Astroparticle Physics & Cosmology

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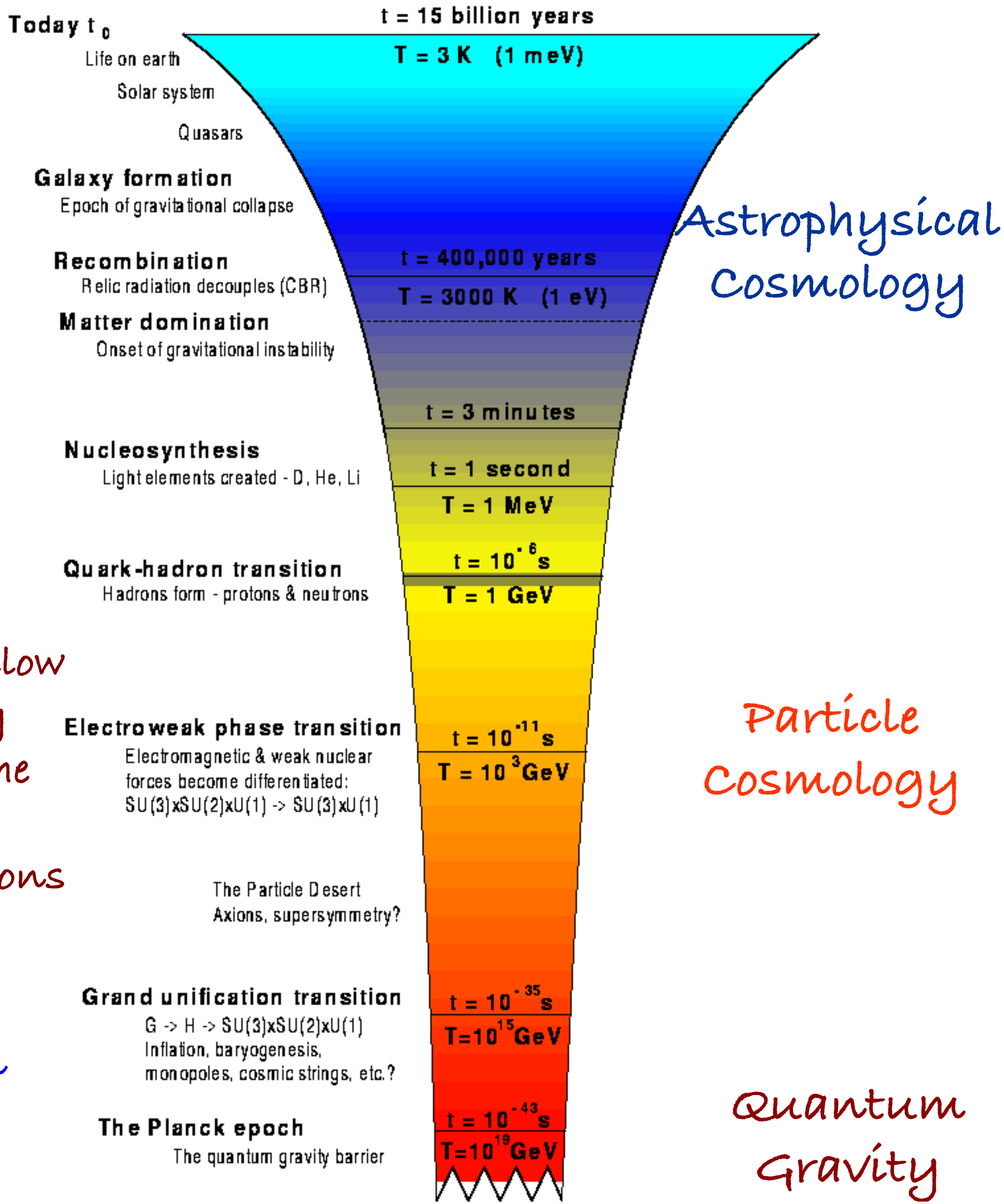
Oxford Physics

- The universe observed
- Reconstructing our thermal history
- Dark matter
- The early universe

The early universe is an unique laboratory for new physics … which must account for the observed asymmetry between matter and antimatter, generate dark matter (and dark energy), as well as the density fluctuations which seeded the formation of structure.

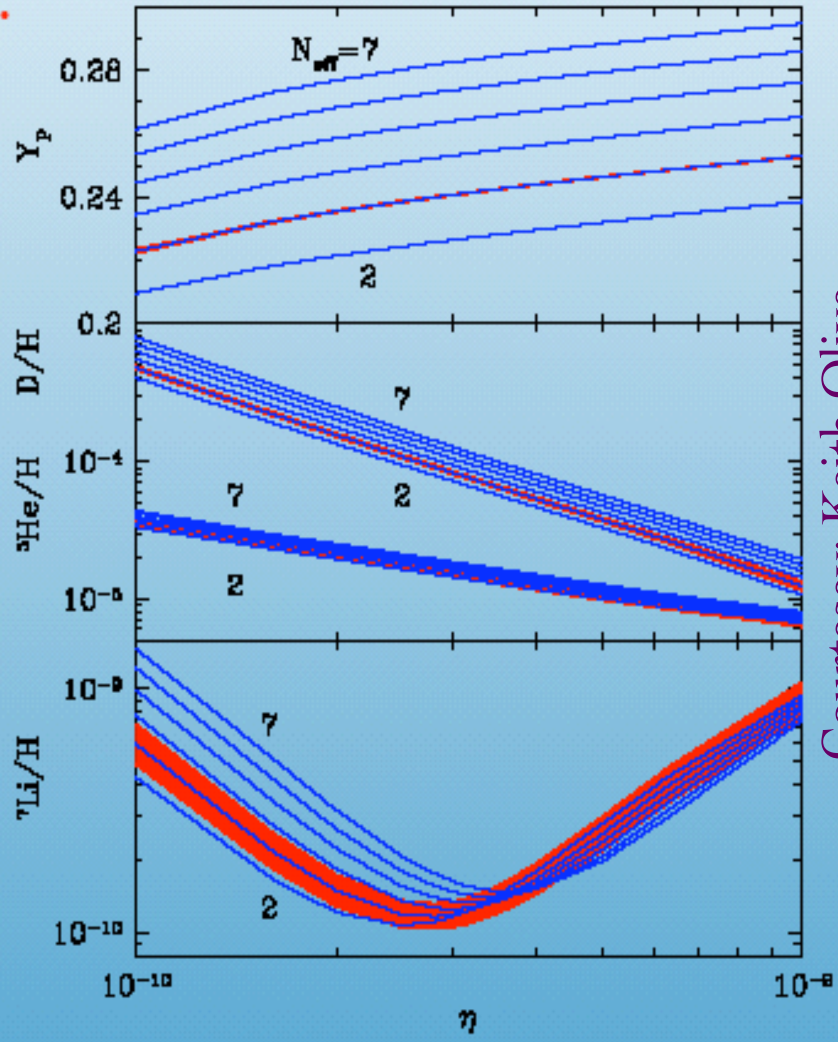
However *direct* observations allow us to probe the thermal history back to only ~10^6 s (using the CMB spectrum) and further back to ~1 s (using observations of primordially synthesised elemental abundances).

On the basis of the SM we can extrapolate further to ~10^{-11} s



Limits on Particle Properties

- BBN Concordance rests on balance between interaction rates and expansion rate.
- Allows one to set constraints on:
  - Particle Types
  - Particle Interactions
  - Particle Masses
  - Fundamental Parameters



Courtesey: Keith Olive

Constraints from balance of weak rates vs Hubble rate

$$G_F^2 T^5 \sim \Gamma(T_f) \sim H(T_f) \sim \sqrt{G_N N} T_f^2$$

through He abunance

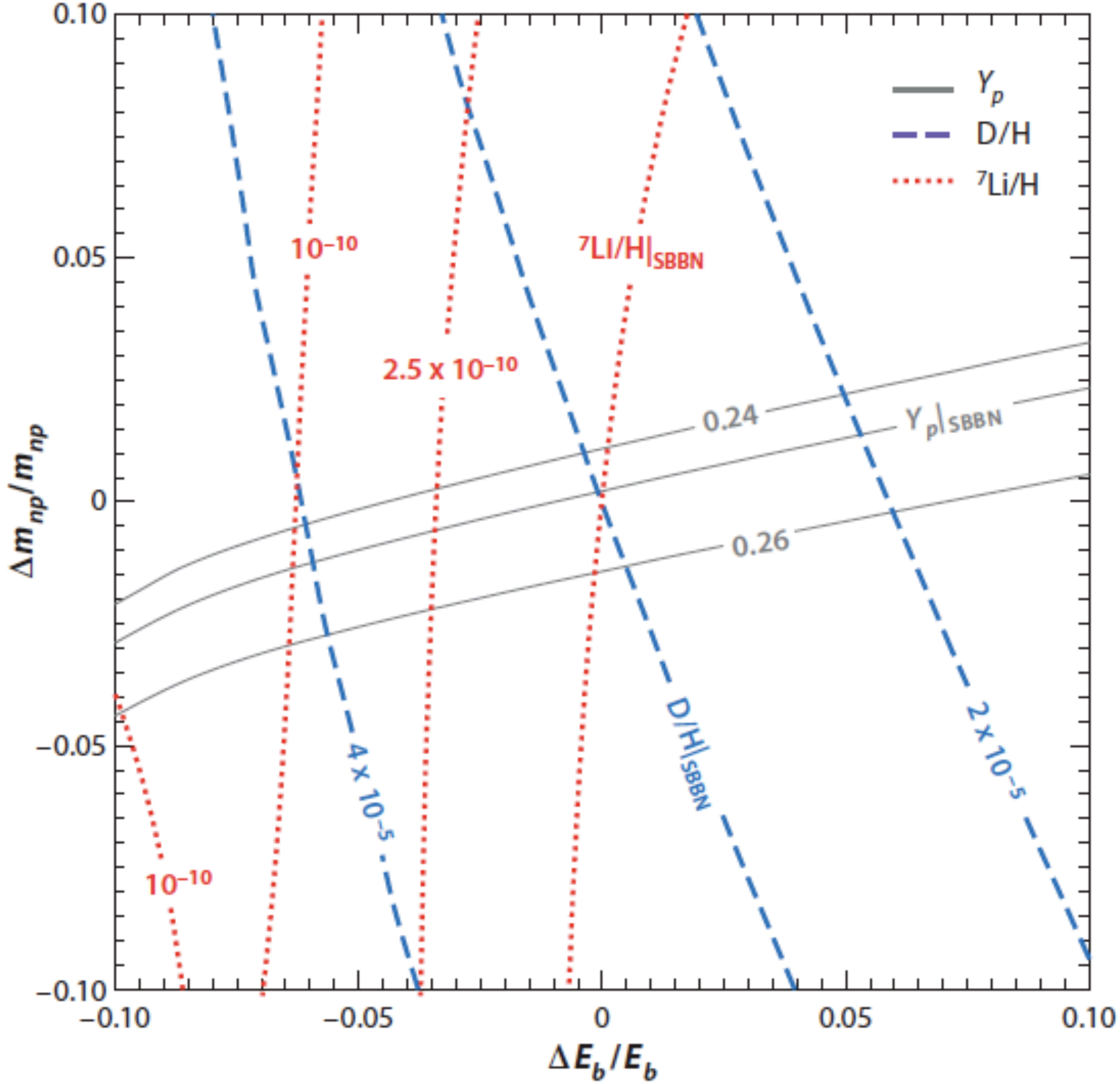
$$\frac{n}{p} \sim e^{-\Delta m/T} \qquad \text{fixed at freezeout} \qquad Y \sim \frac{2(n/p)}{1+(n/p)}$$

Sets constraints on G_F, G_N, N, etc.

Note *n*-*p* mass difference is sensitive to both em and strong interactions, hence ^{4}He abundance is *exponentially* sensitive to *all* coupling strengths

Conversely obtain bound of less than few % on any additional contribution to energy density driving expansion e.g. gravitational waves, `dark radiation', new particles ...

Rule out $\Lambda \sim H^2$ always (since this corresponds to a large 'renormalisation' of G_N)



Pospelov & Pradler, ARNPS 60 (2010) 539

Figure 3

Contours of Y_p, D/H, and ^{7}Li/H are plotted in the parameter space of variable neutron-proton mass difference Δm_{np} and deuteron-binding energy E_d, normalized to their current values. The 5–10% downward change in E_b can significantly reduce the ^{7}Li abundance.

"Neutrino counting"

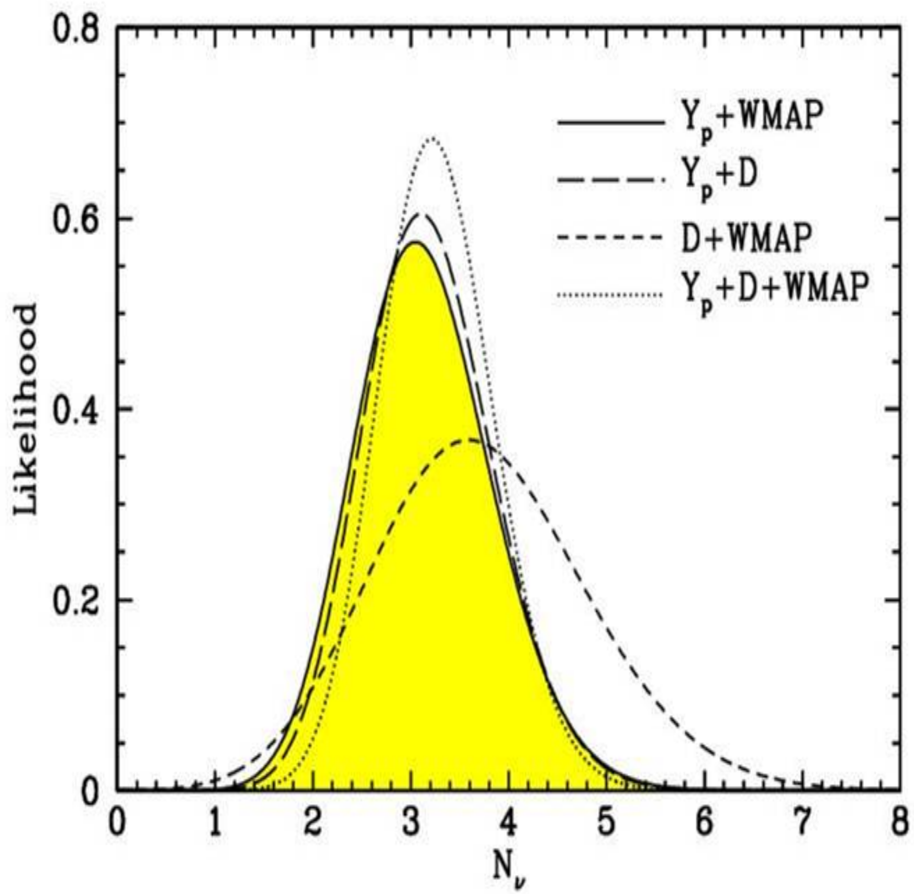
Light element abundances are sensitive to expansion history during BBN

$$H^2 \sim G\rho_{\rm rel}$$

$\Rightarrow$ observed values constrain the relativistic energy density at BBN

$$\rho_{\rm rel} \equiv \rho_{\rm EM} + N_{\nu,\rm eff}\, \rho_{\nu\bar{\nu}}$$

(Hoyle & Taylor 1964, Shvartsman 1969, Steigman, Schramm & Gunn 1977, …)



Cyburt, Fields, Olive & Skillman [astro-ph/0408033]

Pre-CMB:

^{4}He as probe, other elements give η

With η from CMB:

- All abundances can be used
- ^{4}He still sharpest probe
- D competitive if measured to 3%

$$\delta N_\nu \equiv N_\nu - 3 < 1.5$$
@ 95% c.l.

This constrains sterile neutrinos (and other hypothetical particles) which do not couple to the Z^0 … complementary to laboratory bounds e.g from LEP

Limits on α from BBN

Contributions to Y come from n/p which in turn come from Δm_N

Contributions to Δm_N:

Kolb, Perry, & Walker
Campbell & Olive
Bergstrom, Iguri, & Rubinstein

$$\Delta m_N \sim a\alpha_{em}\Lambda_{QCD} + bv$$

Changes in α, Λ_{QCD}, and/or v
all induce changes in Δm_N and hence Y

$$\frac{\Delta Y}{Y} \simeq \frac{\Delta^2 m_N}{\Delta m_N} \sim \frac{\Delta\alpha}{\alpha} < 0.05$$

If $\Delta\alpha$ arises in a more complete theory
the effect may be greatly enhanced:

$$\frac{\Delta Y}{Y} \simeq O(100)\frac{\Delta\alpha}{\alpha} \text{ and } \frac{\Delta\alpha}{\alpha} < \text{few } \times 10^{-4}$$

In fundamental theories e.g. string theory, the physical "constants" do vary with time … but the BBN constraint says that this must have stopped before t ~ 0.1 s

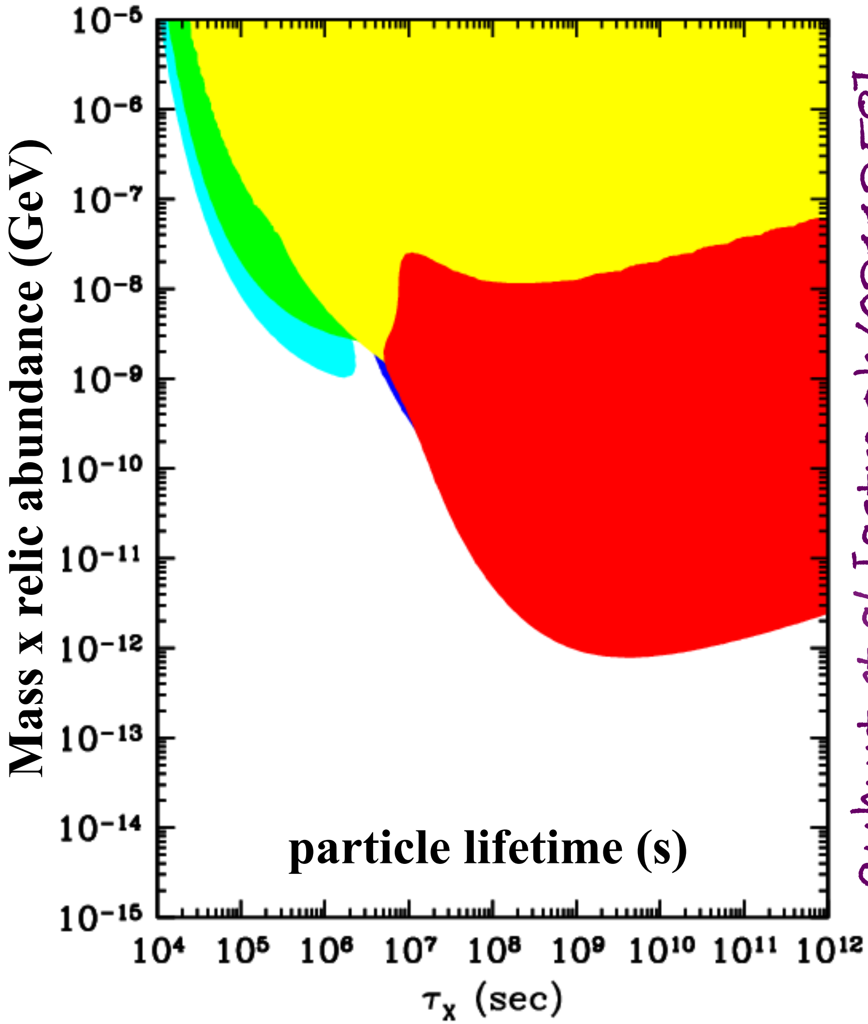
BBN and decaying particles

Extensions of the Standard Model predict new (typically) *unstable* particles, which would have been created (thermally) in the early universe, e.g. weak scale mass gravitinos in supergravity

$$\tilde{G} \to \gamma\gamma \qquad \tau_{3/2} \approx 4\times10^5 \text{ s} \left(\frac{m_{3/2}}{1 \text{ TeV}}\right)^{-3}$$

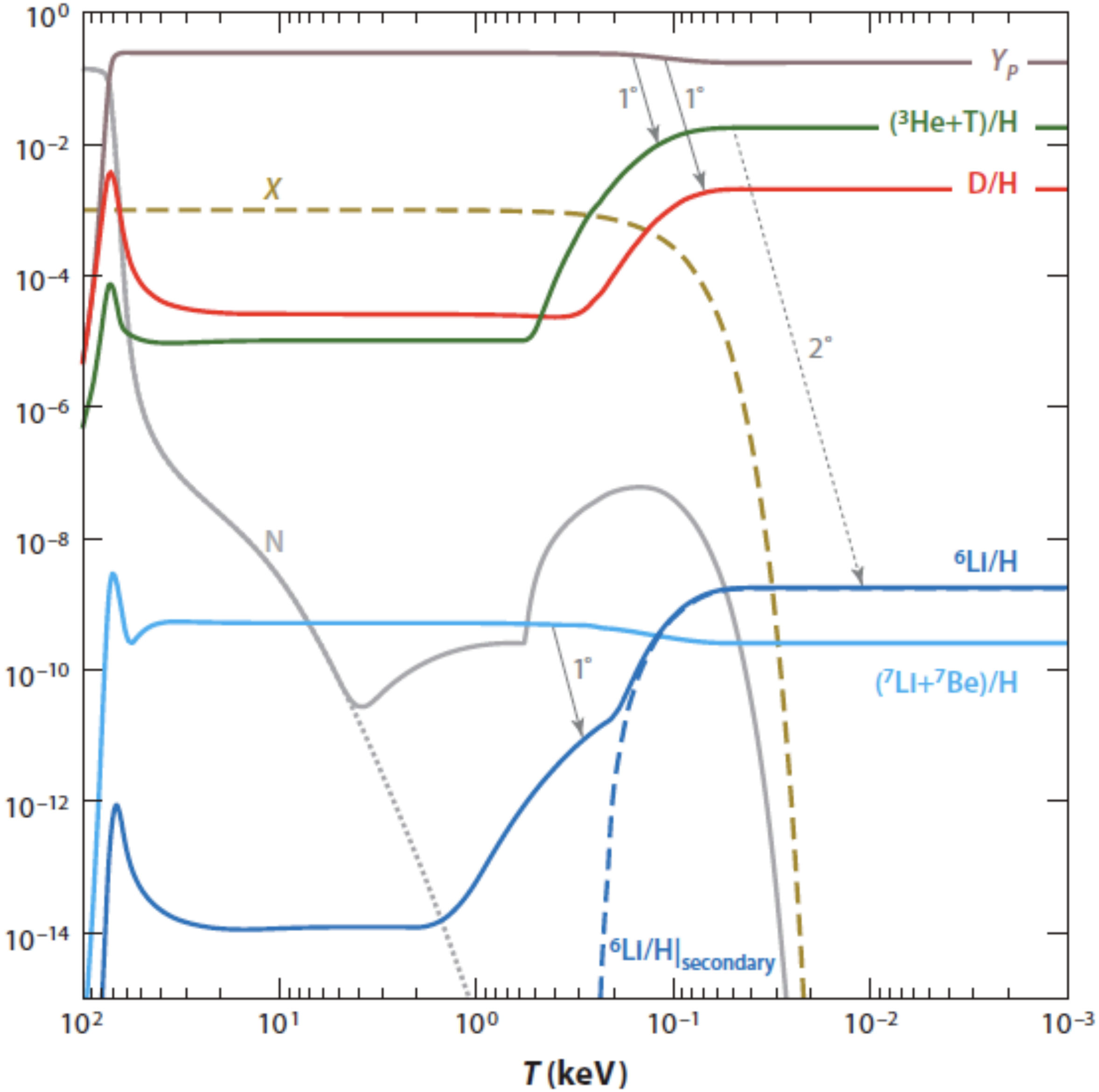
(Weinberg 1982; Khlopov & Linde 1983; Ellis, Nanopoulos & Sarkar 1985; Reno & Seckel 1988)

The high energy photons would have photo-dissociated the synthesized elements $\Rightarrow$ *severe limits on the decaying particle abundance*



Cyburt *et al* [astro-ph/0211258]

Since $n_{3/2}/n_\gamma \sim T_{reheat}/M_P$, this requires that *highest* temperature reached in our past (after inflation) was < 10^8 GeV ➔ severe constraint on baryogenesis



Pospelov & Pradler, ARNPS 60 (2010) 539

Figure 4

Consequences of late decays of a heavy 1-TeV mass particle X that releases half of its rest mass in the form of electromagnetic energy. The threshold of ^{4}He disintegration is clearly visible below 1 keV. Primary abundance flows are indicated by solid arrows, whereas the dashed arrow indicates the secondary transformation of A = 3 nuclei into ^{6}Li. The model is excluded by the overproduction of D, ^{3}He, and ^{6}Li.

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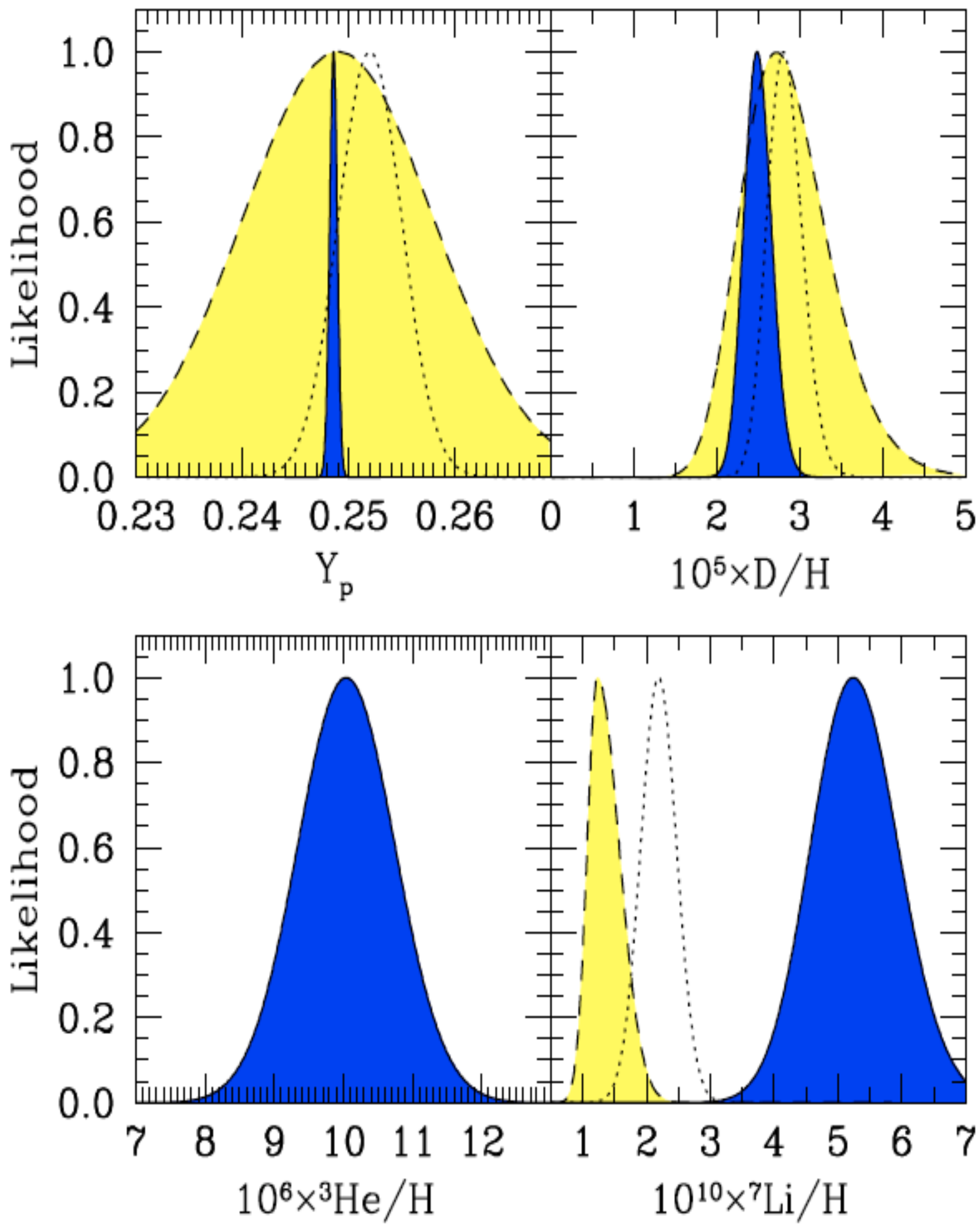
In fundamental theories e.g. string theory, the physical "constants" do vary with time ... but the BBN constraint says that this must have stopped before $t \sim 0.1$ s

However the concordance between the theory and observations may be cracking up

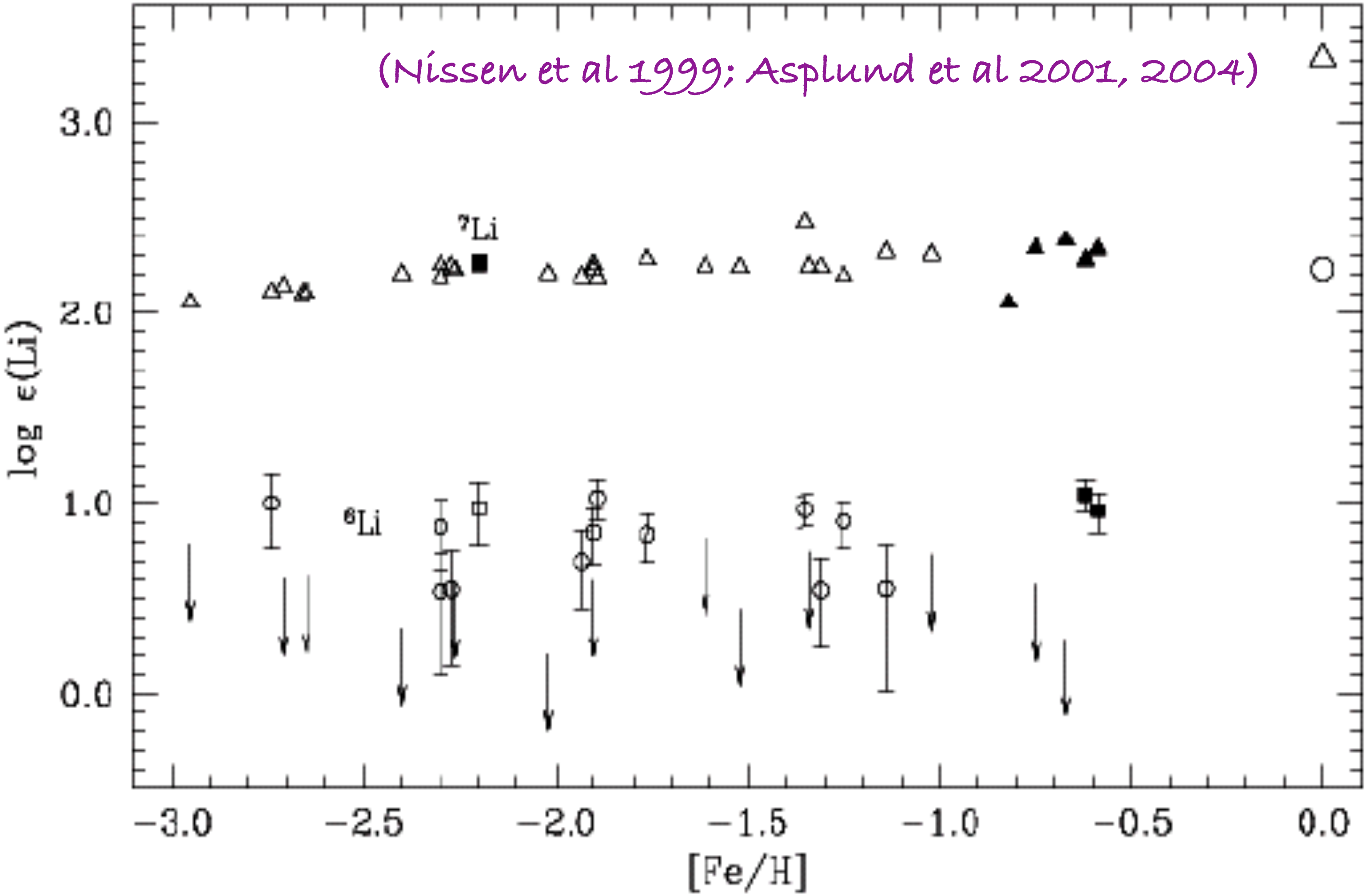
Predict BBN abundances with
WMAP determination of η_{CMB} (blue)
compare with observations (yellow)

- D agreement excellent, ^{4}He also OK
- But ^{7}Li is discrepant
  - systematic errors in observations?
  - theoretical uncertainties?
  - new physics (e.g. decaying relic particles)? → this has additional motivation from the observation that ^{6}Li has also been observed – with an abundance > 10^4 times higher than expected!

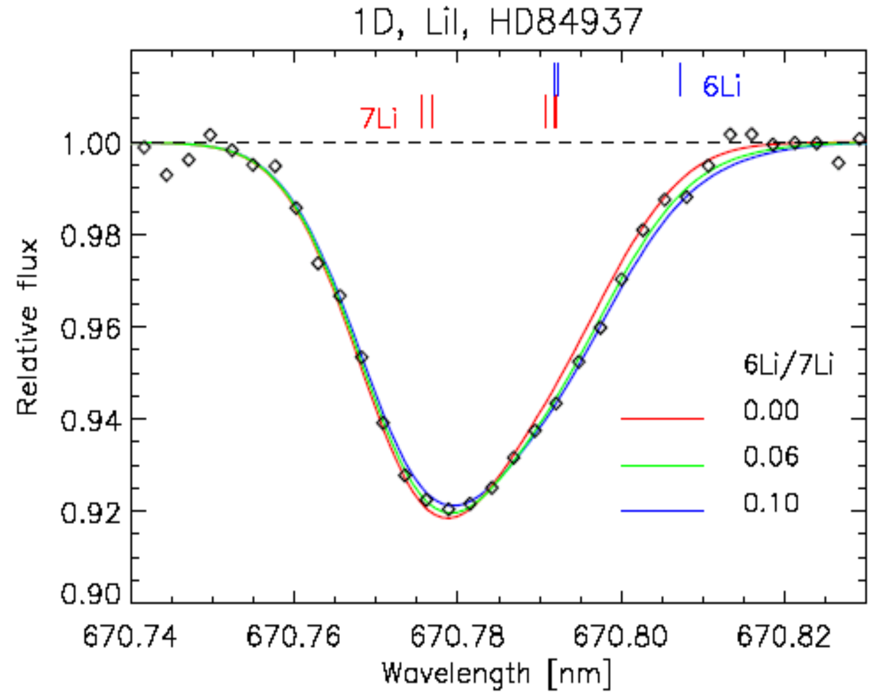


Cyburt, Fields & Olive [arXiv:0808.2818]

Recently a primordial 'plateau' in ^{6}Li is claimed to have been detected with $^6\mathrm{Li}/^7\mathrm{Li} \sim 0.1$ (cf. standard expectation $^6\mathrm{Li}/^7\mathrm{Li} \sim 10^{-5}$)



Coupled with the fact that the ^{7}Li abundance is ~3 times *smaller* than expected, this has refocussed interest on **non-standard BBN**



The Li I 6707 Å resonance doublet in HD 84937 from Smith et al. (1993). The wavelengths of the ^{7}Li and ^{6}Li re indicated at the top of the figure. Synthetic profiles for three ^{6}Li/^{7}Li ratios are shown – courtesy of Martin Asplund.

However the 'detection' of ^{6}Li is based on fits to the line shape … need more data to establish the reality of a '^{6}Li plateau!'

Also stars in which ^{6}Li is detected are close to the main-sequence turn-off in the H-R diagram

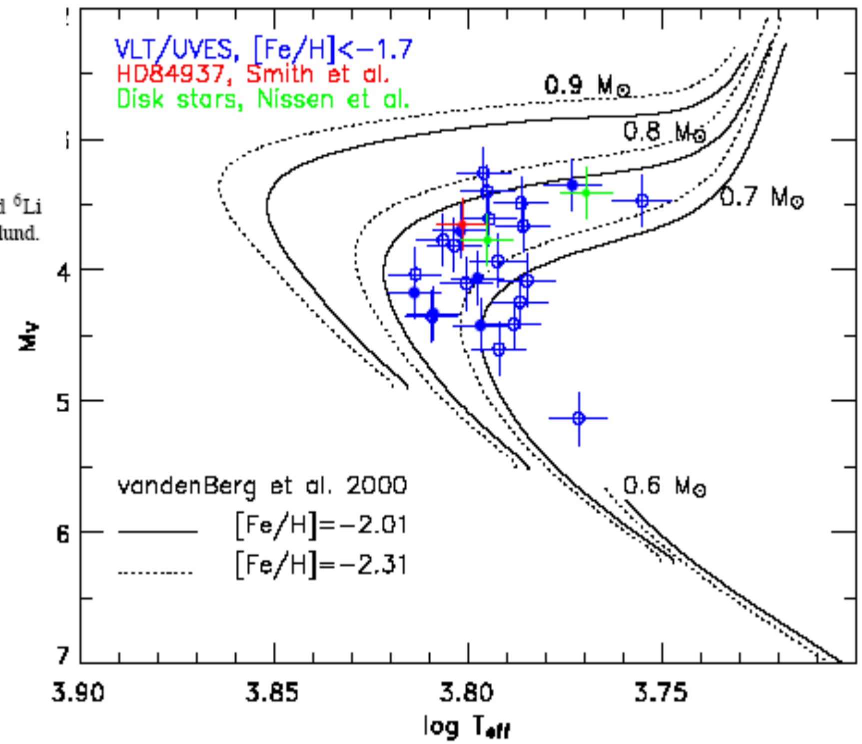


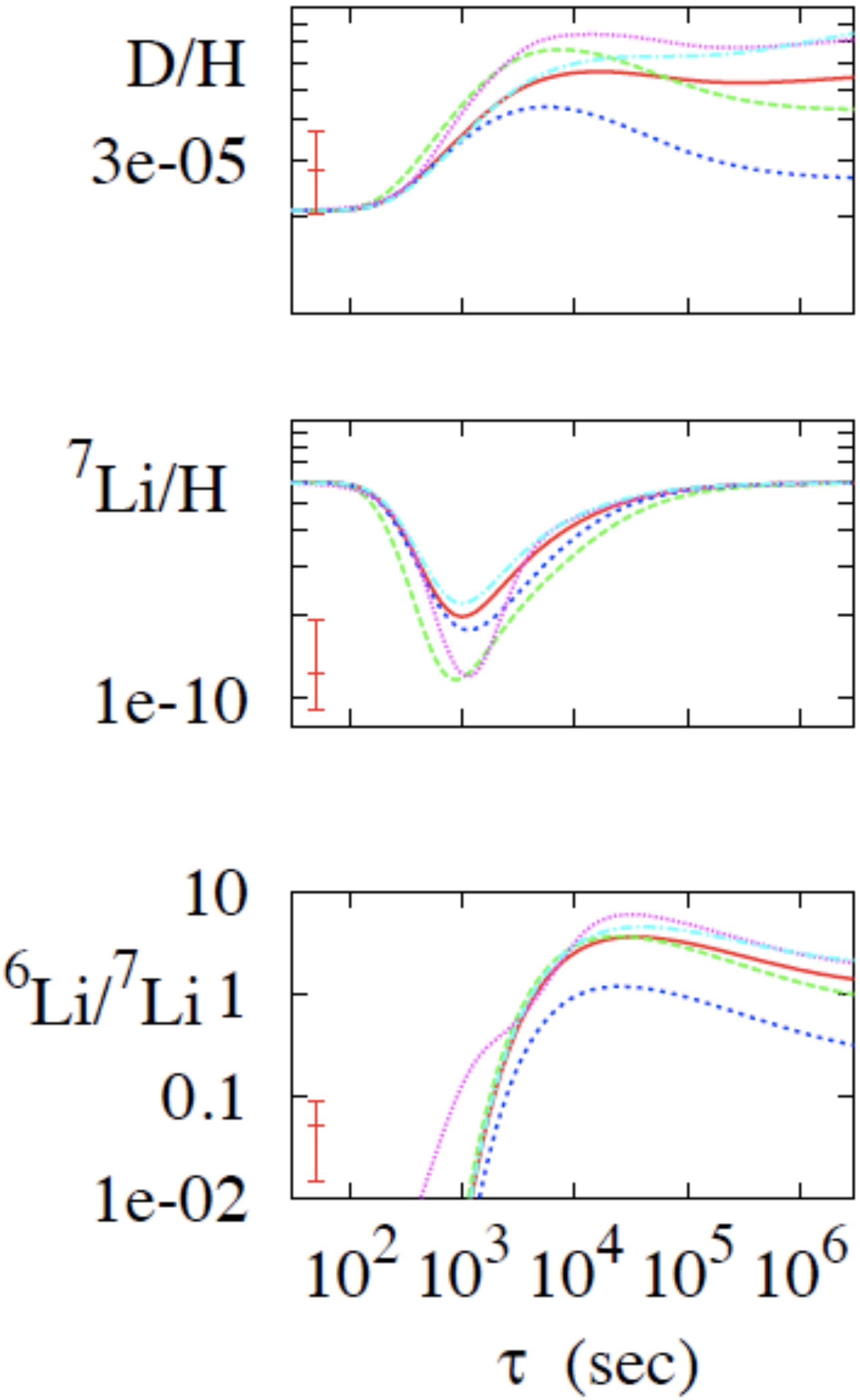
FIGURE 4. The Hertzsprung-Russell diagram for stars from Figure 3 with [Fe/H] < -1.7. Filled symbols denote stars with a detection of ^{6}Li according to the key in the top left corner of the figure. Evolutionary tracks for the indicated stellar masses and metallicities are from VandenBerg et al. (2000).

Lambert (2005)

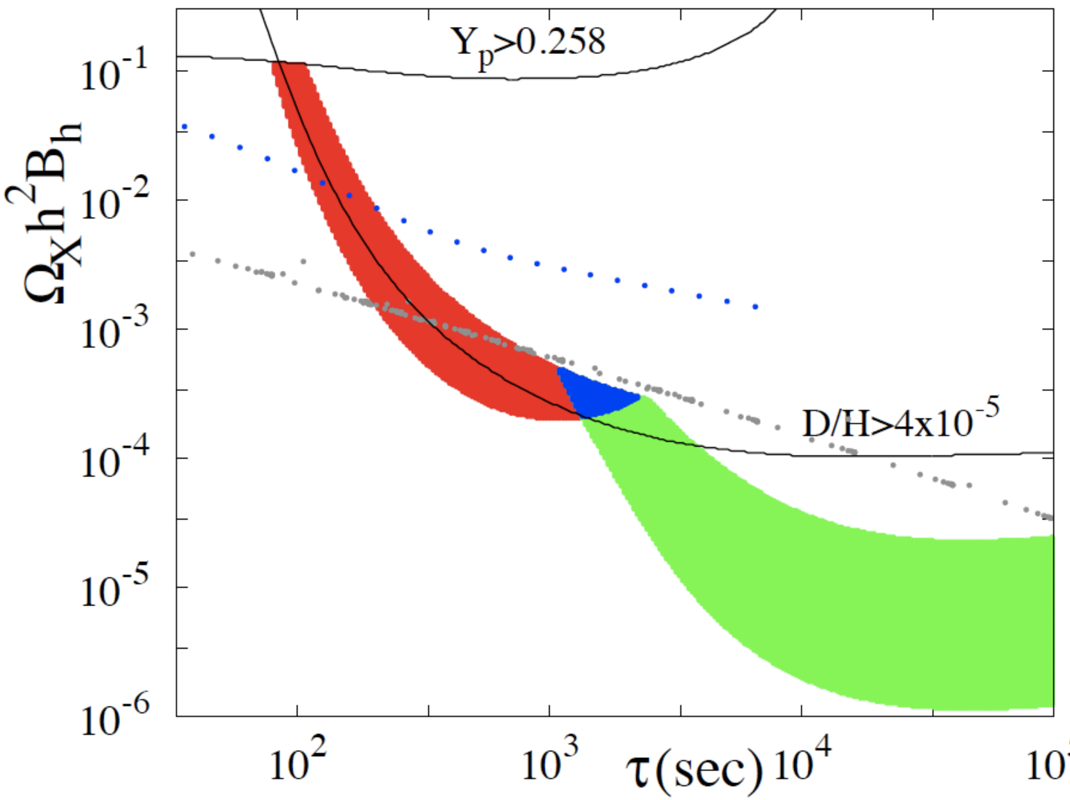
Does the Lithium anomaly imply new physics?

- $^6\mathrm{Li}$ is easily produced in the early Universe by the decay or annihilation of relic particles
- $^7\mathrm{Li}$ is easily destroyed during BBN when a weak non-thermal hadronic source is present
- both problems may be solved simultaneosly by the decay of a relic 1000 sec after the Big Bang

Jedamzik [astro-ph/0402344]



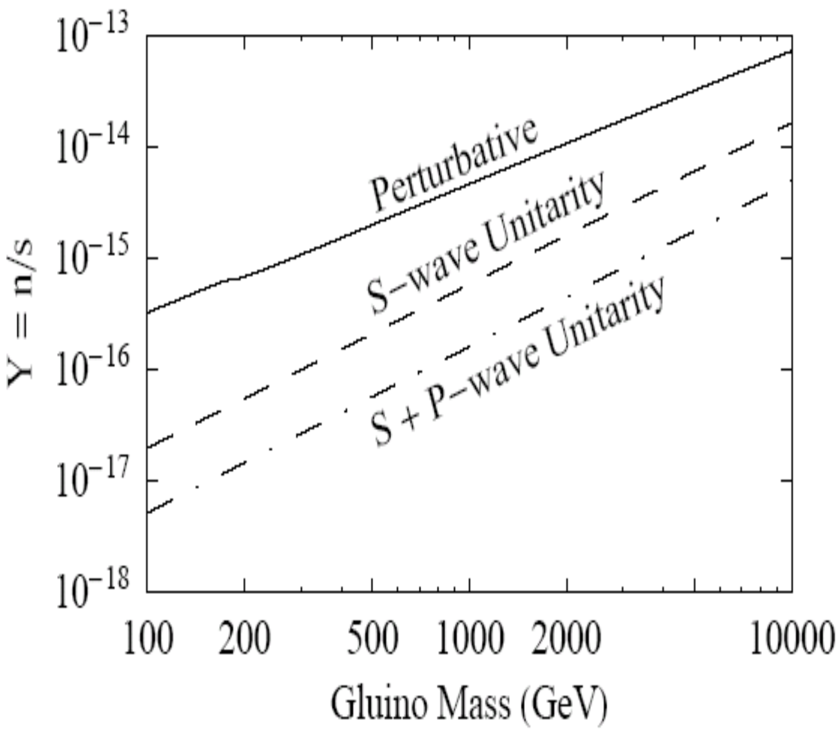
May be possible to solve *both* 'lithium problems' with relic decaying particle having suitable abundance/lifetime e.g. gluino in split supersymmetry, supersymmetric stau Next-to-LSP (with gravitino LSP), …

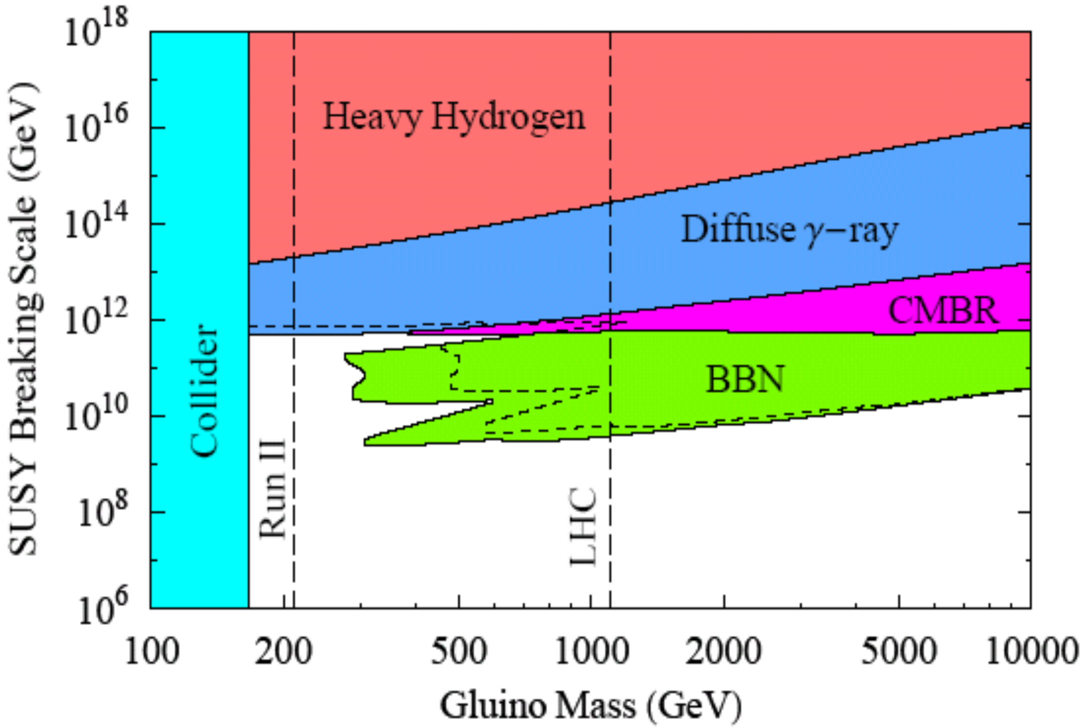


Bailly, Jedamzik & Moultaka [arXiv:0812.0788]

Gluino in 'split' supersymmetry

If mass scale of SUSY scalar superpartners is raised well above a TeV (to evade various problems with weak scale SUSY breaking), then predict *long-lived* gluinos





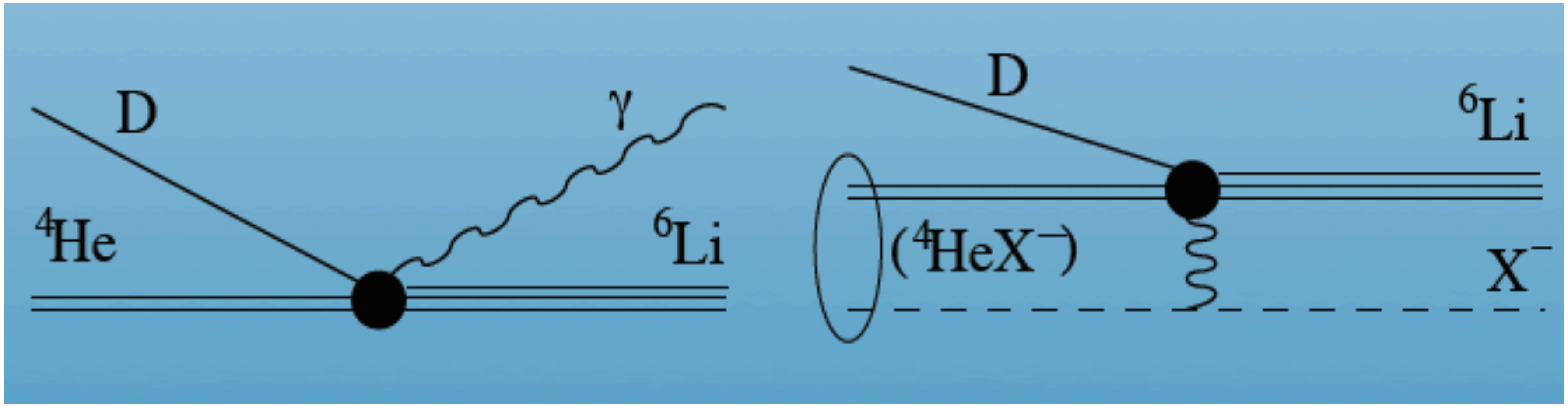
A small number of these would survive annihilation in the early universe and decay during nucleosynthesis → stringent bound from overproduction of D + ^{3}He

This would require supersymmetry breaking scale to be $< 10^{10}$ GeV

Arvinataki, Davis, Graham, Pierce & Walker [hep-ph/0504210]

There may also be new *charged* quasi-stable relic particles in Nature which would form **bound states** with ^{4}He

Although the ^{4}He (D, γ) ^{6}Li reaction is normally highly suppressed, this is not so for the bound state …



Pospelov [hep-ph/06052215]

Thus the lithium anomaly may be due to supersymmetric particles (e.g. “stau”) which catalyse relevant nuclear reactions
… if so these could be seen soon at the LHC!

Summary

Observational inferences about the primordially synthesised abundances of D, ^{4}He and ^{7}Li presently provide the *deepest* probe of the Big Bang, based on an *established* physical theory

The overall concordance between the inferred primordial abundances of D and ^{4}He with the predictions of the standard cosmology requires most of the matter in the universe to be non-baryonic, *and* enables constraints to be placed on any deviations from the usual expansion history (e.g. new neutrinos, dark energy)

Anomalies in the abundances of ^{6}Li and ^{7}Li have been interpreted as indications for new physics beyond the Standard Model (*viz.* unstable supersymmetric particles) … need better understanding of the astrophysical processing of lithium to investigate this further

Nucleosynthesis marked the beginning of the development of modern cosmology … and it is still the final observational frontier as we look back to the Big Bang