

Lecture 31

The cosmic microwave background I: Seeing the universe when it was young

The life of a universe – key facts

- Unless Λ is sufficiently large (which is inconsistent with observations) all cosmological models start with a big bang.
- An universe doesn't change its geometry. A flat universe has always been and will always be flat, a spherical universe is always spherical and so on.
- Two basic solutions:
 - * eventual collapse for large Ω_0 or negative Λ
 - * eternal expansion otherwise

Cosmology: the quest for three numbers

- The Hubble constant H_0
⇒ how fast is the universe expanding
- The density parameter Ω_0
⇒ how much mass is in the universe
- The cosmological constant Ω_Λ
⇒ the vacuum energy of the universe
- current observational situation:
 - $H_0 = 65 \text{ km/s/Mpc}$
 - $\Omega_0 = 0.3; \Omega_\Lambda = 0.7 \Rightarrow$ flat space

Some common misconceptions

- The picture that the Universe expands into a preexisting space like an explosion
- The question “what was before the big bang?”
- Remember: space-time is part of the solution to Einstein’s equation
- Space and time are created in the big bang

So is the big crunch the same as the big bang run in reverse ?

- No. The Universe has meanwhile formed stars, black holes, galaxies etc.
- Second law of thermodynamics:
The entropy (disorder) of a system at best stays the same but usually increases with time, in any process. There is no perpetual motion machine.
- Second law of thermodynamics defines an arrow of time.

Friedmann's equation for $\Lambda=0$, $\Omega_0 < 1$

$$H = \frac{8\pi G}{3} \rho - \frac{kc^2}{R^2}$$

Expansion rate
of the Universe

Falls off like

the cube of R

Falls off like

the square of R

- At early epochs, the first term dominates
 \Rightarrow the early universe appears to be almost flat
- At late epochs, the second term dominates
 \Rightarrow the late universe appears to be almost empty

Friedmann's equation for $\Lambda > 0$, $\Omega_0 < 1$

$$H = \frac{8\pi G}{3} \rho - \frac{kc^2}{R^2} - \frac{\Lambda}{3}$$

Expansion rate
of the Universe

Falls off like
the cube of R

Falls off like
the square of R

constant

- At early epochs, the first term dominates
⇒ the early universe appears to be almost flat
- At late epochs, the third term dominates
⇒ the late universe appears to be exponentially expanding

A puzzling detail

- $\Lambda=0$: for most of its age, the universe looks either to be flat or to be empty
- $\Lambda>0$: for most of its age, the universe looks either to be flat or to be exponentially expanding
- Isn't it strange that we appear to live in that short period between those two extremes ?

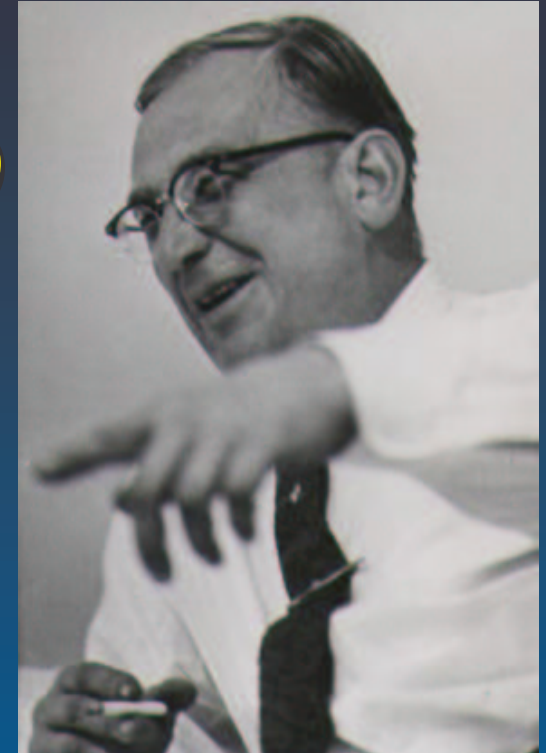
⇒ **Flatness problem**

General acceptance of the big bang model

- Until mid 60ies: big bang model very controversial, many alternative models
- After mid 60ies: little doubt on validity of the big bang model
- Four pillars on which the big bang theory is resting:
 - * Hubble's law $v = H_0 d$
 - * Cosmic microwave background radiation
 - * The origin of the elements
 - * Structure formation in the universe

Georgy Gamov (1904-1968)

- If the universe is expanding, then there has been a big bang
- Therefore, the early universe must have been very dense and hot
- Optimum environment to breed the elements by nuclear fusion (Alpher, Bethe & Gamow, 1948)
 - * success: predicted that helium abundance is 25%
 - * failure: could not reproduce elements more massive than lithium and beryllium (\Rightarrow formed in stars)



What are the consequences ?

- In order to form hydrogen and helium at the right proportions, the following conditions are required:
 - * density: $\rho \approx 10^{-5} \text{ g/cm}^{-3}$
 - * temperature: $T \approx 10^9 \text{ K}$
- Radiation from this epoch should be observable as an isotropic background radiation
- Due to the expansion of the universe to $\rho \approx 3 \times 10^{-30} \text{ g/cm}^3$, the temperature should have dropped to $T \approx 5 \text{ K}$ (-450 F)
- Can we observe this radiation ?

The discovery of the relic radiation

- Gamov's result on the background radiation was not well recognized by the scientific community
- Result was rediscovered by Dicke and Peebles in the early sixties. They started developing an antenna to search for the background radiation
- $T \approx 5 \text{ K} \Rightarrow$ microwaves
- but ...

Penzias and Wilson 1965



- Working at Bell labs
- Used a satellite dish to measure radio emission of the Milky Way
- They found some extra noise in the receiver, but couldn't explain it
⇒ **discovery of the background radiation**
- Most significant cosmological observation since Hubble
- Nobel prize for physics 1978

A quote ...

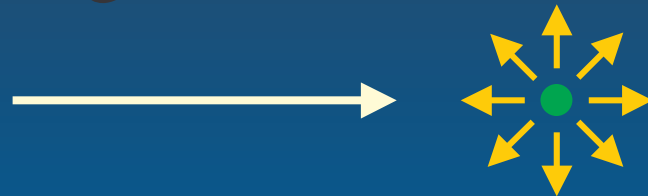
- John Bahcall: "The discovery of the cosmic microwave background radiation changed forever the nature of cosmology, from a subject that had many elements in common with theology to a fantastically exciting empirical study of the origins and evolution of the things that populate the physical universe."

How far can we see ?

- Naked eye: 2 million Lyr (Andromeda galaxy)
- Large telescopes: 14 billion Lyr ($z=5.8$)
- What are the limiting factors ?
 - * there are no bright sources at high z
 - * light is redshifted into the infrared
 - * absorption
- The universe appears to be fairly transparent out to $z=5.8$

When does a gas become opaque?

- A gas appears opaque (e.g. fog) if light is efficiently scattered by the atoms/molecules of the gas



The three important factors are thus

- * the density of the gas
(denser \Rightarrow more particles \Rightarrow more scattering)
- * the efficiency with which each individual particle can scatter light
- * wavelength of the light