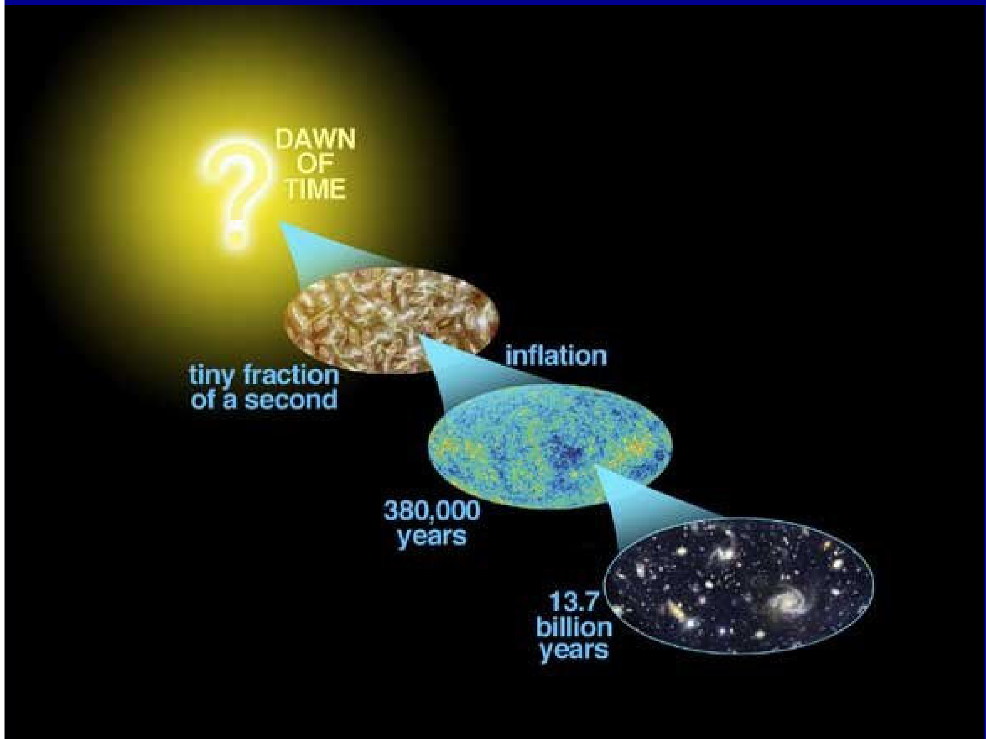
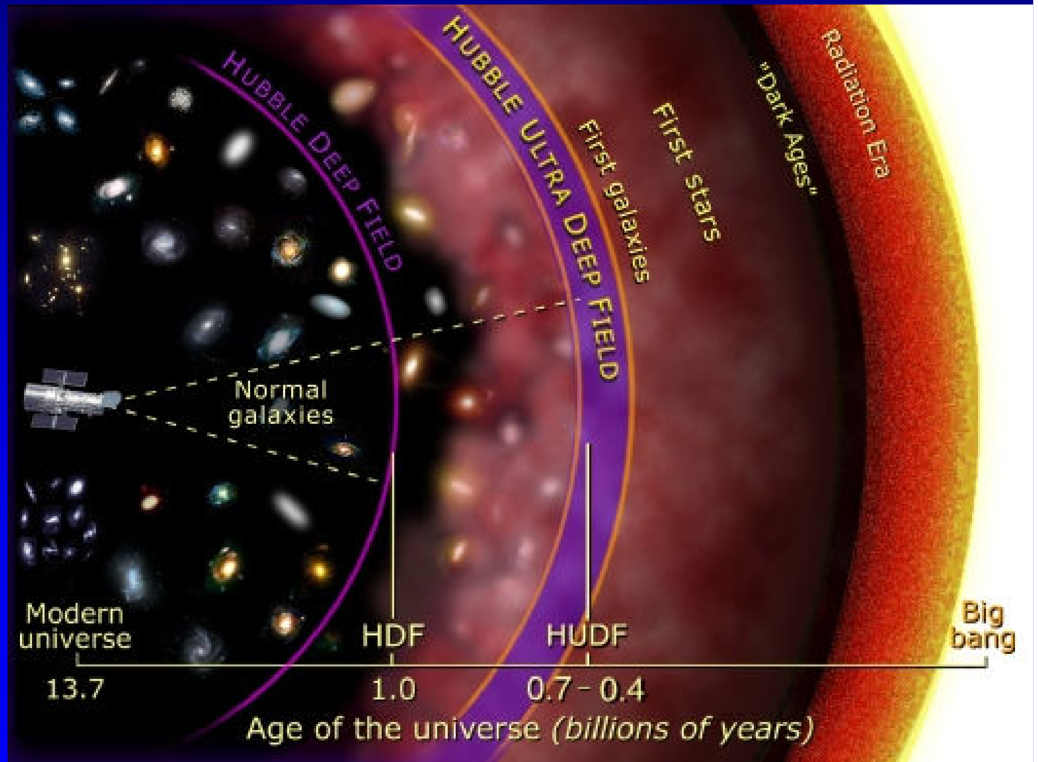
What is the Standard Big Bang Cosmology Scenario?

- The Universe is currently expanding and cooling
- The Universe is expanding from a highly dense state to a low-density state, and cooling

What is the Standard Big Bang Cosmology Scenario?





What is the Standard Big Bang Cosmology Scenario?

- The evolution of the Universe is governed by the equations

$$\left(\frac{\dot{a}(t)}{a(t)}\right)^2 = \frac{8\pi G}{3}\rho(t) - \frac{kc^2}{a(t)^2}$$

$$\dot{\rho}(t) + 3\frac{\dot{a}(t)}{a(t)}\left(\rho(t) + \frac{p(t)}{c^2}\right) = 0$$

What is the evidence for an expanding and cooling Universe?

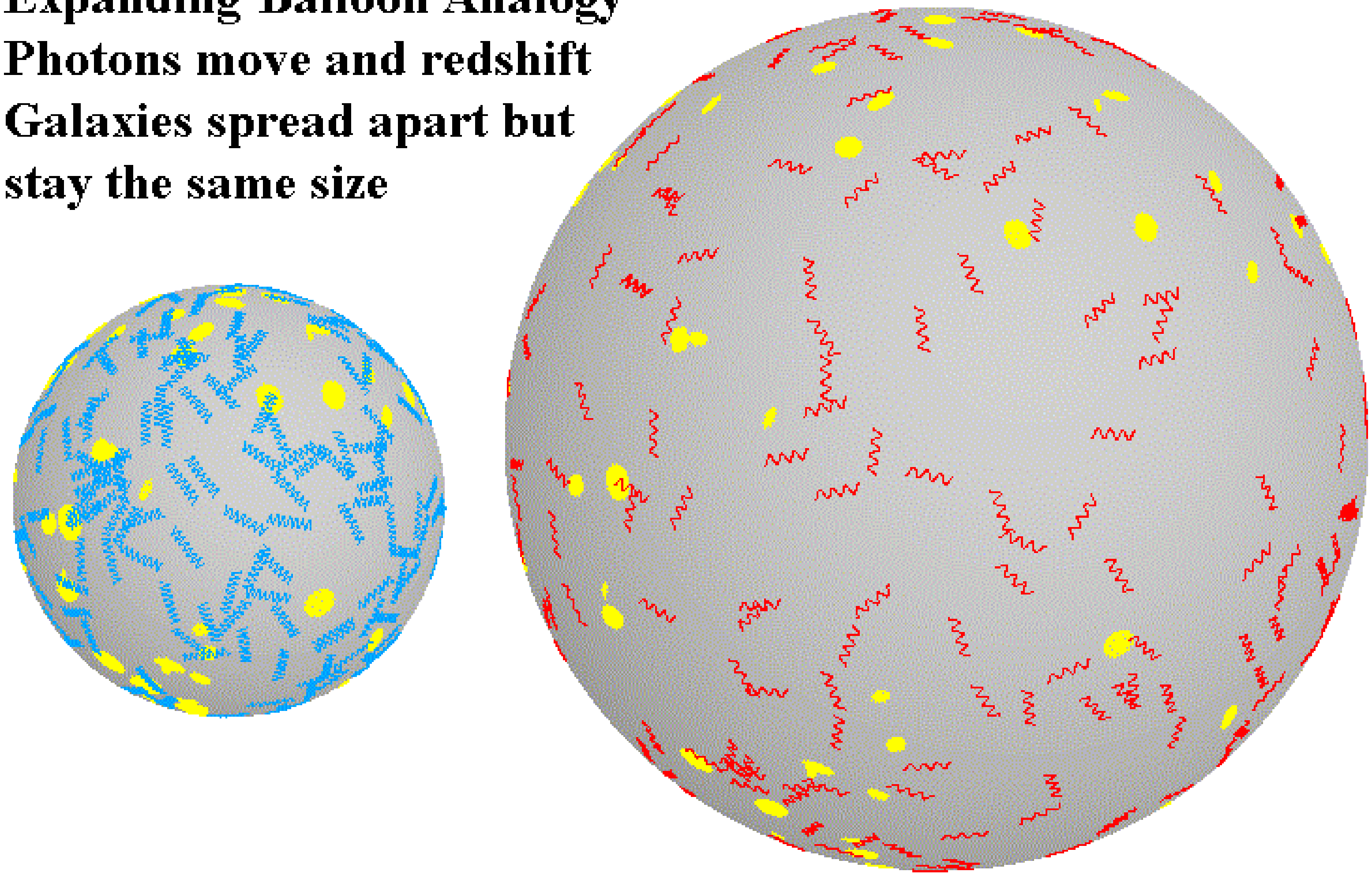
- Redshift of spectral lines in distant objects
- Cosmic Microwave Background
- Primordial Nucleosynthesis
- Darkness of the night sky - Olber’s Paradox
- Time dilation in supernova light curves
- Radio source and quasar counts vs flux

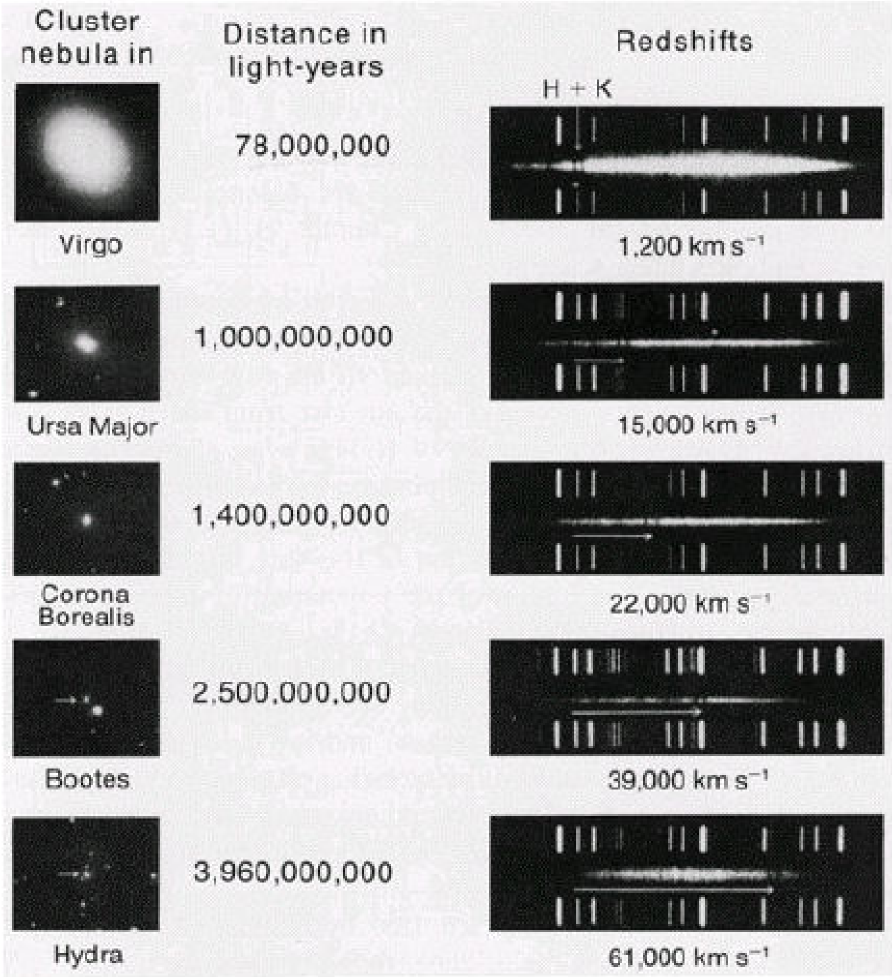
Redshift

- What is the definition?
  - $z = (\lambda_{obs} - \lambda_{em})/\lambda_{em}$
- What trend do we observe in measuring redshift?
  - redshift increases with distance to object
  - Hubble's Law
    - $v = c\,z = H_0\,d$

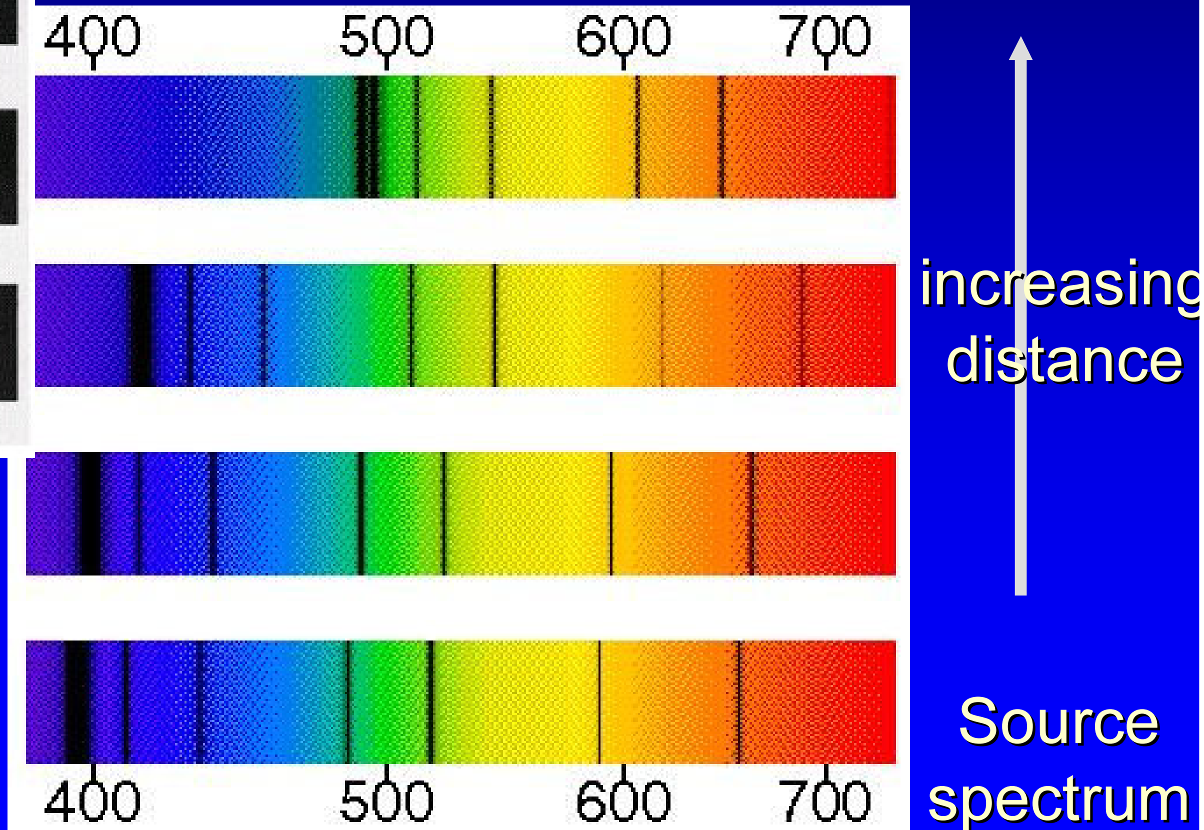
Expansion of the Universe

Expanding Balloon Analogy
Photons move and redshift
Galaxies spread apart but stay the same size





Cluster nebula in
Distance in light-years
Redshifts
H + K
Virgo
78,000,000
1,200 km s⁻¹
Ursa Major
1,000,000,000
15,000 km s⁻¹
Corona Borealis
1,400,000,000
22,000 km s⁻¹
Bootes
2,500,000,000
39,000 km s⁻¹
Hydra
3,960,000,000
61,000 km s⁻¹



400
500
600
700
increasing distance
Source spectrum

Redshift

- Light takes time to get to us
- Redshift, $z = (\lambda_{obs} - \lambda_{em})/\lambda_{em}$
- Redshift related to how long light takes so

$$z \alpha \; t$$

$$z = H\,t$$

$$z = H \; d/c$$

Hubble's Law

What do you say when asked…

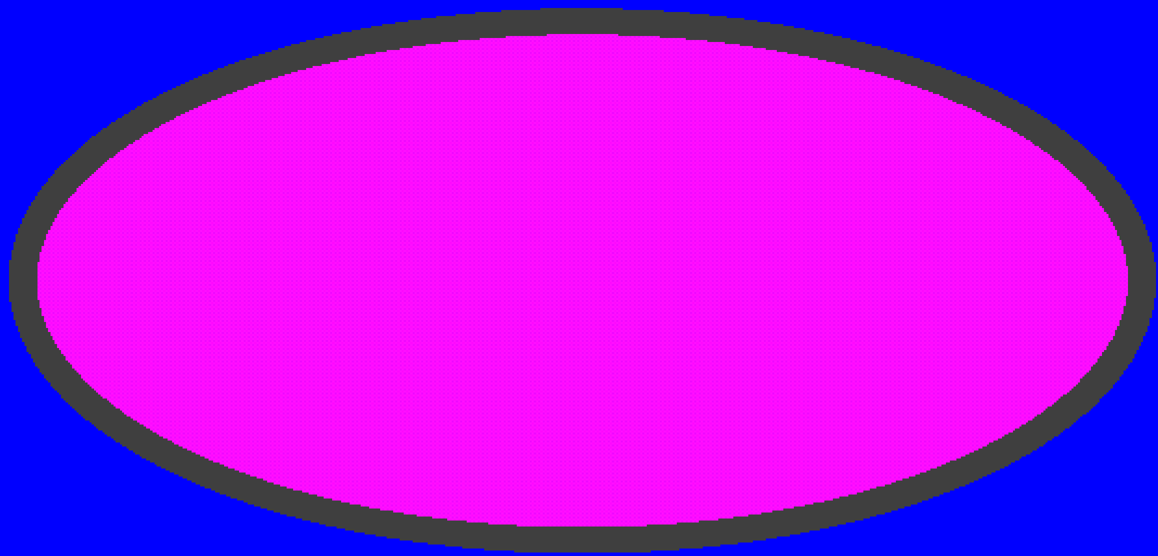
- How can everything be moving away from us – doesn't that mean we have a special position?

- Doesn't it violate special relativity to have objects moving away from us faster than the speed of light?

Cosmic Microwave Background

- What is it?
  - Isotropic bath of microwave photons
- How does it provide evidence for the Big Bang model?
- Could the CMB be scattered starlight?
  - Isotropy suggests cosmological relic
  - Blackbody spectrum implies thermal equilibrium

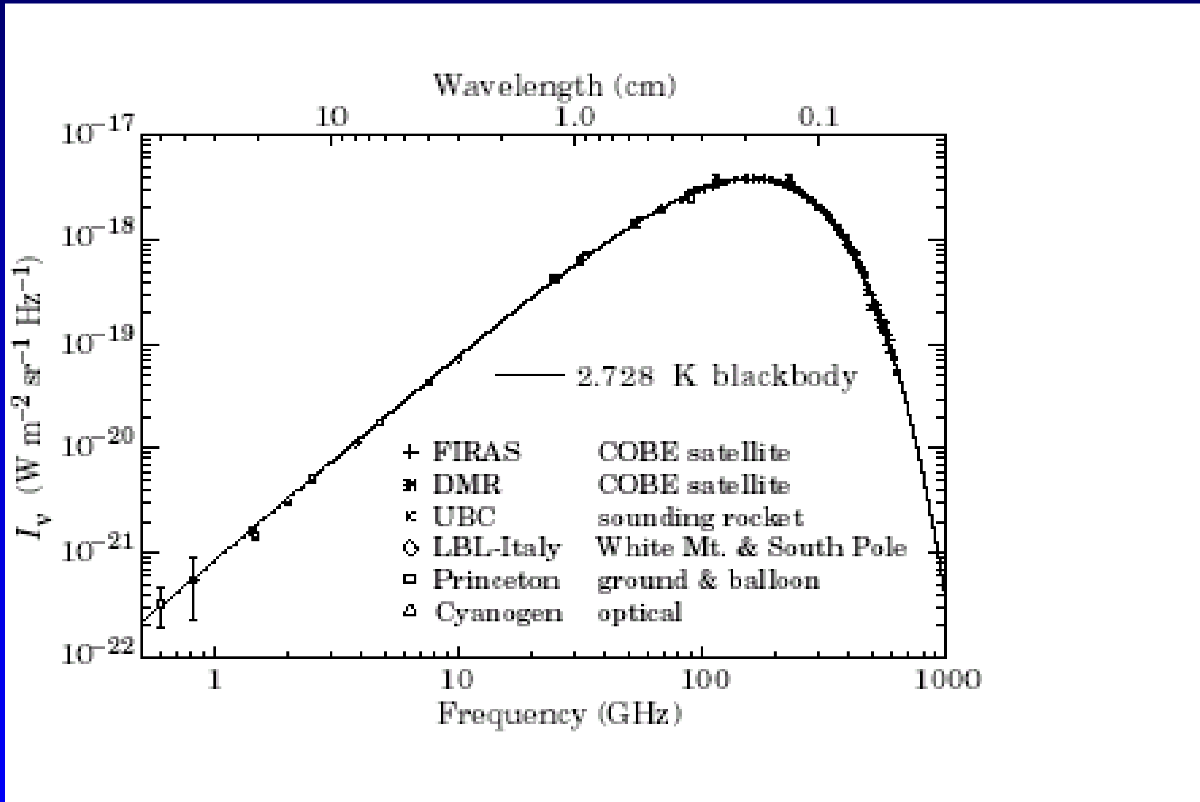
CMB Isotropy



Actual Temperature Data

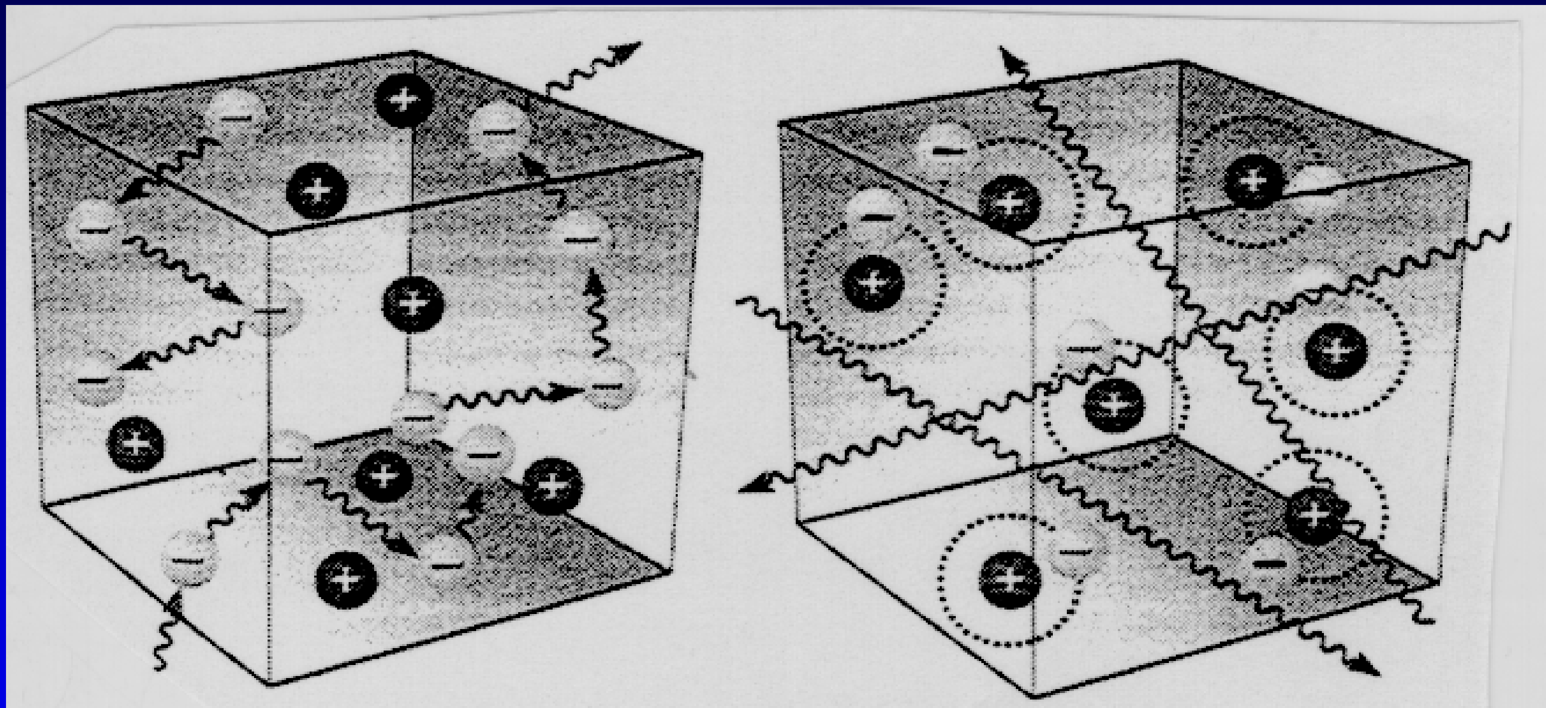
COBE 1992

- The photons have a blackbody radiation distribution, the peak of the distribution is at 0.2cm. This corresponds to a temperature of 2.728 K



- We observe this same distribution in whatever direction we look

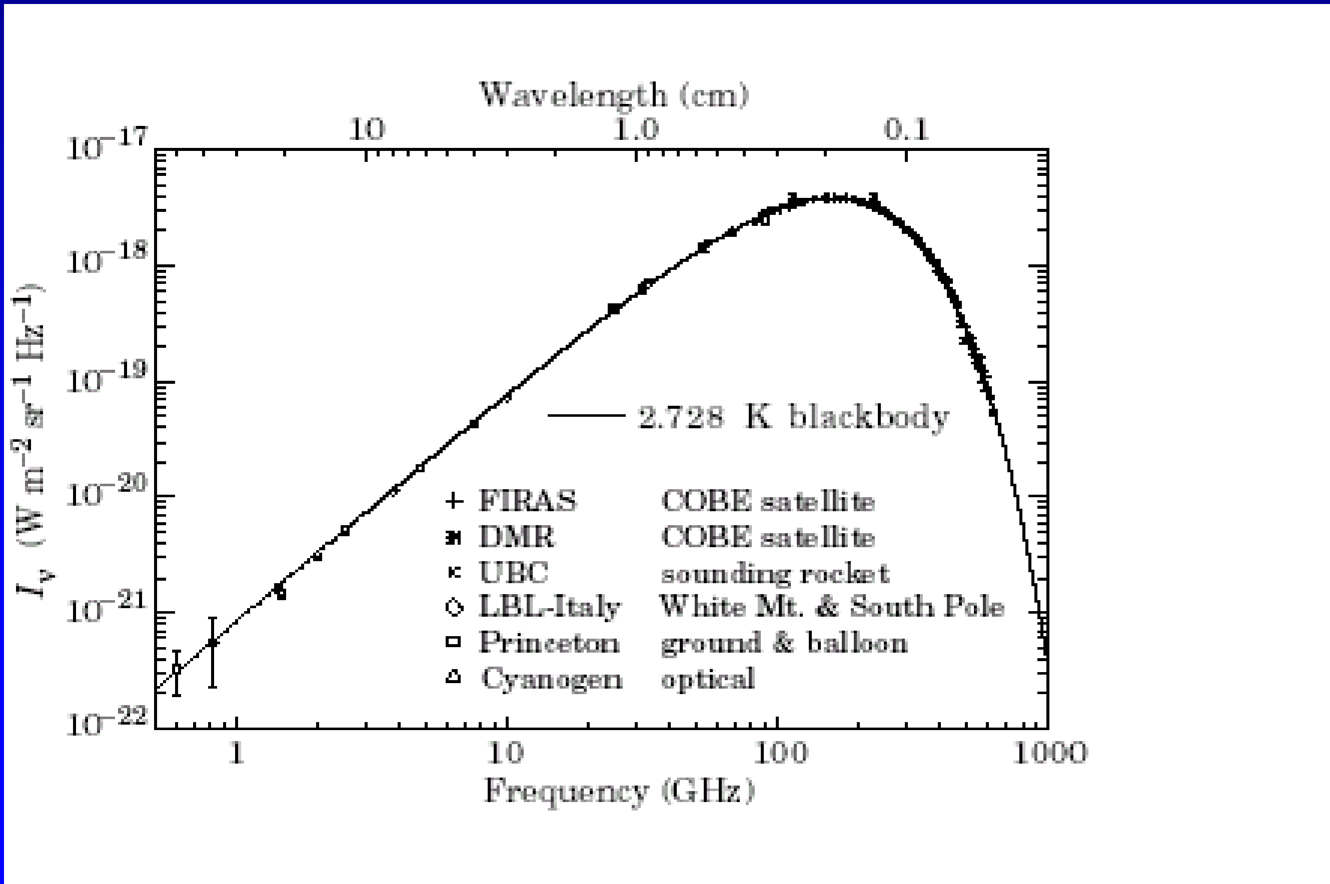
Last Scattering



Before ~300 000 years	After ~300 000 years
$z > \sim 1000$	$z < \sim 1000$

If last scattering was at a redshift of 1000, what was the wavelength (frequency) of the photons then? What was their energy in eV?

$h = 4.14 \times 10^{-15}$ eV s $\quad$ $E=hf$



0.828 eV

But to ionise hydrogen, photons need 13.6 ev…?

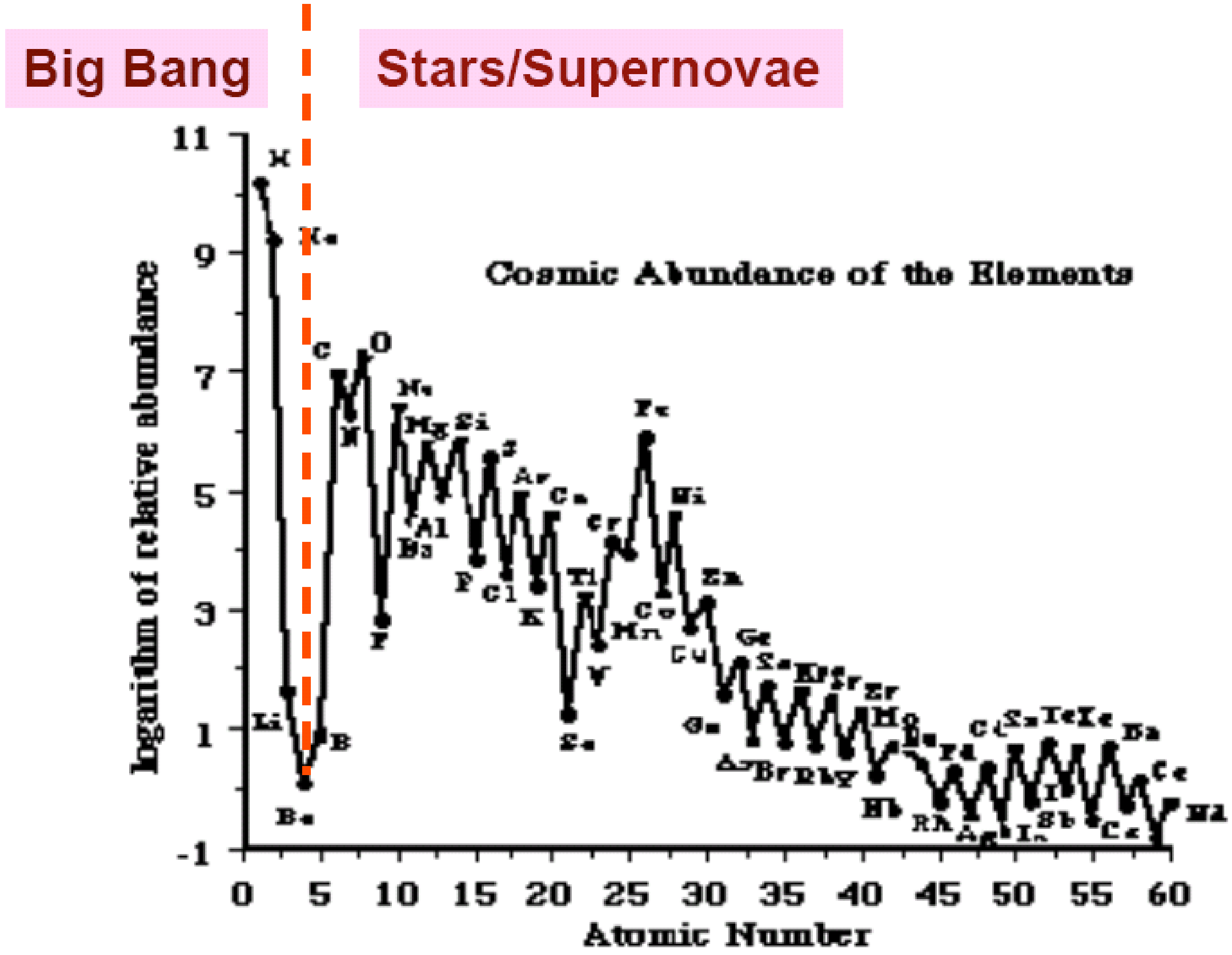
Even though the peak of the distribution is at 0.828 eV, photons in the tail of the energy distribution have 13.6 eV. As there are 10^{10} photons for every proton, there are enough photons in the tail to ionise all the hydrogen.

Photons of all energies scatter readily off electrons

Nucleosynthesis

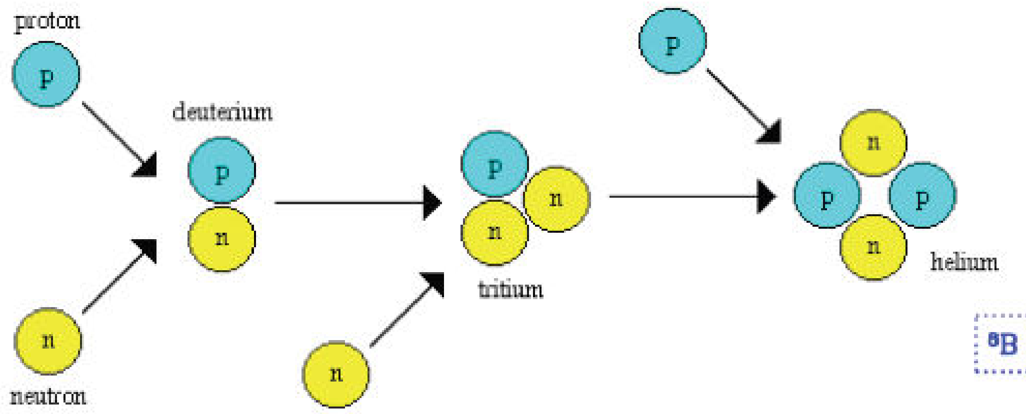
- Nucleosynthesis of light elements

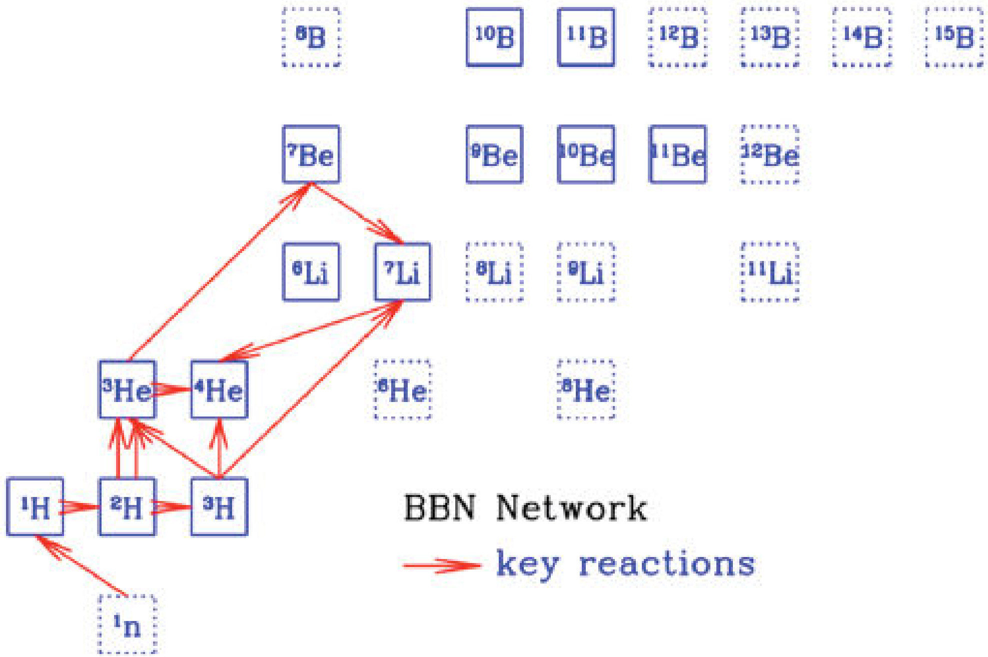
Where did all the elements come from?



Nucleosynthesis

as the Universe cools, protons and neutrons can fuse to form heavier atomic nuclei

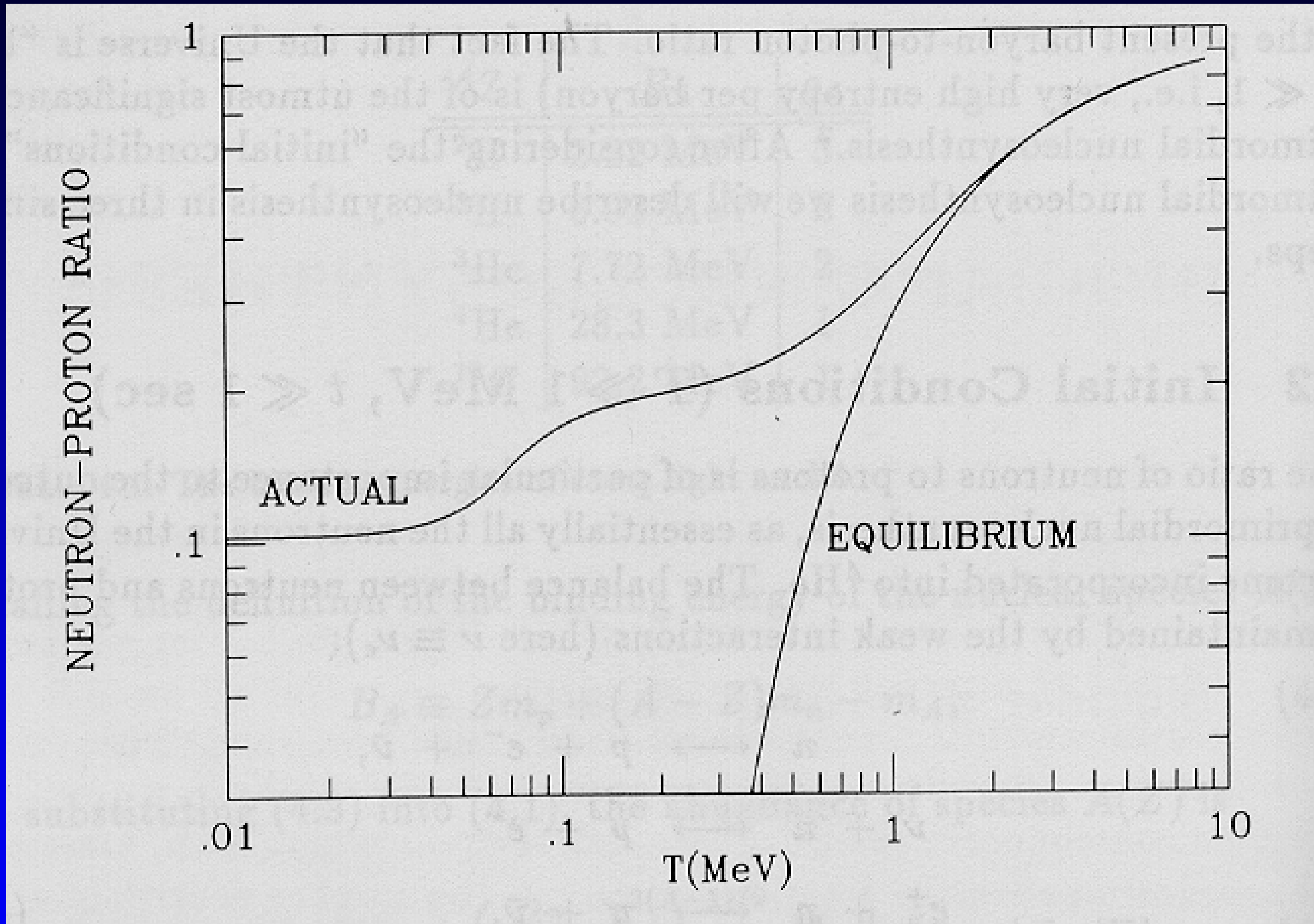




All reactions measured in lab at relevant energies

Nucleosynthesis

- Nucleosynthesis of light elements
- Why is nucleosynthesis such a detailed probe of aspects of the Big Bang Model?
- What is freezeout?



Freezout occurs when $\Gamma \lesssim H$

$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$
$$n + \nu_e \leftrightarrow p + e^-$$
$$n \leftrightarrow p + e^- + \bar{\nu}_e$$

What does H depend on?

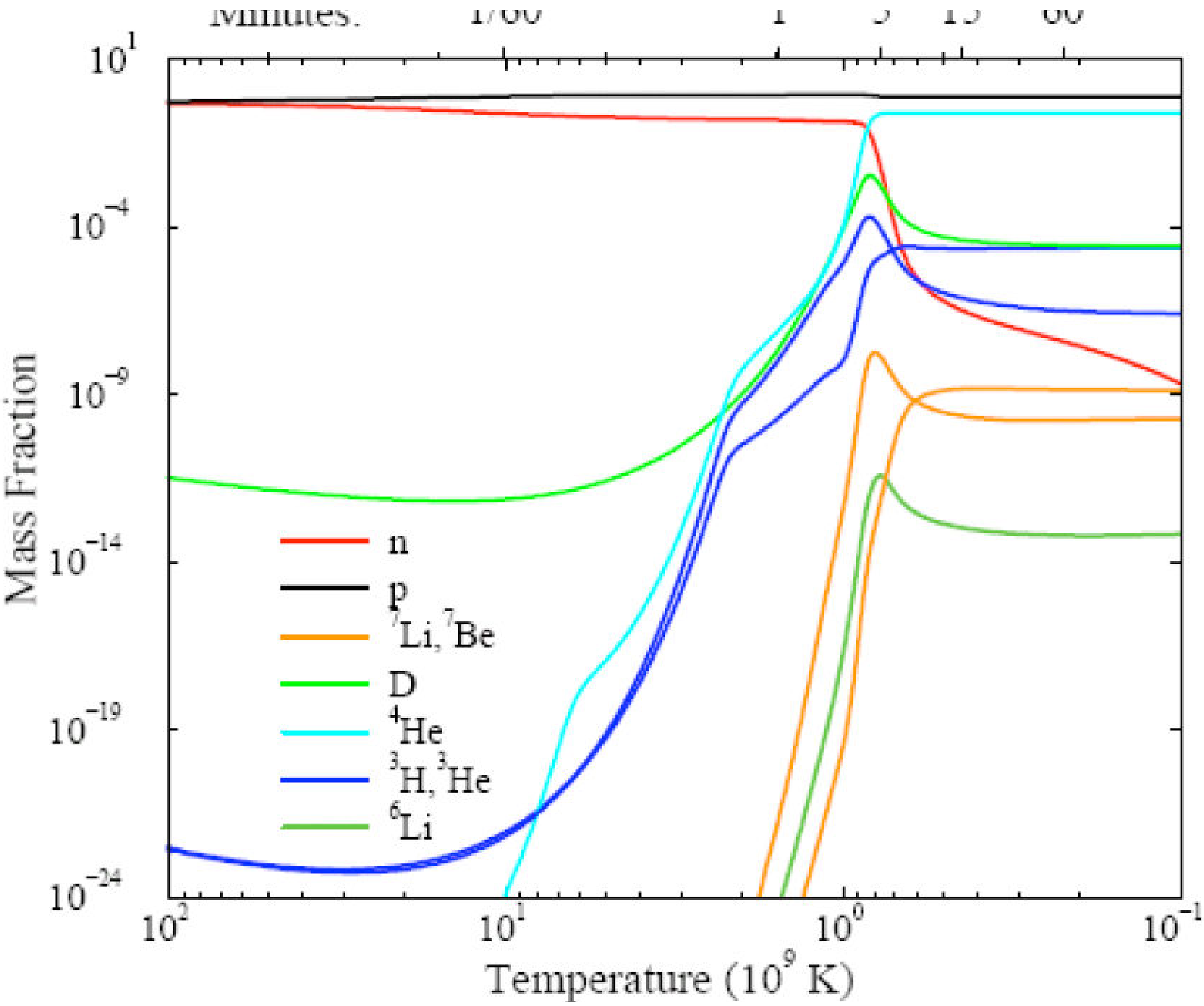
- $H \sim g(T)^{1/2} T^2 / M_{Pl}$ in radiation dominated era

$$\rho c^2 = \frac{g}{(2\pi)^3} \int E(\mathbf{p}) f(\mathbf{p}) d^3|p|$$

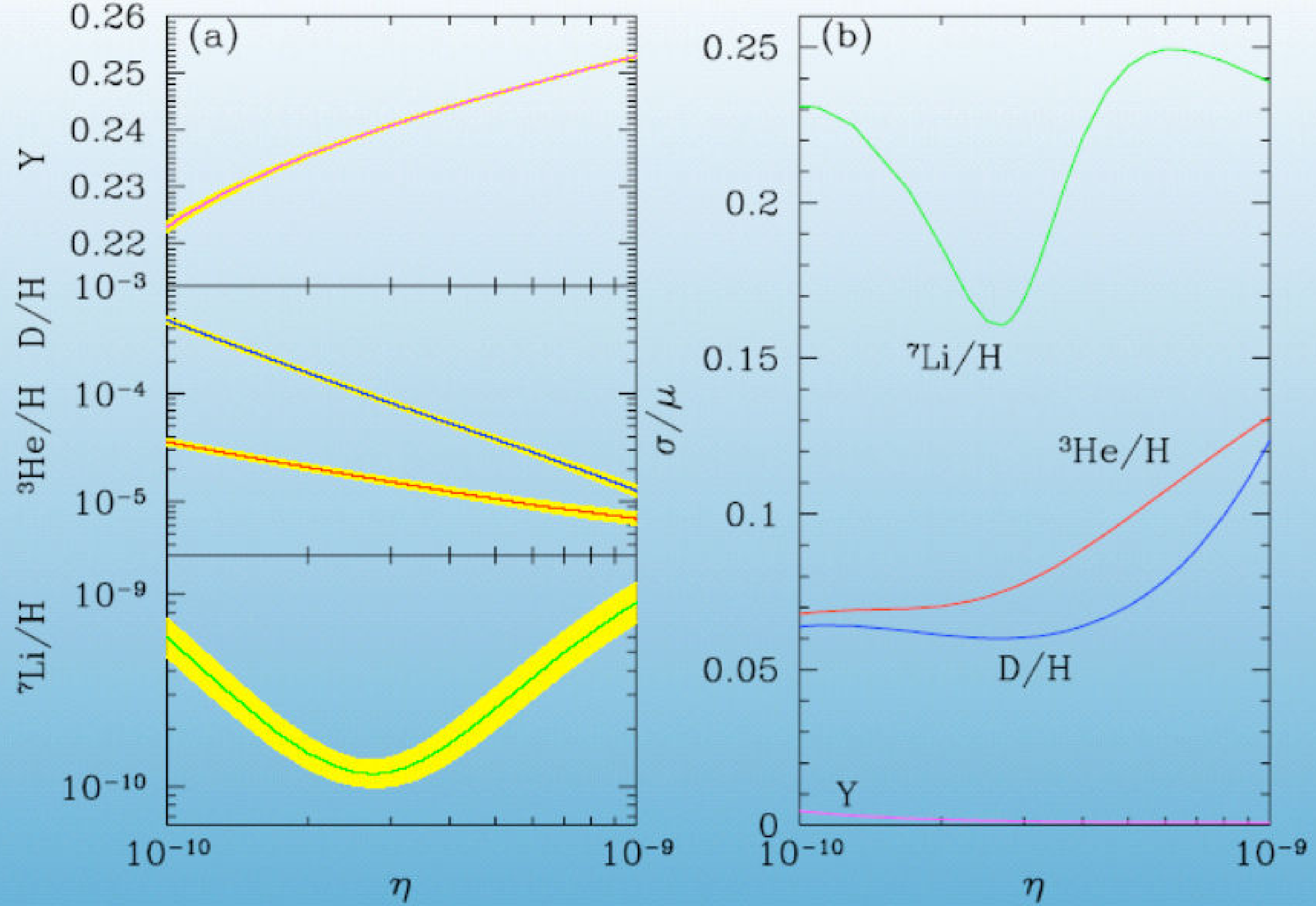
$$f(\mathbf{p}) = (\exp((E-\mu)/T) \pm 1)^{-1}$$

$$\rho c^2 = \begin{cases} (\pi^2/30) g T^4 & \text{Bose} \\ 7/8(\pi^2/30) g T^4 & \text{Fermi} \end{cases}$$

for relativistic particles


Minutes:
1/60
1
3
15
60
10^1
10^-4
10^-9
10^-14
10^-19
10^-24
Mass Fraction
n
p
7Li, 7Be
D
4He
3H, 3He
6Li
10^2
10^1
10^0
10^-1
Temperature (10^9 K)

BBN predictions



line widths ⇒ theoretical uncertainties (neutron lifetime + nuclear cross sections)

The evolution of the Universe is governed by the equations

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$$\dot{\rho}(t) + 3\frac{\dot{a}(t)}{a(t)}\left(\rho(t) + \frac{p(t)}{c^2}\right) = 0$$

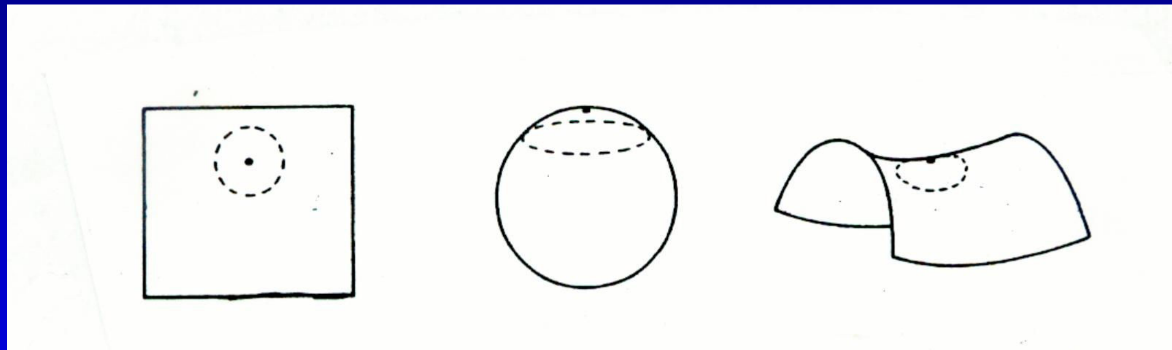
Evolution governed by Einstein's equations

$$R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R_c = -\frac{8\pi T_{\mu\nu}}{M_{\mathrm{P}}^2}$$

- What is the input into these equations?

$$\mathrm{d}s^2 = g_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu = c^2\mathrm{d}t^2 - a^2(t)\left[\frac{\mathrm{d}r^2}{1-kr^2} + r^2(\mathrm{d}\theta^2 + \sin^2\theta \mathrm{d}\phi^2)\right]$$

$$T_{\mu\nu} = p g_{\mu\nu} + (p+\rho) u_\mu u_\nu$$



$k = 0$ $k = 1$ $k = -1$

$$\mathrm{d}s^2 = c^2\mathrm{d}t^2 - a^2(t)\left[\mathrm{d}r^2 + \left.\begin{matrix} R^2\sin^2(r/R) \\ r^2 \\ R^2\sinh^2(r/R) \end{matrix}\right\}(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2)\right]$$

$$r \rightarrow \begin{matrix} \sin(r/R) \\ r \\ \sinh(r/R) \end{matrix}$$

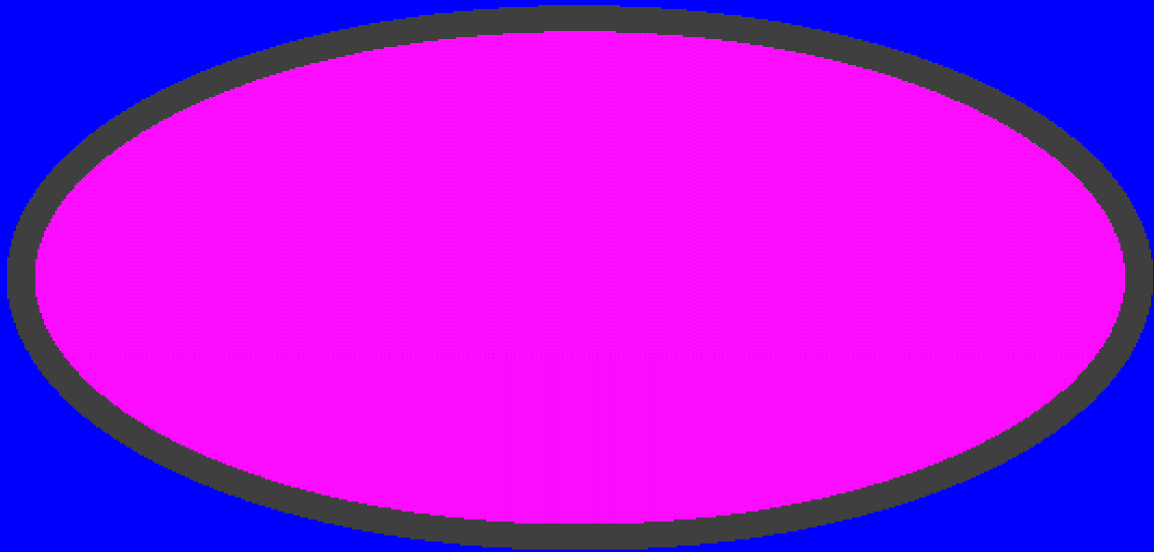
$$a(t) \rightarrow a(t)R$$

Universe – Isotropic and Homogeneous

- Cosmological Principle or Copernican Principle

- What evidence do we have that this is a valid description of our universe? Above what current length scale does this hold?

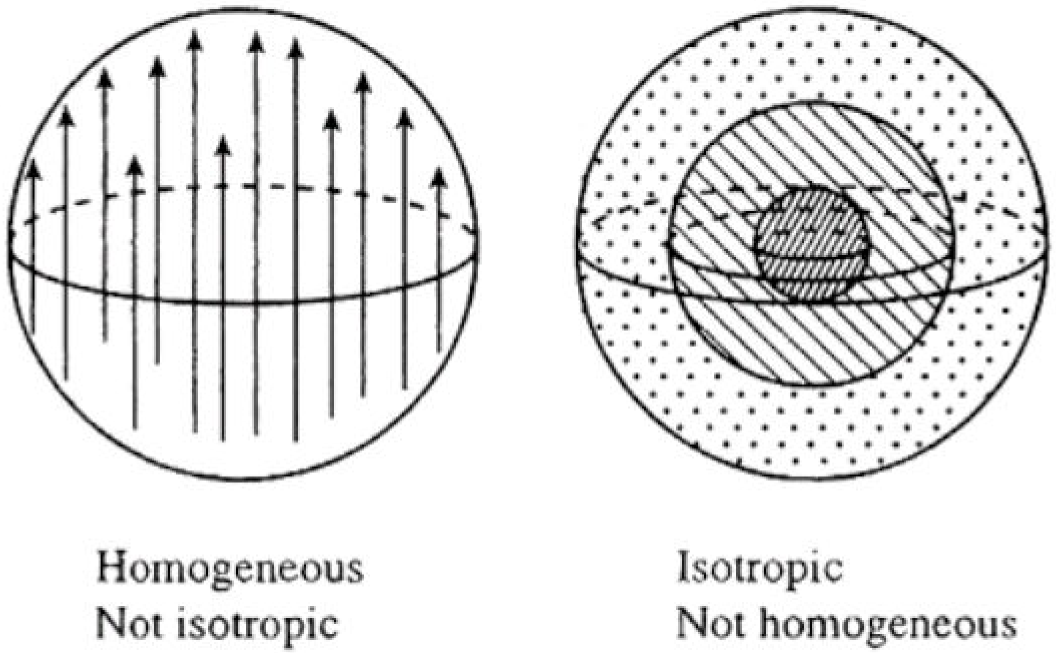
CMB Isotropy



Actual Temperature Data

COBE 1992

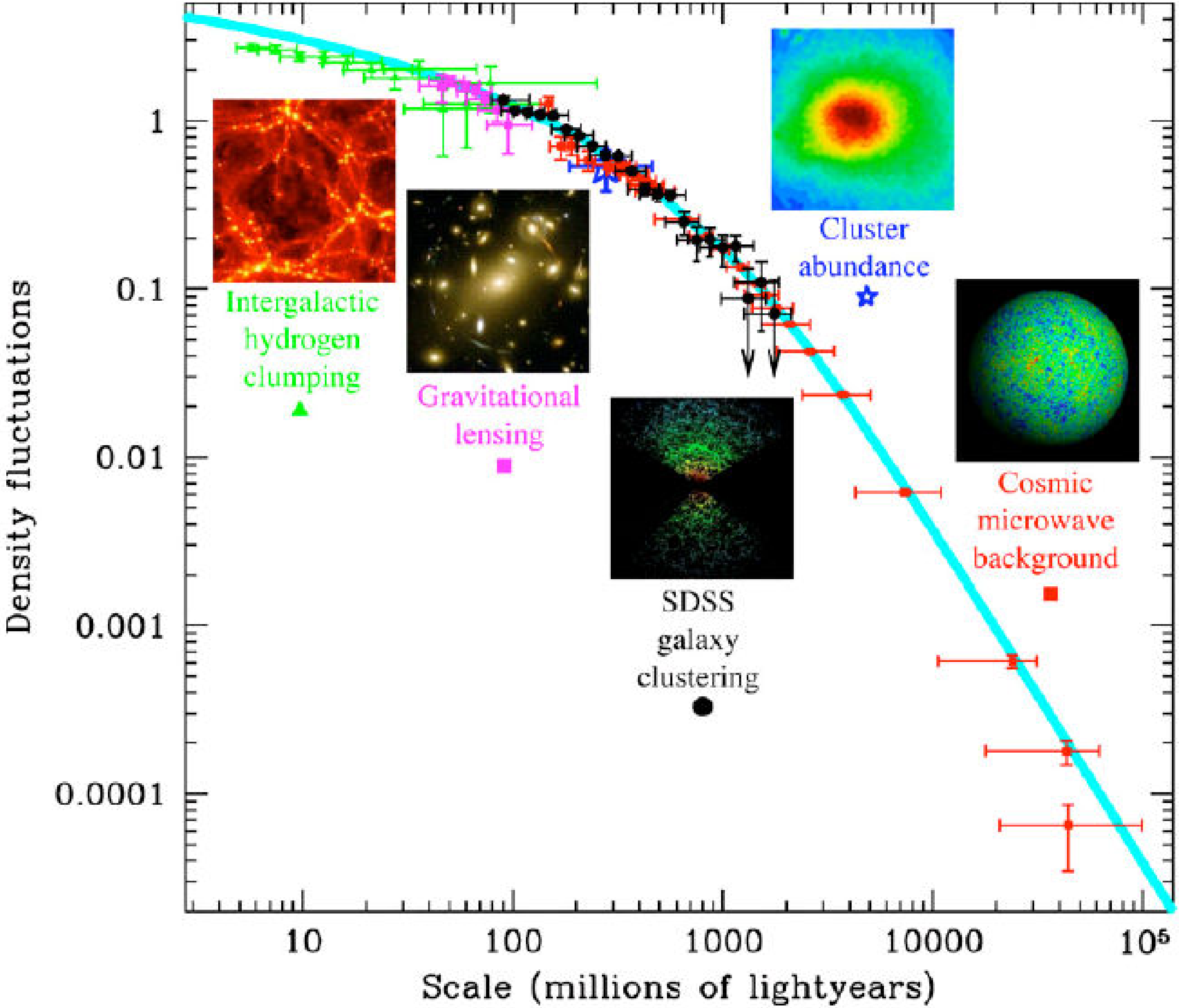
Isotropy does not necessarily imply homogeneity …

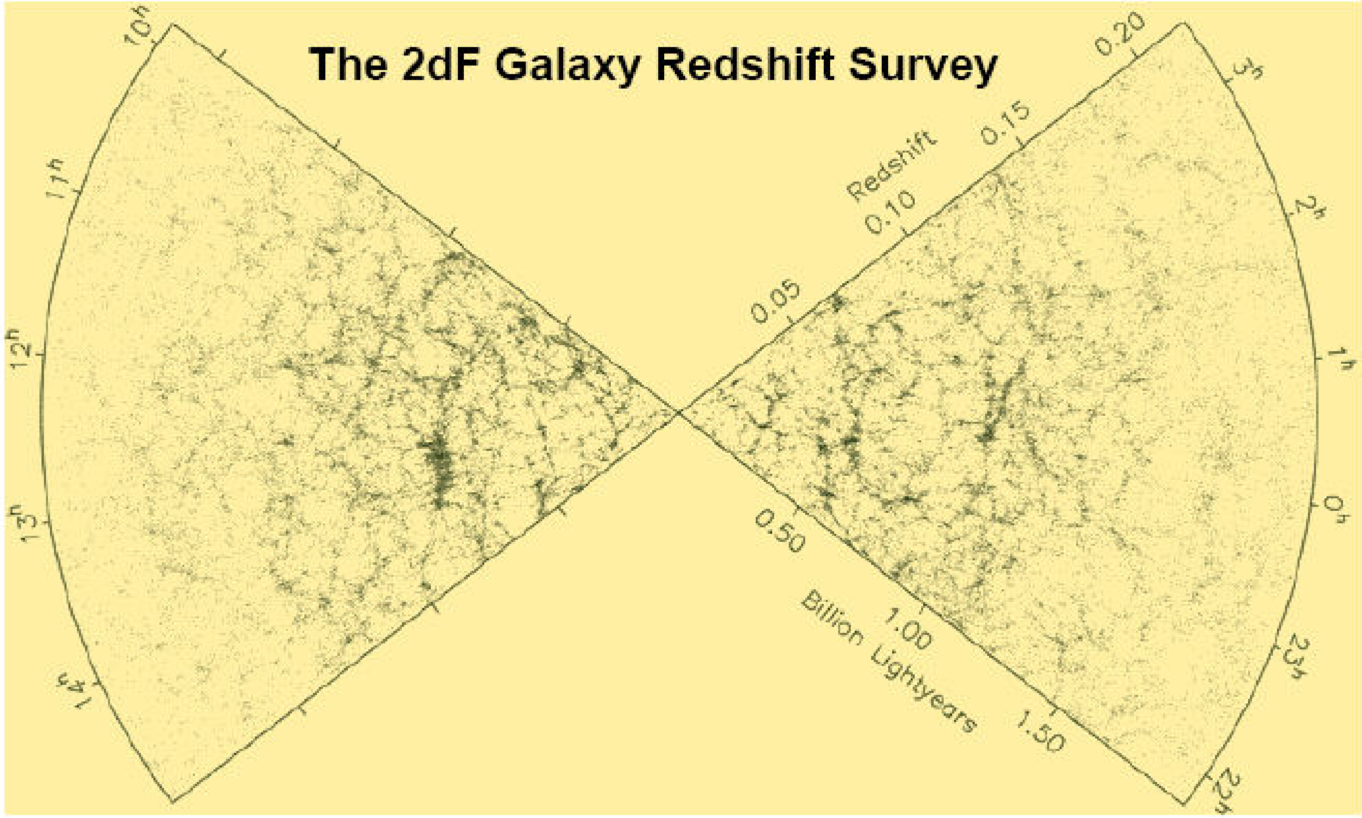


… unless it is so about *every* point in space

But we cannot move (very far) in space so must *assume* that our position is typical - “The Cosmological Principle” (**Milne 1935**)

Although the universe is lumpy, it seems to become smoother and smoother when averaged over larger and larger scales …





The distribution of galaxies is in fact *fractal* on small scales ...
but when averaged over very large scales (>10^{8-9} light years)
the galaxy distribution does *seem* to become homogeneous
although there is *still* structure on such scales ('walls', 'voids')

Einstein's equations with the Robertson-Walker Metric and perfect fluid energy-momentum tensor

$=$

$$\left(\frac{\dot{a}(t)}{a(t)}\right)^2 = \frac{8\pi G}{3}\rho(t) - \frac{kc^2}{a(t)^2}$$

$$\dot{\rho}(t) + 3\frac{\dot{a}(t)}{a(t)}\left(\rho(t) + \frac{p(t)}{c^2}\right) = 0$$

Einstein's equations with the Robertson-Walker Metric =

$$\left(\frac{\dot{a}(t)}{a(t)}\right)^2 = \frac{8\pi G}{3}\rho(t) - \frac{kc^2}{a(t)^2}$$

$$H(t) = \frac{\dot{a}(t)}{a(t)}$$

$$\dot{\rho}(t) + 3\frac{\dot{a}(t)}{a(t)}\left(\rho(t) + \frac{p(t)}{c^2}\right) = 0$$