Test of Gravity w/ Weak Lensing & Redshift-Space Distortions

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DE Workshop, Ringberg Castle, June 2012

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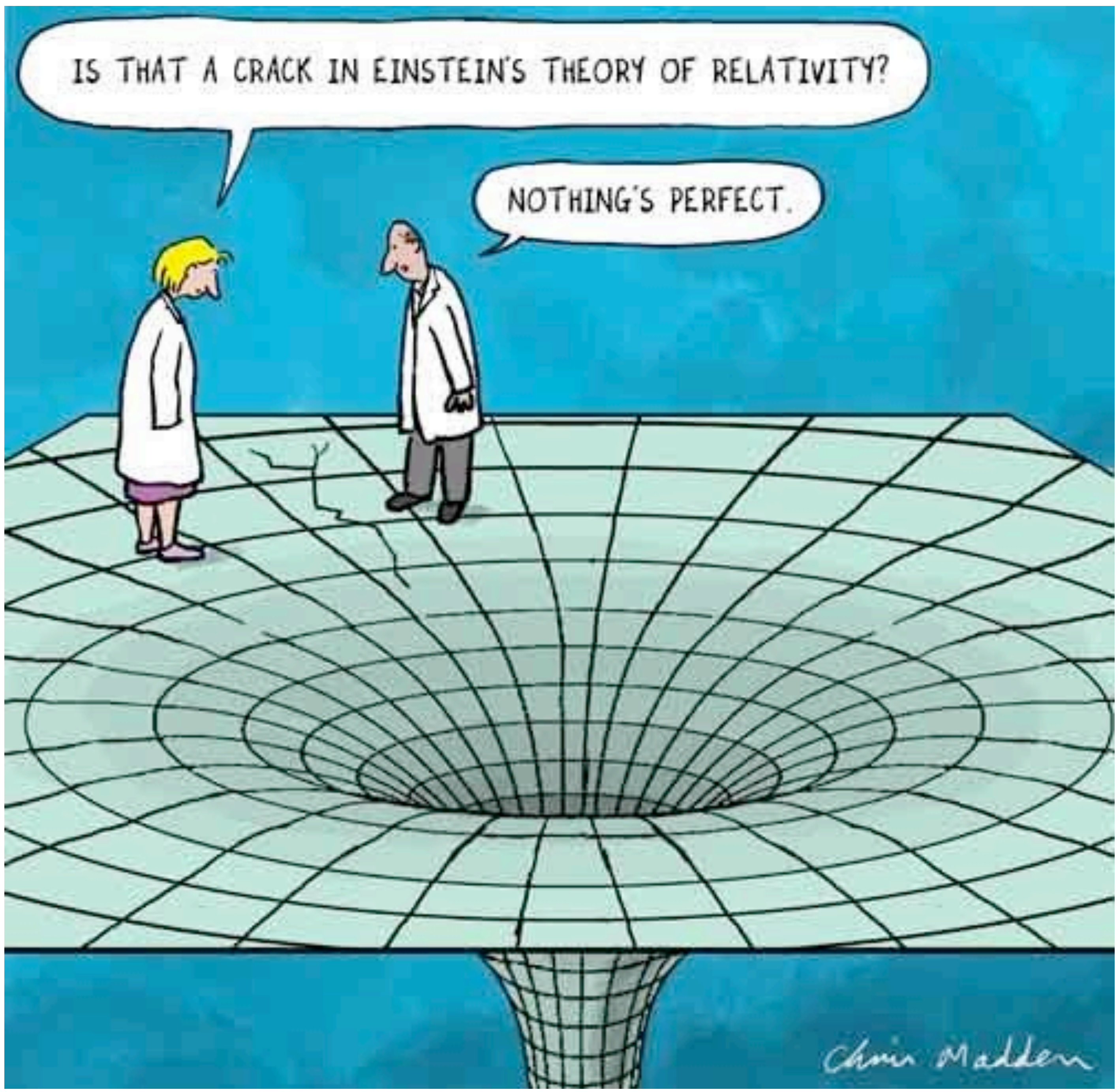
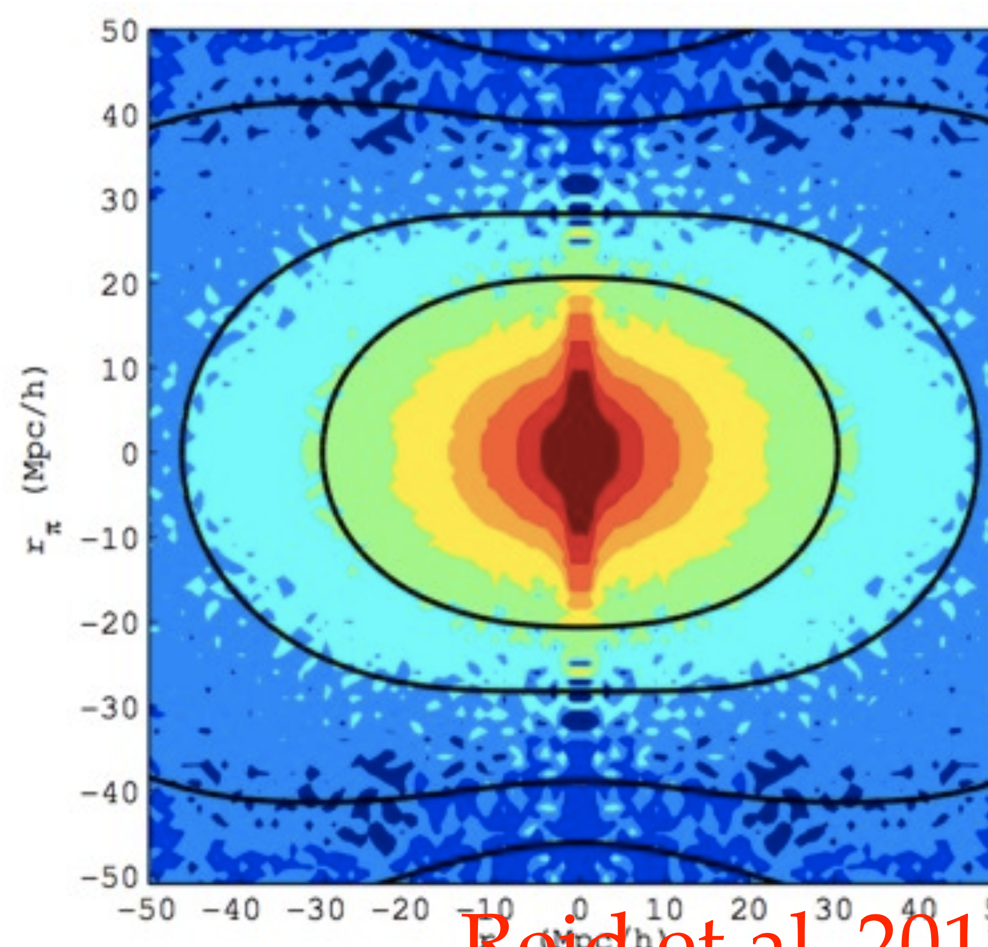
RR et al. 2010, *Nature*, **464**, 256-258

Test of GR: E_G



HST WFPC



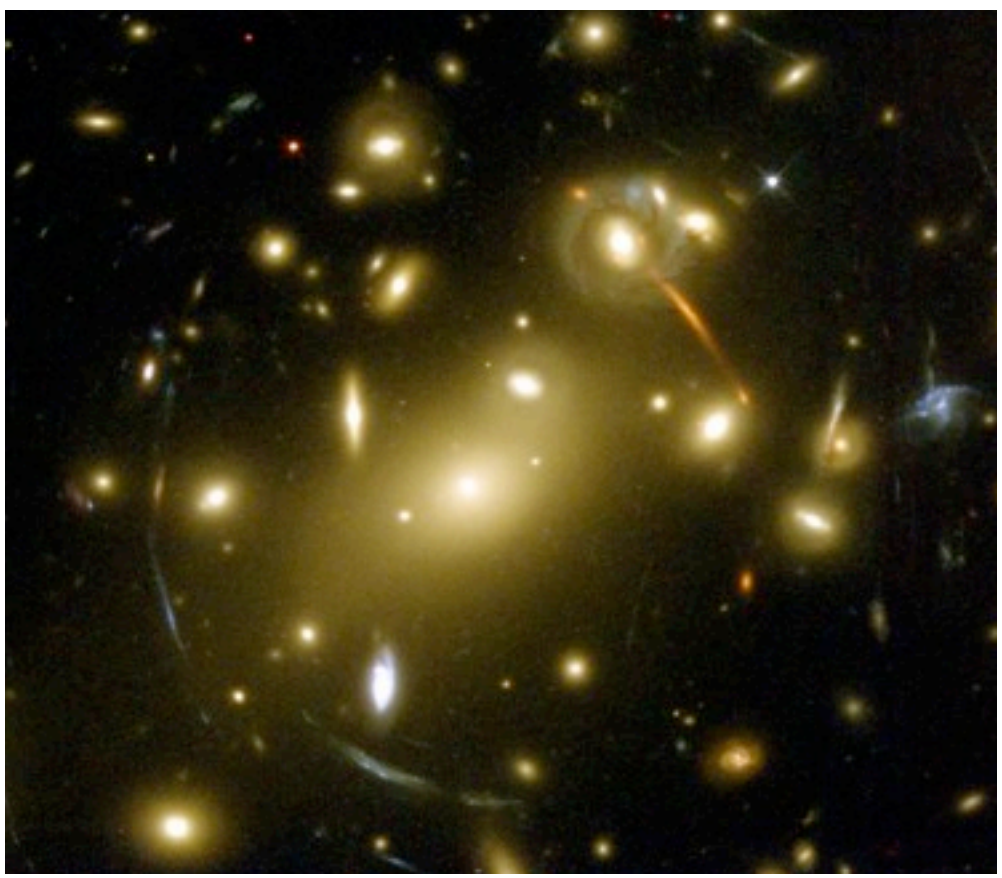
Reid et al. 2012

E_G in a nutshell

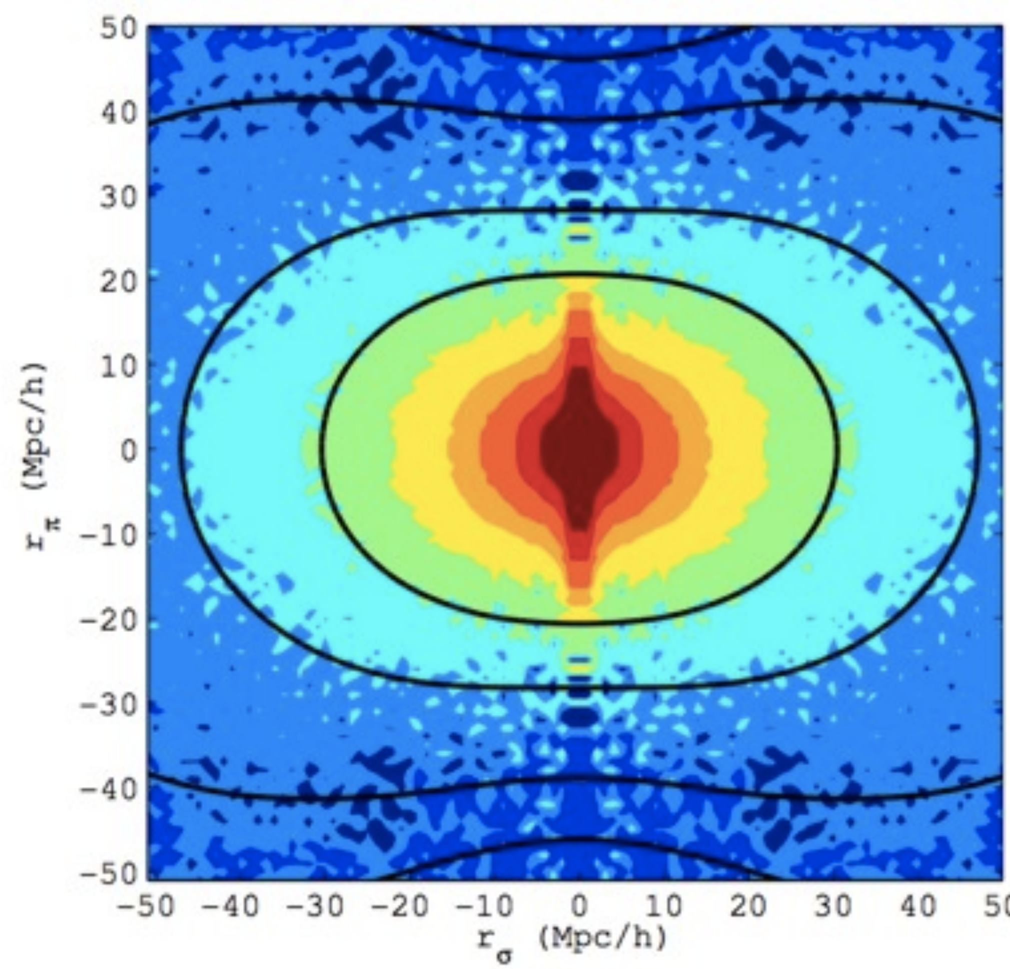
Zhang et al. (2007)

Metric: $ds^2 = -(1+2\Psi)dt^2 + (1-2\Phi)a^2(t)d\vec{x}^2$

- lensing → $(\Phi+\Psi)$
- RSD → Ψ



HST WFPC



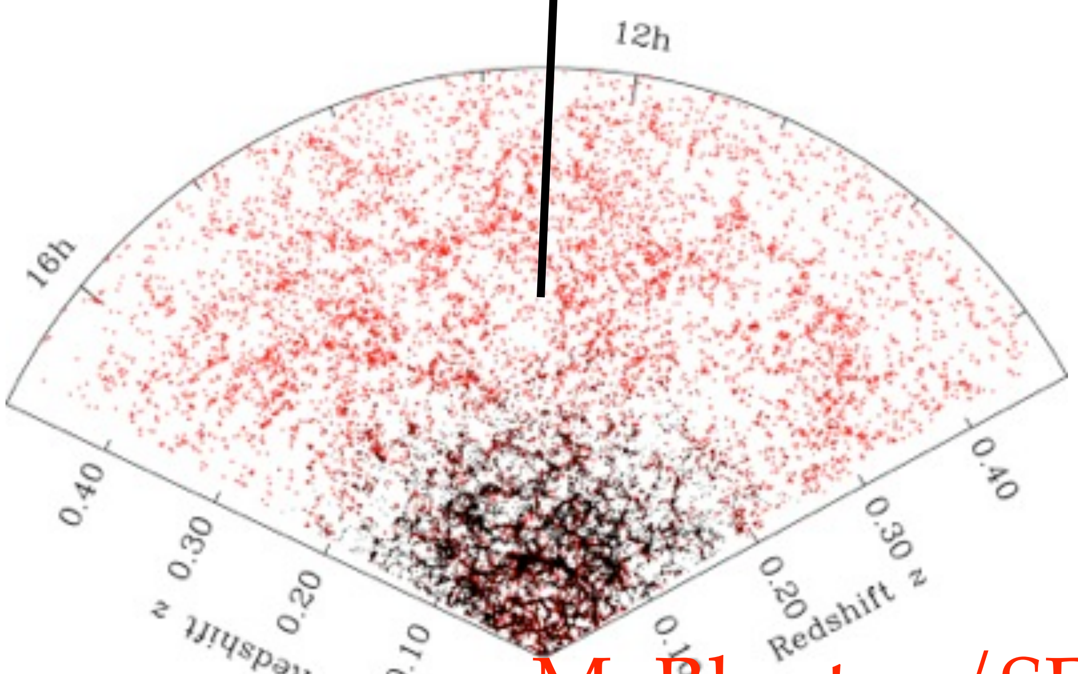
Reid et al. 2012

E_G in a nutshell

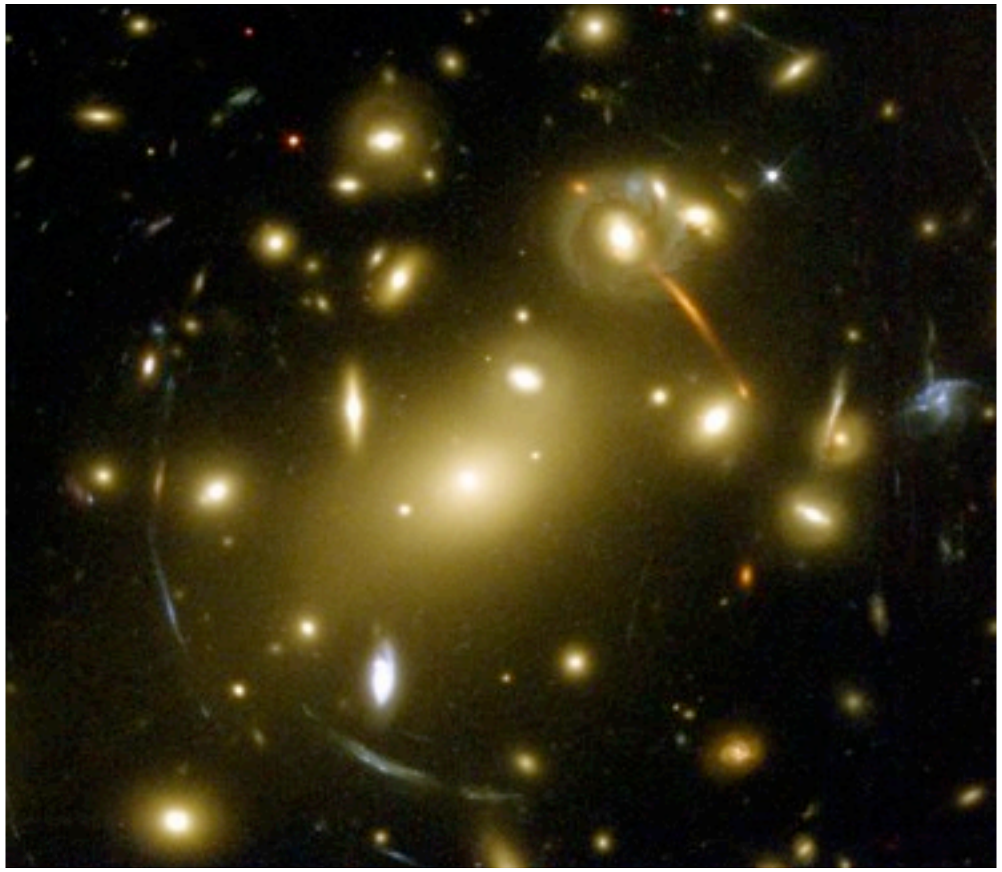
Zhang et al. (2007)

$$E_G \sim \frac{\text{(gravitational lensing)}}{\text{(structure growth)(galaxy clustering)}}$$

$$E_G = \frac{P_{\delta\nabla(\Psi+\Phi)}}{\beta P_{\delta\delta}}$$



M. Blanton/SDSS



HST WFPC

E_G in a nutshell

Zhang et al. (2007)

$$E_G \sim \frac{\text{(gravitational lensing)}}{\text{(structure growth)(galaxy clustering)}}$$

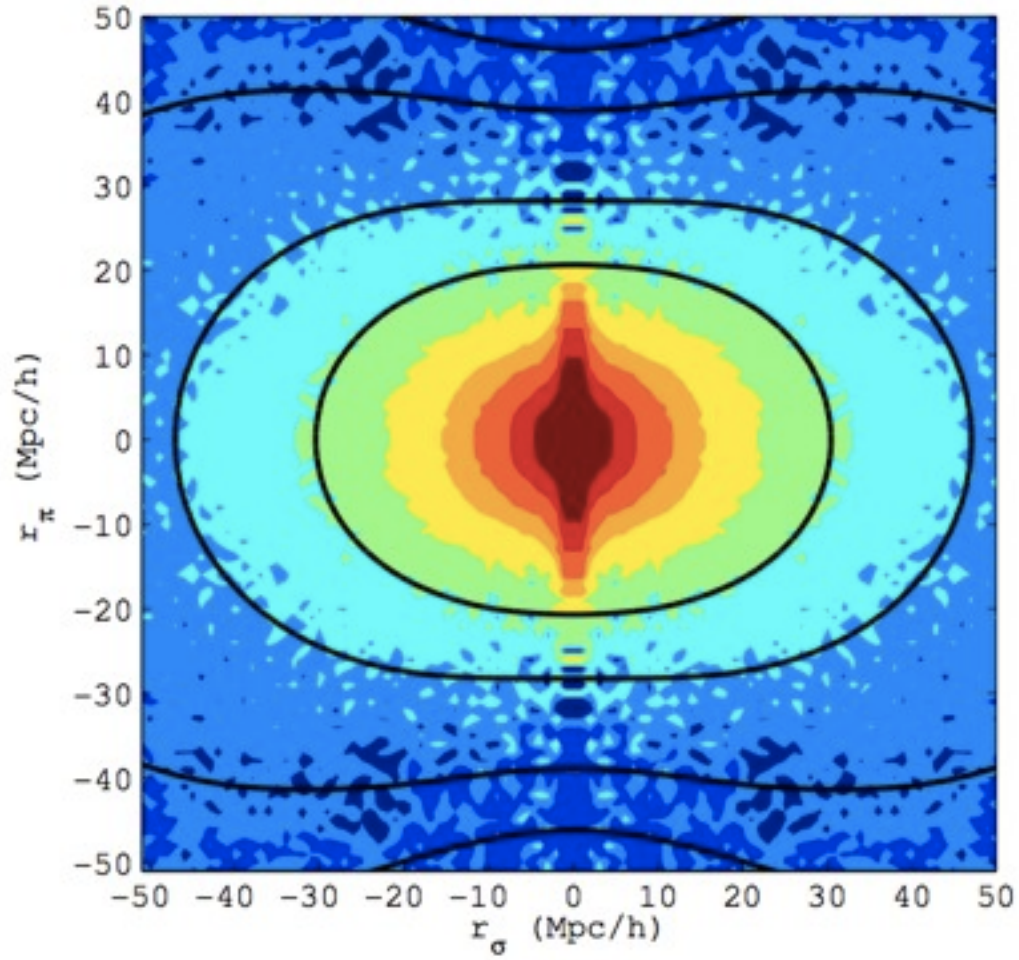
$$E_G = \frac{P_{\delta\nabla(\Psi+\Phi)}}{\beta P_{\delta\delta}}$$

where

$\beta = f / b$

$f = d(\ln D)/d(\ln a)$

$$f(z) \approx [\Omega_m(z)]^\gamma$$ γ=0.55 (GR)



Reid et al. 2012

E_G in a nutshell

Zhang et al. (2007)

KEY POINT I: E_G is *insensitive* to galaxy bias

$$E_G = \frac{P_{\delta\nabla(\Psi+\Phi)}}{\beta P_{\delta\delta}} \Rightarrow E_G \propto \frac{1}{b^{-1}}\frac{bA^2}{b^2A^2}$$

Nuisance parameters: b and A cancel out!

E_G in a nutshell

Zhang et al. (2007)

KEY POINT II: E_G is *sensitive* to deviations from GR

$$E_G = \frac{P_{\delta\nabla(\Psi+\Phi)}}{\beta P_{\delta\delta}}$$

- via ratio of potentials ($\mathbf{\Phi}/\mathbf{\Psi} \neq 1$)
- via growth of structure $f(z) = [\mathbf{\Omega}_m(z)]^{\gamma}$

E_G in a nutshell

Zhang et al. (2007)

TEST: Look for deviations from GR+ΛCDM prediction.

$$E_G = \frac{P_{\delta\nabla(\Psi+\Phi)}}{\beta P_{\delta\delta}}$$

assuming GR+ΛCDM

$$E_G = \frac{\Omega_{m,0}}{f(z)} \approx \frac{\Omega_{m,0}}{[\Omega_m(z)]^{0.55}}$$

= 0.41 ± 0.03 at z=0.3

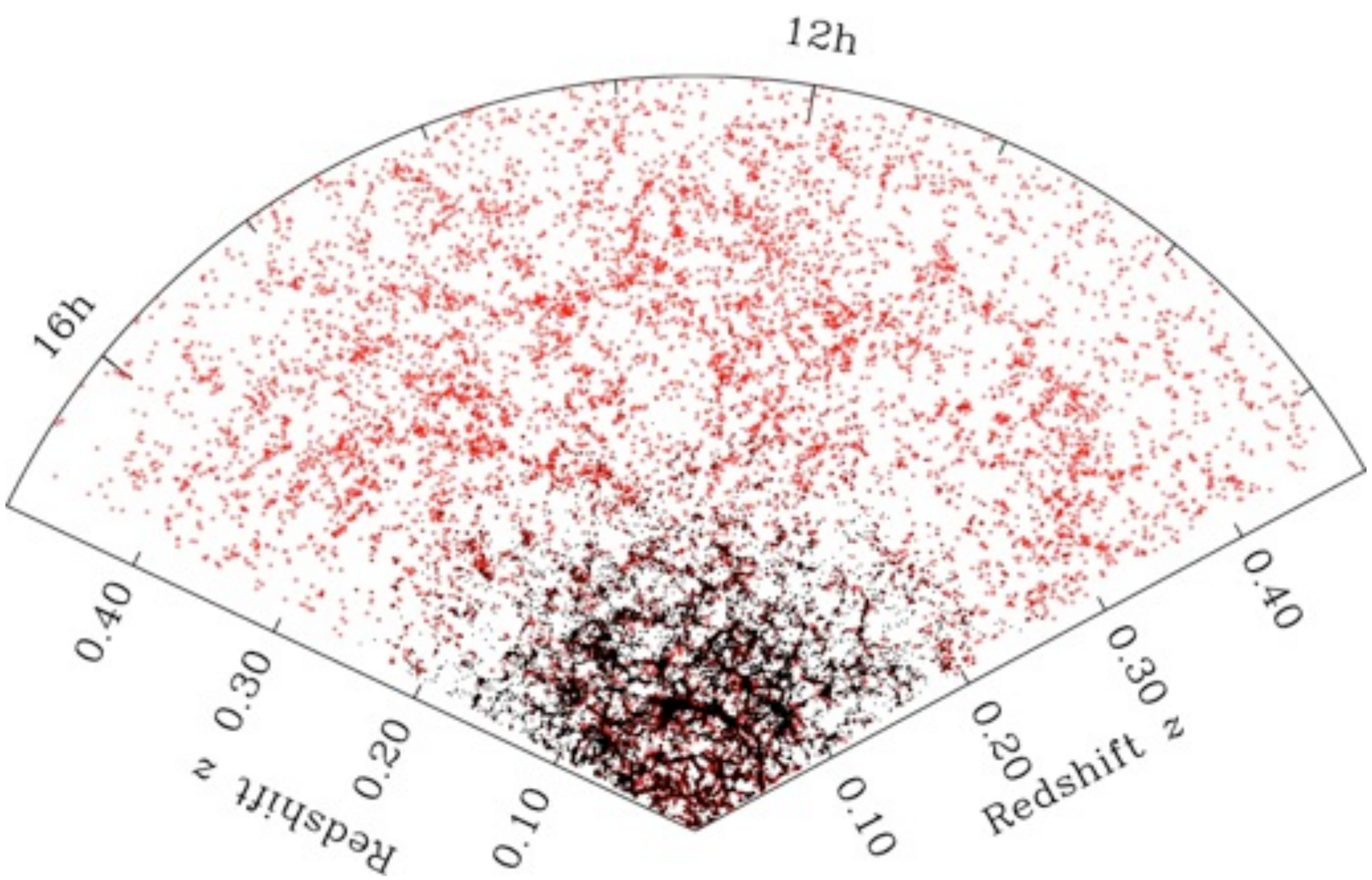
If deviation is found, signature of:

- Modified Gravity *or*
- DE has anisotropic stress *or*
- DE is clustered *or*...

Measuring E_G

Reyes et al. (2010)

Galaxy sample: SDSS luminous red galaxies



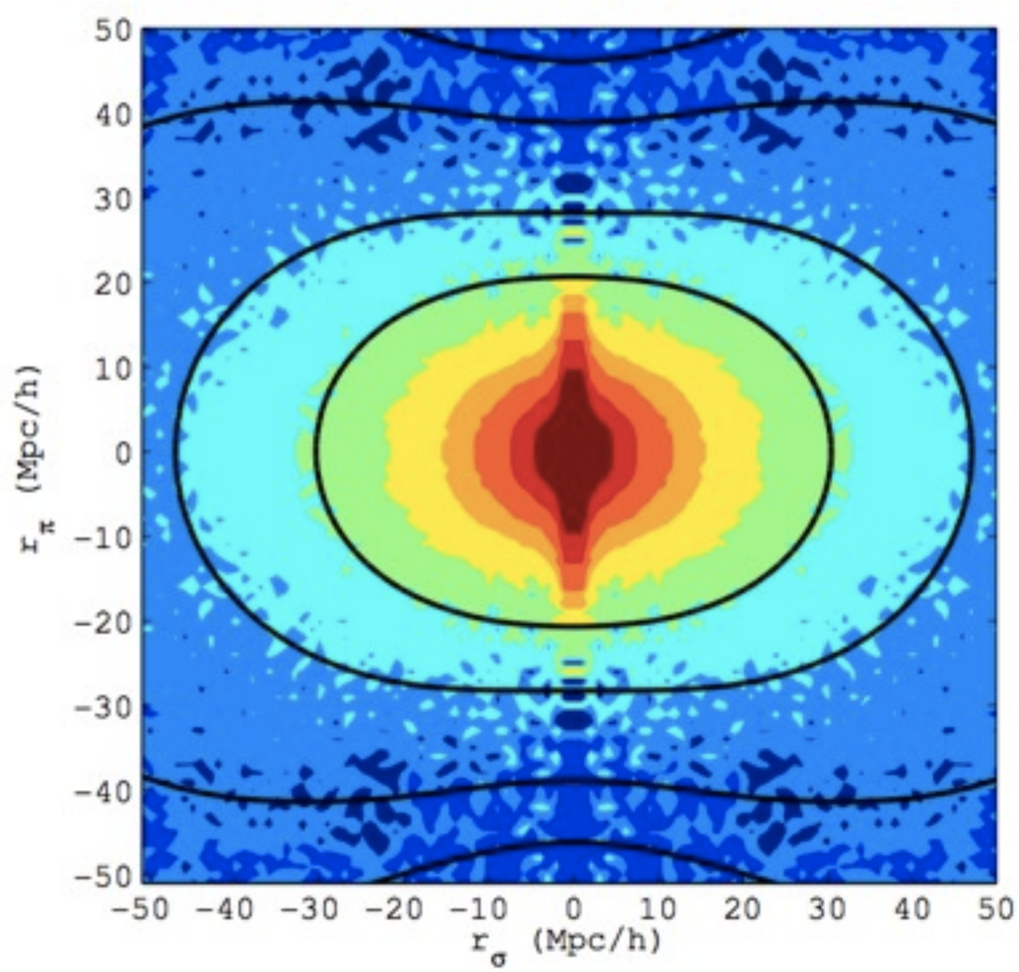
M. Blanton / SDSS

- LRG color-magnitude cuts by Eisenstein et al. (2001)
- $-23.2 < M_g < -21.2$ mag (k-corrected to $z = 0.3$)
- 70,205 LRGs from DR6
- 5,215 sq. deg
- $1.0\ h^{-3}\ \mathrm{Gpc}^3$
- $\langle z \rangle = 0.32$ (0.16–0.48)

Measuring E_G

Reyes et al. (2010)

Measurement I: Redshift-Space Distortions



Reid et al. 2012

Fits to the power spectra of 58,000 SDSS DR4 LRGs (Tegmark et al. 2006):

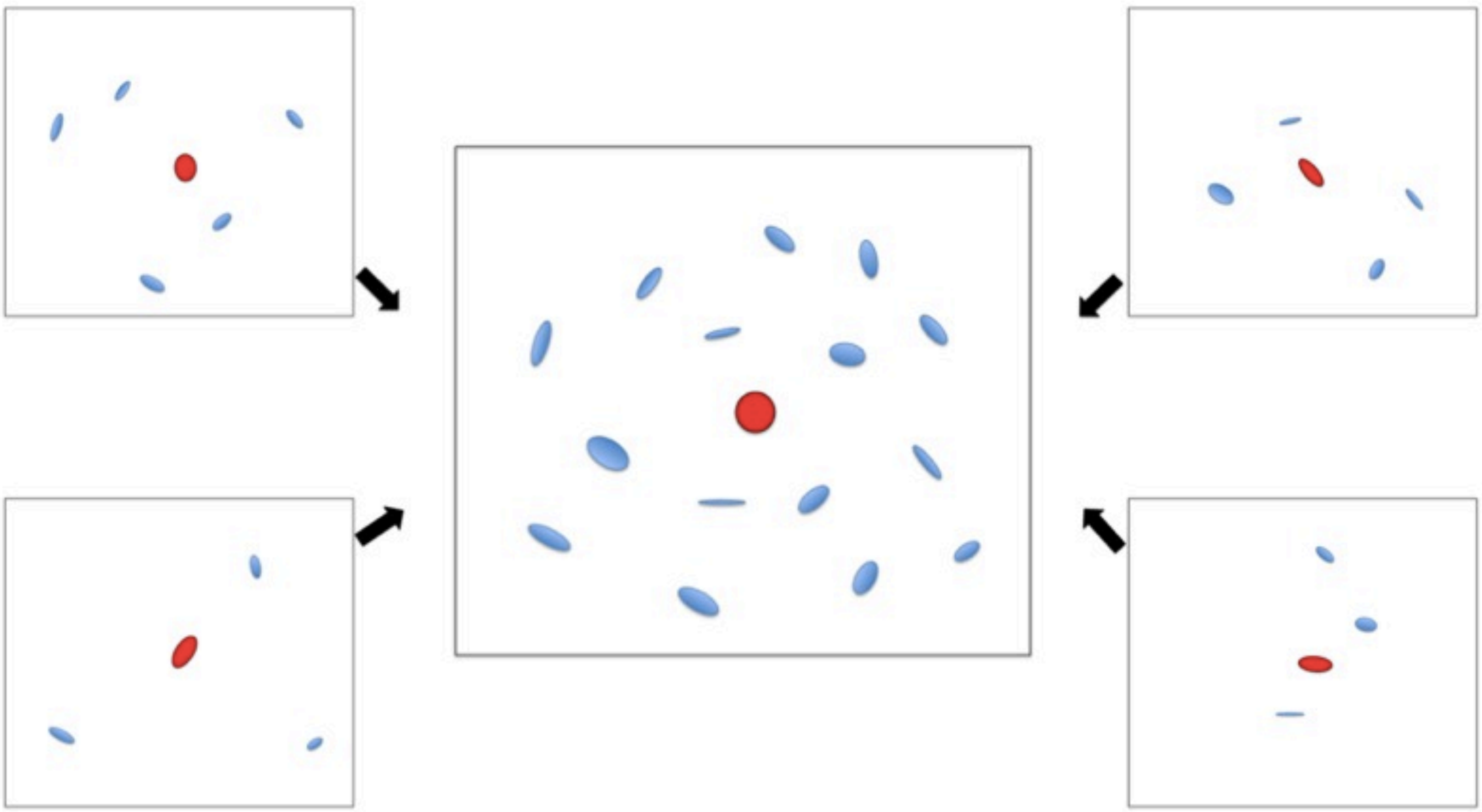
$$P_{gv}(k) = \beta r_{gv} P_{gg}(k)$$
$$P_{vv}(k) = \beta^2 P_{gg}(k)$$

$\rightarrow \beta = 0.309 \pm 0.035$ at $z = 0.3$ and scales $k = 0.01 - 0.09h/\mathrm{Mpc}$

Measuring E_G

Reyes et al. (2010)

Measurement II: Stacked weak lensing

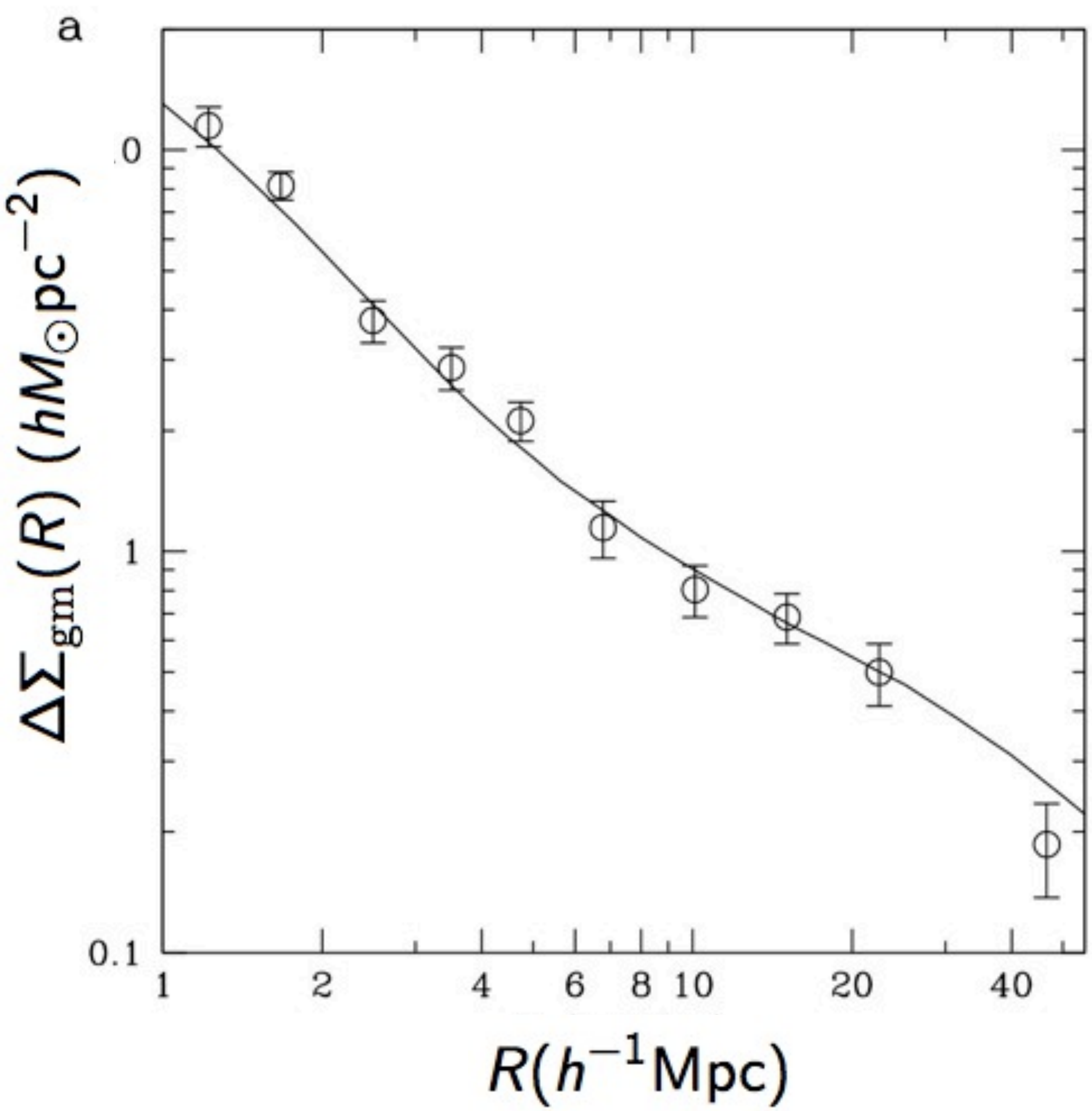


M. Swanson

Measuring E_G

Reyes et al. (2010)

Measurement II: Stacked weak lensing



Galaxy-galaxy lensing:

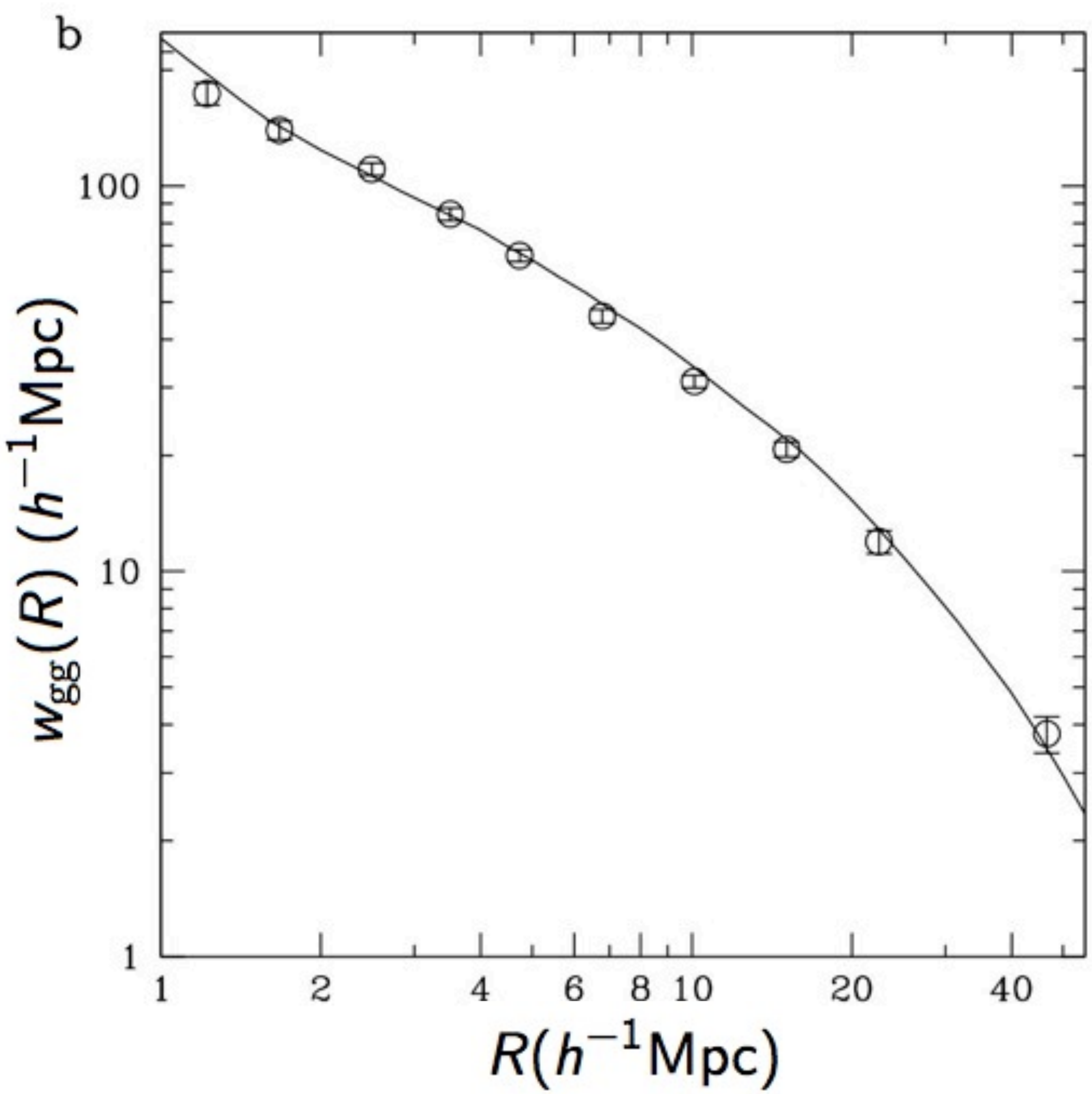
- correlation of shear of background galaxies with mass of foreground galaxies
- stacking over many galaxies yields good S/N
- measures the **surface mass density contrast**

$$\Delta\Sigma_{\rm gm} \equiv \bar{\Sigma}(<R) - \Sigma(R) = \Sigma_{\rm crit} \times \gamma_t(R)$$

Measuring E_G

Reyes et al. (2010)

Measurement III: Galaxy clustering



2-point correlation function:

$[1 + \xi_{gg}(r)]dV$ is the probability of finding two galaxies a distance r apart over that for a random distribution.

Projected 2-point correlation function:

$$w_{gg}(R) = \int \xi_{gg}(\sqrt{R^2 + \chi^2})d\chi$$

Refining E_G (I)

Reyes et al. (2010)

Baldauf et al. (2010)

ADSD statistic Υ: removing small-scale contribution

$$E_G = \frac{P_{\delta\nabla(\Psi+\Phi)}}{\beta P_{\delta\delta}}$$

$$\Rightarrow$$

$$E_G(R) = \frac{1}{\beta}\frac{\Upsilon_{\mathrm{gm}}(R)}{\Upsilon_{\mathrm{gg}}(R)}$$

Refining E_G (I)

Reyes et al. (2010)

Baldauf et al. (2010)

ADSD statistic Υ: removing small-scale contribution

To remove the contribution from small scales, we define the ADSD $\Upsilon_{\rm gm}$:

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

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

$\Upsilon_{\rm gg}(R)$ is defined similarly:

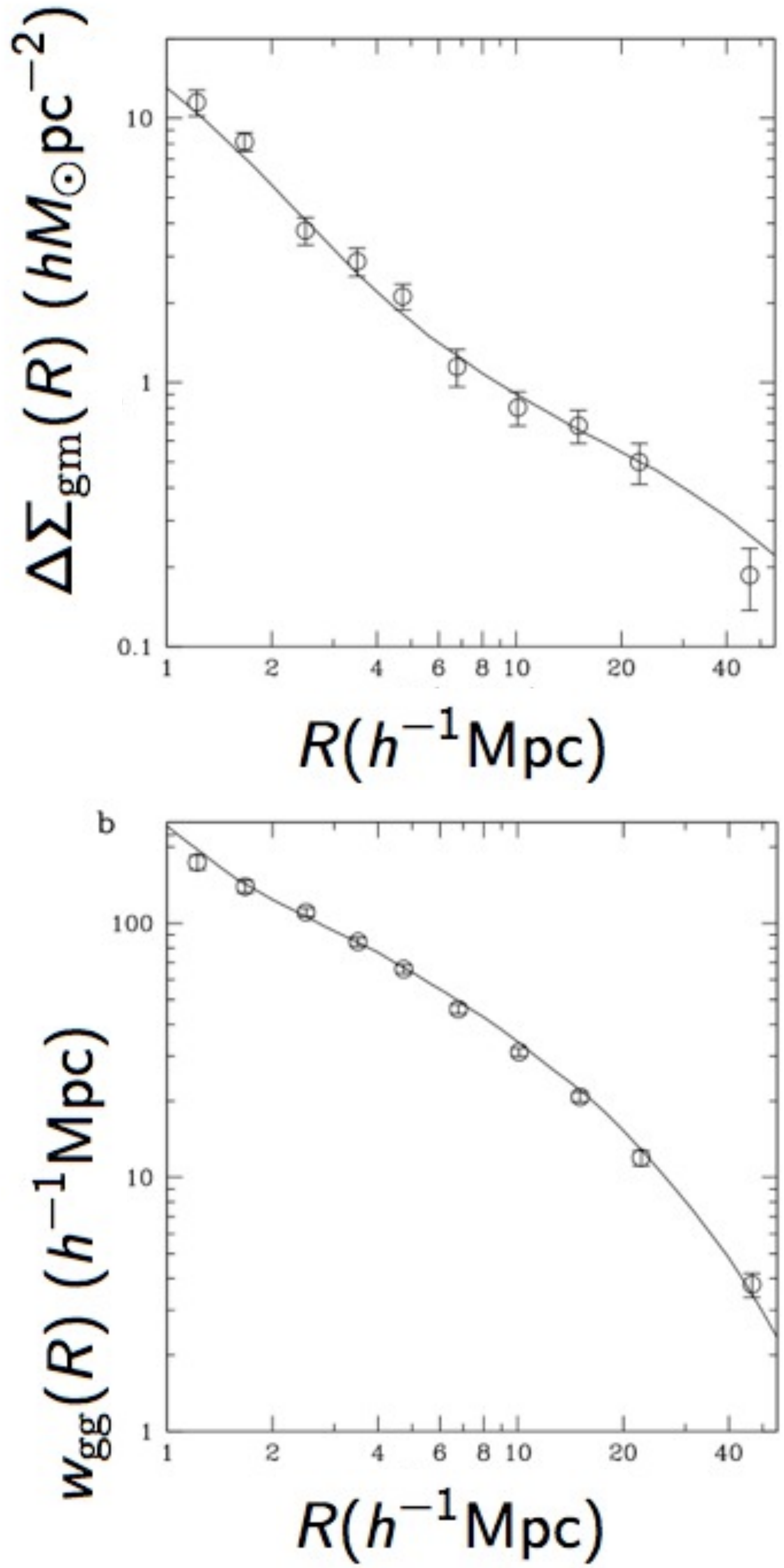
$$\Upsilon_{\rm gg}(R) \equiv \rho_{\rm c}\left[\frac{2}{R^2}\int_{R_0}^{R} dR' R' w_{\rm gg}(R') - w_{\rm gg}(R) + \left(\frac{R_0}{R}\right)^2 w_{\rm gg}(R_0)\right]$$

Refining E_G (II)

Systematic corrections:

Mock galaxy catalogs:

- 8 Zurich horizon simulations (Smith et al. 2009)
  - $1500 h^{-1}$Mpc box
  - $N_\mathrm{p} = 750^3$ DM particles
  - $M_\mathrm{DM} = 5.6 \times 10^{11} h^{-1} M_\odot$
- N-body code GADGET-II
- FoF halo finder ($b = 0.2$)
- Mock galaxies assigned to haloes via HOD model that best matches the observed $\Delta\Sigma_\mathrm{gm}$ and w_gg.

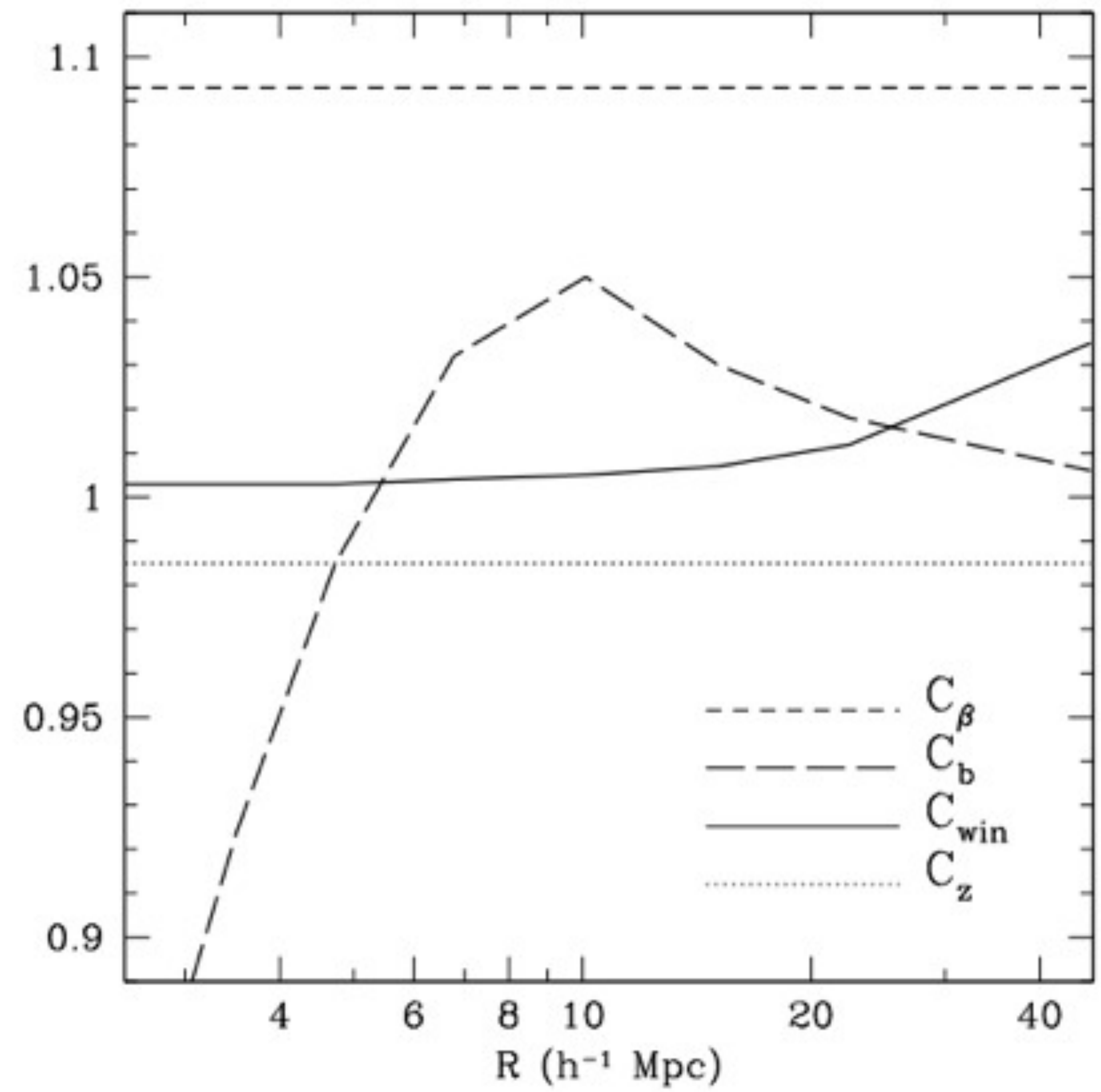


Refining E_G (II)

Reyes et al. (2010)

Systematic corrections:

- $C_\beta = 1.09$ corrects for the over-estimation in β due to effect of FOG compression
- C_b corrects for the scale-dependence of galaxy bias
- $C_{\rm win}$ corrects for the difference in the lensing and clustering window functions
- C_z corrects for the lower effective redshift of the lensing signal



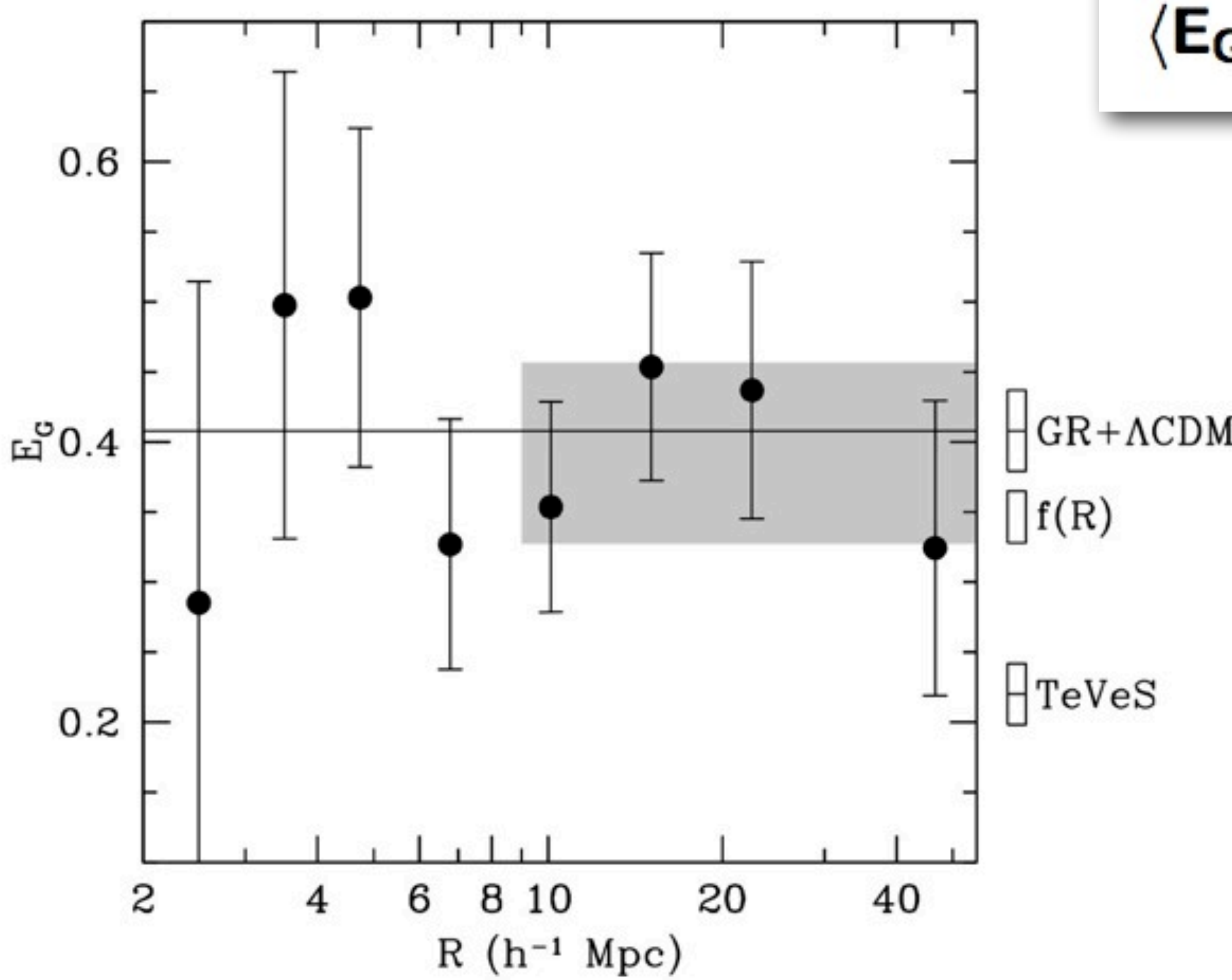
→ systematic effects ~ 5-10%

< 16% statistical uncertainty in E_G

E_G measured

Reyes et al. (2010)

Finally:



$$\langle \mathbf{E_G} \rangle = \mathbf{0.392 \pm 0.065 (16\%)}$$

at $z = 0.32$

and $R = 10h^{-1}$–$50h^{-1}$Mpc

→consistent with GR+ΛCDM

→rules out *a* TeVeS model by >2.5σ

Future prospects

- **larger imaging** (DES, HSC, PANSTARRS, LSST) + **spectroscopy** (EBOSS, BigBOSS, DESpec) **surveys**

→ same galaxy sample or similar population (bias *must* cancel out)

- **stacked RSD analysis** → $Y_{g\theta}(R)$ instead of *single* β

- **better handle of systematics**: scale-dependence of bias, RSD modeling, velocity bias, ...

- **theoretical predictions for alternatives to GR**: modified gravity theories, dynamical DE models