Dark Energy

Key Concepts

1) The Universe is flat.
2) There is a critical density required for space to be perfectly flat.
3) Most of the critical density, it seems, is provided by dark energy.

(1) This space is flat (or Euclidean):

Flat Space

Zero Curvature

“Angles at the vertices of a triangle add to 180°.”

“Parallel lines never meet.”

(2) This space is positively curved:

Spherical Space

Positive Curvature

the “gumball” universe

If space has positive curvature, it has a finite volume, but no boundary.

Analogy: the Earth’s surface has positive curvature. It has a finite area, but no edge.

(3) This space is negatively curved:

Hyperbolic Space

Negative Curvature

the “Pringles” universe

If space has negative curvature or is flat, it has an infinite volume, unless a boundary is imposed.
Measuring curvature is easy, in principle.

Flat: angles of triangle add to 180°
Positive: angles add to >180°
Negative: angles add to <180°

Curvature is hard to detect on scales smaller than the radius of curvature.

Flat = good approximation
Flat = bad approximation

Positively curved space is a magnifying lens; distant galaxies appear anomalously large.
Negatively curved space is a demagnifying lens; distant galaxies appear anomalously small.

And the answer is...
The Universe is flat.

Distant galaxies are neither absurdly small in angle nor absurdly large.

If the universe is curved, radius of curvature is bigger than the Hubble distance (c/H₀ = 4200 Mpc).

Applying Einstein’s theory of relativity to the Universe: space is flat if its mass-energy density equals a special (or critical) density:

\[ \rho_{\text{crit}} = \frac{3H_0^2}{8\pi G} \]

This critical density depends on the gravitational constant \( G \) and on the Hubble constant \( H_0 \).
With $H_0 = 71 \text{ km/sec/Mpc}$, the critical density is:

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

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. Pfft.

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.

Inventory of the universe:

Light = utterly negligible
Ordinary matter = 4%
Dark matter = 23%
Something else = 73%

What is the “something else”?

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?

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.

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

Astronomers call the “something else” dark energy.

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 (in Newtonian terms) a repulsive force.

Newton would not approve!

**Testing for dark energy:**

1) Look at a supernova (an exploding star as bright as a billion Suns): these are good standard candles.
2) Measure its redshift and flux.
3) If the expansion of the universe is speeding up, then a supernova with large redshift will be overly faint.

**An Accelerating Universe**

Careful observations of very far away galaxies tell us that the expansion rate of the Universe is not constant.
- Universe seems to be accelerating.
- Acceleration is a result of some unknown source of energy: *The Dark Energy.*

**Other Constraints**

Get better constraints by combining many different, complementary observations.

**Galaxy Clusters:**
- Measure amount of matter

**Supernova:**
- Measures acceleration

**Cosmic Background Fluctuations:**
- Measures geometry
The Current Bottom Line

These overlapping constraints allow us to better pin down the geometry and the expansion history of the Universe.

Bottom line: We live in a flat, accelerating Universe.

The result:

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

*Science* magazine’s “Breakthrough of the Year” for 1999!

Nobel Prize for physics in 2011!