Minimal sterile neutrino dark matter

Based on Phys. Rev. D 107 (2023) 7, L071702

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TeVPA 2023
12 September 2023

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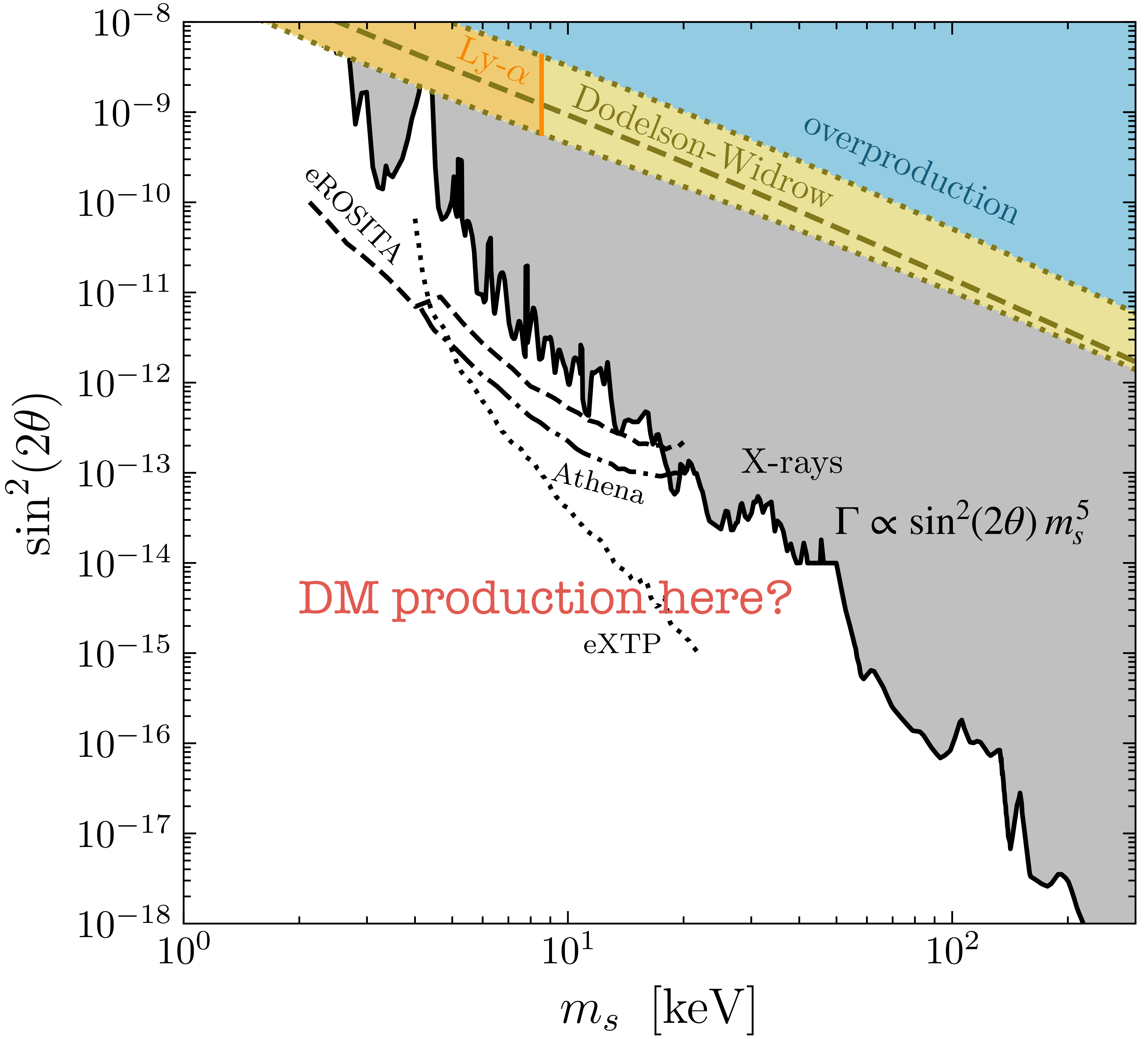
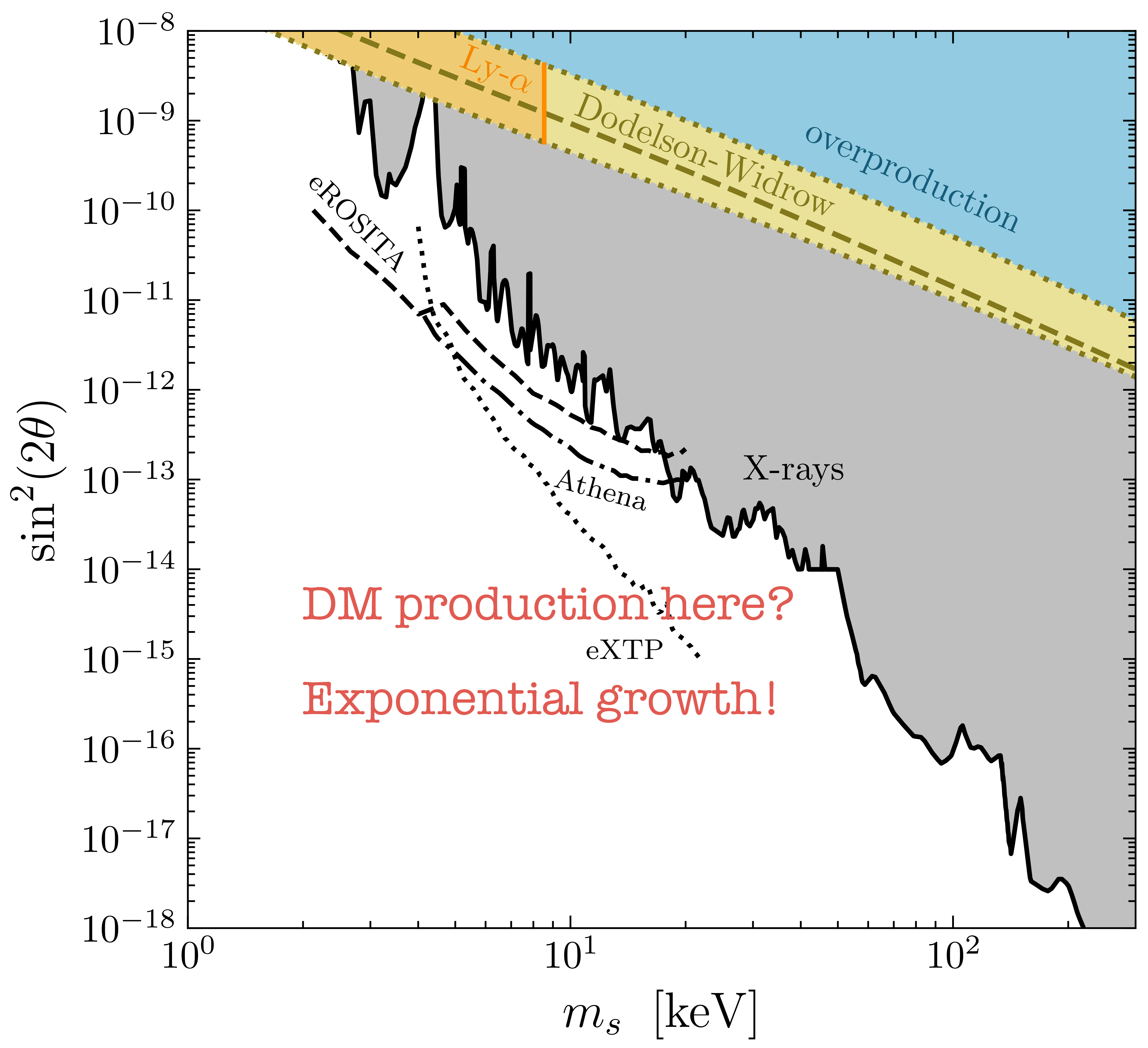
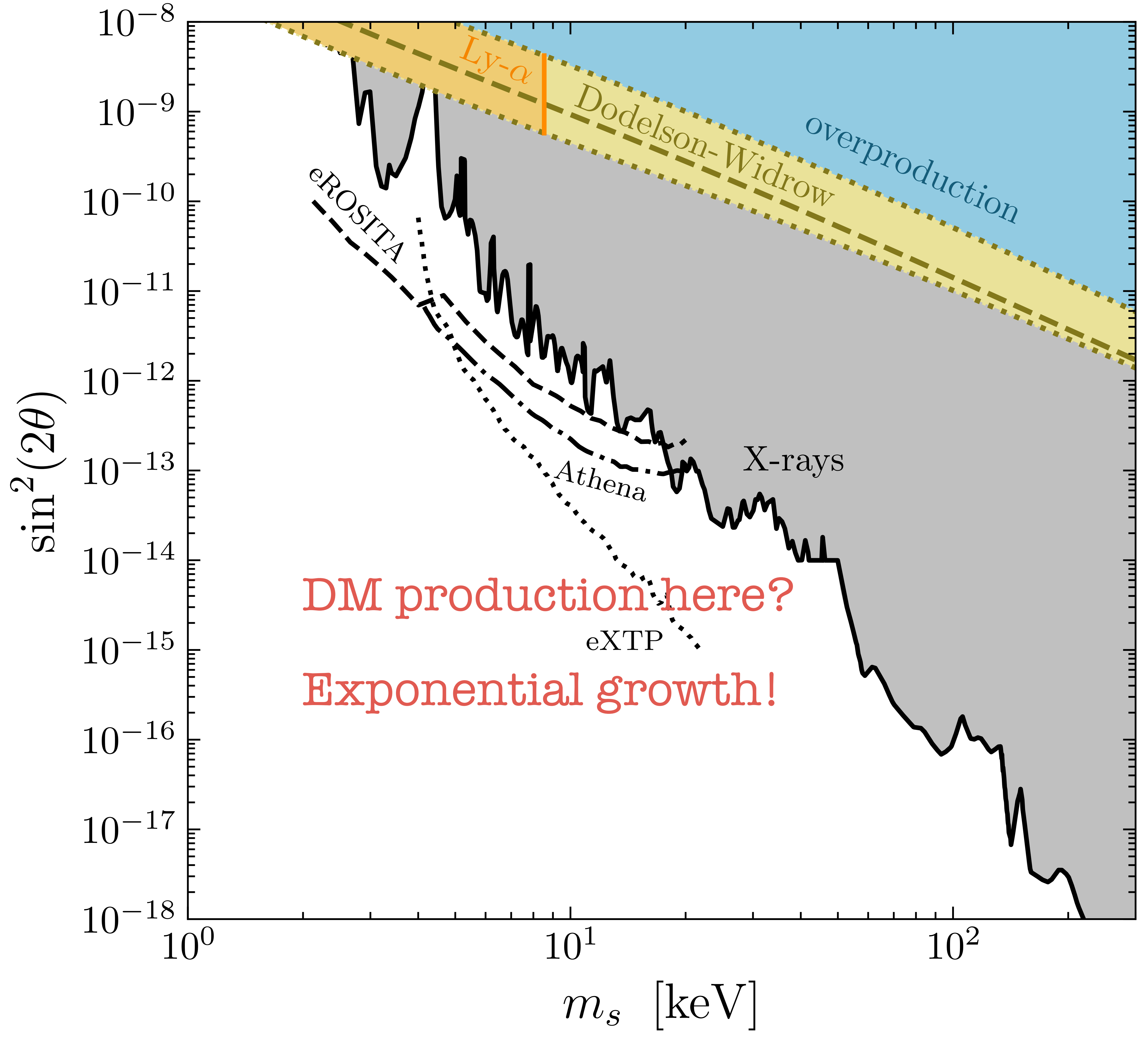


Ly-α
Dodelson-Widrow
overproduction
eROSITA
X-rays
Athena
$\Gamma \propto \sin^2(2\theta)\, m_s^5$
DM production here?
eXTP
$\sin^2(2\theta)$
m_s [keV]



Bringmann, PFD et al. 2103.16572



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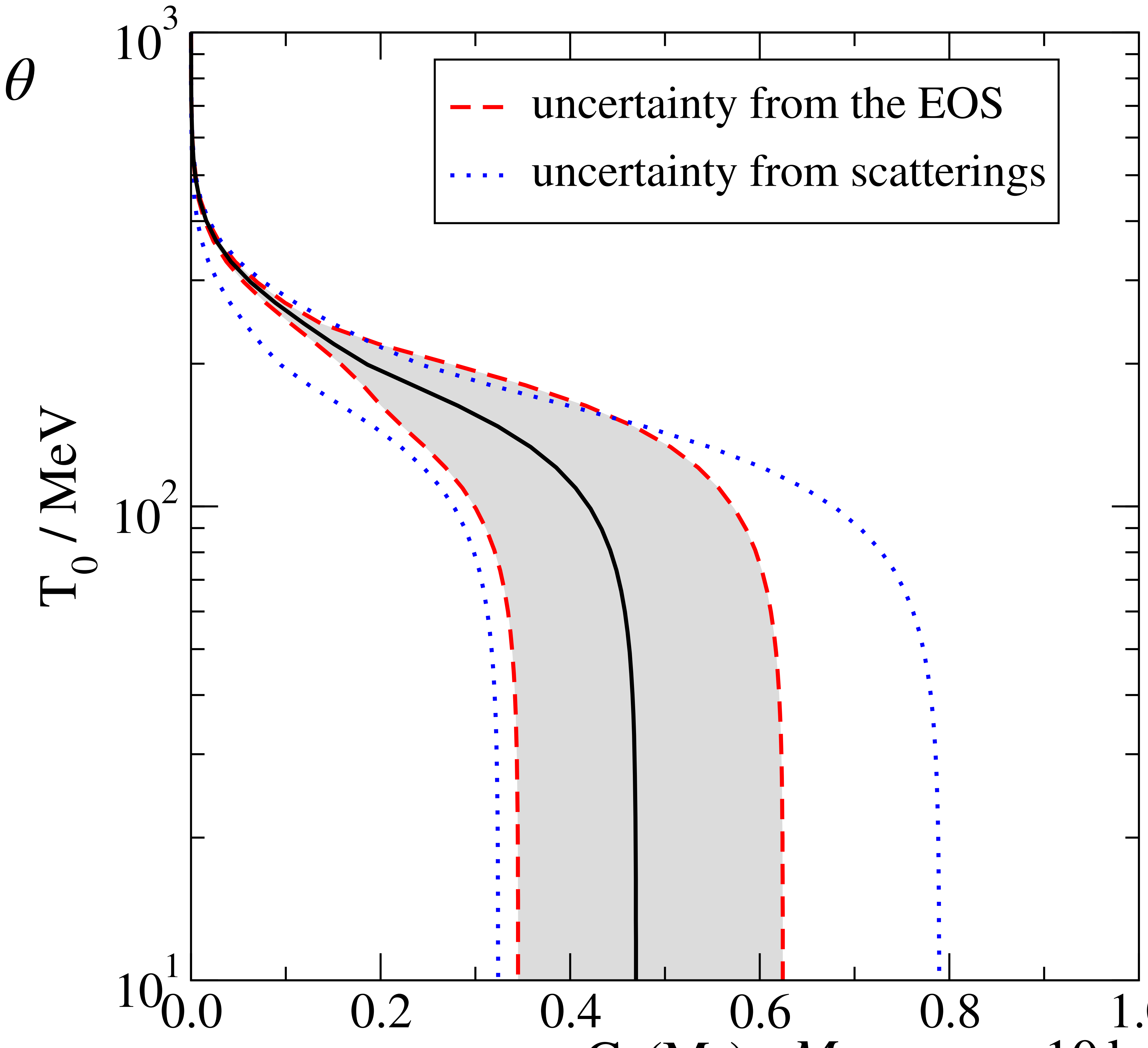
Generally occurs for self-interacting sterile neutrinos!
Simplest allowed model for sterile neutrino DM production!

Outline

- Sterile neutrino dark matter
- Alternative production mechanisms
- Exponential growth of sterile neutrino dark matter
- Conclusions

Sterile neutrino dark matter

- Sterile neutrino (right-handed, gauge singlet, mass mixing θ with active neutrino) is excellent candidate for dark matter
- Dodelson-Widrow mechanism (Dodelson and Widrow hep-ph/9303287)
  - Oscillations between active and sterile neutrinos produce abundance of sterile neutrinos
  - Mostly active around $T \sim 130\,\mathrm{MeV}(m_s/1\,\mathrm{keV})^{1/3}$
  - $\Omega_s h^2 \sim 0.1\,\left(\sin^2(2\theta)/10^{-8}\right)\,(m_s/1\,\mathrm{keV})^2$



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

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

Asaka, Laine, and Shaposhnikov hep-ph/0612182

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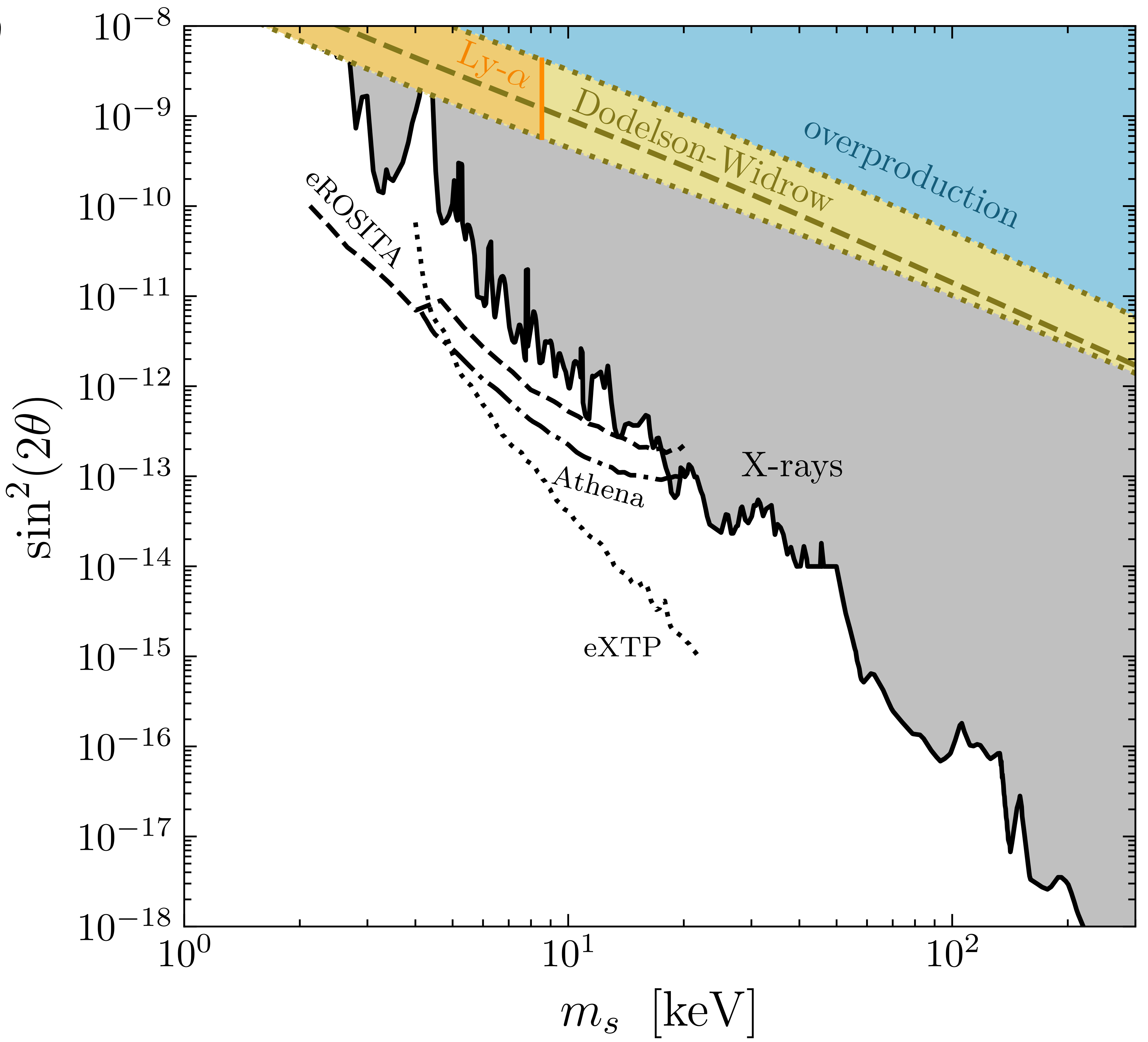
  - $\Omega_s h^2 \sim 0.1\,\left(\sin^2(2\theta)/10^{-8}\right)\,(m_s/1\,\mathrm{keV})^2$
- Decay $\nu_s \to \nu_\alpha \gamma$ at one-loop level (Abazajian, Fuller, and Tucker astro-ph/0106002)
  - $\Gamma_{\nu_s \to \nu_\alpha \gamma} \simeq 2 \times 10^{-23}\,\mathrm{yr}^{-1}\,\left(\sin^2(2\theta)/10^{-8}\right)\,(m_s/1\,\mathrm{keV})^5$
  - Constraints from X-ray searches



Alternative production mechanisms

- Shi-Fuller mechanism (Shi and Fuller astro-ph/9810076):
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- Decay of scalar (Shaposhnikov and Tkachev hep-ph/0604236; Kusenko hep-ph/0609081; Petraki and Kusenko 0711.4646; Roland, Shakya, and Wells 1412.4791; Merle and Trotzauer 1502.01011; König, Merle, and Trotzauer 1609.1289)
- Extended gauge sector (Bezrukov, Hettmansperger, and Lindner 0912.4415; Kusenko, Takashashi, and Yanagida 1006.1731; Dror et al. 2004.09511)
- New interactions of active neutrinos (De Gouvêa et al. 1910.04901; Kelly et al. 2005.03681; Chichi et al. 2111.04087; Benso et al. 2112.00758)
- New interactions of sterile neutrinos (Hansen and Vogl 1706.02707; Johns and Fuller 1903.08296; Bringmann, PFD et al. 2206.10630)

Alternative production mechanisms

New interactions of sterile neutrinos

- Particularly simple as only a scalar and Yukawa couplings are needed, no issues with SU(2) invariance
- Model setup:
  - $\mathscr{L}_m = -\frac{1}{2}\overline{\nu_s^c} m_s \nu_s - \overline{\nu_\alpha} m_{\alpha s} \nu_s - \frac{1}{2}\overline{\nu_\alpha^c} m_\alpha \nu_\alpha + \text{h.c.}$
  - $\mathscr{L}_{\phi,\text{int}} = \frac{y}{2}\phi \overline{\nu_s^c}\nu_s + \text{h.c.} \to \frac{y}{2}\phi\left(\cos^2\theta\,\overline{\nu_s^c}\nu_s - \sin(2\theta)\,\overline{\nu_\alpha}\nu_s + \sin^2\theta\,\overline{\nu_\alpha^c}\nu_\alpha\right) + \text{h.c.}$
  - Scalar potential possibly relevant
- Phenomenology not necessarily restricted to specific model, but can arise generically for self-interacting sterile neutrinos (e.g. vector instead of scalar)

Alternative production mechanisms

New interactions of sterile neutrinos

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- $m_\phi > 2m_s\,,\ y \gtrsim 10^{-6}$ (Bringmann, PFD et al. 2206.10630) $\leftarrow$ this work
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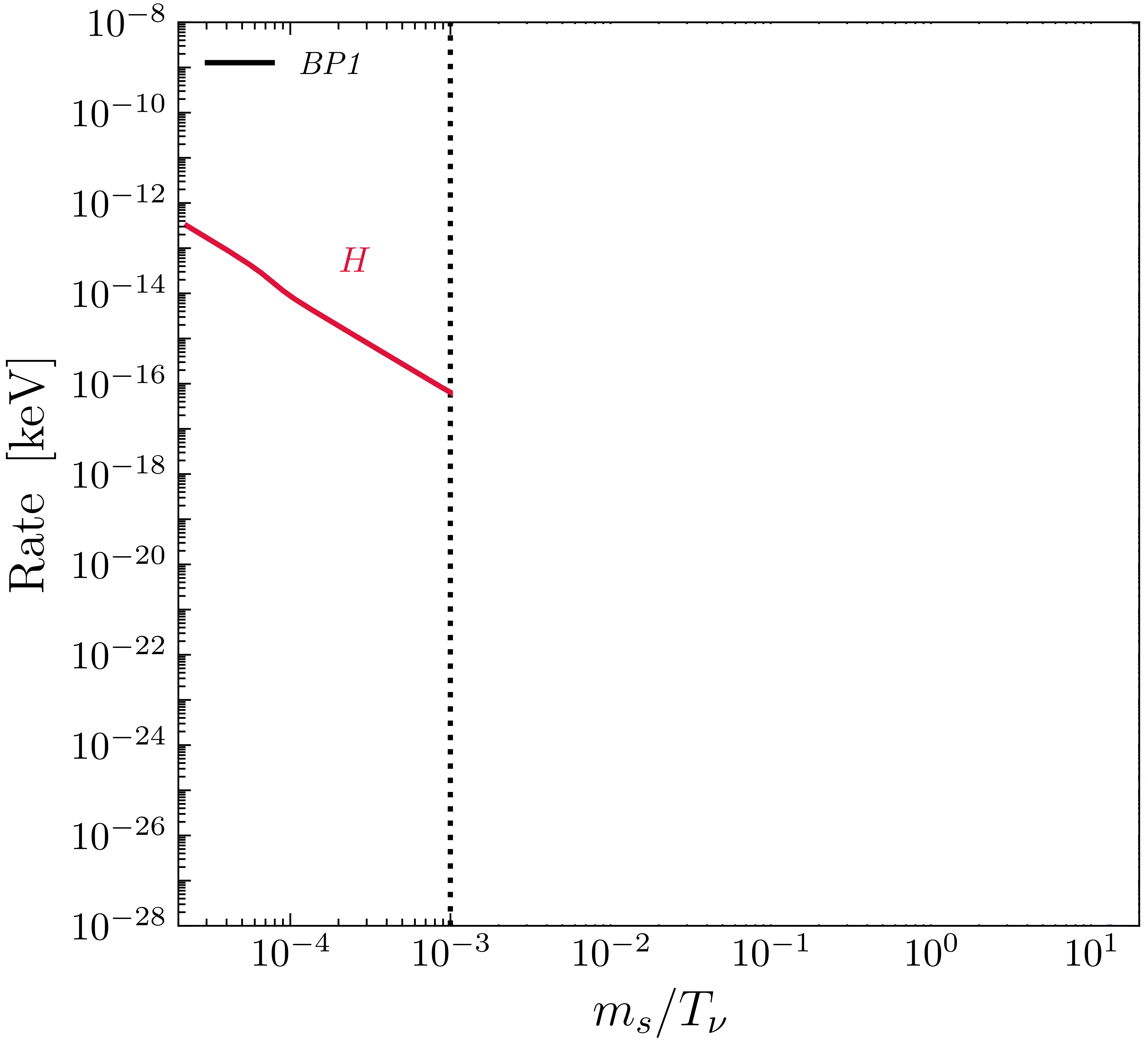
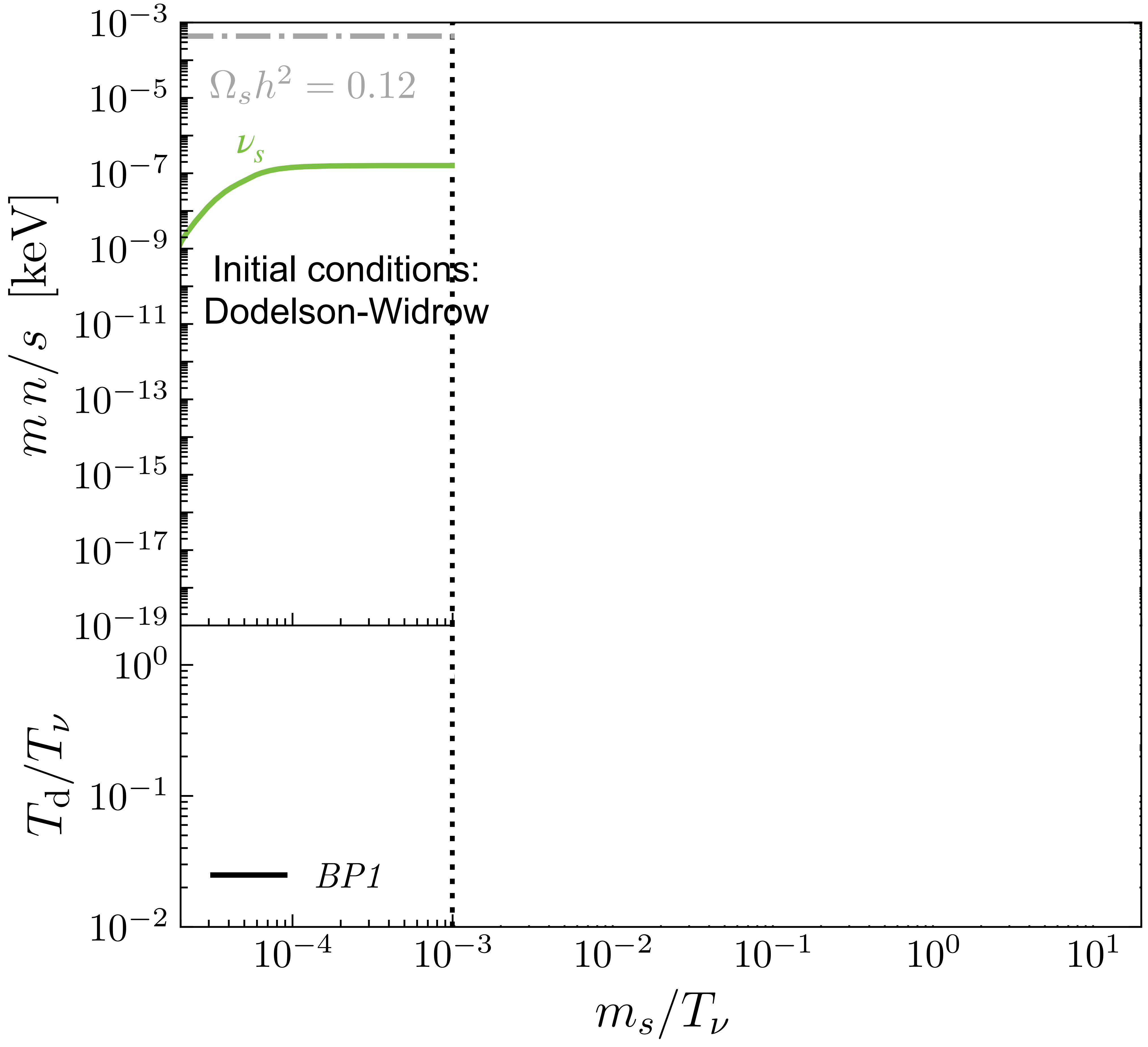
- Further discussion of viable m_ϕ (Dias Astros and Vogl 2307.15565) $\leftarrow$ talk by María Dias

Exponential growth

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





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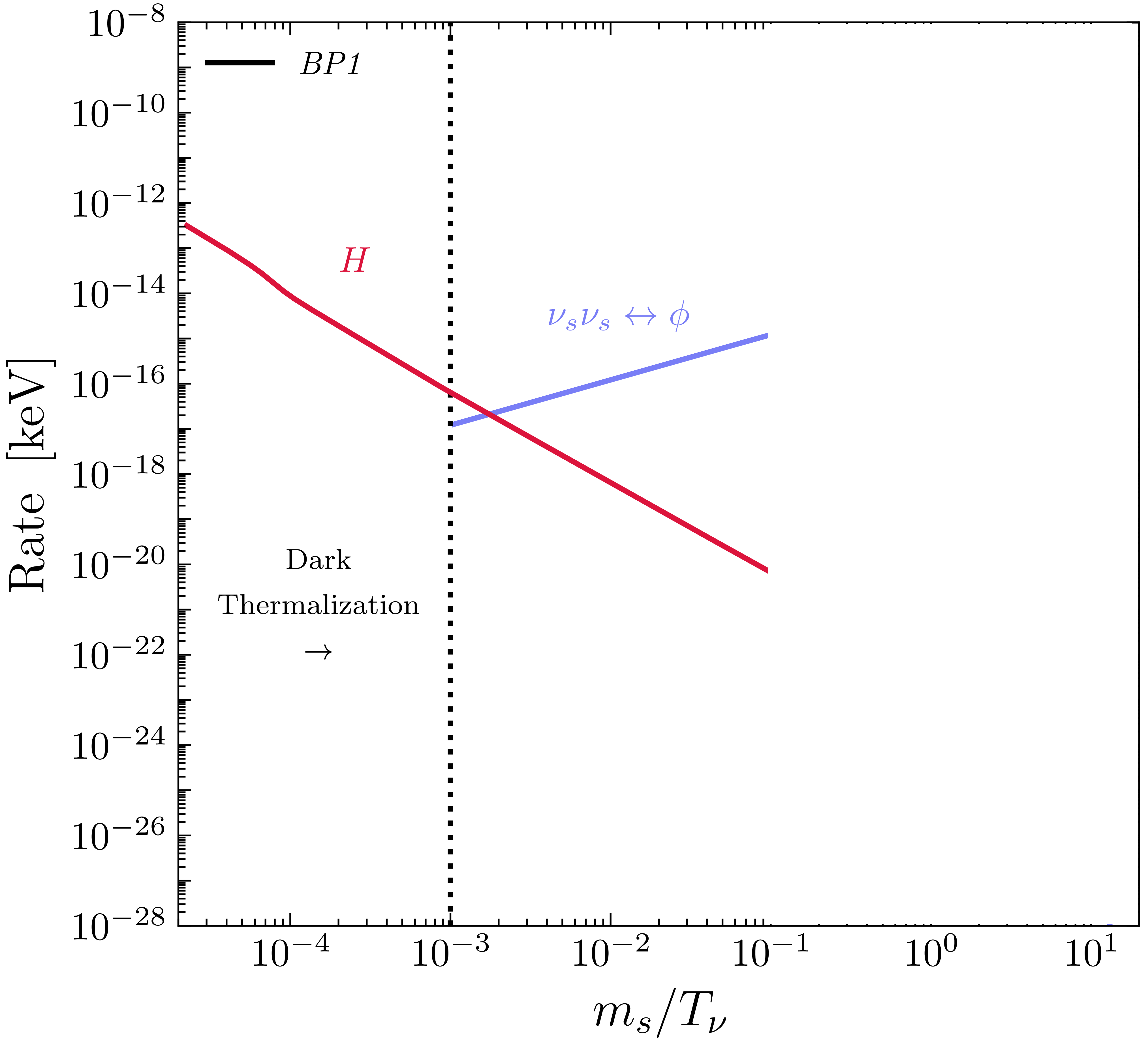

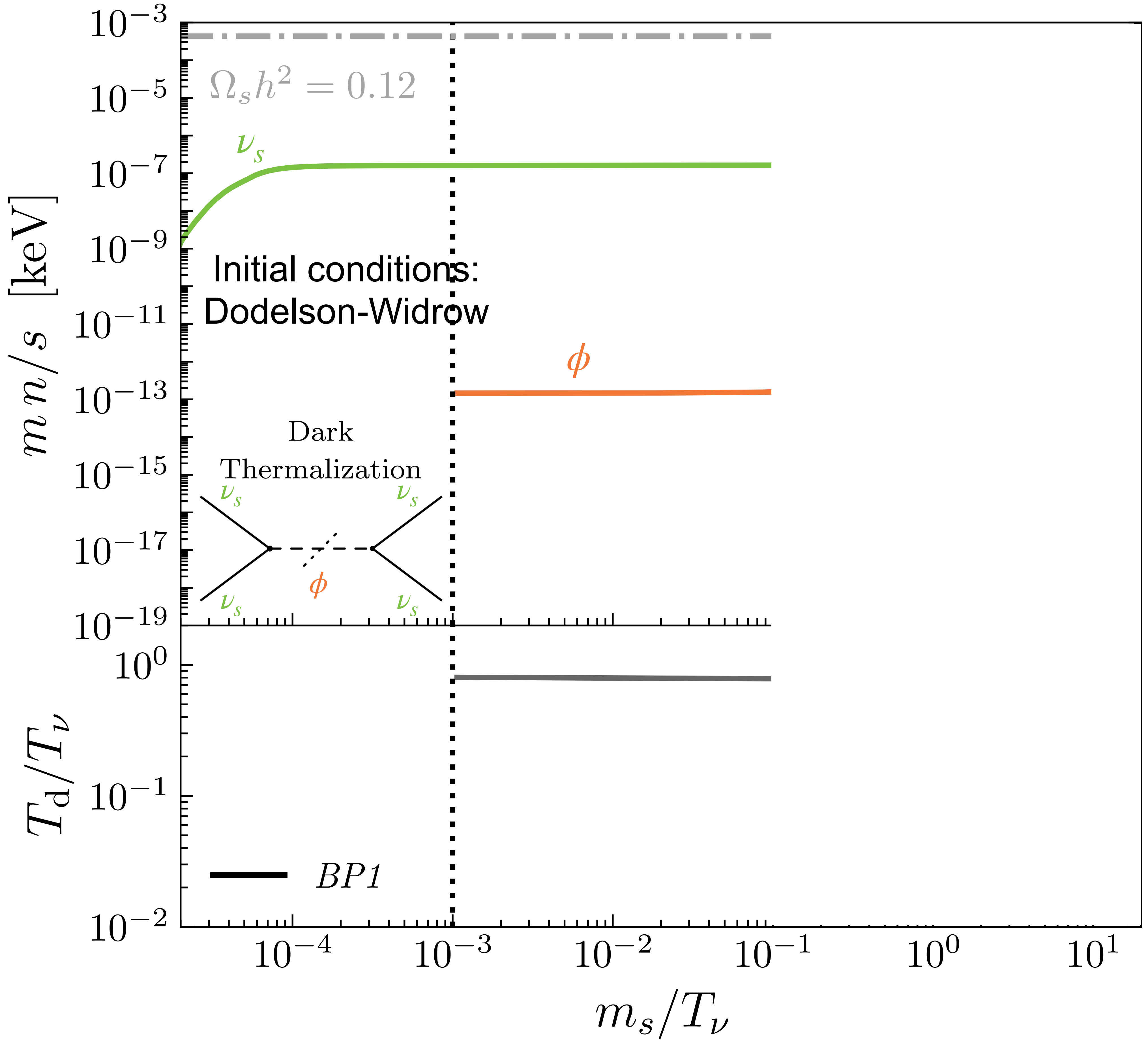

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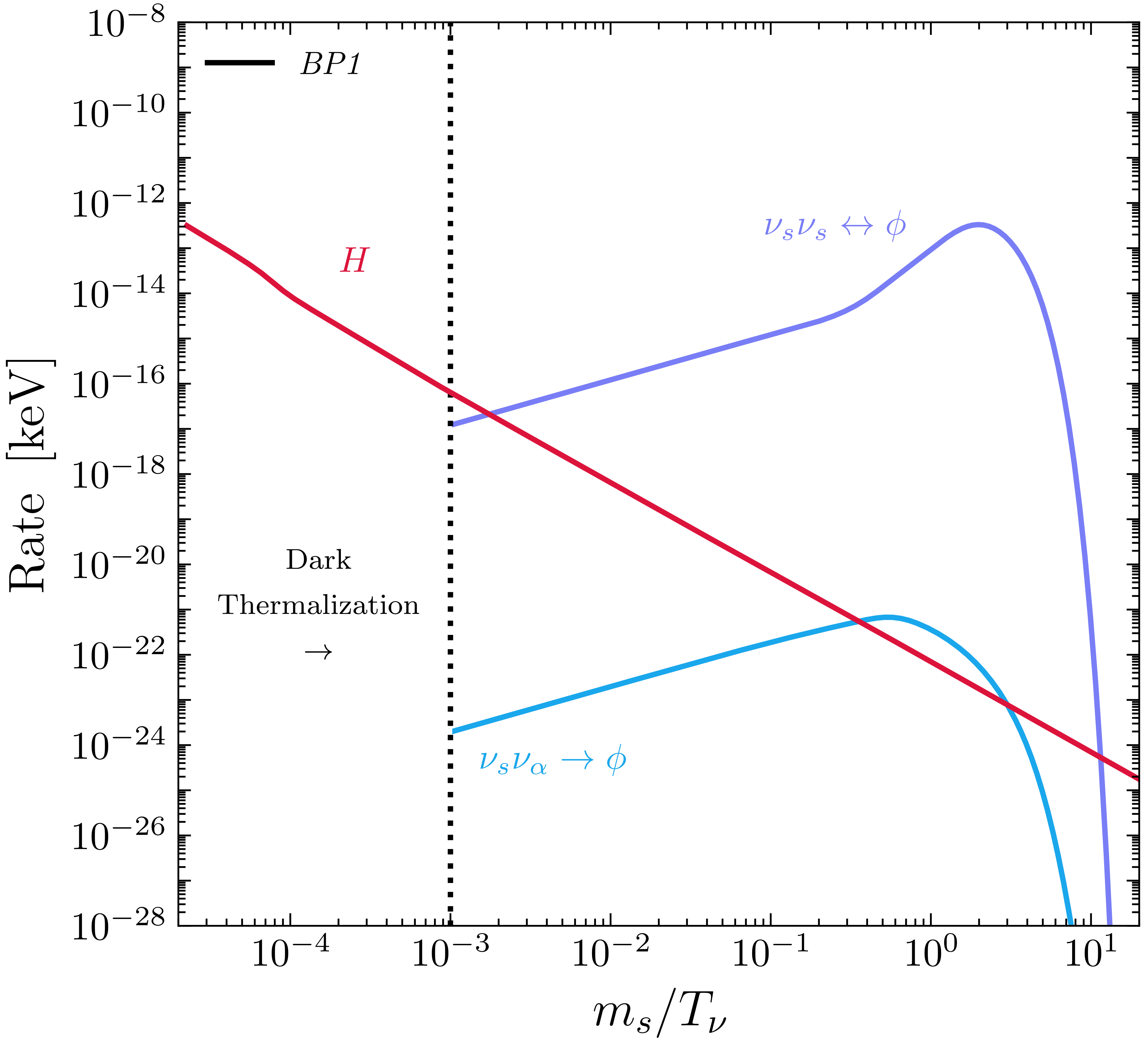

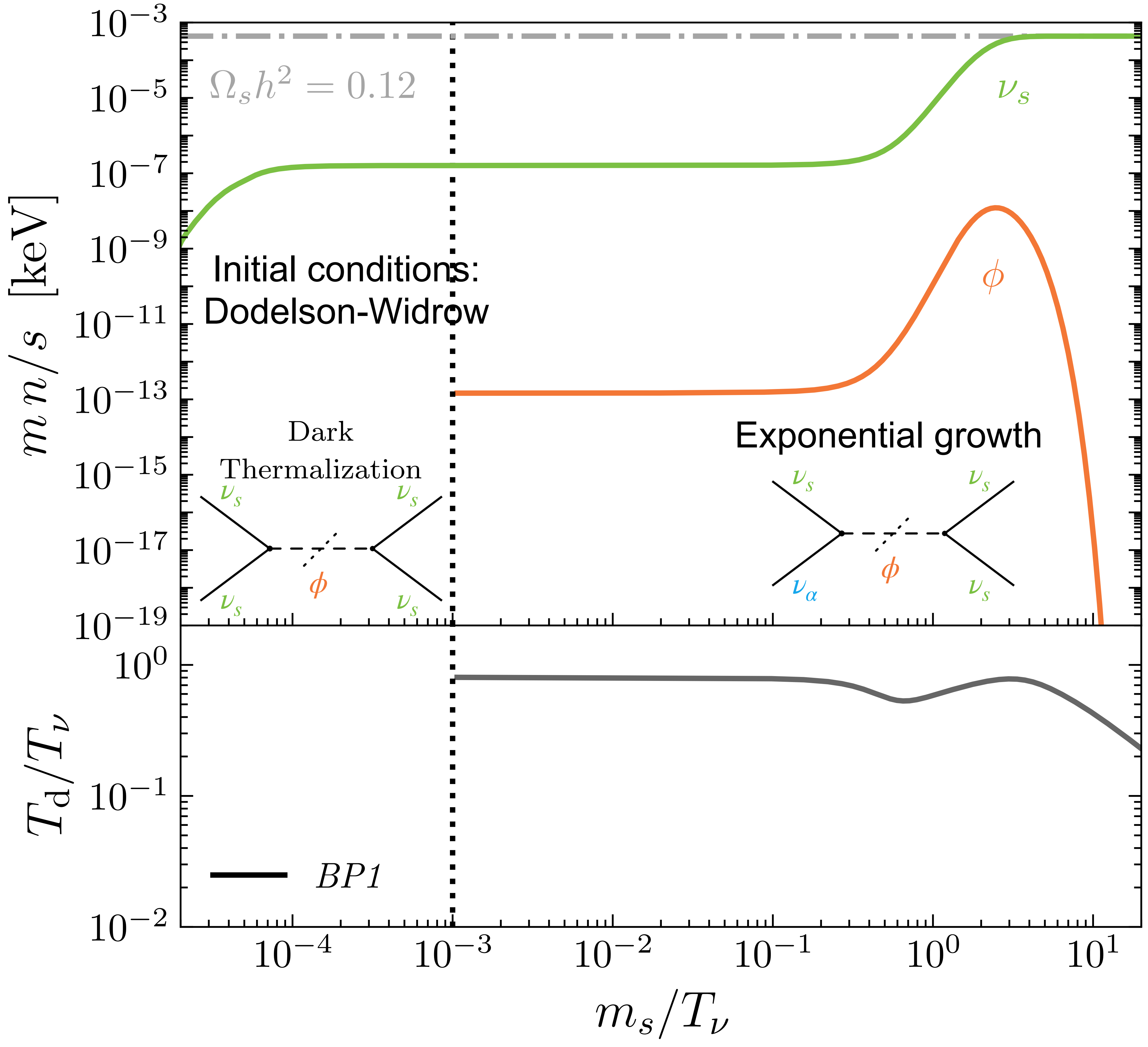

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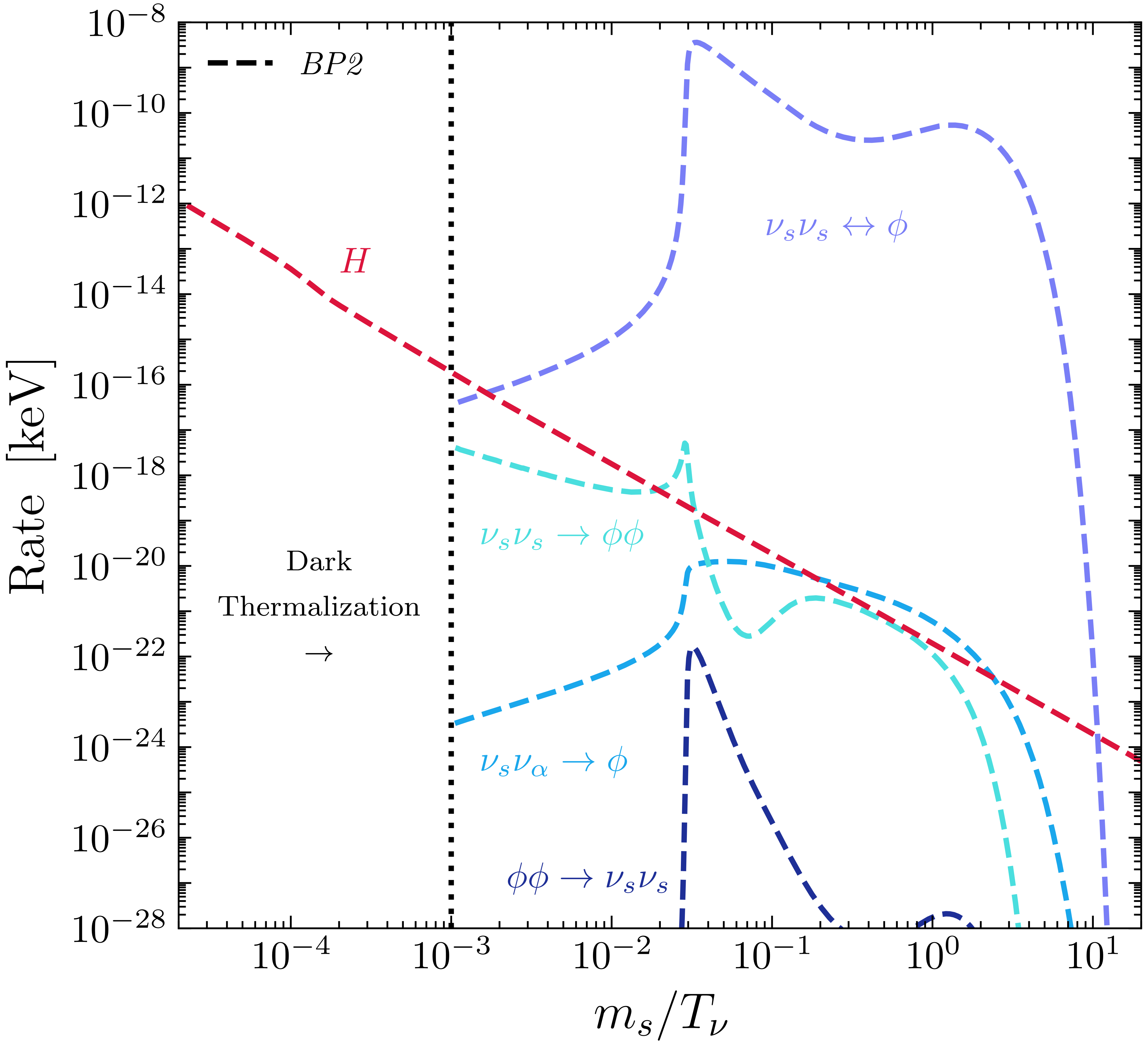
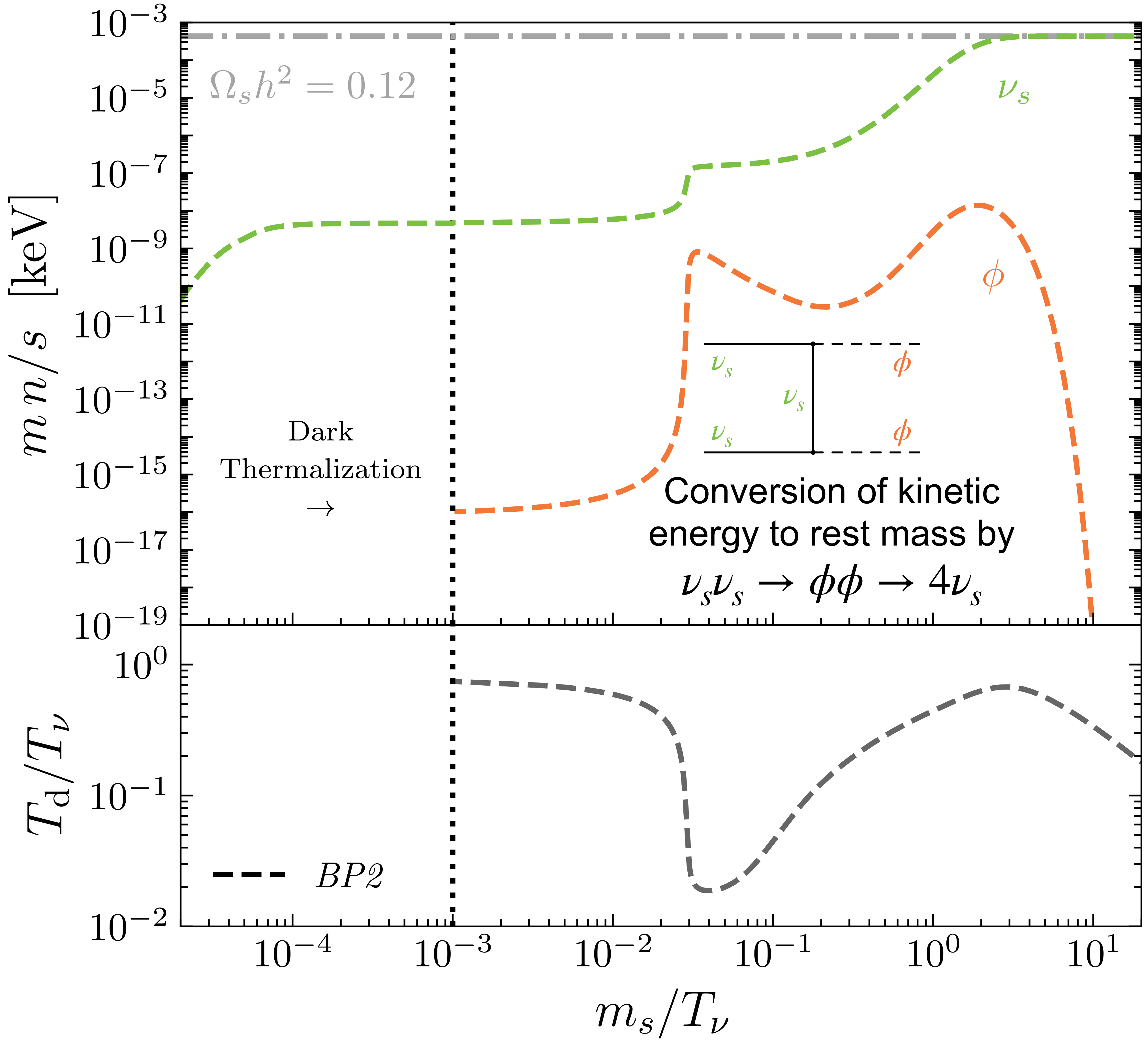
Exponential growth

	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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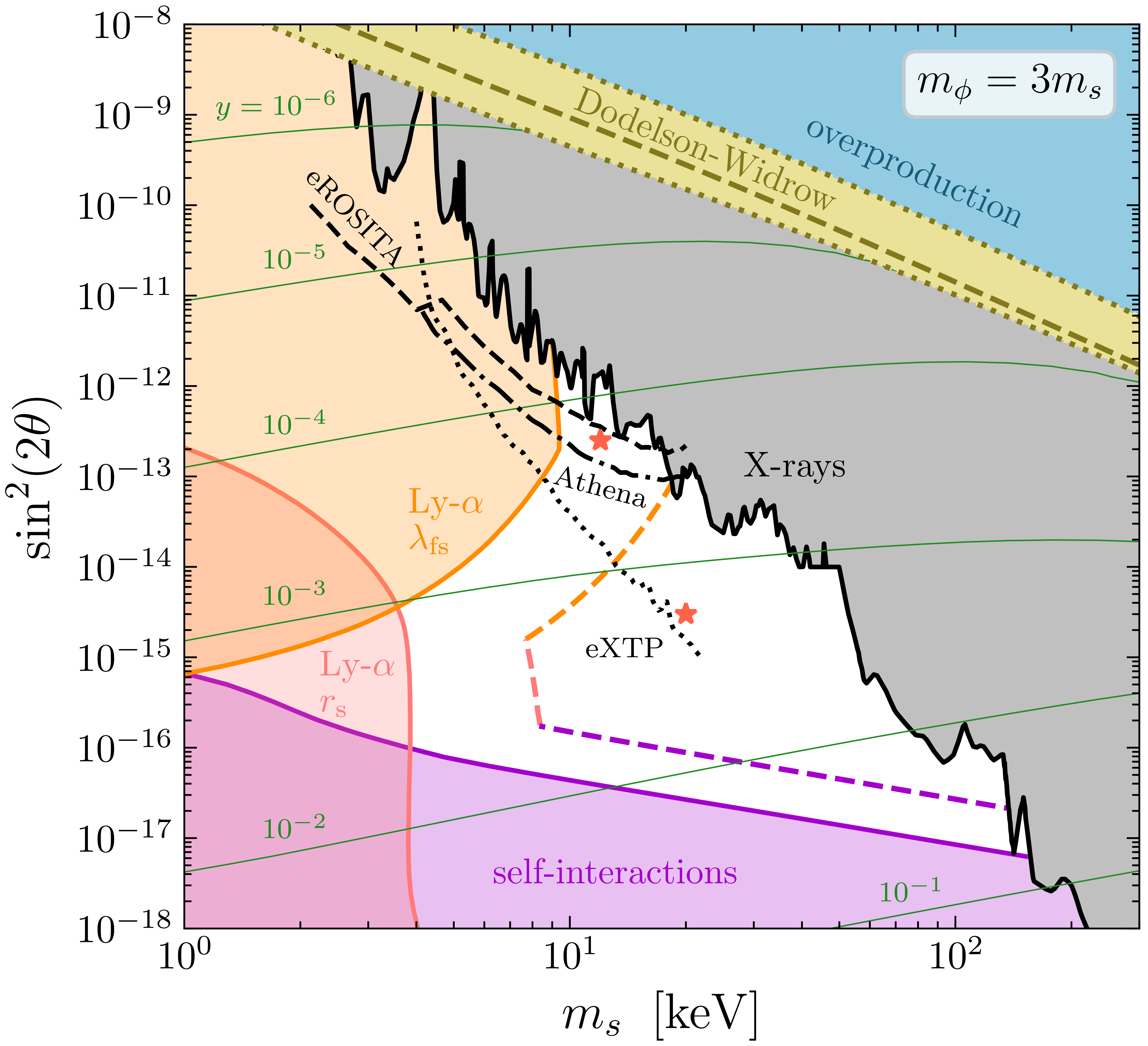
Parameter space



X-ray constraints from DM decays

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
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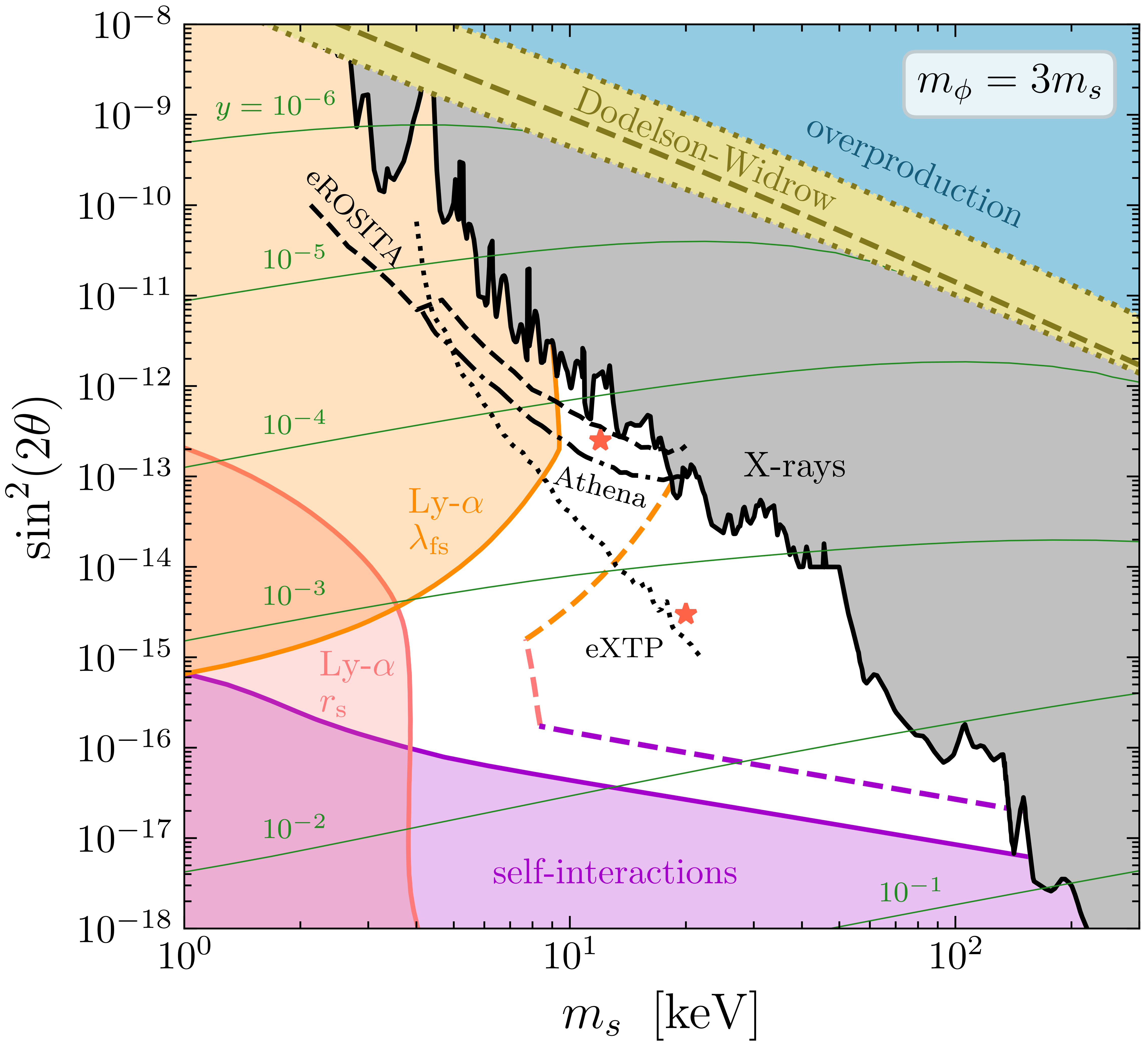

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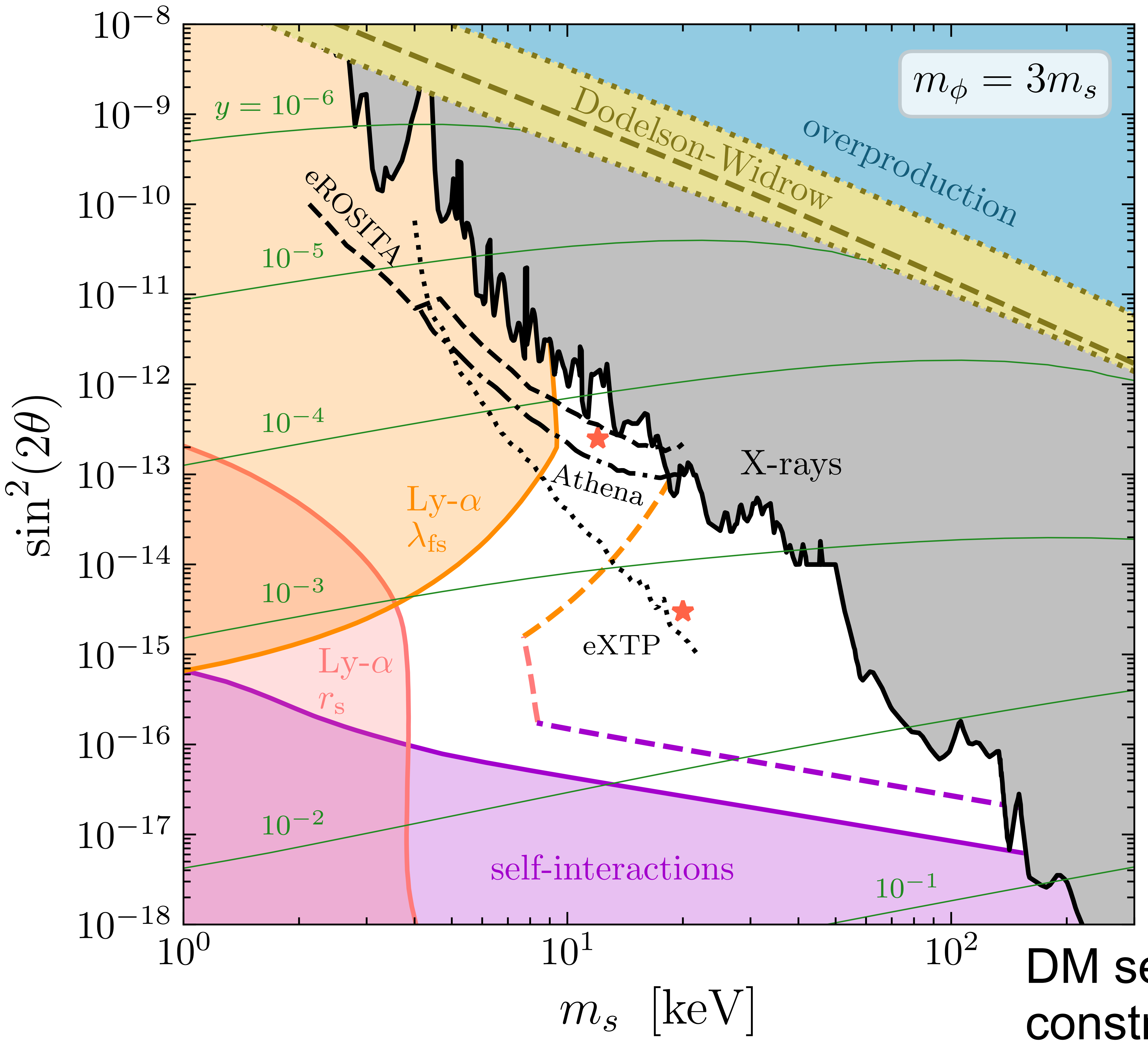

X-ray constraints from DM decays

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
- Many alternative production mechanisms proposed
- 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