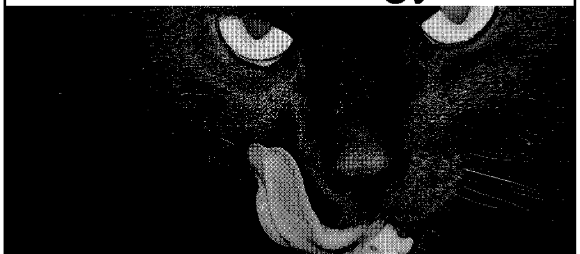
Dark Energy



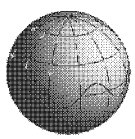
Wednesday, October 28

Hand in P.S. #4, pick up “Mini Exam”.

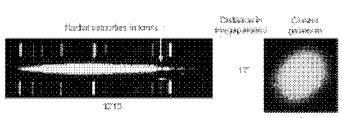
Last planetarium show tonight at 6:30 pm!

The universe is expanding.

As space expands, **wavelength of light** (distance between wave crests) increases.



We now have two ways to think about a galaxy’s redshift.



1) The redshift is the result of a Doppler shift.

2) The redshift is the result of expansion stretching the wavelength.

Example: a galaxy has a redshift
z = $(\lambda-\lambda_0)/\lambda_0$ = 0.01.

Doppler Explanation:

1) Radial velocity of the galaxy is 1% of the speed of light:

v = 0.01 c = 3000 km/sec
d = v/H_0= 42.25 Mpc.

Expansion Explanation:

2) The distance to the galaxy **now** is 1% greater than it was when the light we observe was emitted:

d_{now} = 42.25 Mpc
d_{then}= 42.25 Mpc / 1.01 = 41.84 Mpc

Which way of thinking about redshift (Doppler or expansion) is
The Right Way??

In the limit of small redshift (v < c), they give identical results.

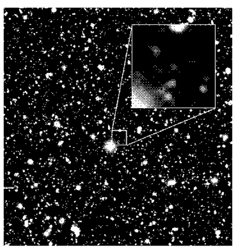
Let's see why!!

Light from galaxy has traveled
$d_{average}$ = 42 Mpc = 137 million light-years
in a time t = 137 million years.

During that time, distance to the
galaxy has expanded by
0.01 $d_{average}$ = 1.37 million light-years.

Average radial velocity =
1.37 million light-years / 137 million years =
0.01 c.

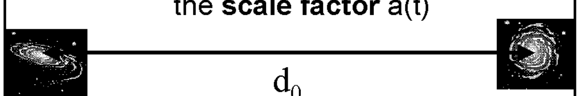
Galaxy with the **highest known redshift**:



Name:
IOK-1
Redshift:
z = 7

For very distant galaxies (z>1),
it's best to think of redshift as
being due to **expansion**.

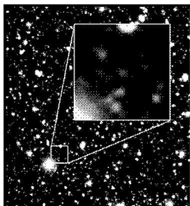
Homogeneous & isotropic expansion
can be expressed by **one** function:
the **scale factor** a(t)



d_0

Two galaxies are currently
separated by a distance d_0.

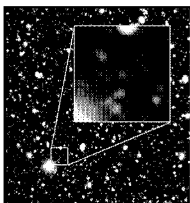
At an earlier time t, they were separated
by a smaller distance $d(t) = a(t) \times d_0$.



Redshift z=7.
What does this mean?

Hydrogen has an emission line at λ_0 = 122 nm. In this galaxy, the line is seen at λ = 8 × 122 nm = 976 nm.

$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{976\,\text{nm} - 122\,\text{nm}}{122\,\text{nm}} = 7$$



Light emitted with λ_0 = **122 nm** has been stretched to λ = **8 × 122 nm** = 976 nm.

The universe has expanded from a scale factor **a = 1/8** (when light was emitted) to **a = 1** (when light is observed).

If we observe a distant galaxy with redshift z, the scale factor a at the time the galaxy's light was emitted was:

$$a = \frac{1}{1+z}$$

Example: $z = 1$ implies $a = 1/(1+1) = ½$.

Example: $z = 3$ implies $a = 1/(1+3) = ¼$.

Photons from distant galaxies aren't stamped with "born on" dates.

However, they **are** stamped with the amount by which the universe has expanded since they were "born".

$$a = \frac{1}{1+z}$$

scale factor (a)

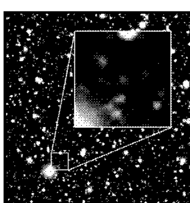
(measurable) redshift (z)

Expansion & curvature of space are described by the **Friedman equation**.

A. Friedman

As the textbook states the Friedman equation,

Math expressing scale factor a(t) & curvature = Math expressing density of mass & energy



When was the light we observe from this galaxy emitted?

t = 0: Big Bang

t ≈ 750 million years: light from distant galaxy emitted

t ≈ 14 billion years: now

The Friedman equation states that space is **flat** (Euclidean) if its density equals a critical density ρ_{crit}.

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

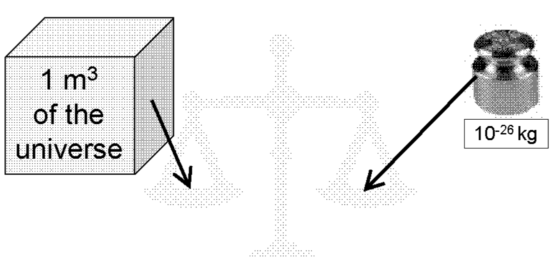
This critical density depends **only** on the gravitational constant G and on the Hubble constant H_0.

With H_0 = 71 km/sec/Mpc, the critical density is:

$$\rho_{crit} = 10^{-26}\ \mathrm{kg/m^3}$$

Yes, this **is** a very low density!
Water: 1000 kg/m^3
Air: 1 kg/m^3

If Einstein is right, the electrons, protons, neutrons, photons, etc. in the universe must sum to (nearly) the critical density.

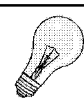


Let’s do an **inventory** of the universe:

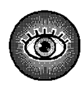
How much mass/energy is contributed by electrons, protons, neutrons, photons, neutrinos, WIMPs, etc.….

Accounts must balance!

First: PHOTONS

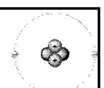


Photons are easily detected!



Inventory: photons provide 0.01% of the critical density. Pffft.

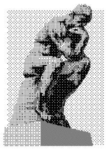
Next: ELECTRONS, PROTONS, & NEUTRONS



Ordinary matter (stars, planets, people, etc.) is made of electrons, protons, & neutrons.

These are easily detected because they emit photons.

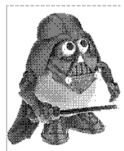
Electrons, protons, & neutrons provide 4% of the critical density.



Light & ordinary matter make up only **4%** of the universe.

Where's the rest of the mass & energy?

To answer that question, we must turn to the **Dark Side**.



Next: Dark Matter (neutrinos & WIMPs)

Add together dark matter around galaxies and in clusters: there is more dark matter than ordinary matter!

Dark matter provides 23% of the critical density.

Inventory of the universe:

Light = utterly negligible

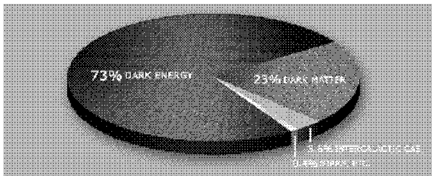
Ordinary matter = 4%

Dark matter = 23%

Something else = 73%

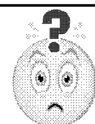
What is the "something else"?

The "something else" isn't ordinary (luminous) matter, dark matter, or energy in the form of photons.



Astronomers call the "something else" **dark energy**.

Dark **energy** is even less well understood than dark **matter**.



Dark energy is a **uniform** energy field (unlike dark matter, it doesn't "clump up").

Since its density is so low everywhere, **how do we know dark energy's there?**

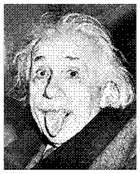
One reason for thinking that dark energy exists:

The universe is flat on large scales; there isn't enough **mass** to do the flattening, so there must be **energy**.

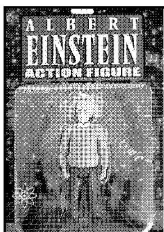
If the energy emitted light, we'd have seen it by now, so it must be **dark** energy.

The **weird** reason for thinking that dark energy exists:

Einstein: a component of the universe whose energy density is **constant** in time and space provides a **repulsive** force.



Newton would not approve!



Einstein called this component of the universe the "cosmological constant": we call it "**dark energy**".

Matter makes the expansion of the universe **slow down**.

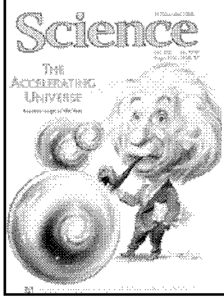
Dark energy makes the expansion of the universe **speed up**!

Testing for dark energy:

- Look at a supernova (an exploding star as bright as a billion Suns)
- Measure its redshift and flux.
- If the expansion of the universe is speeding up, then a supernova with large redshift will be overly faint.

The result:

The expansion is **speeding up**, implying the presence of dark energy.



Science magazine's "Breakthrough of the Year" for 1999!

Friday:

Midterm Exam

Bring your calculator and your favorite writing instrument.

Last planetarium show tonight at 6:30 pm!