BBN-Implications from a metastable (sub)GeV-scale sector

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Perimeter Institute

with Maxim Pospelov

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Outline

Part I

Big Bang Nucleosynthesis as a probe of New Physics

Based on [Pospelov, JP; Ann.Rev.Nucl.Part.Sci. 2010]

Part II

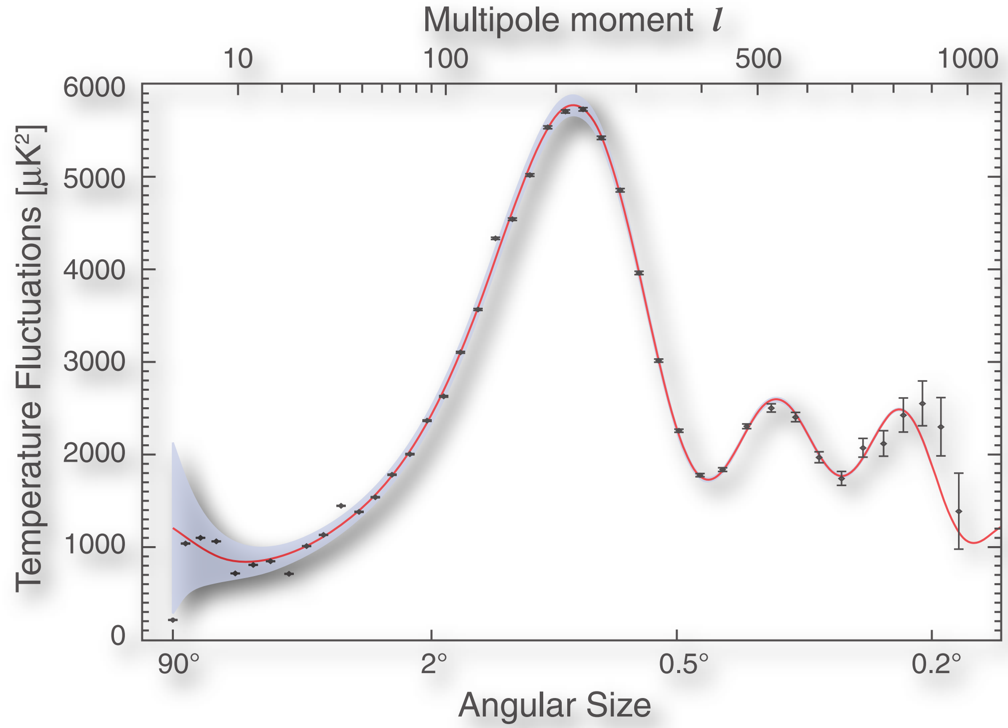
Metastable GeV-scale sector as a solution to the lithium problem

[Pospelov, JP; arXiv: 1006:xxxx]

Part I

Big Bang Nucleosynthesis as a probe of New Physics

ΛCDM and Standard BBN (SBBN)



- Standard cosmological picture

  => WMAP:
  flat Universe filled with baryons, cold dark matter, a cosmological constant and neutrinos fits data

  => Baryon density known to better than **3%** (at $z \lesssim \text{few} \times 10^3$)

$$\eta_\mathrm{b}(t_\mathrm{CMB}) = (6.225 \pm 0.170) \times 10^{-10}$$ [Dunkley et al., 2009]

- Standard BBN: SM + GR

... or more precisely

The Universe at the redshift of a billion:

basic assumptions for SBBN

- 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 $T|_{\rm init} \gg \Delta m_{np} = 1.293 \text{ MeV}$

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

- Particle content & their interactions given by the SM

$$\frac{n_b}{s}(t_{\rm BBN}) = \frac{n_b}{s}(t_{\rm CMB}).$$

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- Particle content & their interactions given by the SM

$\Rightarrow \eta_{\rm b}(t_{\rm CMB})$ as input: SBBN "parameter-free" theory

The Universe at the redshift of a billion:

basic assumptions for SBBN

- tight kinetic coupling of nucleons/nuclei to the radiation field

=> nucleons/nuclei are approximately thermally distributed

=> their abundances are found by solving the coupled set of integrated Boltzmann equations

$$\frac{dY_i}{dt} = -H(T)T\frac{dY_i}{dT} = \sum(\Gamma_{ij}Y_j + \Gamma_{ikl}Y_kY_l + ...),$$

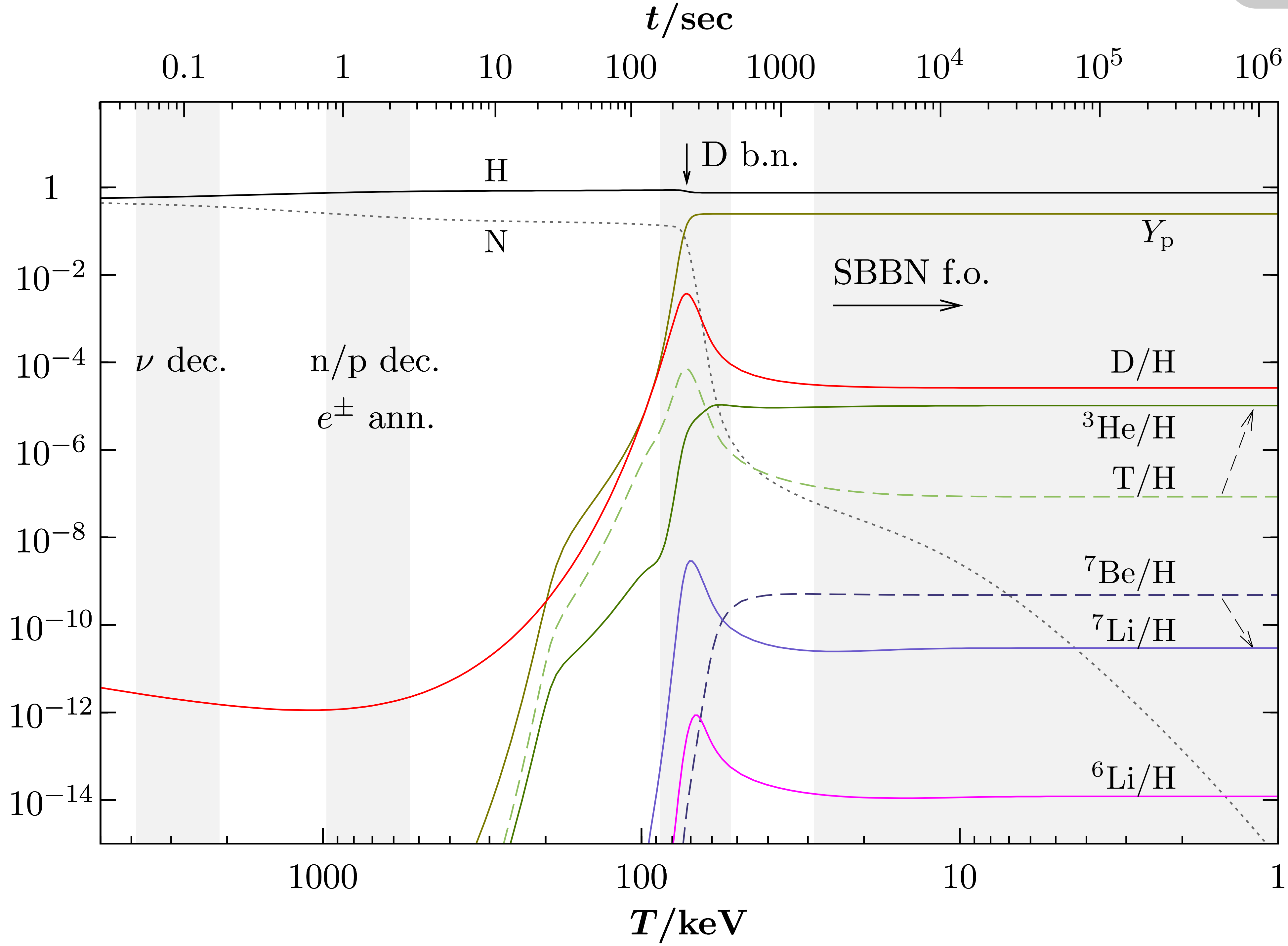
$$Y_i = n_i/n_b$$

$\Gamma_{ij...}$ generalized rates

The Universe at the redshift of a billion:

natural units: $T_9 \equiv \frac{T}{10^9 \text{ K}}$

SBBN predictions



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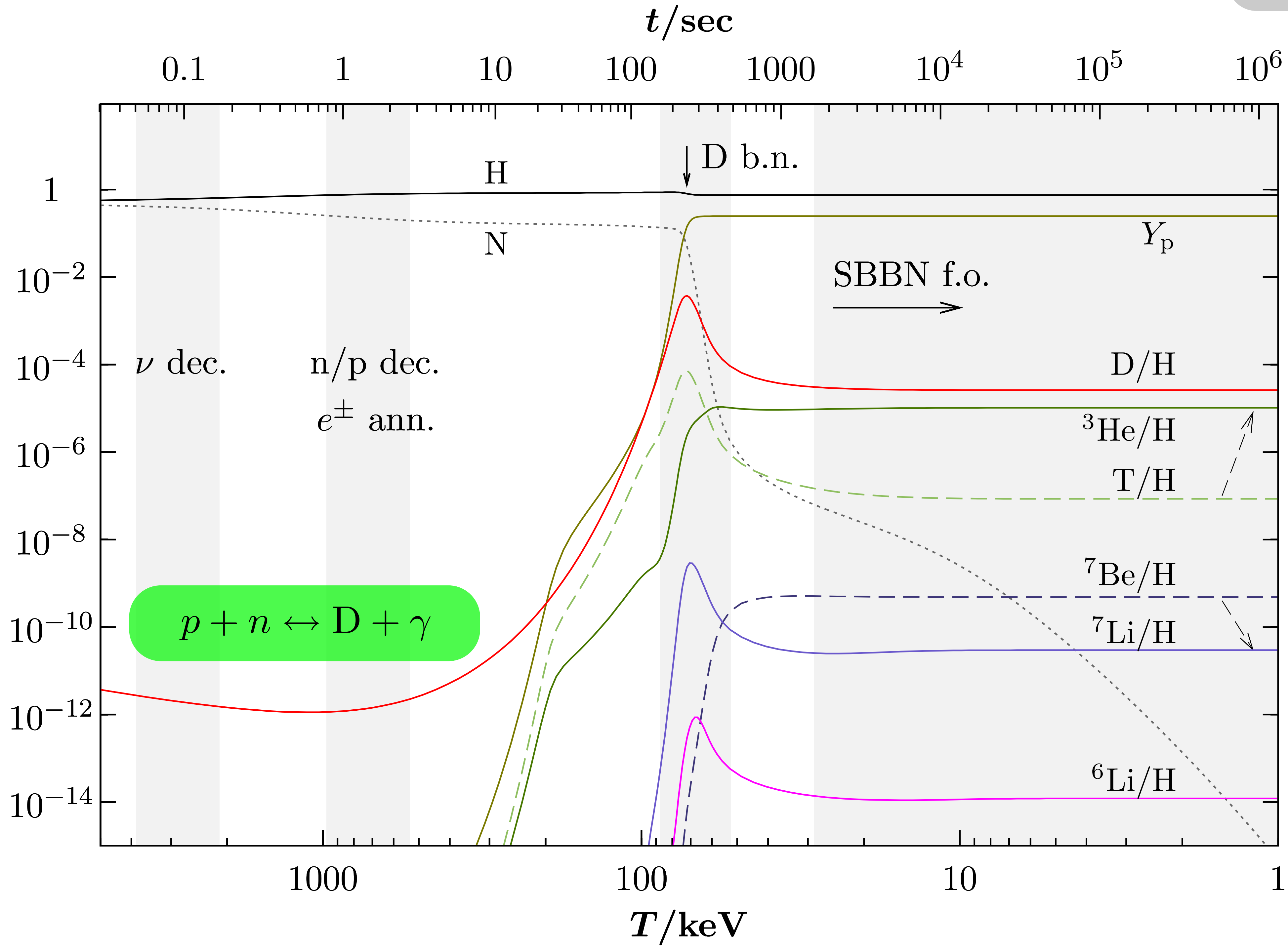

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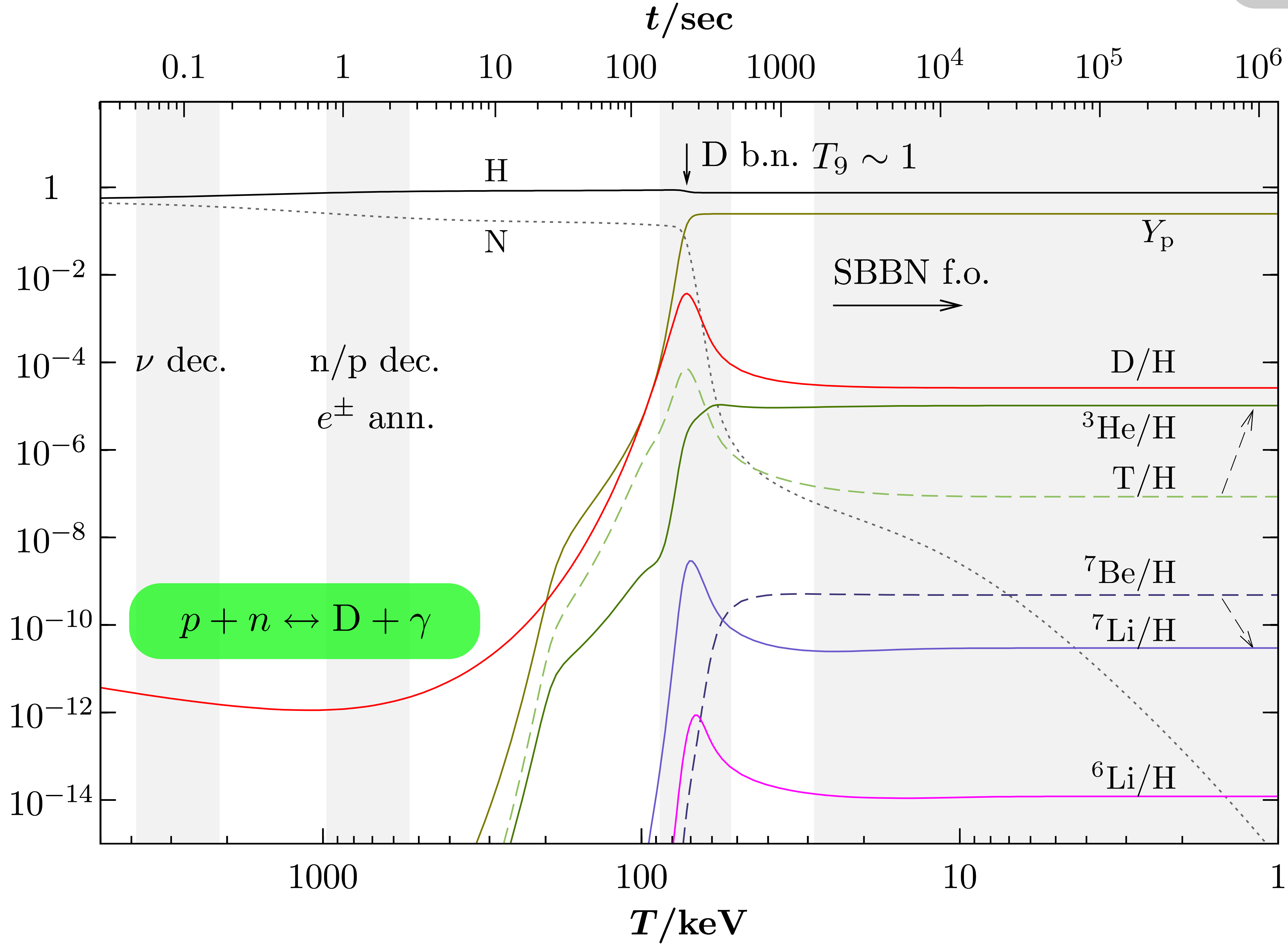


(selected) Light element observations I

- Deuterium:

  - no known astrophysical source (=> monotonic evolution)

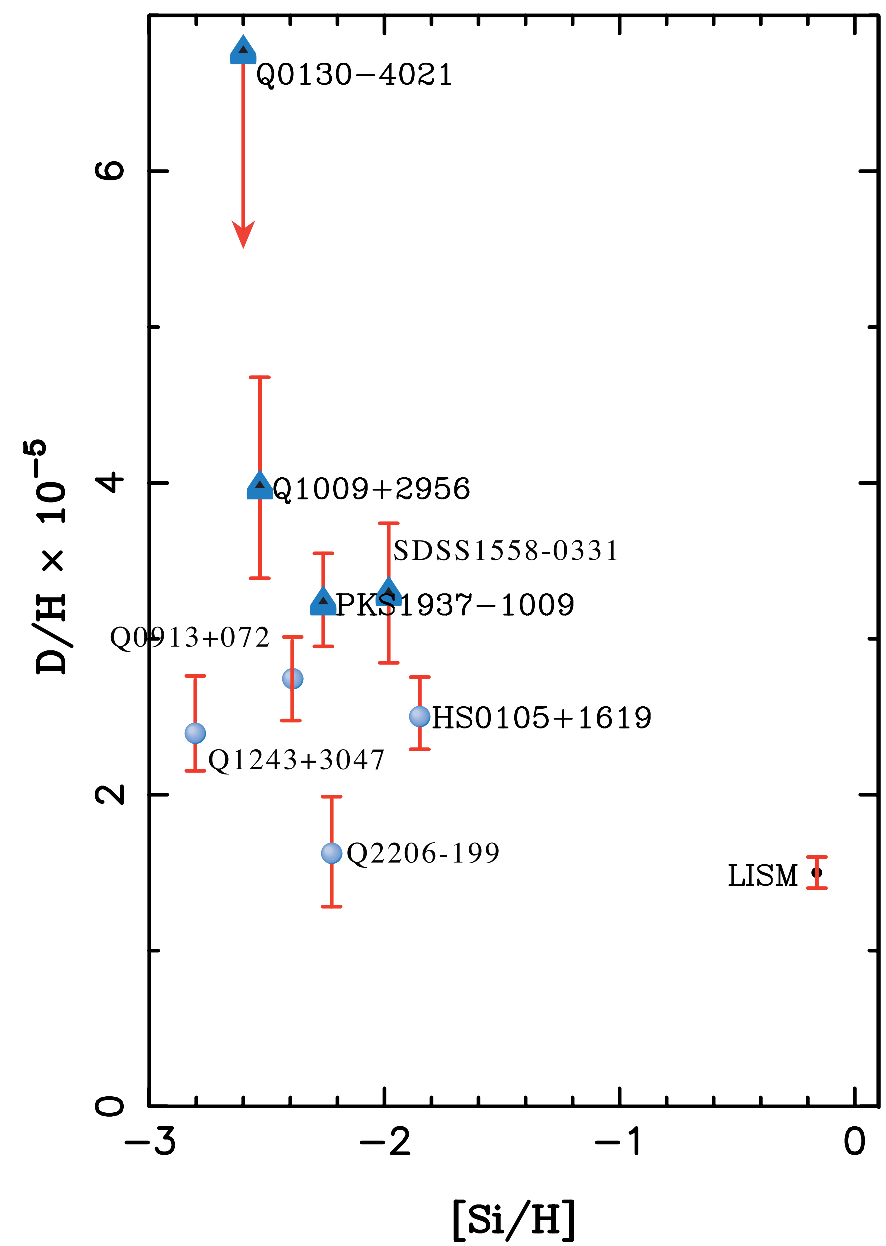
  - recent FUSE measurements [Linsky et al., 2006]

    wide dispersion in the local gas
    => potential D absorption on dust

  - inference of primordial value from Quasar absorption systems recent obs.: [Pettini et al., 2008]

    scatter may indicate underestimated systematics

from [Olive, arXiv:1005.3955]



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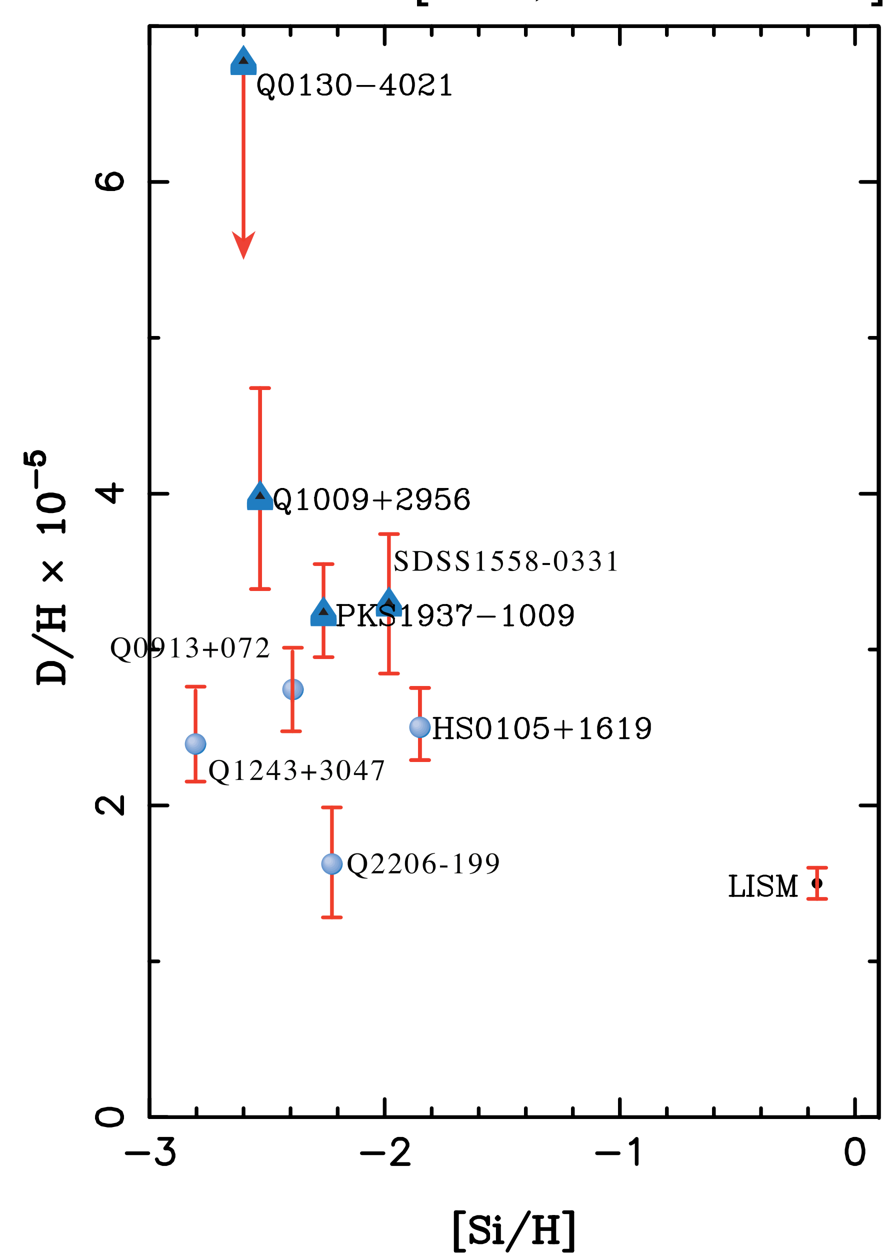
$$D/H|_{\rm SBBN} = (2.49 \pm 0.17) \times 10^{-5}$$

from [Olive, arXiv:1005.3955]



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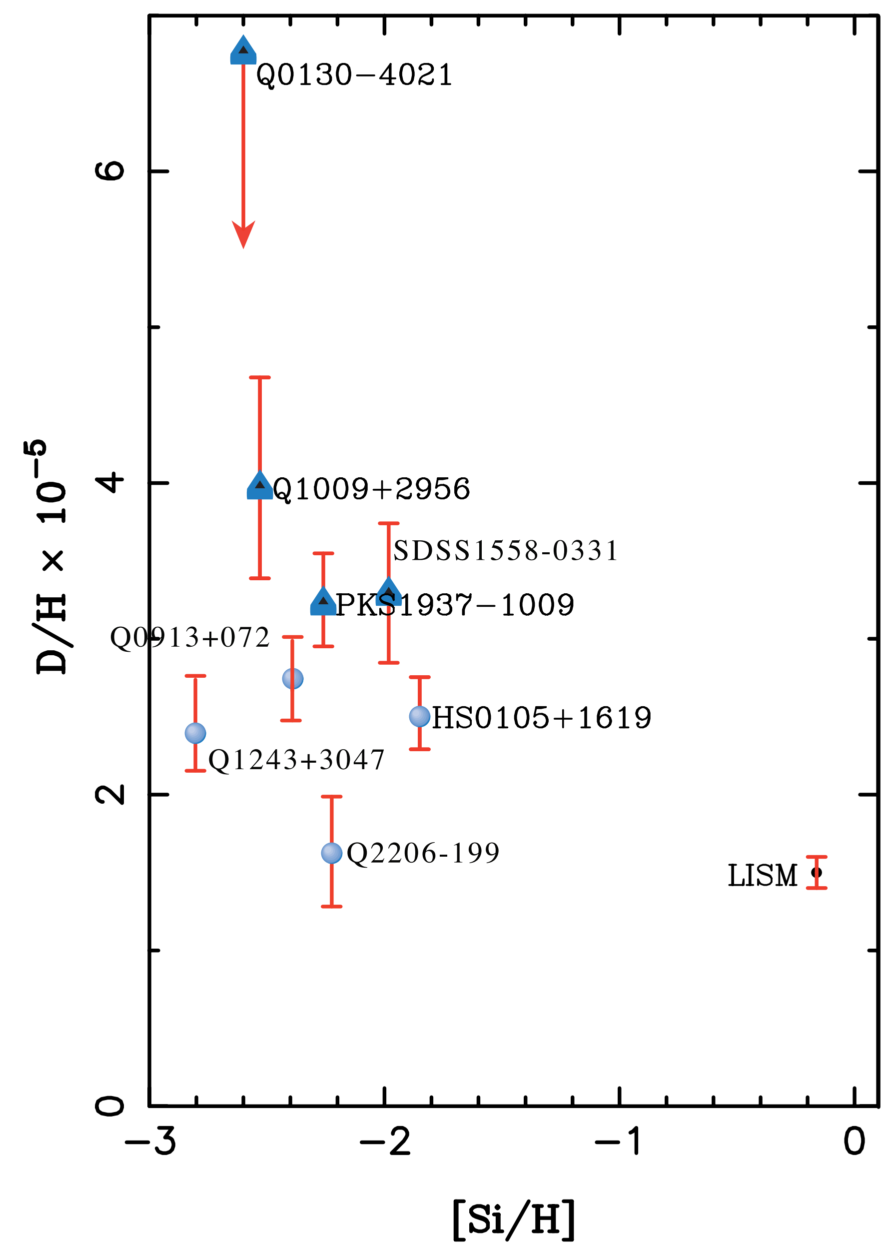


(selected) Light element observations II

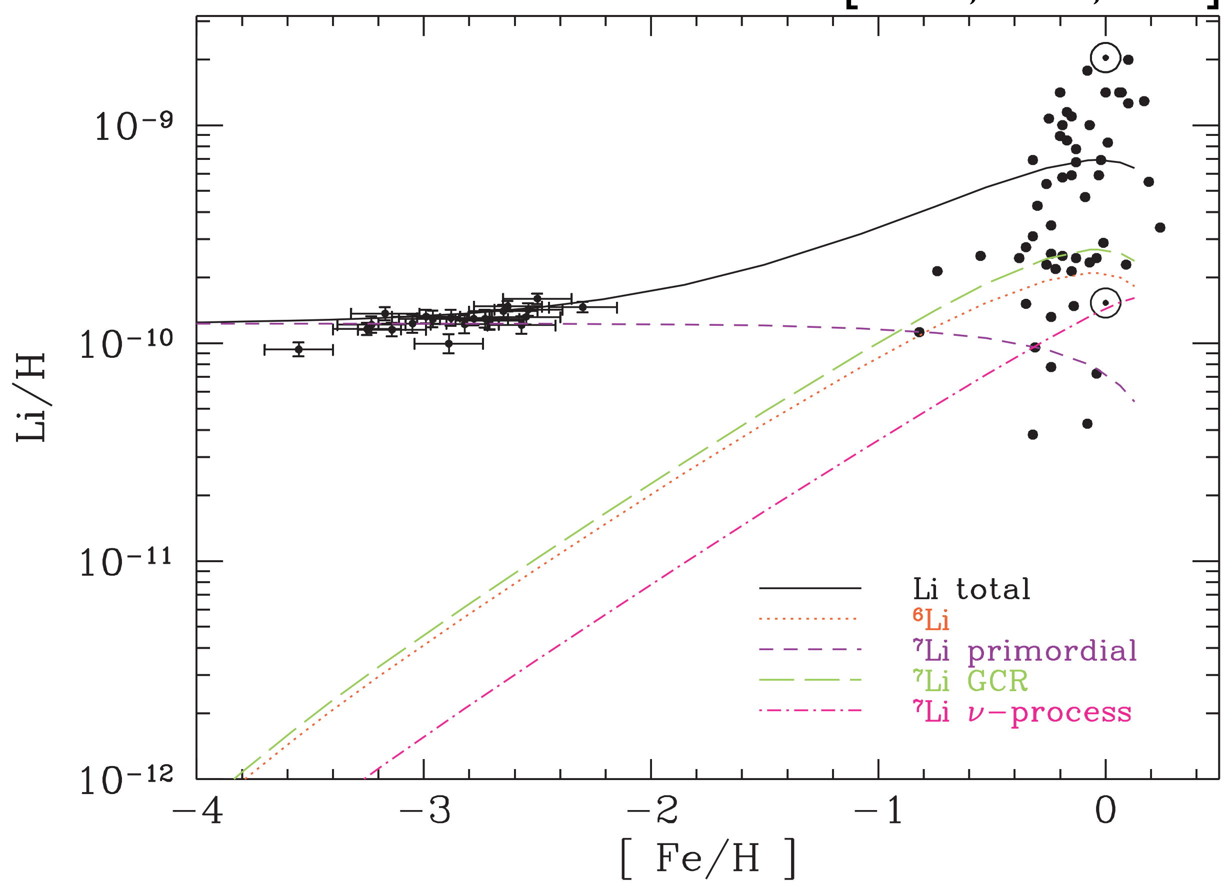
- Lithium:

  - produced in galactic cosmic rays => correlation with metallicity

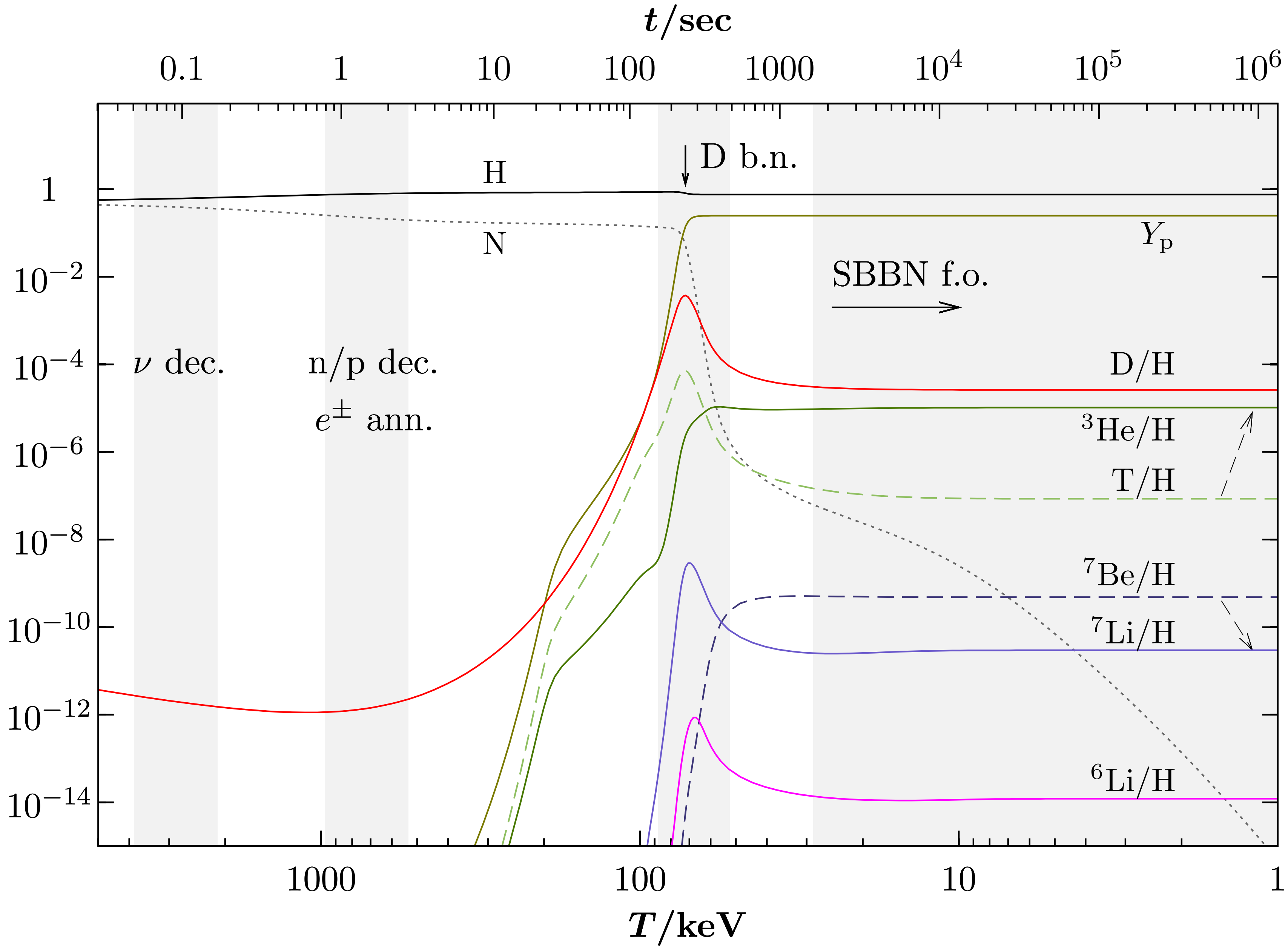
  - unlike deuterium, tiny lithium abundance forbids absorption measurements in extragalactic clouds

  - measured in atmospheres of old, metal-poor halo stars (Pop II)

[Fields, Olive, 1999]



The Li-prediction in SBBN



$$^7\mathrm{Li/H} = (5.24 \pm 0.7) \times 10^{-10}$$

[Cyburt et al., 2008]

WMAP5 + new nuclear data on $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$

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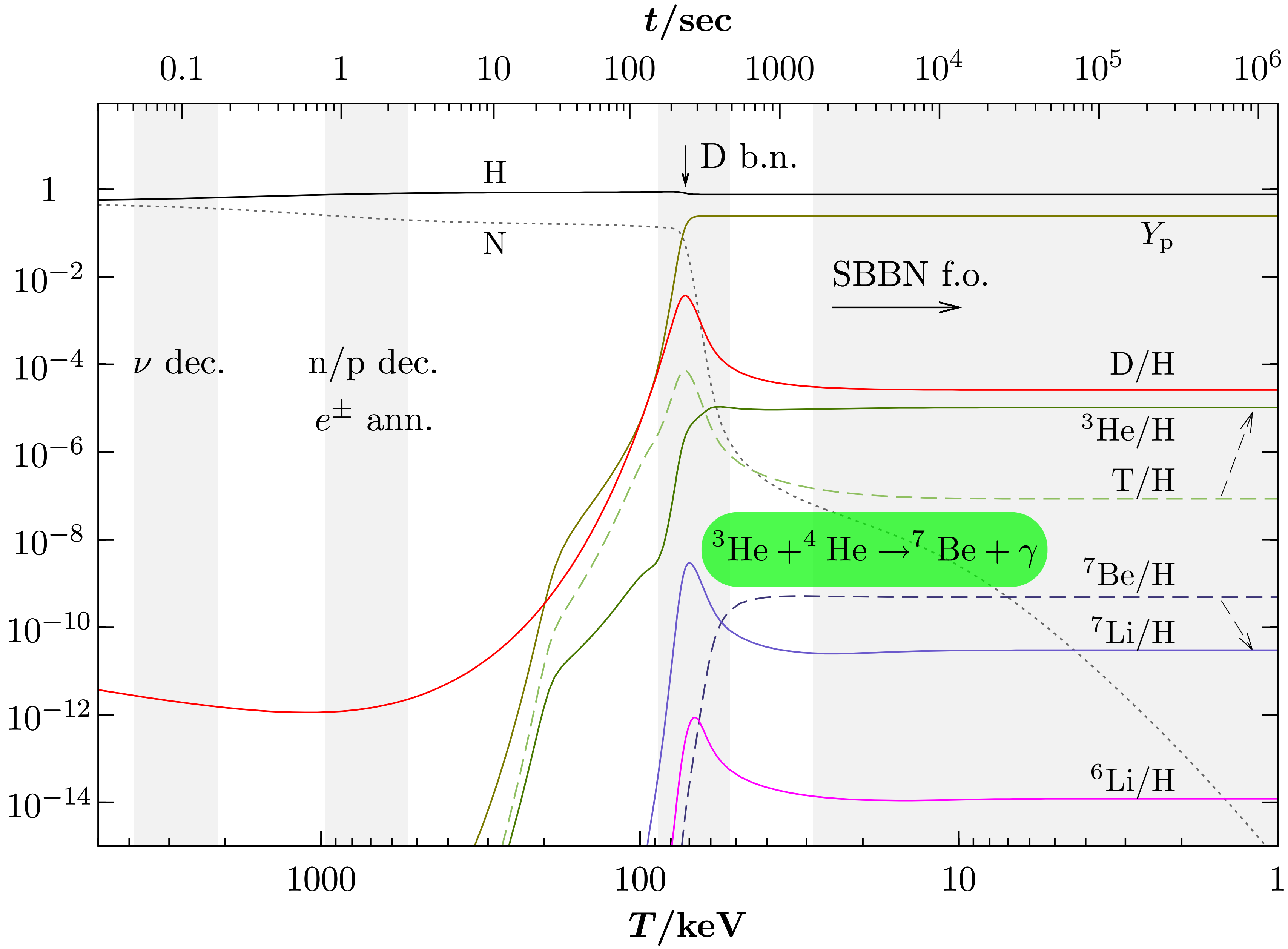

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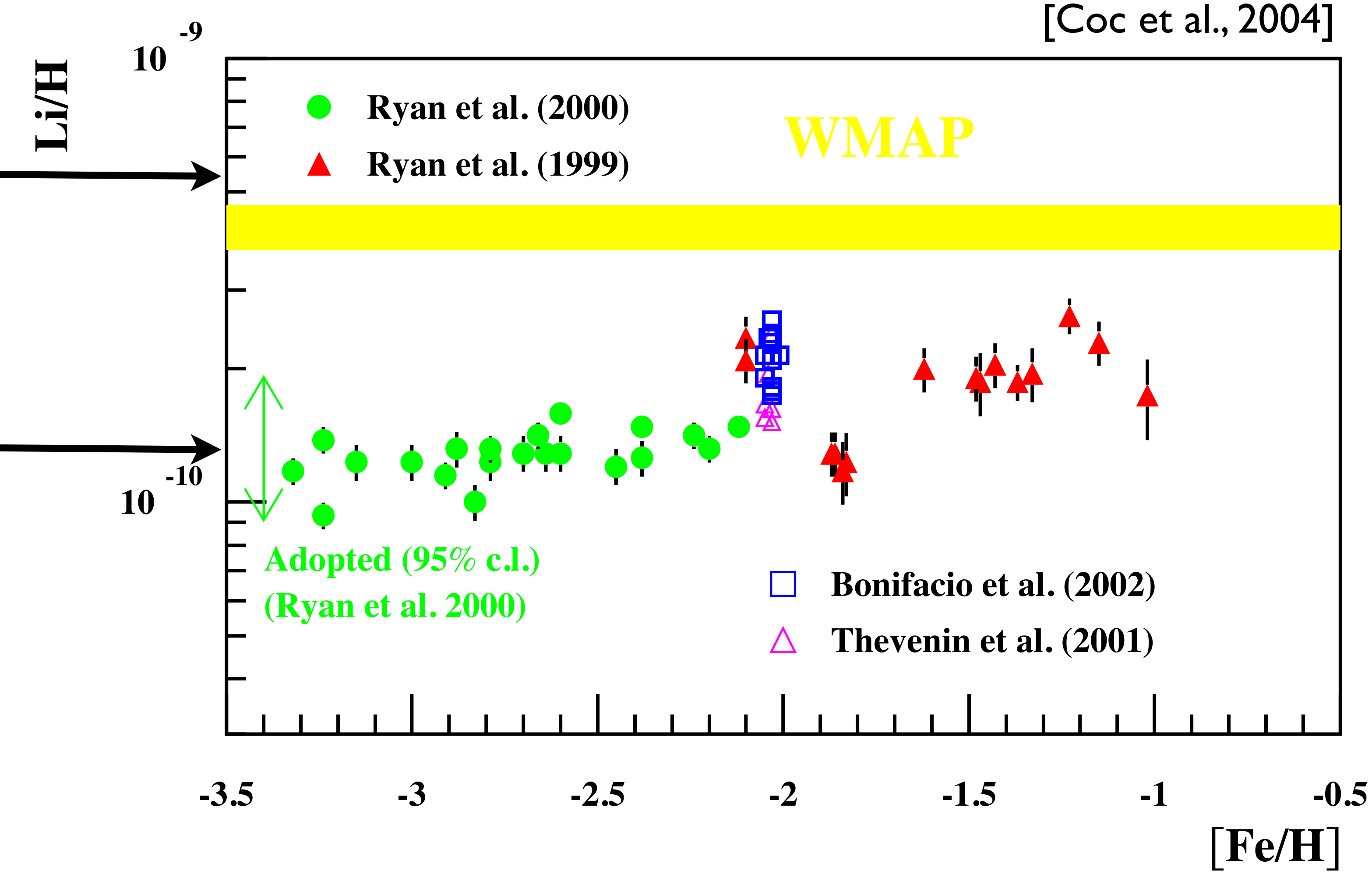
The Li-problem in SBBN

[Coc et al., 2004]

SBBN

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



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

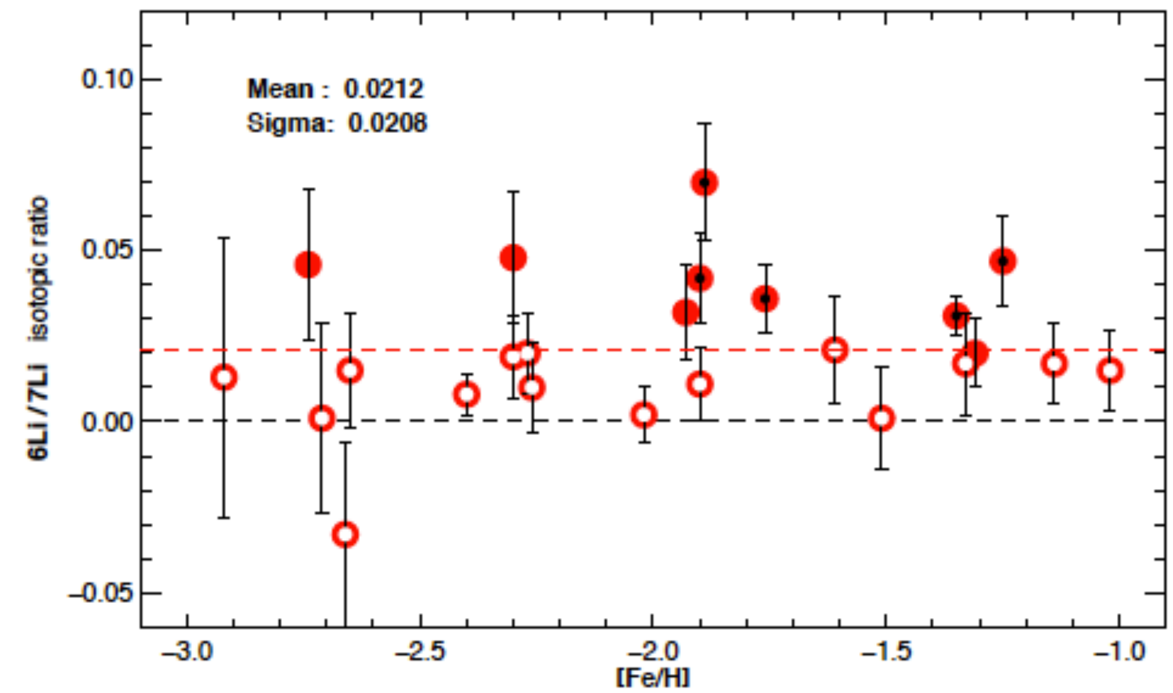
- NB: newest observations show metallicity dependence of Spite-plateau at lowest metallicities [Aoki et al., 2009; Sbordone et al. 2010, Asplund et al. 2010]

The Li-problem in SBBN #2?

- Lithium-6:

  - Claim of (2σ) detections in 9 halo stars [Asplund et al., 2006]

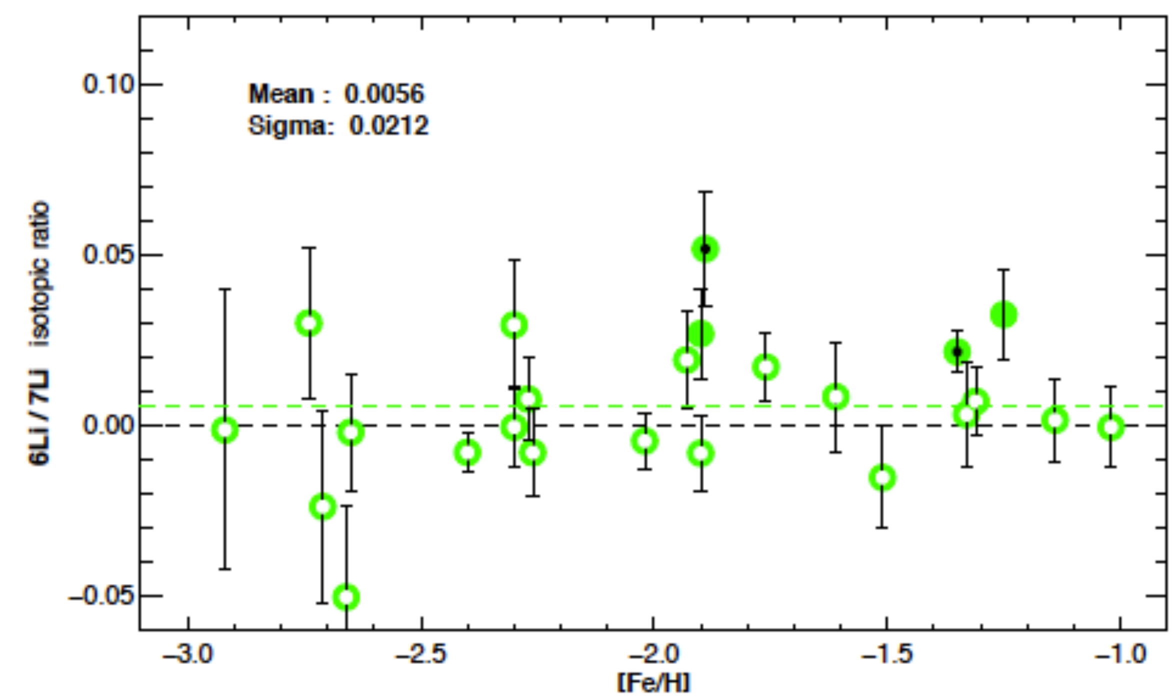
$$^{6}\mathrm{Li}/^{7}\mathrm{Li} \sim 5\%$$



  - Claim challenged [Cayrel et al., 2006]

  => Li-6 mimicked by convective motion of material

  => detections turn into upper limits



Light element predictions from helium to lithium span roughly 9 orders of magnitude in number

↓

in qualitative agreement with observations
impressive success of the hot Big Bang model

At least one quantitative problem: lithium

↓

Solution may turn out to be of astrophysical origin but could also signal new physics operative during BBN

Generic ways to affect BBN

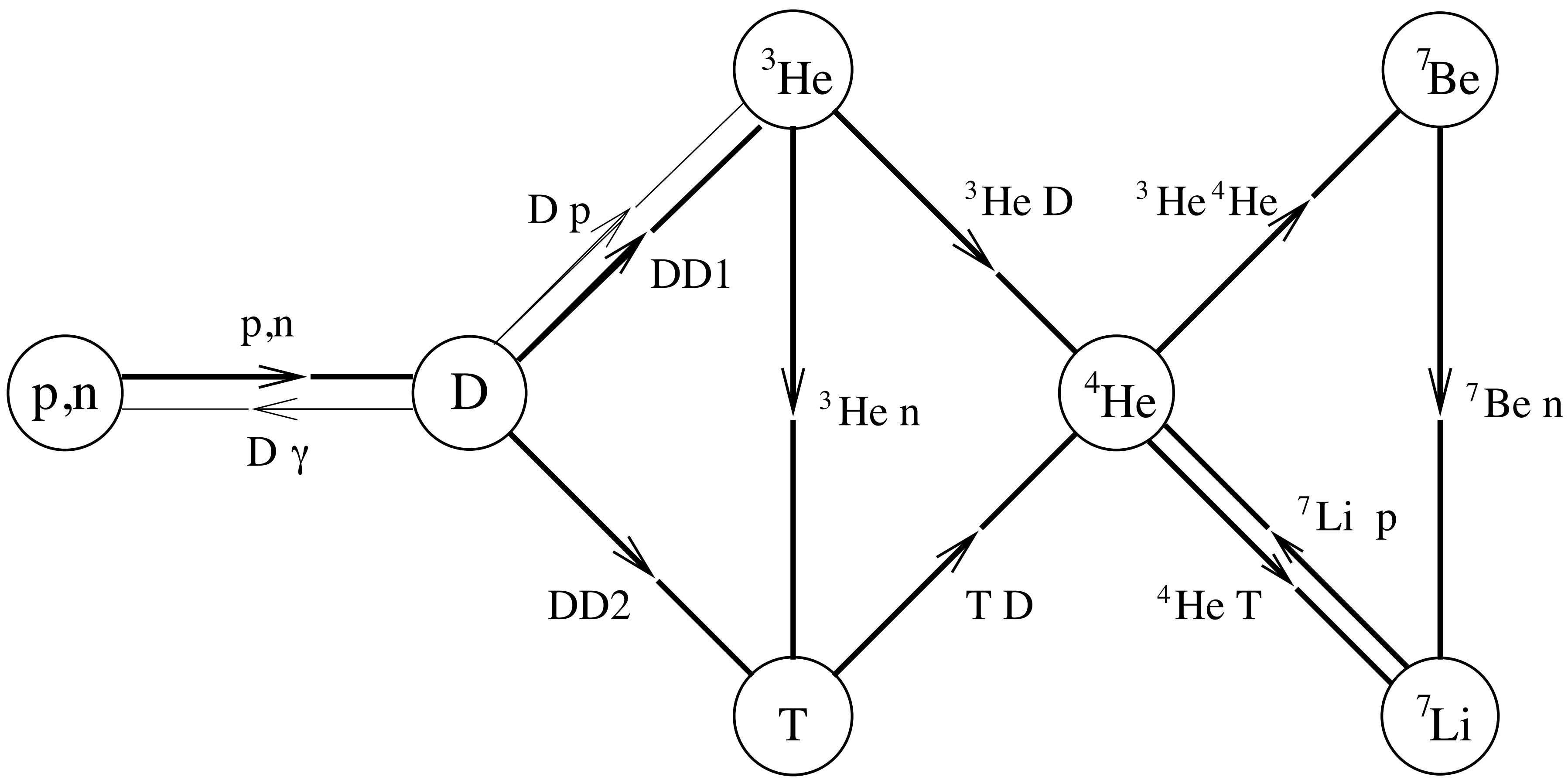
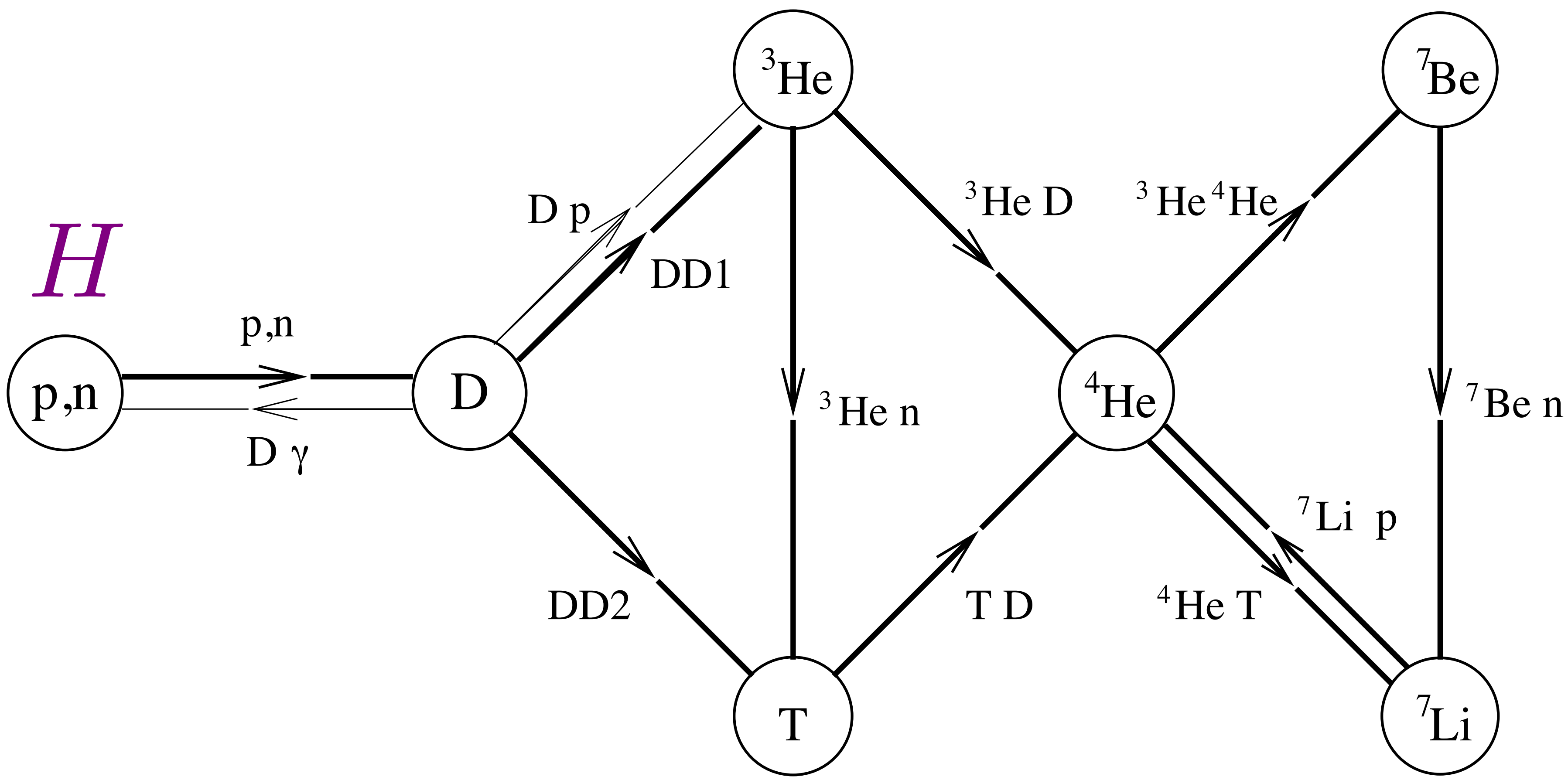


Fig. from [Mukhanov, 2004]

Generic ways to affect BBN



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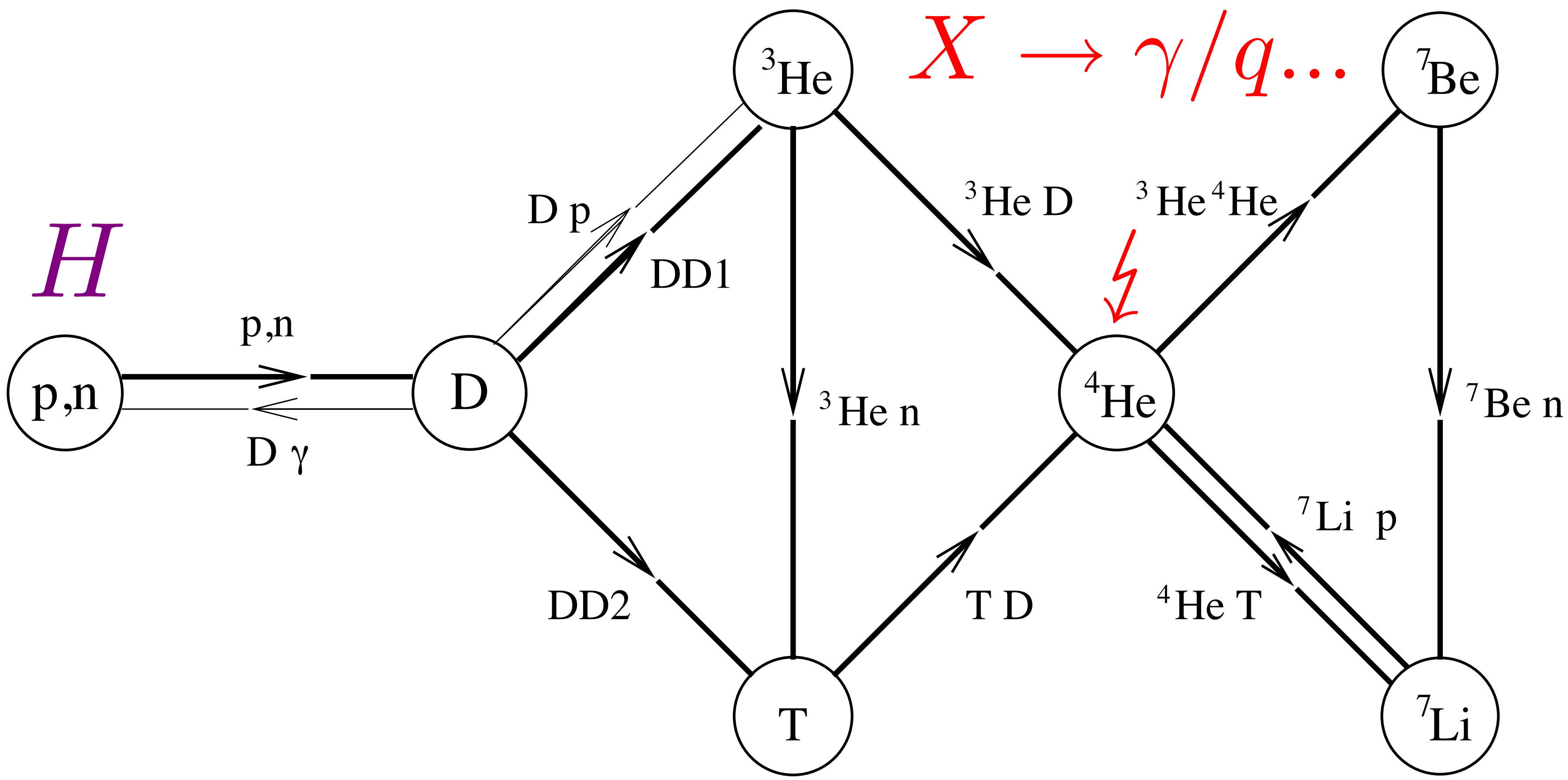
Change in timing

Generic ways to affect BBN



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Change in timing

non-equilibrium BBN

Generic ways to affect BBN

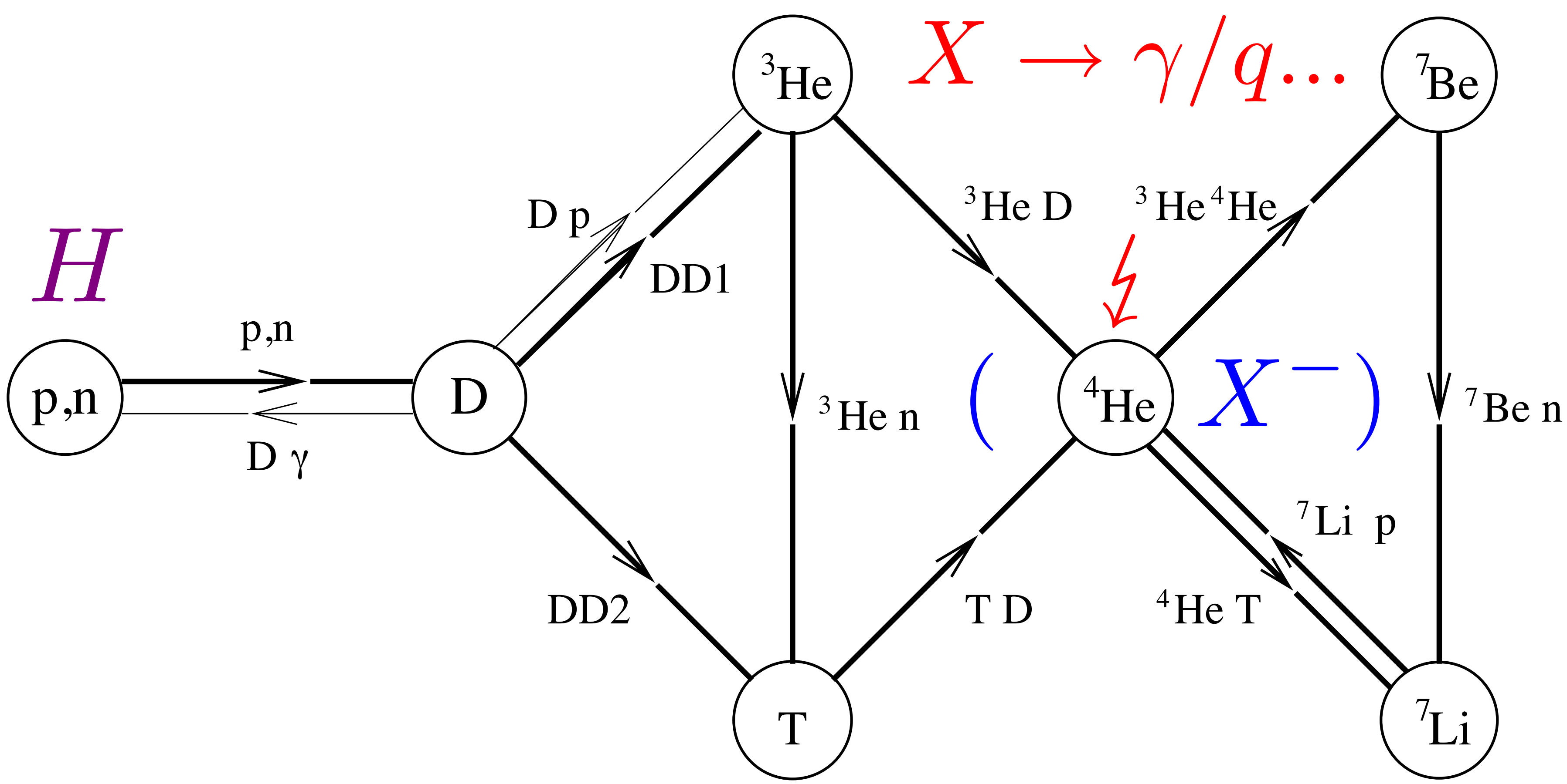


Fig. from [Mukhanov, 2004]

Change in timing

non-equilibrium BBN

catalyzed BBN

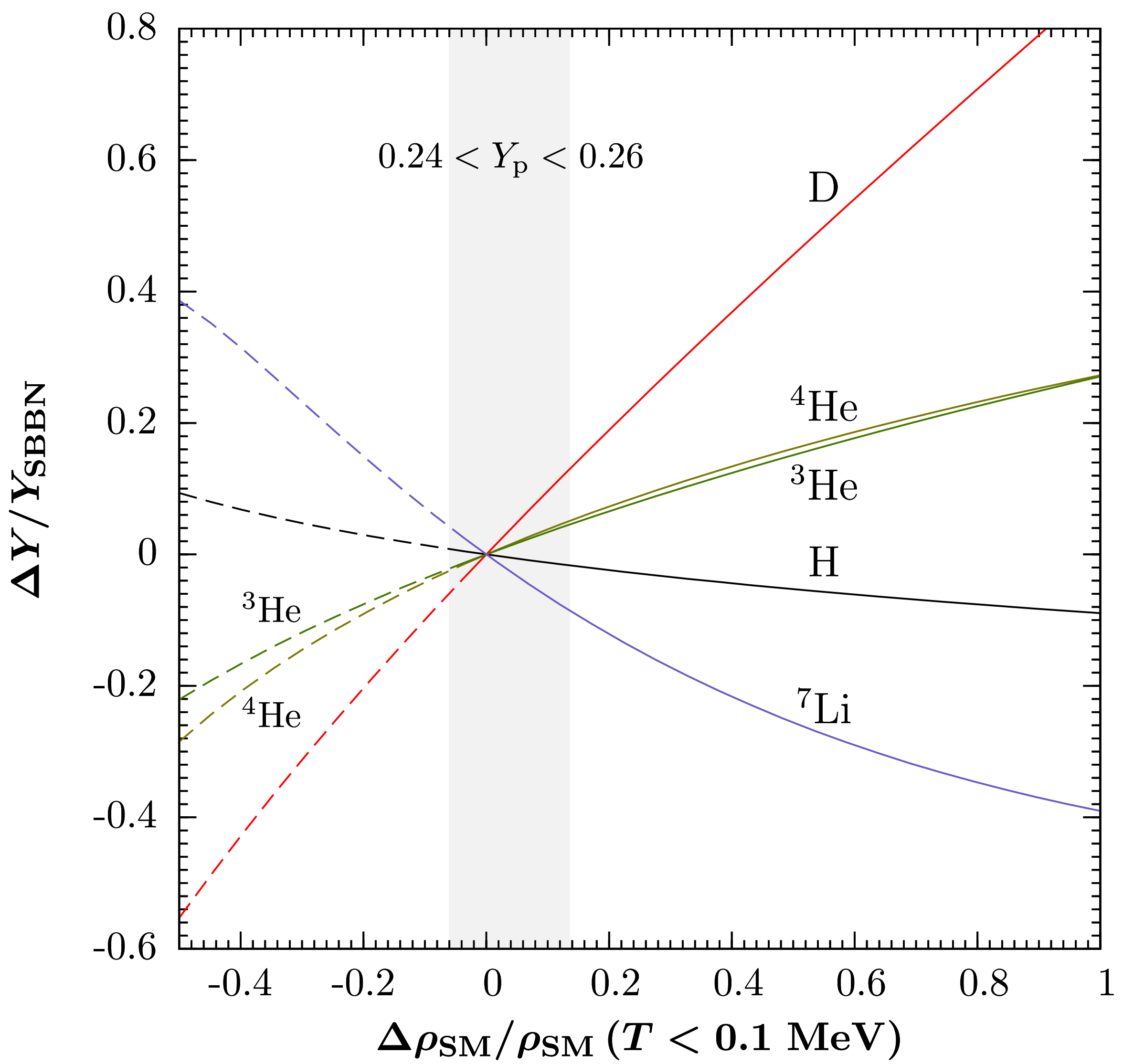
Generic ways to affect BBN

Timing

- defining moment in BBN: end of deuterium bottleneck

  => neutrons incorporated into helium

  => strong dependence of D and He4 on n/p - ratio



"dark radiation"

$$H_{\rm SBBN} \rightarrow H = H_{\rm SBBN}\sqrt{1+\rho_{dr}/\rho_{\rm SM}}$$

can be translated into bound on $N_{\nu,\rm eff}$

Generic ways to affect BBN

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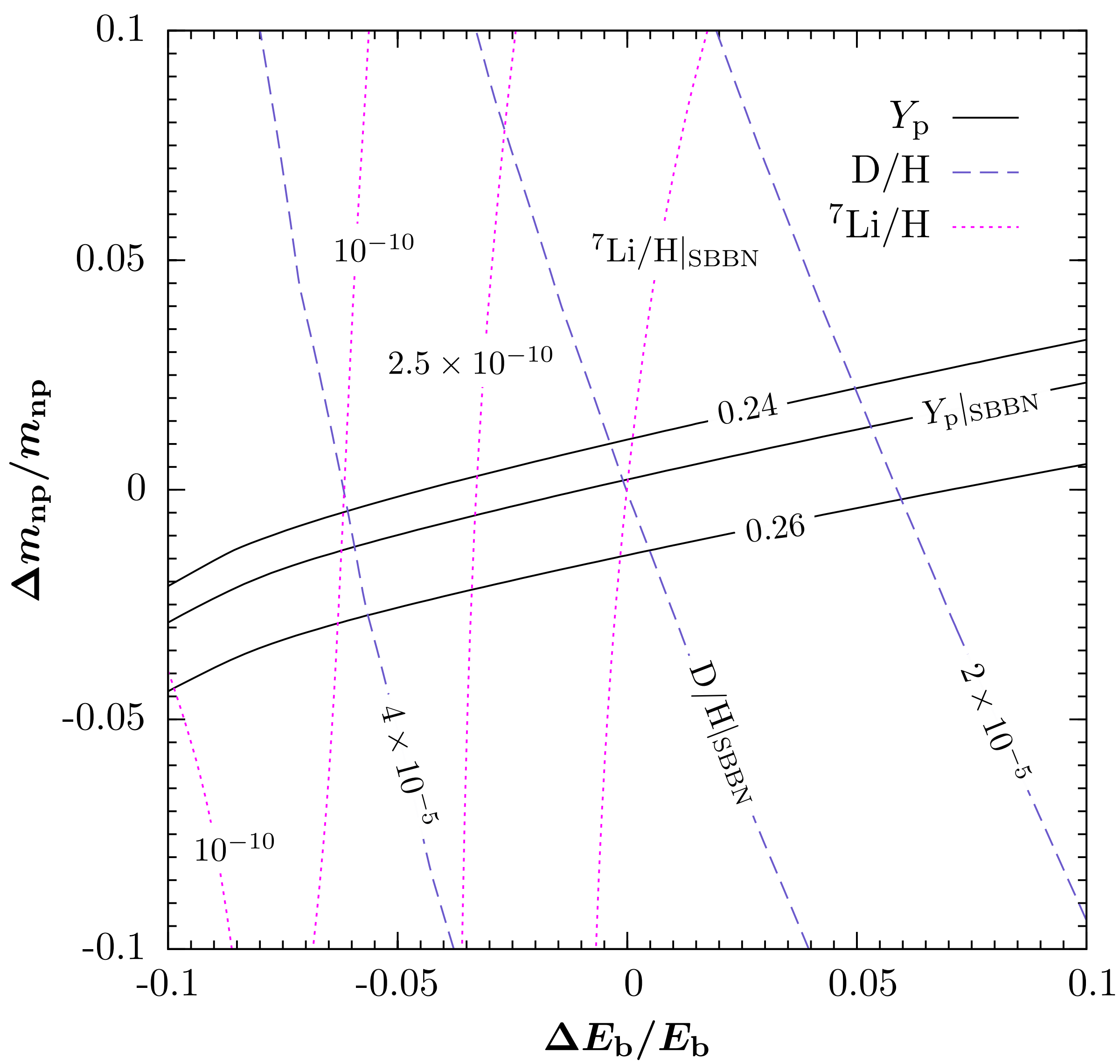


"sliding couplings and mass scales"

exponential sensitivity to

- neutron/proton mass difference

- deuterium binding energy

for concrete realizations, see e.g. [Nollett, Lopez, 2002; Dimitriev et al., 2004; Coc et al. 2007; Dent et al., 2007]

Generic ways to affect BBN

Non-equilibrium BBN

- energy release during SBBN (mass conversion into nuclear binding energy)

  $\sim 2\ \mathrm{MeV/nucleon}$ => marginal effect at $T_9 \sim 1$

- decays/annihilations of non-standard particles

  => a lot of work has been done! e.g. [...., Kawasaki et al. 2004, Jedamzik 2006, Cyburt et al. 2009]

primary decay/ann. channel → electromagnetic energy injection ("clean")

primary decay/ann. channel → hadronic energy injection ("messy")

- relevant because of Dark Matter connection (residual DM annihilation)

Electromagnetic energy injection

- rapid formation of em-cascade; "zeroth-generation" (IC and pair production)

$$p_\gamma(E_\gamma) = \begin{cases} K_0(E_\gamma/E_{\rm low})^{-1.5} & \text{for } E_\gamma < E_{\rm low} \\ K_0(E_\gamma/E_{\rm low})^{-2.0} & \text{for } E_{\rm low} < E_\gamma < E_C \\ 0 & \text{for } E_\gamma > E_C \end{cases}$$

[Protheroe, 1994]

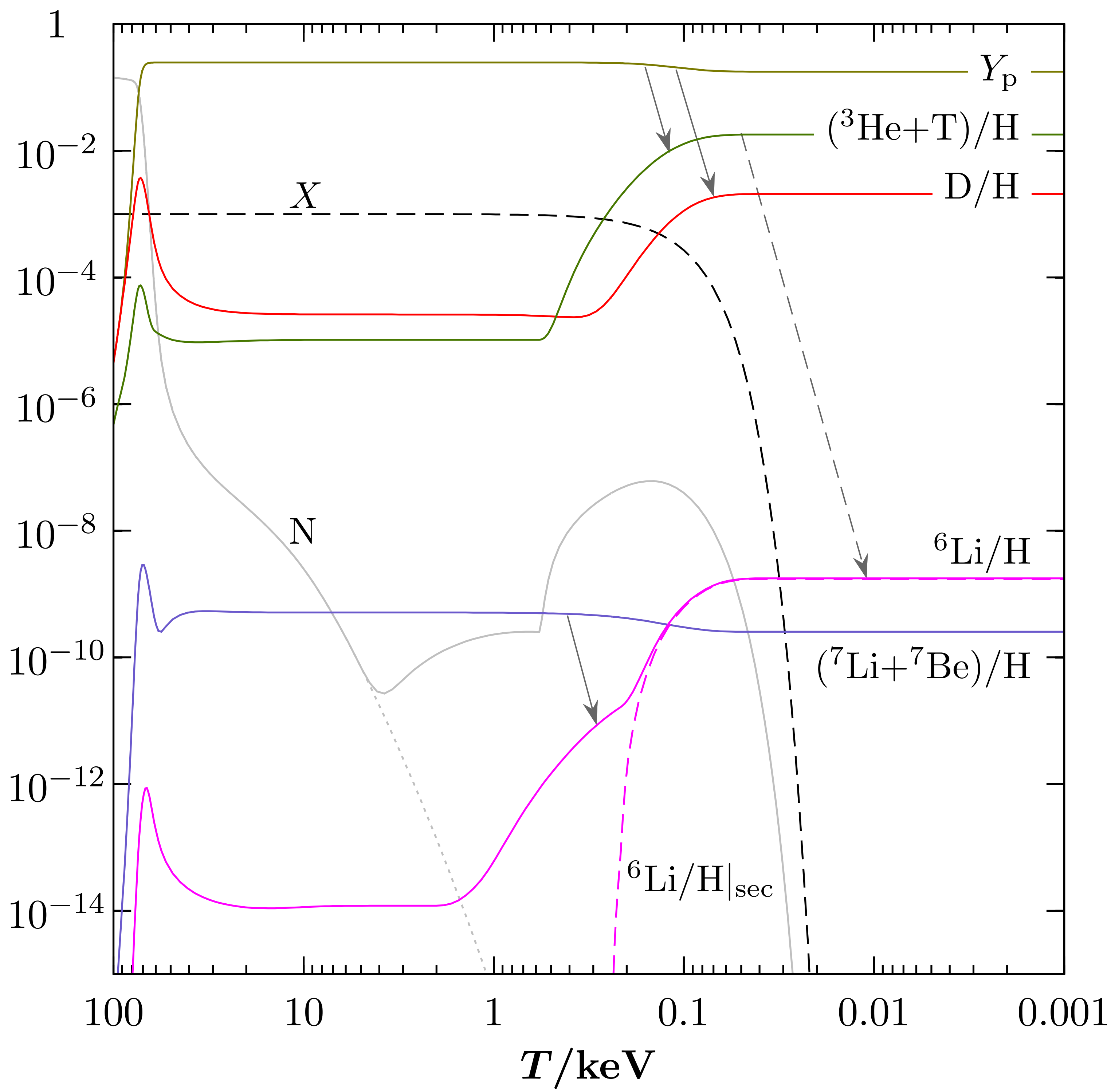
$$\gamma + \gamma_T \to e^- + e^- : E_C \simeq m_e^2/22T$$

[Kawasaki et al, 1994]

- "break-out" photons can dissociate light elements

$$T_{\rm ph} \simeq \begin{cases} 7\,\text{keV} & \text{for } {}^7\text{Be} + \gamma \to {}^3\text{He} + {}^4\text{He} & (E_b = 1.59\,\text{MeV}) \\ 5\,\text{keV} & \text{for } \text{D} + \gamma \to n + p & (E_b = 2.22\,\text{MeV}) \\ 0.6\,\text{keV} & \text{for } {}^4\text{He} + \gamma \to {}^4\text{He(T)} + n(p) & (E_b \simeq 20\,\text{MeV}) \end{cases}$$

Electromagnetic energy injection



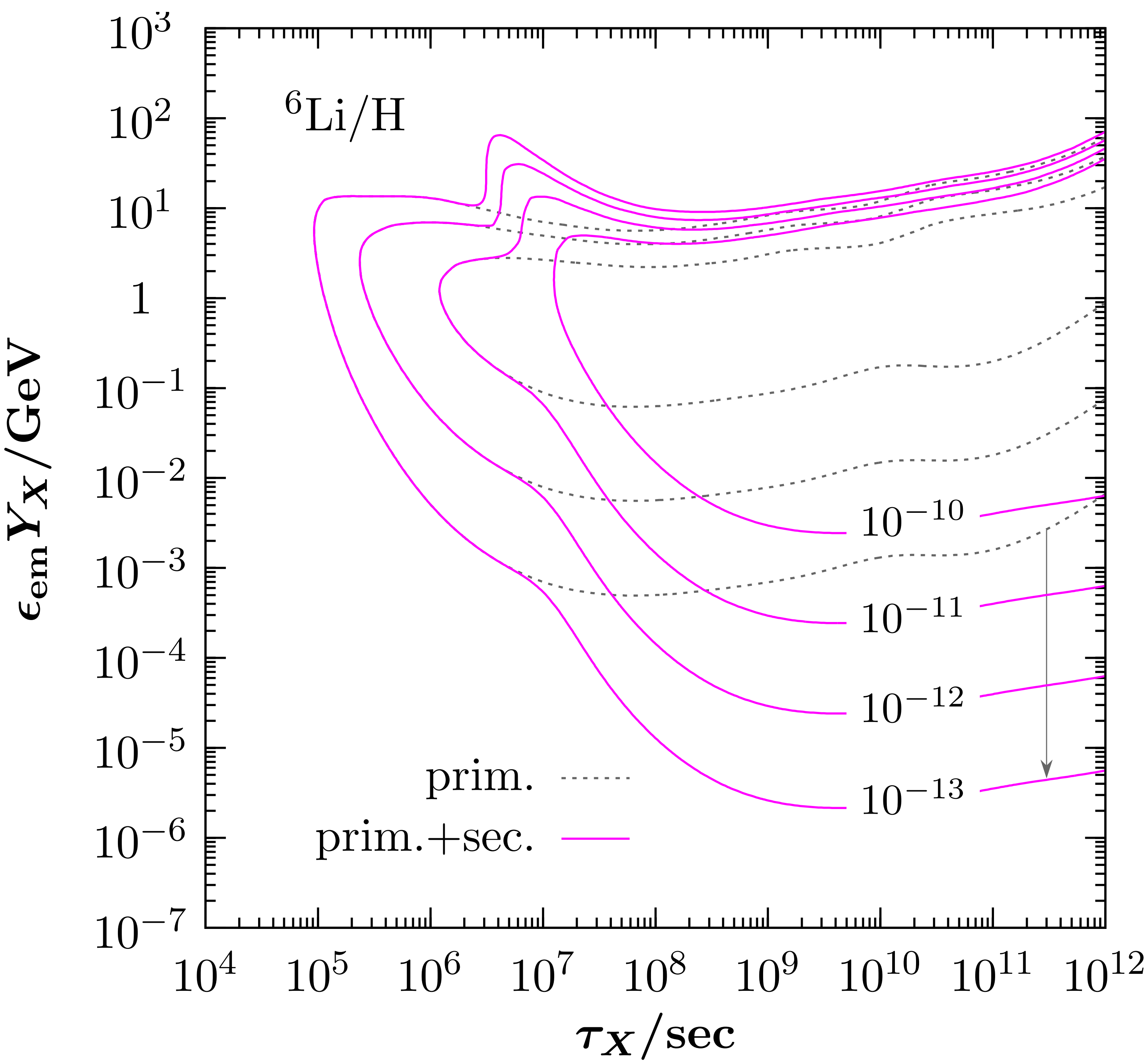
- Important secondary effect:

$$^3H + ^4He \rightarrow ^6Li + n$$

$$^3He + ^4He \rightarrow ^6Li + p;$$

[Dimopulous, 1988, Jedamzik, 2000]

Electromagnetic energy injection



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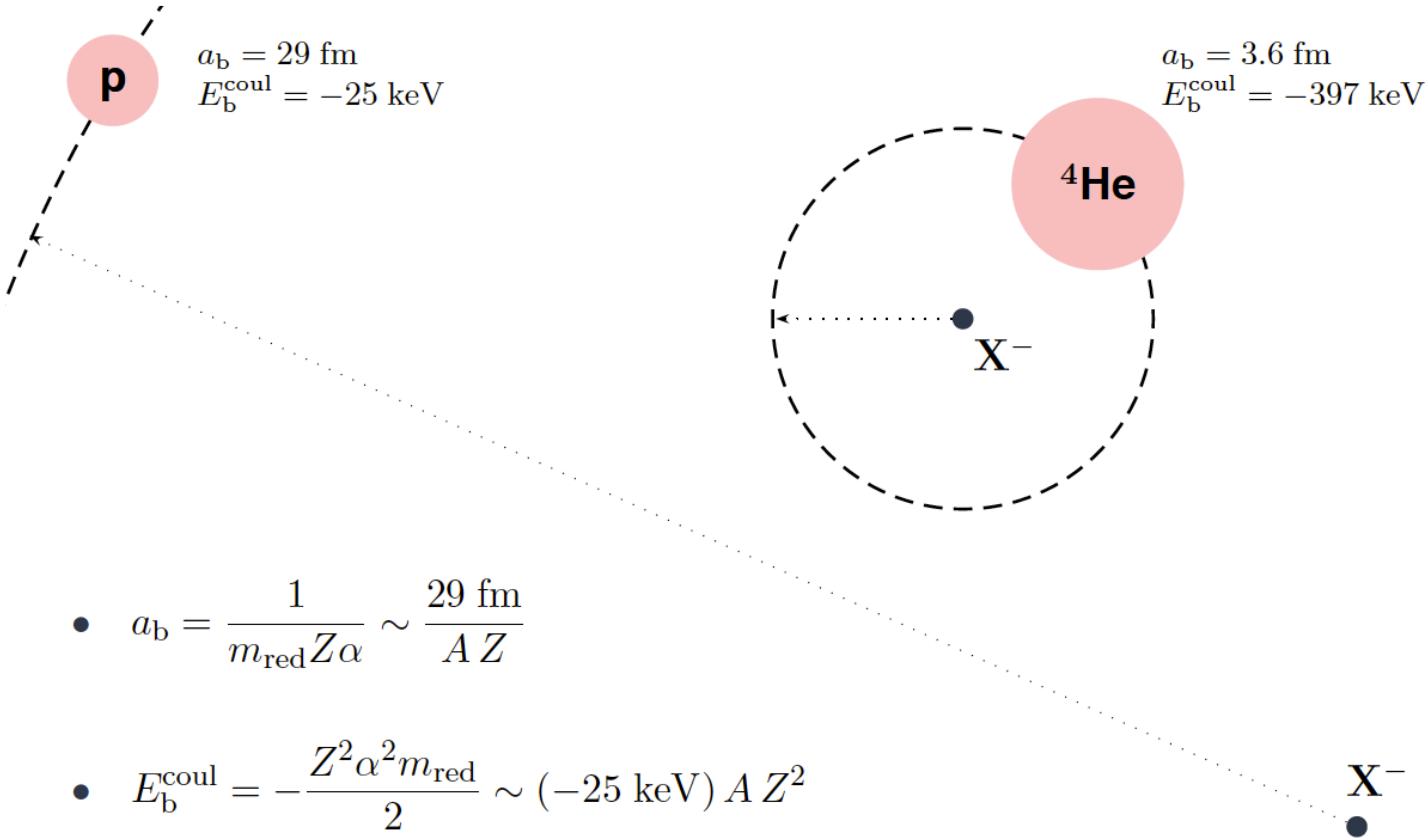
Generic ways to affect BBN

Catalyzed BBN



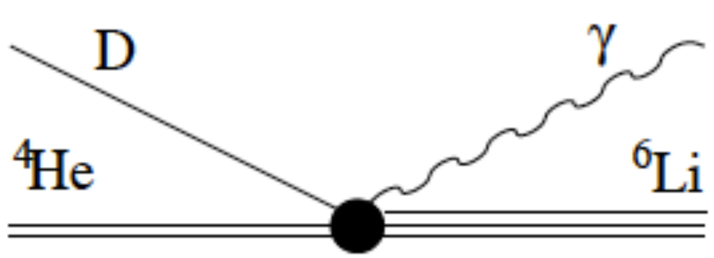
- $$a_b = \frac{1}{m_{red} Z \alpha} \sim \frac{29 \text{ fm}}{A\, Z}$$
- $$E_b^{coul} = -\frac{Z^2 \alpha^2 m_{red}}{2} \sim (-25 \text{ keV})\, A\, Z^2$$

Generic ways to affect BBN

Catalyzed BBN

- standard BBN:

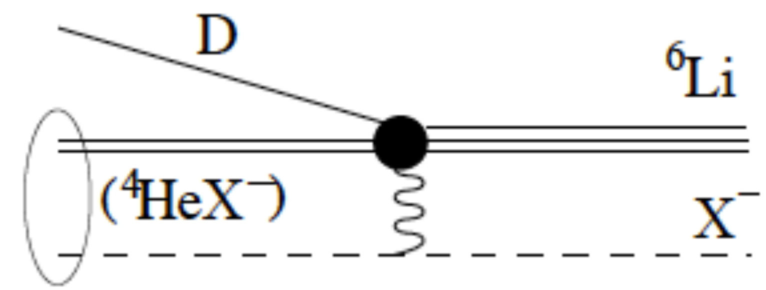
$$^4\mathrm{He} + \mathrm{D} \to {}^6\mathrm{Li} + \gamma$$



quadrupole transition heavily hindered

- bound states: [Pospelov, 2006]

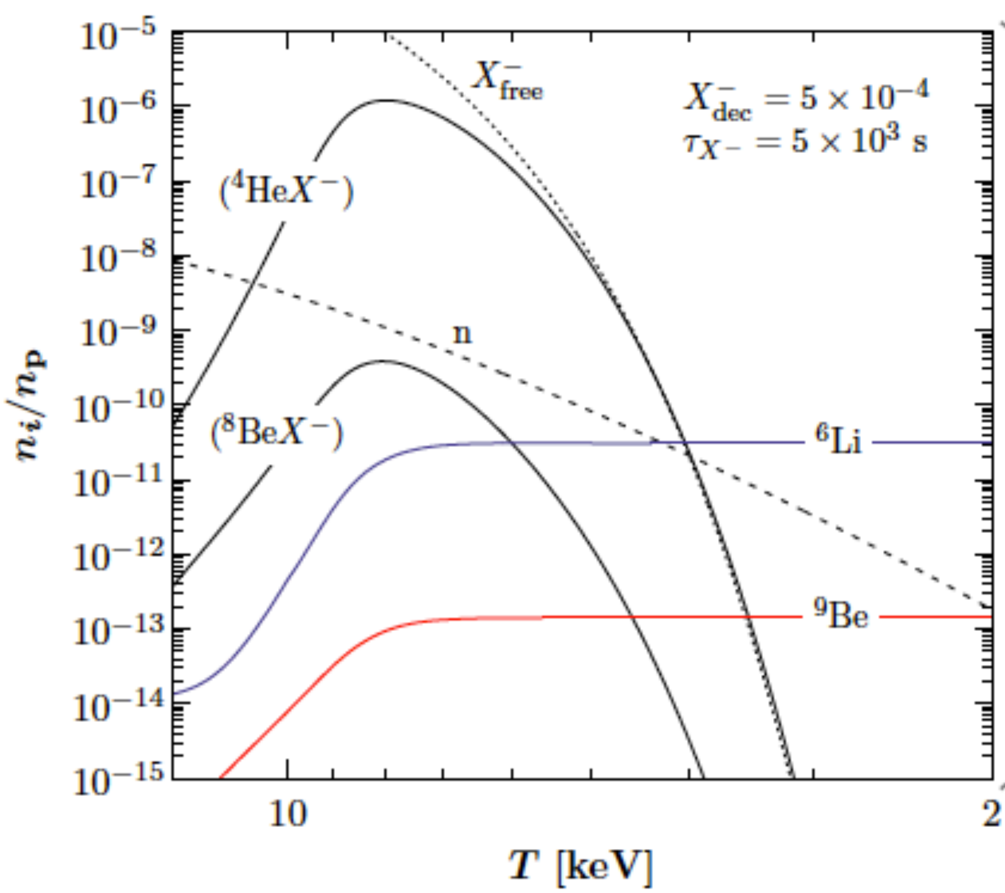
$$(^4\mathrm{He}X^-) + \mathrm{D} \to {}^6\mathrm{Li} + X^-$$

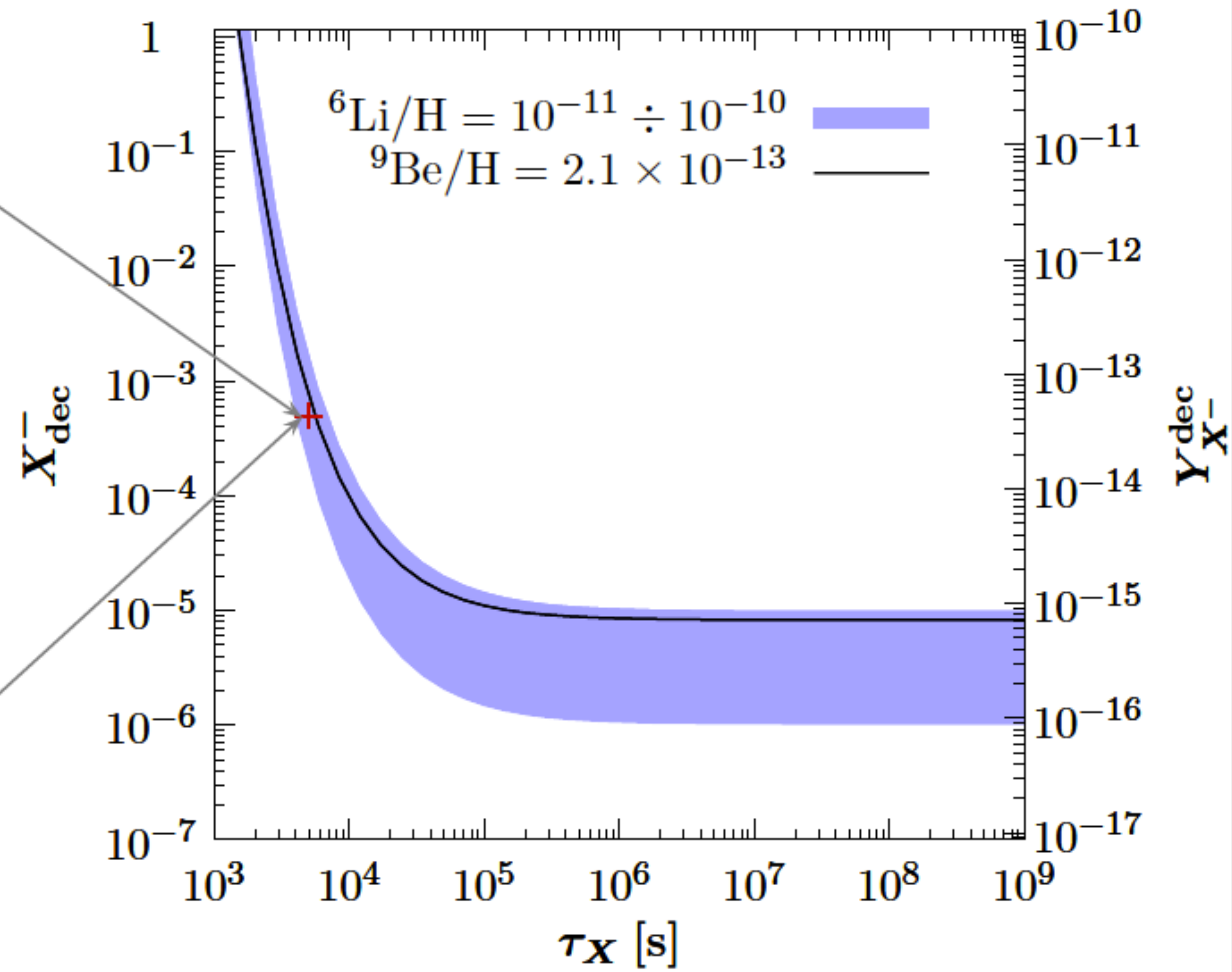


→catalysis of $^6\mathrm{Li}$ production

Generic ways to affect BBN

Catalyzed BBN



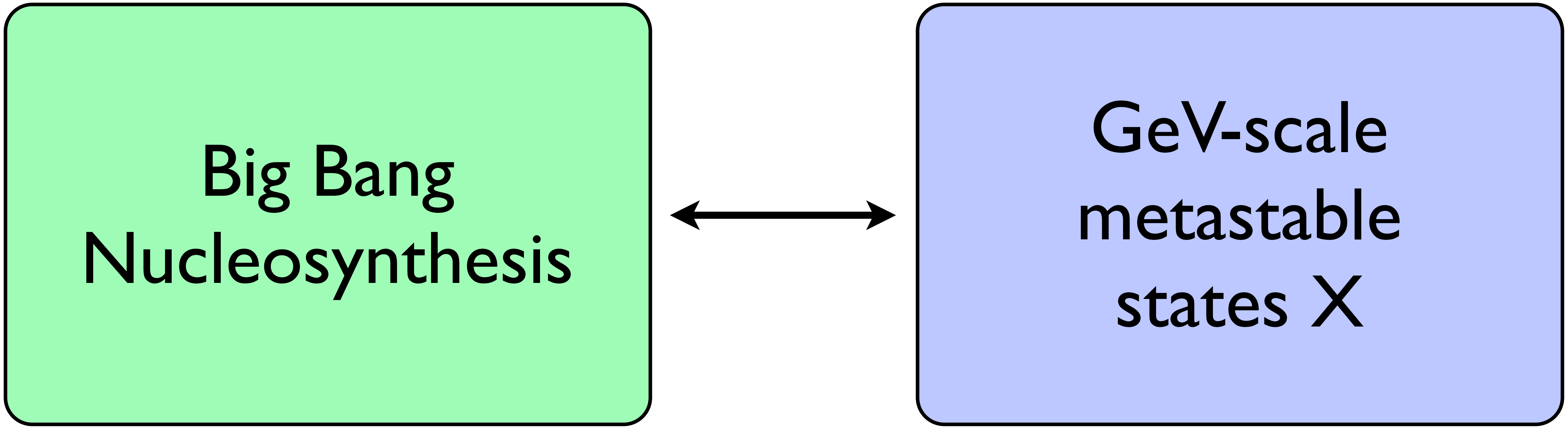


$$Y_{X^-} = \frac{n_{X^-}}{s}$$

[Pospelov, J.P., Steffen 2008]

Part II

Metastable GeV-scale sector as a solution to the lithium problem



- $m_X \sim \mathcal{O}(\mathrm{MeV} - \mathrm{GeV})$
- light sector secluded from the SM => longevity of X $\rightarrow$ SM
  $\tau_X > 1$ s
- recent attention in connection with cosmic ray anomalies (mediator physics)

Solving the Li-problem: mechanism

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

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

↑ 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]

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

  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

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

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

$$\downarrow$$

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

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

$T_9 \sim 0.5$

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

- $p \to n$ interconversion rate:

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

- 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

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

- we need pion-nucleon, pion-He cross sections at threshold

=> can be extracted from measurements of the level widths of pionic hydrogen and helium see e.g. review [Gasser, 2008]

$$\Gamma_{1S} = |\psi_{1S}(0)|^2 (\sigma v)_0$$

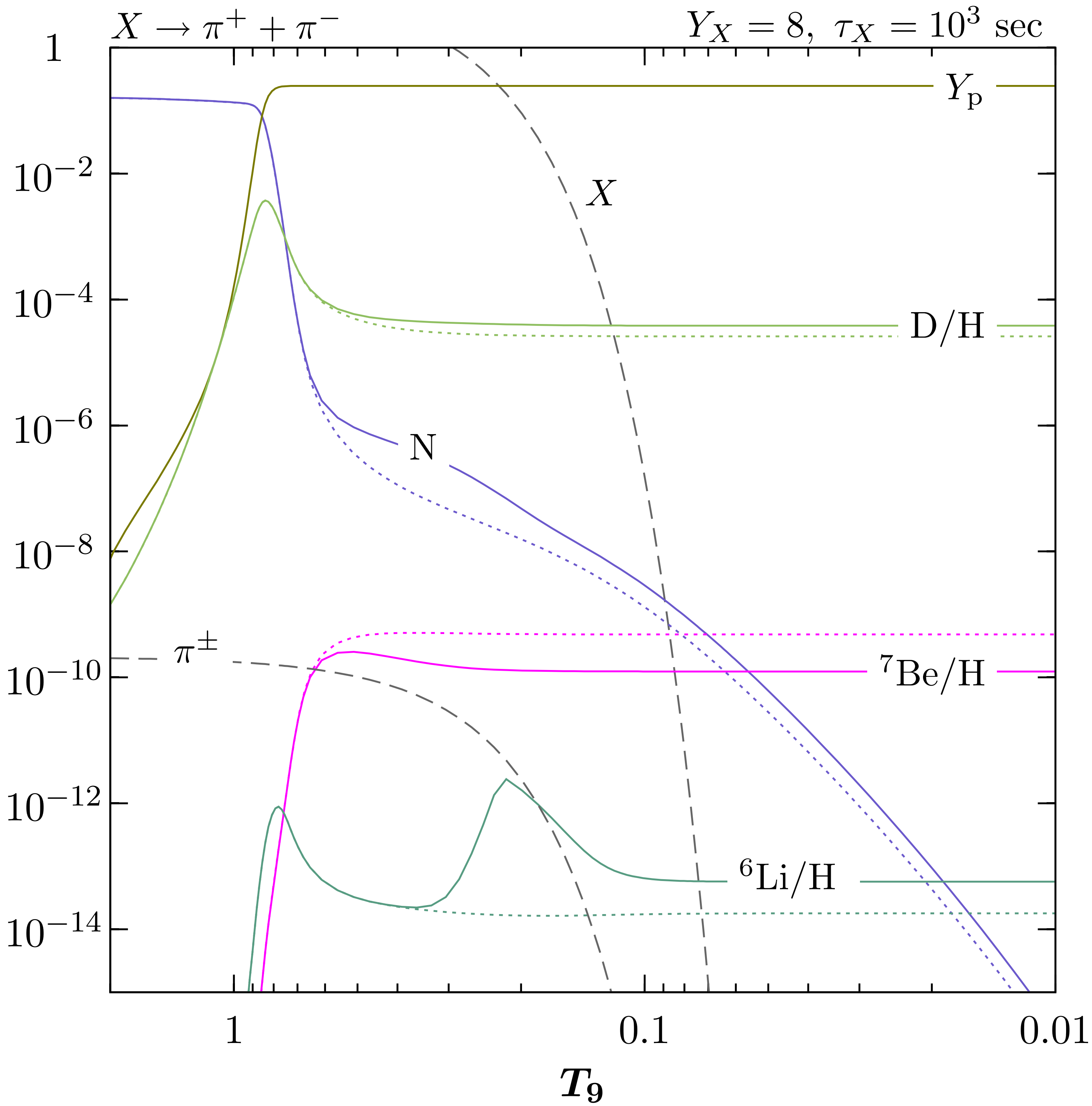
- these cross sections receive Coulomb corrections $\langle \sigma_i v \rangle \simeq F(Z, \langle v \rangle)(\sigma v)_i$

$$F(Z, v) \simeq \frac{2\pi\eta}{1 - e^{-2\pi\eta}}, \quad \eta = \frac{Z\alpha}{v}$$

=> win a factor $F_{p\pi^-} \simeq 2,\ F_{^4\mathrm{He}\pi^-} \simeq 3.5 \text{ at } T_9 \sim 0.5$

πBBN : $X \to \pi^+\pi^-$

$Y_X = n_X/n_b$



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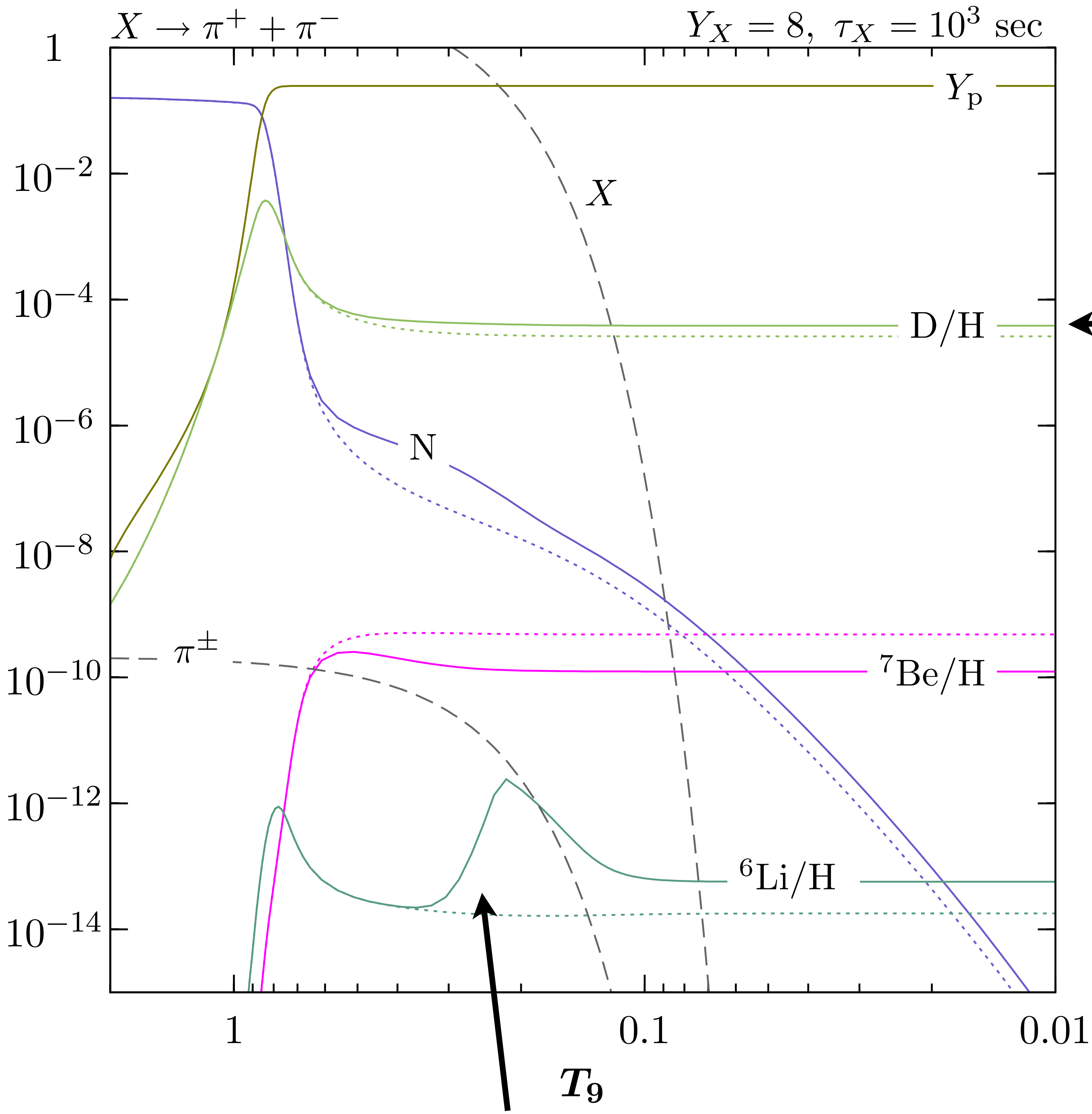

$n + p \to \mathrm{D} + \gamma$

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

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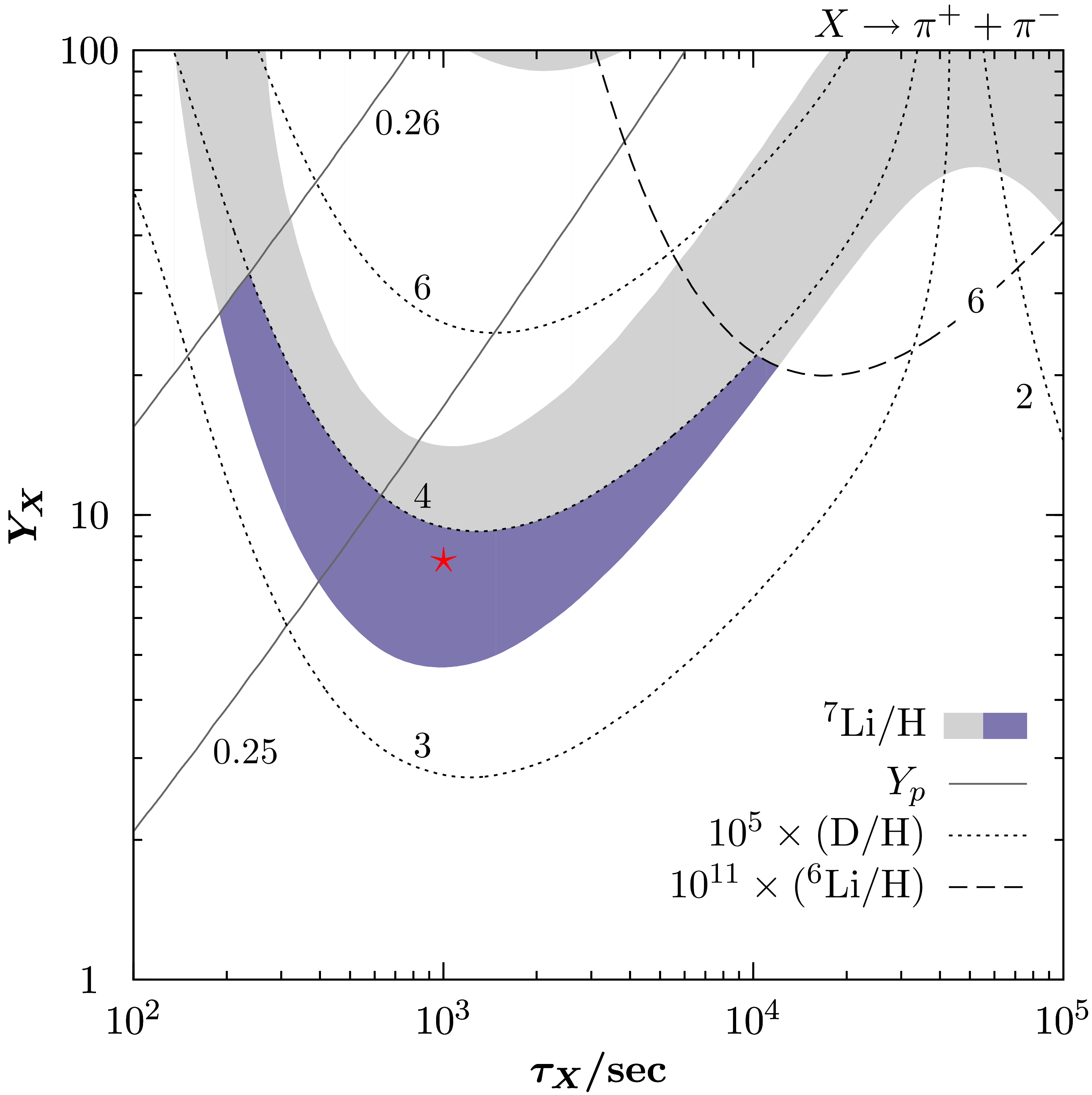

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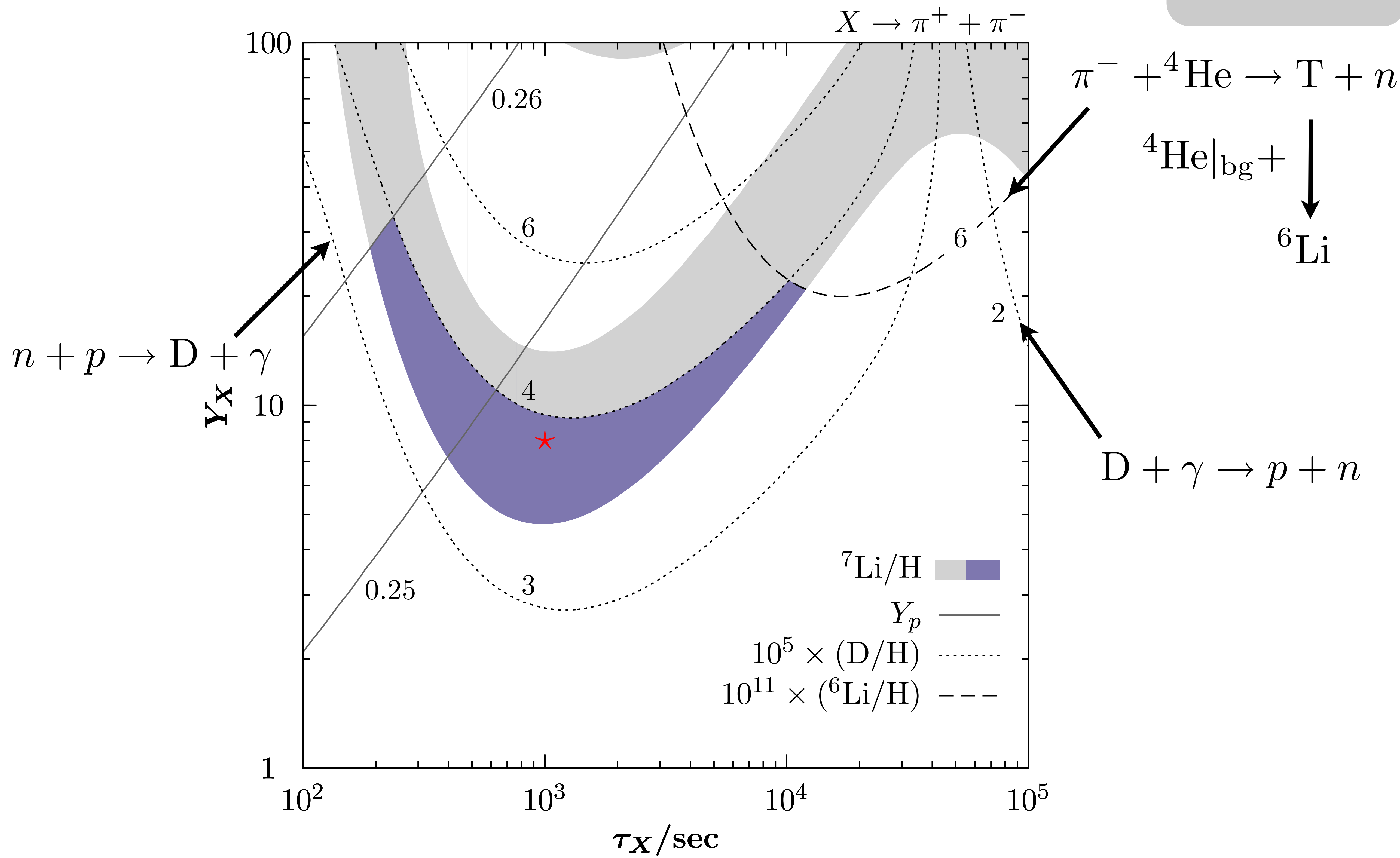


$\nu/\mu\mathrm{BBN} : X \to \mu^+\mu^- \to \bar{\nu}_e{}'s + \ldots$

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

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

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

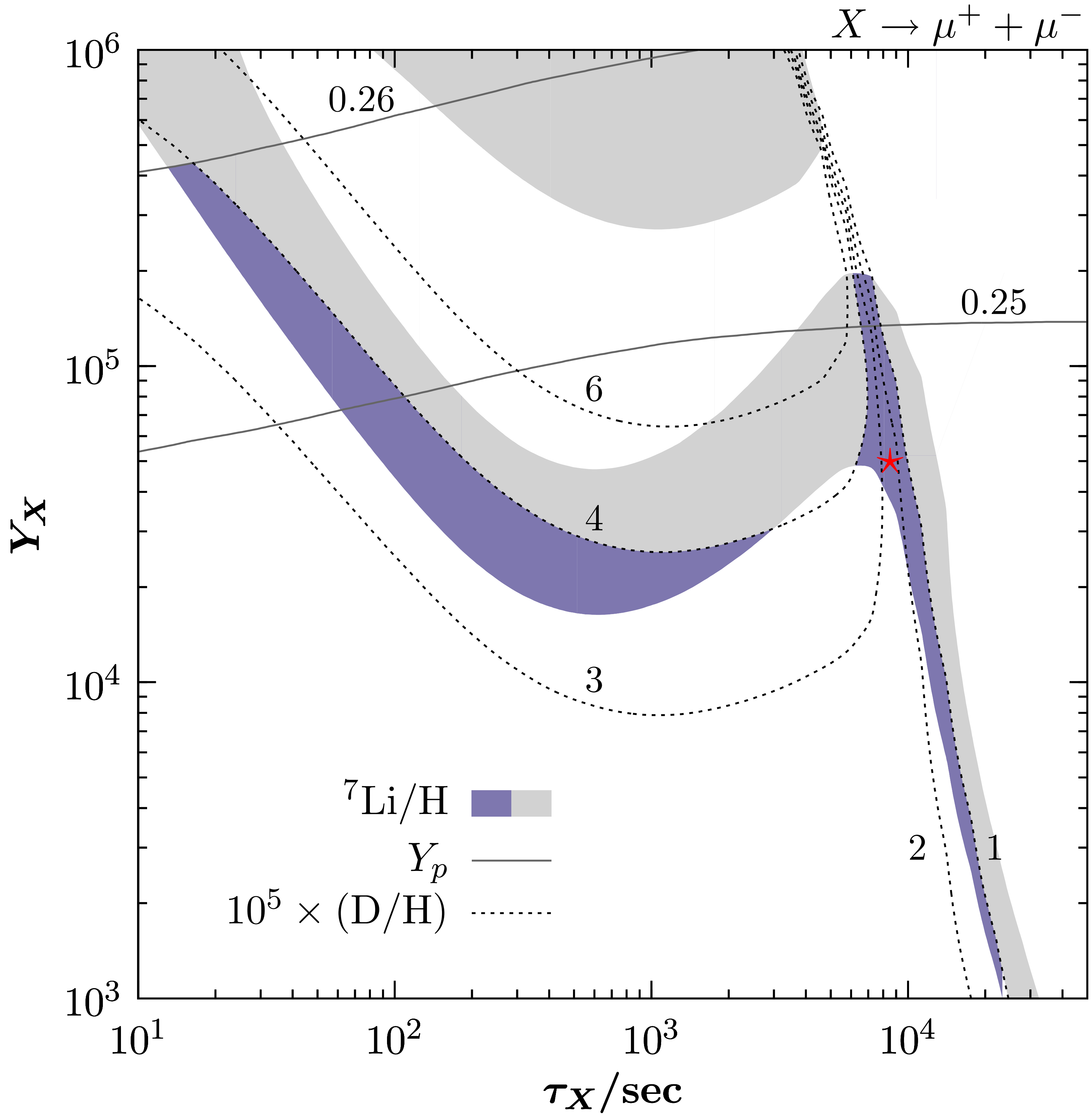
injection of $\mathcal{O}(10^4)$ muon decays/baryon yields $\mathcal{O}(10^{-5})$ neutrons

$P_{p\to n}^\nu << P_{p\to n}^\pi$ 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

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



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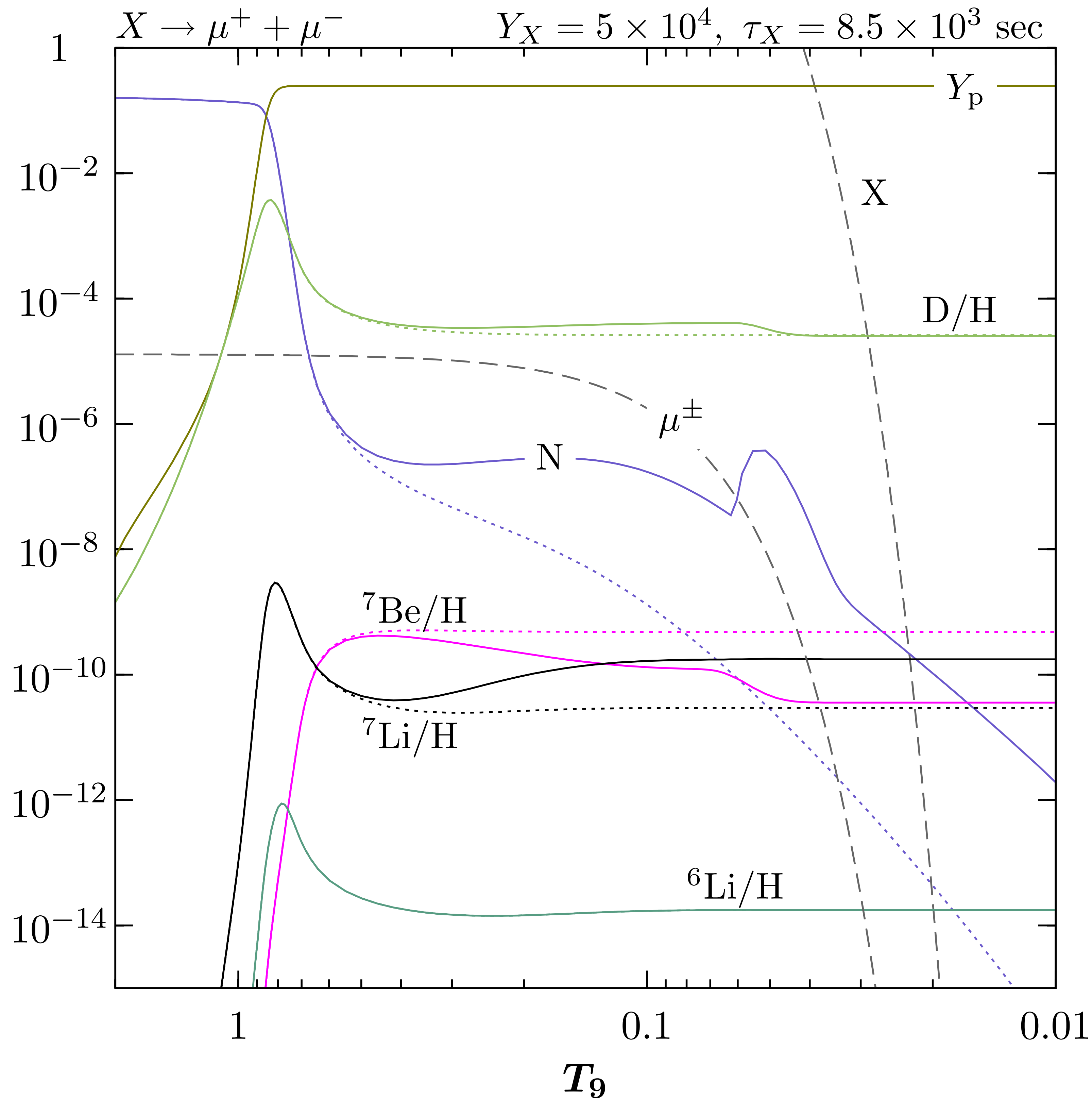
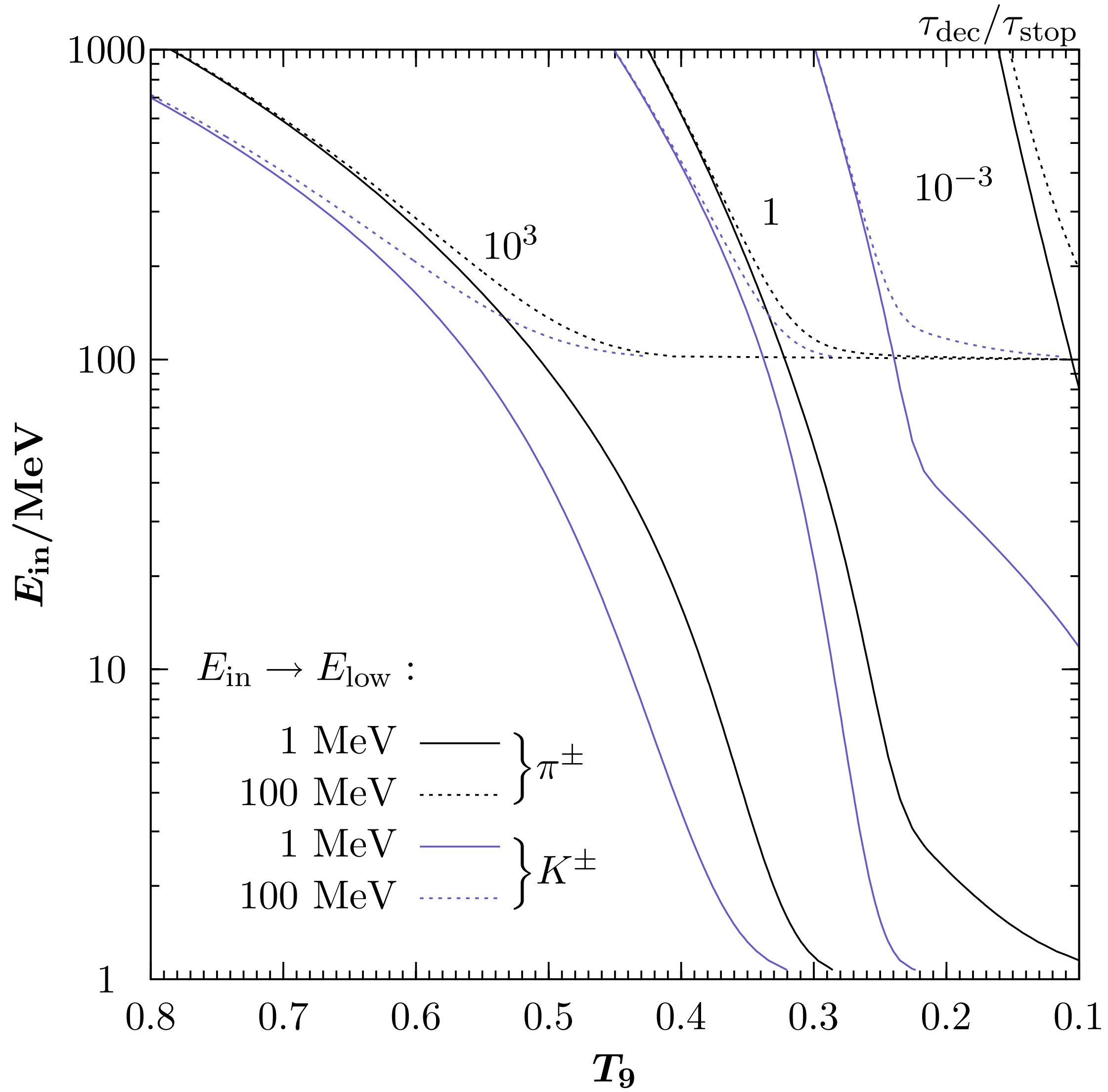
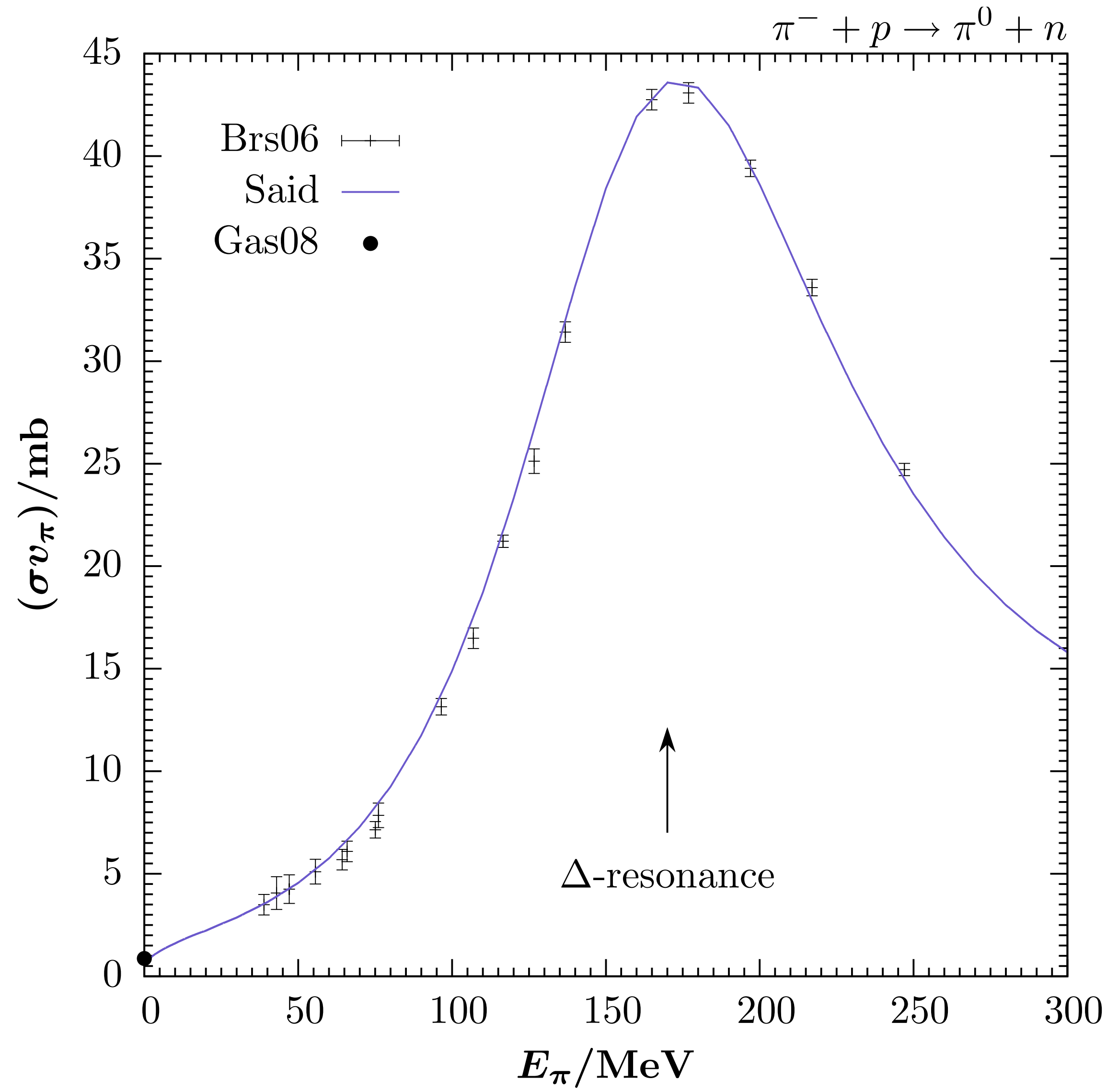


A more comprehensive picture ...

- Stopping power of the plasma falls rapidly with temperature
  => pions poorly stopped for $T_9 \lesssim 0.35$



$\Longrightarrow$

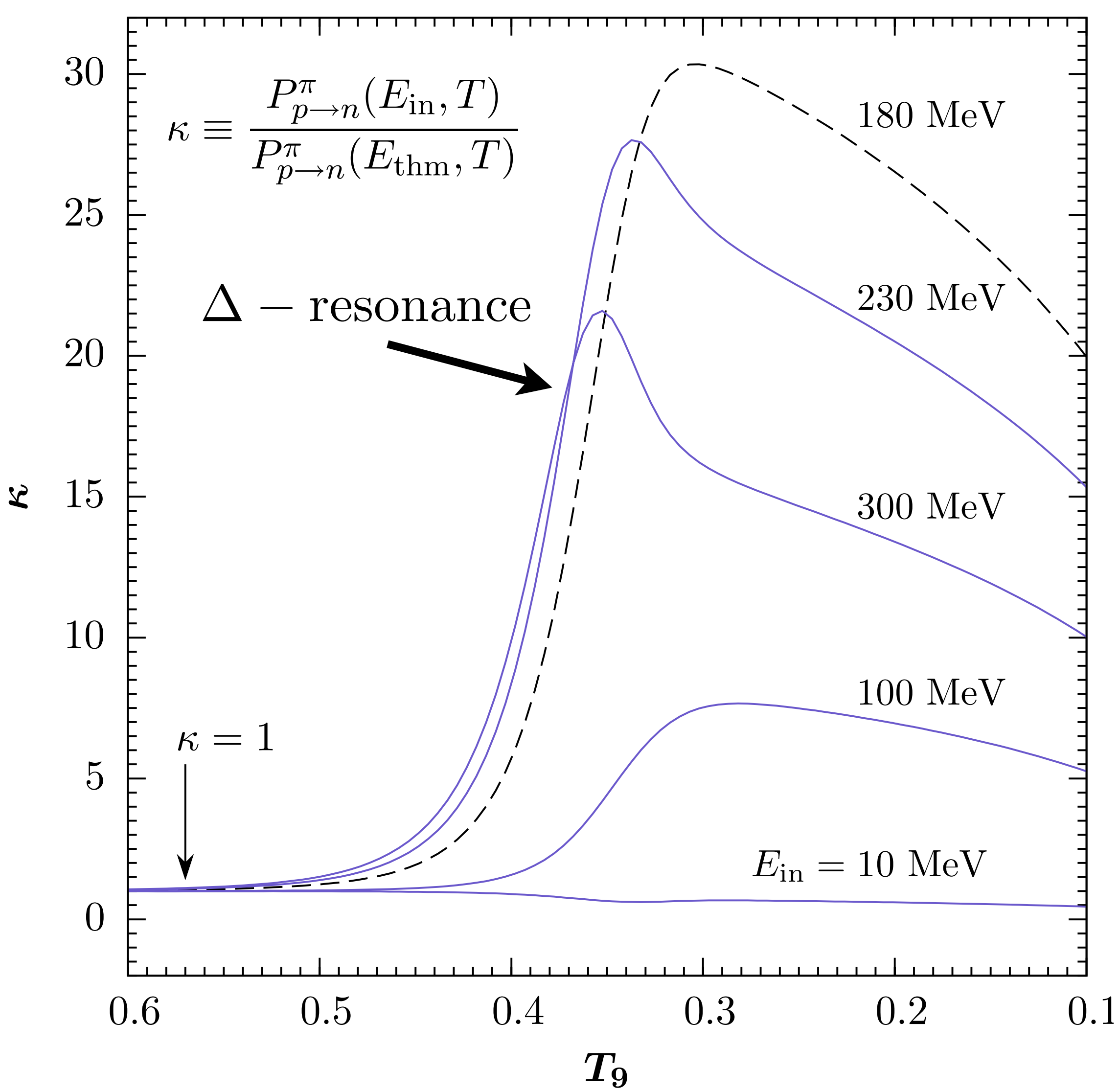


pion reactions enhanced

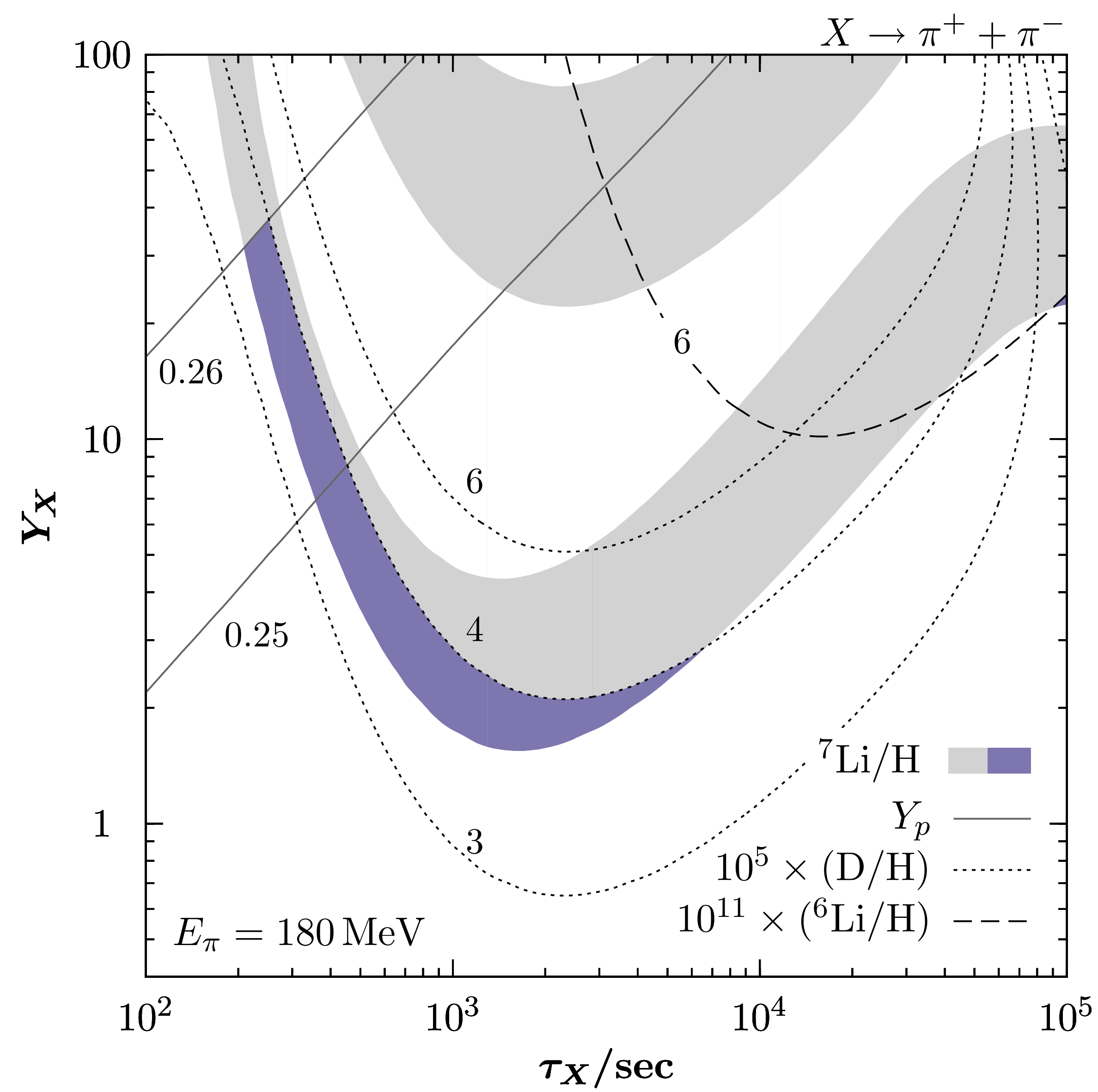
A more comprehensive picture ...

$$\kappa(E_\pi^{\rm in},T) \equiv \frac{P_{p\to n}(E_\pi^{\rm in},T)}{P_{p\to n}(T)} = \frac{1}{\tau_\pi(\sigma v)_{\rm th}}\int_0^\infty dt(\sigma v)_{E(t)}\exp\left(-\int_0^t dt'\frac{1}{\tau_\pi\gamma(E_\pi)}\right).$$

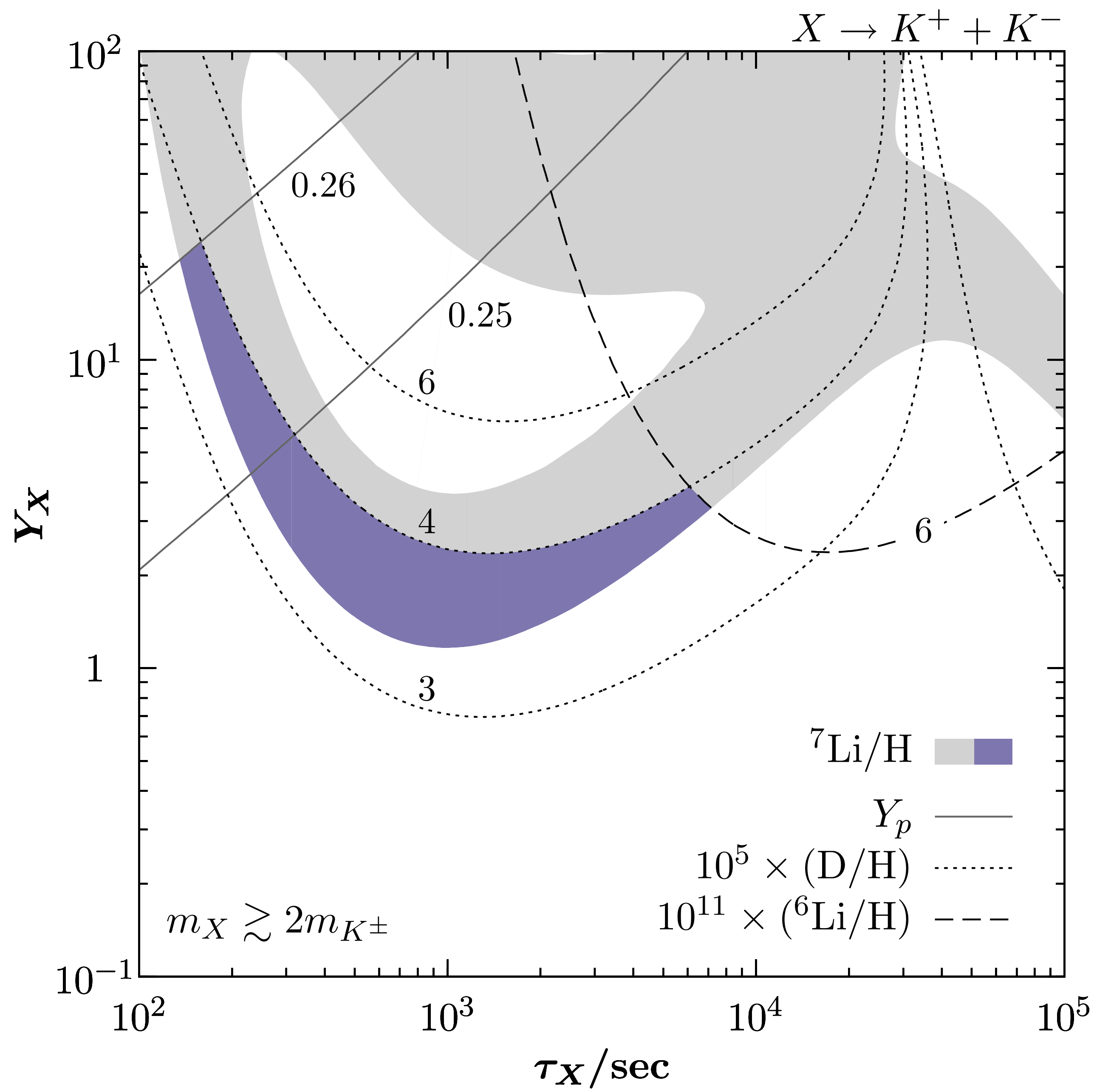
average along the "lifetime-trajectory of pions"



$\Rightarrow$



A more comprehensive picture ...

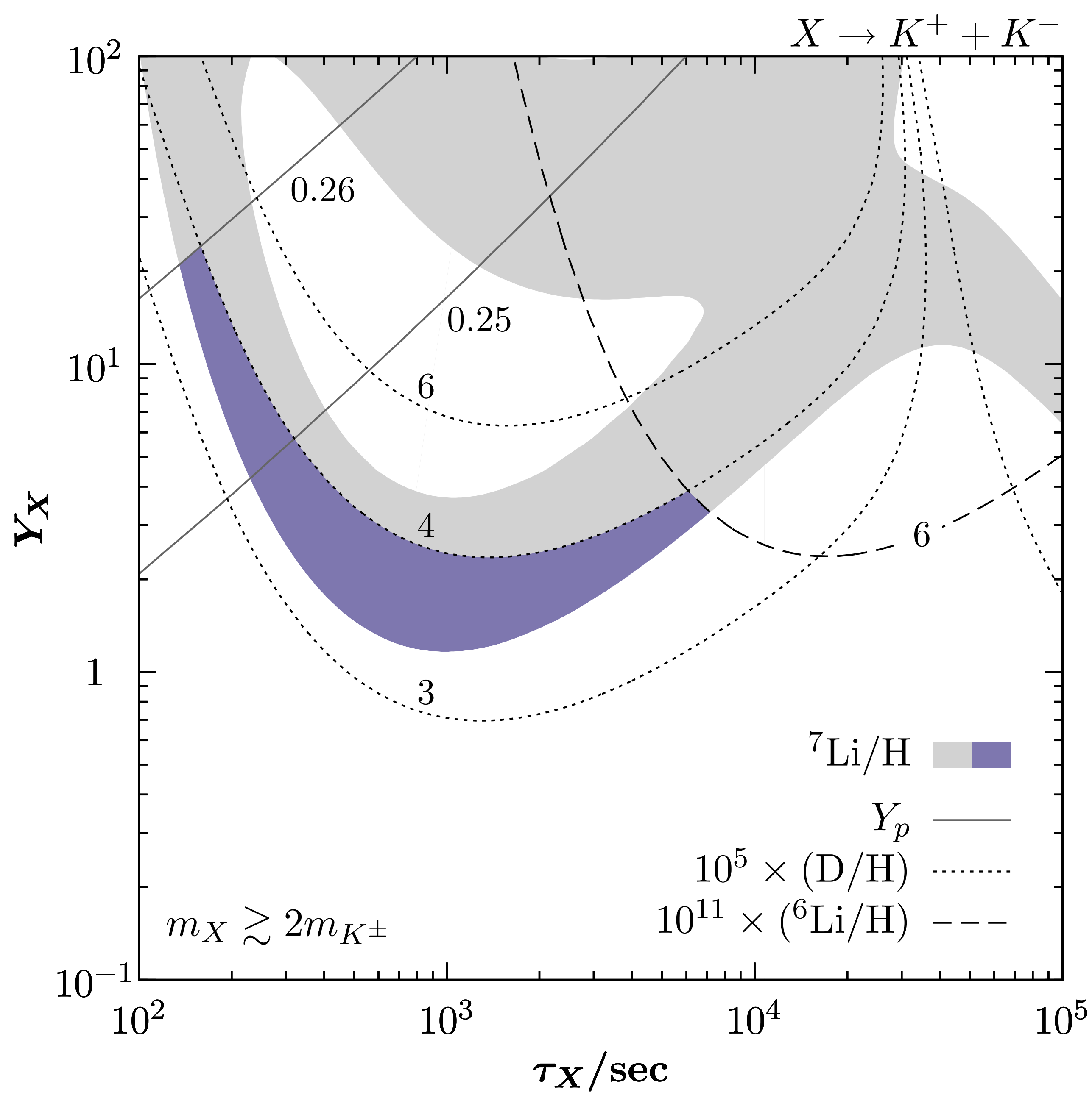


A more comprehensive picture ...

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

$$K^- + p \rightarrow \Sigma^{\pm}\pi^{\mp},\ \Sigma^0\pi^0,\ \Lambda\pi^0$$

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



Examples of secluded sectors

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

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

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

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

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

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

Examples of secluded sectors

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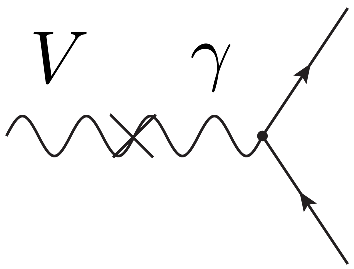
- Vector-portal (new $U(1)'$ broken by Higgs' ϕ) [Holdom 1986]

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

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

Consider V-portal

$\tau_X \sim 10^3$ s



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

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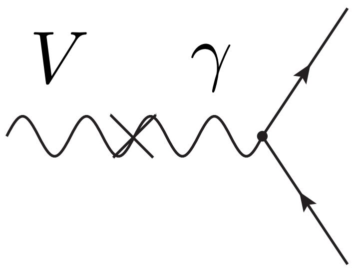

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"super-Wimp" regime

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

$$\Rightarrow m_V < m_{h'}$$
$$\kappa \lesssim 10^{-12}$$

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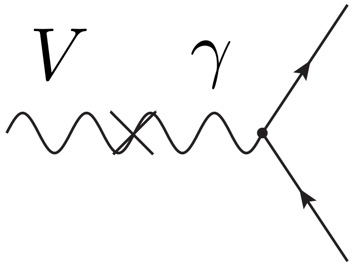

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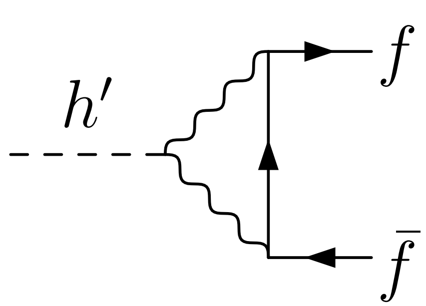
"Wimp" regime

$\Rightarrow m_{h'} < m_V$

naturally long-lived h'



[Batell et al., 2009]

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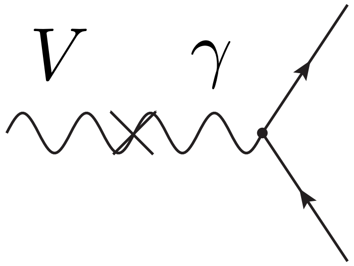

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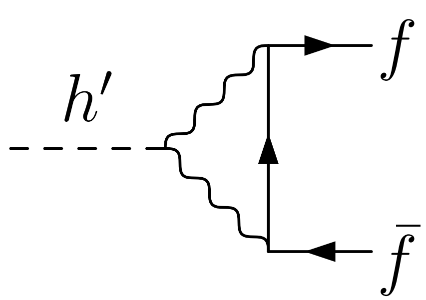

[Batell et al., 2009]

"super-Wimp" regime

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

$\Rightarrow m_V < m_{h'}$

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

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

Y_X

"Wimp" regime: h'

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

[Credit: N. Weiner]

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

easily

Y_X

"Wimp" regime: h'

$$h' + h' \to V + V : \qquad \Gamma_1 \propto (\alpha')^2 \kappa^0 \exp(-m_{h'}/T - 2\Delta m/T)$$

$$h' + V \to l^+ l^- : \qquad \Gamma_2 \propto \alpha' \alpha \kappa^2 \exp(-m_{h'}/T - \Delta m/T)$$

$$h' + l^\pm \to V + l^\pm : \qquad \Gamma_3 \propto \alpha' \alpha \kappa^2 \exp(-\Delta m/T),$$

[Credit: N. Weiner]

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

"super-Wimp": V

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

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

seems somewhat small for "pion-solution", but...

Conclusions

- BBN has become a powerful toolbox to test and constrain new physics

  => every model must pass this cosmological consistency check

- (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