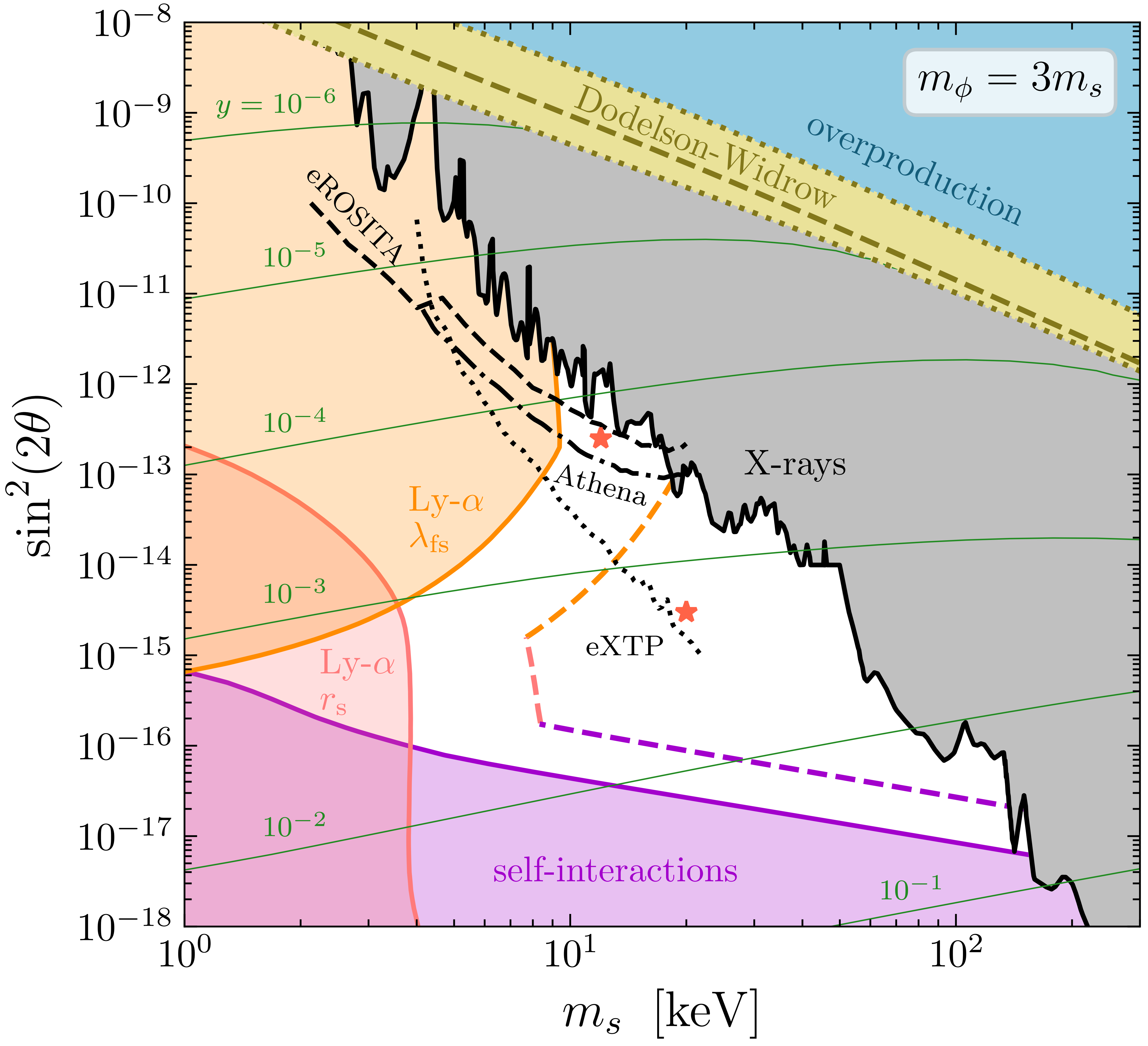


Bringmann, PFD et al. 2206.10630

Lyman-α constraints

Future

- $m_{\mathrm{WDM}} > 1.9\,\mathrm{keV}$ (Garzilli et al. 1912.09397) includes systematic uncertainties from reionization (marginalization)
  - $r_s < 0.34\,\mathrm{Mpc}$, $\lambda_{fs} < 0.24\,\mathrm{Mpc}$ (full)
- Fixed reionization models produce more stringent constraints
  - $m_{\mathrm{WDM}} > 5.3\,\mathrm{keV}$ (Palanque-Delabrouille et al. 1911.09073) $\Rightarrow$ $r_s < 0.09\,\mathrm{Mpc}$, $\lambda_{fs} < 0.07\,\mathrm{Mpc}$
- To estimate future prospects:
  - $r_s < 0.15\,\mathrm{Mpc}$, $\lambda_{fs} < 0.12\,\mathrm{Mpc}$ (dashed), corresponding to $m_{\mathrm{WDM}} > 3.4\,\mathrm{keV}$
- 21-cm might also help in the future to distinguish between sound waves and free streaming (Muñoz et al. 2011.05333)



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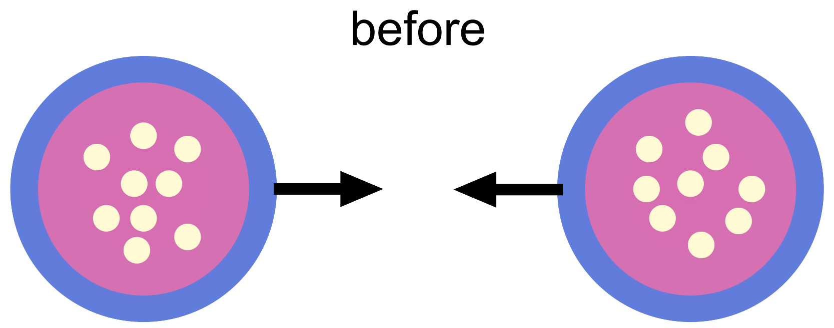
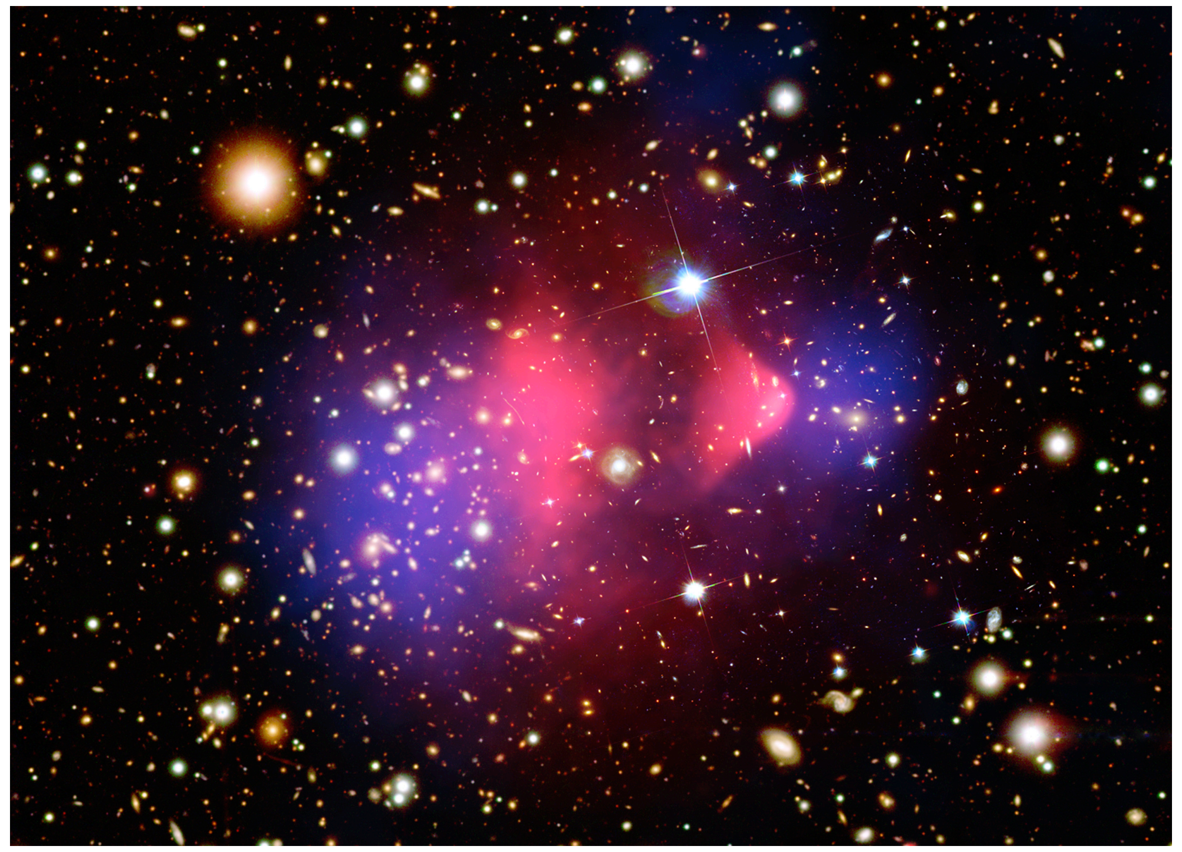
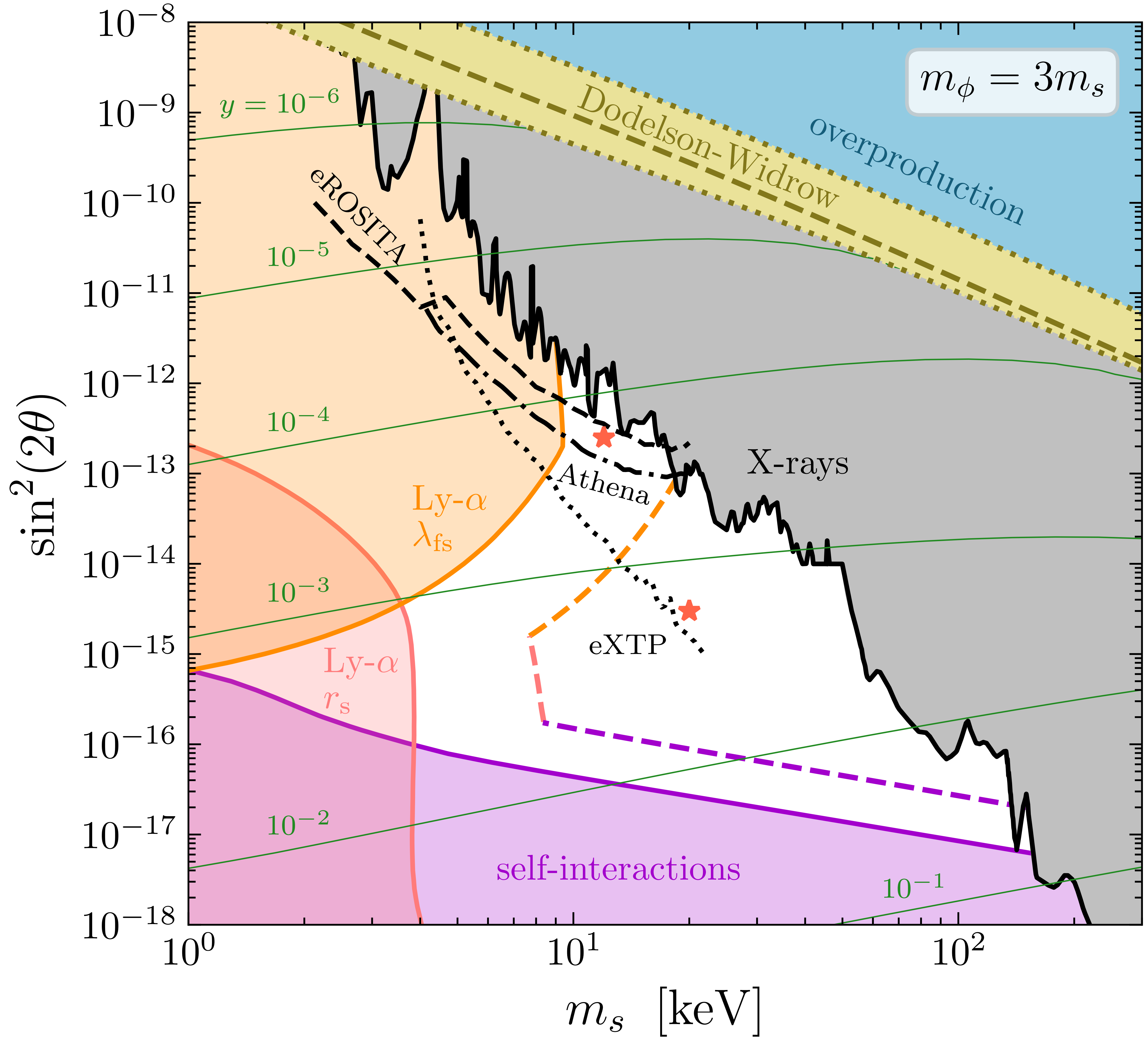
Self-interactions

- DM self-interactions constrained by various astrophysical observations (but also interesting in context of small-scale problems of ΛCDM)





Chandra X-ray observatory



Bringmann, PFD et al. 2206.10630

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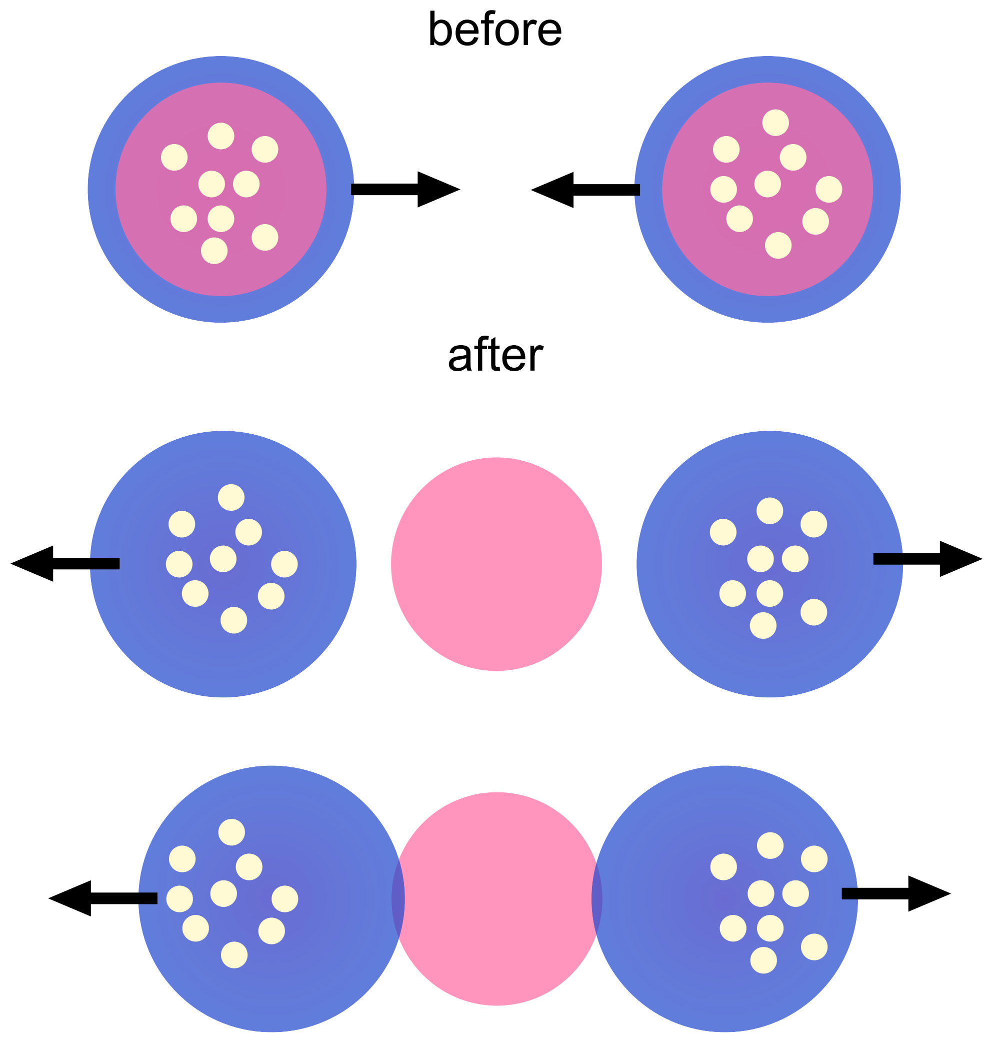
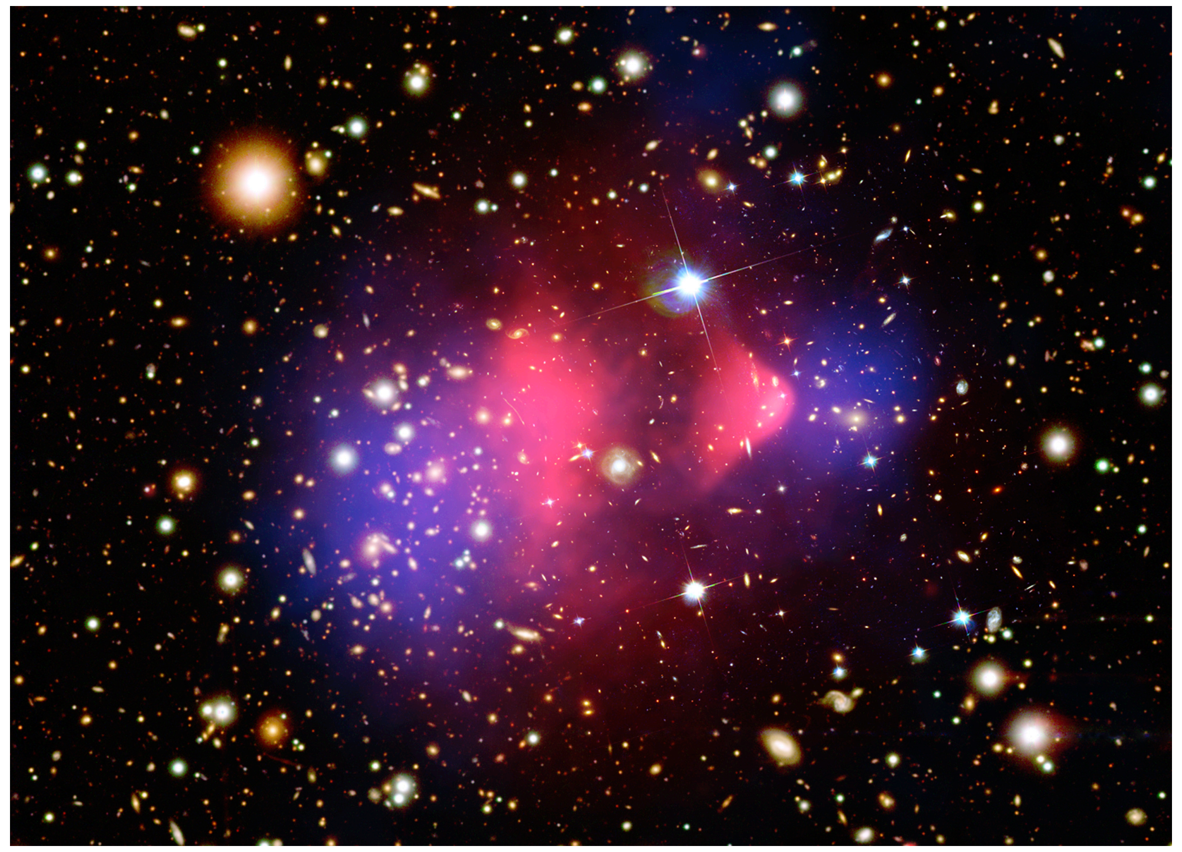
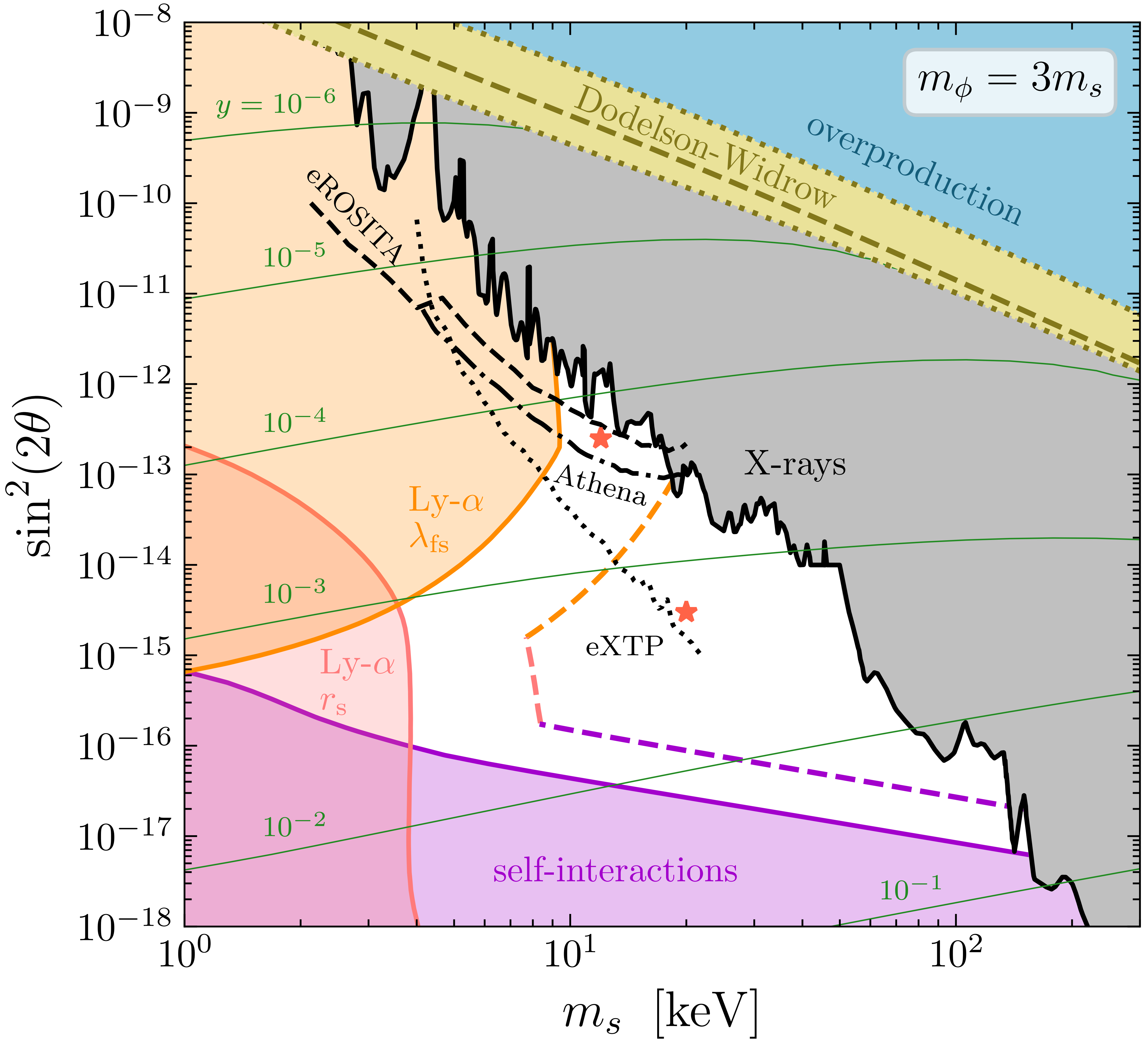




Chandra X-ray observatory

- $\sigma_T/m_s = \frac{4\pi}{m_s}\int_0^1 \mathrm{d}\cos\theta\,(1-\cos\theta)\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \simeq \frac{y^4 m_s}{4\pi m_\phi^4} + \mathcal{O}(v^2)$
- $\sigma_T/m_s < 1\,\mathrm{cm}^2/\mathrm{g}$, for future prospects $< 0.1\,\mathrm{cm}^2/\mathrm{g}$



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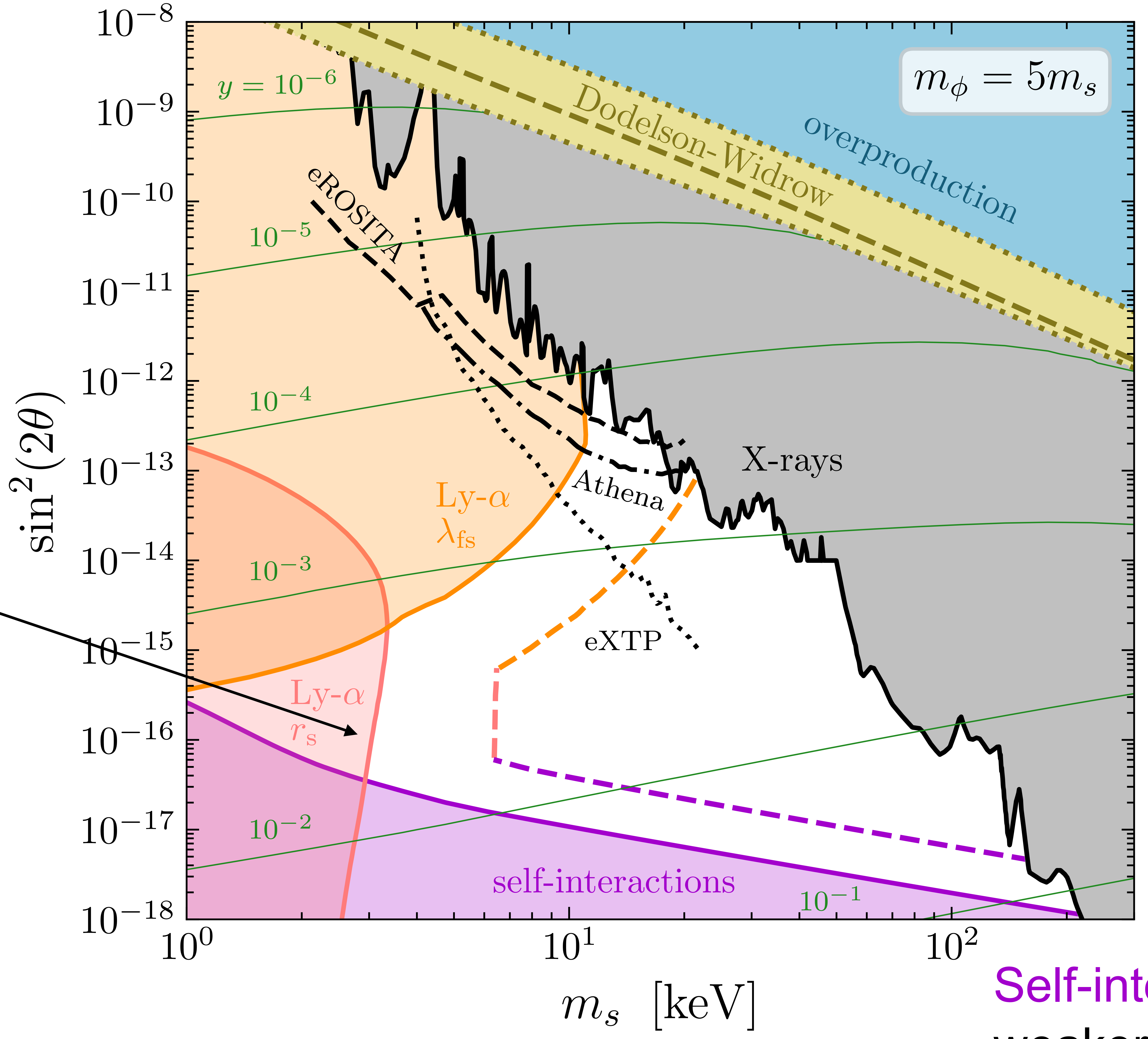
Parameter space

Larger $m_\phi = 5m_s$

Larger $m_\phi \Rightarrow$ earlier kinetic decoupling:

- r_s smaller, weaker constraints
  - At larger y cooling from $\nu_s\nu_s \to \phi\phi$ relevant (decreases r_s)
- λ_{fs} larger, stronger constraints



Self-interaction constraints weaker (smaller σ_T)

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Comments on generalizations

- $m_s < m_\phi < 2m_s$: production of single ϕ cannot produce $2\nu_s$
  - $\sigma_{\nu_\alpha\nu_s\to\nu_s\nu_s} \propto y^4$, not $\propto y^2 \Rightarrow$ number-density does not grow as much
  - Energy injection via $\nu_\alpha\nu_s \to \phi$ still $\propto y^2 \Rightarrow$ much stronger Lyman-α constraints!
  - Possible way around: number-changing interactions from scalar potential could have similar effect as $\nu_s\nu_s \to \phi\phi \to 4\nu_s$ before
- $m_\phi < m_s$: Decays $\nu_s \to \phi\nu_\alpha$ need to be suppressed $\Rightarrow$ even more difficult to construct valid scenario
- Specific model chosen for simplicity, exponential growth regime generally present for self-interacting sterile neutrinos (other interaction structures)

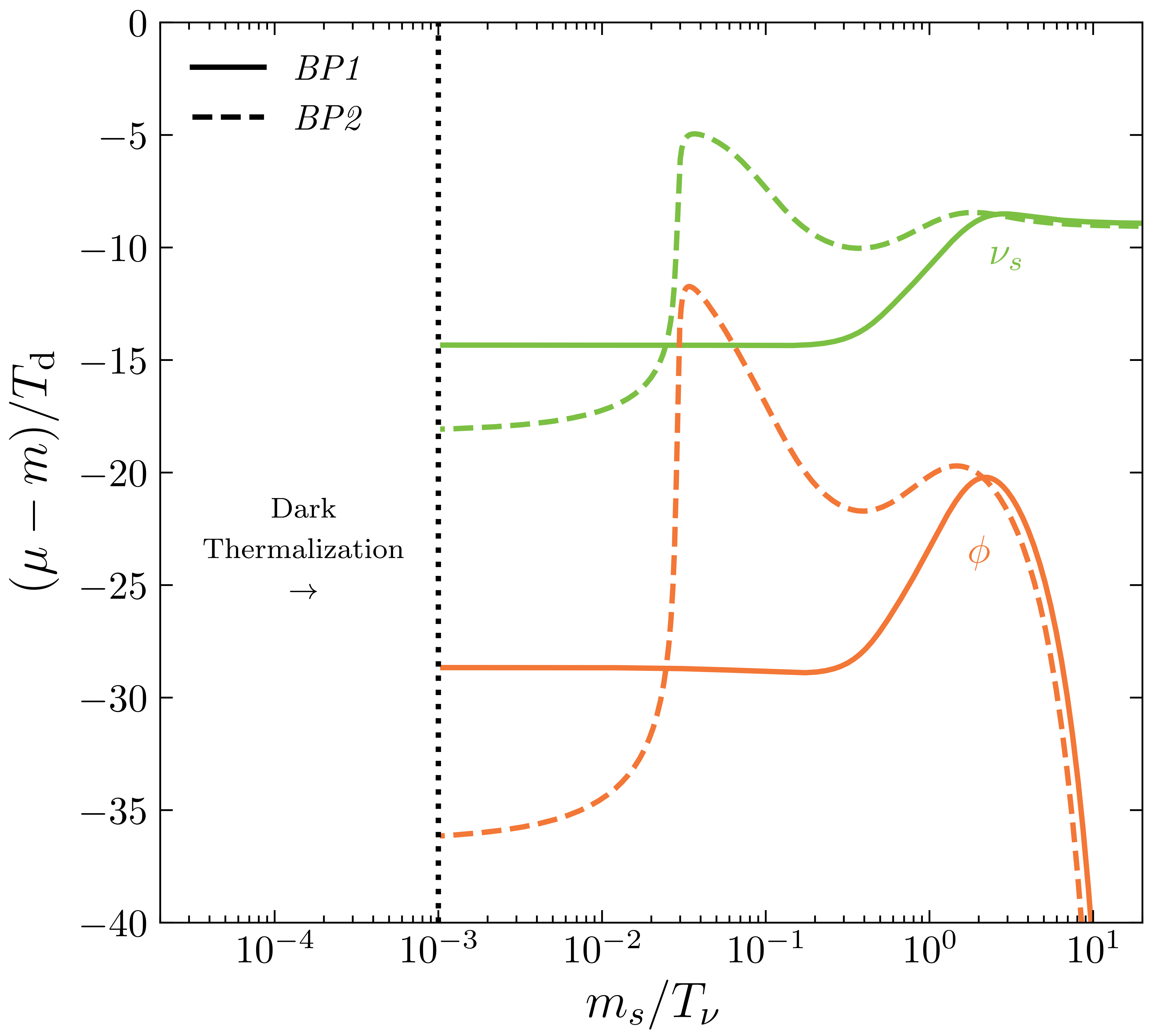
Conclusions

- Sterile neutrinos excellent DM candidate, but simplest realization excluded
- Self-interacting sterile neutrinos can have exponential growth of abundance
- DM production at mixing angles much smaller than in Dodelson-Widrow scenario
- Simplest allowed model for sterile neutrino DM production
- Much of parameter space is testable in the foreseeable future

Thank you!

Chemical potentials

- Dodelson-Widrow produces sterile neutrinos with $\langle p_s \rangle \sim \langle p_\alpha \rangle \sim T_\nu$, but $n_s \ll n_\alpha$
- Dark thermalization comovingly conserves $n_s + 2n_\phi$ and $\rho_s + \rho_\phi$
- Chemical potential $\mu_s = \mu_\phi/2 \ll -T_\mathrm{d}$
- $\nu_s\nu_s \to \phi\phi$ decreases T_d and increases $\mu_s = \mu_\phi/2$
- If $\nu_s\nu_s \leftrightarrow \phi\phi$ comes into equilibrium:
  - $\mu_s = \mu_\phi = \mu_\phi/2 \Rightarrow \mu_s = \mu_\phi = 0$



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