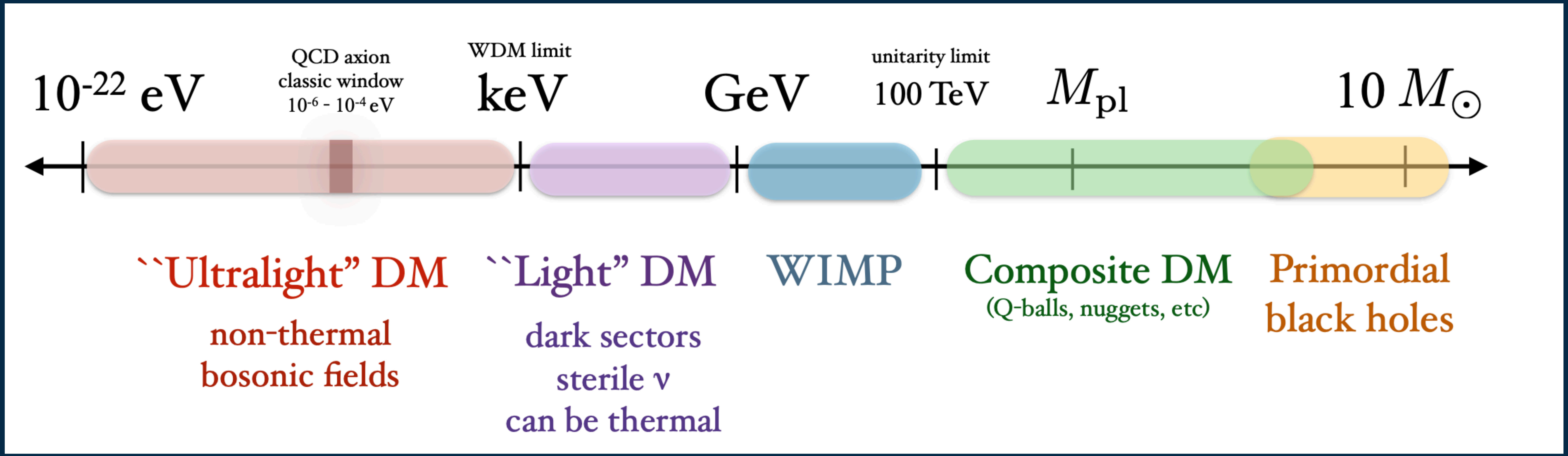
Hadronic Dark Matter Annihilation During Big Bang Nucleosynthesis

Based on work with Adam Ritz, [PRD 113, 035004/ arXiv 2510.11791]

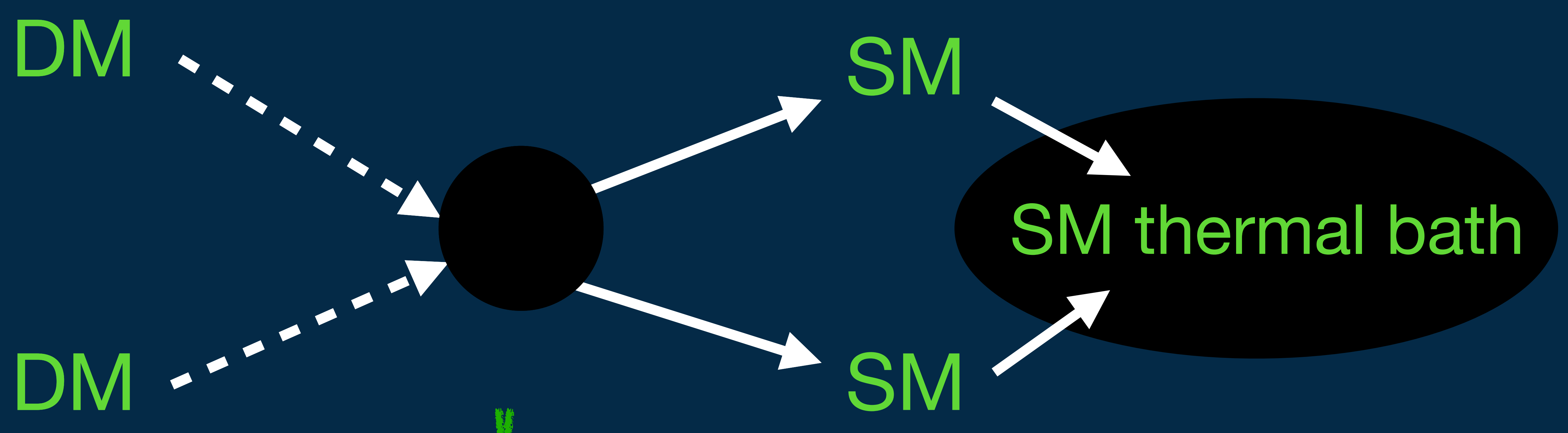
Afif Omar
July, 2026

TRIUMF
UVIC

Light Dark World 2026, Carleton University



T. Lin 1904.07915

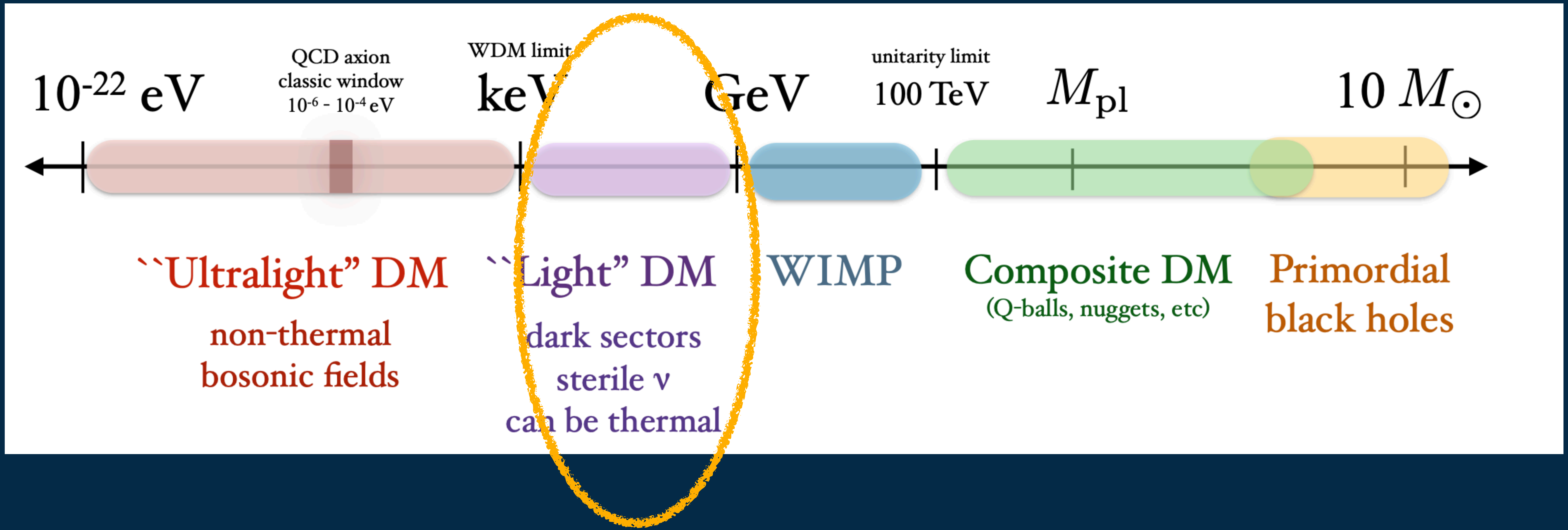


Velocity independent (s-wave)

Velocity dependent (p-wave)

Ruled out by CMB

Evades CMB



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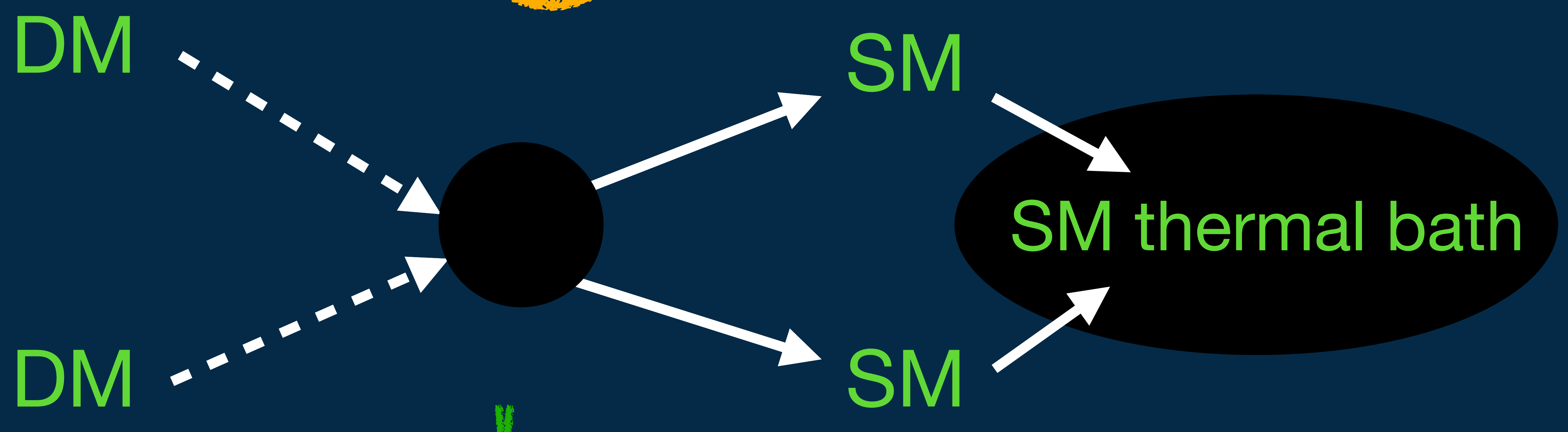

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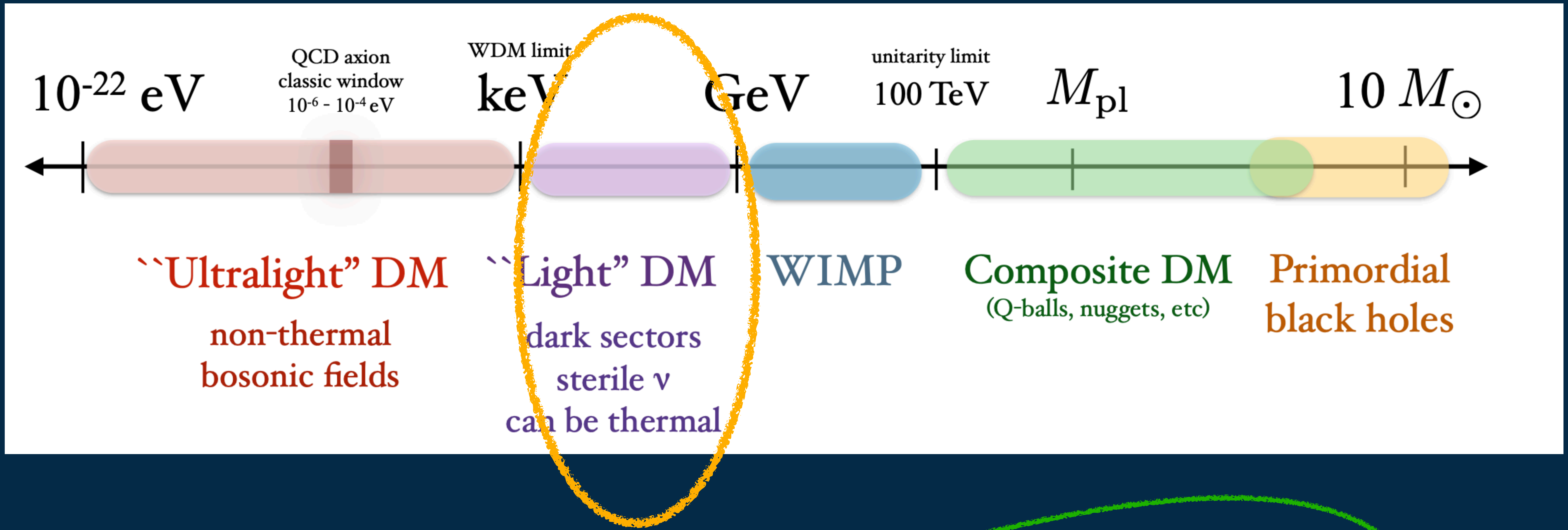

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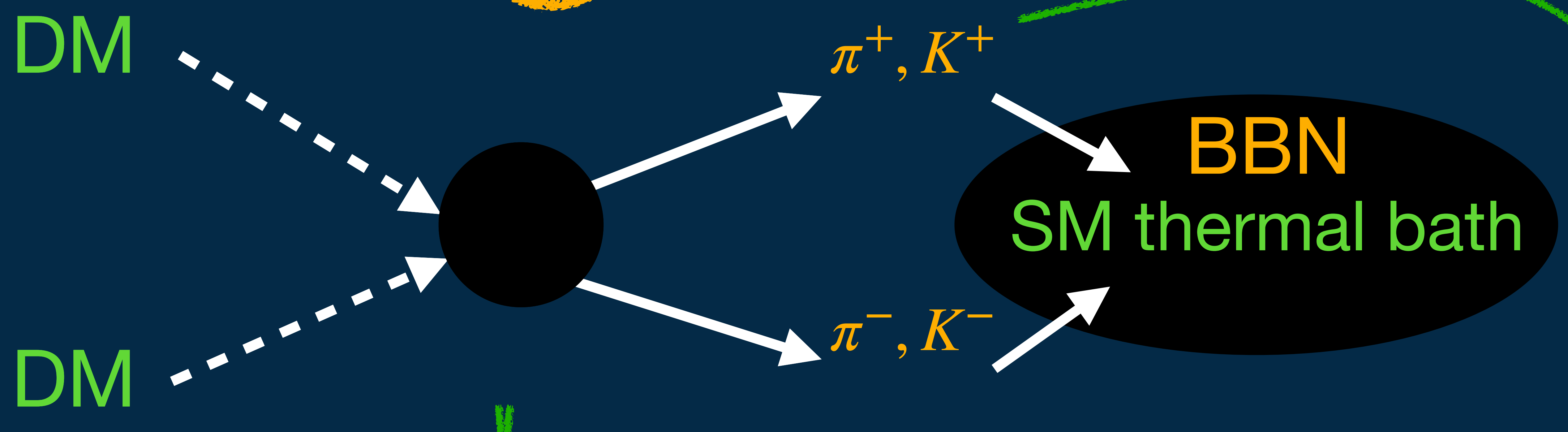


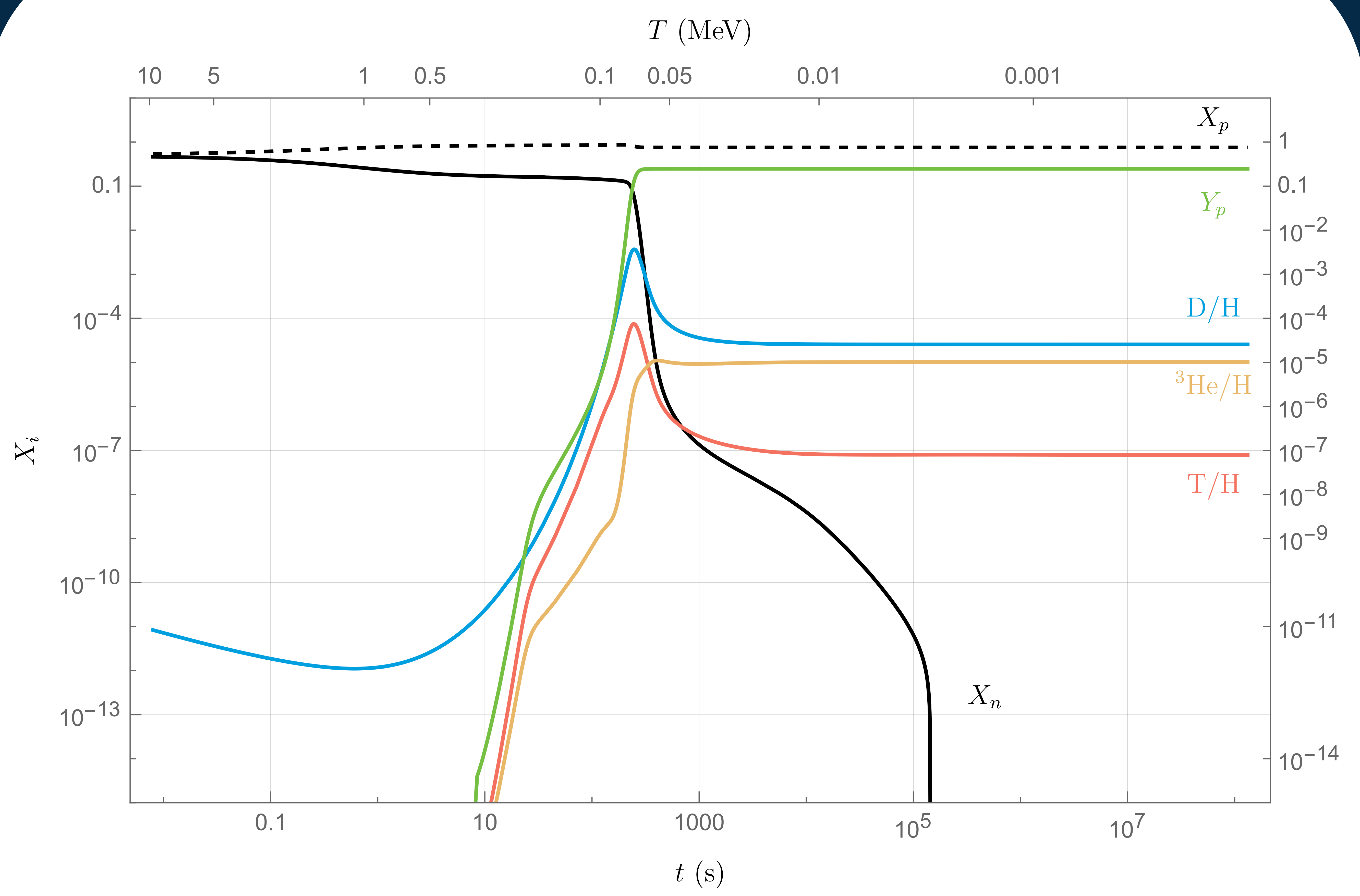
BBN is very sensitive to hadronic injection!

Velocity independent (s-wave)

Velocity dependent (p-wave)

Ruled out by CMB

Evades CMB



D. McKeen, AO 2407.03508

Inputs:

Nuclear interaction rates

Neutron lifetime and weak rates

Hubble rate

Ratio of baryons to photons

…

Output:

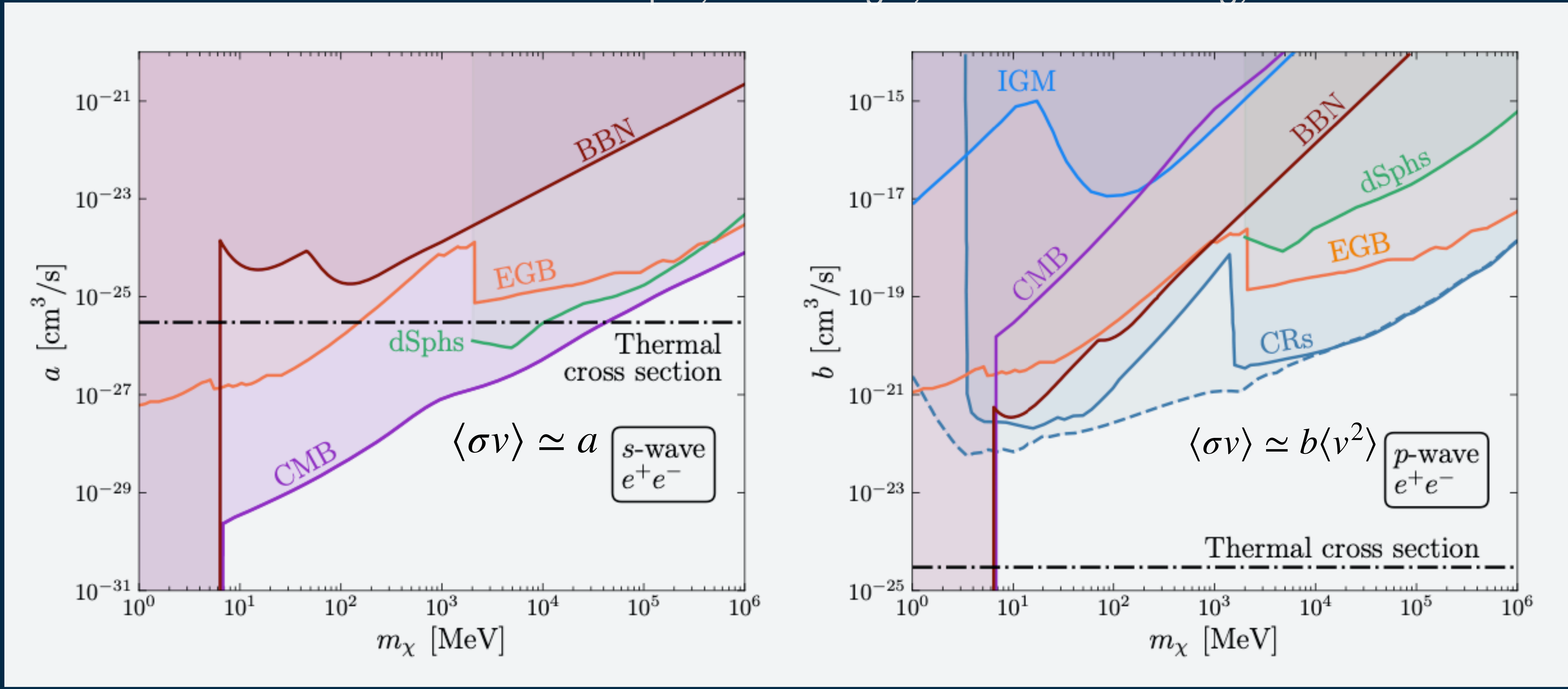
Primordial nuclear abundances

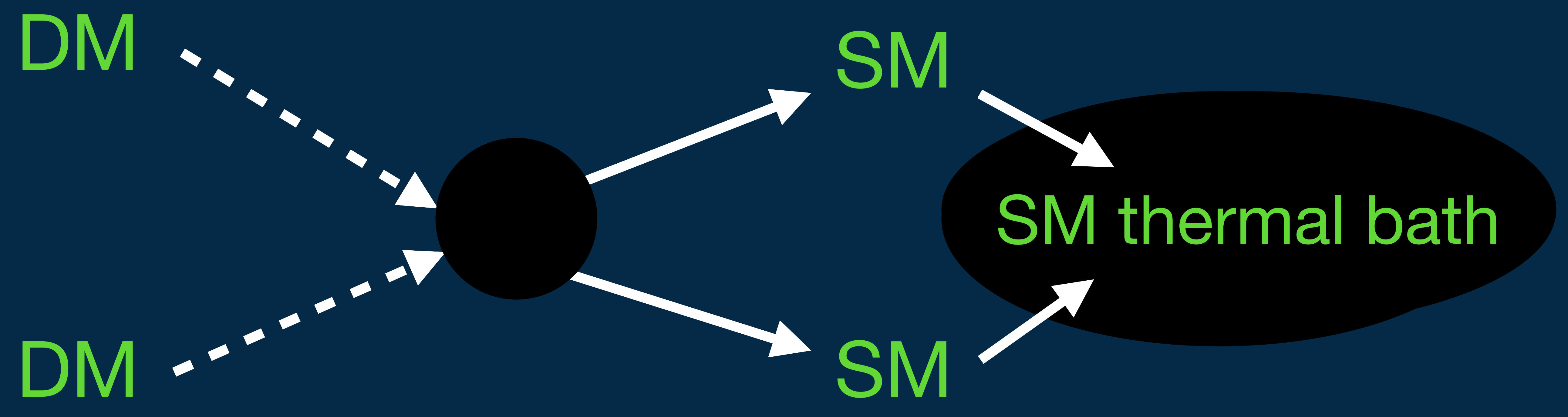
P. F. Depta, M. Hufnagel, K. Schmidt-Hoberg, S. Wild 1901.06944

Entropy injection

Photodisintegration

Hadronic injection?





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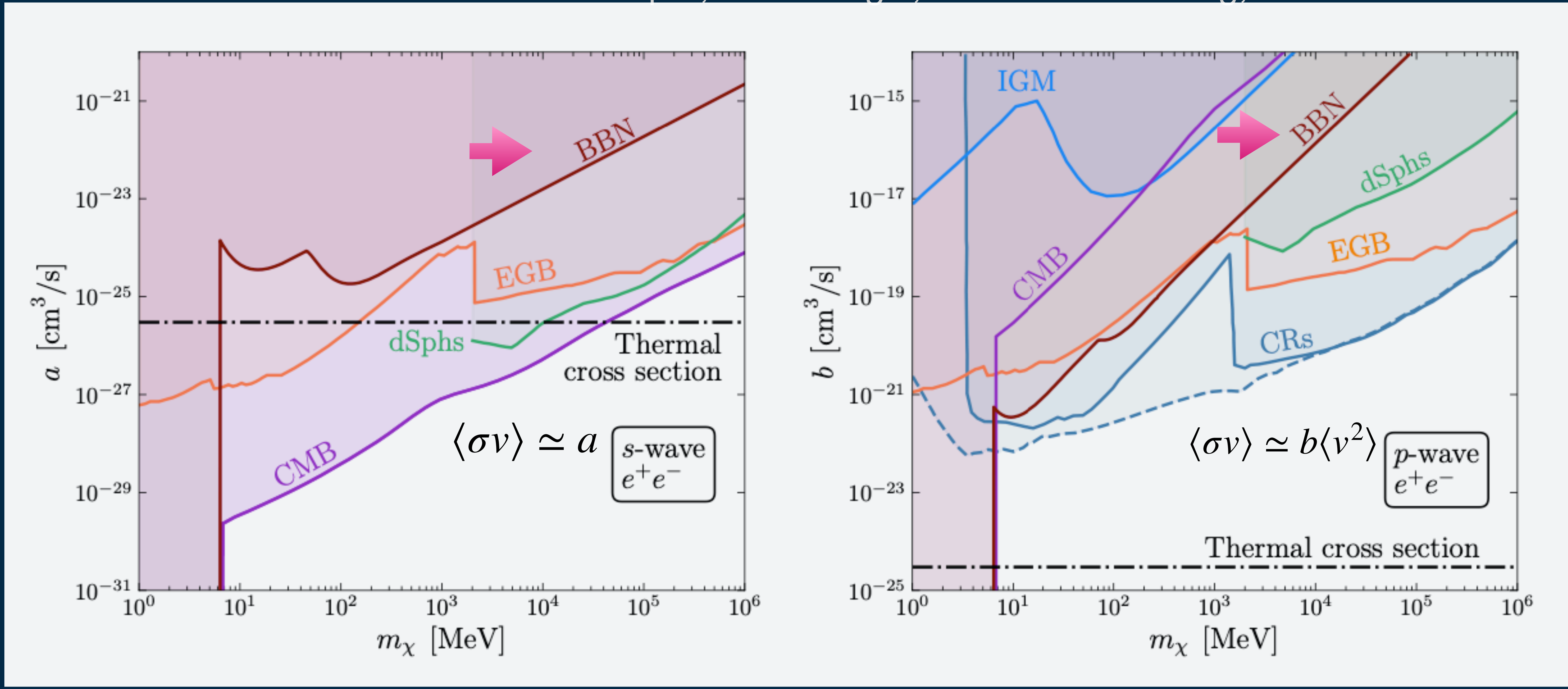
P. F. Depta, M. Hufnagel, K. Schmidt-Hoberg, S. Wild 1901.06944



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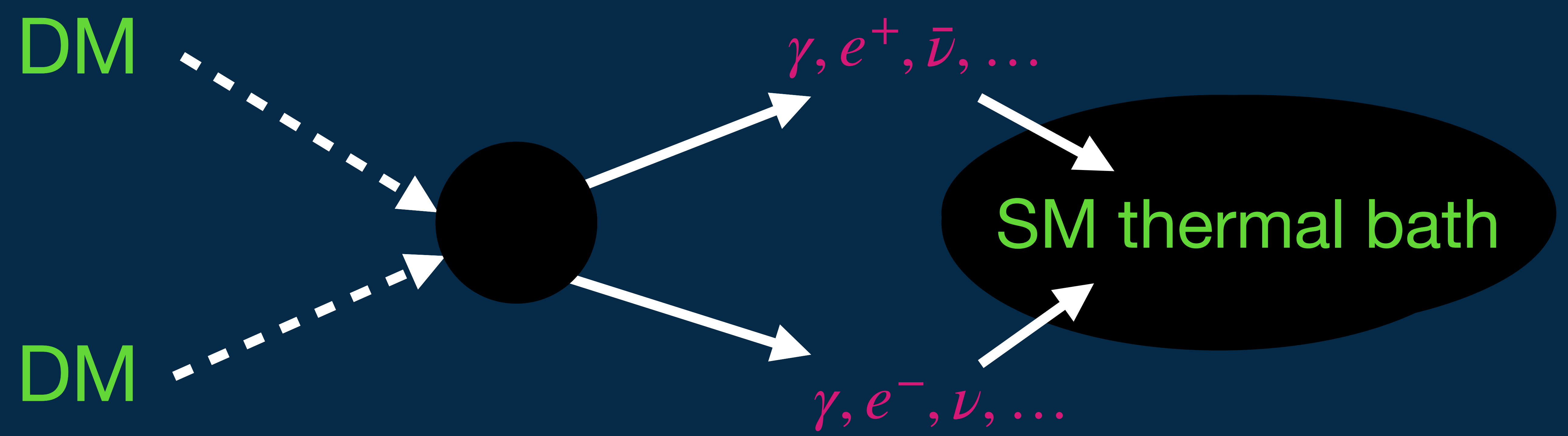

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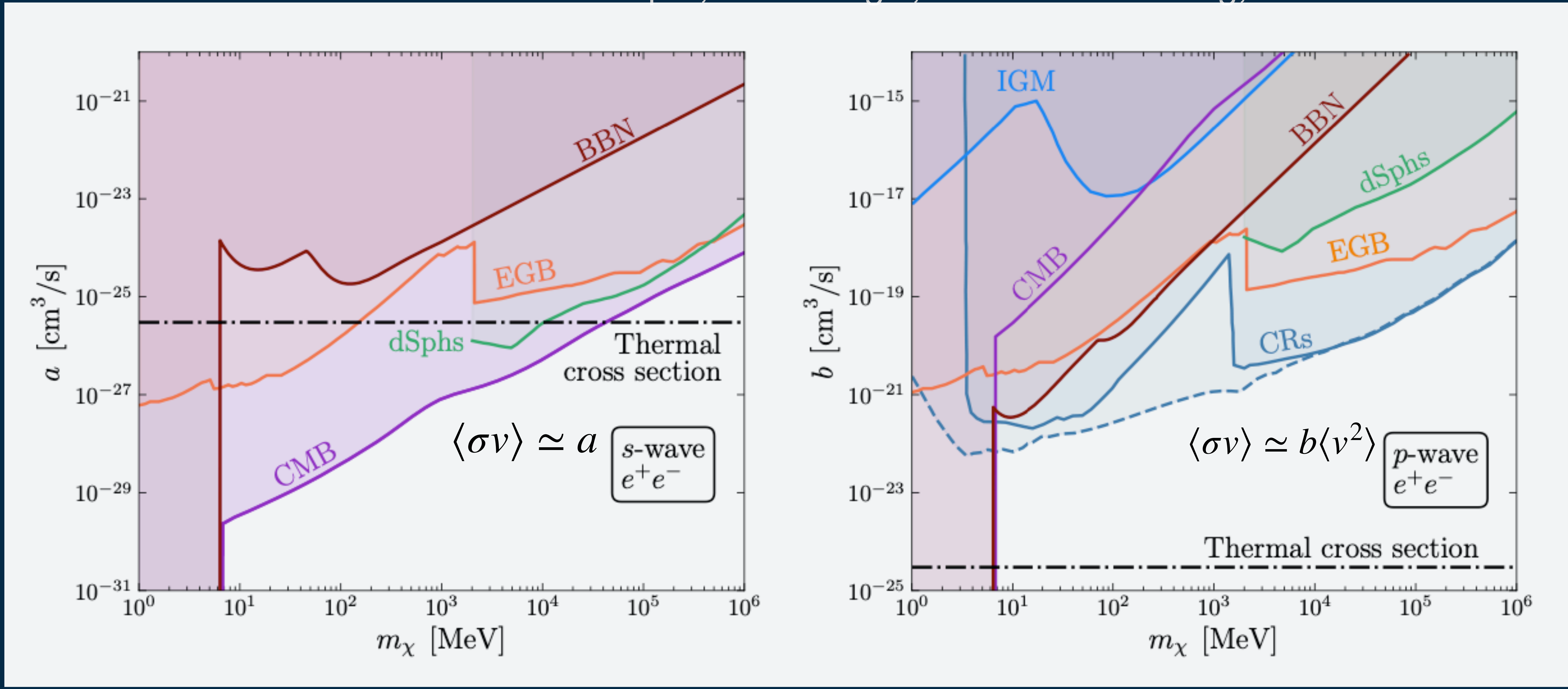
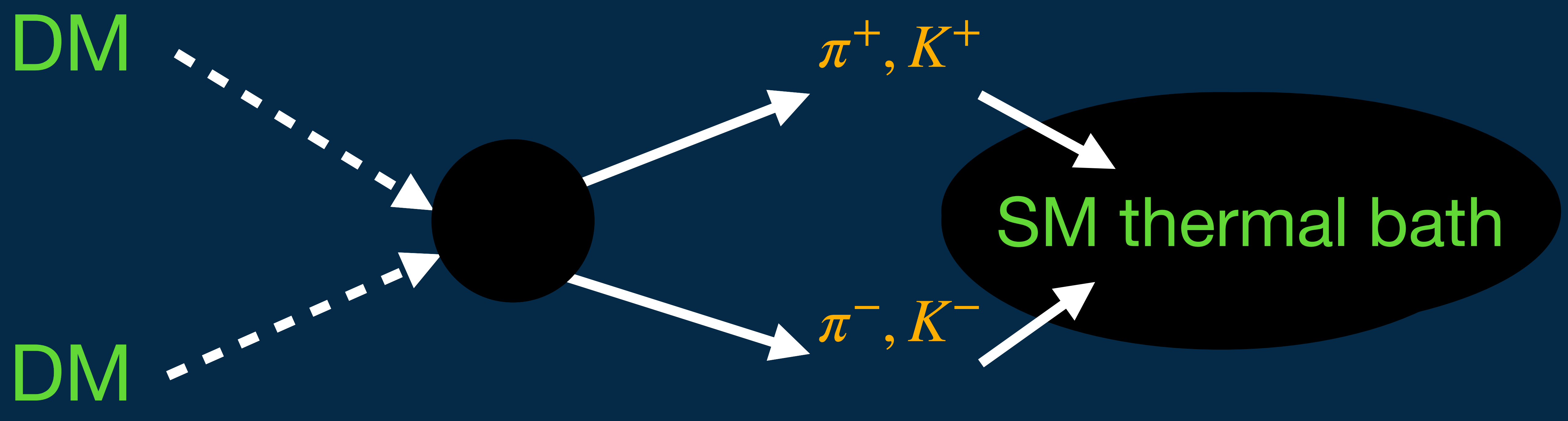


Entropy injection

Photodisintegration

Hadronic injection?

With focus on p-wave to avoid CMB constraints



Nuclear interaction rates

Neutron lifetime and weak rates

Hubble rate

Ratio of baryons to photons

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SBBN

$$\frac{dn_{n,p}}{dt} + 3Hn_{n,p} \propto \text{weak n} \leftrightarrow \text{p rates}$$

$$\frac{dn_{\rm nucl}}{dt} + 3Hn_{\rm nucl} \propto \text{Standard nuclear rates}$$

BBN + Pion injection

$$\frac{dn_{n,p}}{dt} + 3Hn_{n,p} \propto \text{weak n} \leftrightarrow \text{p rates} \quad +\pi^{\pm} \text{ interactions}^{*}$$

$$\frac{dn_{\rm nucl}}{dt} + 3Hn_{\rm nucl} \propto \text{Standard nuclear rates}^{\dagger}$$

$$\frac{dn_{\pi^{\pm}}}{dt} + 3Hn_{\pi^{\pm}} \propto \text{DM injection} - \text{pion decay}$$
$$-\pi^{\pm} \text{ interactions}^{*}$$

*

$$\pi^- + p^+ \to n + \gamma, \quad (\sigma v)^{\pi^-}_{pn\gamma} \simeq 0.57 \text{ mb},$$
$$\pi^- + p^+ \to n + \pi^0, \quad (\sigma v)^{\pi^-}_{pn\pi^0} \simeq 0.88 \text{ mb},$$
$$\pi^+ + n \to p + \pi^0, \quad (\sigma v)^{\pi^+}_{np\pi^0} \simeq 1.7 \text{ mb}.$$

M. Pospelov, J. Pradler 1006.4172

SBBN

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$$\frac{dn_{\text{nucl}}}{dt} + 3Hn_{\text{nucl}} \propto \text{Standard nuclear rates}^\dagger$$

$$\sim \frac{1}{2} n_\chi^2 \langle \sigma v \rangle \qquad \sim \frac{n_{\pi^\pm}}{\tau_\pi}$$

$$\frac{dn_{\pi^\pm}}{dt} + 3Hn_{\pi^\pm} \propto \text{DM injection} - \text{pion decay}$$

$$-\pi^{\pm}\ \text{interactions}^*$$

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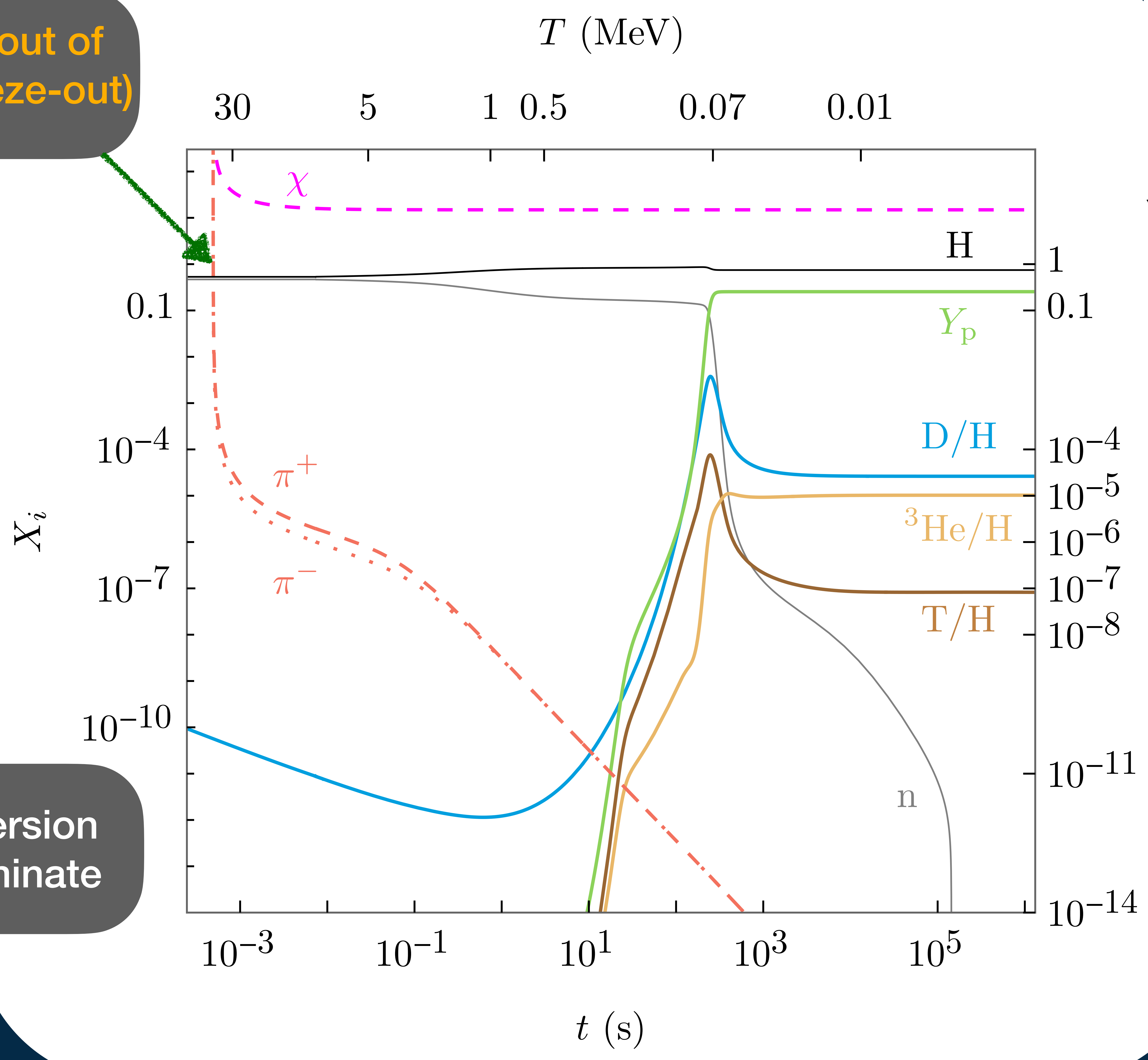
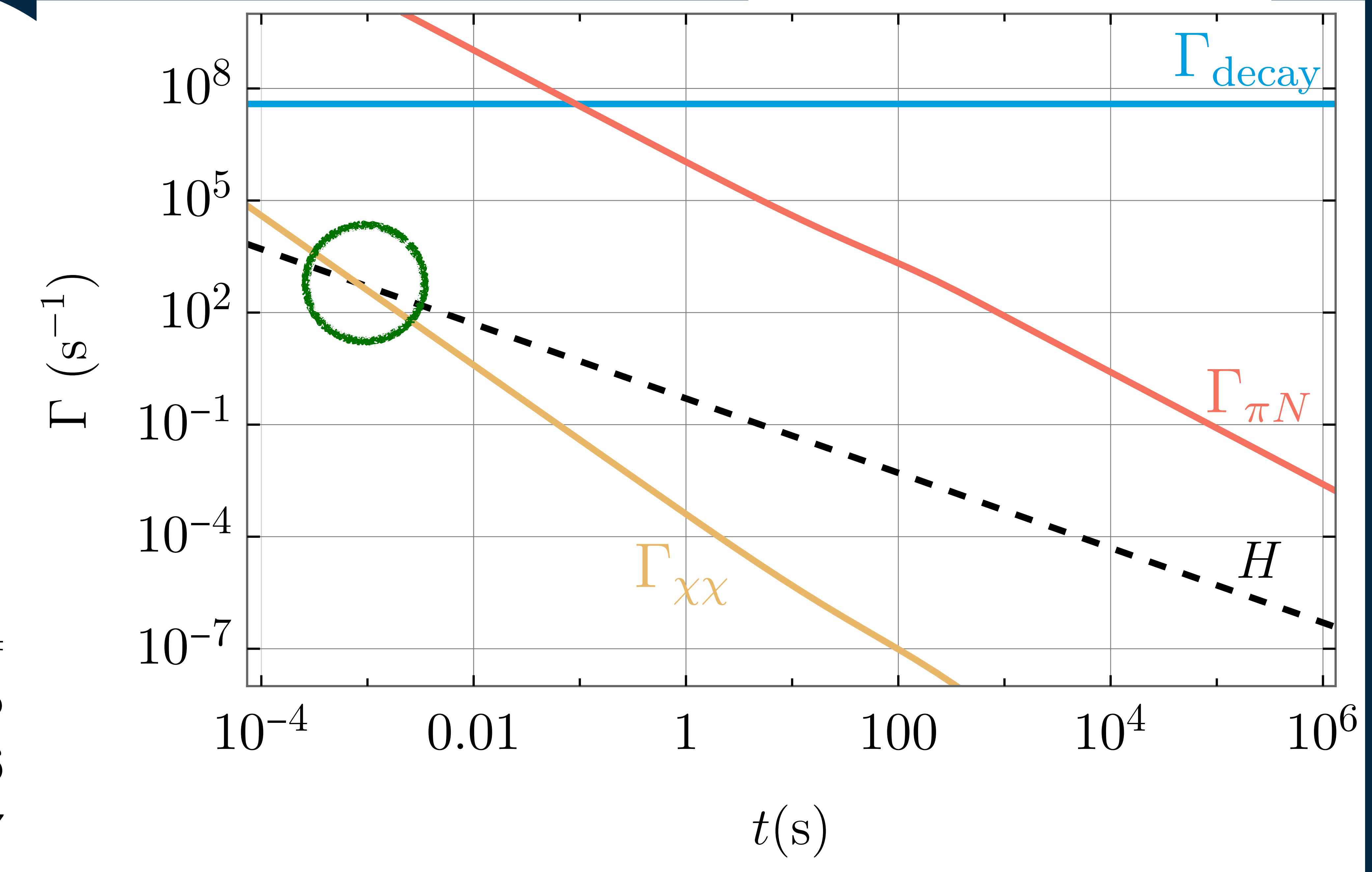
$m_\chi = 400$ MeV
$b = 10^{-23}$ cm^3/s

Pions/DM fall out of equilibrium (freeze-out)





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Charge conversion reactions dominate

Pion decay dominates

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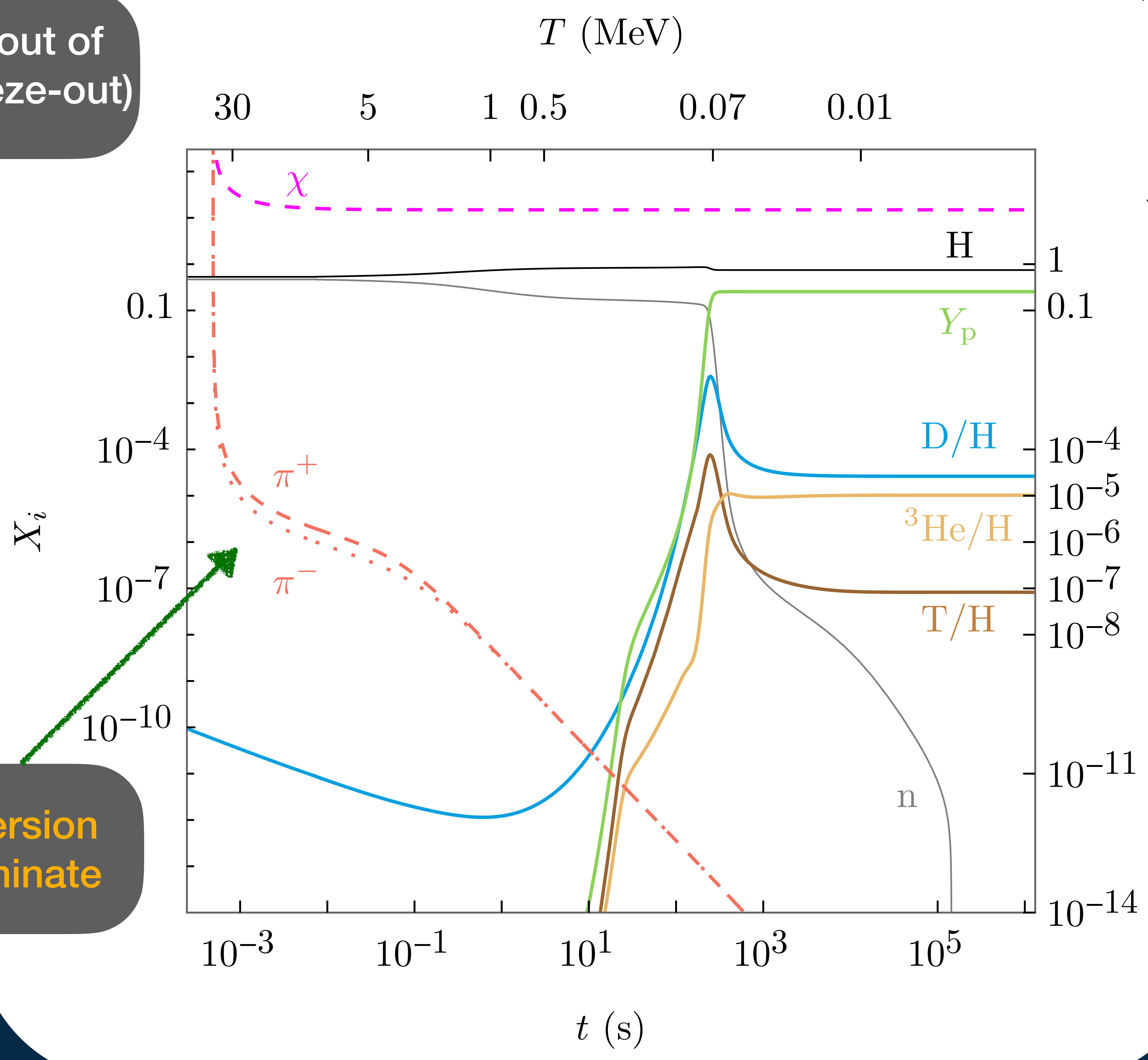

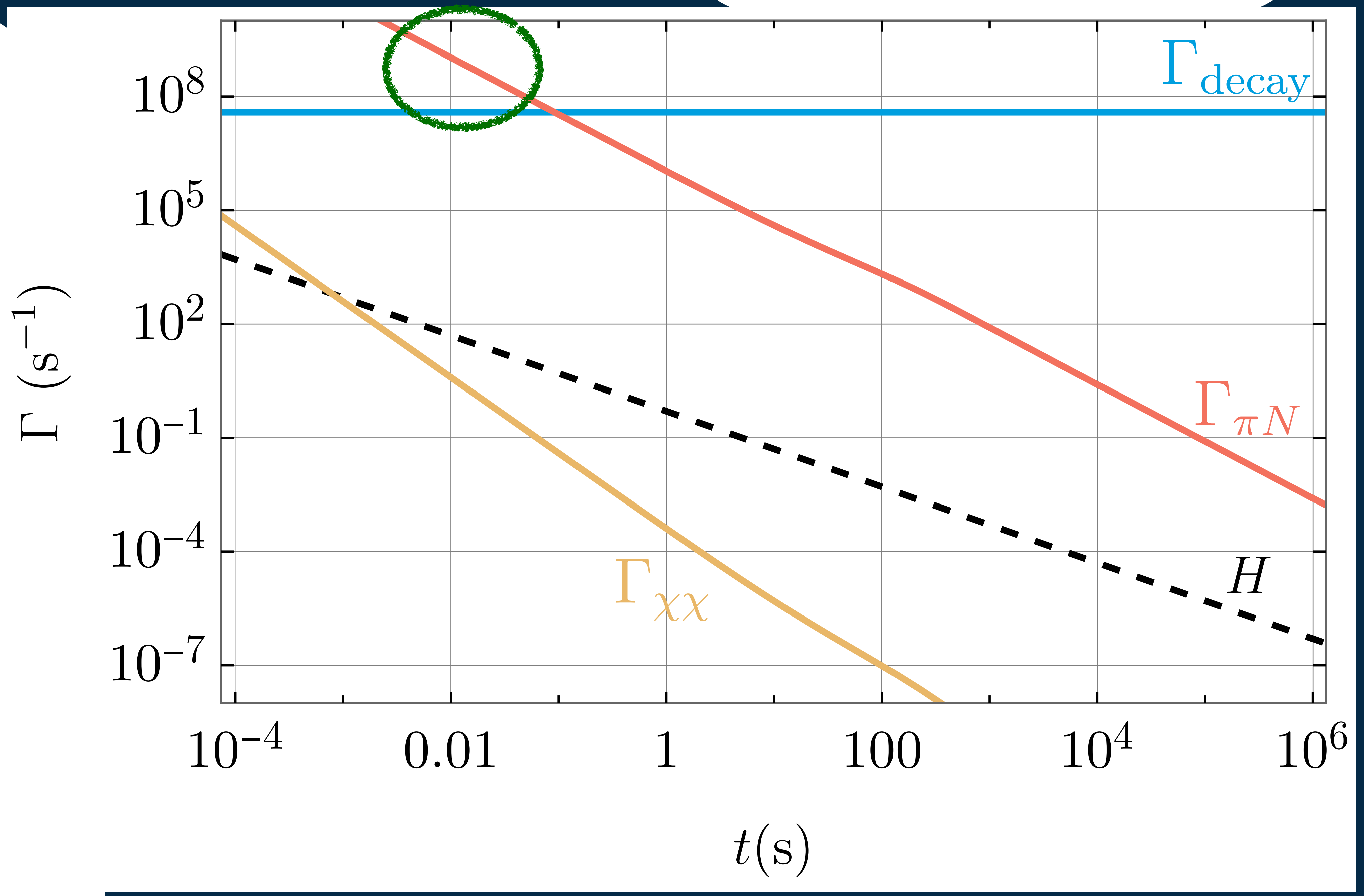

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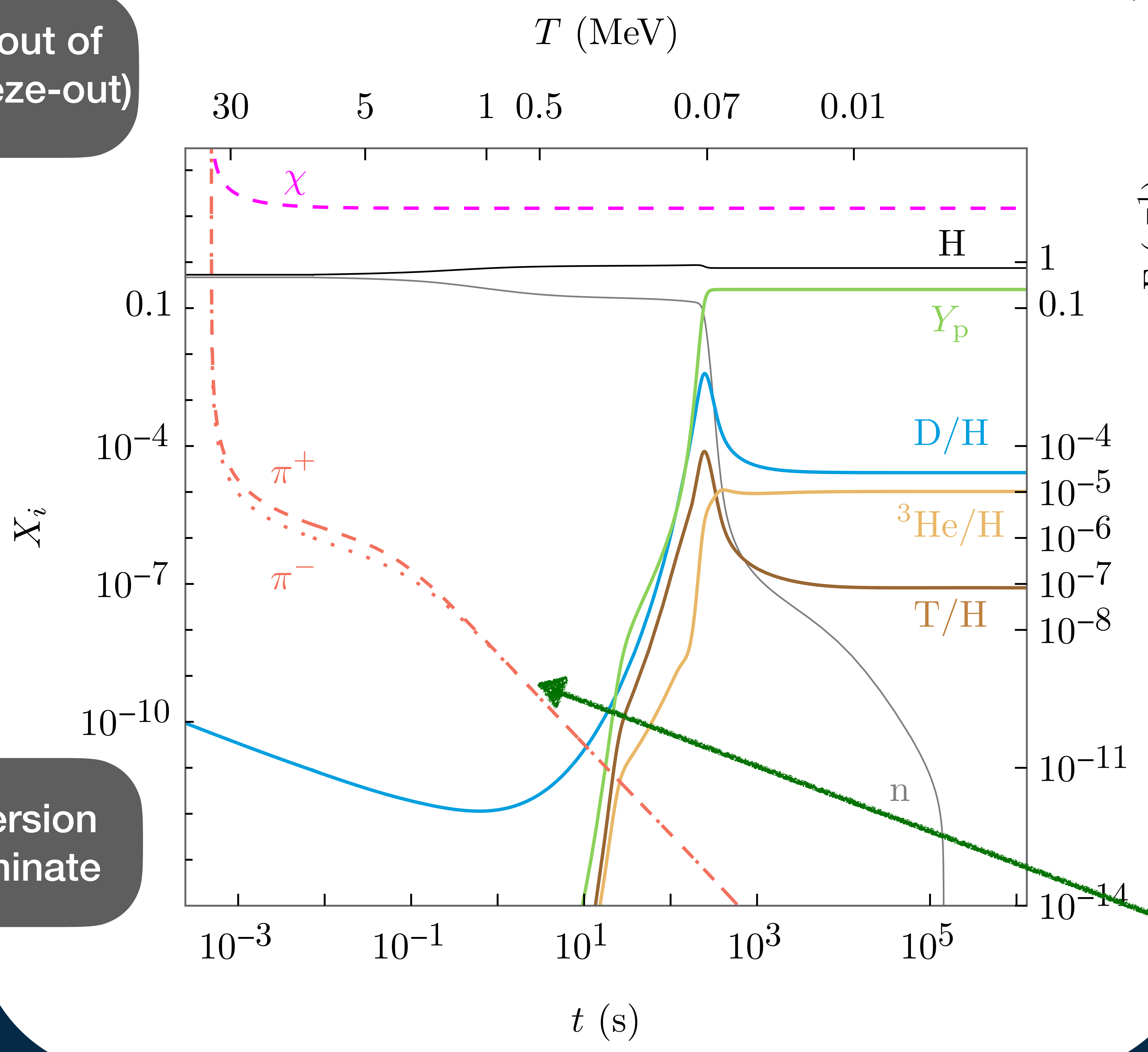

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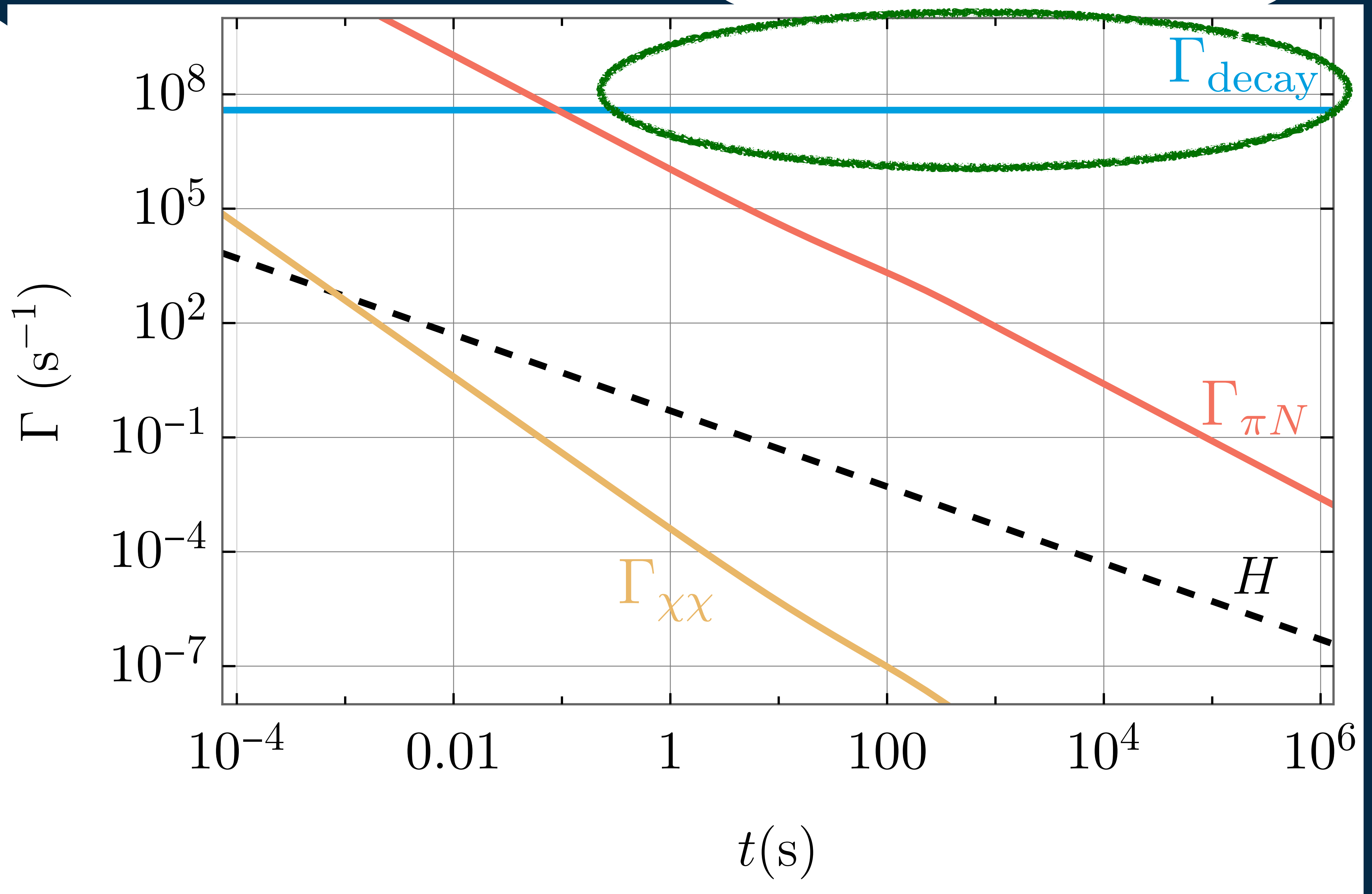

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Pion decay dominates

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Compared with $\mathcal{O}(1)$ mb for $\pi^{\pm}$

Similar analysis as $\pi^{\pm}$

Higher mass threshold ($m_K \simeq$ 494 MeV), but reaction rates are higher.

Must include $K^{\pm}$ decays to $\pi^{\pm}$.

$$K^- + p \to n + X: \quad (\sigma v)^{K^-}_{pn} \simeq 32 \text{ mb},$$
$$K^- + n \to p + X: \quad (\sigma v)^{K^-}_{np} \simeq 13 \text{ mb}.$$

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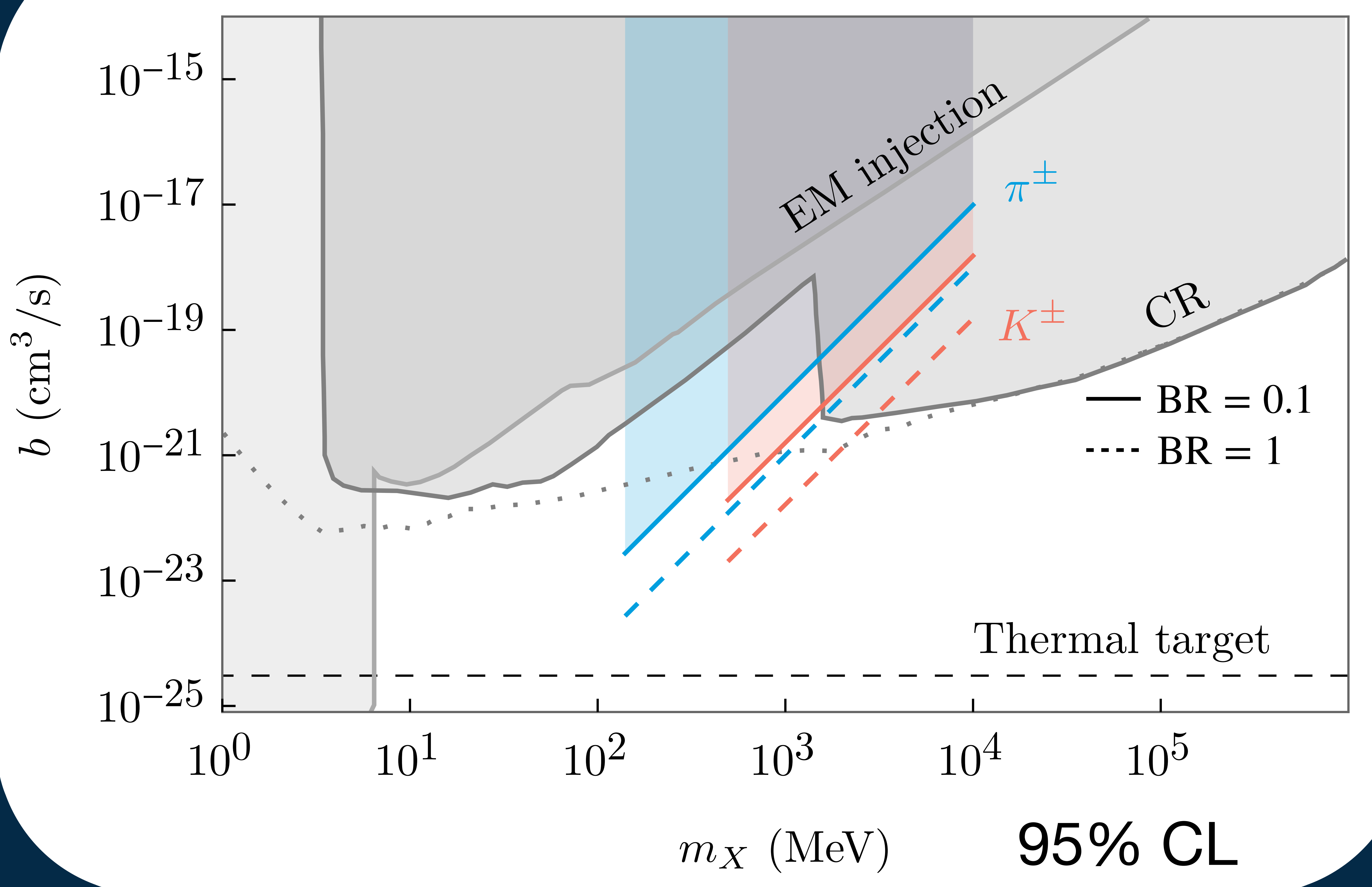
$$K^{\pm} \to \pi^{\pm}\pi^0(\pi^0) \quad \text{BR} = 22.4\%,$$
$$K^{\pm} \to \pi^{\pm}\pi^{\pm}\pi^{\mp} \quad \text{BR} = 5.6\%.$$

PDG (2024)



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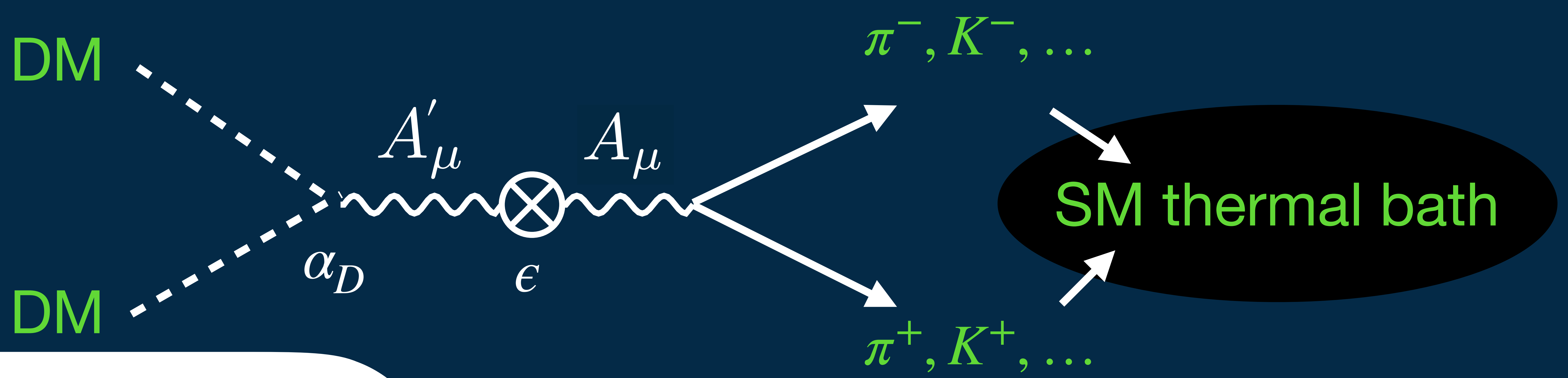
D and ^{4}He observations:

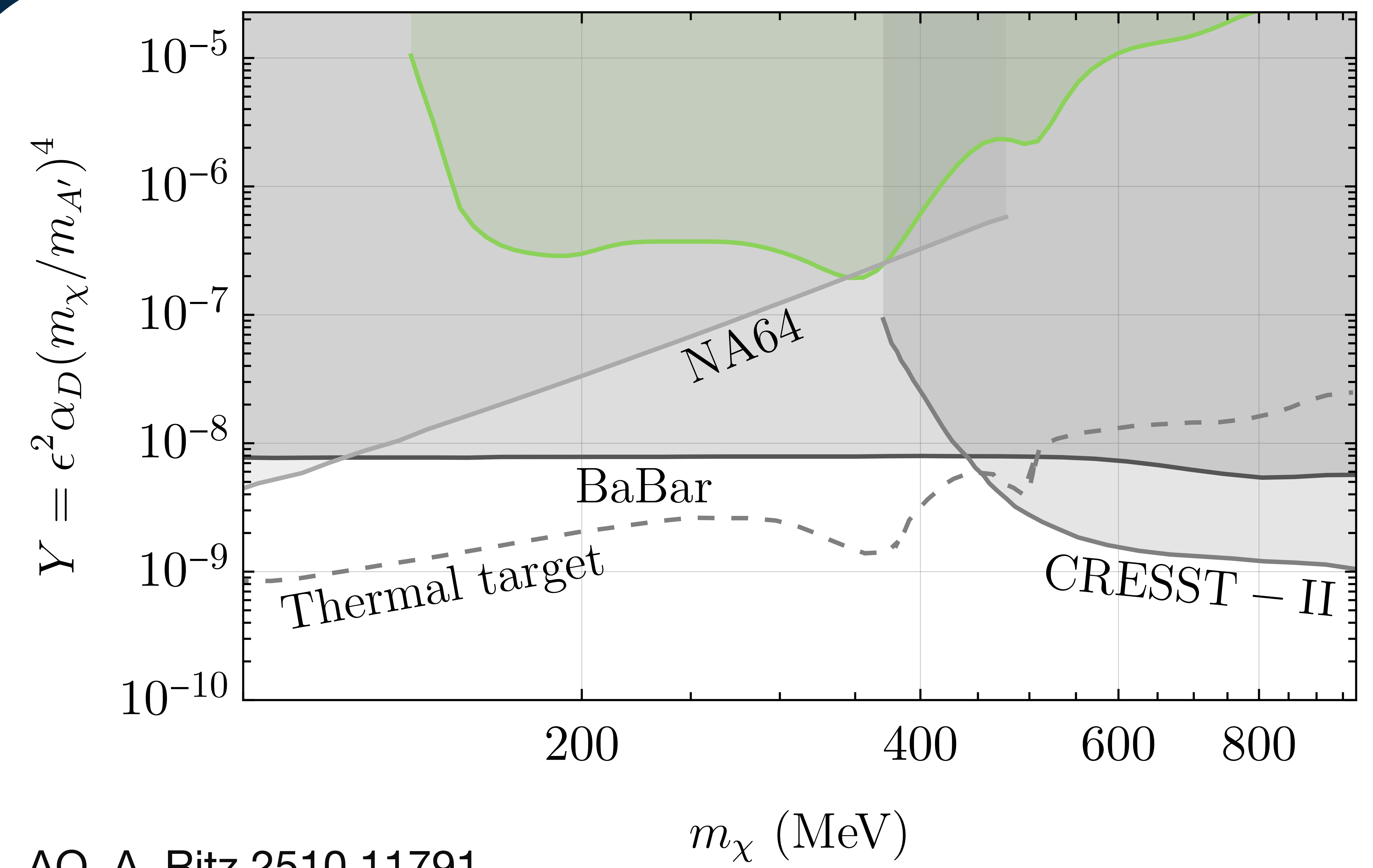
$$D/H \times 10^{-5} = 2.547 \pm 0.025$$

$$Y_p = 0.245 \pm 0.003$$

PDG (2024) and refs within

$$\mathscr{L} \supset -A'_\mu(g_D J^\mu_D + \epsilon e J^\mu_{\mathrm{EM}})$$





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this model imposes a BR less than 10%

$\alpha_D = 0.5$
$m_{A'}/m_\chi = 3$

Takeaways

1. BBN is a viable probe of annihilating DM, especially with hadronic final states.

2. BBN sensitivity does not yet reach the thermal target. Improving D/H and Y_p precision could close that gap.

3. Pseudo-Dirac DM with a small mass splitting, Δm, evades CMB constraints. BBN could potentially impose important constraints on Δm.

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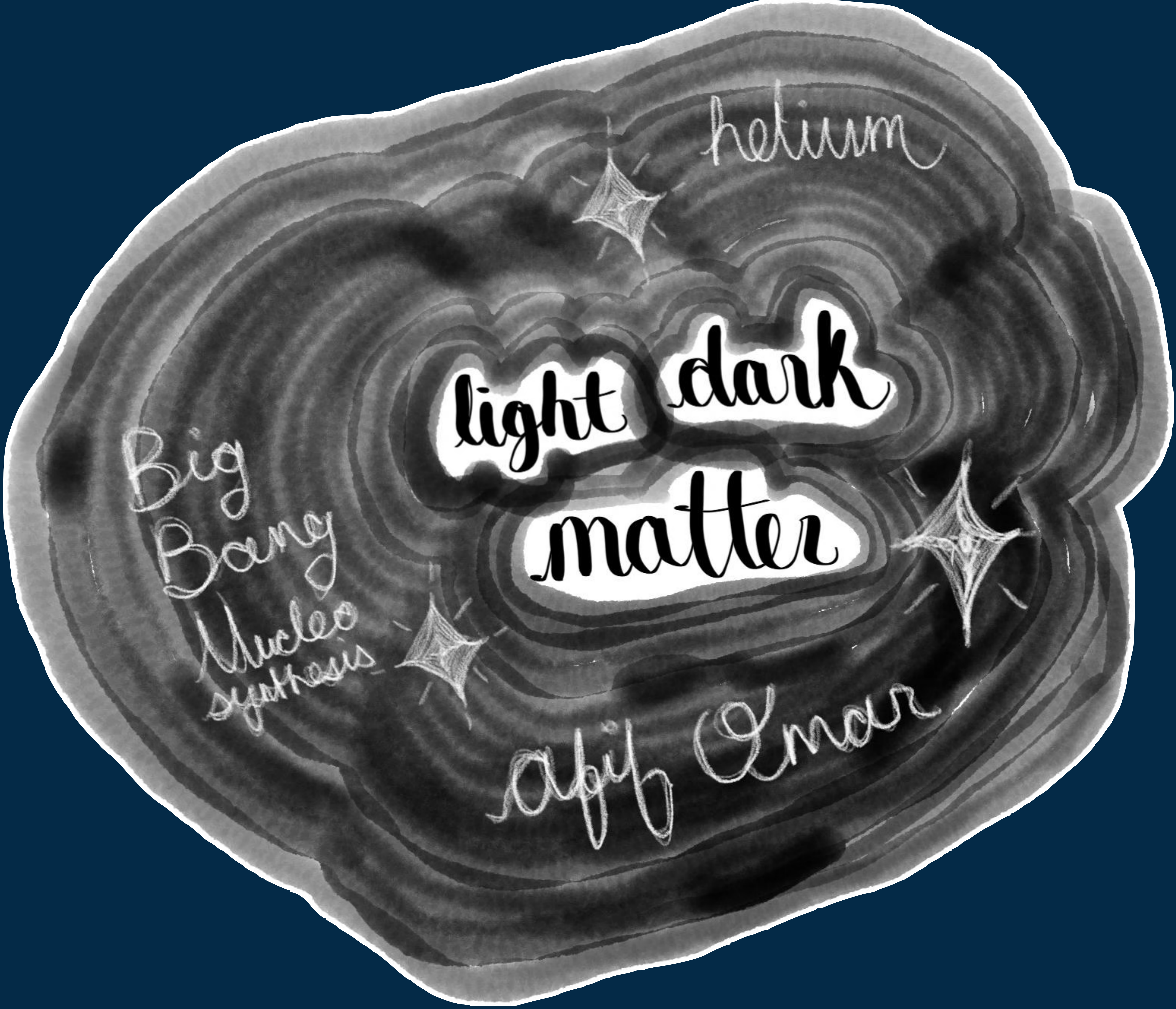


Credit: Amanda Aust

Back up slides

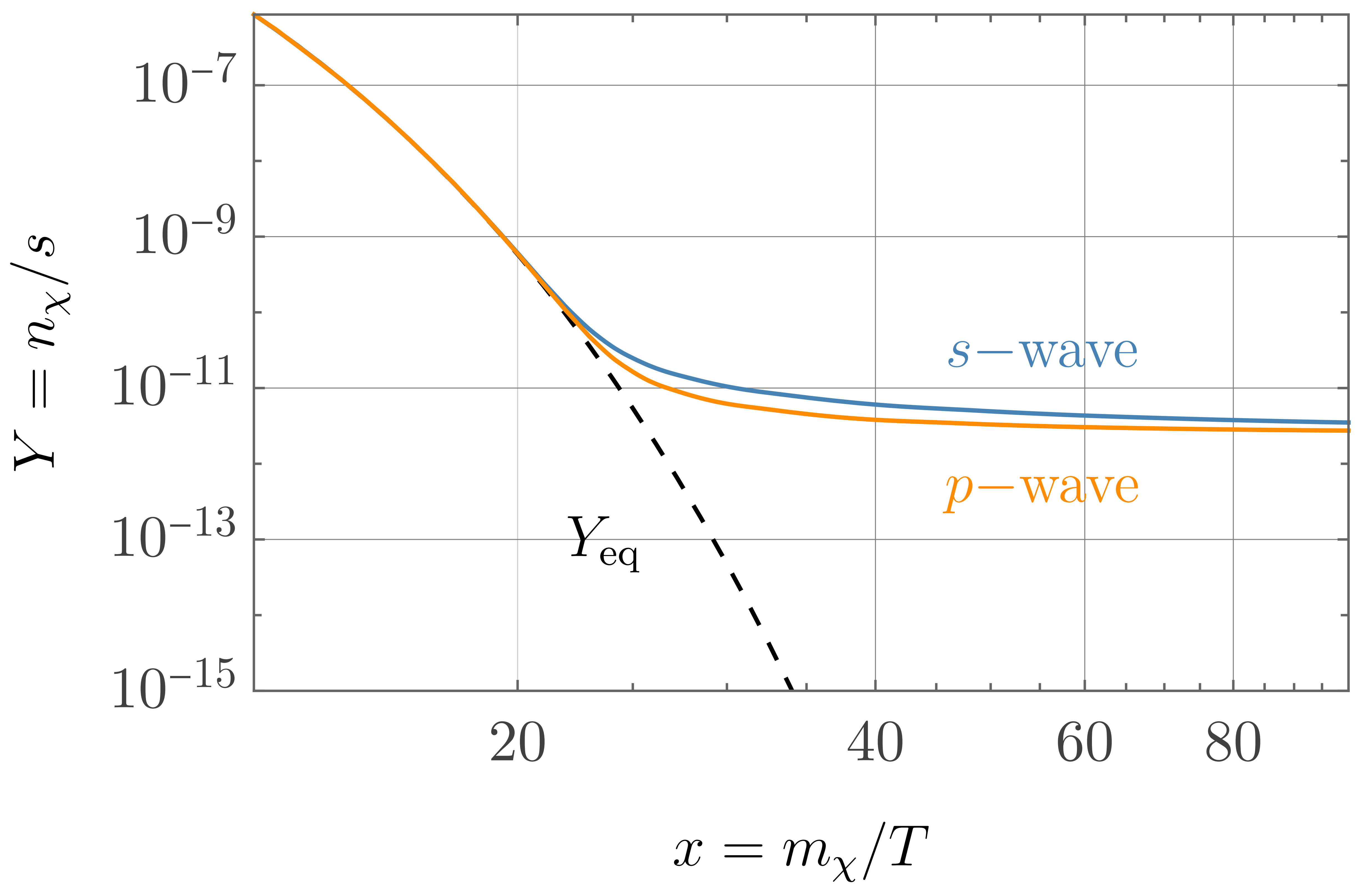
DM freeze-out

DM $\longleftrightarrow$ SM

Thermal equilibrium

Freeze-out DM $\longrightarrow$ SM

$T \lesssim m_\chi$



Boltzmann suppression

$\propto e^{-m_\chi/T}$

Velocity-independent

$\langle \sigma v \rangle \simeq a$

$\Omega_{\rm DM} h \simeq 0.12$

Velocity-dependent

$\langle \sigma v \rangle \simeq b \langle v^2 \rangle$

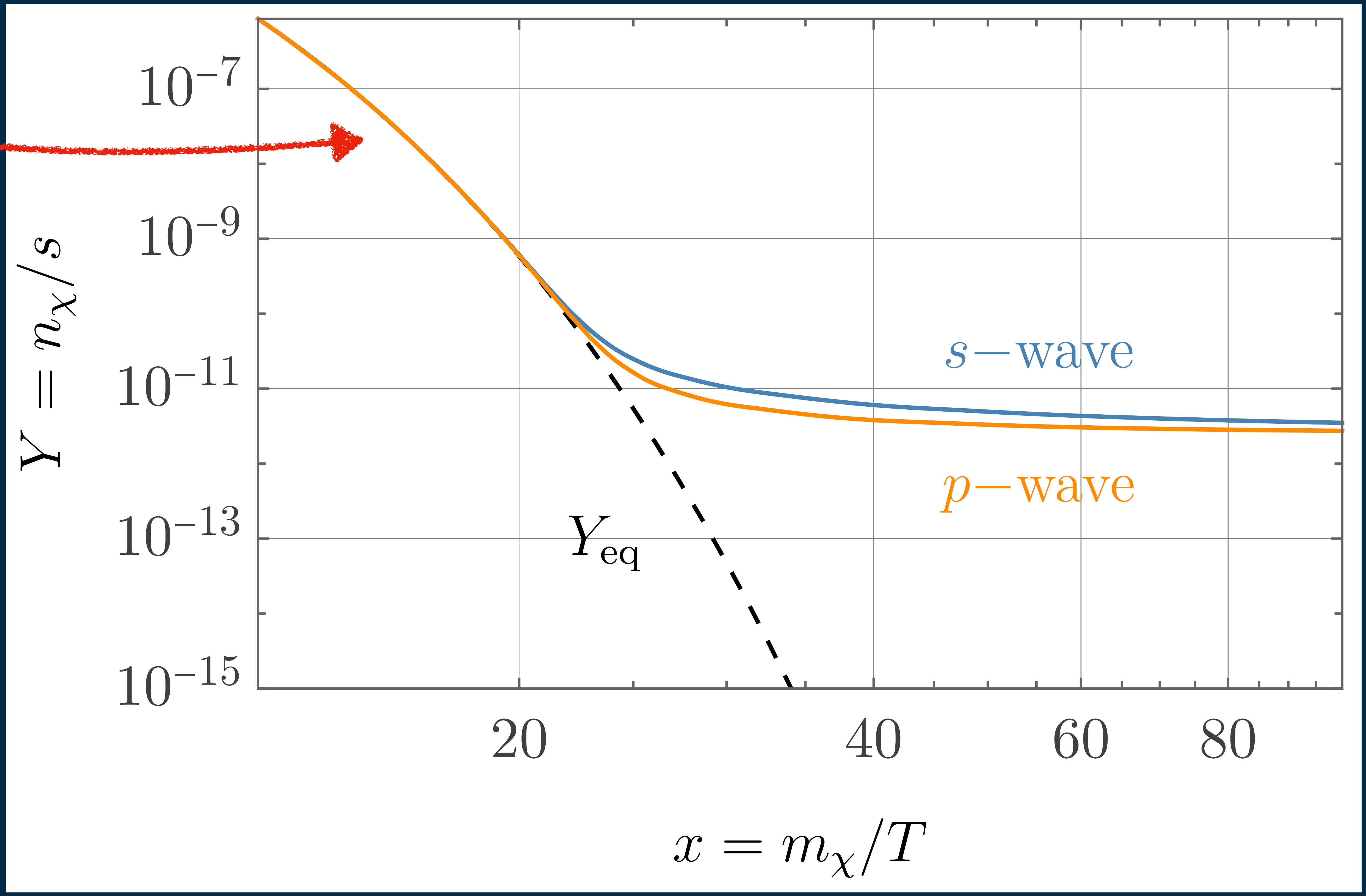
DM freeze-out

DM ⟷ SM

Thermal equilibrium

Freeze-out DM ⟶ SM

$T \lesssim m_\chi$



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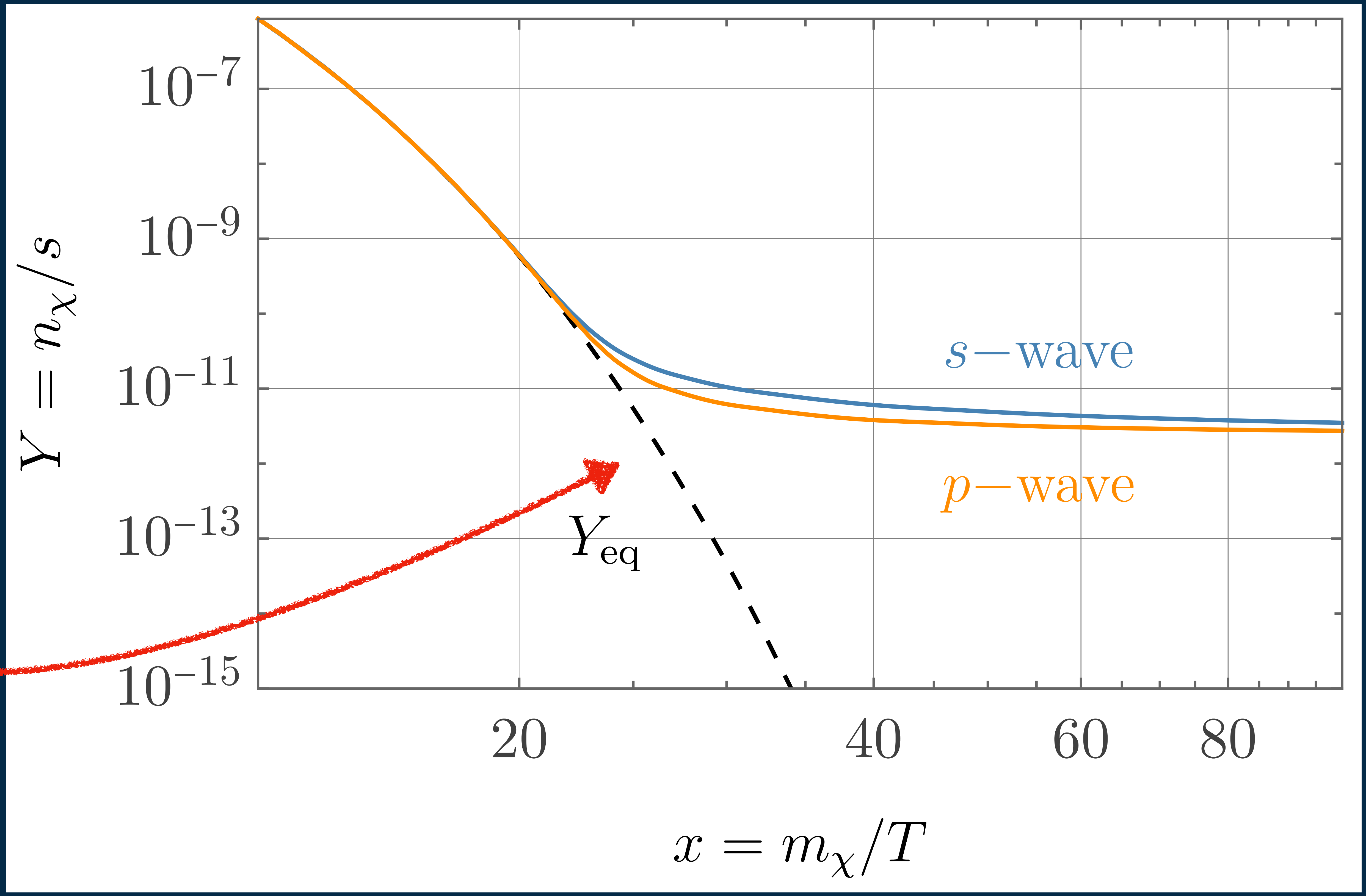

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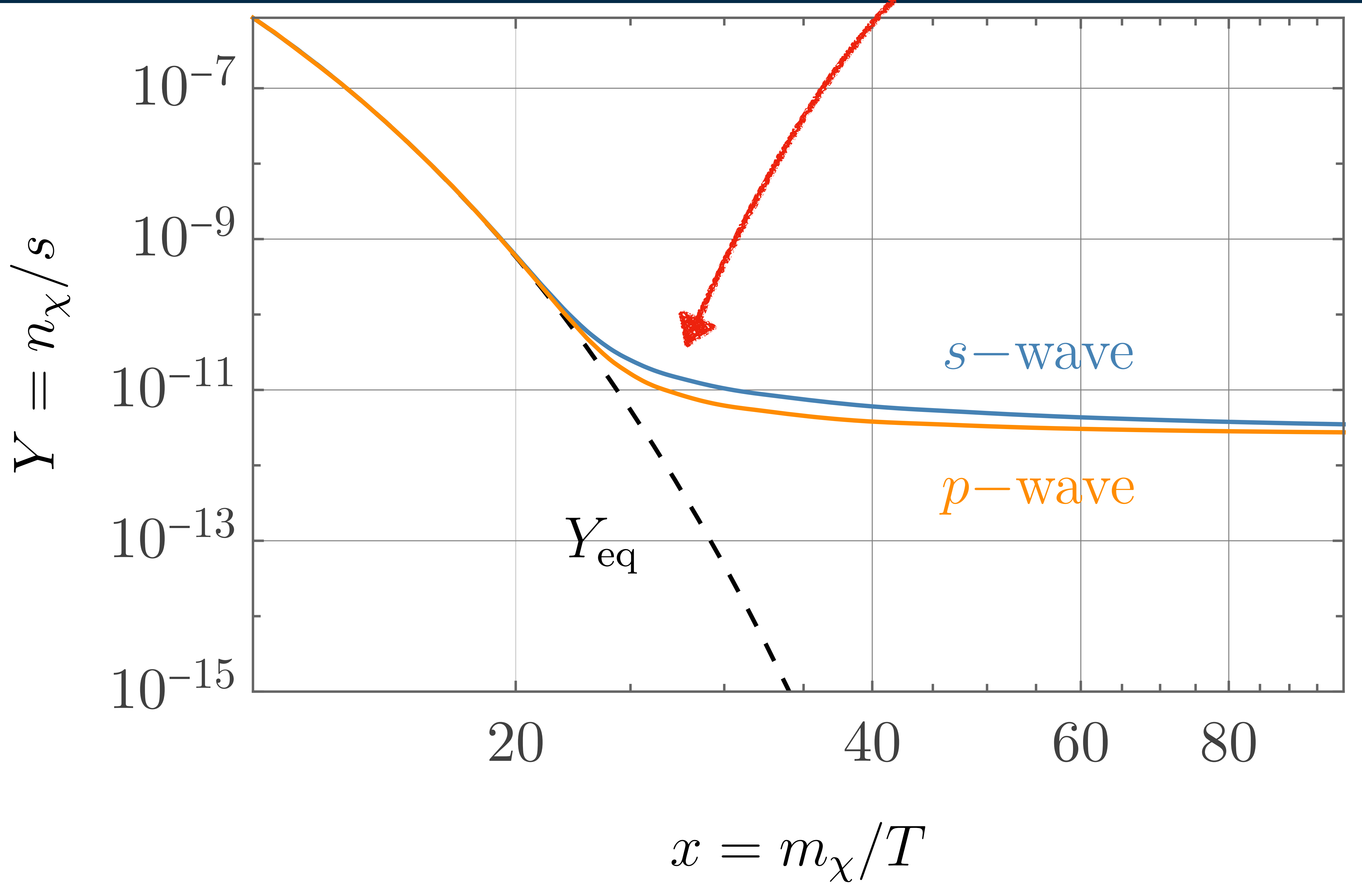

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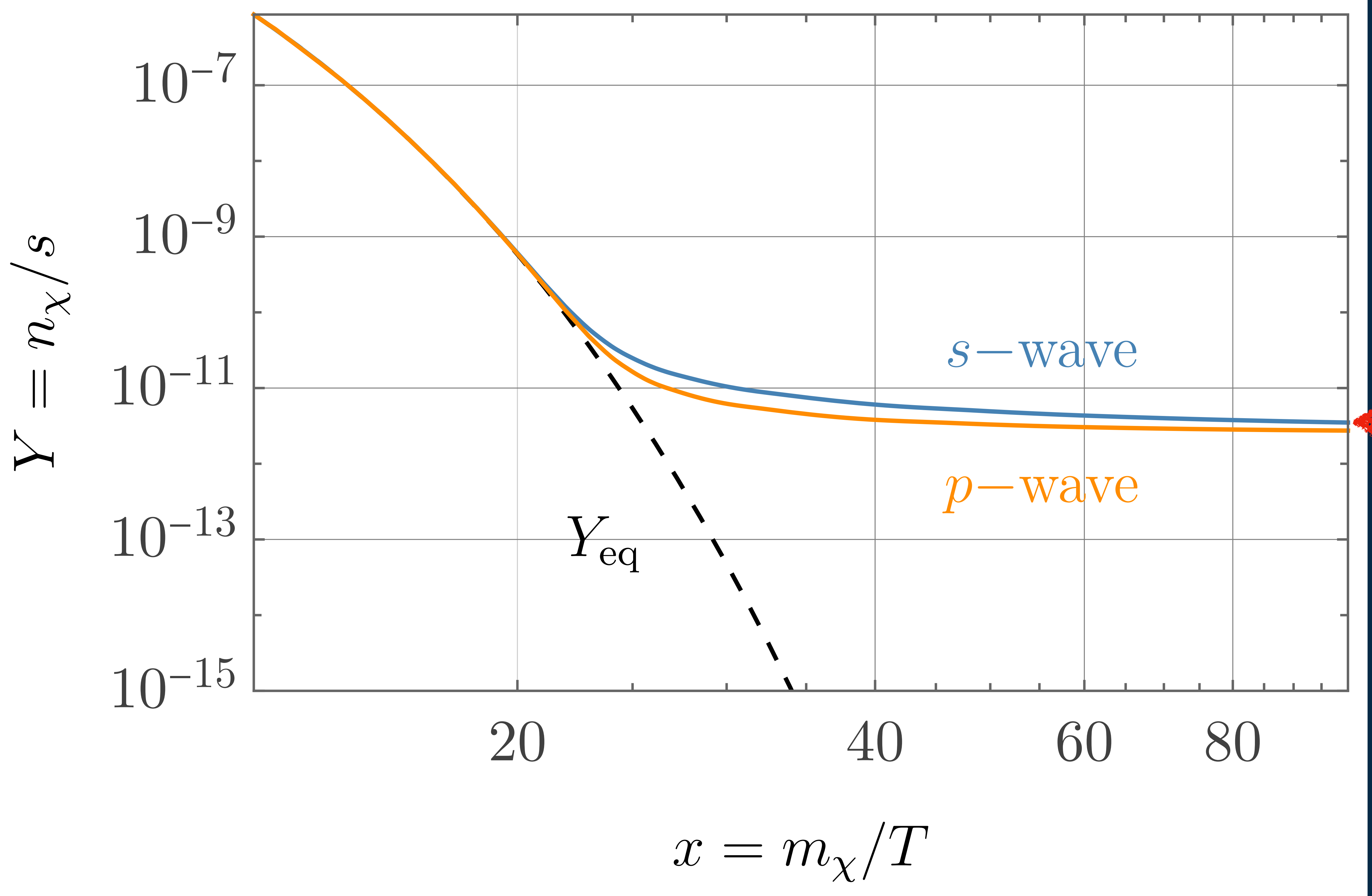

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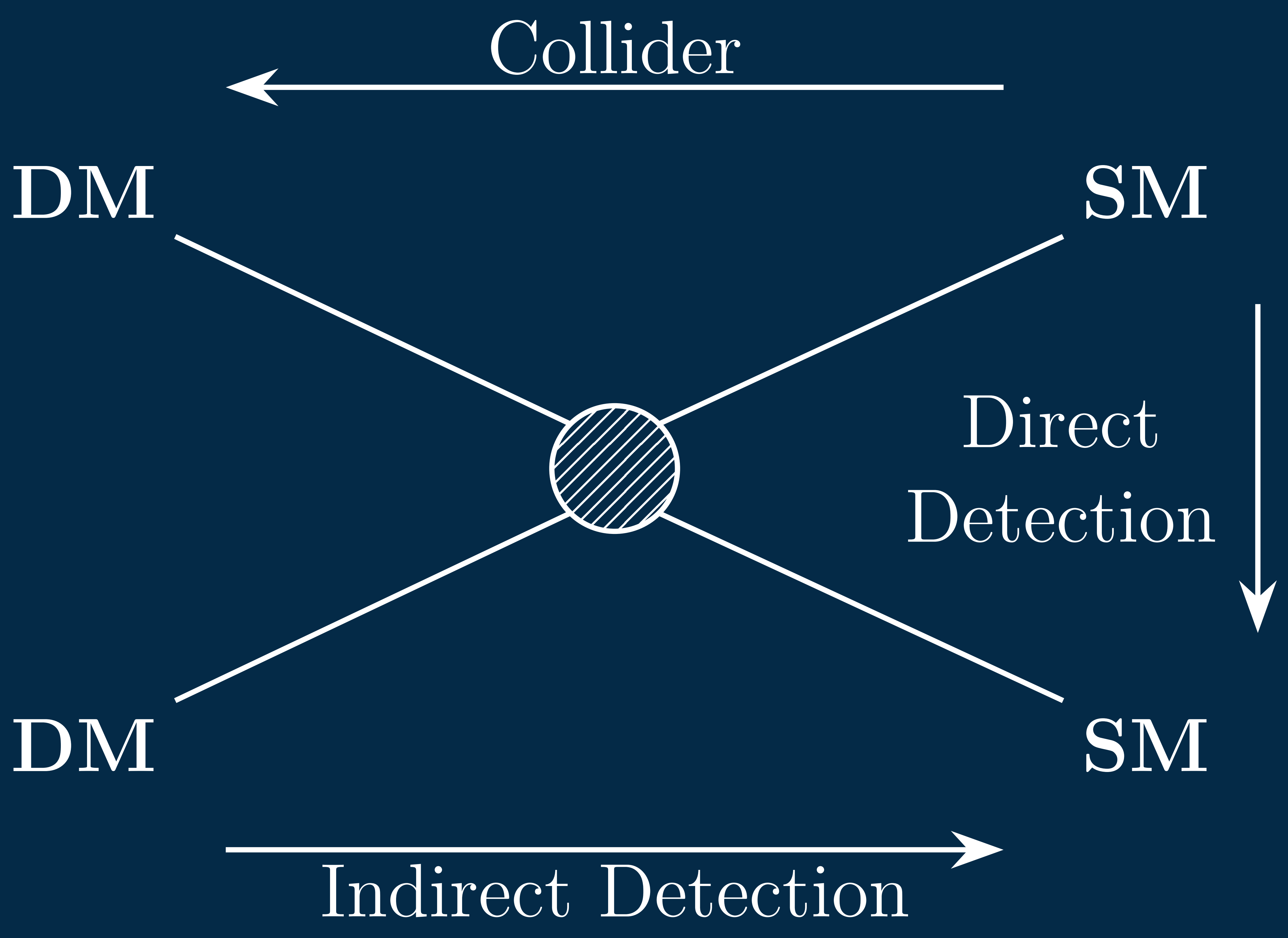
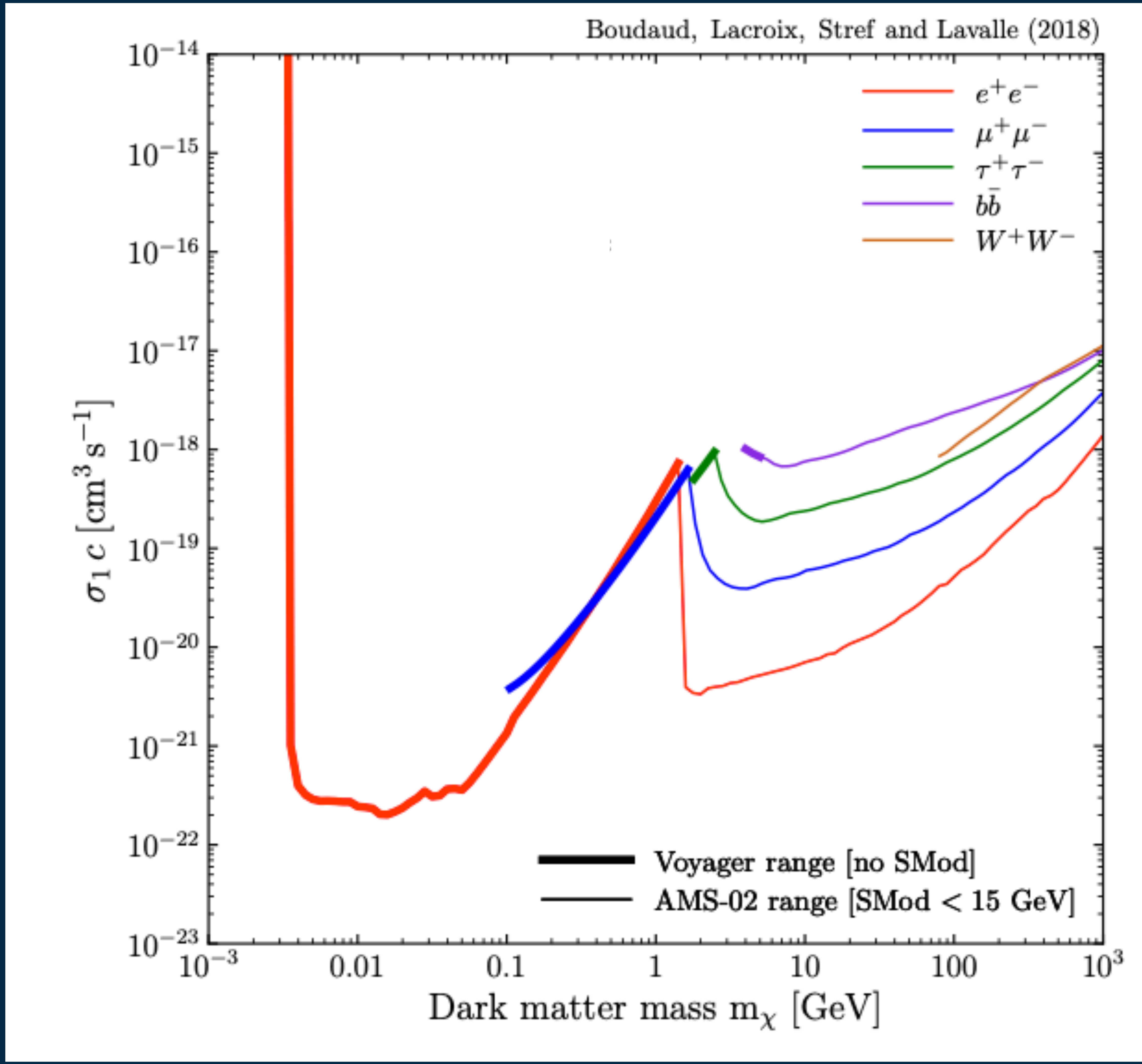
DM detection





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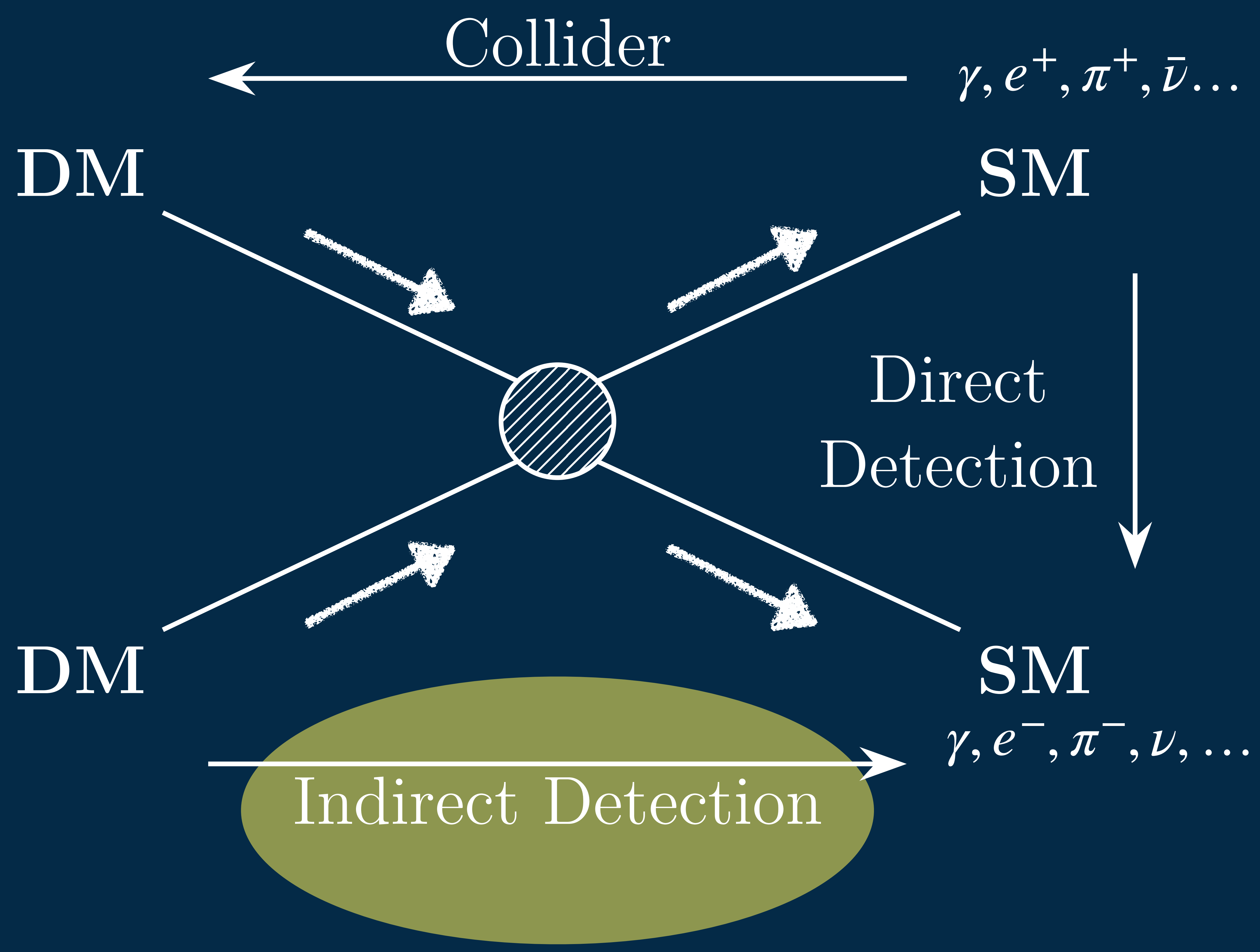

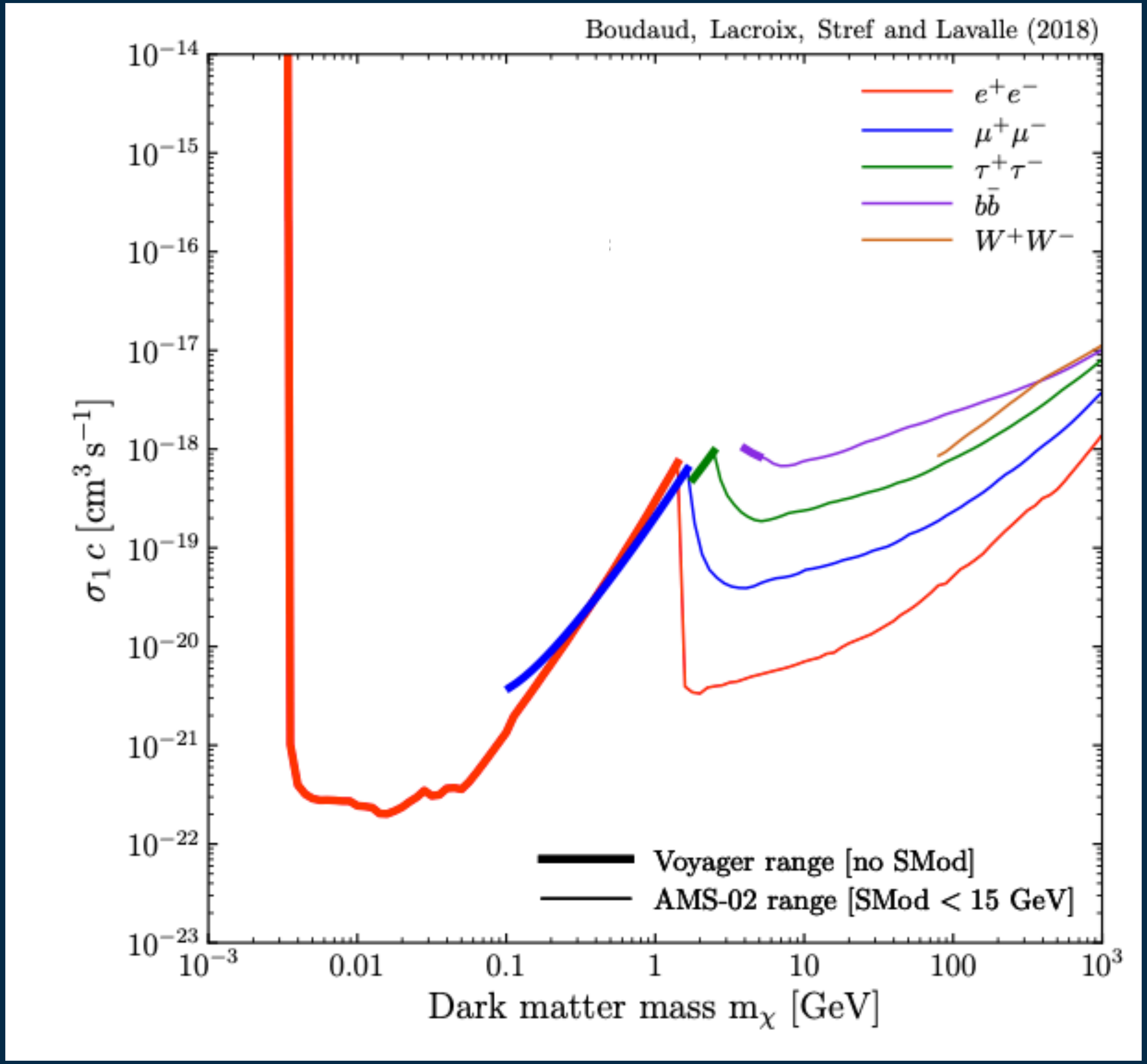

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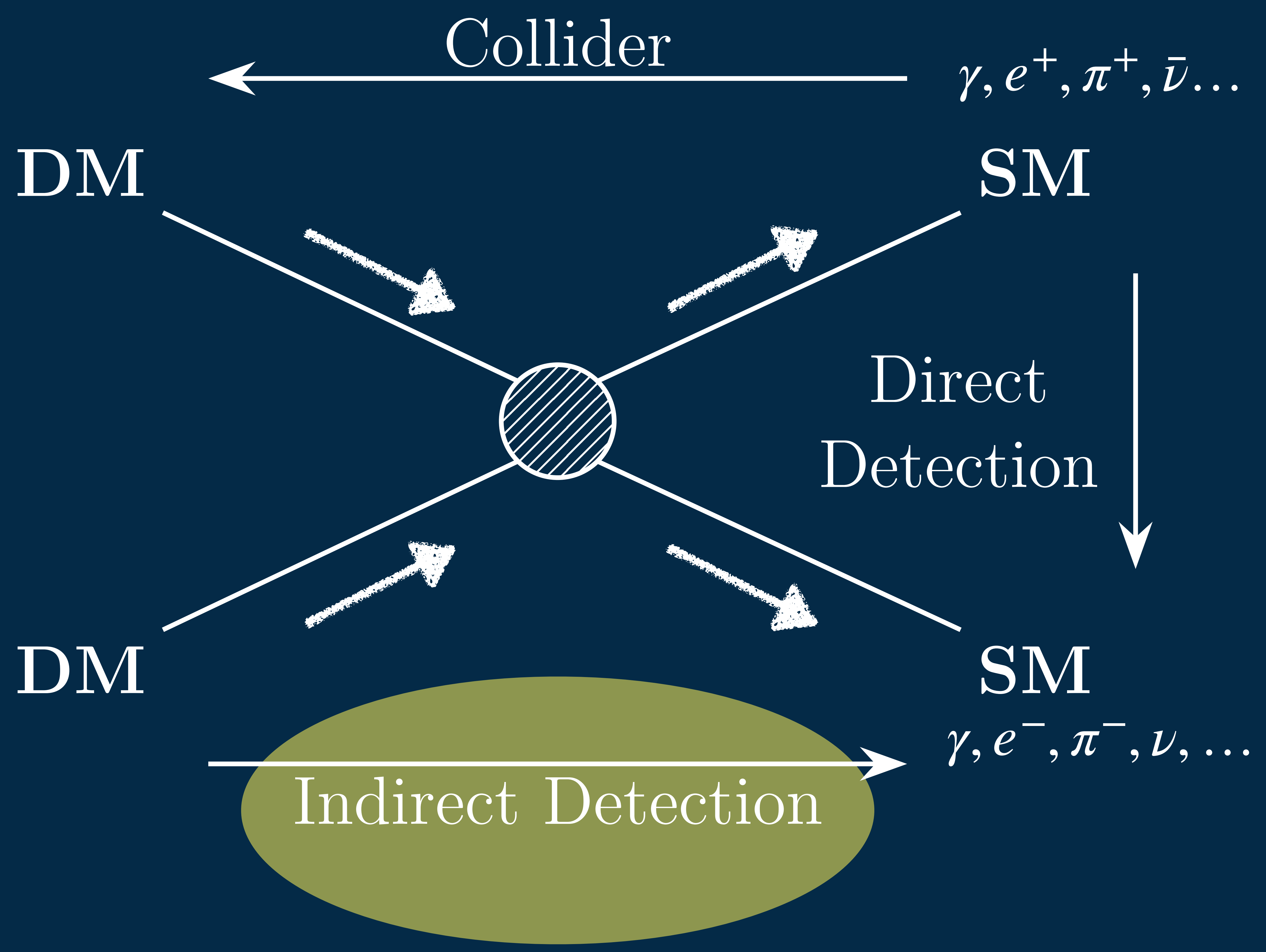

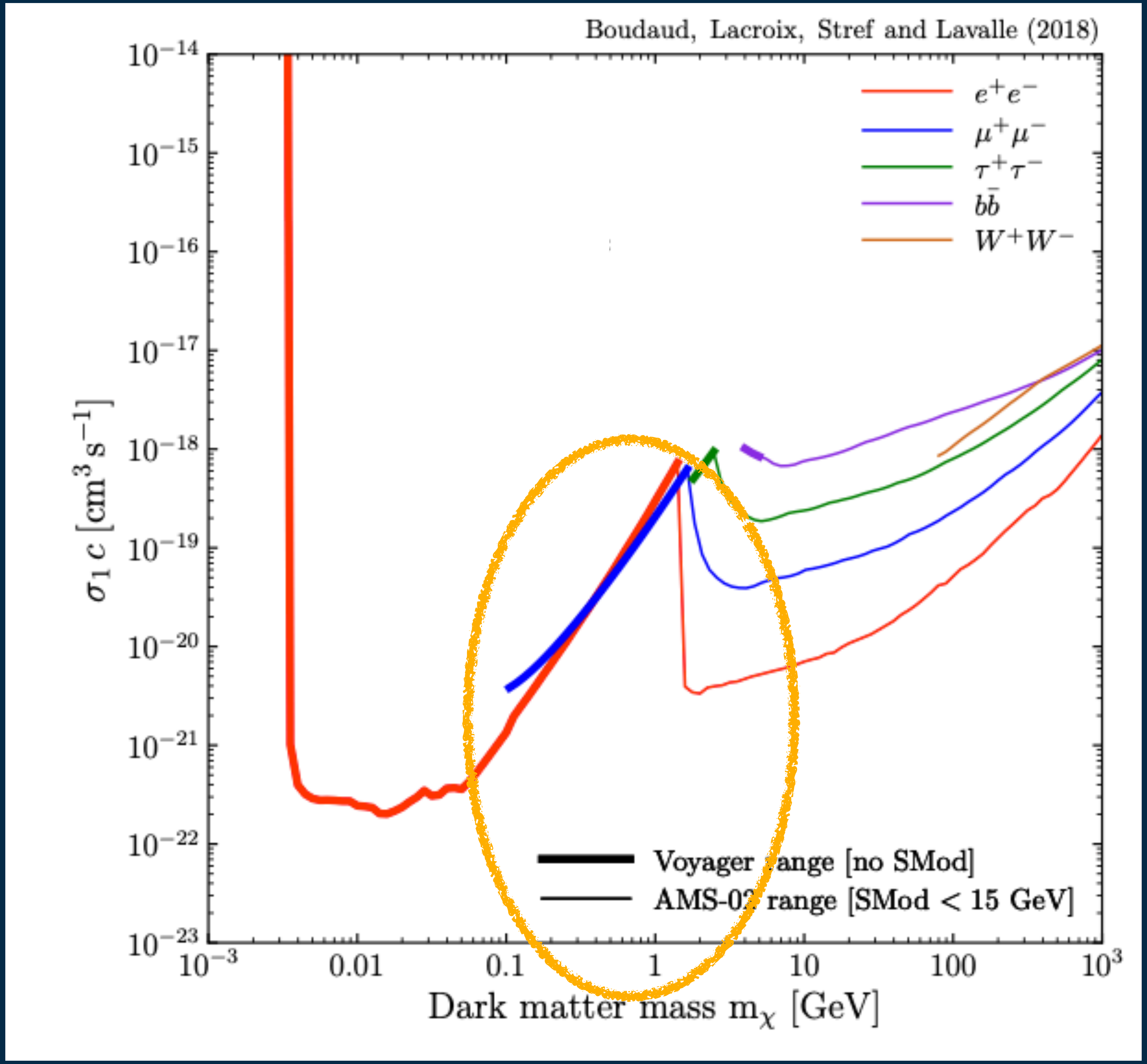

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Could BBN be sensitive to this range?

How DM could influence BBN?

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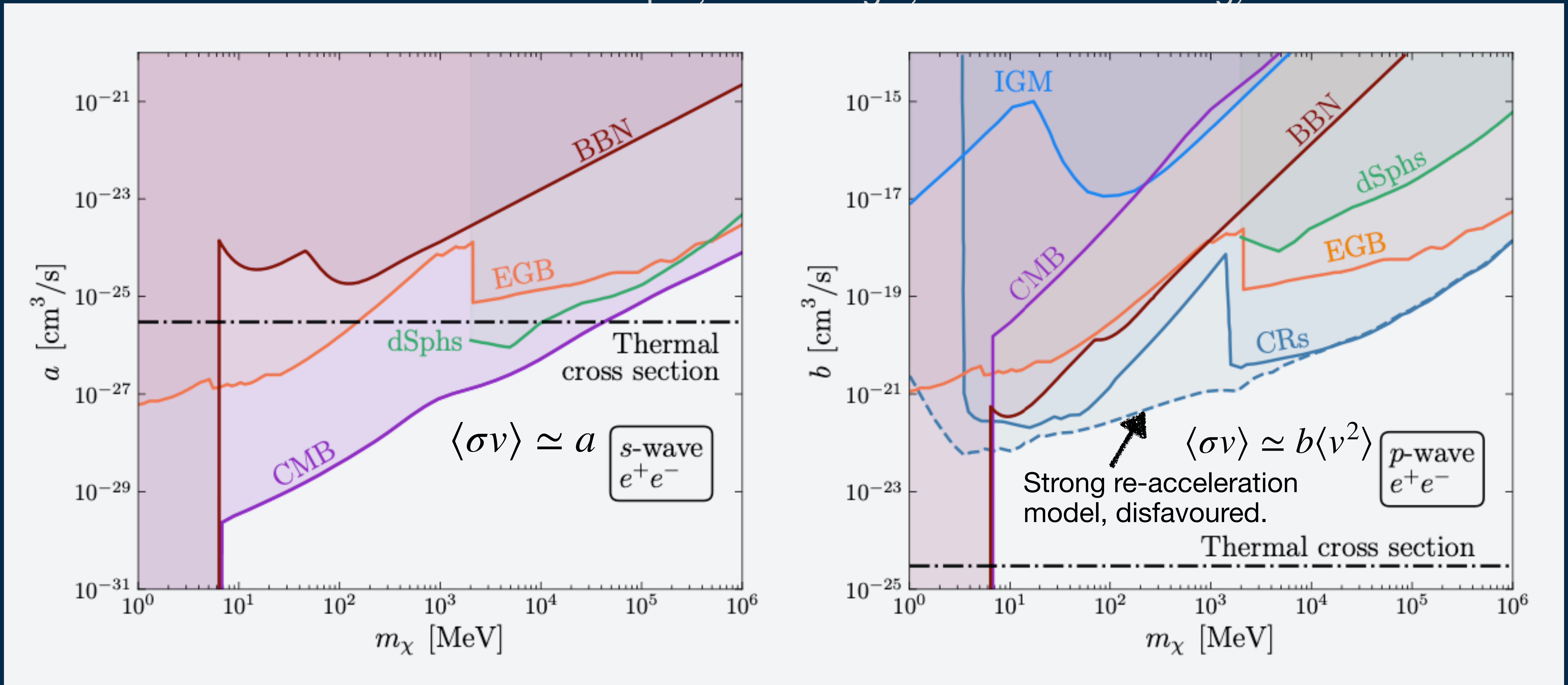


high-redshift intergalactic medium temperature

gamma-ray observations of MW-satellite dwarf galaxies

diffuse extragalactic background

Charged Pion Injection: some analysis considerations

1. DM annihilates entirely into $\pi^{\pm}$

2. $Y_\chi = Y_{\text{relic}}(m_\chi)$ remains constant.

3. Neutrino decoupling is simplified by using $N_\nu \simeq 3.045$ as input.

4. The thermal evolution is unaltered.

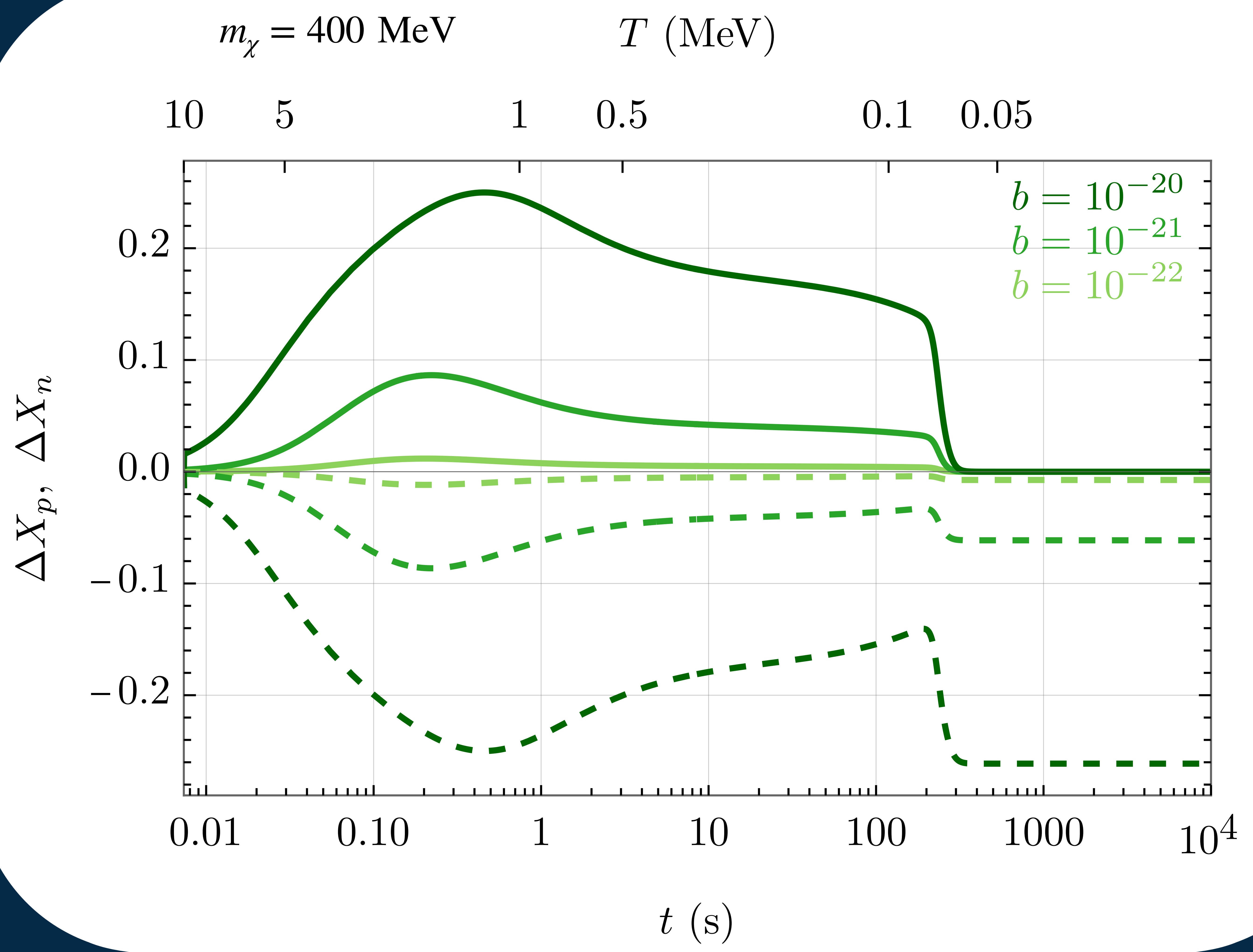
5. The pions are very efficiently stopped

6. The most important interactions are with protons and neutrons.

7. $\pi^+\pi^-$ annihilations, back reactions to DM, and interactions with other mesons are all negligible.

* $\pi^{\pm} \to \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu)$ accounted for, but products are neglected.

Effects of $\pi^{\pm}$ injection on neutrons and protons



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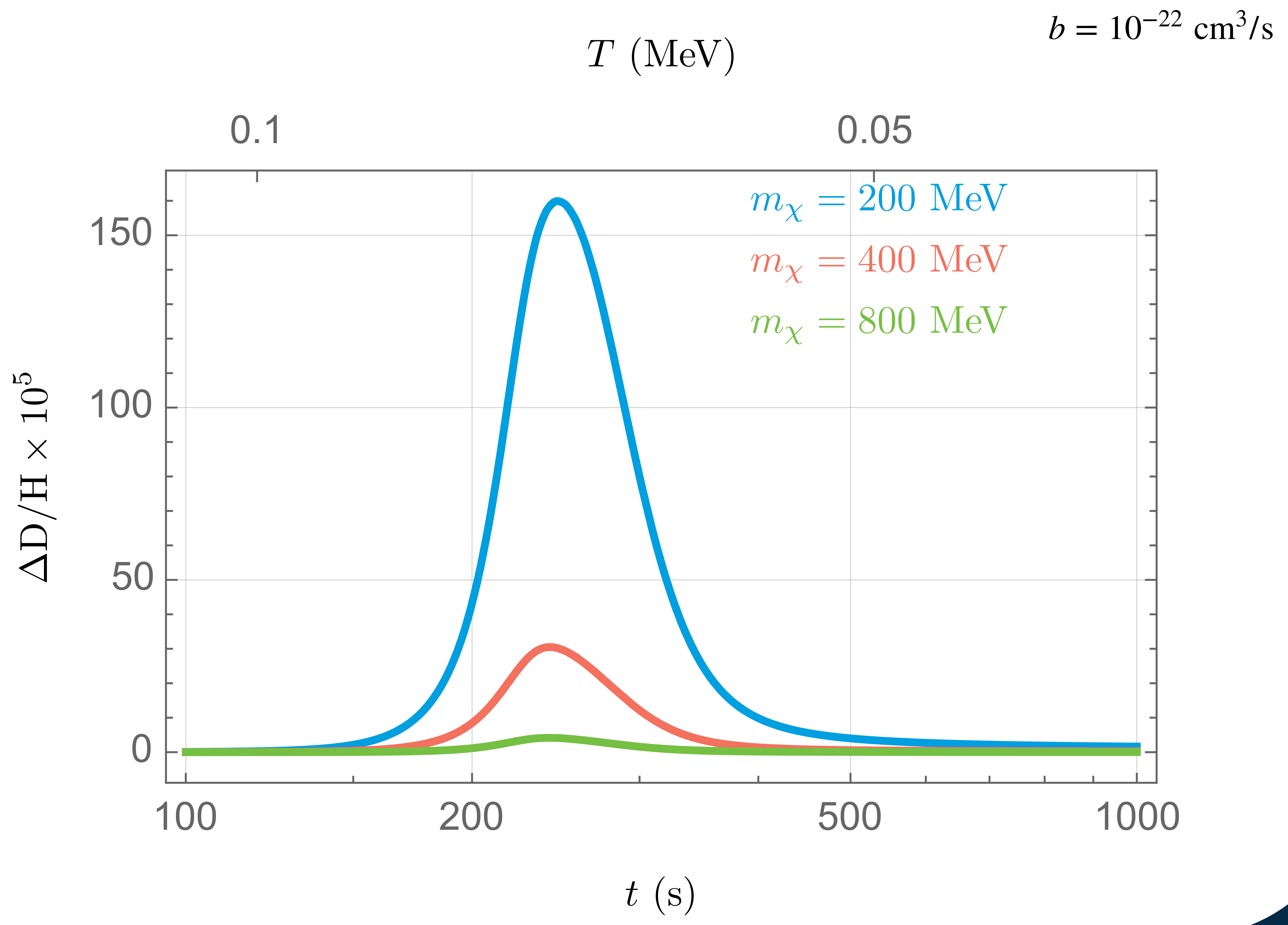
- Neutrons biased due to Coulomb enhanced $\pi^- + p \to n$.
- Excess neutrons are later synthesized into excess ^{4}He.

Generic constraints on velocity suppressed annihilation



We can get constraints on DM interaction rate by demanding that D and ^{4}He predictions match observations*

$$\mathrm{D/H} \times 10^{-5} = 2.547 \pm 0.025$$

$$Y_p = 0.245 \pm 0.003$$

PDG (2024) and refs within

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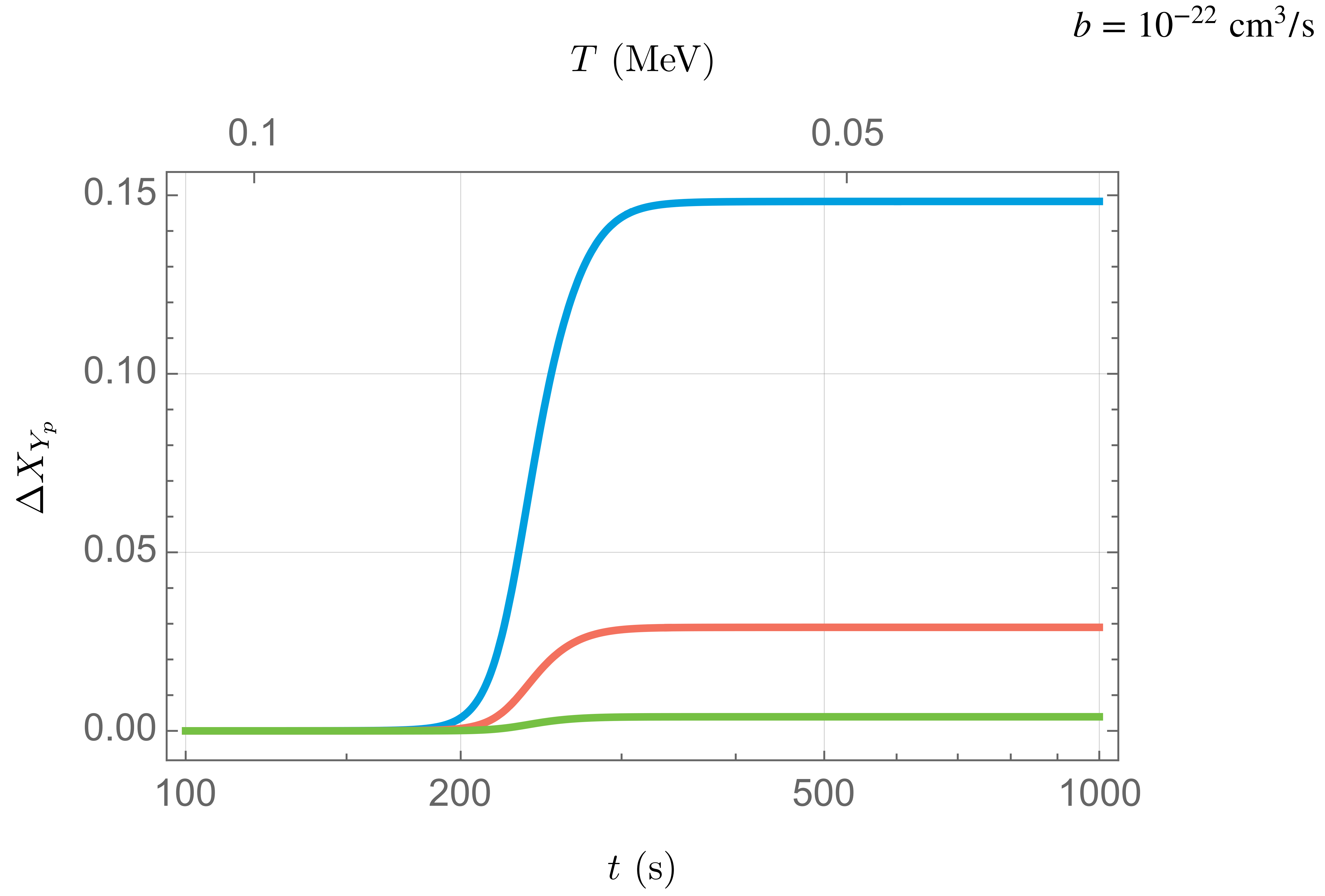

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PDG (2024) and refs within

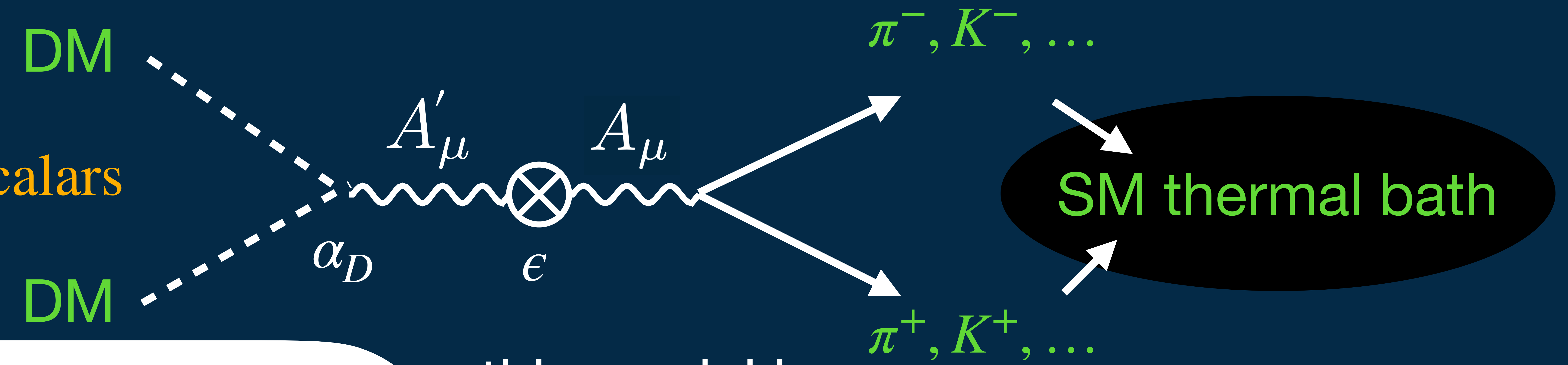
What about neutral mesons?

- Neutral pions have a very short lifetime ($\sim 10^{-18}$ s). The photons they decay to thermalize quickly and have no effect.
- K_S $(\tau \sim 10^{-10}\ \mathrm{s})$ decays to charged pions (BR $\sim 69\,\%$), resulting in a similar effect.
- K_L $(\tau \sim 10^{-7}\ \mathrm{s})$ has a per-particle effect on BBN that is comparable to charged kaons (via hyperon decays).

  ✳Effects depend on the model's BR, but are limited to $\sim \mathcal{O}(1)$.

- In the dark photon model, including effects due to neutral mesons could potential strengthen limits by ~ 10% in the high mass region (near the ϕ resonance, ~1 GeV), so our limits are somewhat conservative.

A DM benchmark model: additional comments



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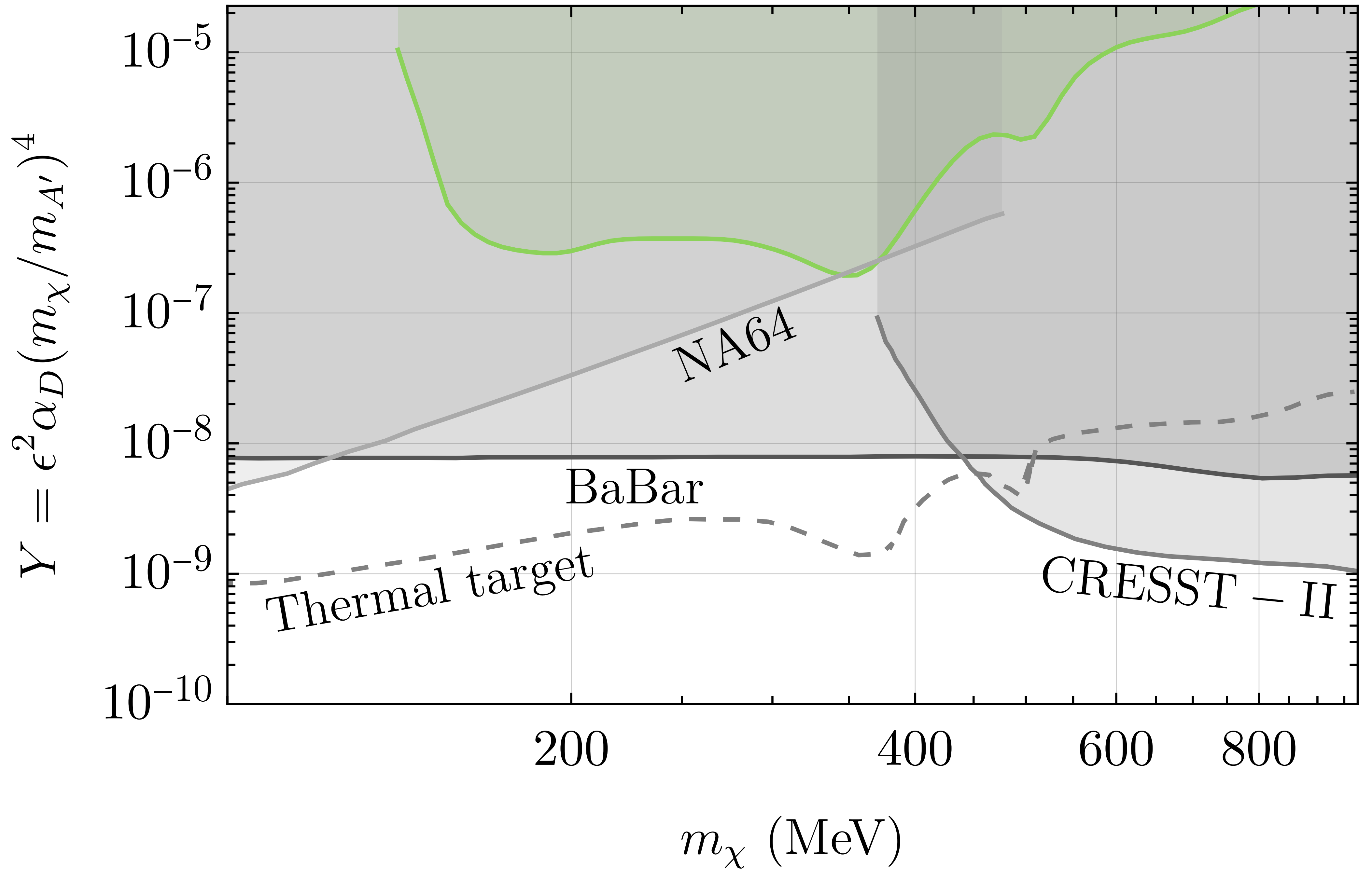

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*The BRs are obtained from on shell DP decay.
*Although the DP is off shell, we approximate the BR to correspond to the on shell branching for $m_{A'} = 2m_\chi$ (as opposed to $3m_\chi$)

$\alpha_D = 0.5$
$m_{A'}/m_\chi = 3$