

## How to learn to Love the BOSS Baryon Oscillations Spectroscopic Survey

**Shirley Ho** 

Anthony Pullen, Shadab Alam, Mariana Vargas, Yen-Chi Chen + Sloan Digital Sky Survey III-BOSS collaboration Carnegie Mellon University SpaceTime Odyssey 2015 Stockholm, 2015

#### What is BOSS ?



Shirley Ho, Sapetime Odyssey, Stockholm 2015



#### What is BOSS ?



Shirley Ho, Sapetime Odyssey, Stockholm 2015



#### BOSS may be ...



Shirley Ho, Sapetime Odyssey, Stockholm 2015





### SDSS III - BOSS Sloan Digital Sky Survey III -Baryon Oscillations Spectroscopic Survey

What is it ? What does it do ?

## What is SDSS III - BOSS ?



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### What is SDSS III - BOSS ?

- A 2.5m telescope in New Mexico
- Collected
  - 1 million spectra of galaxies ,
  - 400,000 spectra of supermassive blackholes (quasars),
  - 400,000 spectra of stars
  - images of 20 millions of stars, galaxies and quasars.





### SDSS III - BOSS Sloan Digital Sky Survey III -Baryon Oscillations Spectroscopic Survey

What is it ? What does it do ?



### SDSS III - BOSS Sloan Digital Sky Survey III -Baryon Oscillations Spectroscopic Survey

BAO: Baryon Acoustic Oscillations AND Many others!

### What can we do with BOSS?

- Probing Modified gravity with Growth of Structures
- Probing initial conditions, neutrino masses using full shape of the correlation function
- Probing velocities of clusters via kinetic Sunyaev Zeldovich
- Understanding the Intergalactic medium and dust in galaxies
- Galaxy/cluster evolution at lower redshift, quasars properties at high redshift
- New way to Test Gravity using CMB lensing and BOSS





### Outline today

- What is really BOSS-BAO ?
   What do we learn from it ?
- What other science we can do with BOSS ? –Many…
  - –Introduce a new probe combining BOSS AND CMBlensing to learn about gravity at the largest scale !



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To measure BAO, we usually calculate the correlation function

Shirley Ho, Sapetime Odyssey, Stockholm 2015



#### What is the correlation function of population during the day?



Shirley Ho, Sapetime Odyssey, Stockholm 2015



What is the correlation function of population during the day?



A bump in 20 miles!

Shirley Ho, Sapetime Odyssey, Stockholm 2015



#### To measure BAO, we first calculate the correlation function



A bump at ~150Mpc

Shirley Ho, Sapetime Odyssey, Stockholm 2015

#### **BAO** and Galaxies

• Pairs of galaxies are slightly more likely to be separated by 150 Mpc than 120 Mpc or 170 Mpc.



Credit: Zosia Rostomian, LBNL

Shirley Ho, Sapetime Odyssey, Stockholm 2015

NOTE: BAO effects highly exaggerated here



### BAO as a Standard Ruler

 This distance of 150 Mpc is very accurately computed from the anisotropies of the CMB.
 -0.4% calibration with current CMB.

Image Credit: E.M. Huff, the SDSS-III team, and the South Pole Telescope team. Graphic by Zosia Rostomian









## SDSS III - BOSS

- In SDSS-III, we use maps of the large-scale structure of the Universe to detect the imprint of the sound waves.
- We use 3 different tracers of the cosmic density map:
  - Galaxies at redshifts 0.2 to 0.7.
  - Quasars at redshifts 2.1 to 3.5.
  - The intergalactic medium as revealed by the Lyman  $\alpha$  Forest, at redshifts 2.1 to 3.5.
- We look for an excess clustering of overdensity regions separated by 150 Mpc





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#### A Slice of BOSS



Credit: D. Eisenstein

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 Clustering Analysis of the BOSS galaxy sample has produced the world's best detection of the latetime acoustic peak.

Anderson et al. 2014; Vargas, Ho et al. 2014; Tojeiro et al. 2014

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**Carnegie Mellon University** 

s (Mpc/h)



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 Clustering Analysis of the BOSS galaxy sample has produced the world's best detection of the latetime acoustic peak.





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• The peak location is measured to 1.0% in our z = 0.57 sample and 2.1% in our z = 0.32 sample





Shirley Ho, Sapetime Odyssey, Stockholm 2015



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### Constraining cosmological models



**SDSSIII** 



### How about Dark Energy?

Combined constraints on Dark Energy



BOSS collaboration 2014



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#### Is it a cosmological constant?

• Combined constraints:



BOSS collaboration 2014



Shirley Ho, Sapetime Odyssey, Stockholm 2015

### Or is it Dark Energy?

• Combined constraints:



BOSS collaboration 2014



Shirley Ho, Sapetime Odyssey, Stockholm 2015

### Comparison with other probes

#### BOSS collaboration 2014

#### Black: Planck +BAO + SN



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#### Testing Gravity by combining CMB lensing and Large Scale structure

 $ds^{2} = (1+\psi)dt^{2} - a^{2}(1+2\phi)dx^{2}$ 



Non-relativistic particles feel the gravitational potential: Motions of these particles probe Dynamical mass



Relativistic particles deflected by spatial curvature

Zhang, Liguori, Bean, Dodelson 2007



#### Testing Gravity by combining CMB lensing and Large Scale structure: Introducing EG



Relativistic particles deflected by spatial curvature

Zhang, Liguori, Bean, Dodelson 2007



#### Testing Gravity by combining CMB lensing and Large Scale structure: Consider GR

$$ds^{2} = (1+\psi)dt^{2} - a^{2}(1+2\phi)dx^{2}$$

$$egin{aligned} E_G(k,z) &= rac{c^2 [
abla^2 (\psi-\phi)]_k}{3 H_0^2 (1+z) heta(k)} \ &= rac{c^2 k^2 (\phi-\psi)}{3 H_0^2 (1+z) heta(k)} \,, \end{aligned}$$



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 $\begin{aligned} k^2\psi = & -4\pi G a^2\rho(a)\delta \\ \phi = & -\psi \,, \end{aligned}$ 

GR

#### Testing Gravity by combining CMB lensing and Large Scale structure: Modifying Gravity!

$$ds^{2} = (1+\psi)dt^{2} - a^{2}(1+2\phi)dx^{2}$$

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$$\label{eq:GR} \begin{array}{c} k^2\psi\!=\!-4\pi Ga^2\rho(a)\delta\\ \phi\!=\!-\psi\,, \end{array}$$

modified gravity 
$$\begin{split} k^2 \psi = & -4\pi G a^2 \mu(k,a) \rho(a) \delta \\ \phi = & -\gamma(k,a) \psi \,, \end{split}$$

Non-relativistic particles feel the gravitational potential: Motions of these particles probe Dynamical mass



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## Testing Gravity by combining CMB lensing and Large Scale structure: General equation of E<sub>G</sub>

$$ds^{2} = (1+\psi)dt^{2} - a^{2}(1+2\phi)dx^{2}$$

$$E_G(k,z) = rac{c^2 [\nabla^2 (\psi - \phi)]_k}{3H_0^2 (1+z) heta(k)} \ = rac{c^2 k^2 (\phi - \psi)}{3H_0^2 (1+z) heta(k)} \,,$$



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$$E_G(k,z)=rac{\Omega_{m,0}\mu(k,a)[\gamma(k,a)+1]}{2f}$$

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#### Testing Gravity by combining CMB lensing and LSS Space (frequency) and time (redshift) dependence of Eg



Pullen, Alam & Ho, 2015

#### if it is General Relativity



#### Testing Gravity by combining CMB lensing and LSS Space (frequency) and time (redshift) dependence of Eg



Pullen, Alam & Ho, 2015



#### Testing Gravity by combining CMB lensing and LSS Space (frequency) and time (redshift) dependence of EG



Pullen, Alam & Ho, 2015

oning 110, capetine cayoocy, crossindlm 2015



Why does it matter that we use CMB lensing instead of galaxy lensing (aka. Reyes et al. 2010)?

- Dramatically increase the z-range of the tracers you can use

- we know the z of CMB lensing exactly (no photo-z needed)
   no intrinsic alignment of CMB
- But we are working on teasing out any systematics now.





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Due to canceling of galaxy bias parameter, this probe is bias free. It has very little dependence on the astrophysical relationship between galaxy and the underlying matter density



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- Dramatically increase the z-range of the tracers you can use
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#### We now translate these into



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#### It is no man's land out there ...



Why does it matter that we use CMB lensing instead of galaxy lensing (Reyes et al. 2010)?

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#### Can we use this new probe with BOSS ?





We probe a complimentary range of scales when compared to using galaxy-lensing instead of CMB-lensing





We start from 30 Mpc/h and have significant signals to larger scales.





## Preliminary look into BOSS X Planck-lensing













**SMALLER** SCALES



1) BAO has come of age, we can make 1% distance measurement using BAO at multiple redshifts

2) This allows us to make quantitative statement of our cosmology AND

3) There are many interesting fronts in LSS that we can work on, and one of them is to think very hard about what we can do with the cross-correlations with current and upcoming CMB experiments and what they provide.



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