6-7 Feb. 2014
APC-YITP collaboration:
mini-workshop on gravitation and cosmology
@YITP

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

Large-scale structure & precision cosmology

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Contents

Overview of recent cosmological results from SDSS-III BOSS & one step beyond consistency test of gravity

- BAO & RSD as new cosmological probes
- BOSS DR10/11 results
- Beyond consistency test of GR
- Summary

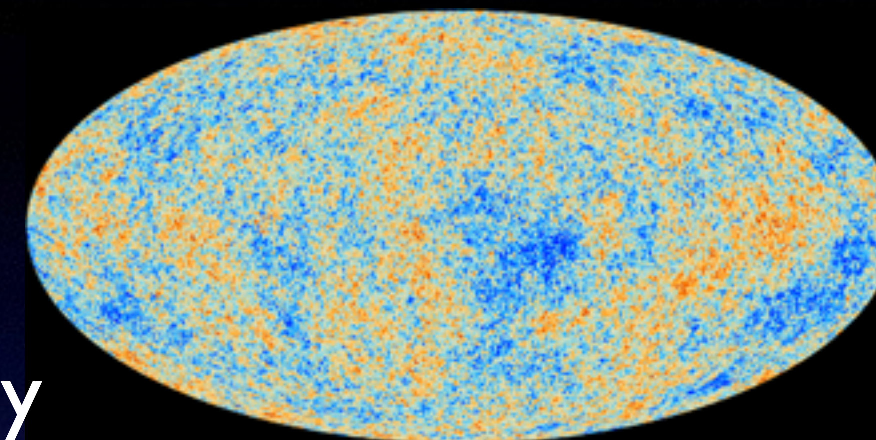
Based on

AT, Koyama, Hiramatsu & Oka, arXiv:1309.6783

Oka, Hiramatsu Koyama, Nishimichi, AT & Yamamoto (in prep.)

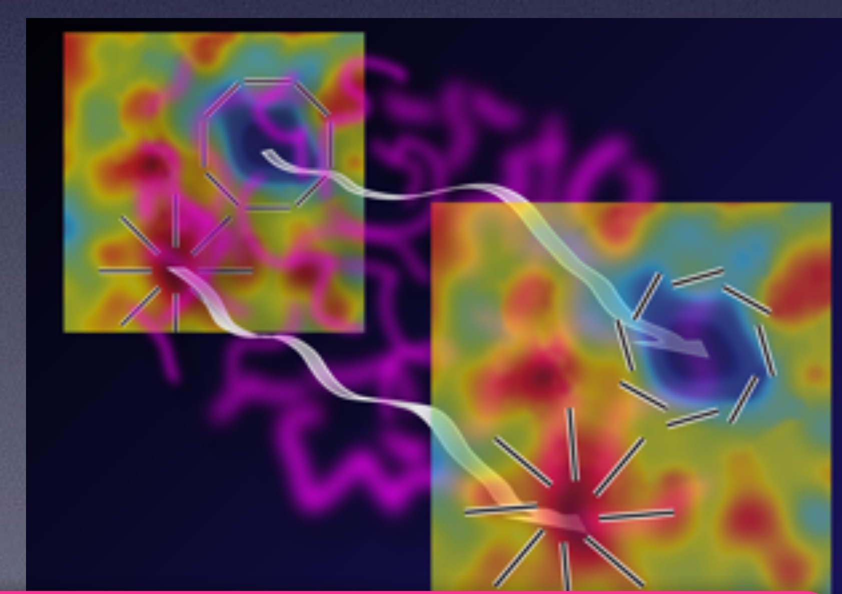
Hightlight over the past year

PLANCK science results



precision cosmological parameters
as basis of precision cosmology

First detection of lensing-induced B-mode



new large-scale structure probe as a byproduct of search for primordial GWs

http://physics.aps.org/articles/v6/107

SDSS-III BOSS DR10/11 science results

Latest results from galaxy redshift survey

Galaxy redshift surveys

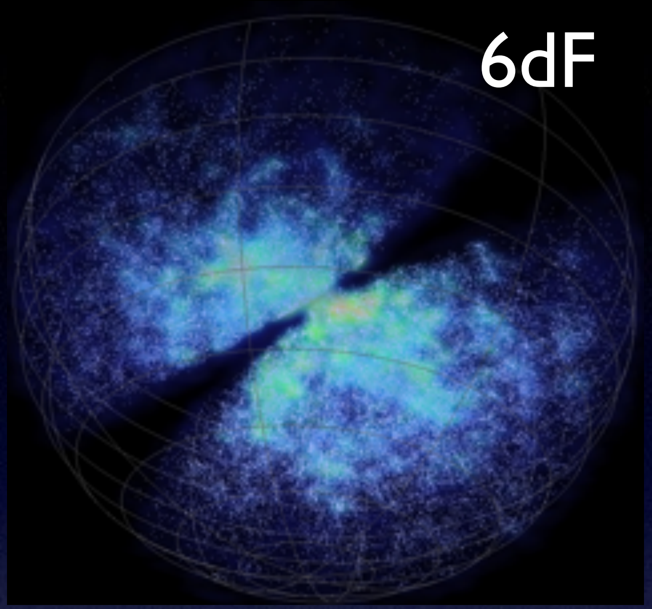
- Traditional large-scale structure probe
  with 3D galaxy map

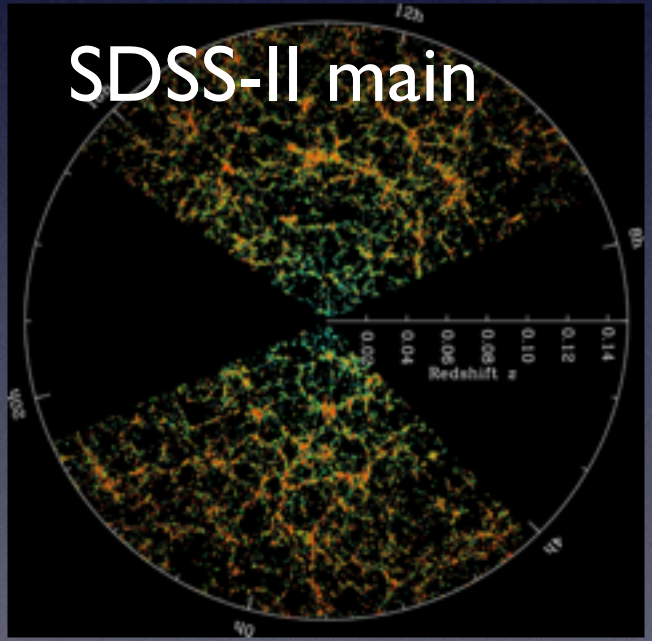
- Useful to pin down late-time universe (z<1-2)
  - ✓Late-time cosmic acceleration
  - ✓Scrutinize the Planck cosmology results

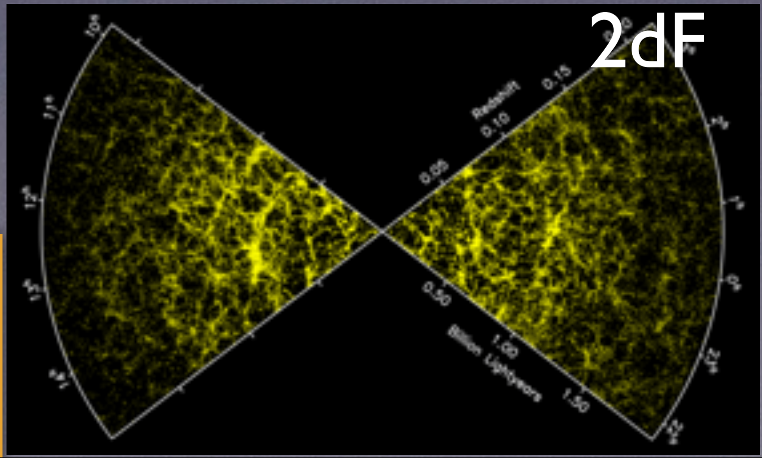
- Upcoming projects

  BigBOSS (2015+)   SuMIRe PFS (2015+)

  WFIRST (2023+)   EUCLID (2020+)





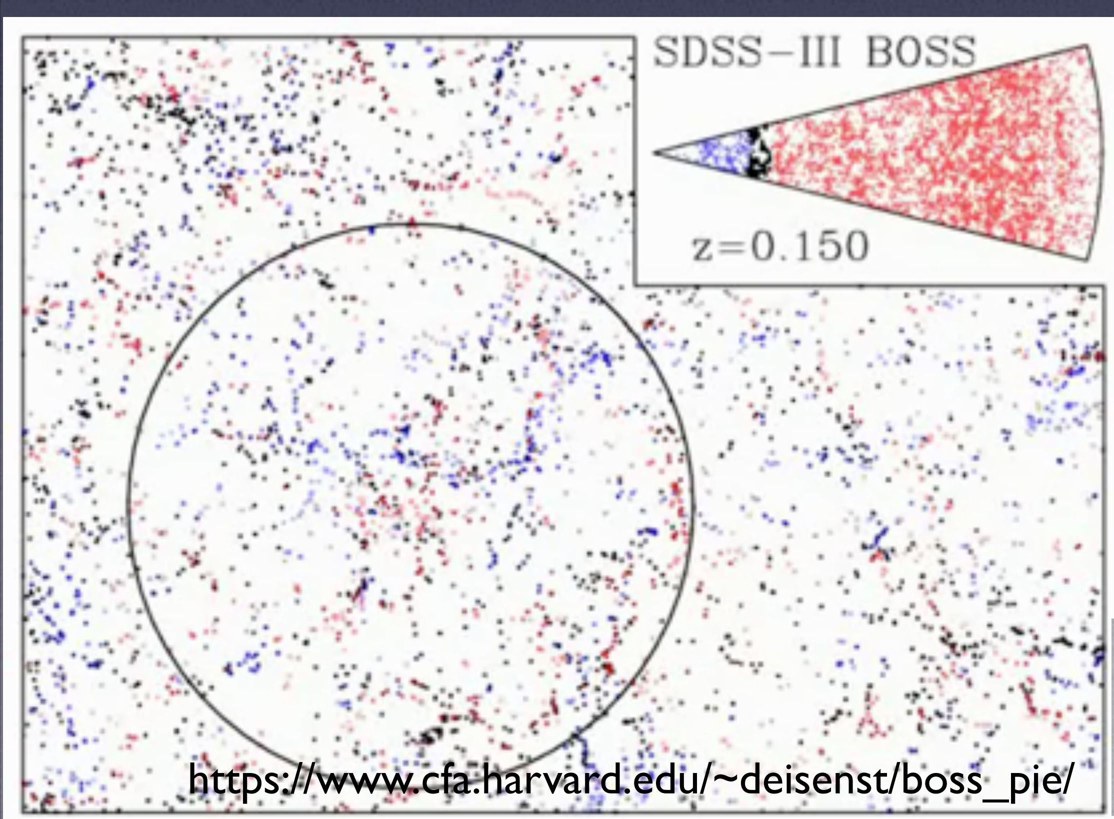


BOSS gives first result of stage-III class survey
(dark energy task force)

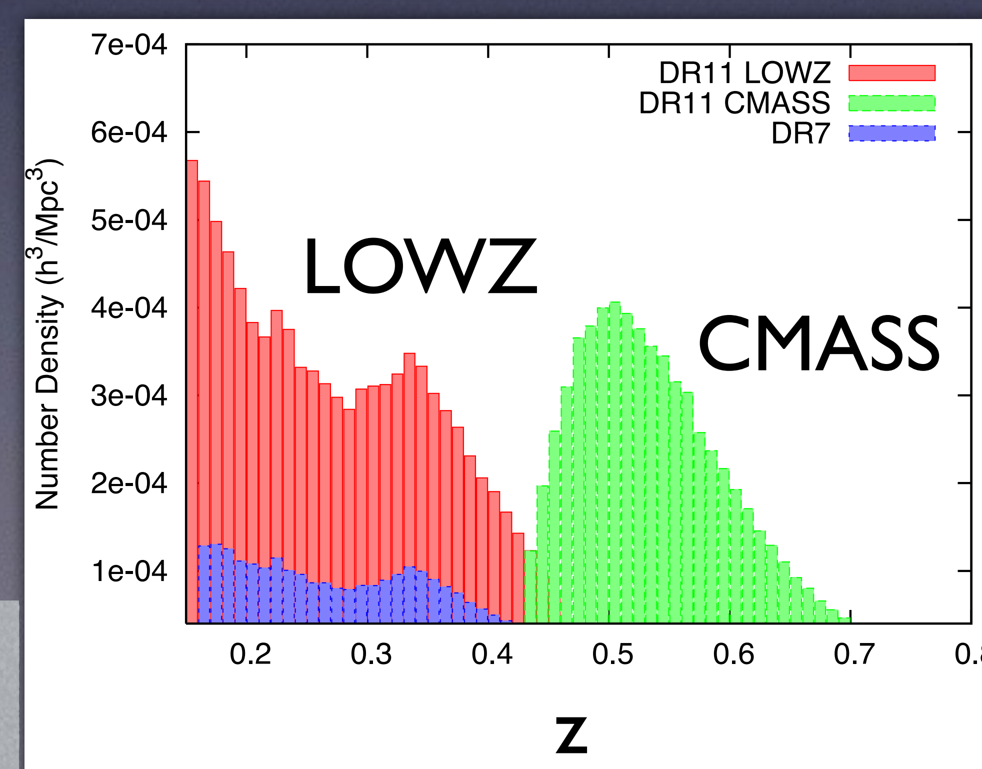
BOSS DR10/11

(Baryon Oscillation Spectroscopic Survey)

- Latest data release of BOSS (a part of SDSS-III)
- CMASS & LOWZ spectroscopic samples :
  - ✓1,000,000 galaxies at 0.2<z<0.7 over 8,400deg^2
  - ✓3D galaxy map with *effective* volume ~ 8.4 Gpc^3 !!



Black circle =150Mpc comoving radius



BOSS DR10/11

(**B**aryon **O**scillation **S**pectroscopic **S**urvey)

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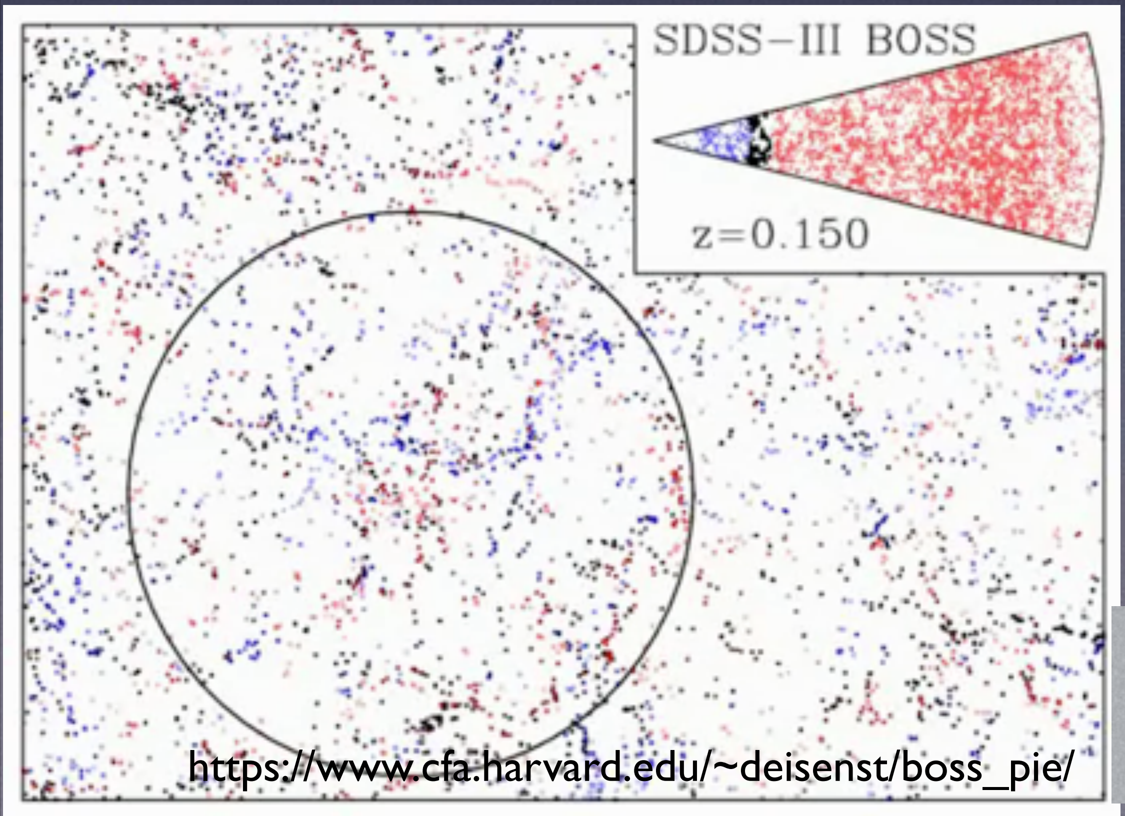
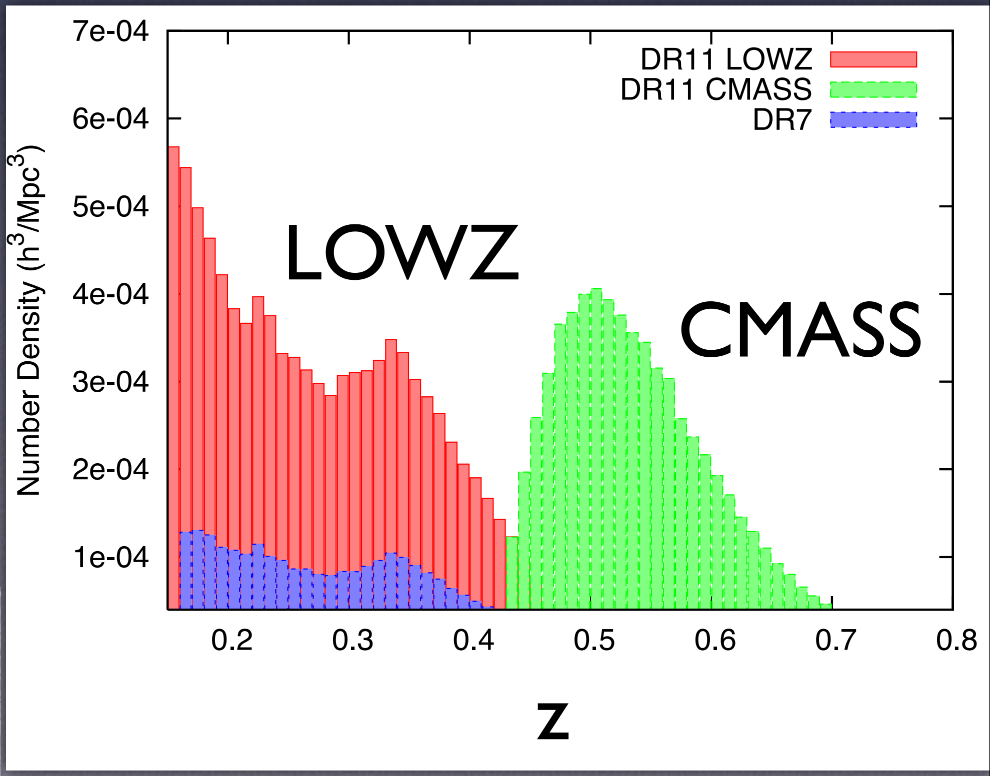


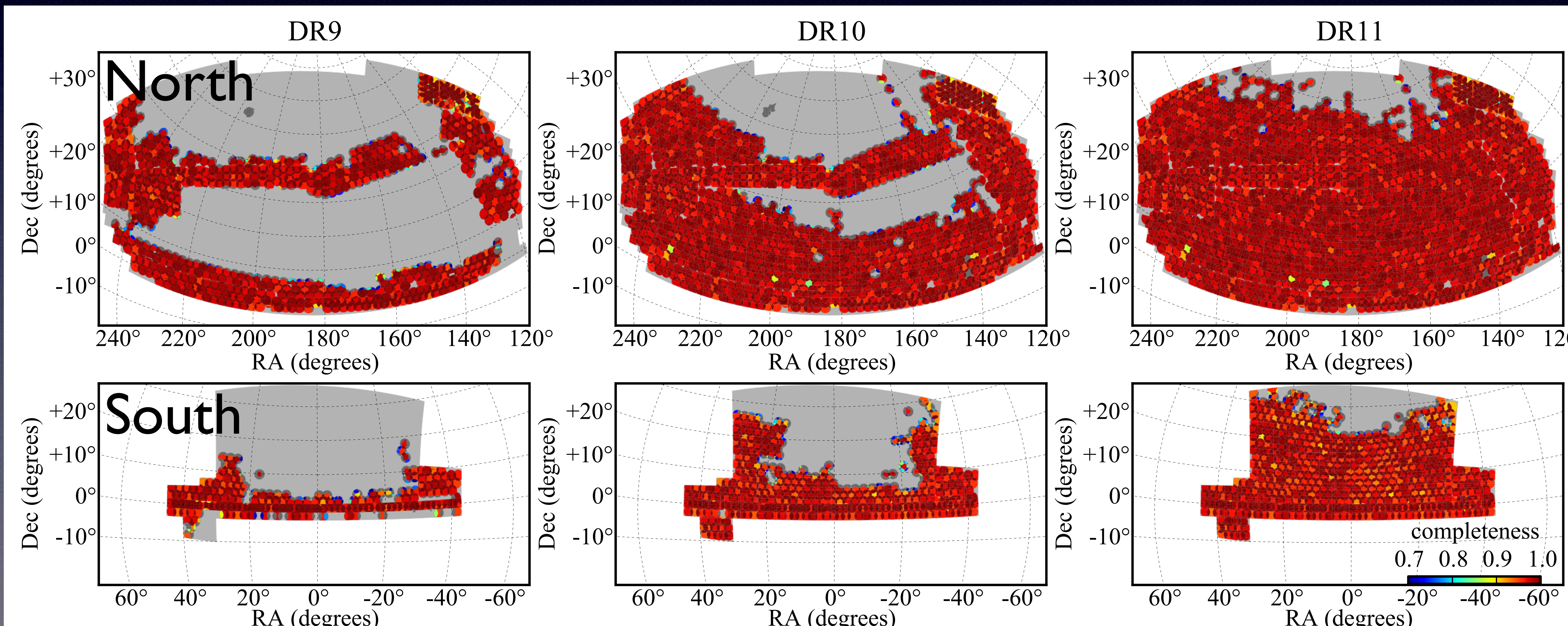
https://www.cfa.harvard.edu/~deisenst/boss_pie/

Black circle =150Mpc comoving radius



BOSS sky coverage

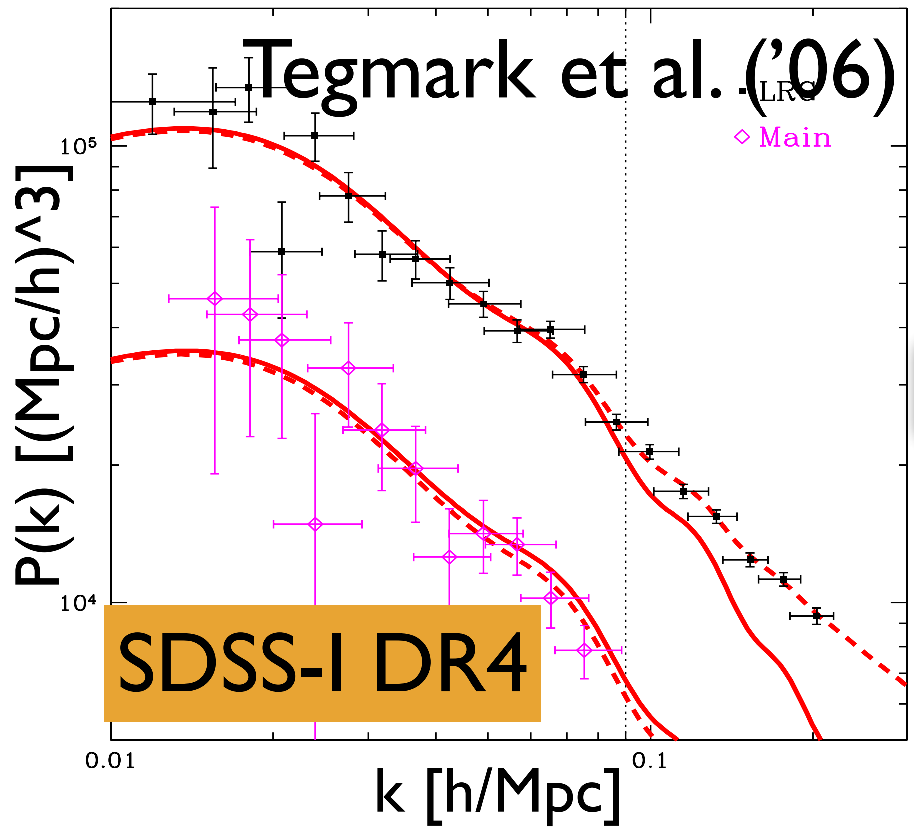
3,300 deg^2 | 6,200 deg^2 | 8,400 deg^2

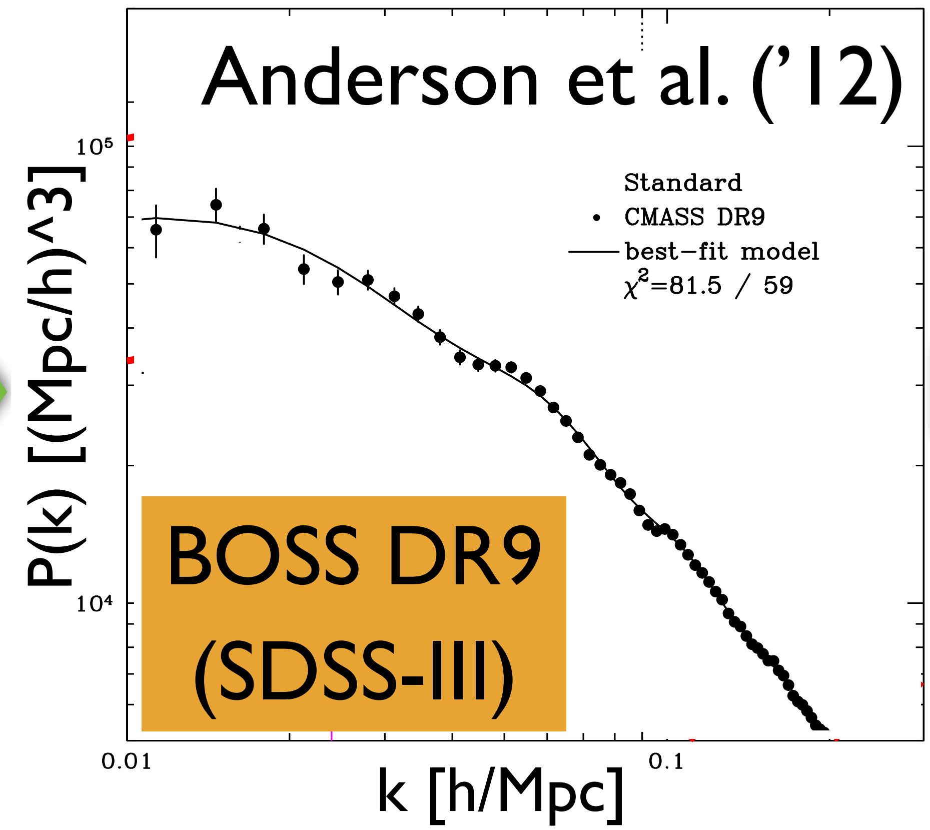


Cosmology with 3D galaxy map

Precision measurement of

Power spectrum P(k), or correlation function ξ(r)





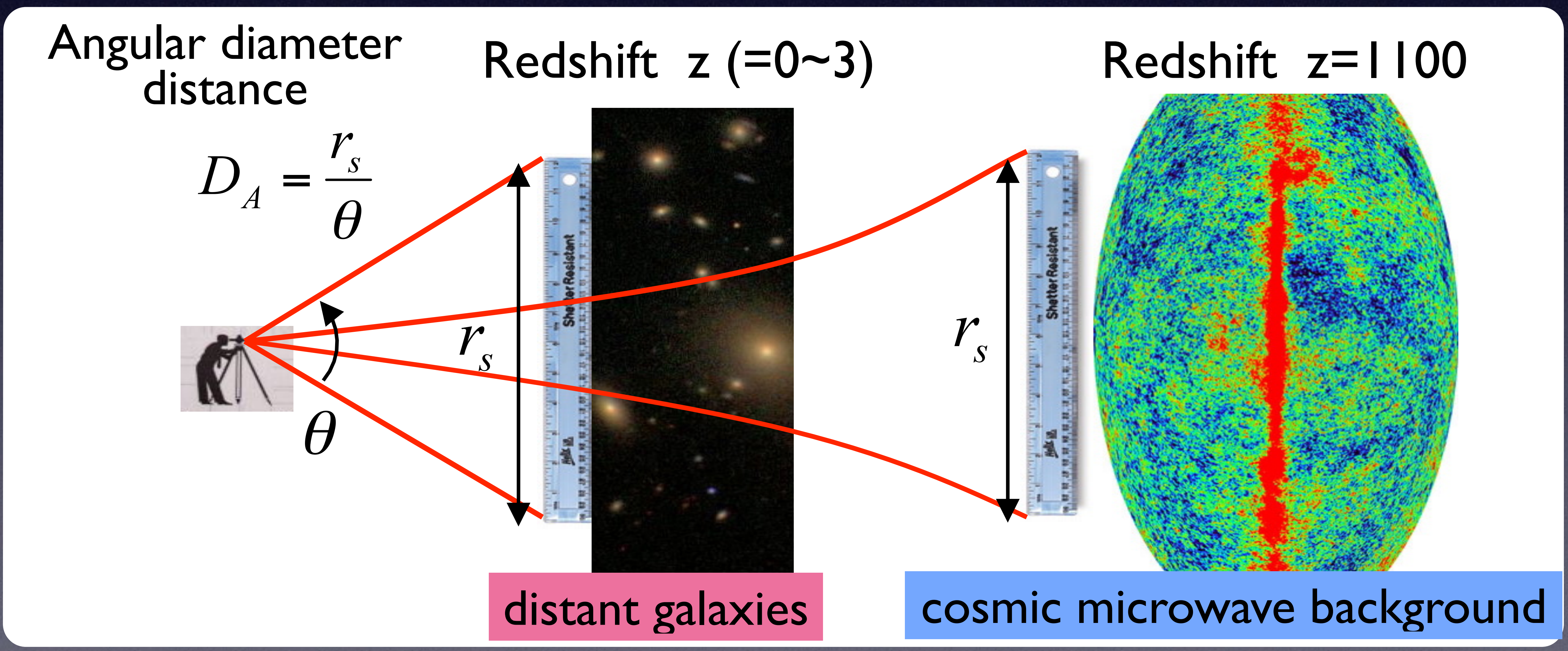
BOSS DR10/11
(SDSS-III)

~1% precision !!

- Clarifying nature of dark energy (cosmic acceleration) with ***baryon acoustic oscillations***
- Testing general relativity on cosmological scales with ***redshift-space distortions***

Baryon acoustic oscillations (BAO)

- Characteristic scale of primeval baryon-photon fluid (~150Mpc) imprinted on P(k) or ξ(r) (⇔ CMB acoustic signal)
- Can be used as standard ruler to estimate distance to galaxies



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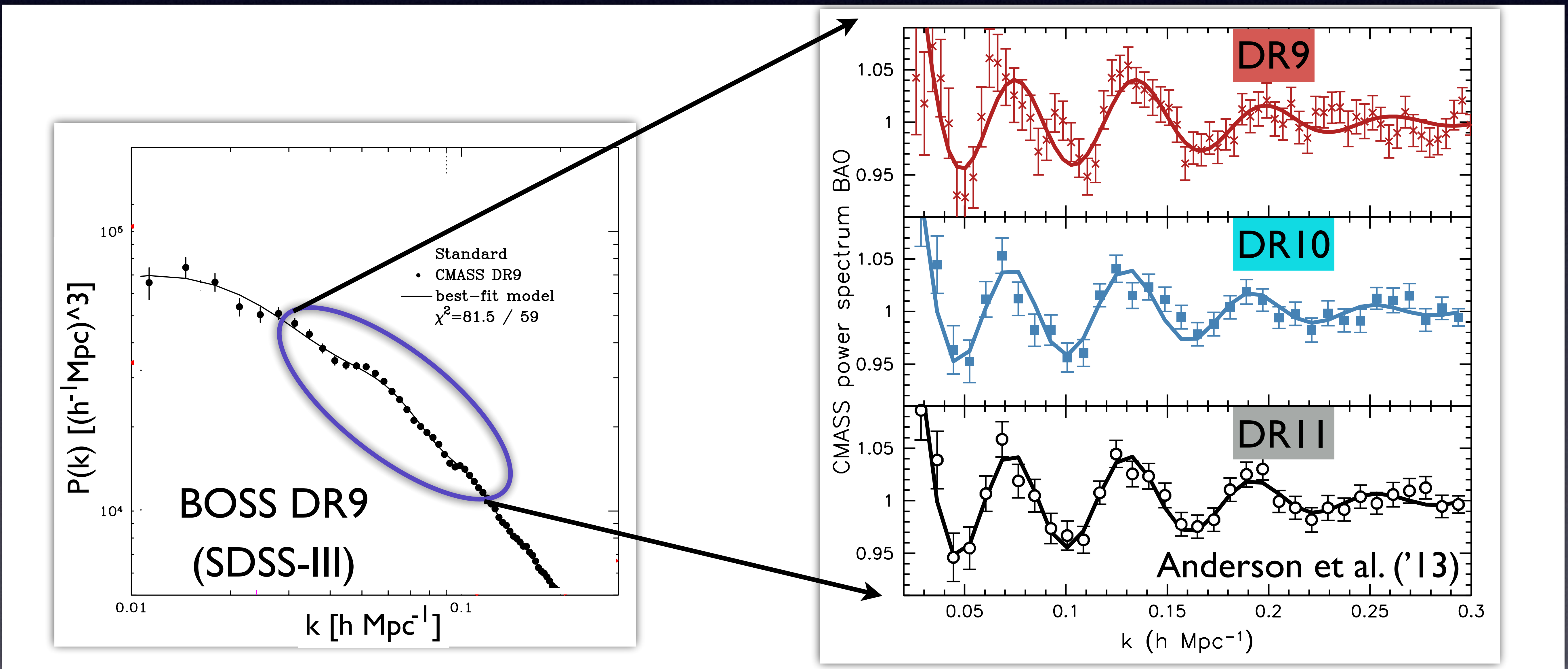
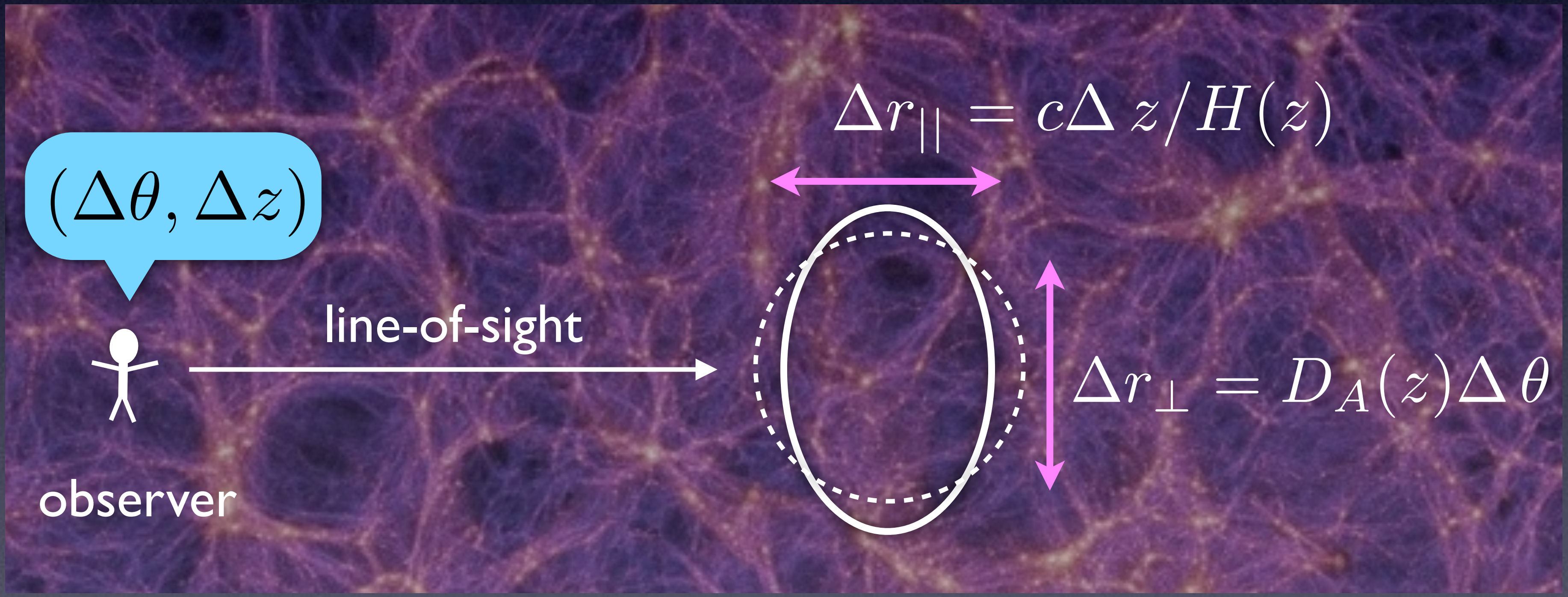


Unlocking the power of BAO

A measurement of anisotropies in BAO
gives you a separate measurement of $D_A(z)$ & $H(z)$ via

✓ **Alcock-Paczynski (AP) effect**

(Alcock & Paczynski '79)



Can be quantified by 2D power spectrum/correlation function
parallel & transverse to line-of-sight direction

$P(k_{||}, k_{\perp})$ $\xi(r_{||}, r_{\perp})$

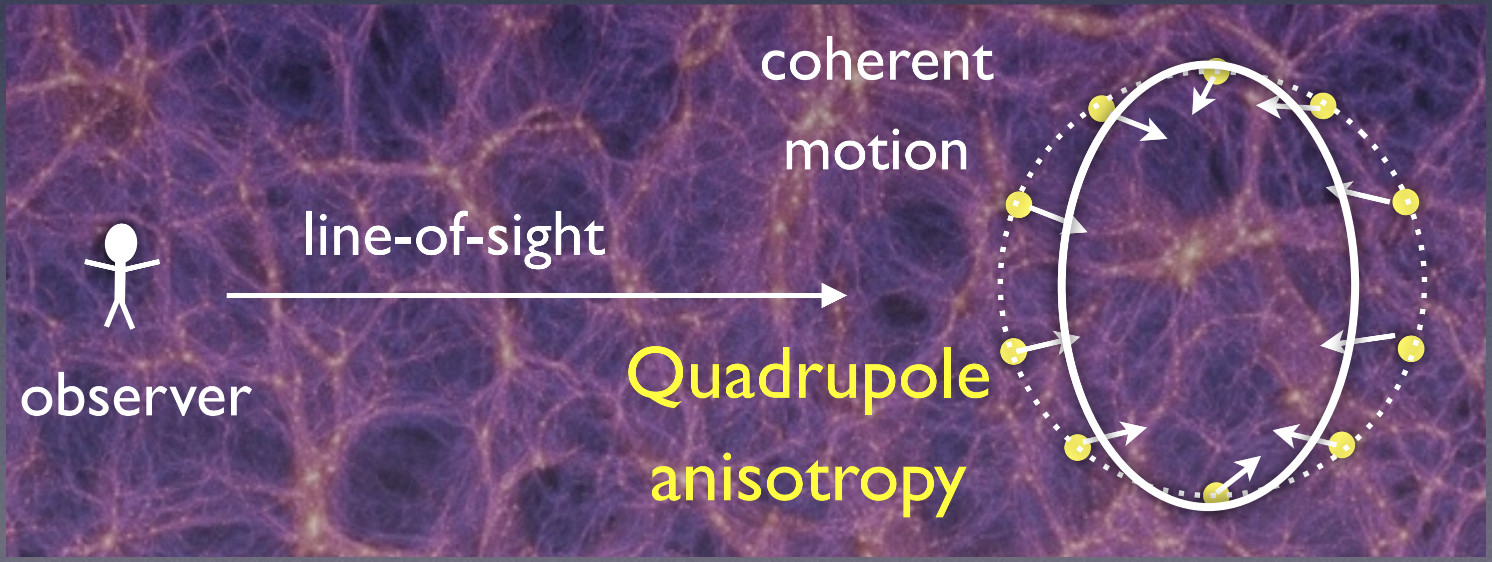
Redshift-space distortions(RSD)

- Yet another anisotropies due to peculiar velocity of galaxies through redshift measurements

redshift space real space

$$\vec{\mathrm{s}} = \vec{\mathrm{r}} + \frac{(\vec{\mathrm{v}} \cdot \hat{\mathrm{z}})}{a\,H(z)}\,\hat{\mathrm{z}}\ ; \quad \begin{cases} \mathrm{v} & : \text{peculiar velocity} \\ \hat{\mathrm{z}} & : \text{observer's line-of-sight direction} \end{cases}$$

- On large-scales of our interest,



magnitude of RSD $\propto$ $f(z) \equiv \dfrac{d \ln D_+}{d \ln a}$

growth of structure induced by **gravity**

(Kaiser '87, Hamilton '92)

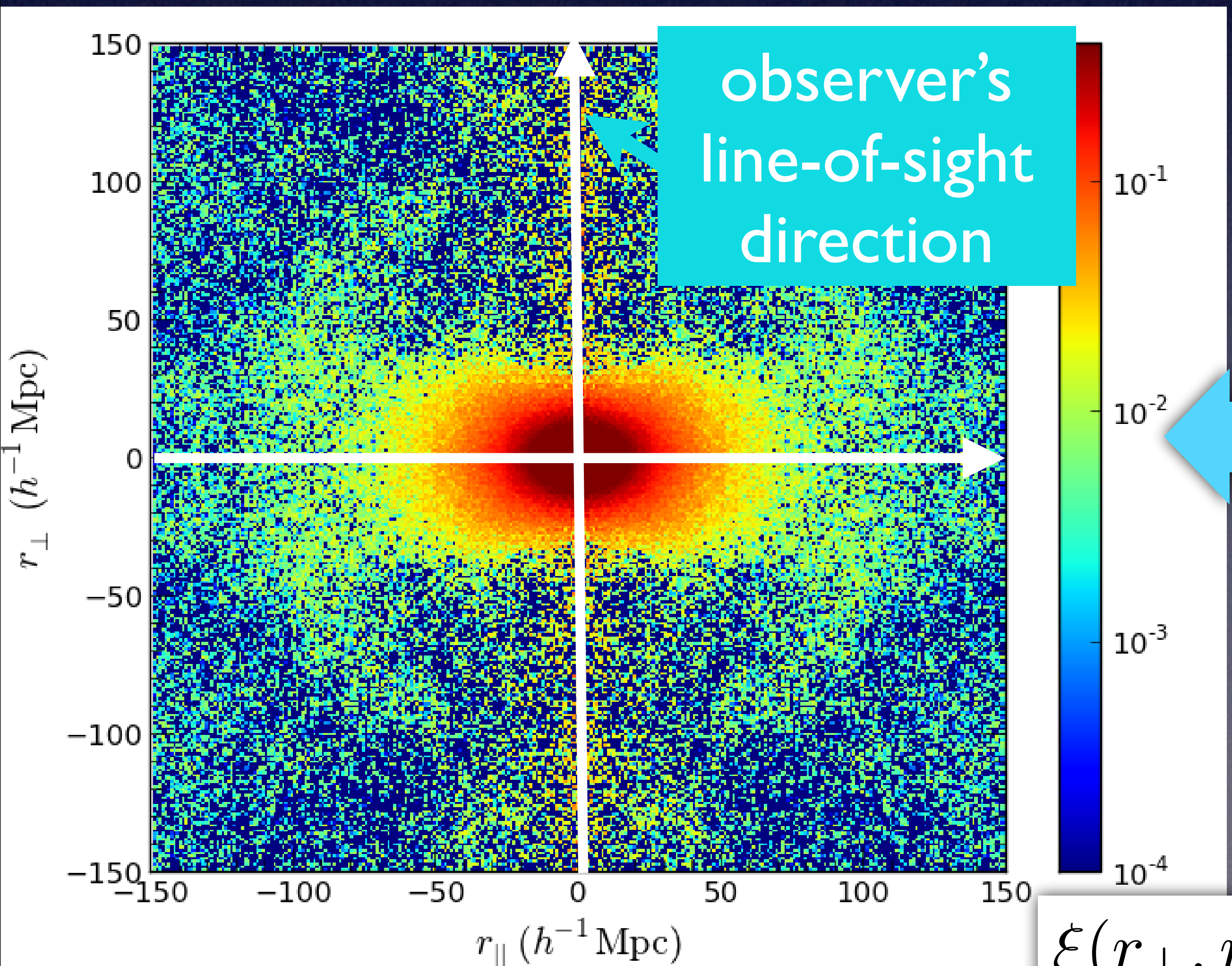
Combining distance measurement with BAO,

RSD provides a sensitive probe of gravity on cosmological scales

Anisotropic correlation function

BOSS DR11, CMASS samples

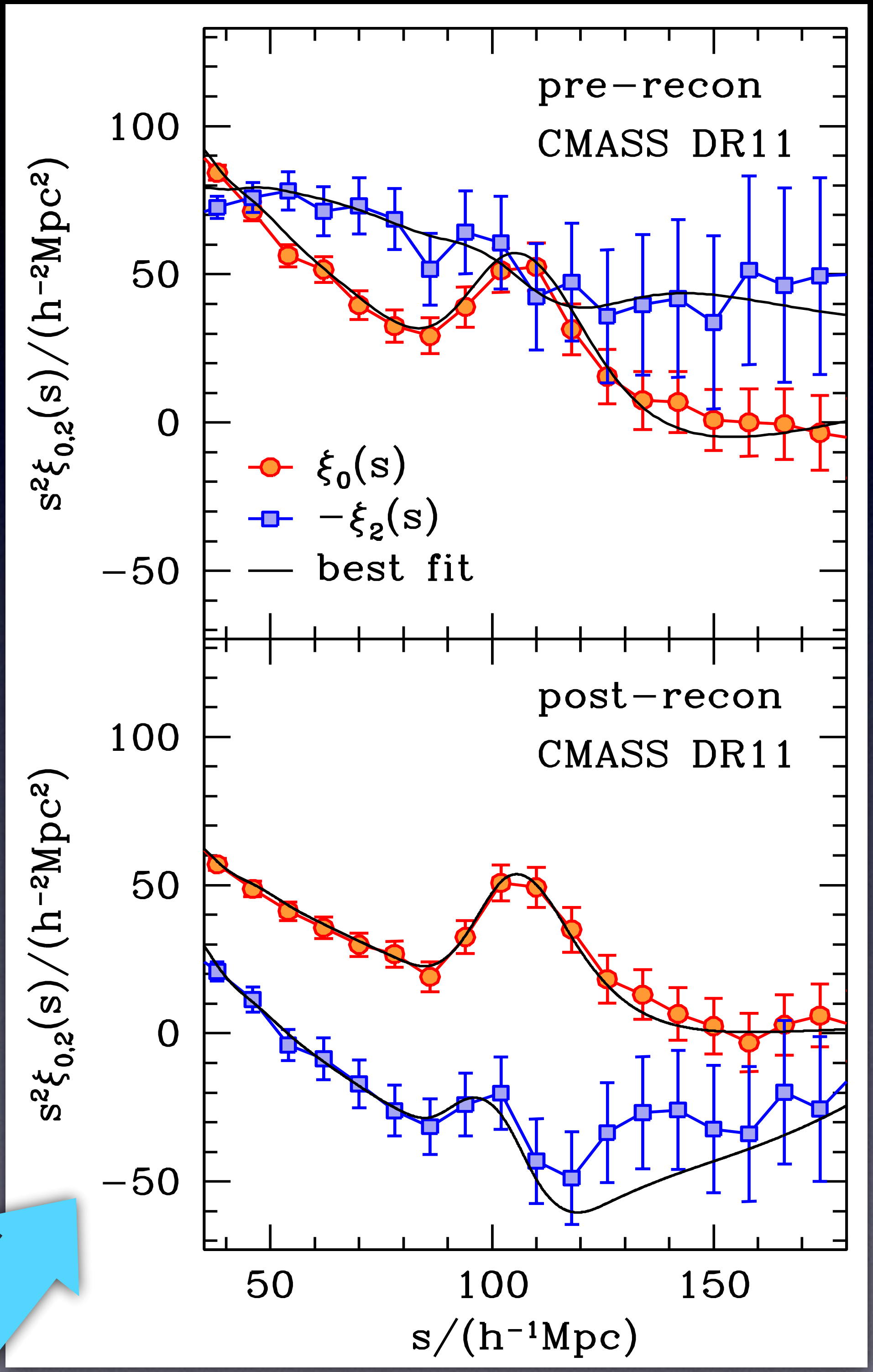
700,000gals @ 0.43<z<0.7



Samushia et al.('13)

$\xi(r_\perp, r_\parallel)$

Anderson et al.('13)

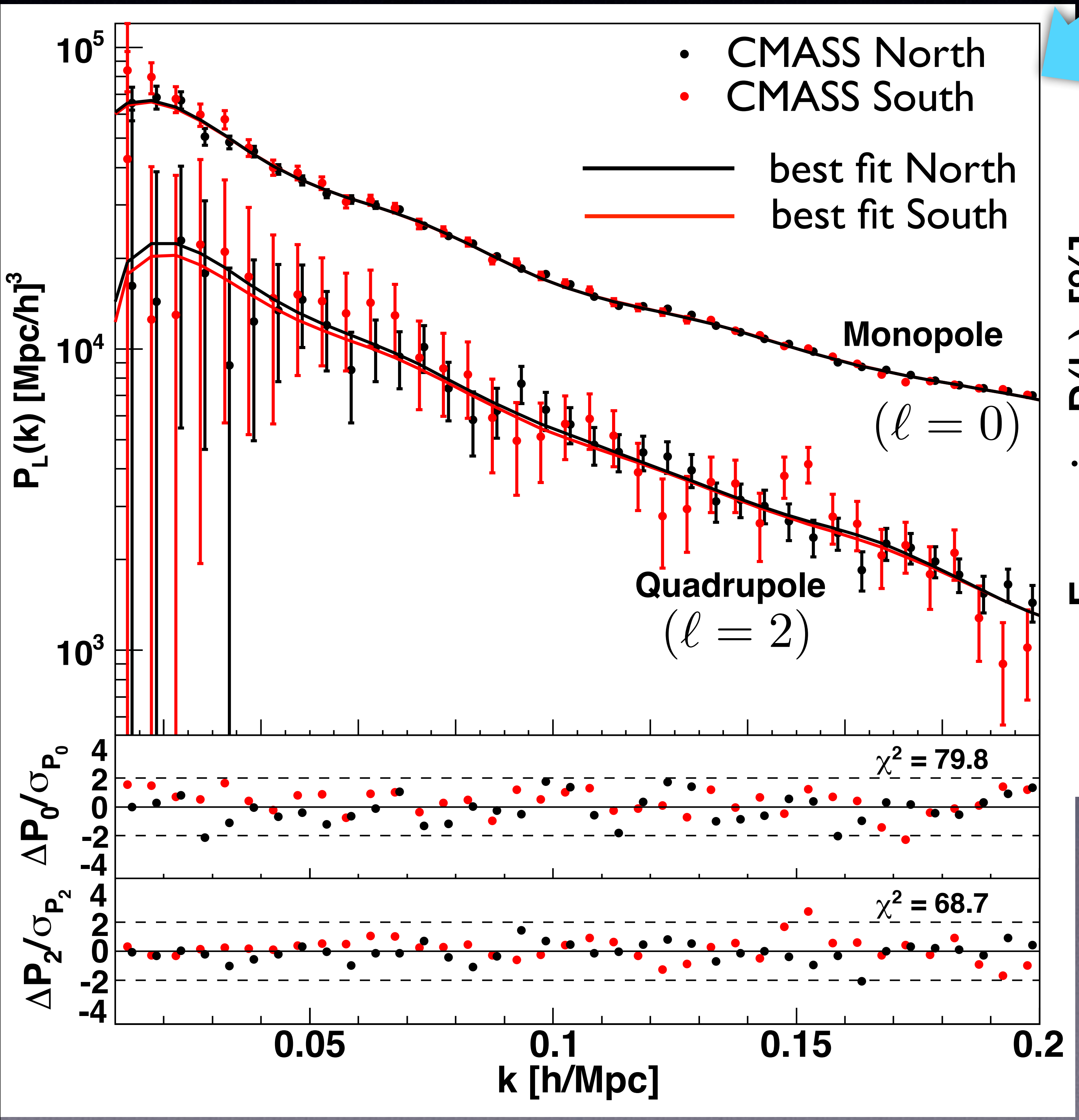


Multipole expansion

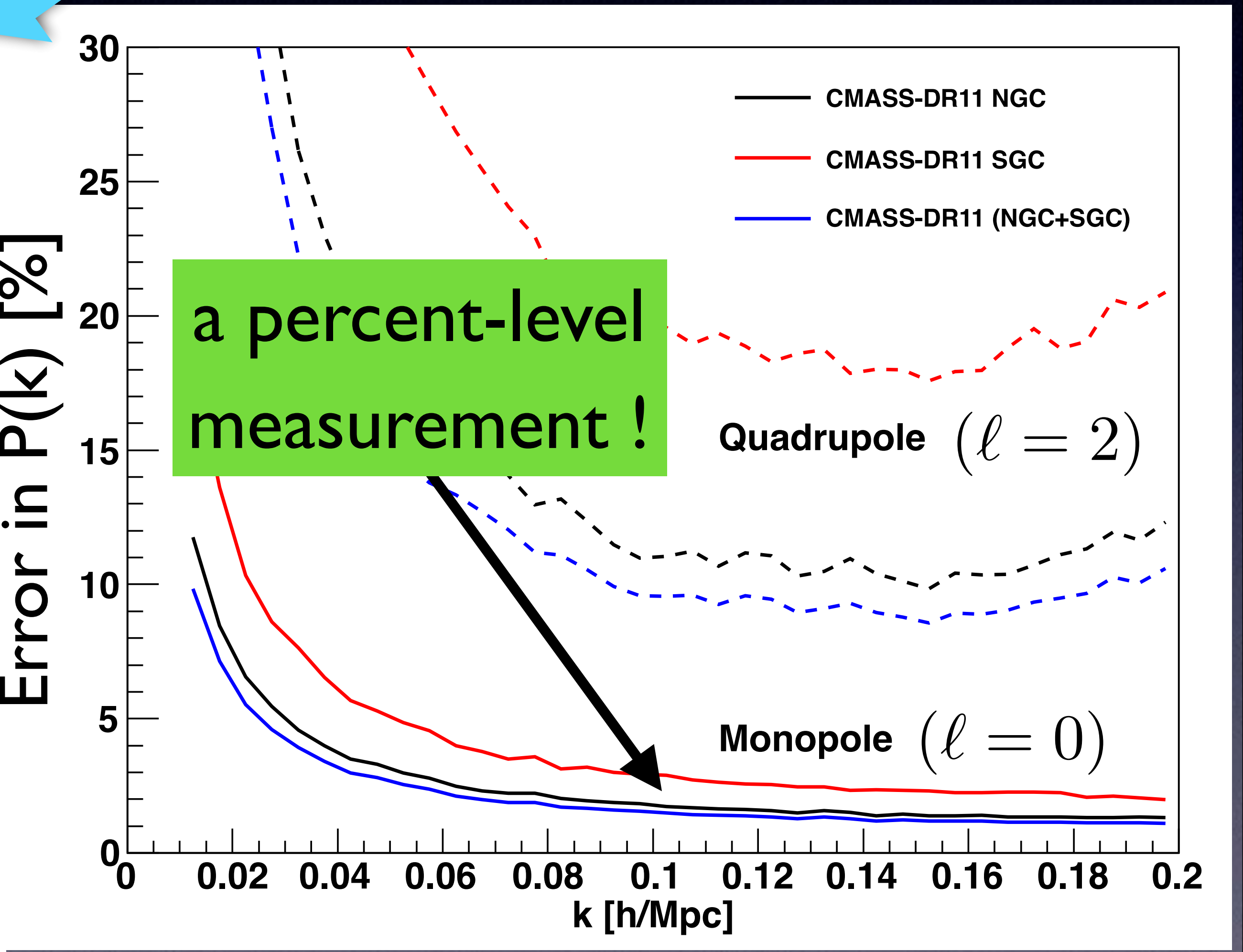
$$\xi(r_\perp, r_\parallel) = \sum_{\ell:\mathrm{even}} \xi_\ell(s)\,\mathcal{L}_\ell(r_\parallel/s)\ ;\ \ s = (r_\perp^2 + r_\parallel^2)^{1/2}$$

Anisotropic power spectra

Beutler et al. ('13)



Based on Yamamoto ('06) estimator



$$P(k_\parallel, k_\perp) = \sum_{\ell:\ \mathrm{even}} P_\ell(k)\,\mathcal{P}_\ell(k_\parallel/k)$$

$$;\ k = (k_\parallel^2 + k_\perp^2)^{1/2}$$

Basic results

Anisotropies in ξ(r) or P(k) for CMASS & LOWZ samples
(z= 0.57) (z= 0.32)

Alcock-Paczynski & RSD effects

- geometric distances :

$$D_A(z) \text{ \& } H(z) \text{ or } D_V(z) = \left[(1+z)^2\, c\, z\, \frac{D_A(z)^2}{H(z)}\right]^{1/3}$$

- structure growth :

$$f(z)\sigma_8(z) = \{\Omega_{\rm m}(z)\}^{\gamma}\,\sigma_8(z)$$

Note-. Derived constraints are sensitive to the analysis method they adopted because of observational & nonlinear systematics

paper	sample	analysis	derived results
Anderson et al.	CMASS / LOWZ	P_0, ξ_0 & ξ_2, $\xi_{//}$ & $\xi_{\perp}$	D_A & H
Beutler et al.	CMASS	P_0 & P_2	D_A, H & f σ_8
Samushia et al.	CMASS	ξ_0 & ξ_2	D_A, H & f σ_8 ++
Chuan et al.	CMASS / LOWZ	ξ_0 & ξ_2	D_A, H & f σ_8
Sanchez et al.	CMASS / LOWZ	shape of $\xi_{//}$ & $\xi_{\perp}$	D_A, H & f σ_8 ++

Basic results

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- structure growth :

  $f(z)\sigma_8(z) = \{\Omega_{\rm m}(z)\}^{\gamma}\, \sigma_8(z)$

Note-. Derived constraints are sensitive to the analysis method they adopted because of observational & nonlinear systematics

Basically *consistent* **with GR and ΛCDM**, but …

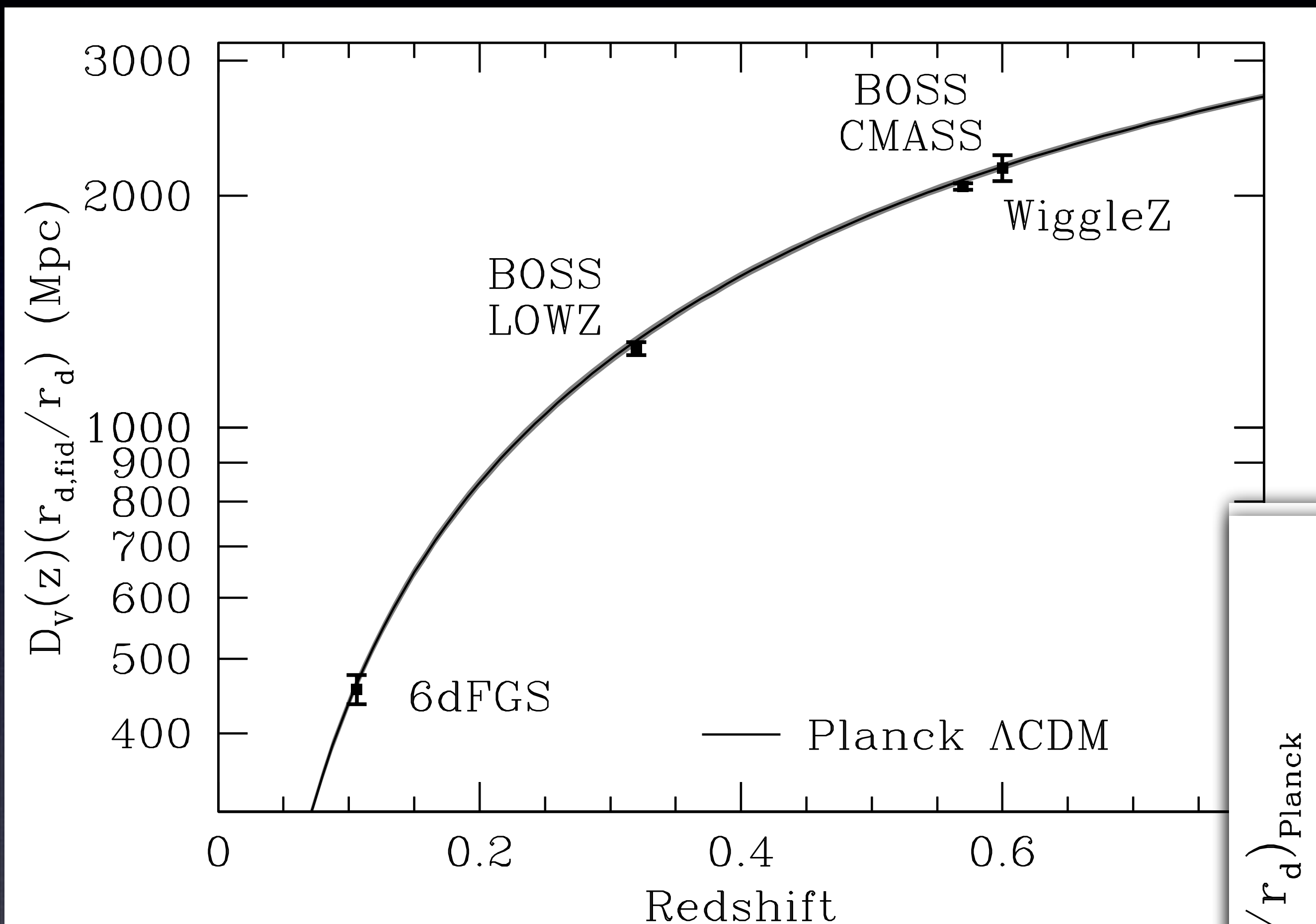
- mild tensions with Planck ΛCDM
- weaker gravity at z<1 seems favorable

Extend ΛCDM ??

New physics ??

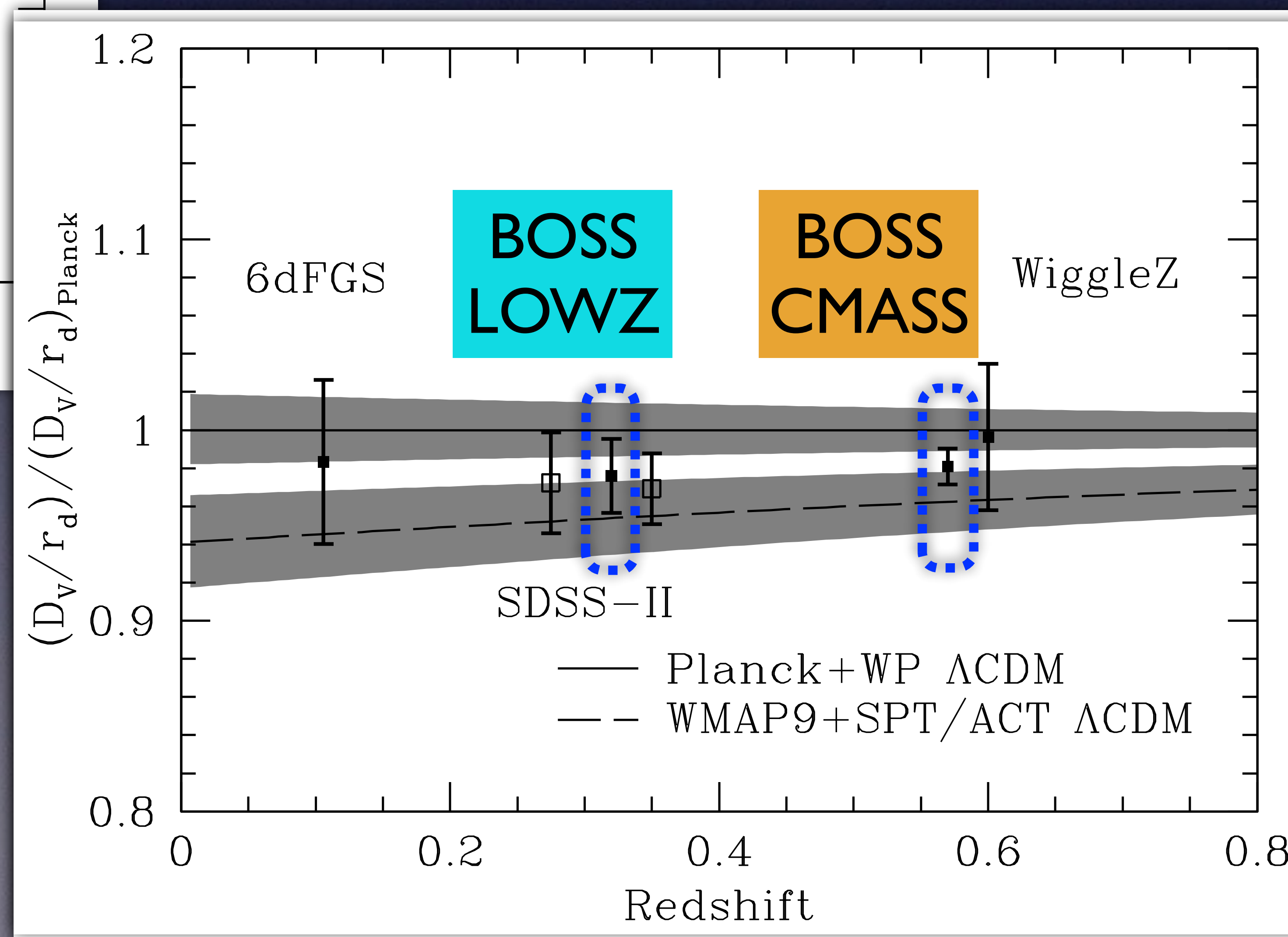
Geometric distances

Anderson et al.('13)



Constraints derived from BAO scale (A-P effect)

Mild tension with Planck & WMAP ΛCDM

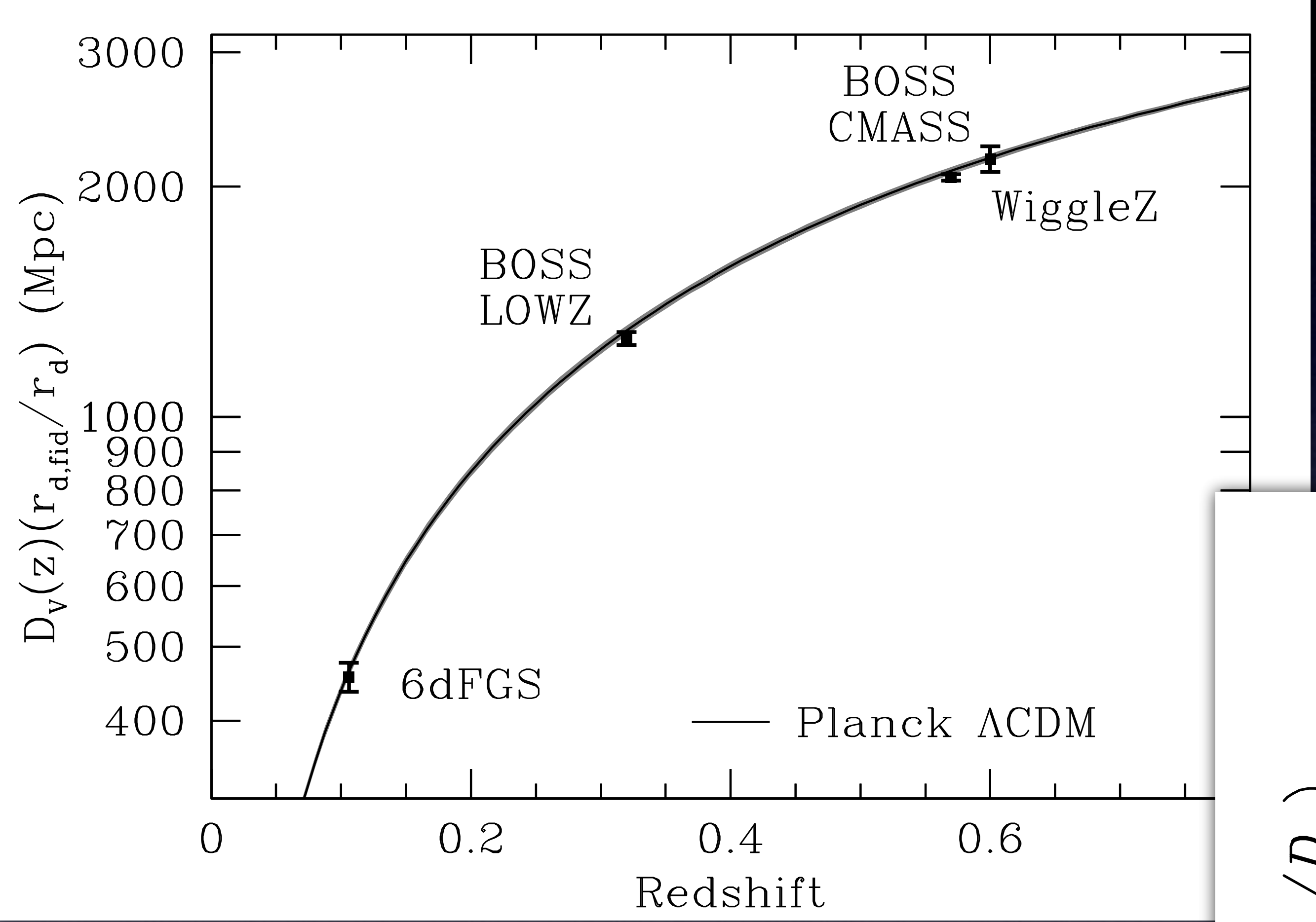


$$Dv(z) = \left[(1+z)^2\, c\, z\, \frac{D_A(z)^2}{H(z)}\right]^{1/3}$$

r_d: sound horizon at drag epoch

Geometric distances

Anderson et al.('13)



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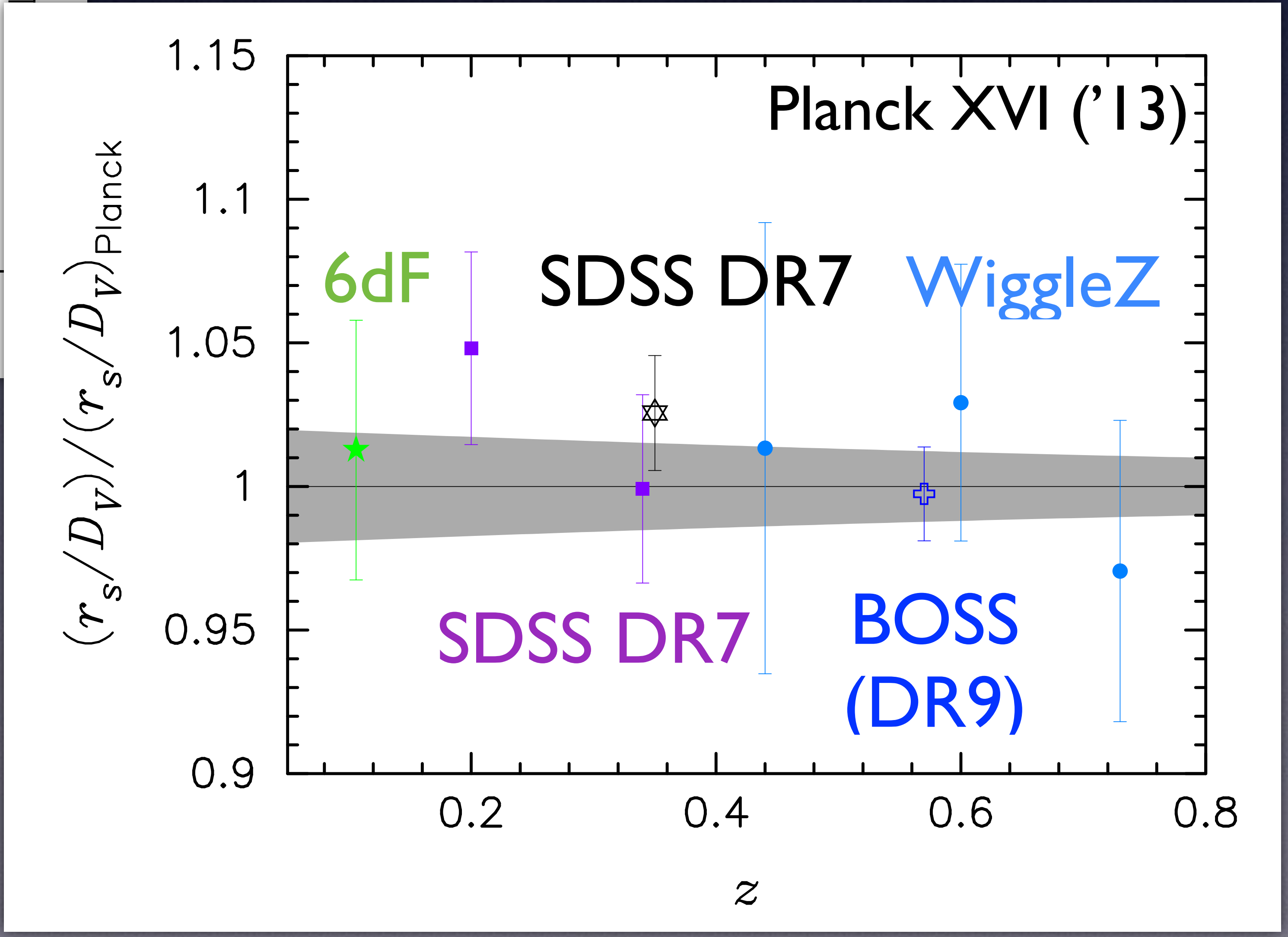

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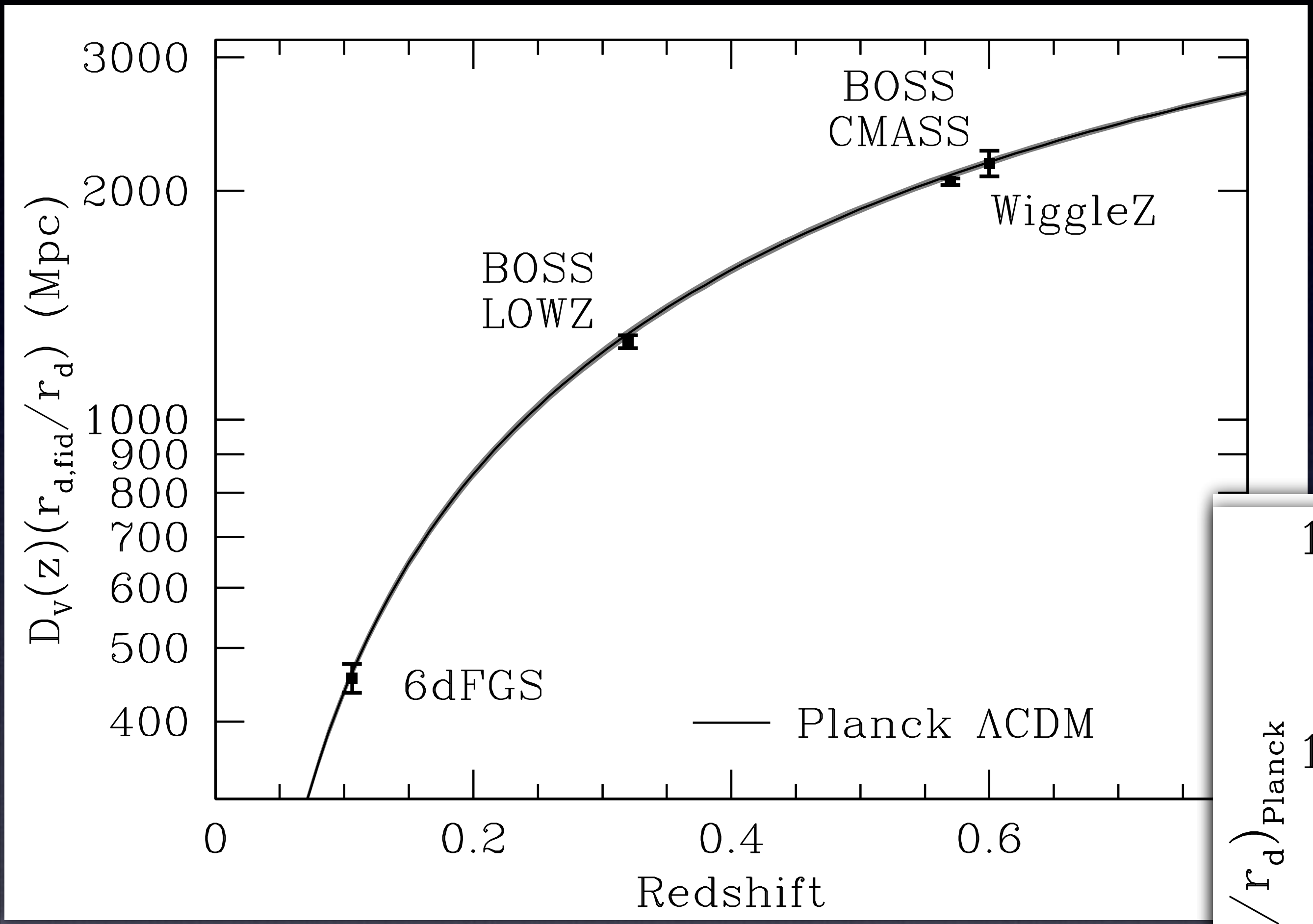
Anderson et al.('13)



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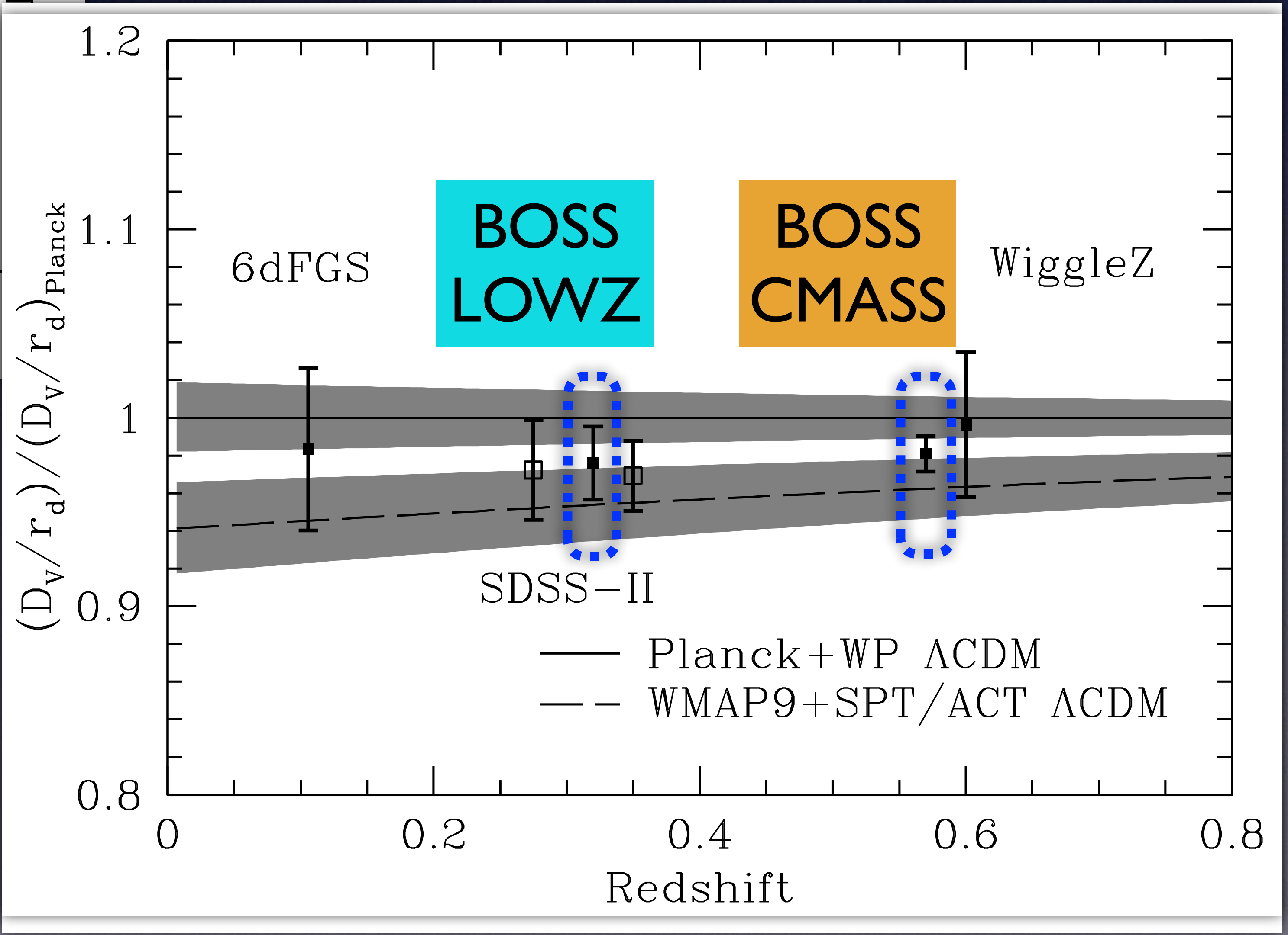
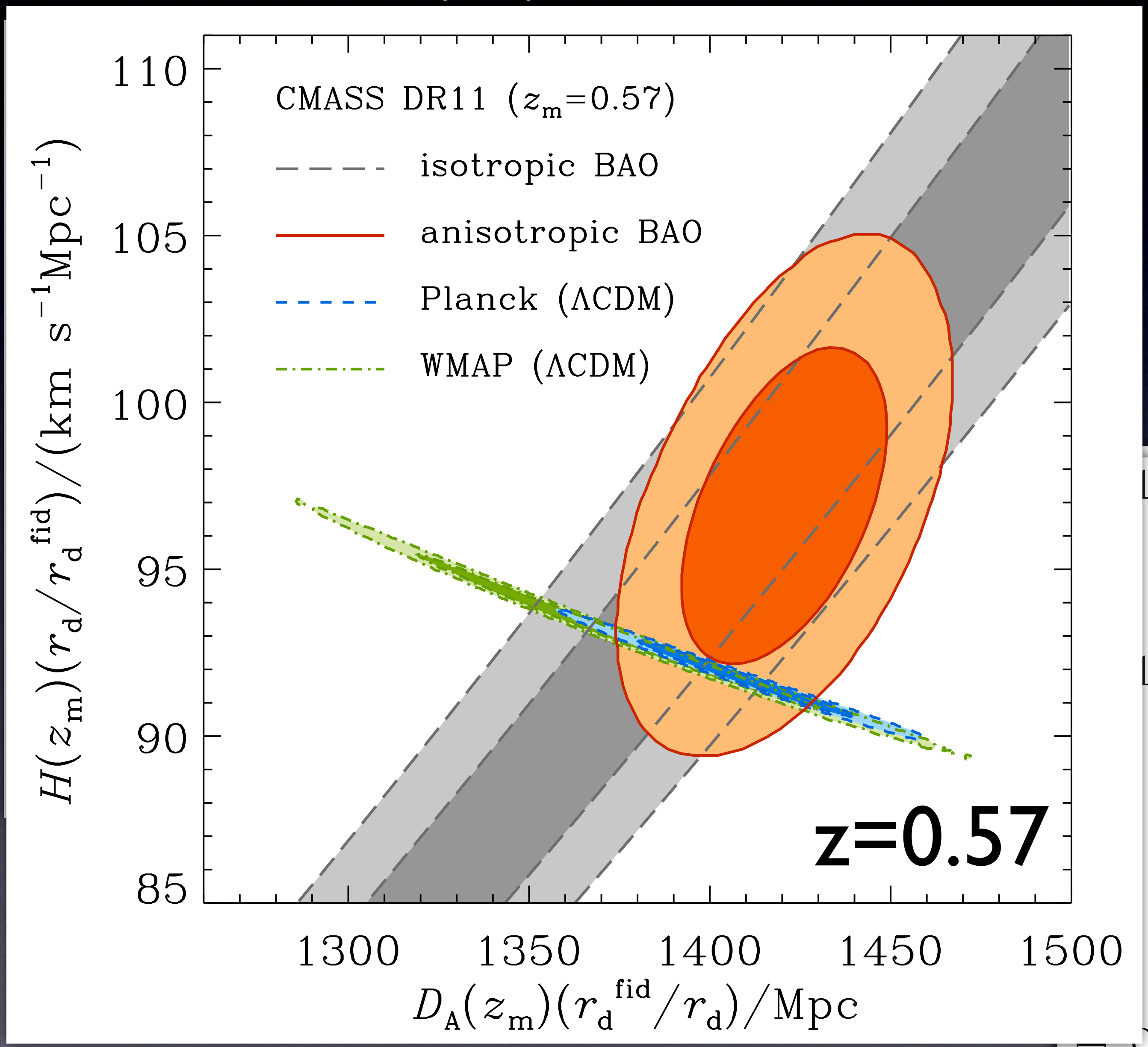


Dv(z) $= \left[(1+z)^2 c z \frac{D_A(z)^2}{H(z)}\right]^{1/3}$

r_d: sound horizon at drag epoch

Geometric distances

Anderson et al.('13)



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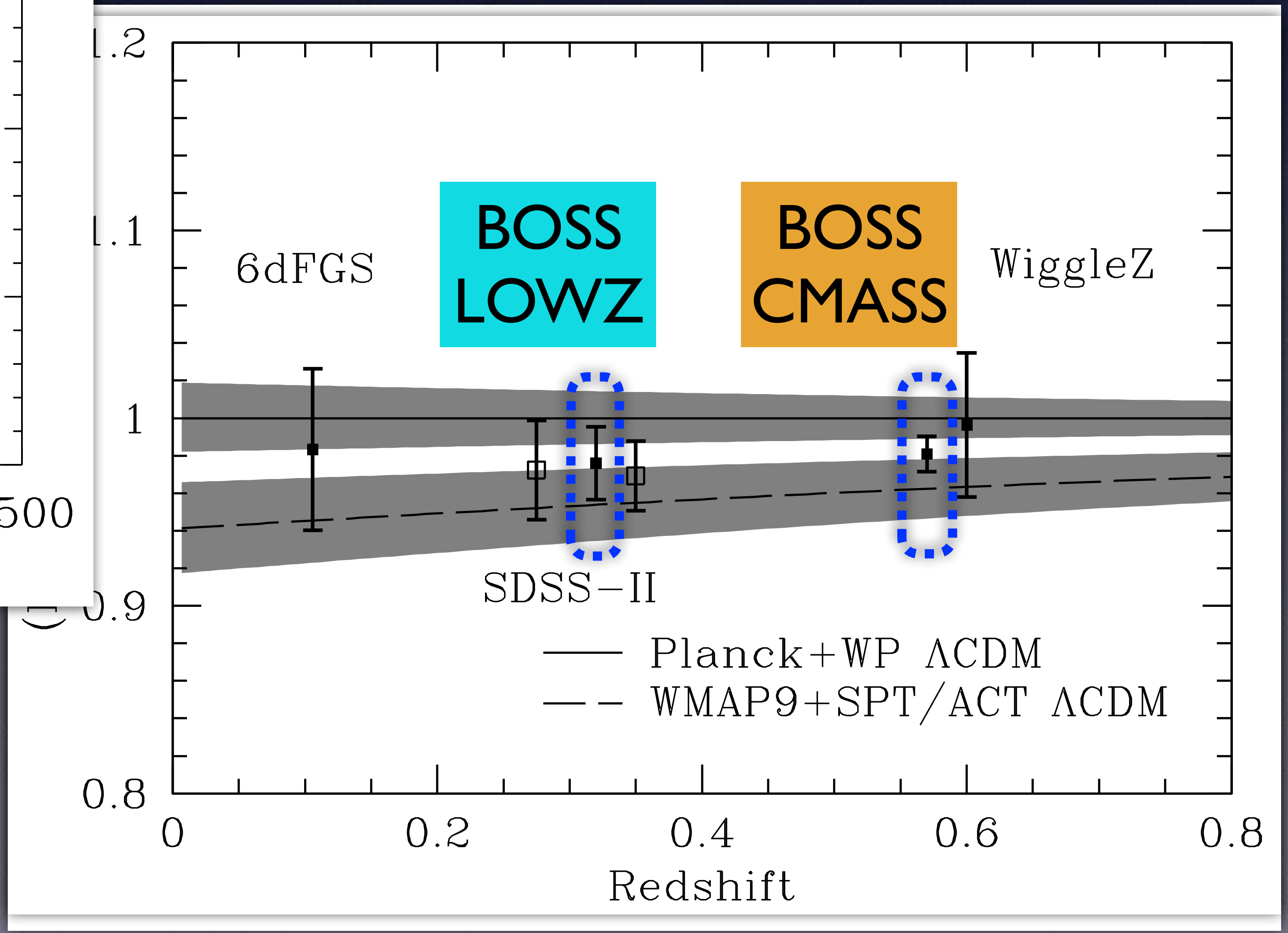


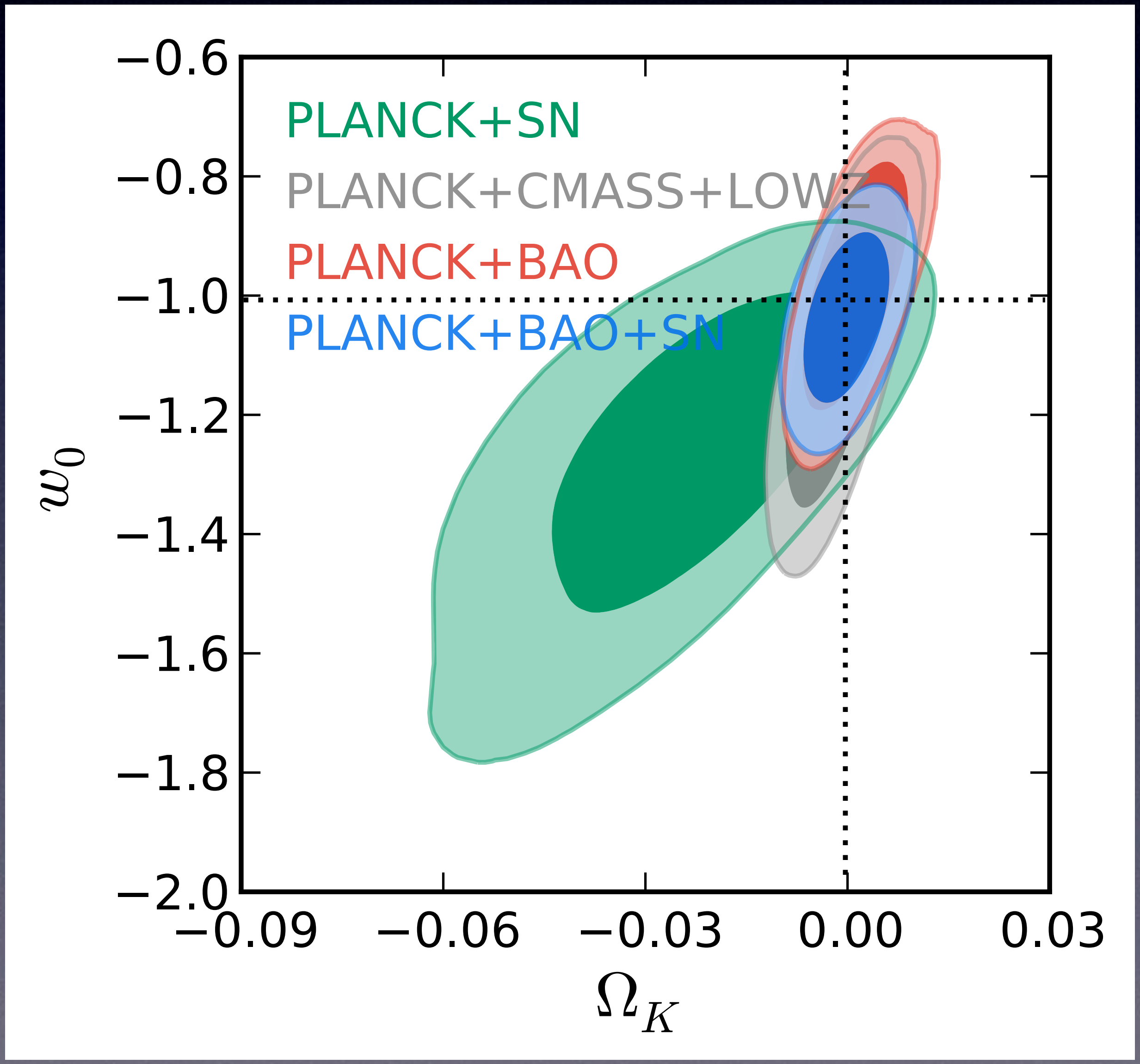
Dv(z) $= \left[(1+z)^2 \, c\, z \, \frac{D_A(z)^2}{H(z)} \right]^{1/3}$

r_d: sound horizon at drag epoch

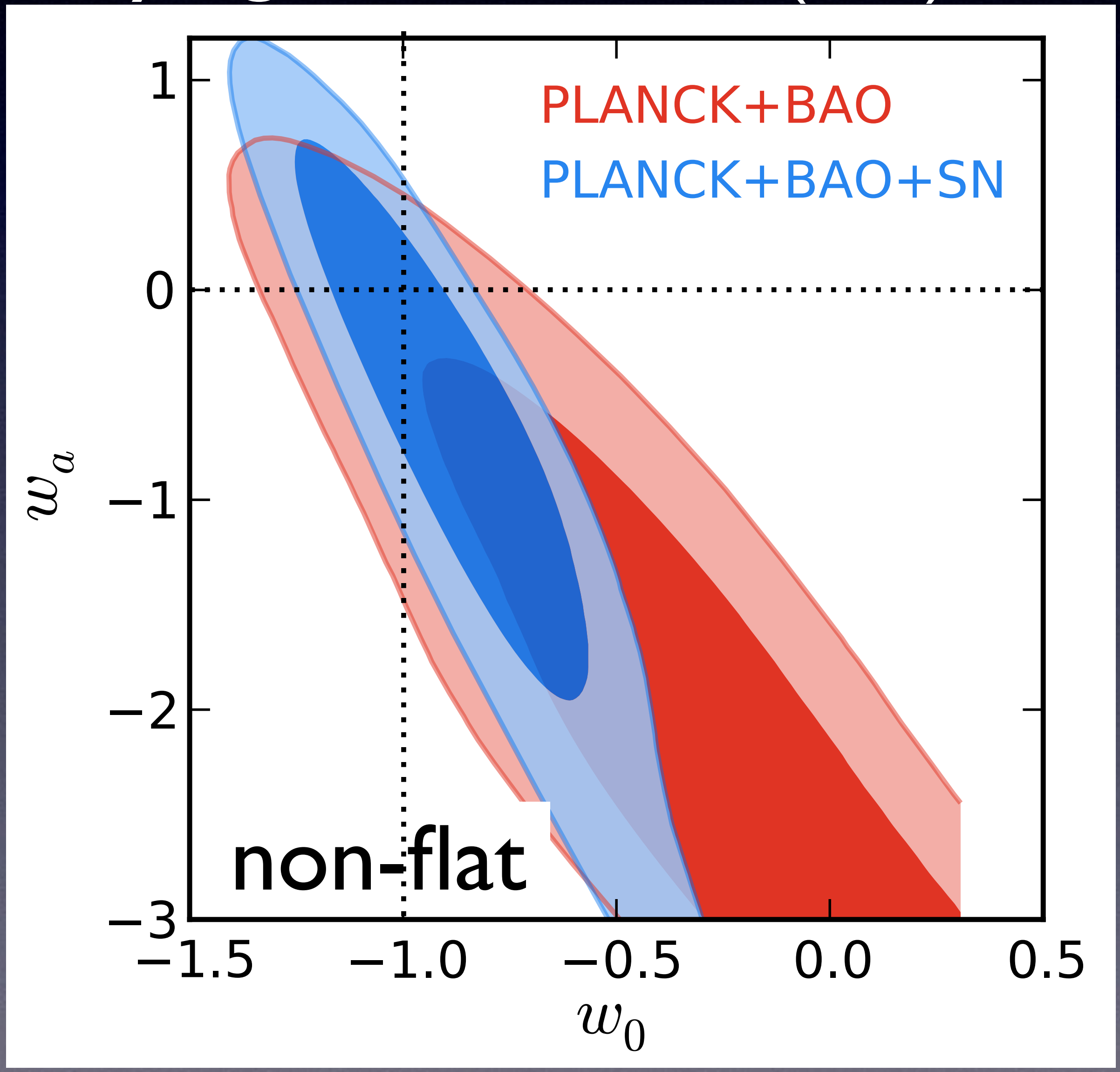
Dark energy & Curvature

Anderson et al.('13)

constant w



varying w $w_0+w_a(1-a)$



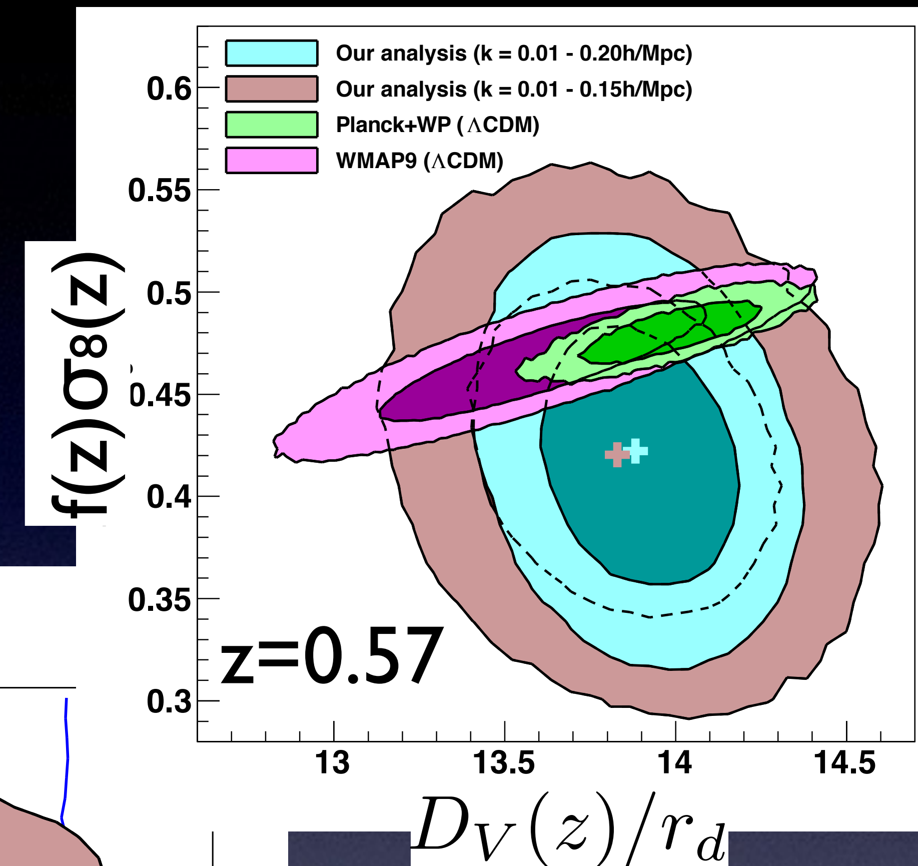
No evidence for $w \neq -1$

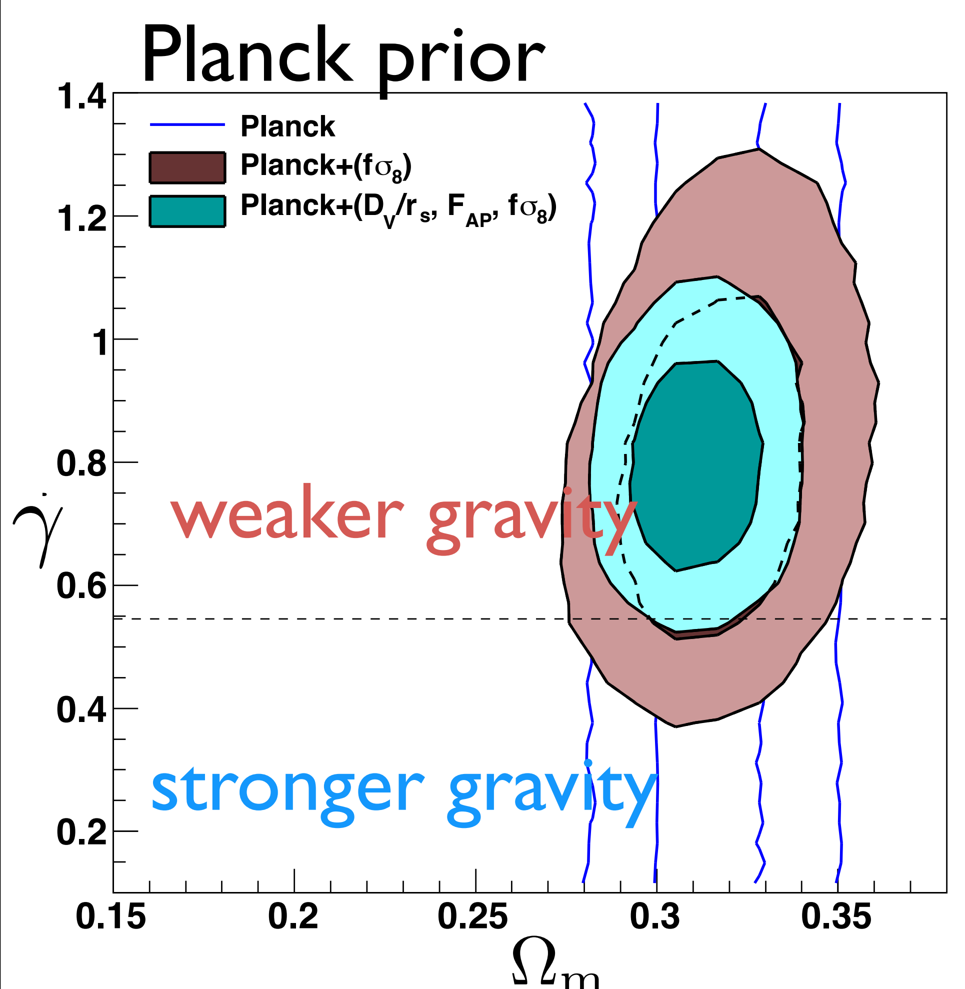
generally consistent with flat ΛCDM

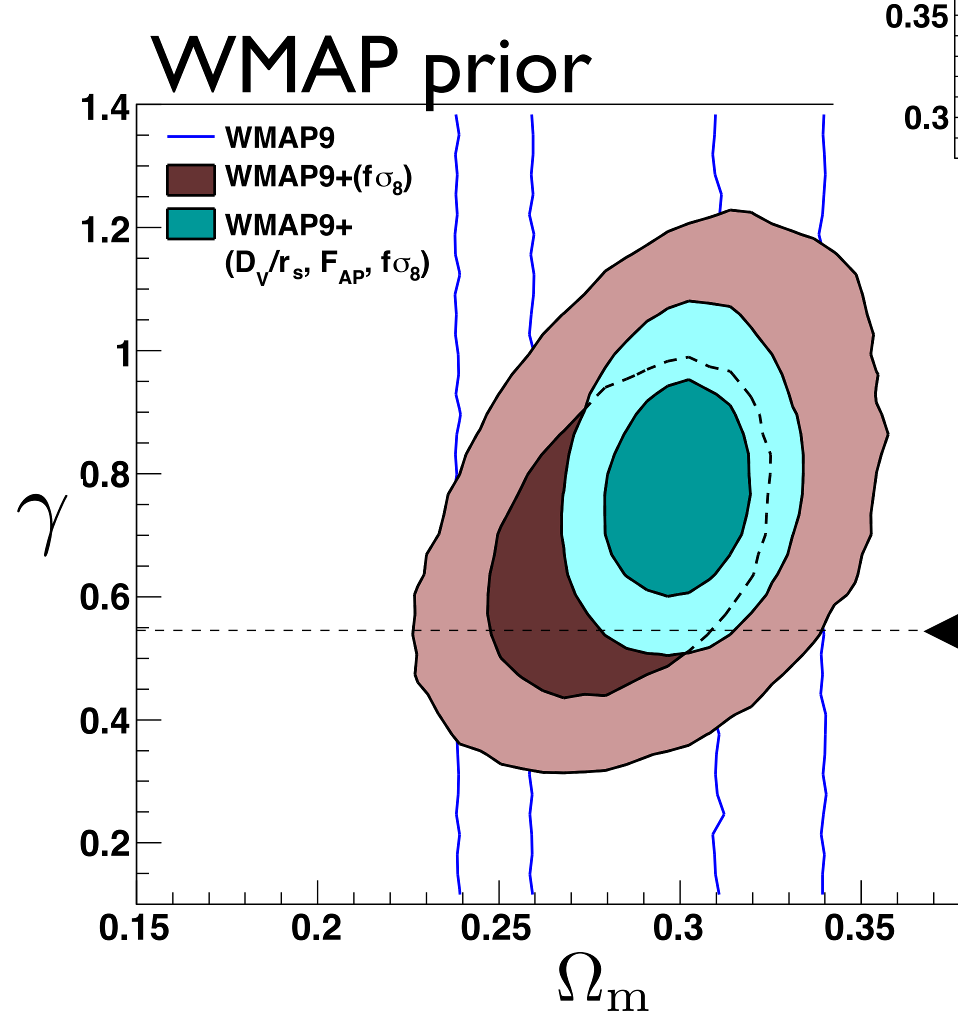
Growth of structure

Constraints derived from redshift-space distortion (RSD) effect

$$f(z)\sigma_8(z) = \{\Omega_m(z)\}^\gamma \, \sigma_8(z)$$







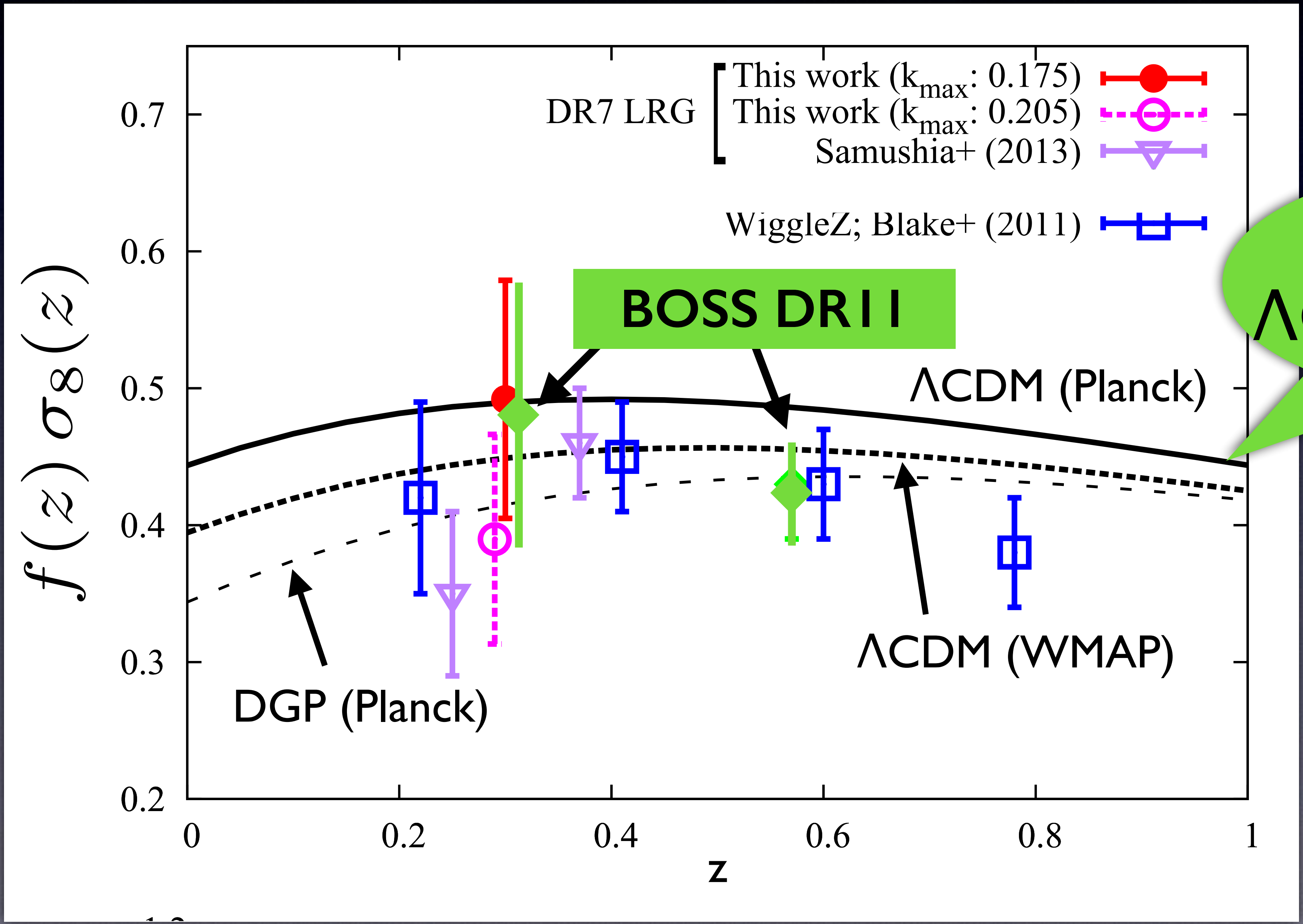
Beutler et al.('13)

General Relativity

Weaker gravity seems favorable <u>for given σ8 prior by CMB</u>

Growth history of structure

Figure taken from Oka et al. ('13)



Discovery of a deviation of gravity from general relativity (GR) ?

Possibility

Fixing $\gamma = 0.55$ (GR)

smaller values of f(z)σ8(z) $= \{\Omega_{\rm m}(z)\}^{\gamma}\,\sigma_8(z)$

together with geometric distance (BAO)

⇒ smaller σ_8

- tension with Planck CMB

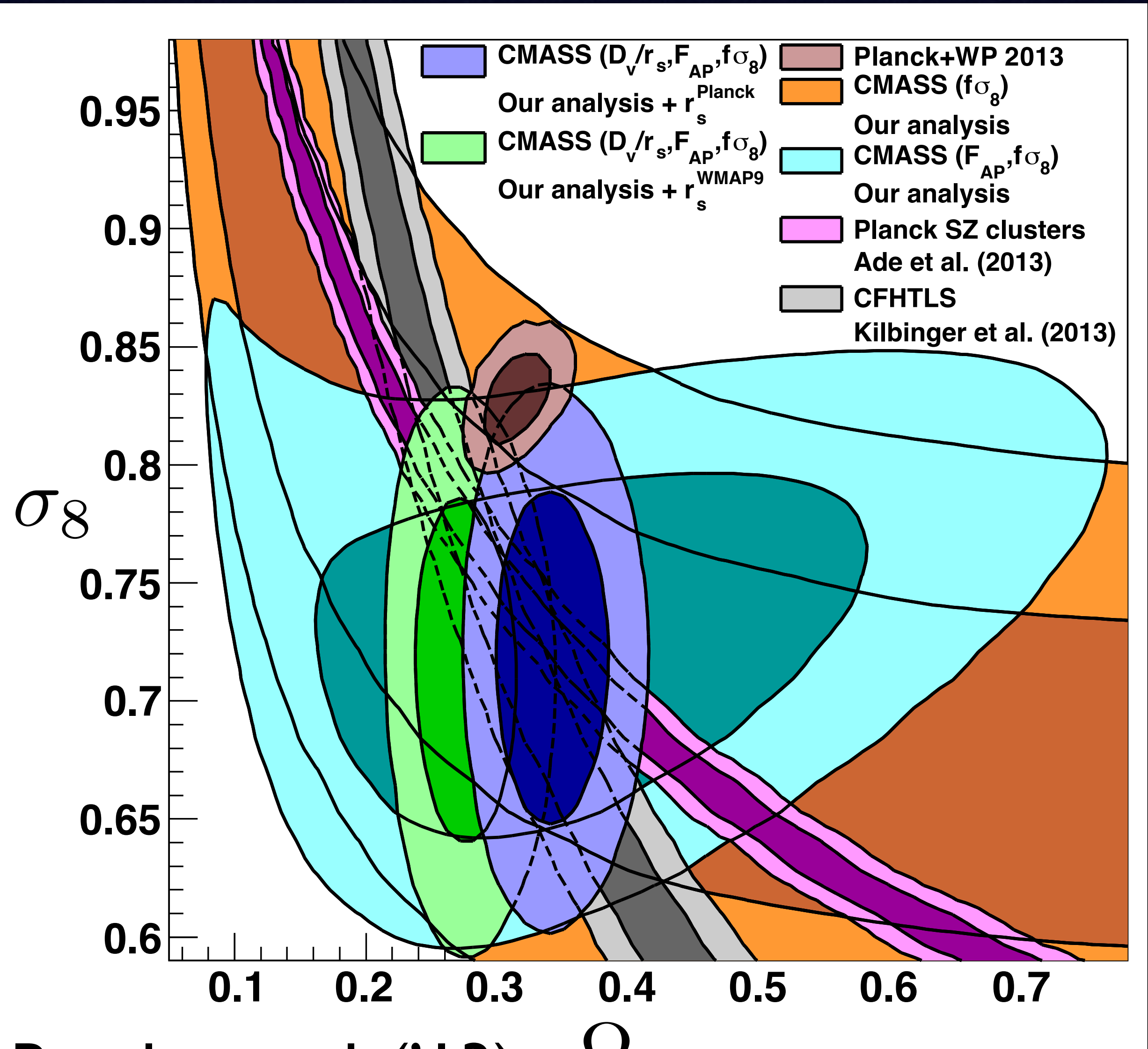
but

- consistent with Planck SZ clusters

Solution ? ····· massive neutrinos

but

required mass seems large (>0.2eV)



Beutler et al. ('13)

Systematics ?

Measured power spectrum (or correlation func.)

$$P_\ell^{\rm obs}(k)$$

Seeing, spec-z failure, fiber collision

Impact of satellites or small-scale phys.

→ next speaker

Yamamoto-san

Theoretical template (model of RSD)

$$P_\ell^{\rm model}(k; D_A, H, f, \cdots)$$

free parameter

Nonlinear systematics arising from

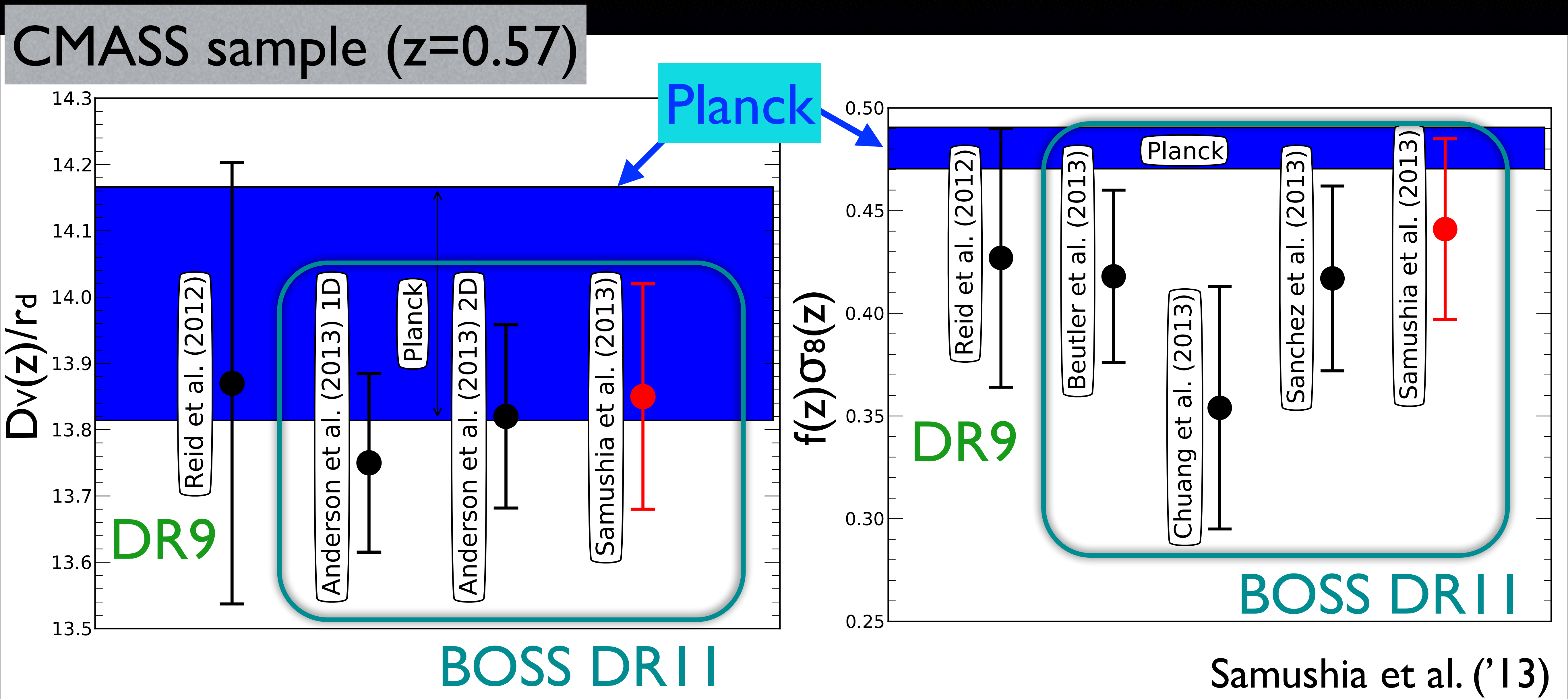
RSD, gravity & galaxy bias

needs to be properly modeled

e.g., with perturbation theory (PT)

→ imperfect model or aggressive use of PT may lead to a biased result

Systematics ?



e.g., with perturbation theory (PT)

$$P_\ell^{\rm model}(k; D_A, H, f, \cdots)$$

free parameter

imperfect model or aggressive use of PT may lead to a biased result

Complication & limitation

Q Suppose possible deviation from GR,
can we say something about gravity beyond GR ?

- Perturbation theory (PT) template at *quasilinear* scales

We need an underlying theory of gravity to control nonlinear systematics (i.e., RSD & gravitational growth)

…… so far, we have adopted GR

- Scale-independent structure growth

Unlike GR, (linear) growth rate is generally *scale-dependent* in modified gravity models (e.g., chameleon f(R))

…… so far, we have assumed scale-indept. 'f'

What we can address is just a consistency with GR !

Beyond consistency test of GR

AT, Koyama, Hiramatsu & Oka ('13)

To address the nature of gravity at quasi-linear scales,

- develop new template in modified gravity (MG) model
- characterize scale-dependent structure growth

Testbed study

including effects of nonlinear RSD & gravitational growth

Based on perturbation theory (PT),

we develop a new power spectrum template in f(R) gravity

Using N-body sim.

- validity check of PT template
- comparison to GR-based template

Application to SDSS-II DR7 data → $|f_{R,0}| \leq 1.5 \times 10^{-4} \quad (1\text{-}\sigma)$

f(R) gravity

$$S = \int d^4x \sqrt{-g} \left\{ \frac{R + f(R)}{2\kappa^2} + L_{\rm m} \right\}$$

Starobinsky ('07)
Hu & Sawicki ('07)

Gravity model that explains late-time cosmic acceleration w/o Λ, while evading solar-system constraint via *Chameleon mechanism*

(Khoury & Weltman '04)

★ $$f(R) \simeq -16\pi G \rho_\Lambda + |f_{R,0}| \frac{R_0^{n+1}}{n R^n}$$

$|R| \gg m^2$ $\quad$ $|f_{R,0}| \ll 1$

ΛCDM-like cosmic expansion

★ New scalar d.o.f coupled to gravity :

Scale-dependent linear growth

$$\frac{1}{a^2}\nabla^2\psi = 4\pi G \bar{\rho}_m \delta - \frac{1}{2a^2}\nabla^2\varphi \quad \varphi = \delta f_R \;\; ; f_R \equiv \frac{d f(R)}{dR}$$

Newton potential (ψ)

Perturbation theory in MG models

Koyama, AT & Hiramatsu ('09)

- **Matter sector** : (Standard) fluid system
- **Gravity sector**: Theory looks like Brans-Dicke (BD) gravity on sub-horizon scales

Continuity eq. $$\frac{\partial\delta}{\partial t}+\frac{1}{a}\nabla\cdot[(1+\delta)\,\boldsymbol{v}]=0$$

Euler eq. $$\frac{\partial\boldsymbol{v}}{\partial t}+H\boldsymbol{v}+\frac{1}{a}(\boldsymbol{v}\cdot\nabla)\boldsymbol{v}=-\frac{1}{a}\nabla\psi$$

Poisson eq. $$\frac{1}{a^2}\nabla^2\psi=4\pi\,G\,\overline{\rho}_m\,\delta-\frac{1}{2a^2}\nabla^2\varphi$$

BD scalar

E.O.M for BD scalar $$(3+2\omega_{\rm BD})\frac{1}{a^2}\nabla^2\varphi=8\pi\,G\,\overline{\rho}_m\,\delta-\mathcal{I}(\varphi)$$

Nonlinear potential *a la* Chameleon

In f(R) gravity,

$$\omega_{\rm BD}=0$$

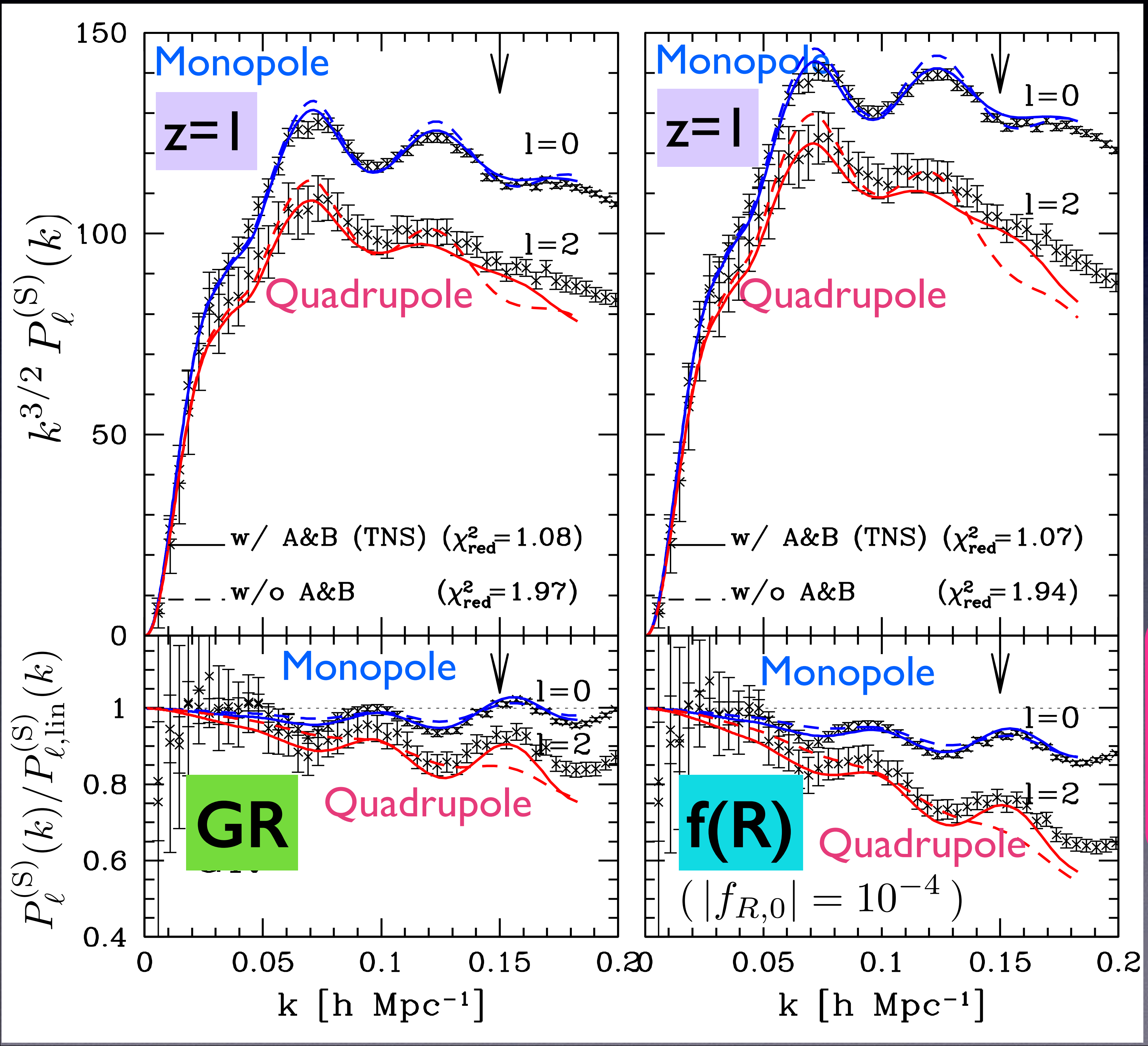
$$\varphi=\delta f_R\,;\,f_R\equiv\frac{d\,f(R)}{dR}$$

$$\Psi_a\equiv\begin{pmatrix}\delta\\ \theta\end{pmatrix}=\Psi_a^{(1)}+\Psi_a^{(2)}+\Psi_a^{(3)}+\cdots \;\Rightarrow\; \langle\Psi_a(\boldsymbol{k})\Psi_b(\boldsymbol{k}')\rangle=(2\pi)^3\delta_D(\boldsymbol{k}+\boldsymbol{k}')\,P_{ab}(k)$$

Redshift-space power spectrum

N-body data: Jennings et al. ('12)

AT, Koyama, Hiramatsu & Oka ('13)



N-body vs PT template (at 1-loop order)

$$f(R) \simeq -16\pi G \rho_\Lambda + |f_{R,0}| \frac{R_0^2}{R}$$

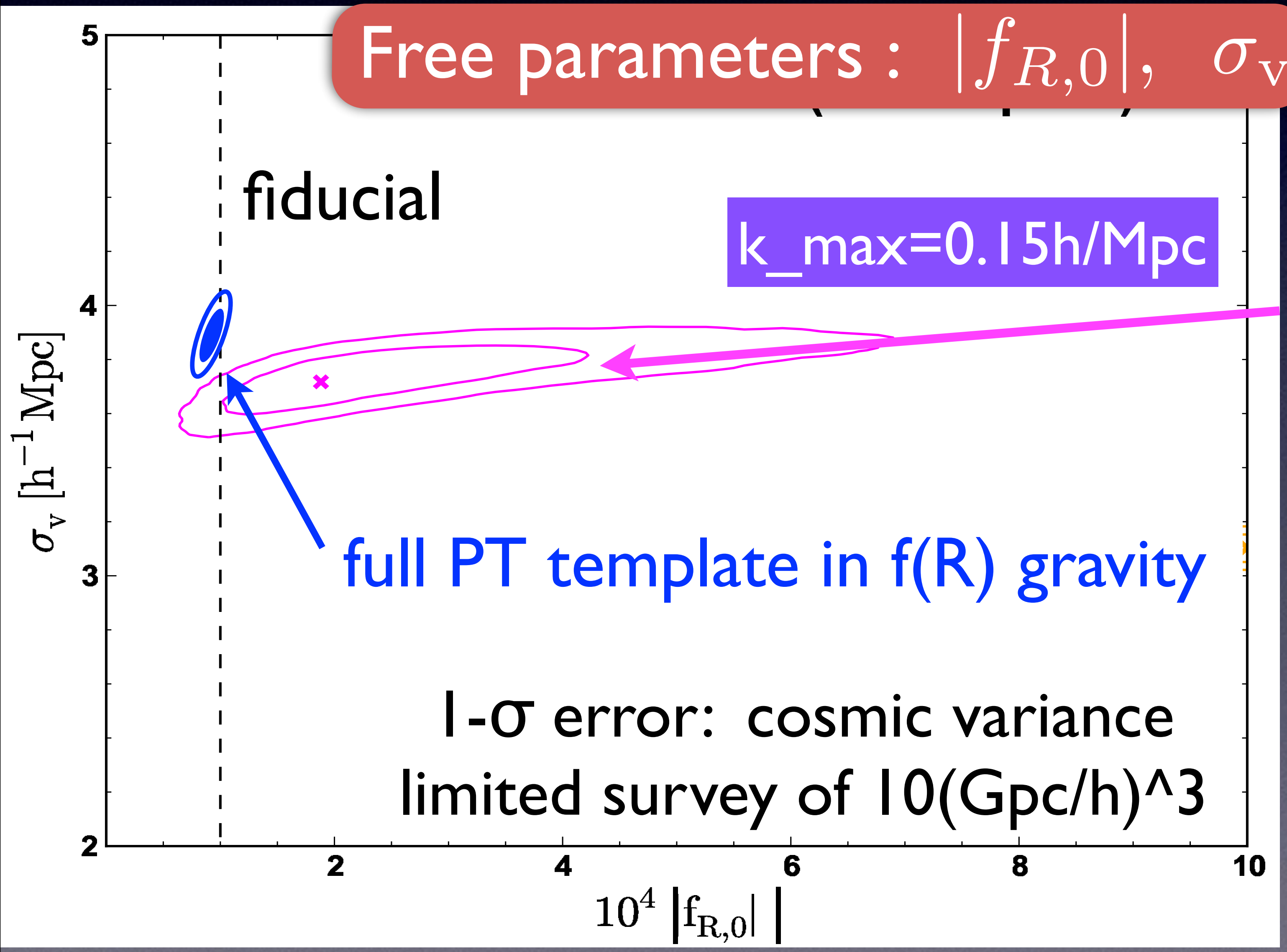
$|f_{R,0}| \lesssim 10^{-4}$

—— PT template with improved model of RSD (AT, Nishimichi & Saito'10)

------ Imperfect PT model

Parameter estimation

Estimation of model parameter, $|f_{R,0}|$, in N-body simulations with PT model of f(R) gravity



GR-based template in which constant growth rate, *f*, is replaced with the scale-dependent one in f(R) gravity

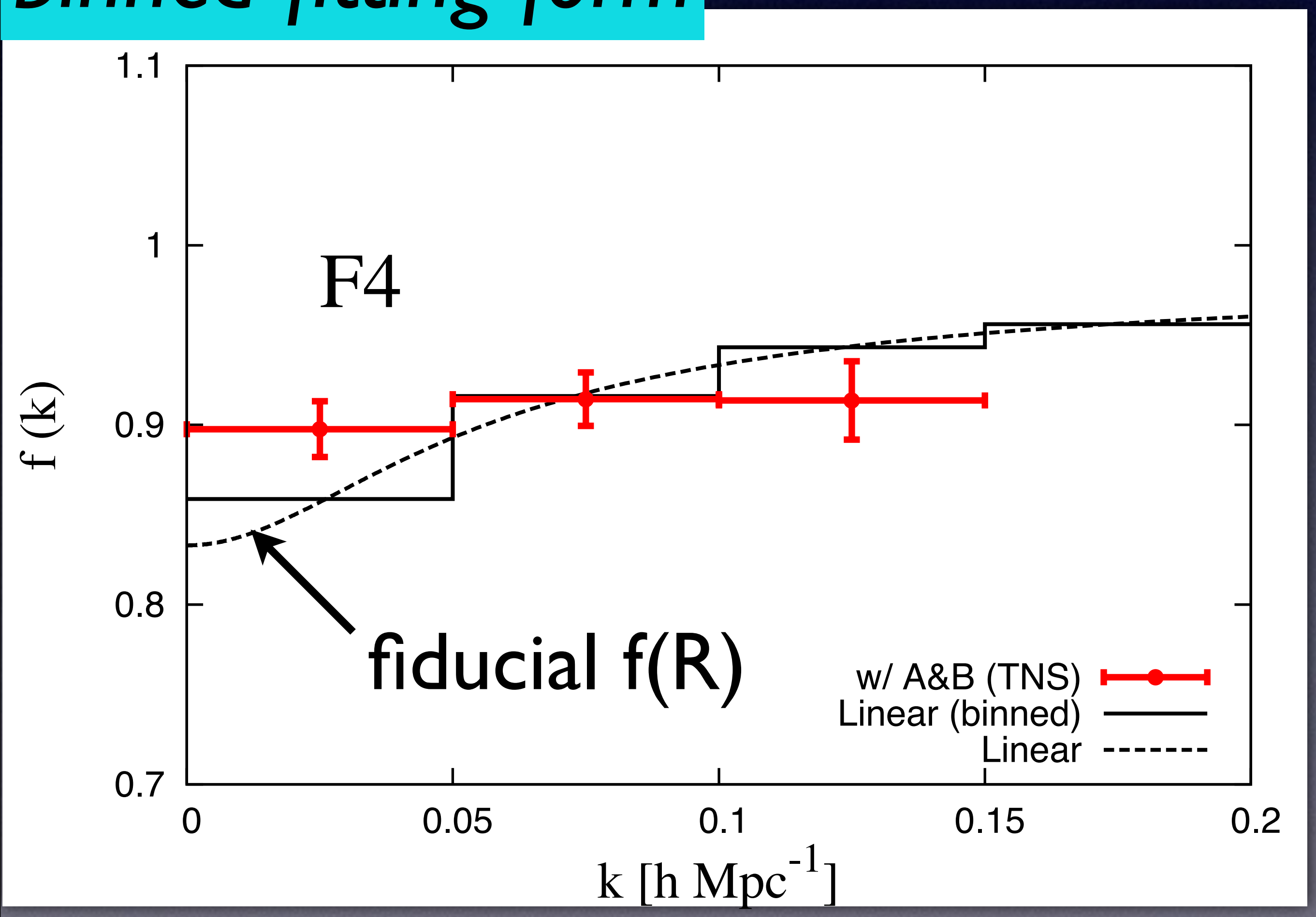
$$P_\ell^{(\mathrm{GR})}(k; f)$$

With GR-based template, constraining power is substantially reduced

Difficulty of model-independent analysis

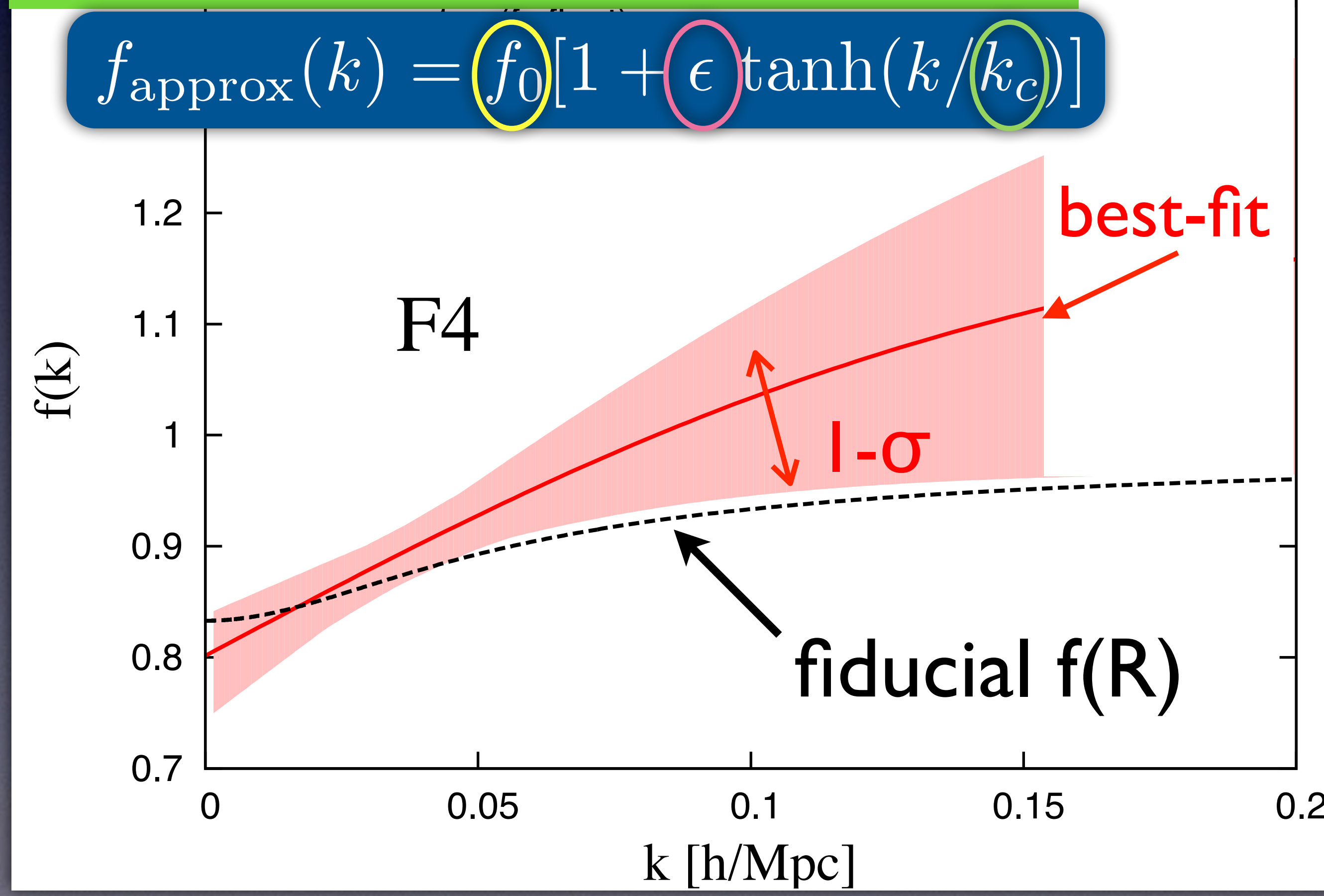
With the GR-based template, we try to characterize the scale-dept. growth rate in a parametric form, but …

binned fitting form



approximate fitting function

$$f_{\rm approx}(k) = f_0[1 + \epsilon \tanh(k/k_c)]$$



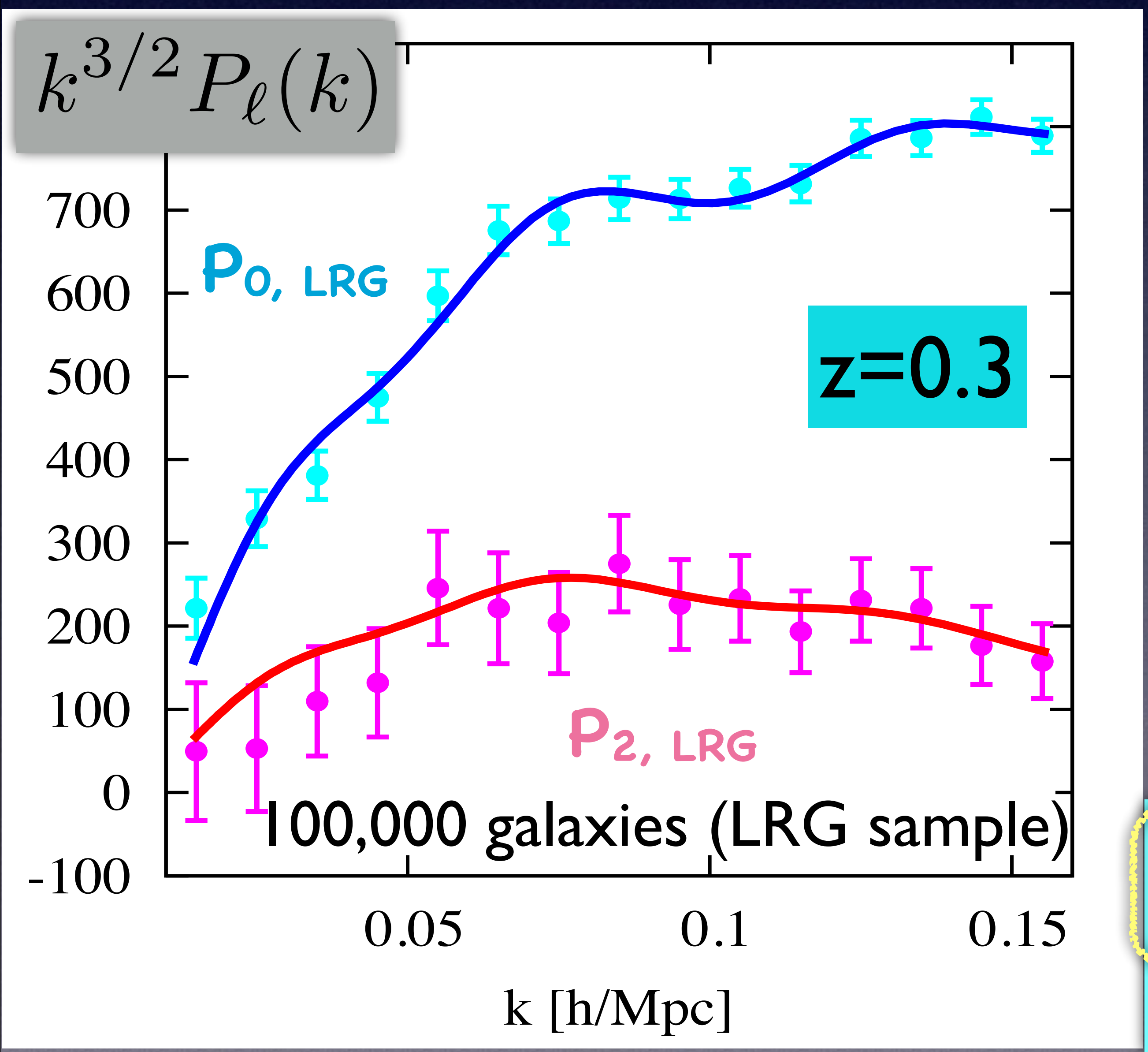
Both cases fail to reproduce fiducial *linear growth rate due to the strong parameter degeneracy*

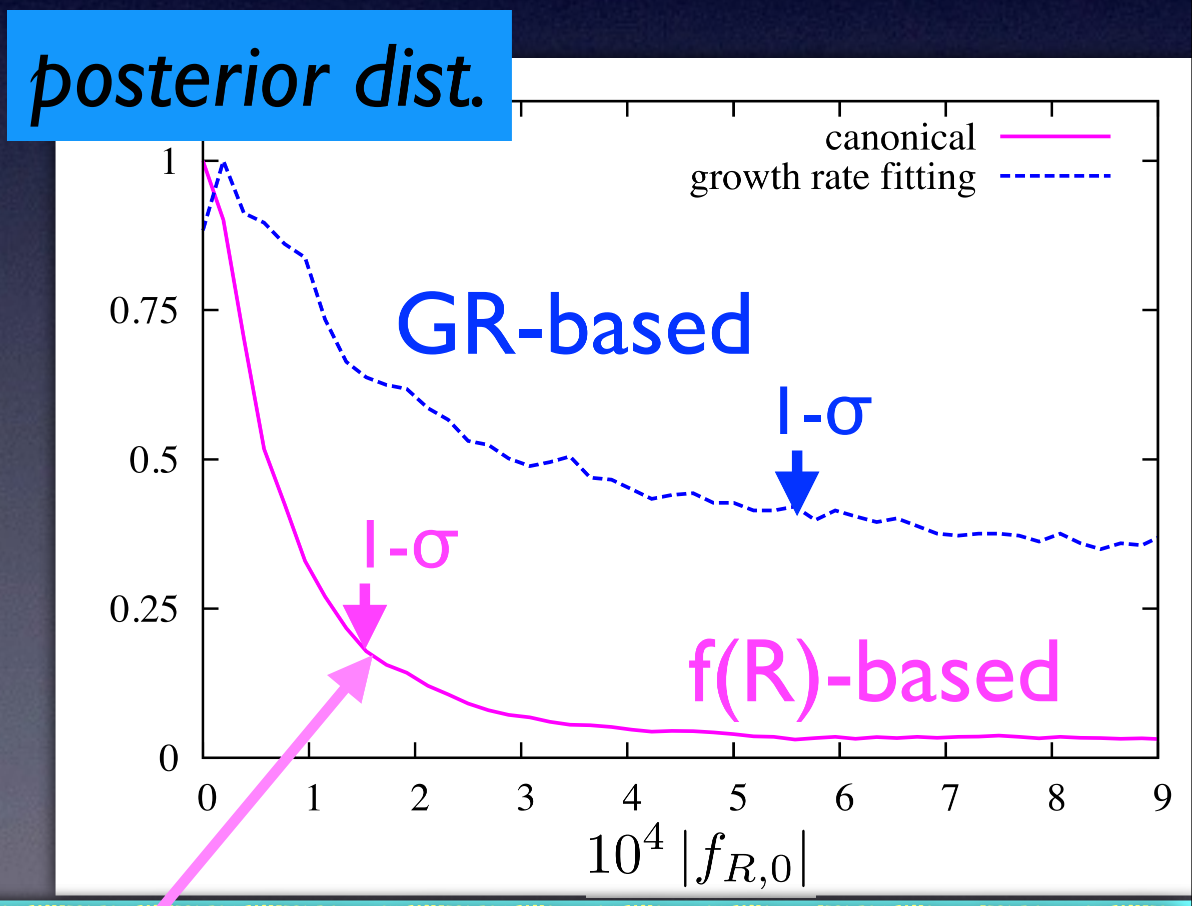
Application to SDSS-II DR7

Oka et al. (in prep.)

Use full shape of P0 & P2 to constrain $|f_{R,0}|$

# of parameters: 5 $\left(|f_{R,0}|,\ \sigma_{\rm v},\ \underline{b_0,\ A_1,\ A_2}\right)$ galaxy bias





f(R)-based template : $|f_{R,0}| \leq 1.5 \times 10^{-4}$ (1-σ)

GR-based template : $|f_{R,0}| \leq 5.6 \times 10^{-4}$

Summary

Measurements of BAO and RSD from BOSS DR10/11
give many interesting cosmological implications

While results are generally consistent with ΛCDM and GR,

- mild tension with ΛCDM
- weaker gravity than GR at z<1?

Need to consider the analysis beyond consistency check of GR

Testbed study in f(R) gravity

✓ robust & unbiased test of gravity is shown to be possible

but

✓ model-independent characterization is found to be difficult

✓ robust constraint on f(R) gravity : $|f_{R,0}| \leq 1.5 \times 10^{-4} \quad (1\text{-}\sigma)$