Constraining gravity on the largest scales with CMB lensing and galaxy velocities

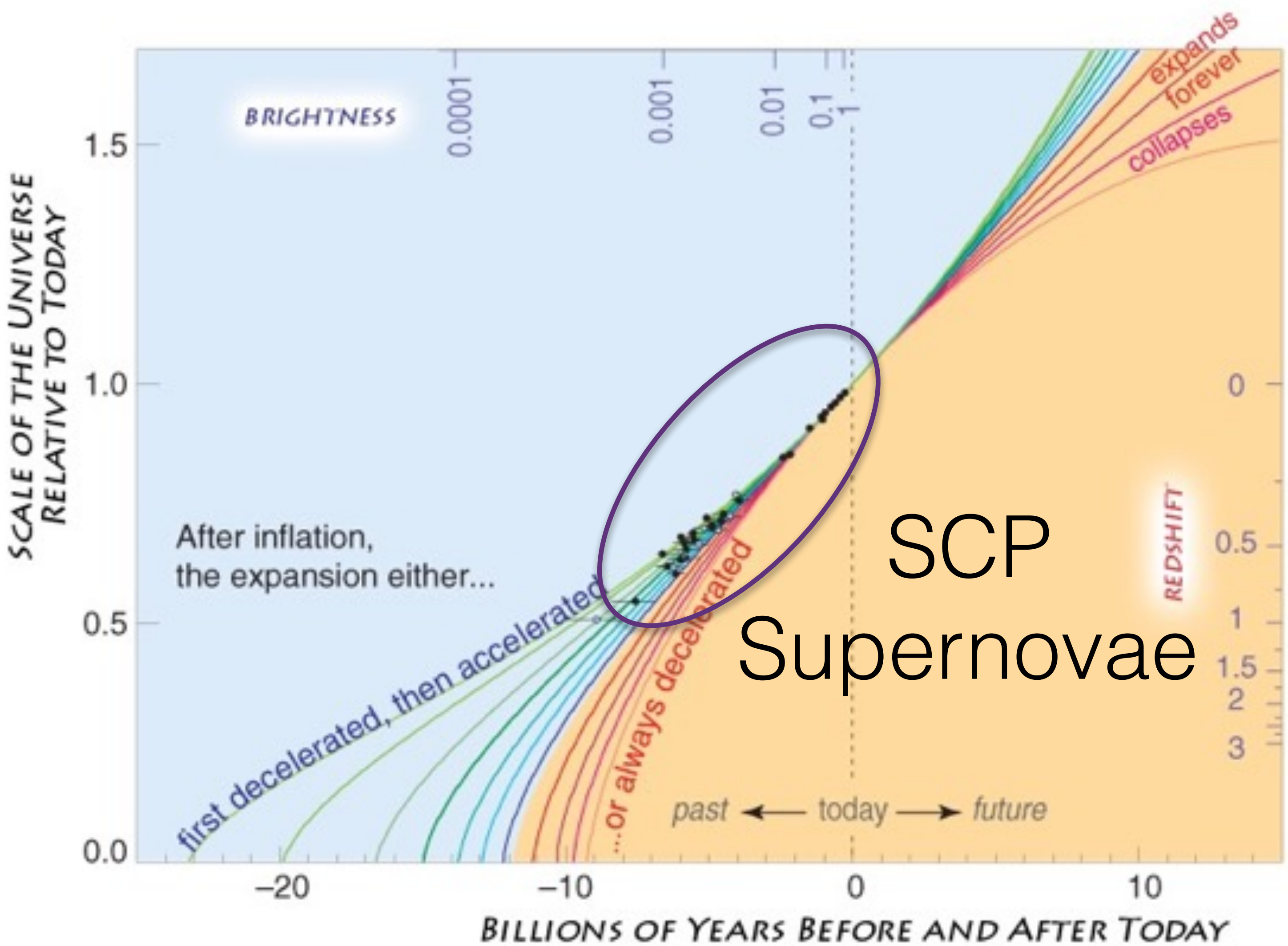
Anthony Pullen
McWilliams Center for Cosmology
Carnegie Mellon University

Shirley Ho, Shadab Alam, Siyu He (CMU)

AP, S. Alam, and S. Ho, arXiv:1412.4454 (MNRAS)
AP, S. Alam, S. He, and S. Ho - *soon on arXiv!*

BCCP Seminar, UC Berkeley/LBNL
Tuesday, Oct 20, 2015

Cosmic expansion is accelerating!



Credit: Saul Perlmutter/Physics Today

- Also seen in BAO
- Consistent with CMB
- Strange, but why?

Supernova Cosmology Project, High-Z Supernova Search Team, Sloan Digital Sky Survey, …

What's causing the acceleration?

$$G_{\mu\nu} = 8\pi \boxed{T_{\mu\nu}}$$ Change Energy

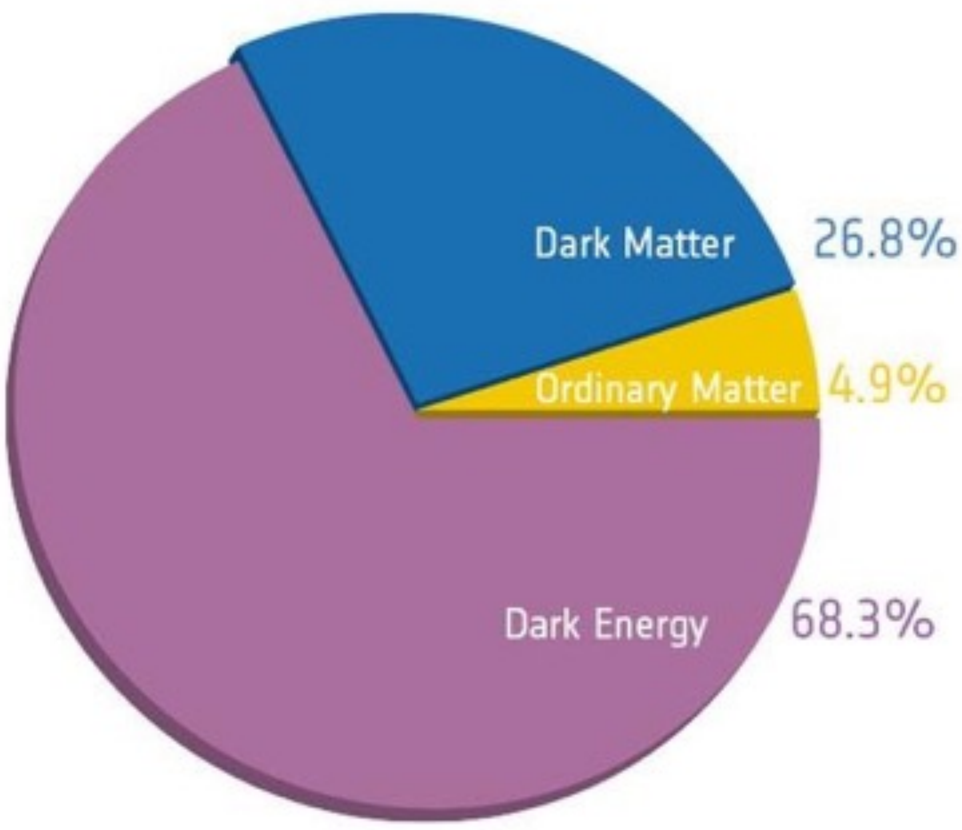
Cosmological Constant

$$p = -\rho$$

Dark Energy

$$p = w(z)\rho$$

$$w < -1/3$$



Credit: Planck Survey

Peebles & Ratra 2003

What's causing the acceleration?

Change Gravity $\boxed{G_{\mu\nu}} = 8\pi T_{\mu\nu}$

Massive Gravity

Extra Dimensions

Fifth Force

- Differs from GR on cosmological scales
- Modifies metric perturbations

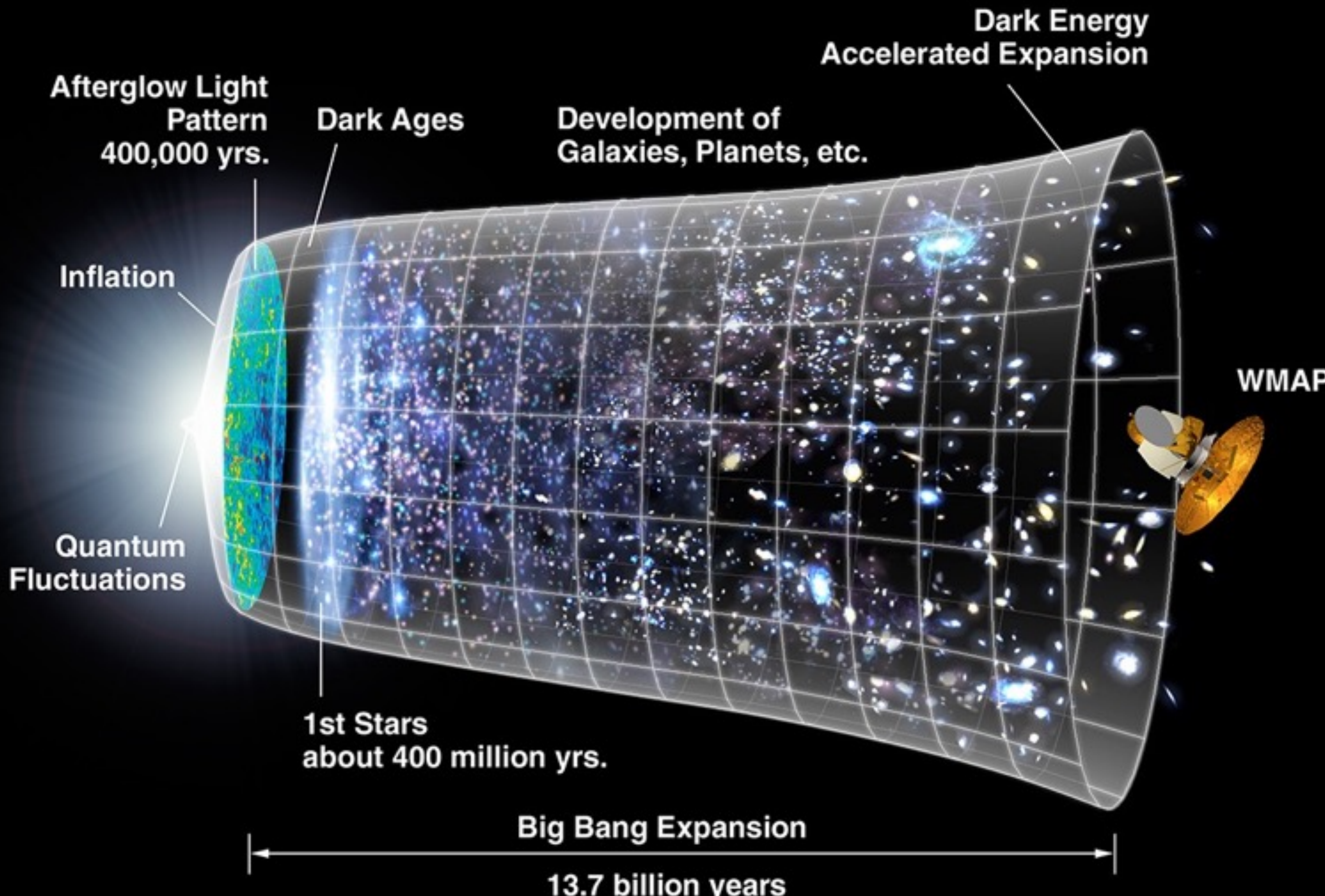
Dvali et al. 2000

Dark Energy or Modified Gravity?

- Cosmic expansion probes (*i.e.* supernovae, BAO) cannot distinguish dark energy from modified gravity.

- Growth of structure helps break degeneracy!

Gravity influences expansion and structure growth!



Credit: NASA/WMAP

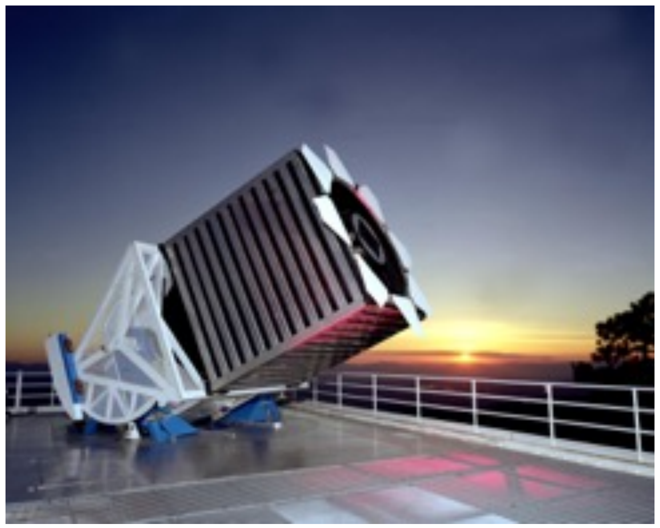
Measuring Structure Growth

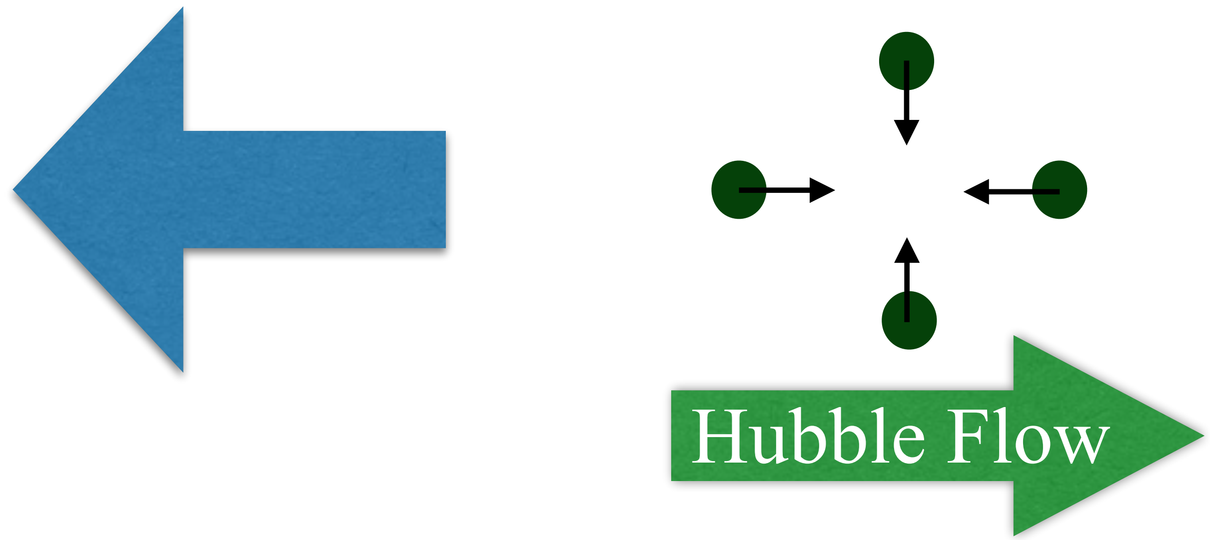
$$\underbrace{\mathbf{v} = H(z)}_{\text{Cosmic Expansion}}\mathbf{r} + \underbrace{\mathbf{v}_p}_{\text{Peculiar Velocity}}$$

- Linear growth rate f determines peculiar velocities
- Total velocity determines Doppler redshift
- Peculiar velocities distort redshift-based distances

Redshift-Space Distortions (RSD)

RSD breaks power spectrum isotropy





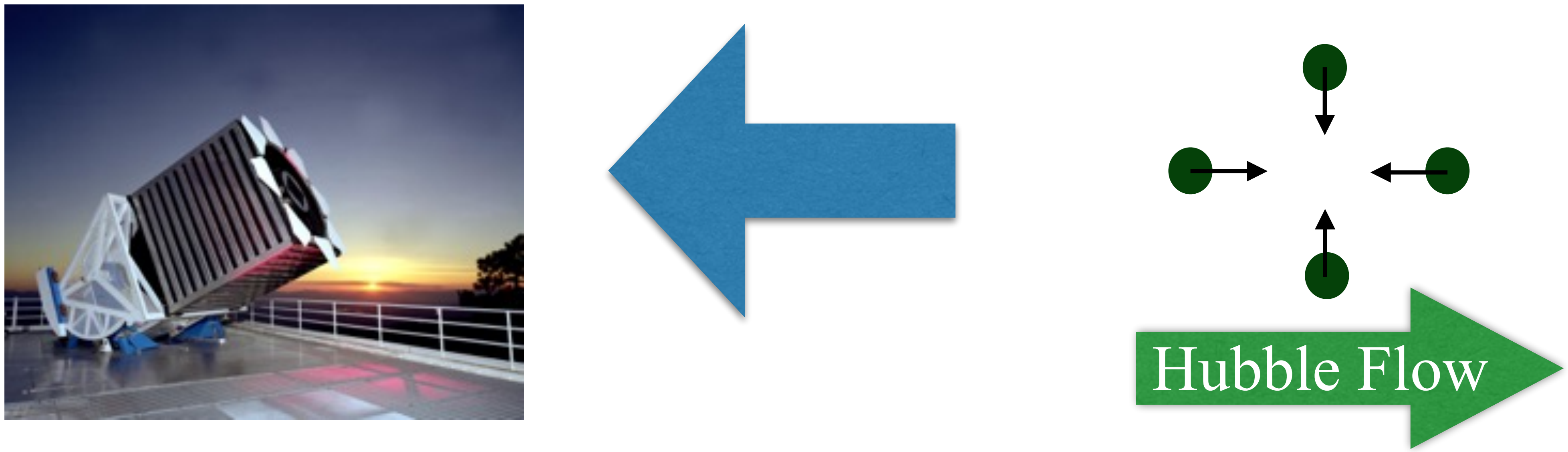
- RSD only affects line-of-sight, not angular, distances
- Introduces anisotropic correlations.

Galaxy Number Variance $$\langle|\delta_g(\mathbf{k})|^2\rangle \sim P_g(k) = b_g^2 P_m(k)$$

clustering bias

dark matter

RSD breaks power spectrum isotropy



- RSD only affects line-of-sight, not angular, distances

- Introduces anisotropic correlations.

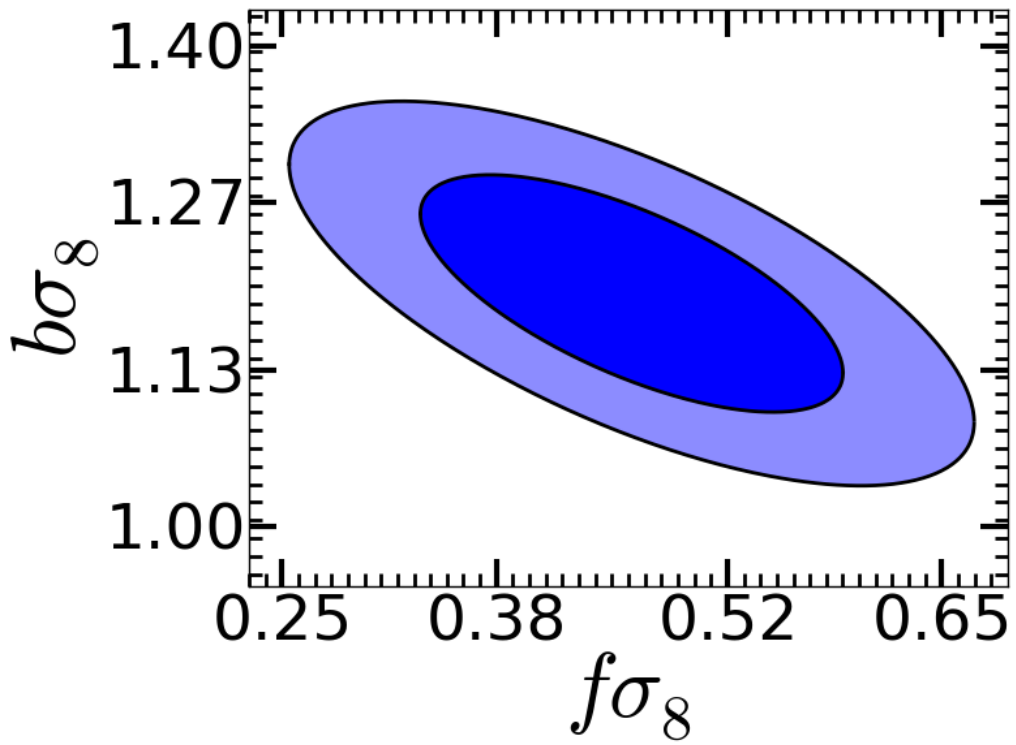
Kaiser formula

$$P_g(k,\mu) = b_g^2(1+\beta\mu^2)^2 P_m(k) \qquad \beta = \frac{f}{b_g}$$

RSD parameter

Growth rate degenerate with clustering

Measurement from anisotropic clustering (Alam et al. 2015)



$$\beta = \frac{f}{b_g}$$

- Several growth rate measurements in the literature!
- Bias and σ_8 must be marginalized over to get growth rate.
- *Better if we could avoid this!*

E_G = New Statistic to Probe Gravity

gravity potentials

$$E_G(k,z) = \frac{c^2k^2\boxed{(\phi - \psi)}}{3H_0^2(1+z)f\delta(k)}$$

Zhang et al. 2007

matter overdensity

GR

$$E_G[\mathrm{GR}] = \frac{\Omega_{m,0}}{f(z)}$$

What Modifies E_G?

Anisotropic Stress

$$\phi = -\gamma(k,z)\psi$$

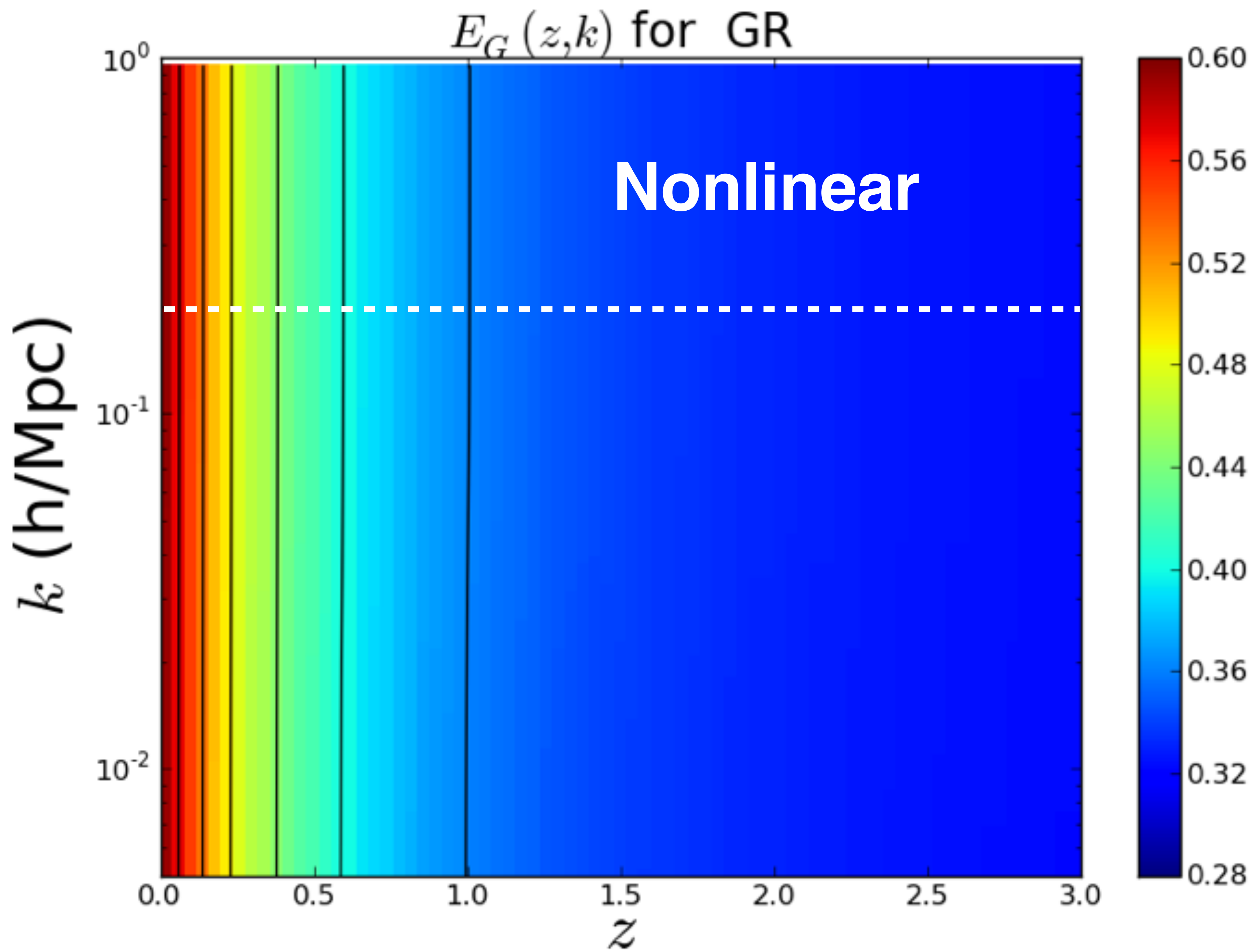
Weak Newton's Constant

$$G(k,z) \neq G_N$$

$$\boxed{E_G(k,z) = \frac{\Omega_{m,0}}{f_{MG}(k,z)}\left(\frac{1+\gamma}{2}\right)\left(\frac{G}{G_N}\right)}$$

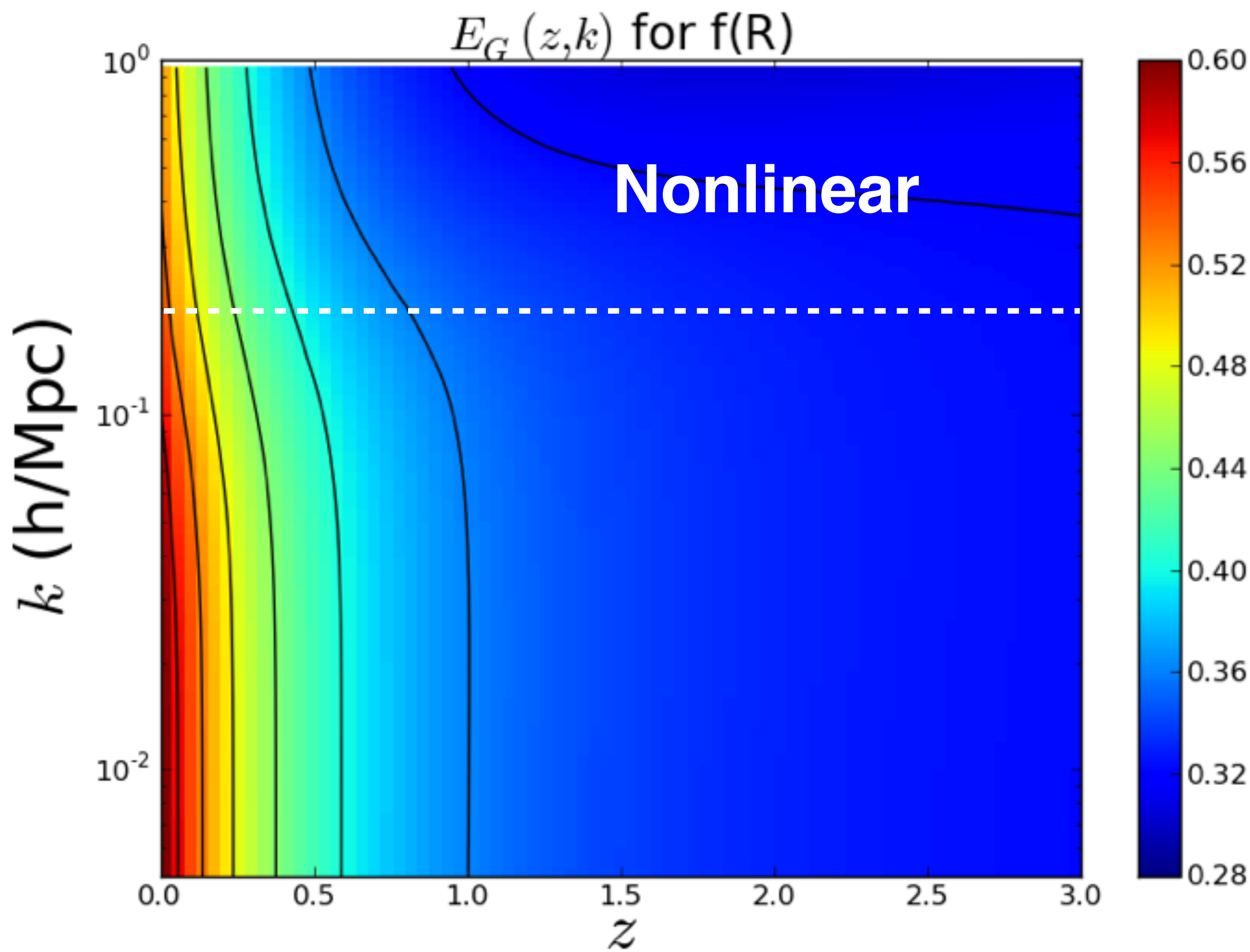
G(k,z) affects growth rate

Modified gravity = scale-dependent E_G



Pullen et al. 2015, Carroll et al. 2004, Song et al. 2007

Modified gravity = scale-dependent E_G



Pullen et al. 2015, Carroll et al. 2004, Song et al. 2007

How to Measure E_G?

Correlate with galaxies

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

Lensing Convergence $\kappa \sim [\nabla^2(\psi-\phi)]_{l.o.s}$ & $f\delta = \beta\delta_g$

$$\boxed{E_G(\ell) = \Gamma \frac{C_\ell^{\kappa g}}{\beta C_\ell^{gg}}}$$

$(\ell \sim 1/\theta)$

Angular Scale

Angular Power Spectrum

Why E_G?

- E_G - Combines lensing, clustering, and RSD
- Bias- and σ_8-independent (on linear scales) = big advantage over growth rate!
- Probes expansion & growth rate; *breaks dark energy - gravity degeneracy!*
- Discriminates GR vs. modified gravity

$$E_G(\ell) = \Gamma \frac{C_\ell^{\kappa g}}{\beta C_\ell^{gg}}$$

Galaxy Lensing

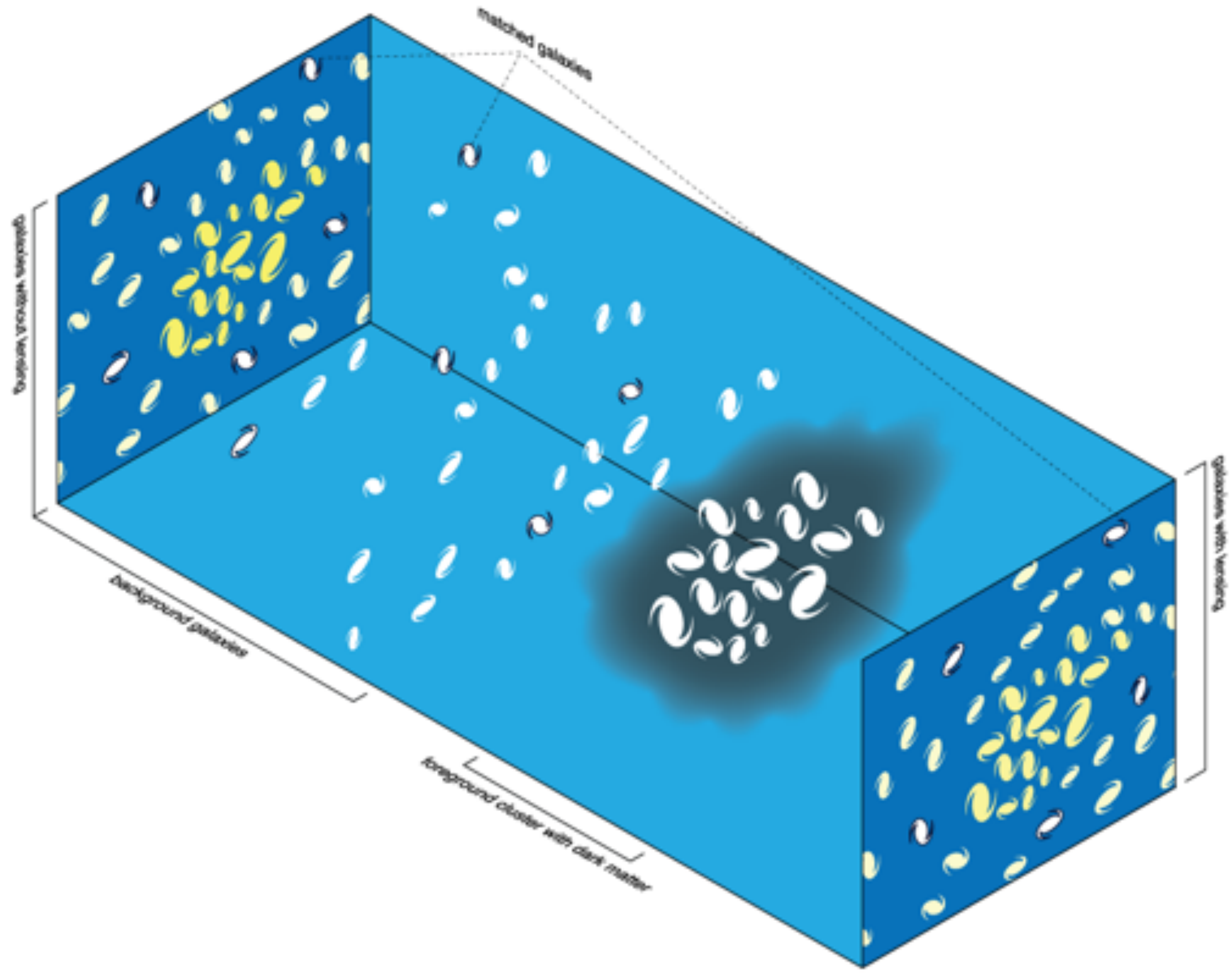
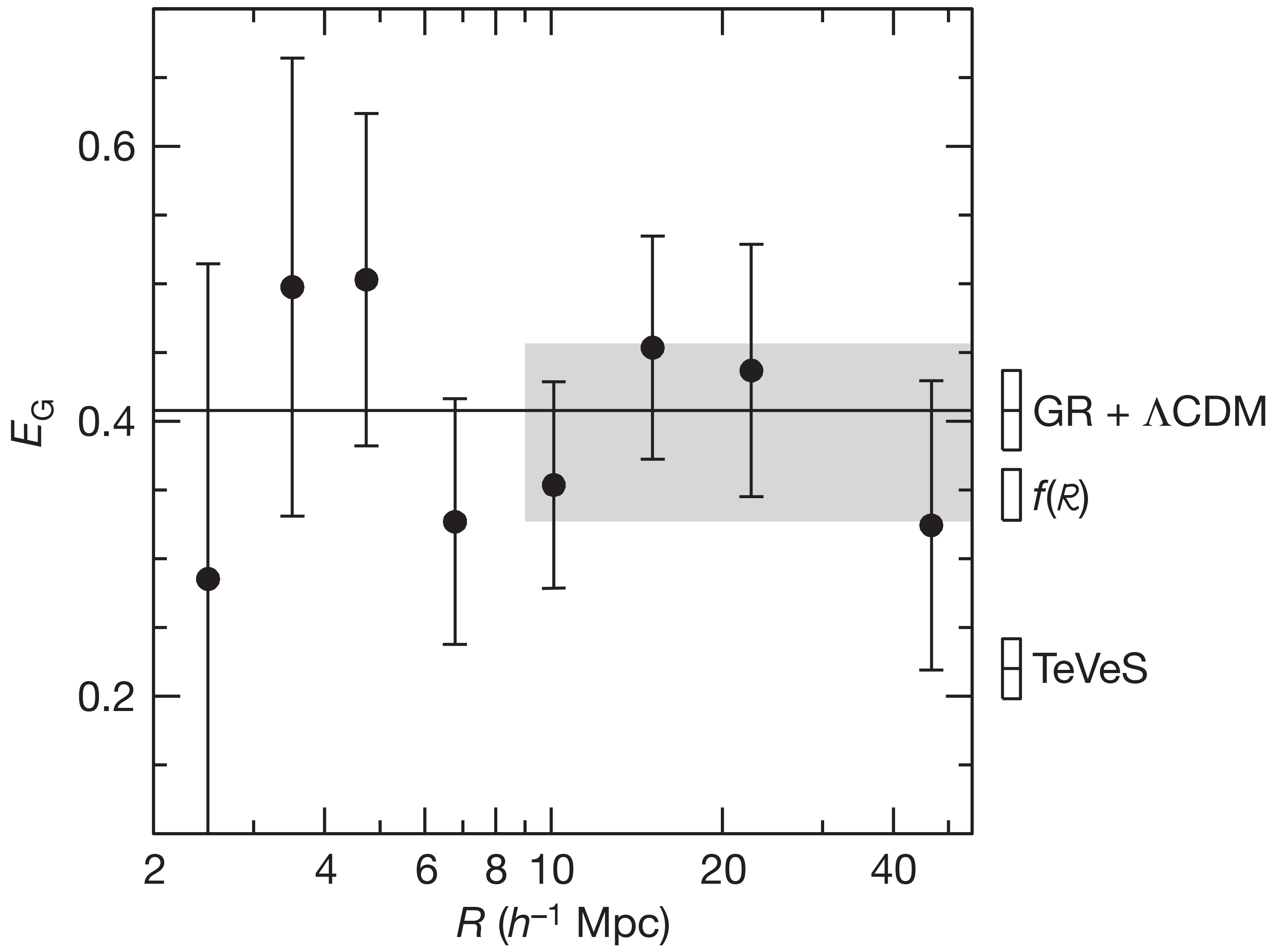


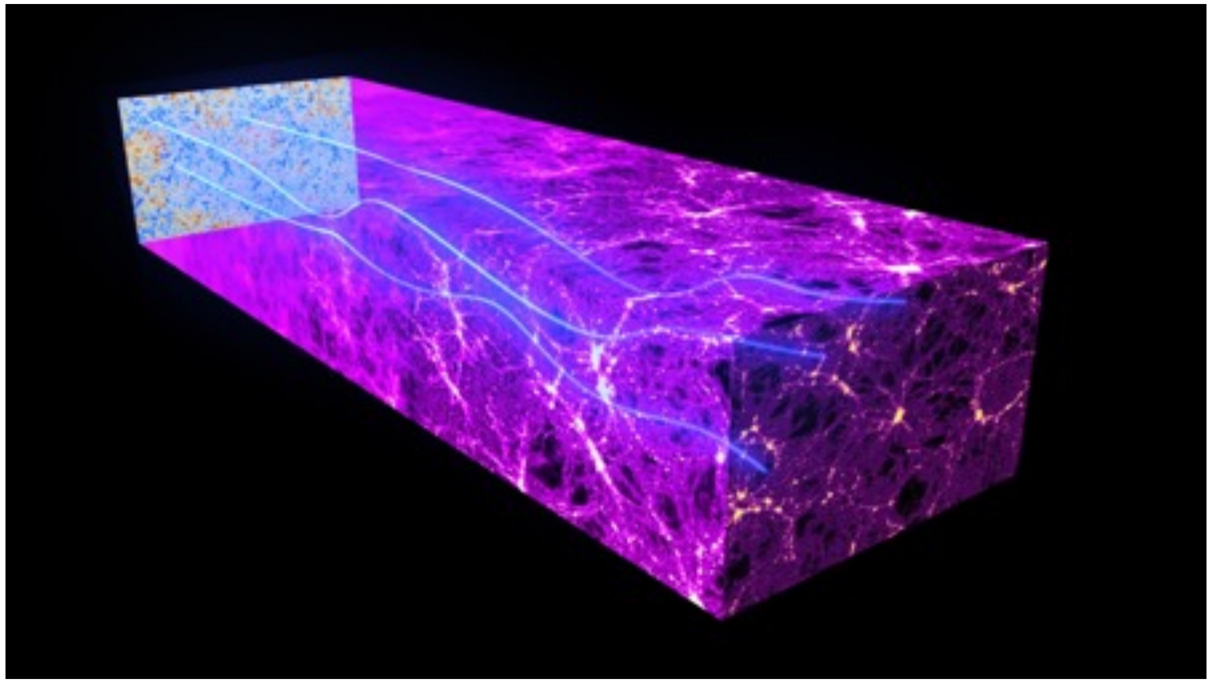
Image Credit: Michael Sachs

First measured using galaxy lensing



Reyes et al. 2010

CMB Lensing



- *We propose measuring E_G using cosmic microwave background (CMB) lensing.*
- CMB lensing advantages: no intrinsic alignments; precise, well-defined source plane.

Tyson et al. 1984, Linder 1988

Image Credit: ESA

Forecasts

Testing Gravity Theories

f(R) gravity - Modifies Hilbert action

- Parametrized by B_0 ~ Compton wavelength of equivalent scalar field

Einstein-Hilbert Action

$$S_H = \int \sqrt{-g} R \, d^4 x$$

Carroll et al. 2004, Khoury & Weltman 2004, Bertschinger & Zukin 2008

Testing Gravity Theories

f(R) gravity - Modifies Hilbert action

- Parametrized by B_0 ~ Compton wavelength of equivalent scalar field

$$S_H = \int \sqrt{-g} f(R) \, d^4x$$

Scalar-Tensor Theories

$$B_0 \propto 1/m_\phi$$

$$B_0[GR] = 0$$

Carroll et al. 2004, Khoury & Weltman 2004, Bertschinger & Zukin 2008

Testing Gravity Theories

- Chameleon gravity - Chameleon Φ mediates fifth force
    - Massive (weak) in high-density regions (lab, solar system) and strong in low-density space
    - Parametrized by B_0 and β_1 ~ coupling to matter

Carroll et al. 2004, Khoury & Weltman 2004, Bertschinger & Zukin 2008

Galaxy Survey

Spectroscopic

Or

Photometric?

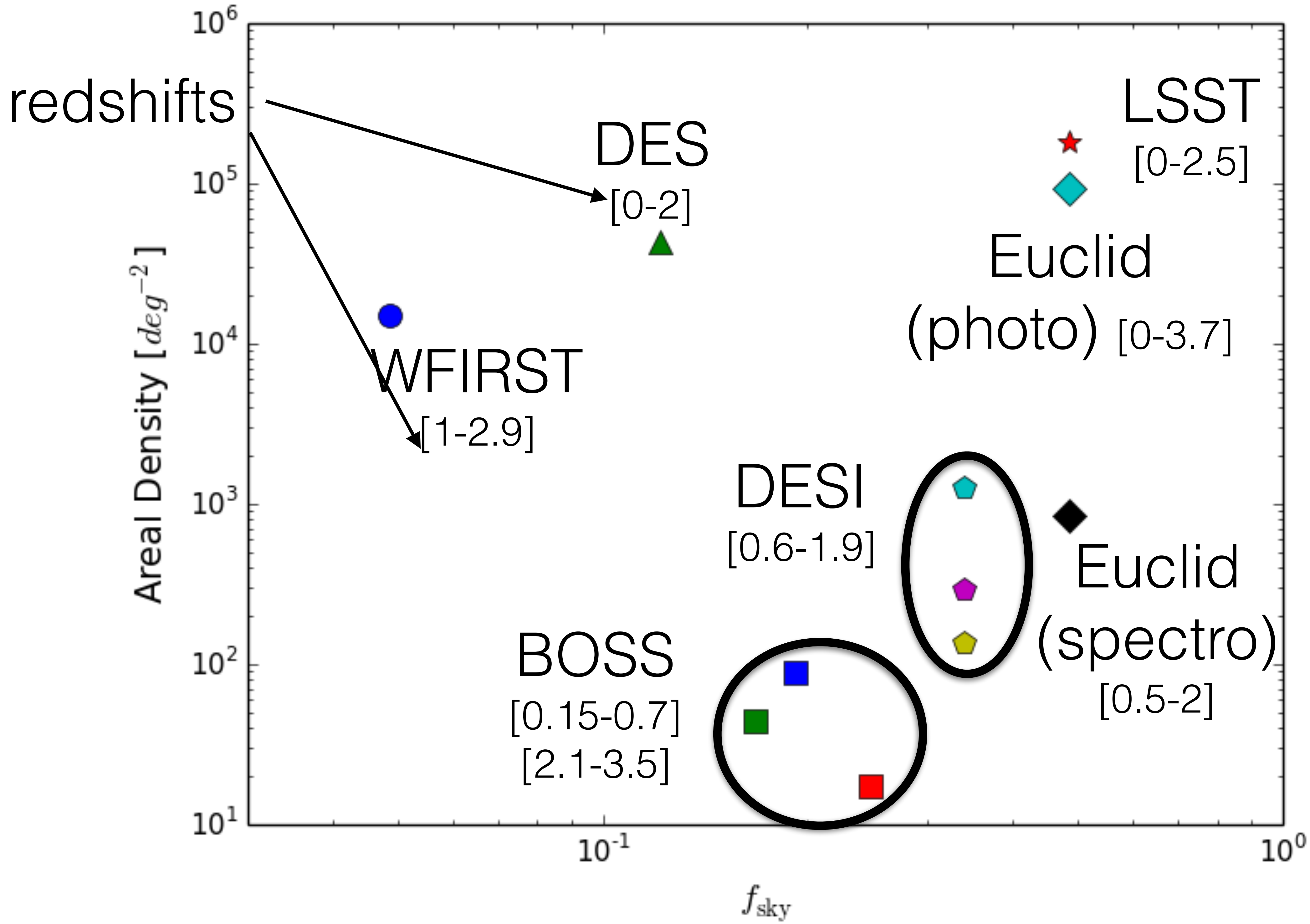
Spectroscopic = Precise Redshifts

- Typically get redshift from several spectral features; $z < 1$
- Emission line survey - identify 1-2 spectral features; $z > 1$
- Allow (almost) unlimited binning in redshift
- Expensive to get redshifts; *necessary* for RSD

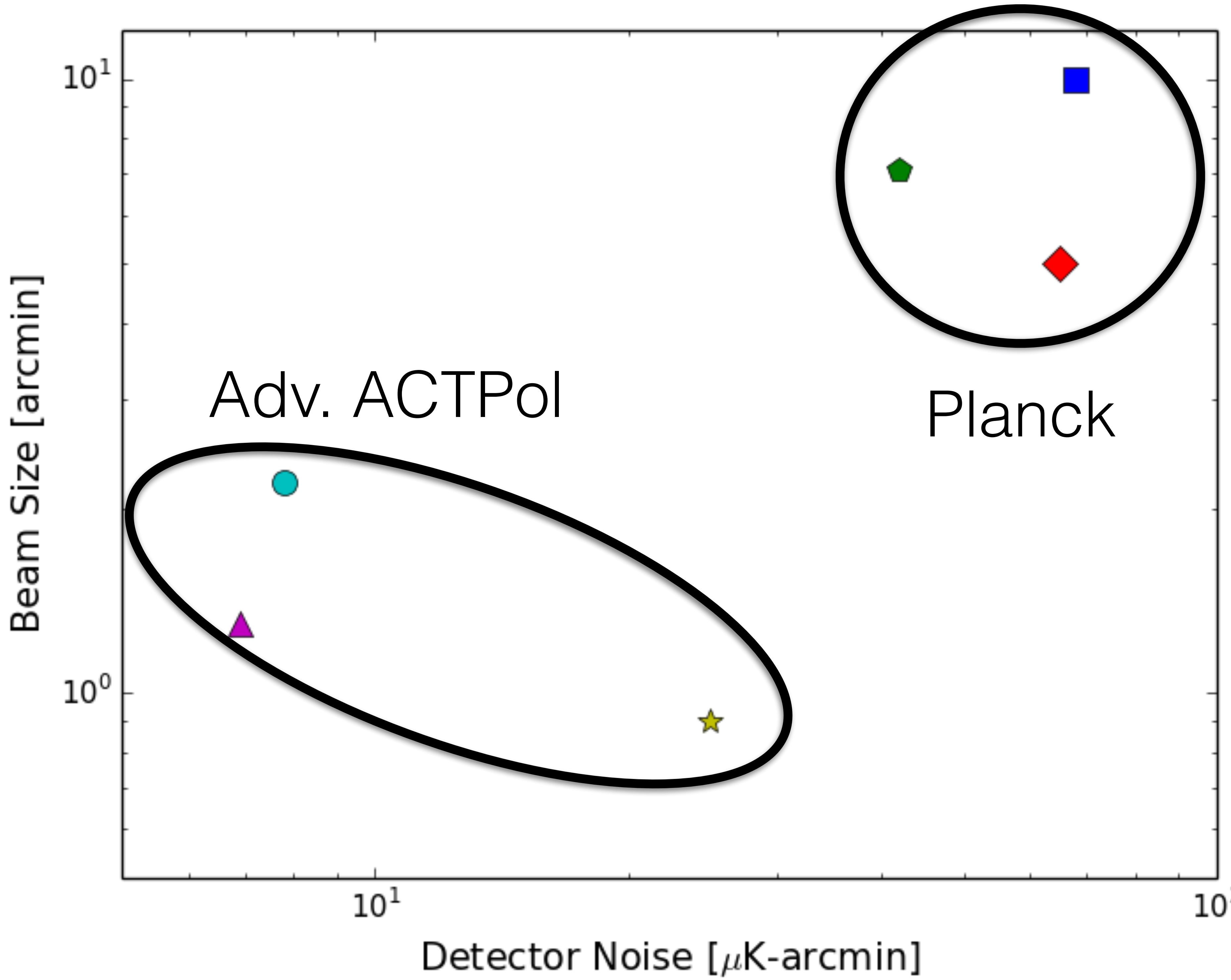
Photometric = High Sampling

- Determine redshift from photometric band fluxes
- Large bands = less precise redshifts
- *But they are cheap!*
- **What's better - more redshift bins or more sampling?**

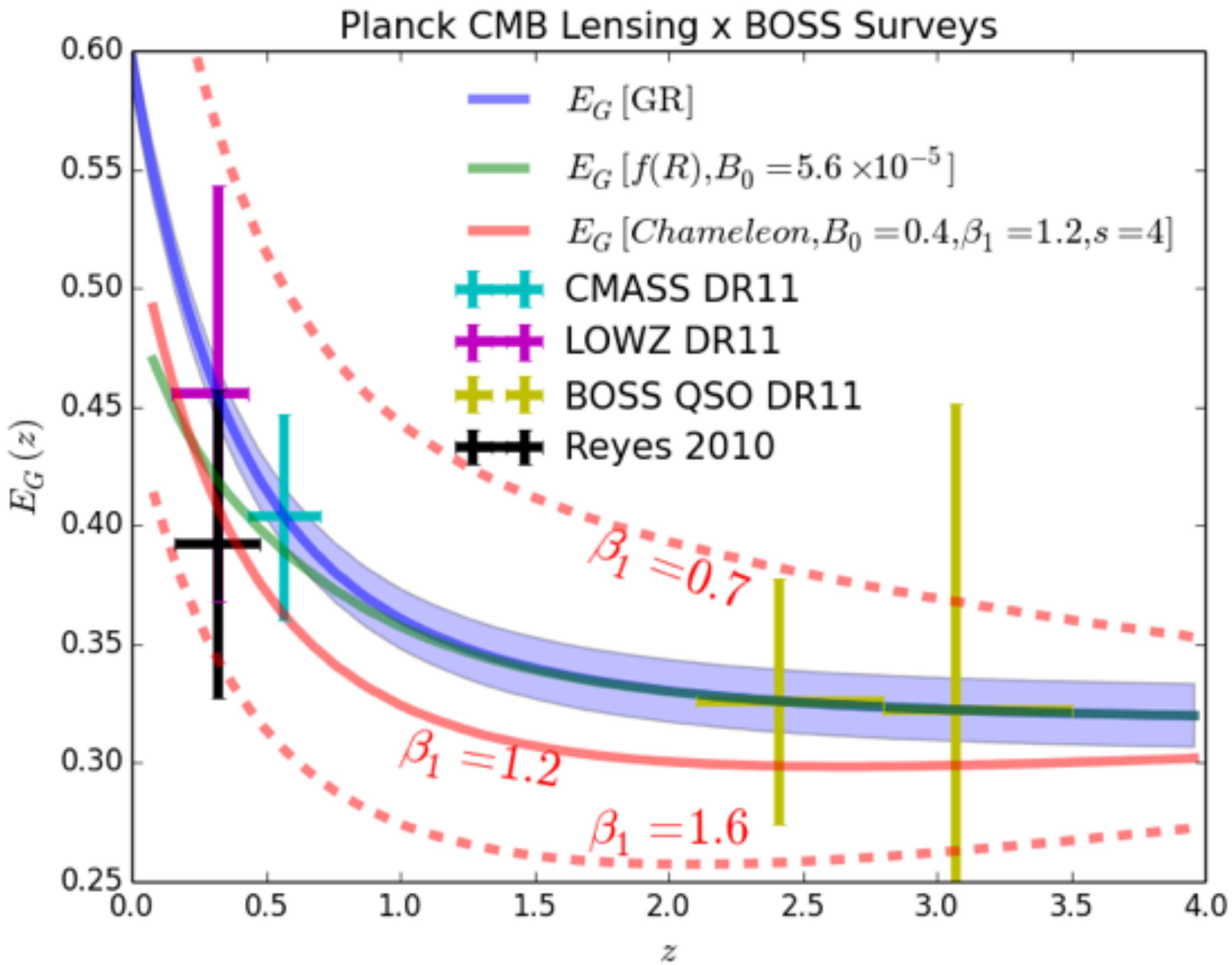
Galaxy Surveys



CMB Surveys

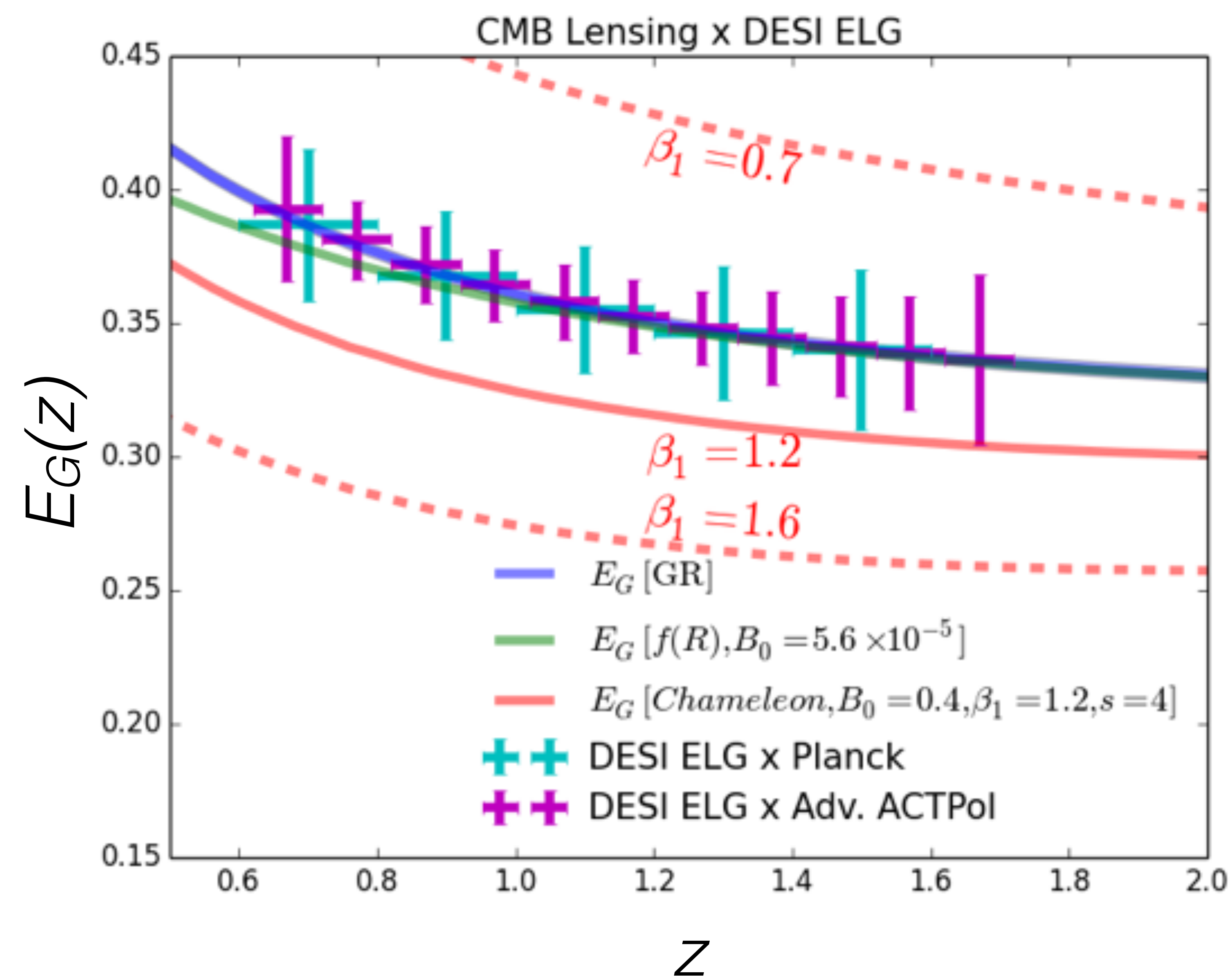

Adv. ACTPol
Planck
10^1
10^0
Beam Size [arcmin]
10^1
10^2
Detector Noise [μK-arcmin]

BOSS Surveys



Spectroscopic Surveys

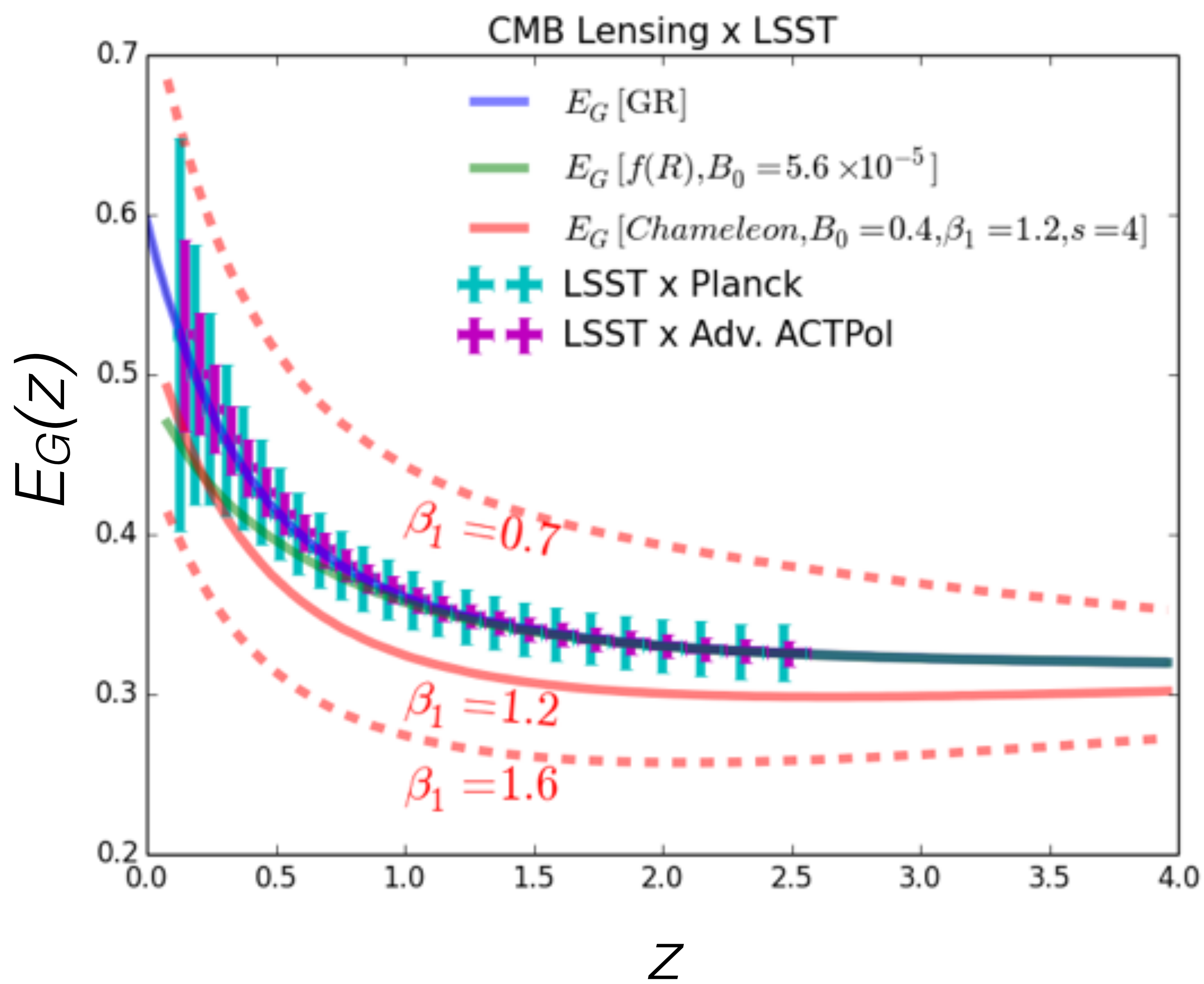
- E_G errors of 2% (Planck) or 1% (Adv. ACTPol)
- Constrains chameleon gravity



Pullen et al. 2015, Dark Energy Spectroscopic Instrument

Photometric Surveys

- E_G errors of 1% (Planck) or less (Adv. ACTPol)
- Discriminates current *f(R)* by 15σ; can probe 100x lower!
- Assumes photo RSD errors of ~8% over $\Delta z \sim 0.1$.



Pullen et al. 2015, LSST, Ross et al. 2011, Asorey et al. 2014

E_G Theory Summary

- E_G is a bias-independent statistic that varies with the nature of gravity.
- CMB lensing extends the utility of E_G.
- Photometric surveys outperform spectroscopic surveys, but both could yield useful gravity constraints!

Measurement

E_G - What can we learn now?

Lensing x galaxies
Planck x CMASS

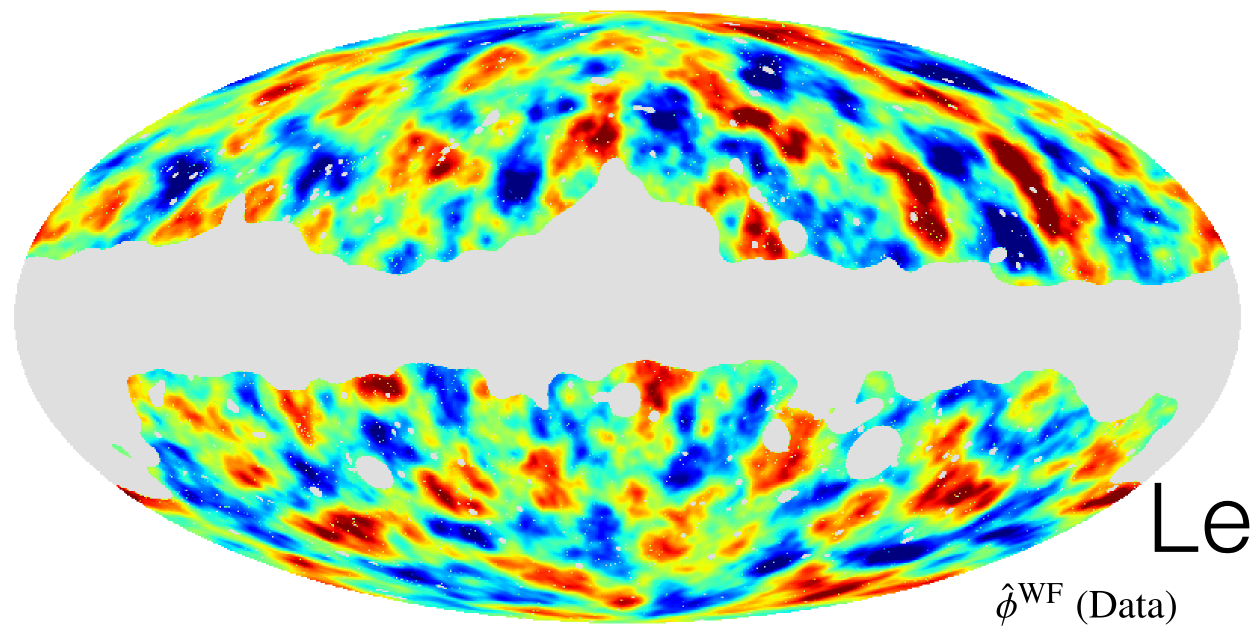
$$E_G(\ell) = \Gamma \frac{C_\ell^{\kappa g}}{\beta C_\ell^{gg}}$$

RSD parameter
CMASS

galaxy auto-correlation
CMASS

We test gravity using current LSS surveys!

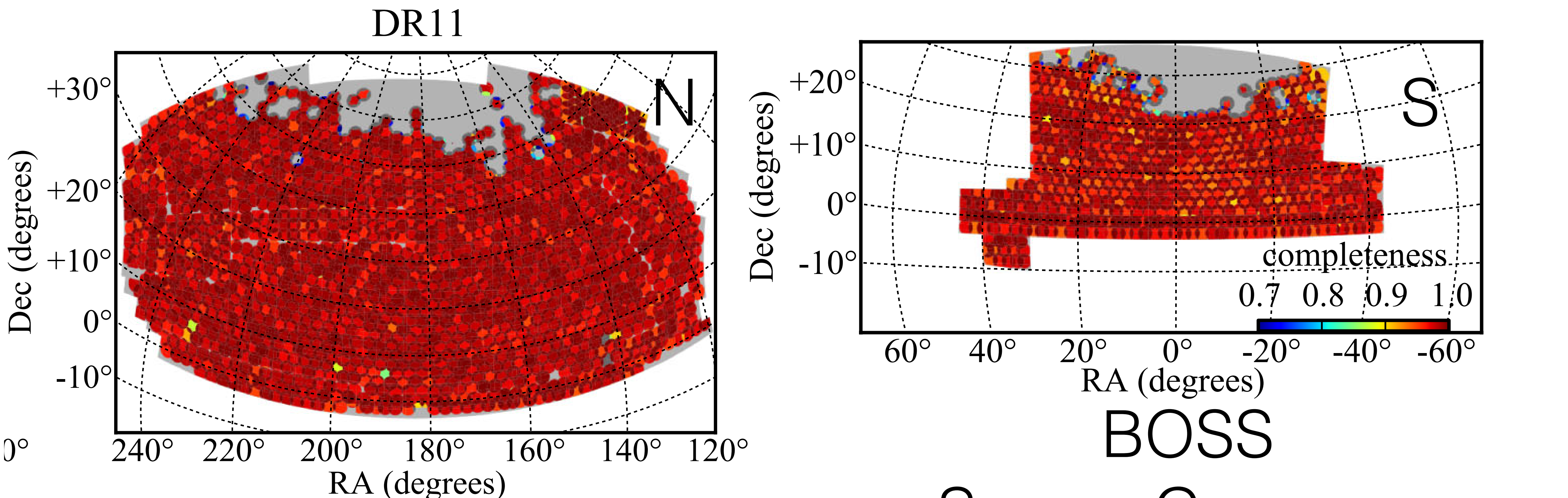
Planck CMB lensing survey



Planck
Lensing Potential

- Lensing convergence map covers 70% of sky
- Estimated from CMB temperature, E-polarization maps
- Checked for contamination from dust, synchrotron, point sources, instrumental bias

CMASS galaxy survey

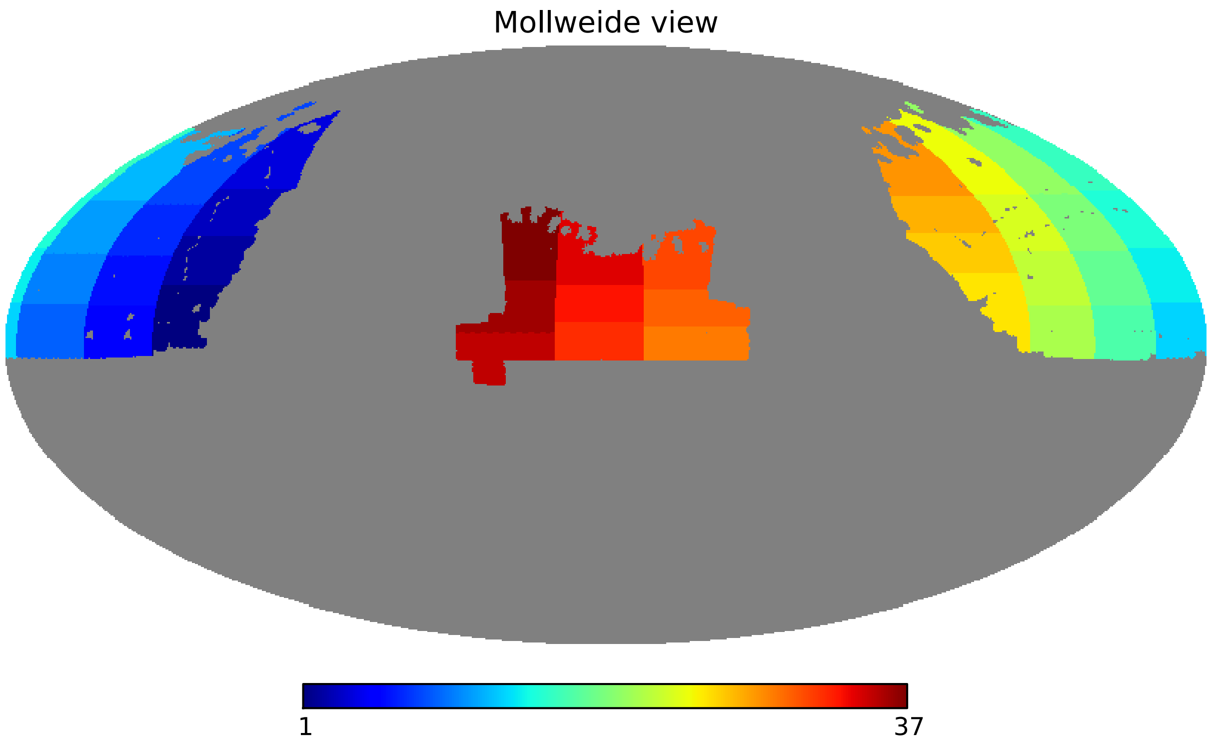


BOSS
Survey Coverage

- ~700,000 galaxies covering 20% of sky
- Redshift Range $0.43 < z < 0.7$; high completeness
- Galaxies weighted for systematic effects

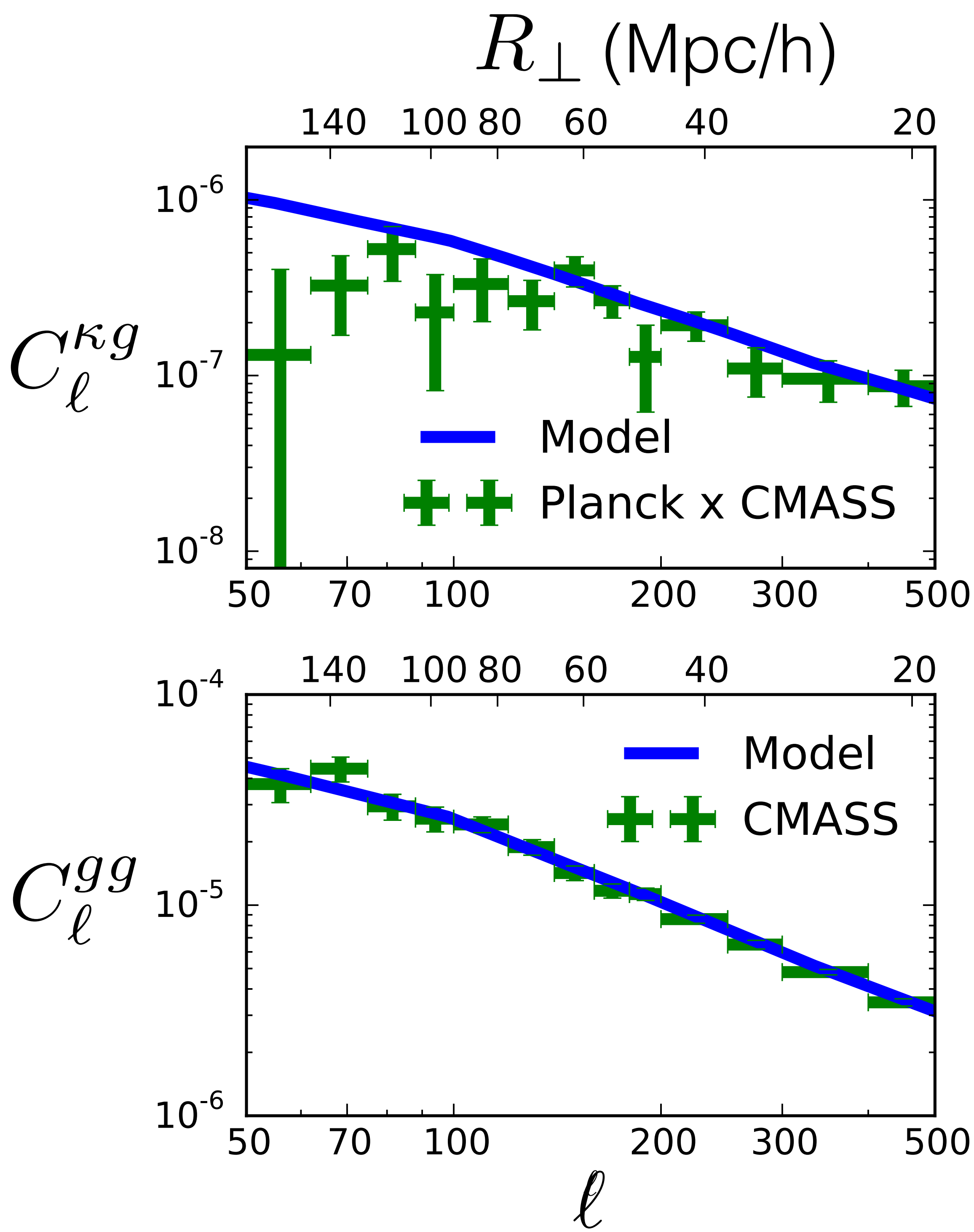
E_G Errors - Jacknives vs Mocks

$$\hat{E}_G(\ell) = \Gamma \frac{\hat{C}_\ell^{\kappa g}}{\hat{\beta}\hat{C}_\ell^{gg}}$$



- Compute full covariance matrix
- Method 1: Jackknife resampling of 37 regions in CMASS survey area
- Method 2: Correlate 100 CMASS mock catalogs with 100 Gaussian CMB simulations

Angular Power Spectra



- Lensing-galaxy correlation using pseudo-C_l estimator
- Galaxy auto-correlation using quadratic MV estimator
- Agrees well with ΛCDM prediction

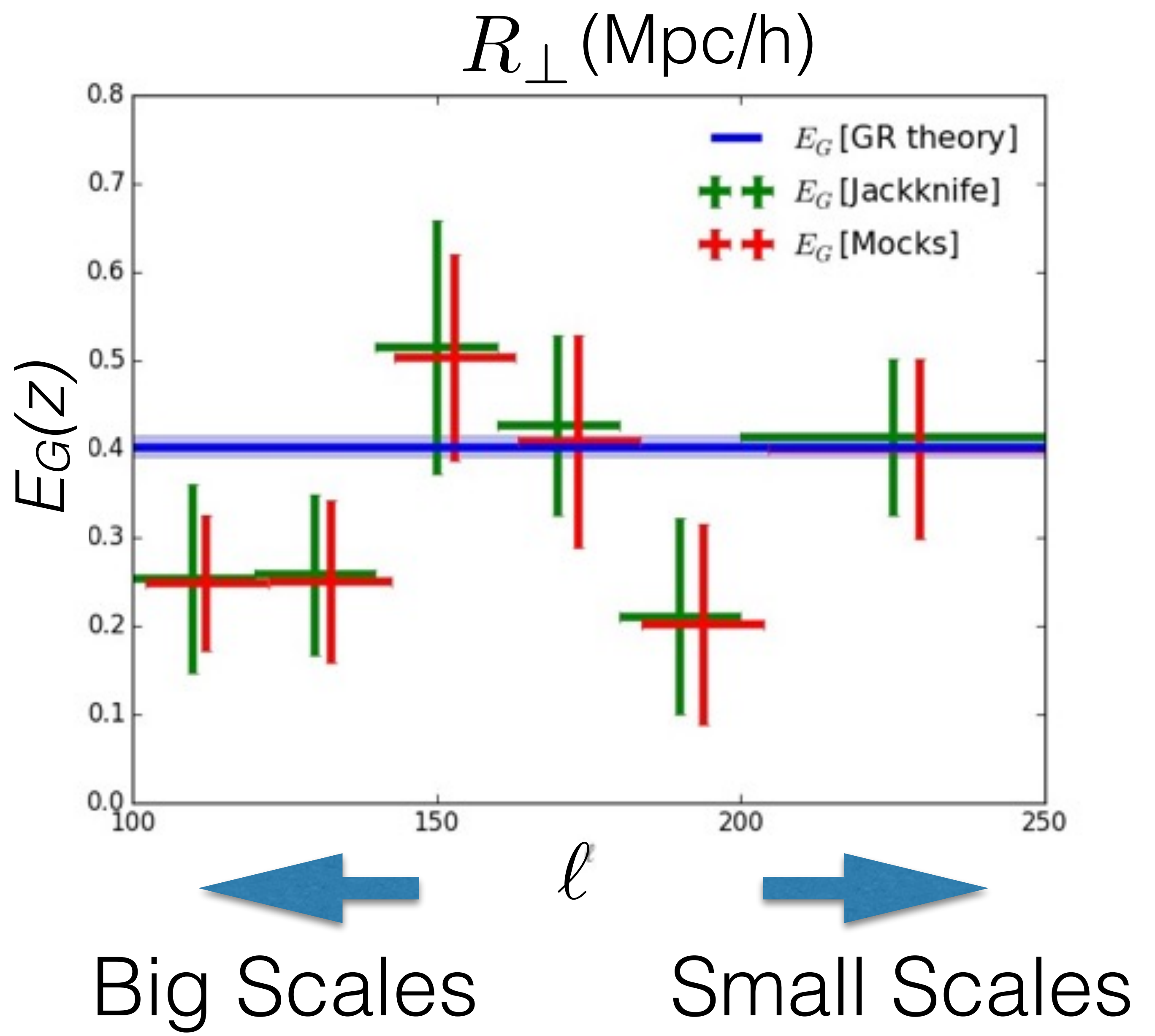
CMASS RSD Measurement

- Correlation function using pair counts (Landy-Szalay Estimator)
- Fit $f\sigma_8$ and $b\sigma_8$ to anisotropic correlation function model
- Take ratio to compute β

$$\beta = 0.368 \pm 0.046$$

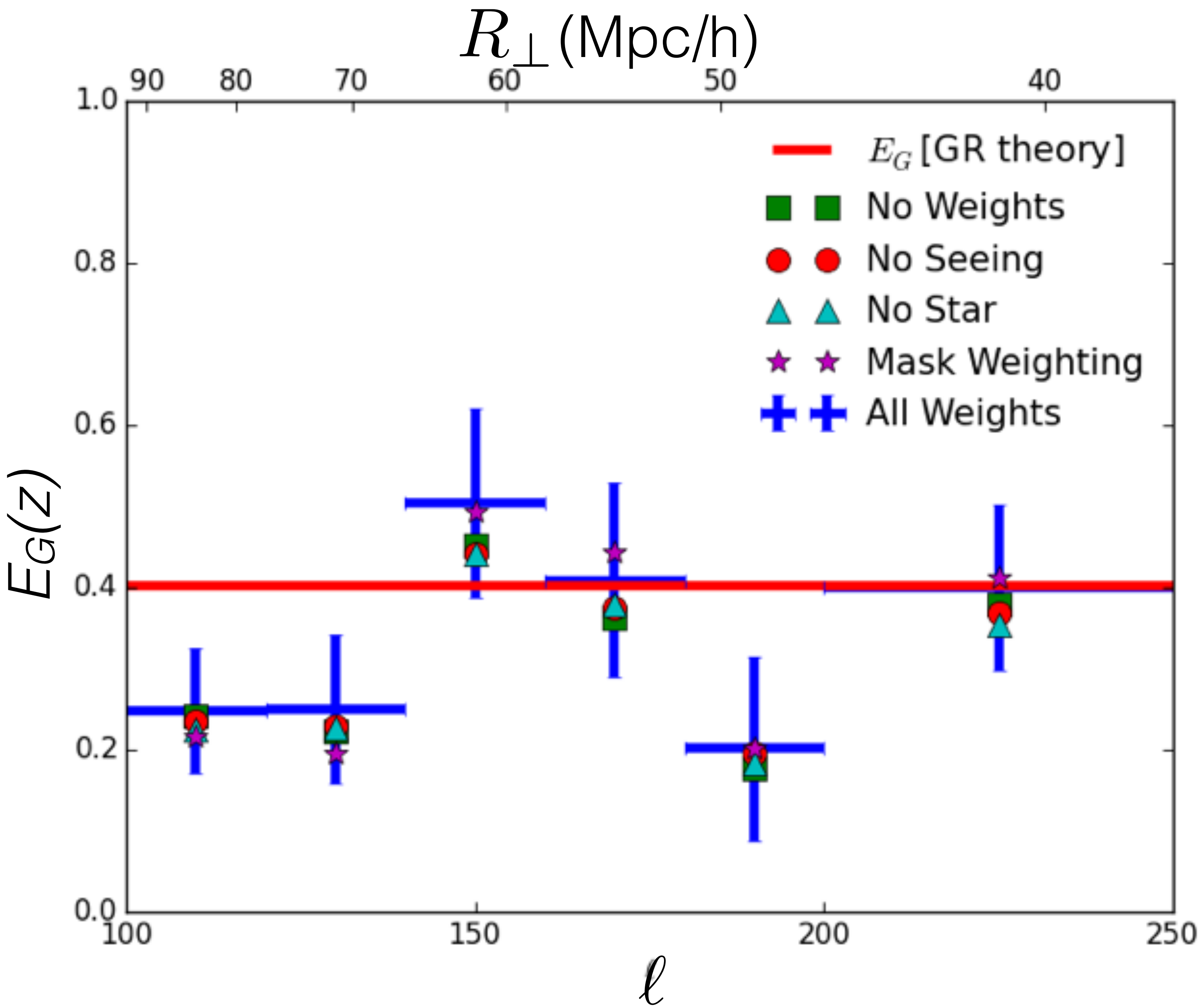
Largest Scale E_G Measure

- We estimate E_G in 6 *l*-bins.
- Results using jackknives and mocks agree.
- 4.5σ detection due to *l*-bin correlations
- Consistent with GR (E_G = 0.402) within 2σ
- Cannot differentiate with current *f(R)*



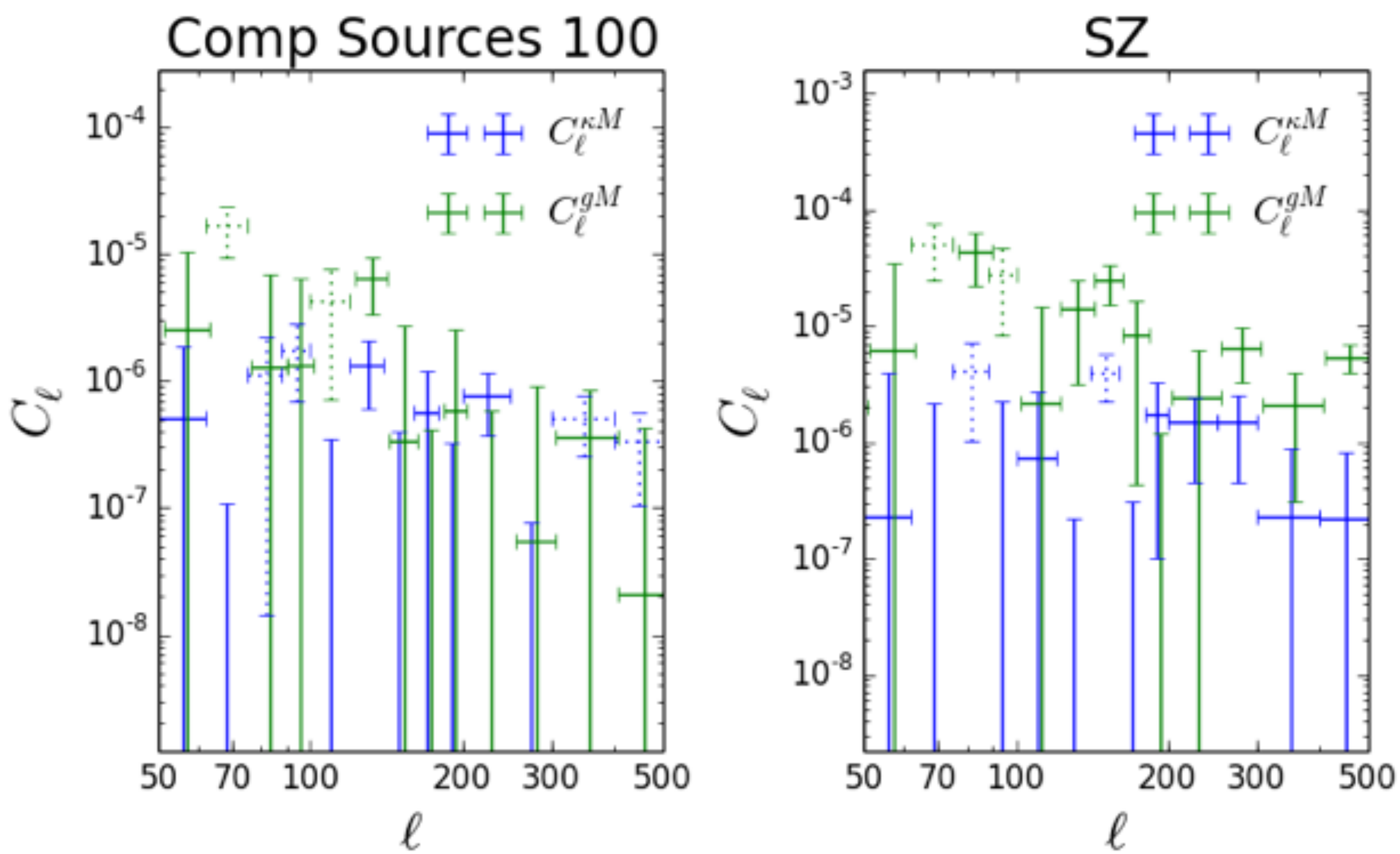
$$E_G(z = 0.57) \\ = 0.288 \pm 0.064\,(\mathrm{stat})$$

CMASS systematic errors are small



3.6% systematic error due to galaxy sample contamination

Point sources small contaminant



- Significant cross-correlations, but only 0.5% E_G error

Nice, but what's next?

We need to consider new theories

- Theorists do not like *f(R)* and Chameleon theories.
- Massive gravity theories (DGP, dRGT, galileons, etc.) have gained new interest.
- Various levels of perturbation theory development
- Potential could be tested with E_G

Considerations for upcoming surveys

- Can RSD be measured with photo-z’s?
- Can foregrounds be sufficiently removed?
- How far can we push into quasi-linear scales?
- How to combine multi-redshift data?
- Combine CMB lensing & galaxy lensing?

Intensity Mapping

- Mapping the intensity of spectral lines will provide the greatest sampling of LSS
- *Ideal for E_G measurements!*
- Could possibly include lensing of 21-cm maps
- Other possibilities: CO, CII, Lyα, voids (?), …

Conclusions

- CMB lensing measures E_G at larger scales to aid in confirming or ruling out gravity models.
- Our current E_G measurement is consistent with GR, but greater precision is needed.
- Upcoming large-area, high-density galaxy surveys could measure E_G to %-level accuracy, potentially ruling out many gravity models.
- Next steps: Consider DGP constraints, test photo-RSD measurement, design survey- and foreground-specific strategies, 21cm intensity mapping, etc.