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

Cosmo15

Warsaw, Poland, 2015

What is BOSS ?

What is BOSS ?

BOSS may be …

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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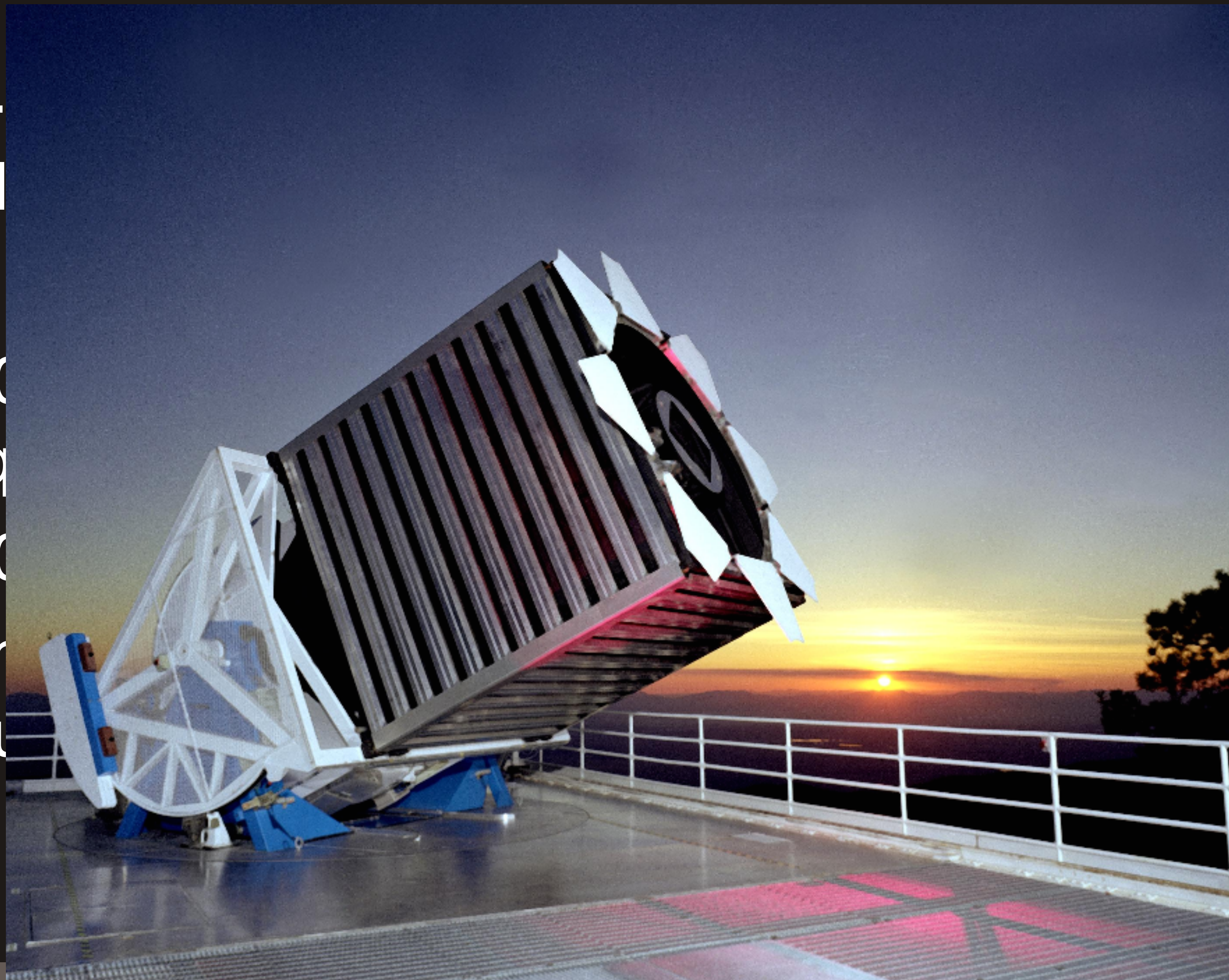

What is SDSS III - BOSS ?

- 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 ?

SDSSIII

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 CMB-lensing to learn about gravity at the largest scale !

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What are Baryon Acoustic Oscillations?

To measure BAO, we usually calculate the correlation function

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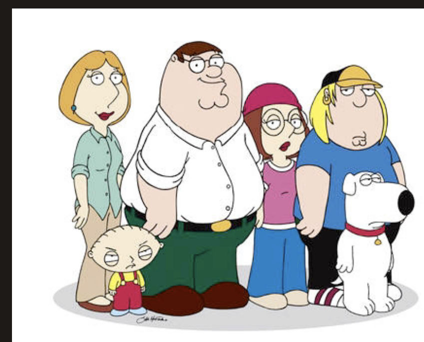
What are Baryon Acoustic Oscillations?

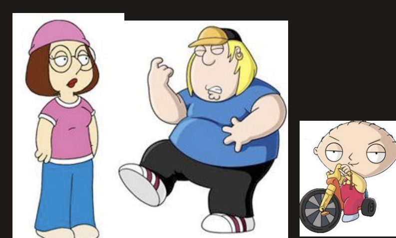
What is the correlation function of population during the day?



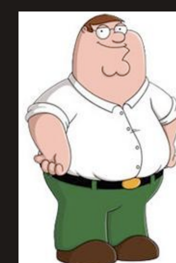
20 miles

Office

HOME/nearby school



20 miles



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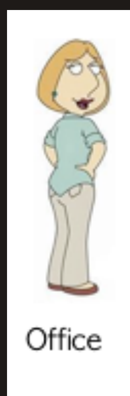
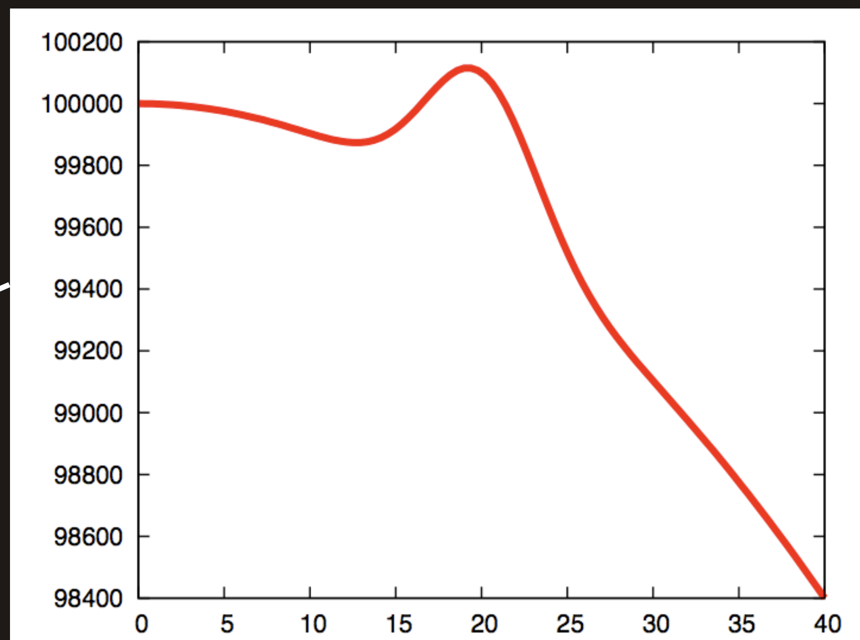
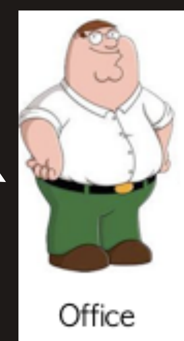


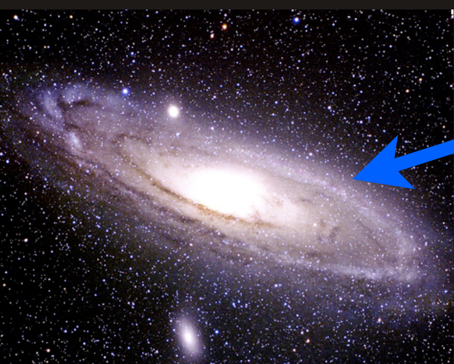


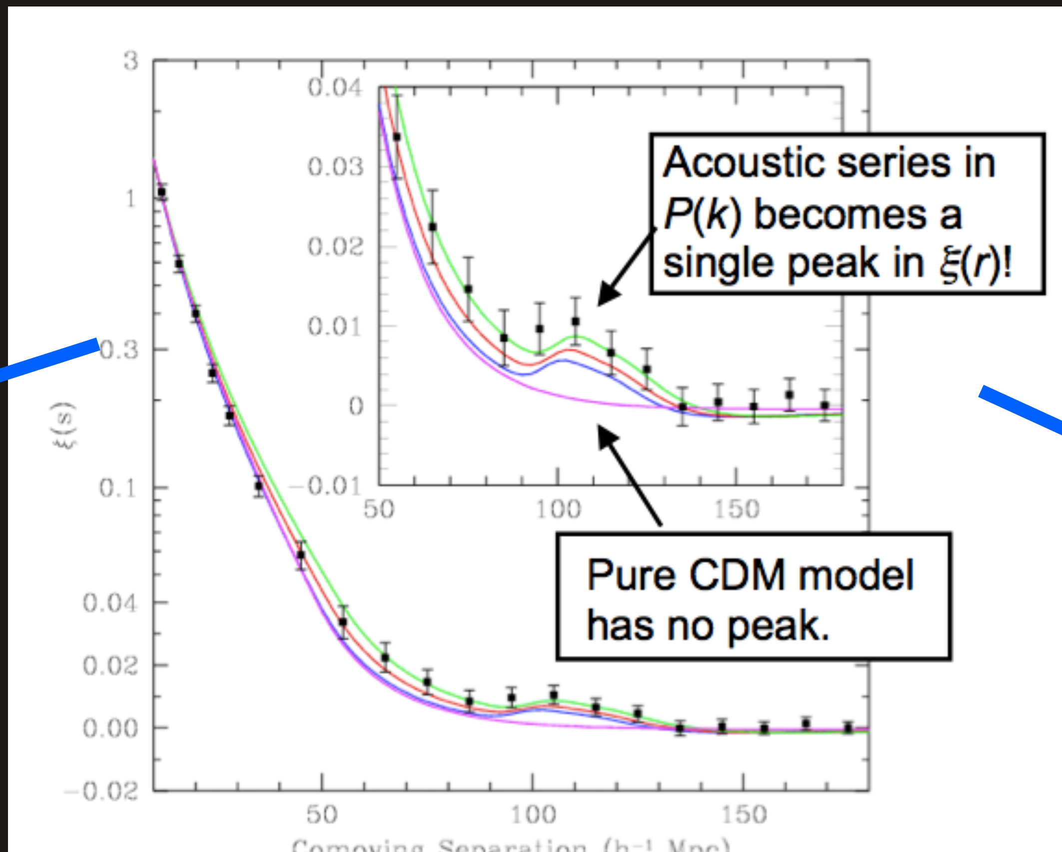


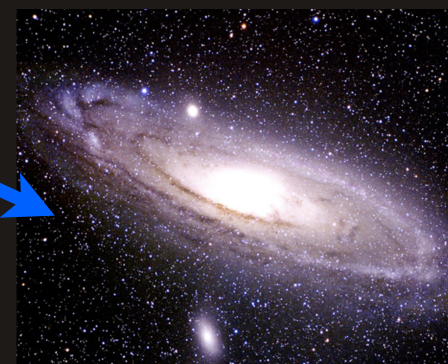
A bump in 20 miles!

What are Baryon Acoustic Oscillations?

To measure BAO, we first calculate the correlation function



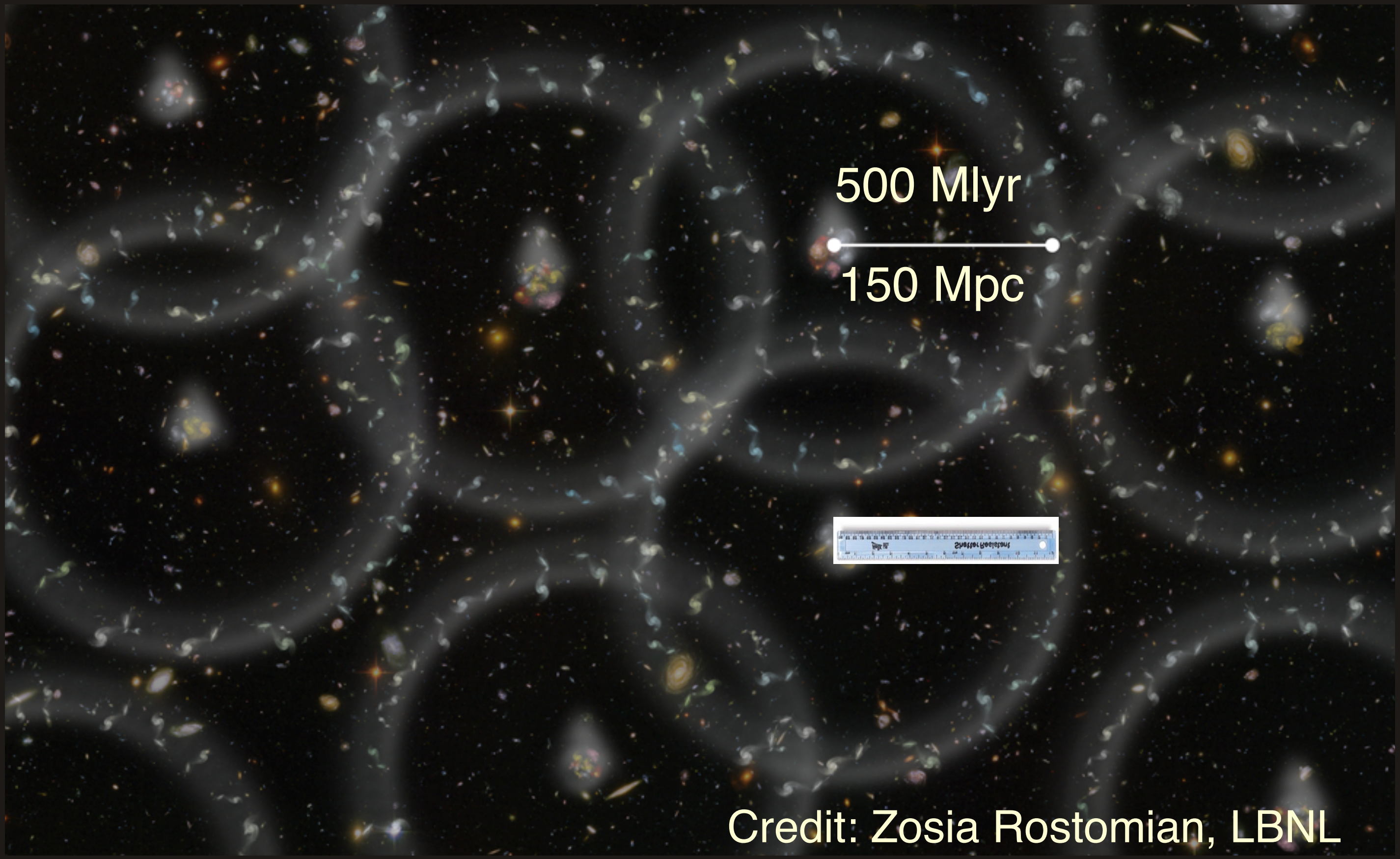




A bump at ~150Mpc

BAO and Galaxies

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



Cosmo15, Warsaw

NOTE: BAO effects highly exaggerated here

SDSS III

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.

Planck 2015

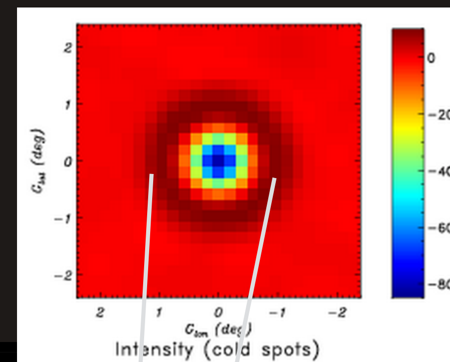
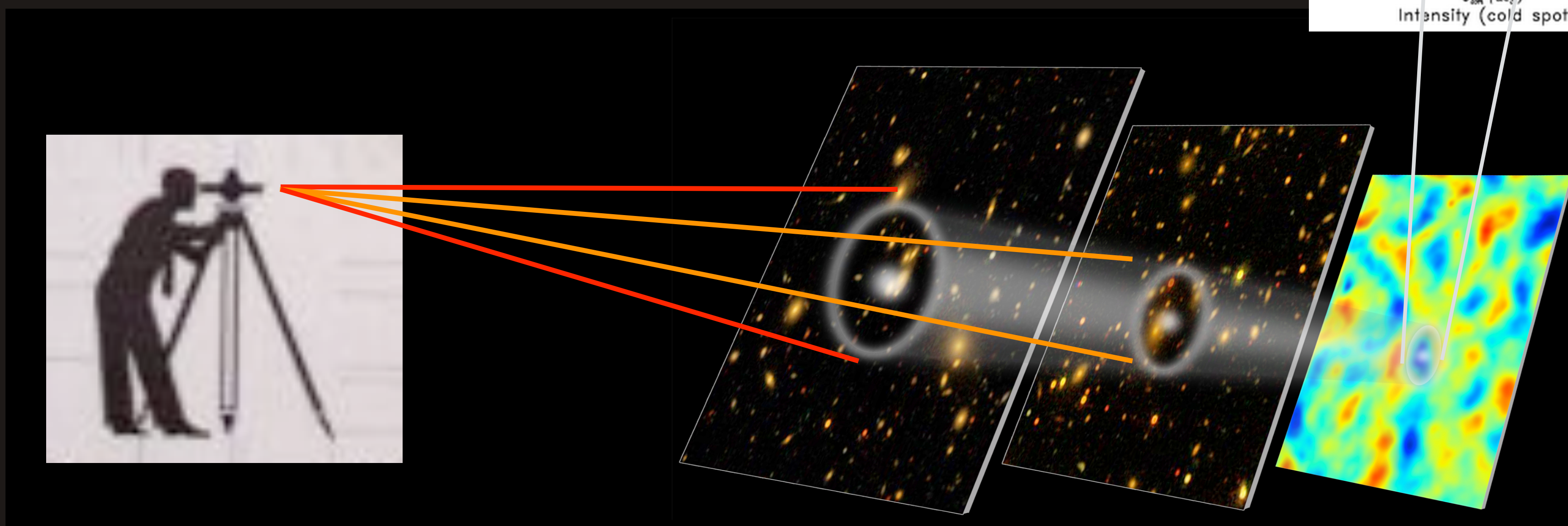


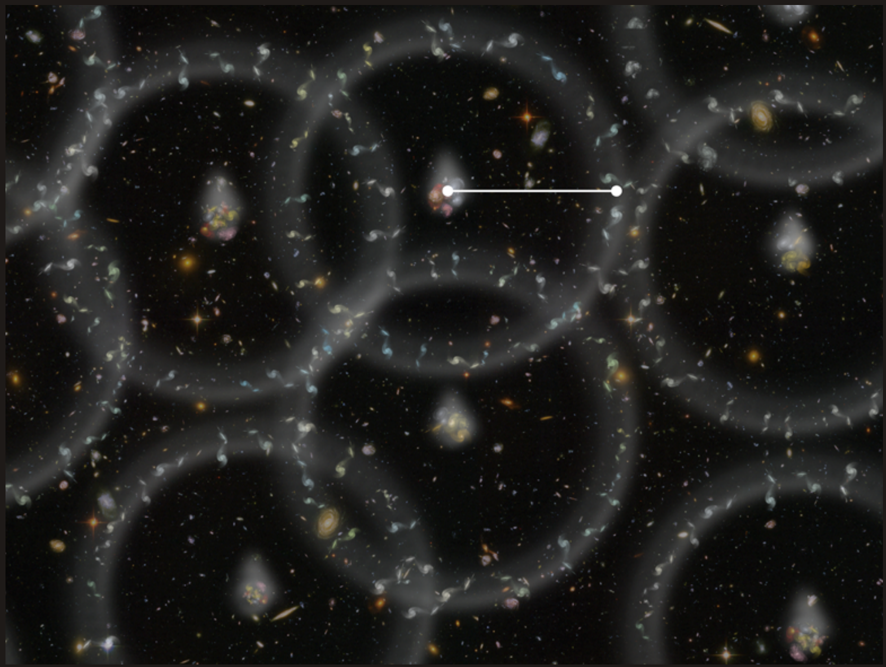
Image Credit: E.M. Huff, the SDSS-III team, and the South Pole Telescope team. Graphic by Zosia Rostomian



SDSS III

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 α 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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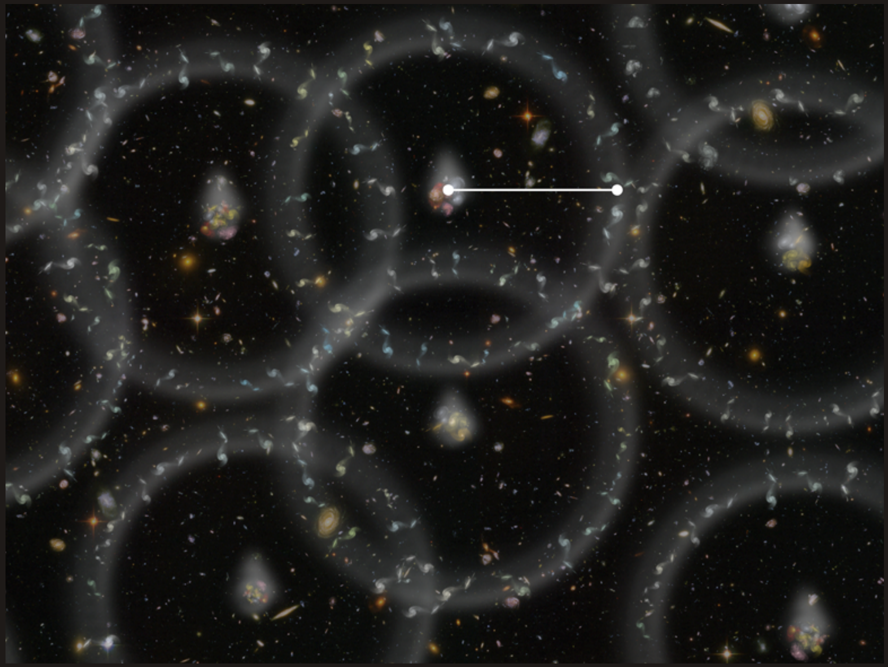

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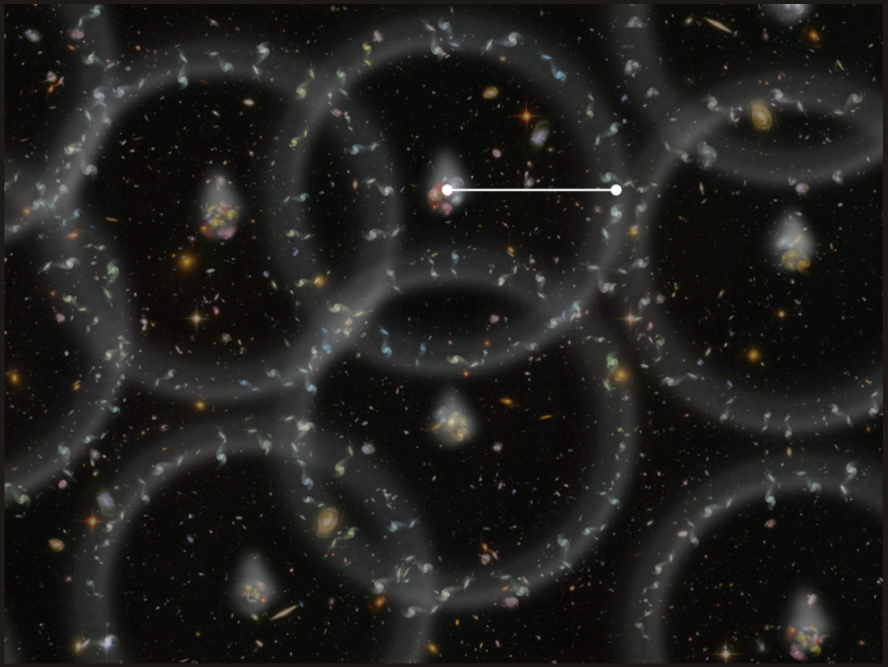
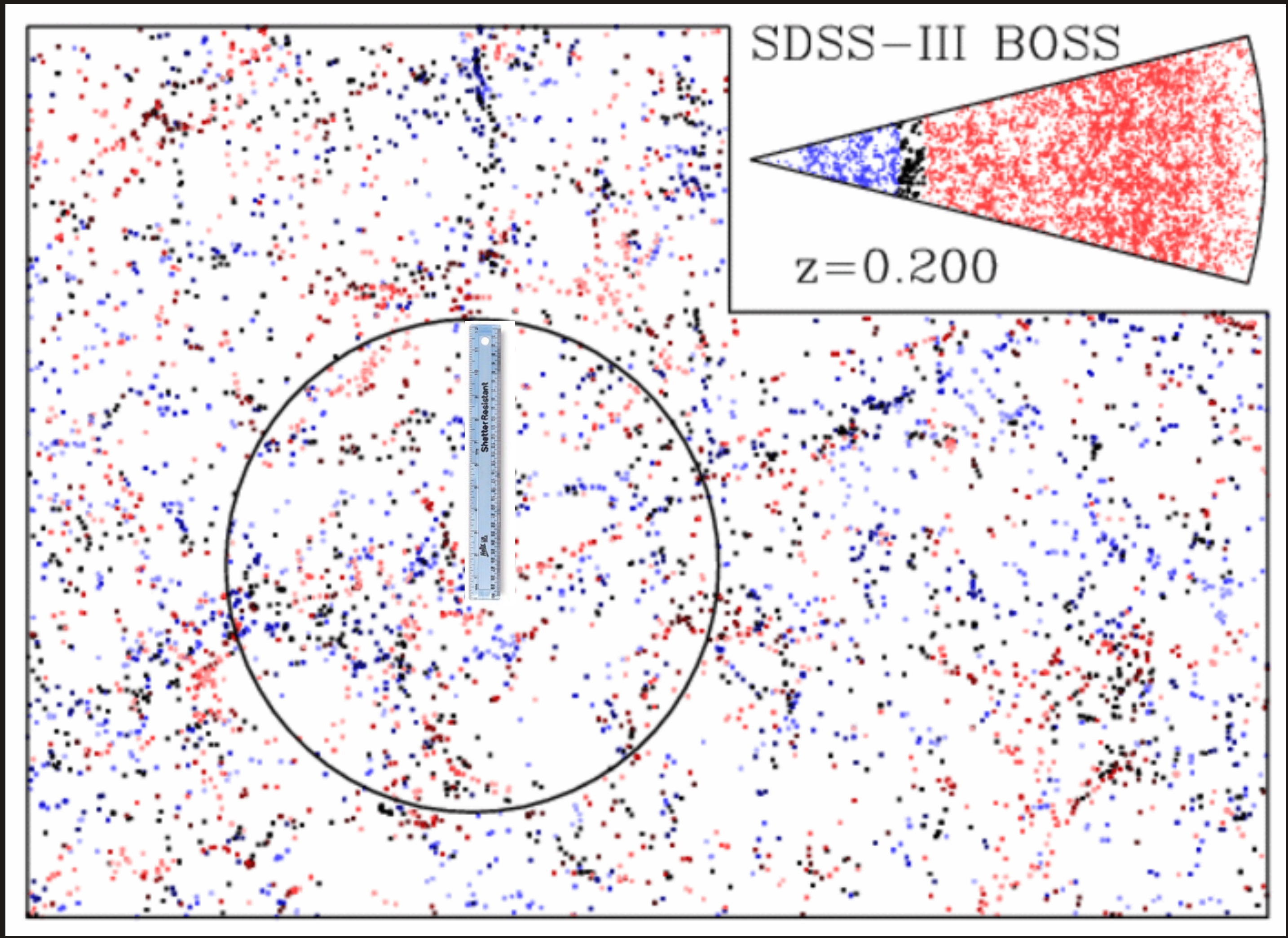


A Slice of BOSS



Credit: D. Eisenstein

BAO in BOSS Galaxies

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

s (Mpc/h)

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

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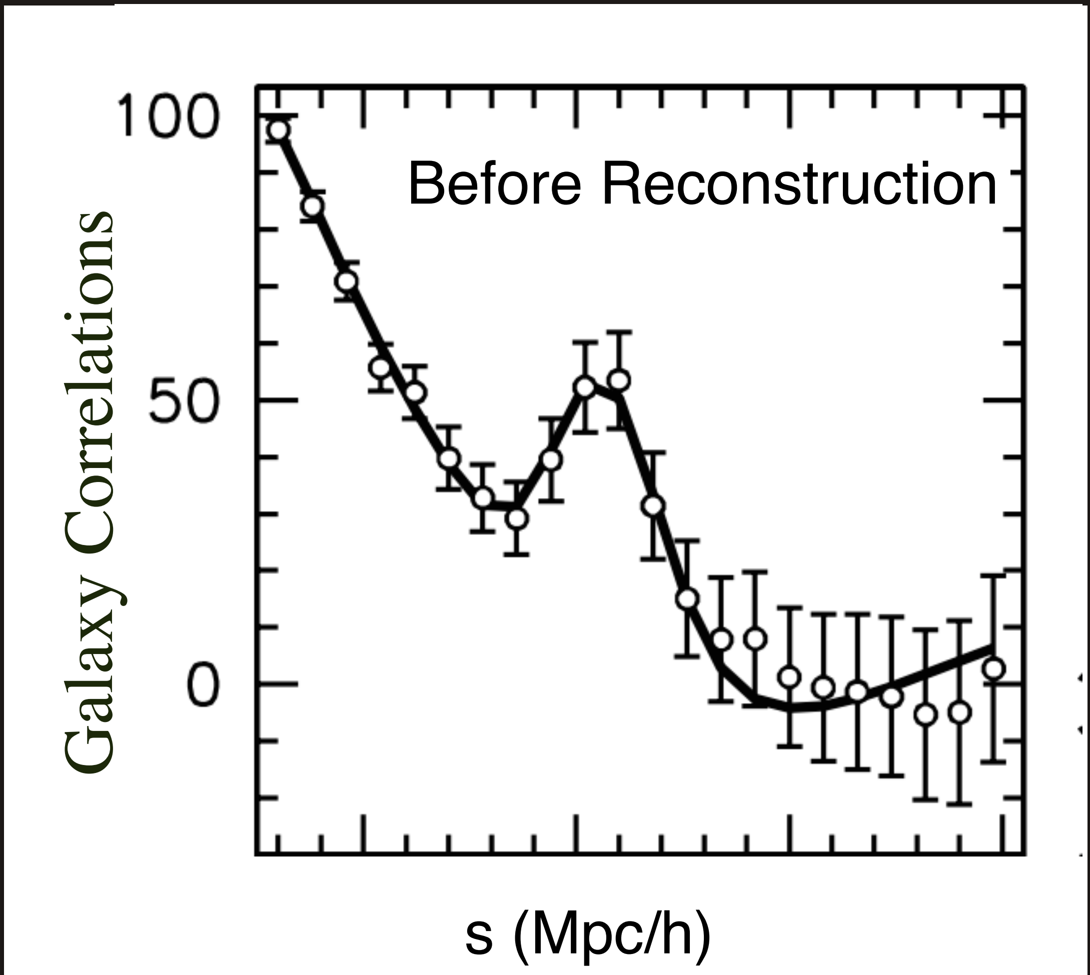

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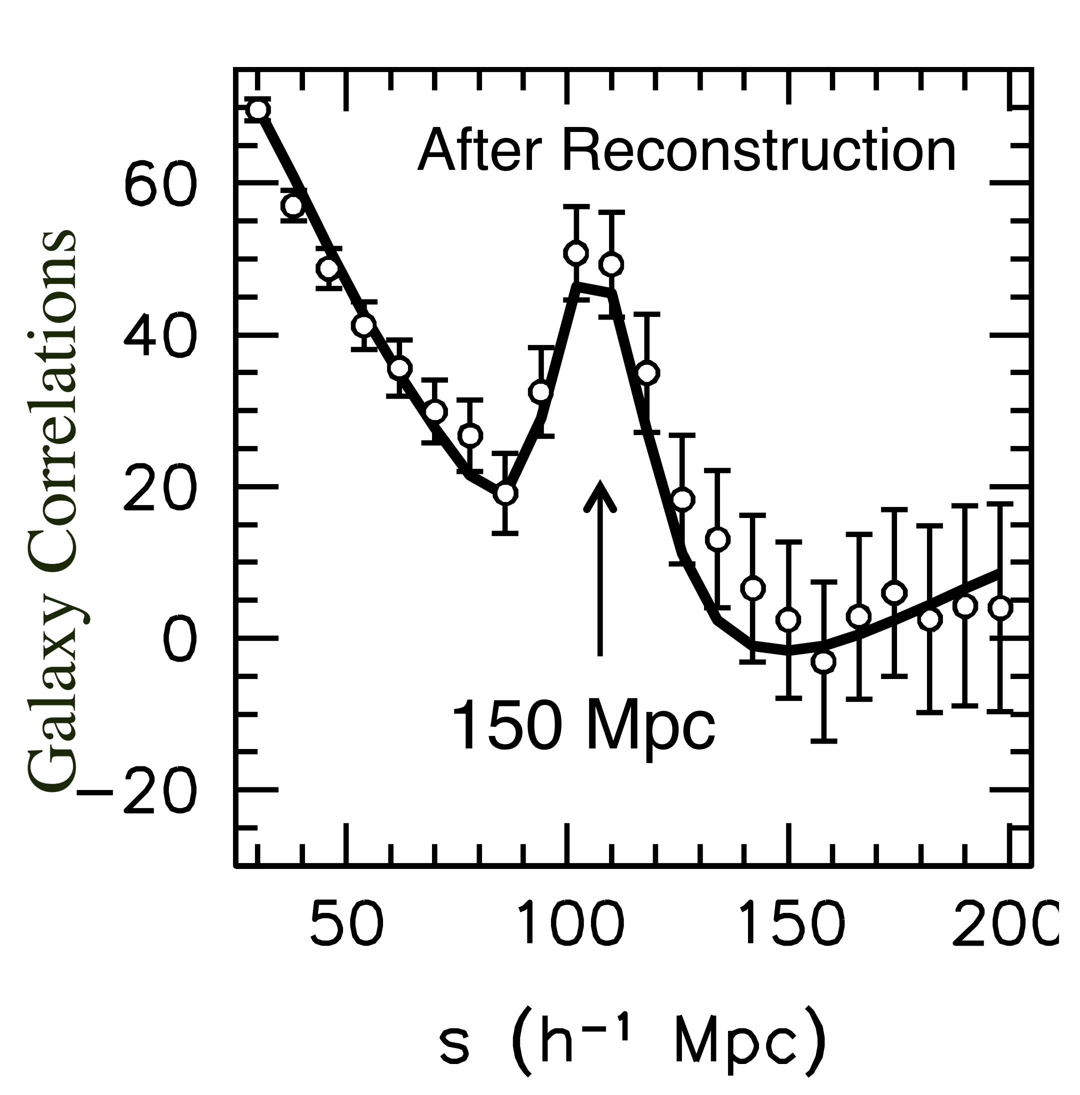
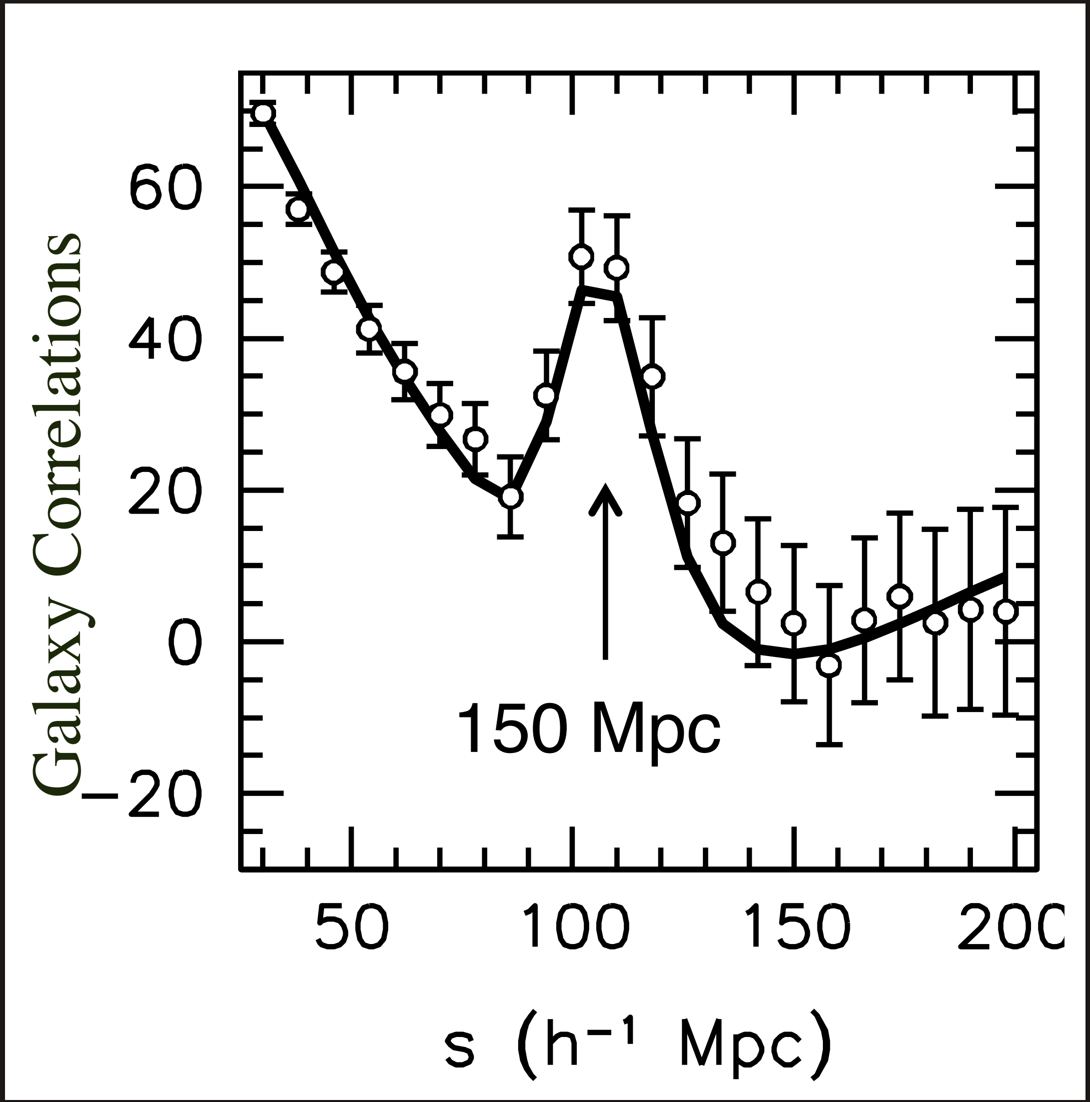


Anderson et al. 2014;
Vargas, Ho et al. 2014;
Tojeiro et al. 2014

BAO in BOSS Galaxies

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



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Outline today

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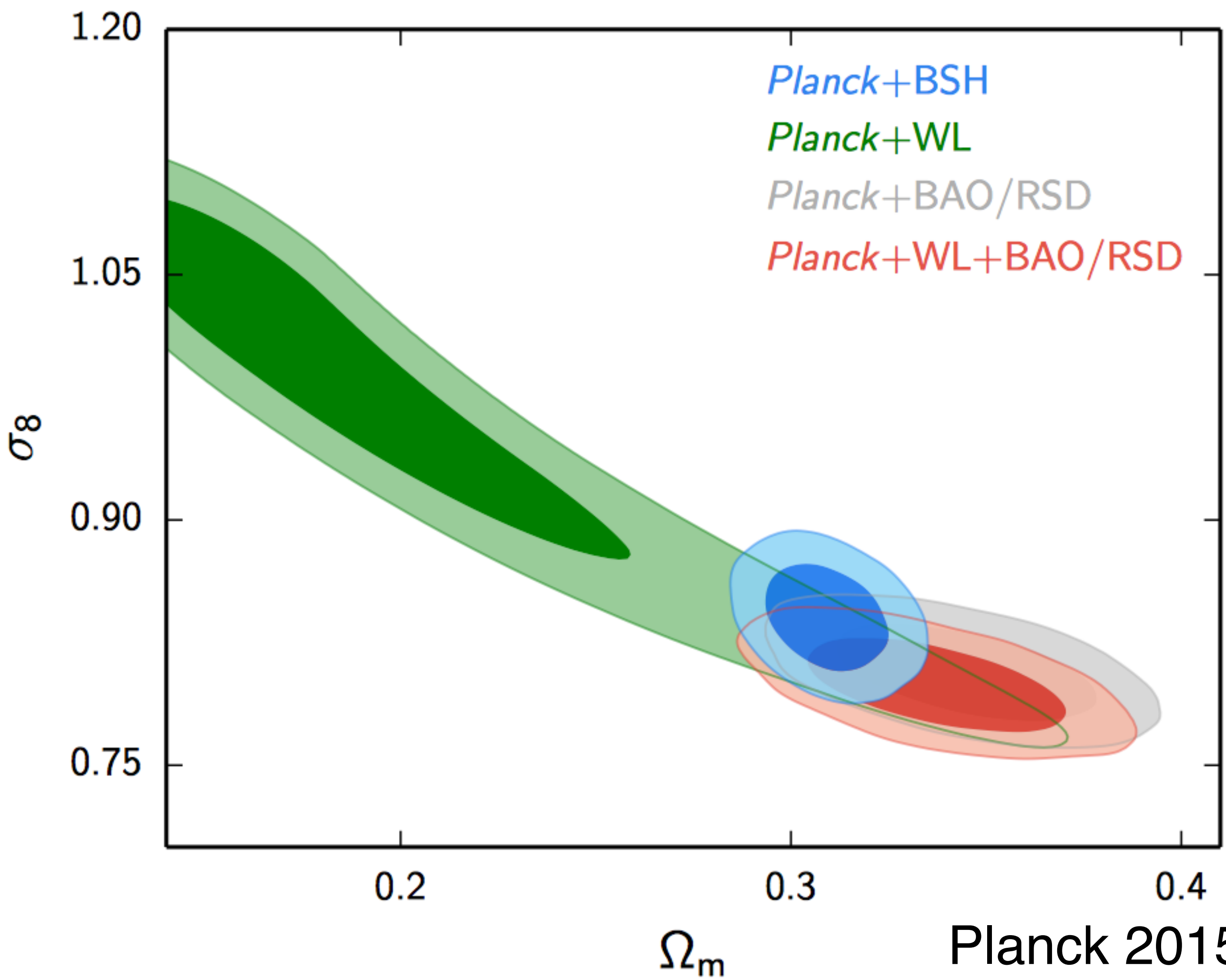
  - Introduce a new probe combining BOSS AND CMB-lensing to learn about gravity at the largest scale !

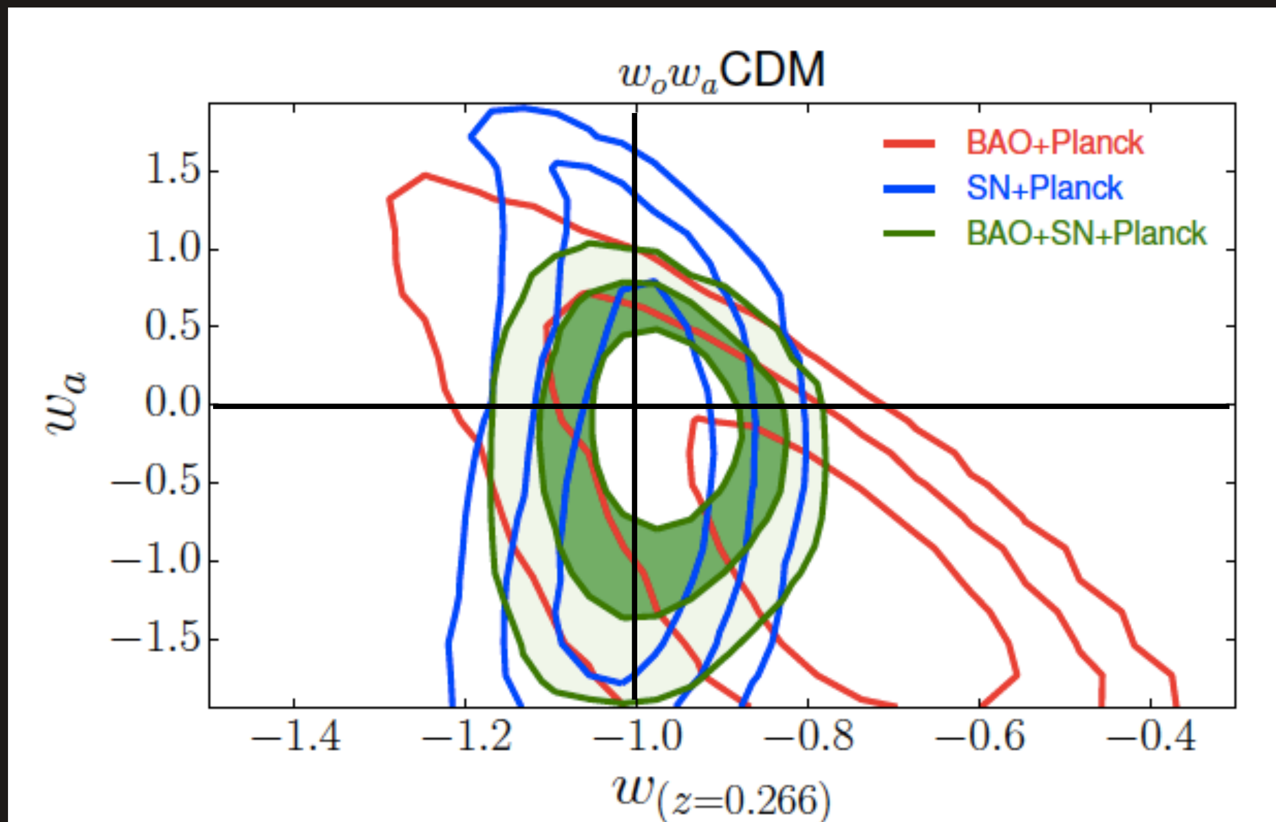
Constraining cosmological models



Planck 2015

How about Dark Energy?

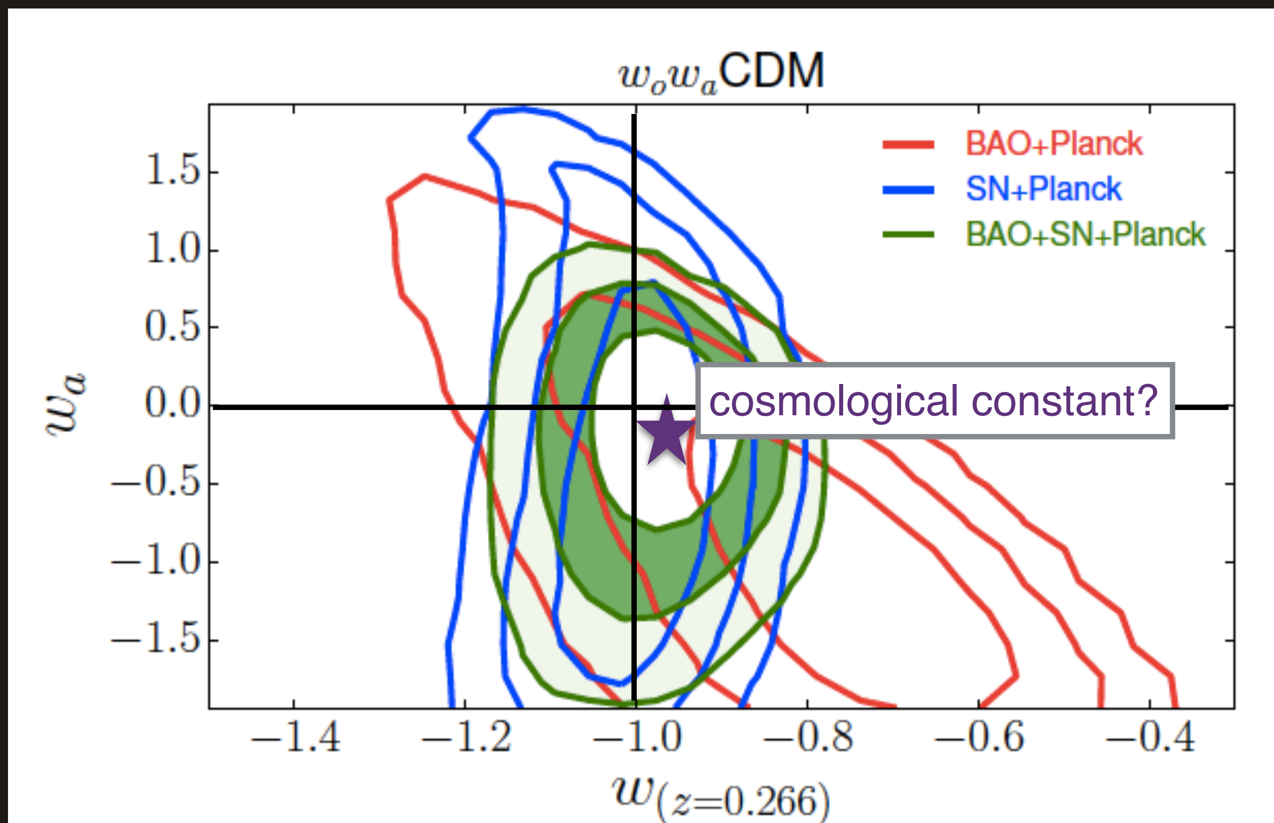
- Combined constraints on Dark Energy



BOSS collaboration 2014

Is it a cosmological constant?

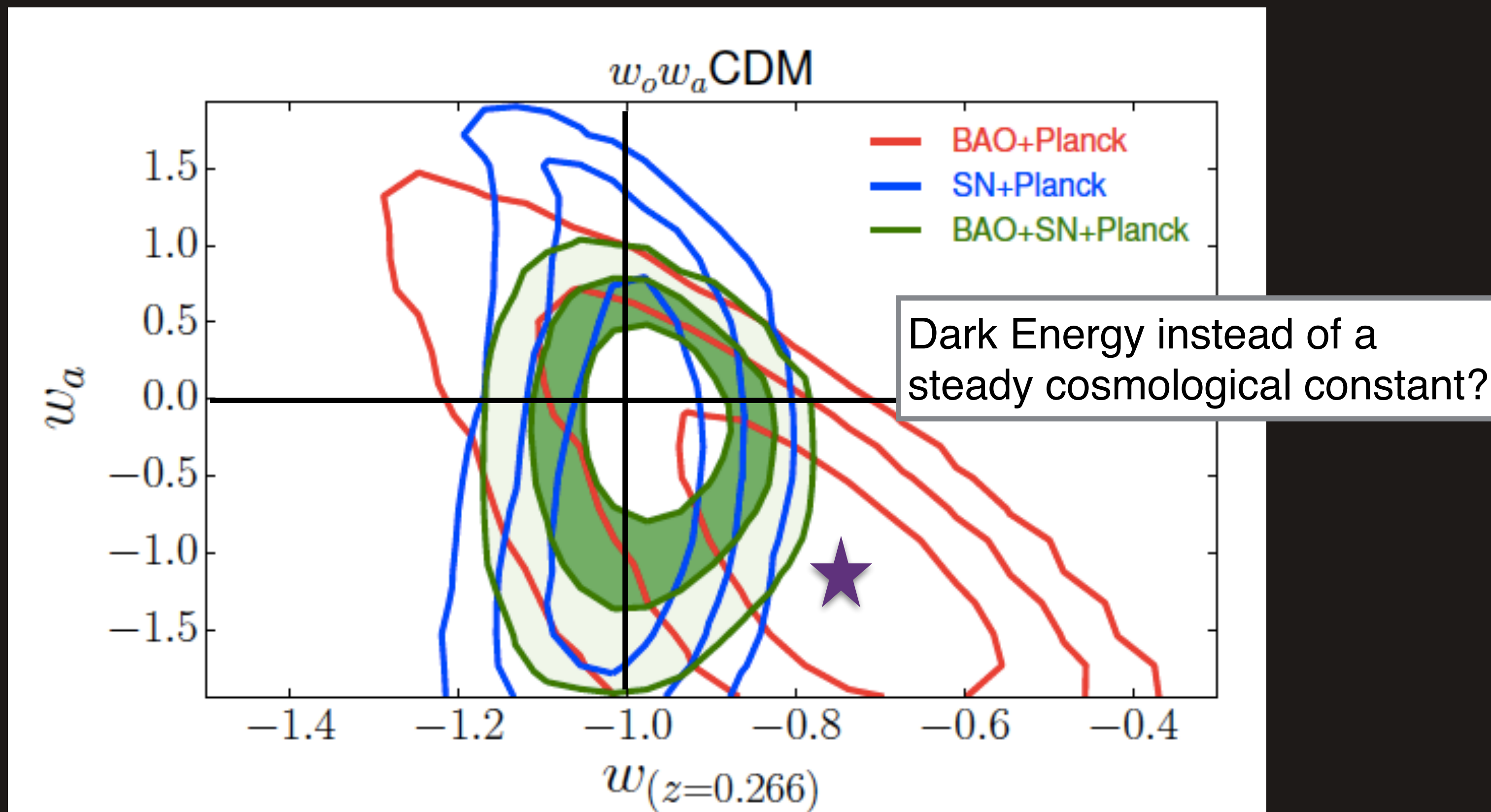
- Combined constraints:



BOSS collaboration 2014

Or is it Dark Energy?

- Combined constraints:

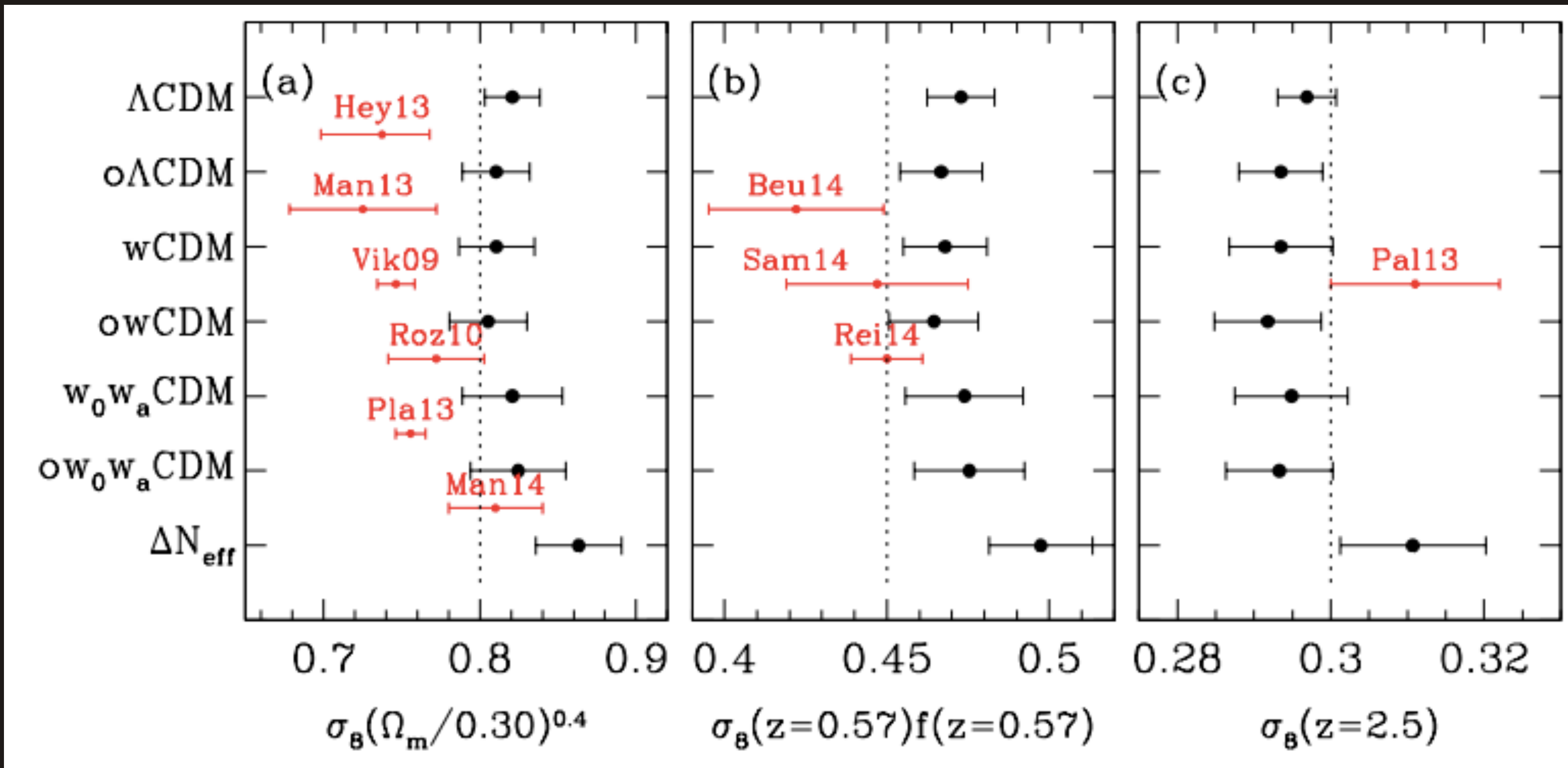


BOSS collaboration 2014

Comparison with other probes

BOSS collaboration 2014

Black: Planck +BAO + SN



Lensing, clusters

Redshift Space Distortions

Lya 1D P(k)

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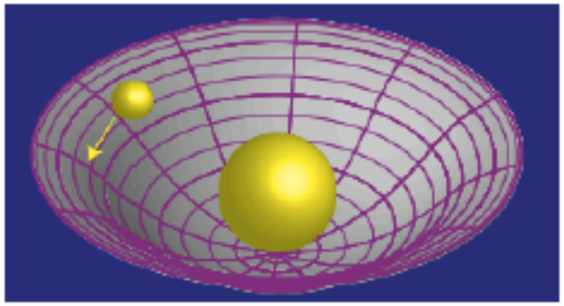
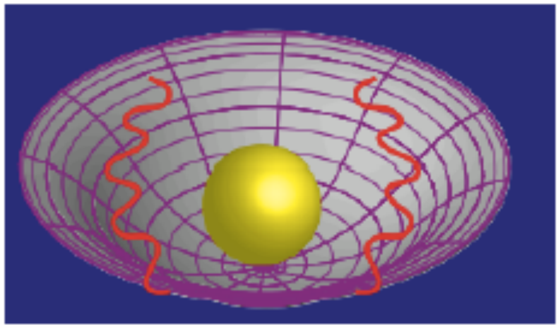
Testing Gravity by combining CMB lensing and Large Scale structure

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



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



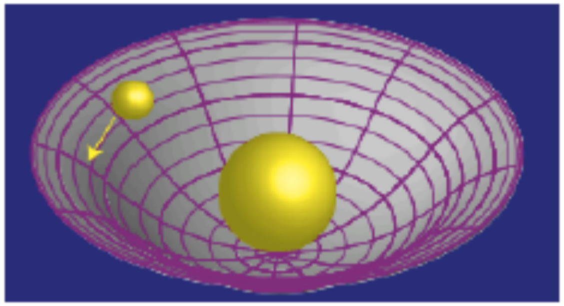
Relativistic particles deflected by spatial curvature

Zhang, Liguori, Bean, Dodelson 2007

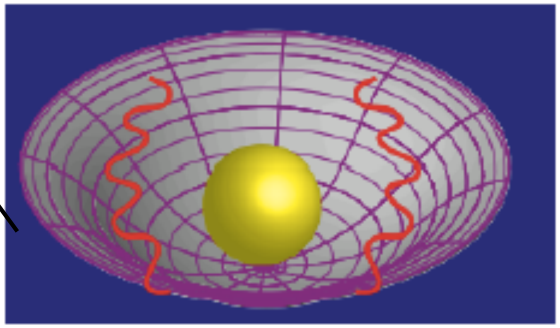
Testing Gravity by combining CMB lensing and Large Scale structure: Introducing E_G

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

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



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

SDSS III

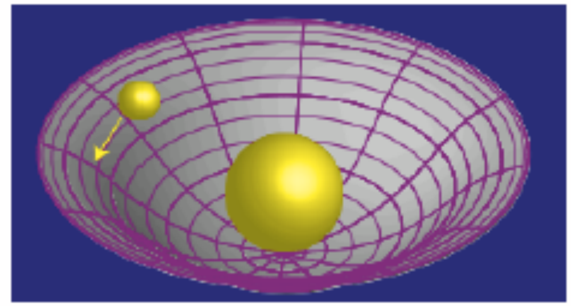
Testing Gravity by combining CMB lensing and Large Scale structure: Consider GR

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

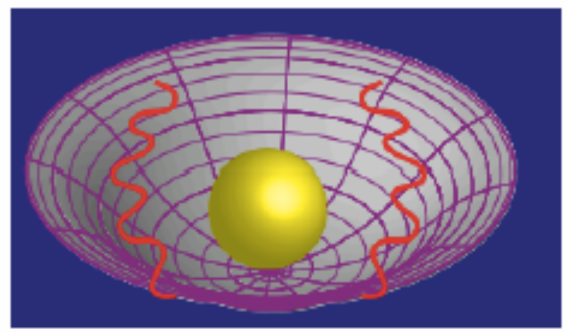
$$E_G(k,z) = \frac{c^2[\nabla^2(\psi-\phi)]_k}{3H_0^2(1+z)\theta(k)} = \frac{c^2k^2(\phi-\psi)}{3H_0^2(1+z)\theta(k)},$$

GR

$$k^2\psi = -4\pi G a^2 \rho(a)\delta$$
$$\phi = -\psi,$$



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

SDSSIII

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

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

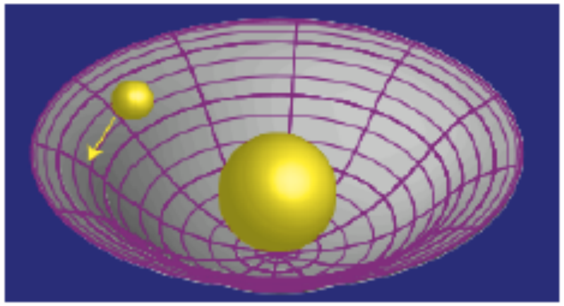
$$E_G(k,z) = \frac{c^2[\nabla^2(\psi-\phi)]_k}{3H_0^2(1+z)\theta(k)} = \frac{c^2k^2(\phi-\psi)}{3H_0^2(1+z)\theta(k)},$$

GR

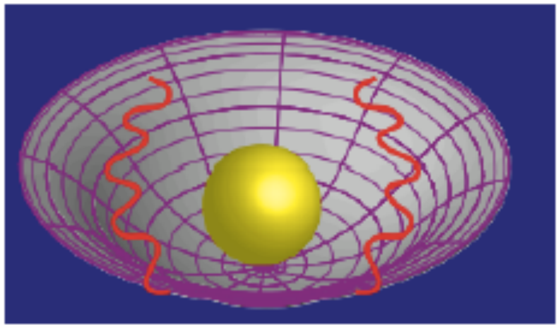
$$k^2\psi = -4\pi G a^2 \rho(a)\delta$$
$$\phi = -\psi,$$

modified gravity

$$k^2\psi = -4\pi G a^2 \mu(k,a)\rho(a)\delta$$
$$\phi = -\gamma(k,a)\psi,$$



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



Relativistic particles deflected by spatial curvature

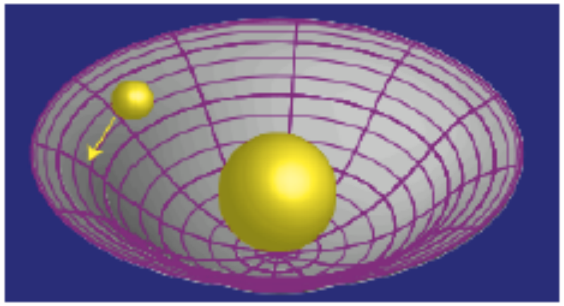
Zhang, Liguori, Bean, Dodelson 2007

SDSS III

Testing Gravity by combining CMB lensing and Large Scale structure: General equation of E_G

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

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



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

GR

$$k^2\psi = -4\pi G a^2 \rho(a)\delta$$
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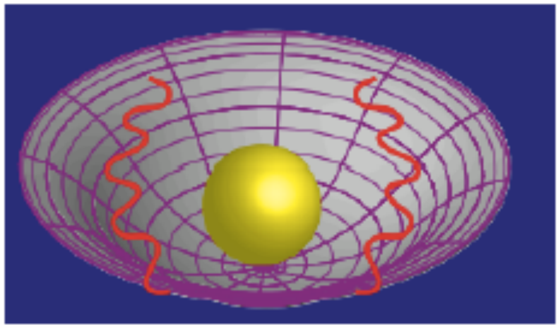


Relativistic particles deflected by spatial curvature

modified gravity

$$k^2\psi = -4\pi G a^2 \mu(k,a)\rho(a)\delta$$
$$\phi = -\gamma(k,a)\psi,$$

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

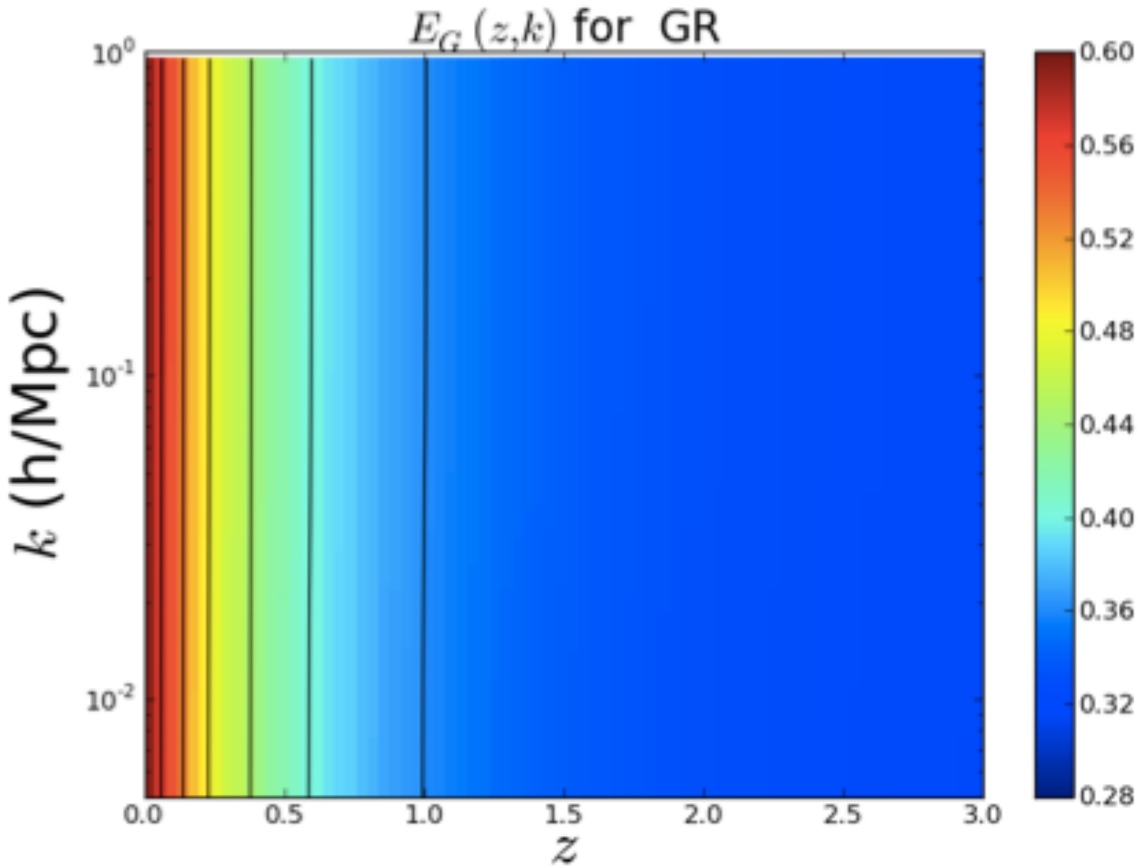
Zhang, Liguori, Bean, Dodelson 2007

SDSS III

Testing Gravity by combining CMB lensing and LSS

Space (frequency) and time (redshift) dependence of E_G

Pullen, Alam & Ho, 2015



$\mu = 1$

$\gamma = 1$

if it is General Relativity

SDSSIII

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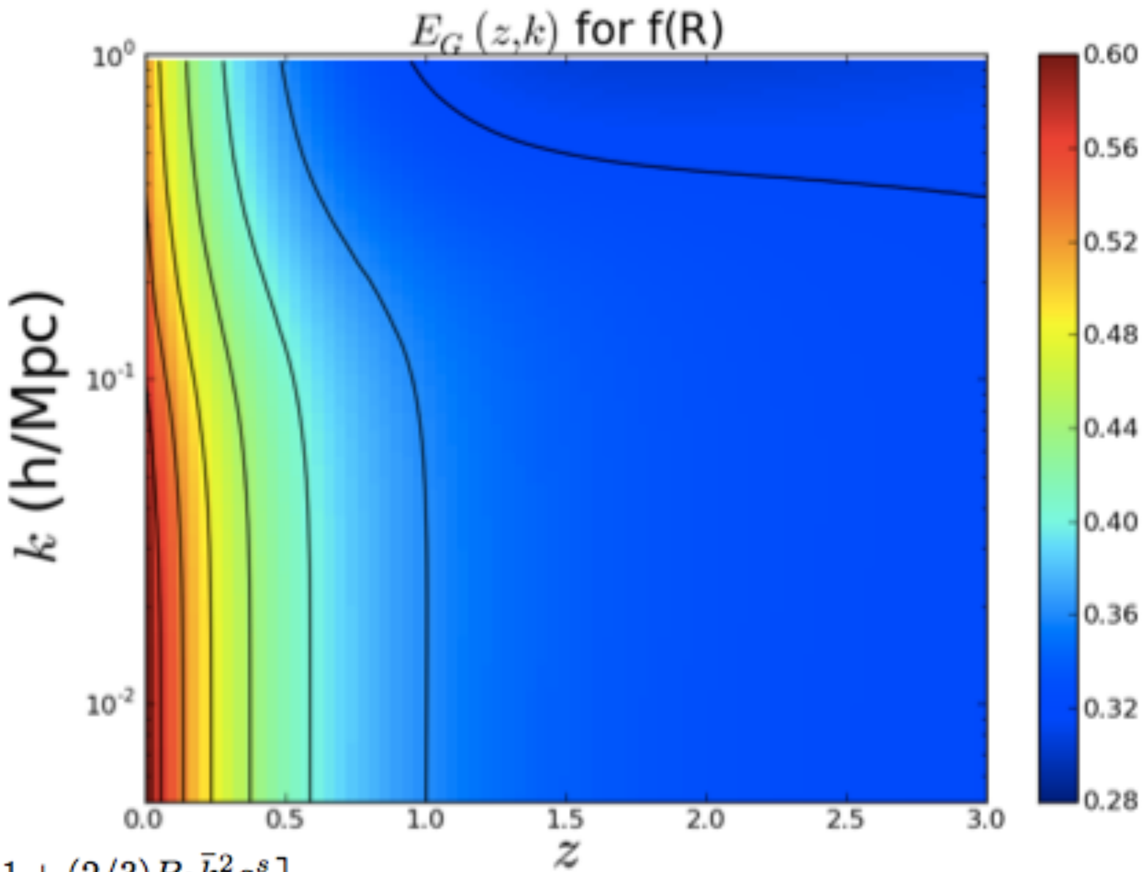
Pullen, Alam & Ho, 2015



$$\mu^{\rm fR}(k,a,) = \frac{1}{1 - B_0 a^{s-1}/6}\left[\frac{1+(2/3)B_0\bar{k}^2 a^s}{1+(1/2)B_0\bar{k}^2 a^s}\right]$$

$$\gamma^{\rm fR}(k,a) = \frac{1+(1/3)B_0\bar{k}^2 a^s}{1+(2/3)B_0\bar{k}^2 a^s},$$

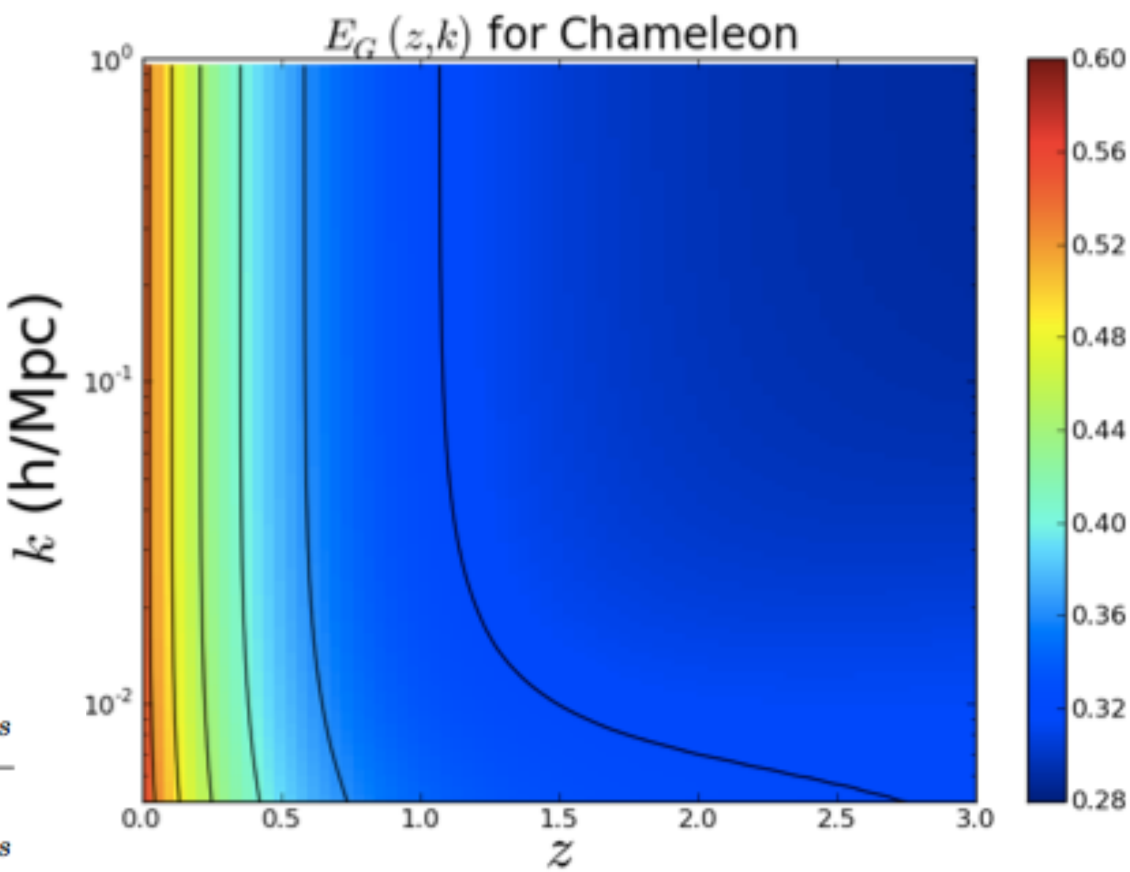
if it is f(R) gravity

SDSS III

Testing Gravity by combining CMB lensing and LSS

Space (frequency) and time (redshift) dependence of E_G

Pullen, Alam & Ho, 2015



$$\mu^{\rm Ch}(k,a) = \frac{1+\beta_1\lambda_1^2 k^2 a^s}{1+\lambda_1^2 k^2 a^s}$$

$$\gamma^{\rm Ch}(k,a) = \frac{1+\beta_2\lambda_2^2 k^2 a^s}{1+\lambda_2^2 k^2 a^s}$$

$$\lambda_2^2 = \beta_1 \lambda_1^2$$

$$\beta_2 = \frac{2}{\beta_1} - 1\,,$$

if it is chameleon model

SDSS III

We now translate these into observables that we can measure:

$$\hat{E}_G(k,z) = \frac{c^2 \hat{P}_{\nabla^2(\psi-\phi)g}(k)}{3H_0^2(1+z)\hat{P}_{\theta g}(k)},$$

↓

$$\hat{E}_G(\ell,\bar{z}) = \frac{2c^2 \hat{C}_\ell^{\kappa g}}{3H_0^2(1+\bar{z})W(\bar{\chi})\Delta\chi\beta(\bar{z})\hat{C}_\ell^{gg}},$$

tracer-CMB lensing

Redshift space distortions

tracer-tracer clustering

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.

SDSSIII

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tracer-CMB lensing (b)

Redshift space distortions (1/b)

tracer-tracer clustering (b*b)

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tracer-CMB lensing (b)

Redshift space distortions (1/b)

tracer-tracer clustering (b*b)

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

- no intrinsic alignment of CMB
- But we are working on teasing out any systematics now.

We now translate these into observables that we can measure:

$$\hat{E}_G(k,z) = \frac{c^2 \hat{P}_{\nabla^2(\psi-\phi)g}(k)}{3H_0^2(1+z)\hat{P}_{\theta g}(k)},$$

↓

$$\hat{E}_G(\ell,\bar{z}) = \frac{2c^2 \hat{C}_\ell^{\kappa g}}{3H_0^2(1+\bar{z})W(\bar{\chi})\Delta\chi\beta(\bar{z})\hat{C}_\ell^{gg}},$$

tracer-CMB lensing

Redshift space distortions

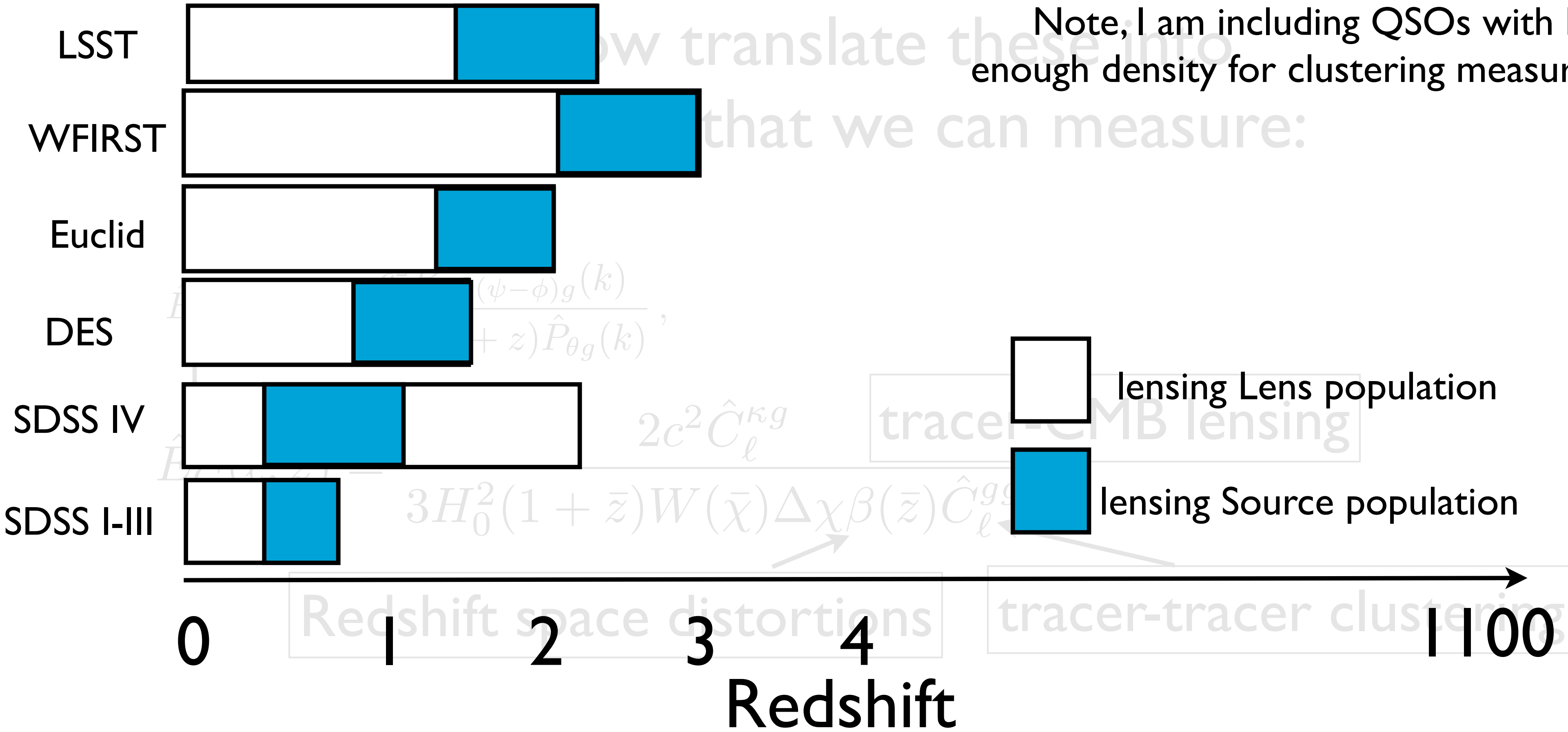
tracer-tracer clustering

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.

SDSSIII

Note, I am including QSOs with high enough density for clustering measurements



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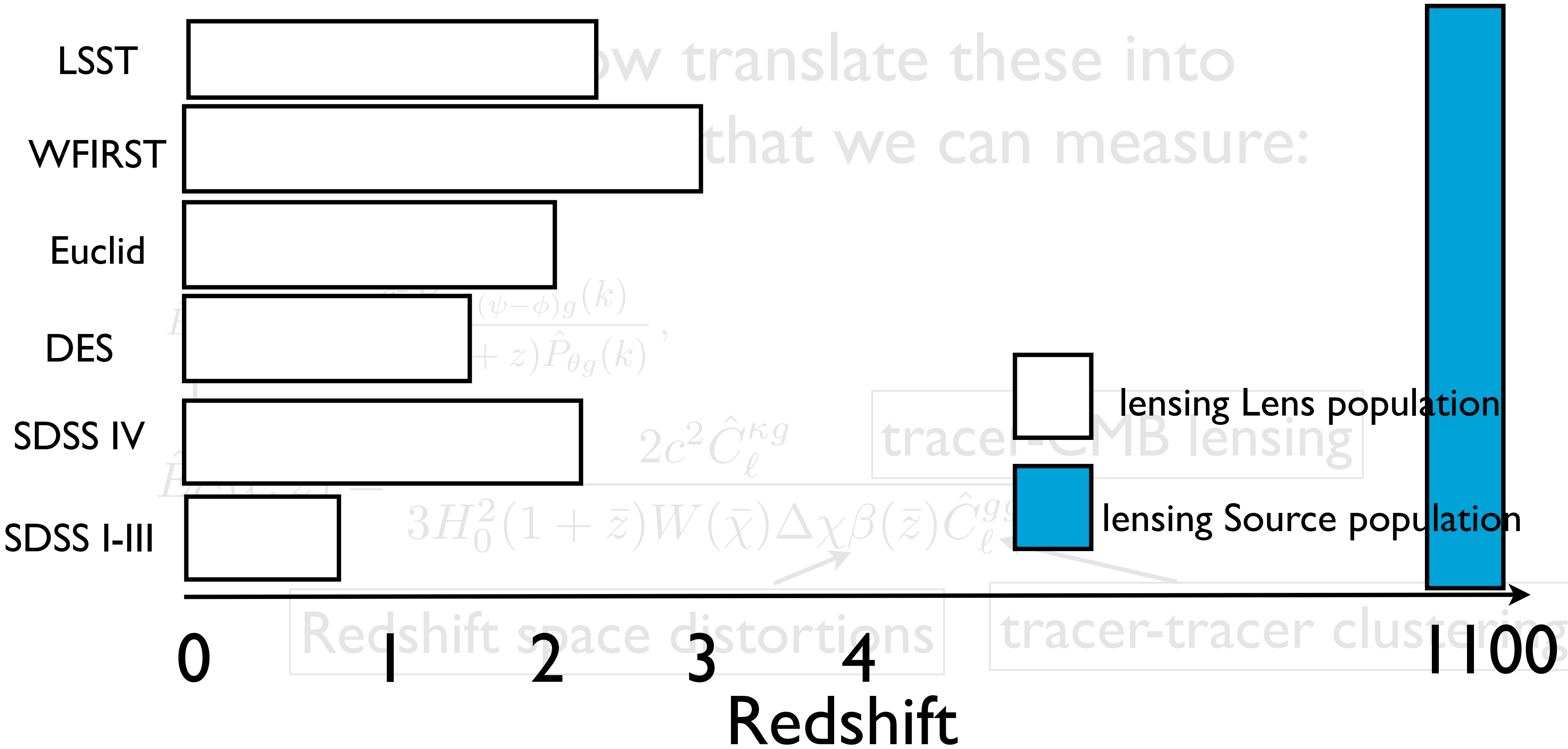

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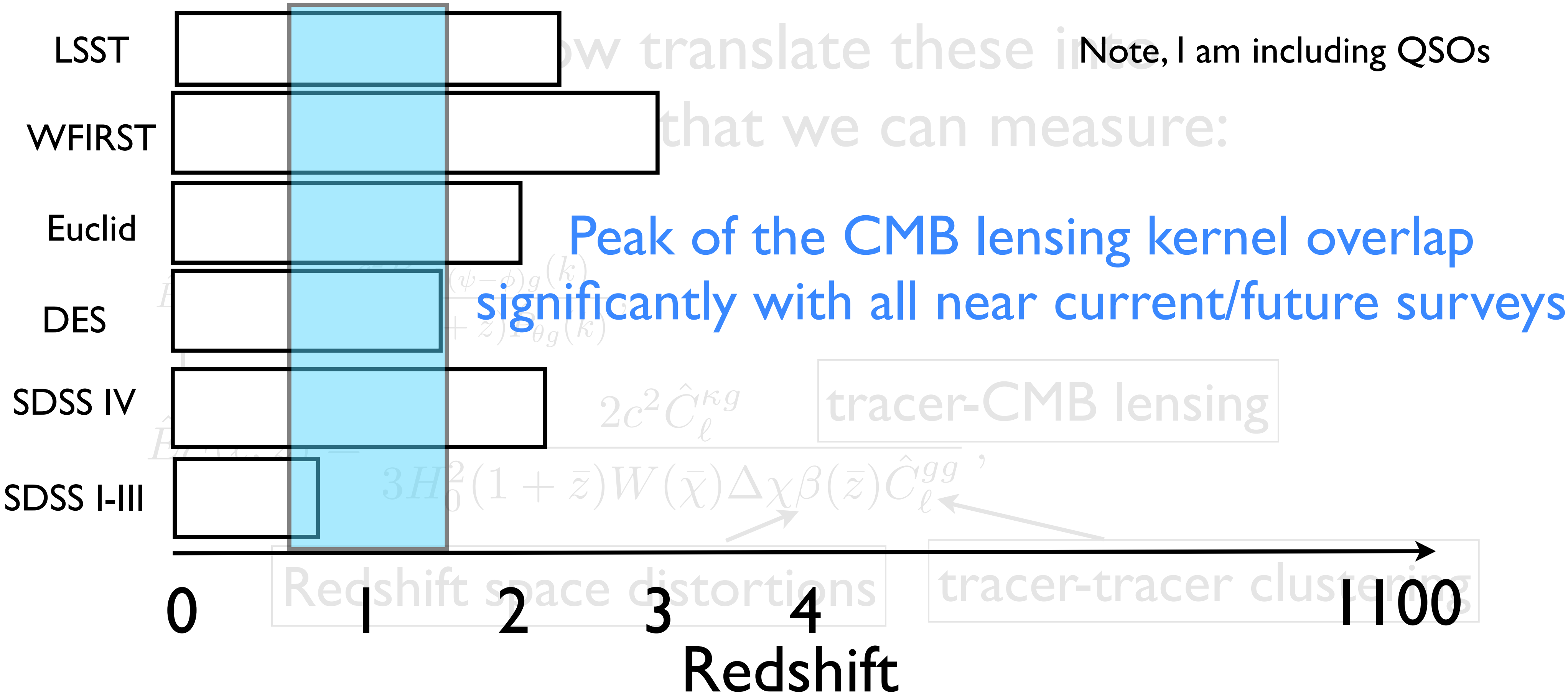

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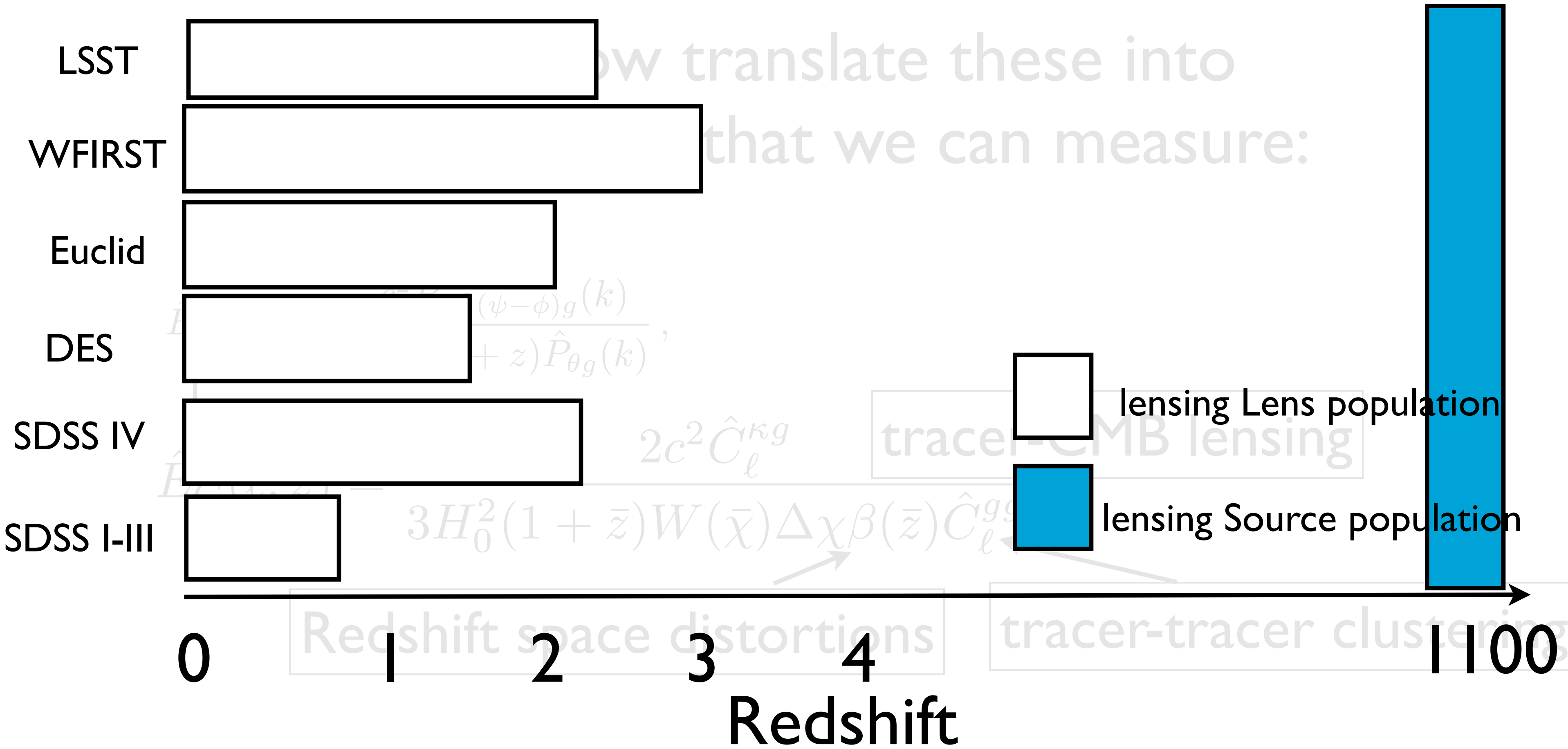

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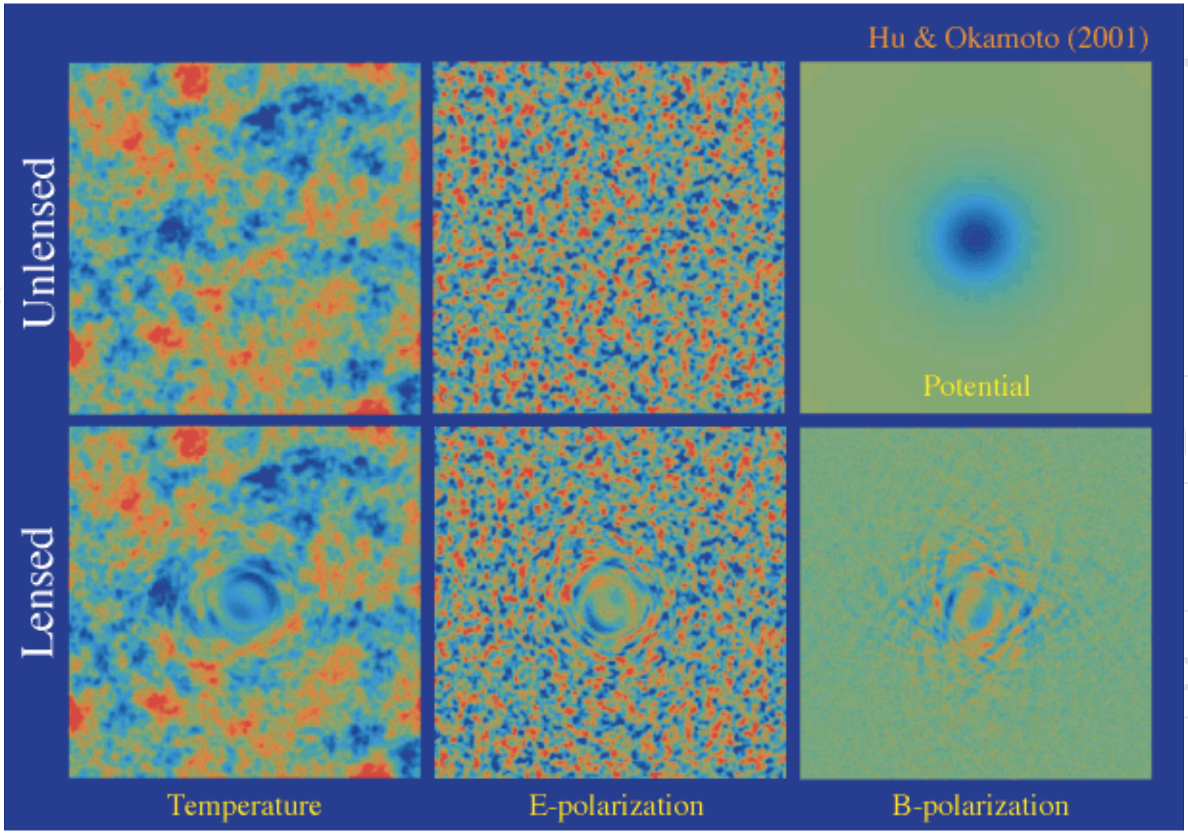
We now translate these into



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- Dramatically increase the z-range of the tracers you can use
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It is no man's land out there ...

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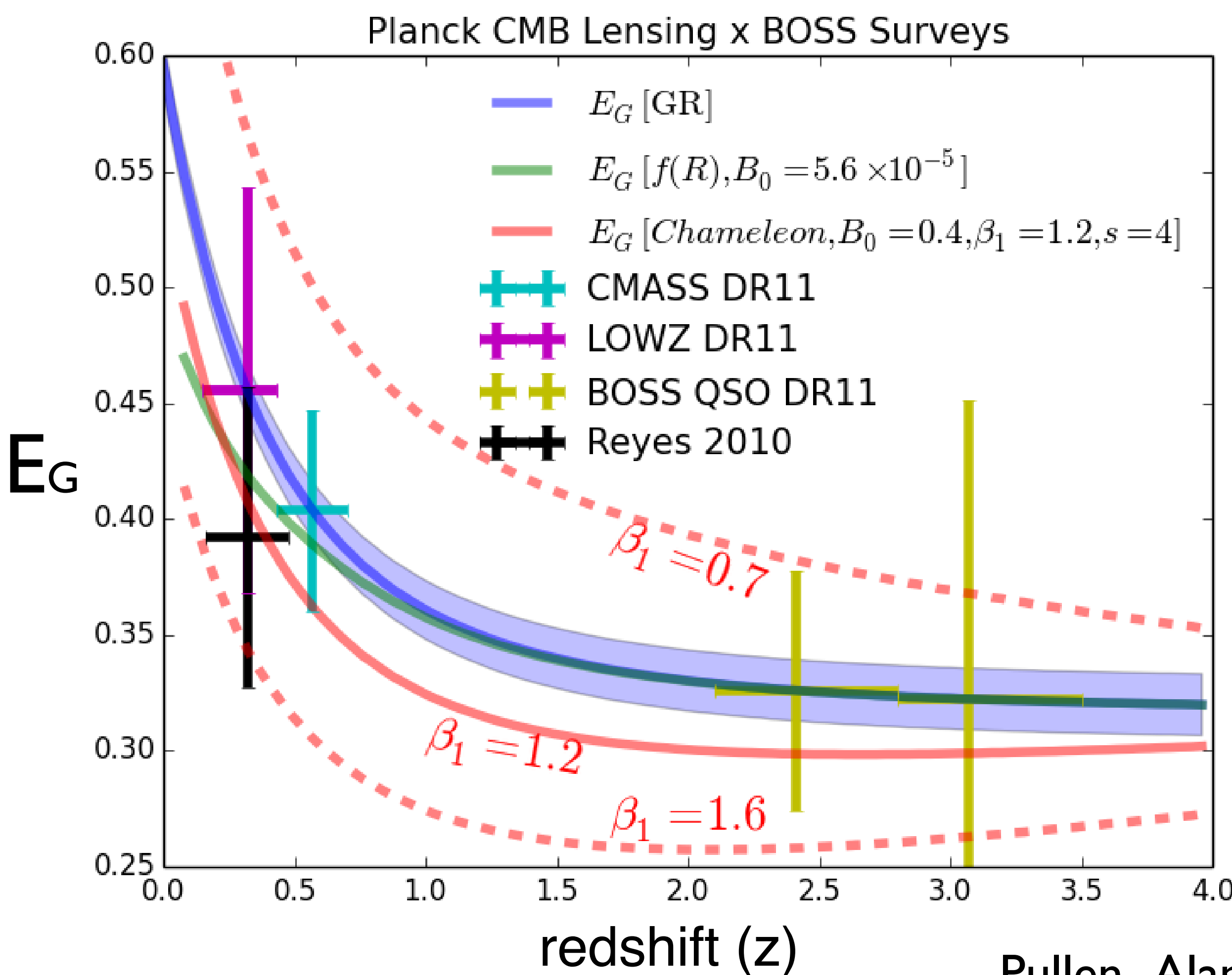
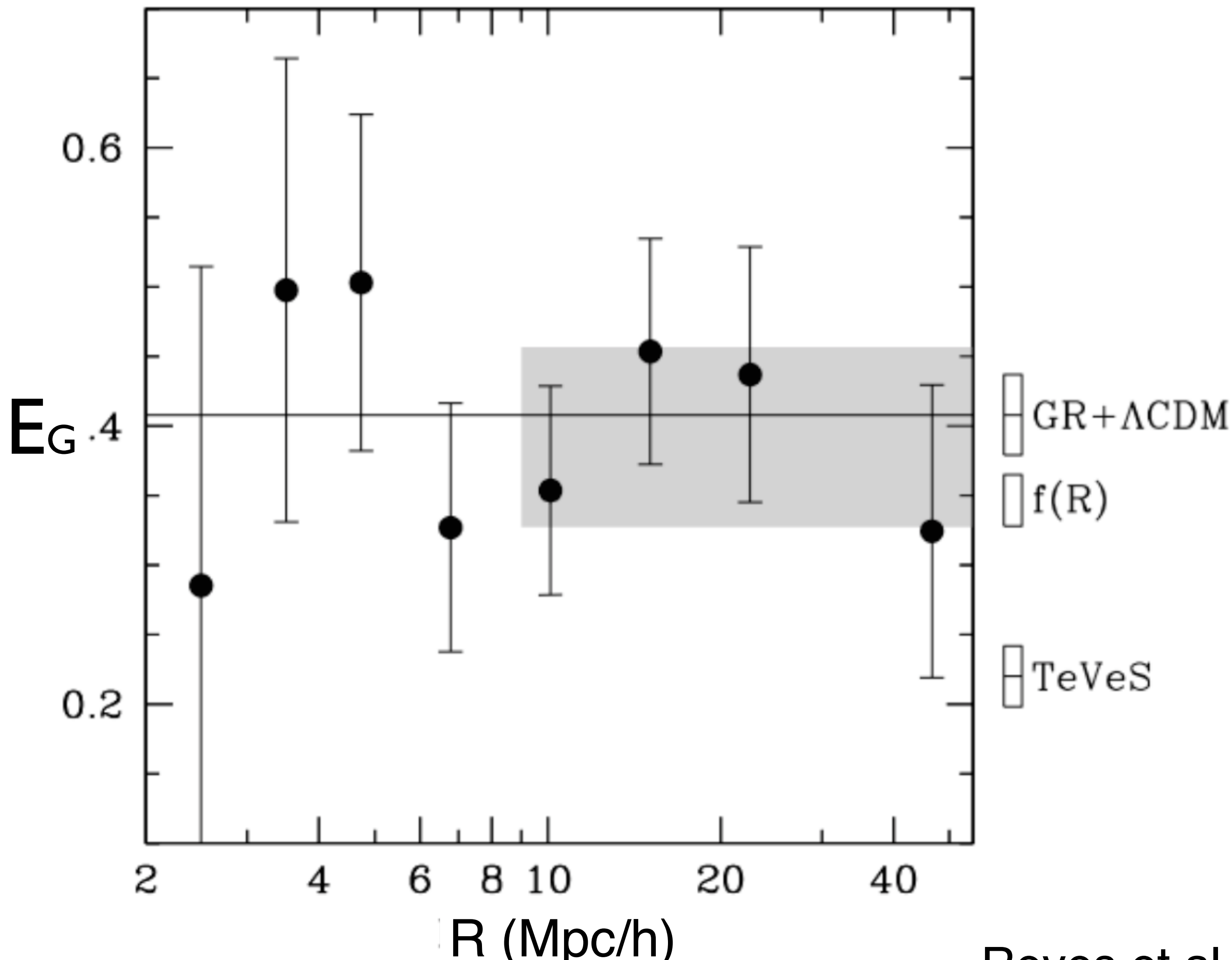
Can we use this new probe with BOSS ?



Pullen, Alam & Ho, 2015

SDSSIII

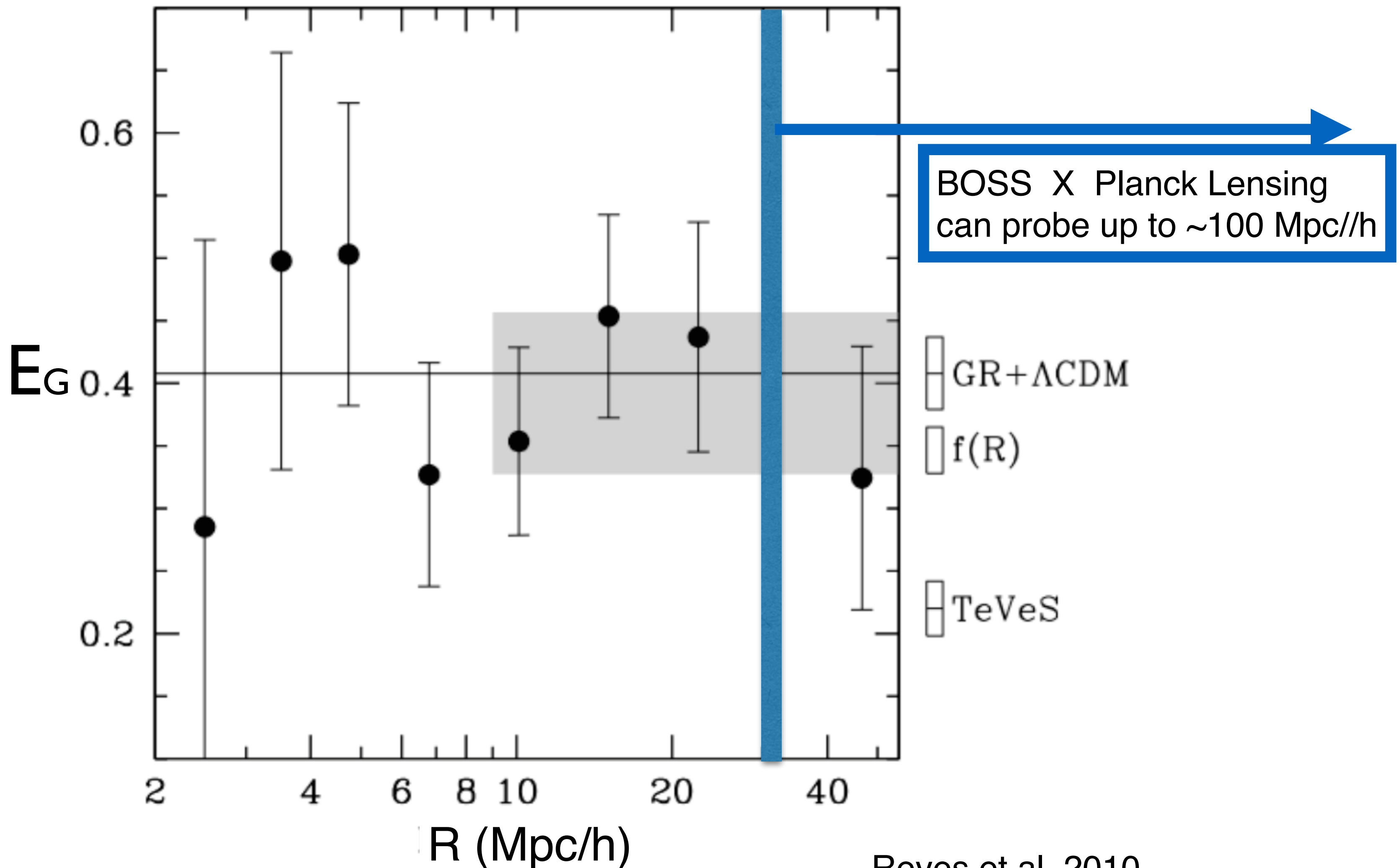
We probe a complimentary range of scales when compared to using galaxy-lensing instead of CMB-lensing



Reyes et al. 2010

SDSSIII

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

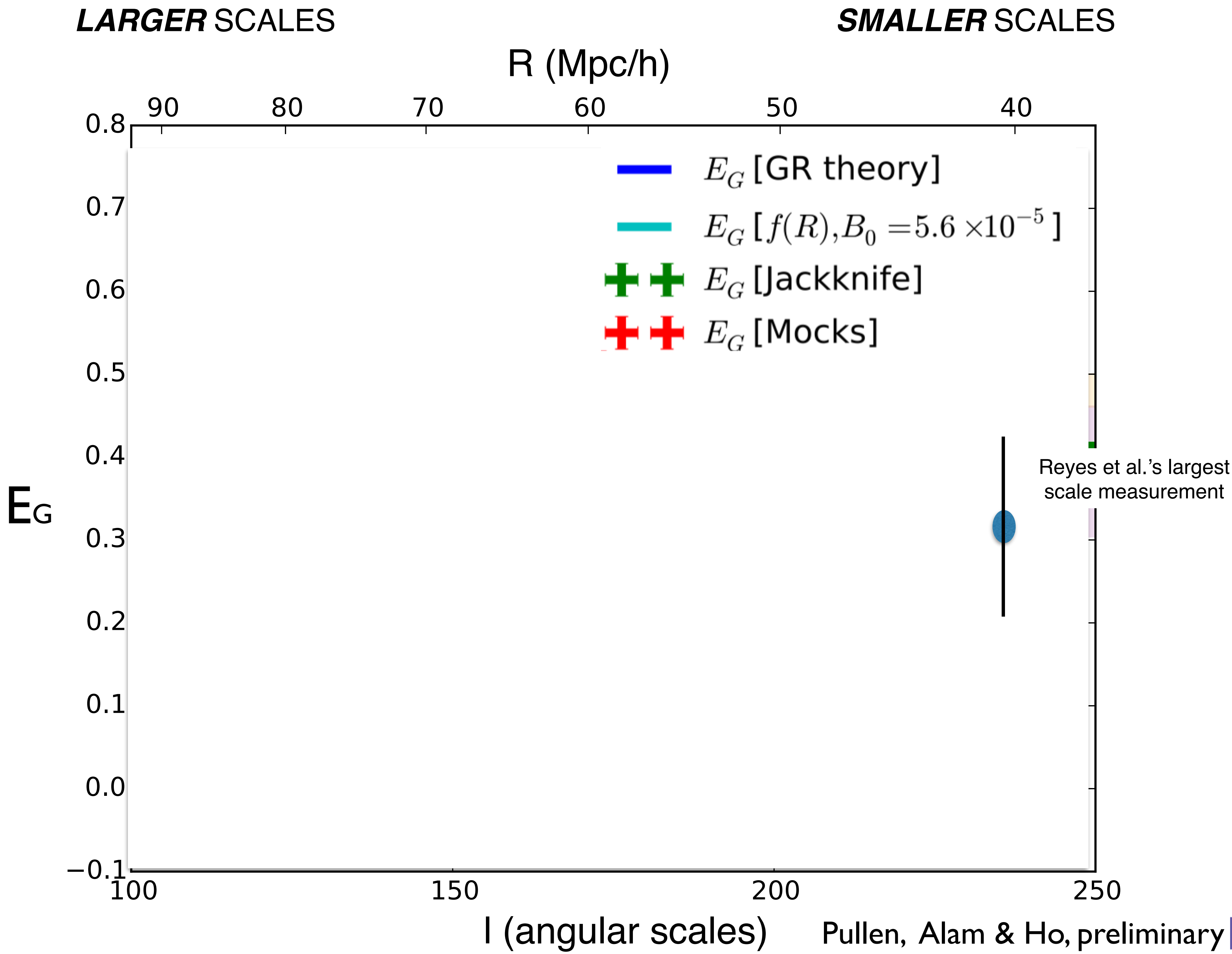


Reyes et al. 2010

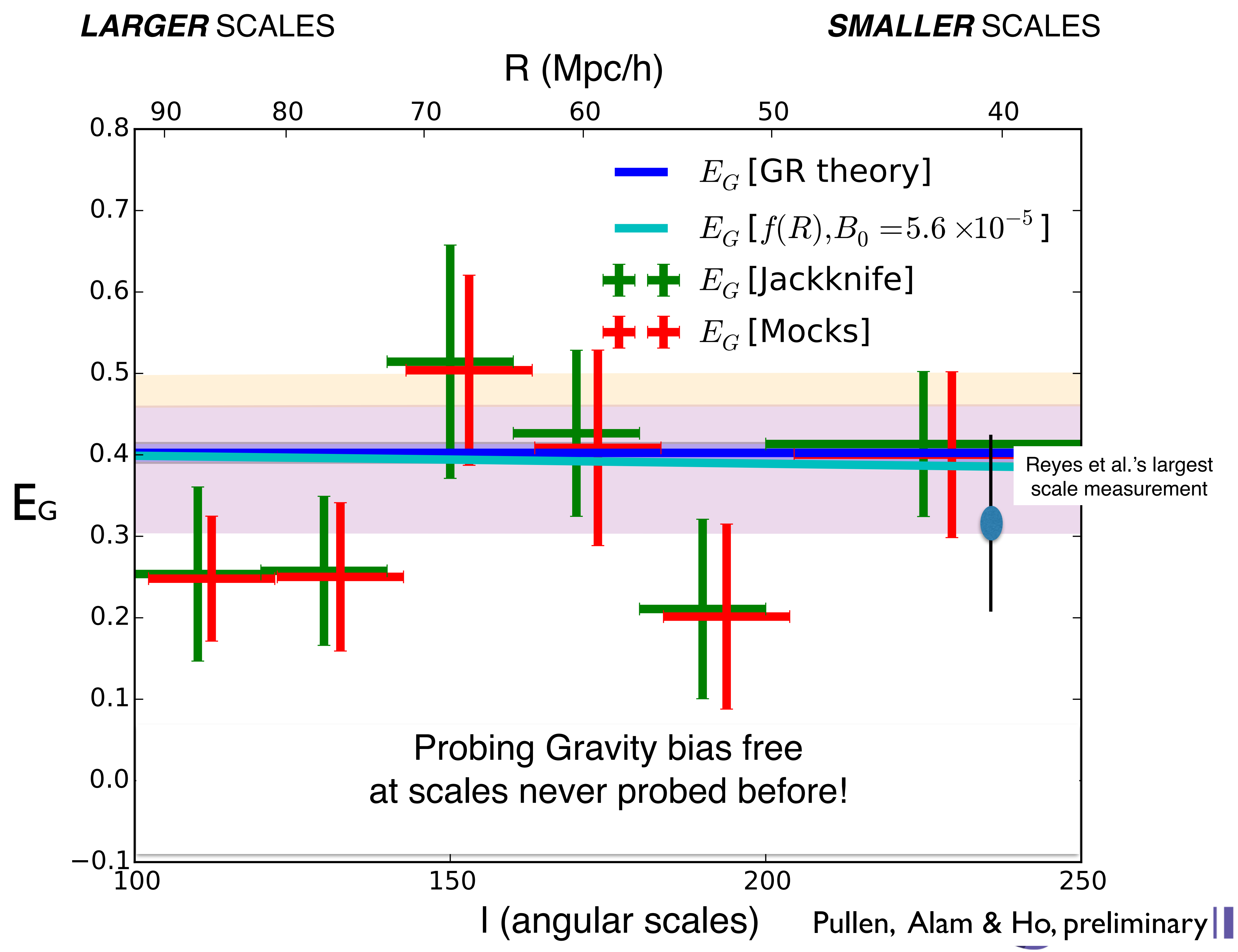
SDSS III

Preliminary look into BOSS X Planck-lensing


WWW.HDWALLPAPERS.IN



Pullen, Alam & Ho, preliminary



LARGER SCALES
SMALLER SCALES
R (Mpc/h)
90
80
70
60
50
40
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
E_G [GR theory]
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Reyes et al.'s largest scale measurement
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Probing Gravity bias free
at scales never probed before!
100
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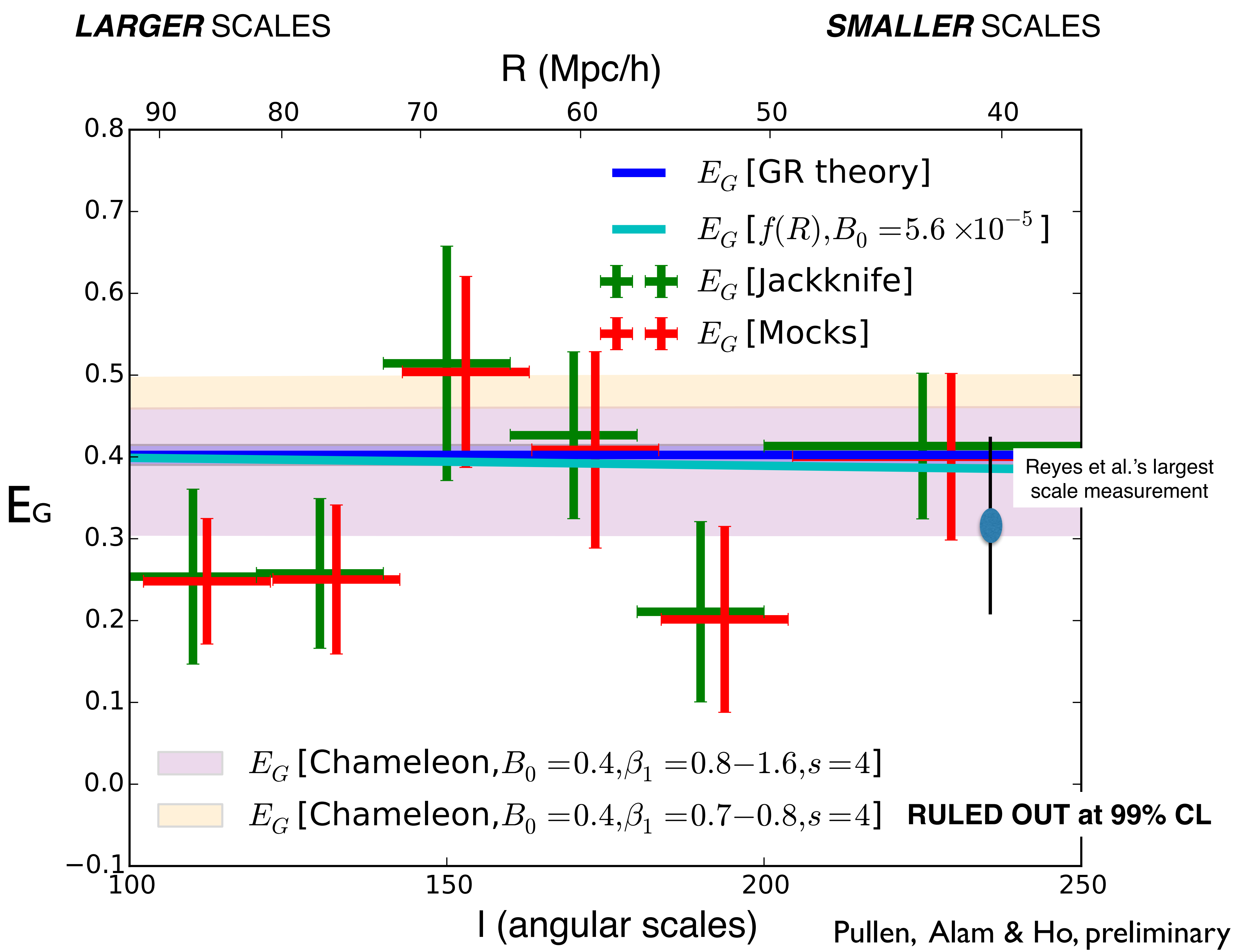

LARGER SCALES
SMALLER SCALES
R (Mpc/h)
90 80 70 60 50 40
0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0 −0.1
E_G
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E_G [Chameleon, $B_0 = 0.4$, $\beta_1 = 0.7-0.8$, $s = 4$]
RULED OUT at 99% CL
100 150 200 250
l (angular scales)
Pullen, Alam & Ho, preliminary

Conclusion

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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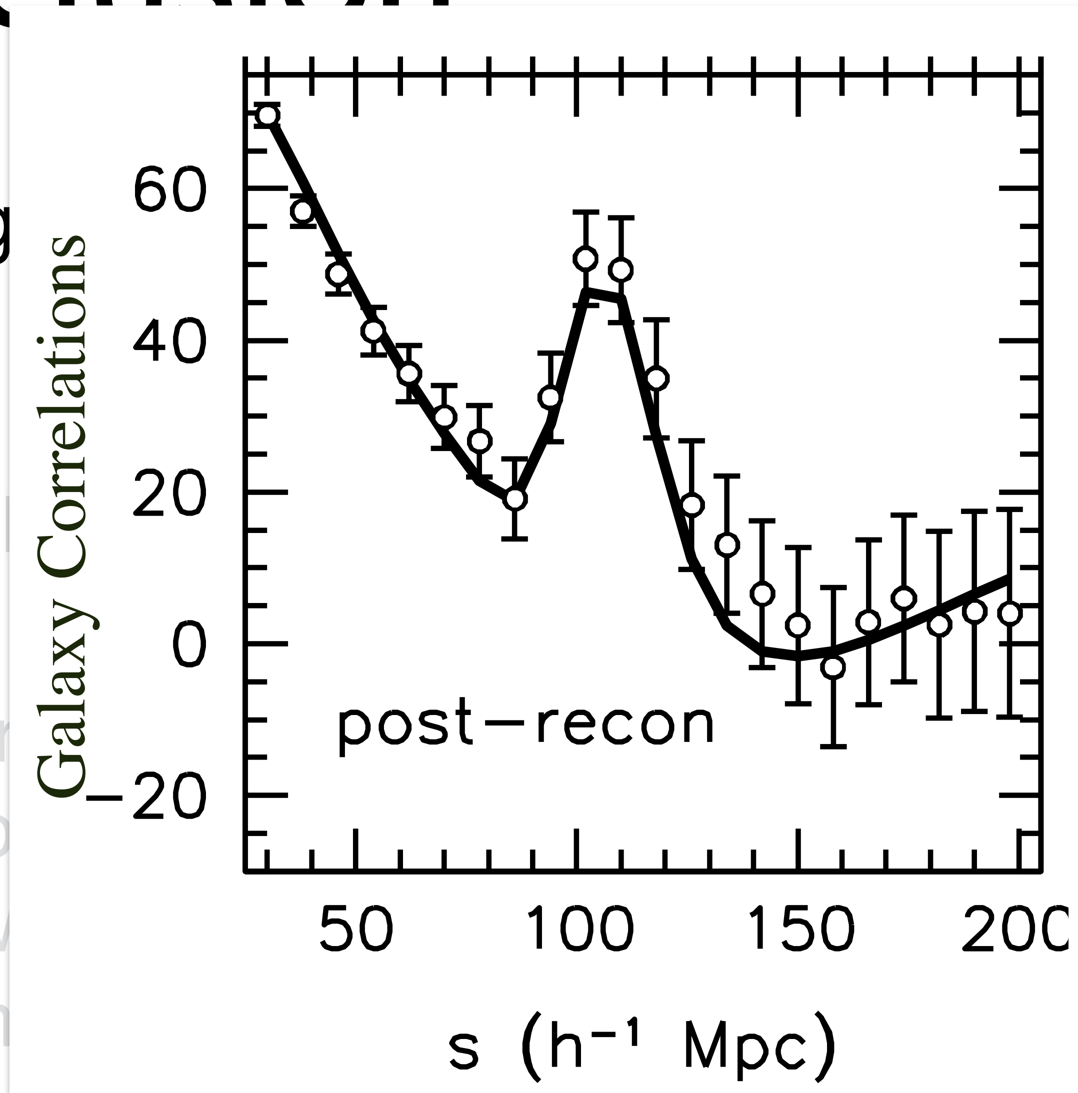

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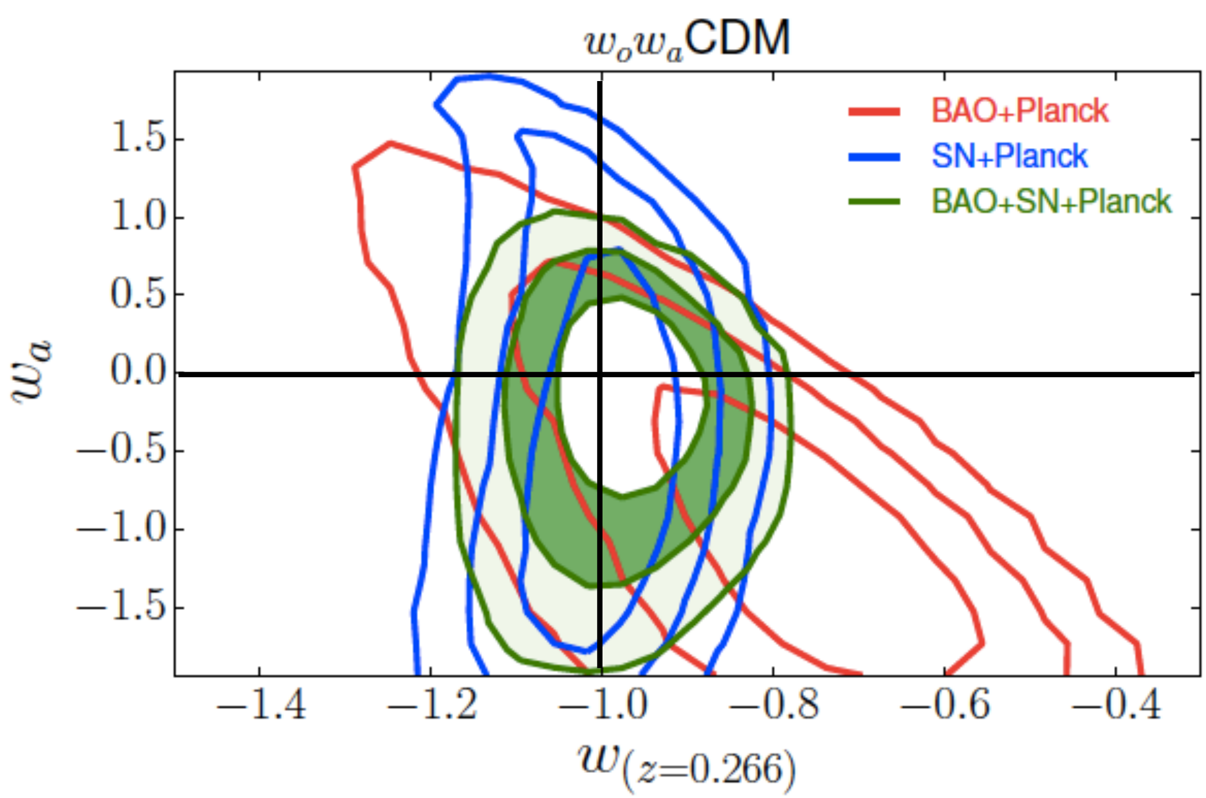

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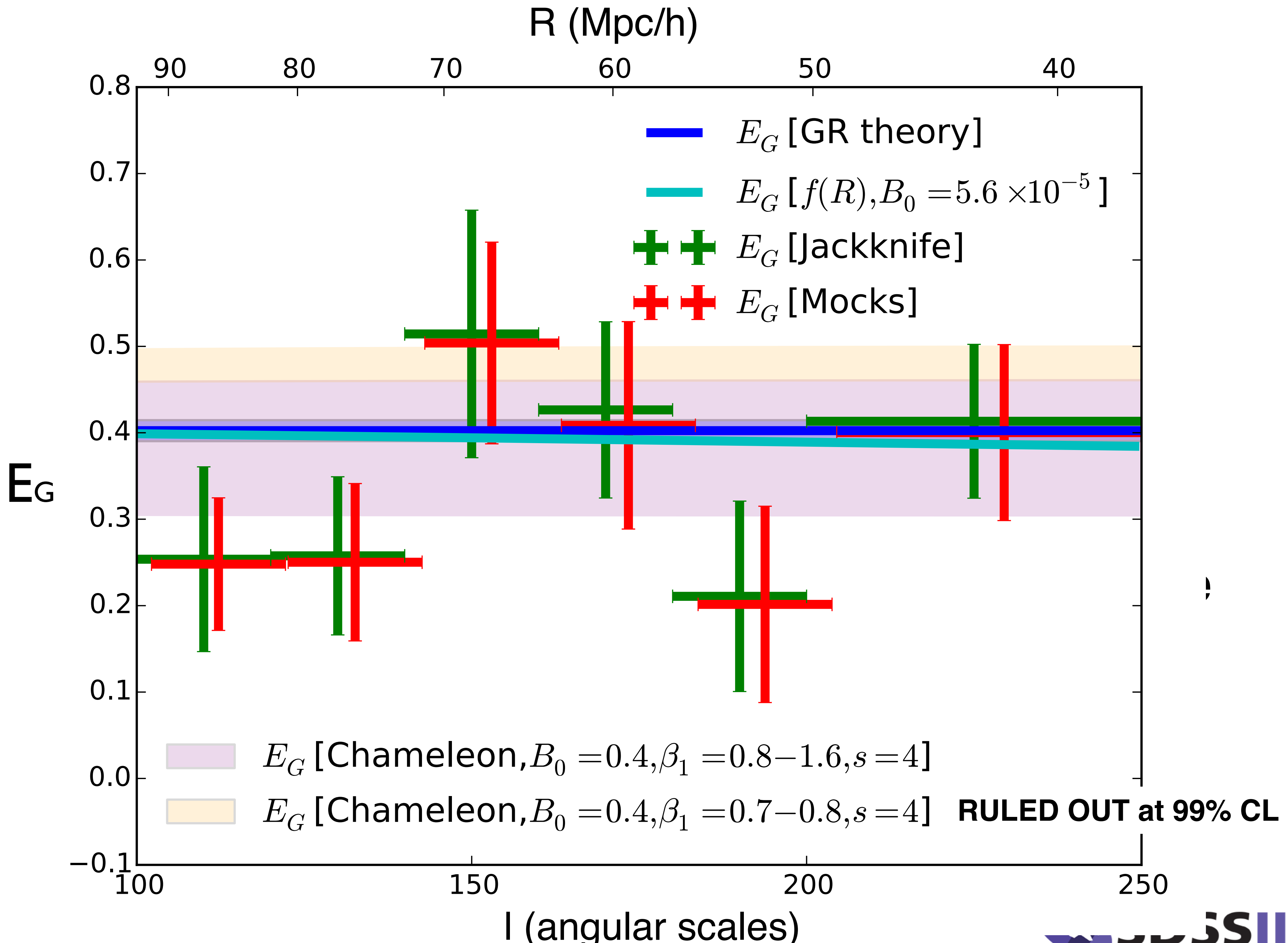

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