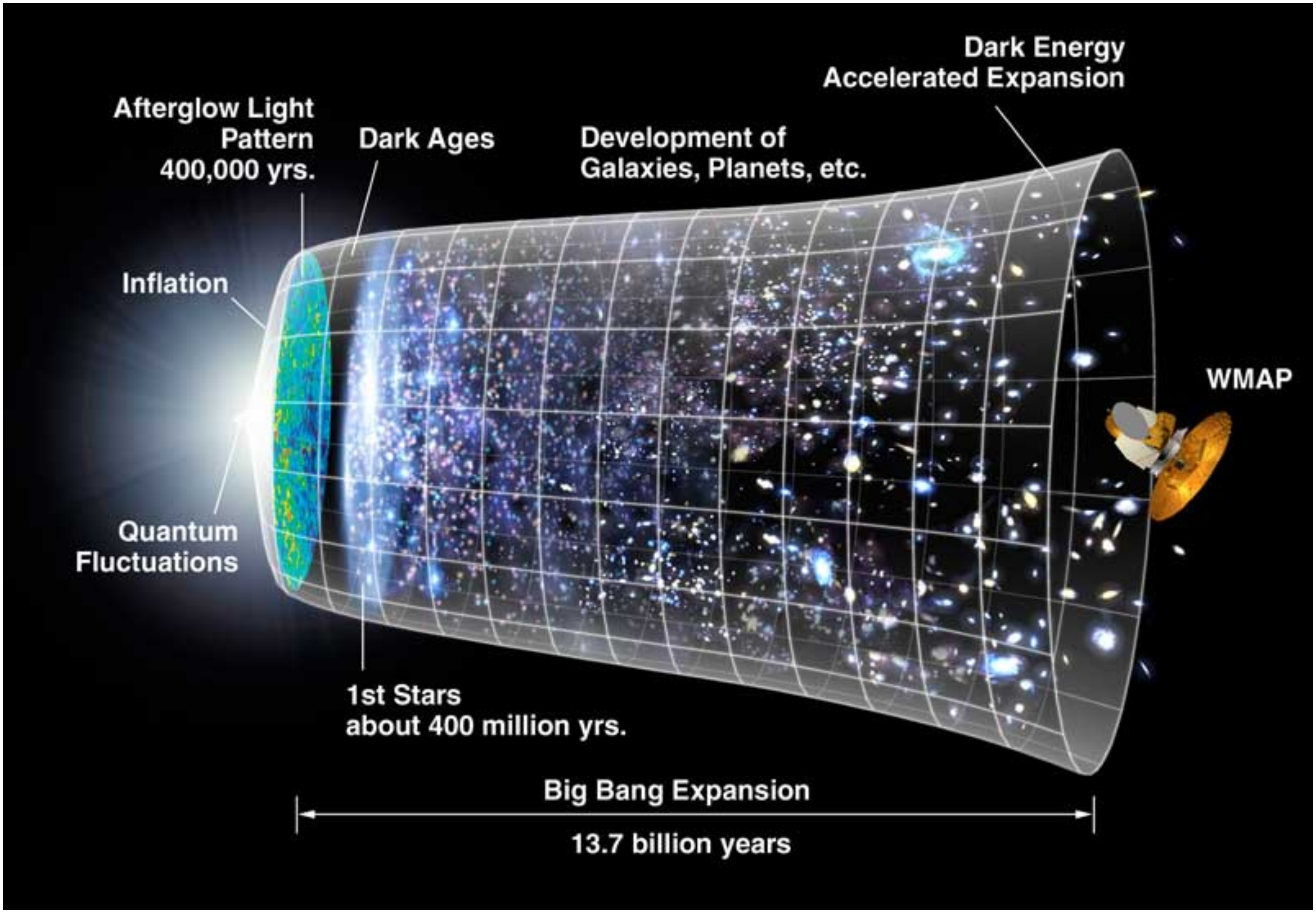
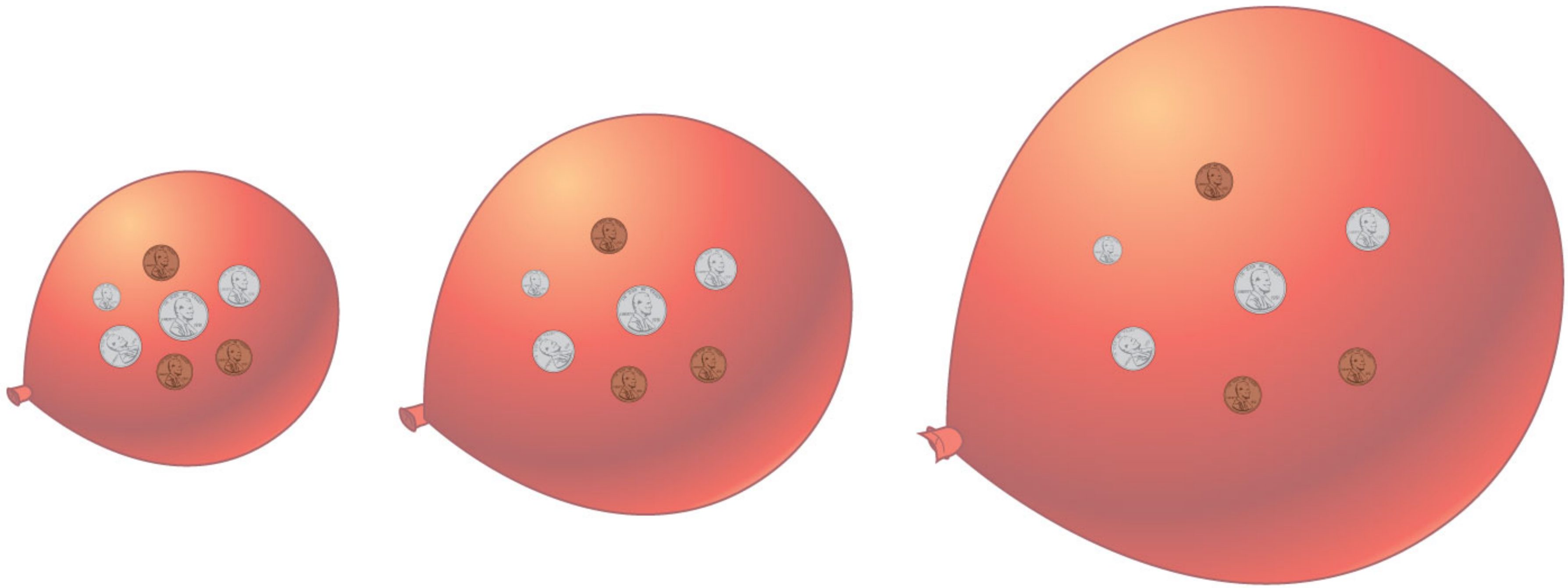
The Big Bang and Cosmology



C&M Chaps. 26, 27

Excellent article: http://www.sciencemag.org/content/284/5419/1481.full

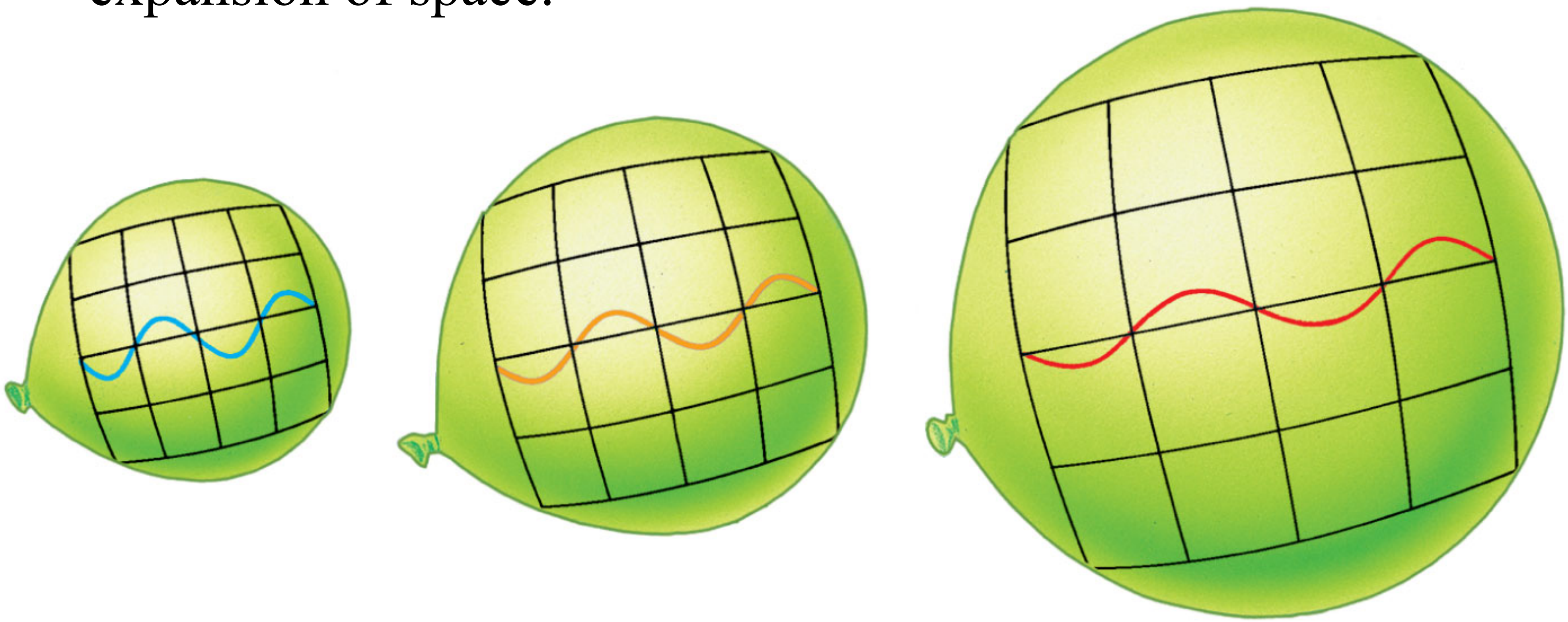
A few mis-conceptions!



Seeing everything receding does not imply we are at the centre!

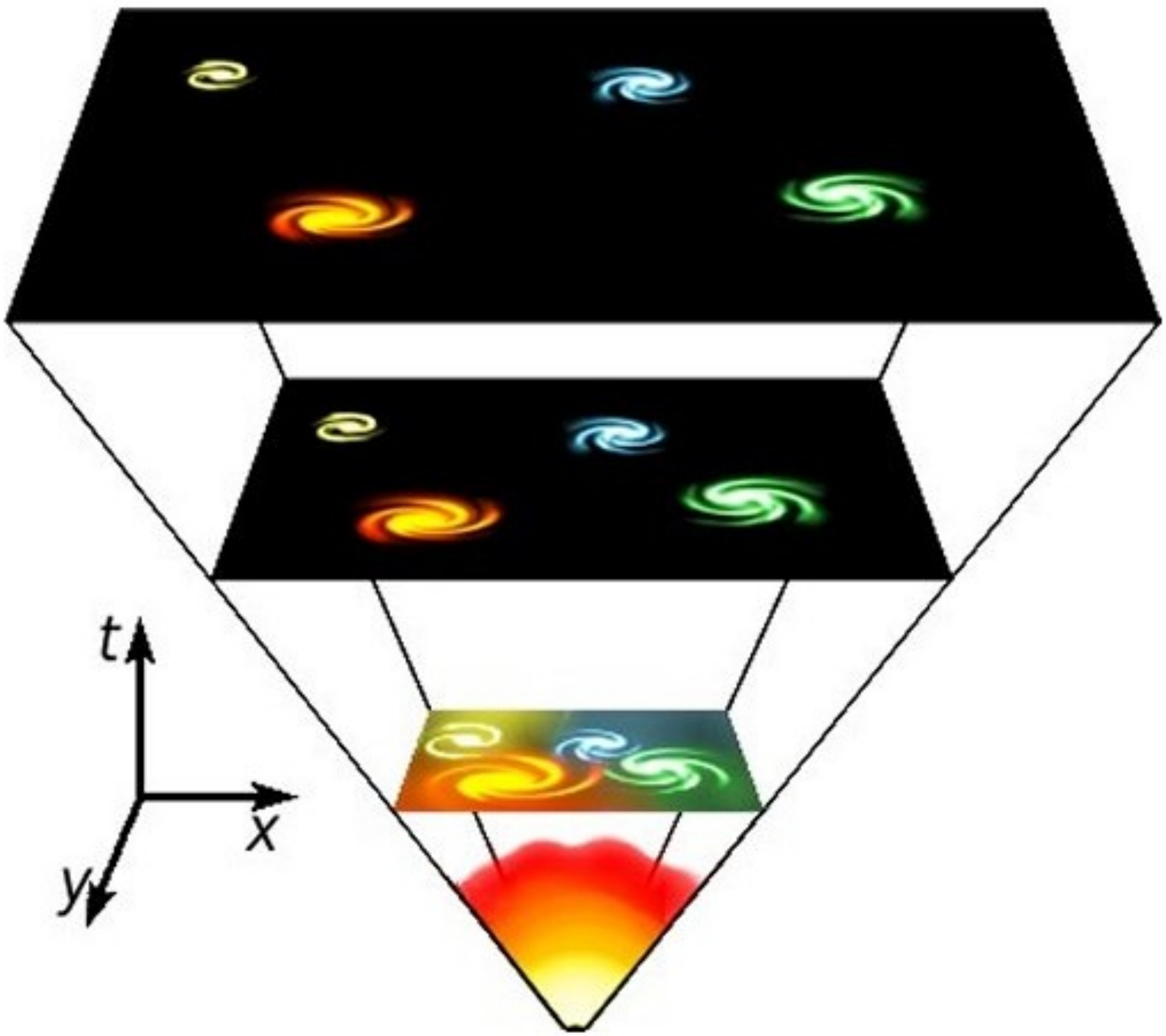
A few mis-conceptions!

Redshift is not a classical Doppler shift. It is caused by the expansion of space.

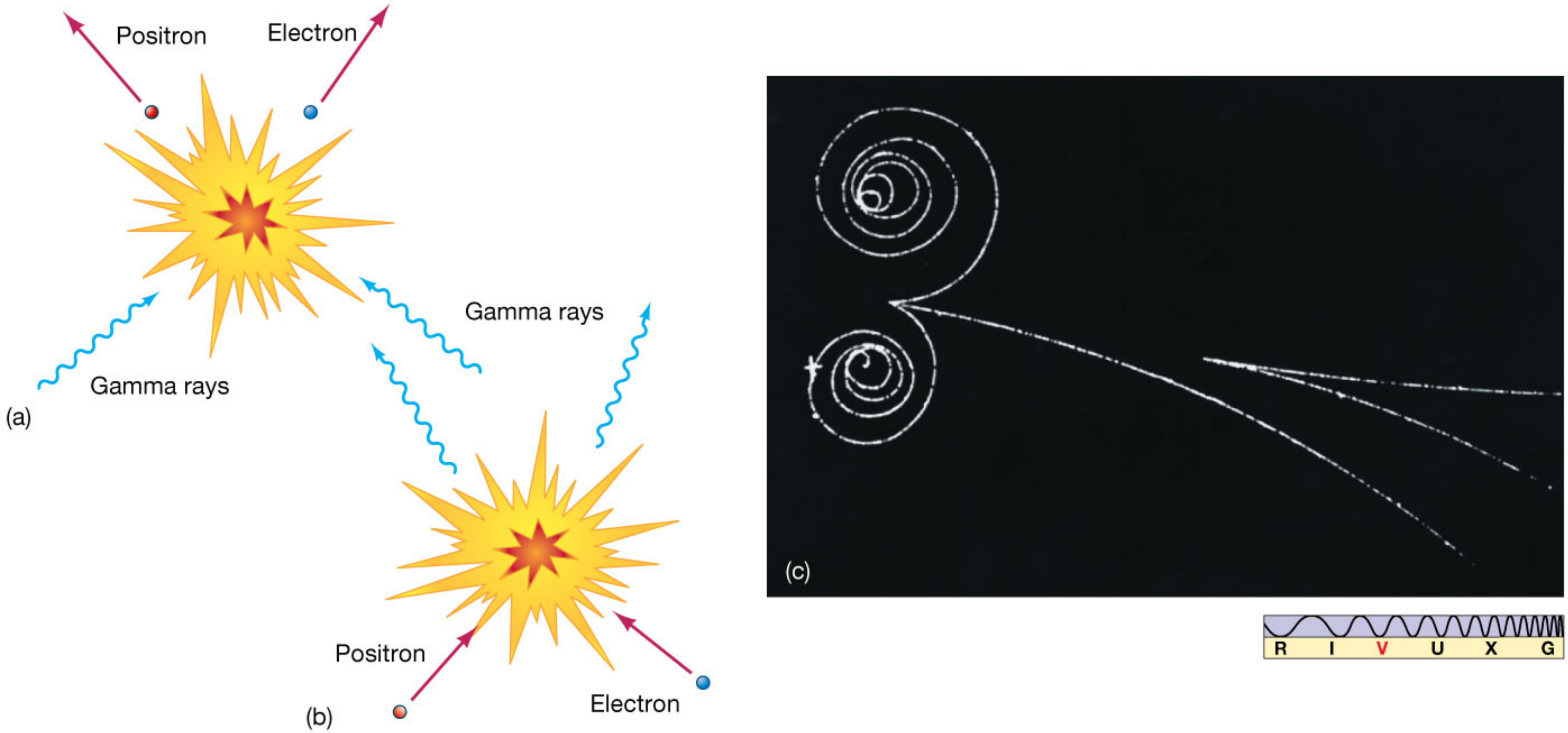


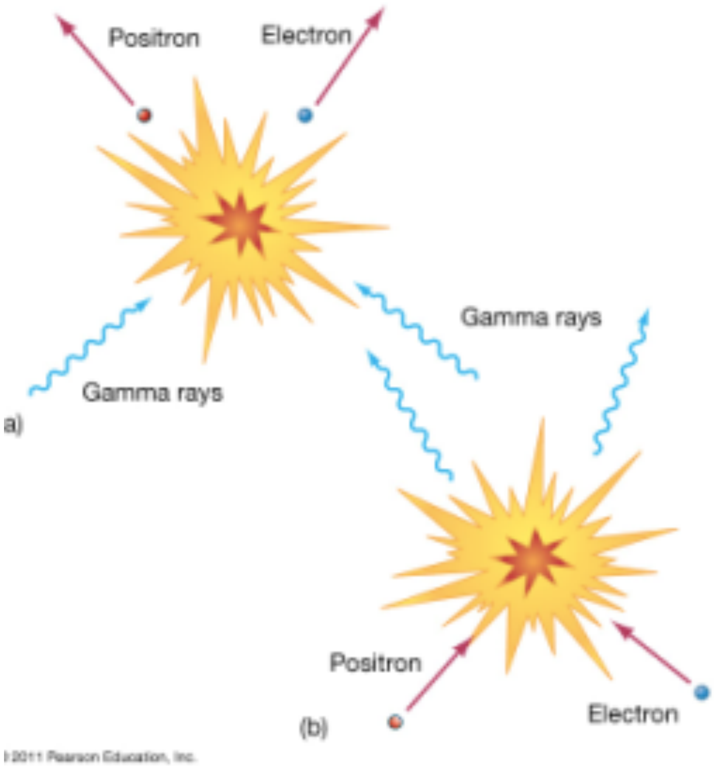
Note: as universe grows, so wavelength increases

Hubble's law implies an expanding universe: dramatic corollary that universe was smaller in the past and started with a "Big Bang".



Matter production in the early universe





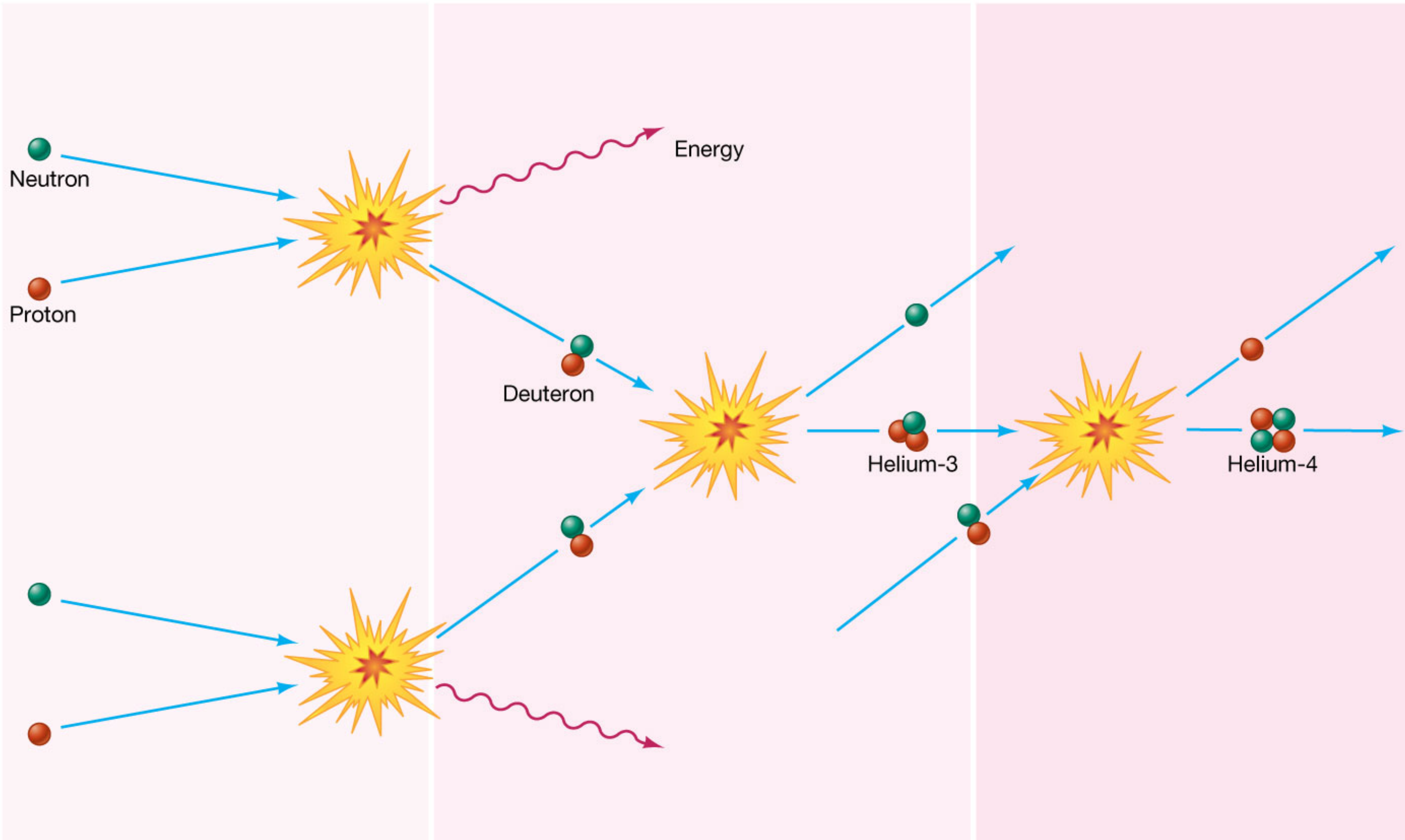
Example: Given that two photons are needed to produce the 2 particles in a pair, how much energy is needed for each photon in proton - anti-proton pair production?

Mass of proton = 1.67×10^{-27} kg

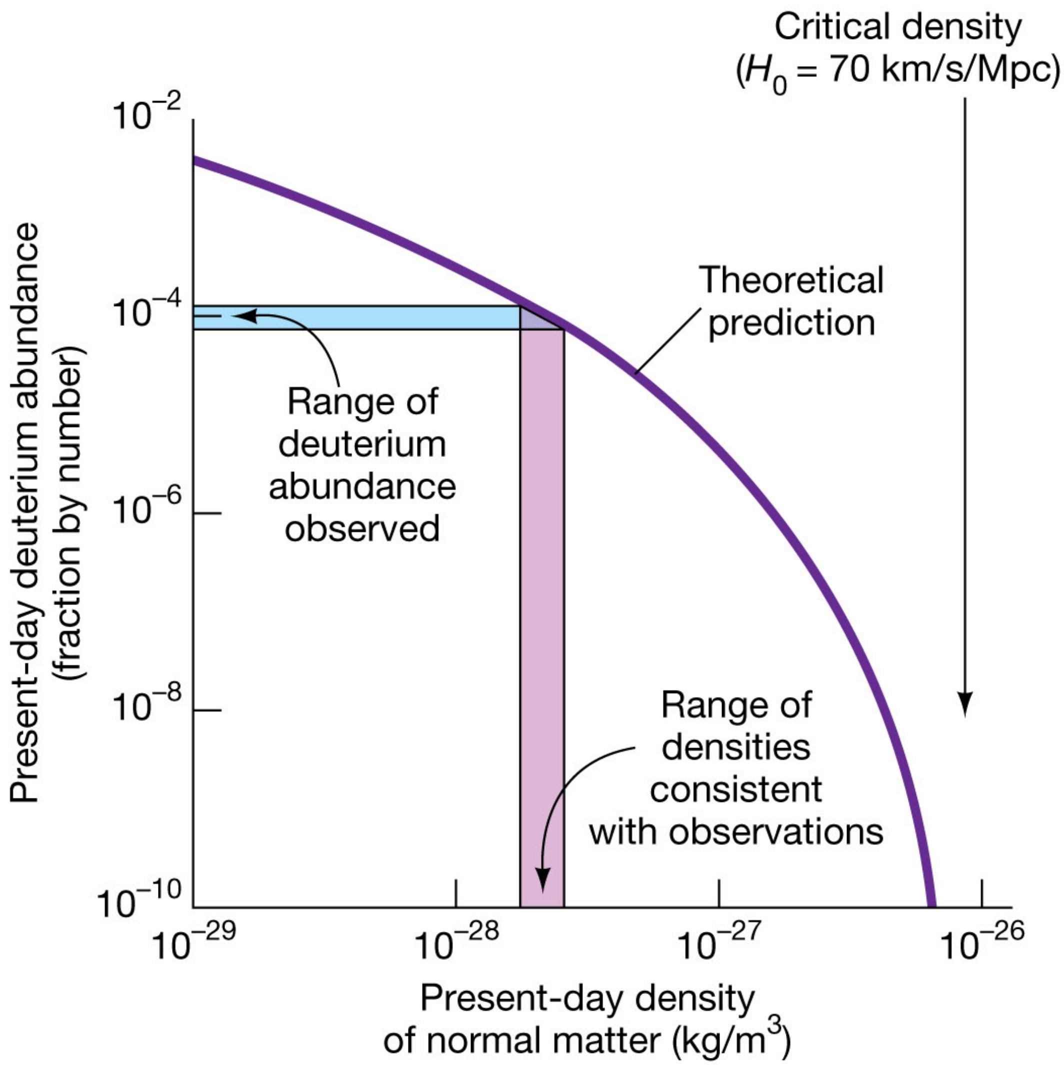
$E = m c^2$

$E = 1.67 \times 10^{-27} \times (3 \times 10^{8})^2$

$E = 1.5 \times 10^{-10}$ Joules

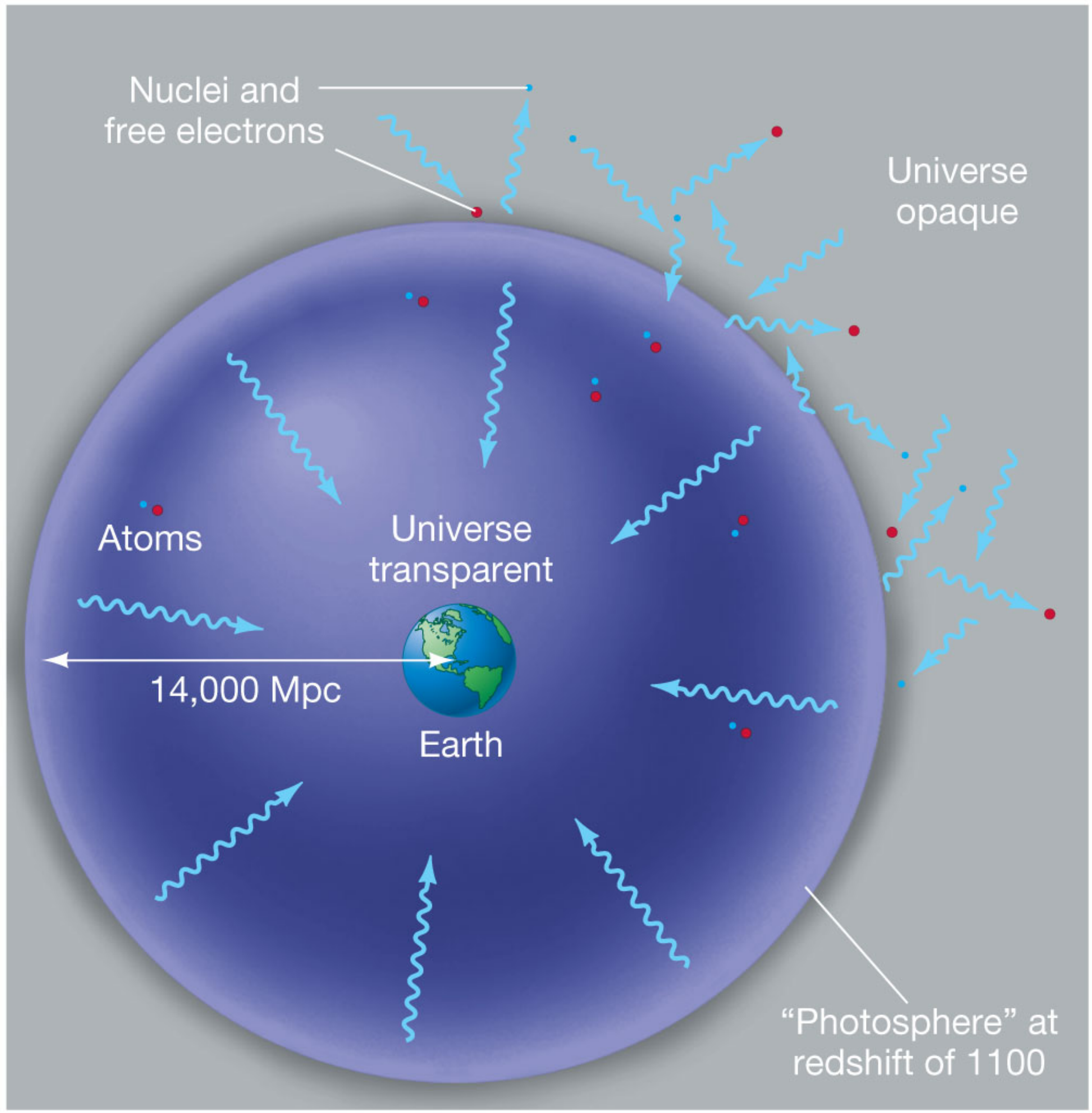

Energy
Neutron
Proton
Deuteron
Helium-3
Helium-4

The importance of deuterium



Measuring the abundance of deuterium tells us how much (normal) matter there is in the universe!

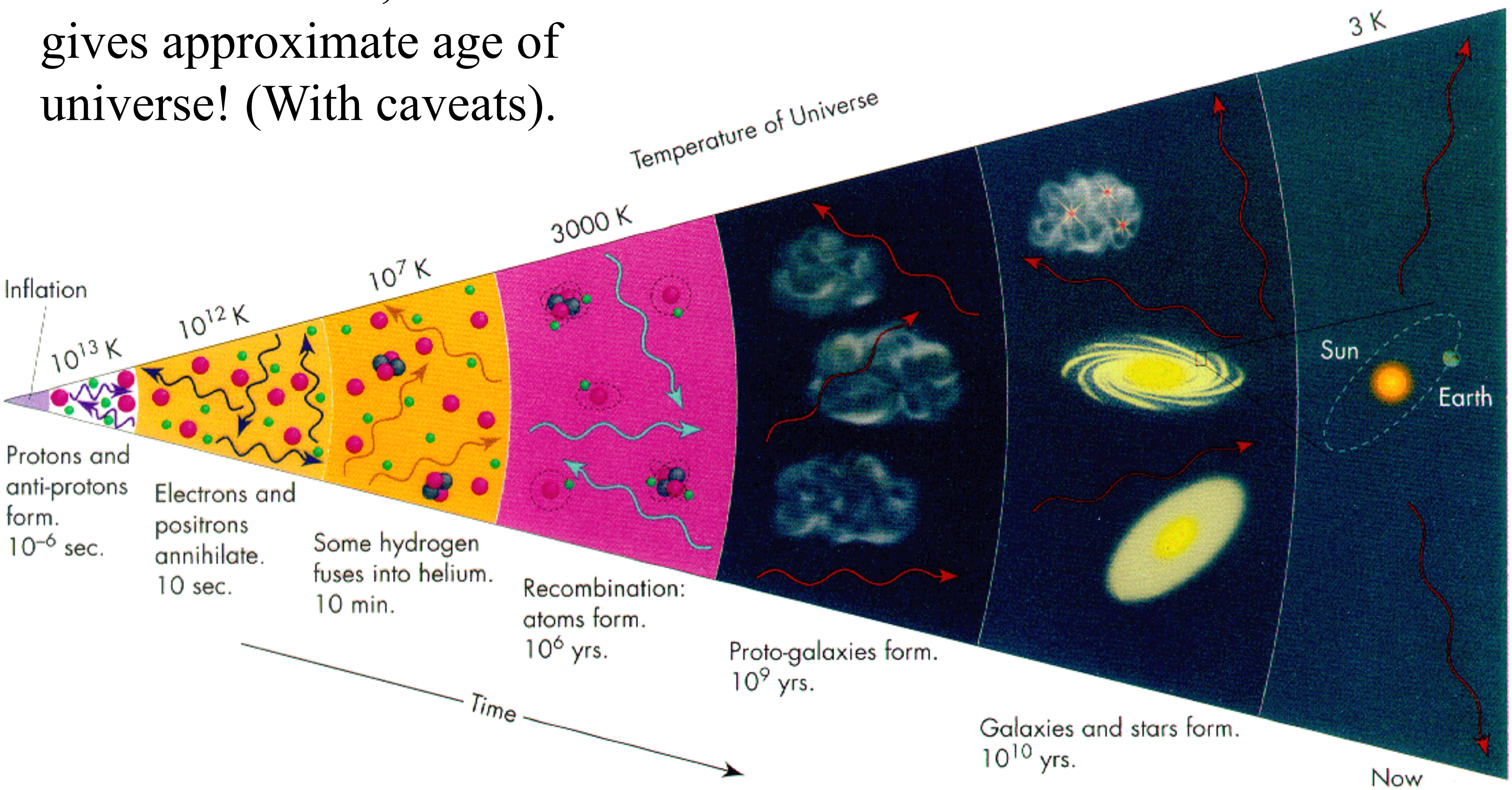
At a redshift z~1100 the universe has cooled to ~3000K. Protons, neutrons and electrons make atoms: "recombination" . Matter and light de-couple and Universe becomes transparent.



Cosmological implications of an expanding Universe

Age of the universe:

t= d/v and v=Hd, so t=1/H gives approximate age of universe! (With caveats).



Example: The current best estimate from WMAP satellite is $H_0 = 73$ km/s/Mpc. What does this imply for the maximum age of the Universe?

Convert units of H_0: 1 Mpc = 3.09×10^{19} km

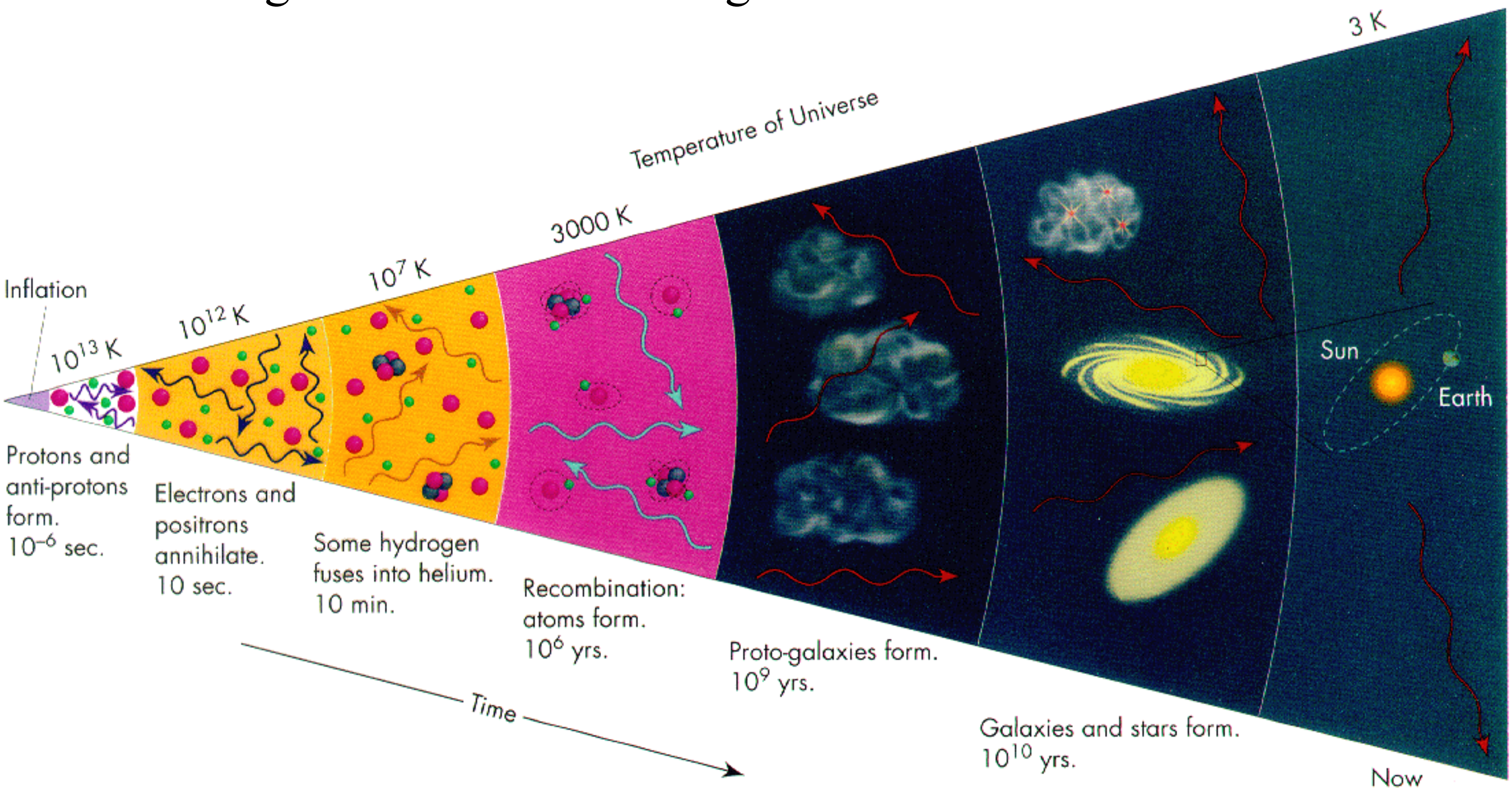
1 km/Mpc = $1/ 3.09 \times 10^{19} = 3.23 \times 10^{-20}$

$H_0 = 73 \times 3.23 \times 10^{-20}\ s^{-1}$
$= 2.36 \times 10^{-18}\ s^{-1}$

$T = 1/H$
$= 1/ 2.36 \times 10^{-18}$
$= 4.24 \times 10^{17}$ s
$= 1.34 \times 10^{10}$ yr
= 13.4 billion years

Cosmological implications of an expanding Universe

Size of the universe: Light stretched during expansion, so change in wavelength tells us about change in size.



Recall that redshift is defined as the change in wavelength relative to rest-frame value:

$$z = \Delta\lambda / \lambda_{rest}$$

$$1 + z = \frac{\Delta\lambda + \lambda_{rest}}{\lambda_{rest}}$$

$$1 + z = \lambda_{obs} / \lambda_{rest}$$

Since size of universe is proportional to wavelength. If R_0 is current size of universe and R is size when light was emitted:

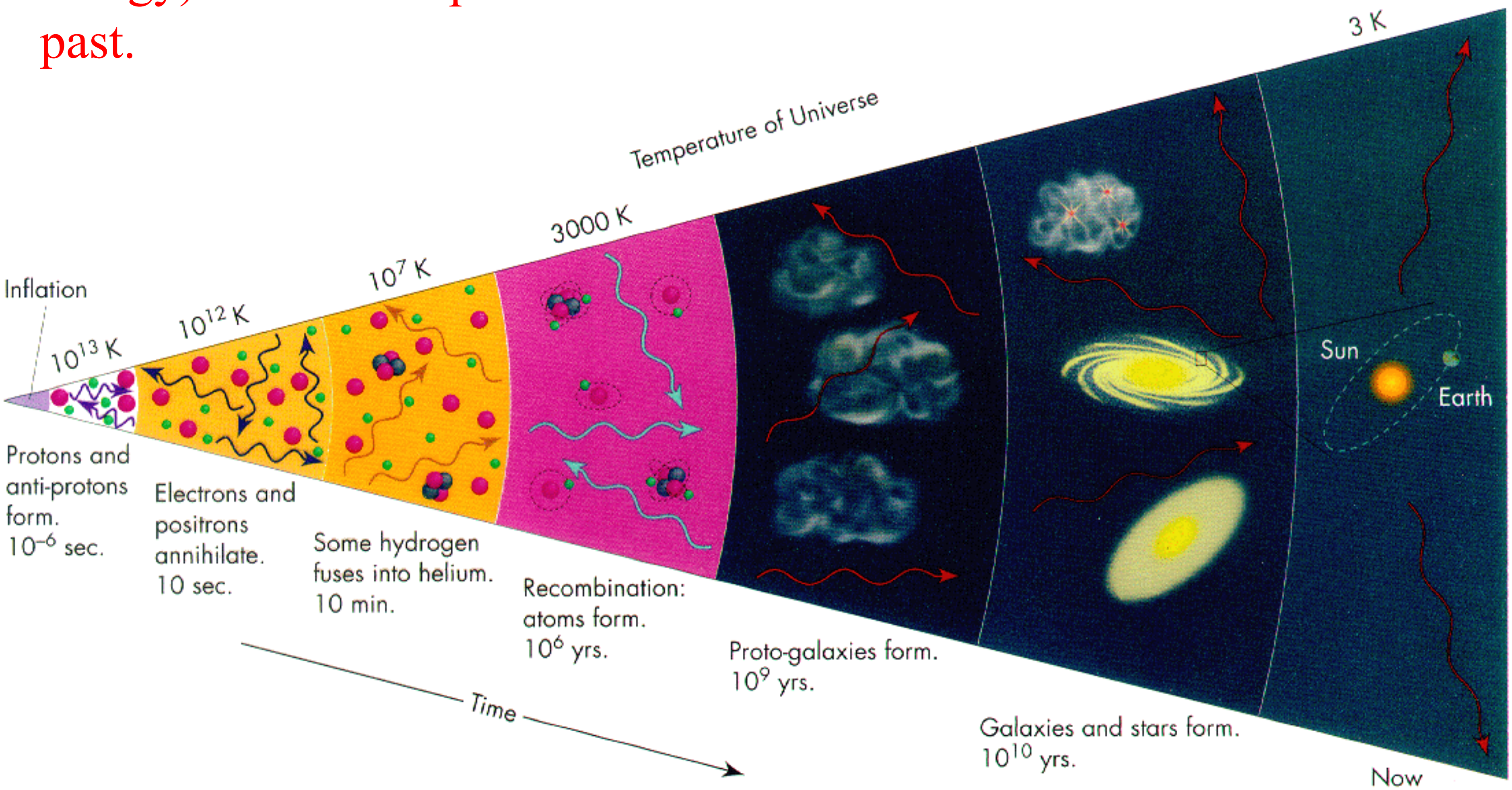
$$R/R_0 = \frac{\lambda_{rest}}{\lambda_{obs}} = \frac{1}{1+z}$$

Example: Observe a galaxy spectrum. Na I 589.0 nm is observed at 689.0nm. What is z? What is size of Universe (relative to now) when light was emitted?

Ans: $z = \Delta\lambda / \lambda = 100 / 589 = 0.170$. Size of Universe relative to present is 1/(1+0.17)=0.855 relative to present.

Cosmological implications of an expanding Universe

The universe has a temperature (measure of energy) and the temperature was hotter in the past.



Temperature is proportional to radiation energy:

$$T \propto E = \frac{hc}{\lambda}$$

Planck's constant:
h=6.626068 x 10^{-34} m^2 kg / s

$$E = \frac{hc}{\lambda_{rest}}$$

Energy when photon emitted

$$E = \frac{hc}{\lambda_{obs}/(1+z)}$$

Energy observed now, E_0

$$E = \frac{hc}{\lambda_{obs}}(1+z)$$

$$E = E_0(1+z)$$

$$\rightarrow T = T_0(1+z)$$

Universe was smaller, hotter, denser in the past!

Fossil radiation from the hot Big Bang

At recombination, which occurs at z~1100, T~3000 K.

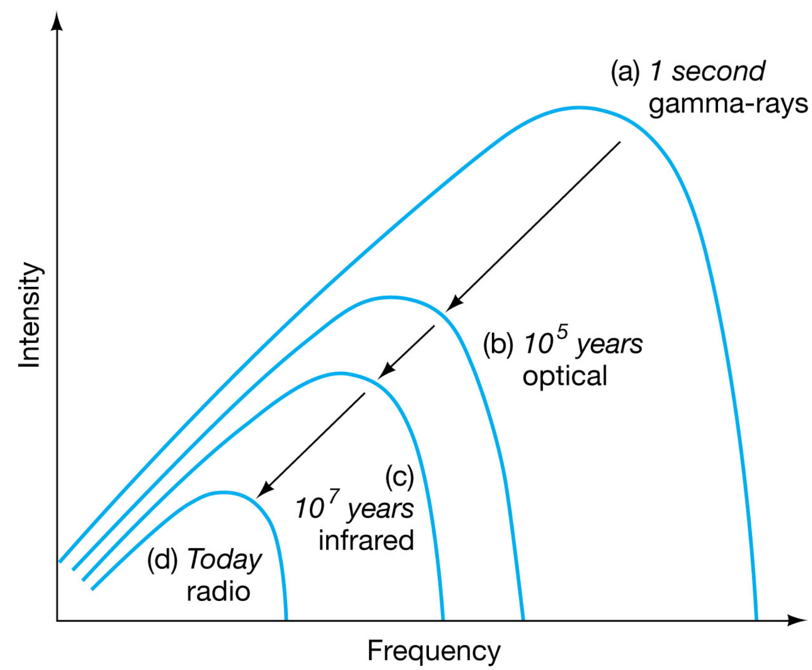
$T_0 = T/(1+z)$
$= 3000 / (1101)$
~ 2.7 K

The current temperature of the universe is about 2.7 K. Treating the universe as a blackbody, from Wien's law:

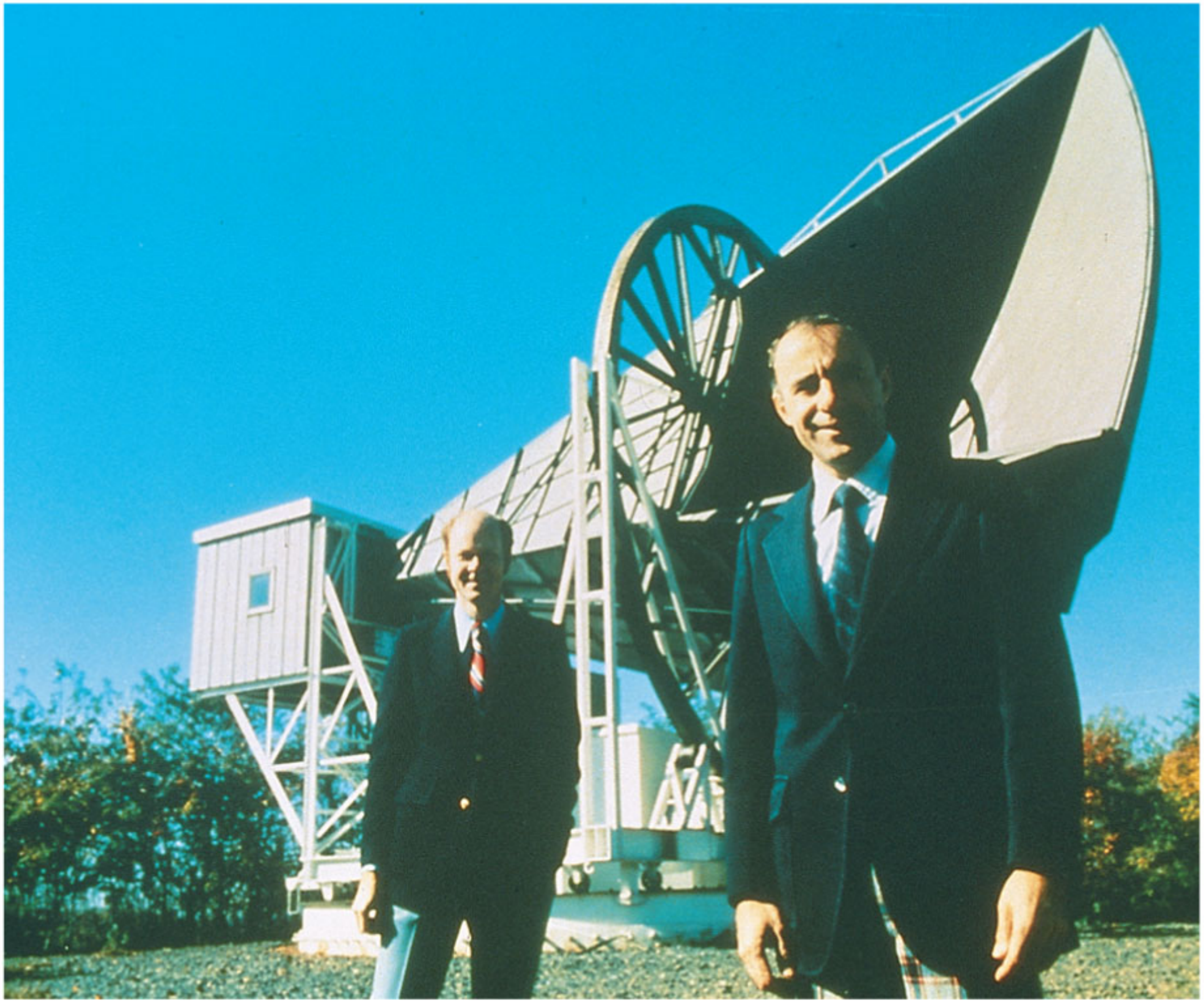
$$\lambda_{max}\,(\text{nm}) = \frac{2.9 \times 10^6}{\text{Temperature (K)}}$$

$$= 1.1 \times 10^6 \text{ nm}$$

This is in the radio/microwave part of the electromagnetic spectrum.



The cosmic microwave background (CMB).



Observational support of the Big Bang! Penzias & Wilson (1978 Nobel prize).
Actual temperature measured to be 2.73 K.

Example: At what redshift did the Universe have a temperature typical of room temperature (about 20 C)?

$T = 20\ C = 293\ K$

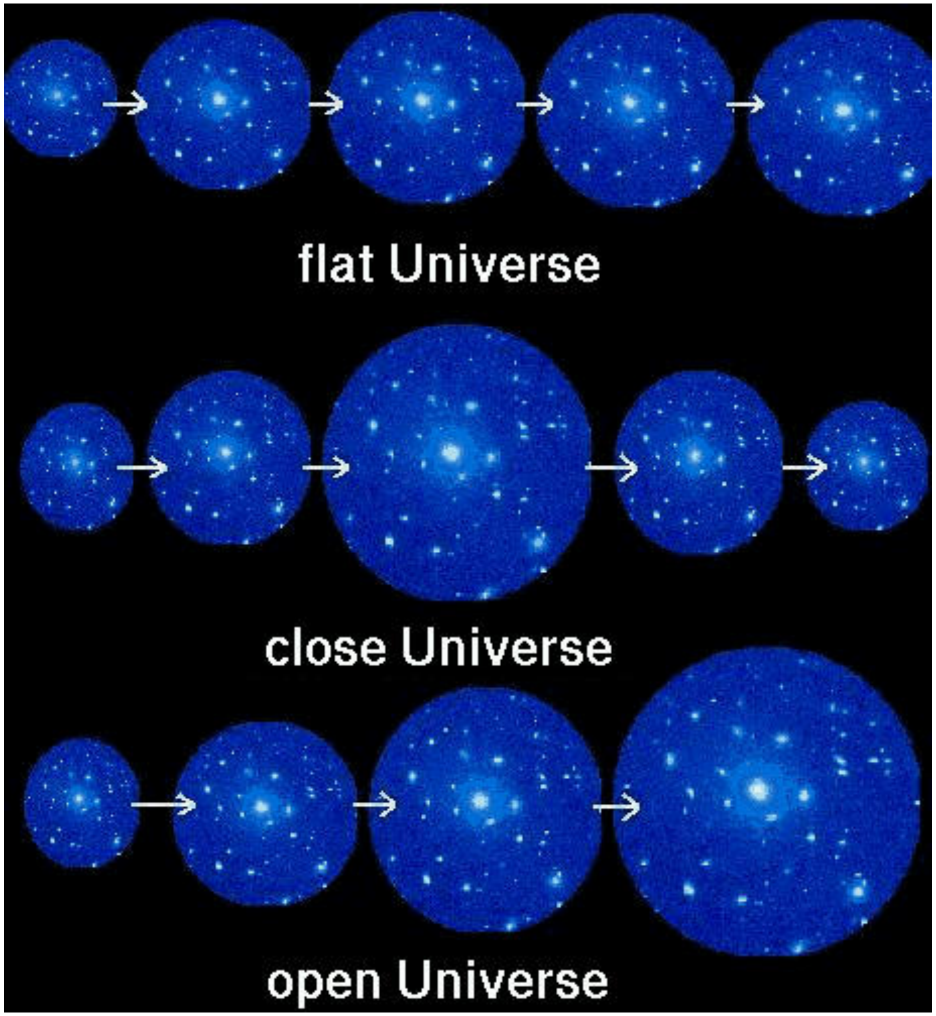
$T = T_0\,(1+z)$ where $T_0 = 2.7\ K$. Re-arranging gives

$$z = T/T_0 - 1$$
$$= 293/2.7 - 1$$
$$= 107.5$$

So, at z=107.5, the Universe had a temperature about room temperature.

The universe was only 15 million years old at a redshift z=107.5, which is 0.1% of its present age!

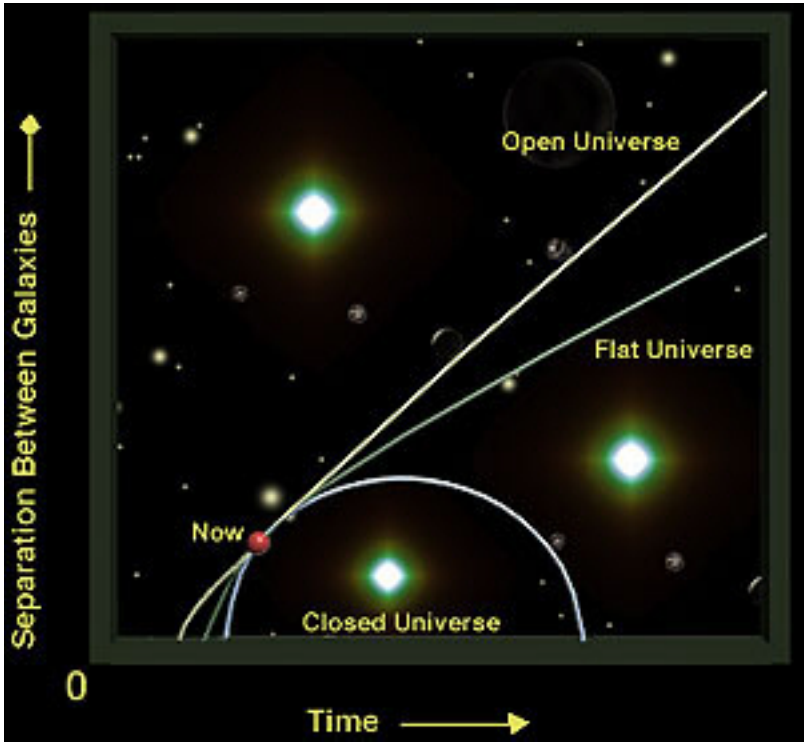
The fate of an expanding universe



Actual density today, ρ_0 , relative to critical density, ρ_{crit}, which is the value just able to "close" the universe:

$$\Omega = \rho_0 / \rho_{crit}$$

For H_0 = 70 km/s/Mpc, $\rho_{crit} = 9 \times 10^{-27}$ kg/m^3.

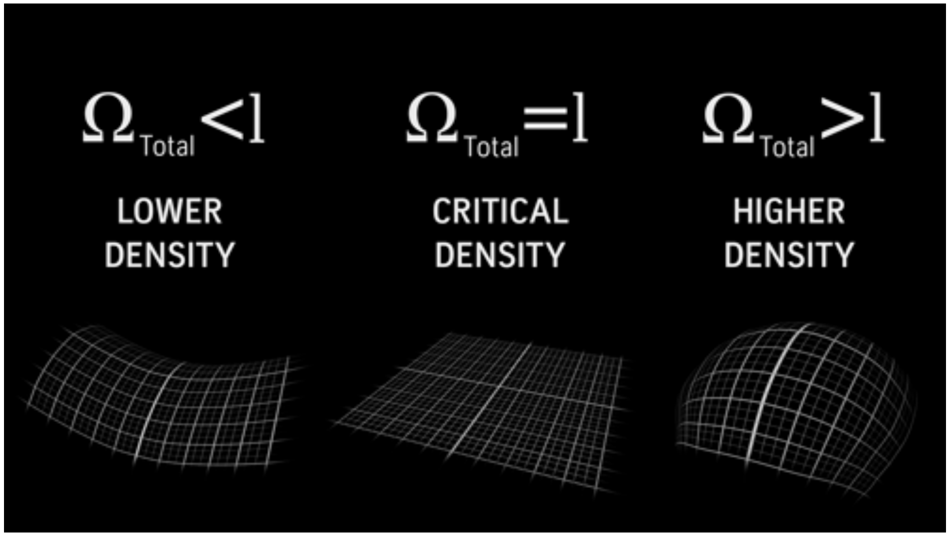


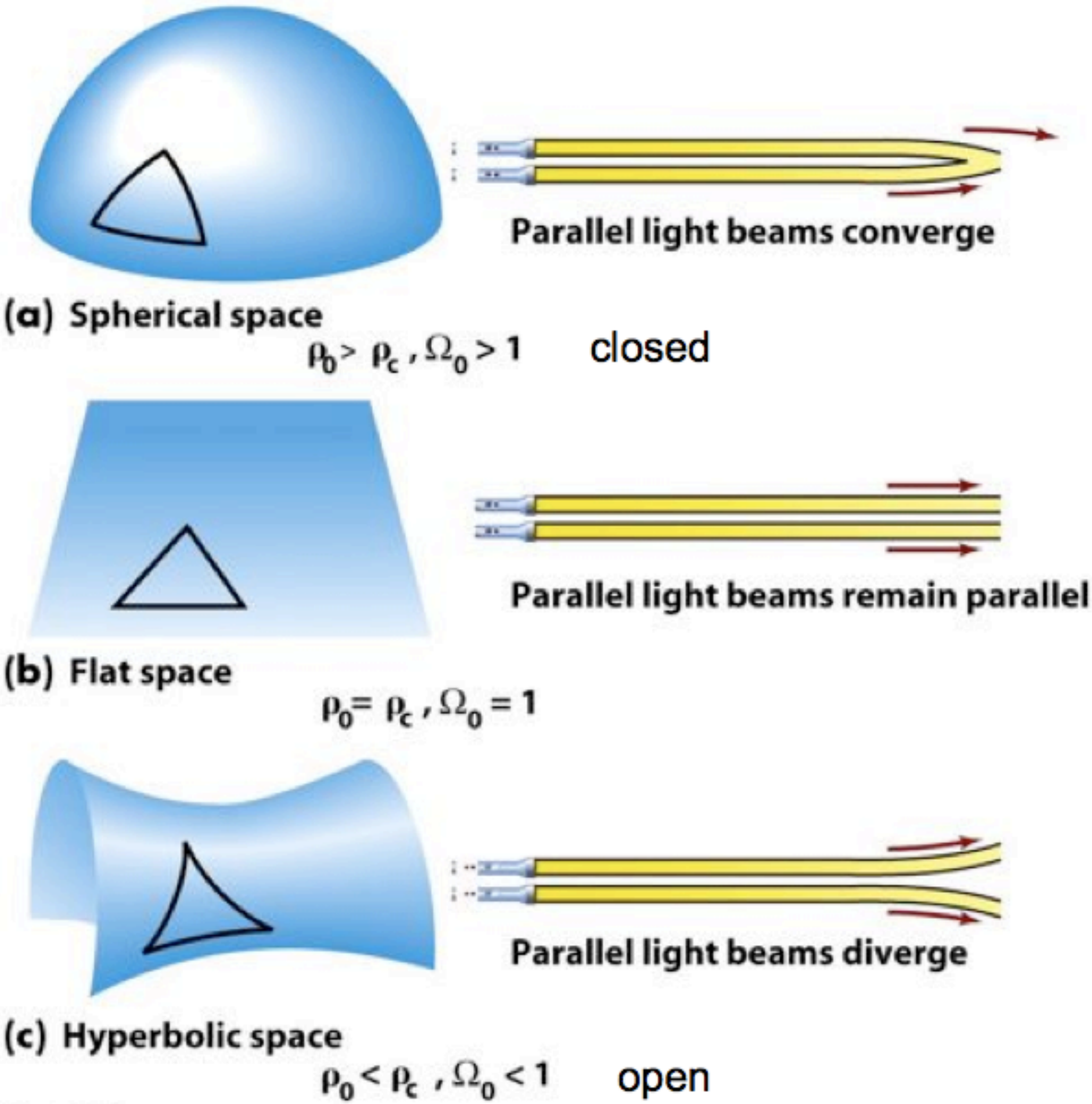
$\Omega < 1$: expanding forever

$\Omega = 1$: reaches a steady state

$\Omega > 1$: big crunch!

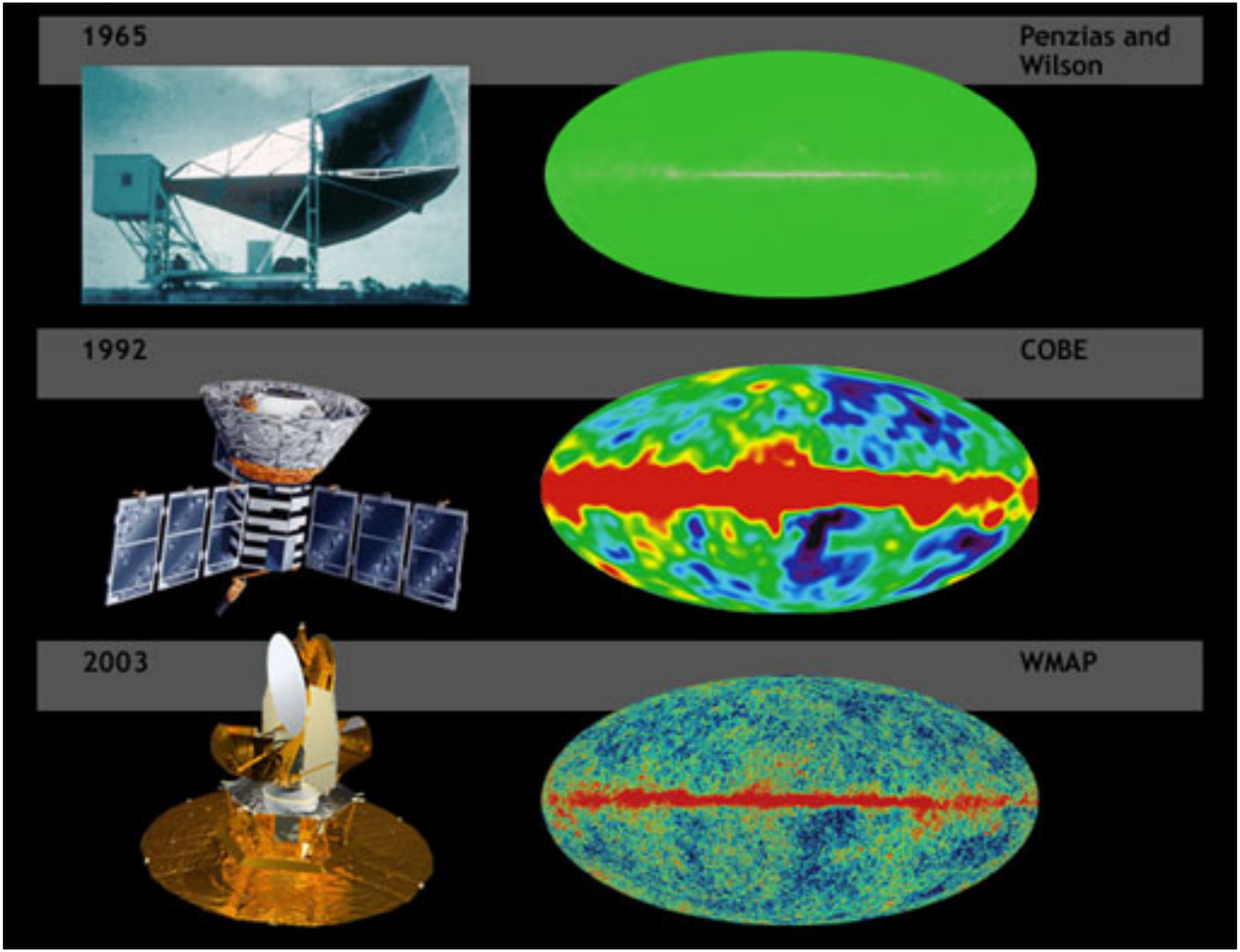
We can determine the "geometry" of the universe because the amount of mass bends space in different ways and light follows space.



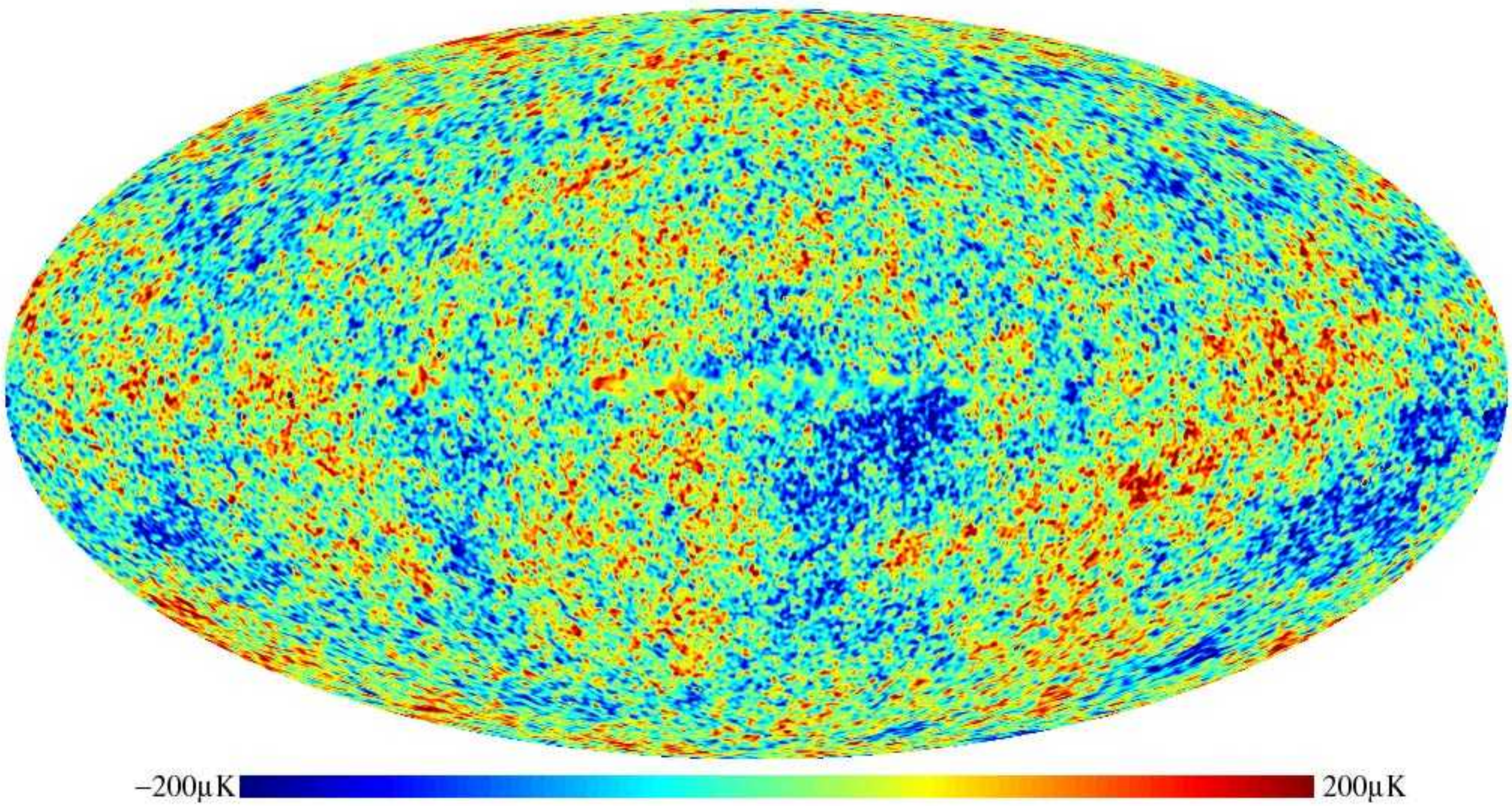


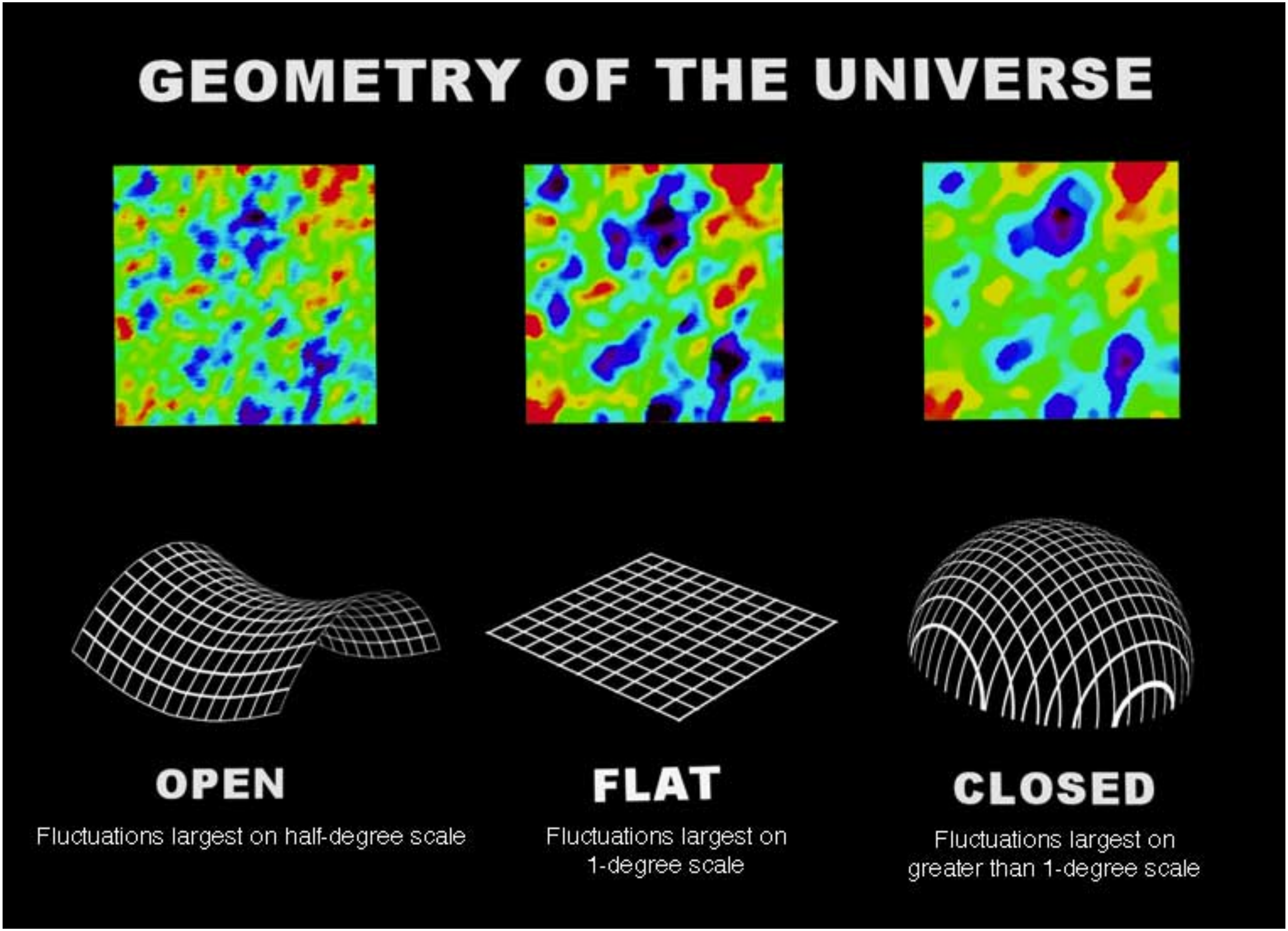
Parallel light beams converge
(a) Spherical space
$\rho_0 > \rho_c$, $\Omega_0 > 1$
closed
Parallel light beams remain parallel
(b) Flat space
$\rho_0 = \rho_c$, $\Omega_0 = 1$
Parallel light beams diverge
(c) Hyperbolic space
$\rho_0 < \rho_c$, $\Omega_0 < 1$
open

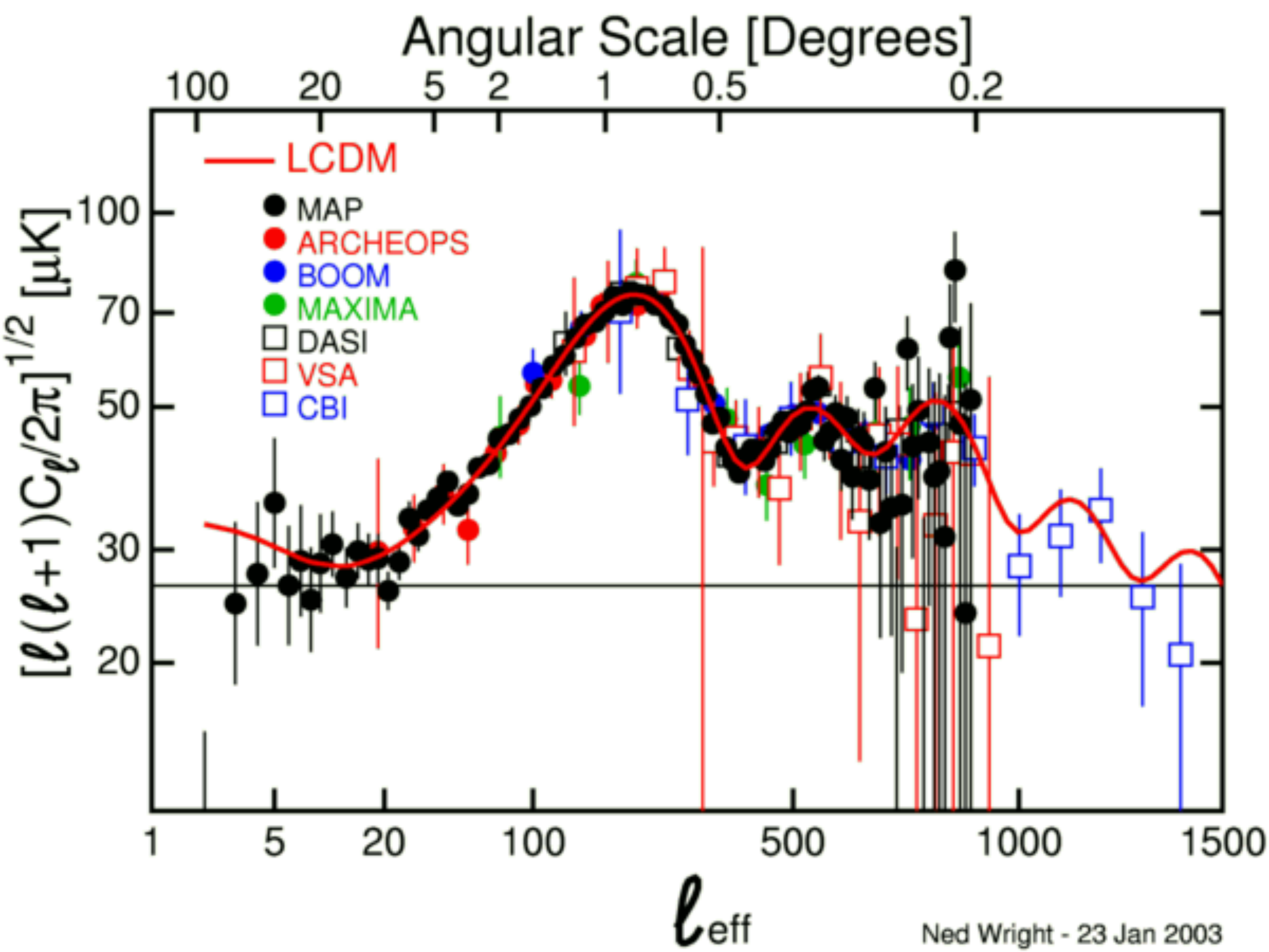
Measuring the path of light with the CMB



In 2003, asatellite called WMAP made the most detailed map ever of the CMB, thanks to its fine resolution. The variations between "hot" and "cold" patches on the sky are only 1/10000 of a degree! Nobel prize in 2006 to John Mather and George Smoot.

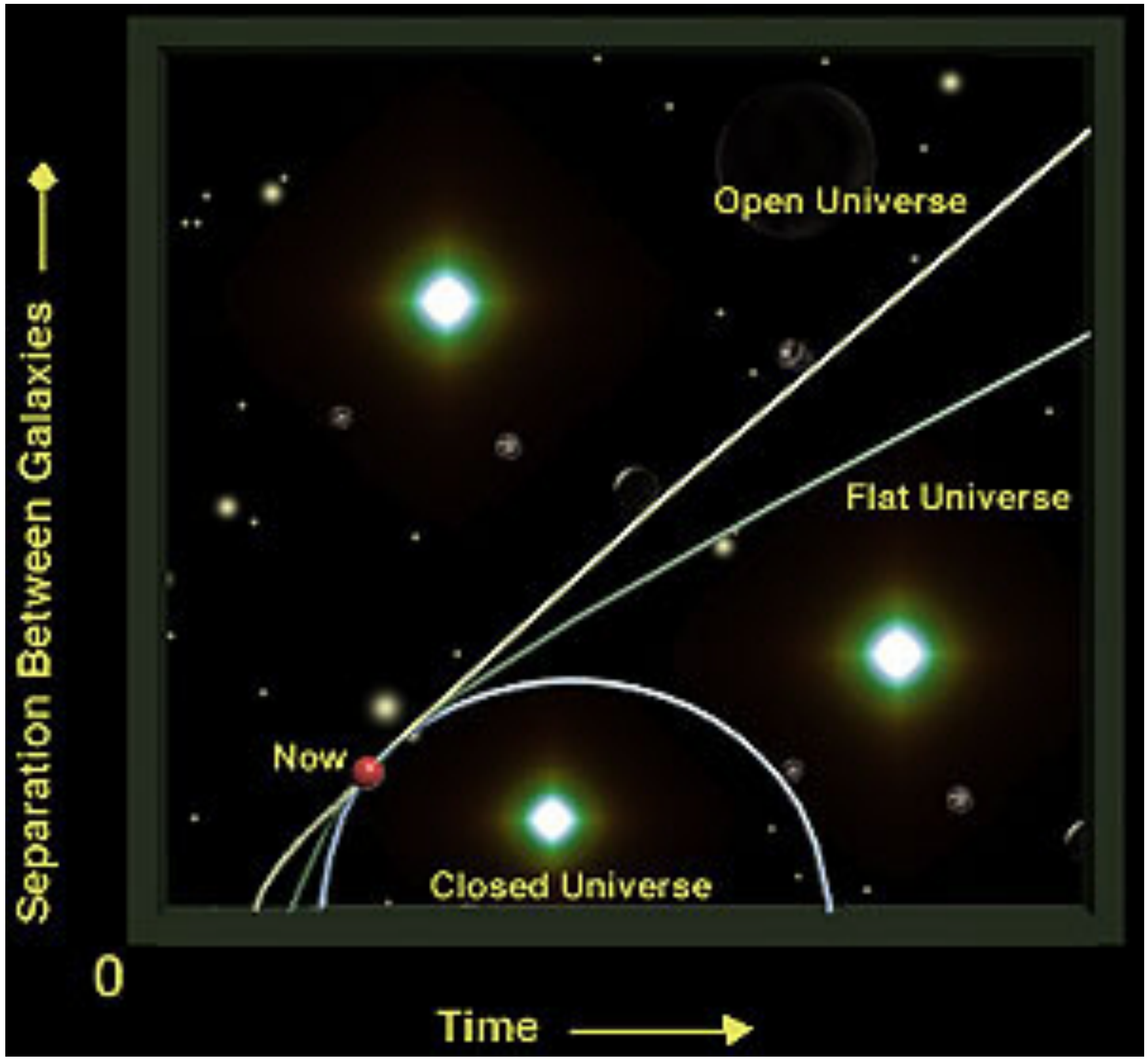



GEOMETRY OF THE UNIVERSE
OPEN
Fluctuations largest on half-degree scale
FLAT
Fluctuations largest on
1-degree scale
CLOSED
Fluctuations largest on
greater than 1-degree scale



Angular Scale [Degrees]
100
20
5
2
1
0.5
0.2
LCDM
MAP
ARCHEOPS
BOOM
MAXIMA
DASI
VSA
CBI
$[\ell(\ell+1)C_\ell/2\pi]^{1/2}$ [μK]
100
70
50
30
20
1
5
20
100
500
1000
1500
ℓ_{eff}
Ned Wright - 23 Jan 2003

$\Omega = 1$, so the Universe will reach its maximum size at infinity, or will it…? These "fates" assume that the only contribution to Ω is matter.



We can test this by checking the Universe is the "right size" based on how much we predict should be there in an $\Omega_M = 1$ universe.

Measuring the size of the universe with standard candles

Recall that, because of the inverse square law, the distance modulus is

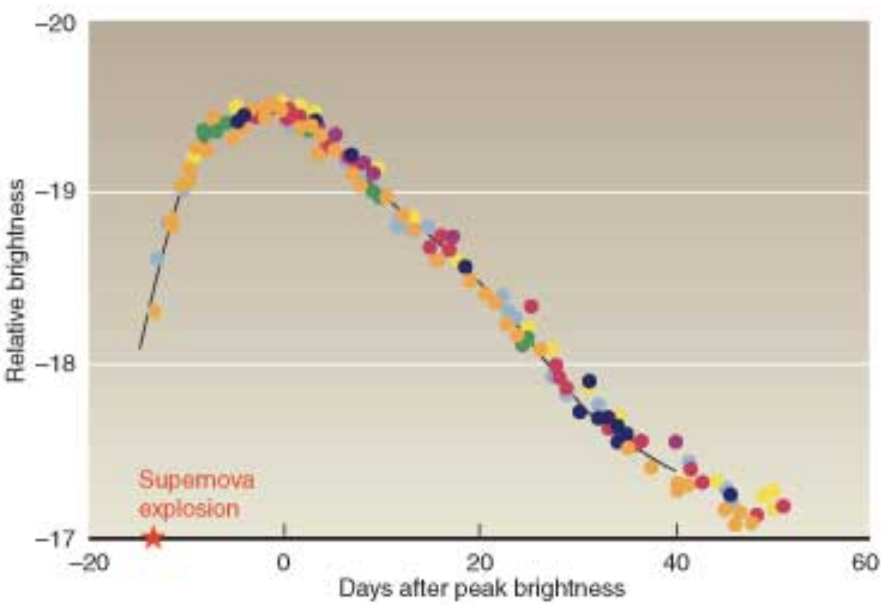
$$m - M = -5 + 5 \log d(pc).$$

For "standard candles" that have a fixed luminosity, hence fixed M:

$$m = const + 5 \log d .$$

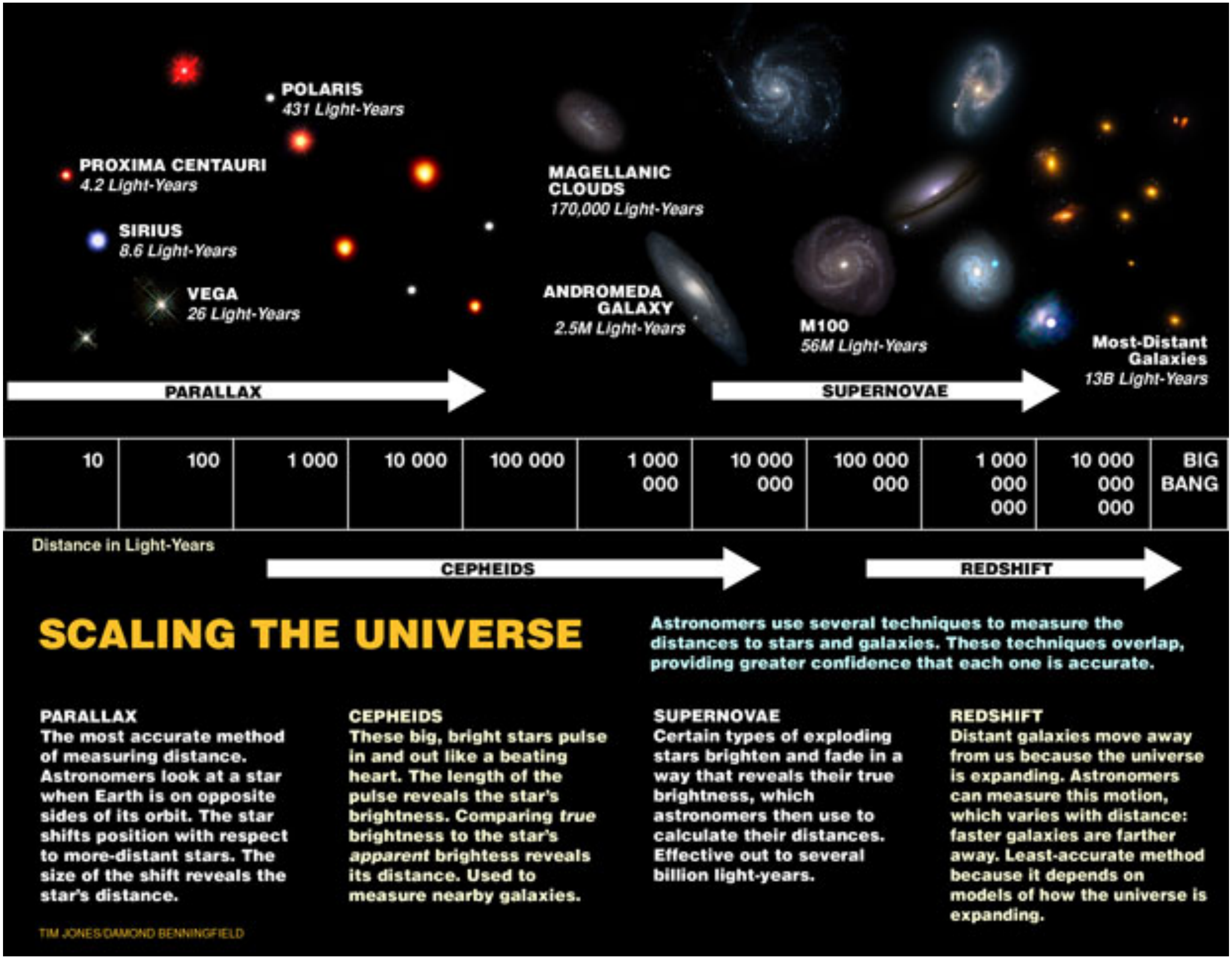
Since d=v/H and d = cz/H

$$m = const + 5 \log z.$$



A special type of supernova called a Type Ia is thought to be such a standard candle.

Aside: complete view of distance measures



Hubble diagram: m = const + 5 log z

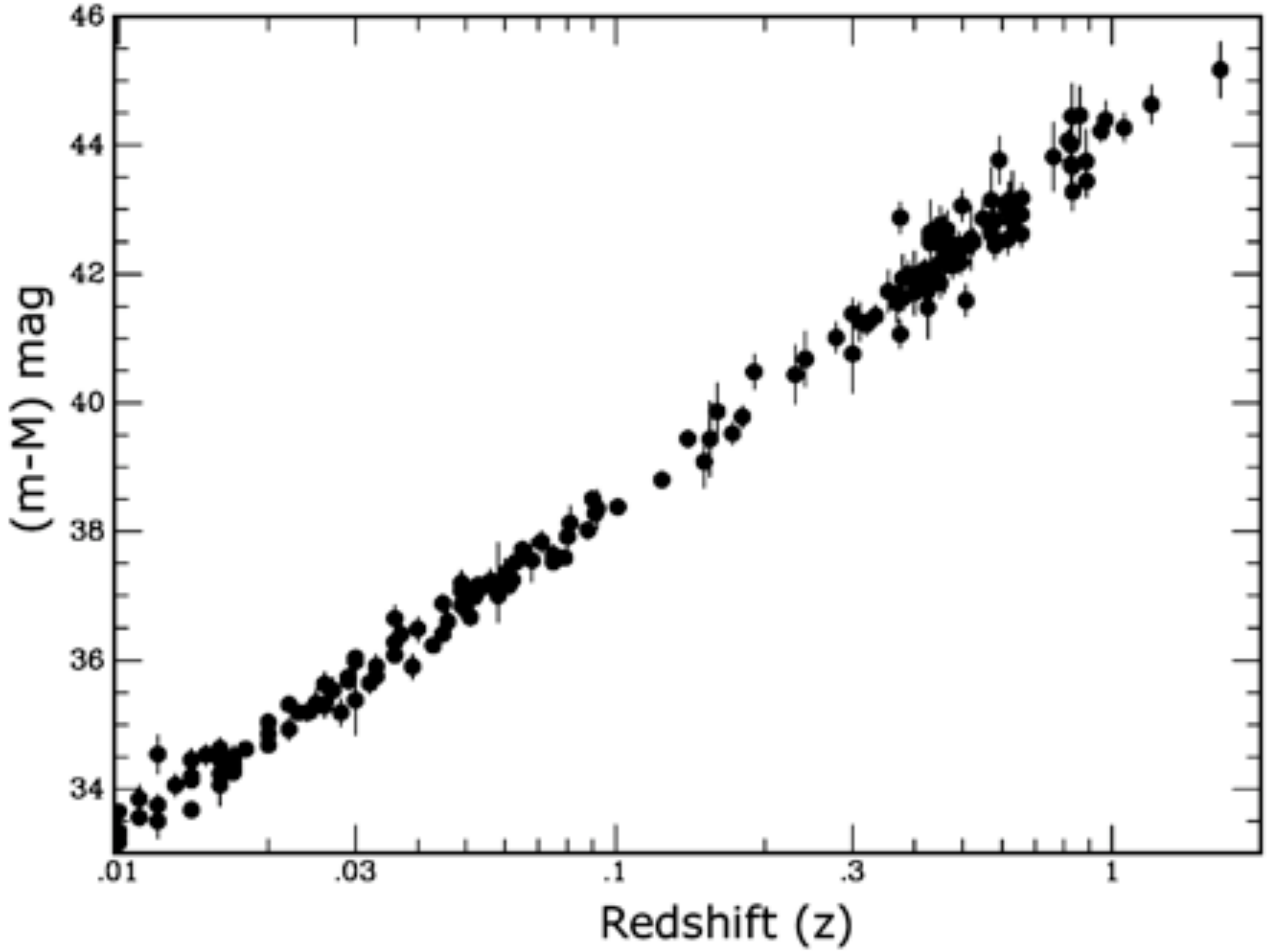
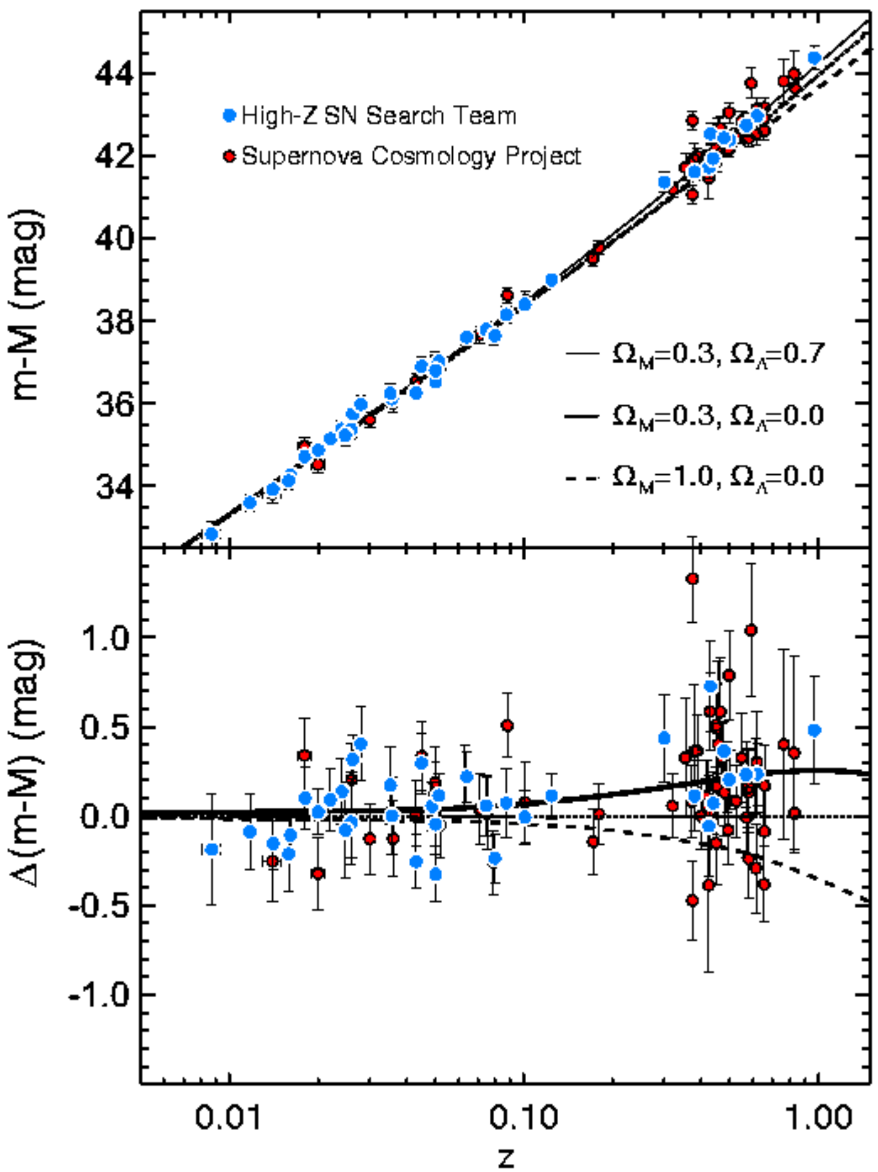
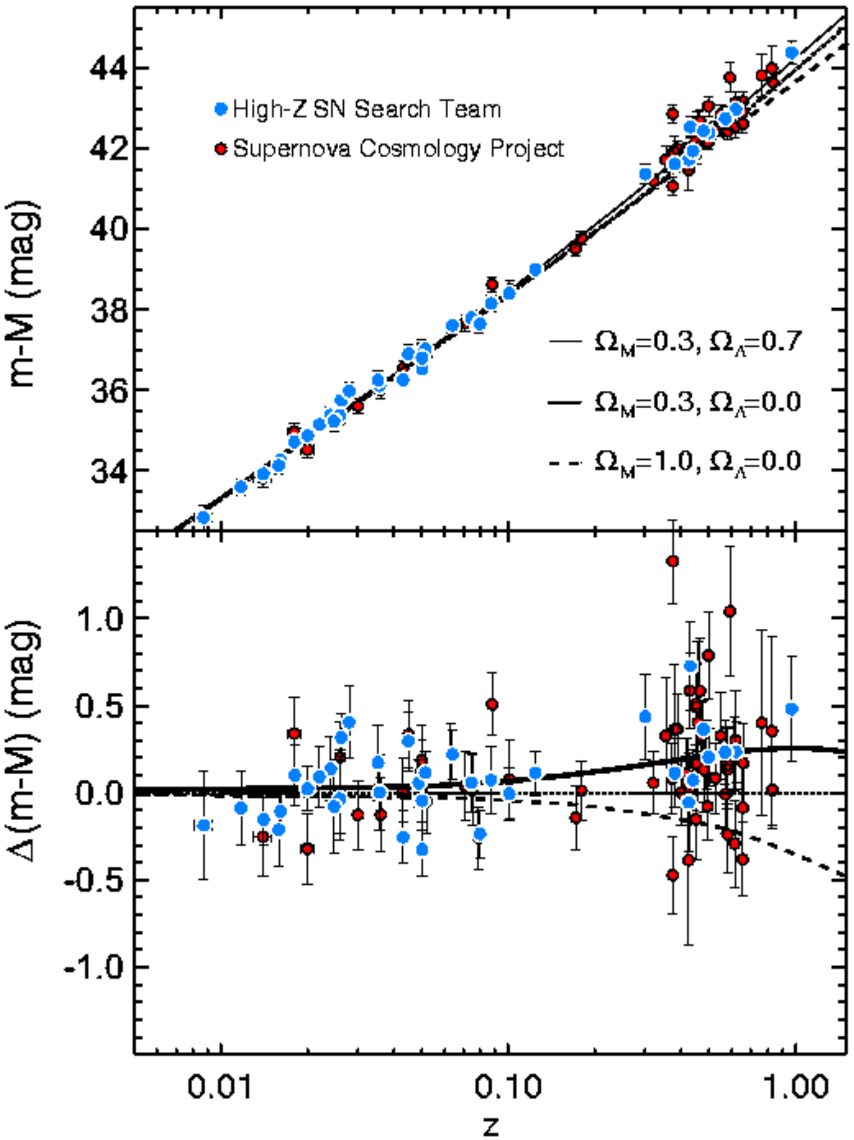


Fig. 4

Supernova measurements indicate that they appear "too faint". Alternatively, they are farther away than we thought (based on simple Ω_M=1 prediction).



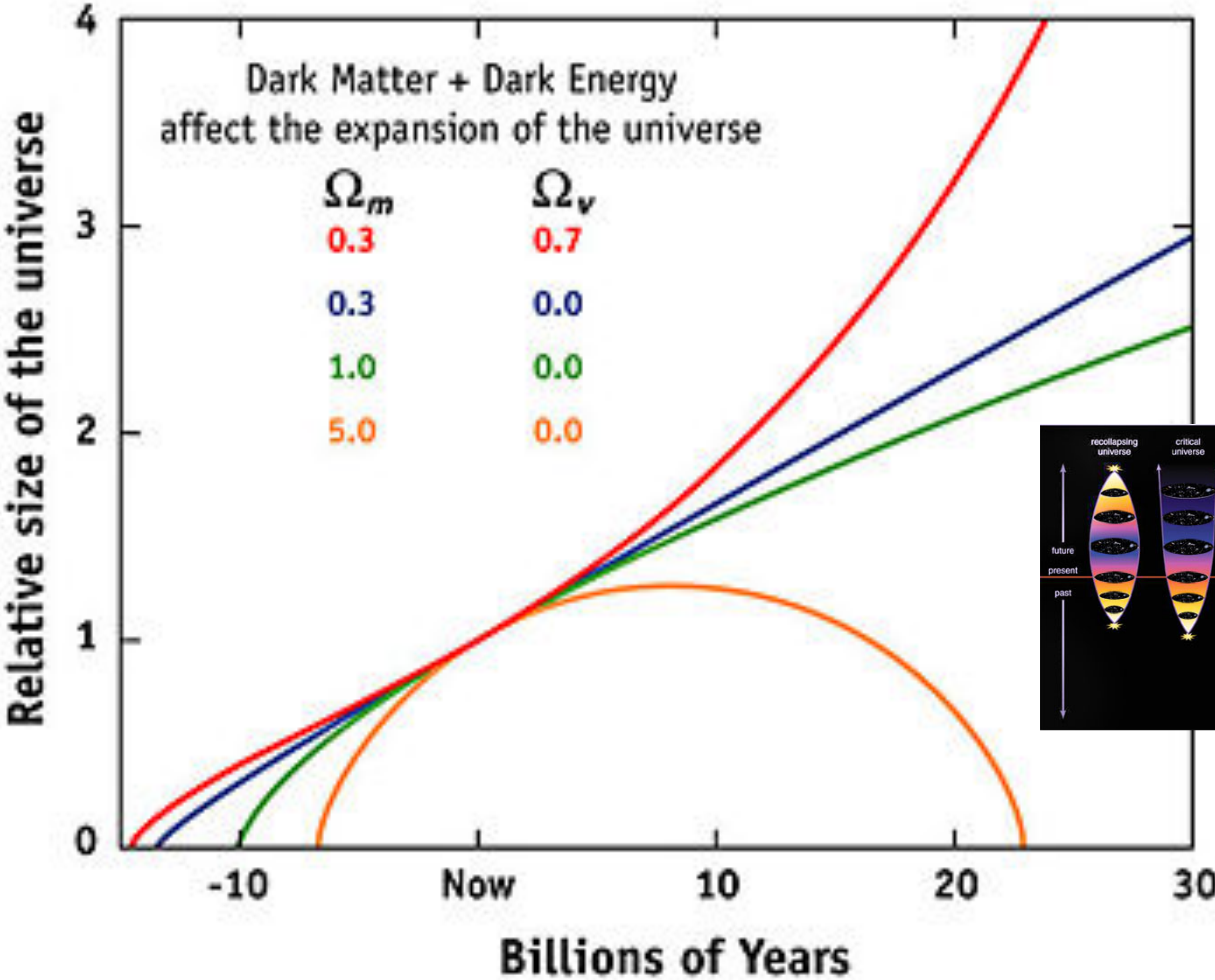
If CMB tells us that Ω=1, but the Universe is bigger than we thought, not all of Ω's contribution is from matter (gravity): repulsive force.

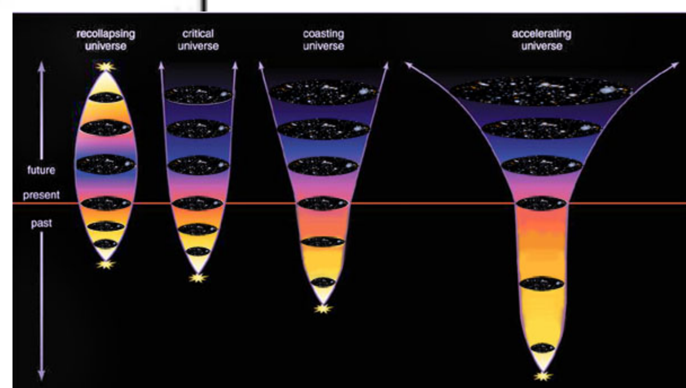


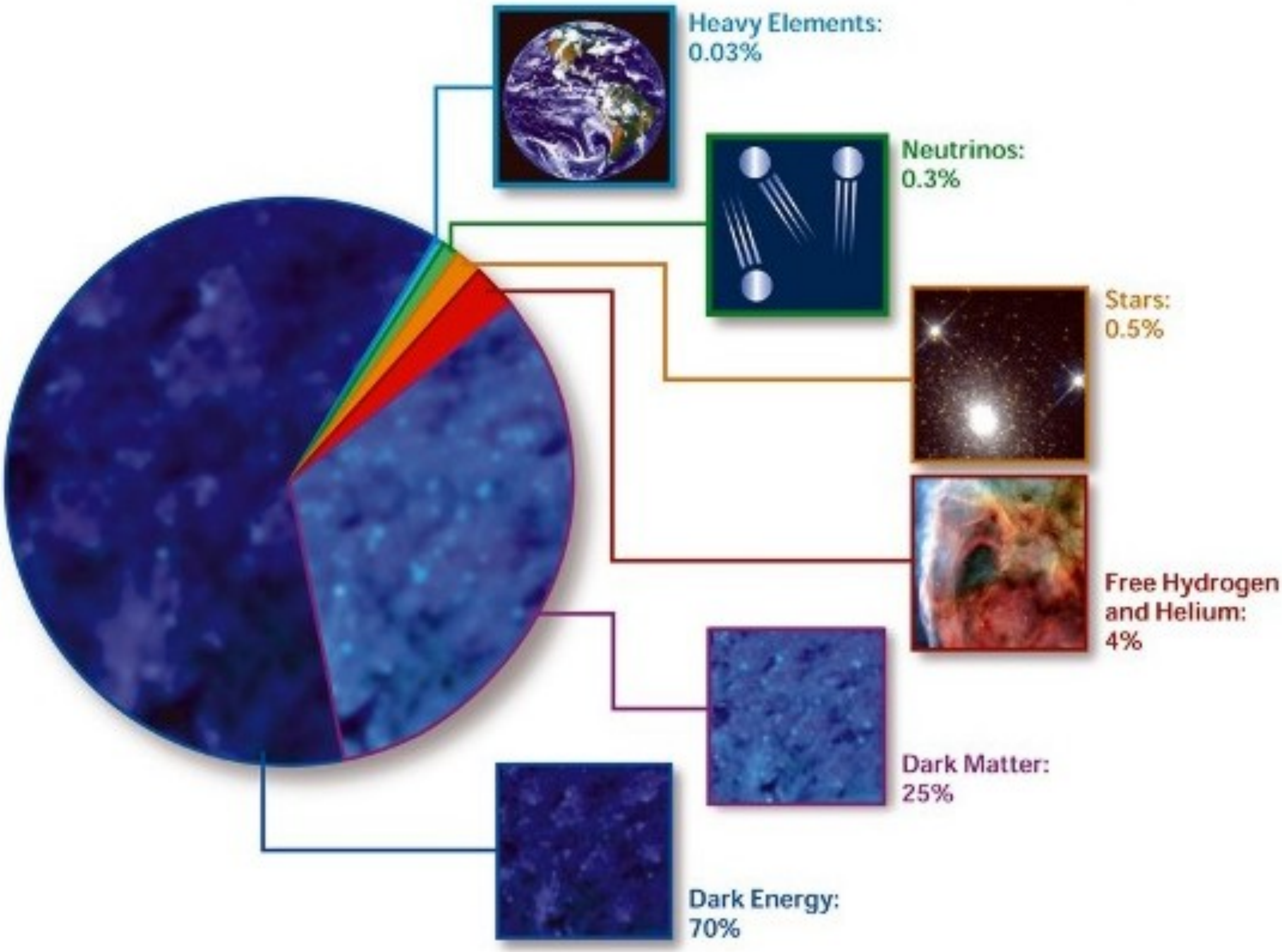
Dark energy!

$\Omega_T = \Omega_M + \Omega_\Lambda$

Expansion of the Universe

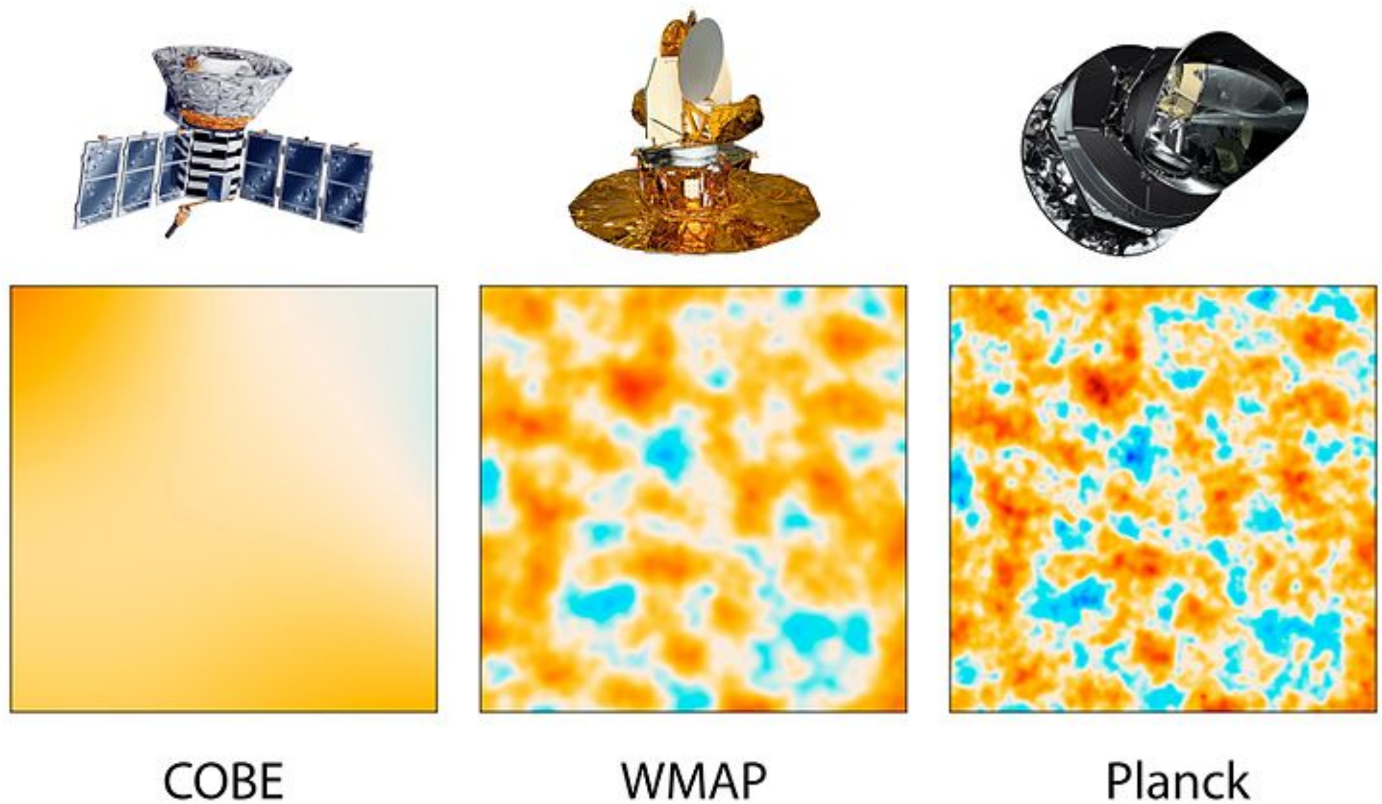






Heavy Elements:
0.03%
Neutrinos:
0.3%
Stars:
0.5%
Free Hydrogen
and Helium:
4%
Dark Matter:
25%
Dark Energy:
70%

State of the art: higher resolution with ESA's Planck satellite (2013):



Parameter	Age of the universe (Gy)	Hubble's constant (km/Mpc·s)	Physical baryon density	Physical cold dark matter density	Dark energy density
Symbol	t_0	H_0	$\Omega_b h^2$	$\Omega_c h^2$	Ω_Λ
Planck Best fit	13.819	67.11	0.022068	0.12029	0.6825