Light particle solutions to the cosmological lithium problem

Maxim Pospelov

Perimeter Institute/U of Victoria

Coc, Vangioni, MP, Uzan, PRD 2015

Goudelis, Pradler, MP, PRL 2016

University of Victoria | British Columbia Canada

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Outline of the talk

- Introduction: In standard BBN ^{7}Li is "over-predicted" ← ***cosmological lithium problem***.

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

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

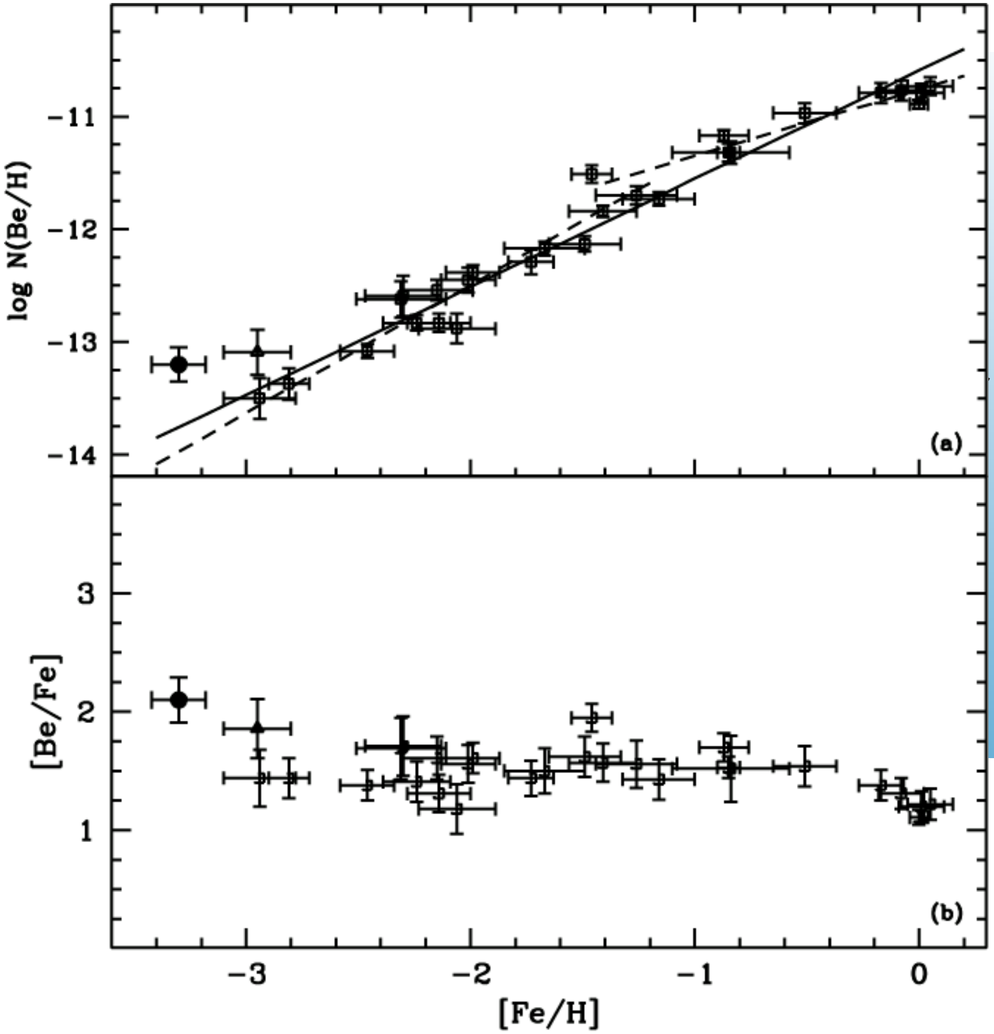
- *Recent observational developments*. Planck results; new accuracy for D/H (?); no ^{6}Li.
- Is anything wrong with nuclear physics? Is anything wrong with cosmology?
- Particle physics speculations: non-thermal decay with extra neutrons; catalysis by charged particles; MeV-scale energy injection.
- Conclusions

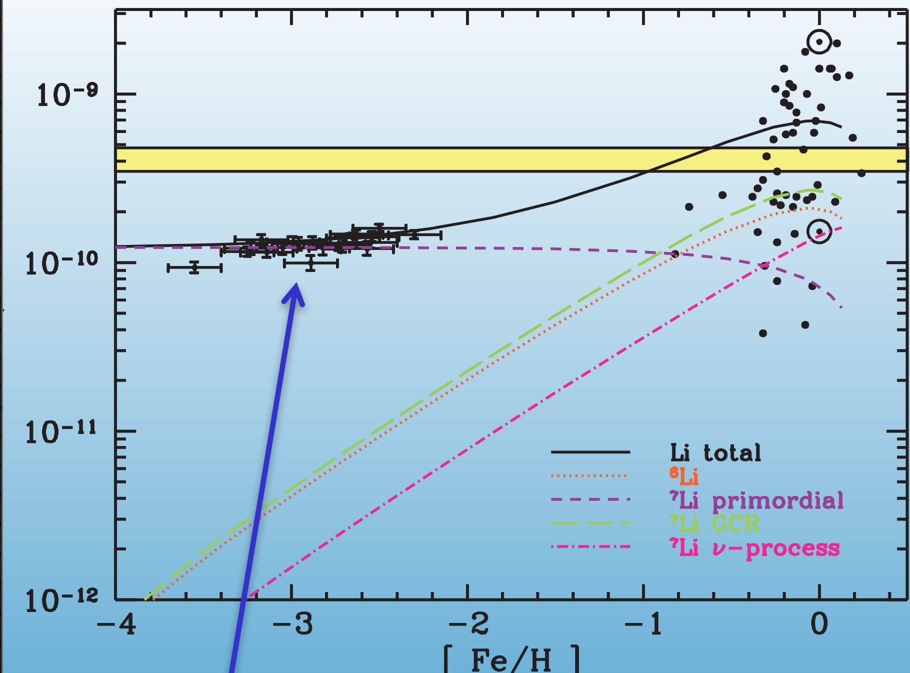
There is no practical implication if we find missing Li

This is not going to happen. Why should anyone care?

1. Li problem may hold clues to non-standard physics that existed at BBN time (e.g. 10 minutes after the Big Bang)
2. Li problem may be trying to tell us something profound about the evolution of the oldest [surviving] stars in the Universe that formed at z ~ 15.

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



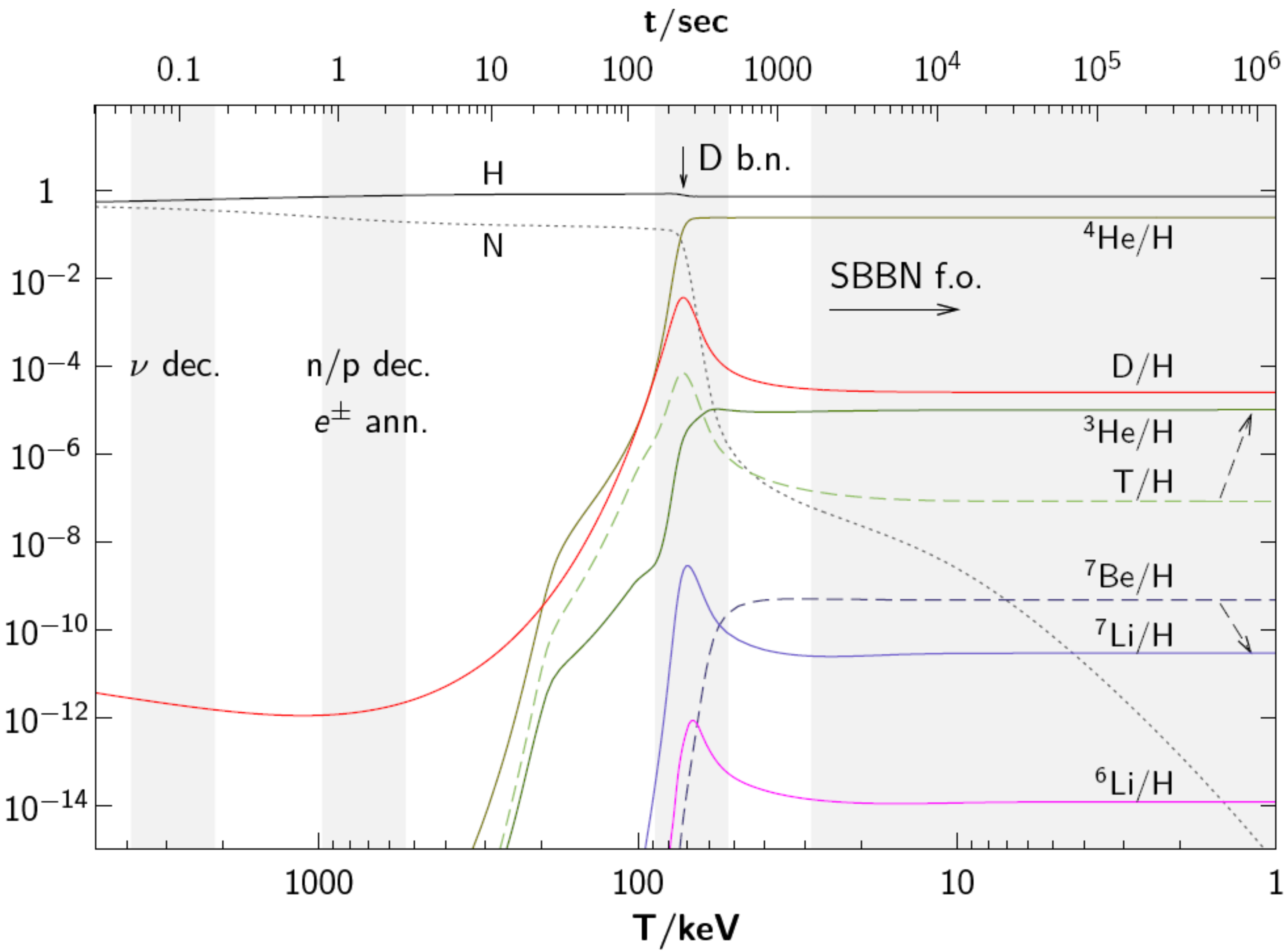


Spite plateau (Ryan et al)

(from Keith's slides)

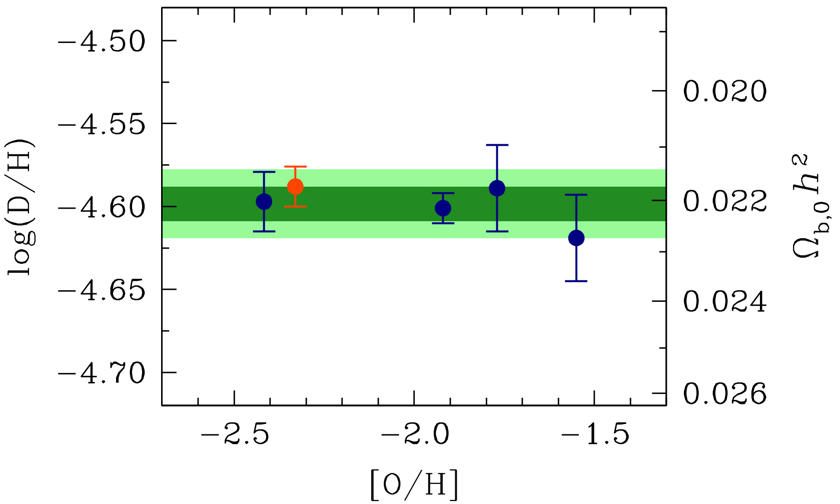
^{7}Li exhibits a "plateau" with low dispersion – indicator or BBN value

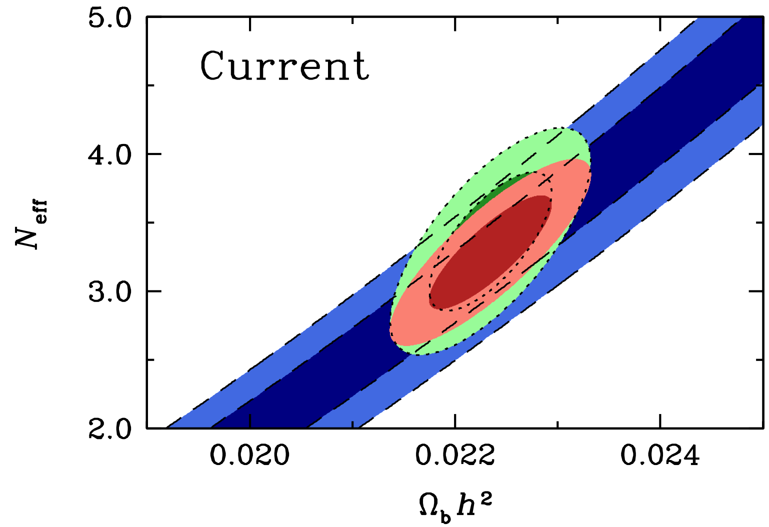
BBN abundances at η_{CMB}



Latest developments (Planck etc)

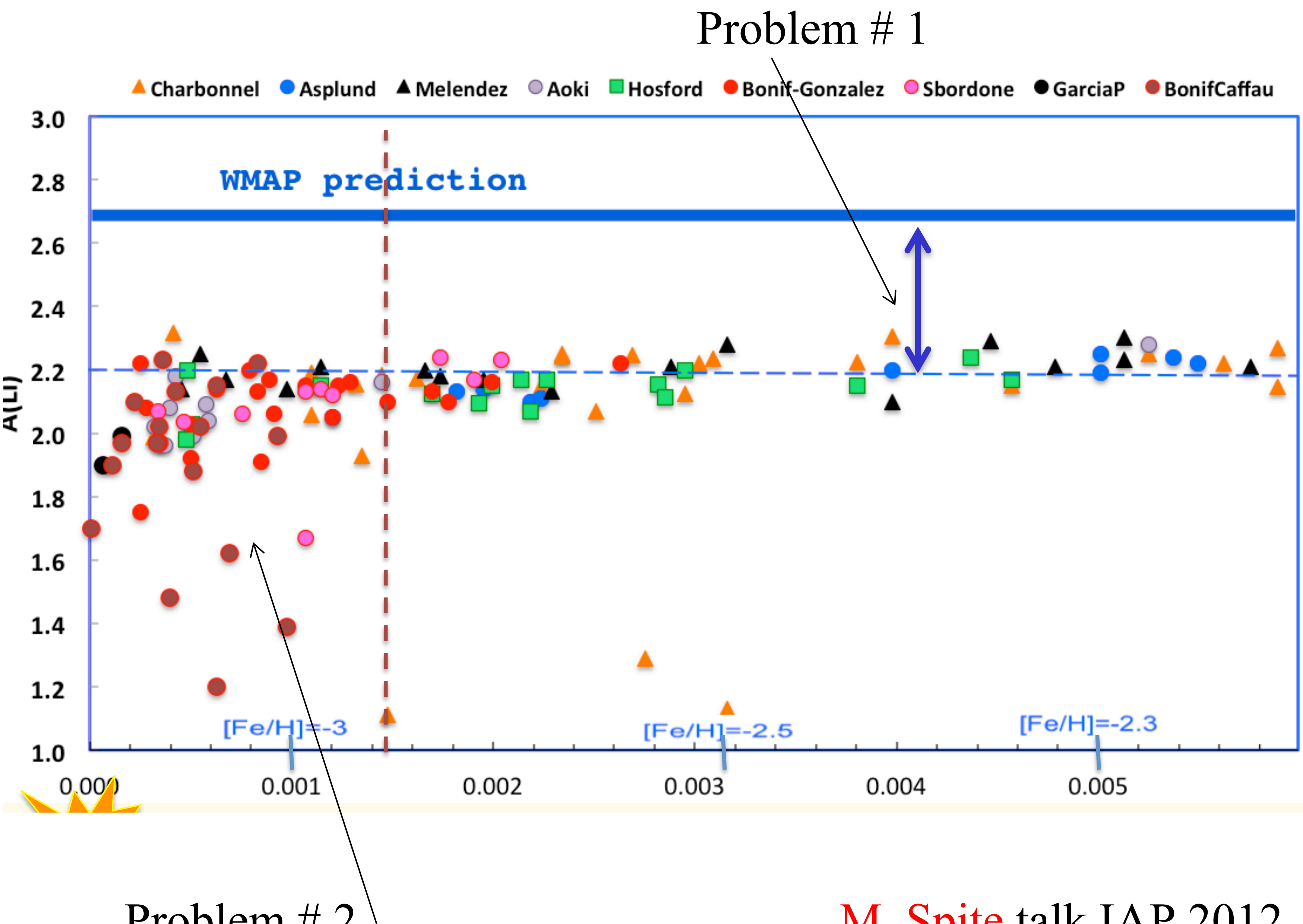
- Planck re-measures most of the cosmological parameters, but there is no drastic change in η compared to WMAP/SPT/ACT.
- Planck determines helium abundance Y_p. Accuracy approaches 10%.
- Cooke et al (2013) claim better accuracy and less scatter for the re-evaluated observational abundance of D/H. Perfect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





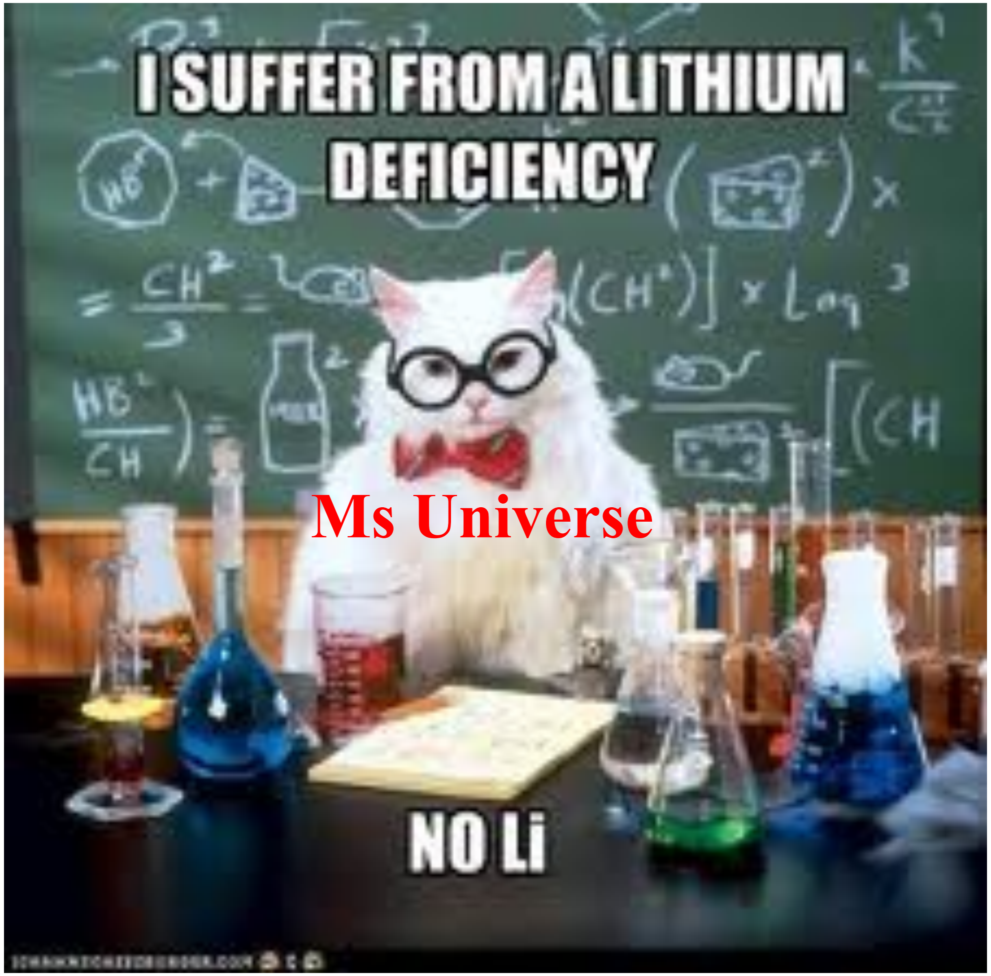
- With latest results, no evidence of ^{6}Li in the stellar atmospheres.
- Only ^{7}Li remains a problem.

More than one problem with ^{7}Li?



M. Spite talk IAP 2012

Lithium deficiency is a serious condition that needs treatment



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 ?

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, MP, Pradler, Goudelis, 2016).

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

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

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

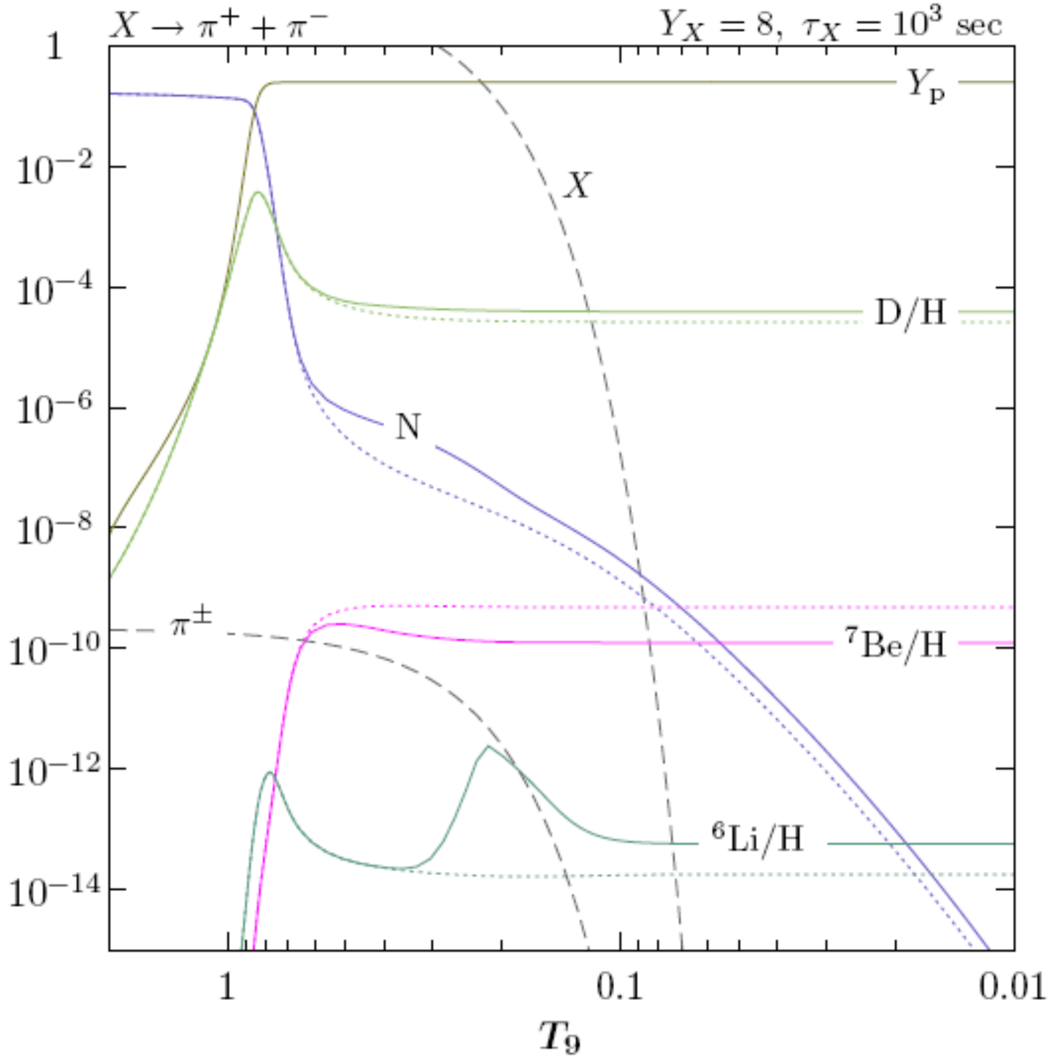
^{3}He+α → ^{7}Be + γ - IN.

^{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.; Keith and Brian's group). 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.

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

No (Shown e.g. in Coc, MP, Vangioni, Uzan, 2014)

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)

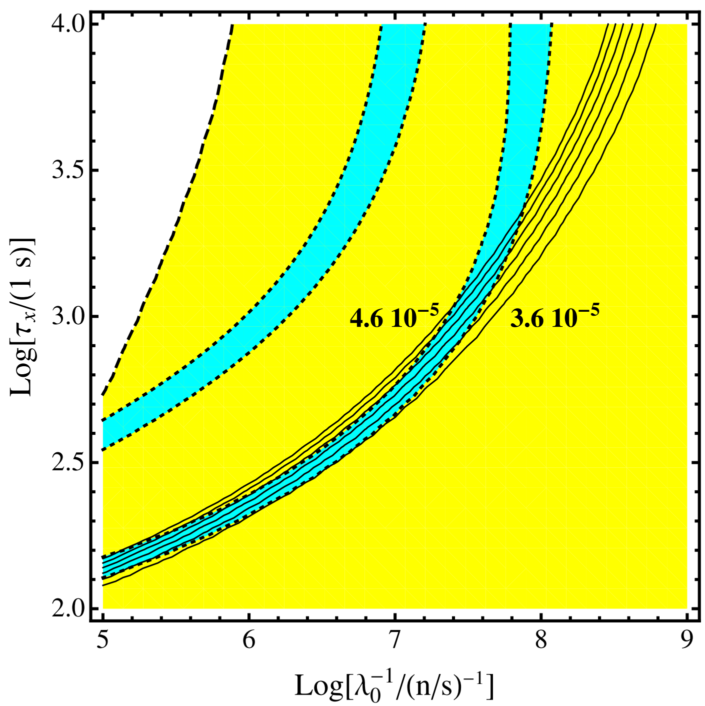


FIG. 5. *Decay of massive particles.* Contour plot assuming $\eta = \eta_{\rm CMB}$ for the two parameters of the model: the lifetime τ_x of the massive particle and the decay rate $\lambda_0 \exp(-t/\tau_X)$. This can be compared to the case 4 of Ref. [14]. The solid dashed lines indicate the prediction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

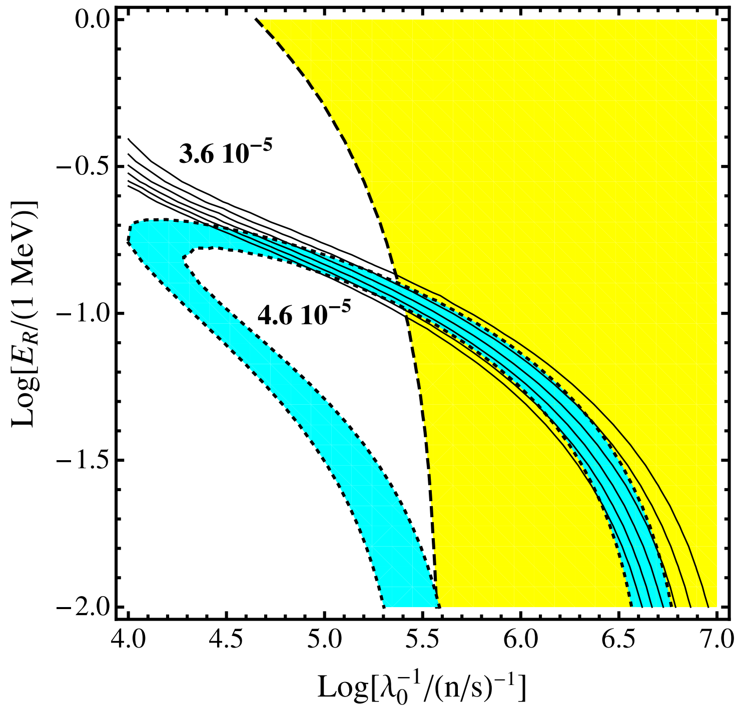


FIG. 8. *Resonnant annihilation.* Contour plot assuming $\eta = \eta_{CMB}$ for the two parameters of the model: the resonance energy E_R and the reaction rate $\lambda_0 \exp(-E_R/\mathrm{k}T)$ (this corresponds to the case 5 of Ref. [14]). The solid dashed lines indicates the prediction of deuterium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

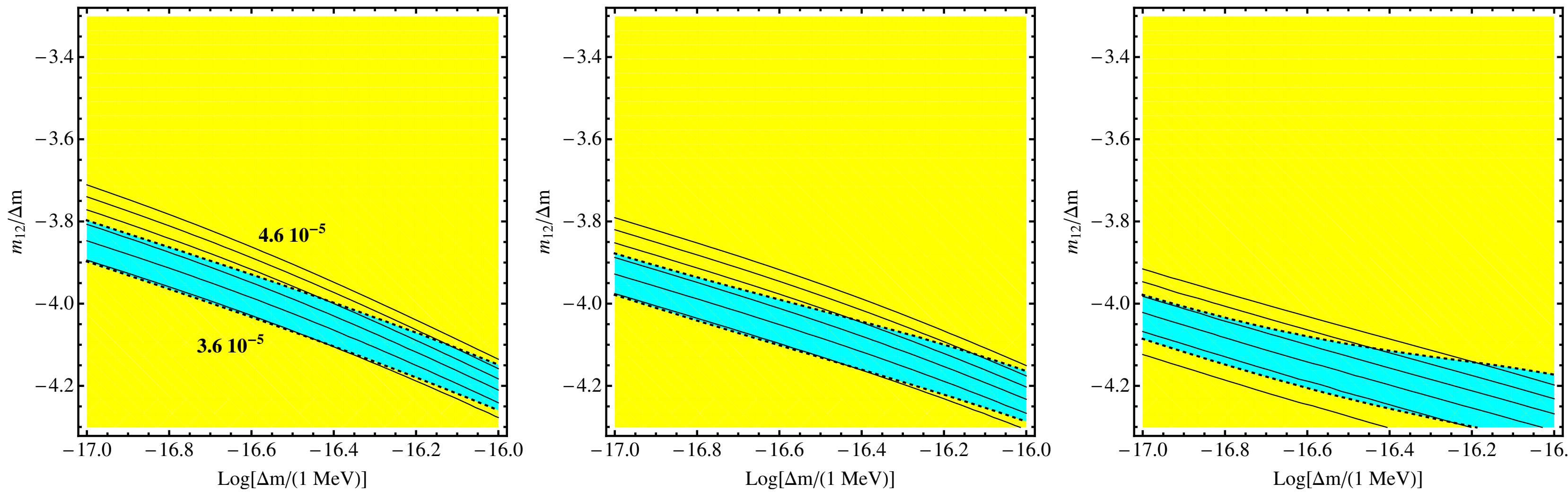


FIG. 4. $n - n'$ oscillation. Contour plots in the space of the two physical parameters $(\Delta m, m_{12})$ assuming $\eta = \eta_{CMB}$ and $x = 0.2$ respectively with $\eta' = 10^{-10}$ (left) and $\eta' = 3 \times 10^{-10}$ (middle) and $x = 0.5$ and $\eta' = 10^{-10}$ (right). The blue strip corresponds 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.

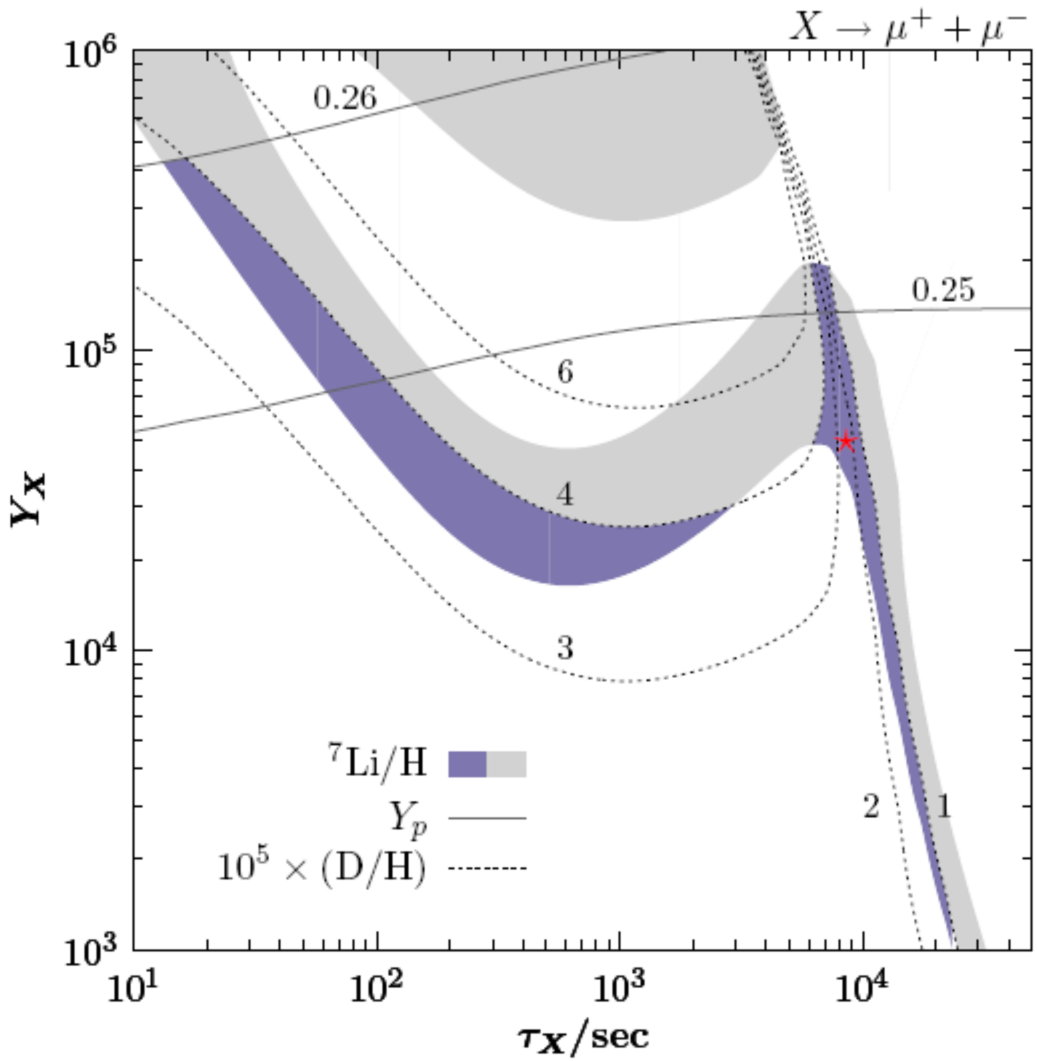
Neutron injection by itself does not solve ^{7}Li problem because it leads to overproduction of D.

- Lithium problem can be solved in combination of two different mechanisms: neutron injection + radiation at ~10000 seconds to reduce D/H "back to normal"

- Decays of EW scale particles is no good, as many other undesirable consequences occur (He3/D is changed too much, Li6 gets generatec etc)

- One scenario that works is *muon injection* (MP, Pradler, 2010). E.g. Unstable particle decay to muon pairs. Antineutrinos from muons convert p → n, and < 50 MeV radiation from subsequent muon decay eradicate excess of D/H

μBBN or νBBN (μ decay; ν+p→ n+e,)



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

Conclusions for decaying particles

- *Straight decays 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 radiation at 10000sec. Lifetime of "X" is ~ 10^4 sec.

Metastable particles absorbed by ^{7}Be or D (Goudelis, MP, Pradler, 2015)

- *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}Be + X → ^{3}He +^{4}He; D + X → n + p; etc will happen with rates proportional to ~ (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 n+p → D + γ

- *Scenario A:*

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

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

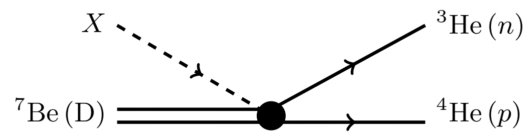
- *Scenario B*:

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

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



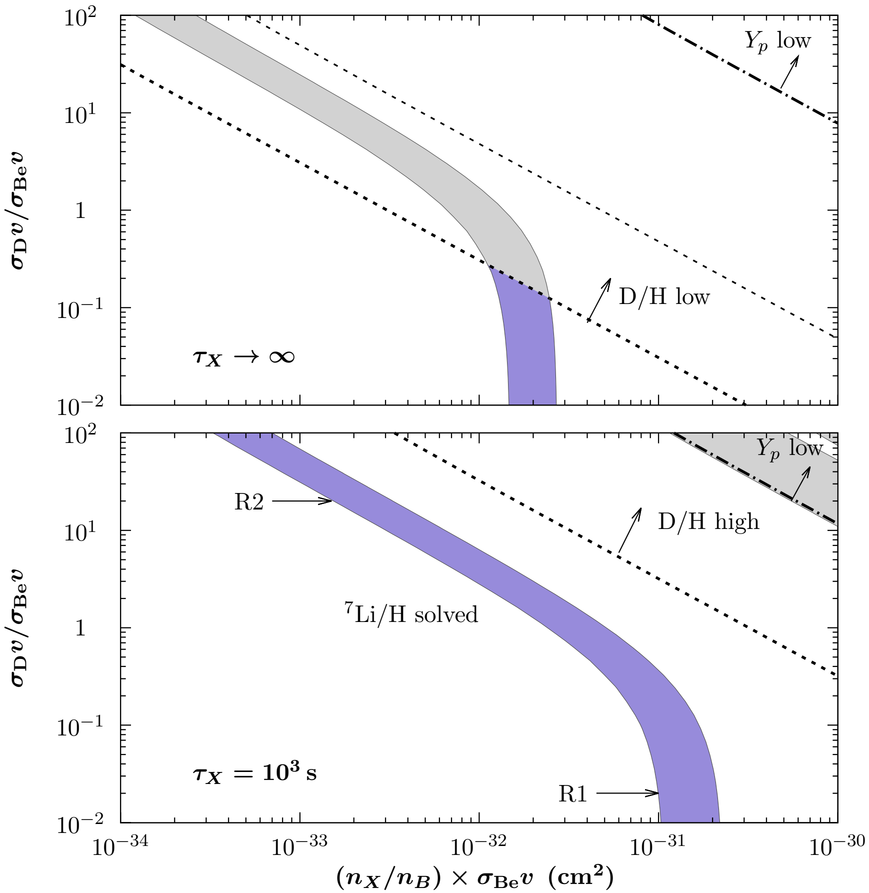


FIG. 2. The contours of light element abundances as a function of the two reaction rates R1 and R2, for $\tau_X \gg t_{\rm BBN}$ (top panel), and $\tau_X = 10^3$s (lower panel). Inside the shaded regions, the lithium problem is solved.

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

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

"Borrowed" neutrons are returned to D

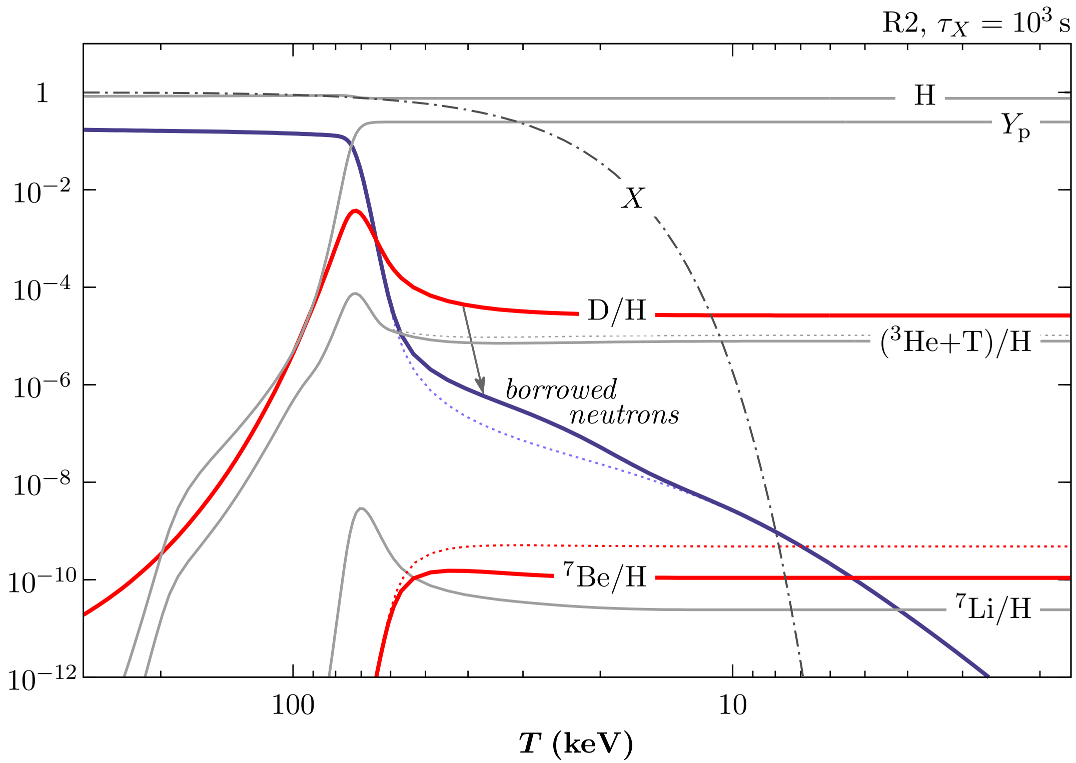


FIG. 3. Temperature evolution of elemental abundances, with BBN modified by R2, initiated by X with $\tau_X = 10^3$ s and $\frac{n_X}{n_b}\sigma_D v = 5 \times 10^{-32}$ cm^2. The temporary increase in n leads to the suppression of ^{7}Be but does not affect $[\mathrm{D/H}]_{\mathrm{BBN}}$.

- "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.*

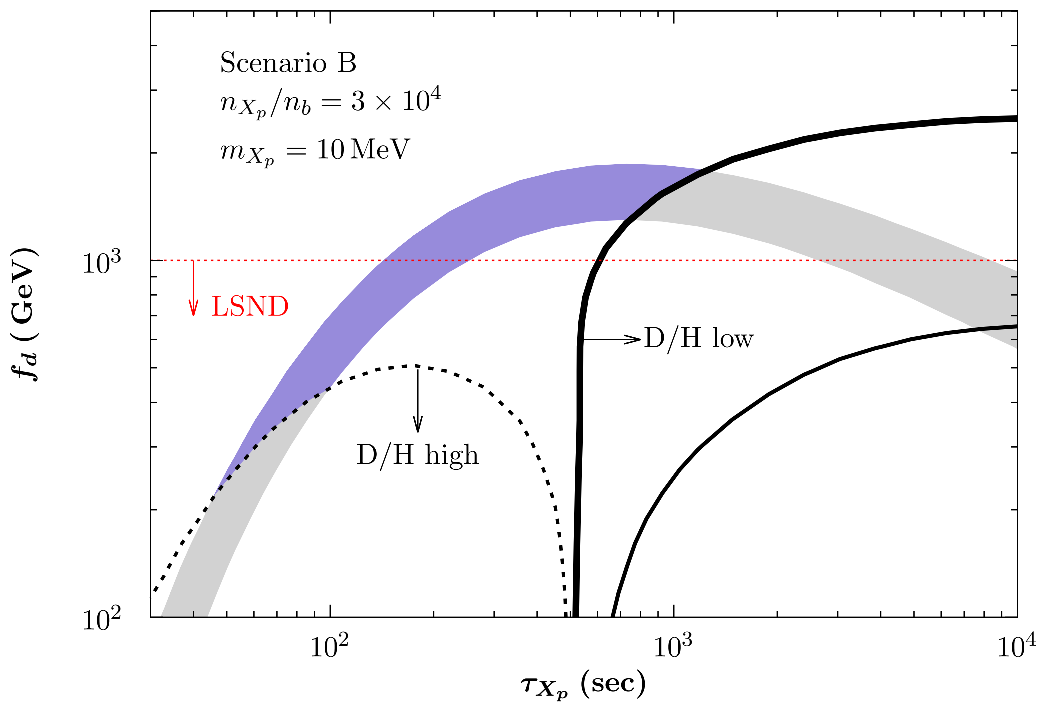
$$\mathcal{L}_{aq} = \frac{\partial_\mu a}{f_d} \bar{d}\gamma_\mu\gamma_5 d \quad \Longrightarrow$$

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

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

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 I

- *"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. Muon injection from metastable particles of 10000sec can have a desirable effect. More neutrons (less Li), and radiation "correction" of D/H.

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.

Conclusions II

- I am honored to speak at Olivefest

- My time at UMN (1998-2001) was extremely productive, even formative, due to mostly Keith and also the rest of the TPI faculty and postdocs.

- I share a lot of good memories of collaborating with Keith, and some of the work we have produced (EDMs, SUSY, changing couplings etc) is still relevant today.

- Thank you, Keith, for your contribution to science and to mentoring of junior colleagues!!! Happy birthday!