Lecture 16 : The Cosmic Microwave Background

- Discovery of the Cosmic Microwave Background
- The Hot Big Bang

This week: read Chapter 12 in textbook

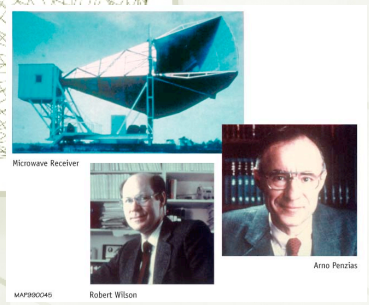
Let's think about the early Universe…

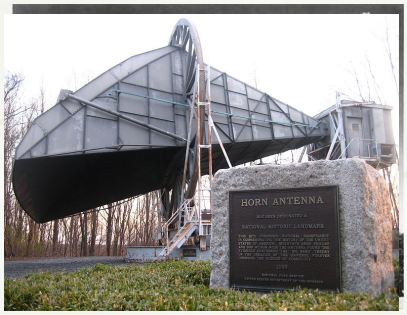
- From Hubble's observations, we know the Universe is expanding
  - This can be understood theoretically in terms of solutions of GR equations
- Earlier in time, all the matter must have been squeezed more tightly together
  - If crushed together at high enough density, the galaxies, stars, etc could not exist as we see them now -- everything must have been different!

Discussion…

- What was the Universe like long, long ago?
  - What were the original contents?
  - What were the early conditions like?
  - What physical processes occurred under those conditions?
  - How did changes over time result in the contents and structure we see today?

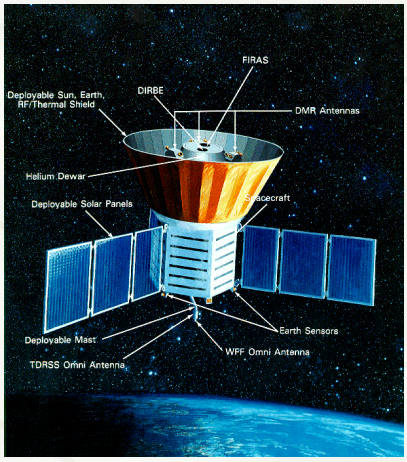
I : The Cosmic Microwave Background



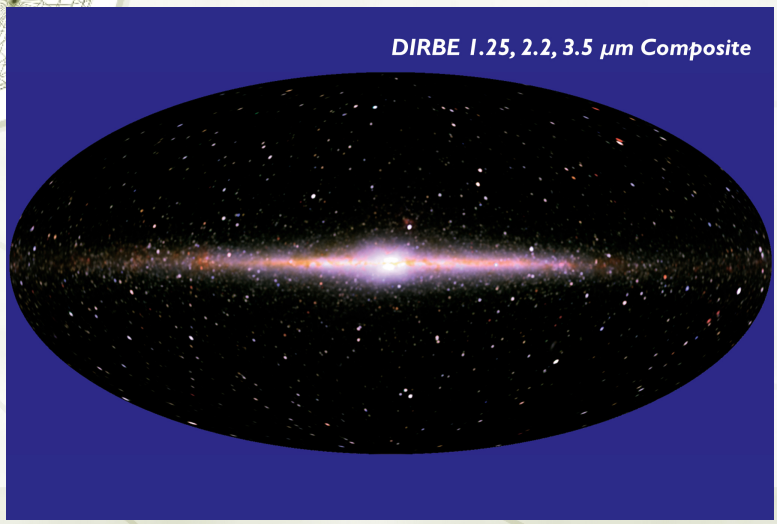


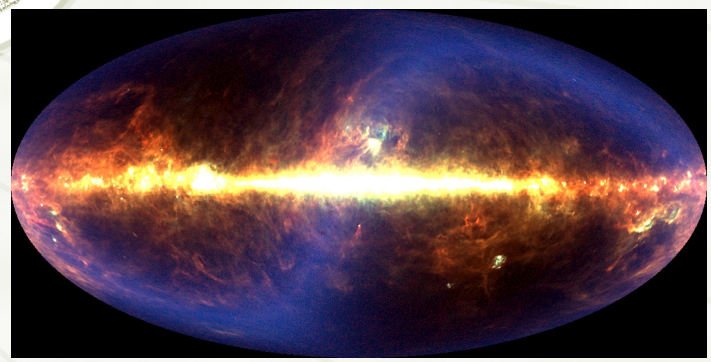
- Arno Penzias & Robert Wilson (1964)
  - Attempted to study radio emissions from our Galaxy using sensitive antenna built at Bell-Labs
  - Needed to characterize and eliminate all sources of noise
  - They never could get rid of a certain noise source… noise had a characteristic temperature of about 3 K.
  - They figured out that the noise was coming from the sky, and was approximately the same in all directions…

- The COBE mission
  - Built by NASA-Goddard Space Flight Center
  - Launched Nov. 1989
  - Purpose was to survey infra-red and microwave emission across the whole sky.
  - Primary purpose – to characterize the CMB.
- Had a number of instruments on it:
  - FIRAS (Far infra-red absolute spectrophotometer)
  - DMR (Differential Microwave Radiometer)
  - DIRBE (Diffuse Infrared background Experiment)

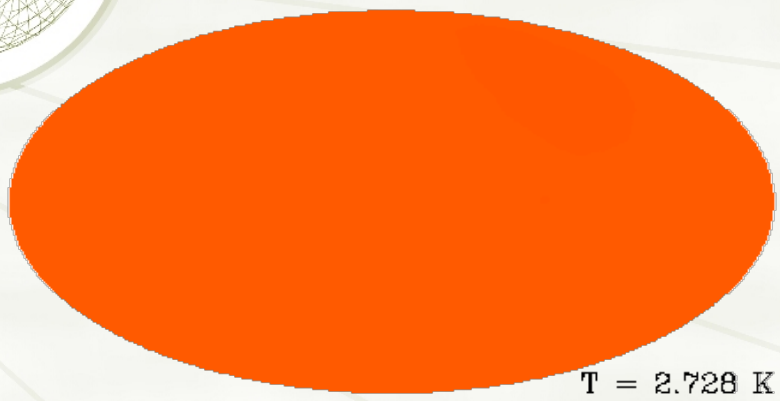


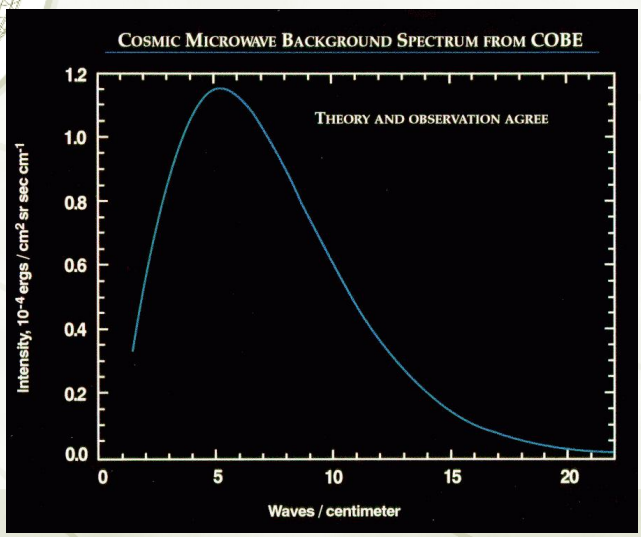
Our Galaxy observed by the DIRBE instrument on COBE



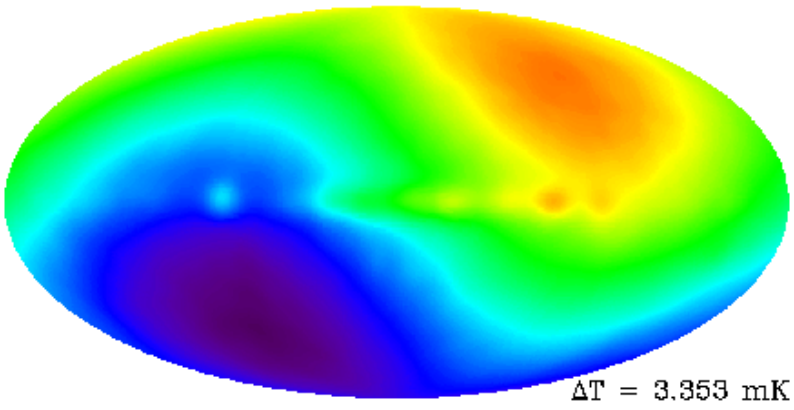


Almost uniform intensity of microwaves in all directions (isotropic 2.7K black body radiation)

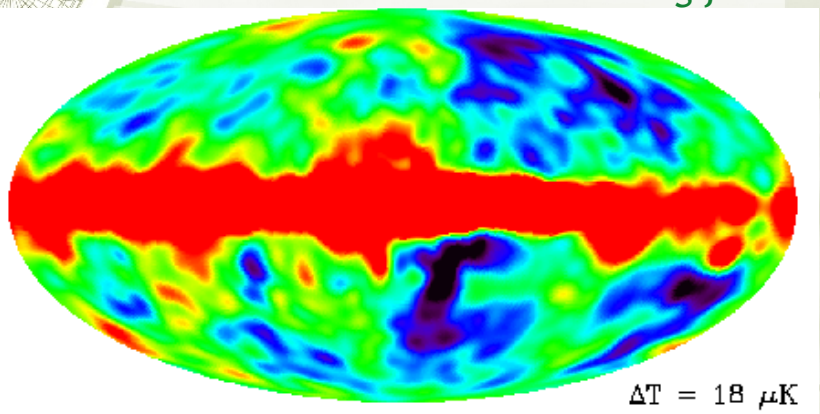




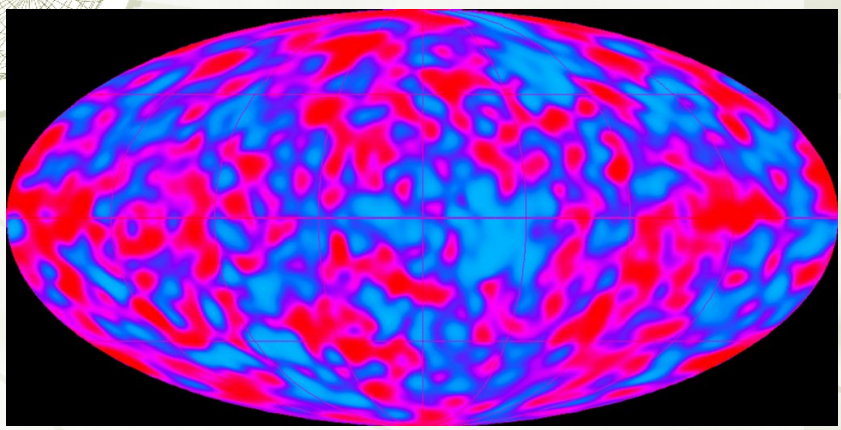
Subtracting off the mean level leaves with a "dipole" pattern… what is this??



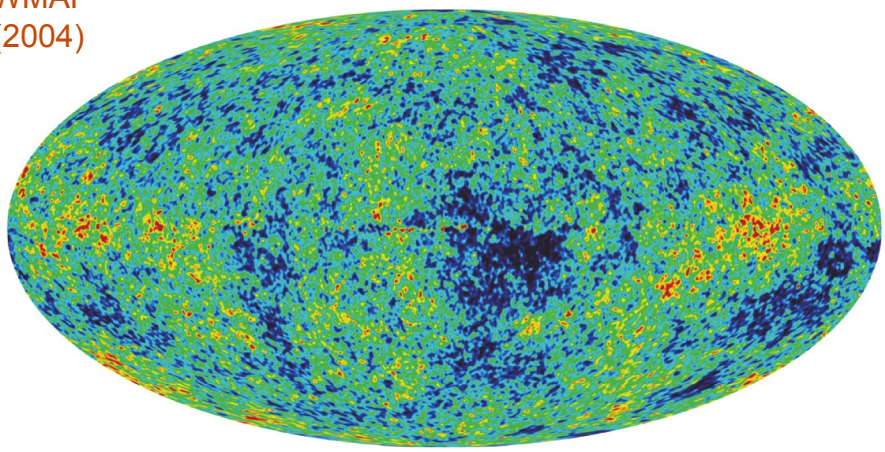
Subtracting off the dipole finally reveals the emission from the Galaxy that Penzias and Wilson were looking for!



Subtracting contribution from Galaxy reveals fluctuations in the CMB

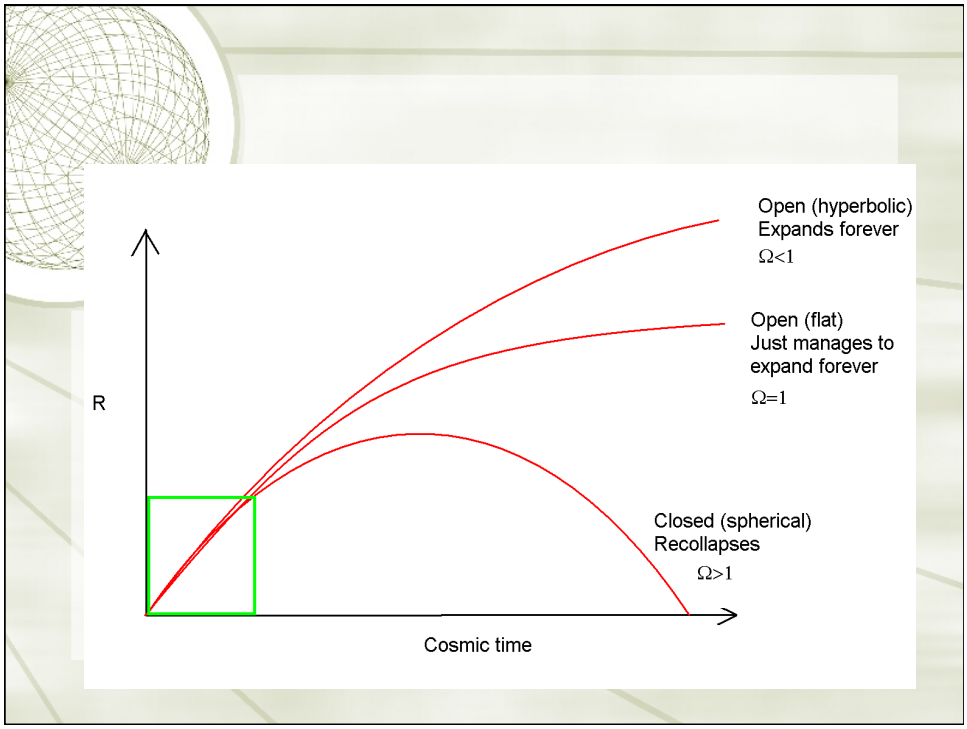


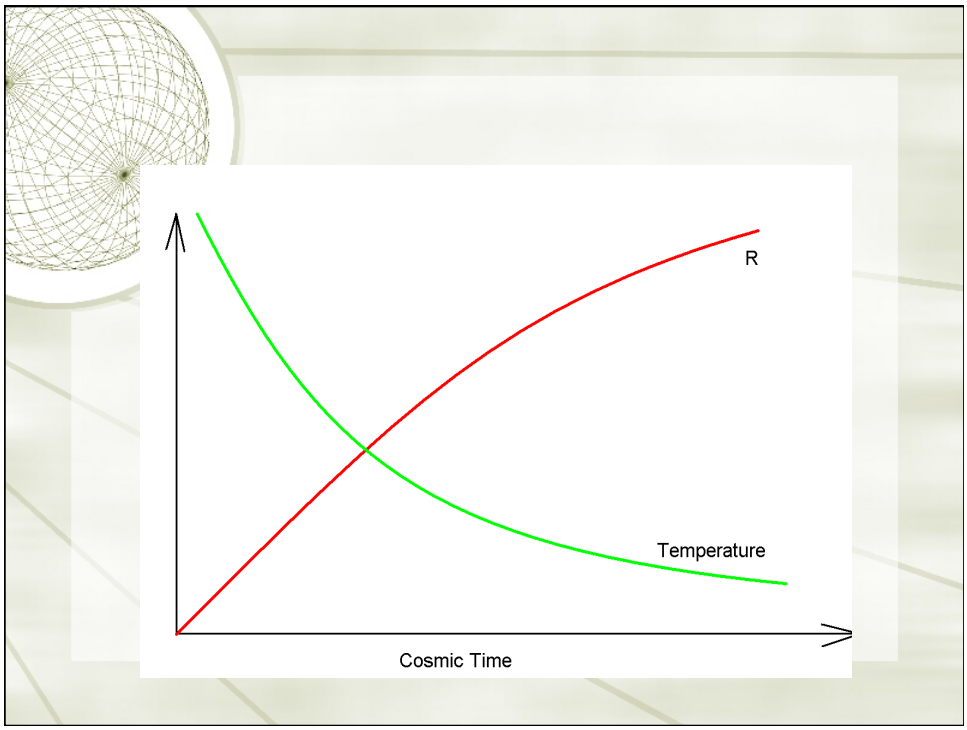
WMAP
(2004)



II : THE HOT BIG BANG MODEL

- Penzias & Wilson had discovered radiation left over from the early universe…
- The hot big bang model…
  - Independently developed by James Peebles and George Gamov
  - They suggested that the universe started off in an extremely hot state.
  - As the Universe expands, the energy within the universe is spread over in increasing volume of space…
  - **Thus the Universe cools down as it expands**


Open (hyperbolic)
Expands forever
Ω<1
Open (flat)
Just manages to
expand forever
Ω=1
R
Closed (spherical)
Recollapses
Ω>1
Cosmic time


R
Temperature
Cosmic Time

Cosmic radiation

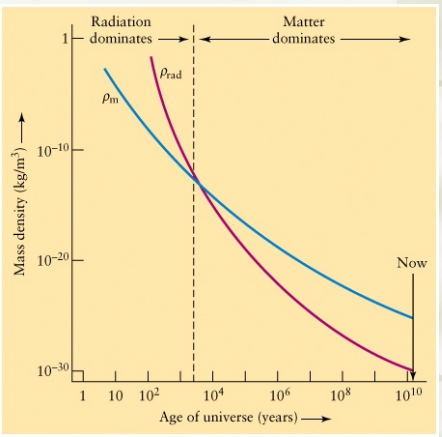
- How does the radiation change with time?
  - The total number of photons per "co-moving volume" remains constant
  - So… number of photons per unit (normal) volume proportional to $(R_0/R(t))^3$
  - Photons get stretched by expanding space… so energy of photon is proportional to $R_0/R(t)$
  - So, energy density of radiation is $(R_0/R(t))^4$
- The CMB has a "blackbody" spectrum characterized by a temperature T
  - The energy density of blackbody radiation is proportional to T^4.
  - So… T proportional $R_0/R(t)=1+z$

Redshift of the CMB

- So, the temperature of the CMB radiation decreases as T=3 K(1+z).The observed temperature of the CMB today is T_0=3 K, but it was T=3000 K at the time of emission. When was the CMB radiation emitted?
  a) When the universe was 13.4 Gyr old
  b) When the universe was about 1000 times smaller than today
  c) At a redshift of z=9
  d) At redshift z=999.

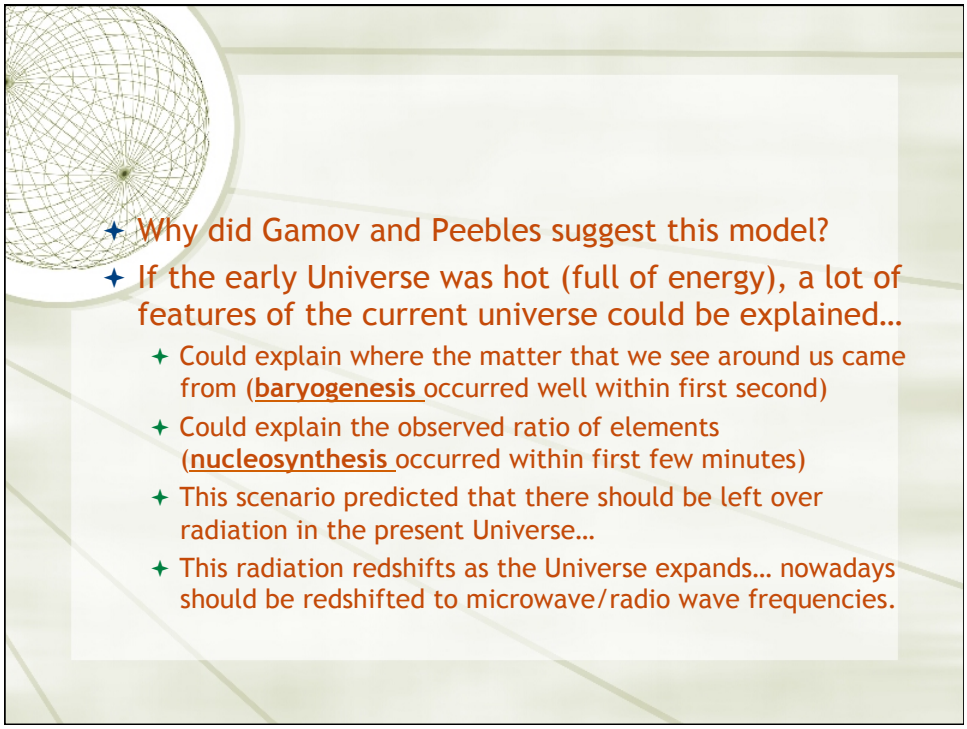
Matter and radiation densities compared

- Already know matter density varies inversely with volume
- Thus:
  - $\rho_{matter} \propto (R_0/R(t))^3 = (1+z)^3$
  - $\rho_{radiation} \propto (R_0/R(t))^4 = (1+z)^4$
- At early times, energy density of CBR must have exceeded energy density of matter!
- When radiation field is strong, matter is heated up
- Therefore earlier and earlier in the Universe, it must have been hotter and hotter
- This suggests that origin of the Universe was a ***hot*** *Big Bang*!



Redshift of the Matter-radiation equality

- So, the density of matter decreases as $0.3(1+z)^3$ and that of radiation as $0.0001(1+z)^4$. When did matter radiation equality happened?
  a) When the universe was 13.4 Gyr old
  b) When the universe was about 3000 times smaller than today
  c) After the CMB radiation was emitted
  d) At redshift of 1 million


Why did Gamov and Peebles suggest this model?
If the early Universe was hot (full of energy), a lot of features of the current universe could be explained…
Could explain where the matter that we see around us came from (baryogenesis occurred well within first second)
Could explain the observed ratio of elements (nucleosynthesis occurred within first few minutes)
This scenario predicted that there should be left over radiation in the present Universe…
This radiation redshifts as the Universe expands… nowadays should be redshifted to microwave/radio wave frequencies.