Hadronic Dark Matter Annihilation During Big Bang Nucleosynthesis

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

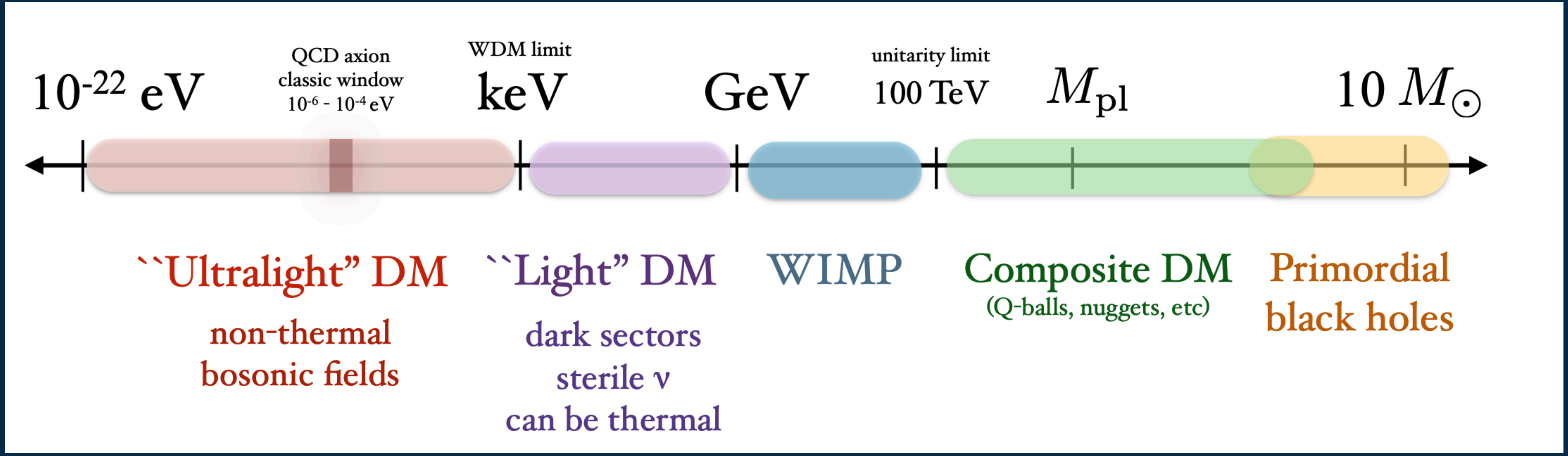
Afif Omar
May, 2026

TRIUMF

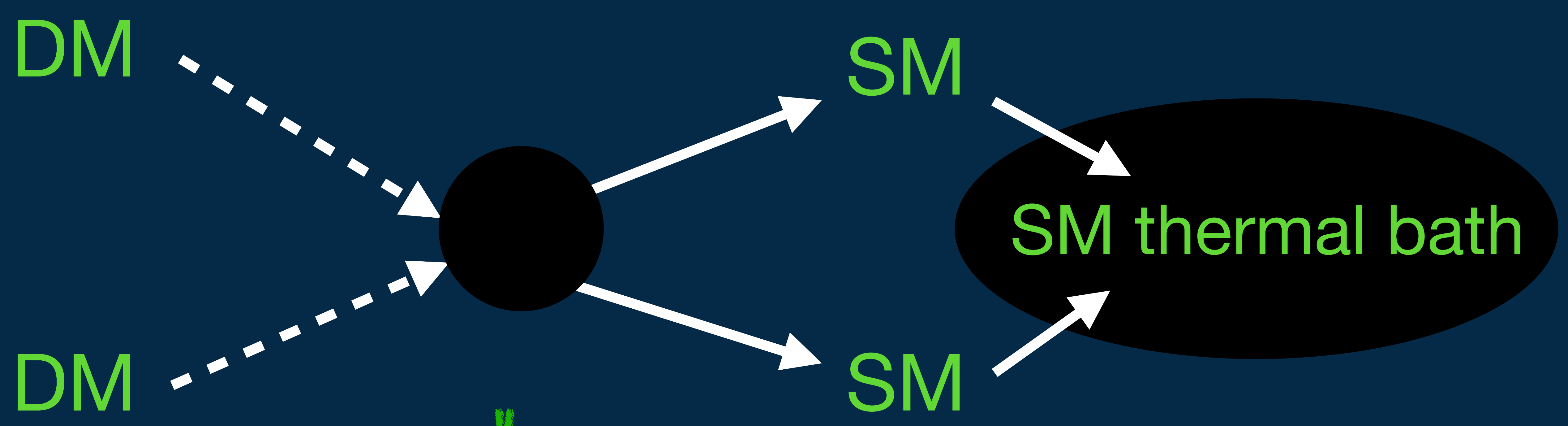
UVIC

Pheno 2026 Symposium

The big picture



T. Lin 1904.07915



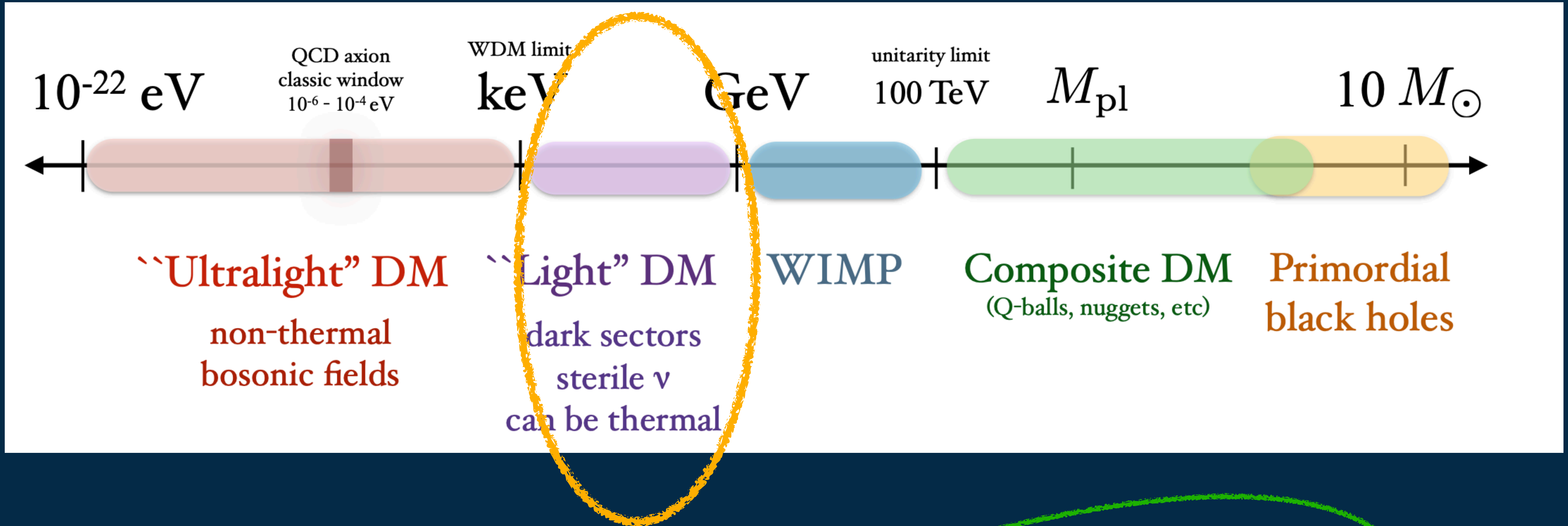
Velocity independent (s-wave)

Velocity dependent (p-wave)

Ruled out by CMB

Evades CMB

The big picture



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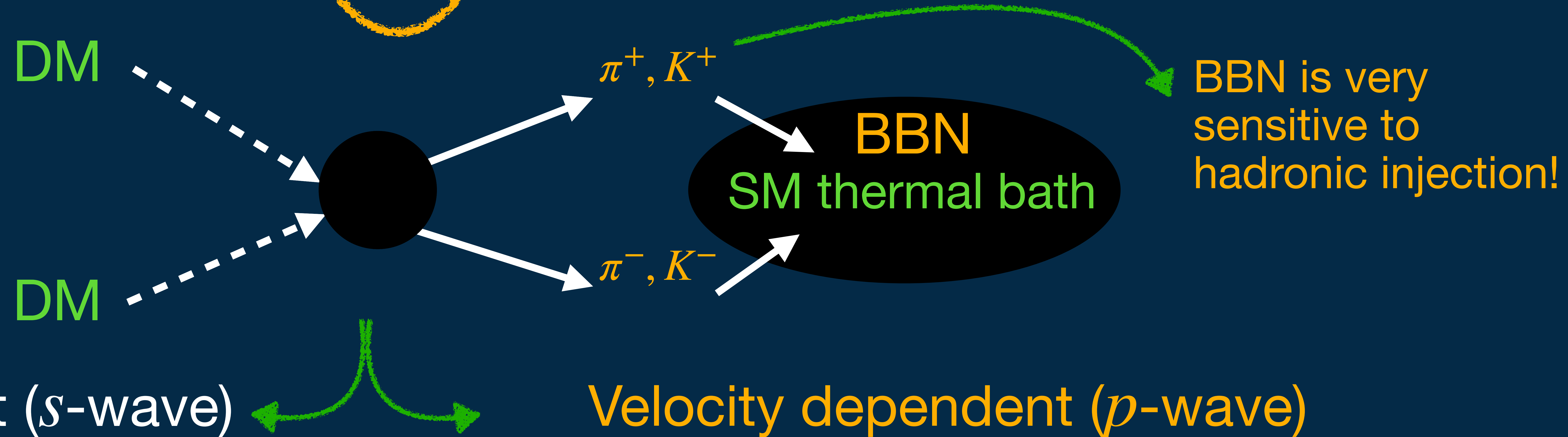

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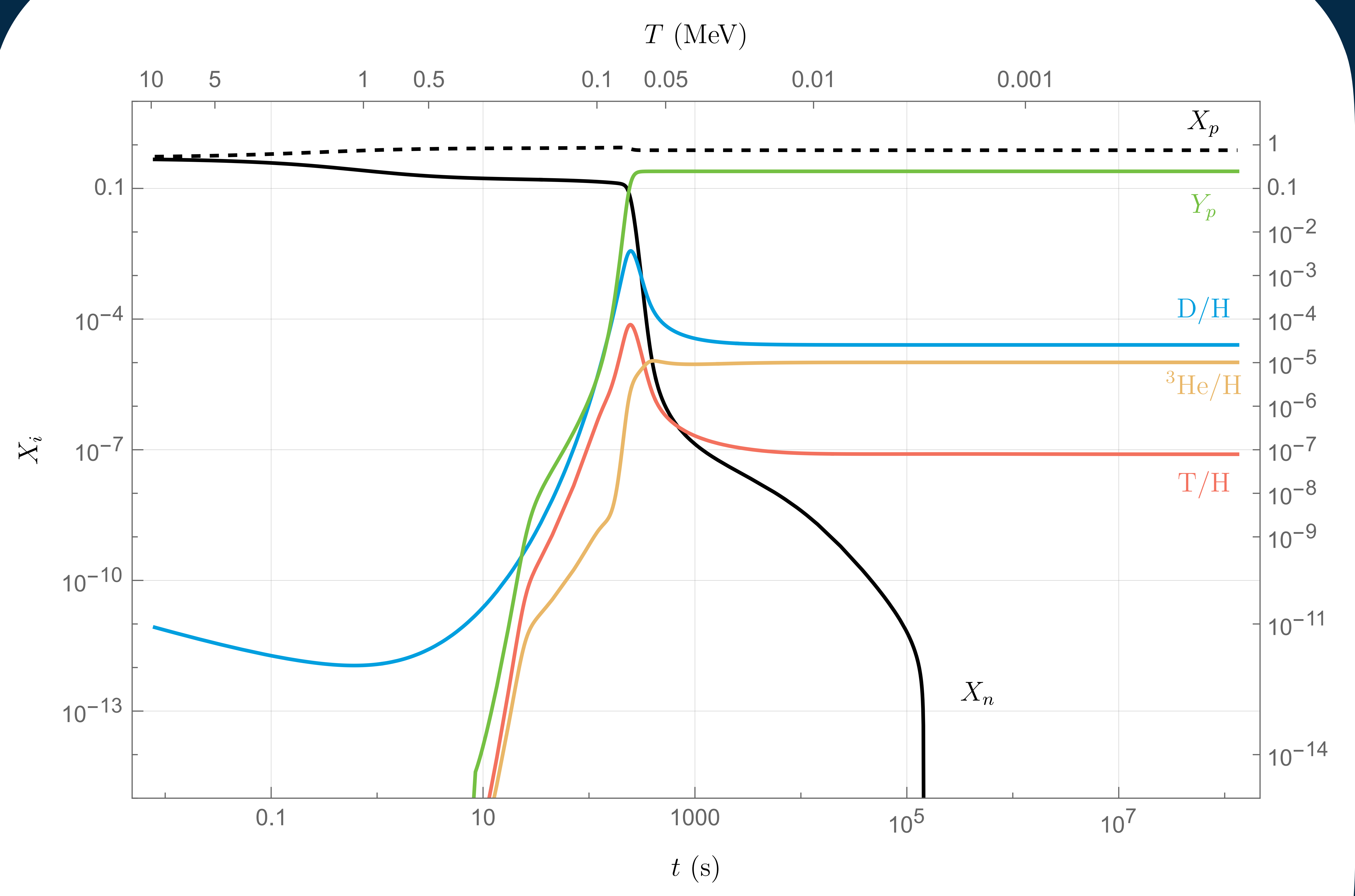
Big bang nucleosynthesis (BBN)



Inputs:

Nuclear interaction rates
Neutron lifetime and weak rates
Hubble rate
Ratio of baryons to photons
…

Output:

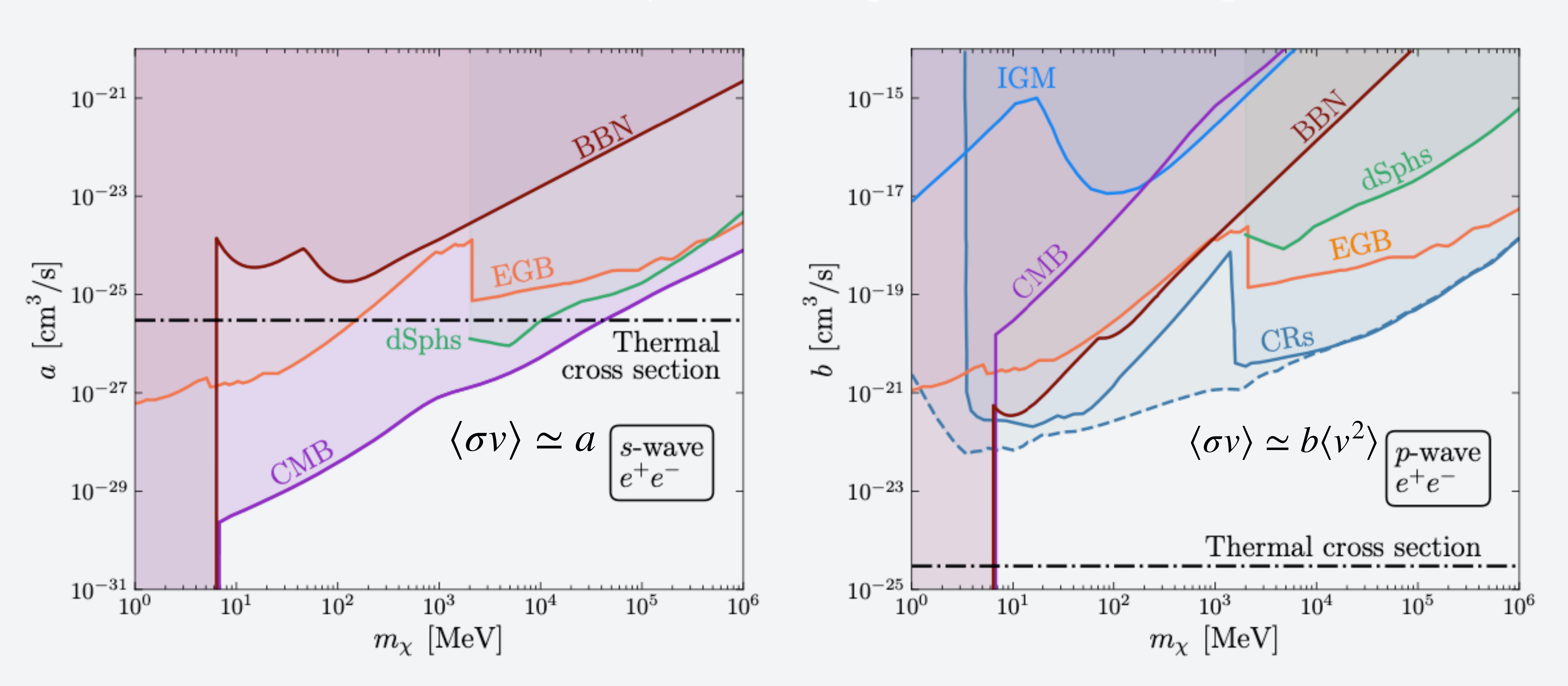
Primordial nuclear abundances

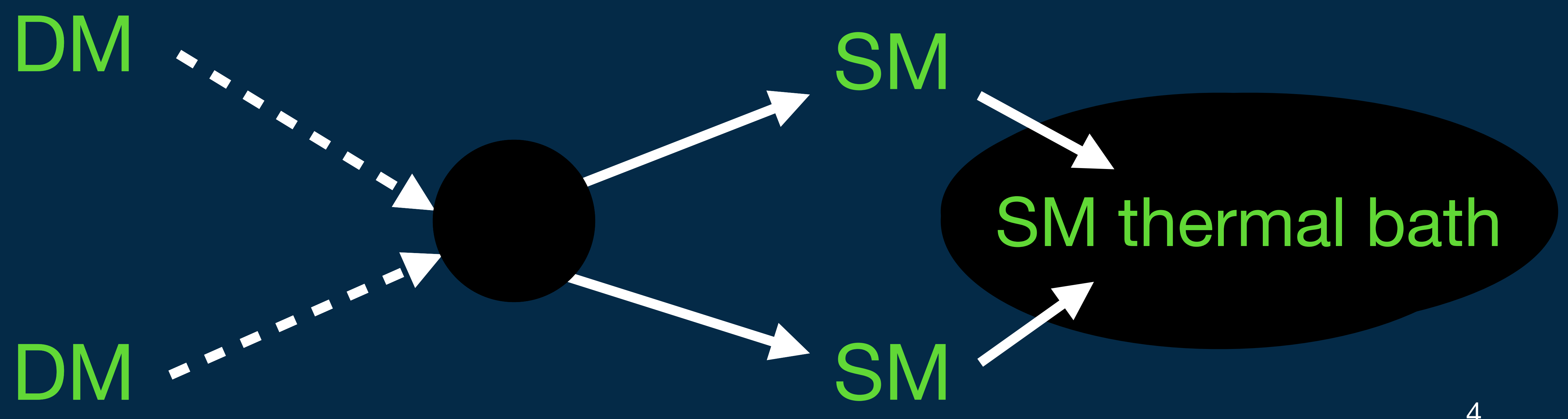
D. McKeen, AO 2407.03508

How DM could influence BBN?

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

- Entropy injection
- Photodisintegration
- Hadronic injection?





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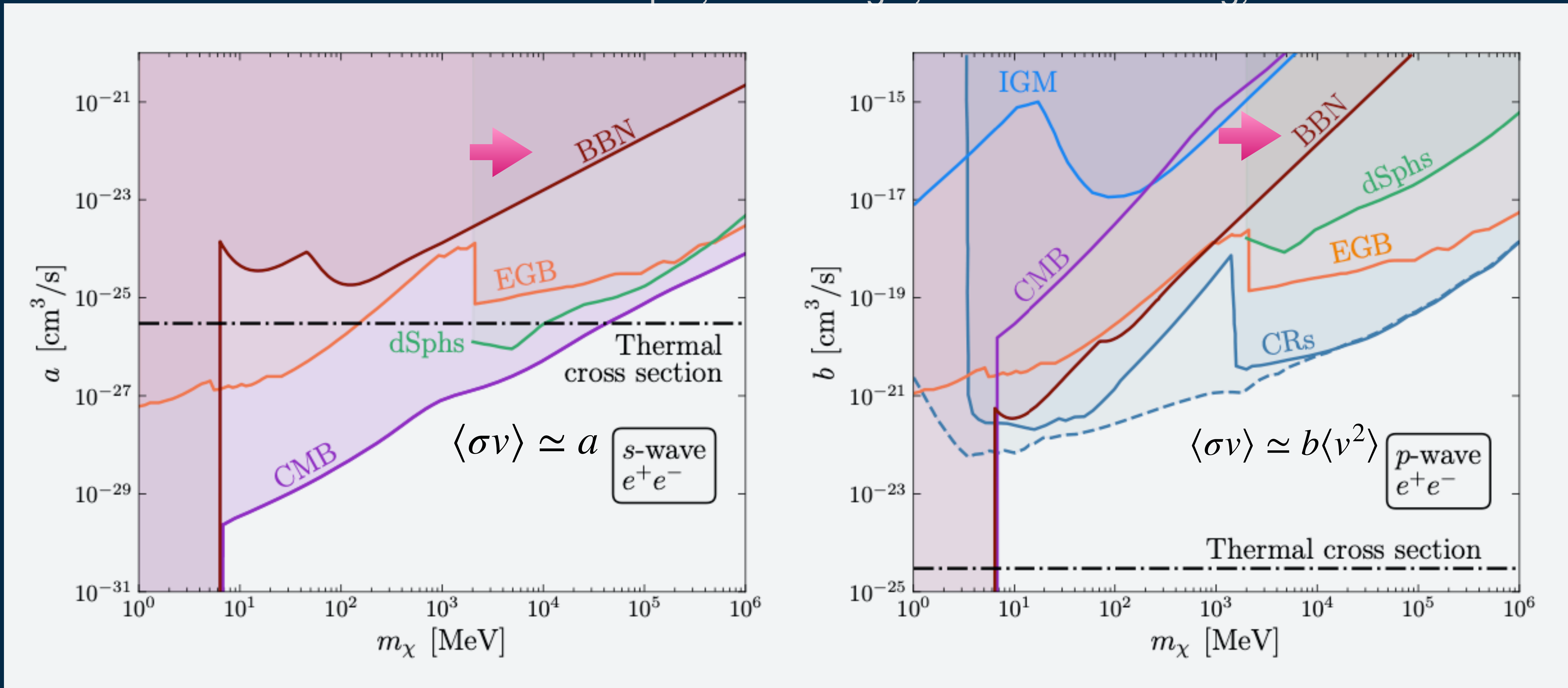

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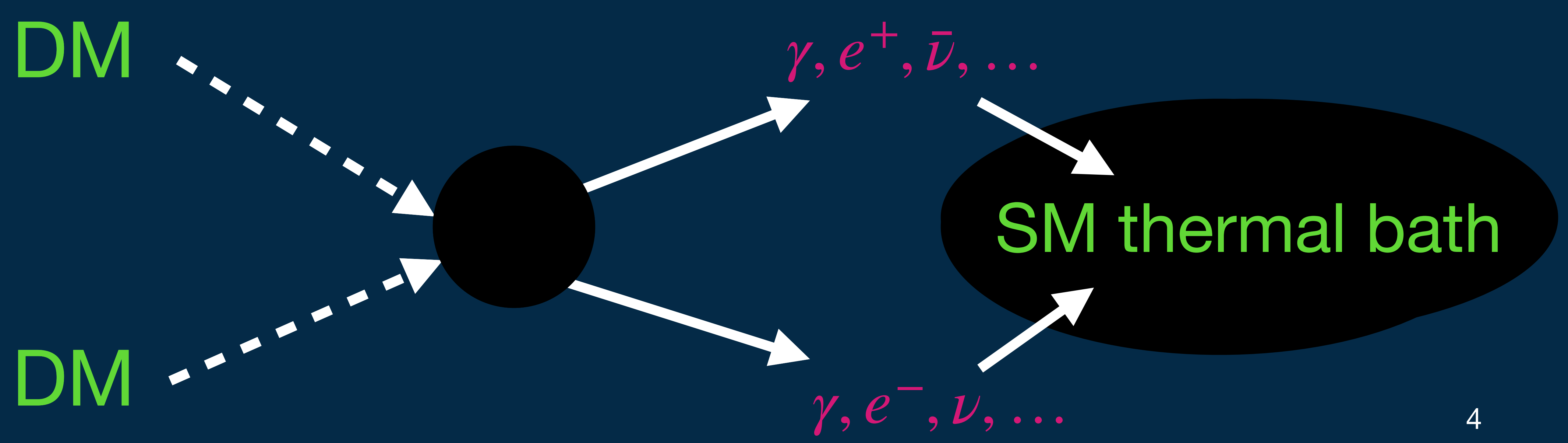

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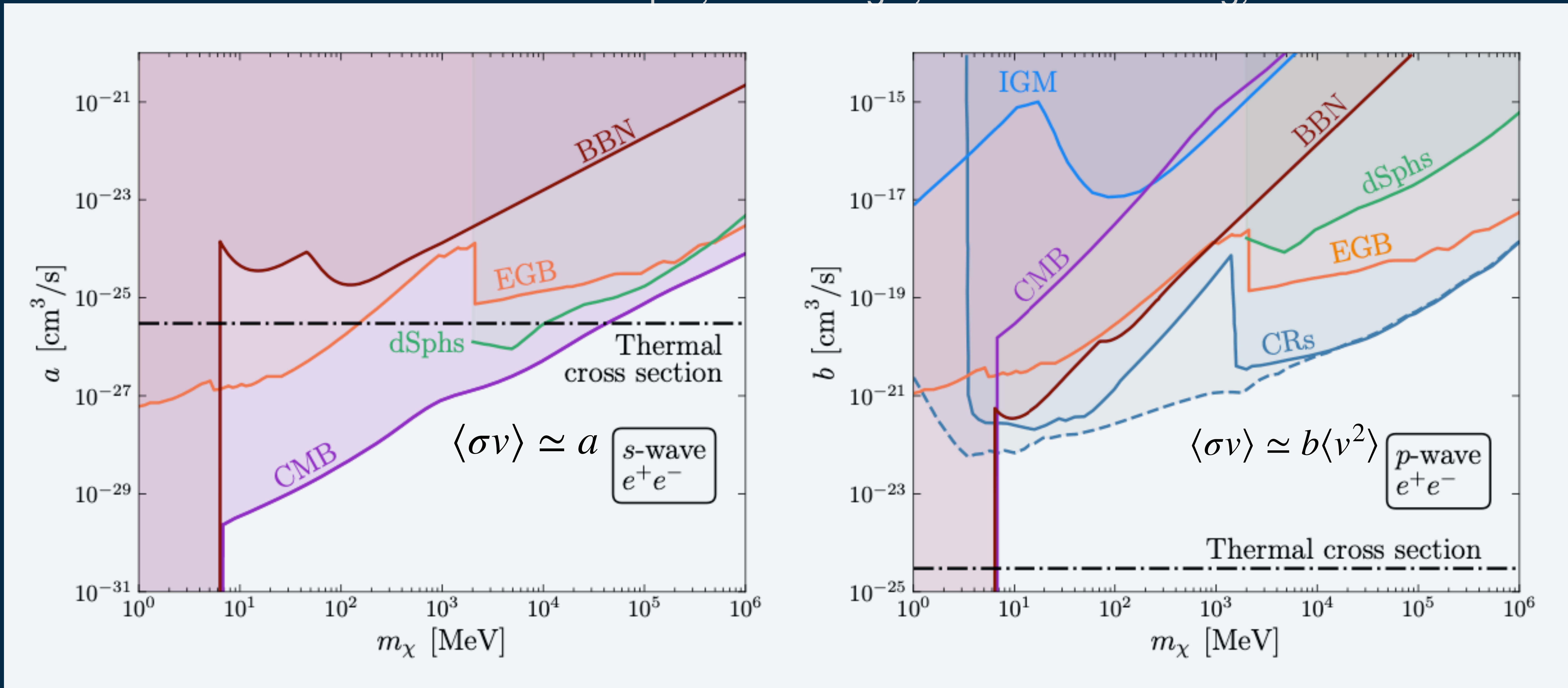
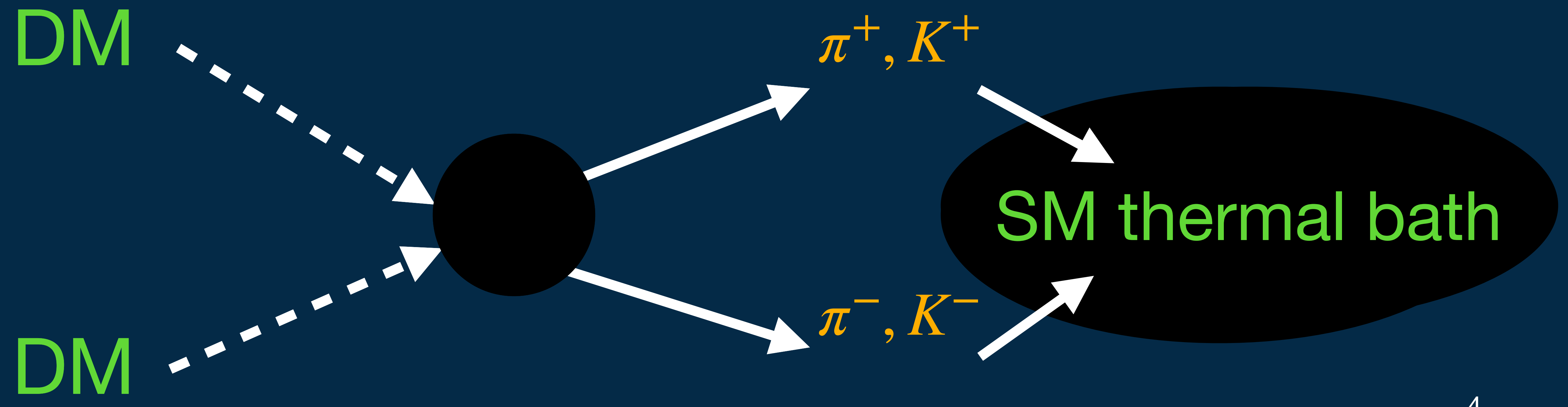
With focus on p-wave to avoid CMB constraints





Nuclear interaction rates

Neutron lifetime and weak rates

Hubble rate

Ratio of baryons to photons

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Modifications to the Boltzmann equations

SBBN

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

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

BBN + Pion injection

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

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

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

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

M. Pospelov, J. Pradler 1006.4172

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$$\frac{dn_{\pi^\pm}}{dt} + 3Hn_{\pi^\pm} \propto \underbrace{\text{DM injection}}_{\sim \frac{1}{2} n_\chi^2 \langle \sigma v \rangle} - \underbrace{\text{pion decay}}_{\sim \frac{n_{\pi^\pm}}{\tau_\pi}} - \pi^{\pm} \text{ interactions}*$$

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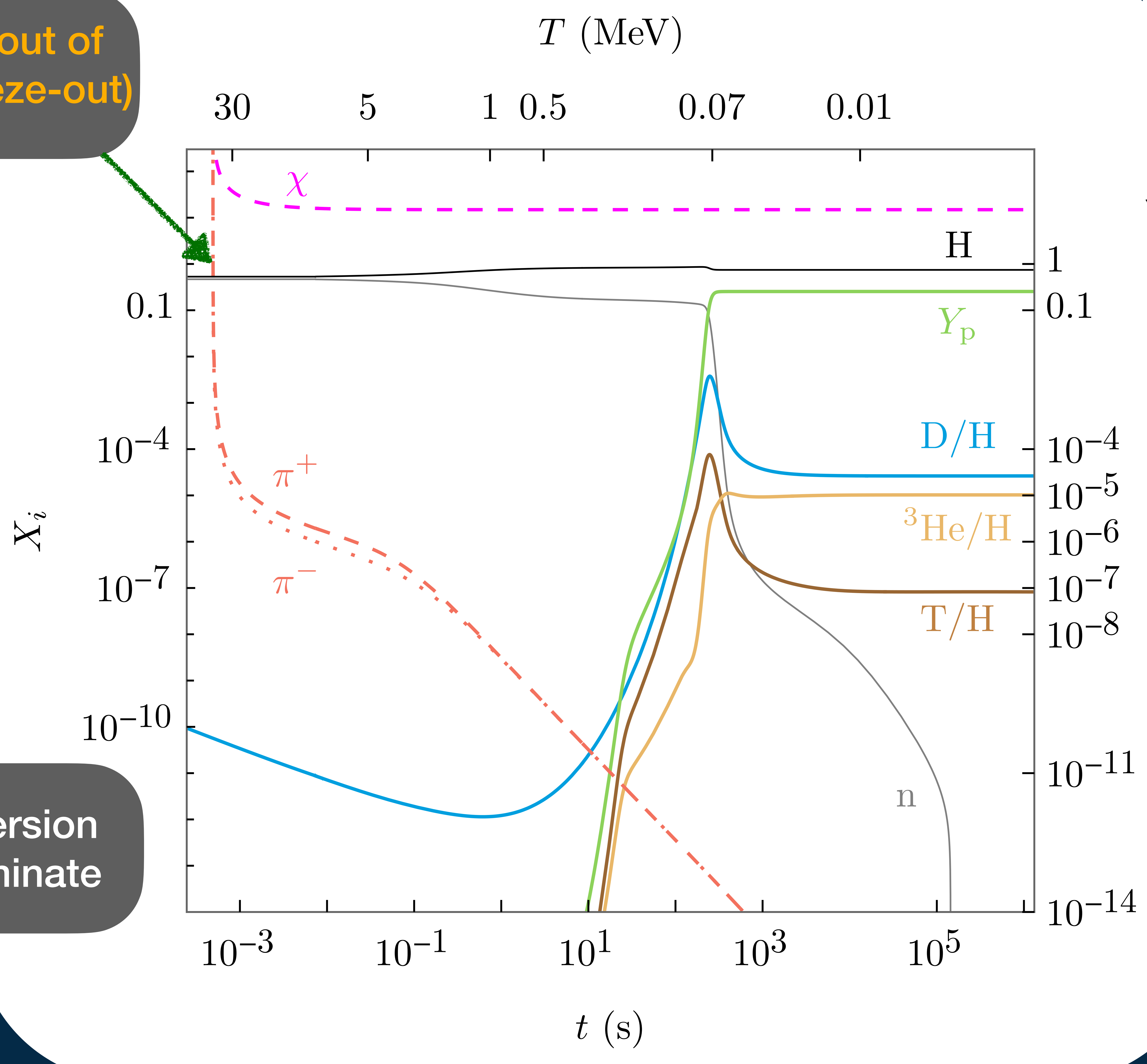
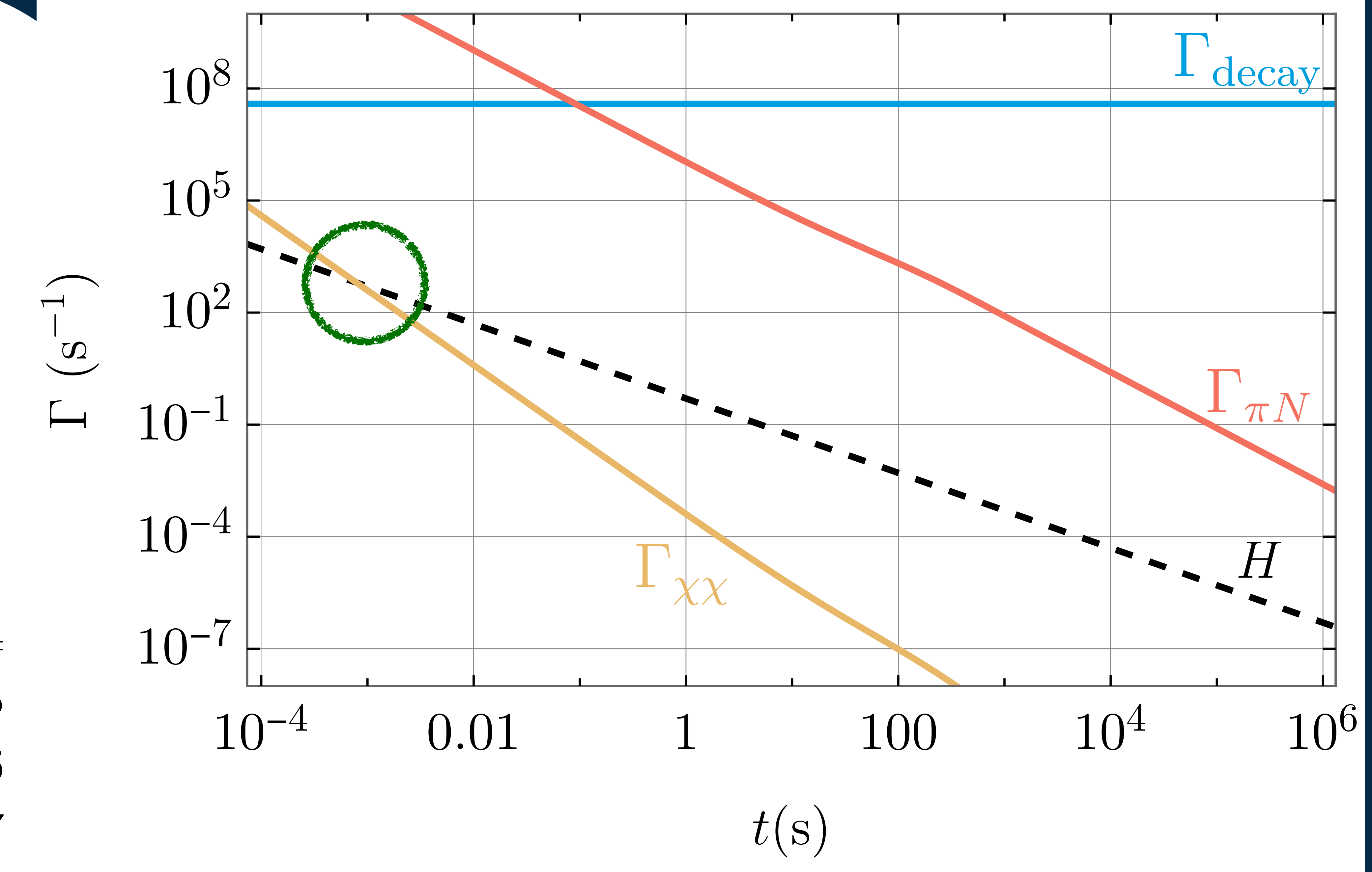
Evolution of $\pi^{\pm}$

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

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



Charge conversion reactions dominate



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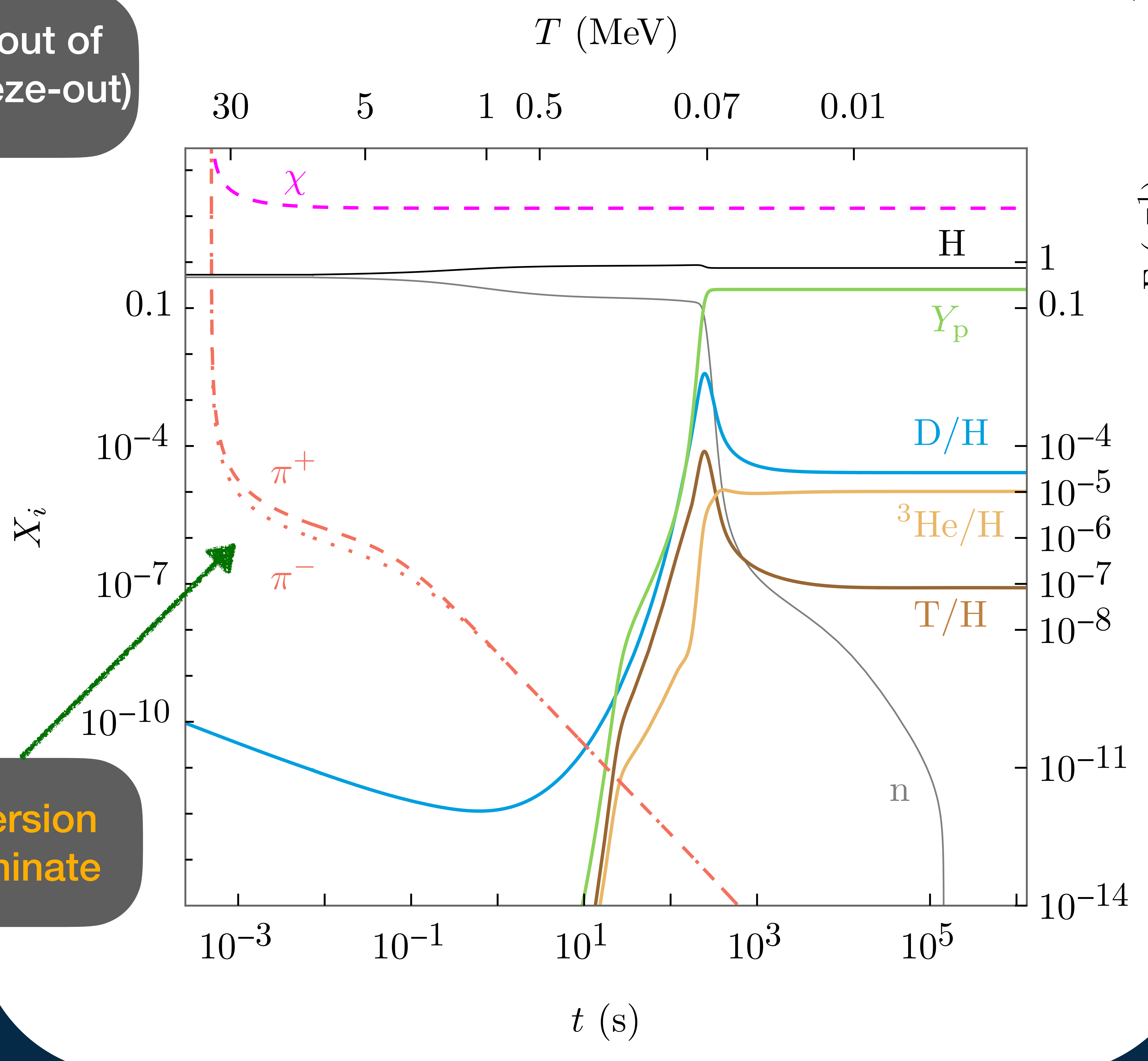

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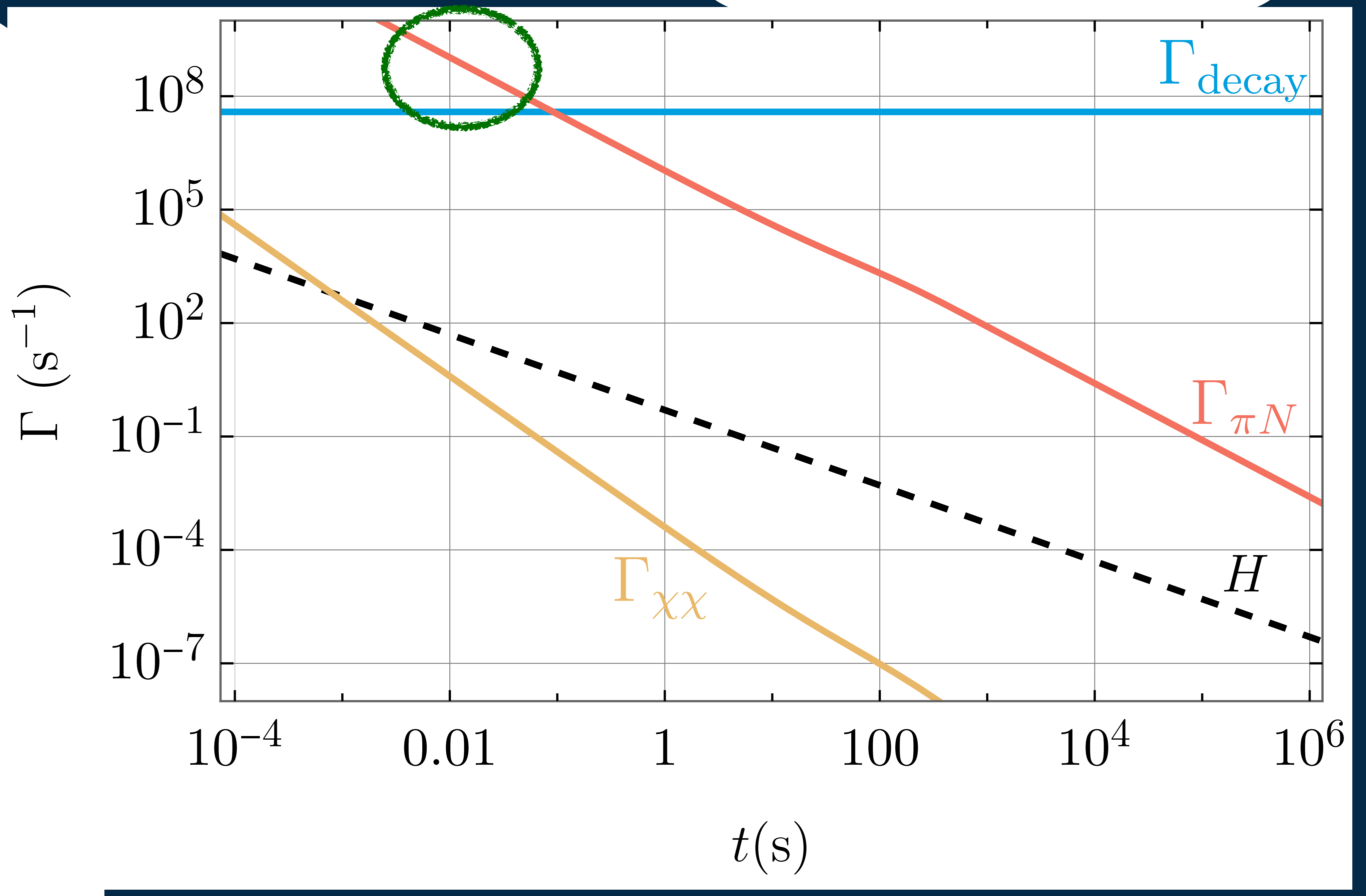

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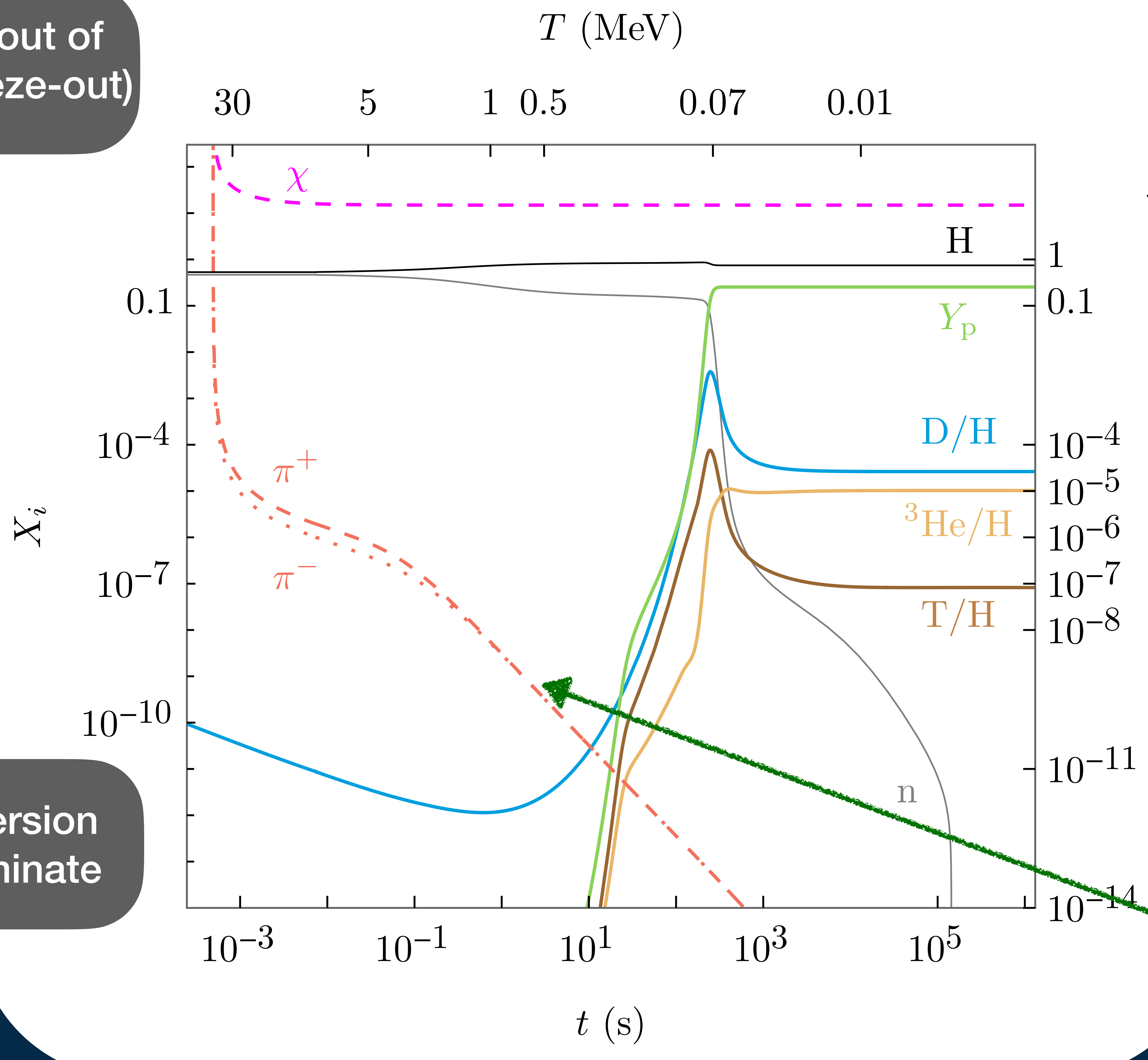

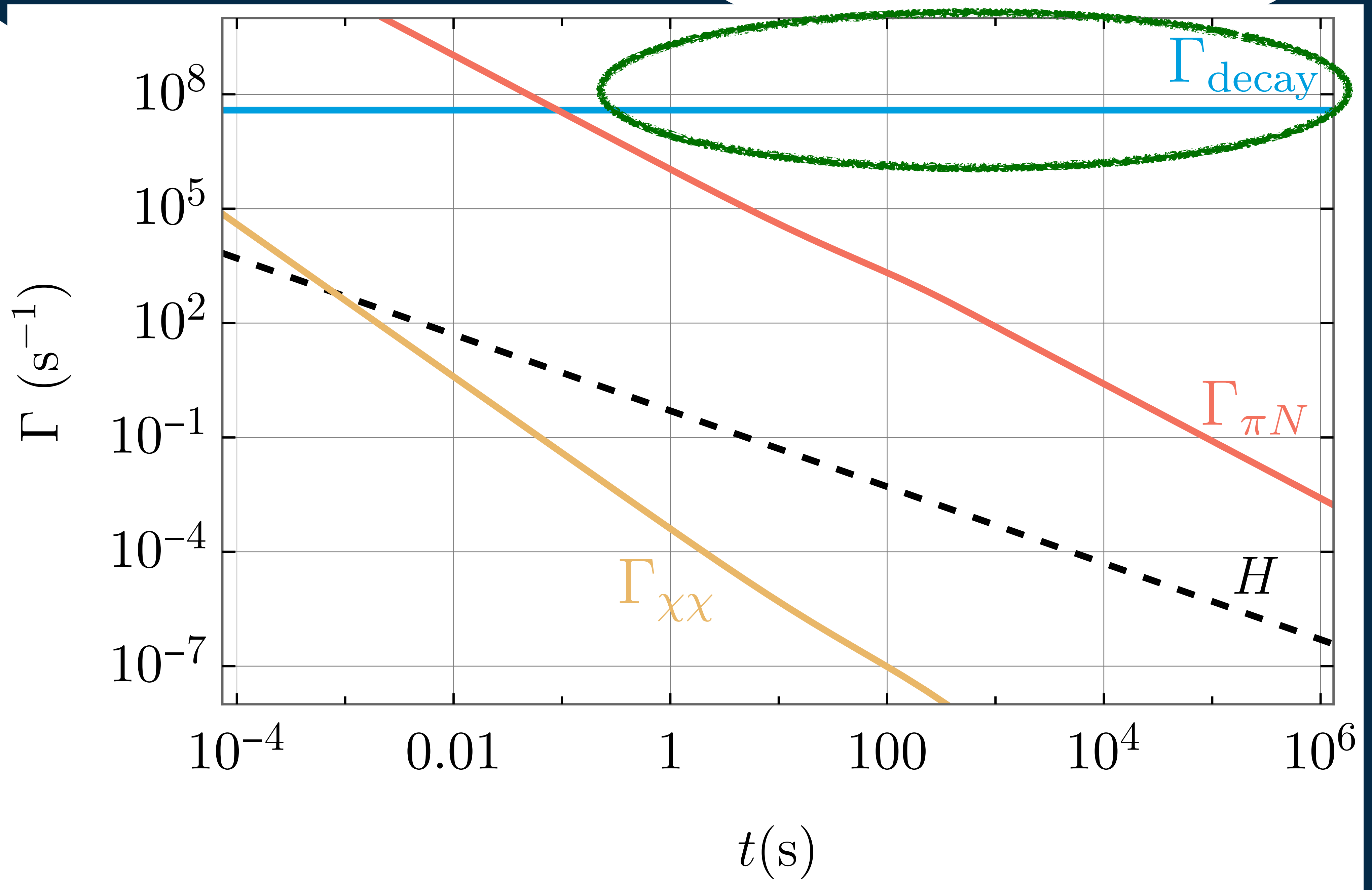

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Charge conversion reactions dominate

Pion decay dominates

Annihilation to kaons

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 $\pi^{\pm}$.

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

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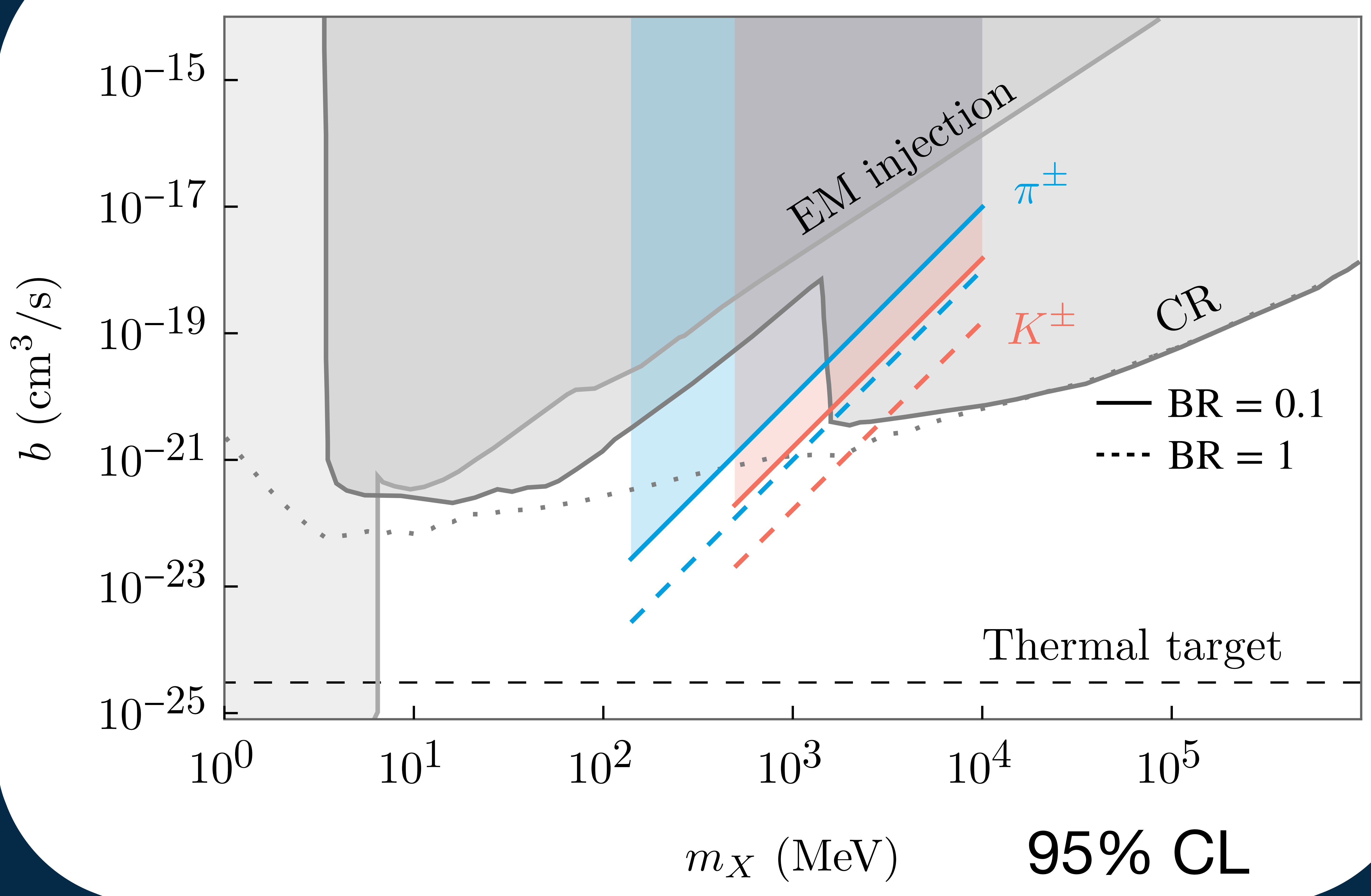
$$K^{\pm} \to \pi^{\pm}\pi^0(\pi^0) \quad \text{BR} = 22.4\%,$$
$$K^{\pm} \to \pi^{\pm}\pi^{\pm}\pi^{\mp} \quad \text{BR} = 5.6\%.$$

PDG (2024)

Generic constraints on velocity suppressed annihilation



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

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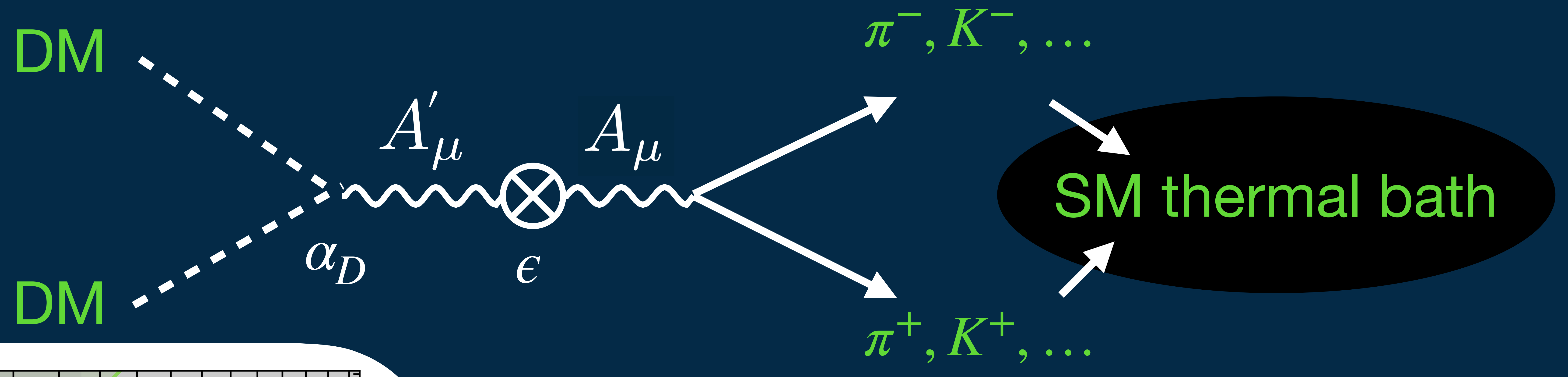
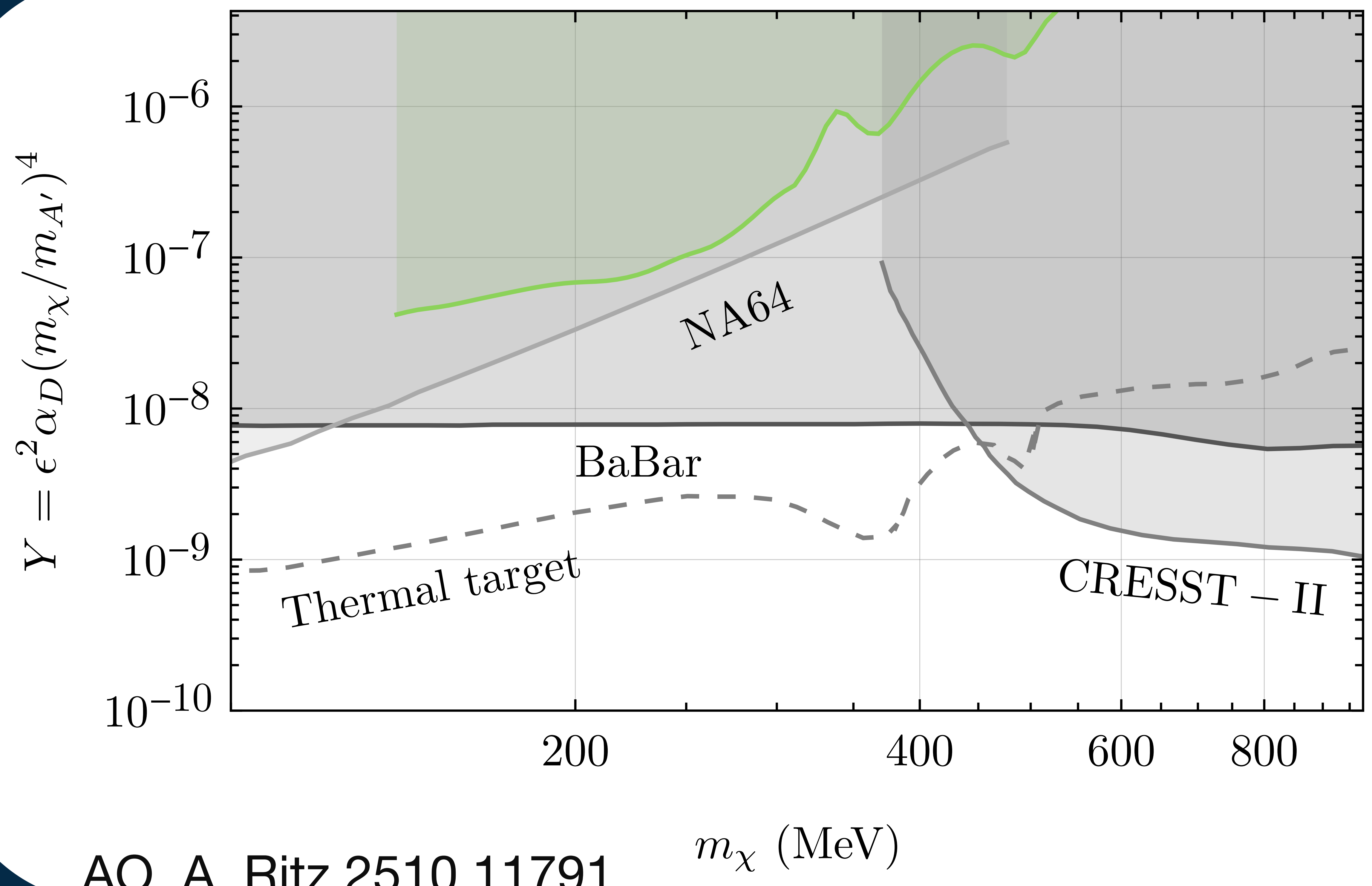
Limits on a DM benchmark model

$$\mathscr{L} \supset -A'_\mu(g_D J_D^\mu + \epsilon e J_{\rm EM}^\mu)$$





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this model imposes a BR less than 10%

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

Concluding remarks

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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~ *Fin.*

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Back up slides

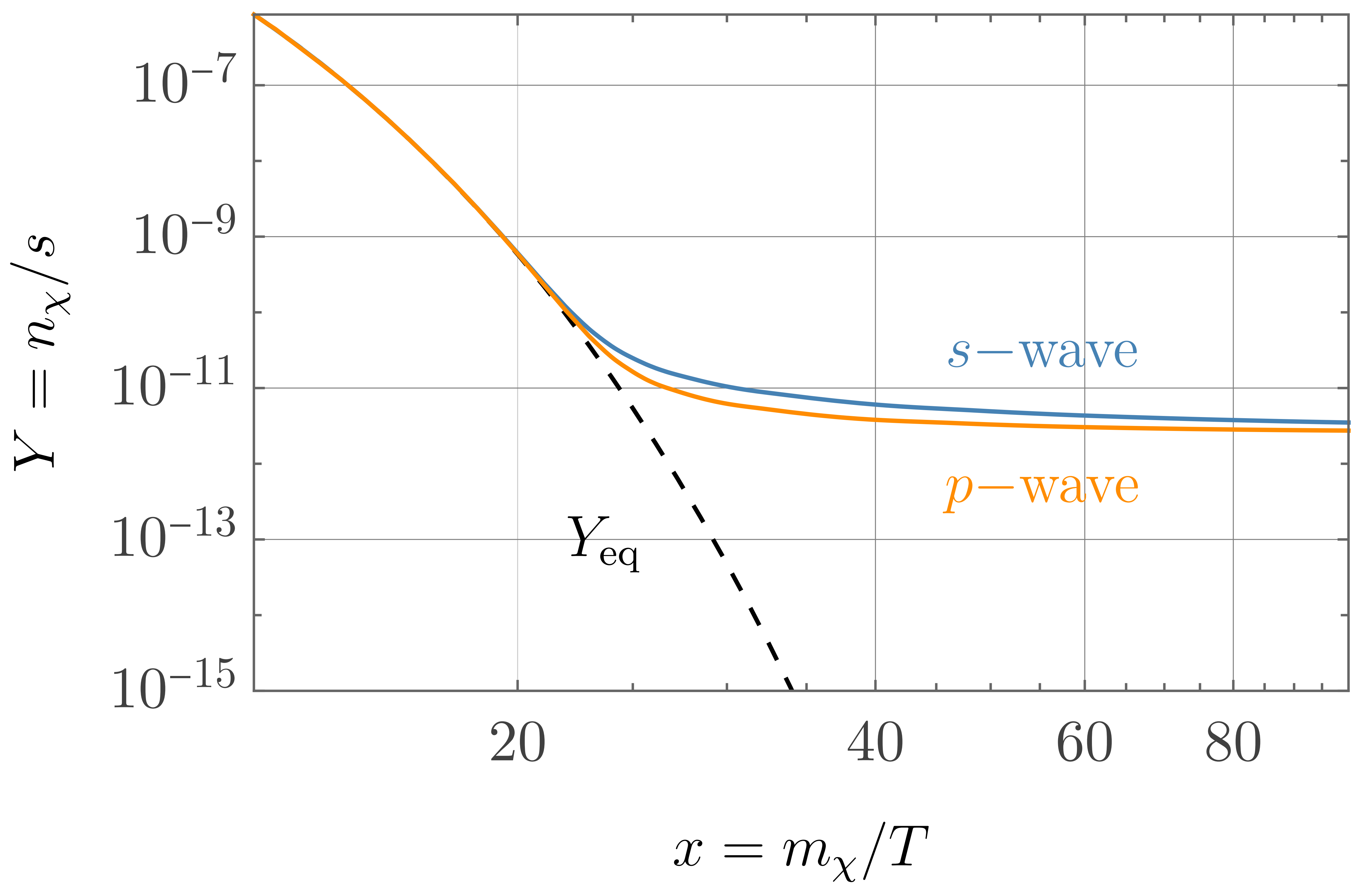
DM freeze-out

DM ⟷ SM

Thermal equilibrium

Freeze-out DM ⟶ SM

$T \lesssim m_\chi$



Velocity-independent

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

$\Omega_{DM} h \simeq 0.12$

Boltzmann suppression

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

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

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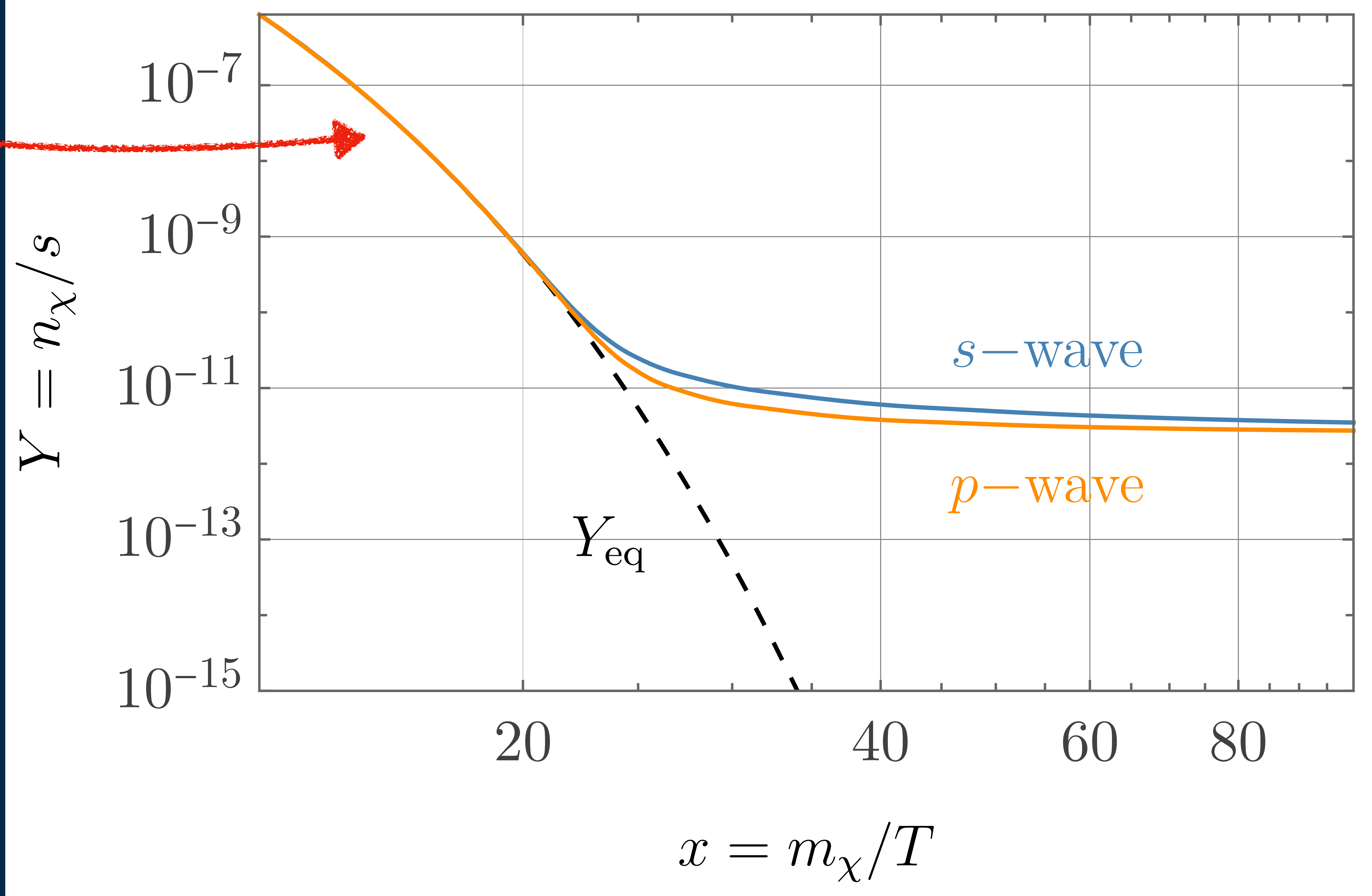

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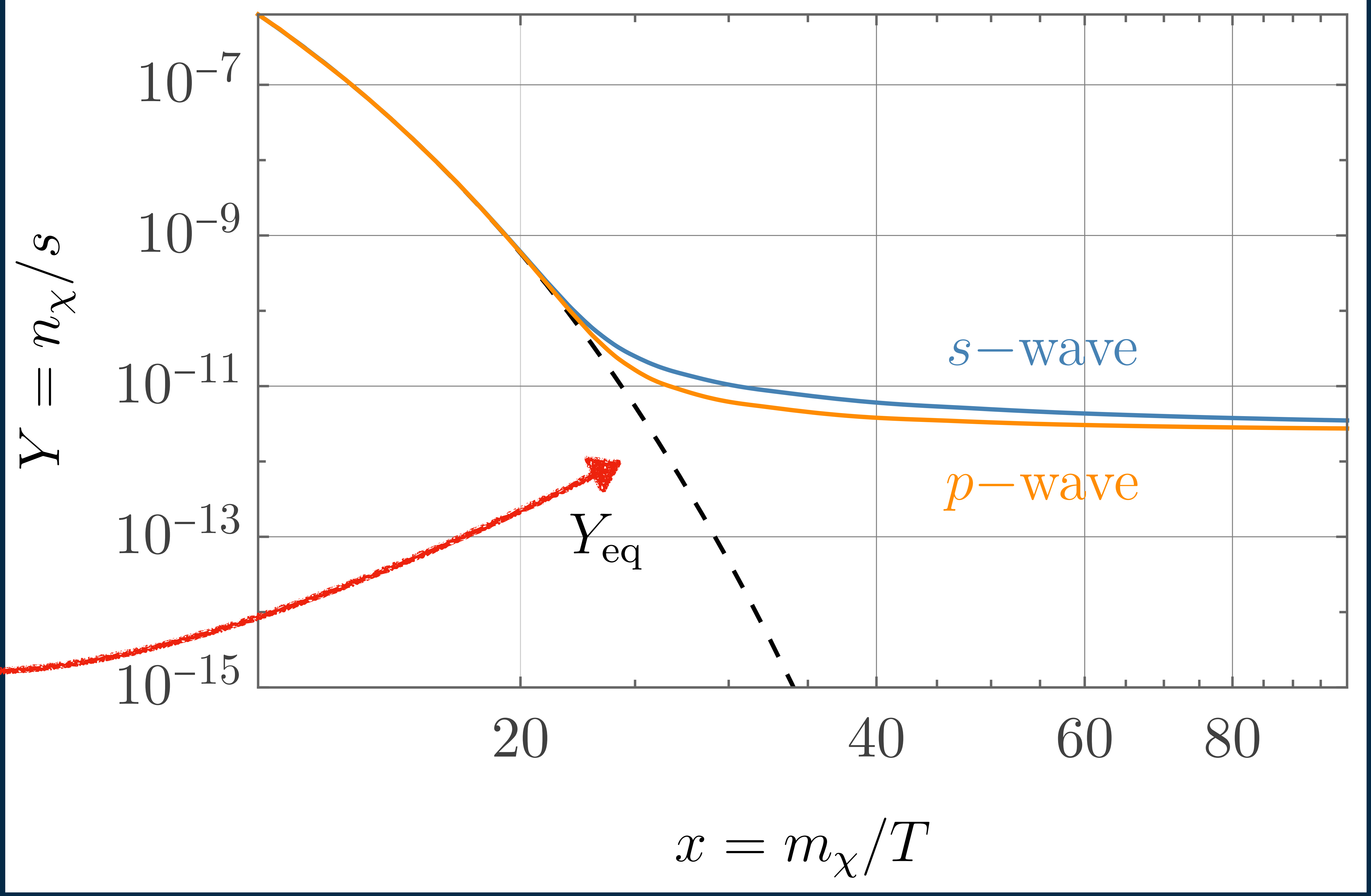

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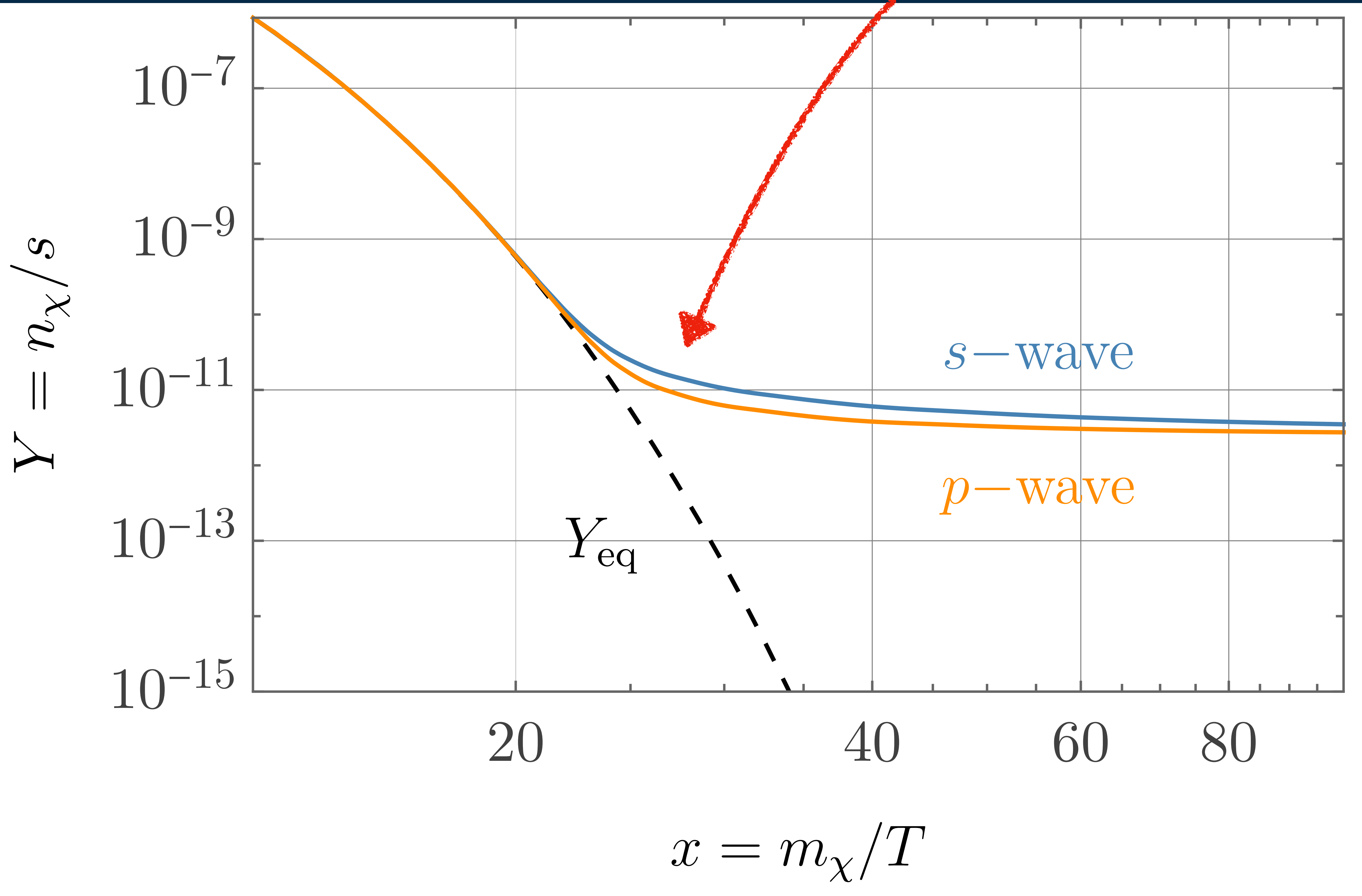

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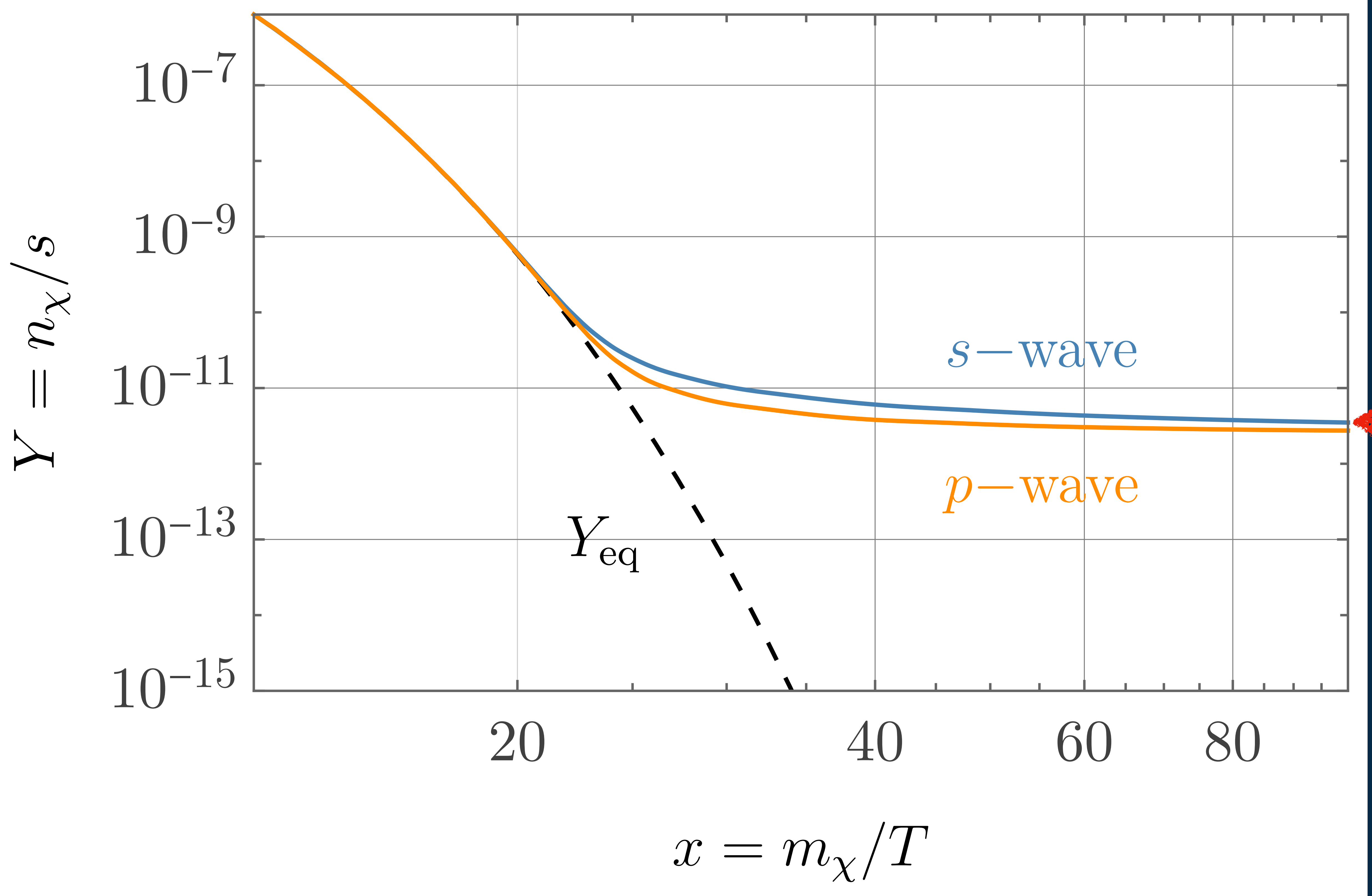

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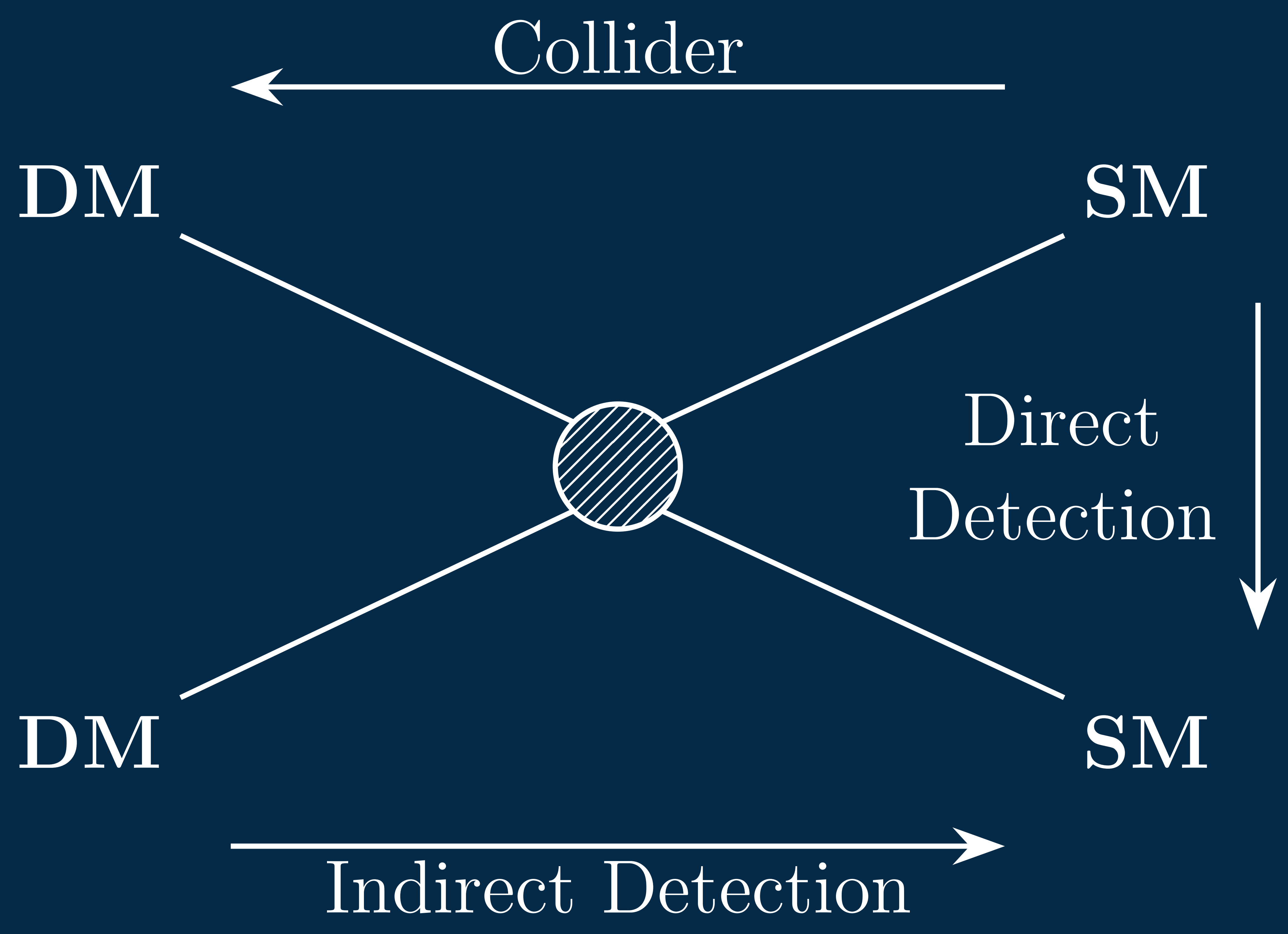
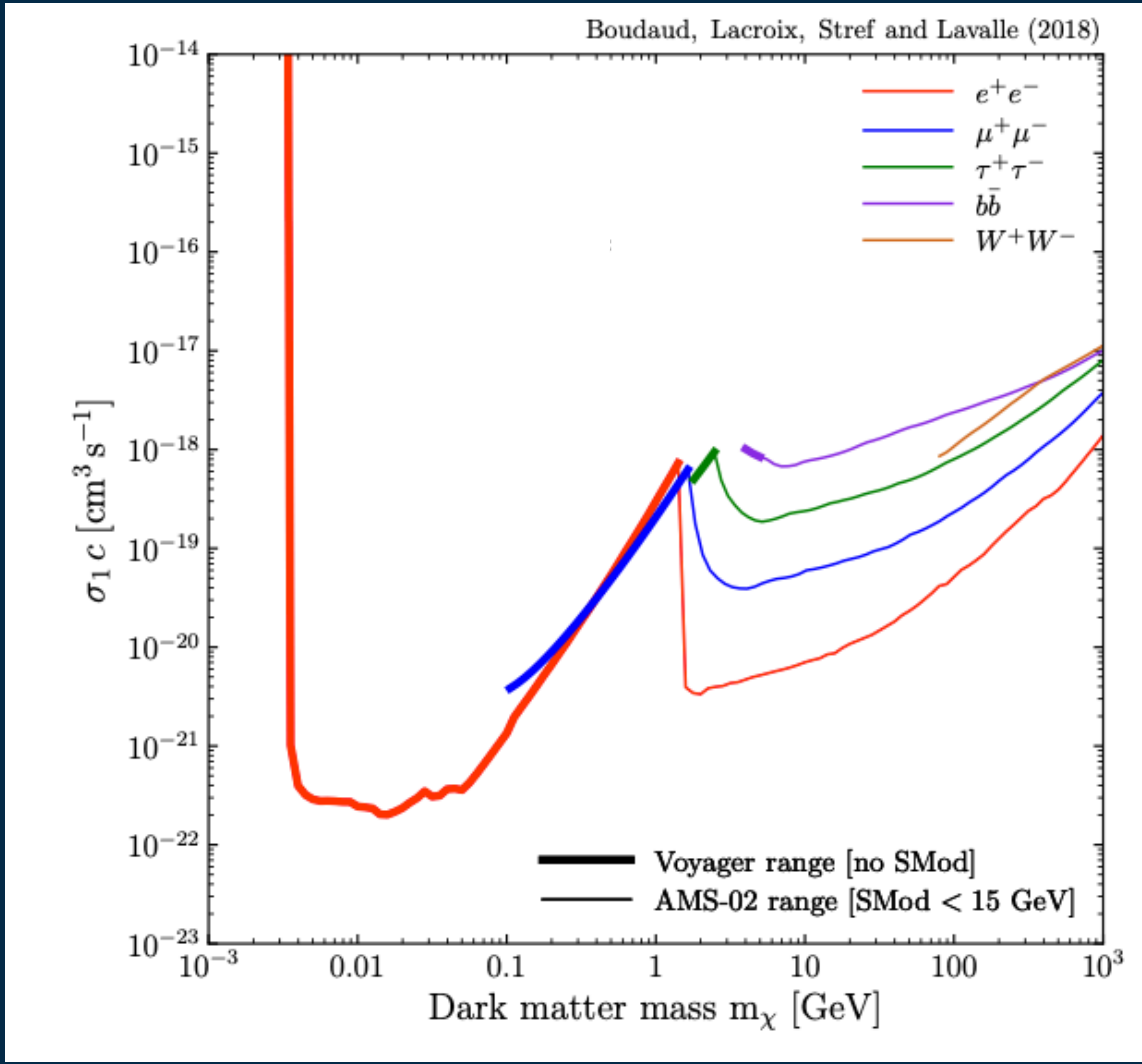
DM detection





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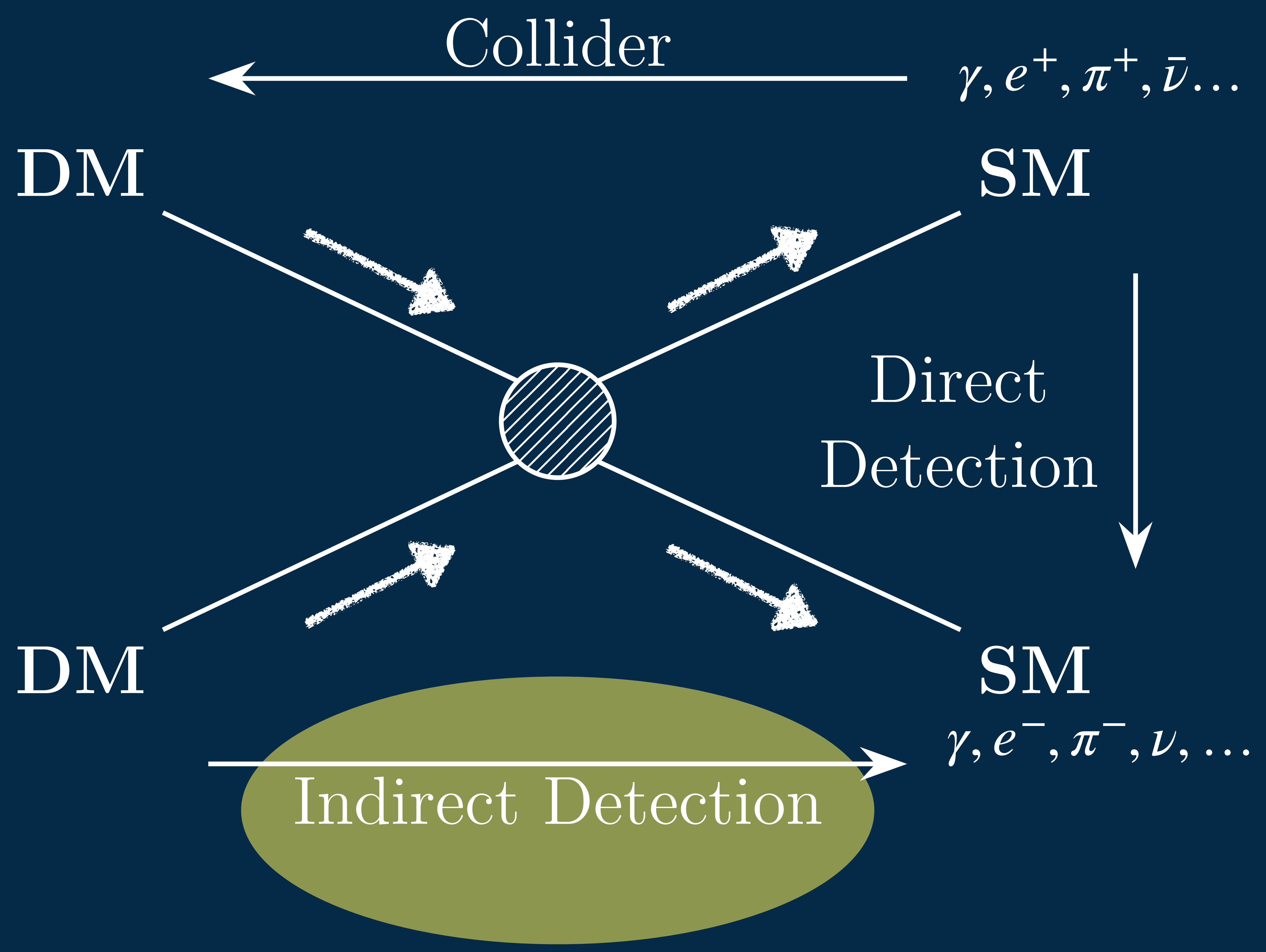

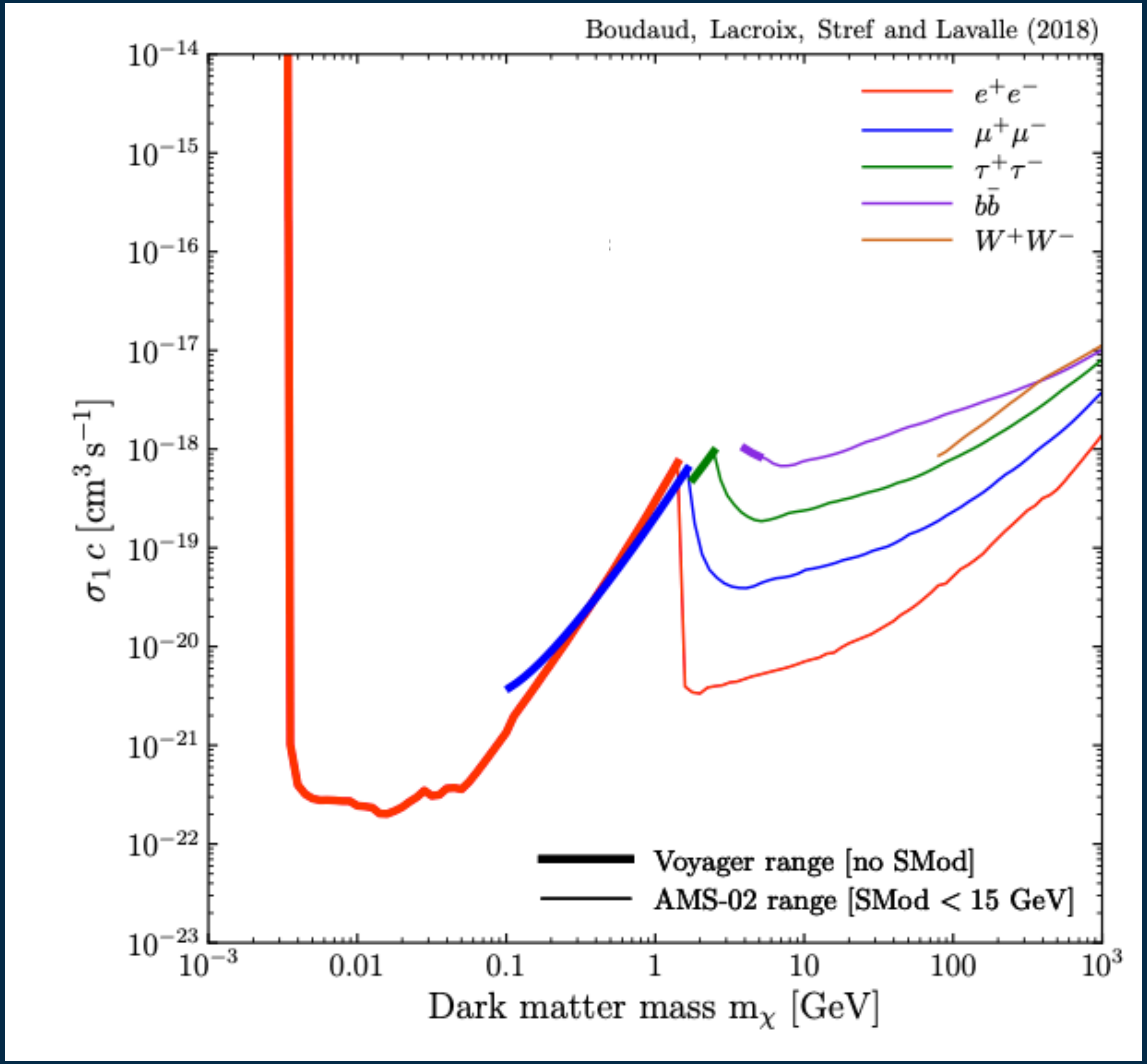

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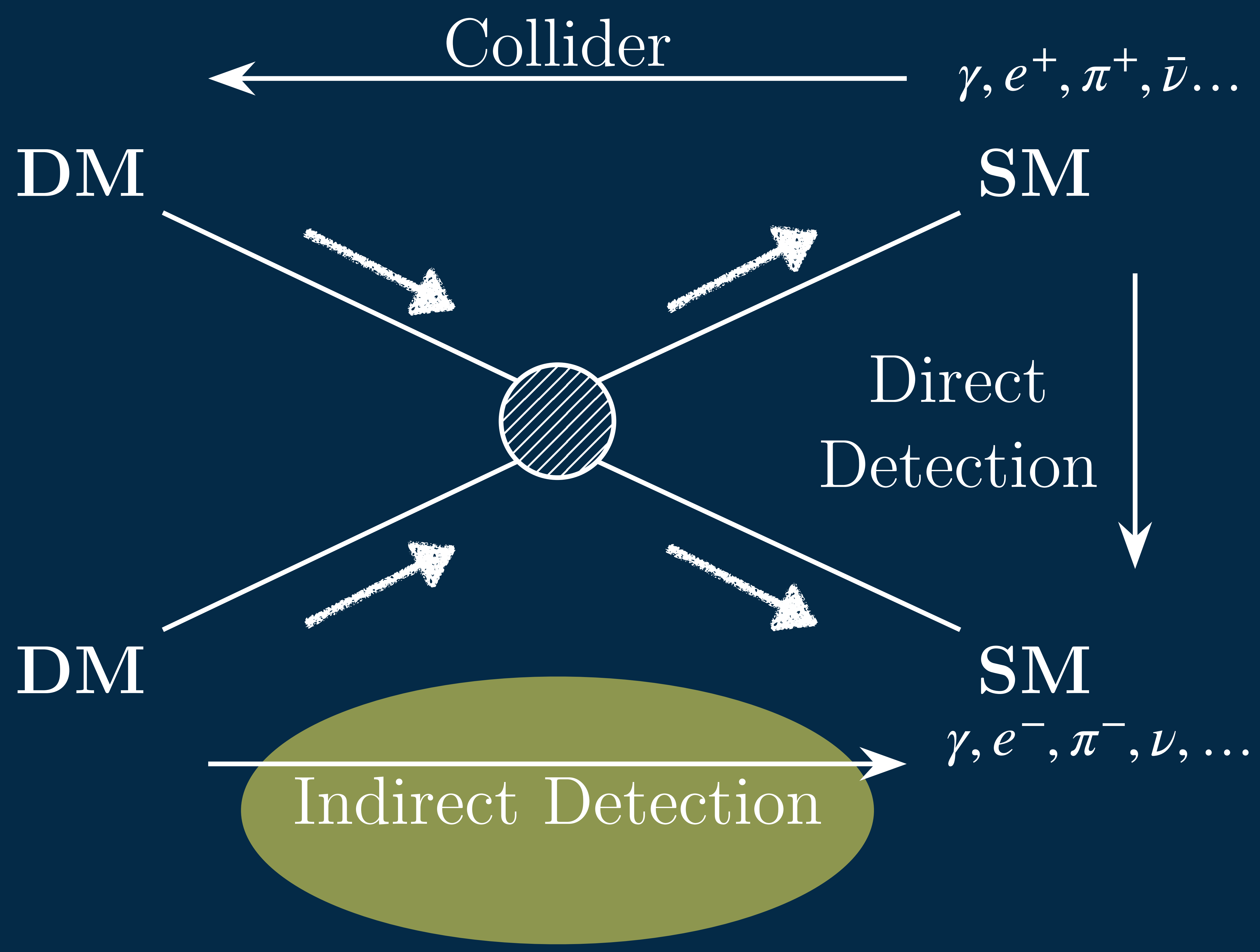

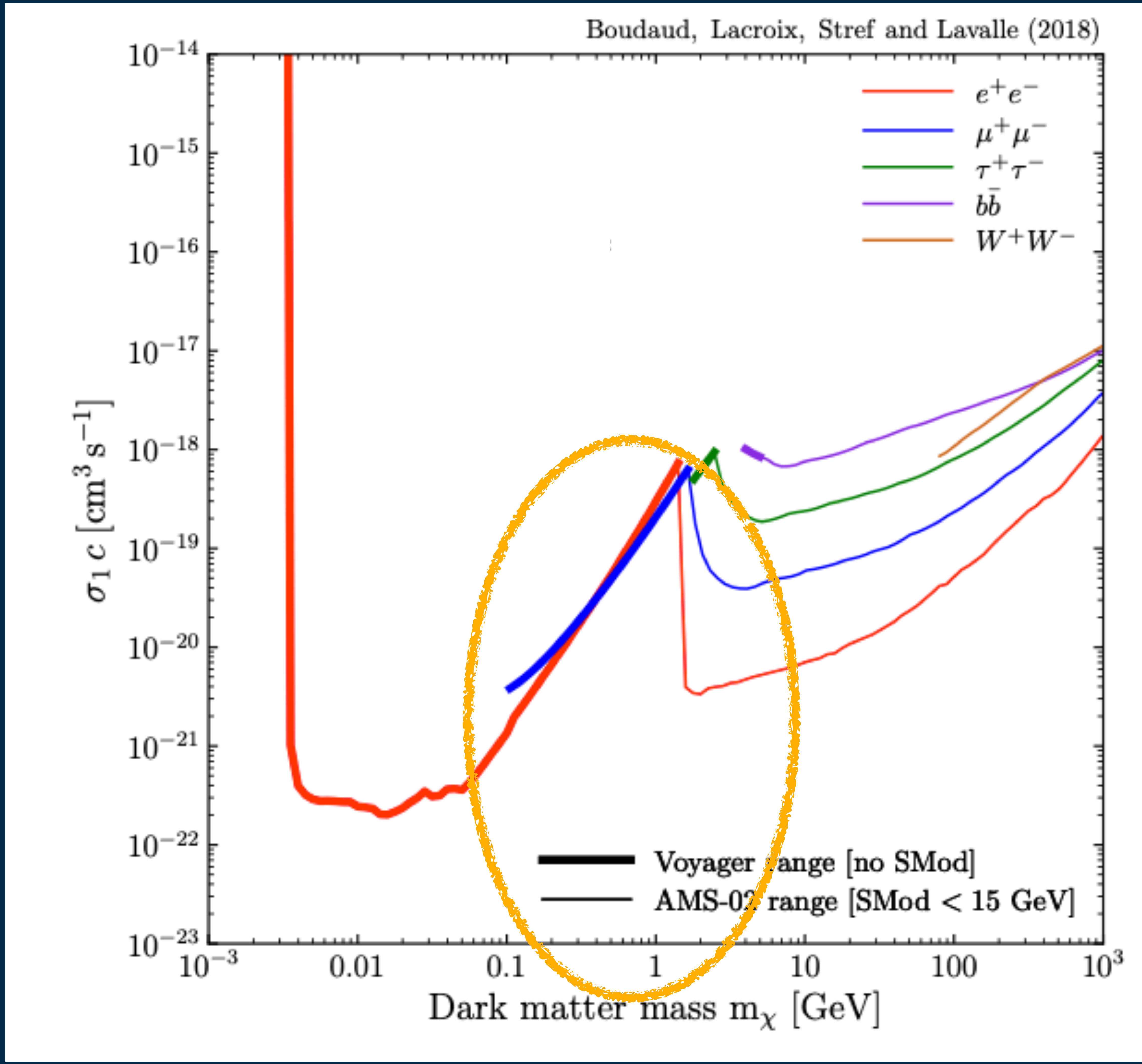

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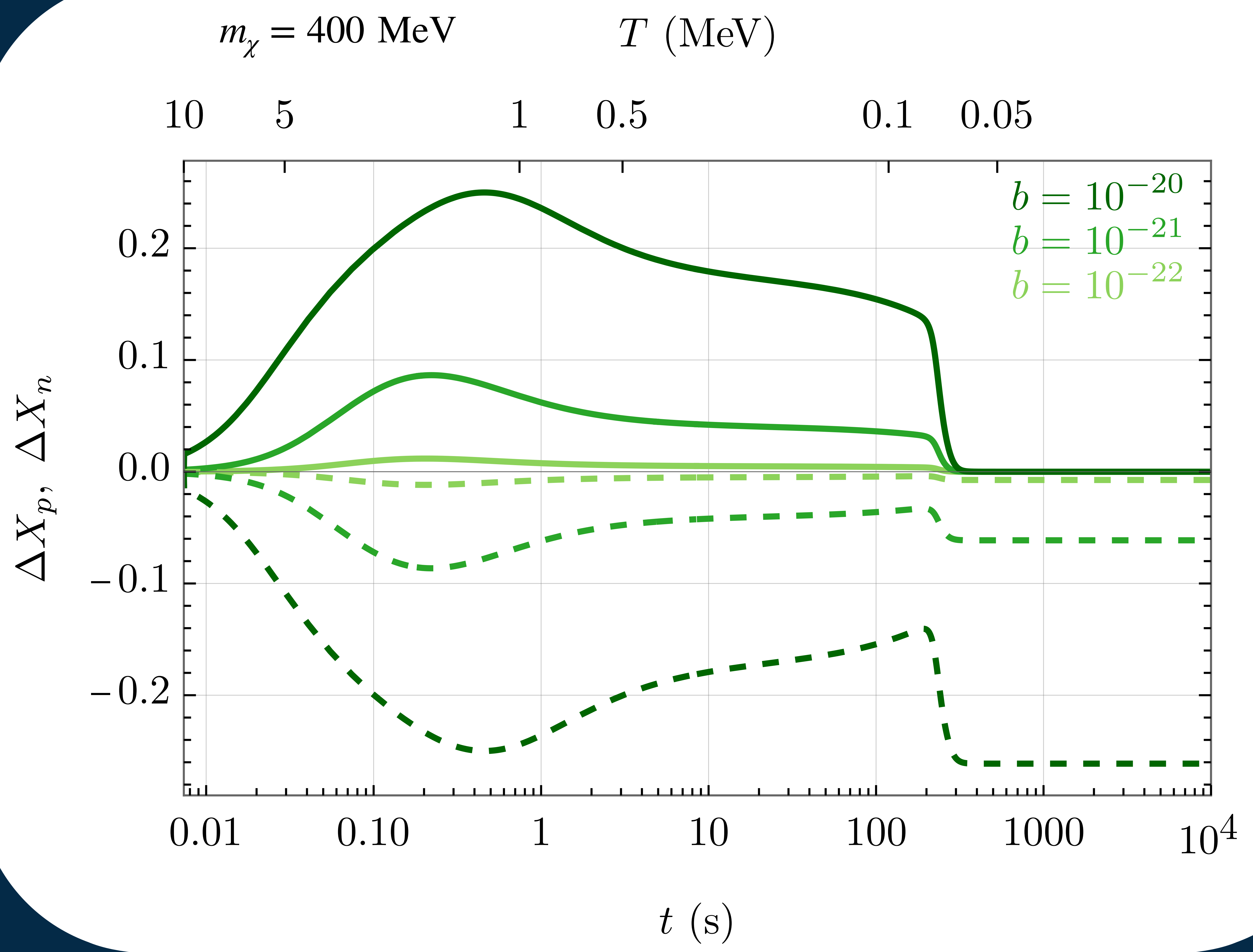
Could BBN be sensitive to this range?

Charged Pion Injection: some analysis considerations

1. DM annihilates entirely into $\pi^{\pm}$
2. $Y_{\chi} = Y_{\rm relic}(m_{\chi})$ 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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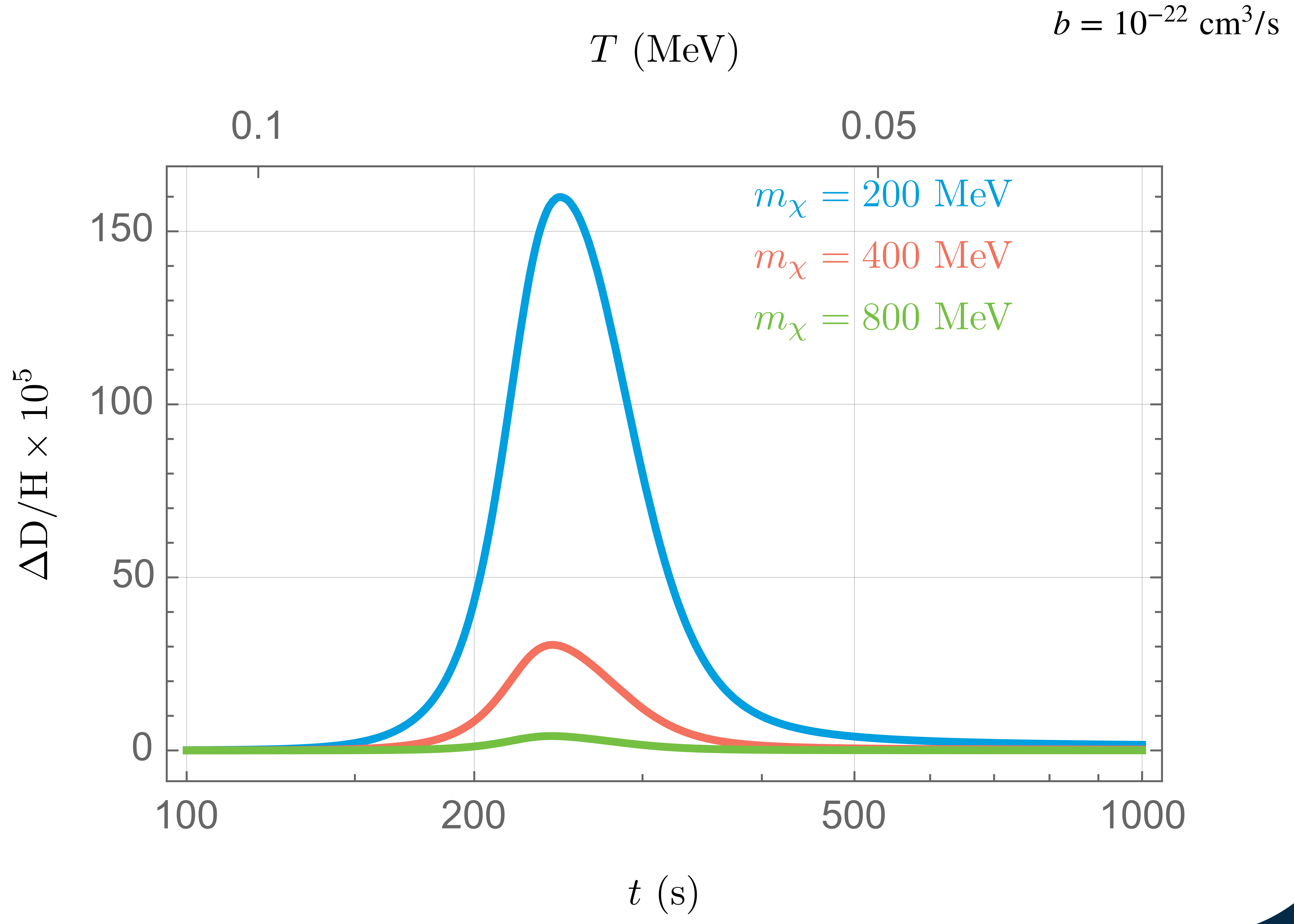
- Neutrons biased due to Coulomb enhanced $\pi^- + p \to n$.
- Excess neutrons are later synthesized into excess ^{4}He.

Generic constraints on velocity suppressed annihilation



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

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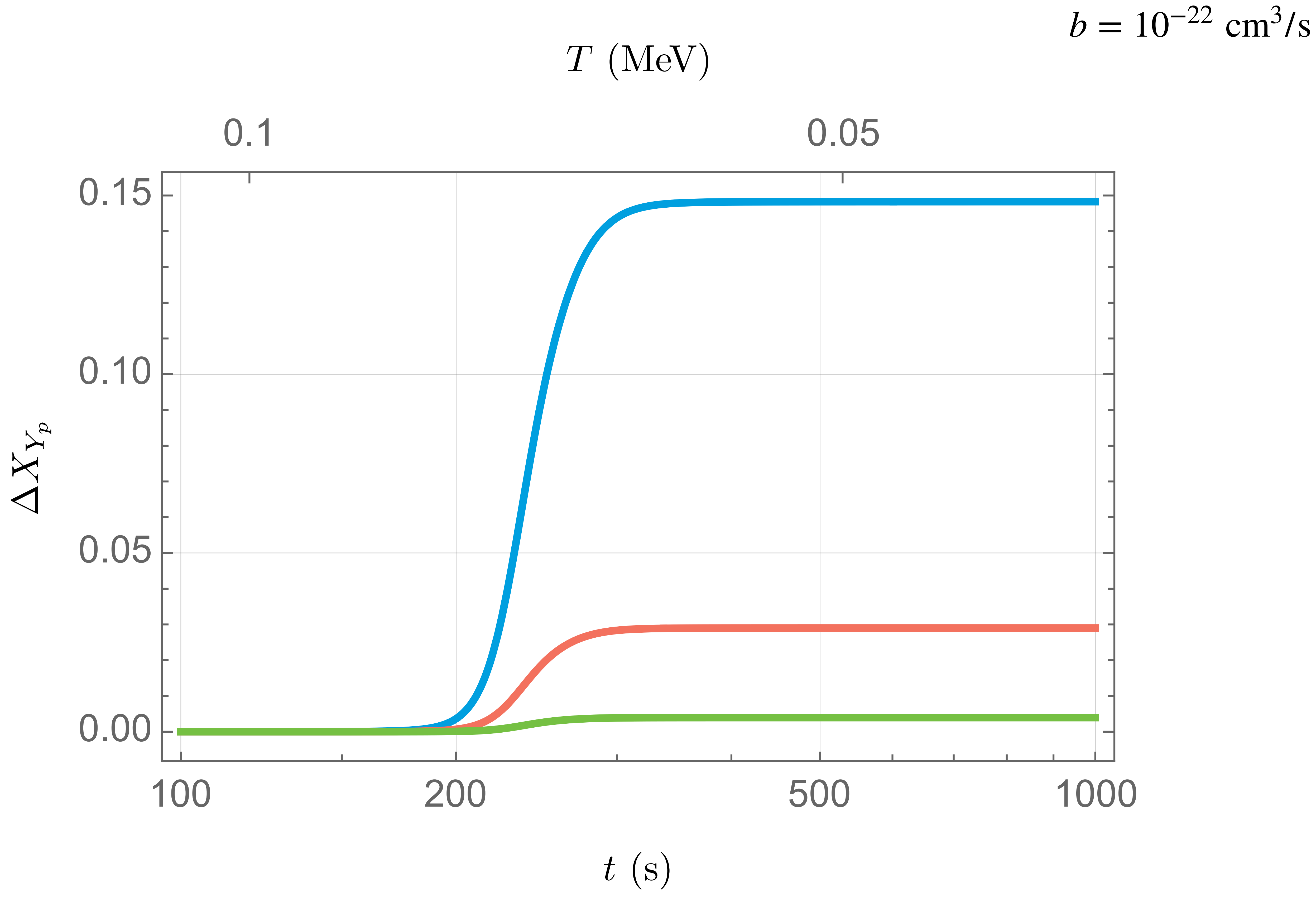

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