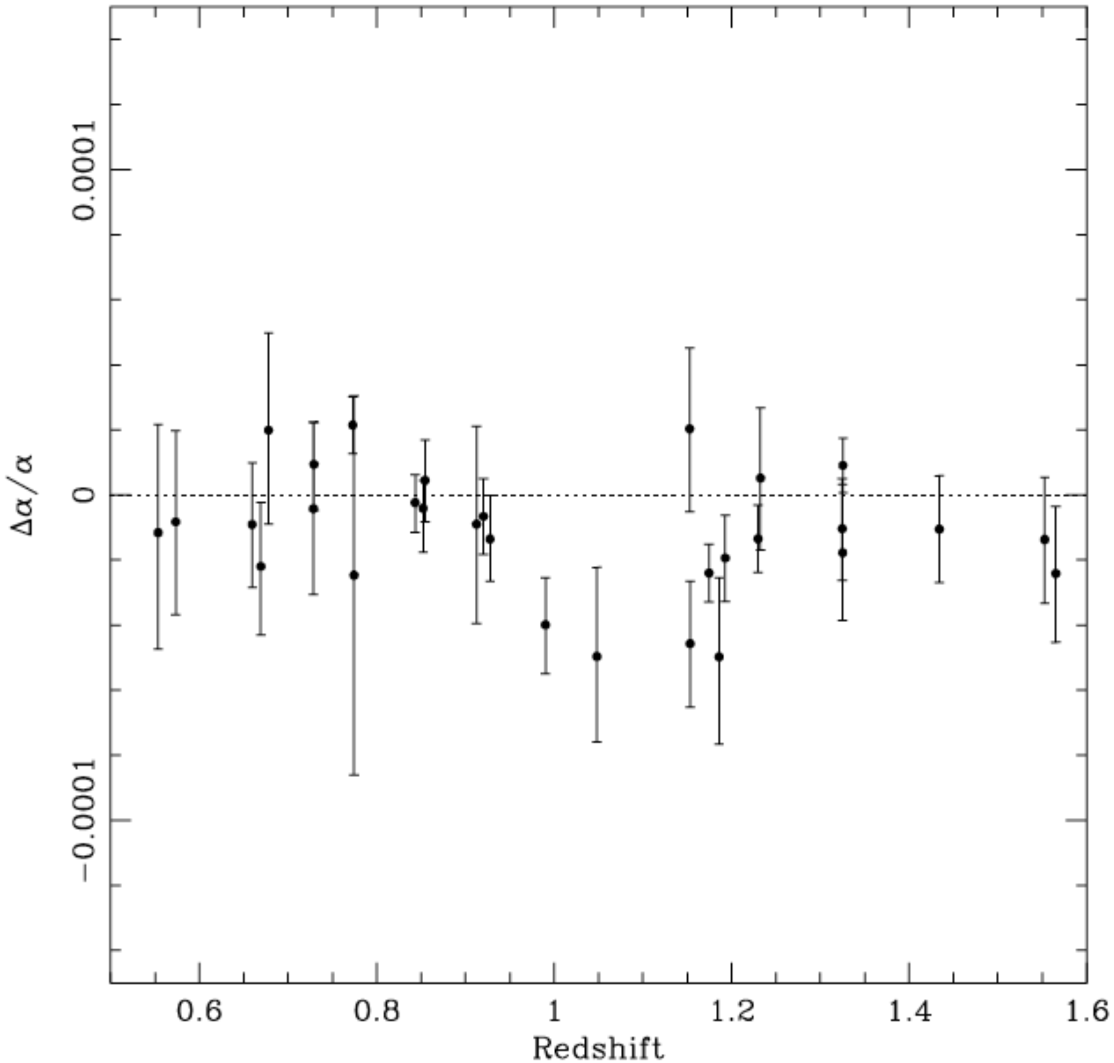
Subir Sarkar

Oxford Physics

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

We can check *experimentally* that physical 'constants' such as α have been sensibly constant for the past ~8 billion years ...



Webb *et al* (1999)

So we are entitled to extrapolate known physical laws back in time with confidence ...

Knowing the **equation of state**, we can solve the Friedman equation ...

For matter: $$\frac{d}{dt}(\rho a^3) = 0 \quad \Rightarrow \quad \rho = \rho_0/a^3 = \rho_0(1+z)^3$$

Hence $$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho_0}{3a^3} \quad \Rightarrow \quad a(t) = \left(\frac{t}{t_0}\right)^{2/3}$$

For radiation: $$\frac{d}{dt}(\rho a^4) = 0 \quad \Rightarrow \quad \rho = \rho_0/a^4 = \rho_0(1+z)^4$$

So radiation will dominate over other components as we go to early times

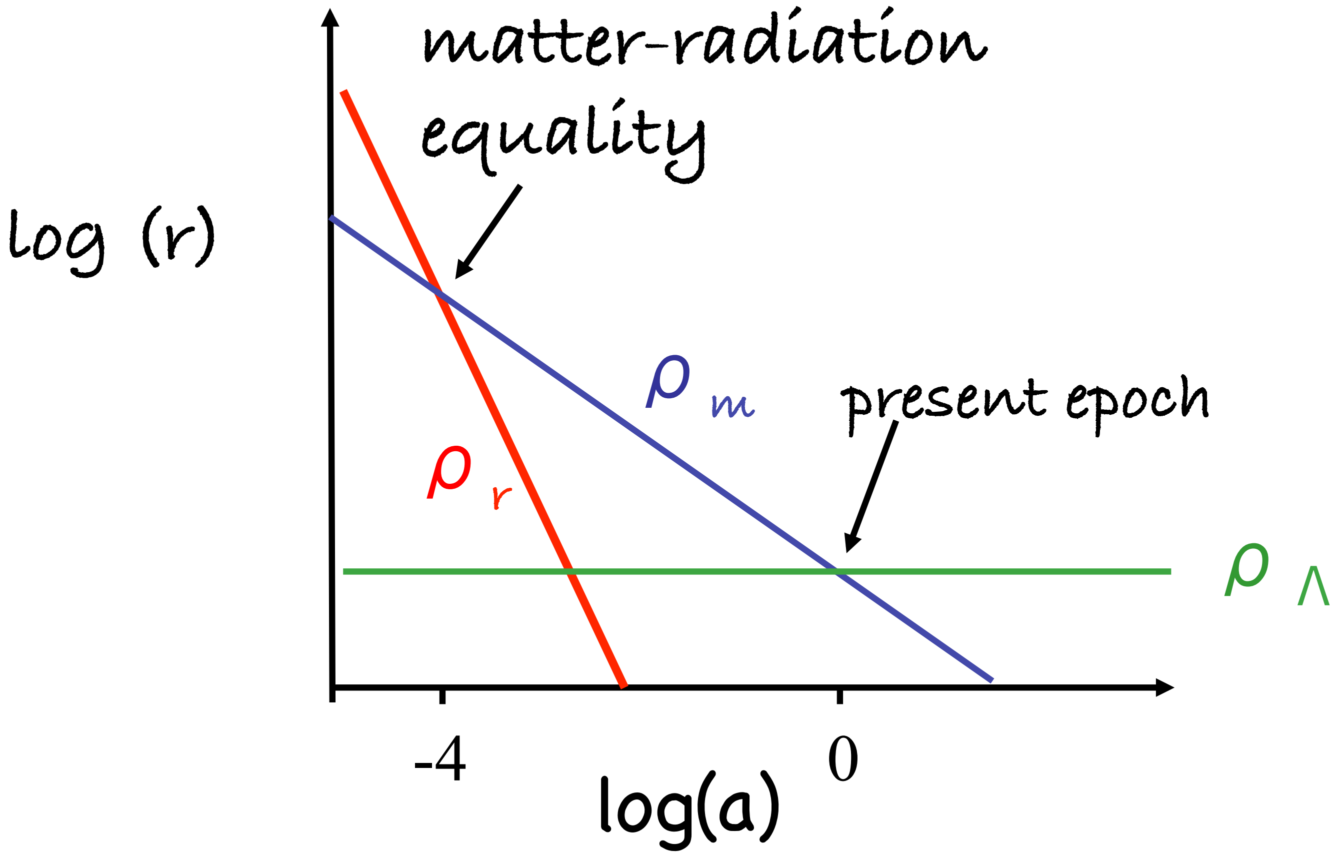
$$a(t) = \left(\frac{t}{t_0}\right)^{1/2} \quad \Rightarrow \quad \rho_{\mathrm{r}} \propto t^{-2}$$

Radiation-dominated era

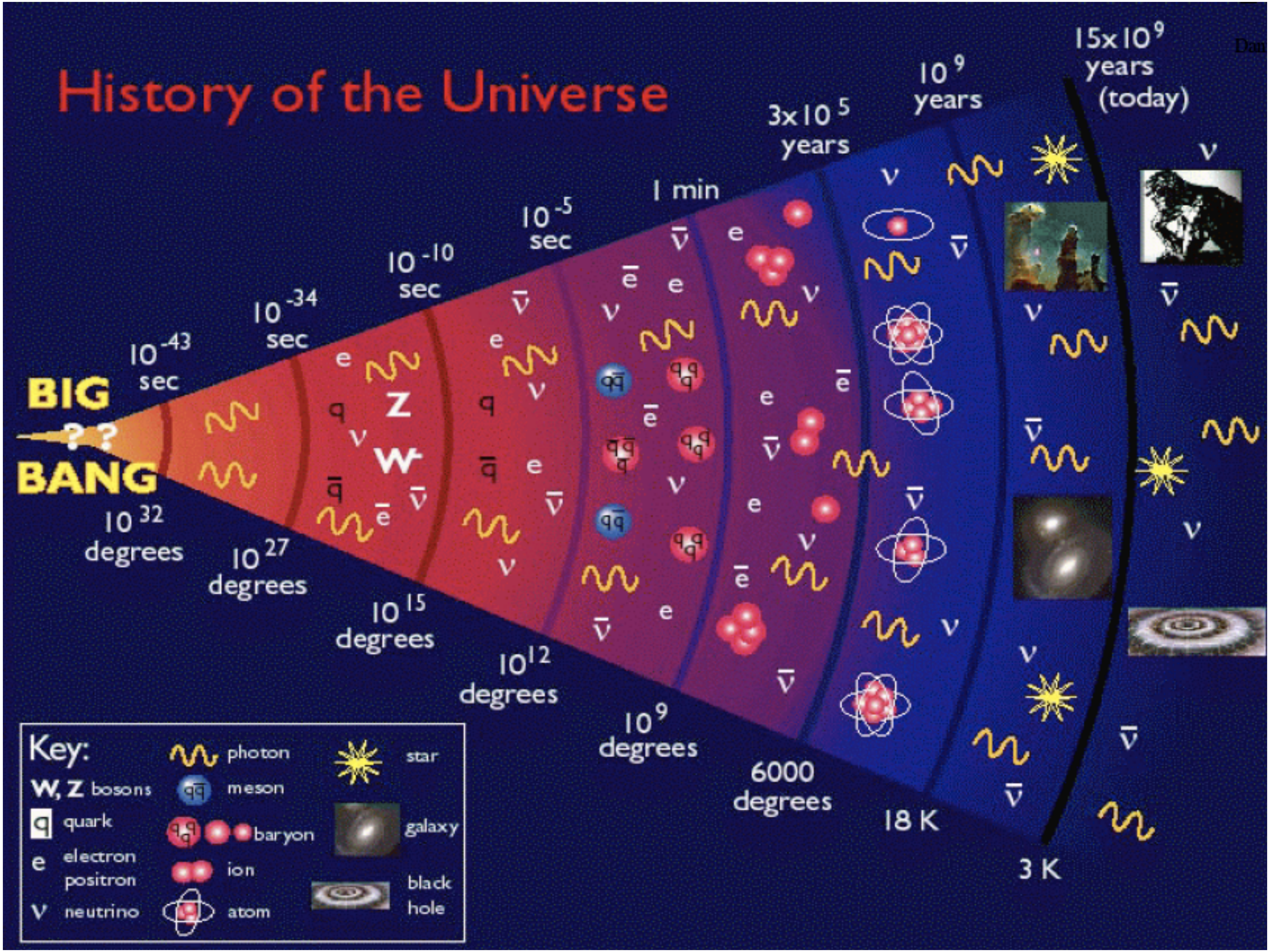
But at $a_{\mathrm{eq}} = \rho_{\mathrm{r},0}/\rho_{\mathrm{m},0}$ the matter density will come to dominate ...

Note that $\rho_{\mathrm{m}} \propto t^{-2}$ during the **Matter-dominated era as well**

Evolution of different energy components



Very recently (at $z \sim 1$), the expansion has supposedly become dominated by a cosmological constant $\Lambda \sim H_0^2 \Rightarrow \rho_\Lambda \sim H_0^2 M_P^2$ ... of which more later



History of the Universe
BIG
??
BANG
10^{-43} sec
10^{-34} sec
10^{-10} sec
10^{-5} sec
1 min
3×10^{5} years
10^{9} years
15×10^{9} years (today)
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{12} degrees
10^{9} degrees
6000 degrees
18 K
3 K
Key:
W, Z bosons
q quark
e electron positron
ν neutrino
photon
meson
baryon
ion
atom
star
galaxy
black hole

The Standard Model of the Early Universe

Thermodynamics of ultra-relativistic plasma:

Number density: $n = \frac{\xi(3)}{\pi^2} g'(T) T^3$

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

Entropy density: $s \equiv \frac{p+\rho}{T} = \frac{2\pi^2}{45} g(T) T^3$

where, the number of relativistic degrees of freedom sum over all bosons and fermions with appropriate weight:

$$g'(T) = g_b(T) + \frac{3}{4} g_f(T)$$

$$g(T) = g_b(T) + \frac{7}{8} g_f(T)$$

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

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

The dynamics is governed by the Friedmann equation:

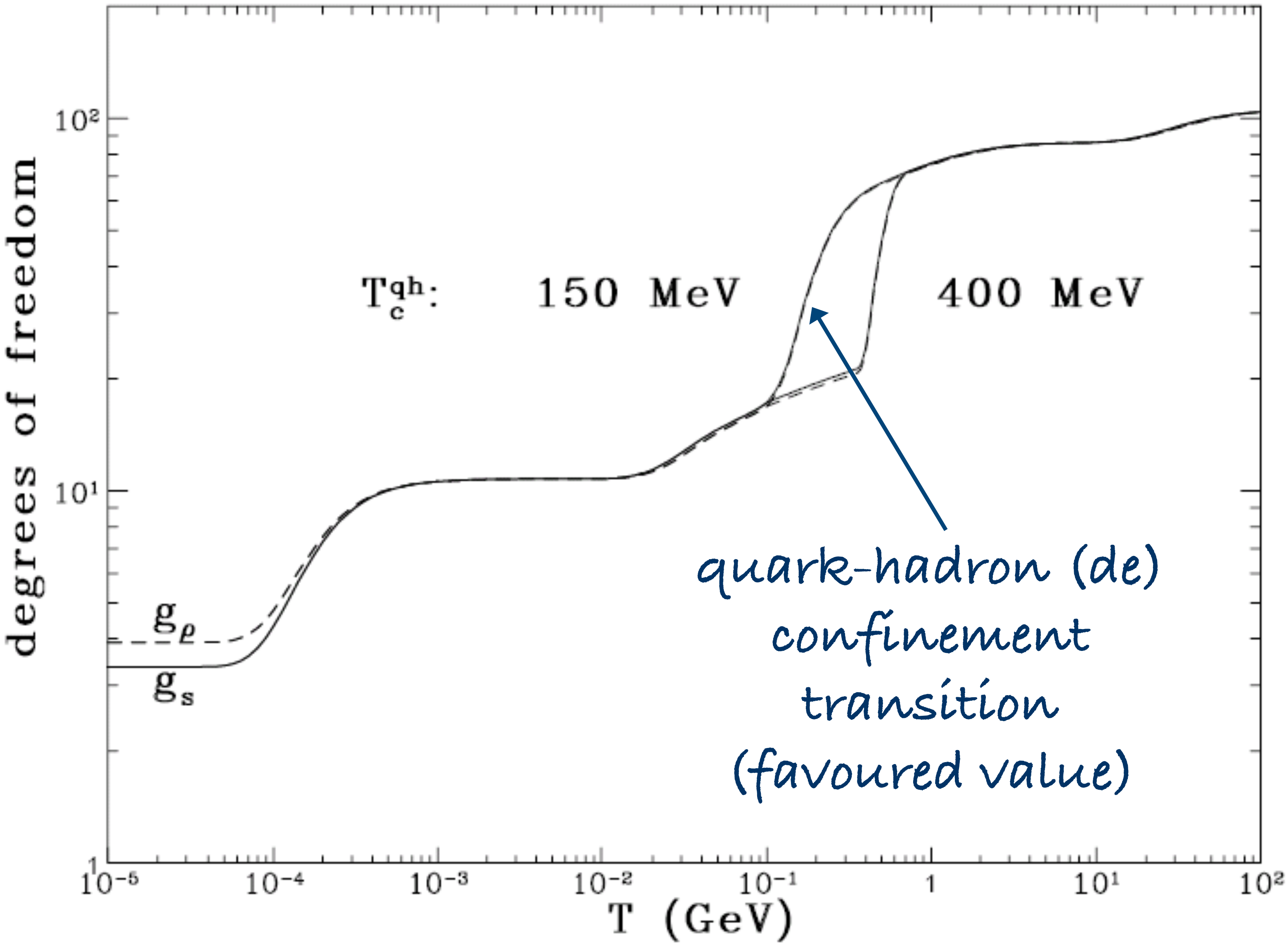
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_{\mathrm{N}}\rho}{3}$$

Integrating this gives the time-temperature relationship:

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

So we can work out when events of physical significance occurred in our past (according to the **Standard Model and beyond**)

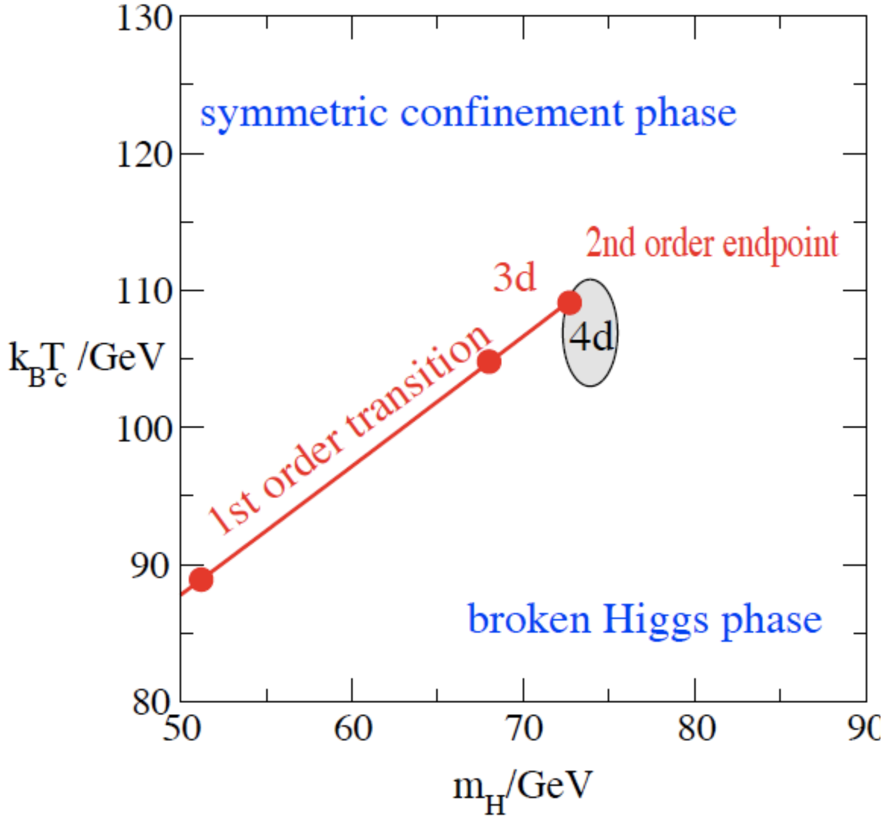
We must count all boson and fermion species contributing to the # of relativistic degrees of freedom … and take into account (our uncertain knowledge of) possible phase transitions

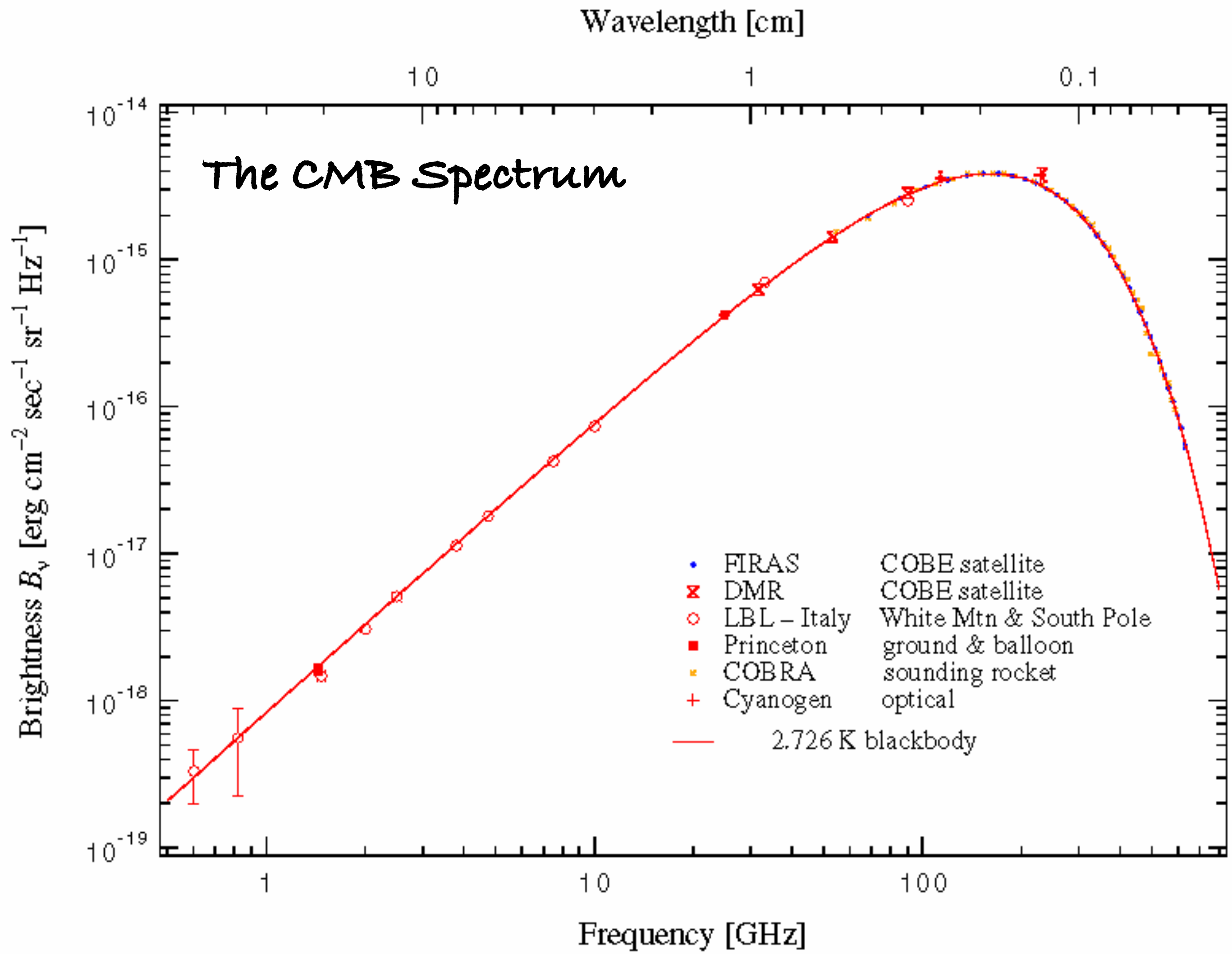


History of $g\,(T)$

$T \sim 200$ 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)	$2 + 5.25(4/11)^{4/3} = 3.36$

The phase diagram of the Standard Model (based on a dimensionally reduced $SU(2)_L$ theory with quarks and leptons, with the Abelian hypercharge symmetry $U(1)_Y$ neglected). The 1st-order transition line ends at the 2nd-order endpoint: $m_H \simeq 72 \pm 2$ GeV/c^2, $k_B T_E \simeq 110$ GeV; for higher Higgs masses the transition is a crossover (Rummukainen *et al*, Nucl. Phys. B532 (1998) 283)

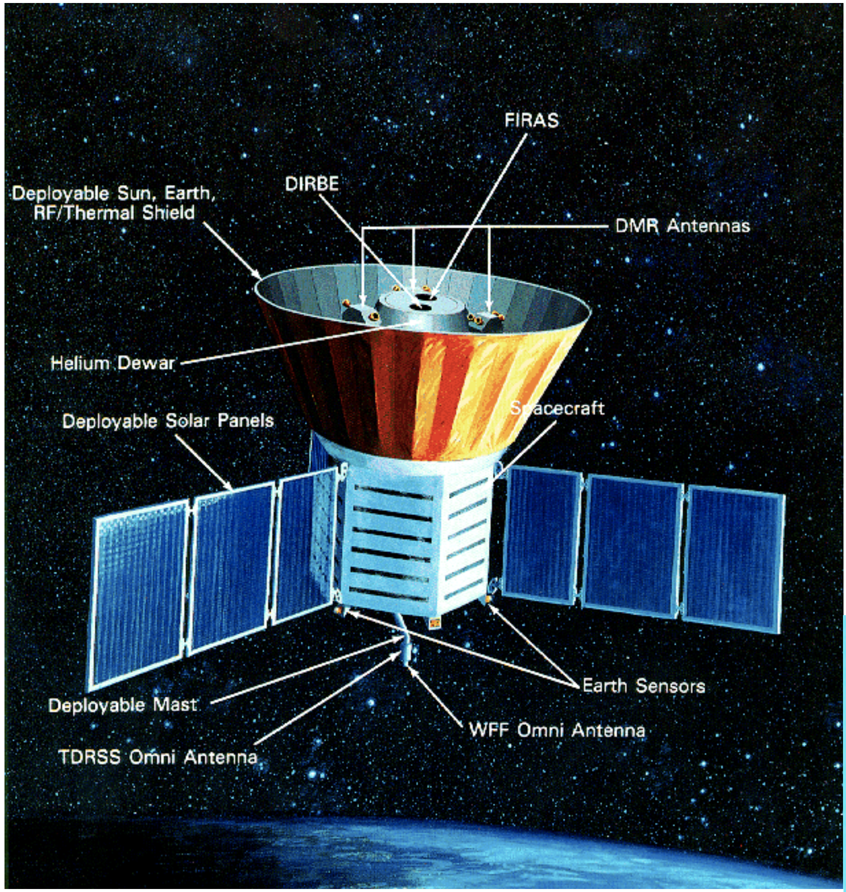




Fixsen, arXiv:0911.1955

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

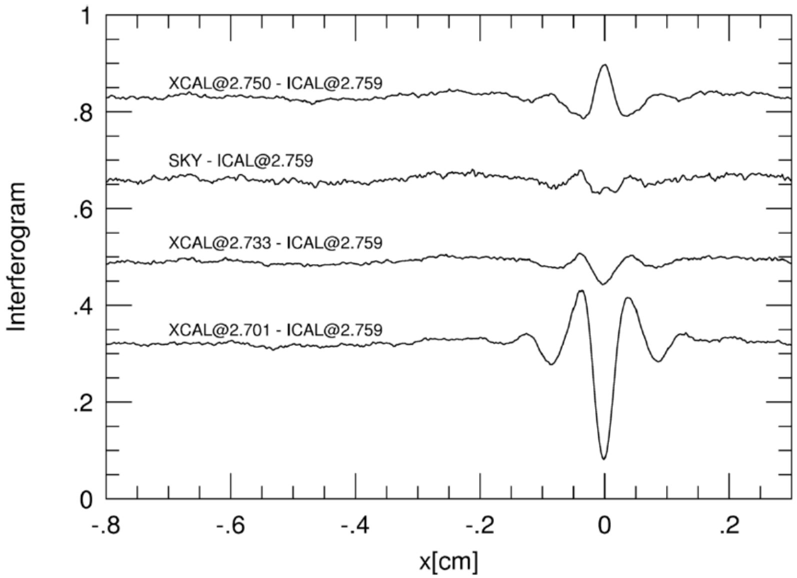
To derive this quantitatively, need to study the themalisation process

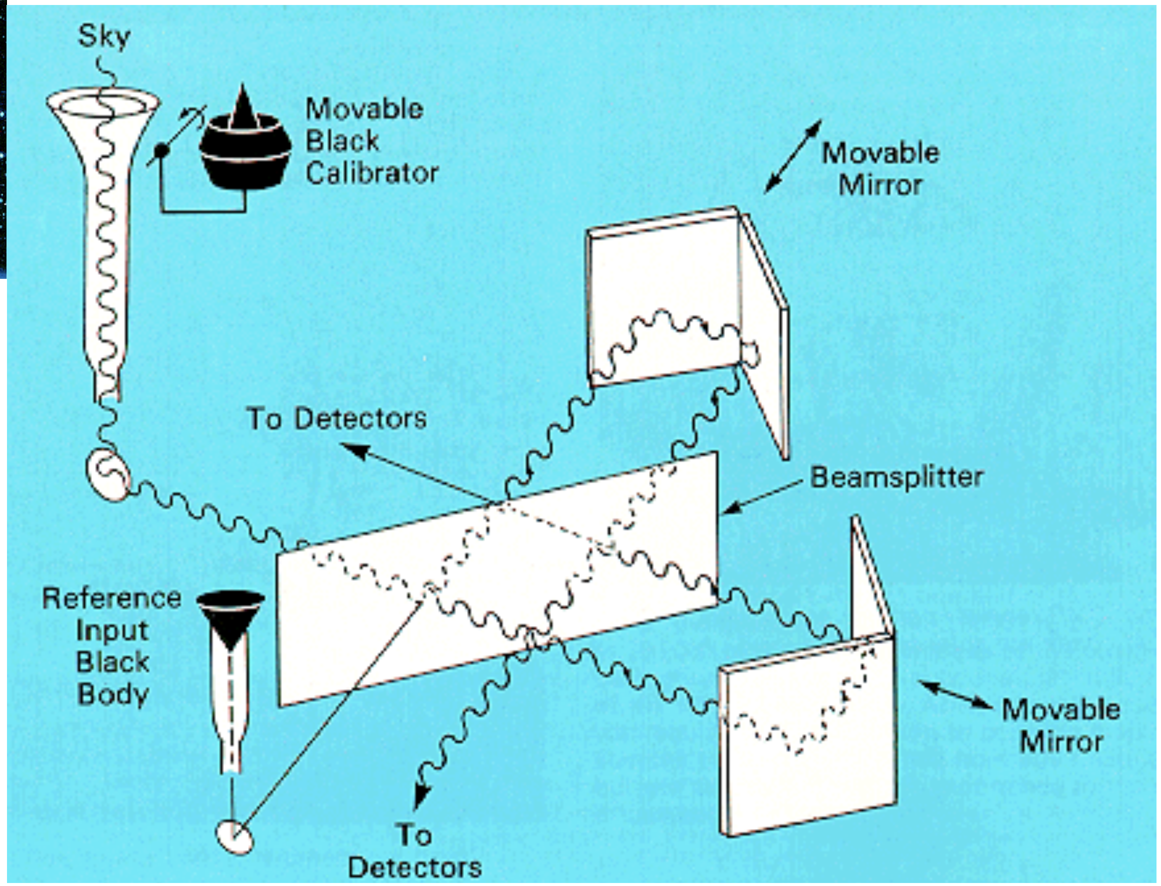


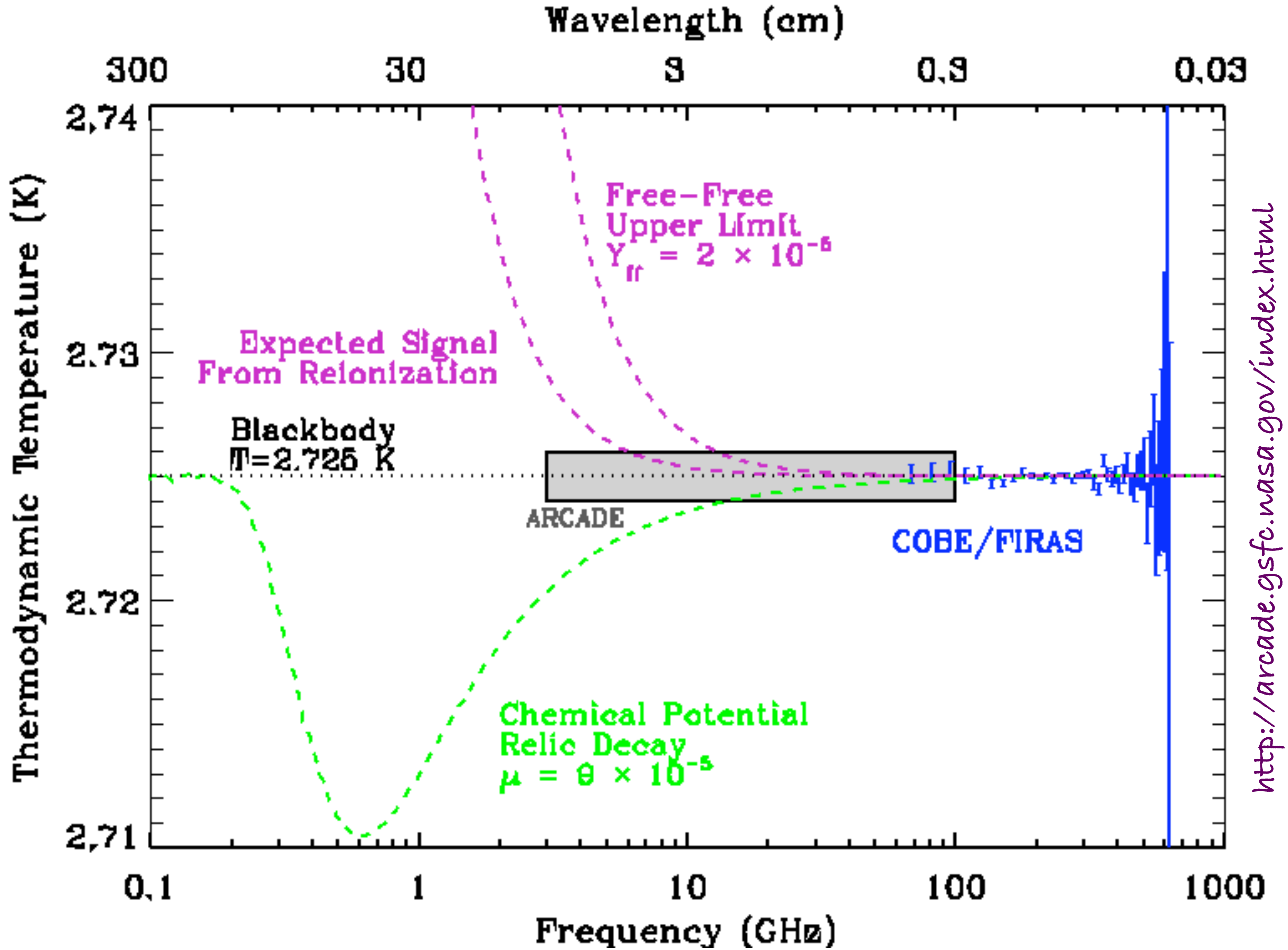
Far InfraRed Absolute Spectrophotometer
(differential polarizing Michelson interferometer)

compare sky temperature
with
internal calibrated blackbody

→ Zero output when the two inputs are equal







Observations at low frequencies are sensitive to possible spectral distortions

The thermalisation of the spectrum proceeds through scattering of hot electrons (at temperature T_e) on the CMB photons, described by:

Kompaneets (1957, Sov. Phys. JETP, 4, 730) equation:

$$\frac{\partial n}{\partial y} = x^{-2}\frac{\partial}{\partial x}\left[x^4\left(n + n^2 + \frac{\partial n}{\partial x}\right)\right]$$

where n is the number of photons per mode ($n = 1/(e^x - 1)$ for a blackbody), $x = h\nu/kT_e$, and the Kompaneets y is defined by

$$dy = \frac{kT_e}{m_e c^2} n_e \sigma_T c dt.$$

Total photon number conserved:

$$\begin{aligned}\frac{\partial N}{\partial y} &\propto \int x^2 \frac{\partial n}{\partial y} dx \\ &= \int \frac{\partial}{\partial x}\left[x^4\left(n + n^2 + \frac{\partial n}{\partial x}\right)\right] dx \\ &= 0\end{aligned}$$

For a pedagogical derivation, see Peebles (*Principles of Physical Cosmology*, 1993)

The stationary solutions $\partial n/\partial y = 0$ are general Bose-Einstein thermal distributions:

$$n = 1/(\exp(x+\mu) - 1)$$

$$\begin{aligned} N &\propto \int \frac{x^2 dx}{\exp(x+\mu) - 1} \\ &= \sum_{k=1}^{\infty} e^{-k\mu} \int x^2 e^{-kx} dx \\ &= 2 \sum_{k=1}^{\infty} \frac{e^{-k\mu}}{k^3} \\ &= 2\left(\zeta(3) - \mu\zeta(2) + \ldots\right) \end{aligned}$$

A similar calculation for the energy density shows that

$$U \propto 6\left(\zeta(4) - \mu\zeta(3) + \ldots\right).$$

For $N = const$, need $\Delta T/T = \mu\zeta(2)/(3\zeta(3))$.

Therefore, the energy density change at constant N is

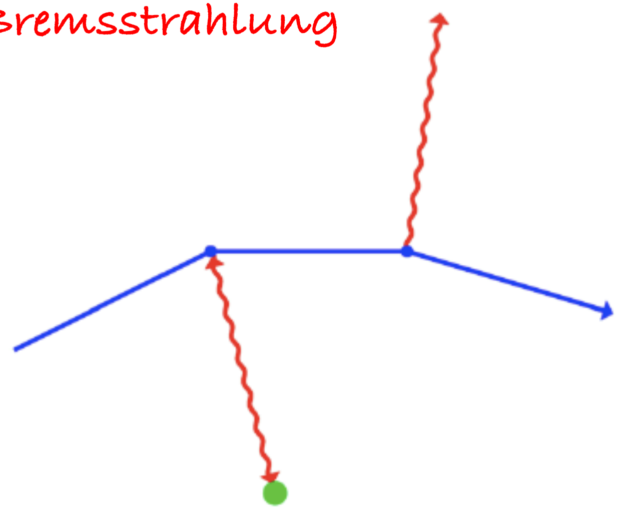
$$\frac{\Delta U}{U} = \left(\frac{4\zeta(2)}{3\zeta(3)} - \frac{\zeta(3)}{\zeta(4)}\right)\mu = 0.714\mu.$$

FIRAS limit $|\mu| < 9 \times 10^{-5}$ implies

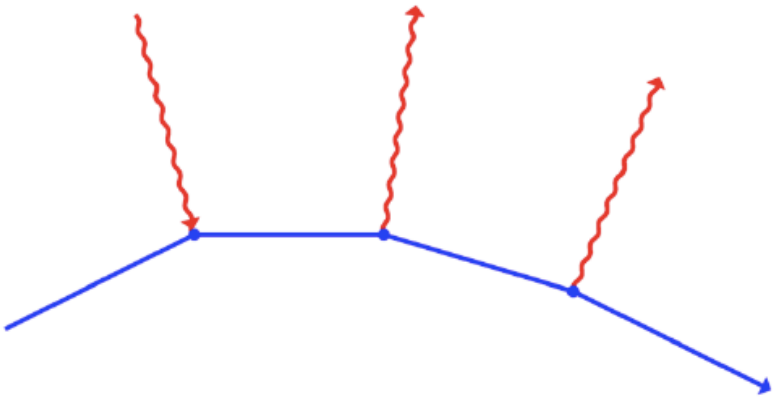
$$\Delta U/U < 6 \times 10^{-5}$$

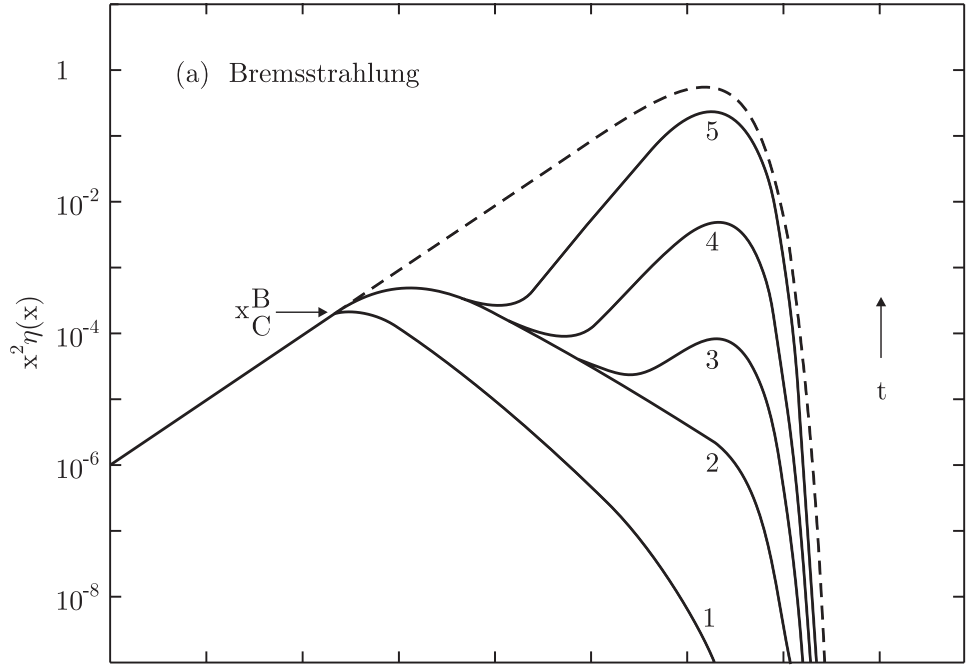
To reduce $\mu \rightarrow 0$ requires the creation of photons i.e. radiative processes

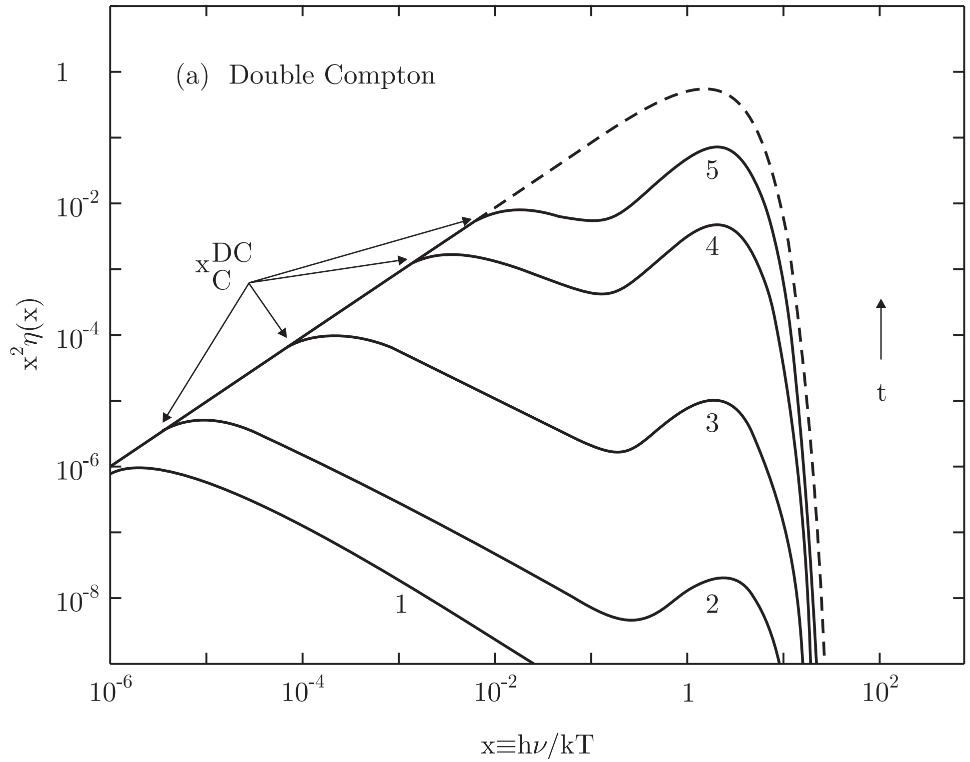
Bremsstrahlung



Double Compton scattering



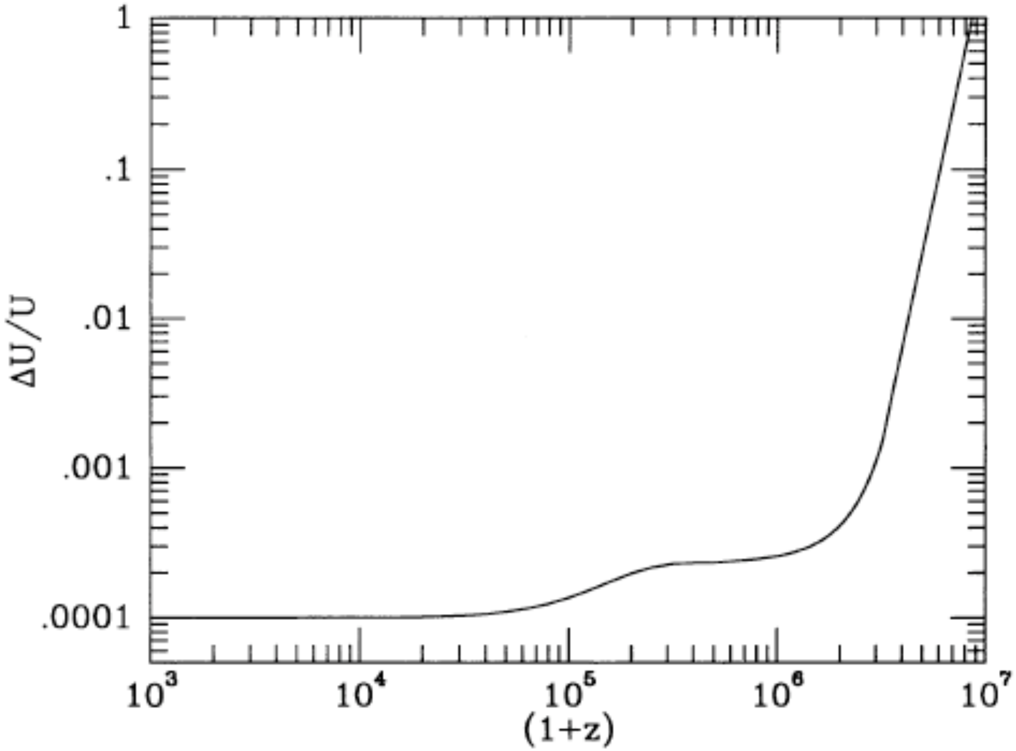




Since $(1+z)\partial y/\partial z \propto \Omega_B h^2 (1+z)^2$, the overall rate for eliminating a μ distortion scales like $\Omega_B h^2 (1+z)^{5/2}$ per Hubble time. A proper consideration (Burigana *et al.* 1991, ApJ, 379, 1-5) of this interaction of the photon creation process with the Kompaneets equation shows that the redshift from which $1/e$ of an initial distortion can survive is

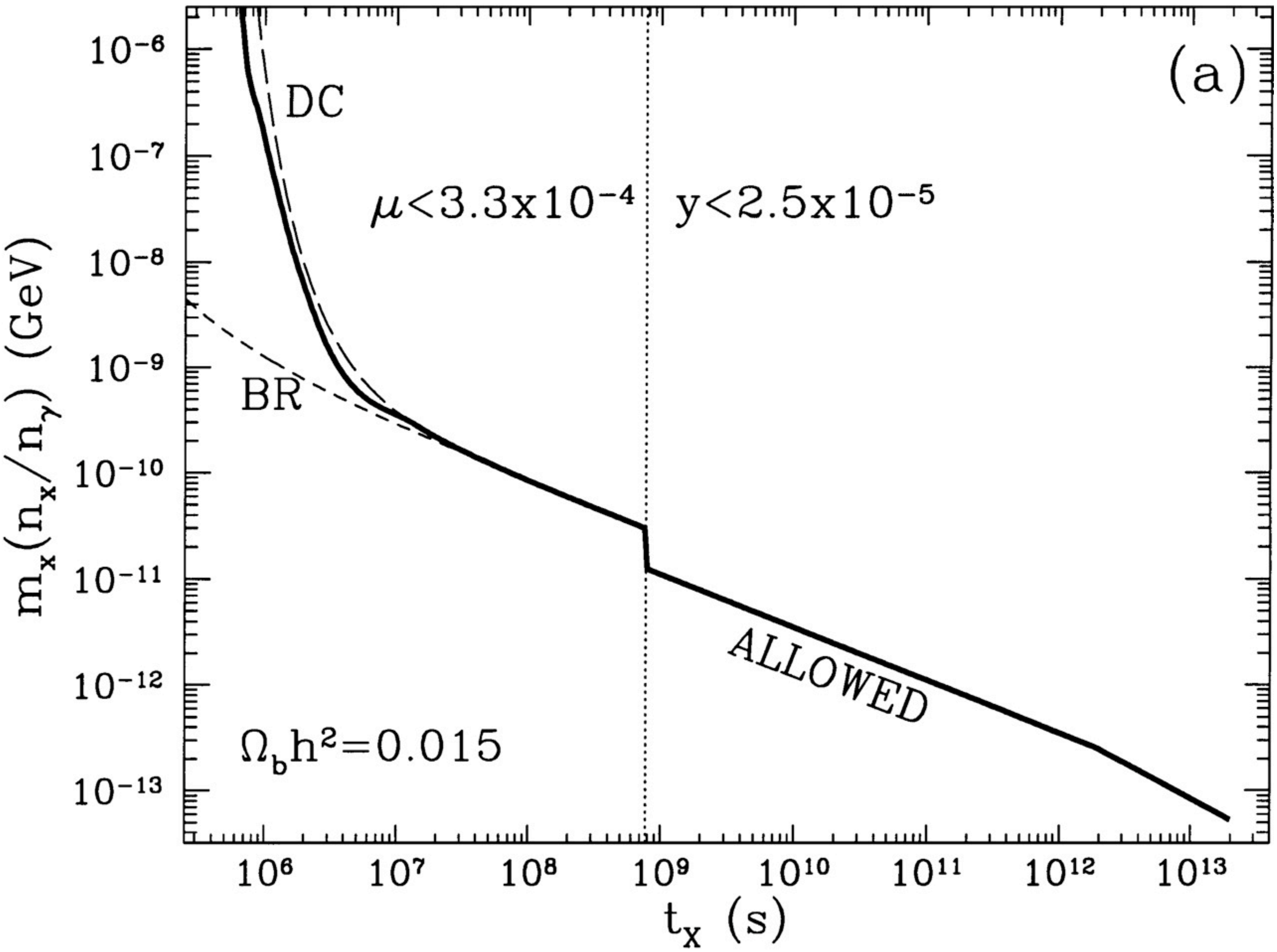
$$z_{th} = \frac{4.24 \times 10^5}{[\Omega_B h^2]^{0.4}} \qquad (2)$$

which is $z_{th} = 1.9 \times 10^6$ for $\Omega_B h^2 = 0.0224$.



Wright et al, ApJ 420:450,1994

Constraint on particles decaying/annihilating into em radiation



Hu & Silk, PR D48:485,1993

Interaction between photons and (non-relativistic) matter

Thomson scattering on electrons: $\gamma + e \to \gamma + e$

Photon interaction rate ($x_e = n_p/n_B$): $\Gamma_{\text{Thomson}} = n_e \langle \sigma_T |v| \rangle \propto x_e T^3 \sigma_T$

cf. expansion rate of the universe (MD era): $H \propto T^{3/2}$

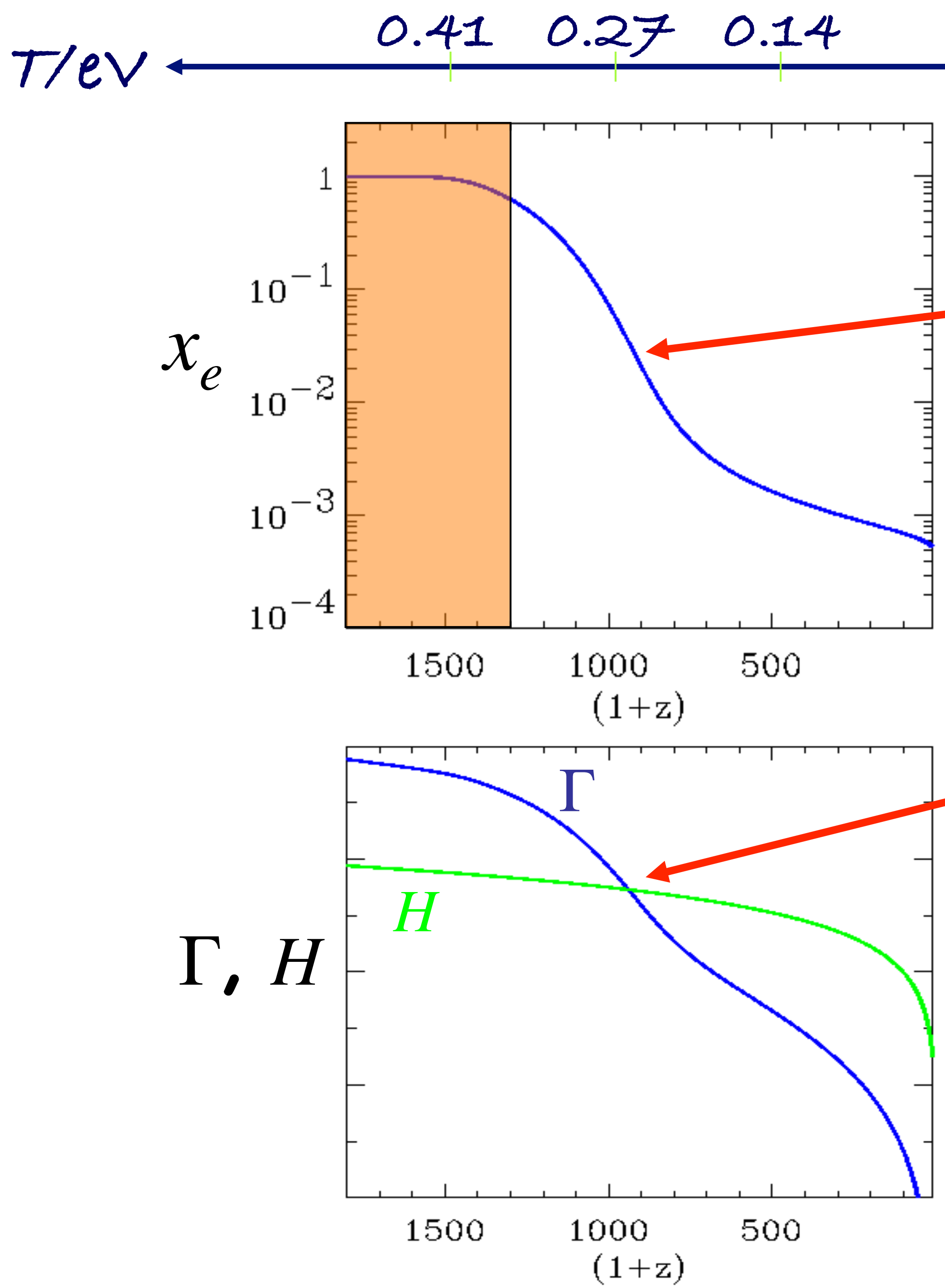
$\Gamma_{\text{Thomson}} > H \Rightarrow$ Photons/matter in equilibrium/ $\Gamma_{\text{Thomson}} < H \Rightarrow$ Photons/matter decouple

The ionisation fraction x_e drops rapidly at (re)combination so the Thomson scattering rate also decreases sharply below the Hubble expansion rate – this defines a ***last scattering surface*** for the relic photons … which we see today as the cosmic microwave background

While $p + e^- \to H + \gamma$ is in **chemical equilibrium**, the chemical potentials obey $\mu_p + \mu_e = \mu_H$ (since $\mu_\gamma = 0$), hence: $n_H = (g_H/g_p g_e) n_p n_e (m_e T/2\pi)^{3/2} e^{B/T}$ (where $B = m_p + m_e - m_H = 13.6$ eV)

In terms of the ionisation fraction x_e and the baryon-to-photon ratio, $\eta = n_B/n_\gamma$, this is the Saha equation:

$$\frac{1 - x_e}{x_e^2} = \frac{4\sqrt{2}\zeta(3)}{\sqrt{\pi}} \eta \left(\frac{T}{m_e} \right)^{3/2} \mathrm{e}^{B/T}$$



Recombination

(according to the Saha ionisation eq.)

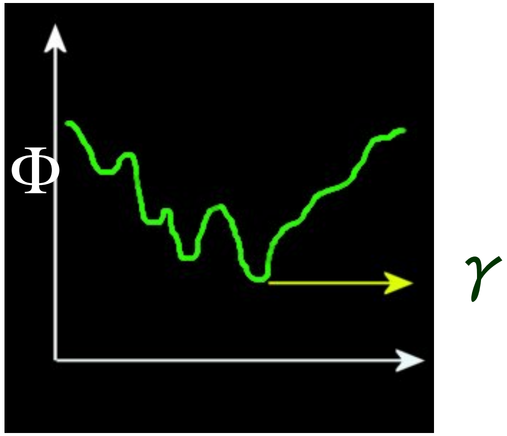
$T_{rec} \sim 0.35$ eV, $z_{rec} \sim 1300$

Decoupling of photons and baryons

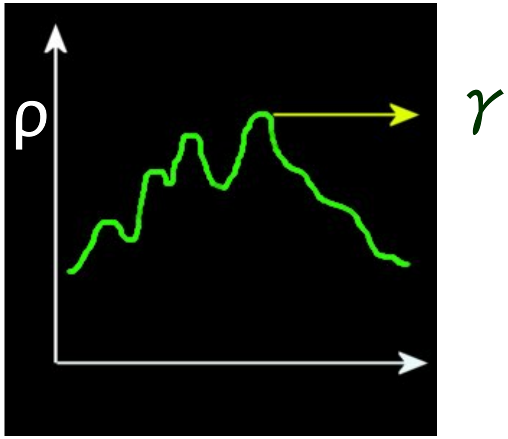
$T_{rec} \sim 0.29$ eV, $z_{dec} \sim 1100$

More precise calculation by
Seager et al, ApJ 523 (1999) L1
(Computer Code: CosmoRec, HyRec)

Fluctuations in the matter density → fluctuations in the CMB temperature

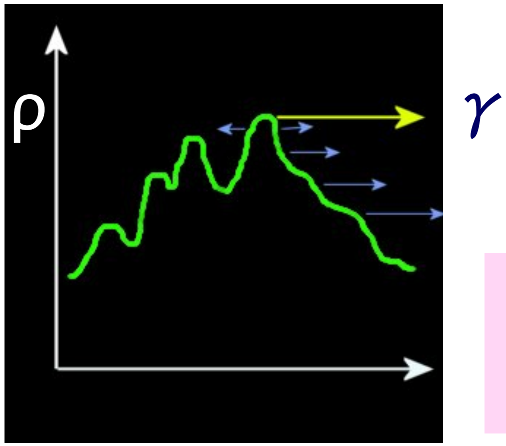


Photons are redshifted as they move out of gravitational potential wells



Dense regions have higher temperature

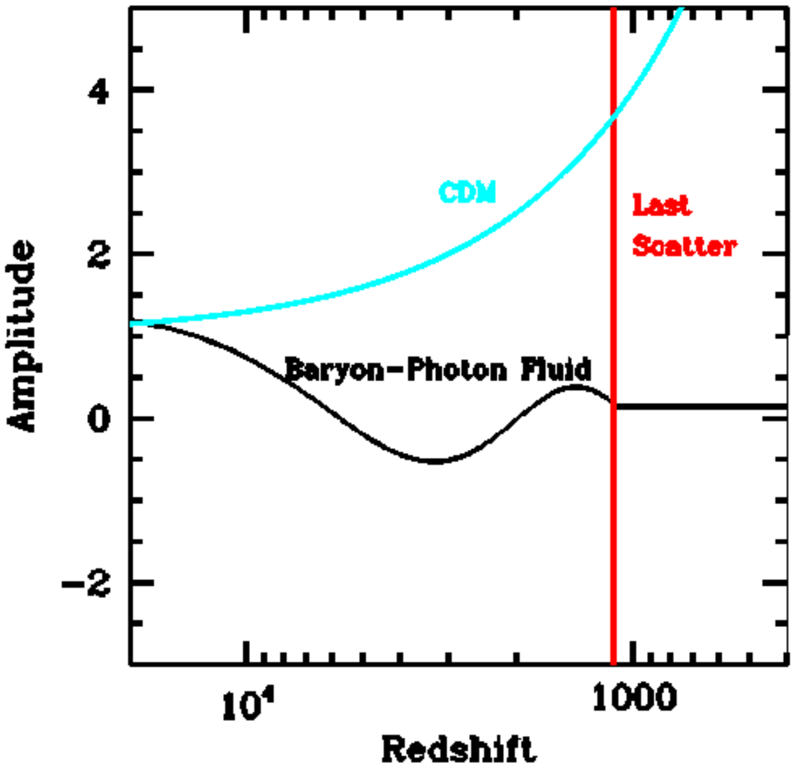
$\Rightarrow$ photons have higher energy

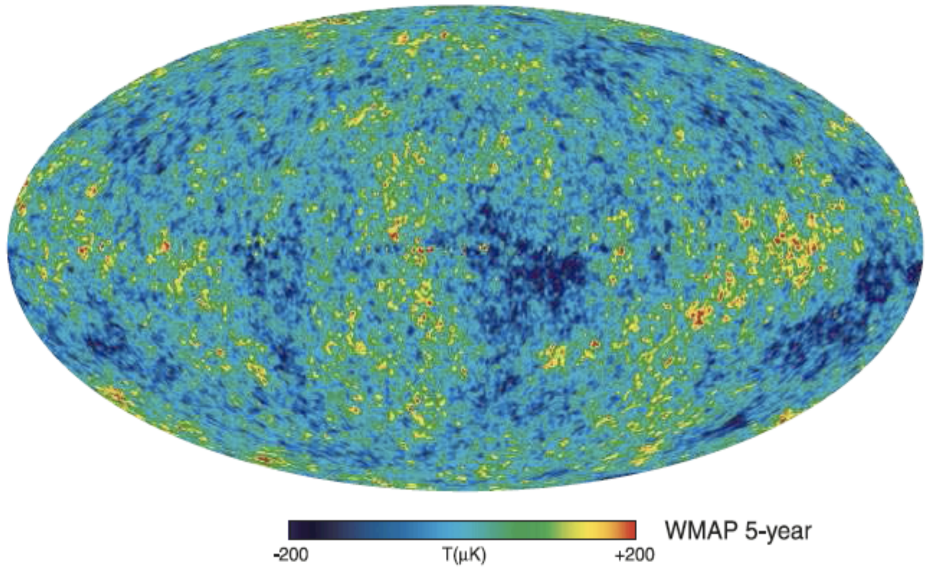


Photons emitted from a moving surface are red/blue-shifted

Fortunately the effects do not *quite* cancel so the CMB carries a memory of the past

Before recombination, the primordial fluctuations just excite **sound waves in the plasma**, but can start growing already in the sea of collisionless dark matter ...





These sound waves leave an imprint on the last scattering surface of the CMB as the universe turns neutral and transparent ... sensitive to the baryon/CDM densities

For a statistically isotropic gaussian random field, the **angular power spectrum** can be constructed by decomposing in spherical harmonics:

$$\Delta T(\mathbf{n}) = \sum a_{lm} Y_{lm}(\mathbf{n})$$

$$C_l \equiv \frac{1}{2l+1} \sum |a_{lm}|^2$$

The CMB angular power spectrum is sensitive to cosmological parameters

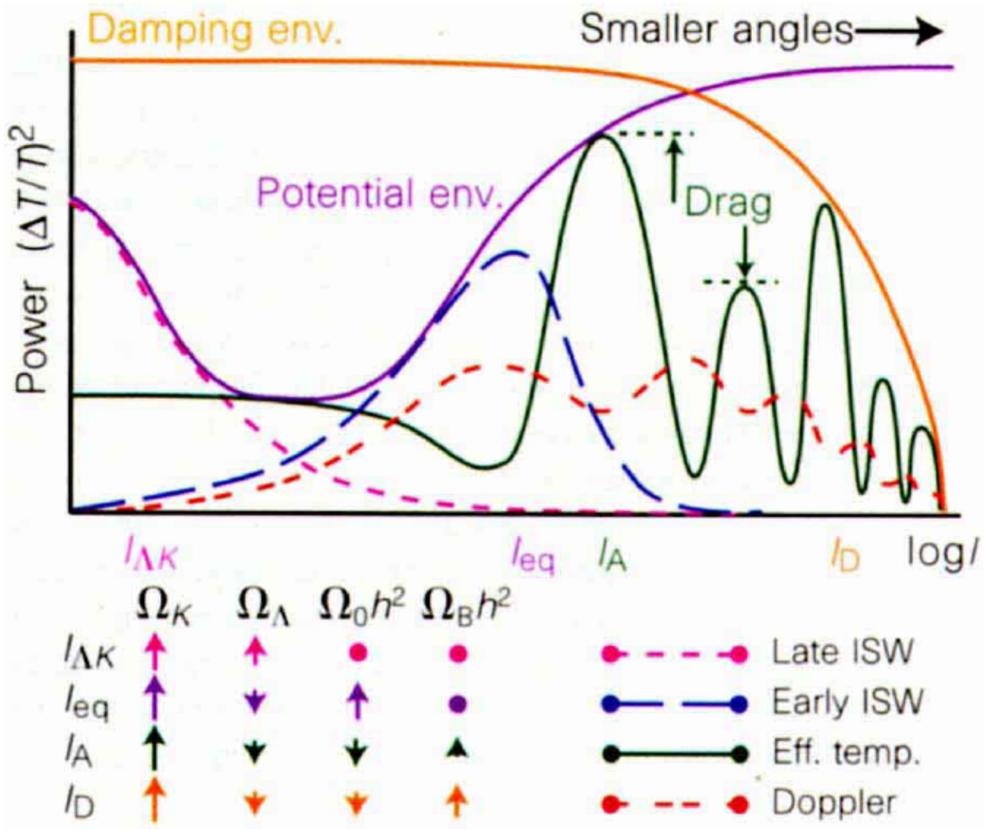
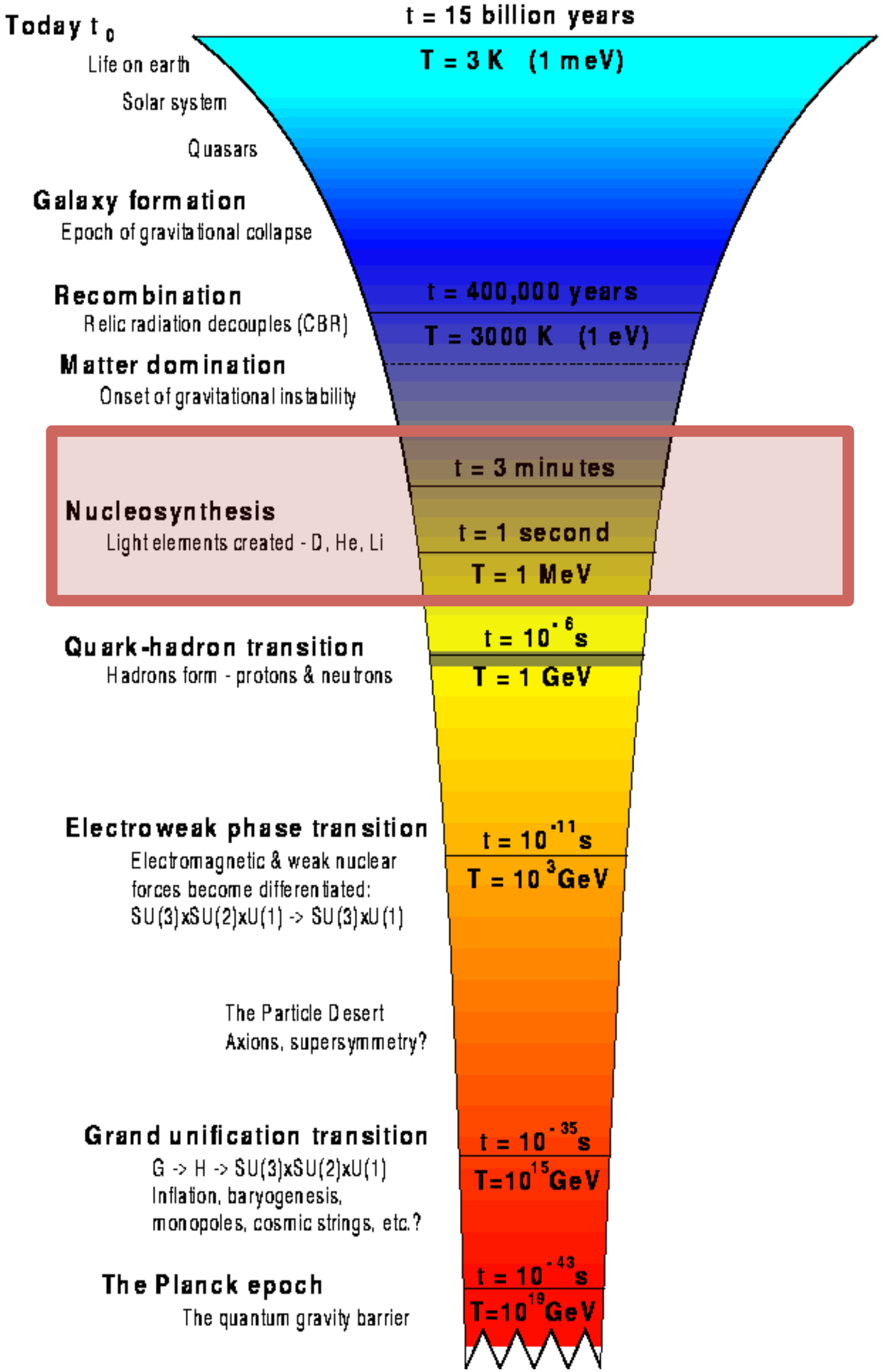


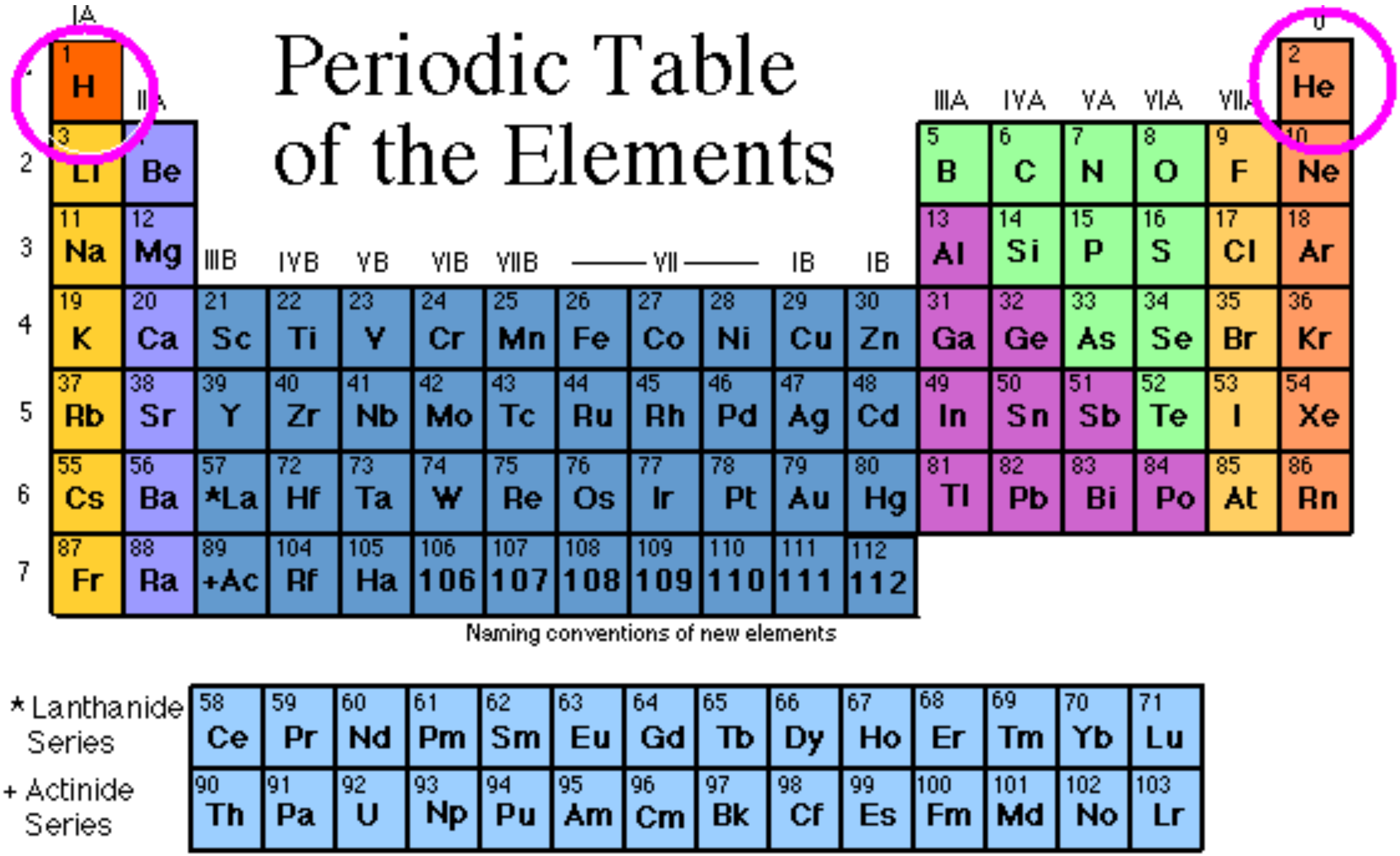
Figure 1 Schematic decomposition of the anisotropy spectrum and its dependence on cosmological parameters, in an adiabatic model. Four fundamental angular scales characterized by the angular wavenumber $l \propto \theta^{-1}$ enter the spectrum: $l_{\Lambda K}$ and l_{eq} which enclose the Sachs–Wolfe plateau in the potential envelope, l_A the acoustic spacing, and l_D the diffusion damping scale. The inset table shows the dependence of these angular scales on four fundamental cosmological parameters: $\Omega_K (\equiv 1 - \Omega_\Lambda - \Omega_0)$, Ω_Λ, $\Omega_0 h^2$ and $\Omega_B h^2$ (see Box 1 for definitions). Baryon drag enhances all compressional (here, odd) maxima of the acoustic oscillation, and can probe the spectrum of fluctuations at last scattering and/or $\Omega_B h^2$. Projection effects smooth Doppler more than effective-temperature features.

Hu, Sugiyama, Silk [astro-ph/9604166]

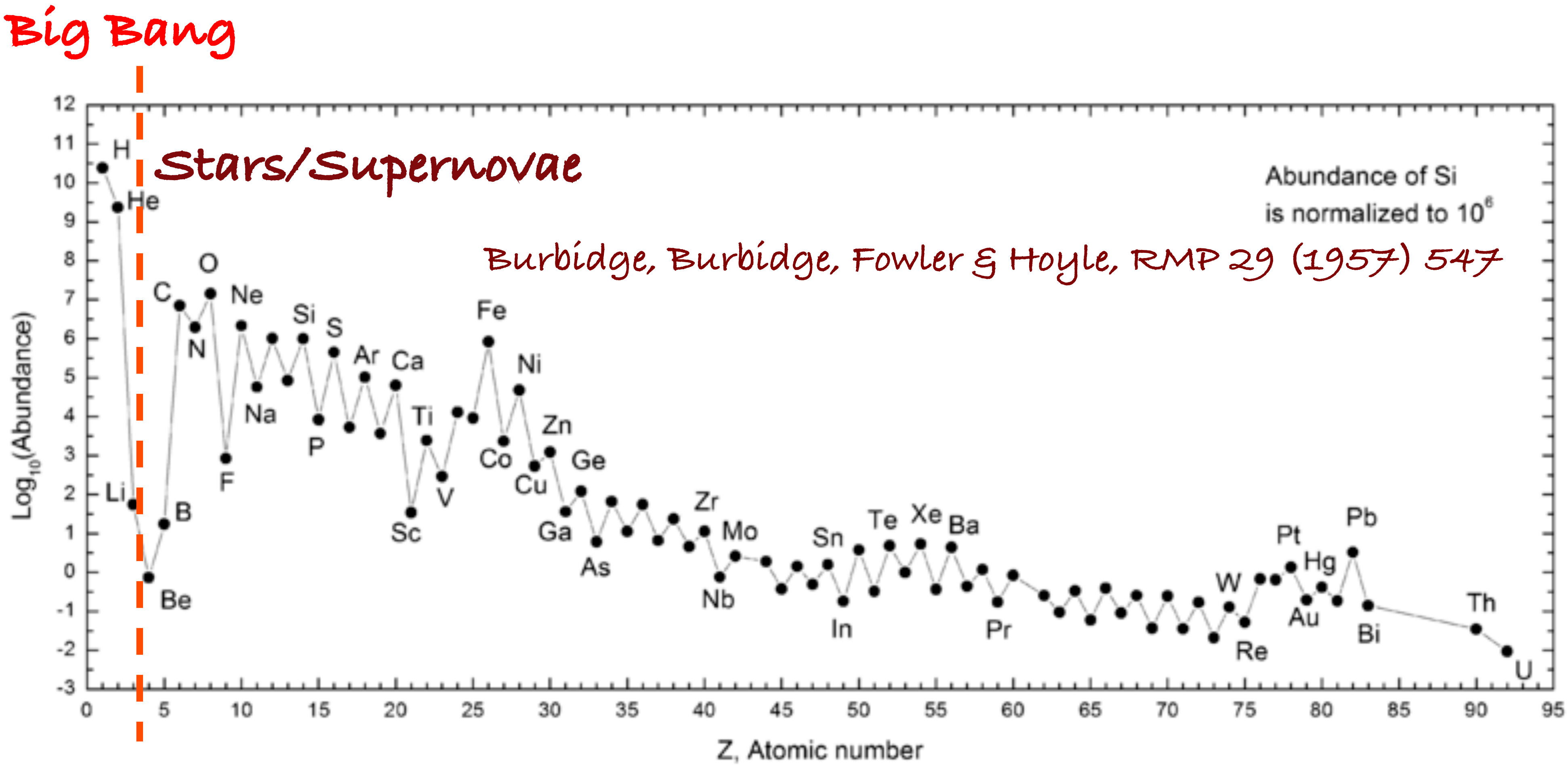
Big Bang Nucleosynthesis



The universe is made mainly of hydrogen (~75%) and helium (~25%) + traces of heavier elements



Where did all the elements come from?

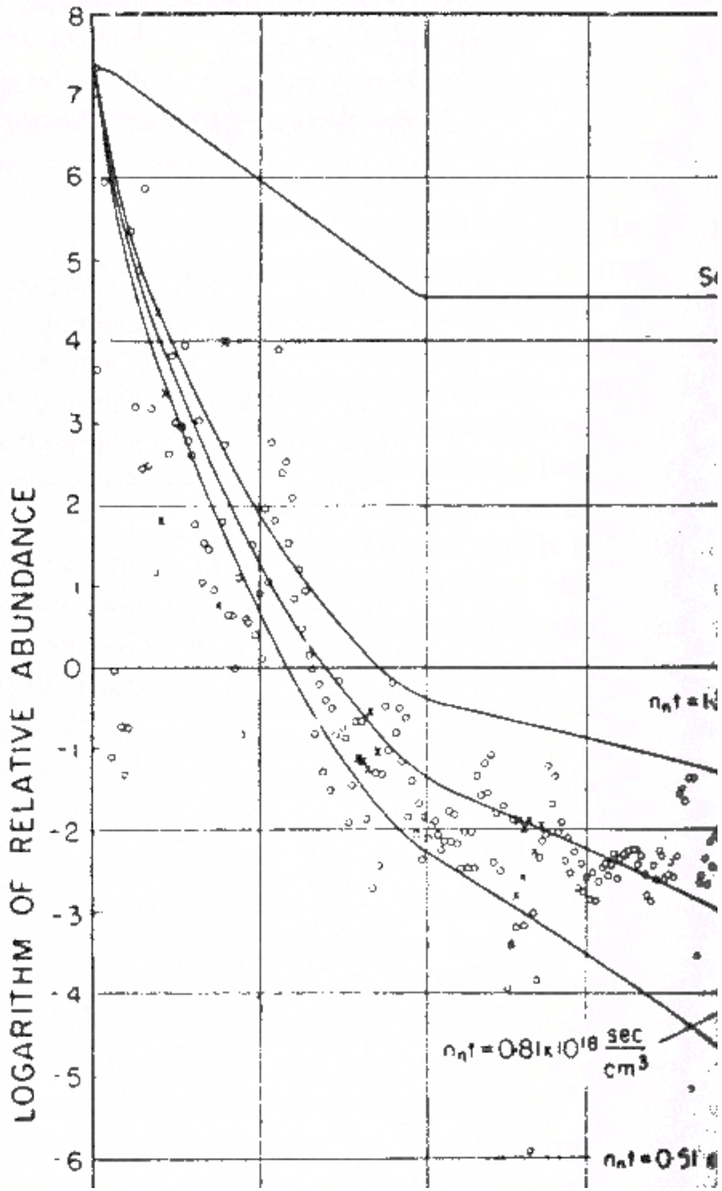


George Gamow is generally credited with having founded the theory of primordial nucleosynthesis and, as a corollary, predicted the temperature of the relic radiation

THE EVOLUTION OF THE UNIVERSE

By Dr. G. GAMOW
George Washington University, Washington, D.C.

THE discovery of the red shift in the spectra of distant stellar galaxies revealed the important fact that our universe is in the state of uniform expansion, and raised an interesting question as to whether the present features of the universe could be understood as the result of its evolutionary development, which must have started a few thousand million years ago from a homogeneous state of extremely high density and temperature. We conclude first of all that the relative abundances of various atomic species (which were found to be essentially the same all over the observed region of the universe) must represent the most ancient archæological document pertaining to the history of the universe. These abundances must have been established during the earliest stages of expansion when the temperature of the primordial matter was still sufficiently high to permit nuclear transformations to run through the entire range of chemical elements. It is also interesting to notice that the observed relative amounts of natural radioactive elements suggest that their nuclei must have been formed (presumably along with all other stable



The real story is that while Gamow had brilliant ideas, he could not calculate too well, so enlisted the help of a graduate student Ralph Alpher (who worked with Robert Herman)

Thermonuclear Reactions in the Expanding Universe

R. A. ALPHER AND R. HERMAN
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland*

AND

G. A. GAMOW
The George Washington University, Washington, D. C.

September 15, 1948

IT has been shown in previous work[1-3] that the observed relative abundances of the elements can be explained satisfactorily by consideration of the building up of nuclei by successive neutron captures during the early stages of the expanding universe. Because of the radioactivity of

[1] R. A. Alpher, H. A. Bethe, and G. A. Gamow, Phys. Rev. **73**, 803 (1948).
[2] R. A. Alpher, Phys. Rev. (in press).
[3] R. A. Alpher and R. C. Herman, Phys. Rev. (in press).

1) was published on 1 April 1948 … including Bethe (who had nothing to do with it) but leaving out Herman because he "… stubbornly refused to change his name to Delter"!

PHYSICAL REVIEW VOLUME 92, NUMBER 6 DECEMBER 15, 1953

Physical Conditions in the Initial Stages of the Expanding Universe*,†

RALPH A. ALPHER, JAMES W. FOLLIN, JR., AND ROBERT C. HERMAN
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland

(Received September 10, 1953)

The detailed nature of the general nonstatic homogeneous isotropic cosmological model as derived from general relativity is discussed for early epochs in the case of a medium consisting of elementary particles and radiation which can undergo interconversion. The question of the validity of the description afforded by this model for the very early super-hot state is discussed. The present model with matter-radiation interconversion exhibits behavior different from non-interconverting models, principally because of the successive freezing-in or annihilation of various constituent particles as the temperature in the expanding universe decreased with time. The numerical results are unique in that they involve no disposable parameters which would affect the time dependence of pressure, temperature, and density.

The study of the elementary particle reactions leads to the time dependence of the proton-neutron concentration ratio, a quantity required in problems of nucleogenesis. This ratio is found to lie in the range $\sim 4.5:1-\sim 6.0:1$ at the onset of nucleogenesis. These results differ from those of Hayashi mainly as a consequence of the use of a cosmological model with matter-radiation interconversion and of relativistic quantum statistics, as well as a different value of the neutron half-life.

The modern theory of primordial nucleosynthesis is based essentially on this paper … which followed the crucial observation by Hayashi (Prog. Theoret. Phys. 5 (1950) 224) that **neutrons and protons were in chemical equilibrium in the hot early universe**

Alpher's achievement was finally recognized when he was awarded the US National Medal of Science (2005):
"For his unprecedented work in the areas of nucleosynthesis, for the prediction that universe expansion leaves behind background radiation, and for providing the model for the Big Bang theory."

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: $p + \nu_e \leftrightarrow n + e^+$

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

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

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

Deuterium bottleneck: $T \sim 1 \rightarrow 0.07$ MeV

D created by $np \rightarrow D\gamma$

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

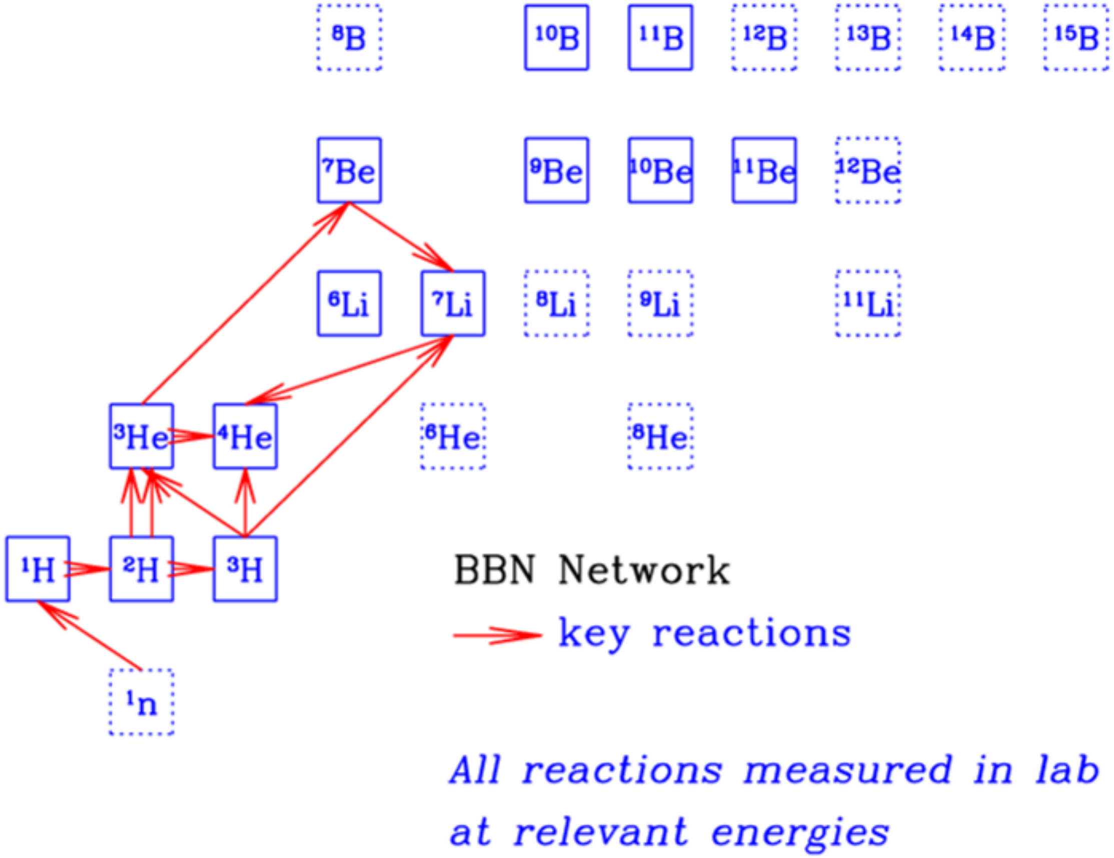
so nucleosynthesis halted until: $T_{\text{nuc}} \sim \Delta_D/\text{-}\ln(\eta)$

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

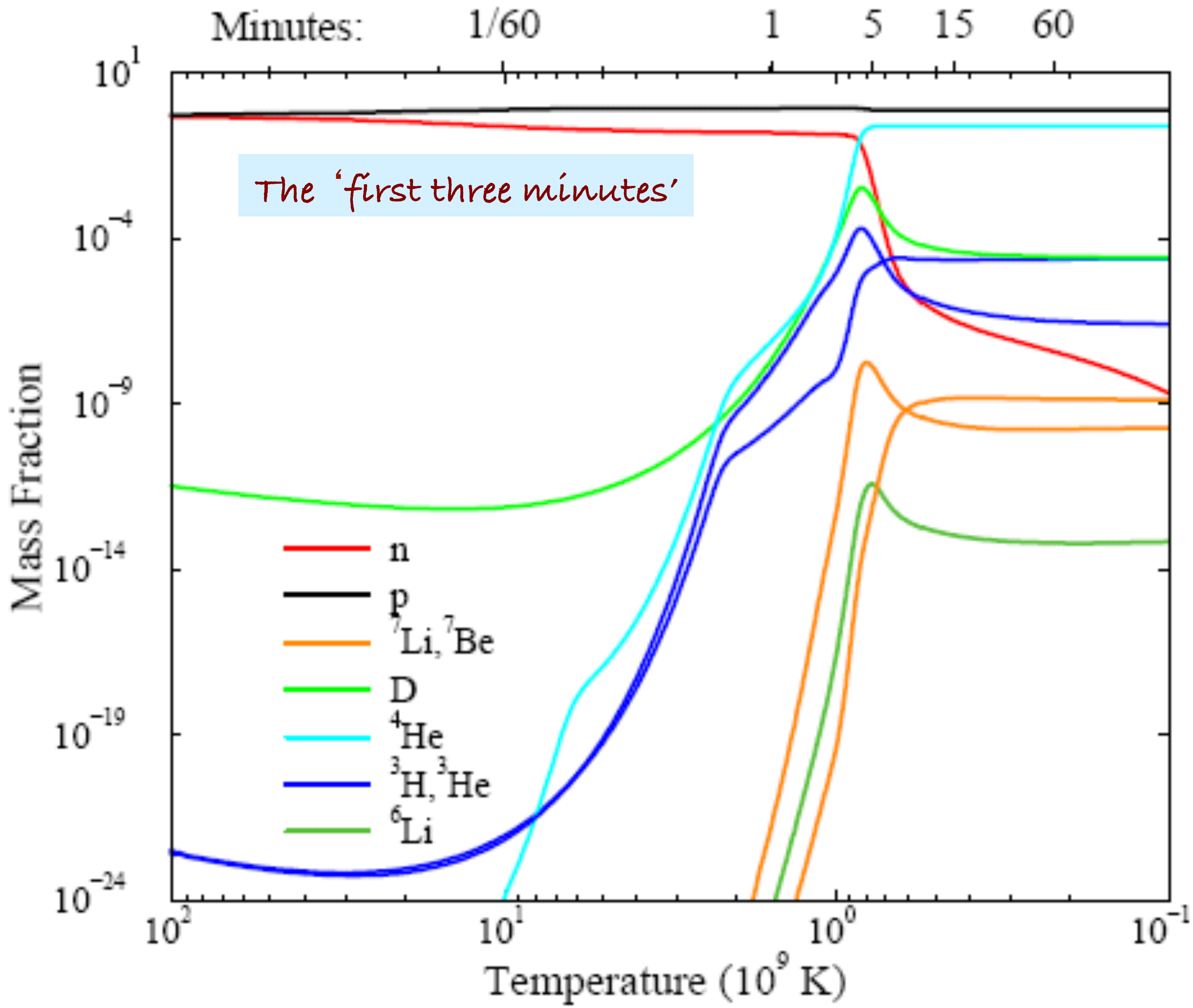
(meanwhile $n/p \rightarrow 1/7$ through neutron β-decay)

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

No heavier nuclei formed in the standard model ... must wait for stars to form after ~billion years and synthesise all the other nuclei in the universe (s-process, r-process, ...)



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



Minutes: 1/60 1 5 15 60
The 'first three minutes'
Mass Fraction
10^{1}
10^{-4}
10^{-9}
10^{-14}
10^{-19}
10^{-24}
n
p
^{7}Li, ^{7}Be
D
^{4}He
^{3}H, ^{3}He
^{6}Li
10^{2} 10^{1} 10^{0} 10^{-1}
Temperature (10^{9} K)

- 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 complete
  - 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

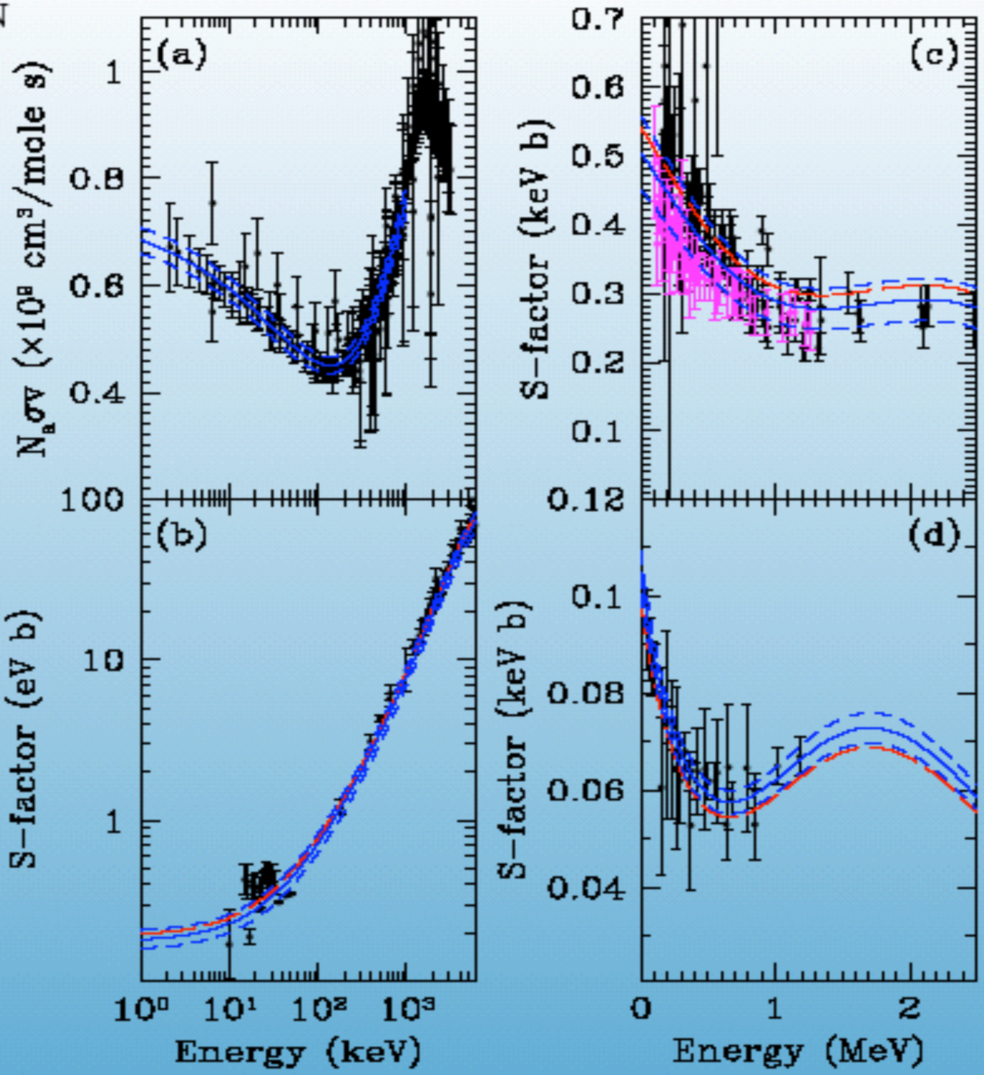
The neutron lifetime normalises the "weak" interaction rate: $\tau_n = 885.7 \pm 0.8$ s

(a recent measurement is 6.5σ lower ... not included by the PDG in the average)

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	

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



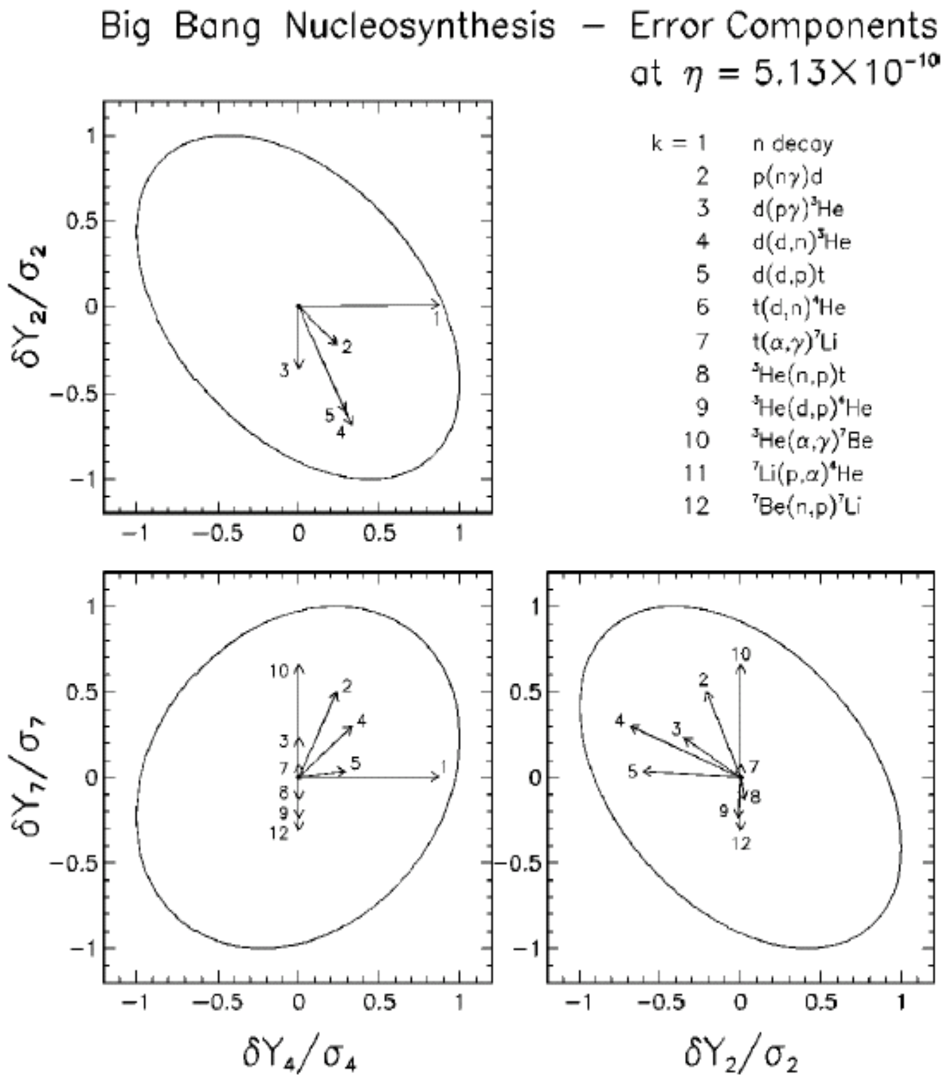
Uncertainties in synthesized abundances are *correlated* ... estimate using Monte Carlo methods

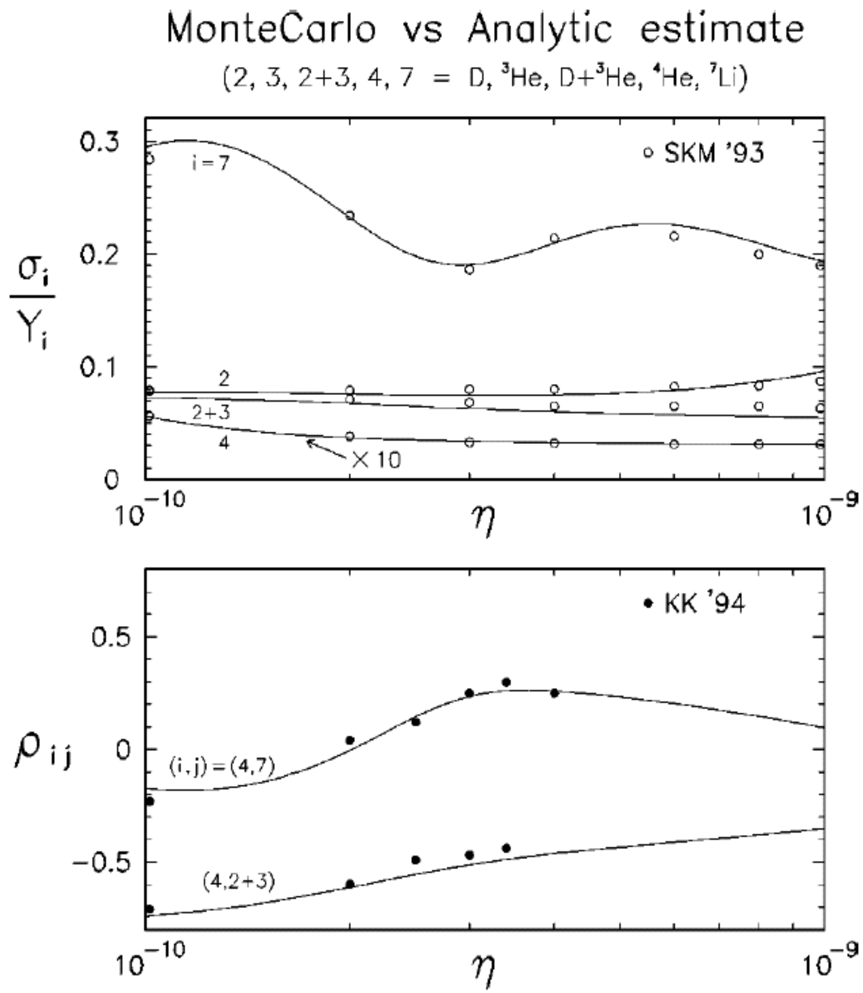
(Krauss, Romanelli '88; Smith, Kawano, Malaney '93; Krauss, Kernan '94; Cyburt, Fields, Olive '04)

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

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

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

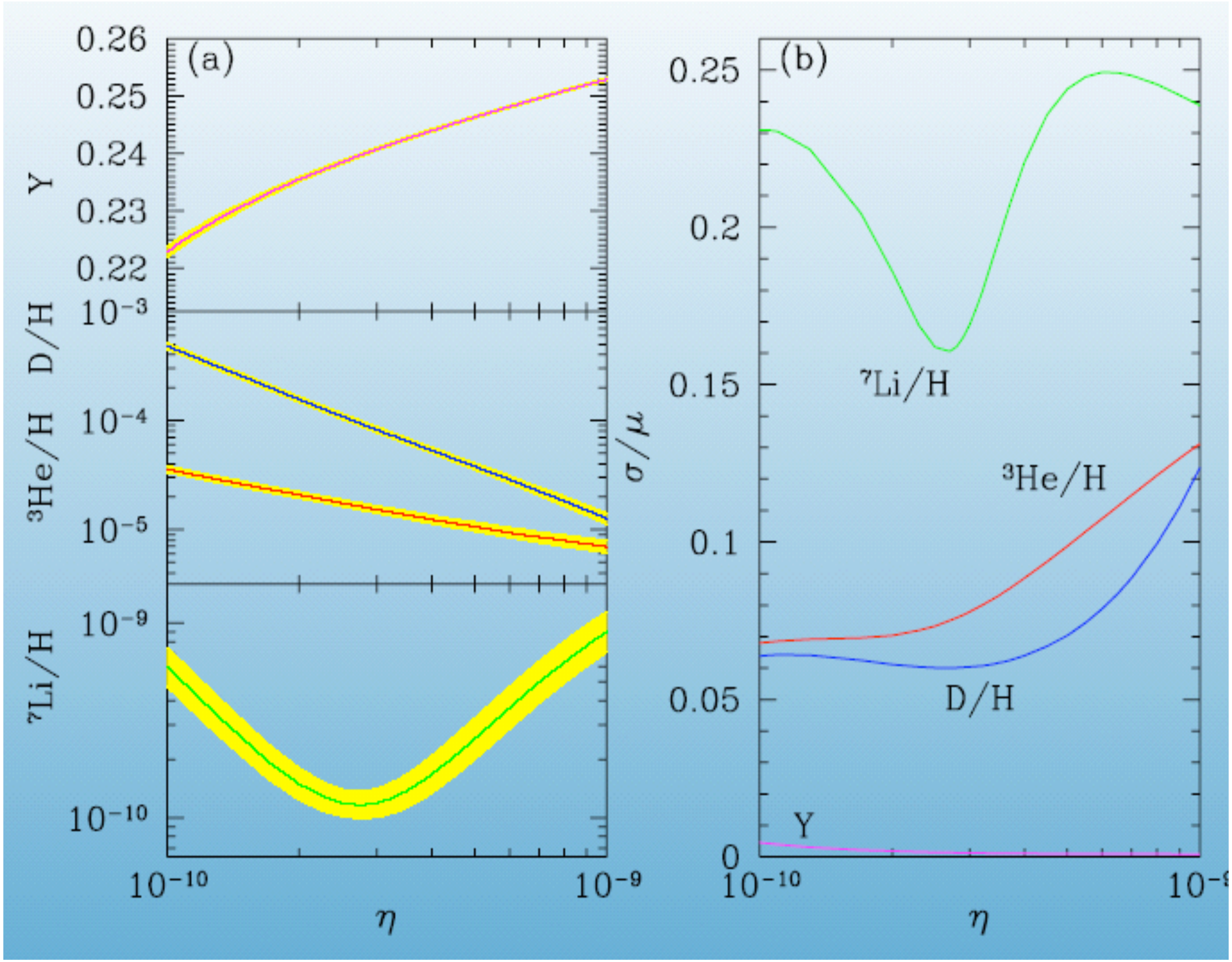




Fiorentini, Lisi, Sarkar, Villante (1998)

BBN Predictions

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



Nucleosynthesis without a computer

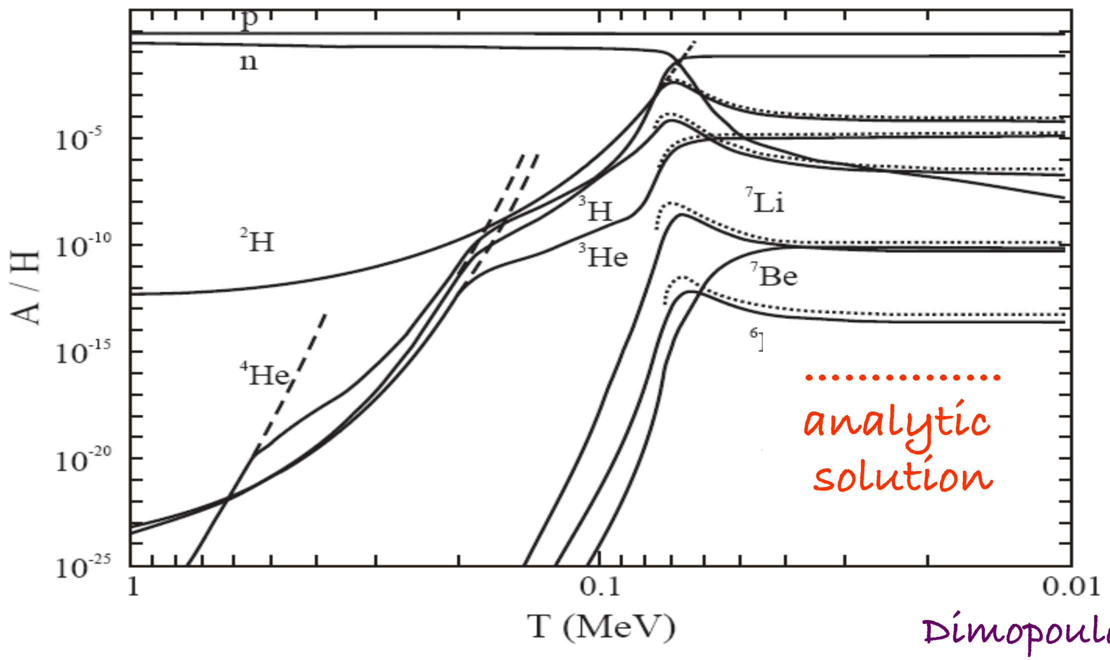
$$\frac{\mathrm{d}X}{\mathrm{d}t} = \underset{\text{source}}{J(t)} - \underset{\text{sink}}{\Gamma(t)X} \quad \Rightarrow \quad X^{\mathrm{eq}} = \frac{J(t)}{\Gamma(t)}$$

... but general solution is:

$$X(t) = \exp\left(-\int_{t_\mathrm{i}}^{t} \mathrm{d}t'\ \Gamma(t')\right)\left[X(t_\mathrm{i}) + \int_{t_\mathrm{i}}^{t} \mathrm{d}t'\ J(t')\ \exp\left(-\int_{t_\mathrm{i}}^{t} \mathrm{d}t''\ \Gamma(t'')\right)\right]$$

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

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



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 (1988)

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

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

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

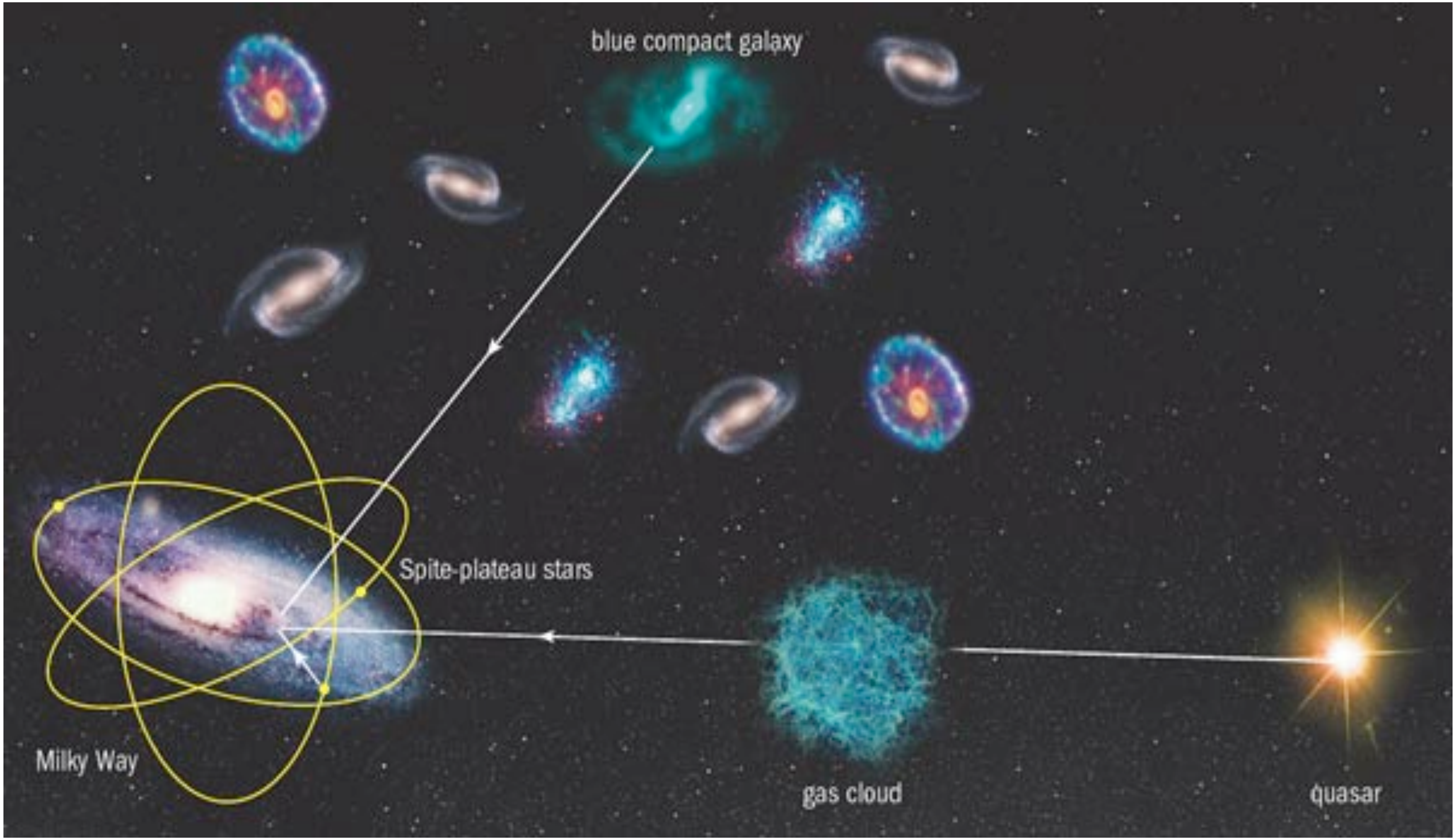
... can therefore employ simple χ^2 statistics to determine best-fit values and uncertainties (*faster* than Monte Carlo + Maximum Likelihood)

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

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

Lisi, Sarkar, Villante (2000)

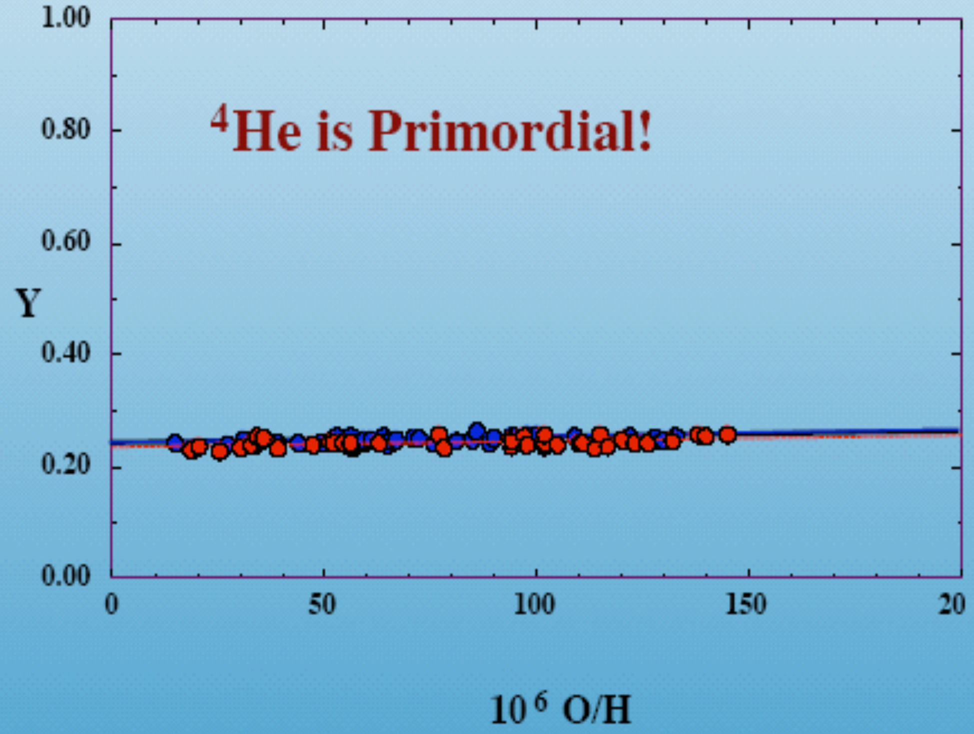
Inferring primordial abundances



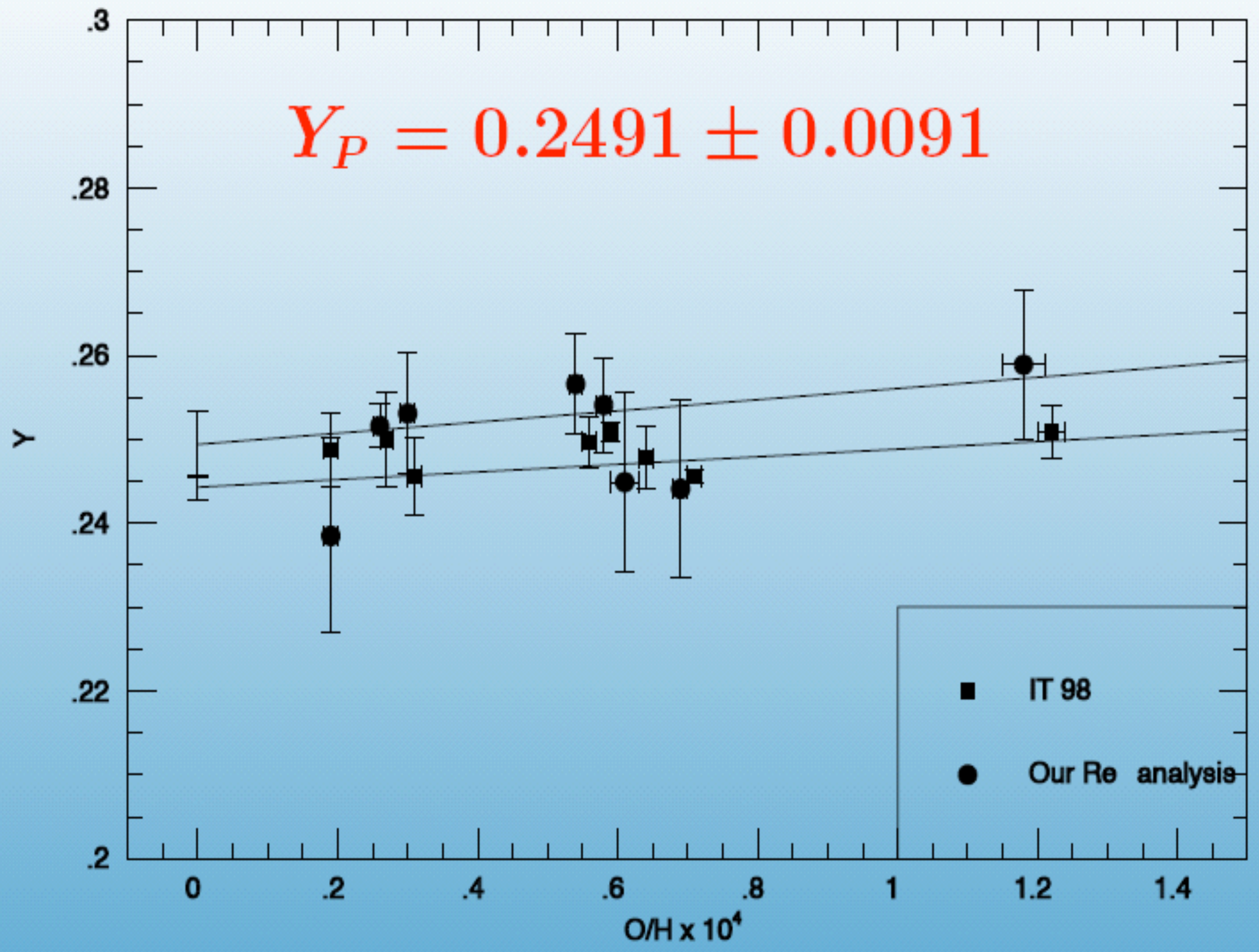
^{4}He

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

$$Y_P = Y(O/H \to 0)$$



This is the value (and uncertainty) presently recommended by the PDG



Olive & Skillman (2004)

Primordial deuterium

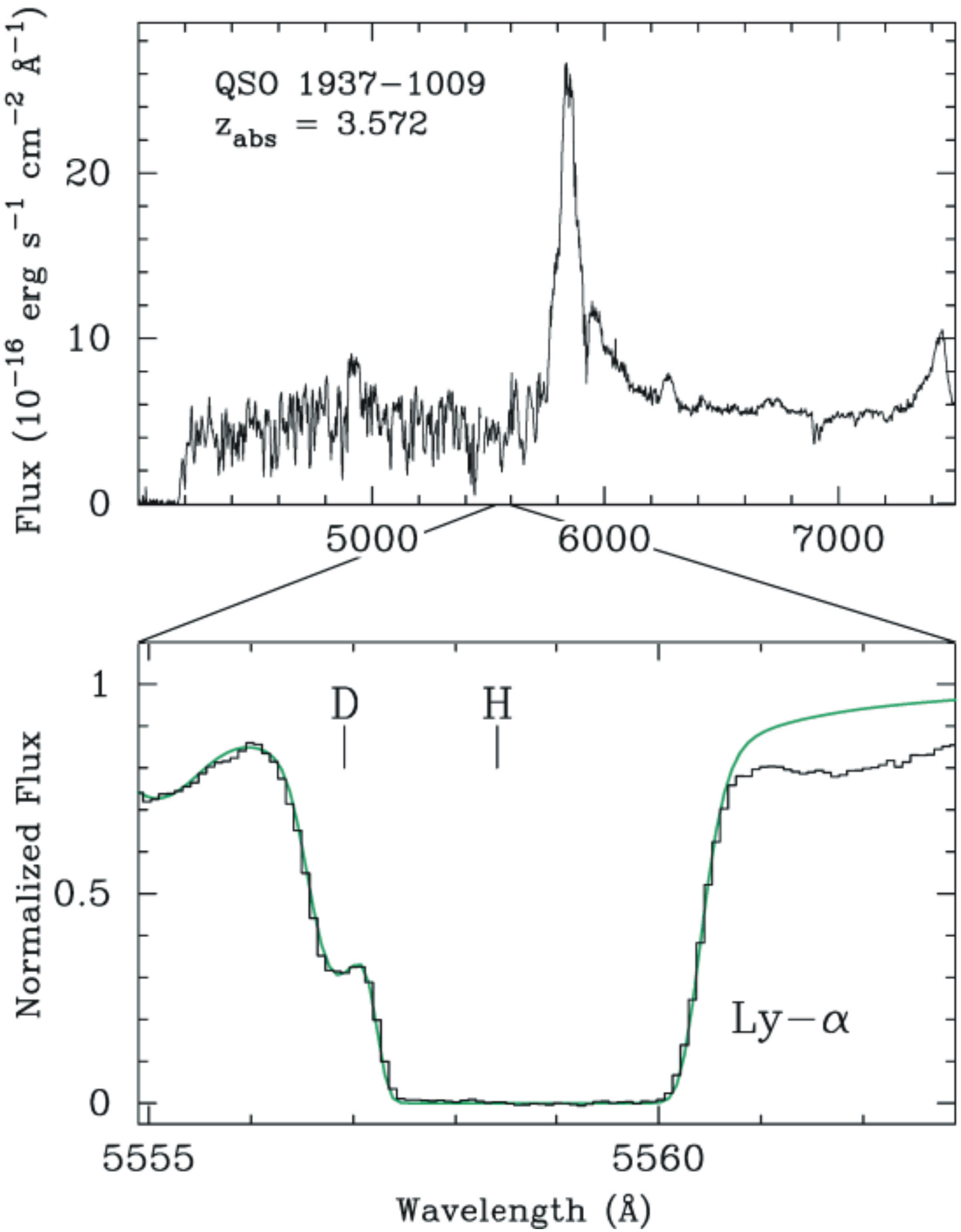
Look in Quasar Absorption Systems – low density clouds of gas seen in absorption along the lines of sight to distant quasars (when universe was only ~10% of its present age)

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

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

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

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

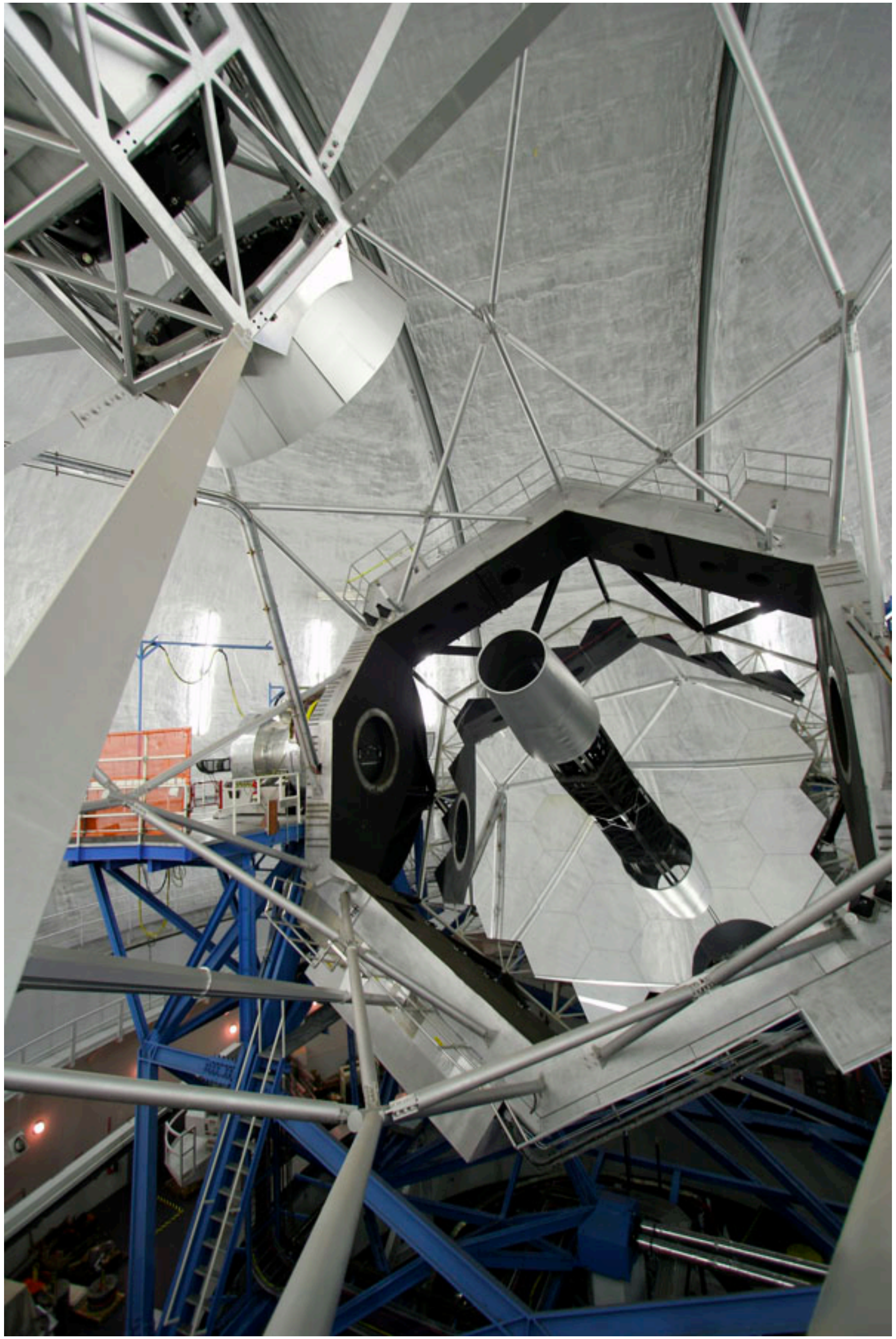


But:

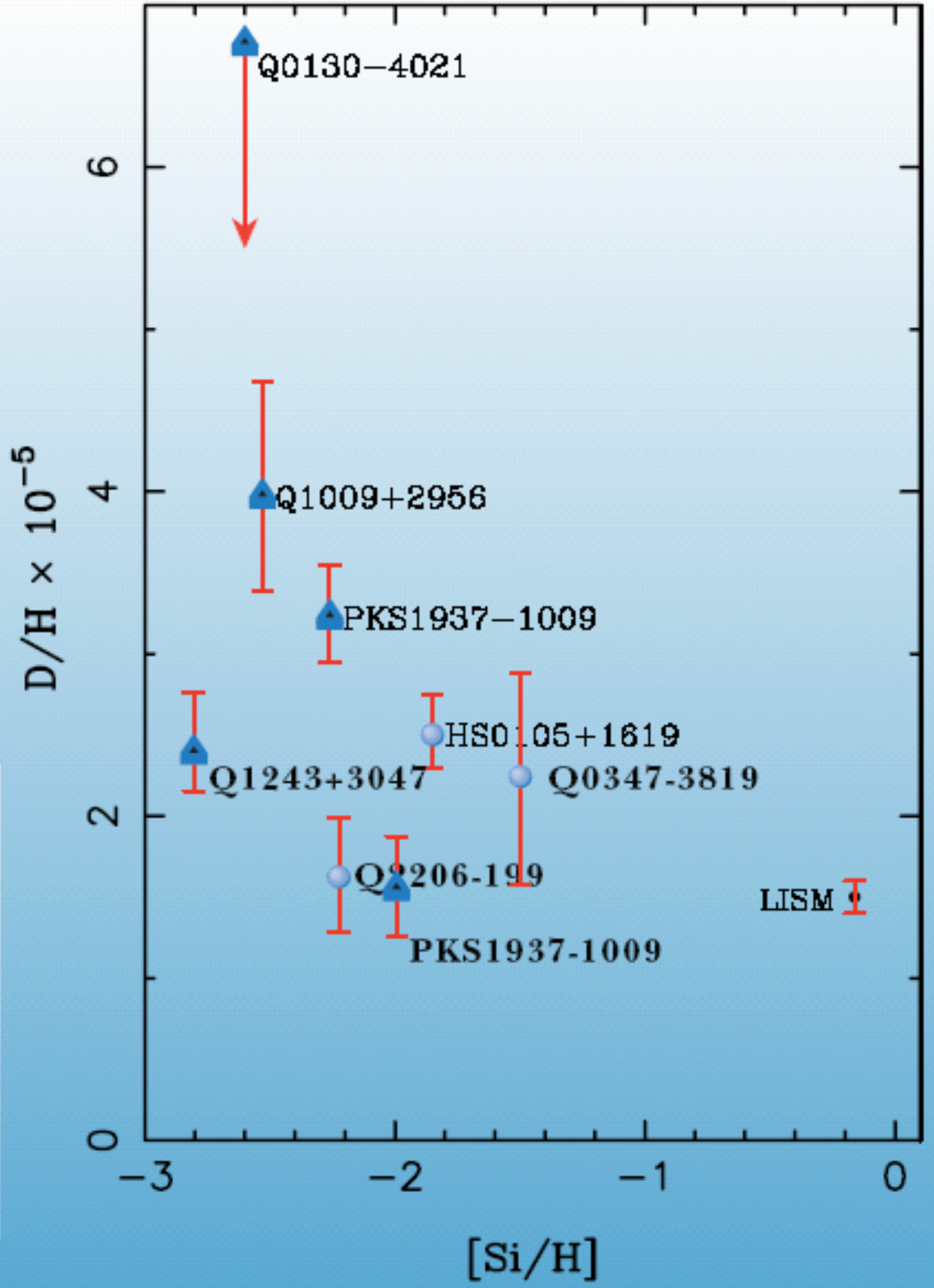
- Hard to find clean systems
- Do not resolve clouds
- Dispersion/systematics?

W. M. Keck Observatory

Spectra with the necessary resolution for such distant objects *can* be obtained with 10 m class telescopes … this has revolutionised the determination of the primordial D abundance



D/H abundances in Quasar apsorption systems



Is the dispersion real?

Is there a correlation with α/H?

Is there a correlation with density?

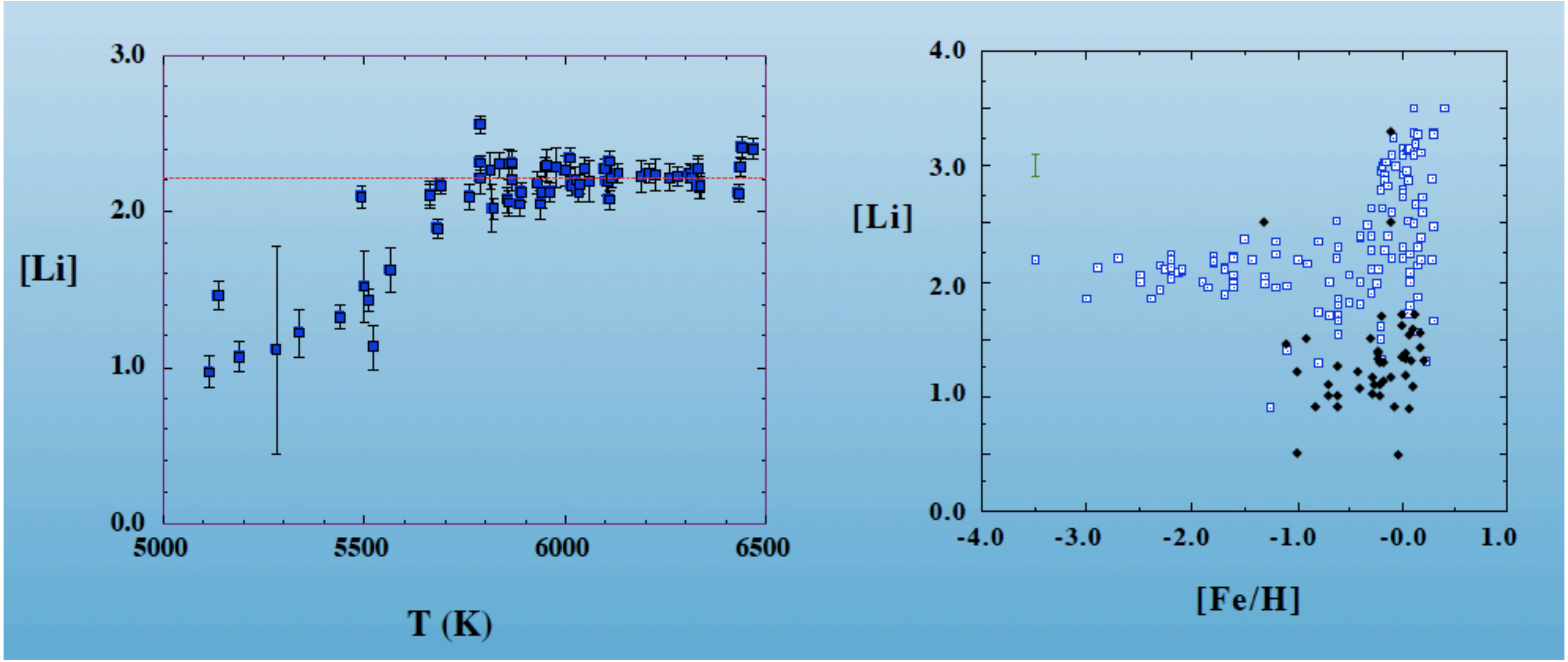
Evidence for evolution?

The observed scatter is *not* consistent with fluctuations about an average value!

Primordial Lithium

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

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



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

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

Inferred primordial abundances

^{4}He observed in extragalactic HII regions:

$$Y_\mathrm{p} = 0.249 \pm 0.009$$

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

$$\mathrm{D/H}|_\mathrm{p} = (2.84 \pm 0.26) \times 10^{-5}$$

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

$$\mathrm{Li/H}|_\mathrm{p} = (1.7 \pm 0.02^{+1.1}_{-0}) \times 10^{-10}$$

(^{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, J. Phys.G37 (2010) 075021)

The Cosmic Microwave Background

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

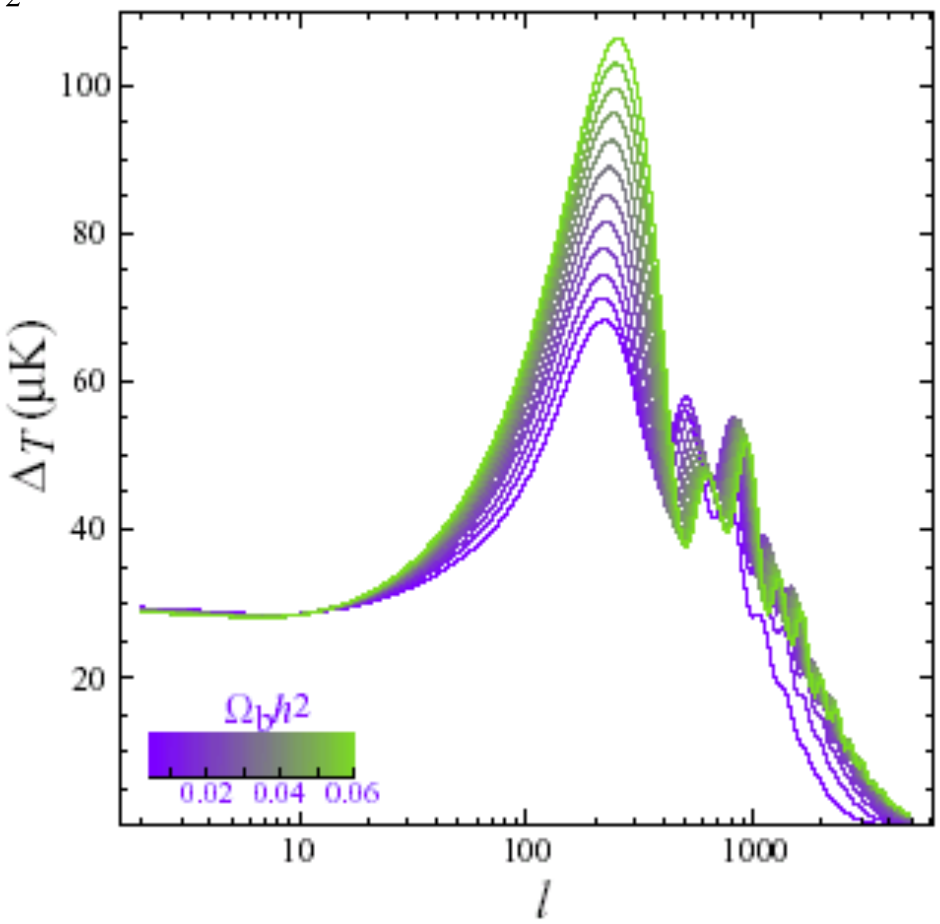
Acoustic oscillations in (coupled) photon-baryon fluids imprint features at small angles ($< 1^o$) in angular power spectrum

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

e.g. ratio of 2nd/1st peak $\Rightarrow$ measure of baryon density

WMAP-5 best-fit:

$$\Omega_B h^2 = 0.02273 \pm 0.00062$$



Bond & Efstathiou, ApJ 285 (1984) L45
Dodelson & Hu [astro-ph/0110414]

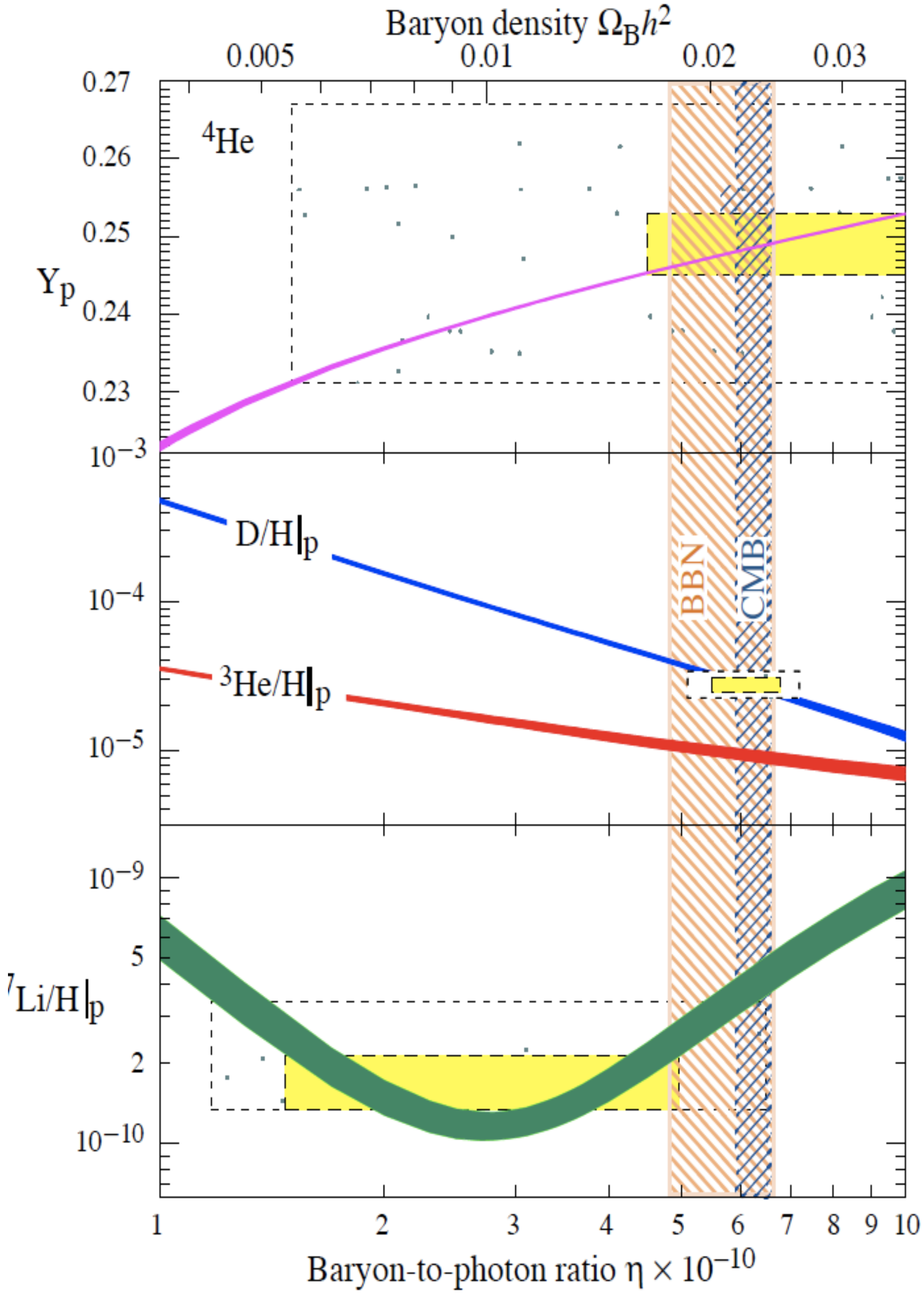
BBN versus CMB

$\eta_{\rm BBN}$ is in agreement with $\eta_{\rm CMB}$
allowing for large systematic
uncertainties in the inferred

$$4.7 \leq \eta_{10} \leq 6.5 \ (95\% \ \mathrm{CL})$$

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:
neutralino? technibaryon? axion? ...



Particle data Group: Fields & Sarkar (2010)

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 or dark energy)

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!