THE MCWILLIAMS
Center for Cosmology

Carnegie Mellon University

Testing Gravity using Galaxy redshift Surveys and CMB

Shadab Alam

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A Big Thanks to everyone involved in these surveys

(Nothing would be possible without them)

What have we learned about universe so far?

The ΛCDM and General Relativity (Broad Picture)

Big Questions?

- What is Dark Matter?
  - particles?
  - scalar field?
- Nature of Dark Energy?
  - stuff which produce cosmic acceleration?

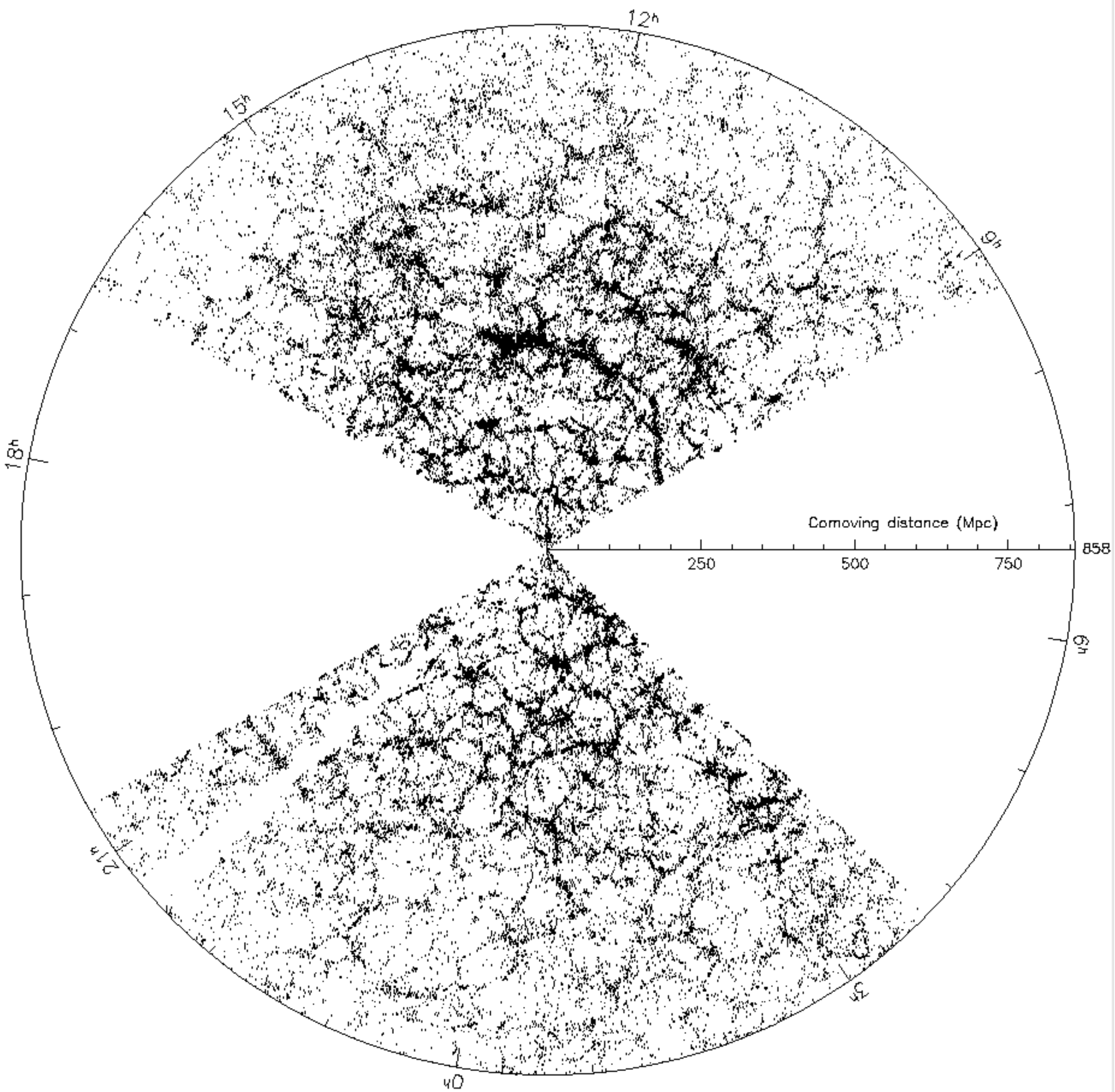
image source: http://www.physicsoftheuniverse.com/cosmological.html

Observations

(My Favorite Tools)

What do we observe?

Millions of massive galaxies



Position
(RA=10.7,DEC=1.16)

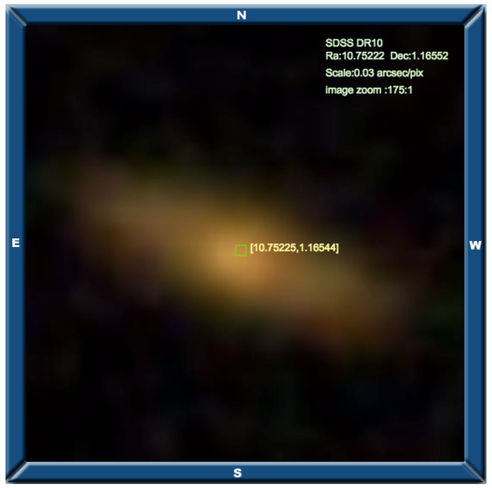


image source: http://skyserver.sdss.org

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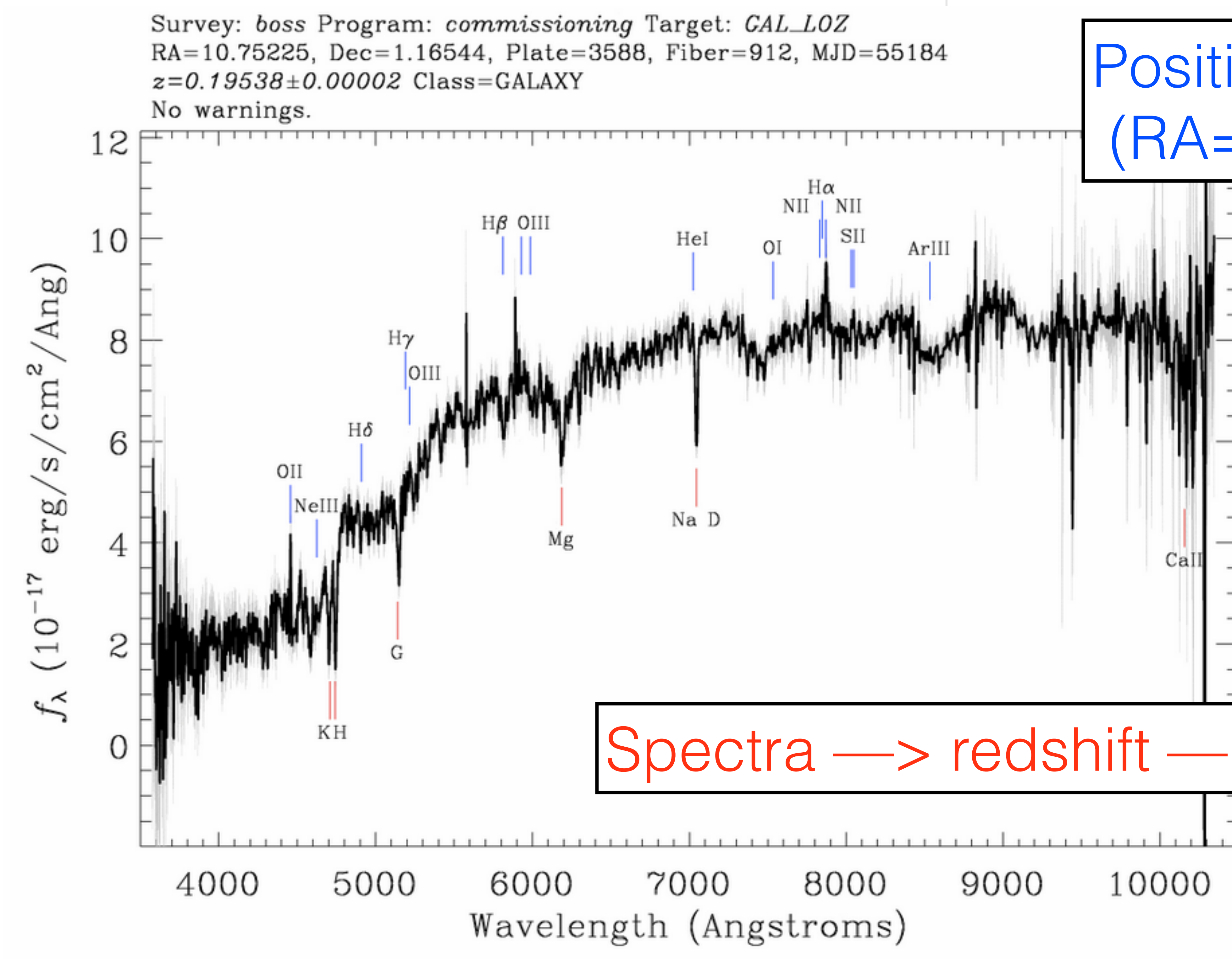
Millions of massive galaxies



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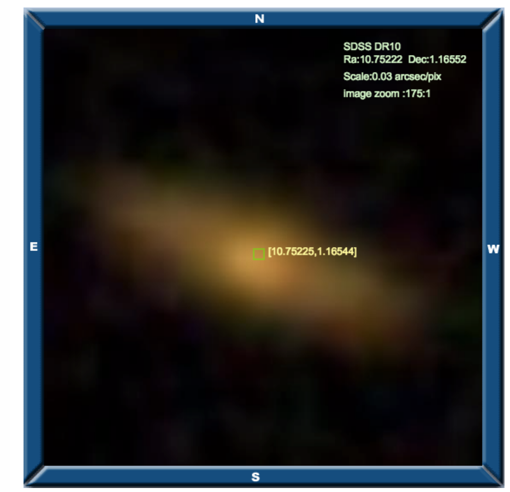


Spectra —> redshift —> LOS distance

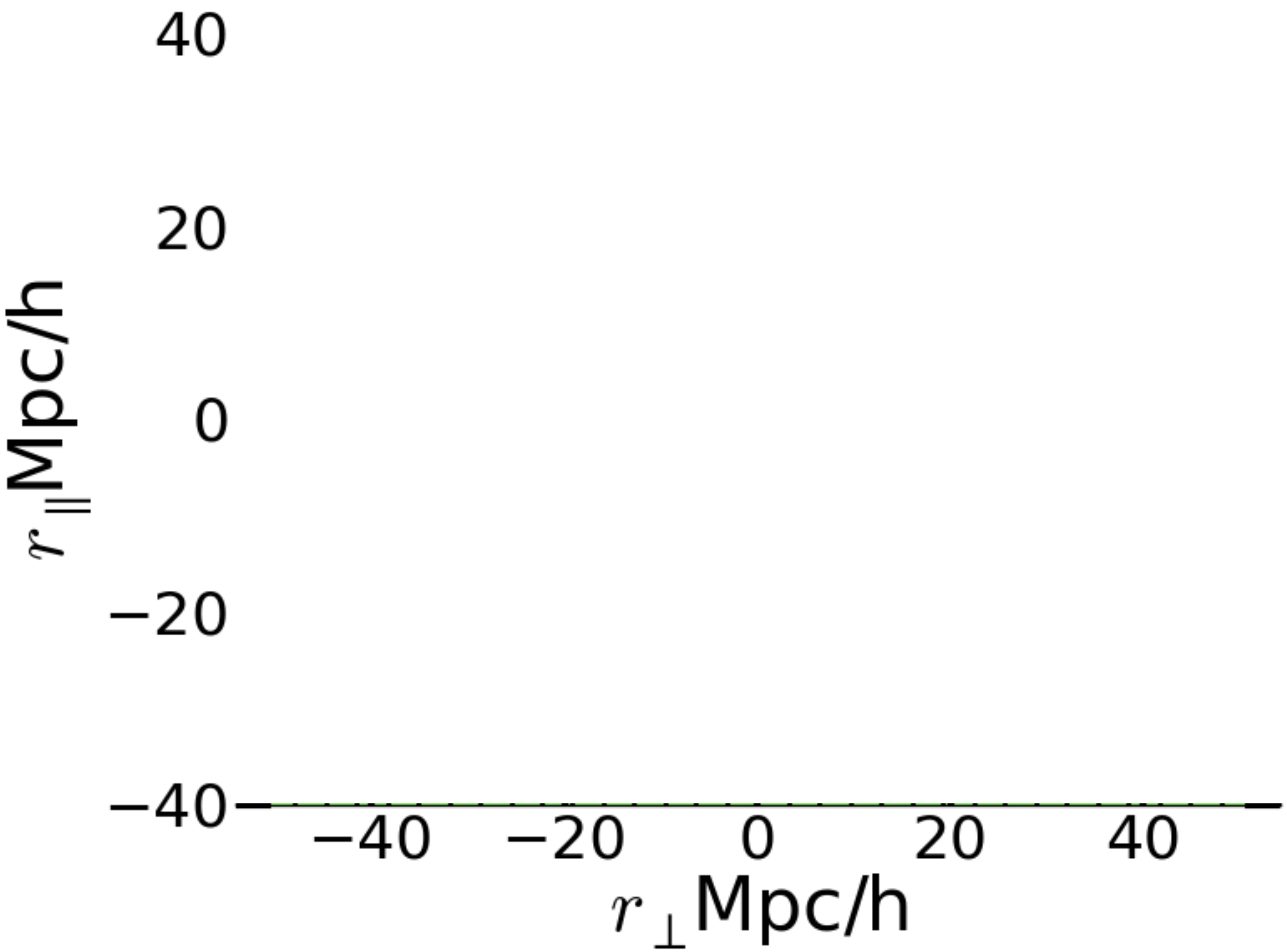
image source: http://skyserver.sdss.org

Redshift Space Distortions (RSD)

(Rich physics)

What do we measure?

2 point correlation function



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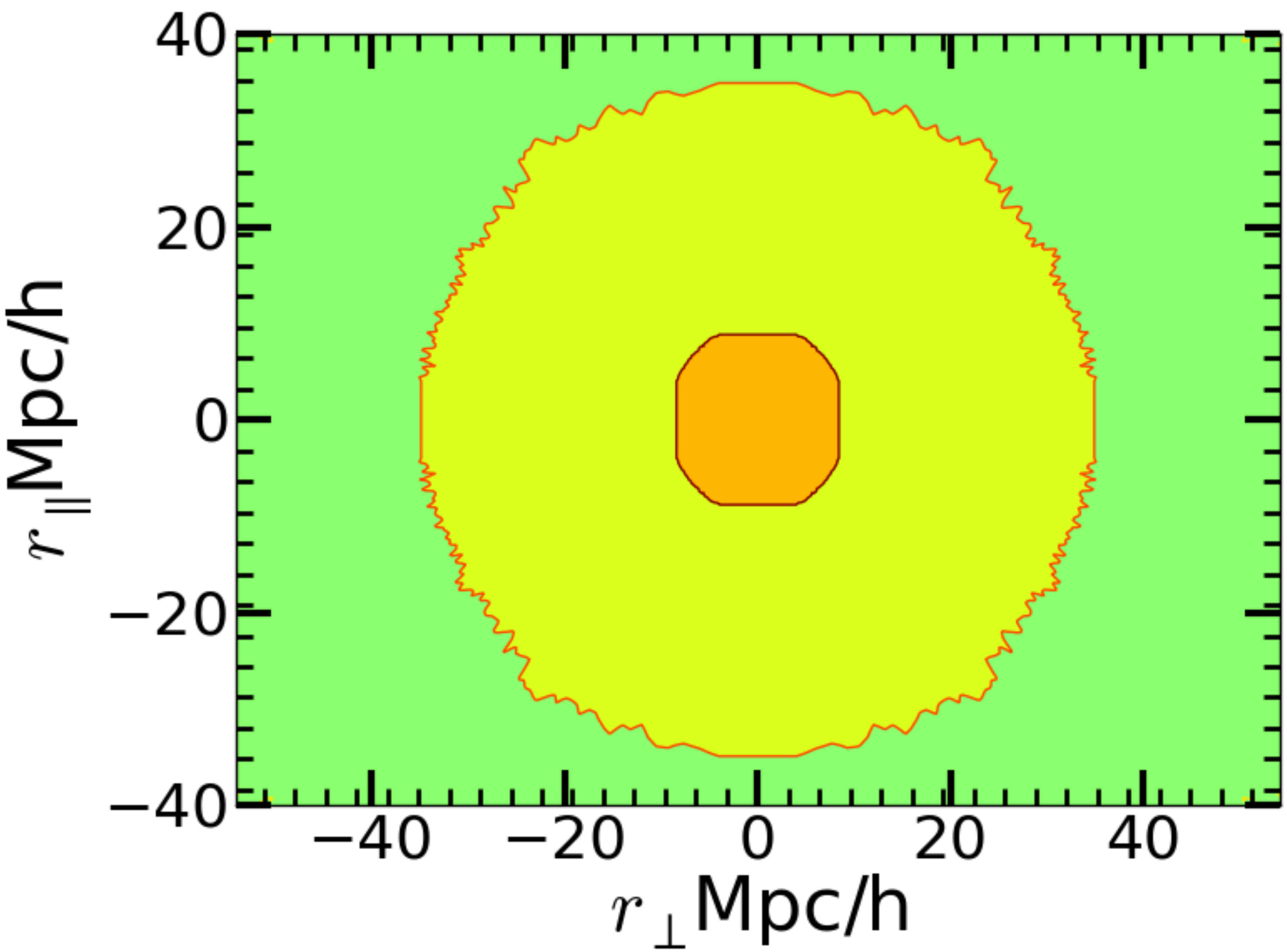
2 point correlation function



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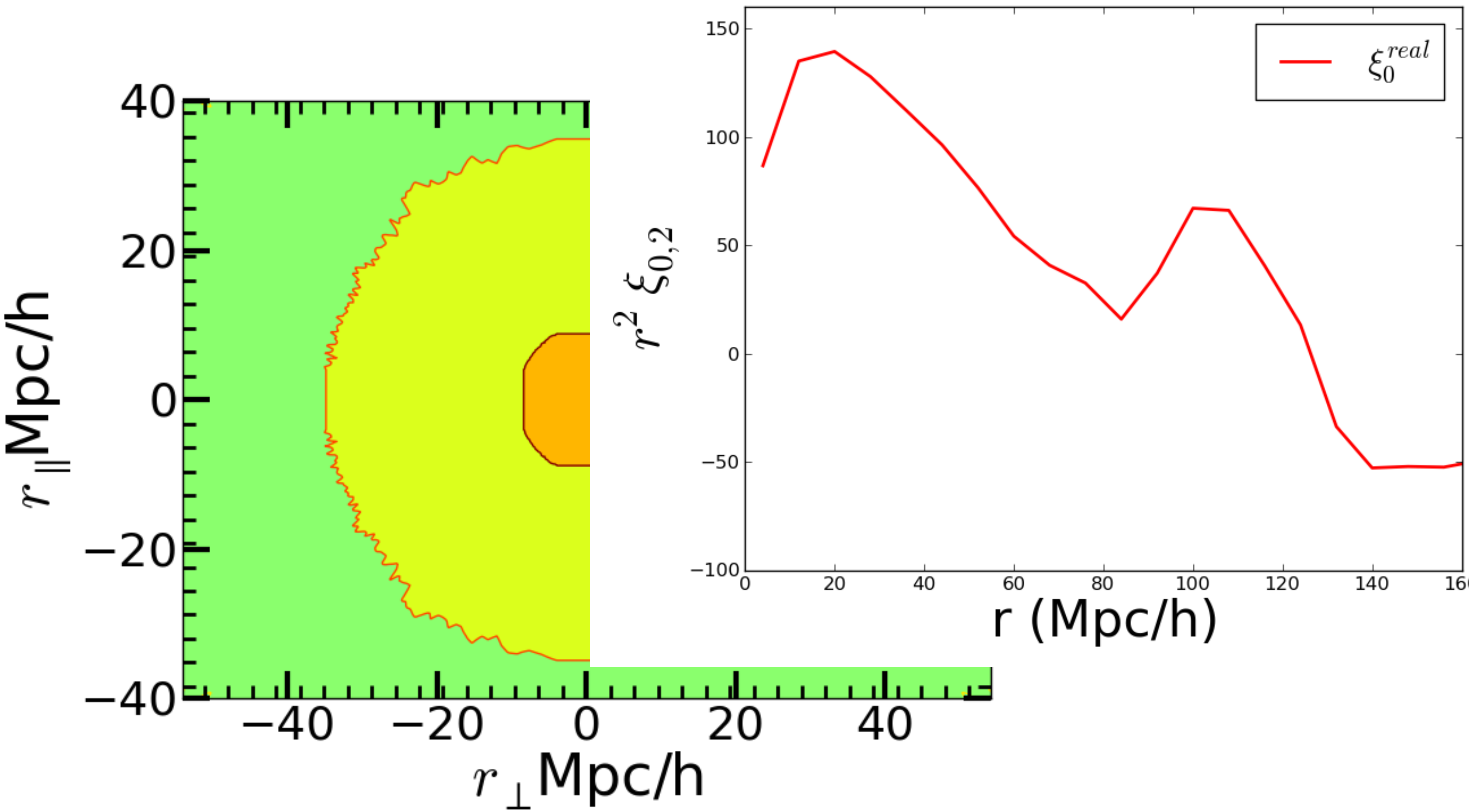

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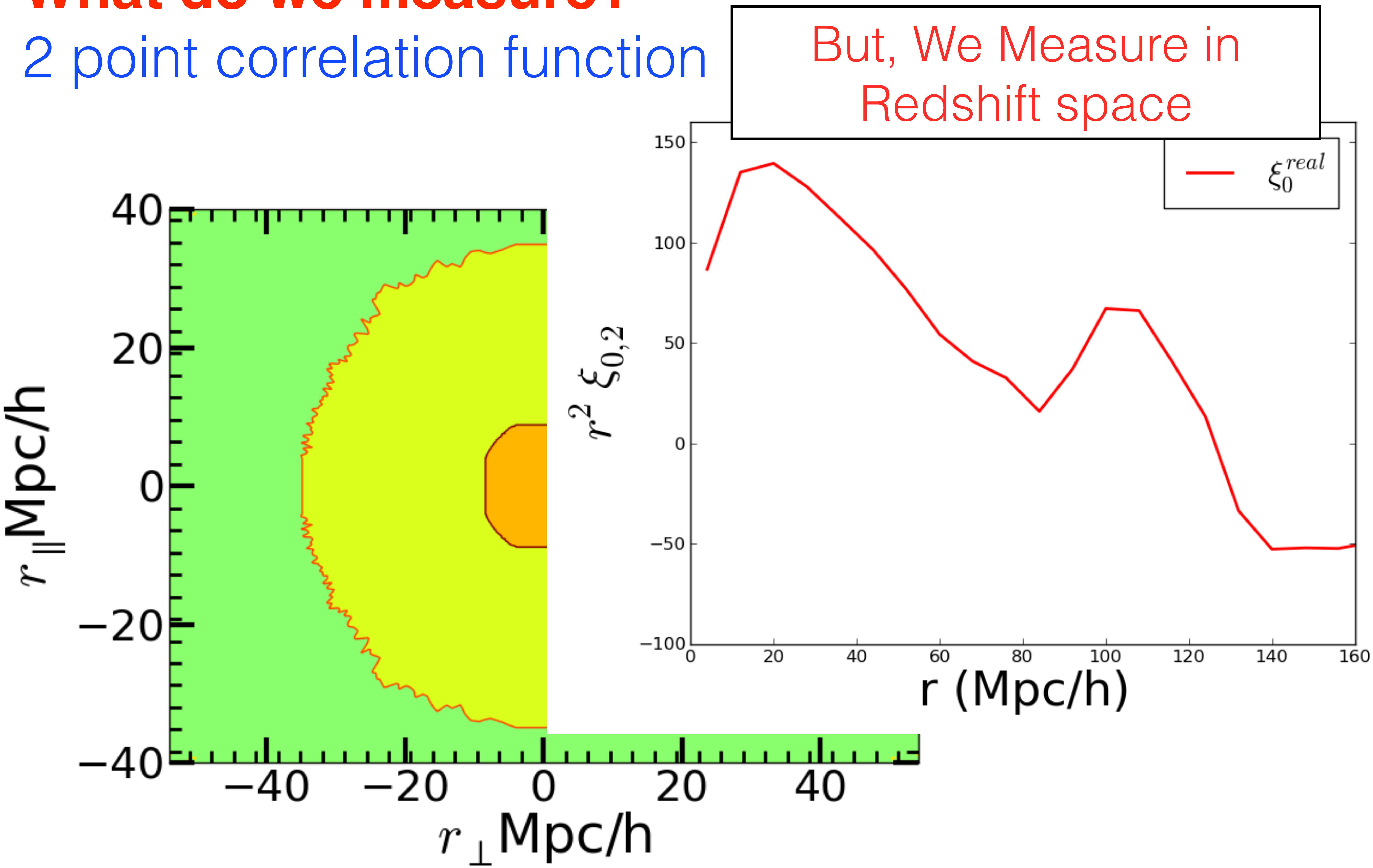
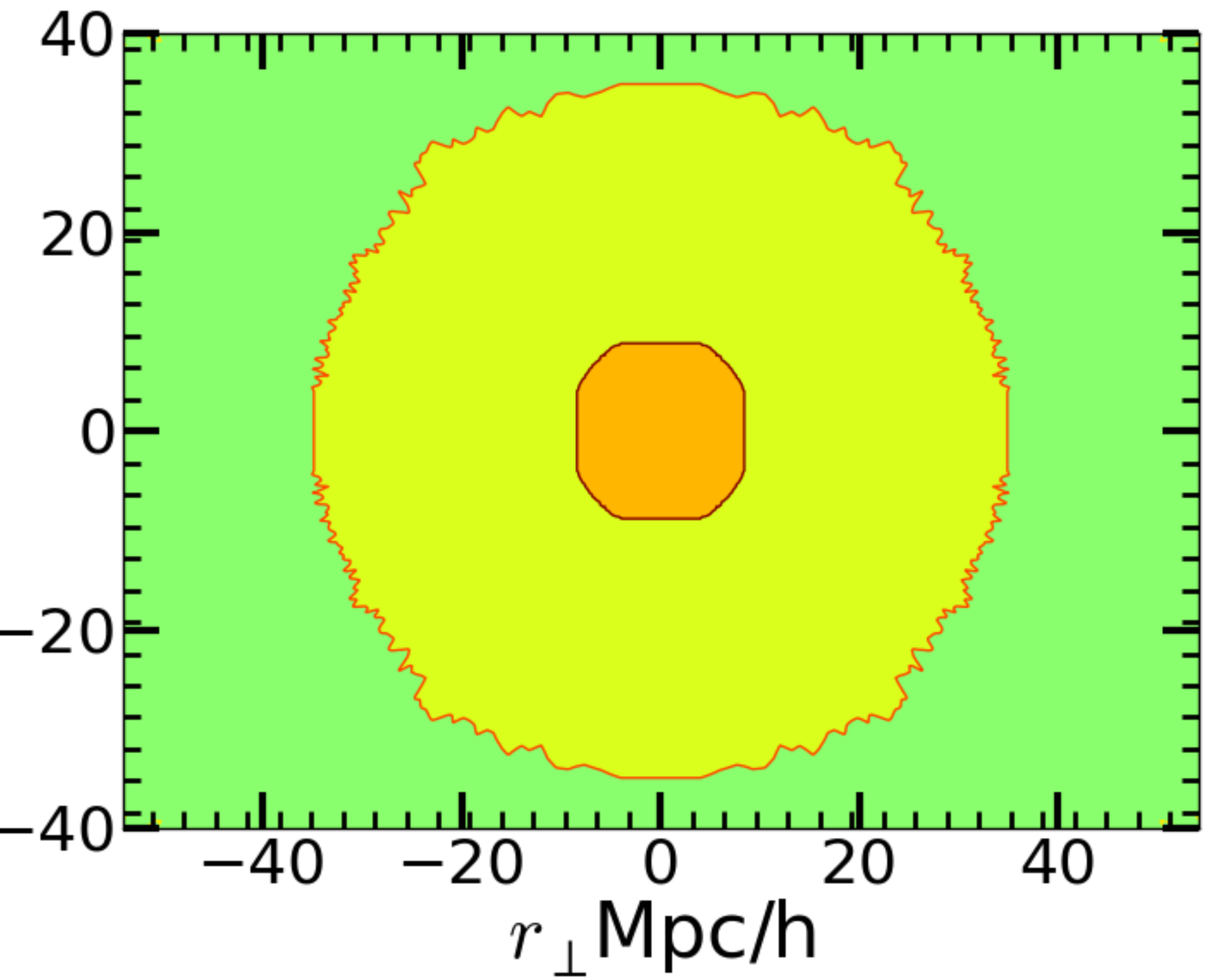


What do we measure?

2 point correlation function

But, We Measure in Redshift space

$$z_{observed} = z_{true} + \frac{\Delta v}{c}$$



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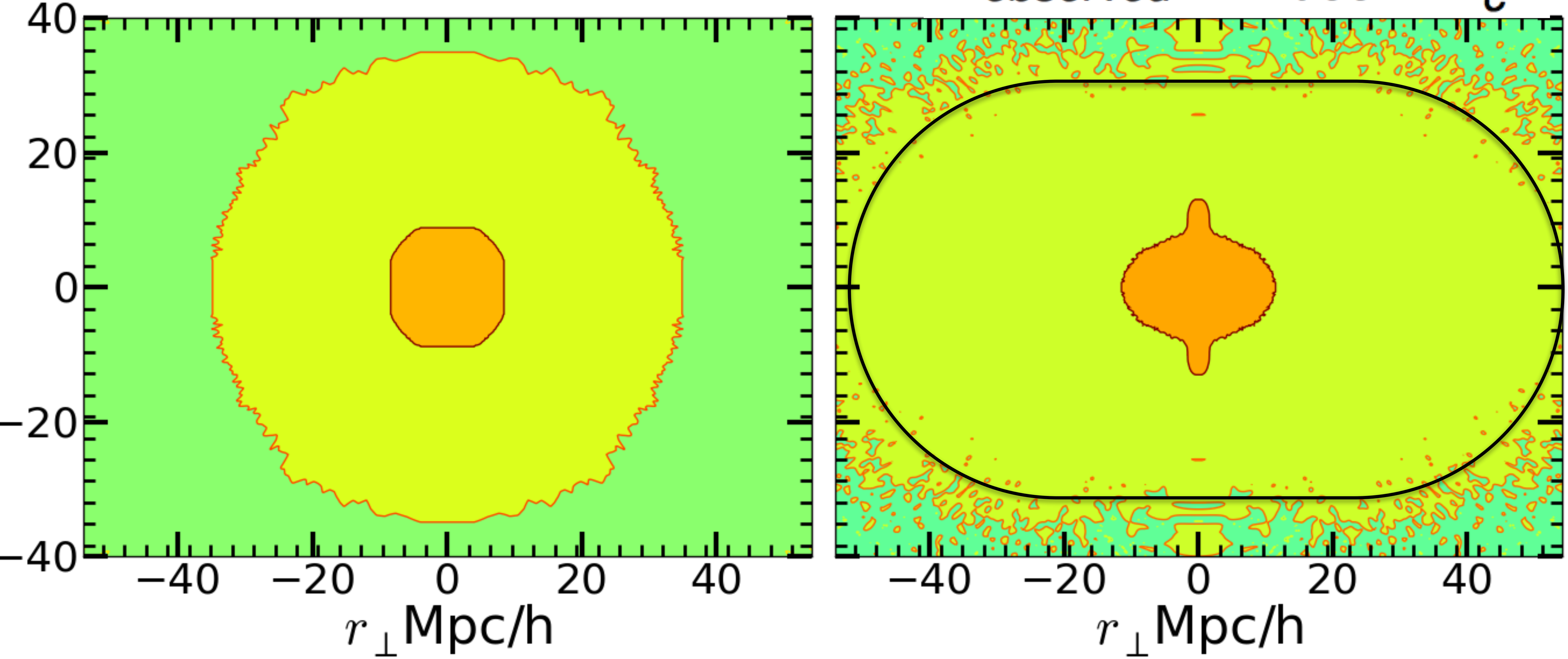

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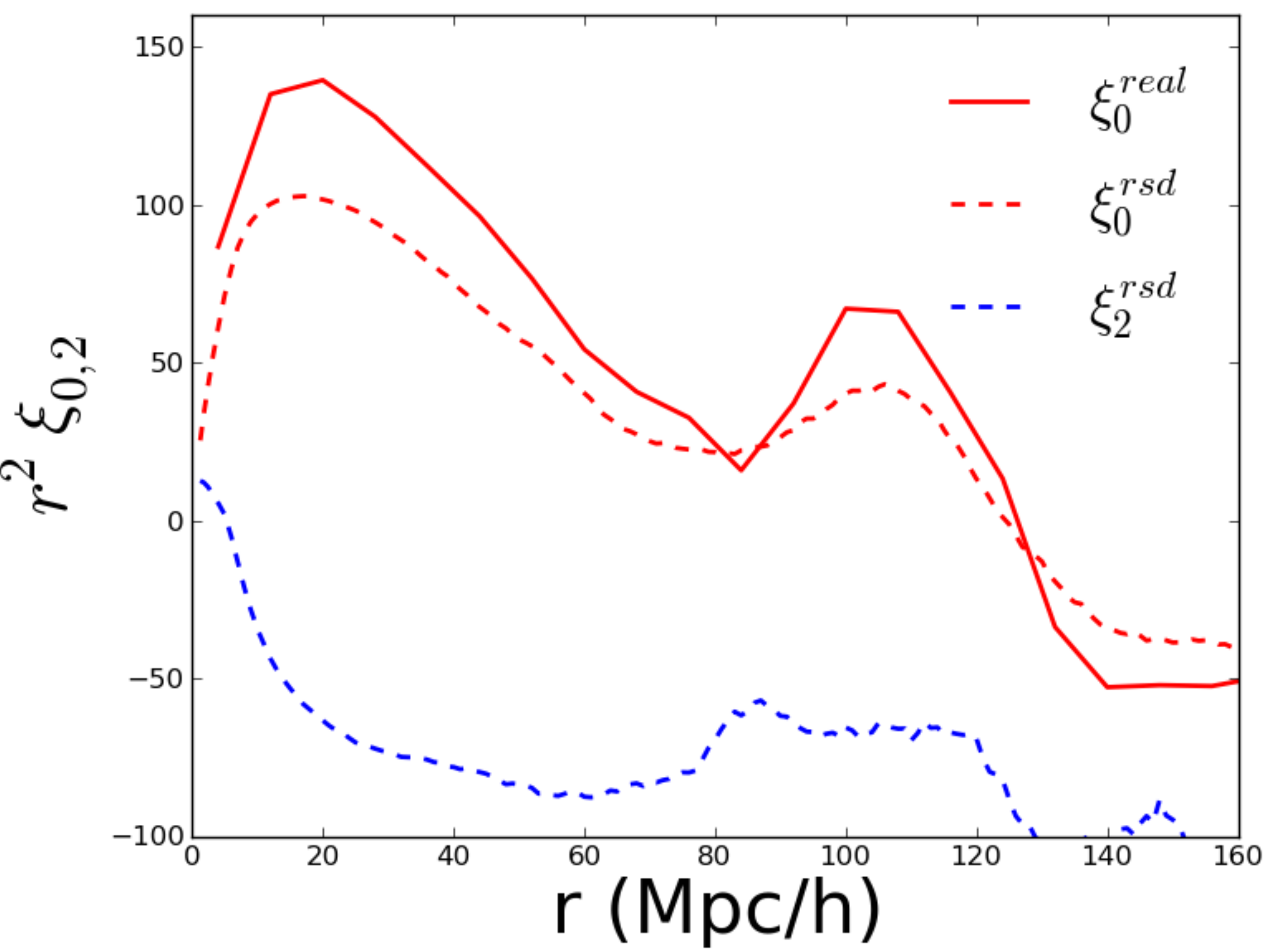
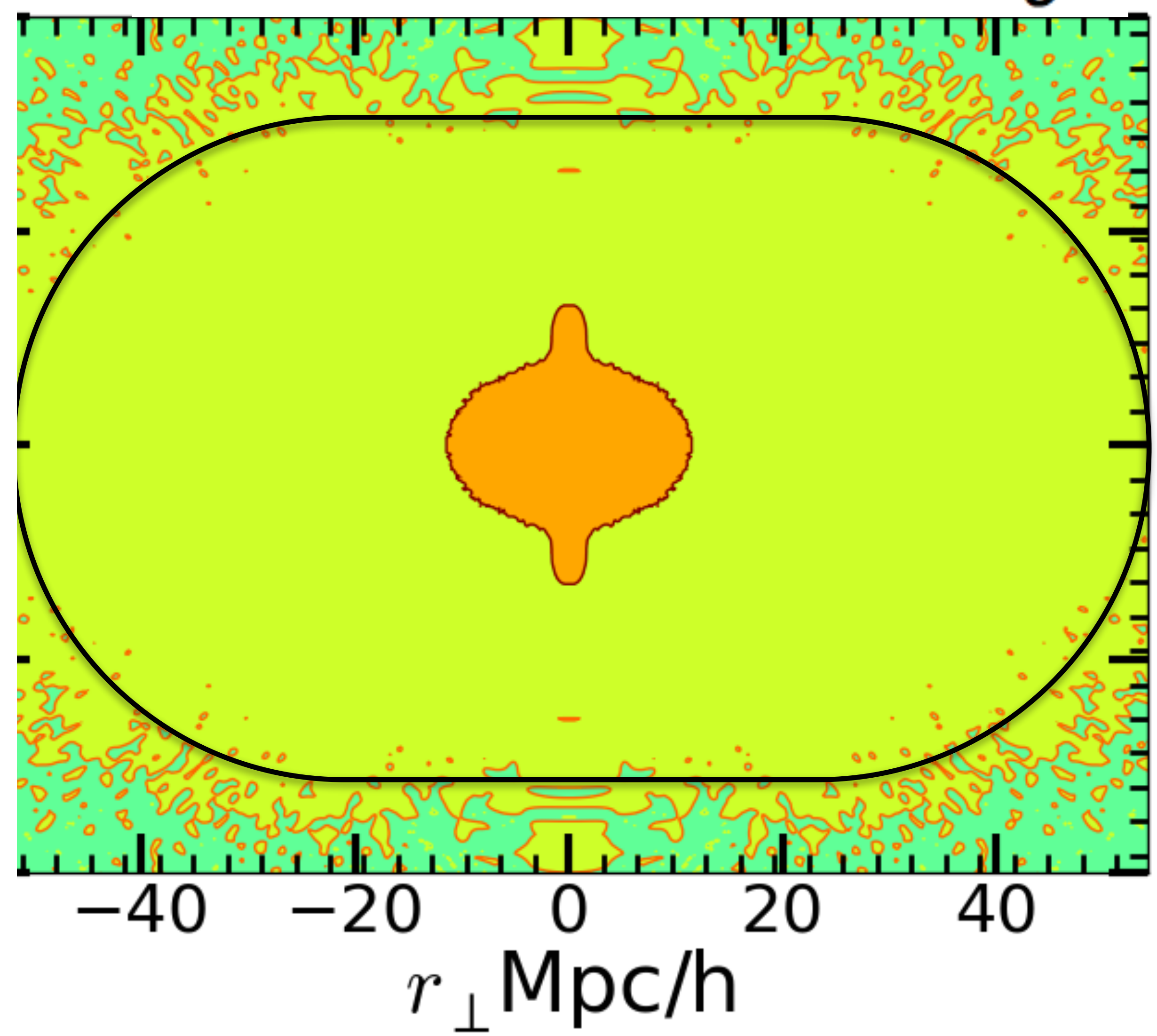


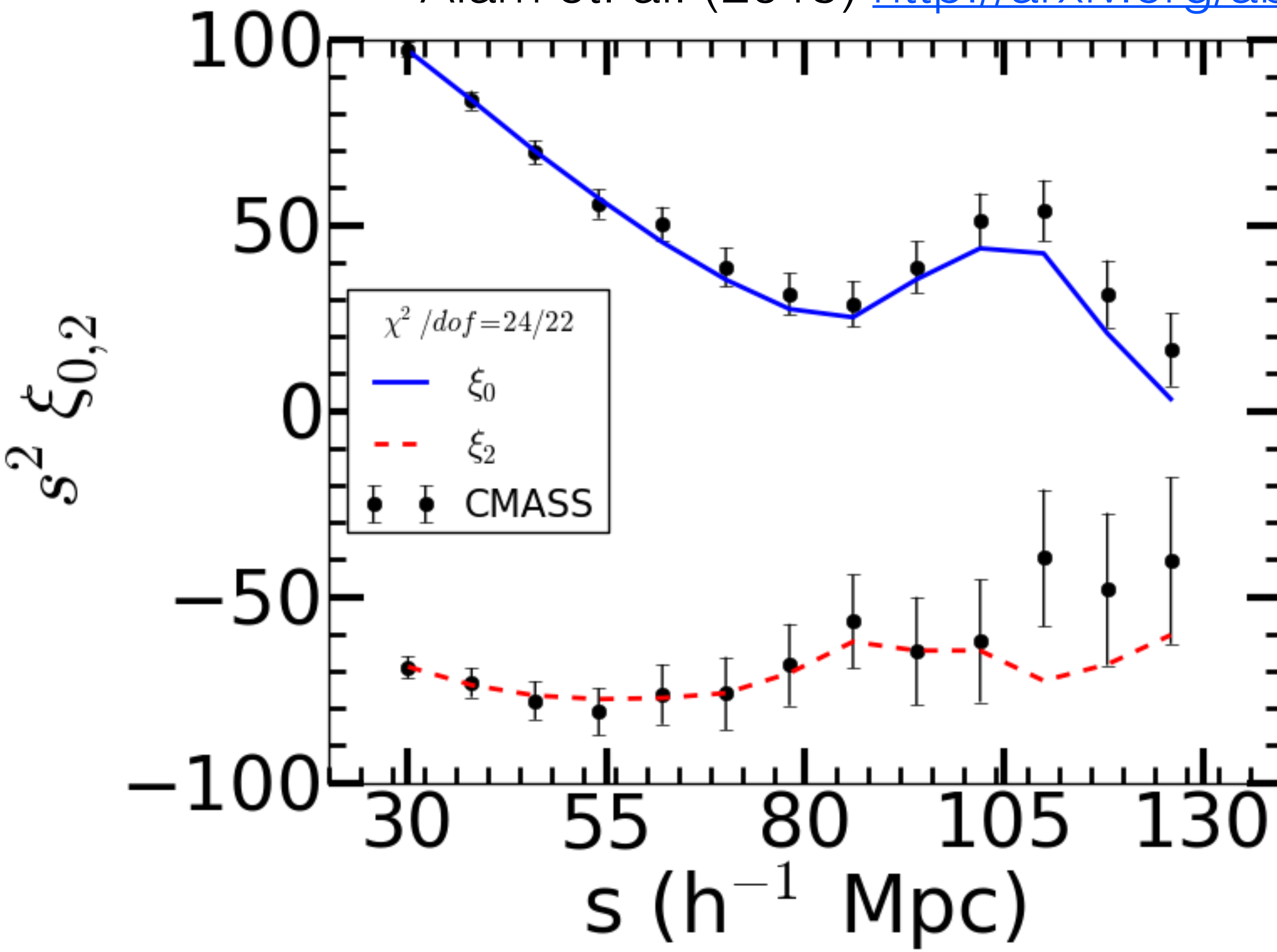


RSD Measurements

(The true universe)

We used perturbation theory to measure growth rate and BAO

Alam et. al. (2015) http://arxiv.org/abs/1504.02100



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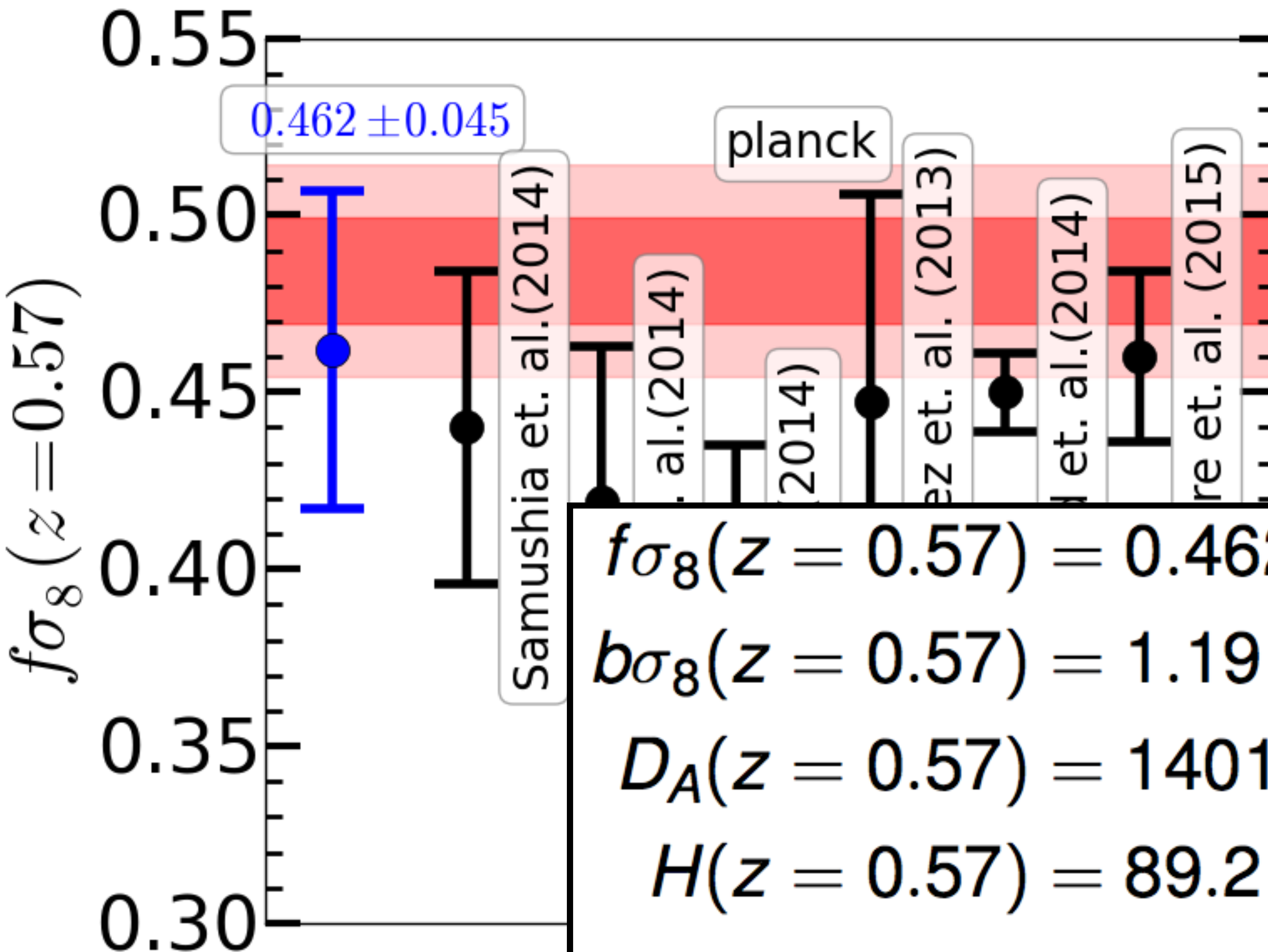


eCMASS

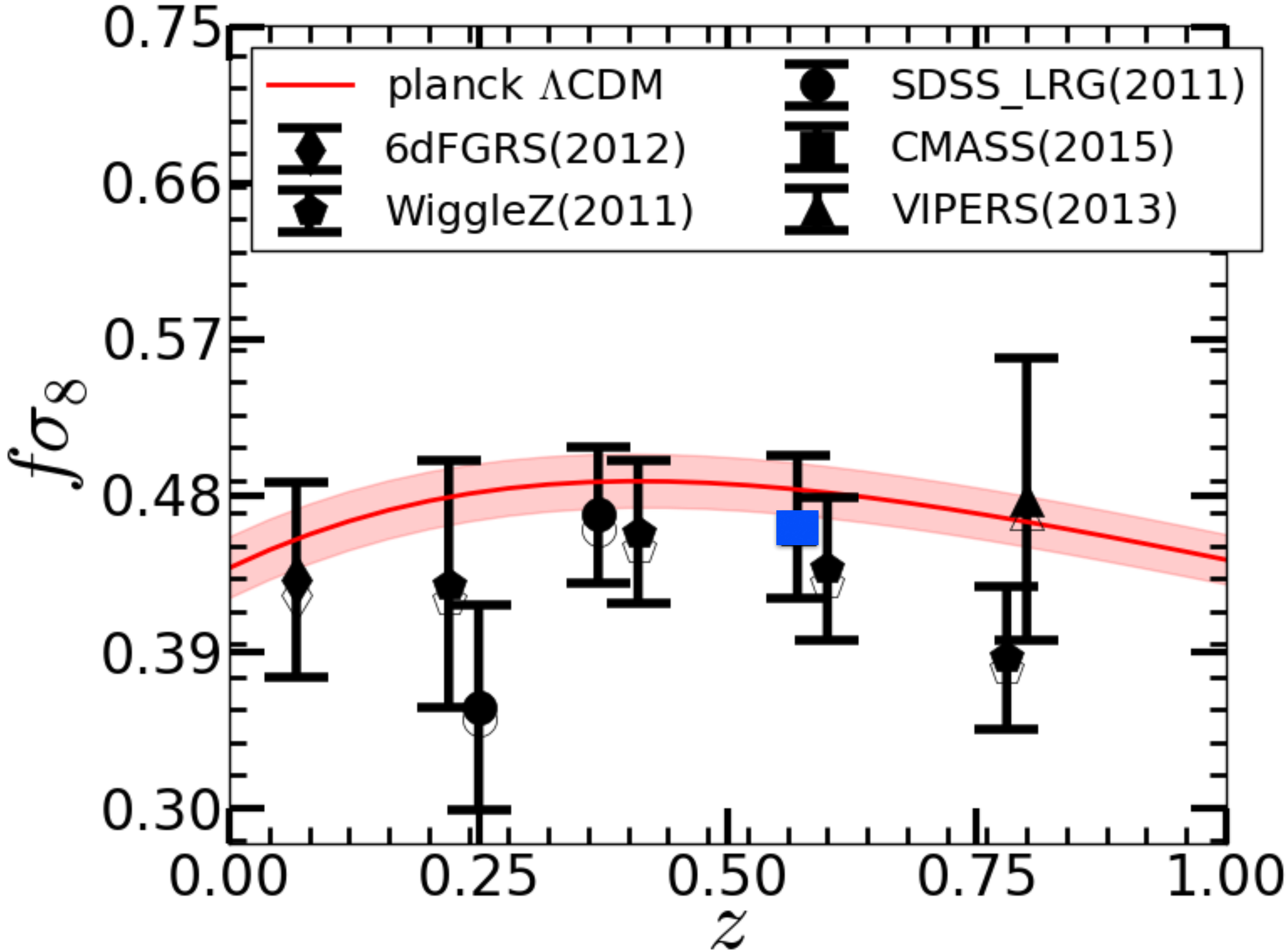
$$f\sigma_8(z=0.57) = 0.462 \pm 0.041$$

$$b\sigma_8(z=0.57) = 1.19 \pm 0.03$$

$$D_A(z=0.57) = 1401 \pm 23$$

$$H(z=0.57) = 89.2 \pm 3.6$$

Growth rate measurements from other surveys



What can we do with these measurements?

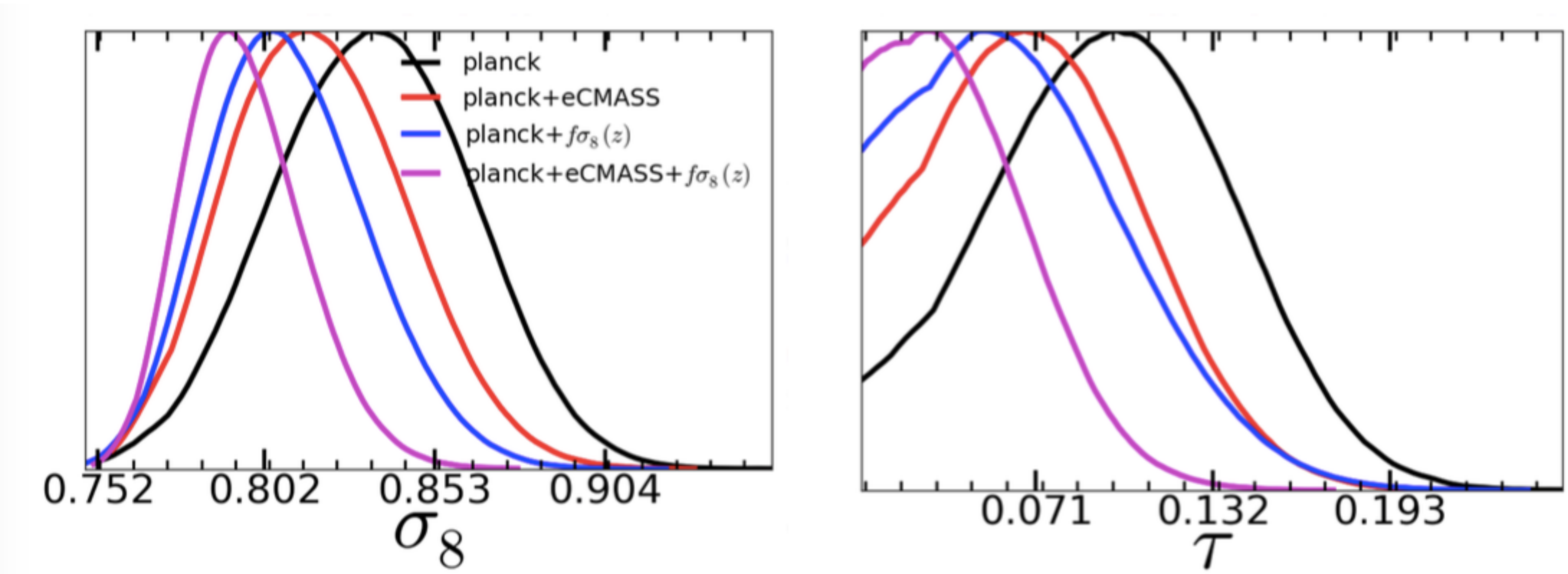
Precision test to some of the basic assumptions of ΛCDM and GR

Constrain the modified gravity parameters to unprecedented precision.

Steps towards understanding the big questions of dark matter and dark energy.

(Alam et. al. (2015) http://arxiv.org/abs/1509.05034)

ΛCDM is an excellent fit



A Strong upper limit on optical depth which indirectly constrain the redshift of reionization.

Dark Energy
(Some stuff causing acceleration)

“ ‘Most embarrassing observation in physics’ – that’s the only quick thing I can say about dark energy that’s also true.”

Edward Witten

“*The reason for the embarrassment was simply that any reasonable calculation of quantum zero-point energy gives an answer that is too big by orders of magnitude – by a lot of orders of magnitude.*”

Views on Dark Energy by Edward Witten

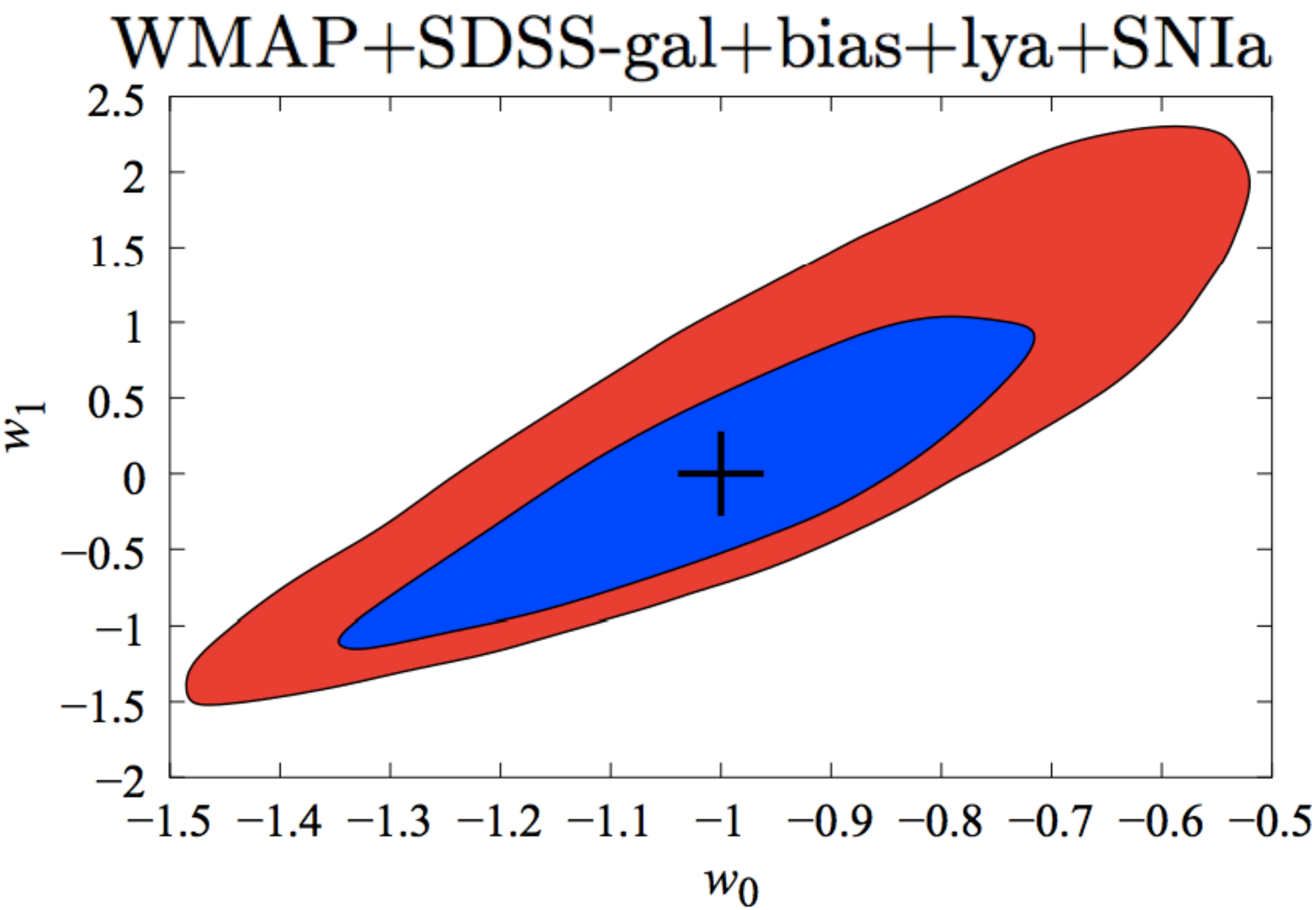
May 2008, STScI

He explained that the true nature of dark energy could reveal if our universe has unique laws of nature (a new particle/field) or just one of the infinite possibilities (multiverse, string theory).

Dark Energy

Chevallier-Polarski-Linder (CPL) Parametrization:

$$w(z) = w_0 + w_a(1 - a)$$



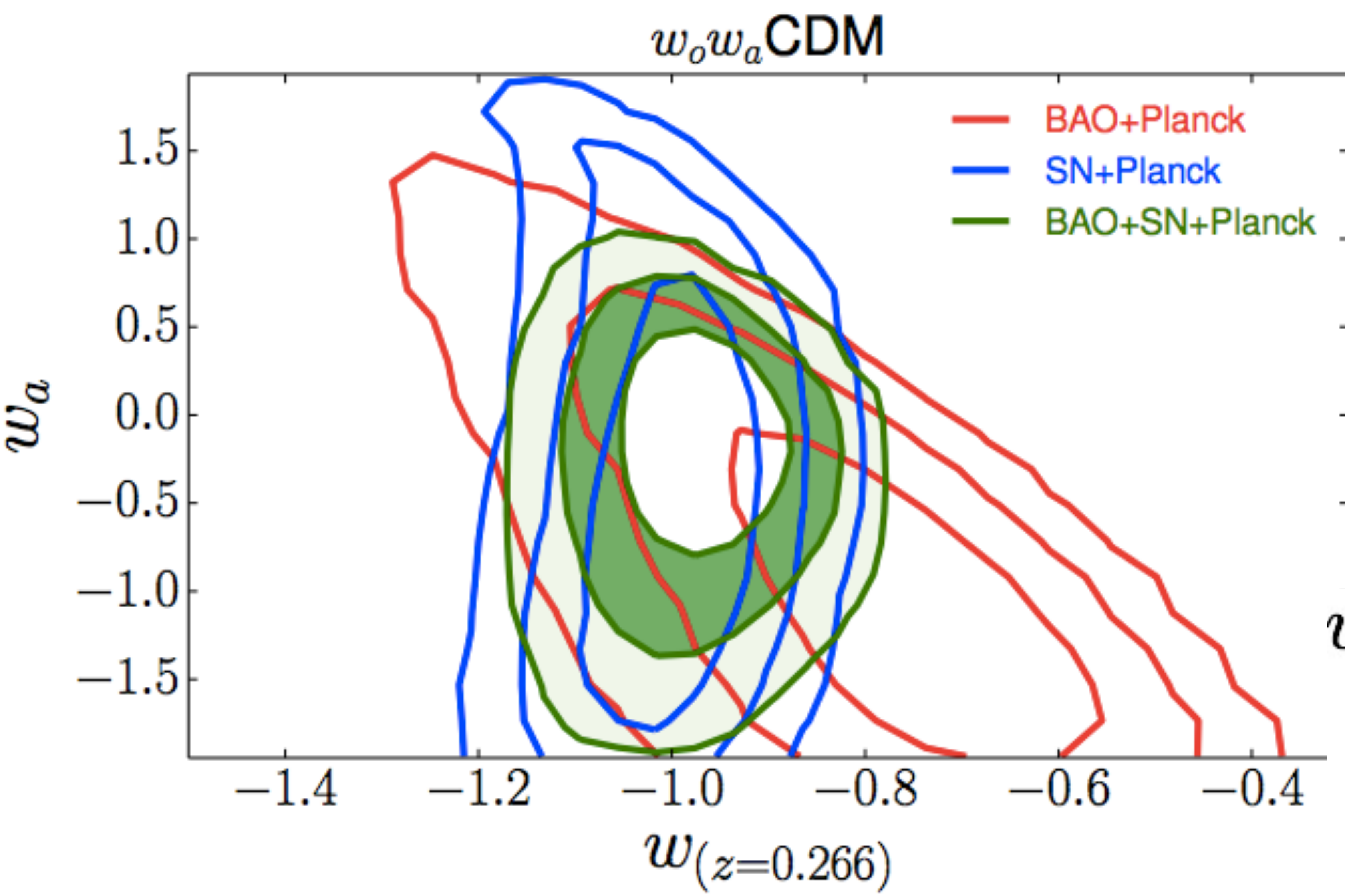
Seljak et. al. (2004)

$$w_0 = [-0.788, -1.174]$$

$$w_a = [-0.60, 0.88]$$

Dark Energy

(Still an embarrassment)



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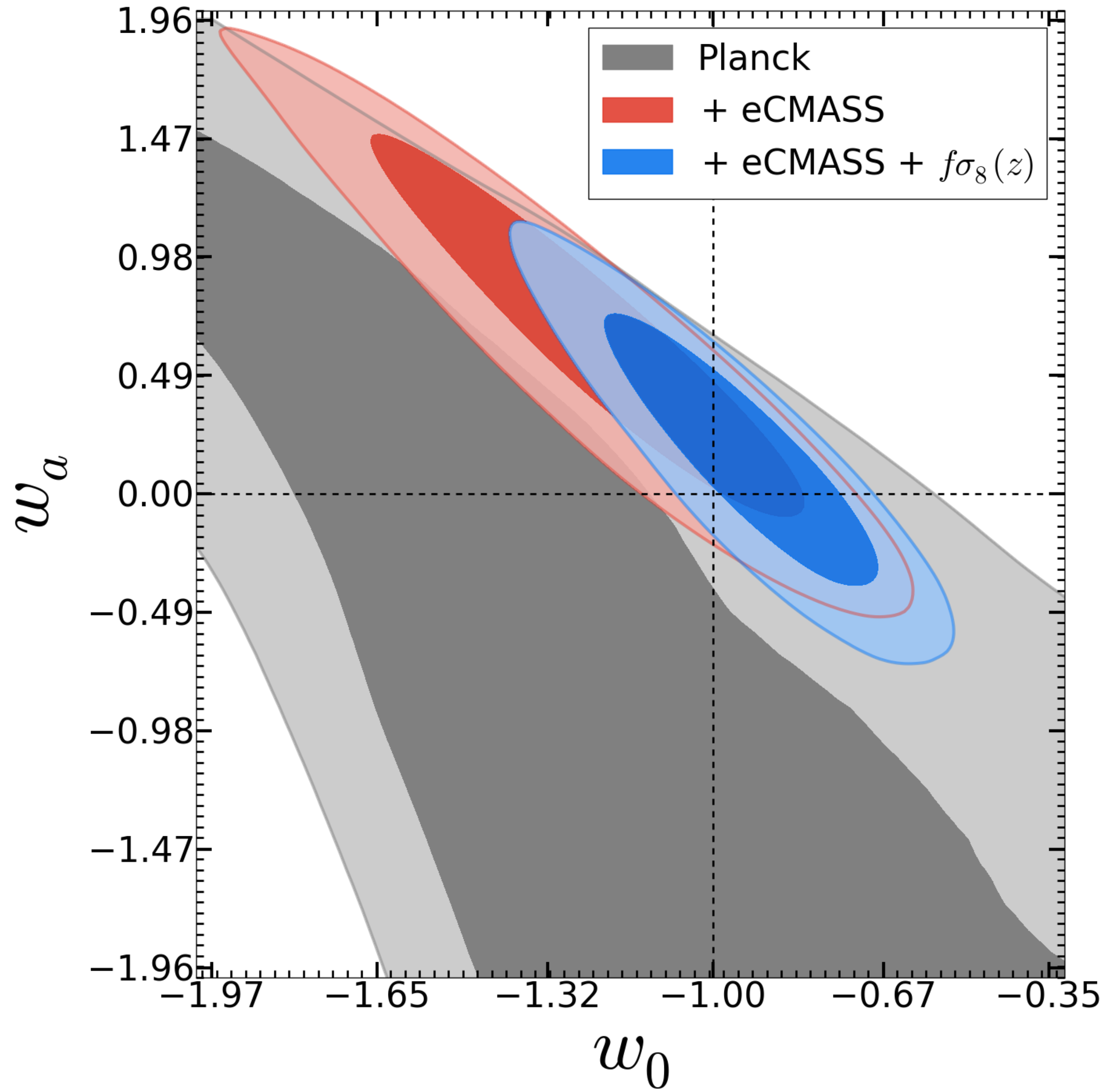
Aubourg et. al. (2014)

$$w(0.266) = [-0.92, -1.02]$$

$$w_a = [-0.60, 0.20]$$

Dark Energy

(Still an embarrassment)



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$$w(0.266) = [-0.92, -1.02]$$

$$w_a = [-0.60, 0.20]$$

Alam et. al. (2015)

$$w_0 = [-0.775, -1.11]$$

$$w_a = [-0.2, 0.52]$$

What does Growth rate says about modified gravity

(A lot!!)

Extended Chameleon gravity

$$\beta_1 = 1 + \frac{1}{2}\left(\frac{d\alpha}{d\phi}\right)^2$$

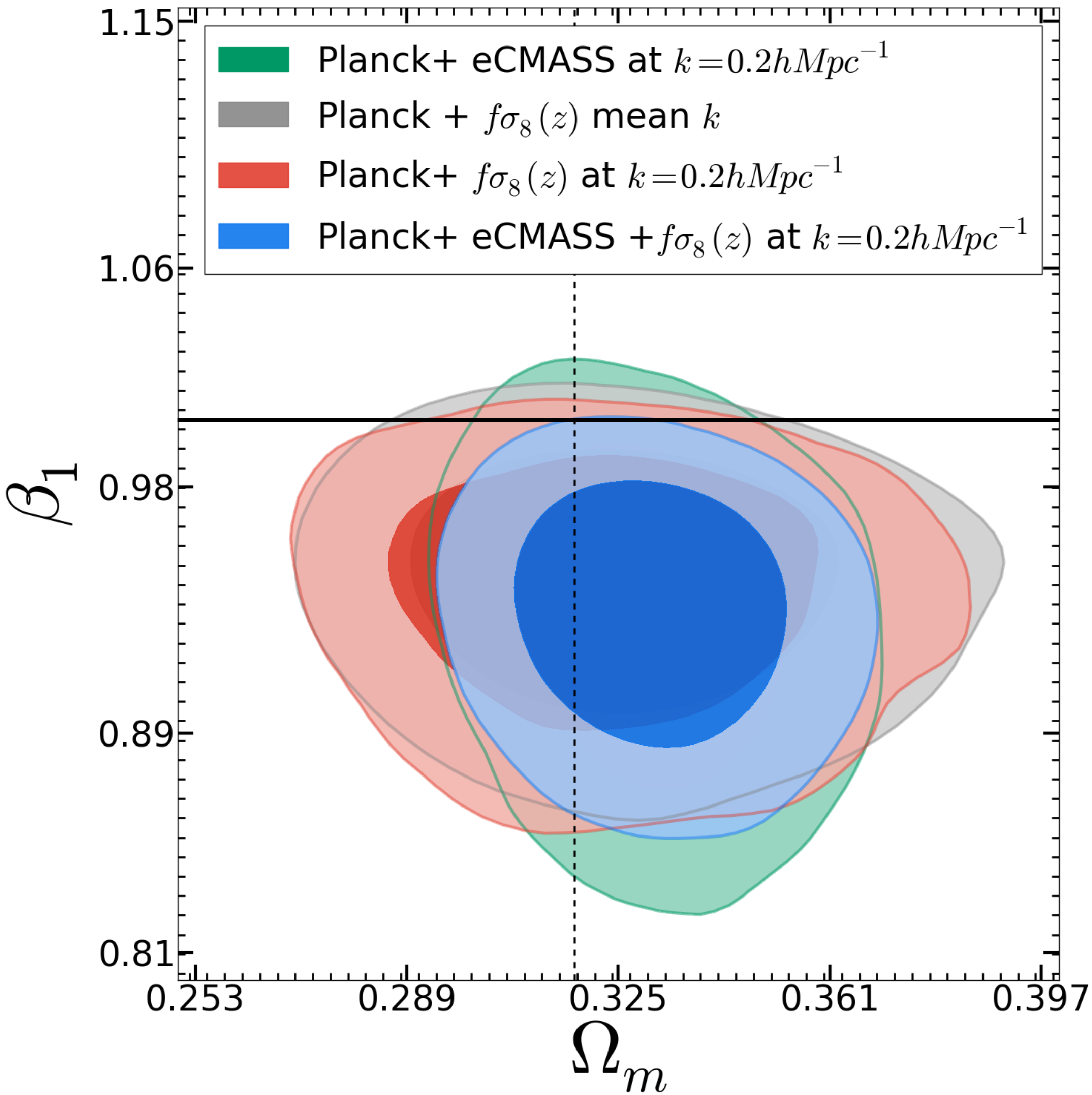
Where $\alpha(\phi)$ is the coupling between scalar field ϕ and matter component.

$\beta_1 = 1$ General Relativity

$\beta_1 > 1$ Chameleon gravity (enhanced growth)

$\beta_1 < 1$ extended Chameleon (Suppressed growth)

eChameleon gravity:
6 times improvement in the precision of coupling



Our result:

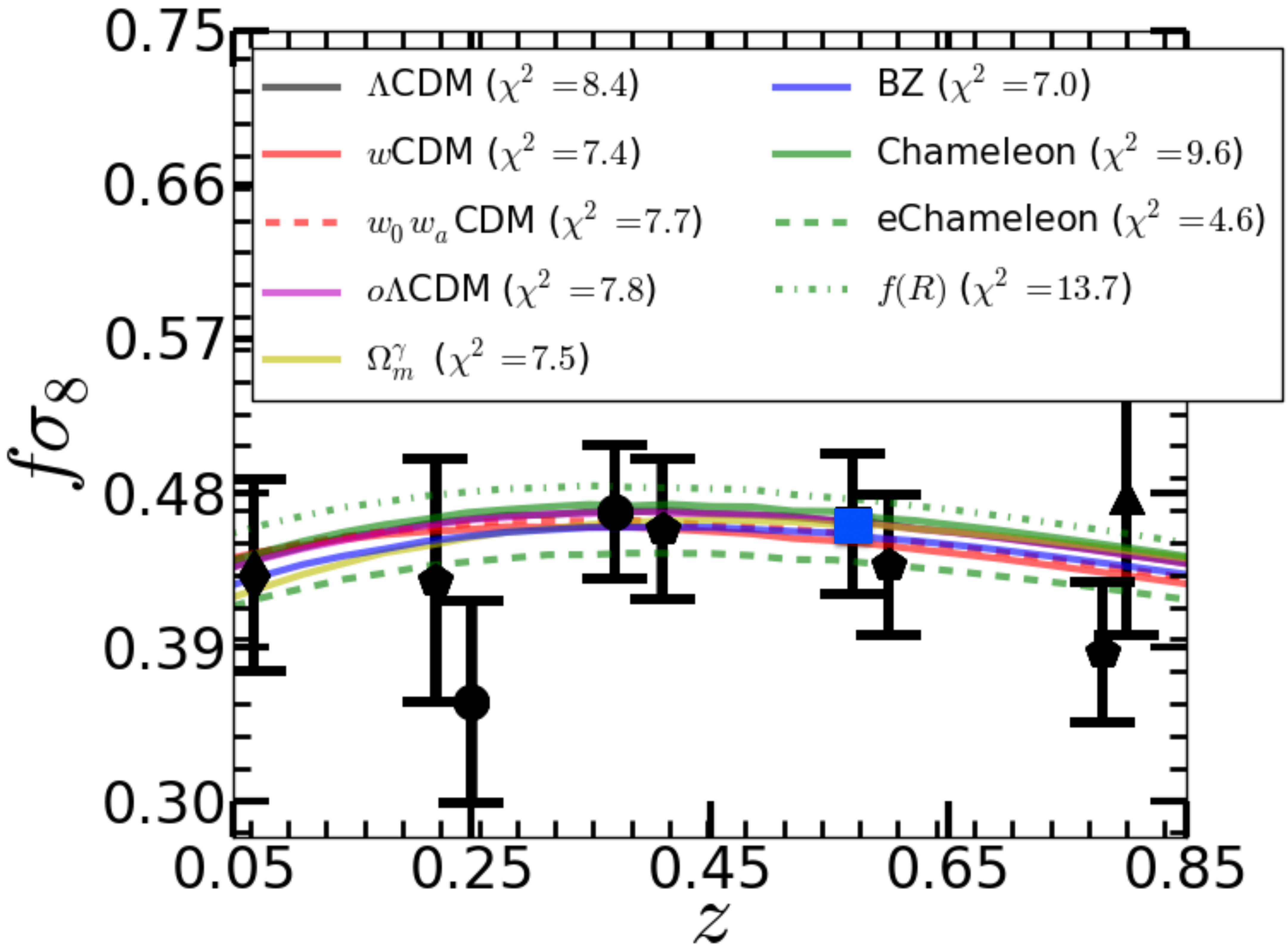
$(\beta_1 = 0.932 \pm 0.031)$

Current best constraint

$\beta_1 = 1.3 \pm 0.25$

Hojjati et. al. 2011

Growth rate/RSD is a very powerful tool and has huge potential in current and future surveys.



Growth rate/RSD is a very powerful tool and has huge potential in current and future surveys.

Gravitational interaction between matter.

Gravitational Lensing:
Deflection of light through gravitational potential

Gravitational interaction between light and matter.

Unique observable: Combination of lensing and redshift space clustering

(Even more powerful than RSD)

Combining Gravitational lensing and redshift space clustering

Theoretical Estimator [4]

$$E_G = \frac{\nabla^2(\Psi(r) - \Phi(r))}{3H_o^2 a^{-1} f\delta}$$

[4] Pengjie Zhang et. al. (2007) PRL99,141302(2007)

Combining Gravitational lensing and redshift space clustering

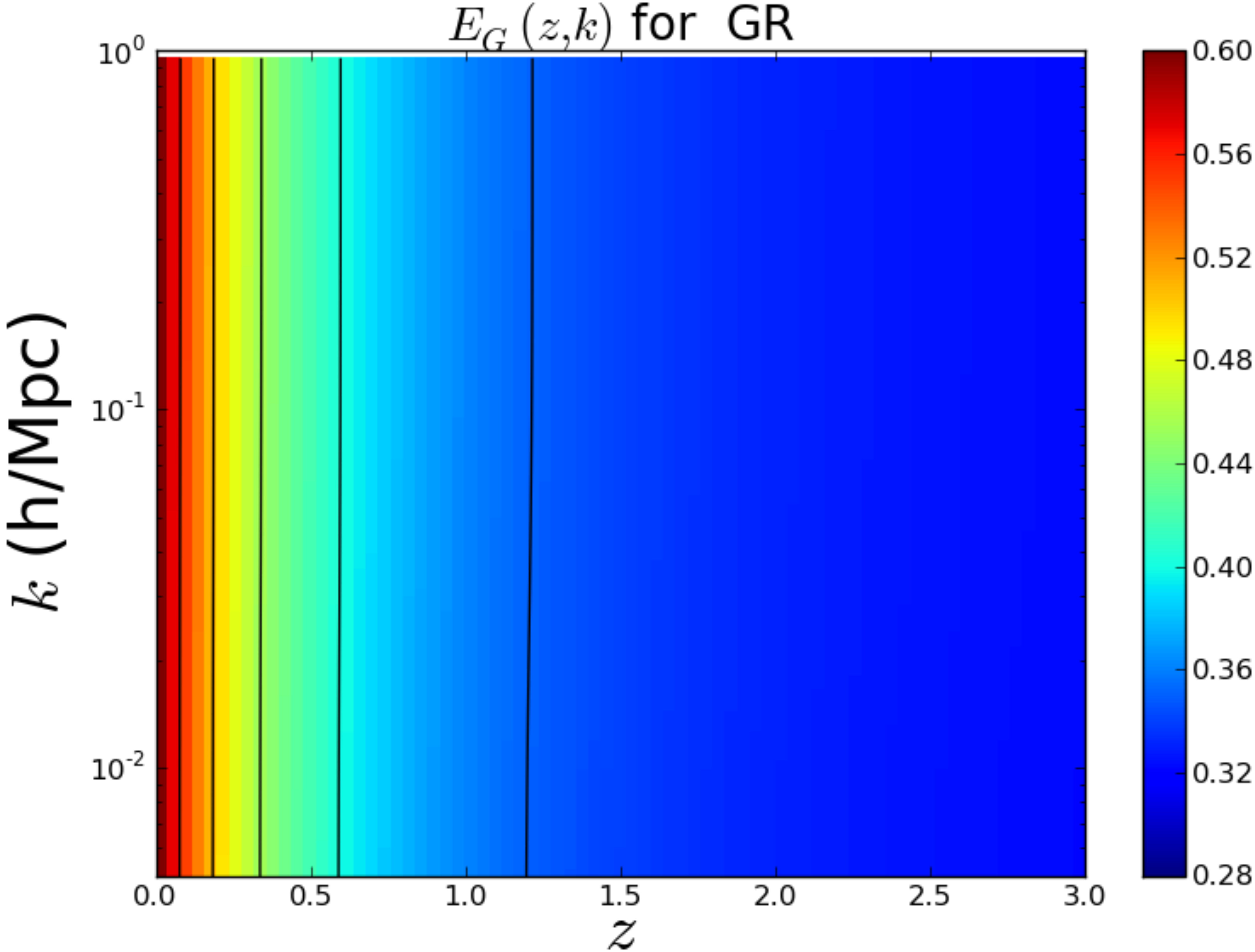
Theoretical Estimator [4]

$$E_G = \frac{\nabla^2(\Psi(r) - \Phi(r))}{3H_o^2 a^{-1} f\delta}$$

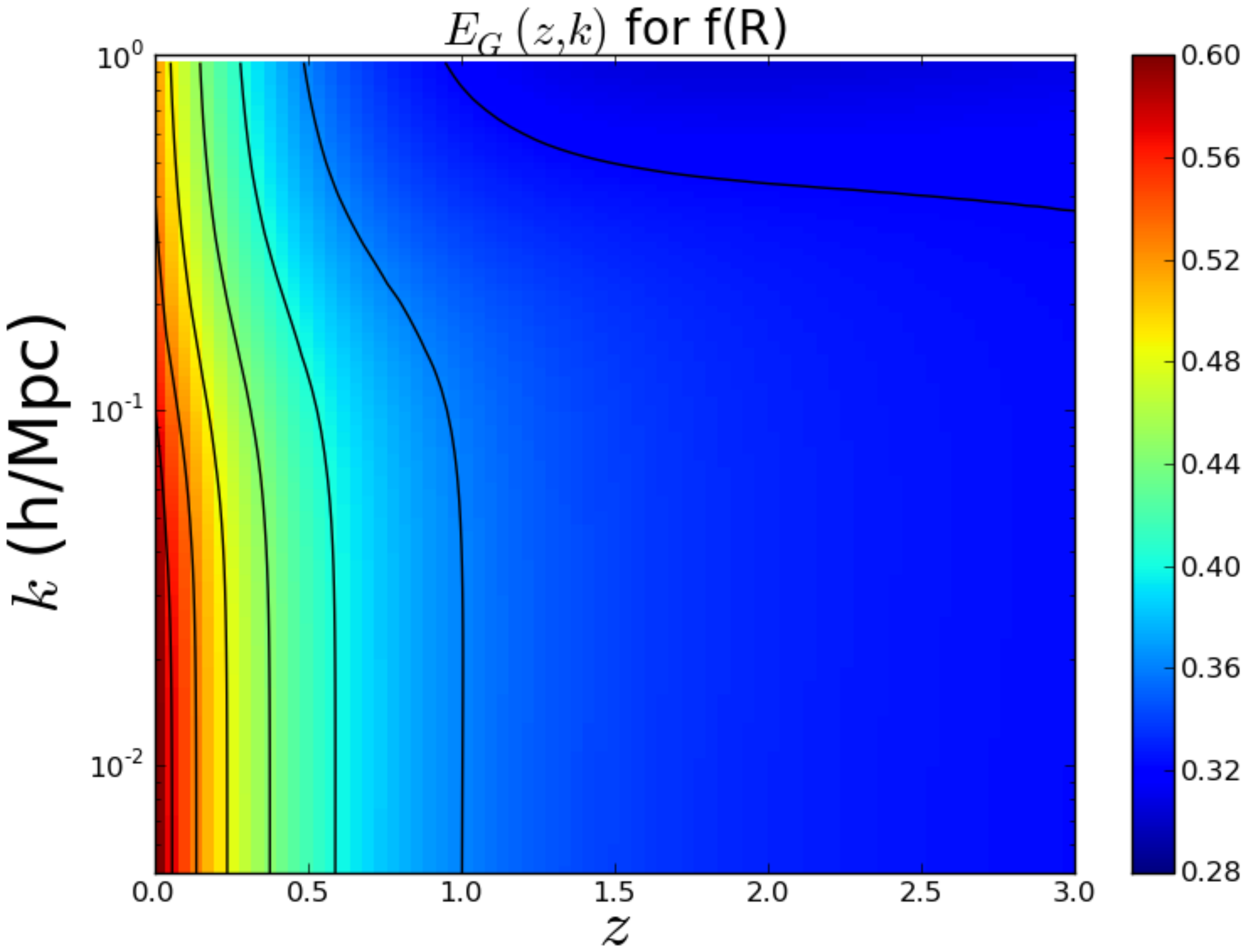
General Relativity $E_G = \frac{\Omega_m(z=0)}{f}$

Modified Gravity $E_G = \frac{\Omega_M(z=0)\mu(k,a)(\gamma(k,a)+1)}{2f}$

[4] Pengjie Zhang et. al. (2007) PRL99, 141302 (2007)



$E_G\,(z{,}k)$ for GR
k (h/Mpc)
10^0
10^{-1}
10^{-2}
0.0
0.5
1.0
1.5
2.0
2.5
3.0
z
0.60
0.56
0.52
0.48
0.44
0.40
0.36
0.32
0.28



$E_G\,(z,k)$ for f(R)
10^0
10^{-1}
10^{-2}
k (h/Mpc)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
z
0.60
0.56
0.52
0.48
0.44
0.40
0.36
0.32
0.28

How Do we Measure it?

Old way to measure E_G : Combining galaxy clustering and galaxy-galaxy lensing

$$E_G(r_p) = \frac{\Upsilon_{gm}(r_p)}{\beta \Upsilon_{gg}(r_p)}$$

Reyes et. al. (2010) http://arxiv.org/abs/1003.2185

Old way to measure E_G : Combining galaxy clustering and galaxy-galaxy lensing

$$E_G(r_p) = \frac{\Upsilon_{gm}(r_p)}{\beta \Upsilon_{gg}(r_p)}$$

$$\Upsilon_{gm}(r_p) \equiv \Delta\Sigma_{gm}(r_p) - \left(\frac{R_0}{r_p}\right)^2 \Delta\Sigma_{gm}(R_0)$$

$$= \frac{2}{r_p^2} \int_{R_0}^{r_p} dR' R' \Sigma_{gm}(R') - \Sigma_{gm}(r_p) + \left(\frac{R_0}{r_p}\right)^2 \Sigma_{gm}(R_0)$$

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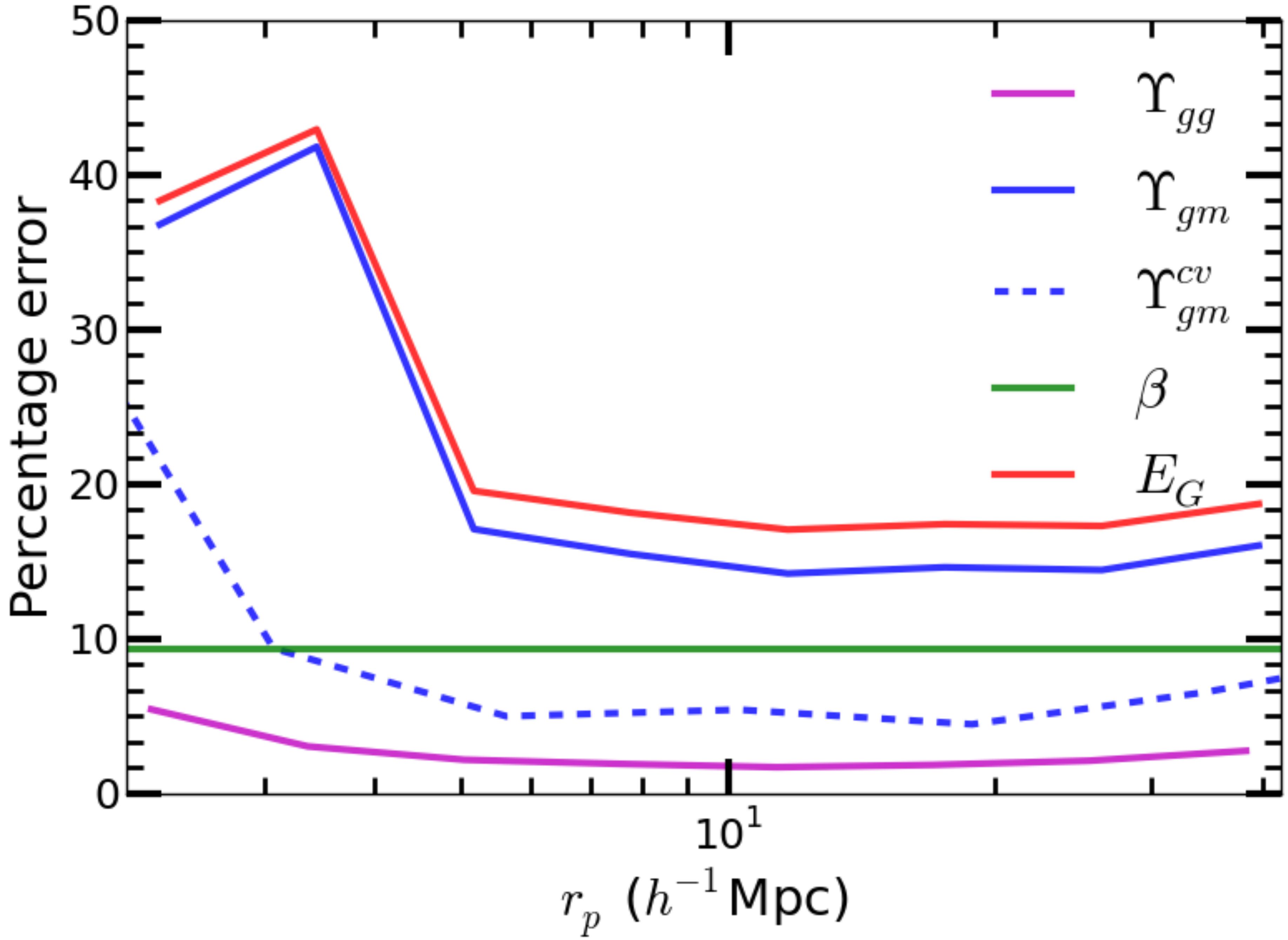
$$\Upsilon_{gg}(r_p) \equiv \rho_{crit} \left[\frac{2}{r_p{}^2} \int_{R_0}^{r_p} dR' R' w_{gg}(R') - w_{gg}(r_p) + \left(\frac{R_0}{r_p}\right)^2 w_{gg}(R_0)\right] ,$$

Reyes et. al. (2010) http://arxiv.org/abs/1003.2185

Measurements of E_G at z=0.57 with galaxy lensing

2 times better measurement

BOSS CMASS DR11 X CFHTLenS



Scale:
5-40 Mpc/h

(By the end of this month: Alam et. al. (2015) on arXiv)

We proposed a new way to measure E_G : Combining galaxy clustering with CMB lensing

$$E_G(\ell) = \Gamma \frac{C_\ell^{\kappa g}}{\beta C_\ell^{gg}} \qquad \Gamma = \frac{2c}{3H_0}\left[\frac{H(z) f_g(z)}{H_0 W(z)(1+z)}\right]$$

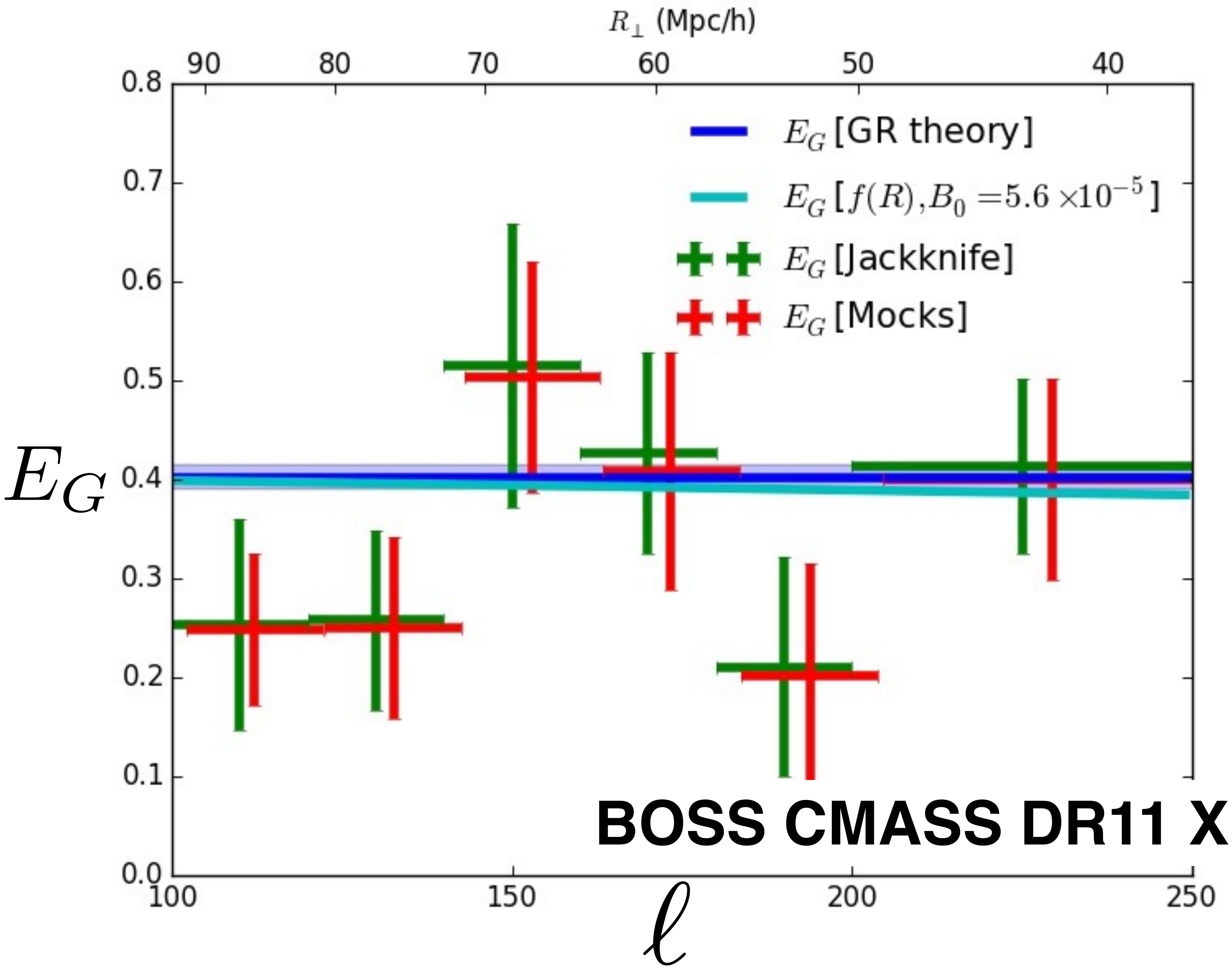
Forecast:

10-15% measurement for CMASS x Planck

2-3% measurement for Euclid x Planck

Pullen et. al. (2015) http://arxiv.org/abs/1412.4454

Measurements of E_G at z=0.57 with CMB lensing
First measurement with CMB lensing



Scale: 40-90 Mpc/h

BOSS CMASS DR11 X Planck Lensing

(Soon on arXiv: Pullen et. al. (2015))

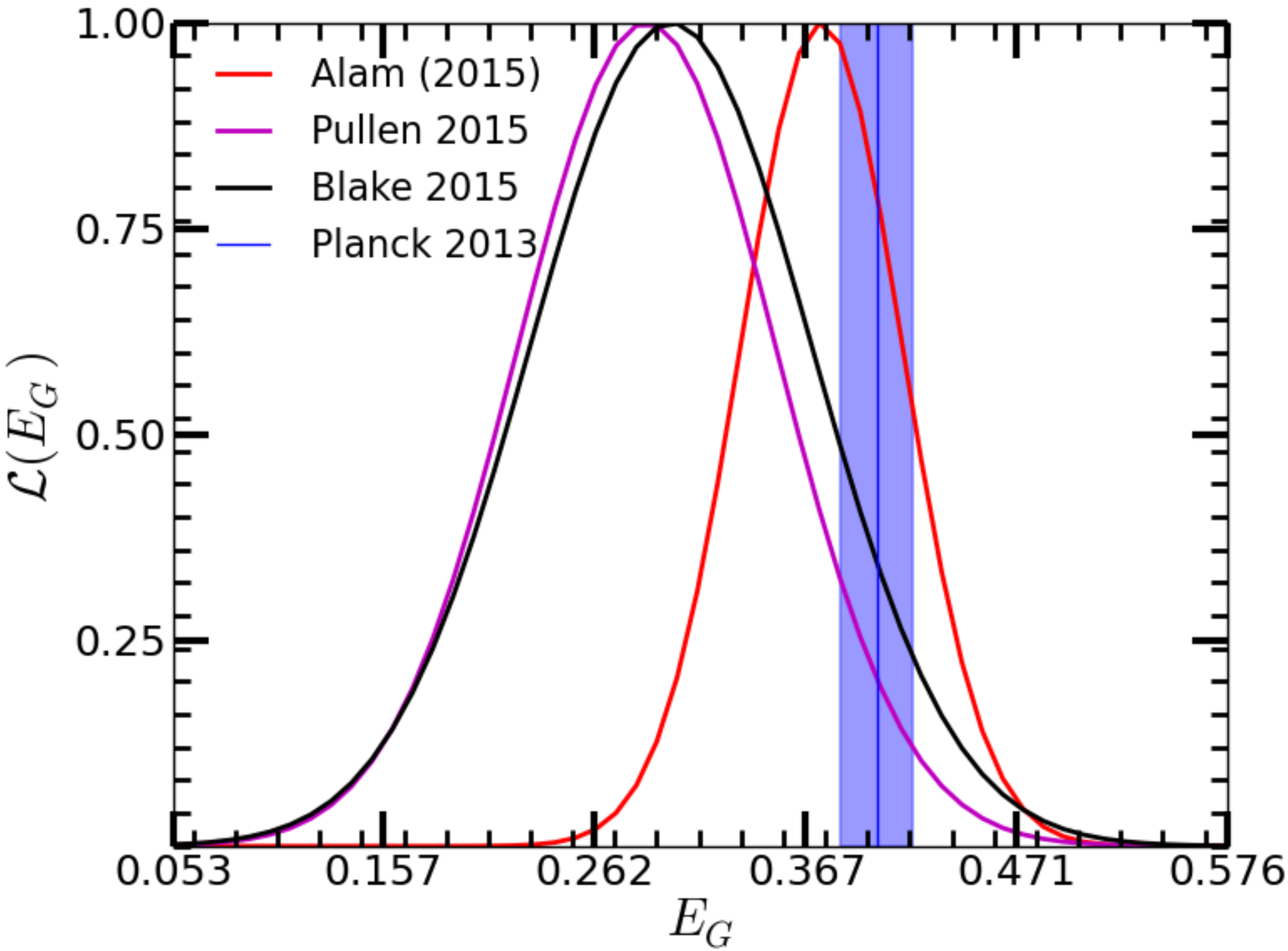
Why E_G is a great tool?

- Independent of bias and σ_8
- Sensitive to modification to gravity
- Test non-trivial relation between lensing and clustering.

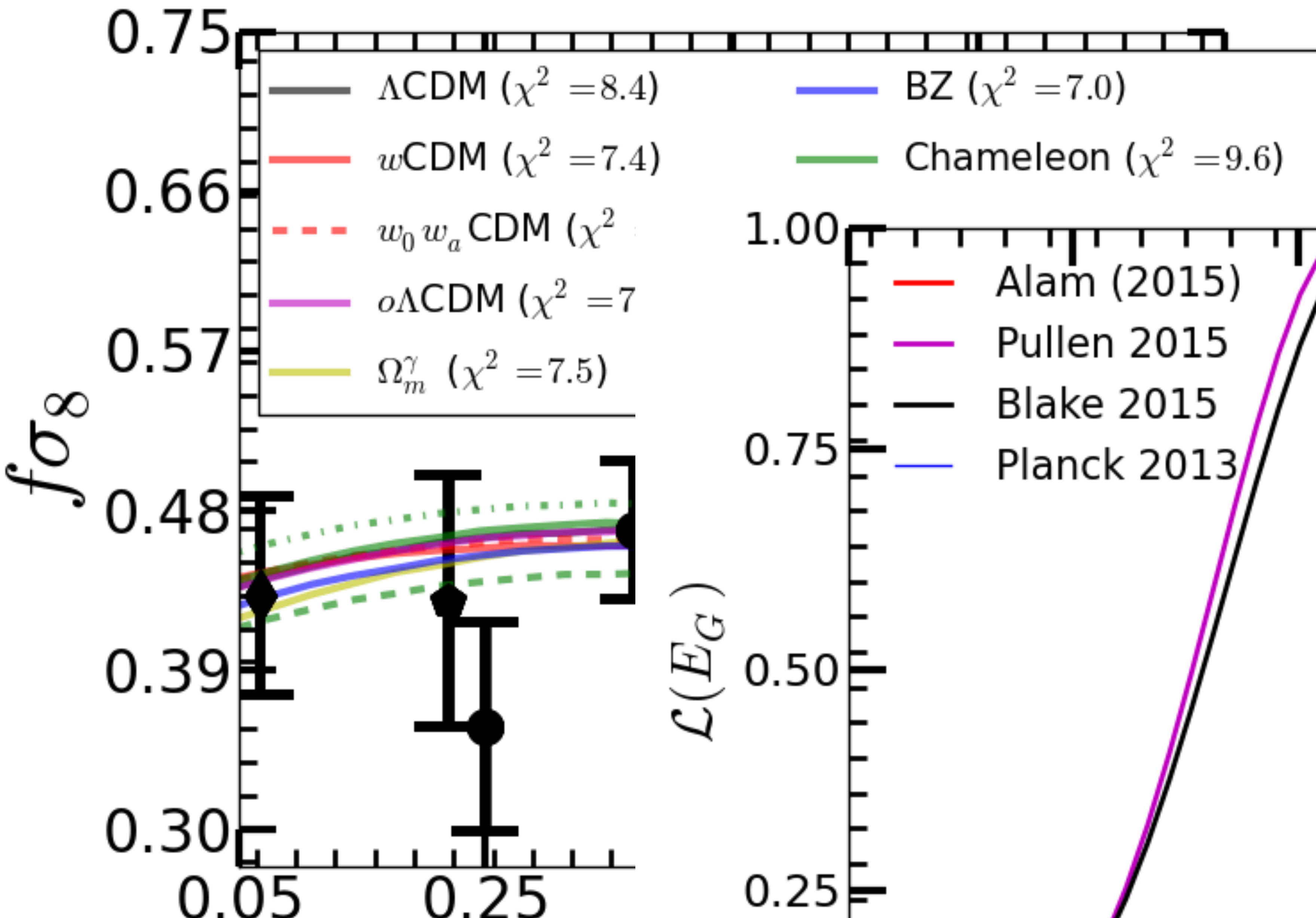
Advantage of using CMB lensing

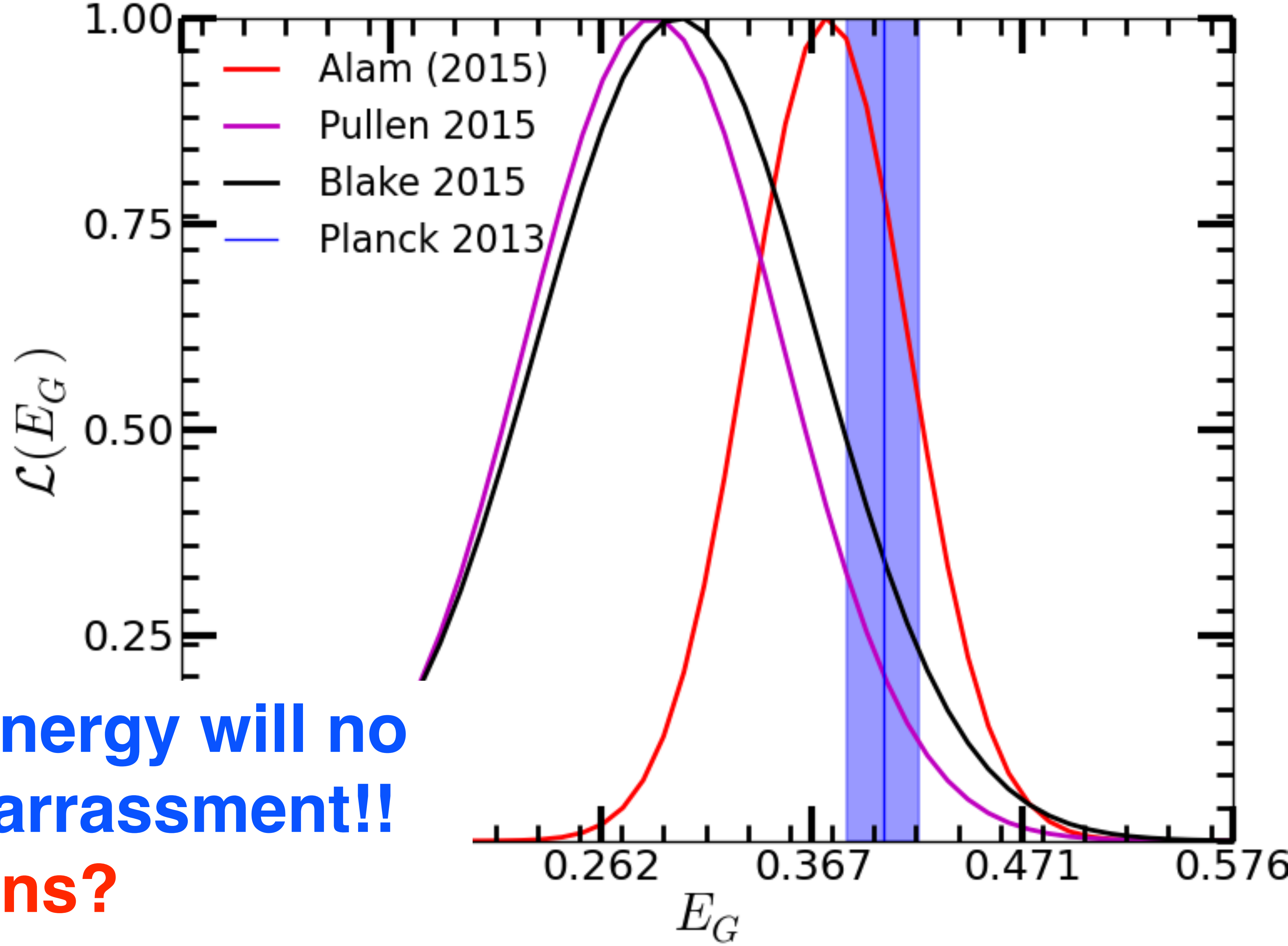
- Free of systematics in galaxy-galaxy lensing
- Can be combined with any LSS survey
- Can measure complimentary scale to galaxy-galaxy lensing

How well did we do with E_G measurement?



RSD and E_G will play an important role in understanding the puzzle of dark matter and dark energy





Hopefully Dark Energy will no more be an embarrassment!!

Questions?

Blank slide

Extra slides

Modified Gravity

(Brief Theory)

General Relativity

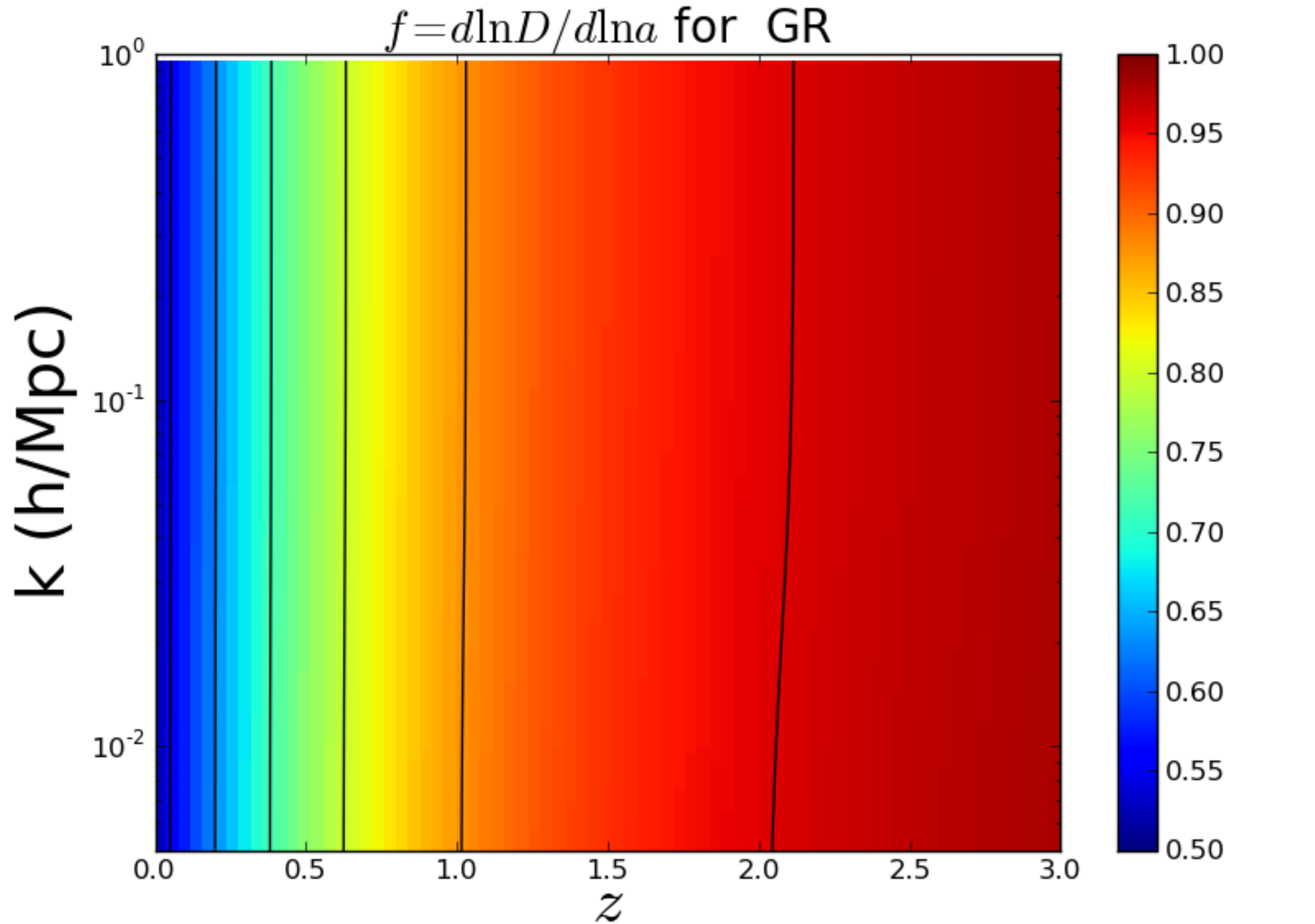
$$S_E = \int d^4x\sqrt{-\tilde{g}}\left[\frac{M_P^2}{2}\tilde{R} - \frac{1}{2}g^{\tilde{\mu}\nu}(\tilde{\nabla}_\mu\phi)\tilde{\nabla}_\nu\phi - V(\phi)\right]$$

FRW Metric:

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

Metric Perturbation

$$k^2\Psi = -\frac{a^2}{2M_P^2} \qquad \rho\Delta \qquad \frac{\Phi}{\Psi} =$$



$f = d\ln D/d\ln a$ for GR
k (h/Mpc)
10^0
10^{-1}
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0.0
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1.0
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0.75
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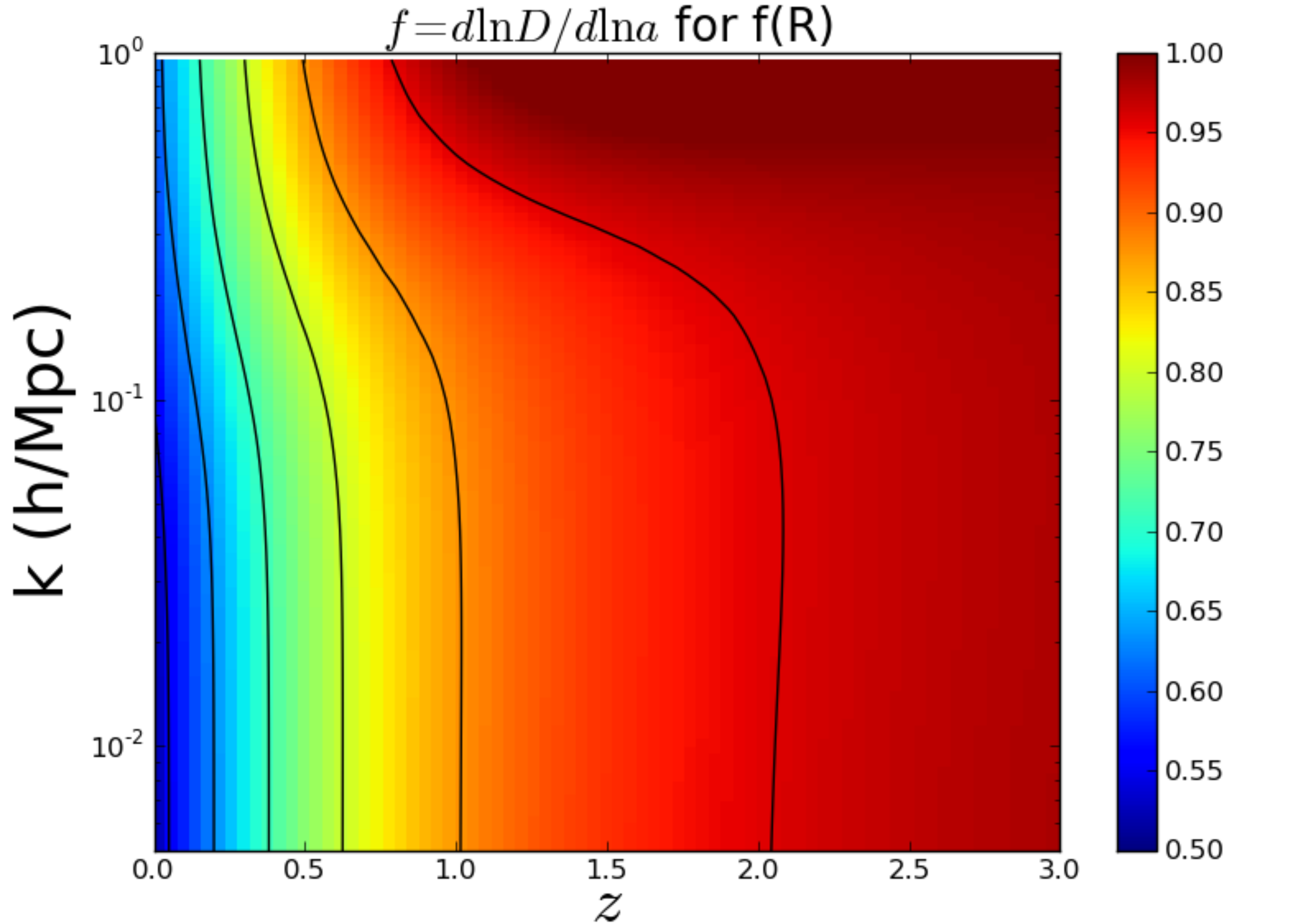
0.65
0.60
0.55
0.50



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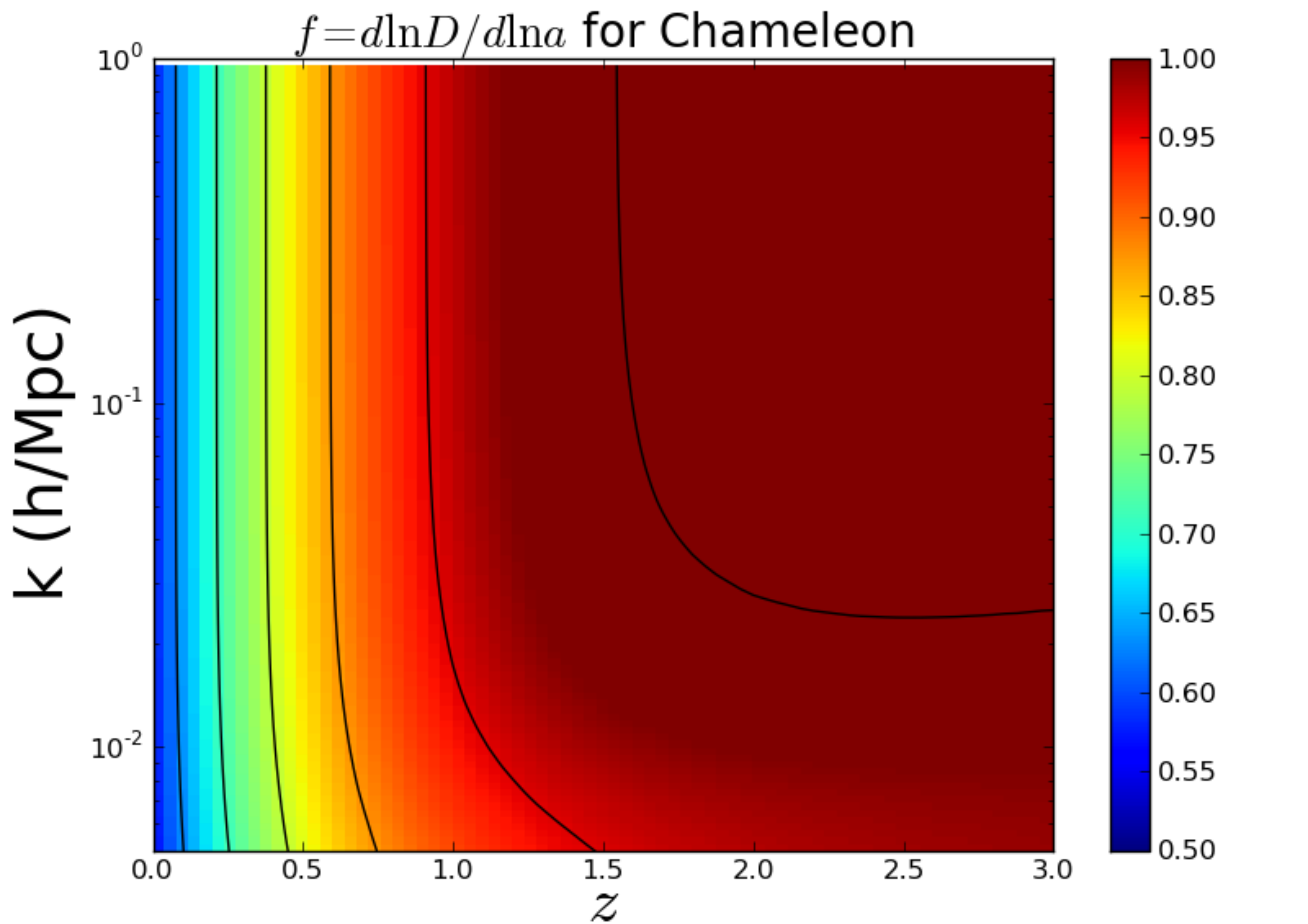
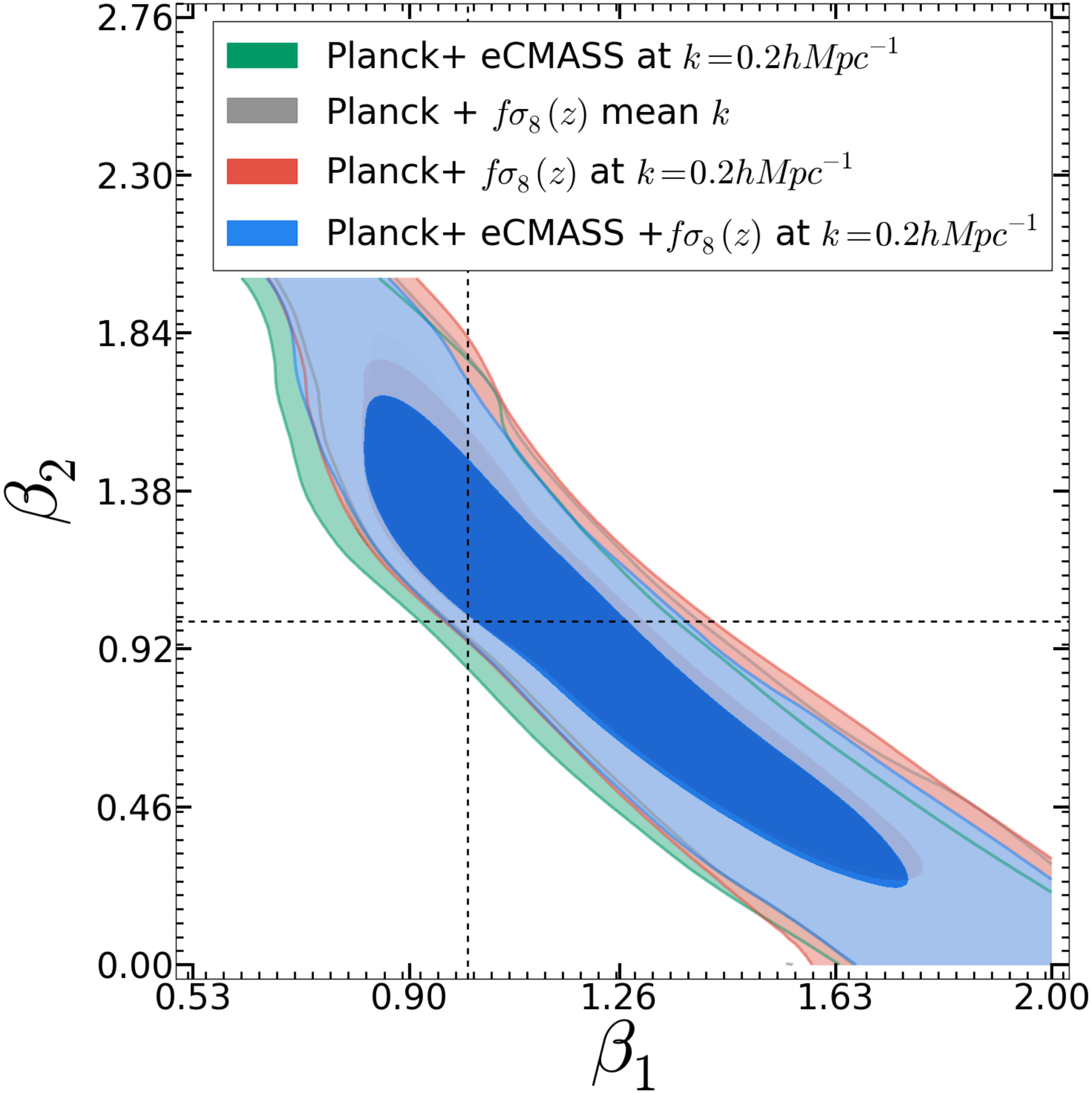


$f = d\ln D/d\ln a$ for Chameleon
k (h/Mpc)
10^0
10^{-1}
10^{-2}
0.0
0.5
1.0
1.5
2.0
2.5
3.0
z
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50

General scalar-tensor gravity :
First constraint on coupling

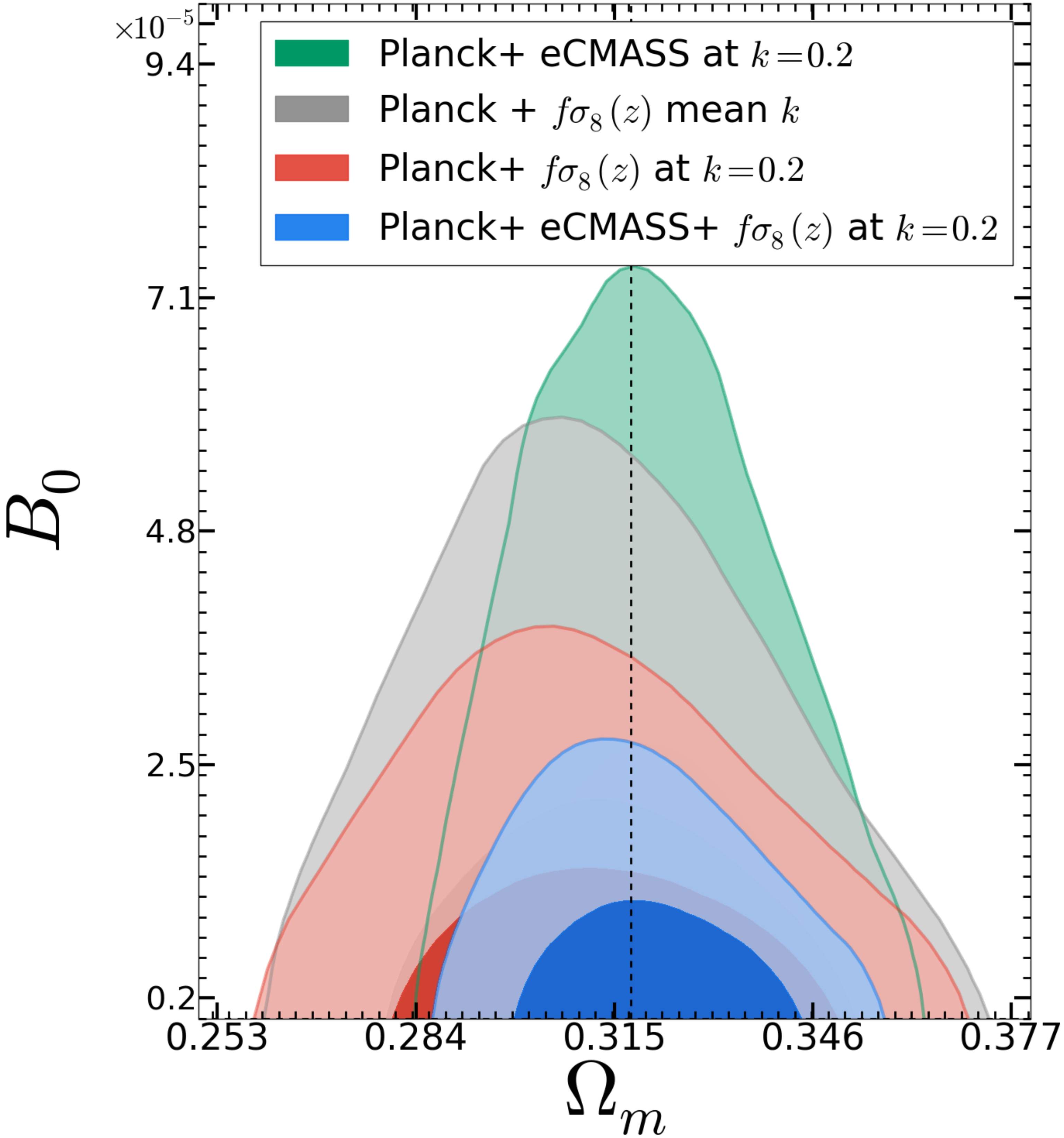


Our result:

$\beta_1 = 1.23 \pm 0.29,$
$\beta_2 = 0.93 \pm 0.44$

No previous constraint

f(R) gravity:
4 times better constraint



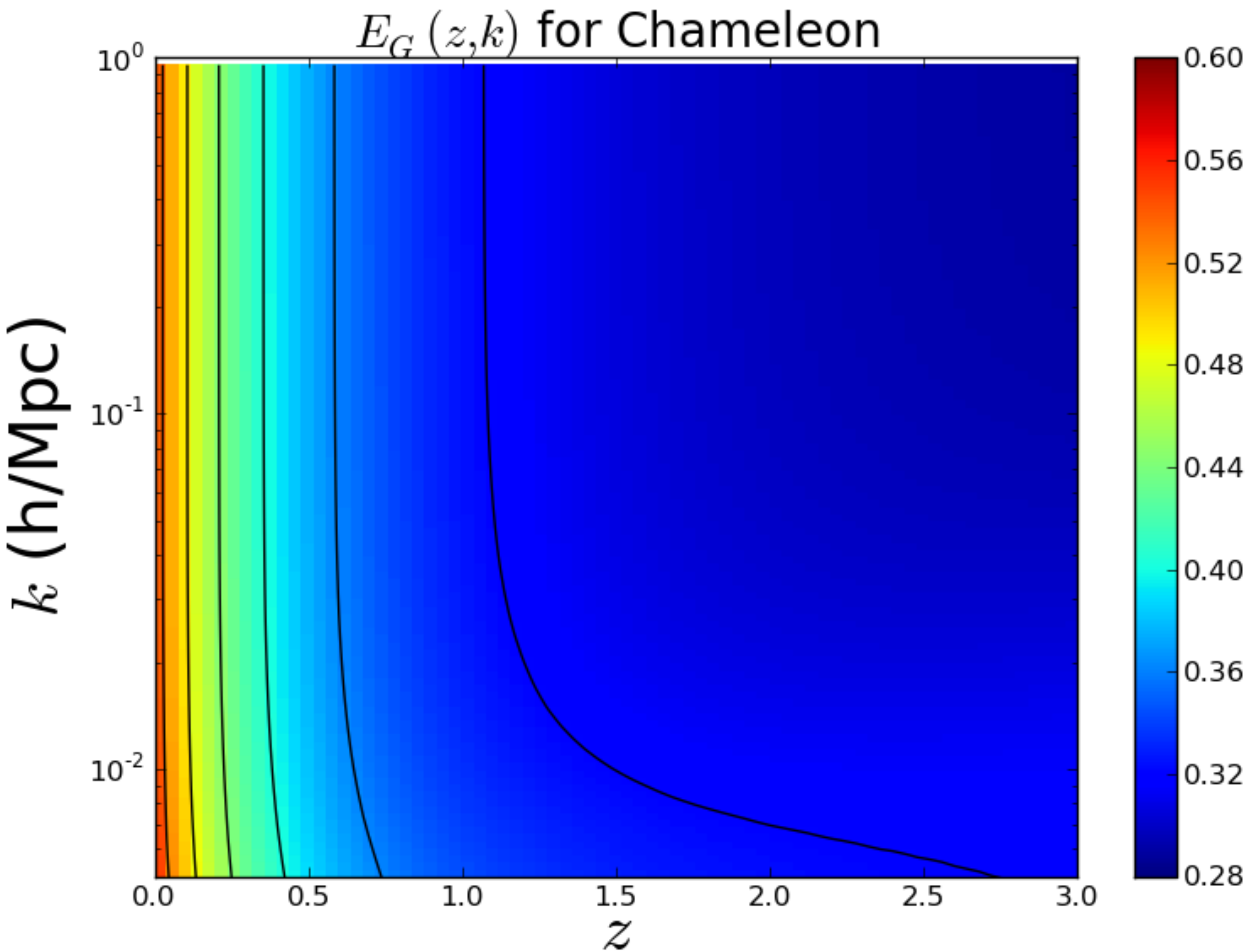
Our result:

$(B_0 < 1.36 \times 10^{-5})$

Current best constraint

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

Xu et. al. 2014



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