AS1001:Extra-Galactic Astronomy

Lecture 9: The Hot Big Bang

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The Cosmological Principle

We can’t see the whole universe

assume that local conditions are representative:

cosmological principle:

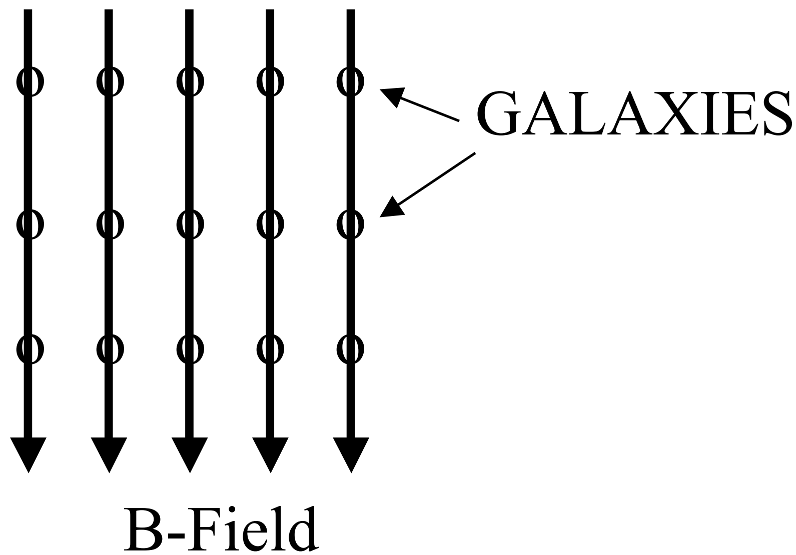
THE UNIVERSE IS ISOTROPIC AND HOMOGENEOUS

Isotropic = the same in all directions

Homogeneous = the same at all locations

The Cosmological Principle

- Although similar to the Copernican Principle it is actually slightly more restrictive.



- e.g., A random distribution of galaxies with aligned magnetic field lines would obey the Copernican but not the Cosmological Principle

Evidence for the CP

- Although the CP obviously fails on small scales (we have planets, stars, galaxies, etc) at some large scale it appears to become valid because of:
  - Deep galaxy counts in different directions
  - Large Scale Galaxy Surveys
  - The Uniformity of the Microwave Background

Deep Galaxy Counts

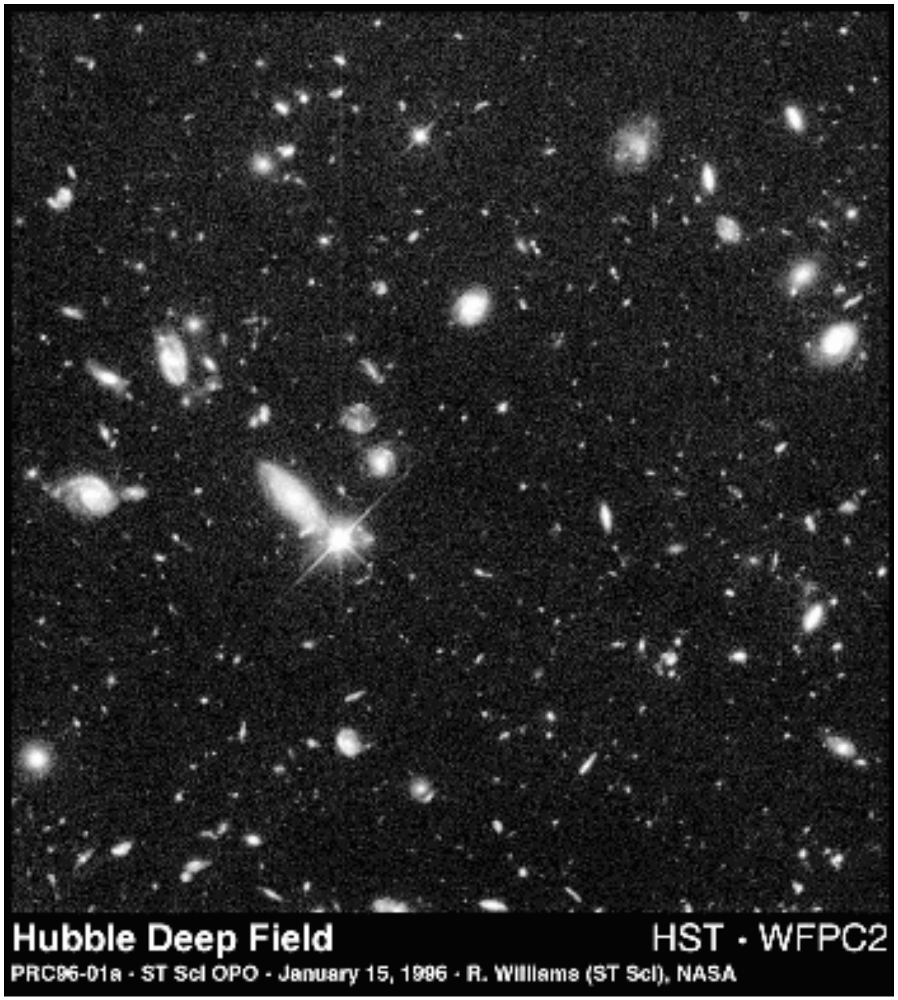
The 2 Hubble Deep Fields are our deepest probes into the Universe along two sight-lines. Exposure times of 10 days or 150 HST orbits. See objects as faint as V~30mags. The HST field of view is 160 arcsecs on a side, or ~ 0.002 square degrees.

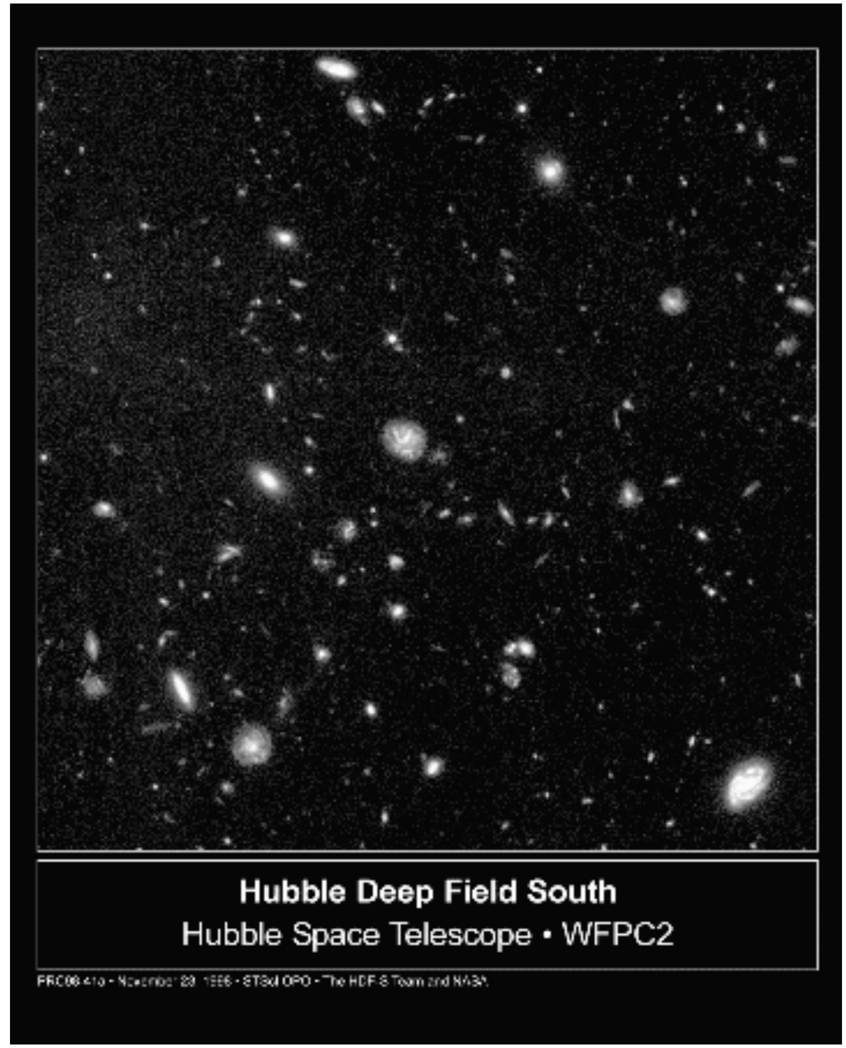
HDF North was released in 1995 and HDF South in 1998. Many extragalactic astronomy and cosmology research projects have resulted from the HDFs.

The distribution of galaxies in the HDFs tell a similar story:

The Hubble Deep Fields

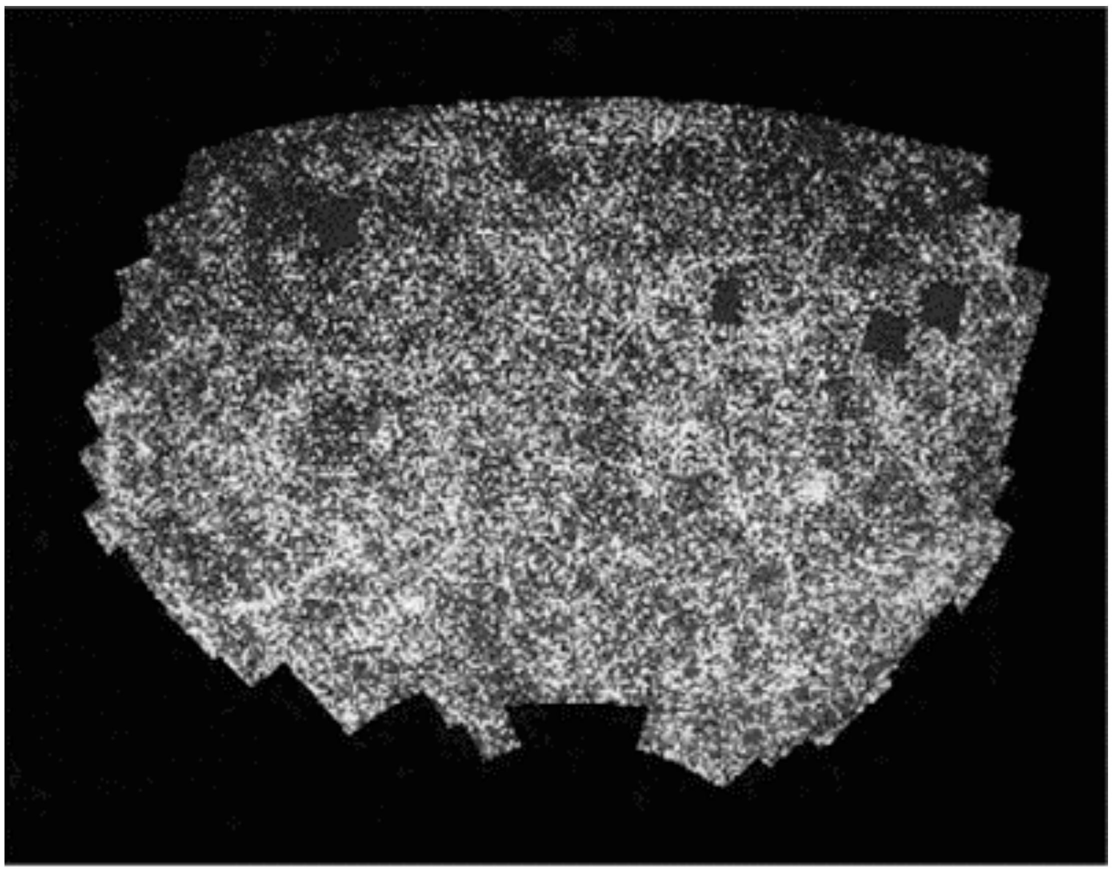
Uniformity of galaxy distributions support the Cosmological principle





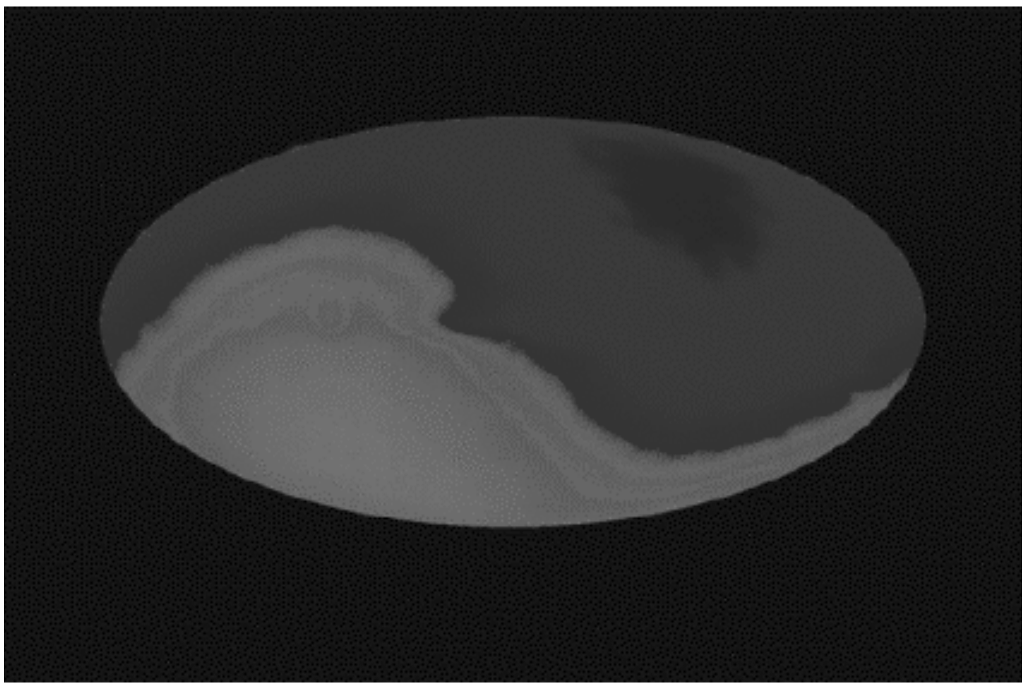
Large Scale Surveys

Large-Scale surveys show an approach towards uniformity on 100Mpc scales (see 2dF+SDSS)



The Microwave Background

- Relic radiation from the Big Bang produces a uniform 2.7K background from all directions



$$T = 2.725 \pm 0.0033\ K$$

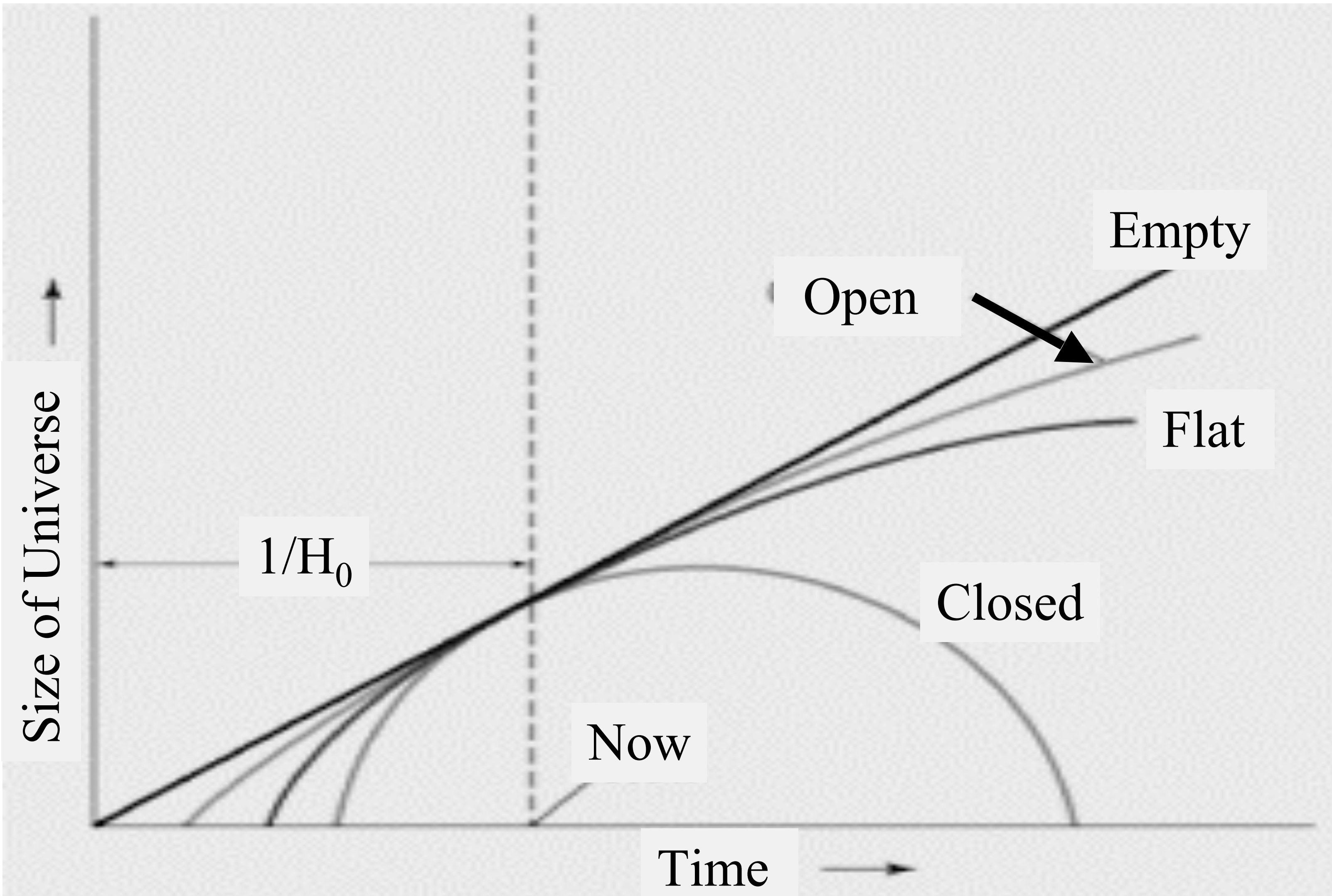
The Contents of the Universe

- AS3006: The derivation of the Friedmann Equations and the construction of a cosmological model.
- The model starts with GR + the CP and the three crucial components of our universe:
  - Matter (Baryonic + Dark)
  - Radiation
  - Vacuum Energy (Cosmological constant or Dark Energy)
- These contents define the curvature of spacetime and their action on it via their pressure and density.
- Their relative abundance ultimately define the end-point to our universe….open or closed ?

The Contents determine the Fate

- Matter (i.e., Baryons and Dark matter)
  - Acts via gravity to pull the universe back together
- Radiation (i.e., Photons and Neutrinos)
  - Acts like a mass (Einstein's equivalence $E=mc^2$)
- Vacuum Energy, Λ (i.e., Dark Energy)
  - Intrinsic curvature of space-time which can act to help expand or contract the universe unless it is flat
- If $\Lambda=0$ (i.e., empty space-time is flat):
  - A high matter+radiation universe will re-collapse
  - A low matter+radiation universe will expand forever

Re-collapse or Eternal Expansion ?



The Anthropic Principle

Is it a surprise that our Universe is so finely balance between collapse and expansion?

What are the odds that our Universe should be so finely balance as to produce matter, metals and life?

The Anthropic Principle

- Two forms of the anthropic principle are used to address this, the weak and strong (see wikipedia !):

- The Weak Anthropic Principle
  - Only in a Universe where life comes about could the question be posed, therefore it is inevitable that we should live in a finely balance Universe.

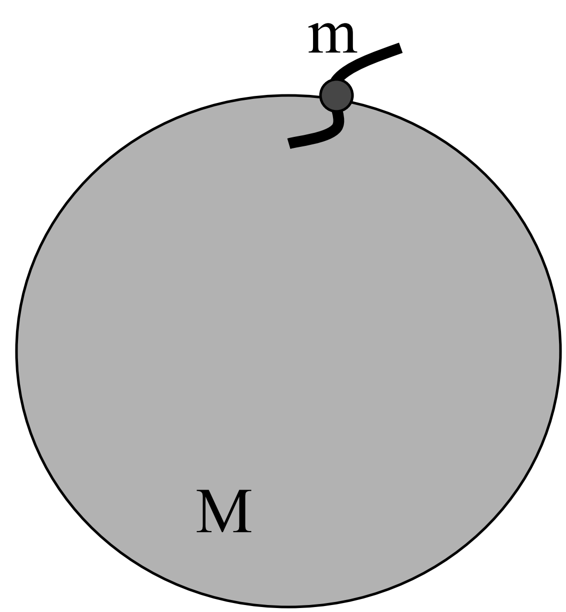
- The Strong Anthropic Principle
  - The laws of physics are such that only a finely balanced Universe can come about and we have yet to understand this physics (Grand Unified Theories and Theories of Everything)

The Critical Density

- Hence there exists a critical balance point which can be derived by balancing a galaxy's kinetic and potential energy:

$$\frac{1}{2}mv^2 = \frac{GMm}{R}$$

$$\frac{1}{2}(H_0R)^2 = \frac{G}{R}\frac{4\pi R^3\rho_c}{3}$$



$$\rho_{\text{CRITICAL}} = \frac{3H_o^2}{8\pi G} \approx 1.1\times10^{-26}\,kg/m^3$$

$$M = \rho_c\frac{4}{3}\pi R^3$$

- From earlier in the course we found that the density of matter as derived from counting galaxies is:

$$\rho_{GALAXIES} \sim 10^{-27} kg / m^3$$

i.e., not enough to close the Universe !

- What about the density of radiation ?

The Hot Big Bang

- The Universe contains radiation,
  - From stars
  - From Big Bang (most of the photons)
- Early universe:
  - Small and dense: thus hot
- From thermodynamics
  - the energy density of the radiation is related to the temperature of the photons by: (i.e., The Stefan-Boltzmann law)

$$\varepsilon = \frac{\sigma T^4}{c}$$

- Hence the early Universe was HOT

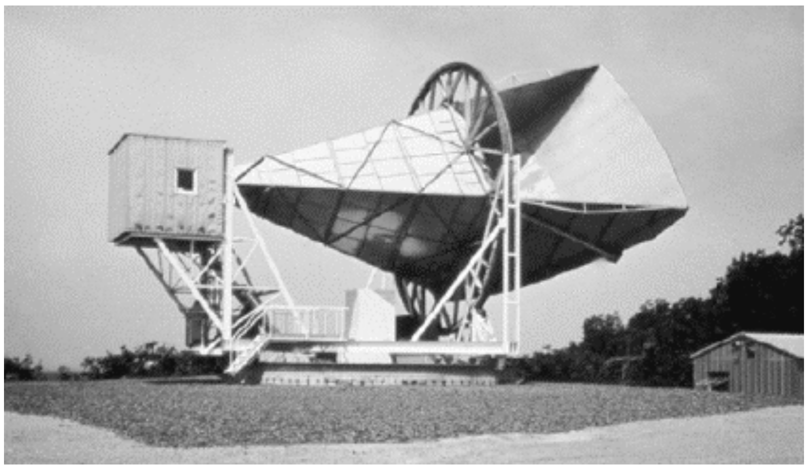
Relic Radiation

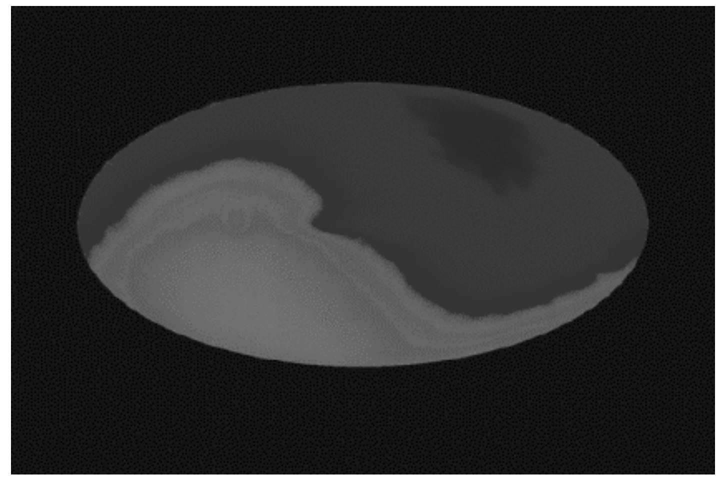
- Early universe opaque
  - Fully ionised
  - Photons scattered by electrons, can’t escape easily
- Universe expands and cools
  - Ions recombine (RECOMBINATION)
  - Photons escape at $T = T_{rec}$ ~(3000 K)

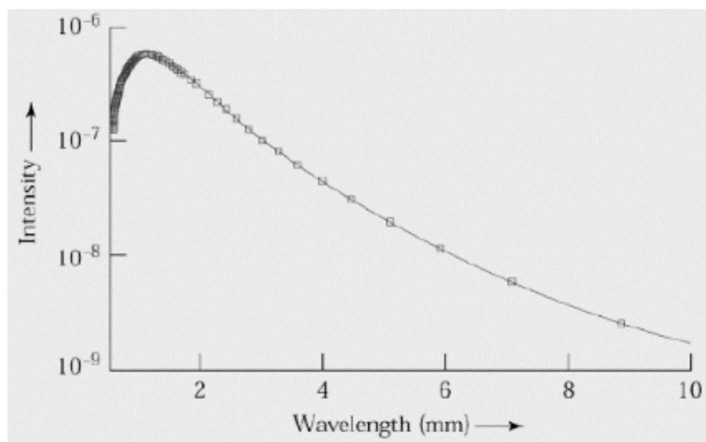
- As the Universe expands the radiation is redshifted to lower (colder) wavelengths. T~ 2.7K
- Detectable now as a uniform low temperature black-body background from all directions.

The Cosmic Microwave Background

- Predicted by Gamov in 1948 and discovered accidentally by Penzias and Wilson in 1965







The Density of Radiation

- Using Einstein's classic formulae relating matter and radiation we can calculate the density of radiation from the Microwave background, i.e.,

$$E = mc^2$$
$$4\varepsilon = \rho c^2$$

$$\Rightarrow \quad \rho_{\mathrm{RAD}} = \frac{4\sigma T^4}{c^3}$$

- As the peak of the CMB is 2.7 K this gives:

$$\rho_{\mathrm{RAD}} = \frac{4 \times 5.67 \times 10^{-8} \times 2.7^4}{(3 \times 10^8)^3}$$
$$\rho_{\mathrm{RAD}} = 4.6 \times 10^{-31}\, kg/m^3$$

The Density of Radiation from Stars

- If one takes the average temperature of a galaxy to consist of solar type stars we can convert the number density of galaxies to a radiation density.
- We find one *M* ~ -21 galaxy per 100/Mpc^3, therefore:

$$\varepsilon_{STARS} = \frac{N_{GALS} L_{\otimes} 10^{-0.4(M_{GAL} - M_{SOLAR})}}{V}$$

$$\varepsilon_{STARS} = \frac{3.9\times10^{26}\times10^{-0.4(-21-5.48)}}{100\times(3\times10^{22})^3}$$

$$\varepsilon_{STARS} = 5.6\times10^{-33} J/m^3$$

$$\varepsilon_{STARS} << \varepsilon_{COSMIC}$$

- Hence the total photons produced by all the stars are negligible compared to those produced during the Big Bang

In Summary we find

- Density of Matter >> Density of Radiation today

$$(\rho_{MATTER} = 10^{-27} kg/m^3) >> (\rho_{RADIATION} = 4\times10^{-31} kg/m^3)$$

- Density of Matter+Radiation < Critical Density

$$(\rho_{ALL} \approx 10^{-27} kg/m^3) << (\rho_{CRIT} = 1.1\times10^{-26} kg/m^3)$$

- For critical density, need to find 10x more matter than found in galaxies
  - (this is in addition to the dark matter required to explain rotation curves)

- What about the Cosmological Constant ?