Metastable GeV-scale particles as a solution to the Li-problem

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Big Bang Nucleosynthesis $\longleftrightarrow$ **GeV-scale metastable states X**

- Standard BBN (SBBN):

  SM physics + GR

- WMAP determination of $\eta_{\rm b}$

  "parameter-free theory"

- => allows for cosmological consistency check

- $m_X \sim \mathcal{O}(\mathrm{MeV} - \mathrm{GeV})$

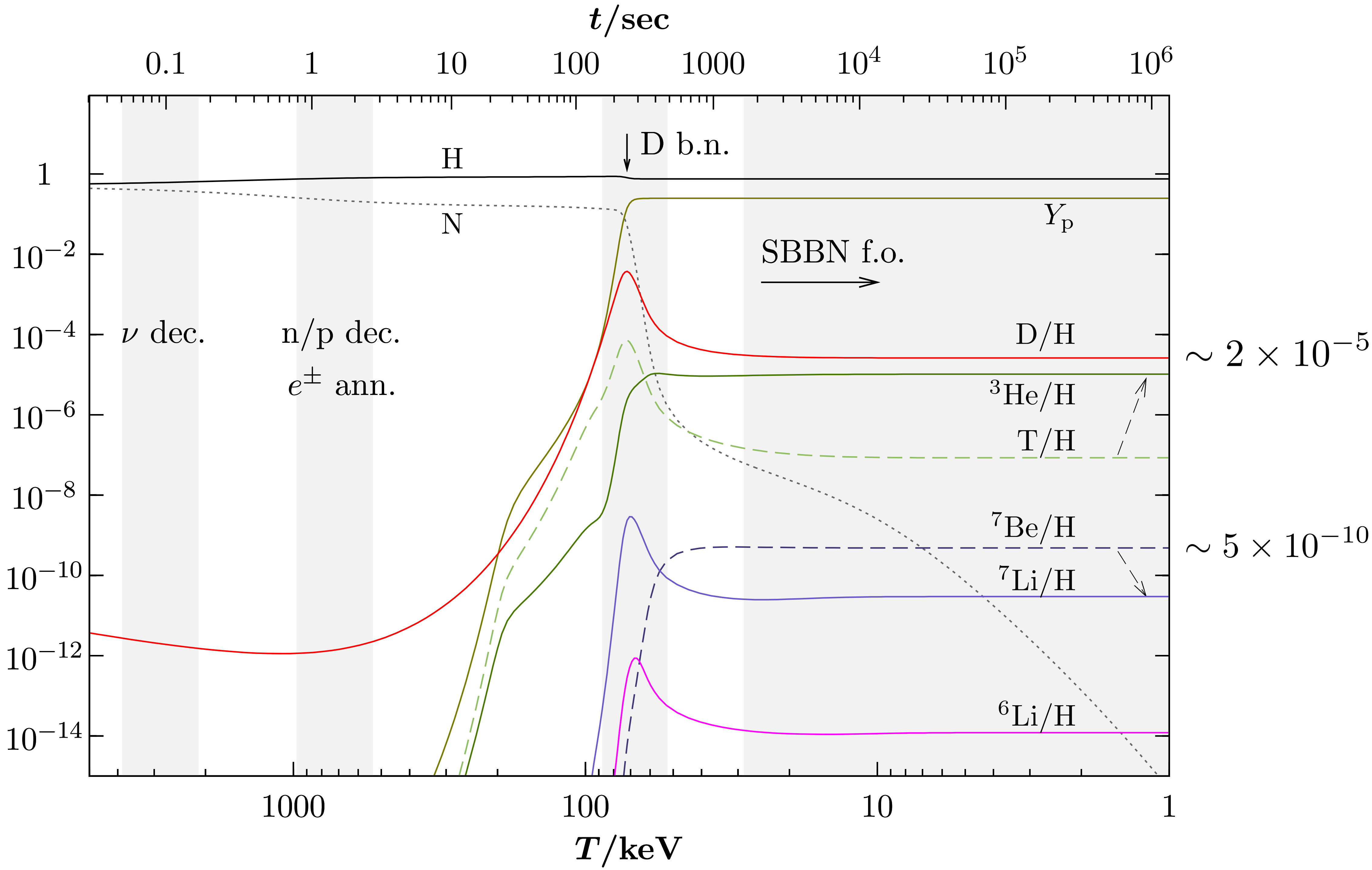
- light sector secluded from the SM => longevity of X $\to$ SM

  $\tau_X > 1$ s

- recent attention in connection with cosmic ray anomalies (mediator physics)

The Li-problem in Standard BBN (SBBN)

- SBBN at $\eta_{\rm b}(\mathrm{CMB}) = 6.23 \times 10^{-10}$



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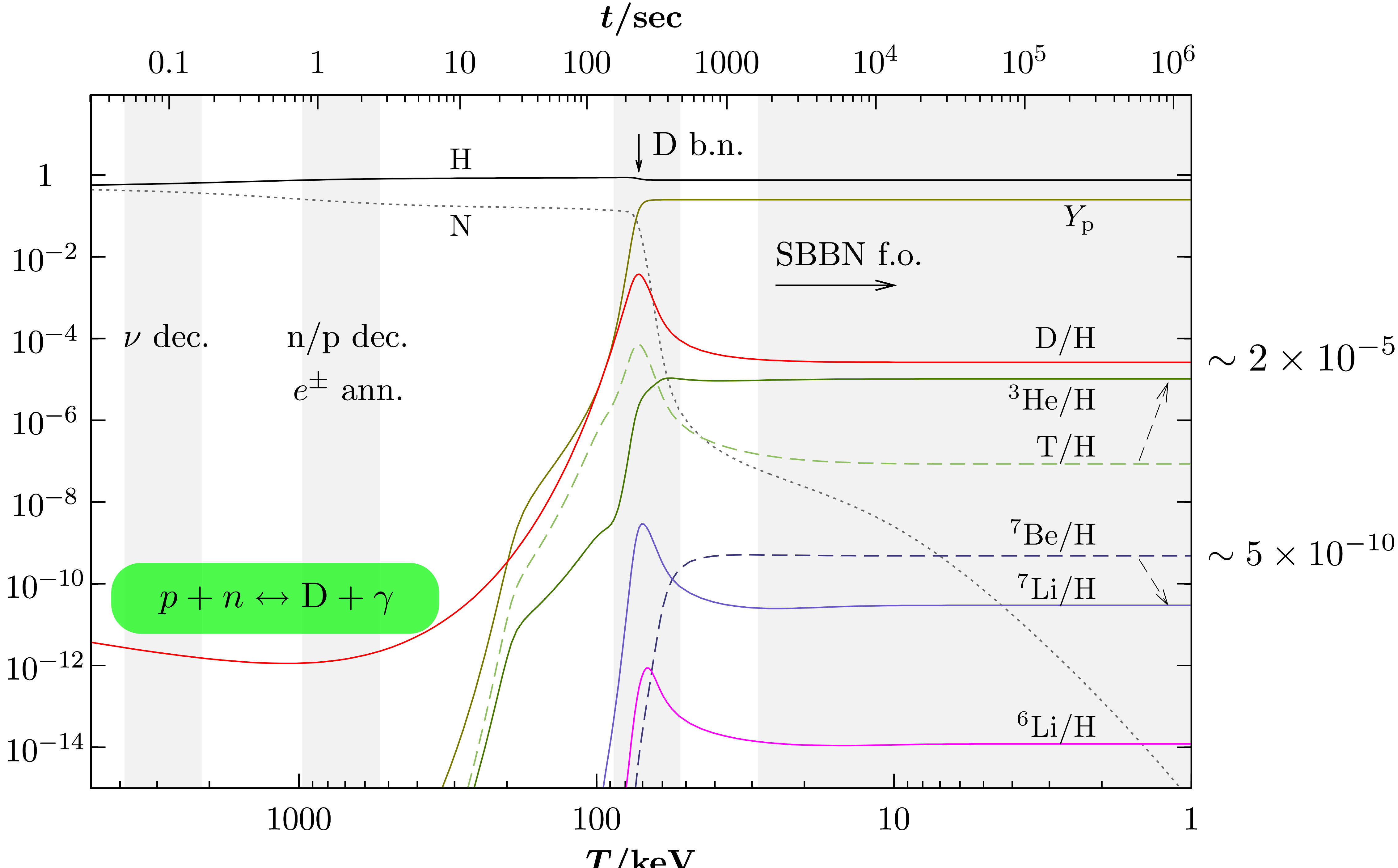

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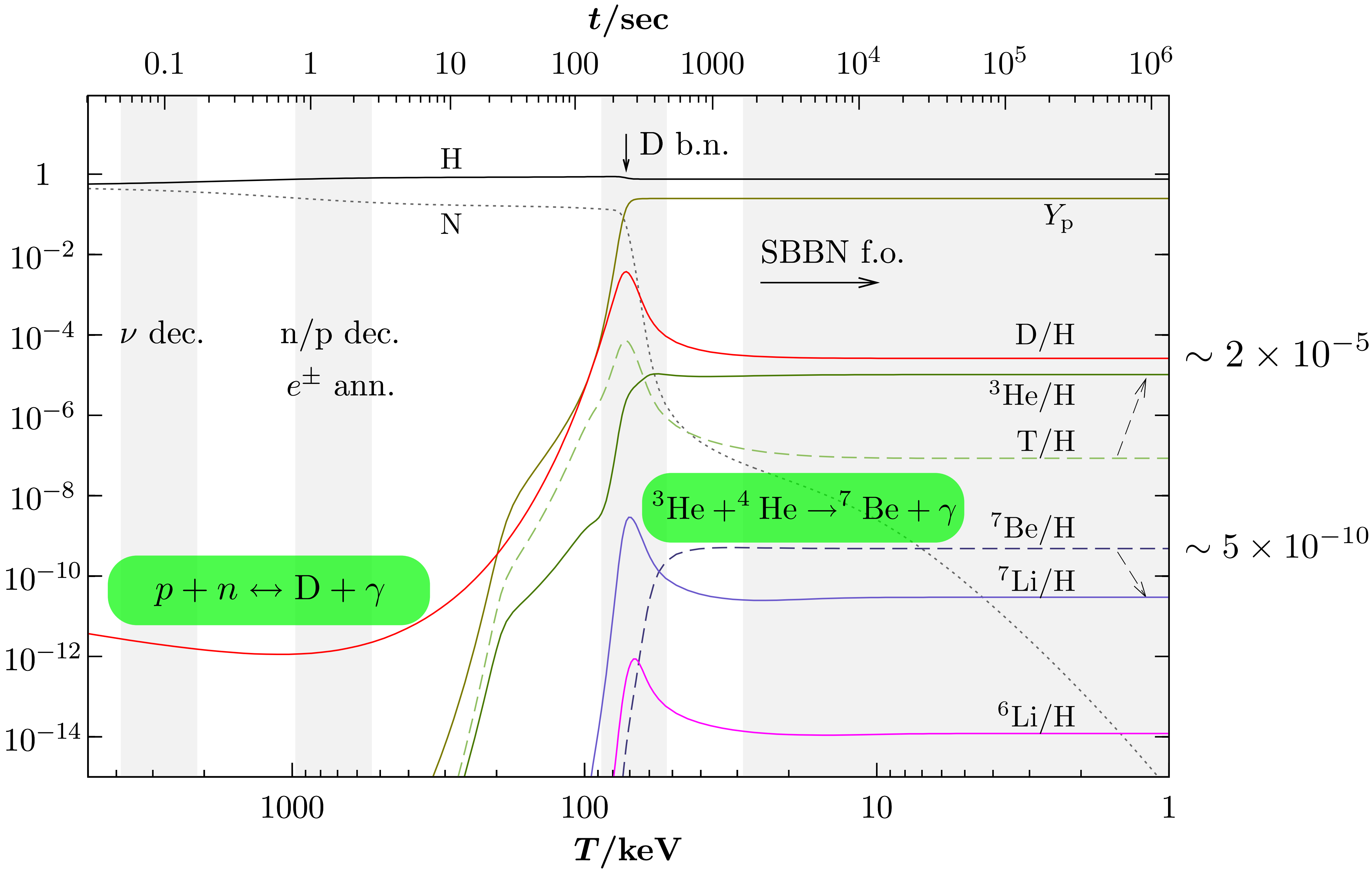
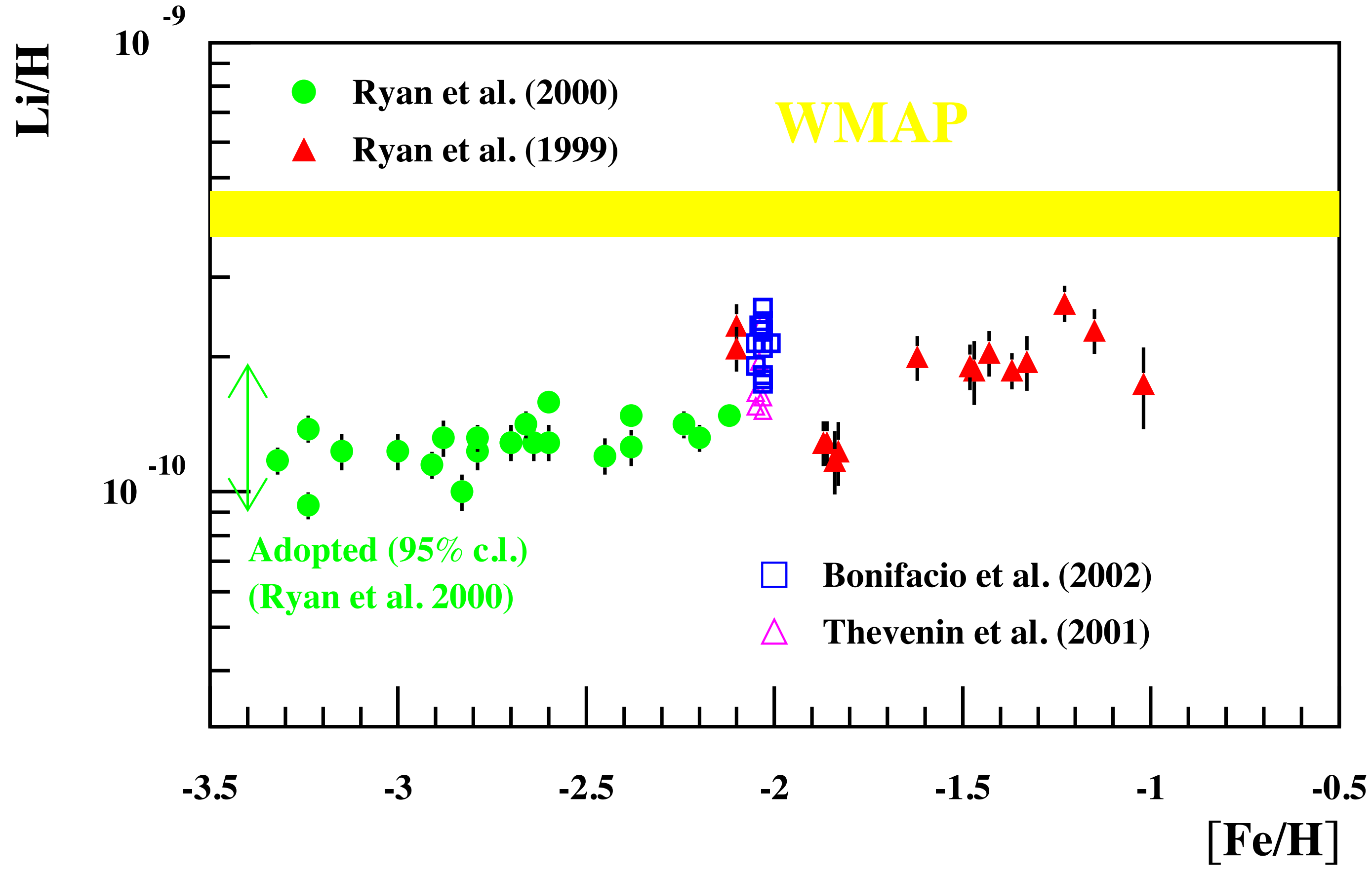


The Li-problem in Standard BBN (SBBN)

- SBBN: $^7\mathrm{Li/H} = (5.24 \pm 0.7) \times 10^{-10}$ [Cyburt et al., 2008]

- $^7\mathrm{Li/H}$ observations ("Spite-plateau"): $^7\mathrm{Li/H}|_\mathrm{obs} = (1 \div 2.5) \times 10^{-10}$



[Coc et al., 2004]

- $(4 \div 5)\sigma$ discrepancy between observations and prediction [Cyburt et al., 2008]

Solving the Li-problem: mechanism

- inject "extra neutrons" at $T_9 \sim 0.5$ [Reno & Seckel 1988]

$$\boxed{{}^7\mathrm{Be} + n \rightarrow {}^7\mathrm{Li} \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}}$$

proton burning

- $n_n/n_\mathrm{b}|_{T_9\sim 0.5} = \mathcal{O}(10^{-5})$ **=>** $\mathcal{O}(1)$ reduction of ${}^7\mathrm{Be} + {}^7\mathrm{Li}$ [Jedamzik 2004]

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- classical BBN scenario with decaying X: $m_X = \mathcal{O}(100\ \mathrm{GeV})$, e.g. $\widetilde{\tau} \rightarrow \widetilde{G} + \mathrm{SM}$

  extensive literature! e.g. [...., Kawasaki et al. 2004, Jedamzik 2006, Cyburt et al. 2009]

=> hadronic and electromagnetic cascades (=> "extra neutrons")

=> large energy depositions
hard to find "Li-sweet-spot" where all observational constraints respected

GeV-scale metastable states X

...below the di-nucleon threshold

$$X \to l\bar{l},\ \pi^+\pi^-,\ \pi^0\pi^0,\ K^+K^-,\ K^0\bar{K}^0\ldots$$

- we get "extra neutrons" e.g. from

$$\text{"}\pi\text{BBN"}:\quad \pi^- + p \to n + \pi^0/n + \gamma$$

$$\text{"}\mu/\nu\text{BBN"}:\quad \mu^- \to e^- + \underbrace{\bar{\nu}_e}_{\downarrow} + \nu_\mu$$

$$\bar{\nu}_e + p \to n + e^+$$

πBBN : $X \to \pi^+\pi^-$

$T_9 \sim 0.5$

- Hierarchy of scales $H \ll \Gamma_p^\pi \ll \Gamma_{\rm dec}^\pi \lesssim \Gamma_{\rm stop}^\pi.$

- $p \to n$ interconversion rate:

$$\Gamma_p^\pi = n_p \langle \sigma v \rangle_{pn}^\pi \simeq (3 \times 10^2 \ {\rm s}^{-1}) \ \frac{T_9^3 \langle \sigma v \rangle_{pn}^\pi}{1 \ {\rm mb}}$$

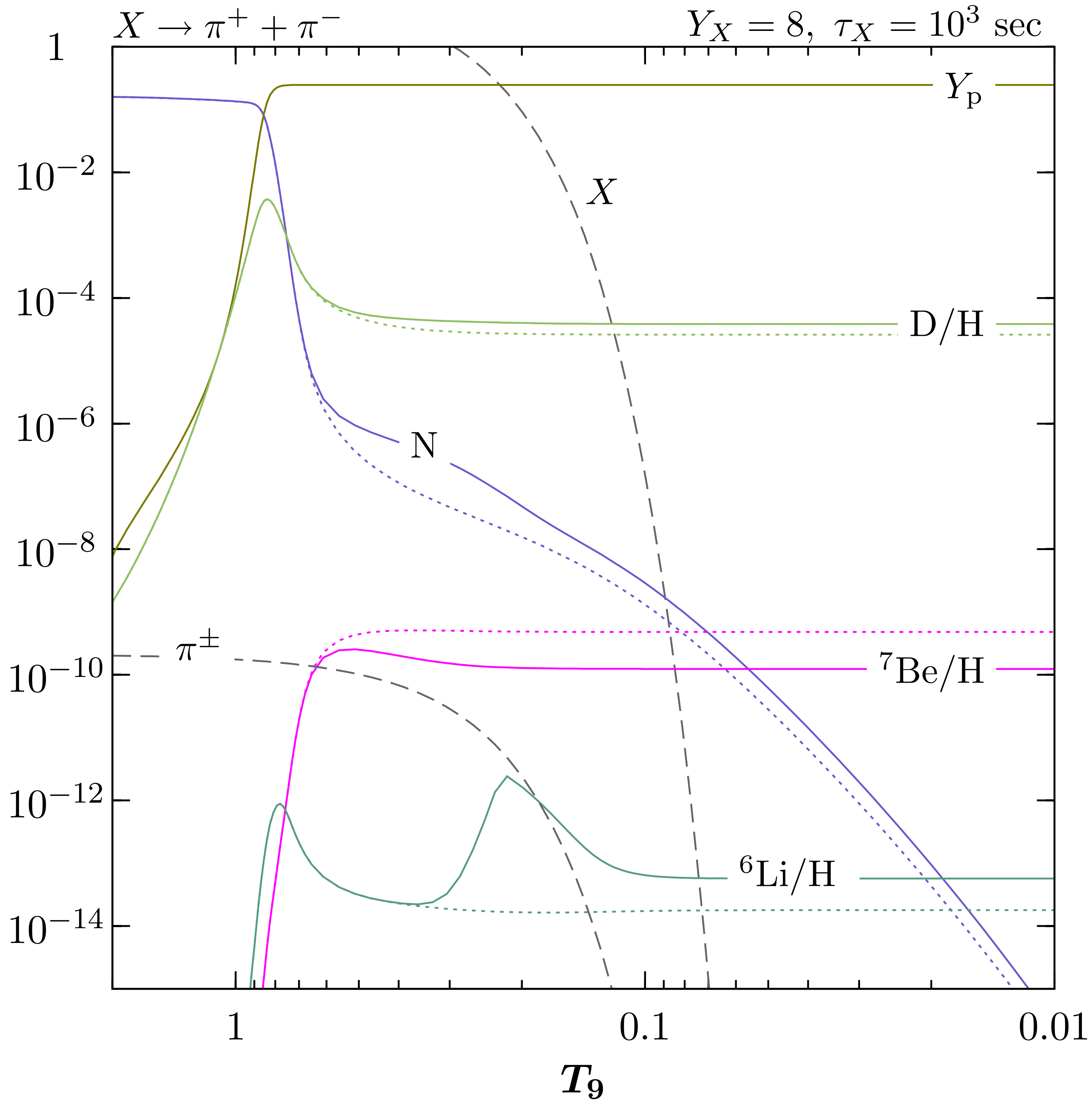
- efficiency of interconversion during pion lifetime:

$$P_{p\to n}^\pi = \int_{t_{\rm inj}}^\infty \exp(-\Gamma_{\rm dec}^\pi (t - t_{\rm inj}))\Gamma_p^\pi dt \simeq \Gamma_p^\pi \tau_{\pi^\pm} \sim O(10^{-6})$$

injection of $\mathcal{O}(10)$ pions/baryon yields $\mathcal{O}(10^{-5})$ neutrons

πBBN : $X \to \pi^+\pi^-$

$Y_X = n_X/n_\mathrm{b}$



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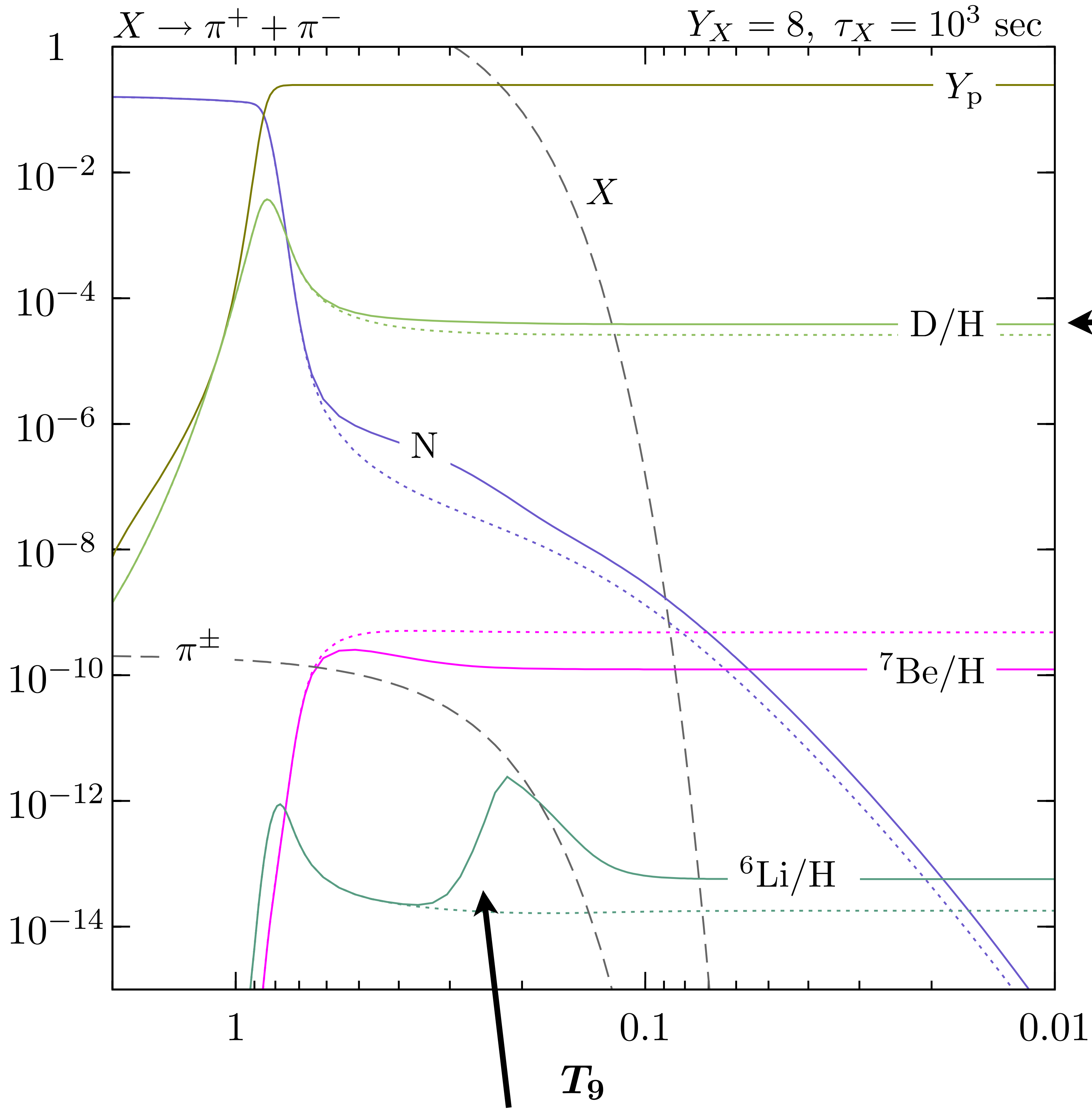

$n + p \to \mathrm{D} + \gamma$

$\pi^- + {}^4\mathrm{He} \to \mathrm{T} + n$

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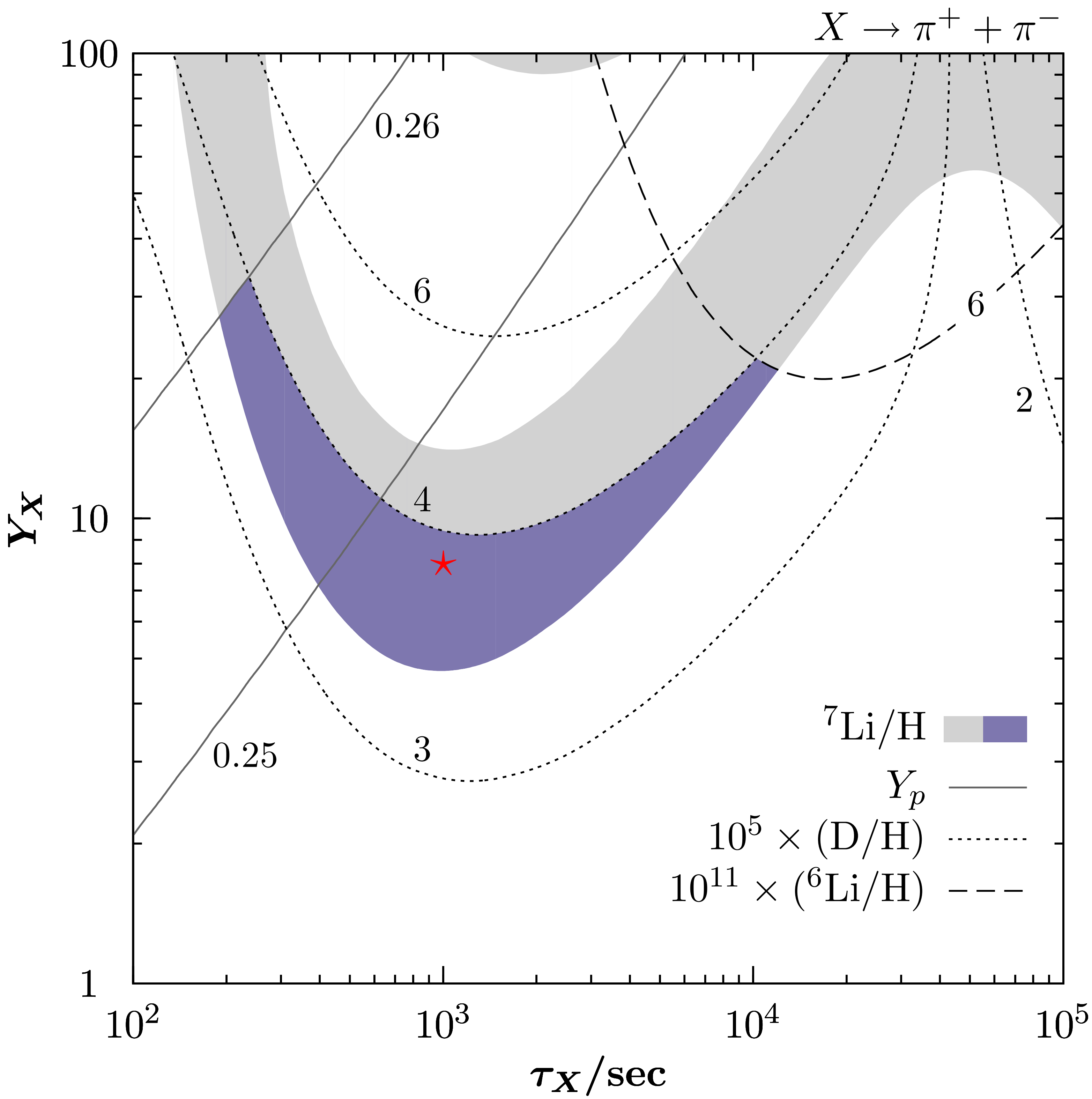

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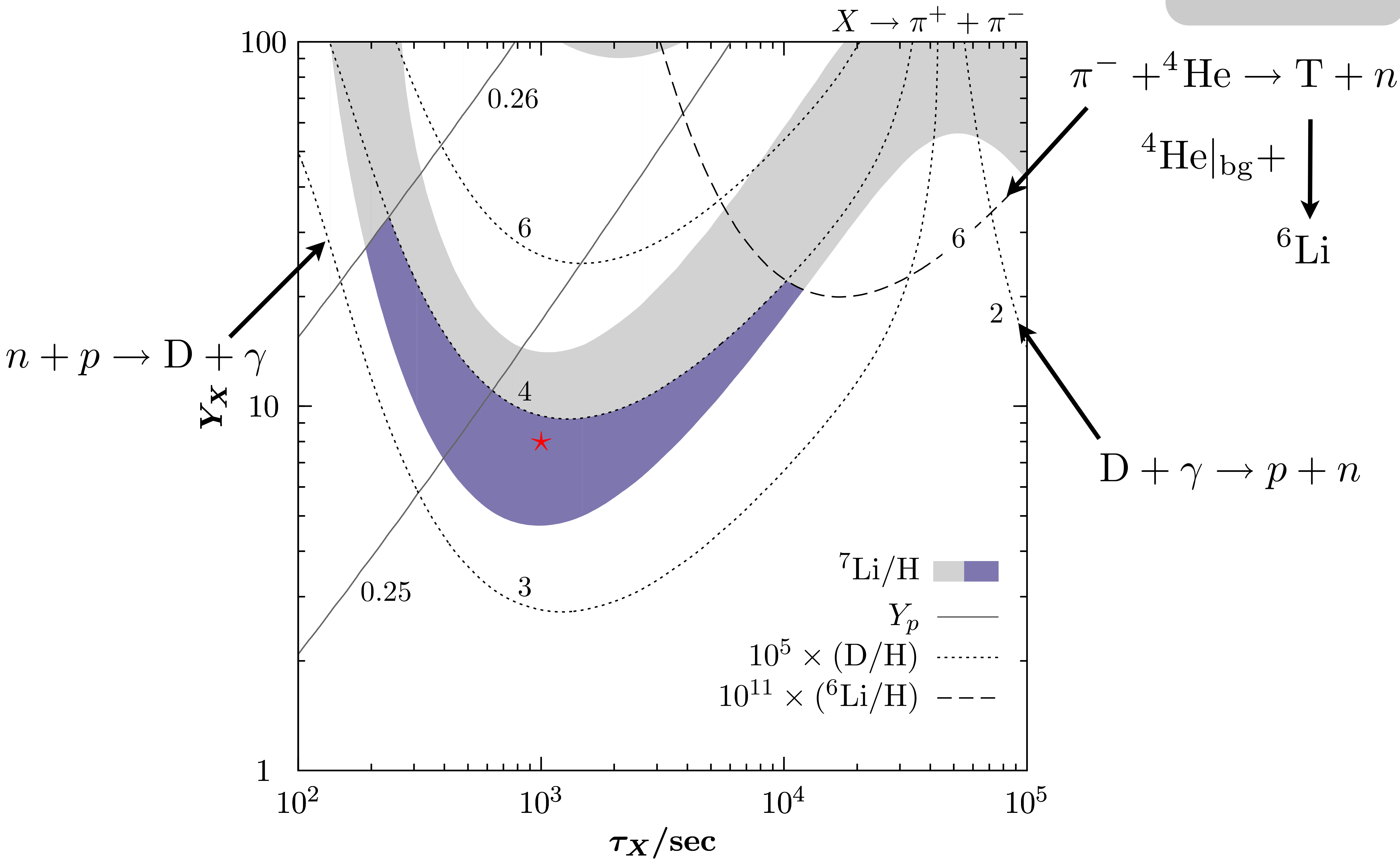


$\nu/\mu\mathrm{BBN} : X \to \mu^+\mu^- \to \bar{\nu}_e{}'s + \ldots$

- completely different hierarchy $\Gamma_p^\nu,\ \Gamma_{\rm stop}^\nu \ll H$
- estimate on efficiency of $p \to n$ interconversion

$$\Gamma_p^\nu = n_p \sigma_{pn}^{\bar{\nu}} \simeq 10^{-41}\ \mathrm{cm}^2 \times \frac{n_p E_\nu^2}{(10\ \mathrm{MeV})^2}$$

$$P_{p\to n}^\nu = \int_{t_{\rm inj}}^\infty \Gamma_p^\nu dt = \frac{1}{3}\frac{\Gamma_p^\nu(T_{\rm inj})}{H(T_{\rm inj})} \sim 2\times 10^{-9}$$

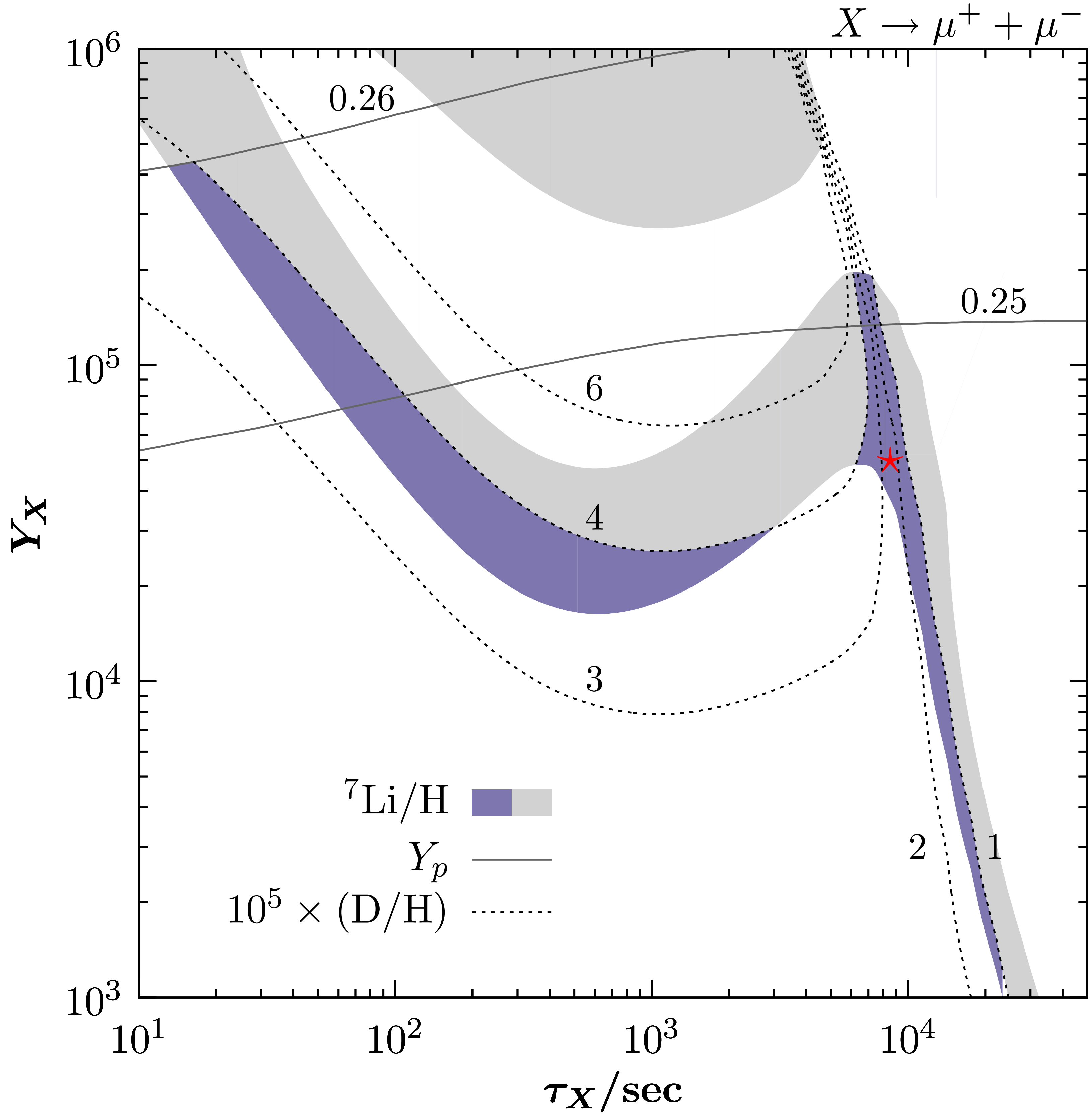
injection of $\mathcal{O}(10^4)$ muon decays/baryon yields $\mathcal{O}(10^{-5})$ neutrons

$P_{p\to n}^\nu << P_{p\to n}^\pi$ decouples $\nu/\mu\mathrm{BBN}$ scenario from $\pi\mathrm{BBN}$

- injected neutrinos redshift, oscillate and build up

=> in the numerical treatment we follow phase-space evolution

$\nu/\mu\mathrm{BBN} : X \to \mu^+\mu^- \to \bar{\nu}_e{}'s + \ldots$



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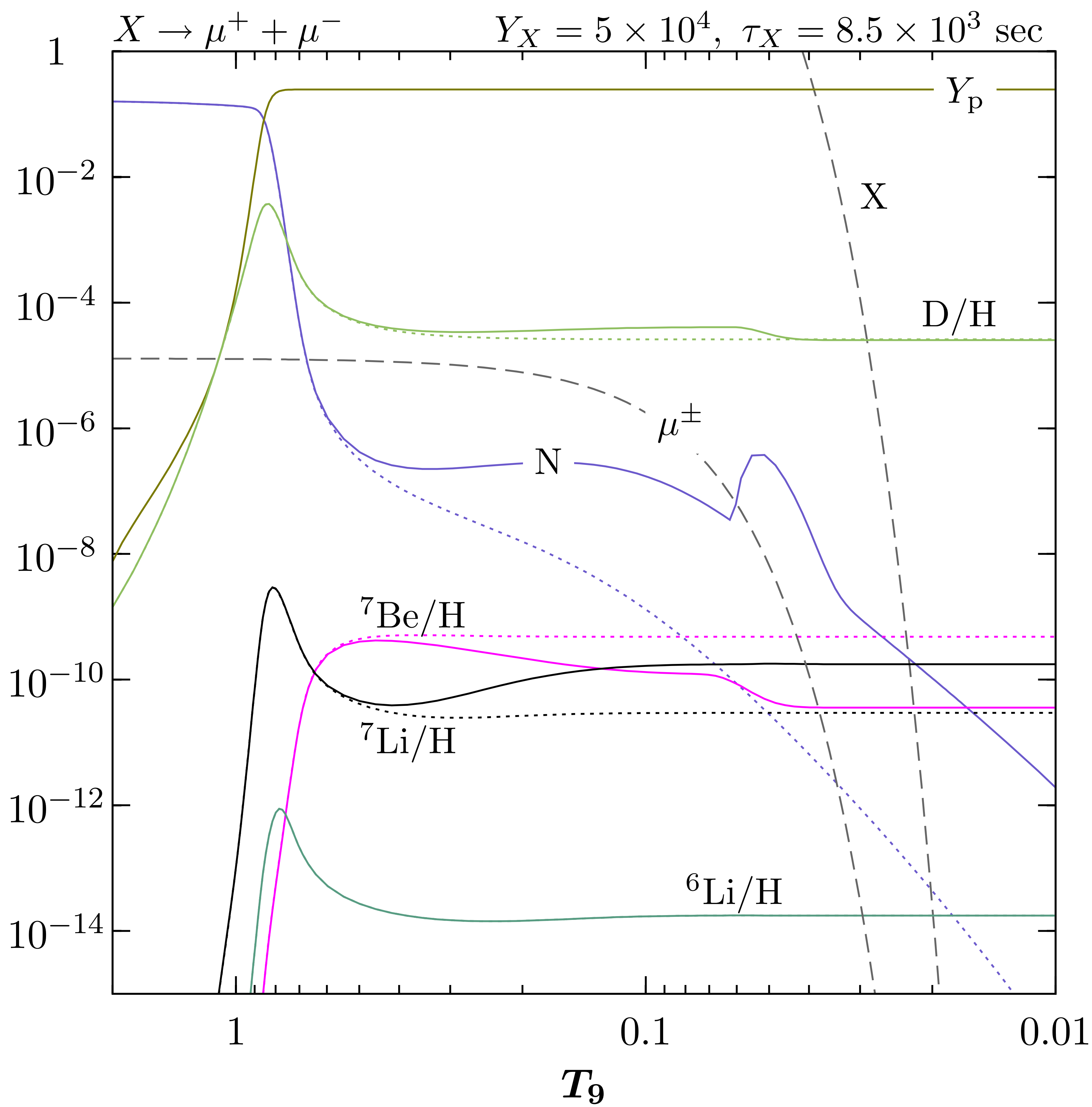

Examples of secluded sectors

- Higgs-portal (Singlet S) [McDonald 1994; Burgess et al 2001]

$$\mathcal{L}_{\rm H-portal} = \frac{1}{2}(\partial_\mu S)^2 - V(S) - (\lambda SS + AS)(H^\dagger H).$$

$A, \ \lambda, \ \text{and} \ m_S^2 \qquad \text{(S-portal)}$

- Vector-portal (new $U(1)'$ broken by Higgs' ϕ) [Holdom 1986]

$$\mathcal{L}_{\rm V-portal} = -\frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}F_{\mu\nu}^Y V^{\mu\nu} + |D_\mu\phi|^2 - V(\phi),$$

$\alpha', \ \kappa, \ m_{h'}, \ \text{and} \ m_V \qquad \text{(V-portal)},$

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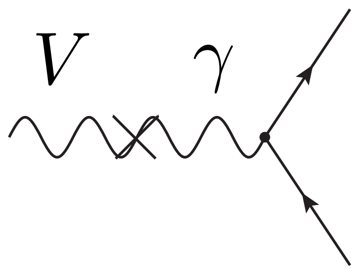
- Vector-portal (new $U(1)'$ broken by Higgs‘ ϕ) [Holdom 1986]

$$\mathcal{L}_{\rm int} = -\frac{\kappa}{2}V_{\mu\nu}F^{\mu\nu} + \frac{m_V^2}{v'}h'V_\mu^2 + \frac{m_V^2}{v'^2}h'^2V_\mu^2 - \frac{m_{h'}^2}{2v'}h'^3 - \frac{m_{h'}^2}{8v'^2}h'^4.$$

$$\alpha',\ \kappa,\ m_{h'},\ \text{and } m_V \qquad \text{(V-portal)},$$

Consider V-portal

$$\tau_X \sim 10^3\ \mathrm{s}$$



$$\tau_V \leq 0.05\ \mathrm{s} \times \left(\frac{10^{-10}}{\kappa}\right)^2 \left(\frac{500\ \mathrm{MeV}}{m_V}\right) \quad \text{for} \quad m_V \gtrsim m_e.$$

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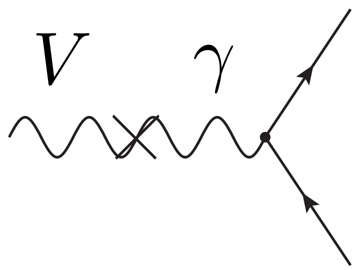

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"super-Wimp" regime

$\Gamma_{\text{prod}}(V) \ll H$

$$\Rightarrow m_V < m_{h'}$$

$$\kappa \lesssim 10^{-12}$$

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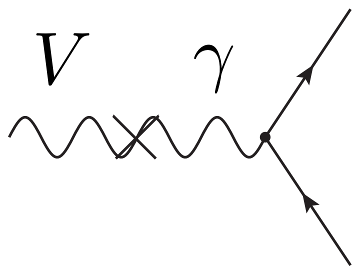

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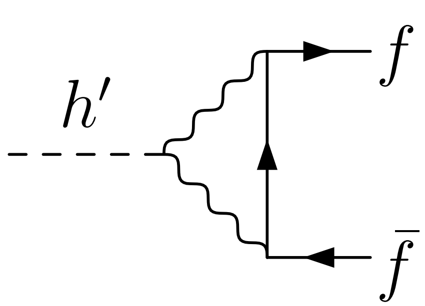
$\Rightarrow m_{h'} < m_V$

naturally long-lived h'



[Batell et al., 2009]

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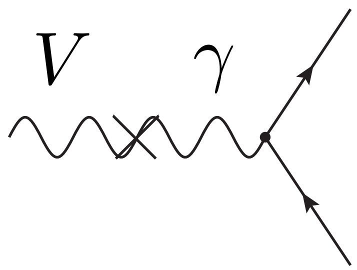

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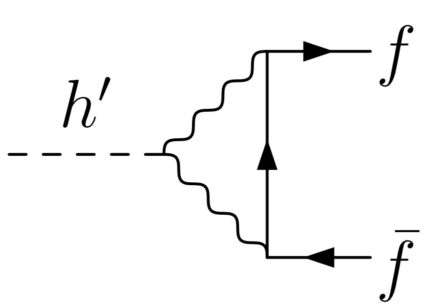

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$$\tau_{h'} \sim (10^3 \div 10^4) \text{ s} \times \left(\frac{\alpha}{\alpha'}\right) \left(\frac{3.4 \times 10^{-5}}{\kappa}\right)^{4} \left(\frac{250 \text{ MeV}}{m_{h'}}\right) \left(\frac{m_V}{500 \text{ MeV}}\right)^2 .$$

Y_X

“Wimp” regime: h’

$$
\begin{aligned}
h' + h' \to V + V &: \quad \Gamma_1 \propto (\alpha')^2 \kappa^0 \exp(-m_{h'}/T - 2\Delta m/T) \\
h' + V \to l^+ l^- &: \quad \Gamma_2 \propto \alpha' \alpha \kappa^2 \exp(-m_{h'}/T - \Delta m/T) \\
h' + l^\pm \to V + l^\pm &: \quad \Gamma_3 \propto \alpha' \alpha \kappa^2 \exp(-\Delta m/T),
\end{aligned}
$$

[Credit: N. Weiner]

$$
Y_{h'} = \begin{cases} 10 & (\pi\mathrm{BBN}) \\ 10^4 & (\nu/\mu\mathrm{BBN}) \end{cases}
$$

easily

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“super-Wimp”: V

production peaks at $m_V \sim \Lambda_{\rm QCD}$ => can only estimate

$$
Y_V \sim 0.3 \times \left(\frac{10^3\ \mathrm{s}}{\tau_V}\right) \left(\frac{\mathrm{GeV}}{m_V}\right)^2 \left(\frac{40}{g_{\rm eff}}\right)^{3/2}
$$

seems somewhat small for “pion-solution”, but...

A more comprehensive picture ...

- Stopping power of the plasma falls rapidly with temperature
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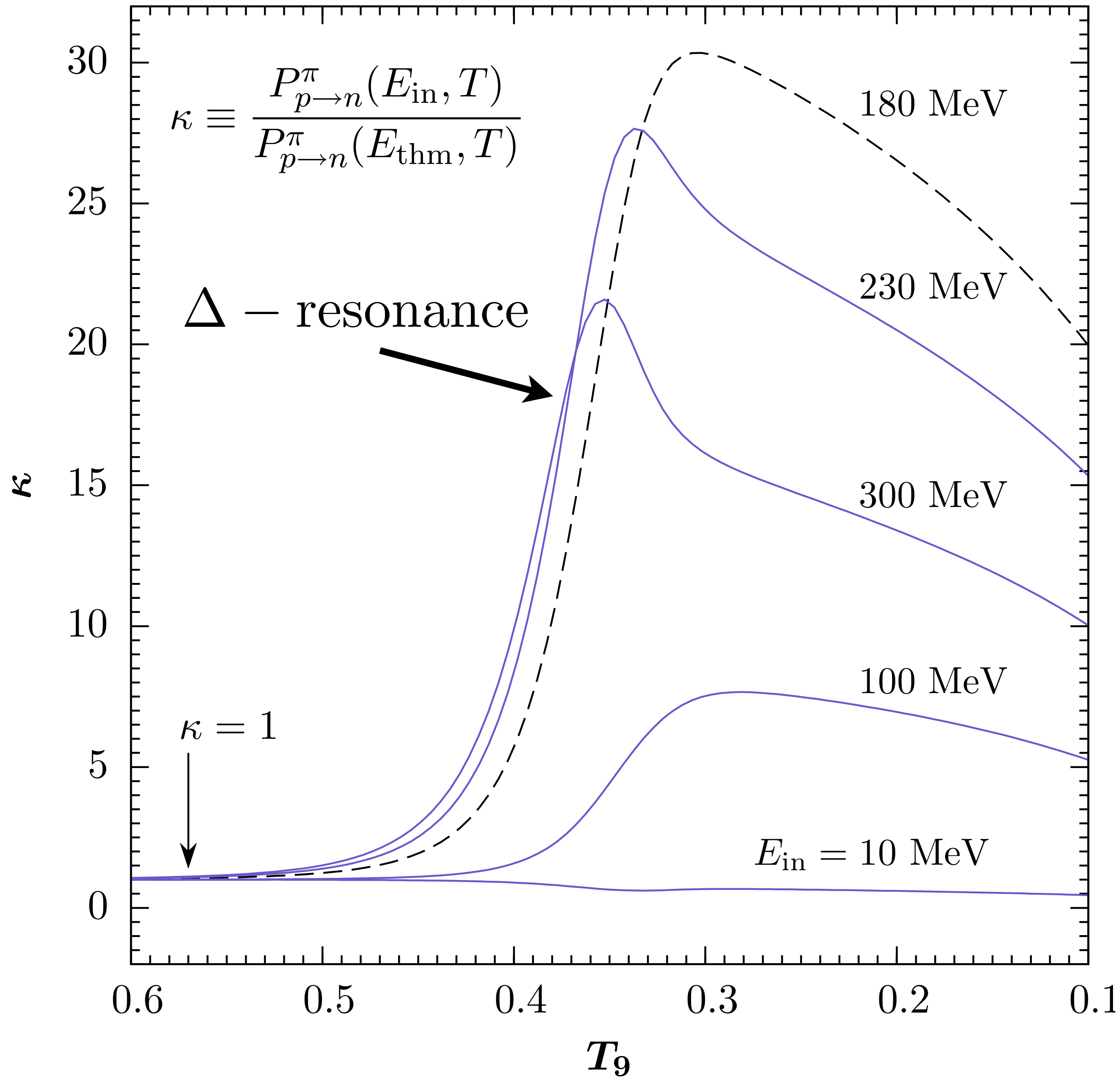

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- X decay to kaons; "s-quark exchange" reactions, e.g.

$$K^- + p \to \Sigma^\pm \pi^\mp,\ \Sigma^0 \pi^0,\ \Lambda \pi^0$$

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- a lot of fun physics ... to appear soon

Conclusions

- (sub-)GeV scale sector which decays at ~ 1000 sec can reconcile Li observations with BBN

  => long lived injected mesons

  => injected neutrinos (accumulative effect)

- not hard to construct a model

  => particularly motivated by galactic cosmic ray signals