John Mather Visit

Nobel Prize in Physics – 2006
for Cosmic Microwave Background measurements

THIS WEEK

- Wednesday 1:30-3:00 BPS 1400
  BS session with astro students & faculty.

- Wednesday 8PM BPS 1410 (refreshments at 7:30)
  Public Lecture
  "The history of the Universe in a nutshell: from the Big Bang to life and the end of time"

- Thursday 4:10 PM BPS 1415 (refreshments at 3:30 in BPS 1400)
  Physics & Astronomy Dept. Colloquium
  "James Webb Space Telescope: Science Opportunities and Mission Progress"

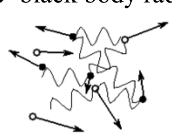
A Prediction

λ_o means observed at present time!

-
  - Cooling of Universe (Alpher & Herman, 1948)
    - Radiation energy density $u_{rad} \propto \dfrac{1}{R(t)^4}$

because $E_{phot}(t) = \dfrac{hc}{\lambda(t)} = \dfrac{hc}{\lambda_o R(t)}$

- Hot universe ➔ filled with free electrons
- Electron opacity ➔ black body radiation field



$$u_\lambda \, d\lambda = \frac{8\pi hc/\lambda^5}{e^{hc/\lambda kT} - 1} \, d\lambda$$

- Cooling universe: at some point, $e^- + H^+$ ➔ H^0
- Universe becomes transparent.
- ➔ relic of black body radiation field should be observable today.

Redshifted radiation ➔ black body radiation field for a lower temperature

$$u_\lambda \, d\lambda = \frac{8\pi hc/\lambda^5}{e^{hc/\lambda kT} - 1} \, d\lambda$$

u_o , λ_o, T = present (observed) values
$u(R)$, λ, $T(R)$ = values when $R=R(t)$

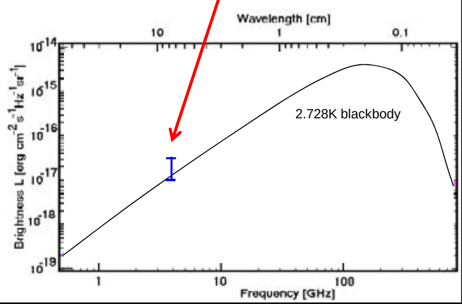
$\lambda = R\lambda_o$
$d\lambda = Rd\lambda_o$

$$u_0 \, d\lambda_0 = R^4 u(R) \, d\lambda(R)$$
$$= R^4 \frac{8\pi hc/R^5\lambda_0^5}{e^{hc/R\lambda_0 kT(R)} - 1} R d\lambda_0$$
$$= \frac{8\pi hc/\lambda_0^5}{e^{hc/\lambda_0 k[RT(R)]} - 1} \, d\lambda_0.$$

- Both shape *and* energy density are predicted.

$$T_0 = RT(R)$$

Penzias & Wilson 1964



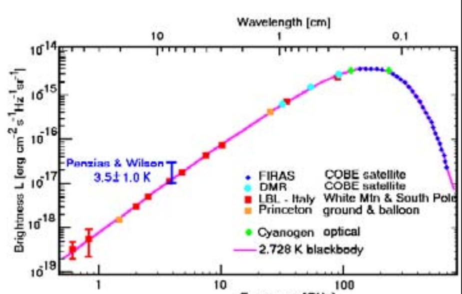
Cosmic Background Explorer

- COBE satellite (1991).

Nobel Prizes

 Penzias & Wilson, 1978

 Mather & Smoot, 2006



Isotropy of the Cosmic Microwave Background

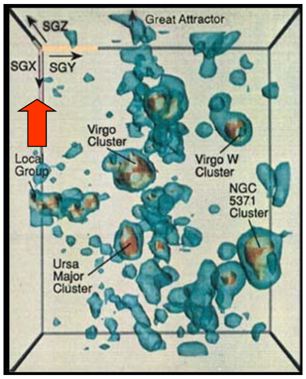
Black body

$$B_\lambda(T) = \frac{2hc^2/\lambda^5}{e^{hc/\lambda kT} - 1}$$

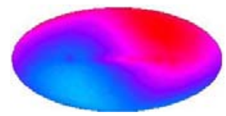
for large λ

$$B_\lambda(T) \simeq \frac{2ckT}{\lambda^4}$$

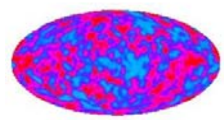
Local Group



Blue = 0°K
Red = 4°K



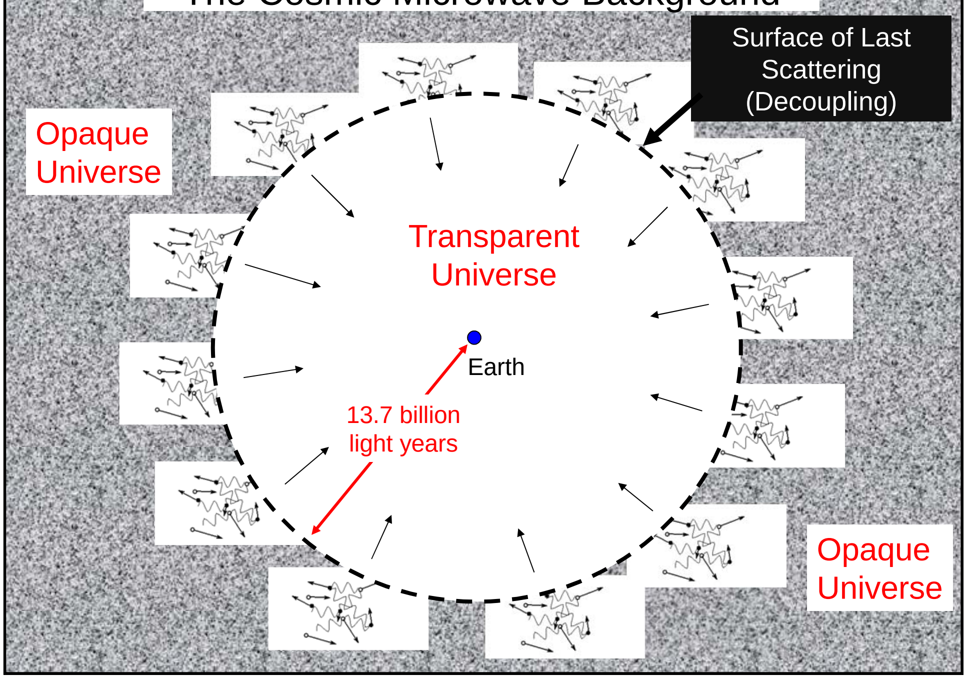
Blue = 2.724°K
Red = 2.732°K
Dipole Anistropy



After removing dipole
Red – blue = 0.0002°K

- Dipole Anisotropy ~ 1 part in 300
  - 600 km/sec motion of Local Group in grav. field of larger scale mass concentrations.

The Cosmic Microwave Background



When did decoupling occur?

- Saha equation: Collisional ionization rate = Recombination rate

$$\frac{N_{H^+}}{N_{H^0}} = \frac{4}{N_e}\left(\frac{2\pi m_e k T}{h^2}\right)^{3/2} e^{-\Delta E / kT} \qquad (8.8)$$

- Solve for $\frac{N_{H^+}}{N_{H^0}} = 1$, using $T = \frac{T_0}{R}$, $N_e \sim \frac{\rho_0}{m_H}\frac{1}{R^3}$ = electron density

  ➔ $R \sim 7.2\text{x}10^{-4}$
  $T \sim 3800$ K

- Taking composition and radiative transfer into account:

  $T_{dec} = 2970\text{K}$ $\qquad z_{dec} = 1089$
  $R_{dec} = 9\text{x}10^{-4}$ $\qquad t_{dec} = 379{,}000$ yrs.

Decoupling also called "**re**combination"

The Radiation Era

$T_0 = RT$
$T = \frac{T_0}{R}$

Energy density (integrated over wavelength):

$$u_{rad} = \frac{4\sigma T^4}{c} = aT^4$$

See [CO pg. 234]

$$\rho_{rad} = \frac{u_{rad}}{c^2} = \frac{aT^4}{c^2} = \frac{\rho_{rad,0}}{R^4}$$

$$\rho_{matter} = \frac{\rho_{matter,0}}{R^3}$$

$$\boxed{\frac{\rho_{rad}}{\rho_{matter}} \propto \frac{1}{R}}$$

$\rho_{matter} = \rho_{rad}$ at

$$R = \frac{aT_0^4}{\rho_0 c^2} = \frac{8\pi G a T_0^4}{3H_0^2 c^2 \Omega_0} \sim 2.5\times10^{-5}\,\Omega_0^{-1} h^{-2}$$

$$z = \frac{1}{R} - 1 \sim 4\times10^4\,\Omega_0 h^2$$

when $T = \frac{T_0}{R} \sim 1.1\times10^5\,\Omega_0 h^2$ K

Knowing *R(t)* as function of *t* ➔ Age of U ~ 3200 yrs
for $\Omega_0 = 1$, h = 0.71

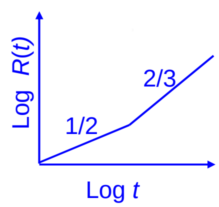
During the Radiation Era:

$$\left[\left(\frac{1}{R}\frac{dR}{dt}\right)^2 - \frac{8}{3}\pi G \rho_{RAD}\right] R^2 = -kc^2$$

$\uparrow k \sim 0$

$$\left(\frac{1}{R}\frac{dR}{dt}\right)^2 = \frac{8}{3}\pi G \frac{\rho_{RAD,0}}{R^4}$$

$$\left(\frac{dR}{dt}\right)^2 \propto \frac{1}{R^2}$$



$$RdR \propto dt$$

$$R \propto t^{1/2}$$

instead of $R \propto t^{2/3}$ in matter era.

also, $T_0 = RT \Rightarrow T \propto t^{-1/2}$

Terminology…

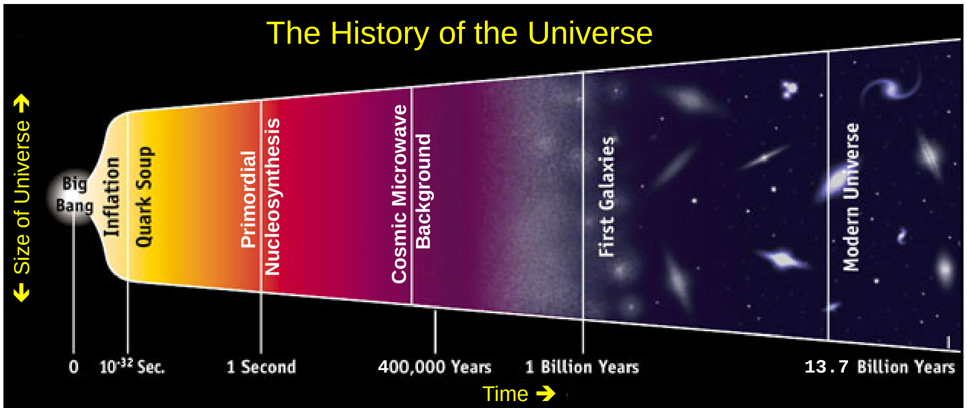
$$\left(\left(\frac{1}{R}\frac{dR}{dt}\right)^2 - \frac{8}{3}\pi G\rho\right)R^2 = -kc^2$$

$$\left(\left(\frac{1}{R}\frac{dR}{dt}\right)^2 - \frac{8}{3}\pi G(\rho_{matter} + \rho_{rel})\right)R^2 = -kc^2$$

CO call it $\rho_{relativistic}$ = photons + neutrinos

$$\rho_{rel} = \frac{u_{rel}}{c^2}$$

$$\Omega_{rel}(t) = \frac{\rho_{rel}(t)}{\rho_{crit}(t)}$$



Planck time | Inflation | Formation of H, He, Li | Decoupling of CMB | Galaxy Formation | Now

Hot → Cool

(10^{32} K) (10^9 K) (3000 K) (3 K)

High density → Low density

Primordial Nucleosynthesis

Radiation era

$R(t) \propto t^{1/2}$

$T(t) \propto t^{-1/2}$

$t = 10^{-4}$ s, $T = 10^{12}$K

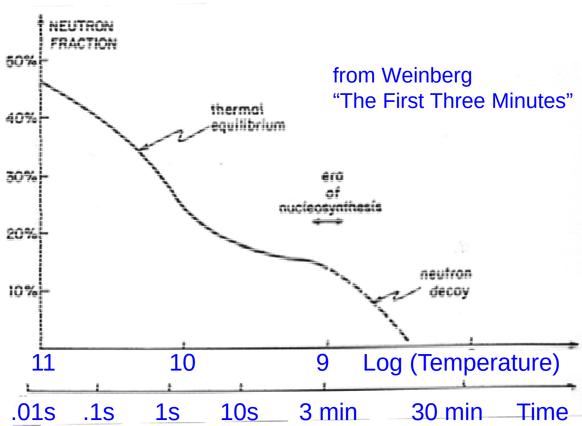
$p^+ + e^- \rightleftarrows n + \nu_e$, etc.

$\gamma \rightleftarrows e^- + e^+$

Statistical equilibrium

$$\frac{n_n}{n_p} = e^{-\Delta E / kT}$$

$$= e^{-1.5\times10^{10} K/T}$$



from Weinberg "The First Three Minutes"

$t \sim 1$ s, $T = 10^{10}$K

Neutrons freeze out

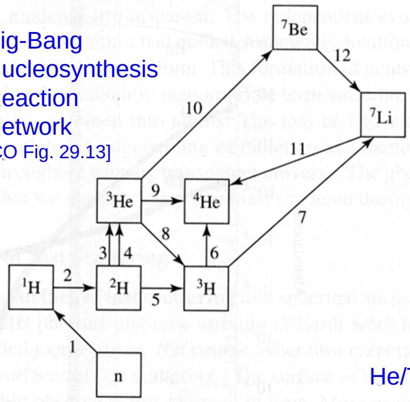
- redshifting of neutrinos.
- lower γ energies

$$\frac{n_n}{n_p} = 0.223$$

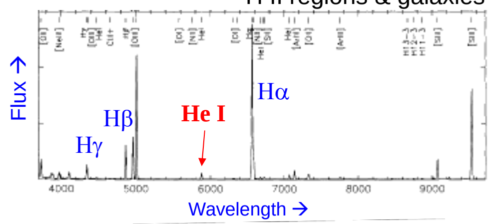
Subsequent β decays → $\frac{n_n}{n_p} \approx 0.176$

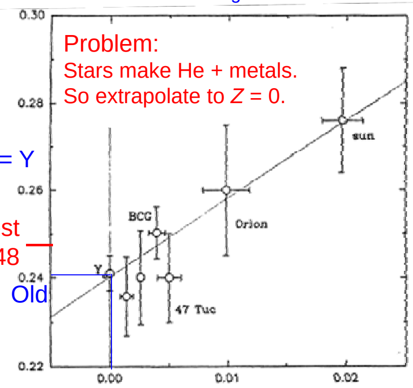
Primordial Nucleosynthesis

Big-Bang Nucleosynthesis Reaction Network
[CO Fig. 29.13]



H II regions & galaxies





He production

~ all neutrons used up in ^{4}He

➔ Mass fraction of ^{4}He / total baryons

$$= \frac{2n_n}{n_n + n_p} \approx 0.299$$

0.245-0.251 ← Confirms Big Bang!

Measuring Baryonic Matter Density – Version I

- ^{4}He/total ➔ doesn't depend on details
- But trace element abundances depend strongly on $\rho_{\mathrm{BARYON}}(t)$, $T(t)$

  ➔ $\rho_{\mathrm{B,o}}$ from RT = constant,

  $\rho = \rho_o/R^3 \propto \rho_o T^3$

> *Baryons:*
> Particles made of 3 quarks
> = protons, neutrons, + …
> = "normal matter"

> ***A Problem:*** d, ^{3}He, ^{7}Li easily destroyed in stars.
> Hard to measure primordial values.

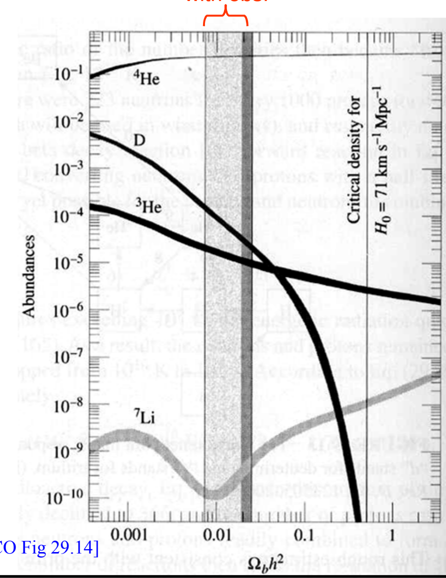
- d, ^{7}Li, ^{3}He ➔

  $$\Omega_{\mathrm{Baryon}} = \Omega_{\mathrm{B}} = \frac{\rho_{\mathrm{B,o}}}{\rho_{\mathrm{c,o}}} = 0.02 - 0.05$$

- Better determination from CMB fluctuations (WMAP)

  $\Omega_{\mathrm{Baryon}} = 0.044$

Consistent with obs.



[CO Fig 29.14]