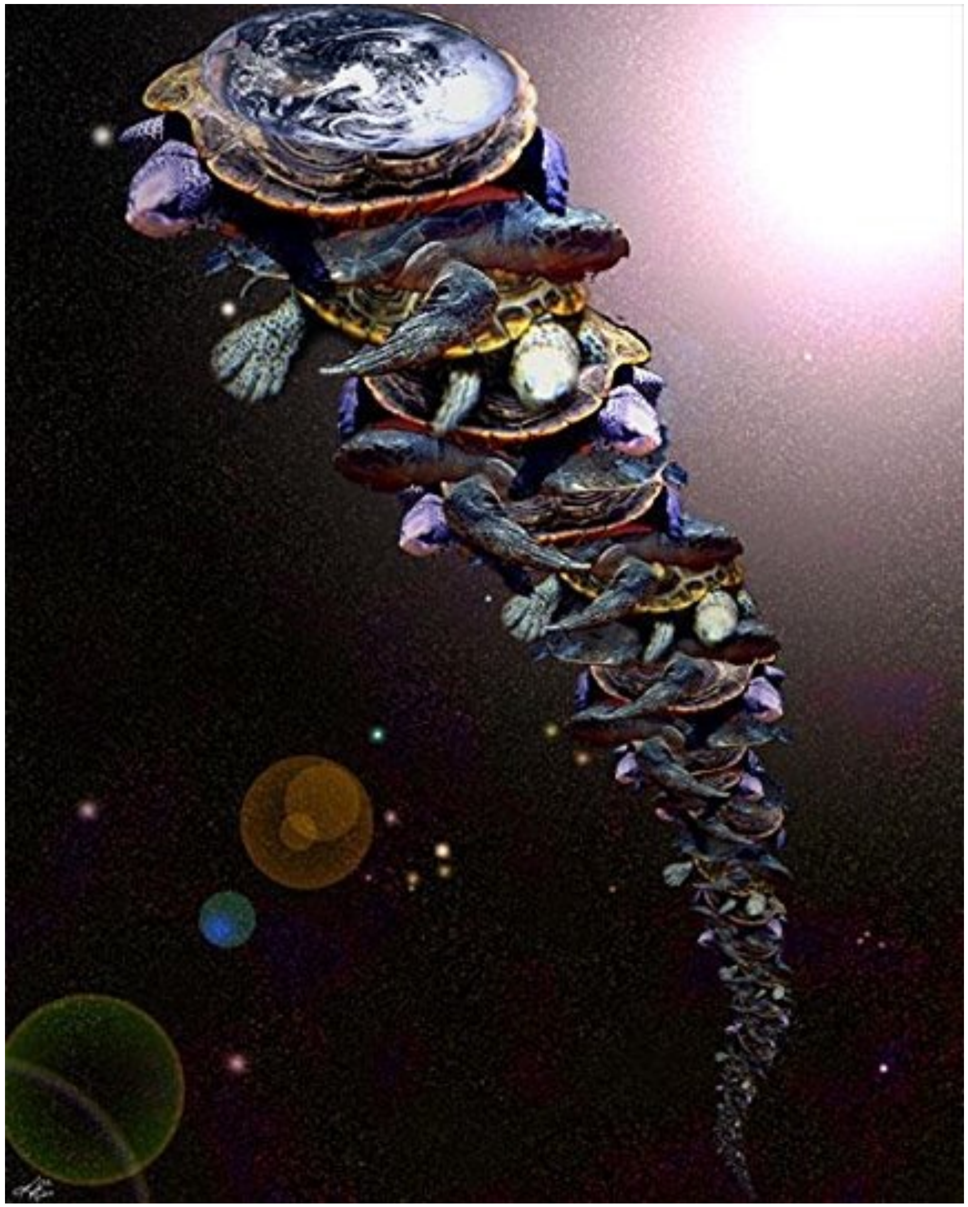
Cosmology



Prevailing theory: the Big Bang

Four pillars:

- Cosmological principle
- Expansion of the Universe
- Origin of the cosmic microwave background
- Synthesis of the light elements

NB: Not the formation of galaxies and large scale structure.

IMPORTANT: Cosmology is based on observations!

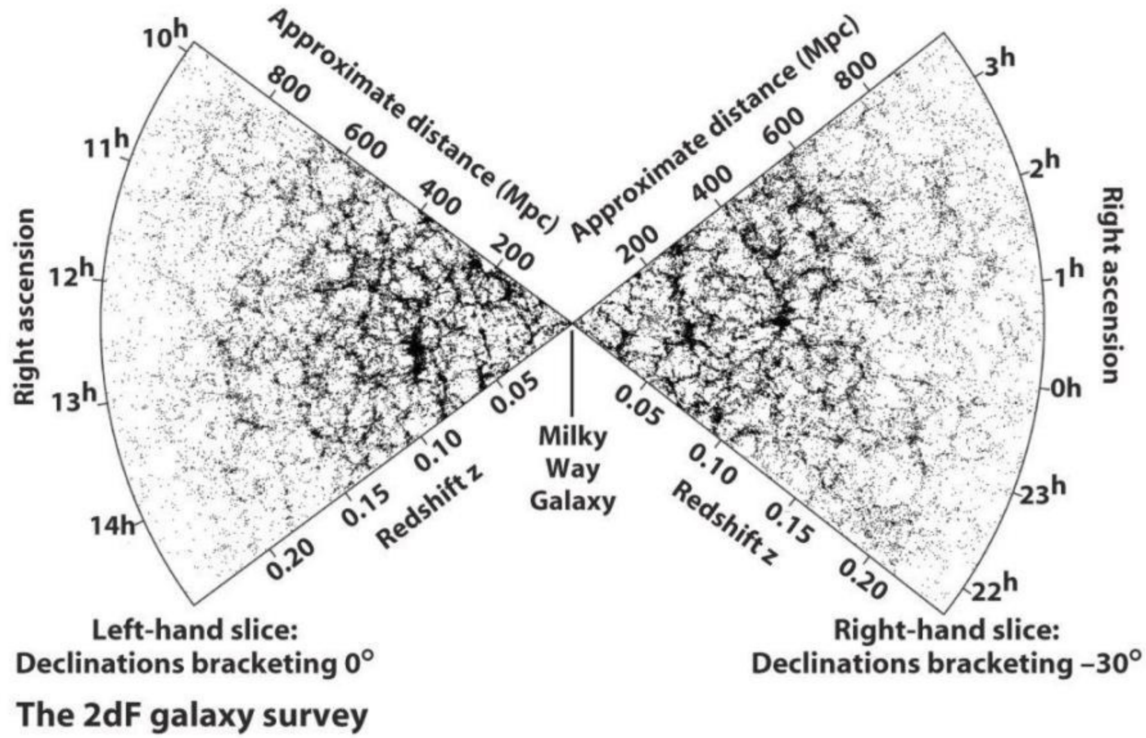
Fundamental observations

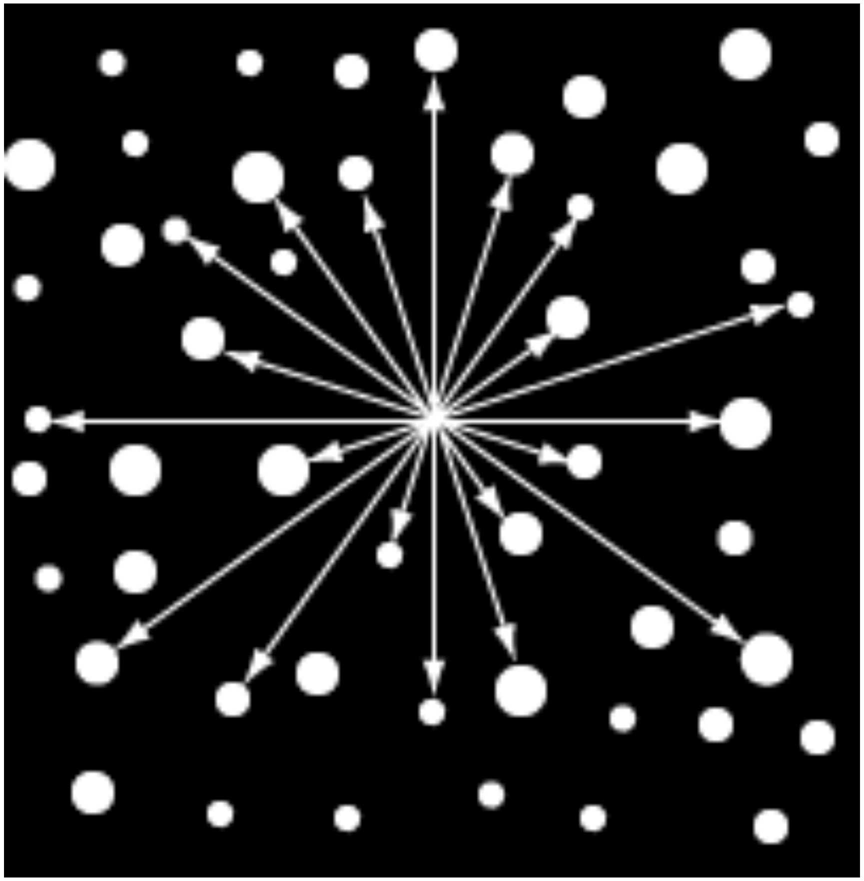
The cosmological principle

- Observational fact: the Universe is homogeneous and isotropic:

- Homogeneous: it is the same everywhere (on scales > few 100 Mpc), no preferred locations.

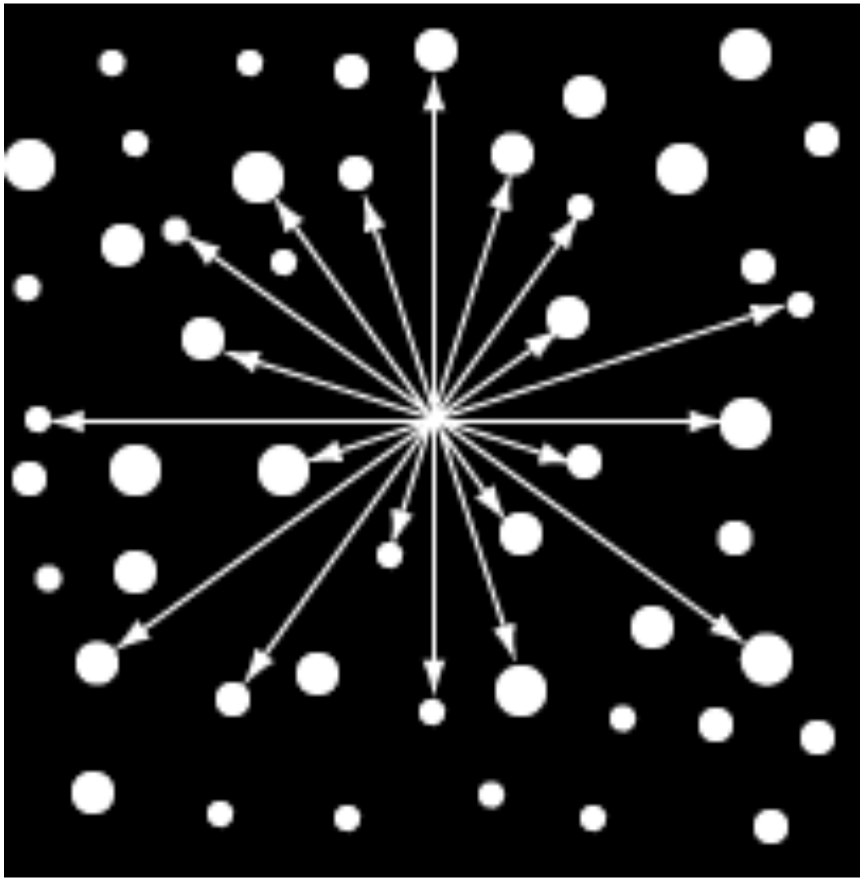
- Isotropic: the same in all directions, no preferred direction.





Olber's paradox

- Why is the sky dark at night? The cosmological principle would imply that the line of sight will always intersect at least one object?
- The sky should be as bright as the surface of a star!



Olber's paradox

- Why is the sky dark at night? The cosmological principle would imply that the line of sight will always intersect at least one object?

- The sky is dark because the Universe has a finite age, and the expansion is reducing the energy radiated from distant stars. And there is dust.

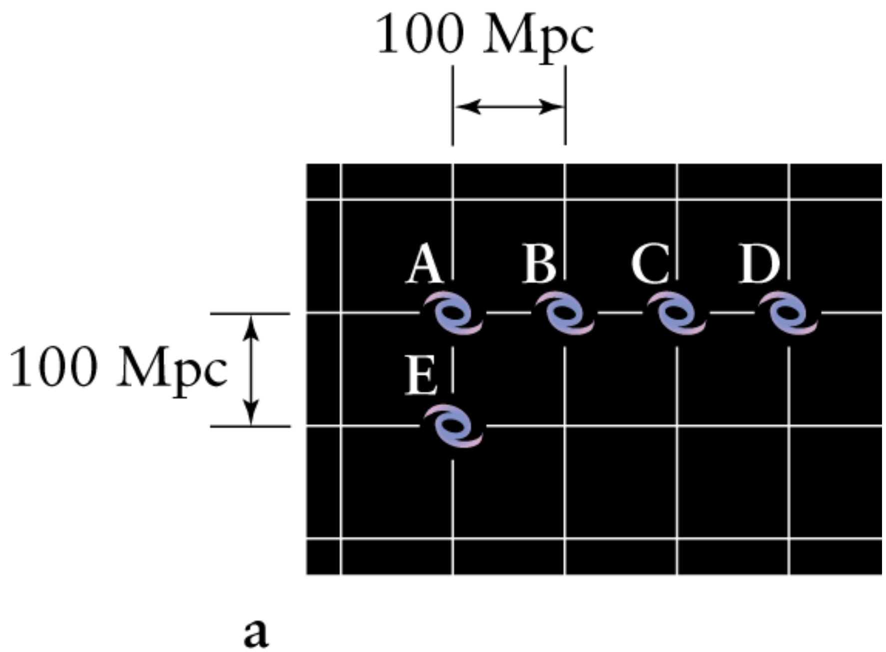
Expansion of the Universe

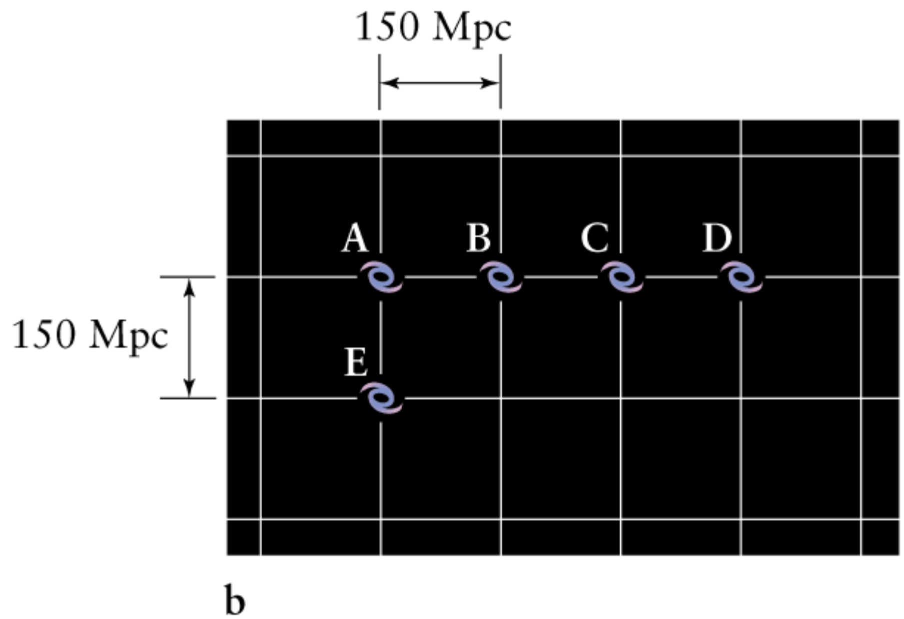
- The Hubble Law is an observational fact with implications:
  - It must have been smaller and denser in the past.
  - At the beginning, must have been incredibly dense – expansion began with an enormous event: 'The Big Bang'.

What are we expanding into?

What was before Big Bang?

Where was Big Bang?

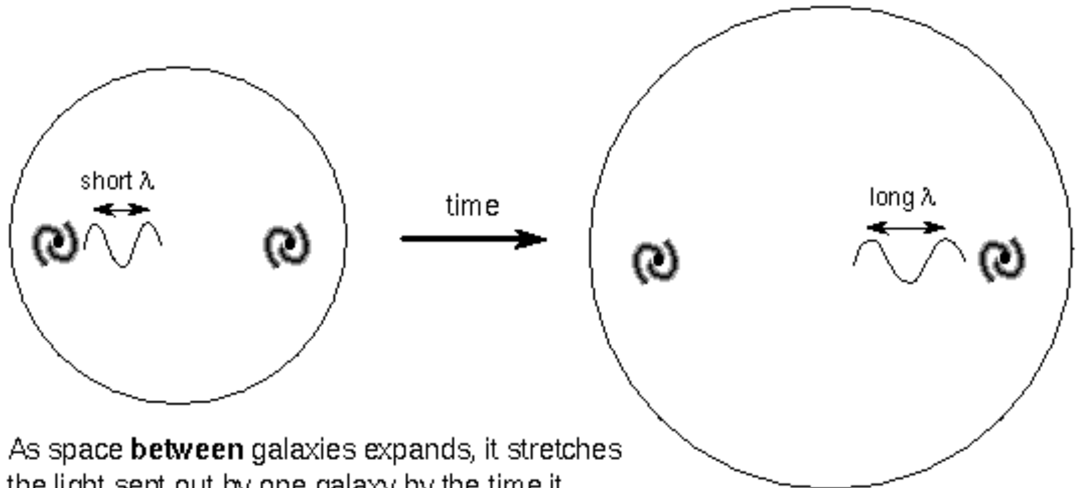




	Original distance (Mpc)	Later distance (Mpc)	Change in distance (Mpc)
A–B	100	150	50
A–C	200	300	100
A–D	300	450	150
A–E	100	150	50

- Key Point:
  - For this kind of expansion, any galaxy will see the others moving away from it in the same way – the farther away a galaxy is, the faster it recedes.
  - $V = H_0 d$ for ALL galaxies, not just the Milky Way!

- Expansion of space explains redshift (z) of galaxies: as space expands, the photons are stretched → longer λ. Ratio $\lambda/\lambda_0 = 1 + z$ is measure of amount of stretching.



As space **between** galaxies expands, it stretches the light sent out by one galaxy by the time it reaches another far away galaxy. Looks like **redshift**.

- The farther away a galaxy is from us, the longer it takes a photon to get here, the more the universe has expanded in the meantime.

- This *cosmological redshift* is not a Doppler shift, but the effect of expanding space.

When did the Big Bang happen? Or How Old is the Universe?

- Simple estimate: Consider two galaxies separated by distance *d*, and moving away from each other with velocity *v*. How long has it been since the galaxies were on top of each other? Assume a Hubble constant of 73.8 km/s/Mpc.

- Worksheet

Reality check: Compare this estimate to the age of the oldest stars (12.5 Gyrs)

When did the Big Bang happen? Or How Old is the Universe?

- Worksheet 15. Calculate the age of the Universe assuming the Hubble constant is 73.8 km/s/Mpc. Simple estimate: Consider two galaxies separated by distance *d*, and moving away from each other with velocity *V*.

- Since $d=Vt$, we can calculate when they were on top of each other, at the time $T_0 = d/V$ ago.

- Now, since $V=H_0 d$:

$$T_0 = d/V = d/(H_0 d) = 1/H_0$$

$$T_0 = 1/H_0 \sim 1/73.8 \text{ km/s/Mpc} = 13.3 \text{ billion years.}$$

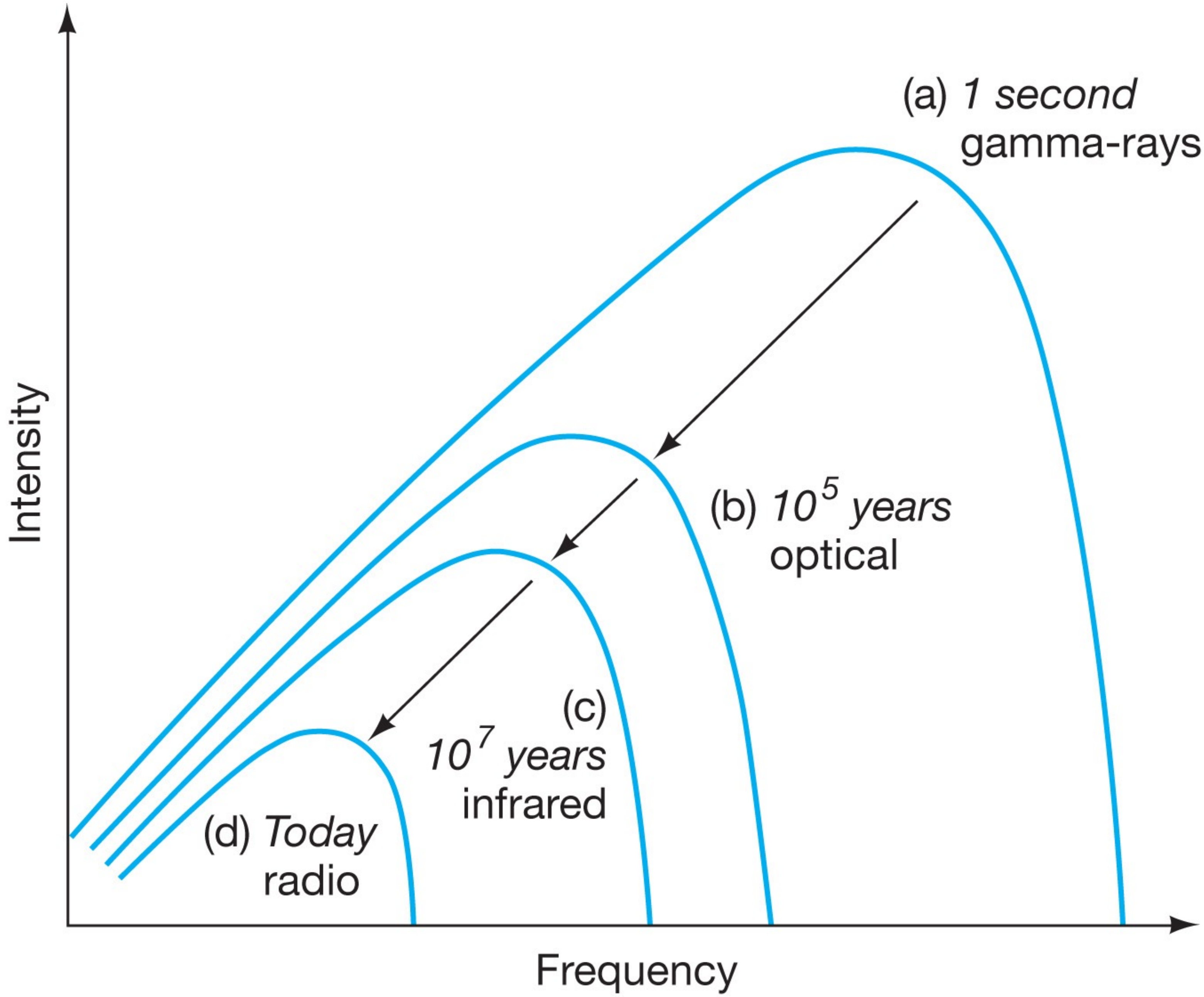
Major support for the Big Bang event

- Cosmic Microwave Background Radiation (CMBR):

  Early universe must have been very hot and dense, with plenty of high energy photons.

- These photons should still be with us, but redshifted.

  CMBR would have a peak λ at ~ 1mm (microwaves). Should be a blackbody of T~ a few K.

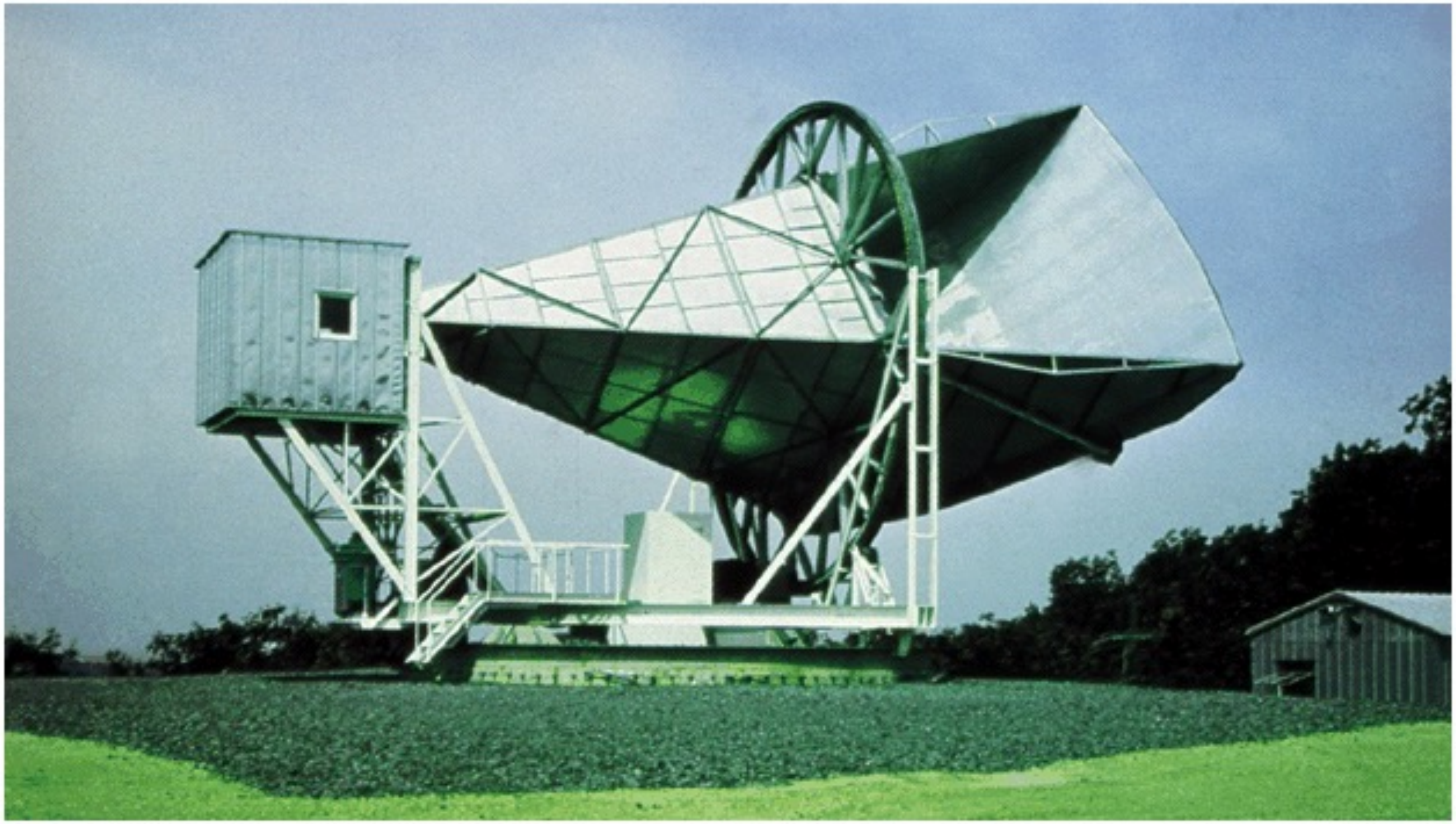


(a) *1 second*
gamma-rays
(b) *10⁵ years*
optical
(c)
10⁷ years
infrared
(d) *Today*
radio
Intensity
Frequency

Discovery of the CMB Timeline

1940: Andrew McKellar (DAO in Canada) discovers CN and CH in clouds in our galaxy.
1941: McKellar determines temperature for interstellar CN of 2.3 K.
1948: Alpher and Herman predict a blackbody relic from the Big Bang at 5 K
1950: Hoyle disses Hot Big Bang and notes that 5 K is warmer than McKellar found.
1957: Denisse et al. report a background with 3 +/- 2 K at 1 GHz but don't make anything of it.
1962: Dicke starts searching for observational evidence of CMB
1965*: Penzias and Wilson report detection of CMB at 4 GHz
1990*: Smoot et al. report on COBE results which nail CMB temp at 2.725 K
* Gets Nobel Prize

The Homdel Horn antenna that Penzias and Wilson used to discover the CMBR at 4 GHz.



- The CMBR was found accidentally in the mid 1960's by two Bell lab employees, trying to minimize noise in microwave phone transmissions.

- The transmissions were being bounced off aluminized balloons (project Echo)

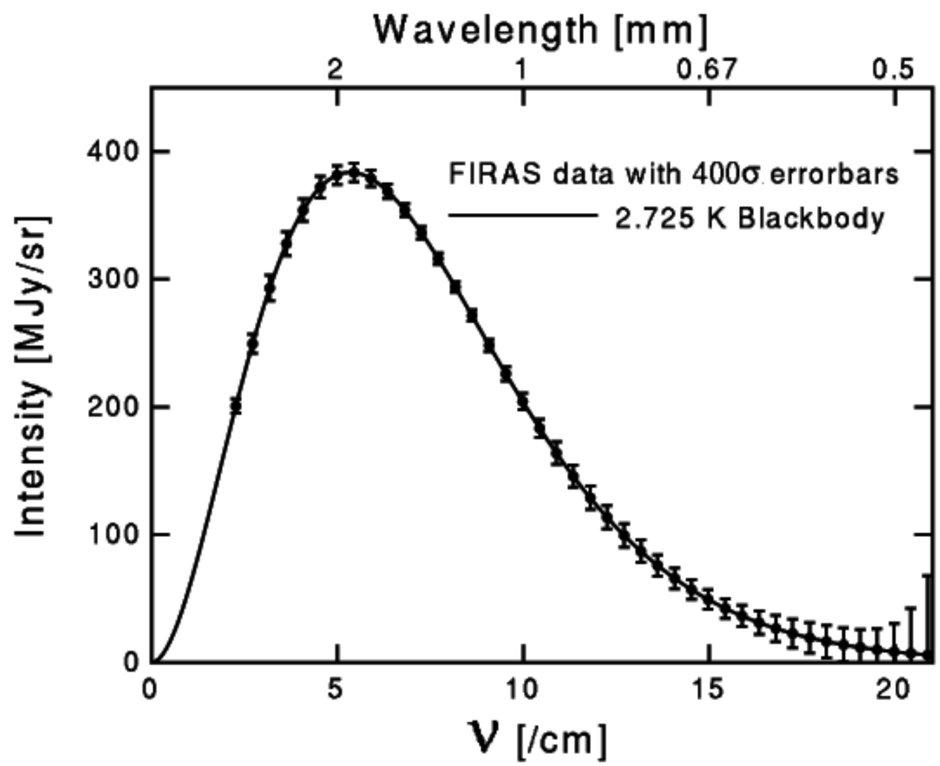
- Penzias and Wilson found the temp to be about 3K. It was isotropic, and later studies showed it to be a remarkably perfect blackbody.

- Bernie Burke (a radio astronomer at MIT) told Penzias about work going on at Princeton by Robert Dicke and Jim Peebles

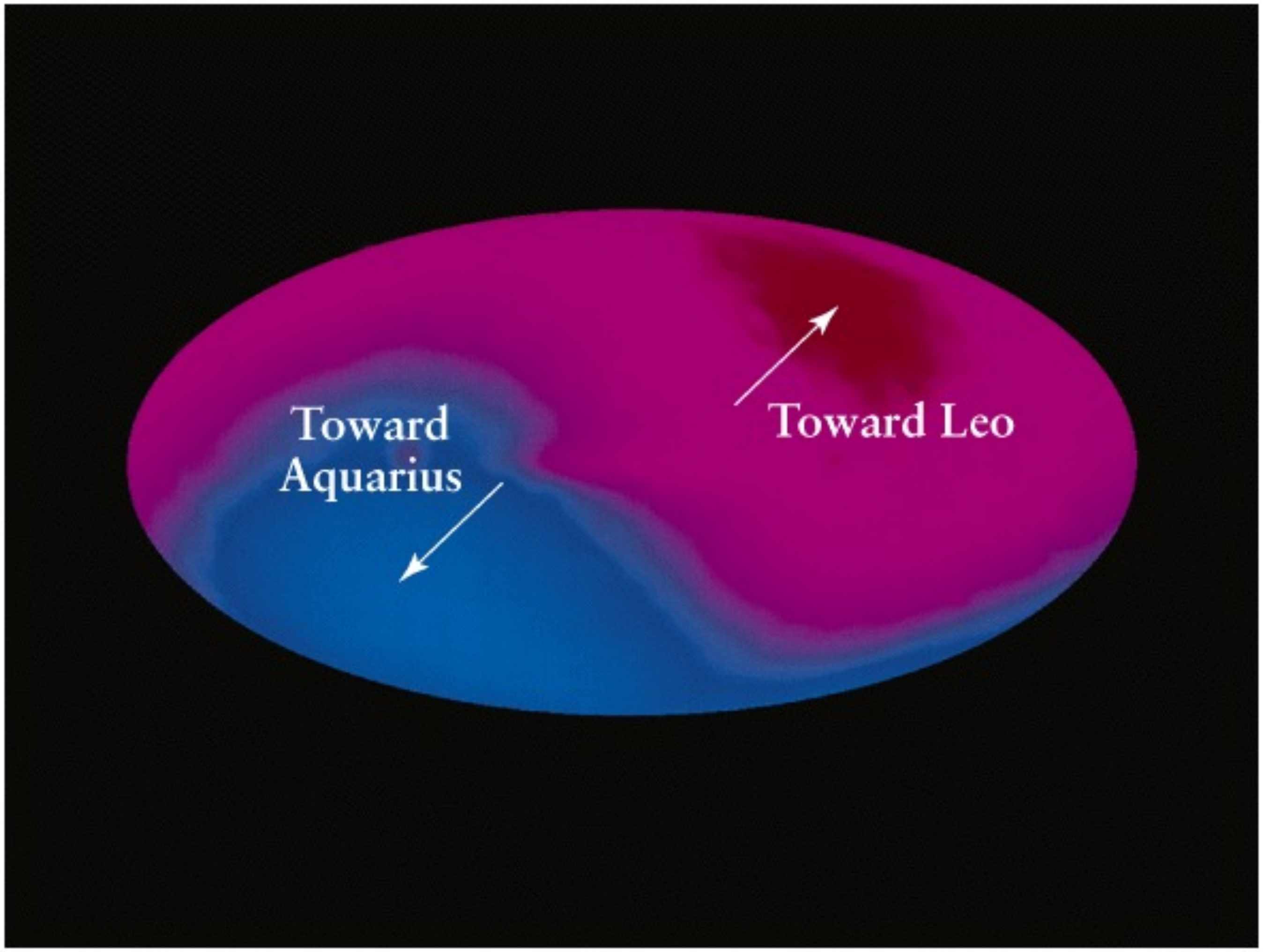
- Penzias & Wilson won the Nobel prize in 1978.

COBE: COsmic Background Explorer

- In 1989 COBE spectacularly confirmed the blackbody curve of predicted temperature.



The CMBR is all around us, with almost the same temperature on the sky. The dipole pattern is due to the motion of the MW through space toward Leo.



Evidence for small-scale structure

Era of recombination

- Photons in the early universe had so much energy that they would not allow atoms to form (everything was ionized)

- At z~1,100 (~380,000 years after Big Bang), the universe had cooled off to T~3,000K. Atoms formed since low-energy photons could not ionize them.

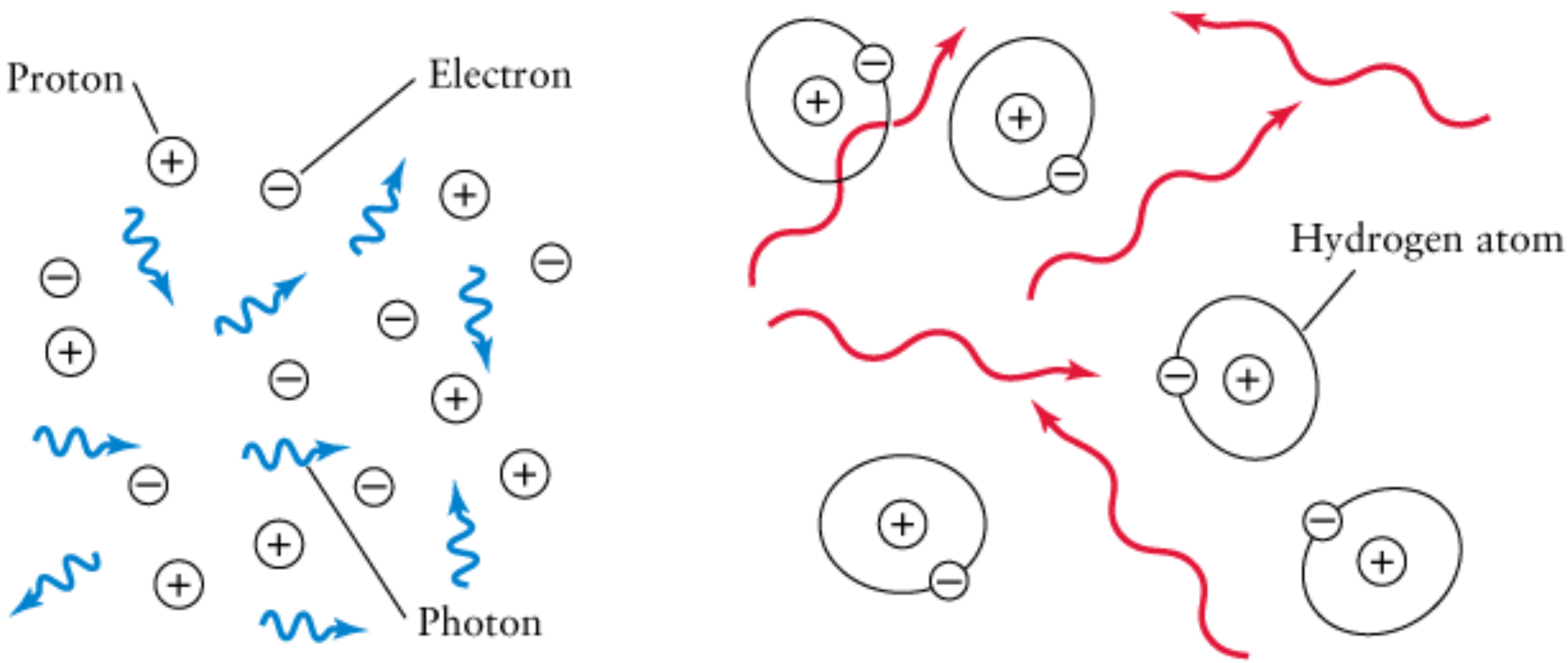
- Space become *transparent* => decoupling of matter and radiation. The decoupled photons ARE the CMBR!

Called decoupling, or 'era of recombination'

- If decoupling happened after 380,000 years, how come we can still see it today?

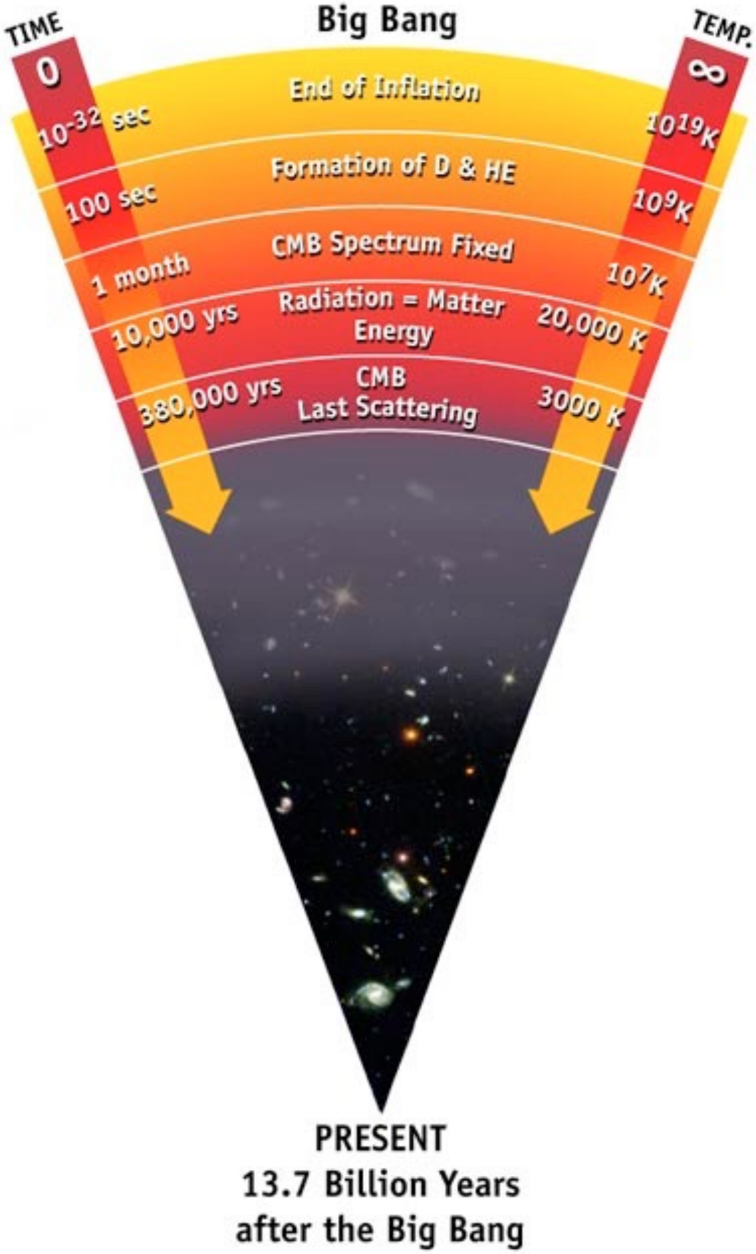
Free nuclei, protons and electrons, bathing in blackbody radiation.

At 3000K, recombination made scattering much less effective and long wavelength photons (like CMB) can travel undisturbed.

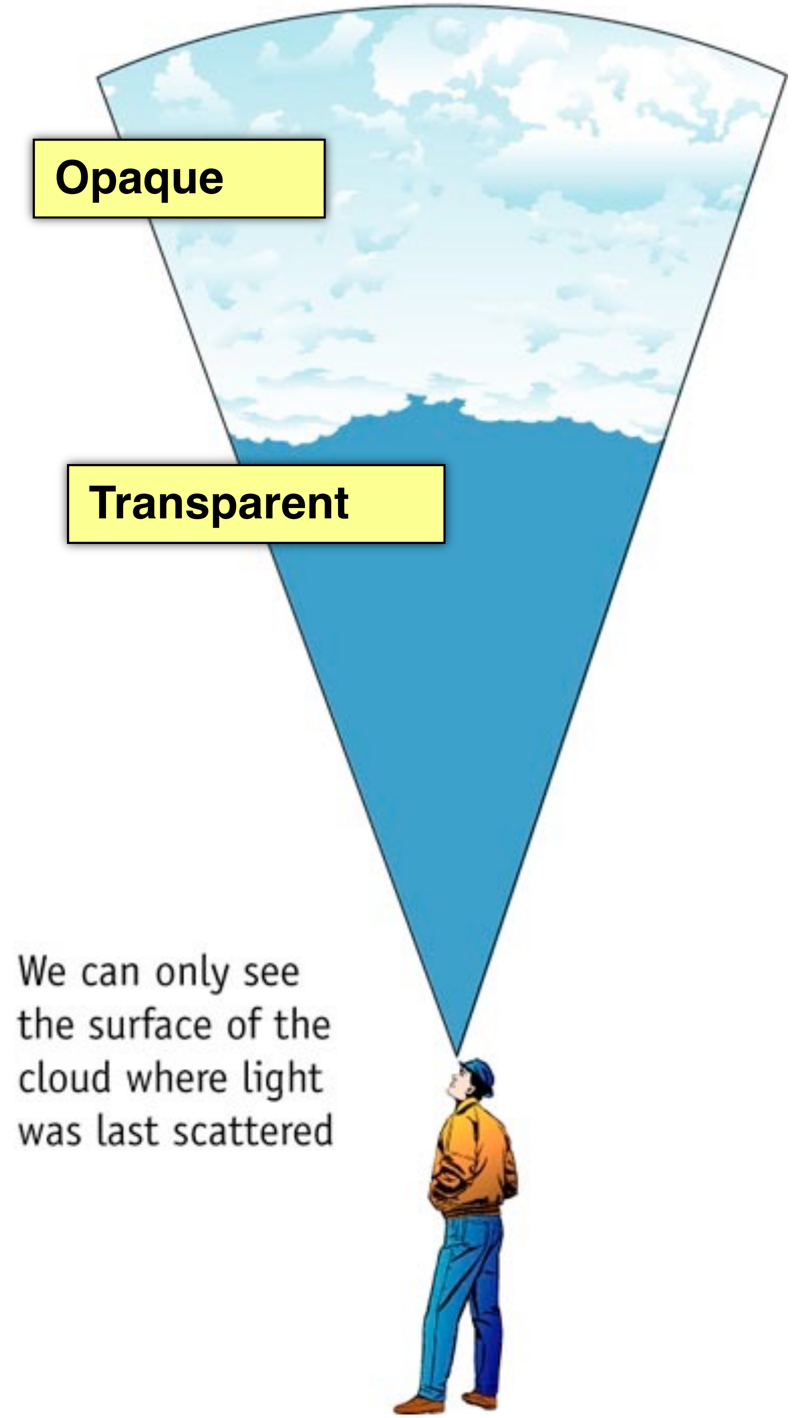


a Before recombination

b After recombination



The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



Matter or energy?

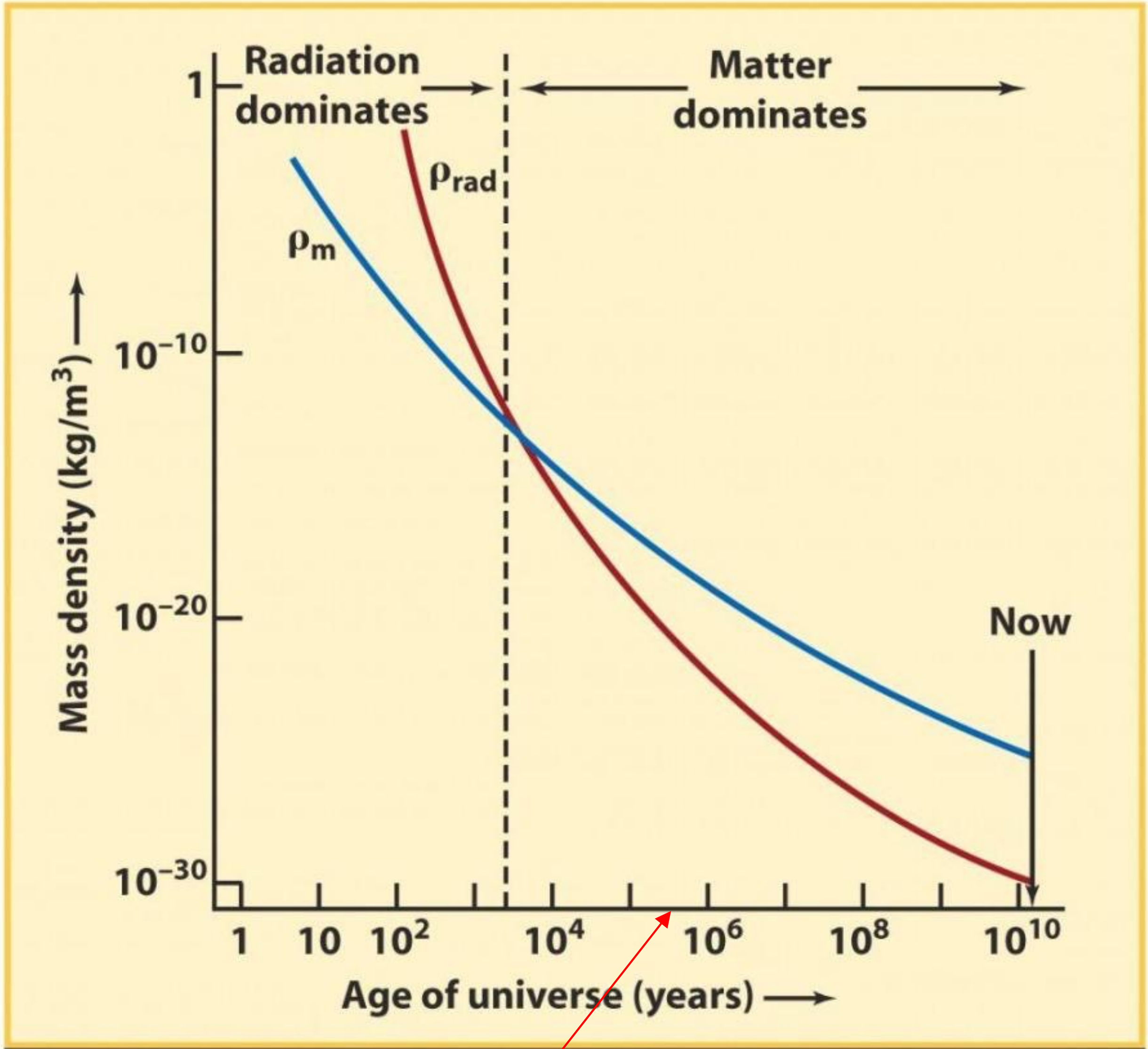
- Average density of matter ρ_m = M/V, where M contains both visible and dark matter.

- M should be constant, $V \sim R^3$ so $\rho_m \sim (1+z)^3$

- Mass density of radiation $\rho_{rad} = E/V = hc/(R^3 \lambda)$

  so $\rho_{rad} \sim (1+z)^4$

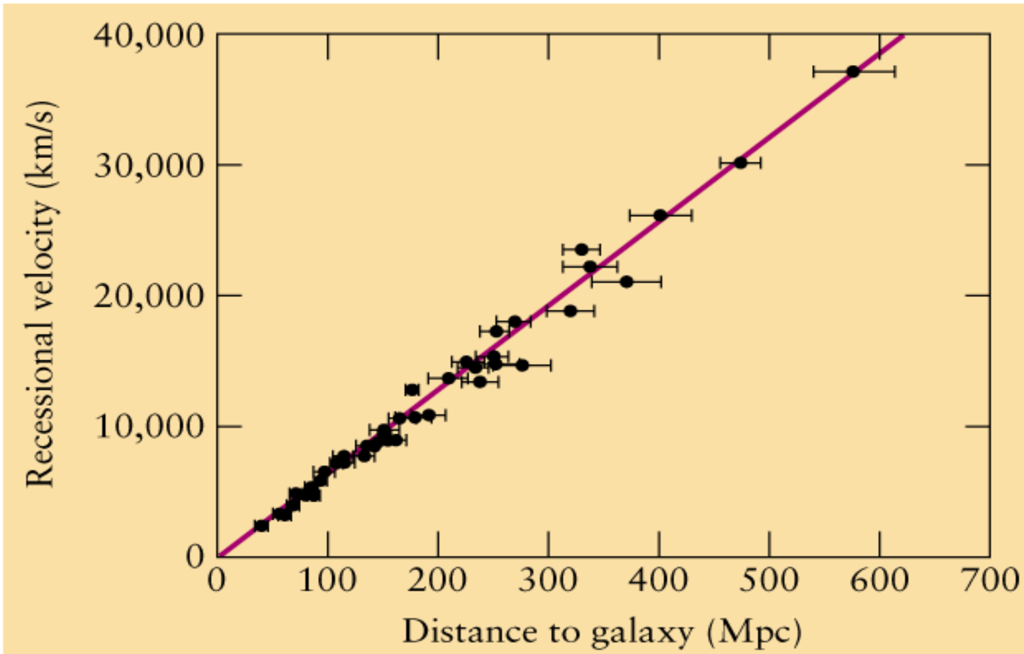
- Relative fraction changes as the Universe expands (increasing V, decreasing T).



Epoch of recombination

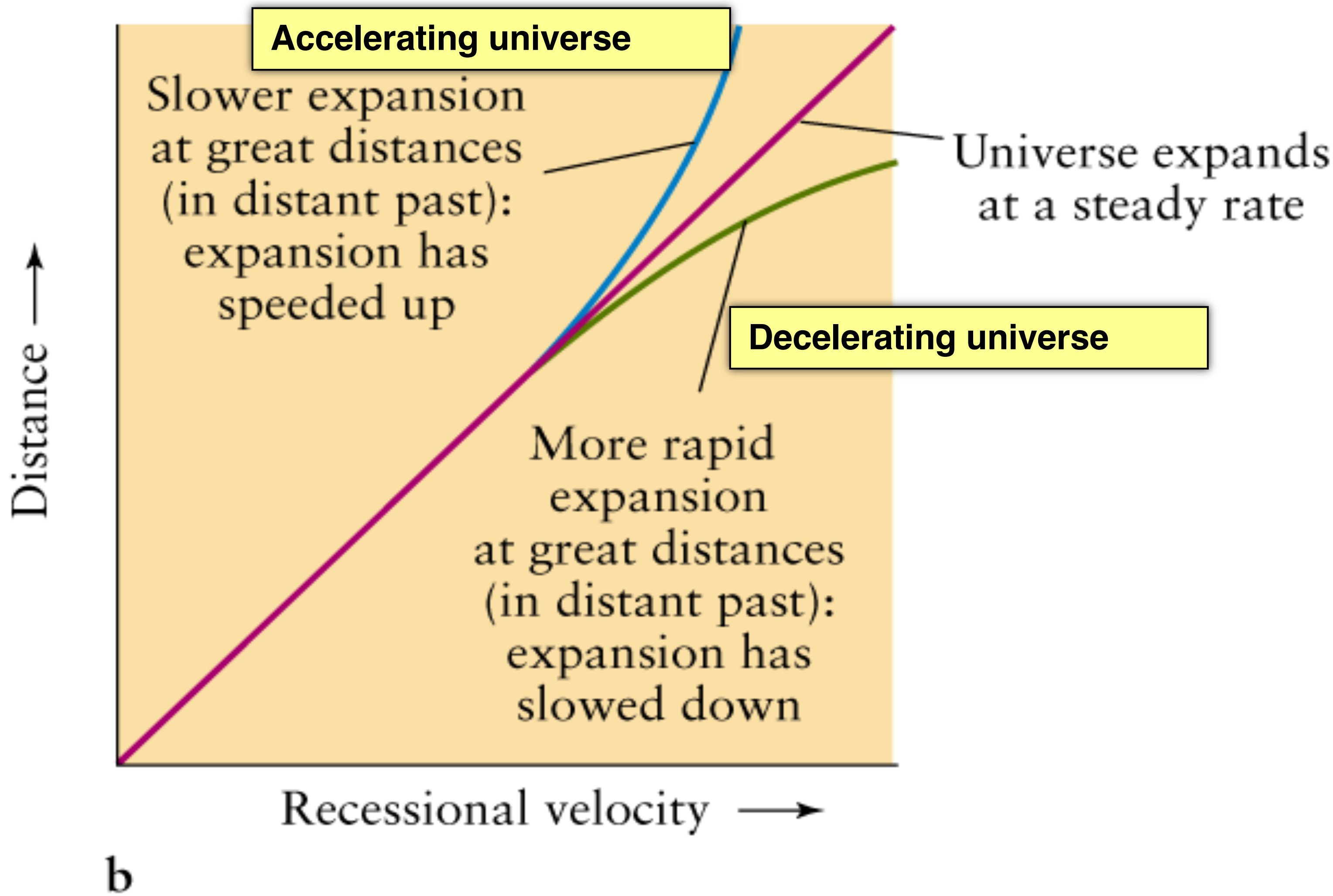
Evolution of the universe

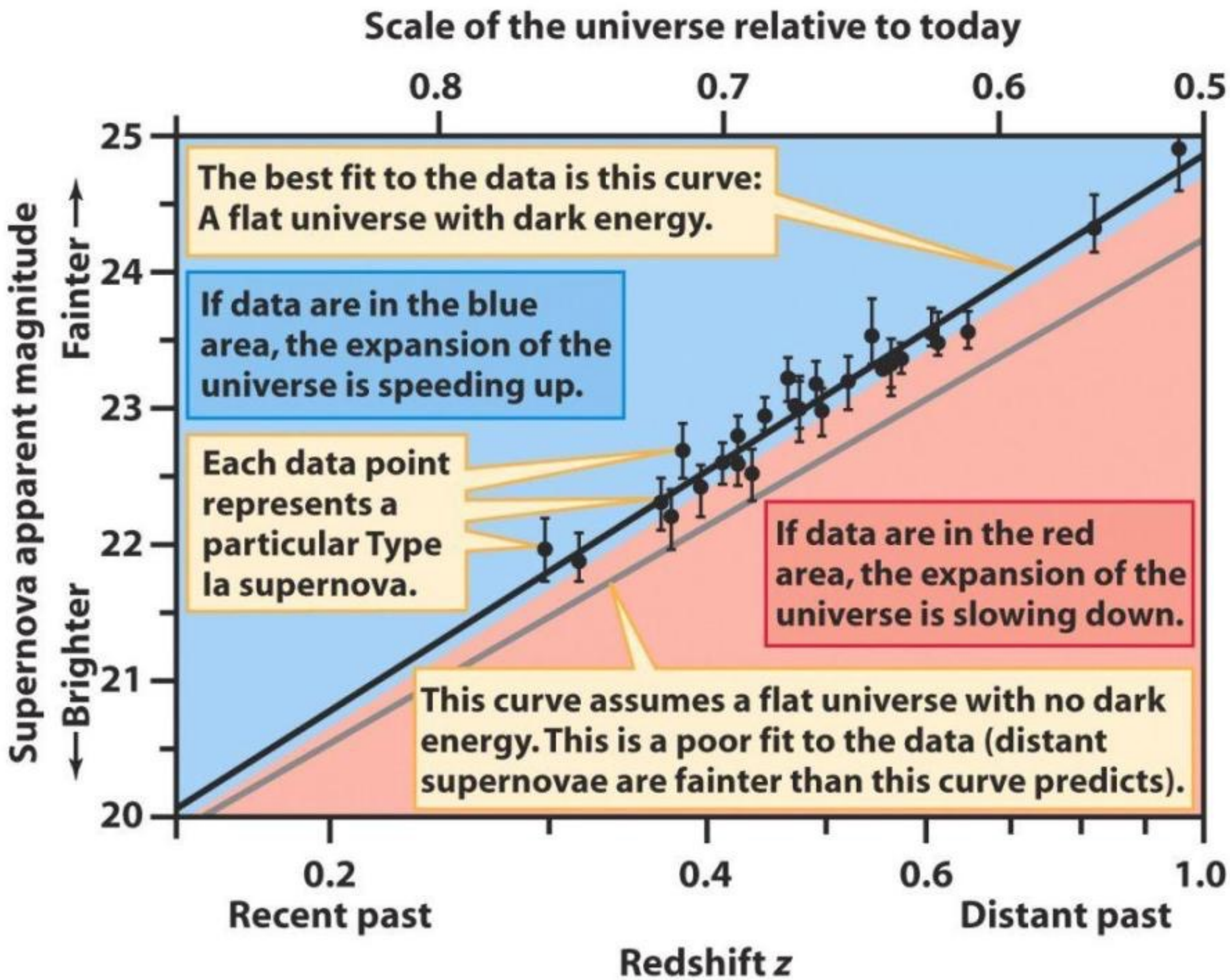
- Galaxies in the local universe follow Hubble's Law, $V=H_0d$.



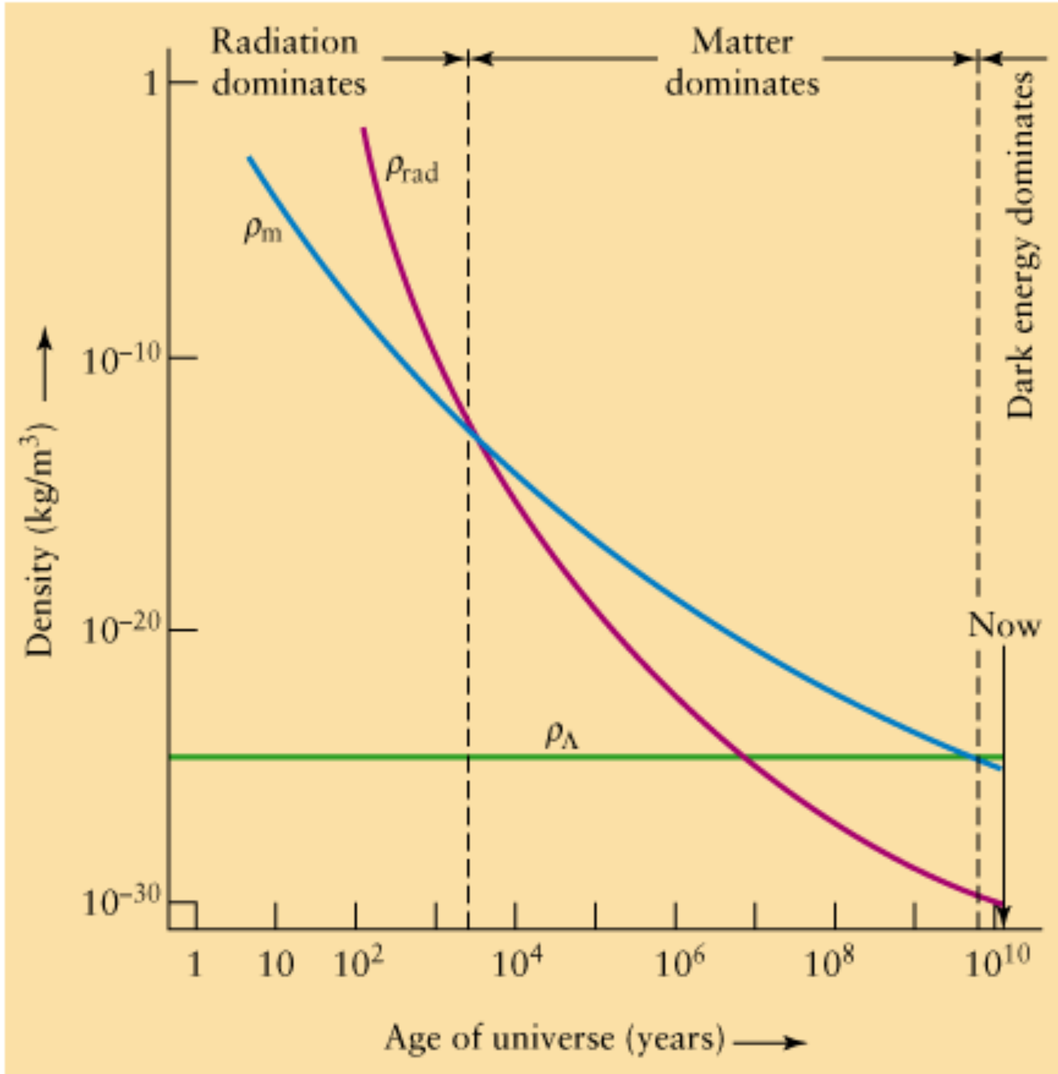
- If rate of expansion of the universe were the same in distant past as now, then distant galaxies would obey this relation.

- If rate of expansion were different in distant past, we would see deviation from linear Hubble Law:





- Using SNe Ia as standard candles, we have found that the expansion of universe is speeding up.



Evidence is we currently live in a dark-energy dominated universe.
Since about 5 billion years go, ρ_Λ has been greater than ρ_m.

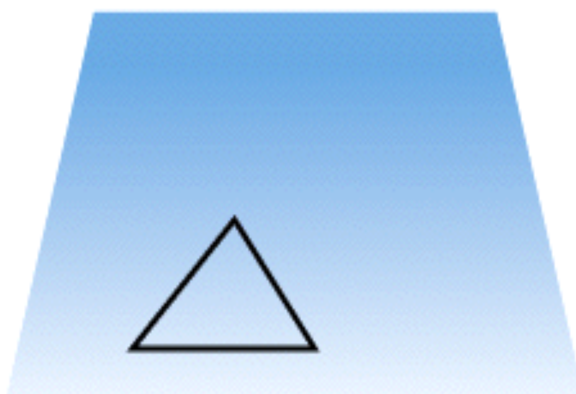
What is driving the acceleration of the Universe?

- Key idea from GR: Energy equivalent to mass ($E=mc^2$), so all forms of energy gravitate as well.
- Matter and energy combined tell spacetime how to curve.
- The combined matter and energy density of the Universe determines how much curvature.

Curvature of space

Consider shining two powerful laser beams into space, starting off parallel. What happens?

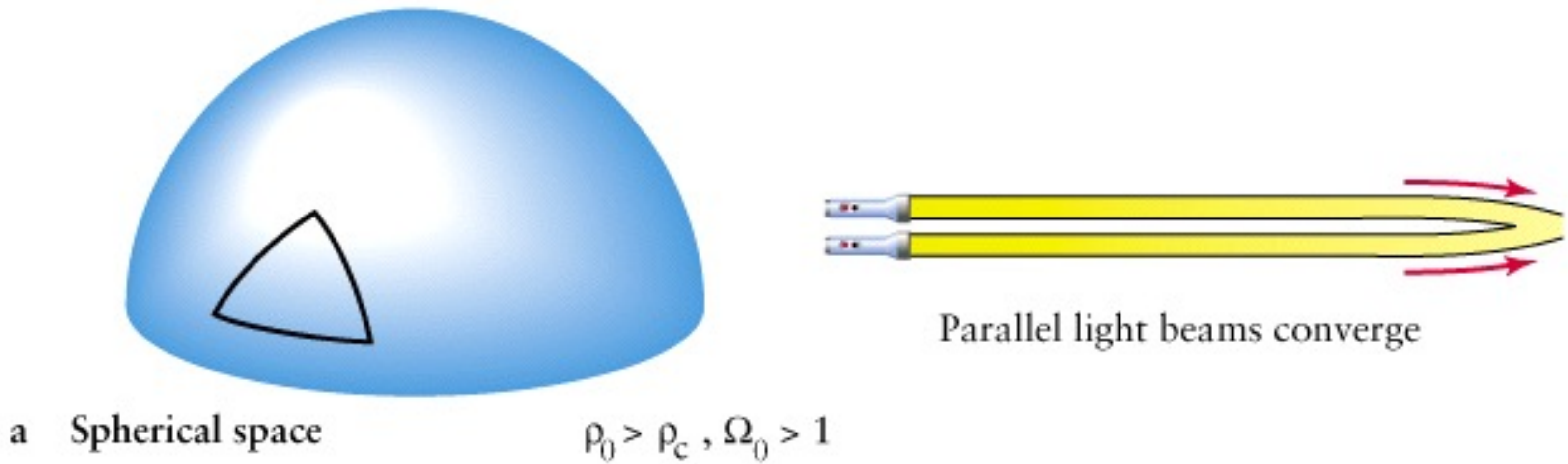
1. They could remain parallel - *flat space*.



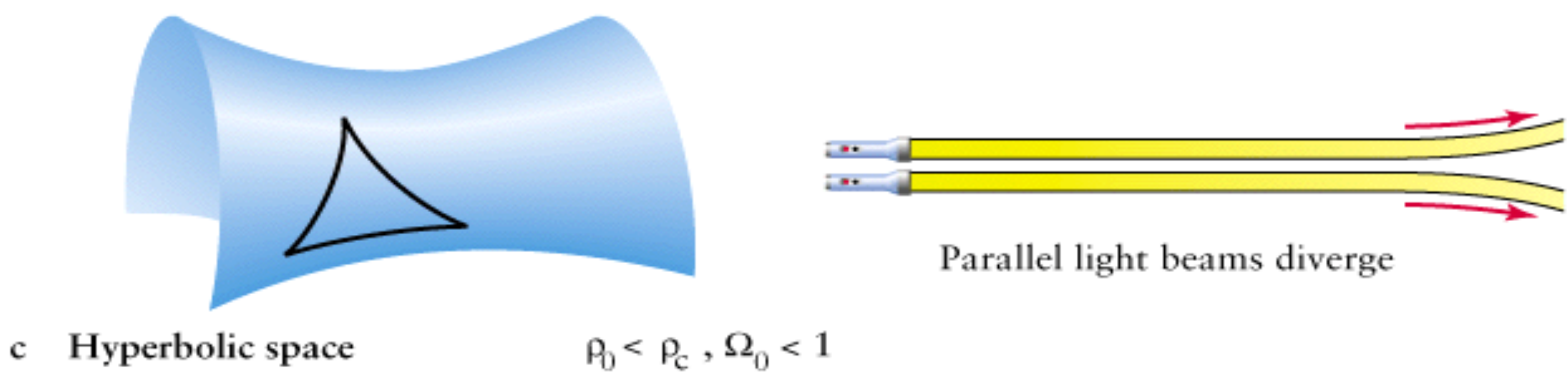
b Flat space $\rho_0 = \rho_c$, $\Omega_0 = 1$

Parallel light beams remain parallel

2. The beams might converge, if space is *curved positively*. 2D analog is sphere.



3. They could diverge, if space is *curved negatively*, or saddle (hyperbolic).



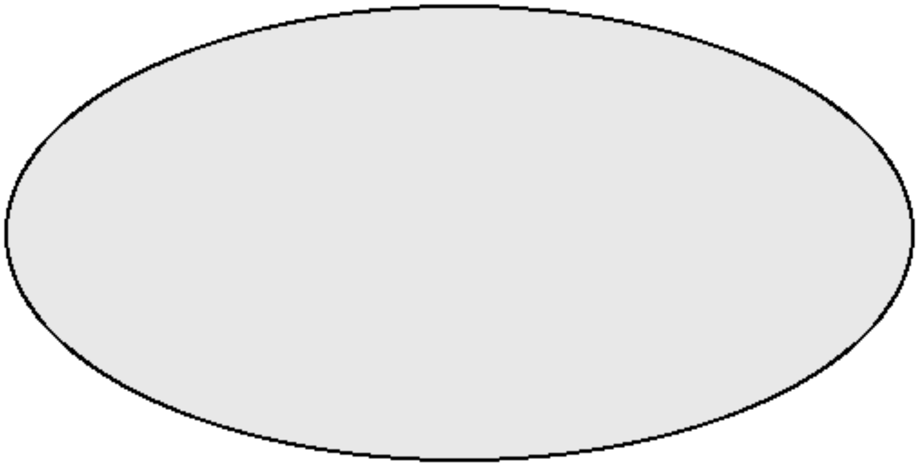
The density parameter Ω_0

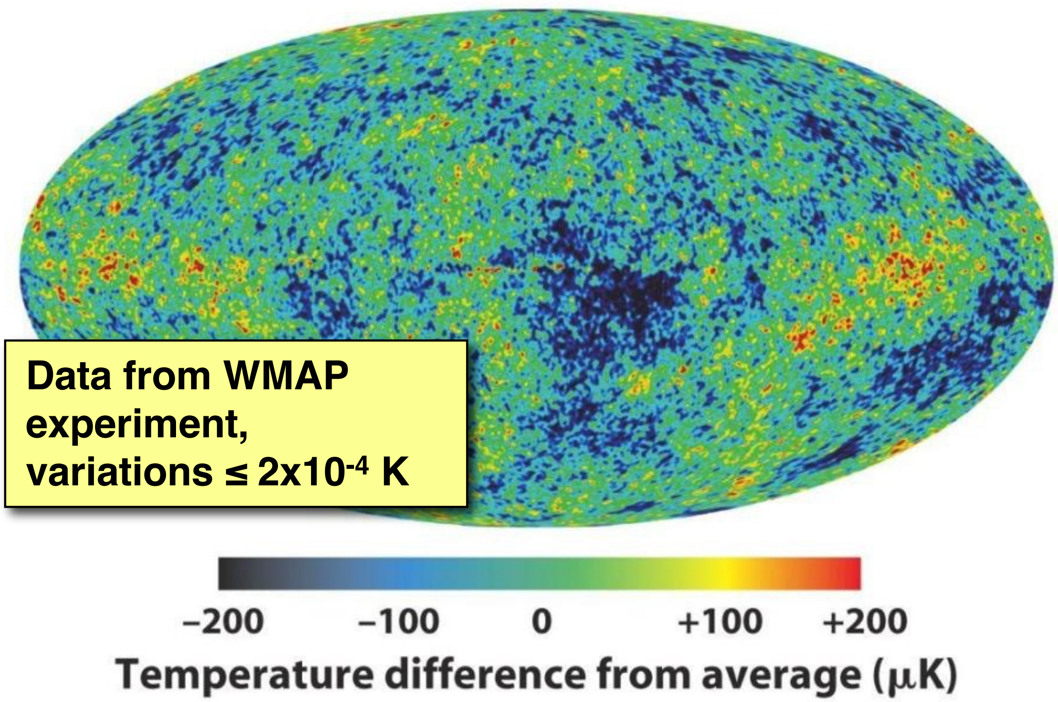
- The geometry of the Universe depends on the total density of matter and energy.
- The curvature says how real mass/energy density, ρ_0, compares to the *critical* density, ρ_c, which is the case of a flat universe.
- Density parameter:

$$\Omega_0 = \frac{\rho_0}{\rho_c}$$

This would be = 1 for a flat universe, >1 for a positively curved universe and <1 for a negatively curved universe.

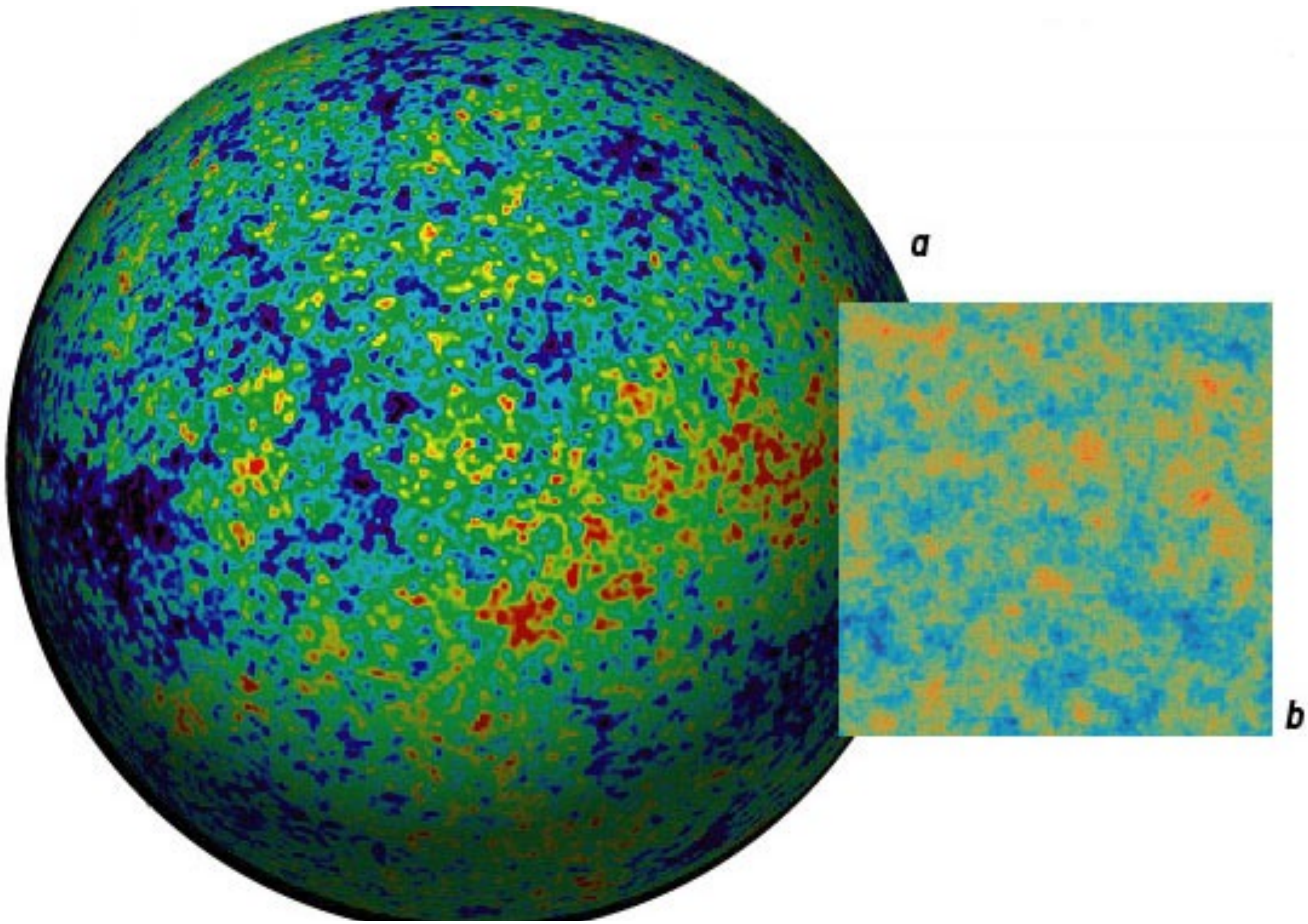
Clues from the CMBR



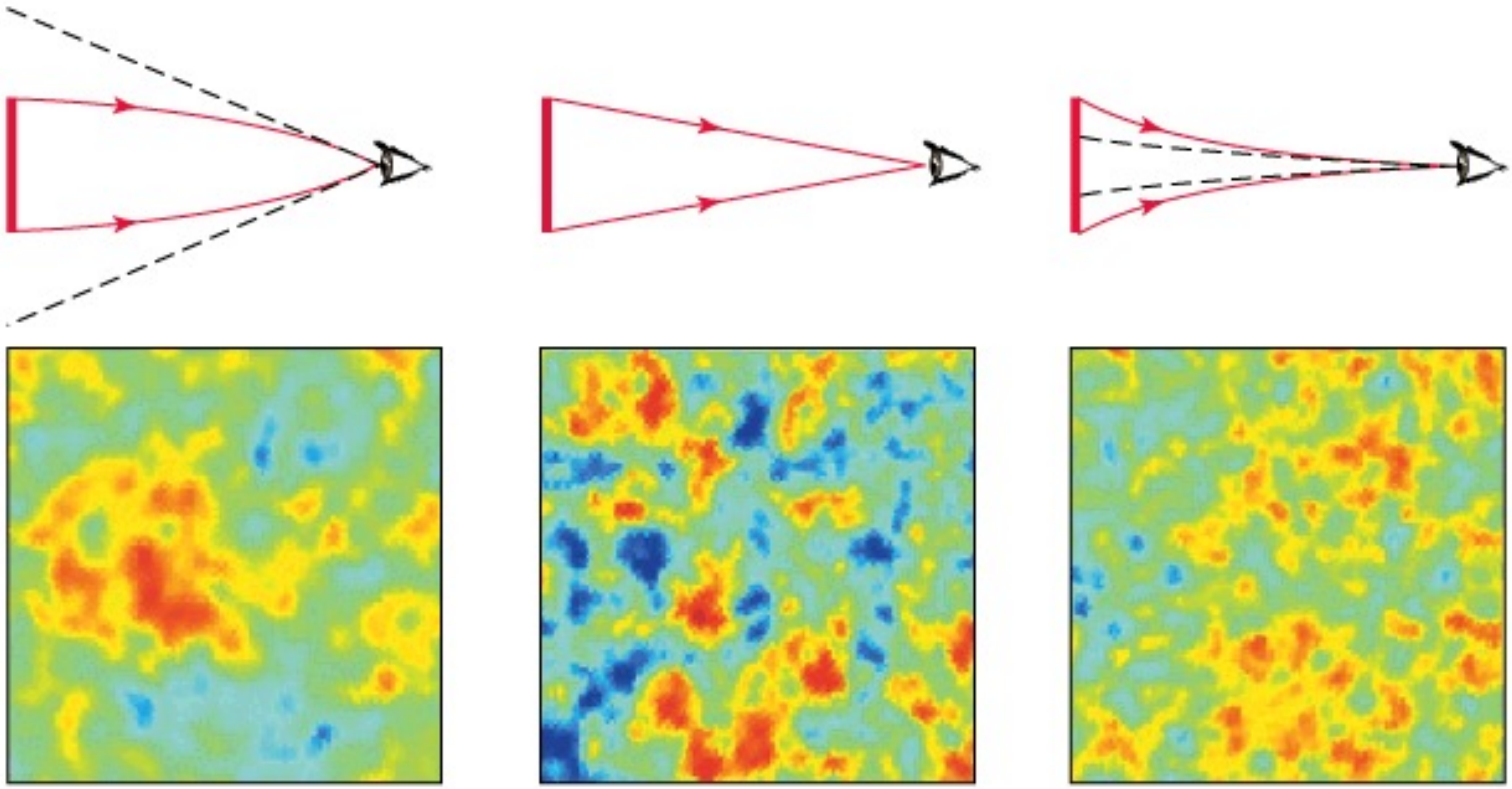


Data from WMAP experiment, variations ≤ $2x10^{-4}$ K

- Inhomogeneities in the CMBR are "hot spots" and "cold spots" due to density fluctuations in gas at the time of decoupling.
- Higher ρ cooler,
  lower ρ hotter.
- Physical size of hot spot is balance of gravity and radiation pressure.



Hu and White 2004



a If universe is closed, "hot spots" appear larger than actual size

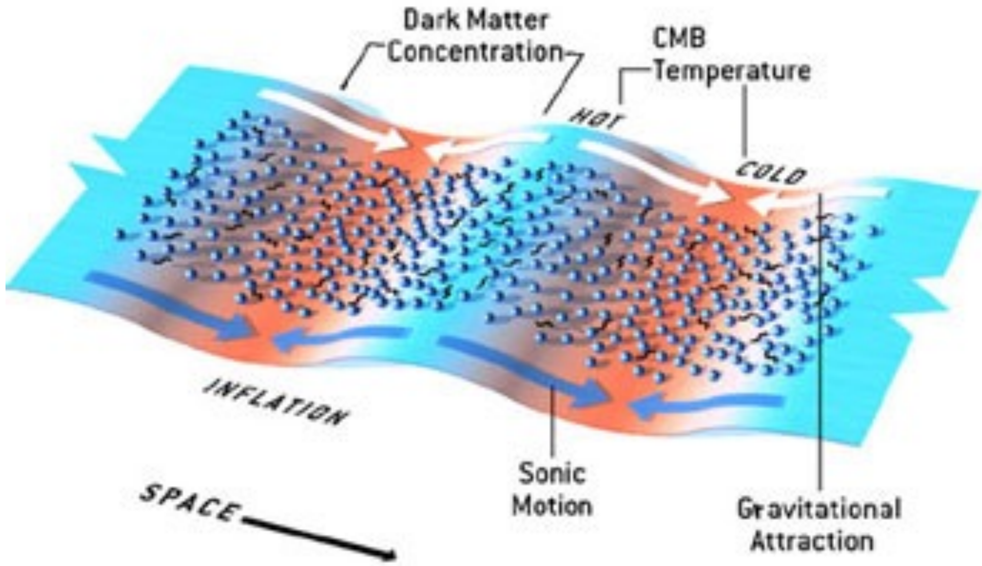
b If universe is flat, "hot spots" appear actual size

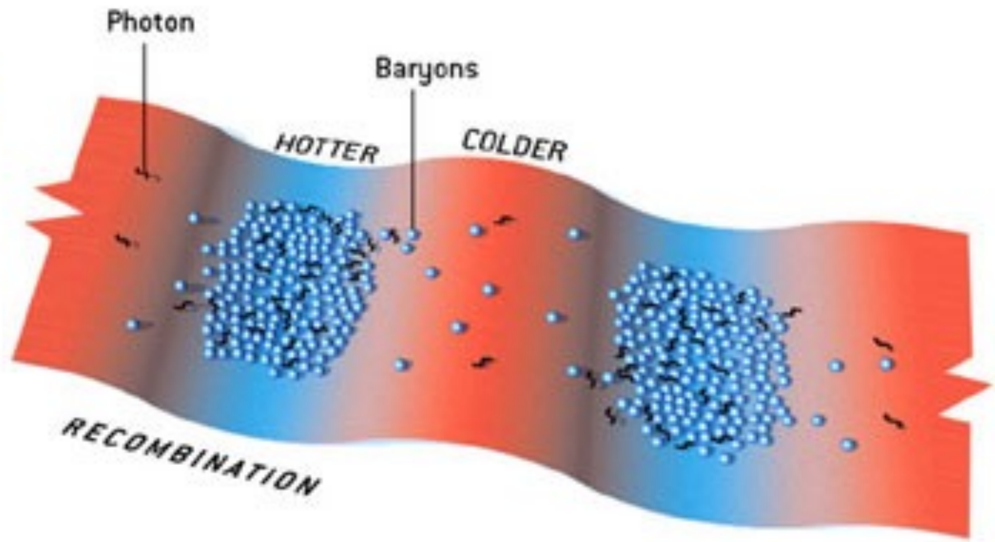
c If universe is open, "hot spots" appear smaller than actual size

Apparent size of spots depends on curvature of space.

See also Wayne Hu's tutorials

http://background.uchicago.edu/~whu/intermediate/angular4.html



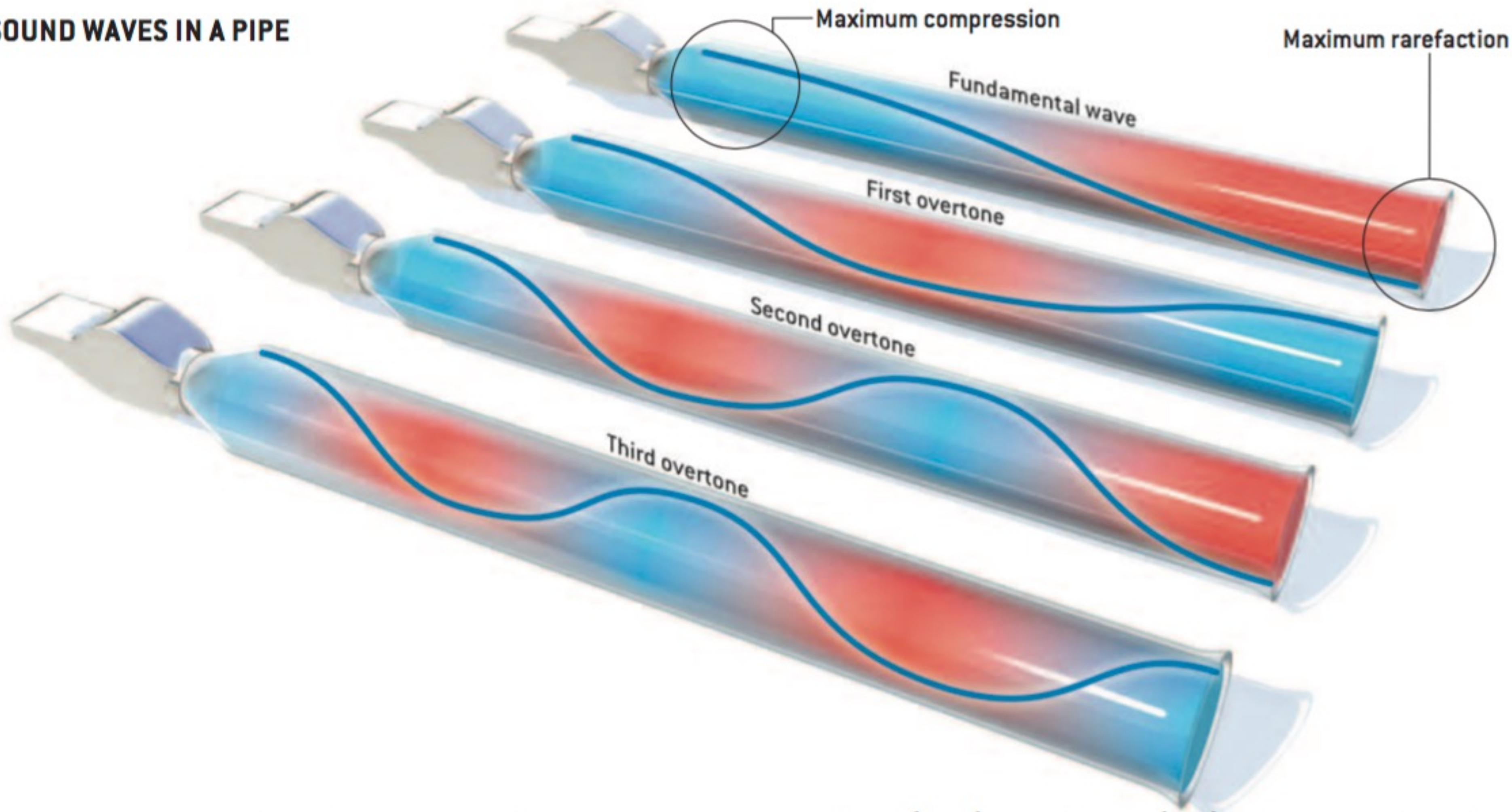


Hu and White 2004

COSMIC HARMONICS

THE SOUND SPECTRUM of the early universe had overtones much like a musical instrument's. If you blow into a pipe, the sound corresponds to a wave with maximum air compression (*blue*) at the mouthpiece and maximum rarefaction (*red*) at the end piece. But the sound also has a series of overtones with shorter wavelengths that are integer fractions of the fundamental wavelength. (The wavelengths of the first, second and third overtones are one half, one third and one fourth as long.)

SOUND WAVES IN A PIPE



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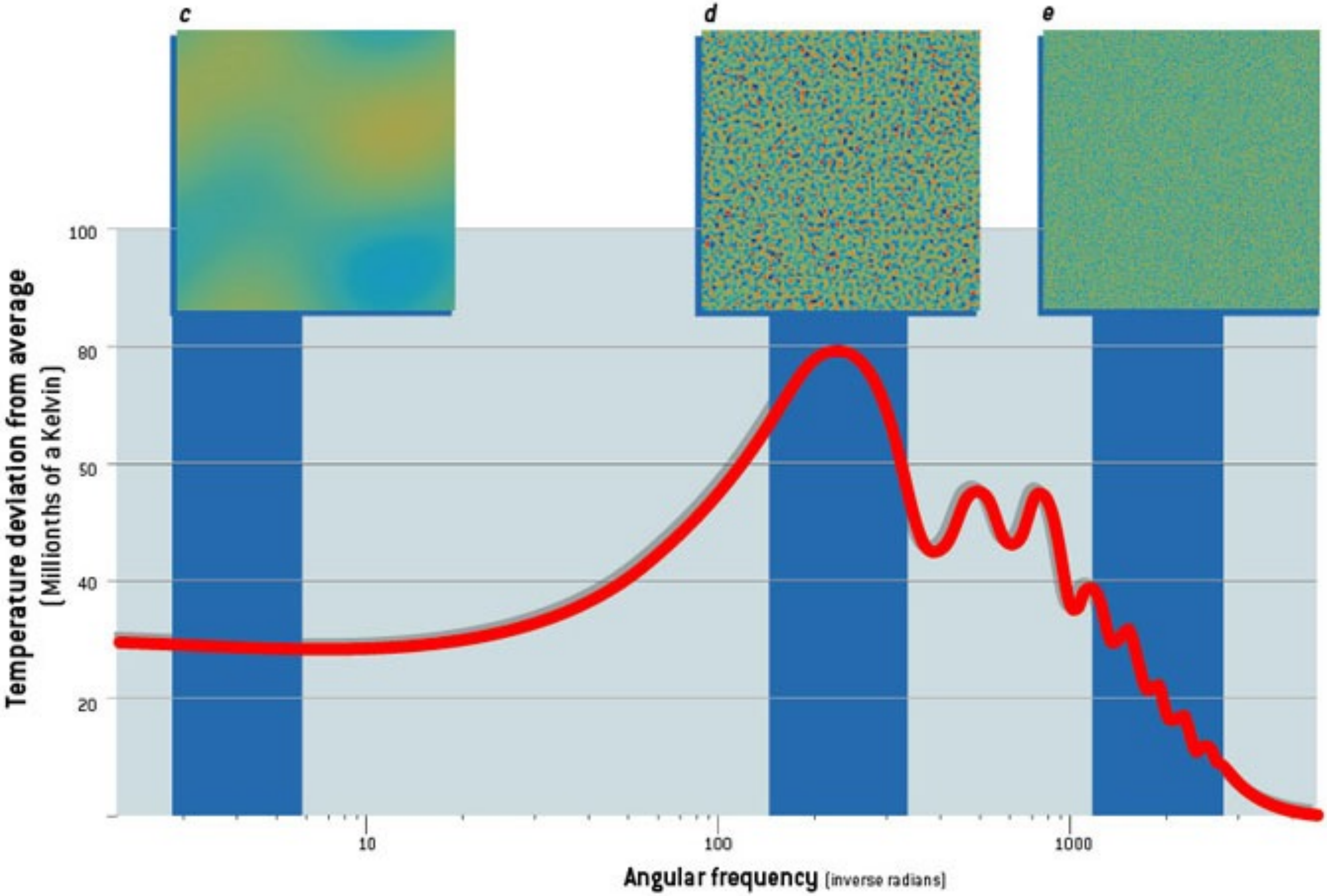

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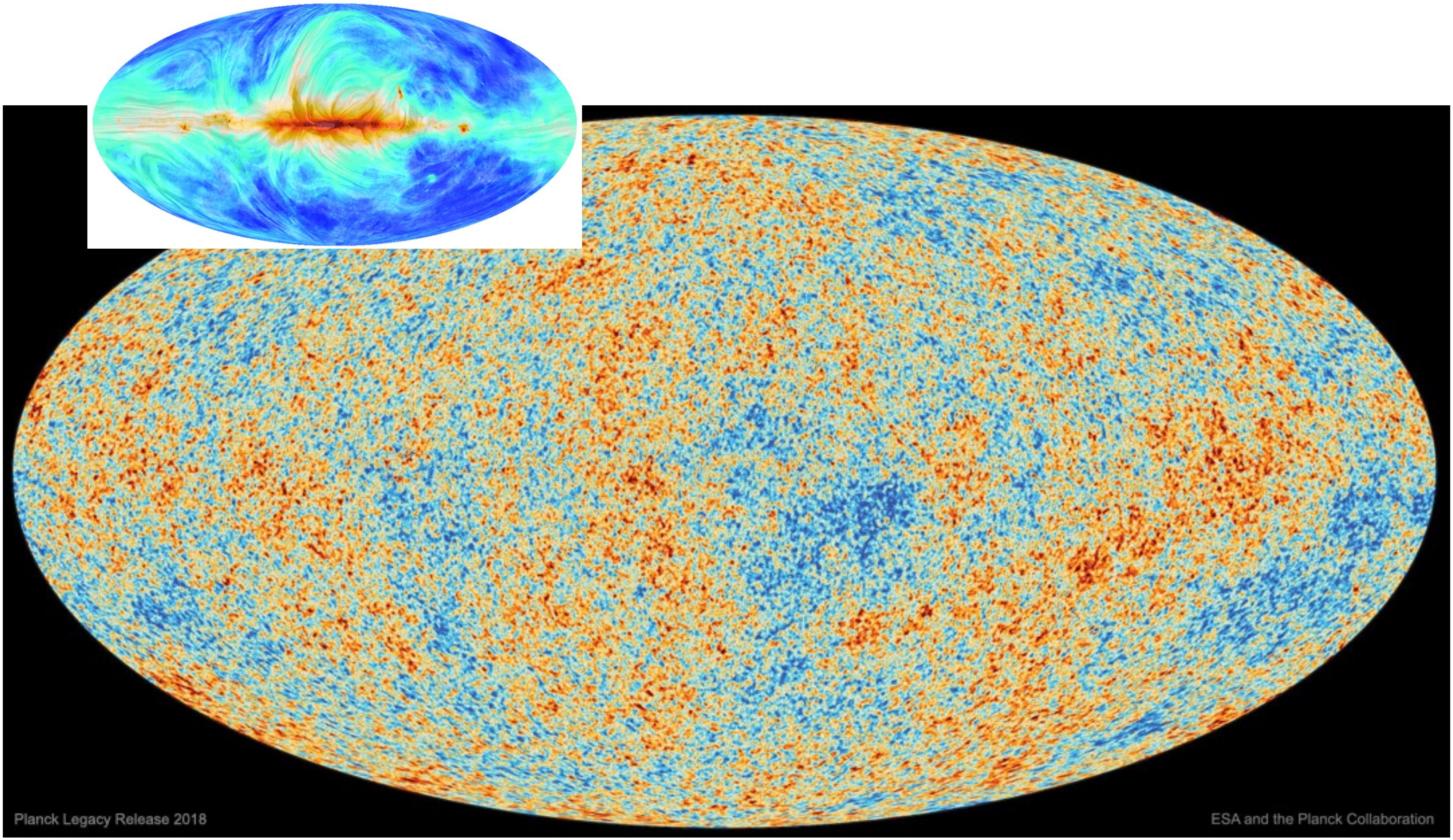
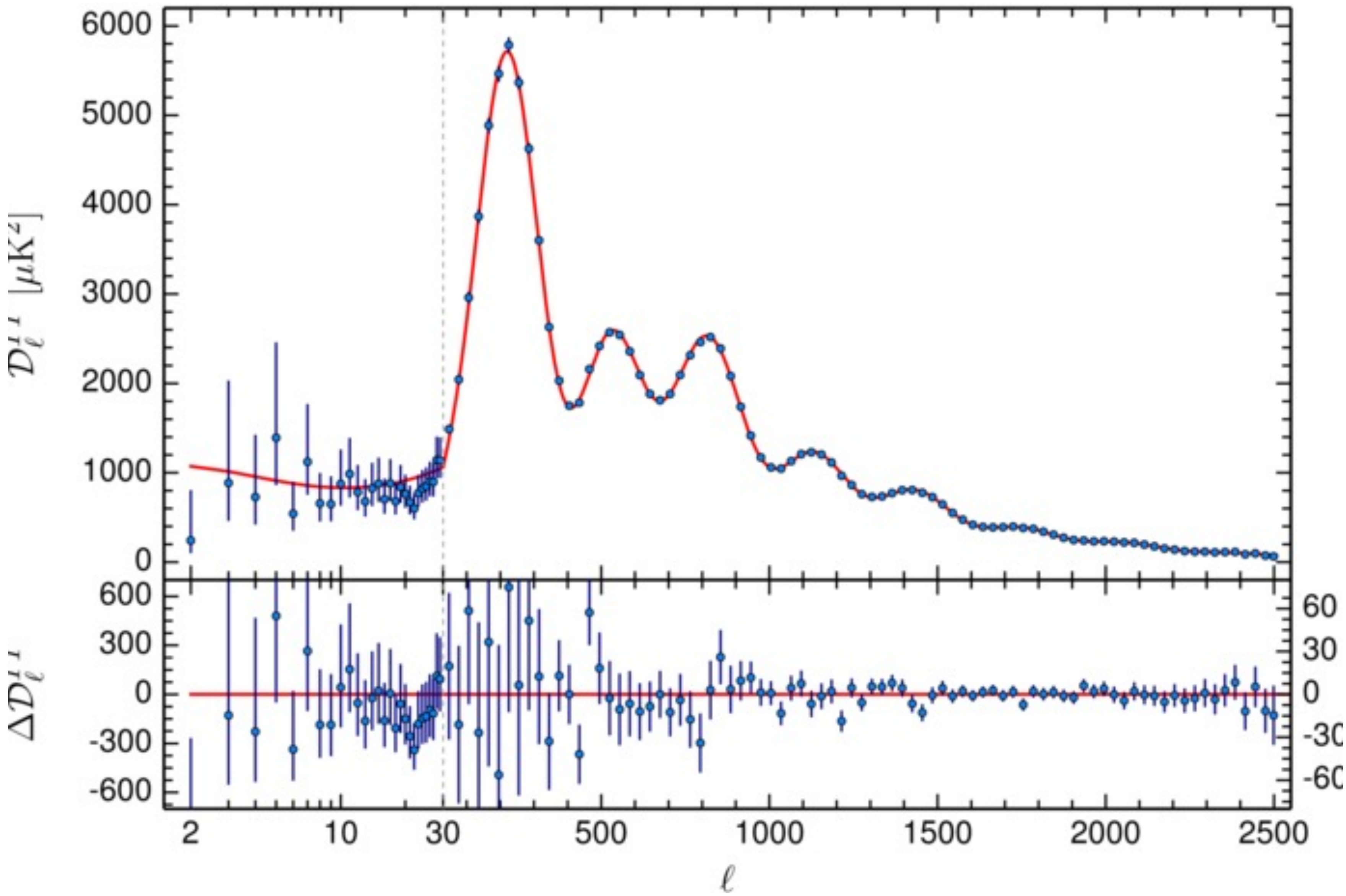
Planck and Precision Cosmology



Planck and Precision Cosmology



Planck and Precision Cosmology ΛCDM

- 6 parameters
  - 2 primordial spectrum $\mathcal{P}_{\mathcal{R}}(k) = \boxed{A_s}\left(\frac{k}{k_0}\right)^{\boxed{n_s}-1}$
  - 1 expansion rate $\boxed{H_0}$
  - 2 paramaters for densities $\boxed{\Omega_b h^2}$ $\boxed{\Omega_c h^2}$
  - reionization $\boxed{\tau}$
- Hypothesis (relaxed for extension)
  - Flat Universe $\Omega_k = 0$
  - No running $dn_s/d\ln k = 0$
  - No tensor $\mathcal{P}_t(k) = A_t\left(\frac{k}{k_0}\right)^{n_t} = 0$
  - 3 neutrinos species $N_{eff} = 3$
  - Standard neutrinos with low mass $\sum m_\nu = 0.06\ eV$

Planck and Precision Cosmology ΛCDM

- 6 parameters
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  - 1 expansion rate $\boxed{H_0}$
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  - reionization $\boxed{\tau}$

TABLE 6
MEAN AND MAXIMUM LIKELIHOOD COSMOLOGICAL PARAMETERS

Parameter	*WMAP* mean	*Planck* mean[a]	*WMAP* m.l.[b]	*Planck* m.l.[c]	*WMAP*−*Planck* m.l.[d]	
$\Omega_b h^2$	0.02264 ± 0.00050	0.02205 ± 0.00028	0.02262	0.02194	0.00068 ± 0.00050	(1.4σ)
$\Omega_c h^2$	0.1138 ± 0.0045	0.1199 ± 0.0027	0.1139	0.1220	-0.0081 ± 0.0049	(1.7σ)
H_0 [km s^{-1} Mpc^{-1}]	70.0 ± 2.2	67.3 ± 1.2	70.0	66.8	3.2 ± 2.3	(1.4σ)
n_s	0.972 ± 0.013	0.9603 ± 0.0073	0.974	0.953	0.020 ± 0.014	(1.4σ)
$10^9 A_{s,0.05}$[e]	2.203 ± 0.067	2.196 ± 0.055	2.203	2.200	0.004 ± 0.042	(0.1σ)
τ	0.089 ± 0.014	$0.089^{+0.012}_{-0.014}$	0.0875	0.0873	0.0002 ± 0.0031	(0.1σ)

Planck and Precision Cosmology

Parameter	*Planck* (CMB+lensing) Best fit	68 % limits	*Planck*+WP+highL+BAO Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025
Ω_Λ	0.6964	0.693 ± 0.019	0.6914	0.692 ± 0.010
σ_8	0.8285	0.823 ± 0.018	0.8288	0.826 ± 0.012
z_{re}	11.45	$10.8^{+3.1}_{-2.5}$	11.52	11.3 ± 1.1
H_0	68.14	67.9 ± 1.5	67.77	67.80 ± 0.77
Age/Gyr	13.784	13.796 ± 0.058	13.7965	13.798 ± 0.037
$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

A flat universe

- By measuring the spot sizes, it appears that space is flat, or very nearly so. This would mean $\Omega_0 = 1$.

- Problem: the mass density of the universe is measured to be 2.4×10^{-27} kg/m^3 (including dark matter). The critical density from theory is 1×10^{-26} kg/m^3. This matter density parameter, Ω_m, is

$$\Omega_m = \frac{\rho_m}{\rho_c} = 0.24$$

- But total Ω_0 is 1: we have missing density.

Missing density

- Must be some energy we cannot detect via gravitational effects, and it cannot emit detectable radiation.

- Dark energy density parameter:

and $$\Omega_\Lambda = \frac{\rho_\Lambda}{\rho_c}$$

- Therefore, dark energy accounts for 76% of the Universe's mass/energy density.

$$\Omega_0 = \Omega_m + \Omega_\Lambda = 1$$