

John Mather Visit

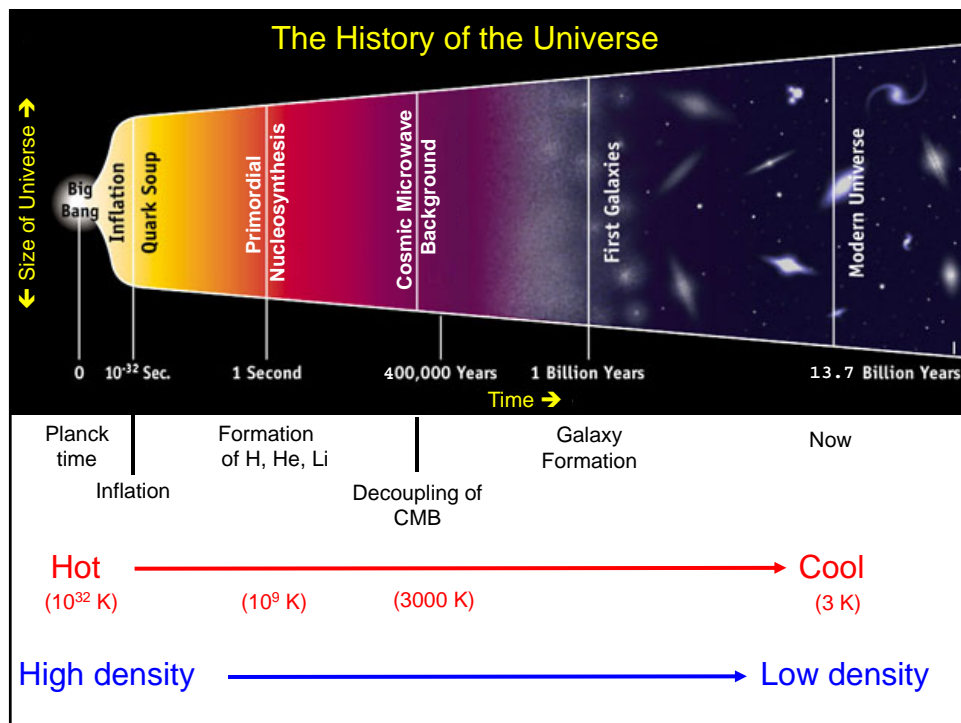
Nobel Prize in Physics – 2006
for Cosmic Microwave Background measurements

NEXT 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”



Cosmology in 1946

- Big-Bang Nucleosynthesis
 - Cooling of Universe (Alpher & Herman, 1948)
 - Radiation energy density $u_{rad} \propto \frac{1}{R(t)^4}$
because $E_{phot}(t) = \frac{hc}{\lambda(t)} = \frac{hc}{\lambda_o R(t)}$
 - Big-Bang Nucleosynthesis
 - Alpher, Bethe & Gamow ($\alpha\beta\gamma$) paper --- all elements built in Big Bang?
 - Later found: can't get much past ${}^4\text{He}$
- Steady State Model
 - Bondi, Gold & Hoyle
 - "Perfect" Cosmological Principle – universe same at all points and at all times
 - U has always been here.
 - Nucleosynthesis in stars
 - B²FH

λ_o means as
observed at
present time!

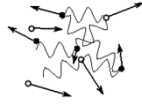
Also... "tired light"

A Prediction

- Cooling of Universe (Alpher & Herman, 1948)
 - Radiation energy density $u_{rad} \propto \frac{1}{R(t)^4}$
because $E_{phot}(t) = \frac{hc}{\lambda(t)} = \frac{hc}{\lambda_o R(t)}$

λ_o means
observed at
present time!

Black-Body Radiation



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

[CO Sect. 3.4]

Black body

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

$$L = A\sigma T^4 \quad \lambda_{\max} T = 0.002897755 \text{ m K}$$

for large λ : (Rayleigh-Jeans tail)

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

also... dilute black body

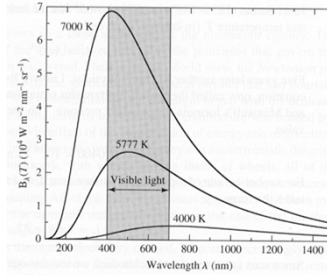
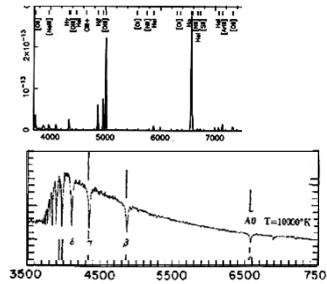


FIGURE 3.8 Blackbody spectrum [Planck function $B_\lambda(T)$].



Redshifted radiation \rightarrow black body radiation field for a lower temperature

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

$u_o, \lambda_o, T =$ present (observed) values
 $u(R), \lambda, T(R) =$ values when $R=R(t)$

$$\lambda = R\lambda_o$$

$$d\lambda = Rd\lambda_o$$

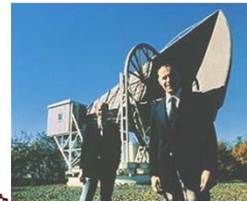
$$u_o d\lambda_o = R^4 u(R) d\lambda(R)$$

$$= R^4 \frac{8\pi hc/R^5 \lambda_o^5}{e^{hc/R\lambda_o kT(R)} - 1} R d\lambda_o$$

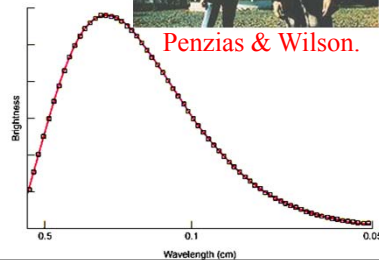
$$= \frac{8\pi hc/\lambda_o^5}{e^{hc/\lambda_o k[RT(R)]} - 1} d\lambda_o.$$

- Both shape *and* energy density are predicted.

$$T_o = RT(R)$$

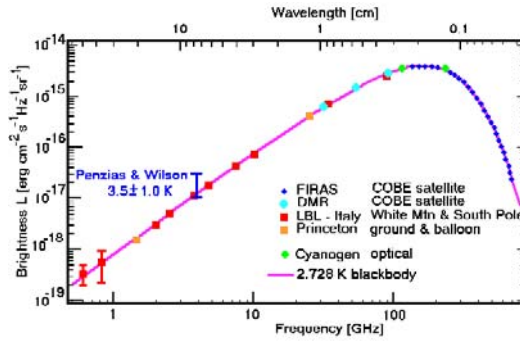
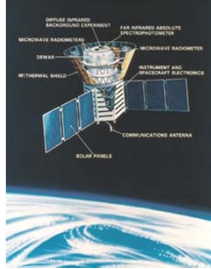


Penzias & Wilson.



How COBE Changed Things

- 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

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

Dipole Anisotropy

~ 1 part in 300.

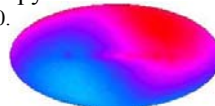
$$T_{\text{moving}} = \frac{T_{\text{rest}} \sqrt{1 - v^2/c^2}}{1 - (v/c) \cos \theta}$$

for $v \ll c$

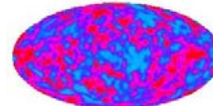
$$T_{\text{moving}} \simeq T_{\text{rest}} \left(1 + \frac{v}{c} \cos \theta \right) \quad (29.62)$$



Blue = 0°K
Red = 4°K



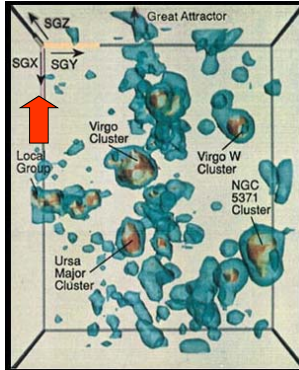
Blue = 2.724°K
Red = 2.732°K
Dipole Anisotropy
→ motion of Sun through Universe.



After removing dipole
Red - blue = 0.0002°K

Isotropy of the Cosmic Microwave Background

Local Group



Black body

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

for large λ

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

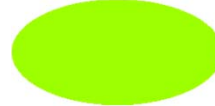
Dipole Anisotropy

~ 1 part in 300.

$$T_{\text{moving}} = \frac{T_{\text{rest}} \sqrt{1 - v^2/c^2}}{1 - (v/c) \cos \theta}$$

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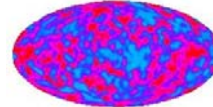
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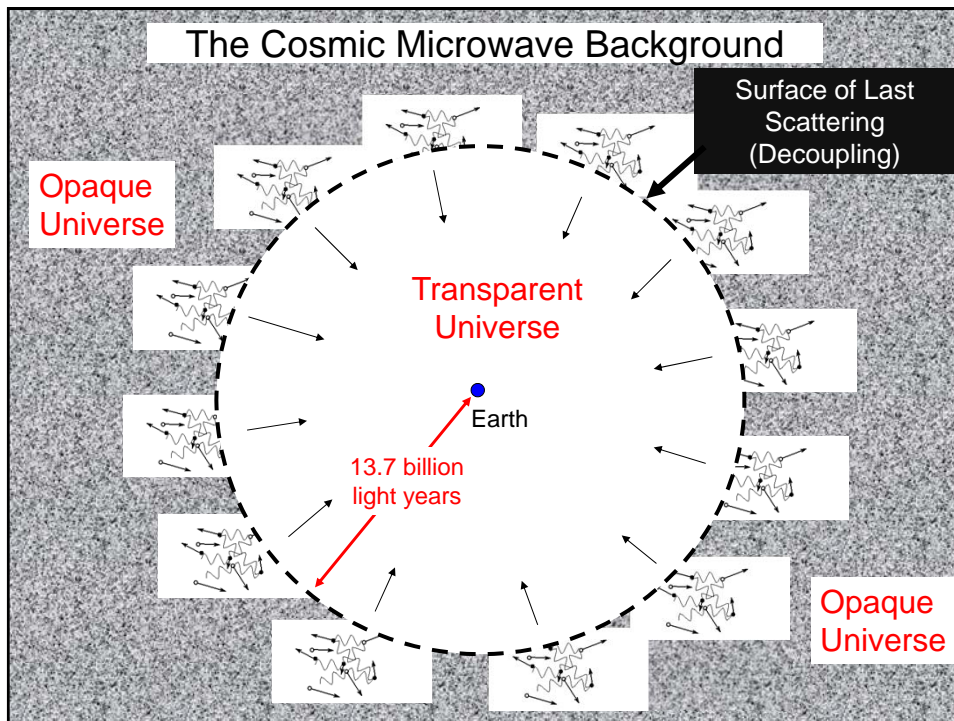


Blue = 2.724°K
Red = 2.732°K
Dipole Anisotropy
→ motion of Sun through Universe.



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.



When did decoupling occur?

- Saha equation: Collisional ionization rate = Recombination rate

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

- 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

$$\rightarrow R \sim 7.2 \times 10^{-4}$$

$$T \sim 3800 \text{ K}$$

- Taking composition and radiative transfer into account:

$$T_{dec} = 2970 \text{ K} \qquad z_{dec} = 1089$$

$$R_{dec} = 9 \times 10^{-4} \qquad t_{dec} = 379,000 \text{ yrs.}$$

Decoupling also called “**re**combination”

The Radiation Era

Energy density (integrated over wavelength):

$$u_{rad} = \frac{4\sigma T^4}{c} = aT^4 \quad \text{See [CO pg. 234]}$$

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

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

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

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

$$R = \frac{a T_0^4}{\rho_0 c^2} = \frac{8\pi G a T_0^4}{3H_0^2 c^2 \Omega_0} \sim 2.5 \times 10^5 \Omega_0^{-1} h^{-2}$$

$$z = \frac{1}{R} - 1 \sim 4 \times 10^4 \Omega_0 h^2$$

$$\text{when } T = \frac{T_0}{R} \sim 1.1 \times 10^5 \Omega_0 h^2 \text{ K}$$

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

$$T_0 = RT$$

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

During the Radiation Era:

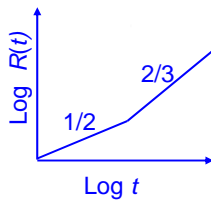
$$\left[\left(\frac{1}{R} \frac{dR}{dt} \right)^2 - \frac{8}{3} \pi G \rho_{\text{RAD}} \right] R^2 = -kc^2 \quad \uparrow k \sim 0$$

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

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

$$R dR \propto dt$$

$$R \propto t^{1/2} \quad \text{instead of } R \propto t^{2/3} \text{ in matter era.}$$



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

Terminology...

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

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

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

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

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