BBN and particle physics

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Coc, Vangioni, MP, Uzan, PRD 2015

Goudelis, Pradler, MP, PRL 2016

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PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Outline of the talk

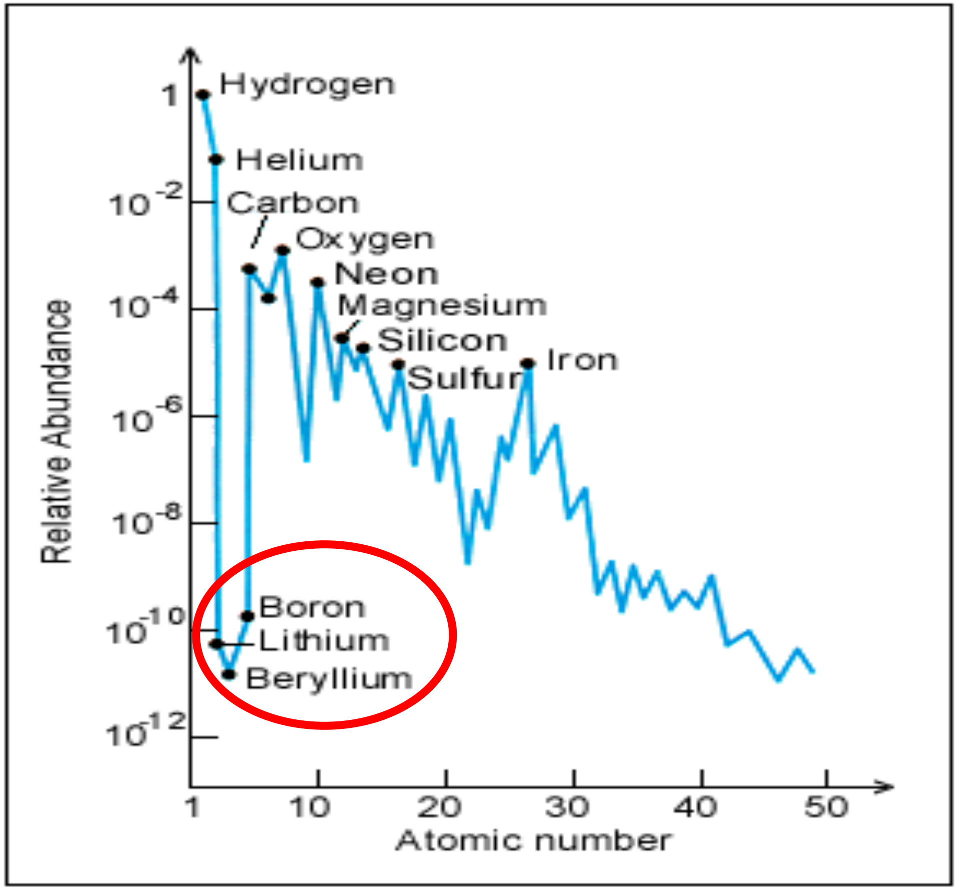
1. Introduction: BBN redux. *Recent observational developments*. Planck results; new accuracy for D/H (?); no ^{6}Li.
2. Applications to light DM, application to the LHC physics.
3. ^{7}Li is "over-predicted" ← ***cosmological lithium problem***.

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

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

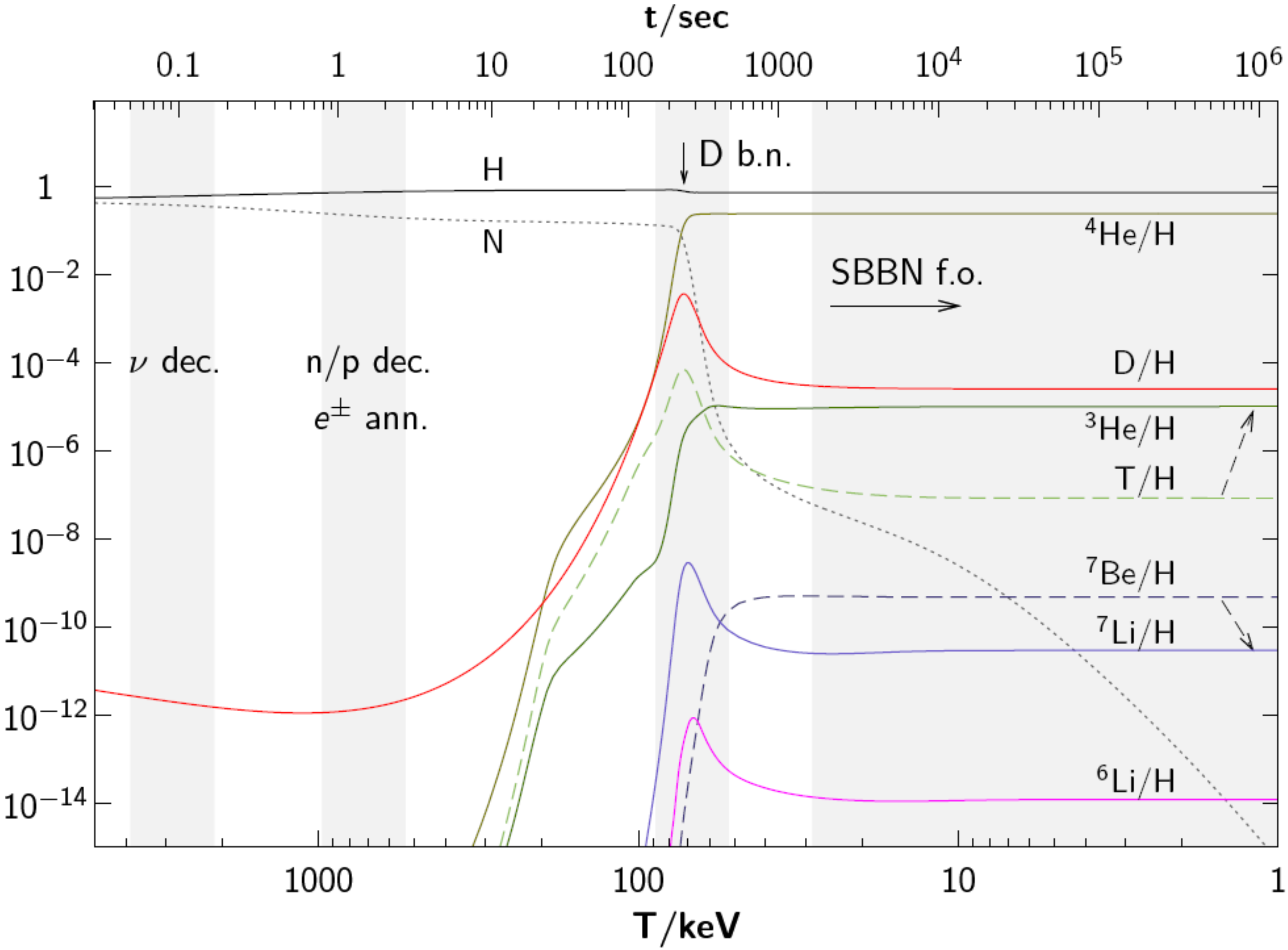
4. Is anything wrong with nuclear physics? Is anything wrong with cosmology? Particle physics speculations: non-thermal decay with extra neutrons; catalysis by charged particles; MeV-scale energy injection.
5. Conclusions

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

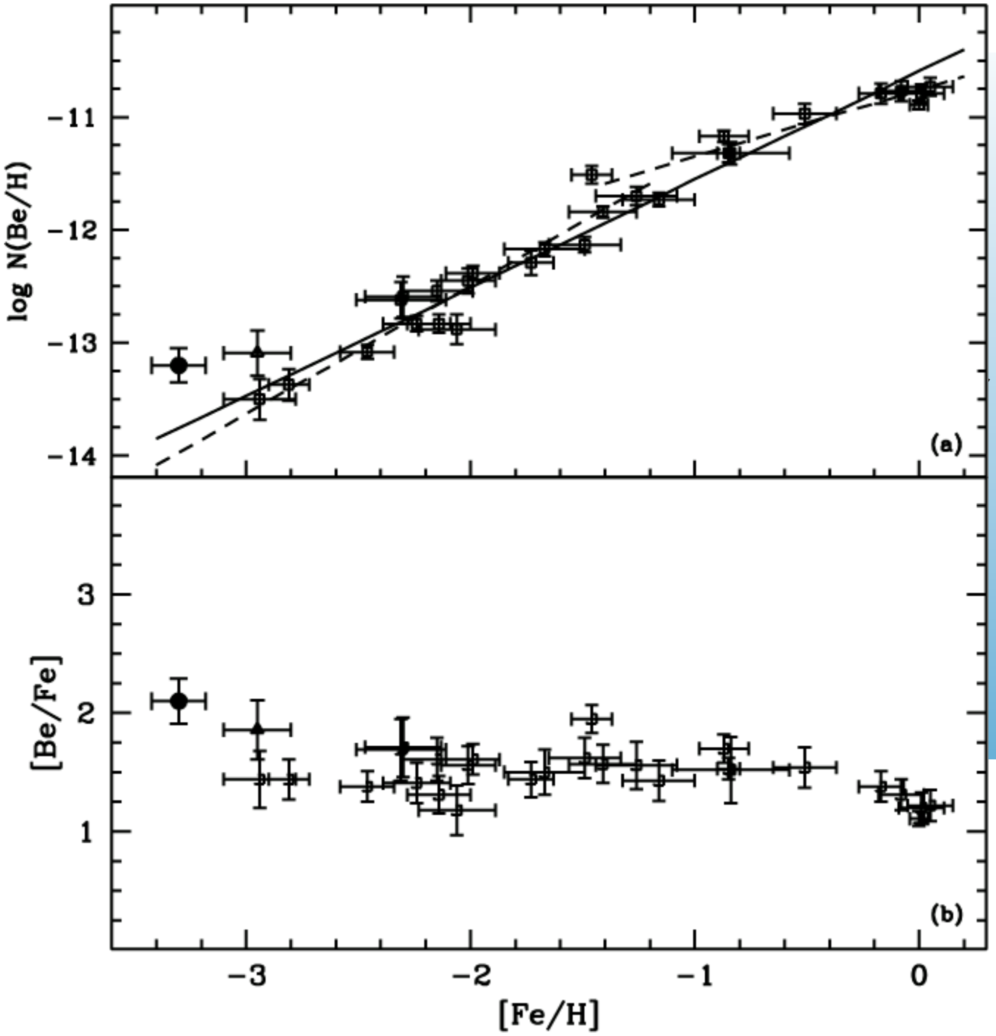


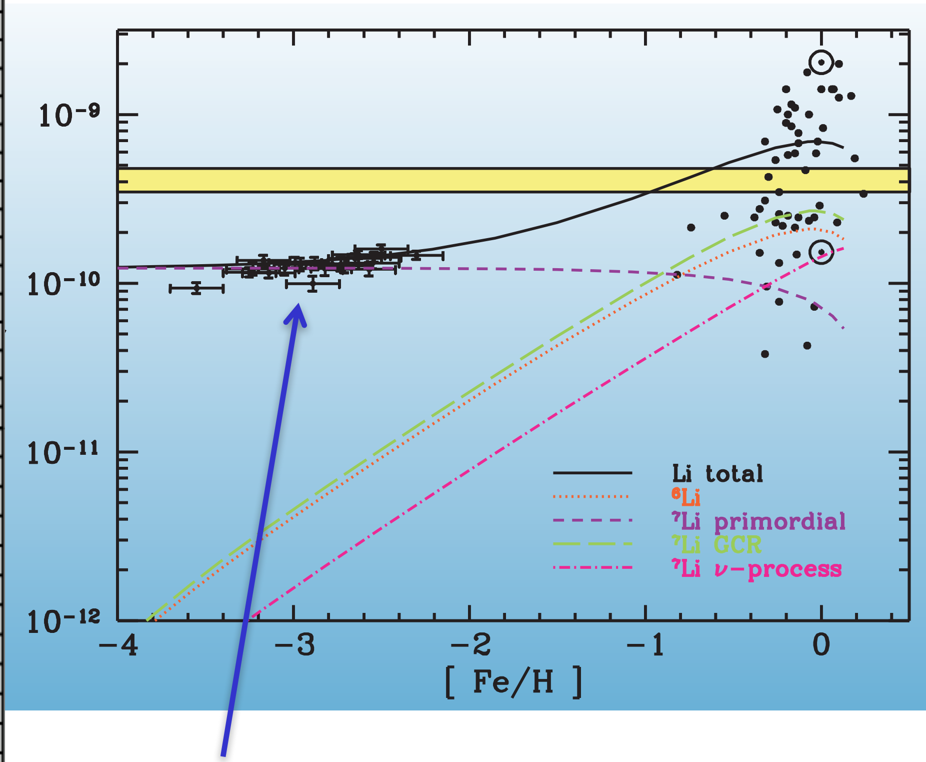
A<1,2,3,4,7 – BBN; A>12 –Stars;
A=6,9,10,11 –“orphans” (cosmic ray spallation)

BBN abundances at η_{CMB}



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

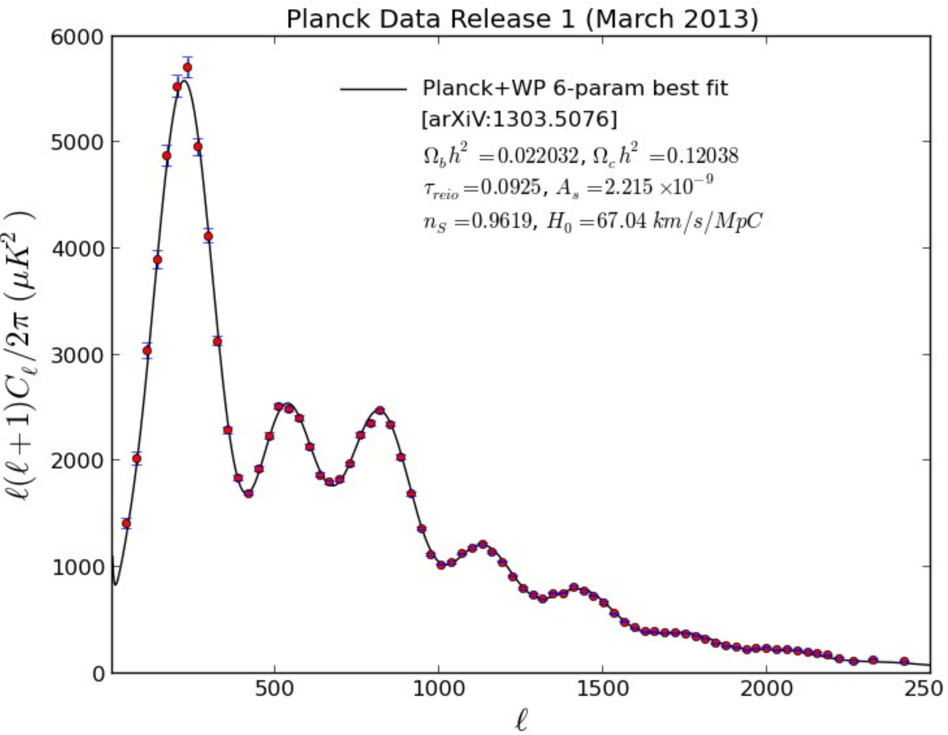


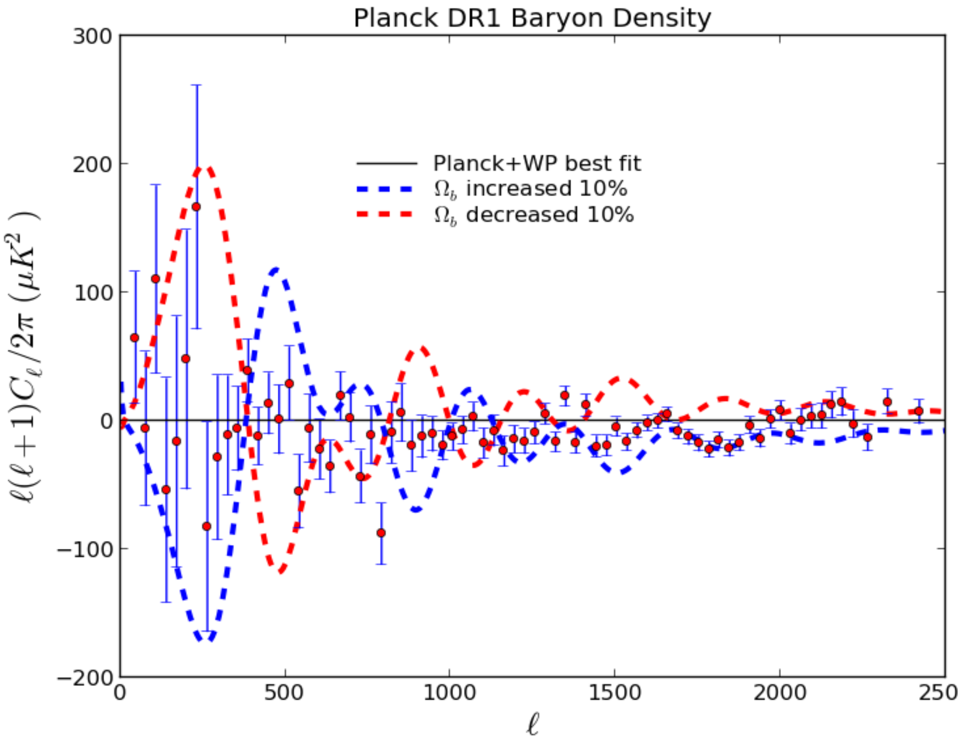


Spite plateau (Ryan et al)

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

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

Planck data (Figures from Kinney, Natoli talks)

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

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

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

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

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

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

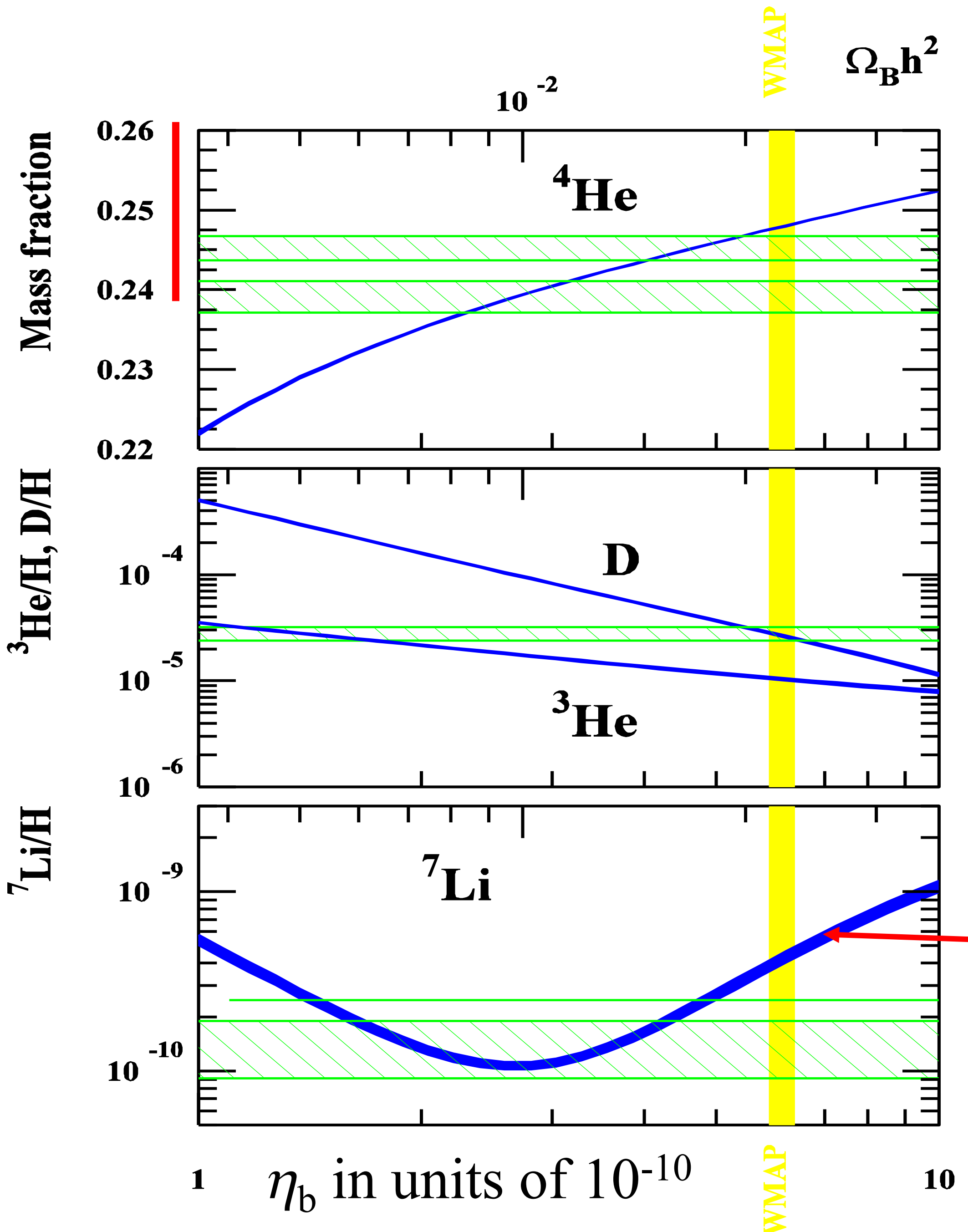
1. Affect the timing of reactions,

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

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

2. Introduce non-thermal channels *e.g.* via late decays or annihilations of heavy particles, $\underline{E > T}$.
3. Provide catalyzing ingredients that change $\underline{<\sigma_{ijk} v>}$. 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

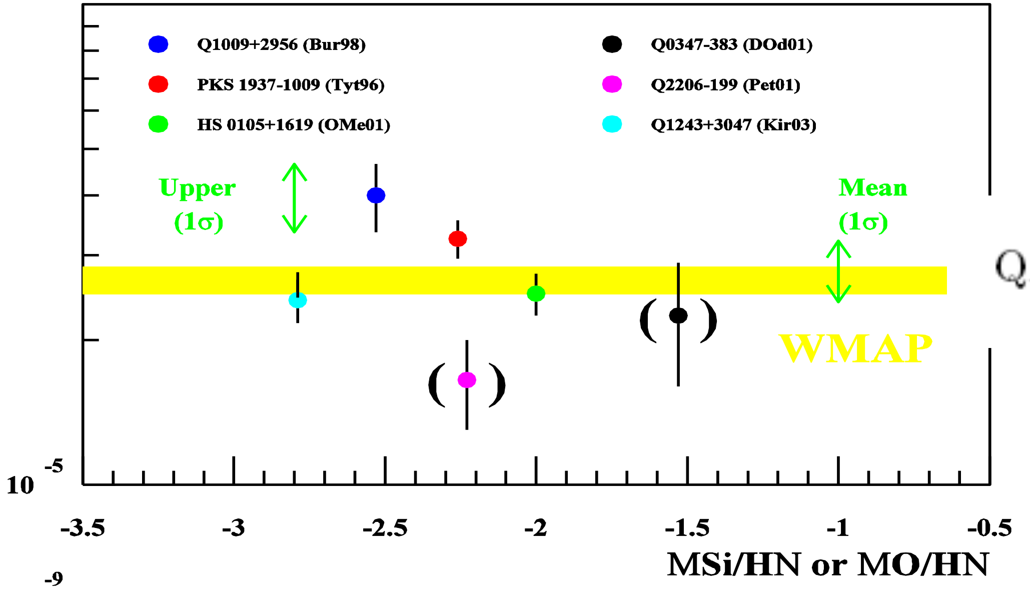
Green bands: observational values for primordial abundances of ^{4}He, D, and ^{7}Li

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

^{7}Be branch

Coc et al, ApJ 2004

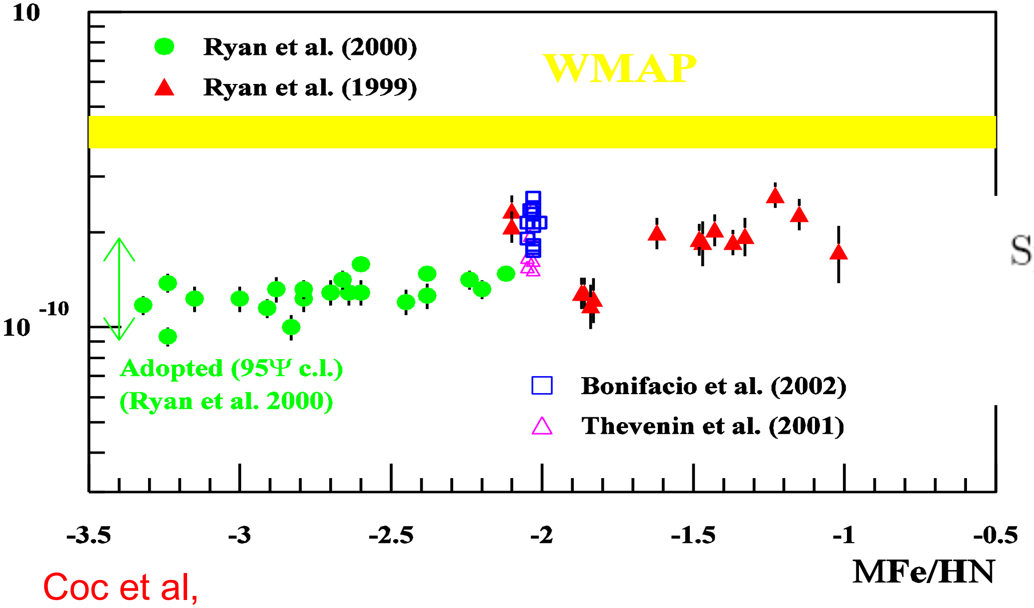
Old status of standard BBN with CMB input ($\eta=6.2\ 10^{-10}$)



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

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

Deuterium seems OK, (but large scatter)



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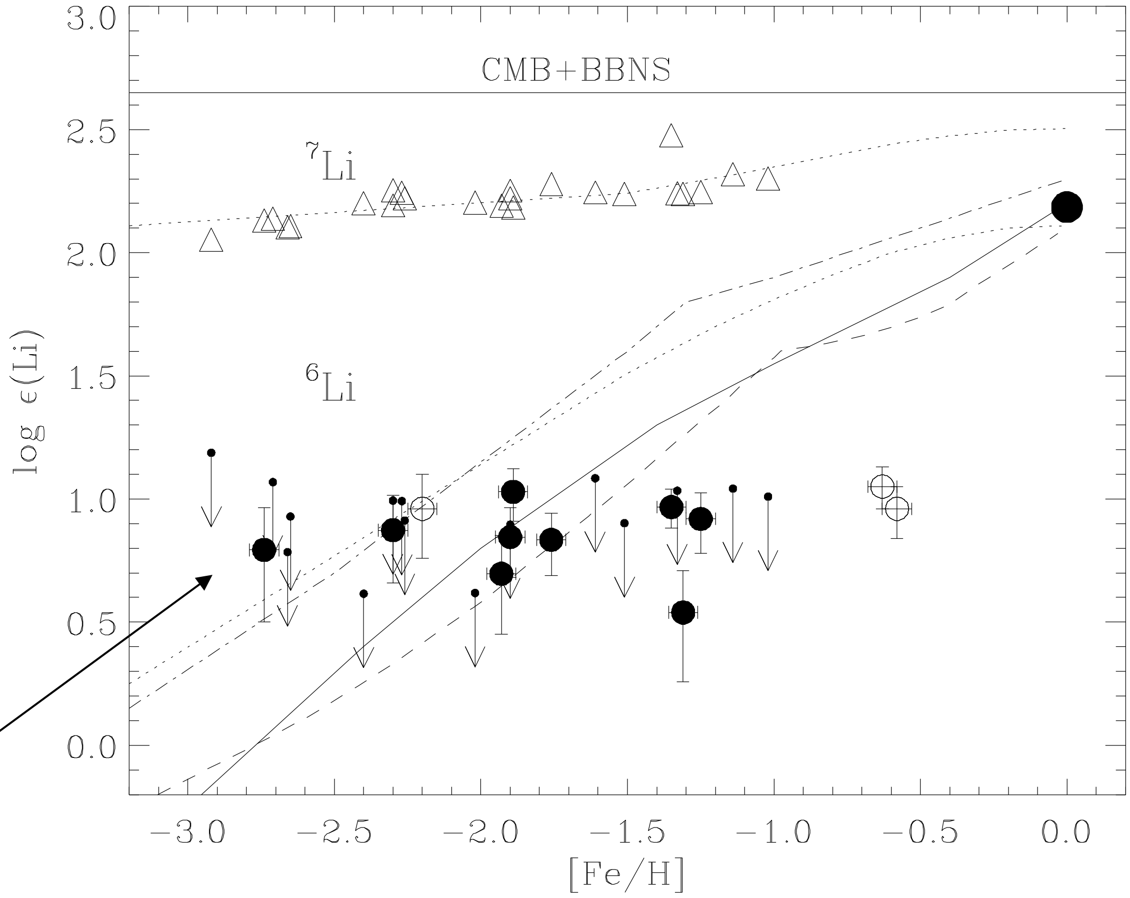
Huge “lithium deficiency”

Lithium problem !!

Coc et al, ApJ 2005

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

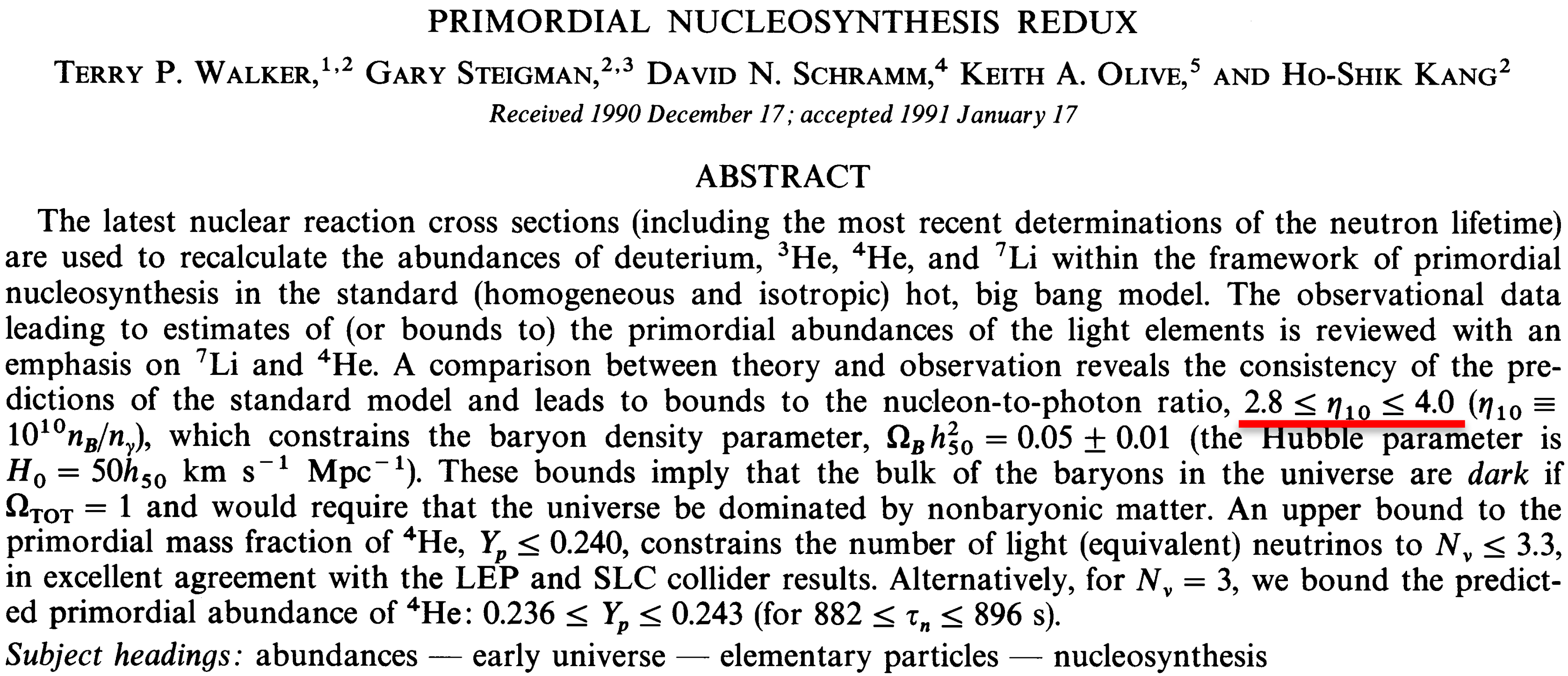


^{6}Li/H ~ 10^{-11}

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*

1991 review



PRIMORDIAL NUCLEOSYNTHESIS REDUX

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ABSTRACT

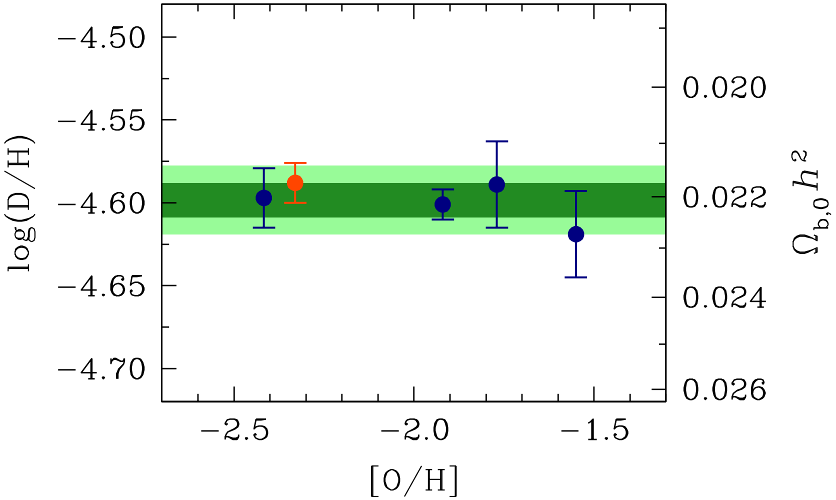
The latest nuclear reaction cross sections (including the most recent determinations of the neutron lifetime) are used to recalculate the abundances of deuterium, ^{3}He, ^{4}He, and ^{7}Li within the framework of primordial nucleosynthesis in the standard (homogeneous and isotropic) hot, big bang model. 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, $2.8 \le \eta_{10} \le 4.0$ ($\eta_{10} \equiv 10^{10} n_B/n_\gamma$), 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 $\Omega_{\rm TOT} = 1$ and would require that the universe be dominated by nonbaryonic matter. An upper bound to the primordial mass fraction of ^{4}He, $Y_p \le 0.240$, constrains the number of light (equivalent) neutrinos to $N_\nu \le 3.3$, in excellent agreement with the LEP and SLC collider results. Alternatively, for $N_\nu = 3$, we bound the predicted primordial abundance of ^{4}He: $0.236 \le Y_p \le 0.243$ (for $882 \le \tau_n \le 896$ s).

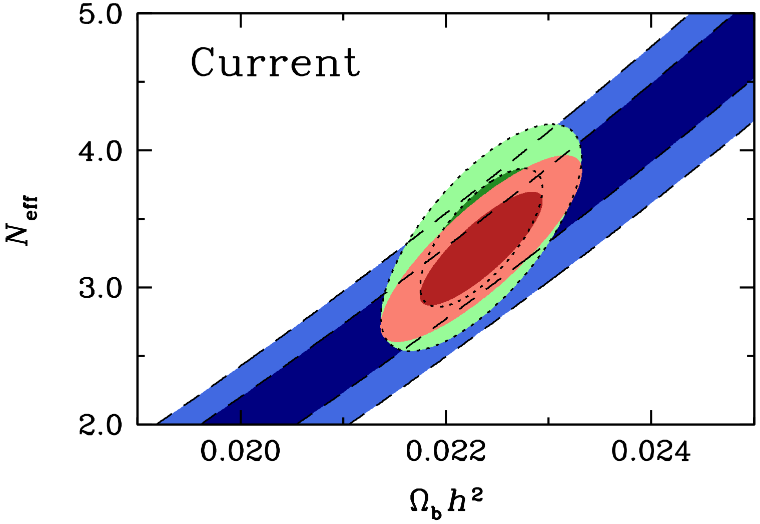
Subject headings: abundances — early universe — elementary particles — nucleosynthesis

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 5yr 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!

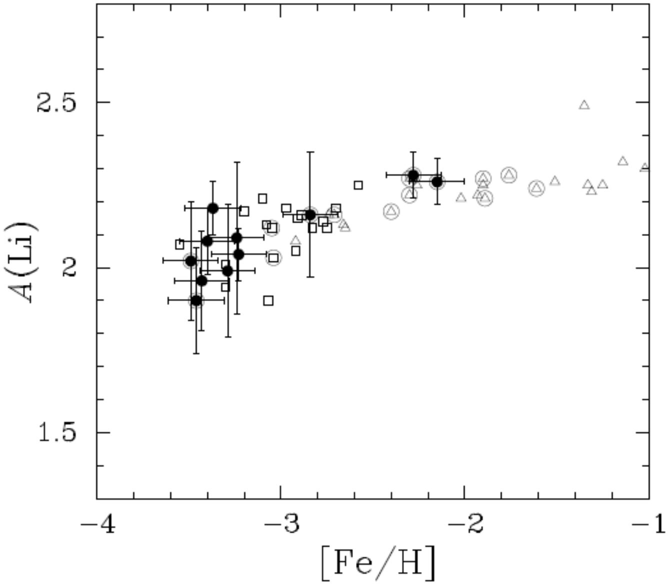


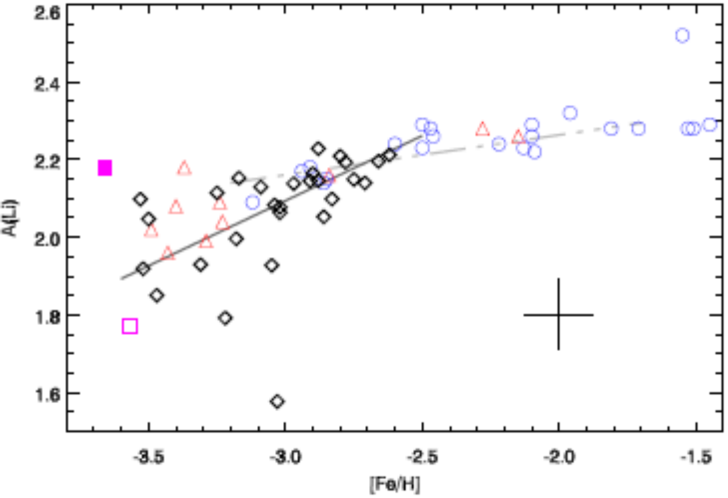


- With latest results, no evidence of ^{6}Li in the stellar atmospheres.
- Only ^{7}Li remains a problem.

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

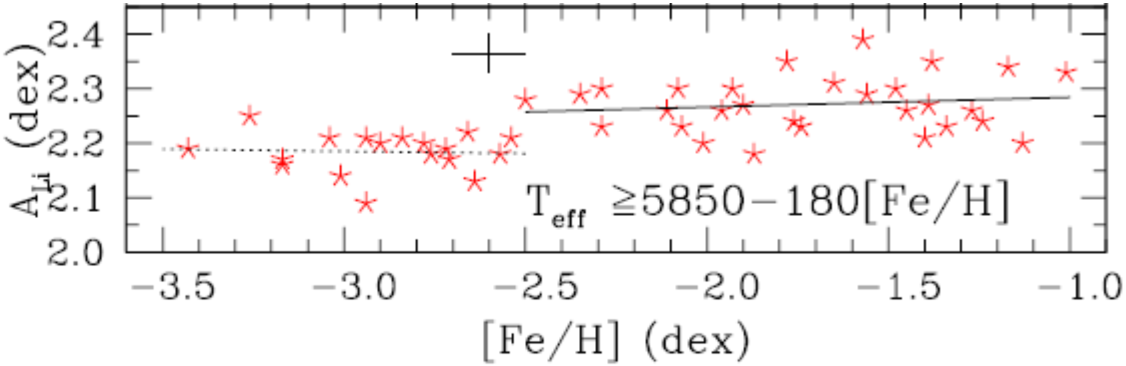
Aoki et al, 2009, reports the suppression of low-metallicity tail of Spite plateau





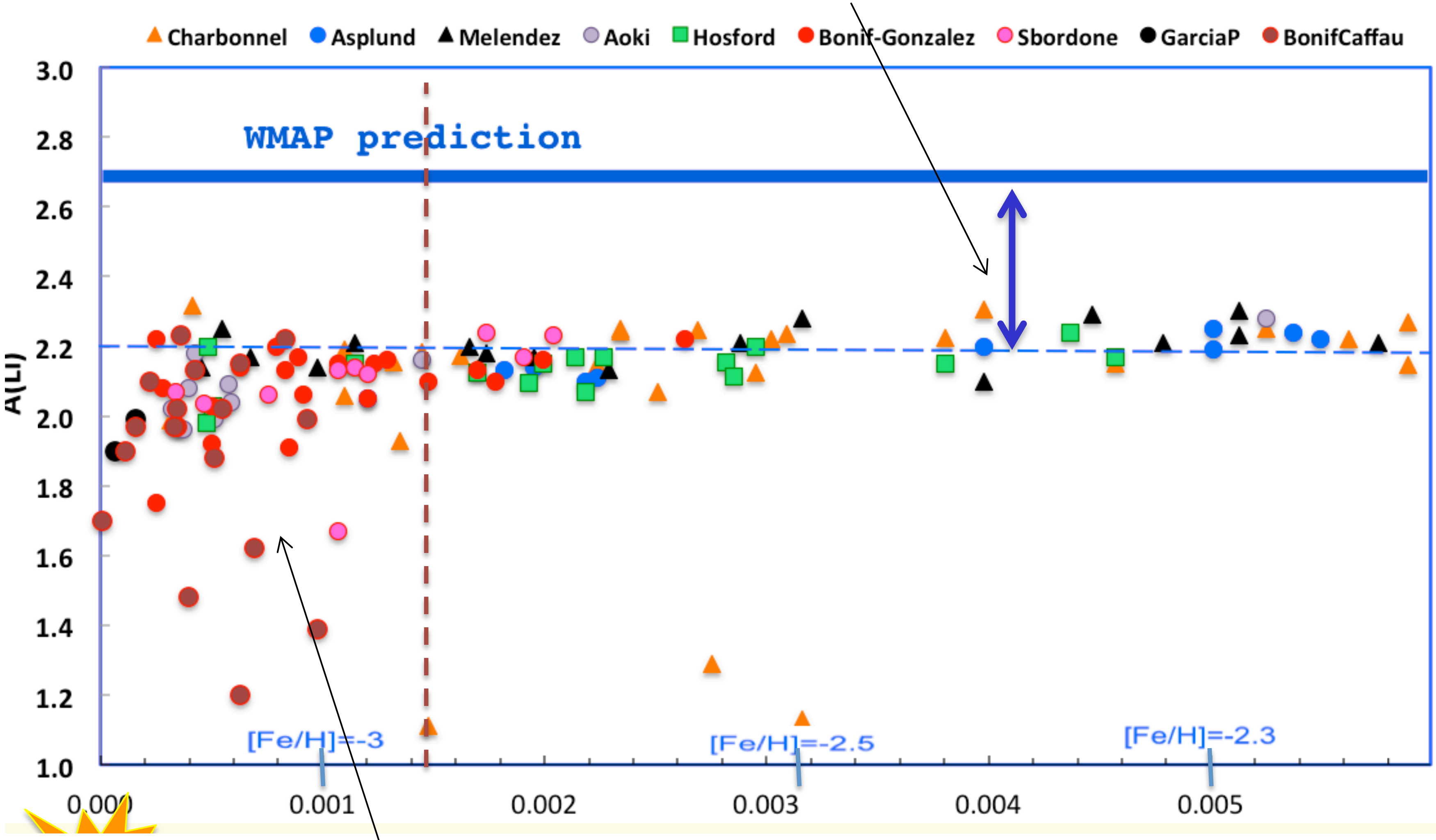
Sbordone et al, 2010, confirms it with higher statistics

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



More than one problem with ^{7}Li?

Problem # 1

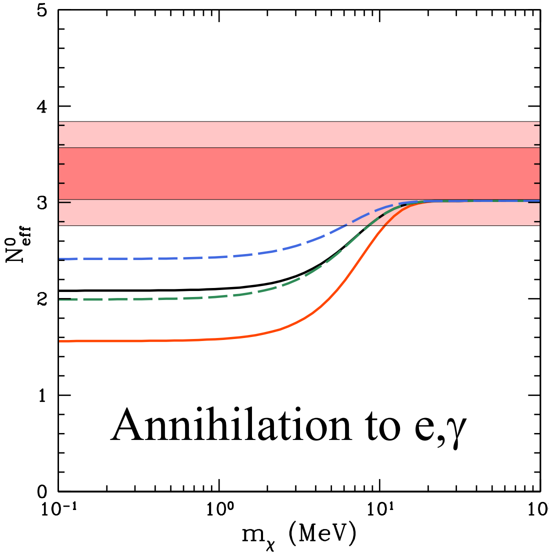


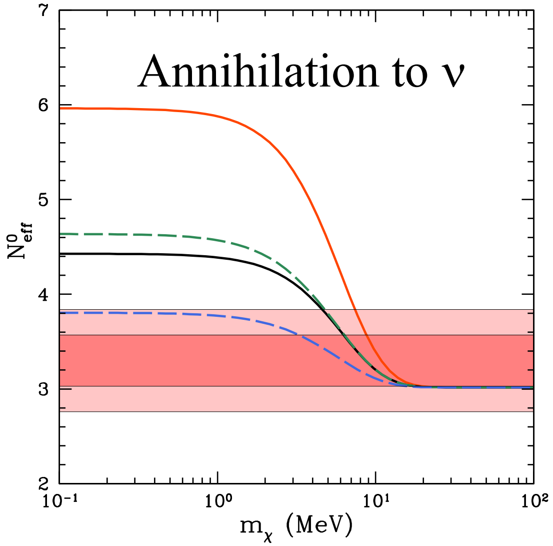
Problem # 2

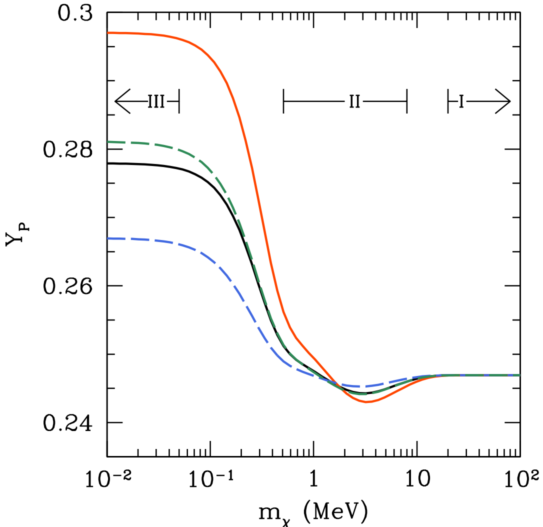
M. Spite talk IAP 2012

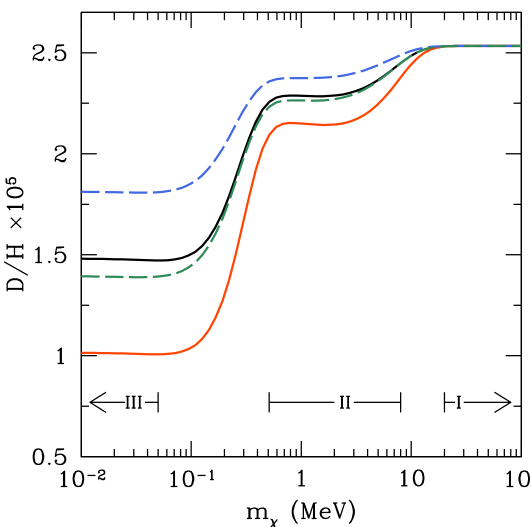
Constraint on WIMP mass range from BBN and Neff: above a few MeV is "safe"

- From Nollett and Steigman, 2014, "safe" range is > few MeV









Application for the LHC

- *New ideas to build a "cheap" detector for a dedicated search of long lived particles in coincidence with hard collisions at the LHC:* Chou, Curtin, Lubatti, 2016. MATHUSLA proposal.

- Signal ~ probability to produce * probability to decay

- BBN may or may not provide a strong cutoff to lifetime.

- Special investigation is warranted: Fradette, Pospelov, PRD to appear.

Higgs portal and light scalars

- At the LHC, we will be concerned with H→ S+S, followed by S decay.
- Consider “an almost” Z_2 symmetric case to maximize the depletion of S in the early universe, and minimize its decay:

$$\mathcal{L}_{H/S} = \mu^2 H^\dagger H - \lambda_H \left(H^\dagger H\right)^2 - V(S) - ASH^\dagger H - \lambda_S S^2 H^\dagger H + \text{kin. terms.}$$

$$\Gamma_{h\to SS} = \frac{\lambda_S^2 v^2}{8\pi m_h}\sqrt{1-\frac{4m_S^2}{m_h^2}},$$

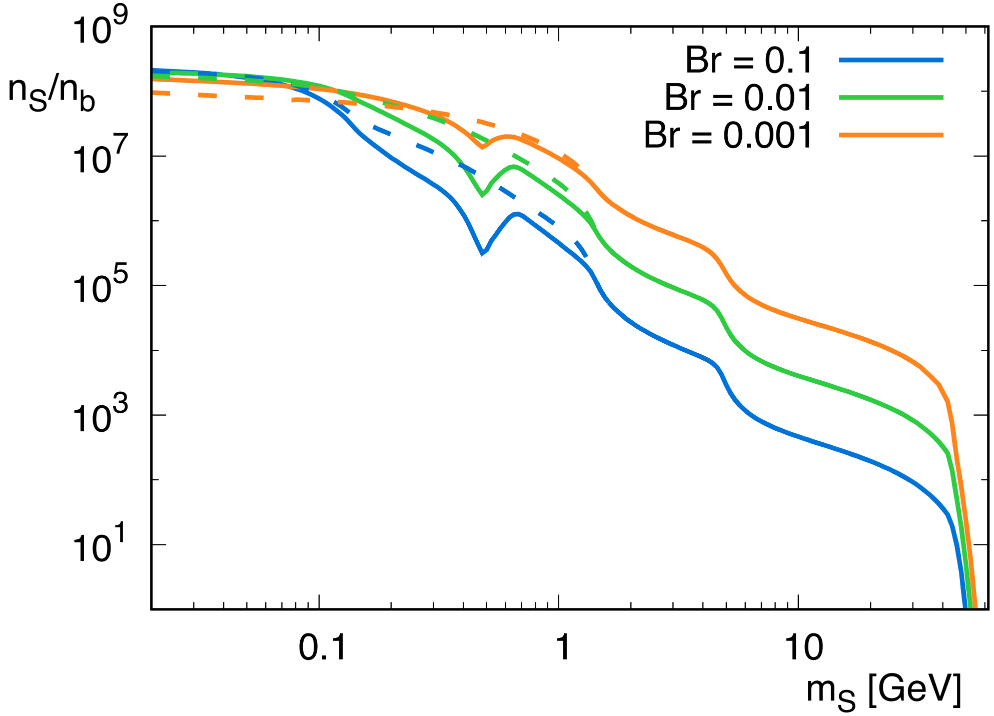
$$Br(h\to SS) = \frac{\Gamma_S}{\Gamma_S+\Gamma_{SM}} \simeq 10^{-2}\left(\frac{\lambda_S}{0.0015}\right)^2,$$

$$\sigma v(s) = \frac{8\lambda_S^2 v^2}{(s-m_h^2)^2+m_h^2\Gamma_{\text{SM}+S}^2}\,\frac{\Gamma_{\text{SM}}^{m_h\to\sqrt{s}}}{\sqrt{s}}, \qquad \langle\sigma v\rangle = \frac{\int_{4m_S^2}^{\infty} ds\,\sigma v(s)\, s\sqrt{s-4m_S^2}\,K_1\left(\frac{\sqrt{s}}{T}\right)}{16 T m_S^4 K_2^2\left(\frac{m_S}{T}\right)}.$$

Cosmological metastable abundance

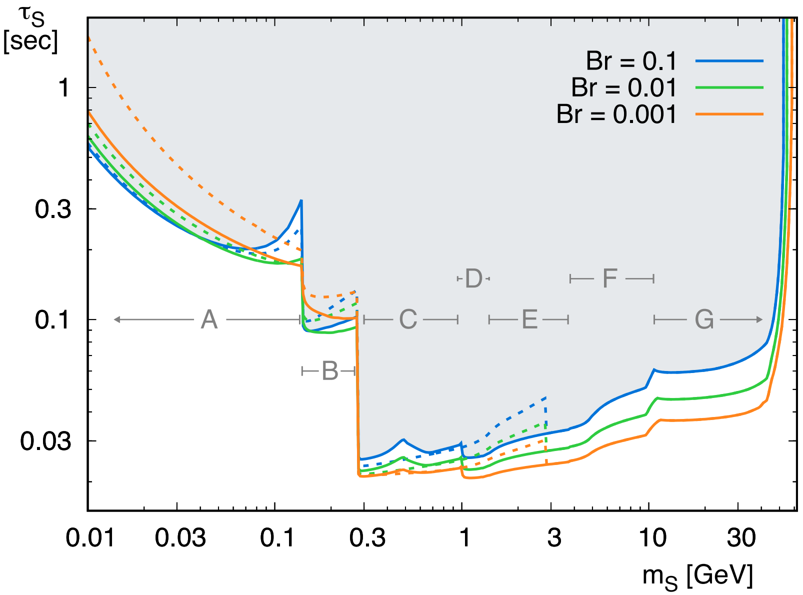
- In the early Universe, the number density is depleted as for the usual WIMP:

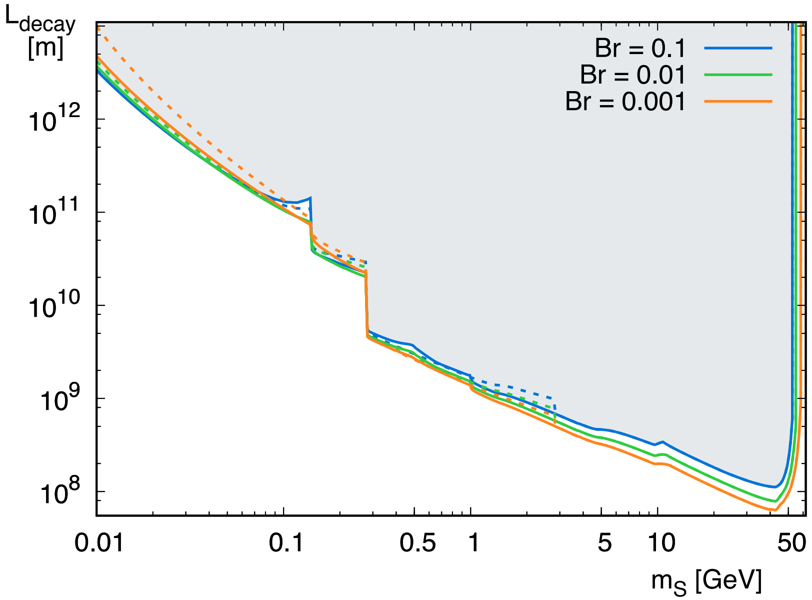
- However, because Higgs mediation is relatively inefficient, the abundance you are stuck with is large,



Constraints on lifetime come mostly from n/p enrichment

- Decay products (nucleons, kaons, pions) induce extra p→n transitions and quite generically increase n/p. This is very constrained.





- For a ~ GeV scale particle, and energy of 200 GeV (broadly consistent with being a decay of the Higgs at 13 or 14 TeV energy), the minimum probability to decay in 100m hangar is ~ 10^{-6}. If the branching of H→SS is sizeable, then it is a detectable signal.

Back to the lithium problem:
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:*

  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***

  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.

More on ^{7}Li generation during the BBN

In fact, it is ^{7}Li+^{7}Be that we are interested in (much later, ^{7}Be captures an electron and becomes ^{7}Li). Things are simple: *there is one reaction in, and one reaction out*

^{3}He+α → ^{7}Be + γ - IN.

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

At T>25 keV, ^{7}Li is unstable being efficiently burned by protons.

^{4}He, ^{3}He, D, p, and n can be all considered as an input for lithium calculation.

1. ^{3}He and n abundances ? All reactions are too well-known. ^{3}He is indirectly measured by the solar neutrino flux.
2. ^{3}He(α,γ)^{7}Be reaction is now known with better than 10% accuracy (thanks to several dedicated experiments in the last 10yr).

New ways of destroying ^{7}Be that were missed ?

Burning of ^{7}Be using deuterium

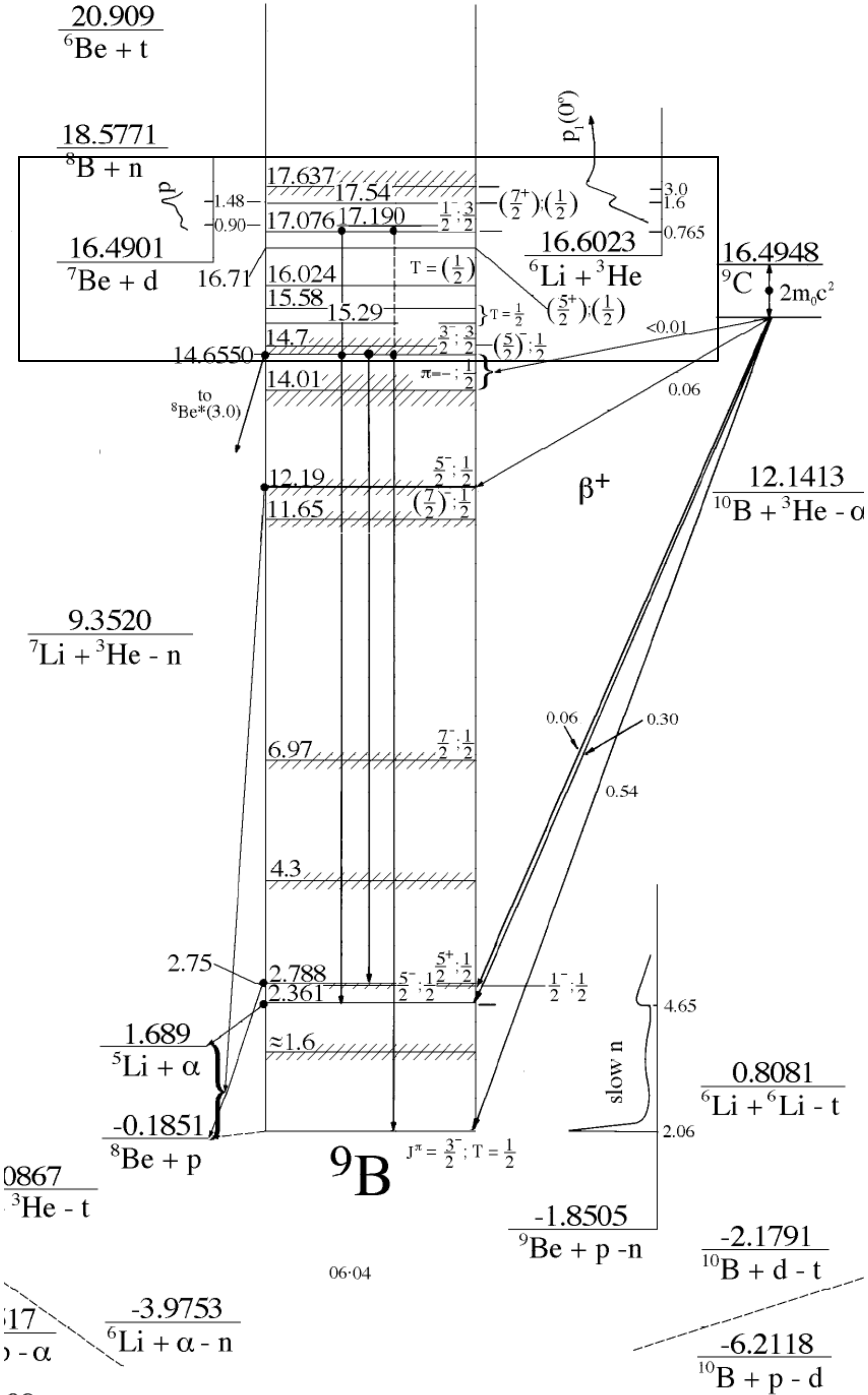
It has been suggested (Coc et al., 2004) that if the reaction rate of ^{7}Be(d,p)$\alpha\alpha$ is arbitrarily increased by a factor of ~ 100, the lithium problem can be "solved" right during the BBN.

Subsequent experimental search (Angulo et al., 2005) have shown *no enhancement in this reaction*.

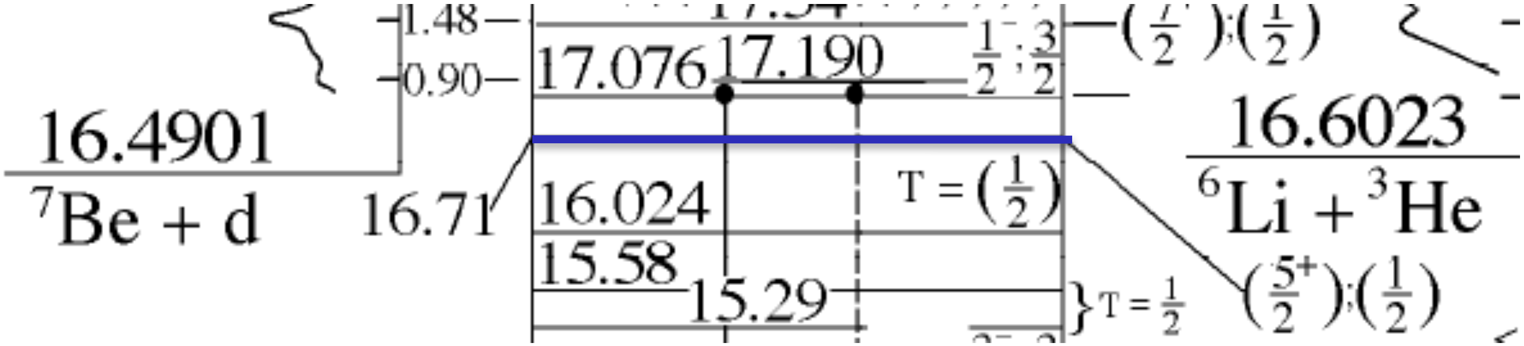
It is important, however, that the search was made at E~400 keV, and the extrapolation to BBN regime was done *assuming* smoothness of astrophysical S-factor (cross section). *There is a loophole to it due to resonances* (MP).

Such assumptions can be spectacularly violated by the presence of near threshold resonances (e.g. F. Hoyle, 1950s).

^{9}B energy levels from TUNL nuclear data project



Zooming in: 16.7 MeV resonance near ^{7}Be +d



Not much is known about 5/2+, 16.7 MeV +/- 100 keV resonance in ^{9}B. Information about mirror nucleus, ^{9}Be, shows that this resonance is extremely narrow, 40 keV.

We (R. Cyburt and MP, 2009) tried to determine parameters of this resonance phenomenologically, and then see if it can be consistent with nuclear physics/quantum mechanics. (Similar suggestions are by Chakraborty et al, 2010; Broggini et al, 2012). The Γ_d width has to be maximal, close to allowed value by QM.

Resonance hypothesis is also excluded…

1. Data from ^{9}Be(^{3}He,t)^{9}B reaction allow to determine the position of the resonance more accurately. Not 16.7 MeV but 16.8 MeV. Resonant energy = 300 keV – too high for the efficient burning of ^{7}Be. (Kirsebom, Davids, 2011)

2. Large entrance width for ^{7}Be + D→^{9}B(16.7MeV) is required, > 10 keV. Implies large elastic contribution to ^{7}Be + D scattering. Was searched for at HRIB (Oak Ridge), not found, entrance width is limited to O(keV) or below – no burning of ^{7}Be. (O'Malley et al., 2011).

there is no [*known or hypothetical*] nuclear solution to the cosmological lithium problem.

Some non-standard particle physics "solutions" to ^{7}Li discrepancy

1. Particle decays that supply extra neutrons (Reno, Seckel, 1980) that lead to the suppression of ^{7}Be.

2. Catalysis of nuclear reactions by *e.g.* negatively charged relics can suppress ^{7}Be. (MP, 2006).

3. **Light particles splitting nuclei (New)**: (MP, Pradler, 2010).

Straight energy injection does not solve ^{7}Li discrepancy

1. Particle decays can supply energy in form of the EM showers

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

2. Maximum energy in such showers is below the Be7 binding energy for a long time

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

When Be7 destruction becomes possible, soon after the D can also be destroyed. One needs O(1) reduction in Be7. And not more than 10% reduction in D. (*Exception: unstable particles in the interval of mass* 1.6-2.2 MeV)

Extra neutrons from particle physics reduce ^{7}Be

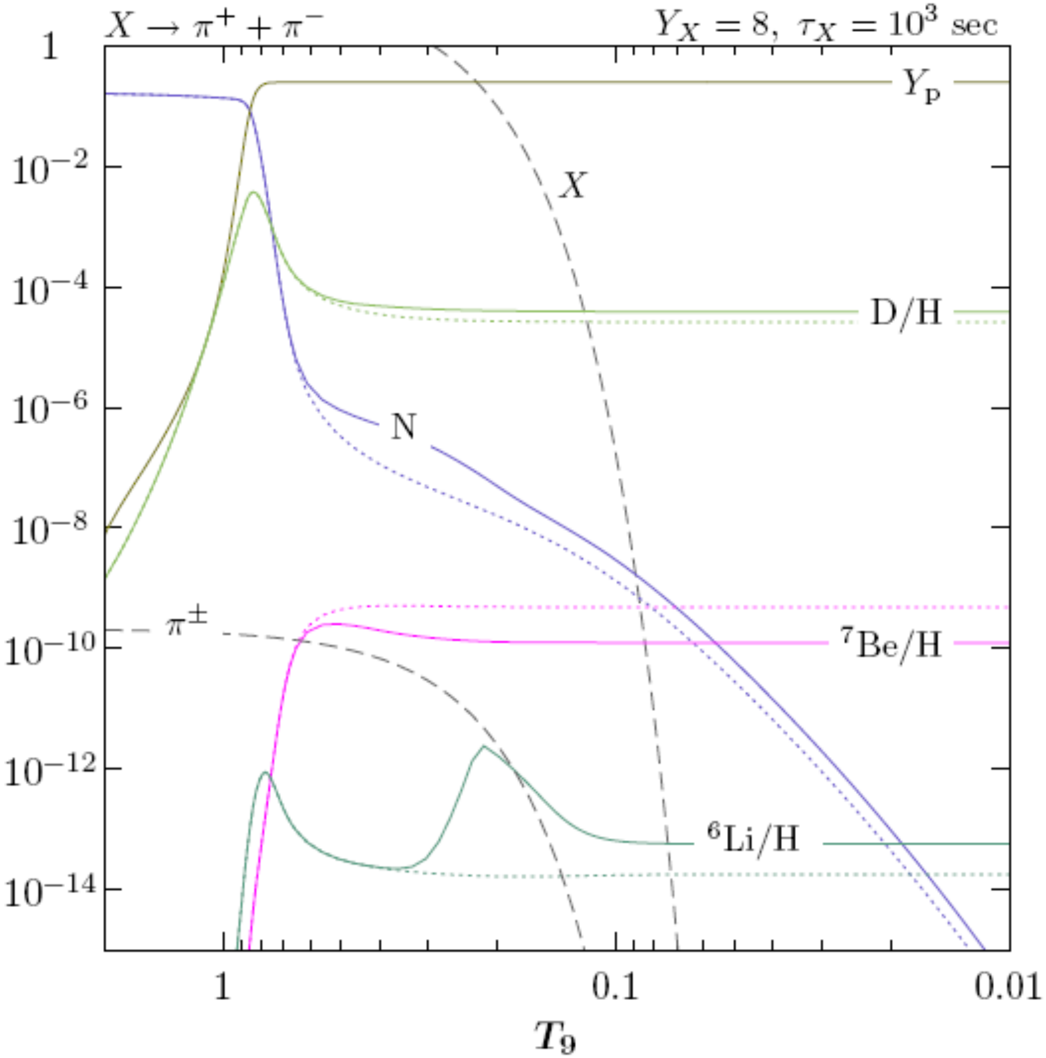
$^3\mathrm{He}+\alpha \rightarrow {}^7\mathrm{Be} + \gamma$ - IN.

$^7\mathrm{Be} + n \rightarrow p + {}^7\mathrm{Li}$ – OUT, (followed by $^7\mathrm{Li}+\mathrm{p} \rightarrow 2\alpha$)

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.

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;).

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

…..

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

Neutrons from decays and annihilation (yellow – He constraint, blue – solution to Li7, black lines contours of D/H)

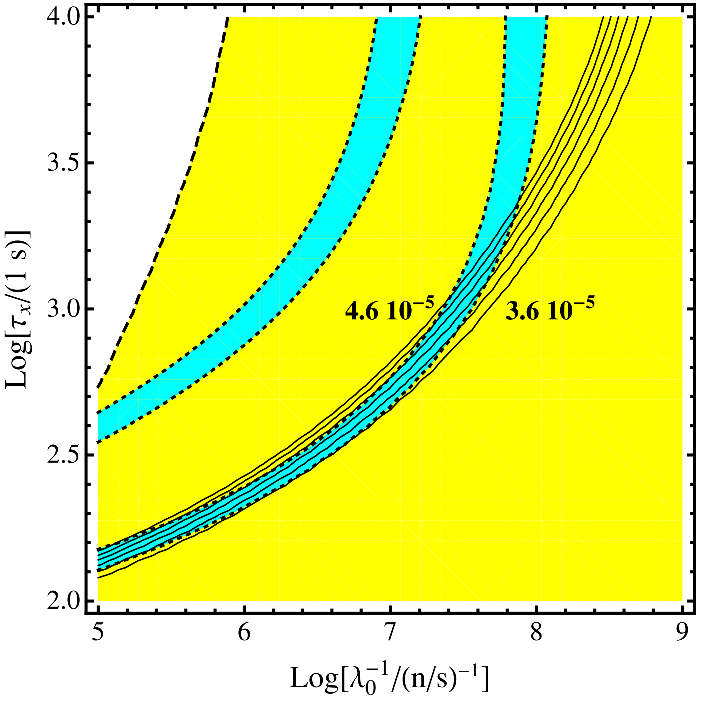


FIG. 5. *Decay of massive particles.* Contour plot assuming $\eta = \eta_{\rm CMB}$ for the two parameters of the model: the lifetime τ_x of the massive particle and the decay rate $\lambda_0 \exp(-t/\tau_X)$. This can be compared to the case 4 of Ref. [14]. The solid dashed lines indicate the prediction of deuterium abundance D/H = {3.6, 3.8, 4.0, 4.2, 4.4, 4.6}×10^{-5} from top to bottom.

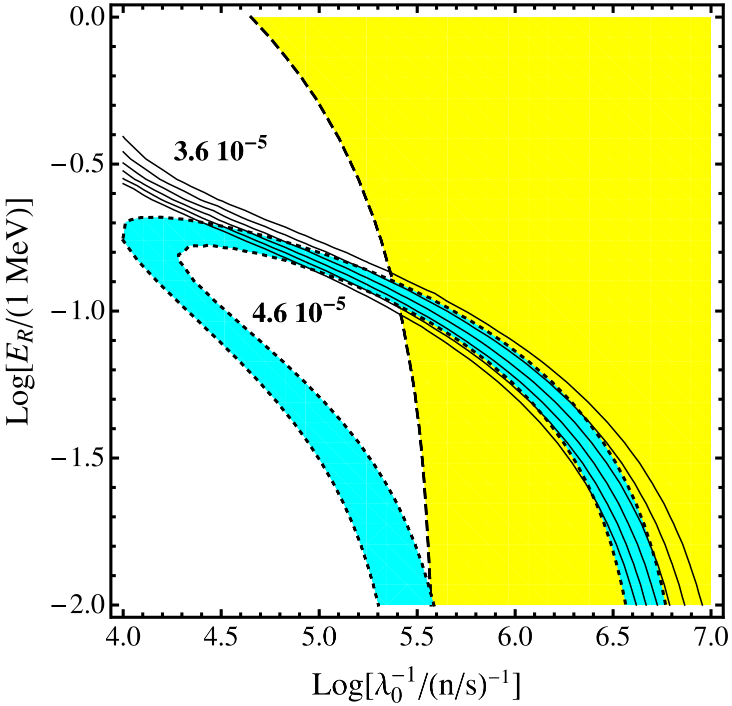


FIG. 8. *Resonnant annihilation.* Contour plot assuming $\eta = \eta_{CMB}$ for the two parameters of the model: the resonance energy E_R and the reaction rate $\lambda_0 \exp(-E_R/kT)$ (this corresponds to the case 5 of Ref. [14]). The solid dashed lines indicates the prediction of deuterium abundance D/H = {3.6, 3.8, 4.0, 4.2, 4.4, 4.6}×10^{-5} from top to bottom.)

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

Neutrons from oscillation from “mirror world” (!) (yellow – He constraint, blue – solution to Li7, black lines contours of D/H)

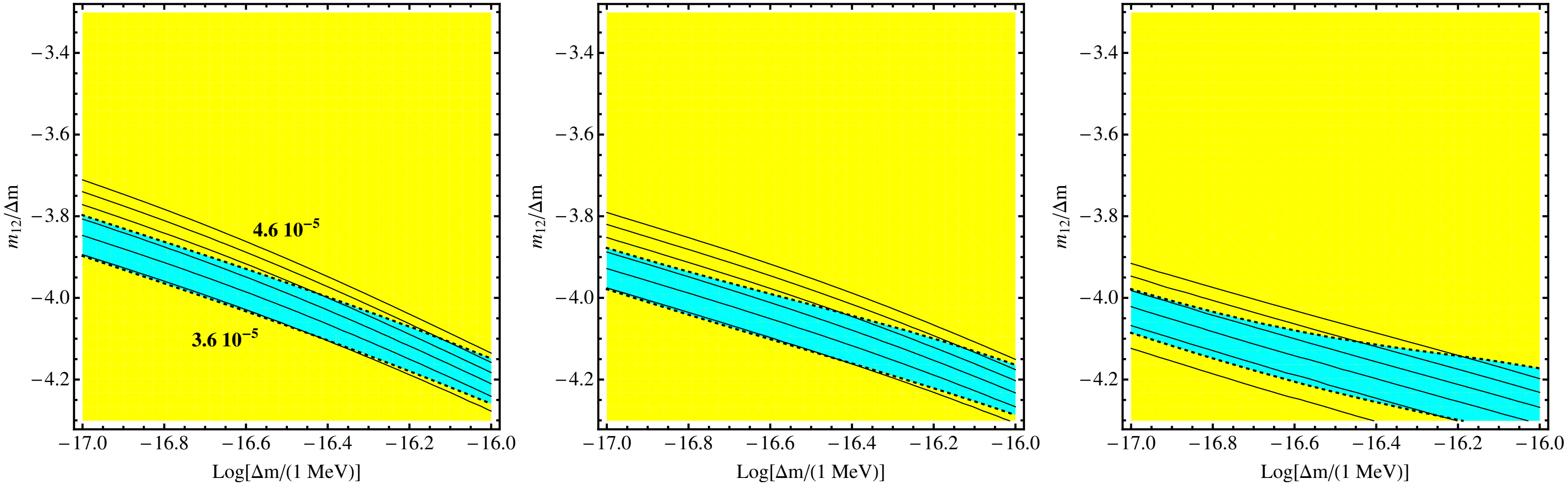
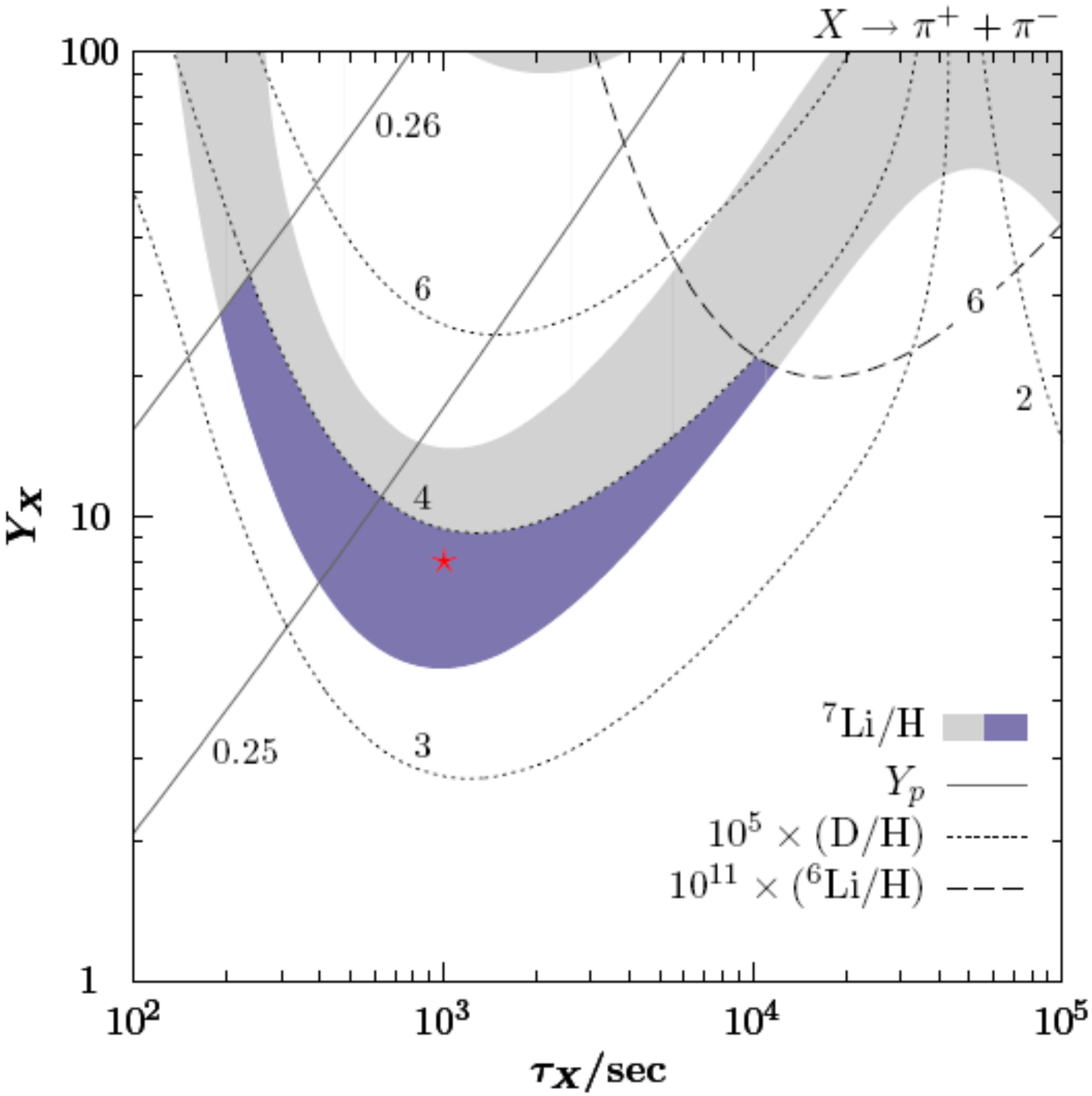


FIG. 4. $n - n'$ oscillation. Contour plots in the space of the two physical parameters $(\Delta m, m_{12})$ assuming $\eta = \eta_{CMB}$ and $x = 0.2$ respectively with $\eta' = 10^{-10}$ (left) and $\eta' = 3 \times 10^{-10}$ (middle) and $x = 0.5$ and $\eta' = 10^{-10}$ (right). The blue strip corresponds to models for which the BBN predictions are compatible with the observational constraints for both helium-4 and lithium-7. The solid lines indicate the prediction of deuterium abundance D/H = $\{3.6, 3.8, 4.0, 4.2, 4.4, 4.6\} \times 10^{-5}$ from top to bottom.

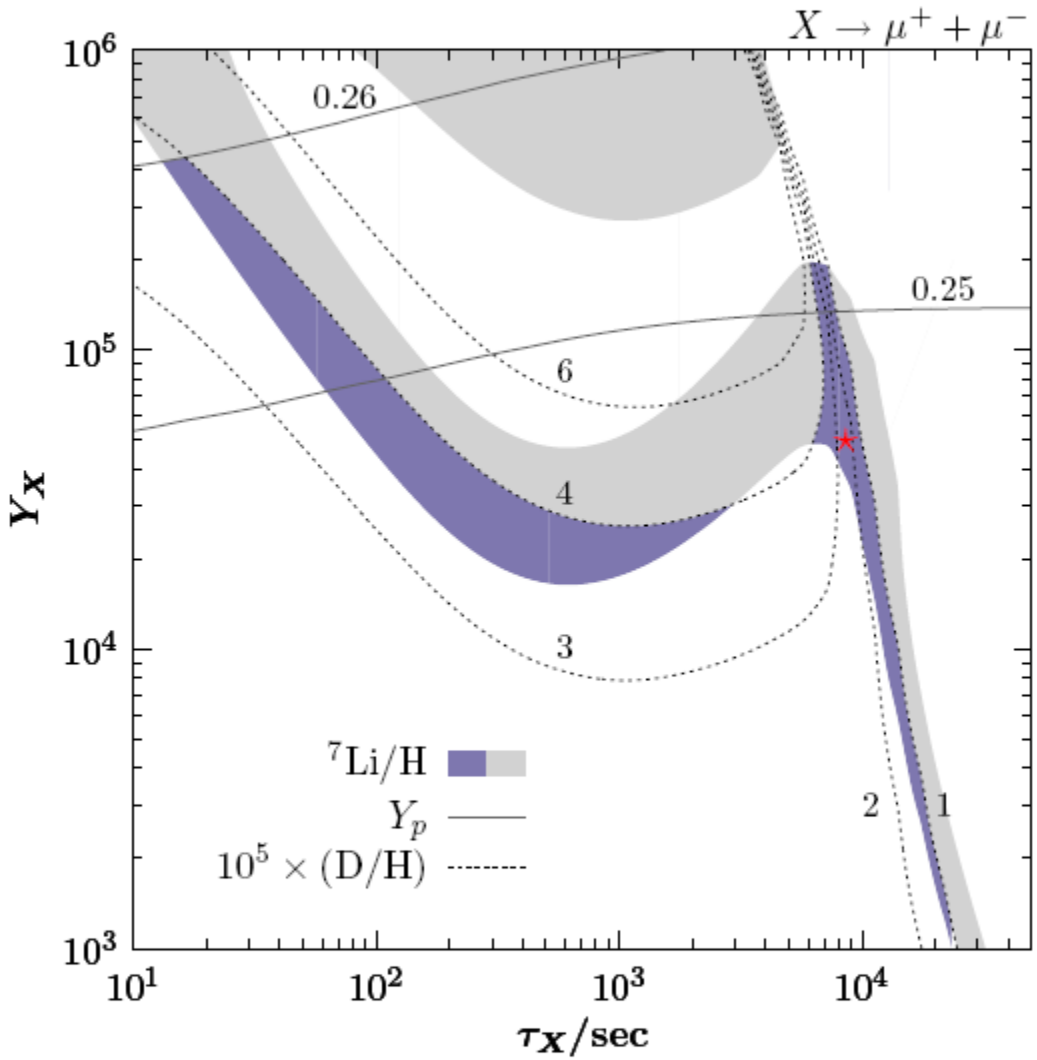
Neutron injection by itself does not solve ^{7}Li problem because it leads to overproduction of D.

^{7}Li reduction from π^{-} injection (π^{-}+p → n+π^{0})



Wide range of lifetimes is suitable (MP, Pradler 2010). But D/H is too high relative to observations.

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



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

Conclusions for decaying particles

- *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.

Metastable particles absorbed by ^{7}Be or D (Goudelis, Pradler, MP, PRL 2016)

- *Idea:* A O(10 MeV) mass particle "X" could survive to t ~ 1000 sec (which is non-trivial) and modify BBN by participating in nuclear reactions
- Interesting regime is when $\rho_B << \rho_V << \rho_\gamma$. (Abundances much larger than thermal – but reduced compared to T^3)
- $m_X <$ ^{4}He binding – otherwise the production of "zombie neutrons" from ^{4}He (credit for the name goes to R. Harnik)
- $^7\text{Be} + \text{X} \rightarrow {}^3\text{He} + {}^4\text{He}$; $\text{D} + \text{X} \rightarrow \text{n} + \text{p}$; etc will happen with rates proportional to $\sim$ (small coupling)^2 n_X
- At t ~ 1000 sec destroyed ^{7}Be cannot be resurrected, but "borrowed" neutrons from spalled D are incorporated back via $\text{n+p} \rightarrow \text{D} + \gamma$

- *Scenario A:*

A new massive particle X, (2 MeV < m_X < 20 MeV), that is directly absorbed by nuclei

$$n_b \lesssim n_X < \frac{T}{E_X} \times n_\gamma$$

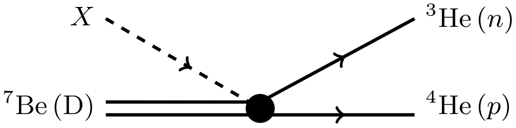
- *Scenario B*:

A progenitor particle X_p decays to *non-thermal* radiation-like states, e.g. $X_p \rightarrow$ XX, and they are gradually red-shifted by the expansion .

(4 MeV < m_{Xp} < 40 MeV)

Metastable particles absorbed by ^{7}Be or D

$$\mathrm{R1}:\ {}^7\mathrm{Be}(X,\alpha)^3\mathrm{He};\quad \mathrm{R2}:\ \mathrm{D}(X,p)n$$



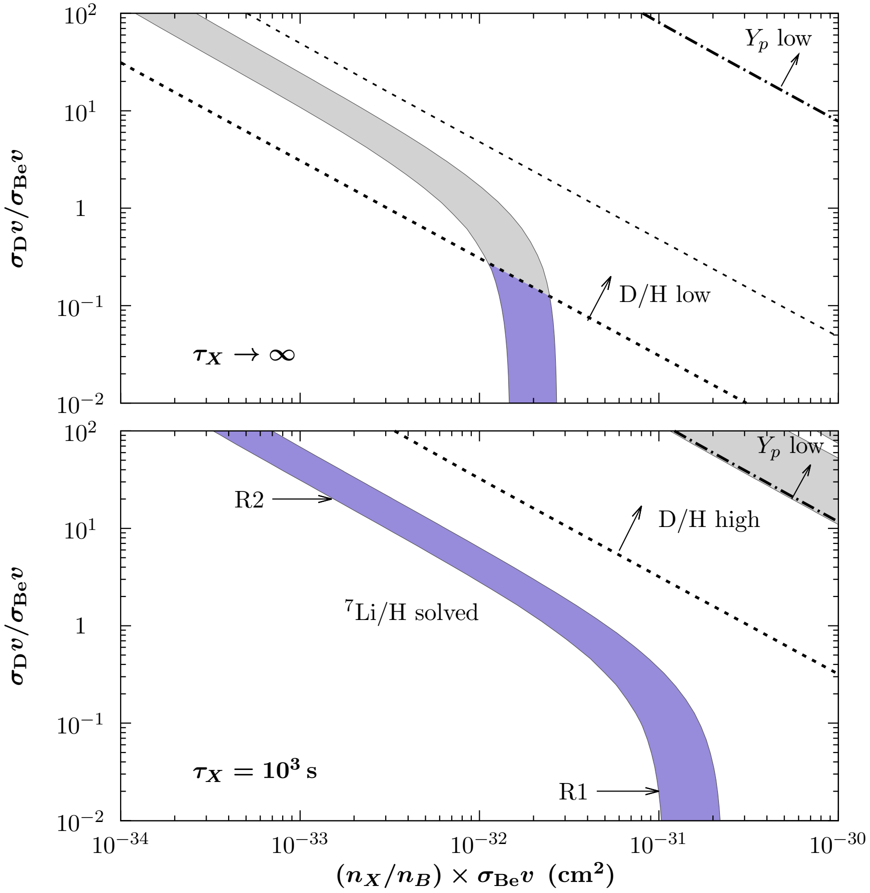


FIG. 2. The contours of light element abundances as a function of the two reaction rates R1 and R2, for $\tau_X \gg t_\mathrm{BBN}$ (top panel), and $\tau_X = 10^3$s (lower panel). Inside the shaded regions, the lithium problem is solved.

$$\mathrm{R1}:\quad (n_X/n_b) \times \sigma_\mathrm{Be} v \simeq (1-2) \times 10^{-31}\ \mathrm{cm}^2,$$

$$\mathrm{R2}:\quad (n_X/n_b) \times \sigma_\mathrm{D} v \simeq (3-7) \times 10^{-31}\ \mathrm{cm}^2.$$

“Borrowed” neutrons are returned to D

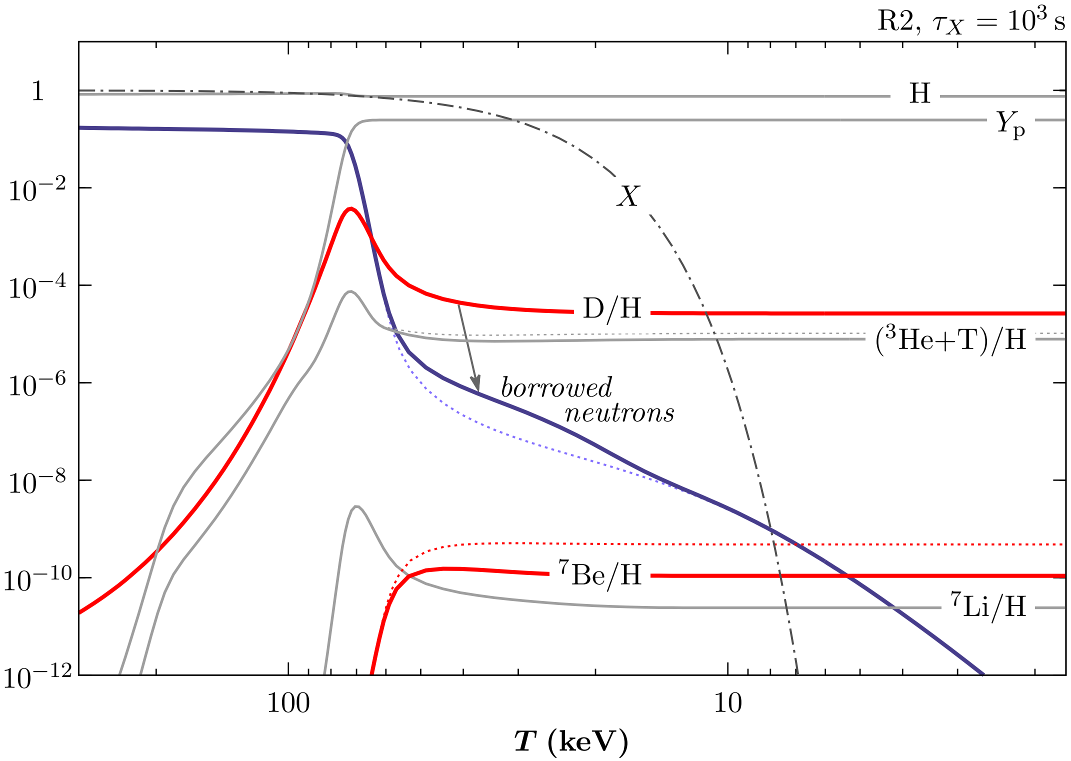


FIG. 3. Temperature evolution of elemental abundances, with BBN modified by R2, initiated by X with $\tau_X = 10^3$ s and $\frac{n_X}{n_b}\sigma_D v = 5 \times 10^{-32}$ cm^2. The temporary increase in n leads to the suppression of ^{7}Be but does not affect $[\text{D/H}]_{\text{BBN}}$.

- “Borrowed” neutrons comes from spalled D, but are incorporated back via n+p → D + γ

Candidate particles ?

- *Must be "leptophobic":* otherwise X → ee decays will shorten the lifetime
- *Many scenarios are tuned:* "dark photon" would not work (not leptophobic), but dark "baryonic vector" V may work, but the coupling to electrons needs to be tuned below the loop-induced value.
- *Axion-like particles (ALPs)* are tightly constrained by flavour physics due to top-W loops. We need ~ 1/TeV couplings…
- *ALPs coupled to down-type quarks.*

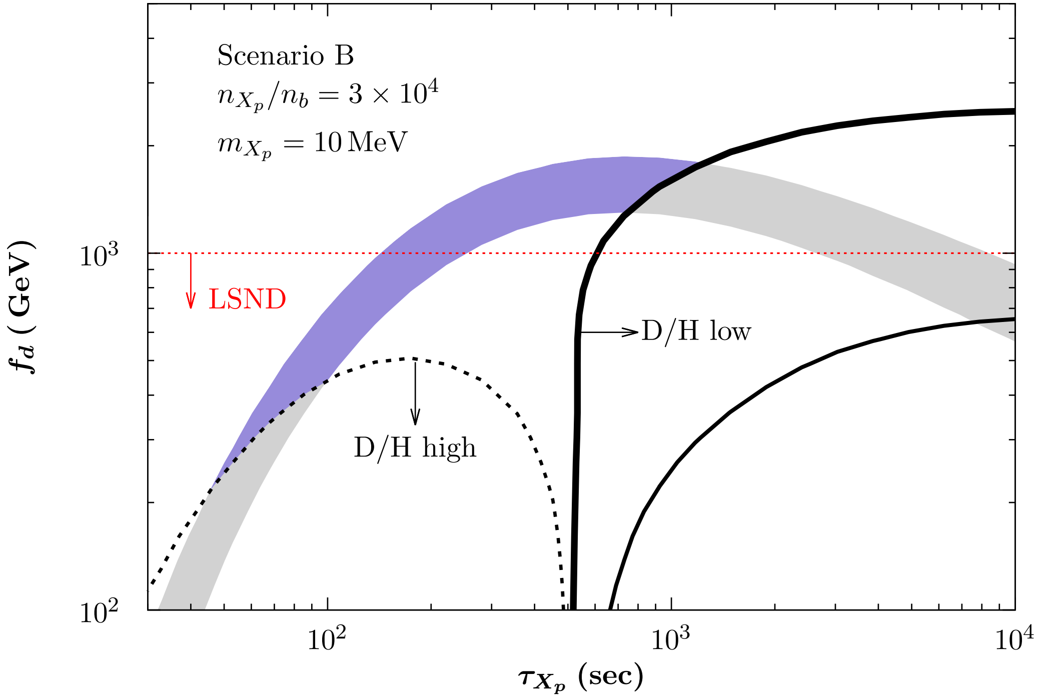
$$\mathcal{L}_{aq} = \frac{\partial_\mu a}{f_d} \bar{d}\gamma_\mu\gamma_5 d \quad \Longrightarrow$$

$$\frac{\sigma_{\mathrm{abs},i} v}{\sigma_{\mathrm{photo},i} c} \simeq \frac{C_i}{4\pi\alpha} \times \frac{m_a^2}{f_d^2},$$

$$\mathcal{L}_{a\pi N} = \frac{\partial_\mu a}{f_d}\left[f_\pi \partial_\mu \pi^0 + \frac{4}{3}\bar{n}\gamma_\mu\gamma_5 n - \frac{1}{3}\bar{p}\gamma_\mu\gamma_5 p\right].$$

ALP couplings suggested by BBN

$$\frac{\sigma_{\mathrm{abs},i} v}{\sigma_{\mathrm{photo},i} c} \simeq \frac{C_i}{4\pi\alpha} \times \frac{m_a^2}{f_d^2},$$



- *Beam dump experiments appear to be very sensitive!*

Conclusions

- *“Carefully chosen” models of new physics can solve “lithium problem” – overproduction of 7Be in standard BBN:*

1. Combination of neutron injection and energy injection. Particles with lifetimes ~ 10^4 sec seem to be needed. Things got harder because D/H shows perfect agreement with standard BBN.
2. *Metastable charged particles, especially those that can induce Be→ Li transition, can reduce* ^{7}*Be. 500 sec < Lifetimes < 2000 sec. [Stable for the LHC.]*
3. ~ 10 MeV relic particles that survive in large numbers to ~ 500-1000 seconds can destroy ^{7}Be, but be harmless for D/H, as neutrons are incorporated back to D.
4. Future? More understanding of Li in atmospheres of Pop II stars and the “meltdown” of Spite plateau at low Z. Increased data sample.

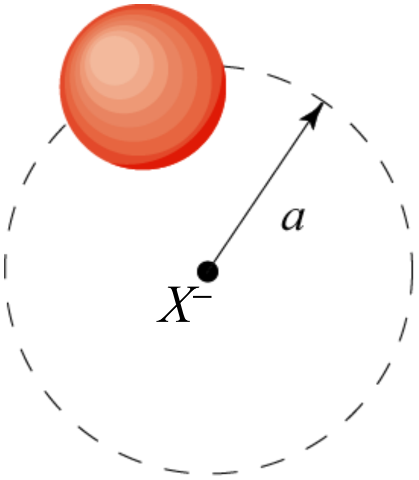
- *Extra slides*

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}HeX$^-$)

Bohr radius is 2 times larger than nuclear

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

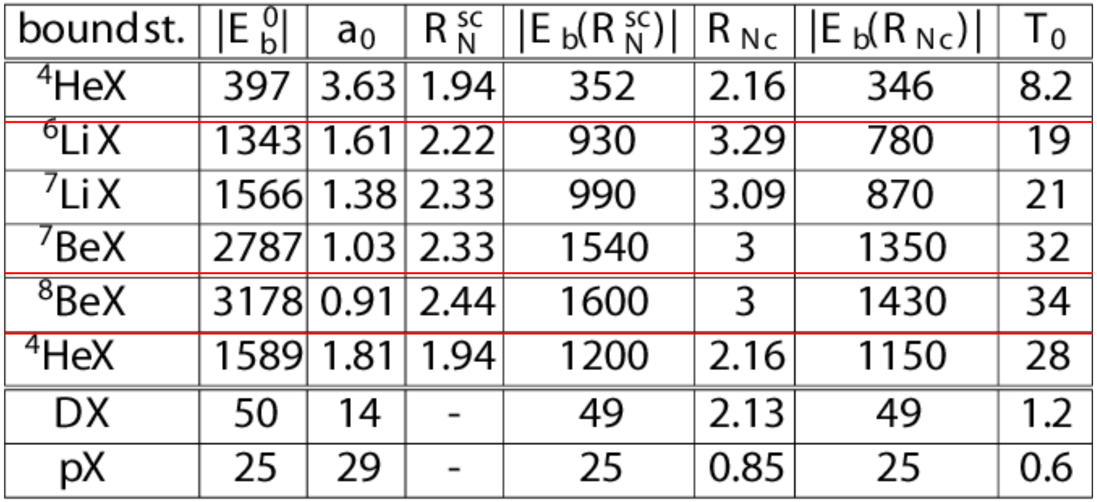
$$E_b = 1350\,\mathrm{KeV};\ a = 1.0\,\mathrm{fm}$$

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

(^{7}BeX$^-$)

Bohr orbit is within nuclear radius

Binding energy and stability thresholds



bound st.	$\vert E_b^0\vert$	a_0	R_N^{sc}	$\vert E_b(R_N^{sc})\vert$	R_{Nc}	$\vert E_b(R_{Nc})\vert$	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.

After bound states have formed, new reaction channels open up (MP, 2006)

- Main SBBN channel for ^{6}Li production

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

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

- Main CBBN channel for ^{6}Li production

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

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

- **Catalytic suppression of ^{7}Be:** $\boldsymbol{(^7\mathrm{Be}X^-) + p \rightarrow (^8\mathrm{B}X^-) + \gamma}$

  or $\boldsymbol{(^7\mathrm{Be}X^-) \rightarrow {}^7\mathrm{Li} + X^0 + \nu}$

- *One can suppress* ^{7}Li+^{7}Be *without affecting* D/H *and keeping* ^{6}Li *under control if* τ_X *is in the interval 500-2000 seconds.*

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

(Bird, Koopmans, MP, 2007)

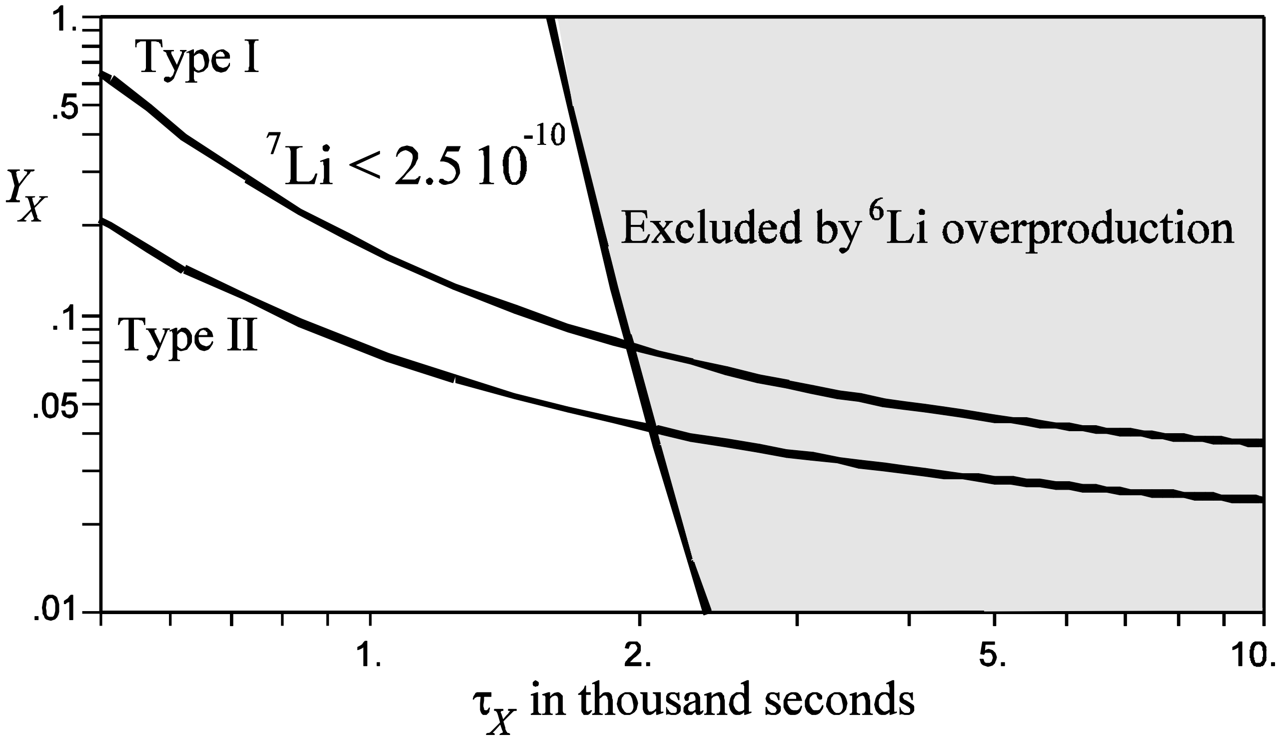
- The “bottleneck” is creation of (^{7}BeX^-) bound states that is controlled by ^{7}Be+X^--> (^{7}BeX^-) + γ reaction
- There are two main destruction channels that are catalyzed:

1. p-reaction: (^{7}BeX^-) + p -> (^{8}BX^-) + γ by a factor of >1000
   relative to ^{7}Be + p -> ^{8}B + γ
2. In models with weak currents, the “capture” of X^- is catalyzed:
   (^{7}BeX^-) -> ^{7}Li + X^0 ,

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

One needs $Y_X = n_X/n_B > O(0.01)$ at T~40 keV to reduce ^{7}Be that way.

Combination 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.

μBBN or νBBN

How many muons (source of antineutrinos) do we need?

Rate for proton-induced conversion of neutrino to neutron is smaller

$$\Gamma_p^\nu = n_p \sigma_{pn}^{\bar{\nu}} \simeq 10^{-41}\ \mathrm{cm}^2 \times \frac{n_p E_\nu^2}{(10\ \mathrm{MeV})^2} \simeq (3.6 \times 10^{-12}\ \mathrm{sec}^{-1}) \times \frac{T_9^3 E_\nu^2}{(10\ \mathrm{MeV})^2}$$

than Hubble rate by about nine orders of magnitude

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

O(10^4) muons per proton is required.

“Easy to arrange”

Non-equilibrium BBN: synthesis of A=6,9 elements in secondary and tertiary collisions

- *Secondary processes*: Hadronic energy injection leads to spallation on ^{4}He, creating energetic A=3 nuclei. A=6 will form:

$$^3\mathrm{H} + {}^4\mathrm{He} \to {}^6\mathrm{Li} + n, \quad Q = -4.78\mathrm{MeV};$$

$$^3\mathrm{He} + {}^4\mathrm{He} \to {}^6\mathrm{Li} + p, \quad Q = -4.02\mathrm{MeV};$$

$$^3\mathrm{H} + {}^4\mathrm{He} \to {}^6\mathrm{He} + p, \quad Q = -7.5\mathrm{MeV},$$

Dimopoulos, Hall, Starkman 80s

Below 5 keV, efficiency ~10^{-3}

Strong constraints on late decays

- *Tertiary processes:* Emerging ^{6}He and ^{6}Li are energetic and will further collide with ^{4}He in the plasma forming ^{9}Be with similar efficiency, MP Pradler 2010.

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

$$^6\mathrm{He} + {}^4\mathrm{He} \to {}^9\mathrm{Be} + n, \quad Q = 0.60\mathrm{MeV}$$

The early time energy injection (T~20 keV) would result in the enhancement of ^{9}Be/^{6}Li.

Astrophysical solutions of ^{7}Li discrepancy

PopII stars can themselves deplete lithium from their atmospheres by by diffusional settling into hot interior [where it gets destroyed]counteracted by turbulent mixing: (G. Michaud et al, 1980s-, Korn et al., 2006, finds evidence for depletion in a GC).

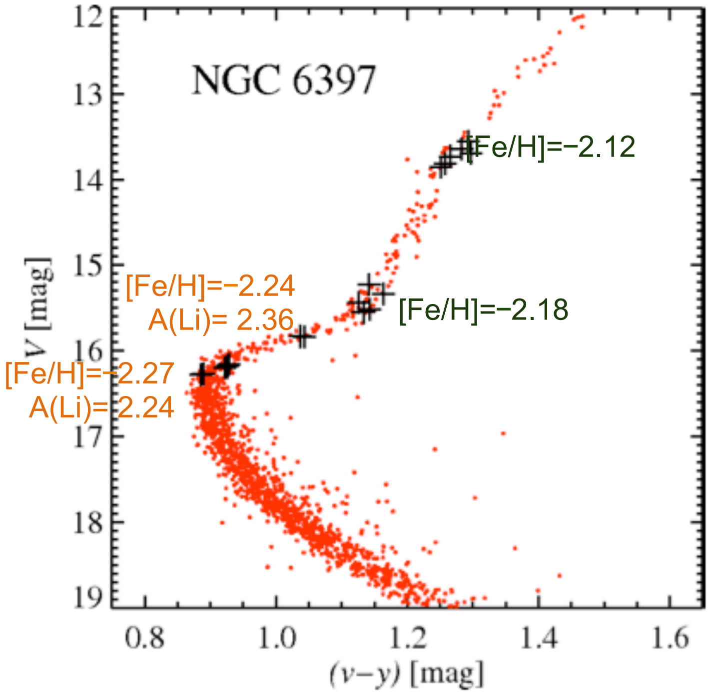


FIG. 2.— Colour-magnitude diagram of NGC 6397 with the four groups of stars (from left to right TOP, SGB, bRGB and RGB stars) marked by crosses.

nt

original lithium abundance
2.24 + 0.26= 2.50 ???

Can it provide a factor of 2-3 suppression?

Can the suppression work uniformly along the Spite plateau, without introducing extra scatter?

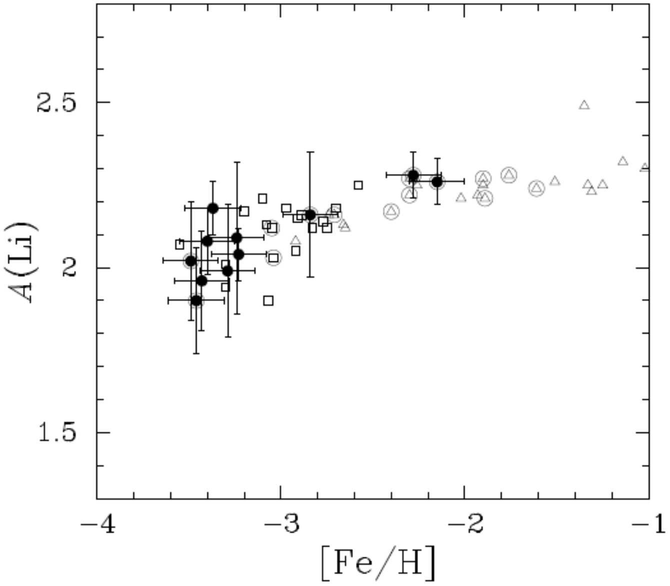
Is there a chance to get rid of ad-hoc parameters for turbulence?

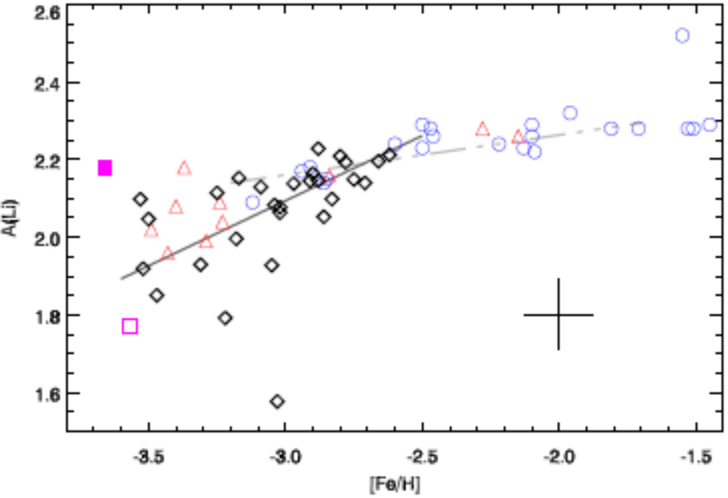
So far it is ad-hoc

M.Spite talk, IAP 2012

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

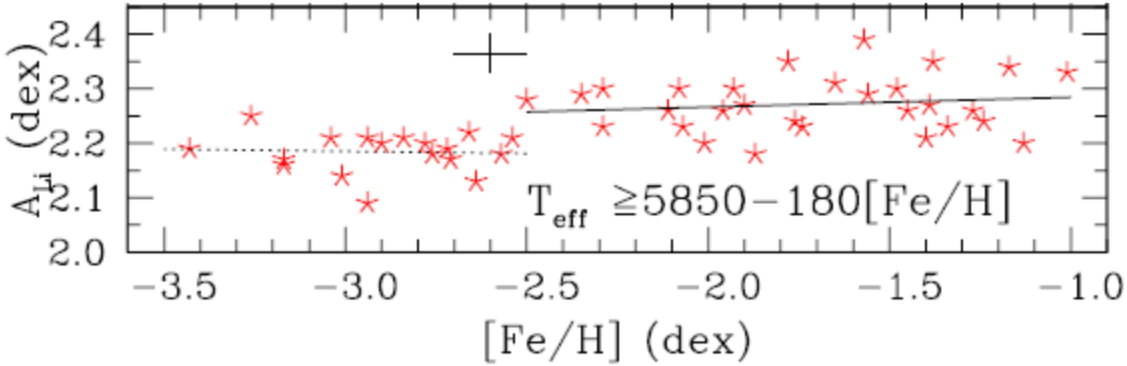
Aoki et al, 2009, reports the suppression of low-metallicity tail of Spite plateau





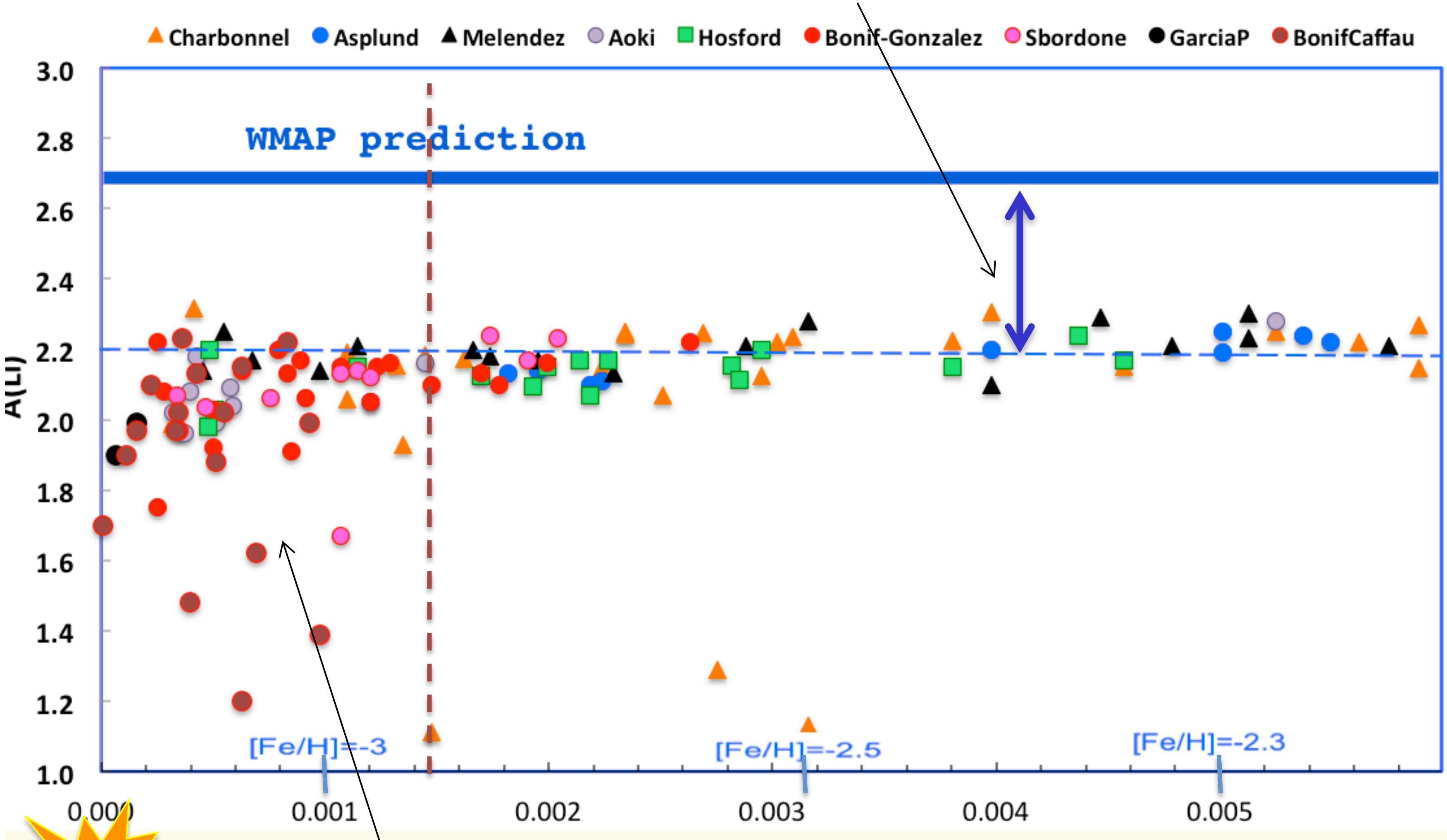
Sbordone et al, 2010, confirms it with higher statistics

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



More than one problem with ^{7}Li?

Problem # 1



Problem # 2

M. Spite talk IAP 2012

What does is mean?

"Crumbling" of the Spite plateau is established below Z < 1.5 10^{-3}. To crown it all, Caffau et al (2011) published the result for the SDSS J102915+172927 star observed with VLT. Z<10^{-6} (!). Otherwise normal looking EMP star. Guess what: ***no lithium detected***. (<10^{-11})

1. It points away from the simple picture that lowest Z stars would "recover" BBN abundances of primordial gas.

2. It makes "new physics" speculations about Li suppression in BBN look a little naïve: it does not fix *all* Li problems.

3. Stellar models with ~ O(3) suppression of Li are also in trouble. Why would it be more suppression at Z→0? Does not make sense...

4. *We have to address* Li *evolution in pre-stellar phase*. What happens to primordial gas, how stars form from it, PopIII etc. (my opinion)

Another look at local variation of Li

$\eta = n_{Baryon}/n_{\gamma}$ is observed globally over many-many-many horizon size patches of the CMB sky.   Lithium is observed in stars in the halo of our galaxy (= not globally).

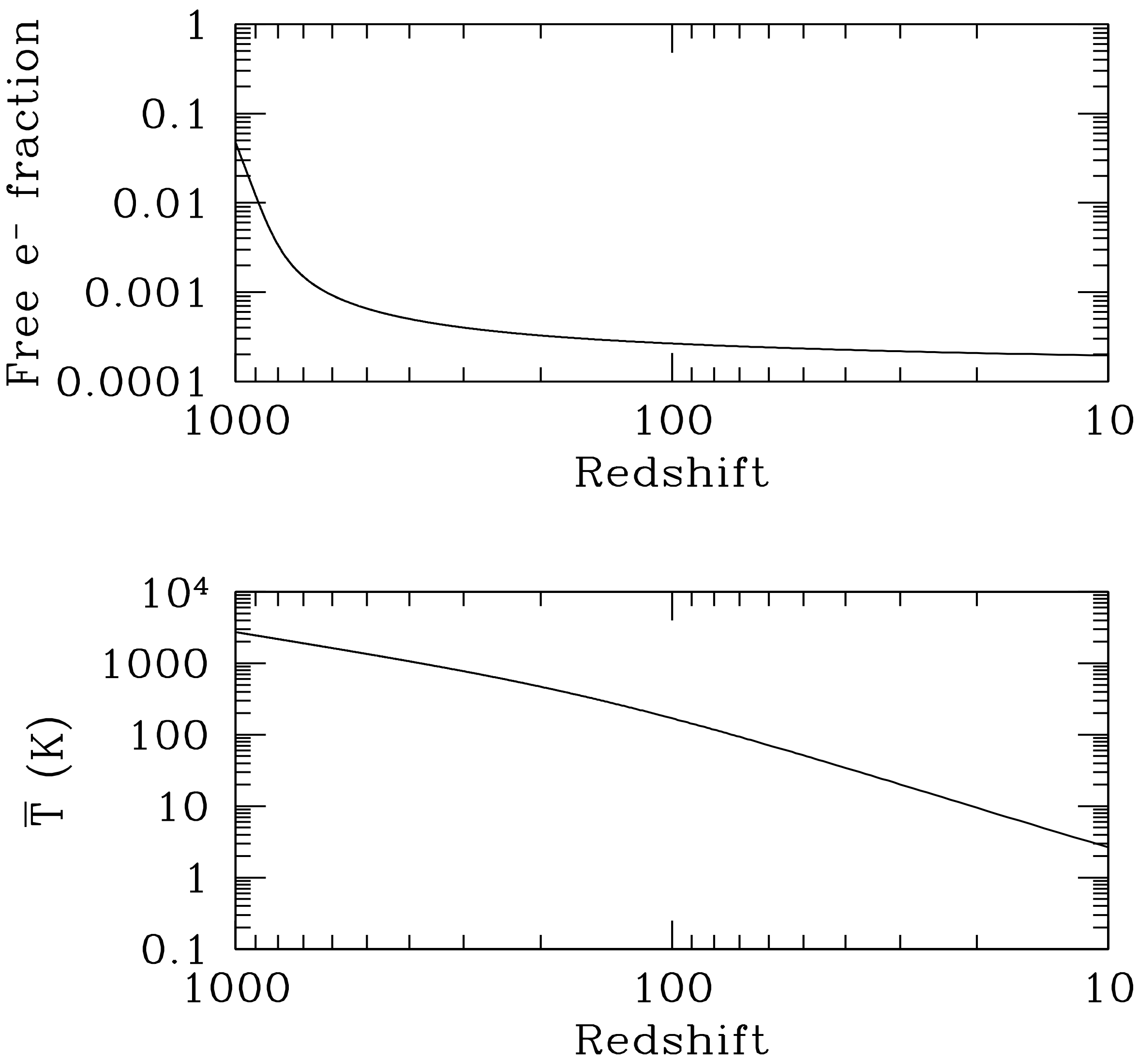
Is there a way of making local Li deficit?

Element-specific processes during gravitational settling of primordial gas in the gravitational wells of dark matter may have led to large local variations of [Li/H]. Is such scenario out of question? Do we expect larger or smaller [Li/H] in gravitational wells?

We (Afshordi, MP, 2012) revisit the issue **of Lithium diffusion after hydrogen recombination** and [astonishingly] find that

$$\mathbf{[Li/H]_{grav\ minimum} < [Li/H]_{BBN}}$$

Evolution of Ionization fraction and T_{gas}



Ionized fraction is small, Y_e ~ few x 10^{-4} but not 0

Lithium stays singly ionized

Li (Z=3) nucleus is the first element to grab first two electrons, and Li^+ ion *never gets its last electron*.

Reasons:

1. Ionization energy for the last electron = 5.39 eV (comp to Hydrogen where it is 13.6 eV). By the time Li+ "wants" to recombine, the fraction of free electrons < 0.01; the rate is < Hubble expansion rate. (Calculations in the 90s showed that up to 50% of Li may get neutral).
2. Non-thermal photons from residual $p + e \rightarrow \mathrm{H} + \gamma$ keep Li singly ionized (Switzer and Hirata, 2005)

No more than few% of Lithium becomes neutral! Are there physical consequences for Li from its charge?

Euler's equation

Consider halos with gas initially dominated by pressure (smaller ones, with mass < Jeans mass), sitting outside of halo virial radius.

$$\frac{\partial \mathbf{v}_a}{\partial t} \simeq -\frac{\nabla P_a}{\rho_a} - \nabla[\phi_g + \frac{q_a \phi_e}{m_a}] - \sum_b \tau_{ab}^{-1}(\mathbf{v}_a - \mathbf{v}_b),$$

acceleration pressure grad gravity electric force scattering (diffusion term)

$$P_a = \rho_a T/m_a, \tau_{ab}^{-1} = \frac{\rho_b \langle \sigma_{ab} v^3 \rangle}{3T m_a m_b (m_b^{-1} + m_a^{-1})^2}$$

Index *a* runs over *species* that include: H, He, *p*, *e*, D, ^{3}He, ^{7}Li

σ_{ab} is a regular transport (momentum-transfer) cross section. When σ_{ab} is infinitely large, diffusion and v_a-v_b is very small, and all primordial soup moves as one liquid, $[n_a/n_b]$ remains constant. As T, P_a and density drop, gas settles to the minimum of ϕ_g while finite σ_{ab} generates diffusion.

Simplified equations: initial moment of structure formation

EM force is much stronger than gravitational. Charges are not separated but E is not 0.

No charge: $\Sigma n_a q_a = 0$. No current: $\Sigma n_a q_a \mathbf{v}_a = 0$.

Let us consider isothermal approximation when elements are initially distributed the same way, and have the same velocity **v** with small variations. Introduce effective residual grav force

$\mathbf{g}_{\mathrm{eff}} = \mathbf{g}_g - d\mathbf{v}/dt$. Same distribution means (Chuzhoy, Nusser)

$$\frac{\nabla P_a}{n_a m_a} = \frac{\sigma n_a m_a}{\sigma n_a}\frac{1}{m_a}\mathbf{g}_{\mathrm{eff}} = \frac{\overline{m}}{m_a}\mathbf{g}_{\mathrm{eff}} \qquad \overline{m} = \frac{4m_p + 12m_p}{1+12} = \frac{16}{13}m_p$$

Then our equations simplify to algebraic relations

$$\left(\frac{\overline{m}}{m_a} - 1\right)\mathbf{g}_{\mathrm{eff}} = \frac{q_a \mathbf{E}}{m_a} + \sum \frac{\mathbf{v}_a - \mathbf{v}_b}{\tau_{ab}}$$

Approximate solutions: H^+ diffuses out

Electron equation gives relation between **E** and $\mathbf{g}_{\text{eff}}$ because $1/m_e$ terms dominate.

$$\mathbf{E} = -\frac{\overline{m}}{e}\mathbf{g}_{\text{eff}}$$

Plugging this into the proton equation we get

$$\frac{\mathbf{v}_p - \mathbf{v}_{\text{H}}}{\tau_{\text{p}-\text{H}}} = -\mathbf{g}_{\text{eff}}\left(\frac{2\overline{m}}{m_p} - 1\right)$$

Ionized Hydrogen (*e* and *p*) diffuses against $\mathbf{g}_{\text{eff}}$. Main physical reason: because of the tight coupling, *e* and *p* "share" the same mass m_p. Effectively *twice lighter* than neutral H.

Where would $^7\mathrm{Li}^+$ go?

Li^+ is a small perturbation. Its mass pulls it “down”; neutral H pushes it down, but free protons push it “up”. Main equation:

$$\mathbf{g}_{\mathrm{eff}}\left(\frac{\overline{m}}{7m_p}-1\right)=-\mathbf{g}_{\mathrm{eff}}\frac{\overline{m}}{7m_p}-\frac{\mathbf{v}_{\mathrm{Li}}-\mathbf{v}_p}{\tau_{\mathrm{Li-p}}}-\frac{\mathbf{v}_{\mathrm{Li}}-\mathbf{v}_{\mathrm{H}}}{\tau_{\mathrm{Li-H}}}$$

Trivially solving for the velocity difference we find:

$$\mathbf{g}_{\mathrm{effective}}\underline{\left(\frac{59}{91}-\frac{19}{13}\frac{\tau_{\mathrm{p-H}}}{\tau_{\mathrm{Li-p}}}\right)}=(\mathbf{V}_{\mathrm{Li}}-\mathbf{V}_{\mathrm{H}})\times\left(\frac{1}{\tau_{\mathrm{Li-H}}}+\frac{1}{\tau_{\mathrm{Li-p}}}\right)$$

Where exactly lithium is “going” depends on the sign of the underlined bracket.

Positive sign: Lithium would “sink”, and $[\mathrm{Li/H}]_{\mathrm{halo}} > [\mathrm{Li/H}]_{\mathrm{BBN}}$

Negative sign: Lithium would “float”, $[\mathrm{Li/H}]_{\mathrm{halo}} < [\mathrm{Li/H}]_{\mathrm{BBN}}$

Main cross sections

We need *ion-atom* and *ion-ion* cross sections.

p-H scattering is complicated. I will use approximation from Massey, Mott textbook:

$$\langle \sigma_{\mathrm{pH}} v^3 \rangle = \langle \text{"Massey} - \text{Mott"} \rangle = 2.2\pi \times \frac{18T}{m_p} \left(\frac{2Ry}{m_p} \right)^{1/2} a^2_{\mathrm{Bohr}}$$

In comparison, Li-p scattering is simple: Rutherford cross section:

$$\langle \sigma_{\mathrm{Lip}} v^3 \rangle = \langle \text{"Rutherford"} \rangle = \frac{8\pi^{1/2}\alpha^2}{\mu^2_{17}} \left(\frac{\mu_{17}}{2T} \right)^{1/2} \ln \Lambda$$

Scattering cross section of charged particles is stronger, and is increasing as temperature drops. Coulomb log is huge.

$$\ln \Lambda \simeq 40 + \frac{3}{2} \ln \left(\frac{T_e}{T \gamma X_e^{1/3}} \right)$$

Lithium diffuses out!

Smallness of Xe is more than compensated by the largeness of the Rutherford cross section

$$\frac{\tau_{\mathrm{p-H}}}{\tau_{\mathrm{Li-p}}} \sim O(1) \times \frac{n_{\text{free protons}}}{n_{\text{neutral H}}} \frac{\langle \sigma_{\mathrm{Lip}} v^3 \rangle}{\langle \sigma_{\mathrm{pH}} v^3 \rangle}$$

$$\sim 400 \times \frac{X_e}{10^{-3}} \times \frac{\ln \Lambda}{40} \left(\frac{0.01\mathrm{eV}}{T_{\mathrm{baryons}}} \right)^{3/2}$$

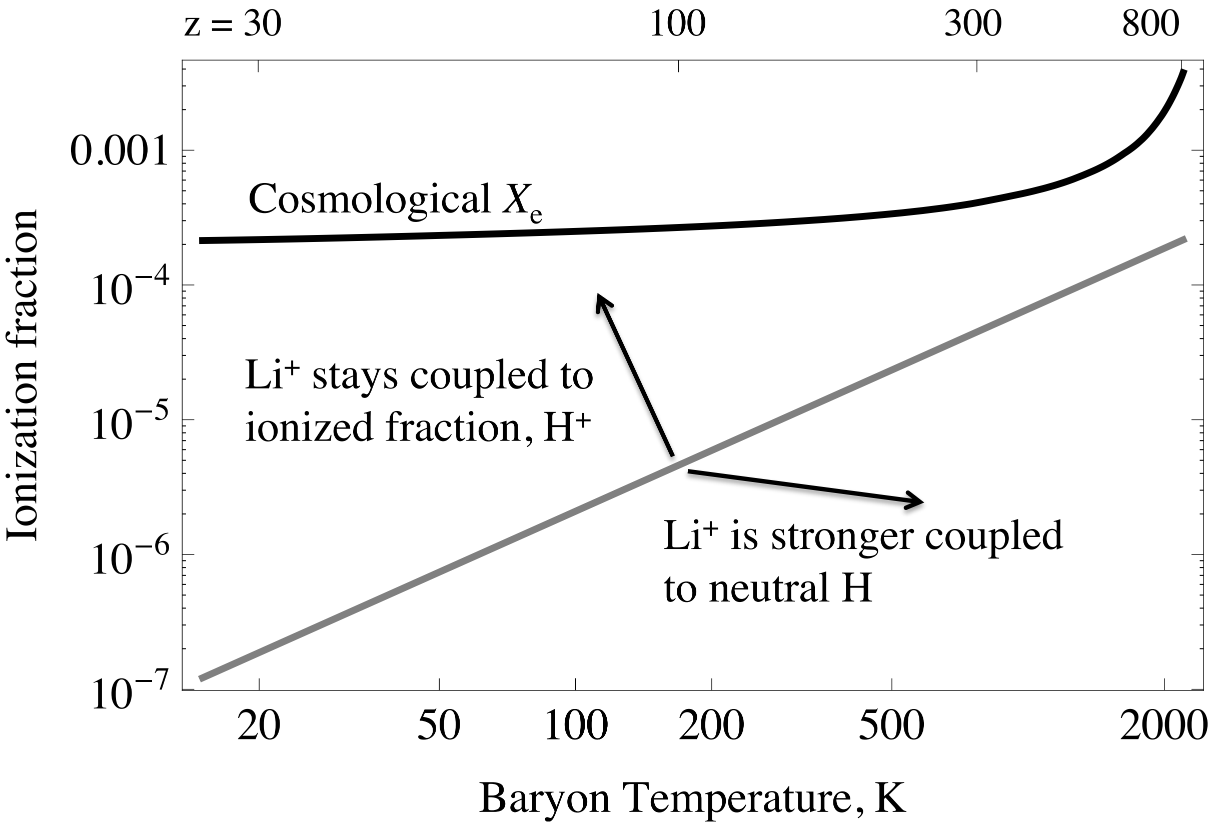
The crucial combination that determines the sign of the diffusion,

$$\frac{59}{91} - \frac{19}{13} \frac{\tau_{\mathrm{p-H}}}{\tau_{\mathrm{Li-p}}} < 0; \quad \mathbf{V}_{\mathrm{Li}} - \mathbf{V}_{\mathrm{H}} \propto -\mathbf{g}_{\mathrm{eff}}$$

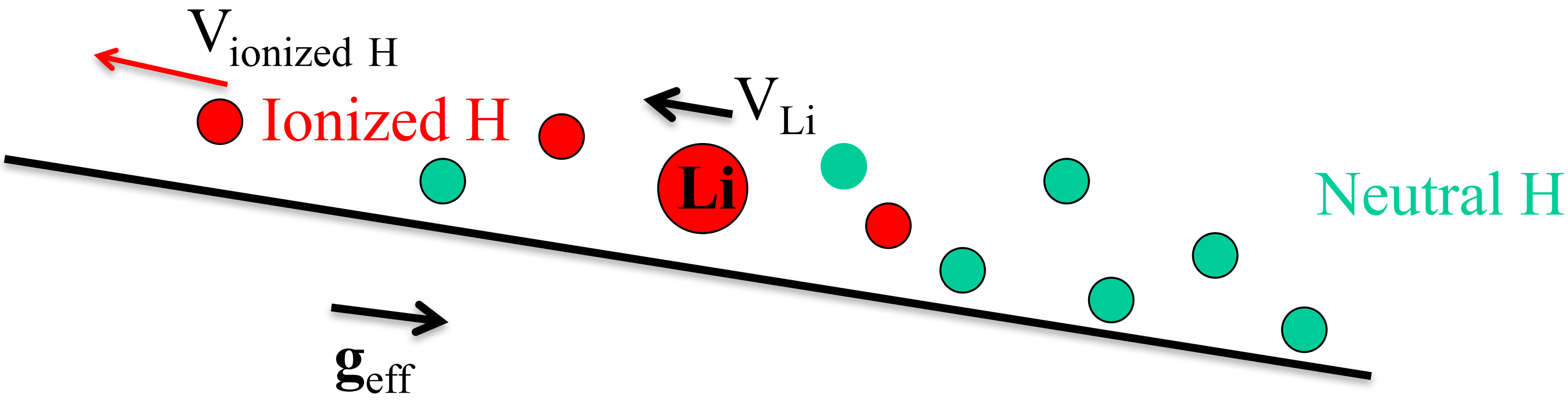
Scattering of charged particles wins, and ^{7}Li stays with ionized H, and therefor effectively diffuses out of over-densities:

$$[\mathrm{Li/H}]_{\text{grav minimum}} < [\mathrm{Li/H}]_{\mathrm{BBN}}$$

Lithium diffuses out!



Pictorially…



$$[\mathrm{Li/H}]_{\text{grav minimum}} < [\mathrm{Li/H}]_{\text{BBN}}$$

While we have proven that the initial direction of Li diffusion reduces its concentration at the bottom of gravitational wells, it is more involved to quantify the resulting deviation from BBN.

Helium, on the other hand, diffuses towards the bottom of the potential well.

Could variation of [Li/H] reach O(1)?

In the limit $Y_e\ \sigma_{\mathrm{Rutherford}} >> \sigma_{\mathrm{Massey\text{-}Mott}}$ Li^+ "stays" with p (in reality, there is a factor of ~10-100 for the ratio of cross sections). Then Li^+ and p spatial variations are related, and we need to quantify how much $n_{\mathrm{ionized\ H}}/n_{\mathrm{neutral\ H}}$ can vary. Introduce variable density parameter, that obeys continuity equation

$$\dot{\delta}_a = -\nabla \cdot \mathbf{v}_a, \quad \delta_a \equiv \ln(\rho_a/\langle\rho_a\rangle).$$

(In my previous treatment δ_a<<1). Variation of density can be integrated within certain time window,

$$\Delta[\mathrm{Li/H}] \simeq \Delta[\mathrm{p/H}] \simeq \int_{t_i}^{t_f} dt \frac{\nabla \mathbf{g}}{1/\tau_{p-\mathrm{H}}}$$

$$\sim O(10^{-4}) \times \int_{t_i}^{t_f} \frac{\rho_{\mathrm{DM\ \ halo}}(t)}{\rho_{\mathrm{DM\ \ cosmic}}(t)} \mathrm{Hubble}(z=10)dt$$

Can reach O(1) only if the value of the integral is large.

Implications for the Li problem

The fact that Li stays ionized and more tightly coupled to ionized than to neutral fraction of H could be a good news for the solution to the puzzle(s) of its abundance.

In my simplistic diffusion-based estimate, one needs a rather large value for the integral. In usual structure formation models $\rho_{\text{halo DM}}(t) \sim 200\, \rho_{\text{cosmic DM}}(t)$. This appears to be able to influence Li abundance at O(%) level. However, we [Milky Way] could have originated from some regions with elevated

$\rho_{\text{halo DM}}(t)/\rho_{\text{cosmic DM}}(t)$, so that variation can be ~ O(1)

We believe that the correct question to ask is not necessarily "who killed Lithium" but what are the [cosmological] chances that $[\mathrm{Li/H}]_{\text{our galaxy + neighbourhood}} \sim 0.3\, [\mathrm{Li/H}]_{\mathrm{BBN}}$?

Conclusions

1. Lithium problem is a “sore point” in modern cosmology: biggest tension between BBN+WMAP and observations.

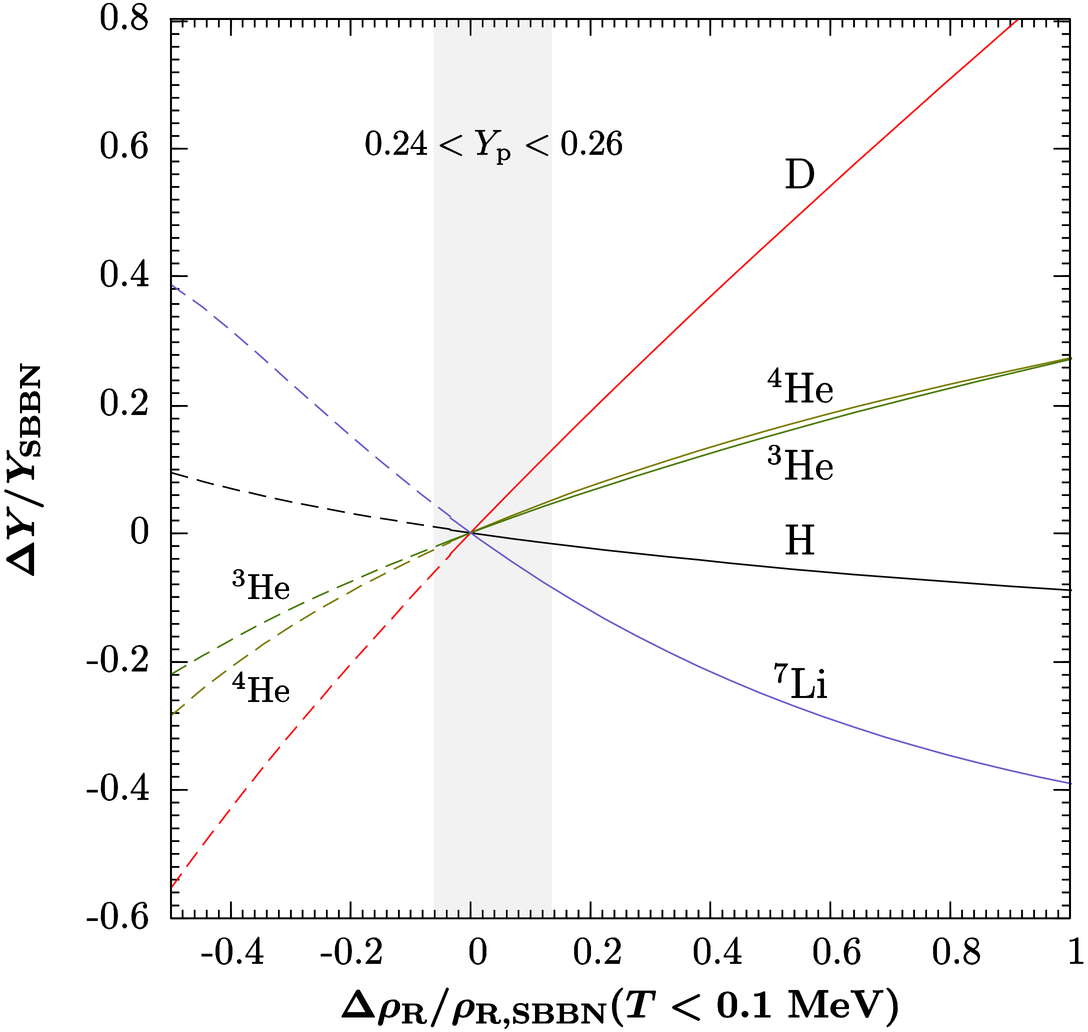
2. Nuclear physics [even in some exotic form] is not responsible for Li under-abundance.

3. Exotic models of particle physics [decaying particles, catalyzed BBN] can reduce ^{7}Li. Need “independent” verification at LHC.

4. Recent observations of scatter/suppression of Li/H at lowest Z lead us to believe that some important ingredients are missing.

1. Between recombination and re-ionization Li remains in a singly ionized state, which ensures its tight coupling to ionized H. Relative to neutral H, Li^{+} diffuse against the direction of gravitational force. As a result $[Li/H]_{\text{grav minimum}} < [Li/H]_{\text{BBN}}$

Sensitivity to Dark Radiation (changing timing)

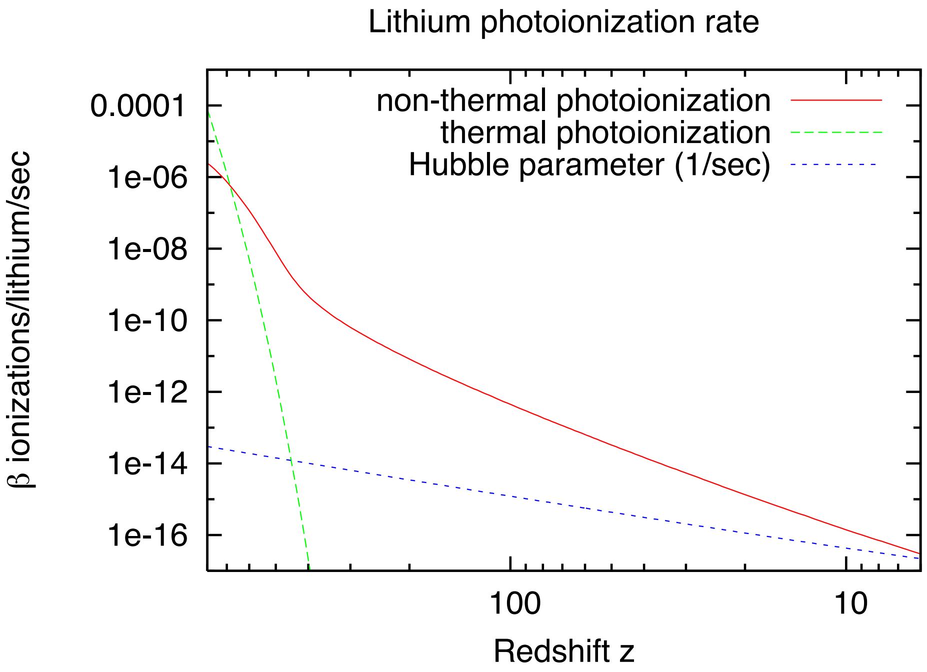


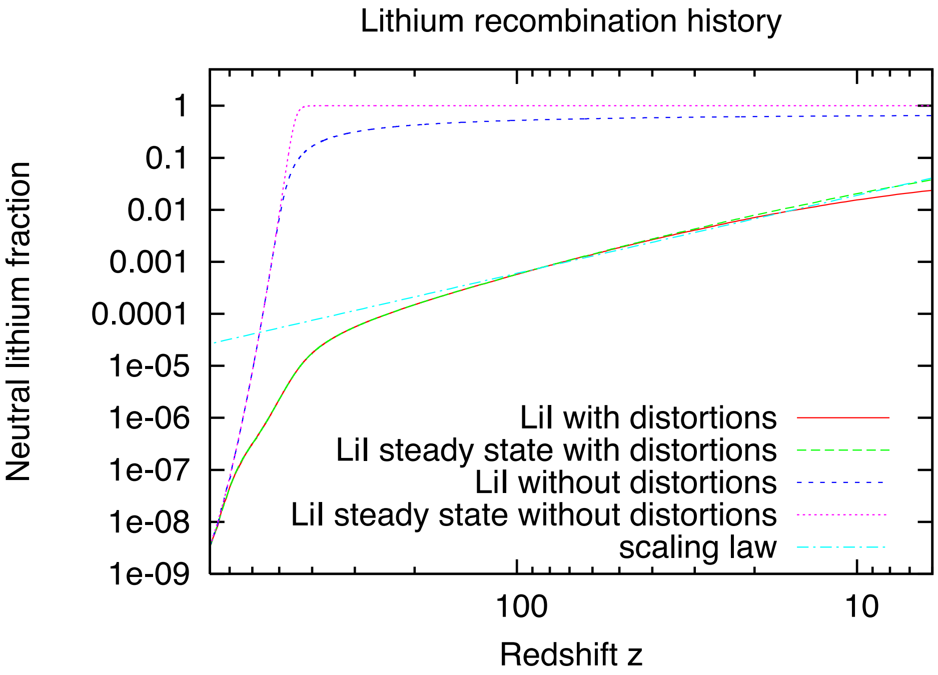
Helium abundance provides evidence for ~ 3+/-1 neutrino species. It does not allow for more than 20% change in the total energy density of the Universe.

Li7 cannot be reduced by varying the amount of "dark radiation".

(From MP, J.Pradler, Ann.Rev.Nucl.Part.Sc. 2010)

5. Switzer and Hirata, 2005

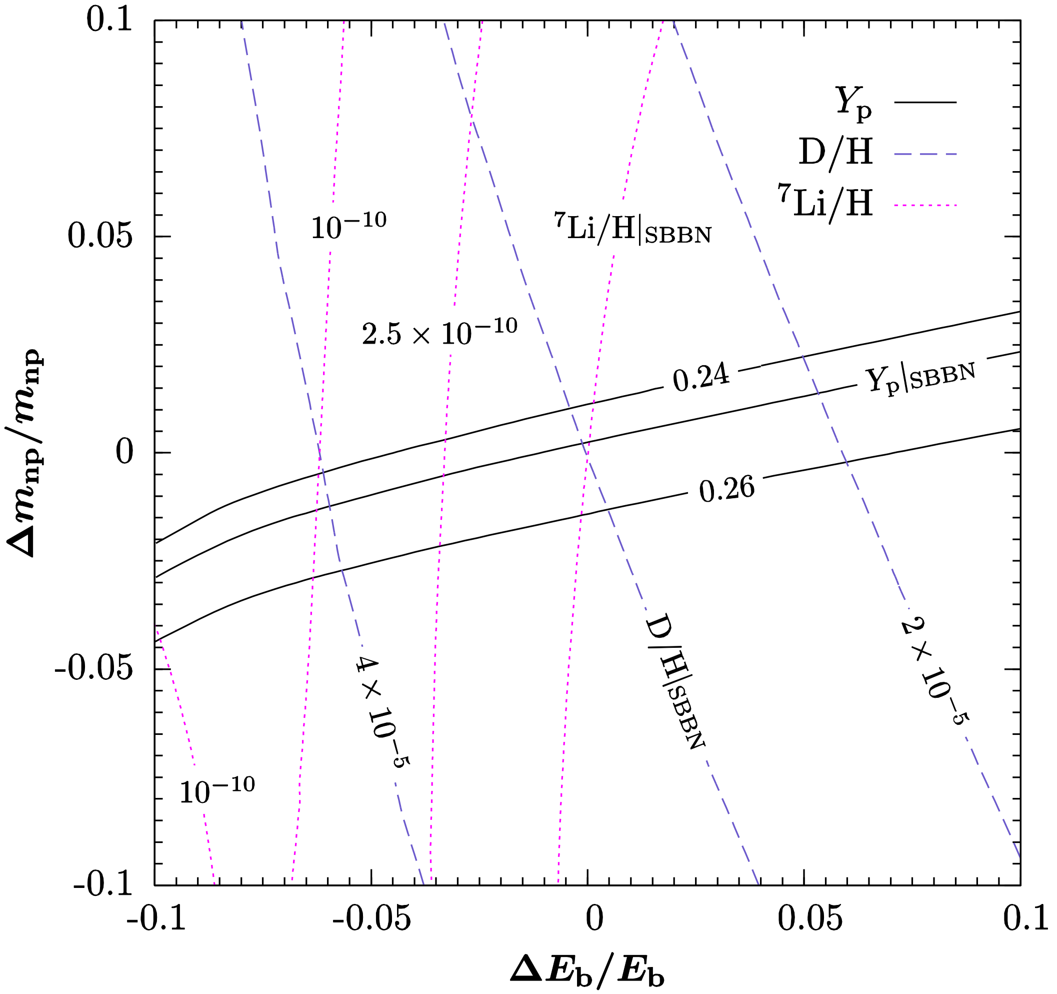

Lithium photoionization rate


Lithium recombination history

(Neglecting non-thermal photons leads to an overestimate of neutral Li abundance by many orders of magnitude)

The fact that Li stays singly ionized was missed in the previous analysis (Medvigy, Loeb, 2001). This is significant for the problem of diffusion as charged particles have different cross sections + EM forcing.

Sensitivity to Changing Couplings (through changing timing)



Helium abundance is sensitive to ¢ m_{np} /m_{np} that affects n/p freeze-out.

D and especially ^{7}Li are super-sensitive to deuterium binding.

5% reduction in D binding reduces ^{7}Li by a factor of 2

(Dmitriev et al 2004, Dent et al. 2007, Cox et al. 2007)

(From MP, J.Pradler, Ann.Rev.Nucl.Part.Sc. 2010)

Why is ^{6}Li so suppressed in SBBN? Why no ^{9}Be or ^{10,11}B is synthesized in SBBN?

^{6}Li can be produced only in ^{4}He(^{2}H,γ)^{6}Li reaction, which is ~ nine orders of magnitude slower than photonless reactions, and four-five orders slower than other γ-reactions. WHY? **The reason is “very special”:** ^{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, ωR_{nucl} » 0.02, this results in a huge suppression:

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

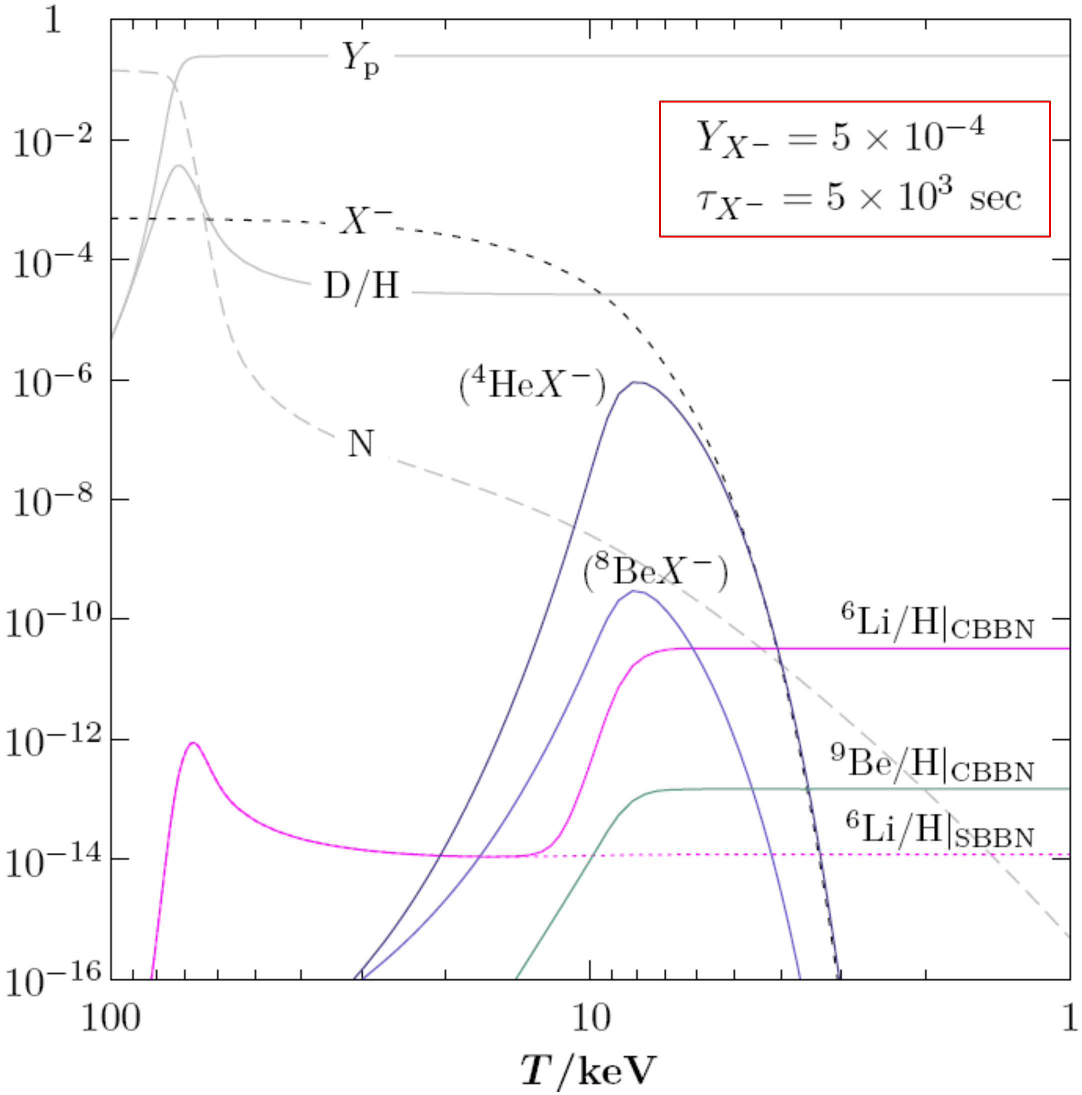
Plus the ^{6}Li + p ! ® + ^{3}He reaction freezes out only below T = 10 keV

^{9}Be and Boron are absent because ^{8}Be is unstable. Probability of triple reactions, e.g. $\alpha + \alpha + n$, is very low.

Any “accidental” suppression of an observable can be turned into a sensitive probe of exotic channels for which this suppression does not apply.

Catalyzed Production of ^{6}Li and ^{9}Be at 10 KeV

(~5:30 a.m, day 1), MP 2006, MP 2007, MP, Pradler, Steffen 2008.



Nuclear catalysis by negatively charged particles (e.g. scalar leptons) is triggered by the formation of bound states with ^{4}He.

Both ^{6}Li and ^{9}Be get a strong enhancement.

For large abundances of Y_X and short lifetimes ^{7}Be+^{7}Li is also reduced (Bird, Koopmans, MP 2007).

Why it is important to study impact of TeV relics on BBN: because you can probe models immune to other tests. LHC may change that!

Suppose nature chose the 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%**

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

Decays of NLSP ! gravitino happens at long time scales: ~ $(M_{\text{Pl}})^2$.

In 25% cases you have catalyzed BBN. In 50% cases you have non-equilibrium BBN

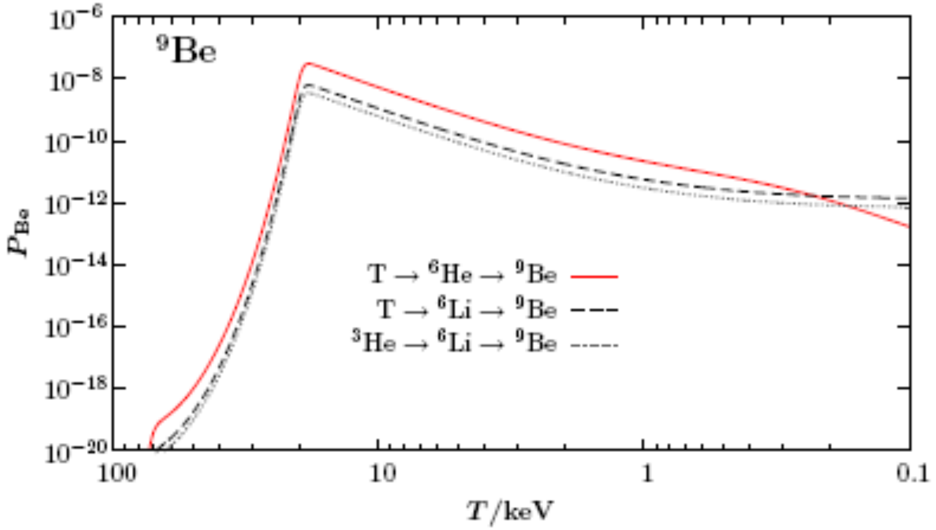
Non-equilibrium generation of ^{9}Be

MP, Pradler, 2010

When “hadronic” energy is injected, the following chain of non-equilibrium transformations becomes possible

$$\mathrm{Energy}_h \rightarrow \ \mathrm{T},\ {}^3\mathrm{He} \ \rightarrow \ {}^6\mathrm{Li},\ {}^6\mathrm{He} \ \rightarrow \ {}^9\mathrm{Be},$$

^{9}Be is observed down to 10^{-14} and is **less** fragile than either ^{6}Li or ^{7}Li. Therefore, one could use ^{9}Be as an extra BBN observable and constrain models with early energy injection.



Probability to create ^{9}Be out of energetic T is about 10^{-8}

Results of the full calculation

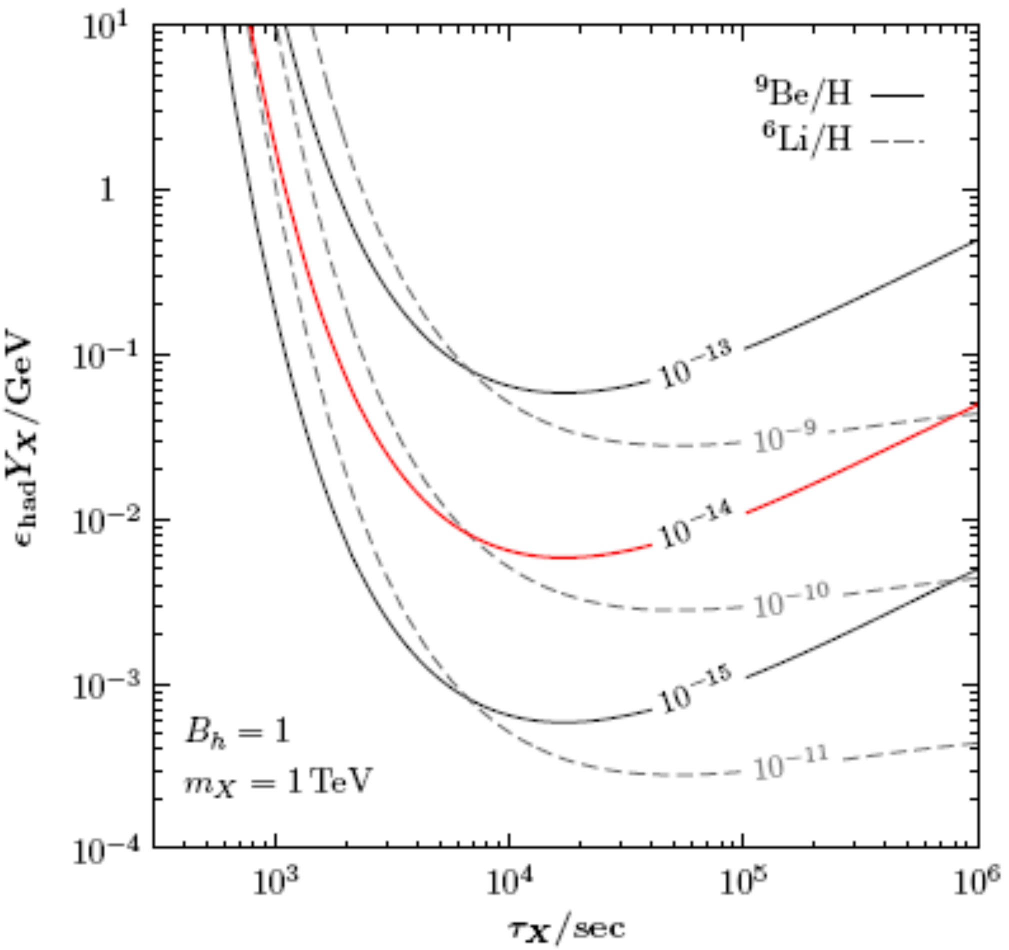


FIG. 3: Contours of constant ^{9}Be (solid lines) and ^{6}Li (dotted lines) as a function of τ_X and $\epsilon_{\mathrm{had}} Y_X$; $B_h = 1$ and $m_X = 1\,\mathrm{TeV}$ is assumed.

^{9}Be can be produced in observable amounts if there are about 10^{-2} GeV per nucleon of energy injected in the form of qq pairs. (10^{-5} decays of TeV scale relics)

Therefore, it can also be used as a BBN "calorimeter" along with ^{6}Li. Unlike with any other elements observational limits on ^{9}Be can be improved.

Models of mediators

Vector portal model: Higgs' can be accidentally long-lived

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

Higgs portal model:

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

Given that some of the mediator particles can be rather long-lived, are there any implications for the Big Bang Nucleosynthesis?

Estimates of p! n efficiency

How many pions do we need ? = what is the probability of producing a neutron within pion lifetime?

Proton capture rate by π^-

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

Probability is small

$$P_{p\to n}^\pi = \int_{t_{\rm inj}}^{\infty} \exp(-\Gamma_{\rm dec}(t - t_{\rm inj}))\Gamma_p dt \simeq \Gamma_p^\pi \tau_{\pi^\pm} \sim O(10^{-6})$$

But not too small, given that we need 10^{-5} extra neutrons per proton.

Therefore about ~10 pions per proton injected around T=40 keV will do the job.

Kaon case is similar. O(1) K^- per proton is enough.

μBBN or νBBN

How many muons (source of antineutrinos) do we need?

Rate for proton-induced conversion of neutrino to neutron is smaller

$$\Gamma_p^\nu = n_p \sigma_{pn}^{\bar{\nu}} \simeq 10^{-41}\ \mathrm{cm}^2 \times \frac{n_p E_\nu^2}{(10\ \mathrm{MeV})^2} \simeq (3.6 \times 10^{-12}\ \mathrm{sec}^{-1}) \times \frac{T_9^3 E_\nu^2}{(10\ \mathrm{MeV})^2}$$

than Hubble rate by about nine orders of magnitude

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

O(10^4) muons per proton is required.

“Easy to arrange”

Model Connections

Two types:

"WIMPs" – initially very abundant (e.g. as photons) – then deplete themselves at T~m, and in our case decay after 100-10^4 sec.

"super-WIMPs" – initially not present at all – get generated by thermal leakage of SM, then decay.

Vector portal model: Ã will be considered in this talk

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

Higgs portal model:

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

WIMP or Super-WIMP depends on strength of couplings

Vector portal model in WIMP regime

Long-lived particle – Higgs' boson, if $m_{h'} < m_V$ (SUSY mass pattern)
Decay rate ~ (mixing angle)^4.

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

In contrast, Vector particle decays in a picosecond.

Perfect candidate – provided that one can somehow reduce its abundance to an acceptable level.

Super-WIMP regime

Take coupling effective coupling constant

$(\kappa)^2$® $= 10^{-26}$

Then vector lives 1000 sec. Model has almost no free parameters. – And it works!

Vectors do not exist initially, then get thermally produced at the level O(1) per baryon, and then decay after 1000 sec or so.

Straight calculation of abundance (well... assuming massless quarks):

$$Y_V = \frac{s}{n_b}\frac{n_V}{s}\bigg|_f \simeq (1.2 \div 4.9) \times \frac{s}{n_b}\frac{1}{h_{\rm eff}(m_V)}\frac{\Gamma_{V\to e^+e^-}}{H(m_V)} \sim 0.3 \times \left(\frac{10^3\ \mathrm{s}}{\tau_V}\right)\left(\frac{\mathrm{GeV}}{m_V}\right)^2\left(\frac{40}{g_{\rm eff}}\right)^{3/2}$$

$M_V \sim 700$ MeV reduces lithium rather efficiently because of the large branching to pions and $E_\pi \sim$ delta resonance.

I see no other probes of this model except BBN. ☹

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 » (0.01–0.05)m_X/TeV.
3. Decay time τ_X is longer than 1000 sec; no constraints on decay channels.

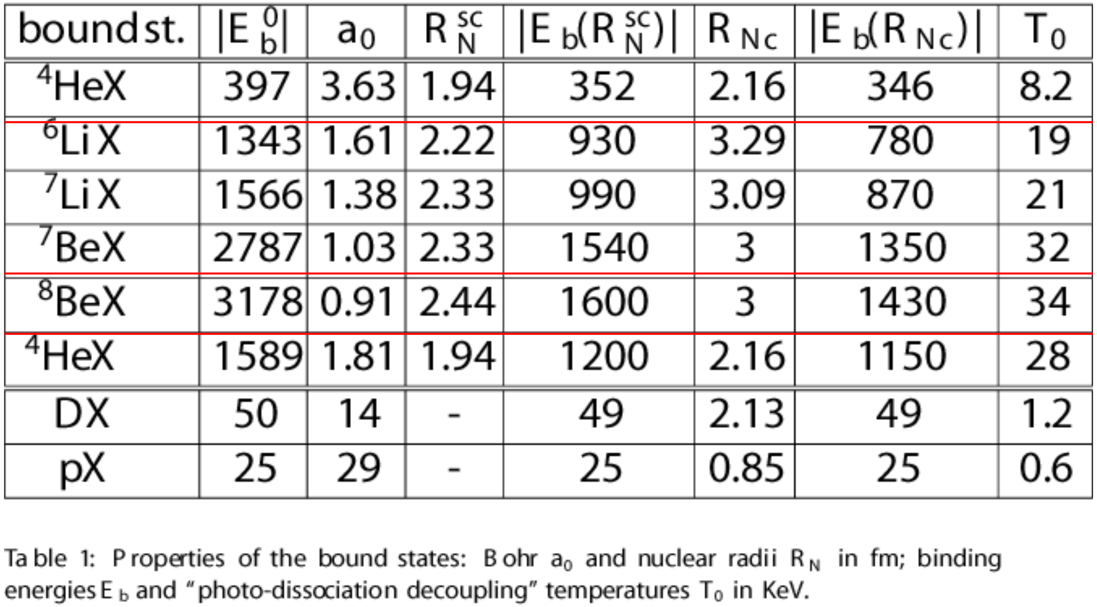
Are there changes in elemental abundances from mere presence of X^-?

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.

Binding energy and stability thresholds

(^{4}HeX) and (^{8}BeX) are the “bottlenecks” for ^{6}Li and ^{9}Be synthesis



boundst.	$\|E_b^0\|$	a_0	R_N^{sc}	$\|E_b(R_N^{sc})\|$	R_{Nc}	$\|E_b(R_{Nc})\|$	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.

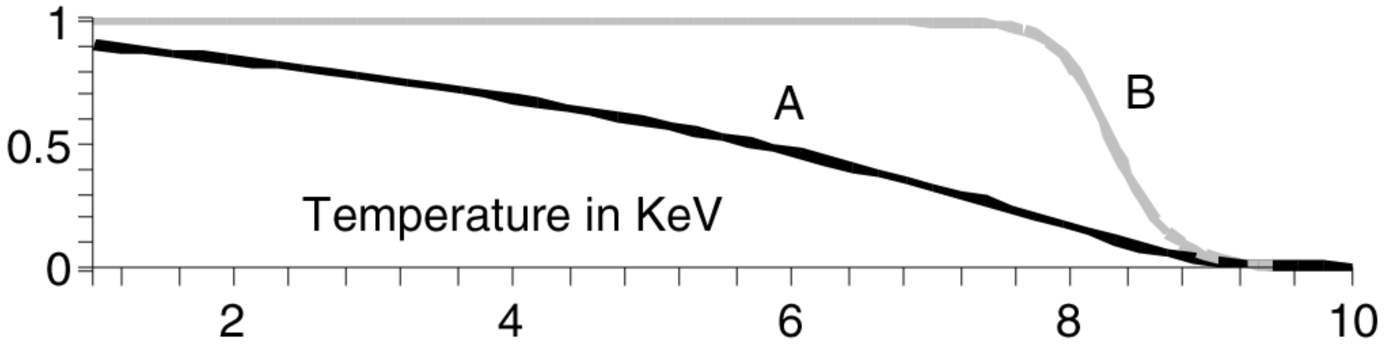
Recombination of ^{4}He and X^-
(^{4}HeX) bottleneck

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. Catalyzed synthesis of ^{6}Li will start below 9keV



Fusion of ^{4}He and (^{4}HeX) (^{8}BeX) bottleneck

The formation of (^{8}BeX) occurs primarily via *resonant* process

(^{4}HeX) + ^{4}He ! *(^{8}BeX, n=3) ! (^{8}BeX, n=3) +γ

For n=3, l=1,2 the resonant energies are 114 and 88 keV.

It turns out that when TÀ Γ_{tot}= Γ_{in}ÀΓ_{out}, the Breit-Wigner formula simplifies

$$\sigma_{BW}(E) = \frac{\sigma_{geom}\Gamma_{in}\Gamma_{out}}{(E-E_R)^2+\Gamma_{tot}^2/4} \to \sigma_{geom}\Gamma_{out} \times 2\pi\delta(E-E_R)$$

and gives a total rate that is independent on Γ_{in} that contains all nuclear physics uncertainties !

$10^5\ T_9^{-3/2}(0.95\exp(-1.02/T_9)+0.66\exp(-1.33/T_9))$

After bound states have formed, new reaction channels open up

- Main SBBN channel for ^{6}Li production

^{4}He + D ! ^{6}Li + γ; Q = 1.47 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) » 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}HeX$^-$) + D ! ^{6}Li + X$^-$; Q = 1.13 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

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

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

$$^{9}\mathrm{Be(SBBN)} \; » \; 10^{-18}$$

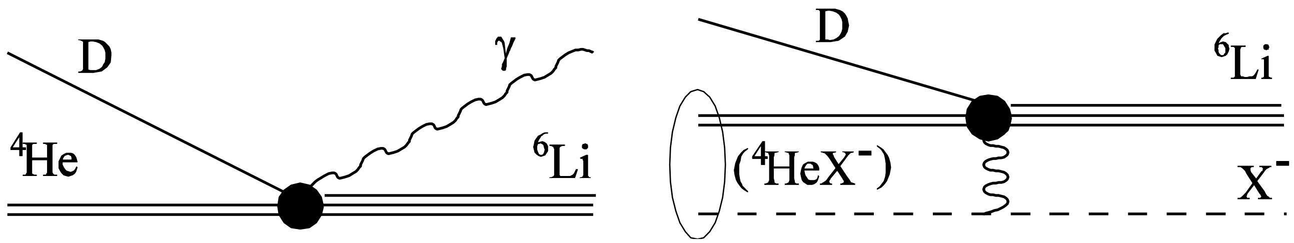
- Main CBBN channel for ^{9}Be production

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

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

This is a large photonless rate dominated by threshold resonance!

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



SBBN CBBN

There are two sources of enhancements:

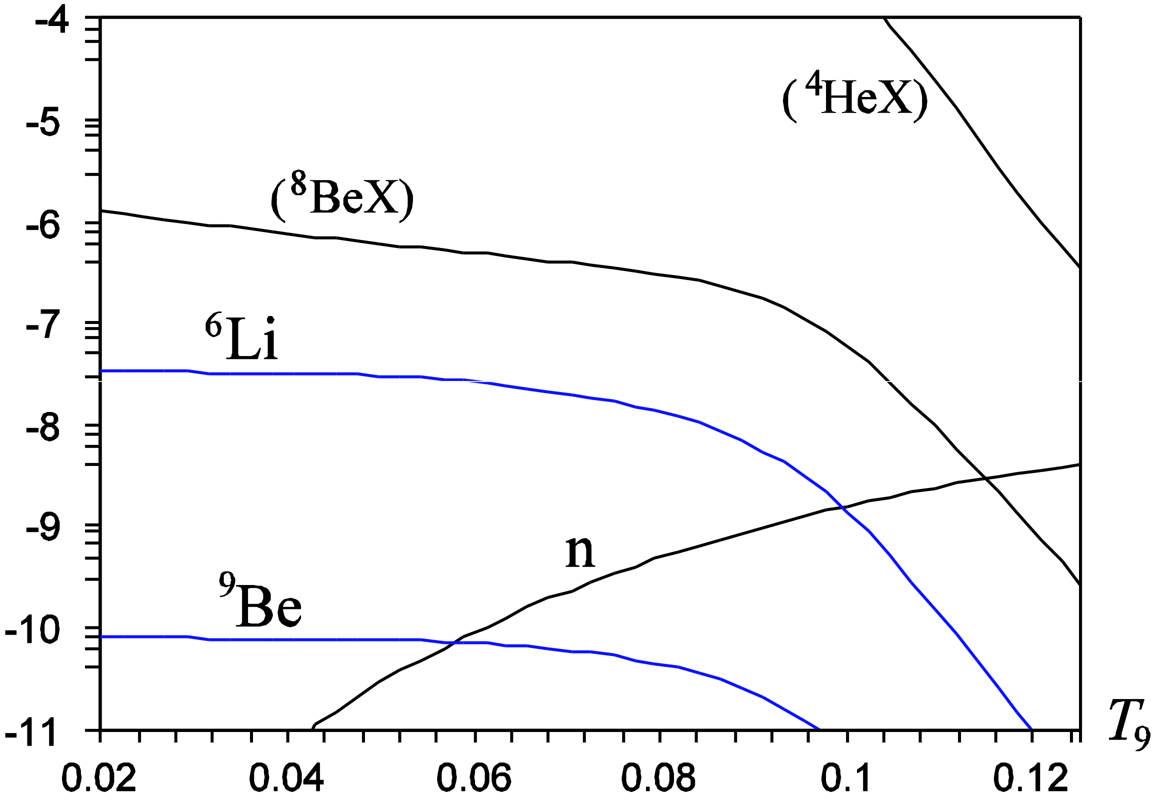
1. Phase space,

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

2. Coulomb screening, E_G^{SBBN}=5249 KeV! 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.

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

CBBN with $Y_X = 5£10^{-3}$, τ_X=1 as a typical example, resulting in ^{6}Li >10^{-8}, and ^{9}Be>10^{-11} – **Excluded!**

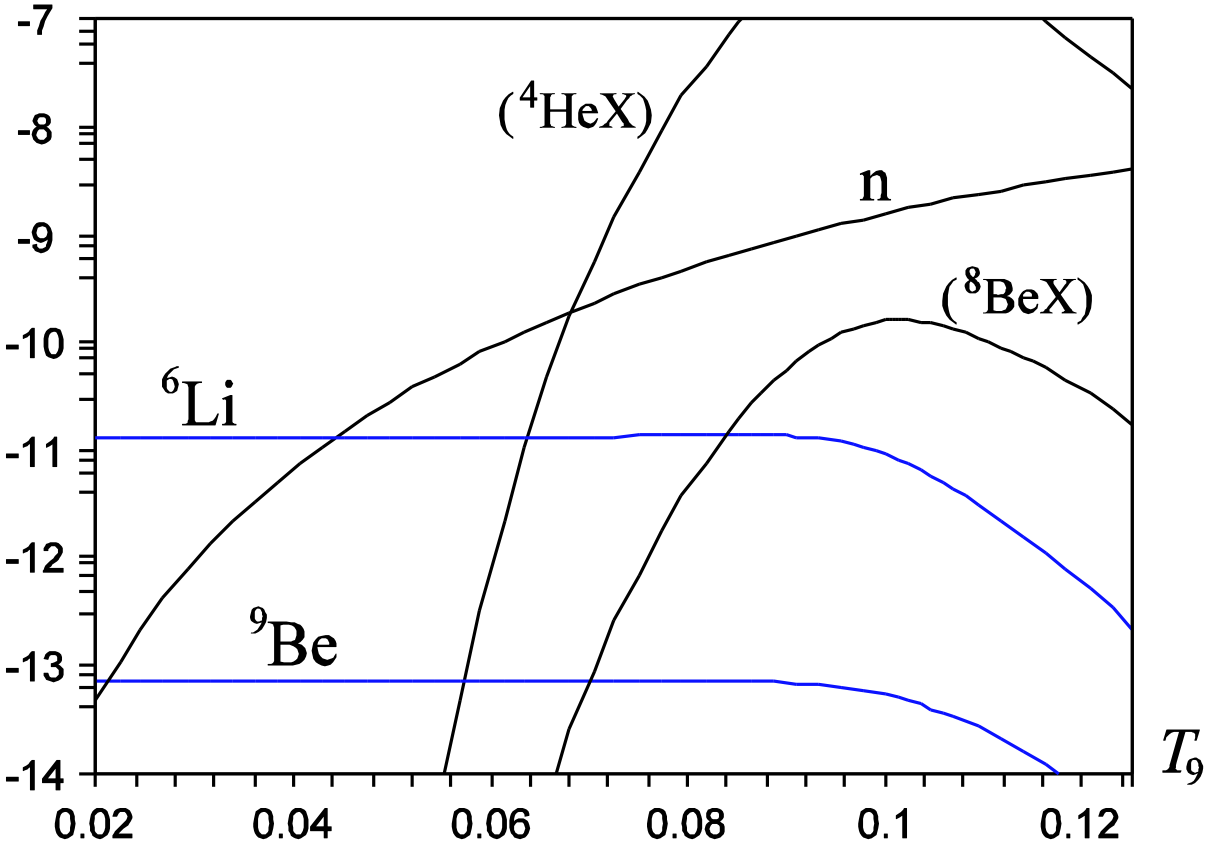


Observationally, ^{6}Li/H < few£ 10^{-11}; ^{9}Be/H<few£ 10^{-13},

Therefore, Y_X(2£10^{4}sec) < 10^{-5} , and typically τ_X < 5£ 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

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

(Bird, Koopmans, MP, 2007)

- The “bottleneck” is creation of (^{7}BeX^-) bound states that is controlled by ^{7}Be+X^-! (^{7}BeX^-) + γ reaction
- There are two main destruction channels that are catalyzed:

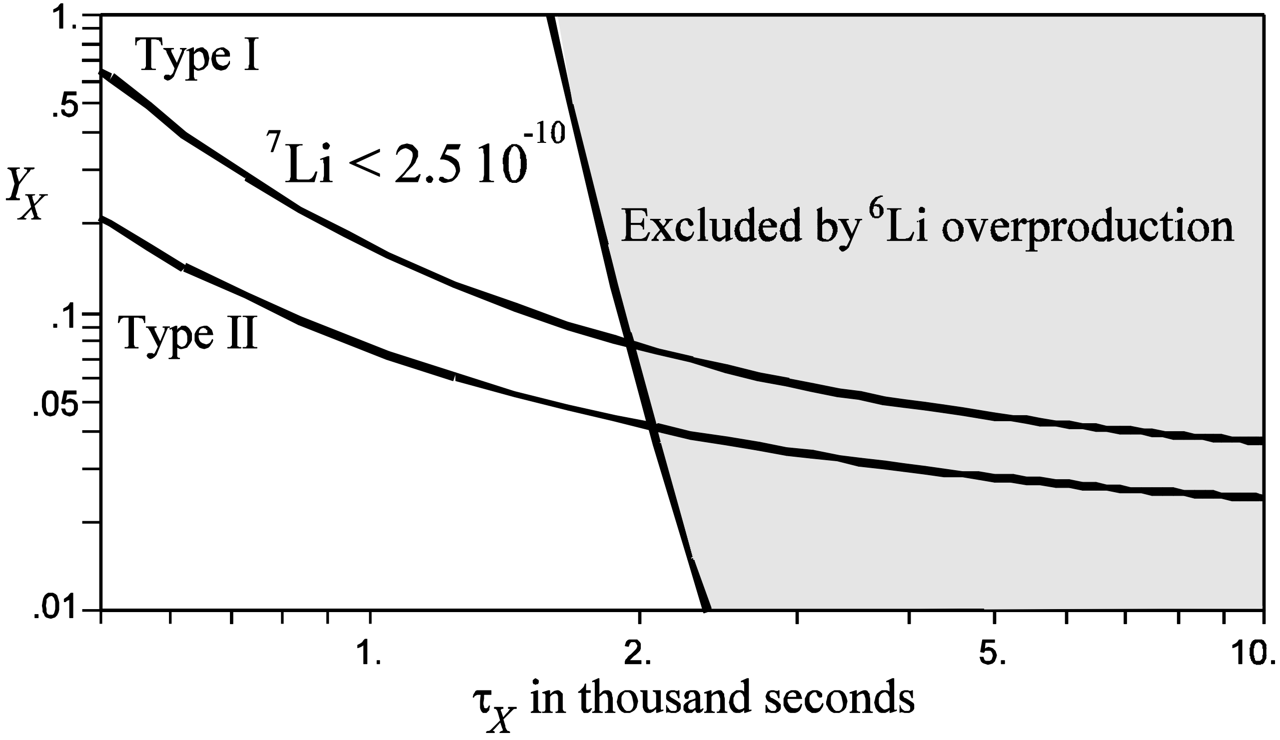
1. p-reaction: (^{7}BeX^-) + p ! (^{8}BX^-) + γ by a factor of >1000
   relative to ^{7}Be + p ! ^{8}B + γ
2. In models with weak currents, the “capture” of X^- is catalyzed:
   (^{7}BeX^-) ! ^{7}Li + X^0 ,

so that lifetime of (^{7}BeX^-) becomes ¿ 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^- ! (X^+X^-) ! SM particles. If this process has hadronic modes, it also affects Li7.

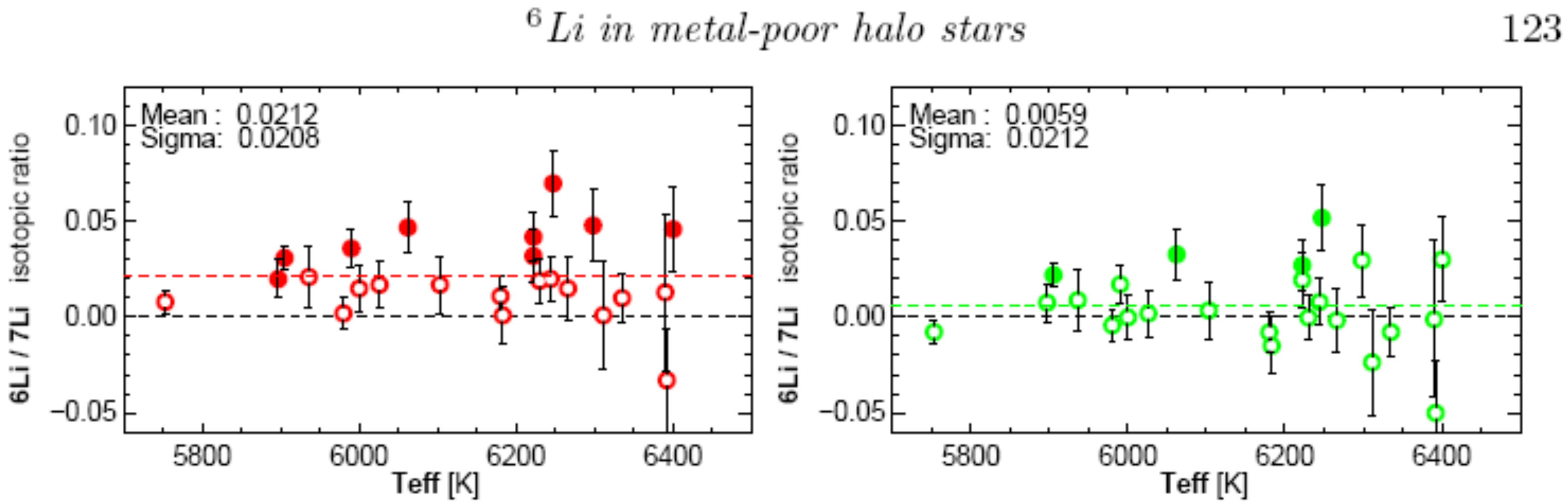
One needs Y_X > O(0.01) at T~40 keV to reduce ^{7}Be that way.

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.

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.