Astro 2: History of the Universe

Lecture 1: Introduction to the Study of COSMOLOGY
What is the shape of the Universe?

Where did it all come from?

What is the Universe made of?

How do we know???

Is there anything special about HERE and NOW????
In this course we will attempt to answer all these questions, at least as far as we understand today...

By the end of this course you will have an understanding of the evidence for the answers to these questions, and be able to extract the clues from the acoustic spectrum of the oldest observable radiation, the Cosmic Microwave Background...

... and we will raise more questions that, hopefully, will be answered in this century!
What is the shape of the Universe?

open? (like a Pringles potato chip)

flat? (like a piece of matzah)

closed? (like a ball)
How can we tell the shape of space?

Parallel lines diverge

Parallel lines meet at the poles

Parallel lines never meet
General Relativity explains and predicts the shape of space and the nature of time:

All accelerations are equivalent.
Gravity is not a force, but a curvature of space.
Mass bends space and slows time

and black holes are the ultimate folding of space and stopping of time
Light follows the curvature of space
large masses act like lenses and distort the images of more distant objects
The Universe today:

Mostly empty
Homogeneous and Isotropic at the largest scales
Expanding

Mostly very, very cold

Clumpy at medium scales
How do we know???

* that the universe is expanding?

Redshifts of the spectral lines from distant galaxies are due to the stretching of light as space expands since the time the light left the galaxy.
What is the Universe made of?

The final accounting seems to be:

- 5% Ordinary Matter
- 25% Dark Matter
- 70% Dark Energy
* What comprises the matter of the Universe?

We can measure the relative abundances of light elements and this limits the possible ways in which they could have formed.
Second surprise: Most of the universe isn't even matter! It's something called **Dark Energy**, which:

- is smoothly distributed through space
- varies slowly (if at all) with time.

Paradigmatic candidate: **vacuum energy** (a/k/a the cosmological constant, $\Lambda$).
An immutable energy inherent in every cubic centimeter of space.

(artist's impression of vacuum energy)
The universe: uniform (homogeneous and isotropic) space expanding with time.

Relative size at different times is measured by the scale factor $a(t)$. 
What makes up the universe?

Stars and gas are slowly-moving (compared to $c$, the speed of light). Most of their energy is rest energy, from their mass ($E = mc^2$).

Anything which is mostly rest energy, cosmologists call "matter". The energy density in matter is its rest energy times its number density $n_M$:

$$\rho_M = n_M m c^2$$

Hence: $\rho_M \propto a^{-3}$, since the number density gets diluted as the volume expands.
In contrast to matter, consider "radiation" (particles moving at speeds close to c). Radiation redshifts as the universe expands, as wavelengths get stretched; each particle loses energy as $1/a$.

Particles redshift and number density dilutes, so the energy density in radiation goes as

$$\rho_R \propto a^{-4}.$$  

Today, there is much more matter than radiation.
Even with dark matter, there is still not as much matter in the universe as we might expect.

Define the density parameter, $\Omega$:

$$\Omega = \frac{8\pi G}{3H^2} \rho$$

Then, from the Friedmann equation,

- $\Omega > 1 \rightarrow \kappa > 0$ (positive curvature)
- $\Omega = 1 \rightarrow \kappa = 0$ (flat)
- $\Omega < 1 \rightarrow \kappa < 0$ (negative curvature)

Observed matter content (ordinary plus dark): $\Omega_M = 0.3$. 
* that the Universe is very uniformly cold?

The radiation spectrum of the Universe is just like that of an ideal black body with its peak output at 2.76 K.
that the Universe is clumpy at medium scales?

Redshift surveys reveal walls and strings and super clusters of galaxies
Clues as to the density of matter, radiation, and dark energy are contained in the small variations in the Cosmic Microwave Background Radiation which were frozen into spacetime at the time when matter and radiation first separated and the Universe became transparent.
Boomerang map of a small patch of sky over Antarctica
Small scale features in the CMB indicate that the universe is flat.
The power spectrum of small temperature variations in the CMB reveals the clues...
Is there anything special about HERE and NOW??

Cosmic Microwave Background Radiation
***YES!***

Type Ia supernovae are standarizable candles; observations of many at high redshift test the time evolution of the expansion rate.

Result: the universe is accelerating!

There must be some sort of energy density which doesn't redshift away.