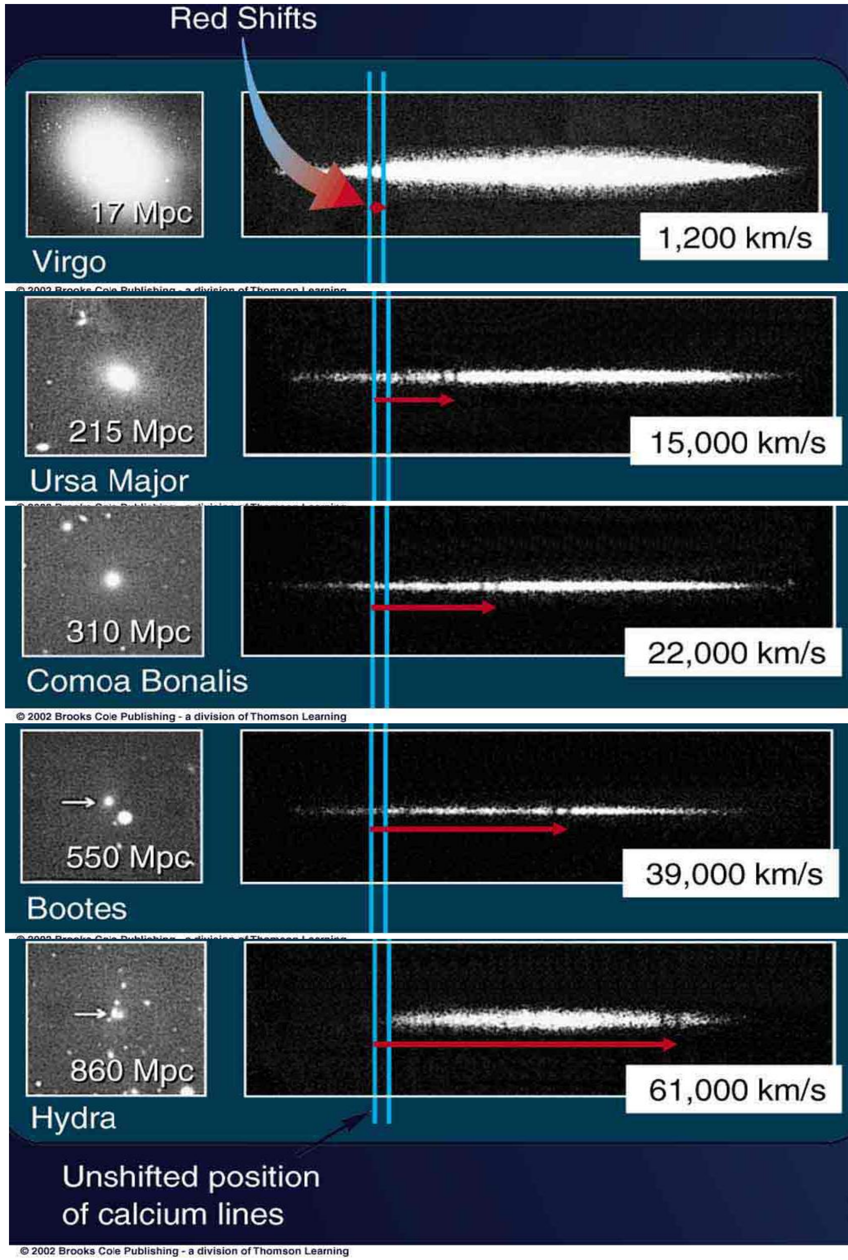
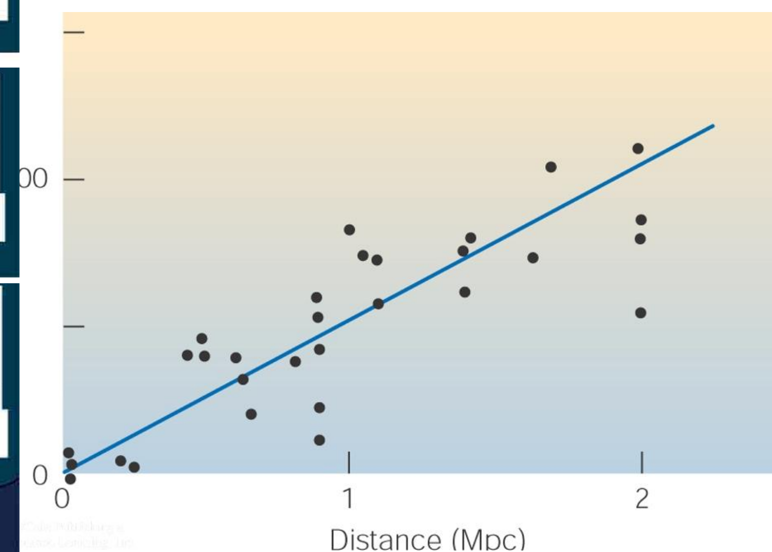
5) Modern Cosmology

Recall….Hubble’s Law



Distant galaxies are receding from us with a speed proportional to distance

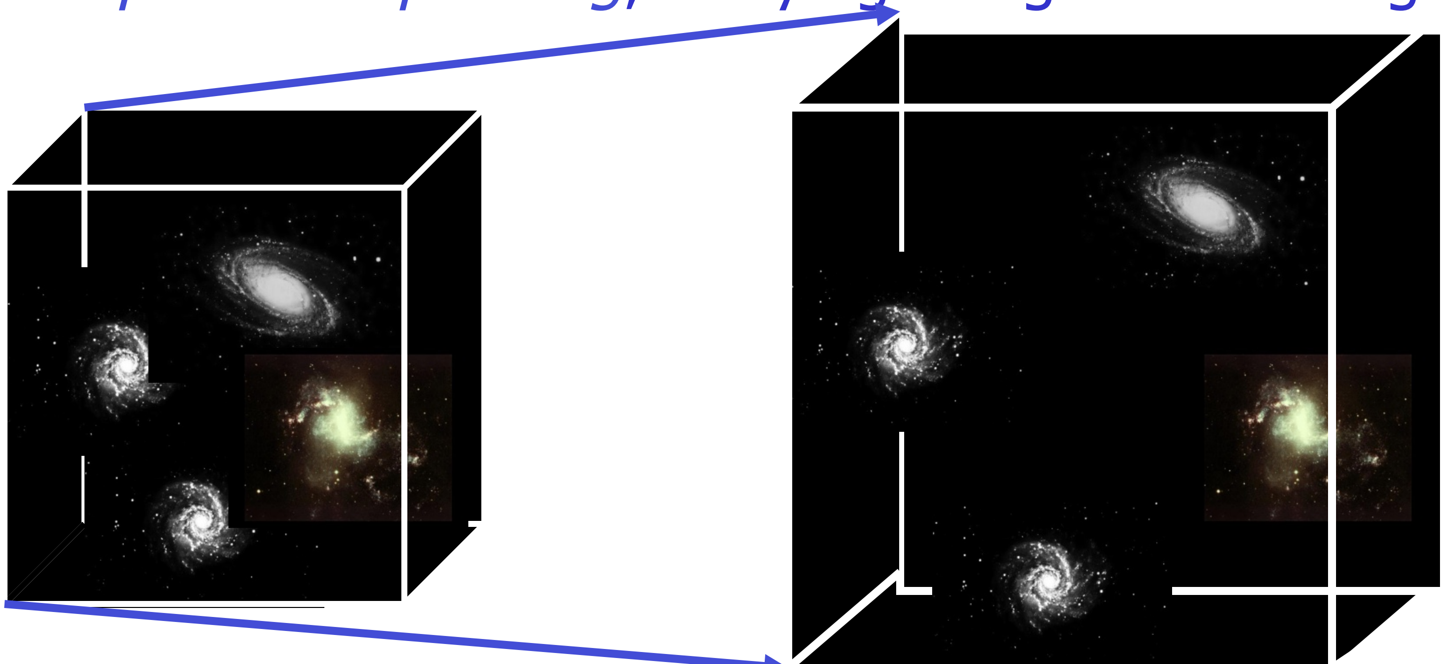


The Expanding Universe

On large scales, galaxies are moving apart, with velocity proportional to distance.

It's not galaxies moving through space.

Space is expanding, carrying the galaxies along!



The galaxies themselves are not expanding!

The Necessity of a Big Bang

If galaxies are moving away from each other with a speed proportional to distance, there must have been a beginning, when everything was concentrated in one single point:

→ Big Bang model

The Hot Big Bang theory

According to the Hot Big Bang theory, the Universe began at a finite time in the past, as an incredibly hot and dense 'fireball' which has been expanding, and cooling, ever since.

Evidence for the Big Bang

1. **Expansion of the Universe**

2. **Evolution of the Universe**

3. **The cosmic microwave background radiation (CMBR)**

4. **Abundances of the lightest chemical elements**

The Age of the Universe

Knowing the current rate of expansion of the universe, we can estimate the time it took for galaxies to move as far apart as they are today:

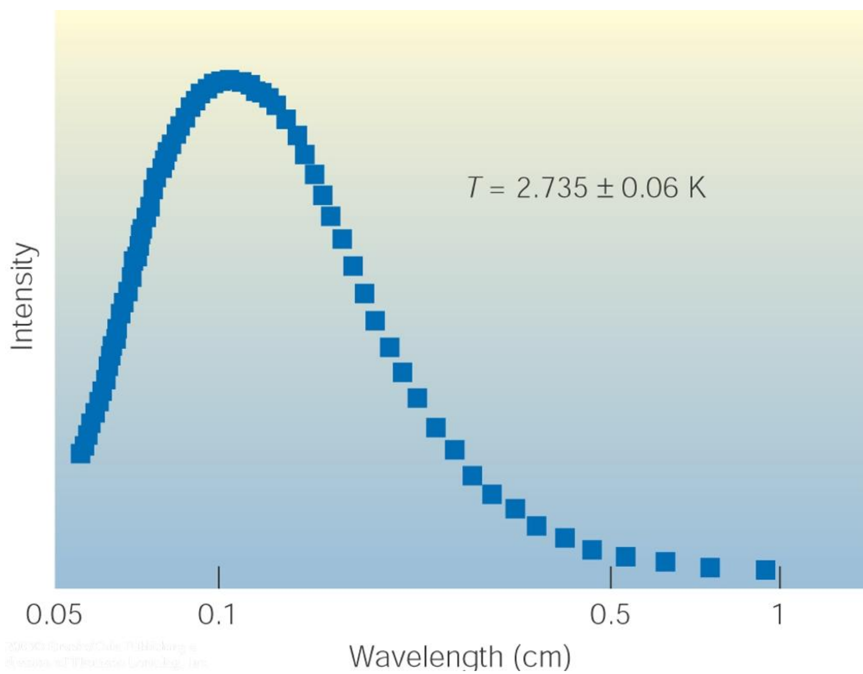
Time = distance / velocity

velocity = (Hubble constant) * distance

$$T \approx d/v = 1/H \sim 14 \text{ billion years}$$

The Cosmic Background Radiation

The radiation from the very early phase of the universe should still be detectable today

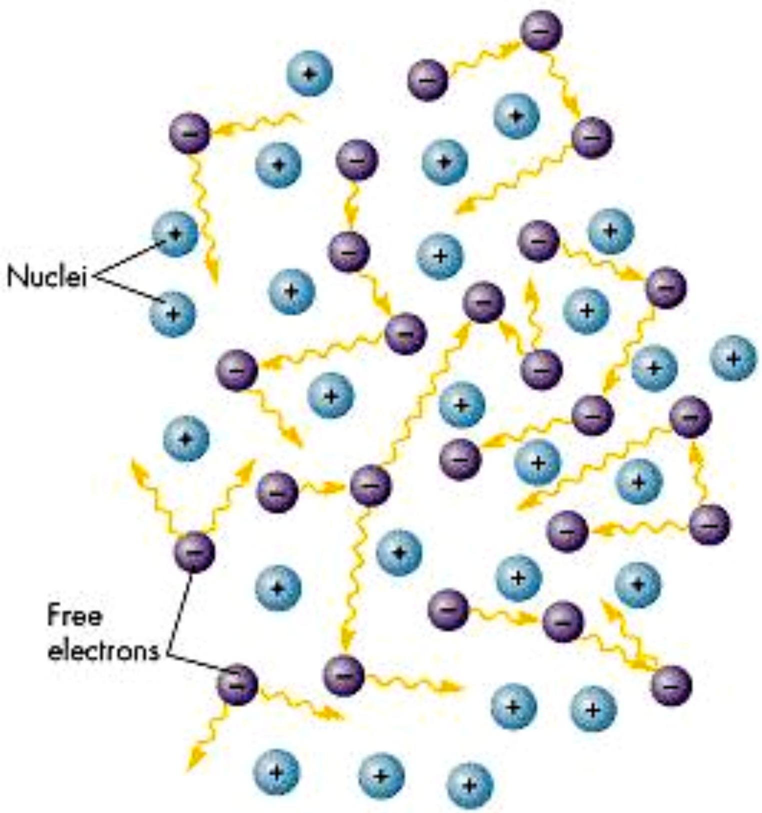


Was, in fact, discovered in mid-1960s as the **Cosmic Microwave Background:**

Blackbody radiation with a temperature of T = 2.73 K

Before

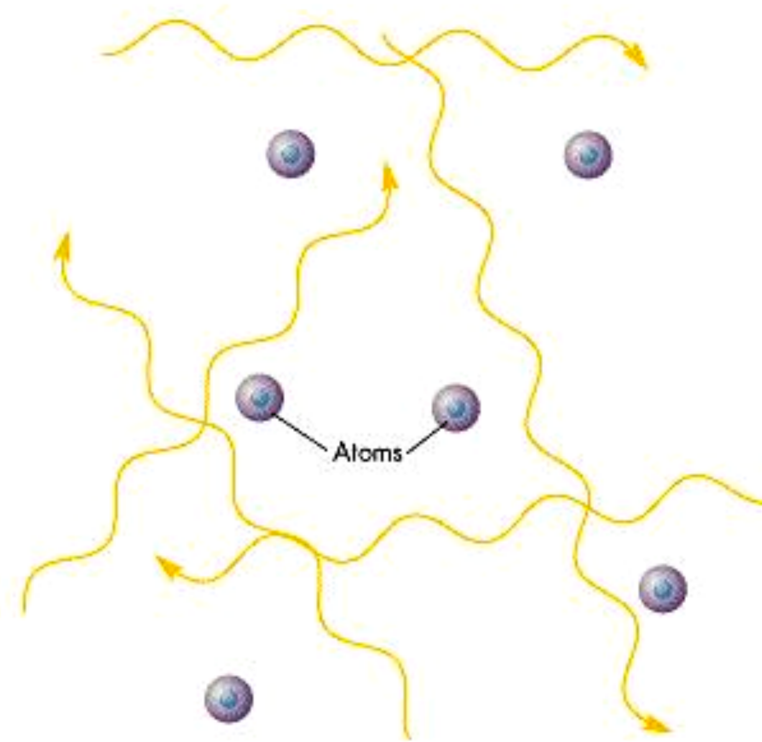
$$T_{\text{Universe}} > 3000\text{K}$$



Photons continually scattered, absorbed and re-emitted by fog of free electrons.

After

$$T_{\text{Universe}} < 3000\text{K}$$



No more free electrons. Photons now able to travel freely through the Universe: the fog has cleared!

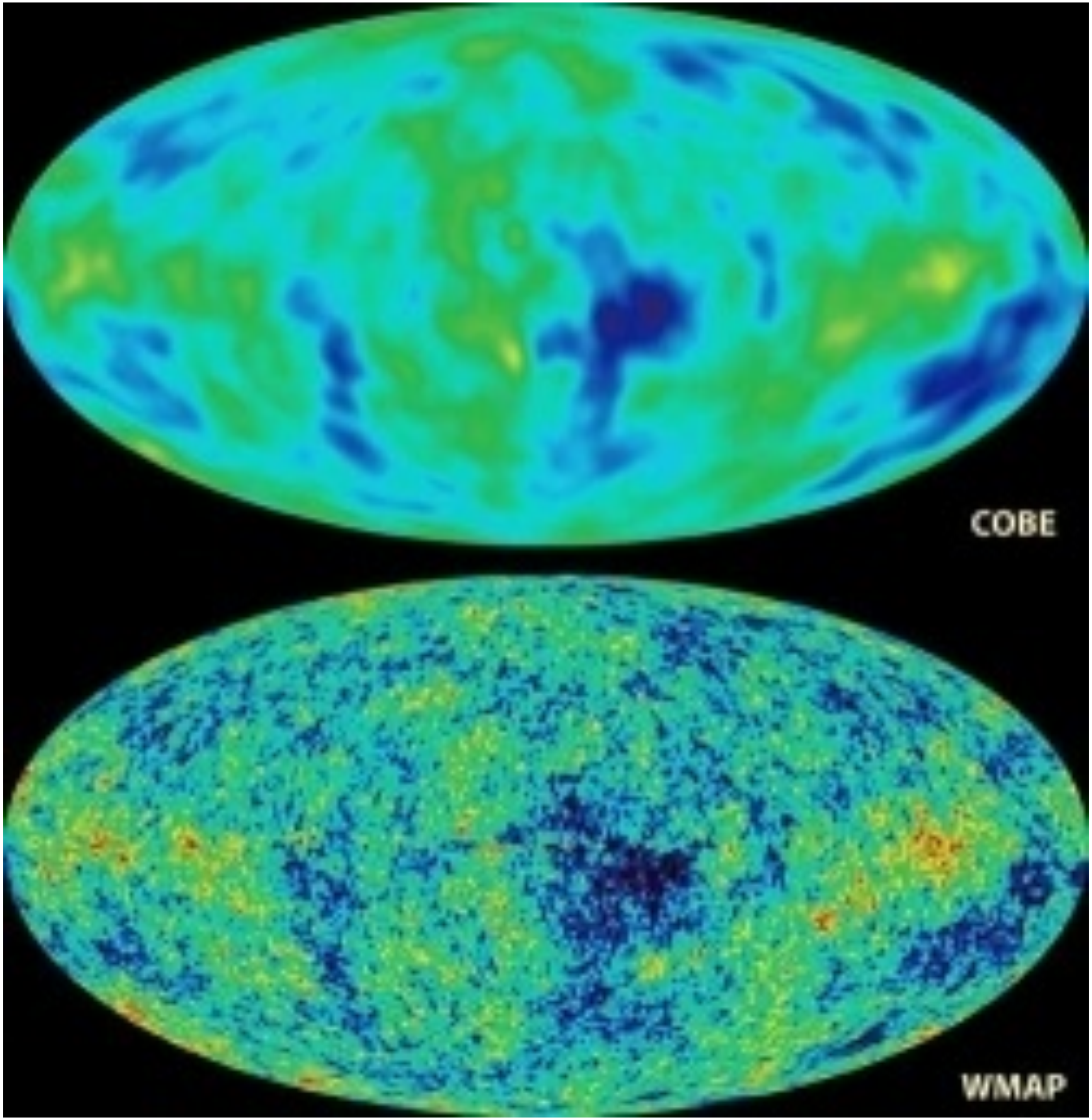
Relic radiation: the Cosmic Microwave Background (CMB)

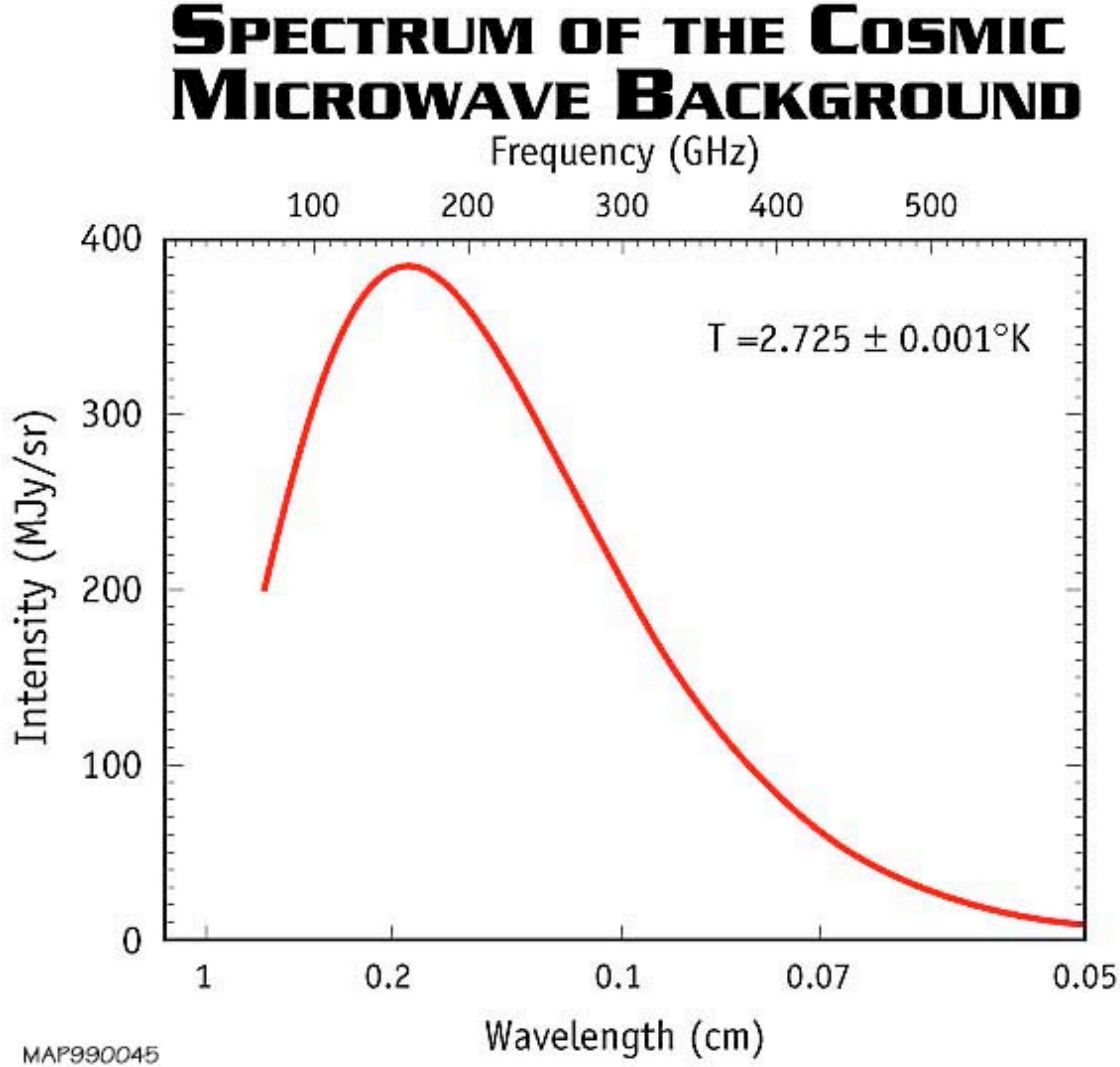
Initially, the universe was fully ionized, and opaque (because of electron scattering).

Matter and radiation strongly interacted → black-body distribution of radiation

Eventually, the universe cooled sufficiently for (hydrogen) atoms to form (T = 3000K, t = 100,000yr, z = 1000).

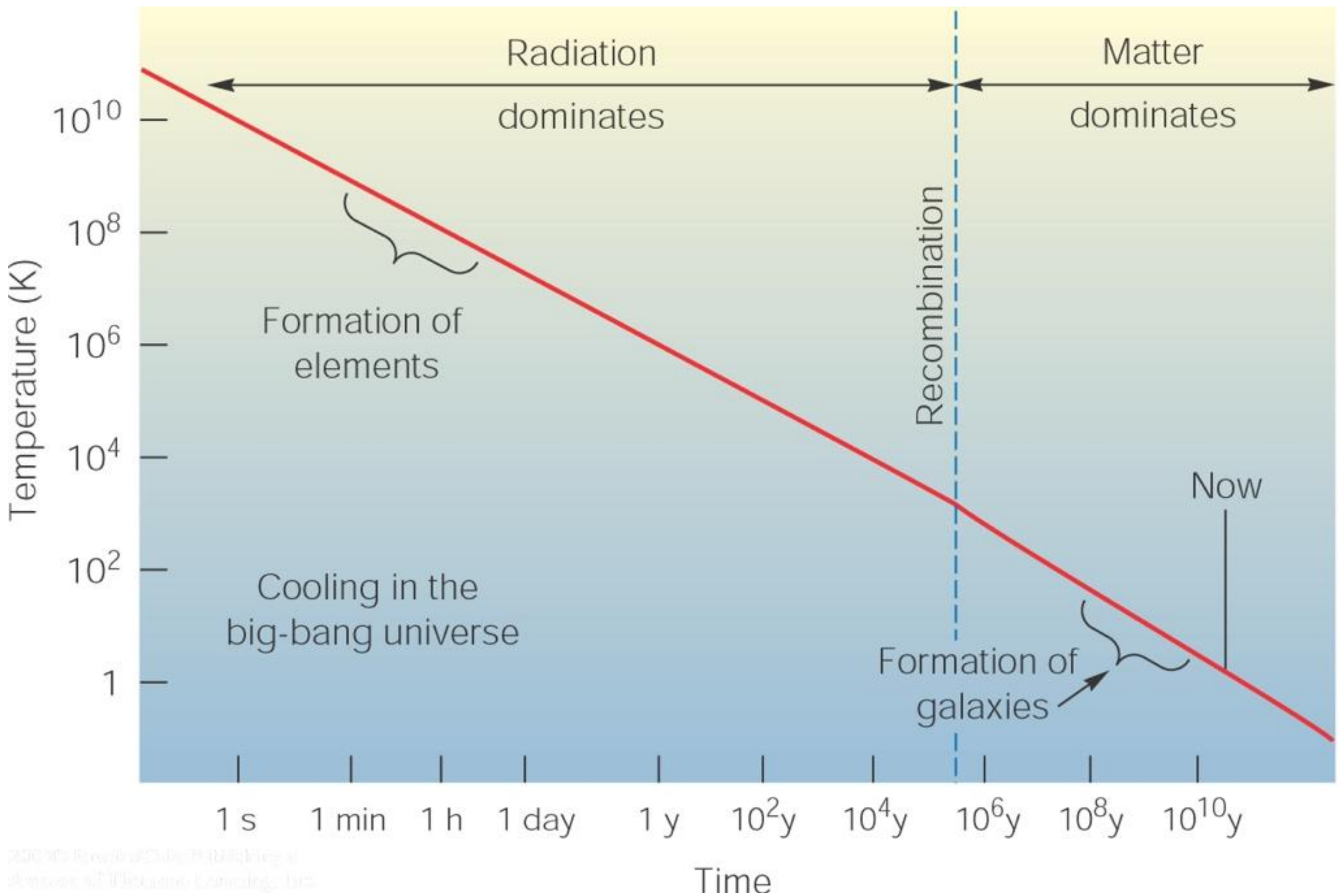
Radiation decoupled from matter, and has flowed through the universe ever since. We see this 'last scattering surface' redshifted, and it appears to us as a black body at T = 3K (or 2.7K, or 2.725K, depending on how picky you are)


COBE
WMAP



COBE spectrum: the most precise black body in nature
(ca. 50 datapoints)

The History of the Universe



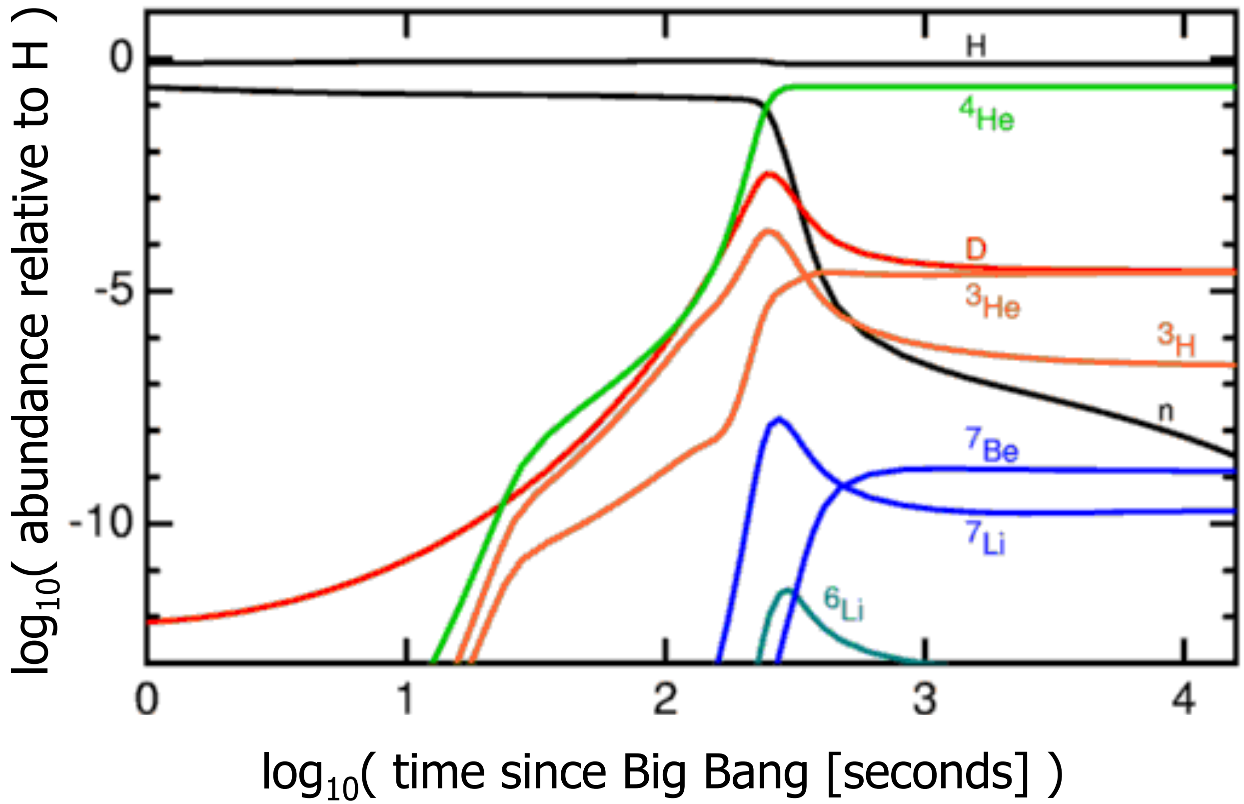
Universe cools down as time passes

Universe expands as time passes

Abundances of the Lightest Elements

From about 20 mins after the Big Bang, the abundances remain constant:

Universe too cool for any more 'cooking' of elements + not enough high-energy photons to 'blast' apart the elements already formed.



Remarkably, the predicted element abundances match what we observe extremely well – a major success of the Big Bang model.

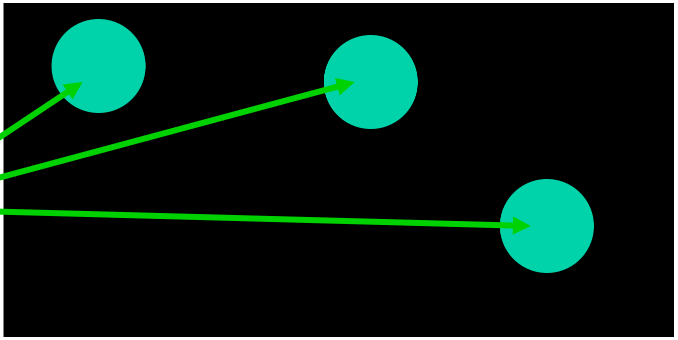
(but to make them match gives us important clues about dark matter; see earlier)

The Cosmological Principle

Considering the largest scales in the universe, we make the following fundamental assumptions:

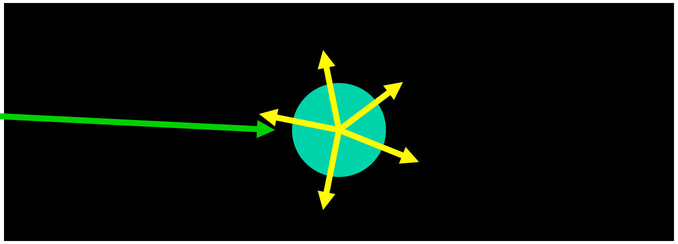
1) Homogeneity: On the largest scales, the local universe has the same physical properties throughout the universe.

Every region has the same physical properties (mass density, expansion rate, visible vs. dark matter, etc.)



2) Isotropy: On the largest scales, the local universe looks the same in any direction that one observes.

You should see the same large-scale structure in any direction.



3) Universality: The laws of physics are the same everywhere in the universe.

DYNAMICS OF THE UNIVERSE

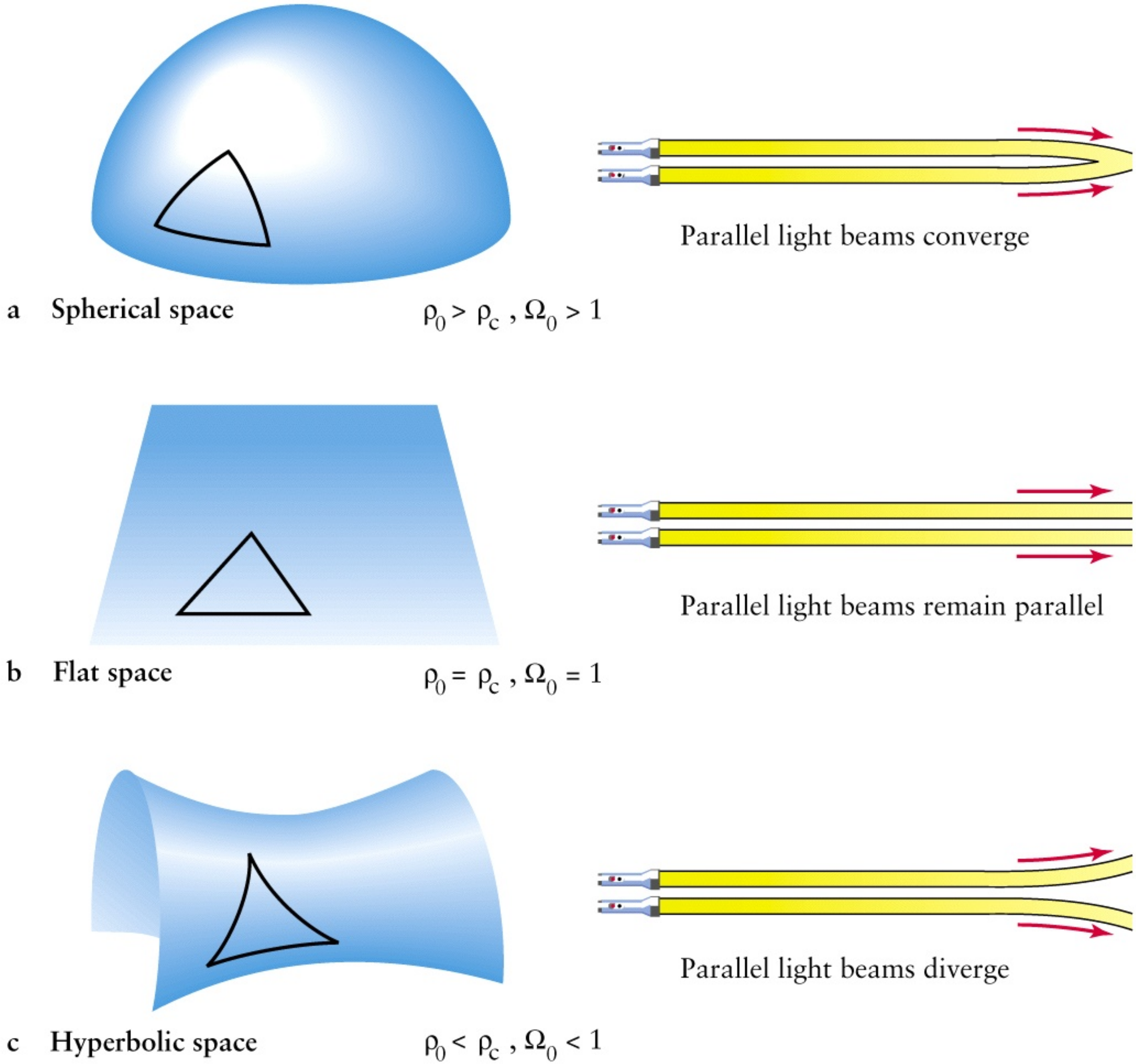
The Friedmann Equation describes this:

$$\dot{R}^2(t) = \frac{8\pi G\rho R^2(t)}{3} - kc^2 + \frac{\Lambda}{3}R^2(t).$$

***R* is the ‘scale factor’**

Λ is the ‘cosmological constant’ term

***k* is the ‘curvature’: -1, 0, +1 = negative, flat, positive geometry**

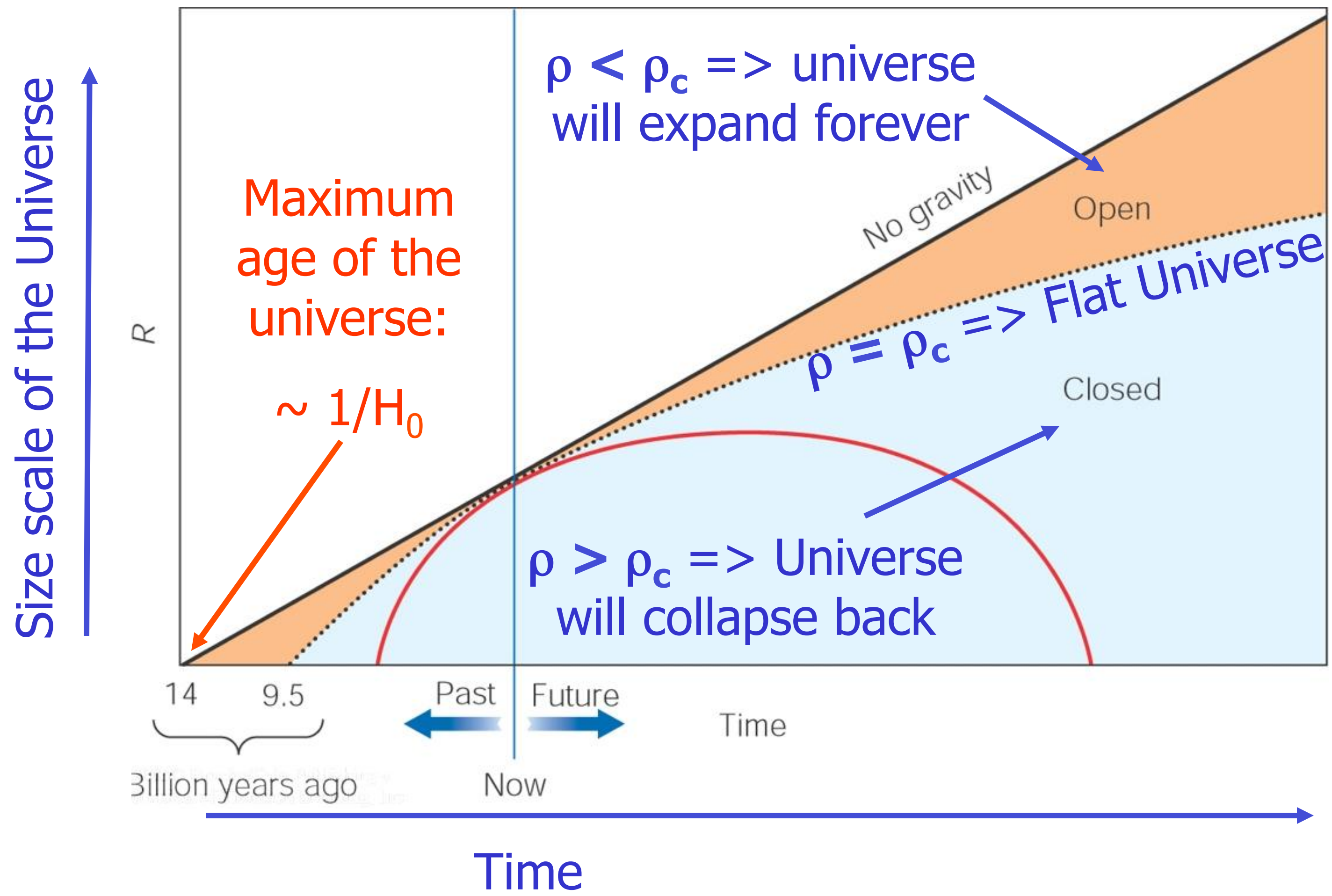


Parallel light beams converge
a Spherical space
$\rho_0 > \rho_c$, $\Omega_0 > 1$
Parallel light beams remain parallel
b Flat space
$\rho_0 = \rho_c$, $\Omega_0 = 1$
Parallel light beams diverge
c Hyperbolic space
$\rho_0 < \rho_c$, $\Omega_0 < 1$

Deceleration of the Universe

- Expansion of the universe should be slowed down by mutual gravitational attraction of the galaxies.
- Fate of the universe depends on the matter density in the universe.
- Define "critical density", ρ_c, which is just enough to slow the cosmic expansion to a halt at infinity.

Model Universes



If the density of matter equaled the critical density, then the curvature of space-time by the matter would be just sufficient to make the geometry of the universe flat!

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

$$H_0 = 72\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

We write $\Omega = \rho / \rho_{crit}$

dimensionless density parameter

Curvature has a simple but limited dynamical interpretation <u>IF</u> only gravity matters; then positive geometry corresponds to a closed universe (recollapses), negative geometry corresponds to an open universe (expands forever)

$\rho > \rho_c$ – matter will stop universal expansion after finite time (followed by recollapse, and a 'Big Crunch');
a closed universe
Geometry: positive curvature, $k = +1$

$\rho < \rho_c$ – gravity will never stop the expansion (an open universe)
Geometry: negative curvature, $k = -1$

$\Omega_M = 1$ – a critical universe
Geometry: flat (Euclidean), $k = 0$

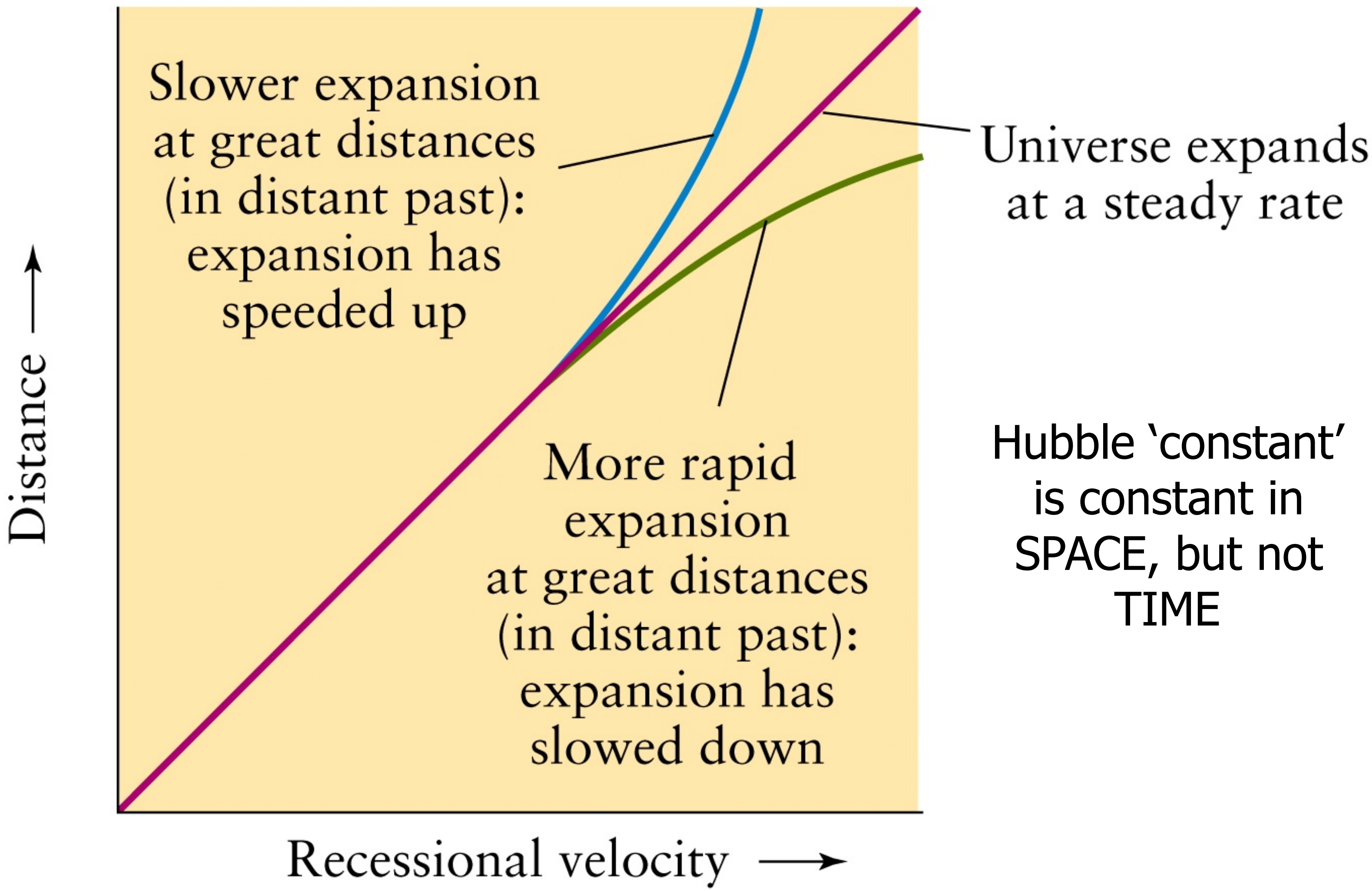
Measuring the Deceleration of the Universe

By observing type Ia supernovae, astronomers can measure the Hubble relation at large distances

Distance ← recession speed

Size scale of the universe ← rate of expansion

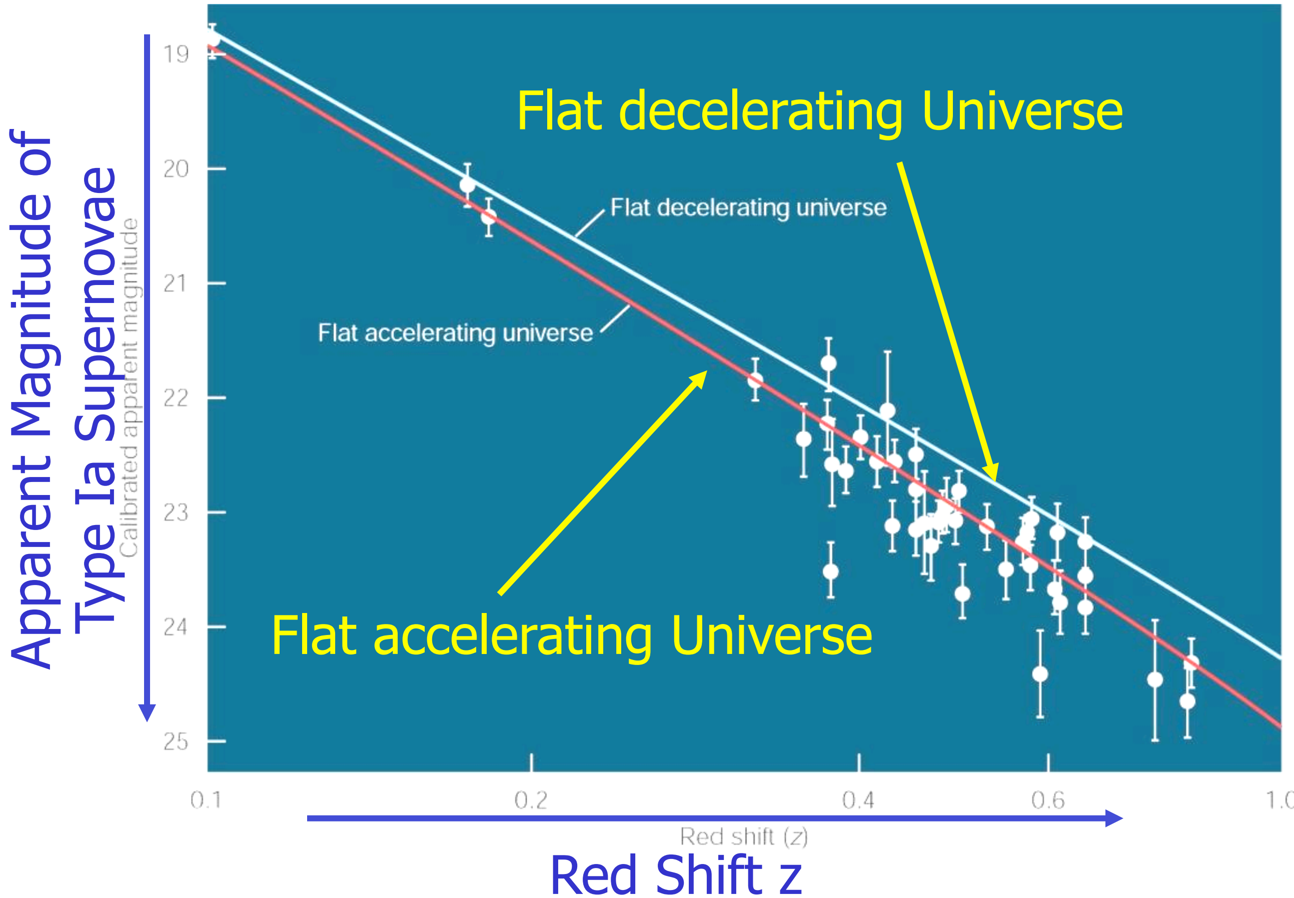
It was expected that this would measure the deceleration of the universe, but …



b

Hubble ‘constant’ is constant in SPACE, but not TIME

The Accelerating Universe



In fact, SN Ia measurements showed that the universe is accelerating!

The Cosmological Constant

- Cosmic acceleration can be explained with the "Cosmological Constant", Λ (upper-case lambda)

- Λ is a free parameter in Einstein's fundamental equation of general relativity; previously believed to be 0.

- Energy corresponding to Λ can account for the missing mass/energy ($E = m*c^2$) needed to produce a flat space-time.

$\rightarrow$ "Dark Energy"

We generalize Ω to include not just matter, but all forms of mass/energy:

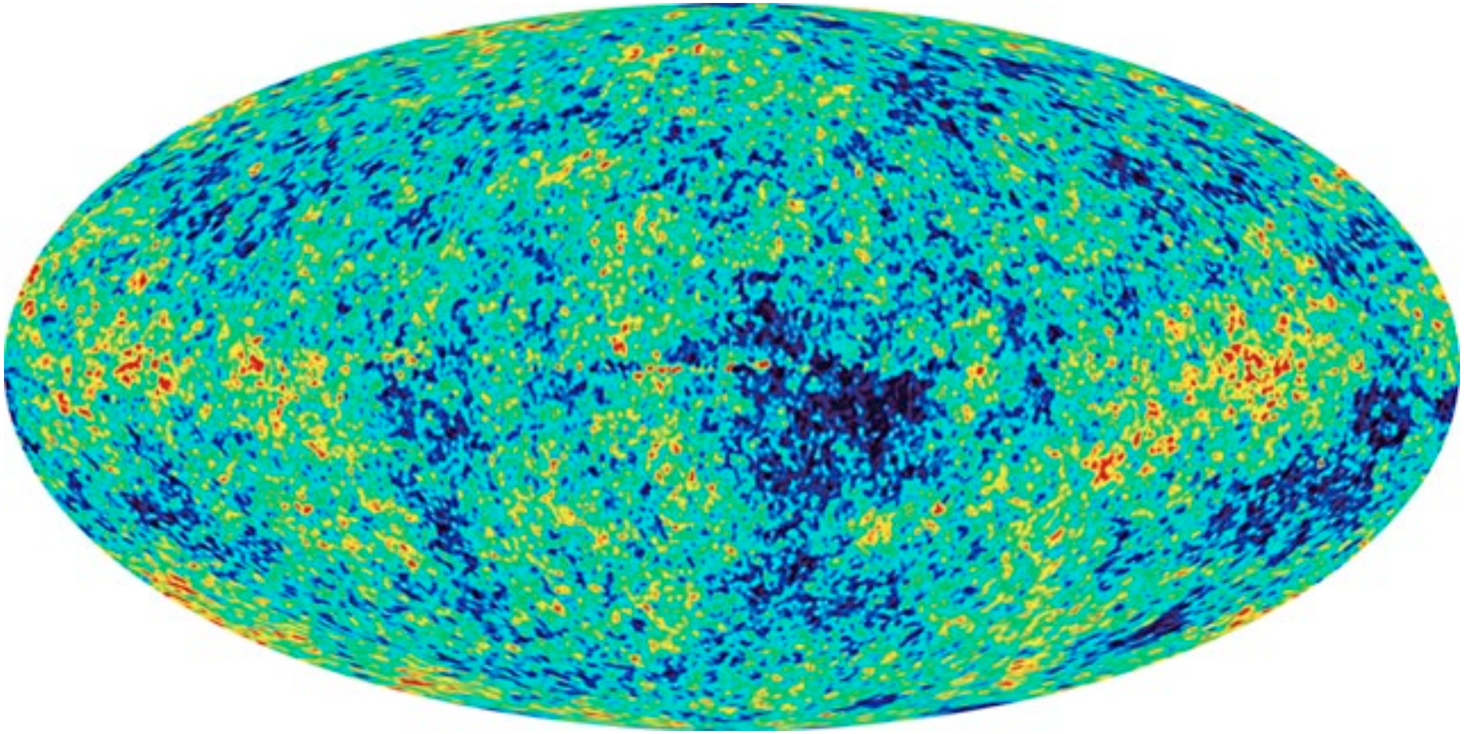
(matter) $\Omega_M = \Omega_B + \Omega_{DM}$

(Total) $\Omega = \Omega_M + \Omega_\Lambda$

What is the geometry (i.e., what is Ω_{total}?)

Cosmology with the Cosmic Microwave Background

If the universe were perfectly homogeneous on all scales at the time of reionization (z = 1000), then the CMB should be perfectly isotropic over the sky.



Instead, it shows small-scale fluctuations:

Geometry of Space

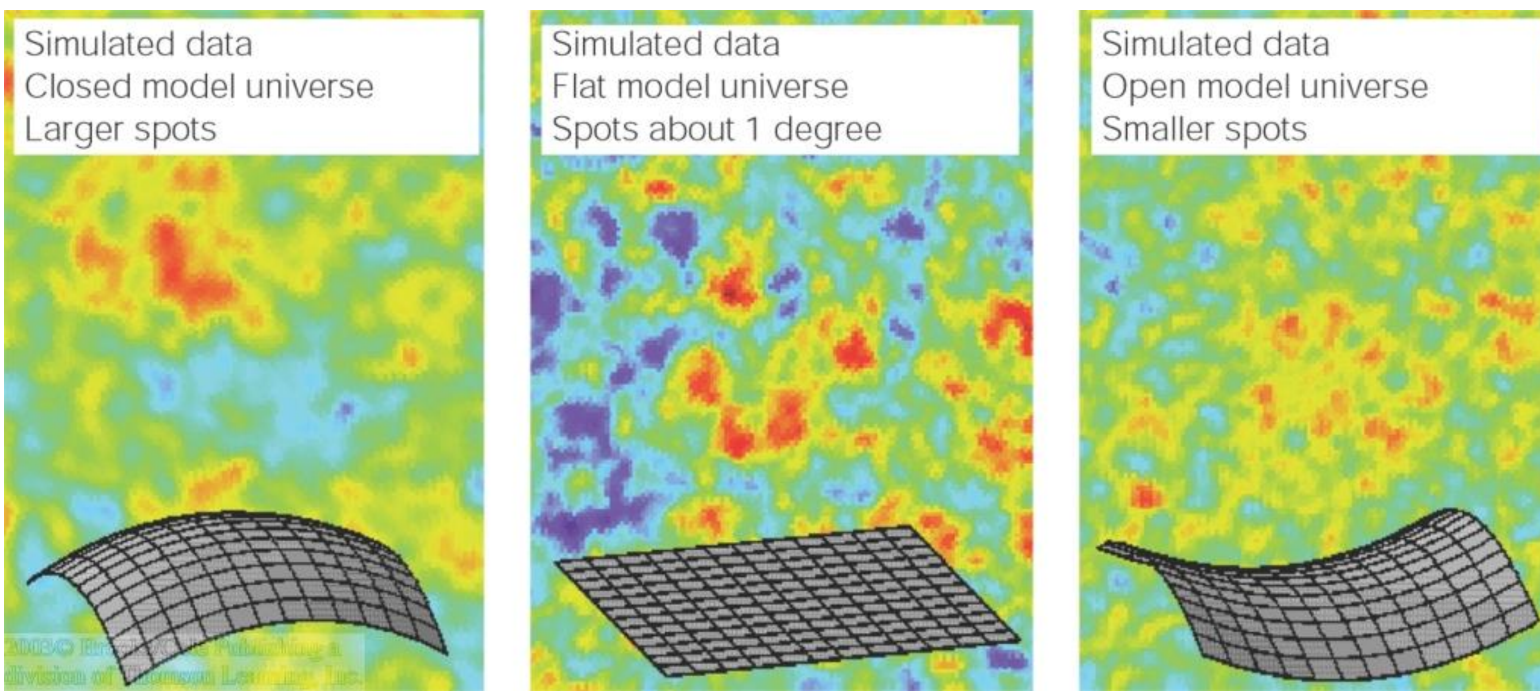
CMB tells us about the geometry of space - flat? curved?

But not much about evolution (snapshot) or dark energy (too early).

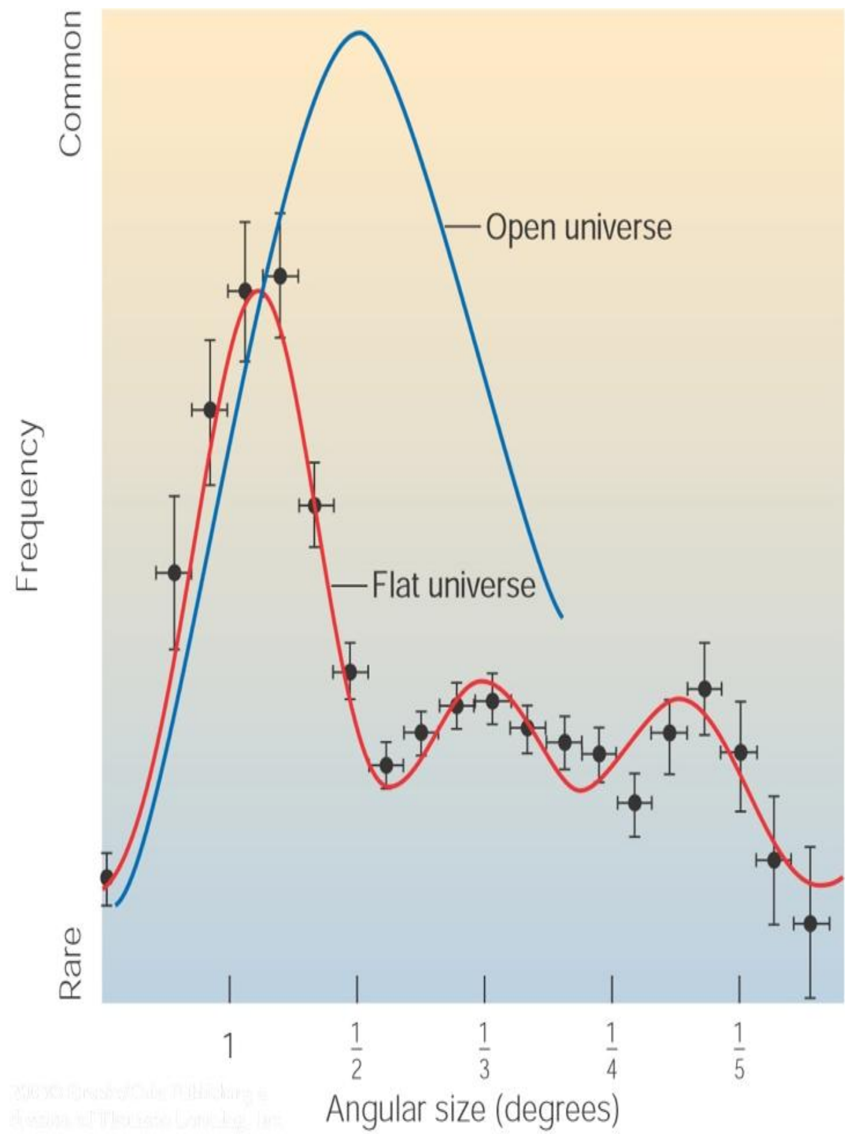
Fluctuations in the Cosmic Microwave Background

Angular size of the CMB fluctuations allows us to probe the geometry of space-time!

CMB fluctuations have a characteristic size of 1 degree.



Analysis of the Cosmic Background Fluctuations



Analyze frequency of occurrence of fluctuations on a particular angular scale

→ Universe has a flat geometry

In seeking to determine the deceleration of the universe, it turns out that it's not decelerating at all;

the universe is accelerating!

What is its future?

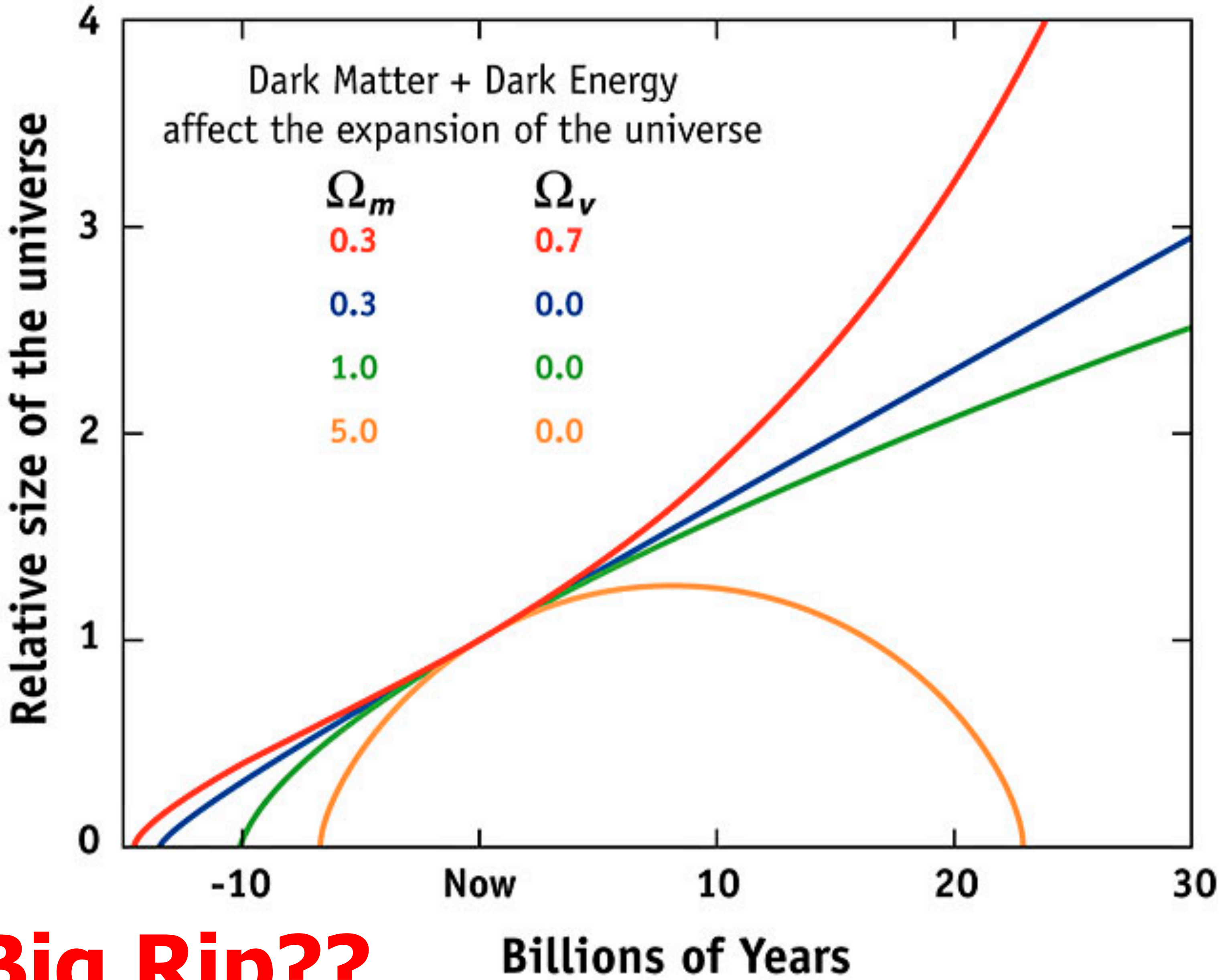
The geometry of the Universe is *flat* ($\Omega_{\text{Total}} = 1$) to within a few per cent (implies very close to flat)

But observationally, $\Omega_B = 0.04$, and $\Omega_{DM} = 0.23$

What makes up the rest? Not starlight, not neutrinos, not CMB but ***dark energy***
(the cosmological constant/vacuum energy)
$\boldsymbol{\Omega_\Lambda = 0.77}$

→ **'Concordance Model'**

Expansion of the Universe



Big Rip??

Inflation...(another acceleration!)

Period of inflation: accelerated expansion in the very early Universe ($t < 10^{-34}\,\mathrm{s}$), first proposed in 1980.

Inflation not yet accepted by everyone, but explains a lot of puzzles:

- why is $\Omega_\Lambda + \Omega_{\mathrm{matter}} = 1$?
- why is the CMBR so smooth?
- where do the tiny CMBR ripples come from?

Flatness problem: *why* is Ω so close to 1?

Even if you don't believe it's 1, it's certainly

within a factor 10 of 1 – which means it must have been really close to 1 previously.

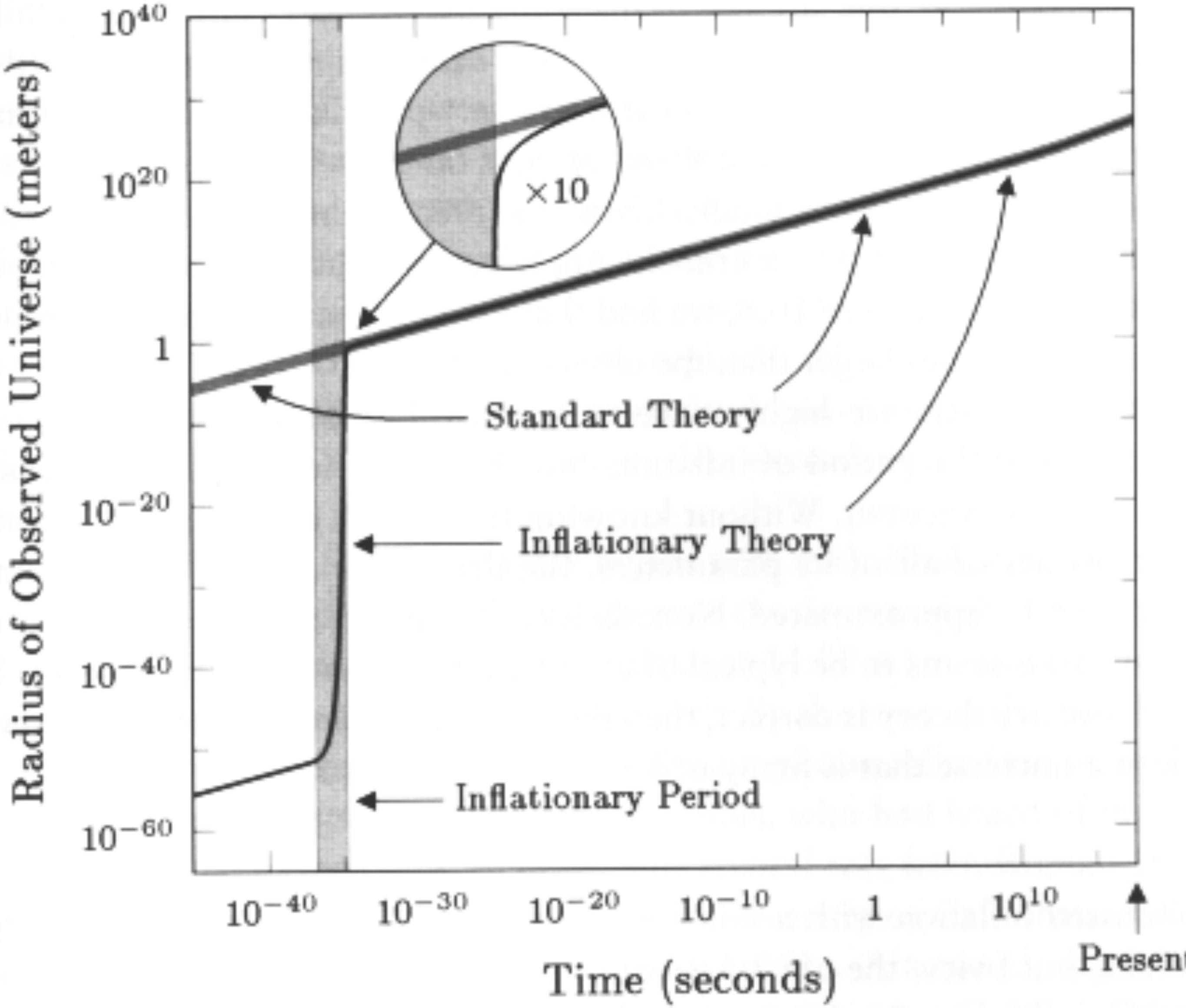
In GR, pressure has associated with it a gravitational field!

Negligible under normal circumstances (air pressure has a gravitational field 10^{-11} of the field generated by the air's mass density), but in the (very!!) early universe pressures were enormous – and mattered

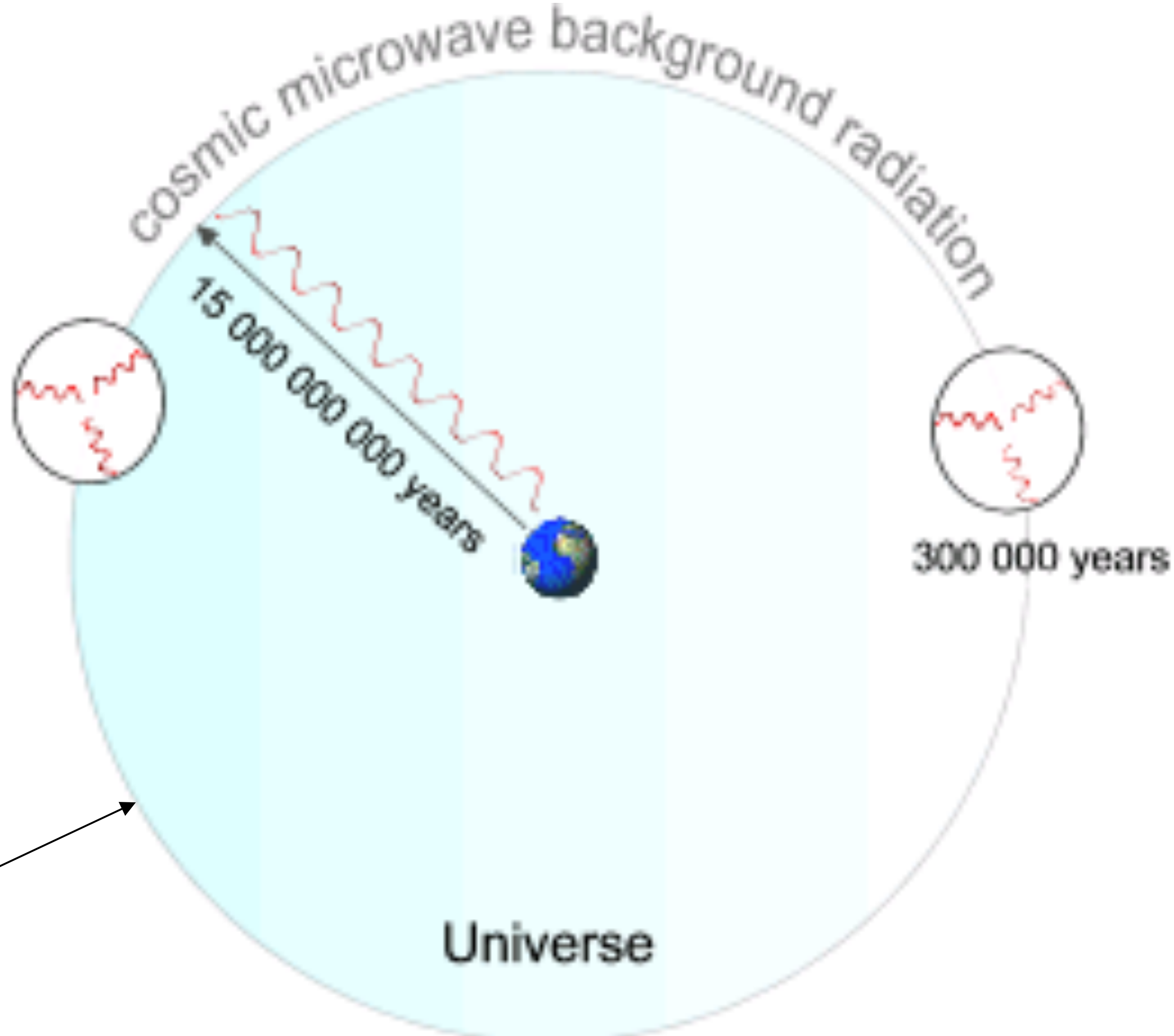
Solving the equations of motion (we won't), we find that

$$R(t) \sim \exp(Ct)$$

i.e., the universe expands exponentially (with a time constant of 10^{-34} or 10^{-33}s) ➔ inflation



Radius of Observed Universe (meters)
10^{40}
10^{20}
1
10^{-20}
10^{-40}
10^{-60}
×10
Standard Theory
Inflationary Theory
Inflationary Period
10^{-40}
10^{-30}
10^{-20}
10^{-10}
1
10^{10}
Present
Time (seconds)



the cosmic
'horizon'