AS1001: Extra-Galactic Astronomy

Lecture 9: The Hot Big Bang

The Cosmological Principle

We can't see the whole universe.

Copernican Principle:

OUR LOCATION/VIEW IS TYPICAL, NOT SPECIAL

Cosmological Principle:

THE UNIVERSE IS ISOTROPIC AND HOMOGENEOUS

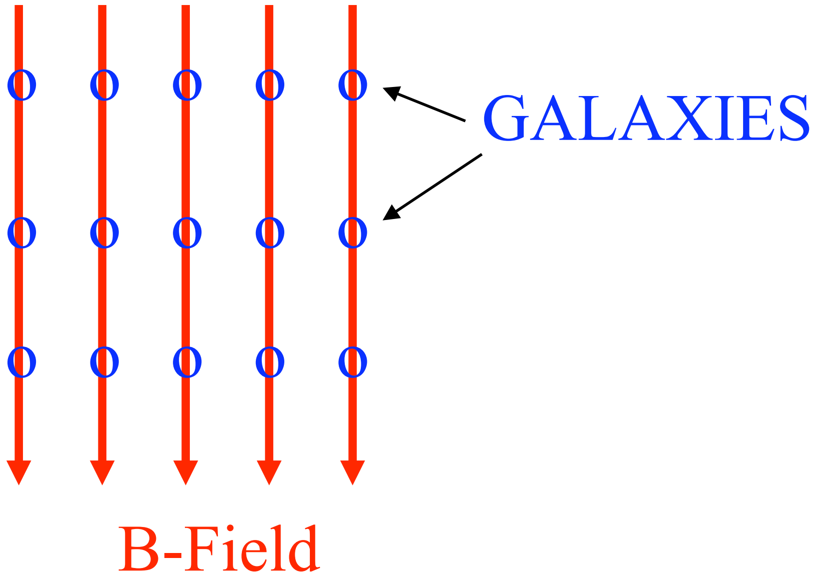
Isotropic = the same in all directions

Homogeneous = the same at all locations

The Cosmological Principle

- The Cosmological Principle is more restrictive.

Homogeneous, but not isotropic.



- A random distribution of galaxies with aligned magnetic field lines (preferred direction) would obey the Copernican but not the Cosmological Principle.

Evidence for the CP

- The CP obviously fails on small scales (planets, stars, galaxies, etc)
- On large scales (>100 Mpc) it appears to become valid:
  - 1. Deep galaxy counts in different directions
  - 2. Large Scale Galaxy Surveys
  - 3. Isotropy of the Microwave Background

1. Deep Galaxy Counts

Hubble Deep Fields:

Our deepest probes into the Universe, along two sight-lines.

Exposure times: 10 days (150 HST orbits).
Faintest galaxies: V~30 mag.
Field of view: 160 arcsecs on a side, 0.002 square degrees.

HDF North (1994). ***HDF South*** (1998).

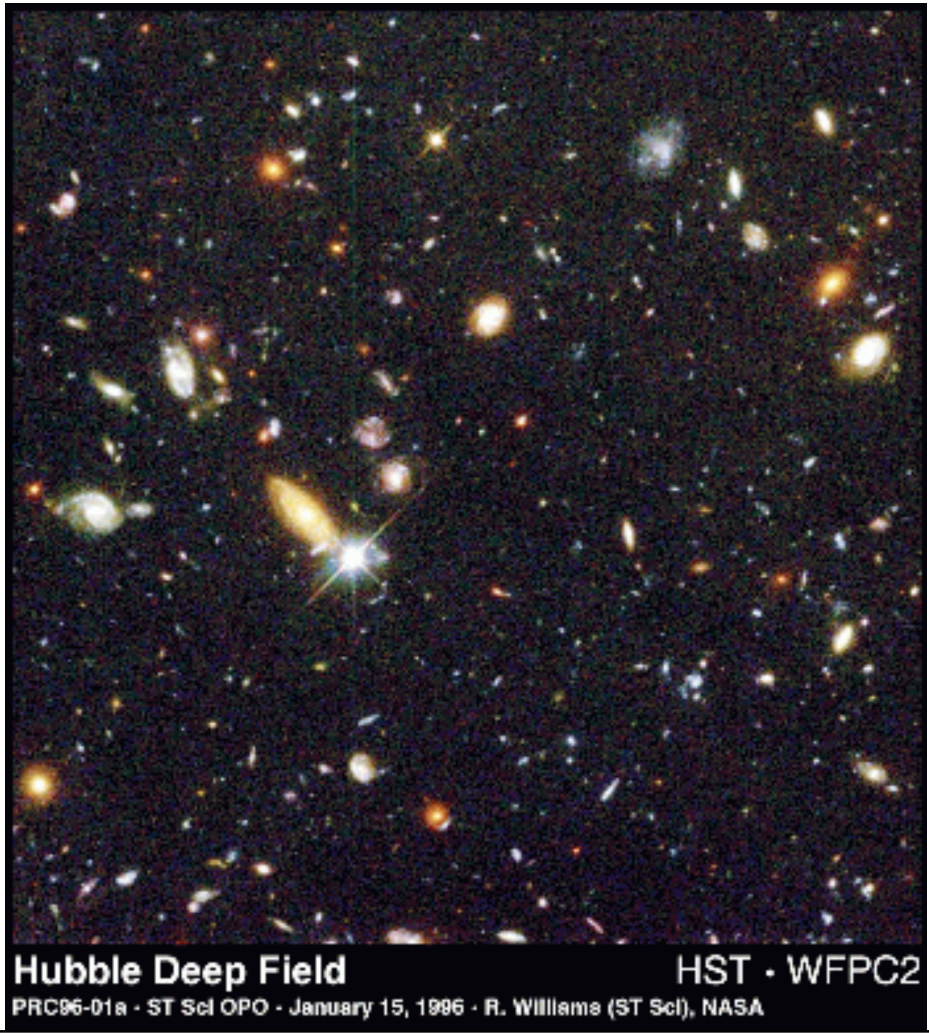
The galaxy population in the two HDFs tell a similar story:

The Hubble Deep Fields

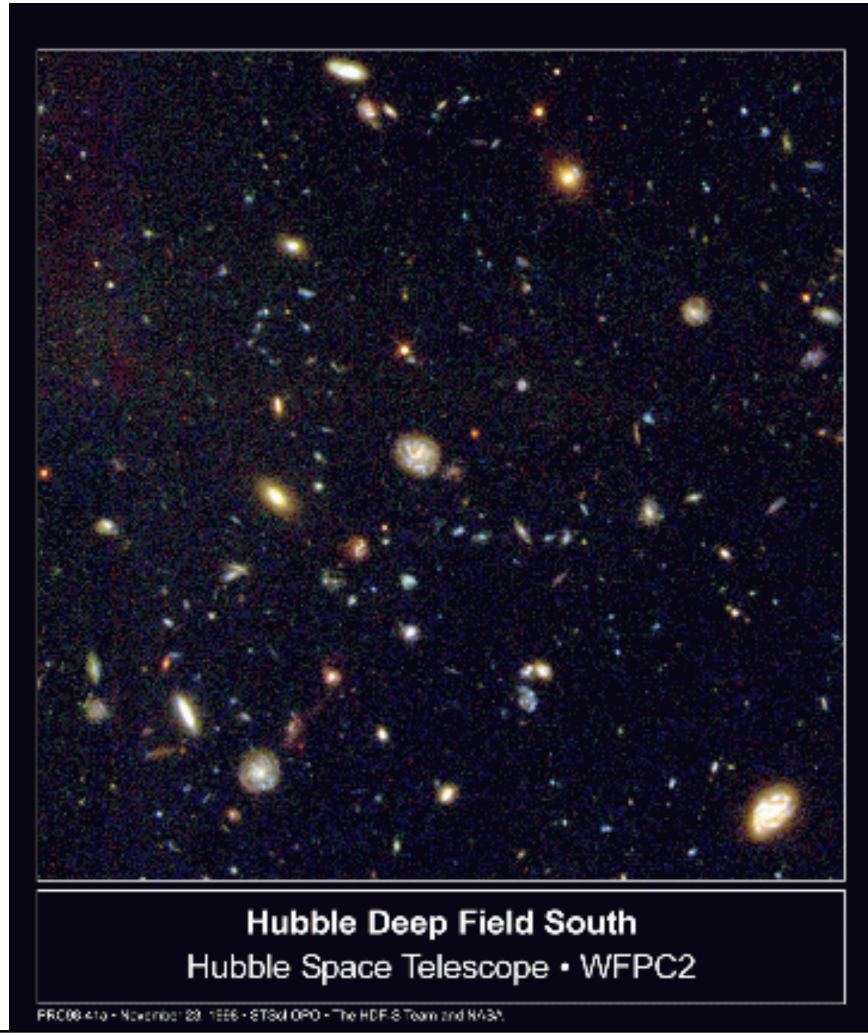
Thousands of galaxies, just a few stars.

Similar galaxy distributions, supporting the Cosmological Principle.

HDF North

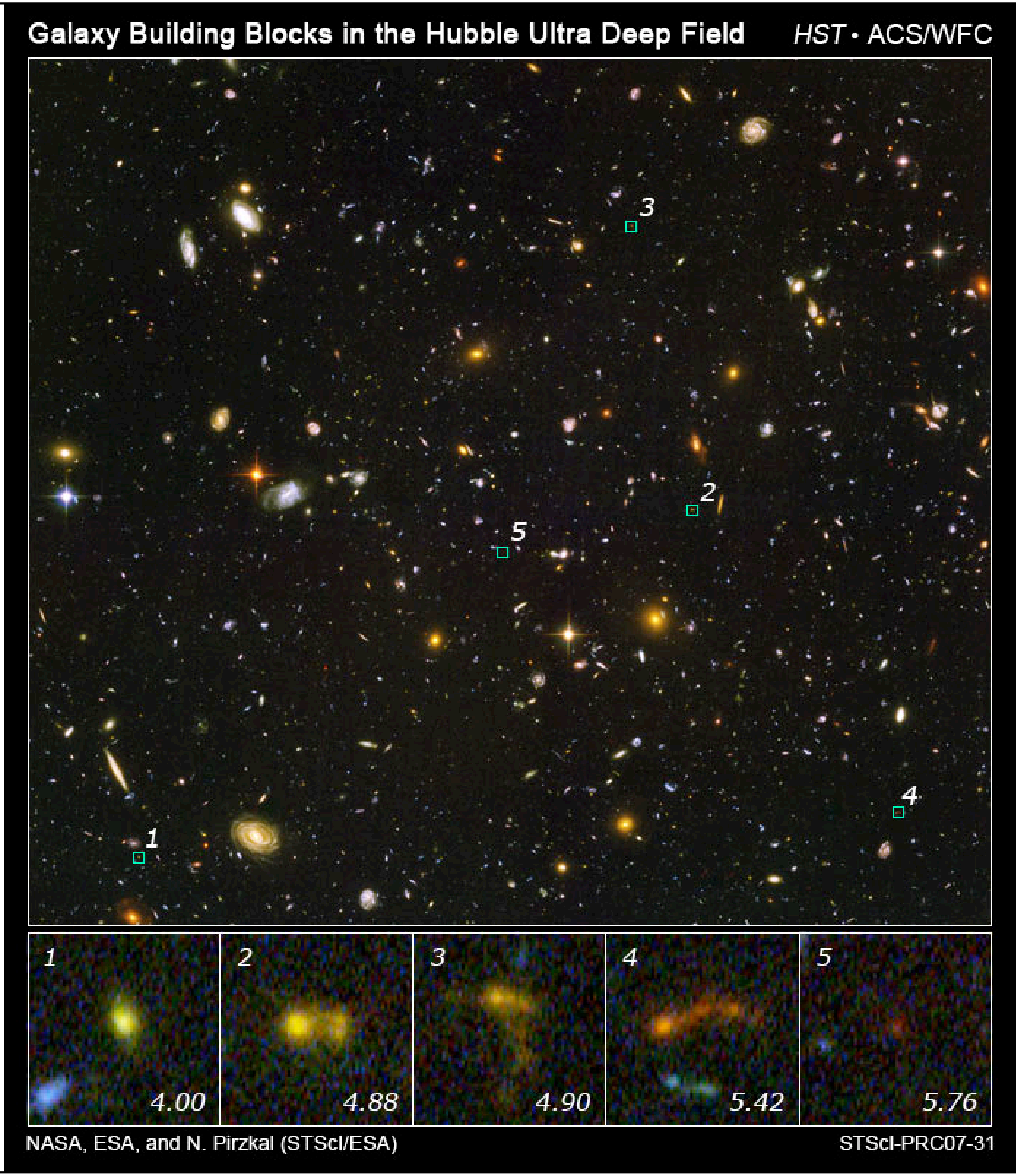


HDF South



Hubble Ultra-Deep Field:

Faintest galaxies seen at redshifts z = 4-6



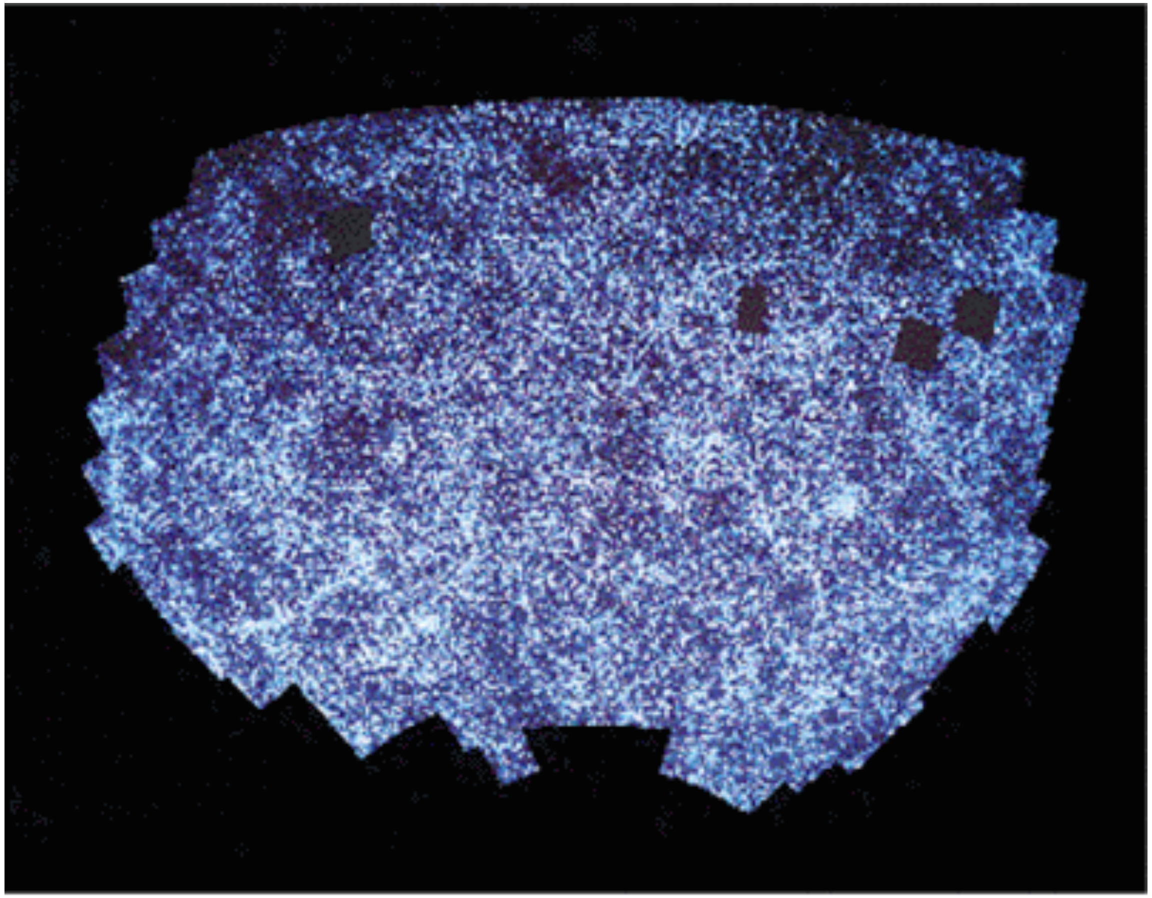
2. Large Scale Surveys

Large-Scale surveys show an approach towards uniformity on 100 Mpc scales:

From *images*:
galaxy type and direction on the sky.

From *spectra*:
redshifts, z, hence distances via Hubble's law:

$d = c\,z\,/\,H_0$

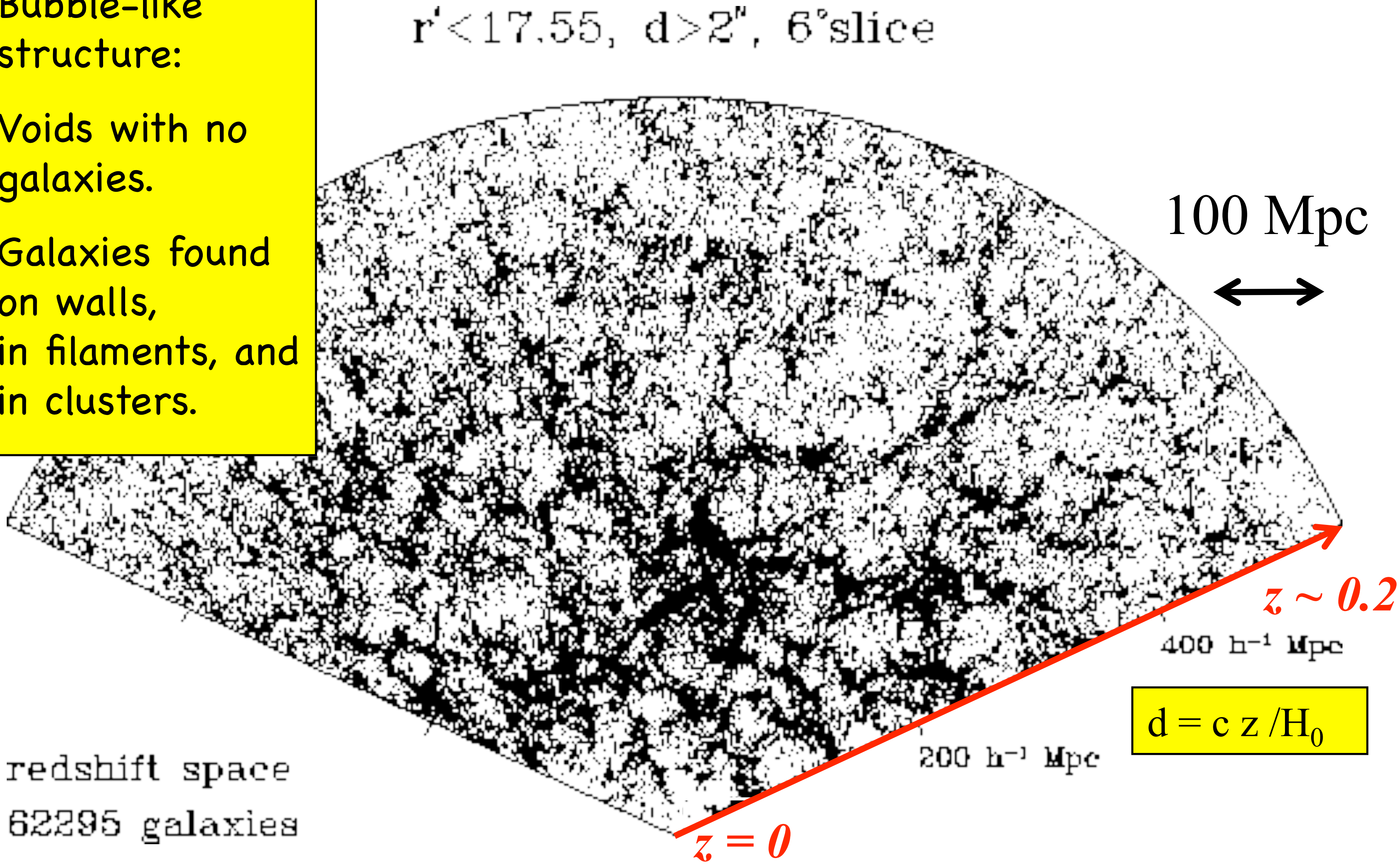


Galaxy Redshift Surveys

Bubble-like structure:

Voids with no galaxies.

Galaxies found on walls,
in filaments, and
in clusters.



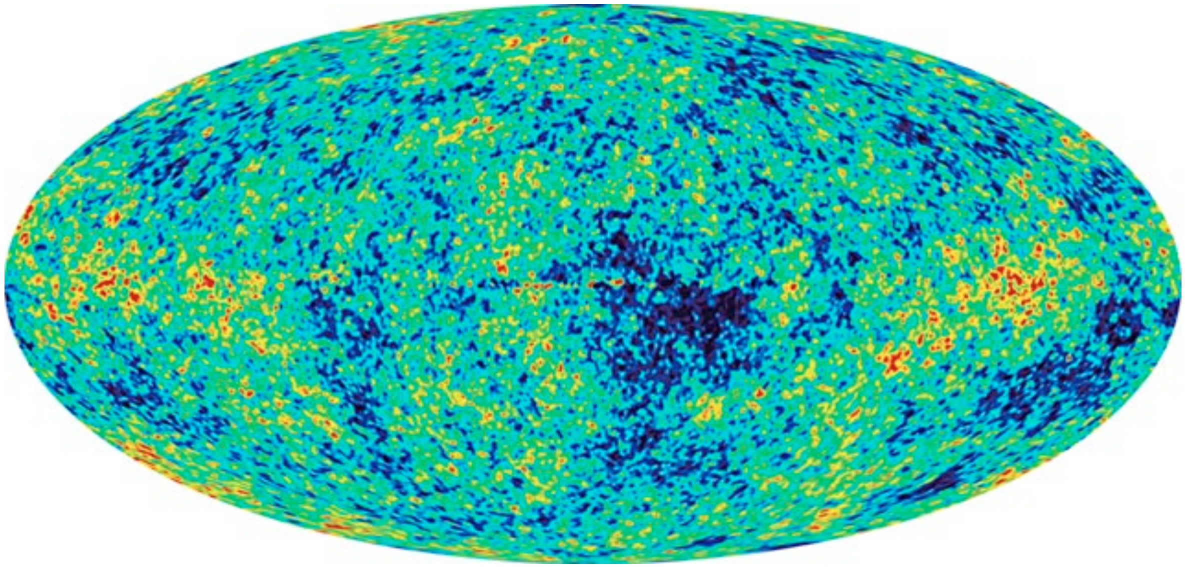
$d = c\,z\,/H_0$

3. The Microwave Background

- Relic radiation from the Big Bang, seen today as a uniform 2.7K background from all directions.

$$T = 2.725\ K$$

$$\frac{\Delta T}{T} \sim 10^{-5}$$



2004 all-sky map from WMAP satellite.

Snapshot of the Universe at redshift z = 1100.

Tiny ripples = seeds for later galaxy formation.

Cosmic Evolution: A Sketch

- Based on GR + CP (see AS2001, AS4022 for more depth).
  - Friedmann Equation governs evolution.
  - Size (radius of curvature) of Universe: R(t)
- ***Three components***:
  - **Matter** (Baryons + Dark Matter)
  - **Radiation** (Photons + Neutrinos)
  - **Vacuum** (Cosmological Constant Λ or "Dark Energy")

Densities evolve differently.

Pressures also different.

$\rho_M \propto R^{-3} \quad p_M \approx 0$

$\rho_R \propto R^{-4} \quad p_R = \rho_R / 3$

$\rho_\Lambda \propto R^{0} \quad p_\Lambda = -\rho_\Lambda$

- Evolving density ρ and pressure p determine
  - the geometry of spacetime (flat vs curved)
  - how the Universe evolves (acceleration vs deceleration).

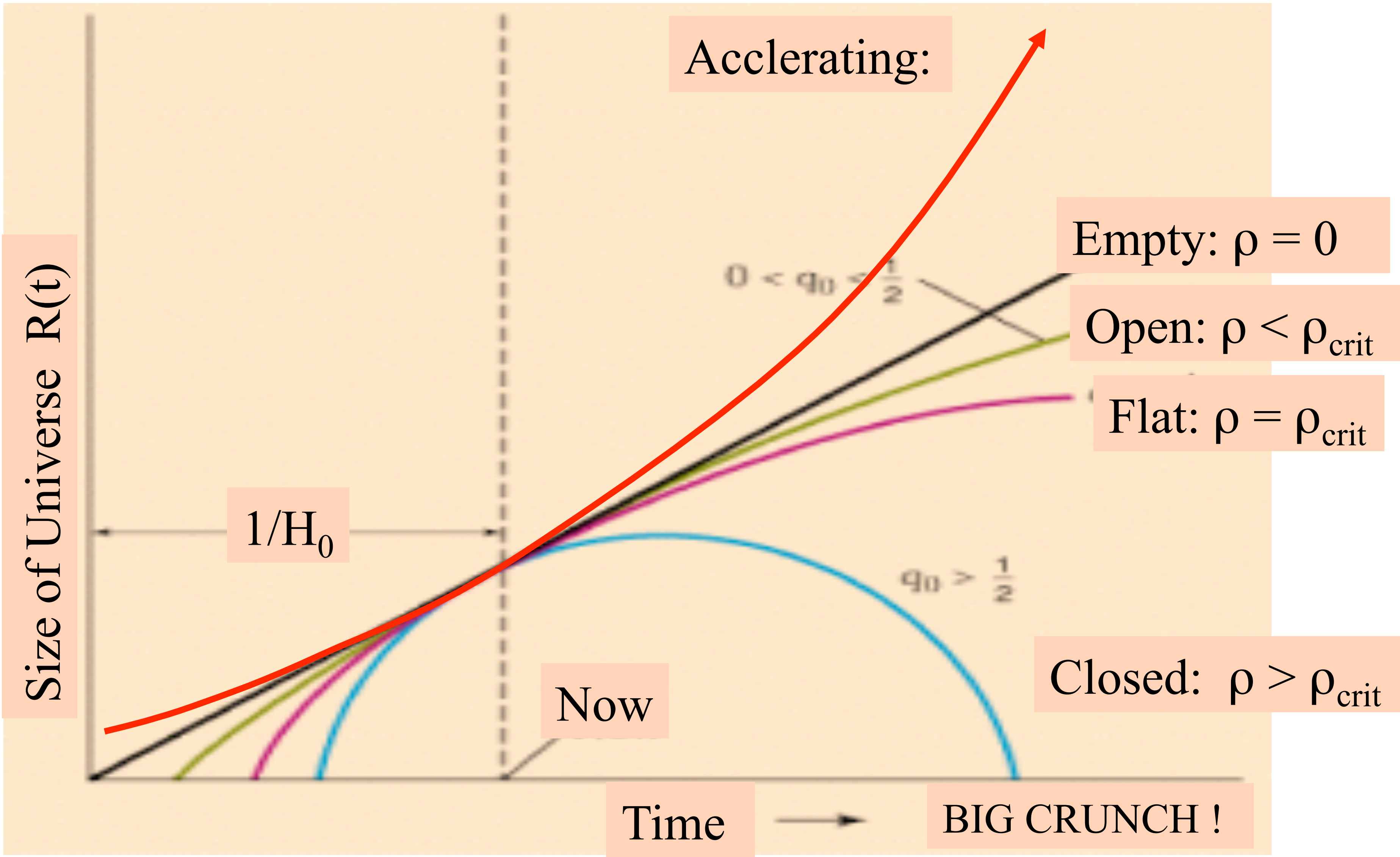
The Contents determine the Fate

- **Matter**
  - Acts via gravity to pull the Universe back together
- **Radiation**
  - Acts like mass (Einstein's equivalence $E=mc^2$)
- **Vacuum**
  - Empty space (vacuum) accelerates the expansion.
  - Observed but not understood theoretically.
- **Critical Density (for $\Lambda = 0$, no Dark Energy):**

$$\rho_{CRIT} = 3\, H_0^2 \,/\, 8\, \pi\, G$$

  - Low-density ==> expand forever.
  - High-density ==> re-collapse to a BIG CRUNCH.

Re-collapse or Eternal Expansion ?



Fine-Tuning Problem

Our Universe is finely balanced between collapse and expansion.

Low density => Expand too fast:
no stars form.

High density => Re-collapse to
Big Crunch before stars form.

Why is our Universe finely balanced,
so as to produce stars, planets and life?

The Anthropic Principle

- Weak Anthropic Principle
  - Only in a Universe where life arises can the question be posed. Thus, inevitable that we live in a finely balanced Universe.
  - Implies ours is but one of many possible Universes (or pieces of a much larger Universe), most of which have no life.

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

The Critical Density

Expand forever if $\rho < \rho_{CRIT}$

Re-collapse if $\rho > \rho_{CRIT}$

- Newtonian derivation:
  - Balance kinetic and potential energy:

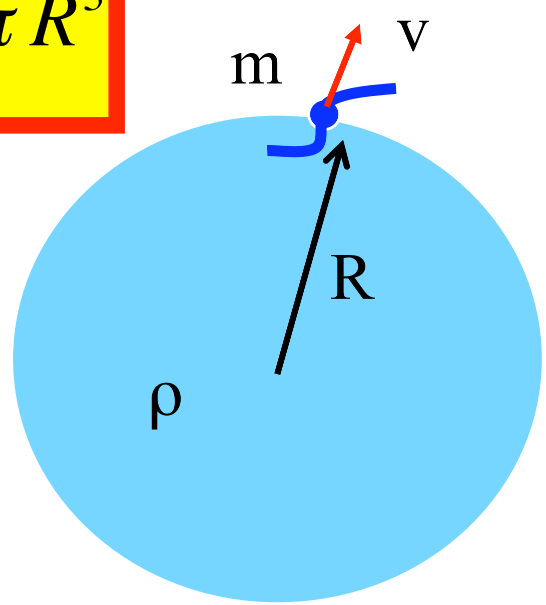
$$\frac{1}{2} m \mathrm{v}^2 = \frac{G M m}{R}$$

$$\frac{1}{2} (H_0 R)^2 = \frac{G}{R} \frac{4\pi R^3 \rho}{3}$$

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

$$\mathrm{v} = H_0 R$$

$$\rho_{\mathrm{CRIT}} = \frac{3 H_0^2}{8 \pi G} \approx 10^{-26}\ \mathrm{kg/m^3}$$



Matter Density

- From counting galaxies:

$$\rho_{GALAXIES} \sim 10^{-27} \mathrm{kg/m^3}$$
$$\sim 0.1\,\rho_{CRIT}$$

- 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 (T=2.7K, most of the photons)
- Early Universe:
  - Small and dense: thus hot: (T scales as 1/R)
- Black-body radiation
  - Energy density scales as T^4 :
  - The Stefan-Boltzmann law:

$$\varepsilon_{RAD} = \frac{4\sigma T^4}{c}$$

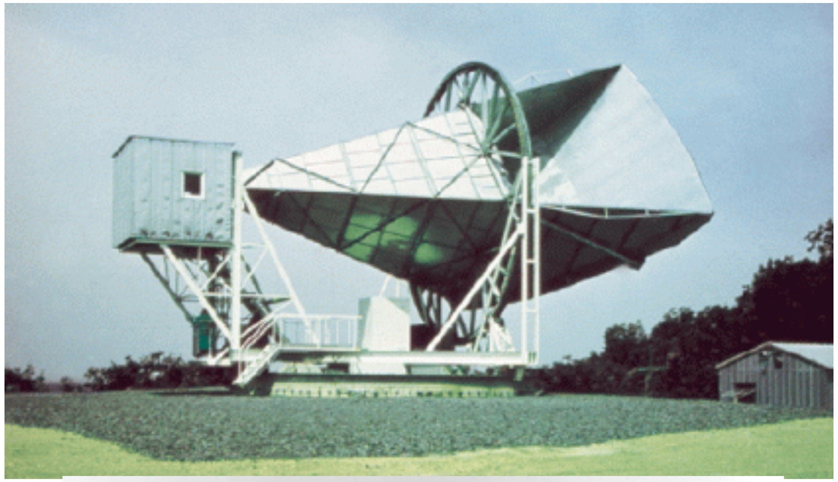
- Hence the early Universe was HOT

Relic Radiation

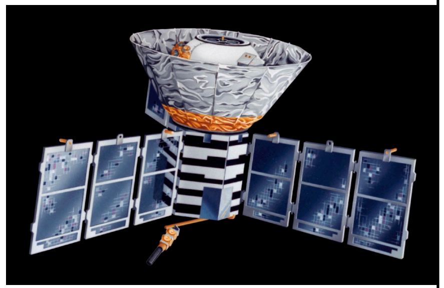
- Early Universe was opaque:
  - Fully ionised
  - Photons, scattered by electrons, can't travel far.
- Universe expands and cools:
  - Ions recombine (RECOMBINATION)
  - Photons break free at T = 3000 K ($\lambda \sim 10^{-6}$ m)
- Radiation is redshifted as Universe expands:
  - photon wavelengths stretch to $\lambda \sim 1$ mm
  - longer wavelengths -> lower T. T => 2.7K
- Detectable today as a uniform
  T = 2.7K black-body background
  from all directions.

Cosmic Microwave Background

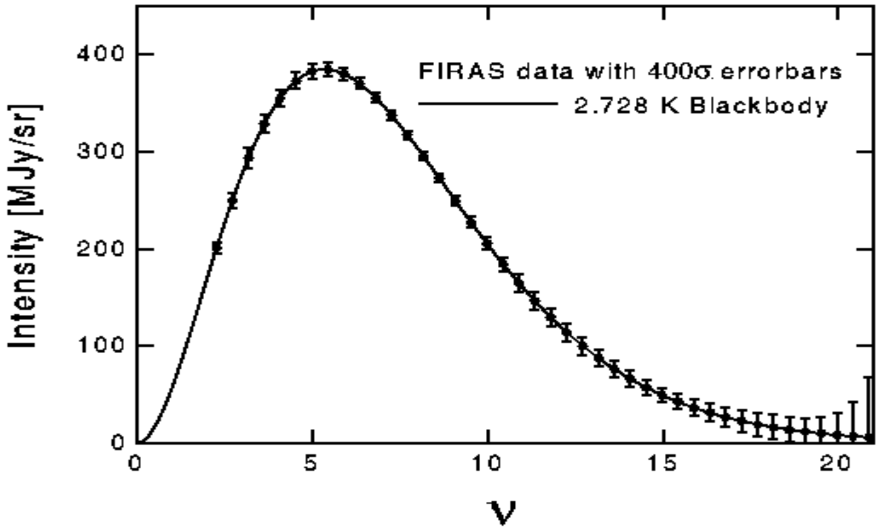
- CMB predicted (T=5K) by Gamov in 1948 and discovered by Penzias and Wilson in 1965.



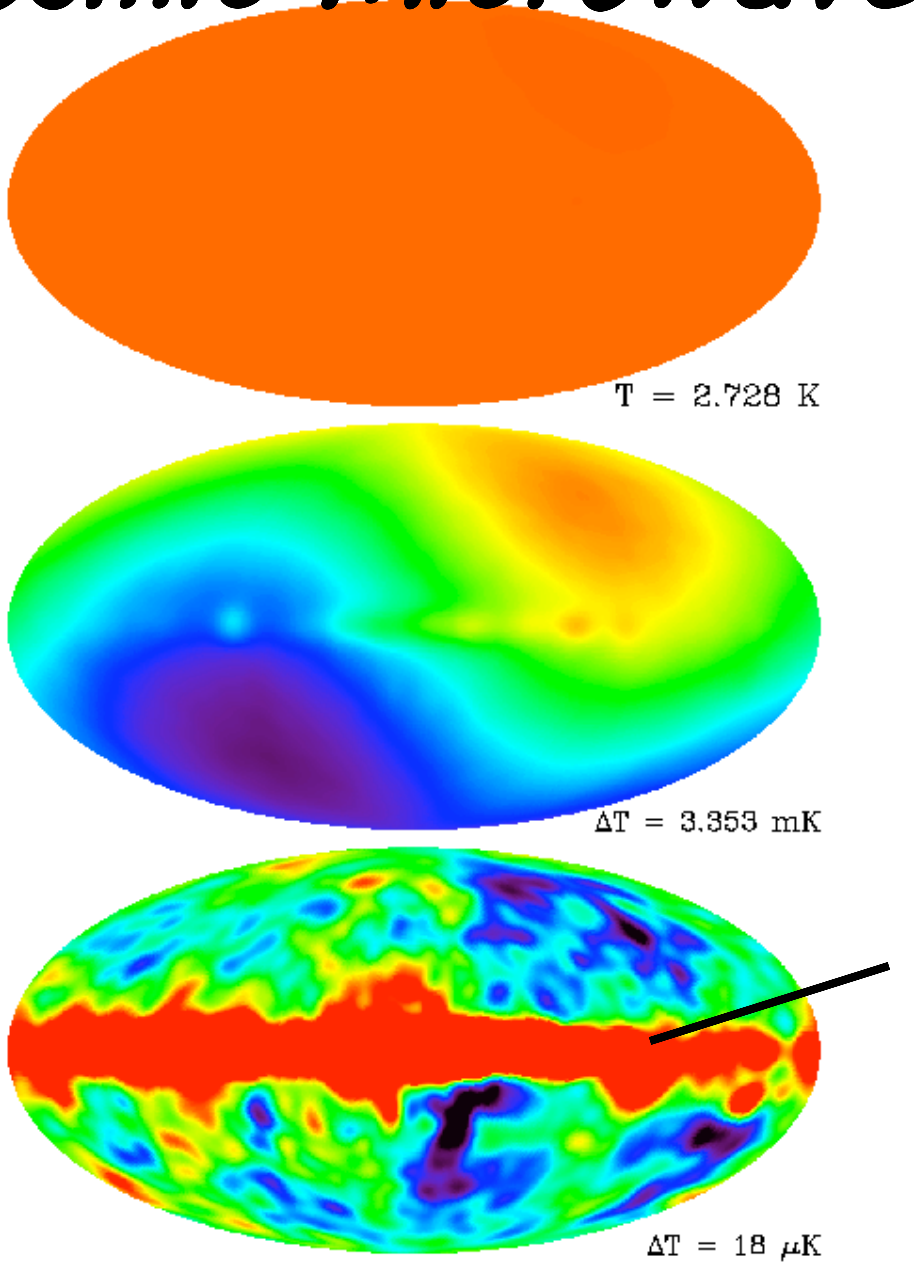
1992 NASA - COBE
COsmic Background Explorer



A perfect Blackbody!



Cosmic Microwave Background



Almost isotropic

$T = 2.728$ K

Dipole anisotropy

$$\frac{V}{c} = \frac{\Delta\lambda}{\lambda} = \frac{\Delta T}{T} \approx 10^{-3}$$

Our velocity:

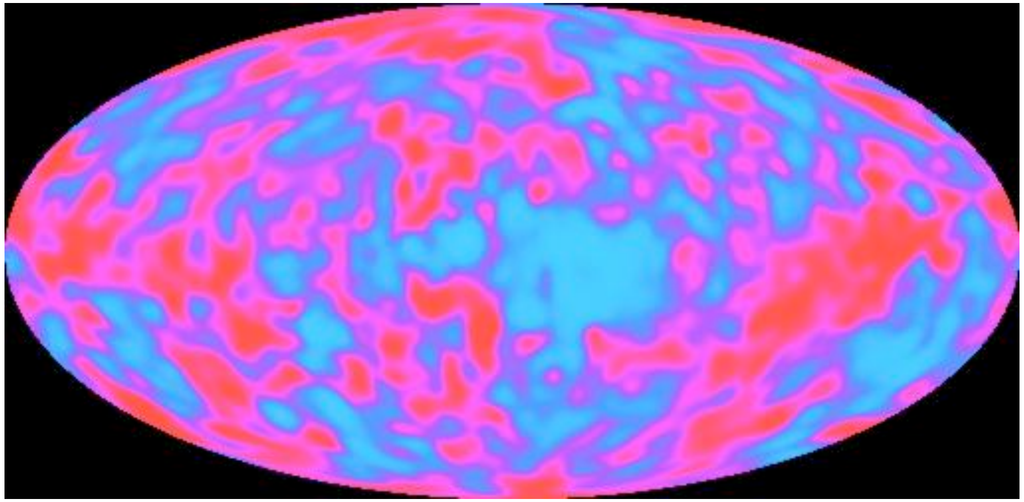
$V \approx 400$ km/s

Milky Way sources

$$+ \text{ anisotropies } \frac{\Delta T}{T} \sim 10^{-5}$$

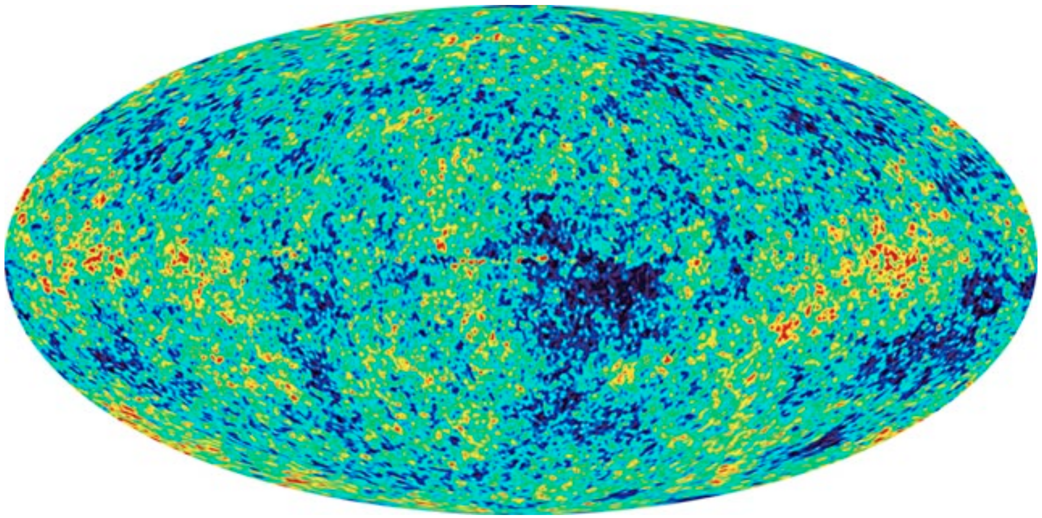
CMB Anisotropies

COBE
1994



$$\frac{\Delta T}{T} \sim 10^{-5}$$

WMAP
2004



$$\Delta\theta \sim 1^{\circ}$$

Snapshot of Universe at z = 1100, when T=3000K

Density of Radiation

- Using Einstein's classic formula E = mc^2, calculate the density of CMB radiation

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

=>

$$\rho_{\mathrm{RAD}} = \frac{\varepsilon_{\mathrm{RAD}}}{c^2} = \frac{4\sigma T^4}{c^3}$$

- For T = 2.7 K this gives:

$$\rho_{\mathrm{RAD}} = \frac{4 \times \left(5.67 \times 10^{-8}\right) \times (2.7)^4}{(3 \times 10^8)^3}$$
$$= 5 \times 10^{-31}\,\mathrm{kg/m^3}$$
$$= 5 \times 10^{-5}\,\rho_{\mathrm{CRIT}}$$

Radiation Density of Starlight

- Convert the number density of galaxies to a radiation density.
  - Assume galaxies filled with Sun-like stars, M_V = +5.5 mag.
  - Assume one M_V = −21 mag galaxy per 100/Mpc³.

$$\varepsilon_{STARS} = \frac{N_{GALS}\, L_{\otimes}\, 10^{-0.4[M_V(GAL)-M_V(SUN)]} \times \text{time}}{\text{volume}}$$

$$= \frac{\left(4\times10^{26}\,\text{J/s}\right)\times10^{-0.4(-21-5.5)}\times\left(15\,\text{Gyr}\right)\times\left(3\times10^{15}\,\text{s/Gyr}\right)}{100\,\text{Mpc}^3\times(3\times10^{22}\,\text{m/Mpc})^3}$$

$$= 3\times10^{-16}\,\text{J/m}^3$$

$$\varepsilon_{CMB} = 5\times10^{-14}\,\text{J/m}^3$$

- Photons from all the stars are negligible compared to the photons left over from the Big Bang.

In Summary we find

- Density of Matter >> Density of Radiation today

$$(\rho_M \approx 10^{-27}\,\mathrm{kg/m^3}) \quad >> \quad (\rho_R = 4 \times 10^{-31}\,\mathrm{kg/m^3})$$

- Density of Matter+Radiation < Critical Density

$$(\rho_{ALL} \approx 10^{-27}\,\mathrm{kg/m^3}) \sim 0.1\,(\rho_{CRIT} = 10^{-26}\,\mathrm{kg/m^3})$$

- Critical Density is 10x more than that found in galaxies
  - includes the Dark Matter required by flat rotation curves of galaxies.

- What about the Cosmological Constant ?

(Next lecture)