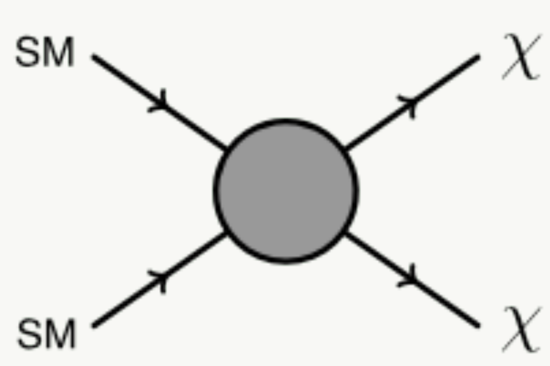
FREEZE-IN OF LIGHT SCALARS

-Saniya Heeba (RWTH Aachen)

Based on: **SH**, Felix Kahlhöfer, Patrick Stöcker, **1809.09849**

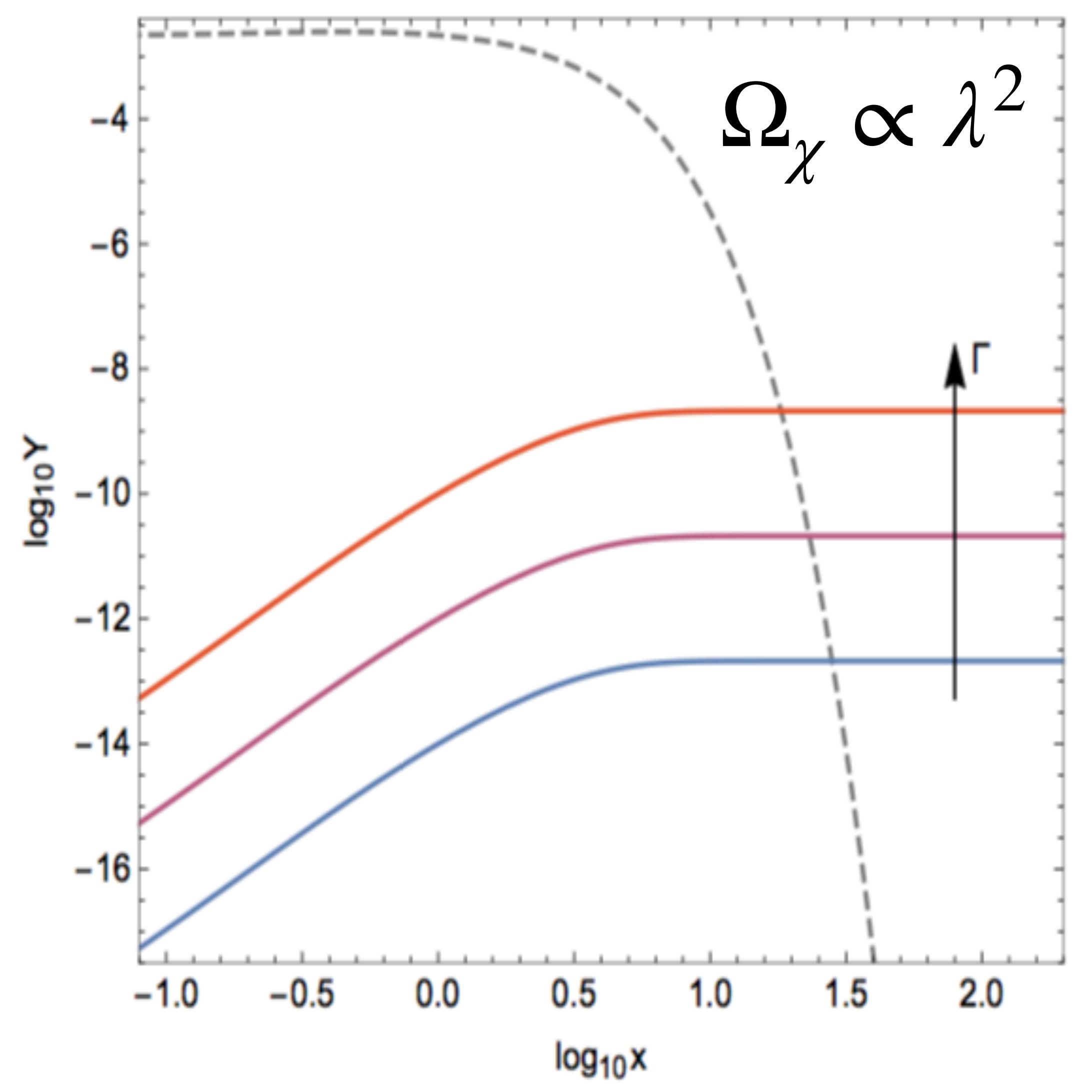
FREEZE-IN BASICS:



DM ABUNDANCE CALCULATED BY:

$1 \to 2:$ $$\frac{\mathrm{d}Y_\chi}{\mathrm{d}x} = 2\frac{\Gamma_{B\to\chi\chi}}{H\,x}\frac{K_1(x)}{K_2(x)}\,Y_B^{\mathrm{eq.}}$$

$2 \to 2:$ $$\frac{\mathrm{d}Y_\chi}{\mathrm{d}x} = C_{ab}\frac{s}{H\,x}\langle\sigma v\rangle\,Y^2_{ab,\,\mathrm{eq.}}$$



(Bernal et al.: 1706.07442)

THE MODEL

MODEL PARAMETERS:

$$\mathscr{L} = \mathscr{L}_{\text{kin.}} + \frac{1}{2}\mu_s^2(v_s + s)^2 - \frac{\lambda_s}{4}(v_s + s)^4 - \frac{\lambda_{hs}}{2}(v_s + s)^2 |\Phi|^2$$

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- No $\mathbb{Z}_2 \Rightarrow$ scalar is unstable but cosmologically viable for small λ_{hs} and $m_s \sim \text{keV} - \text{MeV}$.
- Parameters to keep in mind:
  - Mass: $m_s = \sqrt{2\,\lambda_s} v_s$
  - Mixing: λ_{hs} , determines freeze-in abundance.
  - Self-coupling: λ_s , determines scalar self-interactions and phenomenology after freeze-in.

WHEN SYMMETRIES (AND CALCULATIONS) BREAK DOWN…

- Phenomenology different before and after Electroweak Phase Transition (EWPT).

$$\mathscr{L} \supset -\frac{\lambda_{hs}}{2}(v_s + s)^2 \,|\,\Phi\,|^2$$

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Before EWPT

- No mixing between s and H
- No coupling to SM fermions

Note: At $T \gtrsim T_{\mathrm{EW}}$, temperature corrections to the Higgs mass are important!

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Before EWPT

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After EWPT

$$\mathscr{L} \supset -\lambda_{hs} v_s v\, s\, h$$

- Mixing determined by θ
- Coupling to SM fermions

$$\theta \approx \frac{\lambda_{hs}\, v_s\, v}{m_h^2 - m_s^2}$$

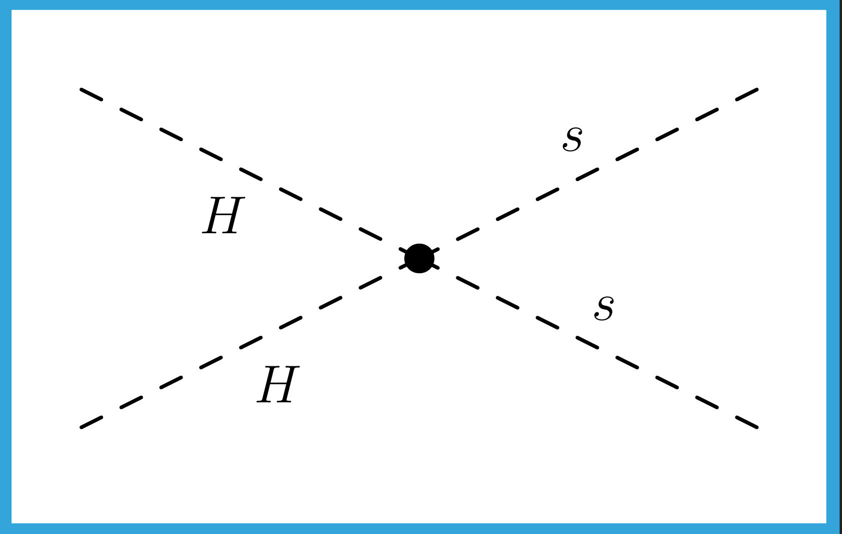
Note: At $T \gtrsim T_{\mathrm{EW}}$, temperature corrections to the Higgs mass are important!

THE FIVE STAGES OF FREEZE-IN

STAGE I: PRODUCTION BEFORE EWSB

$$\mathscr{L}_s \supset -\frac{\lambda_{hs}}{2}(v_s + s)^2 |\Phi|^2$$

Main production channel:



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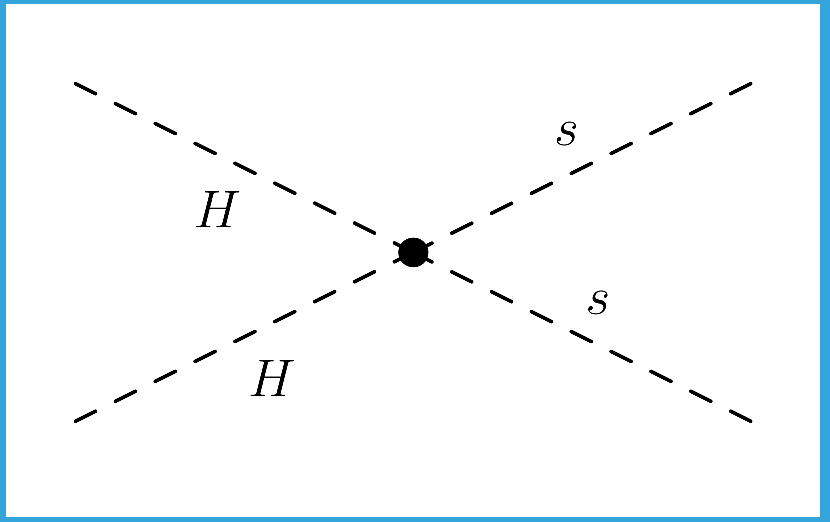

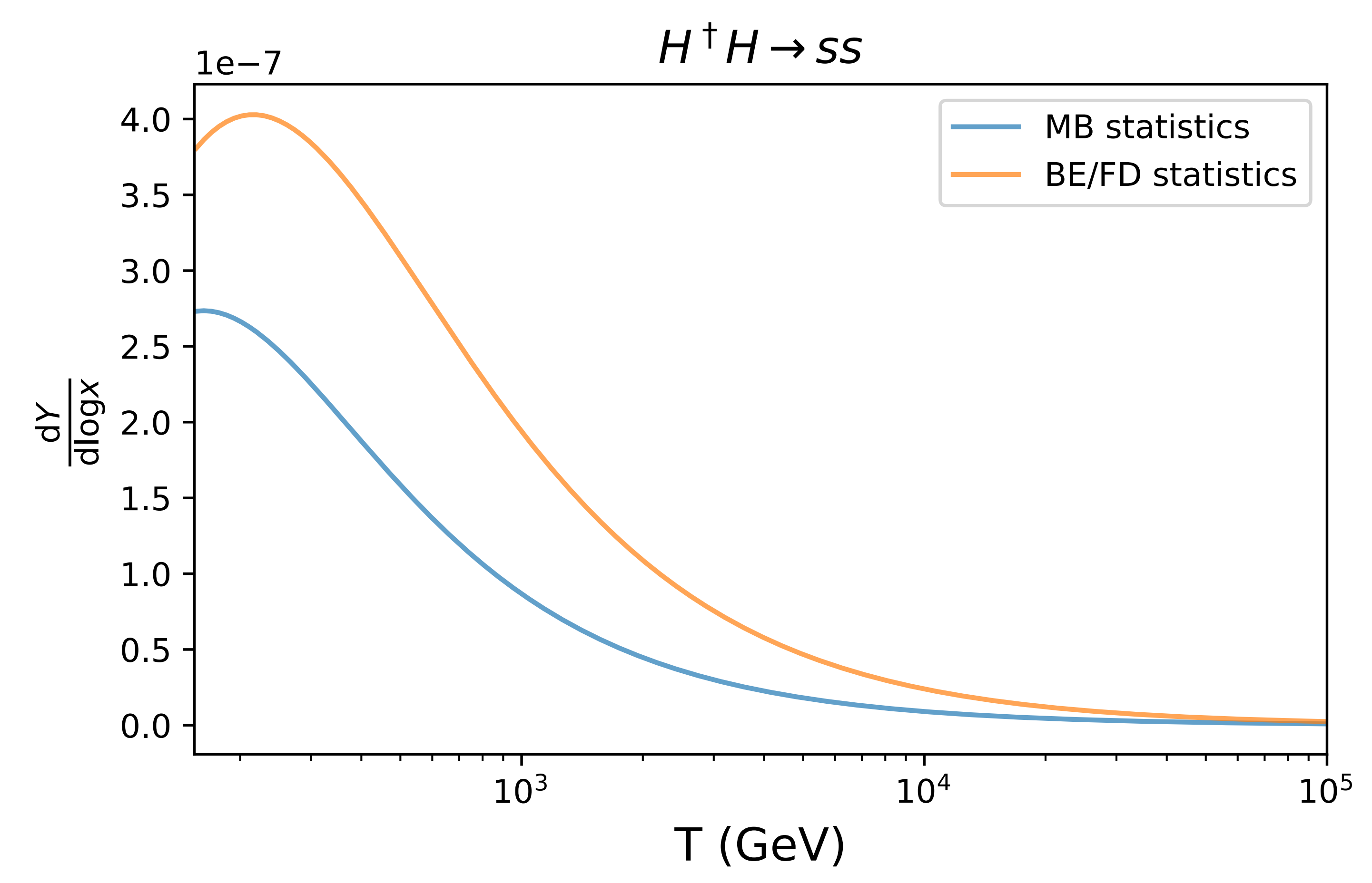

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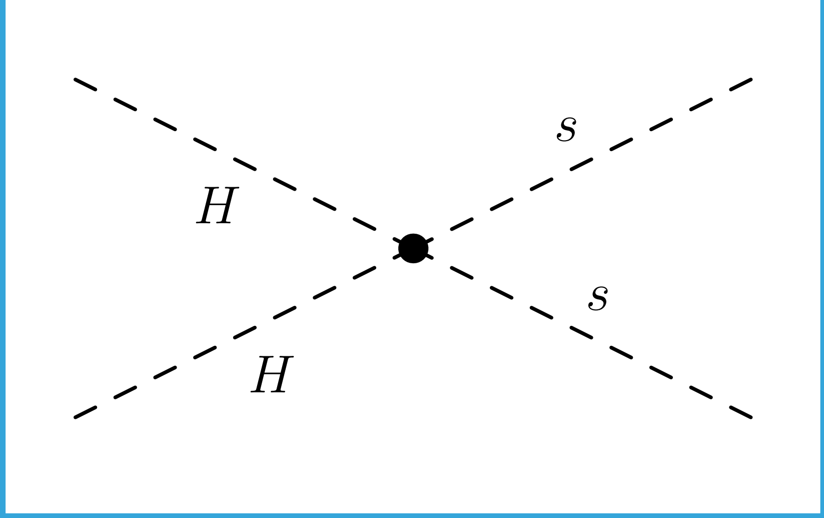
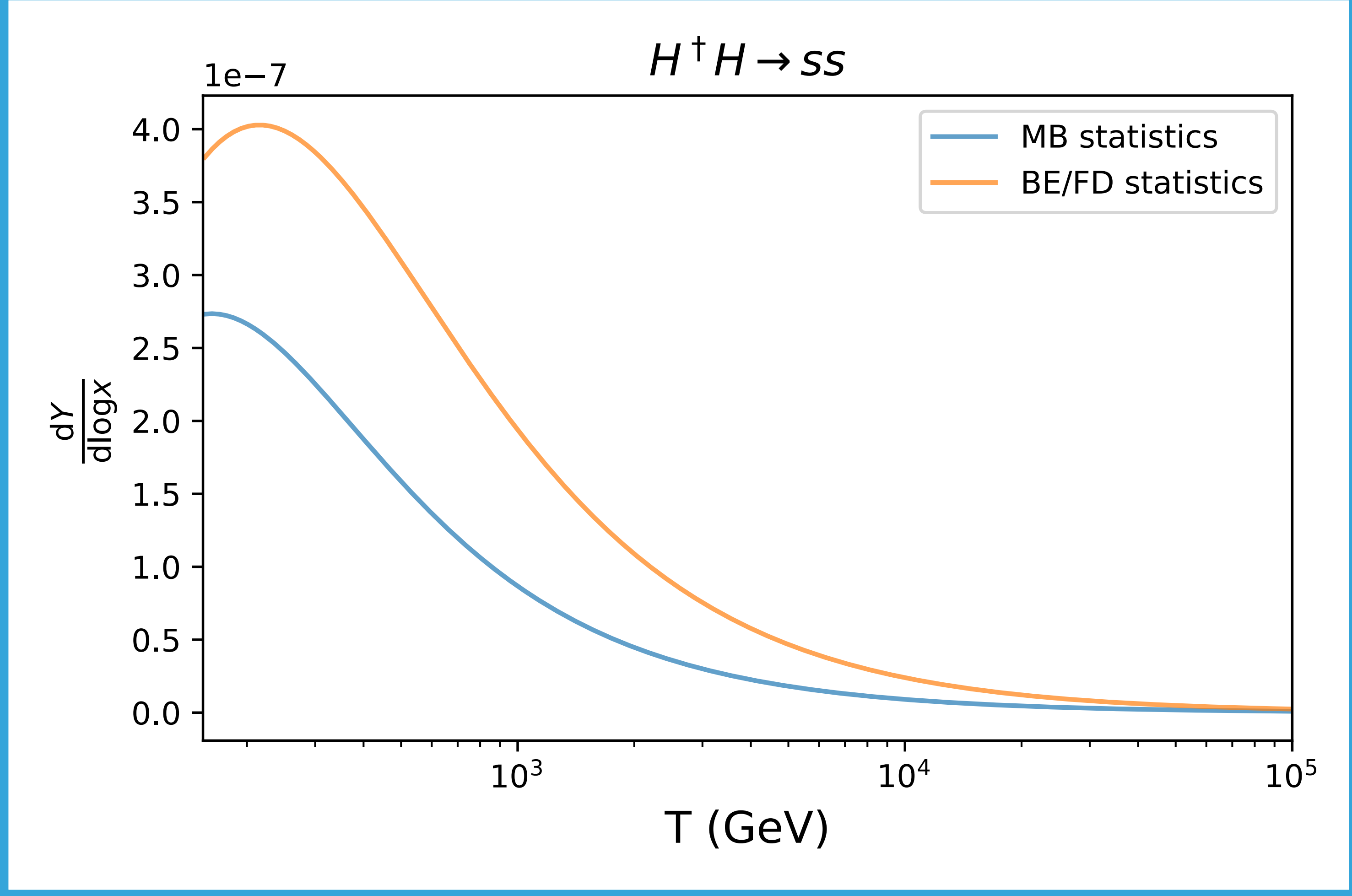
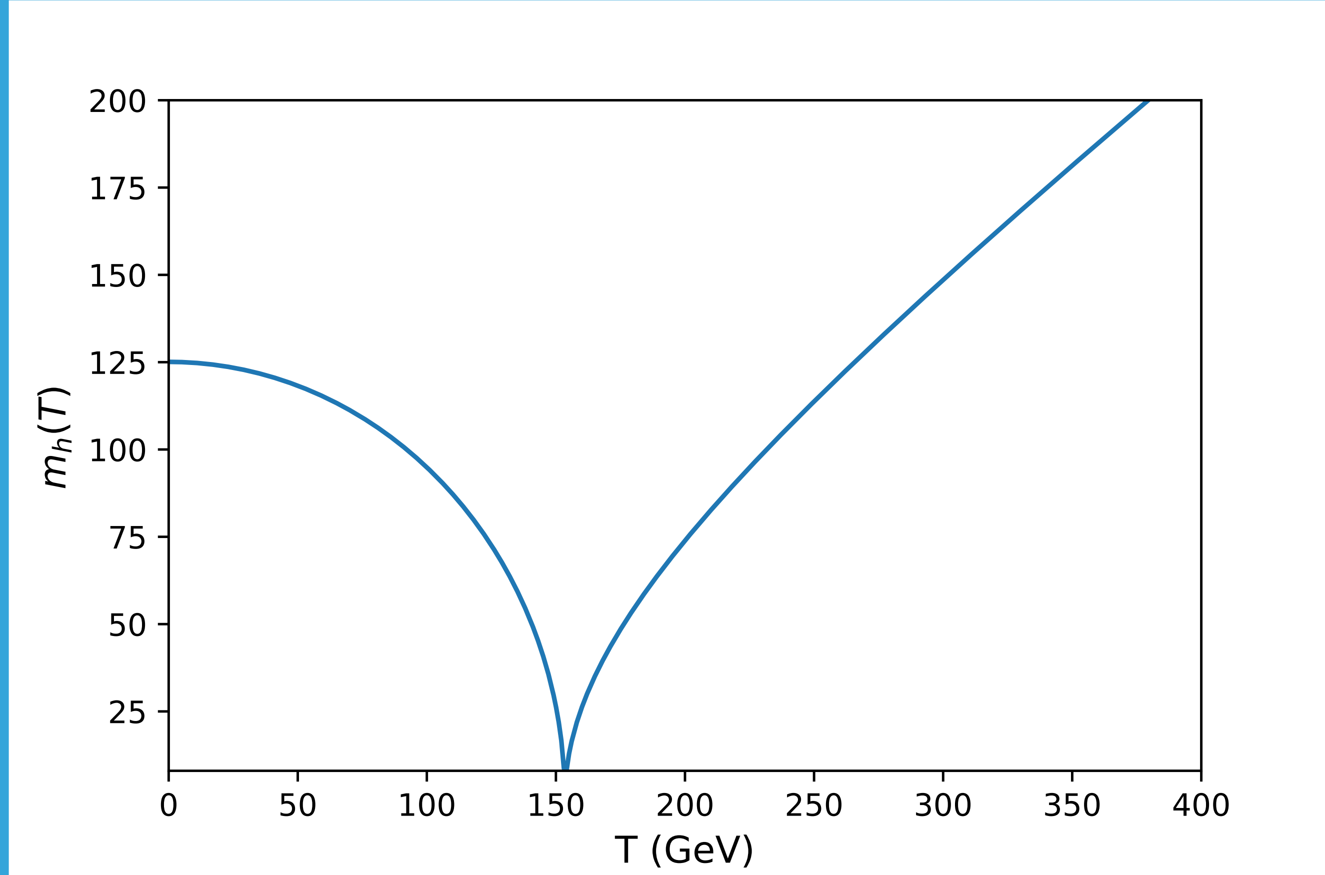




DM abundance before EWPT: $Y_{s,1} \approx (7.22 \times 10^9)\, \lambda_{hs}^2$

STAGE II: PRODUCTION DURING* EWPT

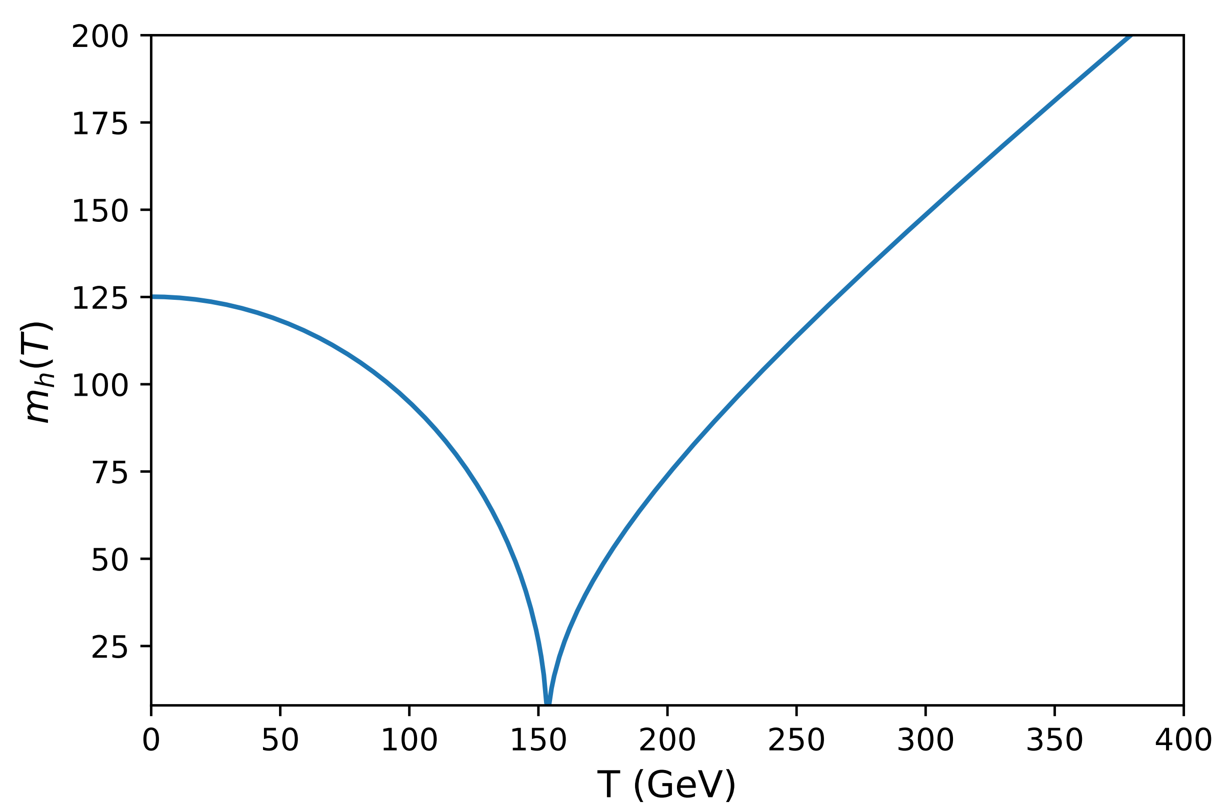
$$\theta(T) \approx \frac{\lambda_{hs} v_s v}{m_h(T)^2 - m_s^2}$$



STAGE II: PRODUCTION DURING* EWPT

$$\theta(T) \approx \frac{\lambda_{hs} v_s v}{m_h(T)^2 - m_s^2}$$

- For $m_h(T) \sim m_s$, θ is enhanced
- Higgs can oscillate into scalar. **(Redondo & Postma, 0811.0326)**
- Rate of conversion depends on:
  - Mixing parameter, λ_{hs}
  - Variation of m_h with respect to temperature, $\frac{\mathrm{d}m_h^2}{\mathrm{d}T}$



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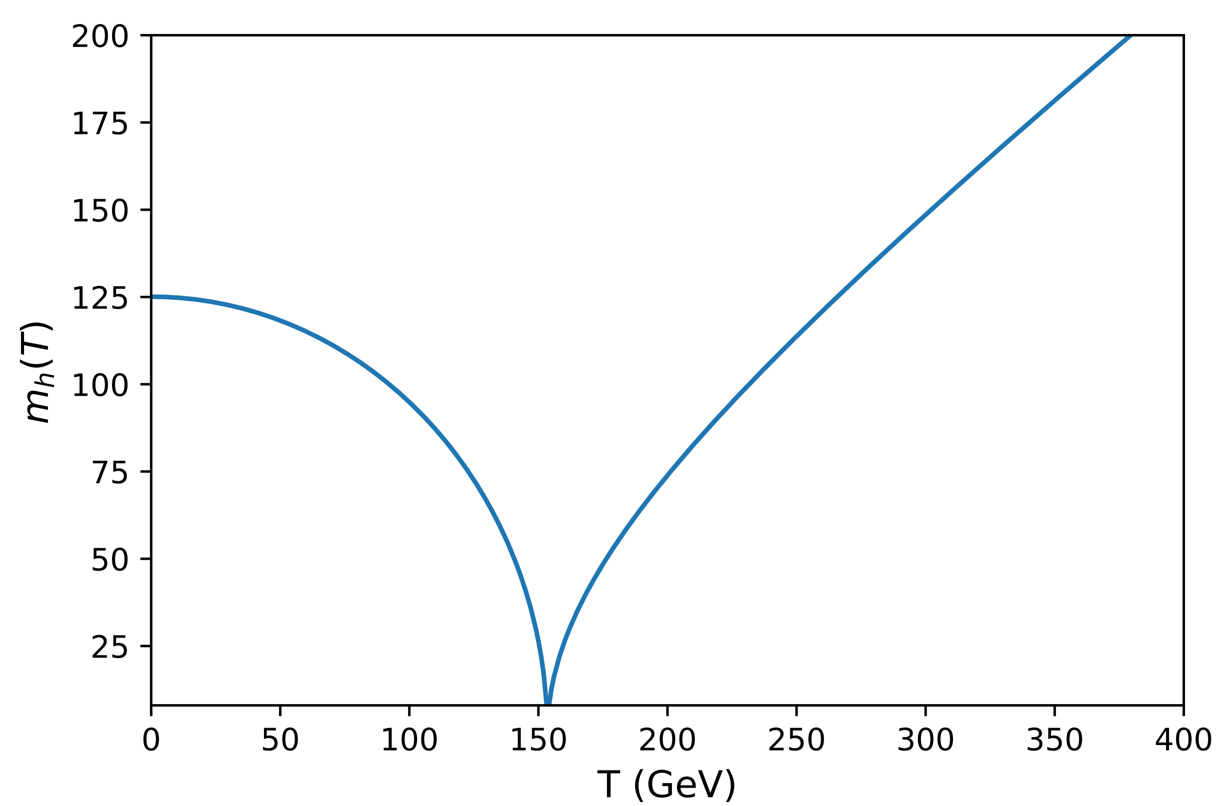
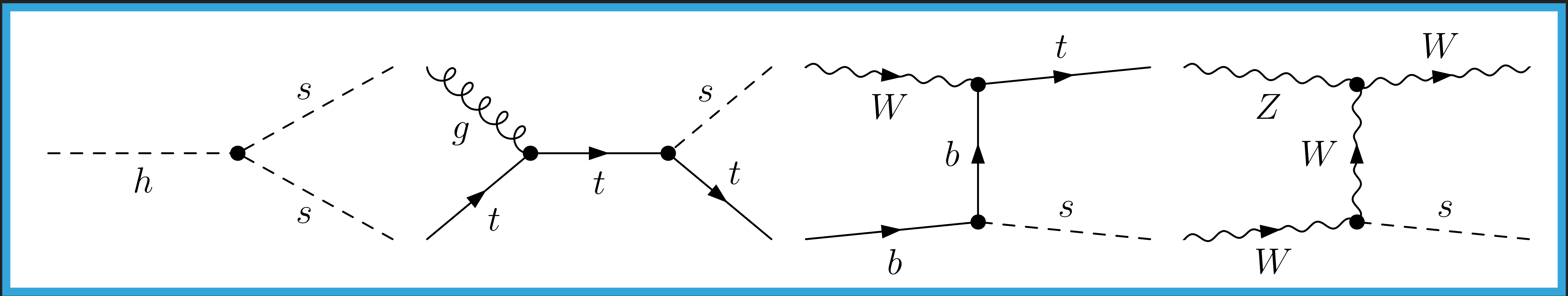


DM abundance during EWPT:

$$Y_{s,2} \approx (3 \times 10^5\,\mathrm{GeV}^{-4})\,\lambda_{hs}^2\, m_s^2\, v_s^2$$

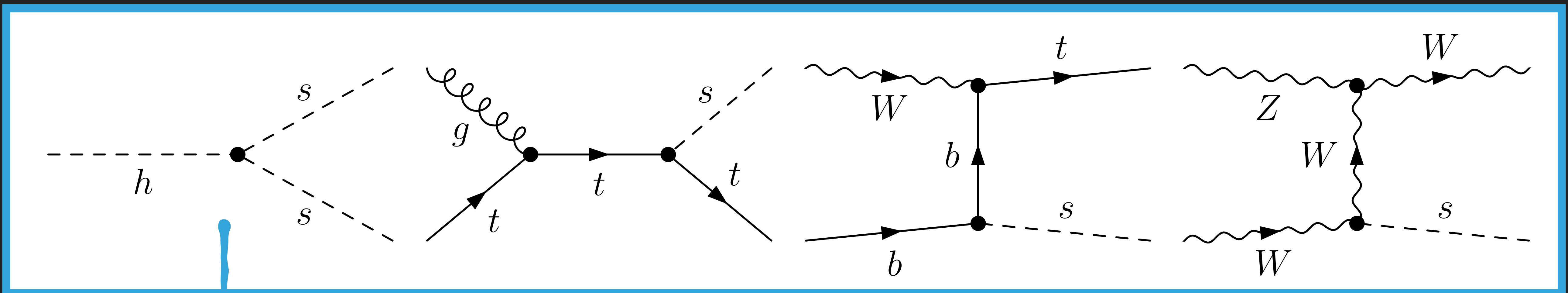
STAGE III: PRODUCTION AFTER EWPT



+ many more!

Possible to divide the parameter space in two parts based on how the different cross-sections scale with the scalar vev

STAGE III: PRODUCTION AFTER EWPT



+ many more!

$$\sigma \propto \left(\frac{\sin\theta}{v_s}\right)^2 \sim \lambda_{hs}^2$$

Dominant channel when $v_s \leq 100\,\mathrm{GeV}$

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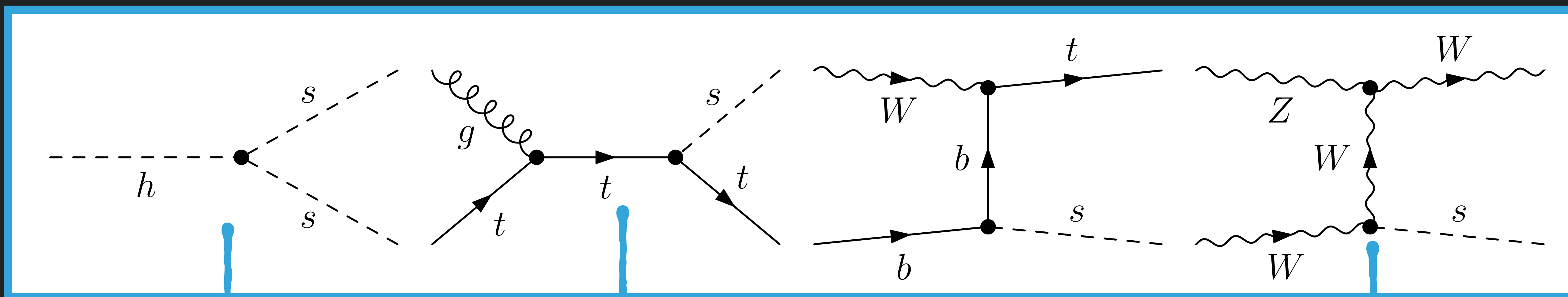

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$$\sigma \propto \left(\frac{\sin\theta}{v_s}\right)^2 \sim \lambda_{hs}^2$$

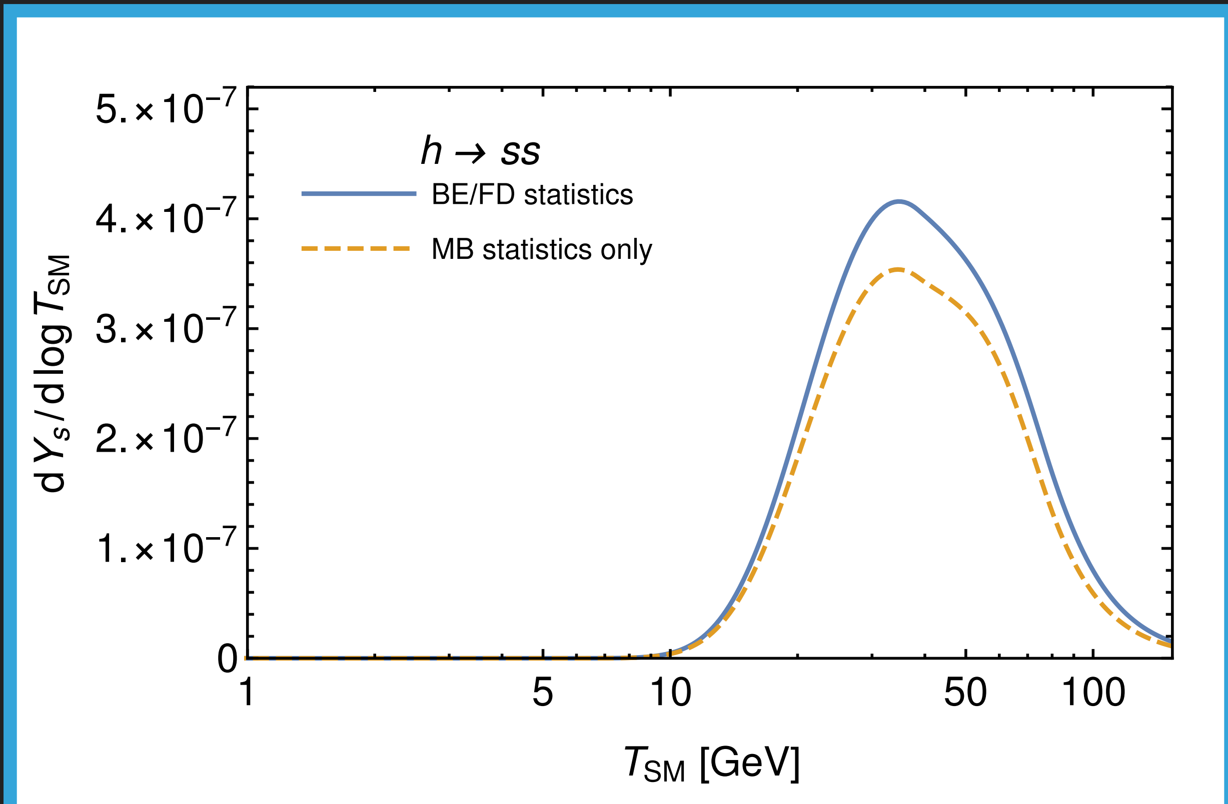
Dominant channel when $v_s \leq 100\,\mathrm{GeV}$

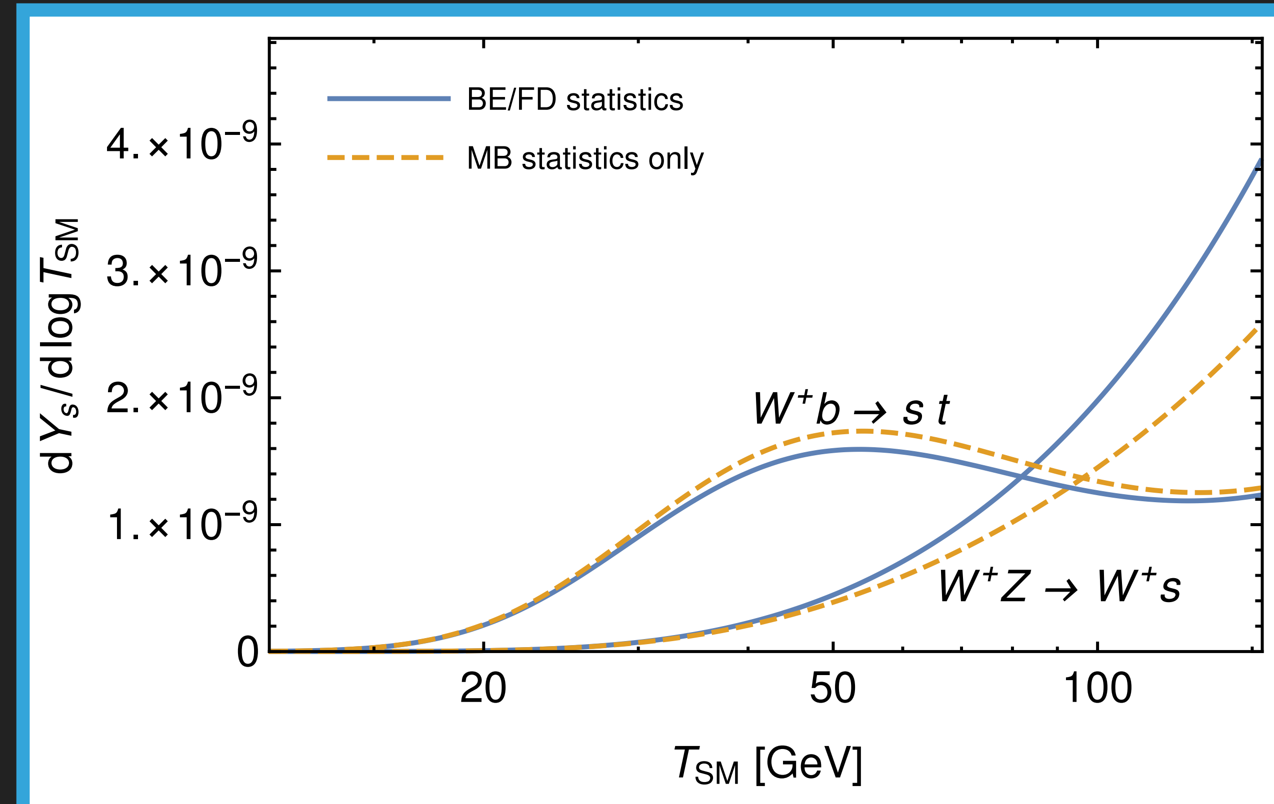
$$\sigma \propto \sin^2\theta \sim \lambda_{hs}^2 v_s^2$$

Dominant channels when $v_s \geq 100\,\mathrm{GeV}$

Possible to divide the parameter space in two parts based on how the different cross-sections scale with the scalar vev

STAGE III: PRODUCTION AFTER EWPT



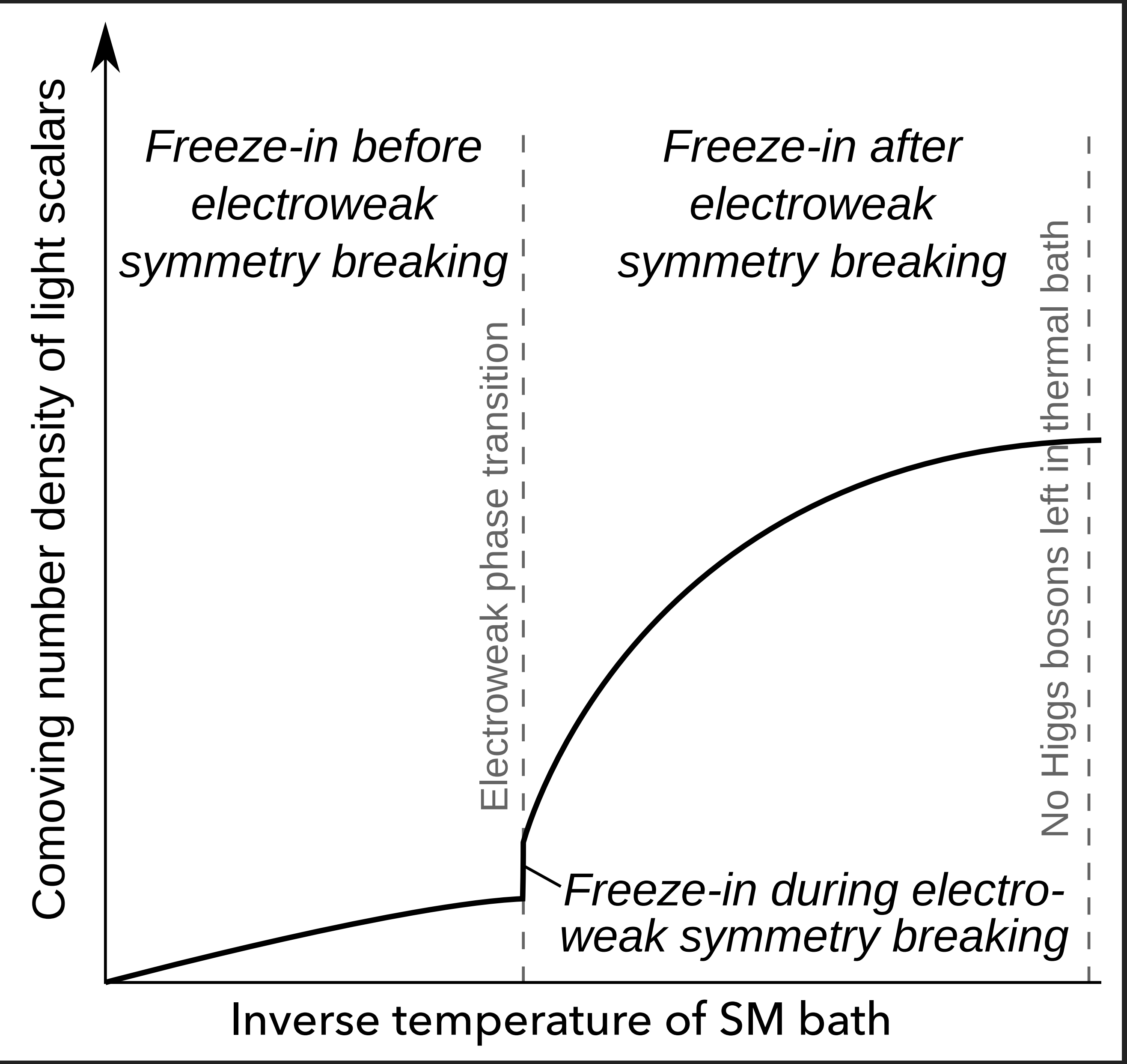


$$Y_{s,3}^{\rm decay} \approx (2.2 \times 10^{12})\, \lambda_{hs}^2$$

$$Y_{s,3}^{2\to2} \approx (1.7 \times 10^{8}\,{\rm GeV}^{-2})\, \lambda_{hs}^2\, v_s^2$$

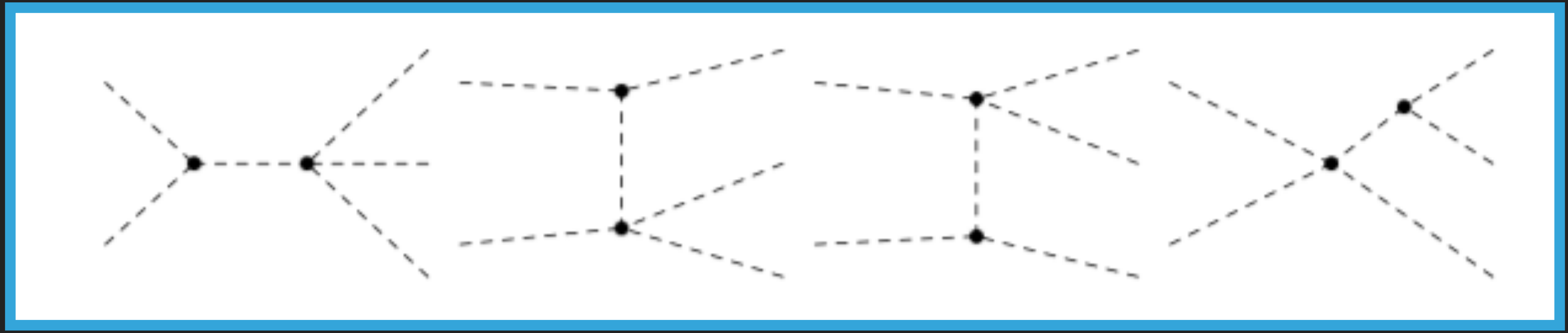
Maximum production after EWPT!

UNTIL NOW:


Comoving number density of light scalars
Freeze-in before electroweak symmetry breaking
Freeze-in after electroweak symmetry breaking
Electroweak phase transition
No Higgs bosons left in thermal bath
Freeze-in during electroweak symmetry breaking
Inverse temperature of SM bath

STAGE IV: DARK SECTOR THERMALISATION

- Does the DM comoving number density remain constant after freeze-in?
  - λ_s induces self-interactions! (Kinetic equilibrium)
  - Absence of $\mathbb{Z}_2$ symmetry implies $2 \to 3$ and $3 \to 2$ processes allowed. (Chemical equilibrium?)



- Do these interactions always *thermalise* the dark sector?

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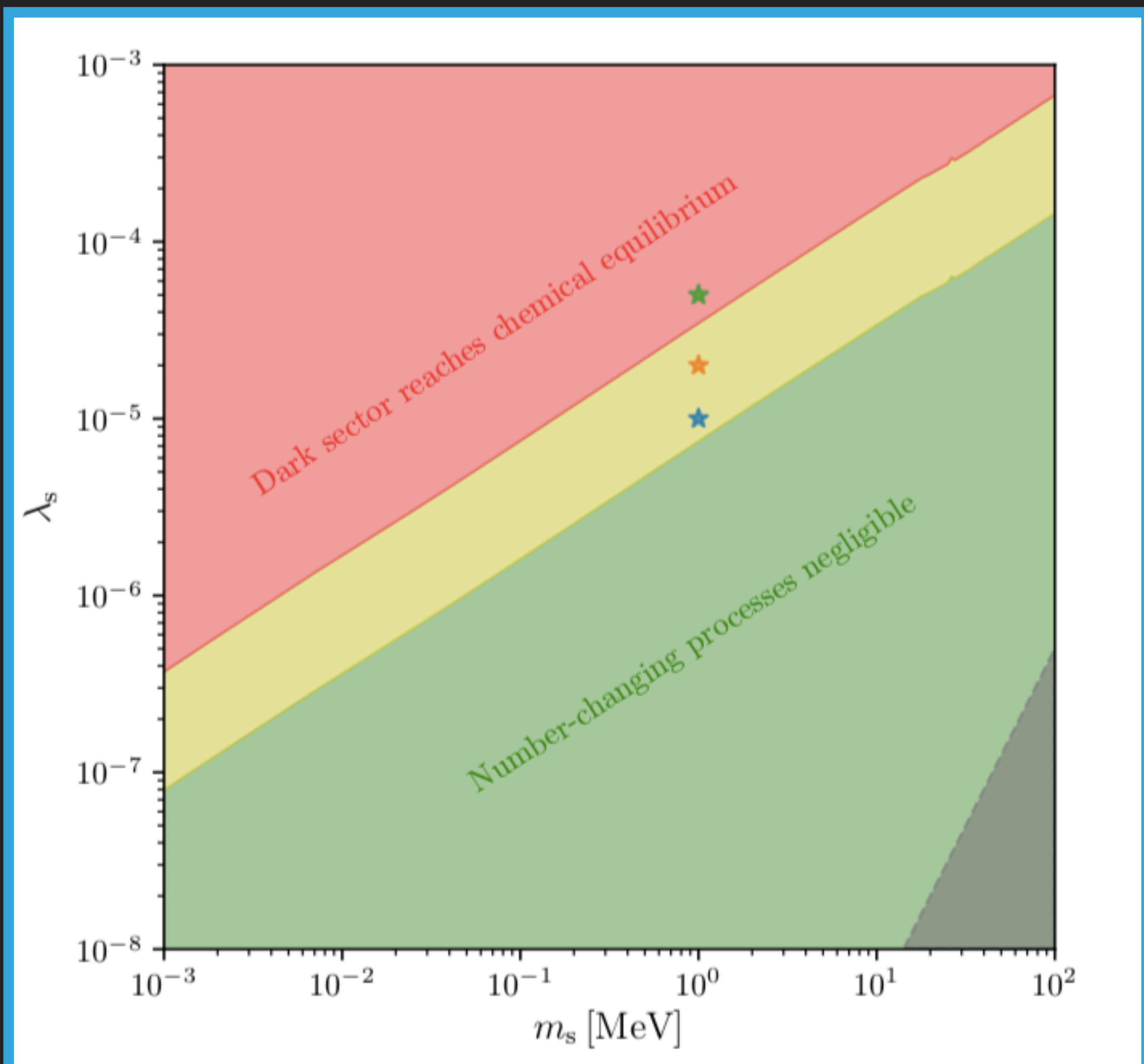


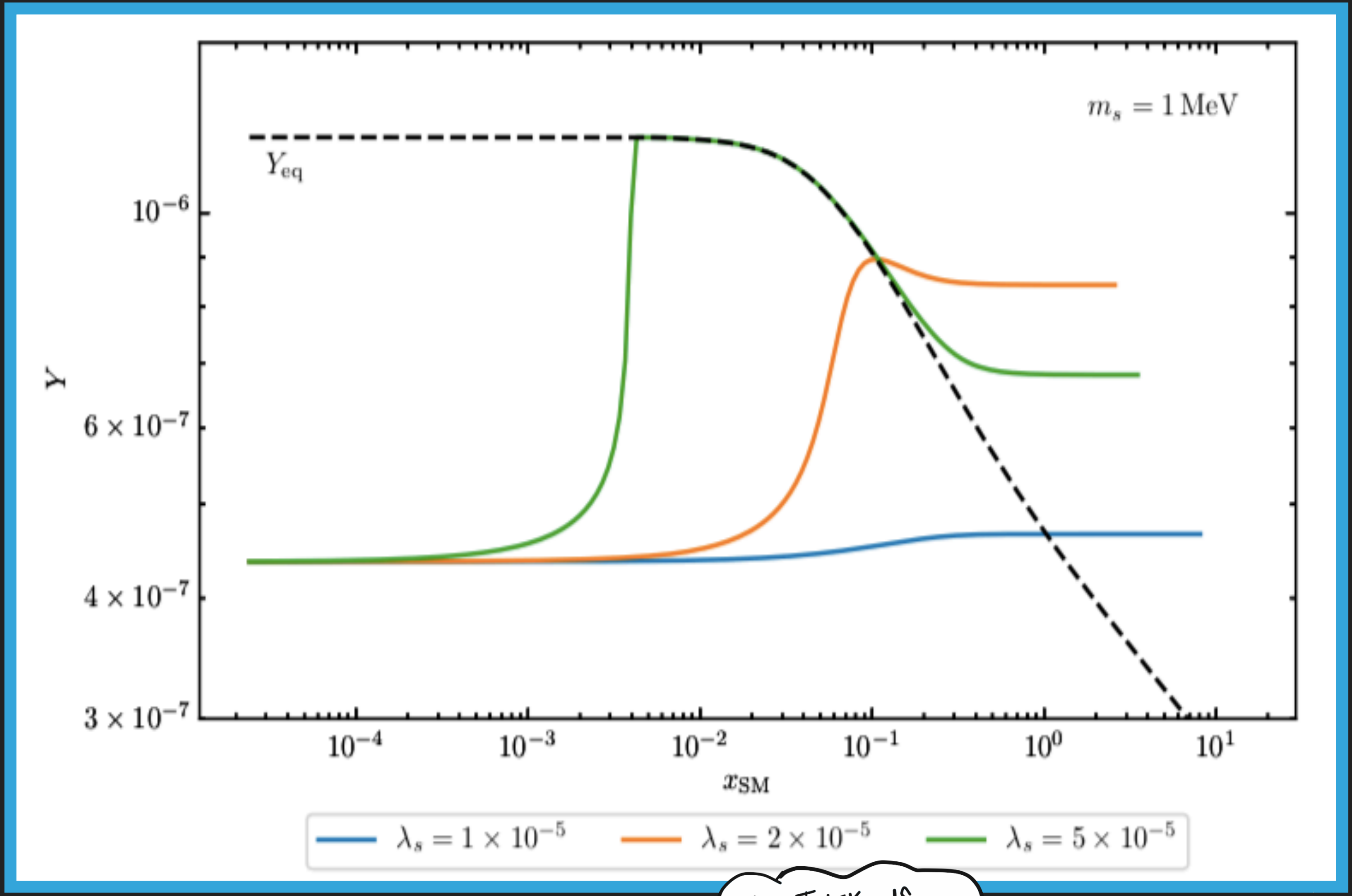
- The presence of number changing processes implies that the DM number density can change after freeze-in has ended.

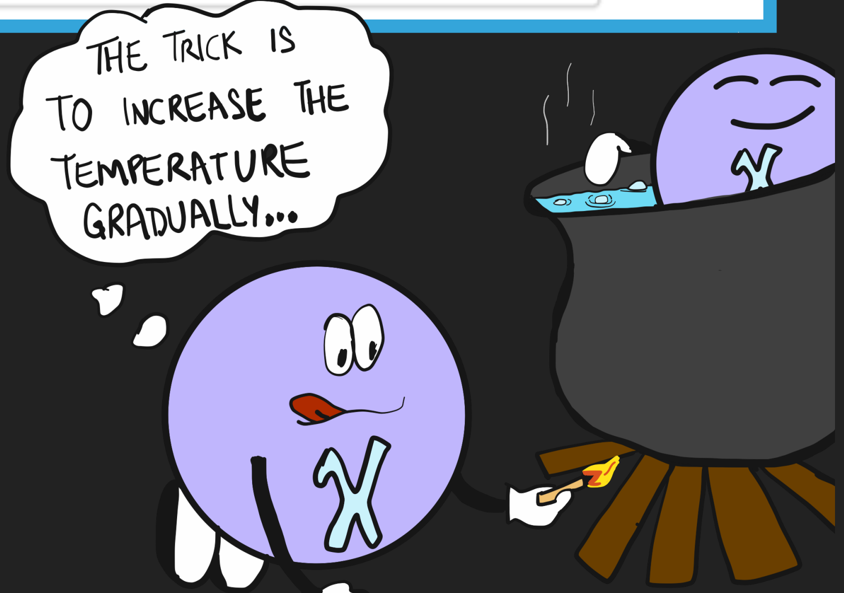
STAGE V: DARK SECTOR FREEZE-OUT

If DM in chemical equilibrium:

BREEDING

$2 \to 3$ processes
populate the dark sector





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<u>If DM in chemical equilibrium:</u>

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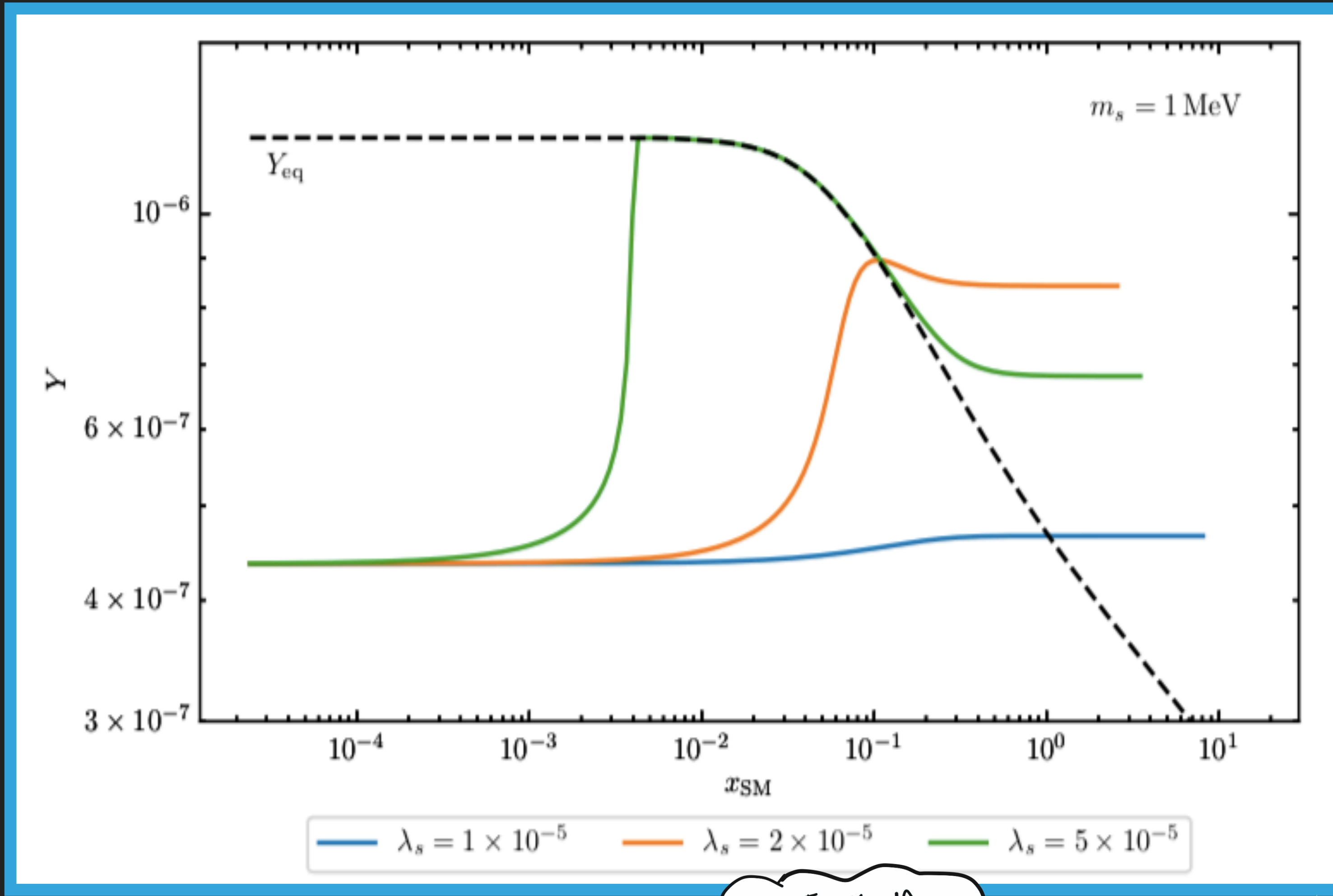
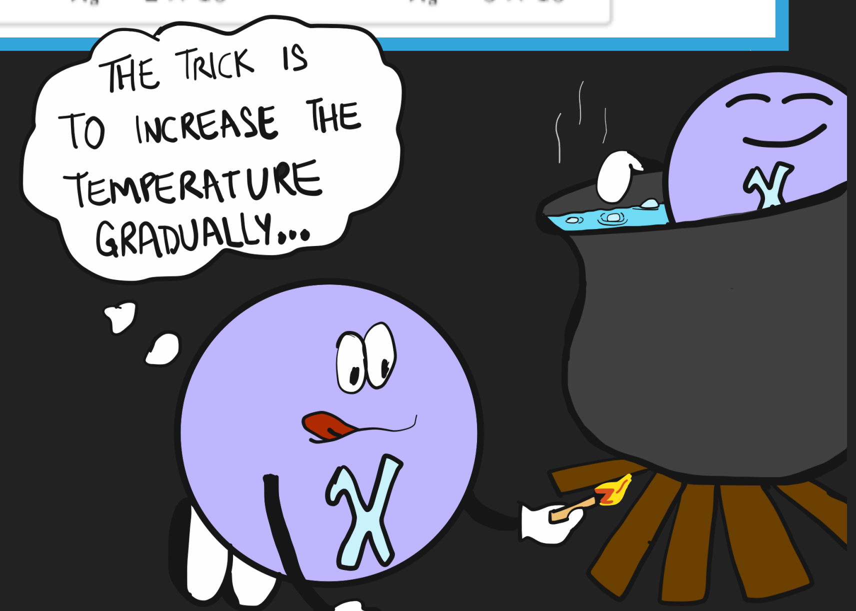
populate the dark sector

COHABITATION

$2 \rightarrow 3$ and $3 \rightarrow 2$
processes equally efficient





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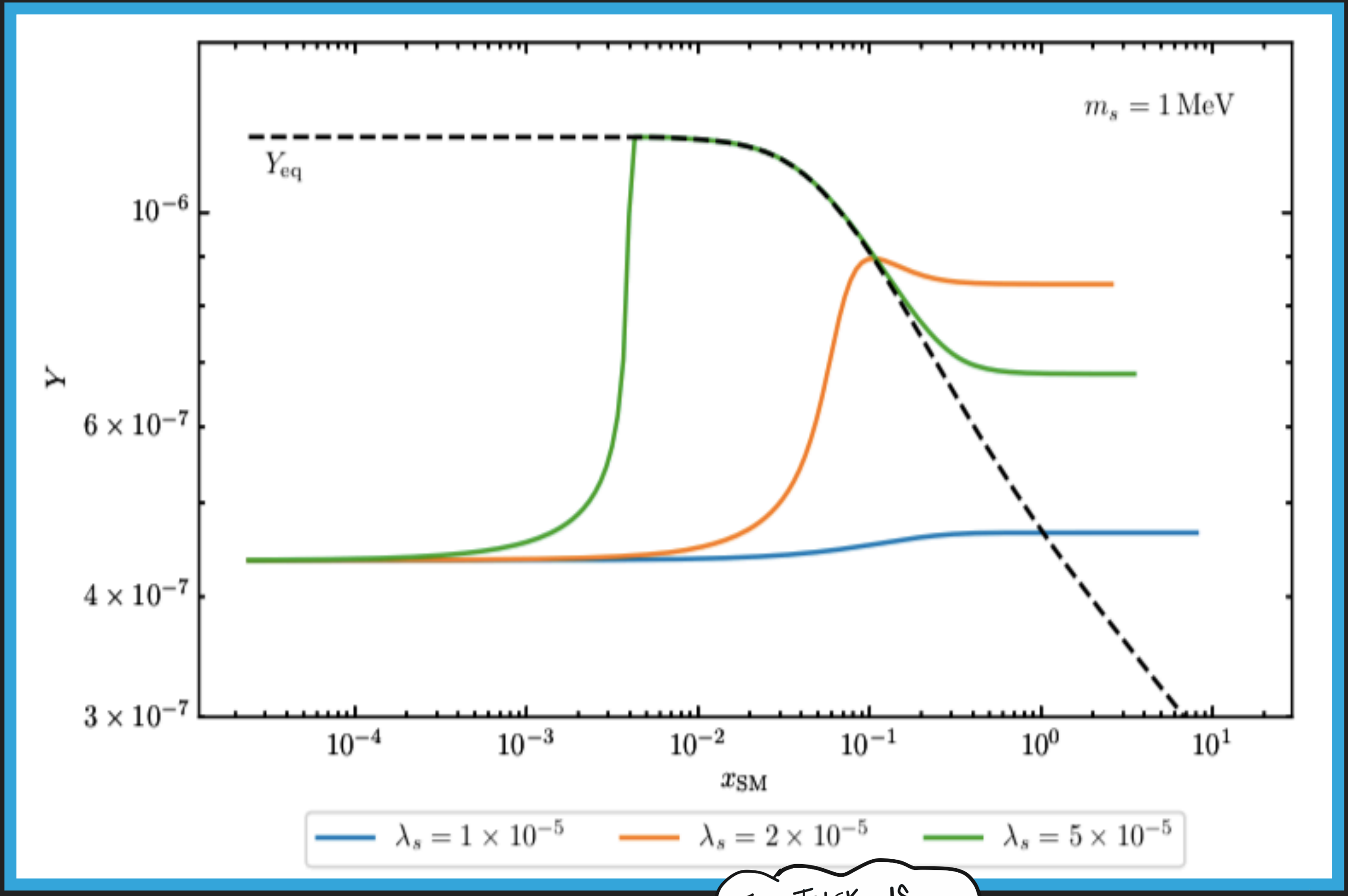
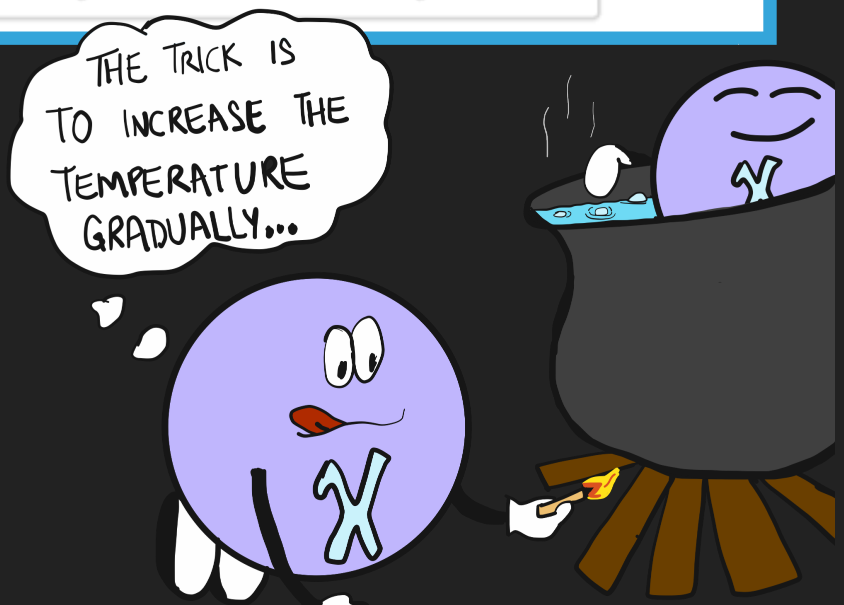
CANNIBALISM

$3 \to 2$ processes increase dark sector temperature





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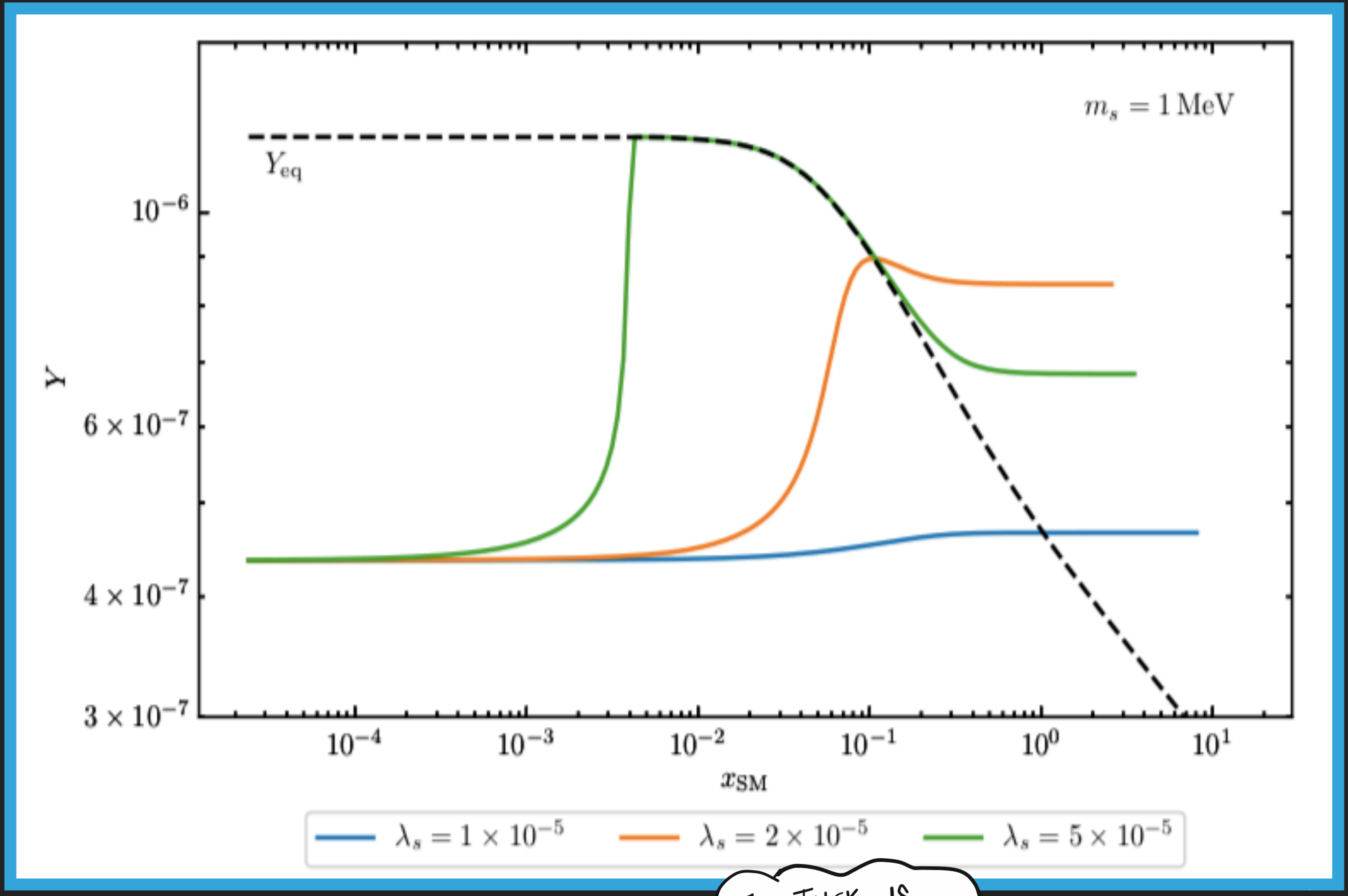
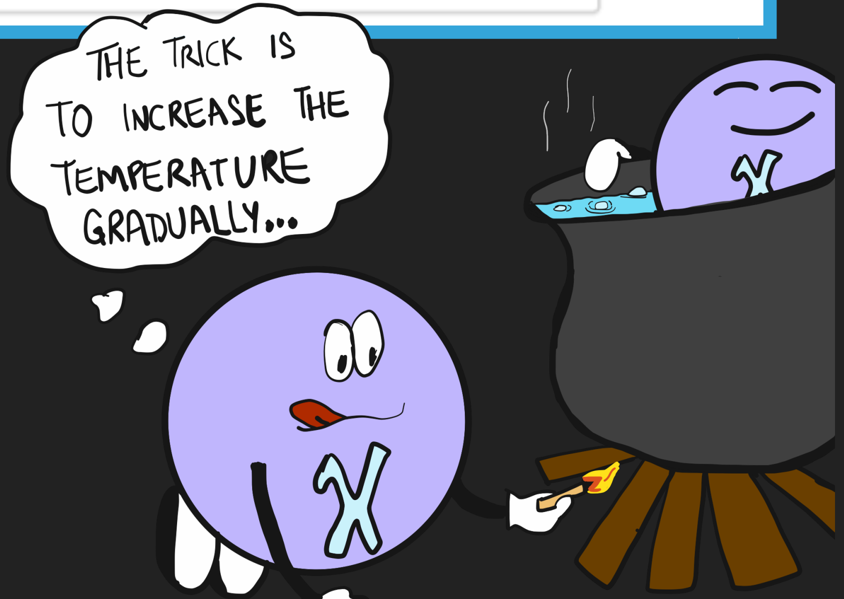
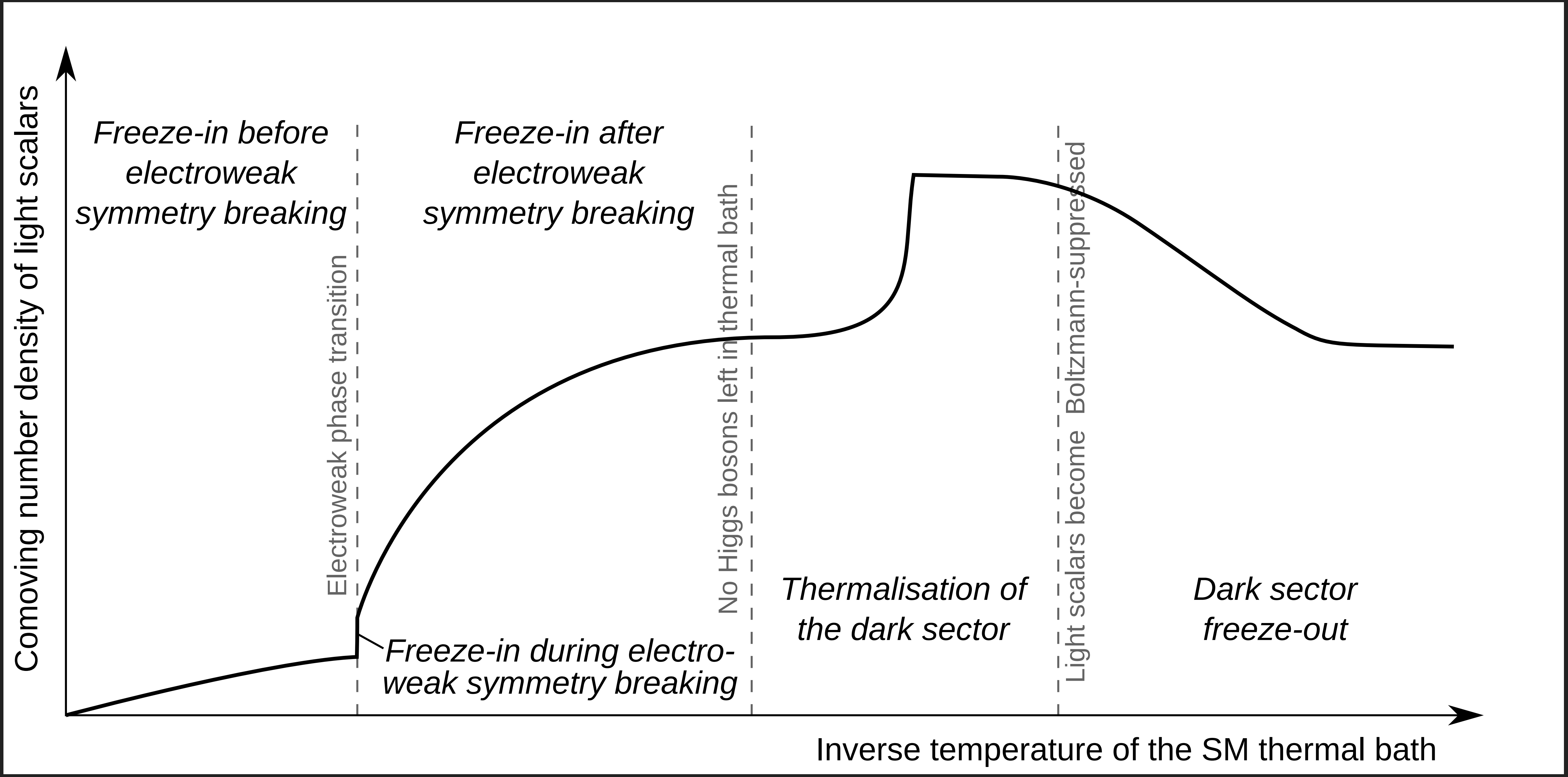
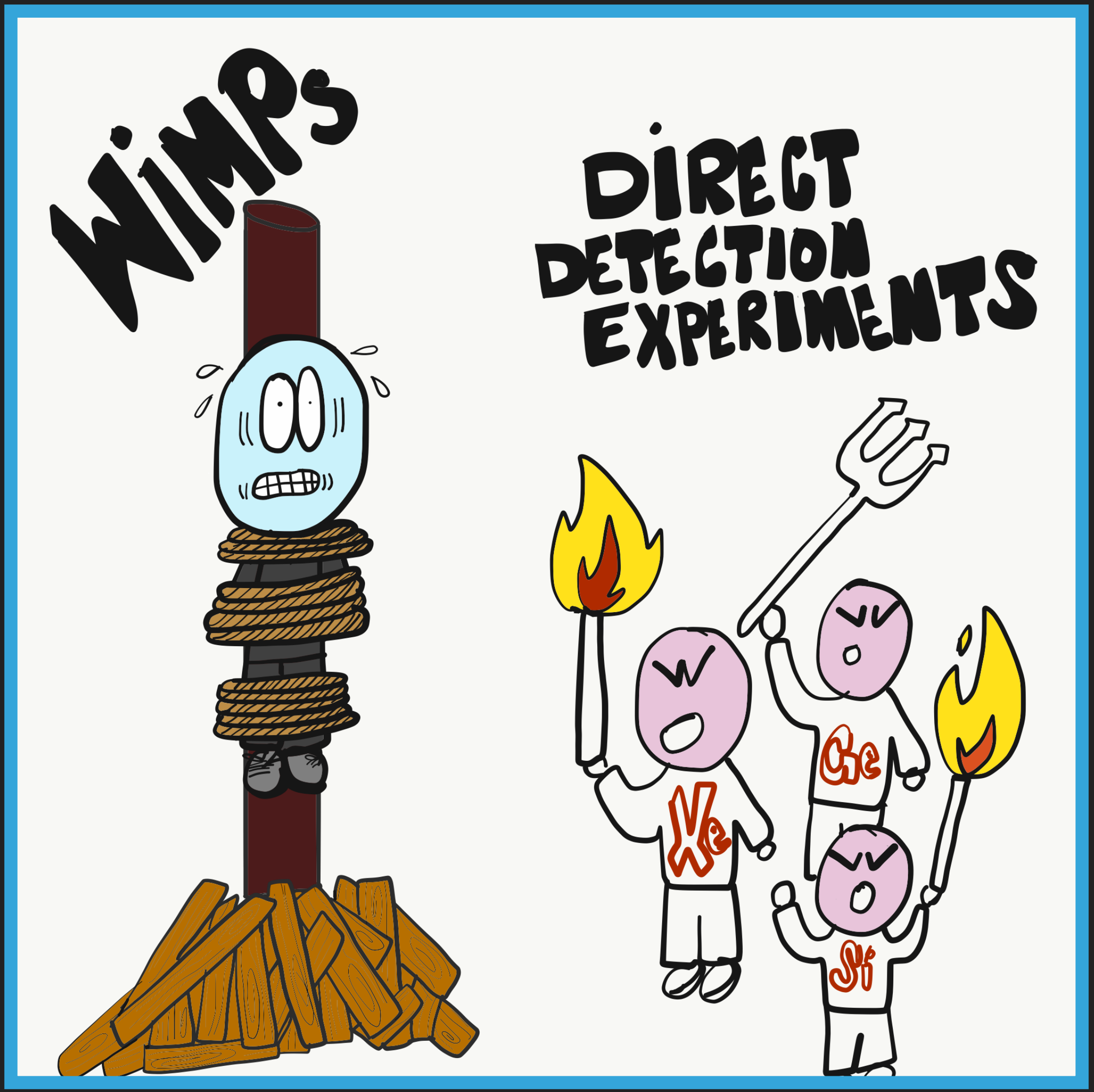
FREEZE-OUT





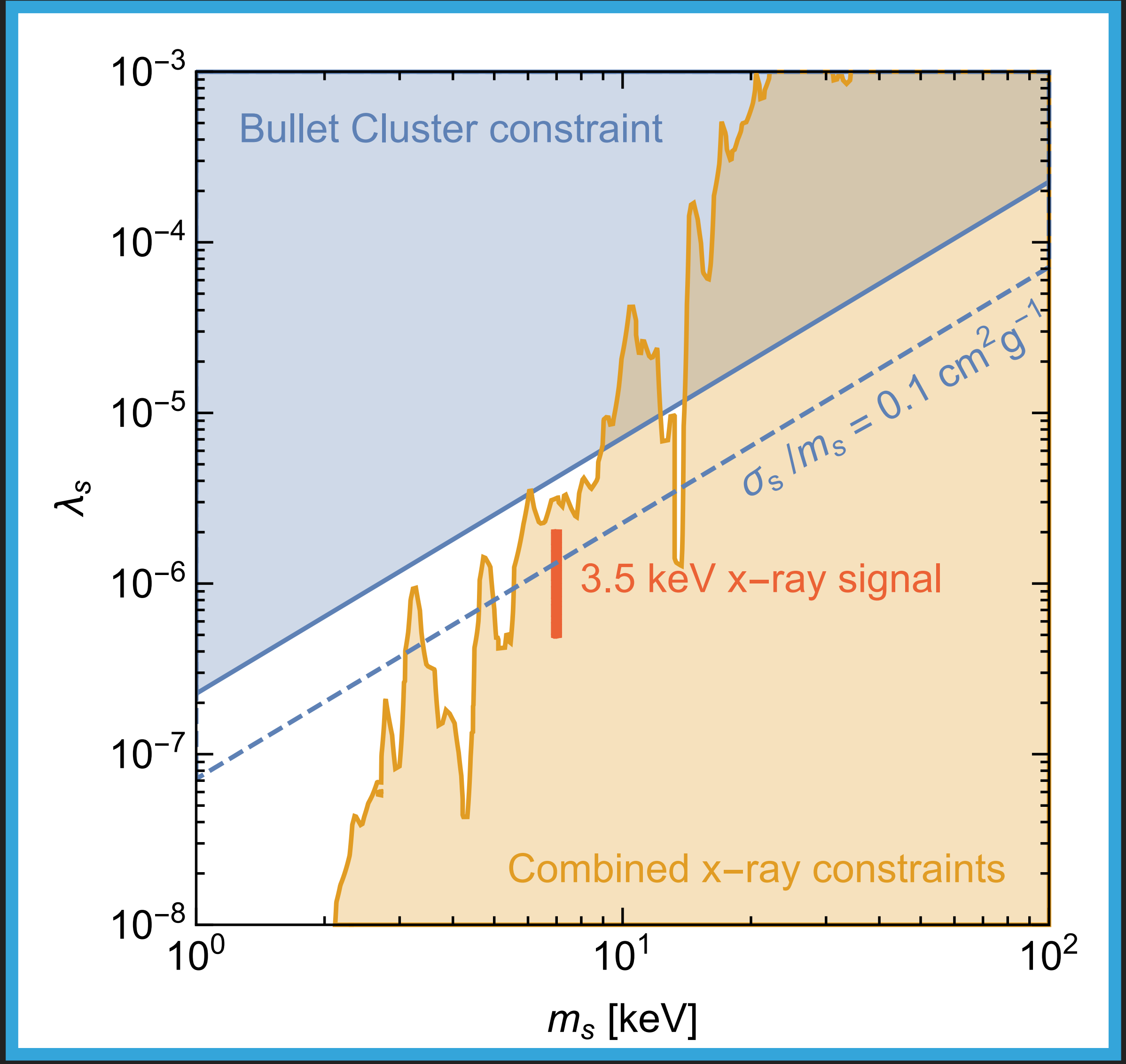
THE BIG PICTURE:





CONSTRAINTS

PHENOMENOLOGY: CONSTRAINTS

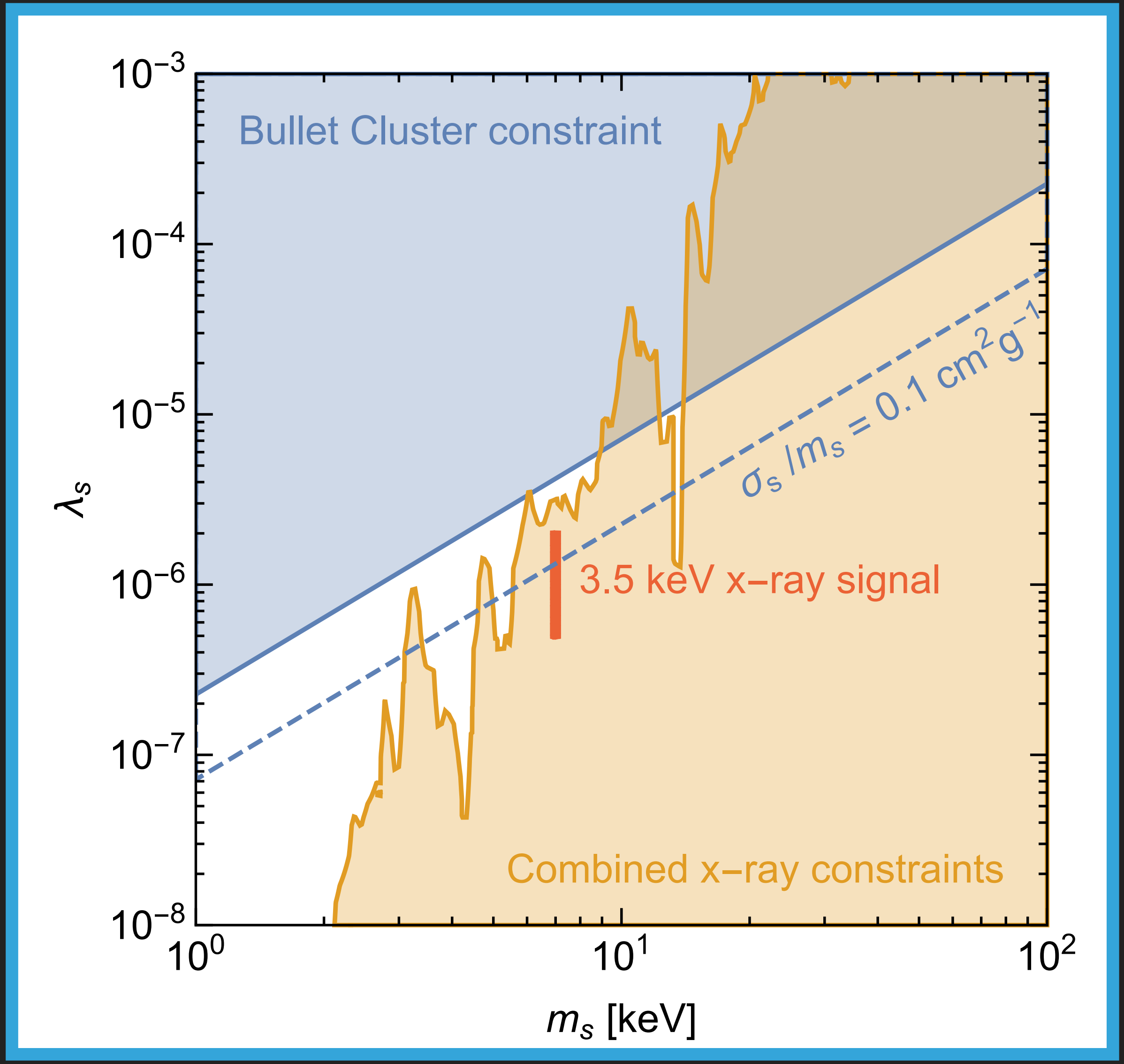


More details: **1809.09849!**

PHENOMENOLOGY: CONSTRAINTS

DECAYS:

- $1\,\mathrm{keV} < m_s < 100\,\mathrm{MeV}$, relevant decay modes $s \to \gamma\gamma$ or $s \to e^+e^-$.
- To satisfy CMB constraints, $m_s < 1\,\mathrm{MeV}$
- $s \to \gamma\gamma$ gives a striking search signature: mono energetic photon line.



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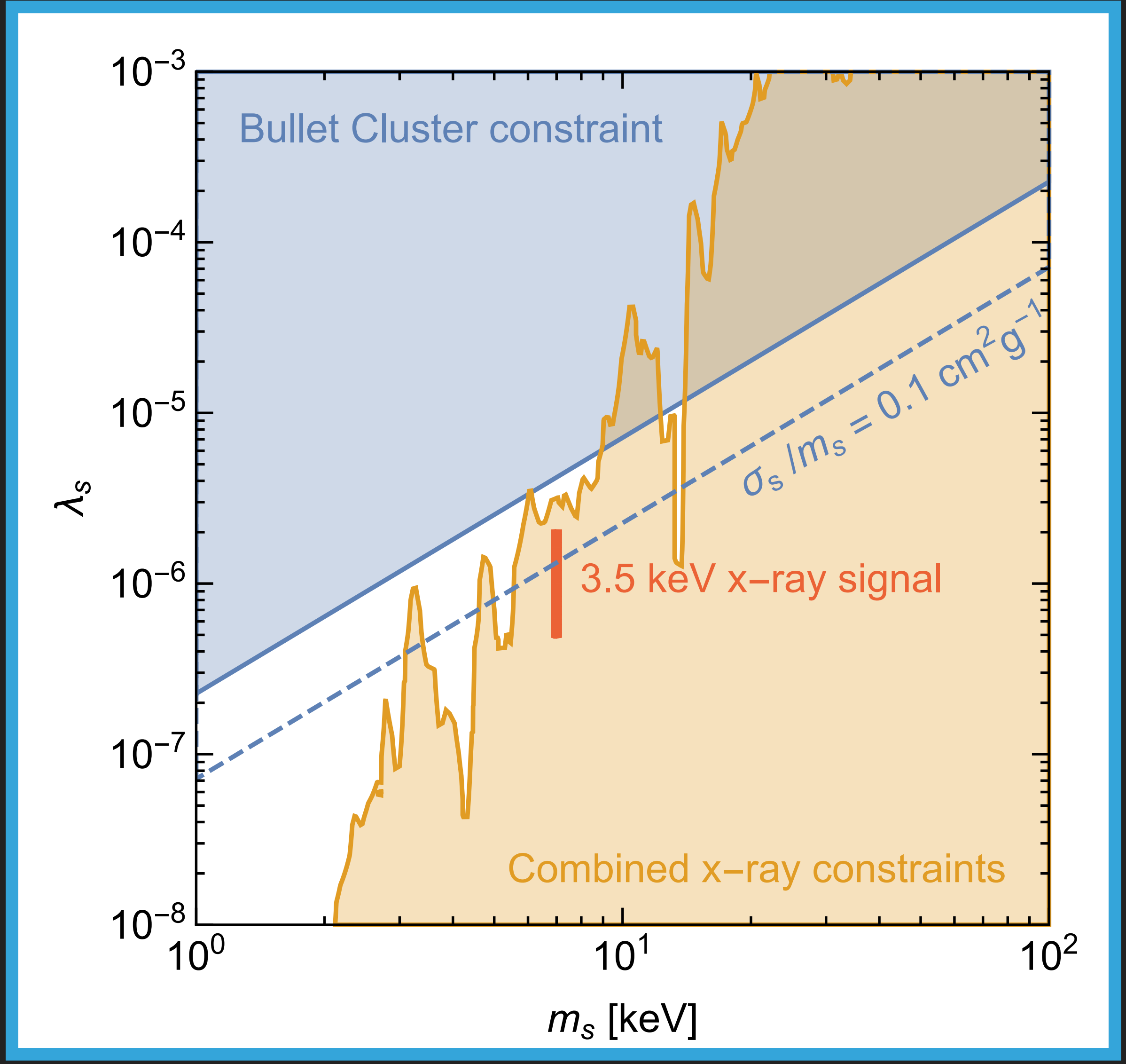
ASTROPHYSICAL CONSTRAINTS:

- Self-interactions: $\dfrac{\sigma_s}{m_s} = \dfrac{9\lambda_s^2}{32\pi m_s^3}$
- Bullet cluster: $\sigma/m \lesssim 1\,\mathrm{cm}^2/\mathrm{g}$



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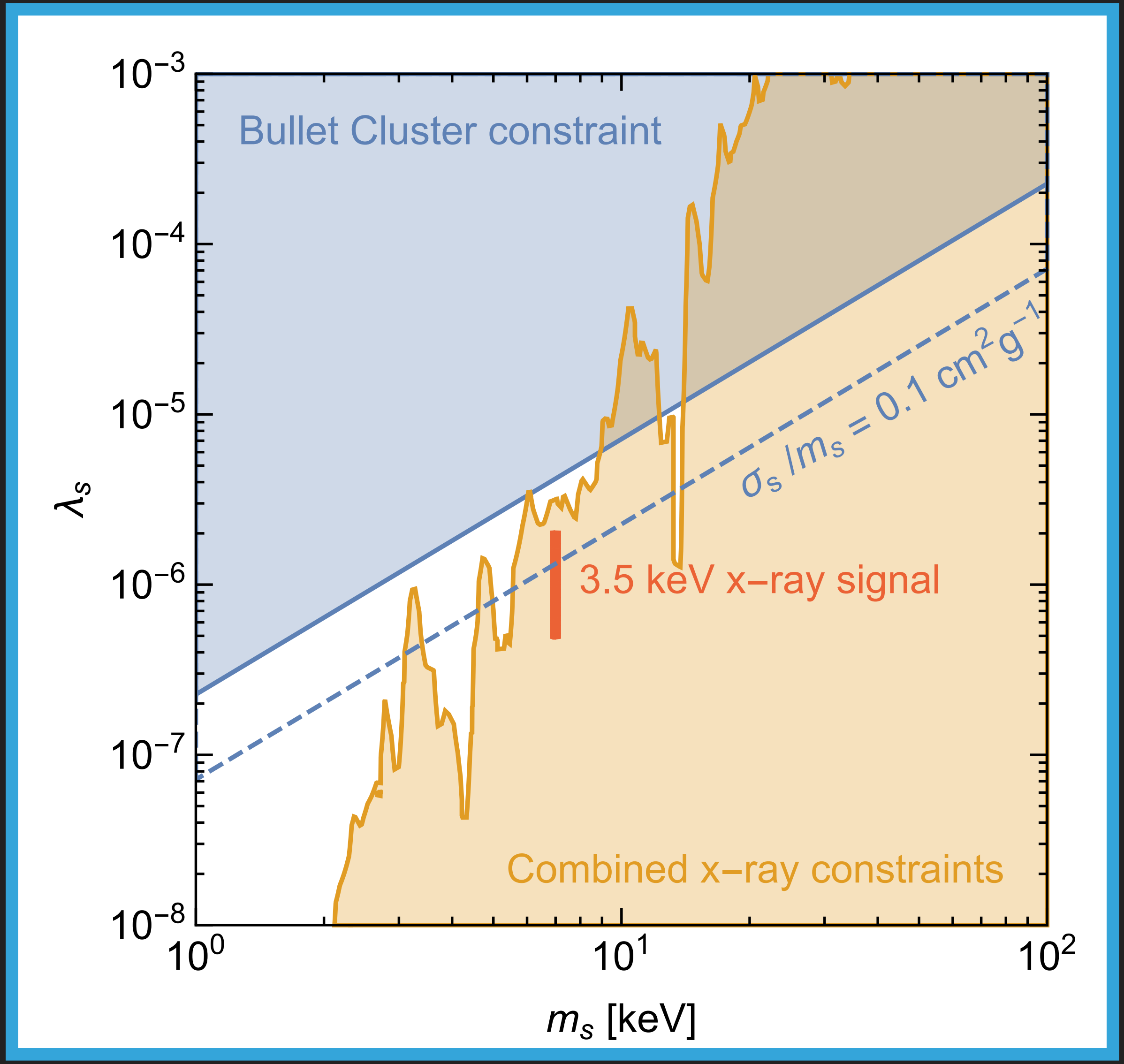


More details: **1809.09849!**

We can accommodate the 3.5 keV line and have sizeable dark-matter self-interactions!

APPENDIX

TEMPERATURE CORRECTIONS TO THE HIGGS MASS:

- Finite-temperature corrections to the Higgs potential:

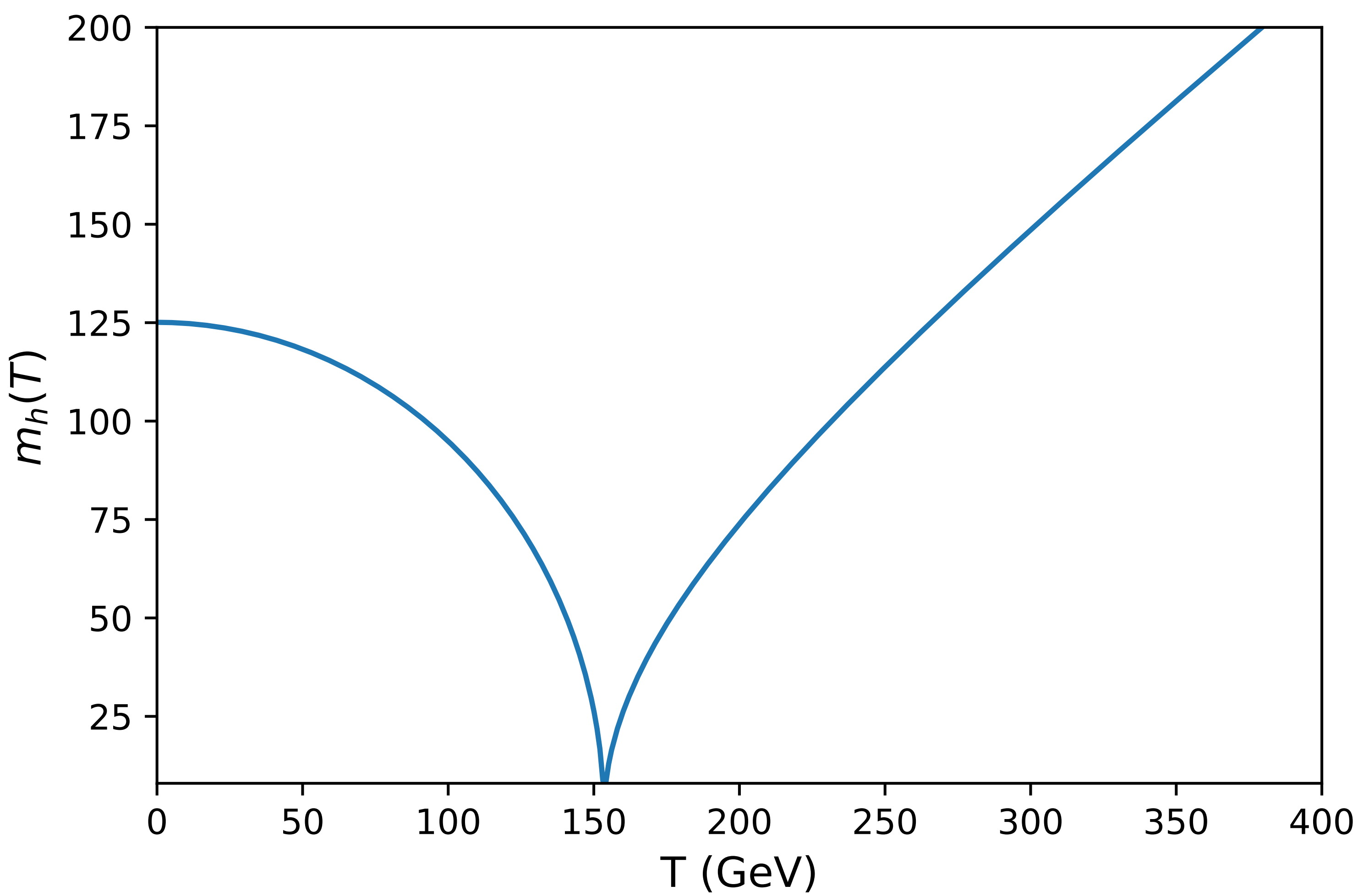
$$V(\phi, T) = D(T^2 - T_{\mathrm{EW}}^2)\,\phi^2 + \frac{\lambda(T)^4}{4}\,\phi^4$$

For $T > T_{\mathrm{EW}}$:

$$m_H(T)^2 = D(T^2 - T_{\mathrm{EW}}^2)$$

For $T < T_{\mathrm{EW}}$

$$m_h(T)^2 = 2\,\lambda(T)\,v(T)^2$$
$$= 4D(T_{\mathrm{EW}}^2 - T^2)$$



LAGRANGIAN AFTER PHASE TRANSITION:

General: $\mathscr{L} \supset \frac{1}{2}\mu_s^2(v_s + s)^2 - \frac{\lambda_s}{4}(v_s + s)^4 - \frac{\lambda_{hs}}{2}(v_s + s)^2\frac{(v + h)^2}{2}$

$\supset -\lambda_{hs}\, v_s\, v\, s\, h$

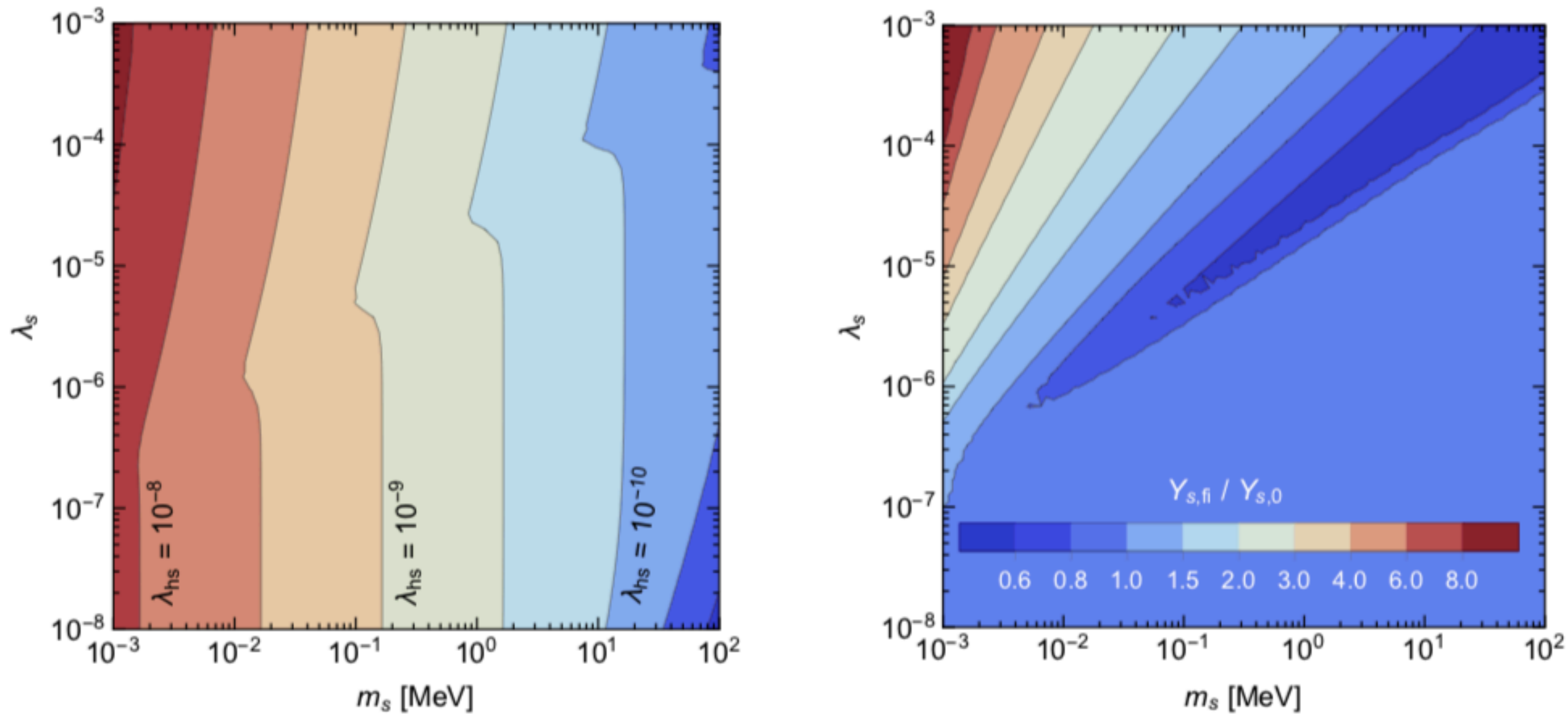
Mixing!

$$\begin{pmatrix} s' \\ h' \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} s \\ h \end{pmatrix} \qquad \theta \approx \frac{\lambda_{hs}\, v_s\, v}{m_h^2 - m_s^2}$$

Due to feeble coupling, we can use:

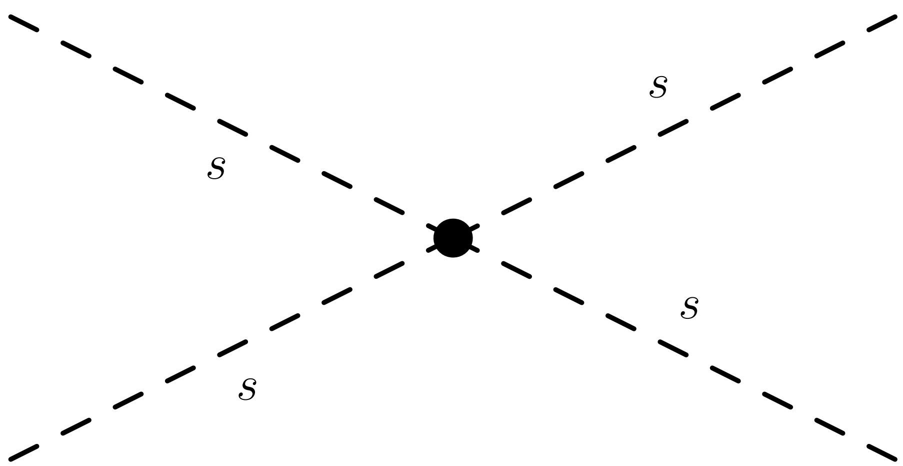
$$s' \equiv s$$
$$h' \equiv h$$

PHENOMENOLOGY: TOTAL ABUNDANCE



- Small $\lambda_s \Rightarrow 2 \leftrightarrow 3$ processes inefficient, relic abundance set by freeze-in
- Increasing $\lambda_s \Rightarrow 2 \leftrightarrow 3$ processes efficient, relic abundance set by dark sector freeze-out

DARK MATTER SELF-INTERACTIONS:



$$\Rightarrow \frac{\sigma_{\mathsf{SI}}}{m_s} = \frac{9\,\lambda_s^2}{32\pi\, m_s^3}$$

$$\Rightarrow \lambda_s \lesssim 0.007 \left(\frac{m_s}{1\,\mathrm{MeV}}\right)^{3/2}$$

Structure formation?

- Diffusion length: determines length scales over which energy transfer is efficient.

$$l_s^2 \approx \int_0^{a_{\mathsf{NR}}} \frac{\mathrm{d}a}{H\,a^3\,n_s\,\langle\sigma v\rangle}$$

- Matter power spectrum remains unaffected on visible scales for $\lambda_s > 10^{-10}$.

$$l_s \approx \frac{10^{-11}\,\mathrm{Mpc}}{\lambda_s}$$