Outline:
1. Observing inflation + dark energy
2. BAO experiments
3. CMB experiments
4. Future experiments
Dark Energy
An observational question:
Has the Dark Energy Tooth Fairy come once or twice?

1st Age of Dark Energy
\[ t \sim 10^{-35} \text{ sec} \]
Phase of accelerating expansion dubbed “inflation”
“Dynamic”, because it turned off
Imprinted density fluctuations + grav. waves

2nd Age of Dark Energy
\[ t \sim \text{now} \]
Phase of accelerating expansion dubbed “dark energy”
Observable at \( t > 2 \) billion years, possibly dynamic
An observational question:
Has the Dark Energy Tooth Fairy come once or twice?

1st Age of Dark Energy
$t \sim 10^{-35} \text{ sec}$
Phase of accelerating expansion dubbed “inflation”
“Dynamic”, because it turned off
Imprinted density fluctuations + grav. waves
Deceleration from gravity

Acceleration from Dark energy

Timeline of Dark Energy

Acceleration from Inflation

380,000 years

13.7 billion years

DAWN OF TIME
Toolset for Dark Energy are geometrical measures

Measurements that are per-object:
- supernovae

Measurements that are statistical:
- features + scales in density maps (galaxies, CMB)

All imply extra volume between us and high redshift
Baryon Acoustic Oscillations (BAO) standard ruler at 147 Mpc

BAO imprinted in the microwave background at $z=1100$

... and forever more in galaxy maps

These fluctuations of 1 part in $10^5$
gravitationally grow into...

...these ~unity fluctuations today

Universe at 380,000 years old
(CMB)

Universe today (galaxy map)
Baryon Acoustic Oscillations (BAO) standard ruler at 147 Mpc

BAO imprinted in the microwave background at \( z=1100 \)
...and forever more in galaxy maps

These fluctuations of 1 part in \( 10^5 \) gravitationally grow into...

Universe at 380,000 years old (CMB)

...these ~unity fluctuations today

Universe today (galaxy map)

standard ruler

BOSS BAO at \( z=0.57 \)

\( \alpha = 1.01 \)
\( \chi^2 = 30 \)
Anderson et al (2012)
Large volumes required to sample BAO scale at 147 Mpc

3-d maps measure more modes than 2-d maps
Higher redshifts have more volume

\[ \theta_s = 0.596724 \pm 0.00038 \text{ deg} \]

BAO standard ruler from Planck

BAO standard ruler from BOSS Lyman-\(\alpha\) map

BAO standard ruler from BOSS galaxy map
Baryon Oscillation Spectroscopic Survey (BOSS)
Most capable instrument today for mapping the Universe

2.5-meter Sloan Telescope
3 degree field-of-view
Image sky
Select targets
Design plug-plates
Plug fibers
Observe!
Spectra + redshifts
Make 3-D maps
Cosmology

SDSS-III/BOSS imaging completed in Dec 2009
- 10,400 deg$^2$ extragalactic footprint
- 5 filters (ugriz)
  $1\%$ photometric precision

Camera is now retired at the Smithsonian
BOSS targeted
- 1.5 million Luminous Red Galaxies at $z < 0.7$
- 160,000 $z > 2.15$ quasars
1000 targets observed on each plate (increased from 640 in original SDSS)
Image sky
Select targets
Design plug-plates
Plug fibers
Observe!
Spectra + redshifts
Make 3-D maps
Cosmology
Image sky

Select targets

Design plug-plates

Plug fibers

Observe!

Spectra + redshifts

Make 3-D maps

Cosmology
Image sky
Select targets
Design plug-plates
Plug fibers

Observe!

Spectra + redshifts
Make 3-D maps
Cosmology

Sloan Foundation Telescope, New Mexico
7 sq deg FOV
Image sky
Select targets
Design plug-plates
Plug fibers
Observe!

Spectra + redshifts

Make 3-D maps

Cosmology

Fully automated spectral reductions
360-1000 nm coverage for all targets
Automated classifications, >98% for galaxies

Example:
Galaxy at \(z=0.6489\)

Example:
QSO at \(z=2.873\)
BOSS completed main survey, April 2014
1.5 million galaxies + 160,000 Lyman-alpha quasars
Four distinct BAO measures in BOSS Data Release 11
- LOWZ galaxies at $z=0.32$
- CMASS galaxies at $z=0.57$
- Lyman-alpha forest auto-correlation at $z=2.3$
- Lyman-alpha + Quasar cross-correlation at $z=2.3$

$S^2 \xi(s)\,\text{(Mpc/)}$

Anderson et al.

Delubac et al. (2014)
BAO as a ruler measures the expansion history, even with no physical scale.

BAO measured near its cosmic variance limit at $z=0 \rightarrow z=0.7$.
Future improvement can only be ~2X better there.
BAO at $z > 0.7$ nowhere near cosmic variance limit.

Aubourg et al 2014
Dark energy is needed to explain galaxy+quasar BAO

Angular acoustic scale of the CMB is put on the same system with simple assumptions about recombination era

One standard ruler from $z=1100 \rightarrow z=0.1$

Aubourg et al 2014
Dark energy need not be dynamic to explain the data today

$w_0 = -1$, $w_a = 0$, equivalent to a cosmological constant

CMB + BAO
Planck Collaboration 2015
Inflation
Toolset for Inflation?

Matter fluctuations
  Primordial fluctuation power spectrum ($n_s$)
Non-gaussianities
Flatness ($\Omega_\kappa$)

Gravitational wave background
  Direct measure of grav. waves
Imprinted grav. waves as B-modes in CMB
Most inflation-era measures are upper limits

- Spatial curvature ($\Omega_K$) is flat to $<0.5\%$

- Non-gaussianities ($f_{NL}$) are not detected

- Primordial fluctuations are adiabatic (growing mode), not isocurvature

over-densities from the Big Bang

derunder-densities
At least one inflation-era measure is measured!

Primordial fluctuation spectrum ($n_s$) is not scale-free

CMB + BAO
Planck Collaboration 2015
At least one inflation-era measure was incorrect

Indirect measure of grav. waves imprinted on CMB B-modes
At least one inflation-era measure was incorrect

The signal was real
Sourced from dust in the Milky Way
Mis-interpreted as grav. waves imprinted upon CMB

BICEP2 2014
Future Experiments
• 2D BAO in Fourier and Configuration space

• joint BAO-RSD analysis

Credit: Antonio Cuesta

\( \xi_0(s) \) \((h^{-2}\text{Mpc}^2)\)

Credit: Antonio Cuesta

Northern Galactic Cap

Credit: Hector Gil-Marin

!Preliminary!
Final results from BOSS in prep.
Uses final Data Release 12, which was made public Jan 2015

Credit: Antonio Cuesta
Statistical power increases with # of modes

Cosmic variance limit for BAO only reached at $z<0.7$ & $z=1100$

More modes at smaller scales

Galaxy + CMB lensing will sample integral of density fields
-> Complex, but powerful
Future BAO experiments will sample $z > 0.7$

eBOSS, HETDEX, DESI, PFS, Euclid

DESI @Kitt Peak
BOSS sampled a volume of $5 \, h^{-3} \text{Gpc}^3$
DESI will sample a volume $>50 \, h^{-3} \text{Gpc}^3$
Redshift surveys increasing exponentially in size
Large enough for BAO starting in 2005

- All visible galaxies
- CfA1, 1983: 1840
- CfA-2, 1998: 18,000
- LCRS, 1996: 18,678
- 2dF, 2003: 221,414
- SDSS, 2009: 929,000
- BOSS, 2014: 1.5 million
- DESI, 2024: 24 million
Redshift surveys increasing exponentially in size
Large enough for BAO starting in 2005

This will only be possible in China?

log N(authors)

530,000

CfA1, 1983
4 authors

SDSS, 2009
204 authors

1980
Year
2061
Future CMB experiments racing to detect B-modes

BICEP2/Keck/BICEP3, ACTPol, SPTPol, Polarbear/Simons Array
SPIDER, EBEX
Summary

- BAO measured expansion history from z=0.1->1100
- Dark energy consistent with a cosmological constant
- Future experiments will be dramatically larger, esp. at z>0.7

- Inflation-era primordial fluctuations definitively measured, and not scale-free
- Inflation era non-gaussianianities not detected
- No detection yet of primordial gravitational waves, but future CMB B-mode experiments racing to measure 450 million light years