

Particle Physics Catalysis of thermal Big Bang Nucleosynthesis

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Other works

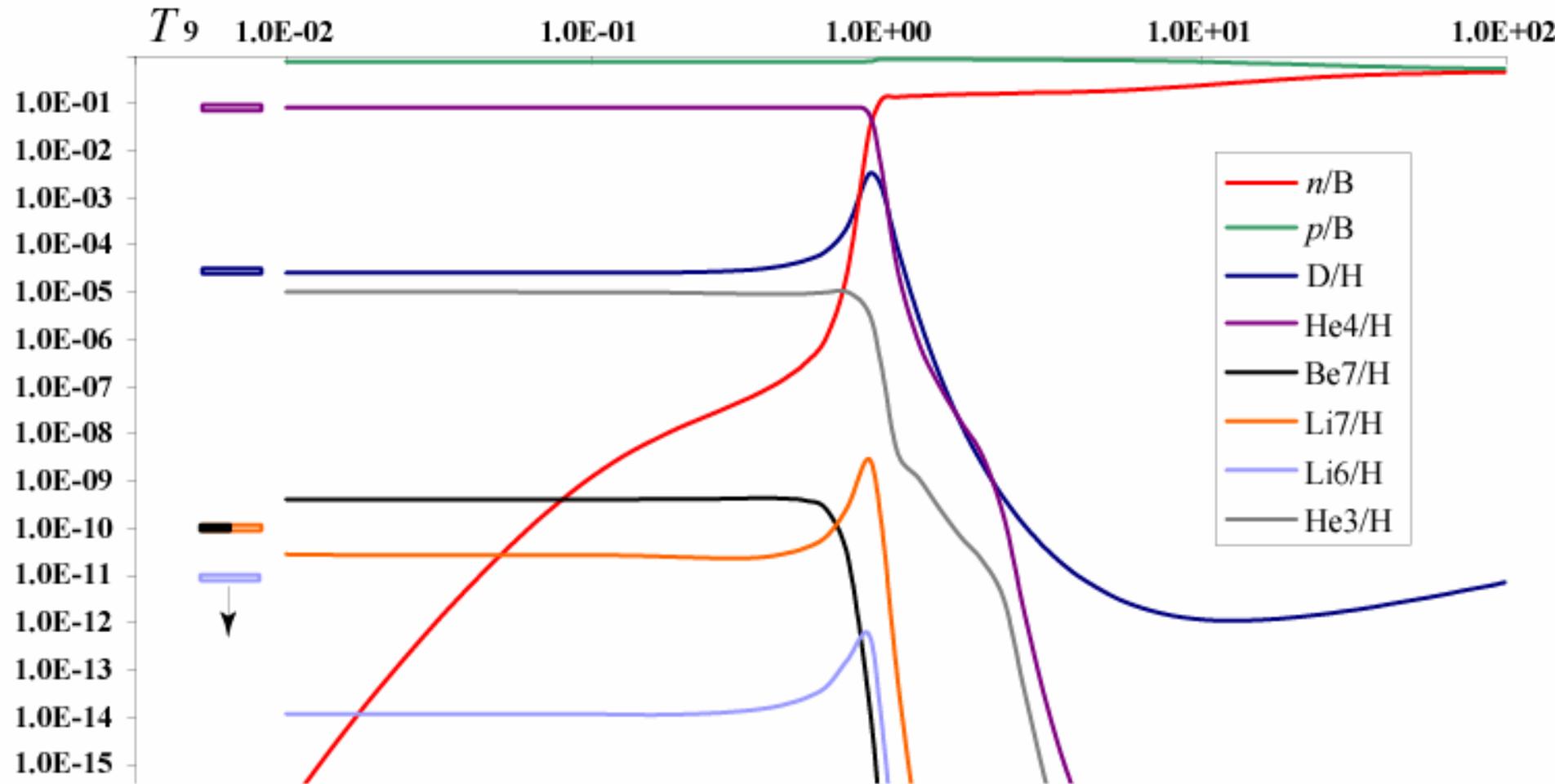
- Earlier works (90s): **Dimopoulos, Starkman, ...**
- Immediately after hep-ph/0605215 two papers on charged particles & bound states with nuclei appeared [missing main CBBN effects],
Kohri and Takayama (2006)
Kaplinghat and Rajaraman (2006)
- Cyburt et al (2006): combined CBBN with energy injection
- Hamaguchi et al (2007): first ab-initio nuclear calculation of CBBN rate
- O(10) papers on CBBN is expected this year by various groups

Outline of the talk

1. Implication of BBN for Particle physics. Summary of results. **Catalyzed Big Bang Nucleosynthesis.**
2. Standard Big Bang Nucleosynthesis (BBN). Current status, future directions. **Problem with ${}^7\text{Li}$ (?).**
3. Catalysis of nuclear reactions by heavy relic charged particles.
4. Dramatic change in the ${}^6\text{Li}$ and ${}^7\text{Be} + {}^7\text{Li}$ abundances caused by CBBN. Implications for particle physics models.
5. Conclusions and future directions.

- **Big Bang Nucleosynthesis** is the earliest epoch in Universe's history that finds conclusive evidence in observations. BBN was completed by $t = \text{few } 1000$ seconds and thus **occurred during the first day of Creation**.
- It **involves the combination of all forces of nature**: weak and strong interactions, electromagnetism and gravity (general relativity), acting together in a coordinated way to produce primordial abundances of **hydrogen, helium and lithium** (and their isotopes).
- Standard BBN requires the input of only one free parameter, η_b , and therefore is a **sensitive test of new particle physics models** and new models of gravity.

Gamow's creation curves



Early days of Big Bang Model

Gamow's ideas (~1944–46)	True/False
Friedmann-Lemaitre expansion traced back in time implies Hot Big Bang Universe. Atoms are ionized and nuclei decomposed to n and p	True
The rate of Helium production inside stars is too slow to account for more than 10% of ${}^4\text{He}$ of the total visible mass	True
Initial state of the Universe is a soup of primeval neutrons and photons	False
All observed chemical elements must have come from Big Bang	False
Large curvature term is responsible for rapid expansion at $t \sim 1\text{s}$	False
There must be remnant Big Bang photons of \sim few K temperature still present today	True

BBN and Particle Physics

$$\frac{dn_i}{dt} = -H(T)T \frac{dn_i}{dT} = \langle \sigma_{ijk} v \rangle n_j n_k + \dots - \dots$$

Energy of reactants \sim MeV or less; Initial conditions $n_p \approx n_n$; other $n_i = 0$.

Particle physics can

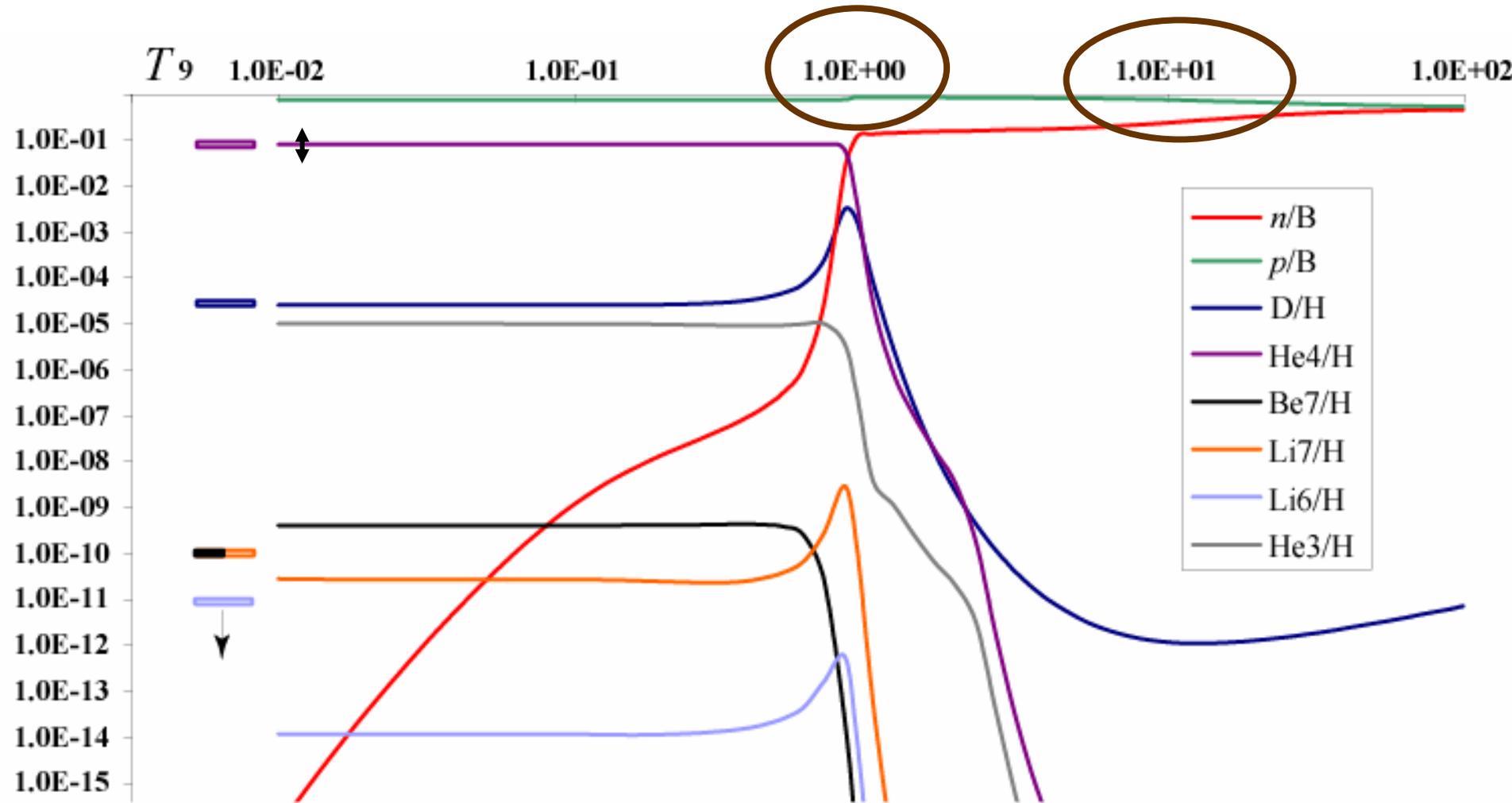
- **Affect the timing of reactions,**

$$H(T) = \text{const} \times N_{\text{eff}}^{1/2} \frac{T^2}{M_{\text{Pl}}}; \quad \underline{N_{\text{eff}}} = 2 + \frac{7}{8} \times 2 \times 3 + N_{\text{boson}}^{\text{extra}} + \frac{7}{8} N_{\text{fermion}}^{\text{extra}}$$

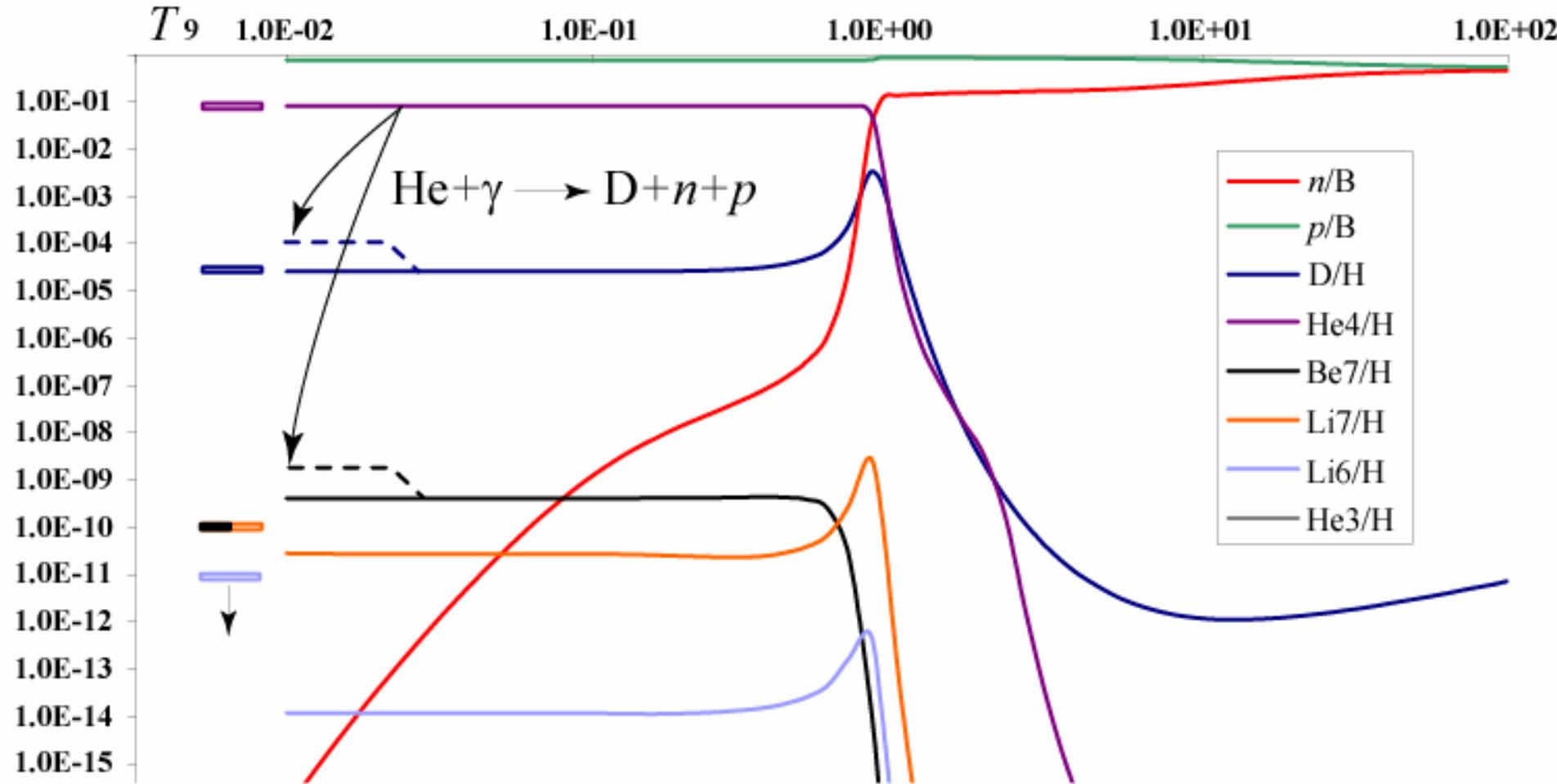
via e.g. new thermal degrees of freedom

- **Introduce non-thermal channels** e.g. **via late decays** or annihilations of heavy particles, $E \gg T$.
- **Provide catalyzing ingredients** that change $\langle \sigma_{ijk} v \rangle$ (MP, 2006).
Possible catalysts: electroweak scale remnants charged under $U(1)$ or color $SU(3)$ gauge groups.

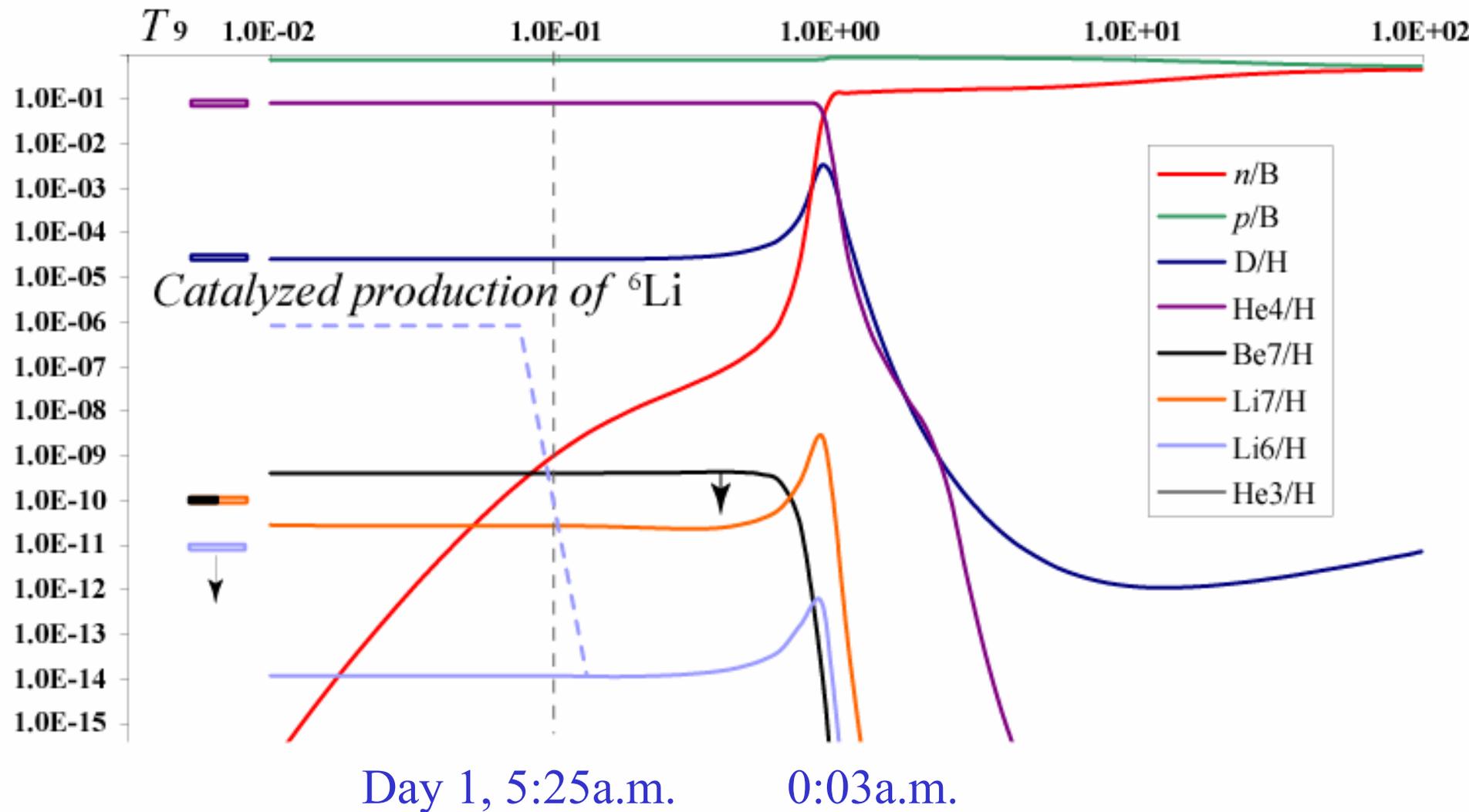
Change in the timing of reactions due to e.g. N_{eff}



Non-thermal change of elemental abundances due to late time energy injection



Catalyzed Production of ${}^6\text{Li}$ at 8 KeV, suppression of ${}^7\text{Be}+{}^7\text{Li}$ at 35 KeV



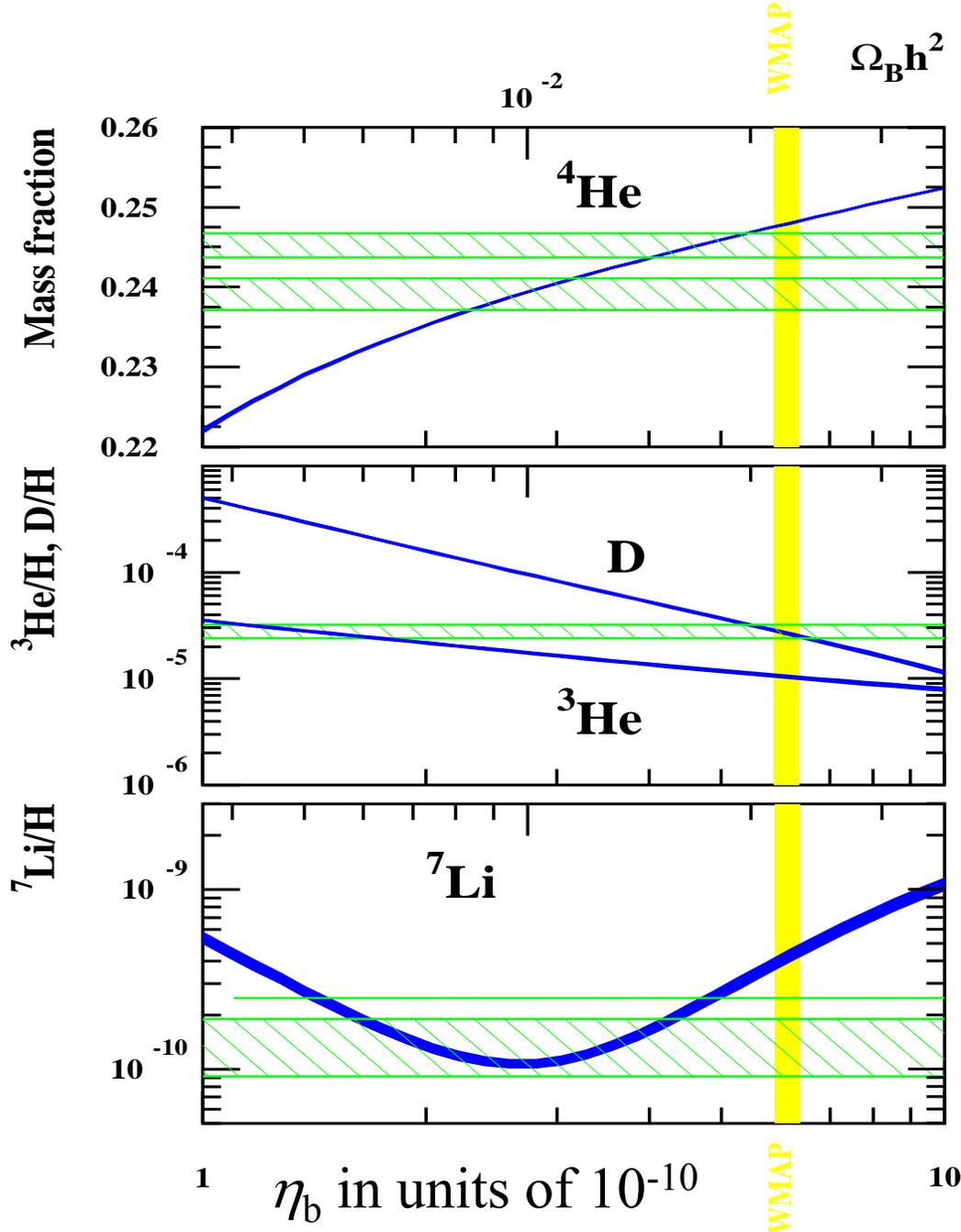
Summary of Results

- Catalysis of primordial nuclear reactions by heavy relics is a new way how particle physics can change the outcome of the BBN.
- Heavy relics that interact via strong or electromagnetic force can catalyze nucleosynthesis reactions by up to 8 orders of magnitude.
- The mechanism for catalysis is the formation of new bound states of relics and nuclei, for example (${}^4\text{He}X^-$) at $T=8\text{KeV}$, (${}^7\text{Be}X^-$) at $T=35\text{KeV}$. Formation of bound states open new reaction channels and reduces Coulomb penetration factors.
- Abundance of ${}^6\text{Li}$, ${}^7\text{Li}$, ${}^7\text{Be}$ are primarily affected. ${}^4\text{He}$, D, ${}^3\text{He}$ are not affected.

Summary of Results

- ${}^6\text{Li}$ is "accidentally" suppressed in standard BBN. (${}^4\text{He}X^-$) opens a photonless production channel for ${}^6\text{Li}$ at 8KeV, increasing its abundance by many orders of magnitude.
- Observations of ${}^6\text{Li}$ give sensitivity to $n_X/\text{entropy} \sim 10^{-17}$, which is **one of the most sensitive probes of new particles in cosmology**. Lifetime of X^- in typical models (e.g. SUSY) is constrained to be less than 5000 seconds.
- Lifetime $\tau_X \sim (1-2) \times 10^3$ sec and $Y_X \sim (3-5) \times 10^{-2}$ are able to reduce ${}^7\text{Li}+{}^7\text{Be}$ by a factor of 2, providing a resolution to the existing discrepancy between observations and theory. It suggests a possibility of catalyzed BBN, if "lithium problem" is taken seriously.

Current Status



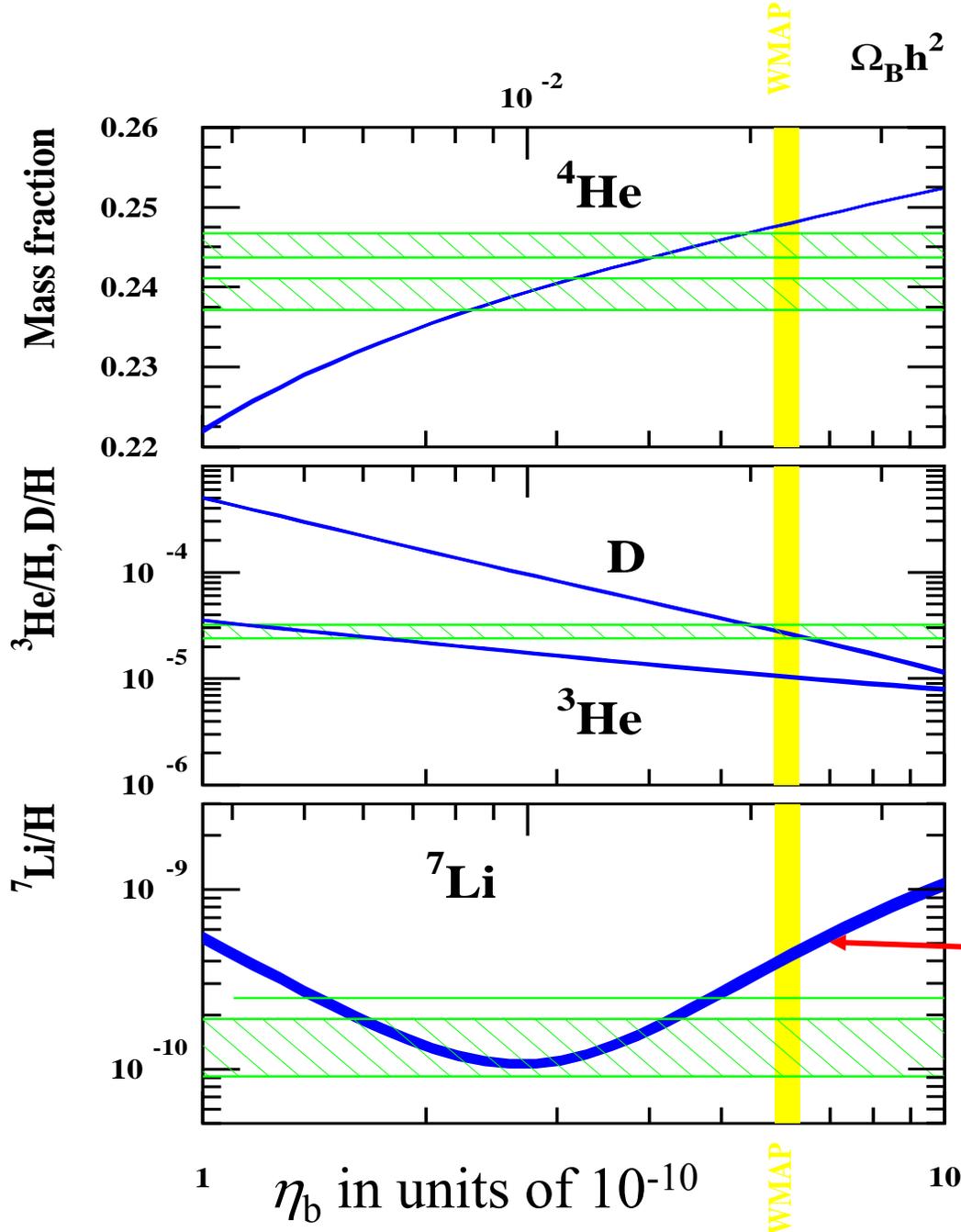
Blue lines: theoretical predictions of abundances as functions of η_b

Green bands: observational values for primordial abundances of ^4He , D, and ^7Li

Yellow band: WMAP-suggested input for baryon to photon ratio $\eta_b = 6 \cdot 10^{-10}$

Coc et al, ApJ 2004

Current Status



Blue lines: theoretical predictions of abundances as functions of η_b

Green bands: observational values for primordial abundances of ^4He , D, and ^7Li

Yellow band: WMAP-suggested input for baryon to photon ratio $\eta_b = 6.1 \times 10^{-10}$

^7Be branch

Coc et al, ApJ 2004

BBN after WMAP

1. The fraction of energy density in baryons is measured rather precisely, $\Omega_b = 0.044 \pm 0.004$. This translates into

$$\eta_b = (6.1 \pm 0.3) \times 10^{-10}$$

No more wiggle room with η_b for BBN.

2. There is a neat agreement of predictions and observations for D, and "sort of" agreement for ^4He .

3. There is a noticeable tension between predicted and observed amounts of ^7Li , ($^7\text{Li}+^7\text{Be}$, to be precise). $^7\text{Li}_{\text{th}} \simeq (4-5) \times 10^{-10}$ vs. $^7\text{Li}_{\text{obs}} \simeq (1-2) \times 10^{-10}$

A. Measurements have an unaccounted **systematic error**.

B. We do not understand the **cycling of ^7Li in stars**.

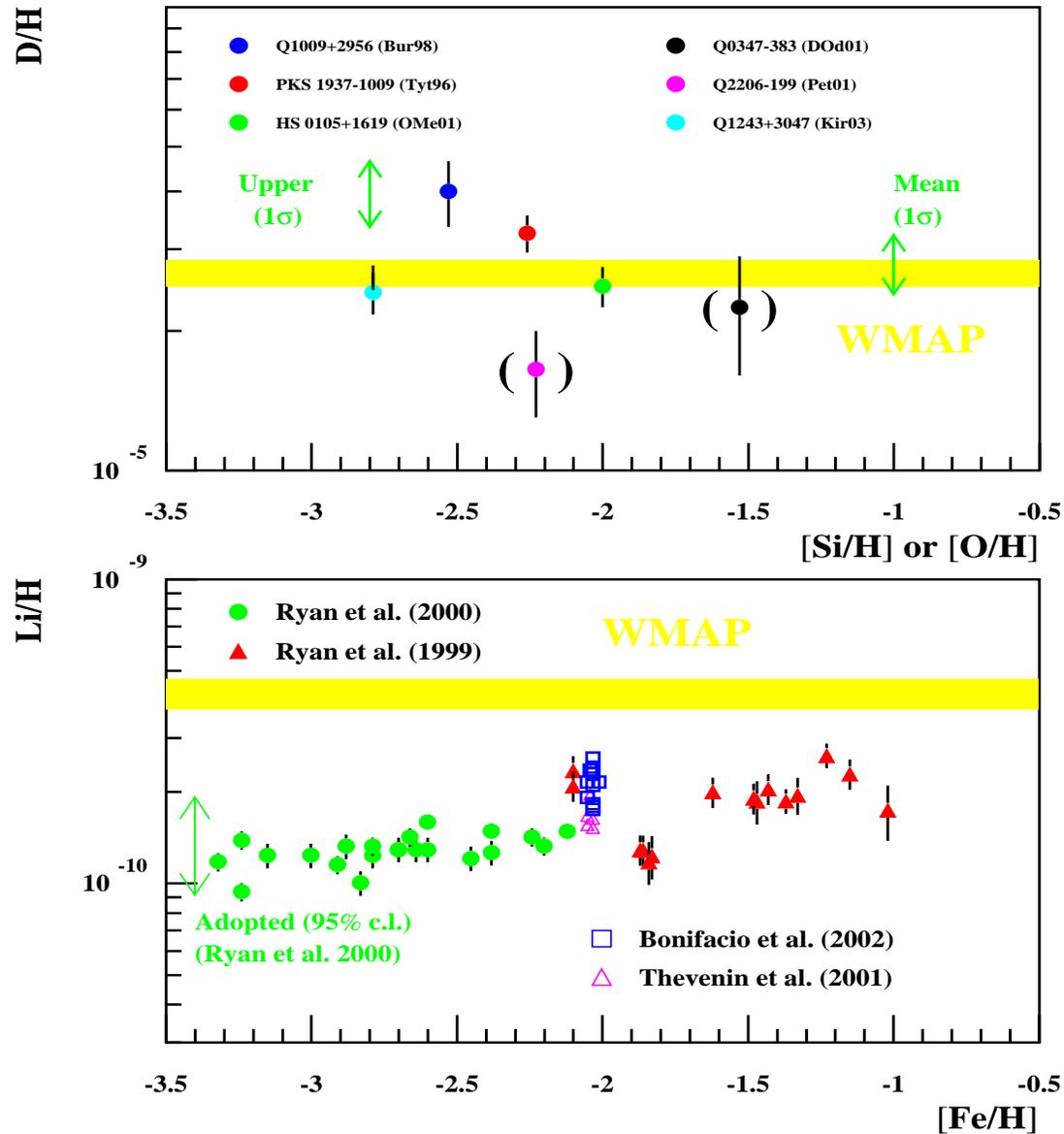
What we see is not primordial.

C. **Calculations** (e.g. nuclear rates) **are wrong**.

D. **New Physics interference**. What kind of new physics?

4. Emergent ^6Li problem? Not yet...

Deuterium and Lithium abundances



Coc et al,
ApJ 2004

Physics Beyond SM and BBN

1. **Timing of reactions** can be changed by adding new thermally excited degrees of freedom. Accuracy of observations are sensitive to $N_{\text{eff}} \sim \mathcal{O}(1)$. In other words, there is sensitivity to $\Delta\rho_{\text{extra}}/\rho_{\text{total}} \sim 0.3$.
2. **Energy injection** (e.g. late decays of particles) will have an effect on mostly D, ${}^6\text{Li}$, ${}^7\text{Li}$, and ${}^3\text{He}/\text{D}$ if $\tau_X > 10^3$ sec for hadronic decays and $\tau_X > 10^5$ sec for electromagnetic decays. Best sensitivity may reach $\Delta E n_x/n_\gamma < 10^{-13}$ GeV at $\tau_X > 10^7$ sec.
3. **Catalysis of nuclear reactions** (via formation of bound states of charged relics X^- with nuclei) will have an effect on ${}^6\text{Li}$, ${}^7\text{Li}$, and ${}^9\text{Be}$. Best sensitivity to $n_x/n_\gamma < 10^{-17}$ for $\tau_X > 10^4$ sec.

Input parameters for Catalyzed BBN

Suppose that there is an electroweak scale remnant X^- (and X^+), e.g. SUSY partner of electron, μ or τ , with the following properties:

1. Masses are in excess of 100 GeV to comply with LEP/Tevatron.
2. Abundances per baryon Y_X are $O(0.1-0.001)$. In a fully specified model of particle physics they scale as $Y_X \sim (0.01-0.05)m_X/\text{TeV}$.
3. Decay time τ_X is longer than 1000 sec; no constraints on decay channels.

Are there changes in elemental abundances from mere presence of X^- ?

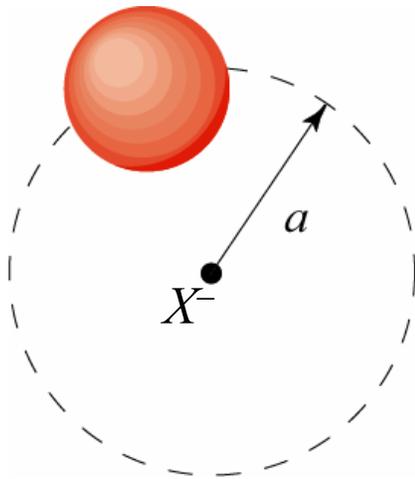
Yes!

Properties of bound states

$$E_{Bohr} = \frac{Z_{He}^2 \alpha^2 m_{He}}{2} = 397 \text{ KeV}$$

$$E_b = 350 \text{ KeV}; a = 3.6 \text{ fm}$$

$$T_{recomb} = 8.3 \text{ KeV}; r_c = 1.7 \text{ fm}$$



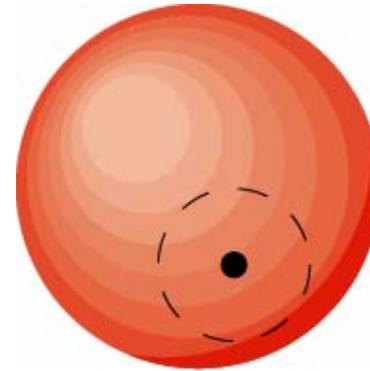
$(^4\text{HeX}^-)$

Bohr radius is 2 times larger than nuclear

$$E_{Bohr} = \frac{Z_{Be}^2 \alpha^2 m_{Be}}{2} = 2787 \text{ KeV}$$

$$E_b = 1350 \text{ KeV}; a = 1.0 \text{ fm}$$

$$T_{recomb} = 35 \text{ KeV}; r_c = 2.5 \text{ fm}$$



$(^7\text{BeX}^-)$

Bohr orbit is within nuclear radius

Binding energy and stability thresholds

boundst.	$ E_b^0 $	a_0	R_N^{SC}	$ E_b(R_N^{SC}) $	R_{Nc}	$ E_b(R_{Nc}) $	T_0
^4HeX	397	3.63	1.94	352	2.16	346	8.2
^6LiX	1343	1.61	2.22	930	3.29	780	19
^7LiX	1566	1.38	2.33	990	3.09	870	21
^7BeX	2787	1.03	2.33	1540	3	1350	32
^8BeX	3178	0.91	2.44	1600	3	1430	34
^4HeX	1589	1.81	1.94	1200	2.16	1150	28
DX	50	14	-	49	2.13	49	1.2
pX	25	29	-	25	0.85	25	0.6

Table 1: Properties of the bound states: Bohr a_0 and nuclear radii R_N in fm; binding energies E_b and "photo-dissociation decoupling" temperatures T_0 in KeV.

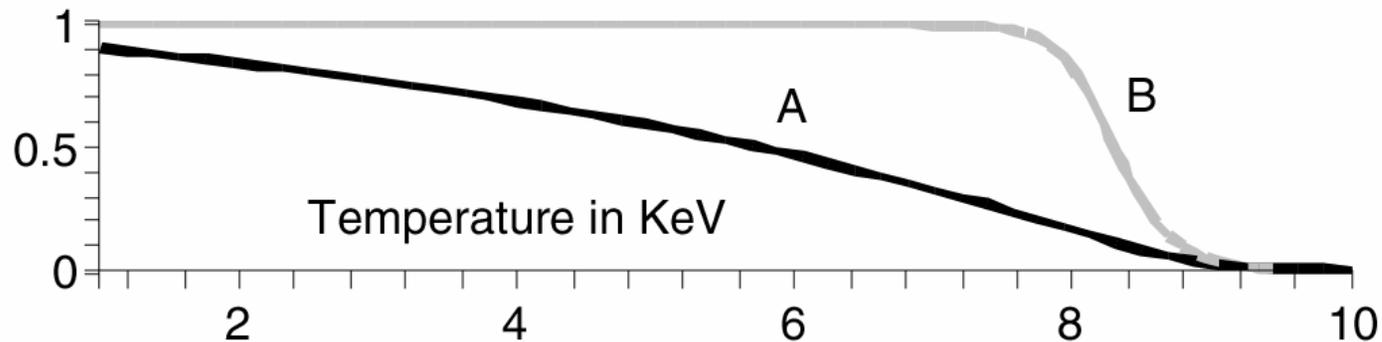
Recombination of ${}^4\text{He}$ and X^-

Naive equilibrium Saha-type equation

$$\frac{n_{\text{He-X}}(T)}{n_X(T)} = \frac{1}{1 + n_{\text{He}}^{-1} (m_{\text{He}} T / 2\pi)^{3/2} \exp(-E_b / T)} \approx \underline{\theta(8.3 \text{ KeV} - T)}$$

gives a rapid switch from 0 to 1 at 8.3 KeV

Realistic solution to Boltzmann equation leads to a gradual increase of the number of bound states:



Coulomb penetration factor

(Gamow; Condon and Gurney)

- Classical cross section = 0, if Kinetic Energy $< U_{max}$
Classical thermal rate $\sim \exp(-U_{max}/T) \sim \exp(-1000)$ for
 $T \sim 100$ KeV; $U_{max} \sim 10$ MeV. **Does not work.**

- Quantum cross section** $\sigma \propto \exp(-\sqrt{E_G / E})$
$$E_G = 2\pi^2 Z_1^2 Z_2^2 \alpha^2 m_{reduced}$$

Quantum cross section multiplied by the Maxwell distribution, $\exp(-E/T)$, has a [Gamow] peak, and the thermal rate
 $\propto \exp\{-(27E_G / 4T)^{1/3}\}$, enabling nuclear reactions.

For BBN reactions, the rate is typically $\sim \exp(-O(10)/T_9^{1/3})$,
where T_9 is temperature in units of 10^9 K. [10^9 K \equiv 86 KeV]

- $$2.20 \times 10^4 T_9^{-2/3} \exp(-3.869/T_9^{1/3})$$
- $$\times (1 + .108 T_9^{1/3} + 1.68 T_9^{2/3} + 1.26 T_9 + .551 T_9^{4/3} + 1.06 T_9^{5/3})$$
12. $Li_6 + p \rightarrow \gamma + Be_7(65.062)$
- $$6.69 + 5 T_{9a}^{5/6} T_9^{-3/2} \exp(-8.413/T_{9a}^{1/3})$$
13. $Li_6 + p \rightarrow He_4 + He_3(46.653)$
- $$3.73 \times 10^{10} T_9^{-3/2} \exp(-8.413/T_9^{1/3} - (T_9/5.50)^2)$$
- $$\times (1 + .050 T_9^{1/3} - .061 T_9^{2/3} - .021 T_9 + .006 T_9^{4/3} + .005 T_9^{5/3})$$
- $$+ 1.33 \times 10^{10} T_9^{-3/2} \exp(-17.763/T_9) + 1.29 \times 10^9 T_9^{-1} \exp(-21.820/T_9)$$
14. $Li_7 + p \rightarrow He_4 + He_4(201.321)$
- $$6.13 \times 10^8 T_9^{-2/3} \exp(-8.473/T_9^{1/3} - (T_9/30.068)^2)$$
- $$\times (1 + .0492 T_9^{1/3} + 1.56 T_9^{2/3} + .539 T_9 - .966 T_9^{4/3} - .845 T_9^{5/3})$$
- $$+ 1.07 \times 10^{10} T_9^{-3/2} \exp(-30.443/T_9) + 1.54 \times 10^6 T_9^{-3/2} \exp(-4.479/T_9)$$
15. $d + He_4 \rightarrow \gamma + Li_6(17.100)$
- $$30.1 T_9^{-2/3} \exp(-7.423/T_9^{1/3})$$
- $$\times (1 + .056 T_9^{1/3} - 4.85 T_9^{2/3} + 8.85 T_9 - .585 T_9^{4/3} - .584 T_9^{5/3})$$
- $$+ 85.5 T_9^{-3/2} \exp(-8.228/T_9)$$
16. $H_3 + He_4 \rightarrow \gamma + Li_7(28.63)$
- $$1.10 \times 10^6 T_9^{-2/3} \exp(-8.08/T_9^{1/3})$$
- $$\times (1 + .0516 T_9^{1/3} - .408 T_9^{2/3} - .148 T_9 + .102 T_9^{4/3} + .0940 T_9^{5/3})$$
17. $He_3 + He_4 \rightarrow \gamma + Be_7(18.407)$
- $$5.79 \times 10^6 T_{9B}^{5/6} T_9^{-3/2} \exp(-12.826/T_{9B}^{1/3})$$
18. $d + d \rightarrow n + He_3(37.938)$
- $$3.97 \times 10^8 T_9^{-2/3} \exp(-4.258/T_9^{1/3})$$
- $$\times (1 + .098 T_9^{1/3} + .876 T_9^{2/3} + .600 T_9 - .041 T_9^{4/3} - .071 T_9^{5/3})$$
19. $d + d \rightarrow p + H_3(46.802)$
- $$4.17 \times 10^8 T_9^{-2/3} \exp(-4.258/T_9^{1/3})$$
- $$\times (1 + .098 T_9^{1/3} + .518 T_9^{2/3} + .355 T_9 - .010 T_9^{4/3} - .018 T_9^{5/3})$$

New Reaction Channels

- Main **SBBN** channel for ${}^6\text{Li}$ production



$$\langle \sigma_{SBBN} v \rangle = \underline{30} T_9^{-2/3} \exp(-\underline{7.435} / T_9^{1/3})$$

in usual astrophysical units.

NB: typical pre-exponents for γ reactions are 10^5 – 10^6 ,

for photon-less reactions 10^8 – 10^{10}

- Main **CBBN** channel for ${}^6\text{Li}$ production



$$\langle \sigma_{CBBN} v \rangle = \underline{2 \times 10^9} T_9^{-2/3} \exp(-\underline{5.37} / T_9^{1/3})$$

Why is ${}^6\text{Li}$ so suppressed in SBBN

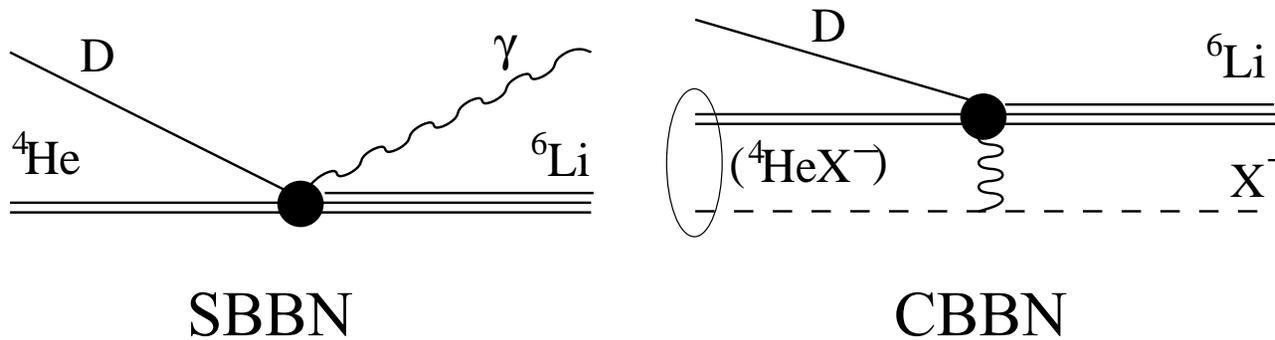
compared to ${}^7\text{Li}+{}^7\text{Be}$? **The rate for ${}^4\text{He}({}^3\text{H},\gamma){}^7\text{Li}$ is almost five orders of magnitude larger than ${}^4\text{He}({}^2\text{H},\gamma){}^6\text{Li}$ but why?**

The reason is “accidental”: ${}^6\text{Li}$ is well described by ${}^4\text{He}$ -D cluster. In this cluster, $q_1/m_1 = q_2/m_2$, and thus **electric dipole transition is forbidden, and only quadrupole transition is allowed.** Given that the wavelength of emitted γ is much larger than a typical nuclear size, $\omega R_{nucl} \sim 0.02$, this results in a huge suppression:

$$\Gamma_{E1} = \langle d \rangle^2 \omega^3; \quad \Gamma_{E2} = \langle Q \rangle^2 \omega^5; \quad \frac{\Gamma_{E2}}{\Gamma_{E1}} = \left(\omega \frac{Q}{d} \right)^2 \approx (\omega R_{nucl})^2 \propto 10^{-4} - 10^{-3}$$

Any “accidental” suppression of an observable can be turned into a sensitive probe of exotic channels for which this suppression does not apply. But you have to be careful about possible errors as well.

Photon-less production of ${}^6\text{Li}$ in CBBN



SBBN

CBBN

There are two sources of enhancements:

1. **Phase space,**

$$\frac{\text{CBBN}}{\text{SBBN}} = \left(\frac{R_{nucl} / \lambda_{virtual}}{R_{nucl} / \lambda_{real}} \right)^5 \propto \left(\frac{\lambda_{real}}{a_B} \right)^5 \propto \underline{10^7}$$

2. **Coulomb screening,** $E_G^{\text{SBBN}} = 5249 \text{ KeV} \rightarrow E_G^{\text{CBBN}} = 1973 \text{ KeV}$.

This gives ~ 10 times enhancement at $T = 8 \text{ KeV}$.

Factorization estimate

- Astrophysical S-factors , $S(E) = E\sigma / \exp(-\sqrt{E/E_G})$
in the limit of Bohr radius $\gg R_{\text{nucleus}}$ can be related by an approximate formula

$$S_{CBBN}(0) = S_{SBBN}(0) \times \frac{8}{3\pi^2} \frac{p_f a_0}{(\omega a_0)^5} \left(1 + m_D / m_{He}\right)^2$$

$$\langle \sigma_{CBBN} v \rangle = 2 \times 10^9 T_9^{-2/3} \exp(-5.37 / T_9^{1/3})$$

${}^6\text{Li}$ at 8 KeV

Nuclear fusion at 8 KeV (${}^4\text{HeX}^-$ recombination) is exceedingly simple: CBBN synthesis reaction, and ${}^6\text{Li}(p,\alpha){}^3\text{He}$ burning:

$$-HT \frac{d{}^6\text{Li}}{dT} = D(n_{BS} \langle \sigma_{CBBN} v \rangle + n_{\text{He}} \langle \sigma_{SBBN} v \rangle) - {}^6\text{Li} n_p \langle \sigma_p v \rangle$$

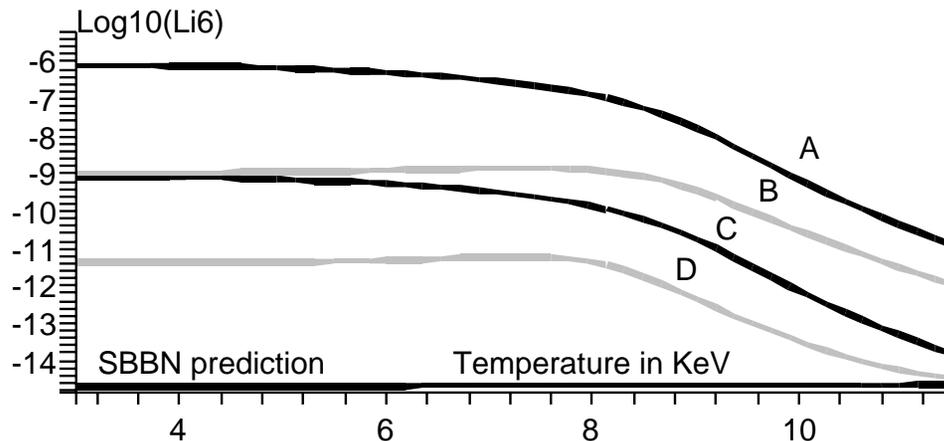
Numerical solutions are given below:

A: $Y_X = 10^{-2}$, $\tau_X = \infty$;

B: $Y_X = 10^{-2}$, $\tau_X = 4000\text{s}$;

C: $Y_X = 10^{-5}$, $\tau_X = \infty$;

D: $Y_X = 10^{-5}$, $\tau_X = 4000\text{s}$;



${}^6\text{Li}$ at 8 KeV

Comparing with observed amounts ${}^6\text{Li}/\text{H} \sim 2 \times 10^{-11}$ that originate from cosmic rates and/or solar-like flares, we get

$${}^6\text{Li}/\text{H} < 2 \times 10^{-11} \rightarrow Y_X < 3 \times 10^{-7}, \text{ or } n_X/\text{entropy} < 2.5 \times 10^{-17}$$

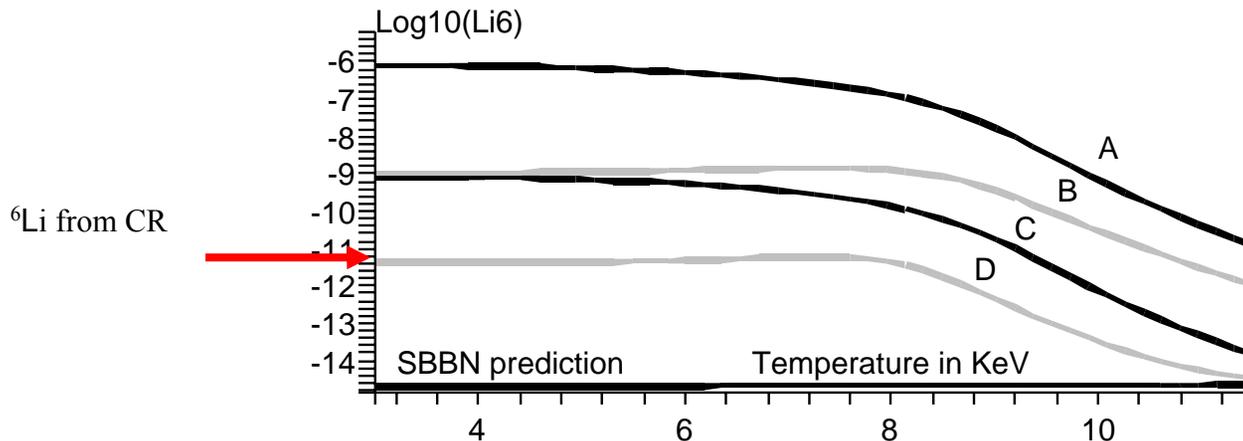
Among numerical solutions given below A, B, and C are excluded

~~A: $Y_X = 10^{-2}$, $\tau_X = \infty$;~~

~~B: $Y_X = 10^{-2}$, $\tau_X = 4000\text{s}$;~~

~~C: $Y_X = 10^{-5}$, $\tau_X = \infty$;~~

D: $Y_X = 10^{-5}$, $\tau_X = 4000\text{s}$;



Recent updates

Recent *ab initio* three-body nuclear calculation, **hep-ph/0702274**,
(Hamaguchi, Hatsuda, Kammimura, Kino and Yanagida) finds the
S-factor for the CBBN reaction,

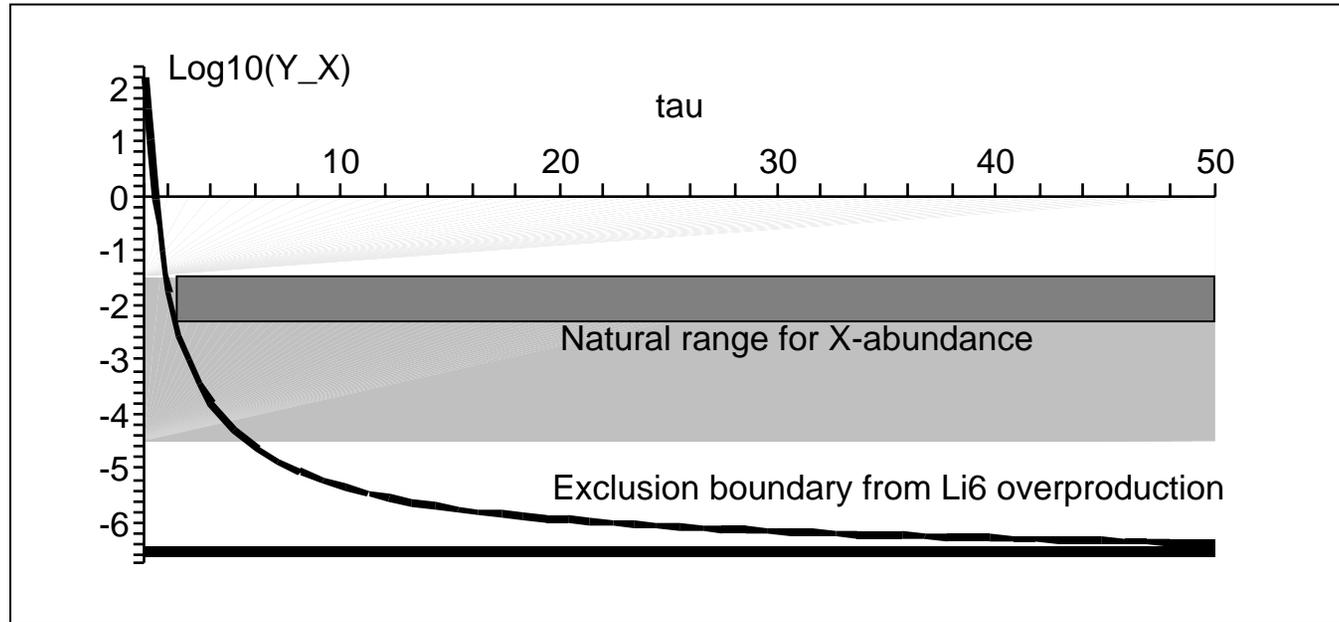


to be a factor of 8 smaller than my original estimate.

Instead of ~ 0.3 MeV bn it appears to be 0.04 MeV bn

(Compared with SBBN reaction $S(0) = 18$ meV bn, it is of course still a huge enhancement factor)

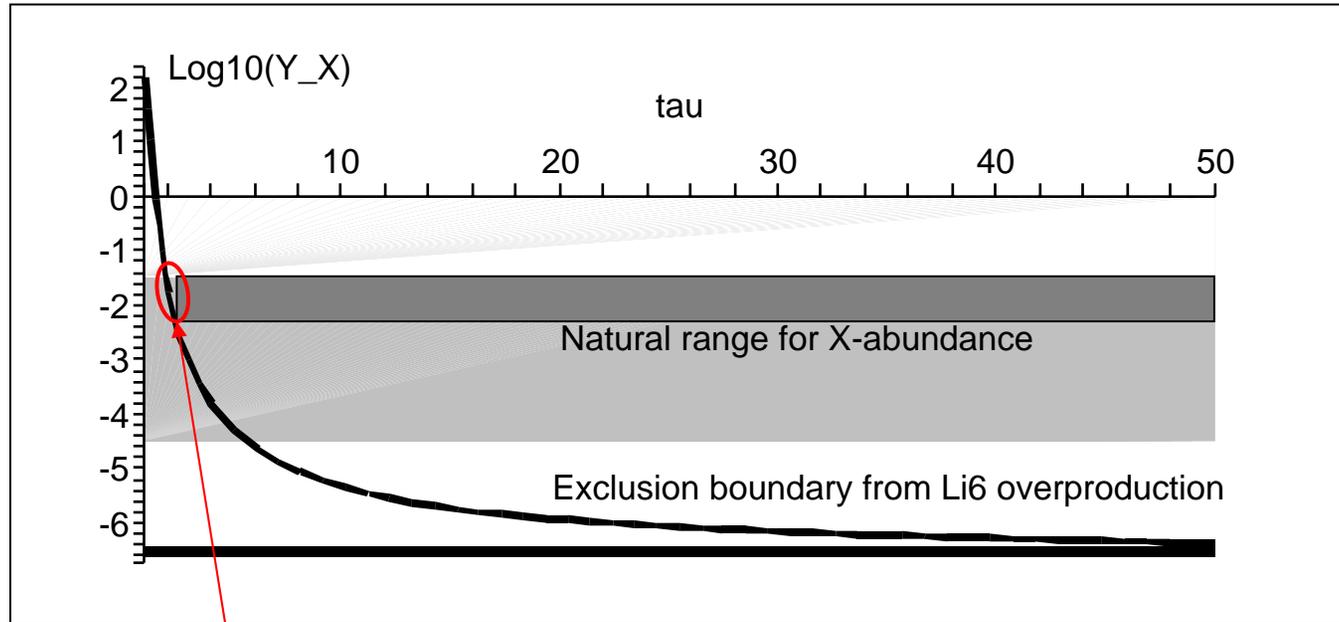
Constraints on the lifetime τ_X



Assuming ${}^6\text{Li}/\text{H} < 2 \times 10^{-11}$, we get $\tau_X < 5000 \text{ sec}$

(For a typical stau-NLSP/gravitino-LSP model, the abundance is in the dark gray band, so that stau lifetime is severely constrained)

Constraints on the lifetime τ_X



With lifetimes in the interval τ_X around **2000 sec** and $Y_X > 10^{-2}$, $O(10^{-11})$ of ${}^6\text{Li}$ can be created and ${}^7\text{Li}$ abundance can be suppressed by a factor of ~ 2 .

Constraints on particle physics models

Type I: $X^- \rightarrow \text{SM}^- [X^0]$, $\Delta E \sim M_X$. **Longevity because of small couplings.**

Examples:

NLSP slepton (stau, smuon...) \rightarrow Gravitino LSP

NLSP slepton (stau, smuon...) \rightarrow "Dirac" RH sneutrino LSP

Long-lived EW scale triplet Higgs decaying to SM

Type I requires taking care of "nonthermal" BBN effects.

Type II: $X^- \rightarrow X^0 + e^- [\nu]$; $\Delta E \sim \text{few MeV}$ or less.

Longevity because of the small energy release.

Examples:

Closely degenerate stau-neutralino system

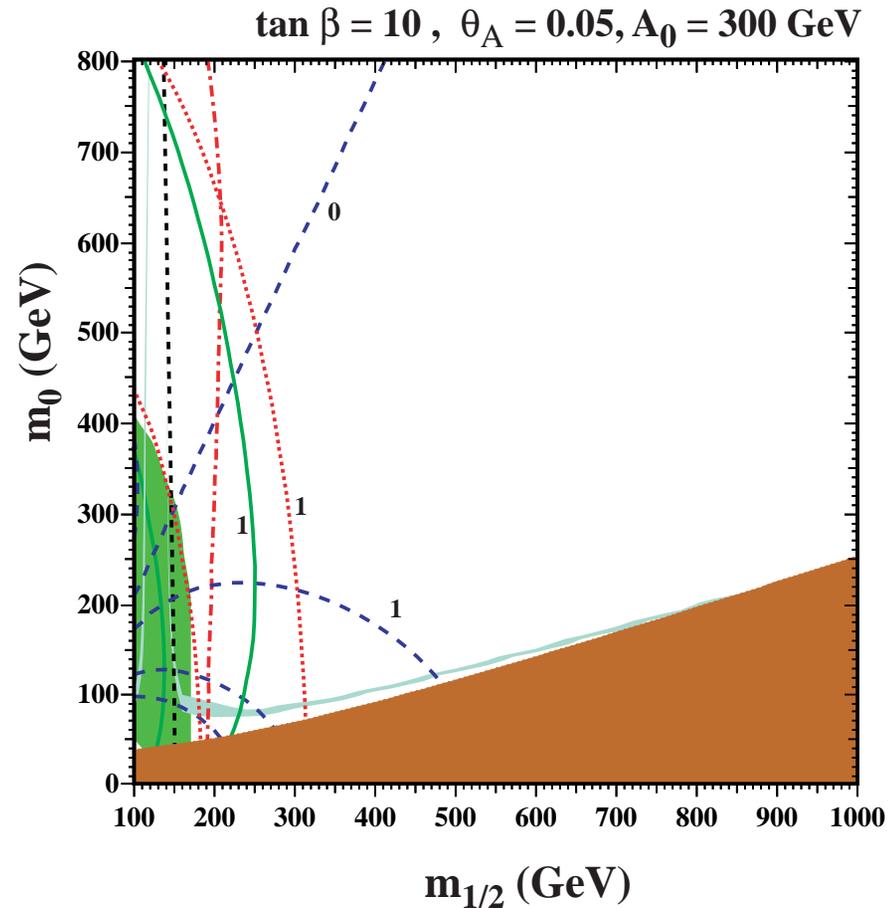
Closely degenerate chargino-neutralino ($O(\text{MeV})$ splitting)

Dark matter as heavy EW multiplet ($O(\text{MeV})$ splitting)

Before CBBN, models of Type II were believed to be unconstrained by physics of the Early Universe.

Implications for SUSY

- In the orthodox CMSSM stau-neutralino should not be more degenerate than 50 MeV
- In the stau-NLSP/gravitino-LSP the constraint on the lifetime (< 5000 s) requires small gravitino mass. *Excludes the possibility of measuring this mass in the decays of staus...which could be used for measuring M_{planck}* (Feng et al, Hamaguchi et al...)



What is Catalysis anyway?

Suppose you have two atoms (nuclei, molecules, ..., people), **A** and **B**, and you need to produce their bound state, **(AB)**. The direct reaction to form their bound state is weak:



by some e.g. symmetry (or any other) reasons.

You find a catalytic agent **C** that binds to one of those,



and facilitates



where **C** is released.

There are several important conditions:

1. **(AC)** must be a sufficiently weakly bound state, $E_{AC} < Q_{R1}$, otherwise it will not participate in reaction 3 or **C** would not be released.
2. Reaction 3 should be fast, avoiding suppression mechanisms of R1.
3. Reaction 2 also should be fast, otherwise one would need large quantities of **C**.

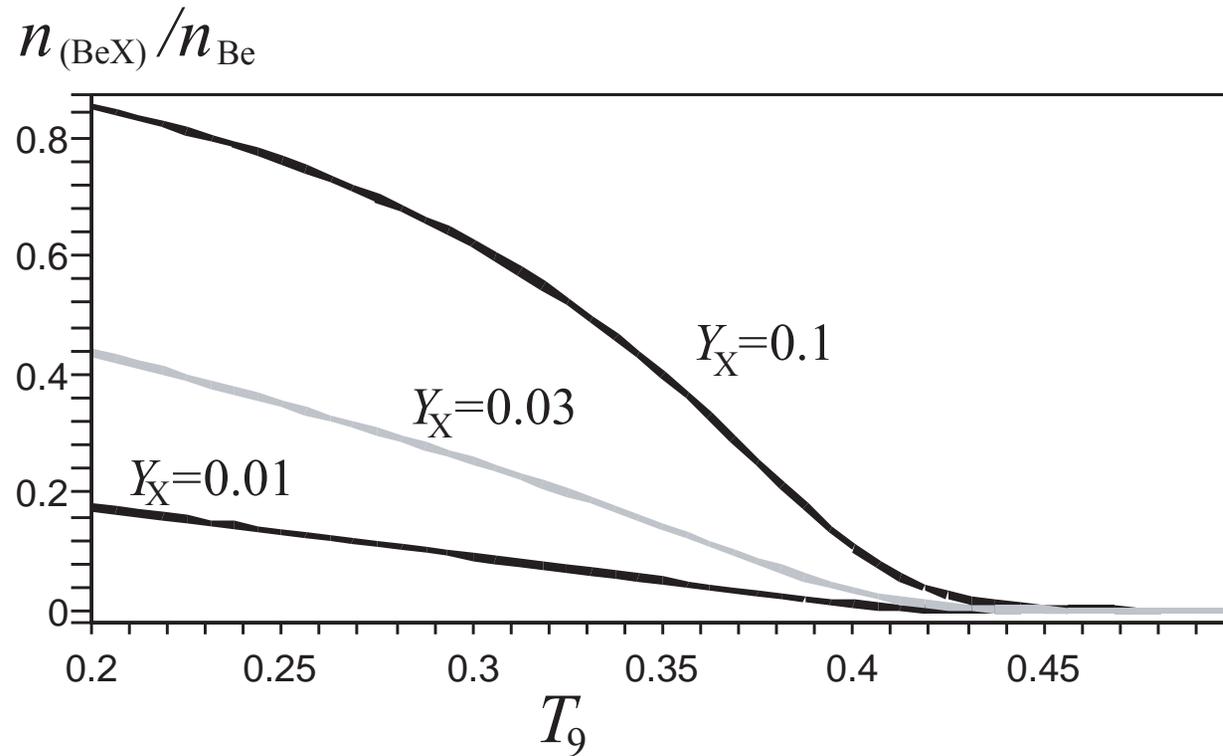
All three conditions are satisfied in our example, with **A**=⁴He, **B**=D, **C**=X⁻ and **(AB)**=⁶Li.

Catalytic suppression of ${}^7\text{Be} + {}^7\text{Li}$

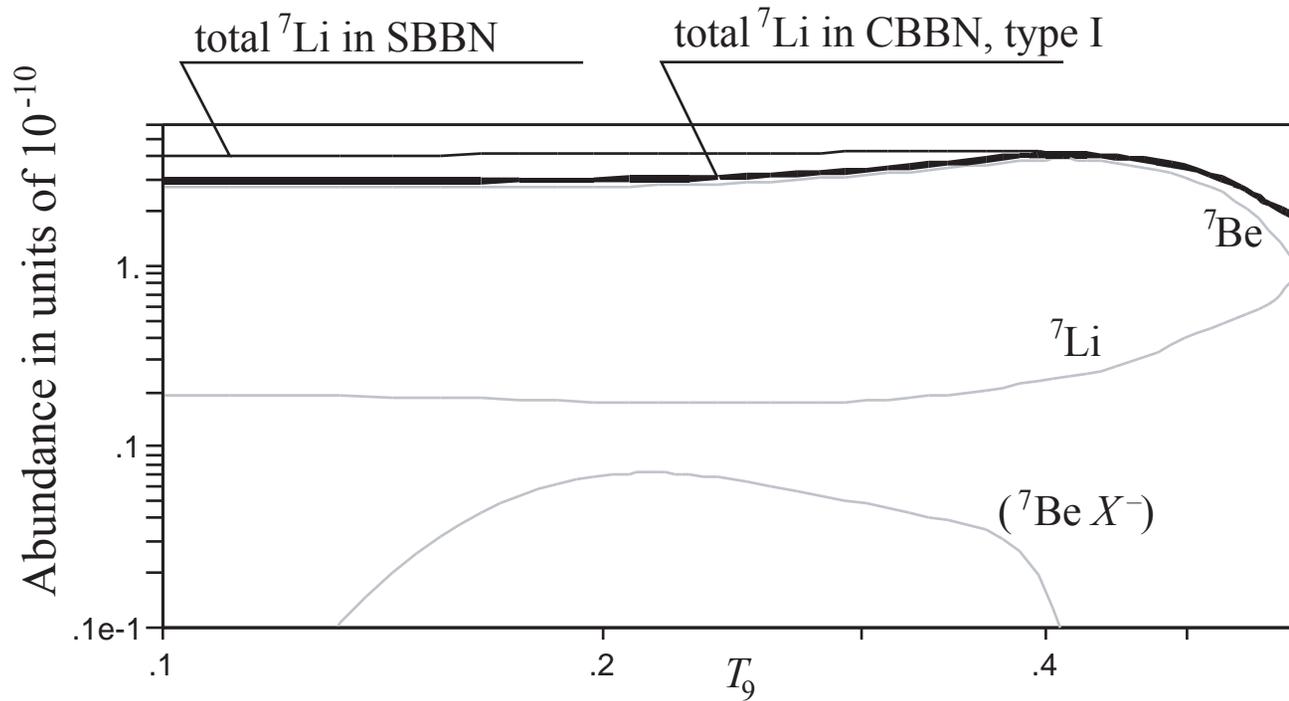
- The “bottleneck” is creation of $({}^7\text{Be}X^-)$ bound states that is controlled by ${}^7\text{Be} + X^- \rightarrow ({}^7\text{Be}X^-) + \gamma$ reaction
- There are two main destruction channels that are catalyzed:
 1. p-reaction: $({}^7\text{Be}X^-) + \text{p} \rightarrow ({}^8\text{B}X^-) + \gamma$ by a factor of >1000 relative to ${}^7\text{Be} + \text{p} \rightarrow {}^8\text{B} + \gamma$
 2. In models of type II, the “capture” of X^- is catalyzed:
 $({}^7\text{Be}X^-) \rightarrow {}^7\text{Li} + X^0$,
so that lifetime of $({}^7\text{Be}X^-)$ becomes $\ll 1$ sec. ${}^7\text{Li}$ is significantly more fragile and is destroyed by protons “on the spot”.
 3. There is significant energy injection via
 $X^+ + X^- \rightarrow (X^+X^-) \rightarrow \text{radiation}$. If this process has hadronic modes, it also affects $\text{Li}7$.

Be7 + X recombination

- Neglecting nuclear effects,

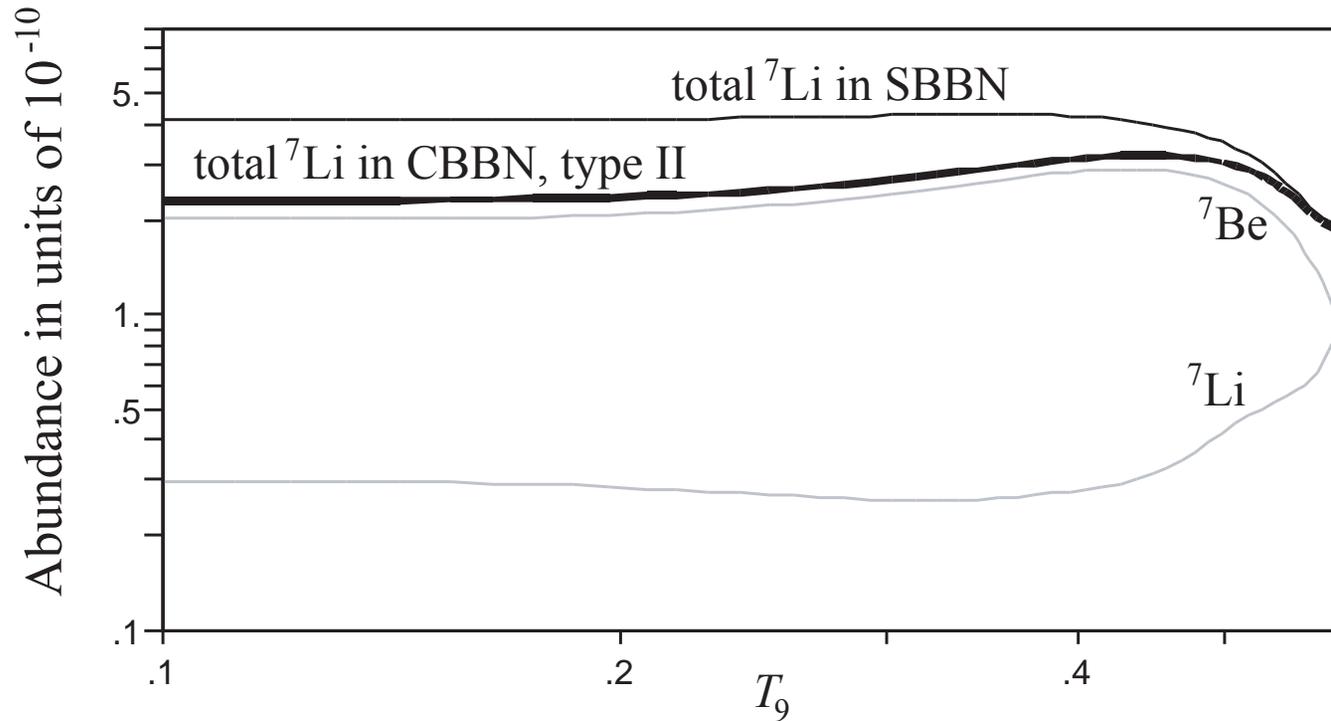


${}^7\text{Be}+{}^7\text{Li}$ at 35 KeV



Type I model (no internal capture), $Y_X=0.05$, $\tau=2000\text{s}$

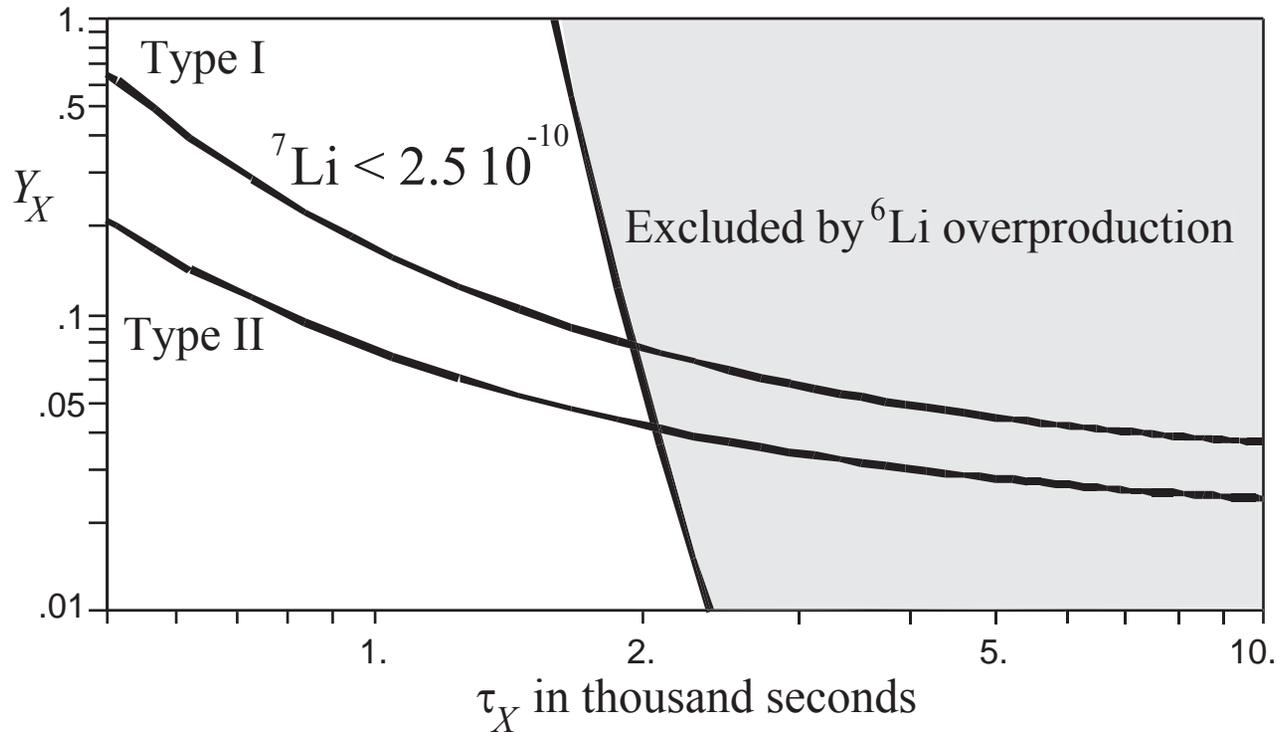
${}^7\text{Be}+{}^7\text{Li}$ at 35 KeV



Type II model (fast internal capture),

$Y_X=0.05$, $\tau=2000\text{s}$

Combined Fit of ${}^6\text{Li}$ and ${}^7\text{Be}+{}^7\text{Li}$ constraints



Lifetimes $1000 < \tau_X < 2000$ sec and $0.05 < Y_X < 0.1$ satisfy ${}^6\text{Li}$ constraint and suppress ${}^7\text{Be}+{}^7\text{Li}$ by a factor of 2.

Does ${}^7\text{Li}$ Problem have mundane explanation?

Nuclear Physics. ${}^7\text{Be}$ abundance depends on

1. **Abundance of ${}^3\text{He}$ at $T_9 \simeq 0.5$.** Seems OK, as it is one-to-one correlated with D.
2. **${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$ reaction.** The direct measurement of astrophysical $S_{34}(0)$ is difficult. A factor of 2 error is unlikely. SNO (solar) neutrino flux depends on this reaction 100%.
3. **${}^7\text{Be}(n, p){}^7\text{Li}$ reaction,** the main destruction mechanism. It is known/measured way too well for a factor of 2 error.
4. Previously poorly measured **${}^7\text{Be}(D, p)\alpha\alpha$ reaction,** which needs to be enhanced by ~ 100 to be relevant. Recently it has been remeasured at Louvain, with no enhancement found at 350 KeV. *However, there ${}^9\text{B}$ has a resonance at 200 ± 100 KeV away from ${}^7\text{Be}+D$ threshold, which might be relevant.* (Cyburt, MP, in progress).

Does ${}^7\text{Li}$ Problem have mundane explanation?

- Stellar Astrophysics. **Most likely reason for the discrepancy.**
 1. Suppression of lithium in atmospheres of Pop II stars by a factor of 20-30% or more seems possible. (Richard et al., 2005; Korn et al., 2006). More sophisticated stellar models that include the impact of diffusion and turbulent mixing on ${}^7\text{Li}$ are needed.
 2. Must explain low scatter in the suppression rate for different stars.
 3. ${}^6\text{Li}$ “plateau” is questionable, and ${}^6\text{Li}/{}^7\text{Li} \sim 0.05$ might be coming from solar-like flares (V. Tatischeff et al.).
 4. Other sources of exploring the primordial lithium abundance should be explored (e.g. CMB anisotropies).

Conclusions

1. Catalysis of nuclear fusion is a [new] generic mechanism of how particle physics can affect the BBN predictions for lithium and beryllium.
2. ${}^6\text{Li}$ and ${}^7\text{Li}+{}^7\text{Be}$ abundances are drastically affected even by mere presence of charged particles during BBN. Sensitivity to New Physics via Li6 abundance $\sim [X^-]/[\text{gamma}] \sim 10^{-16} - 10^{-17}$
3. Future directions will include: catalysis by strongly interacting particles; catalysis by X^{--} ; detailed predictions for ${}^9\text{Be}$, ${}^{10}\text{B}$ and ${}^{11}\text{B}$; analysis of specific particle physics models; 3-body nuclear calculations of catalyzed rates.

Genesis According to Gamow

(cited from S. Singh's "Big Bang")

In the beginning God created radiation and ylem [primordial mix of particles]. And ylem was without shape and number, and the nucleons were rushing madly over the face of the deep.

And God said: "Let there be mass two". And there was mass two. And God saw deuterium, and it was good.

And God said: "Let there be mass three". And there was mass three. And God saw tritium, and it was good.

And God continued to call numbers until He came to transuranium elements. But when He looked back on his work, He found that it was not good. In the excitement of counting, He missed calling for mass five and so, naturally, no heavier elements could have been formed.

God was very much disappointed, and wanted first to contract the Universe again, and to start all over from the beginning. But it would be much too simple. Thus, being God almighty, God decided to correct His mistake in a most impossible way.

Genesis According to Gamow (continued)

And God said: “Let there be Hoyle”. And there was Hoyle. And God looked at Hoyle and told him to make heavy elements in any way he pleased.

And Hoyle decided to make heavy elements in stars, and spread them around by supernova explosions. But in doing so, he had to obtain the same abundances which would have resulted from nucleosynthesis in ylem, if God would not have forgotten to call for mass five.

And so, with the help of God, Hoyle made heavy elements in this way, but it was so complicated that nowadays neither Hoyle, nor God, nor anybody else can figure out exactly how it was done.

Amen