New physics solutions to the lithium problem

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Newton 1665 online seminar

Potential Lithium Solutions

Sorry, nothing "hot off the press" but then - it's BBN...

1. sub-GeV scale energy injection

   Pospelov, JP PRD 2010

2. MeV scale absorption

   Goudelis, Pospelov, JP, PRL 2016

NB: general review on BBN as probe for new physics:

Pospelov, JP Ann.Rev.Nucl.Part.Sci. 2010

The Universe at the redshift of a billion

Basic assumptions for “Standard BBN”

Universe is flat, spatially homogeneous and isotropic and dominated by radiation => GR:

$$H \equiv \frac{\dot{a}}{a} = \sqrt{8\pi G_N \rho/3} \simeq \frac{1}{2t}$$

Universe was “hot” enough $T|_{\text{init}} \gg \Delta m_{np} = 1.293 \text{ MeV}$

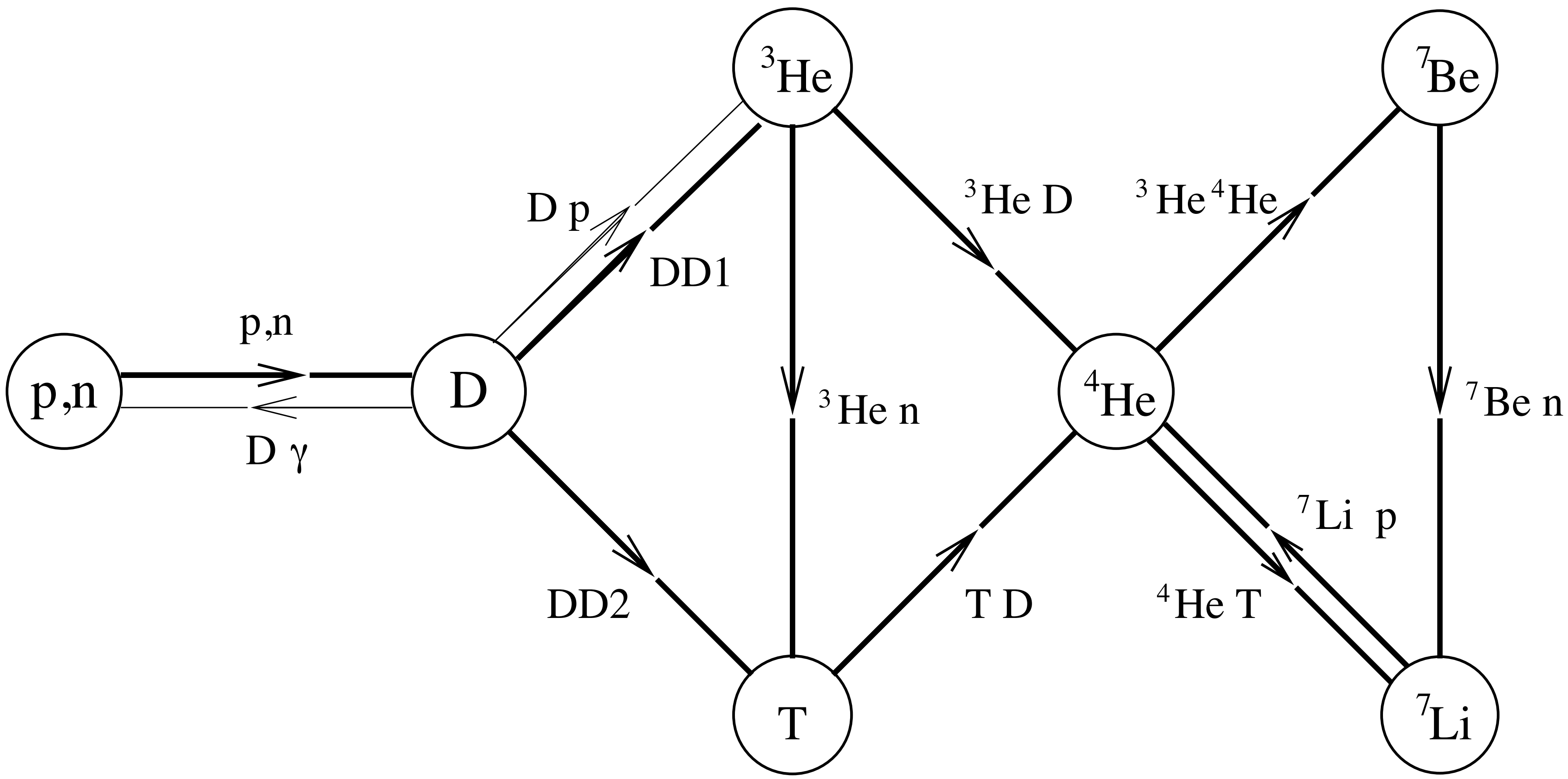
$$(n_n \simeq n_p)|_{T \gg \Delta m_{np}} = \frac{1}{2} n_b$$

Particle content & their interactions given by the SM

$$\frac{n_b}{s}(t_{\text{BBN}}) = \frac{n_b}{s}(t_{\text{CMB}}).$$ => “parameter free theory”

The Universe at the redshift of a billion

Nuclear reaction network

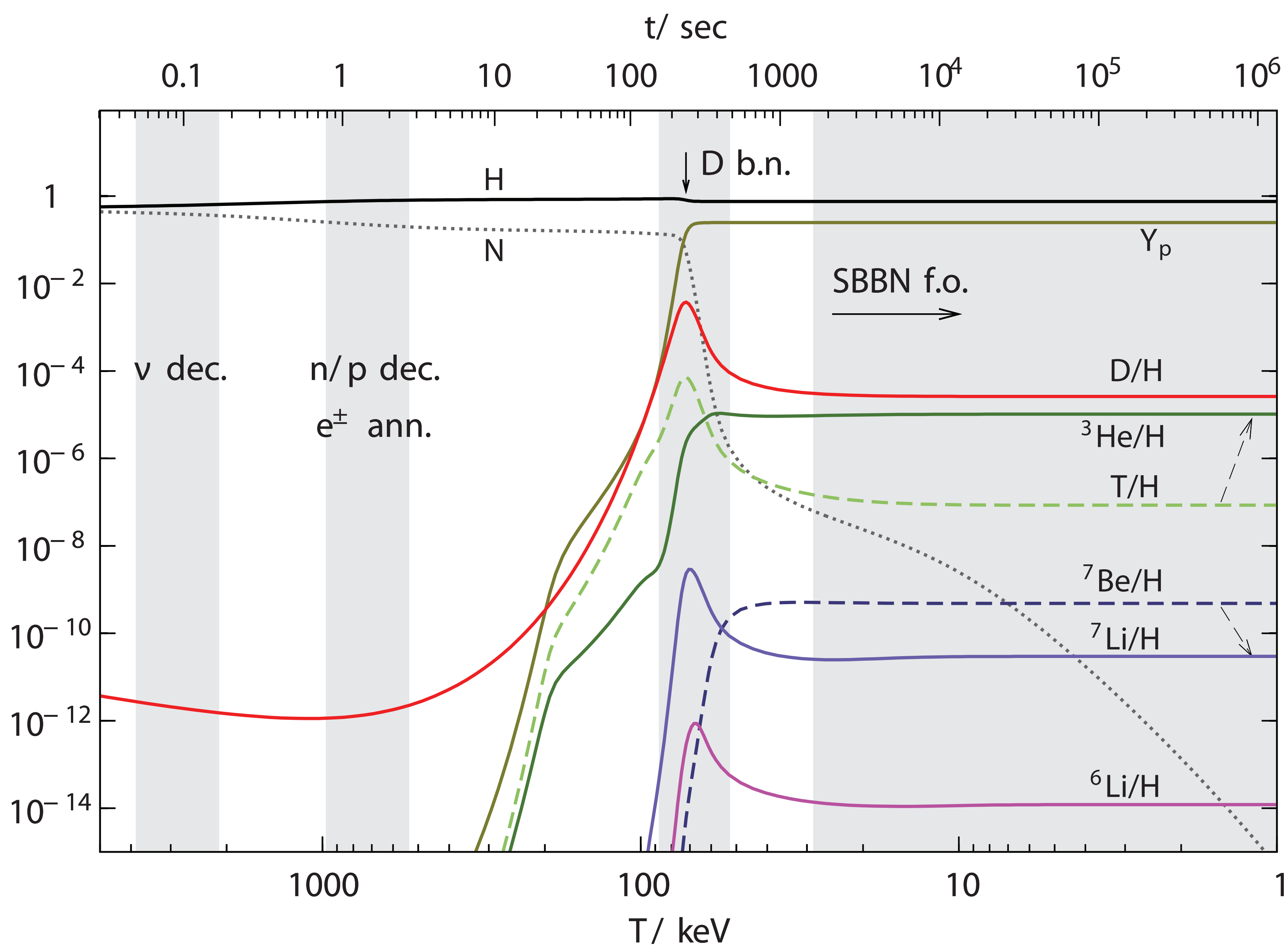


see Mukhanov "BBN without a computer"

The origin of chemistry: t = 100 sec

p, n, photons, electrons, neutrinos

Big Bang Nucleosynthesis



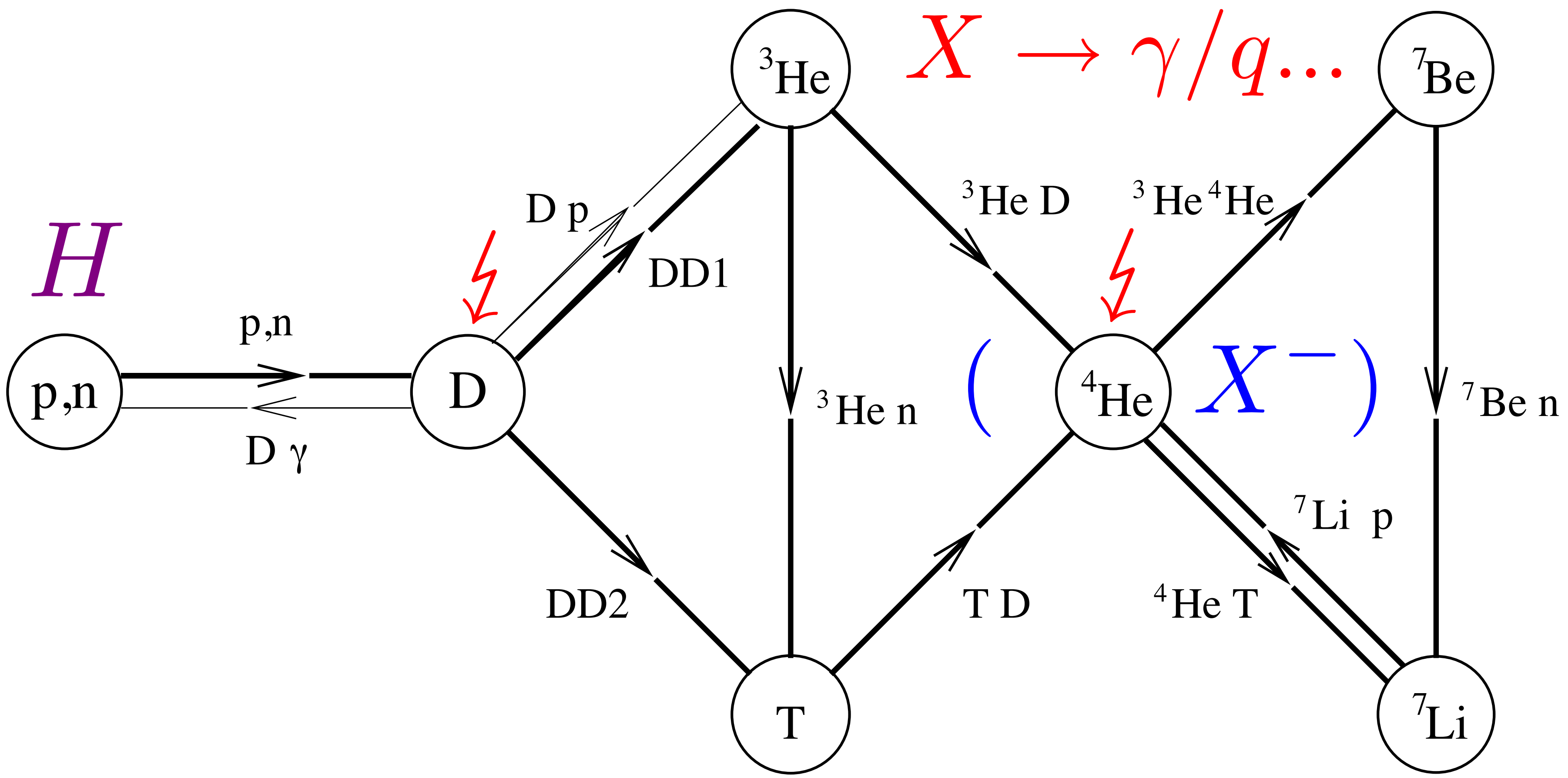
light elements have formed

HOT

time

COLD

Beyond SBBN

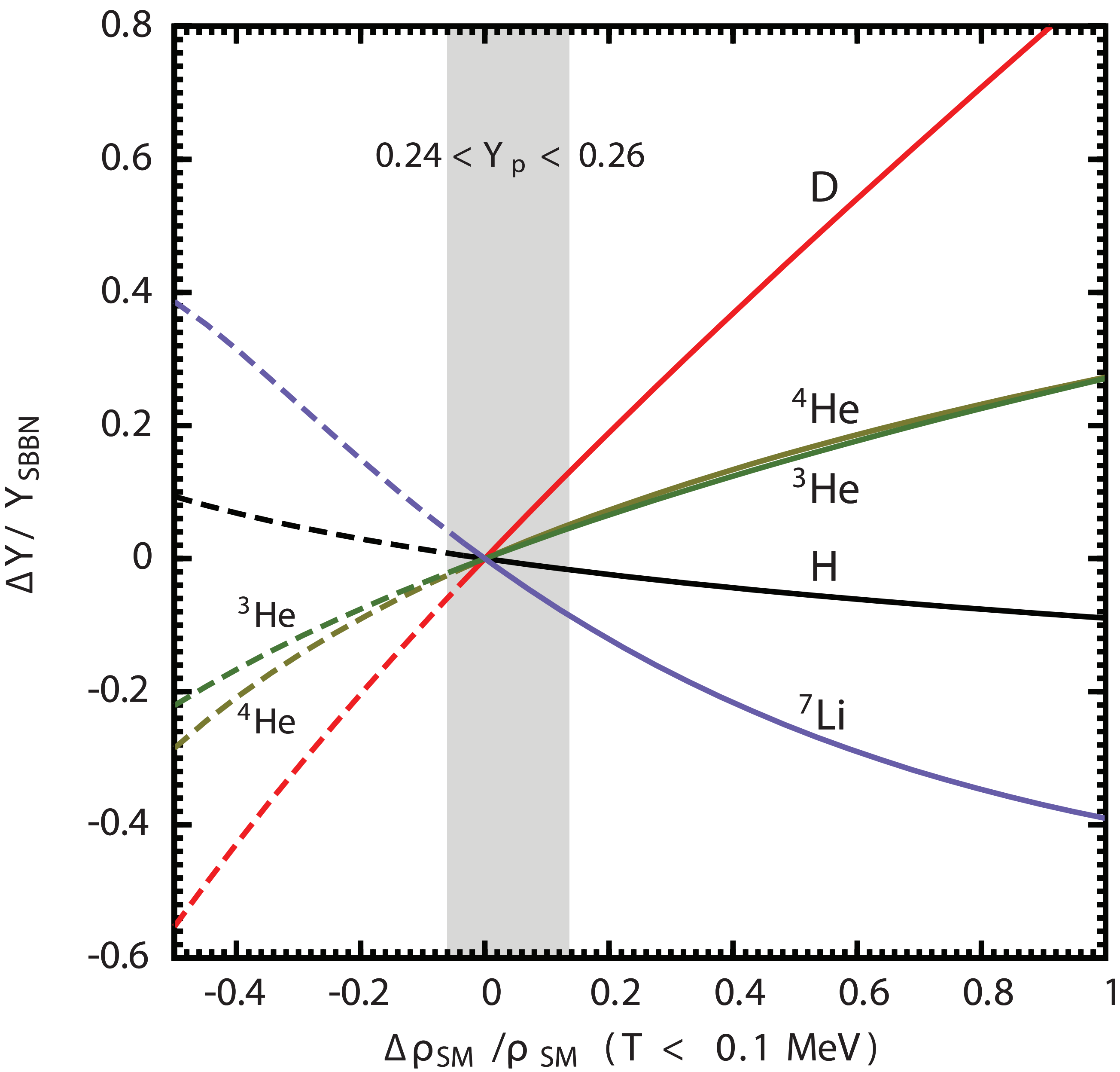


Change in timing

non-equilibrium BBN

catalyzed BBN

Change in Timing

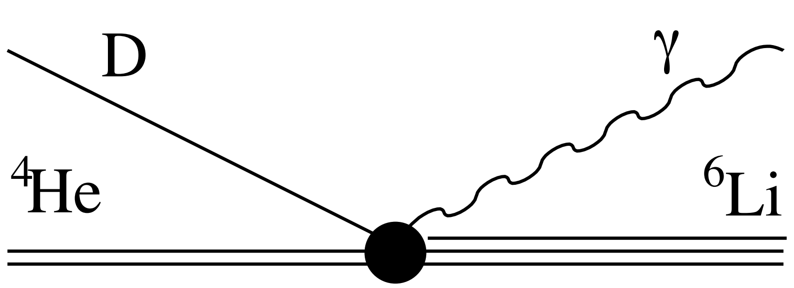


$$\rho_{\rm rad} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

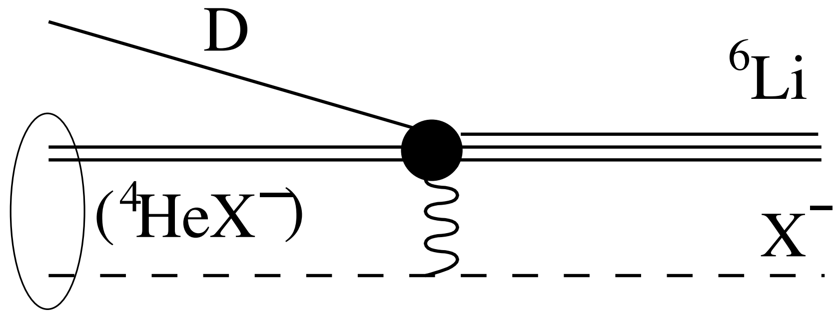
Catalysis of BBN

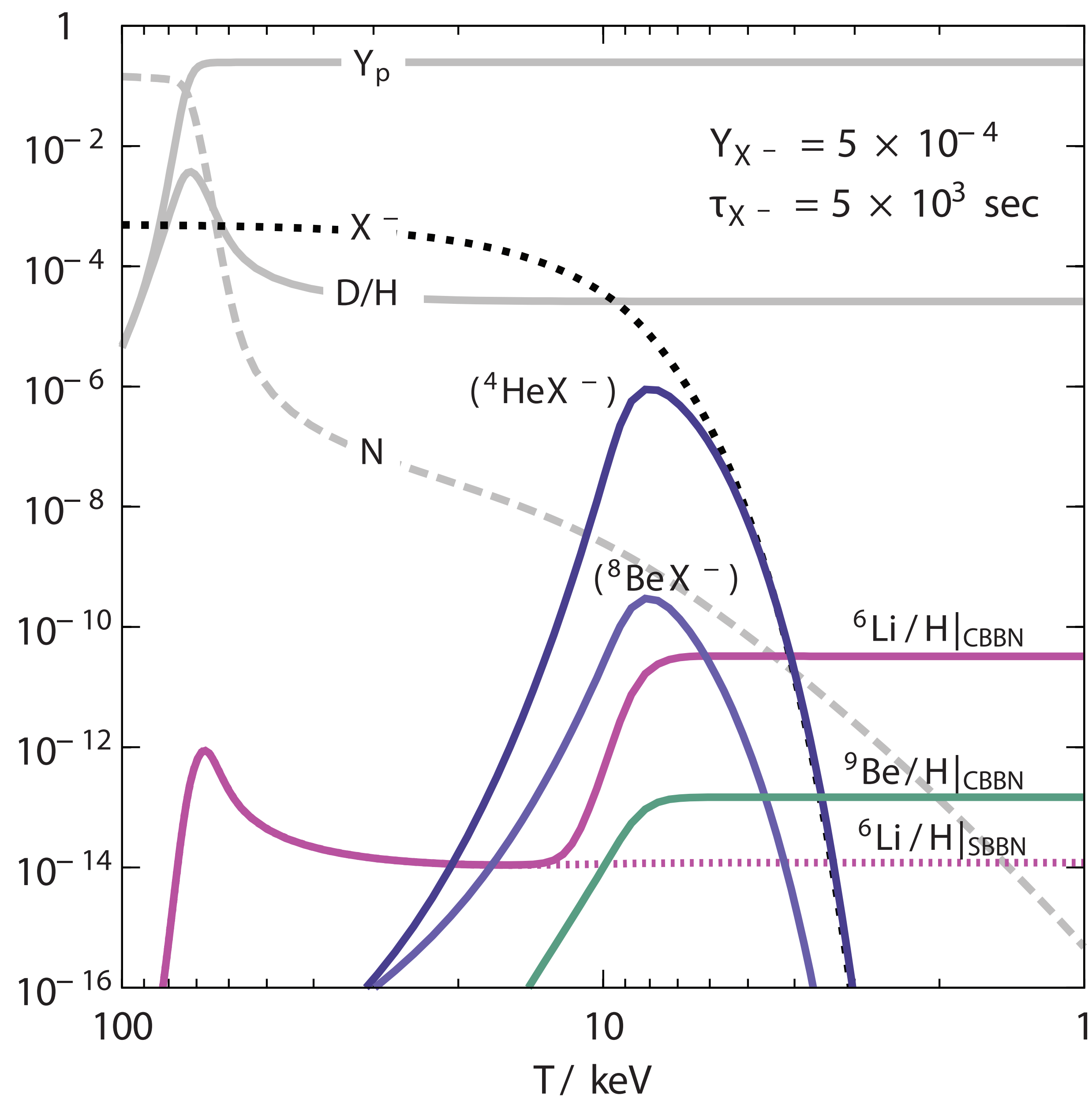
CHAMPs during BBN lead to severe overproduction of 6Li from bound states with He.

standard BBN:



catalyzed BBN:





Pospelov PRL 2006

Non-equilibrium BBN
Energy injection

Energy release during SBBN (mass conversion into nuclear binding energy)
$\sim 2 \text{ MeV/nucleon}$ => marginal effect at $T_9 \sim 1$

Most prominent class: decays of long-lived particles X

=> classic works focused on $m_X = \mathcal{O}(100 \text{ GeV})$, e.g. $\widetilde{G} \to SM + \widetilde{\chi}^0$

e.g. [Ellis et al 1985, … Dimopoulos 1988, …., Kawasaki et al. 2004, Jedamzik 2006, Cyburt et al. 2009, ...]

=> yield *massive* electromagnetic and hadronic showers which dissociate light elements

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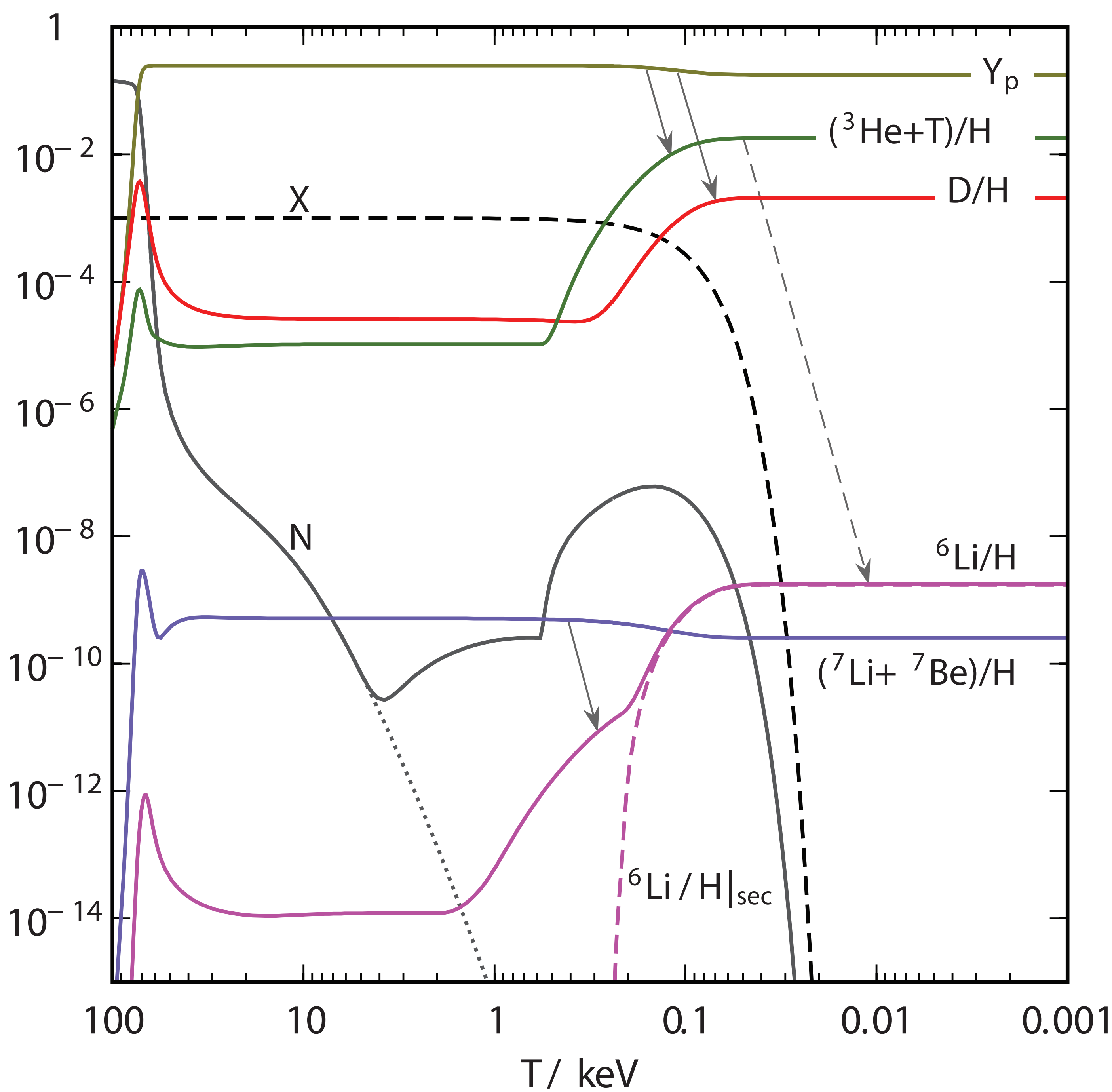
What if X is light? => this talk

EM energy injection

t > 10^6 sec



- photons in EM-cascade below $e^{\pm}$ threshold are not efficiently dissipated

  => spallation of nuclei

  see recent Poulin, Serpico 2015

- Important secondary effect:

$$^3\mathrm{H} + {}^4\mathrm{He}|_{bg} \rightarrow {}^6\mathrm{Li} + n$$

$$^3\mathrm{He} + {}^4\mathrm{He}_{bg} \rightarrow {}^6\mathrm{Li} + p$$

[Dimopulous, 1988, Jedamzik, 2000]

Soft hadronic injection

t > few sec

Lithium solution?!

- for X above di-pion threshold

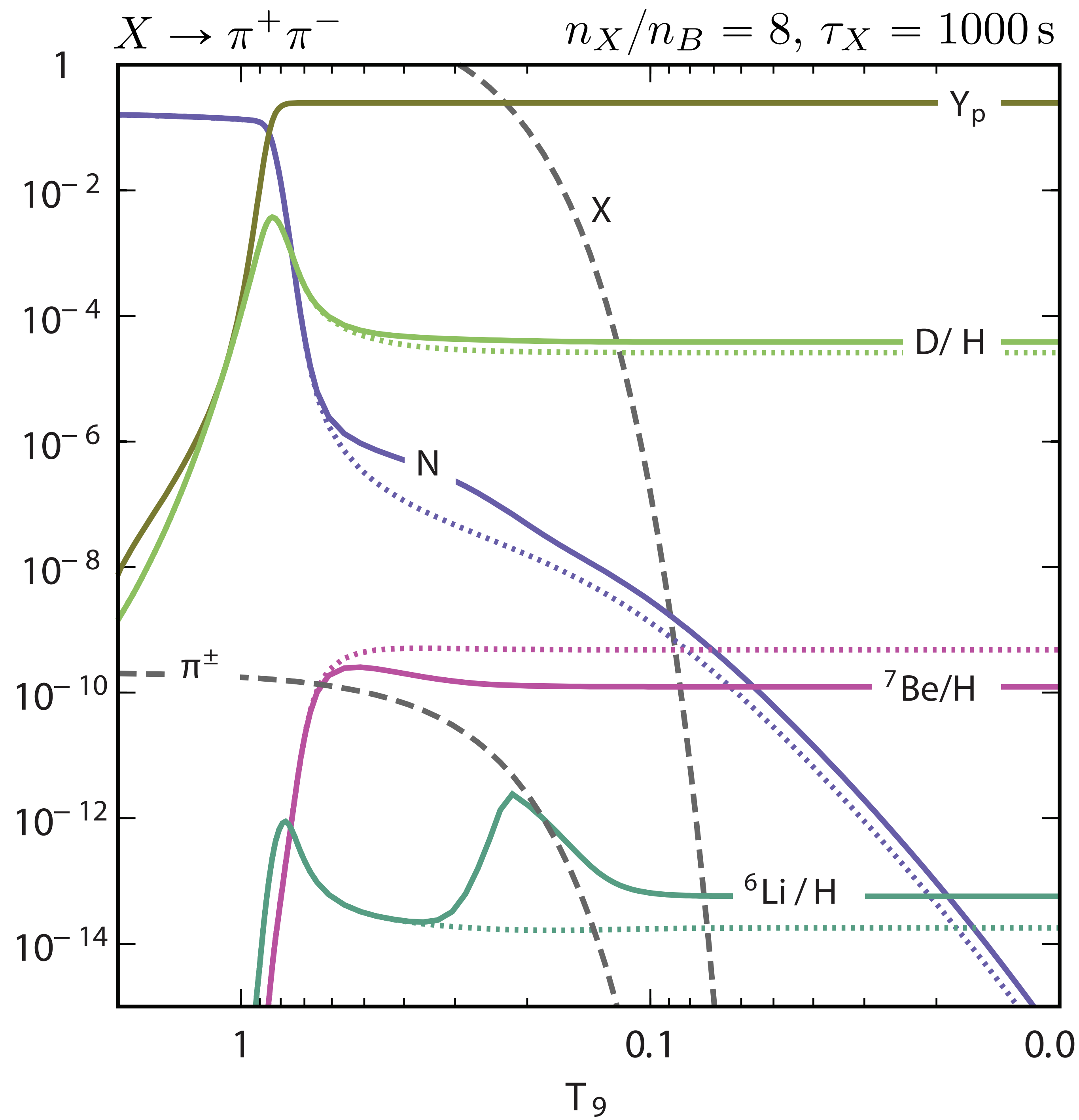
$$\pi^- + p \rightarrow \pi^0 + n$$

"extra neutrons"

- a generic solution to the lithium problem

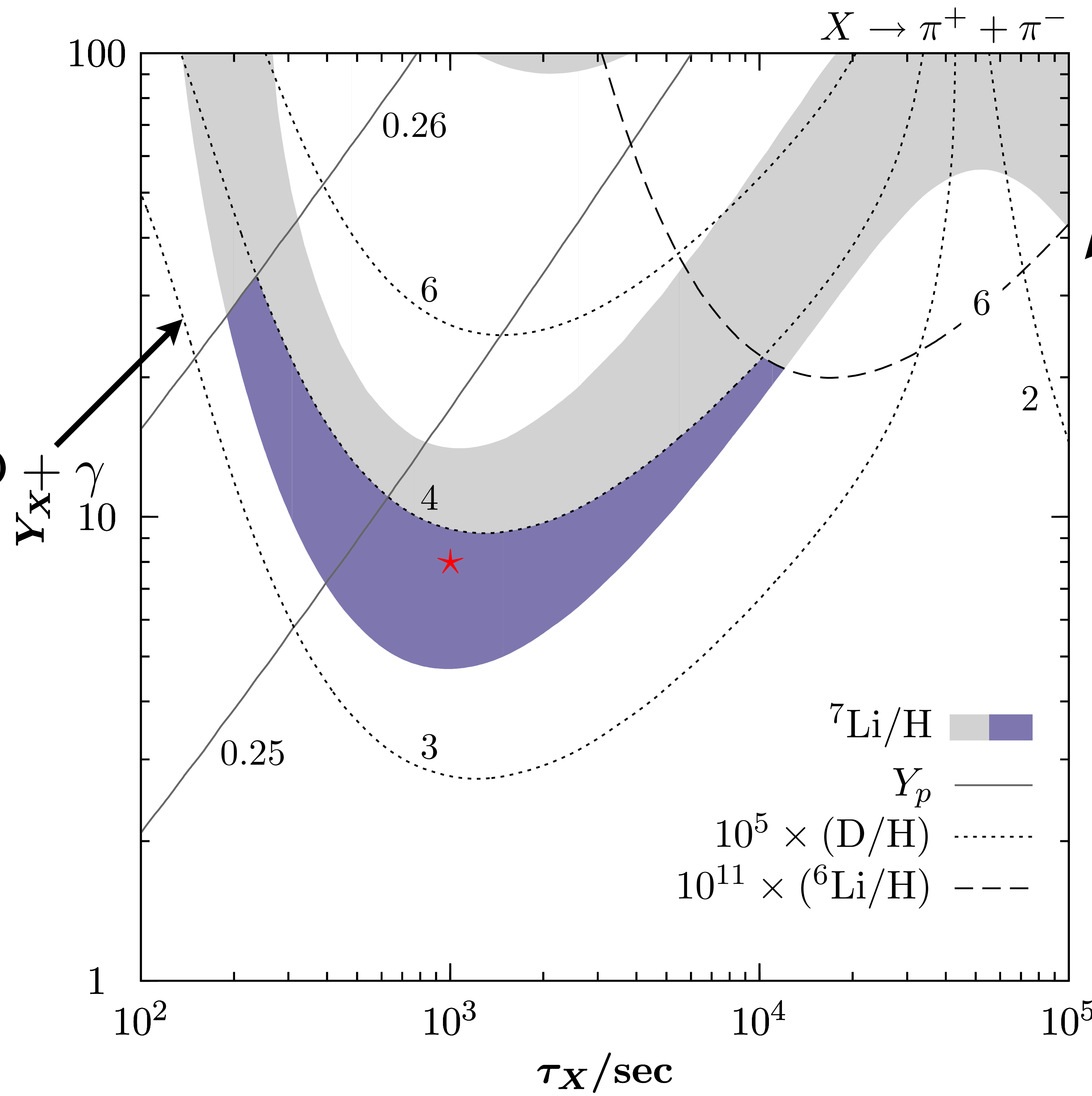
$$^7\mathrm{Be} + n \rightarrow {}^7\mathrm{Li} + p$$

$$^7\mathrm{Li} + p \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He}$$



$\pi\mathrm{BBN} : X \to \pi^+\pi^-$

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



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

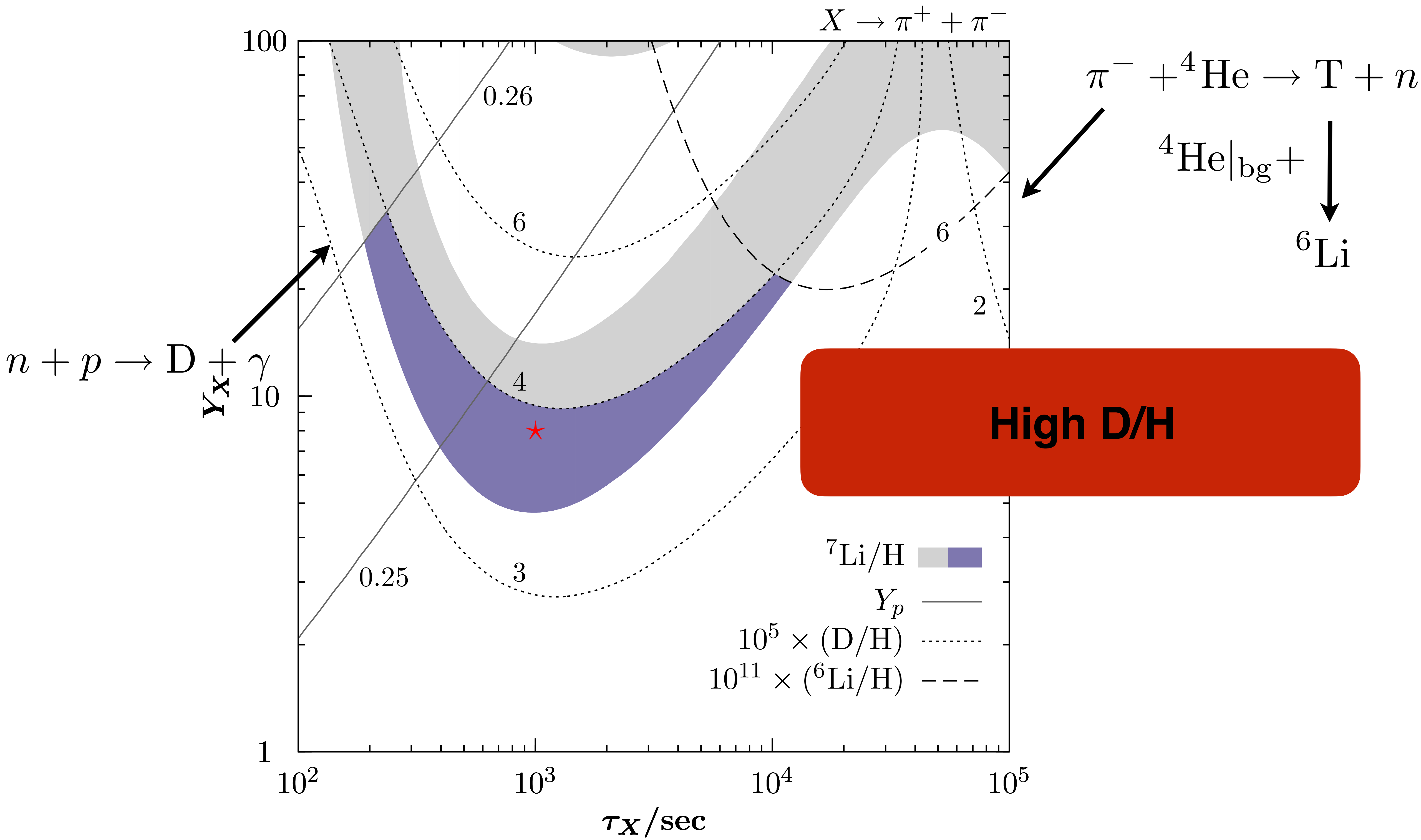
${}^4\mathrm{He}|_{\mathrm{bg}} +$

${}^6\mathrm{Li}$

πBBN : $X \rightarrow \pi^+\pi^-$

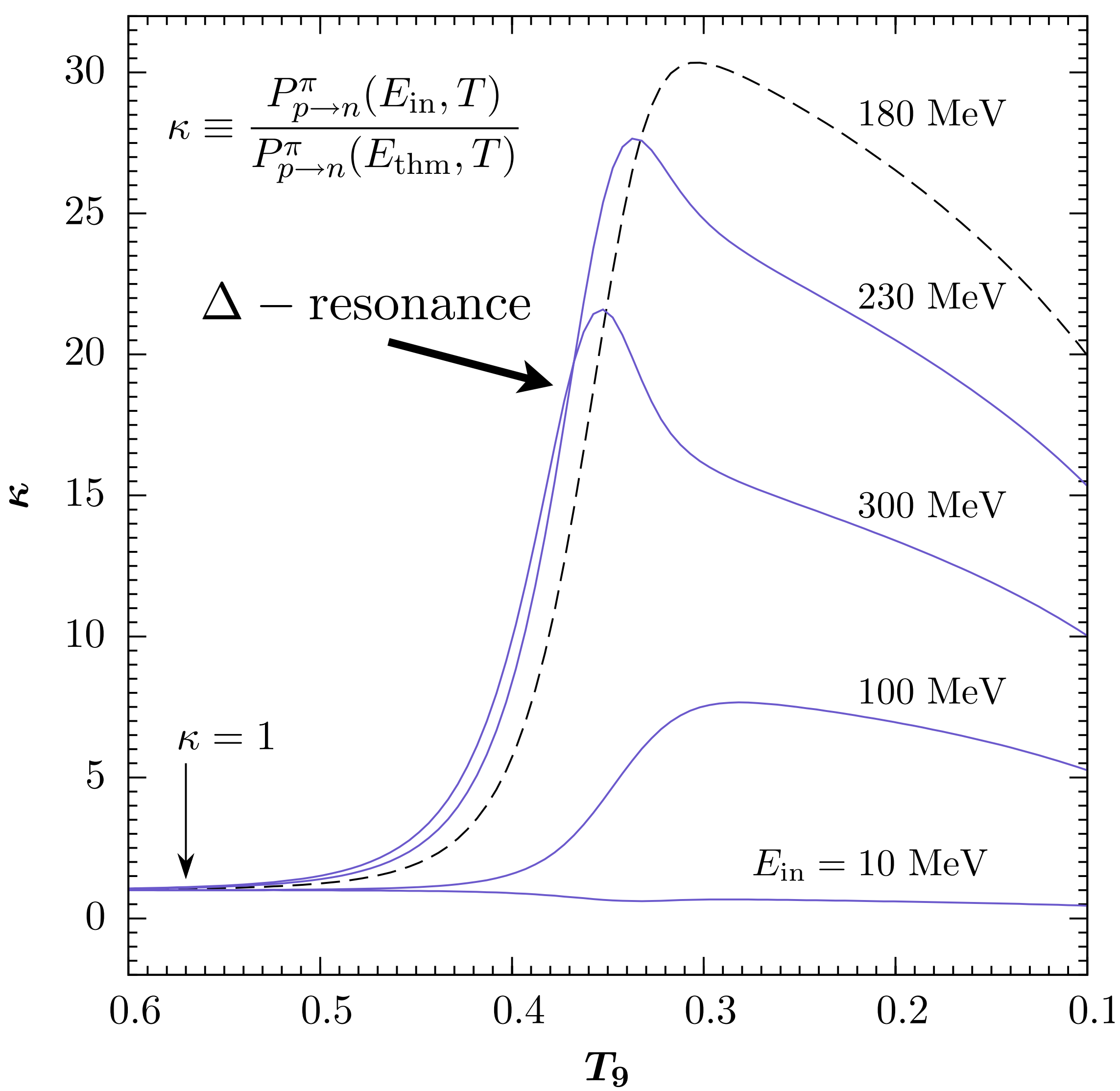
$10^5(\mathrm{D/H})_\mathrm{P} = 2.527 \pm 0.030$

Cooke, Pettini, Steidel 2018

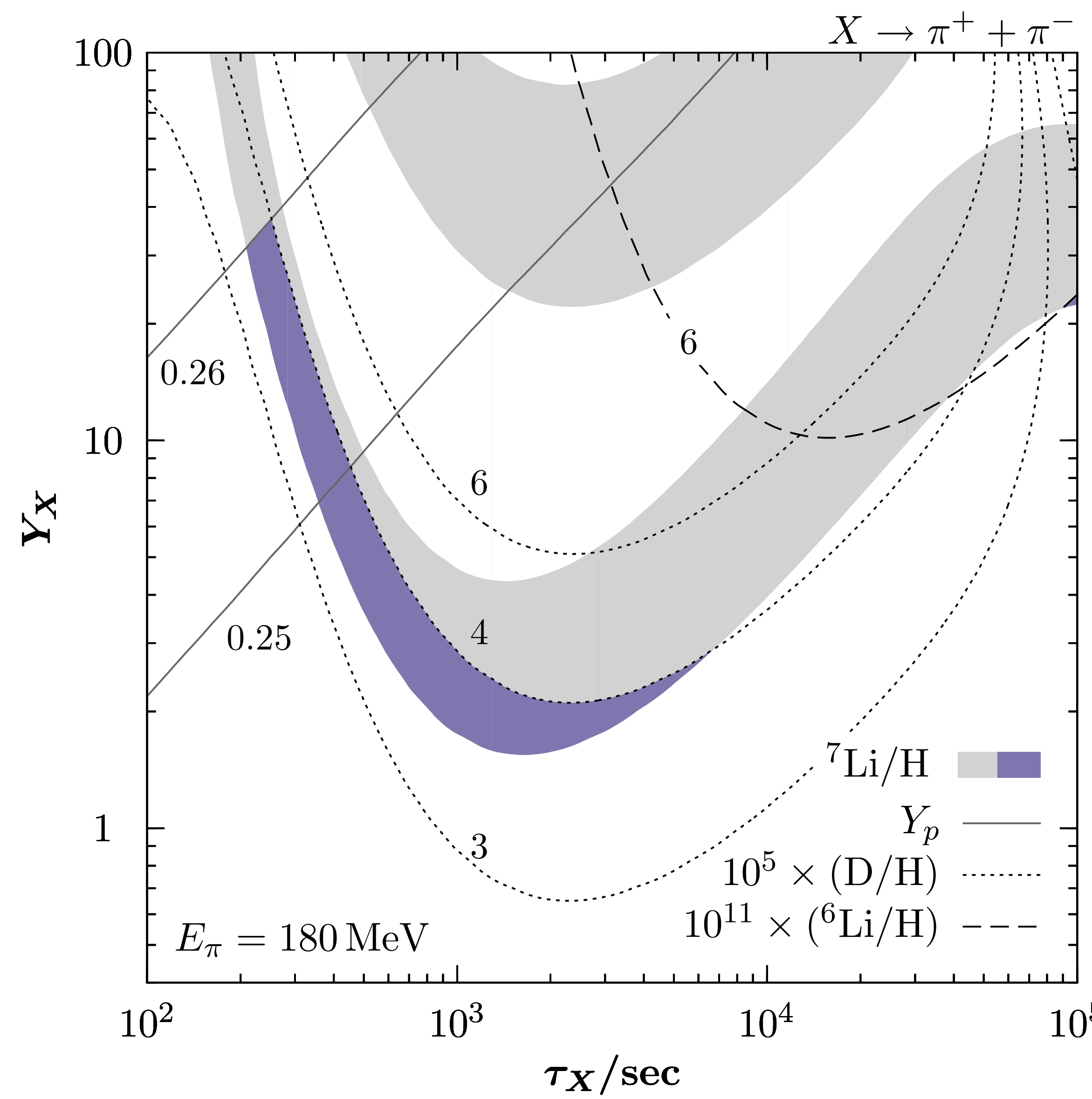


πBBN - getting it right

Enhancement by incomplete pion stopping => Delta-resonance in p to n conversion



$\Rightarrow$



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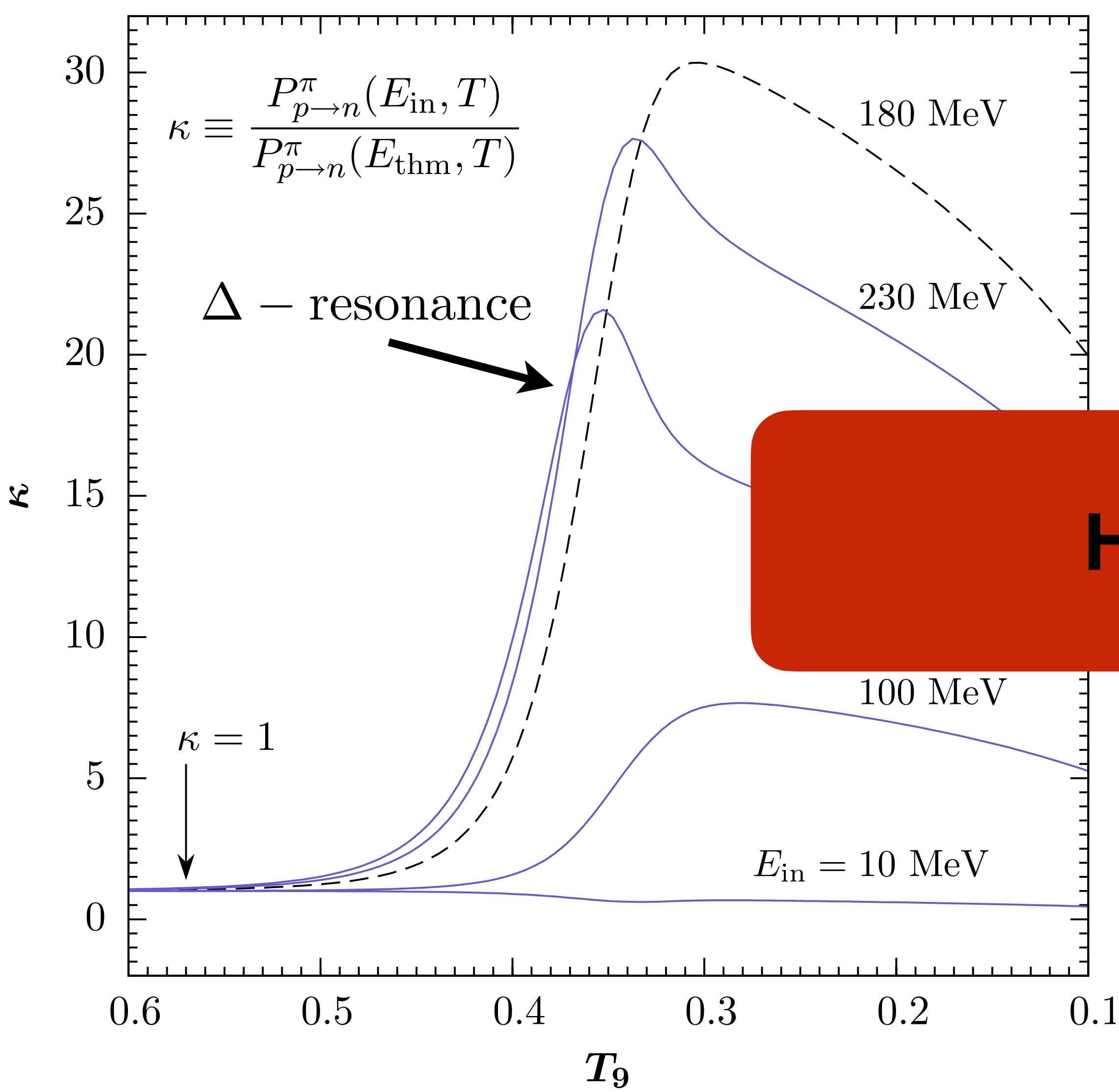
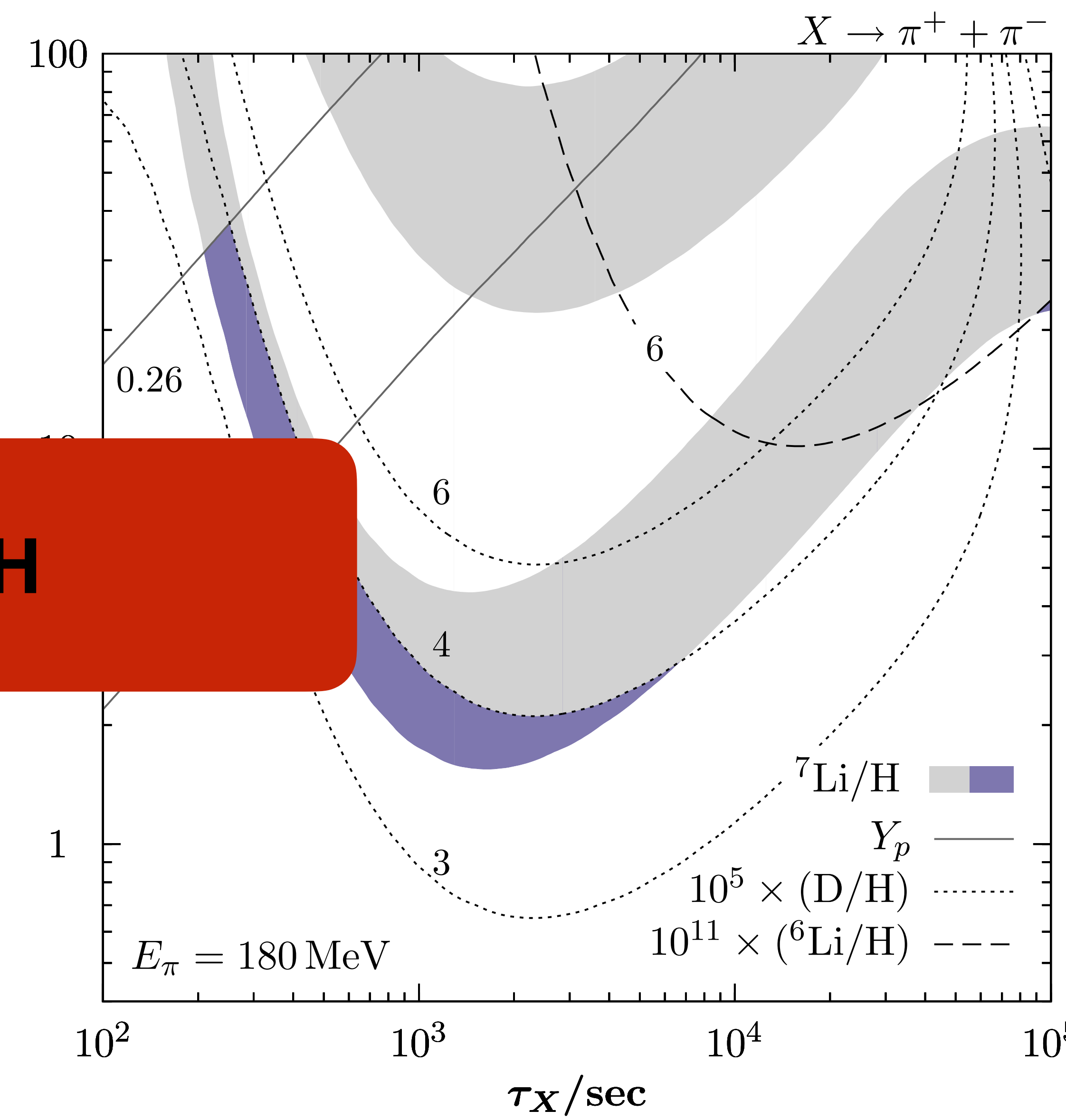




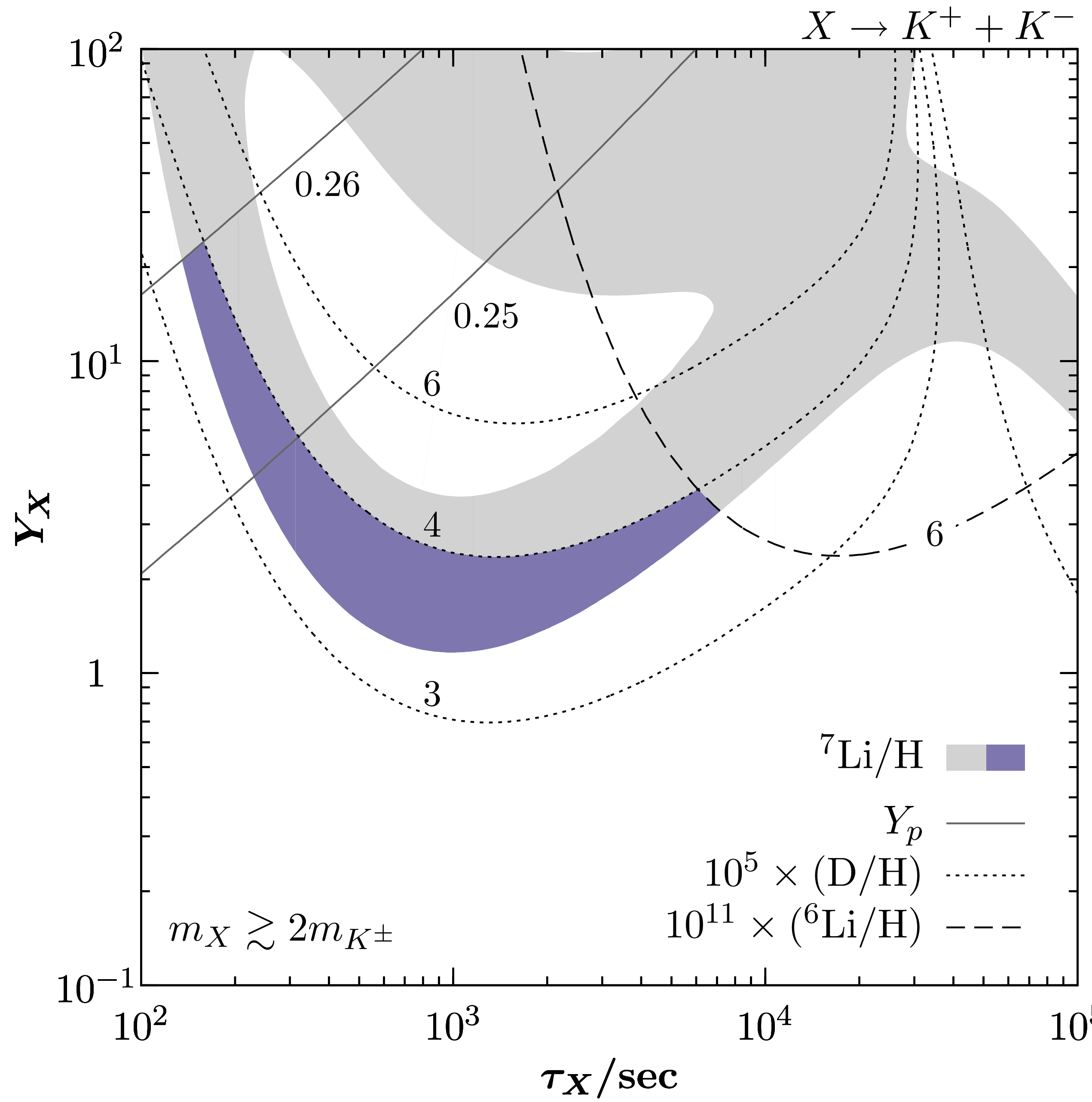
High D/H

Kaon-BBN

- Kaon absorption on helium, e.g.

$$K^- + {}^4\mathrm{He} \to \Lambda(\Sigma^0)(pnn)$$

- Kaon decays inject pions
- Pions inject EM energy...



Kaon-BBN

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

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

$$K^- + n \to \Sigma^- \pi^0,\ \Sigma^0\pi^-,\ \Lambda\pi^-$$

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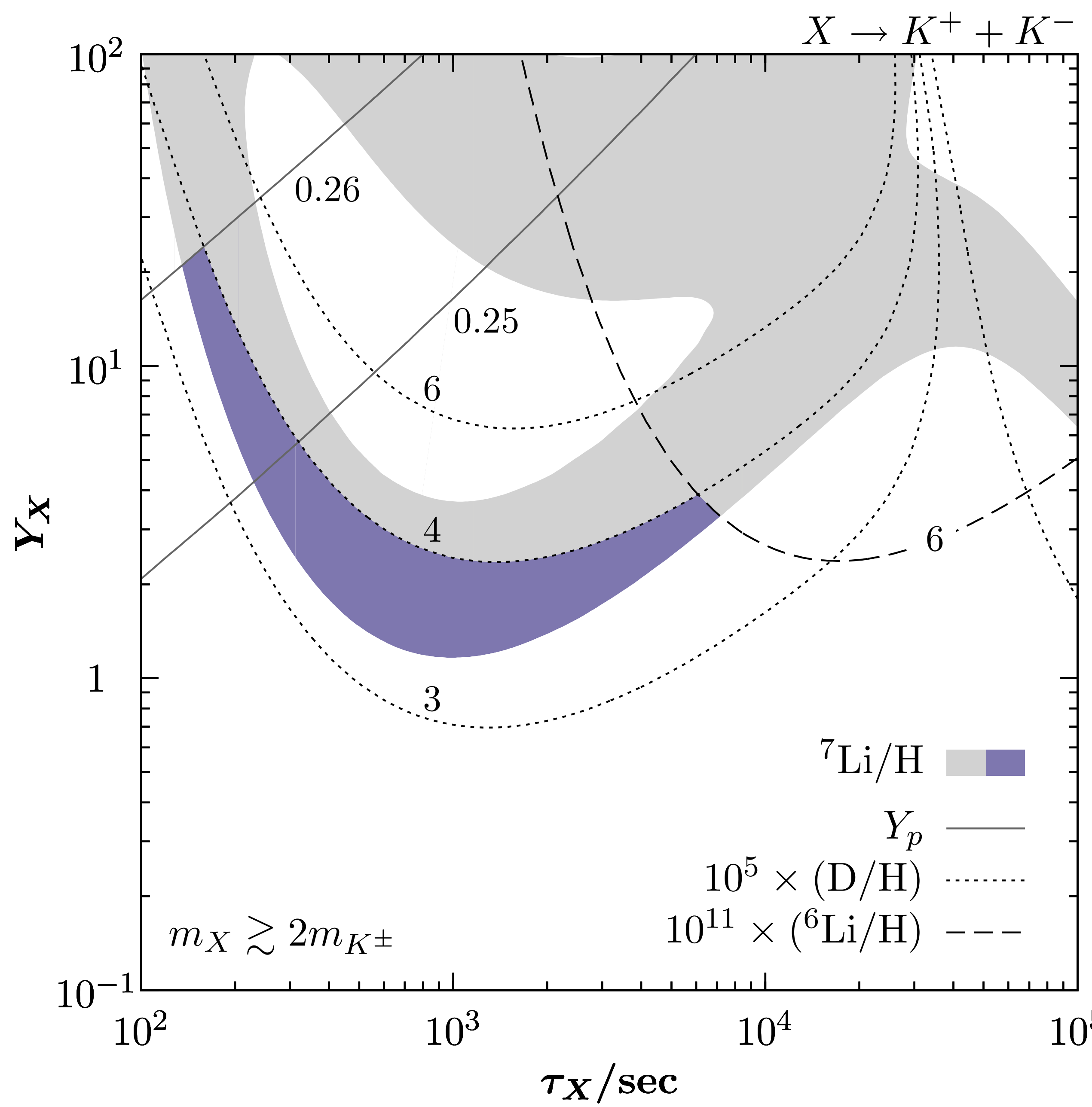

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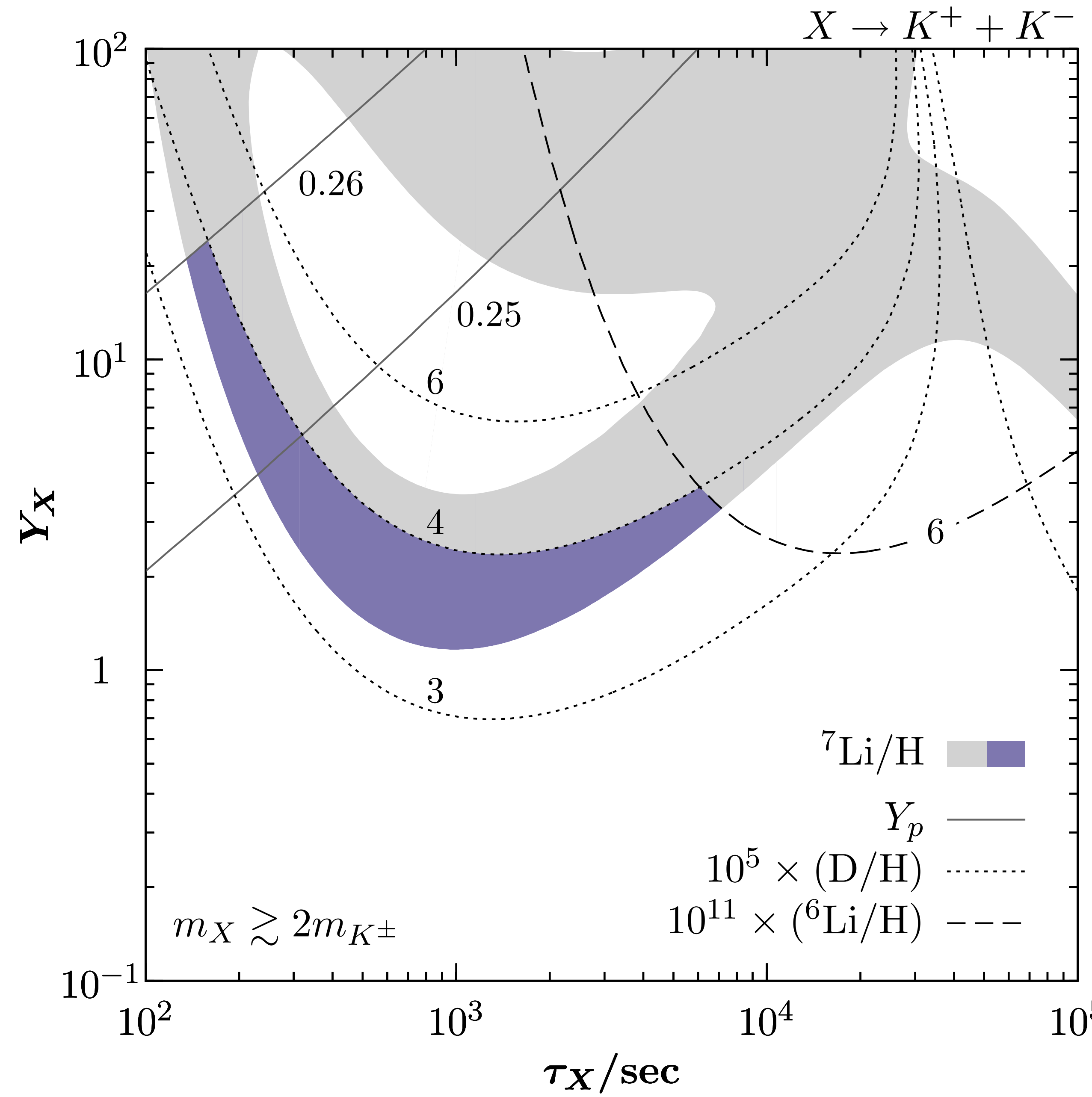
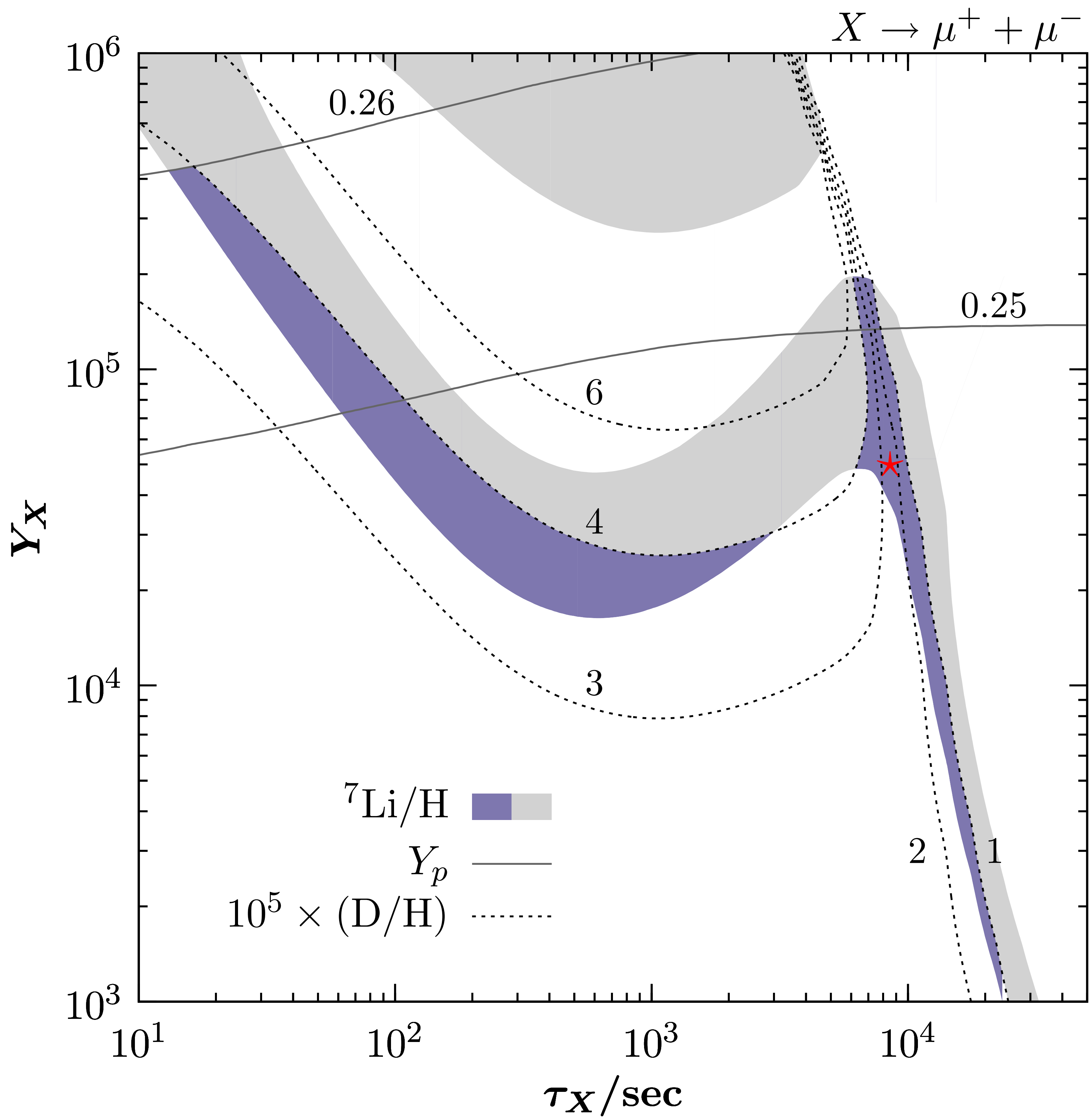


$\nu/\mu\mathrm{BBN}: X \to \mu^+\mu^- \to \bar{\nu}_e{}'s + \ldots$

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



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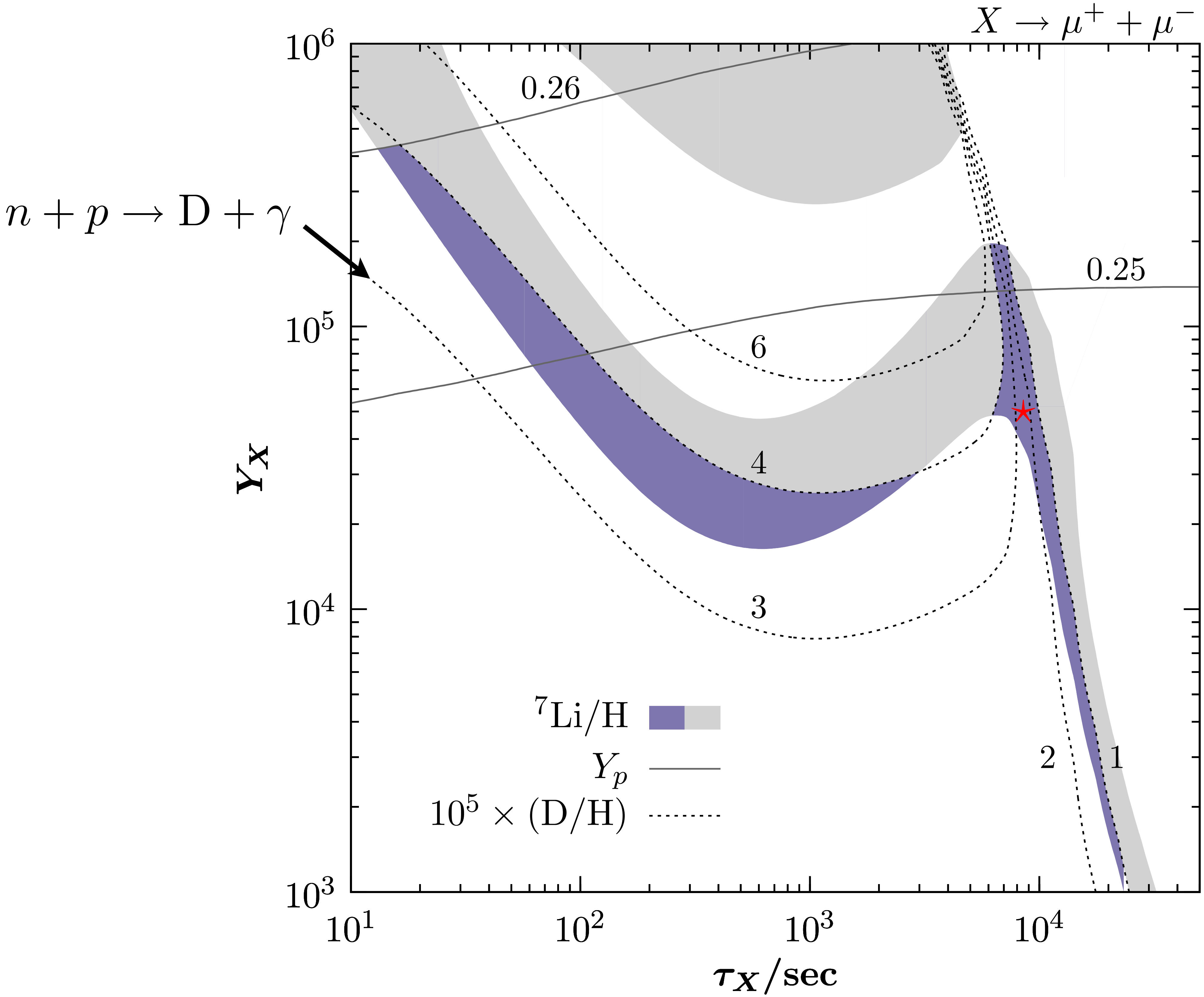

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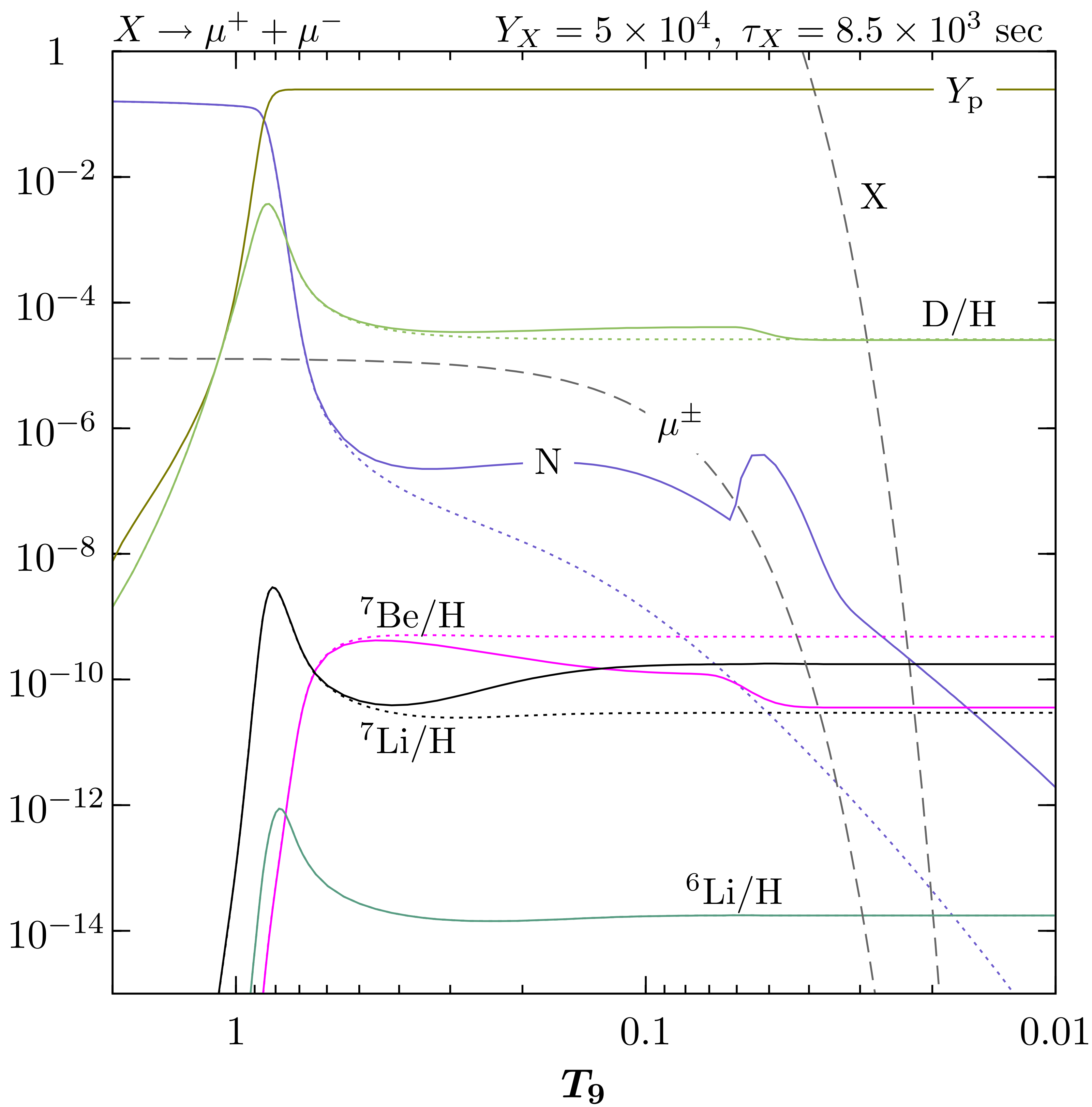

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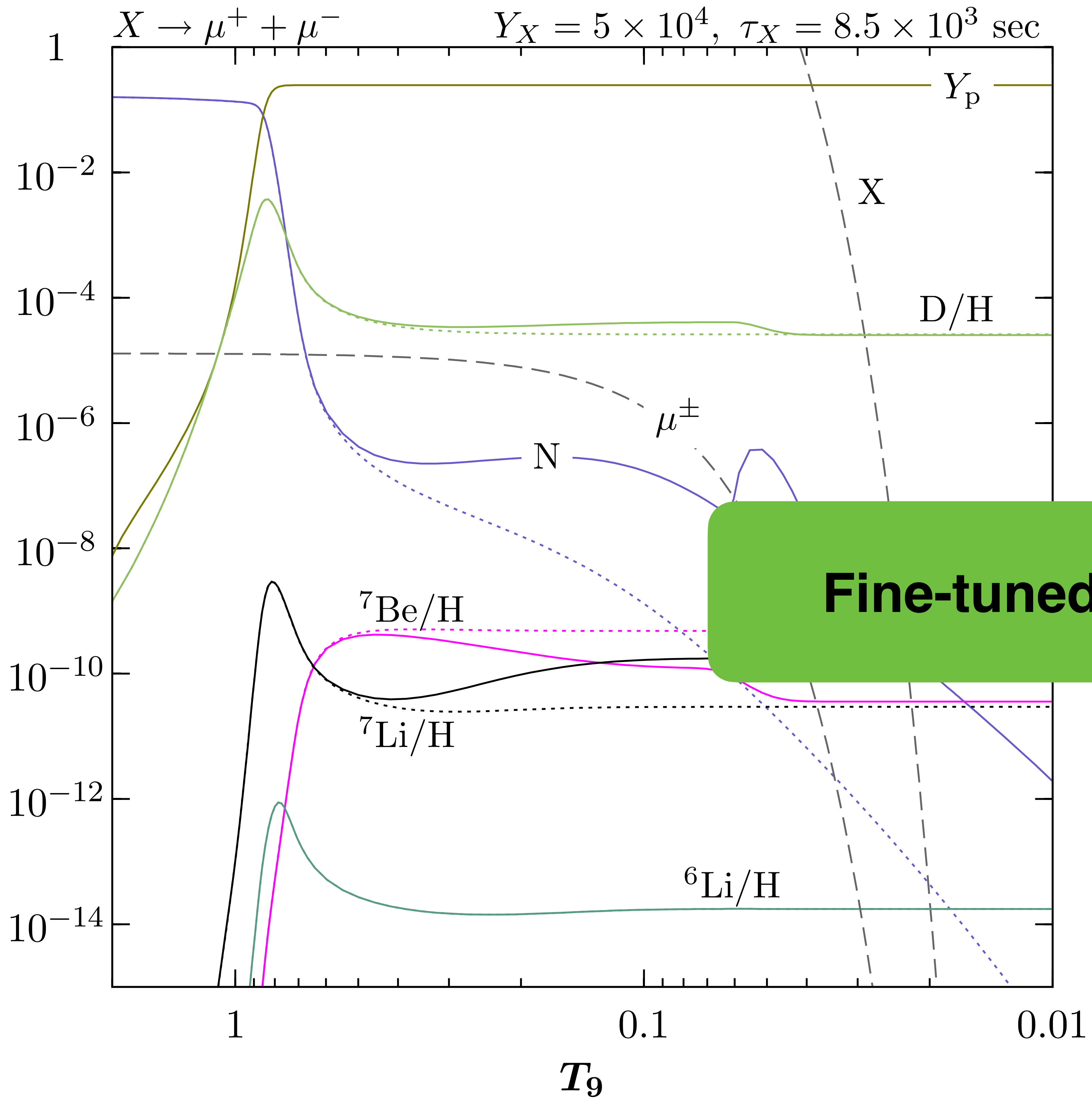
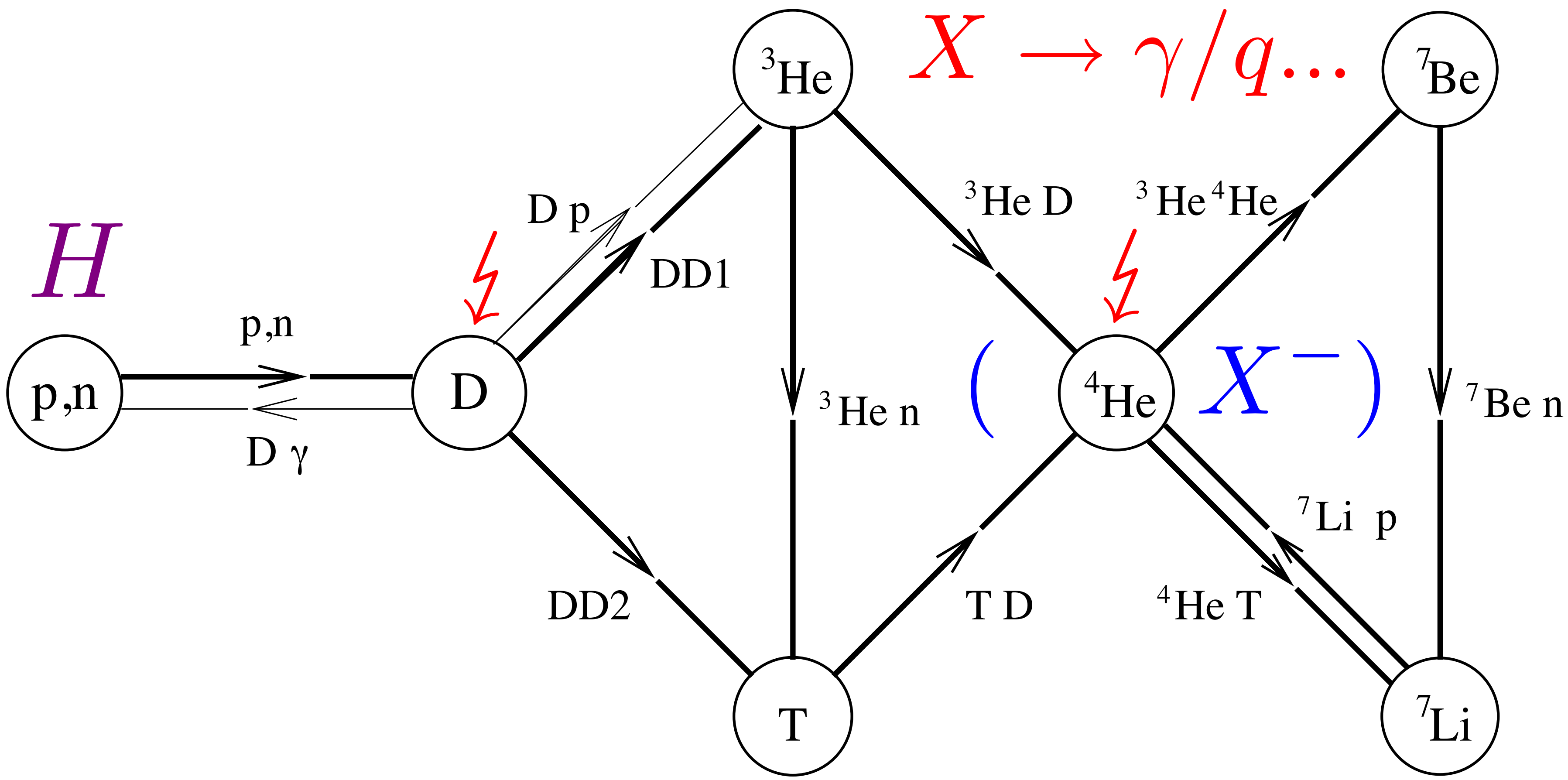


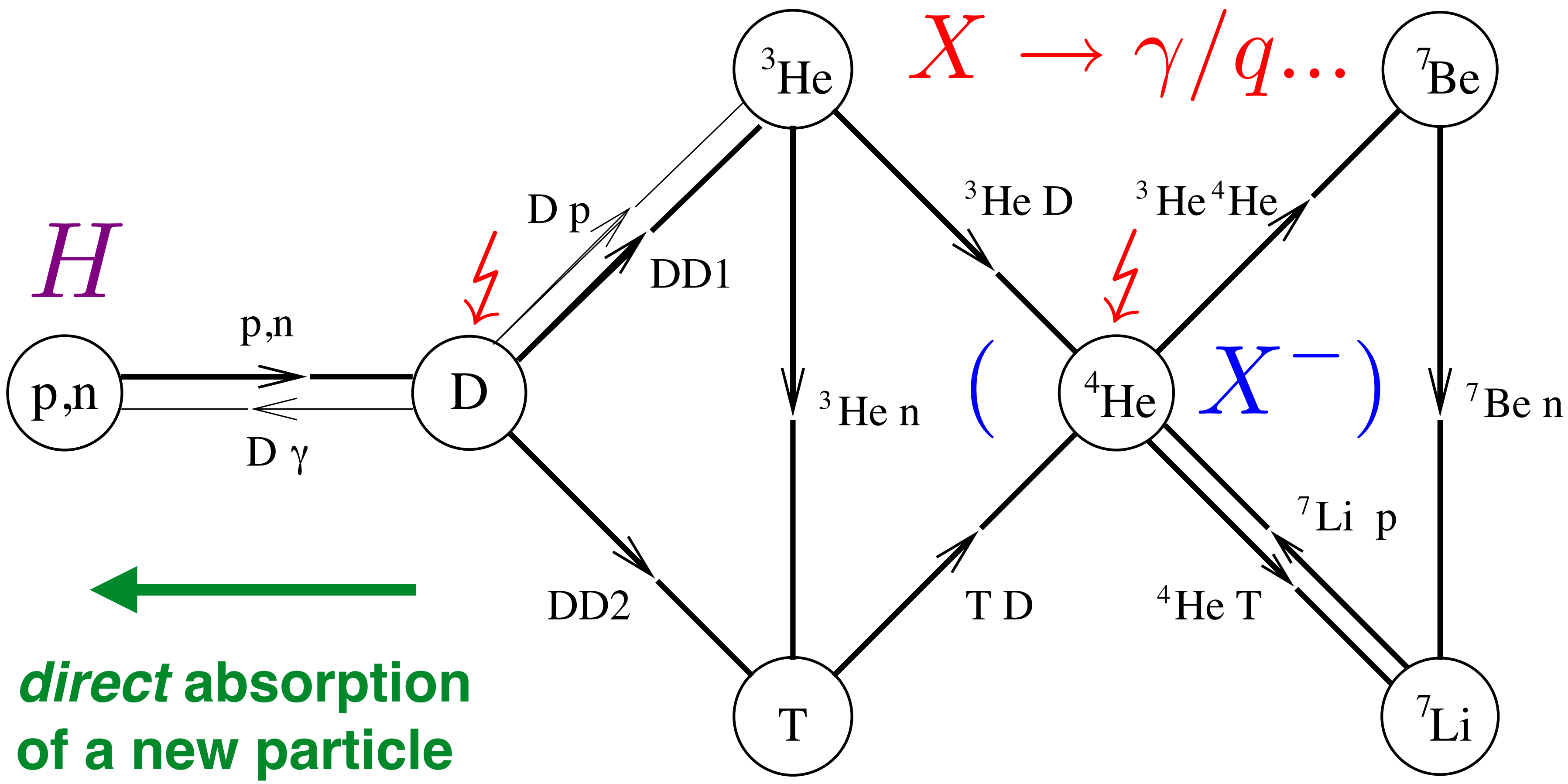
Fine-tuned solution

Beyond SBBN - Lithium solution?



Precise D/H measurements disfavor lithium solutions that utilize energy injection to spall ^{7}Be (albeit fine-tuned solutions exist!)

Beyond SBBN - Lithium solution?



Change in timing

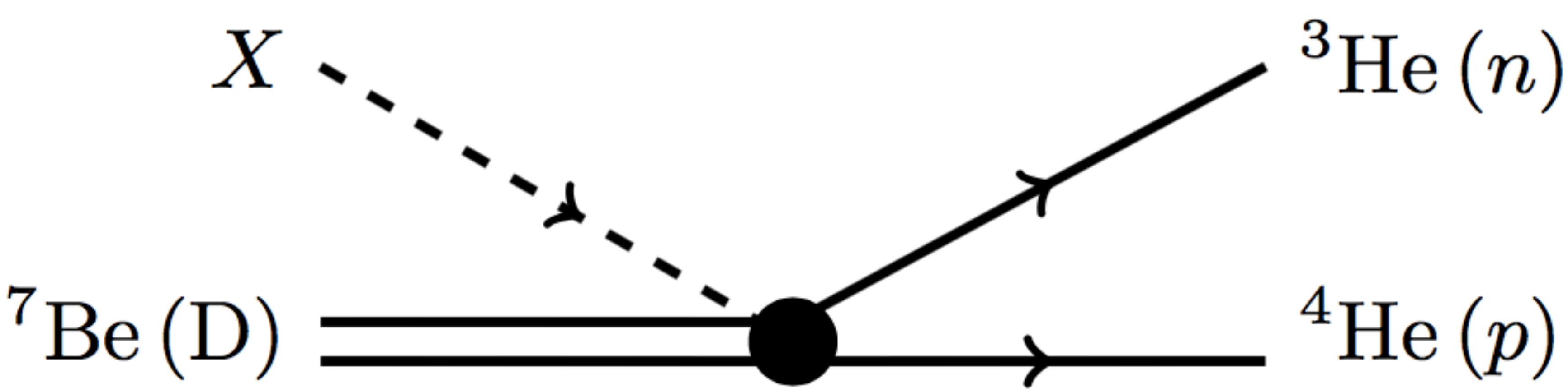
non-equilibrium BBN

catalyzed BBN

A real solution to the lithium problem

Ingredients: a bosonic state X that

1. lives 100 sec or longer
2. couples to quarks
3. has a mass/energy between 1.6 - 20 MeV
4. is abundant (relative to baryons)



binding 2.2 MeV

binding 1.6 MeV

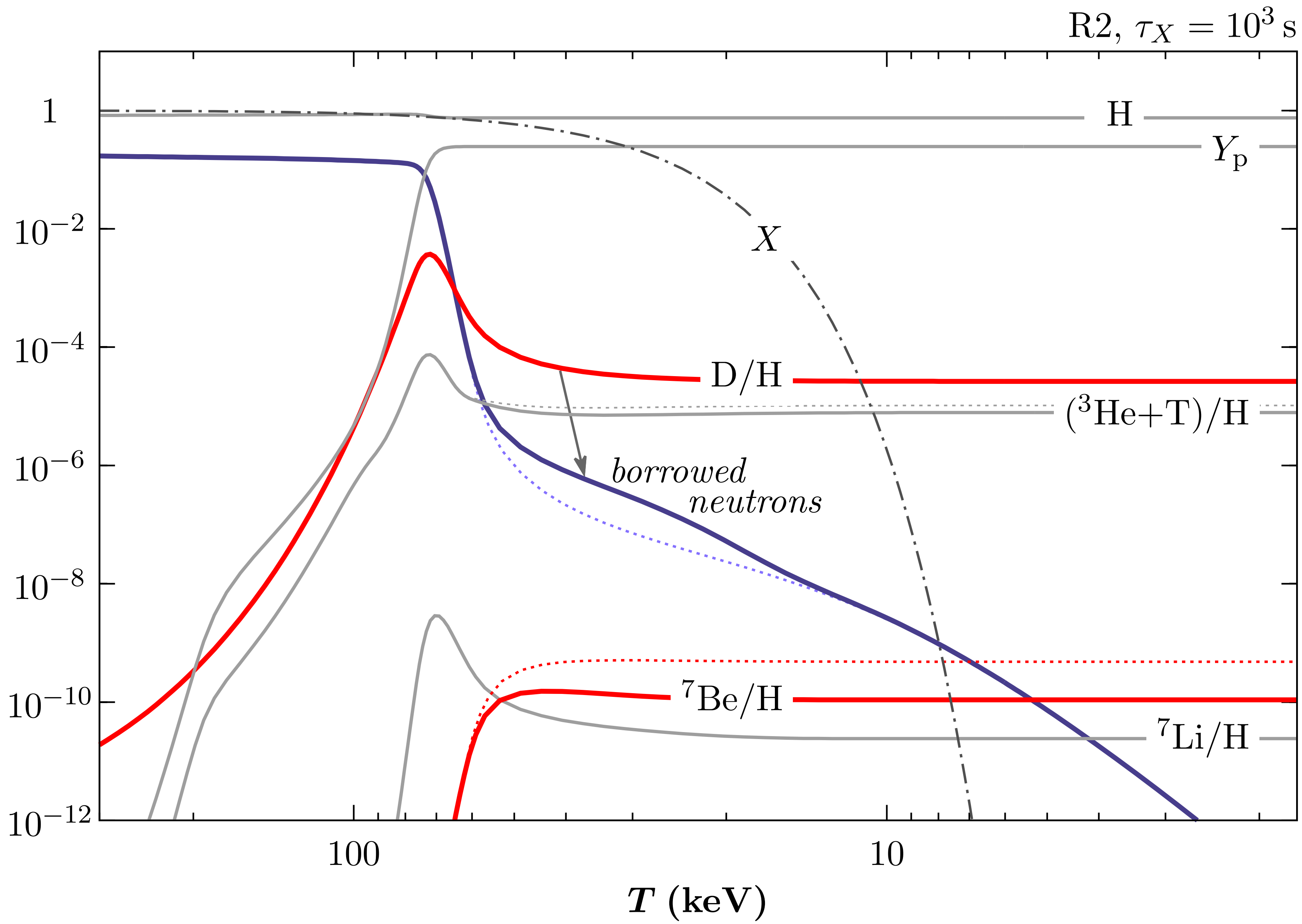
=> use mass/energy of X
to undo the binding

“Borrowed neutrons” as a solution to the lithium problem

neutrons are dug from their nuclear graves; they set in motion a ^{7}Be depleting sequence:

$$^{7}\mathrm{Be} + n \to {}^{7}\mathrm{Li} + p$$

$$^{7}\mathrm{Li} + p \to {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$$



Keeps all other element yields unchanged!

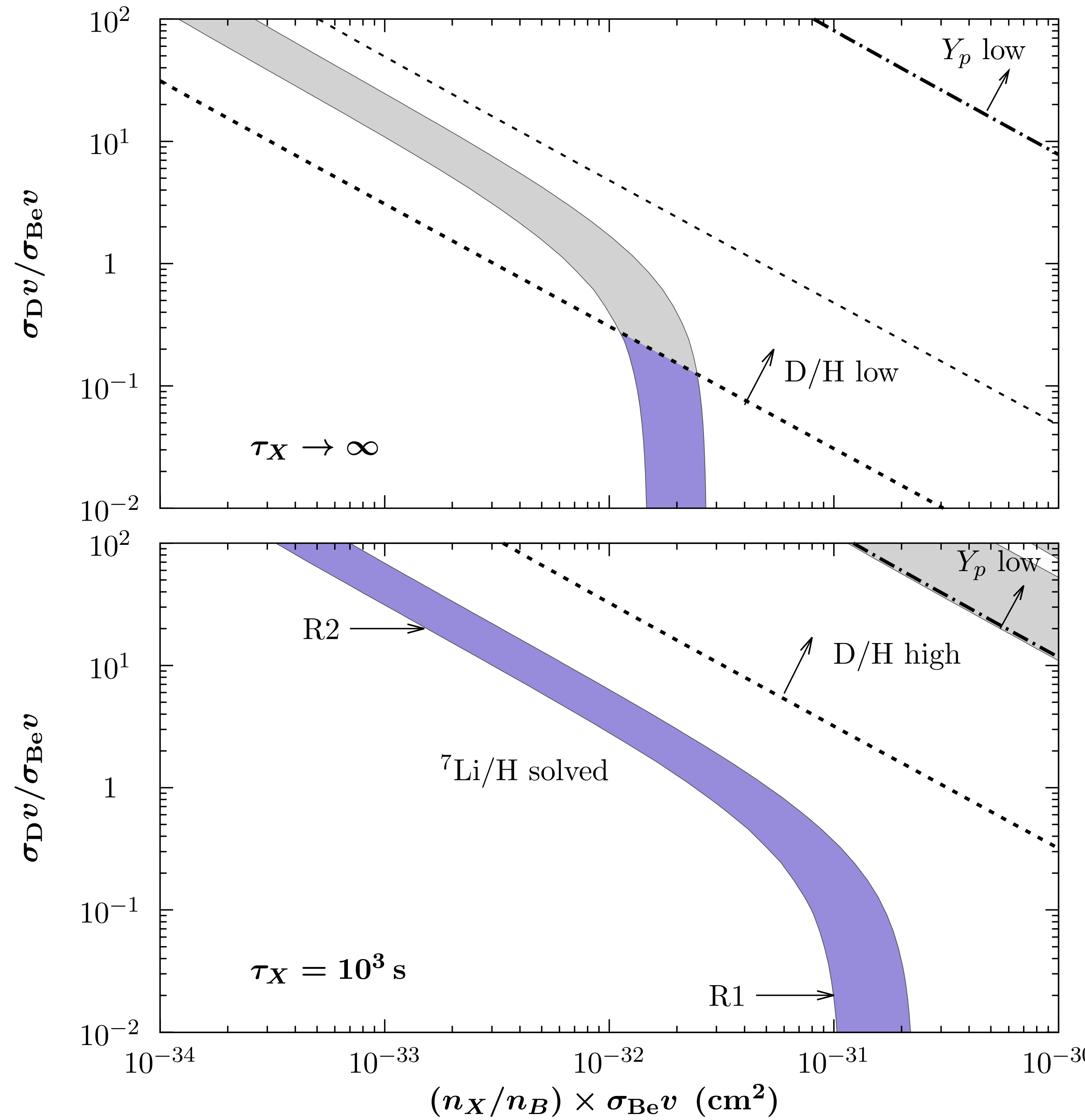
A new solution to the lithium problem

$$\mathrm{R1}: \ {}^7\mathrm{Be}(X,\alpha)^3\mathrm{He}$$

$$\mathrm{R2}: \ \mathrm{D}(X,p)n$$

lifetime >> 1000 sec:
replenishment of D inhibited by ongoing X absorption and n decay

lifetime ~1000 sec:
neutrons are only borrowed and return to D



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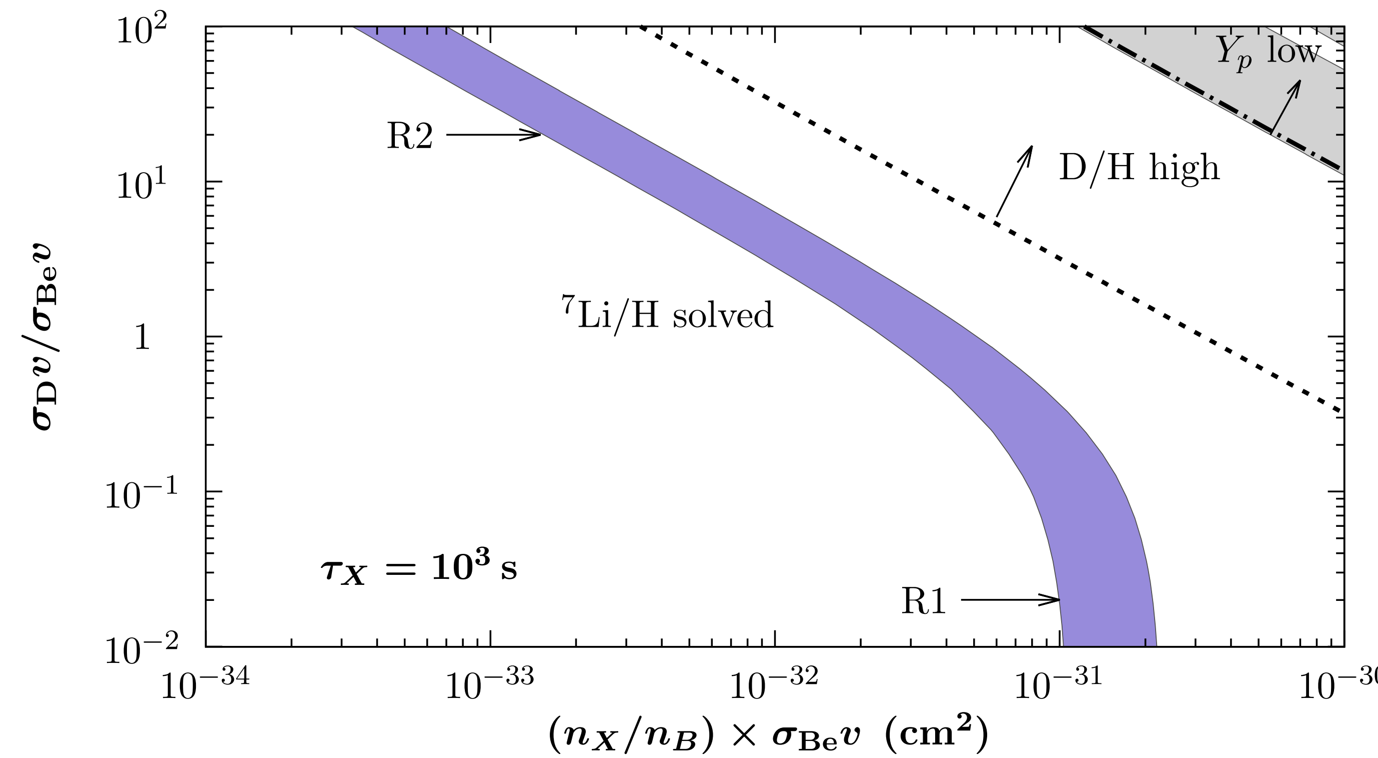


In blue band, essentially,

$$n_X \sigma_{\mathrm{abs}} v \sim H$$

at ^{7}Be formation (~50 keV)

E.g. 5 MeV particle, 1% of photon energy density

=> $\sigma_{\mathrm{abs}} v \sim 10^{-38} \ \mathrm{cm}^2$

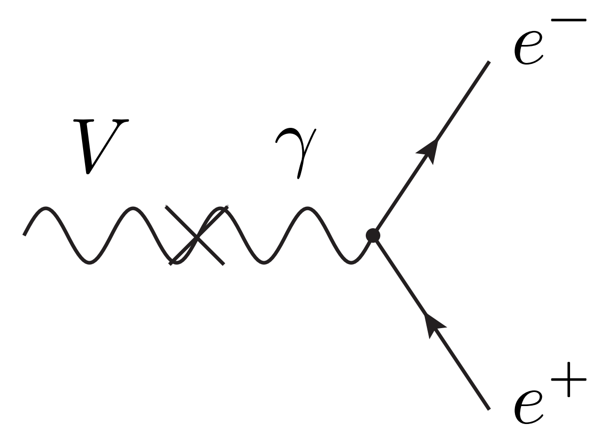
=> much smaller than photo-nuclear reactions, and much larger than weak interactions, but lifetimes comparable to β decays

=> very small couplings to electrons, photons, and neutrinos to make it work (“leptophobic models”)

What could X be?

Dark Photon?

decays to fast
for required
coupling



A $U(1)_B$ vector?

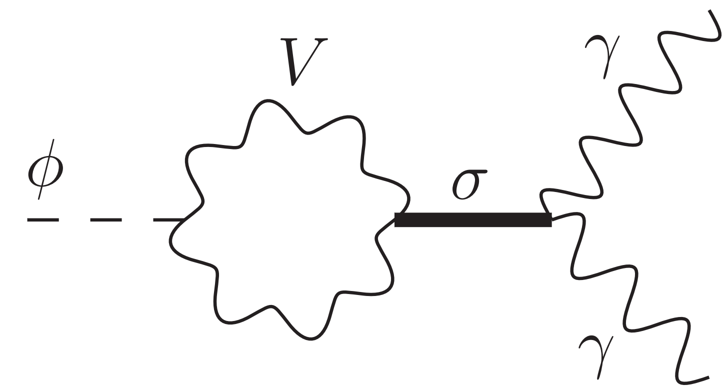
radiatively generated kinetic
mixing will have to be tuned
to be suppressed

What could X be?

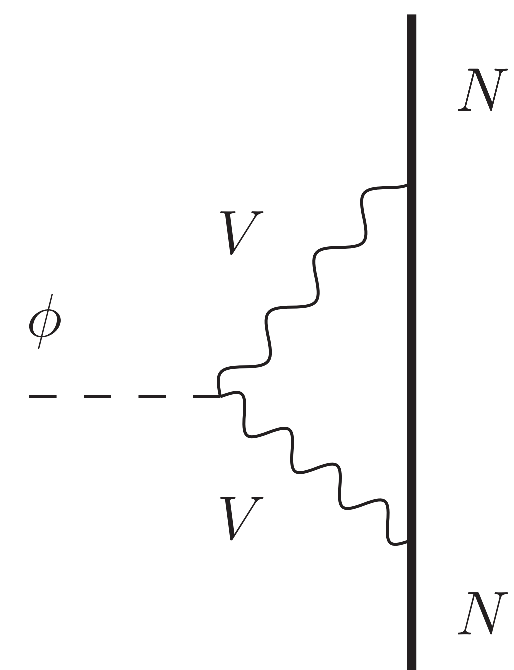
The Higgs that breaks $U(1)_B$?

It is long lived

$m_\phi < 2m_V$



Couples to nucleons and
can be absorbed by light elements



What could X be?

Axion-like particle (a.k.a. “ALP”) that couples to down-quarks

$$\mathcal{L}_{aq} = \frac{\partial_\mu a}{f_d} \bar{d}\gamma_\mu\gamma_5 d$$

At low energies $$\mathcal{L}_{a\pi N} = \frac{\partial_\mu a}{f_d}\left[f_\pi \partial_\mu \pi^0 + \frac{4}{3}\bar{n}\gamma_\mu\gamma_5 n - \frac{1}{3}\bar{p}\gamma_\mu\gamma_5 p\right]$$

w/ naive quark model estimates for spin content of nucleons

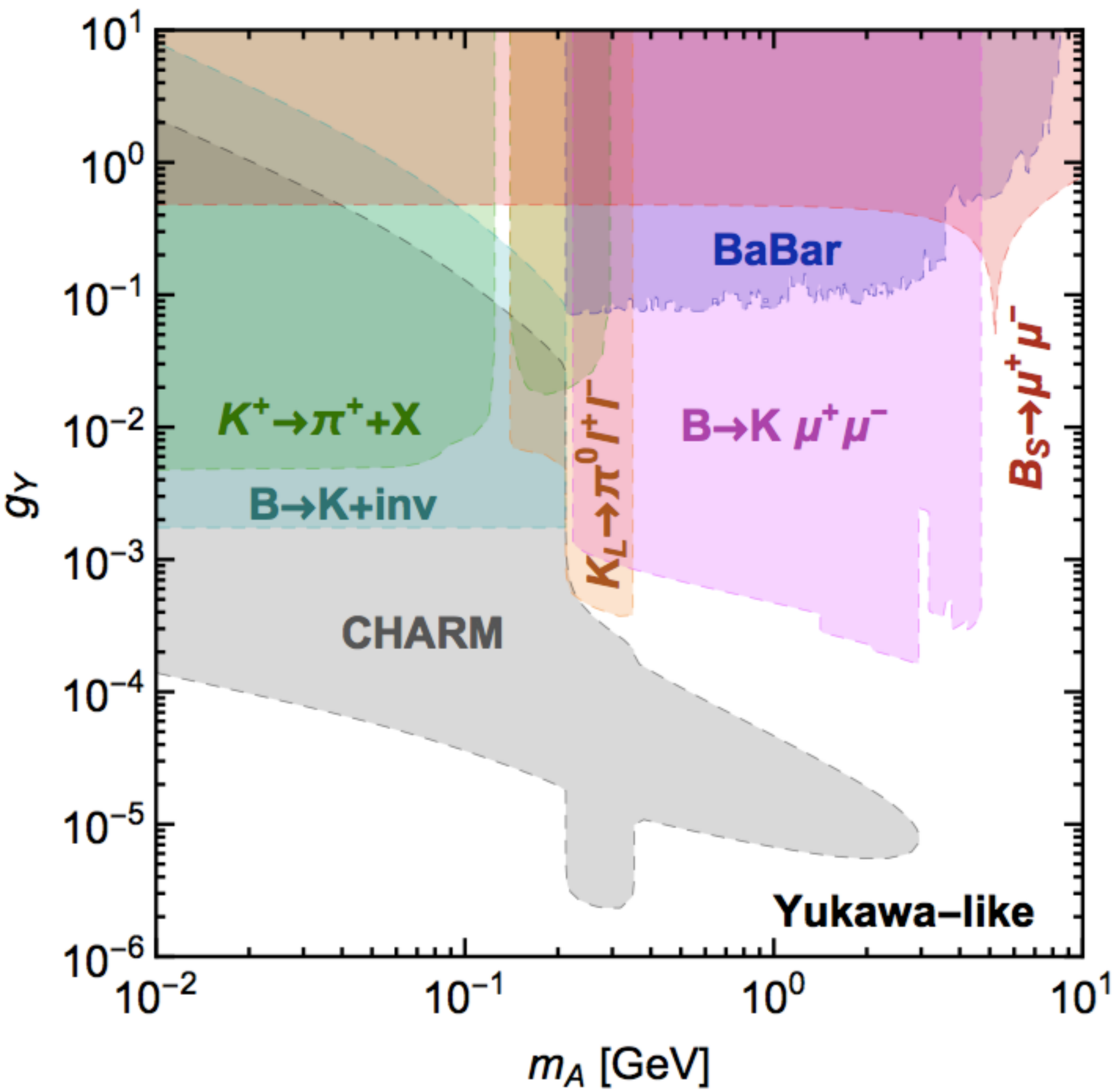
Decays through $a - \pi$ mixing

$$\theta = (f_\pi/f_d)\times(m_a^2/m_\pi^2)$$

$$\Gamma^a_{\gamma\gamma} \simeq \theta^2 \left(\frac{m_a}{m_\pi}\right)^3 \Gamma^{\pi^0}_{\gamma\gamma} = \left(\frac{1\ \mathrm{TeV}}{f_d}\right)^2 \left(\frac{m_a}{5\ \mathrm{MeV}}\right)^7 \frac{1}{100\ \mathrm{s}}$$

ALP like particles with TeV-scale f_d

Dolan et al 2014



We couple it to d-quarks to be compatible with $K^+ \to \pi^+ + \mathrm{inv}$

$$\mathrm{BR}(K^+ \to \pi^+ + \mathrm{inv}) \lesssim 4 \cdot 10^{-10}$$

UV completion:

$$H_u H_d \exp\{ia/f_a\}$$

$$f_d \gg f_u \quad \text{when} \quad \langle H_u \rangle \gg \langle H_d \rangle$$

Scenario B: Axion sourced from decay of X_p

Once X=a is injected, the particles free stream

$X_p \to aa$

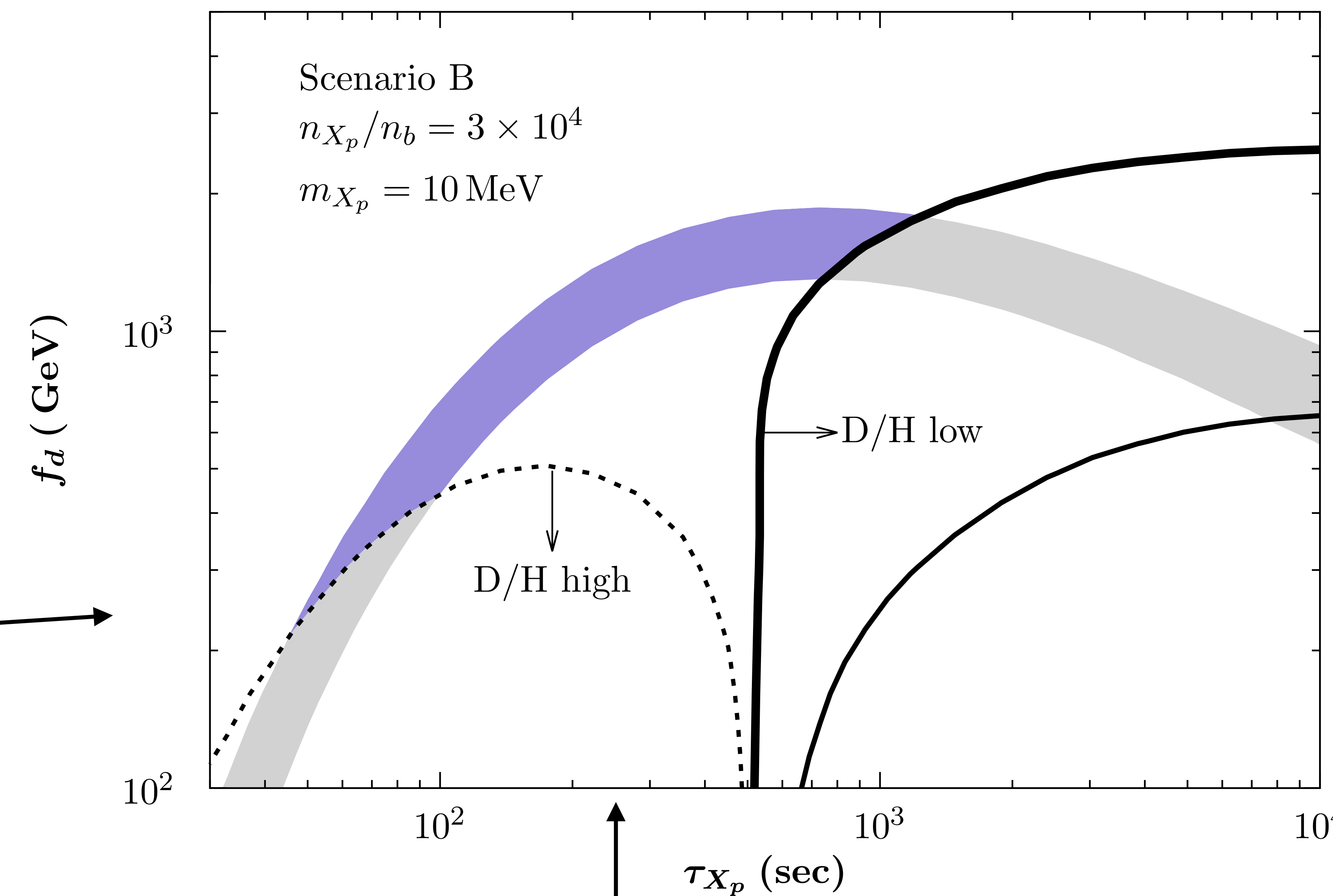
=> “piled-up” of axions $g(T,E) = 2\int_T dT_1 \frac{\Gamma_{in} Y_{X_p}(T_1)}{H(T_1) T_1}\delta\left(\frac{T}{T_1}E_{in} - E\right)$

=> absorption rate

$$\Gamma_{\rm abs} = \int_{|E_B|}^{E_{in}} dE\, g(T,E) s(T) \sigma_{\rm abs}(E) v(E) \qquad \frac{\sigma_{{\rm abs},i}}{\sigma_{{\rm photo},i}} \simeq \frac{D_i}{4\pi\alpha} \times \frac{E_a^2}{f_d^2}$$

Scenario B: ALP solution to Li

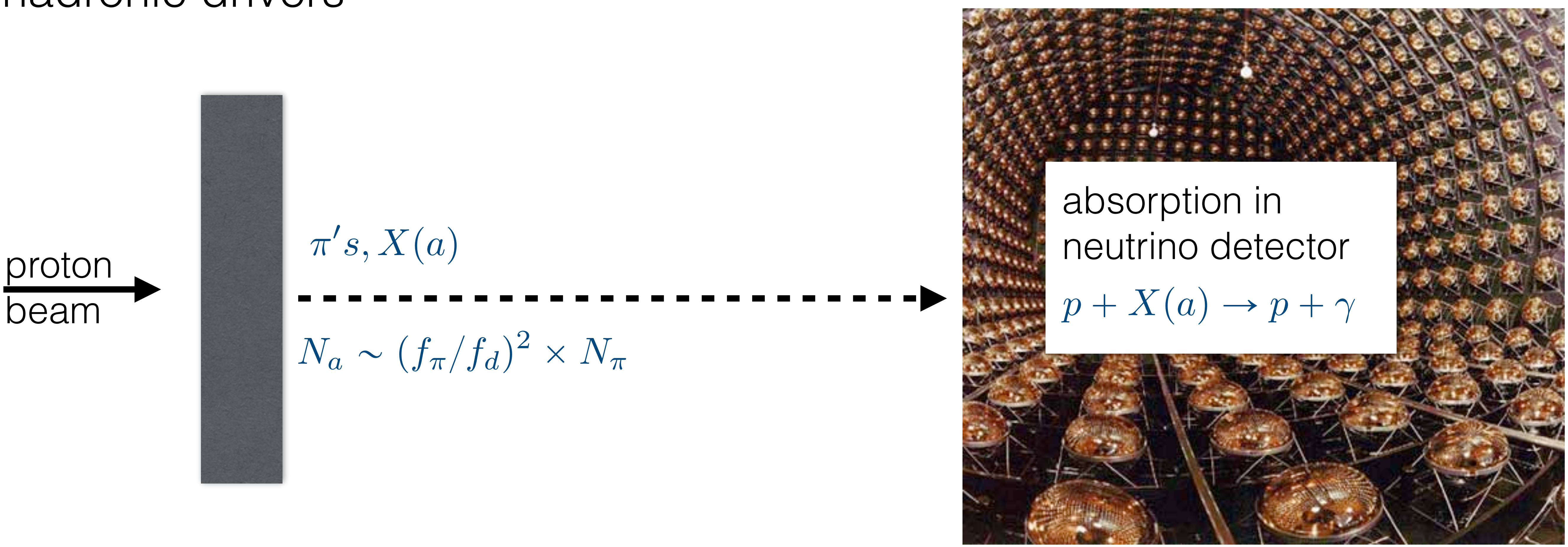
Abundance of X_p determines the vertical position of curves



D only forms, here but a from early decays survive

Intensity frontier prospects

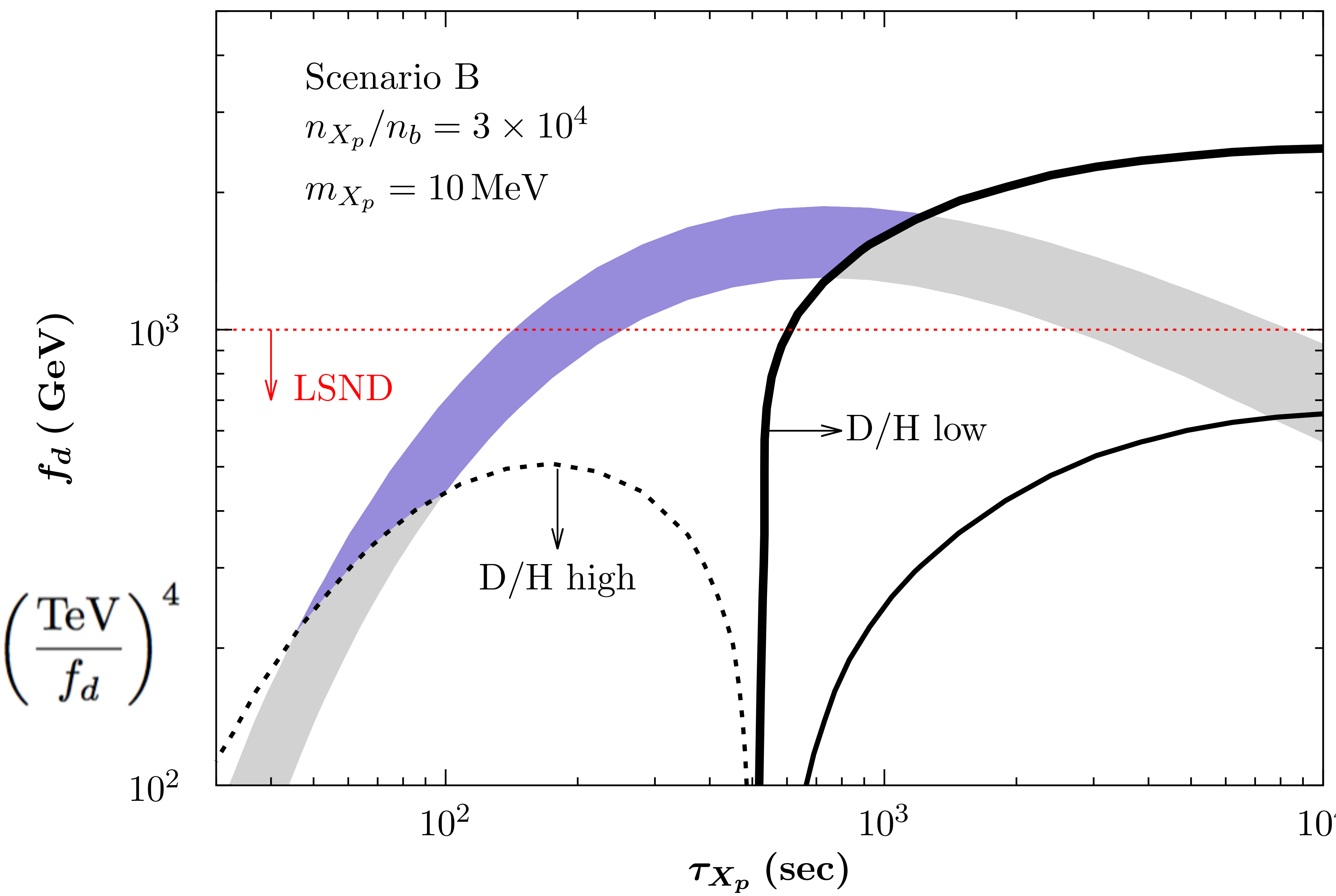
Target for neutrino experiments with hadronic drivers



Intensity frontier prospects

LSND puts most stringent limits (adopted from their measurement of neutrino-electron elastic scattering)

$$N_{\text{events}} \sim \frac{N_a N_p \sigma_{ap}}{4\pi L^2} \sim 6 \times \left(\frac{\text{TeV}}{f_d}\right)^4$$



A more detailed intensity frontier / astro-constraints study is planned [J.L-Kuo, JP]

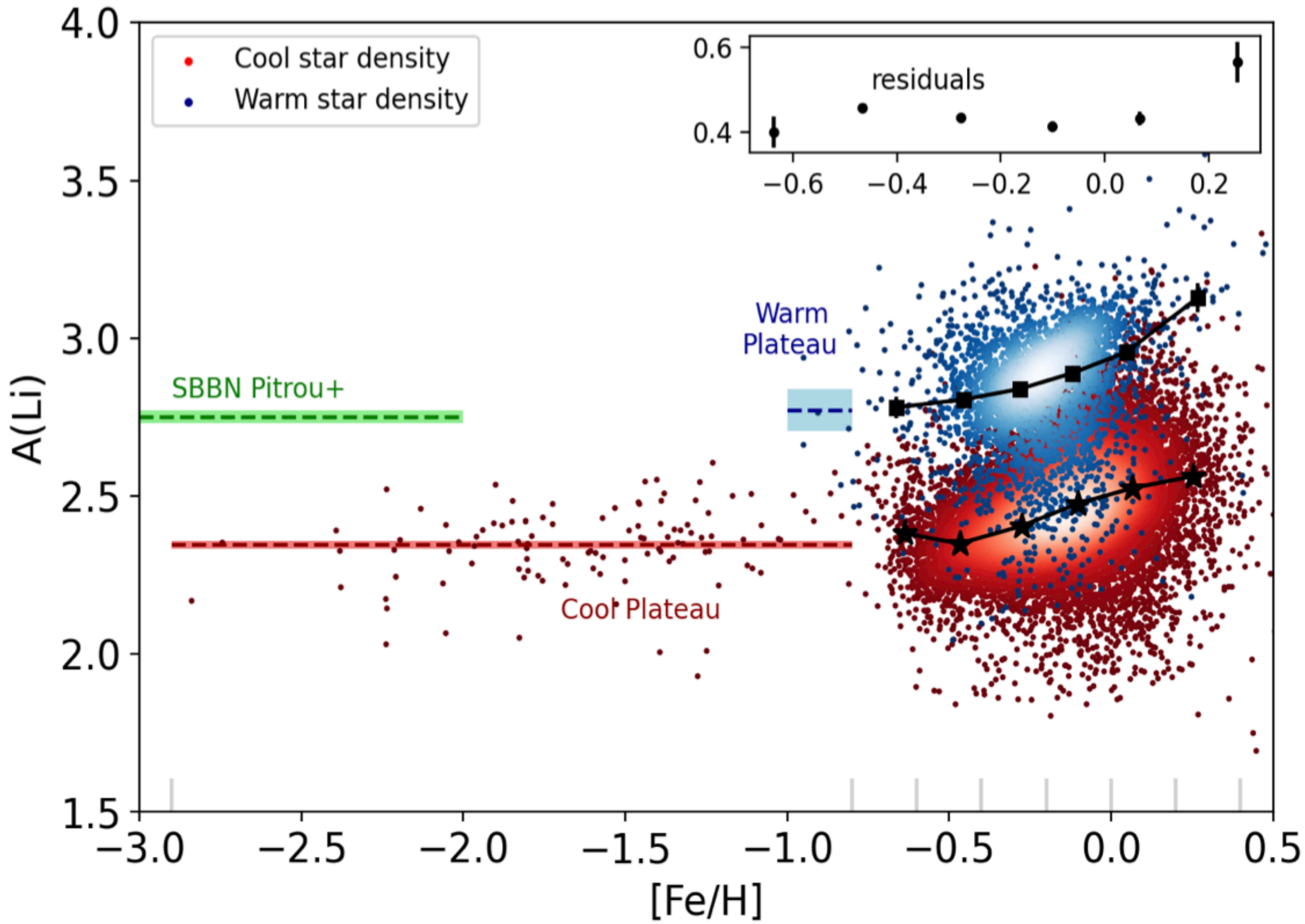
Conclusions and Outlook

- BBN provides a non-trivial cosmological test to any new physics models with particle content present at 1 sec after Big Bang

- *One quantitative problem in BBN:* Lithium abundance has been high by a factor of 3-5 for many years. Role of stars potentially important, but a clear picture has yet to emerge

  => soft energy injections sets off a lithium depleting chain by creating extra neutrons. Trouble is the now very precise measurements of D/H

  => absorption of MeV-energy particles works as selective fix to lithium, keeps D/H in place; searchable at the intensity frontier;



Gao et al 2020