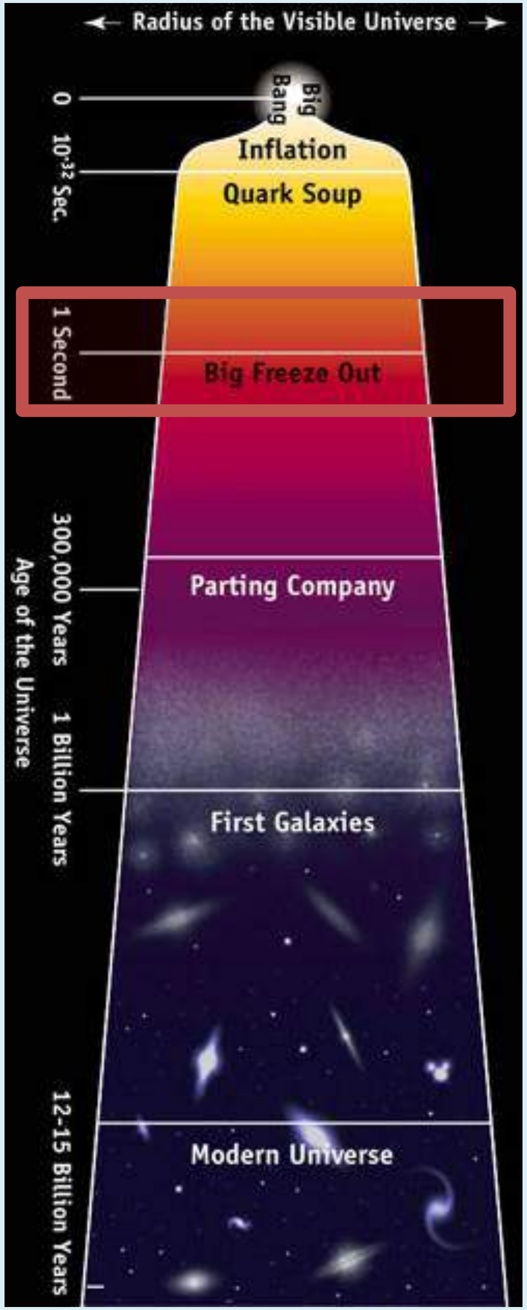
Big Bang Nucleosynthesis

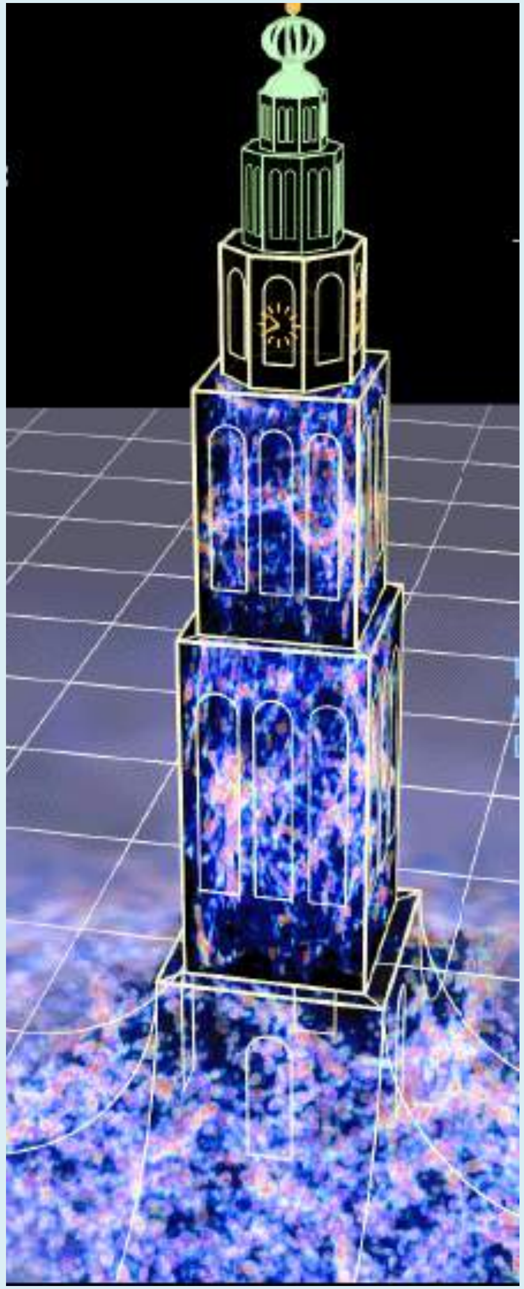
The Lithium-~~6~~ Problem

Subir Sarkar

Oxford Physics

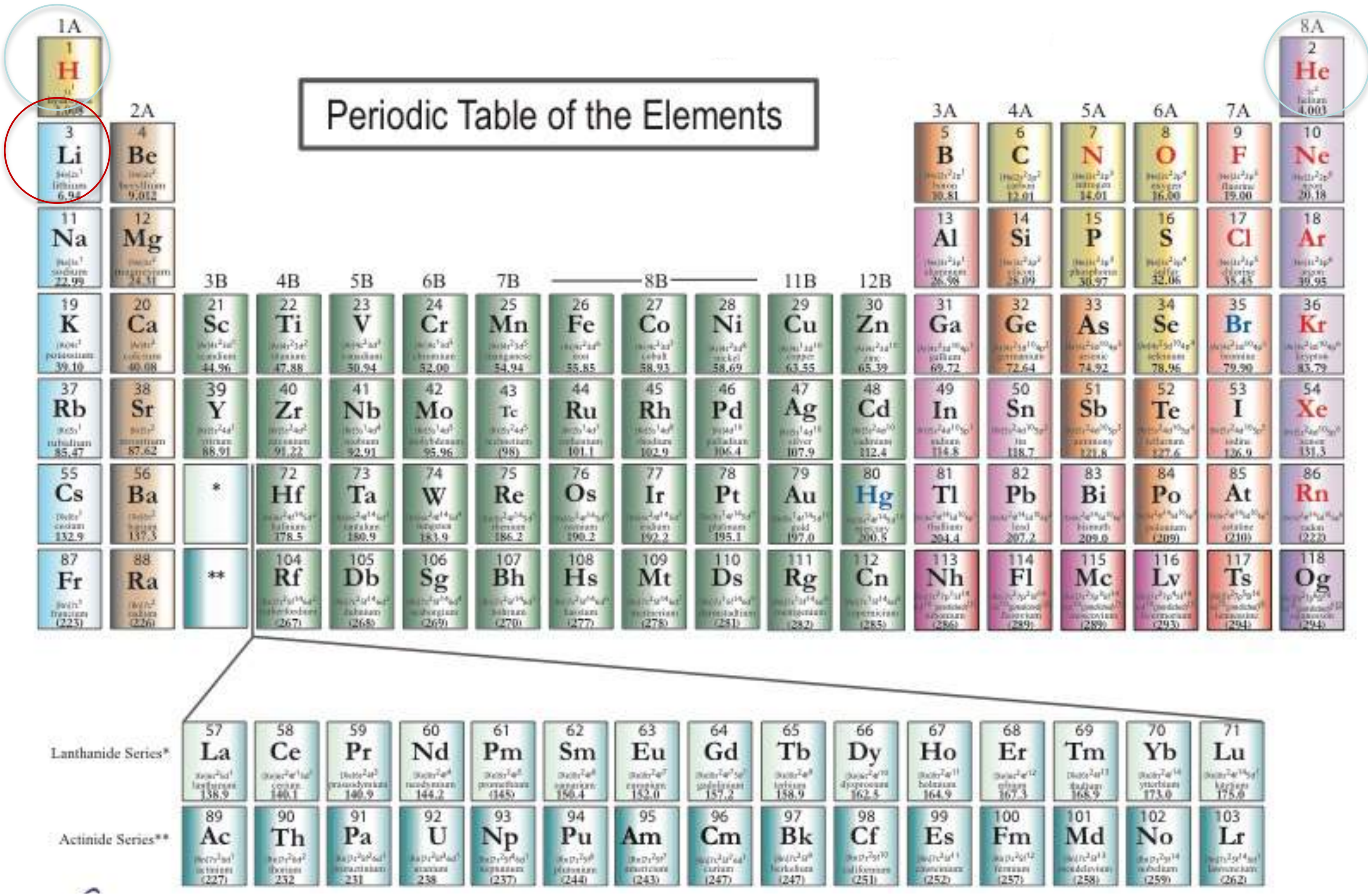


The Drunken Alcibiades Interrupting the Symposium
Pietro Testa (1648)

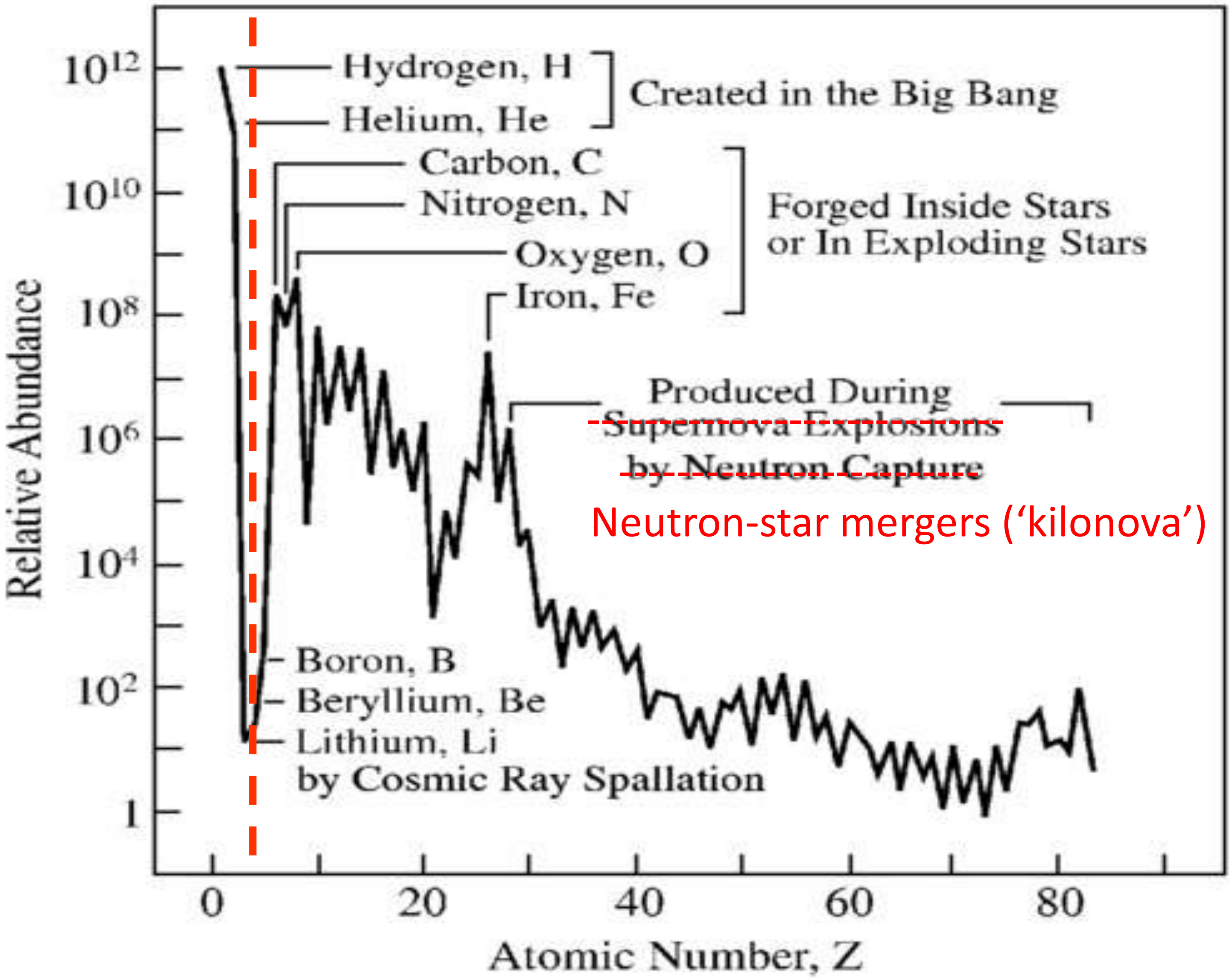


The Ninth Quantum Universe Symposium
University of Groningen, 18 April 2019

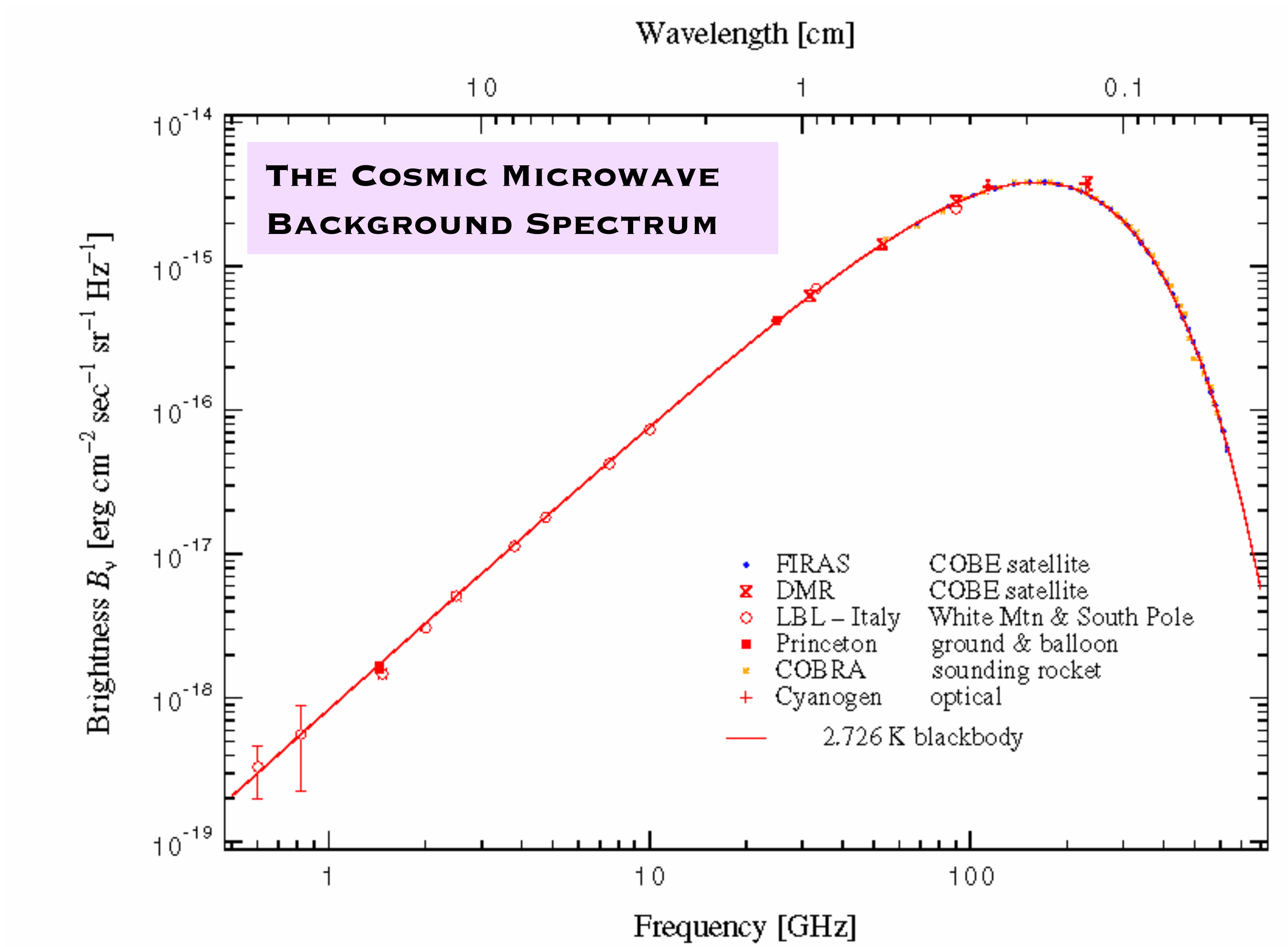
The hydrogen (~75% by mass) is created in primordial baryogenesis (how?) and the helium (~25% by mass) then arises naturally from primordial nucleosynthesis … but there is a *problem* with understanding the origin of the next heavier element: lithium



Where did all the elements come from?



Burbidge, Burbidge, Fowler & Hoyle, RMP **29**:547,1957



This *perfect* **blackbody** is testimony to our hot, dense past and directly demonstrates that the expansion was indeed **adiabatic** (with negligible energy release) back at least to $t \sim 1$ day

… we can go back *further* to $t \sim 1$ s by studying element synthesis

In the absence of dissipative processes (e.g. phase transitions which generate entropy) the **comoving entropy** is conserved:

$$\frac{d}{dt}(sa^3) = 0 \quad \Rightarrow \quad s \propto 1/a^3 \qquad \text{i.e.} \qquad T \propto 1/a$$

The dynamics is governed by the Friedmann equation:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N \rho}{3}$$

$$\rho = 3p = \frac{\pi^2}{30} g(T) T^4$$

Integrating this gives the time-temperature relationship:

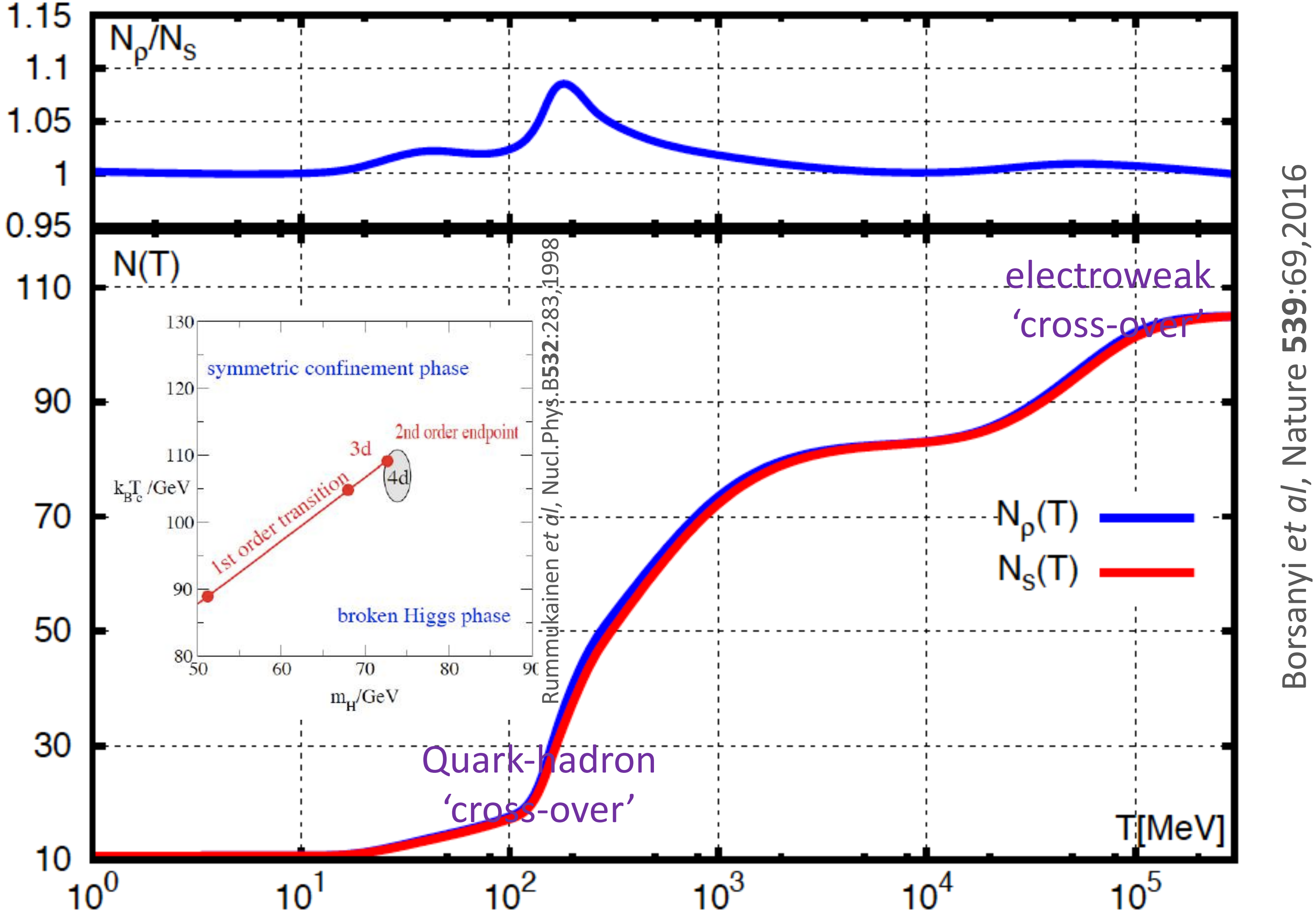
$$t\,(\mathrm{s}) = 2.42\, g^{-1/2}\, (T/\mathrm{MeV})^{-2}$$

The Standard Model of the Early Universe

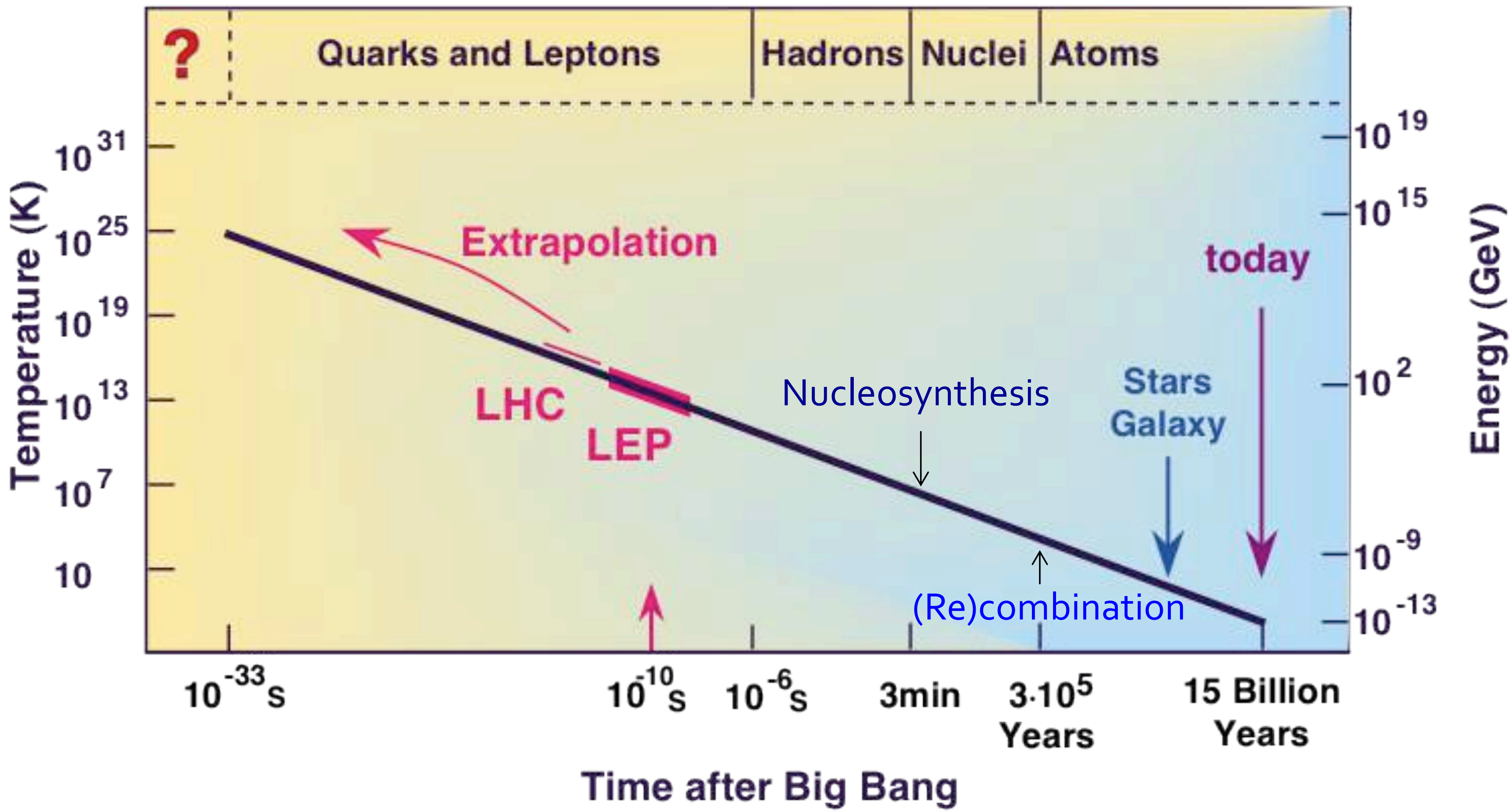
History of $g\,(T)$

$T \sim 200$ GeV	all present	106.75	
$T \sim 100$ GeV	EW transition	(no effect)	
$T < 170$ GeV	top-annihilation	96.25	
$T < 80$ GeV	$W^\pm$, Z^0, H^0	86.25	
$T < 4$ GeV	bottom	75.75	
$T < 1$ GeV	charm, τ^-	61.75	
$T \sim 150$ MeV	QCD transition	17.25	(u,d,g$\rightarrow \pi^{\pm,0}$, $37 \rightarrow 3$)
$T < 100$ MeV	$\pi^\pm$, π^0, μ^-	10.75	$e^\pm$, ν, $\bar{\nu}$, γ left
$T < 500$ keV	e^- annihilation	(7.25)	$2 + 5.25(4/11)^{4/3} = 3.36$

To construct our thermal history we must then count all boson and fermion species contributing to the number of relativistic degrees of freedom … and take into account our understanding of (possible) phase transitions



The blackbody temperature can be used as a clock (assuming adiabatic expansion: aT = constant), so our thermal history can be reconstructed



The furthest we 'see' directly is back to $t \sim 1$ s when light elements were synthesised (the small fluctuations in CMB temperature must have been generated *much* earlier)

WEAK INTERACTIONS AND NUCLEAR REACTIONS IN EXPANDING, COOLING UNIVERSE

(Hayashi 1950, Alpher, Follin & Herman 1953, Peebles 1966, Wagoner, Fowler & Hoyle 1967)

Dramatis personae:

Radiation (dominates) $\gamma, e^{\pm}, 3\nu\bar{\nu}$

Matter n, p

baryon-to-photon ratio (only free parameter) $n_B/n_\gamma \equiv \eta \simeq 2.74 \times 10^{-8}\Omega_B h^2$

Initial conditions: *T* >> 1 MeV, *t* << 1 s

n-*p* weak equilibrium: $n + \nu_e \leftrightarrow p + e^-$

neutron-to-proton ratio: $p + \bar{\nu}_e \leftrightarrow n + e^+$

$$\tau_{\text{weak}}(n \leftrightarrow p) \geq t_{\text{universe}} \Rightarrow T_{\text{freeze-out}} \sim \left(G_N / G_F^2\right)^{1/3}$$

Weak freeze-out: $T_f \sim 1$ MeV, $t_f \sim 1$ s

which fixes: $n/p = e^{-(m_n - m_p)/T_f} \approx 1/6$

Deuterium bottleneck: *T* ~ 1 → 0.07 MeV

D created by $np \to D\gamma$

but destroyed by high-E photon tail: $D\gamma \to np$

so nucleosynthesis halted until: $T_{\text{nuc}} \sim \Delta_D/\text{-}\ln(\eta)$

Element synthesis: $T_{\text{nuc}} \sim 0.07$ MeV, $t_{\text{nuc}} \sim 3$ min

(meanwhile *n*/*p* ➛ 1/7 through neutron *β*-decay)

nearly all *n* ➛ ^{4}He ($Y_P \sim 25\%$ by mass) + left-over traces of D, ^{3}He, ^{7}Li (with ^{6}Li/^{7}Li ~ 10^{-5})

No heavier nuclei formed in standard, homogeneous hot Big Bang … must wait for stars to form after a ~billion years and synthesise all the other nuclei in the universe (s-process, r-process, …)

- **Time < 15 s, Temperature > 3 x 10^9 K**
  - universe is soup of protons, electrons and other particles … so hot that nuclei are blasted apart by high energy photons as soon as they form

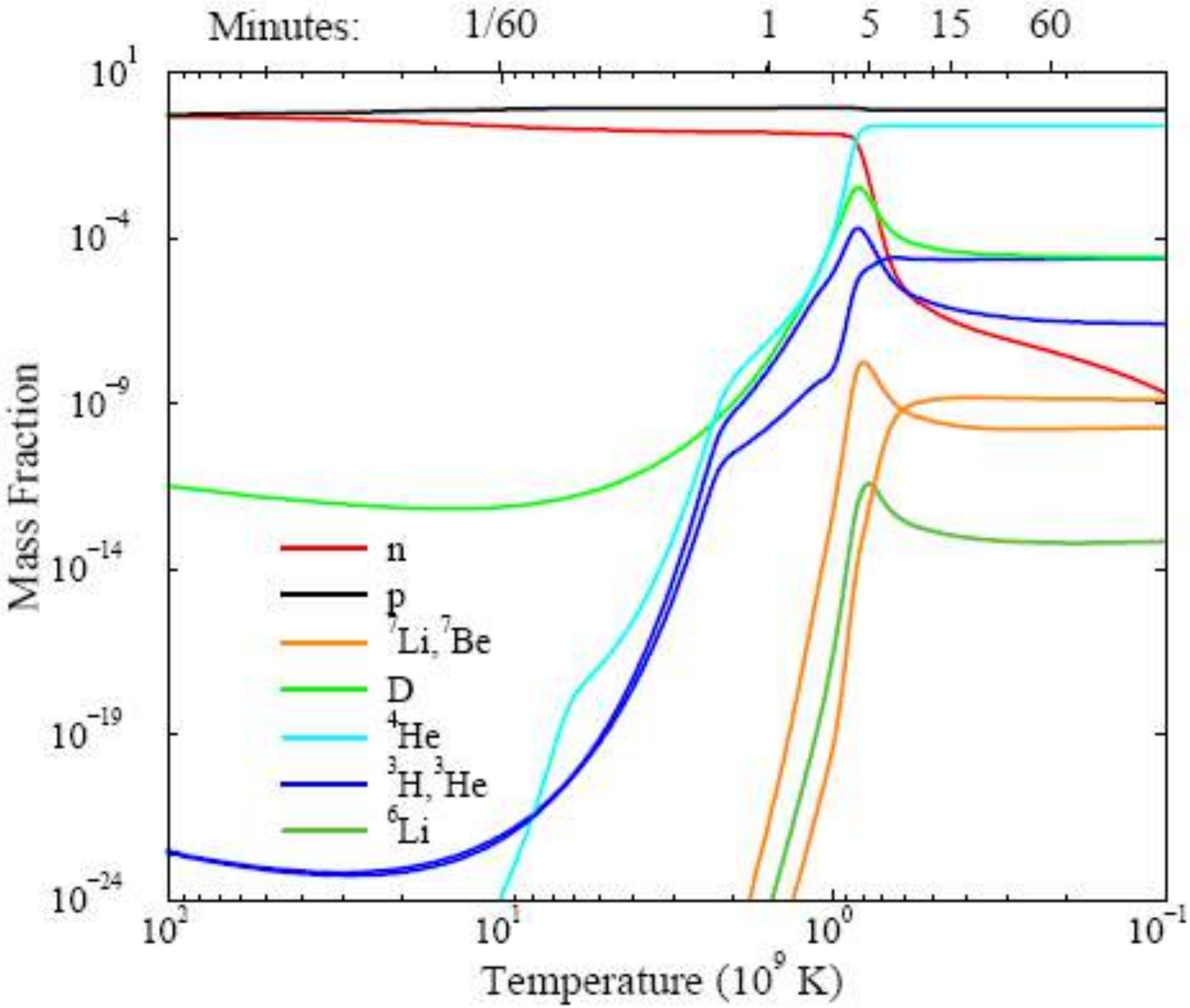
- **Time = 15 s, Temperature = 3 x 10^9 K**
  - Still too hot for Deuterium to survive
  - Cool enough for Helium to survive, but too few building blocks

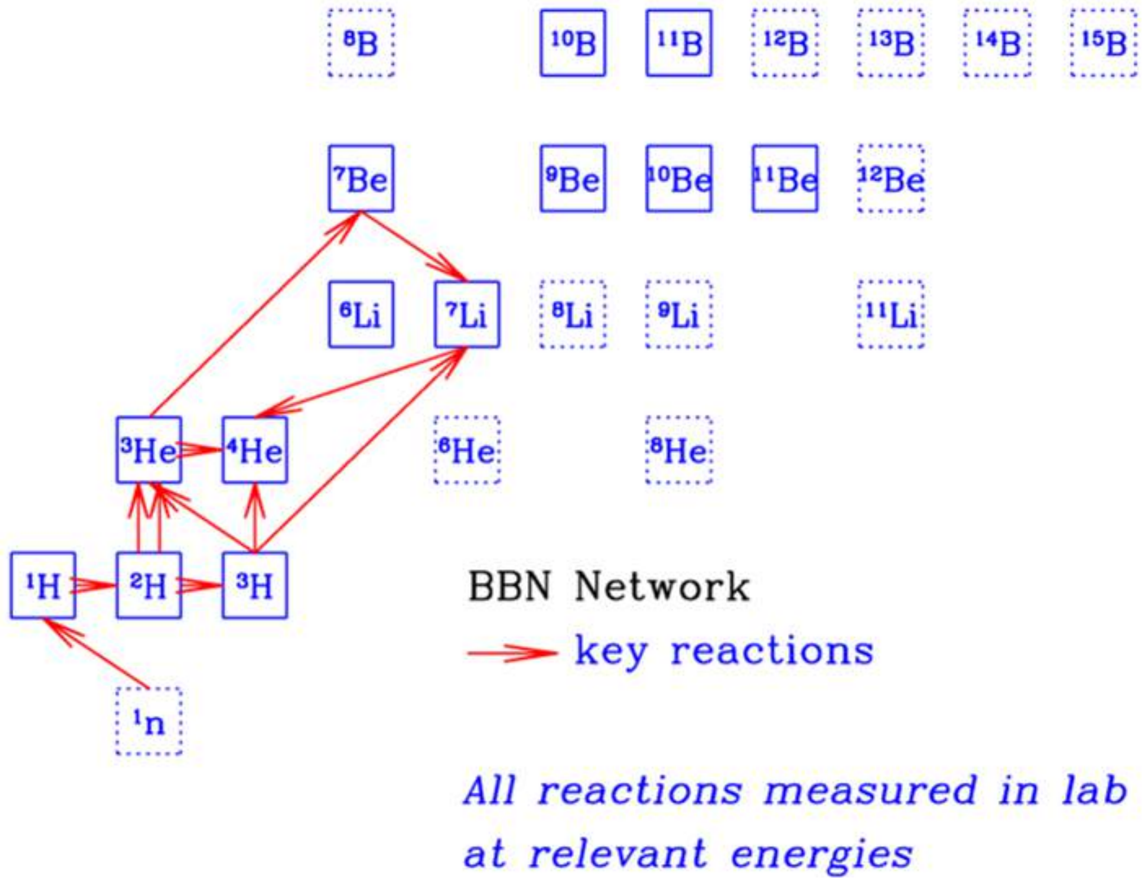
- **Time = 3 min, Temperature = 10^9 K**
  - Deuterium survives and is quickly fused into He
  - no stable nuclei with 5 or 8 nucleons, and this restricts formation of elements heavier than Helium
  - trace amounts of Lithium are formed

- **Time = 35 min, Temperature = 3 x 10^7 K**
  - nucleosynthesis essentially complet (still hot enough to fuse He, but density too low for appreciable fusion)

Model makes predictions about the relative abundances of the light elements ^{2}H, ^{3}He, ^{4}He and ^{7}Li, as a function of the nucleon density

The 'first three minutes'





- Computer code by Wagoner (1969, 1973) .. updated by Kawano (1992), other codes: PArthENoPE (2007), AlterBBN (2012)
- Coulomb & radiative corrections, ν heating et cetera (Dicus *et al* 1982)
- Nucleon recoil corrections (Seckel 1993)
- Covariance matrix of correlated uncertainties (Fiorentini *et al* 1998)
- Updated nuclear cross-sections (NACRE 2003)

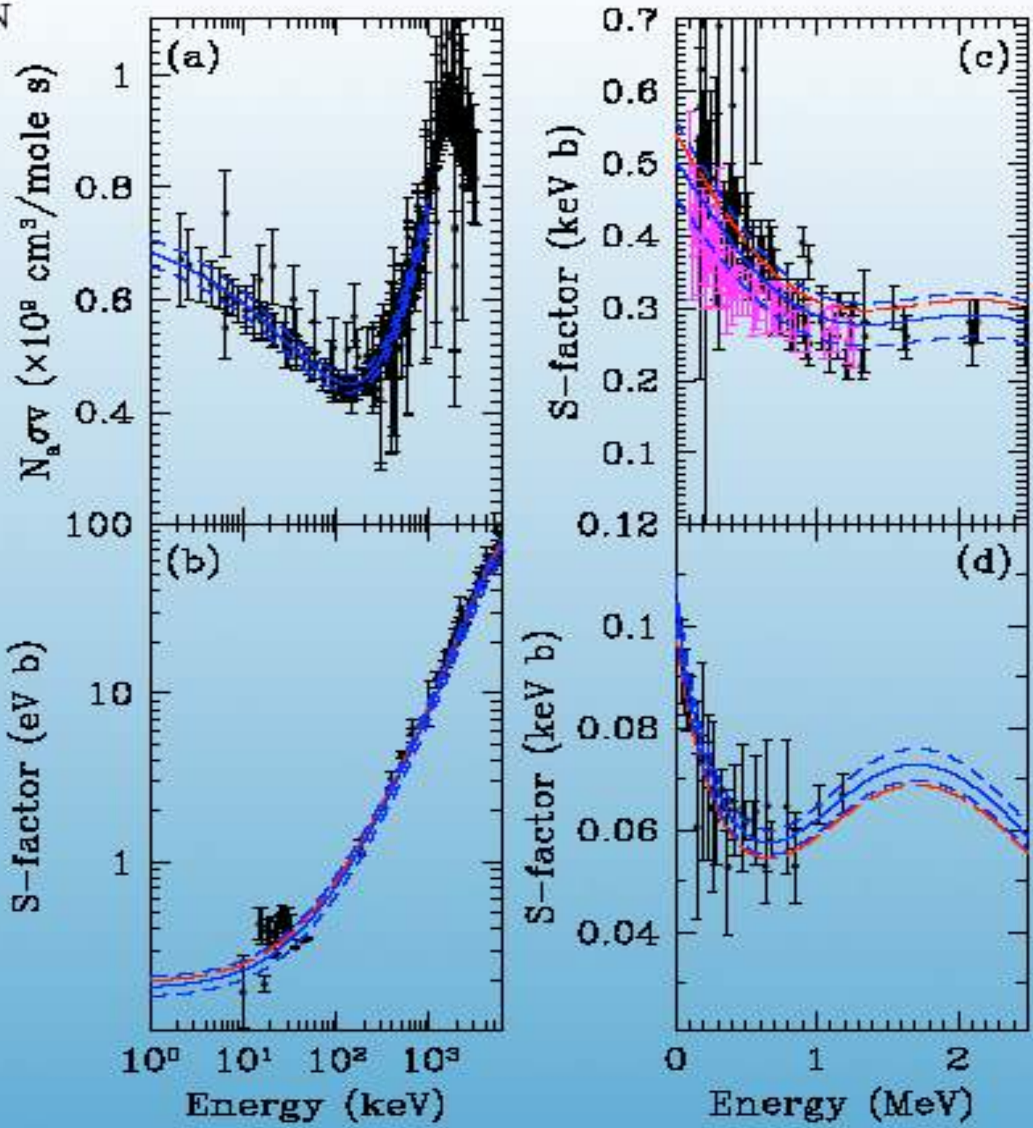
The neutron lifetime normalises the "weak" interaction rate: $\tau_n = 880.0 \pm 0.9$ s

(has recently dropped in value by **5σ** because of *one* new measurement!)

Table 1: Key Nuclear Reactions for BBN

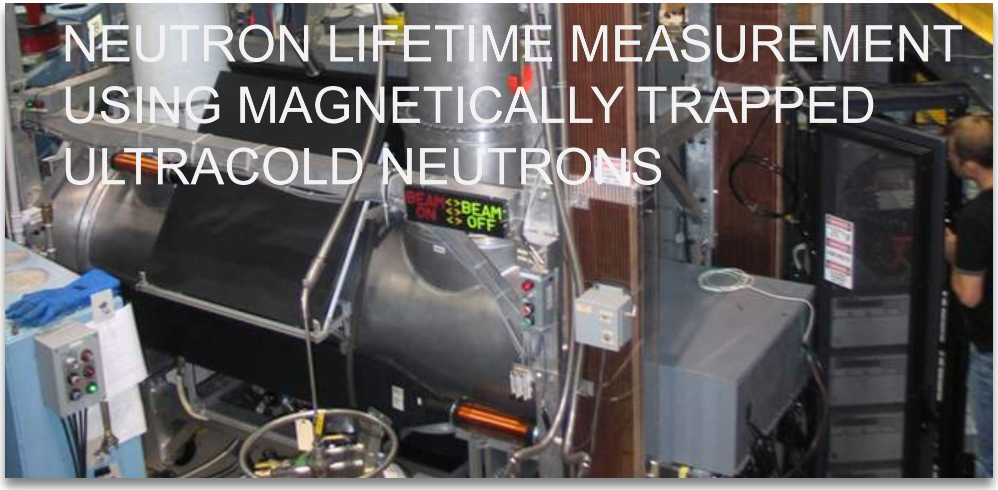
Source	Reactions	
NACRE	$d(p,\gamma)^3\mathrm{He}$	(b)
	$d(d,n)^3\mathrm{He}$	
	$d(d,p)t$	
	$t(d,n)^4\mathrm{He}$	
	$t(\alpha,\gamma)^7\mathrm{Li}$	(d)
	$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$	(c)
	$^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$	
SKM	$p(n,\gamma)d$	
	$^3\mathrm{He}(d,p)^4\mathrm{He}$	
	$^7\mathrm{Be}(n,p)^7\mathrm{Li}$	
This work	$^3\mathrm{He}(n,p)t$	(a)
PDG	τ_n	

NACRE
Cyburt, Fields, KAO
Nollett & Burles
Coc et al.

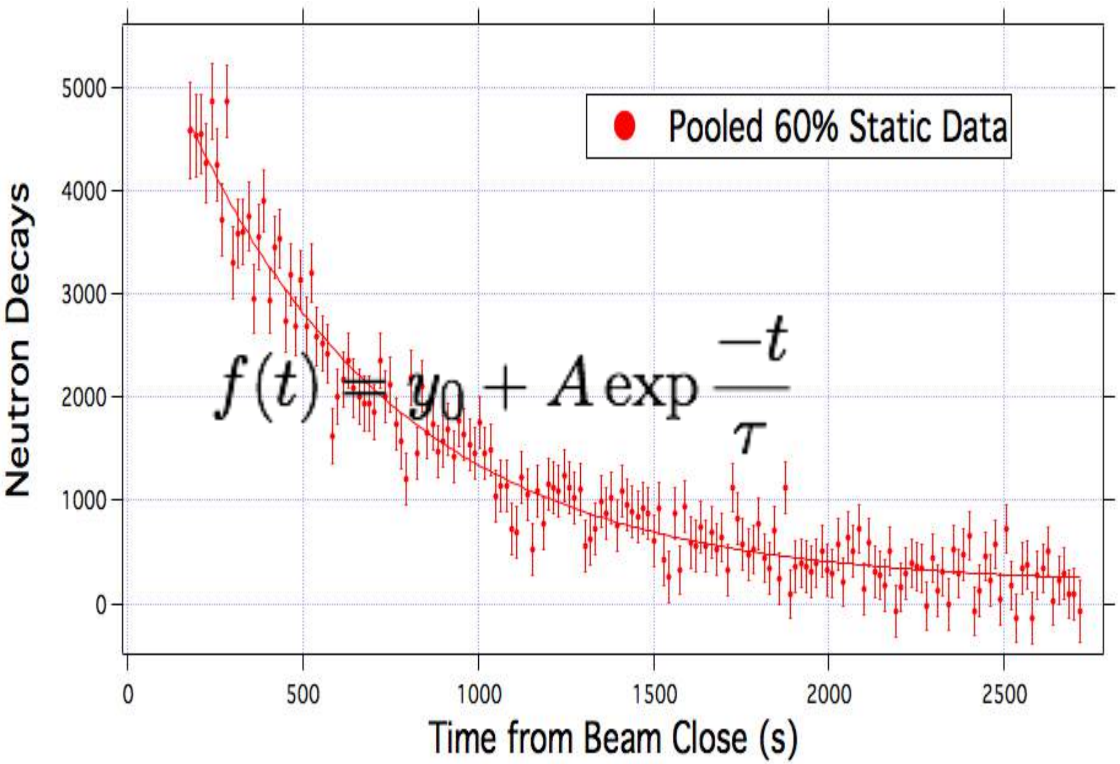


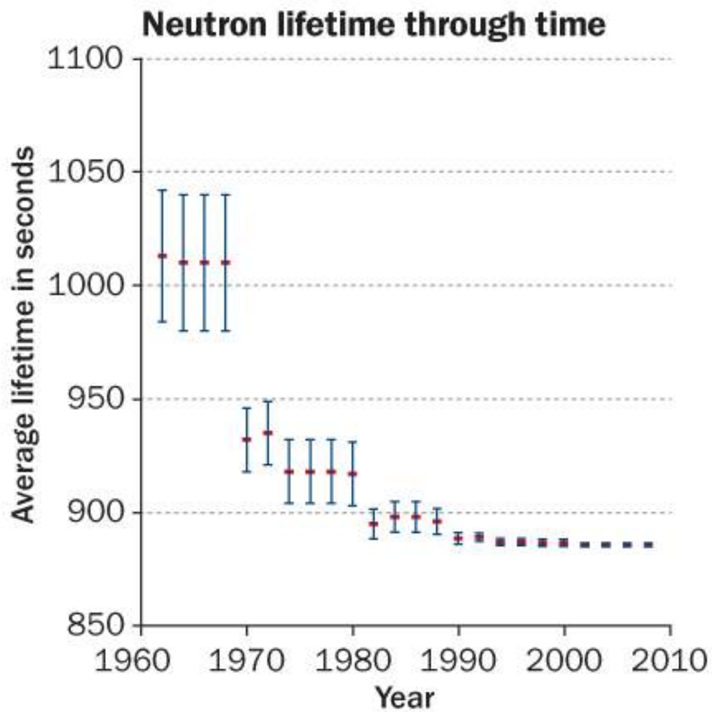
Uncertainties in synthesized abundances are *correlated* … estimate using Monte Carlo

(Smith, Kawano, Malaney 1993; Krauss, Kernan 1994; Cyburt, Fields, Olive 2004)



The neutron lifetime cannot be accurately computed theoretically (even knowing the weak interaction coupling G_F *very* well) because there are corrections due to the strong interactions (which alter g_A/g_V away from unity) .. so it has to be measured experimentally

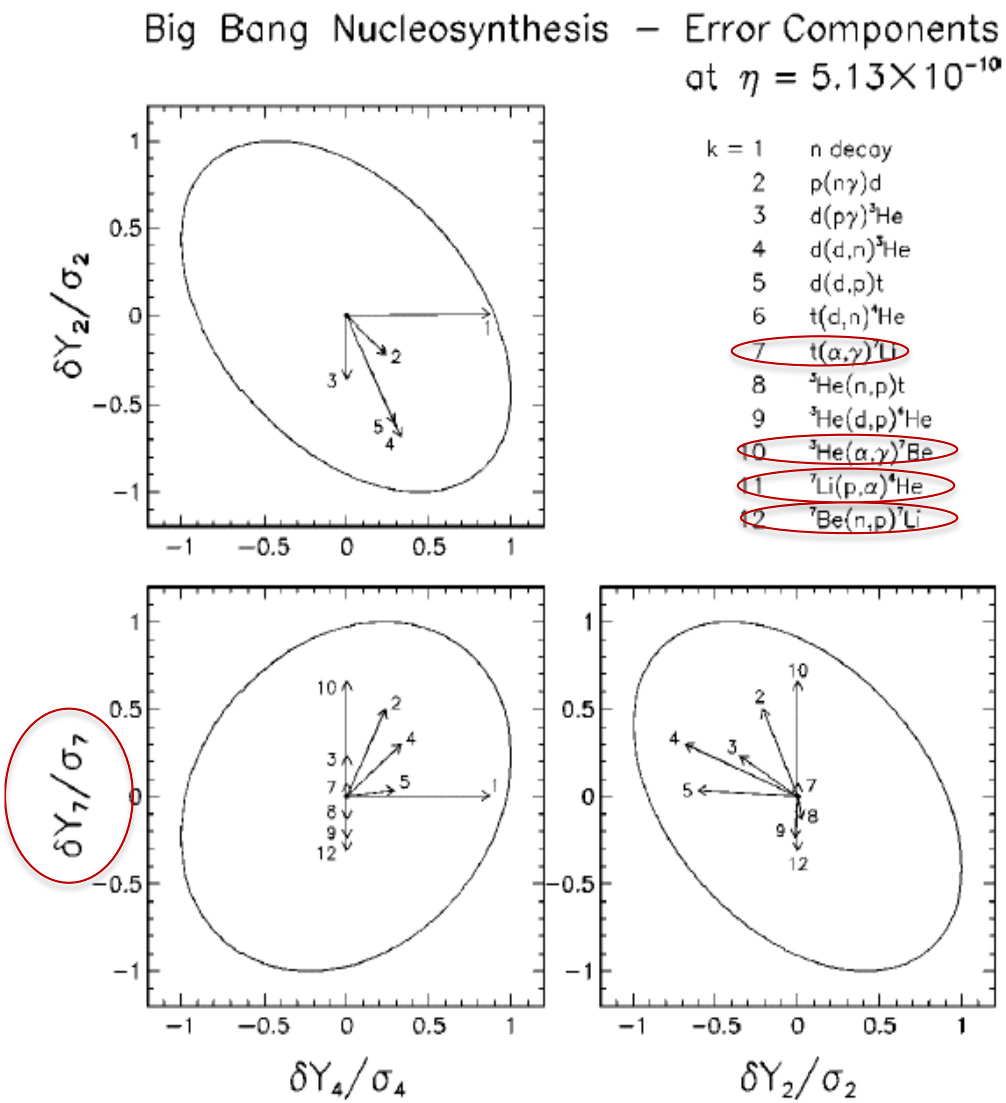


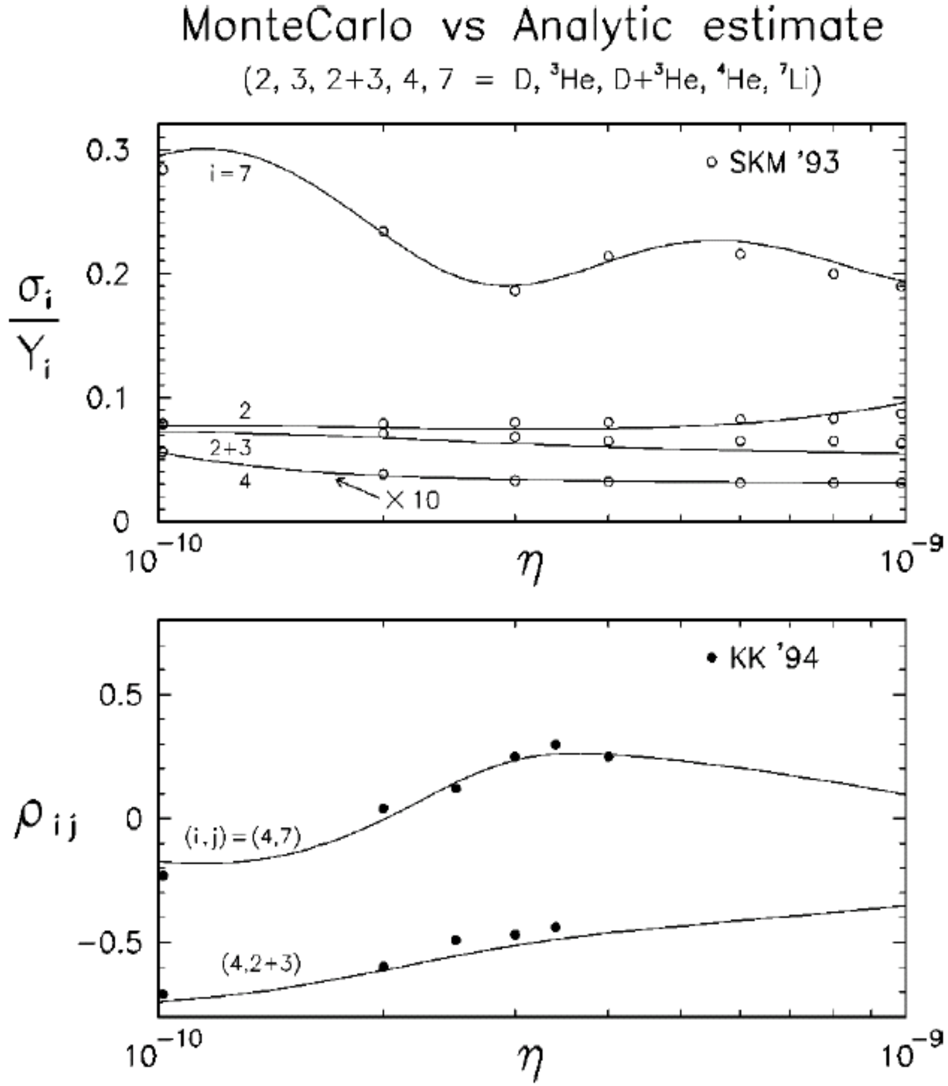


Linear propagation of errors → **covariance matrix** (in *agreement* with Monte Carlo results)

$$Y_i = Y_i(\eta) \pm \sigma_i(\eta) \;\rightarrow\; \delta Y_i(\eta) = Y_i(\eta) \sum_k \lambda_{ik}(\eta) \frac{\delta R_k}{R_k}\,, \quad \lambda_{ik}(\eta) = \frac{\partial \ln Y_i(\eta)}{\partial \ln R_k(\eta)}$$

$$\sigma^2_{ij}(\eta) = Y_i(\eta) Y_j(\eta) \sum_k \lambda_{ik}(\eta) \lambda_{jk}(\eta) \left(\frac{\Delta R_k}{R_k}\right)^2 \;\rightarrow\; \sigma_i(\eta) = \sqrt{\sigma^2_{ii}(\eta)}\,, \quad \rho_{ij}(\eta) = \frac{\sigma^2_{ij}(\eta)}{\sigma_i(\eta)\sigma_j(\eta)}$$

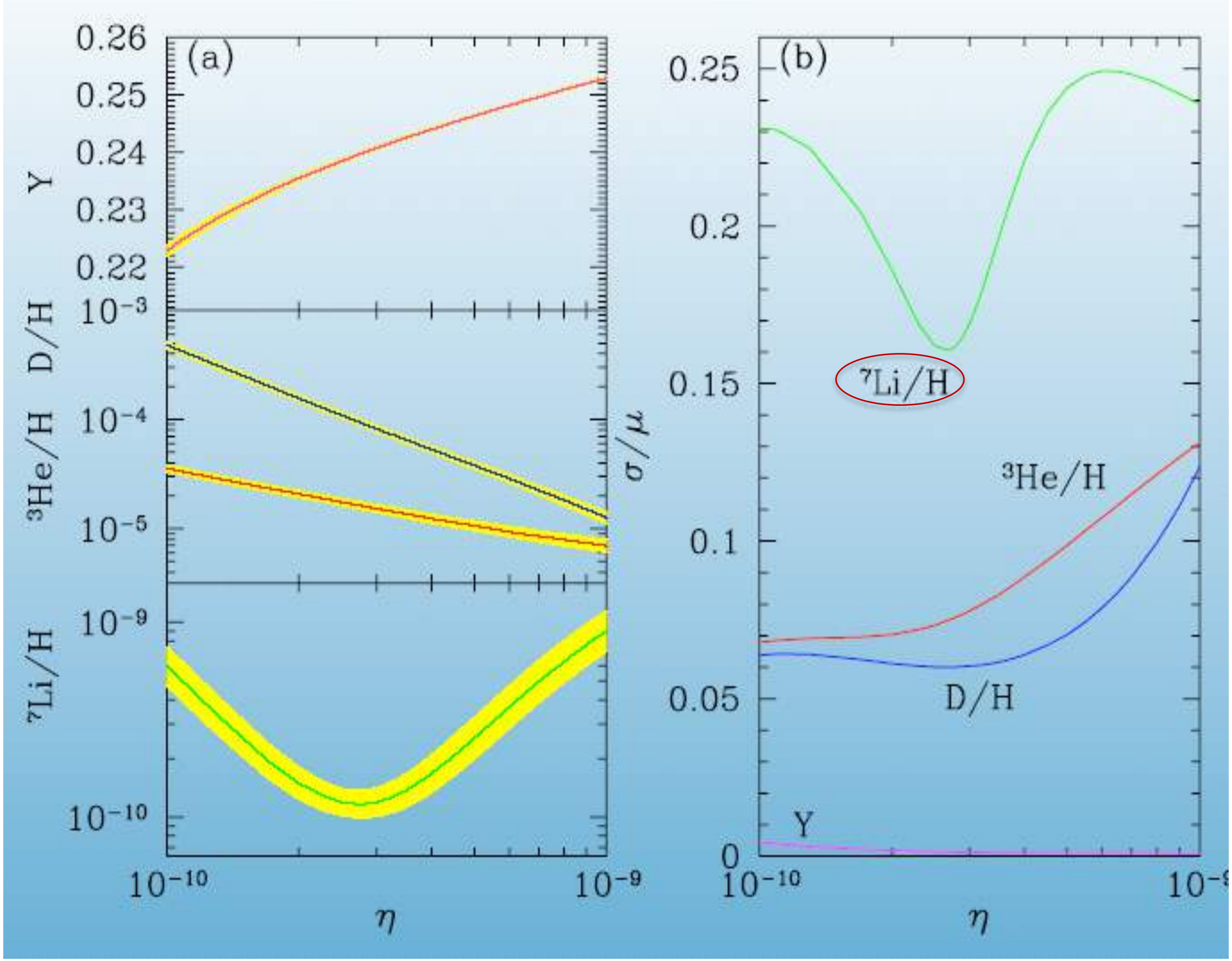




Fiorentini, Lisi, Sarkar, Villante, Phys.Rev.D58:063506,1998

BBN Predictions

line widths ⇒ theoretical uncertainties (neutron lifetime, nuclear #-sections)



Nucleosynthesis *without* a computer

$$\frac{dX}{dt} = J(t) - \Gamma(t)X \quad \Rightarrow \quad X^{eq} = \frac{J(t)}{\Gamma(t)}$$

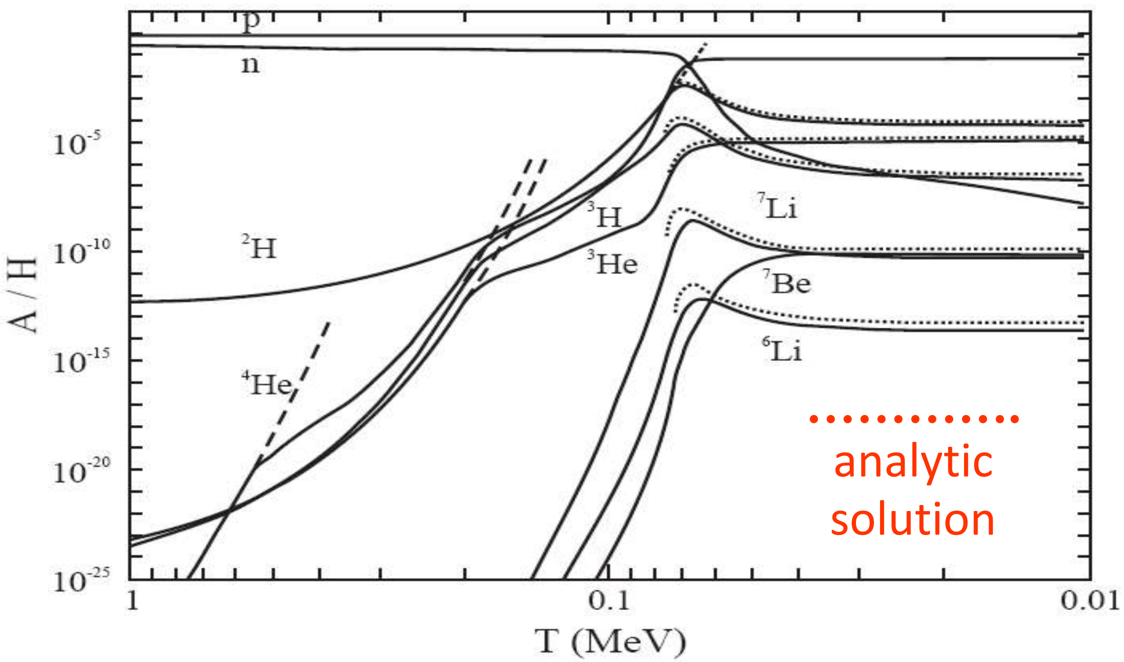
source sink

... but general solution is:

$$X(t) = \exp\left(-\int_{t_i}^{t} dt'\, \Gamma(t')\right)\left[X(t_i) + \int_{t_i}^{t} dt'\, J(t')\, \exp\left(-\int_{t_i}^{t} dt''\, \Gamma(t'')\right)\right]$$

If $\left|\frac{\dot{J}}{J} - \frac{\dot{\Gamma}}{\Gamma}\right| \ll \Gamma$ ... then abundances approach equilibrium values

Freeze-out occurs when: $\Gamma \simeq H \quad \Rightarrow \quad X(t \to \infty) \simeq X^{eq}(t_{fr}) = \frac{J(t_{fr})}{\Gamma(t_{fr})}$

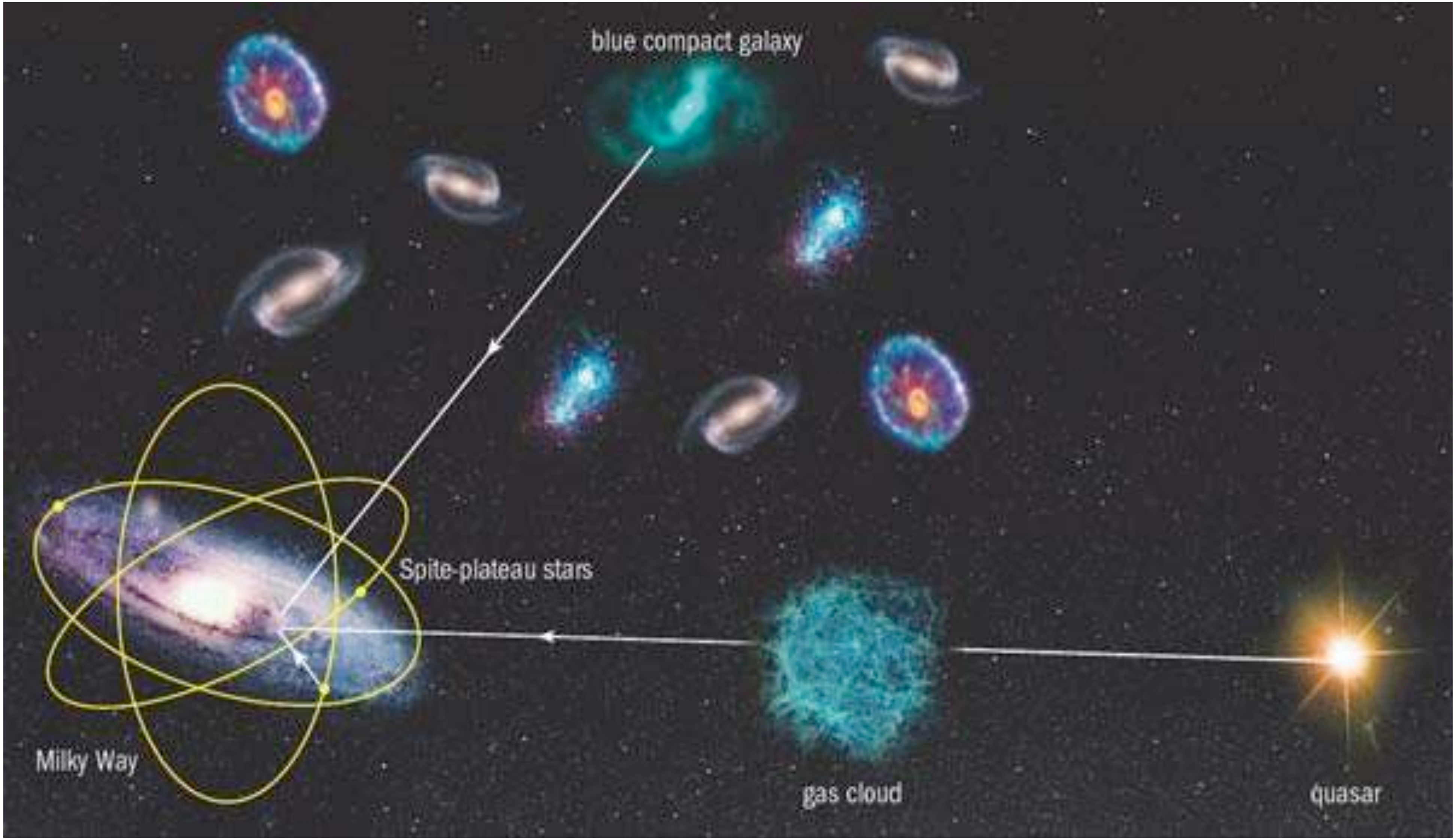


Examine reaction network to identify the largest 'source' and 'sink' terms

obtain D, ^{3}He and ^{7}Li to within a factor of ~2 of exact numerical solution, and ^{4}He to within a few %

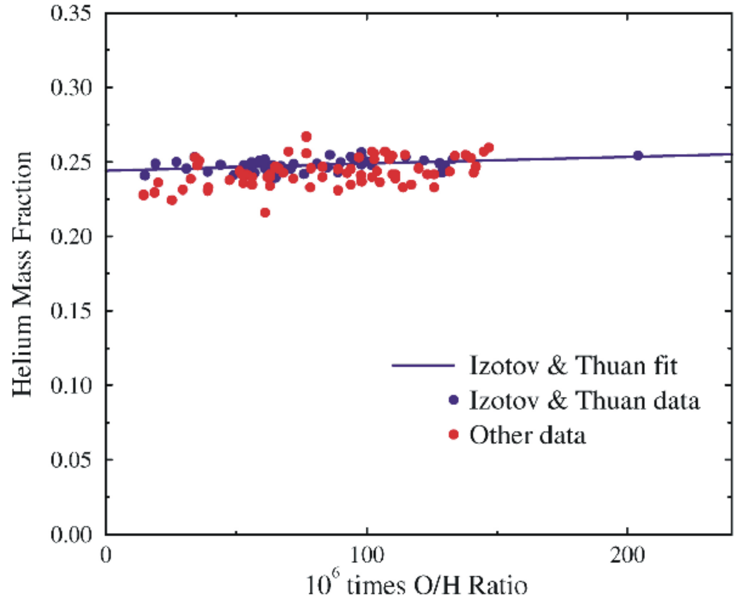
Dimopoulos, Esmailzadeh, Hall, Starkman, ApJ **378**:504,1991

Inferring primordial abundances

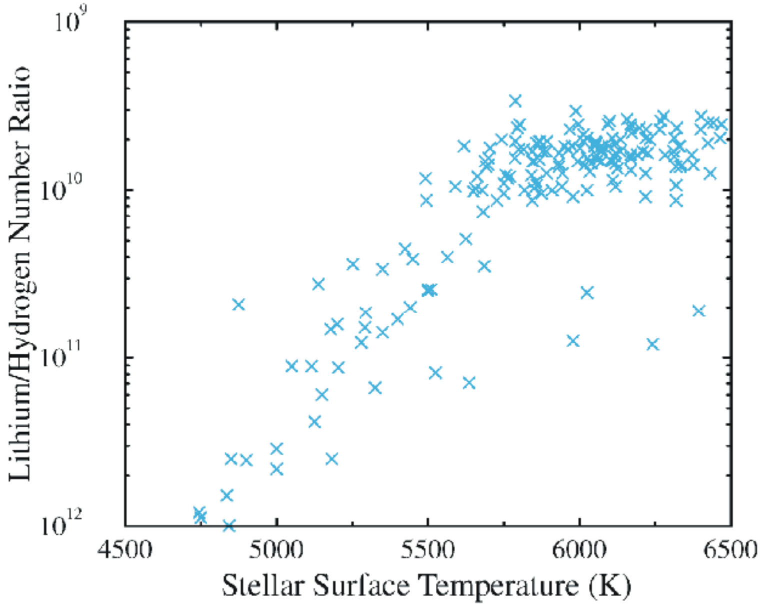


Observations of the light elements He and Li

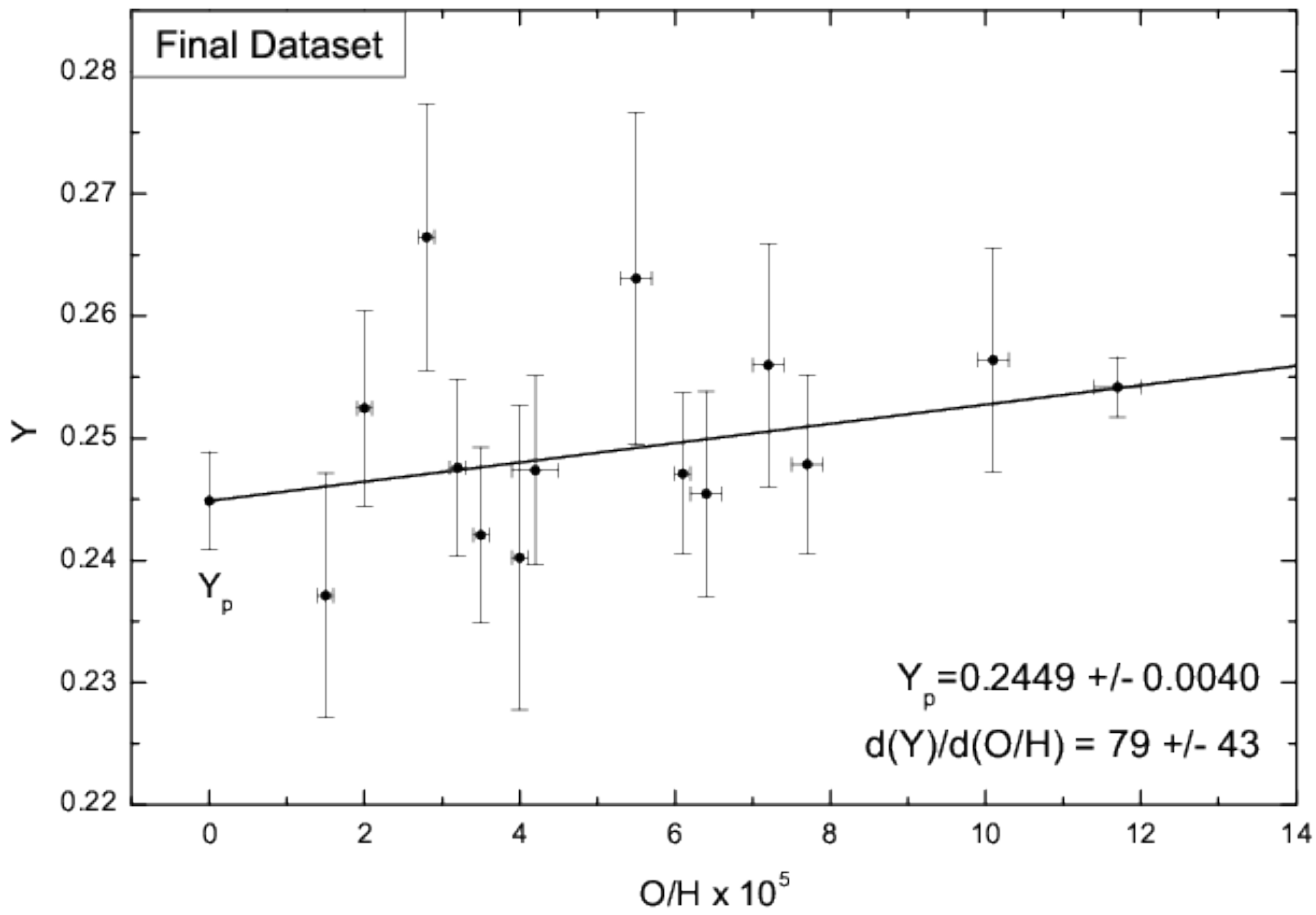
- **Helium Abundance**
  - –measured in extragalactic HII regions with lowest observed abundances of heavier elements such as Oxygen and Nitrogen
  - (i.e. smallest levels of contamination from stellar nucleosynthesis)



- **Lithium Abundance**
  - –measured in halo Pop II stars
  - –Lithium is easily destroyed hence observe the transition from low mass stars (low surface temp) whose core material is well mixed by convection, to higher mass stars (higher surface temp) where mixing of core is not efficient



For a quantity of such fundamental cosmological importance, relatively *little* effort has been spent on measuring the primordial helium abundance … for decades the determinations by (~3-4) different groups have been discrepant

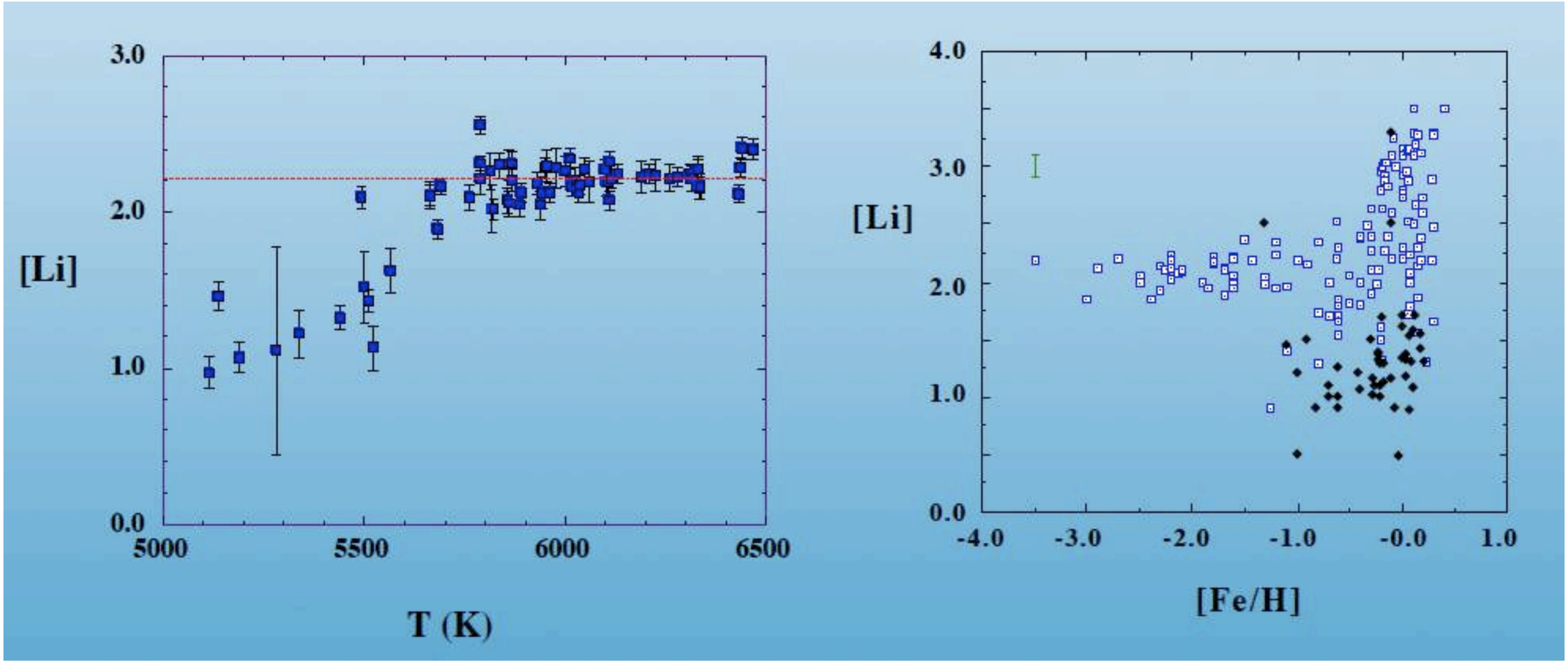


Recent reevaluations are however consistent with $Y_P = 0.245 \pm 0.003$, e.g. Aver *et al*, JCAP 07:011,2015, Izotov *et al*, MNRAS **445**:778,2014

Primordial Lithium

Observe in primitive (Pop II) stars: (most abundant isotope is ^{7}Li)

- Easily destroyed hence see transition from low mass/surface temp stars (core well mixed by convection) to higher mass/temp stars (mixing of core is not efficient)
- Li-Fe correlation ⇒ mild evolution



'Plateau' at low Fe (high T) ⇒ constant abundance at early epochs

… so *infer* observed '^{7}Li plateau' is primordial (Spite & Spite 1982)

Primordial deuterium?

Look in **Q**uasar **A**bsorption**S**ystems - low density clouds of gas seen in absorption along the lines of sight to distant quasars (when universe was only ~10% of its present age)

The difference between H and D nuclei causes a *small* change in the energies of electron transitions, shifting their absorption lines apart and enabling D/H to be measured

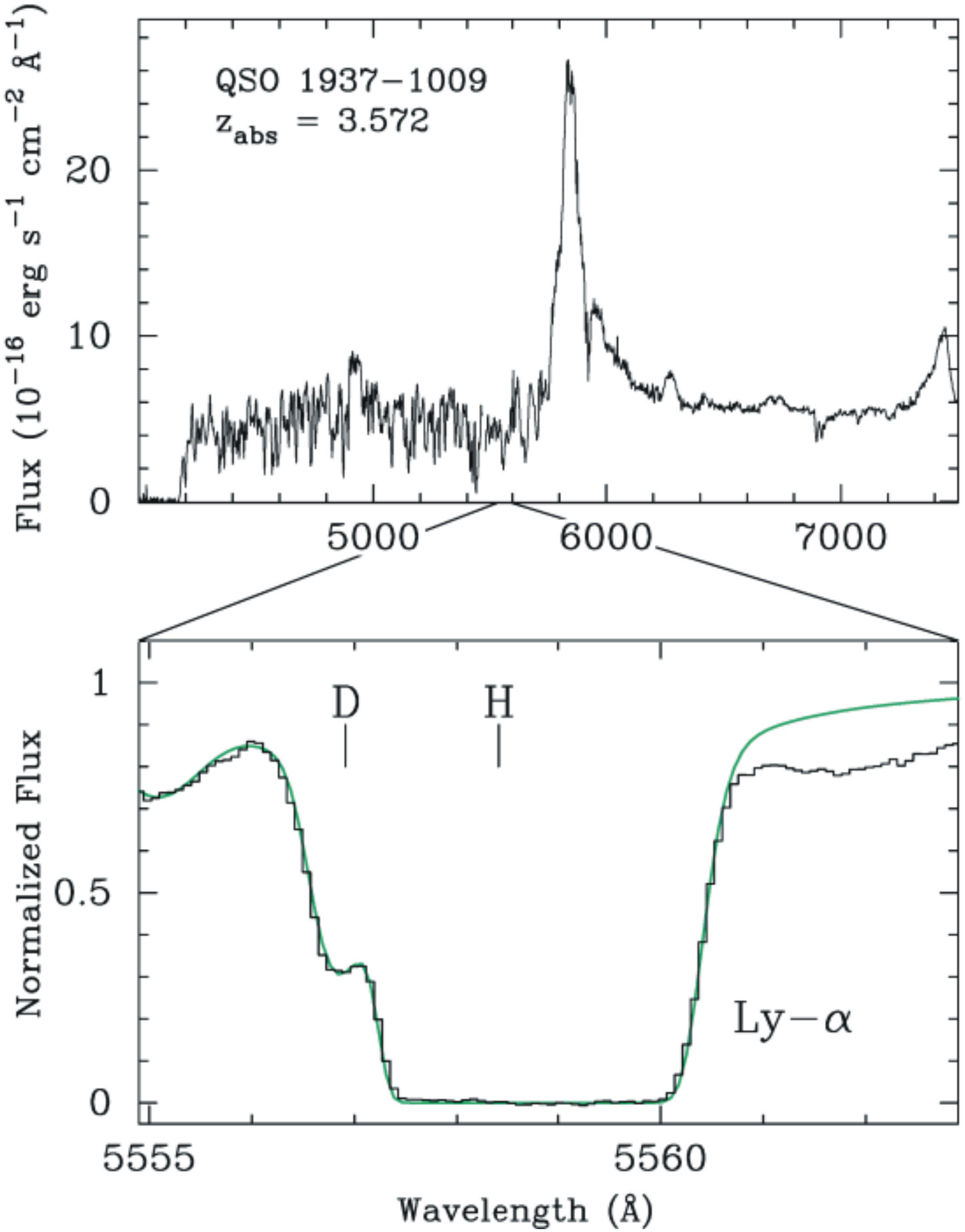
$$E_{\mathrm{Ly}-\alpha} \sim \alpha^2 \mu_{\mathrm{reduced}}$$

$$\frac{\delta\lambda_{\mathrm{D}}}{\lambda_{\mathrm{H}}} = -\frac{\delta\mu_{\mathrm{D}}}{\mu_{\mathrm{H}}} = -\frac{m_e}{2m_p}$$

$$c\delta z = 82 \ \ \mathrm{km/s}$$

But:

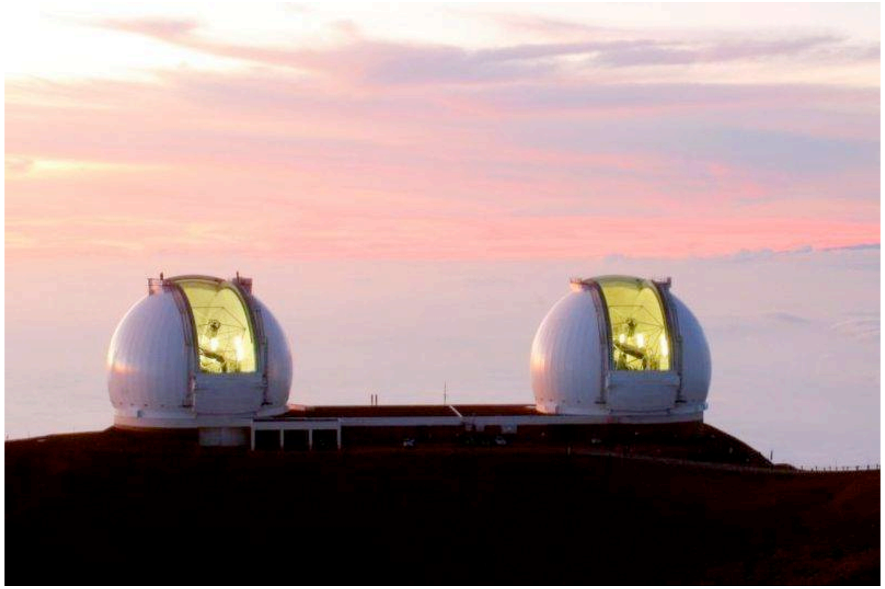
- Hard to find clean systems
- Do not resolve clouds
- Dispersion/systematics?

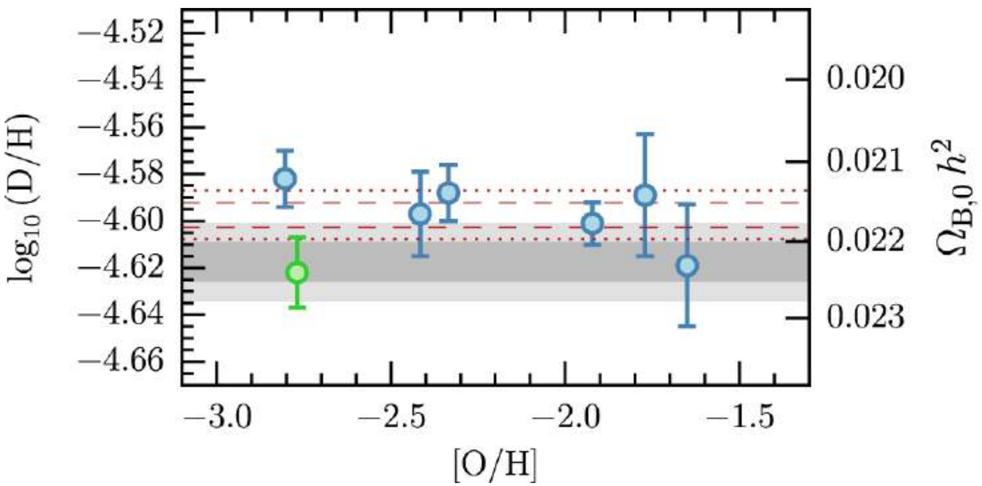


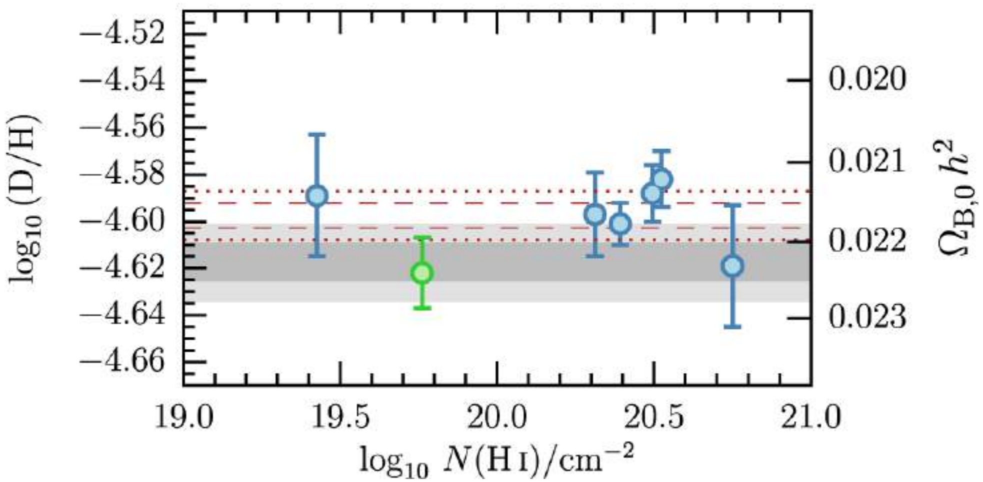
Kirkman, Tytler, Suzuki, O'Meara, Lubin, ApJS 149:1,2003

Progress made by looking at 'damped Ly-α' systems in which the H column density can be precisely measured and resolved D absorption lines are seen

(e.g. Cooke *et al*, ApJ **830**:148,2016, Riemer-Sørensen *et al*, MNRAS **468**:3239,2017)







Measurement of primordial abundance of D now with the *per cent* level accuracy

Cooke, Pettini &and Steidel, Ap.J.**855**:102,2018

Inferred primordial abundances

^{4}He observed in extragalactic HII regions:

$$Y_P = 0.245 \pm 0.003$$

^{2}H observed in quasar absorption systems (and ISM):

$$D/H|_P = (2.569 \pm 0.027) \times 10^{-5}$$

^{7}Li observed in atmospheres of dwarf halo stars:

$$Li/H|_P = (1.6 \pm 0.3) \times 10^{-10}$$

(^{3}He can be both created & destroyed in stars … so primordial abundance *cannot* be reliably estimated)

Systematic errors have been re-evaluated based on scatter in data

(Particle Data Group, Phys.Rev.D**98**:030001,2018)

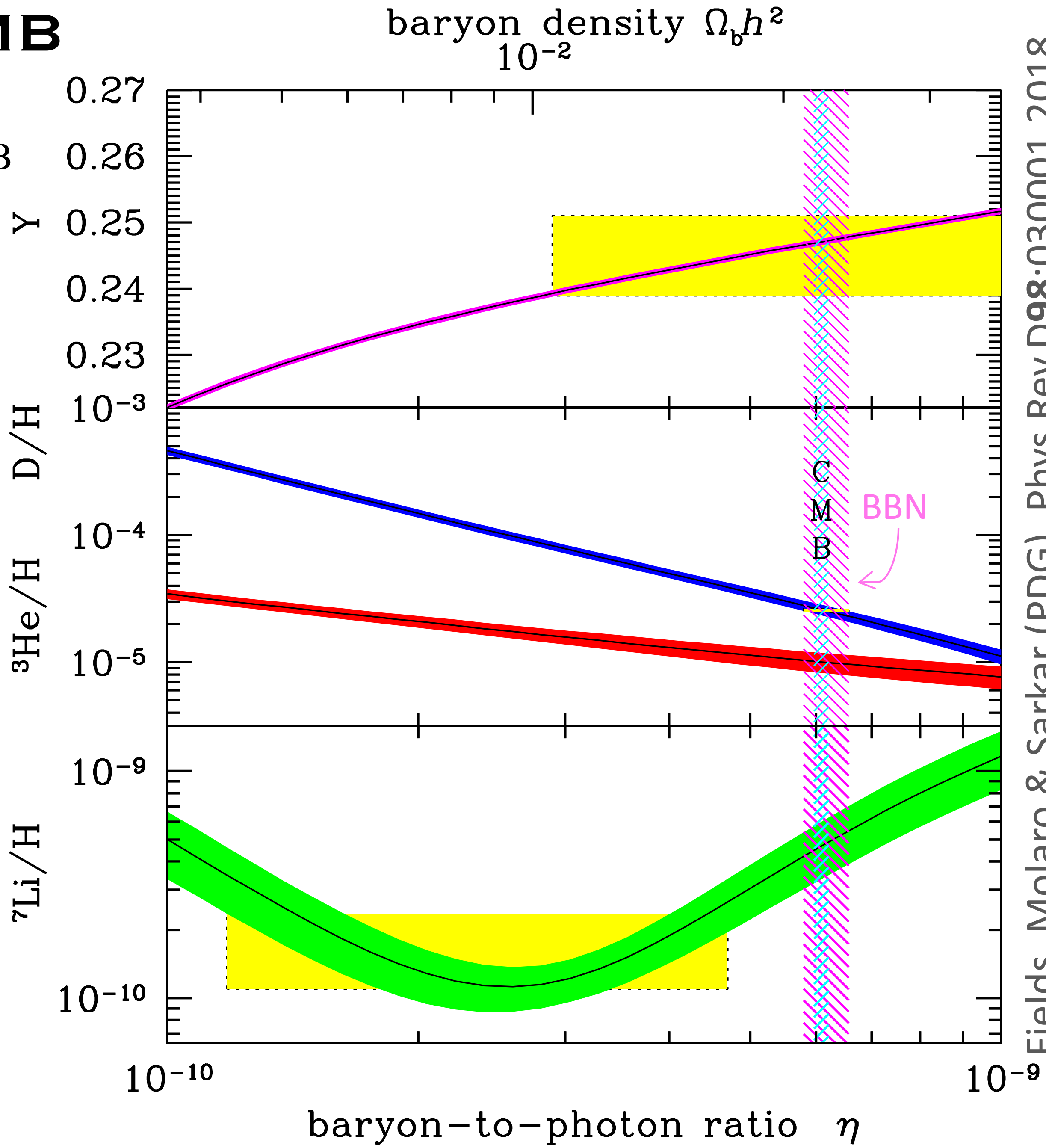
BBN versus CMB

η_{BBN} is in agreement with η_{CMB}
allowing for large uncertainties
in the *inferred* abundances
$5.7 < \eta_{10} < 6.7$ (95% CL)

Confirms and sharpens the
case for (two kinds of)
dark matter

Baryonic Dark Matter:
warm-hot IGM, Ly-α , X-ray gas
+
Non-baryonic dark matter: ?

Constrains the Hubble
expansion rate at $t \sim 1$ s
⇒ bounds on new particles



Fields, Molaro & Sarkar (PDG), Phys.Rev.D**98**:030001,2018

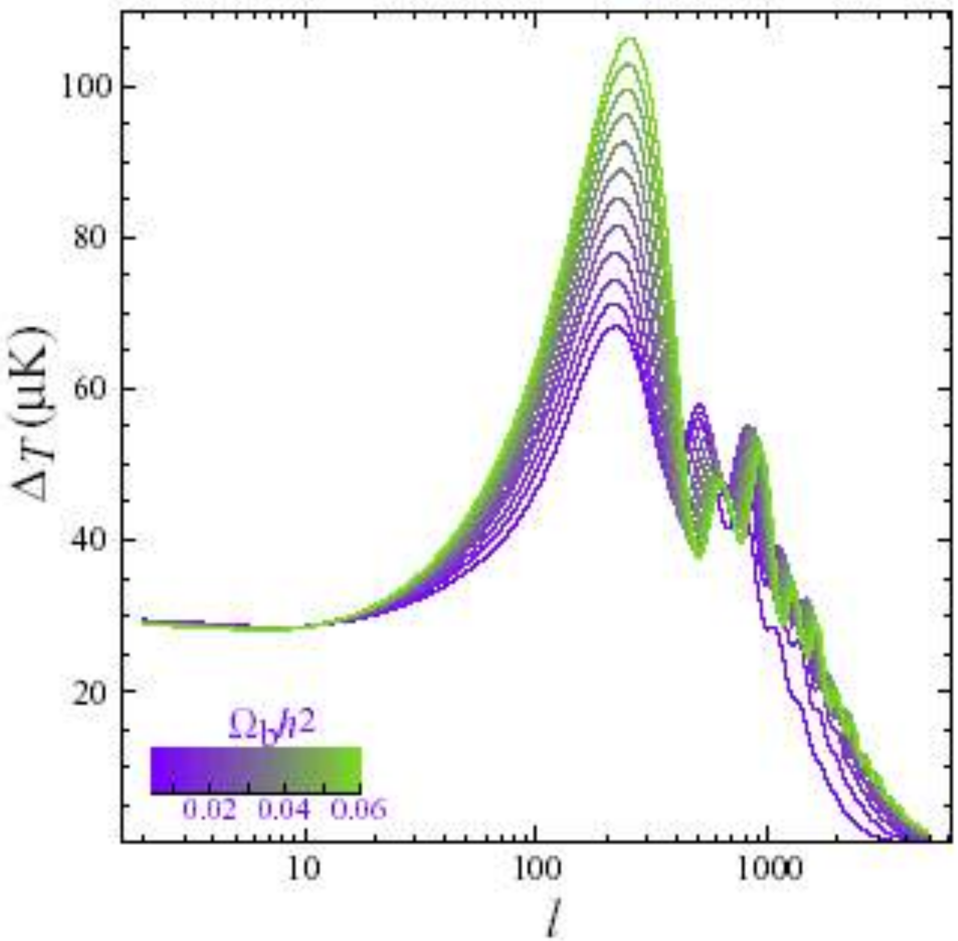
There is a “lithium problem” *possibly* indicative of non-standard physics

The Cosmic Microwave Background

ΔT_ℓ provide *independent* measure of $\Omega_b h^2$

Acoustic oscillations in (coupled) photon-baryon fluids imprint features at small angles (< 1^o) in CMB angular power spectrum

Detailed peak positions, heights, … sensitive to cosmological parameters
e.g. 2nd/1st peak ratio ⇒ baryon density



e.g. Planck best-fit:
$\Omega_b h^2 = 0.0223 \pm 0.0002$
$\Rightarrow \eta_{10} = 6.09 \pm 0.06$
(NB: degeneracies with e.g. n_s, τ …)

Bond & Efstathiou, ApJ **285**:L45,1984
Dodelson & Hu, ARAA **40**:171,2002

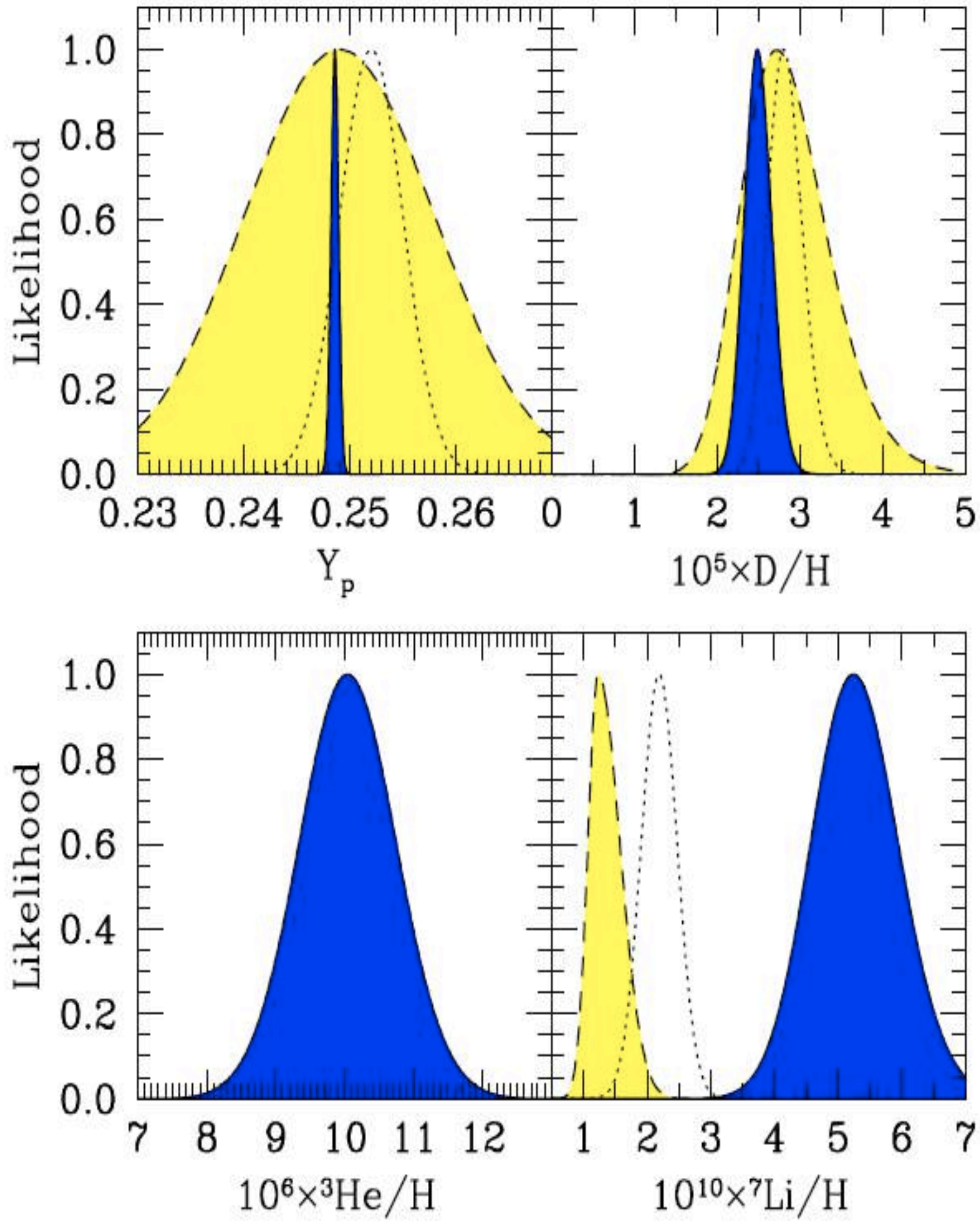
NB: The CMB measure of the baryon-to-photon ratio is at t~400,000 yr, *cf*. t~1 s for BBN, so the two should agree only if there has been no dissipation of energy in between ….

… IN MORE DETAIL

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 may also have been observed – with an abundance > 10^4 times higher than expected!



Cyburt, Fields & Olive (2008)

Systematic Errors in the inferred Lithium abundance

Observational systematics

Measure Li I absorption line(s) to infer ^{7}Li/H … T_{eff} critical (mostly Li II)
But required shift in T scale is ~500 K - *very* unlikely

Melendez & Ramirez (2004); Fields, Olive & Vangioni-Flam (2005)

Astrophysical systematics

Stellar depletion over ~10^{10} yr … if Li burned need to correct Li_p *upward*
But *no* scatter seen around "Spite plateau" - also ^{6}Li preserved

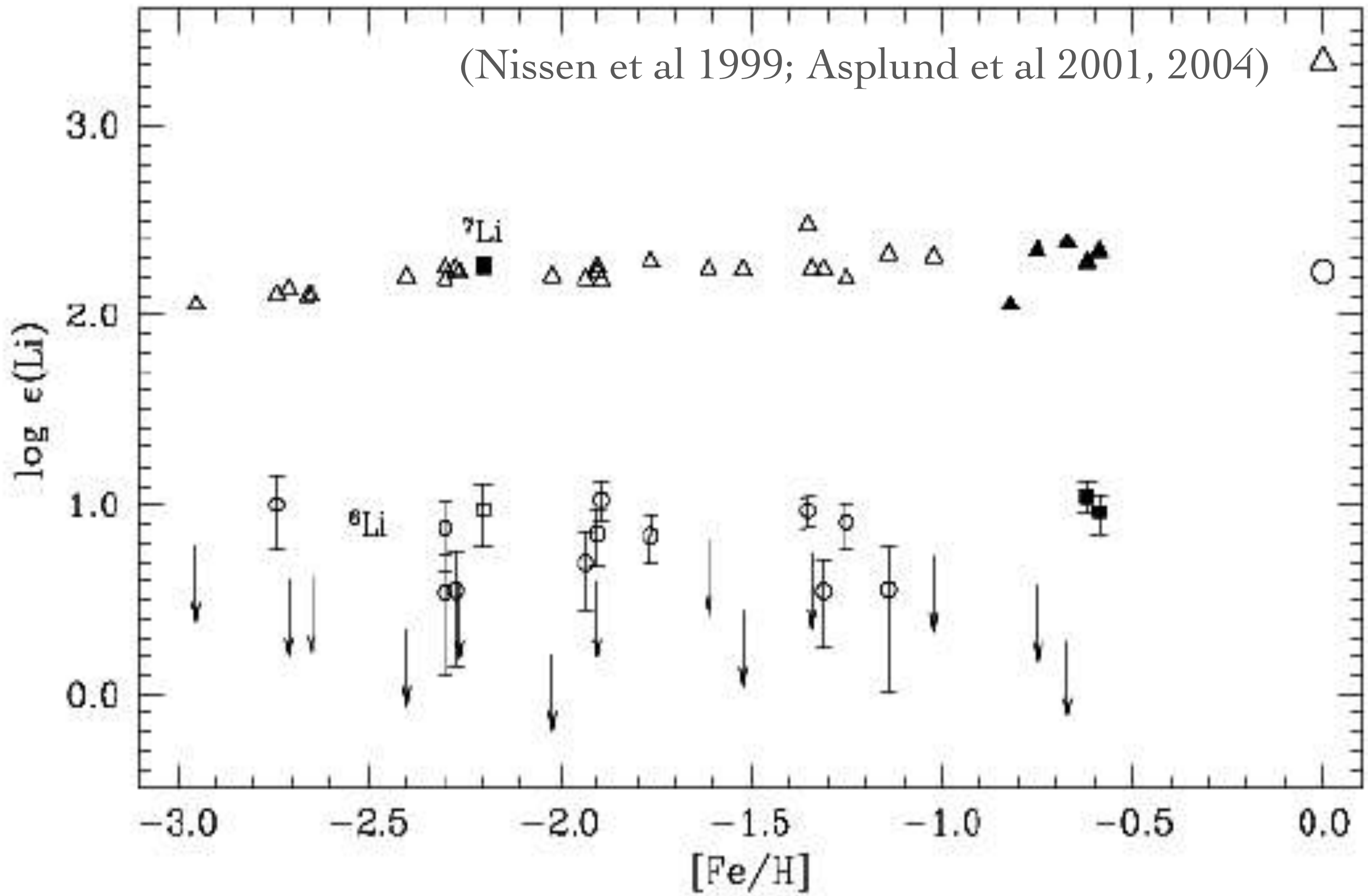
Ryan *et al* (2000)

Nuclear Systematics

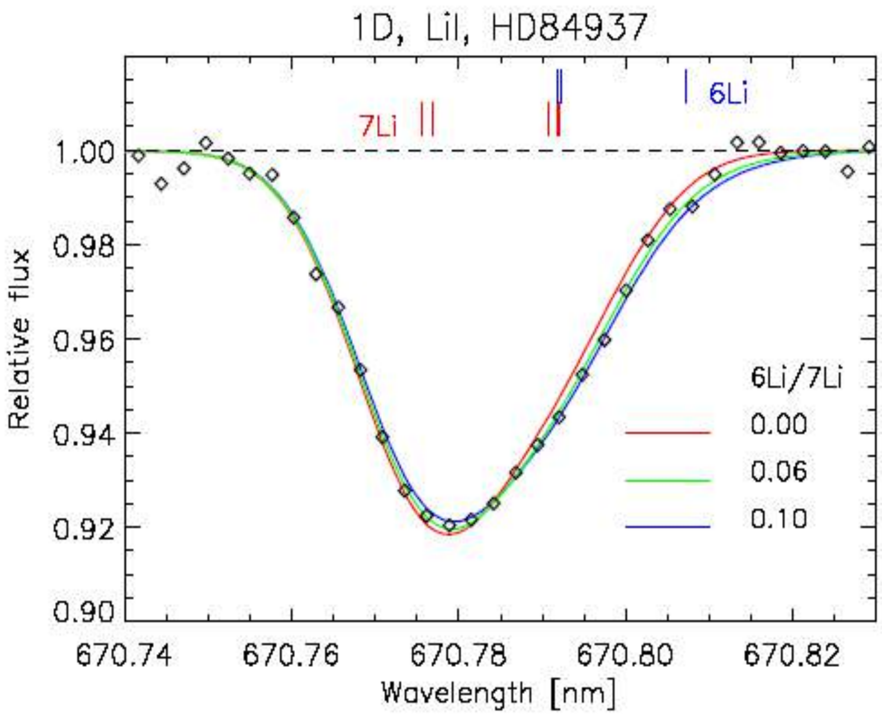
^{7}Li production channel - ^{3}He (α, γ) ^{7}Be - normalisation error?
But same reaction also key for Solar neutrinos … standard Solar model OK!

Cyburt, Fields & Olive (2004)

A primordial 'plateau' in ^{6}Li has been claimed with ^{6}Li/^{7}Li ~ 0.1
(cf. standard expectation ^{6}Li/^{7}Li ~ 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 are 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 delicate fits to the line shape … the reality of a '^{6}Li plateau' is not established!

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

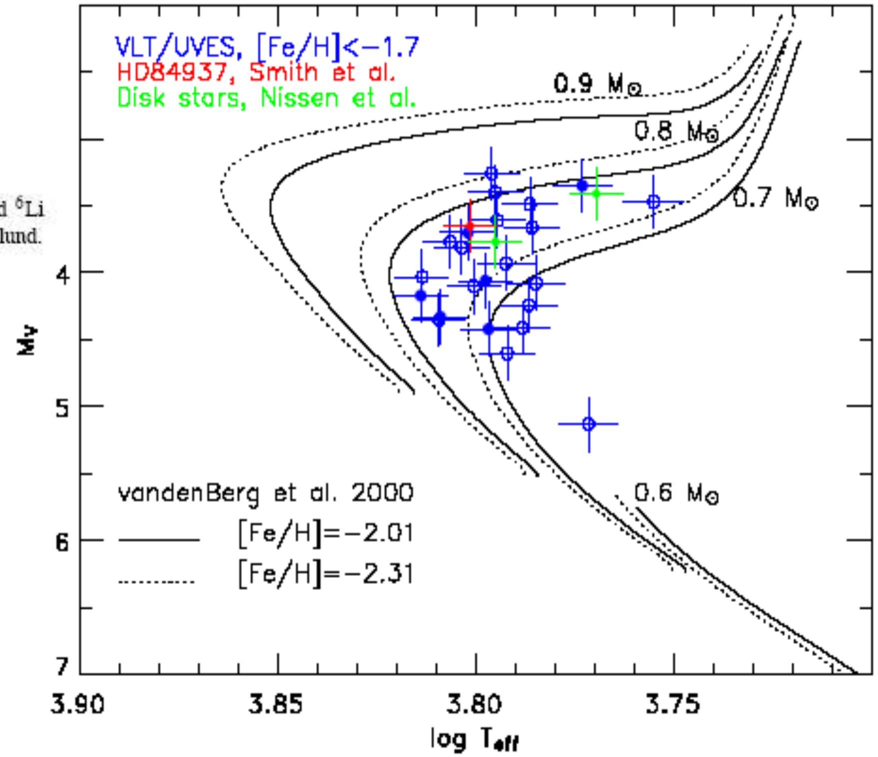


FIGURE 4. The Hertzsprung-Russell diagram for stars from Figure 3 with [Fe/H] < −1.7. Filled symbols denote stars with a detection of ^{6}Li according to the key in the top left corner of the figure. Evolutionary tracks for the indicated stellar masses and metallicities are from VandenBerg et al. (2000).

Lambert (2005)

Might 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 & Rehm, Phys.Rev.D**64**:023510,2001, Jedamzik, Phys.Rev.D**70**:063524,2004

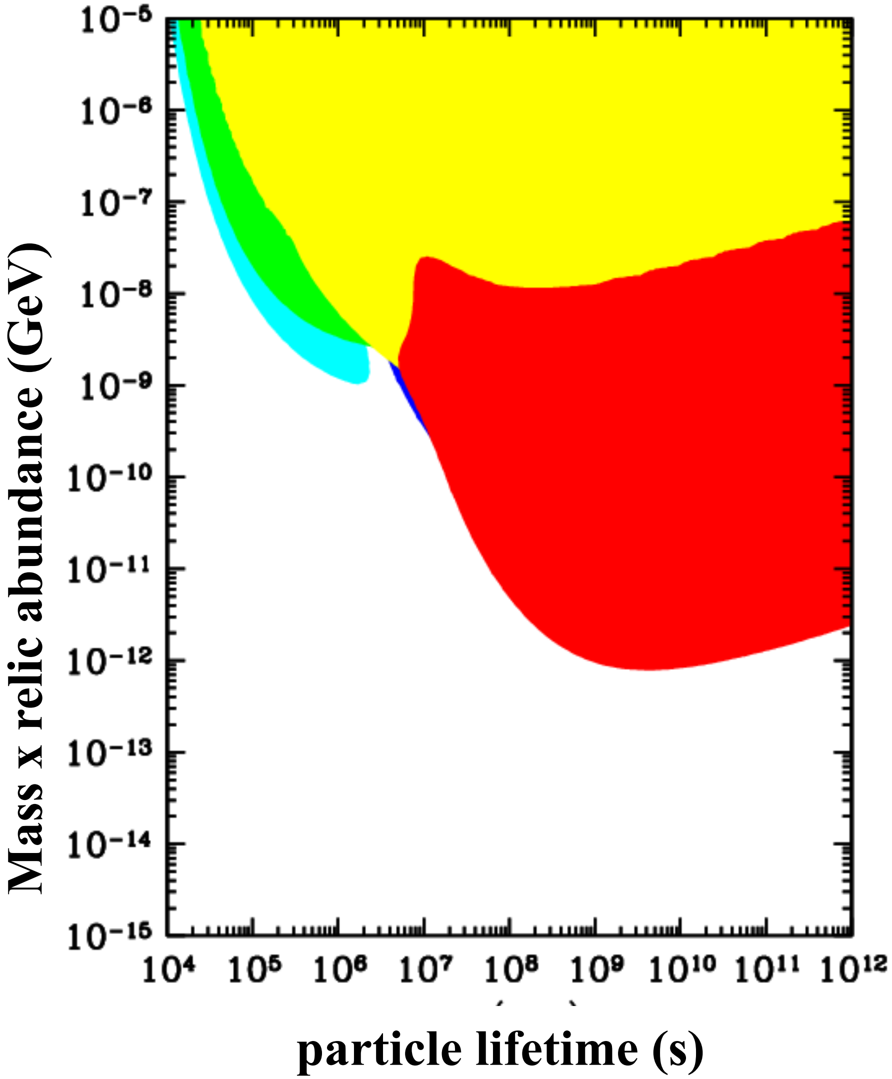
BBN & DECAYING PARTICLES

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

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

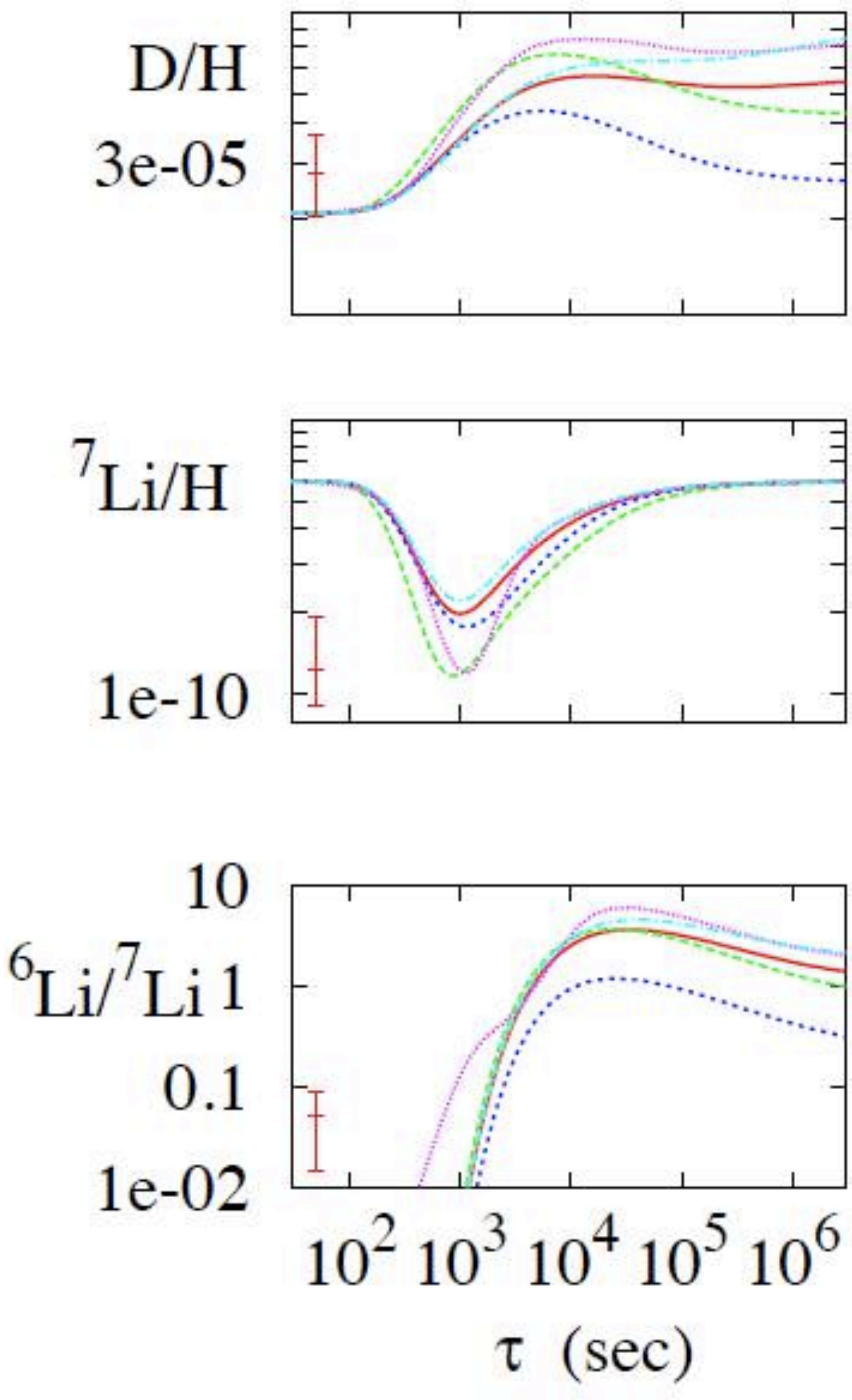
(Weinberg 1982; Khlopov & Linde 1983; Ellis, Nanopoulos & Sarkar 1985; Reno & Seckel 1988)

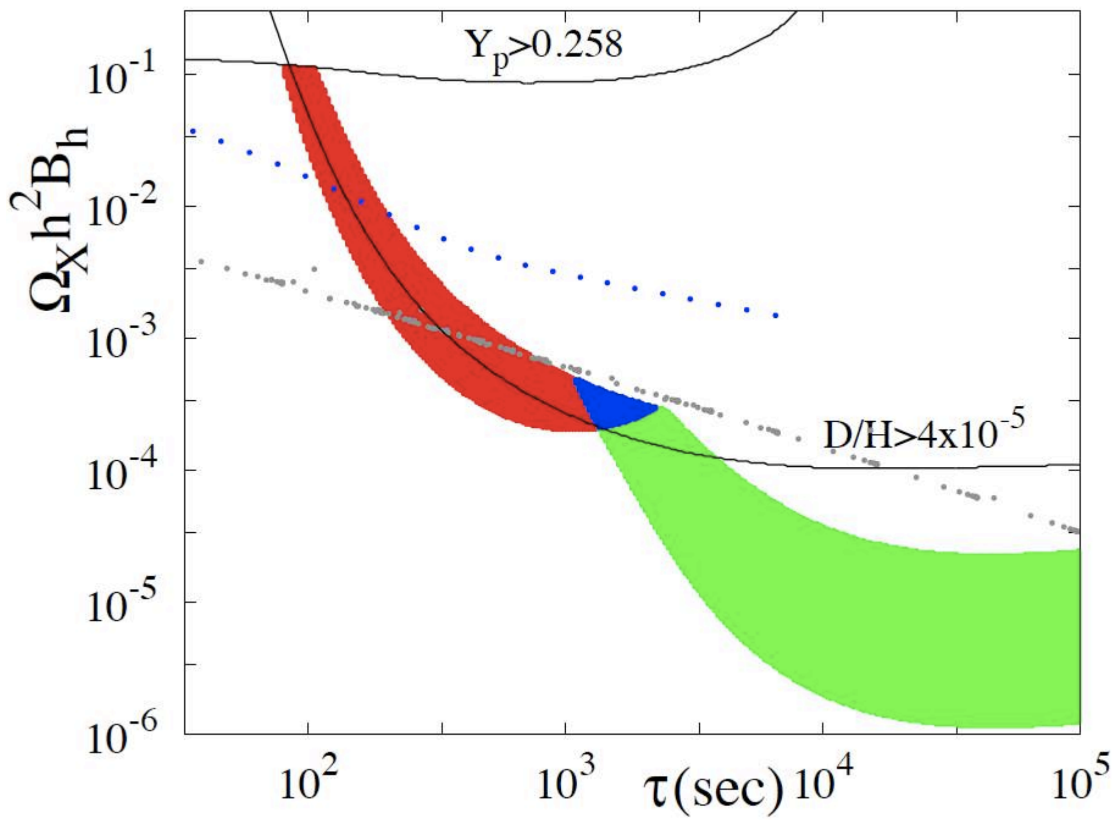
The high energy photons in the EM radiation cascade would have photo-dissociated the synthesized elements
⇒ most sensitive constraint comes from possible over production of D+^{3}He from breakup of ^{4}He … also creates both ^{7}Li and ^{6}Li



Ellis *et al*, Nucl.Phys.B**373**:399 1992,
Cyburt *et al*, Phys.Rev.D**67**:103521,2003

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-Lightest-SUSY-Particle (with gravitino LSP), …

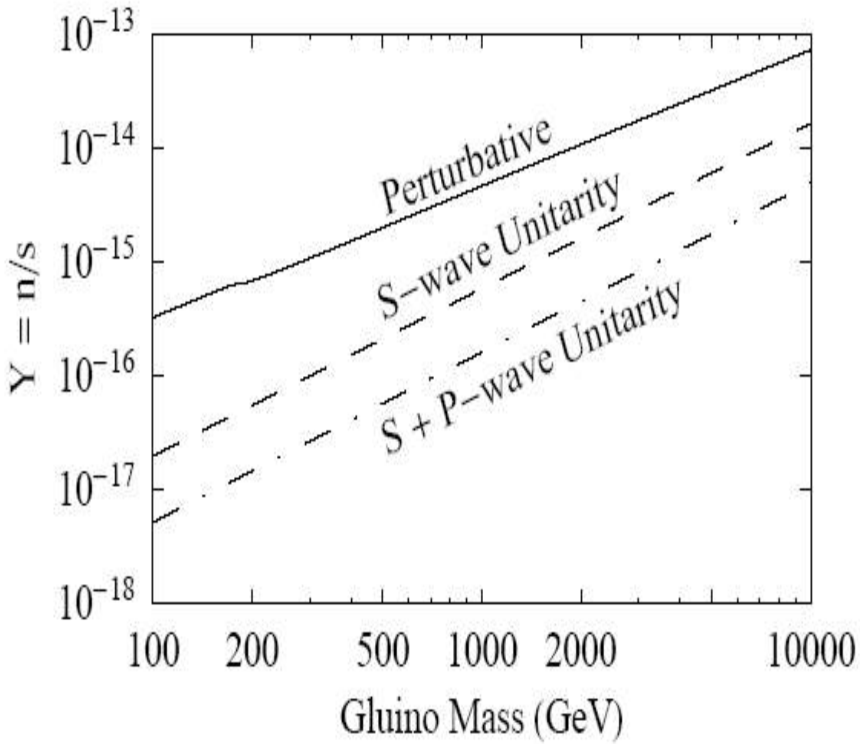


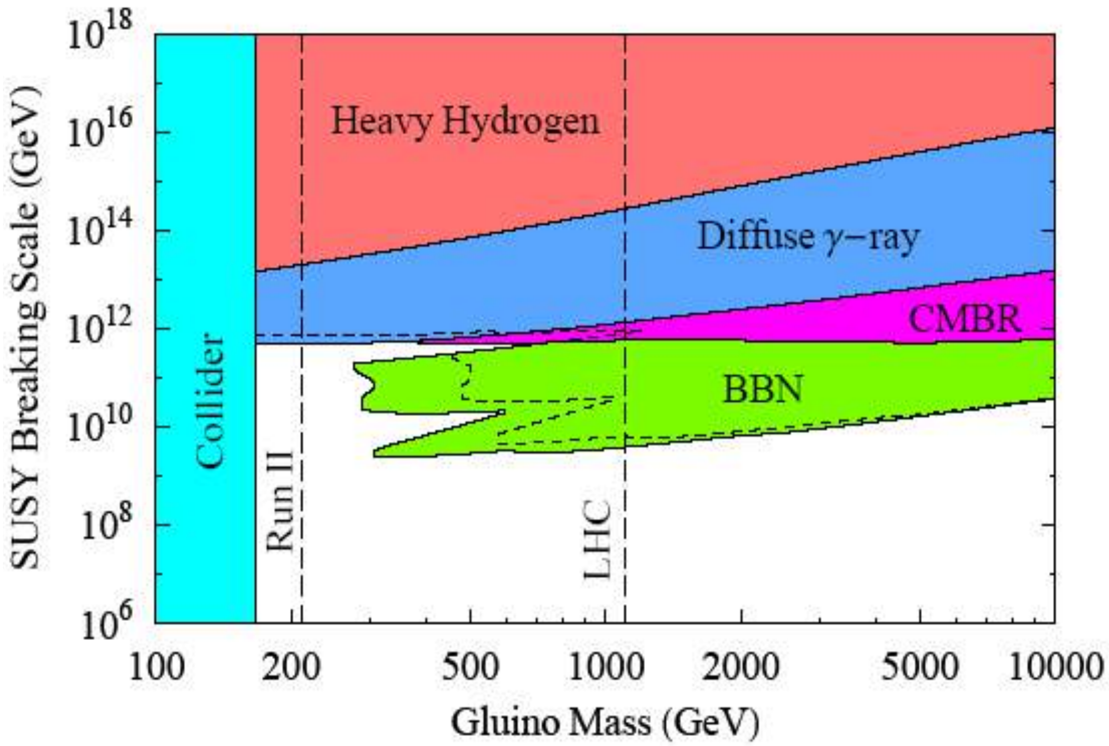


Bailly, Jedamzik & Moultaka 2008

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





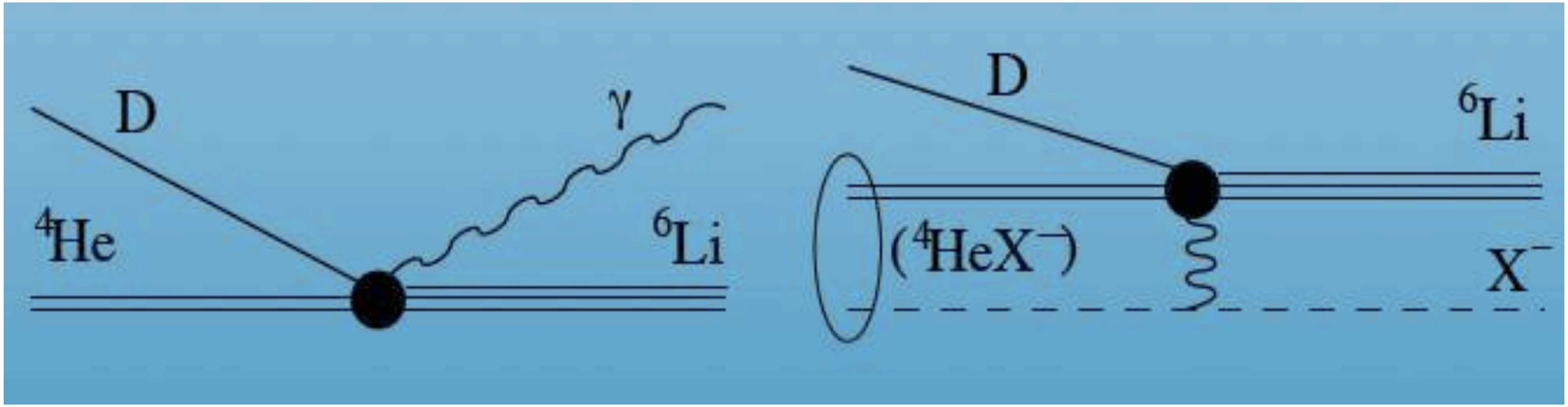
A small number of these would survive annihilation in the early universe and decay during nucleosynthesis → stringent bound from overproduction of D + ^{3}He

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

Arvinataki, Davis, Graham, Pierce & Walker (2005)

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 (2006)

Thus the lithium anomaly may be due to supersymmetric particles (e.g. "stau") which catalyse relevant nuclear reactions … if so these should 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 places constraints on any deviations from the usual expansion history (e.g. new neutrinos) … however the abundance of ^{7}Li is a factor of 3 smaller than expected ➝ new physics?

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