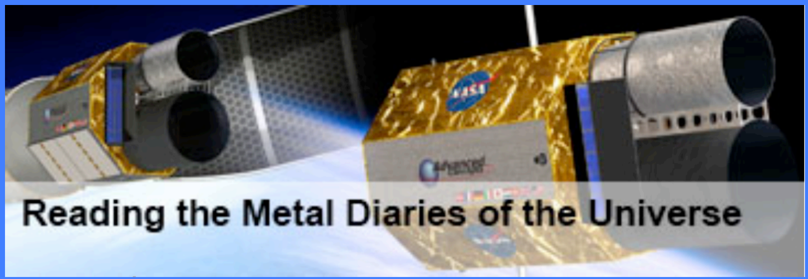
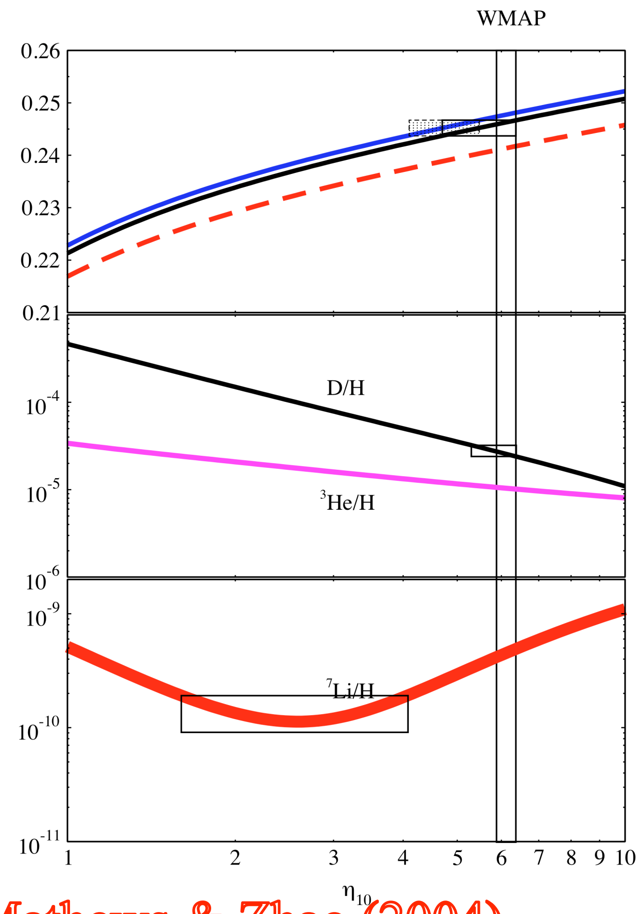
Big Bang Nucleosynthesis and Early Star Formation

G. J. Mathews
- University of
Notre Dame



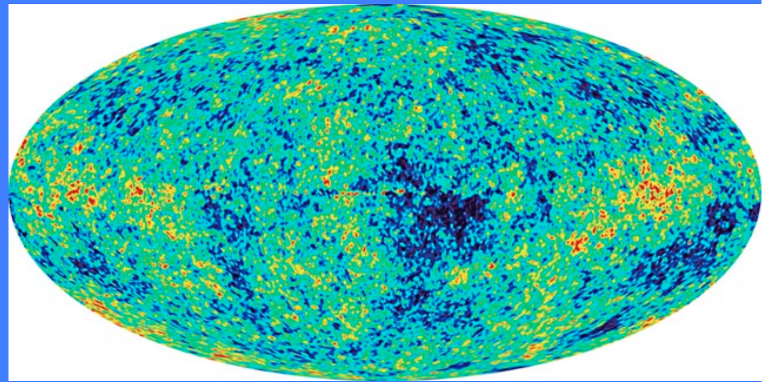


Mathews & Zhao (2004)

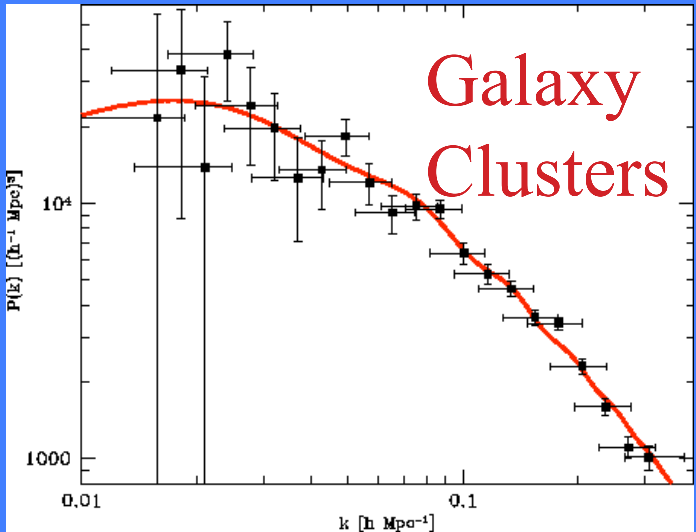
Xenia Cosmic Chemical Evolution Workshop

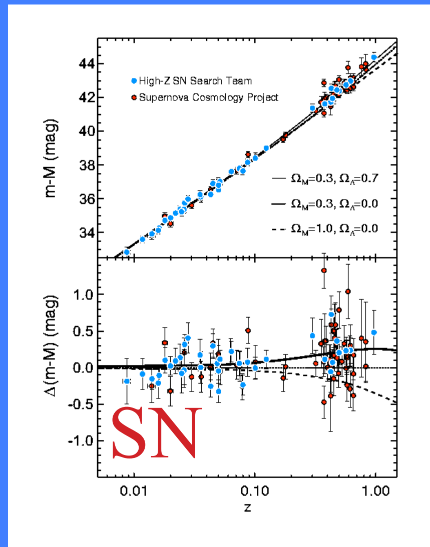
St. Michaels, MD June 2-4, 2010

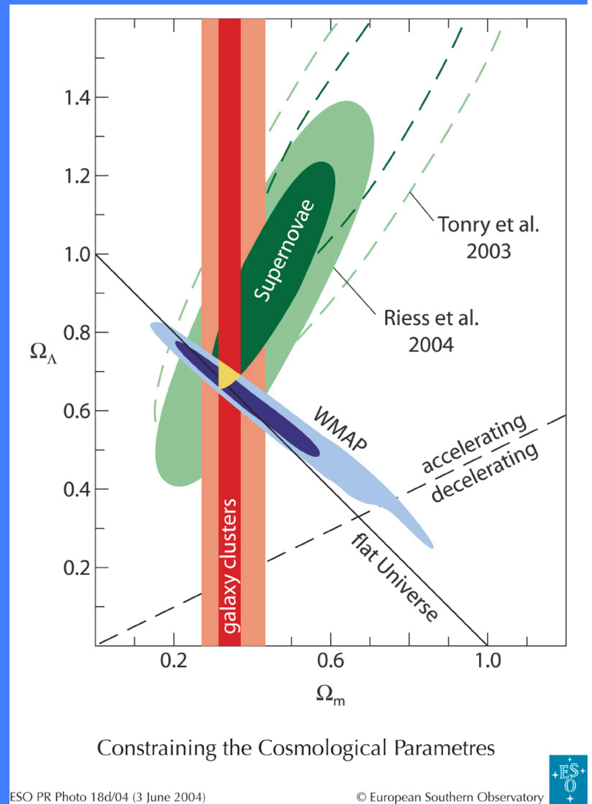
We are in the Age of Precision Cosmology



- Baryons - $\Omega_b = 0.045 \pm 0.003$
- Dark Matter - $\Omega_{CDM} = 0.22 \pm 0.03$
- Dark Energy - $\Omega_\Lambda = 0.73 \pm 0.03$

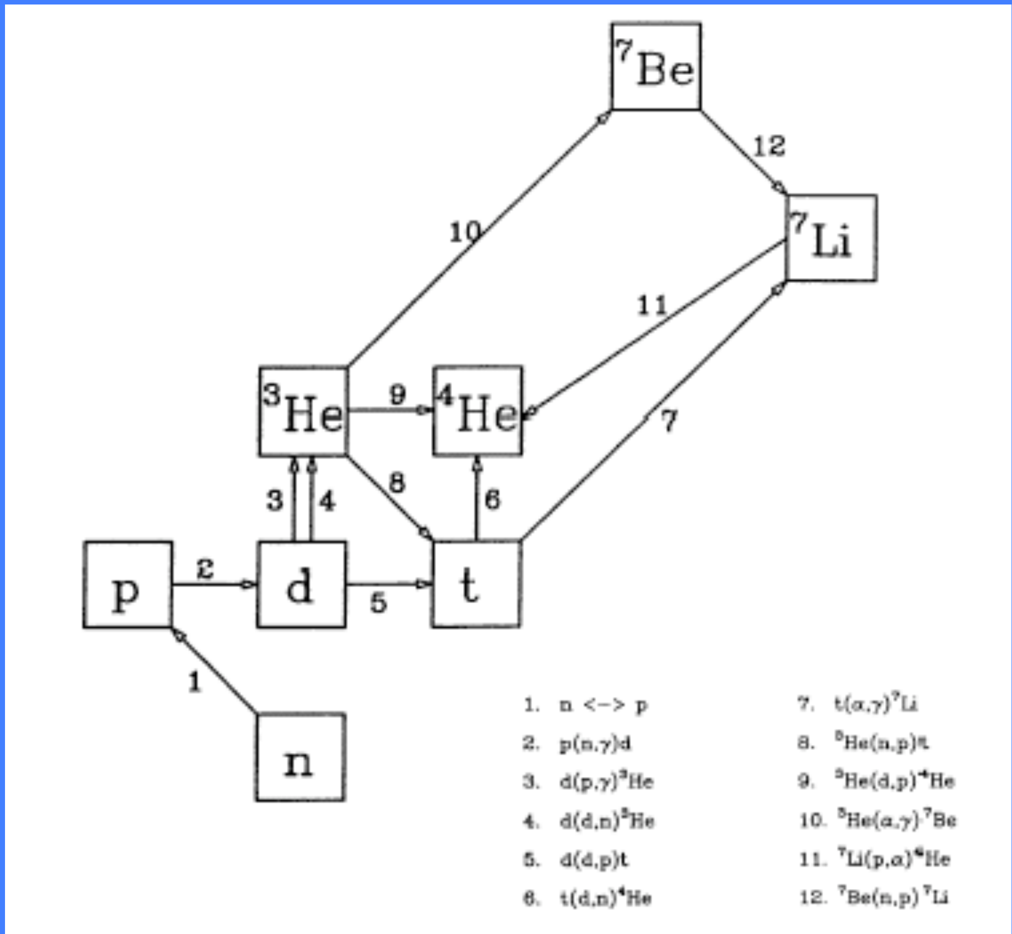






- Now is the time to look to for a deeper understanding

Why is Big Bang Nucleosynthesis Important?

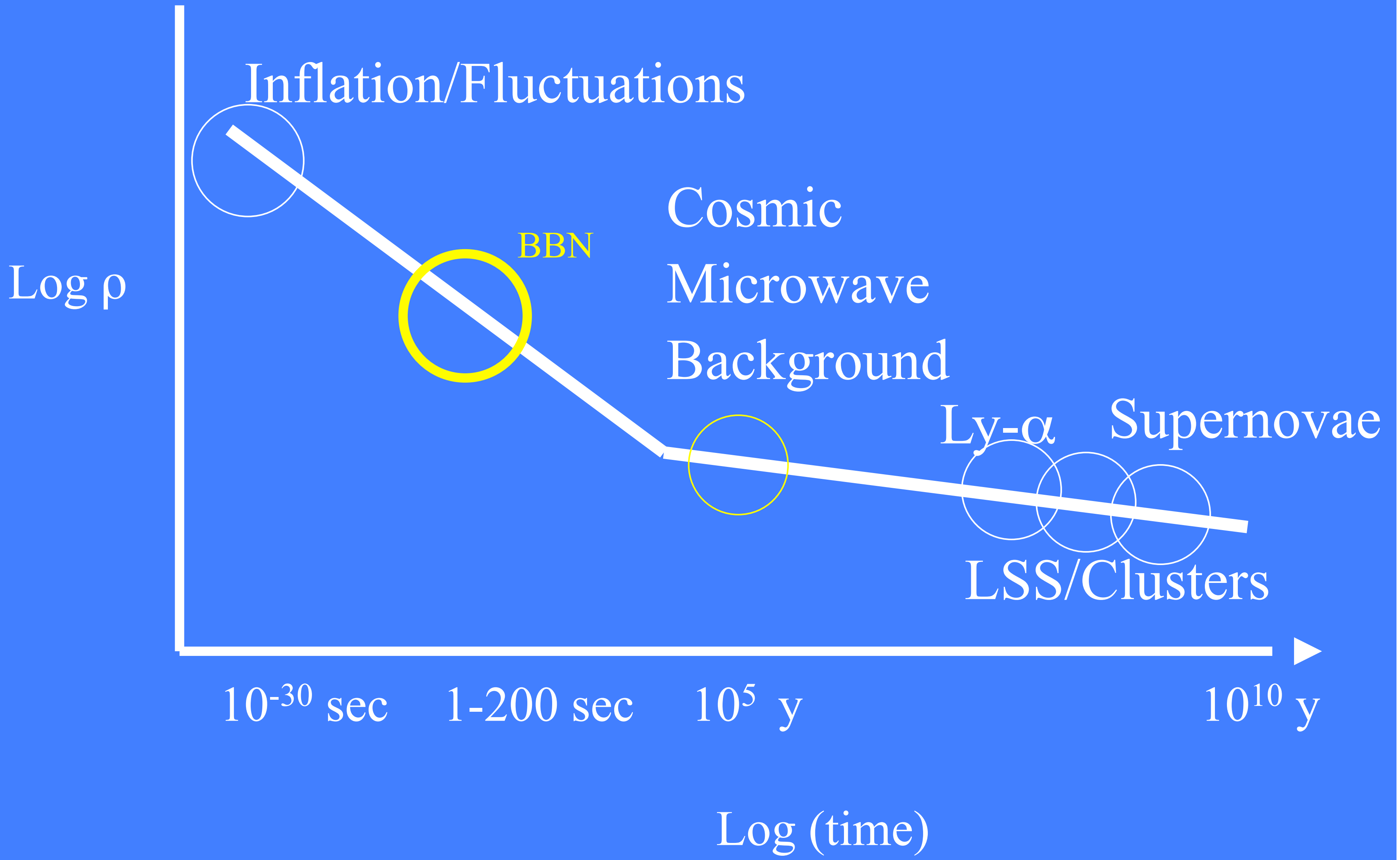


It is the only probe of the radiation dominated epoch

$t = 1 \rightarrow 10{,}000$ sec

$T = 10^{10} \rightarrow 10^{7}$ K

Cosmological probes



The Power of BBN is that the Physics is Accessible

- Expansion

$$H^2(t) = \left(\frac{1}{R}\frac{dR}{dt}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} - \frac{k}{R^2}$$

- Thermodynamic Equilibrium

$$n_i(p)dp = \frac{1}{2\pi^2} g_i\, p^2 \left[\exp\left(\frac{E_i(p) - \mu_i}{kT}\right) \pm 1\right]^{-1} dp$$

$$\rho_i = \int p\,[n_i(p) + n_{\bar{i}}(p)]\, dp$$

$$\rho_\gamma = \frac{\pi^2}{15}(kT_\gamma)^4 \quad , \quad \rho_{\nu_i} = \frac{7}{8}\frac{\pi^2}{15}(kT_\nu)^4$$

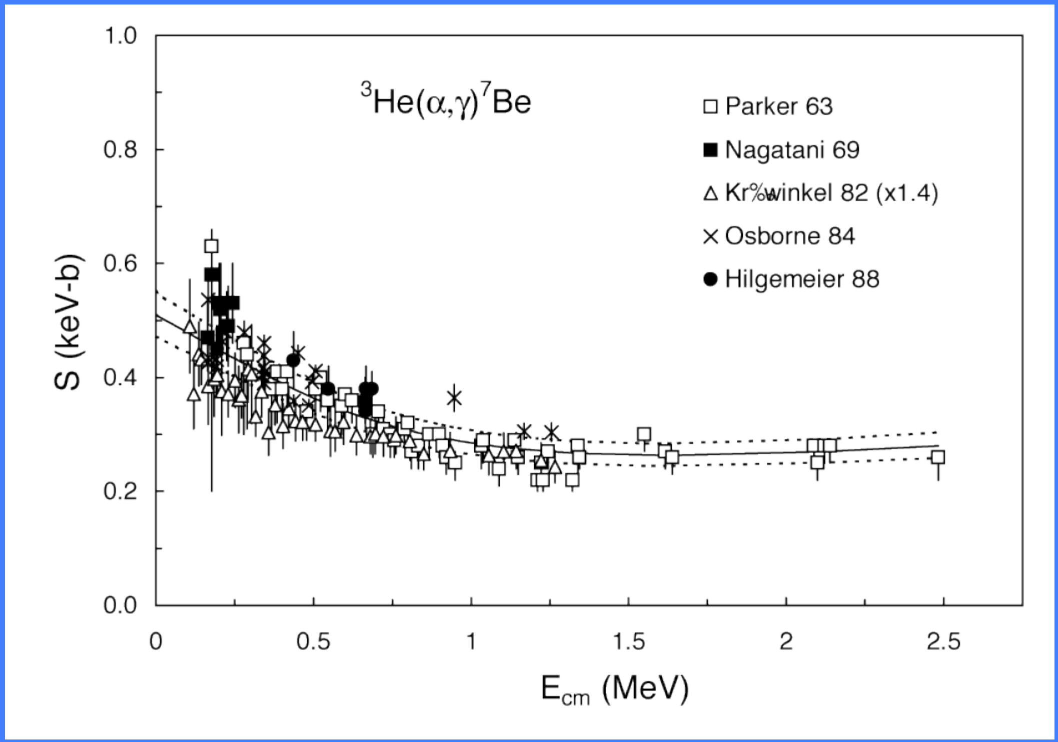
$$\rho = \rho_\gamma + \rho_{\nu_i} + \rho_i = \frac{\pi^2}{30} g_{eff}(kT)^4$$

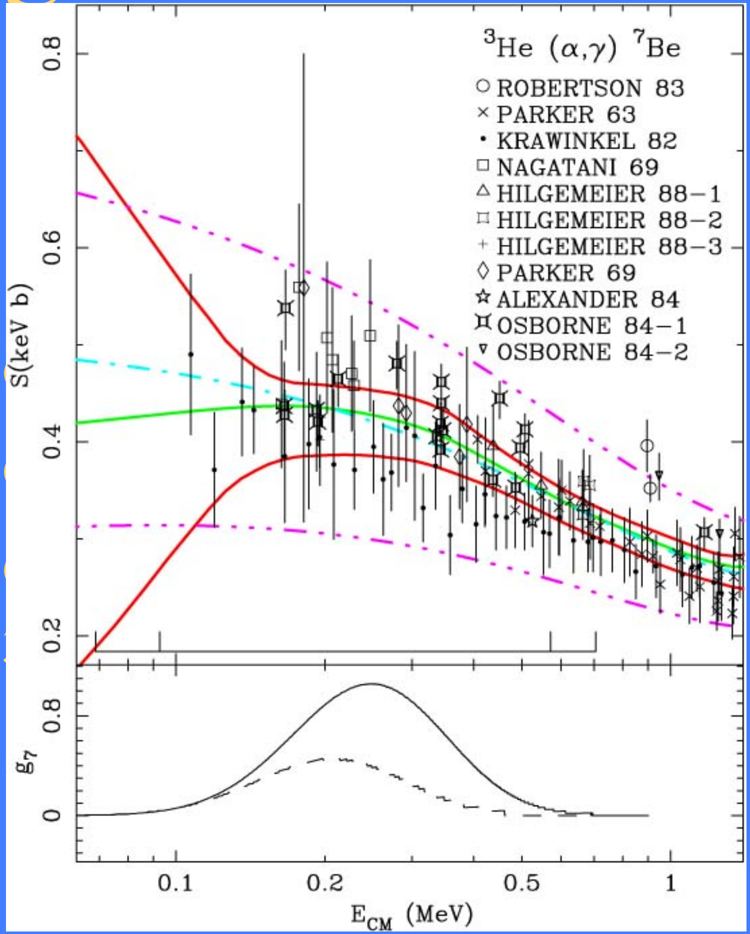
$$g_{\rm eff}(T) = \sum_{\rm bose} g_{\rm bose} + \frac{7}{8}\sum_{\rm fermi} g_{\rm fermi}$$

- Nuclear Reactions

$$\frac{dY_i}{dt} = \sum_{ijk} N_i \left(\frac{Y_l^{N_l} Y_k^{N_k}}{N_l! N_k!}\langle n_k \sigma_{lk} v\rangle - \frac{Y_i^{N_i} Y_j^{N_j}}{N_i! N_k!}\langle n_j \sigma_{ij} v\rangle\right)$$

BBN Nuclear Uncertainties are Improving



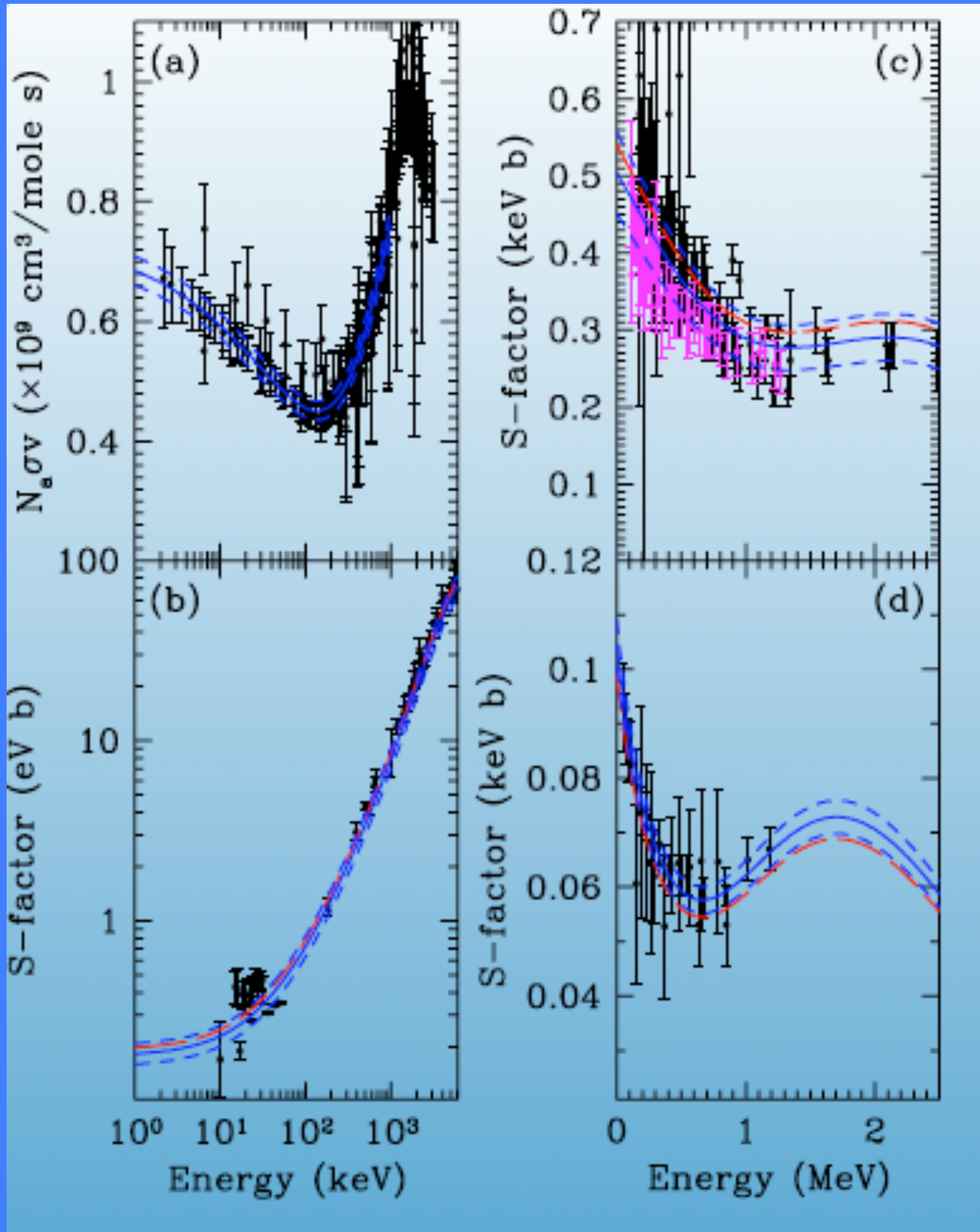


•Descouvemont, Adahchour, Angulo, Coc, Vangioni-Flam. ApJ, (2004)

•Nollett & Burles, PRD, 61, 123505 (2000)

Table 1: Key Nuclear Reactions for BBN

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



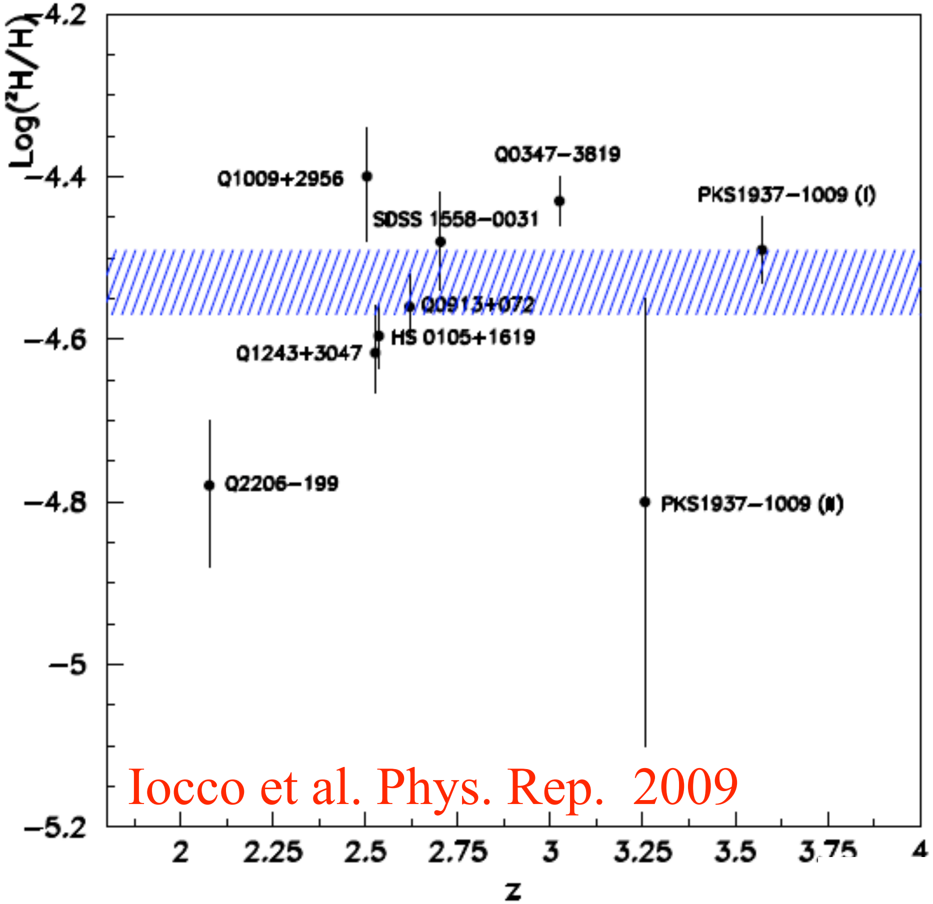
Cyburt et al. 2004

Key Issues of BBN and Cosmic Chemical Evolution:

- What are the primordial abundances?
  - Deuterium fluctuations/destruction
  - Primordial Helium Systematics
  - Stellar and galactic evolution of Li isotopes

Each species determined in a different environment
Each determination is plagued with systematic uncertainties

Primordial D/H

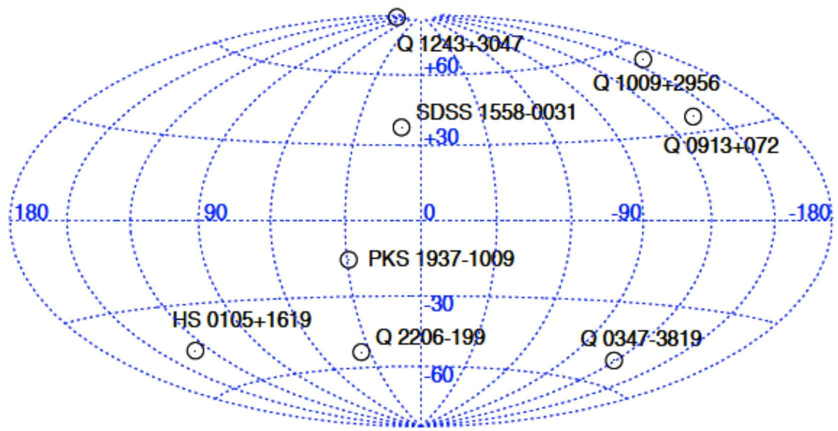


Iocco et al. Phys. Rep. 2009

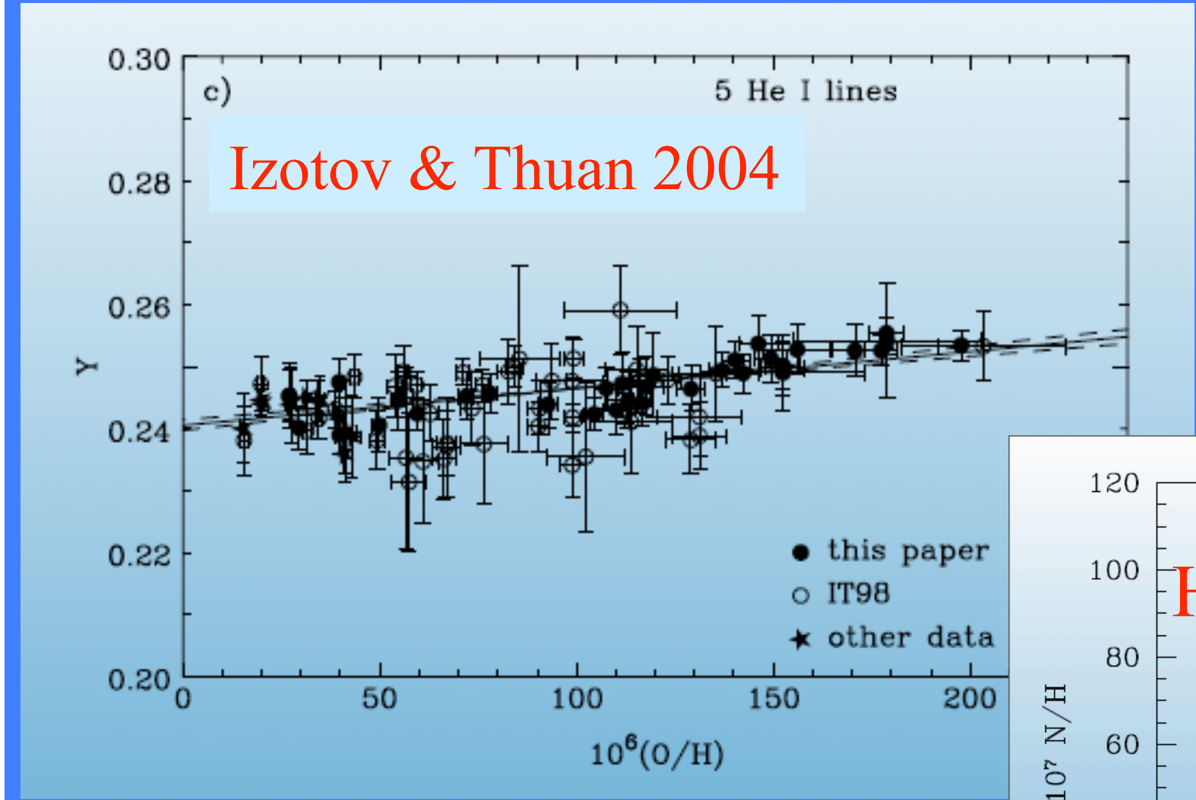
- Determined in narrow line quasar absorptions systems

- Only a handful with:
  - low vel. dispersion
  - low metallicity
  - Right col. Density
- Unexpectedly Large Dispersion

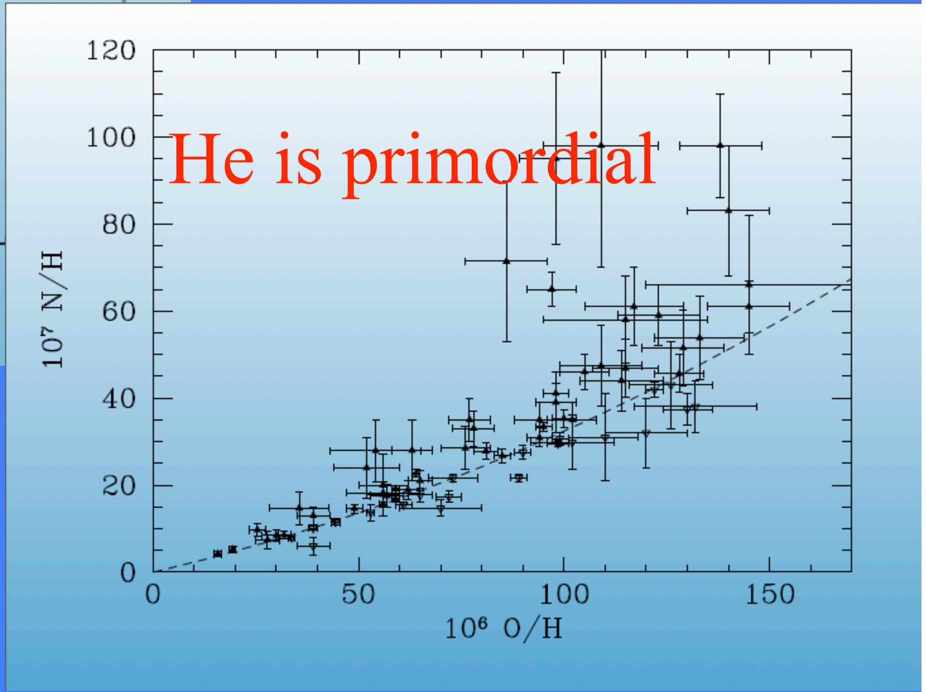
$$D/H = 2.87^{+0.22}_{-0.21} \times 10^{-5}$$



Primordial Helium Abundance?



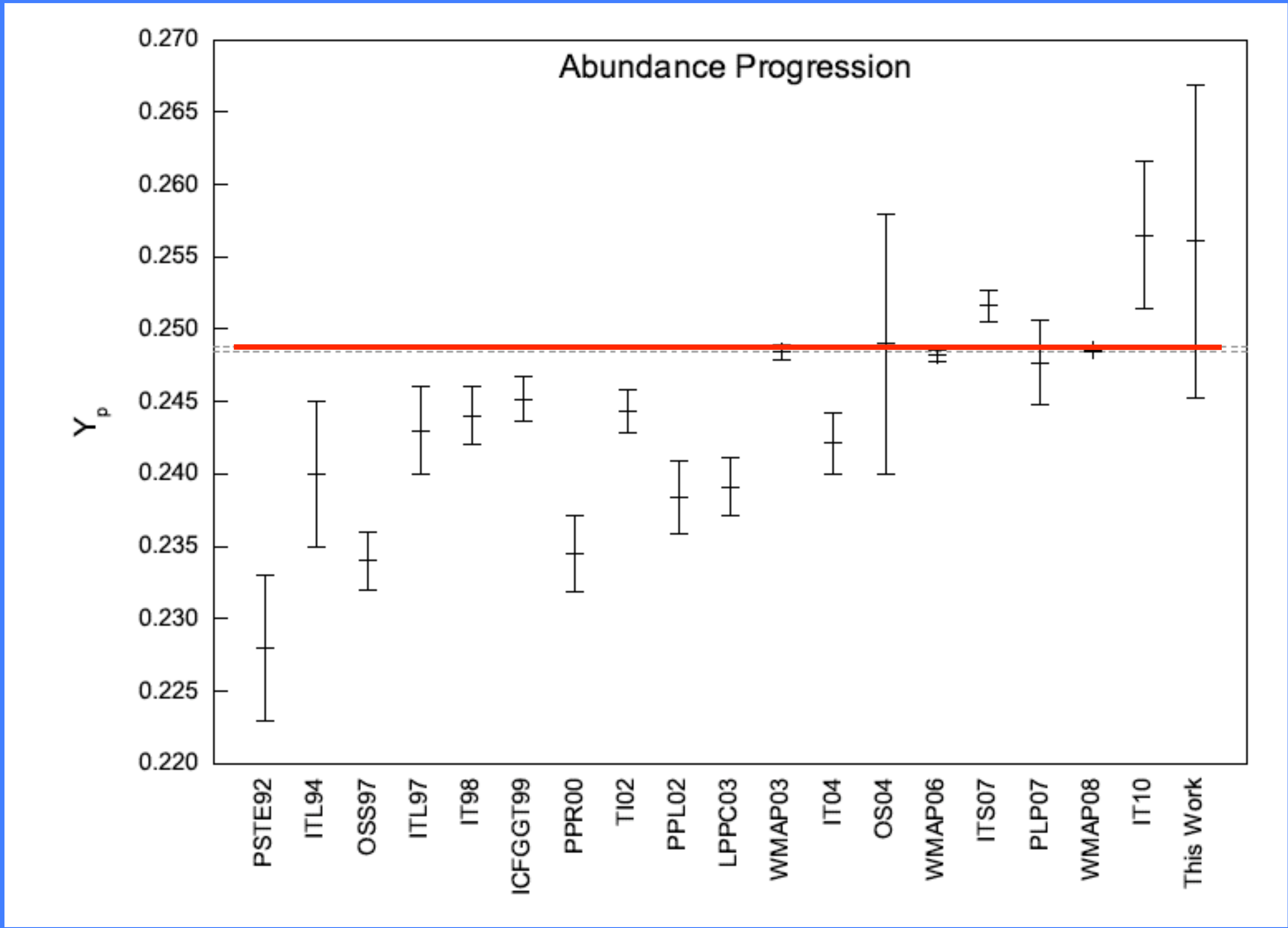
Determined in HII regions in low-metallicity irregular/ Blue Compact galaxies



$Y_p = 0.247 \pm 0.002 \pm 0.004$

Iocco et al. Phys. Rep. 2009

Problem: Inferred Y_p has grown with time

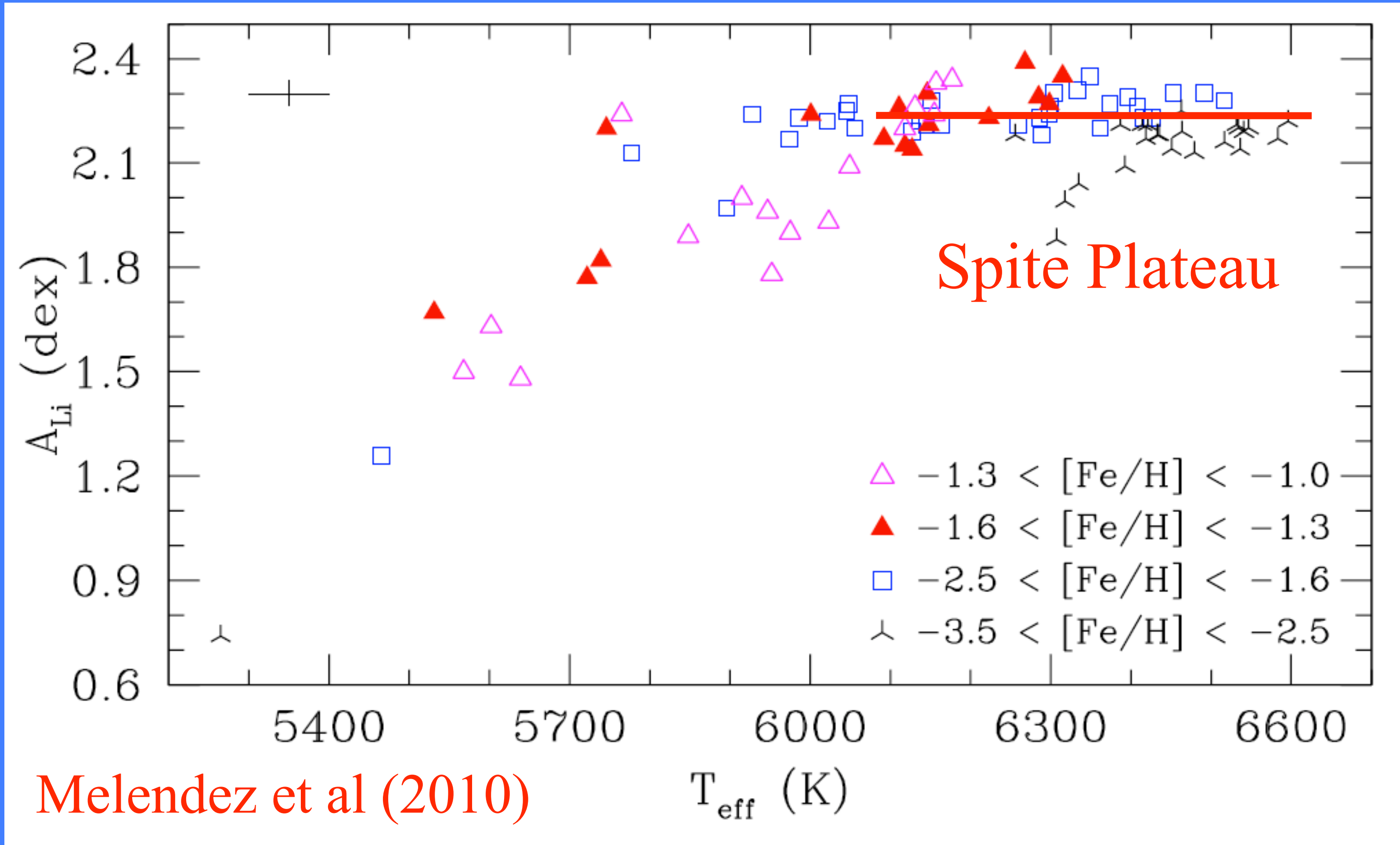


WMAP

Ayer, Olive, Skillman (2010)

Primordial Lithium Abundance

Determined from metal poor stars in the Galactic Halo

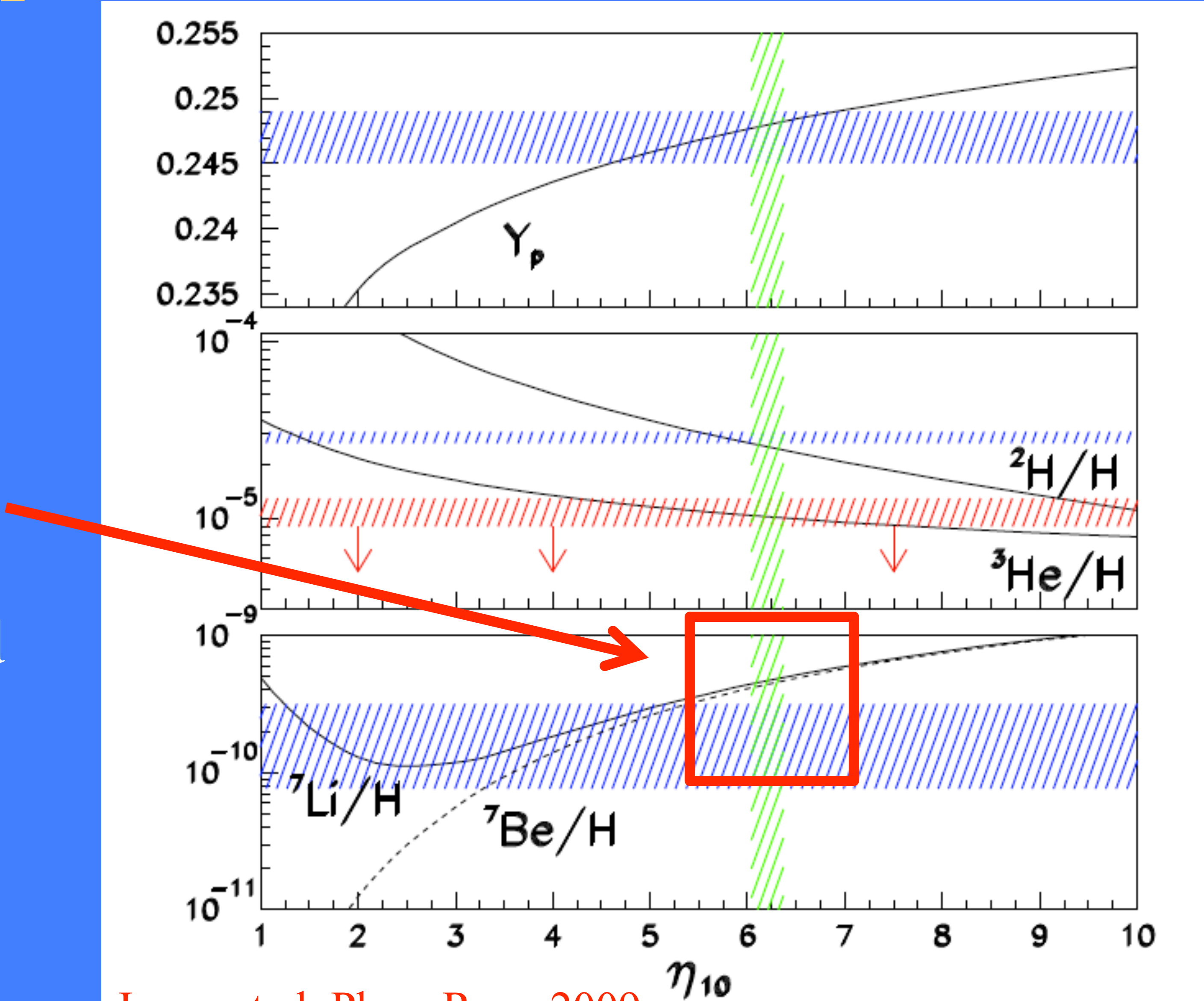


$$7Li/H = 1.86^{+1.30}_{-1.10} \times 10^{-10}$$

Uncertainty from Li depletion in stars

Comparison with Observations

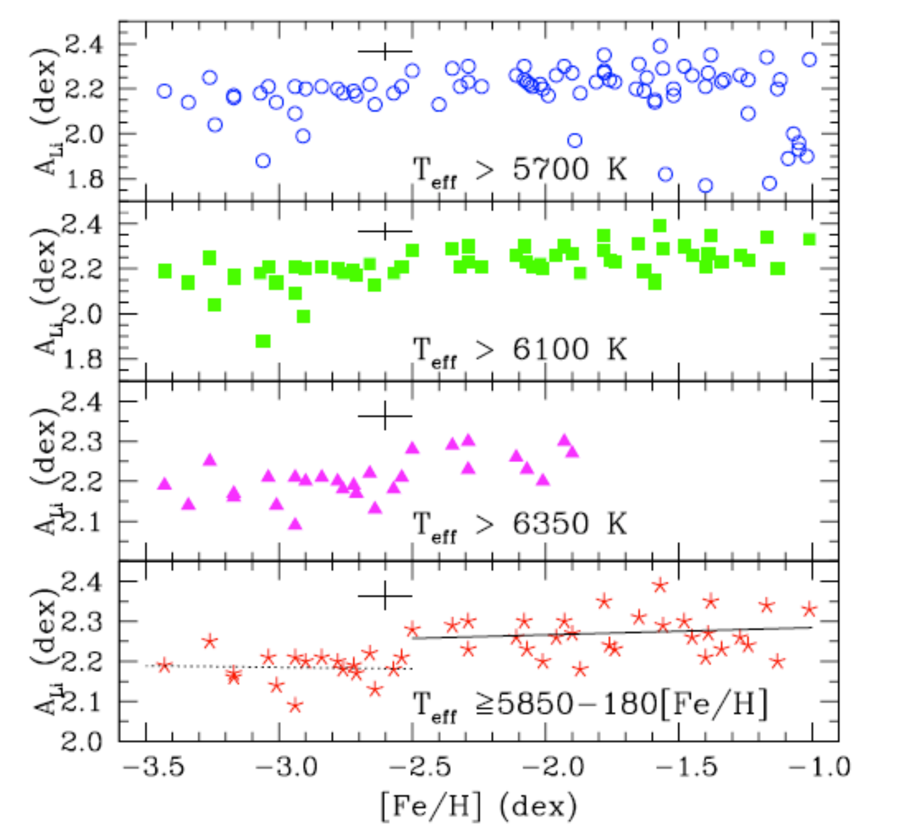
Predicted
Lithium
3x Observed



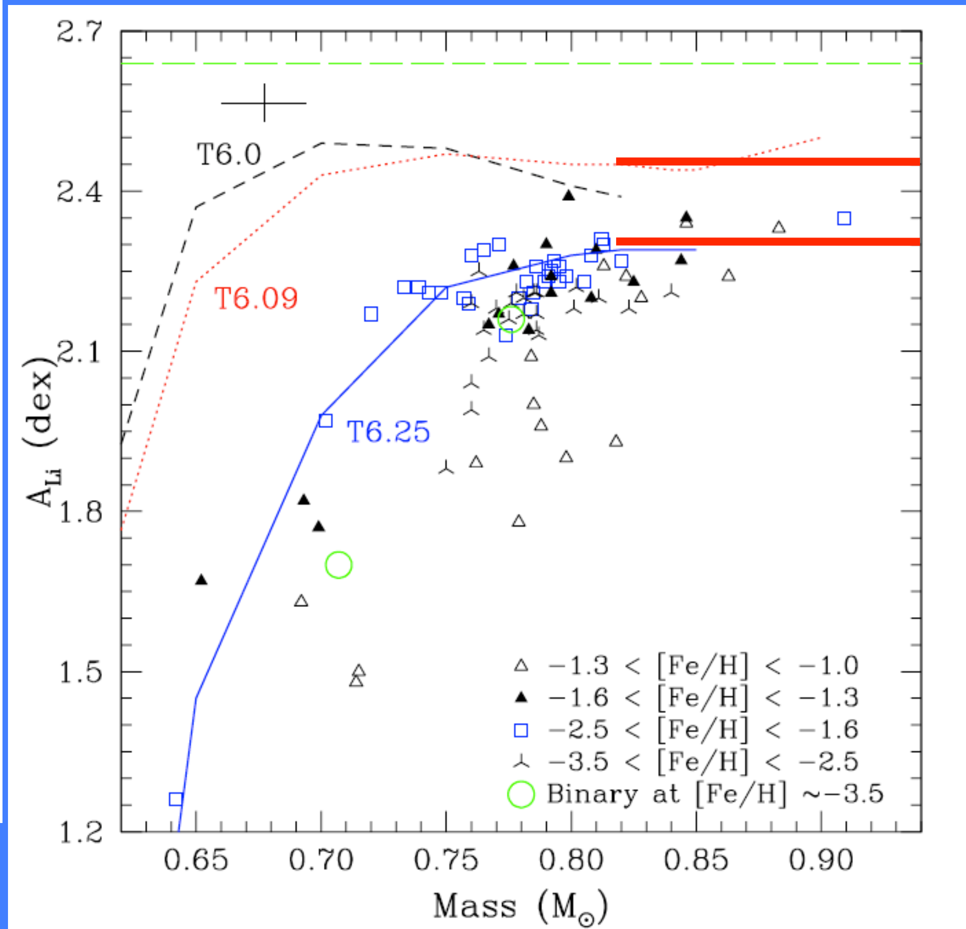
Iocco et al. Phys. Rep. 2009

Has Lithium Been Depleted in Halo Stars?

Plateau changes with Mettalicity



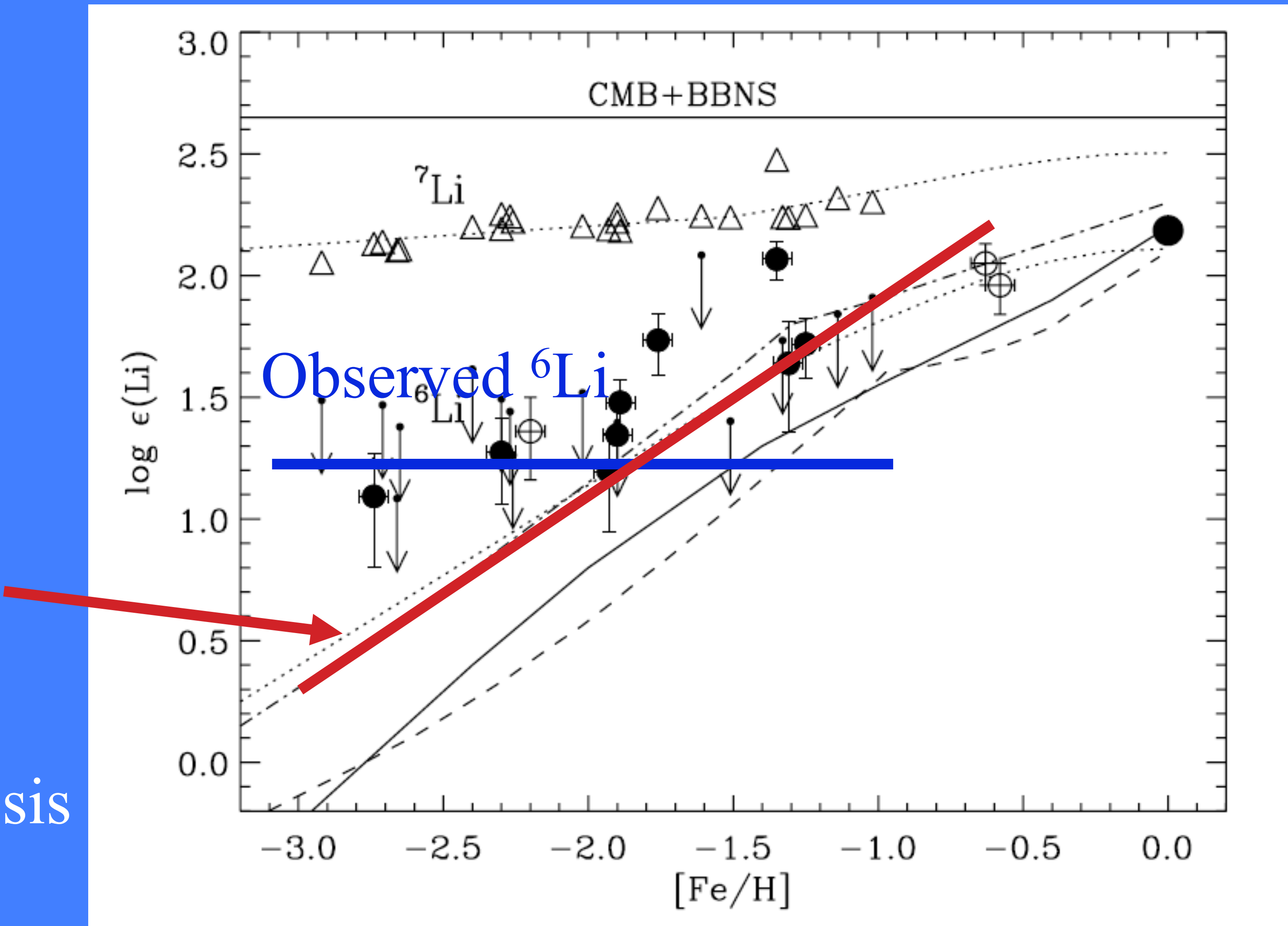
Models



Melendez et al. 2010

Puzzle of ^{6}Li

Asplund, et al. ApJ, 644, 229 (2006)



Expected ^{6}Li
Cosmic-ray
Nucleosynthesis

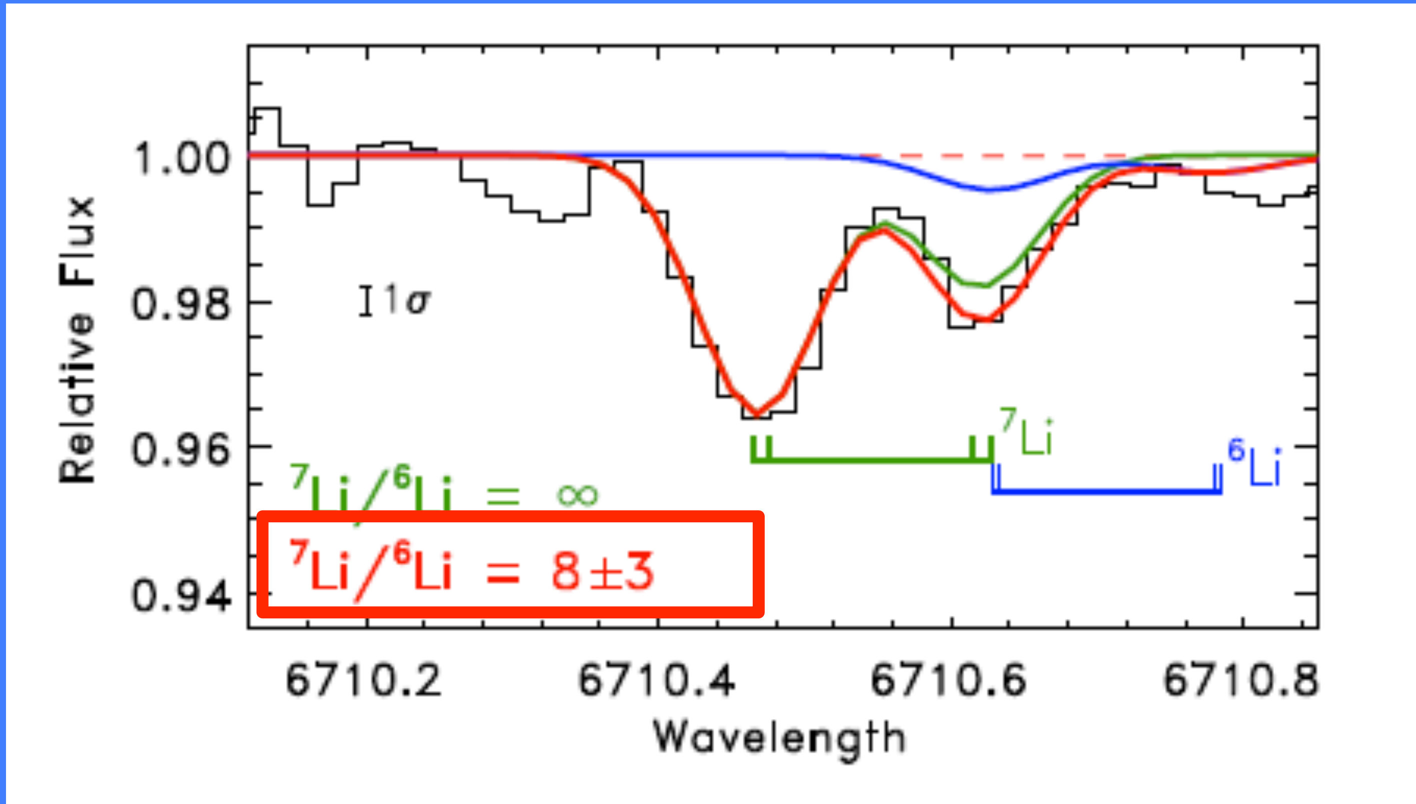
Has ^{6}Li been detected?

Asplund & Lind (2010)

- Not yet certain
- NLTE/3D effects may account for some detections
- does not explain away all stars

A possible solution

- Search for Li Absorption in low-metallicity clouds



- ^{6}Li in the SMC

Howk, Lehner, Fields, Mathews (2010)

Problems

- Is there an obsered underabundance of ^{7}Li
- Overabundance of ^{6}Li (+Y_P?)

Is This Evidence of New Cosmology?

- Extra Dimensions/Dark Radiation?
- Cosmic Quintessence?
- Time Varying Constants?
- Decaying Planck-Mass and/or SUSY Particles?
- Early Galactic Evolution effects?

^{6}Li cannot be made in the standard Big Bang?

$\alpha + d \rightarrow {}^{6}Li + \gamma$ (E2) Suppressed

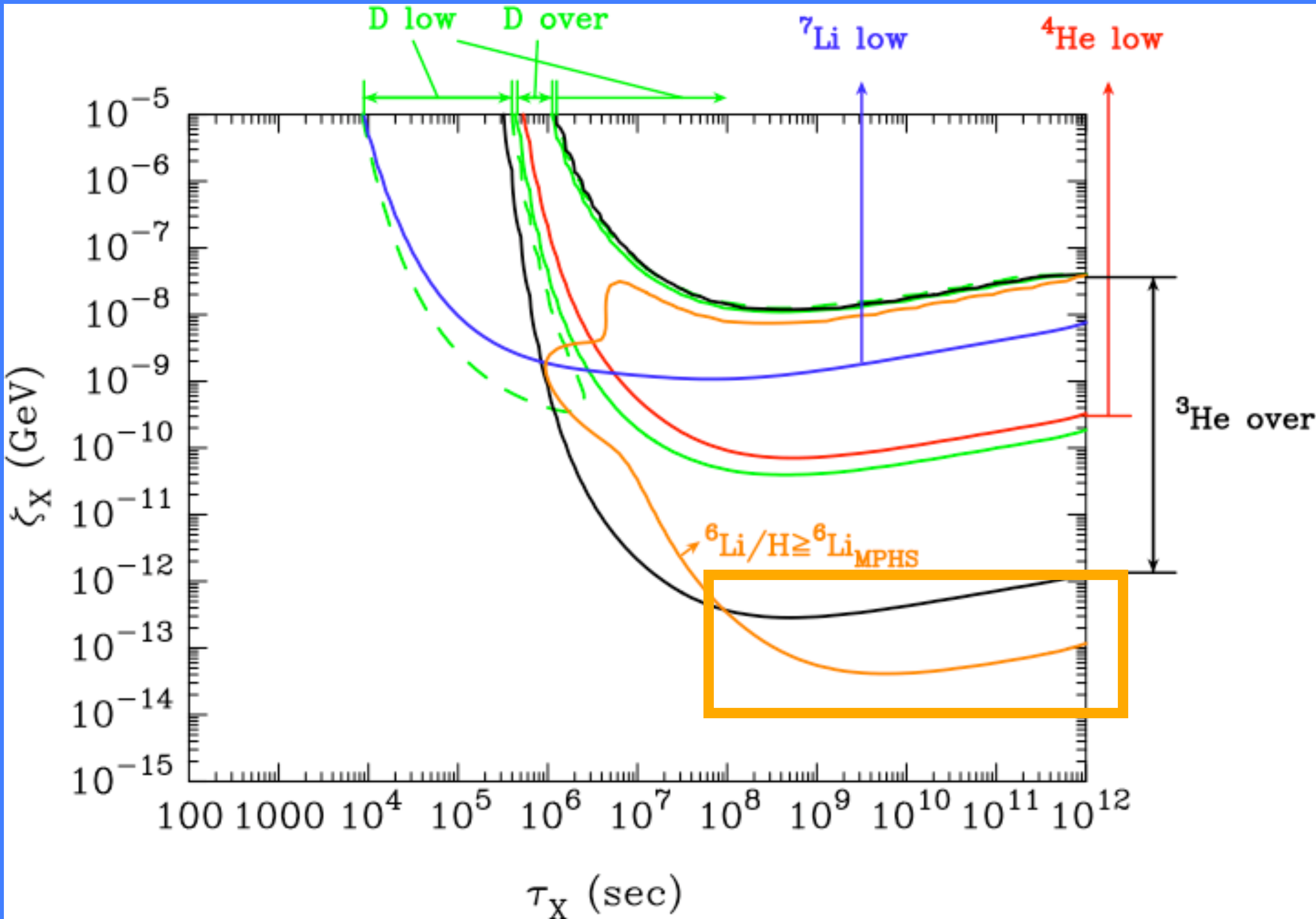
Possible means to produce ^6Li

1. Enhanced cosmic ray $\alpha+\alpha \rightarrow {}^6Li, {}^7Li$
   - Modifies other CR abundances
2. Nonthermal Production from decaying heavy SUSY particles
   - Difficult to satisfy other light element constraints
3. Catalyzed by negatively-charged SUSY particles
   - Possible?

^{6}Li Production by the Radiative Decay of Massive Particles

Kusakabe, Kajino, Mathews, PRD 74, 023526 (2006)

Energy injection ⇒Nonthermal $^{3}H(\alpha,n)^{6}Li$, $^{3}He(\alpha,p)^{6}Li$



The X^- solution to the ^{6}Li and ^{7}Li problems

Cyburt 2006; Kiplinghat & Rajaraman 2006; Kohri & Takayam 2006; Pospelov 2006;Hamaguchi et al. 2007; Bird et al. 2007; Kusakabe, Mathews, et al. PRD (2008); PRD (2010).

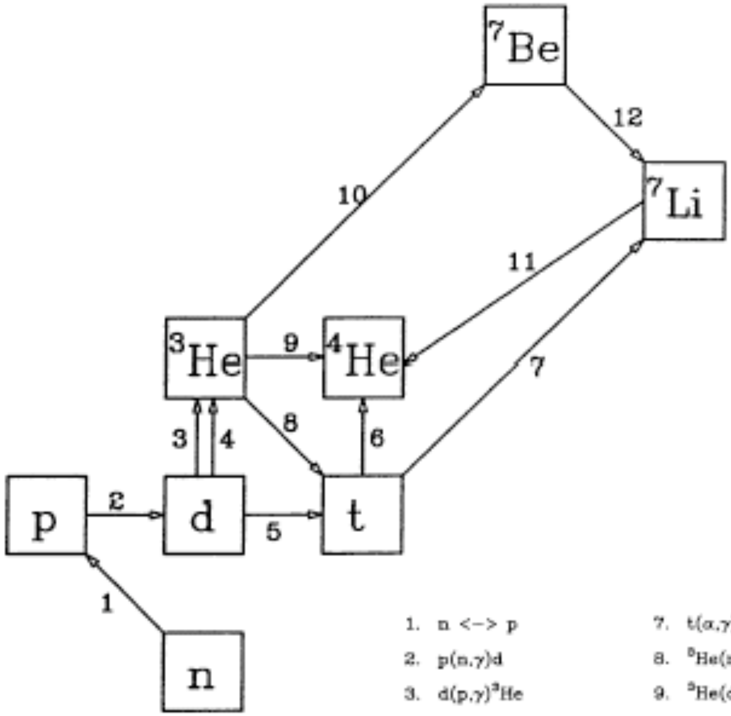
$X^+ + X^-$ pairs should be produced in the early universe
e.g. X = supersymmetric *stau* **NLSP**

$X^- + (A,Z) \rightarrow$ lower coulomb barrier

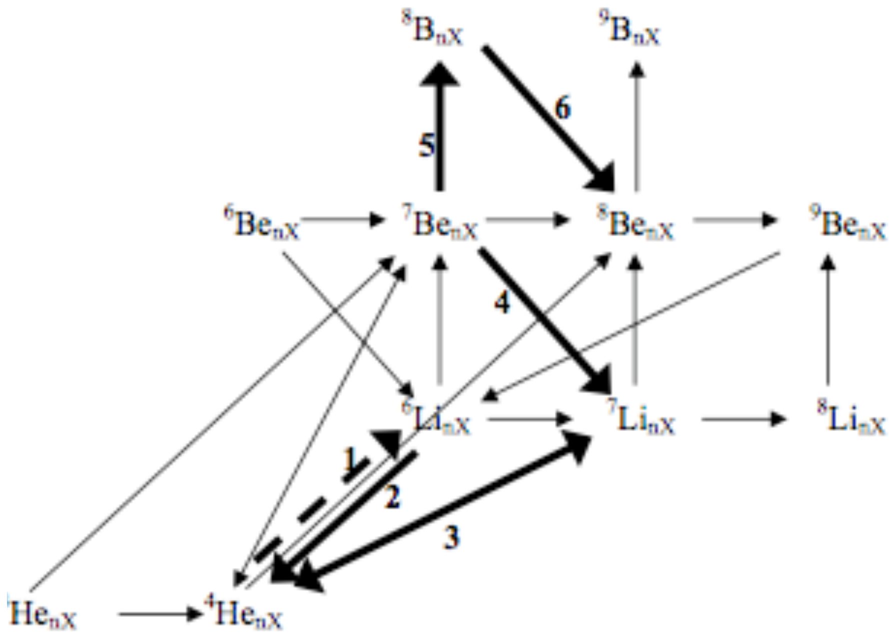
^{4}He (d, γ) ^{6}Li $\rightarrow$ ^4He_X (d, X^-) ^{6}Li => production

$^7Be_X(p,\gamma)^8B^*_X$ => ^{7}Li destruction

Modified Nuclear Reaction Network

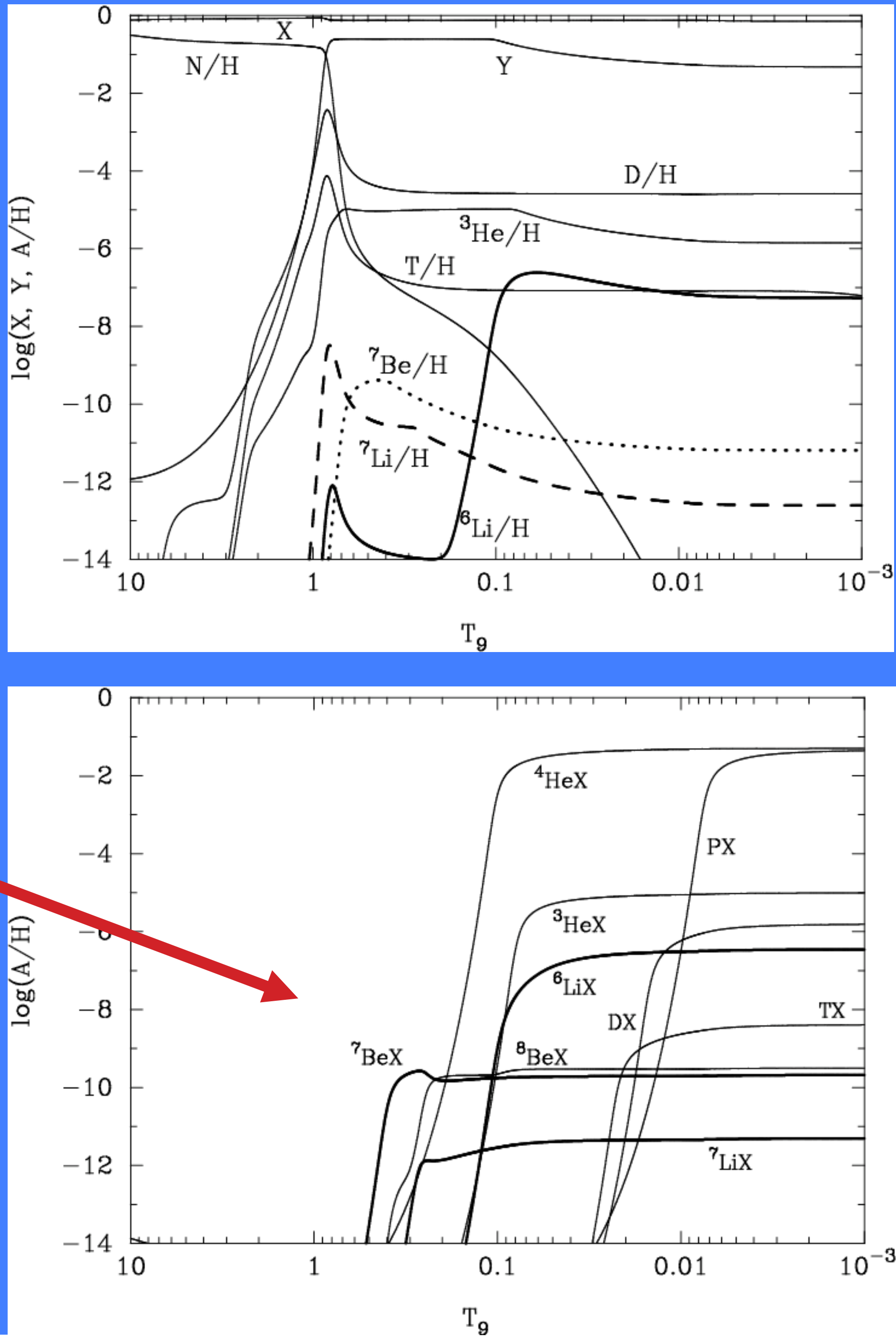


1. $n <-> p$
2. $p(n,\gamma)d$
3. $d(p,\gamma)^3He$
4. $d(d,n)^3He$
5. $d(d,p)t$
6. $t(d,n)^4He$
7. $t(\alpha,\gamma)^7Li$
8. $^3He(n,p)t$
9. $^3He(d,p)^4He$
10. $^3He(\alpha,\gamma)^7Be$
11. $^7Li(p,\alpha)^4He$
12. $^7Be(n,p)^7Li$



Modified History

- A second nucleosynthesis epoch :
- First 3 minutes→ First 6 Hours



Other Key Issues:

Is there Evidence for Large Extra Dimensions?

Higher Dimensional Gravity

- $G_{AB} = \kappa_5^2\, T_{AB}$, $\kappa_5^2 = 1/2M_5^3$, $A,B = (0,1,2,3,5)$
- $ds^2 = e^{\{-2\mathbf{k}|z|\}}\eta_{\mu\upsilon}\, dx^\mu dx^\upsilon - dz^2$
- $T^A{}_B\,(brane) = (\delta(z)/b)\,diag(-\tau-\rho, -\tau+p, -\tau+p, -\tau+p, 0)$
- $T^A{}_B\,(vacuum) = diag(-\Lambda_5, -\Lambda_5, -\Lambda_5, -\Lambda_5, -\Lambda_5)$
- Leads to a new Friedmann equation for cosmic expansion

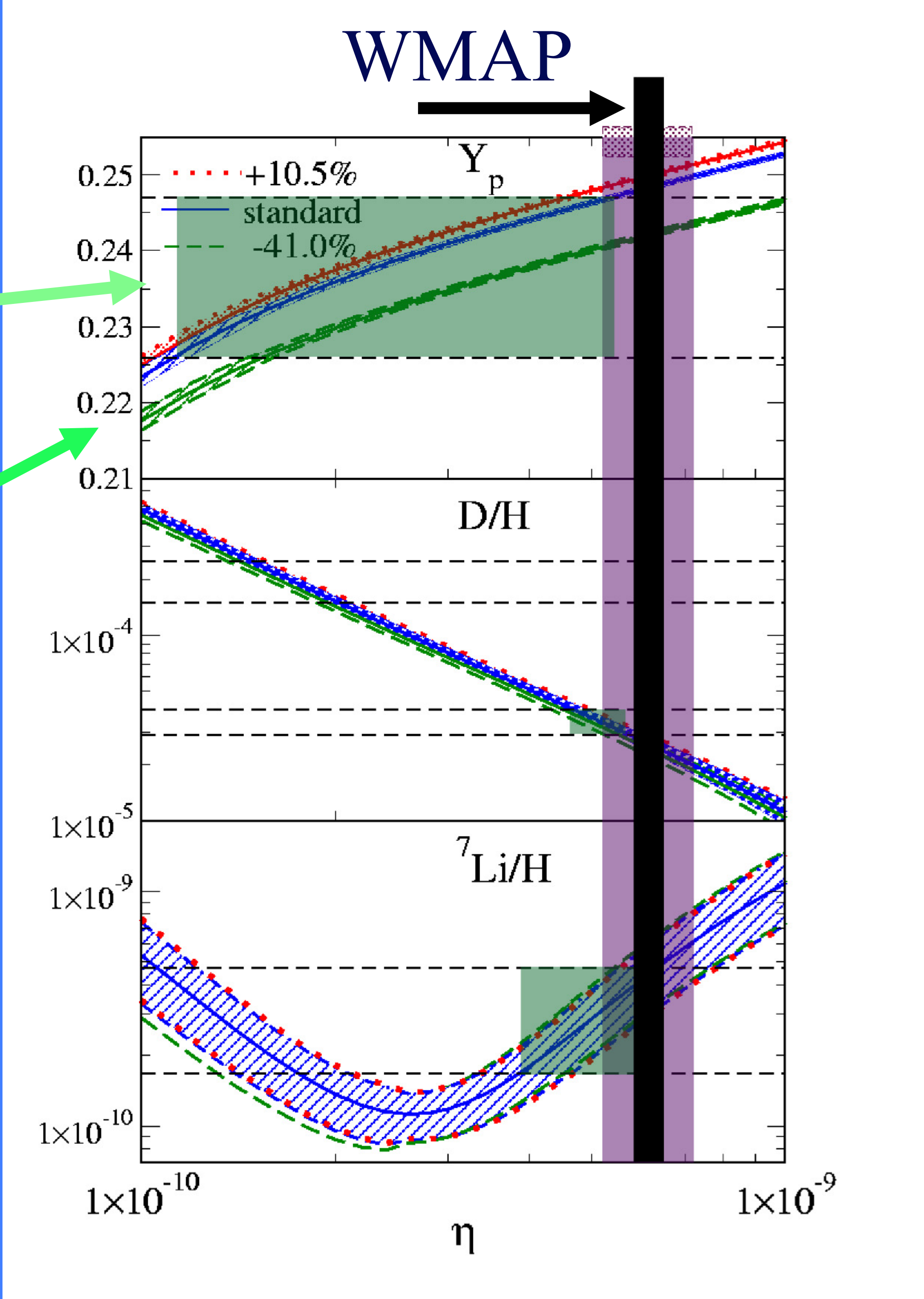
$$H^2 = \frac{8\pi G_N}{3}\rho - \frac{k}{a^2} + \frac{\Lambda_4}{3} + \frac{\kappa_5^4}{36}\rho^2 + \frac{C}{a^4}$$

$G_N = \kappa_5^2\, \tau^2/48\pi$, $\Lambda_4 = \kappa_5^4\, \tau^2/12 + 3\,\Lambda_5/4$

Dark Radiation

K. Ichiki, M. Yahiro, T. Kajino, M. Orito, G. J. Mathews PRD 66, 043521 (2002)

Standard BBN



Dark Radiation relaxes the tension between the CMB and ^{4}He limits on the baryon/photon ratio

How and When was the dark energy created?

Is the Dark Energy Quintessence?

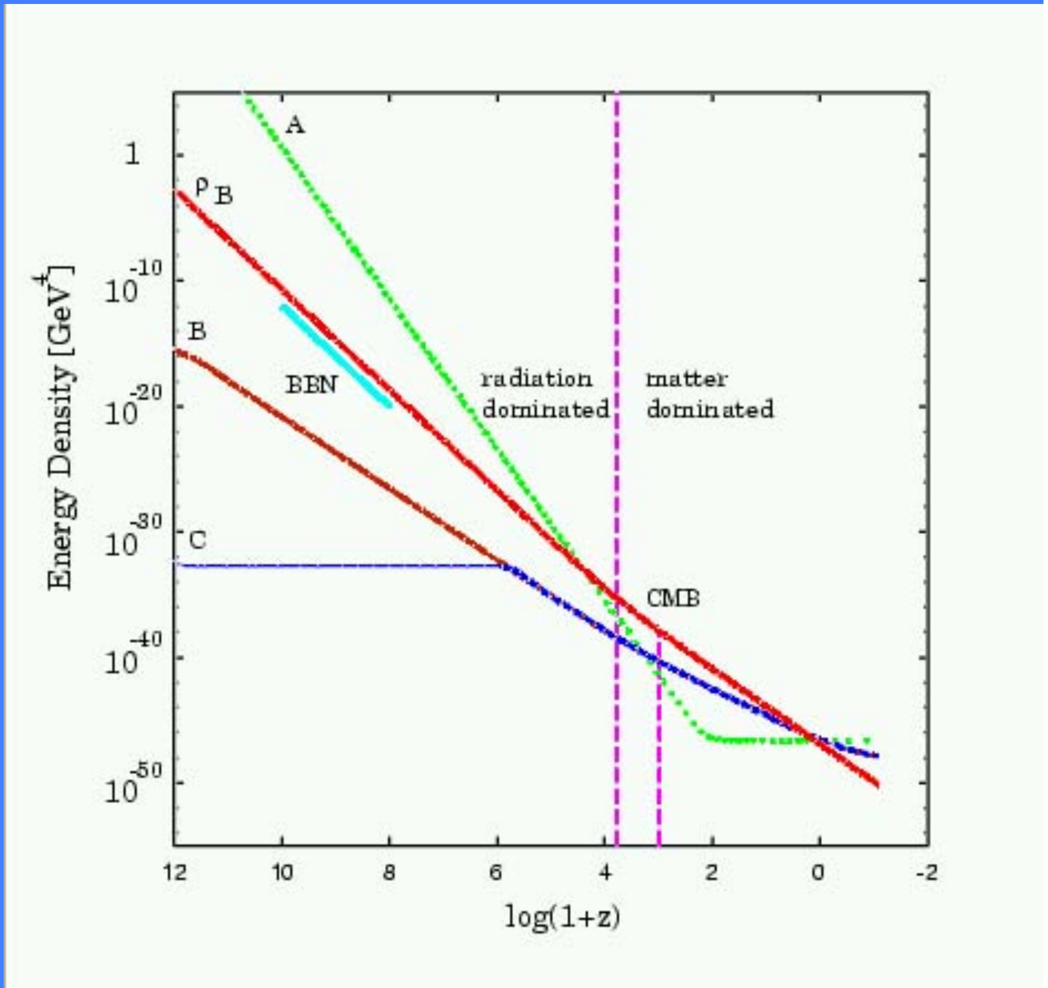
Yahiro , Mathews, Ichiki, Kajino, Orito, PRD, 65, 063502 (2002)

- Attractor Solution: ~ independent of initial conditions

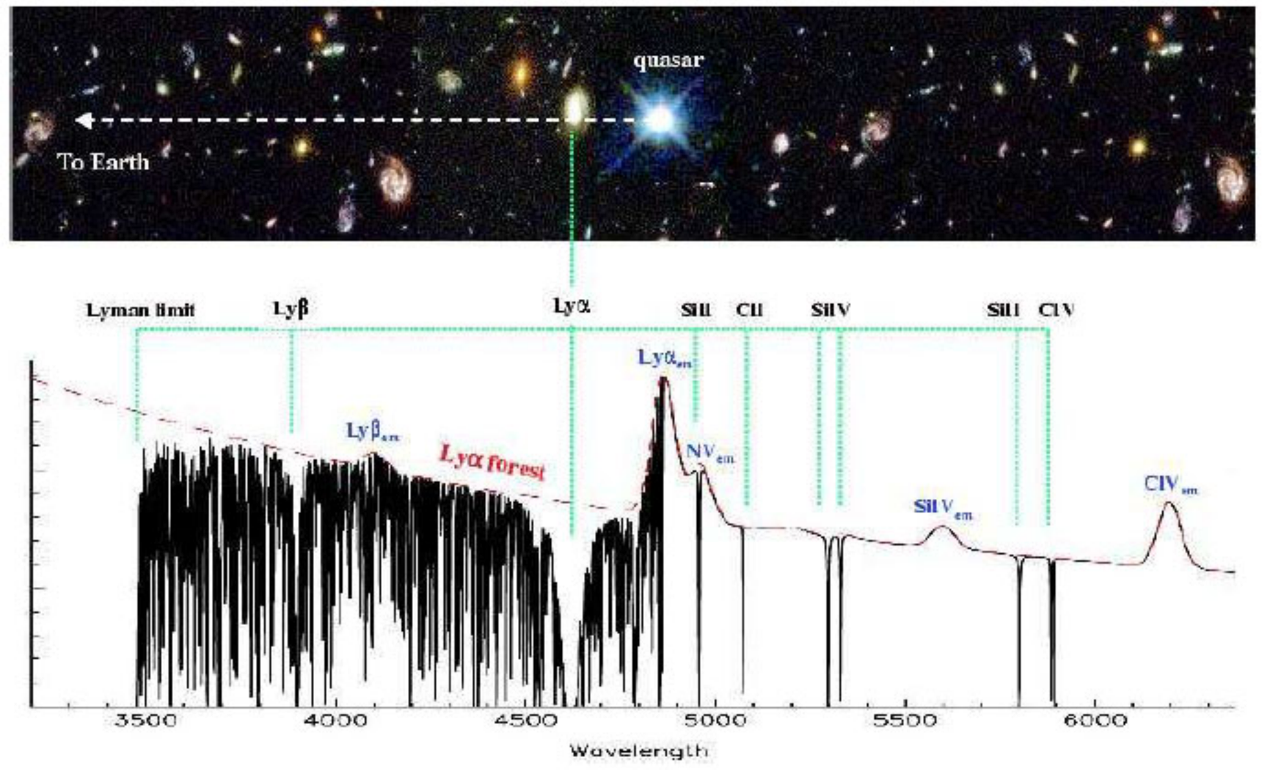
•Explains why $\rho_\Lambda \sim \rho_M$

•Avoids Fine Tuning/ Smallness?

•Matter Creation/ Quintessential Inflation



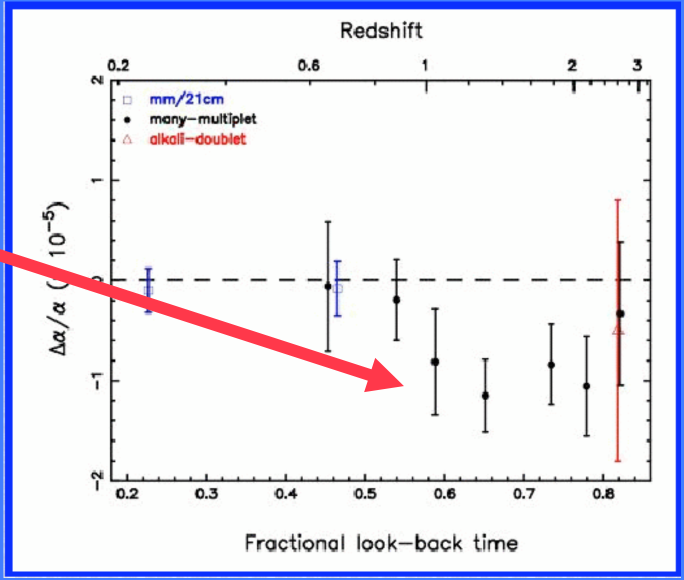
How and when did the fundamental constants obtain their present value?



Webb et al, 1999, Murphy et al. 2001,2003

Time Varying electromagnetism?

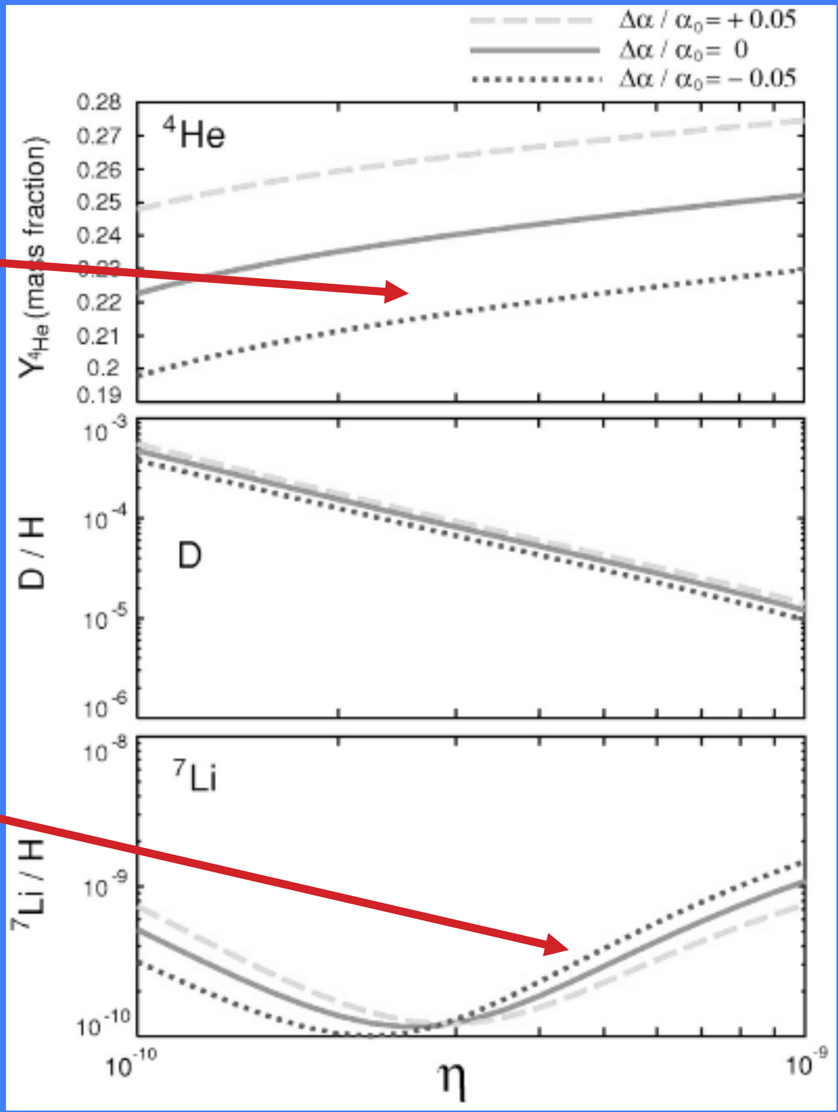
$\alpha = e^2/(2\varepsilon_o hc)$



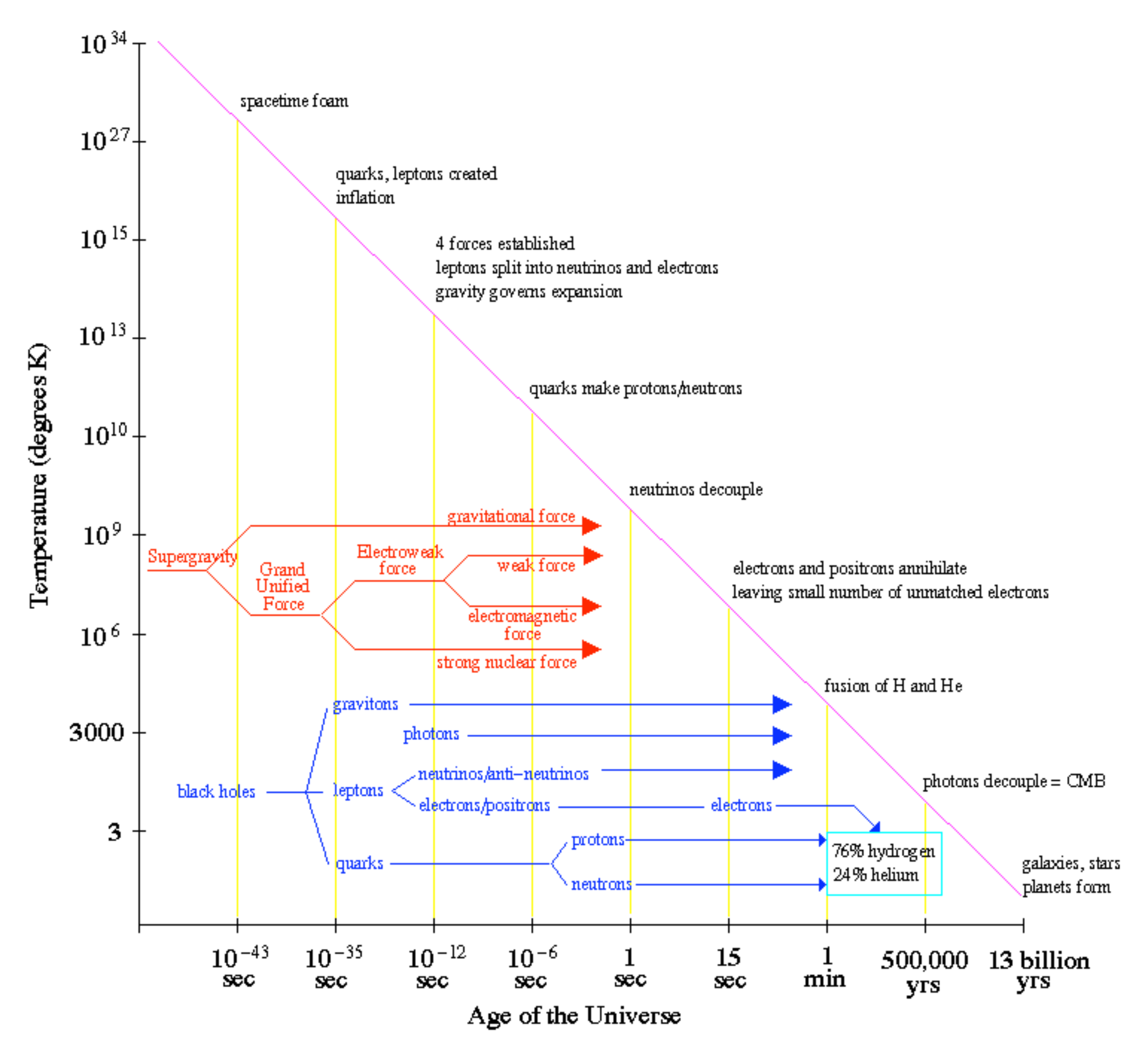
BBN Limit on Time varying α

Ichikawa & Kawasaki PRD 2004

- $Y_p = 2n_n/(n_n+n_p) = 2/(1+\exp\{\Delta m/T_f\})$
- $\Delta m_{MeV}=2.05-0.76(\alpha/\alpha_0)$
- $\sigma(E) = (S(E)/E) \times \exp\{-2\pi\alpha Z_i Z_j(\mu/2E)^{1/2}\}$

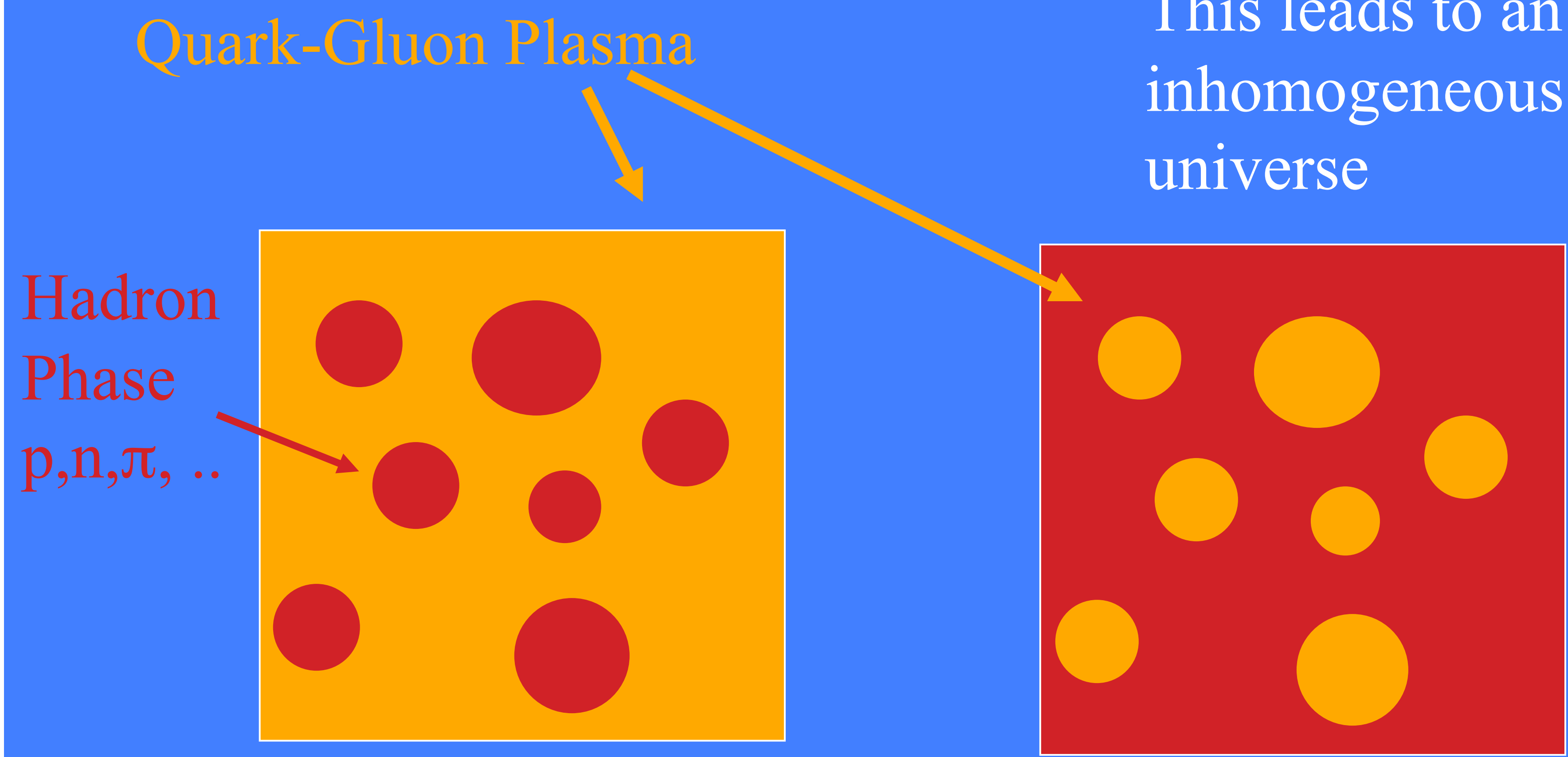


Is there Evidence of Cosmic Phase Transitions?



Big Bang Nucleosynthesis and the Cosmic Quarks-Hadron Phase Transiton

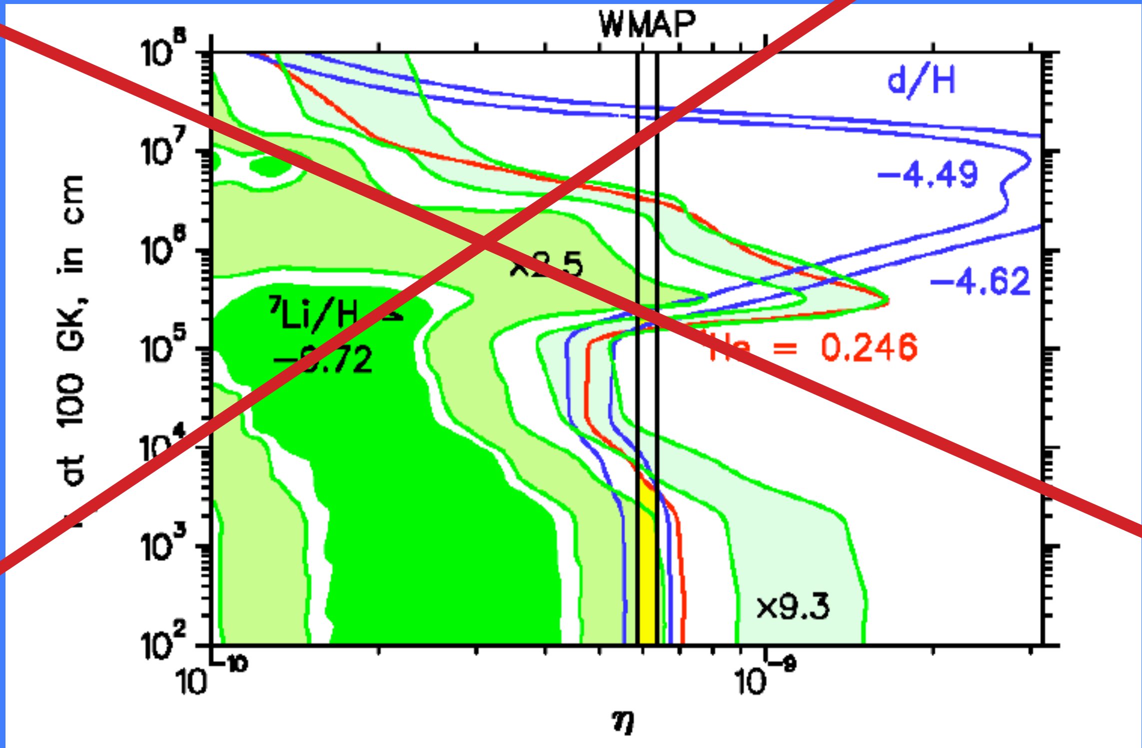
This leads to an inhomogeneous universe



Evidence of the cosmic QCD transition?

Primordial nucleosynthesis?

Primordial black holes?



Lara, Kajino, Mathews, PRD (2006)

Conclusions

- Although we have entered the age of "precision cosmology", BBN remains as a key constraint of the physics of the big bang during the radiation dominated epoch.

- There are significant remaining issues regarding the primordial abundances which require and understanding of the cosmic chemical evolution of the light elements.