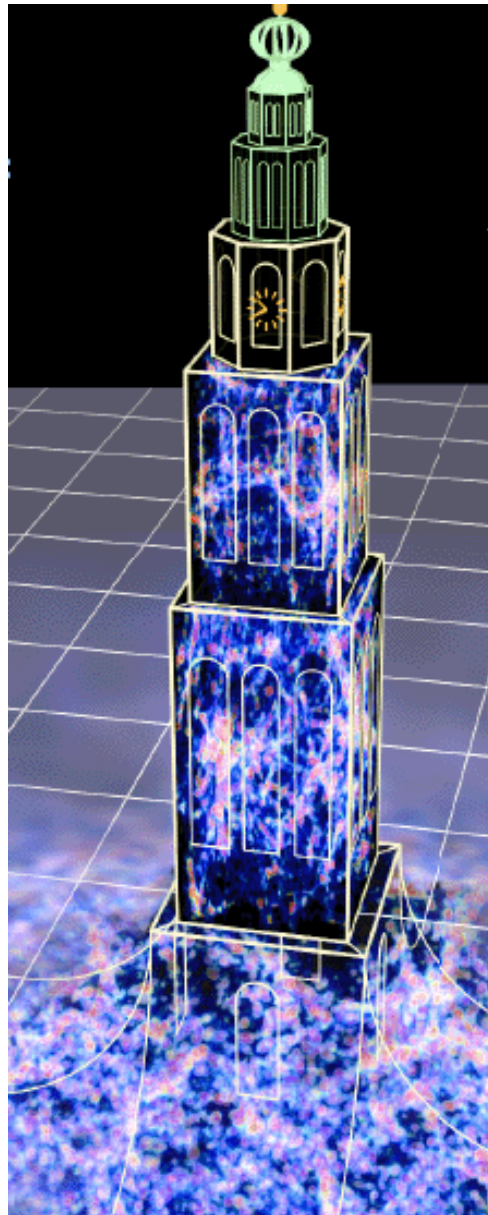
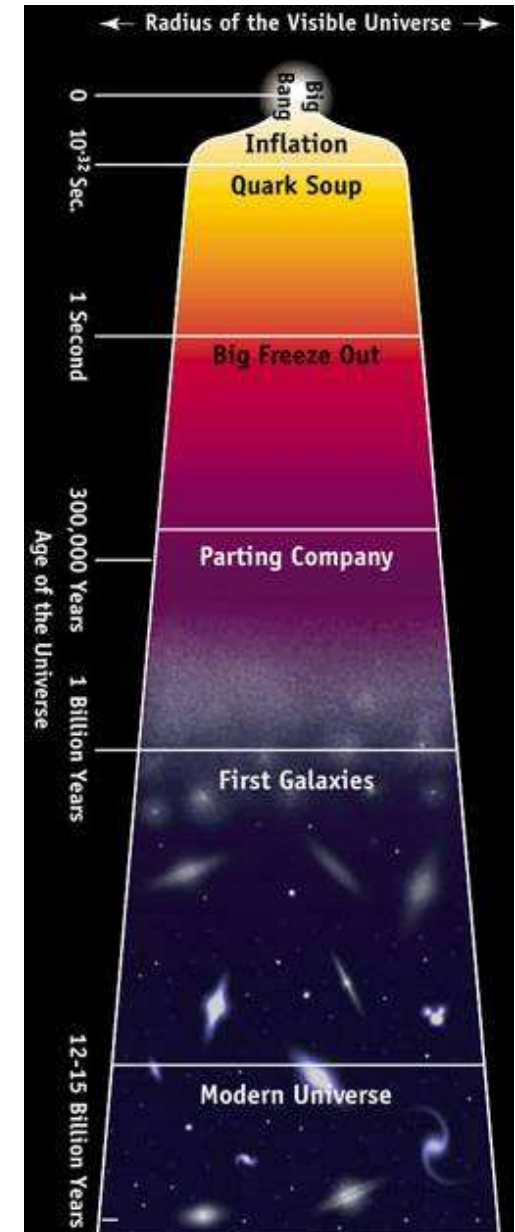


Big bang nucleosynthesis and new physics



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Weak interactions and nuclear reactions in expanding, cooling

universe .. (Gamow 1948; Havashi 1950; Alpher, Follin & Herman 1953; Peebles 1966;

Dramatis personae:

Radiation (dominates) $\gamma, e^\pm, 3\nu\bar{\nu}$
 Matter n, p
 baryon-to-photon ratio $\frac{n_B}{n_\gamma} \equiv \eta \sim 2.74 \times 10^{-8} \Omega_{\text{Bh}}^2$
 → the only free parameter

Initial conditions: $T \gg 1 \text{ MeV}, t \ll 1 \text{ sec}$

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

$p + \nu_e \leftrightarrow n + e^+$
 neutron-to-proton ratio: $n/p = e^{-(m_n - m_p)c^2/kT}$

Weak freeze-out: $T_f \sim 1 \text{ MeV}, t_f \sim 1 \text{ sec}$

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

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

Deuterium bottleneck: $T \sim 1 \rightarrow 0.07 \text{ MeV}$

D created by $np \rightarrow D\gamma$
 but destroyed by high-E photon tail: $D\gamma \rightarrow np$
 so nucleosynthesis halted until: $T_{\text{nuc}} \sim \Delta_D / -\ln(\eta)$

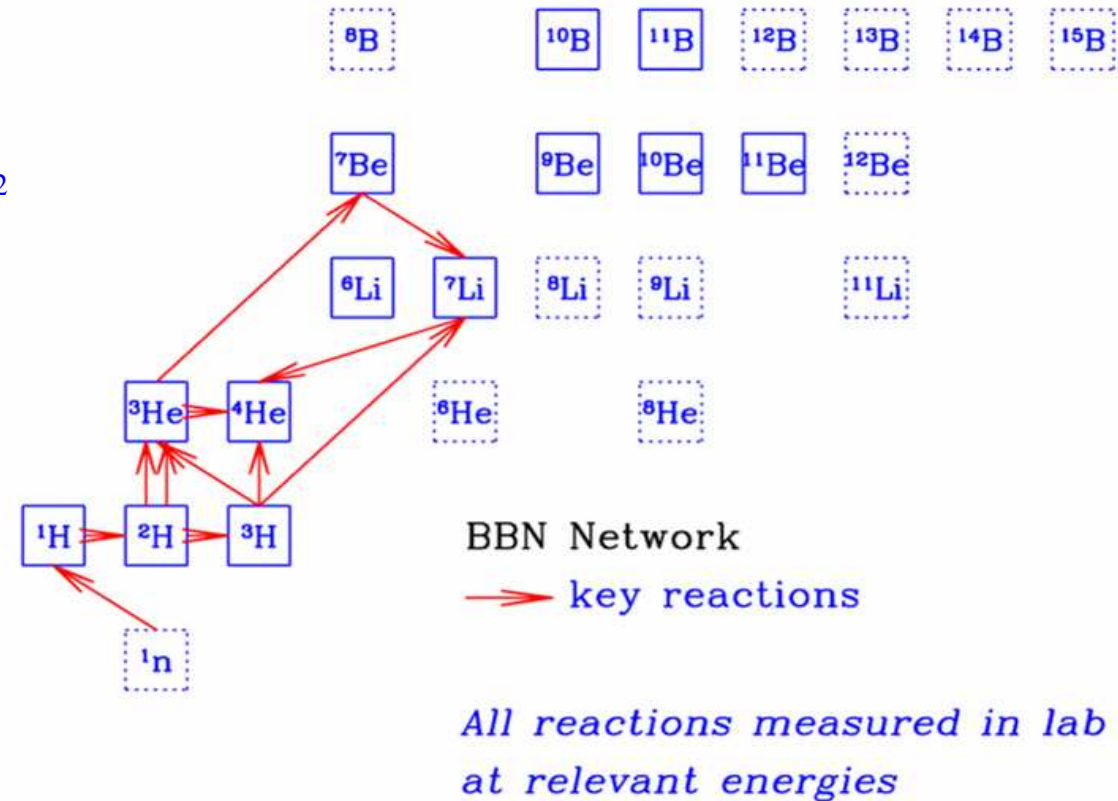
Element synthesis: $T_{\text{nuc}} \sim 0.07 \text{ MeV}, t_{\text{nuc}} \sim 3 \text{ min}$

$n/p \rightarrow 1/7$ through neutron β -decay

essentially all $n \rightarrow {}^4\text{He}$ ($Y_p \sim 25\%$ by mass)

+ traces of 'left-over' D, ${}^3\text{He}$, ${}^7\text{Li}$ (${}^6\text{Li}/{}^7\text{Li} \sim 10^{-5}$)

(no heavier nuclei formed in standard, homogeneous model)



Computer code by Wagoner (1969, 1973)
 ...updated by Kawano (1992)

Coulomb & radiative corrections, ν heating, plasma effects *etc* (Dicus *et al* 1982)

Nucleon recoil corrections (Seckel 1993)

Updated cross-sections (NACRE 2003)

BBN Predictions

line widths \Rightarrow theoretical uncertainties (neutron lifetime + nuclear cross sections)

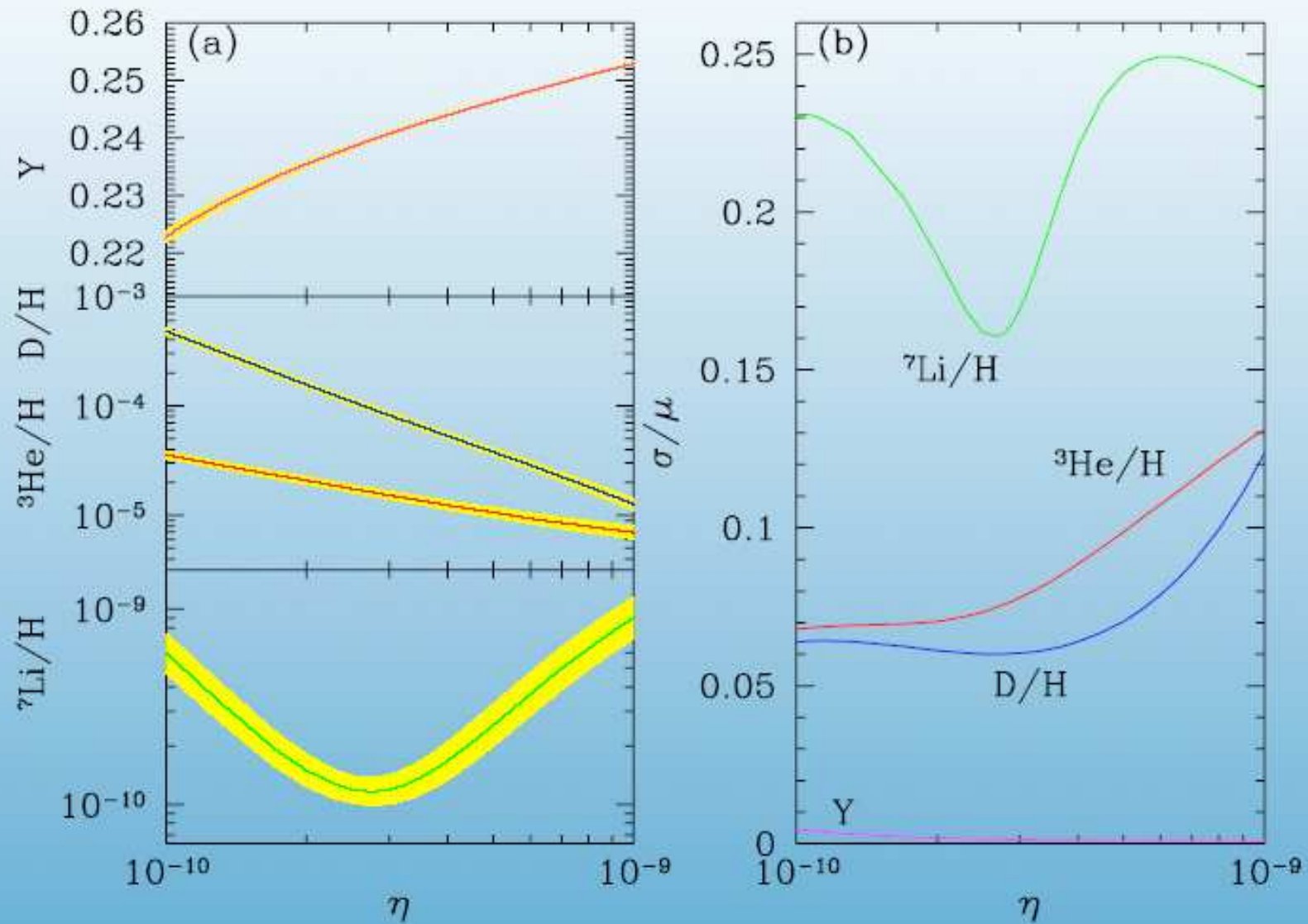
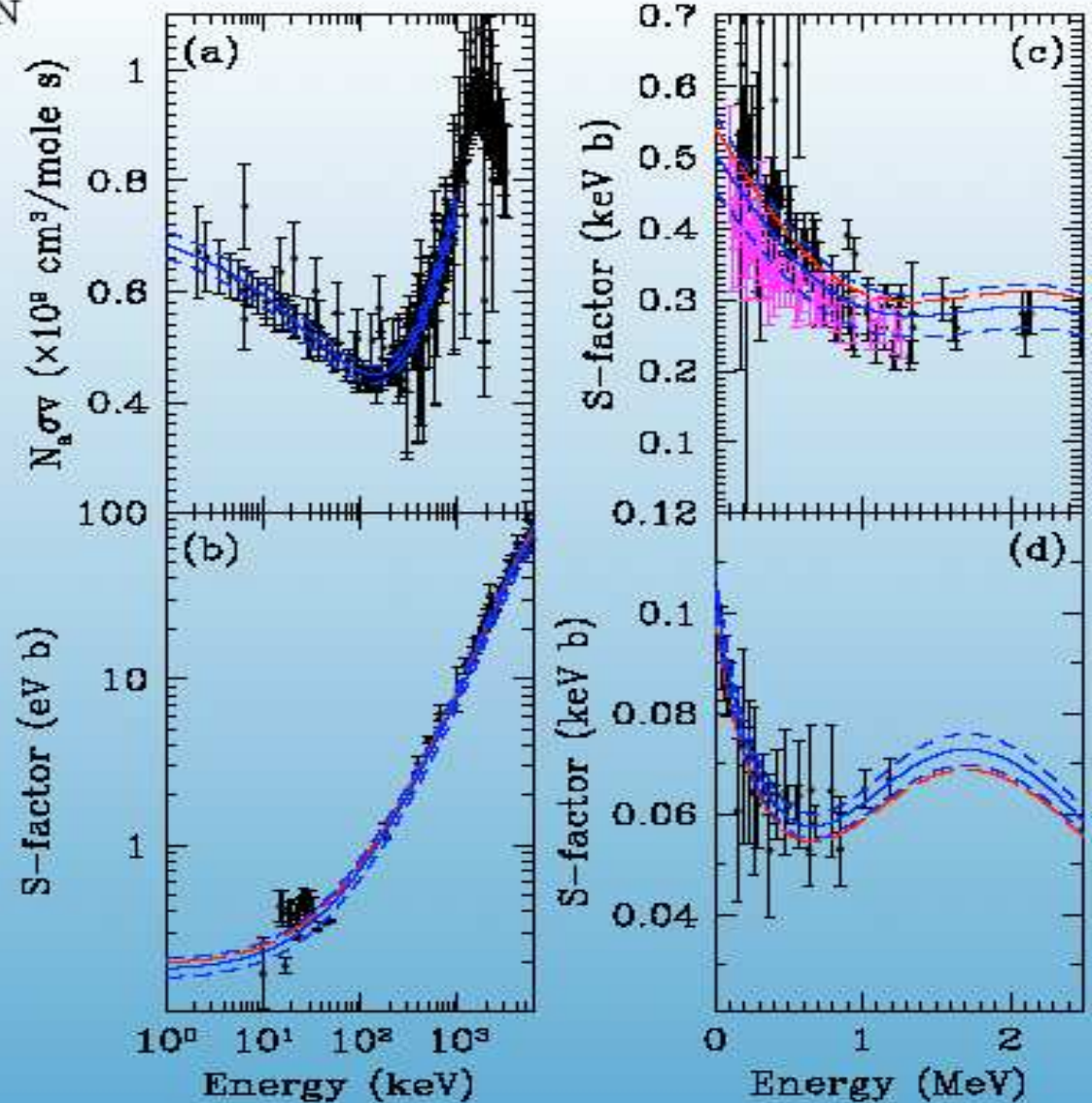


Table 1: Key Nuclear Reactions for BBN

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

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



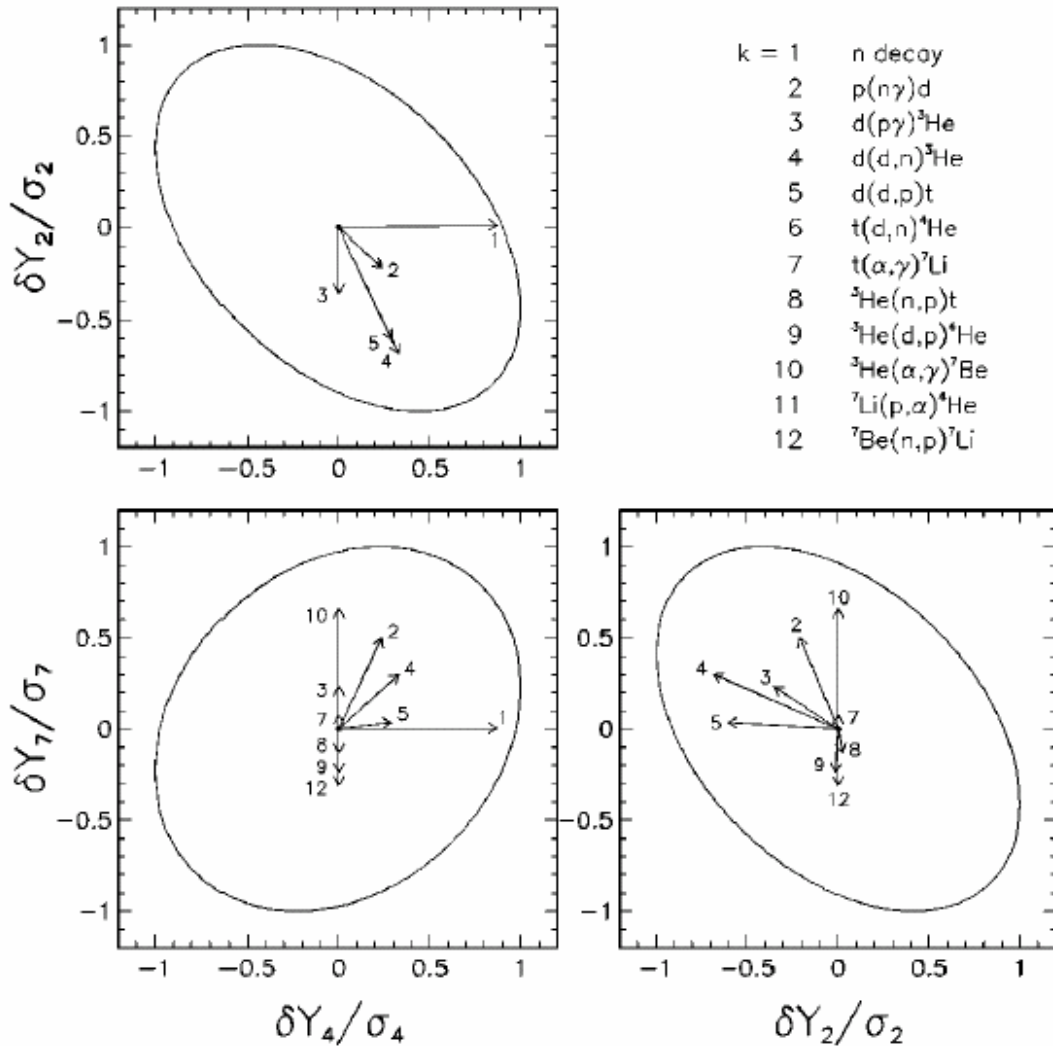
Uncertainties in synthesized abundances are *correlated* ... estimate using Monte Carlo methods
 (Krauss & Romanelli 1988; Smith, Kawano & Malaney 1993; Krauss & Kernan 1994; Cyburt, Fields & Olive 2004)

Linear propagation of errors → covariance matrix ... gives excellent agreement with Monte Carlo results

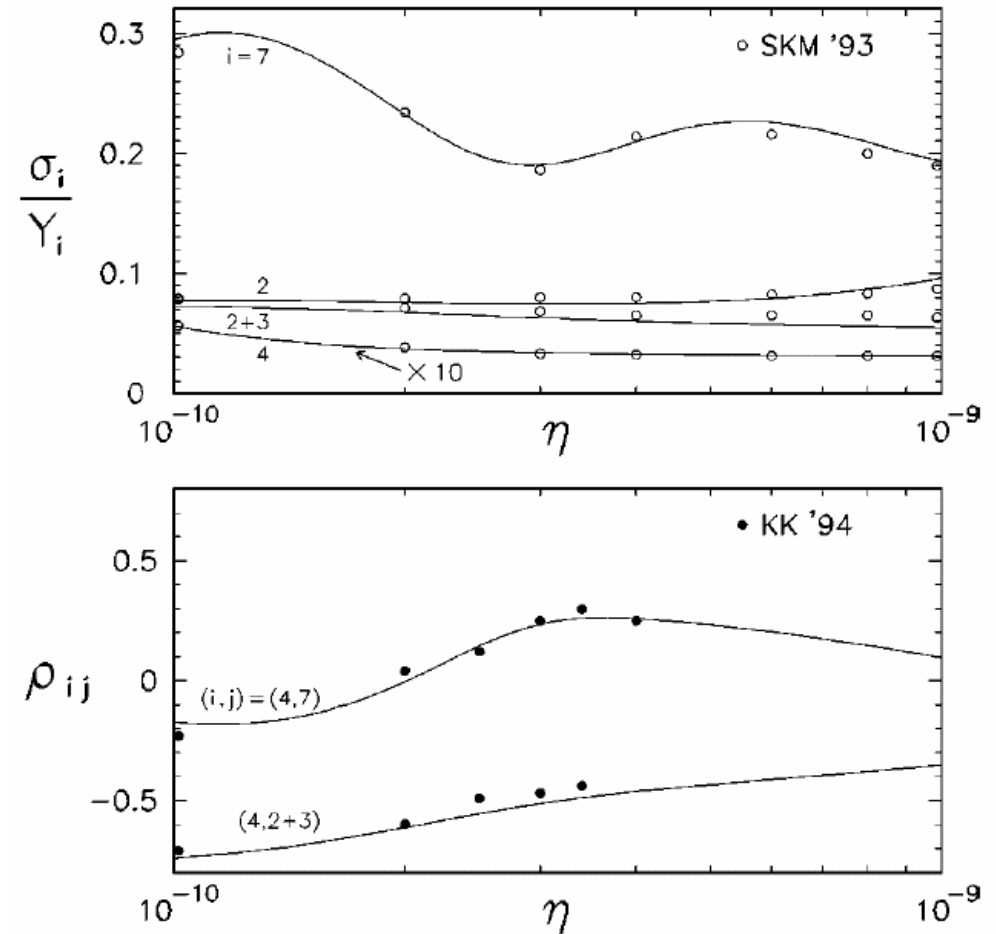
$$Y_i = Y_i(\eta) \pm \sigma_i(\eta) \Rightarrow \delta Y_i(\eta) = Y_i(\eta) \sum_k \lambda_{ik}(\eta) \frac{\delta R_k}{R_k}, \quad \lambda_{ik}(\eta) = \frac{\partial \ln Y_i(\eta)}{\partial \ln R_k(\eta)}$$

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

Big Bang Nucleosynthesis – Error Components at $\eta = 5.13 \times 10^{-10}$



MonteCarlo vs Analytic estimate
(2, 3, 2+3, 4, 7 = D, ³He, D+³He, ⁴He, ⁷Li)



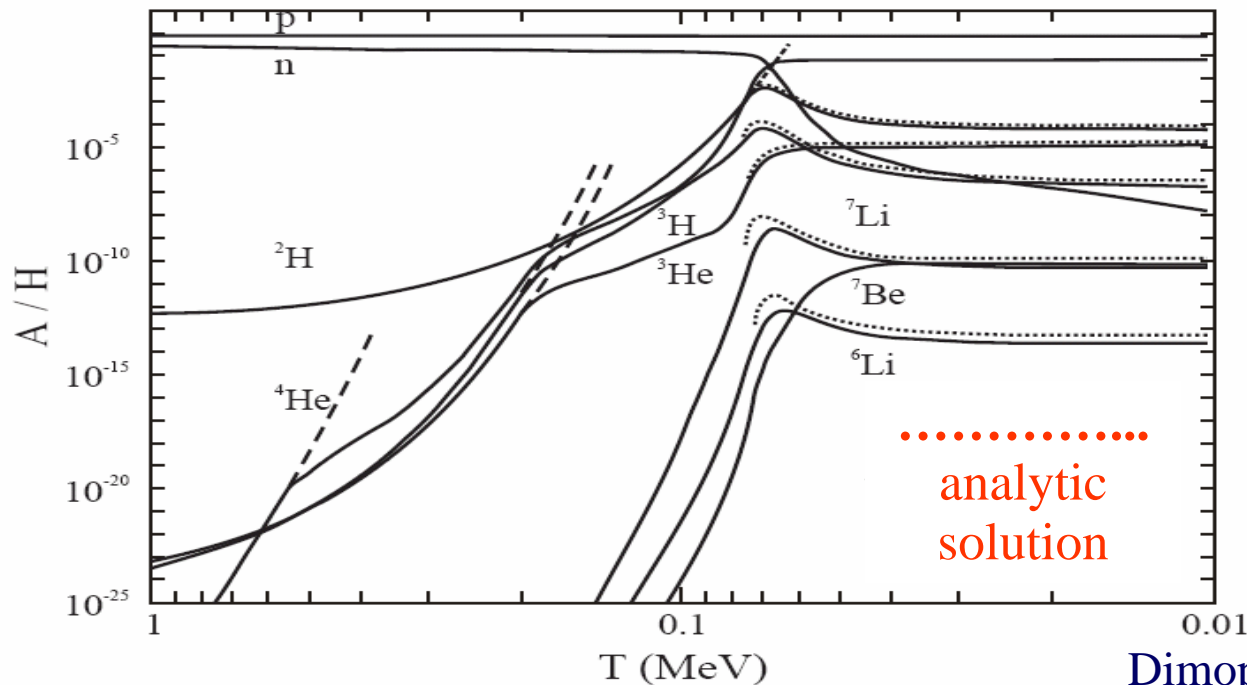
Nucleosynthesis *without* a computer

$$\frac{dX}{dt} = \underbrace{J(t)}_{\text{source}} - \underbrace{\Gamma(t)X}_{\text{sink}} \quad \Rightarrow \quad X^{\text{eq}} = \frac{J(t)}{\Gamma(t)} \quad \dots \text{ but general solution is:}$$

$$X(t) = \exp\left(-\int_{t_1}^t dt' \Gamma(t')\right) \left[X(t_1) + \int_{t_1}^t dt' J(t') \exp\left(-\int_{t_1}^{t'} dt'' \Gamma(t'')\right) \right]$$

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

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



Examine reaction network to identify the largest 'source' and 'sink' terms ... obtain D, ^3He and ^7Li to within a factor of ~ 2 of exact numerical solution, ^4He good to few %

... can use this formalism to determine *joint* dependence of abundances on expansion rate as well as baryon-to-photon ratio

$$\frac{dY_i}{dt} \propto \eta \sum_{+,-} Y \times Y \times \langle \sigma v \rangle_T \quad \text{and} \quad dT/dt \propto -T^3 \sqrt{g_\star} \quad \text{so:}$$

$$\frac{dY_i}{dT} \propto -\frac{\eta}{g_\star^{1/2}} T^{-3} \sum_{+,-} Y \times Y \times \langle \sigma v \rangle_T \Rightarrow \log \eta - \frac{1}{2} \log g_\star = \text{const}$$

... can therefore employ simple χ^2 statistics to determine best-fit values and uncertainties (*faster* than Monte Carlo + Maximum Likelihood)

$$S_{ij}^2(\eta) = \sigma_{ij}^2(\eta) + \bar{\sigma}_{ij}^2 \quad \bar{\sigma}_{ij}^2 = \delta_{ij} \bar{\sigma}_i \bar{\sigma}_j \quad W_{ij}(\eta) = [S_{ij}^2(\eta)]^{-1}$$

$$\chi^2(\eta) = \sum_{ij} [Y_i(\eta) - \bar{Y}_i] W_{ij}(\eta) [Y_j(\eta) - \bar{Y}_j]$$

The Cosmic Microwave Background: *a powerful baryometer*

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

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

Detailed peak positions, heights, ... sensitive to cosmological parameters

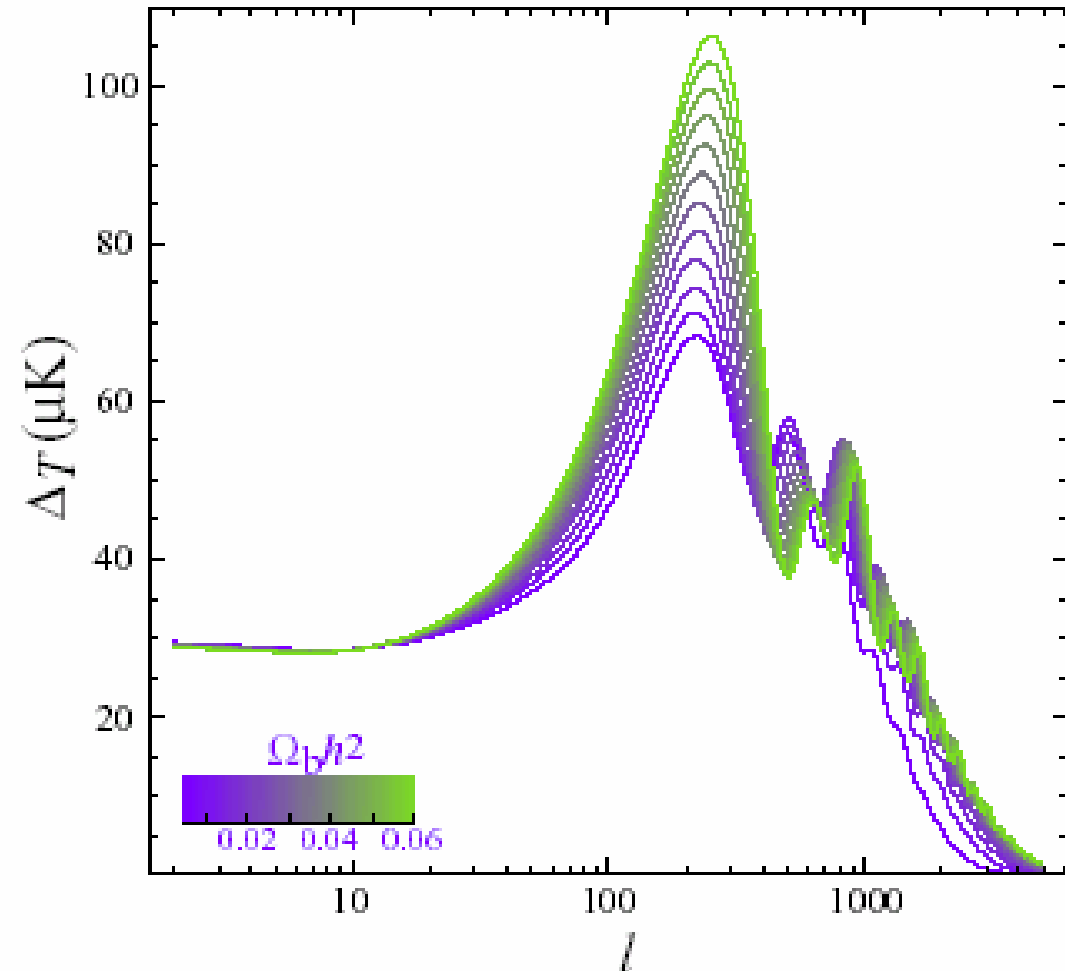
e.g, 1st peak \Rightarrow curvature of space,

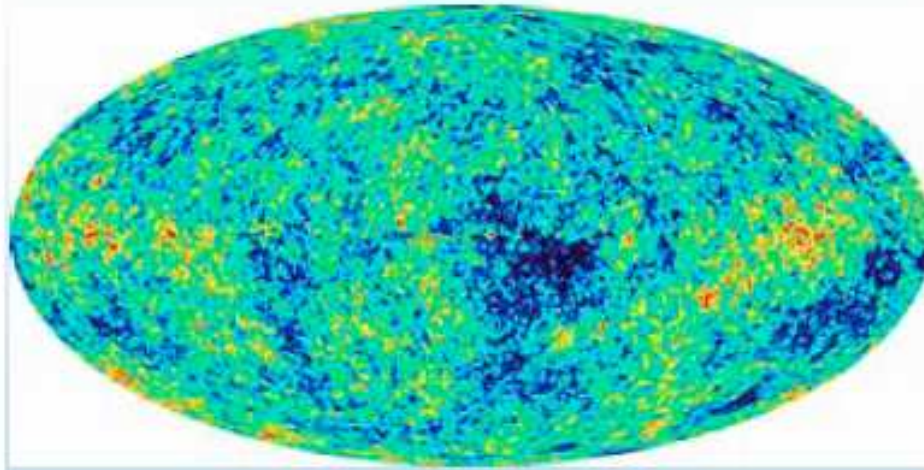
2nd, 3rd peaks/1st peak \Rightarrow baryon density

BBN vs CMB determinations

\rightarrow fundamental test of cosmology ...

thermal history between $z \sim 10^3$ & 10^{10}

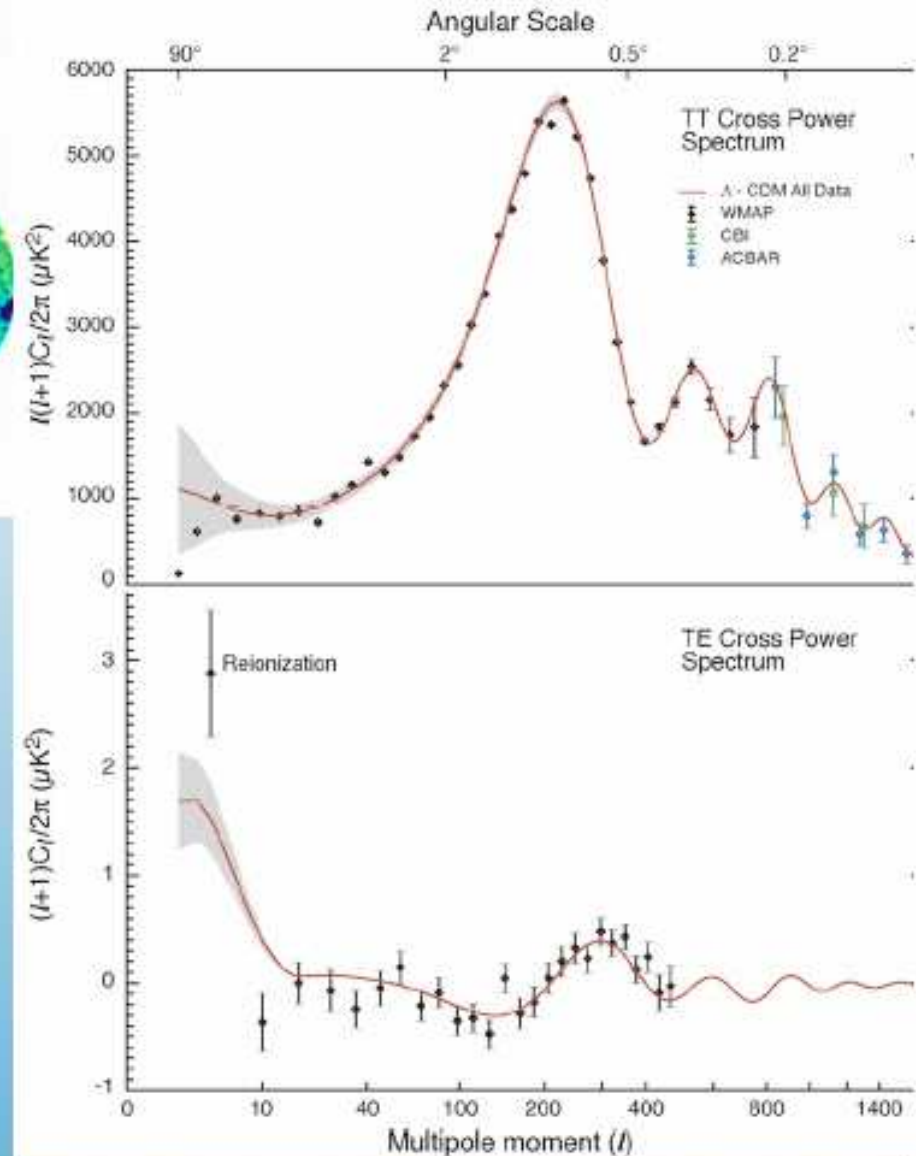




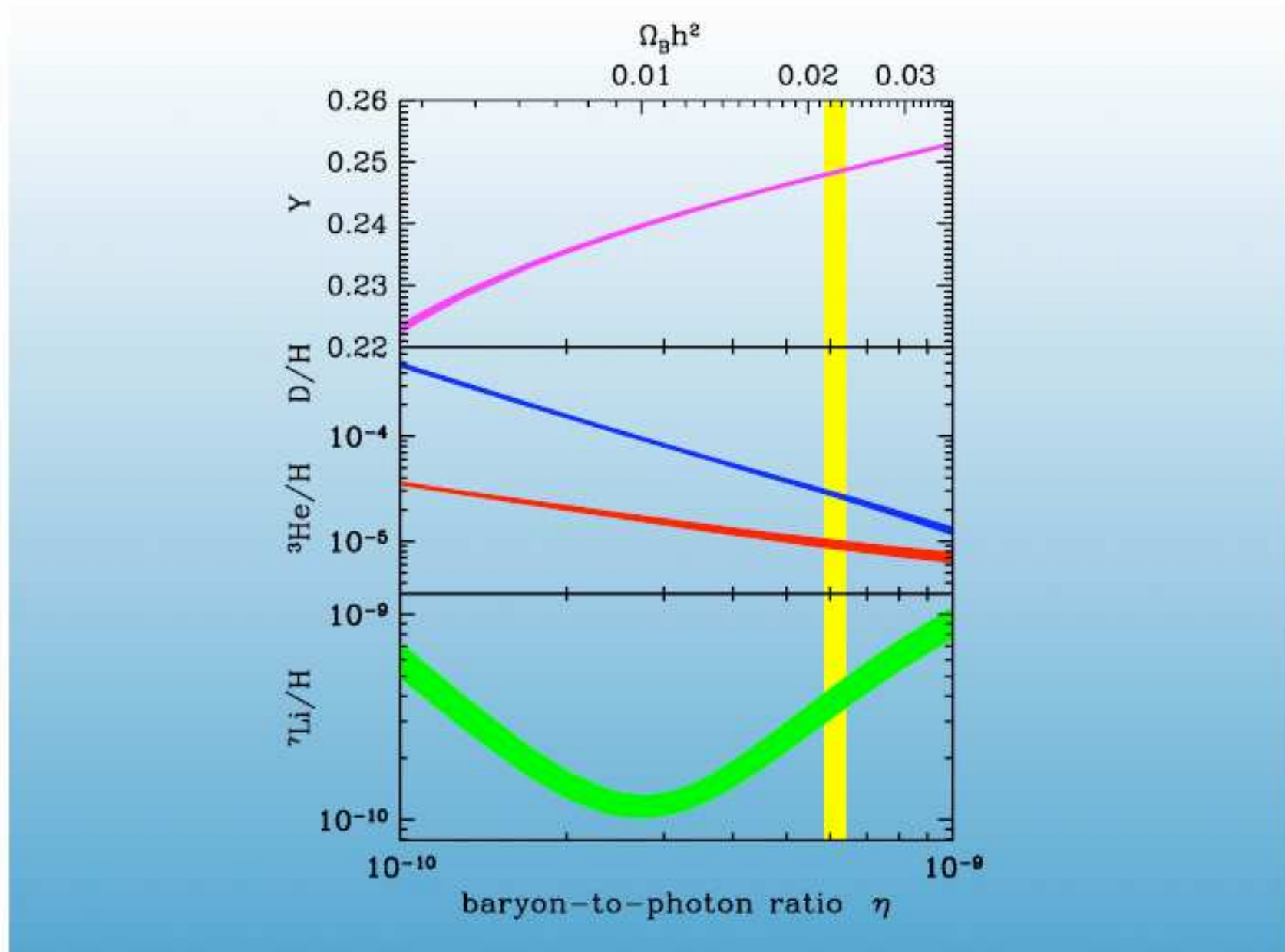
WMAP best fit
 (WMAPext + 2dFGRS +
 Lyman α +running sp.
 index)

$$\Omega_B h^2 = 0.0224 \pm 0.0009$$

$$\eta_{10} = 6.14 \pm 0.25$$



Predictions of BBN + baryon density from CMB



Comparison with inferred primordial abundances

⁴He observed in extragalactic HII regions:
abundance by mass = 25%

⁷Li observed in the atmospheres of dwarf halo stars:
abundance by number = 10^{-10}

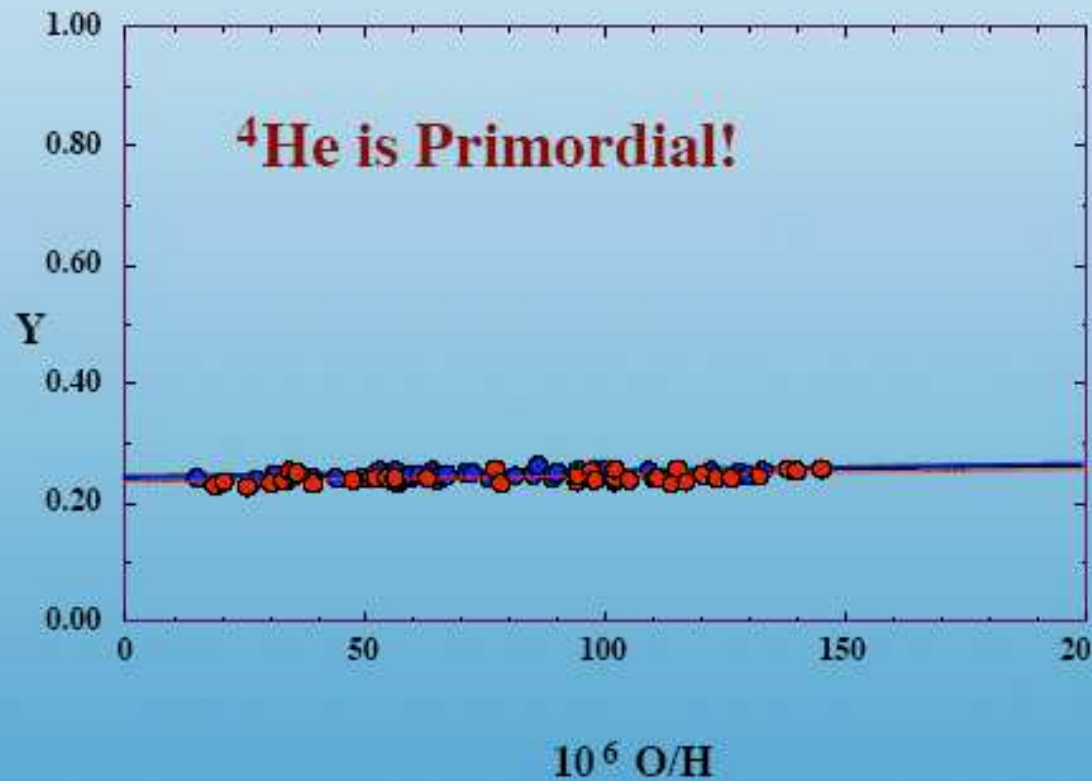
D observed in quasar absorption systems (and locally):
abundance by number = 3×10^{-5}

³He in solar wind, in meteorites, and in the ISM:
abundance by number = 10^{-5}

${}^4\text{He}$

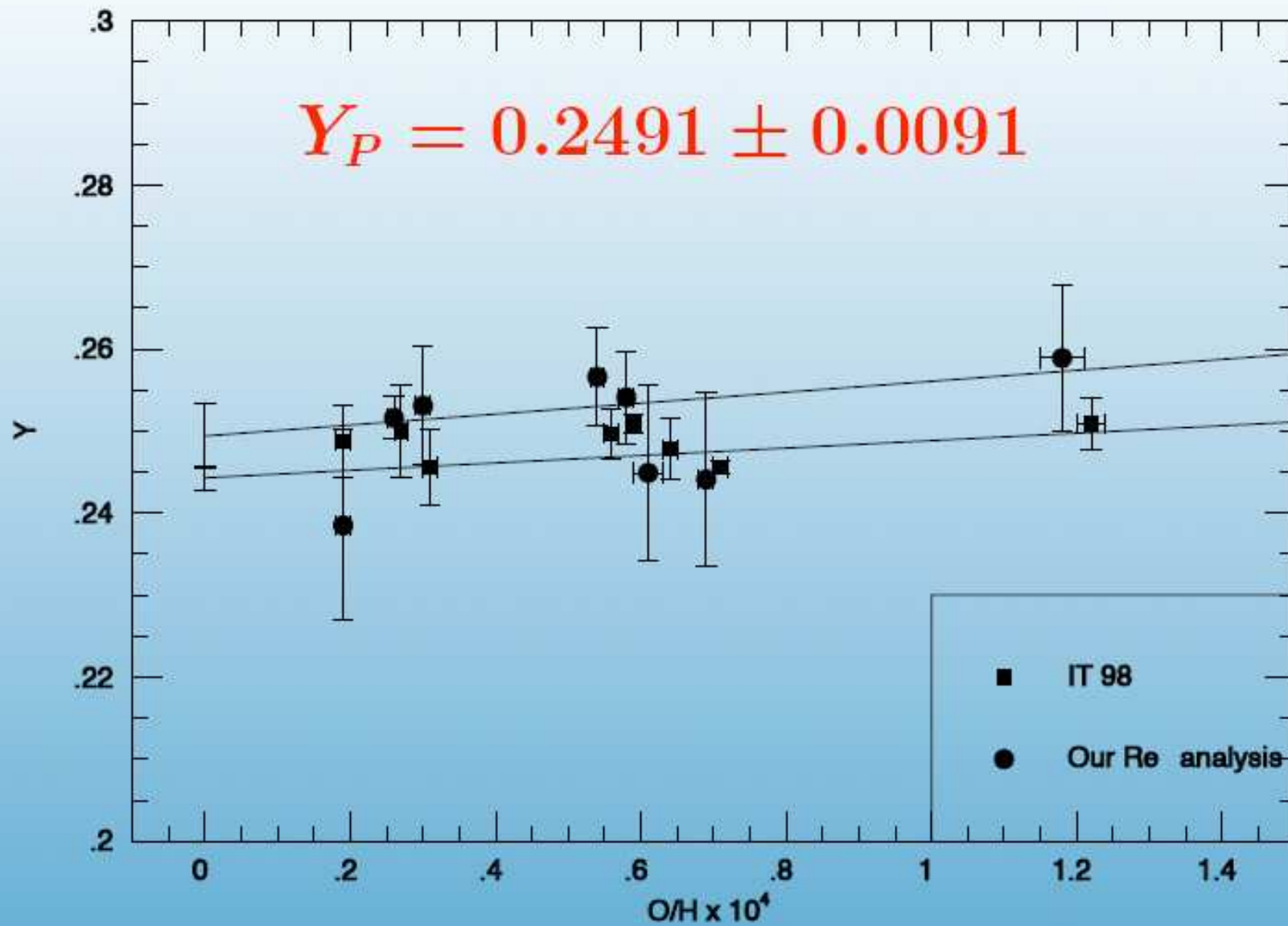
Measured in low metallicity extragalactic HII regions (~ 100) together with O/H and N/H

$$Y_P = Y(\text{O/H} \rightarrow 0)$$

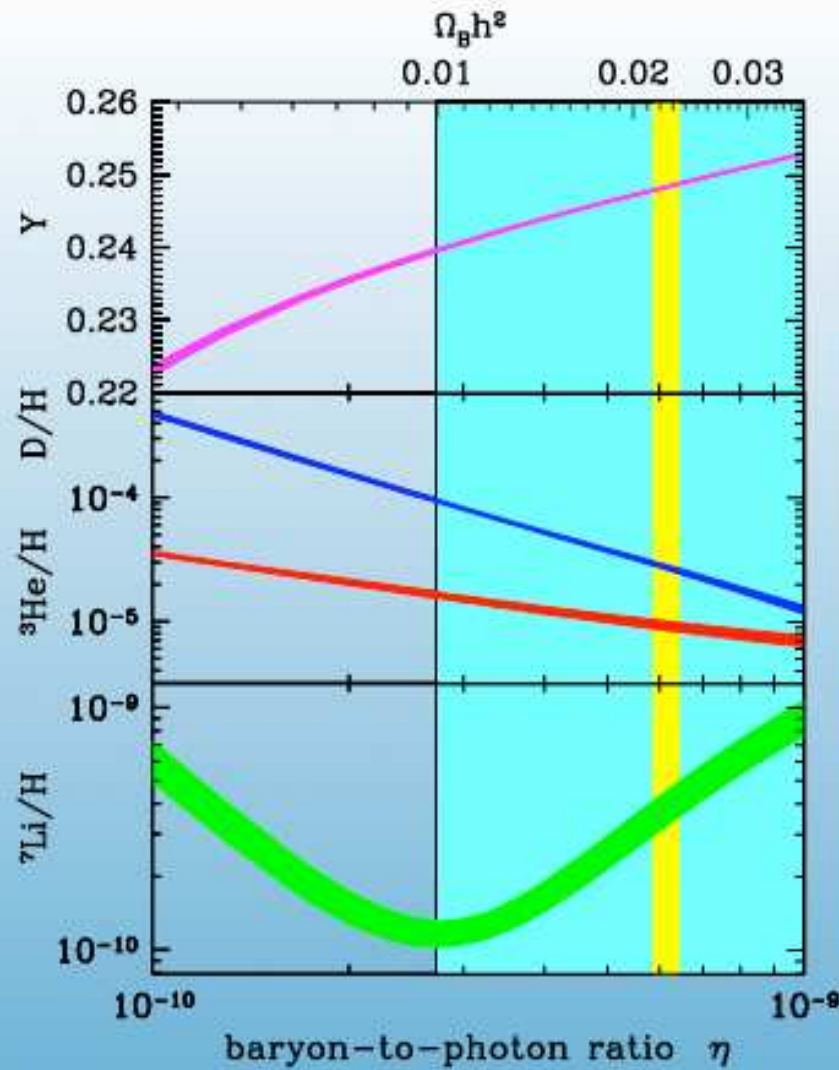


- 0.228 ± 0.005 Pagel et al
S II densities
- 0.244 ± 0.002 Izotov et al
“self consistent”
- 0.238 ± 0.002 Fields & KAO
S II densities
- 0.234 ± 0.003 Peimbert et al
“self consistent”
(the latter is based on a single careful measurement of
 $Y = 0.240 \pm 0.002$ for the SMC at $[O/H] = -.8$)
- 0.2384 ± 0.0025 Peimbert et al
“self consistent”
- 0.2421 ± 0.0021 Izotov et al
“self consistent”
- 0.2491 ± 0.0091 KAO & Skillman
“self consistent”

There is clearly some underlying systematics which must be sorted out!



BBN + CMB η + ^4He abundance



Courtesy: Keith Olive

Primordial Deuterium?

Deuterium Ly- α shifted from H:

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

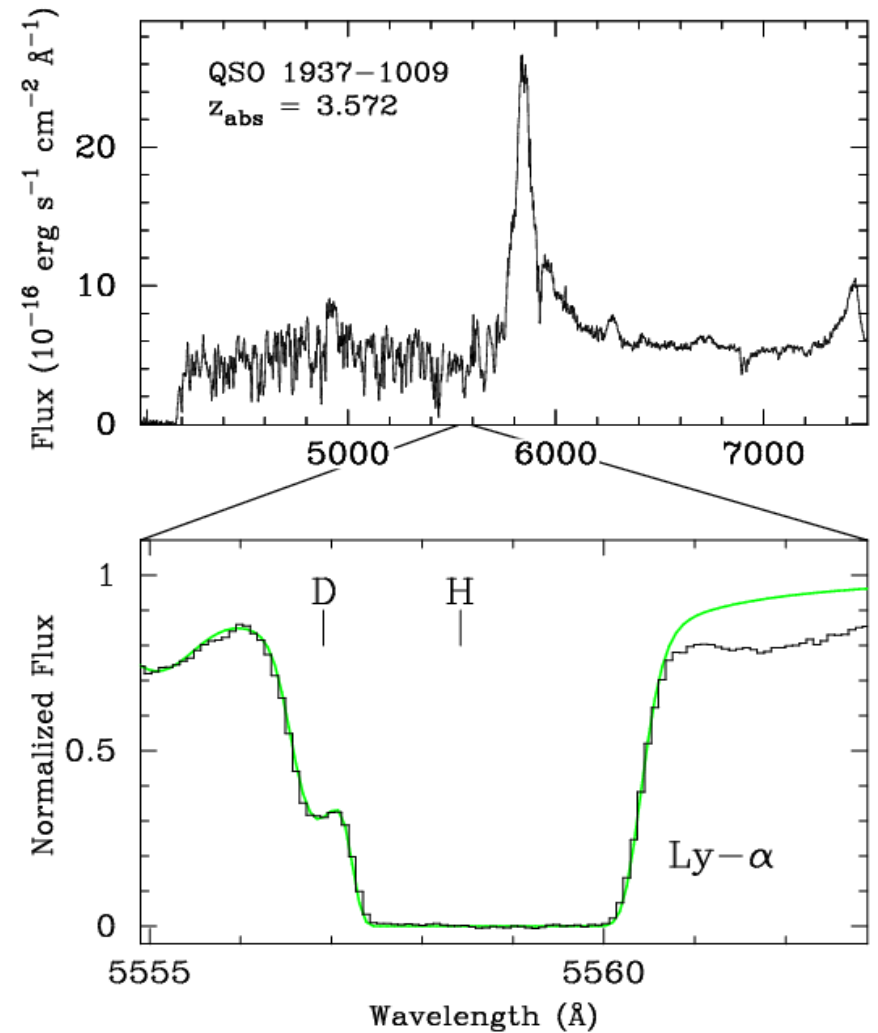
$$\frac{\delta\lambda_{\text{D}}}{\lambda_{\text{H}}} = -\frac{\delta\mu_{\text{D}}}{\mu_{\text{H}}} = -\frac{m_e}{2m_p}$$

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

Using high resolution spectroscopy,
can measure D *directly* at high- z

But:

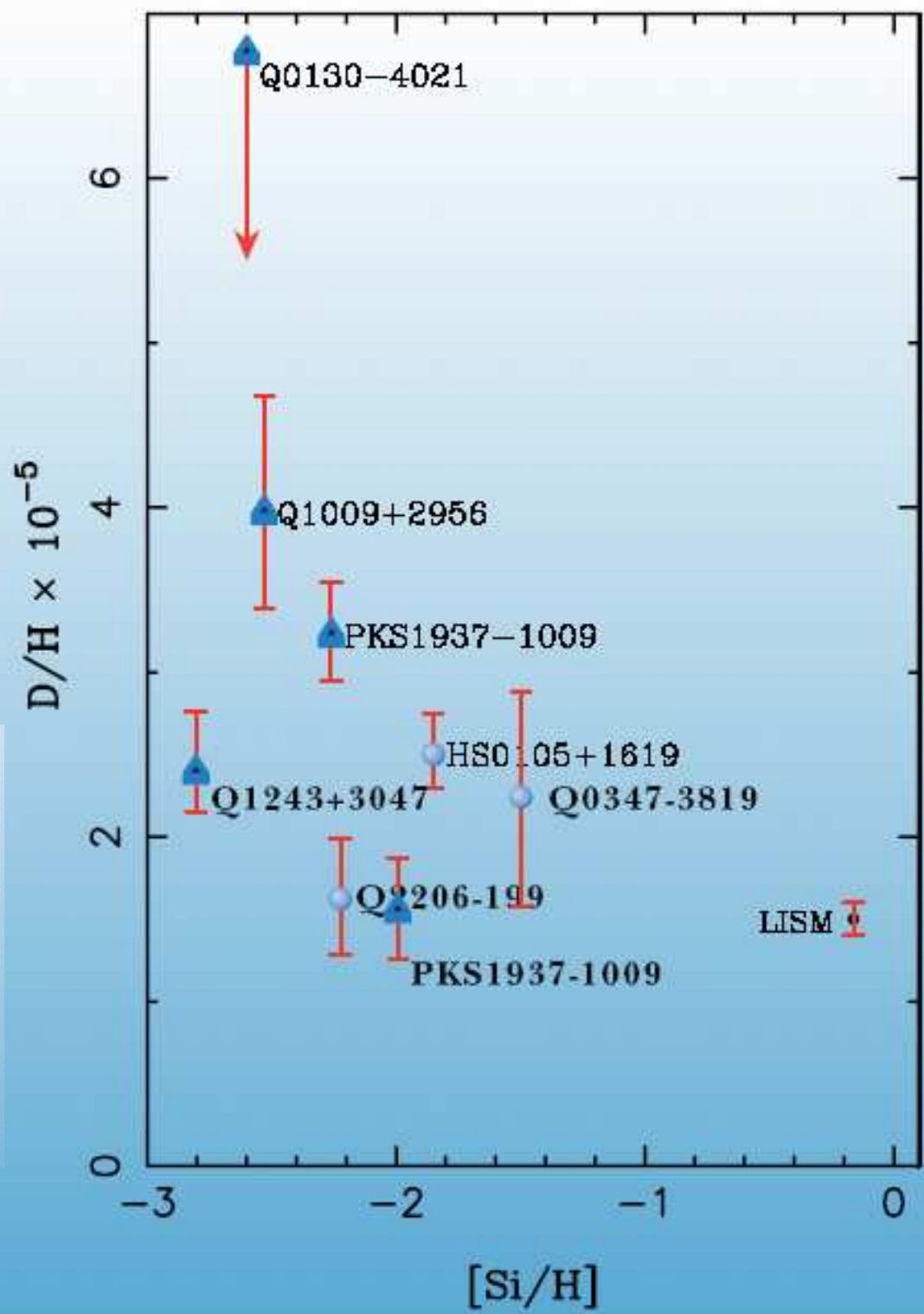
- Hard to find clean systems
- Do not resolve clouds
- Dispersion/systematics?



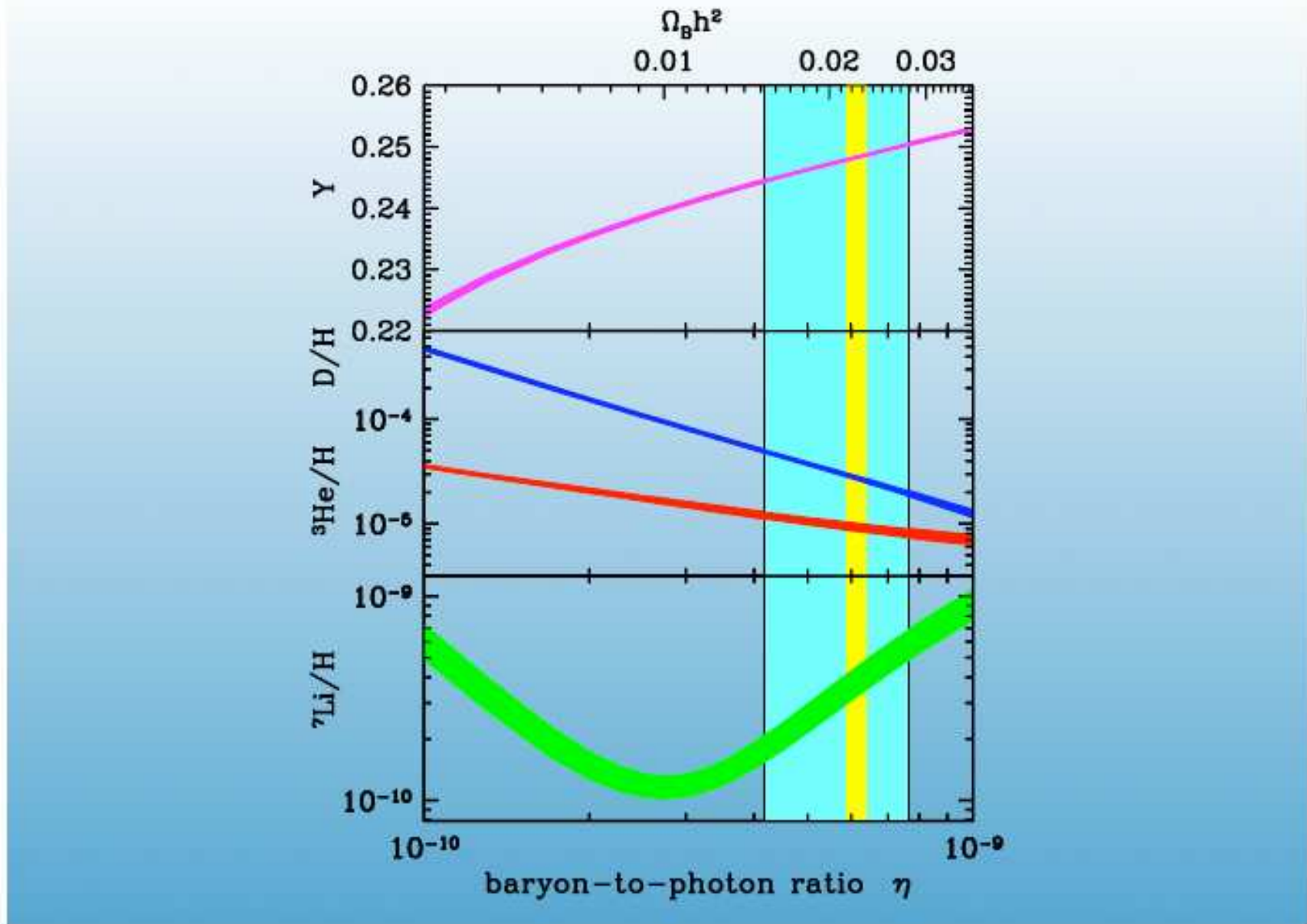
Tytlar & Burles (2000)

D/H abundances in Quasar absorption systems

Is the dispersion real?
Is there a correlation with α/H ?
Is there a correlation with density?
Evidence for evolution?



BBN + CMB η + D abundance



Courtesy: Keith Olive

Primordial Lithium?

Observe in primitive (Pop II) stars

Li-Fe correlation \Rightarrow mild evolution

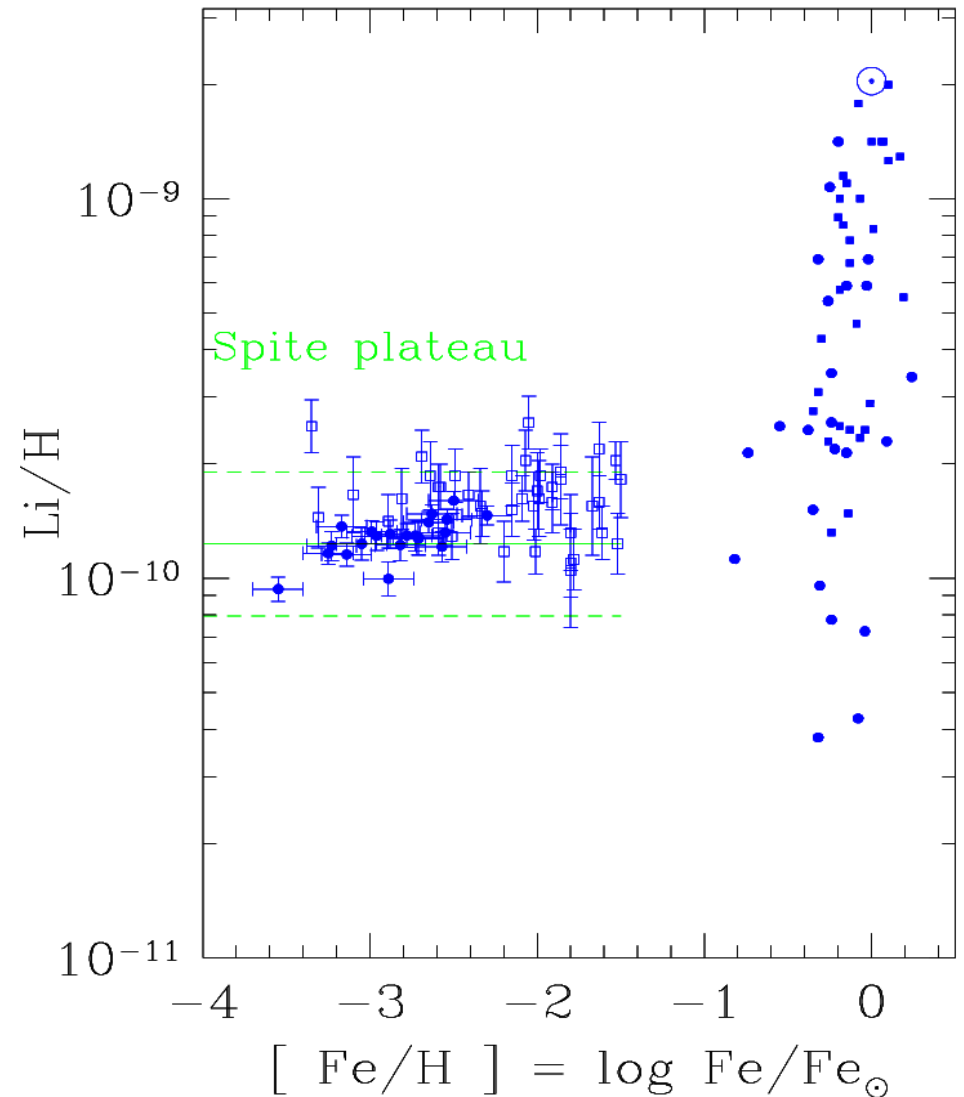
Note most abundant isotope is ${}^7\text{Li}$

‘Plateau’ at low Fe (Spite & Spite 1982)

\Rightarrow constant abundance at early epochs

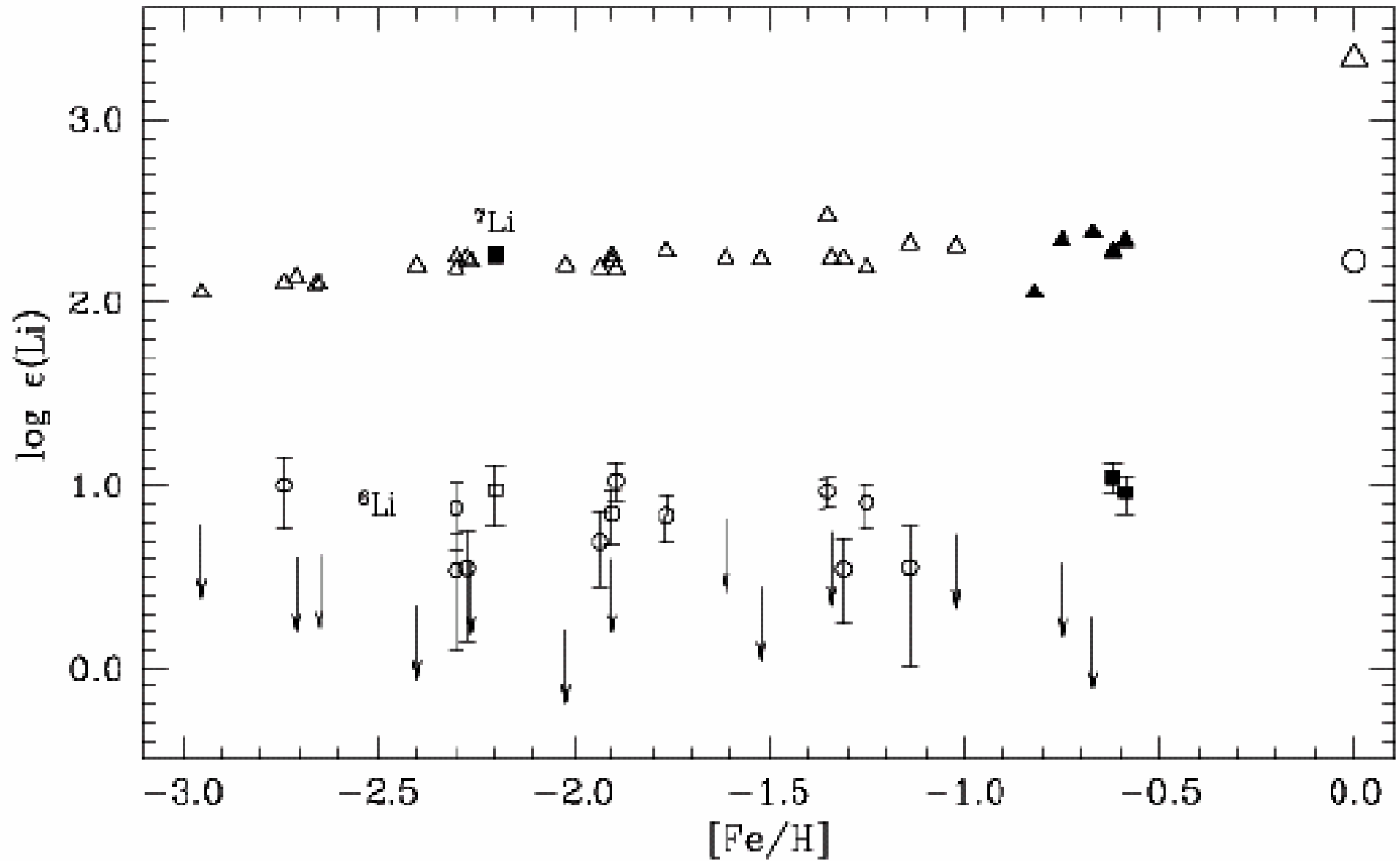
... so infer observed ${}^7\text{Li}$ is primordial

Measured in over 100 halo stars



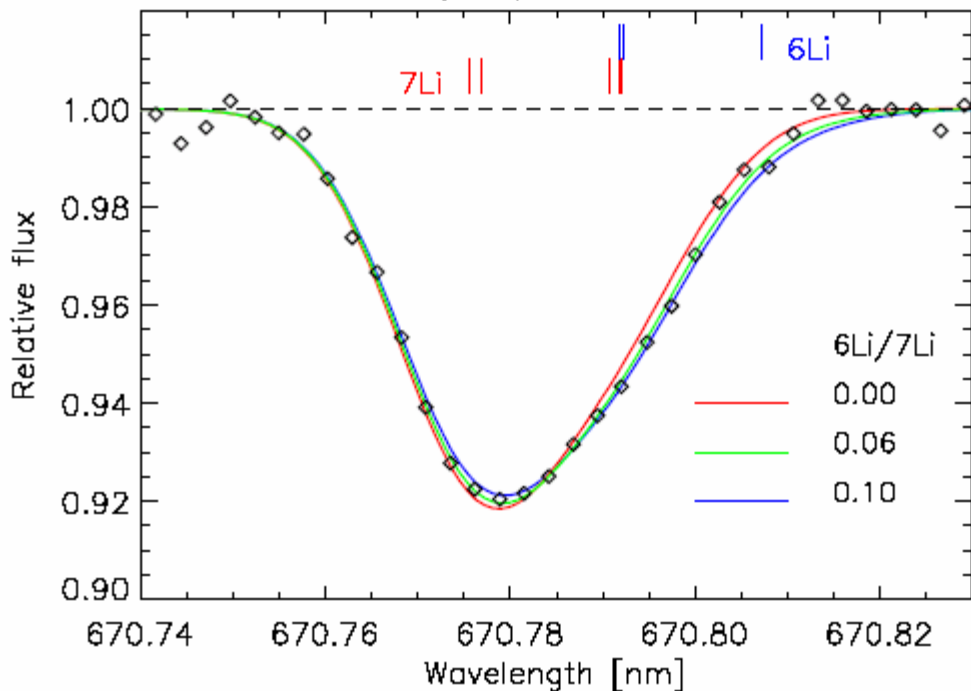
Recently a similar 'plateau' in ${}^6\text{Li}$ has also been claimed with ${}^6\text{Li}/{}^7\text{Li} \sim 0.1$

(Nissen et al 1999; Asplund et al 2001, 2004)



But the standard expectation is ${}^6\text{Li}/{}^7\text{Li} \sim 10^{-5}$!

1D, LiI, HD84937



The ‘detection’ of ${}^6\text{Li}$ is based on detailed fits to the lineshape ... need more data to establish this

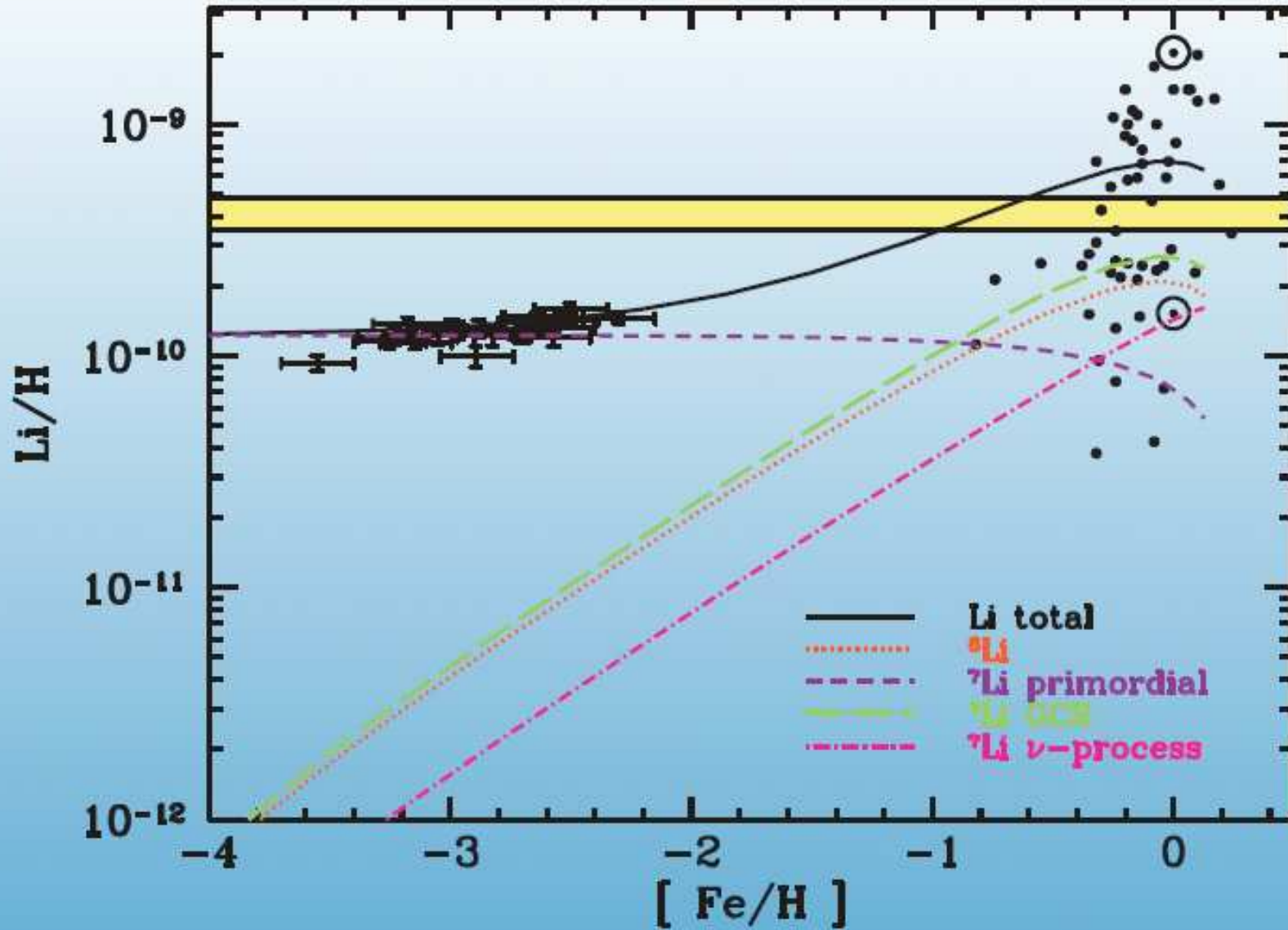
The Li I 6707 Å resonance doublet in HD 84937 from Smith et al. (1993). The wavelengths of the ${}^7\text{Li}$ and ${}^6\text{Li}$ are indicated at the top of the figure. Synthetic profiles for three ${}^6\text{Li}/{}^7\text{Li}$ ratios are shown – courtesy of Martin Asplund.

Stars in which ${}^6\text{Li}$ 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 $[\text{Fe}/\text{H}] < -1.7$. Filled symbols denote stars with a detection of ${}^6\text{Li}$ 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).

- Observations based on
 - “old”: $\text{Li}/\text{H} = 1.2 \times 10^{-10}$ Spite & Spite +
 - Balmer: $\text{Li}/\text{H} = 1.7 \times 10^{-10}$ Molaro, Primas & Bonifacio
 - IRFM: $\text{Li}/\text{H} = 1.6 \times 10^{-10}$ Bonifacio & Molaro
 - IRFM: $\text{Li}/\text{H} = 1.2 \times 10^{-10}$ Ryan, Beers, KAO, Fields, Norris
 - $\text{H}\alpha$ (globular cluster): $\text{Li}/\text{H} = 2.2 \times 10^{-10}$ Bonifacio et al.
 - $\text{H}\alpha$ (globular cluster): $\text{Li}/\text{H} = 2.3 \times 10^{-10}$ Bonifacio
 - $\lambda 6104$: $\text{Li}/\text{H} \sim 3.2 \times 10^{-10}$ Ford et al.
- Li depends on T, $\ln g$, $[\text{Fe}/\text{H}]$, depletion, post BBN-processing, ...
- Strong systematics



BBN versus CMB

η_{BBN} is in *agreement* with η_{CMB}

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

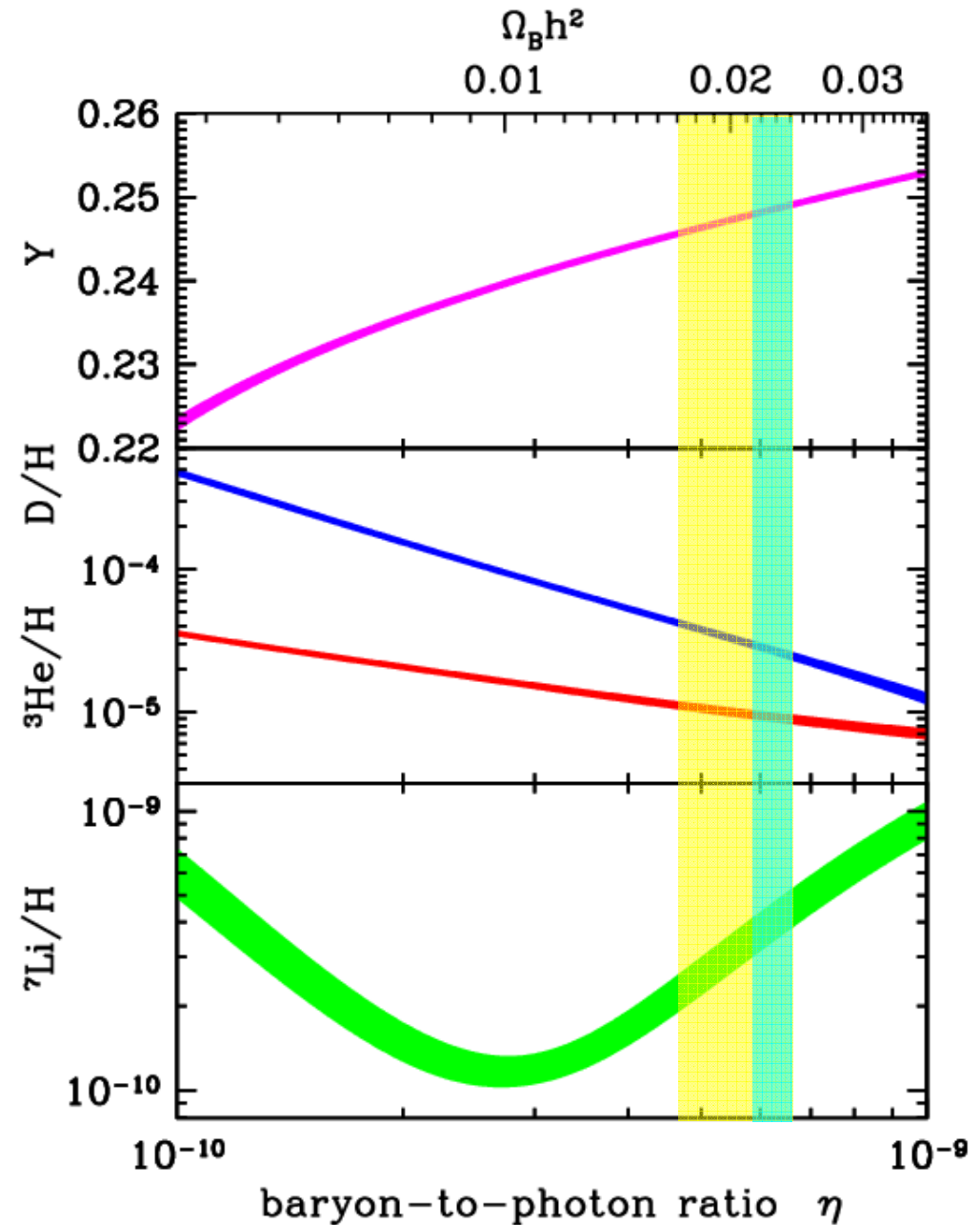
Baryonic Dark Matter:

warm-hot IGM, Ly- α , X-ray gas ...

+

Non-baryonic dark matter:

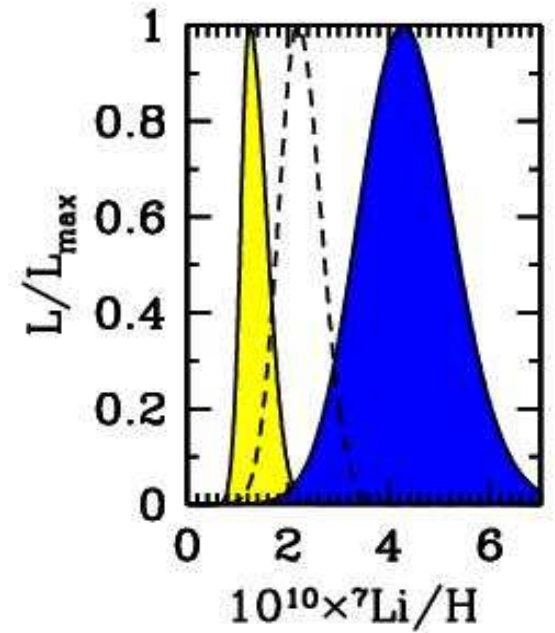
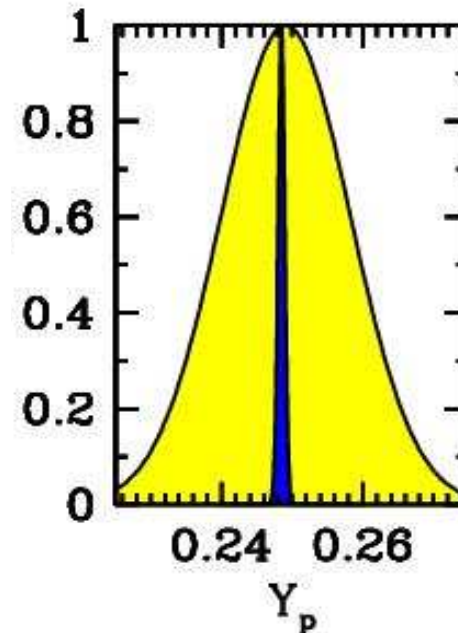
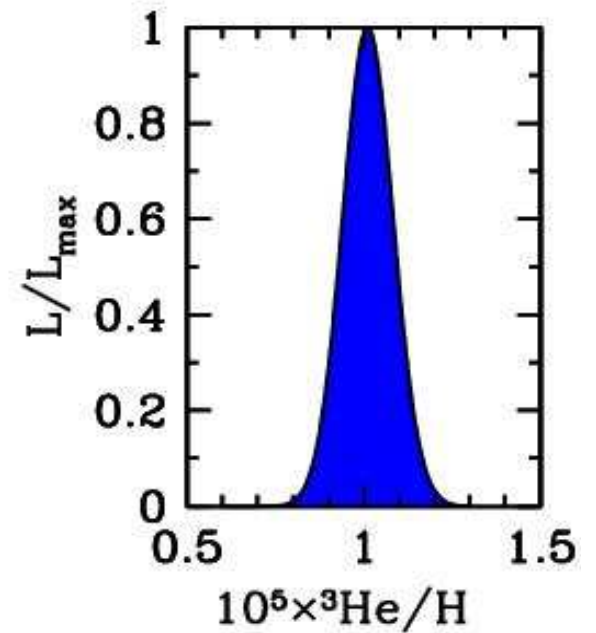
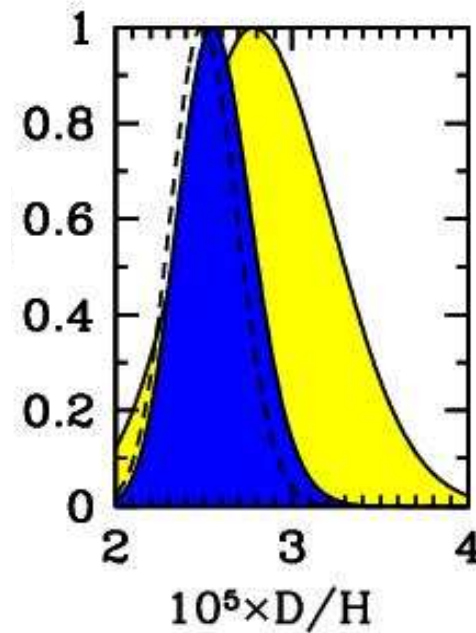
neutralino? axion? ...

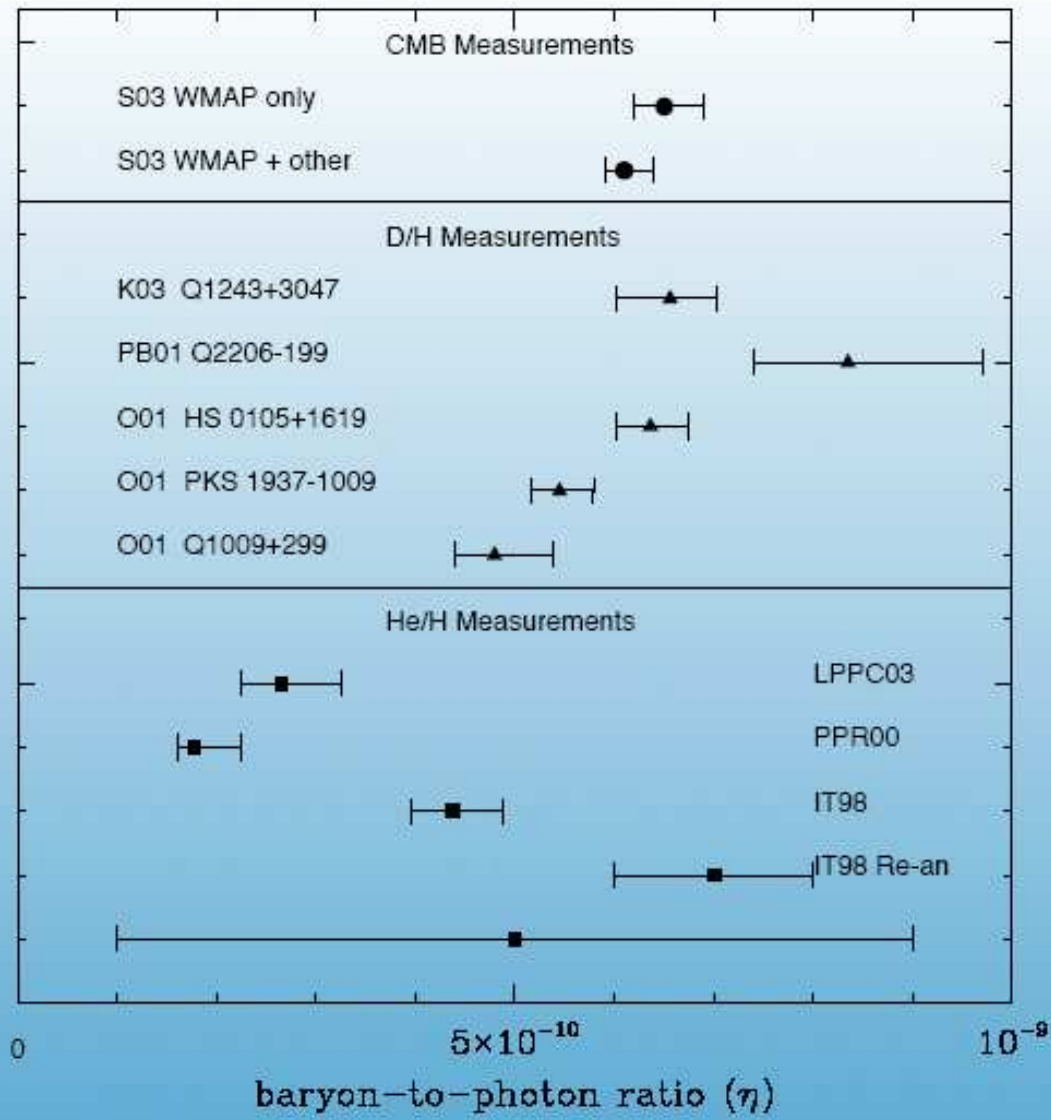


... in more detail

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

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





Courtesy: Keith Olive

Lithium Systematic Errors

Observational systematics

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

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

Astrophysical systematics

Stellar depletion over $\sim 10^{10}$ yr ... if Li burned need to correct Li_p *upward*
But *no* scatter seen around “Spite plateau” - also ${}^6\text{Li}$ preserved

Ryan *et al* (2000)

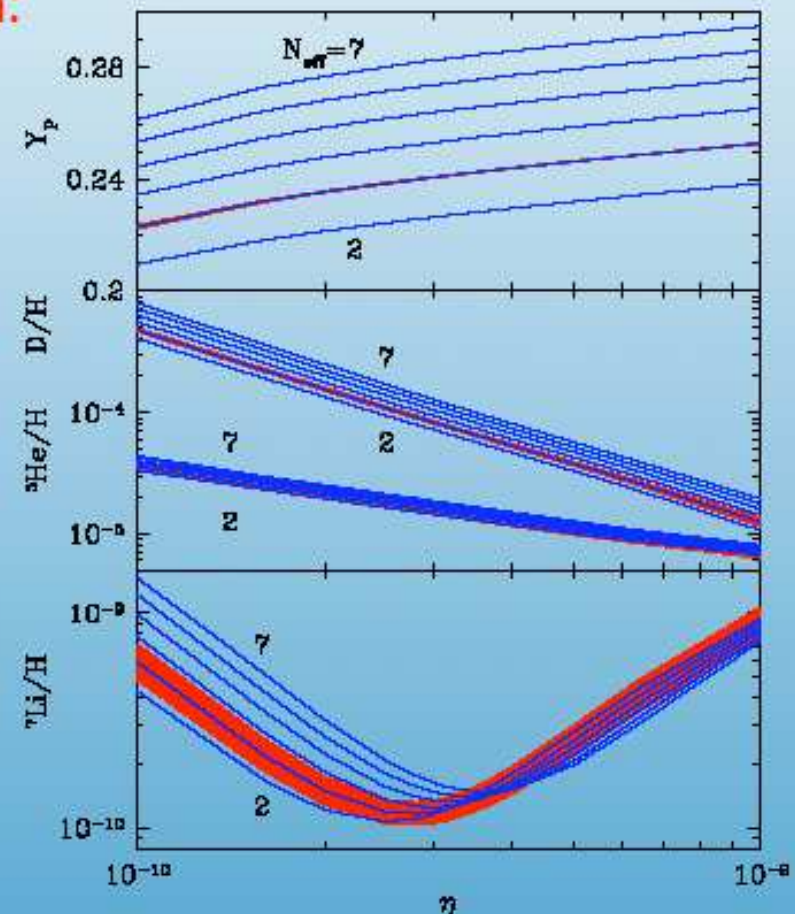
Nuclear Systematics

${}^7\text{Li}$ production channel - ${}^3\text{He} (\alpha, \gamma) {}^7\text{Be}$ - normalization error?
But same reaction also key for Solar neutrinos ... standard Solar model OK!

Cyburt, Fields & Olive (2004)

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



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 abundance

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

Sets constraints on G_F , G_N , N , etc.

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

Conversely obtain bound of < few % on any additional contribution to energy density driving expansion ... e.g. rules out Λ of $O(H^2)$ *always*

Example: “Neutrino Counting”

Element abundances sensitive to expansion history during BBN

⇒ observed values constrain relativistic energy density

$$H^2 \sim G\rho_{\text{rel}} \quad \rho_{\text{rel}} \equiv \rho_{\text{EM}} + N_{\nu, \text{eff}} \rho_{\nu\bar{\nu}}$$

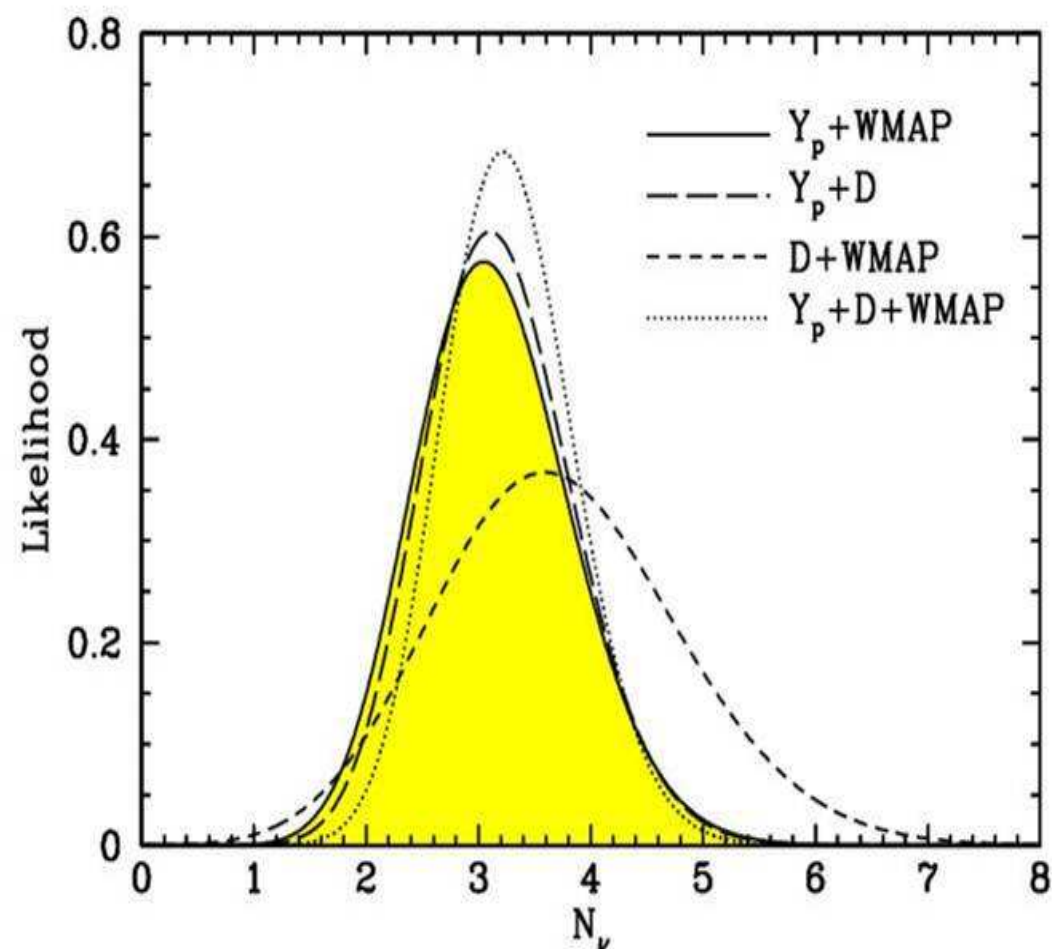
(Hoyle & Taylor 1964, Peebles 1966; Shvartsman 1969; Steigman, Schramm, & Gunn 1977)

Pre-CMB:

^4He as probe, other elements give η

With η from CMB:

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



Cyburt, Fields, Olive & Skillman (2004)

$$\delta N_\nu = N_\nu - 3 < 1.6$$

so singlet neutrino (cf. LSND) is *allowed*

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:

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

BBN and Decaying Particles

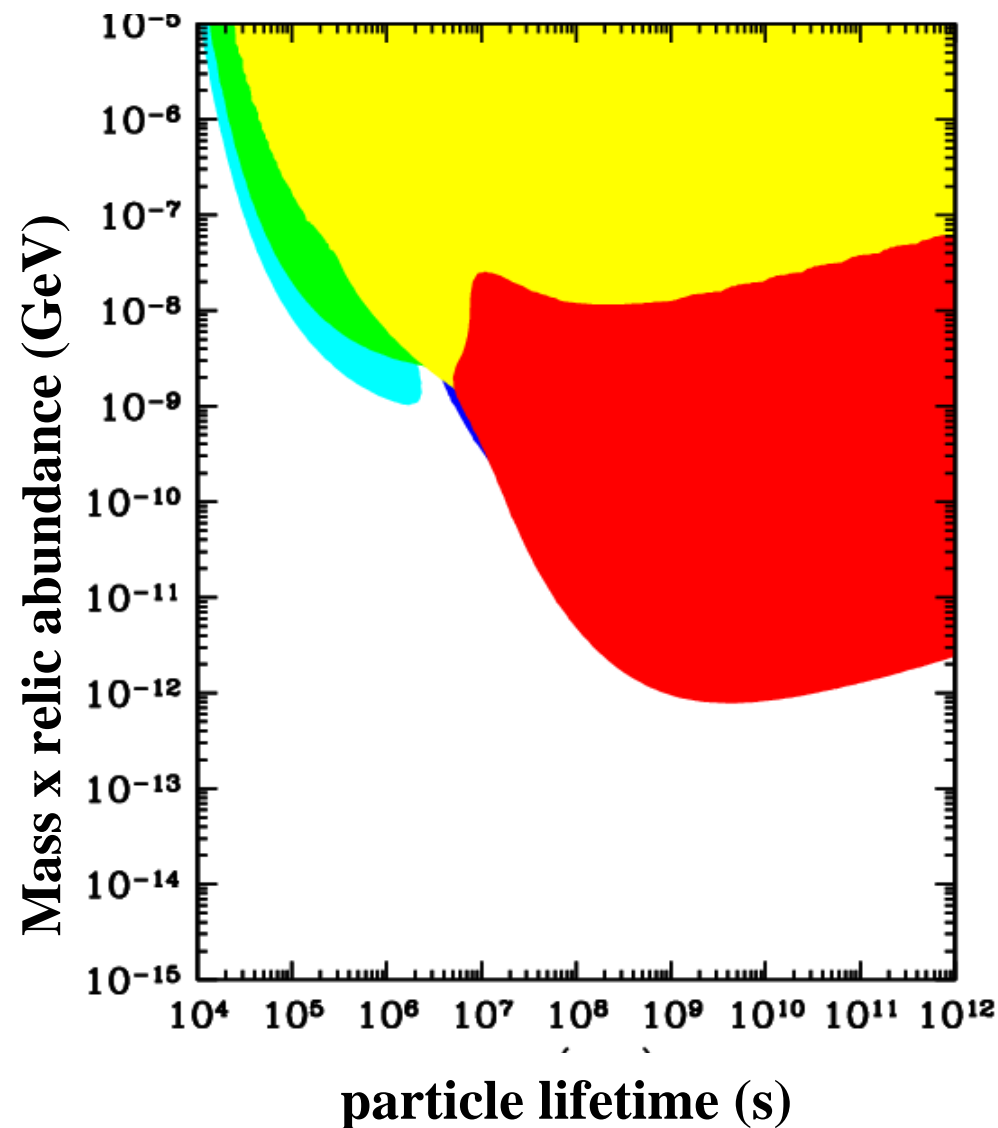
Extensions of the Standard Model predict new, (typically) *unstable* particles, which would have been created (thermally) in early Universe, e.g. TeV mass gravitinos in supergravity

$$\tilde{G} \rightarrow \gamma\gamma \quad \tau_{3/2} \approx 4 \times 10^5 \text{ s} \left(\frac{m_{3/2}}{1 \text{ TeV}} \right)^{-3}$$

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

The high energy photons would have photodissociated the synthesized elements \Rightarrow severe limits on decaying particle abundance as a function of its lifetime

This implies that the highest temperature reached in our past (after inflation) was $< 10^8$ GeV - constraint on baryogenesis!



Does the Lithium anomaly imply new physics?

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

Summary

Observational inferences about the primordially synthesised abundances of D, ^4He and ^7Li 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 ^4He 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 gross deviations from the usual expansion history (e.g. additional neutrinos or dark energy)

However anomalies in the abundances of ^6Li and ^7Li 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 still marks the final frontier as we look back to the Big Bang!