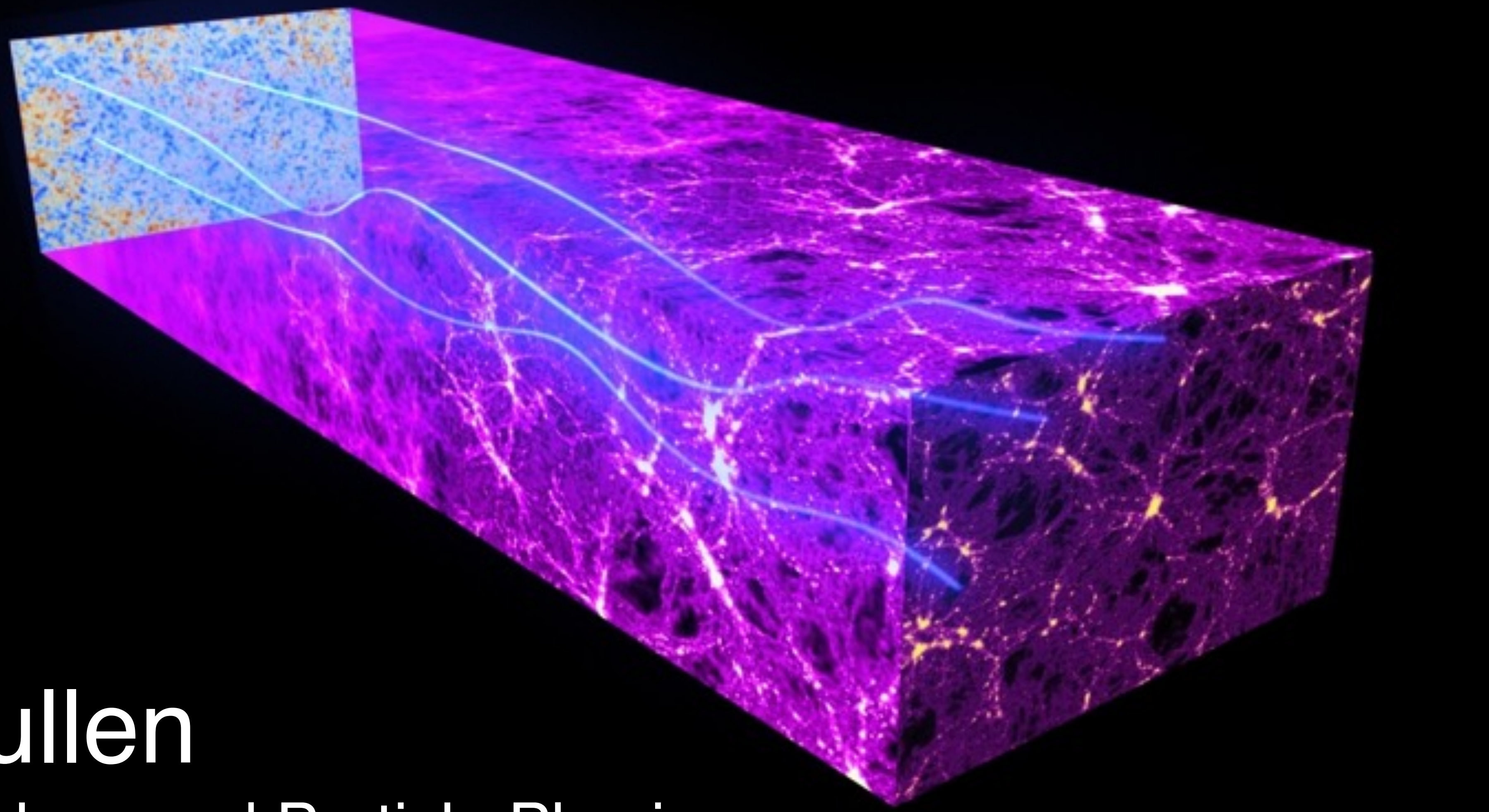
Testing Gravity with the CMB:

E_G and Implications for CMB-S4

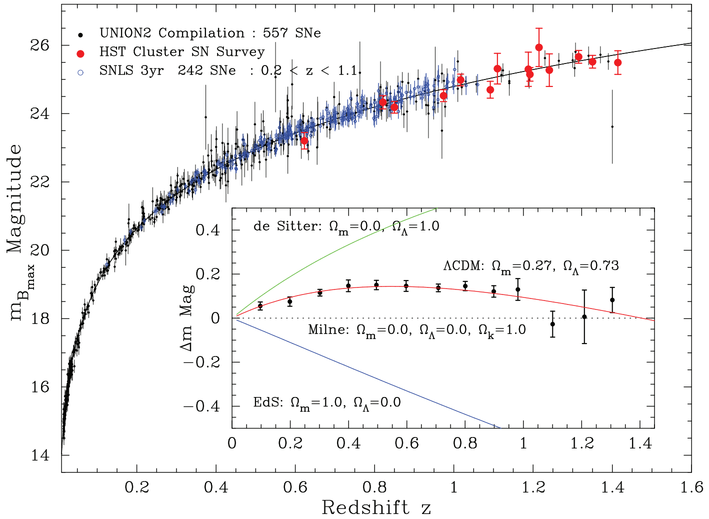


Anthony Pullen
Center for Cosmology and Particle Physics
New York University

CMB-S4/FCS, KICP/U Chicago
Wednesday, Sept 21, 2016

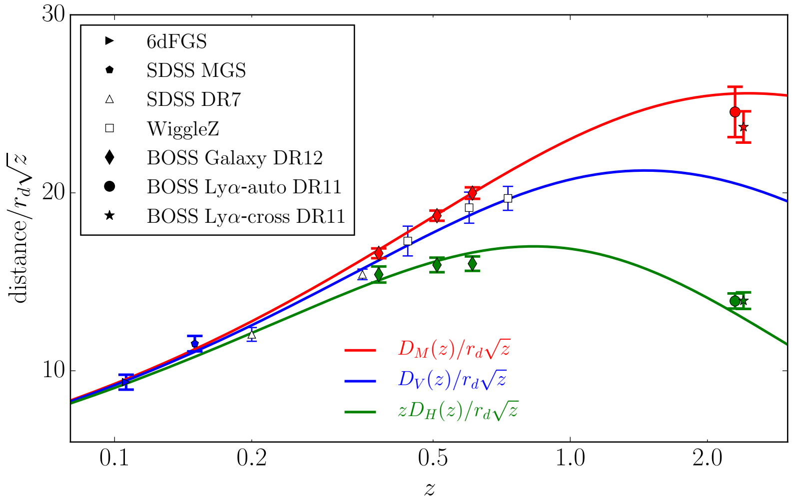
Expansion and Growth of Structure distinguish dark energy and modified gravity

Type Ia Supernova



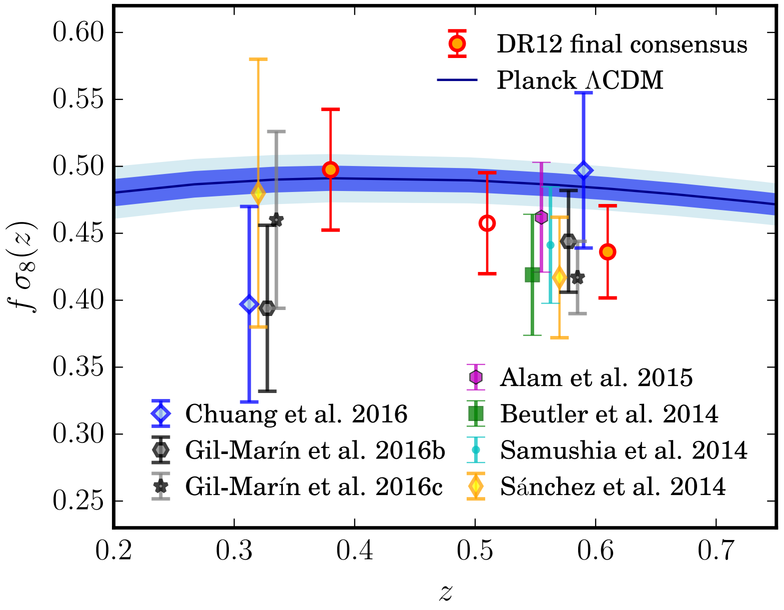
Credit: Union2.1 (SCP)
Legacy Survey

Baryon Acoustic Oscillations



Credit: BOSS survey

Redshift-Space Distortions

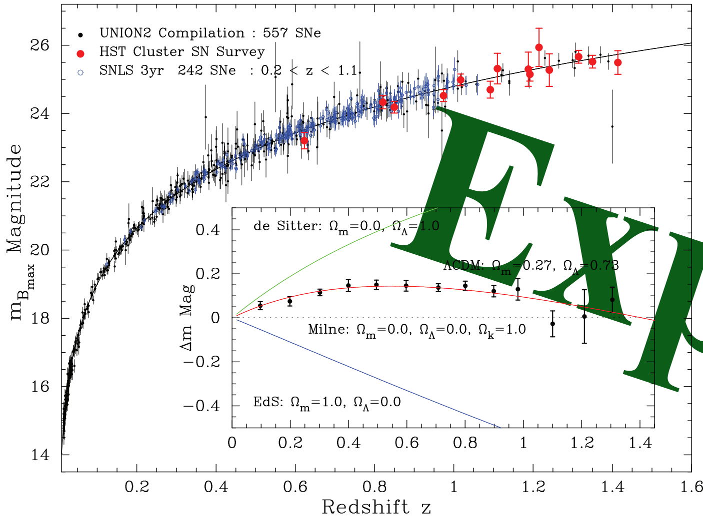


Credit: BOSS survey

f = rate of structure growth

Expansion and Growth of Structure distinguish dark energy and modified gravity

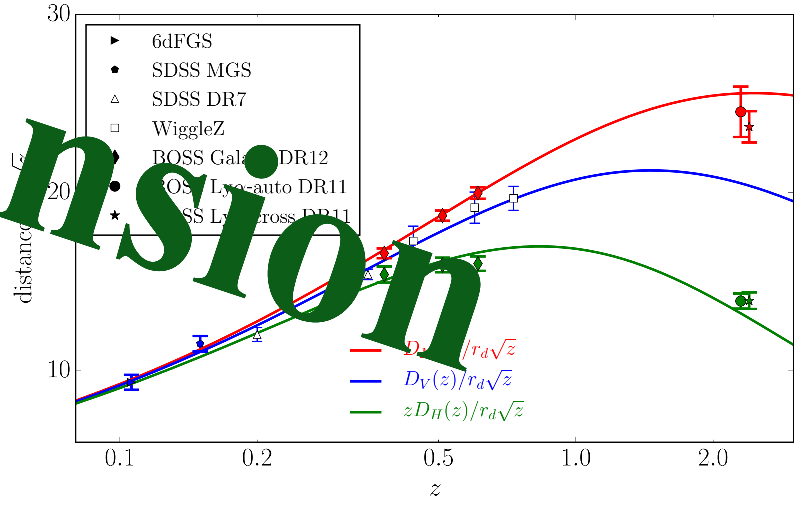
Type Ia Supernova



Credit: Union2.1 (SCP)
Legacy Survey

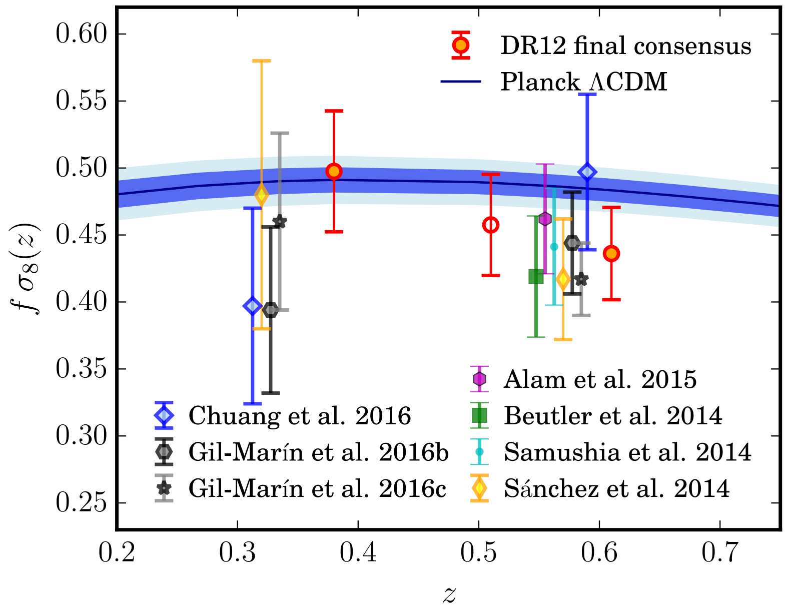
Expansion

Baryon Acoustic Oscillations



Credit: BOSS survey

Redshift-Space Distortions

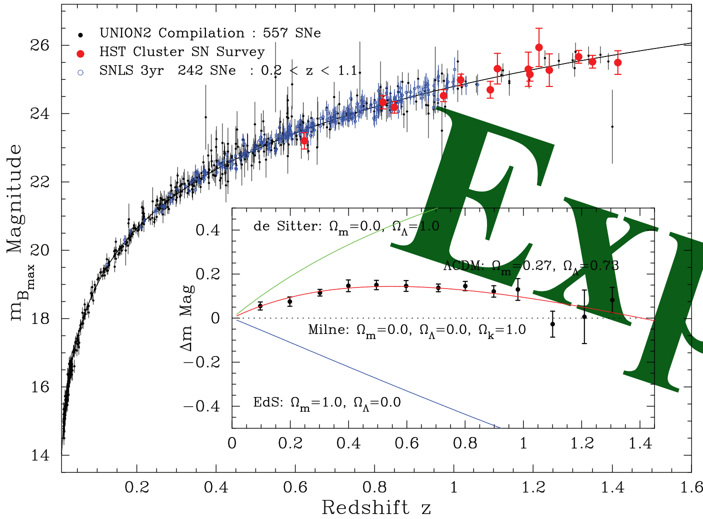


Credit: BOSS survey

f = rate of structure growth

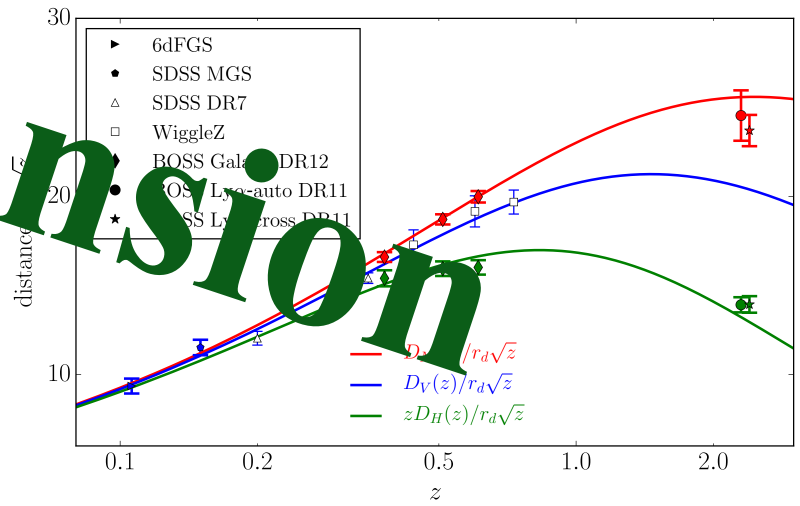
Expansion and Growth of Structure distinguish dark energy and modified gravity

Type Ia Supernova



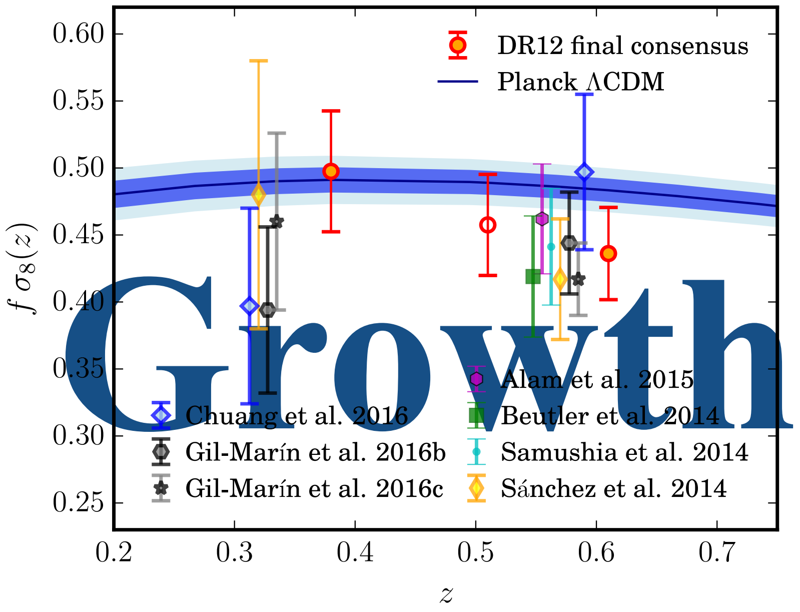
Credit: Union2.1 (SCP)
Legacy Survey

Baryon Acoustic Oscillations



Credit: BOSS survey

Redshift-Space Distortions



Credit: BOSS survey

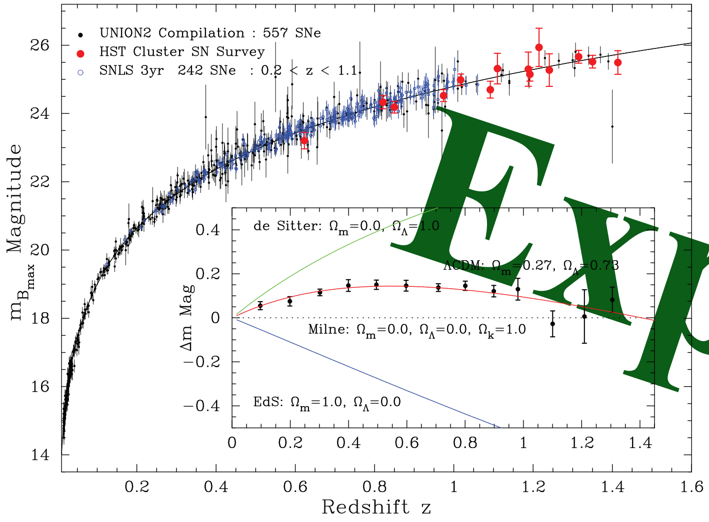
Expansion

Growth

f = rate of structure growth

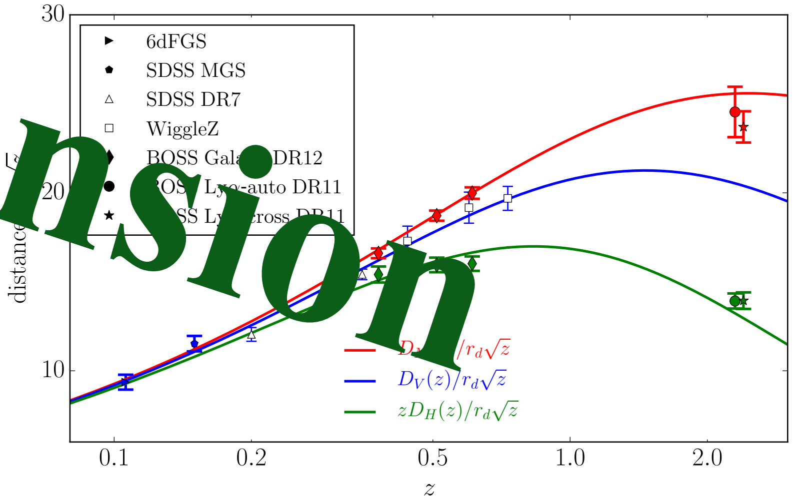
Expansion and Growth of Structure distinguish dark energy and modified gravity

Type Ia Supernova



Credit: Union2.1 (SCP)
Legacy Survey

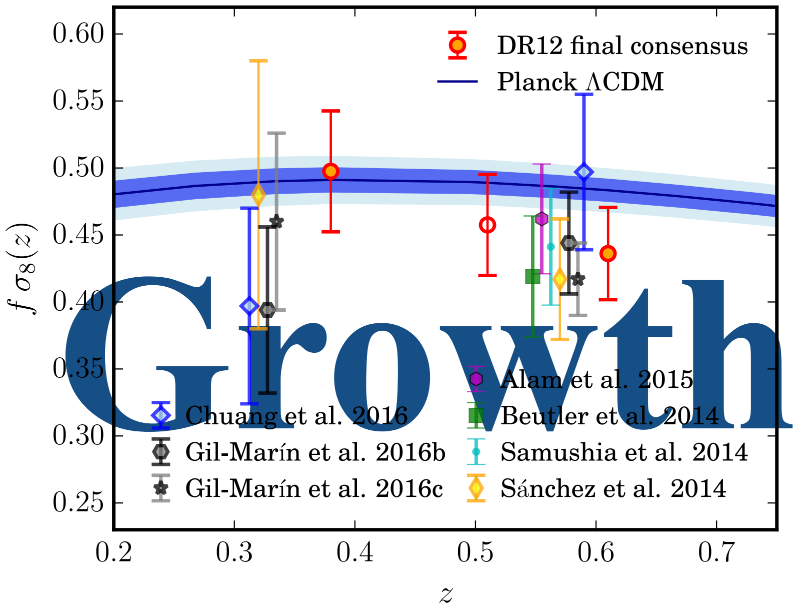
Baryon Acoustic Oscillations



Expansion

Credit: BOSS survey

Redshift-Space Distortions



Growth

Credit: BOSS survey

f = rate of structure growth

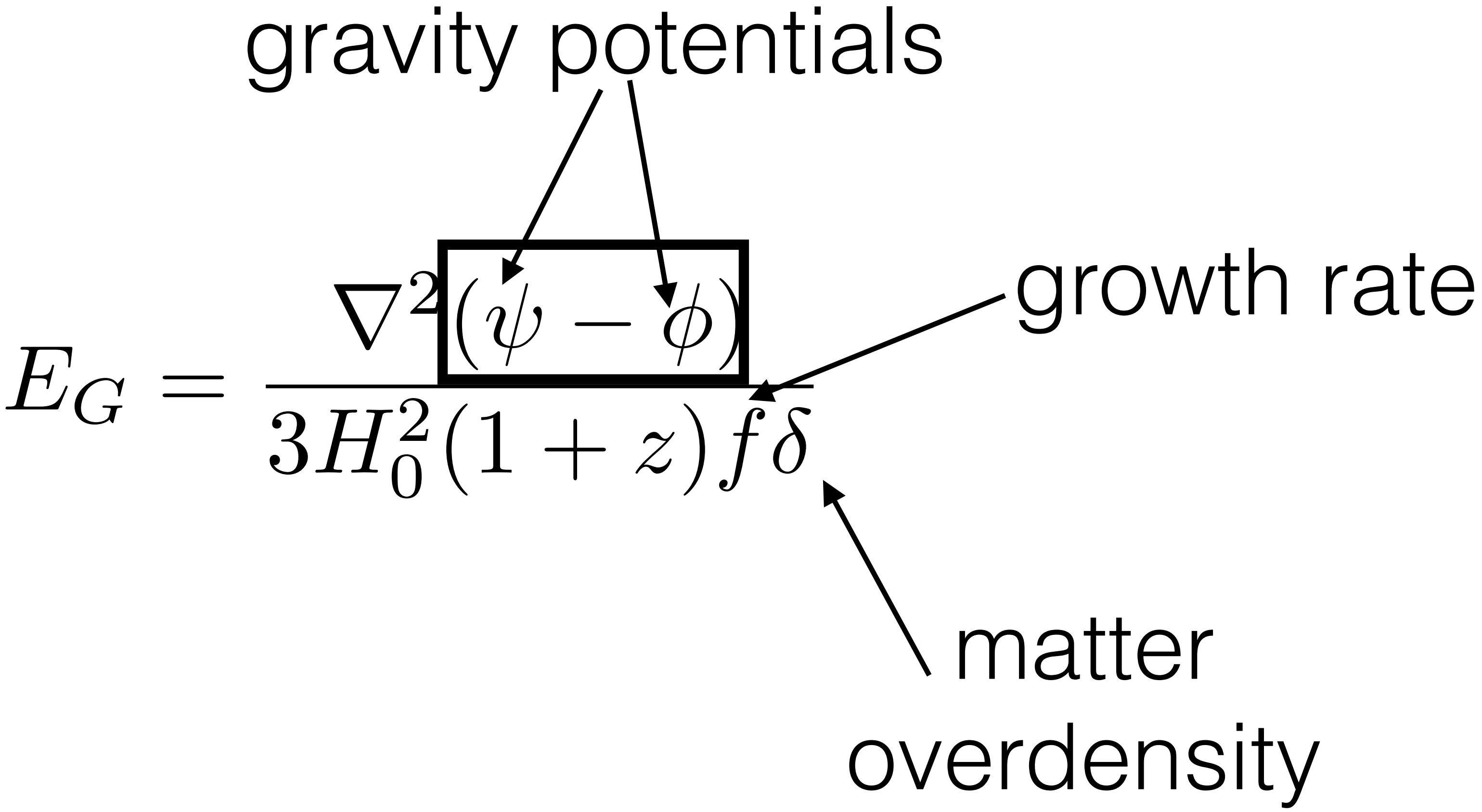
Probing 2 gravitational processes break degeneracy!

E_G = New Statistic to Probe Gravity

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

Zhang et al. 2007

E_G = New Statistic to Probe Gravity



gravity potentials

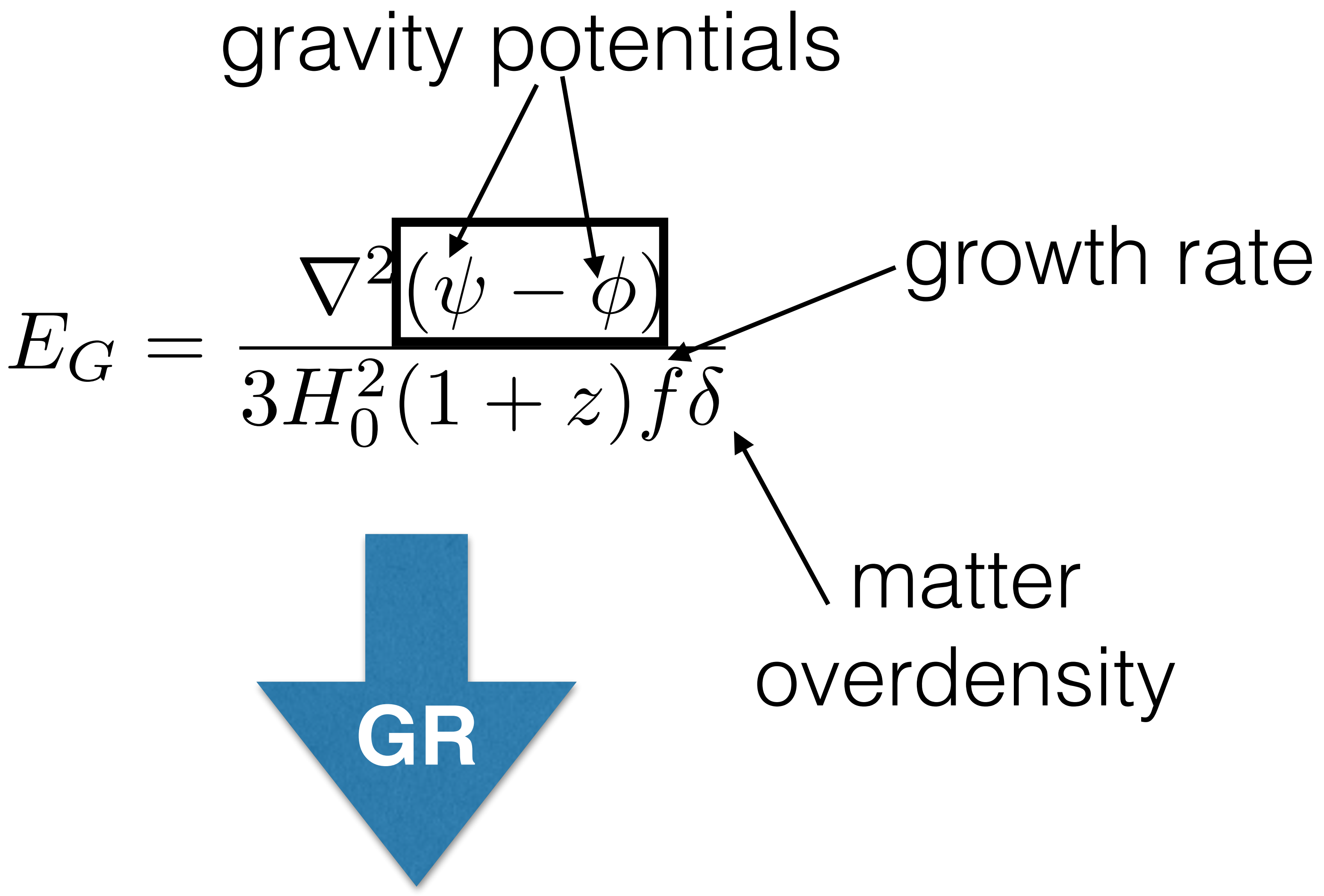
growth rate

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

matter
overdensity

Zhang et al. 2007

E_G = New Statistic to Probe Gravity



gravity potentials

growth rate

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

matter overdensity

GR

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

Zhang et al. 2007

E_G = New Statistic to Probe Gravity

gravity potentials

growth rate

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

matter overdensity

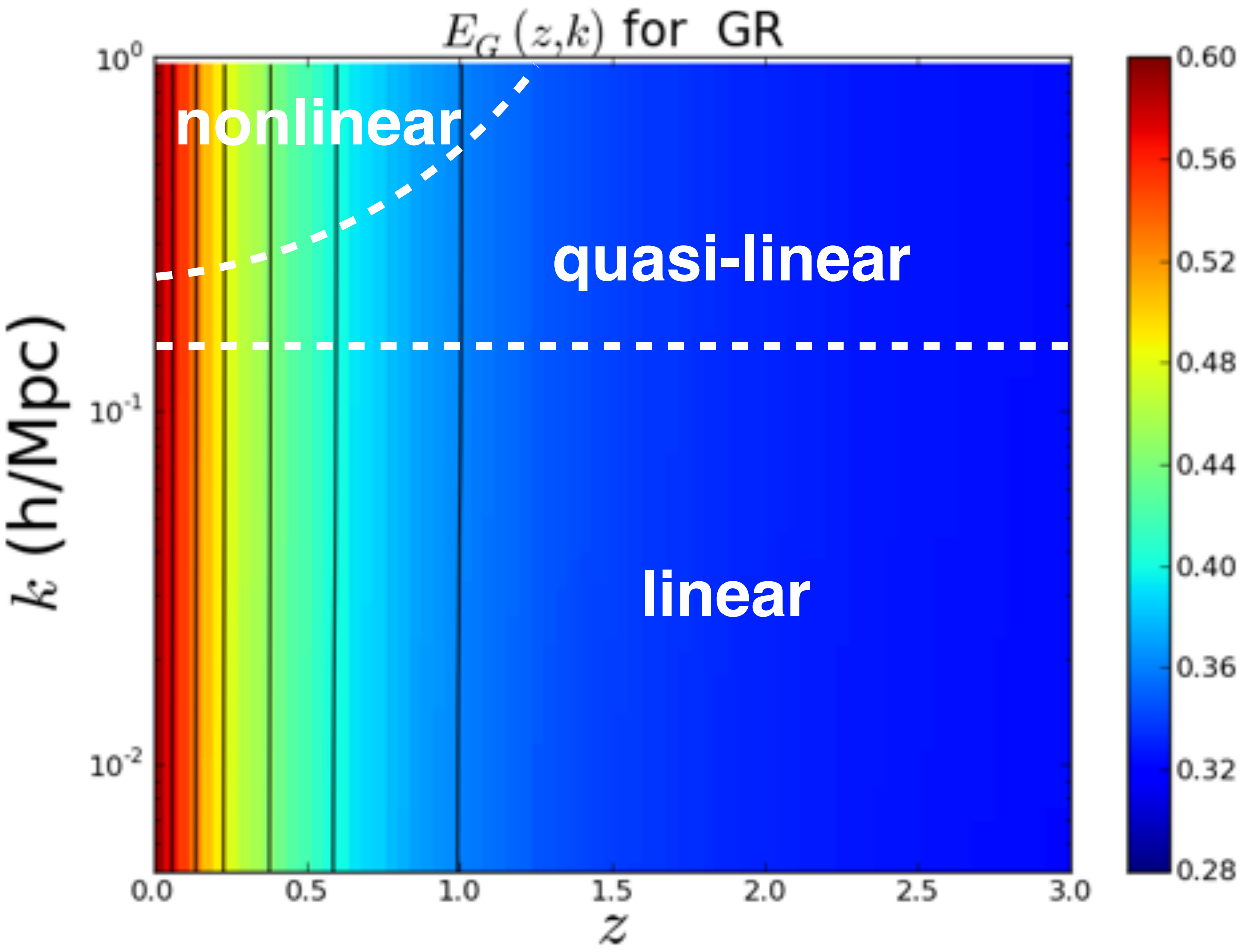
GR

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

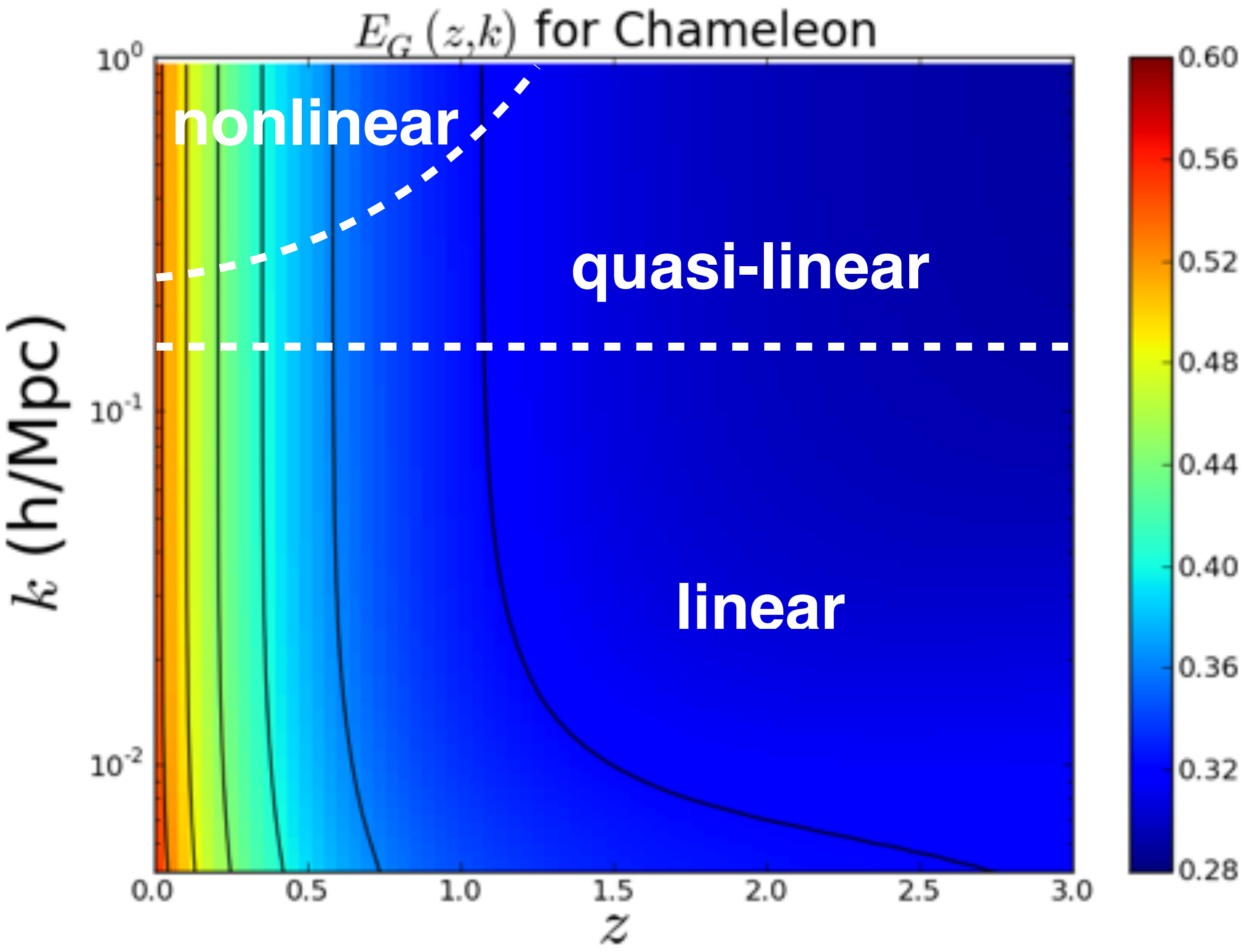
Modified by anisotropic stress & weak gravity

Zhang et al. 2007

Modified gravity = scale-dependent E_G



General Relativity



Chameleon Gravity

Pullen, Alam & Ho 2015

$\mathrm{E_G}$ Estimator

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

Pullen, Alam & Ho 2015

E_G Estimator

$$E_G = \frac{\nabla^2(\psi - \phi)}{3H_0^2(1+z)f\delta} \times \frac{g}{g} \text{ per Fourier mode}$$

Pullen, Alam & Ho 2015

E_G Estimator

$$E_G = \frac{\nabla^2(\psi - \phi)}{3H_0^2(1+z)f\delta} \times \frac{g}{g} \quad \text{per Fourier mode}$$

⬇

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

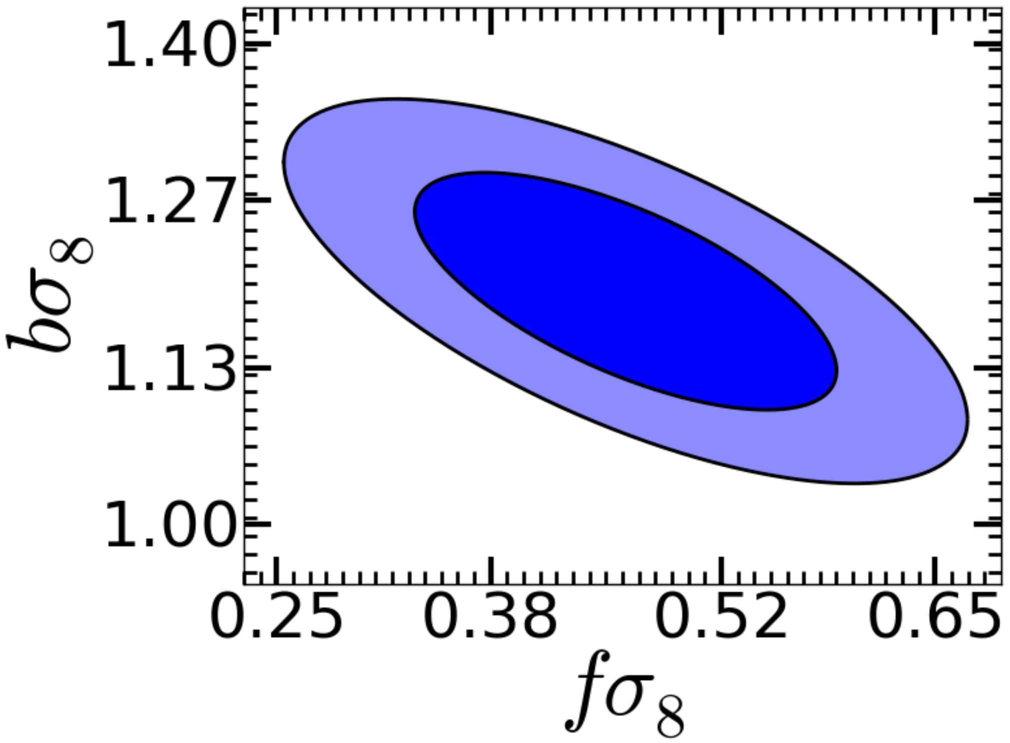
Pullen, Alam & Ho 2015

Growth rate degenerate with bias

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

clustering bias

RSD parameter



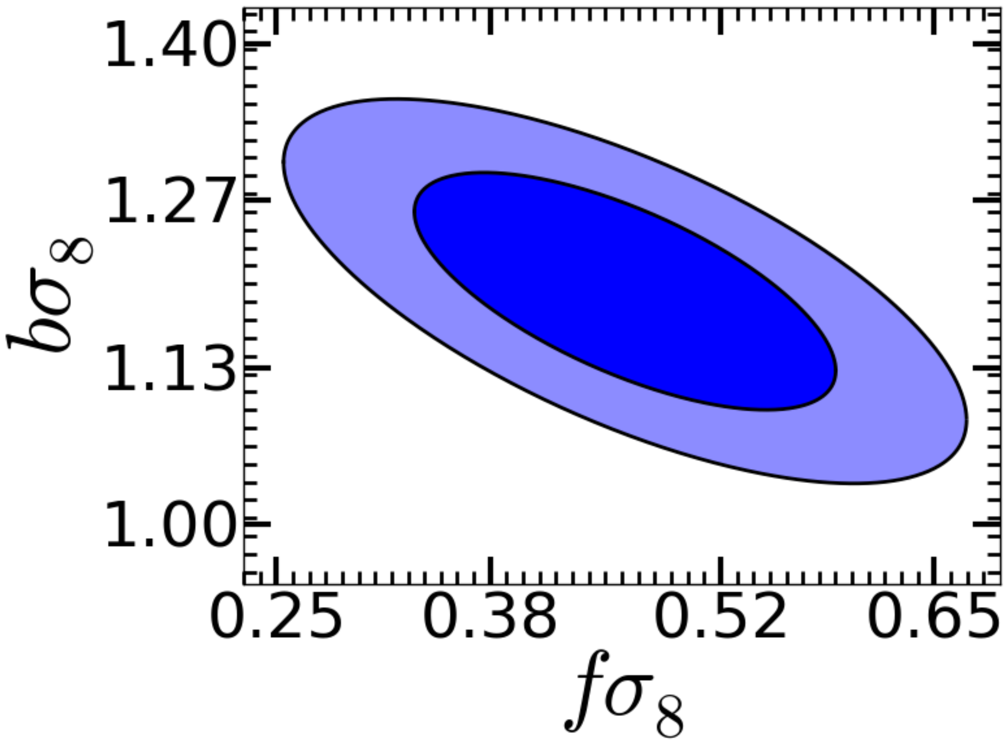
Credit: Alam et al. 2015 (BOSS)

Growth rate degenerate with bias

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

clustering bias

RSD parameter



Credit: Alam et al. 2015 (BOSS)

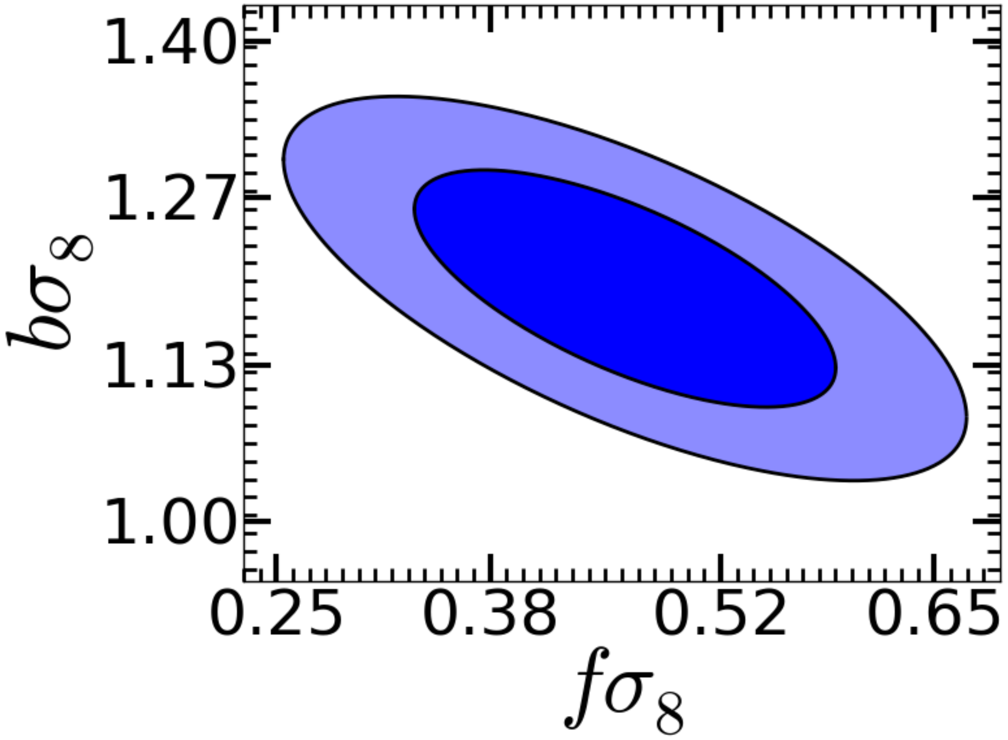
- Clustering bias relates galaxy and matter perturbations.

Growth rate degenerate with bias

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

clustering
bias

RSD parameter



Credit: Alam et al. 2015 (BOSS)

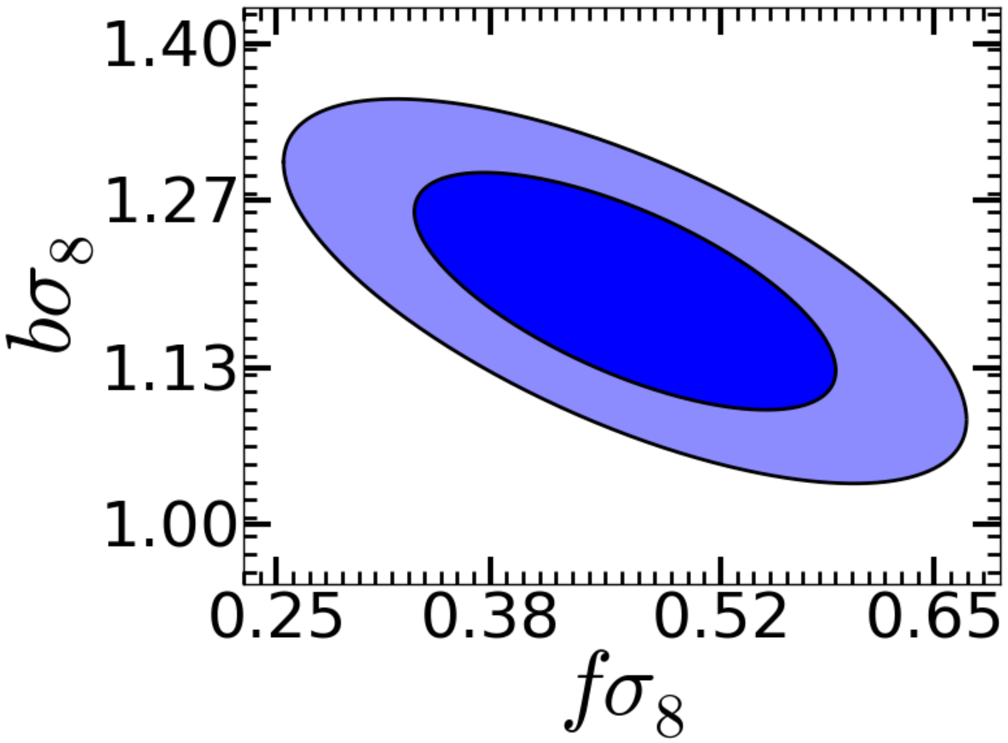
- Clustering bias relates galaxy and matter perturbations.
- Bias and σ_8 must be marginalized over to get f.

Growth rate degenerate with bias

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

clustering bias

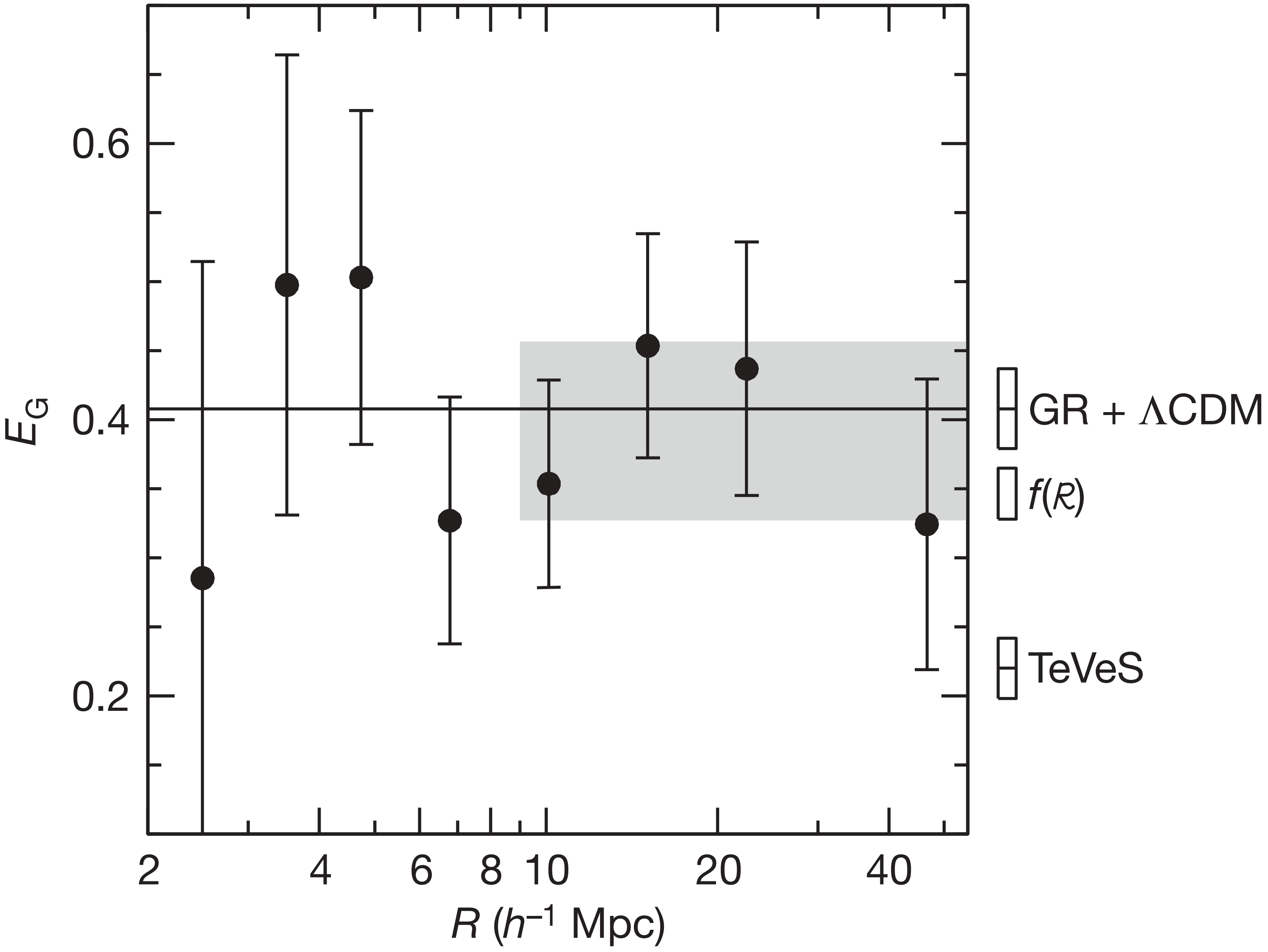
RSD parameter



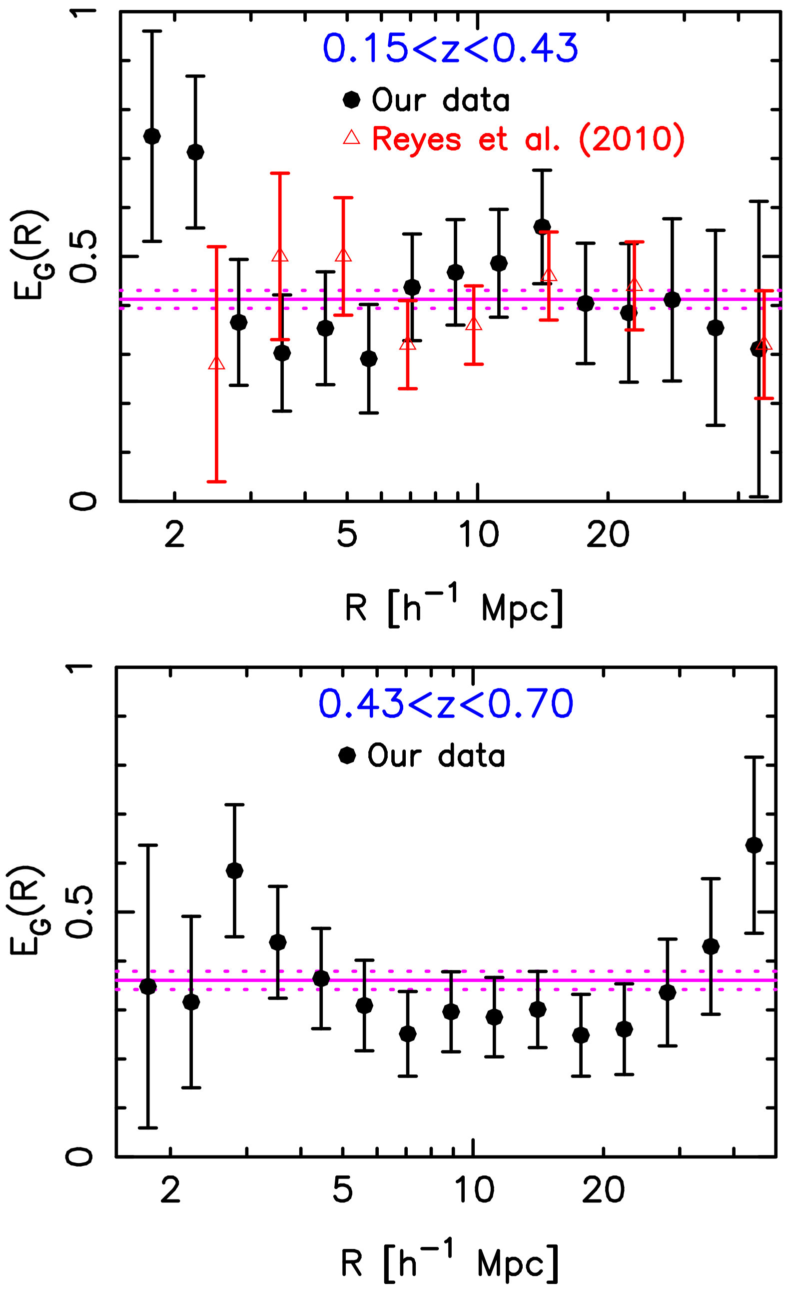
Credit: Alam et al. 2015 (BOSS)

- Clustering bias relates galaxy and matter perturbations.
- Bias and σ_8 must be marginalized over to get f.
- *E_G is independent of clustering bias and σ_8!*

First measured using galaxy lensing



Reyes et al. 2010



Blake et al. 2015

E_G measurements consistent with GR and f(R) gravity

CMB lensing has advantages over galaxy lensing

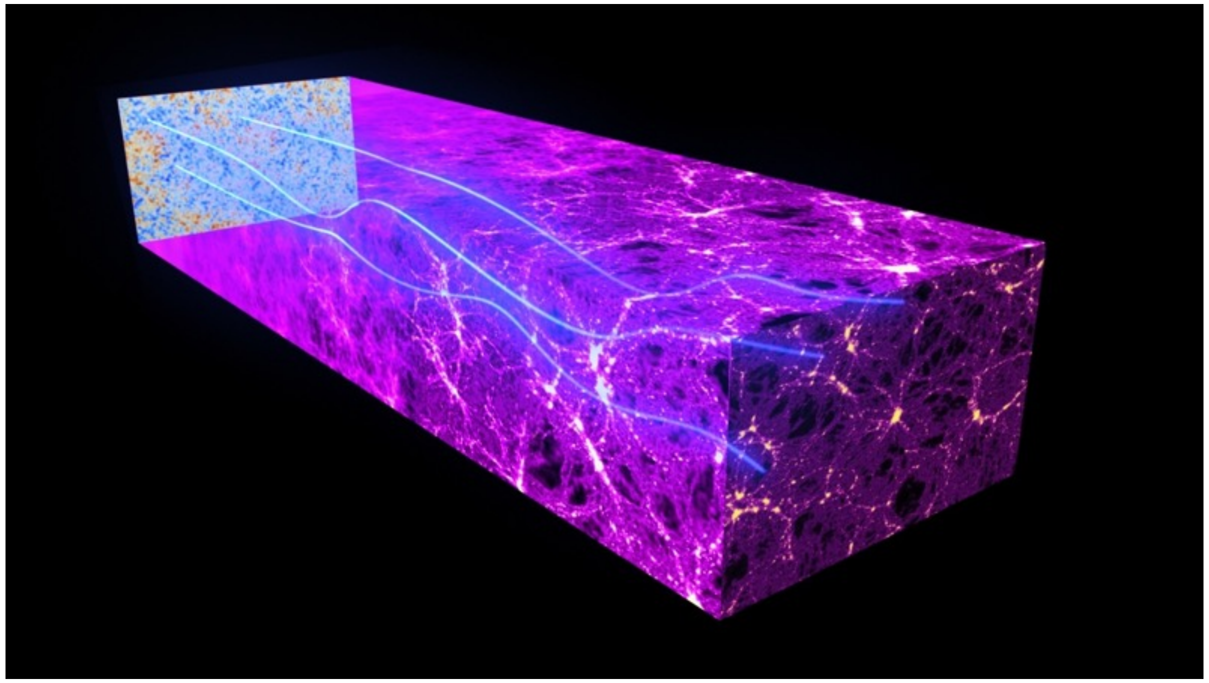


Image Credit: ESA

Pullen, Alam & Ho 2015

CMB lensing has advantages over galaxy lensing

- Probes the integrated matter distribution out to last-scattering surface of the CMB

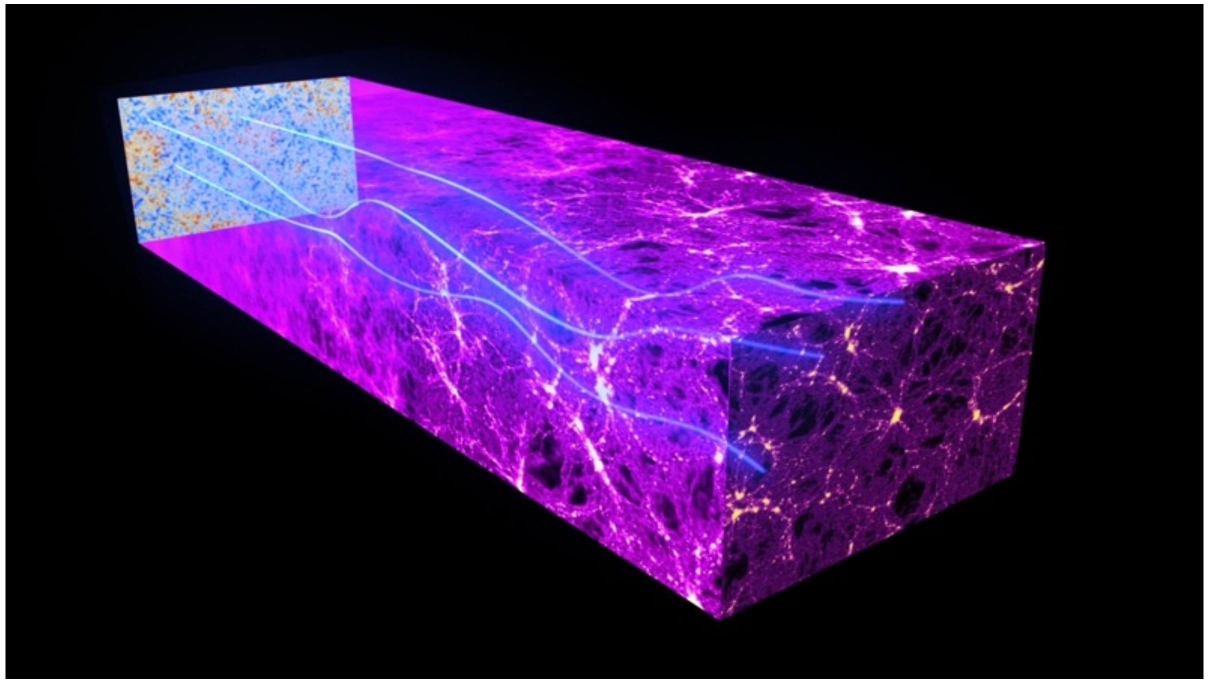


Image Credit: ESA

Pullen, Alam & Ho 2015

CMB lensing has advantages over galaxy lensing

- Probes the integrated matter distribution out to last-scattering surface of the CMB

- Precise, well-defined source plane

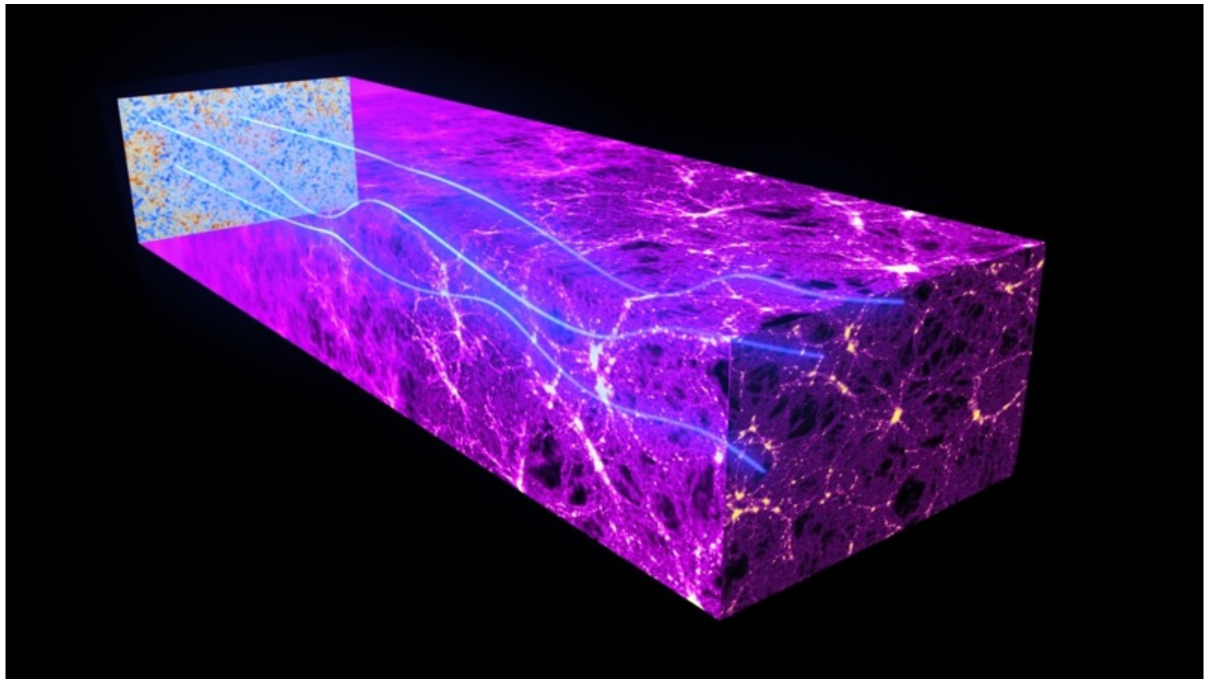


Image Credit: ESA

Pullen, Alam & Ho 2015

CMB lensing has advantages over galaxy lensing

- Probes the integrated matter distribution out to last-scattering surface of the CMB
- Precise, well-defined source plane
- High source redshift

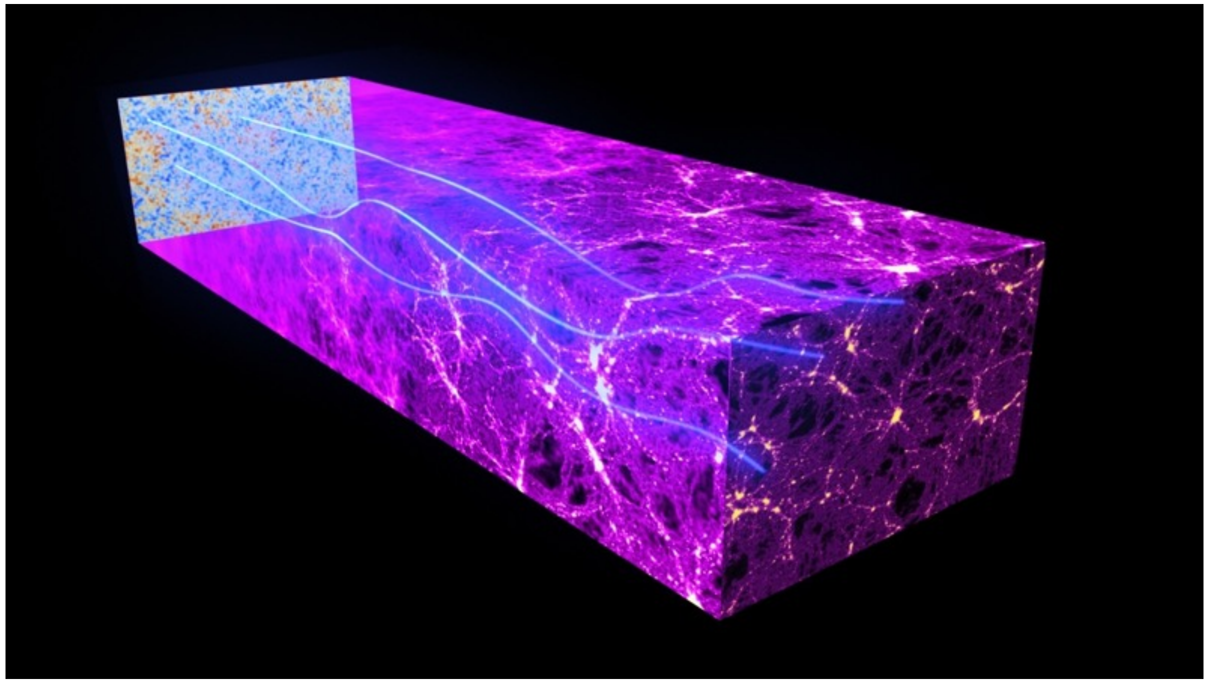


Image Credit: ESA

Pullen, Alam & Ho 2015

CMB lensing has advantages over galaxy lensing

- Probes the integrated matter distribution out to last-scattering surface of the CMB
- Precise, well-defined source plane
- High source redshift
- No intrinsic alignments, astro systematics in CMB

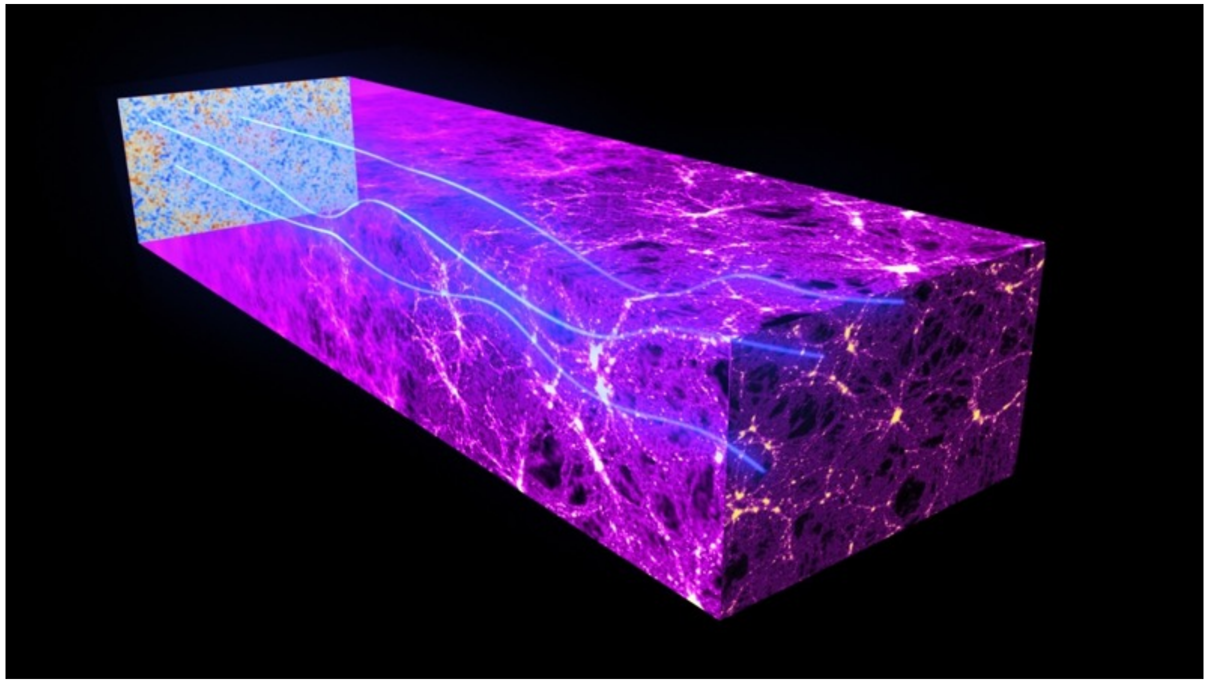
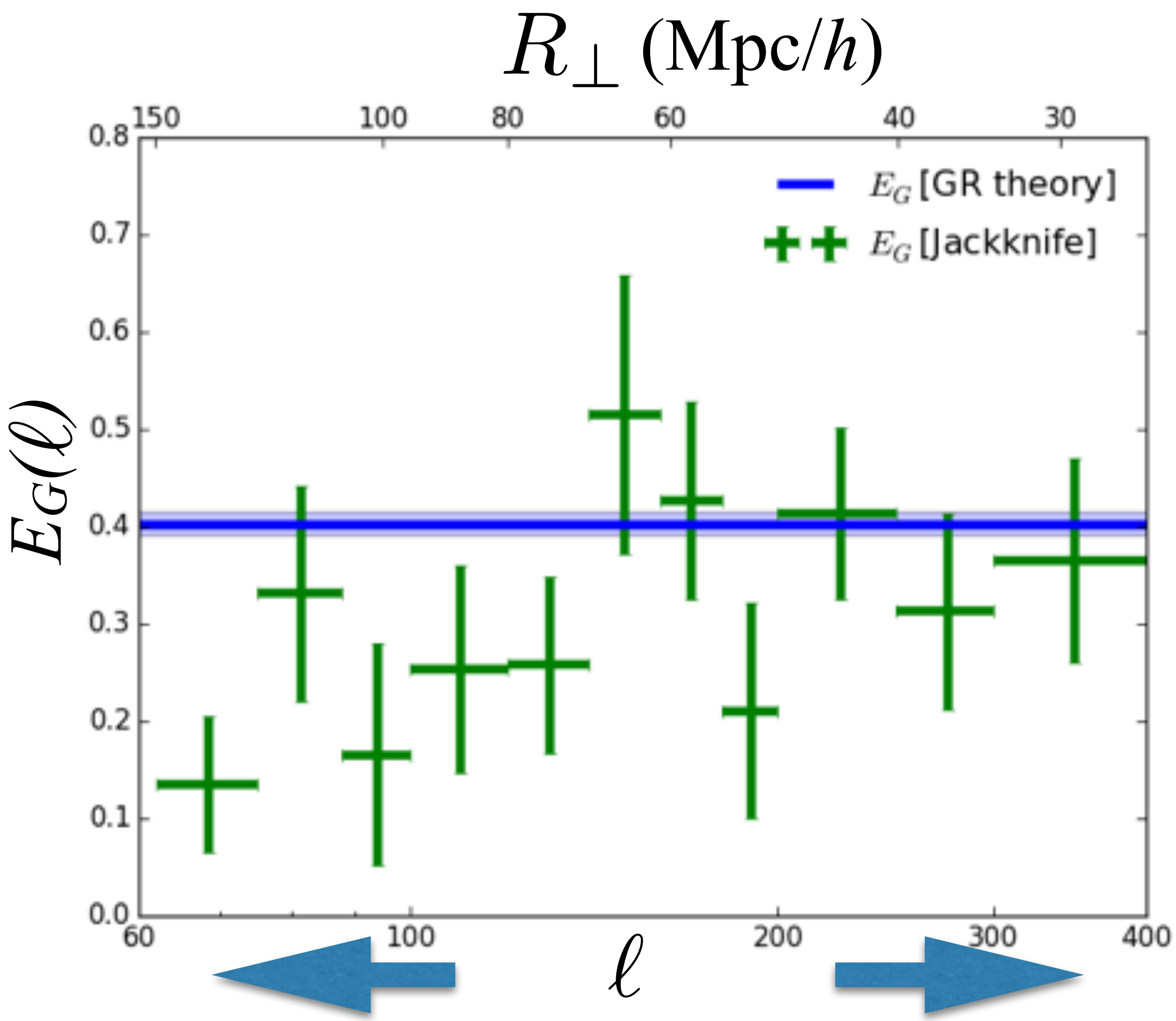


Image Credit: ESA

Pullen, Alam & Ho 2015

Largest Scale E_G Measure



Large Scales

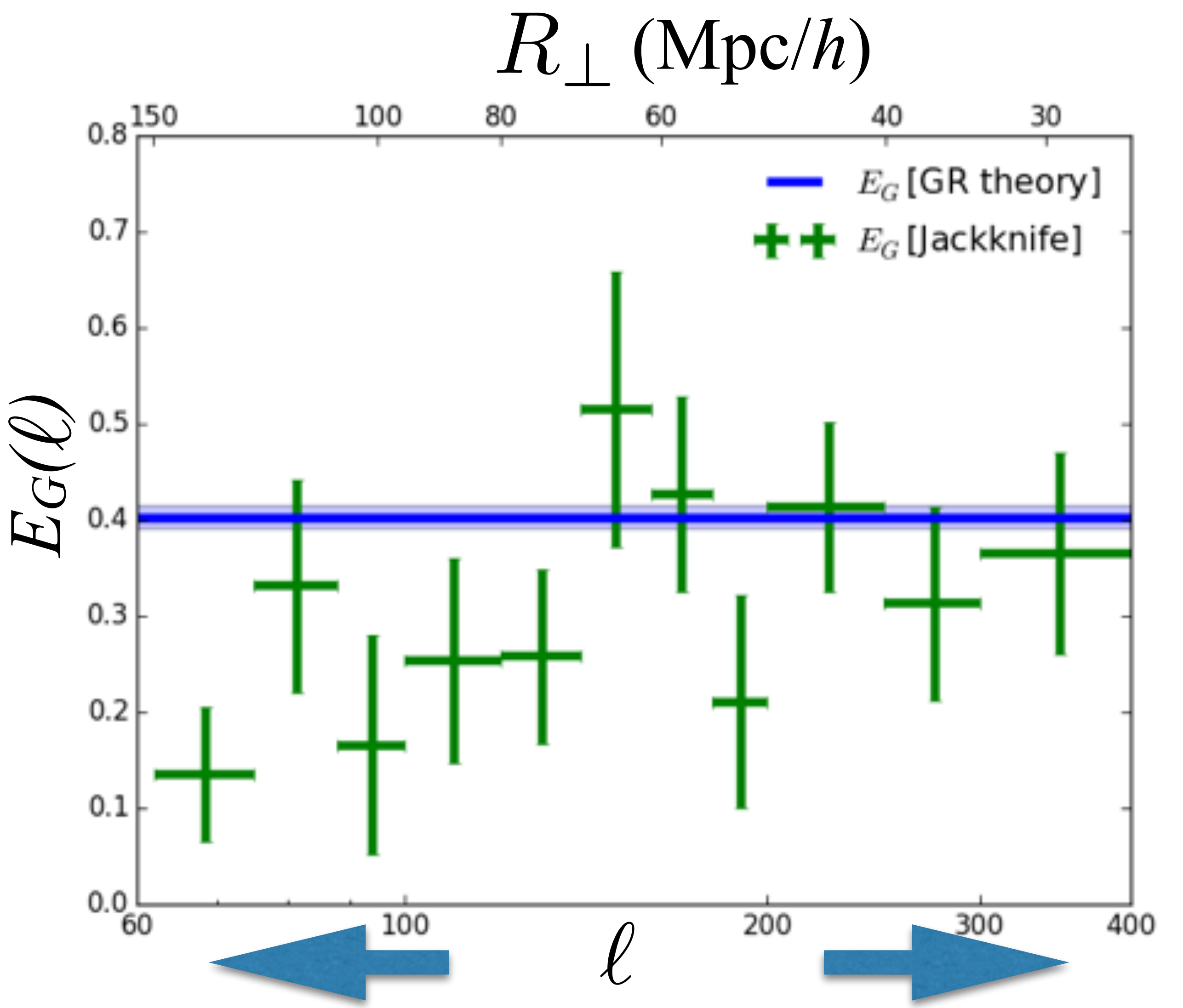
Small Scales

$$\boxed{\begin{aligned} E_G(z = 0.57) \\ = 0.243 \pm 0.060 \end{aligned}}$$

Pullen, Alam, He & Ho 2015

Largest Scale E_G Measure

- We estimate E_G in 11 l-bins out to 150 Mpc/h!



Large Scales

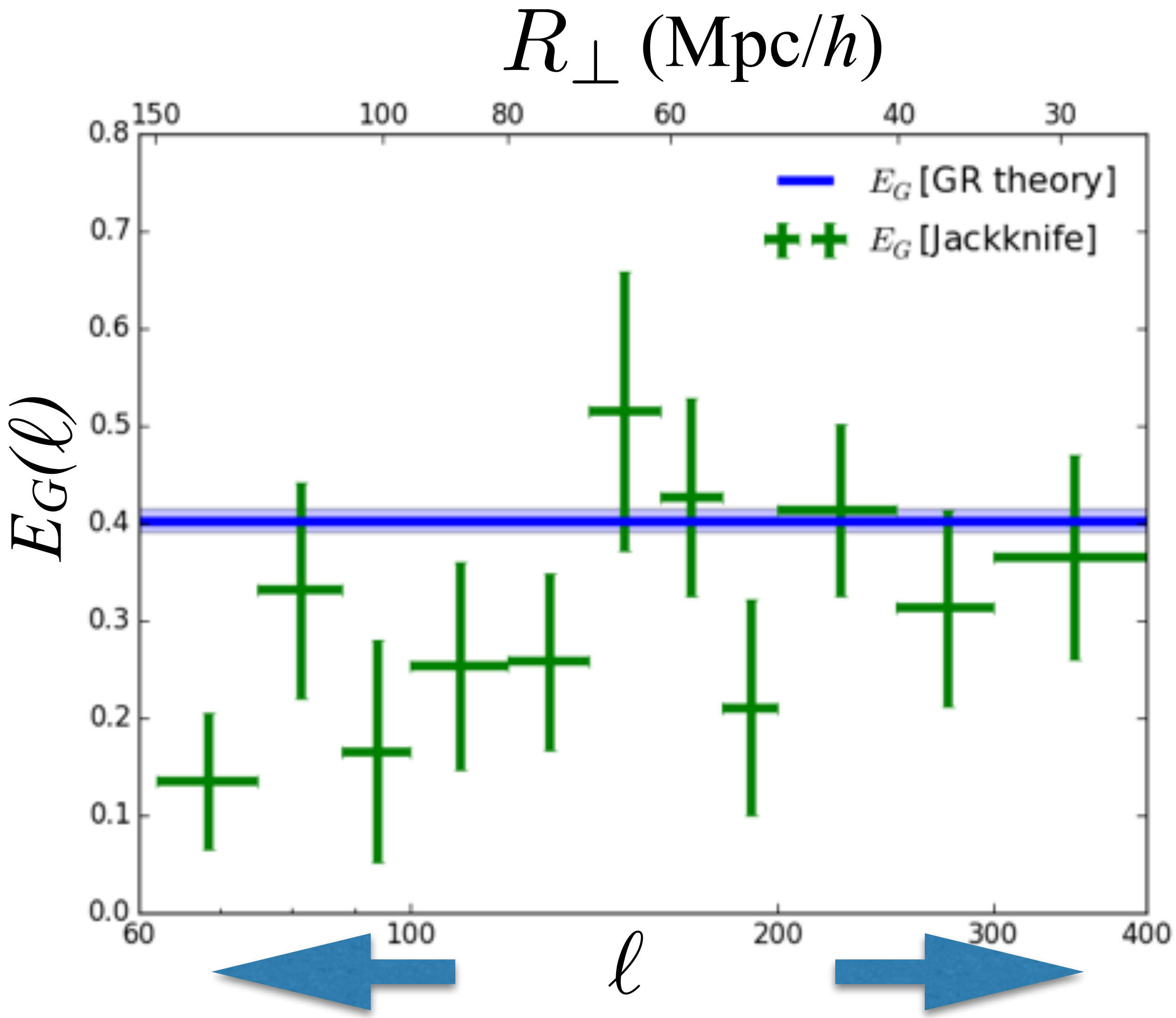
Small Scales

$$\boxed{E_G(z=0.57) = 0.243 \pm 0.060}$$

Pullen, Alam, He & Ho 2015

Largest Scale E_G Measure

- We estimate E_G in 11 l-bins out to 150 Mpc/h!
- Results using jackknives and mocks agree.



Large Scales

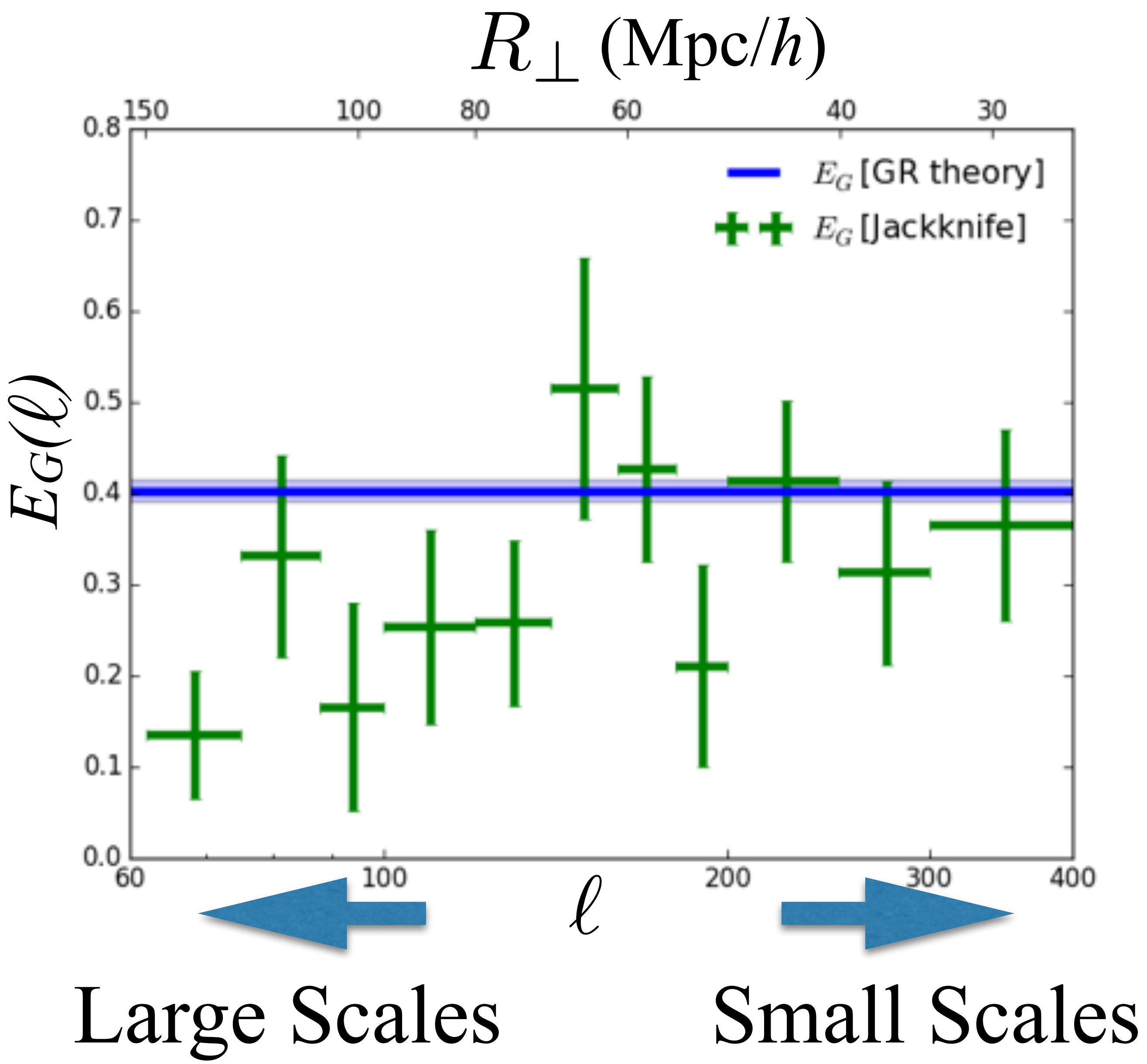
Small Scales

$$\boxed{\begin{aligned} E_G(z = 0.57) \\ = 0.243 \pm 0.060 \end{aligned}}$$

Pullen, Alam, He & Ho 2015

Largest Scale E_G Measure

- We estimate E_G in 11 l-bins out to 150 Mpc/h!
- Results using jackknives and mocks agree.
- Tension with GR ($E_G = 0.402$) at 2.6σ

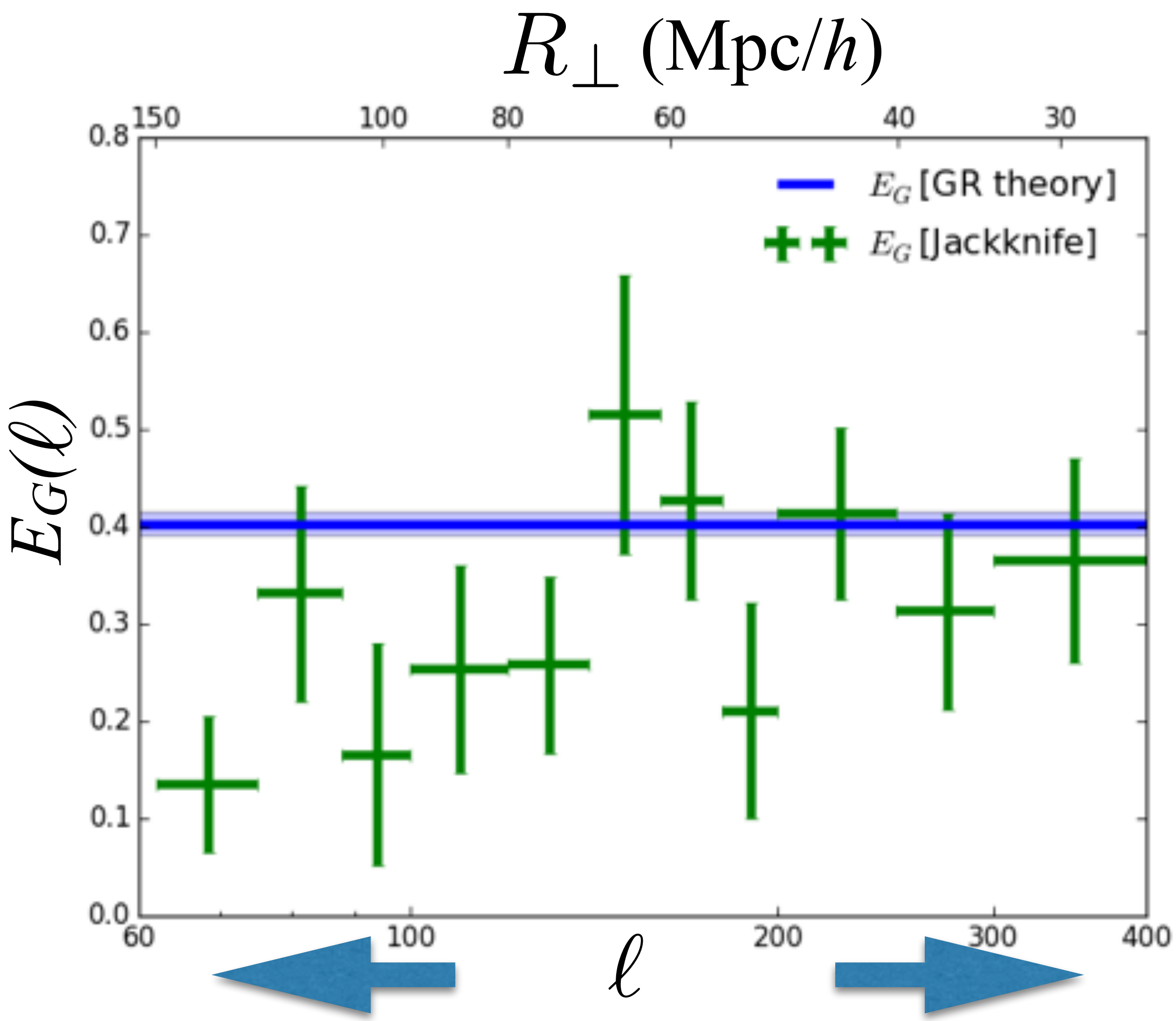


$$\boxed{E_G(z = 0.57) = 0.243 \pm 0.060}$$

Pullen, Alam, He & Ho 2015

Largest Scale E_G Measure

- We estimate E_G in 11 l-bins out to 150 Mpc/h!
- Results using jackknives and mocks agree.
- Tension with GR ($E_G = 0.402$) at 2.6σ
- Small systematics (5.3%)



Large Scales

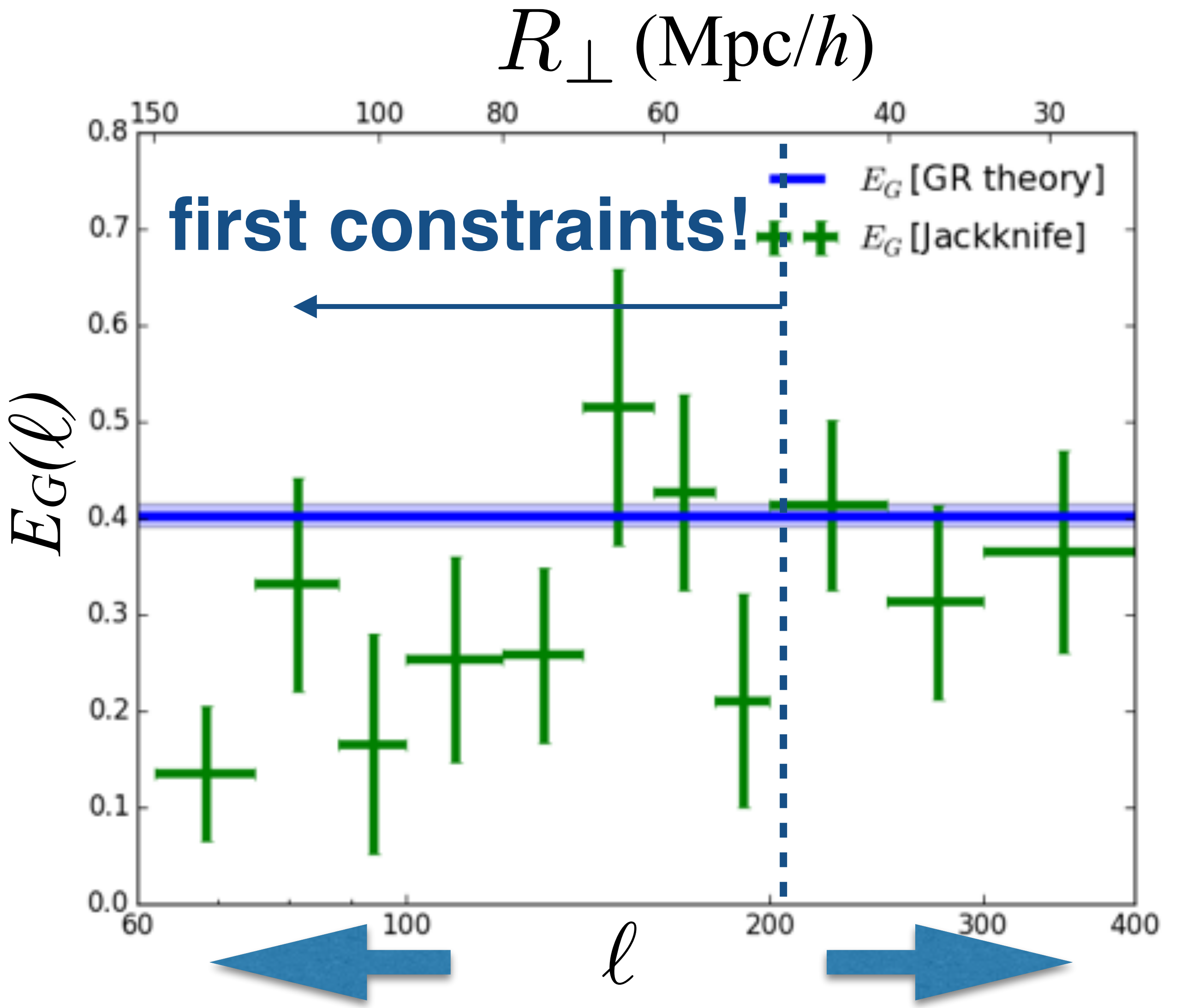
Small Scales

$$\boxed{\begin{aligned} E_G(z = 0.57) \\ = 0.243 \pm 0.060 \end{aligned}}$$

Pullen, Alam, He & Ho 2015

Largest Scale E_G Measure

- We estimate E_G in 11 l-bins out to 150 Mpc/h!
- Results using jackknives and mocks agree.
- Tension with GR ($E_G = 0.402$) at 2.6σ
- Small systematics (5.3%)



Large Scales

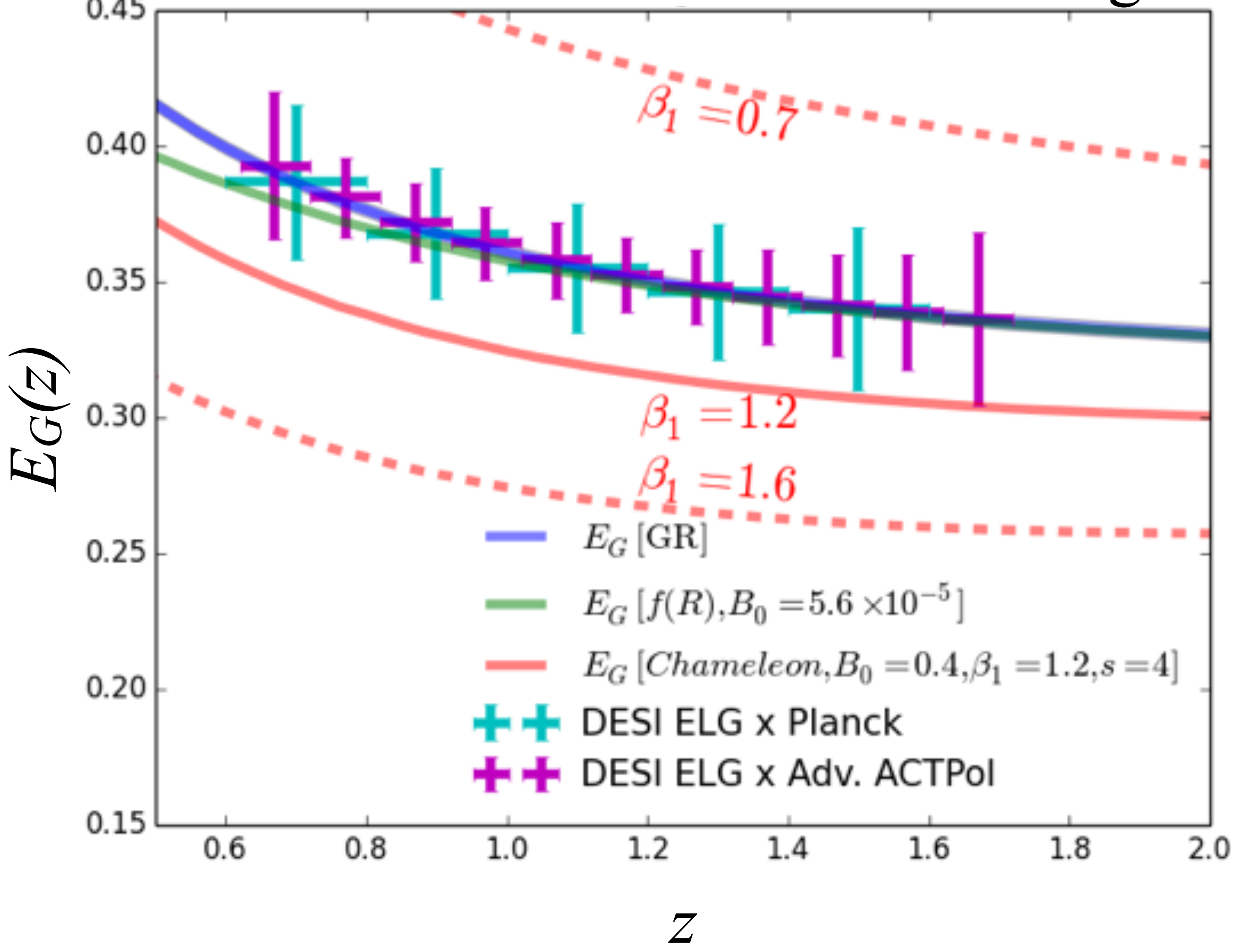
Small Scales

$$\boxed{\begin{aligned} E_G(z &= 0.57) \\ &= 0.243 \pm 0.060 \end{aligned}}$$

Pullen, Alam, He & Ho 2015

Spectroscopic Surveys

DESI x Planck/AdvACT Lensing



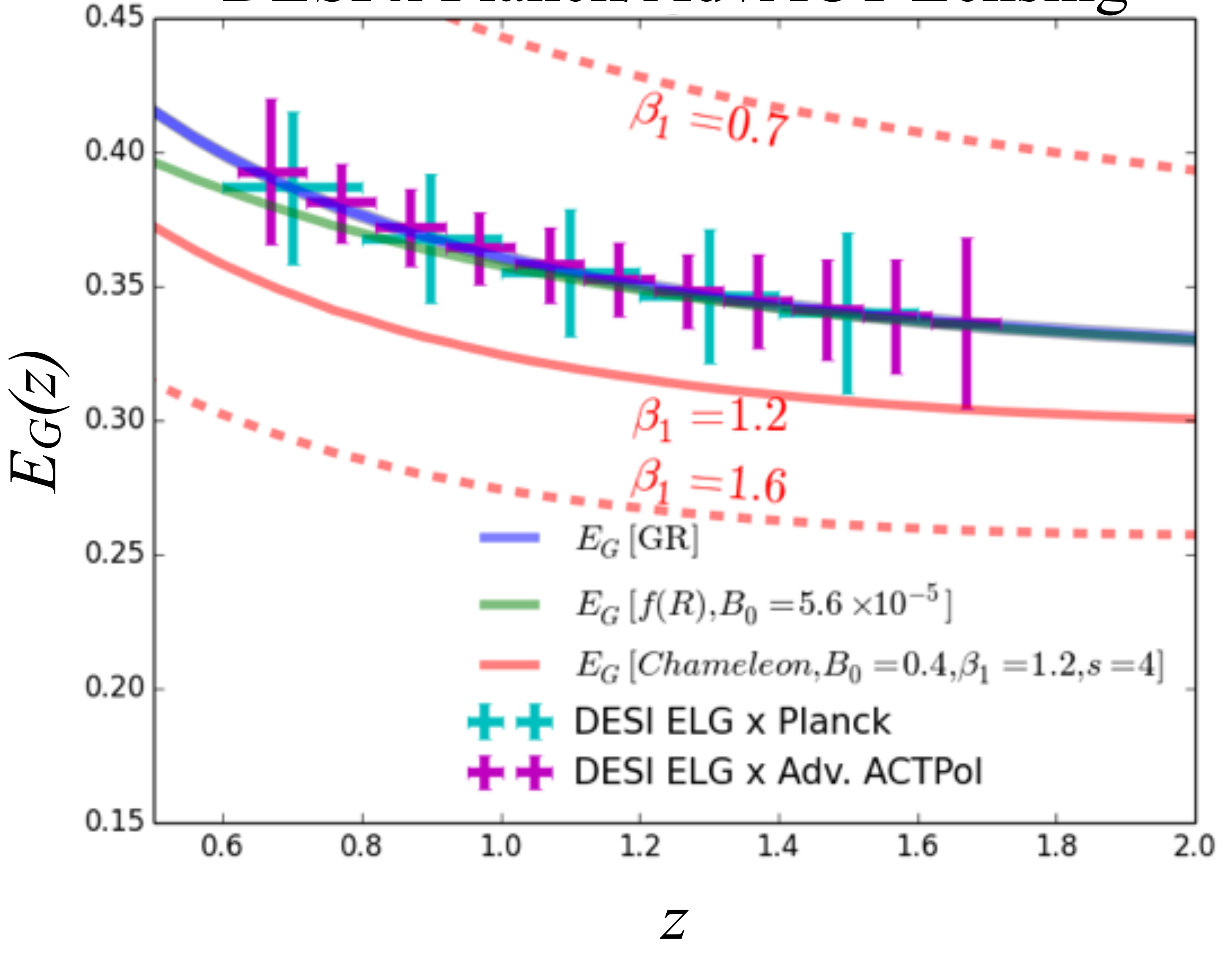
Credit: **Pullen**, Alam & Ho 2015

Dark Energy Spectroscopic Instrument

Spectroscopic Surveys

- Galaxy redshifts from spectra

DESI x Planck/AdvACT Lensing



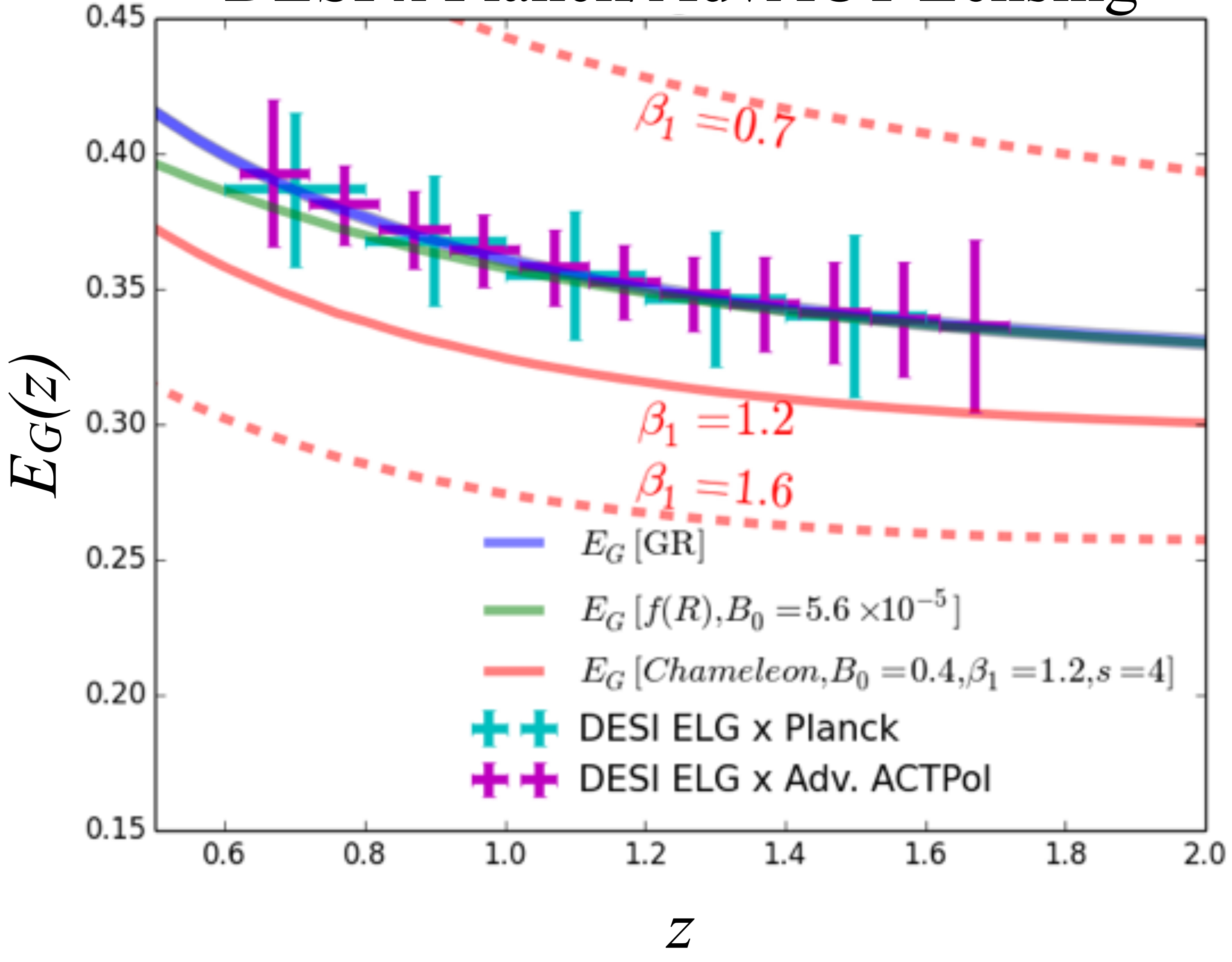
Credit: **Pullen**, Alam & Ho 2015

Dark Energy Spectroscopic Instrument

Spectroscopic Surveys

- Galaxy redshifts from spectra
- Expensive but necessary for RSD

DESI x Planck/AdvACT Lensing



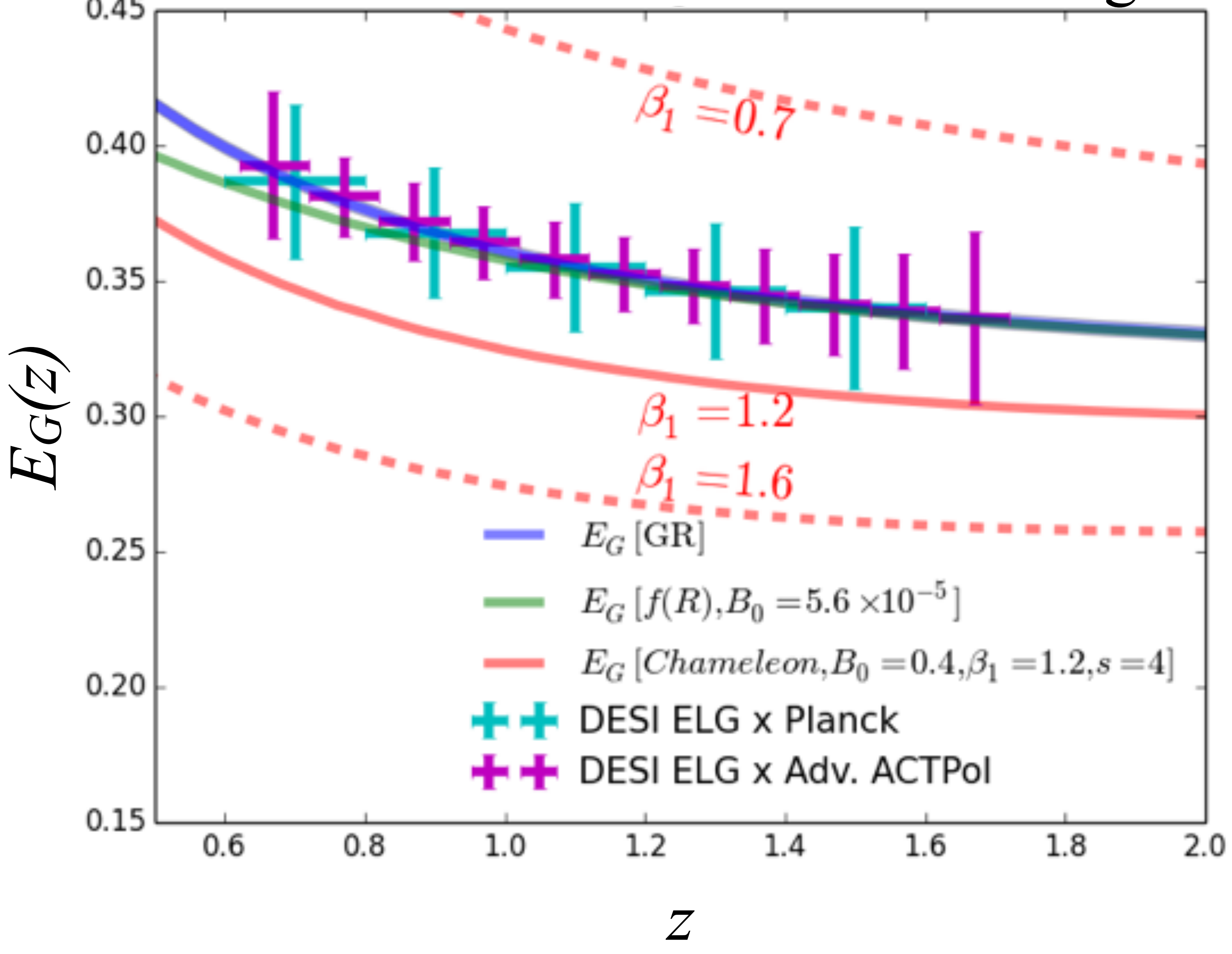
Credit: **Pullen**, Alam & Ho 2015

Dark Energy Spectroscopic Instrument

Spectroscopic Surveys

- Galaxy redshifts from spectra
- Expensive but necessary for RSD
- E_G errors of 2% (Planck) or 1% (Adv. ACTPol)

DESI x Planck/AdvACT Lensing

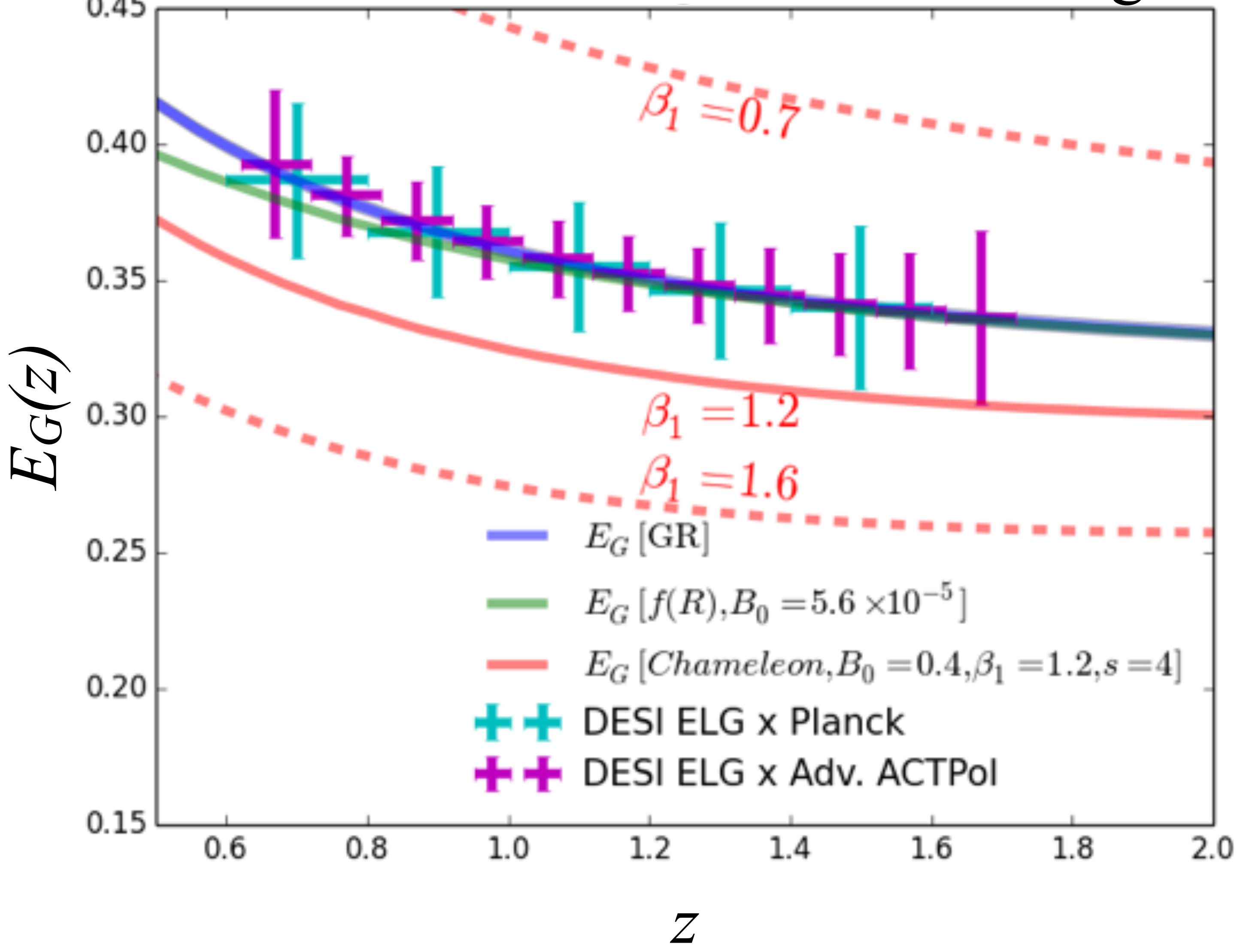


Credit: **Pullen**, Alam & Ho 2015

Dark Energy Spectroscopic Instrument

Spectroscopic Surveys

- Galaxy redshifts from spectra
- Expensive but necessary for RSD
- E_G errors of 2% (Planck) or 1% (Adv. ACTPol)
- **CMB-S4 is ~10% better (cosmic variance limited)**



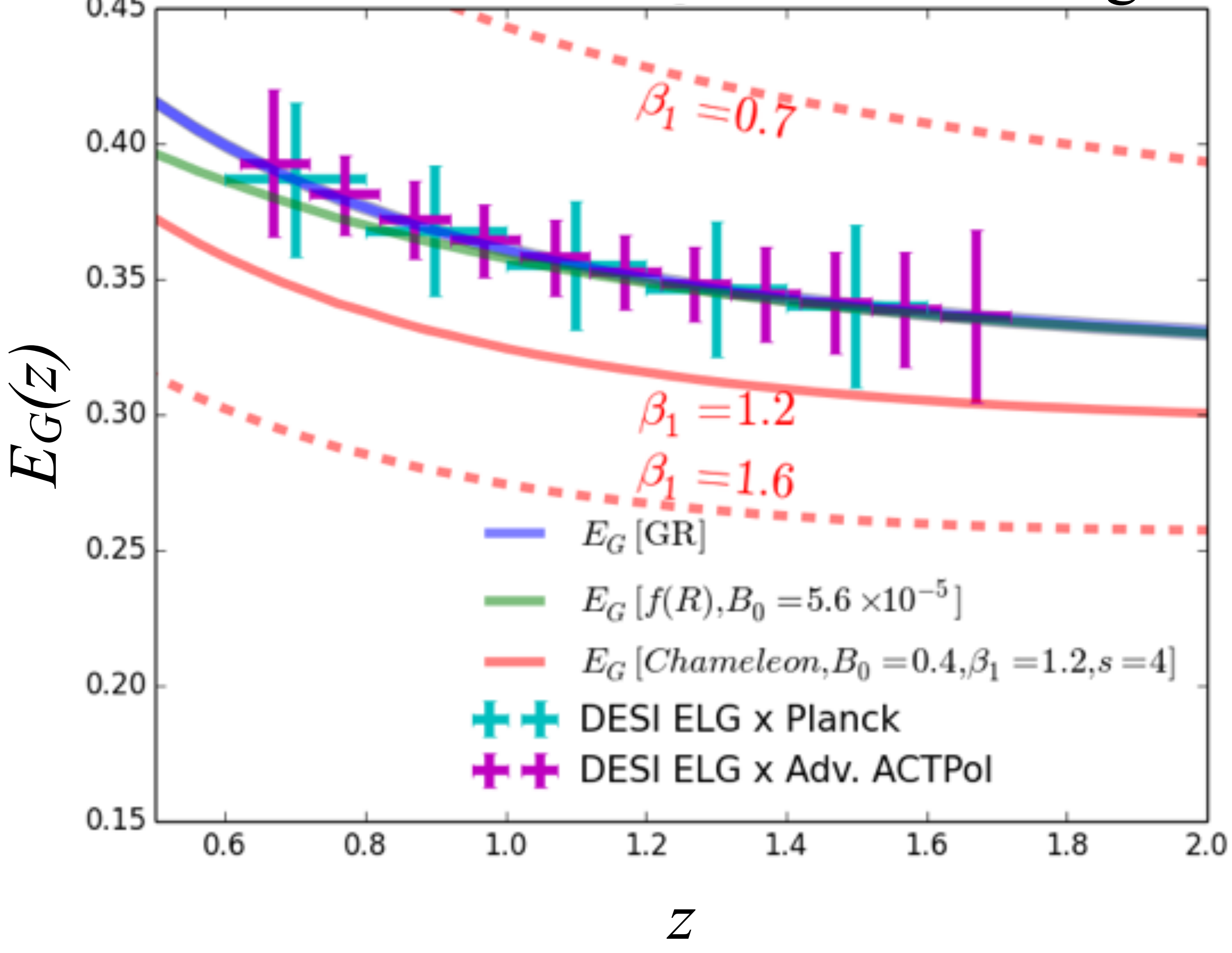
DESI x Planck/AdvACT Lensing

Credit: **Pullen**, Alam & Ho 2015

Dark Energy Spectroscopic Instrument

Spectroscopic Surveys

- Galaxy redshifts from spectra
- Expensive but necessary for RSD
- E_G errors of 2% (Planck) or 1% (Adv. ACTPol)
- **CMB-S4 is ~10% better (cosmic variance limited)**
- Constrains chameleon gravity



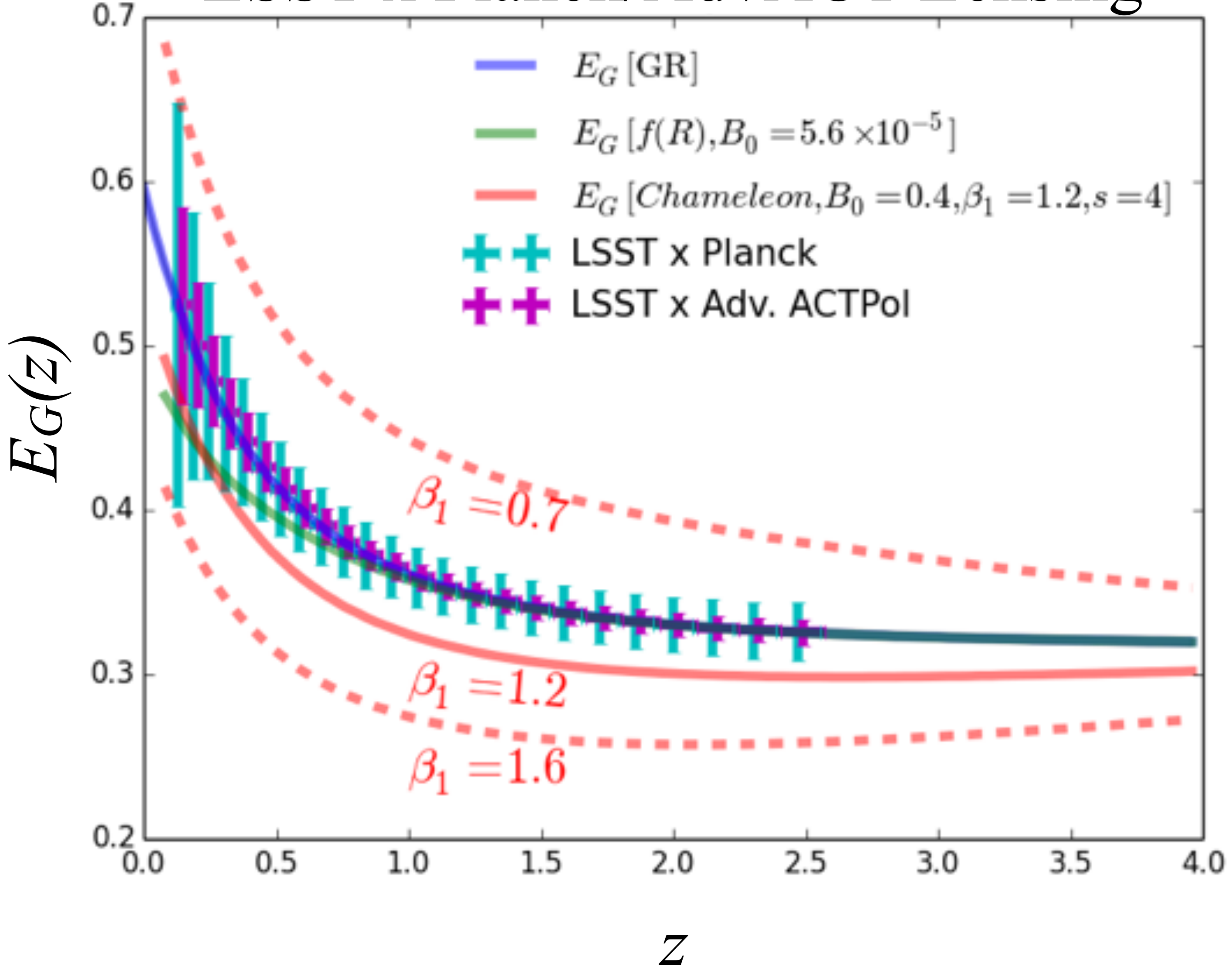
DESI x Planck/AdvACT Lensing

Credit: **Pullen**, Alam & Ho 2015

Dark Energy Spectroscopic Instrument

Photometric Surveys

LSST x Planck/AdvACT Lensing

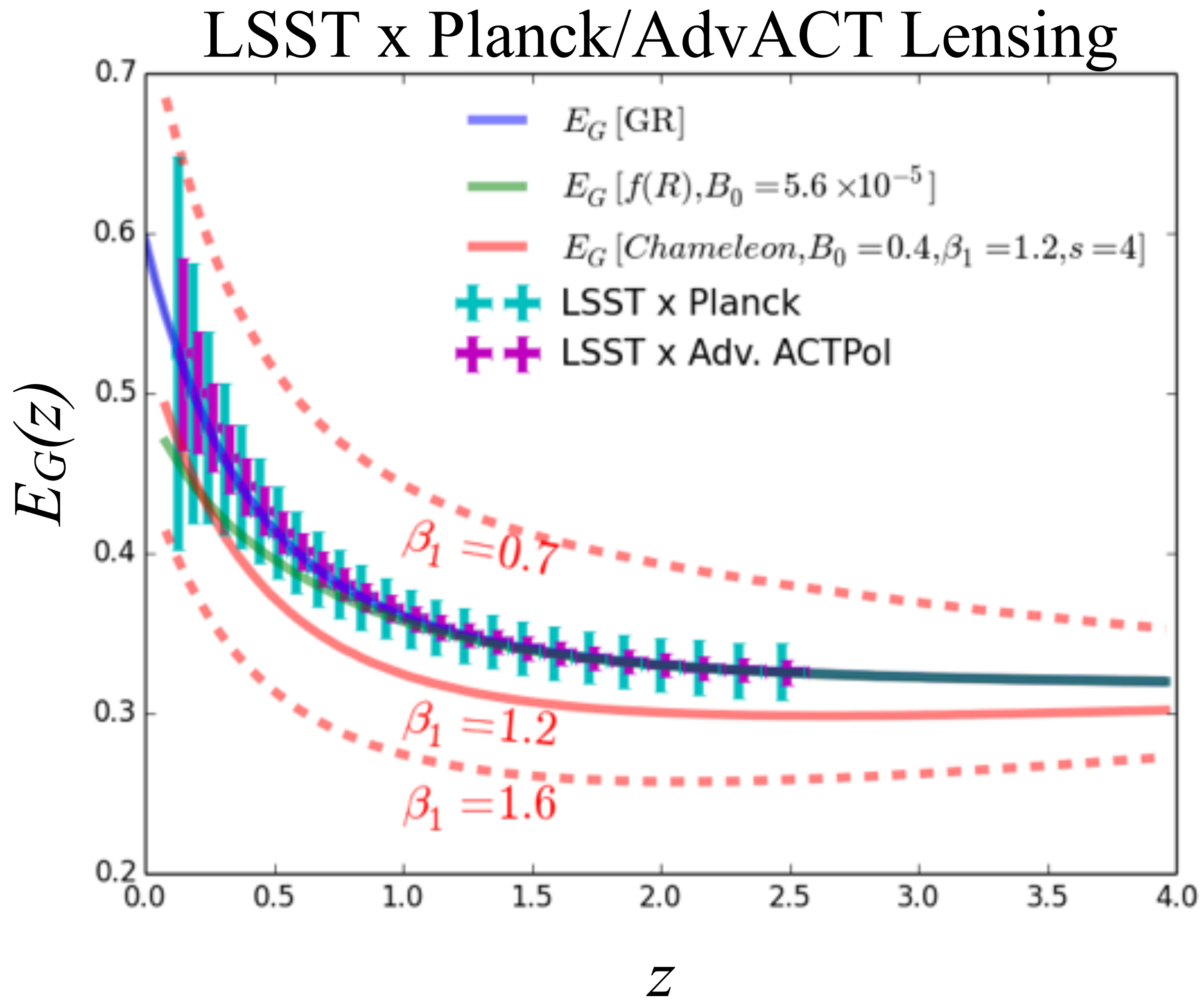


Credit: **Pullen**, Alam & Ho 2015

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

Photometric Surveys

- Galaxy redshifts from colors


LSST x Planck/AdvACT Lensing

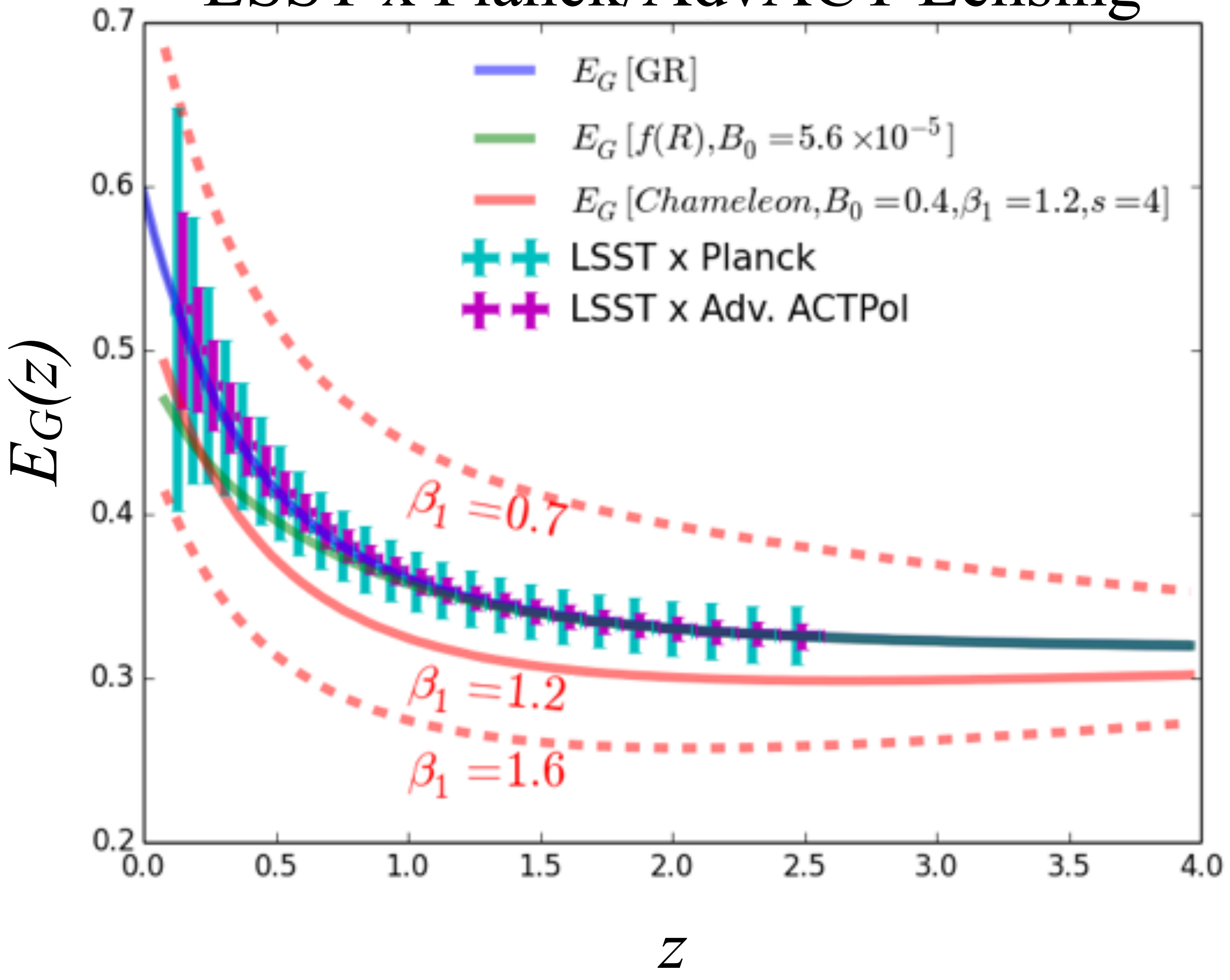
Credit: **Pullen**, Alam & Ho 2015

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

Photometric Surveys

- Galaxy redshifts from colors
- Less precise but inexpensive!

LSST x Planck/AdvACT Lensing



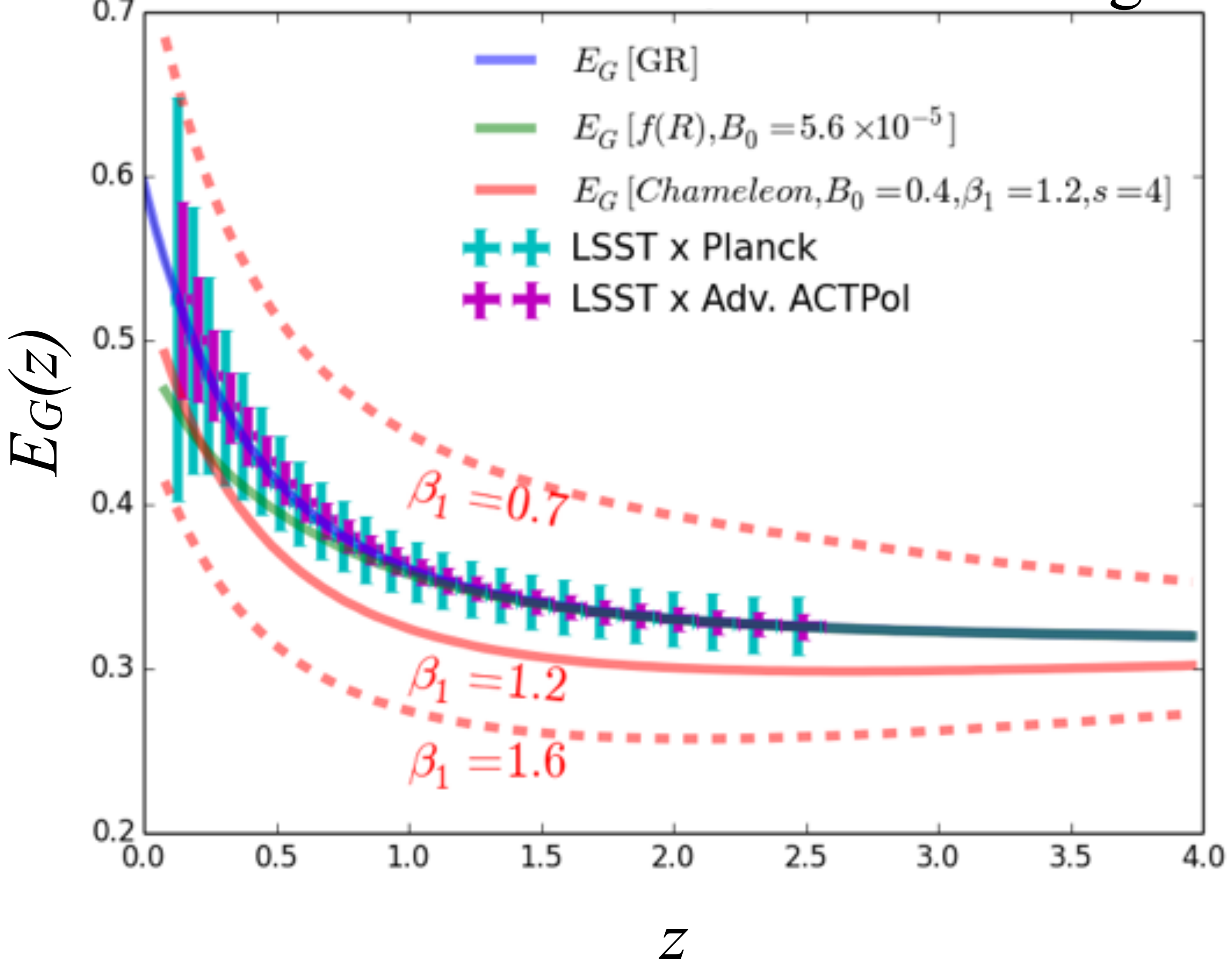
Credit: **Pullen**, Alam & Ho 2015

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

Photometric Surveys

- Galaxy redshifts from colors
- Less precise but inexpensive!
- Assumes photo RSD errors of ~8% over $\Delta z \sim 0.1$.

LSST x Planck/AdvACT Lensing



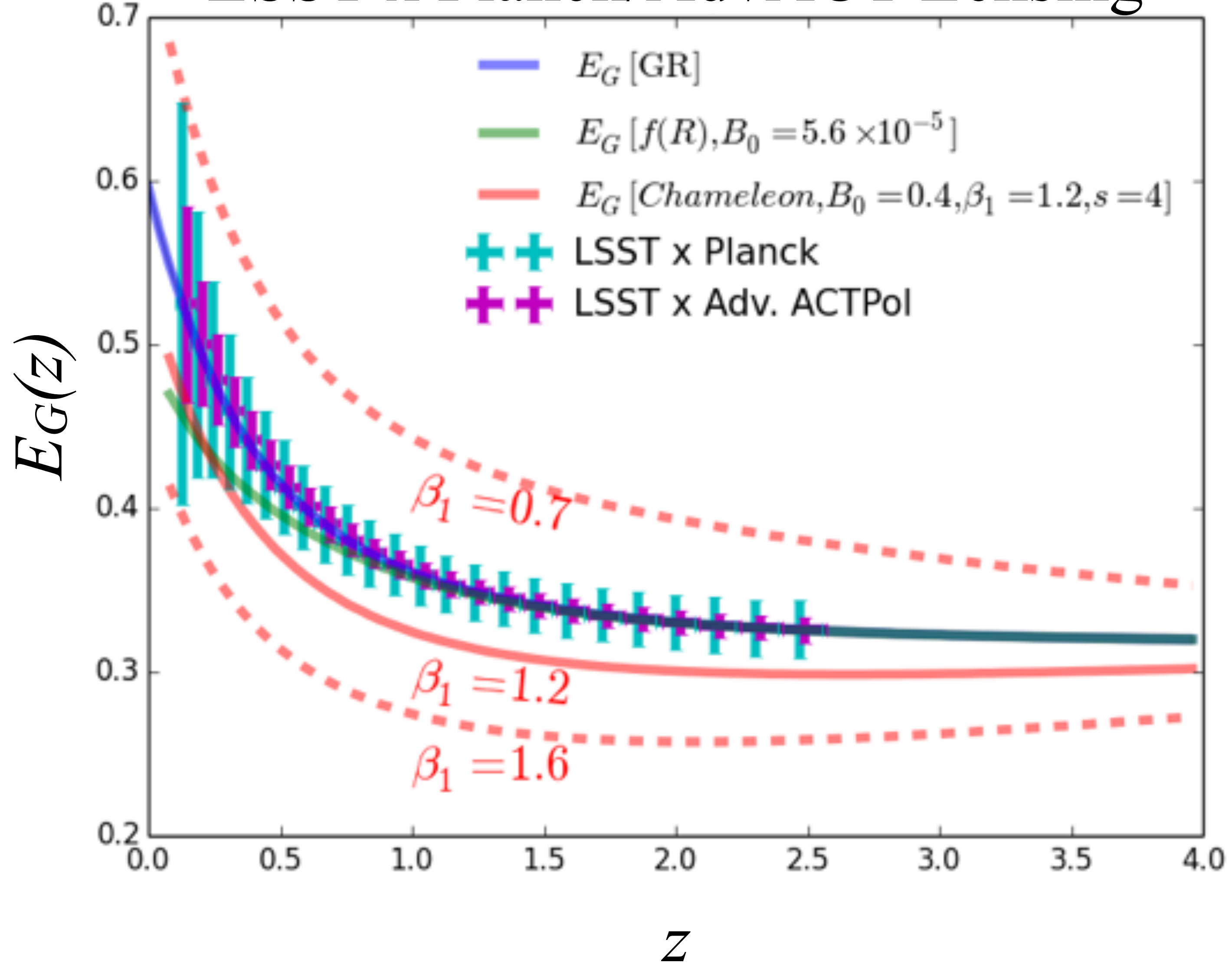
Credit: **Pullen**, Alam & Ho 2015

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

Photometric Surveys

- Galaxy redshifts from colors
- Less precise but inexpensive!
- Assumes photo RSD errors of ~8% over $\Delta z \sim 0.1$.
- E_G errors of 1% (Planck) or less (Adv. ACTPol, **CMB-S4**)

LSST x Planck/AdvACT Lensing



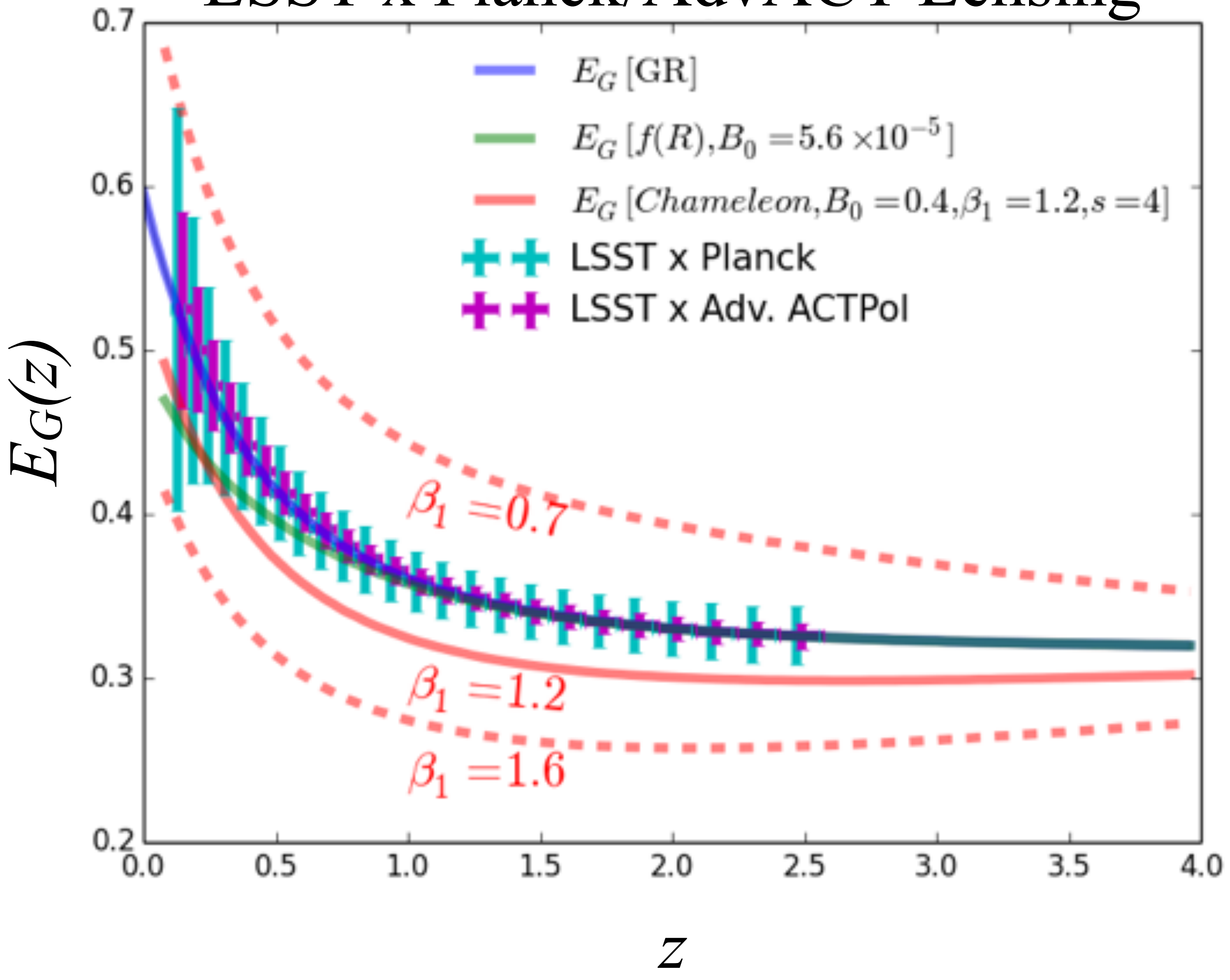
Credit: **Pullen**, Alam & Ho 2015

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

Photometric Surveys

- Galaxy redshifts from colors
- Less precise but inexpensive!
- Assumes photo RSD errors of ~8% over $\Delta z \sim 0.1$.
- E_G errors of 1% (Planck) or less (Adv. ACTPol, **CMB-S4**)
- Discriminates current *f(R)* by 15σ; can probe 100x lower!

LSST x Planck/AdvACT Lensing



Credit: **Pullen**, Alam & Ho 2015

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

In Short…

Photometric surveys (number density) outperform spectroscopic surveys (precise redshifts), but both could yield useful gravity constraints!

Magnification Biases E_G

Dizgah & Durrer 2016

Magnification Biases E_G

- Number counts are distorted due to lensing field

Dizgah & Durrer 2016

Magnification Biases E_G

- Number counts are distorted due to lensing field
- Affects $C_\ell^{\kappa g}$ and C_ℓ^{gg} - makes E_G bias and scale-dependent

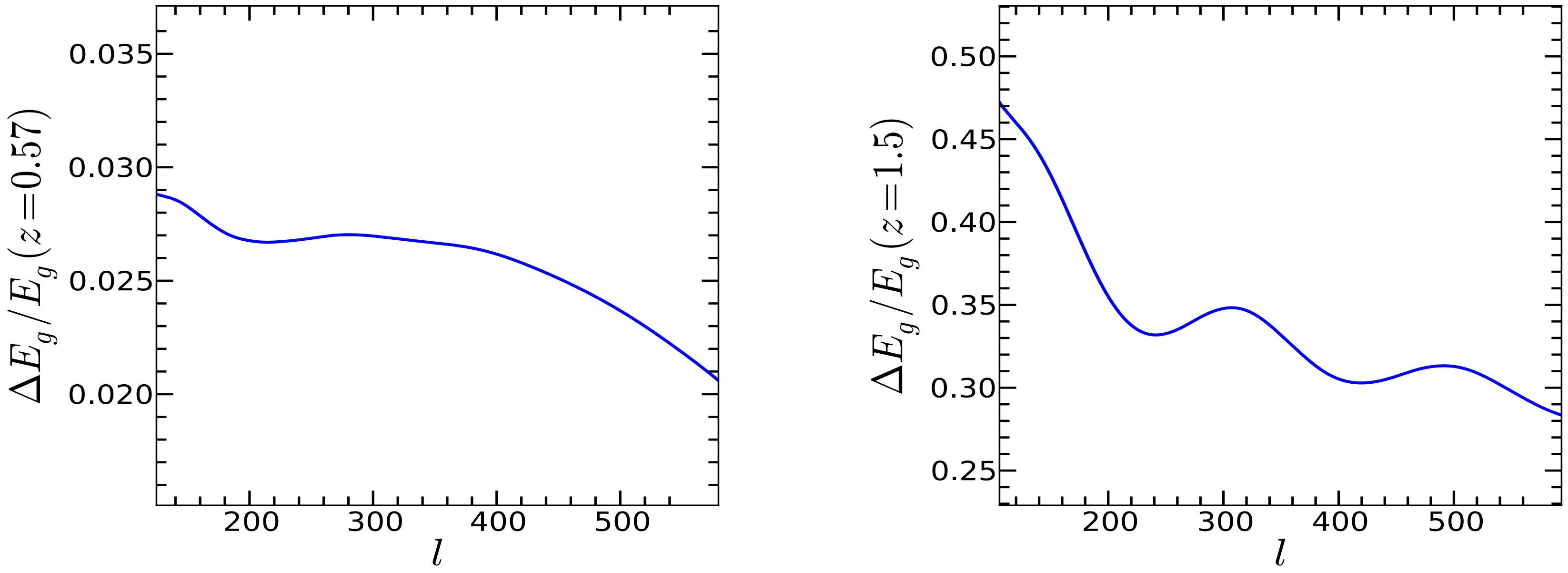
Dizgah & Durrer 2016

Magnification Biases E_G

- Number counts are distorted due to lensing field
- Affects $C_\ell^{\kappa g}$ and C_ℓ^{gg} - makes E_G bias and scale-dependent
- Biases low and high redshift measurements

Dizgah & Durrer 2016

Magnification Biases E_G

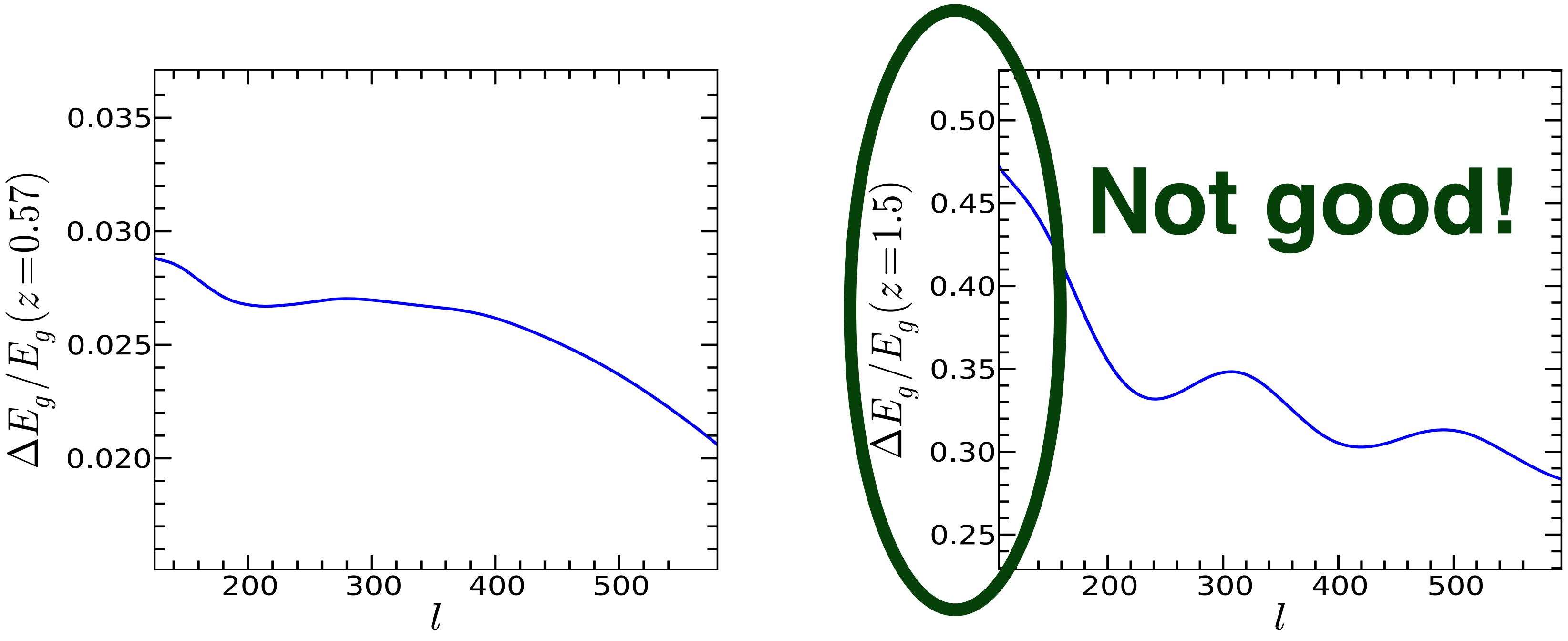


Credit: Dizgah & Durrer 2016

- Number counts are distorted due to lensing field
- Affects $C_\ell^{\kappa g}$ and C_ℓ^{gg} - makes E_G bias and scale-dependent
- Biases low and high redshift measurements

Dizgah & Durrer 2016

Magnification Biases E_G

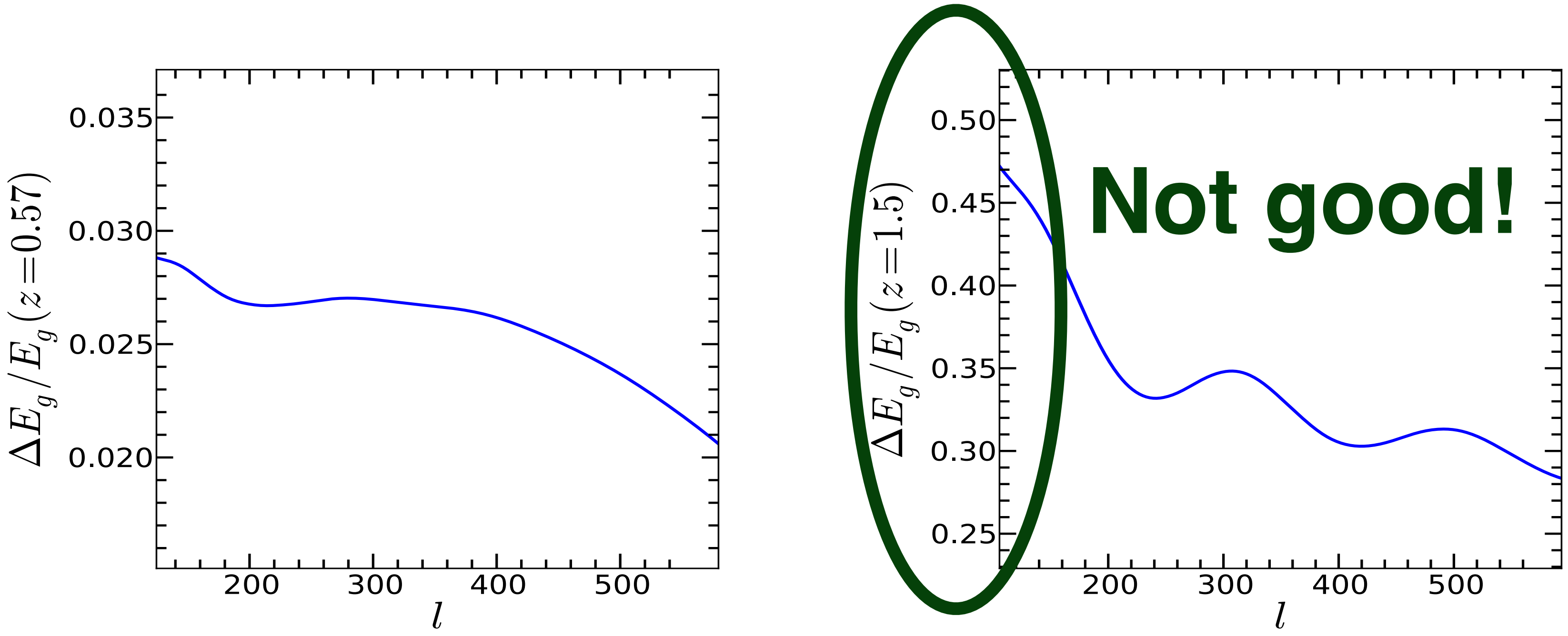


Credit: Dizgah & Durrer 2016

- Number counts are distorted due to lensing field
- Affects $C_\ell^{\kappa g}$ and C_ℓ^{gg} - makes E_G bias and scale-dependent
- Biases low and high redshift measurements

Dizgah & Durrer 2016

Magnification Biases E_G



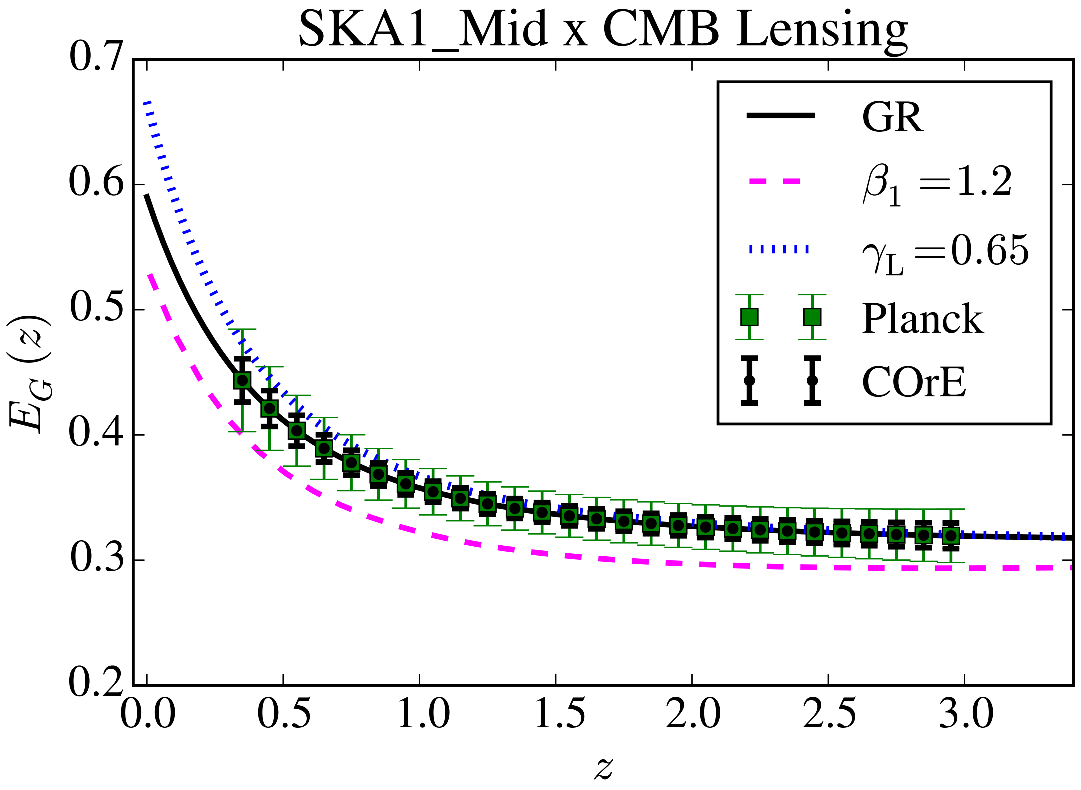
Not good!

Credit: Dizgah & Durrer 2016

- Number counts are distorted due to lensing field
- Affects $C_\ell^{\kappa g}$ and C_ℓ^{gg} - makes E_G bias and scale-dependent
- Biases low and high redshift measurements
- May be mitigated using galaxy-galaxy lensing to identify magnification bias

Dizgah & Durrer 2016

Intensity Mapping for E_G

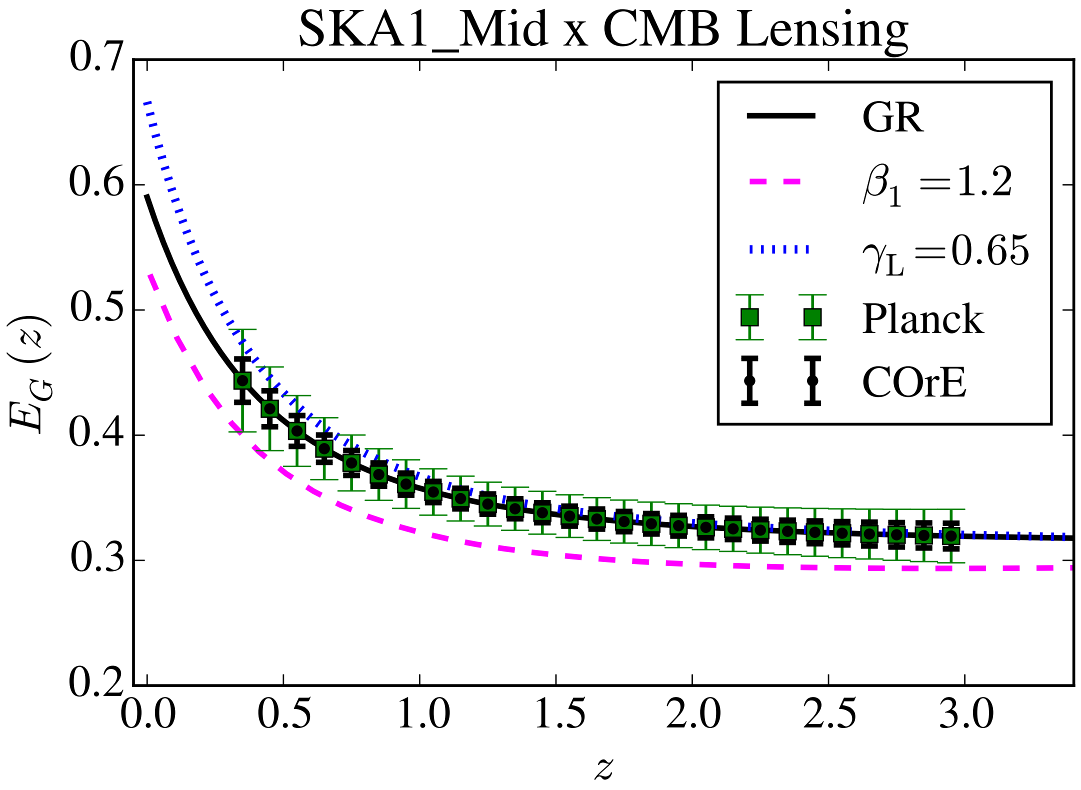


Credit: Pourtsidou 2016

Pourtsidou 2016

Intensity Mapping for E_G

- Mapping the intensity of spectral lines will provide high sampling of LSS

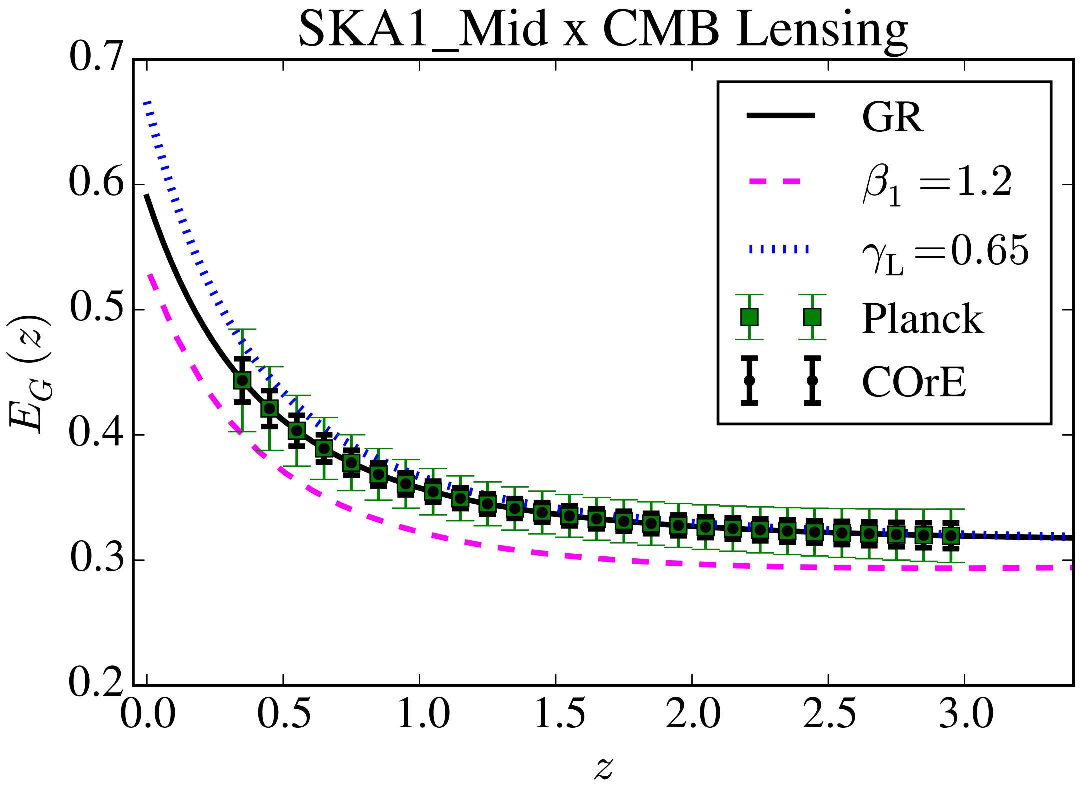


Credit: Pourtsidou 2016

Pourtsidou 2016

Intensity Mapping for E_G

- Mapping the intensity of spectral lines will provide high sampling of LSS
- No magnification bias - surface brightness conserved

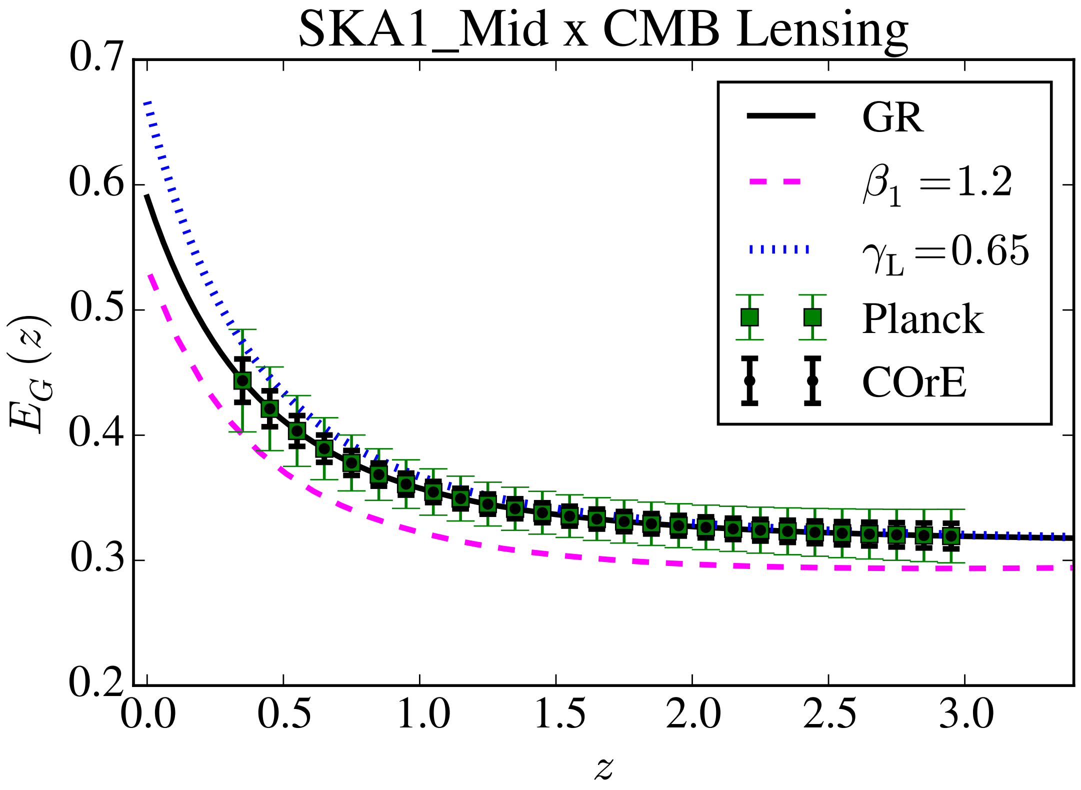


Credit: Pourtsidou 2016

Pourtsidou 2016

Intensity Mapping for E_G

- Mapping the intensity of spectral lines will provide high sampling of LSS
- No magnification bias - surface brightness conserved
- *Ideal for E_G measurements!*

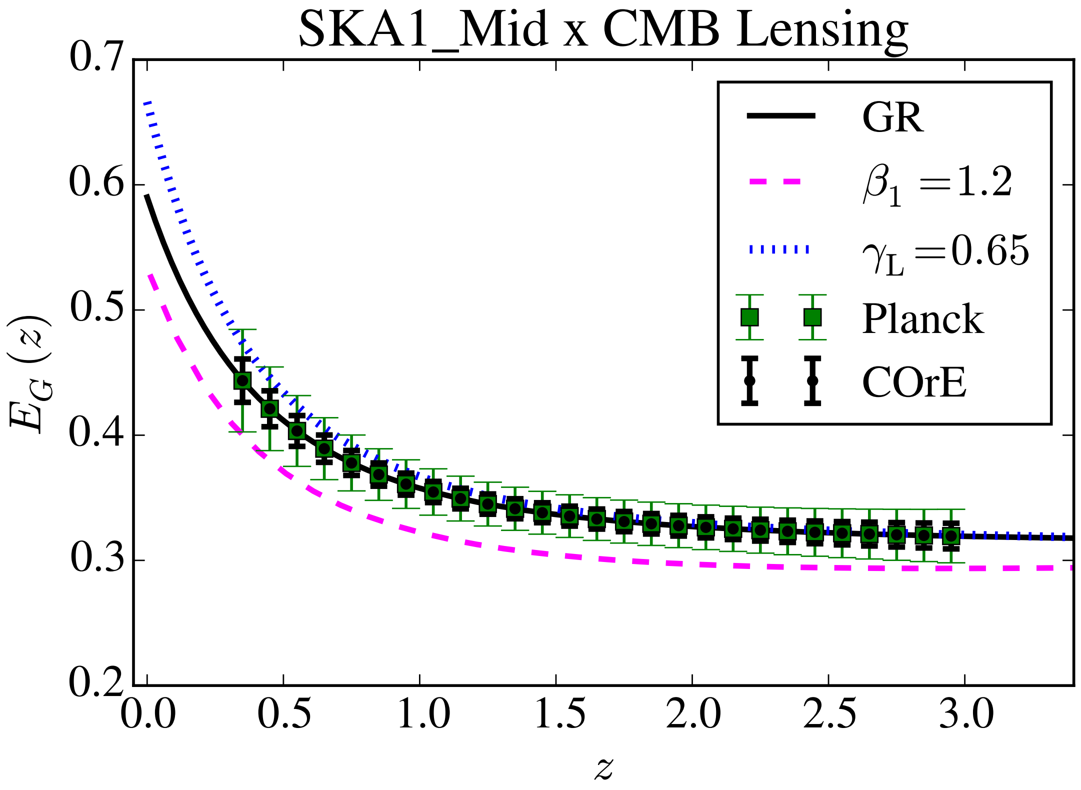


Credit: Pourtsidou 2016

Pourtsidou 2016

Intensity Mapping for E_G

- Mapping the intensity of spectral lines will provide high sampling of LSS
- No magnification bias - surface brightness conserved
- *Ideal for E_G measurements!*
- SKA would measure E_G with similar errors as LSST *without photo-z's!*

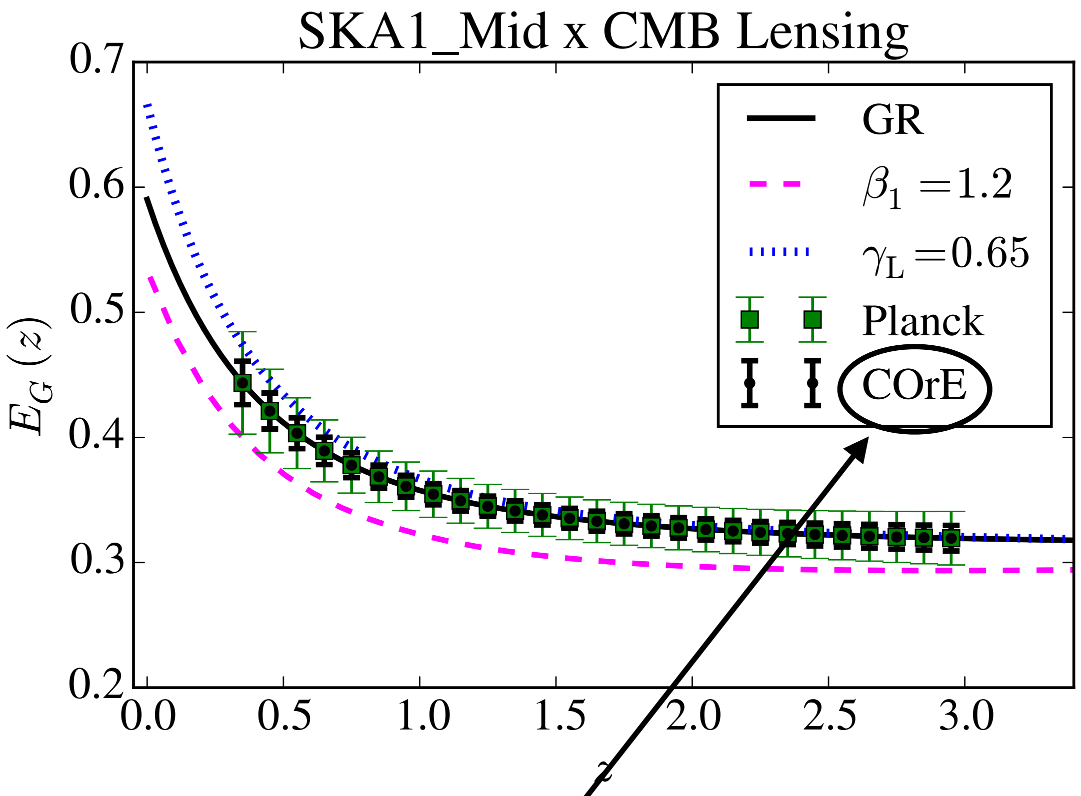


Credit: Pourtsidou 2016

Pourtsidou 2016

Intensity Mapping for E_G

- Mapping the intensity of spectral lines will provide high sampling of LSS
- No magnification bias - surface brightness conserved
- *Ideal for E_G measurements!*
- SKA would measure E_G with similar errors as LSST *without photo-z's!*



Credit: Pourtsidou 2016

3x lower sensitivity with CMB-S4

Pourtsidou 2016

E_G Preparation Program

- Optimize CMB/LSS survey match for E_G measurement
- Measure growth rate/E_G using a photo-z survey (DES/LSST) or low-res spectroscopy
- Consider joint CMB lensing & galaxy lensing
- Predict E_G/constraints for modern modified gravity theories, *e.g.* massive gravity, galileons, Horndeski, etc.
- Plan for CMB lensing x intensity mapping studies

Extra Slides

What Modifies E_G?

Pullen, Alam & Ho 2015

What Modifies E_G?

Anisotropic Stress

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

Pullen, Alam & Ho 2015

What Modifies E_G?

Anisotropic Stress

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

Weak Newton's Constant

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

Also affects growth rate

Pullen, Alam & Ho 2015

What Modifies E_G?

Anisotropic Stress

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

Weak Newton's Constant

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

Also affects growth rate

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

Pullen, Alam & Ho 2015

We measure E_G using CMB lensing

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

Pullen, Alam & Ho 2015

We measure E_G using CMB lensing

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

line-of-sight

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

Pullen, Alam & Ho 2015

We measure E_G using CMB lensing

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

line-of-sight

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

$(\ell \sim 2\pi/\theta)$

Angular
Scale

Angular
Power Spectra
(Variance on the sky)

Pullen, Alam & Ho 2015

We measure E_G using CMB lensing

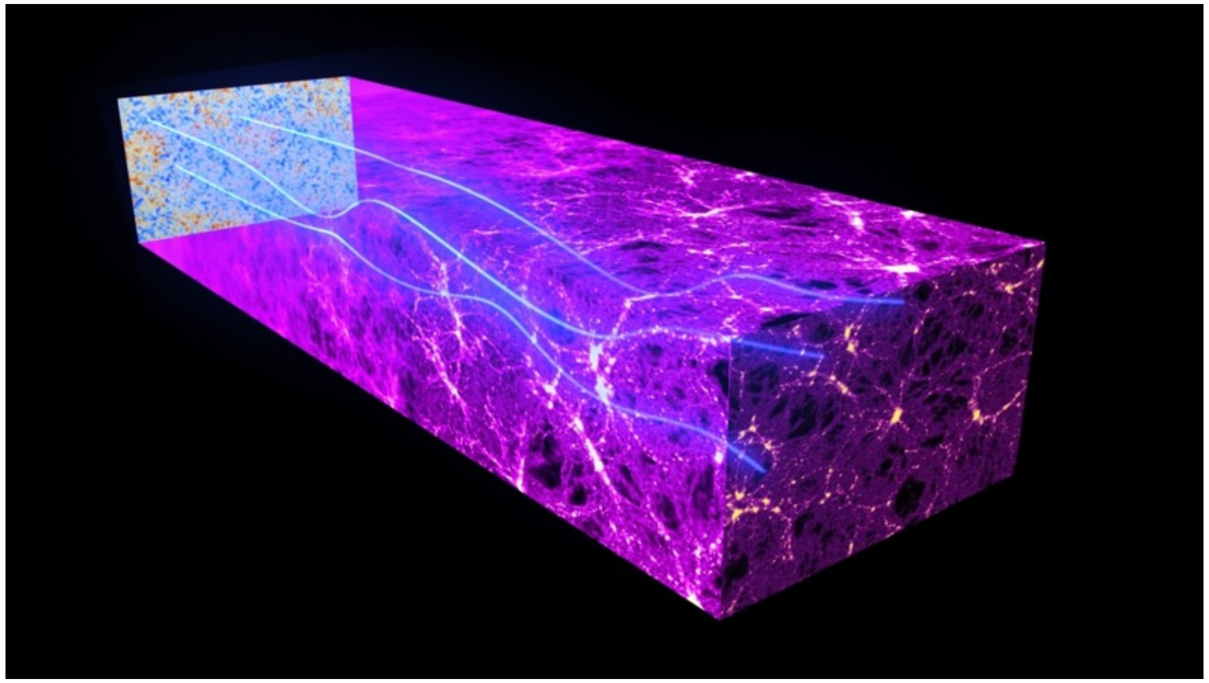


Image Credit: ESA

Pullen, Alam & Ho 2015

We measure E_G using CMB lensing

- CMB photons are gravitationally lensed by LSS

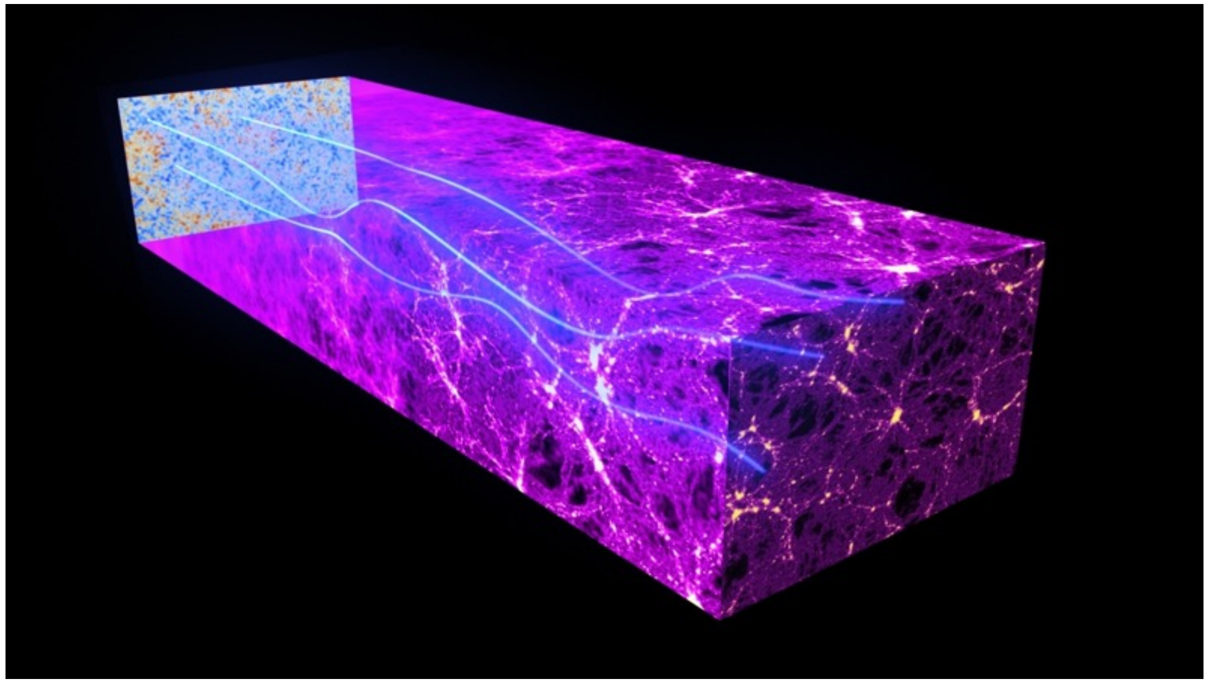


Image Credit: ESA

Pullen, Alam & Ho 2015

We measure E_G using CMB lensing

- CMB photons are gravitationally lensed by LSS
- Lensing convergence is reconstructed from CMB maps

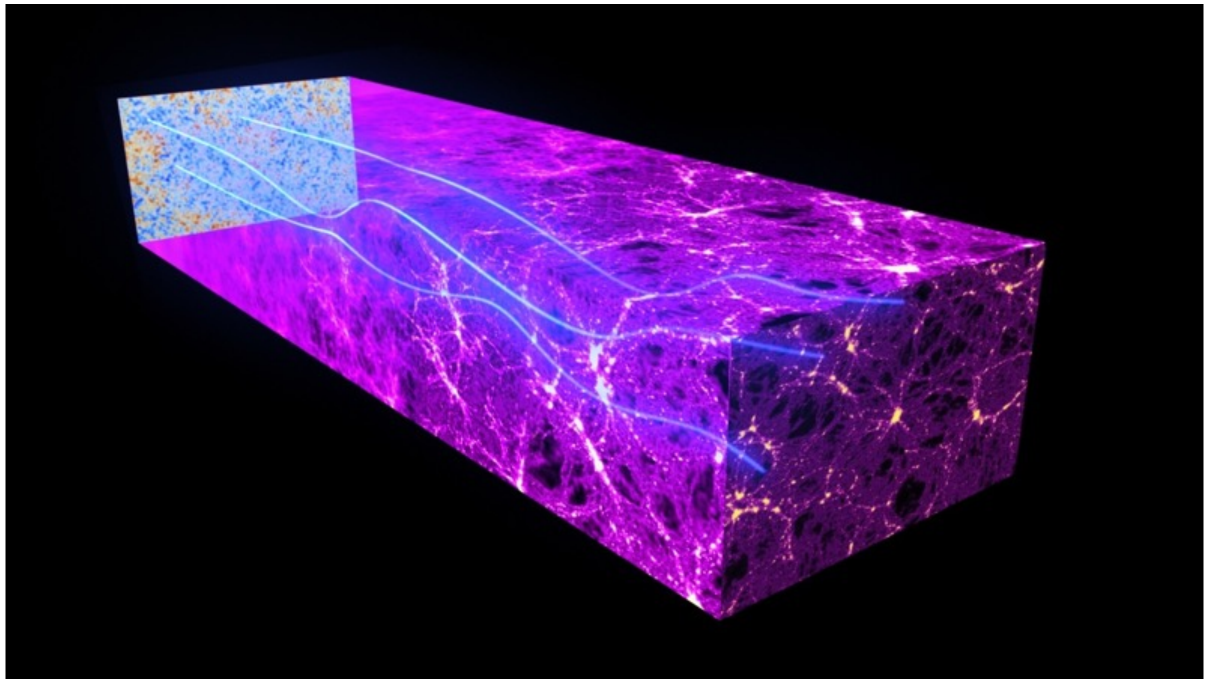


Image Credit: ESA

Pullen, Alam & Ho 2015

We measure E_G using CMB lensing

- CMB photons are gravitationally lensed by LSS
- Lensing convergence is reconstructed from CMB maps
- Probes the integrated matter distribution out to last-scattering surface of the CMB

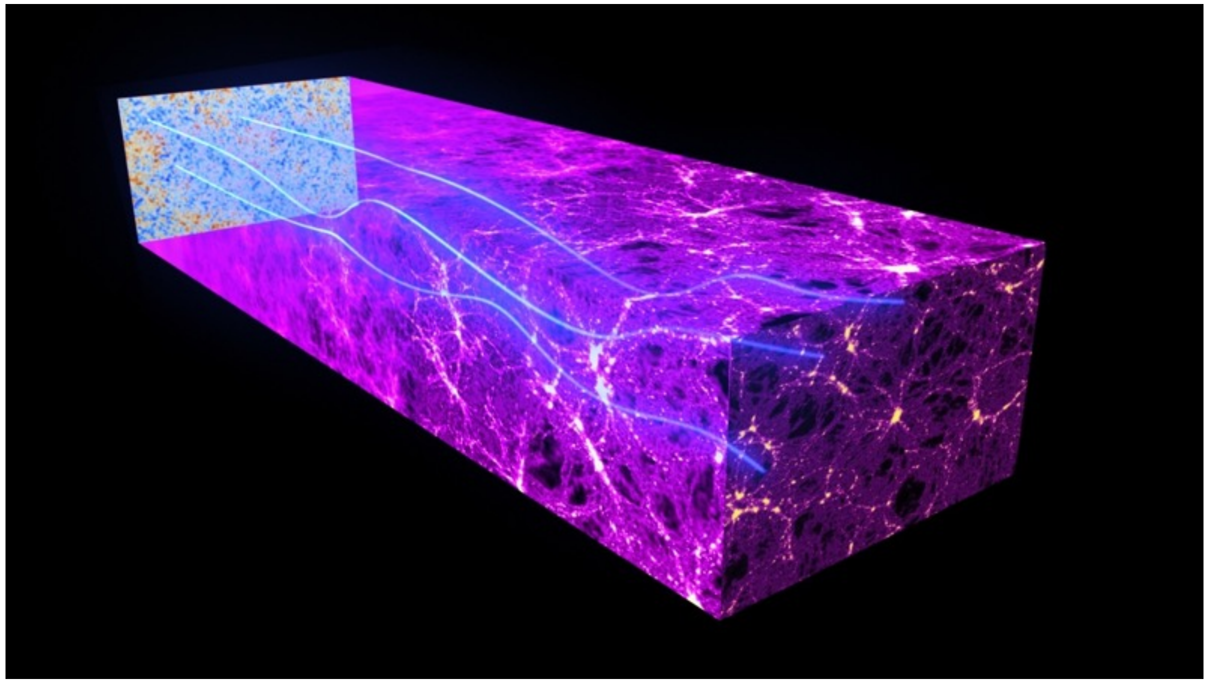


Image Credit: ESA

Pullen, Alam & Ho 2015

We measure E_G using CMB lensing

- CMB photons are gravitationally lensed by LSS
- Lensing convergence is reconstructed from CMB maps
- Probes the integrated matter distribution out to last-scattering surface of the CMB
- Our paper *first* formalism/forecasts of CMB lensing as E_G probe

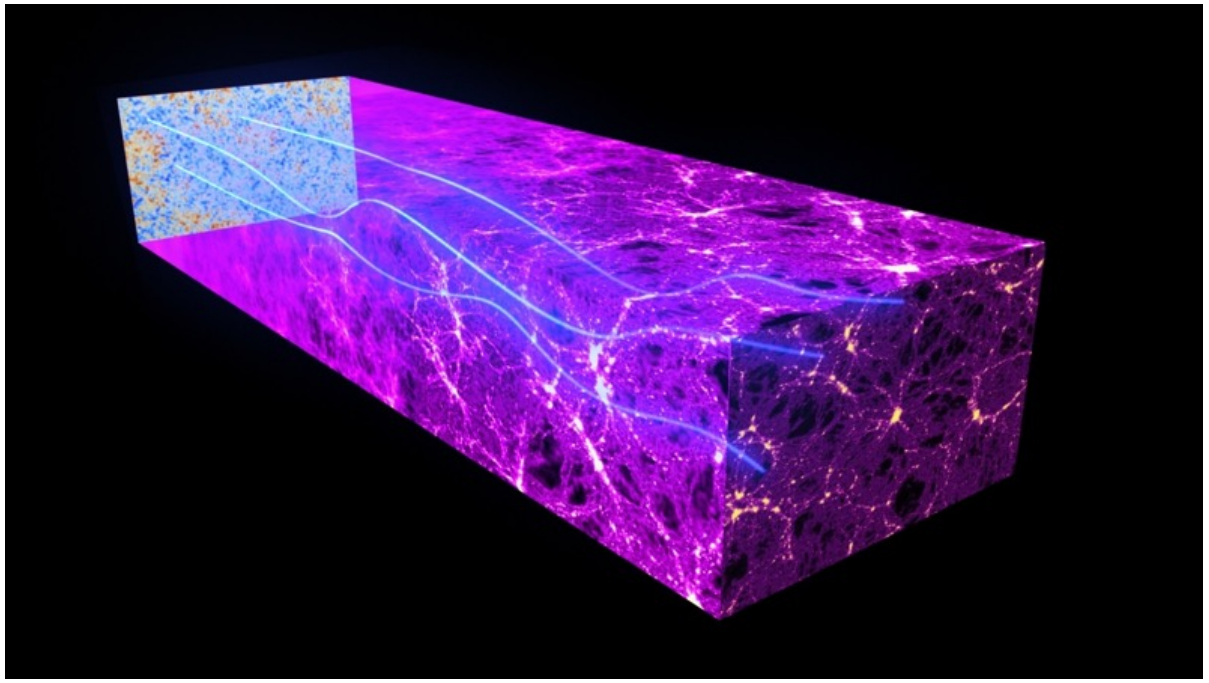
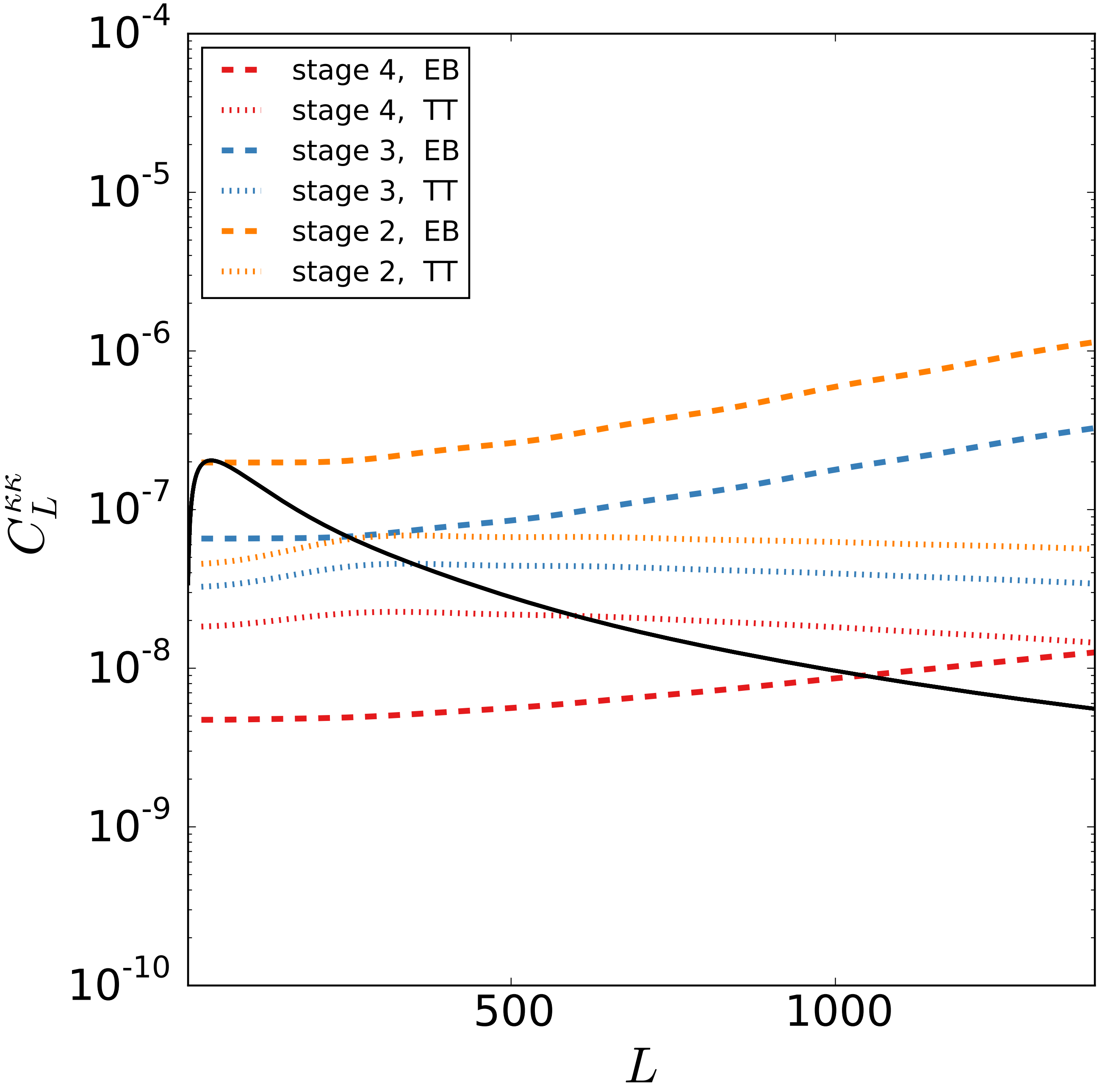


Image Credit: ESA

Pullen, Alam & Ho 2015



CMB-S4 Science Book

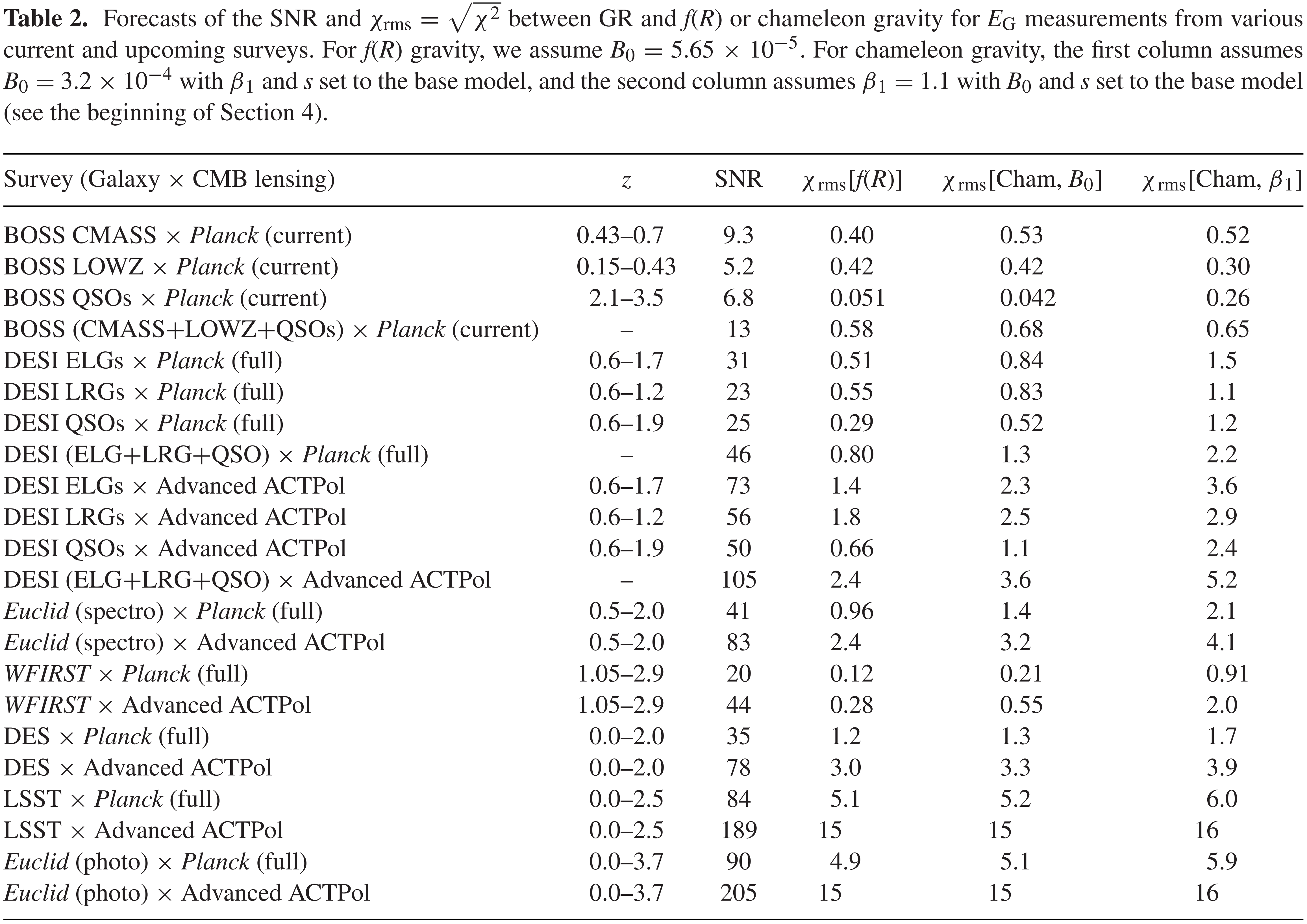


Table 2. Forecasts of the SNR and $\chi_{\rm rms} = \sqrt{\chi^2}$ between GR and *f*(*R*) or chameleon gravity for $E_{\rm G}$ measurements from various current and upcoming surveys. For *f*(*R*) gravity, we assume $B_0 = 5.65 \times 10^{-5}$. For chameleon gravity, the first column assumes $B_0 = 3.2 \times 10^{-4}$ with β_1 and *s* set to the base model, and the second column assumes $\beta_1 = 1.1$ with B_0 and *s* set to the base model (see the beginning of Section 4).

Survey (Galaxy × CMB lensing)	z	SNR	$\chi_{\rm rms}[f(R)]$	$\chi_{\rm rms}[\text{Cham}, B_0]$	$\chi_{\rm rms}[\text{Cham}, \beta_1]$
BOSS CMASS × *Planck* (current)	0.43–0.7	9.3	0.40	0.53	0.52
BOSS LOWZ × *Planck* (current)	0.15–0.43	5.2	0.42	0.42	0.30
BOSS QSOs × *Planck* (current)	2.1–3.5	6.8	0.051	0.042	0.26
BOSS (CMASS+LOWZ+QSOs) × *Planck* (current)	–	13	0.58	0.68	0.65
DESI ELGs × *Planck* (full)	0.6–1.7	31	0.51	0.84	1.5
DESI LRGs × *Planck* (full)	0.6–1.2	23	0.55	0.83	1.1
DESI QSOs × *Planck* (full)	0.6–1.9	25	0.29	0.52	1.2
DESI (ELG+LRG+QSO) × *Planck* (full)	–	46	0.80	1.3	2.2
DESI ELGs × Advanced ACTPol	0.6–1.7	73	1.4	2.3	3.6
DESI LRGs × Advanced ACTPol	0.6–1.2	56	1.8	2.5	2.9
DESI QSOs × Advanced ACTPol	0.6–1.9	50	0.66	1.1	2.4
DESI (ELG+LRG+QSO) × Advanced ACTPol	–	105	2.4	3.6	5.2
Euclid (spectro) × *Planck* (full)	0.5–2.0	41	0.96	1.4	2.1
Euclid (spectro) × Advanced ACTPol	0.5–2.0	83	2.4	3.2	4.1
WFIRST × *Planck* (full)	1.05–2.9	20	0.12	0.21	0.91
WFIRST × Advanced ACTPol	1.05–2.9	44	0.28	0.55	2.0
DES × *Planck* (full)	0.0–2.0	35	1.2	1.3	1.7
DES × Advanced ACTPol	0.0–2.0	78	3.0	3.3	3.9
LSST × *Planck* (full)	0.0–2.5	84	5.1	5.2	6.0
LSST × Advanced ACTPol	0.0–2.5	189	15	15	16
Euclid (photo) × *Planck* (full)	0.0–3.7	90	4.9	5.1	5.9
Euclid (photo) × Advanced ACTPol	0.0–3.7	205	15	15	16

Pullen, Alam, & Ho 2015

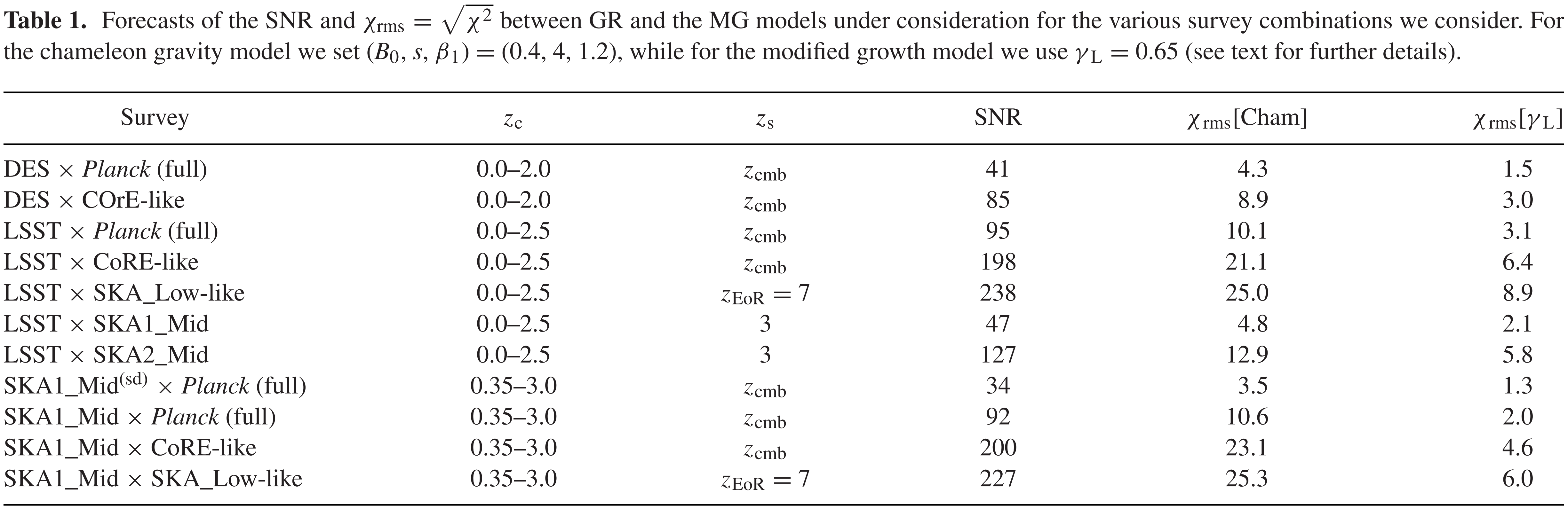


Table 1. Forecasts of the SNR and $\chi_{\rm rms} = \sqrt{\chi^2}$ between GR and the MG models under consideration for the various survey combinations we consider. For the chameleon gravity model we set $(B_0, s, \beta_1) = (0.4, 4, 1.2)$, while for the modified growth model we use $\gamma_{\rm L} = 0.65$ (see text for further details).

Survey	$z_{\rm c}$	$z_{\rm s}$	SNR	$\chi_{\rm rms}$[Cham]	$\chi_{\rm rms}[\gamma_{\rm L}]$
DES × *Planck* (full)	0.0–2.0	$z_{\rm cmb}$	41	4.3	1.5
DES × COrE-like	0.0–2.0	$z_{\rm cmb}$	85	8.9	3.0
LSST × *Planck* (full)	0.0–2.5	$z_{\rm cmb}$	95	10.1	3.1
LSST × CoRE-like	0.0–2.5	$z_{\rm cmb}$	198	21.1	6.4
LSST × SKA_Low-like	0.0–2.5	$z_{\rm EoR} = 7$	238	25.0	8.9
LSST × SKA1_Mid	0.0–2.5	3	47	4.8	2.1
LSST × SKA2_Mid	0.0–2.5	3	127	12.9	5.8
SKA1_Mid$^{\rm (sd)}$ × *Planck* (full)	0.35–3.0	$z_{\rm cmb}$	34	3.5	1.3
SKA1_Mid × *Planck* (full)	0.35–3.0	$z_{\rm cmb}$	92	10.6	2.0
SKA1_Mid × CoRE-like	0.35–3.0	$z_{\rm cmb}$	200	23.1	4.6
SKA1_Mid × SKA_Low-like	0.35–3.0	$z_{\rm EoR} = 7$	227	25.3	6.0

Pourtsidou 2016

The kernels of the galaxy number count and the CMB lensing are given by

$$W_\ell^\kappa(k, z_*) = \frac{3\Omega_{m0}H_0^2}{2}\int_0^{z_*}\frac{dz}{H(z)}\frac{\chi(\chi_* - \chi)}{\chi_*}(z)D(z)j_\ell(k\chi(z)) \tag{2.16}$$

$$W_\ell^g(k, z) = \int_0^{z_*} dz\; w(z)\frac{dN}{dz}T_\ell^g(z, k) \tag{2.17}$$

where $w(z)$ is the window function describing the redshift bin in a given survey and $\chi_* = \chi(z_*)$. $D(z)$ is the growth function defined by

$$\delta_m(z, k) = \frac{D(z)}{1+z}\delta_0(k)\,,$$

where $\delta_0(k)$ is the (linear) density fluctuation today and $P(k)$ is its power spectrum. dN/dz is the redshift distribution of the galaxies considered. The transfer function $T_\ell^g(z, k)$ is given by

$$T_\ell^g(z, k) = \left[j_\ell(k\chi(z))b\frac{D(z)}{1+z} + 2W_\ell^\kappa(k, z)\right]\,,$$

where the galaxy bias, b in general depends on redshift and on scale. This includes the terms of Eq. (2.13), assuming $\Phi = \Psi$. It is a good approximation when the redshift slice is

Dizgah & Durrer 2016

Redshift-space GPS probes growth!

growth rate

$$P_g(k,\mu) = b_g^2(1+\beta\mu^2)^2 P_m(k)$$

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

$\hat{\mathbf{n}} \cdot \hat{\mathbf{k}}$

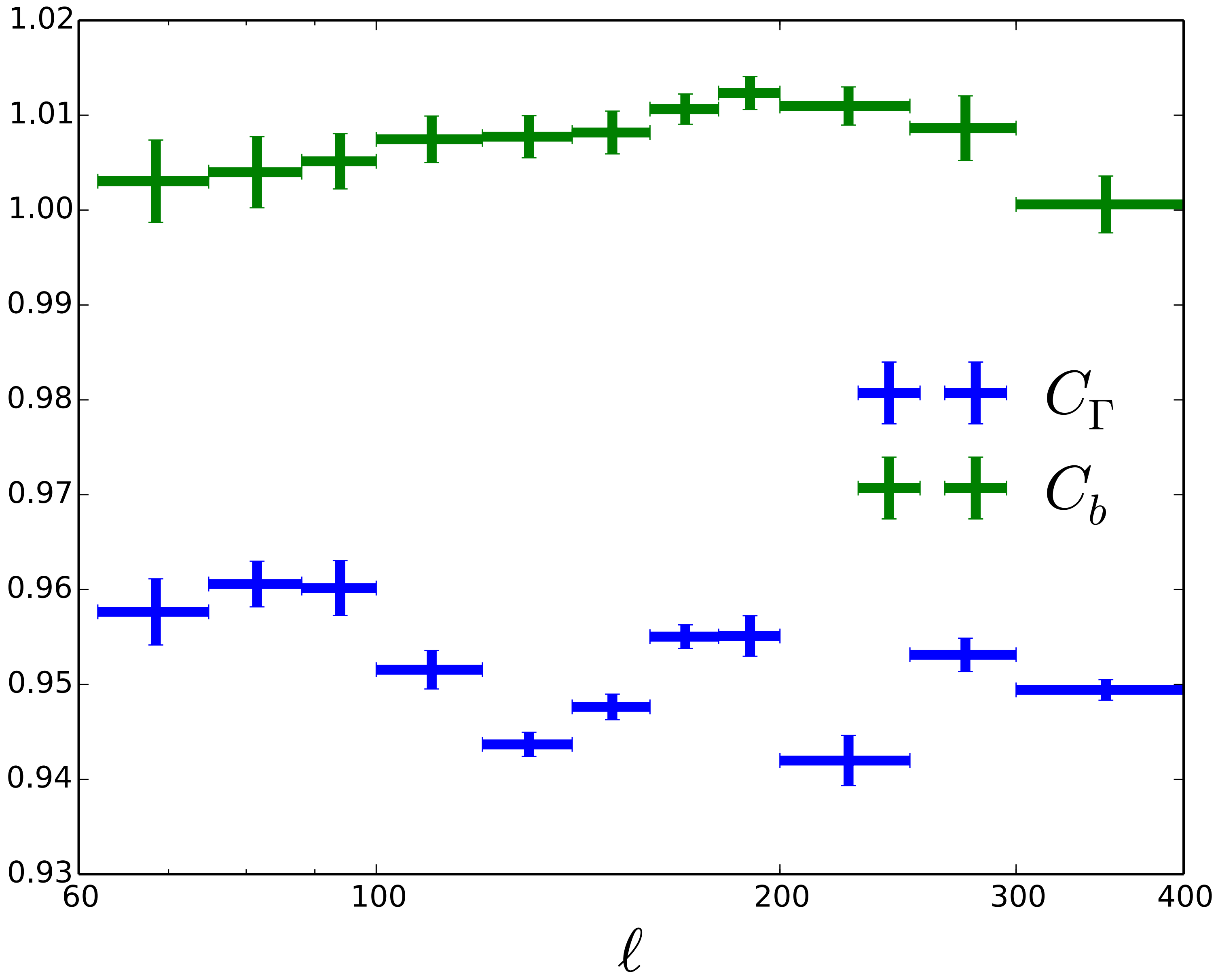
line-of-sight

RSD parameter

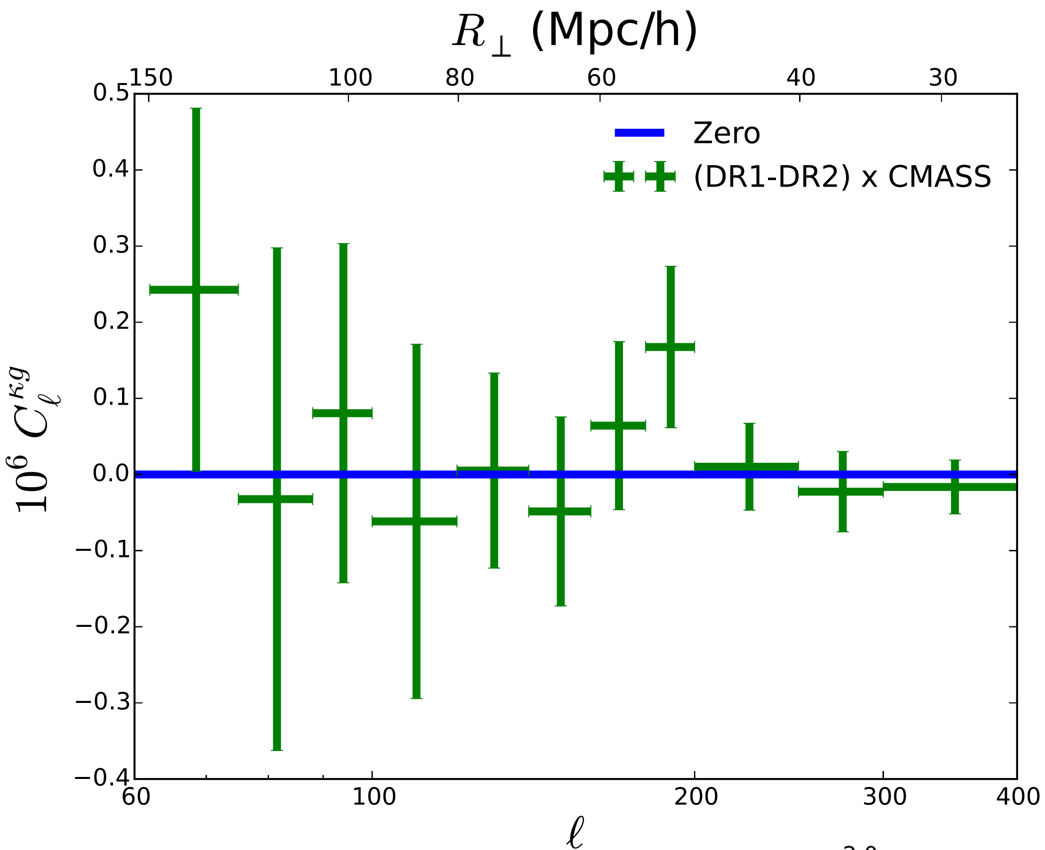
- Line-of-sight velocities induce anisotropies in power spectrum.
- Velocities determined by growth rate *f*, influenced by gravity.
- These redshift-space distortions (RSD) appear in correlation measurements.

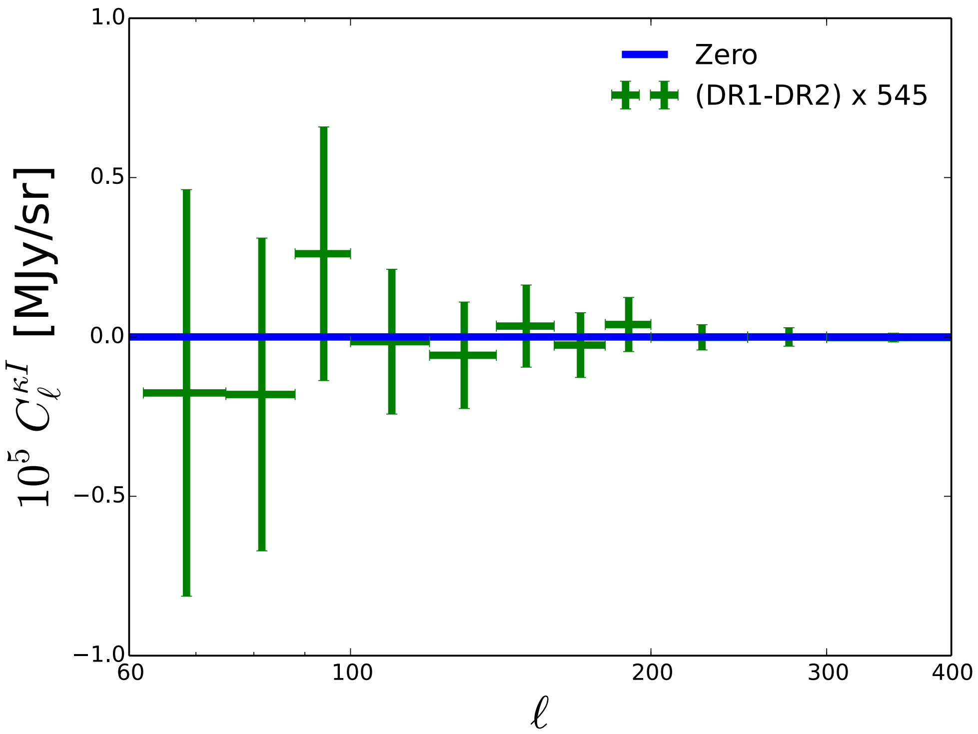
E_G Corrections

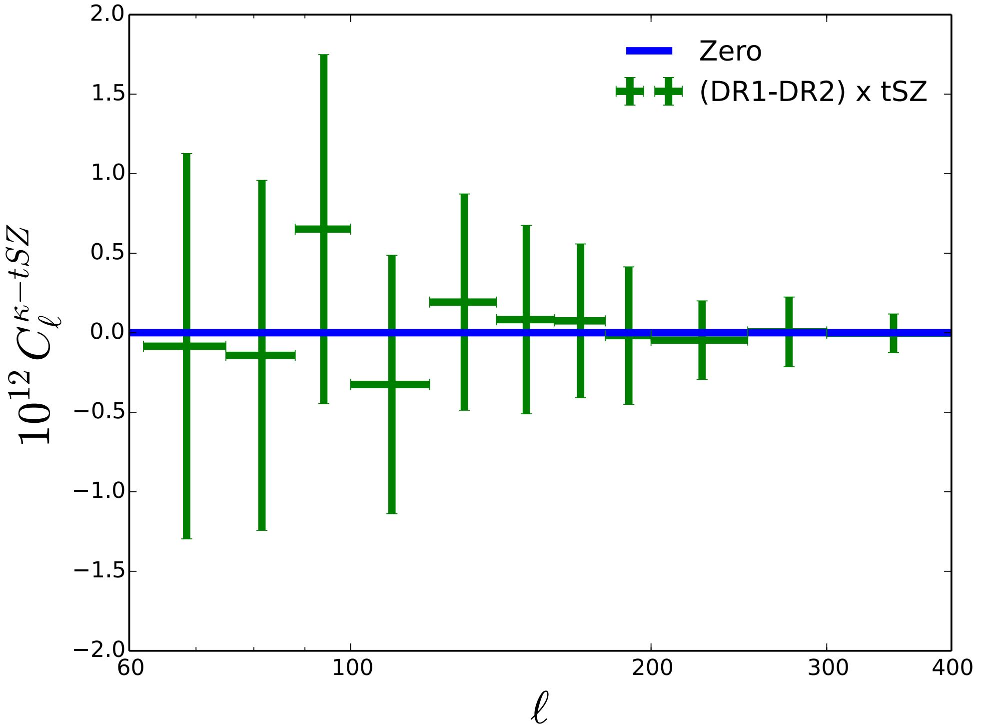
$$\Gamma = \frac{W(\chi)\beta(z)(1+z)}{2f_g(\chi)}$$



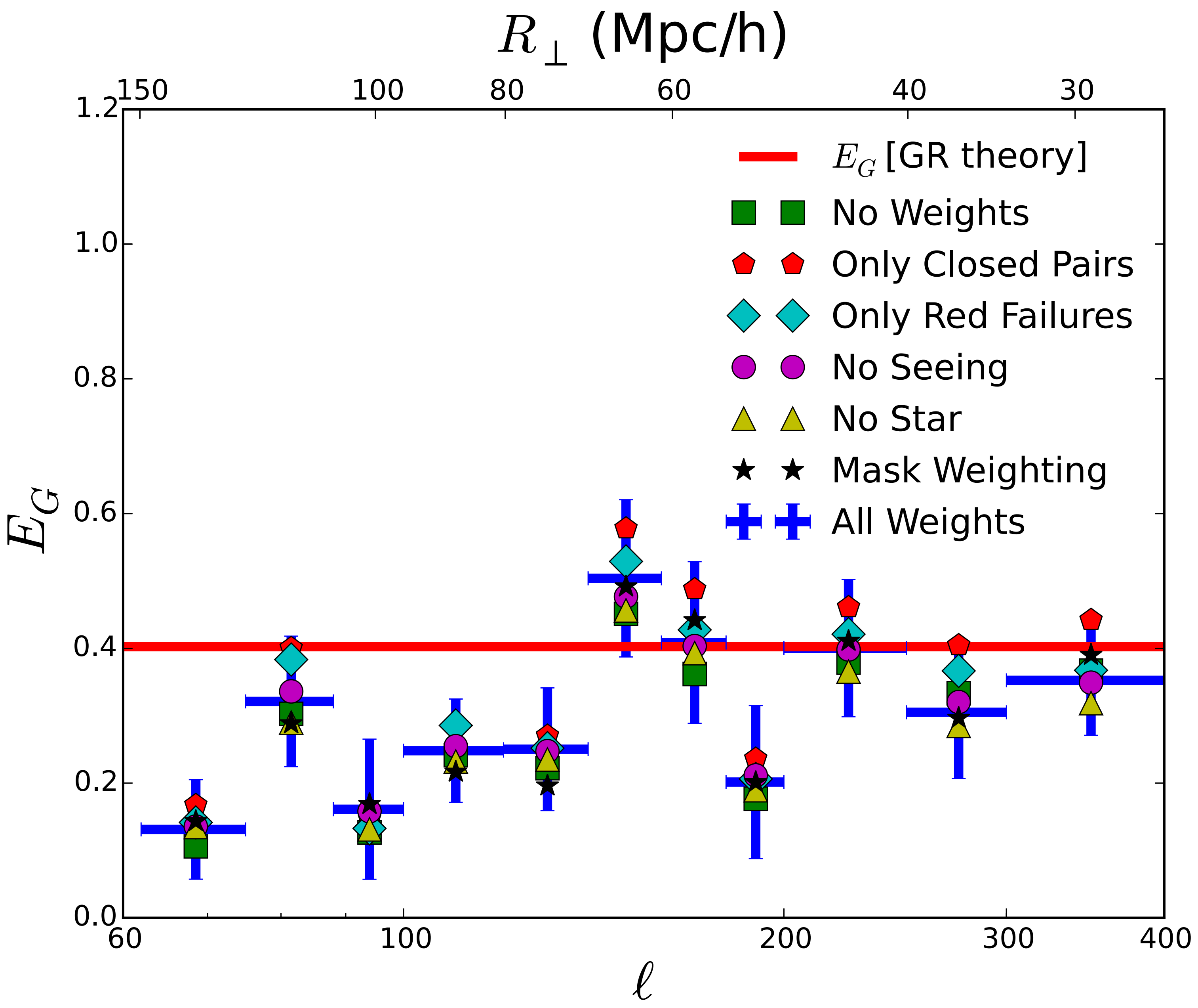
Planck Data Release Tests







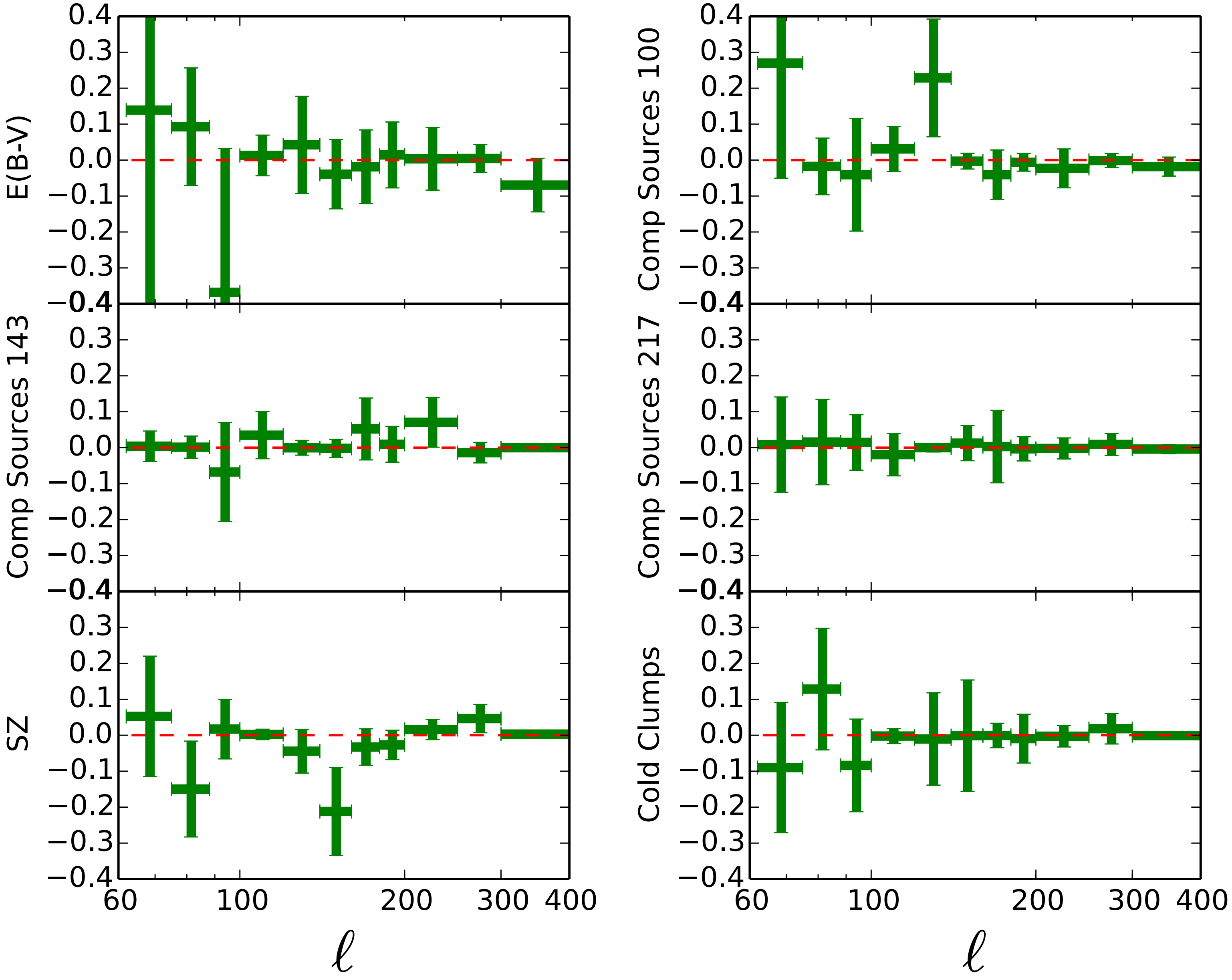
BOSS systematic errors are small



4.5% systematic error due to galaxy sample contamination

Pullen, Alam, He & Ho 2015

No evidence of point sources contamination



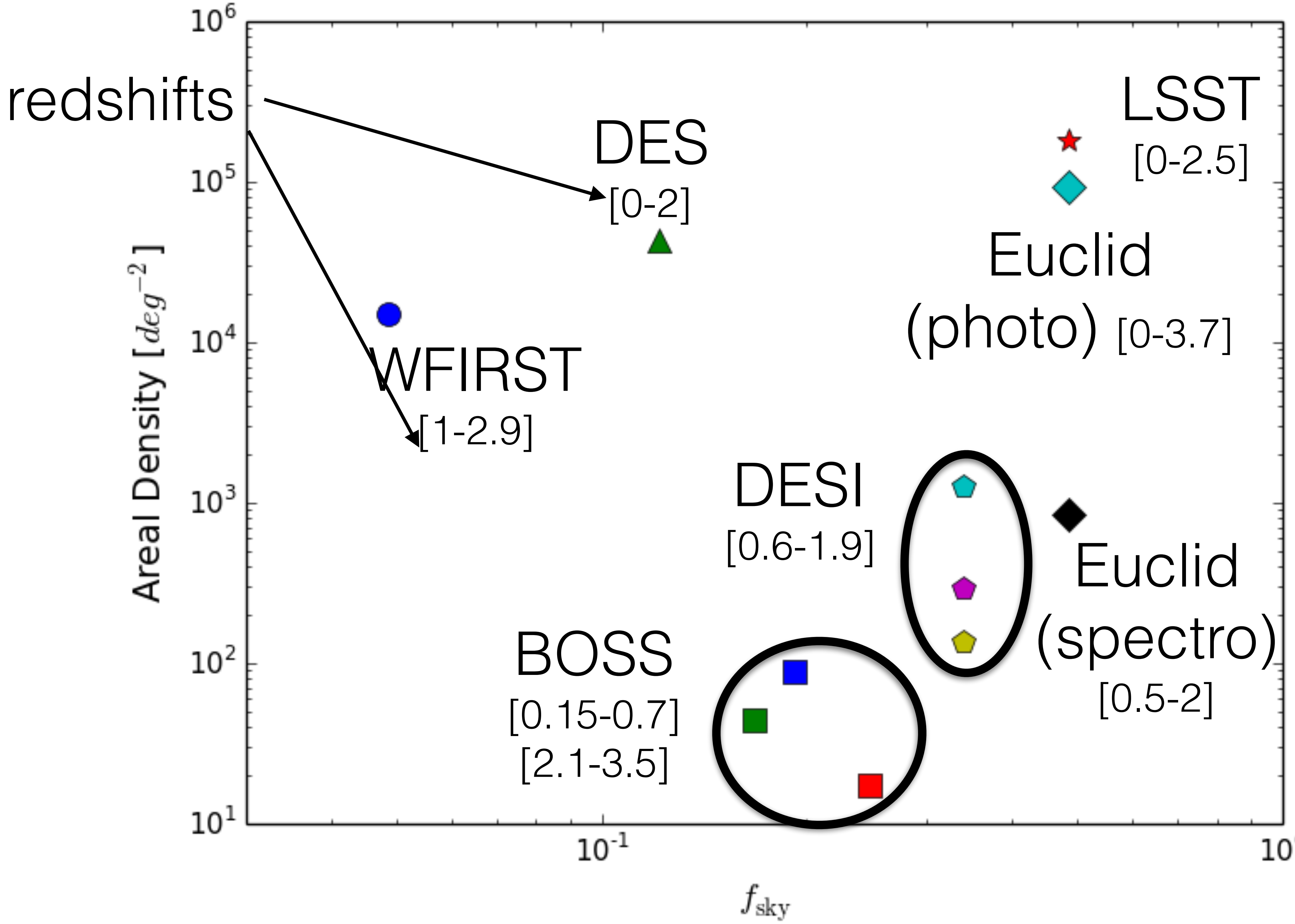
Lensing-galaxy bias

$$\Delta C_{\ell,i}^{\kappa g} = \frac{C_\ell^{\kappa M_i} C_\ell^{g M_i}}{C_\ell^{M_i M_i}}$$

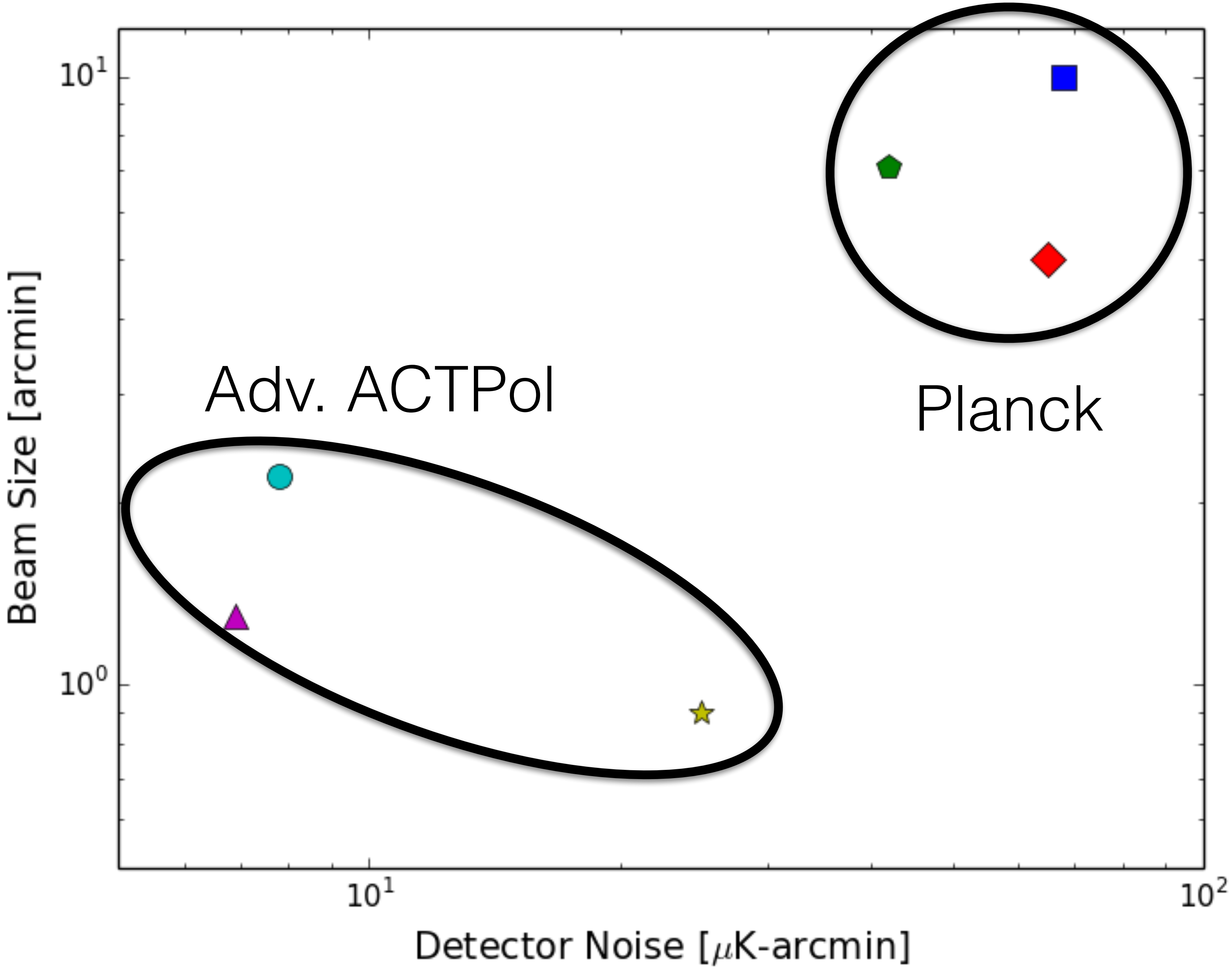
2.7% systematic error due to lensing-galaxy bias

Pullen, Alam, He & Ho 2015

Galaxy Surveys



CMB Surveys


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