The Lure of the Dark and Mysterious: Observational cosmology at Illinois

Thanks to my Dark Energy Survey collaborators, especially Brenna Flaugher (many slides stolen from her).
The History of the Universe
(Compressed by $10^{16}$)

- **Big Bang** (The early universe was small and hot.)
- **Small primordial fluctuations** (due to inflation?)
- The universe expands (and cools)
- **Perturbations grow** (stars, galaxies, bugs)

Any questions?
What We (think we) Know

Size is not to scale!

Speculation

Shaky th.

Solid theory

Indirect obs.

Direct observation

Expansion

Structure

Big Bang

Inflation

Quark Soup

0

10^{-32} Sec.

1 Second

Big Freeze Out

300,000 Years

1 Billion Years

Age of the Universe

12-15 Billion Years

Ionized plasma (opaque)

Neutral gas (transparent)

Light elements (≤ lithium) produced

Cosmic microwave background produced

Heavy elements produced

Dark energy becomes dominant

I’ll talk about these

Temperature (K)

hot!!

10^9

3000

2.7

Temperature (K)
What I’ll Discuss

• Measure the expansion rate as a function of time.
  (Hubble parameter)

• Measure the growth of “lumpiness”.
  (structure formation)

• To make predictions (test the theory), we need initial conditions.
  (provided by the CMB)

The initial conditions are determined by the first 300,000 years of history. I will not discuss this.
The Hubble Expansion

Discovered in 1929. (Hubble, Slipher, Leavitt)

Imagine a rubber sheet that is being uniformly stretched:

\[ \frac{v_1}{r_1} = \frac{v_2}{r_2} \equiv H_0 \sim 70 \text{ km/s / Mpc} = 1 / 14.0 \text{ Gy} \]

The age of the universe ??
The Hubble Expansion

We don’t expect the expansion rate to be constant; we (used to) expect it to slow down,
due to the gravitational attraction between the various objects (stars, black holes, etc.)

A ball thrown up slows down and falls to the ground, (unless it exceeds the escape velocity).

A natural question:

Does the cosmic expansion rate exceed the “escape velocity”? 
Two Plausible Scenarios

Here’s how one might expect the expansion rate to behave:

- Measure the past
- Predict the future

$H$ is the slope

- Expands forever
- Collapses to a big crunch

“size” vs. time
If general relativity is correct:

The fate of the universe is determined by the amount and gravitational properties of its constituents. (matter, radiation, …)
The Properties of the Constituents
We care about energy density and pressure

We can think of the constituents as ideal fluids. Their densities and pressures are related by equations of state.

Approximately: $P = w\rho$

$\rho + 3P$ is the Lorentz invariant that describes a fluid’s gravitational behavior.

- Nonrelativistic matter: $w = 0$  
  Atoms, galaxies, black holes
- Relativistic matter: $w = 1/3$  
  Photons & neutrinos
- Dark energy: $w = -1(?)$  
  We don’t have a clue.

Negative pressure? Rubber bands have negative pressure.
Cosmological Parameters
Partial list

- **H(t)**  Expansion rate
  \[ H^2(z) = H_0^2 \left[ \Omega_M (1+z)^3 + \Omega_R (1+z)^4 + \Omega_\Lambda (1+z)^3(1+w) + (\Omega-1) (1+z)^2 \right] \]
  Numerical integration is required.

- **Ω**  Total energy density \( \Rightarrow \) geometry (open/closed).
  \[ \Omega_i = \rho_i / \rho_c, \text{ where } \rho_c = 3H^2/8\pi G \text{ (critical density)} \]

- **w, w’** “Equation of state” of DE. \( w' \equiv dw/dz \)
  \[ w = -1, w' = 0 \text{ is Einstein’s cosmological constant.} \]
  Any \( w < -1/3 \) \( (\rho+3P < 0) \) will cause acceleration.
How to Measure $H(t)$

When we look at distant objects, we are looking back in time, due to the finite speed of light.

So, measuring $v/r$ as a function of $r$ ought to tell us $H(t)$.

We can measure $v$ using the Doppler shift (the cosmological “red shift”, $z$).
Note: Given $H(t)$, $z \leftrightarrow t$.

Distances are hard to measure. The best method now is to use type Ia supernovas as “standard candles”. (They all have $\sim$ the same intrinsic brightness.)
A Supernova!
One Complication
Non-Euclidean Geometry

Open ("Saddle")

Closed ("Sphere")

Geometry affects the observed luminosity:
Open: \[ C > 2\pi r \Rightarrow \text{Stars are dimmer than } 1/r^2. \]
Closed: \[ C < 2\pi r \Rightarrow \text{Stars are brighter than } 1/r^2. \]
How Are Supernovas Found?

Beautiful supernovas in nearby galaxies are rare.

This pair of pictures shows a more typical supernova discovery.

Not wonderful, but good enough to measure its:

- **Color** (red shift)
- **Luminosity** (distance)
Supernovas are 10% dimmer than they would be without DE.

The two curves are the predictions for universes that differ by 1% DE content.
The universe is older (~13.7 Gy) than without DE.

The universe will expand forever (exponentially, if $w = -1$).
Cosmological Parameters

Constraint from 2000 Supernovas

Assuming a flat universe:
\[ \Omega_M + \Omega_\Lambda = 1 \]

We know this within \( \sim 2\% \) from CMB data.

Data analysis by Helic Leung

Strong correlation \( \Rightarrow \) Make a measurement with different correlations. (structure growth)

Dark energy equation of state

Dark matter density

\[ W \]

\[ \Omega_M \]
The Growth of Structure

Here is a “big picture” simulation of structure growth:

Growth rate depends on the amount and gravitational properties of the stuff that fills the universe.

Each lump is a cluster of galaxies.

Caveat: These diagrams don’t show the expansion of the universe.

One must specify the initial conditions.
A Temperature Map of the Universe at $t = 300,000$ years

The universe was extremely uniform.

(but not exactly)
Enhance the contrast by $10^5$

The universe is not quite homogeneous

- The hot spots (red) are $\sim 10^{-5}$ K warmer than the cold spots (blue).
- They are also slightly more dense. $\Rightarrow$ gravitational instability
Density Perturbations

• Expand temperature fluctuations as a sum of spherical harmonics, $Y_{lm}$ (average over $m$).

• $\delta \equiv \delta \rho / \rho$ is the deviation from uniform density. $\delta \sim 10^{-5}$ then.
Density Perturbations

The amplitude of density perturbations grows with time:

- Two tests of the theory:
  - Does structure today agree with the CMB measurements? Not very sensitive, due to systematic errors.
  - Does the time dependence follow the expected curve? Requires a deep survey of galaxy distributions.

- Our universe
- No dark energy (matter only)
- Dark energy suppresses structure at late times, because things are farther apart than they would be otherwise.

- Dark energy causes the first stars to form earlier.
Weak Gravitational Lensing

Observational issues:
- Galaxies aren’t round. Statistical analysis. The more galaxies, the better.
- Small lens mass → small shear. Must control systematics.
- Best sensitivity requires source galaxies at twice the distance. Our sources will have $<z> \sim 0.7$. 

DES result, if:
- 20 gal/arcmin$^2$
- PSF = 0.9 arcsec

Hu & Jain, astro-ph/0312395

$\sigma(w) = 0.1$
$\sigma(w) = 0.06$
Dark Energy Survey
Fermilab, Illinois, Chicago, Michigan, OSU, LBNL, CTIO/NOAO
Britain, Spain, Brazil

We will completely rebuild the prime focus cage:

Will Brown has been writing control software.
Dark Energy Survey
Focal plane

Very good in IR
Not good in UV

Quantum Efficiency (%) vs. Wavelength (nm)

Thinned CCD, Deep Depleted, LBNL high resistivity
Dark Energy Survey

Simulated image

500 megapixels
1 GB per image
120 s exposures