Cosmology through the Large-Scale Structure of the Universe

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Illustration by Sam Moorfield
What does everybody in this room have in common?
What does everybody in this room have in common?

We get pleasure from solving puzzles.

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To solve a puzzle, we need information to analyze, and would like to compare results to fundamental ideas.

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from LSS we measure
the cosmic expansion,
ground on large-scales

Earth, Right here
Right Now

a lot of

cosmological
information

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DM simulation, Kim et al. (2009)
My Cosmological Tool Box

The Baryonic Acoustic Feature
Testing Geometry

SDSS DR7 LRG Result
LCDM Mock Catalogs

$z$-Distortions
Testing Gravity

$Q(s) \sim \xi_2 / \xi_0$

$\beta \approx \Omega_M(z) / b_1$

The Sloan Digital Sky Survey (SDSS)
physicists & astronomers

Newtonian Gravity

Einstein's General Relativity

Moon & Tides
(I hope Bill O'Reilly is not in the audience... we wouldn't want miscommunication ...)

Mercury's precession

Dark Matter

Dark Energy

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Why believe in DM?

signature observed in many gravitational probes

Galaxy Rotation Curves
Gravitational Lensing
Galaxy Clusters

Cosmic Microwave Background
Galaxy Distribution

the "Bullet" Cluster

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A (brief) history of (our understanding of) the cosmic expansion

• 1925: Friedman applies GR on Universe -- it could potentially expand!
• 1929: Hubble’s distance-velocity correlation -- the Universe is expanding?
• 1949: Fred Hoyle ridicules the expansion idea coining it the “Big Bang”
• 1968: Penzias & Wilson detect the predicted Cosmic Microwave Background -- first smoking gun for expansion!
• 1998: Reis et al. and Perlmutter et al. measure SNe distance-redshift -- the observed Universe is accelerating!
The Accelerating Universe?

When?

- Now! In the last 7.7 (of 13.6) Gyr
- Inflation era (t<<1 sec after Big Bang)
The Accelerating Universe?

When?

• Now! In the last 7.7 (of 13.6) Gyr
• Inflation era (t<<1 sec after Big Bang)

Why? Current best guesses:

• Cosmological Constant (Dark Energy)
• Modified Gravity (breakdown of GR?)

How do we measure?

• By measuring large-scale geometry
Large-Scale Structure

$\delta \sim 1$

$t = 8.6 - 13.6$ Gyears ABB

$\delta \sim 10^{-5}$

$t = 300,000$ years After Big Bang

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ΛCDM- the standard theory in the age of precision science

CDM- cold dark matter, ``seen” gravitationally

Λ- dark energy, explaining the cosmic acceleration
Cosmologist Jargon

- comoving distance
Comoving Distance Units

unit length = \expansion \times M^1 \times M^2

unit length = a^* \times x

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Cosmologist Jargon

- comoving distance
- distance units: par-sec (pc) = 3.26 ly; $h^{-1}$Mpc
- redshifts $z\sim$ look back time, look back distance
- baryons = regular matter = electrons, protons
Large-Scale Structure

The Millennium Simulation Project

Dark Matter Distribution

Springel et al. (2005)
Quantifying Clustering

\[ \Omega(x) = \Omega(1 + \delta(x)) \]

- \( \Omega \) - density
- \( \delta \) - overdensity
- \( \delta \geq -1 \)

2 point functions

correlation function \( \xi(r) \) ≡

\[ \langle \delta(x) \delta(x+r) \rangle_{\text{volume}} \]

Power Spectrum \( P(k) \) ≡

\[ \int d^3x e^{-ikr} \xi(r) \]

Springel et al. (2005)

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Quantifying Clustering

50 Mly

3 Gly from Earth

R.A.
Quantifying Clustering

The correlation function

$$\xi(r) = \langle \delta(x) \delta(x+r) \rangle_{\text{Volume}}$$

To deal with point "dots" and boundary conditions, we compare the data to a random point distribution:

$$\xi(r) = \frac{DD(r)}{RR(r)} - 1$$

where, normalized d-d, r-r pairs:

$$DD(r) = \sum 1 \quad \text{for all data-data pairs in within distance } r$$

$$RR(r) = \sum 1 \quad \text{for all random-random pairs}$$

$$\xi(r) = \frac{DD(r) + RR(r) - 2DR(r)}{RR(r)}$$

minimizes variance

Landy & Szalay (1993)

3 Gly from Earth

50 Mly
Large-Scale Structure

The Millennium Simulation Project

Dark Matter Distribution

Mock Galaxy Distribution

Springel et al. (2005)

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The acoustic wave

An initial perturbation in otherwise uniform plasma, consisting of DM, electrons + protons, radiations (photons)

Eisenstein, Seo & White (2006)
The acoustic wave

Photons pressure electrons, which pull protons. This plasma fluid propagates in acoustic fashion in a shell from origin.
The acoustic wave

Acoustic wave propagates for 100,000 years.
After $10^5$ years, first Hydrogen forms, and photons decoupled. Atoms eventually come to a halt.

The acoustic wave

~300,000 yr ABB

opaque Universe

transparent Universe
The acoustic wave

The photons continue to stream away while the baryons, having lost their motive pressure, remain in place.
The acoustic wave
The acoustic wave

The photons have become almost completely uniform, but the baryons remain overdense in a shell 100Mpc in radius. In addition, the large gravitational potential well which we started with starts to draw material back into it.
The acoustic wave

As the perturbation grows by $\sim 10^3$ the baryons and DM reach equilibrium densities in the ratio $\Omega_b/\Omega_m$.

The final configuration is our original peak at the center (which we put in by hand) and an “echo” in a shell roughly 100Mpc in radius with width $\sim 10\%$. 

from talk by Martin White
The Baryonic Acoustic Feature

Feature in the early universe:
CMB Temperature Fluctuations

Larson et al. (2010)

\[ \frac{\ell(\ell+1)C_\ell}{2\pi} \] vs Multipole Moment (\( \ell \))

- \( z \approx 1100 \)
- \( t \approx 300,000 \) years ABB

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The Baryonic Acoustic Feature

Feature in the recent universe:

Distribution of Galaxies

Eisenstein et al. (2005)

SDSS - 45,000 Galaxies

Detection!!

Comoving Separation (h^(-1) Mpc)

z ~ 0.35
t ~ 9.8G years ABB

Feature in the early universe:

CMB Temperature Fluctuations

Larson et al. (2010)

WMAP 7yr
ACBAR
QUaD

z ~ 1100
t ~ 300,000 years ABB
The Baryonic Acoustic Feature

- A firm prediction of $\Lambda$CDM
- A ``standard ruler''
The Baryonic Acoustic Feature as a Standard Ruler

**Early Universe** \((z_{\text{dec}} \sim 1090)\):
CMB temp fluctuations determines
\(r_s \sim 479\) M light-year \((\delta r_s/r_s \sim 1.3\%; \text{WMAP-5} \text{ Komatsu et al. 2009})\)

**Late Universe**:  
**SDSS-II, -III**  
Luminous Red Galaxies \((z \sim 0.3, 0.6)\)  
QSOs Lyman-\(\alpha\) Forest \((z > 2.5)\)  
Galaxy Clusters

**Wiggle-Z**  
Blue Galaxies \((z \sim 0.2, 0.4, 0.6, 0.8)\)
Current and future $z < 1$ galaxy redshift surveys

- BOSS LRGs [? 2009–2014]
- WFMOS z=1 [? 2016–2020]
- WiggleZ [2006–2010]
- SDSS–DR6 LRGs
- SDSS–DR6 main
- 2dFGRS
- DEEP–2
Current and future $z < 1$ galaxy redshift surveys

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- SDSS–DR6 LRGs
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- 2dFGRS

Graph details:
- Description of data points and trends
- Units: Gpc$^3$, s$^2$/s, km/s, Mpc
- Redshift range: 0 to 1
- Survey volume: 0.1 to 100 Gpc$^3$

From talk by Chris Blake
The Sloan Digital Sky Survey
Luminous Galaxy Sample

>100,000 luminous galaxies
look-back time ≈ 4.8 Gyr (z < 0.47)
Sky Coverage ≈ 1/5

sample available at: http://cosmo.nyu.edu/~eak306/SDSS-LRG.html
The Sloan Digital Sky Survey
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sample available at: [http://cosmo.nyu.edu/~eak306/SDSS-LRG.html](http://cosmo.nyu.edu/~eak306/SDSS-LRG.html)

BOSS LRGs (exp 2014)

>1.2M galaxies
\( \sim 6.8 \text{ Gyr} \) (\( z < 0.8 \))
Sky Coverage \( \sim 1/4 \)
3 times as dense
The Baryonic Acoustic Feature in the SDSS Galaxy Sample

$z \approx 0.28$
$t \approx 10.5G$ years ABB

Using peak position (@ $\approx 0.5Gly$), we calculate the distance to $\approx 3.6Gly$ to an accuracy of $\approx 3.5\%$!
The Baryonic Acoustic Feature in the SDSS Galaxy Sample

Kazin et al. (2010)

Cosmic variance

Uncertainties are covariant

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Sloan Digital Sky Survey

2.5m designated telescope, Apache Point, NM

Final Imaging released in January 11’
Sloan Digital Sky Survey - Imaging

14,555 deg² (~35% of sky)

30 2MX2M pixel CCDs

Filter Response

\[ \lambda \text{ (Angstrom)} \]

images ➞ 2D mapping

gallery
Sloan Digital Sky Survey - Spectroscopy

1000 fiber plugs connecting between spectrograph and plate

spectra
➤ redshift
➤ distance
(3D mapping)

9274 deg² (22% of sky)
Sloan Digital Sky Survey - in numbers

Data Release 8
(publicly available since Jan 2011):

Imaging: 469 Million objects

60 Terabytes

Spectra: 1.6 Million objects

- Galaxies 860 thousand
- Quasars 116 thousand
- Stars 521 thousand
- Unclassified 37 thousand
- (Sky 93 thousand)

5.5 Terabytes
Clustering as Function of Angle

\[ \xi(\theta, s) \]

\[ s \text{ [Mpc]} \]

\[ \theta \text{ [degrees]} \]

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Clustering as Function of Polar Angle

no dynamical distortions
(linear theory)

$\xi(\theta, s)$

BA Feature

$100$

$0$

$100$

$200$

$s$ [h$^{-1}$ Mpc]

$\theta$ [degrees]

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Clustering as Function of Polar Angle

no dynamical distortions  
(linear theory)

\[ \xi(\theta, s) \]

BA Feature

Real Space

\[ \Delta \chi_s \]

Redshift Space

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Clustering as Function of Polar Angle

no dynamical distortions (linear theory)

squashing effect only (linear theory)

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Clustering as Function of Polar Angle

redshift distortions
(N-body simulated mock catalogs)

squirashing effect only
(linear theory)

$s_\theta(s)$

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Clustering as Function of Polar Angle

redshift distortions (N-body simulated mock catalogs)

SDSS-II Results (0.16<z<0.47)

\(\xi(\theta, s)\)

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Galaxy dynamics is caused by gravity.
Gravity strength depends on matter abundance.
Hence squashing effect can be used to measure matter abundance ($\Omega_M$).
Alternatively, assuming $\Omega_M$, it can be used to test gravity.

\[
\beta \propto \Omega_M
\]

Quadrupole Test: No dependence on scale!

\[
Q \equiv \frac{\xi_2(r)}{\xi_0(r)} = \frac{(4/3 \beta + 4/7 \beta^2)}{(1 + 2/3 \beta + 1/5 \beta^2)}
\]
$\beta$ through the Quadrupole Test
N-Body Simulations (Mock Surveys)

$Q \sim \frac{\xi_2(s)}{\xi_0(s)} = \frac{(4/3 \beta + 4/7 \beta^2)}{(1 + 2/3 \beta + 1/5 \beta^2)}$

Mock Galaxies, Not observation!!

(uncertainties given a SDSS volume)

$\beta \approx \Omega_M(z)/b_1$
\( \beta \) through the Quadrupole Test
SDSS-II Results

\[ Q \sim \frac{\xi_2(s)}{\xi_0(s)} = \frac{4/3 \beta + 4/7 \beta^2}{1 + 2/3 \beta + 1/5 \beta^2} \]

\( \xi(\theta, s) \)

\( Q(s) \)

lines: Mocks
symbols: SDSS-II LRGs

Kazin et al. (in prep.)

\( \beta \approx \Omega_M(z)/b_1 \)

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BOSS- Substantially Improving Our Cosmological Tools

SDSS-II

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Simulated Results

DR7 Volume Limited Sample
(0.16<z<0.36; ~62,000 LRGs)

LCDM prediction using SDSS-II Mock Catalogs

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BOSS- Substantially Improving Our Cosmological Tools

Simulated Results

SDSS-III

DR7 Volume Limited Sample
(0.16<z<0.36; ~62,000 LRGs)

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Cosmology through the Large-Scale Structure of the Universe

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Illustration by Sam Moorfield
SDSS-III

Building on the legacy of the Sloan Digital Sky Survey (SDSS) and SDSS-II, the SDSS-III Collaboration is carrying out a program of four surveys to map the structure and dynamics of the Milky Way, to find and characterize extrasolar planetary systems, and to understand dark energy and the nature of the universe.

Between 2008 and 2014, SDSS-III's four surveys are using Apache Point Observatory's 2.5-meter telescope. SDSS-III will continue the SDSS tradition of public data releases, with the first release scheduled for January 2011. The survey will also continue its commitment to making its data available and useful to students, teachers, and citizen scientists.

The SDSS-III Collaboration includes many institutions from around the globe. Inquiries from interested parties to join the collaboration are welcome. For a detailed description of SDSS-III, see the Project Description, available as a PDF document.
Welcome to Galaxy Zoo, where you can help astronomers explore the Universe

Galaxy Zoo: Hubble uses gorgeous imagery of hundreds of thousands of galaxies drawn from NASA’s Hubble Space Telescope archive. To understand how these galaxies, and our own, formed we need your help to classify them according to their shapes — a task at which your brain is better than even the most advanced computer. If you're quick, you may even be the first person in history to see each of the galaxies you're asked to classify.