General Relativity and Universe

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Λ – term in the General Relativity

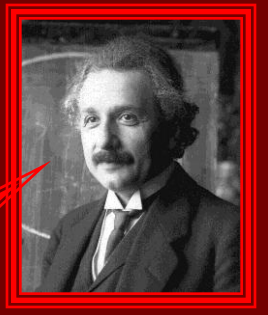
1. Mach's principle: source of inertia - masses of the Universe

No inertia relative to spacetime, but inertia of masses relative to one another.

Ernst Mach (1938-1916)

2. Imbalanced Gravitation:

"…the newly introduced universal constant Λ defines both the mean density of distribution ρ which can remain in equilibrium and also the radius … of the spherical space."



Einstein (1917)

$$\Delta\varphi - \Lambda\varphi = 4\pi\rho G$$

This seemed to solve a problem that troubled even Newton – why did the entire Universe not collapse under its own gravitational attraction? In Einstein's view, the Λ introduces a screening length which cuts off the influence of the gravitational potential beyond a certain radius, thereby allowing the motion of stars and nebulae to approach equilibrium.

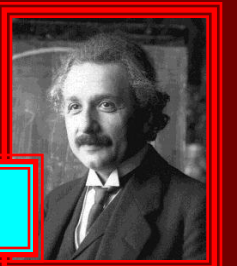
Einstein-de Sitter space

Nicolas Copernicus (1473-1543)

First mathematical model of the Universe

Copernican Principle gives way to Cosmological Principle

Model of the Universe as spatially homogeneous, isotropic.



Einstein vacuum equations with Λ – term

Static, closed Universe (1917)

$$R_{ik} - \frac{1}{2} g_{ik} R = -\Lambda g_{ik}, \quad \Lambda = const > 0$$

De Sitter solution

Willem de Sitter (1872-1934)

$$ds^2 = \left(1 - \frac{\Lambda r^2}{3}\right) c^2 dt^2 - \left(1 - \frac{\Lambda r^2}{3}\right)^{-1} dr^2 - r^2 \left(d\theta^2 + \sin^2 \theta d\varphi^2\right)$$

$$\rho > 0,\ P = 0,\ \Lambda > 0,\ k > 0$$

$$\Rightarrow \ddot{a}(t) = \dot{a}(t) = 0 \ \text{ for all } t$$

Einstein closed, static Universe

Radius of the Universe

$$R_U = \sqrt{\frac{3}{\Lambda}}$$

Friedman's Universe

$$R_{ik} - \frac{1}{2} g_{ik} R + \Lambda g_{ik} = \frac{8\pi G}{c^4} T_{ik}$$

Aleksandr Friedman (1888-1925)

Where T_{ik} is the Energy momentum tensor of an ideal fluid

$$T_{ik} = \left(\rho + \frac{P}{c^2} \right) u_i u_k - P g_{ik}$$

density

4-velocity

pressure

$$u_i = \frac{dx_i}{d\tau} = \left(\frac{dt}{d\tau}, \frac{dx}{d\tau}, \frac{dy}{d\tau}, \frac{dz}{d\tau} \right)$$

time component

proper time (time at the rest system)

space components

Friedman's Equations 1

"Equation of motion" for the whole Universe

$$ds^2 = c^2dt^2 - R^2(t)\left(\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right)$$

Metric of the Universe

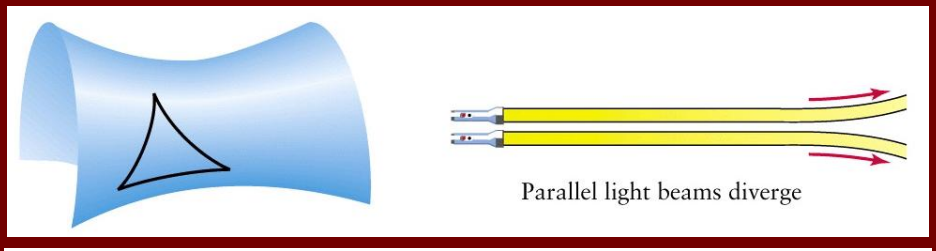
$$1.\ \ddot{R} = -\frac{4\pi G\rho}{3}R\left(+\frac{\Lambda R}{3}\right)$$

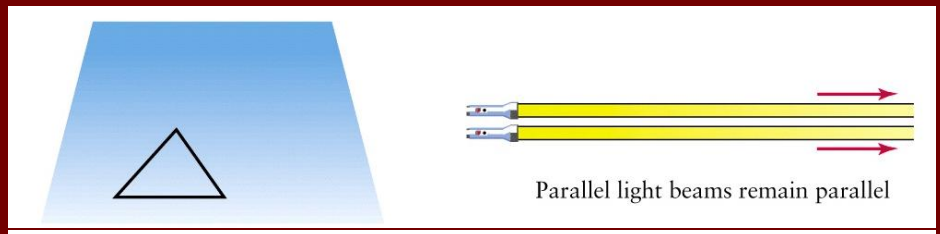
$$2.\ \dot{R}^2 = \frac{8\pi G\rho}{3}R^2 - kc^2\left(+\frac{\Lambda R^2}{3}\right)$$

The Friedmann Equations describe the evolution of the Universe

(1922)

k = -1 : Hyperbolic Space

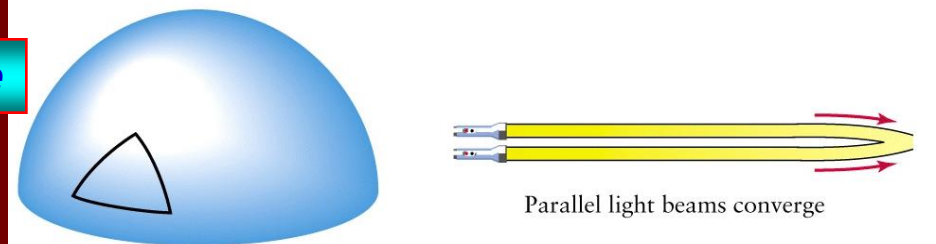




k = 0 : Flat Space

$$\rho_\Lambda = \frac{\Lambda}{4\pi G}$$

k = +1 : Spherical Space

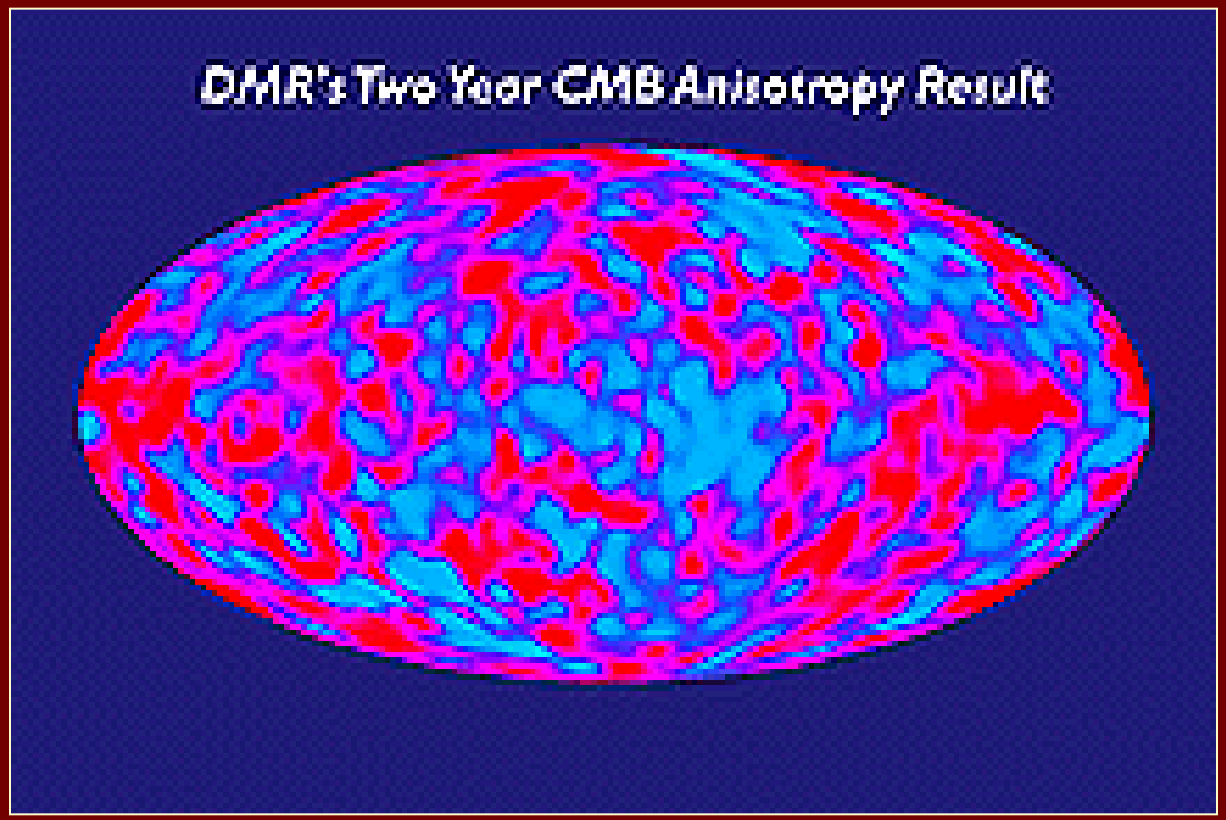


COBE data/DMR

John Mather

These fluctuations have been called the "wrinkles on the face of God"

George Smoot



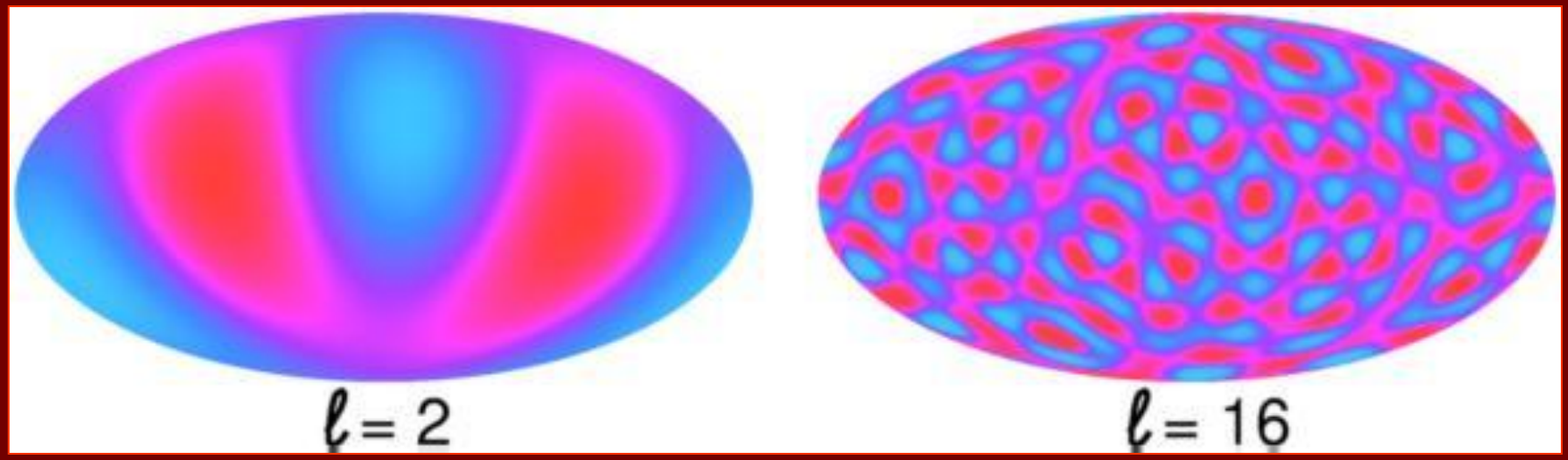
Cosmic Background Explorer Satellite (COBE).

2006 Nobel prize in Physics awarded to George Smoot!

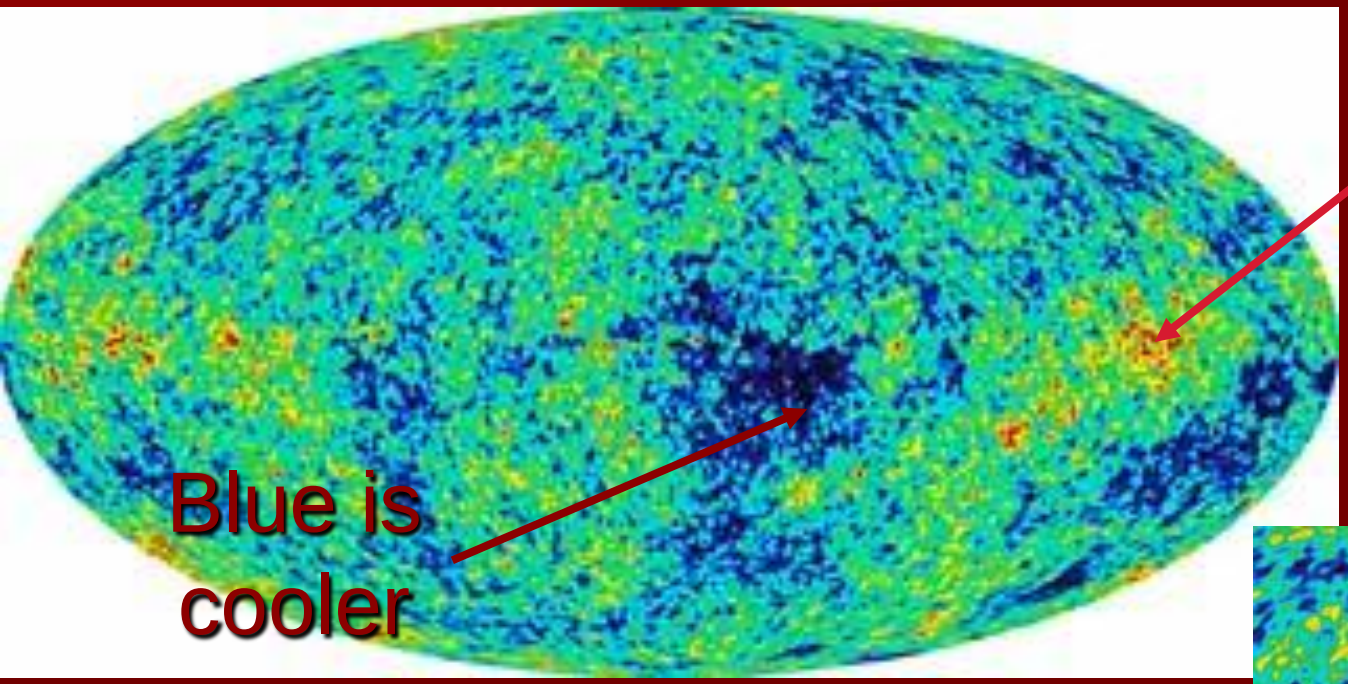
(Also John Mather for measuring temperature of CMBR precisely at 2.7 K with FIRAS on COBE.)

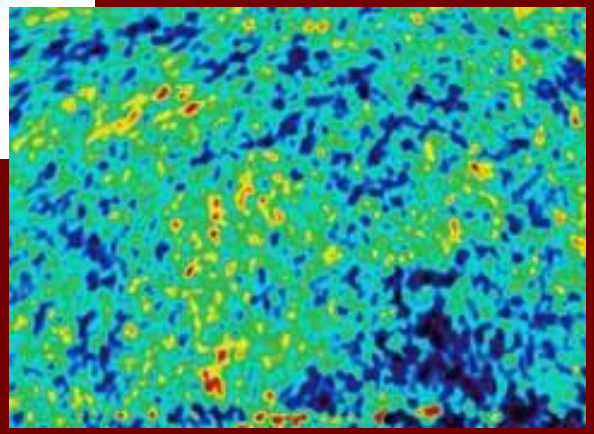
CMB Fluctuations

COBE measures the angular fluctuations on large scales, down to about $l=16$



Universe's Baby Pictures

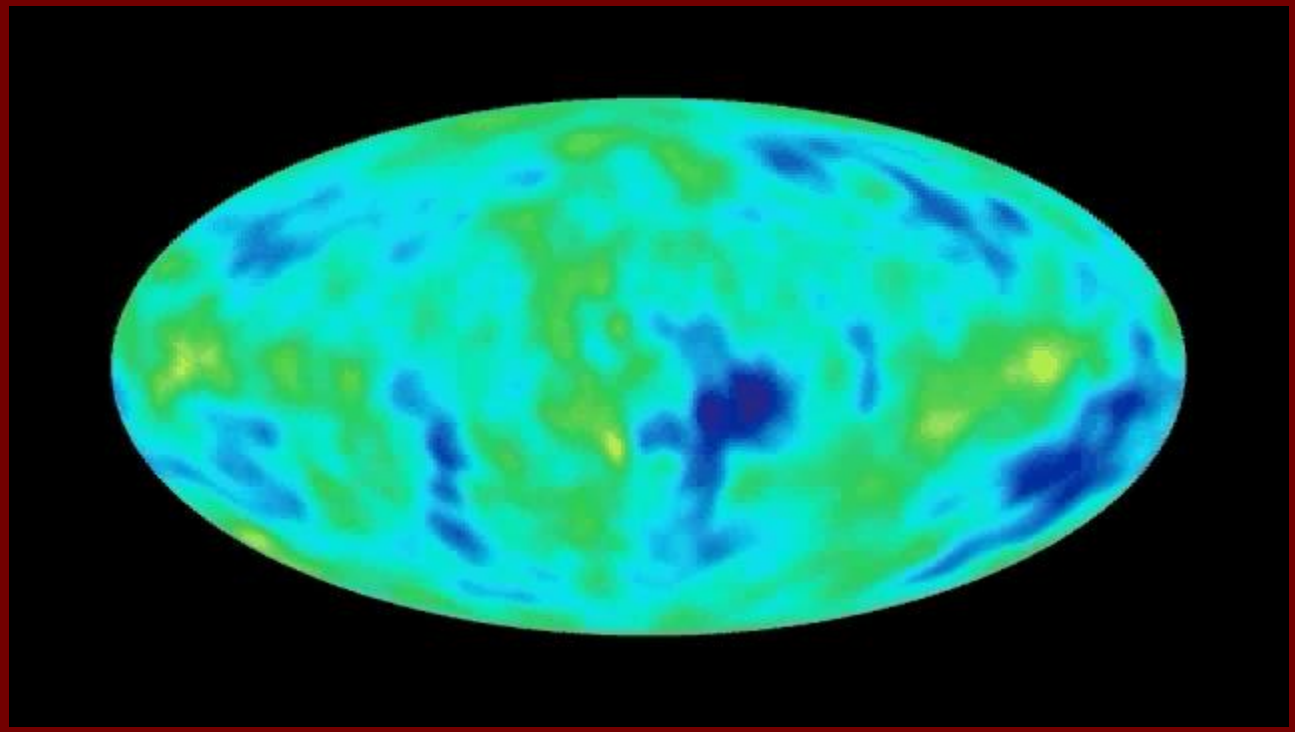




Credit:
NASA/WMAP

Compare to COBE

The WMAP image brings the COBE picture into sharp focus.

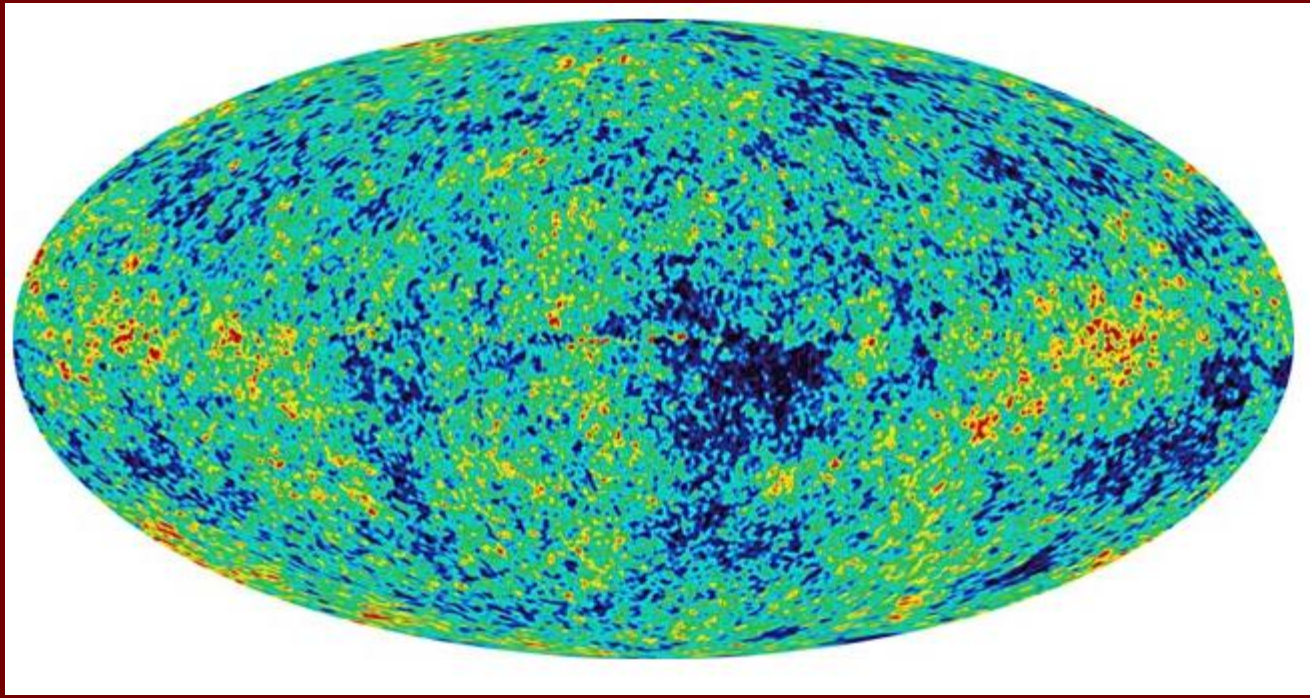


movie

Evidence from Cosmic Microwave Background Radiation (CMB)

1. CMB is an almost isotropic relic radiation of T=2.725±0.002 K
2. CMB is a strong pillar of the Big Bang cosmology
3. It is a powerful tool to use in order to constrain several Cosmological parameters
4. The CMB power spectrum is sensitive to several Cosmological parameters

This is how the Wilkinson Microwave Anisotropy Probe (WMAP) sees the CMB



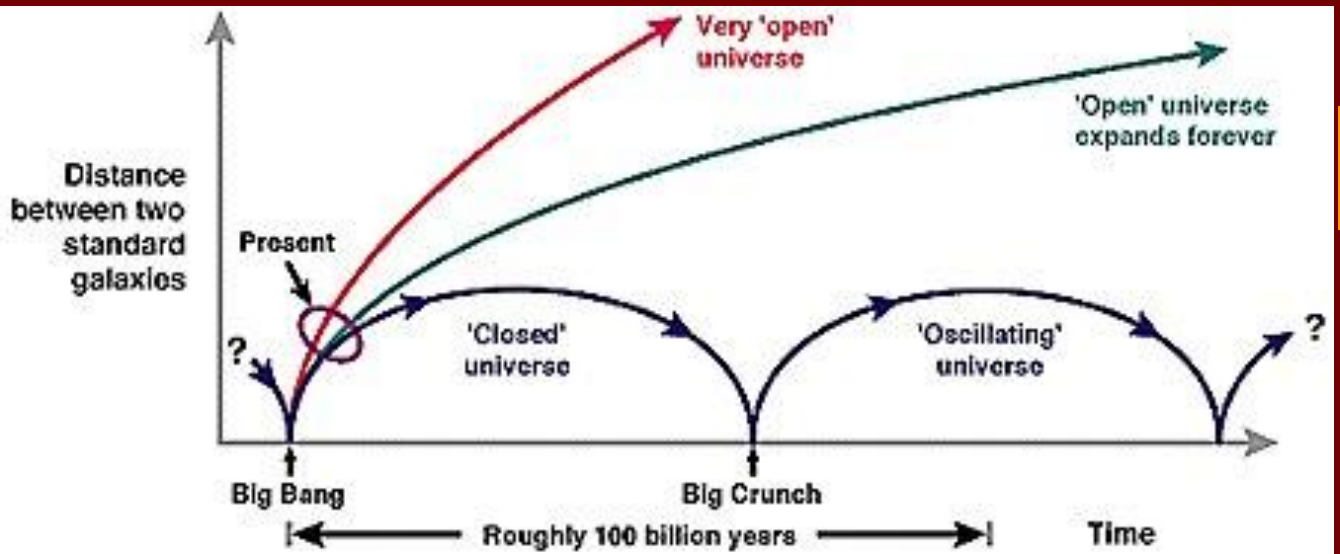
Friedman's Equations 2

2. $$\left(\frac{dR_S}{dt}\right)^2 = \frac{8\pi}{3}\frac{G\rho_0 R_0^3}{R_s} - \frac{8\pi}{3}GR_0^2(\rho_0 - \rho_c)$$

If current density is greater than critical density then the second term is negative and there will exist a time in which $\frac{dR_s}{dt} = 0$

The expansion will then stop and the Universe will collapse back to the initial state

If current density is smaller than critical density then the second term is positive and the derivative will never get down to zero. Expansion will go on forever.



Critical density

$$\rho_c = \frac{3H^2{}_0}{8\pi G} = 9.47 \cdot 10^{-27} kg/m^3$$

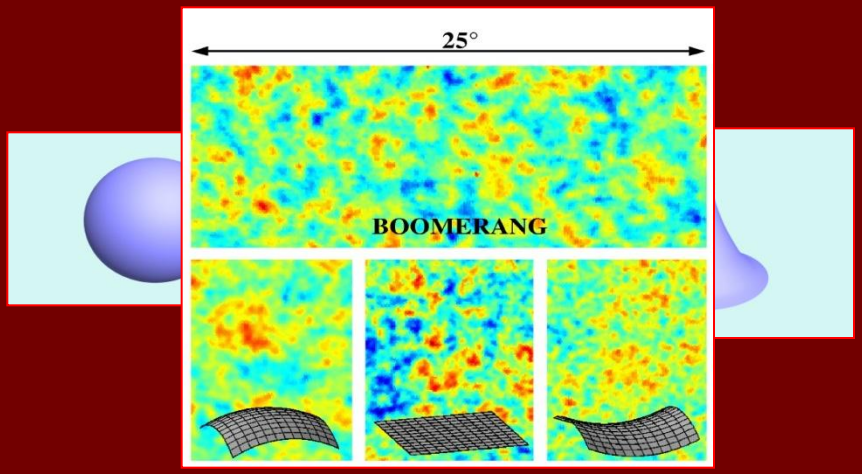
Hubble constant (WMAP data)

$$H_0 = 71\ km/c/Mpc$$

The geometry of the Universe

- Crucial information from each of these is the amplitude of fluctuation as a function of scale (the '**Power Spectrum**')
- E.g. the CMB power spectrum has encoded the geometry of the Universe:
- The picture shows the typical sky appearance for different types of Universe geometry – **closed, flat** and **open** - with actual CMB results at the top

Results from a balloon-borne experiment: Boomerang



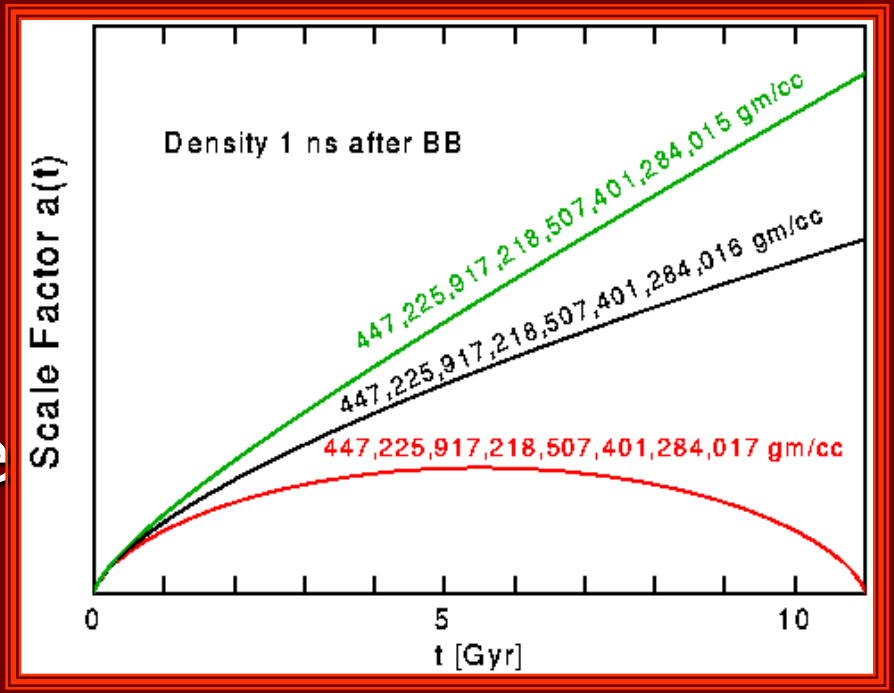
Left: Universe closed – spatial geometry is like a sphere

Middle: Universe flat – geometry is just that of Euclidean 3 space

Right: Universe open – geometry is hyperbolic

Flatness Problem

1. Why does the Universe today appear to be near the critical dividing line between an open and a closed Universe?
2. Density of early Universe must be correct to 1 part in 10^{60} in order to achieve the balance that we see.



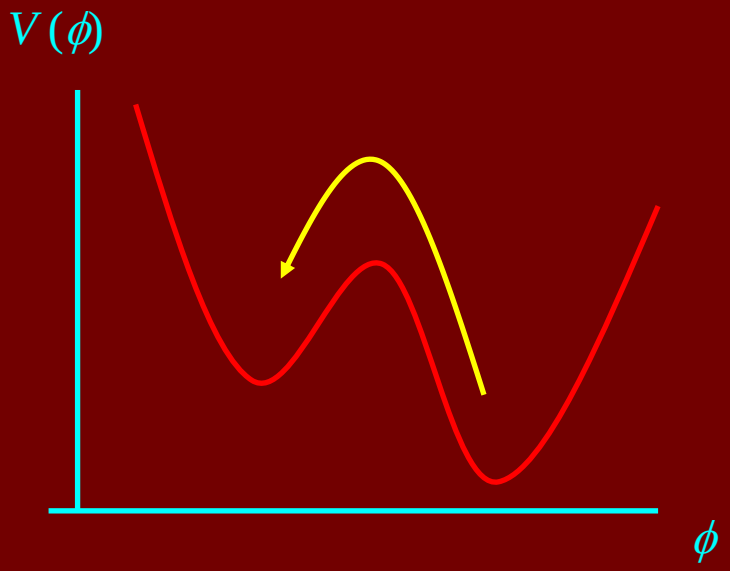
Quantum fluctuations can produce new Universes

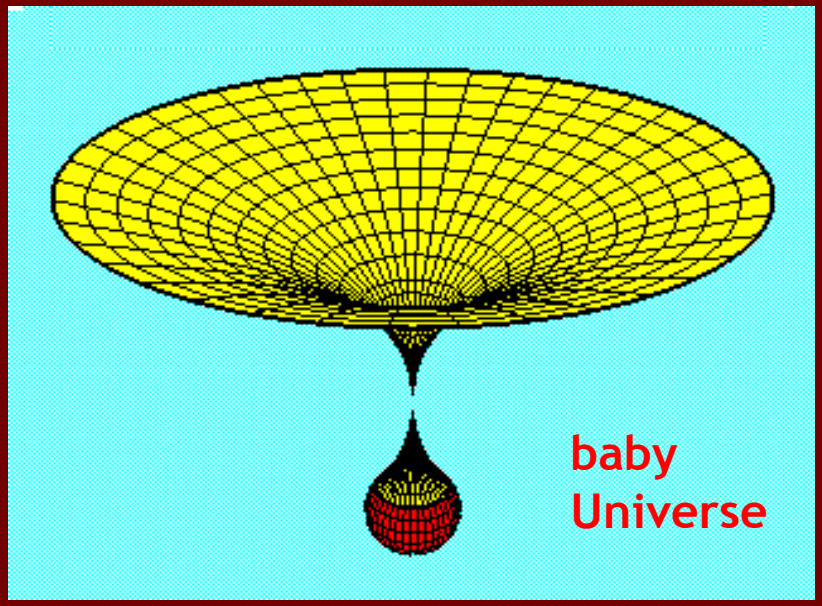
Spontaneous vacuum symmetry breaking

There exists a lot of Universes

Hugh Everett
(1930-1982)

background space





A baby Universe will pinch off from the background spacetime, expanding and creating more entropy.

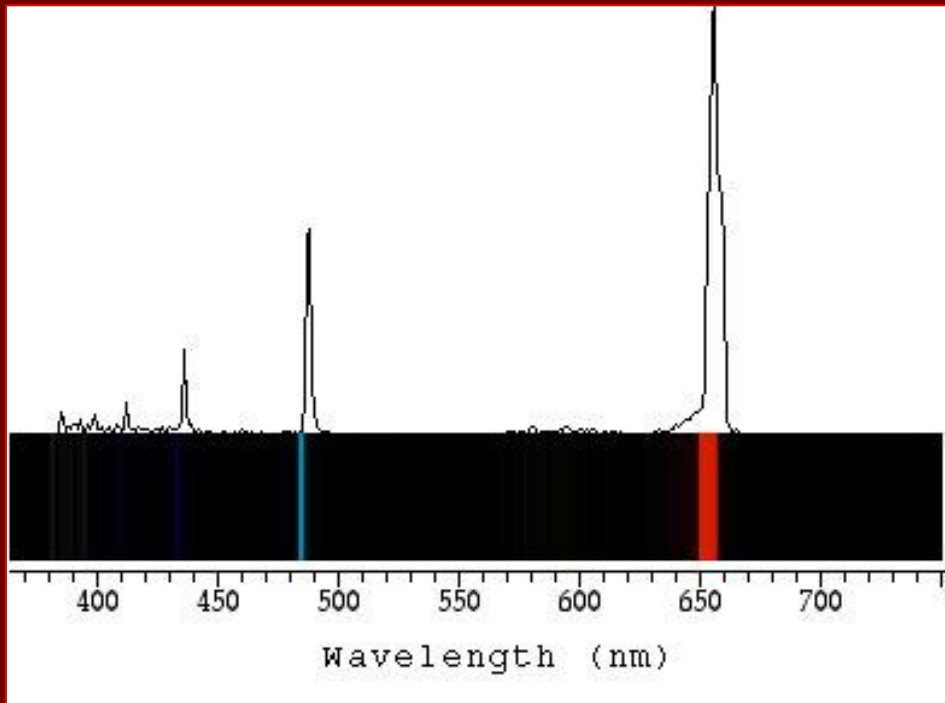
Evidence for an expanding Universe

Vesto Slipher
(1875-1969)

Hydrogen lamp

The spectrum of hydrogen gas is the unique fingerprint of that element.

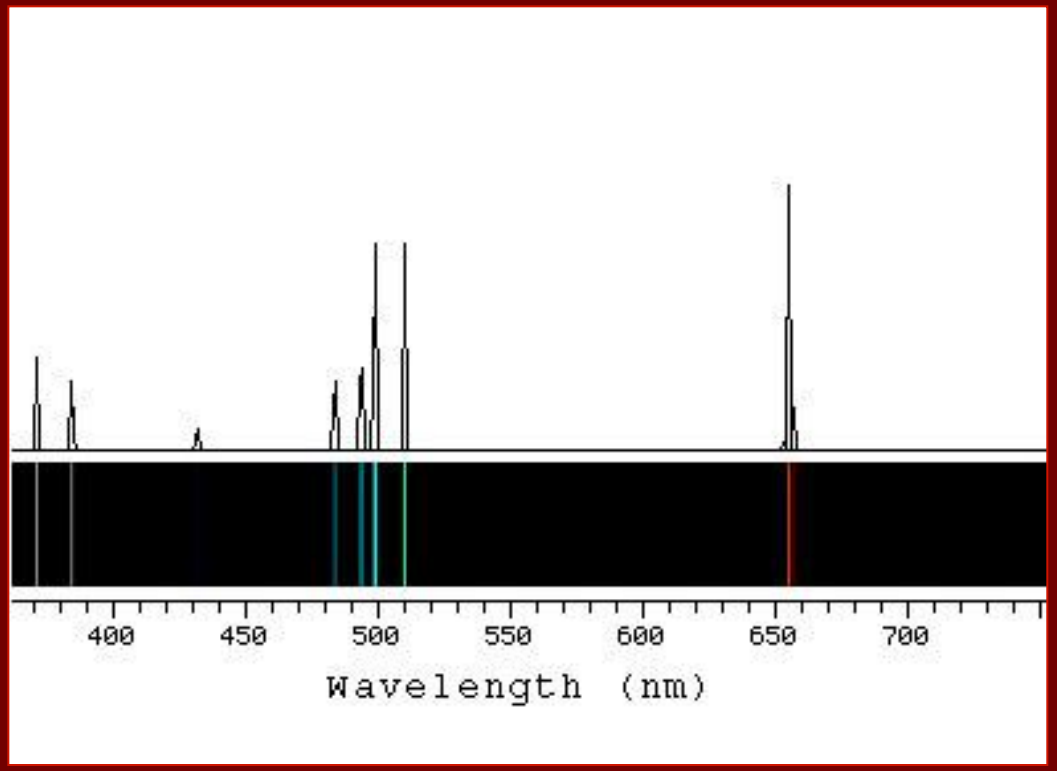
Edwin Hubble
(1889-1953)



Evidence for an expanding Universe 1

Orion Nebula

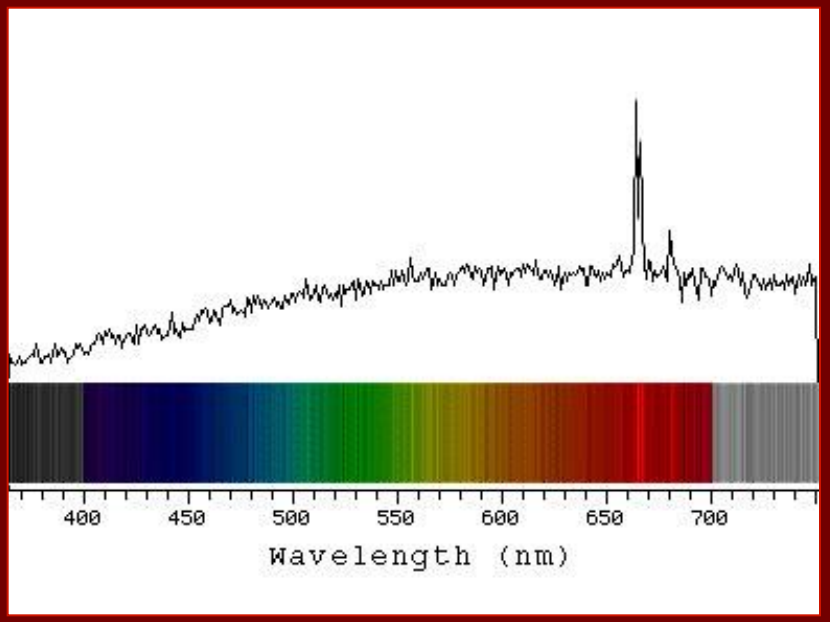
When we see a repeat of the pattern that we saw in the Lab, we know that hydrogen is present.



Evidence for an expanding Universe 2

Galaxy UGC 12915

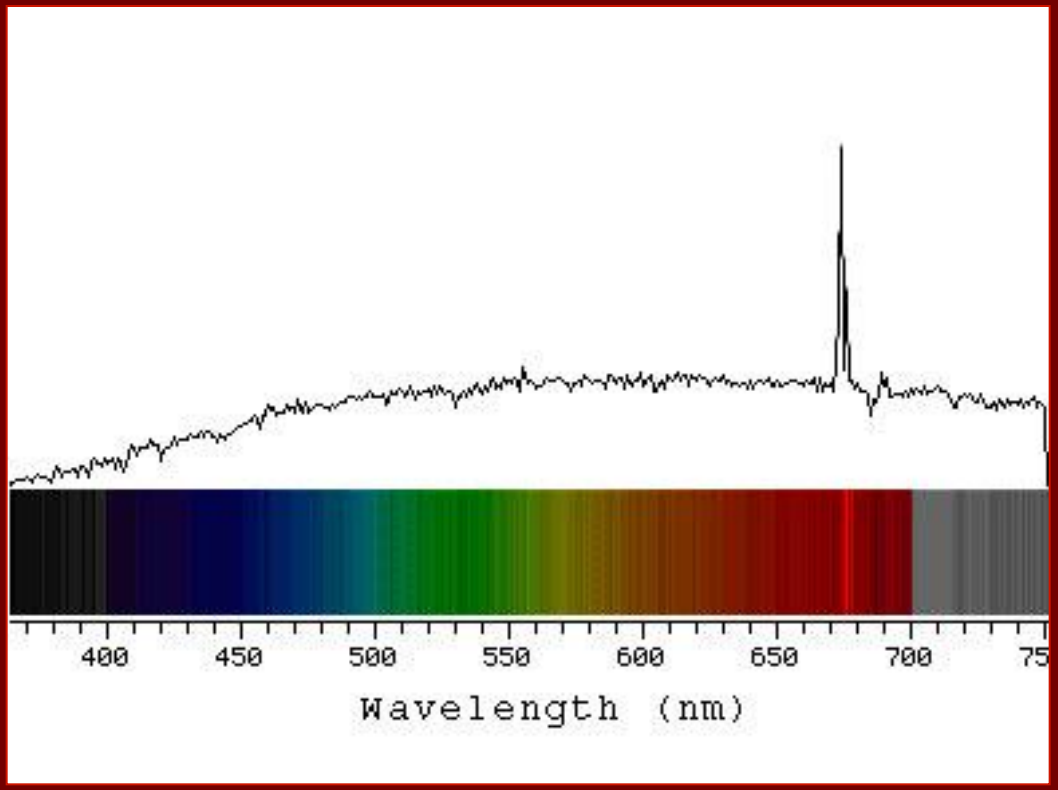
We see the same repeating pattern of lines in a galaxy, but displaced to the red.



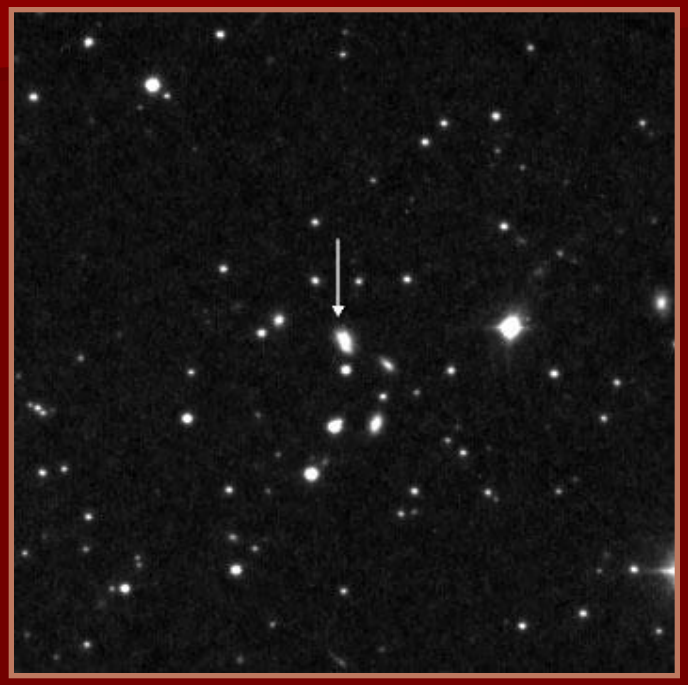
Evidence for an expanding Universe 3

Galaxy UGC 12508

The further the galaxy is,
the more it shifts to the red.

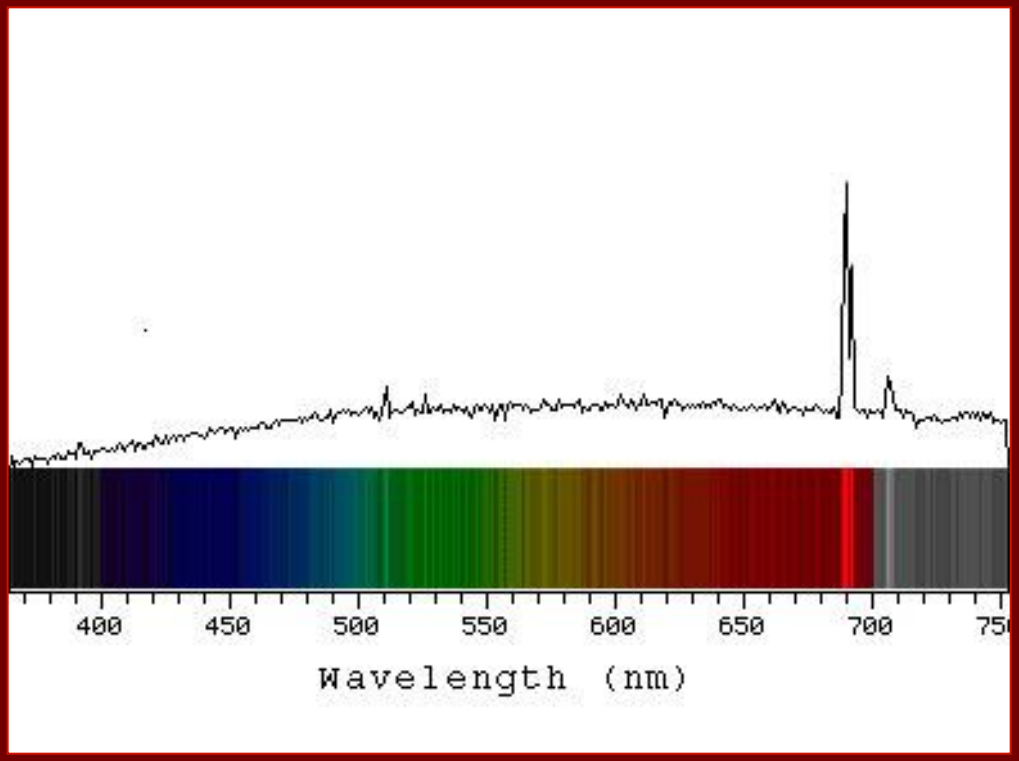


Evidence for an expanding Universe 4

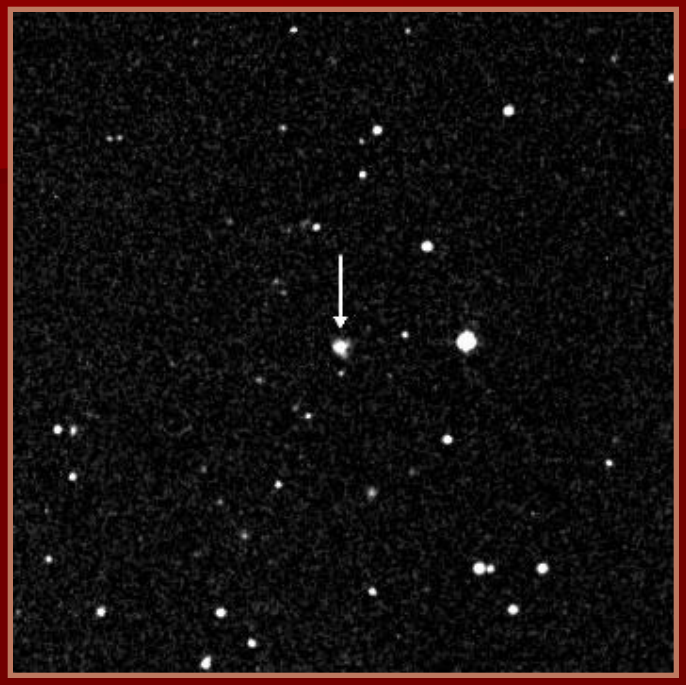


Galaxy KUG 1750

The greater the red shift is, the faster the galaxy is receding.

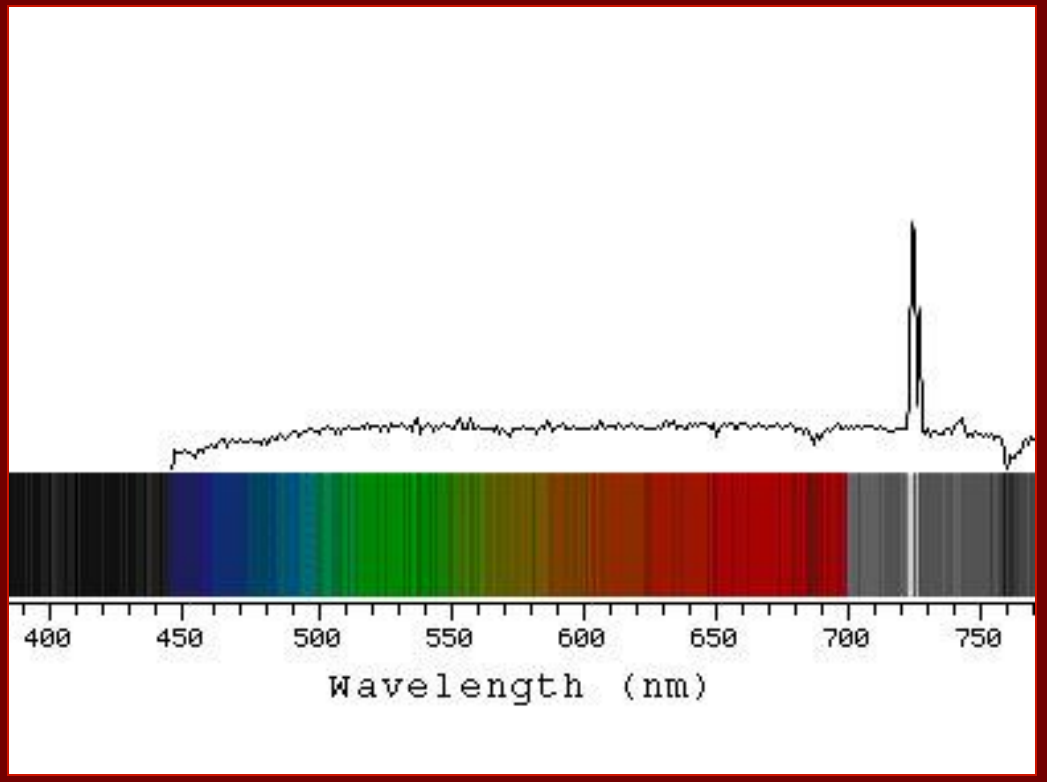


Evidence for an expanding Universe 5



Galaxy KUG 1217

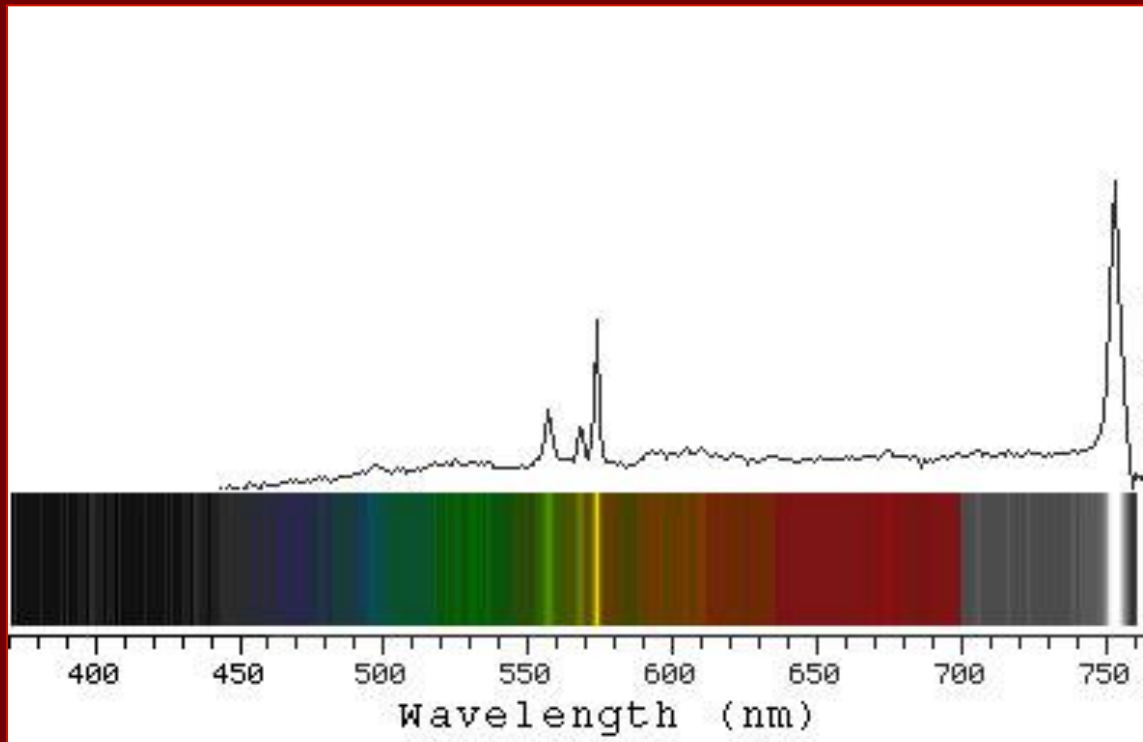
The red shift is caused by the expansion of space.



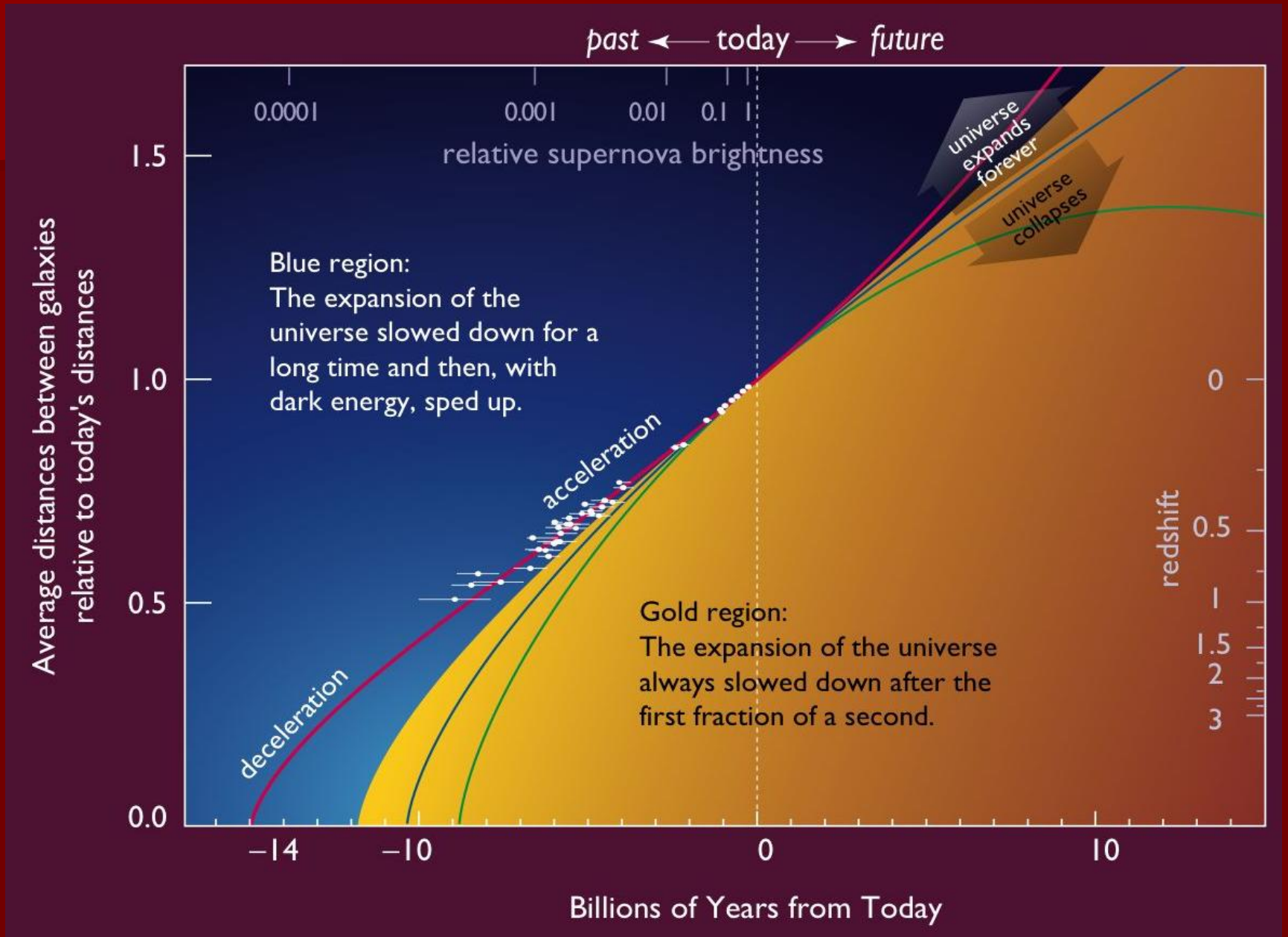
Evidence for an expanding Universe 6

Galaxy IRAS F09159

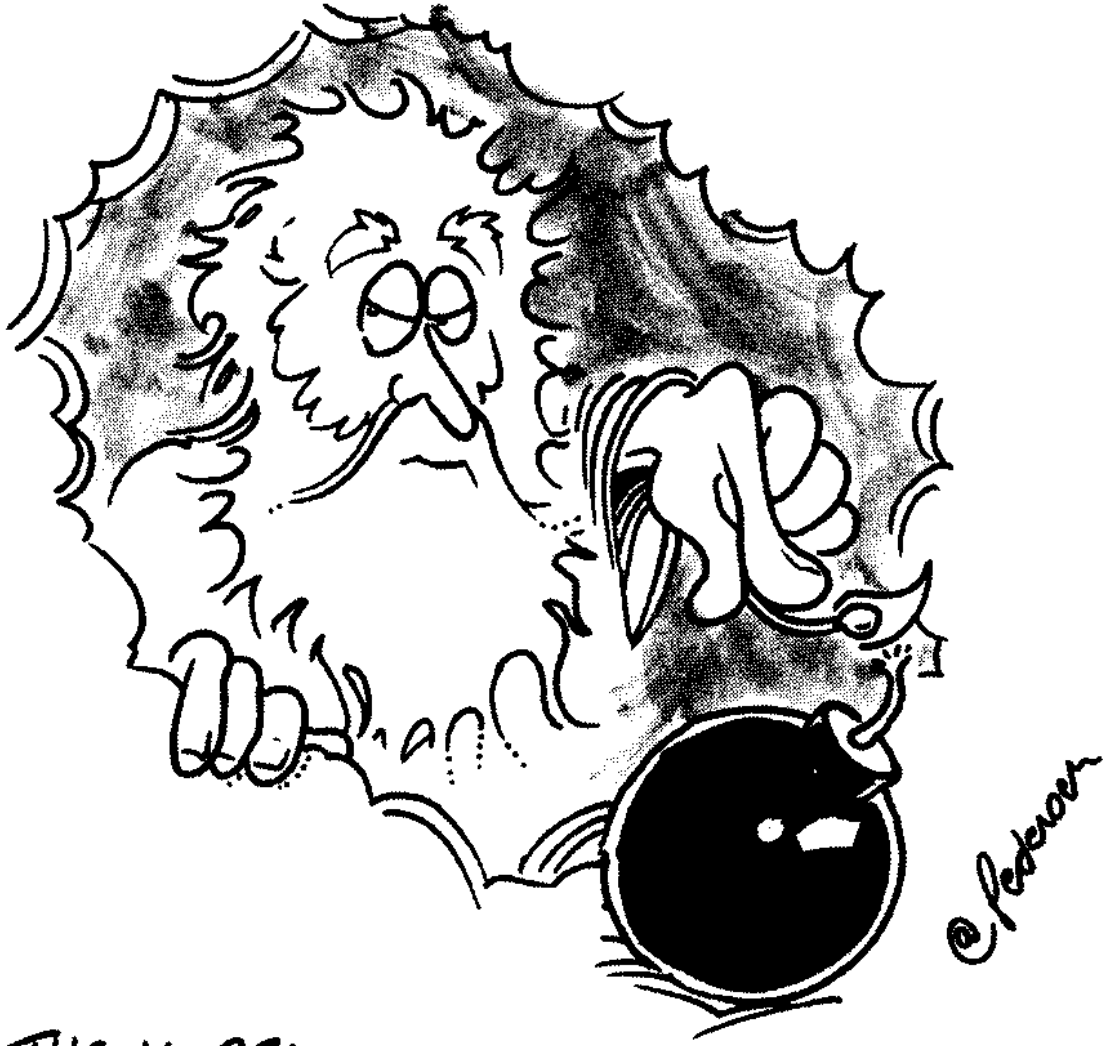
The red shift is evidence of an expanding Universe.



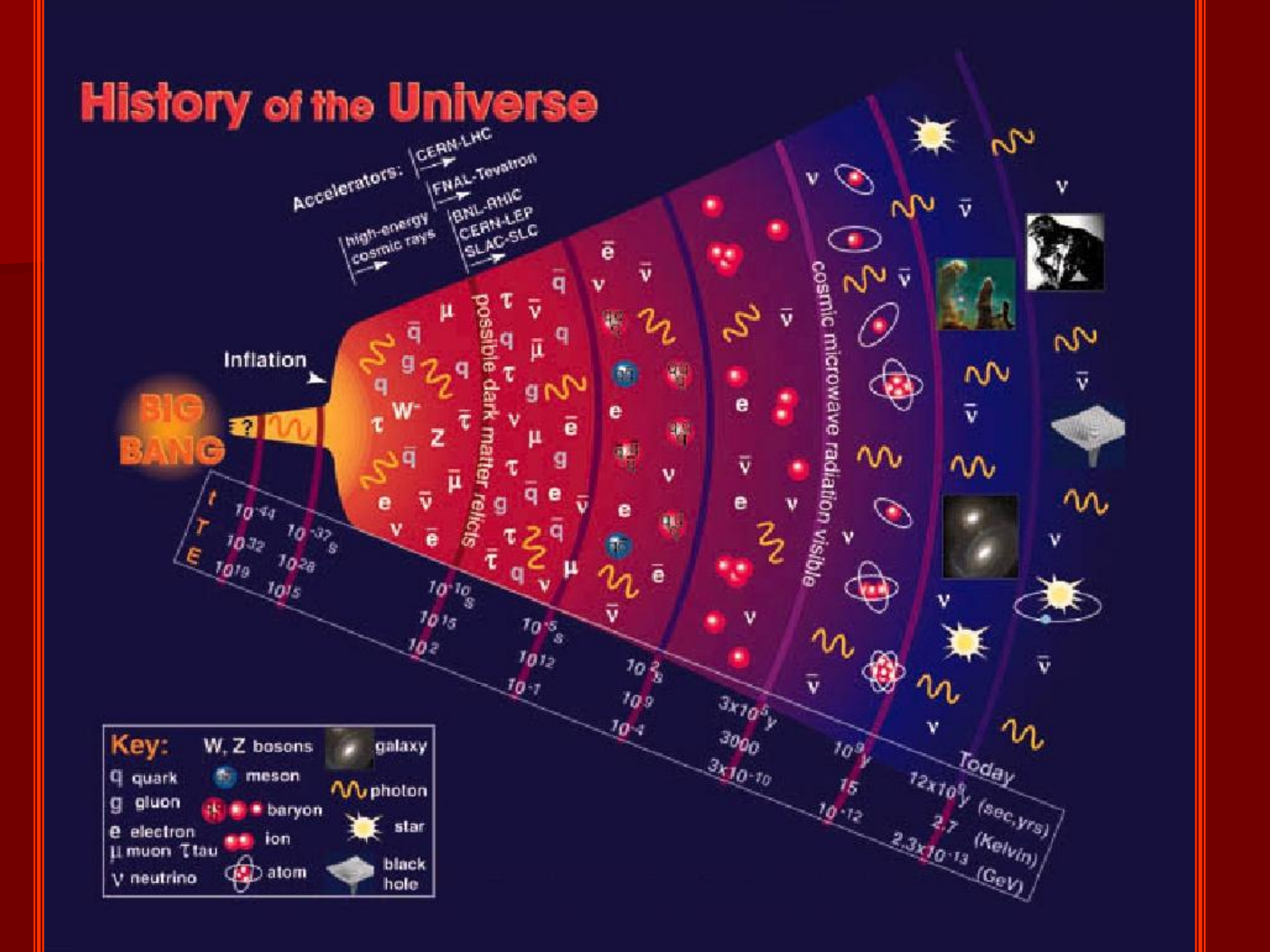
Discovery! Acceleration



Big Bang?



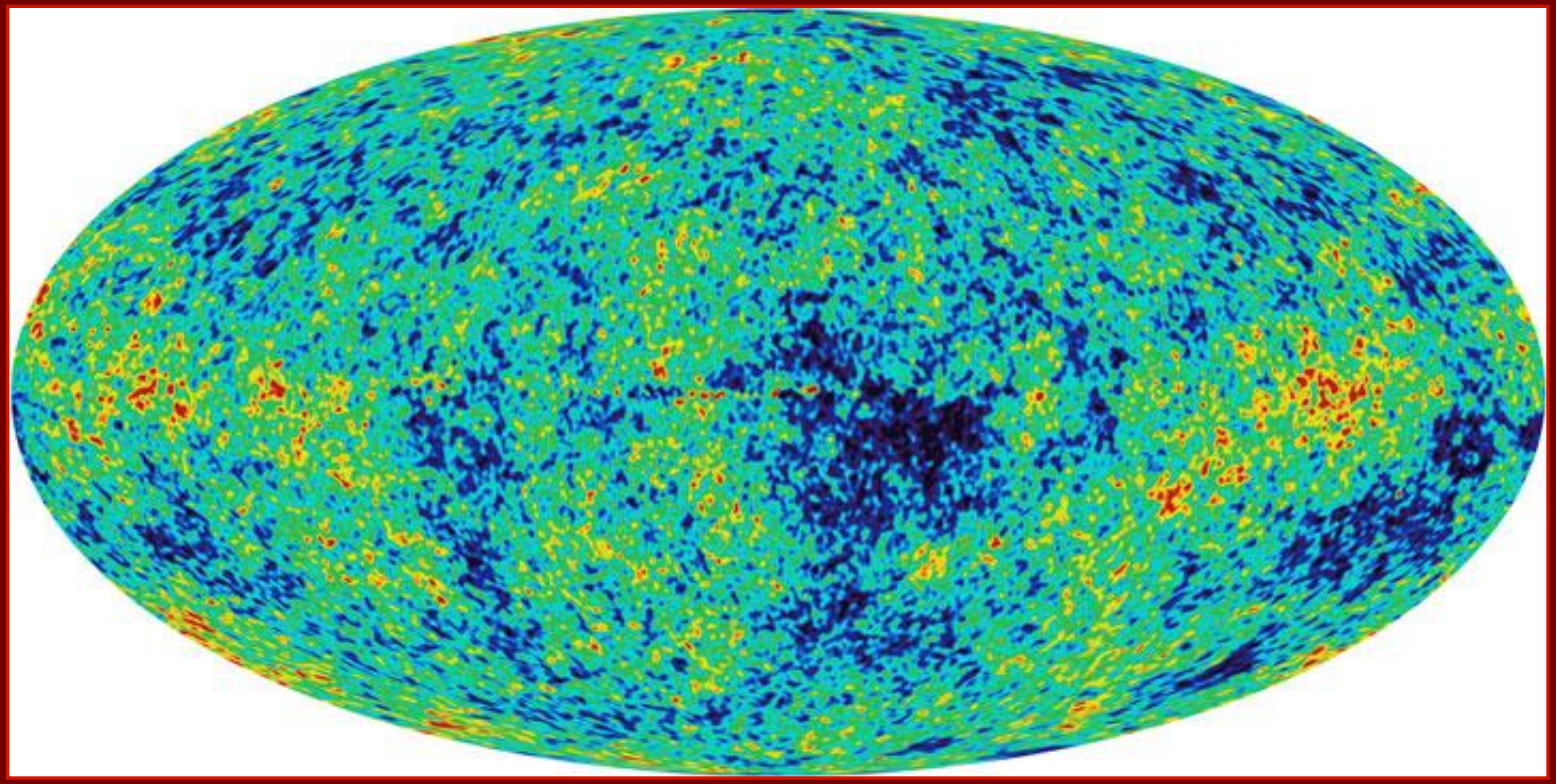
THE HUBBLE TELESCOPE FINALLY SEES THE BEGINNING OF THE UNIVERSE.


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
t
T
E
10-44
10-37 s
1032
1028
1019
105
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
galaxy
photon
star
black hole

Testing the Big Bang model

Prediction: **If the Universe was denser and hotter in the past, we should see the evidence of left-over heat from an early Universe.**

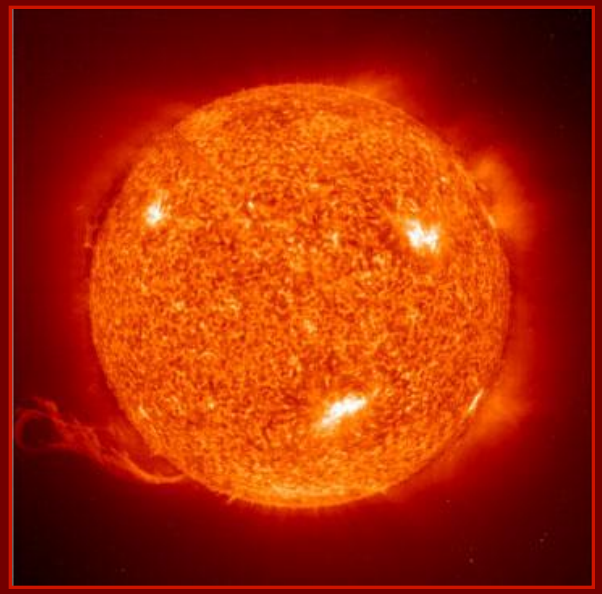
Observation: **Left-over heat from an early Universe.**
(Penzias and Wilson, 1965)



Testing the Big Bang model

Prediction: A hot and dense expanding Universe should be predominantly hydrogen and helium.

Observation: Universe is ~75% hydrogen, ~25% helium by mass



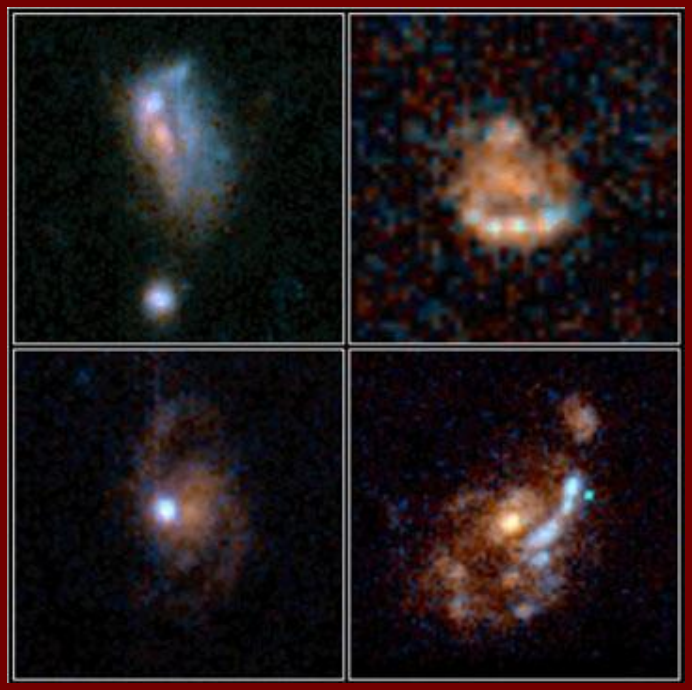
The Sun: 74.5% H, 24% He by mass

Cecilia Payne

Testing the Big Bang model

Prediction: An expanding Universe is evolving over the time. If we look at an early Universe, it should appear to be different.

Observation: Distant galaxies less evolved, physically and chemically.



Testing the Big Bang model

Observation: 90% of matter is an unknown form: Dark Matter.

Refine: A new and unknown form of matter exists. But its gravity works in the same way and its presence is needed to explain how the Universe looks.

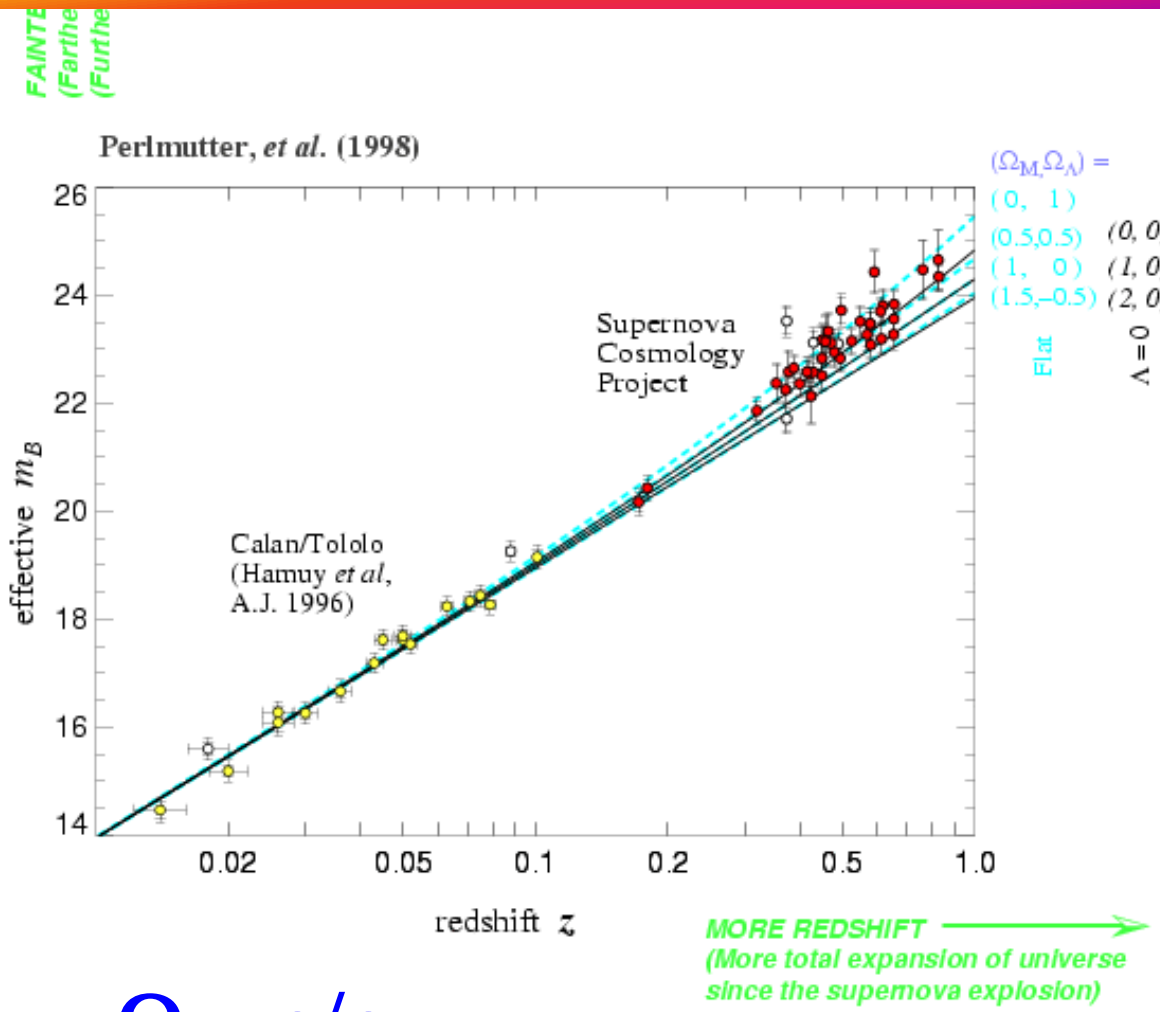
Vera Rubin

Dark Energy

Dark Energy - is the Energy of Physical Vacuum in the Space

Perlmutter et al., 1998
Riess et al., 1998

The Universe was expanding slower in the distant past!



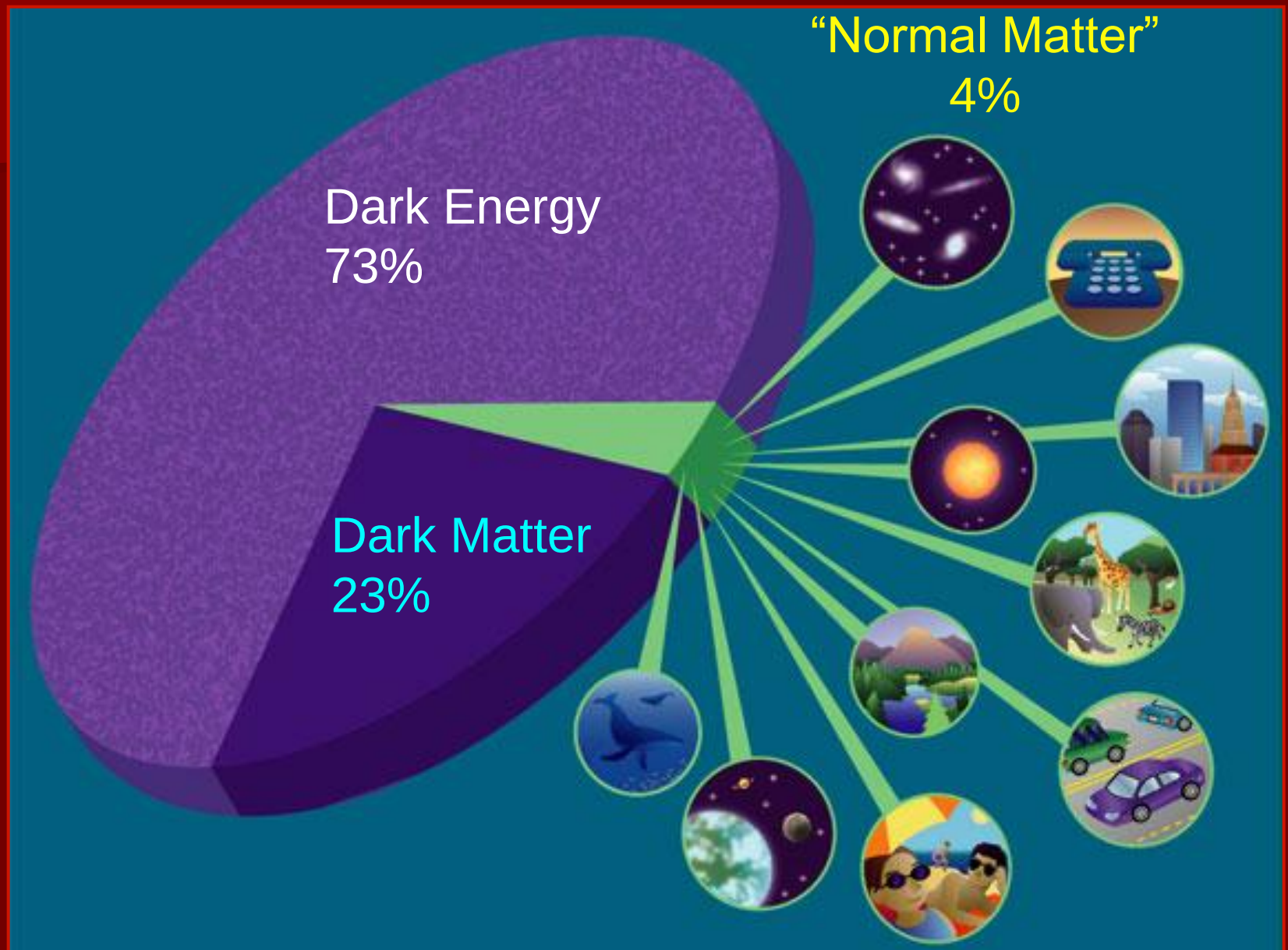
$\Omega = \rho/\rho_c$

In flat universe: $\Omega_M = 0.28$ [± 0.085 statistical] [± 0.05 systematic]
Prob. of fit to $\Lambda = 0$ universe: 1%

Dark Matter Halo

1. The rotating disks of the spiral galaxies that we see are not stable
2. Dark matter halos provide enough gravitational force to hold the galaxies together
3. The halos also maintain the rapid velocities of the outermost stars in the galaxies (violation of the Kepler's laws)

Energy budget of Universe



The summary on the General Relativity and Universe

1. Big Bang model describes our current understanding of the Universe.

2. New discoveries, such as Dark Matter and accelerating expansion (Dark Energy), lead us to refine our model, but there is no crisis in our understanding (yet).

The End

Kob Khun Krab!

Thank You for Your Attention