Cosmology

Thornton and Rex, Ch. 16

Expansion of the Universe

- 1923 - Edwin Hubble resolved Andromeda Nebula into separate stars.

- 1929 - Hubble compared radial velocity versus distance for 18 nearest galaxies. He found that on average they were receding with velocity proportional to their distance.

- Hubble's Law: $\boxed{v = H R}$

  H = Hubble constant = 72 km/s/Mpc
  (1 pc "parsec" = 3.26 light-years)

- Soon verified with better data from more distant galaxies.

- Radial velocity determined by doppler shift (“red shift”).

- Distance is much harder to measure. Requires a “standard candle”-some object in the galaxy whose intrinsic brightness is known, to calibrate the distance. Hubble used a type of variable star called a Cepheid Variable. This is only possible for the most nearby galaxies.

- Hubble constant was uncertain by a factor of 2 until very recently (1998). Supernovae in the more distant galaxies helped pin down H with greater precision.

General Relativity

1917 - Einstein completed his General Theory of Relativity. He then set out to solve his equations for the universe, assuming it was:

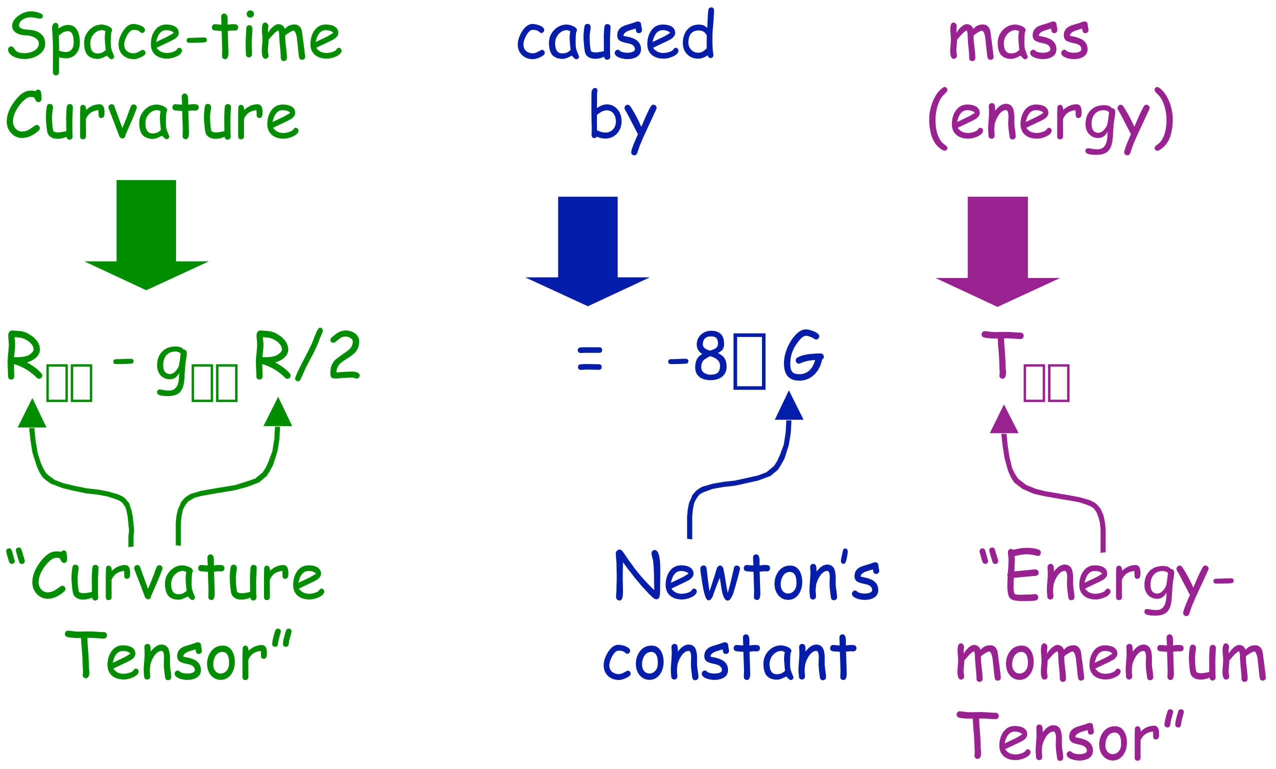
1) Isotropic - It looks the same in all directions.
2) Homogeneous - It looks the same from any place in the universe.
3) Static - It looks the same at all times.

Einstein found no solutions!

He modified his equations by adding a term called "the Cosmological Constant".

"My biggest blunder" - Einstein

General Relativity



Space-time Curvature

caused by

mass (energy)

$R_{\square\square} - g_{\square\square} R/2 \quad = \quad -8\square G \quad T_{\square\square}$

"Curvature Tensor"

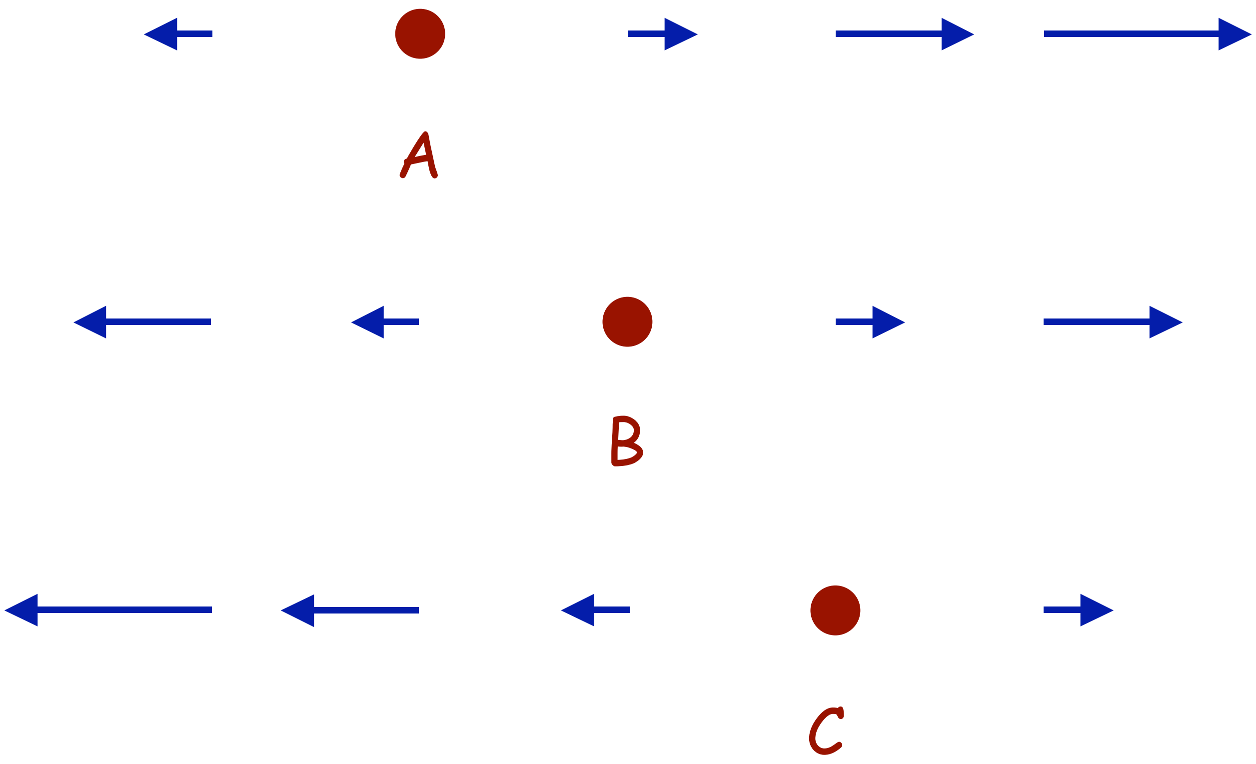
Newton's constant

"Energy-momentum Tensor"

Adding a cosmological constant

$$R_{\square\square} - g_{\square\square} R/2 \quad = \quad -8\square G \; (T_{\square\square} - \; \square \, g_{\square\square})$$

- A few years later Alexandre Friedmann solved Einstein's original equations.



"Homogeneity implies Hubble's Law"

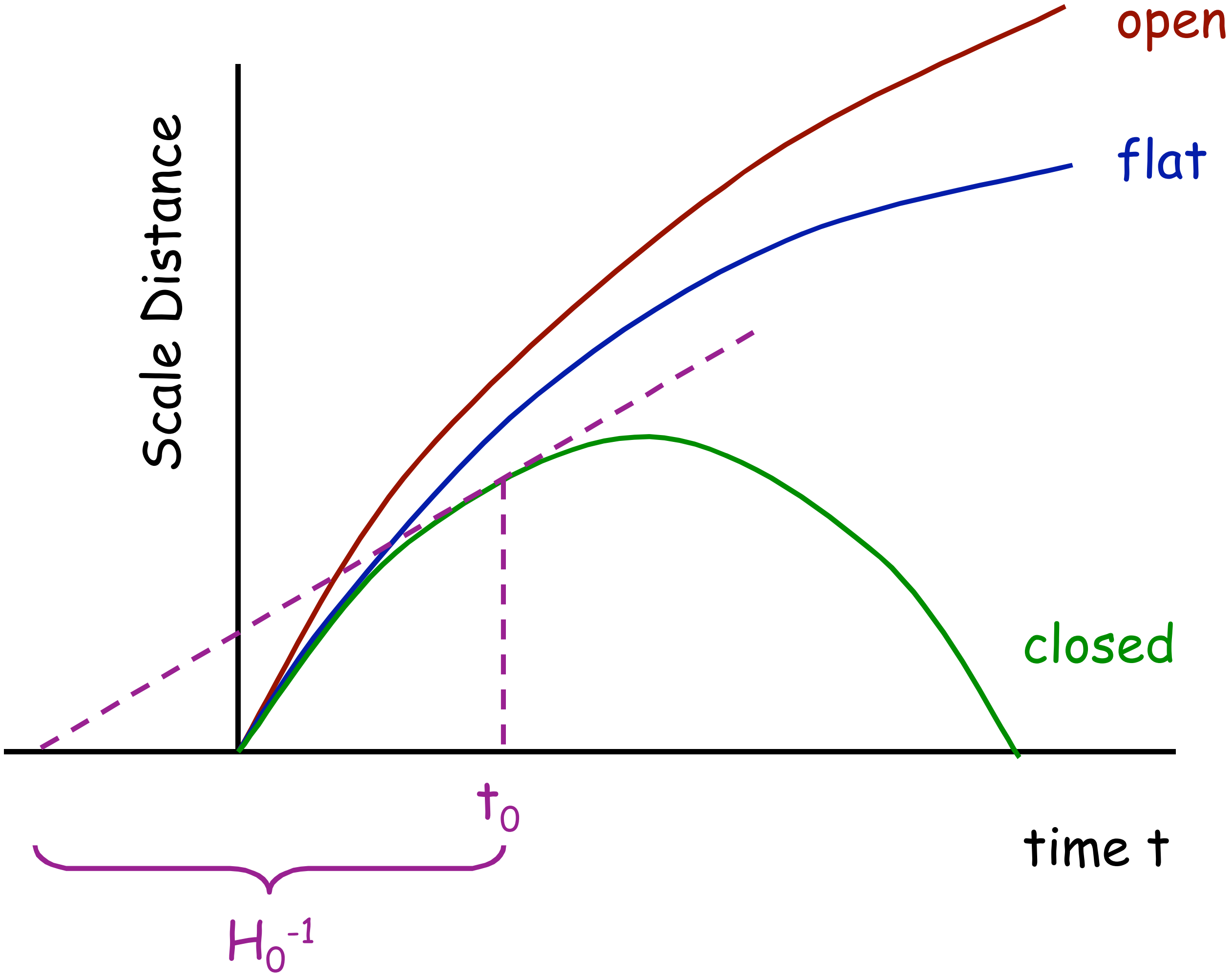
$$v = H R$$

Friedmann found 3 qualitatively different solutions, depending on the density of matter ρ in the universe:

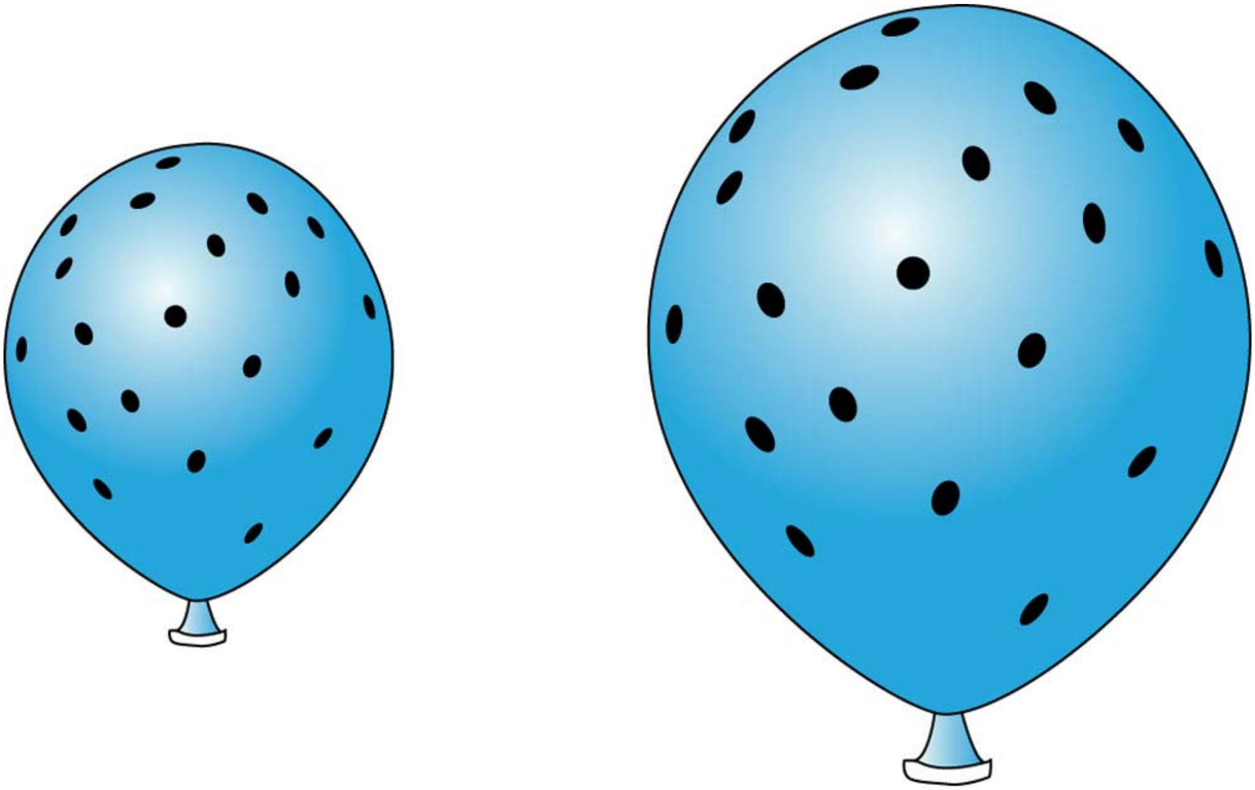
1) Closed universe, $\rho > \rho_{crit}$ (finite)

2) Open universe, $\rho < \rho_{crit}$ (infinite)

3) Flat universe, $\rho = \rho_{crit}$ (infinite)



Hubble Expansion of Universe



From the curves, we see

1) Hubble constant is constant in space. It is not constant in time. H_0 is the constant now at time t_0.

2) The equations predict that the universe was a point at some time in the past - "The Big Bang." The age of the universe must be less than

$$(H_0)^{-1} \approx 14 \text{ billion years}$$

The critical density is

$$\boxed{\rho_{crit} = \frac{3}{8\pi G}(H_0)^2}$$

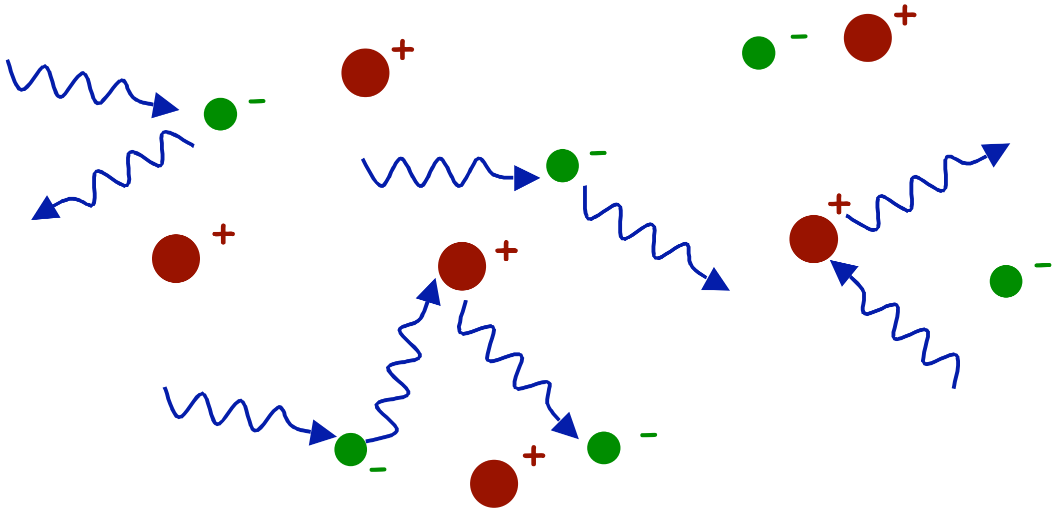
Cosmic Microwave Background Radiation

- 1964 - Penzias and Wilson discovered radiation coming from the sky, corresponding to a blackbody temperature of 3 K.
- About the same time, Peebles had predicted this radiation as a remnant of the “big bang” and Dicke was setting up an experiment to look for it.
- Dicke’s group corroborated the observation of Penzias and Wilson.

(This radiation had been predicted much earlier in the 40’s and 50’s by calculations of Gamow, Alpher, and Herman.)

Explanation of the CMB Radiation

- Very early universe, less than 7 x 10^5 years after the "big bang.
  - The energy of photons was high enough to keep electrons and protons from combining into neutral atoms.
- Photons were in thermal equilibrium with charged particles.
- The spectrum of the radiation was a blackbody spectrum with characteristic temperature T.



- As the universe expanded, the temperature fell. Around T~3000 K, the average photon energy,

  $E \sim 3/2\ k\ T \sim$ less than 1 eV,

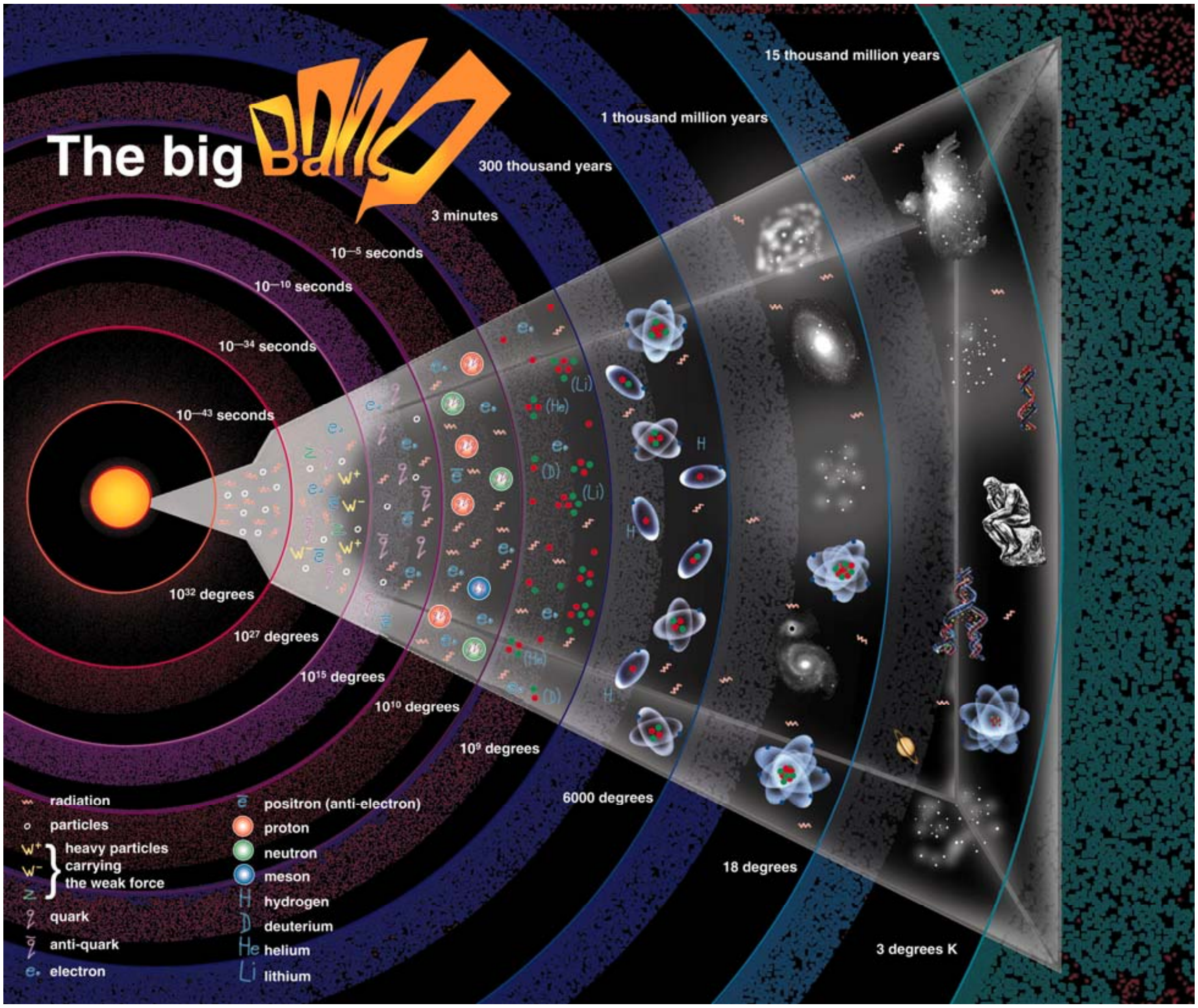
  became too small to keep atoms from forming. At that point the universe become transparent, the photons decoupled from matter, and fell out of thermal equilibrium.

- As the universe continued to expand, electromagnetic waves stretch with the universe. The blackbody spectrum remains, but the effective temperature falls.

- We see the spectrum today as a blackbody spectrum at 2.73 K.

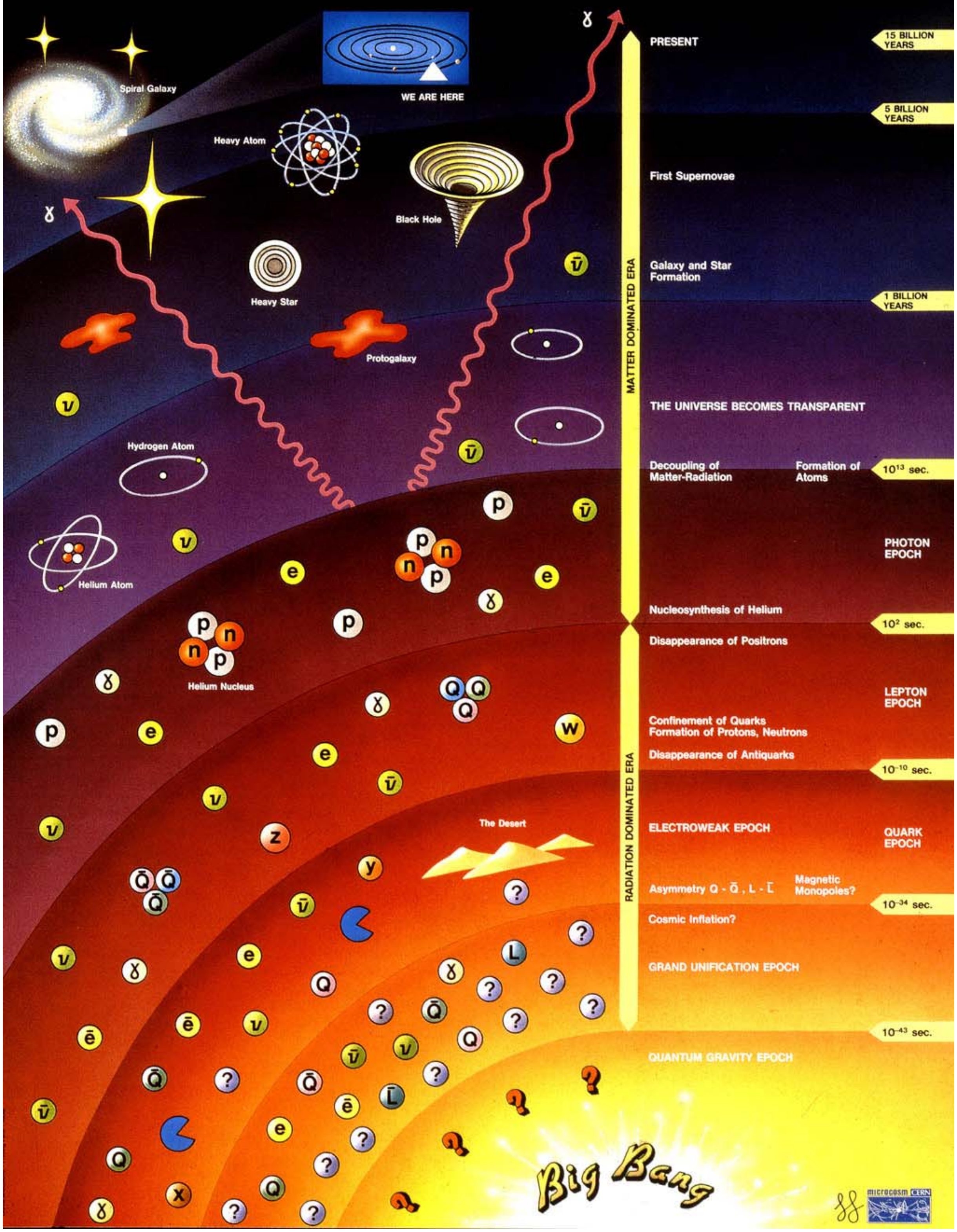
- The radiation is very isotropic (i.e, the temperature changes little in all directions of the sky).

- However, in the early 1990's the Cosmic Background Explorer (COBE) satellite found small deviations. Recently, this has been refined to amazing precision by the Wilkinson Microwave Anisotropy Probe (WMAP).



The big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10—5 seconds
10—10 seconds
10—34 seconds
10—43 seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
18 degrees
3 degrees K
H
(He)
(Li)
(D)
radiation
particles
W+ W− Z heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
H hydrogen
D deuterium
He helium
Li lithium

History of the Universe



MATTER DOMINATED ERA

PRESENT — 15 BILLION YEARS

5 BILLION YEARS

First Supernovae

Galaxy and Star Formation

1 BILLION YEARS

THE UNIVERSE BECOMES TRANSPARENT

Decoupling of Matter-Radiation — Formation of Atoms — 10^{13} sec.

PHOTON EPOCH

Nucleosynthesis of Helium

10^{2} sec.

RADIATION DOMINATED ERA

Disappearance of Positrons

LEPTON EPOCH

Confinement of Quarks
Formation of Protons, Neutrons

Disappearance of Antiquarks

10^{-10} sec.

ELECTROWEAK EPOCH

QUARK EPOCH

Asymmetry $Q - \bar{Q}$, $L - \bar{L}$ — Magnetic Monopoles?

10^{-34} sec.

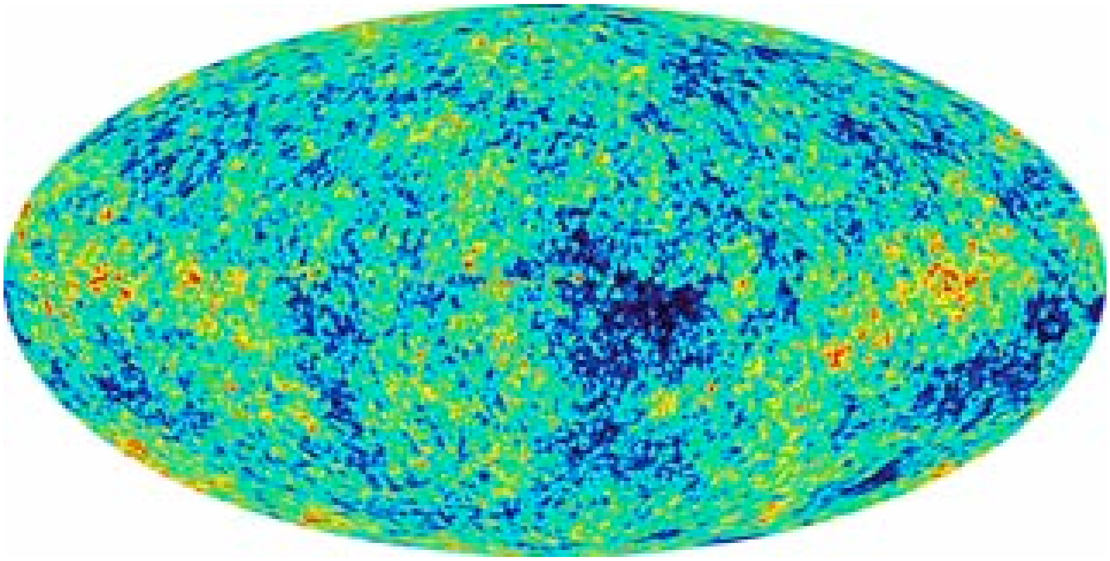
Cosmic Inflation?

GRAND UNIFICATION EPOCH

10^{-43} sec.

QUANTUM GRAVITY EPOCH

Wilkinson Microwave Anisotropy Probe (WMAP)



The average temperature of the Microwave Background radiation is 2.73 K. This map shows the tiny fluctuations ($\Delta T \sim 10^{-6}$ K) around this temperature on the sky.

The fluctuations correspond to “seeds” for structure formation in the early universe.

Conclusions from WMAP (and others)

The universe is 13.7 Billion Years old.

The universe is flat. It will not re-contract.

Only 4% of the universe is made of Baryonic matter (essentially atoms). The rest is 23% unknown matter (called Cold Dark Matter) and 73% "Dark energy". The dark energy could be Einstein's cosmological constant.

Open Questions

- Why is the universe flat?

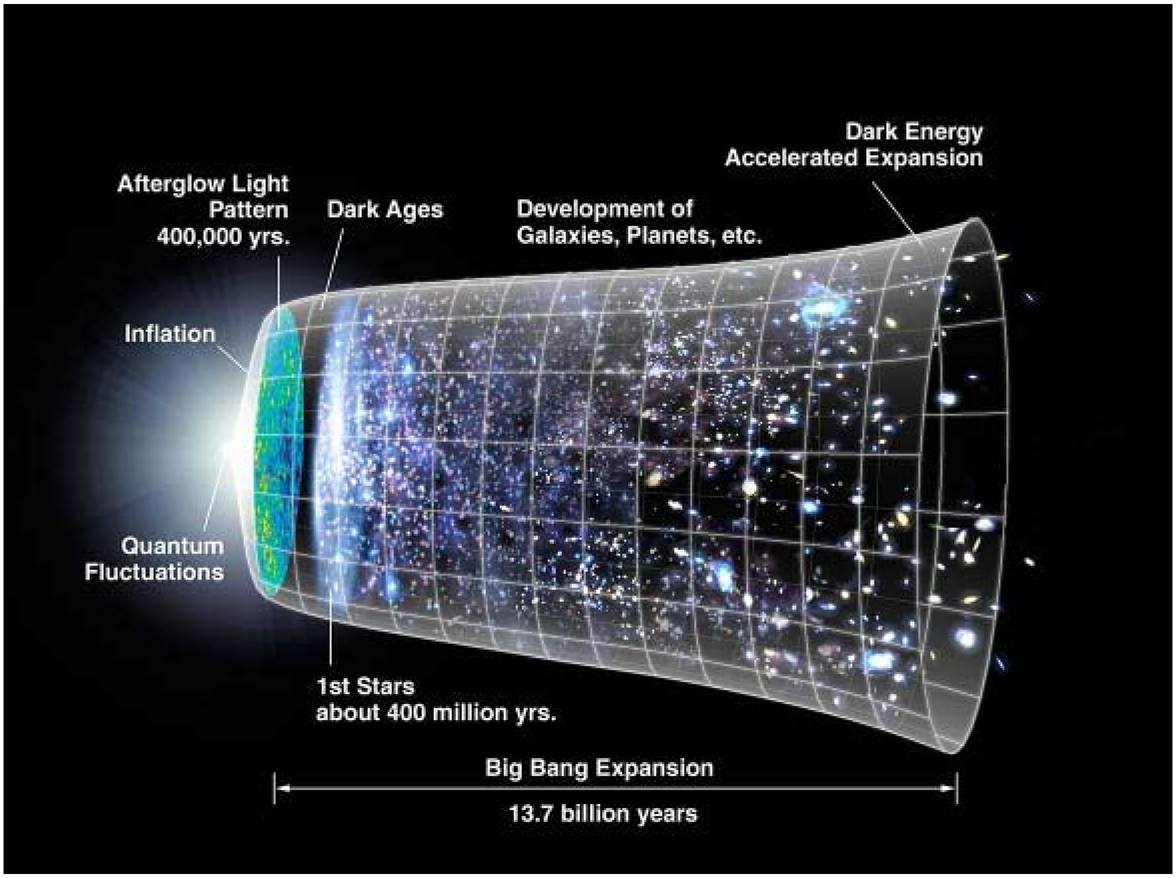
- How can different areas of the universe be in thermal equilibrium, if light has not had time to travel between them? (the "horizon problem")

Inflation, a theory where the universe expanded exponentially for a brief period of time, may be able to solve these problems.

- What is the Cold Dark Matter?

- What is the Dark Energy?

- Why is the universe made of matter, but no anti-matter?


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years