Did the Universe undergo the stage of catalyzed nuclear fusion?

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M. Pospelov, hep-ph/0605215; PhysRevLett.98.231301
C. Bird, K. Koopmans, and M. Pospelov, hep-ph/0703096
M.Pospelov, arXiv:0712.0647

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Outline of the talk

1. Implication of BBN for Particle physics. Current status, future directions. “Lithium problem”.
2. Catalyzed Big Bang Nucleosynthesis.
3. ^{6}Li: strong enhancement
4. ^{7}Be + ^{7}Li: factor of ~2 suppression
5. ^{9}Be: strong enhancement
6. Particle physics implications
7. Conclusions

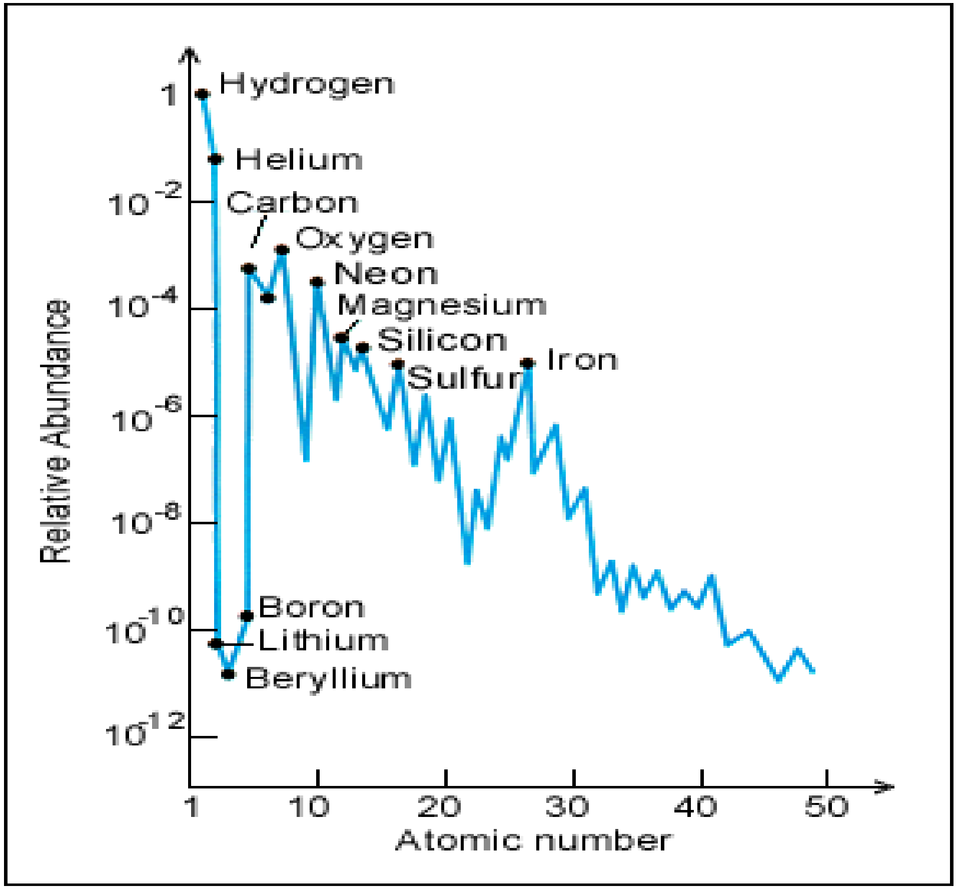
Signature of CBBN

- Big Bang Nucleosynthesis is the earliest epoch in Universe's history that finds conclusive evidence in observations. BBN was completed by t = 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).

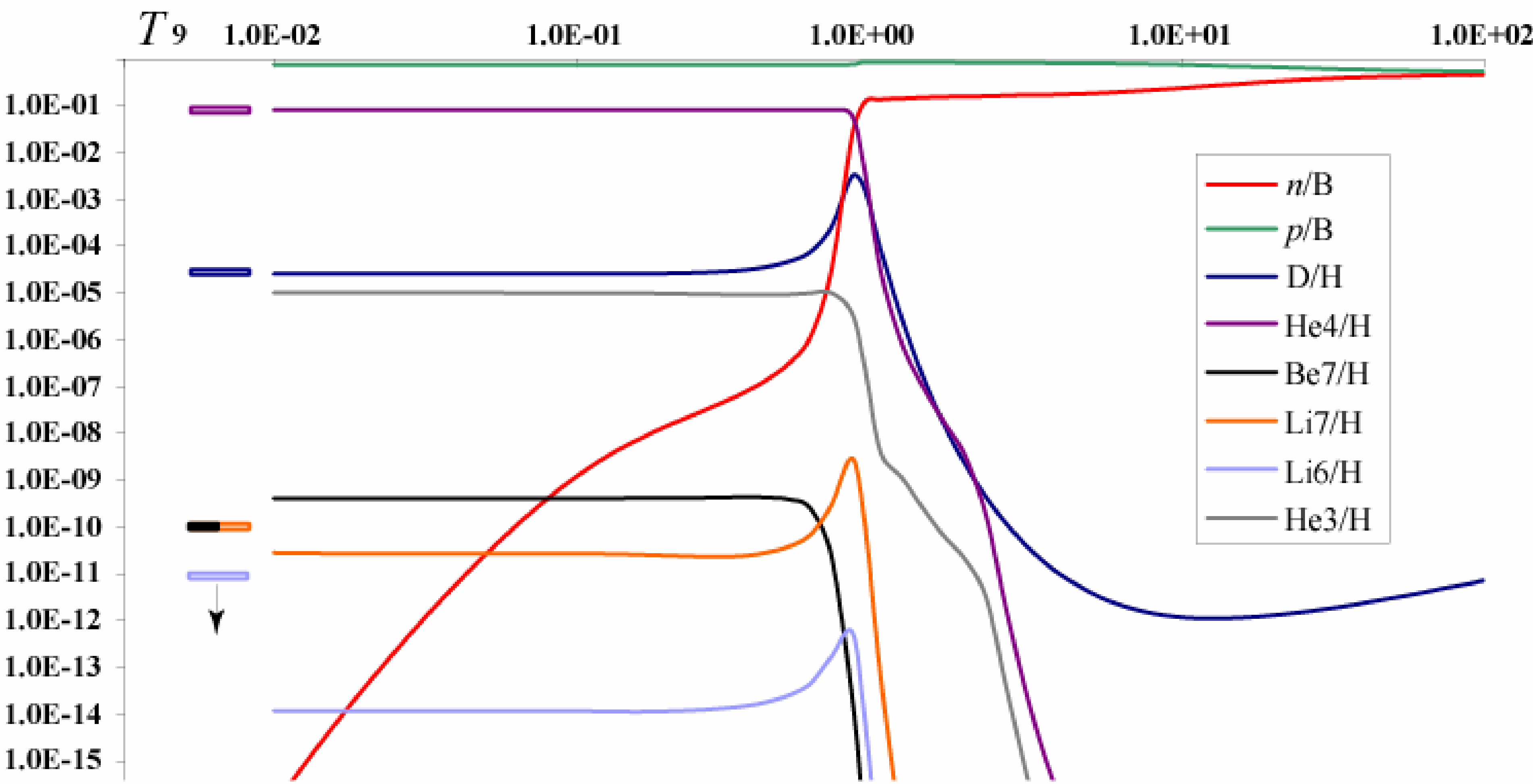
- Standard BBN requires the input of only one free parameter, η_b, and therefore is a sensitive test of new particle physics models and new models of gravity.

Elemental Abundance



A<1,2,3,4,7 – BBN; A>12 –Stars;
A=6,9,10,11 –“orphans” (cosmic ray spallation)

Gamow's creation curves



BBN and Particle Physics

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

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

Particle physics can

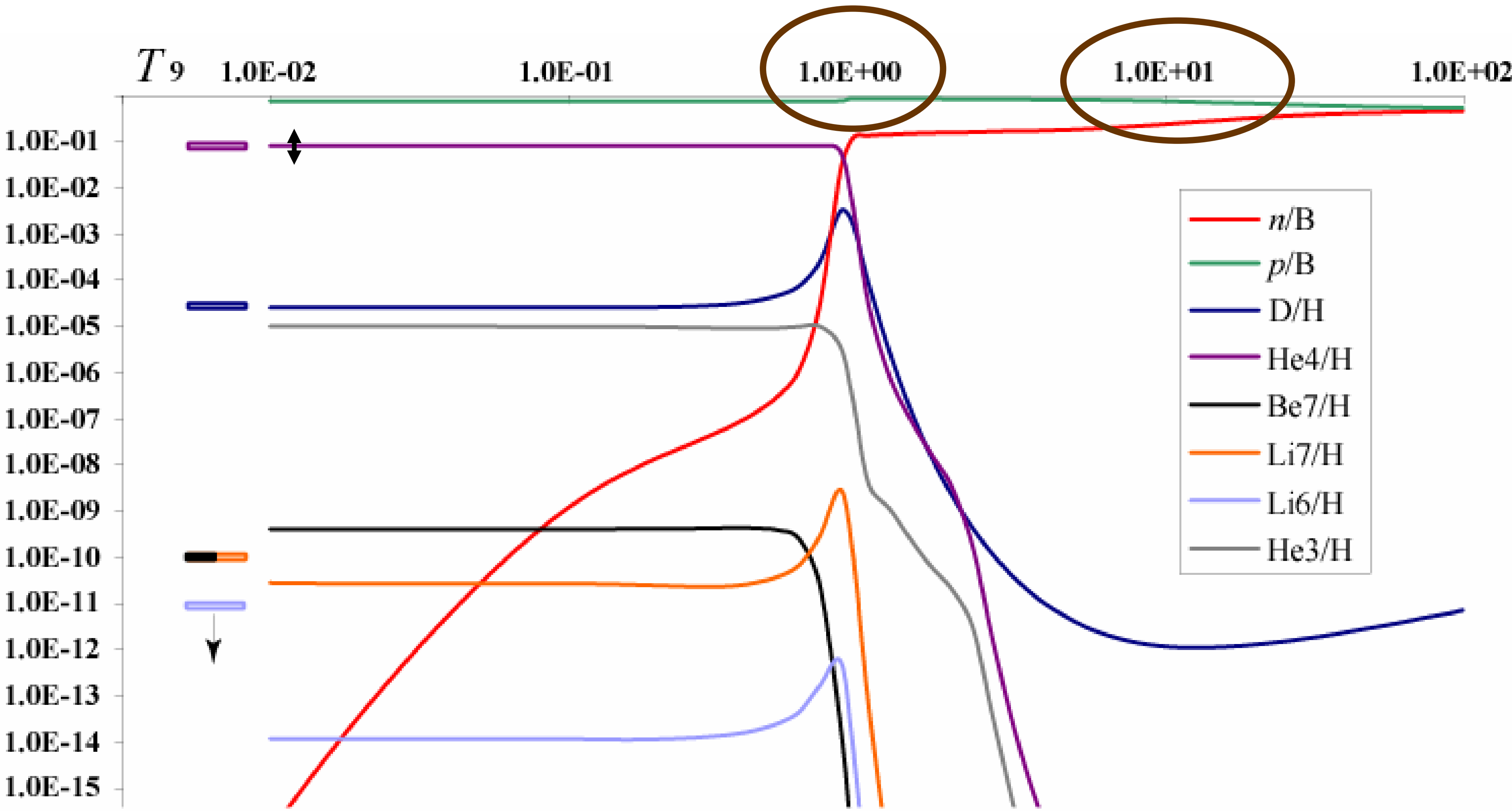
- Affect the timing of reactions,

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

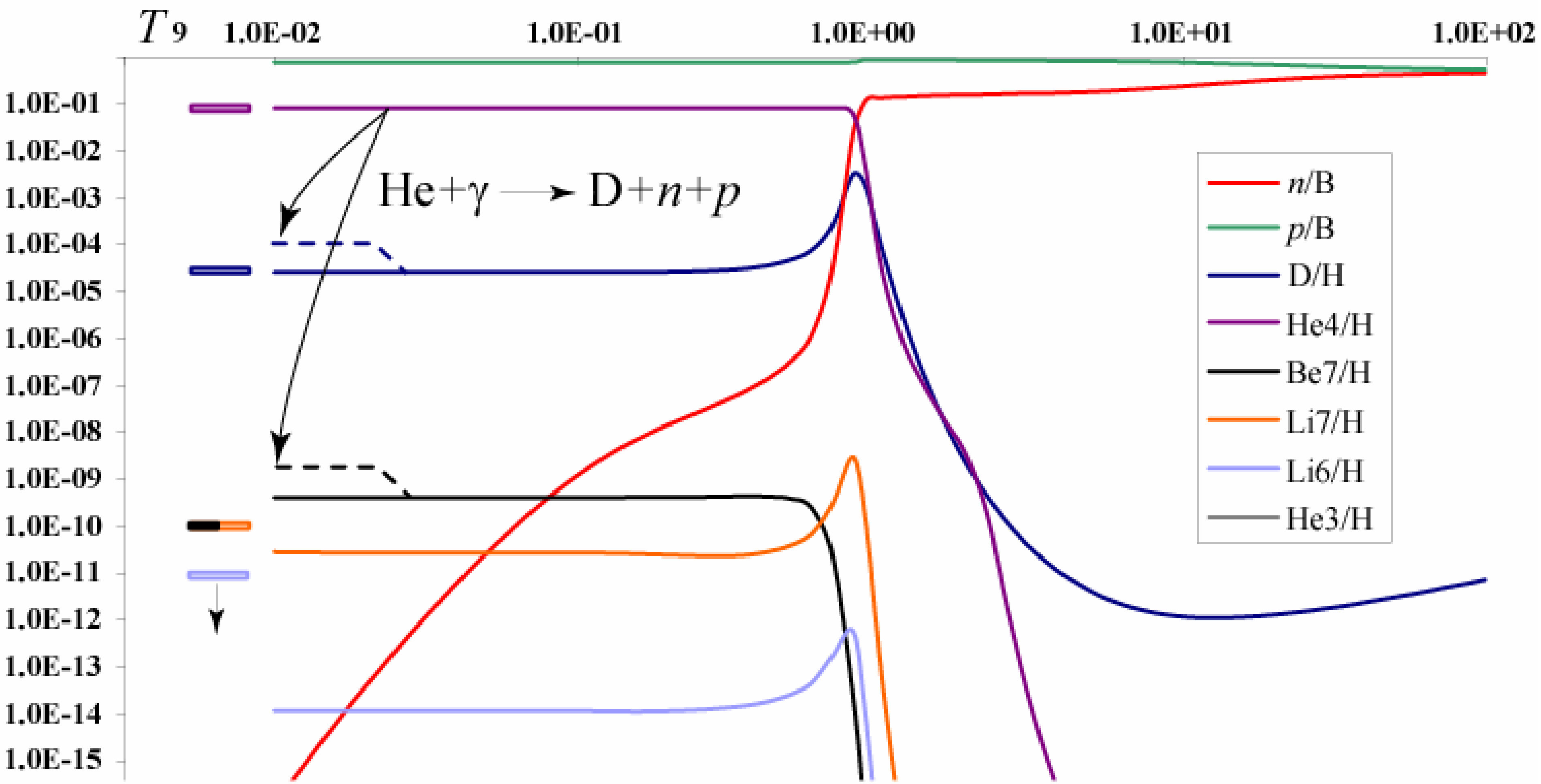
  via e.g. new thermal degrees of freedom

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

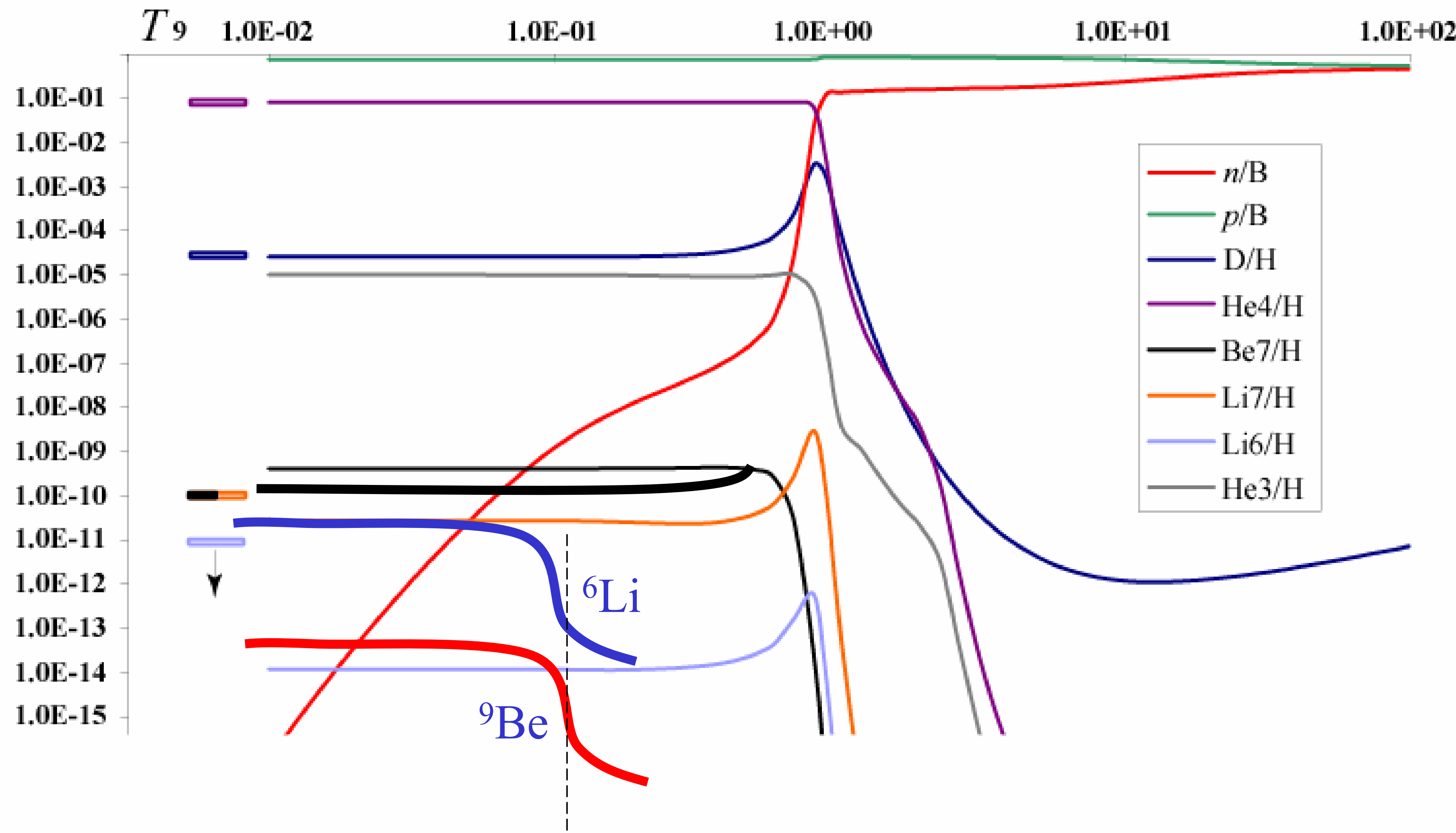
Change in the timing of reactions due to e.g. N_{eff}



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

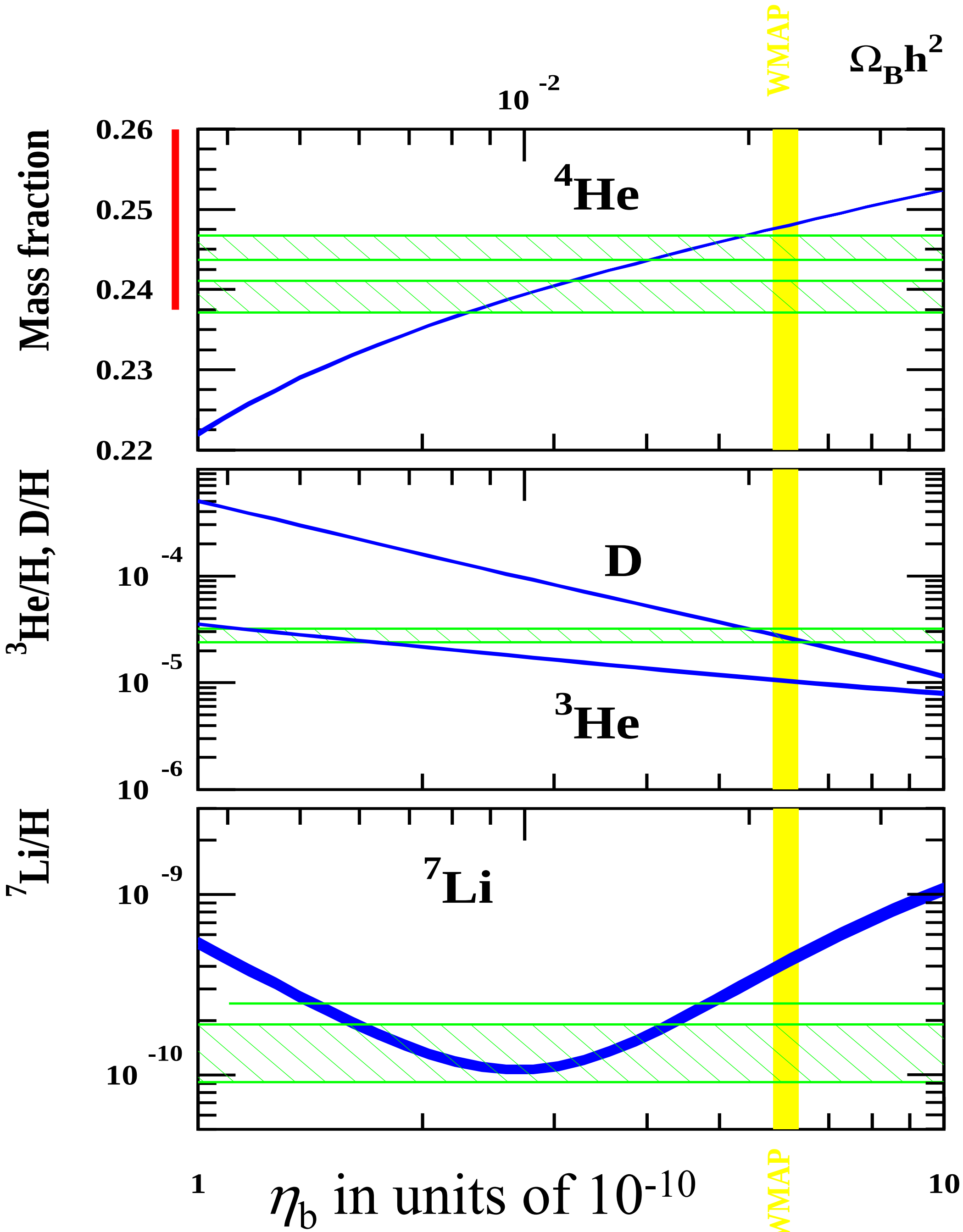


Catalyzed Production of ^{6}Li and ^{9}Be at 8 KeV, suppression of ^{7}Be+^{7}Li at 35 KeV



Catalyzed nucleosynthesis at 5:25a.m., Day 1

Current Status



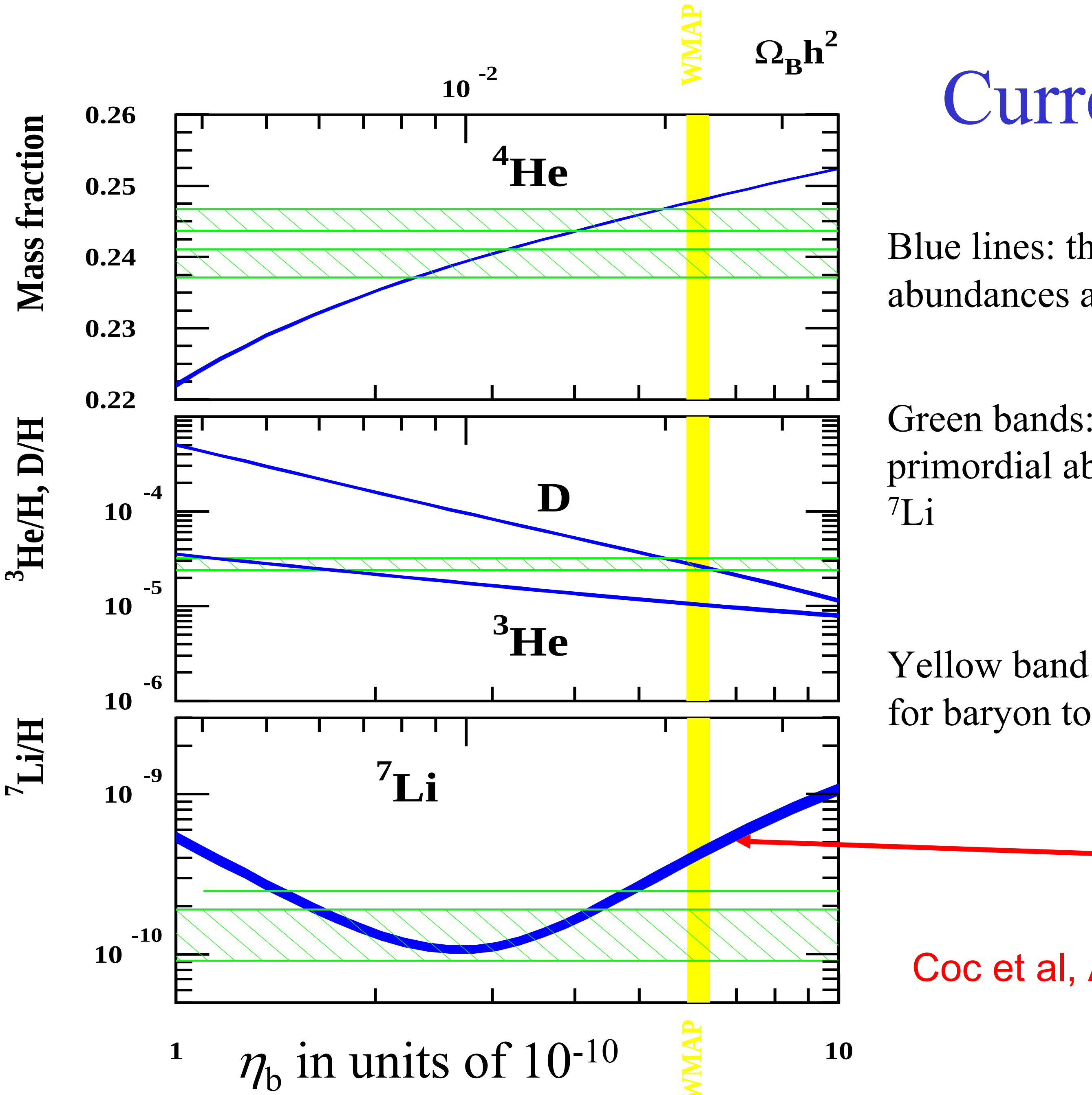
Blue lines: theoretical predictions of abundances as functions of η_b

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

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

Coc et al, ApJ 2004

Current Status



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

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 ^{4}He.

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

A. Measurements have an unaccounted systematic error.

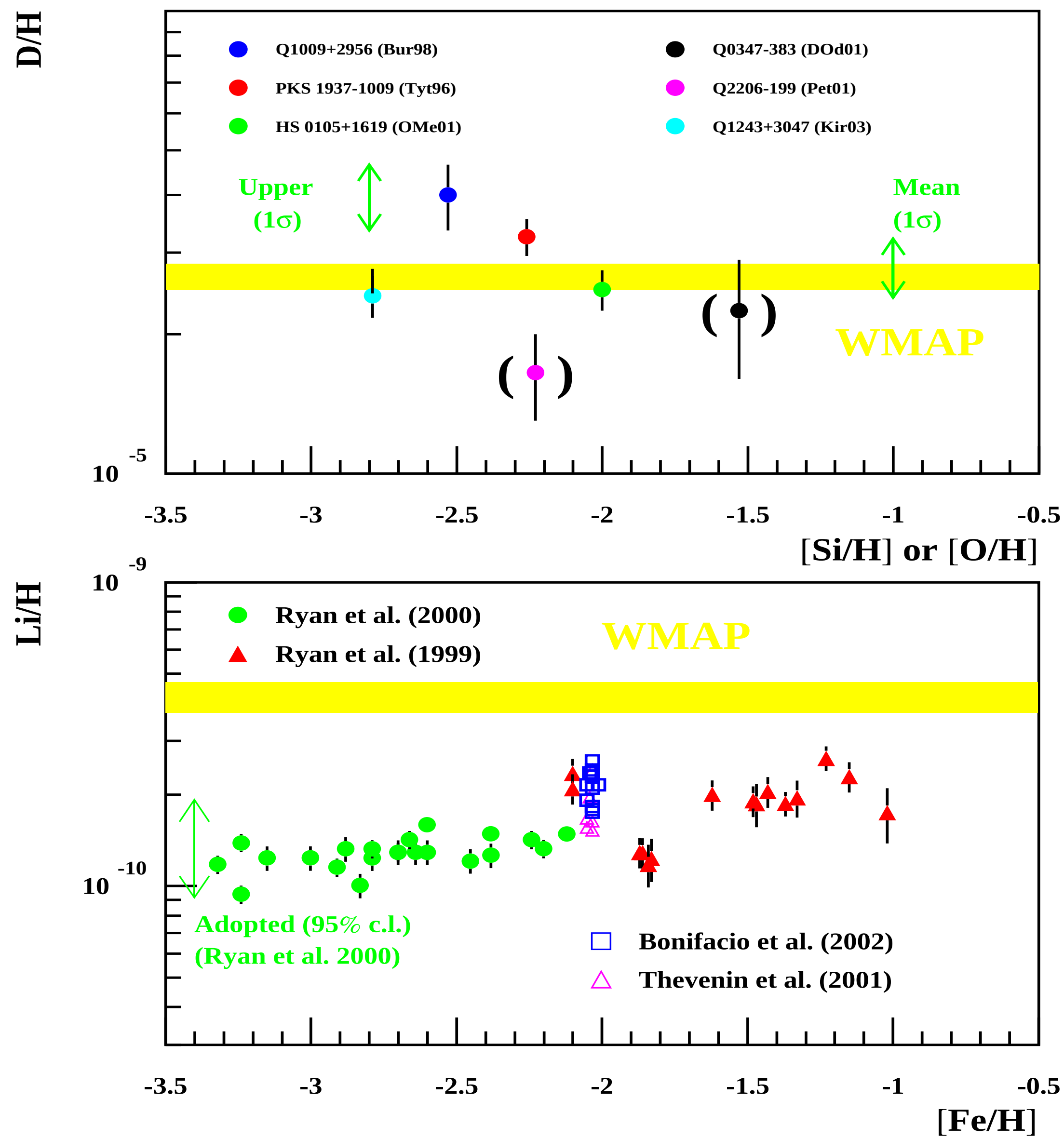
B. We do not understand the cycling of ^{7}Li in stars. What we see is not primordial.

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

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

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

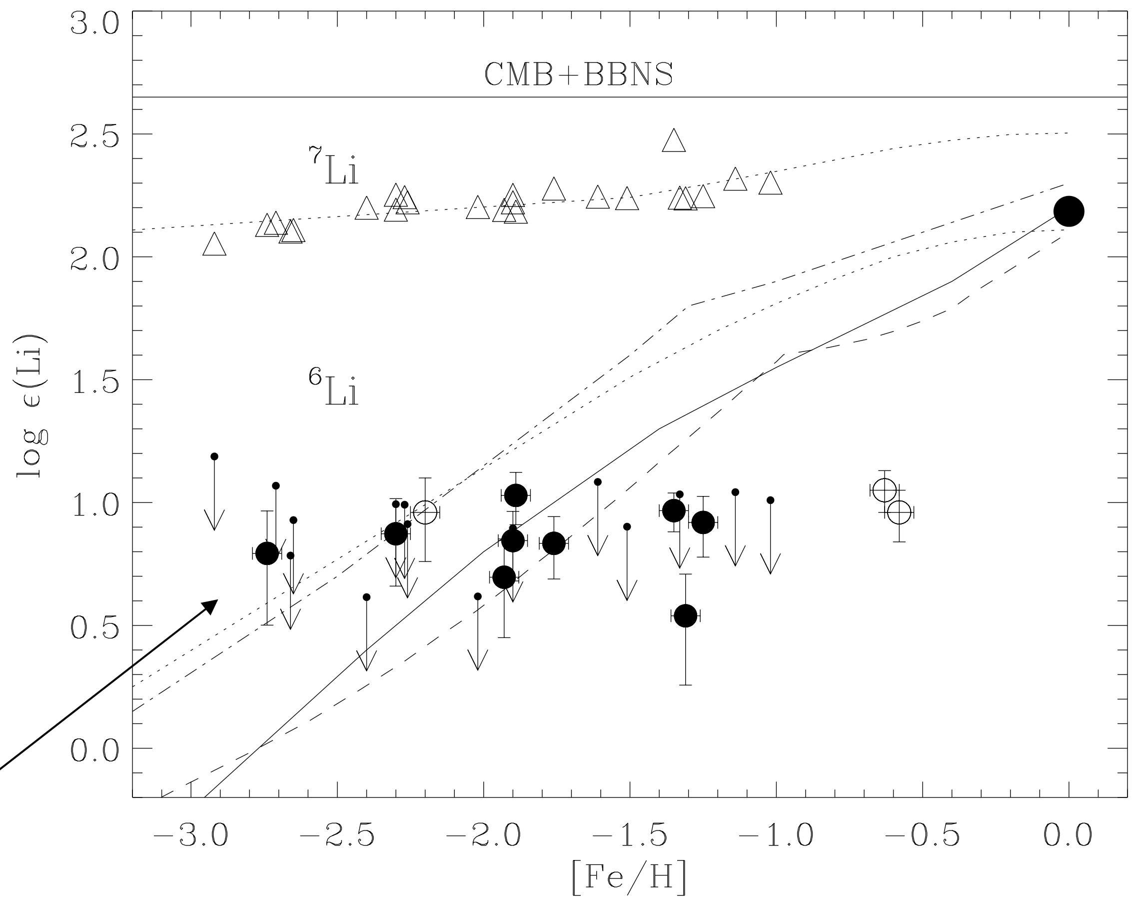
Deuterium and Lithium abundances



Coc et al,
ApJ 2004

Emerging ^{6}Li problem?

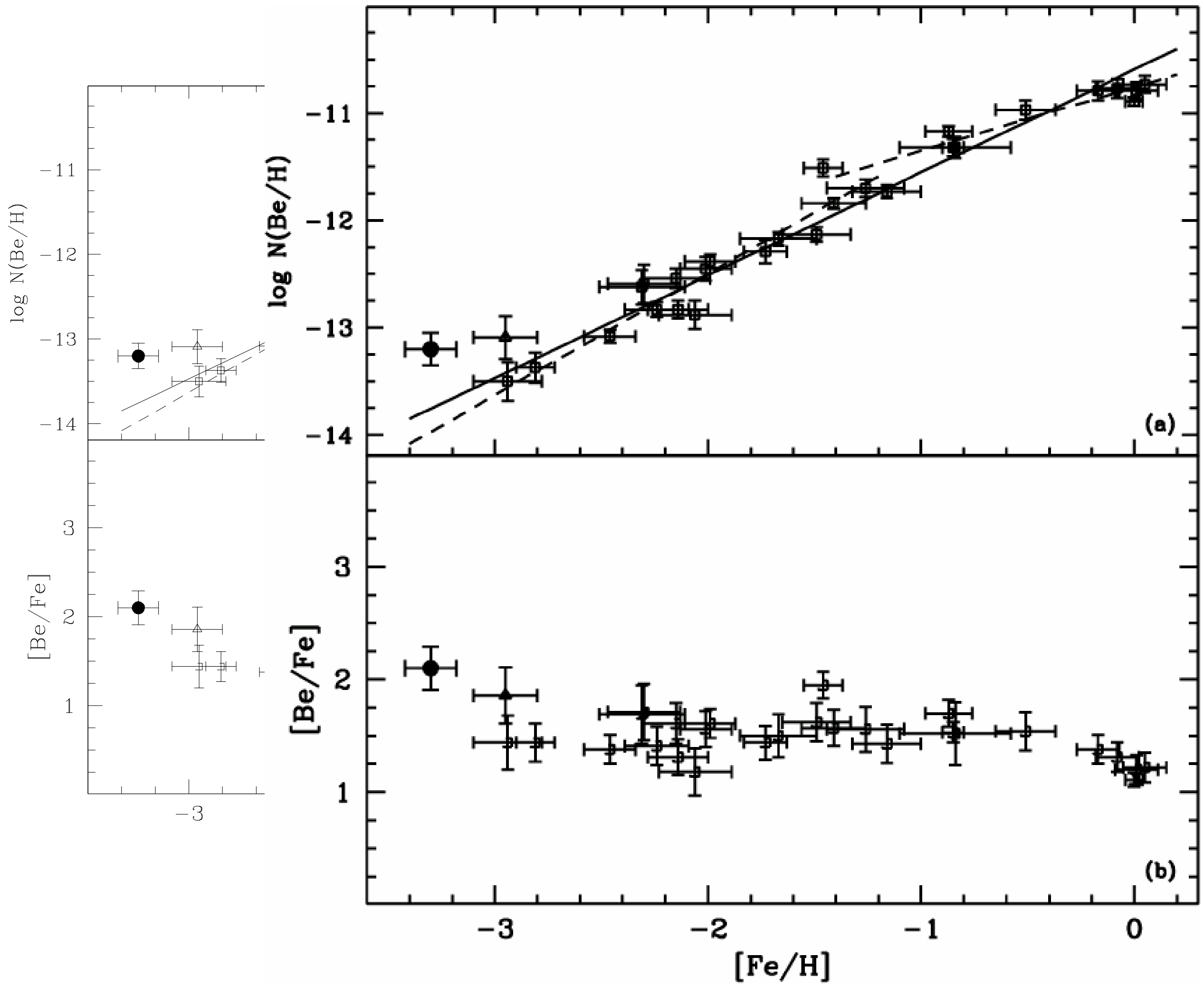
A lot of speculations about primordial ^{6}Li!



$^{6}Li/H \sim 2 \times 10^{-11}$

Unexpected plateau (?) of ^{6}Li with metallicity (Asplund et al., 2005)

^{9}Be vs metallicity
Is there a hint on a "lifted tail"? (Primas et al., 2001)



No serious BBN models ever predicted anything in excess of 10^{-15}

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 $N_{\mathrm{eff}} \sim O(1)$. In other words, there is sensitivity to $\Delta\rho_{\mathrm{extra}}/\rho_{\mathrm{total}} \sim 0.3$.

2. Energy injection (e.g. late decays of particles) will have an effect on mostly D, ^{6}Li, ^{7}Li, and ^{3}He/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}Li, ^{7}Li, and ^{9}Be. Best sensitivity to $n_x/n_\gamma < 10^{-16}$ for $\tau_X > 10^4$ sec.

Digression: how "natural" are long-lived X^-?

Suppose nature chose weak scale supersymmetry.

There are two types of regular superpartners:

Neutrals: neutralinos, sneutrinos.

Charged: charged sleptons, squarks, charginos

All masses are at ~ TeV or less [one would hope!]

"Probability" of $m_{\text{lightest charged}} < m_{\text{lightest neutral}}$: **50%**

Gravitino mass is a free parameter, not linked to weak scale

"Probability" of $m_{\text{gravitino}} < m_{\text{lightest charged}} < m_{\text{lightest neutral}}$: **25%**

In 25% cases SUSY models would have long-lived charged or strongly interacting relics!

Same thing goes about "universal extra dimensions"

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 $Y_X \sim (0.01–0.05)m_X/\mathrm{TeV}$.
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! ***Anything at all that*** **sticks to He with binding energy between 150 KeV and 1500 KeV will lead to the catalysis of ^{6}Li production!**

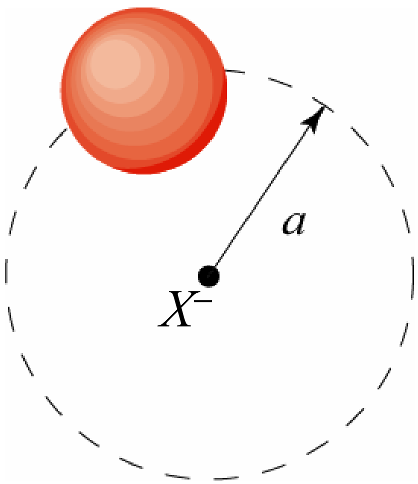
Any quantities of (^{8}BeX) in excess of 10^{-10} at 8 keV will lead to the catalysis of ^{9}Be to $>10^{-13}$ level.

Properties of bound states

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

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

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



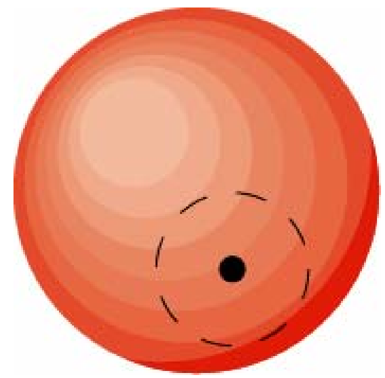
(^{4}HeX$^-$)

Bohr radius is 2 times larger than nuclear

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

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

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



(^{7}BeX$^-$)

Bohr orbit is within nuclear radius

Binding energy and stability thresholds

bound st.	$\lvert E_b^0 \rvert$	a_0	R_N^{sc}	$\lvert E_b(R_N^{sc}) \rvert$	R_{Nc}	$\lvert E_b(R_{Nc}) \rvert$	T_0
^{4}HeX	397	3.63	1.94	352	2.16	346	8.2
^{6}LiX	1343	1.61	2.22	930	3.29	780	19
^{7}LiX	1566	1.38	2.33	990	3.09	870	21
^{7}BeX	2787	1.03	2.33	1540	3	1350	32
^{8}BeX	3178	0.91	2.44	1600	3	1430	34
^{4}HeX	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.

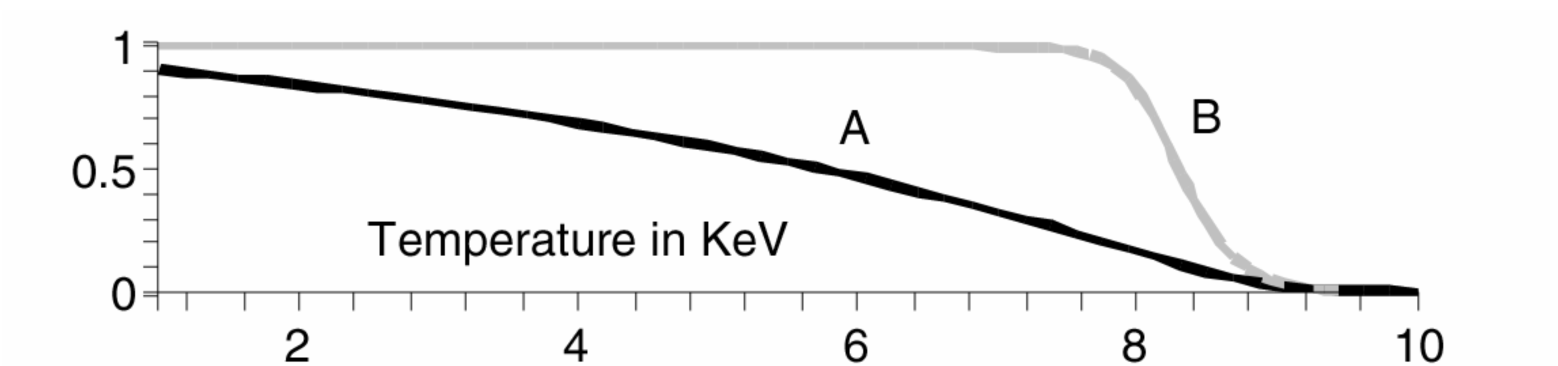
Recombination of ^{4}He and X$^-$

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:



New Reaction Channels

- Main SBBN channel for ^{6}Li production

$$^4\mathrm{He} + \mathrm{D} \rightarrow {}^6\mathrm{Li} + \gamma; \quad \mathrm{Q} = 1.47\ \mathrm{MeV}$$

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

in usual astrophysical units. ^{6}Li(SBBN) $\sim 10^{-14}$

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}Li production

$$({}^4\mathrm{He}X^-) + \mathrm{D} \rightarrow {}^6\mathrm{Li} + X^-; \quad \mathrm{Q} = 1.13\ \mathrm{MeV}$$

$$\langle \sigma_{CBBN} v \rangle = \underline{2.4 \times 10^8} T_9^{-2/3} \exp(-\underline{5.37} / T_9^{1/3})$$

New Reaction Channels

- A possible SBBN channel for ^{9}Be production

$$^8\text{Be} + n \rightarrow {}^9\text{Be} + \gamma; \quad Q = 1.66 \text{ MeV}$$

$$\langle \sigma_{SBBN} v \rangle \approx 0. \text{ Requires triple collisons as } {}^8\text{Be is unstable}$$

$$^9\text{Be(SBBN)} \sim 10^{-18}$$

- Main CBBN channel for ^{9}Be production

$$(^8\text{BeX}^-) + n \rightarrow {}^9\text{Be} + X^-; \quad Q = 0.26 \text{ MeV}$$

$$\langle \sigma_{CBBN} v \rangle = 2.0 \times 10^9$$

This is a large photonless rate dominated by threshold resonance!

Why is ^{6}Li so suppressed in SBBN

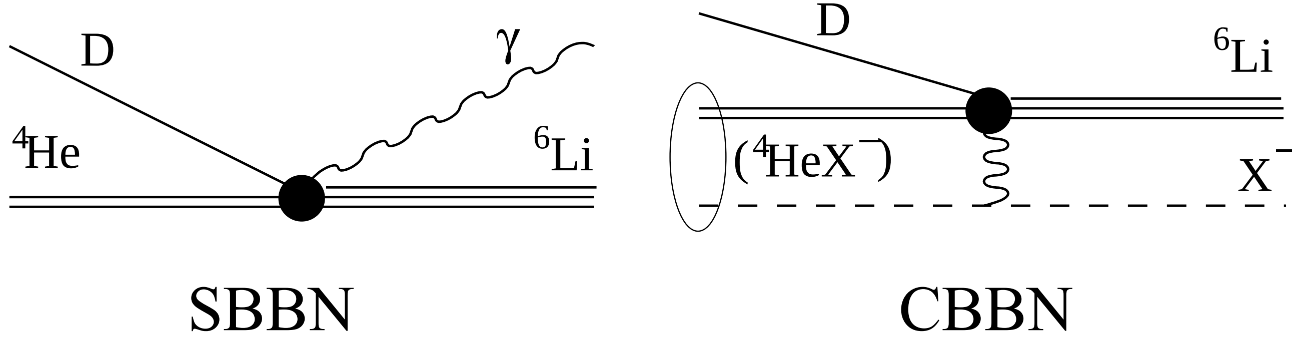
compared to ^{7}Li+^{7}Be? The rate for ^{4}He(^{3}H,γ)^{7}Li is almost five orders of magnitude larger than ^{4}He(^{2}H,γ)^{6}Li but why?

The reason is "accidental": ^{6}Li is well described by ^{4}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:

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

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}Li in CBBN



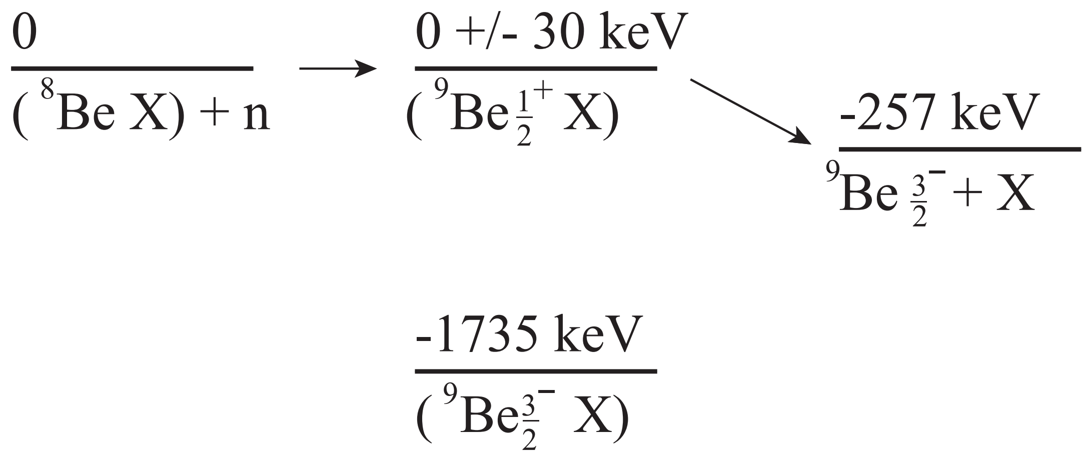
There are two sources of enhancements:

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^{SBBN}=5249 KeV$\rightarrow$ E_G^{CBBN}=1973 KeV. This gives ~10 times enhancement at T=8 KeV. Three-body nuclear calculation, **hep-ph/0702274**, (Hamaguchi, et al.) finds S-factor 8 times smaller than my original estimate.

Photon-less production of ^{9}Be in CBBN

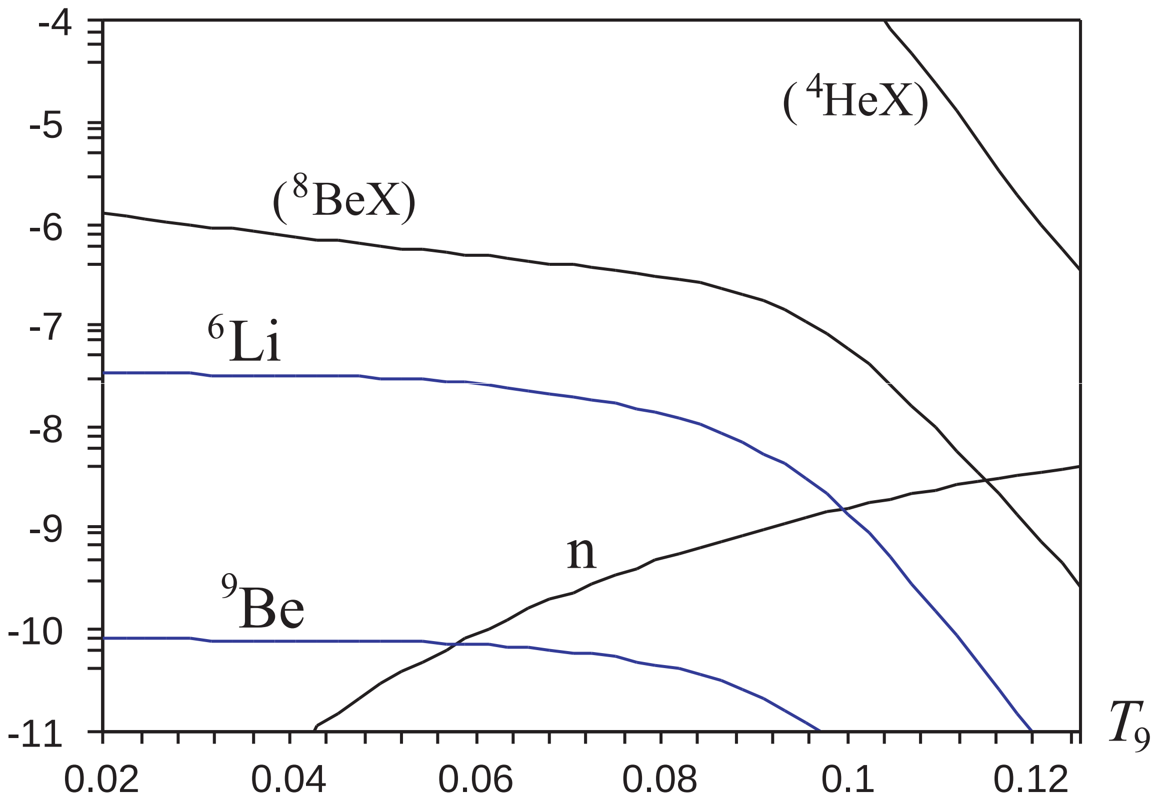


. Within error bars the $\frac{1}{2}^+$ resonance in (^{9}BeX$^-$) is *exactly* at the (^{8}BeX$^-$) + n continuum threshold.

$$\Gamma_{in} \simeq 2(192E_n/\mathrm{keV})^{1/2}, \qquad \Gamma_{out} = 5\ \mathrm{keV}$$

^{6}Li and ^{9}Be at 8 KeV

CBBN with $Y_X = 5\times10^{-3}$, $\tau_X = \infty$ as a typical example, resulting in ^{6}Li >10^{-8}, and ^{9}Be>10^{-11} – **Excluded!**

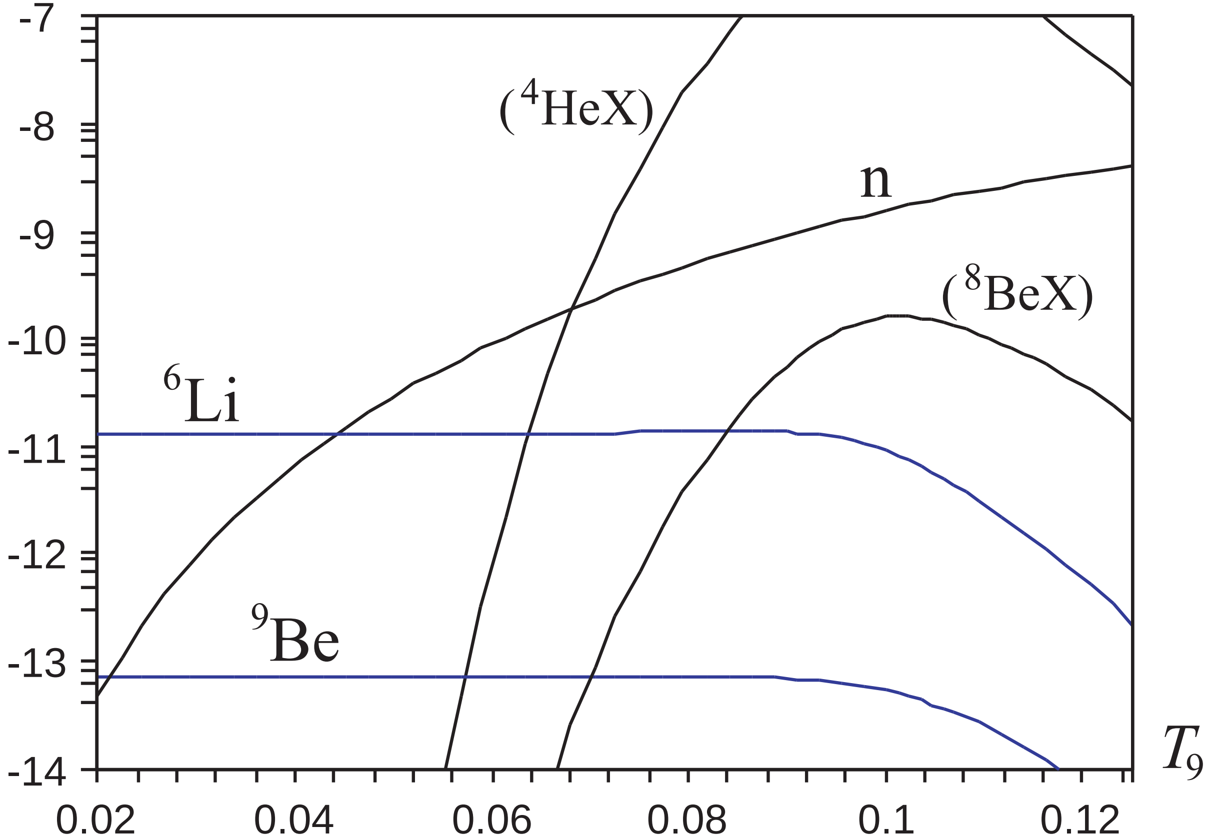


Observationally, ^{6}Li/H < few× 10^{-11}; ^{9}Be/H<few× 10^{-13},

Therefore, $Y_X(2\times10^4\,\mathrm{sec}) < 10^{-5}$, and typically $\tau_X < 5\times 10^3$ s.

^{6}Li and ^{9}Be at 8 KeV

CBBN with $Y_X = 10^{-1}$, τ_X=2000s as a "just so" scenario



^{6}Li/H=1.3× 10^{-11}; ^{9}Be/H=7× 10^{-14}: A very intriguing pattern!!!

^{9}Be/^{6}Li = (2-5)× 10^{-3} - a typical "footprint" of CBBN

Constraints on particle physics models

Type I: $X^- \to SM^-[X^0]$, $\Delta E \sim M_X$. **Longevity because of small couplings.**
Examples:
NLSP slepton (stau, smuon...) $\to$Gravitino LSP
NLSP slepton (stau, smuon...) $\to$ "Dirac" RH sneutrino LSP
Long-lived EW scale triplet Higgs decaying to SM
Type I requires taking care of "nonthermal" BBN effects.

Type II: $X^- \to X^0 + e^-[\nu]$; $\Delta E \sim$ few MeV or less.
Longevity because of the small energy release.
Examples:
Closely degenerate stau-neutralino system
Closely degenerate chargino-neutralino (O(MeV) splitting)
Dark matter as heavy EW multiplet (O(MeV) splitting)
Before CBBN, models of Type II were believed to be unconstrained by physics of the Early Universe.

Conclusions

1. Catalysis of nuclear fusion is a new generic mechanism of how particle physics can affect the BBN predictions for lithium and beryllium. CBBN imposes important constraints on particle physics models that cannot be [yet] probed in other ways; this includes some TeV-scale SUSY models.

2. ^{6}Li and ^{9}Be abundances are drastically enhanced, with ratio ^{6}Li/^{9}Be = (2-5) $\times$ 10^{-3}, affected by mere presence of charged particles during BNN. ^{7}Li+^{7}Be can be suppressed by a factor of ~ 2.

3. Future directions will include: catalysis by strongly interacting particles; catalysis by X^{--}; analysis of specific particle physics models; refined nuclear calculations of catalyzed rates.

This year is 50th anniversary of the famous B^2FH paper

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)

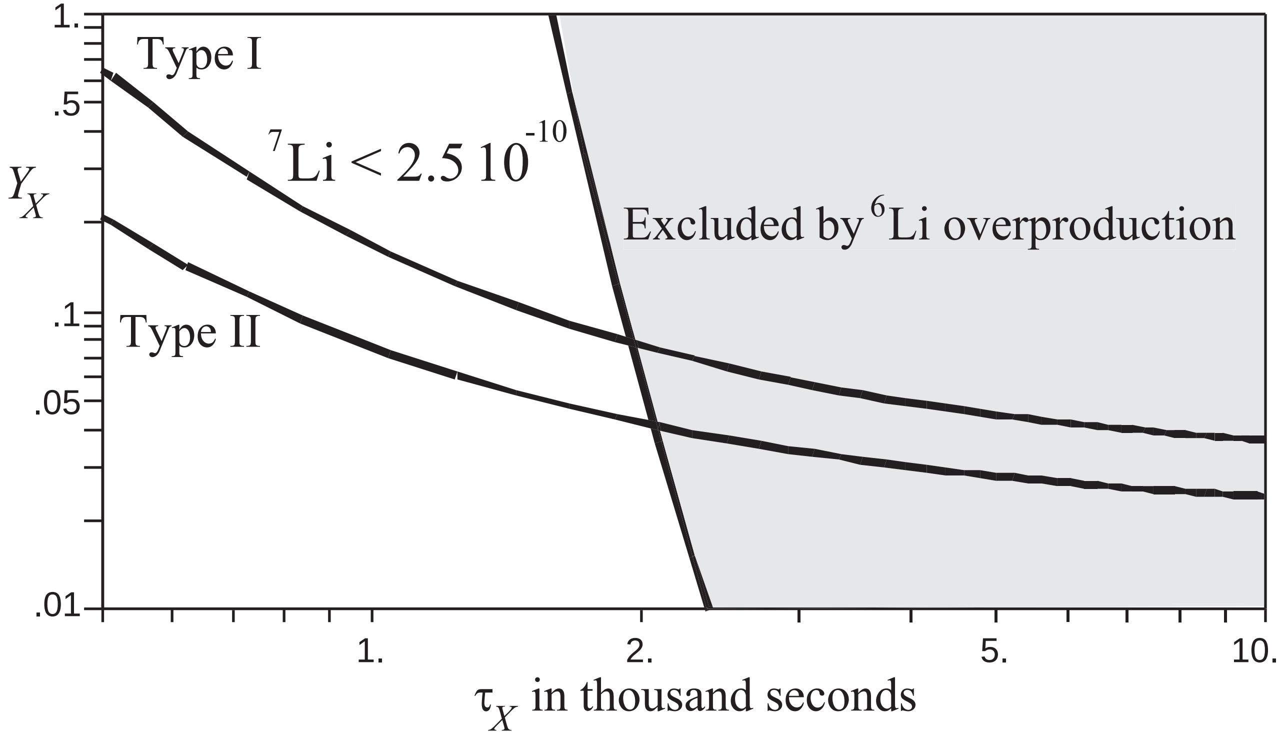
And God said: "Let there be Hoyle". And there was Hoyle. And God looked at Hoyle and told him to make heavy elements in any way he pleased.

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

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



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

Catalytic suppression of ^{7}Be + ^{7}Li

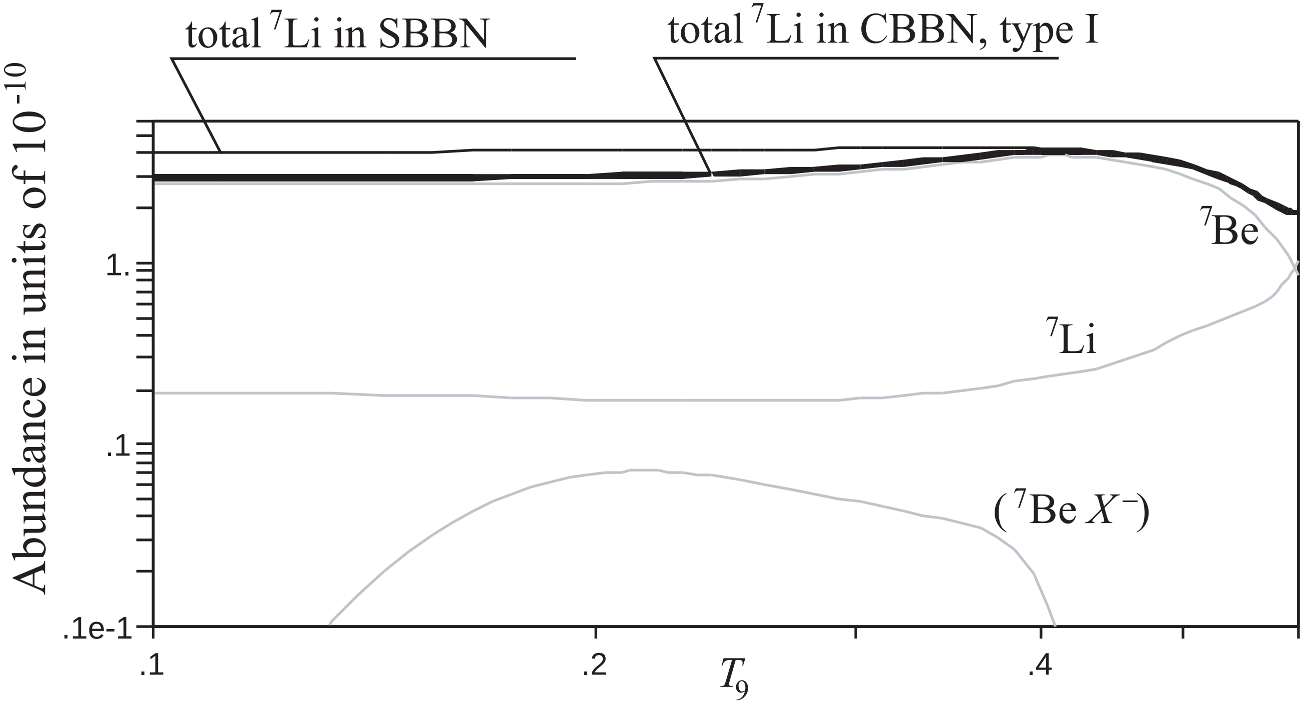
- The "bottleneck" is creation of (^{7}BeX^-) bound states that is controlled by $^7\mathrm{Be}+X^- \to (^7\mathrm{Be}X^-) + \gamma$ reaction
- There are two main destruction channels that are catalyzed:

1. p-reaction: $(^7\mathrm{Be}X^-) + \mathrm{p} \to (^8\mathrm{B}X^-) + \gamma$ by a factor of >1000 relative to $^7\mathrm{Be} + \mathrm{p} \to {}^8\mathrm{B} + \gamma$
2. In models of type II, the "capture" of X^- is catalyzed: $(^7\mathrm{Be}X^-) \to {}^7\mathrm{Li} + X^0$,

so that lifetime of (^{7}BeX^-) becomes $\ll$ 1 sec. ^{7}Li is significantly more fragile and is destroyed by protons "on the spot".

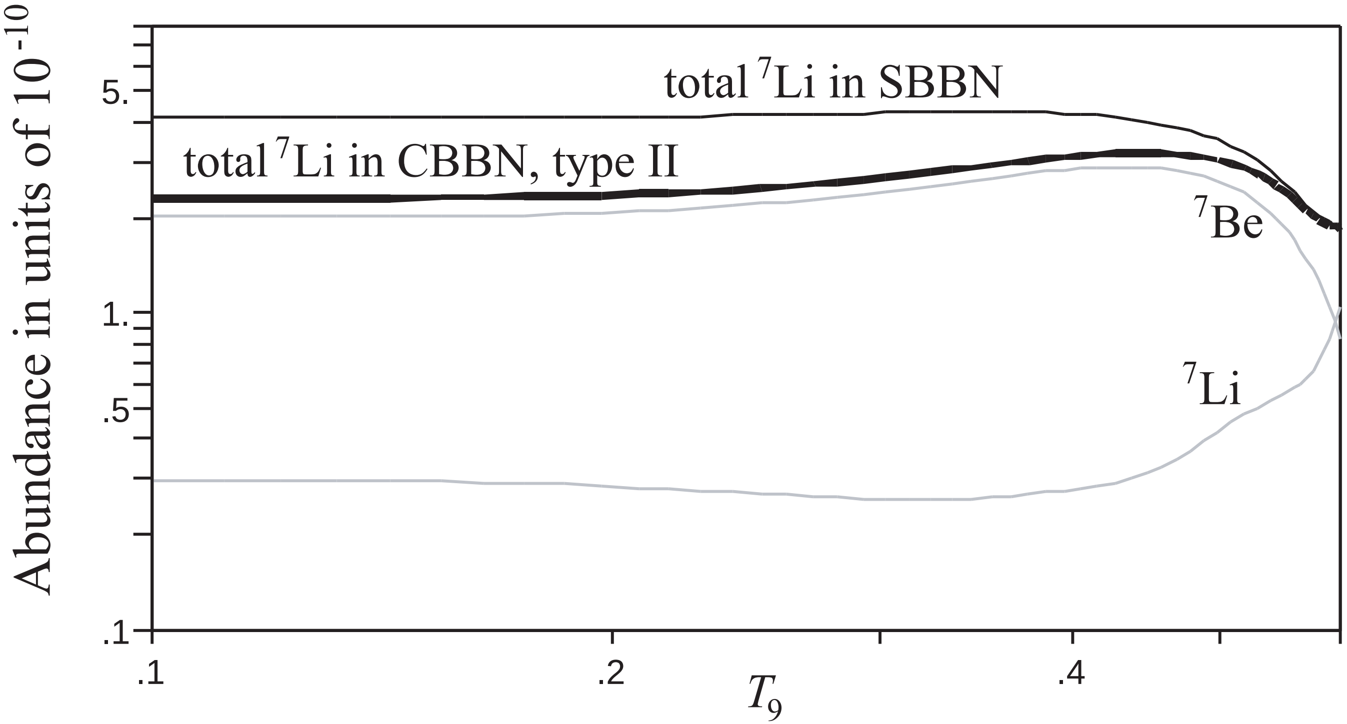
3. There is significant energy injection via $X^+ + X^- \to (X^+X^-) \to$ radiation. If this process has hadronic modes, it also affects Li7.

$^7Be + ^7Li$ at 35 KeV



Type I model (no internal capture), Y_X=0.05, τ=2000s

$^7Be+^7Li$ at 35 KeV



Type II model (fast internal capture),

Y_X=0.05, τ=2000s

Does ^{7}Li Problem have mundane explanation?

1. Abundance of ^{3}He at $T_9 \simeq 0.5$. Seems OK, as it is one-to-one correlated with D. ^{3}He(α,γ)^{7}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%. ^{7}Be(n,p)^{7}Li reaction, the main destruction mechanism. It is known/measured way too well for a factor of 2 error.
2. Previously poorly measured ^{7}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}B *has a resonance at* 200±100 KeV *away from* ^{7}Be+D *threshold, which might be relevant.* (Cyburt, MP, in progress).
3. Stellar Astrophysics. Perhaps most likely reason for the discrepancy(Richard et al., 2005; Korn et al., 2006). More sophisticated stellar models with microscopic model for diffusion and turbulent mixing of ^{7}Li are needed.

The End – Thank you!