How to learn to Love the BOSS

Baryon Oscillations Spectroscopic Survey

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Martin White, Anthony Pullen, Shadab Alam, Mariana Vargas +

Sloan Digital Sky Survey III-BOSS collaboration

Large Scale Structure Conference

MPA, Munich, 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 ?

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 (DePutter et al. 2012, Giusarma et al. 2014)
- Finding missing baryons via kinetic Sunyaev Zeldovich (Preliminary work with Emmanuel Schaan, Simone Ferraro, Kendrick Smith, Mariana Vargas, David Spergel)
- Understanding the Intergalactic medium and dust in galaxies (Menard et al. 2010)
- Galaxy/cluster evolution at lower redshift, quasars properties at high redshift (Guo et al., White et al., Tinker et al., Maraston et al.)
- New way to Test Gravity using CMB lensing and BOSS

Outline today

- What is really BOSS-BAO ?
  - Can we improve the analysis ?
  - What do we learn from it ?
- What other science we can do with BOSS ?
  - Many…
  - Constraining Gravity !
  - Introduce a new probe combining BOSS AND CMB-lensing to learn about gravity at the largest scale !

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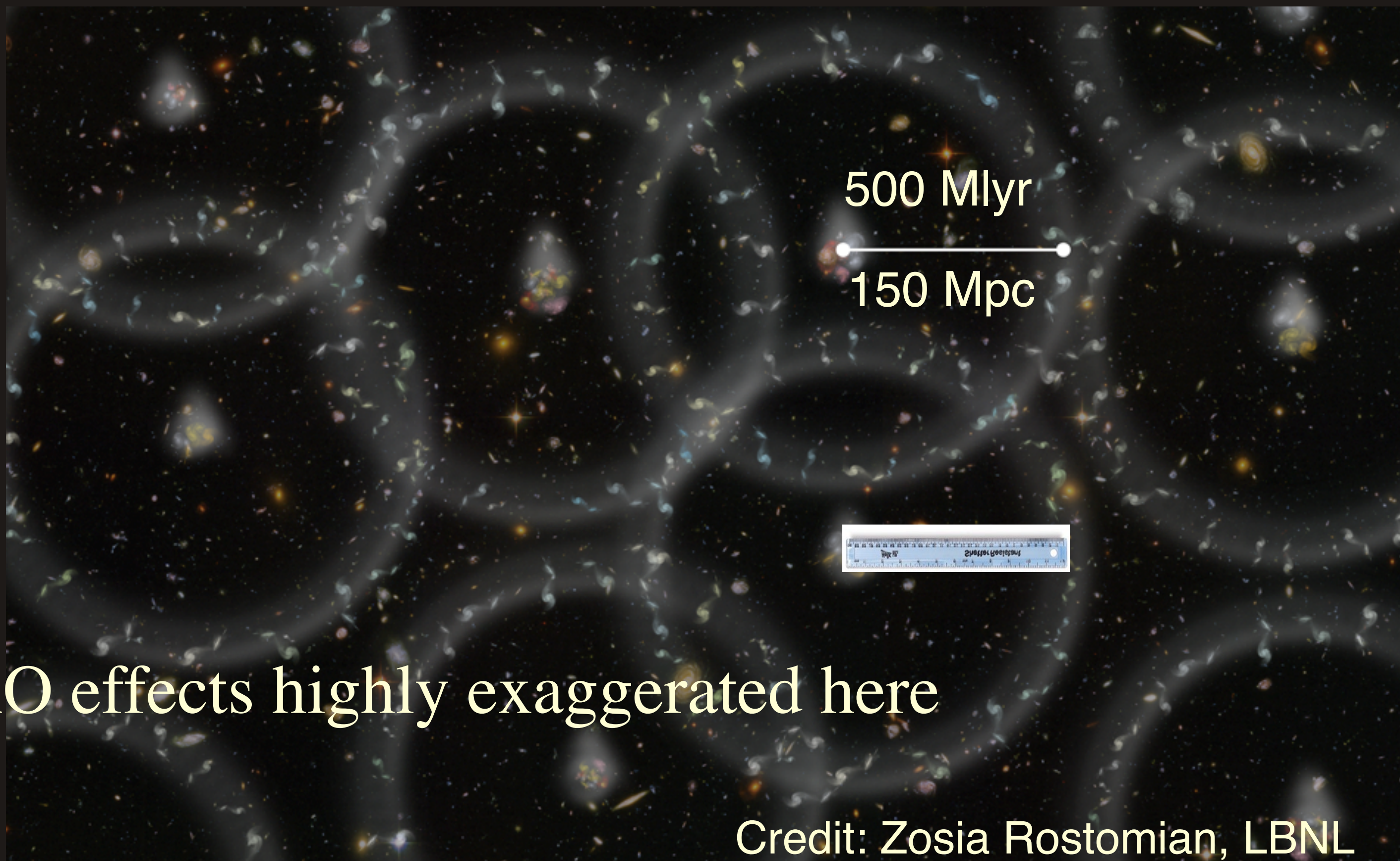
BAO and Galaxies

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



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.

Planck 2015

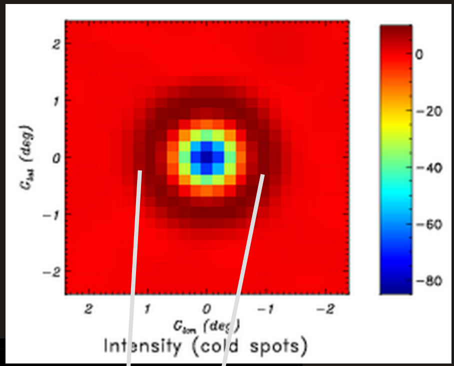
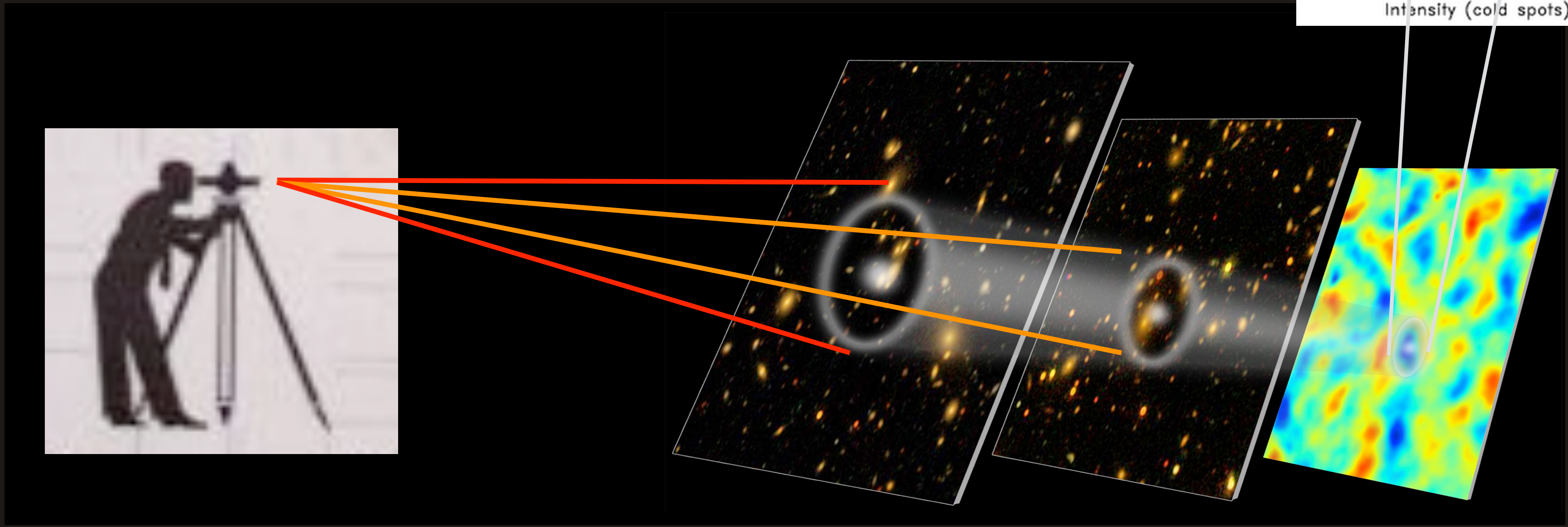
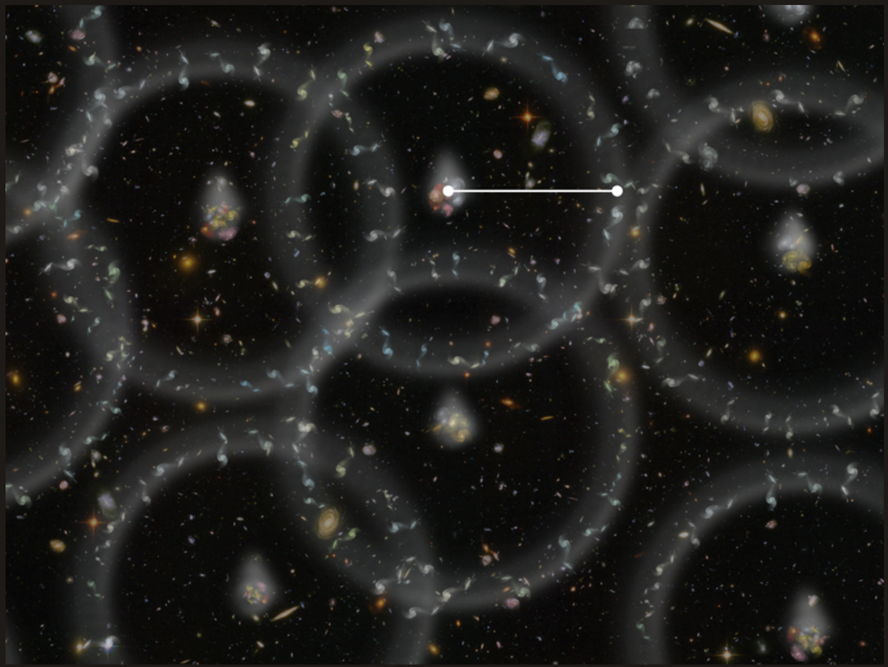


Image Credit: E.M. Huff, the SDSS-III team, and the South Pole Telescope team. Graphic by Zosia Rostomian



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 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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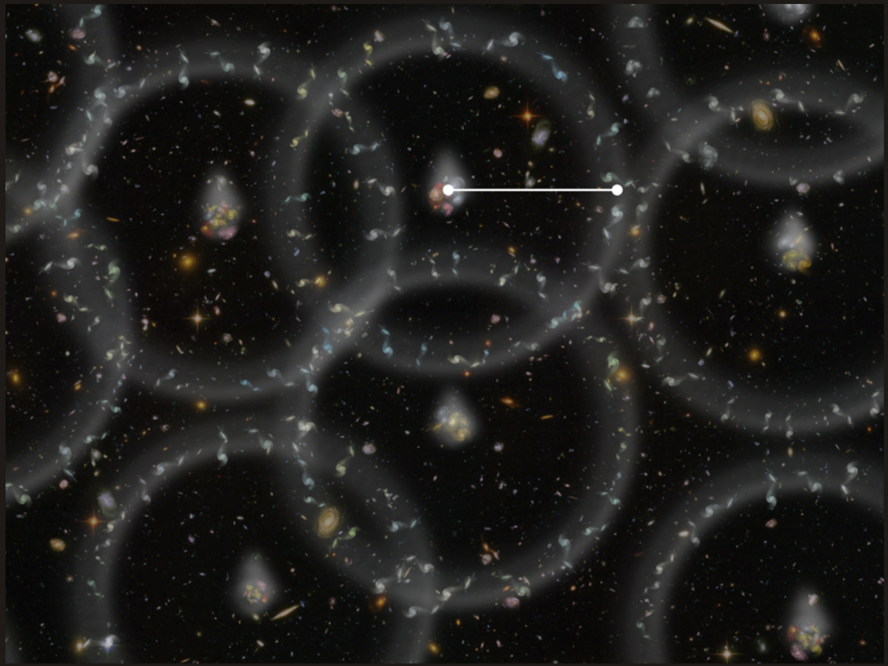

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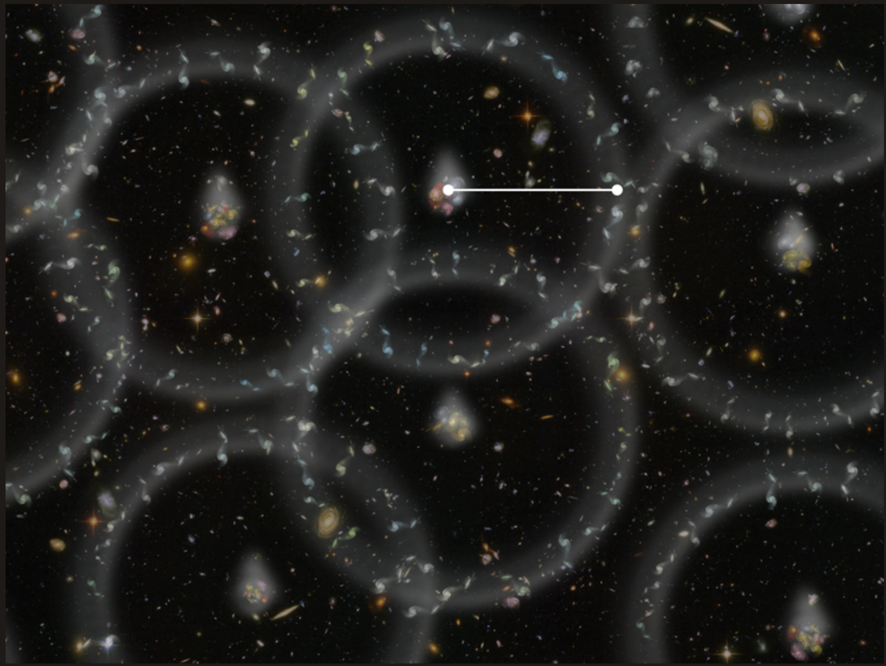
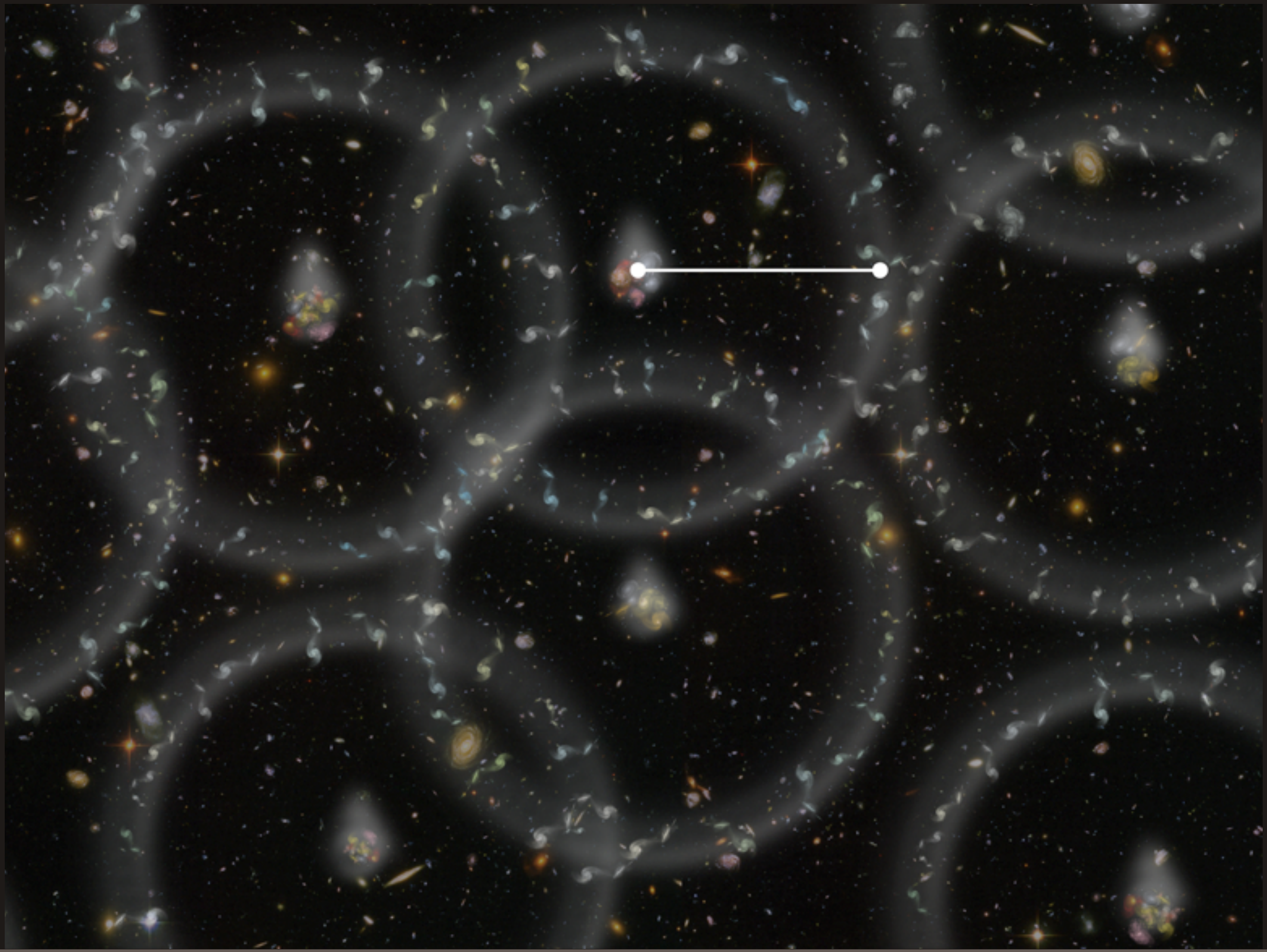


A Slice of BOSS



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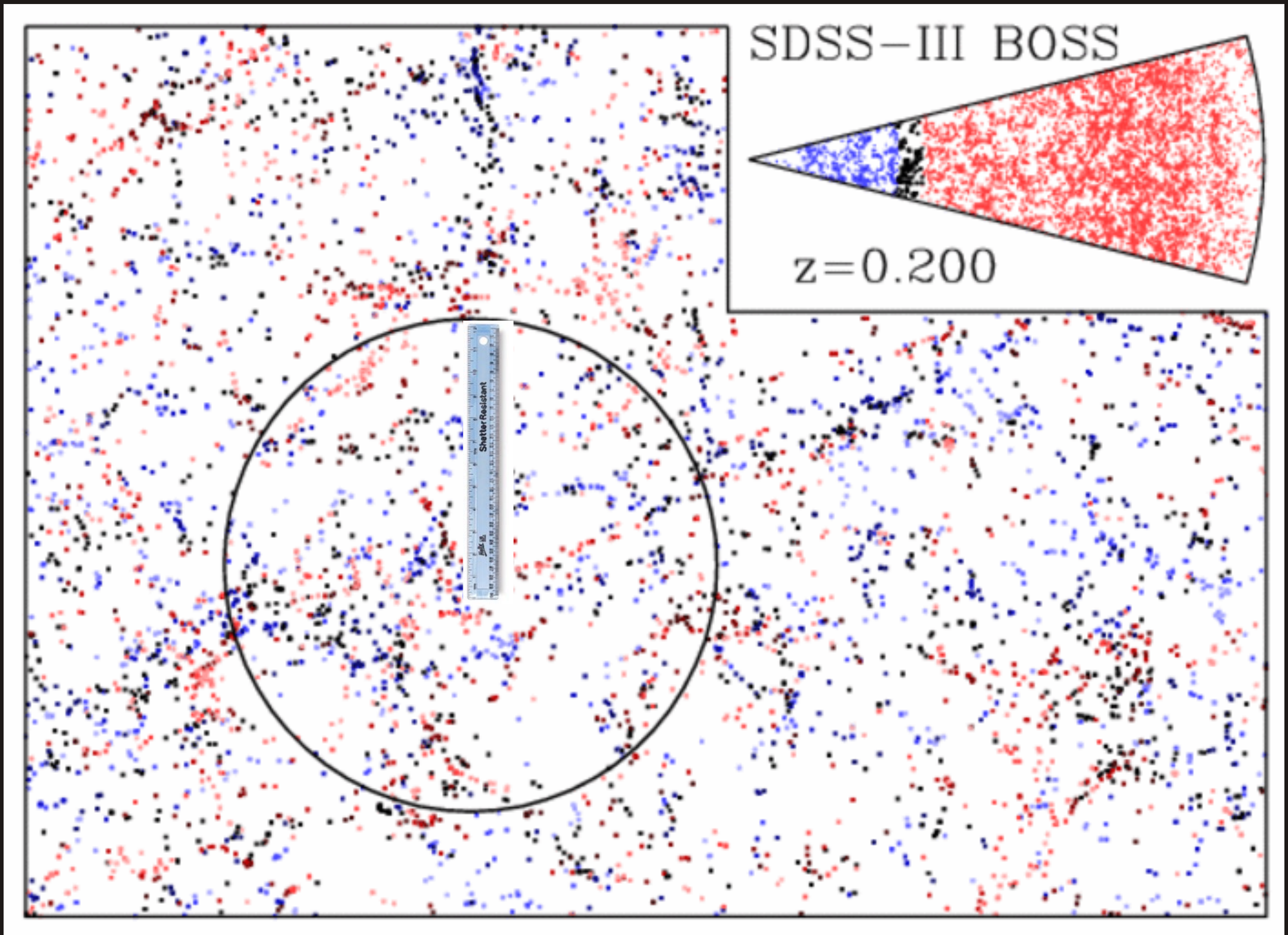

Credit: D. Eisenstein

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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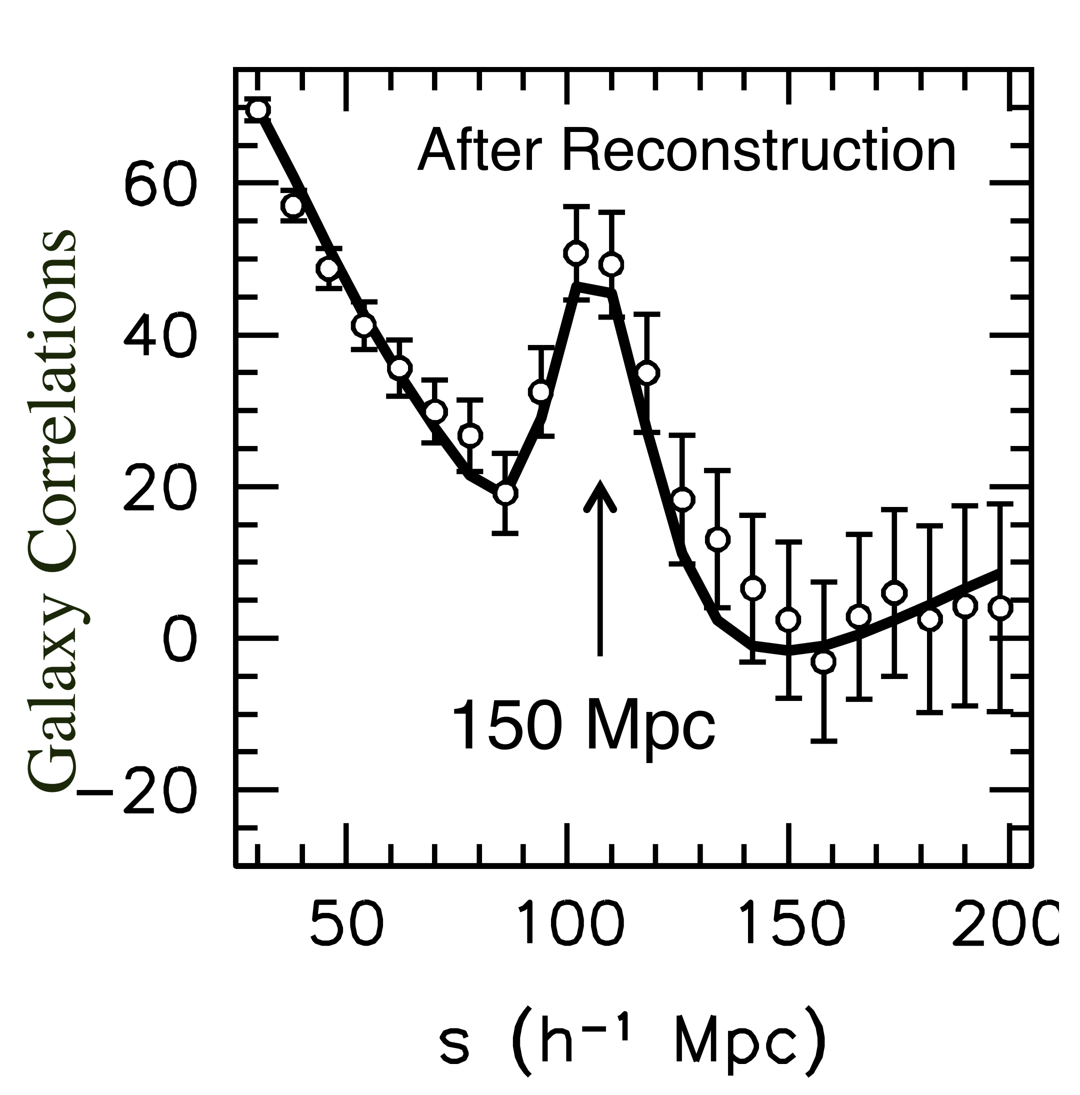

Anderson et al. 2014;
Vargas, Ho et al. 2014;
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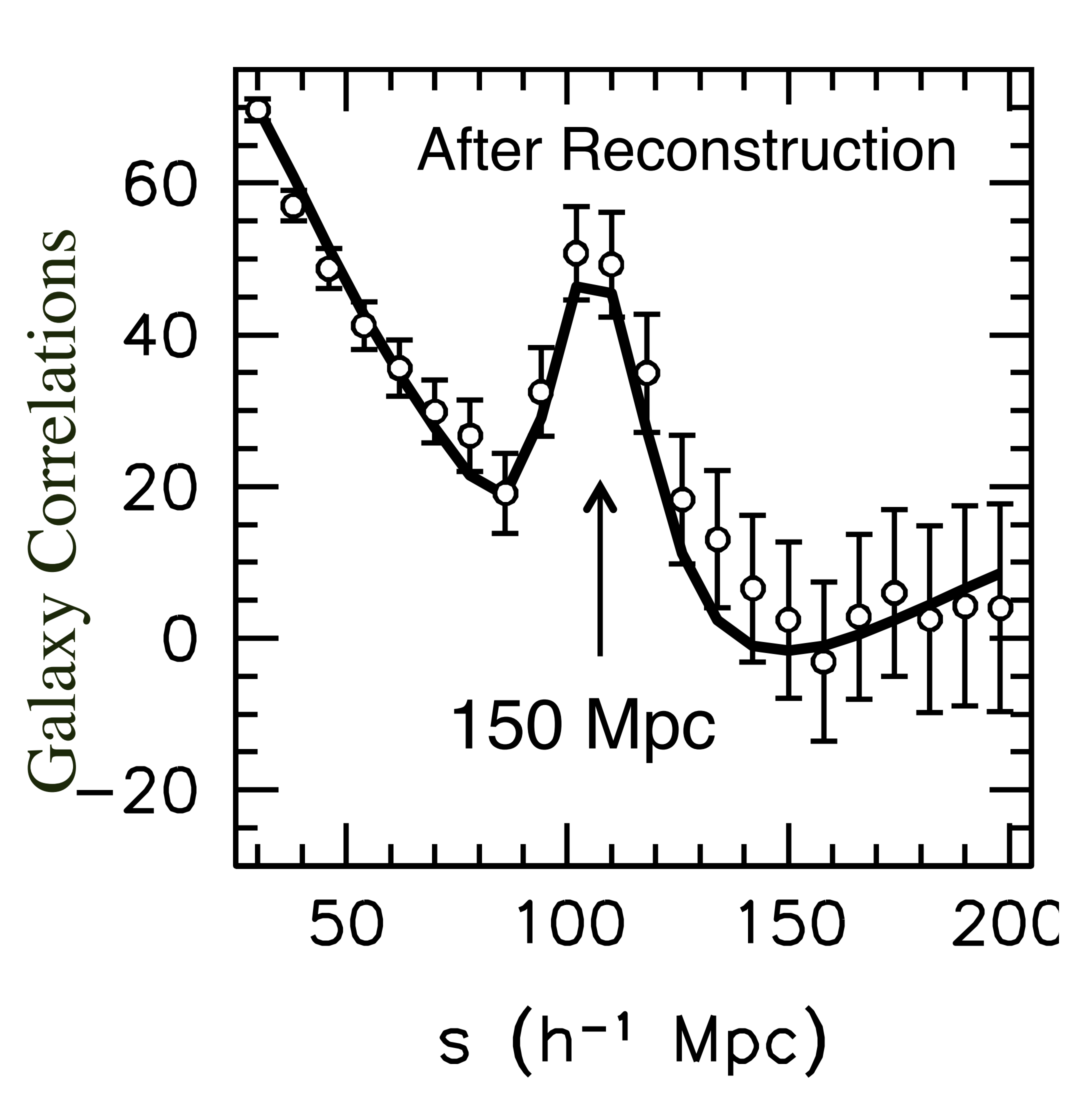
BAO in BOSS Galaxies

- 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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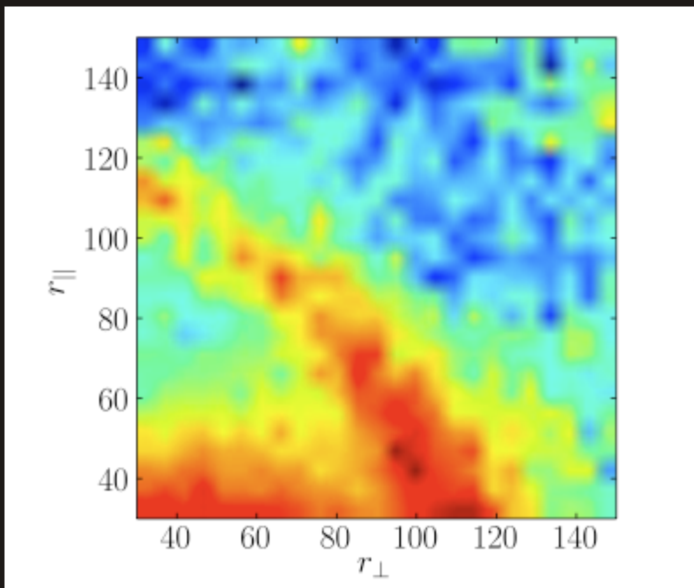
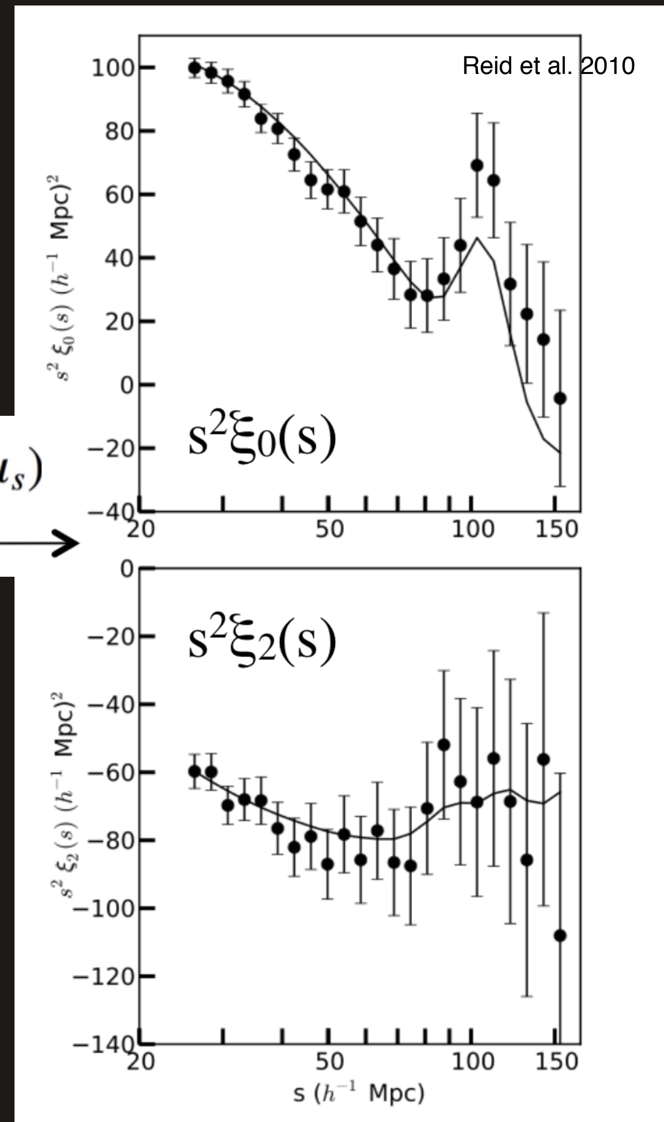
Full 2D correlation function contains information on both BAO and RSD



$$\xi(s, \mu_s) = \sum_{\ell} \xi_\ell(s) L_\ell(\mu_s)$$



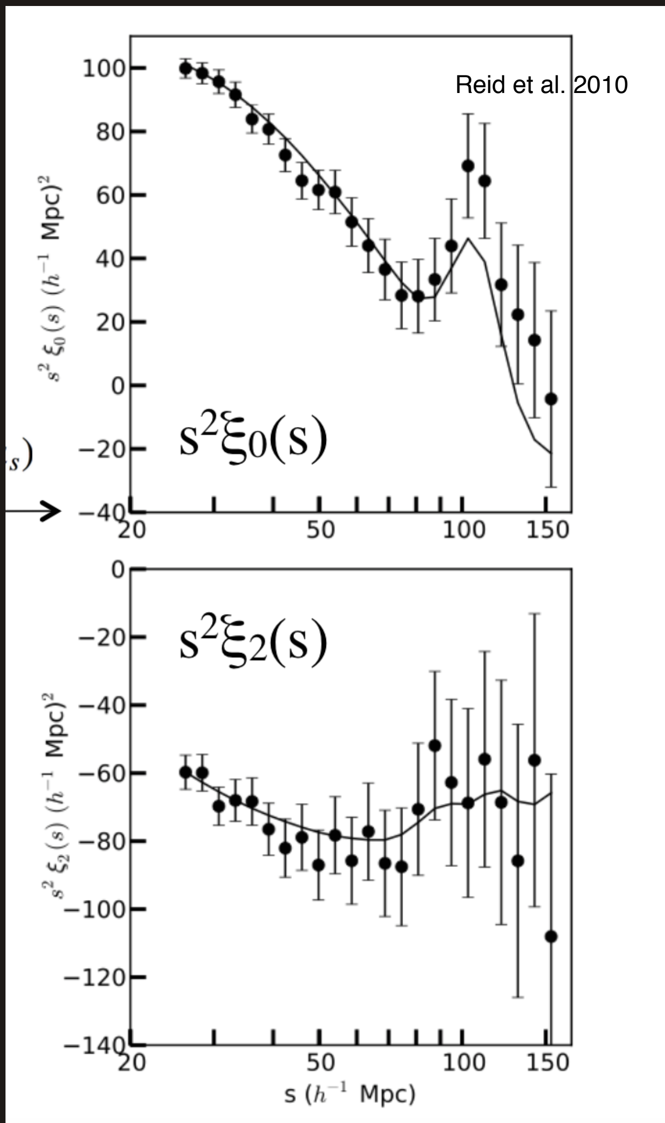
Using full model of the 2D correlation function,we can constrain:

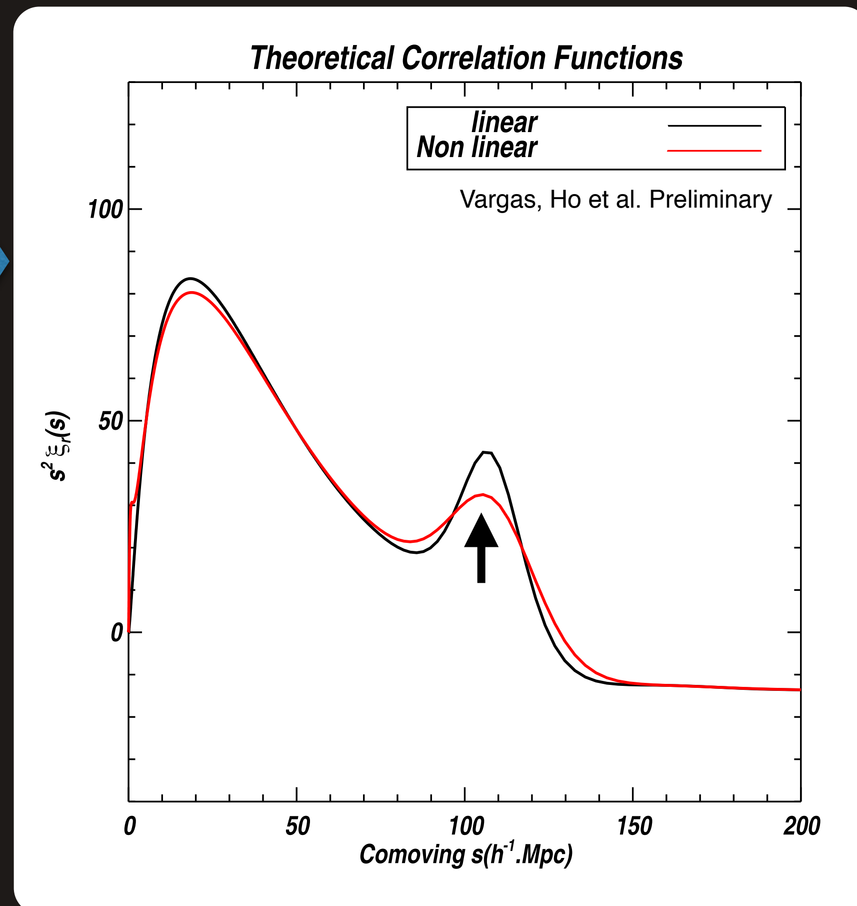
- Angular diameter distance and H(z)
- growth of structure (f sigma8)

NOTE: f sigma8= dD/dln(a)

SDSS III

Reconstruction to increase signal to noise of BAO

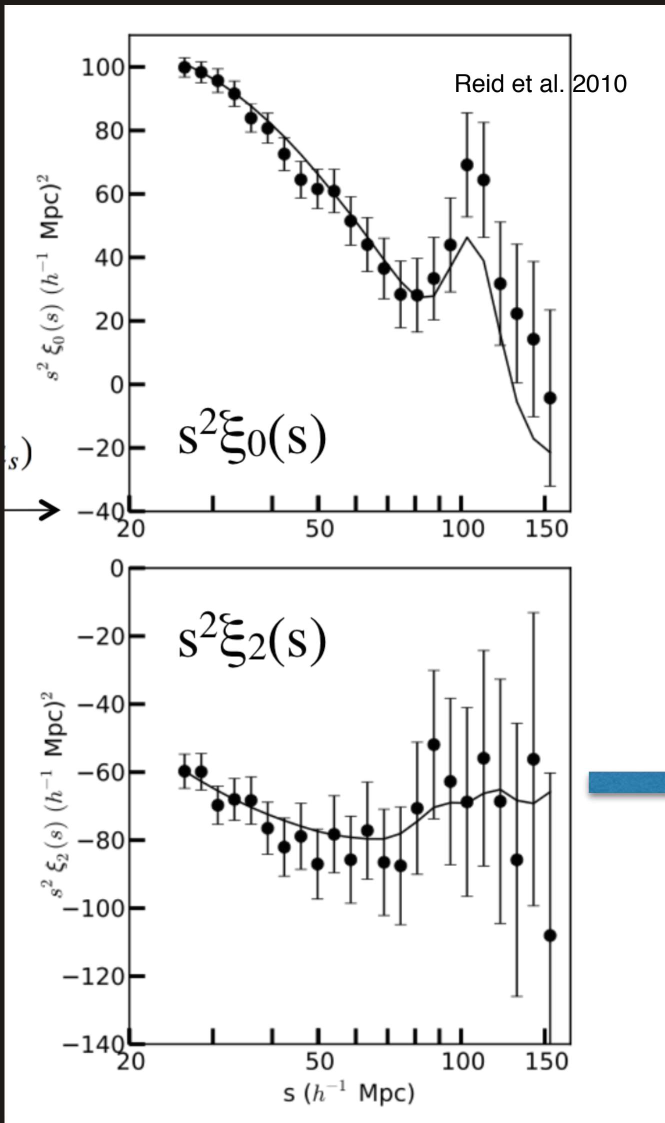


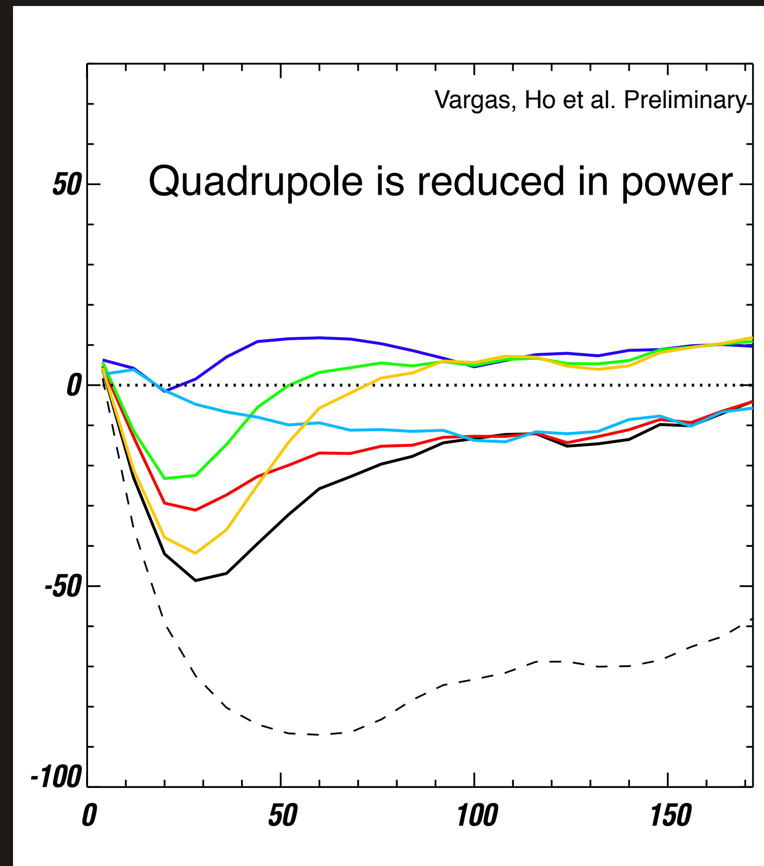


Eisenstein, Seo, Sirko & Spergel 2007
Padmanabhan et al. 2012
Burden et al. 2014
Vargas, Ho et al. 2014

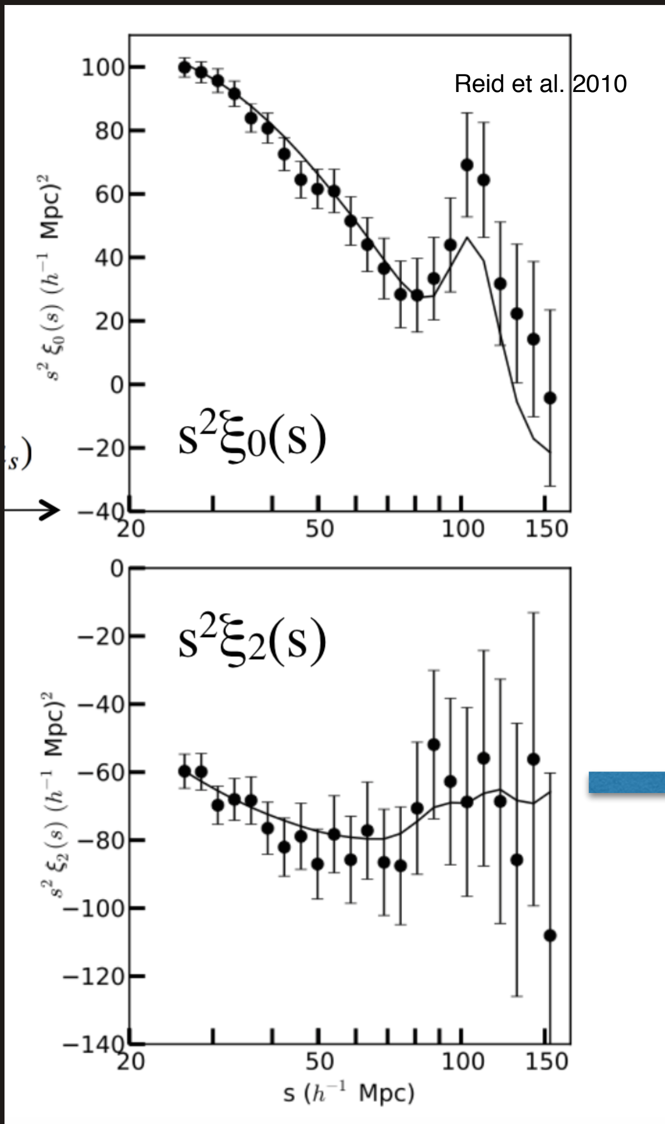
SDSS III

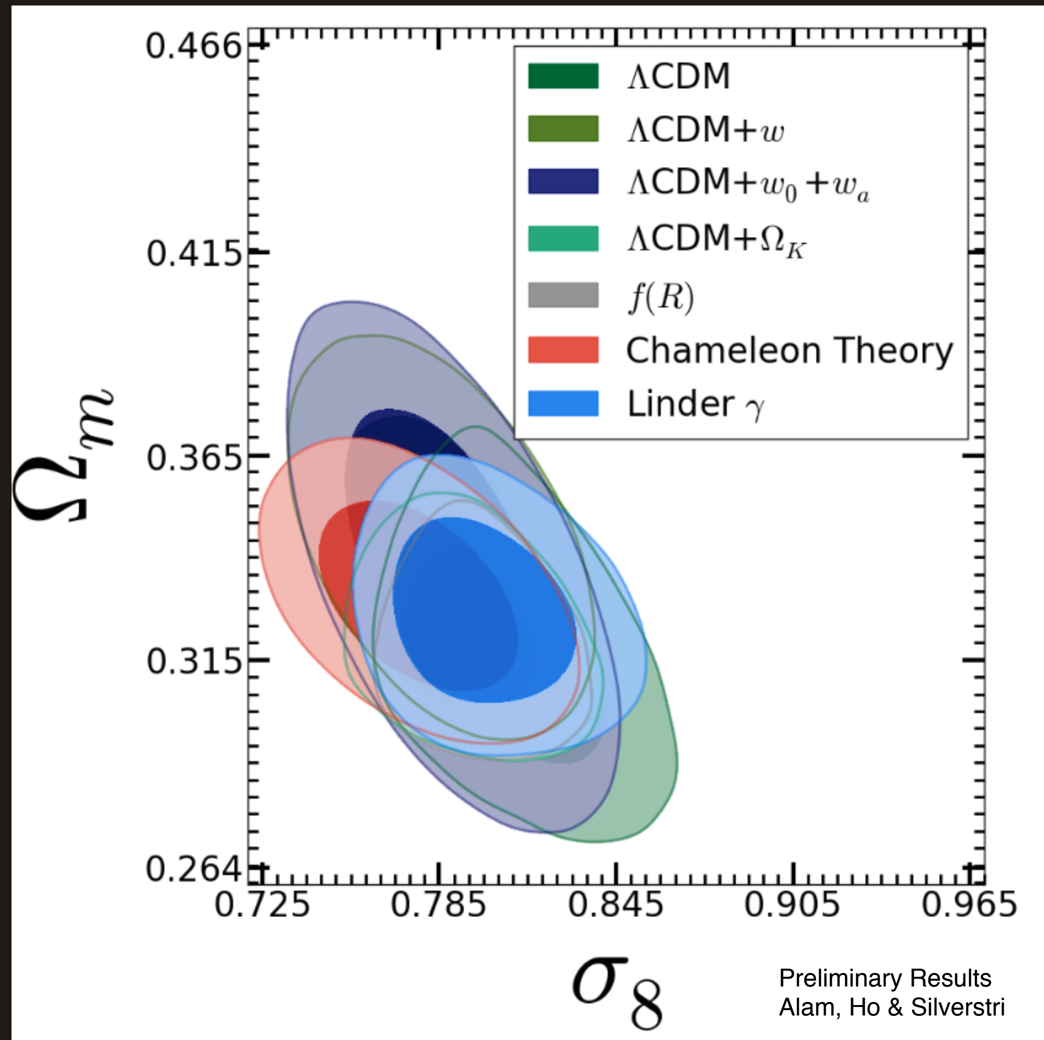
Current implementation of reconstruction reduces power in quadrupole





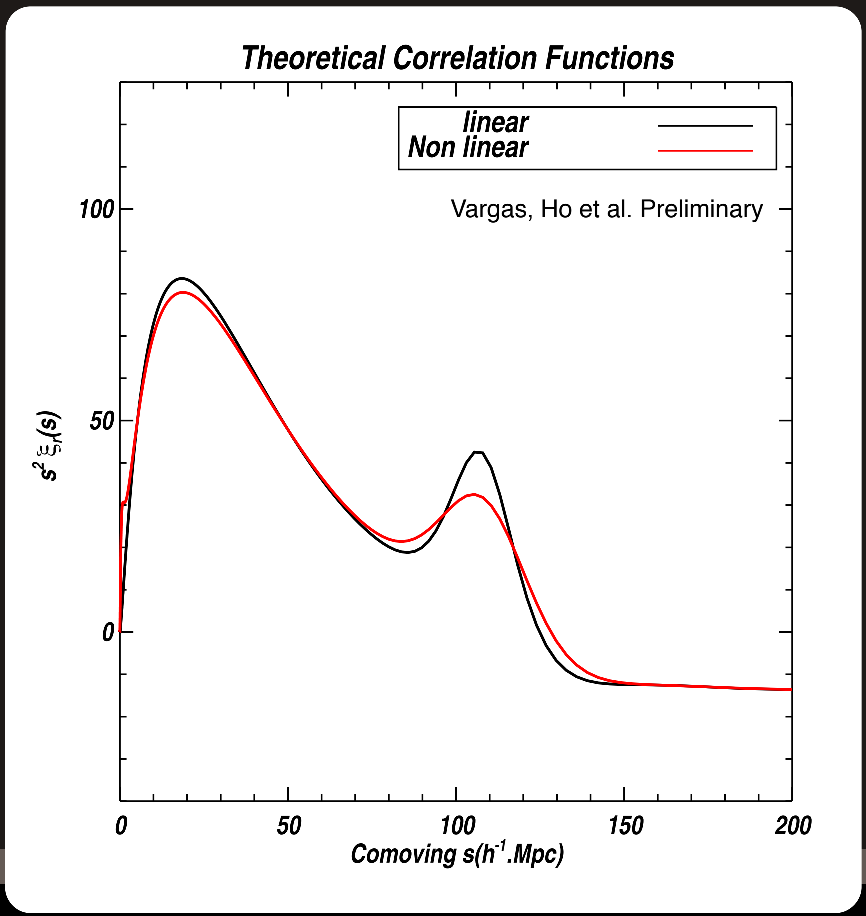
Full quadrupole needed for Redshift Space Distortions! To constrain growth of structure

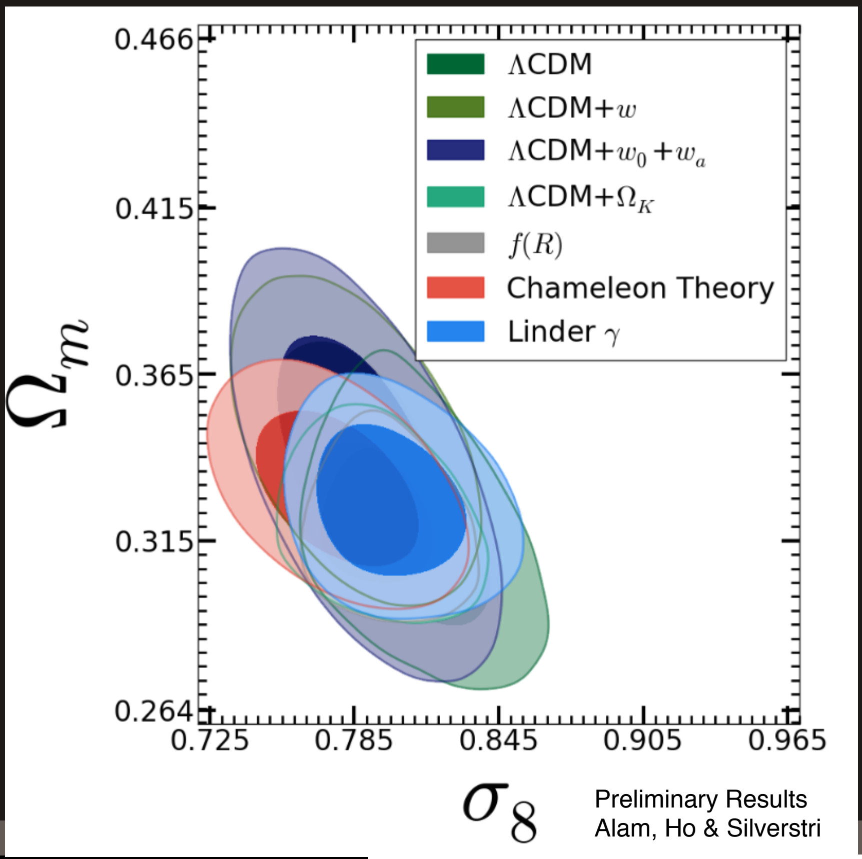




A single framework to fit both ?

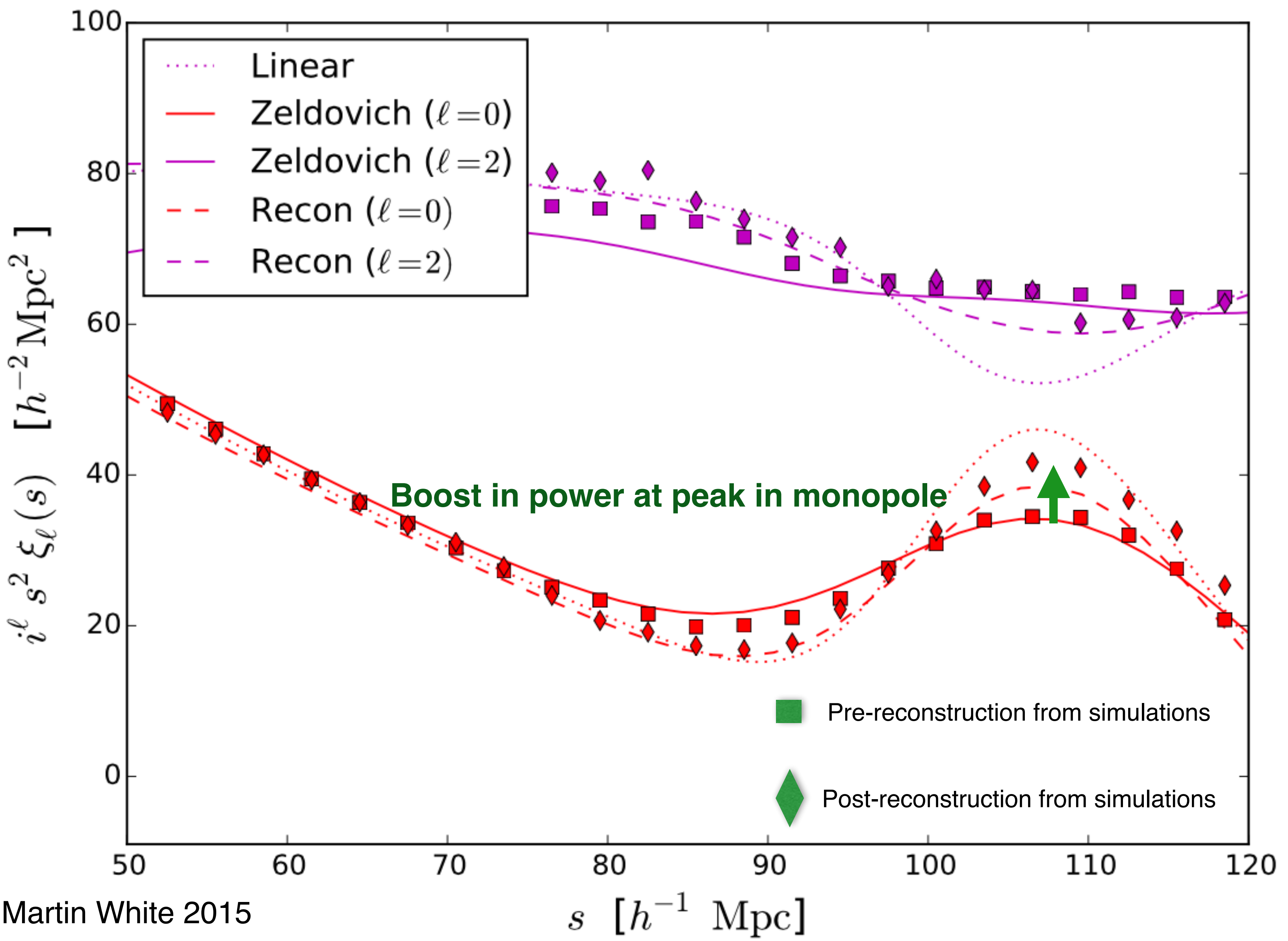
- Both post-reconstructed BAO
- **AND** Redshift Space Distortions?





SDSSIII

Fit Zeldovich Approximation theory to halo correlation function



Martin White 2015

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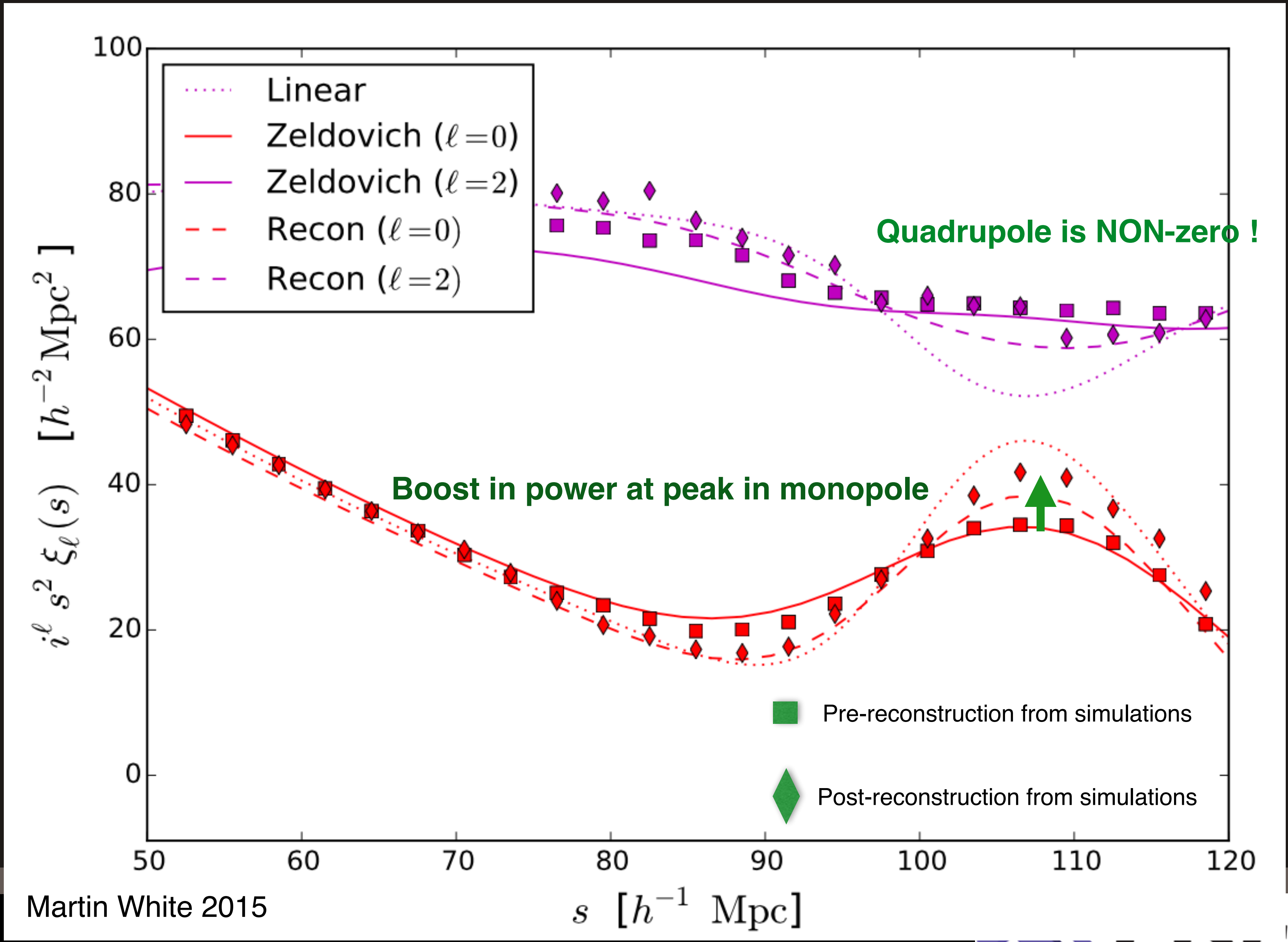

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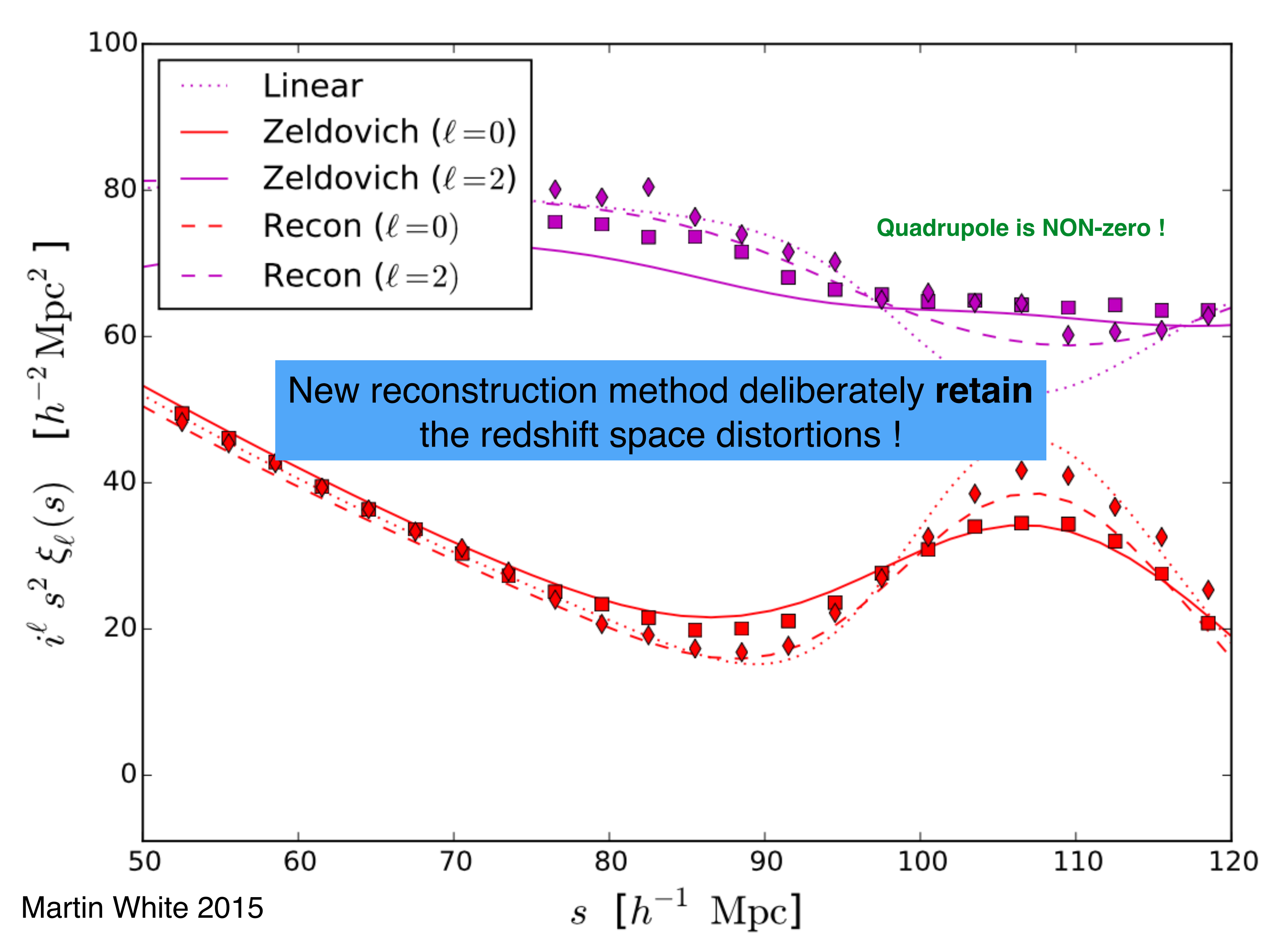

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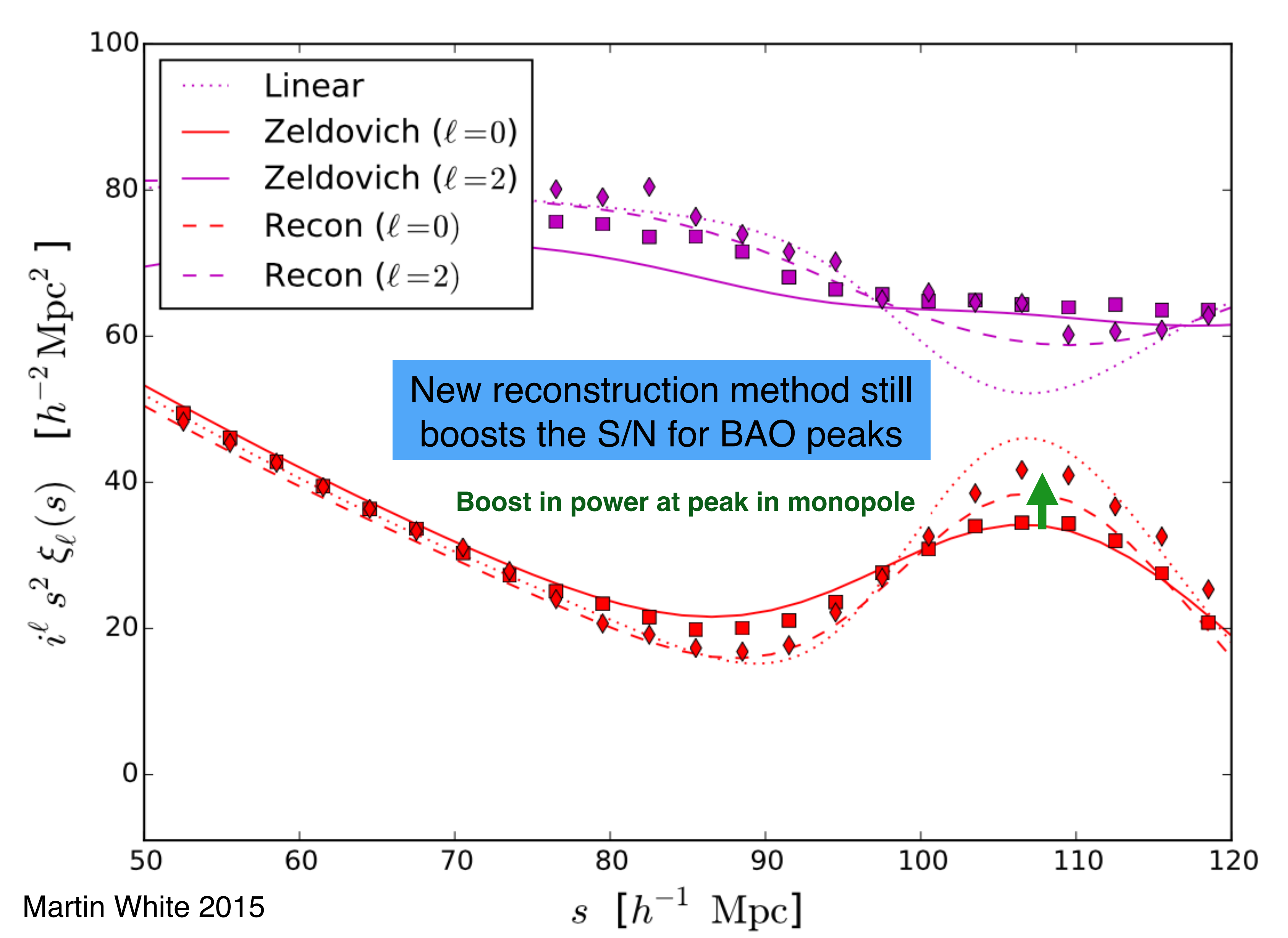

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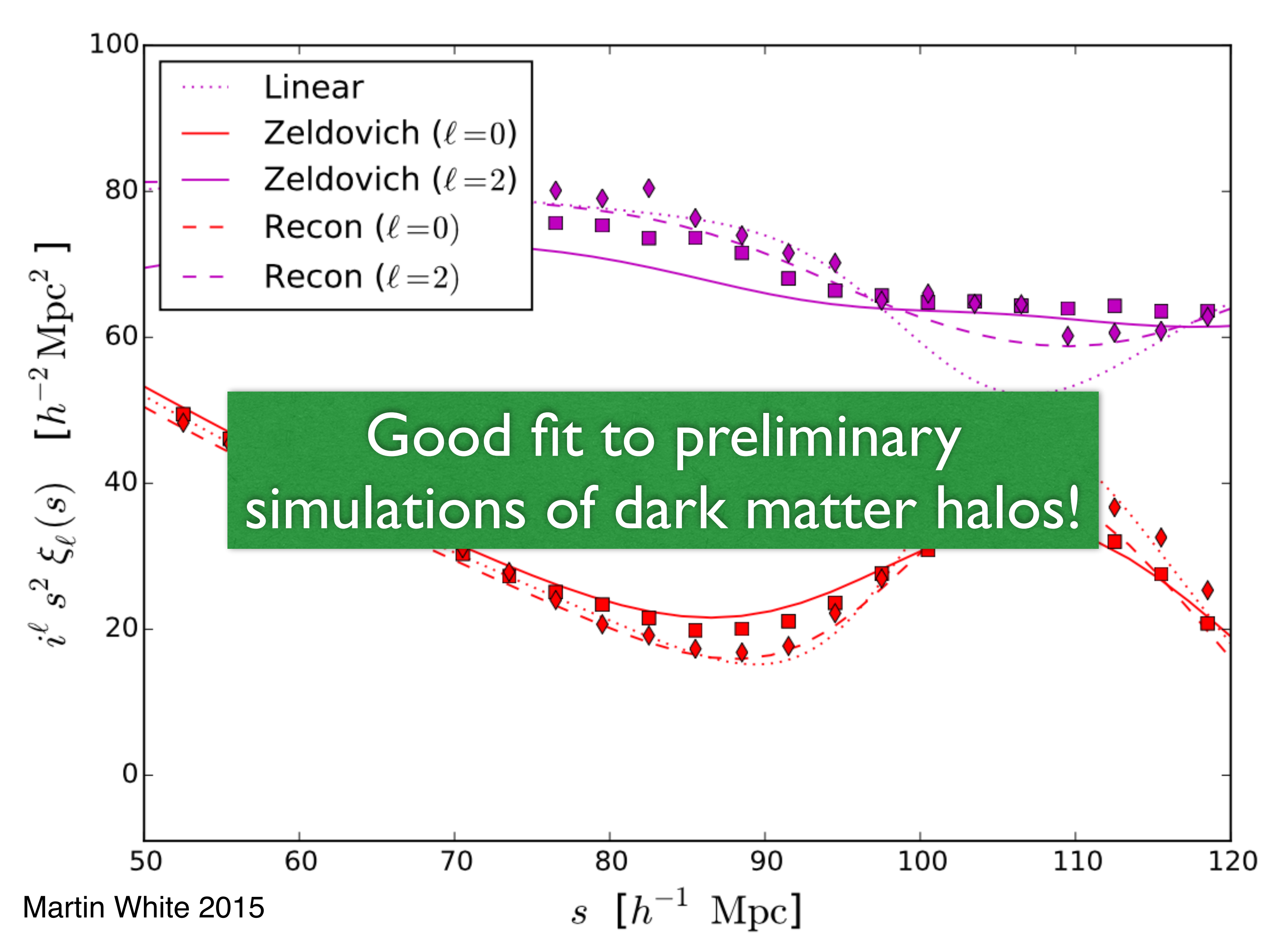

Need to test this out on BOSS-like sim!

- Fit the average correlation function over 1000 survey like sims using chi^2 from the mock-based covariance matrix
- Allowing 4 parameters to vary: a peak height (ν) which defines the large-scale bias, the two distance scaling parameters $\alpha_{||}$ and $\alpha_{\perp}$ and a parameter controlling the EFT terms (A_s).
- Hold the linear theory power spectrum fixed using the input to the QPM simulation,
- Hold “f" fixed at 0.76 and use a sigma=10Mpc/h Gaussian filtering for reconstruction.

SDSSIII

Fit Pre-recon multipoles with Zeldovich Approximated Theory

Pre-reconstruction,
Distance Ratios are expected to be not equal to 1,
due to non-linear evolution

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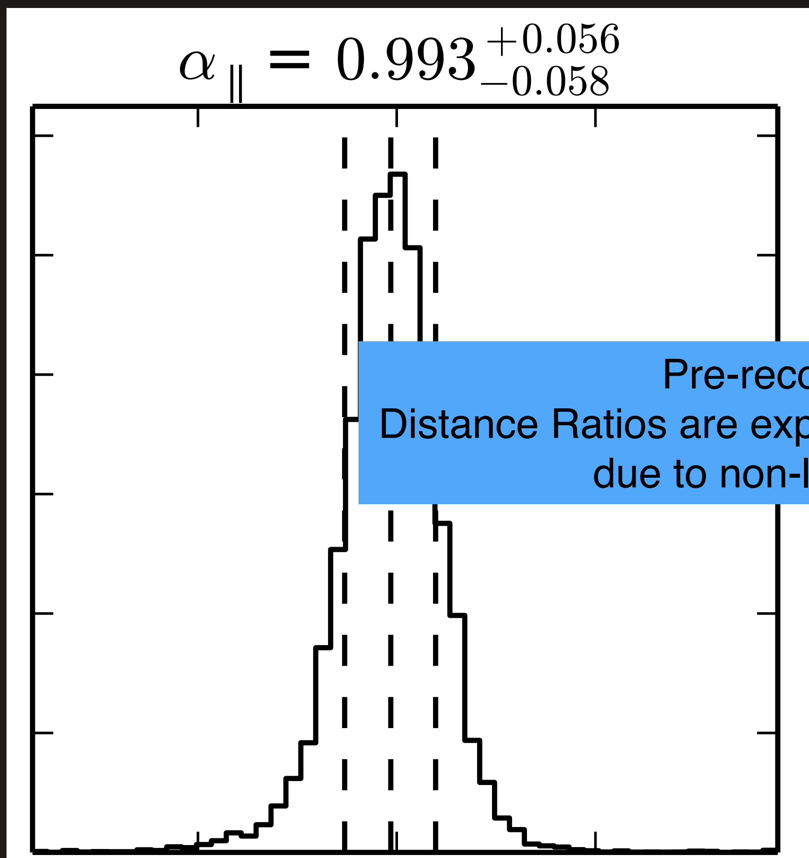

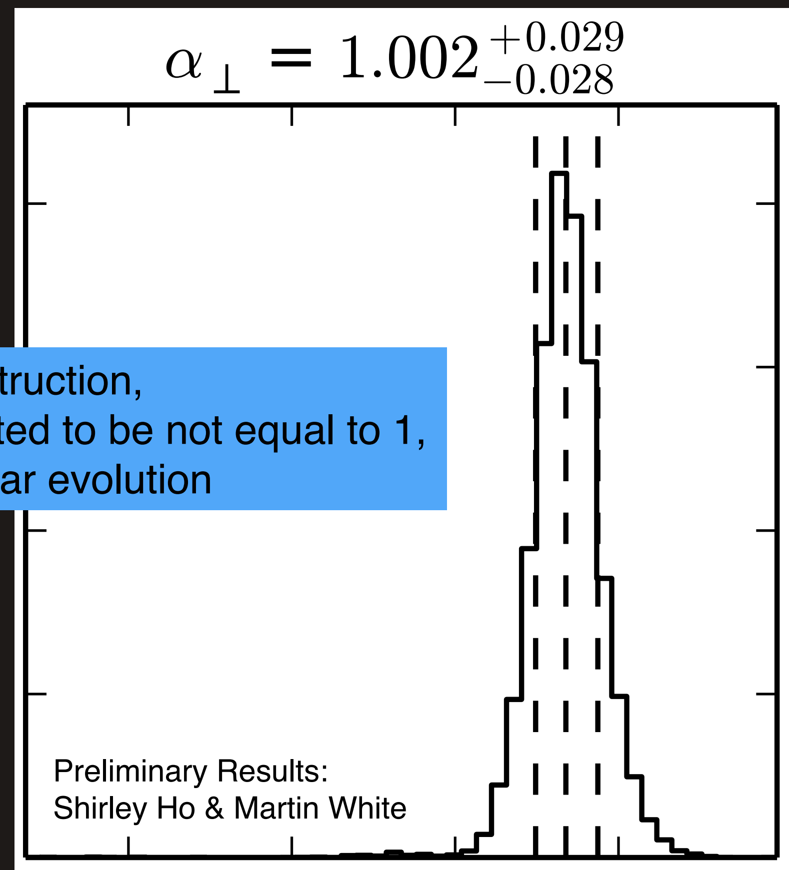

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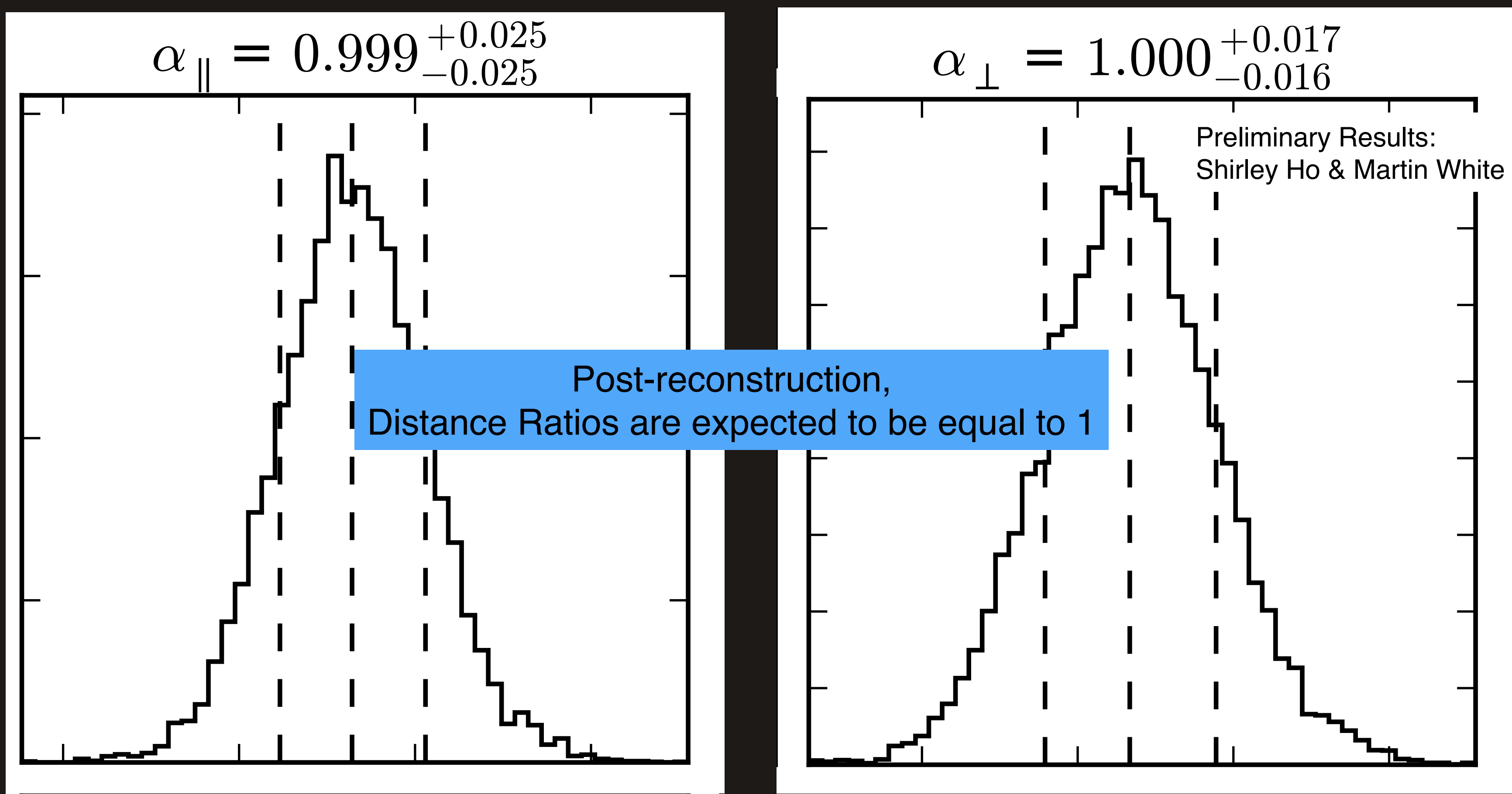
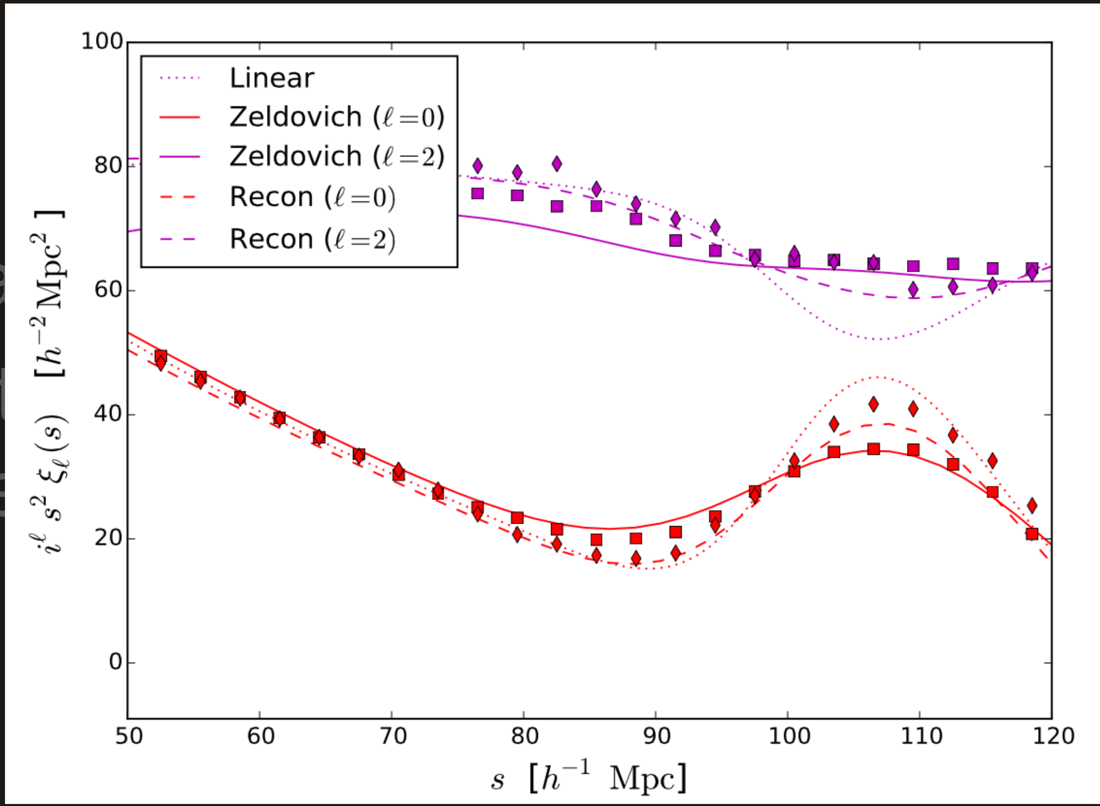
Post-reconstruction,
Distance Ratios are expected to be equal to 1

Fit Post-recon multipoles with Zeldovich Approximated Theory



Combining both BAO and RSD in one fit !

- allow using BAO reconstruction and fitting RSD in one swoop
- unified theory model
- unbiased recovery of dista
- Very few parameters for fit traditional BAO fitting sche



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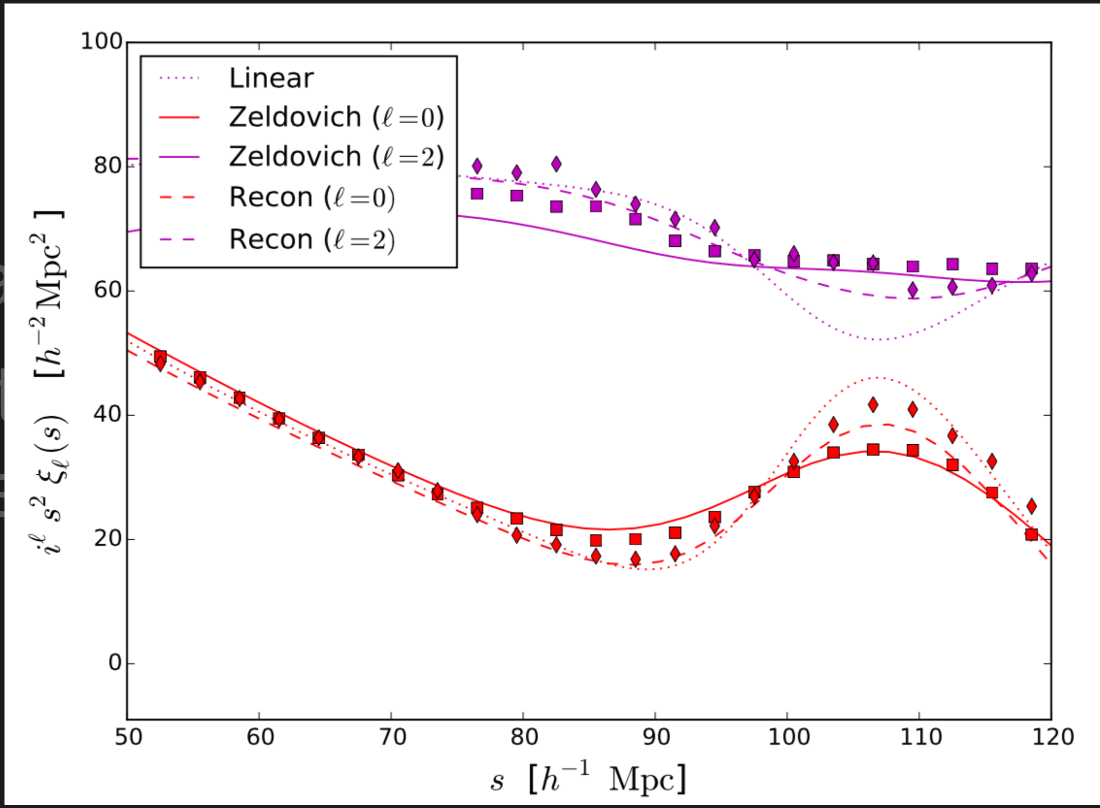

SDSS III

Combining both BAO and RSD in one fit !

- allow using BAO reconstruction and fitting RSD in one swoop
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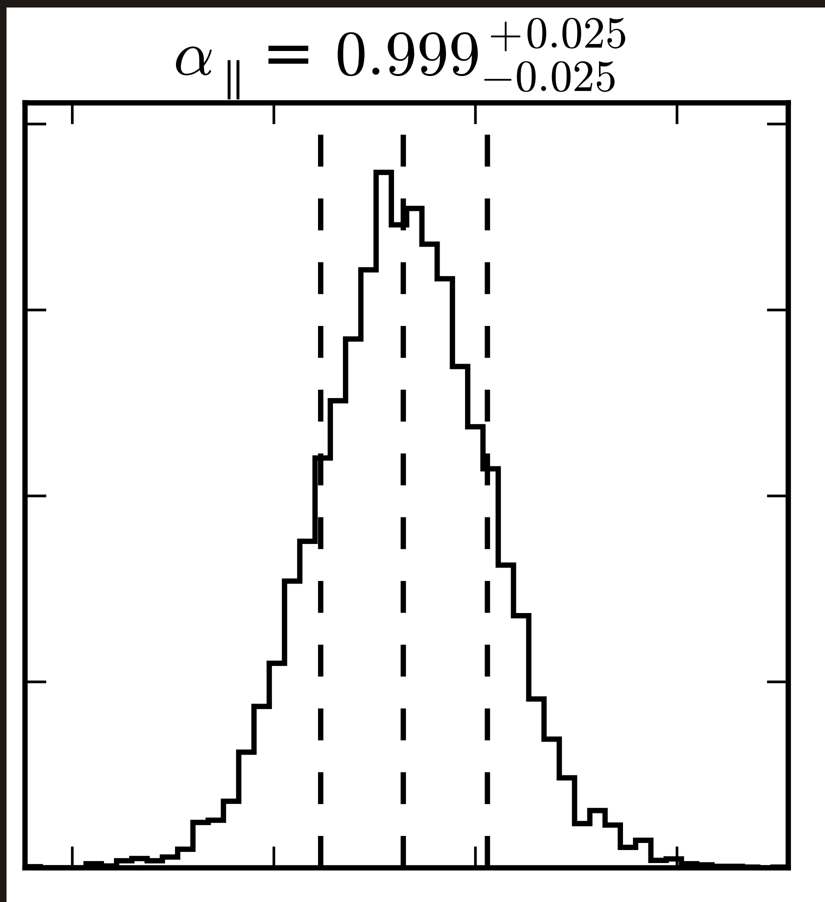
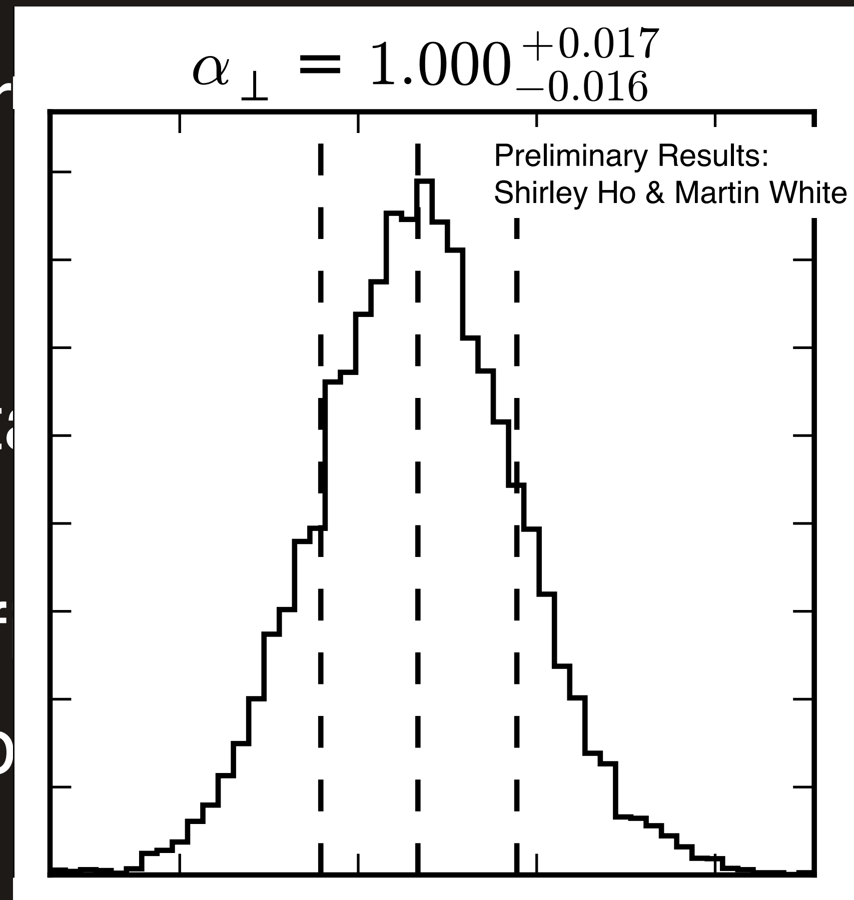
- unbiased recovery of distance scales in both direction
- Very few parameters for fitting (especially compared to traditional BAO fitting schemes)

DESI - Combining both BAO and RSD in one fit !





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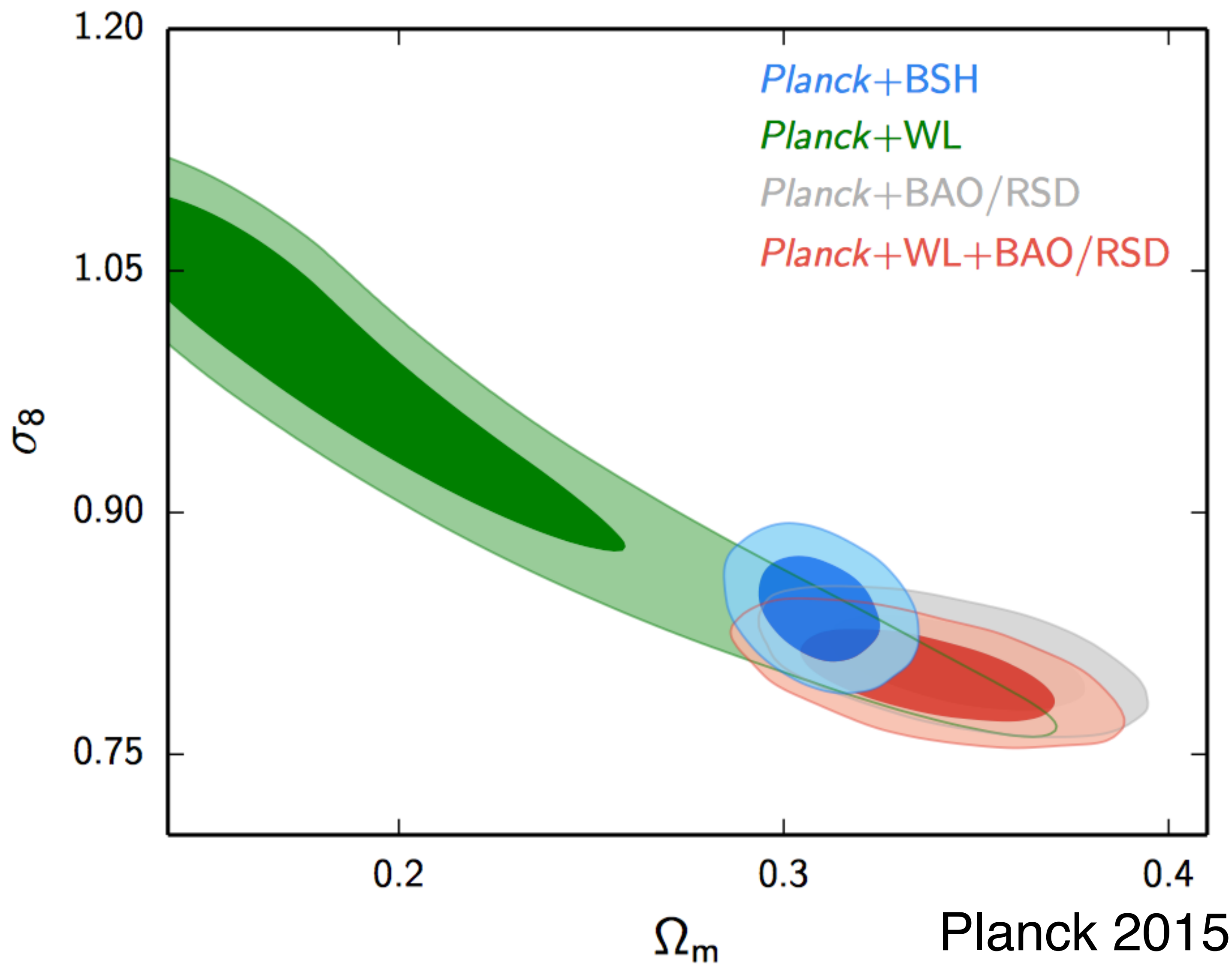
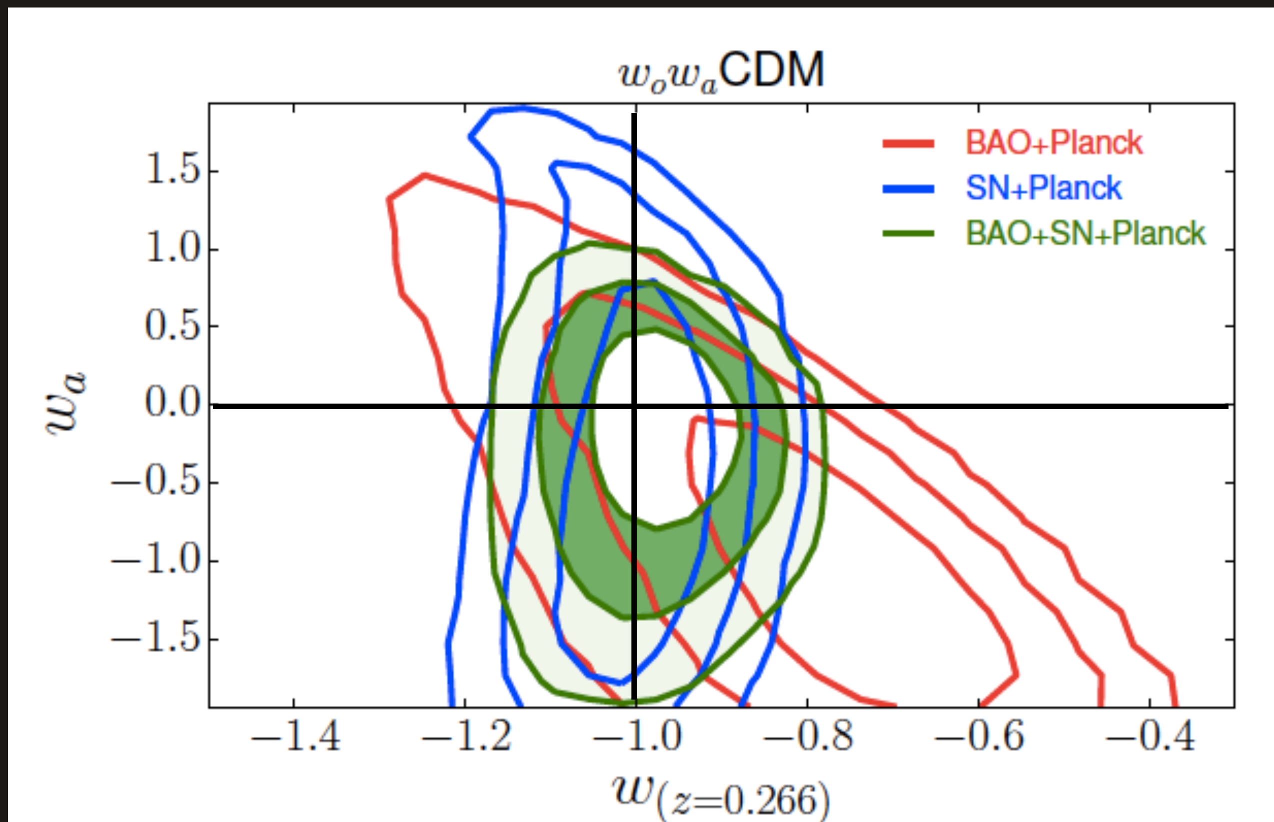
Constraining cosmological models



Planck 2015

How about Dark Energy?

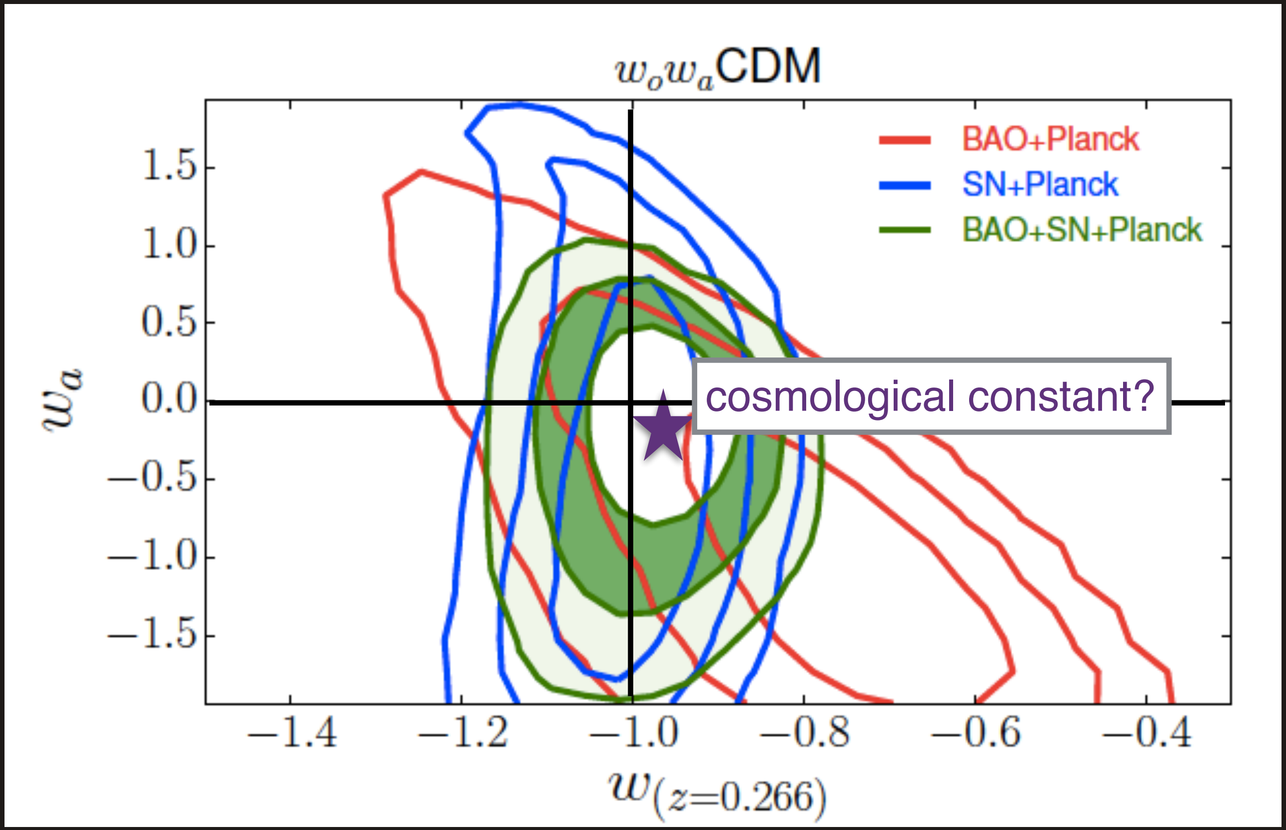
- Combined constraints on Dark Energy



BOSS collaboration 2014

Is it a cosmological constant?

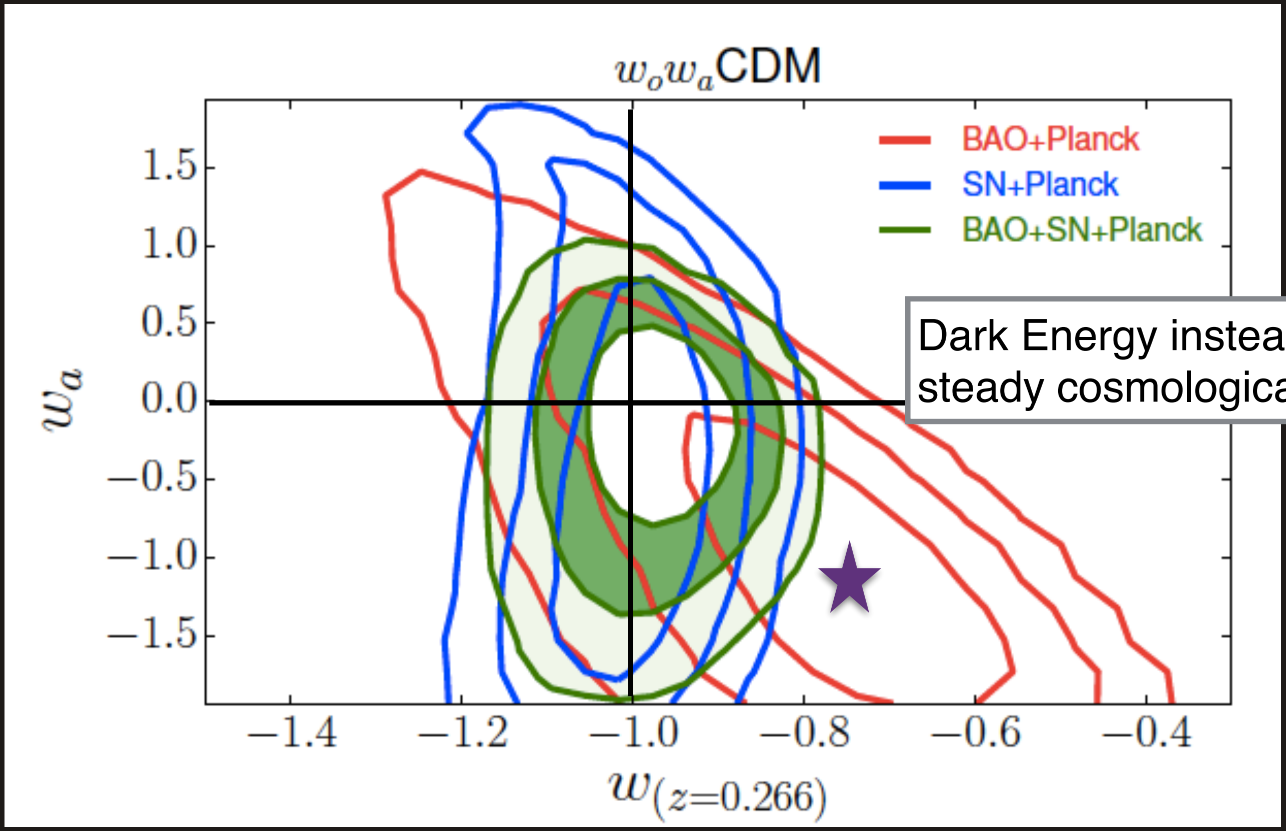
- Combined constraints:



BOSS collaboration 2014

Or is it Dark Energy?

- Combined constraints:



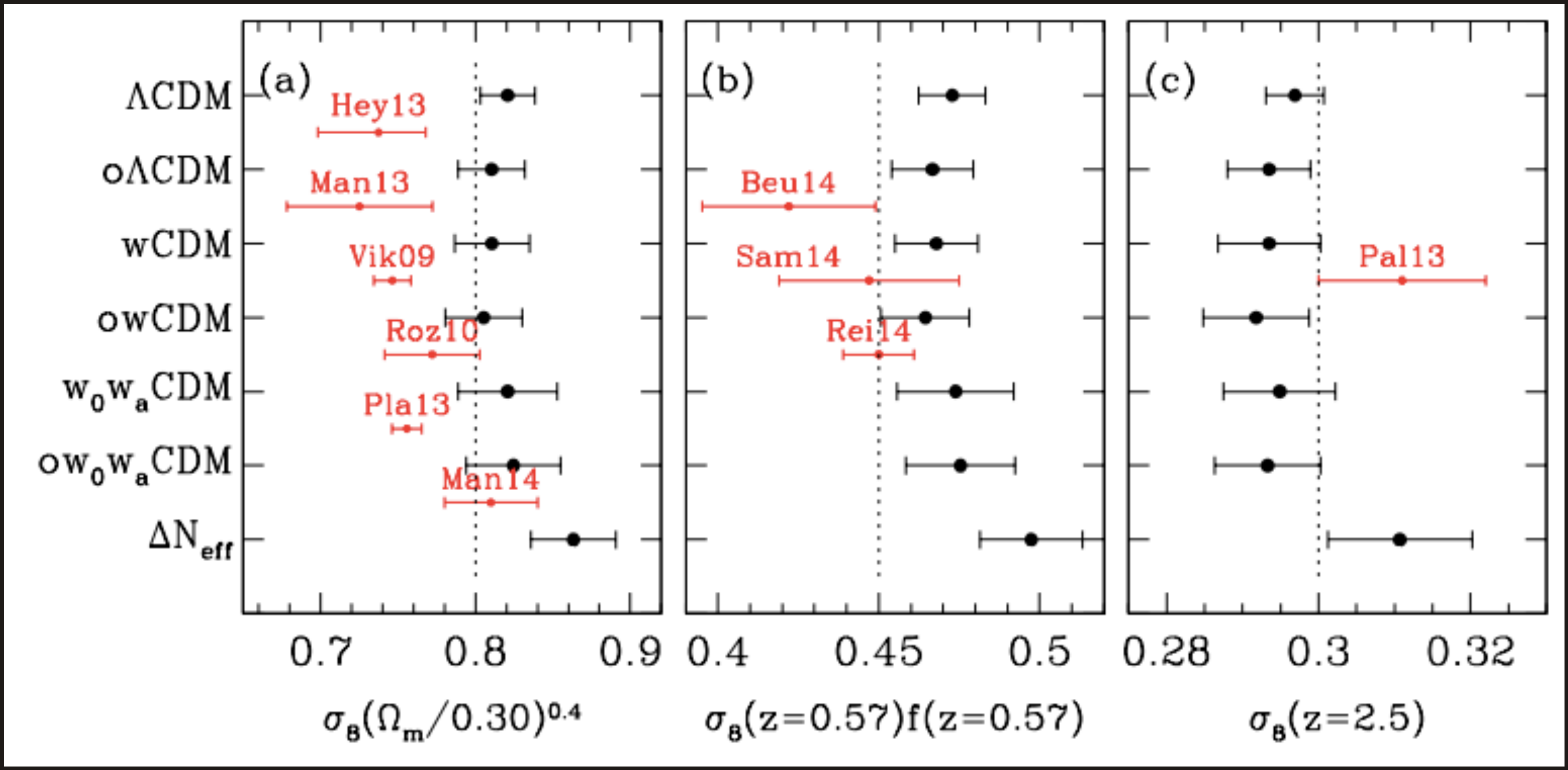
Dark Energy instead of a steady cosmological constant?

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 with Redshift Space Distortions *Theory* — Convoluted Lagrangian Perturbation Theory

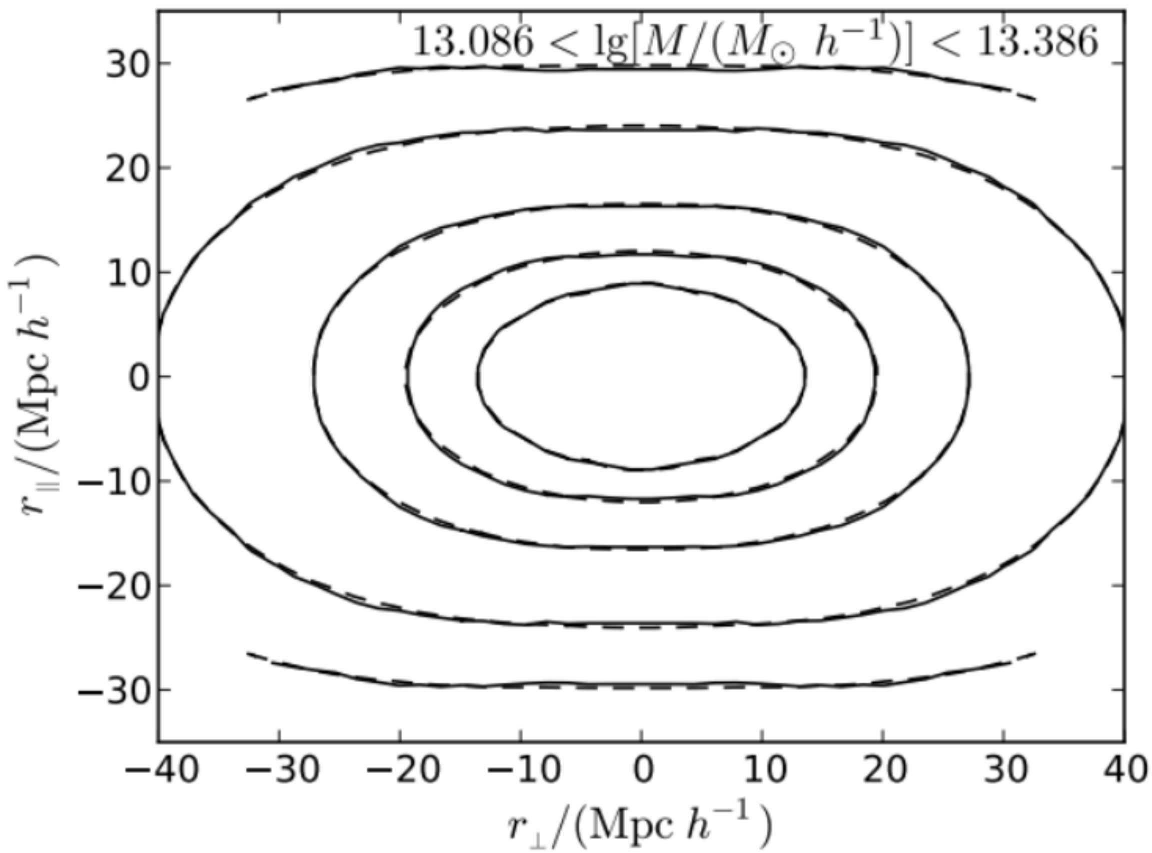
Dashed line : Theory
Solid line: Average of Simulations

Wang, Reid & White 2013

Many many other theories that I am missing the references here,
but a selected few are: Kaiser 1987, Scoccimarro 2004, Reid & White 2010

SDSS III

Testing Gravity with Redshift Space Distortions
Theory — Convoluted Lagrangian Perturbation Theory
We pick the Best **theory model** out there!



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SDSS III

Testing Gravity with Redshift Space Distortions
Checks with Simulations: Do we recover the truth?

Recovered Growth Factor
from every simulation

How well do we fit ?

Alam, Ho, Vargas et al. arXiv:1504:02100

SDSSIII

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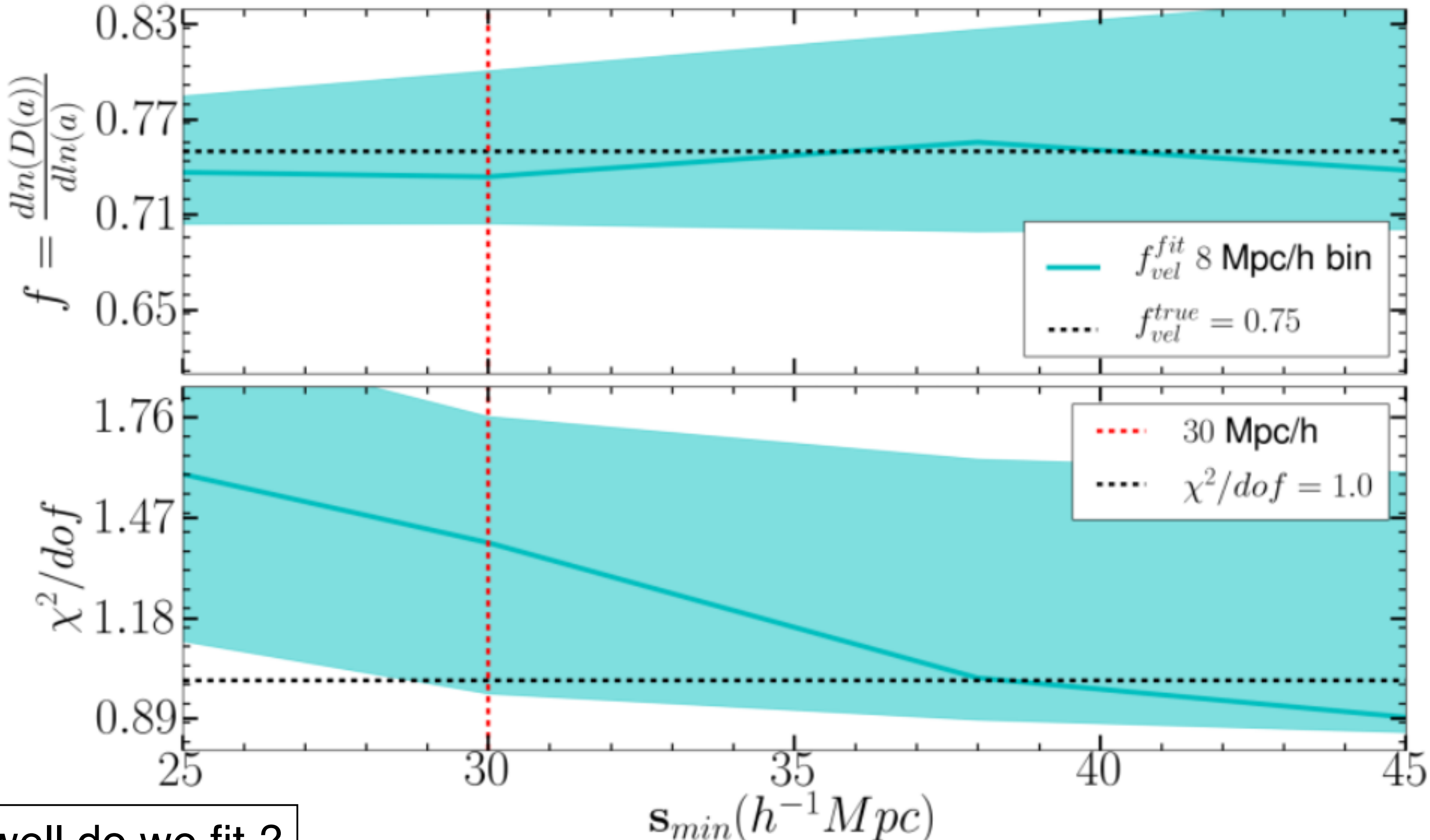

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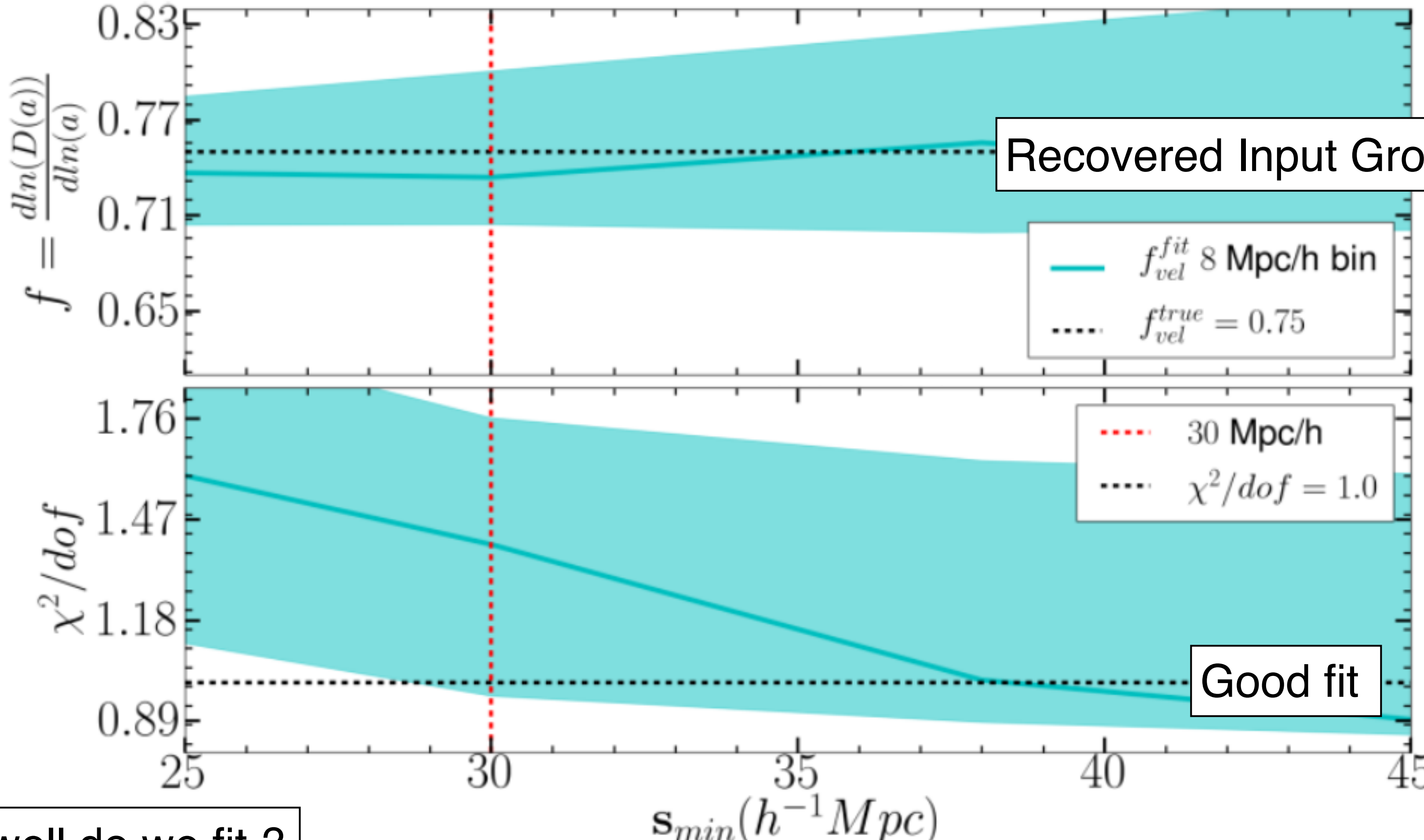


How well do we fit ?

Alam, Ho, Vargas et al. arXiv:1504:02100

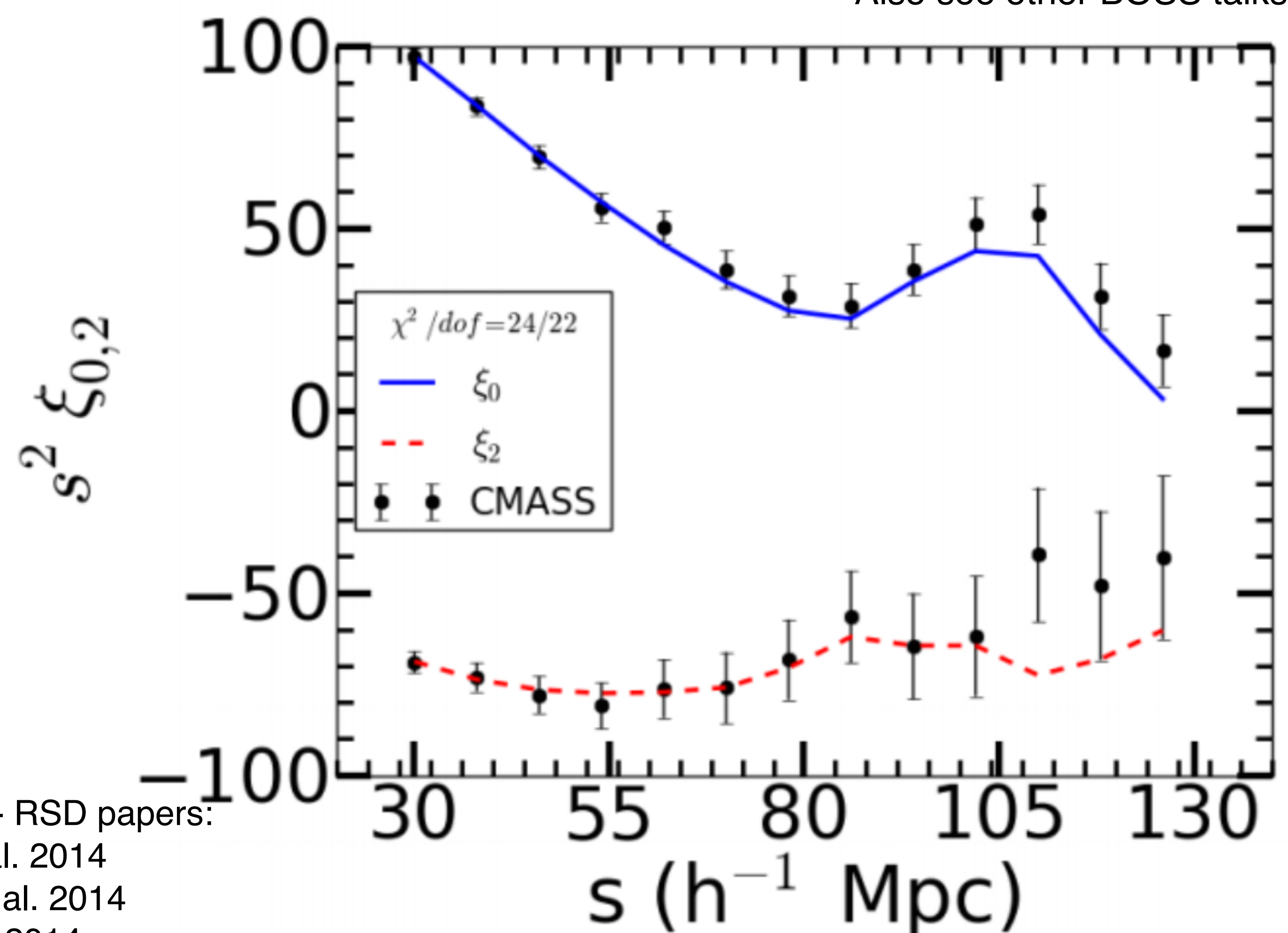
Testing Gravity with Redshift Space Distortions
Data + Best fit of the theory

Other BOSS- RSD papers:
Sanchez et al. 2014
Samuisha et al. 2014
Beutler et al. 2014
Chuang et al. 2013
Reid et al. 2014
Moore et al. 2015

Alam, Ho, Vargas et al. arXiv:1504:02100

Testing Gravity with Redshift Space Distortions
Data + Best fit of the theory

Also see other BOSS talks today: e.g. Sanchez et al.



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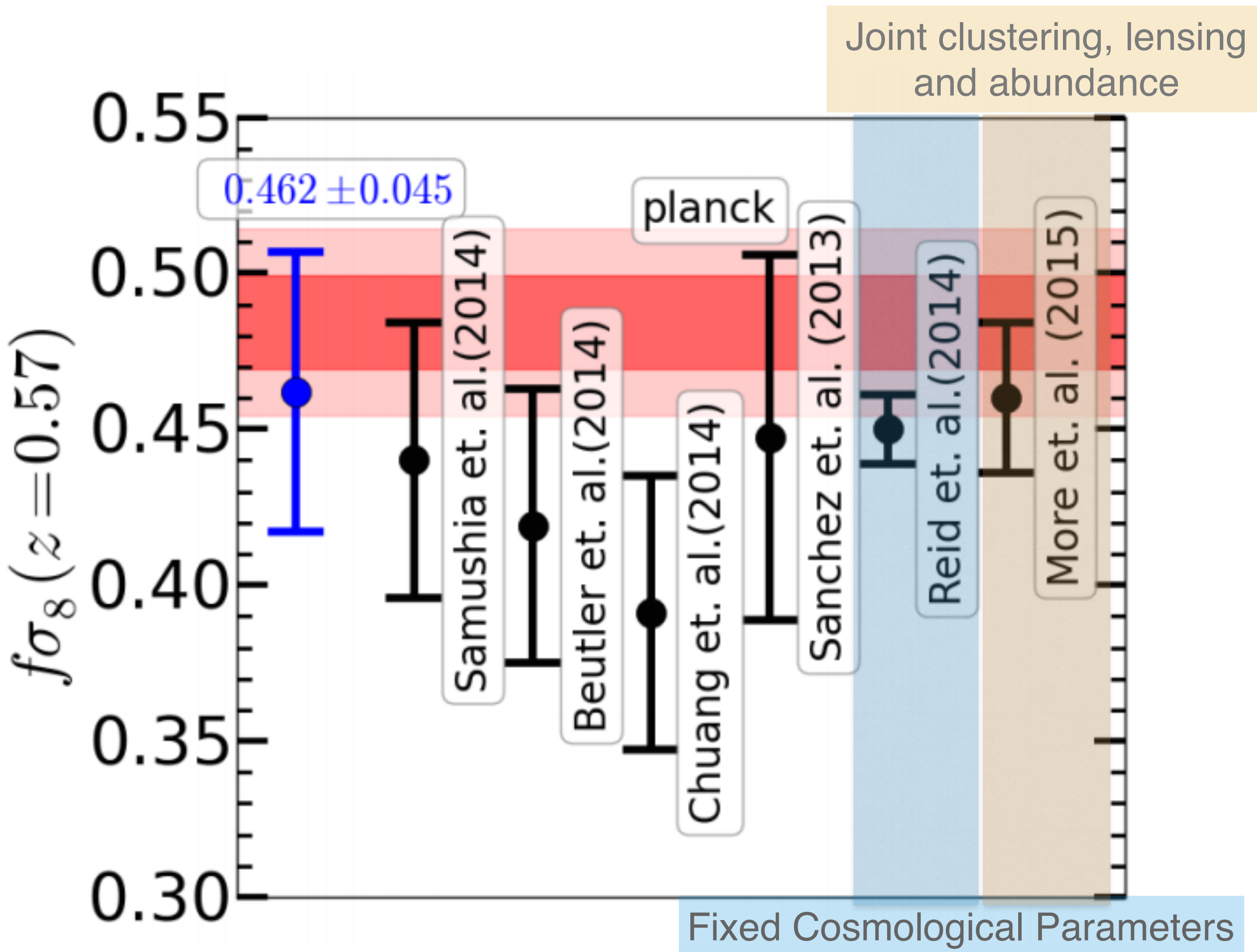
Testing Gravity with Redshift Space Distortions
Constraints on Growth of Structure!



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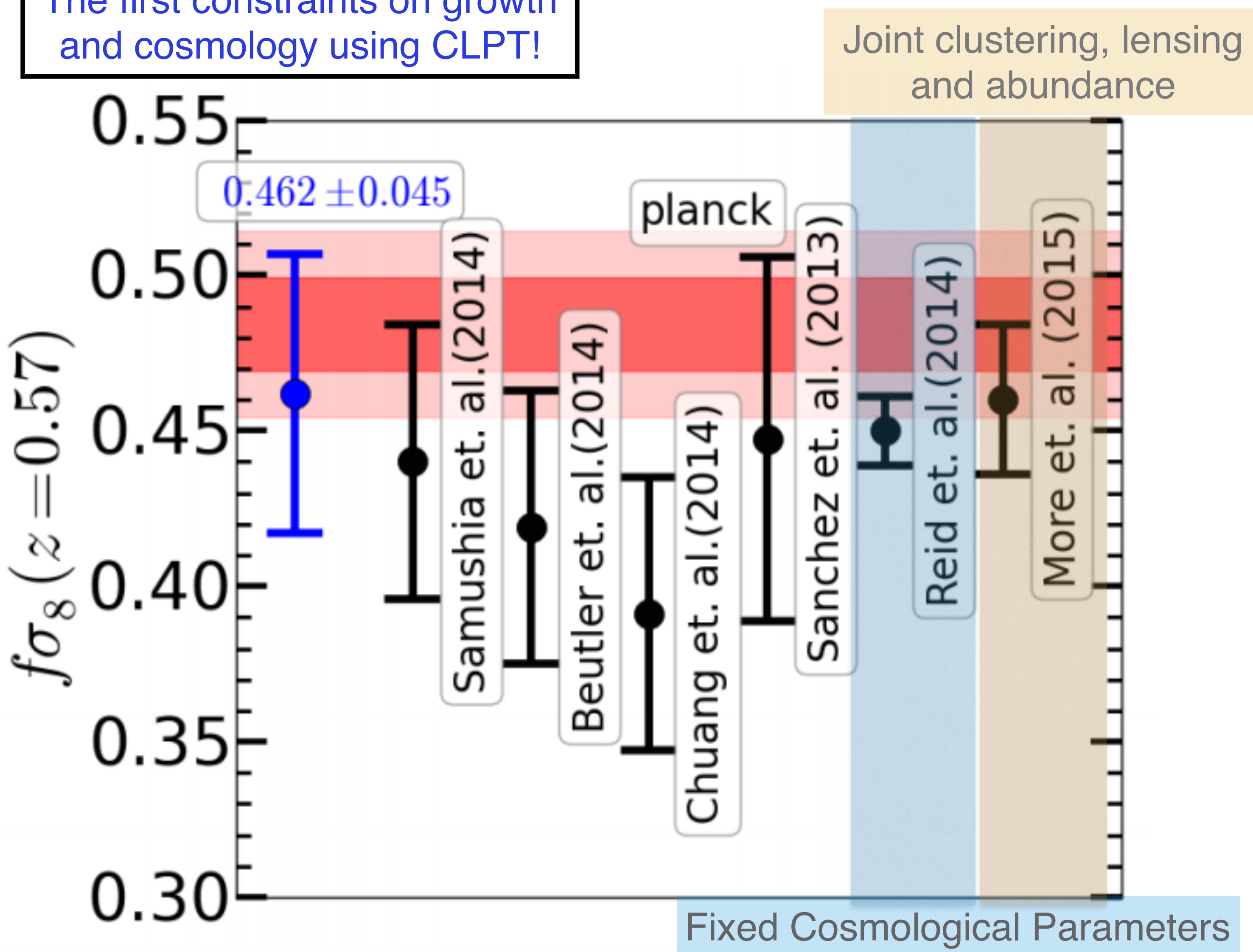
Testing Gravity with Redshift Space Distortions
Constraints on Growth of Structure!

The first constraints on growth and cosmology using CLPT!



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SDSS III

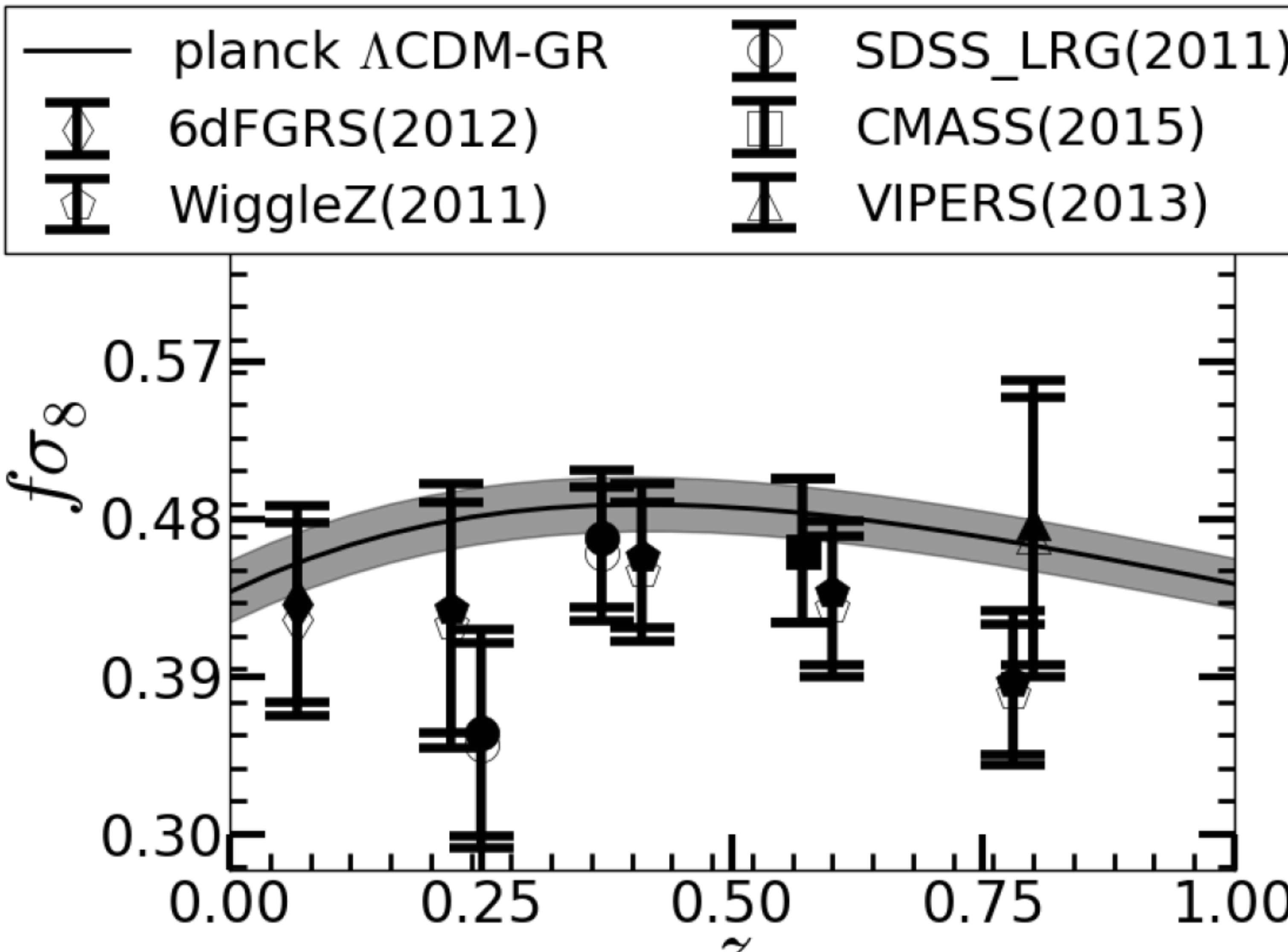
What about the promised constraints on modified Gravity?

Preliminary results: Alam, Ho & Silverstri

SDSSIII

What about the promised constraints on modified Gravity?

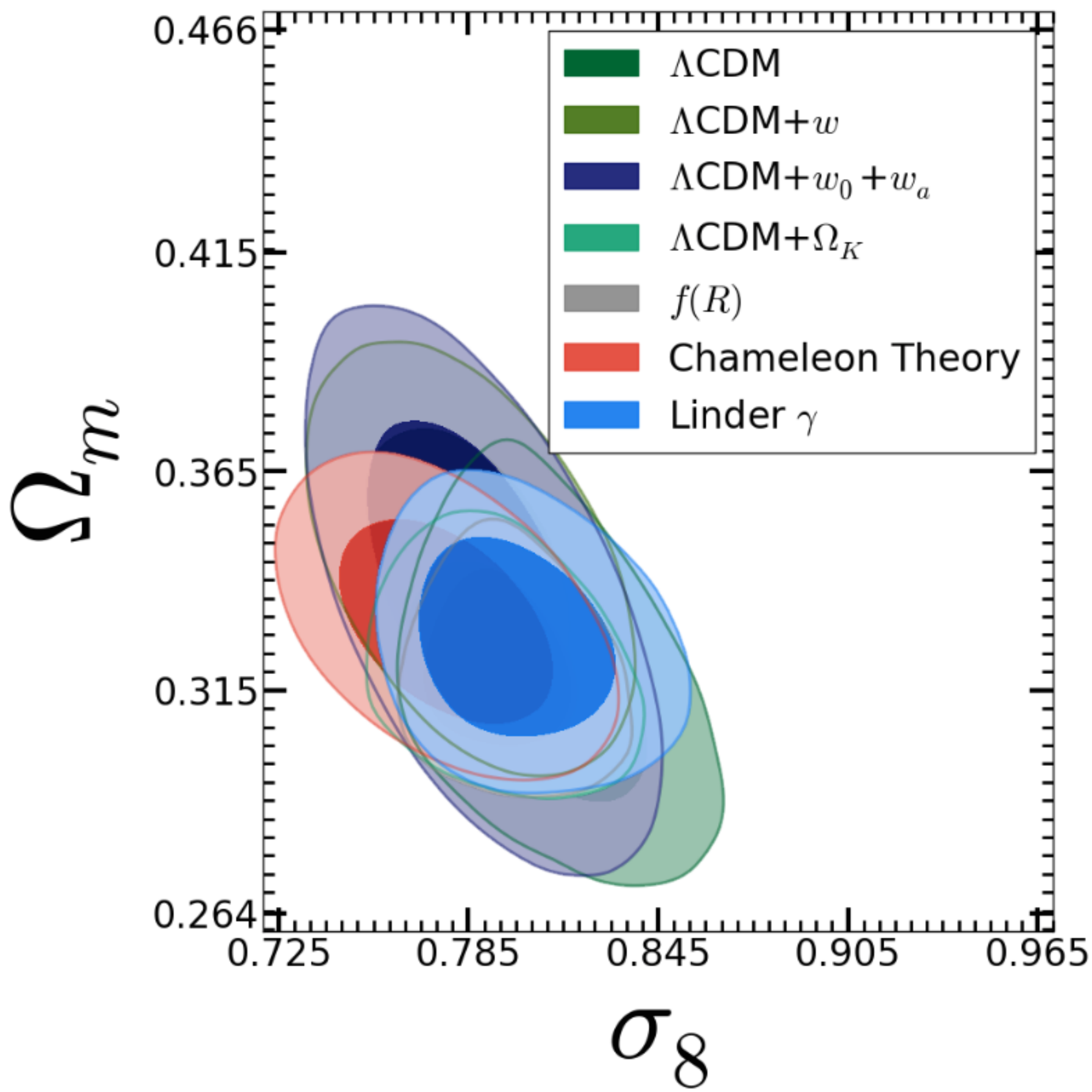
We need more than one redshift!



Preliminary results: Alam, Ho & Silverstri

SDSS III

Models considered:



Preliminary results: Alam, Ho & Silverstri

SDSSIII

The *current* best constraints on modified gravity using RSD

Chameleon Theory

$$\beta_1 = 1.3 \pm 0.25$$

Parameterizes the dynamics
GR -> 1

Hojjati et. al. 2011

Linder parameterization
phenomenological

$$\gamma = 0.69 \pm 0.11$$

GR -> 0.55

Samuisha et al. 2013

f(R) Gravity

$$B_0 < 5.7 \times 10^{-5}$$

Inverse of relavant Mass scales in f(R)
GR -> 0

Xu et al. 2015

Preliminary results: Alam, Ho & Silverstri

The *NEW* best constraints on modified gravity using RSD

Chameleon Theory

$$\beta_1 = 1.3 \pm 0.25$$

Parameterizes the dynamics
GR -> 1

Hojjati et. al. 2011

$$\beta_1 = 0.932 \pm 0.032$$

Linder parameterization
phenomenological

$$\gamma = 0.69 \pm 0.11$$

GR -> 0.55

Samuisha et al. 2013

$$\gamma = 0.59 \pm 0.08$$

f(R) Gravity

$$B_0 < 5.7 \times 10^{-5}$$

Xu et al. 2015

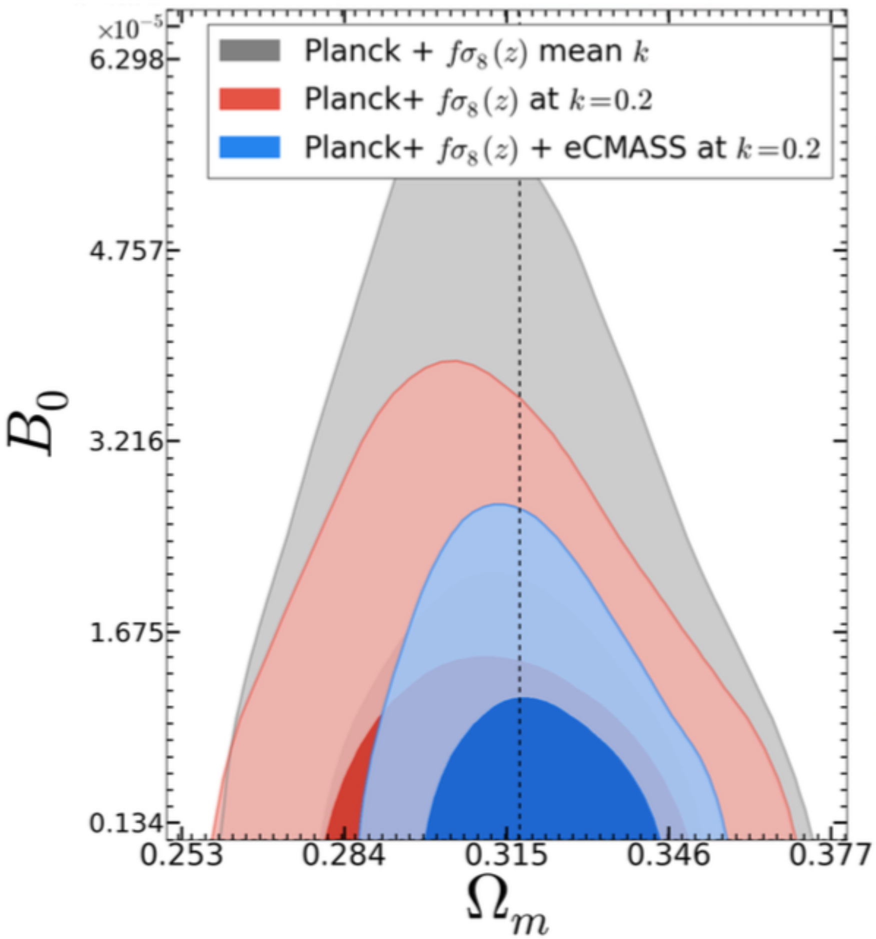
Inverse of relavant Mass scales in f(R)
GR -> 0

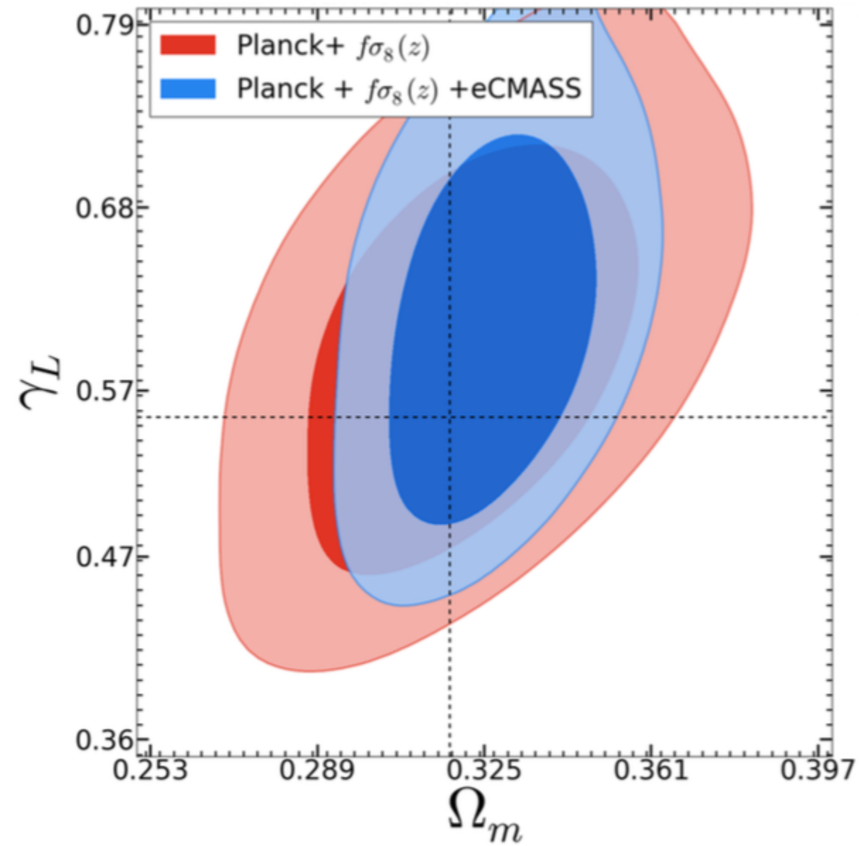
$$B_0 < 1.36 \times 10^{-5} (1\sigma C.L.)$$

Preliminary results: Alam, Ho & Silverstri

SDSSIII

The *NEW* best constraints on modified gravity using RSD



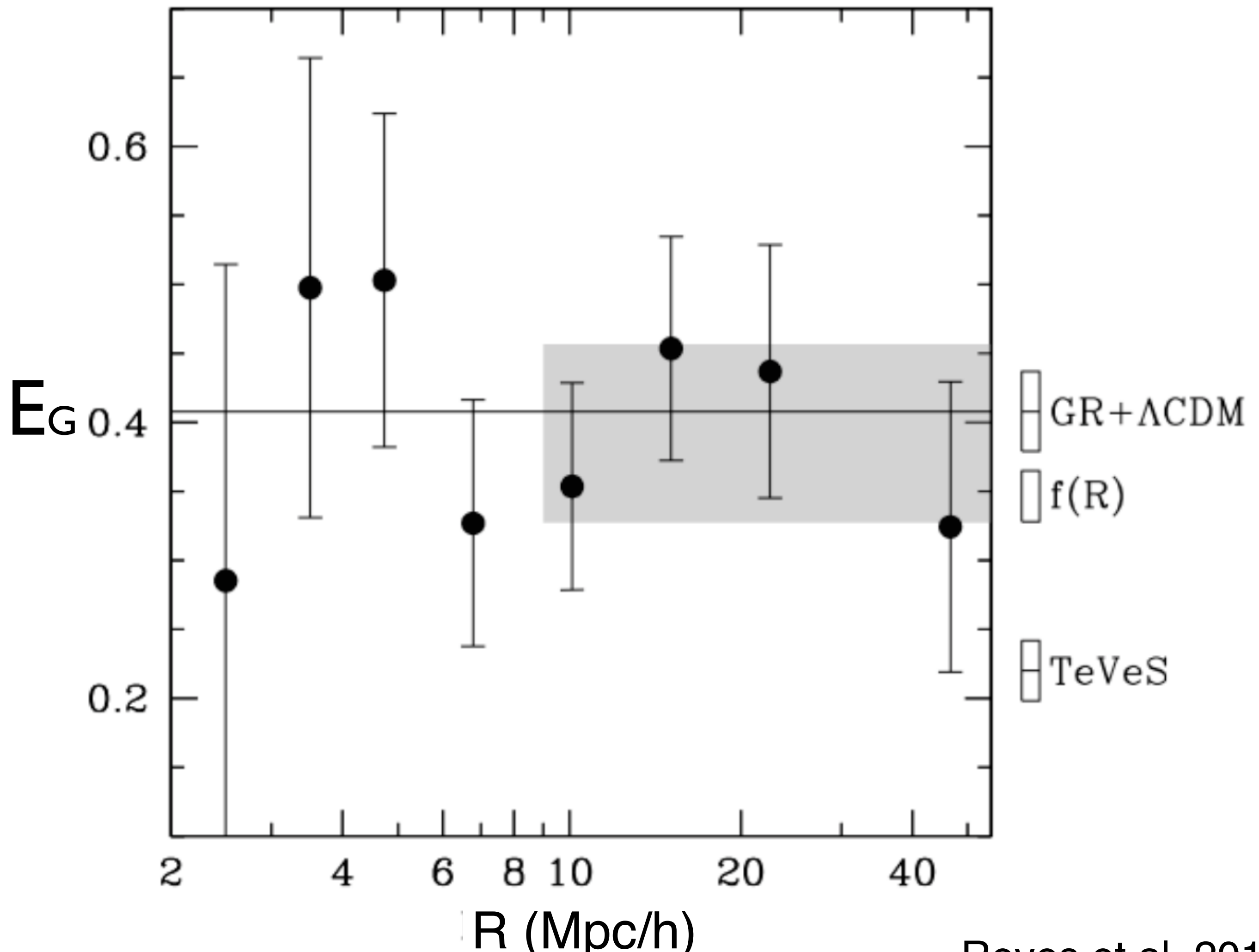


Preliminary results: Alam, Ho & Silverstri

Outline today

- What is really BOSS-BAO ?
  - Can we improve the analysis ?
  - What do we learn from it ?
- What other science we can do with BOSS ?
  - Many…
  - Constraining Gravity !
  - Introduce a new probe combining BOSS AND CMB-lensing to learn about gravity at the largest scale !

Recall bias-free probe of gravity,
combining galaxy-clustering and galaxy-lensing!



Reyes et al. 2010

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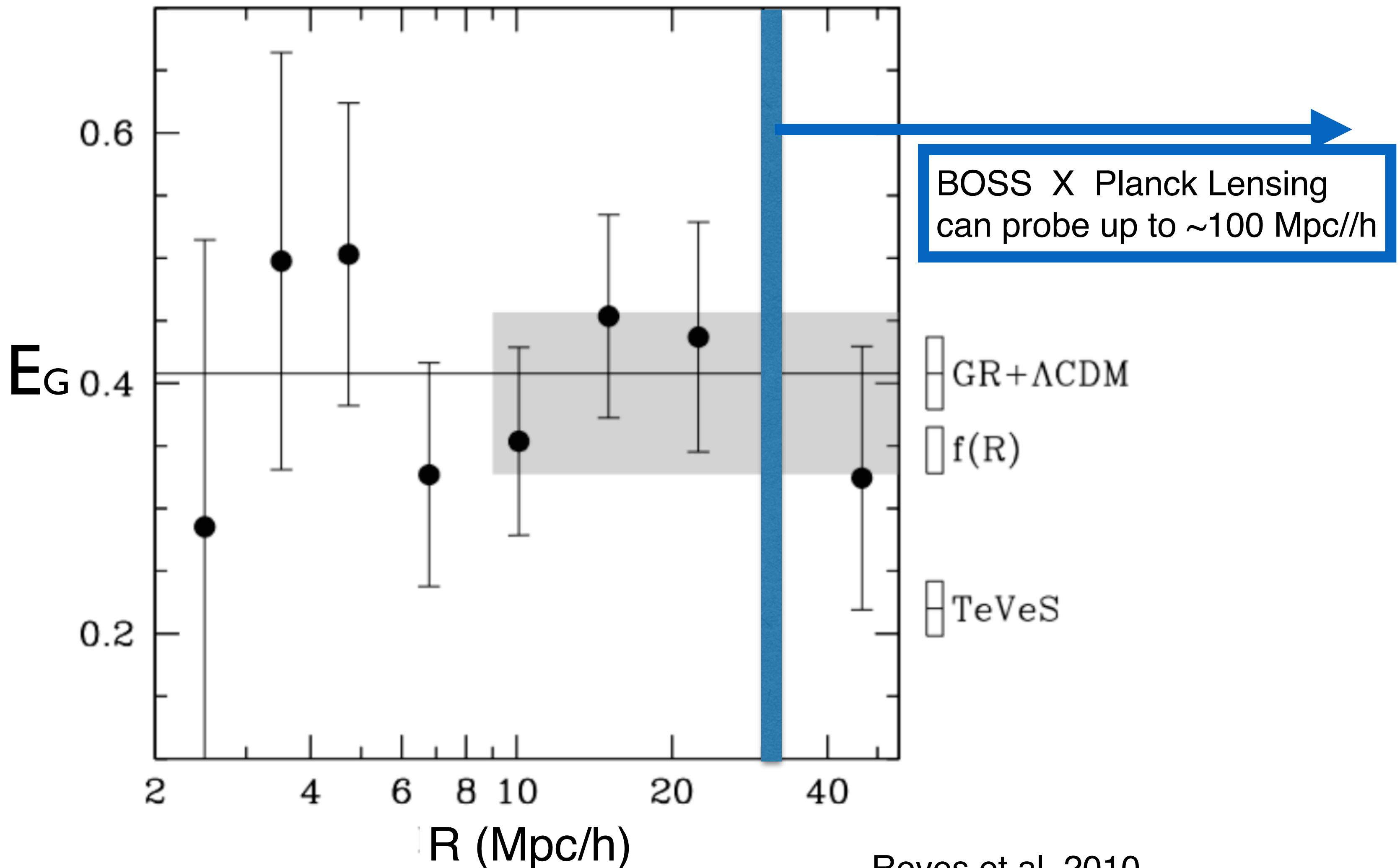
We start from 30 Mpc/h and have significant signals to larger scales.



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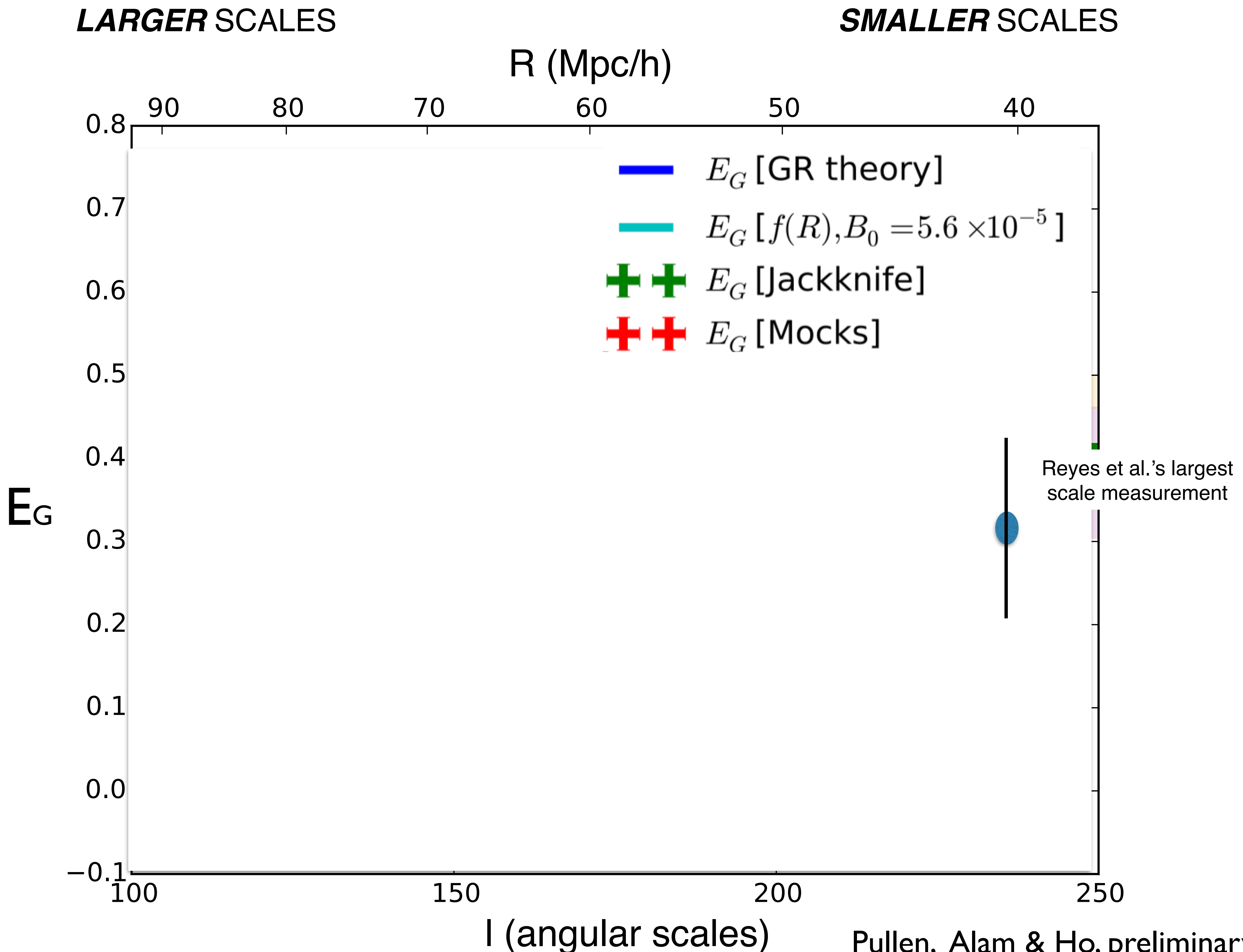
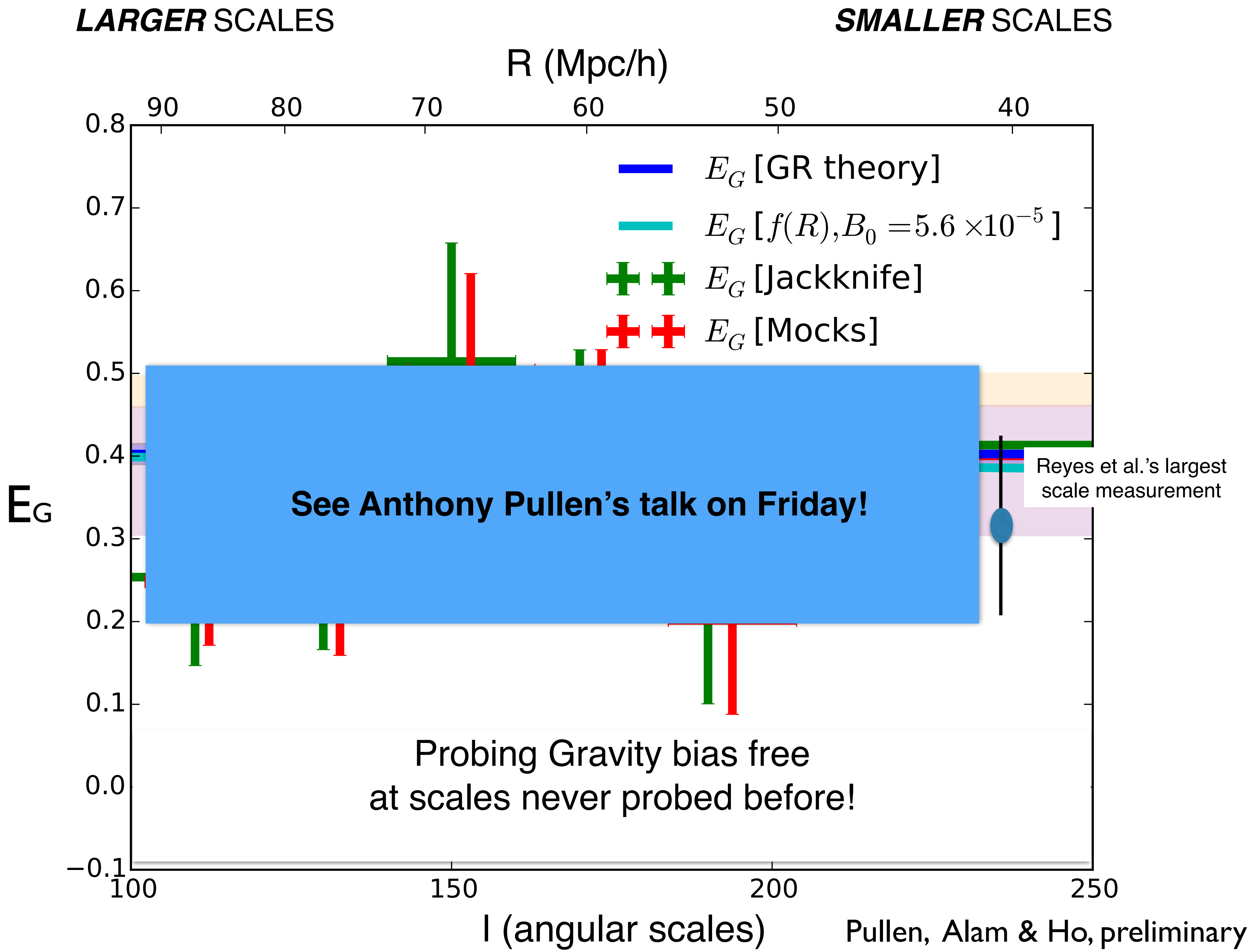
SDSSIII



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]
E_G [$f(R), B_0 = 5.6 \times 10^{-5}$]
E_G [Jackknife]
E_G [Mocks]
See Anthony Pullen's talk on Friday!
Reyes et al.'s largest scale measurement
Probing Gravity bias free
at scales never probed before!
EG
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.

SDSSIII

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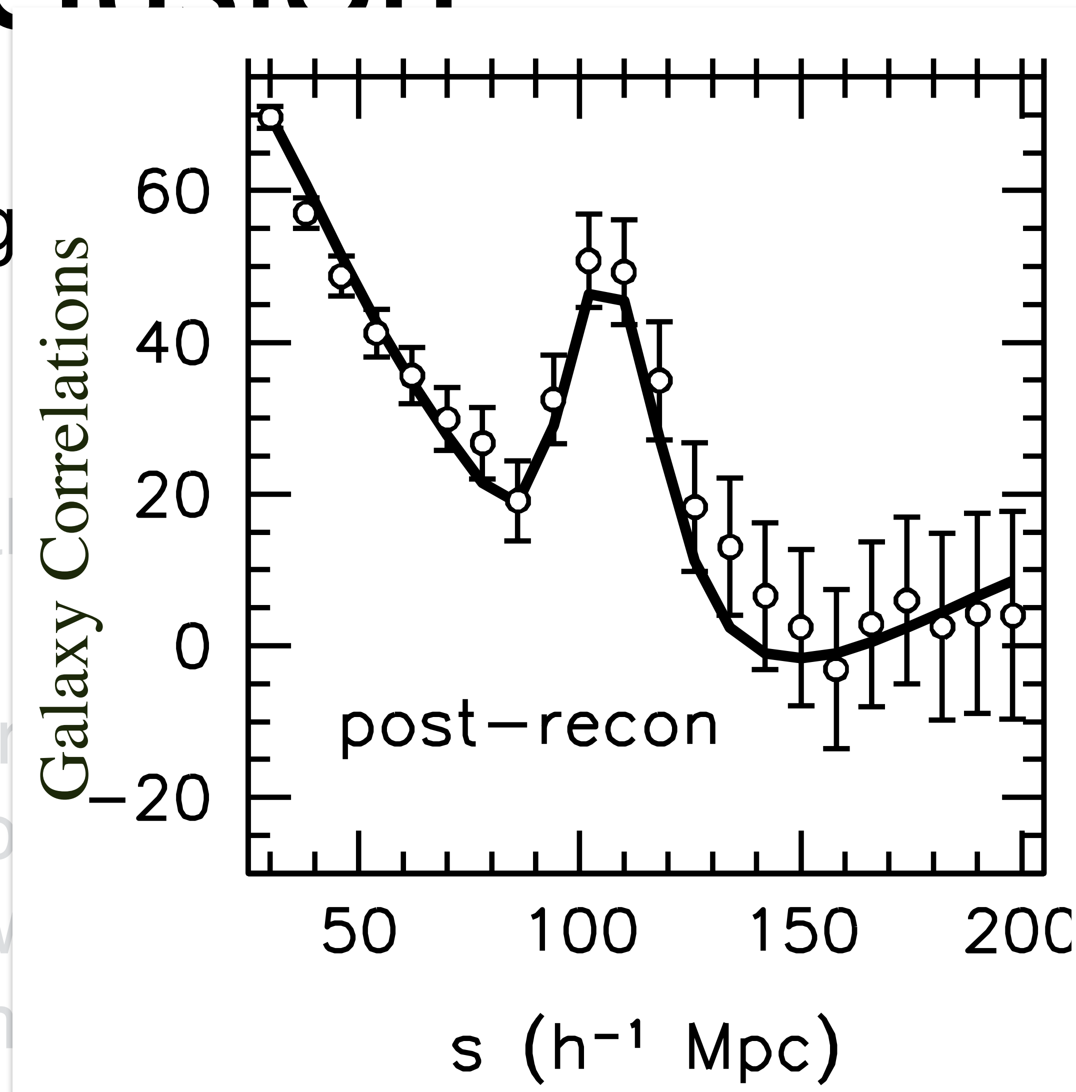

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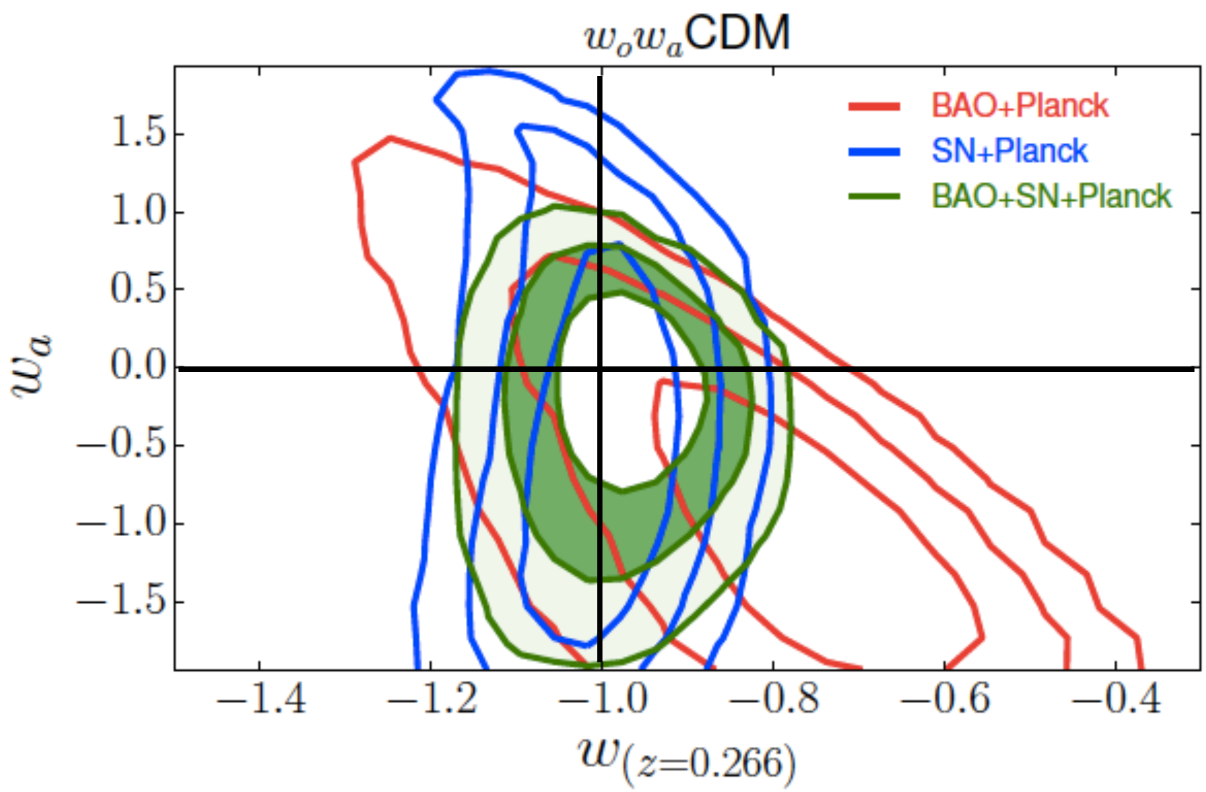

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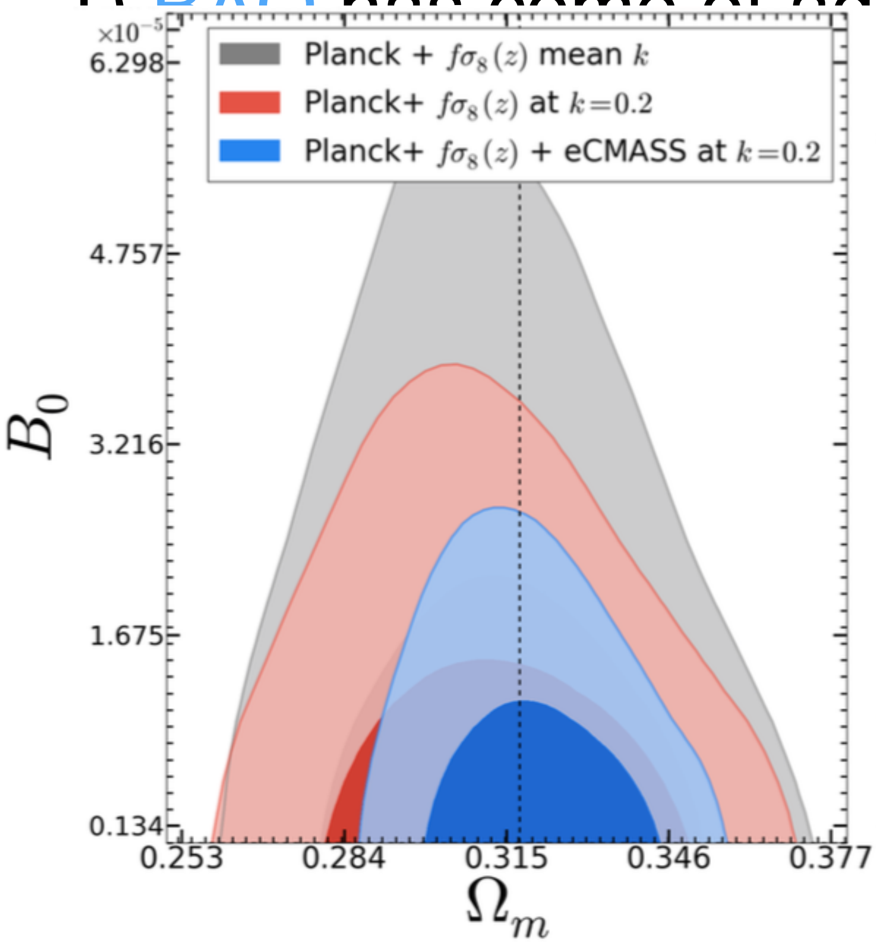

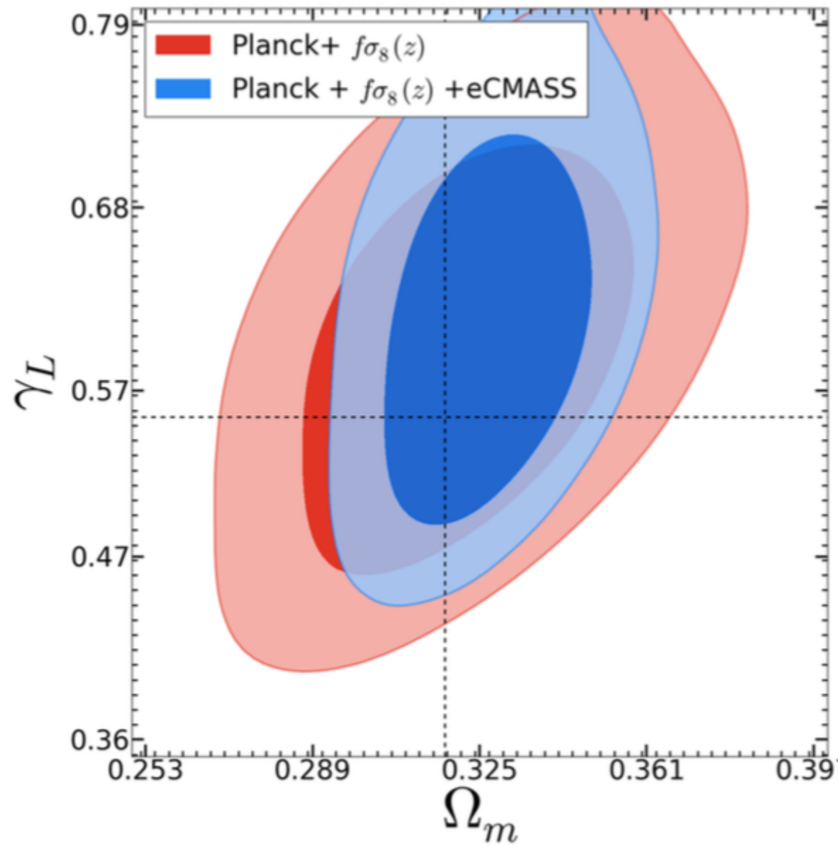

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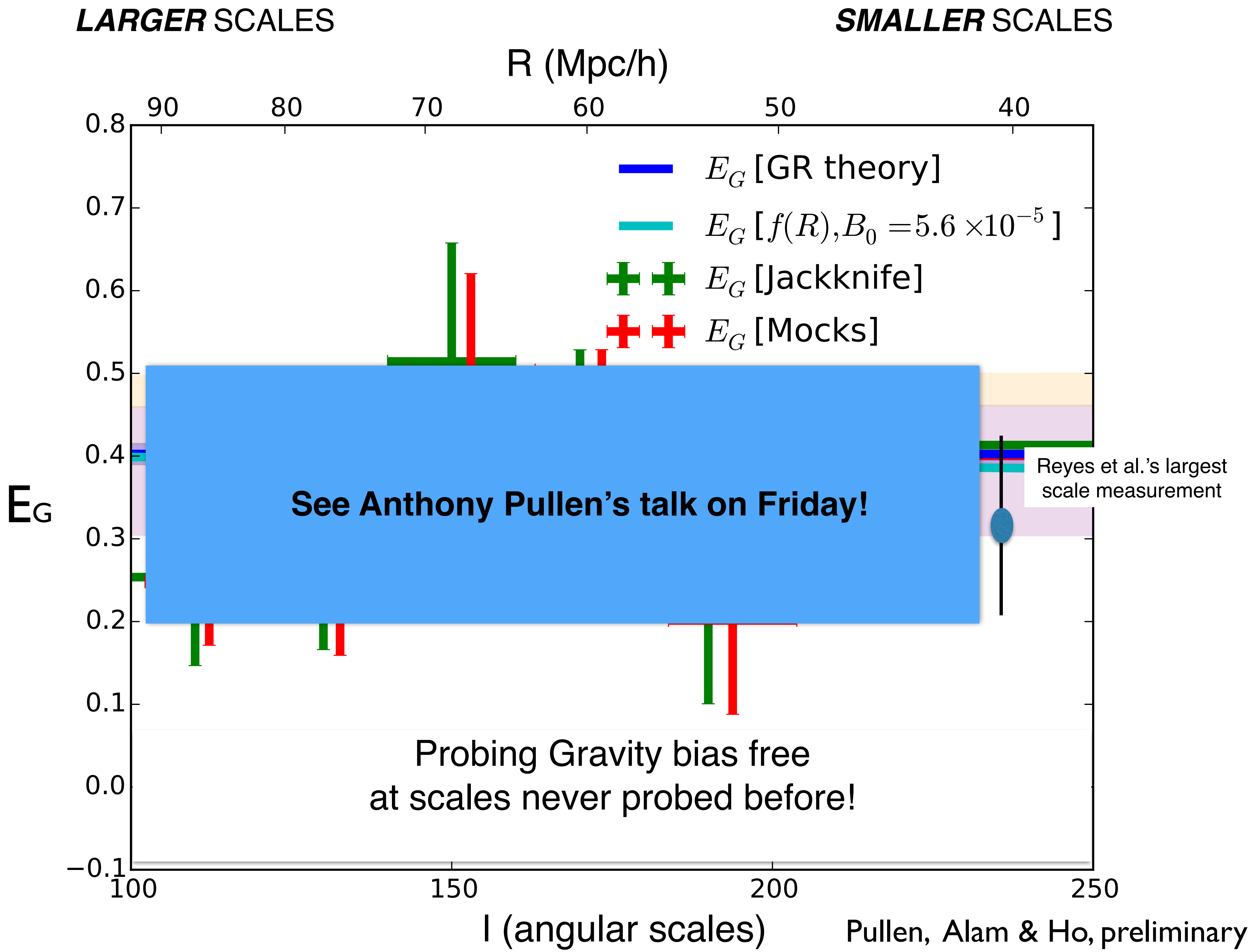
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