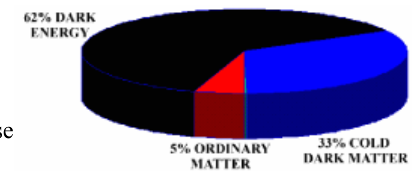
The New Cosmology



- flat, critical density, accelerating universe
- early period of rapid expansion (inflation)
- density inhomogeneities produced from quantum fluctuation during inflation
- composition: 2/3 dark energy; 1/3 dark matter; 1/200 bright stars
- matter content: 30% cold dark matter; 4% baryons; 0.3% neutrinos
- current temperature: T=2.73 Kelvin
- current age: 14 billion years (Gyr)
- current expansion rate (hubble's constant): 72 km/s/Mpc

Expansion of the Universe

The expansion of the universe is governed by the equation:

$$\ddot{a}/a = -\text{constant} \times (\rho + 3p) + \Lambda/3$$

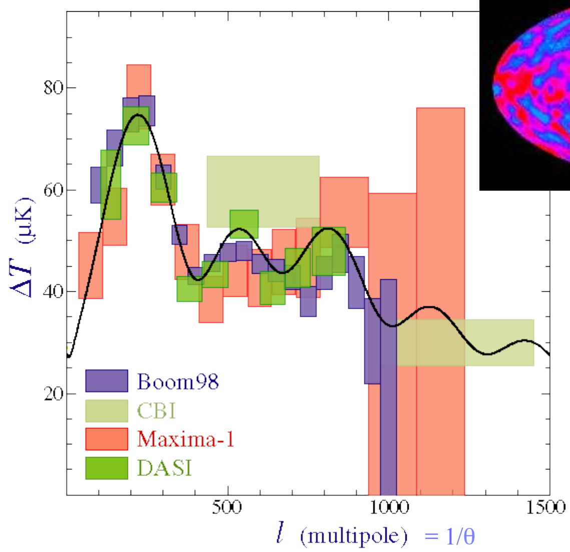
$\ddot{a}/a$ = acceleration of size, a, of the universe
(>0 speeding up)
(<0 slowing down)

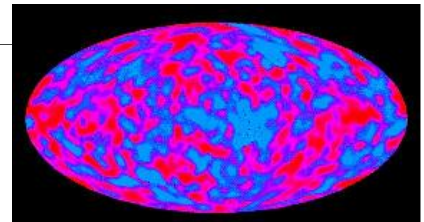
ρ = density of matter in the universe
(gravitational term; contributes to <0, slowing down of expansion)

p = pressure exerted by matter
(contributes to <0, slowing down of expansion)

Λ = cosmological constant
(mysterious anti-gravity term; contributes >0, speeding up of expansion)

The CMB Spectrum- Temperature Fluctuations vs. Angular Separation





You pick two spots on the map separated by some angle $\theta=1/l$ and compute the temperature difference.
You do this for every point on the sky and them bin the data into a distribution
(as is done for your test grades).

Inflation Theory

We learned that the CMB is very uniform; the temperature at all locations in the sky is remarkable the same (though there are very small variations).

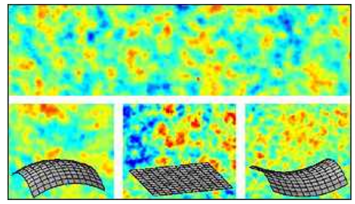
This means that all parts of the universe were causally connected at one point in the past. This means that every point in the universe at one time had to be able to "communicate" with every other part (recall that the fastest that information can travel is the speed of light).

However, when we run the clock back via previous expansion equation, we never achieve a causally connected universe after matter was created.

This is called the **horizon problem**. It was solved by assuming a non-zero cosmological constant, Λ, at very early times. This causes a period of rapid expansion called Inflation. There is lots more to it than this.

The cosmological constant must have dominated over gravity at the dawn of the universe. In GUTs, this is explained using the vacuum energy.

The Building Evidence for Inflation
The Universe is Flat
$\Omega_0 = 1$



The first peak in the CMB spectrum provides powerful measurement of the curvature of the universe. We find that the curvature radius is 50 times greater than the size of the universe, i.e. it is virtually flat; $\Omega_0 = 1$.

Since the 1970's, we knew the universe was *really* close to being flat and not *really* open or *really* closed. This was called the **flatness problem**. Inflation naturally predicts a flat universe and theoretically solved this problem. The CMB spectrum is powerful support of *Inflationary Cosmology*.

The remaining peaks in the CMB spectrum provide the powerful means to measure the spectrum of primordial density perturbations from which structure (i.e. galaxies, clusters, large scale structure) grows. We observe that they are scale invariant. This means that *there is no shape to the over-density spectrum*; that is, all sizes of over-densities are equally frequent in the universe. This was also predicted, and mandated by Inflation theory!

If the CMB had given different answers, inflation would be a dead theory.

The Cosmological Density Equation

- We defined $\Omega_0=\rho_0/\rho_c$, where ρ_c is the critical density
- The critical density is that which makes the universe flat.

Therefore, if $\Omega_0=1$, then the universe is a flat.

Total Density = Matter Density + Energy Density

$$\Omega_0 = \Omega_M + \Omega_E$$

Matter Content

The total matter density, Ω_M, is the sum of baryonic matter (stars and gas) and dark matter (unknown form that is, so far, detected only through gravity)

$$\Omega_M = \Omega_B + \Omega_{DM}$$

We are able to measure Ω_B from two *very different* cosmic events:

1. Big bang nucleosynthesis
   cosmic elemental abundances (deuterium, helium, hydrogen)
   redshift = 1 billion! (age = few minutes)
   nuclear physics (strong and weak nuclear forces)

2. Recombination
   CMB spectrum shape (sizes and shapes of peaks)
   redshift = 1000 (age = 1 million yrs)
   atomic physics (electromagnetic force)

Both give $\Omega_B = 0.02$ (ordinary matter)

Matter Content, cont.

The ratio of all matter (anything that clusters- baryons, neutrinos, dark matter) to that of ordinary matter (baryons) can be measured using both the CMB spectrum and the clustering of galaxies.

CMB gives $\Omega_M/\Omega_B = 7$

Clusters give $\Omega_M/\Omega_B = 9$

Two things:

1. These numbers are consistent with one another, again from very different physics (CMB-recombination and clustering-gravitation).

2. The results imply dark matter is more abundant than ordinary matter by a factor of 7-9 (not accounting for neutrinos)

From this we infer: $\Omega_M = 0.33$

What about those pesky neutrinos?

Because Ω_M/Ω_B is so large, and its measurement involves clustering, we infer that the dark matter clusters and is therefore "cold" (moving slowly).

But…

Neutrinos are created in the nuclear reactions of every star (100 billion stars each creating 10^{38} neutrinos per second!!!) and in every supernova explosion.

Evidence is strong that neutrinos have a very tiny mass (1 ten millionths of an electron's mass). This is measured from neutrino oscillations, a result that resolved the solar neutrino problem.

Still…

Neutrinos are "hot", fast moving matter that does not cluster well. Clustering data and mass budget of neutrinos renders neutrinos only 0.3% of the matter density. Neutrinos are not an important contribution to Ω_M, nor to Ω_0.

Matter Content, Recap.

$$\Omega_M = \Omega_B + \Omega_{DM}$$

$\Omega_B = 0.02$ — Ordinary Matter (Stars & Gas)
From big bang nucleosynthesis and CMB

$\Omega_M/\Omega_B = 7\text{-}9$ — Ratio of all matter that clusters to ordinary matter
From Clustering and CMB

$\Omega_M = 0.33$ — All matter, including dark matter

So, What is the value of Ω_E ?

We know that:

$$\Omega_0 = \Omega_M + \Omega_E$$

where

$\Omega_0 = 1$ From CMB spectrum measurements (flat universe)

$\Omega_M = 0.33$ From CMB spectrum measurements and clusters, were matter includes stars+gas (baryonic matter) and dark matter (unknown form)

The energy density is then indirectly inferred from the sum

$$\Omega_E = \Omega_0 - \Omega_M = 0.67$$

But this tells us nothing about the nature of this energy!

Graphical Representation

$$\Omega_E = \Omega_0 - \Omega_M = 0.67$$

We used to think that the universe was nearly FLAT and Λ=0 (green circle). That is, we used to think that Ω_M=1.

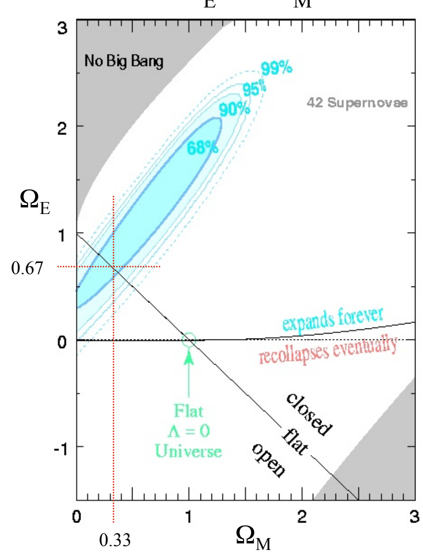
Now, we know that

$\Omega_0 = 1$
$\Omega_M = 0.33$

We are constrained to the FLAT universe curve in the diagram from W0 = 1.

Where it crosses Ω_M=0.33 gives the value of Ω_E.

Ω_E vs. Ω_M



Nature of the (dominating) Energy Density. Evidence 1

There are two lines of evidence that this mysterious energy behaves as if it has negative pressure.

The first is an *indirect argument*, as follows:

To escape detection, the energy must be distributed uniformly throughout space. Because it is smoothly distributed, if Ω_E dominated in the past it would have inhibited the growth of structure in the universe. The universe would not look like it does today.

Thus, Ω_E must have been much smaller than Ω_M in the past. The only way for that to happen is if the ratio of the pressure to the density, $\omega = p/\rho$, to be less than zero (that is, p is negative). The parameter ω is called the equation of state. The CMB data constrain it to have

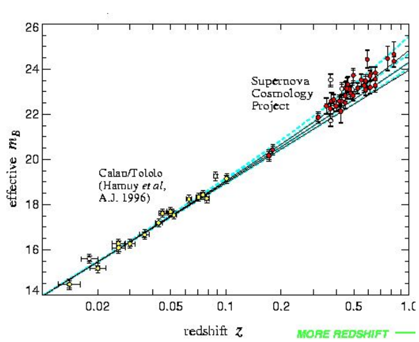
$$\omega < -0.5$$

Inflation theory predicts (insists) that $\omega = -1$.

Nature of the (dominating) Energy Density. Evidence 2

The second is *direct* and was *very recently* found using supernovae (standard candle method) and the Hubble Diagram!

It was always assumed that the expansion of the universe was *slowing down* with cosmic time (decelerating). The supernovae data show that the expansion of the universe is currently *speeding up* with time (accelerating).



Supernovae brightness as a function of redshift. The curves show the expected magnitudes for different accelerations of the universe.

Note the high redshift points are all too high, indicating that they are *dimmer than predicted* for a universe that is decelerating (slowing down)– they are further away than expected!!! *The universe is accelerating* (speeding up).

http://panisse.lbl.gov/

This means that the energy behaves *like* anti-gravity and has a negative pressure! We do not know what this energy is! We call it Dark Energy!

Properties of the Dark Energy

1. It emits no light
2. It has negative pressure, $p \sim -\rho$
3. It is homogeneous and ubiquitous (does not cluster)
4. It is more energy-like than matter-like

Dark energy is not a replacement for dark matter (which clusters).
Dark energy is qualitatively very different from dark matter.

The Cosmological Constant Conundrum

Is the dark energy related to the cosmological constant, Λ?

$$\underbrace{\ddot{a}/a}_{\text{acceleration in size of universe}} = \underbrace{-\text{constant} \times (\rho + 3p)}_{\text{deceleration term}} + \underbrace{\Lambda/3}_{\text{acceleration term}}$$

The only theory that yields a quantity having the exact mathematical form as Λ comes from quantum field theory. The quantum vacuum energy provides a natural explanation for Λ.

The quantum vacuum energy is the "energy tension" *between matter* that results in *virtual*, fleeting matter and anti-matter *particles pairs* being created out of "nothing" and then annihilating one another back into "nothing" (this is from Einstein's $E=mc^2$)

THE CONUNDRUM IS THAT the quantum vacuum energy density is too large by 150 powers of 10!
There is no theory that explains the current energy density of the dark energy!!!!

Whatever the Dark Energy is and However it relates to the Cosmological Constant, one thing is clear…

If the dark energy is the same energy that drove inflation, then it was very dominant at the beginning of the universe and is now only becoming dominant again. *(Recall, the reason we know it was not dominant in the interim is because of structure growth in the universe, which would have been suppressed if the dark energy was always dominant over matter).*

Why should it change with time?

Why should it only now be increasing so dominate over the matter energy again? Are we fooling ourselves here? Why so recently (now)?

http://focus.aps.org/v5/st8.html