# Physics 662

Particle Ph[illegible]henology

March 9, 2004

NOTE - I am having trouble with making PDF files, so some images on this file are corrupted. - JEB

# Particle Physics and Cosmology

- Hubble's law and the expanding universe ✓
- Cosmological Models ✓
- Friedmann equation ✓
- Cosmic microwave radiation: the hot Big Bang
- Radiation and matter eras
- Nucleosynthesis in the Big Bang
- Baryon-antibaryon asymmetry
- Dark matter
- Inflation

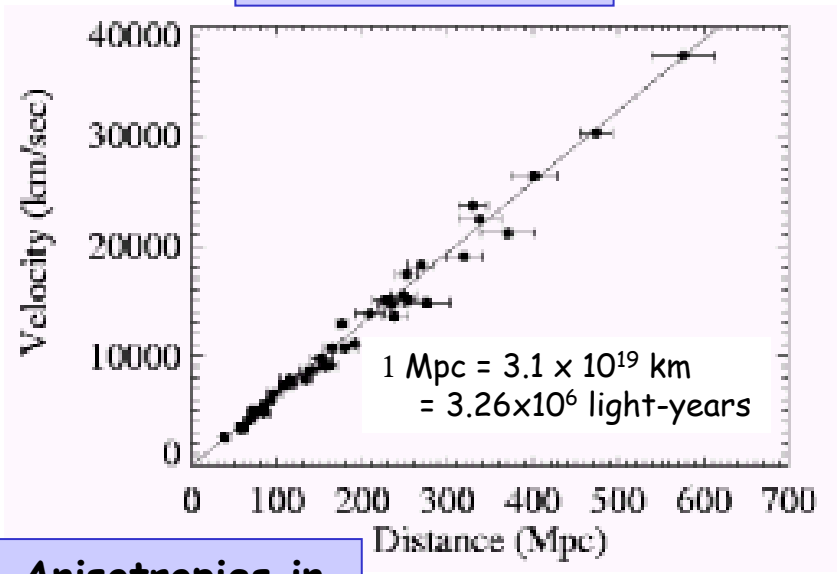
- References: Donald H. Perkins, Introduction to High Energy Physics, Fourth Edition
  Bergstrom and Goobar, Cosmology and Particle Astrophysics

# Particle Physics and Cosmology

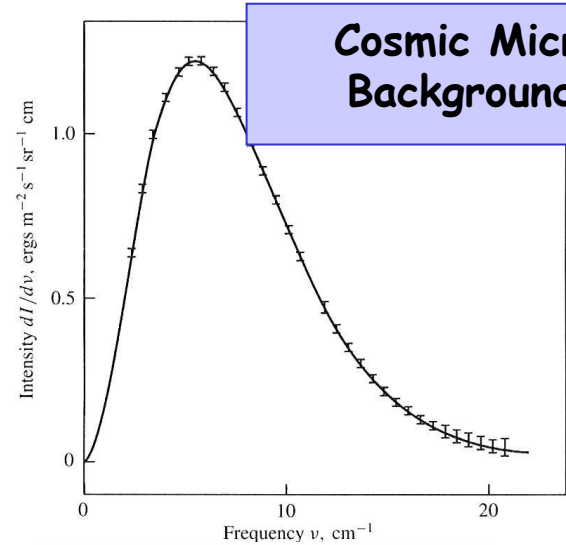
- The 'Standard Model' of the early universe is support by the following understood pieces of observational evidence
  - Hubble's Law
  - the cosmic microwave background radiation
  - the cosmic abundances of the light elements
  - anisotropies in the background radiation

# Four Evidences for the Big Bang

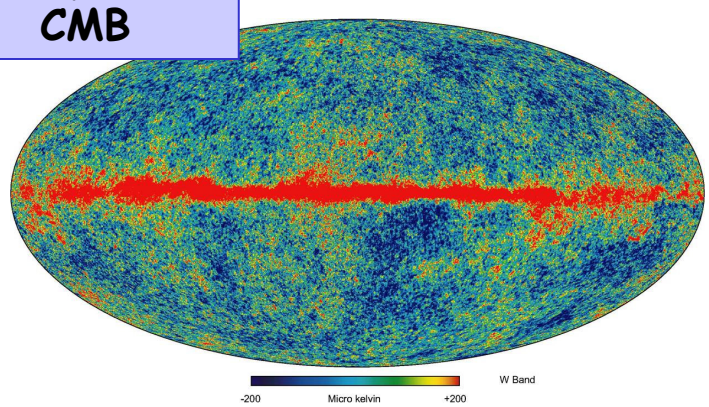
**Hubble's Law**



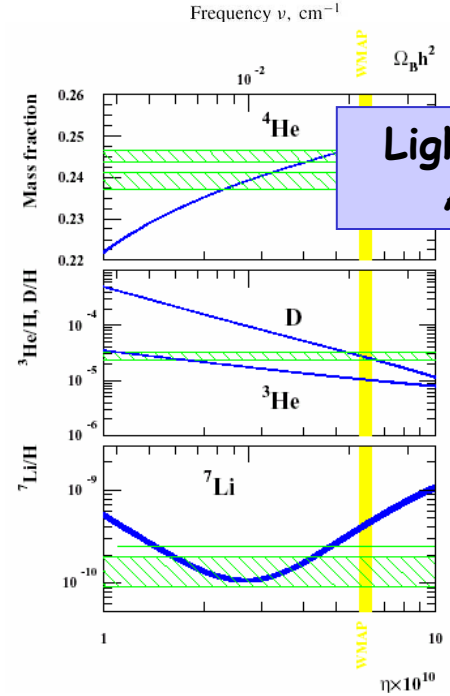

**Cosmic Microwave Background(T=2.7K)**




**Anisotropies in CMB**




**Light Element Abundances**



# Friedmann Equation

- Einstein's equations can be solved for a homogeneous and isotropic Universe to yield the temporal development of the Universe, known as the Friedmann equation

$$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G_N \rho}{3} - \frac{Kc^2}{R^2} + \frac{\Lambda}{3}$$

- Note, to close universe (K=0) for a null cosmological constant ($\Lambda$=0), we require:

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

# Friedmann Equation

## critical density ($\rho_c$)

- What matter density will just close the Universe (for $\Lambda$=0)?

if $$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G_N \rho}{3}$$ then K=0

$$\rho_c = \frac{3}{8\pi G_N} H_0^2 = 1.88 \times 10^{-26} h_0^2 \text{ kg m}^{-3}$$

$$H_0 = 100 h_0 \text{ km s}^{-1} \text{ Mpc}^{-1}$$
$$h_0 = 0.7 \pm 0.1$$

- The actual density is related to the critical density

$$\Omega \equiv \frac{\rho}{\rho_c} = 1 + \frac{K c^2}{H^2 R^2}$$

- so we have they relations

| | |
|---|---|
| K = 0 | $\Omega$ = 1 |
| K = 1 | $\Omega$ > 1 |
| K = -1 | $\Omega$ < 1 |

# Friedmann Equation

## actual density

- Visible matter

$$\rho_{\rm lum} \simeq 2 \times 10^{-29}\ {\rm kg\ m^{-3}} \qquad \Omega_{\rm lum} \simeq 0.003 h_0^{-2}$$

- Density of baryons (most invisible) inferred form baryogenisis

$$\rho_{\rm baryon} = (3 \pm 1.5) \times 10^{-28}\ {\rm kg\ m^{-3}} \qquad \Omega_{\rm baryon} \simeq (0.01\text{–}0.03) h_0^{-2}$$

- Total matter density (from galactic rotation curves)

$$\rho_m \geq 5 \times 10^{-27}\ {\rm kg\ m^{-3}} \qquad \Omega_m \geq 0.3$$

- Conclusions
  - most baryonic matter is non-luminous and most matter is non-baryonic

# Cosmic Microwave Radiation: the Hot Big Bang

- Even though matter now dominates the Universe, earlier radiation would have dominated

  $\rho_m \propto R^{-3}$

  $\rho_r \propto R^{-4}$, due to the redshift of the radiation

- Early Universe, radiation dominant period

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G_N \rho}{3} - \frac{Kc^2}{R^2} + \frac{\Lambda}{3}$$

the energy density term will dominate over the K and $\Lambda$ terms

$$\dot{R}^2 = \frac{8\pi G_N}{3}\rho_r R^2$$

$$\frac{\dot{\rho}_r}{\rho_r} = -\frac{4\dot{R}}{R} = -4\left(\frac{8\pi G_N \rho_r}{3}\right)^{1/2}$$

# Cosmic Microwave Radiation: the Hot Big Bang

$$\frac{\dot{\rho}_r}{\rho_r} = -\frac{4\dot{R}}{R} = -4\left(\frac{8\pi G_N \rho_r}{3}\right)^{1/2}$$

integrating:

$$\rho_r = \left(\frac{3c^2}{32\pi G_N}\right)\frac{1}{t^2}$$

a photon gas in equilibrium:

$$\rho_r = aT^4 = \frac{4\sigma}{c}T^4 = \left(\frac{\pi^4}{15}\right)\frac{(kT)^4}{\pi^2\hbar^3c^3}$$

where the Stefan-Boltzmann constant is $\sigma = \pi^2 k^4/60\hbar^3c^2$

leading to $kT = \left(\frac{45\hbar^3c^5}{32\pi^3 G_N}\right)^{1/4}\frac{1}{t^{1/2}} \approx \frac{1\ \mathrm{MeV}}{t^{1/2}}$ or $T \approx \frac{10^{10}\ \mathrm{K}}{t^{1/2}}$

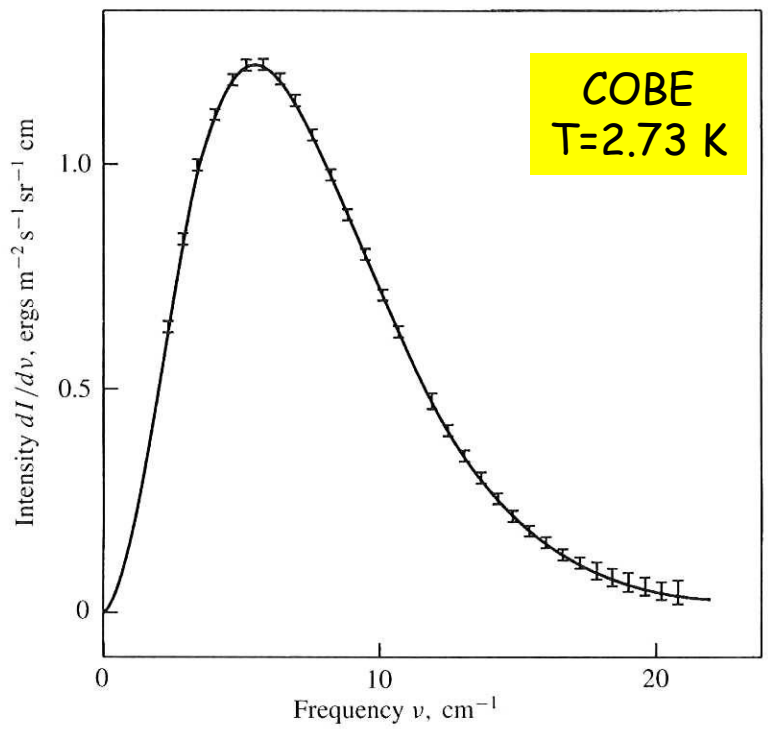
(t in seconds)

for $t_0 \sim 10^{10}$ years $\sim$ $3\times 10^{17}$ seconds $T \approx 10^{10}\ \mathrm{K} / 5 \times 10^8 \sim 20\ \mathrm{K}$

# Cosmic Microwave Radiation: the Hot Big Bang

- The 20 K estimate is expected to be an overestimate since the radiation will cool more quickly during the matter dominated era

- Since $\rho_m \propto R^{-3}$ ( while $\rho_r \propto R^{-4}$), and the universe expands as $t^{2/3}$ during the matter dominated era, kT of the radiation goes like $t^{-2/3}$ during that era



# Vacuum Dominated Era

- We now have discovered we reside in a vacuum dominated universe (dark energy)

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G_N \rho}{3} - \frac{Kc^2}{R^2} + \frac{\Lambda}{3}$$

- During this era:

$$R(t) \propto e^{\sqrt{\Lambda/3}t}$$

- Exponential Expansion!!

# Cosmic Microwave Radiation: the Hot Big Bang

- Energy density of the photons

$$N(E)dp = \frac{p^2 dp}{\pi^2 \hbar^3 [\exp(E/kT) - 1]} \left(\frac{g_\gamma}{2}\right)$$

$$N_\gamma = \frac{2.404}{\pi^2} \left(\frac{kT}{\hbar c}\right)^3 = 410.9 \left(\frac{T}{2.726}\right)^3 = 411 \text{ cm}^{-3}$$

$$\rho_r = 0.261 \text{ MeV m}^{-3}$$

or

$$\rho_r / c^2 = 4.65 \times 10^{-31} \text{ kg m}^{-3}$$

which is 4 orders of magnitude below the matter density

# Cosmic Microwave Radiation: the Hot Big Bang

- Energy density of the fermions
  - we must consider the contribution of fermions to the energy density

$$N(E)dp = \frac{p^2 dp}{\pi^2 \hbar^3 [\exp(E/kT) + 1]} \left(\frac{g_f}{2}\right)$$

  - In the relativistic limit, $kT \gg mc^2$

$$\rho_f = \frac{7}{8}\left(\frac{\pi^4}{15}\right)\frac{(kT)^4}{\pi^2 \hbar^3 c^3}\left(\frac{g_f}{2}\right)$$

- so $\rho_r + \rho_f = \left(\frac{\pi^4}{15}\right)\frac{(kT)^4}{\pi^2 \hbar^3 c^3}\ \frac{1}{2}\left(g_\gamma + \frac{7}{8}\sum g_f\right)$

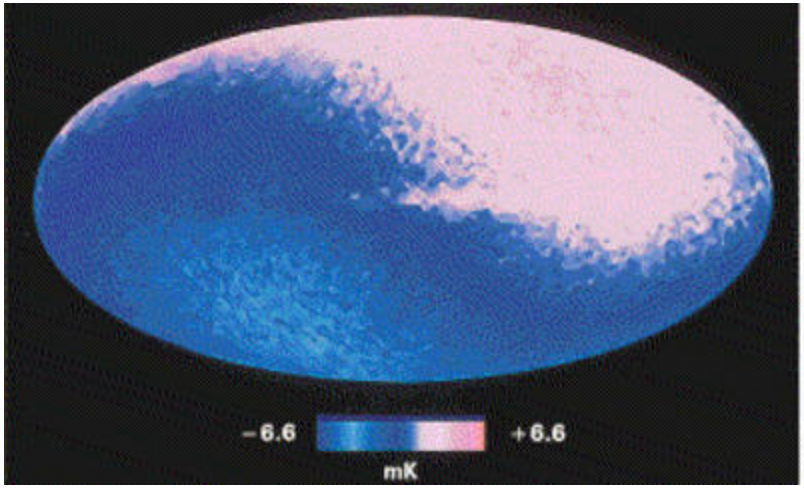
# Cosmic Microwave Radiation: the Hot Big Bang

- All the fermions and bosons of the Standard Model would have been created in the Big Bang, as long as the temperature were high enough.
- As expansion lowered the temperature, heavy particles were lost through decay
- When the temperature fell below about 100 MeV, even the relatively light antinucleons annihilated away, leaving a residue of nucleons
- Today, the relativistic fermions contributing to the energy density are the electron and the three neutrinos, and their antiparticles. Therefore $\Sigma g_f = 4+2+2+2 = 10$,

so $N = \frac{1}{2}\left(g_\gamma + \frac{7}{8}\sum g_f\right) = 43/8$

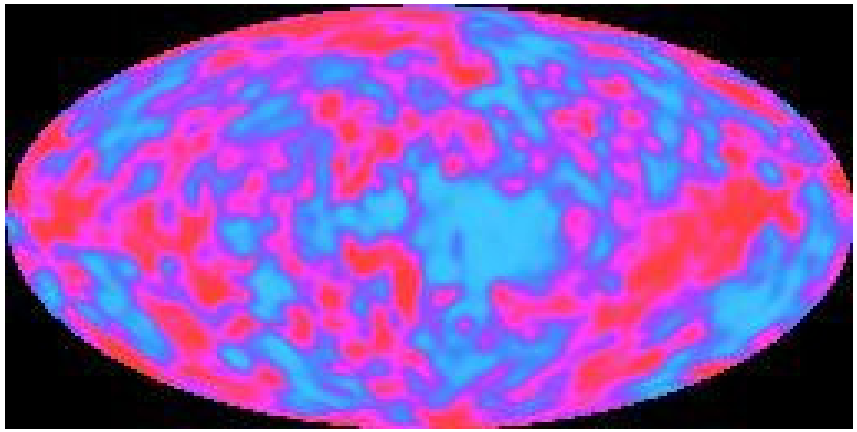
- so $\rho_r + \rho_f = {}^{43}/_{8} \left(\frac{\pi^4}{15}\right) \frac{(kT)^4}{\pi^2 \hbar^3 c^3}$ and $T \approx \frac{6.6 \times 10^9 \text{ K}}{t^{1/2}}$

# Cosmic Microwave Radiation: the Hot Big Bang




milli-Kelvin fluctuations

micro-Kelvin fluctuations



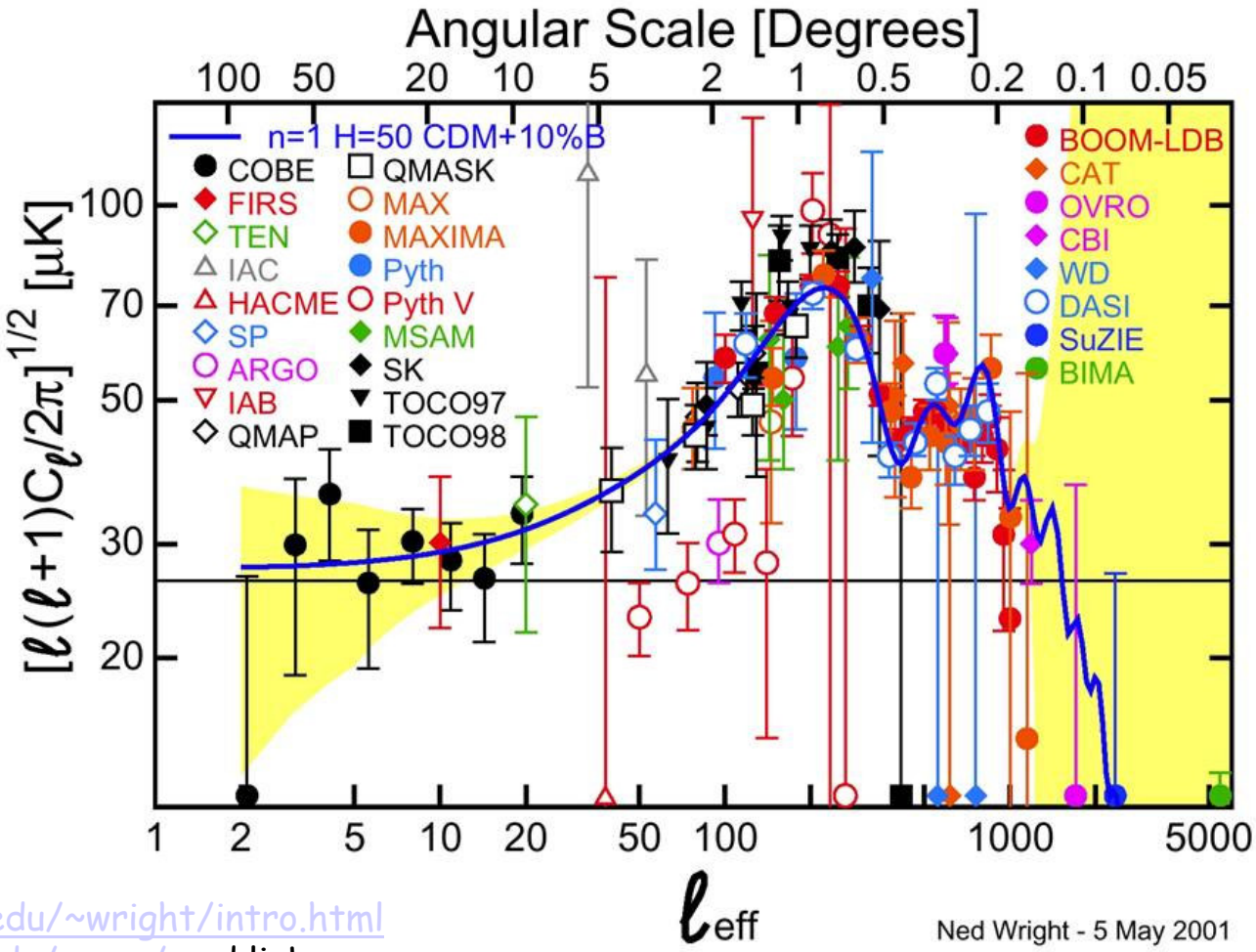
We can quantify these fluctuations ⇒

# Cosmic Microwave Radiation: the Hot Big Bang

The Moments

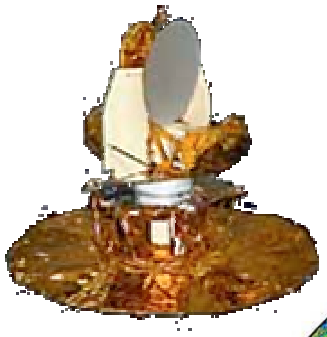
$$\frac{\Delta T(\theta,\phi)}{T} = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta,\phi).$$

$$C_l = \frac{1}{2l+1}\sum_m |a_{lm}|^2$$

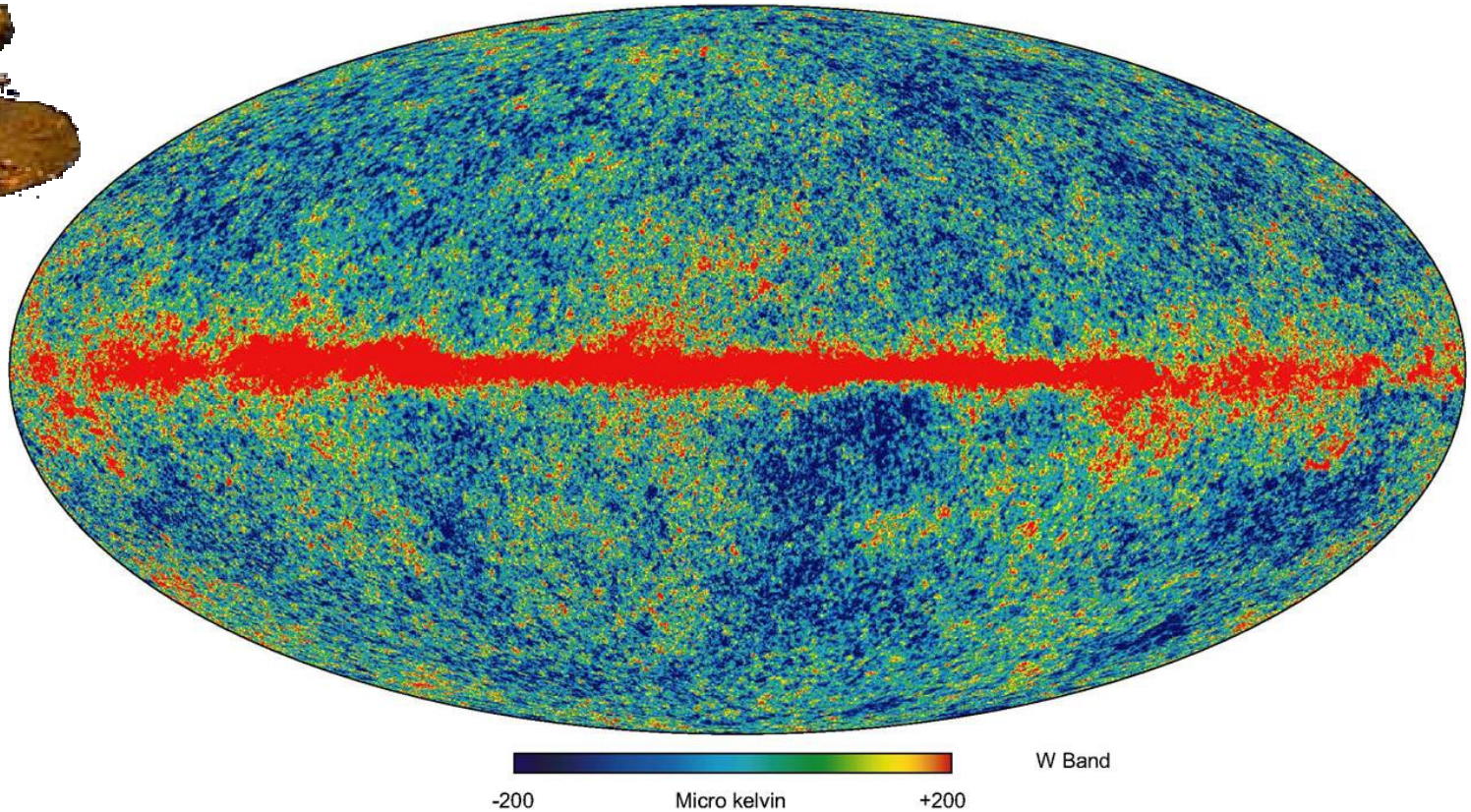



See http://www.astro.ucla.edu/~wright/intro.html and http://www.hep.upenn.edu/~max/ and links therein

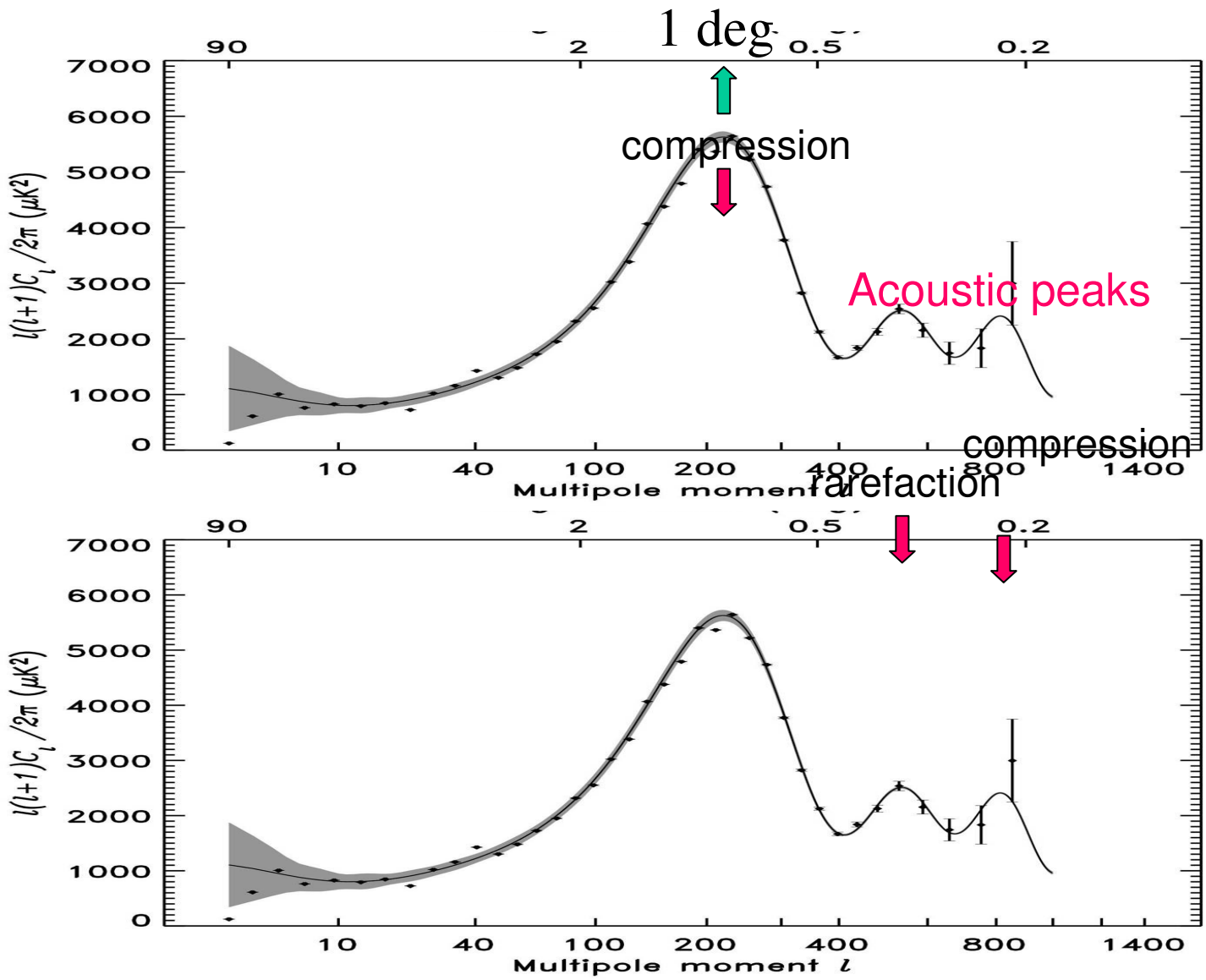
# Cosmic microwave background radiation



WMAP, 2003



# Cosmic Microwave Background



# WMAP fits

WMAP only (TT+TE), flat LCDM (Spergel et al. 2003)

CMB appears to be Gaussian. (Komatsu et al.)

- 15% of CMB was re-scattered in a reionized universe.
- The estimated reionization redshift ~20, or 200 million years after the Big-Bang.

## Flat LCDM still fits:

6 parameters fit *1348 points*

$$\frac{\chi^2}{\nu} = \frac{1431}{1342} = 1.07$$

DM density $(2.25 \pm 0.38) \times 10^{-27}$ Kg/m$^3$

atomic density $(2.7 \pm 0.1) \times 10^{-7}\, cm^{-3}$

$\eta = (6.5^{+0.4}_{-0.3}) \times 10^{-10}$

Age at decoupling $372 \pm 14\, Kyr$

Age $13.4 \pm 0.3$ Gyr

$\sigma_8 = 0.9 \pm 0.1$

$z_{reion} \approx 17$

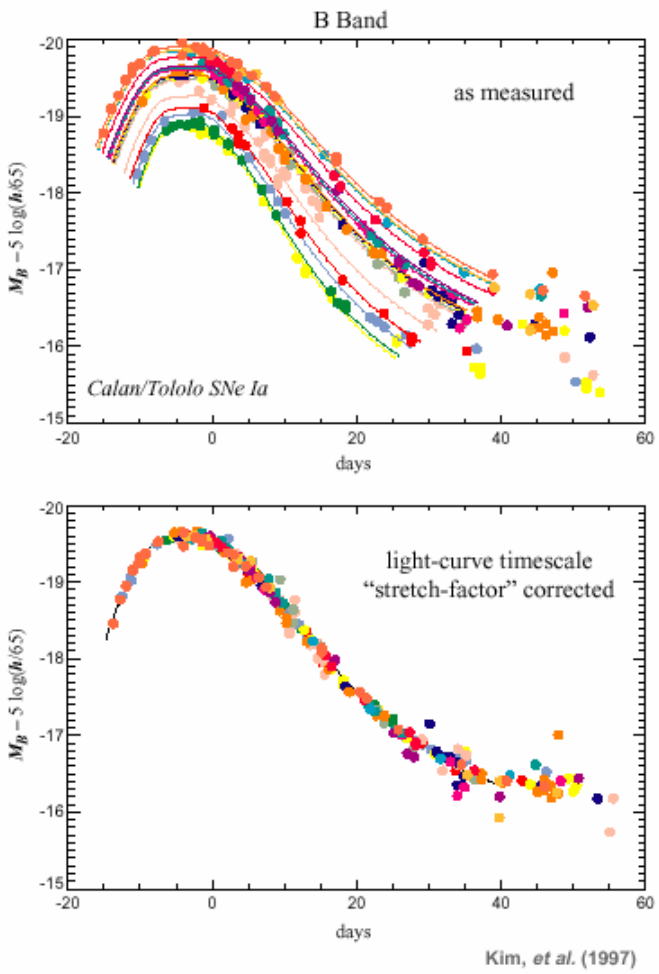
$1\sigma$ marginalized

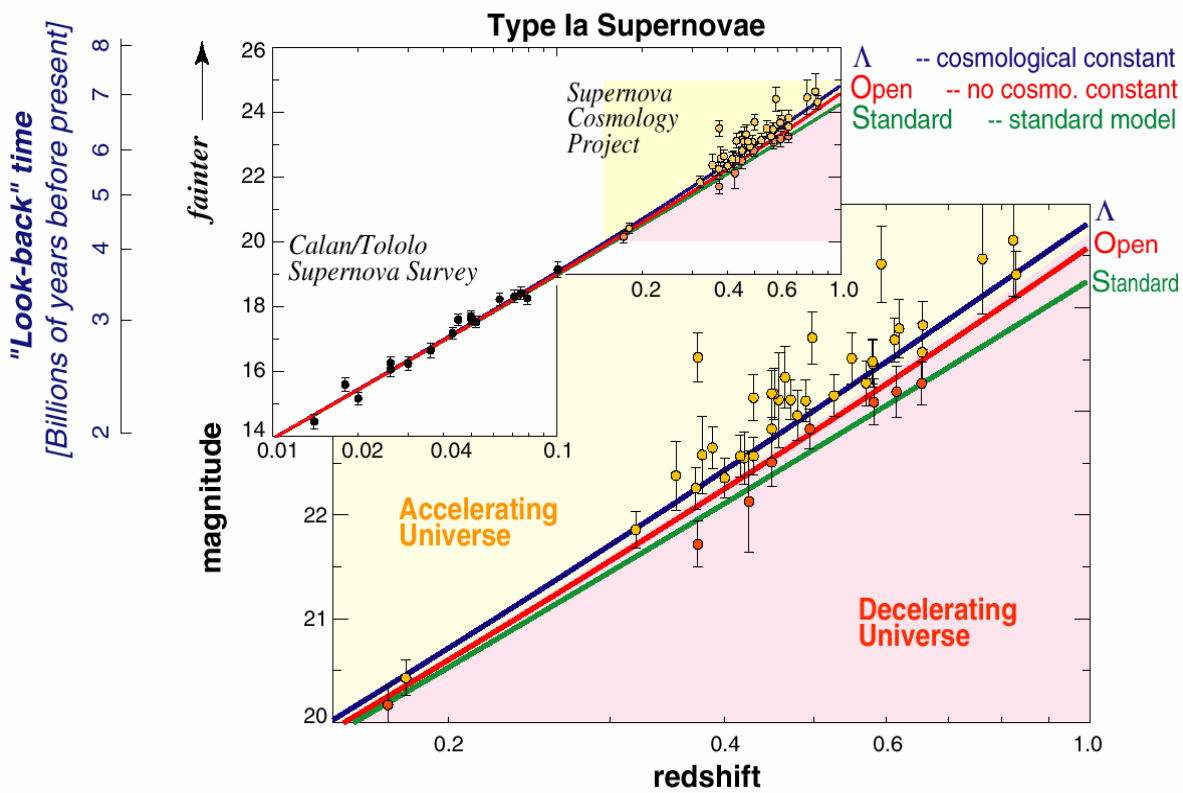
**Fits not only the CMB but also a host of other cosmological observables.**

# More on the Expansion of the Universe

Type Ia SN to measure the expansion rate.

Expansion rate appears to be increasing

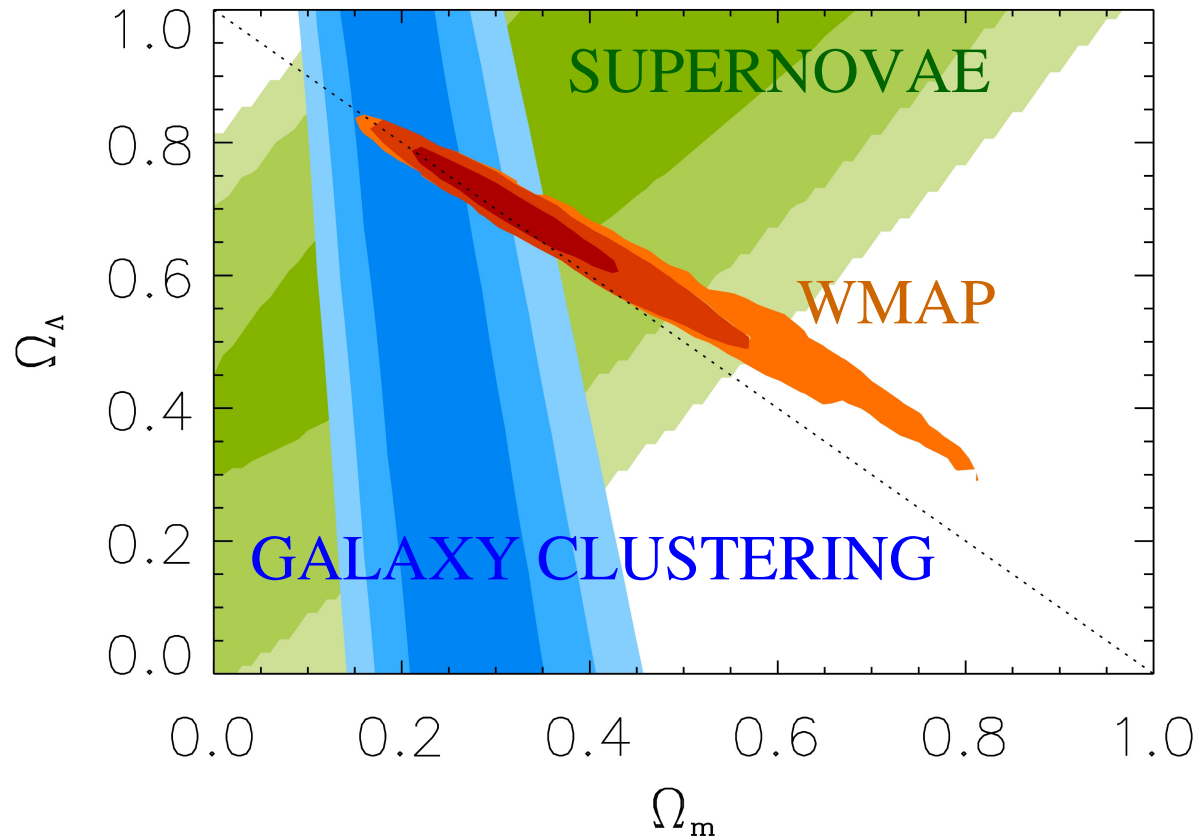


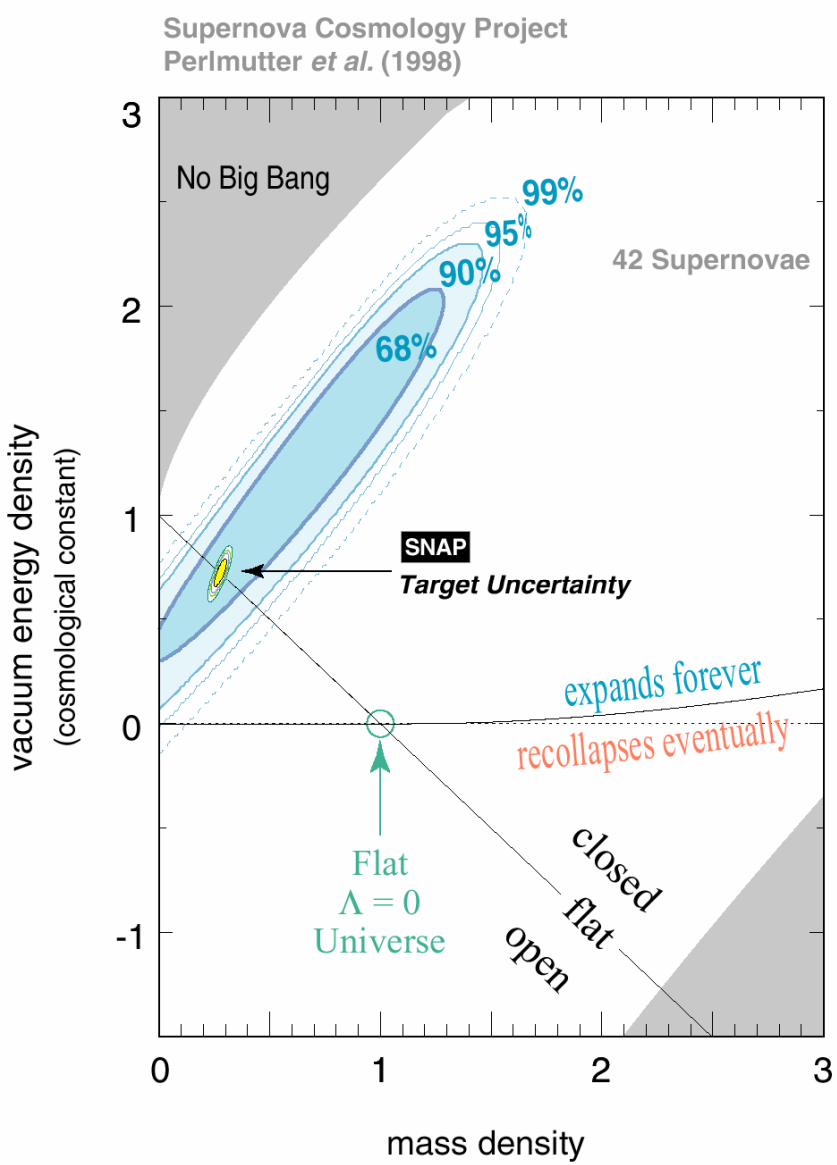
# Fluctuations and a Flat Universe

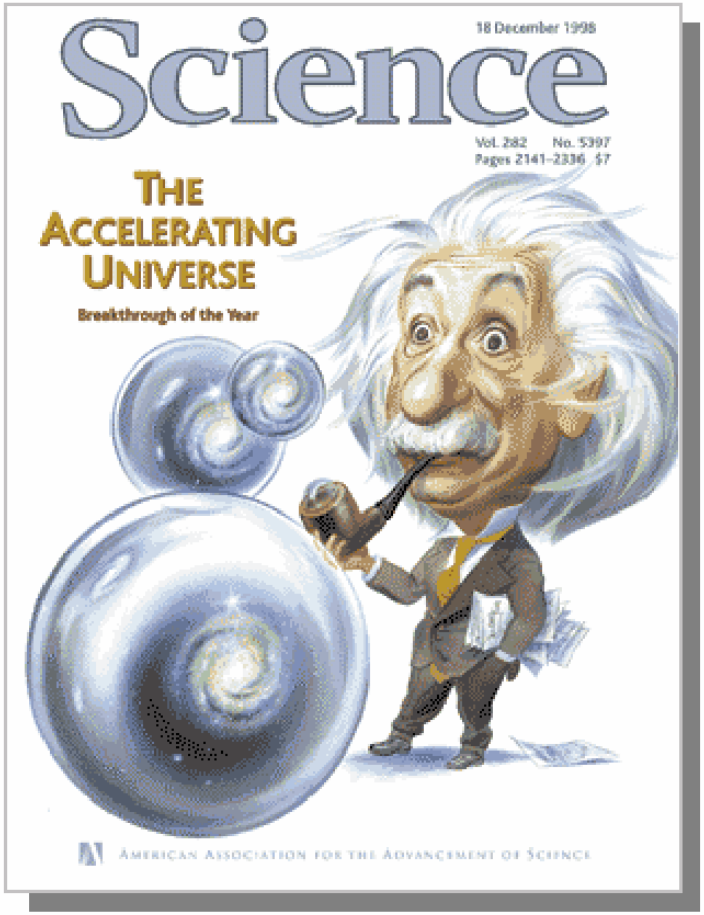
Fluctuations measured by WMAP are consistent with

$\Omega_\Lambda + \Omega_M = 1.0$

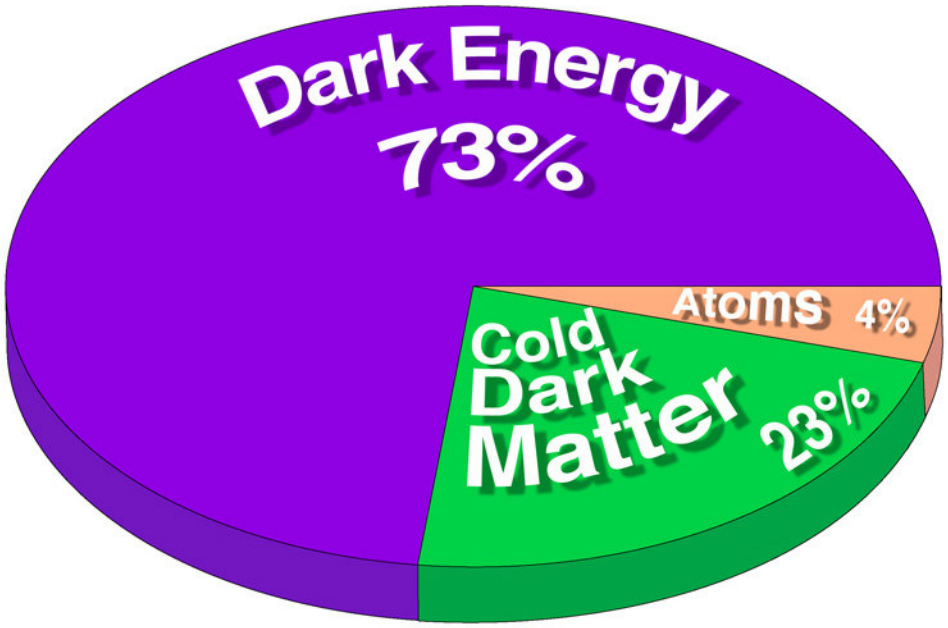


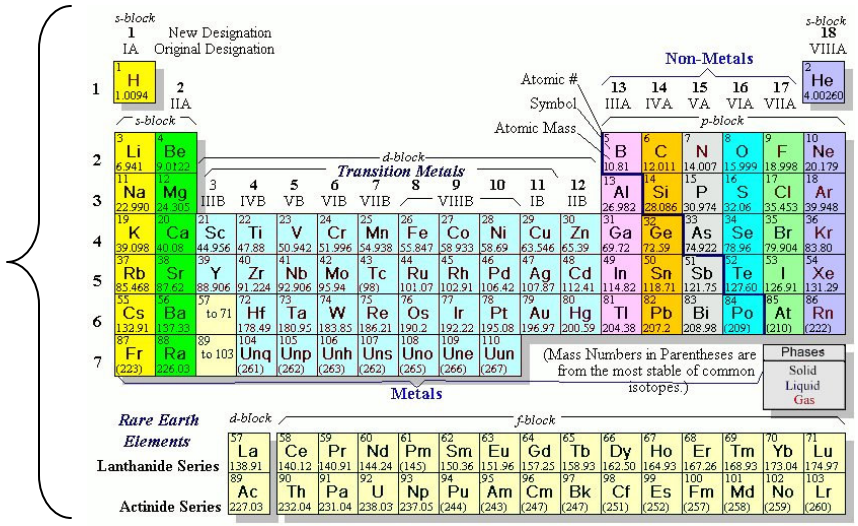
# Implications of expansion rate



We (and all of chemistry) are
a small minority in the Universe.

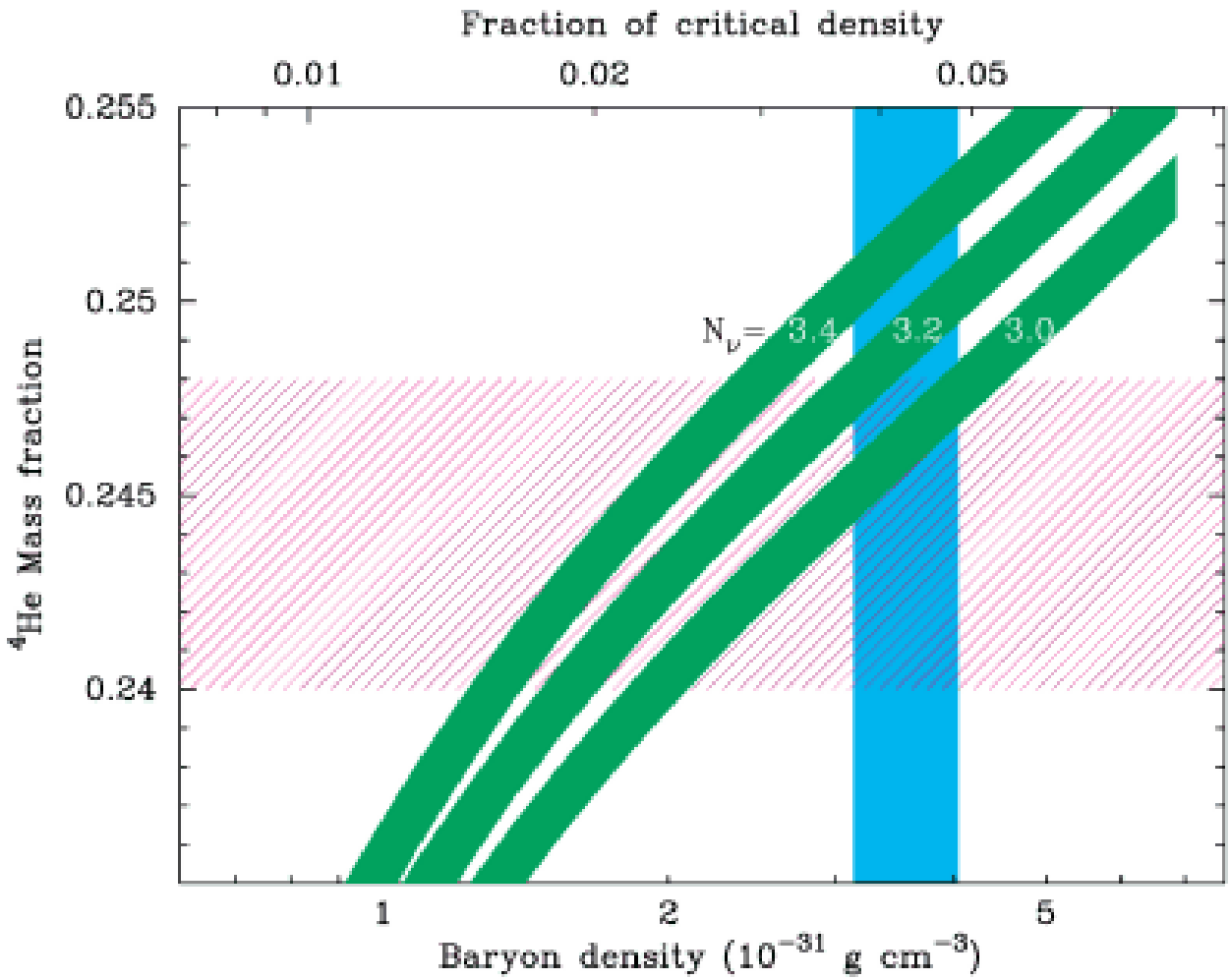


# Baryonic Matter

- Dominated by hydrogen and helium
  - helium abundance (~24%) too large to have been produced in stars
- $\eta_B = n_B / n_\gamma \approx 10^{-9}$
  - reveals early universe matter/antimatter asymmetry
- abundances of light elements consistent with theory
  - constrains number of neutrino species

# Constrained number of neutrino species



# Radiation and Matter Eras

- Very early, when $kT \gg Mc^2$ for all masses, all these particles would have been in thermal equilibrium and present in comparable numbers
- Thermal equilibrium requires the collision time be short compared to the age of the Universe (many collisions could occur)

$$W = \langle N v \sigma \rangle \gg t^{-1}$$

- Particle numbers will fall below the equilibrium number when
  - Temperature falls below the threshold energy
    for example when $kT \ll M_p c^2$ $\quad \gamma\gamma \not\rightarrow p\,\bar{p}$
  - production cross-section is too small to sustain reaction rate
    this is the case for $e^+ + e^- \rightleftharpoons \nu + \bar{\nu}$ (weak interaction) when $kT < 3$ MeV ($t > 10^{-2}$ s)

    (this means the neutrino fireball decouples from matter and expands independently)

# Radiation and Matter Eras

- For 100,000 years, matter (protons, electrons, hydrogen) were in equilibrium with the photons

$$e^- + p \rightleftharpoons \gamma + H + Q \qquad Q = 13.6 \text{ eV}$$

- At temperature T, the mean photon energy is 2.7kT

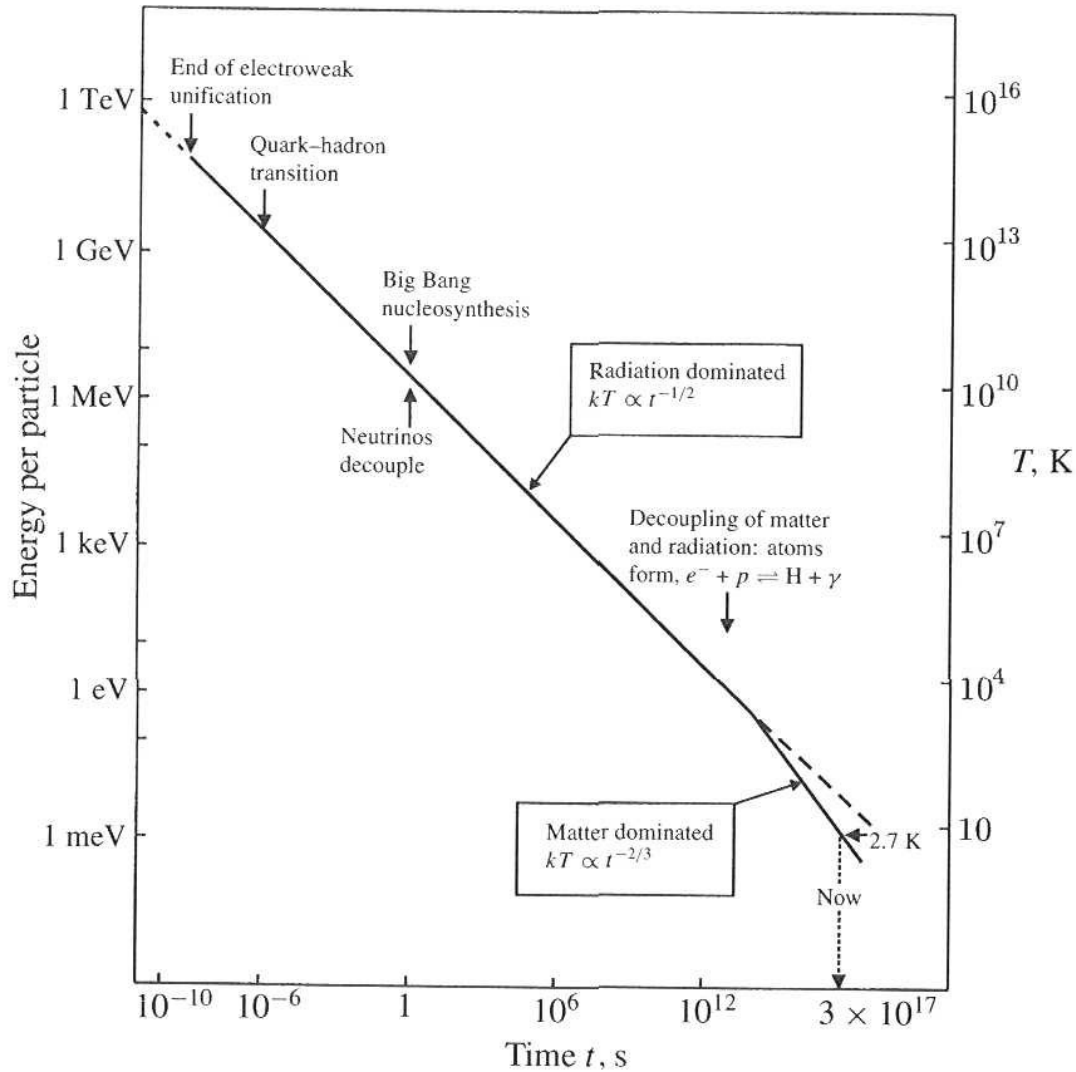
  for kT = 5 eV, $\langle E_\gamma \rangle \sim Q = 13.6$ eV

- Since the photons outnumber the hydrogen by a billion to one, the process above will continue for much lower temperatures, as the tail of the photon energy spectrum has enough energy for the reaction

- At kT ~ 0.3 eV, the process turns off, and the matter become transparent to the photons (decoupling at t ~ $10^{13}$ s = $3 \times 10^5$ yr.)

# Radiation and Matter Eras

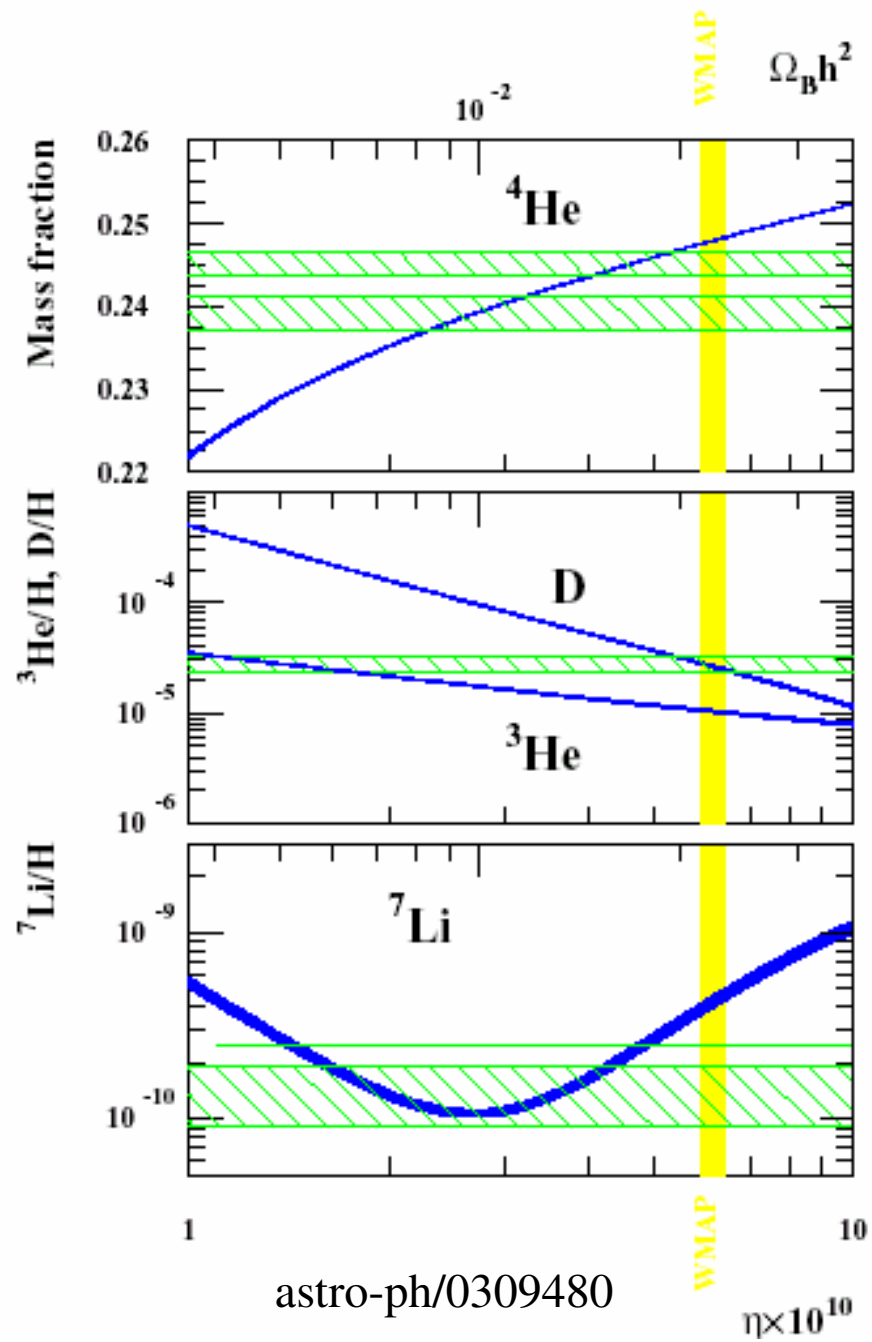
- Early ($t < 10^{13}$ sec)
  - radiation dominates
  - $kT \sim t^{-1/2}$
- Later ($t > 10^{13}$ sec)
  - radiation decouples
- Even later ($t > 3\times10^{13}$ sec)
  - matter density equals radiation density
  - from then on, matter dominates, since
    - $\rho_m \propto R^{-3}$
    - while $\rho_r \propto R^{-4}$
- Except, we now have discovered that today the dark energy is dominating



# Relative abundances

$$\eta_{10} = \eta \times 10^{10}$$
$$= n_B/n_\gamma \times 10^{10}$$
$$\approx 6.1 \text{ (WMAP)}$$

(baryon to photon ratio)




astro-ph/0309480

# Nucleosynthesis in the Big Bang

- After t ~ 1 second, heavy particles were gone, and remaining particles were:
  - photons
  - leptons
  - neutrons
  - protons
- Numbers of protons and neutrons were determined by the weak processes

$$\nu_e + n \rightleftharpoons e^- + p$$
$$\bar{\nu}_e + p \rightleftharpoons e^+ + n$$
$$n \rightarrow p + e^- + \bar{\nu}_e$$

- For $kT < M_p c^2$, the equilibrium ratio of n/p is

$$\frac{N_n}{N_p} = \exp\left(\frac{-Q}{kT}\right), \qquad Q = (M_n - M_p)c^2 = 1.293 \text{ MeV}$$

# Nucleosynthesis in the Big Bang

- As the Universe cools, the weak reaction rate becomes too slow to maintain equilibrium.
- This happens when kT = 0.87 MeV

$$N_n(0)/N_p(0) = \exp(-Q/kT) = 0.23$$

- Then neutrons disappear through decay

$$N_n(0)e^{-t/\tau} \text{ neutrons} \quad \text{and} \quad N_p(0) + N_n(0)(1 - e^{-t/\tau}) \text{ protons}$$

$$\begin{aligned} {}^2\mathrm{H} + n &\rightarrow {}^3\mathrm{H} + \gamma \\ {}^3\mathrm{H} + p &\rightarrow {}^4\mathrm{He} + \gamma \\ {}^2\mathrm{H} + p &\rightarrow {}^3\mathrm{He} + \gamma \\ {}^3\mathrm{He} + n &\rightarrow {}^4\mathrm{He} + \gamma \end{aligned}$$

- and the ratio of neutrons to protons decreases

- $$\frac{N_n(t)}{N_p(t)} = \frac{0.23e^{-t/\tau}}{1.23 - 0.23e^{-t/\tau}}$$ where $\tau = 896 \pm 10$ sec

# Nucleosynthesis in the Big Bang

- Nucleosynthesis locks the neutrons into nuclei before they can decay away

- First the formation of deuterium comes into equilibrium

$$n + p \rightleftharpoons {}^2\mathrm{H} + \gamma + Q$$

Q = 2.22 MeV

  - this lasts until kT ~ Q/40 = 0.05 MeV since there are so many more photons than nucleons

- Next, helium production takes over

$$\begin{aligned}
{}^2\mathrm{H} + n &\rightarrow {}^3\mathrm{H} + \gamma \\
{}^3\mathrm{H} + p &\rightarrow {}^4\mathrm{He} + \gamma \\
{}^2\mathrm{H} + p &\rightarrow {}^3\mathrm{He} + \gamma \\
{}^3\mathrm{He} + n &\rightarrow {}^4\mathrm{He} + \gamma
\end{aligned}$$

Neutron decay ceases
For kT = 0.05 MeV, t ~ 400 s

$$r = \frac{N_n}{N_p} = 0.14$$

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