Title: Big Bang Nucleosynthesis as a probe of new physics

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Abstract:

Big Bang Nucleosynthesis as a probe of new physics

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M. Pospelov, JP, PRD82 (2010)103514, arXiv:1010.4079

M. Pospelov, JP, Ann.Rev.Nucl.Part.Sci. 60 (2010)

Feb. 15, 2011

PI-CITA day

The beginnings ...

... or when known physics probed the Big Bang

- mid 40's: contemplation that all chemical elements are made from successive n-capture reactions at T=1MeV

- Gamow (1946): rapid expansion of the Universe due to mass-density requires a non-equilibrium dynamic calculation of element abundances
- Alpher, Bethe, Gamow (1948) - no blackbody radiation.
- Later in 1948: CMB drives expansion
- Alpher, Hermann (1948): prediction of today's CMB temperature ~5K

BBN ever since

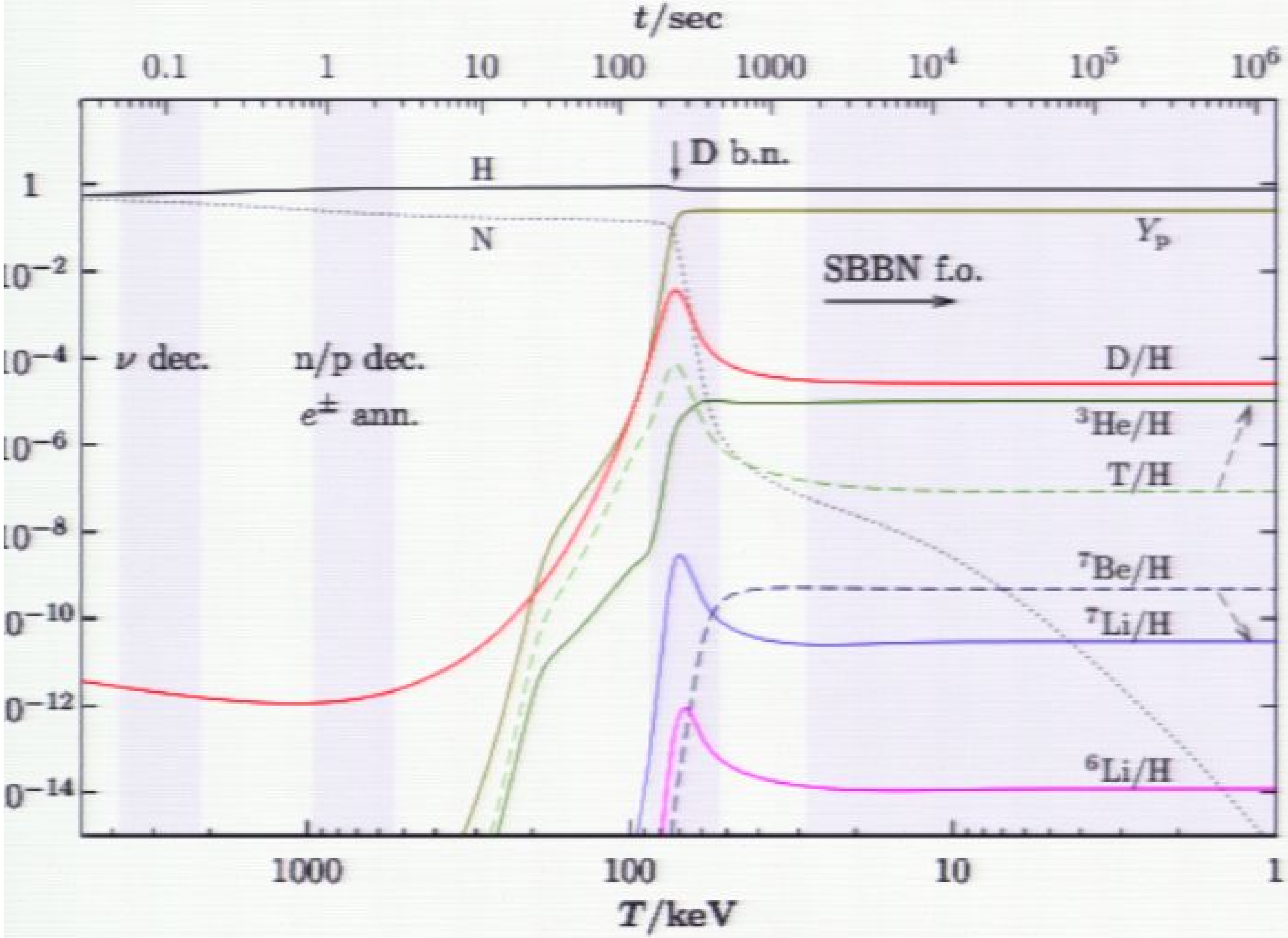
- instability gaps at A=5 and A=8 prevent formation of heavier elements (Fermi & Turkevich) (e.g. $\tau_{^8\mathrm{Be}} \simeq 10^{-16}$ s)
- basic physics of BBN in place 1953 (Alpher, Follin, Herman)
- CMB discovered (Penzias & Wilson, 1965)!
- ....
- new millennium: baryon density known to better than 3% (at $z \lesssim \mathrm{few} \times 10^3$)

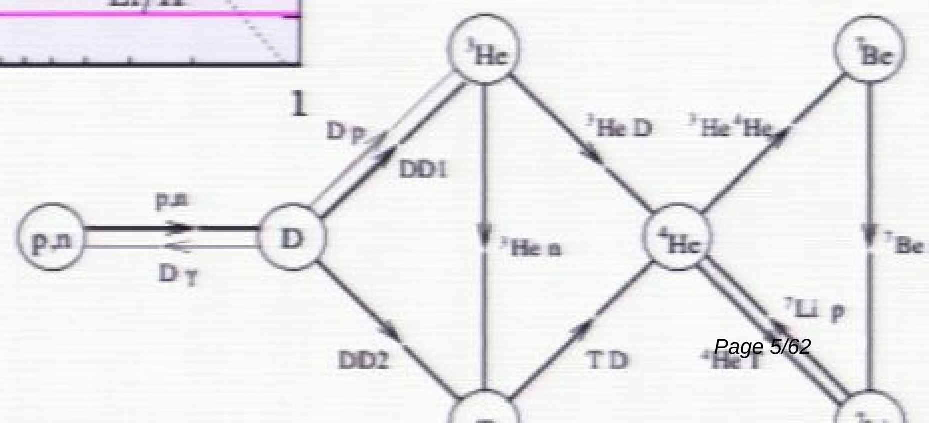
$$\eta_\mathrm{b}(t_\mathrm{CMB}) = (6.225 \pm 0.170) \times 10^{-10}$$ [Dunkley et al., 2009]

assume: Standard model + FRW

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

The Universe at the redshift of a billion: ← natural units: $T_9 \equiv \frac{T}{10^9\ \mathrm{K}}$





SBBN predictions @ $\eta_{\rm WMAP}$

$\mathcal{O}(0.1)$ $\quad Y_p = 0.2486 \pm 0.0002$

$\mathcal{O}(10^{-5})$ $\quad \mathrm{D/H} = (2.49 \pm 0.17) \times 10^{-5}$

$\quad {}^3\mathrm{He/H} = (1.00 \pm 0.07) \times 10^{-5}$

$\mathcal{O}(10^{-10})$ $\quad {}^7\mathrm{Li/H} = 5.27^{+0.71}_{-0.67} \times 10^{-10}$

$\mathcal{O}(10^{-14})$ $\quad {}^6\mathrm{Li/H} \simeq 10^{-14}$

see e.g. [Cyburt et al., 2008]

Deuterium observations:

- measured in Quasar absorption systems
- no known astrophysical source (monotonic)
- ISM measurements by FUSE [Linsky et al., 2006]

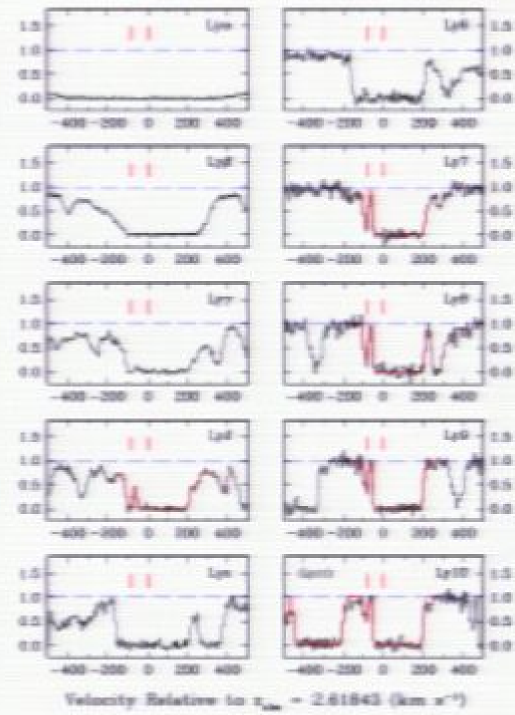
  dispersion in the local gas

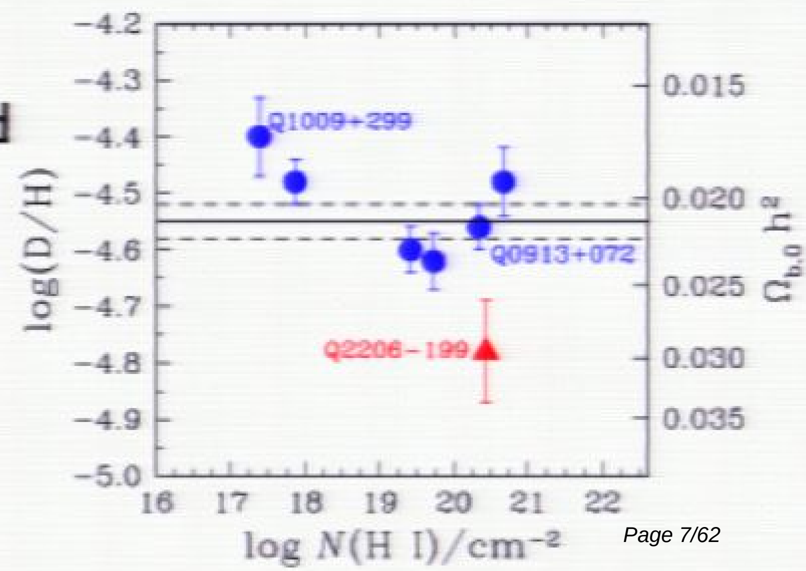
  potential D-absorption on dust

- scatter in ISM may indicate underestimated systematics in QAS

$$(\mathrm{D/H})_p = (2.81 \pm 0.21) \times 10^{-5}$$

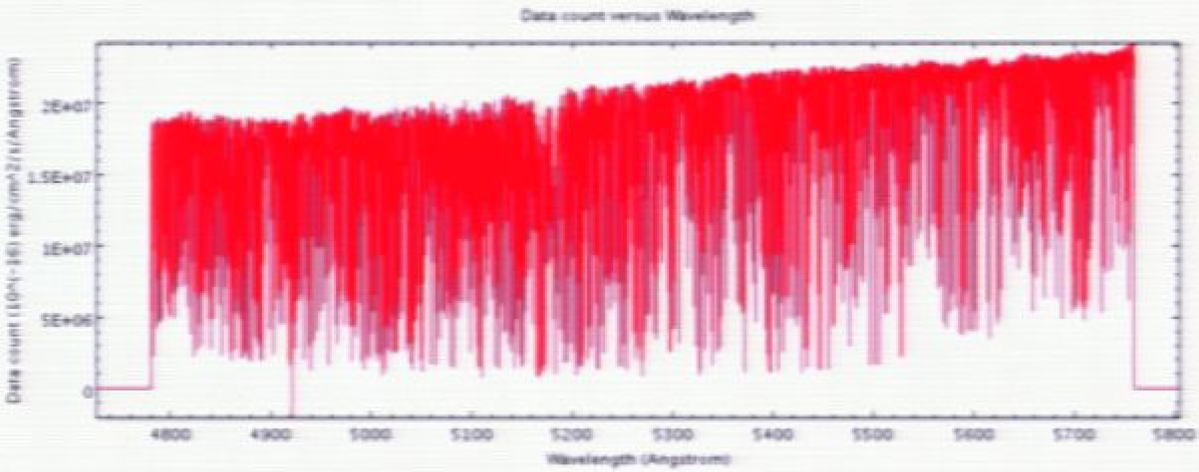
$$(\mathrm{D/H})_p \lesssim 4 \times 10^{-5}$$



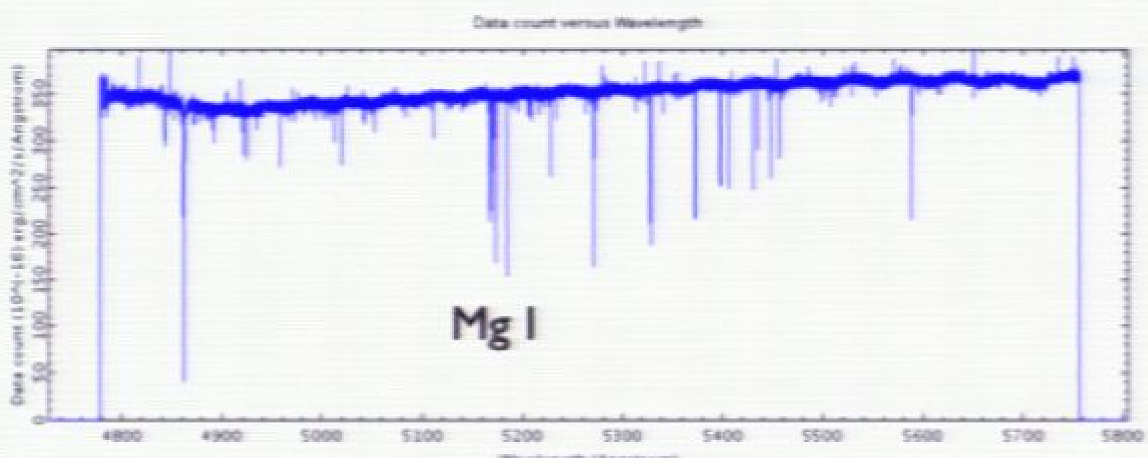


Lithium observations:

- can be observed in atmospheres of stars
- metallicity traces age => stars (formed) at lowest metallicities are thought to represent the chemical composition of the pre-galactic gas



HD 124897
[Fe/H] = -0.5



Spectra obtained with applet "SPLAT" [http://star-www.dur.ac.uk/]

CD-38-245
[Fe/H] = -4

The Spite plateau:

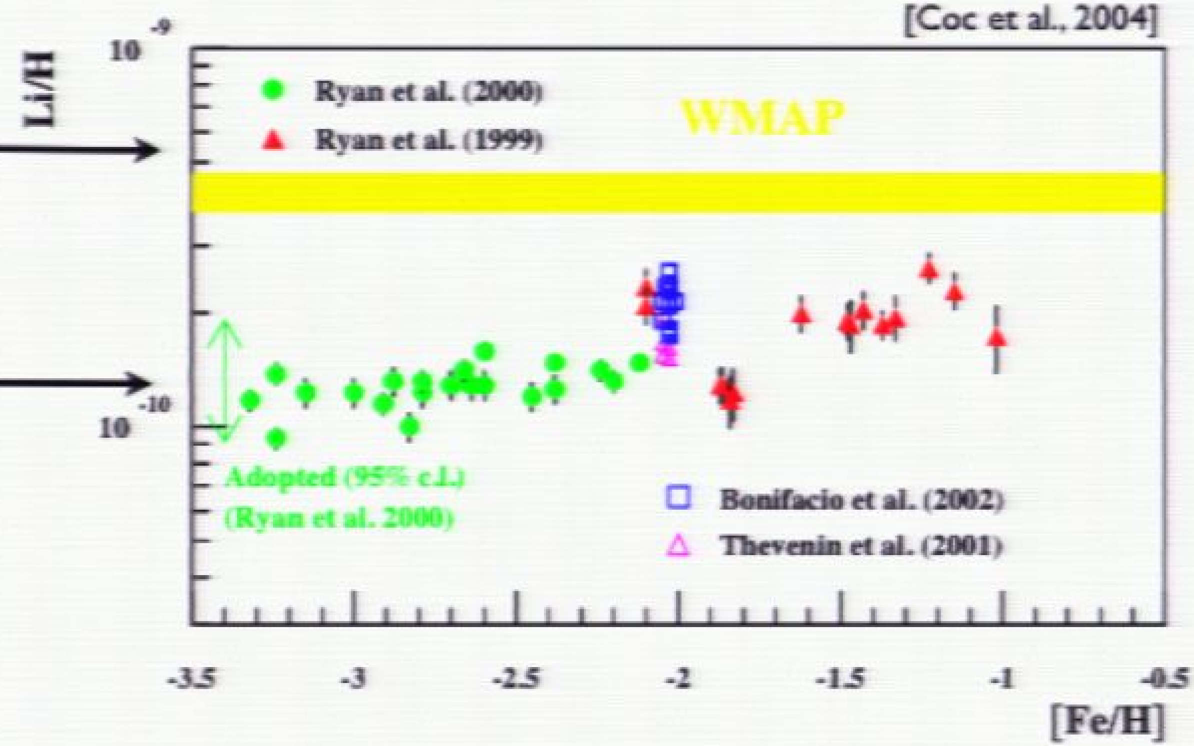
- Li shows plateau structure with small scatter at lowest metallicities: "Spite plateau" (1982) => points towards primordial origin

SBBN

"cosmological Li-problem"

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

[Coc et al., 2004]



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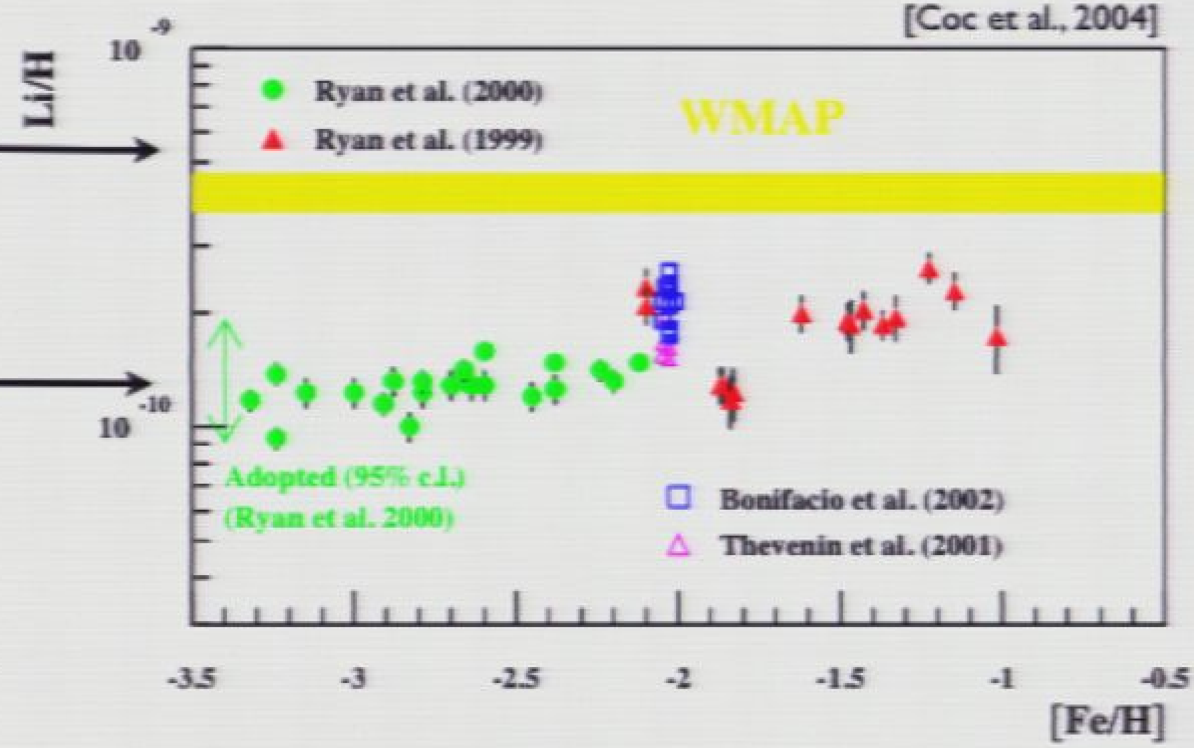

The Spite plateau in 2011:

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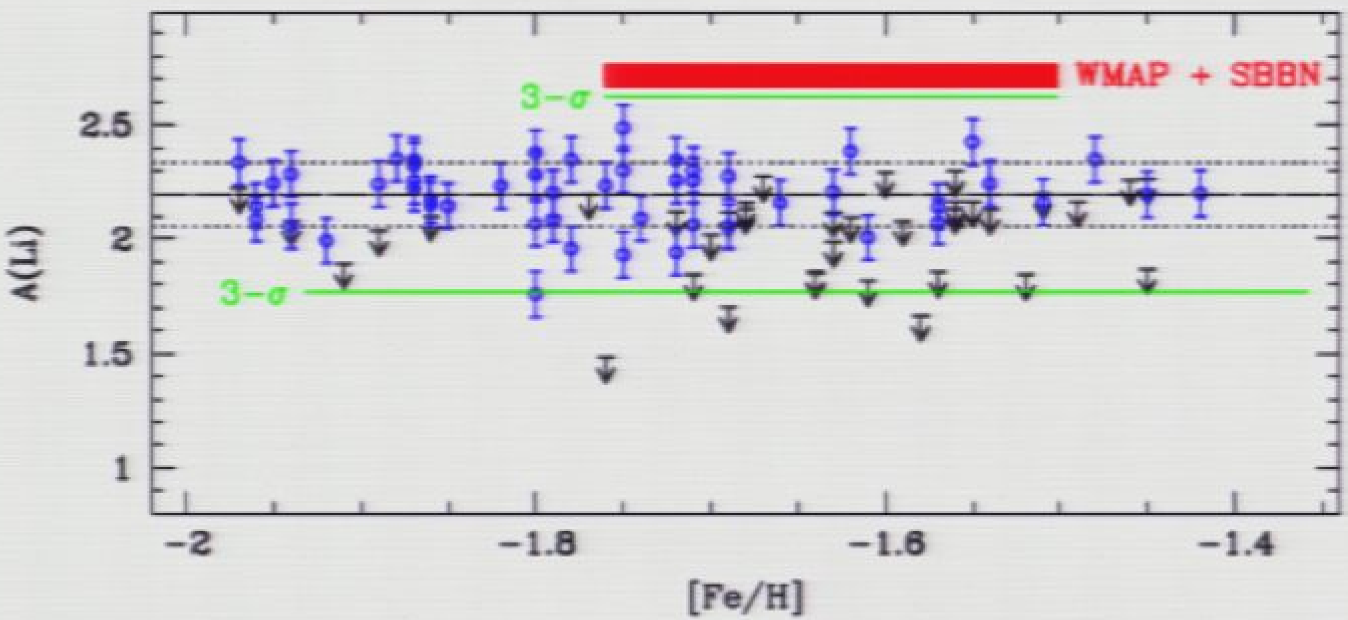

$$[A(\mathrm{Li}) = \log_{10}(\mathrm{Li/H}) + 12]$$

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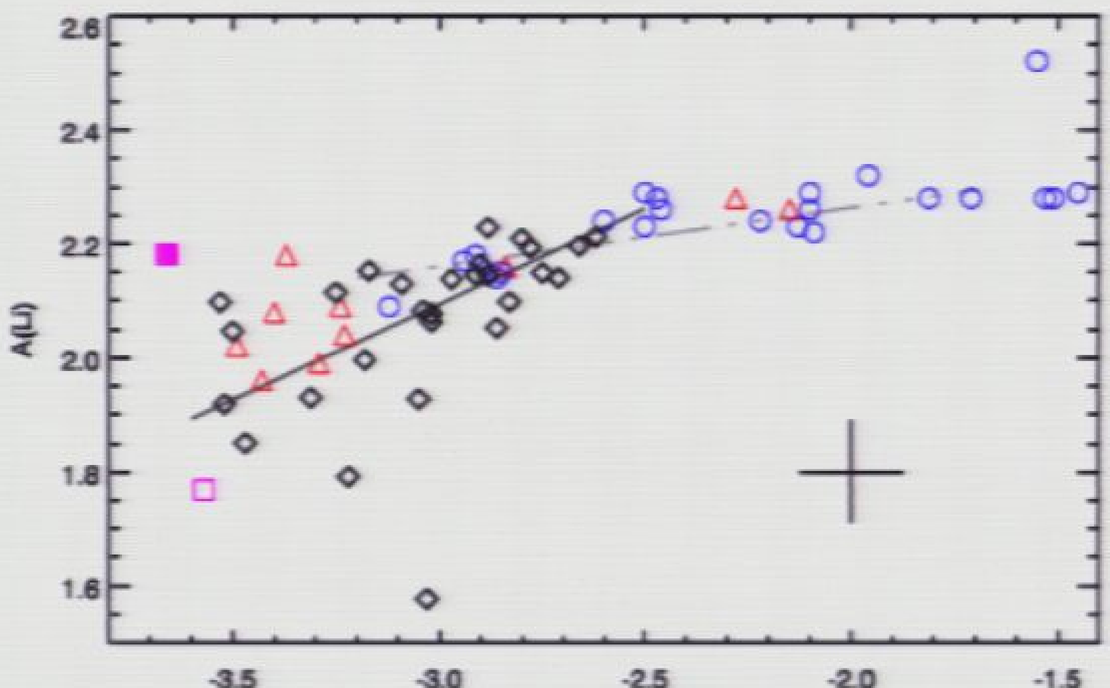

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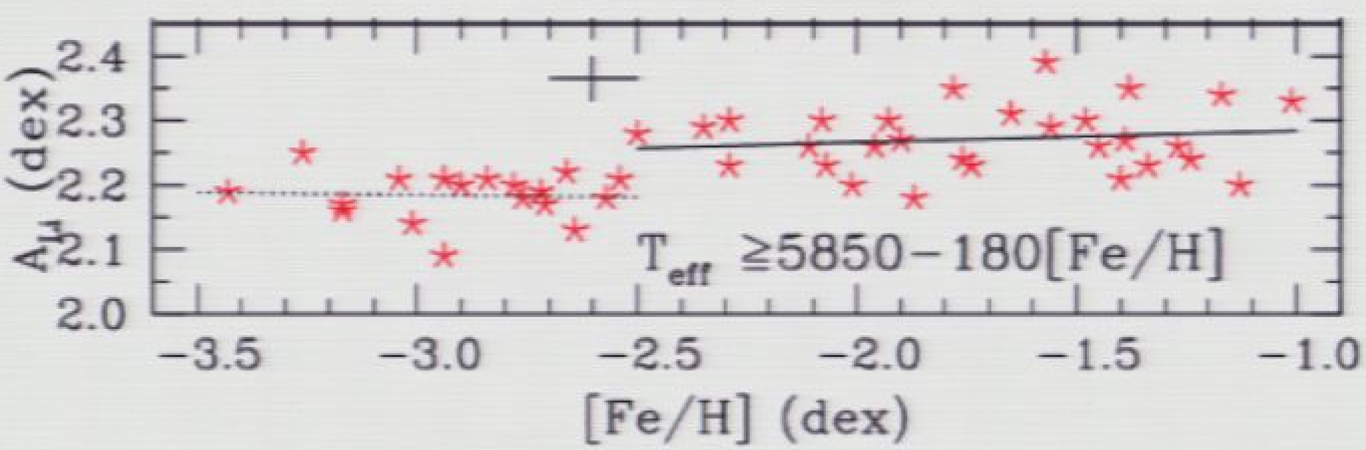

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latter two results are puzzling but do not alleviate the tension between SBBN and observations!

SBBN predictions @ η_{WMAP} | Observations

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$\mathcal{O}(10^{-10})$	$^7\mathrm{Li/H} = 5.27^{+0.71}_{-0.67} \times 10^{-10}$	$(^7\mathrm{Li/H})_p = (1.5 - 2) \times 10^{-10}$	↯
$\mathcal{O}(10^{-14})$	$^6\mathrm{Li/H} \simeq 10^{-14}$	$(^6\mathrm{Li}/^7\mathrm{Li})_p = 0.05\,?$ subject to astrophys. uncertainties	

see e.g. [Cyburt et al., 2008]

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Can we fix the Li-problem? Let's tinker with BBN...

Generic ways to affect BBN

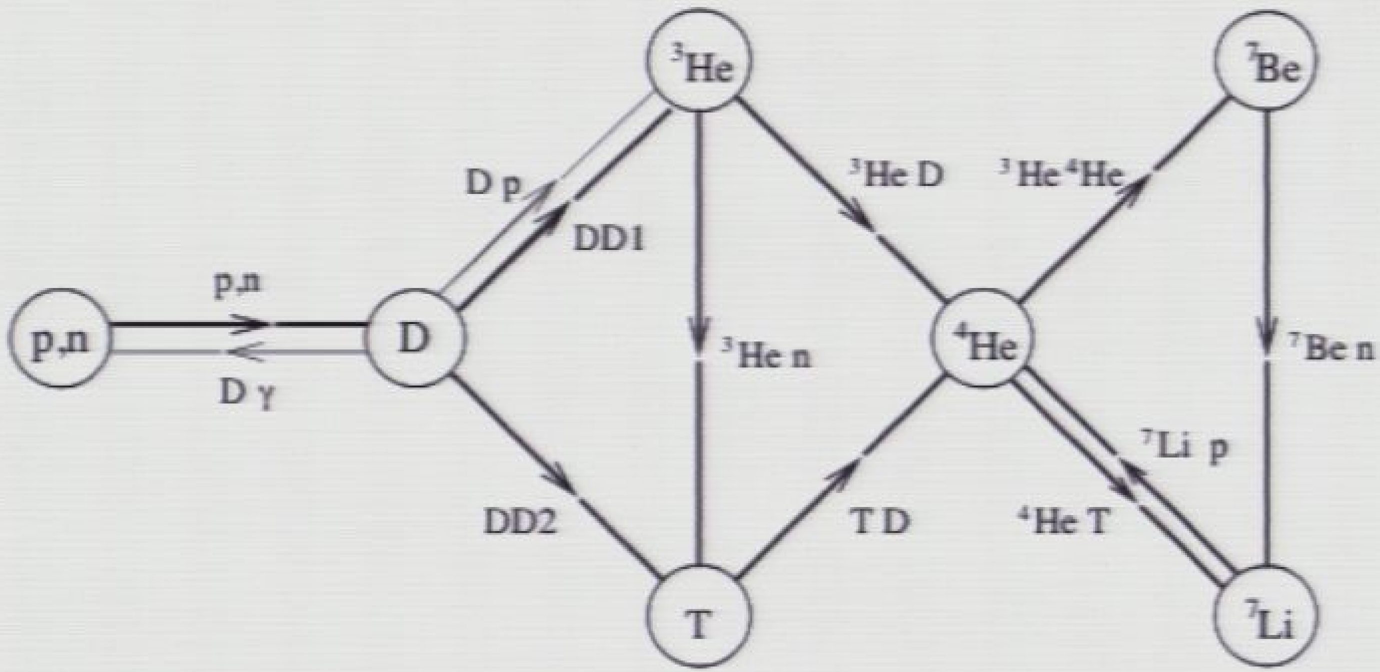
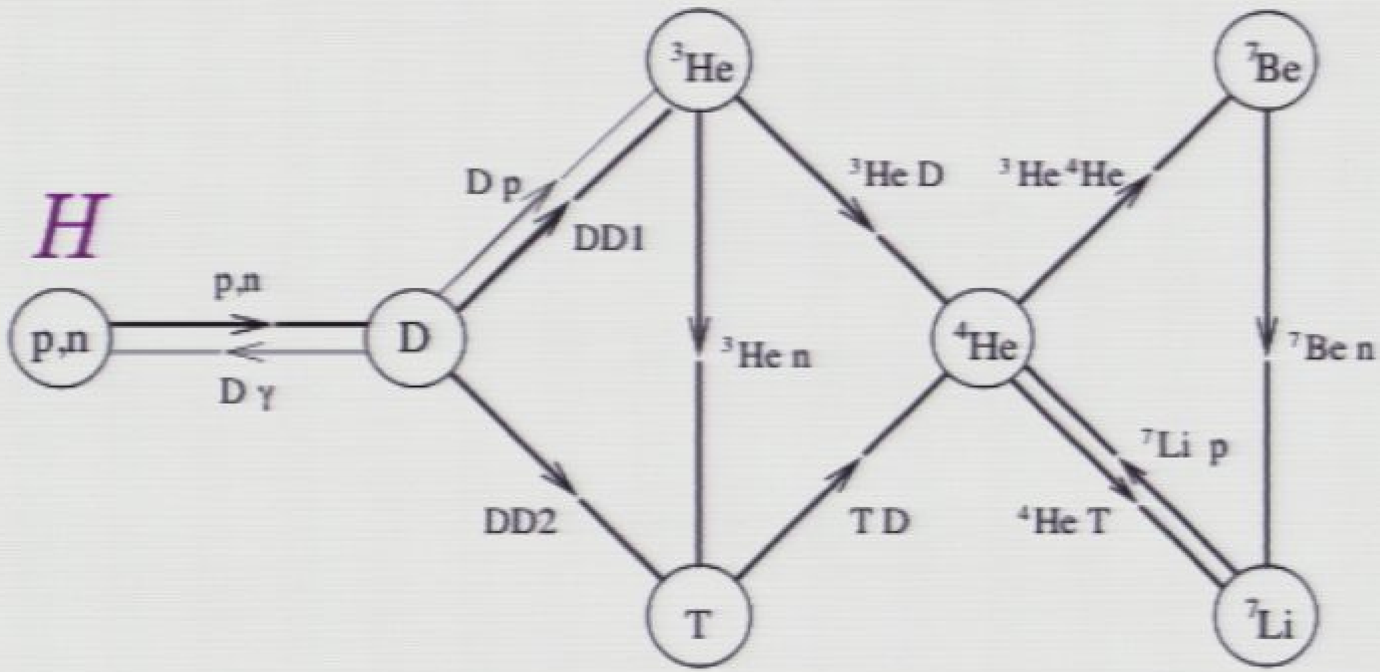


Fig. from [Mukhanov, 2004]

Generic ways to affect BBN

H



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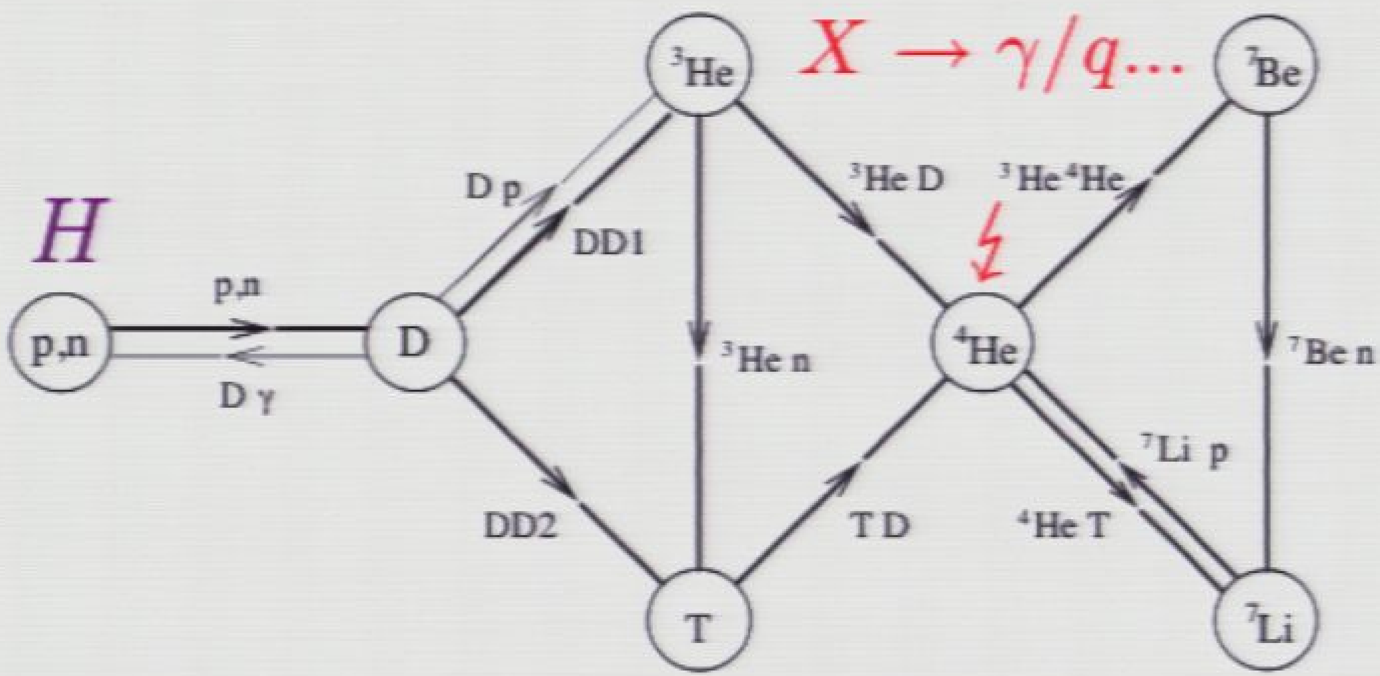
Change in timing

Generic ways to affect BBN



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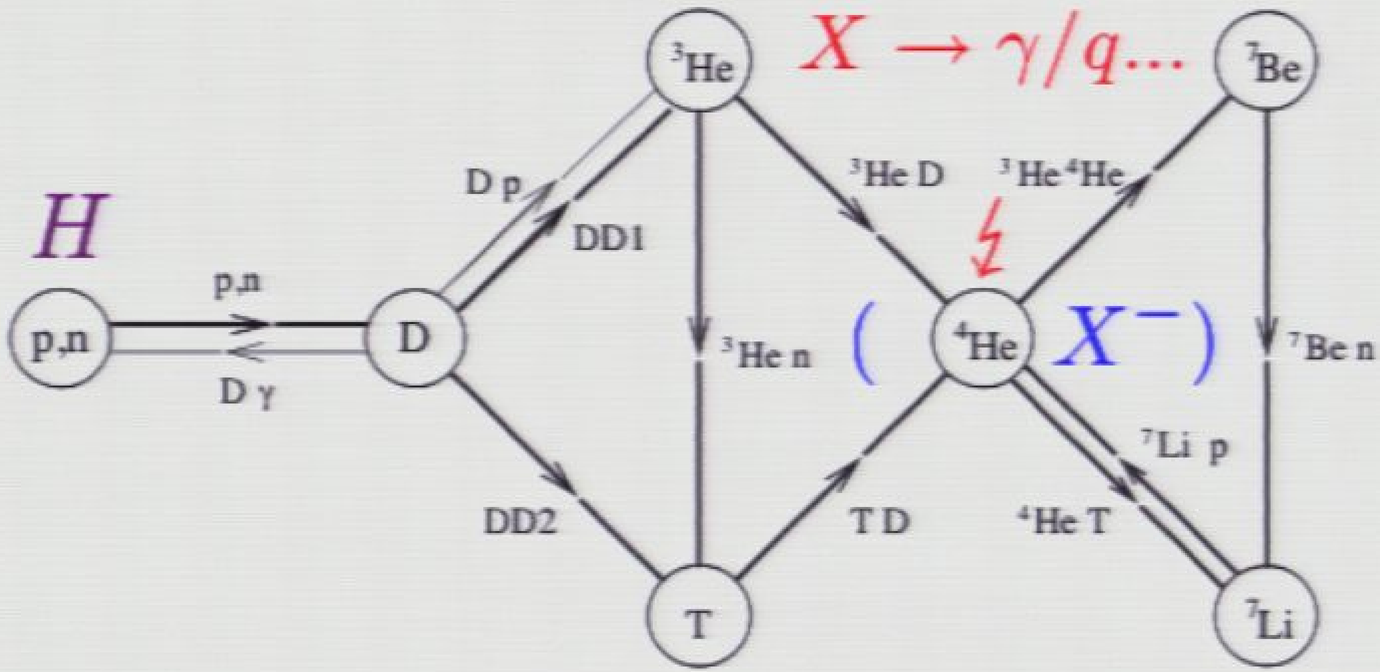
Change in timing non-equilibrium BBN

Generic ways to affect BBN



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Change in timing

non-equilibrium BBN

catalyzed BBN

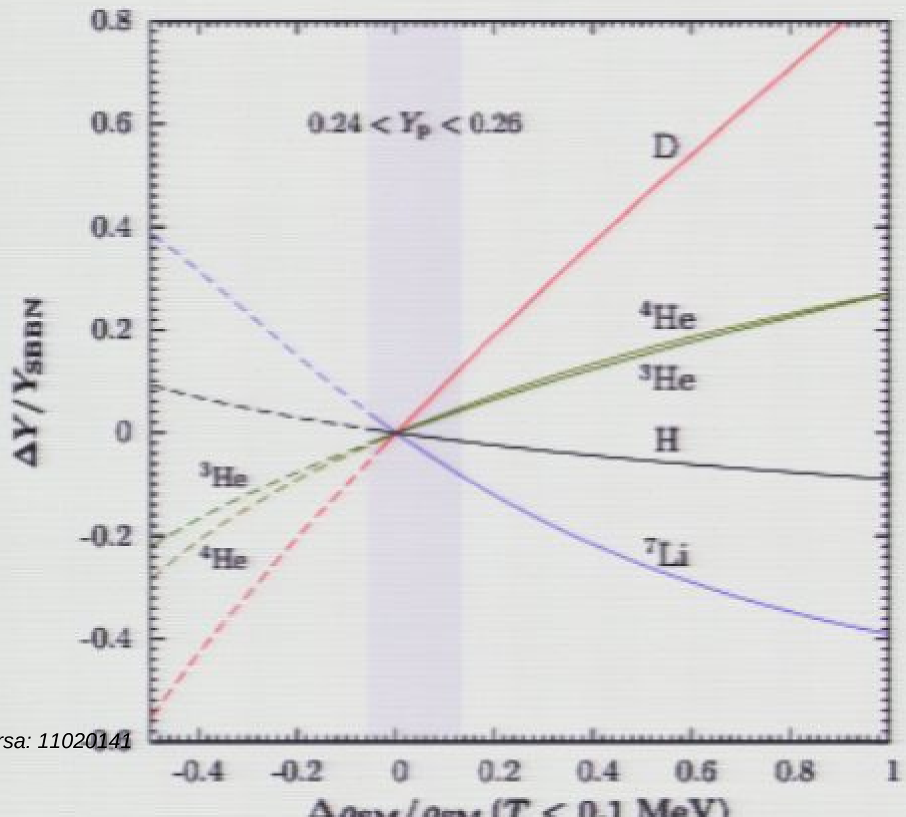
Generic ways to affect BBN

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"

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

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

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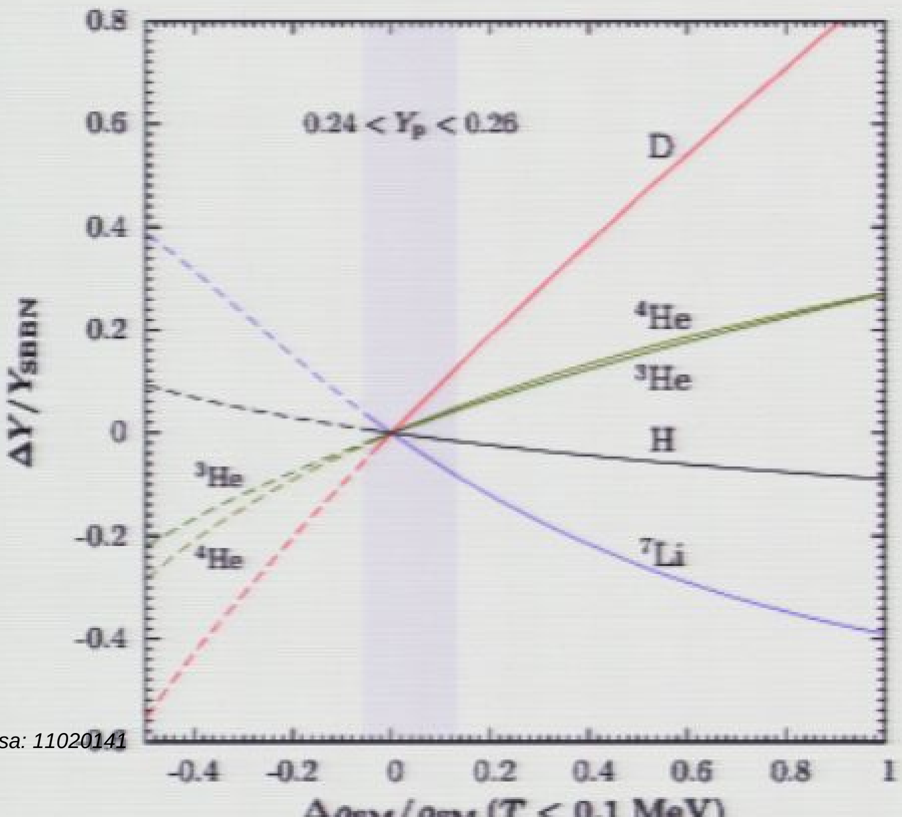


"dark radiation"

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

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

won't work for lithium!

Generic ways to affect BBN

"Inject neutrons at $T_9 \sim 0.5$"

- most neutrons intercepted by p

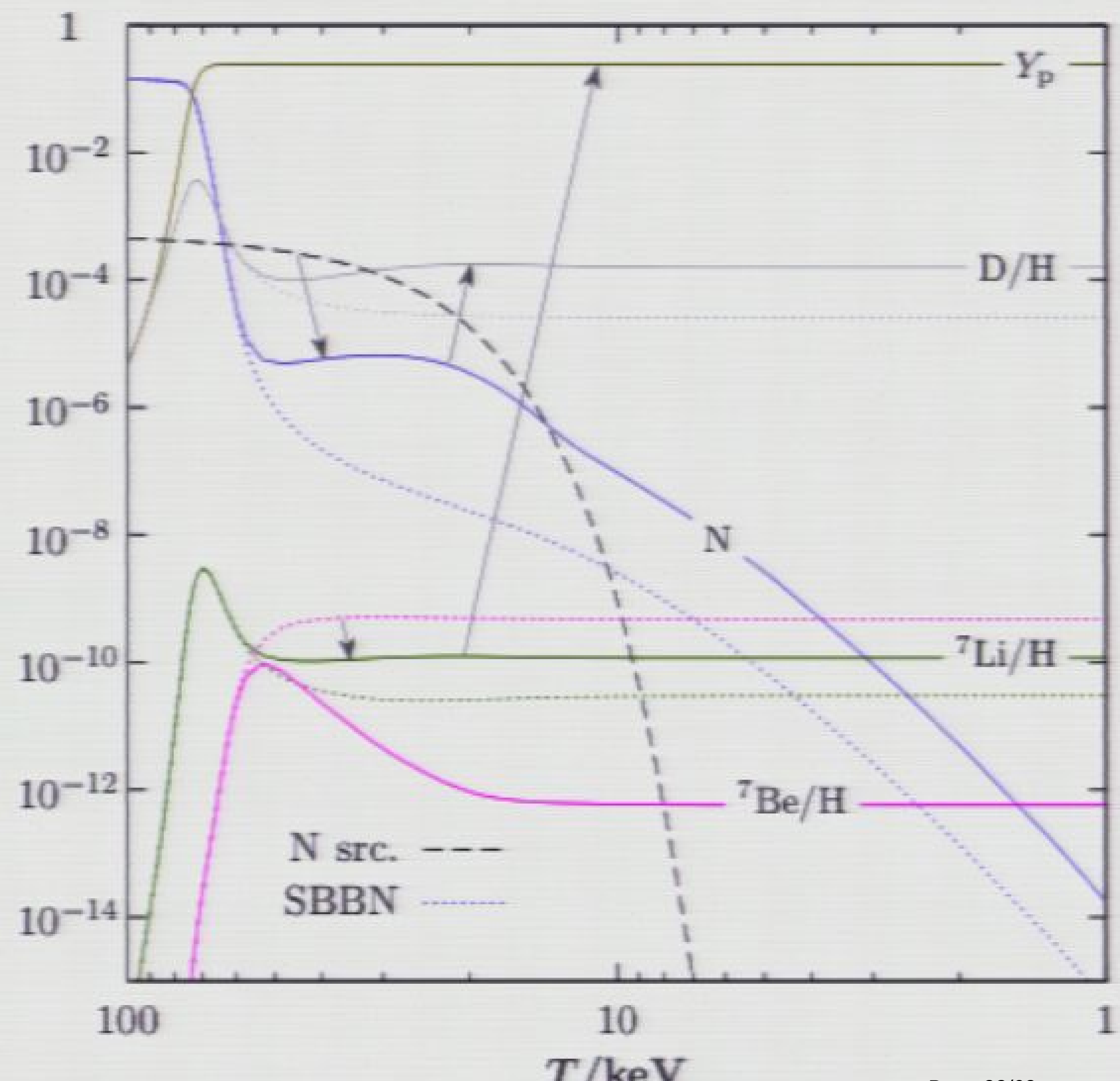
  => high D

- some of neutrons will charge exchange on A=7

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

↑ proton burning

[Reno & Seckel 1988]



Where to take the neutrons from?

How about non-equilibrium BBN

- most prominent class: decays of long-lived particles X

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

e.g. [...., Kawasaki et al. 2004, Jedamzik 2006, Steffen 2006, Cyburt et al. 2009]

=> yield electromagnetic and hadronic showers which dissociate light elements

- very difficult to find "lithium sweet-spots"

"violent process"

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  => yield electromagnetic and hadronic showers which dissociate light elements

- very difficult to find "lithium sweet-spots"

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but what if X is light?

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

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

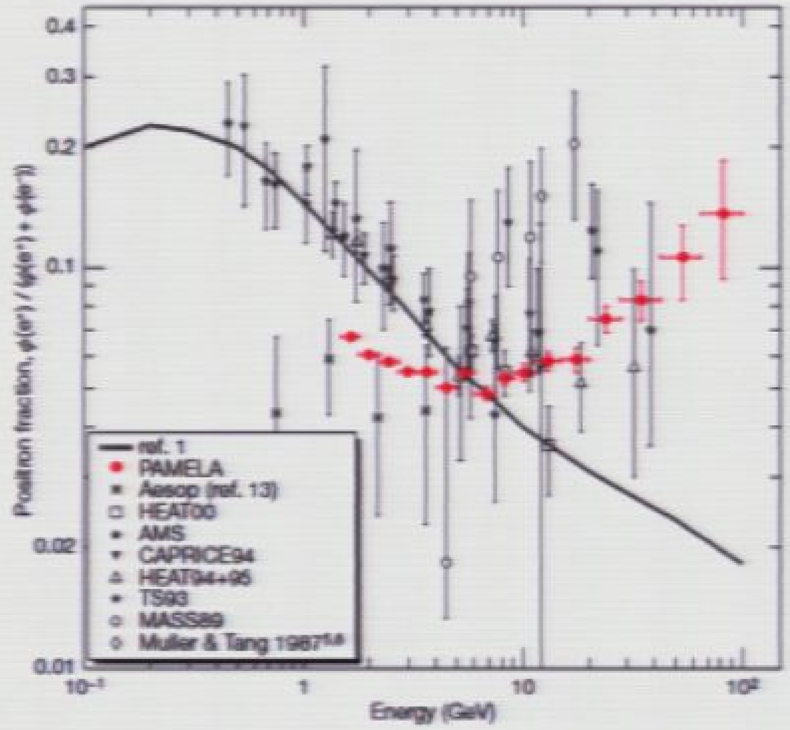
$$\text{"}\mu/\nu\text{BBN"}: \quad \mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

$$\downarrow$$

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

Motivation for light X

[Adriani et al, 2009]



- interpretation of cosmic ray anomalies e.g. from PAMELA and FERMI as Dark Matter annihilations

=> boost factor $\mathcal{O}(10^3)$ required

=> leptons in the final state

=> use mediating sector: "dark forces"

[Arkani-Hamed et al, 2009; Poseplov & Ritz 2009]

Standard Model ⟷ Dark Matter

Mediators X

Sommerfeld enhancement for

$$m_V \lesssim m_{\rm dm} v_{\rm gal} \sim 100 \text{ MeV} \div 1 \text{ GeV}$$

$$S \sim \frac{\pi \alpha'}{v}$$

Examples of secluded sectors

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

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

$A,\ \lambda,$ and m_S^2 (S-portal)

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

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

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

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

α', κ, $m_{h'}$, and m_V (V-portal),

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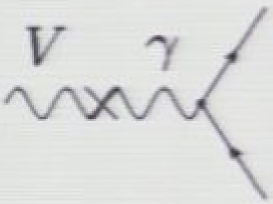
$\alpha',\ \kappa,\ m_{h'},$ and m_V (V-portal),

we want a state with $\tau_X \gtrsim \mathcal{O}(100\ \mathrm{s})$

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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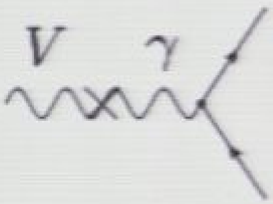

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"super-Wimp" regime

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

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

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

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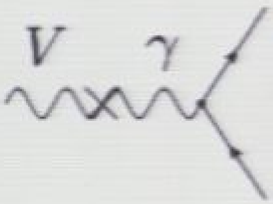

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"Wimp" regime

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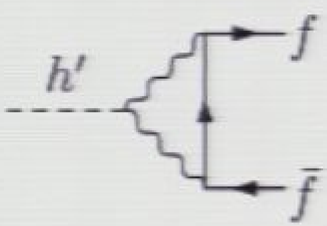
naturally long-lived h'



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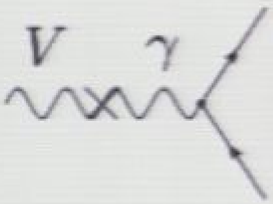

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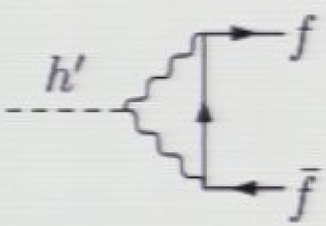


[Batell et al., 2009]

$\Rightarrow m_V < m_{h'}$

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

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

X-abundance

$Y_X = n_X / n_b$

"Wimp" regime: h'

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

"super-Wimp": V

production stops below $m_V \sim \Lambda_{\rm QCD}$ => can only estimate

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

πBBN : $X \to \pi^+\pi^-$

$m_X > 2m_\pi$

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

- $p \to n$ interconversion rate:

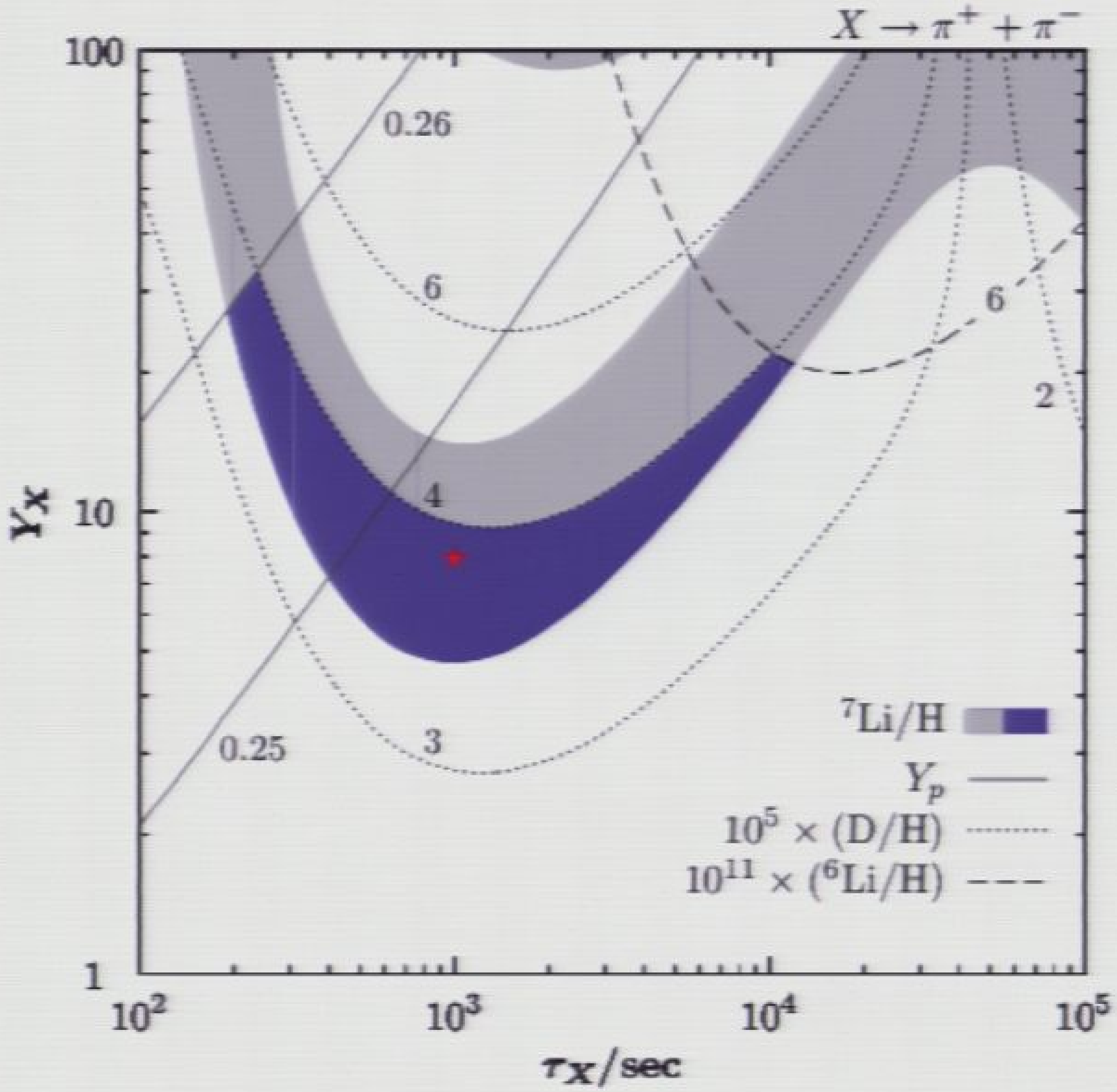
$$\Gamma_p^\pi = n_p \langle \sigma v \rangle_{pn}^\pi \simeq (3 \times 10^2\ {\rm s}^{-1})\ \frac{T_9^3 \langle \sigma v \rangle_{pn}^\pi}{1\ {\rm mb}}$$

- 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

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



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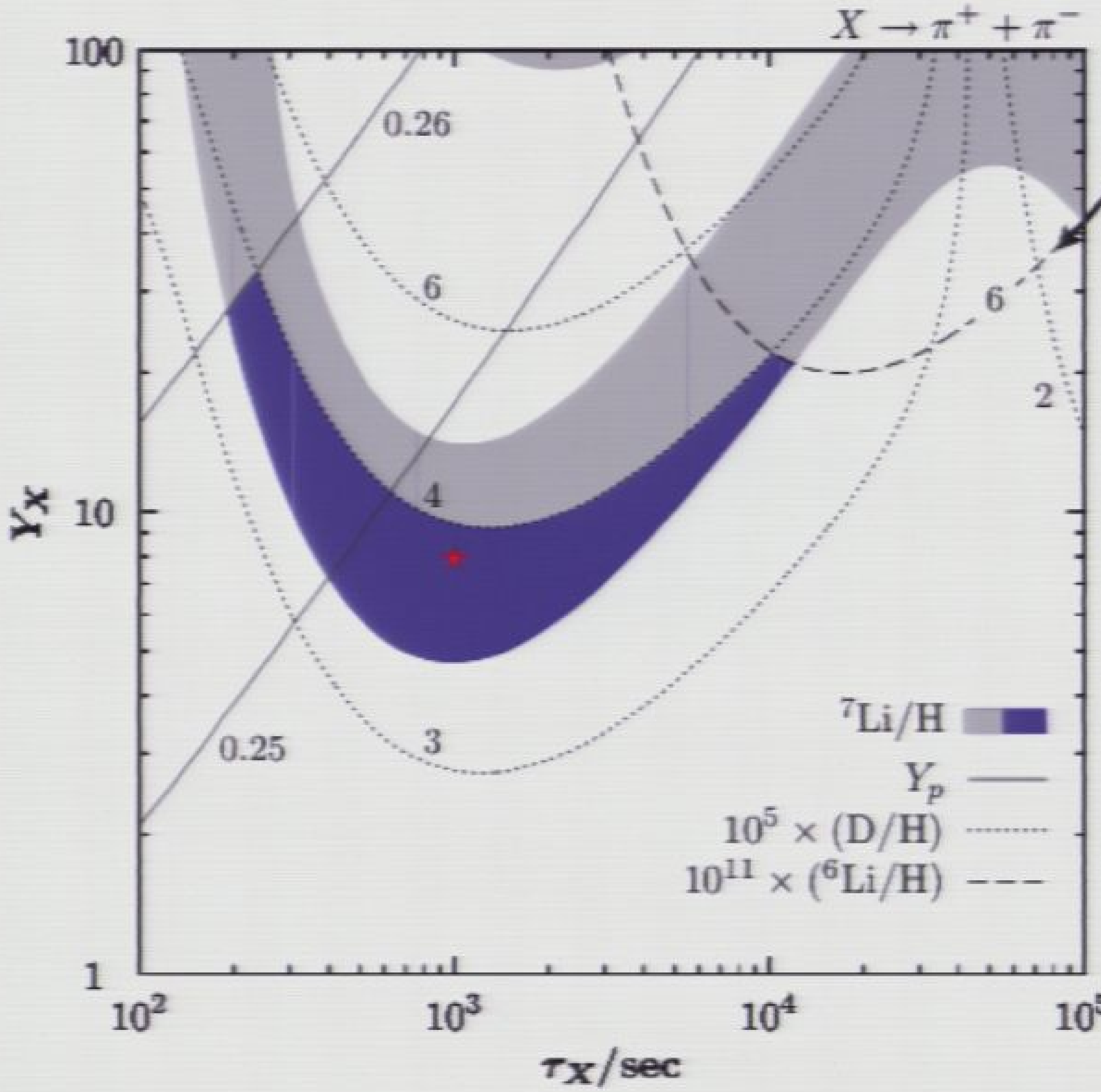


$\pi^- + {}^4\text{He} \to \text{T} + n$

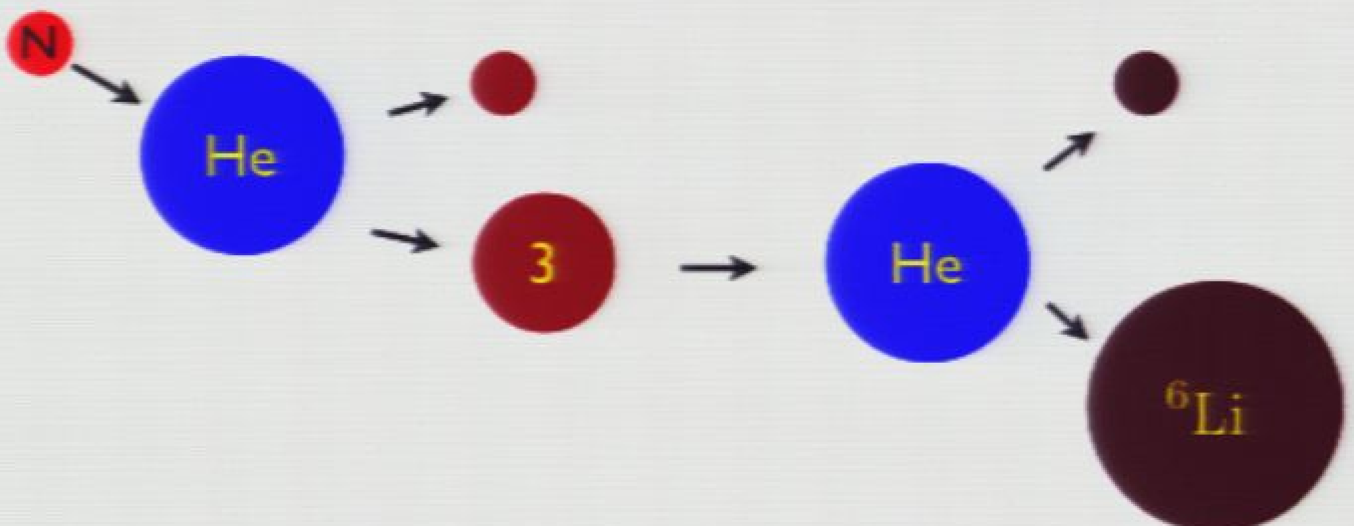
$^4\text{He}|_{\text{bg}} +$

$\downarrow$

^{6}Li

...this brings us back to non-equilibrium BBN:

Li-6 production is an issue!



[Dimopoulos et al., 1988]
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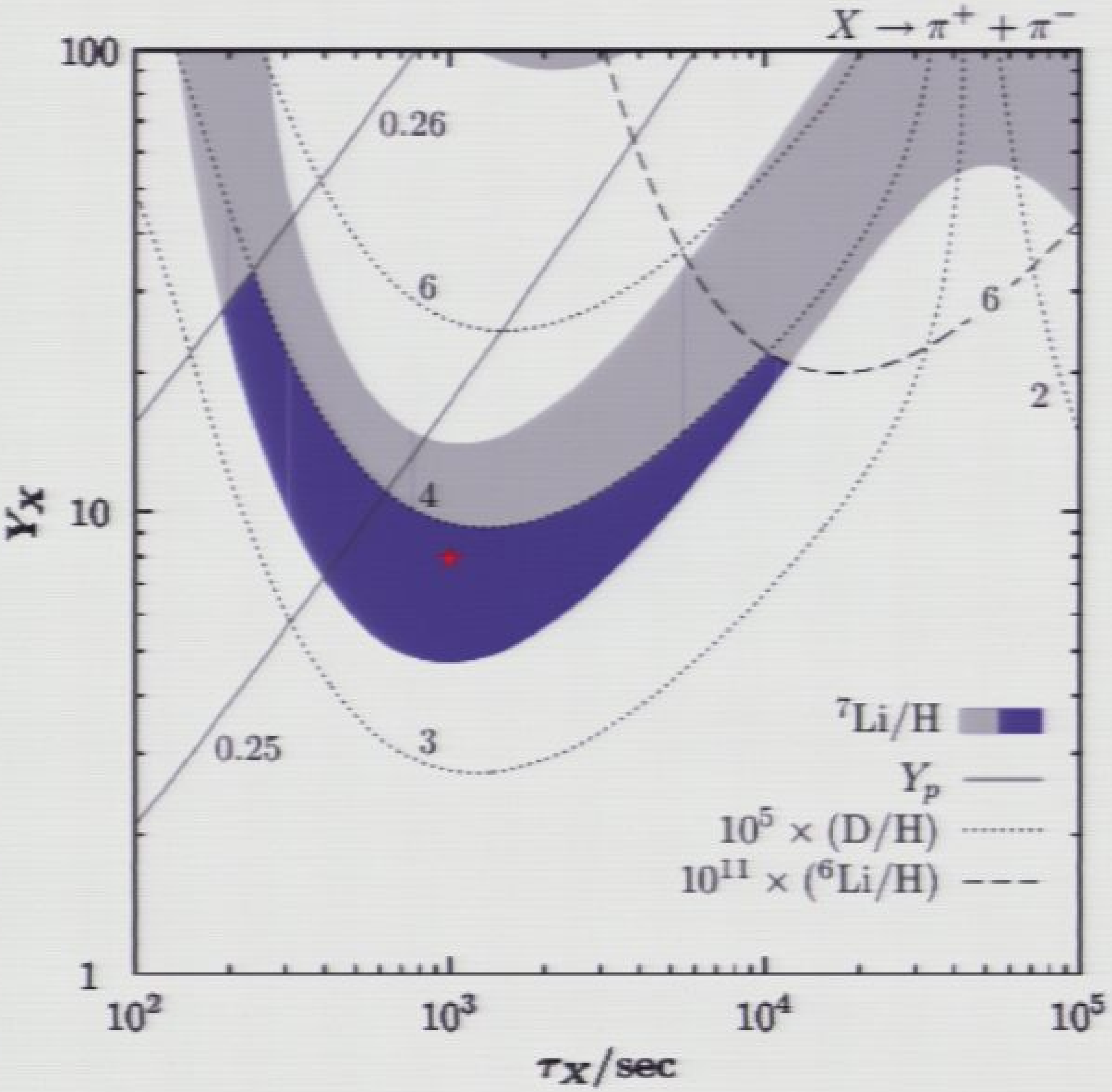

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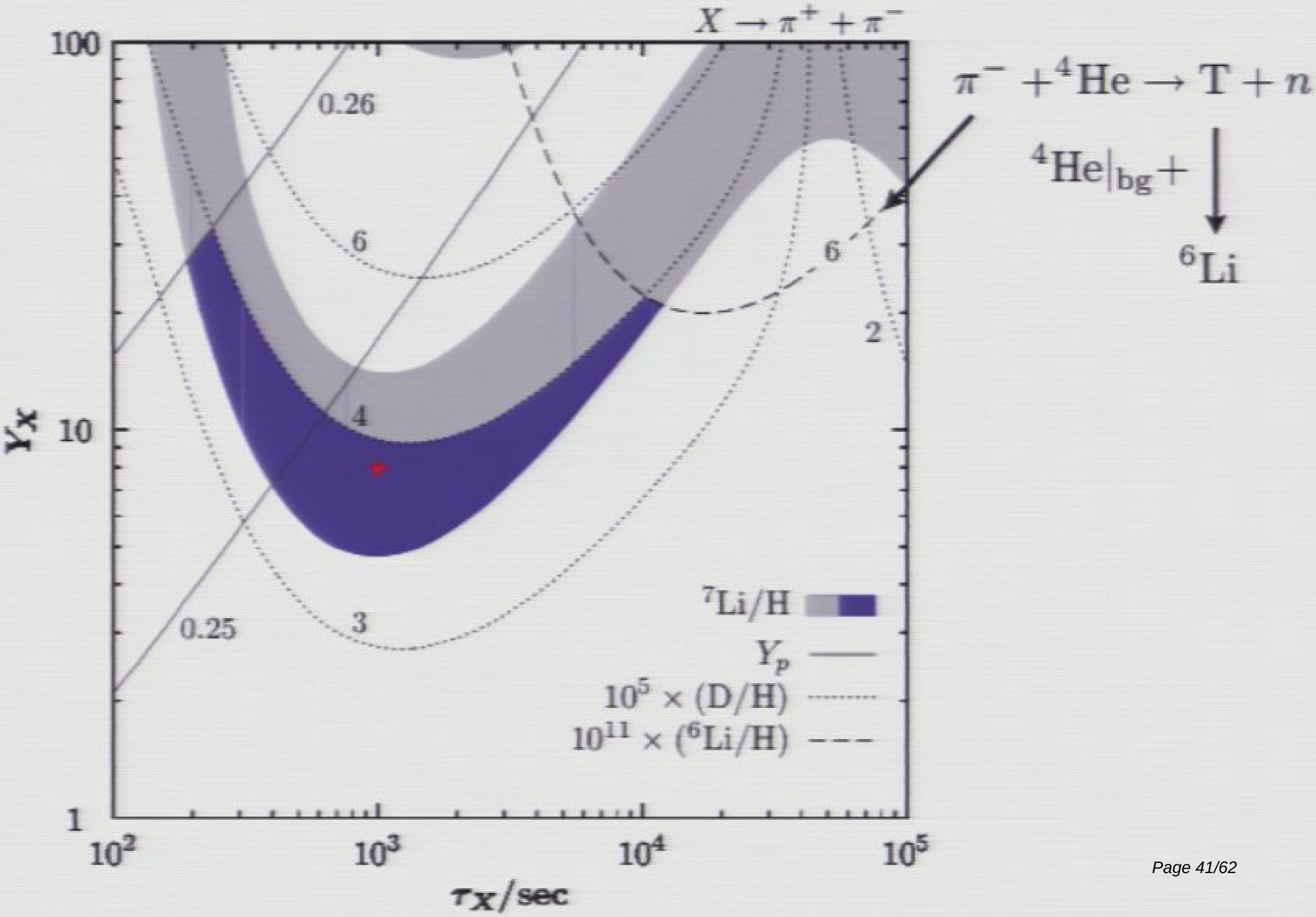

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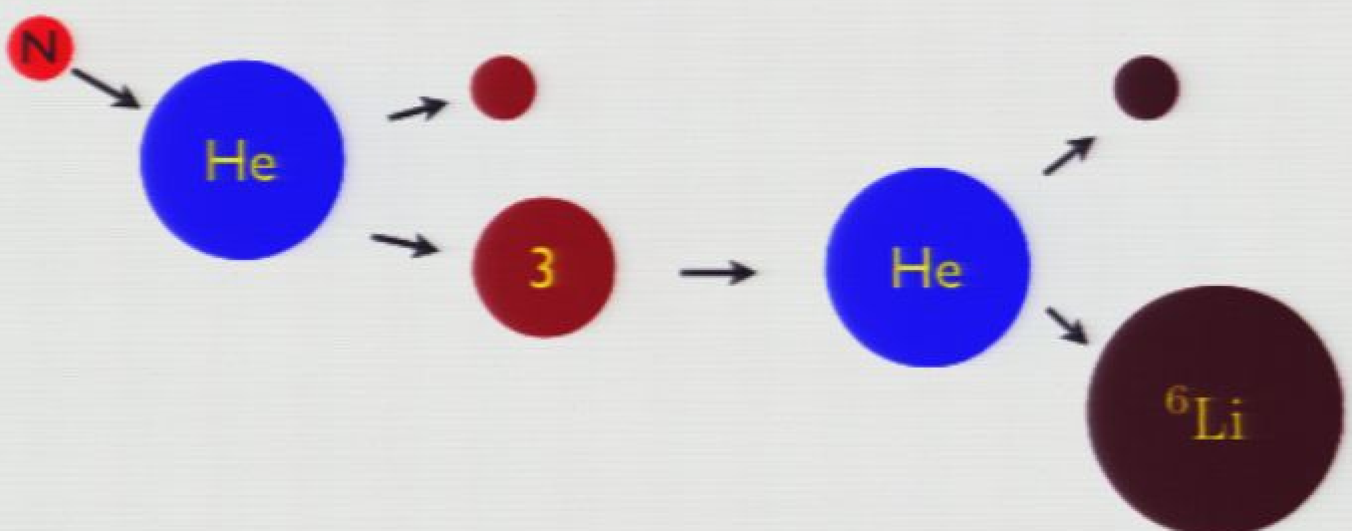

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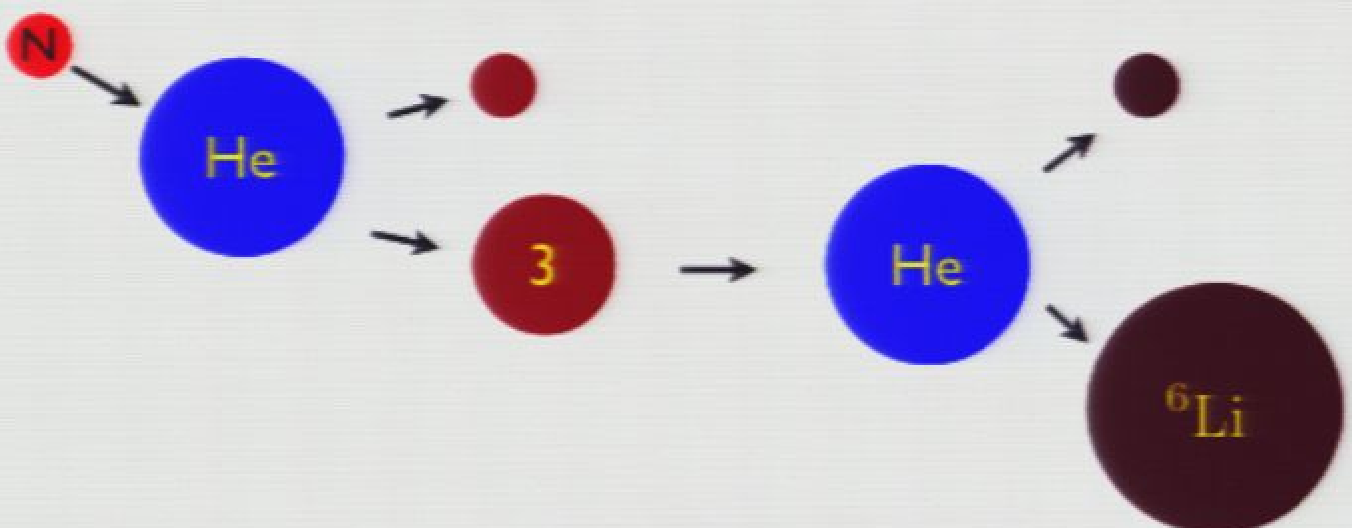
[if there is an limit on its primordial abundance]



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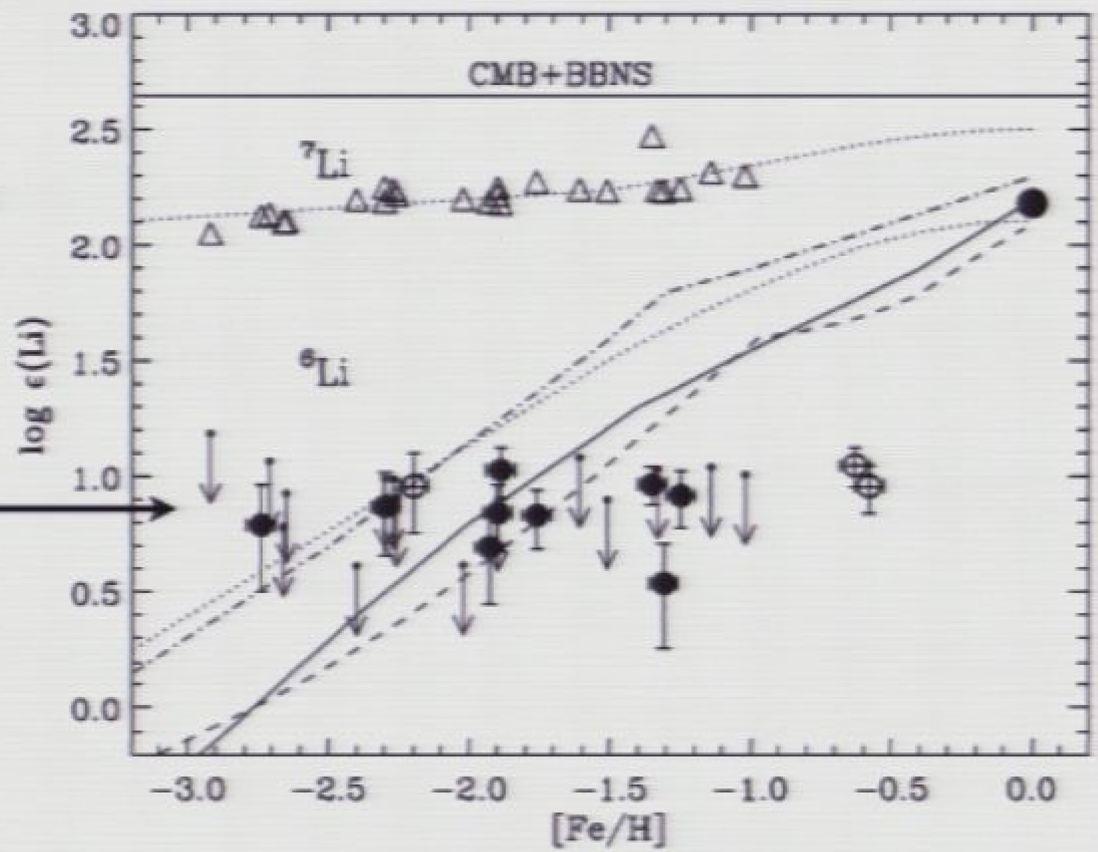
Is Li-6 primordial?

- Lithium-6:
  - Claim of (2σ) detections in 9 halo stars [Asplund et al., 2006]

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

plateau



- profound cosmological implications: $^6\mathrm{Li}$ primoridal?

$$\frac{^6\mathrm{Li}|_{\mathrm{obs}}}{^6\mathrm{Li}|_{\mathrm{SBBN}}} \sim 1000$$

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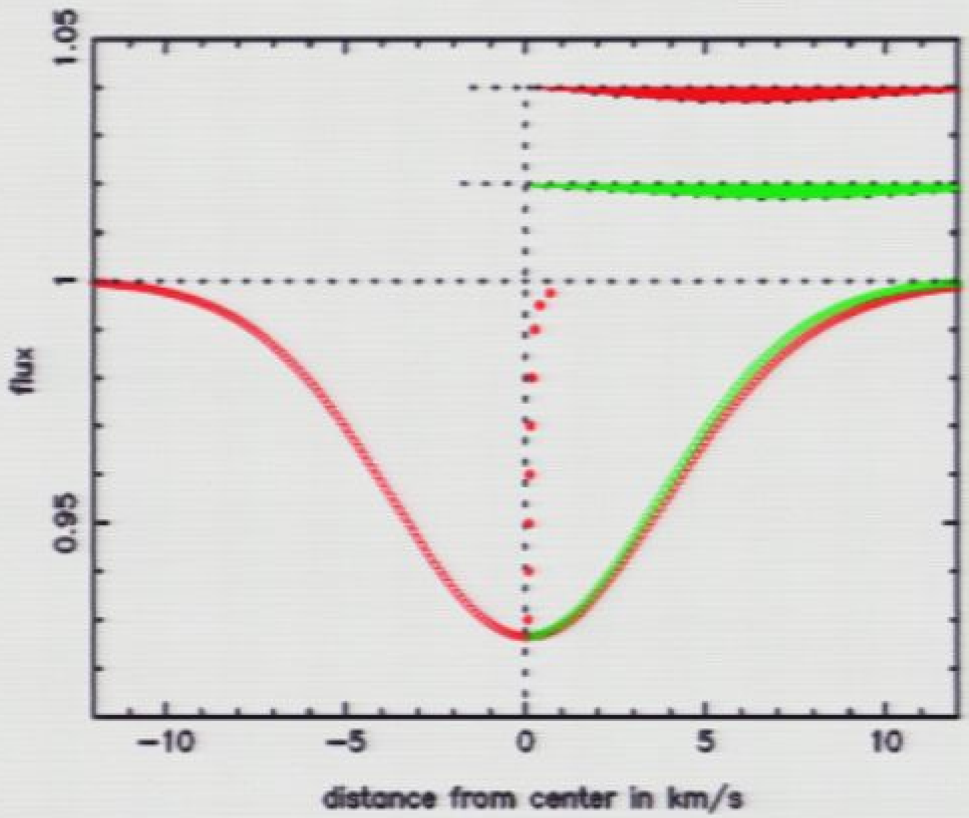
  - Claim challenged [Cayrel et al., 2006&2010]

  => Li-6 mimicked by convective motion of material

  => detections turn into upper limits



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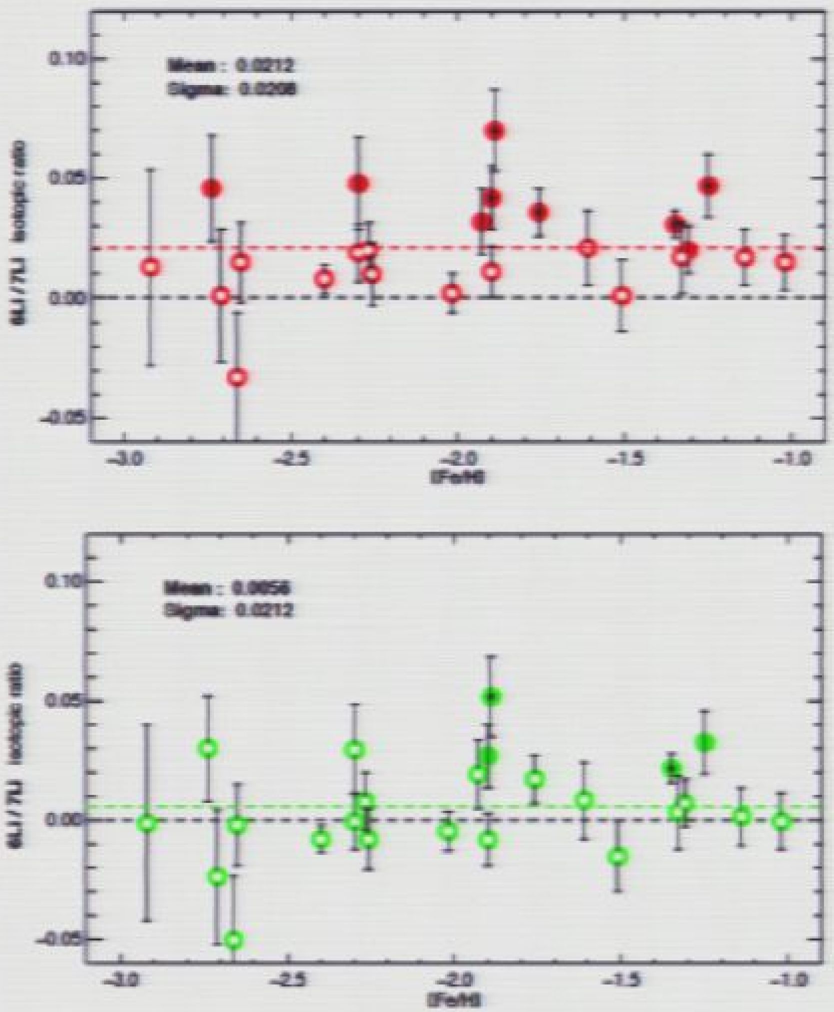

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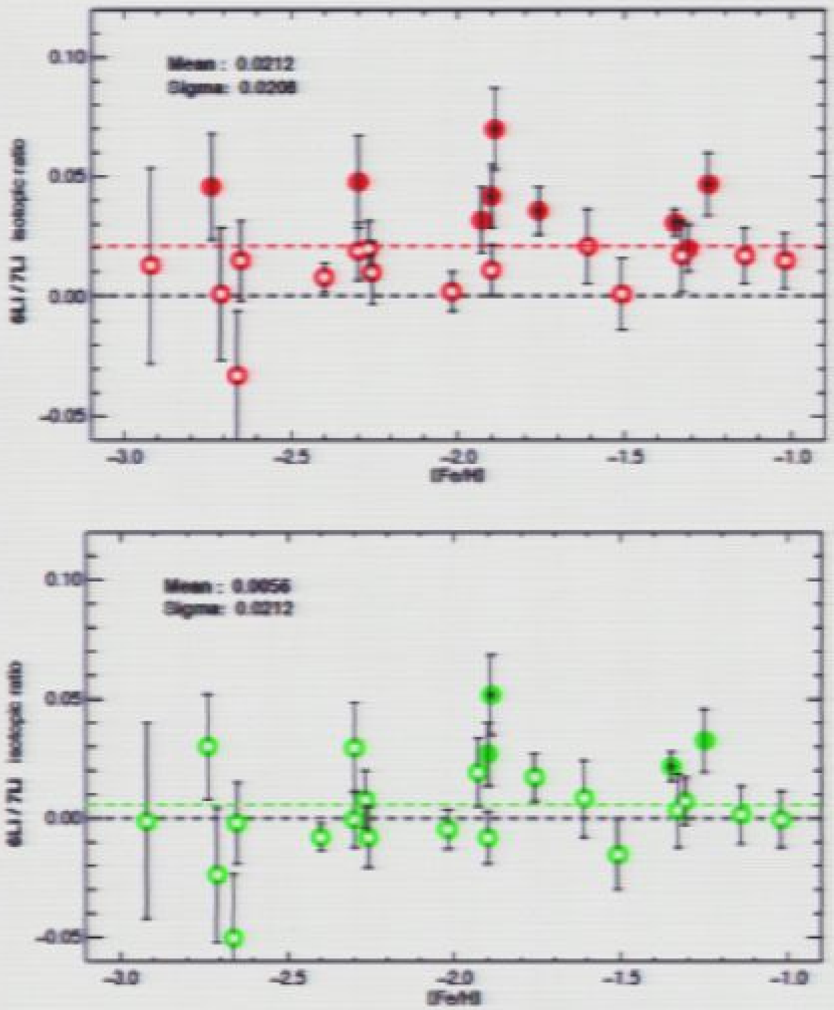


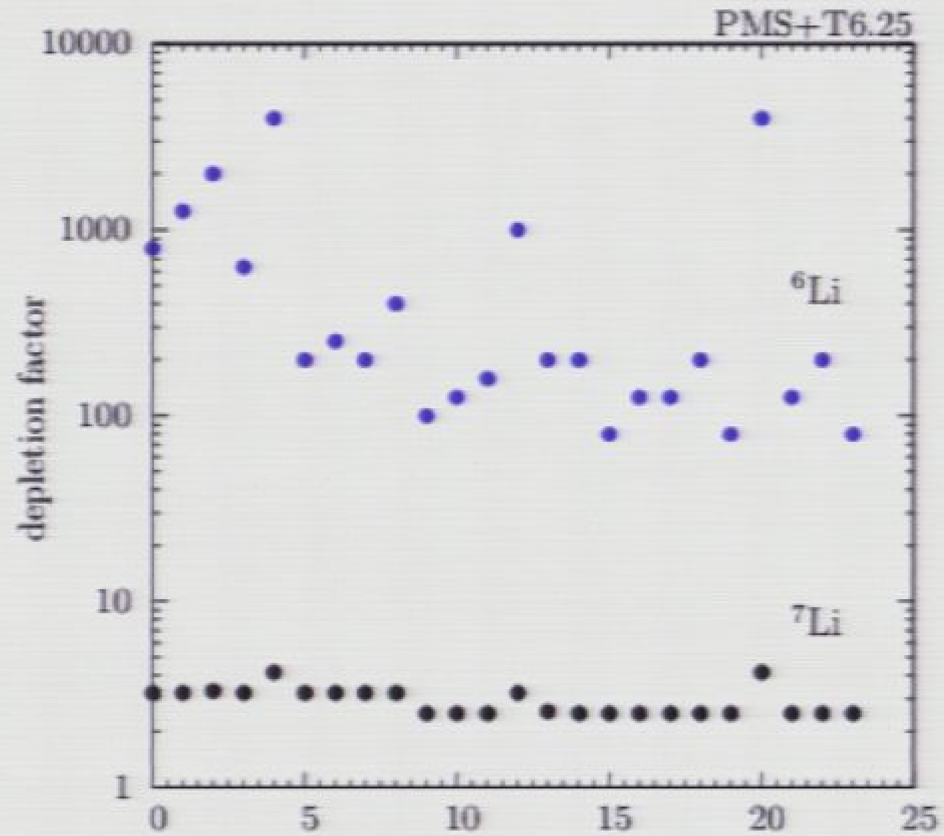
[Cayrel et al., 2010]

observational status doubtful

Moreover:

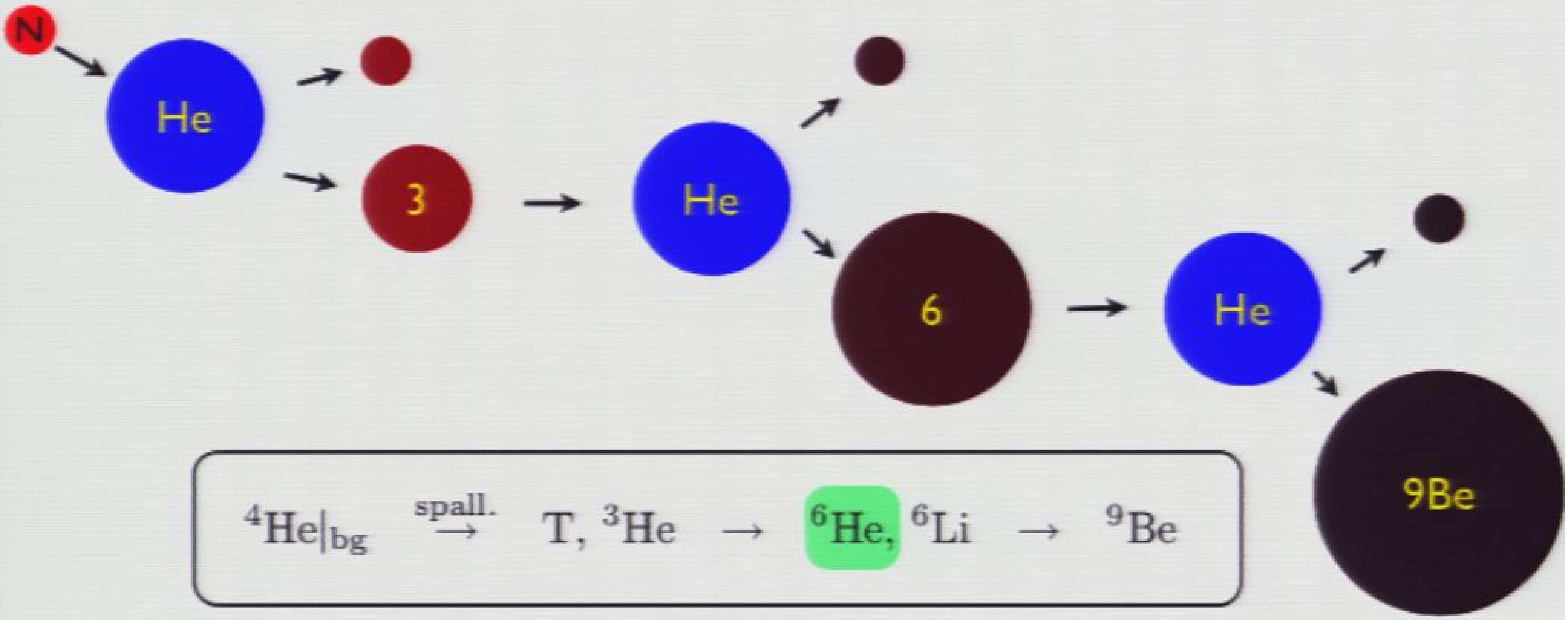
What if solution of the lithium problem is indeed of astrophysical origin?

- say, Li-7 is destroyed by a uniform factor of a few in stars
- => then Li-6 could have been depleted by a much larger factor
- Seek other observational handles on non-equilibrium BBN?



[stars from the Asplund 2006 sample]

Non-thermal "tertiary" Be-9 production



$$^4\mathrm{He}|_{\mathrm{bg}} \stackrel{\mathrm{spall.}}{\rightarrow} \mathrm{T},\ ^3\mathrm{He} \rightarrow\ ^6\mathrm{He},\ ^6\mathrm{Li} \rightarrow\ ^9\mathrm{Be}$$

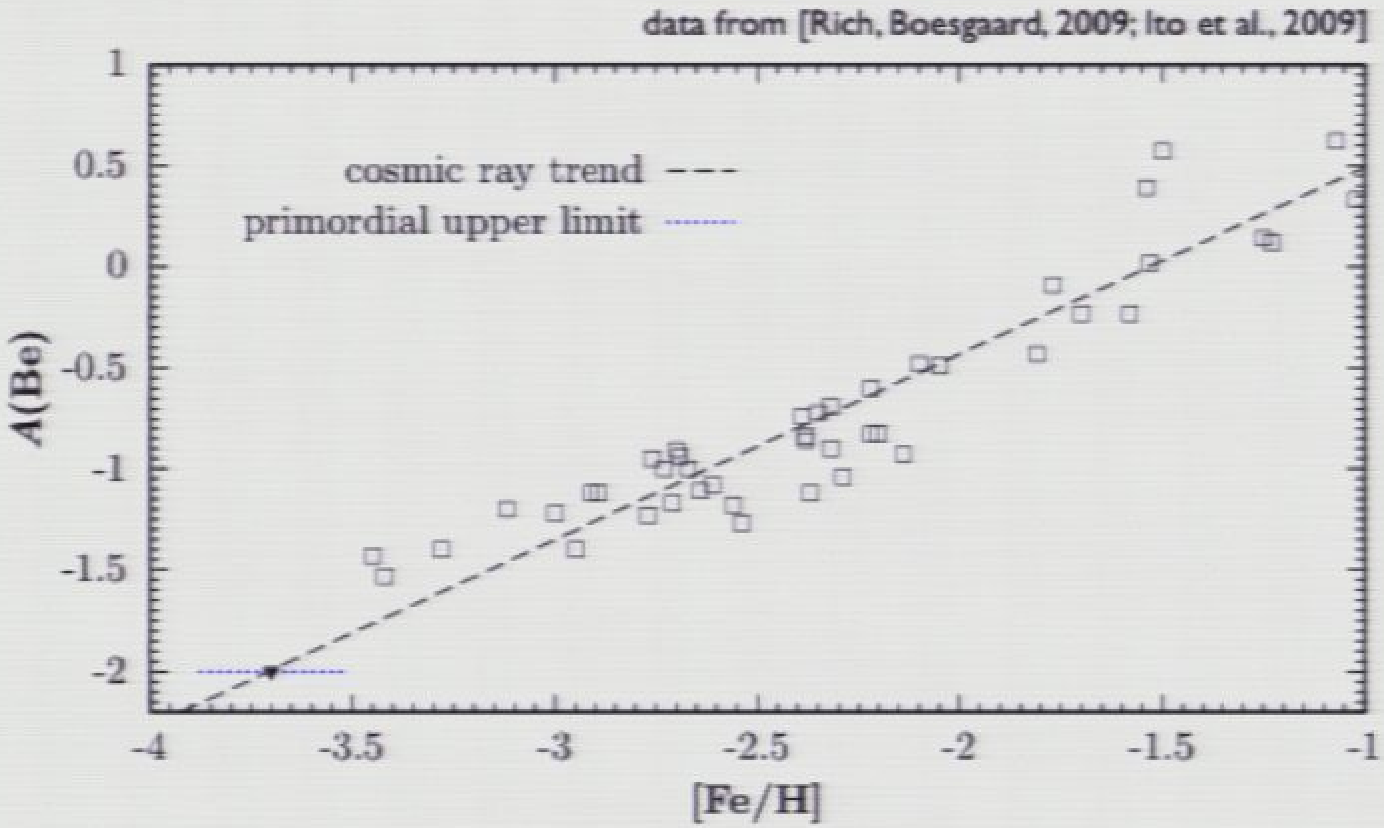
- $^6\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^9\mathrm{Be} + n, \quad Q = 0.60\mathrm{MeV},$ exoergic!

  $^6\mathrm{Li} + {}^4\mathrm{He} \rightarrow {}^9\mathrm{Be} + p, \quad Q = -2.13\mathrm{MeV}$

- Can we produce Be in observable quantities?

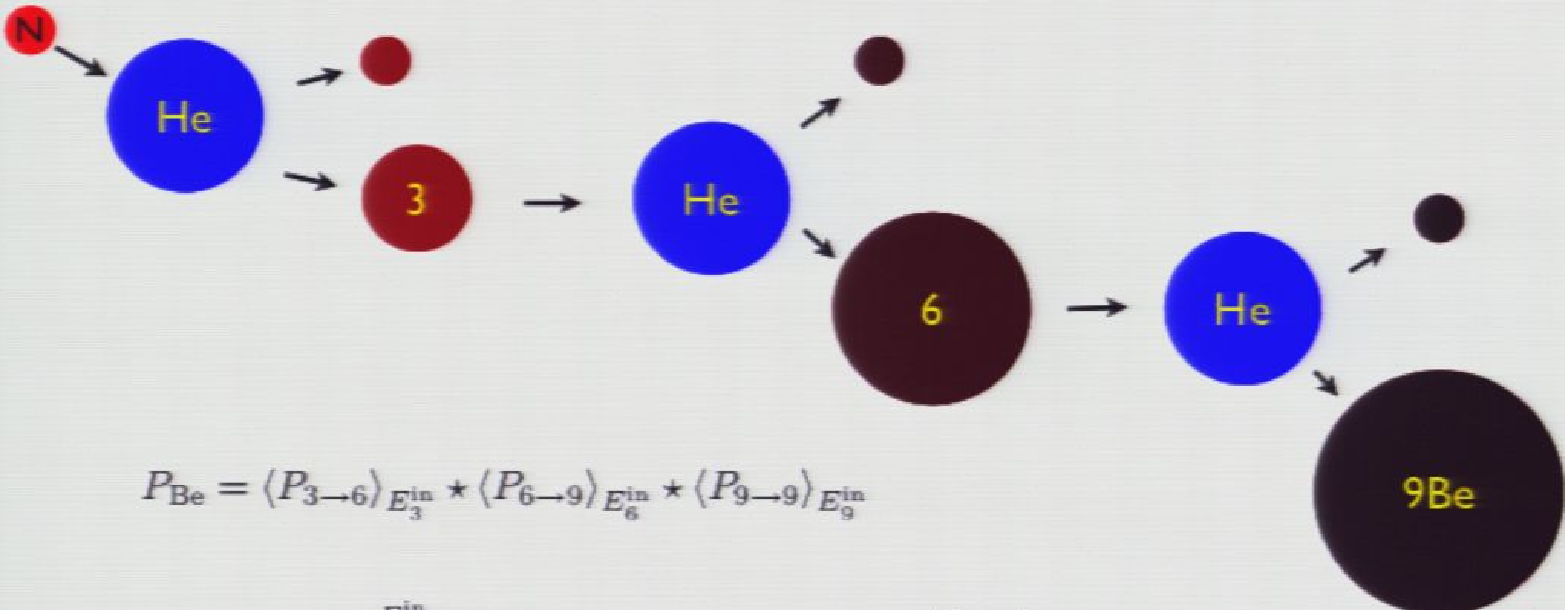
$\mathrm{NB} : {}^9\mathrm{Be/H}|_{\mathrm{SBBN}} < 10^{-18}$

Beryllium observations



- no indication of a plateau structure: $(^9\mathrm{Be/H})_p \lesssim 10^{-14}$
- cosmic ray production leads to a clear correlation with metallicity
- Be-9 firmly observed, observational status not in doubt

Non-thermal "tertiary" Be-9 production



$$P_{\rm Be} = \langle P_{3\to 6}\rangle_{E_3^{\rm in}} \star \langle P_{6\to 9}\rangle_{E_6^{\rm in}} \star \langle P_{9\to 9}\rangle_{E_9^{\rm in}}$$

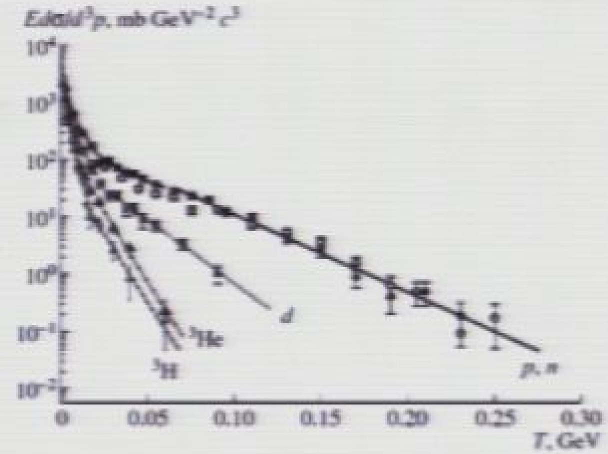
$$P_{A_1\to A_2} = \int_{\max\{E_{A_2}^{\rm th}, E_{A_2}^{\rm thm}\}}^{E_{A_1}^{\rm in}} dE_{A_1} \frac{n_{^4{\rm He}}\sigma_{A_1\to A_2}(E_{A_1})}{|dE_{A_1}/dx|}$$

dominantly Coulomb stopping (strong T dependence)

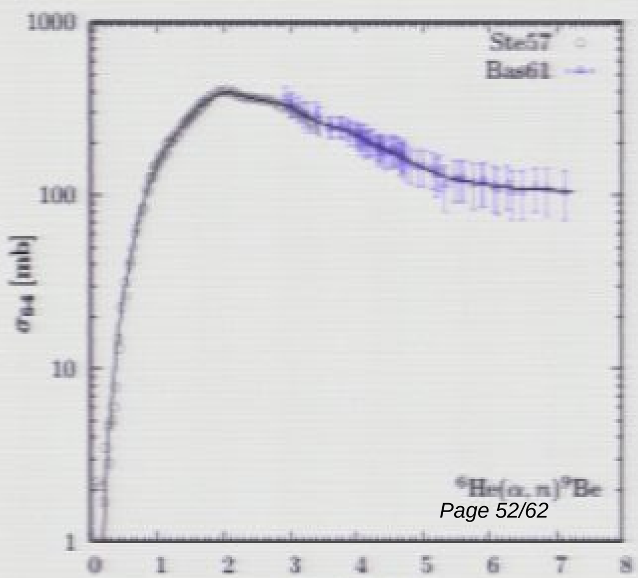
Non-thermal "tertiary" Be-9 production

P_{Be}

- crucially depends on the A=3 injection spectrum
- relies largely on experimental data



[Blinov, Chadeyeva, 2006]



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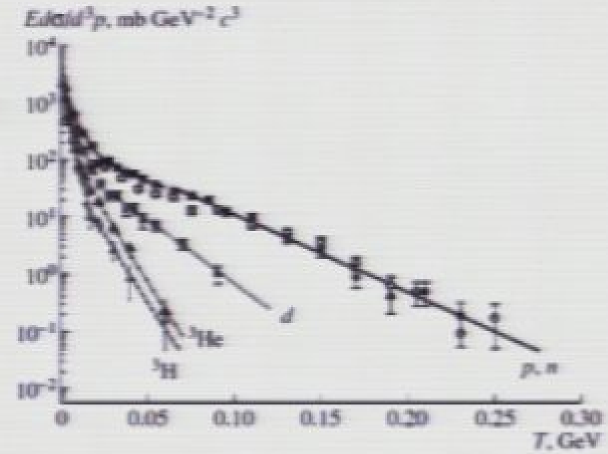

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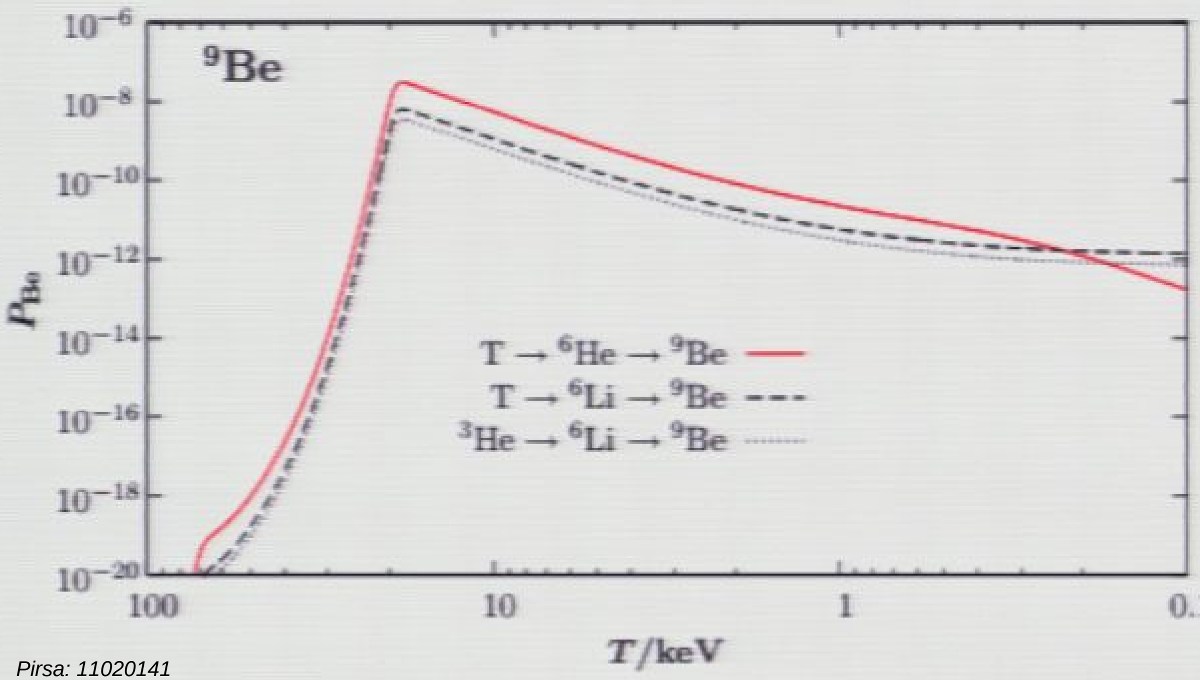

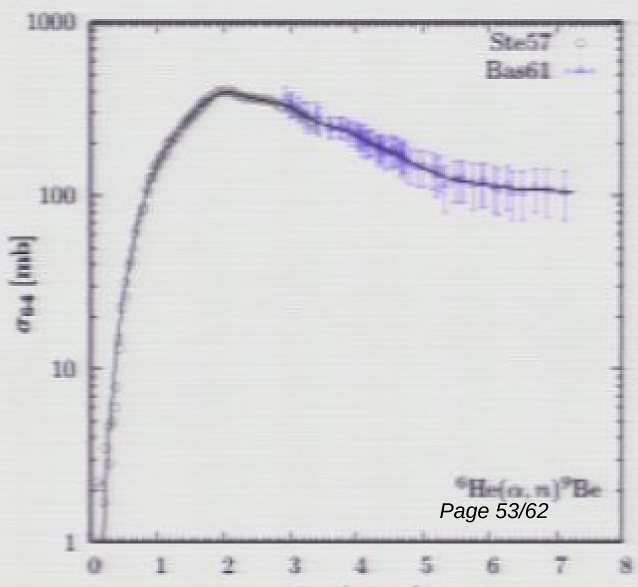

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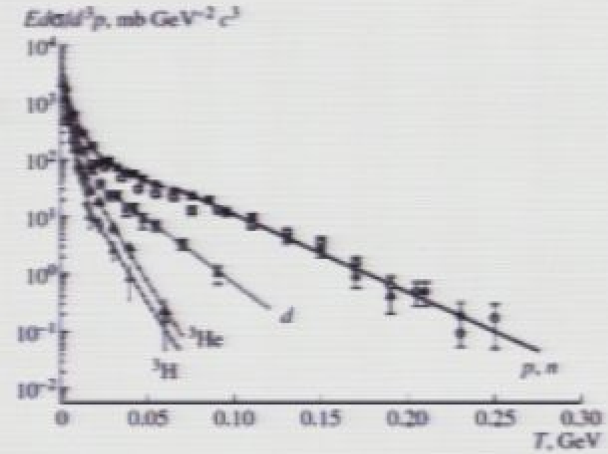

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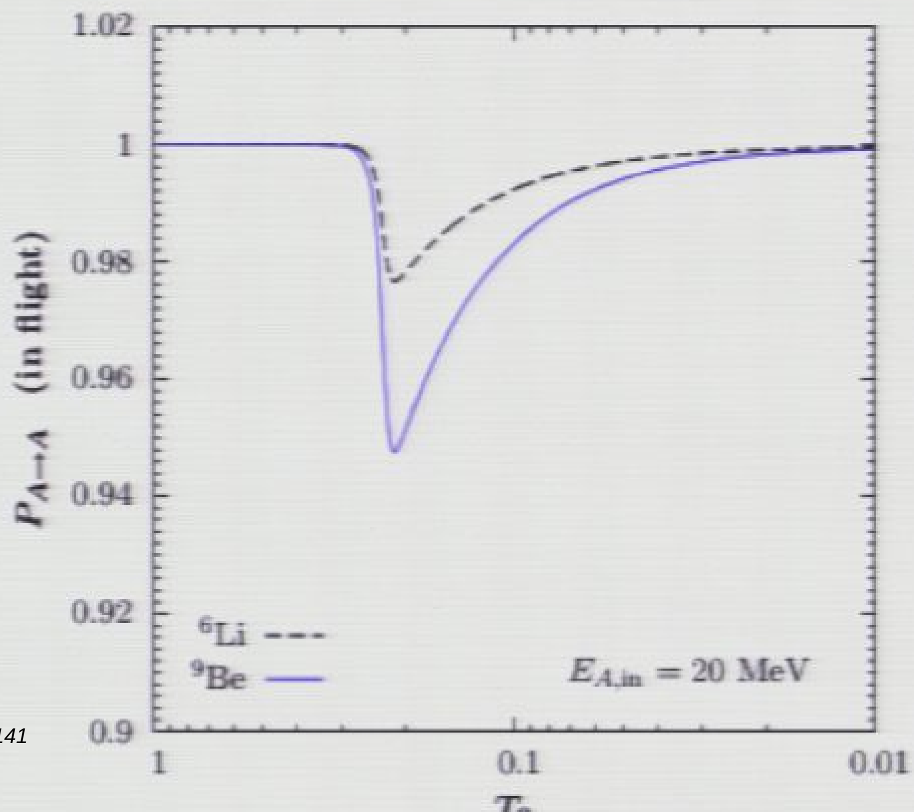
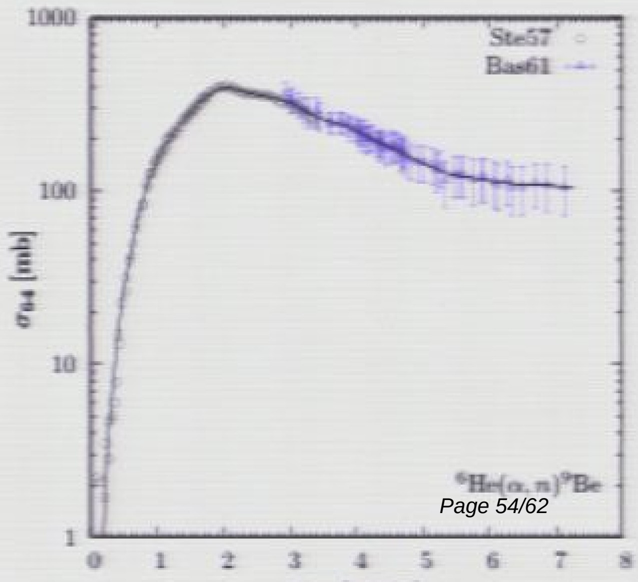




Be-9 yield

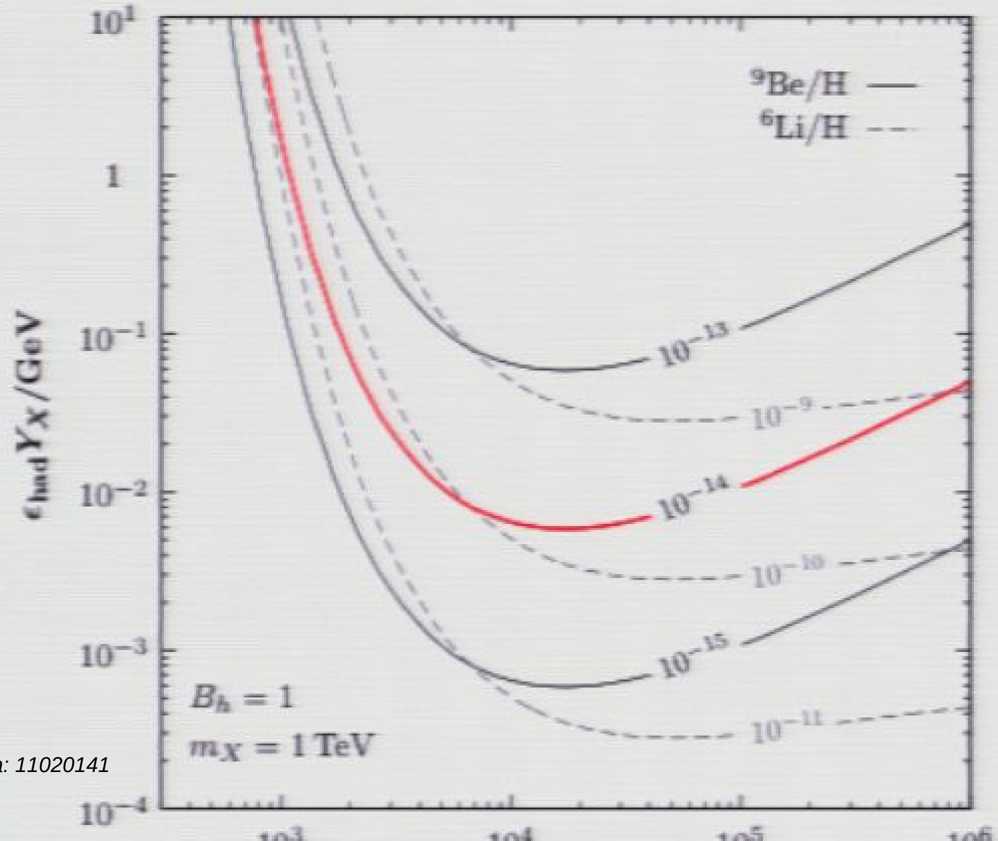
$$\left.\frac{dn_{^9\mathrm{Be}}}{dt}\right|_{\mathrm{n.th.}} = n_{^4\mathrm{He}}\Gamma_{4\to 3} \star P_{\mathrm{Be}}, \qquad \Gamma_{4\to 3} = n_X \sum_{i=n,p} \int_{E_{4,\mathrm{th}}}^{\epsilon_{\mathrm{had}}/2} d\epsilon\, N_i(\epsilon)\, \sigma^{(i)}_{4\to 3}(\epsilon) v_i(\epsilon)$$

spallation rate

number of nucleons/X-decay

$$\partial_t N_i = J_i - \Gamma_{i,\mathrm{sc}} N_i - \partial_\epsilon \left(\epsilon\, \Gamma_{i,\mathrm{stop}} N_i\right)$$

[Cyburt et al., 2009]



Be-9 probes energy depositions down to 10 MeV / baryon

Be-9 robust against stellar depletion!

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

$m_X > 2m_\pi$

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

- $p \to n$ interconversion rate:

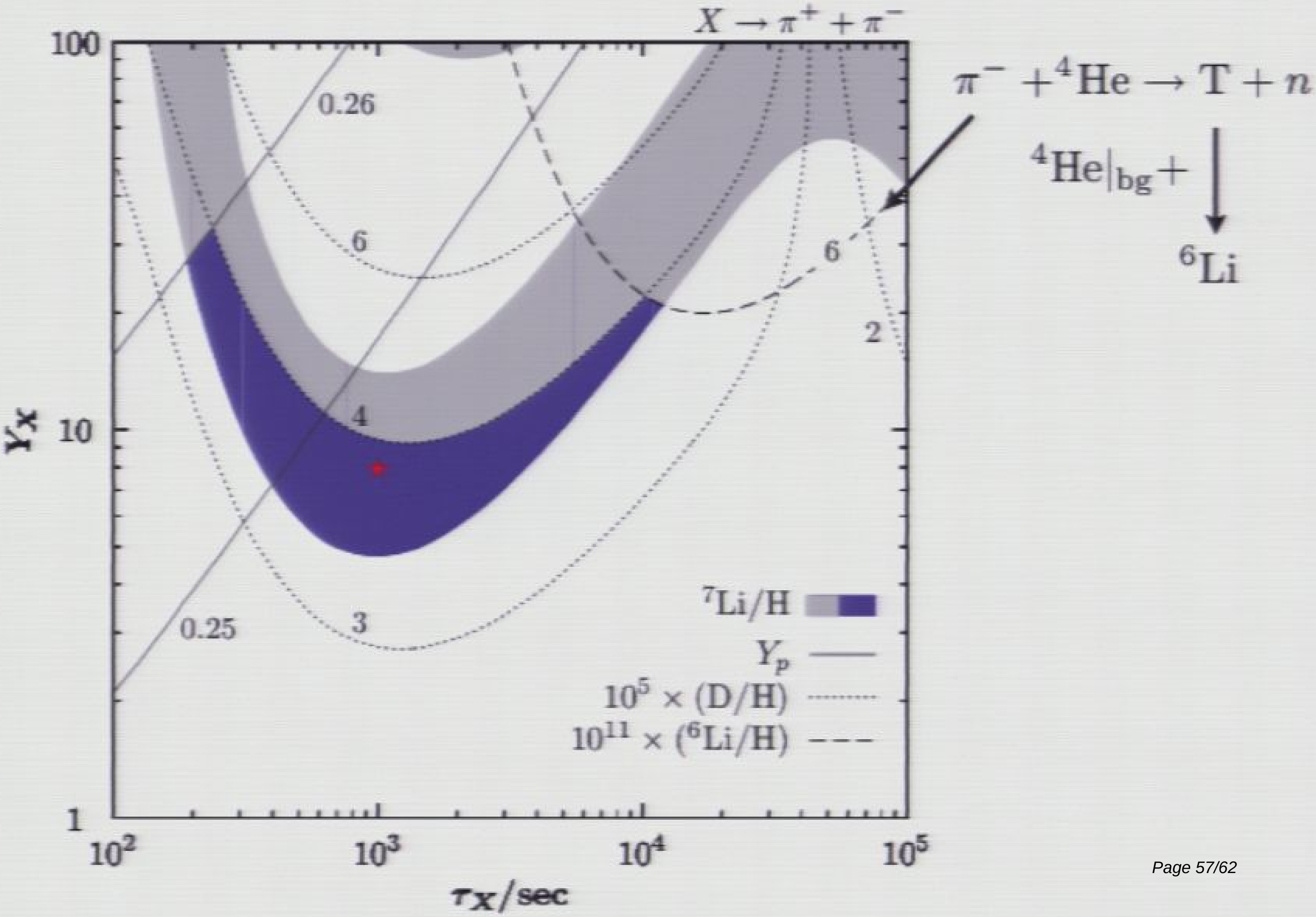
$$\Gamma_p^\pi = n_p \langle \sigma v \rangle_{pn}^\pi \simeq (3 \times 10^2\ \text{s}^{-1})\ \frac{T_9^3 \langle \sigma v \rangle_{pn}^\pi}{1\ \text{mb}}$$

- 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 : $X \to \pi^+\pi^-$



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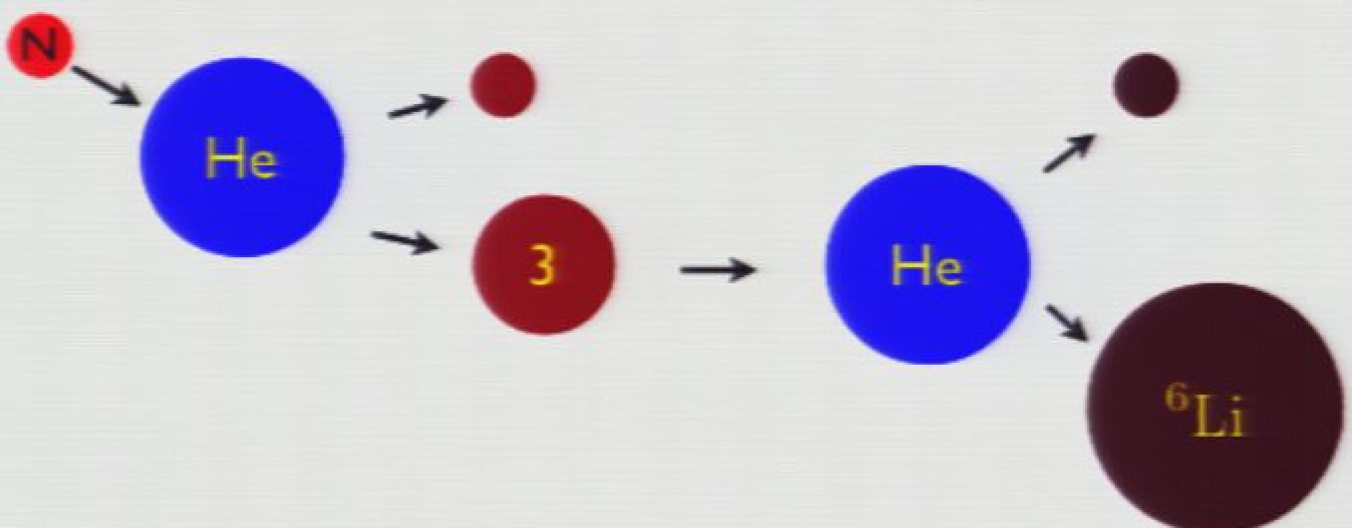

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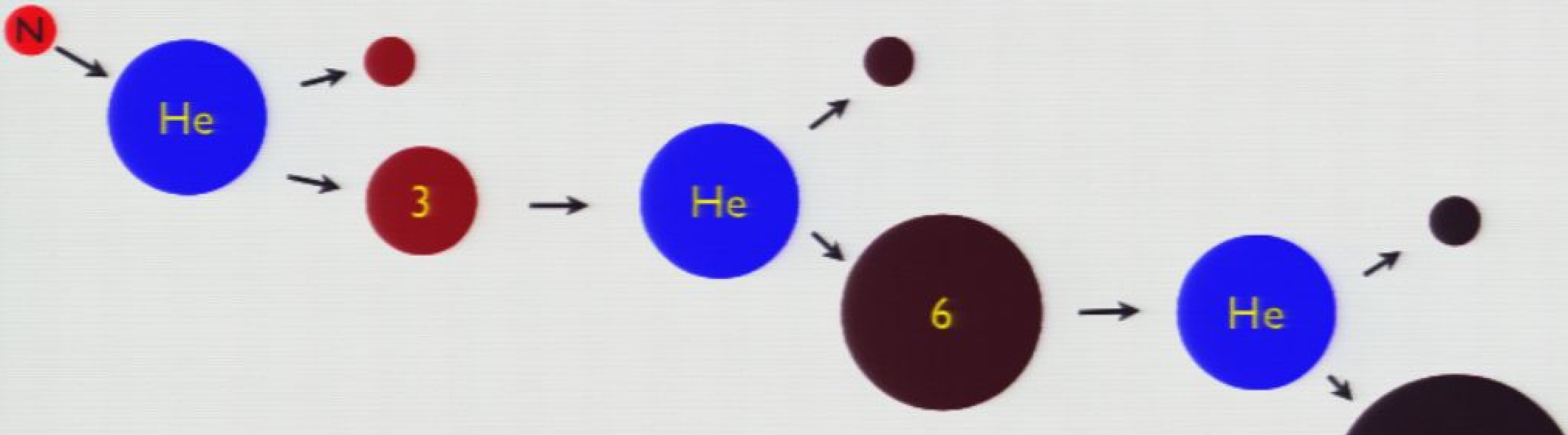

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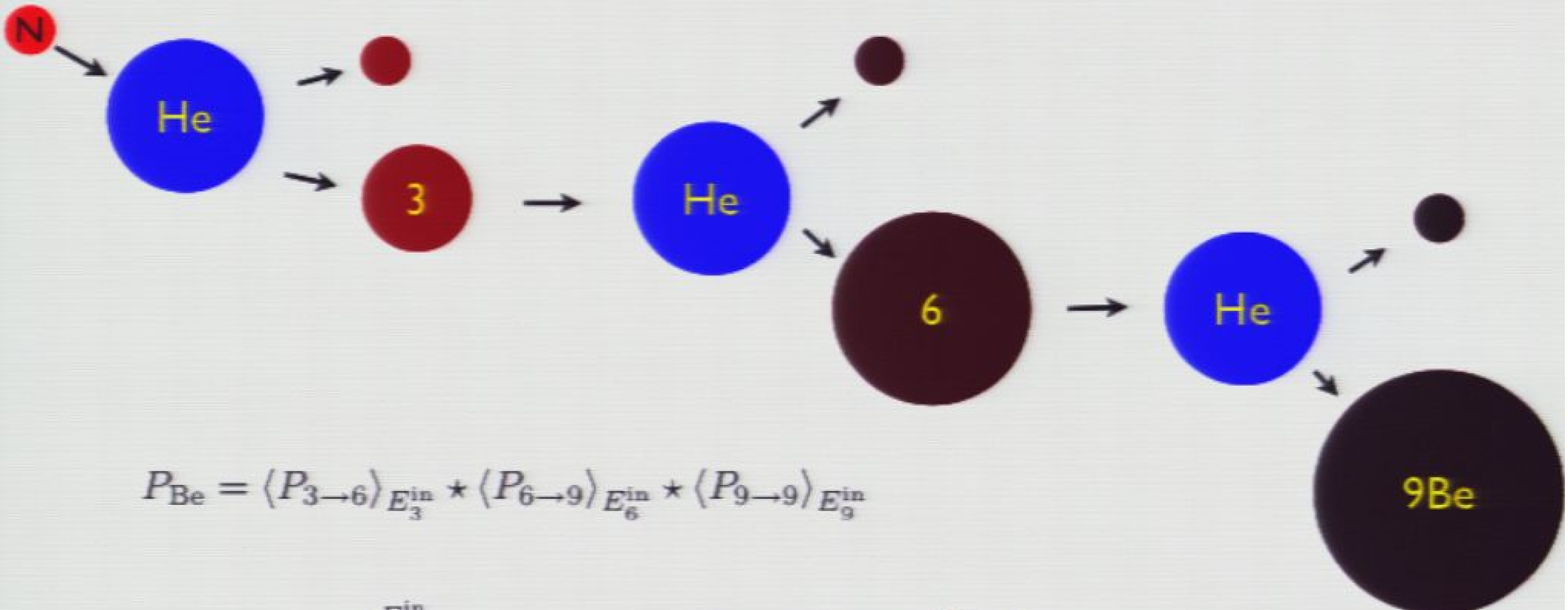

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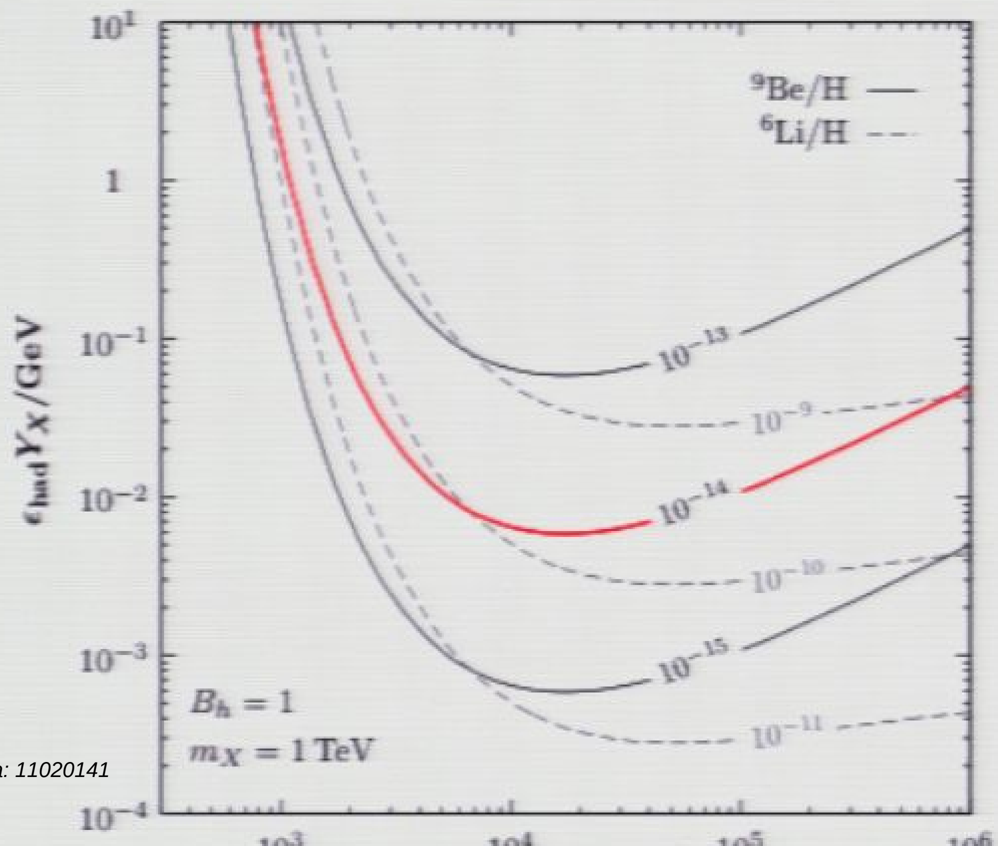

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Conclusions

- BBN can be a powerful tool to test and constrain new physics scenarios

  => every model must pass this cosmological consistency check

- (sub-)GeV scale sector which decays at ~ 1000 sec can reconcile Li-7 observations with BBN

  => long lived injected mesons

  => injected neutrinos (accumulative effect)

- Be-9 acts as a calorimeter for hadronic X-decays

  => may serve as a robust constraint