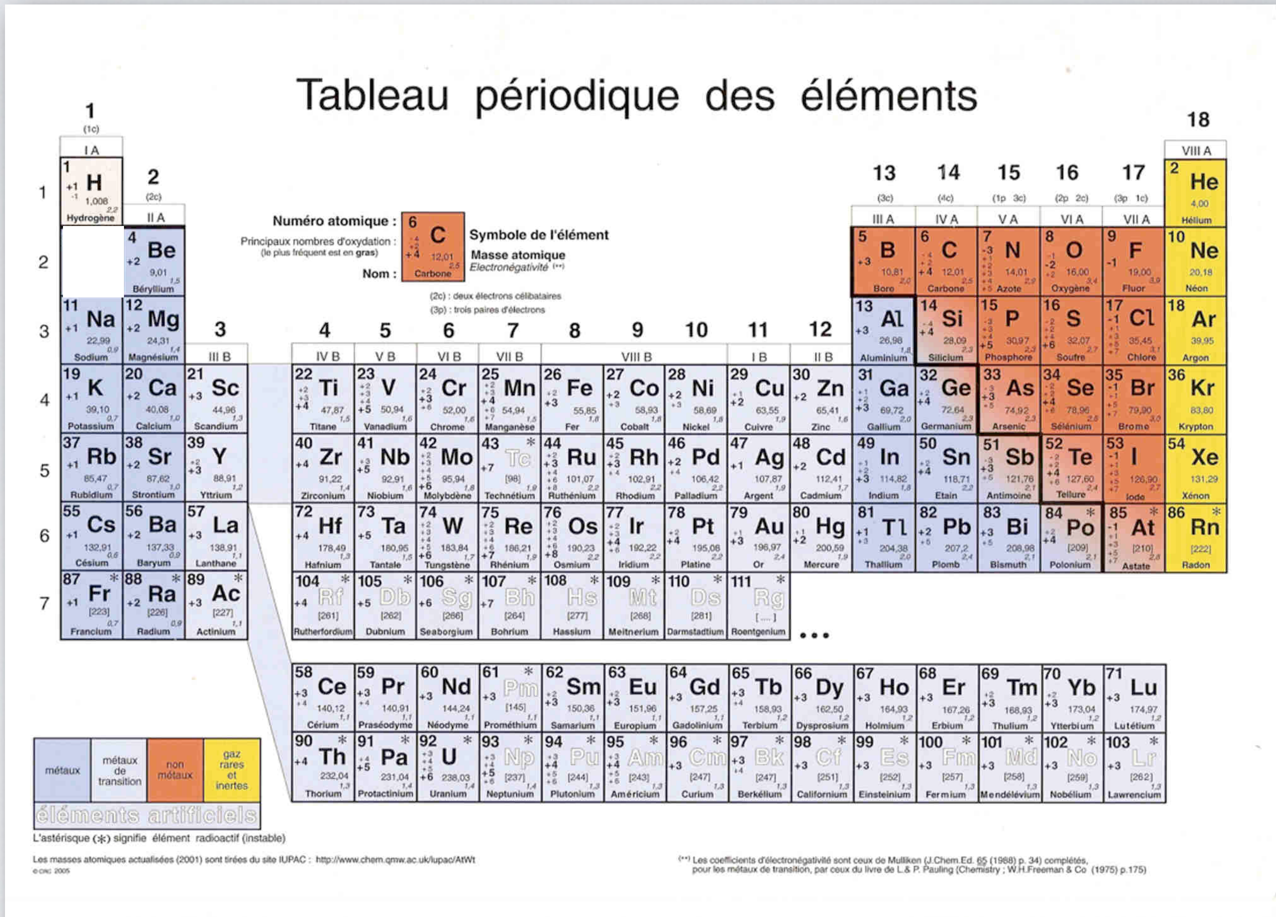
Où est passé le ^{7}Li produit aux premiers instants de l'Univers ?



Pasquale Dario Serpico (Annecy-le-Vieux)

Journées SFP-BTPN - Paris, 21/06/2016

PLAN

- Petit résumé de nucléosynthèse primordiale, introduction au “problème du lithium”

- Une possible solution nucléaire ? Réponse négative !

- Un regard de plus près à l’ astrophysique :
Mesure du Lithium “primordial”& processus d’altération possibles

- Solution exotiques en physique des particules : anciennes difficultés et dernières nouvelles

BBN IN FOUR STEPS

- T>> 1 MeV: initial conditions dictated by NSE & input parameters.

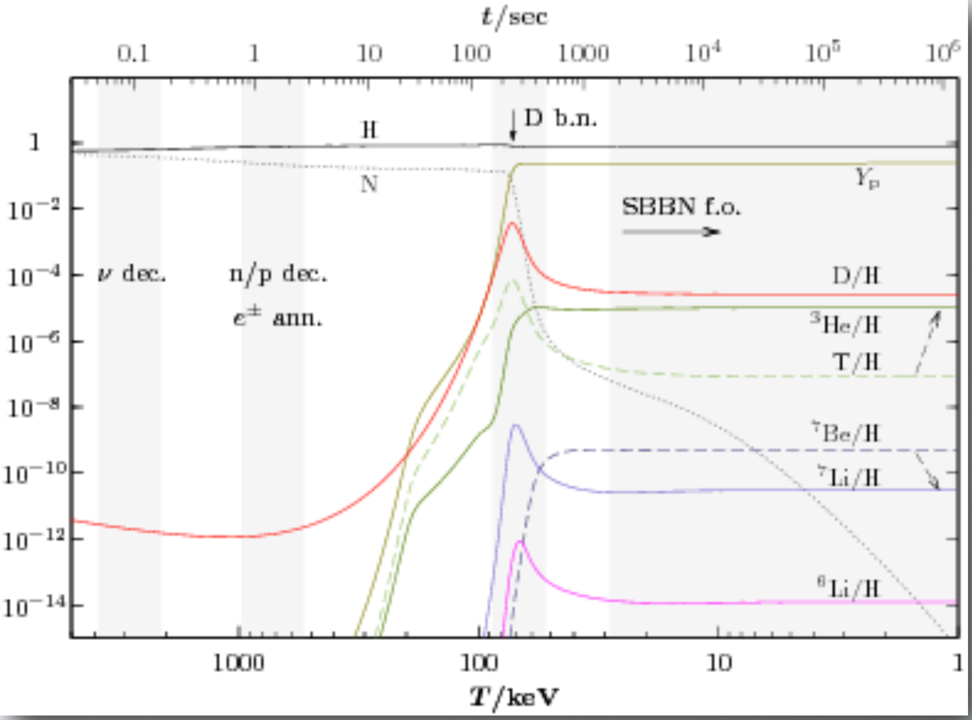
- T~ 1 MeV: $p \leftrightarrow n$ freeze-out (weak physics… ^{4}He yield tracks n/p)

(departure from isospin equilibrium)

- T~ 0.1 MeV Deuterium bottleneck opens *(late, due to high entropy per baryon!)*
- 0.1~T~ 0.01 MeV nuclear reactions take place.

(departure from NSE equilibrium)

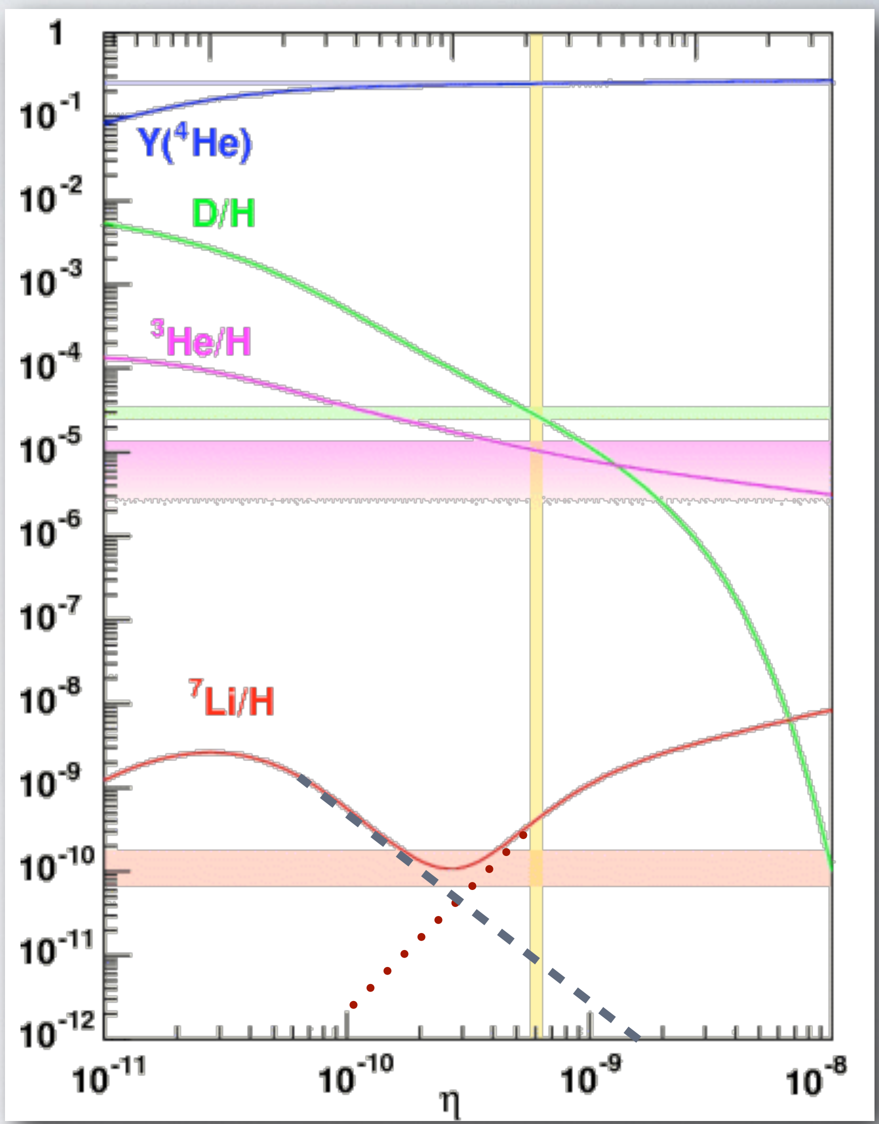
Despite availability of high-T,
BBN starts late and ends soon!
(inefficient combustion, leaving
fragile nuclear ashes behind)



A BBN SUMMARY

BBN is an overconstrained theory: all relevant observables **depend only** on the **baryon to photon number density ratio η.**

CMB provides an independent measurement of **$\eta \sim 6\times10^{-10}$**, hence BBN is parameter-free (a single nuclide determination suffices to test cosmology, wonderfully provided by D/H)



Only "disturbing feature", ^{7}Li disagreement

Depending on the range of η , one of two reactions dominate production (turns out that we should be talking of a ^{7}Be problem!)

Destruction always dominated by

$$^7\mathrm{Li} + p \to {}^4\mathrm{He} + {}^4\mathrm{He}$$

together with the isospin-equilibrium react.

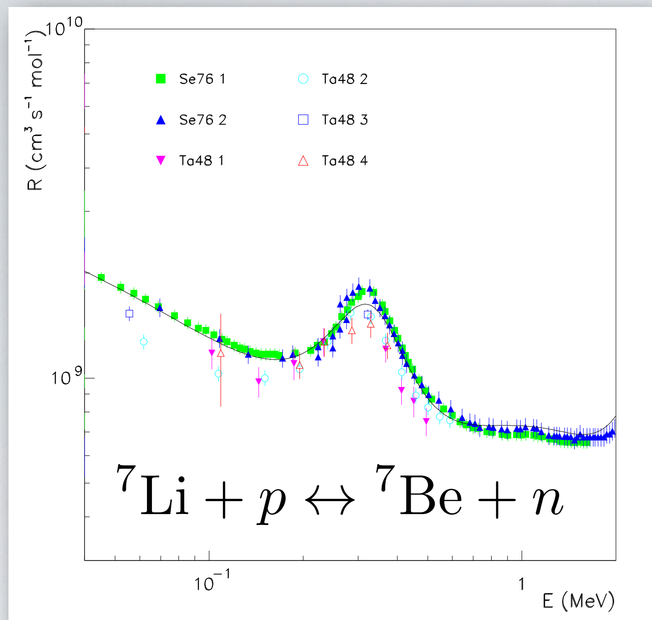
$$^7\mathrm{Li} + p \leftrightarrow {}^7\mathrm{Be} + n$$

$$^4\mathrm{He} + {}^3\mathrm{H} \to \gamma + {}^7\mathrm{Li}$$

$$^4\mathrm{He} + {}^3\mathrm{He} \to \gamma + {}^7\mathrm{Be}$$

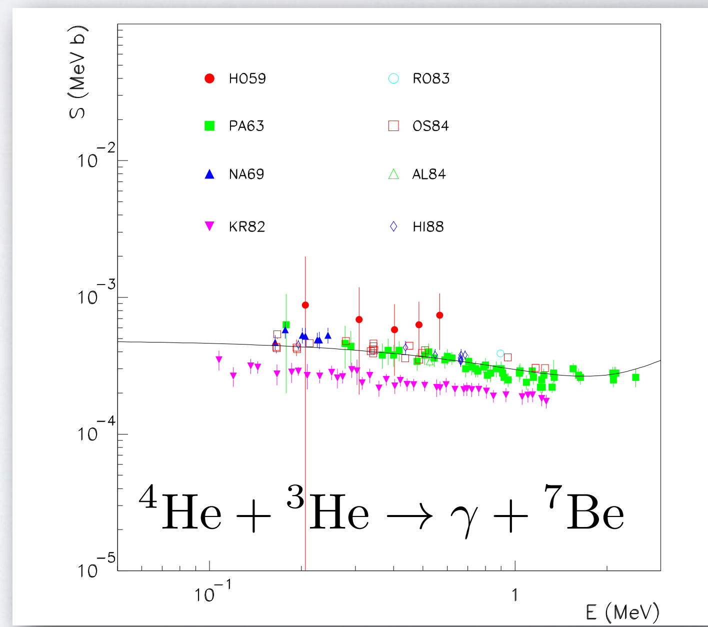
EC

RELEVANT REACTIONS WELL KNOWN



Over the past 10-15 years, the completeness and error budget have been extensively reviewed, by several independent groups. E.g.

P. D. Serpico et al. "Nuclear reaction network for primordial nucleosynthesis: A detailed analysis of rates, uncertainties and light nuclei yields," JCAP 0412, 010 (2004)



Wrt these reaction, scaling established

$$^7\mathrm{Li/H} \sim 5.4 \times 10^{-10} R_{\tau\alpha}^{0.96} R_{\mathrm{Li}pn}^{-0.71}$$

No room for errors of a factor 4 or more!

Are we missing some other relevant reaction?

…DOES NOT SEEM TO BE THE CASE

Even assuming order of magnitude uncertainty in poorly known secondary nuclear reactions, no room for nuclear resolution according to the analysis in

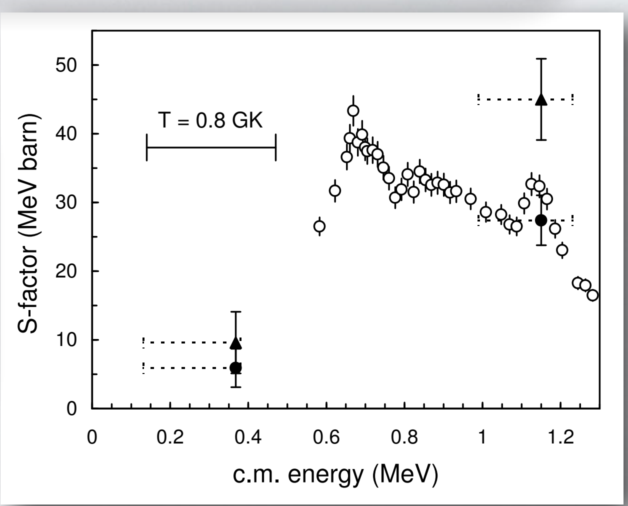
P. D. Serpico et al. "Nuclear reaction network for primordial nucleosynthesis: A Detailed analysis of rates, uncertainties and light nuclei yields," JCAP 0412, 010 (2004)

Some hope? 2 orders of magnitude uncertainty in poorly measured ^{7}Be(d,p)2 ^{4}He claimed a possible way out:

A. Coc et al. ApJ 600, 544 (2004)

eventually this possibility was experimentally ruled out

C.Angulo et al.,
"The ^{7}Be(d,p)2 ^{4}He cross section at big bang energies and the primordial ^{7}Li abundances,"
ApJ 630, L105 (2005) [astro-ph/0508454].



Solution either astrophysical, or due to new particle physics/cosmology

"PRIMORDIAL LITHIUM"?

Main problem

We cannot observe *primordial* abundances:
Stars easily burn Li, but other processes pre-galactic or galactic
(CR Spallation, ν process in SNae, novae…) could have increased it

Observe systems with little chemical processing

Warm (5700 K $< T < 6500$ K) metal poor dwarf stars in the halo

Correct for chemical evolution?

"metallicity plateau" found, means it's primordial?

Spite & Spite '82

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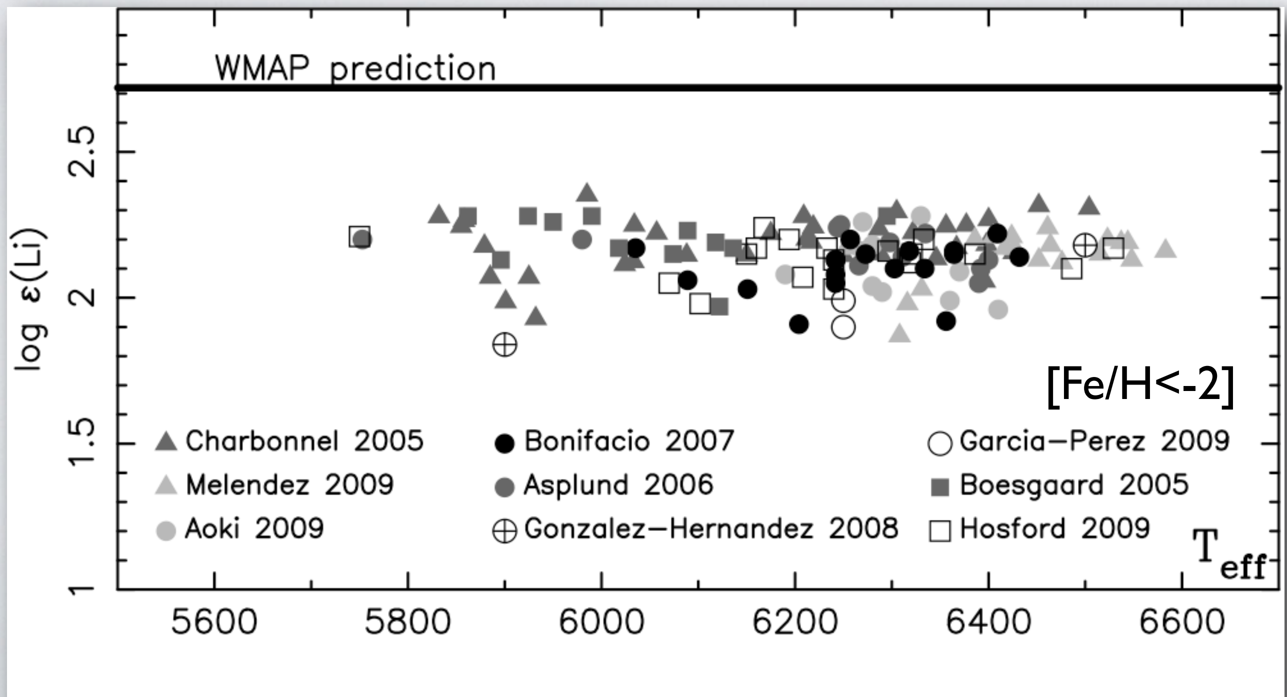


A factor ~4 problem?

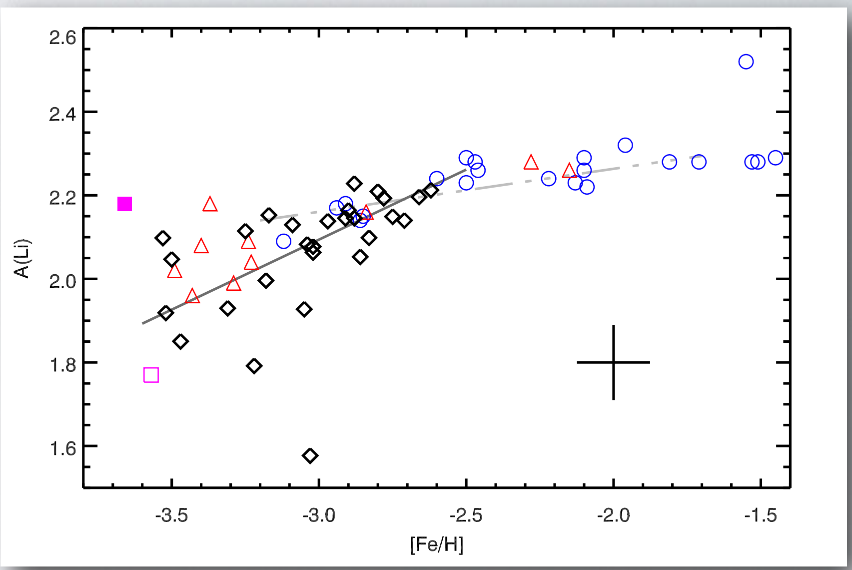
Caveat...

[Spite & Spite '10]

"PRIMORDIAL LITHIUM"? (CONT'D)

Anomalous dispersion around the average & trend with metallicity established!!

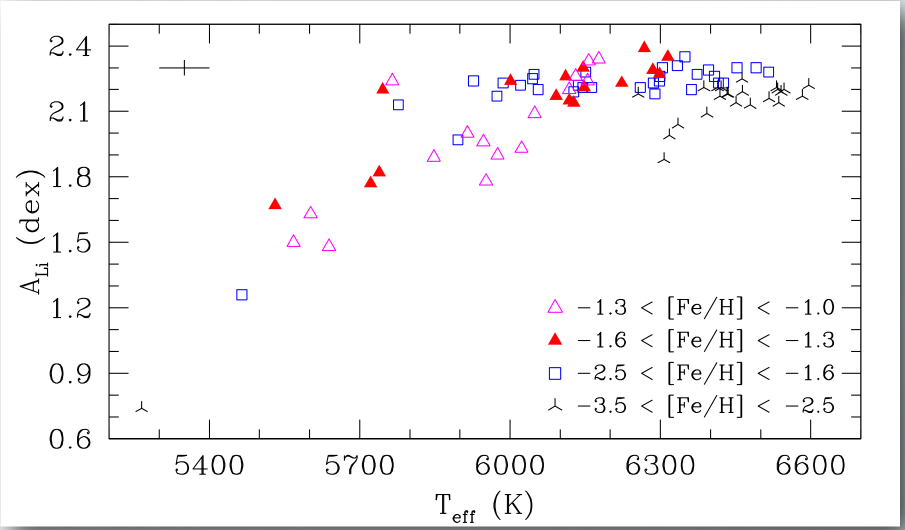
e.g. Sbordone et al. A&A 522 (2010) A26 [arXiv:1003.4510]



(cross is typical error size)

"Our results imply that the Li abundances observed in Li plateau stars have been depleted from their original values and therefore do not represent the primordial Li abundance."

Melendez et al., A&A Letters, 515 (2010) L3 [arXiv:1005.2944]



SO, WHY THE "PLATEAU"?

safe conclusion is that *some post-primordial processing is at play*; no simple astrophysical model universally accepted; it is still possible to interpret "the envelope" of the observed plateau values as primordial, which would be differ by a factor ~4 from predictions.

some hypotheses discussed

1. **MW** Halo stars did not form "unpolluted primordial gas" (**Astration,** Piau et al 2006).

Troubles with ω Cen, likely from captured dwarf, showing same Li (1008.1817)?

2. **Universal early or pre-galactic synthesis** (pop-III, flares, etc.)
Main issue is: why not other element 'anomalies'? Energetics required? CS 22876 binary?

3. in situ **Depletion** (via diffusion/turbulence): appears likely but in most cases one has to fine tune "effective parameters" to get a "quasi-plateau"

A RECENT DEVELOPMENT

X. Fu, A. Bressan, P. Molaro, P. Marigo "Lithium evolution in metal-poor stars: from pre-main sequence to the Spite plateau" MNRAS 452, 3256–3265 (2015) [1506.05993]

propose the following possible scenario (sketch/personal summary):

- **Primordial ^{7}Li all destroyed in early (pre-MS) phase, during ^{2}H burning.**
- **If stars form in an environment with residual gas available (*depends on metallicity range!*) accretion restores part of the ^{7}Li**
- **Process stops when the star enters MS phase, its UV photons heat up the gas and wipe it away in a wind (*auto-regulation responsible for the plateau*)**
- **Too cool stars (=large convective region) destroy newly accreted one; warm ones (=thin convective region) preserve it (*T range where plateau observed*)**

Promising, but yet to include more realistic effects like rotation, find "predictive" confirmation…

WHAT IF DUE TO PARTICLE PHYSICS?

Surprisingly enough, not easy to cook up a recipe to solve it! Why?

1. Solutions via annihilations/decays of exotic particle (cascades in the early universe) usually face the difficulty to alter *only* ^7Li while saving the agreement of other nuclei.

2. Those which manage to do so, usually require some mild "fine-tuning", in order to work (usually dictated by nuclear physics, more later)

3. Even so, more often then not they violate other cosmological bounds (e.g. lead to too large CMB spectral distortions) and/or involve fine-tuned effects of multiple interactions (strong, e.m., weak).

Some recent developments (that solve at least 1 and 3, albeit not 2)

- Revisit the treatment of electromagnetic cascades leading to non-thermal BBN via photodisintegrations. Loophole found in the "standard physics" treatment, could resurrect solutions thought ineffective!
  V. Poulin and PDS, Phys. Rev. Lett. 114, 9, 091101 (2015)

- Invoke one (or more) ***light*** particles, interacting via a ***new force***
  A. Goudelis, M. Pospelov and J. Pradler, Phys. Rev. Lett. 116, 21, 211303 (2016)

RECAP OF STANDARD LORE

Basic processes (in a high-entropy, radiation dominated background)

$$\gamma\,\gamma_{\rm th} \to e^+e^-$$

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Particle multiplication and energy redistribution

RECAP OF STANDARD LORE

Basic processes (in a high-entropy, radiation dominated background)

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Particle multiplication and energy redistribution

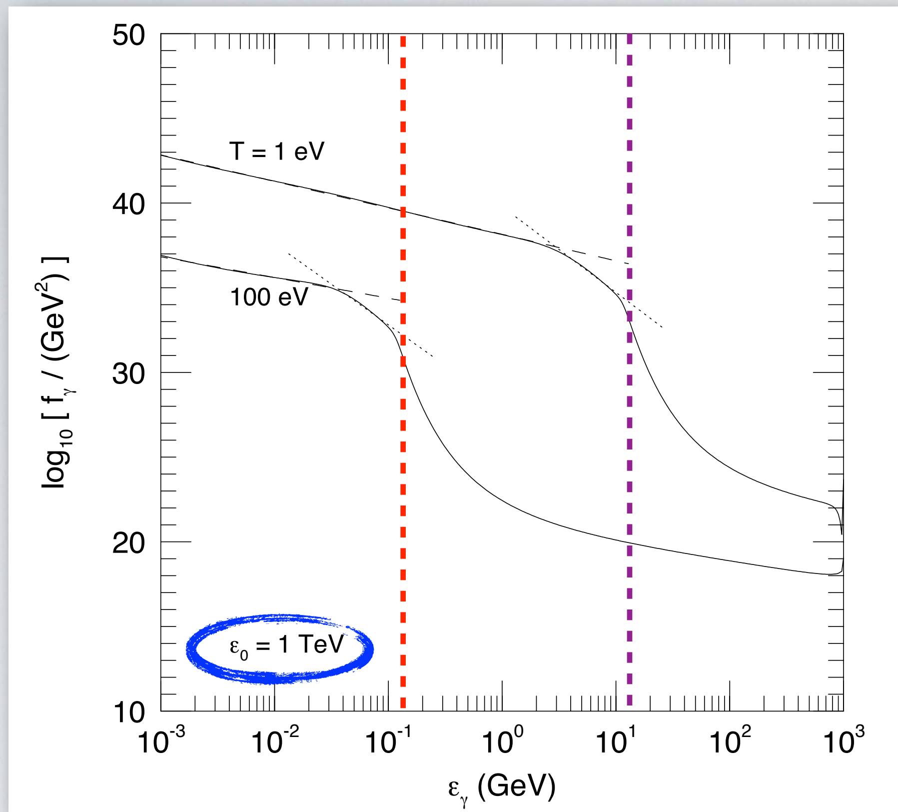
At threshold for P.P., $E_e \sim E_{thresh}/2$ and the corresponding maximal IC photon energy $E_X \sim E_{thresh}/3$

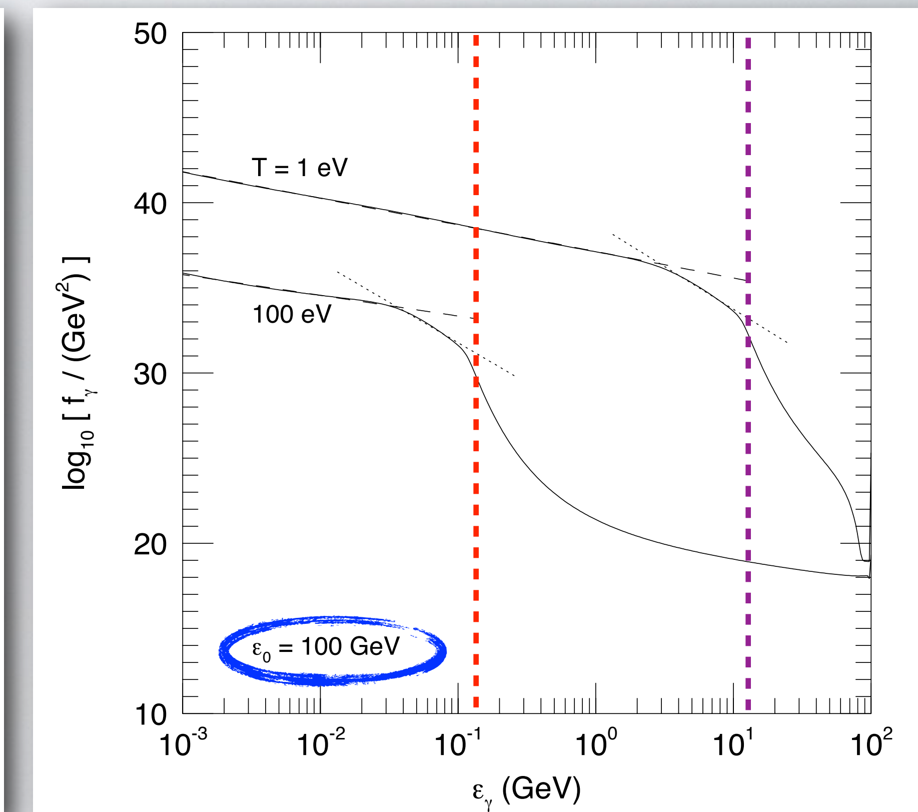
Below E_X, number of particles fixed by the number of e "available" (no more multiplication possible) and the Thomson-limit result $E_\gamma \propto E_e^2$ implies a scale-invariant spectrum goes as $E_\gamma^{-3/2}$

Above E_X and below the effective cutoff imposed by P.P., the **energy** of particles in the cascade is **conserved** ($E^2 dN/dE \sim$ const), hence spectrum **E^{-2}**

On physical grounds we expect **$E_{cutoff} \sim \# \, m_e^2/T$** Detailed simulations (for cosmo) yield **$\# \sim 1/20$**

EXAMPLES





E_{cutoff}(100 eV)~120 MeV

E_{cutoff}(1 eV)~12 GeV

& universal
(indep. of injected photon energy)

M. Kawasaki and T. Moroi,
"Electromagnetic cascade in the early universe and its application to the big bang nucleosynthesis,"
ApJ 452, 506 (1995) [astro-ph/9412055].

AN UNEXPLORED CORNER...

All cases simulated inject $E_\gamma >> E_{cutoff}$
But this is a **theoretical bias**
(new physics must be "at high scale")
not a physical necessity!

$E_{cutoff}(T=100\ eV) \sim 120\ MeV$
$E_{cutoff}(T=1\ keV) \sim 12\ MeV$

M. Kawasaki and T. Moroi, ApJ 452, 506 (1995) [astro-ph/9412055]

Photo-disintegration energies E_{pd} for light nuclei range from **~1.6 MeV** of ^{7}Be to **O(20) MeV** for ^{4}He

What if $E_{pd} < E_\gamma < E_{cutoff}$, i.e. pair production is not operational but above threshold for photodisint.? Previous theory inapplicable!

This situation is physically possible at times after the end of standard BBN (~10 keV), which we focused on

Temperature	P_{low}	N_{low} GeV^2	P_{pp}	N_{pp} GeV^2
$\epsilon_{\gamma 0} = 10$ TeV				
1 eV	-1.57	1.6×10^8	-5.10	6.9×10^{-18}
10 eV	-1.34	5.4×10^8	-5.20	6.0×10^{-18}
100 eV	-1.22	1.7×10^9	-4.84	1.1×10^{-17}
$\epsilon_{\gamma 0} = 1$ TeV				
1 eV	-1.56	1.4×10^8	-5.07	6.2×10^{-18}
10 eV	-1.34	4.9×10^8	-5.17	5.5×10^{-18}
100 eV	-1.22	1.4×10^9	-4.79	1.0×10^{-17}
$\epsilon_{\gamma 0} = 100$ GeV				
1 eV	-1.56	1.4×10^8	-5.01	5.7×10^{-18}
10 eV	-1.33	4.7×10^8	-5.15	5.3×10^{-18}
100 eV	-1.22	1.3×10^9	-4.74	1.1×10^{-17}
$\epsilon_{\gamma 0} = 10$ GeV				
1 eV	—	—	—	—
10 eV	-1.33	4.5×10^8	-5.12	5.5×10^{-18}
100 eV	-1.22	1.3×10^9	-4.77	9.6×10^{-18}

SOLUTION FOR THE NEW REGIME

Need to account for remaining processes kinematically allowed

$$\gamma + \gamma_{\rm th} \to \gamma + \gamma$$ *photon-photon scattering*

$$\gamma + N \to e^{\pm} + N$$ *Bethe-Heitler pair production*

$$\gamma + e^{\pm}_{\rm th} \to \gamma + e^{\pm}$$ *Compton scattering*

Assuming all interactions are catastrophic, the relevant Boltzmann equation writes

$$\frac{\partial f_\gamma(E_\gamma)}{\partial t} \simeq -\Gamma_\gamma(E_\gamma, T(t)) f_\gamma(E_\gamma, T(t)) + \mathcal{S}(E_\gamma, t)$$

whose stationary solution is

$$f_\gamma^{\rm S}(E_\gamma, t) = \frac{\mathcal{S}(E_\gamma, t)}{\Gamma_\gamma(E_\gamma, t)}$$

(Hubble expansion is much slower than all these particle physics interaction rates, but can be accounted for)

where for a decaying particle $$\mathcal{S}(E_\gamma, t) = \frac{n_\gamma^0 \zeta_X (1 + z(t))^3\, e^{-t/\tau_X}}{E_0 \tau_X} p_\gamma(E_\gamma, t)$$

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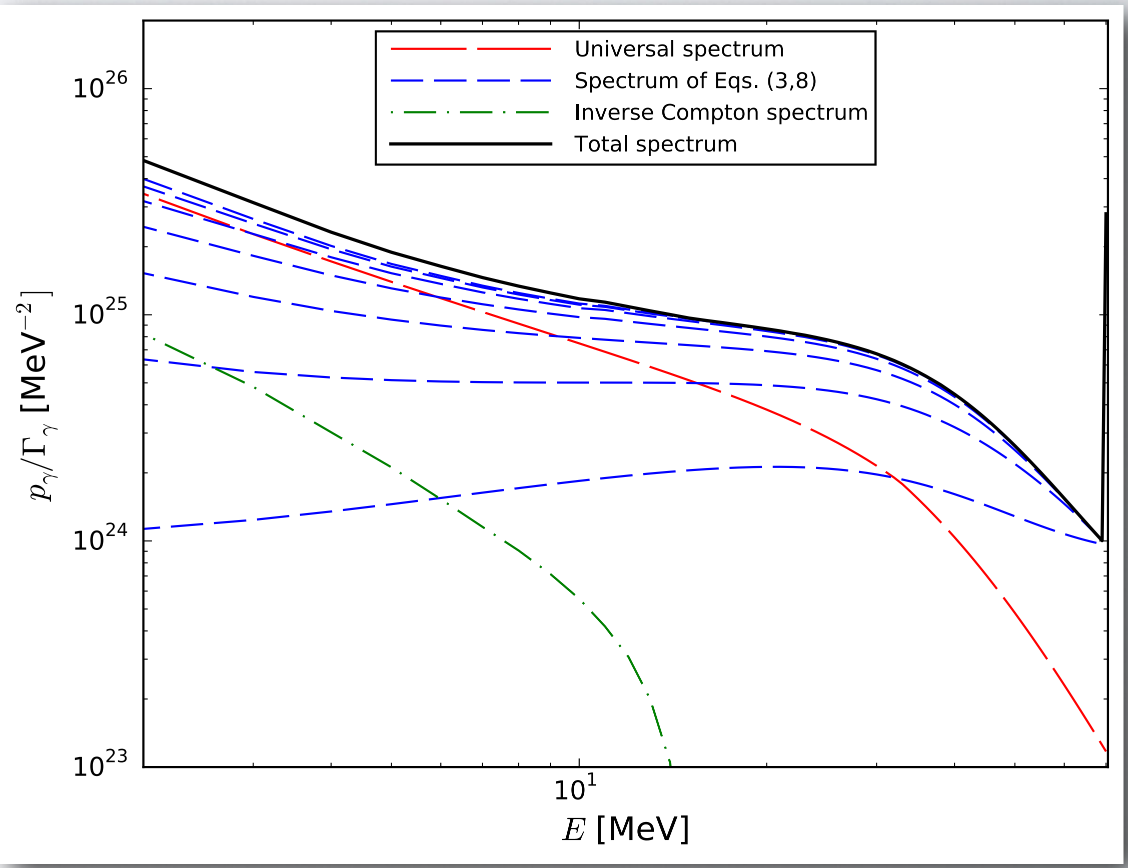
ITERATIVE SOLUTION

Exact at high-E, need to account for re-injection for the lower energy

$$\mathcal{S}(E_\gamma,t) \to \mathcal{S}(E_\gamma,t) + \int_{E_\gamma}^{\infty} dx\, K_\gamma(E_\gamma,x,t) f_\gamma(x\,,t)$$

- At lower energies, also some effect due to up-scattered thermal photons by non-thermal electrons produced by 1st-generation photons ("tertiary" component)

- The method converges quickly (<10% errors with 4 iterations) and can be generalized to fully account for the coupled eq. for the electrons



PROOF OF PRINCIPLE

- Inject γ's with E>1.6 MeV (^{7}Be photodis. threshold, ^{7}Be=dominant progenitor of ^{7}Li into which it eventually decays) & E<2.2 MeV (^{2}H photodis. threshold, next to most fragile nuclide)
- By construction, this does not perturb all other nuclear yields, one can adjust normalization to deplete by a factor 3-4. The solution is analytical:

$$\ln\left(\frac{Y_{^7\mathrm{Be}}(z_i)}{Y_{^7\mathrm{Be}}(z_f)}\right) = \int_{z_f}^{z_i} \mathrm{d}z' \, \frac{n_\gamma^0 \zeta_X \, \sigma_\star(E_0) \, c \, e^{\frac{-1}{2H_r^0 \tau_X (z'+1)^2}}}{E_0 H_r^0 \tau_X \Gamma(E_0, z')}$$

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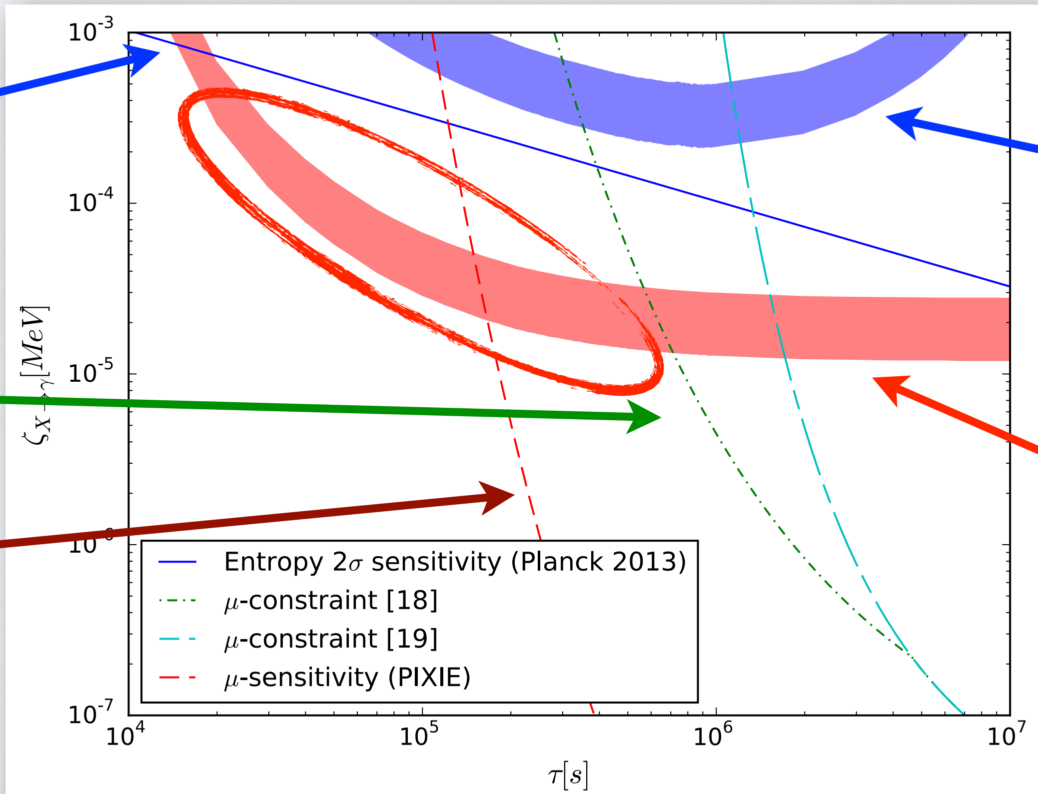
Entropy difference bound

Current CMB distortion bound

forecast CMB distortion sensitivity PIXIE



solution computed with "naive spectrum" fails to pass other constraints

"correct" solution has still allowed parameter space

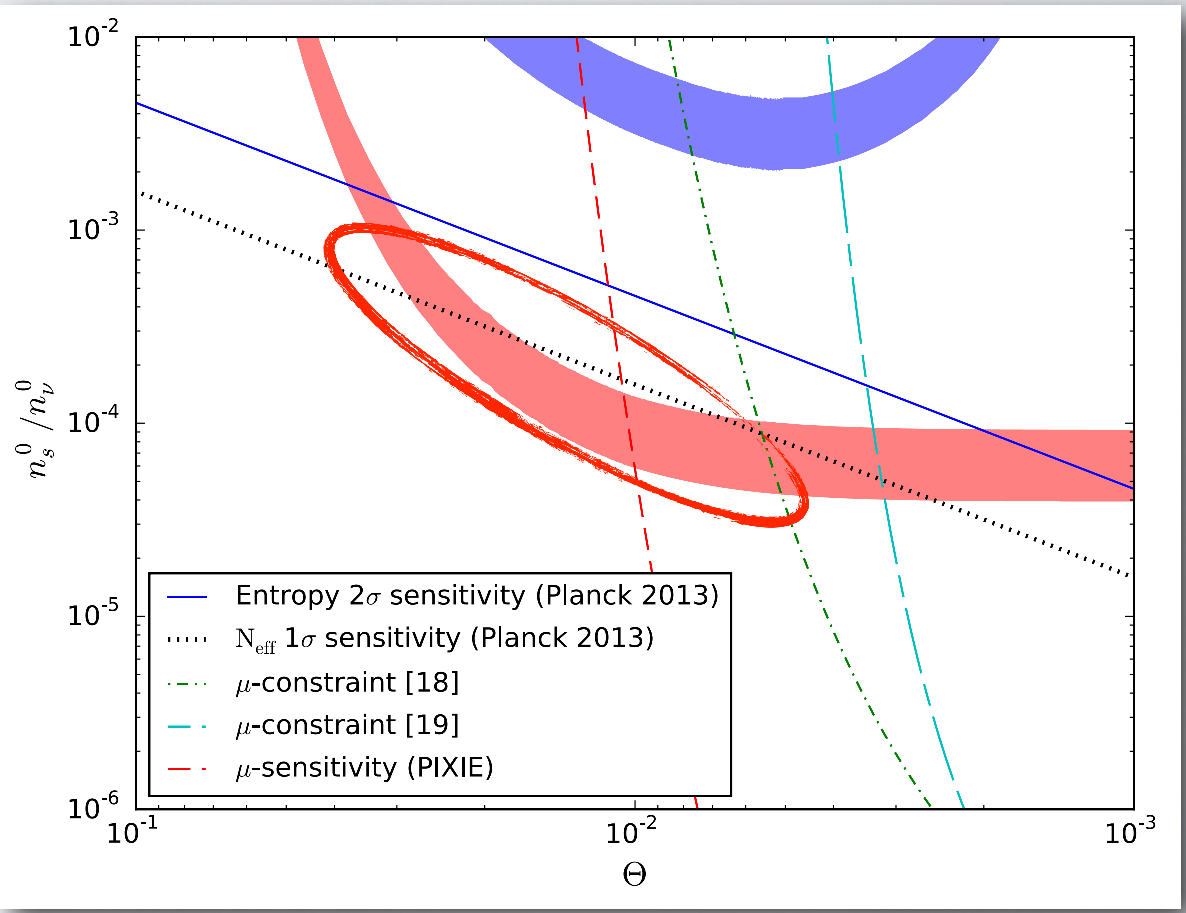
ACTUAL (SIMPLE) MODEL

Maybe proof of principle too idealized, can it be realized in actual models? It can, for parameters that pass both cosmological and laboratory bounds!
Below, results for sterile ν, ~4 MeV mass (+-20%) mixing mostly with ν_μ and/or ν_τ
Branching ratios for decay~ 1:0.1:0.01 in 3ν : νe^+e^- : νγ

If using "universal" spectrum, this type of simple models known to fail, see

H. Ishida, M. Kusakabe and H.Okada, PRD 90, 8, 083519 (2014)

Obviously, we do not claim that this is the solution. We just stress that relatively simple models (naively discarded as badly ineffective) can do the job

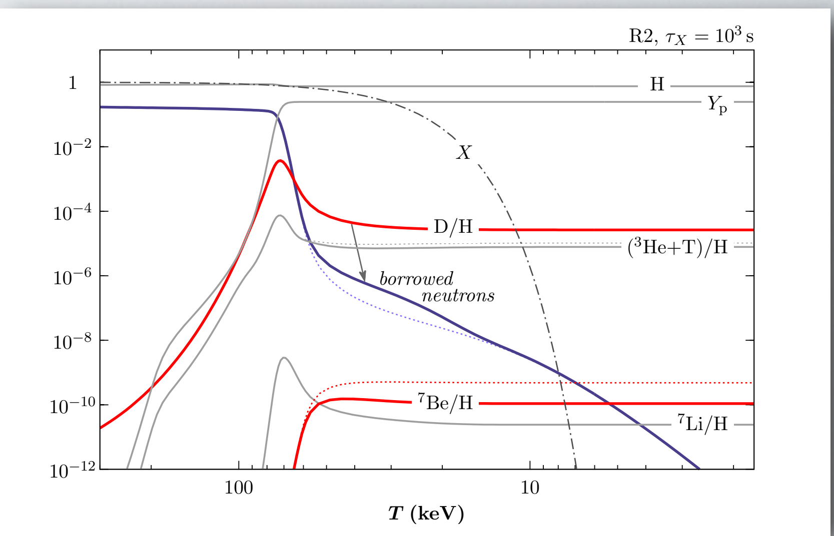


NEW LIGHT PARTICLES & NEW FORCES?

New metastable particle, X, with lifetime ~10^3 s, sufficiently light not to disrupt He (m_X~5 MeV), sufficiently abundant/interacting with ^{7}Be and D via

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

can do the job in a sufficiently wide parameter space!

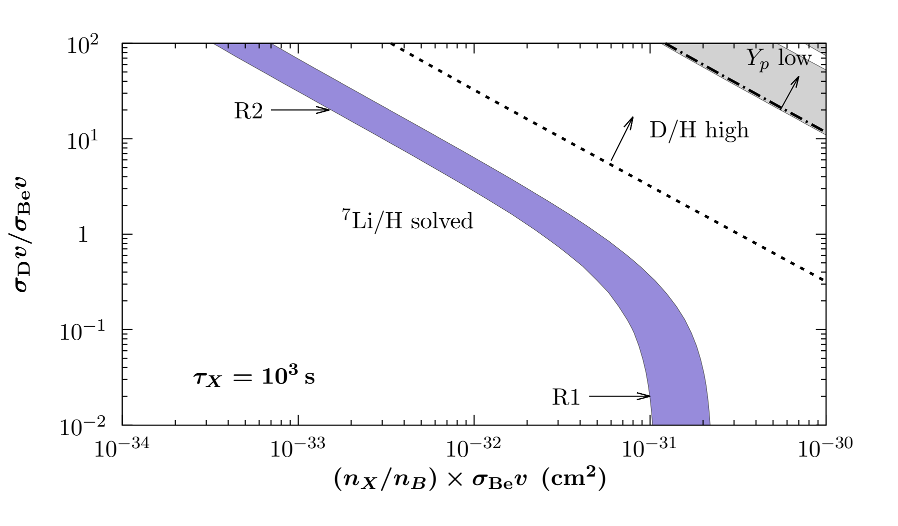


Key trick: you allow D destruction at the same time, but provided it stops by t~10^3 s (X decay), neutrons are recaptured, and reform D!

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

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

Actual model: e.g. axion-like particle coupled mostly with d-quarks in a multiple Higgs scenario (f_d~TeV scale)



A. Goudelis, M. Pospelov and J. Pradler, Phys. Rev. Lett. 116, 21, 211303 (2016)

CONCLUSIONS

- The long-standing *Lithium problem* appears to be due either to astrophysical or particle physics/cosmological causes, not to lack of nuclear physics data/theory.

- In the former possibility, the goal is to have *testable* models that possibly offer dynamical arguments for the Spite & Spite plateau.

- Particle physics solutions have not come easy, either. New developments seem to offer unexpected hope either from better treatment of standard model processes at ***low scales*** or from new physics (with ***light*** degrees of freedom).

- There may be room for an interplay with nuclear physics. E.g.

- in *V. Poulin, PDS, Phys. Rev. D 91, 10, 103007 (2015)*, we pointed out possible need for photo disintegration data in the ~100 MeV range, to compute realistic BBN bounds on cascades in the early universe.

- In *A. Goudelis, M. Pospelov, J. Pradler, Phys. Rev. Lett. 116, 21, 211303 (2016)* simple recipe to compute relevant "exotic" nuclear reactions, such as: How well does this approximation work?

spin factors

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

Merci pour votre attention!