Cosmological Constraints on Doubly Charged particles

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In collaboration with Evgeny Akhmedov (Heidelberg),

to appear

Outline of the talk

1. Introduction: exotic metastable particles and ”practical” interest in them.
2. BBN redux. ^{7}Li is “over-predicted” ***cosmological lithium problem***. Different types of constraints on particle physics from BBN.
3. *Last 10 years of developments*. Planck results; new accuracy for D/H (?); no ^{6}Li. Arguments in favor of new limits on ^{6}Li from interstellar abundance.
4. BBN catalysis by the doubly charged particles, enhancement of Li/Be/B production.
5. Conclusions

Interest in metastable charged particles

1. During high hopes for supersymmetric models, a model with next-to lightest SUSY particle (NLSP) with a charge (e.g. scalar electron or scalar tau), and lightest SUSY particle gravitino was very popular. Scalar lepton → gravitino decay is delayed, leading to the consequence for light elements (BBN).

2. Speculation about dark matter in form of bound states with Helium. Belotsky, Khlopov et al., ($^4HeX^{--}$) is a neutral particle that can be hidden dark matter.

Interest in metastable charged particles

3. Last two years, the LHC (ATLAS) had claims of abnormal tracks consistent (2205.06013) with the highly ionizing particle tracks of metastable heavy particles. And in particular consistent with Q = 2. (Giudice, McCullough, Teresi, 2205.0473)

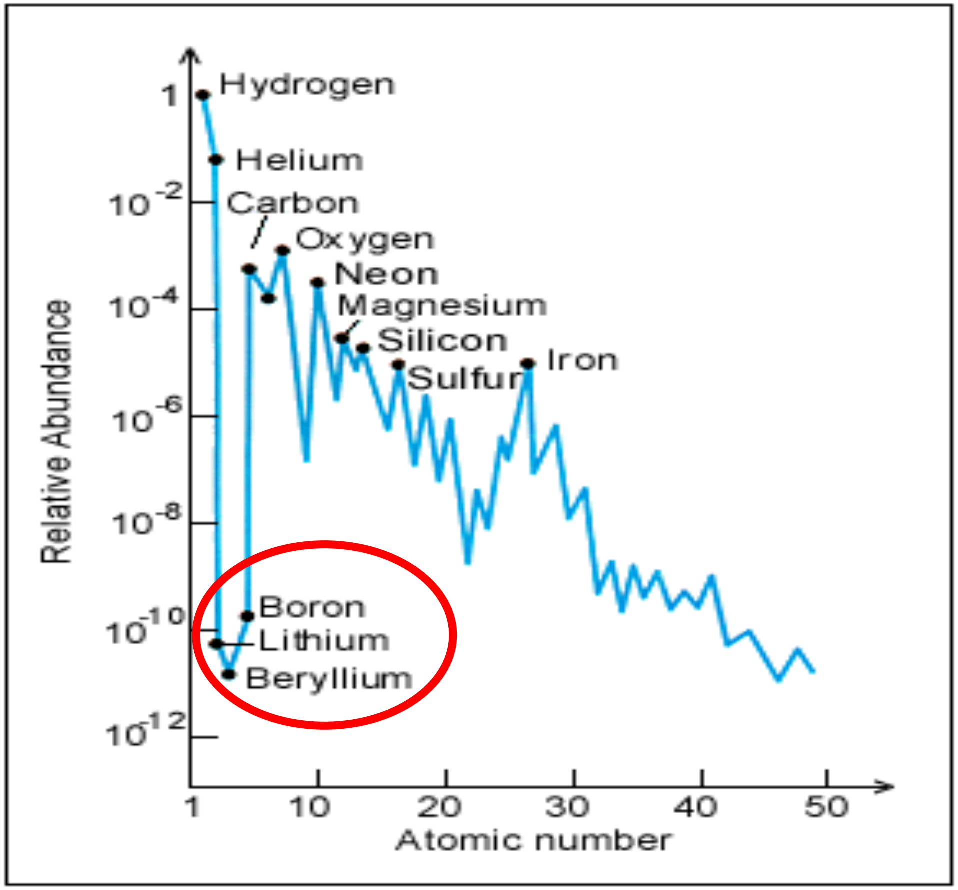
4. Finally, Evgeny Akhmedov argues (2109.13960) that X^{--} particles – should they be somehow obtained and trapped in a lab (either obtained via LHC or somehow extracted from the environments) – will be able to catalyze thermonuclear reactions (c.f. muon catalysis) and have a positive balance in terms of the energy obtained vs spent (unlike the muon catalysis).

Long-lived heavy charged particles will definitely have an impact on the Big Bang Nucleosynthesis and will be tightly constrained.

What are these constraints?

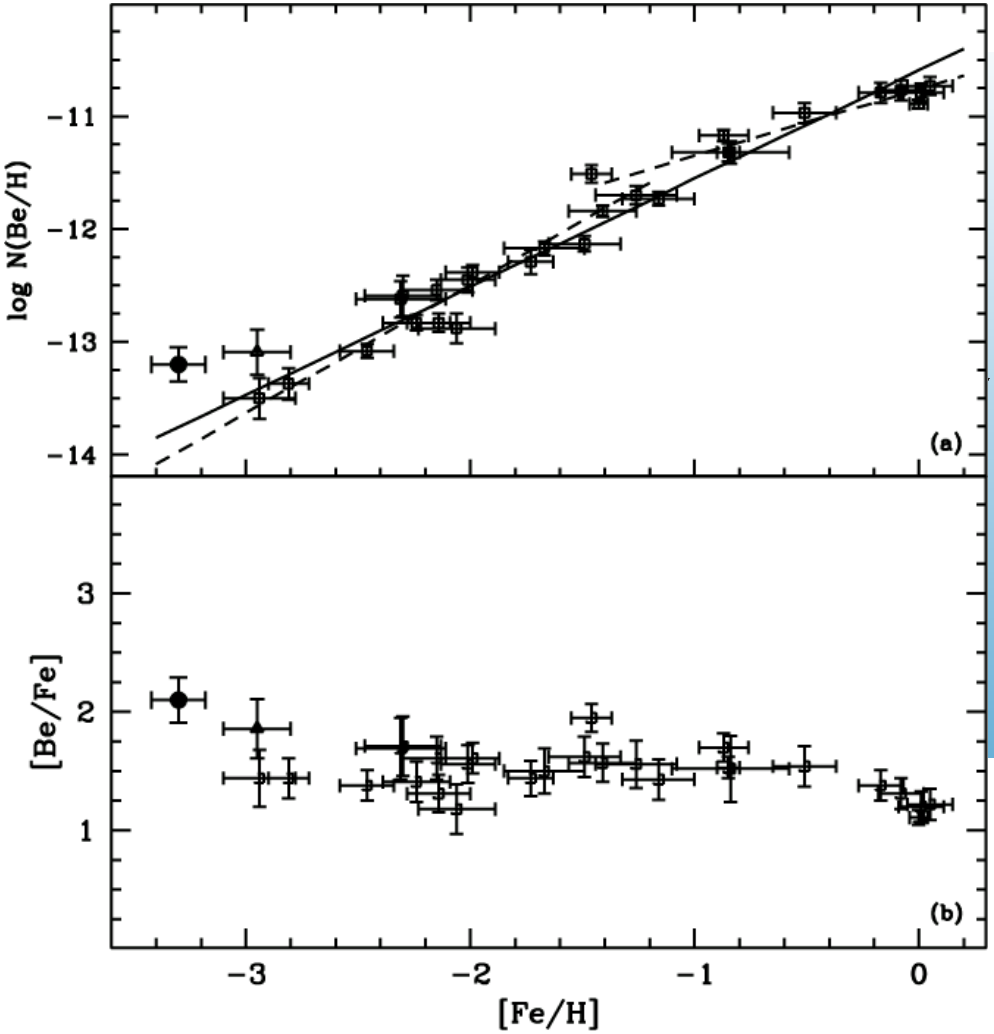
Given prior experience (MP 2006) with BBN catalysis by singly charged particles, we know that the main constraints will come from the catalysis of the Lithium chain.

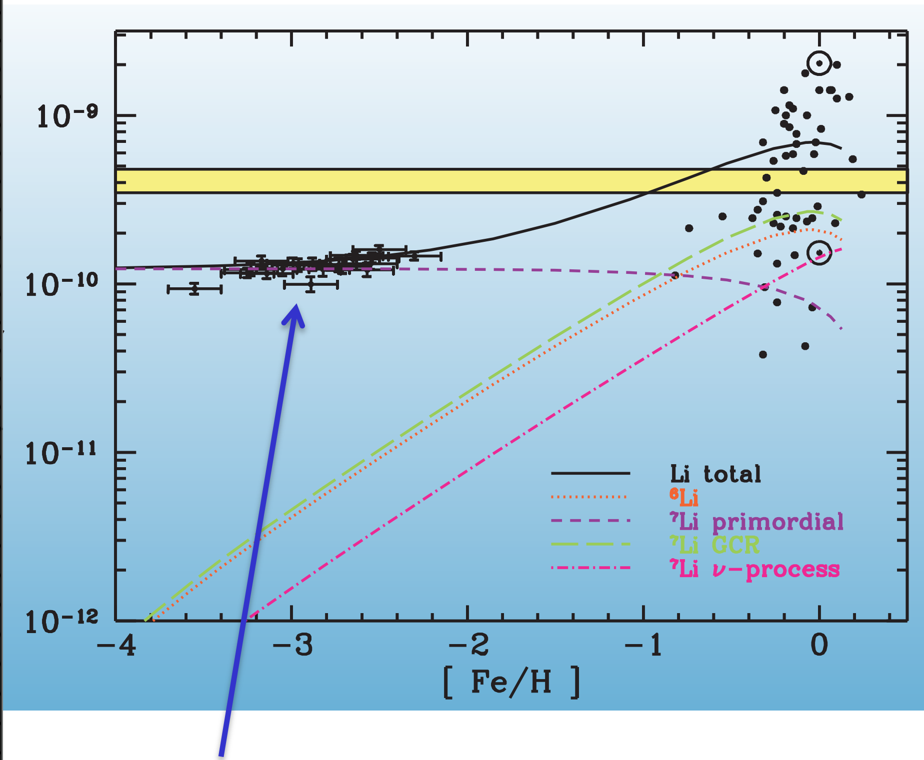
Lithium is a fragile element, difficult to produce and easy to destroy



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

>30 yr since the F. and M. Spite discovery of ^{7}Li plateau in Population II stars

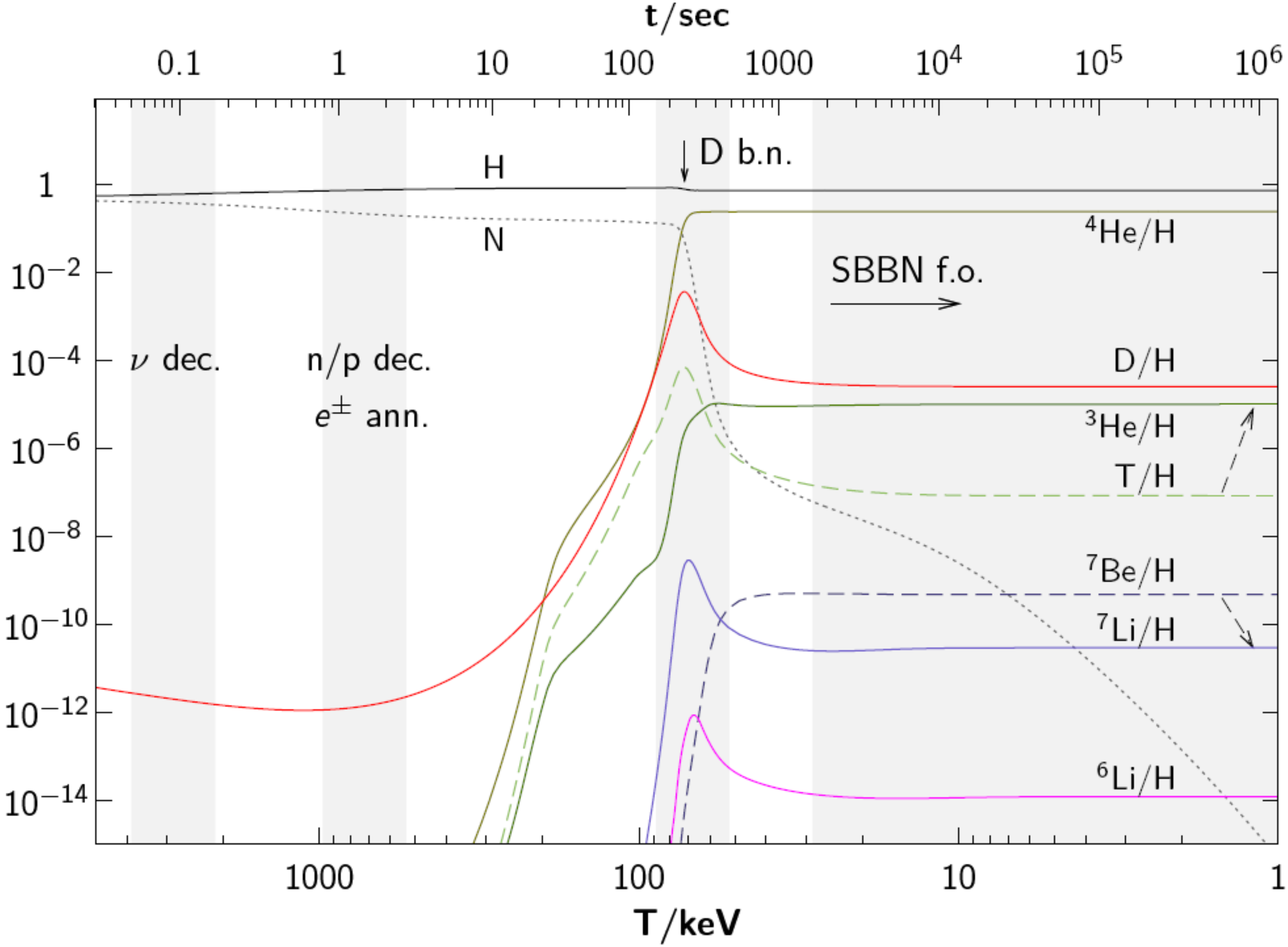




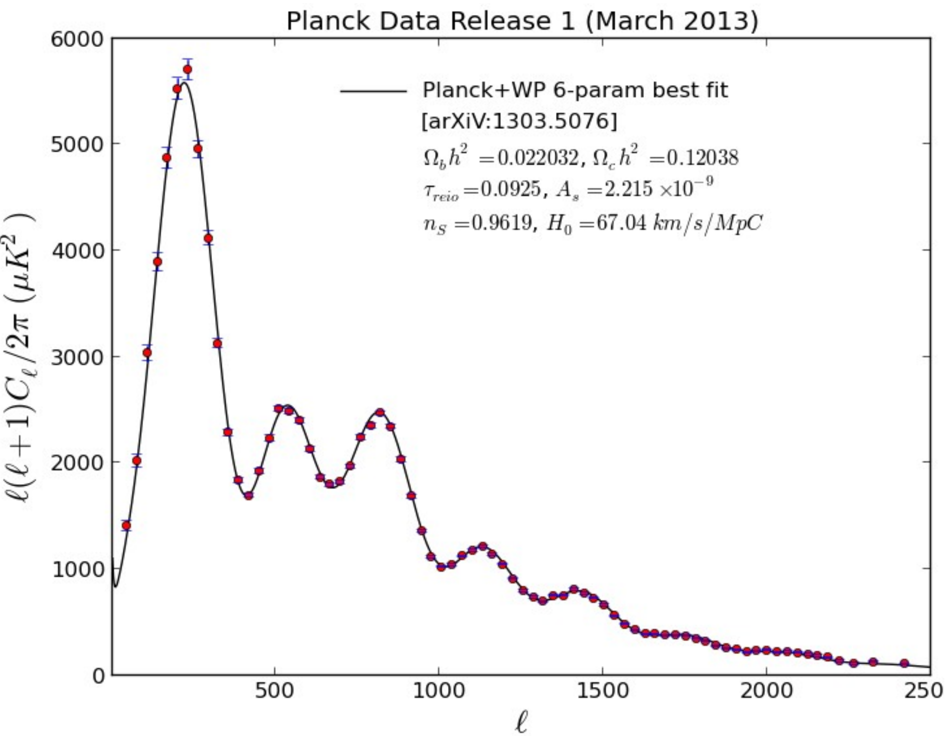
Spite plateau (Ryan et al)

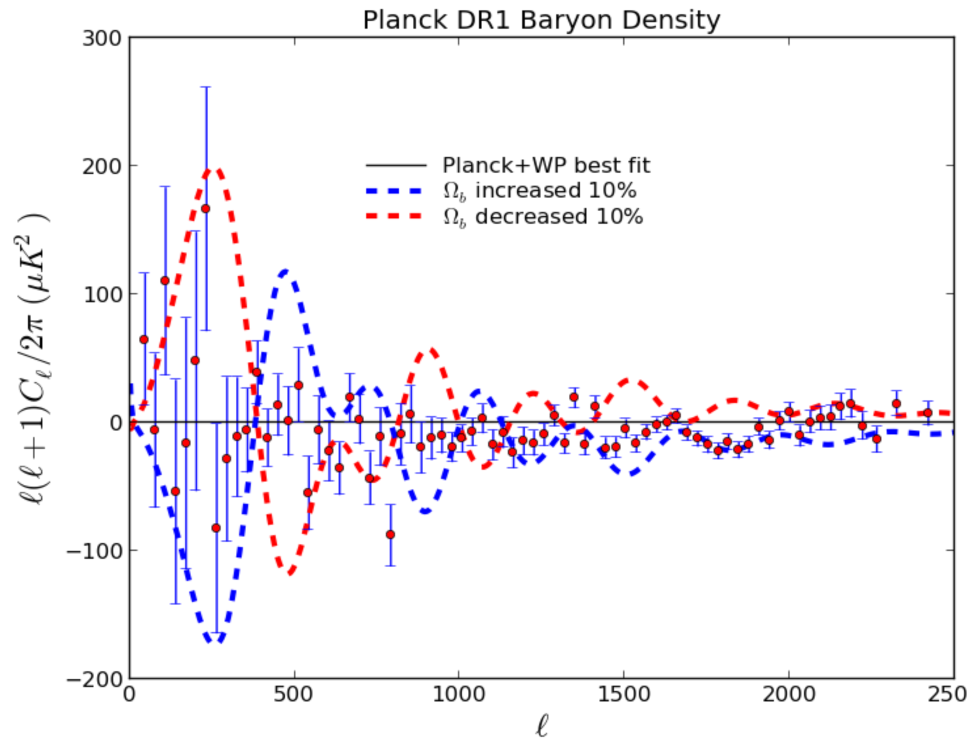
^{7}Li exhibits a "plateau" with low dispersion – indicator or BBN value

BBN abundances at η_{CMB}



CMB data give precise value of eta_baryon





Parameter	Value (68%)
$\Omega_b h^2$	0.02207±0.00027
$\Omega_c h^2$	0.1198±0.0026 (is it high?)
$100\theta_*$ (acoustic scale at recombination)	1.04148±0.00062 (~ 500 parts per million accuracy)
τ	0.091±0.014 (WMAP seeded)
$\ln(10^{10}A_s)$	3.090±0.025
n_s	0.9585±0.0070 (<1 at > 5 σ)

Parameter	Value (95%)
Ω_K	-0.0005±0.006
$\Sigma\, m_\nu$ (eV)	<0.23
N_{eff}	3.30±0.54
Y_P	0.267±0.040

BBN is very simple… One free parameter $\eta = n_b/n_\gamma$

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

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

Li abundance *can be easily calculated as a separate small exercise* using He(T), n(T) and main reactions, which are:

^{3}He+α → ^{7}Be + γ - IN.

^{7}Be +n → p +^{7}Li – OUT, (followed by ^{7}Li+p → 2α)

The main observable is ^{7}Li + ^{7}Be, and the lithium-7 problem is basically "too much beryllium-7".

Why particle theorists love BBN

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

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

Particle theorists love it because it is sensitive to New Physics

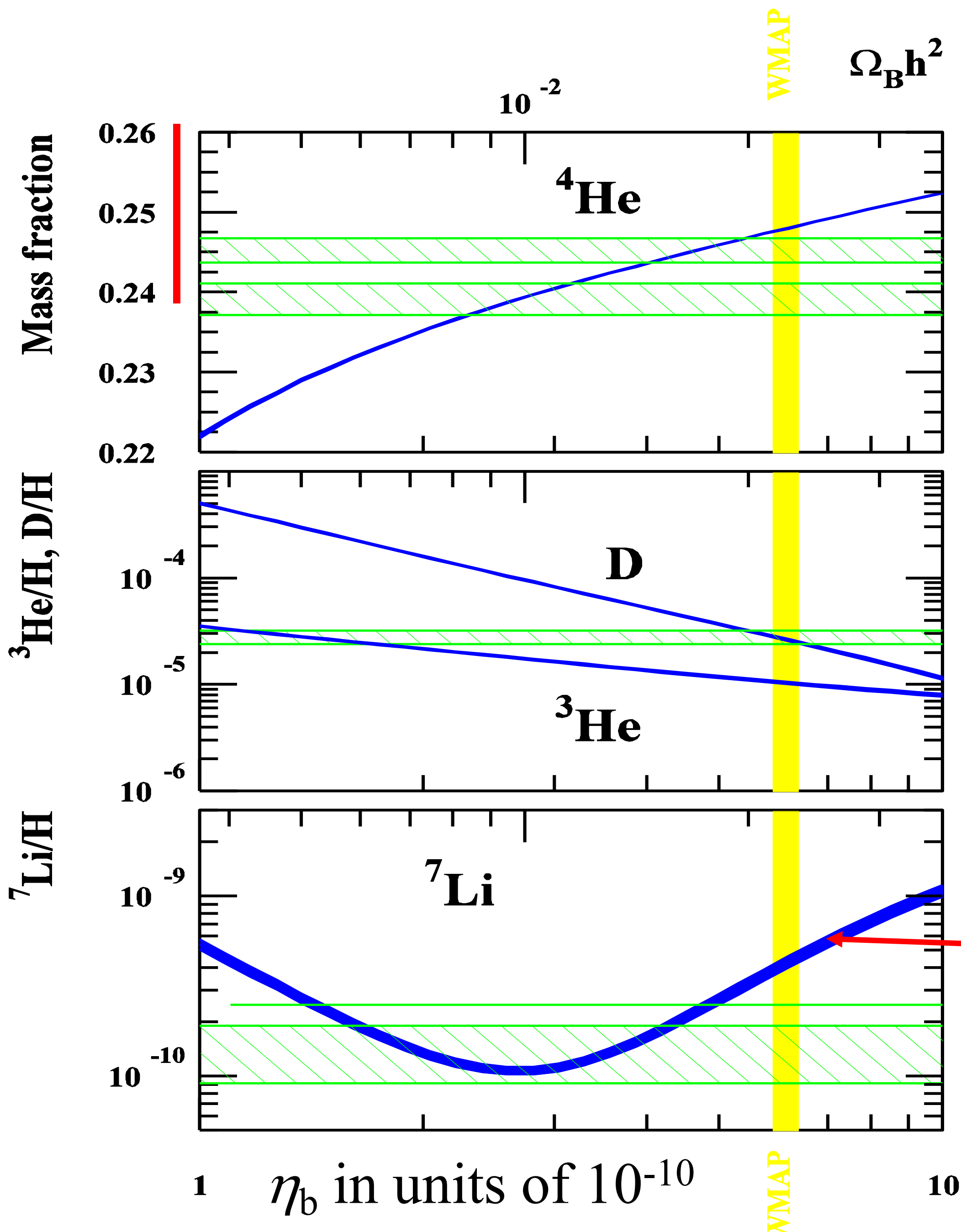
1. Affect the timing of reactions,

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

via e.g. new thermal degrees of freedom or via changing couplings.

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

2003 Status after WMAP I



Blue lines: theoretical predictions of abundances as functions of η_b

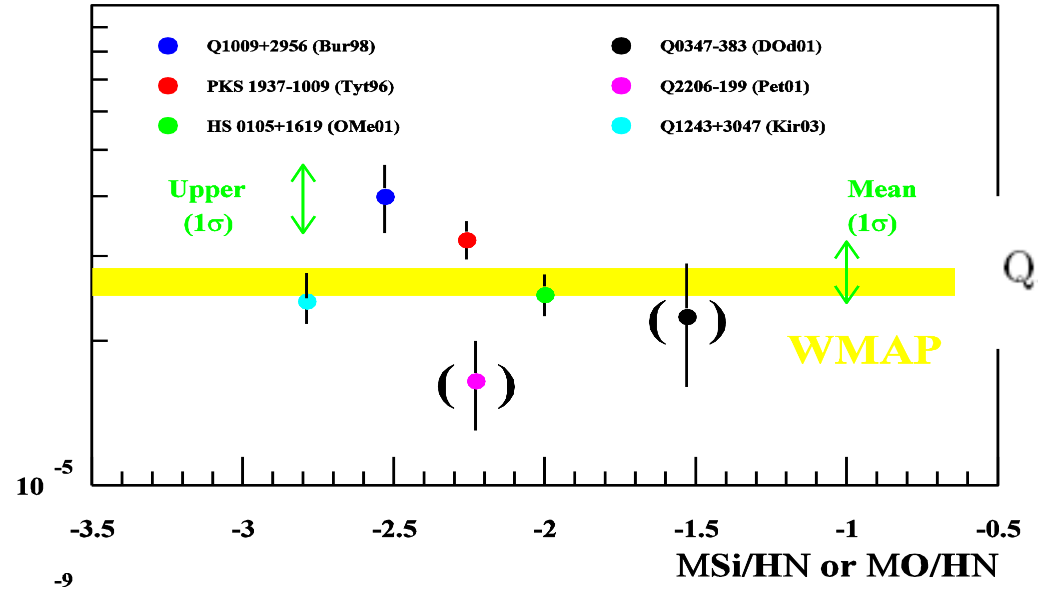
Green bands: observational values for primordial abundances of ^{4}He, D, and ^{7}Li

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

^{7}Be branch

Coc et al, ApJ 2004

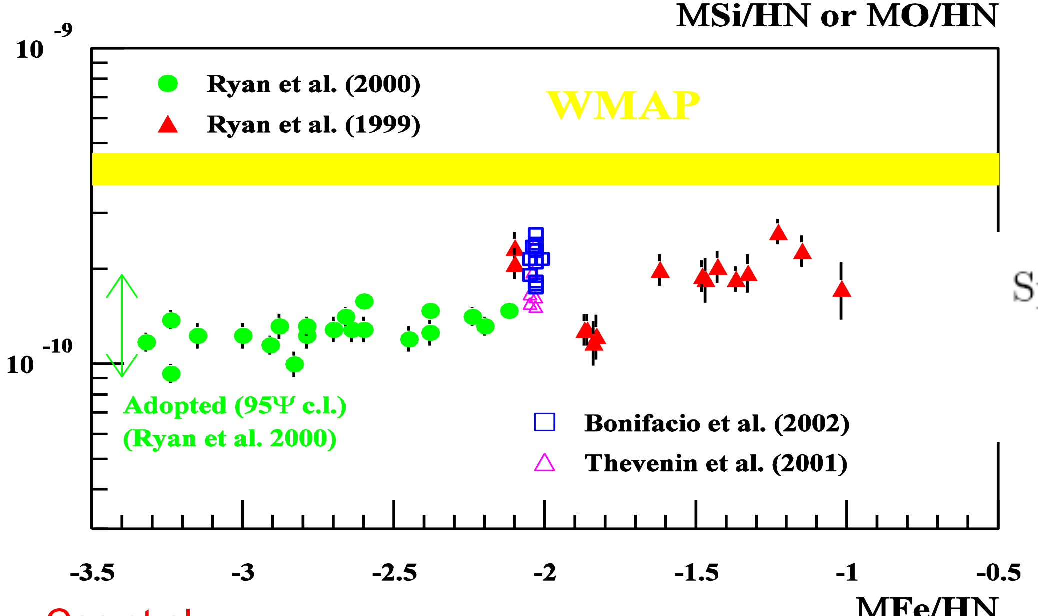
Old status of standard BBN with CMB input (η=6.2 10^{-10})



$$\text{SBBN}: \quad D/H = 2.49 \pm 0.17 \times 10^{-5}$$

$$\text{QALS observations}: \quad \frac{D}{H} = (2.82 \pm 0.21) \times 10^{-5}.$$

Deuterium seems OK, (but large scatter)



$$\text{Spite plateau value}: \quad \frac{^7\text{Li}}{\text{H}} = 1.23^{+0.34}_{-0.16} \times 10^{-10}$$

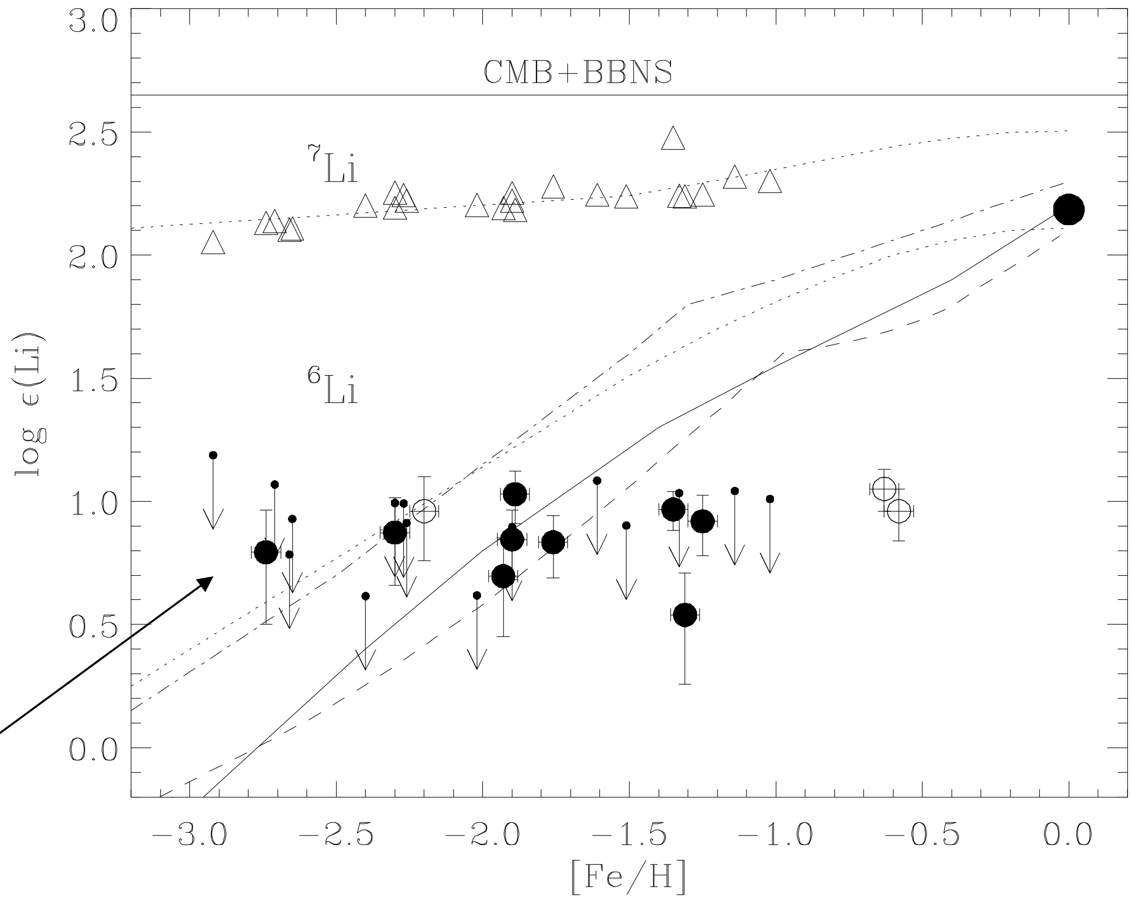
$$\text{BBN theory}: \quad \frac{^7\text{Li}}{\text{H}} = 5.24^{+0.71}_{-0.67} \times 10^{-10}$$

Huge “lithium deficiency”

Lithium problem !!

Coc et al, ApJ 2005

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

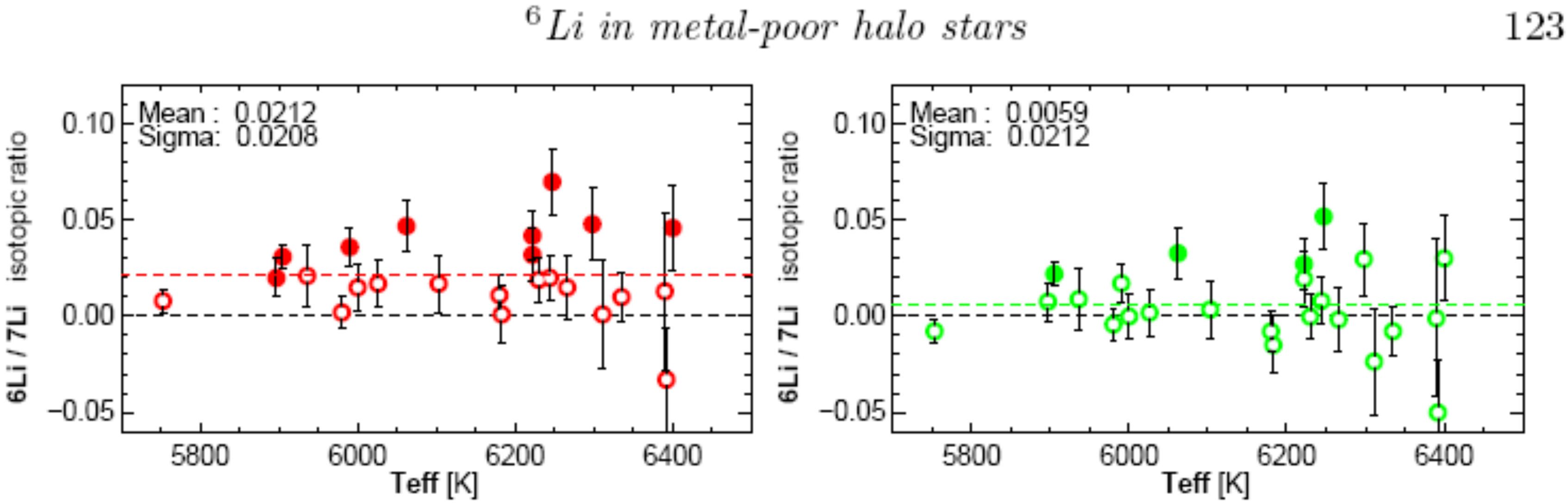


^{6}Li/H ~ 10^{-11}

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

Claim is challenged in Cayrel et al, 2007. *Unlikely a problem at this point*

Existence of ^{6}Li plateau is challenged



Cayrel et al, 2009 concludes that ^{6}Li>0 in only 4 stars.

Asplund replies (2010): "…In summary, it is not yet possible to say that ^{6}Li has definitely been detected but it is definitely too early to say that ^{6}Li has not been detected…"

May be lithium problem(s) pose an interesting puzzle, but at this point cannot be over-dramatized. ^{6}Li is probably an artifact of line fitting… Over-production of ^{7}Li can possibly be corrected by stars themselves. Intriguingly, both isotopes can be indication on new physics, especially ^{6}Li.

1991 review

PRIMORDIAL NUCLEOSYNTHESIS REDUX

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ABSTRACT

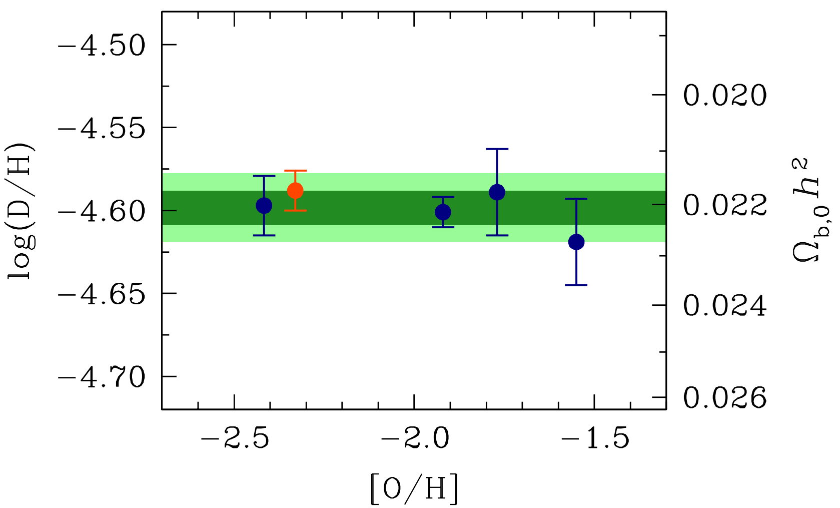
The latest nuclear reaction cross sections (including the most recent determinations of the neutron lifetime) are used to recalculate the abundances of deuterium, ^{3}He, ^{4}He, and ^{7}Li within the framework of primordial nucleosynthesis in the standard (homogeneous and isotropic) hot, big bang model. The observational data leading to estimates of (or bounds to) the primordial abundances of the light elements is reviewed with an emphasis on ^{7}Li and ^{4}He. A comparison between theory and observation reveals the consistency of the predictions of the standard model and leads to bounds to the nucleon-to-photon ratio, $2.8 \leq \eta_{10} \leq 4.0$ ($\eta_{10} \equiv 10^{10} n_B/n_\gamma$), which constrains the baryon density parameter, $\Omega_B h_{50}^2 = 0.05 \pm 0.01$ (the Hubble parameter is $H_0 = 50 h_{50}$ km s^{-1} Mpc^{-1}). These bounds imply that the bulk of the baryons in the universe are *dark* if $\Omega_{TOT} = 1$ and would require that the universe be dominated by nonbaryonic matter. An upper bound to the primordial mass fraction of ^{4}He, $Y_p \leq 0.240$, constrains the number of light (equivalent) neutrinos to $N_\nu \leq 3.3$, in excellent agreement with the LEP and SLC collider results. Alternatively, for $N_\nu = 3$, we bound the predicted primordial abundance of ^{4}He: $0.236 \leq Y_p \leq 0.243$ (for $882 \leq \tau_n \leq 896$ s).

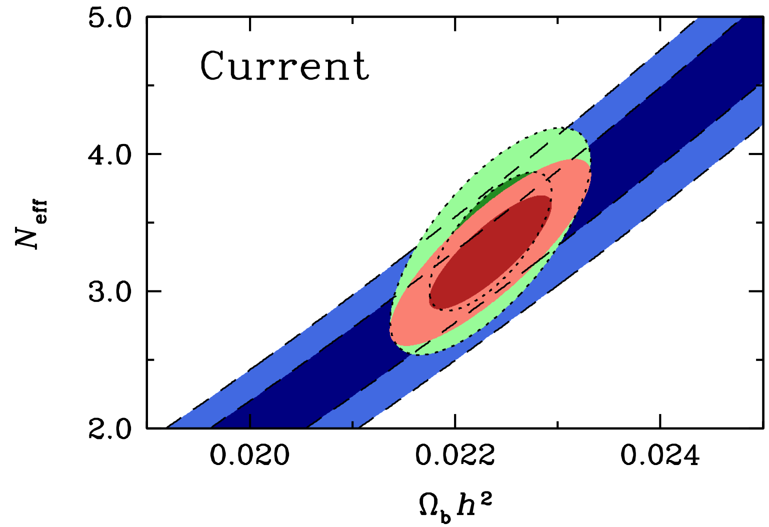
Subject headings: abundances — early universe — elementary particles — nucleosynthesis

Current value $\eta_{10} = 6.1$ is well outside the "BBN range of 1991" 2.8-4.0. *At that time particle physicists did take ^{7}Li seriously.*

Last 10yr developments (Planck etc)

- Planck re-measures most of the cosmological parameters, but there is no drastic change in η compared to WMAP/SPT/ACT.
- Planck determines helium abundance Y_p. Accuracy approaches 10%.
- Cooke et al (2013) claim better accuracy and less scatter for the re-evaluated observational abundance of D/H. Perfect agreement, it seems!

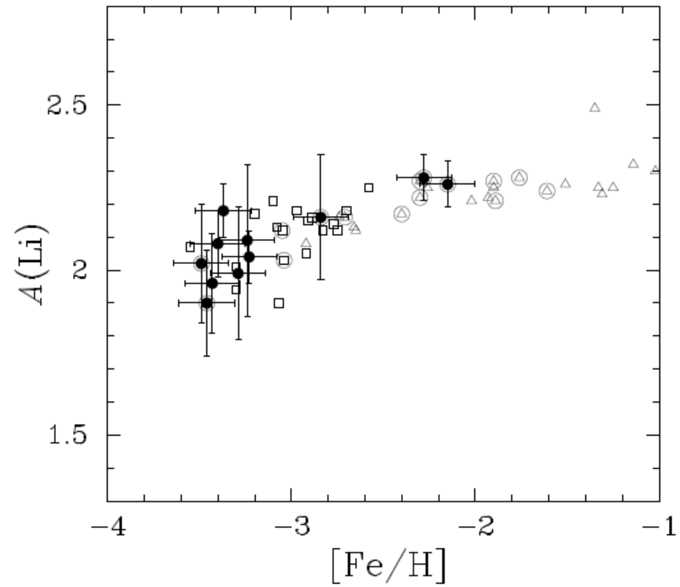


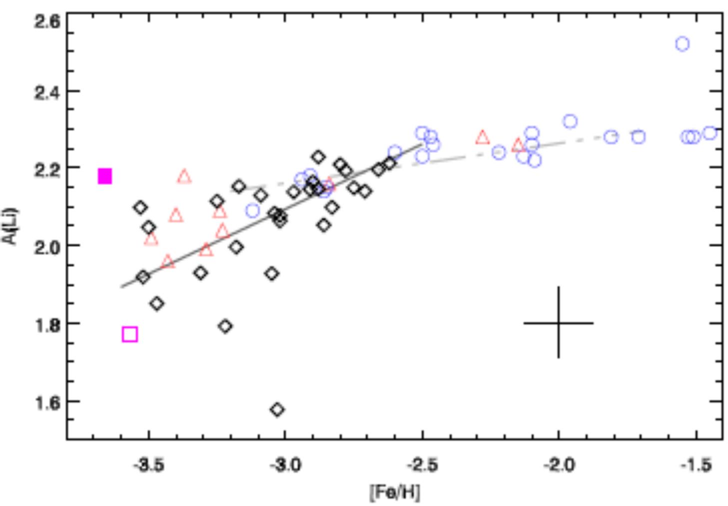


- With latest results, no evidence of ^{6}Li in the stellar atmospheres.
- Only ^{7}Li remains a problem.

Recent observations are *confusing*. ^{7}Li story is even more complicated than anyone thought

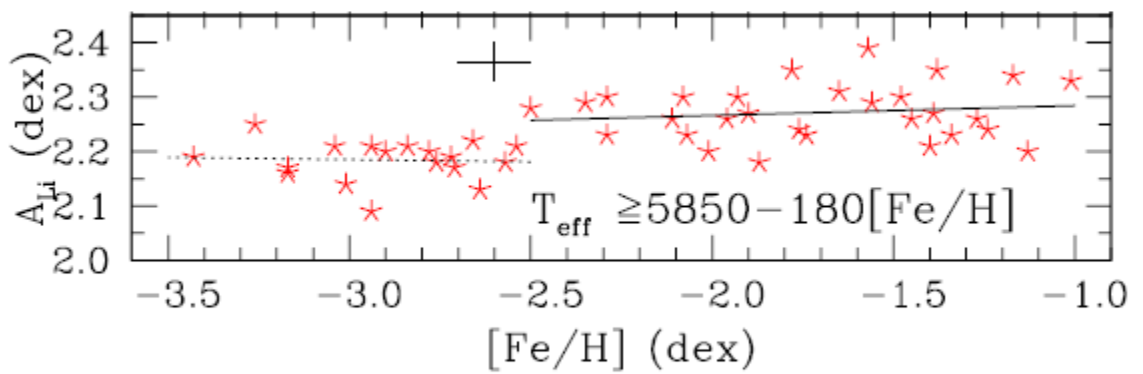
Aoki et al, 2009, reports the suppression of low-metallicity tail of Spite plateau



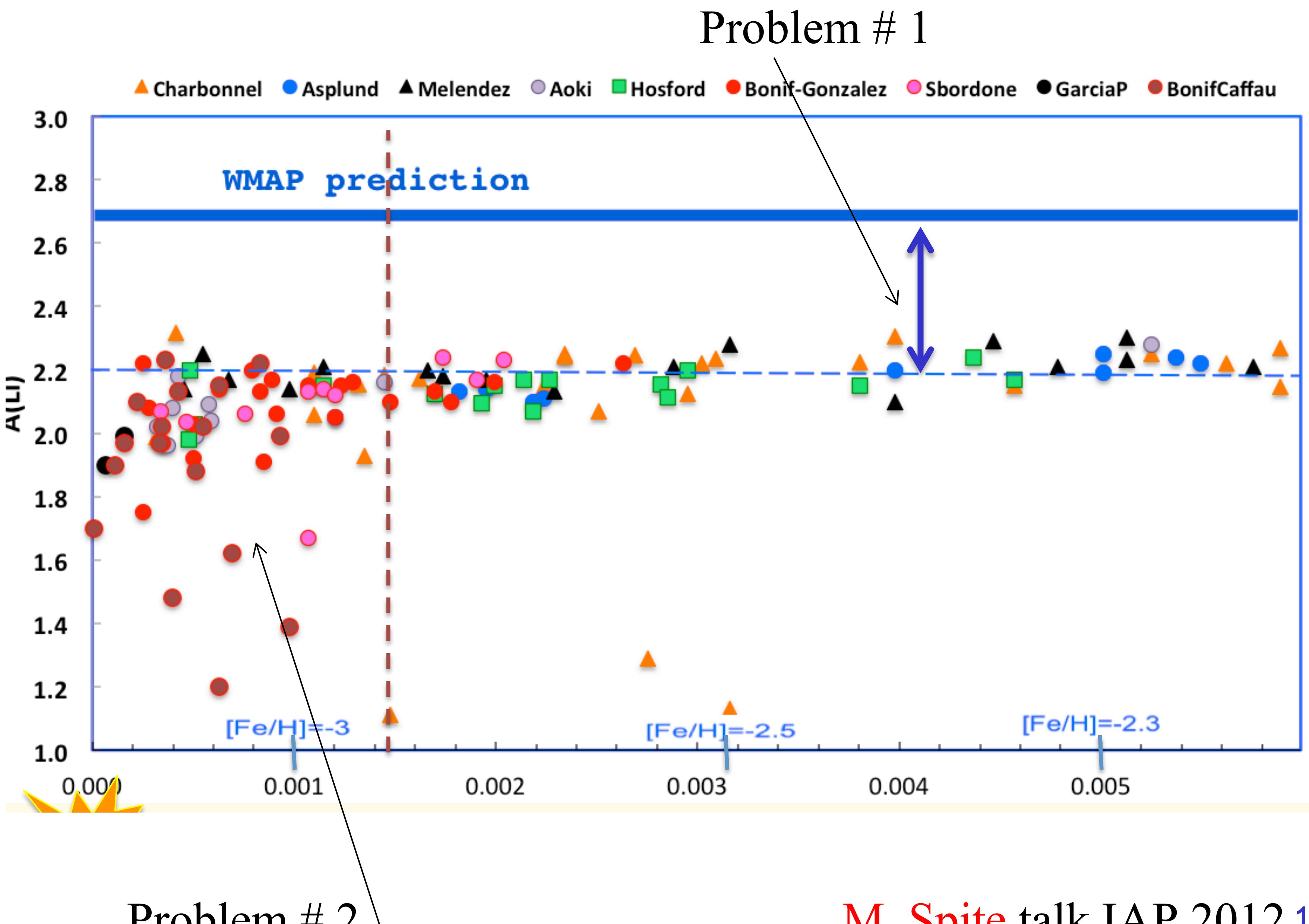


Sbordone et al, 2010, confirms it with higher statistics

Melendez et al, 2010, argues that there are two Spite plateaus



More than one problem with ^{7}Li?



M. Spite talk IAP 2012

Ways the ^{7}Li problem can be resolved

- *Nuclear:*

  May be SBBN prediction is somehow not correct. Some subdominant but poorly known reactions play a role?

- *Astrophysical:*

  Depletion of lithium along Spite plateau is ~ 3 – 5.

- *Particle physics:*

  Decays of heavy relics can reduce ^{7}Li.

  ^{7}Li can also be destroyed in catalyzed reactions.

- *Cosmological:*

  ^{7}Li is measured *locally*, while D and especially baryon-to-photon ratio *globally*. If there is a downward fluctuation of baryon density in proto-Milky Way region, local ^{7}Li/H can be smaller.

Ways the ^{7}Li problem can be resolved

- *Nuclear:* ← **Ruled out recently including hidden resonances**

  May be SBBN prediction is somehow not correct. Some subdominant but poorly known reactions play a role?
- *Astrophysical:* ← **Definitely can alleviate Li problem *at least partially. What is the primordial value range then??***

  Depletion of lithium needed along Spite plateau is ~ 3 – 5.
- *Particle physics:*

  Decays of heavy relics can reduce ^{7}Li. ^{7}Li can also be destroyed in catalyzed reactions. **Energy injection models are ruled out by D/H**
- *Cosmological:*

  ^{7}Li is measured *locally*, while D and especially baryon-to-photon ratio *globally*. If there is a downward fluctuation of baryon density in proto-Milky Way region, local ^{7}Li/H can be smaller. **Implies that we live precisely placed inside large underdense region of Universe.**

Extra neutrons from particle physics reduce ^{7}Be

^{3}He+α → ^{7}Be + γ - IN.

^{7}Be + n → p + ^{7}Li – OUT, (followed by ^{7}Li+p → 2α)

Addition of O(10^{-5}) neutrons per proton at T~40 keV accelerates burning of ^{7}Be. It does not matter how you generate extra neutrons (particle decays, annihilation etc). (Reno, Seckel; Jedamzik; Kohri et al.). This mechanism is sensitive to hadronic fraction of decays/annihilation.

Candidates: scalar lepton NLSP → gravitino LSP decays (many studies); gravitino decays; R-parity violating decays; super-WIMP decays… You can have arbitrarily many models that do that. They *may or may not* have associated collider signatures.

Is extra-neutron triggered reduction of ^{7}Li consistent with D/H?

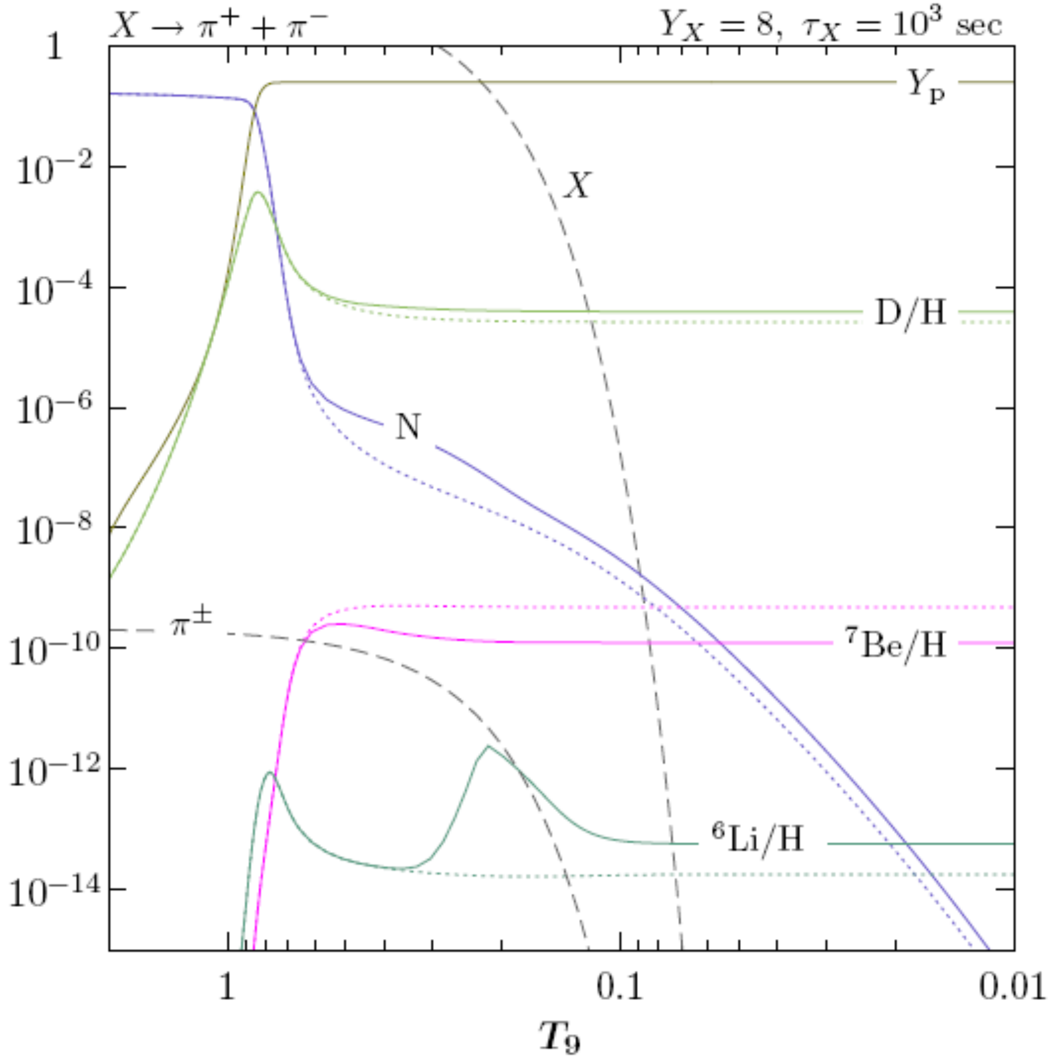
No (Shown in Coc, MP, Vangioni, Uzan)

This can be shown by scanning over all possible different physical methods of particle injection:

1. Neutrons from decays
2. Neutrons from annihilations, including resonant annihilation
3. Neutrons from oscillations from mirror sector

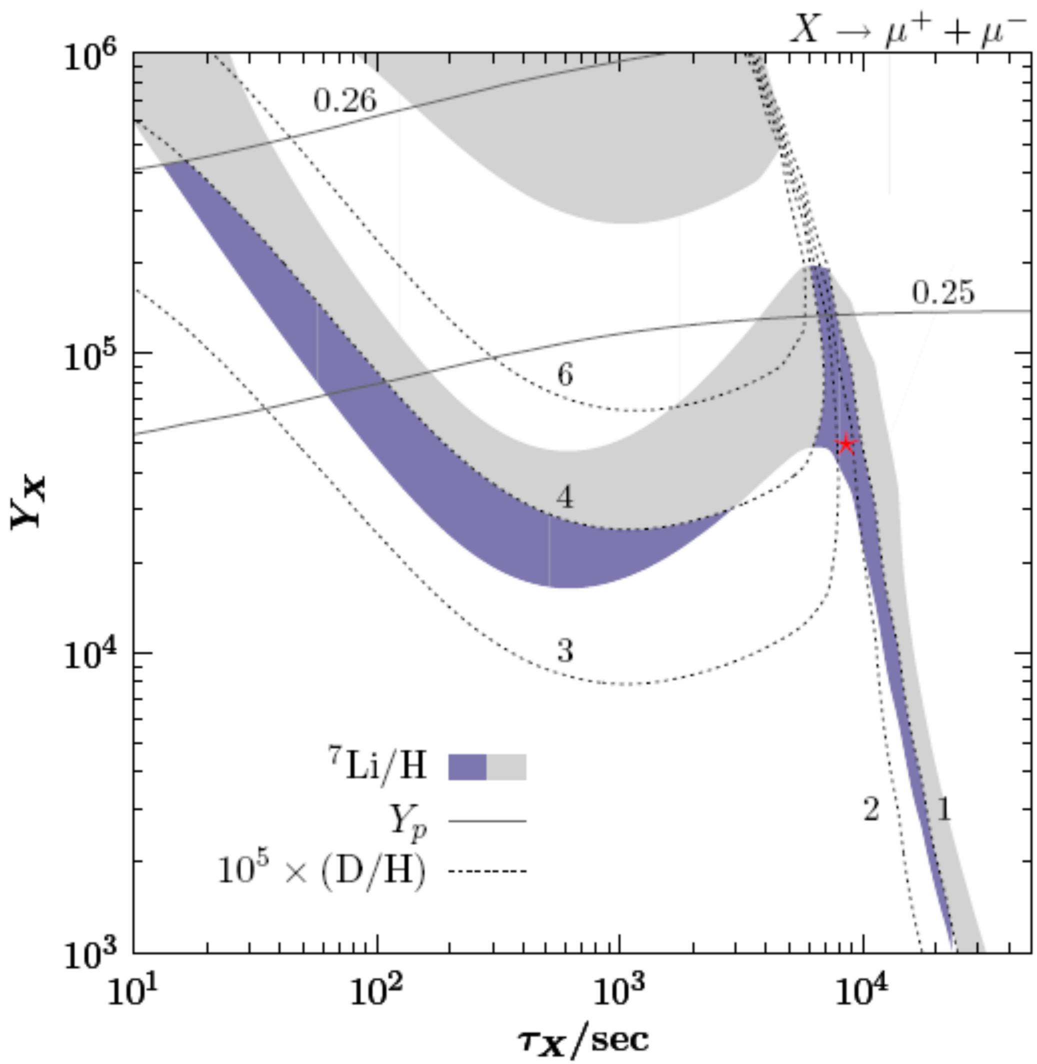
…..

Time evolution of abundances in nBBN



Most of the models of neutron injection are disfavored because of elevated D/H. (Coc, MP, Vagioni, Uzan, 2014;).

μBBN or νBBN (μ decay; ν+p→ n+e, + extra radiation)



Extra region at lifetime ~3hr. Energy injection corrects D/H back to SBBN

Decaying particles and Li problem

- *Straight decay into radiation do not work* because reduction of ^{7}Li also leads to reduction of D/H. (Unless "exactly" 2 MeV particle)
- *Neutron injection (decays, annihilation etc)* at t~ 500 sec for a long time thought to be a solution – *not anymore*. D/H > 3.6 10^{-5}, while observations give 2.5 10^{-5} in agreement with SBBN.
- *Combination of EM energy injection and neutrino injection* (e.g. from unstables particles decaying to muons) *can do the job*. Extra energetic neutrinos produce a conversion of some protons to neutrons, reducing Li and elevating D, but D gets destroyed by e at 10000sec. Lifetime of "X" is ~ 10^4 sec.

Astrophysical solutions

- *Most reasonable assumption is that Lithium diffuses out of photosphere/gets destroyed.*

- Some evidence corroborating this is provided by efficient destruction of $^6Li/H$ that is currently observed less than the cosmic ray models typically predict (see Fields, Olive, 2204.03167).

- Constraints on abnormally produced ^6Li can be derived from observation of ^6Li in Milky Way and SMC in the interstellar medium. Simultaneous presence of ^6Li and D proves that the material was not 100% recycled in stars. This allows to deduce the upper bound $\mathbf{^7Li/H < 10^{-9}}$ $\mathbf{^6Li/H < 2*10^{-10}}$. (Akhmedov, MP, in prep)

Catalyzed BBN

- Negatively charged X forms bound states (HeX) with helium via (α,gamma) reactions. Reacting twice, can also form (^{8}BeX).

- (He X) reacts with subdominant species such as D, ^{3}He, to form lithium 6 and 7, in a *photon-less* reaction

- Traces of Boron are also generated via the reaction with ^{7}Be.

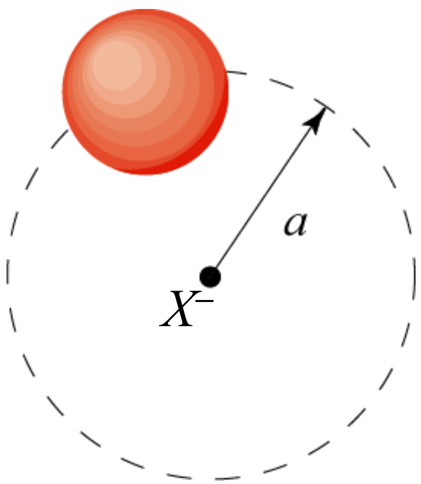
- Main goal is to derive CBBN yield, Li/Be/B per X-particle, which then allows to constrain X/baryons.

Catalyzed BBN: bound states of X⁻ with nuclei

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

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

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



$(^4\mathrm{He}X^-)$

Bohr radius is 2 times larger than nuclear

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

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

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

$(^7\mathrm{Be}X^-)$

Bohr orbit is within nuclear radius

Binding energies for doubly charged particles

Table 1: Bound state energies for (NX^{--})

Nucleus N	r.m.s. charge radius in fm	Binding energy in MeV
^{4}He	1.67	1.156
^{5}Li	2.6	2.15
^{8}Be	2.5	3.40
^{9}B	2.5	4.61

Conclusions:

- Binding energies with Helium are ~ factor of 2 less than the binding energy of deuteron → expect a new bottleneck at 80 keV/2 = 40 keV
- A=5 elements are not stable (^{5}LiX) decays to (^{4}HeX) and *p*.
- ^{8}Be and ^{9}B are stabilized when attached to a massive negative X.

Reactions leading to bound states

$$
\begin{aligned}
{}^4\mathrm{He} + X^{--} &\to ({}^4\mathrm{He}X^{--}) + \gamma, \quad Q = 1.15\,\mathrm{MeV} \\
({}^4\mathrm{He}X^{--}) +^4 \mathrm{He} &\to ({}^8\mathrm{Be}X^{--}) + \gamma, \quad Q = 2.25\,\mathrm{MeV} \\
({}^8\mathrm{Be}X^{--}) + p &\to ({}^9\mathrm{B}X^{--}) + \gamma, \quad Q = 1.0\,\mathrm{MeV}
\end{aligned}
$$

- First reaction is calculable without nuclear physics involved, similar to textbook calculations.
- The resonant part of second reaction (to n=3,l=0 state of BeX) can be calculated with minimal nuclear uncertainties.
- Non-resonant part, E1 transition to n=2,l=1 state, can be calculated using α-cluster model for Be wave function. Somewhat less precise estimates can be done for (^{9}BX)
- Reactions leading to (BeX) and (BX) are very important because they reduce catalyzed yields by hiding X behind the Coulomb barrier.

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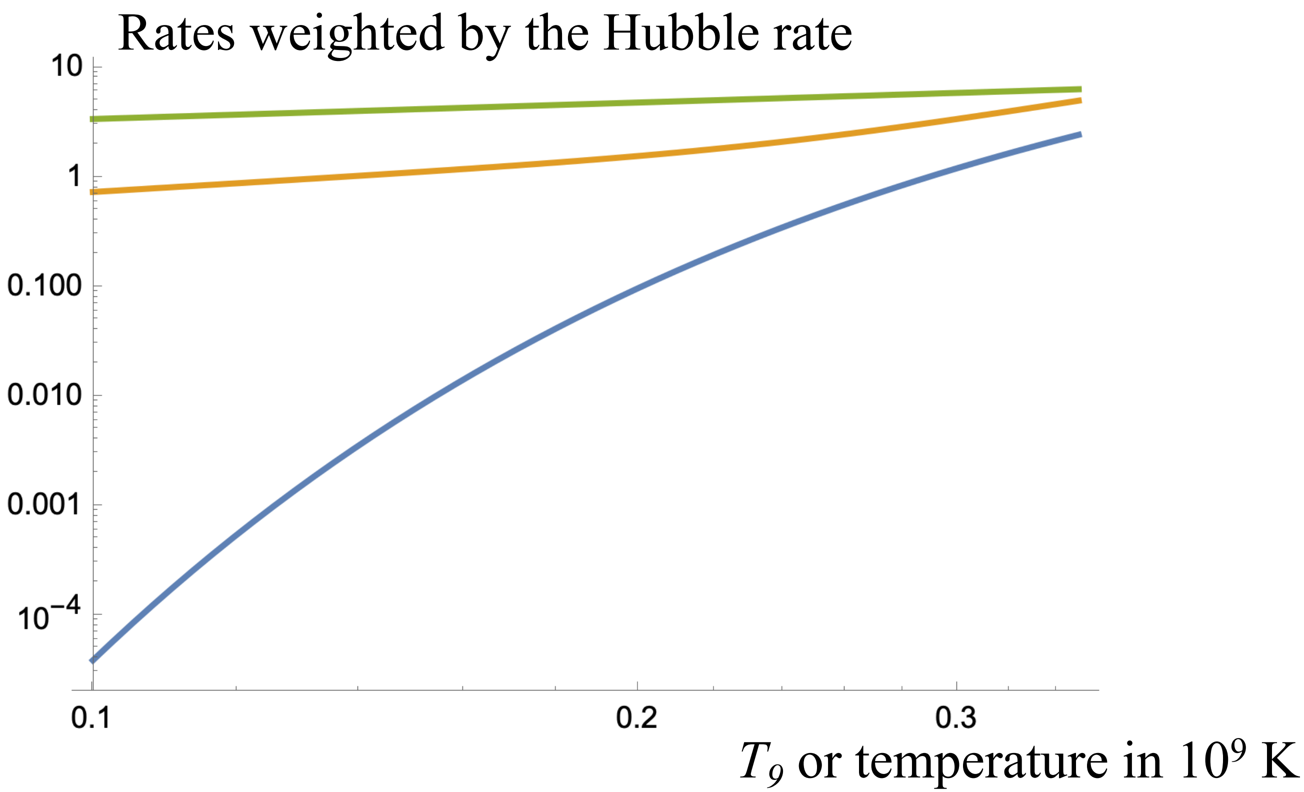
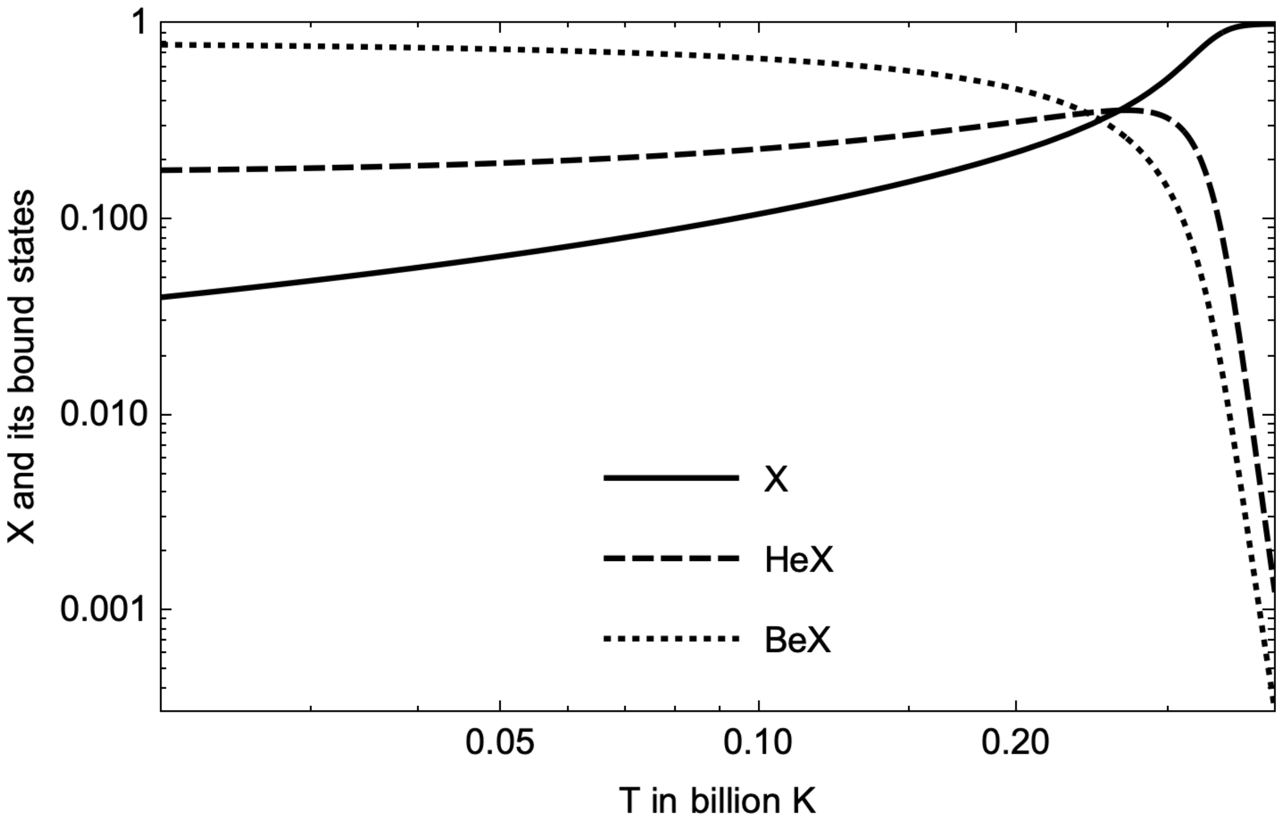
Reactions leading to bound states



- Green: Formation of (HeX), stays above 1 at all times.
- Blue: Resonant rate to (BeX), drops quickly with T.
- Yellow: Total rate to (BeX), stays above 1 for T > 0.2

Bound state yield per X particle



- Nearly 100% of X will be consumed by bound states.
- Dominant component will be BeX, with 80% yield, while HeX is also present in large numbers, 20%.

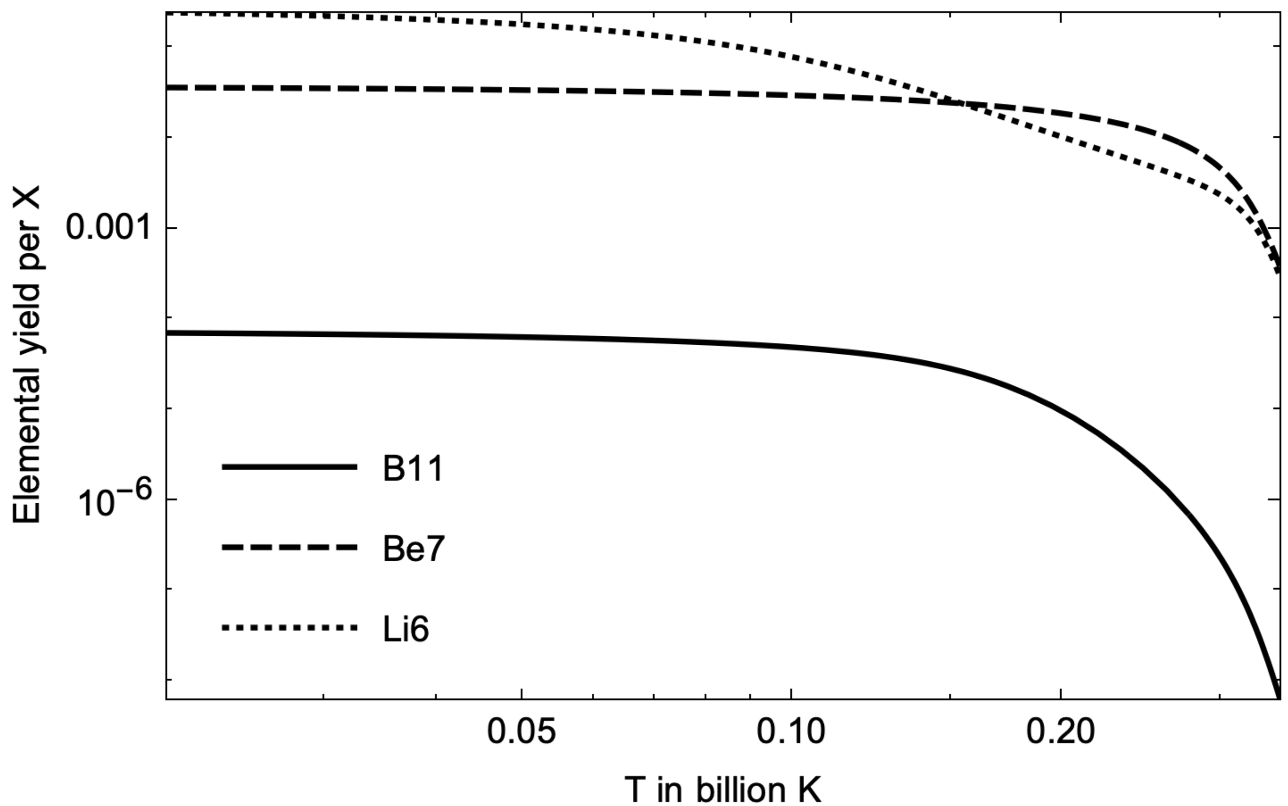
Catalyzed reactions

$$({}^4\text{He}X^{--}) + \text{D} \to X^{--} + {}^6\text{Li}, \quad Q = 0.31\,\text{MeV} \quad (1)$$
$$({}^4\text{He}X^{--}) + \text{T} \to X^{--} + {}^7\text{Li}, \quad Q = 1.31\,\text{MeV} \quad (2)$$
$$({}^4\text{He}X^{--}) + {}^3\text{He} \to X^{--} + {}^7\text{Be}, \quad Q = 0.41\,\text{MeV} \quad (3)$$
$$({}^8\text{Be}X^{--}) + \text{D} \to X^{--} + {}^{10}\text{B}, \quad Q = 2.6\,\text{MeV} \quad (4)$$
$$({}^8\text{Be}X^{--}) + \text{T} \to X^{--} + {}^{11}\text{B}, \quad Q = 7.8\,\text{MeV} \quad (5)$$
$$({}^8\text{Be}X^{--}) + {}^3\text{He} \to X^{--} + {}^{11}\text{C}, \quad Q = 5.8\,\text{MeV} \quad (6)$$
$$({}^8\text{Be}X^{--}) + {}^4\text{He} \to X^{--} + {}^{12}\text{C}, \quad Q = 3.97\,\text{MeV} \quad (7)$$
$$({}^9\text{B}X^{--}) + n \to X^{--} + {}^{10}\text{B}, \quad Q = 4.0\,\text{MeV} \quad (8)$$
$$({}^9\text{B}X^{--}) + p \to X^{--} + {}^{10}\text{C}, \quad Q = -0.37\,\text{MeV} \quad (9)$$

- Examples of catalyzed reactions. *We will work in X/p << 1 limit*
- (1) and (3) are the most important.
- Rates can be rescaled by using Kamimura et al. results for catalyzed rates with singly charged X. Reaction to ^{6}Li > Hubble

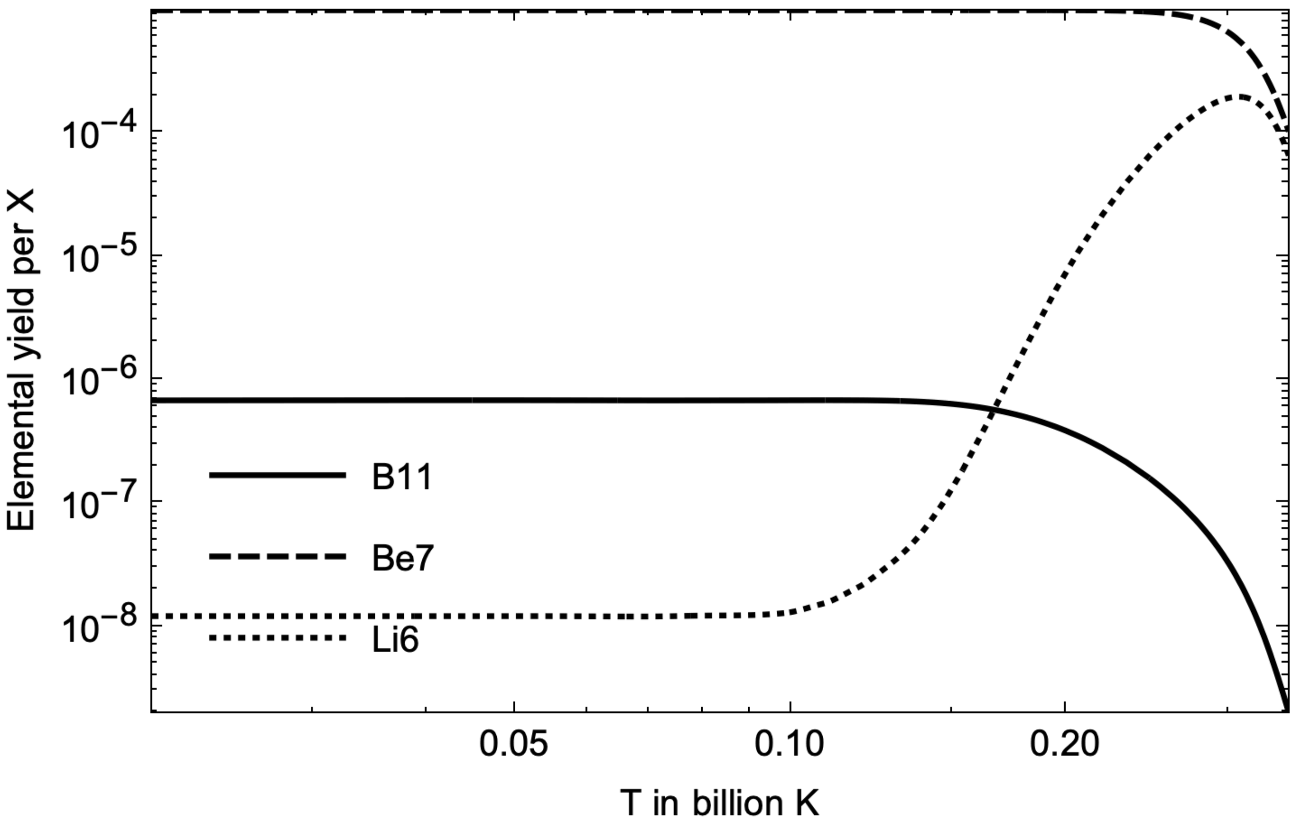
$$\Gamma({}^4\text{HeX} + \text{D} \to {}^6\,\text{Li} + \text{X}) = 0.03 T_9^3\ 1/\text{sec}$$
$$\Gamma({}^4\text{HeX} + {}^3\,\text{He} \to {}^7\,\text{Be} + \text{X}) = 1.1 \times 10^{-3} T_9^3\ 1/\text{sec}$$

Catalyzed Yields (main results)



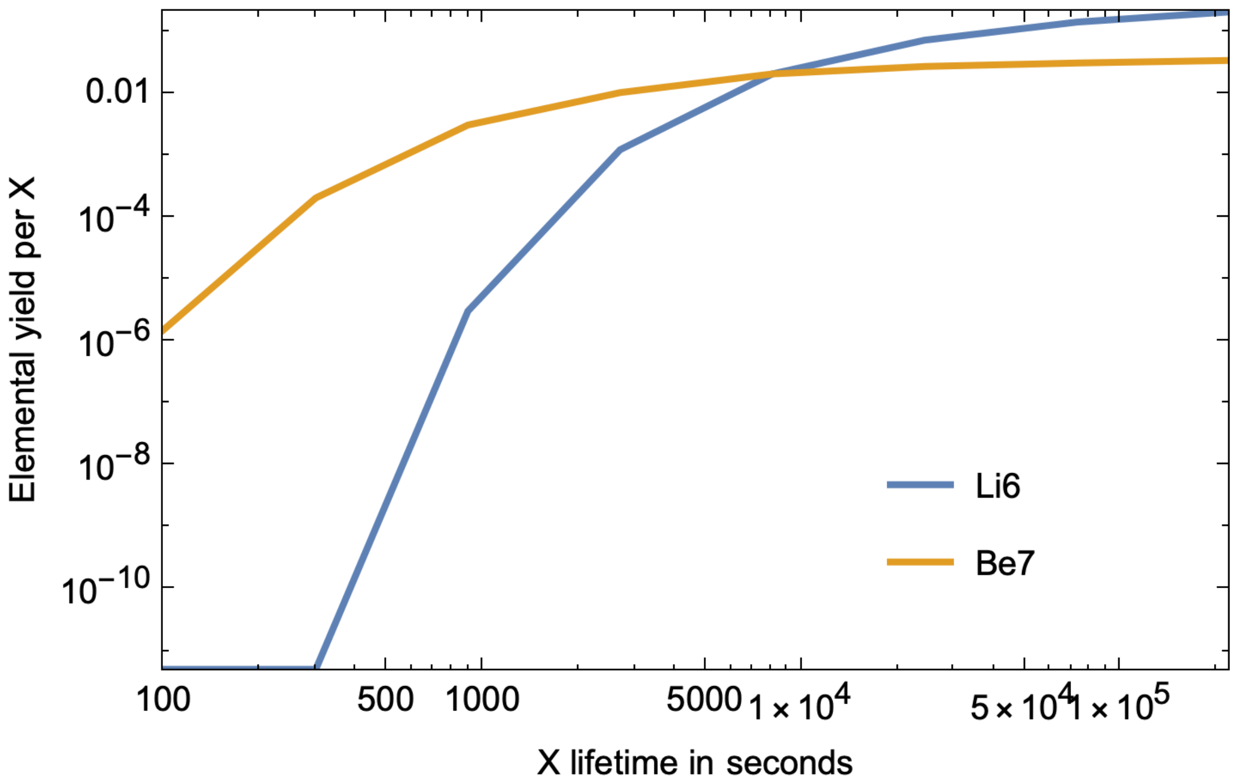
- Parametrically long lifetimes (above 10^5 seconds, e.g. stable)
- ^{6}Li/X = 0.8; (^{7}Be→^{7}Li)/X = 0.03. ^{6}Li will dominate constraints.
- ^{11}B is created via ^{11}C, using HeX + ^{7}Be → ^{11}C + X, yield = 10^{-4}

Catalyzed Yields (main results)



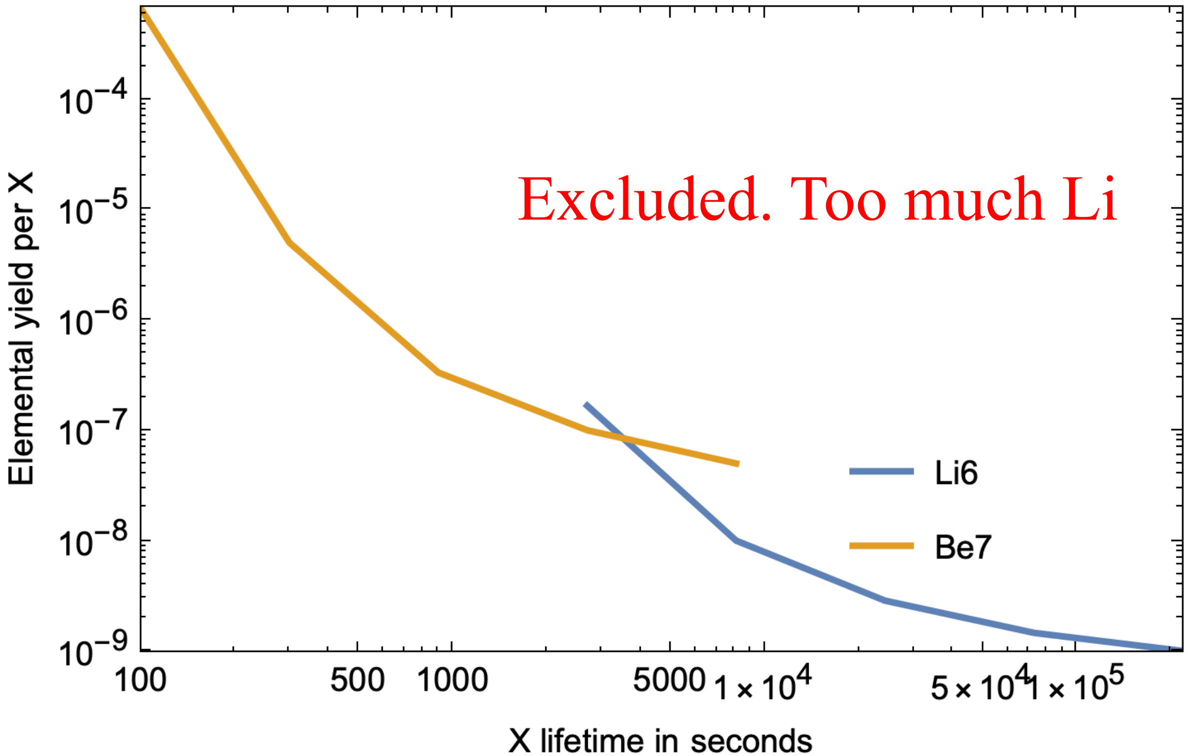
- 500 seconds lifetime (an example)
- ^{6}Li/X = 10^{-8}; (^{7}Be→^{7}Li)/X = 10^{-3}. ^{7}Li will dominate constraints.
- ^{11}B is created via ^{11}C, using HeX + ^{7}Be → ^{11}C + X, yield ~ 10^{-6}

Catalyzed Yields vs lifetime



- As expected, catalized yield has ^{6}Li/^{7}Li > 1 for long lifetimes, and only ^{7}Li is important for short lifetimes.
- Can now be easily turned into constraints on abundance

Constraint on lifetime vs abundance



- As expected, catalized yield has ^{6}Li/^{7}Li > 1 for long lifetimes, and only ^{7}Li is important for short lifetimes.
- Uncertainties in this treatment are O(1). "Permissible" for log-log treatment.

Consequences

- Infinite lifetime → abundance relative to H is less than 10^{-9}.
- If X^{--} is "missing mass", e.g. dark matter, then the mass has to be in $5*10^9$ GeV range and larger. Such particles will not be stopped by the rock and will be seen as highly ionizing tracks with all the usual constraints to apply.
- For the infinite lifetimes, (LiX) bound states will appear as "abonormal hydrogen" and constraints may be even better.
- If we insist on TeV and sub-TeV scale particles (like implied by the ATLAS search), AND on standard cosmology with $T \sim m_X$, then the abundance is ~ (0.001 - 1) *baryon abundance. This implies the lifetime limit of 100 seconds or less. (Making speculations on thermonuclear catalysis in the lab more difficult.)

Conclusions

- BBN continues to be an important chapter in Early Universe's history. D/H and He/H is relatively consistent, while Li is smaller than BBN prediction by a factor of ~3. The most reasonable assumption is suppression in stars.
- One could turn interstellar abundance of Li into an upper bound of what one can have, and one can conservatively infer $Li/H < 10^{-9}$. It would be great to measure Li/H and D/H in the same systems.
- We can turn it into a powerful tool for constraining BSM physics and catalyzed BBN is one such example.

thank you