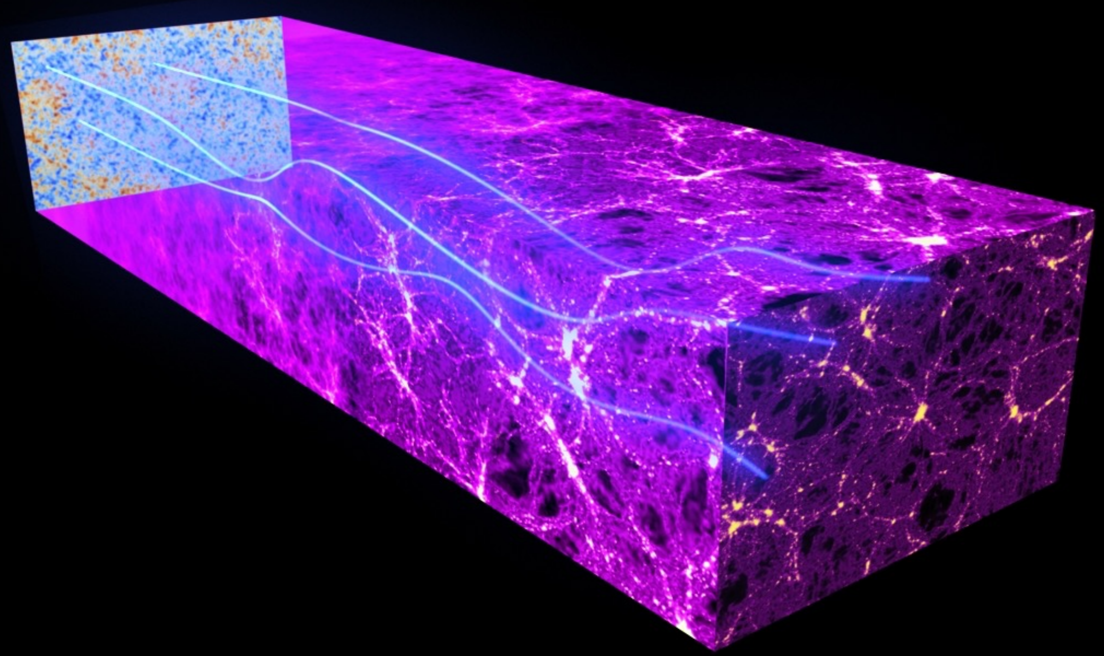
# Precision Tests of Gravity with CMB Lensing Cross-correlations



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Accurate Lensing in the Era of Precision Cosmology
Berkeley Center for Cosmological Physics
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# $E_G$ = Statistic to Probe ΛCDM

- $E_G$ combines 2 tracers of LSS growth: Lensing and RSD
- Growth of structure helps break degeneracy!
- Scale-dependence from modified gravity, not ΛCDM
- Estimated using cross-correlations with galaxies; independent of clustering bias

gravity potentials

growth rate

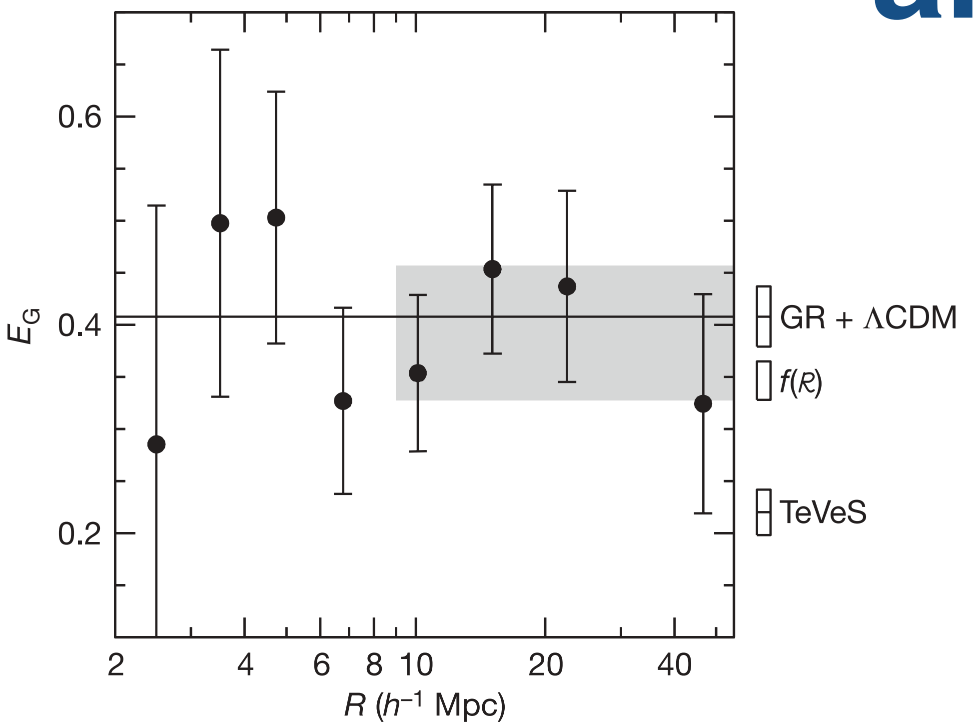
$$E_G = \frac{\nabla^2 \boxed{(\psi - \phi)}}{3H_0^2(1+z)f\delta}$$

matter overdensity

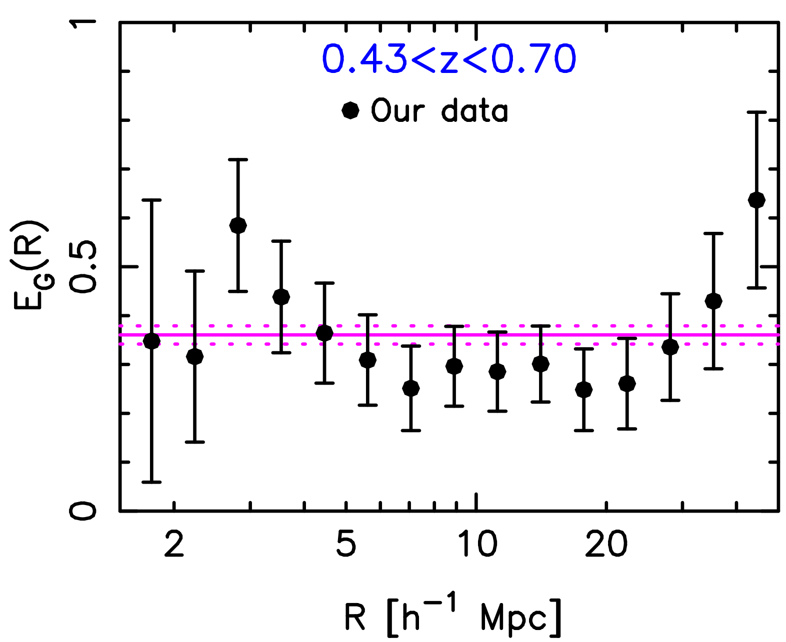
$$\boxed{E_G(\ell) = \Gamma \frac{C_\ell^{\kappa g}}{\beta C_\ell^{gg}}}$$

Zhang et al. 2007; **Pullen**, Alam & Ho 2015

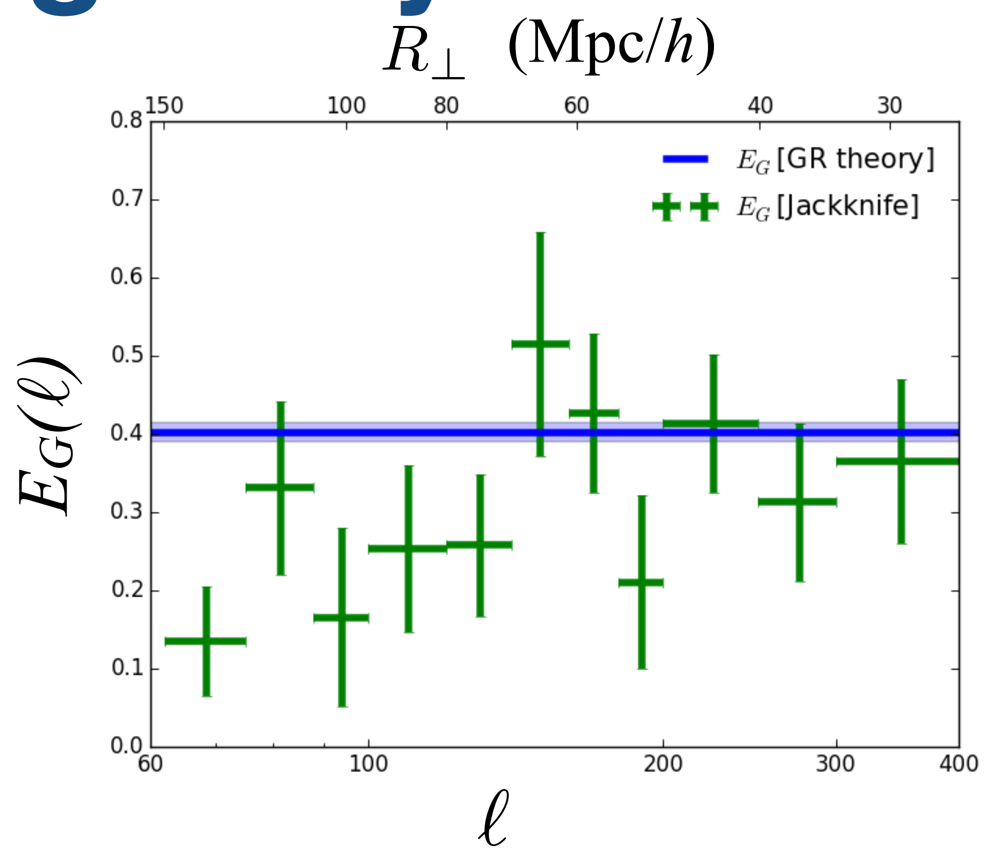
# Measurements consistent with GR and f(R) gravity




Reyes et al. 2010




Blake et al. 2015




**Pullen**, Alam, He & Ho 2015

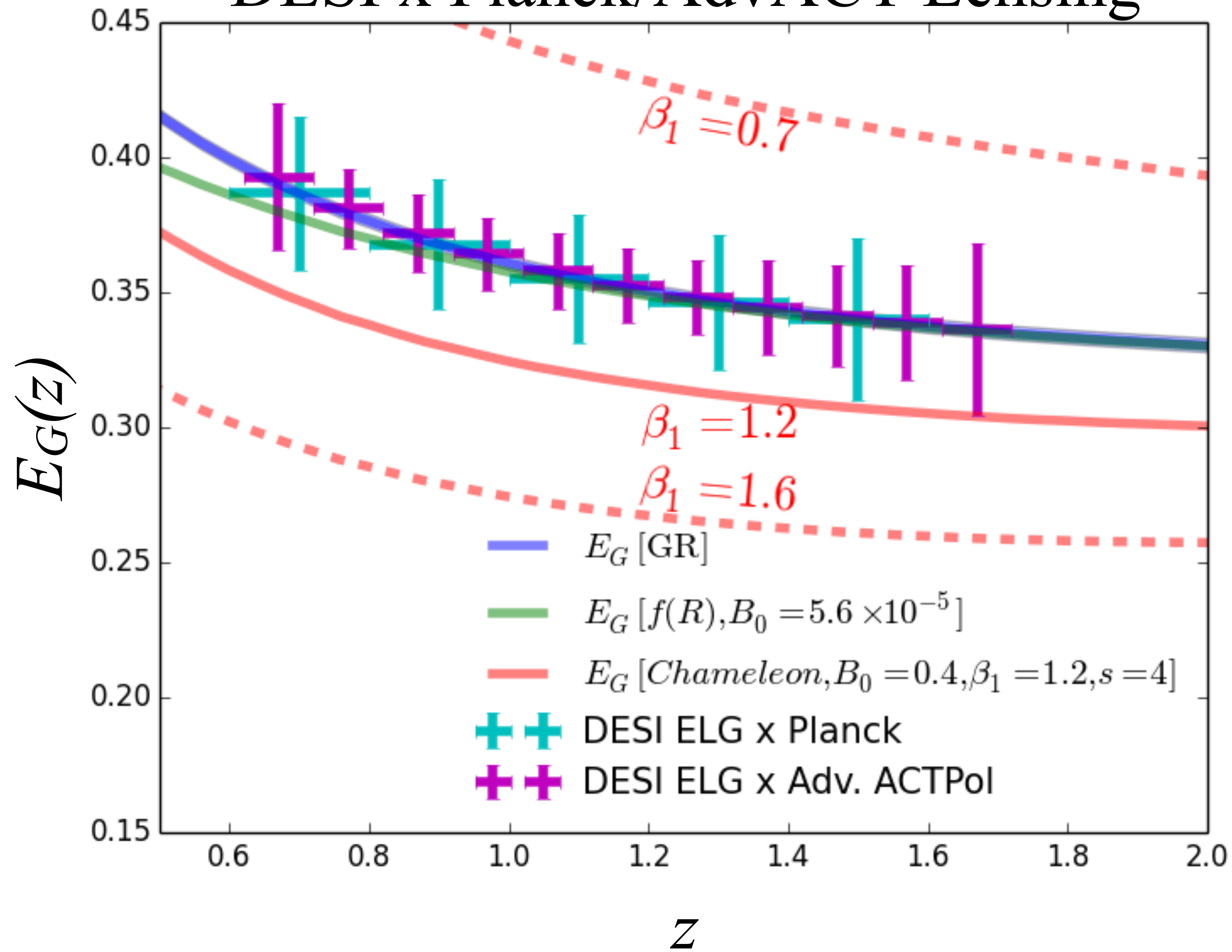
Singh et al. 2018

(see Sukhdeep's Talk)

# $E_G$ Program in Progress

- Measurements from several groups have been performed
- Measurements consistent with ΛCDM out to 70 Mpc/*h* - 10-15% errors
- Upcoming surveys seek 1-2% errors or lower
- IM weak lensing could possibly improve this further

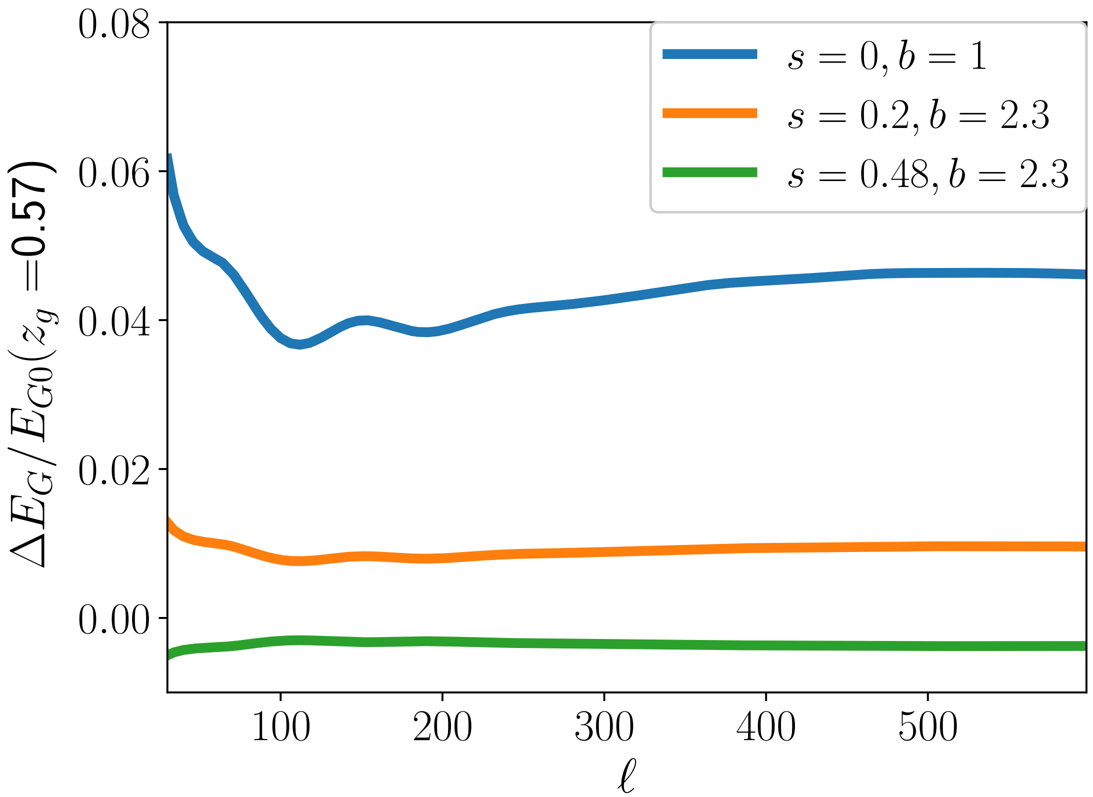
DESI x Planck/AdvACT Lensing

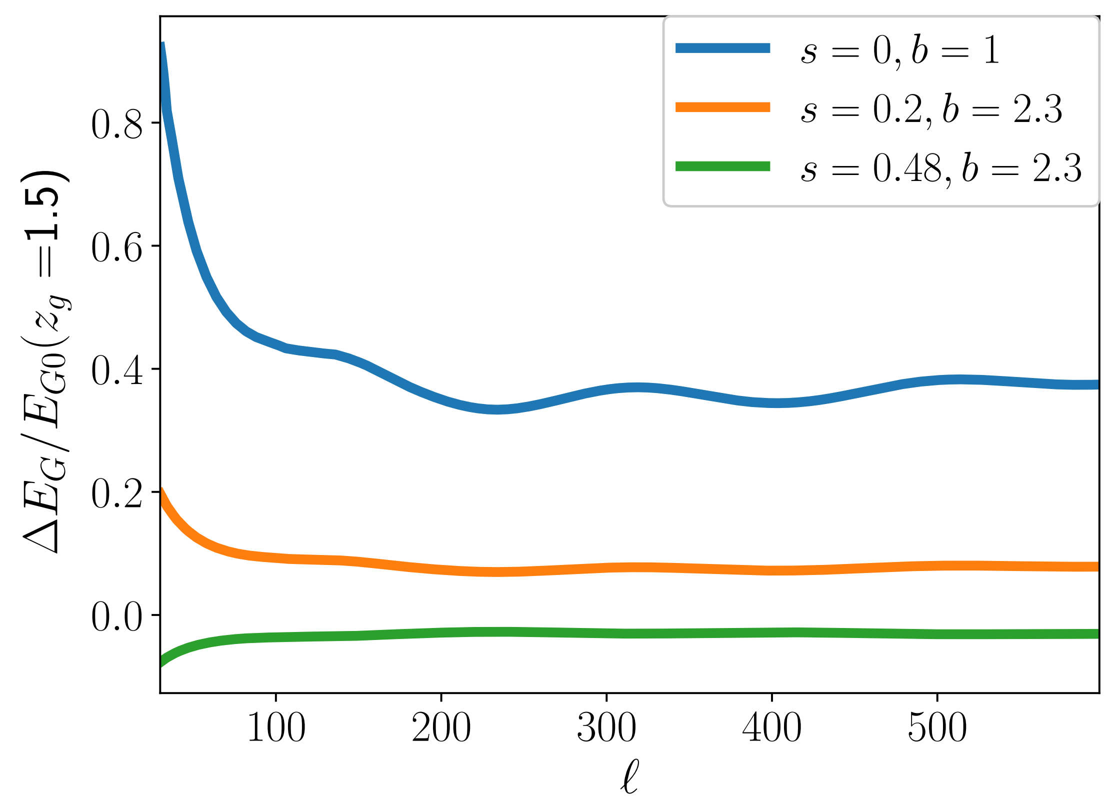



Credit: **Pullen**, Alam & Ho 2015

Reyes et al. 2010, Blake et al. 2015, **Pullen** et al. 2016, Singh et al. 2018

# Magnification bias distorts $E_G$




$$\Delta E_G \propto (5s - 2)/b$$

LRGs, QSOs ✔
(high clustering bias)

ELGs ?
(lower clustering bias)

Yang & **Pullen** (2018)

# Can calibrations reduce bias?

$$\Delta C_\ell^{\kappa_{\rm CMB}\,g} \propto (5s-2) C_\ell^{\kappa_{\rm CMB}\,\kappa_g}$$

$\kappa_g$ = lensing from foreground galaxies

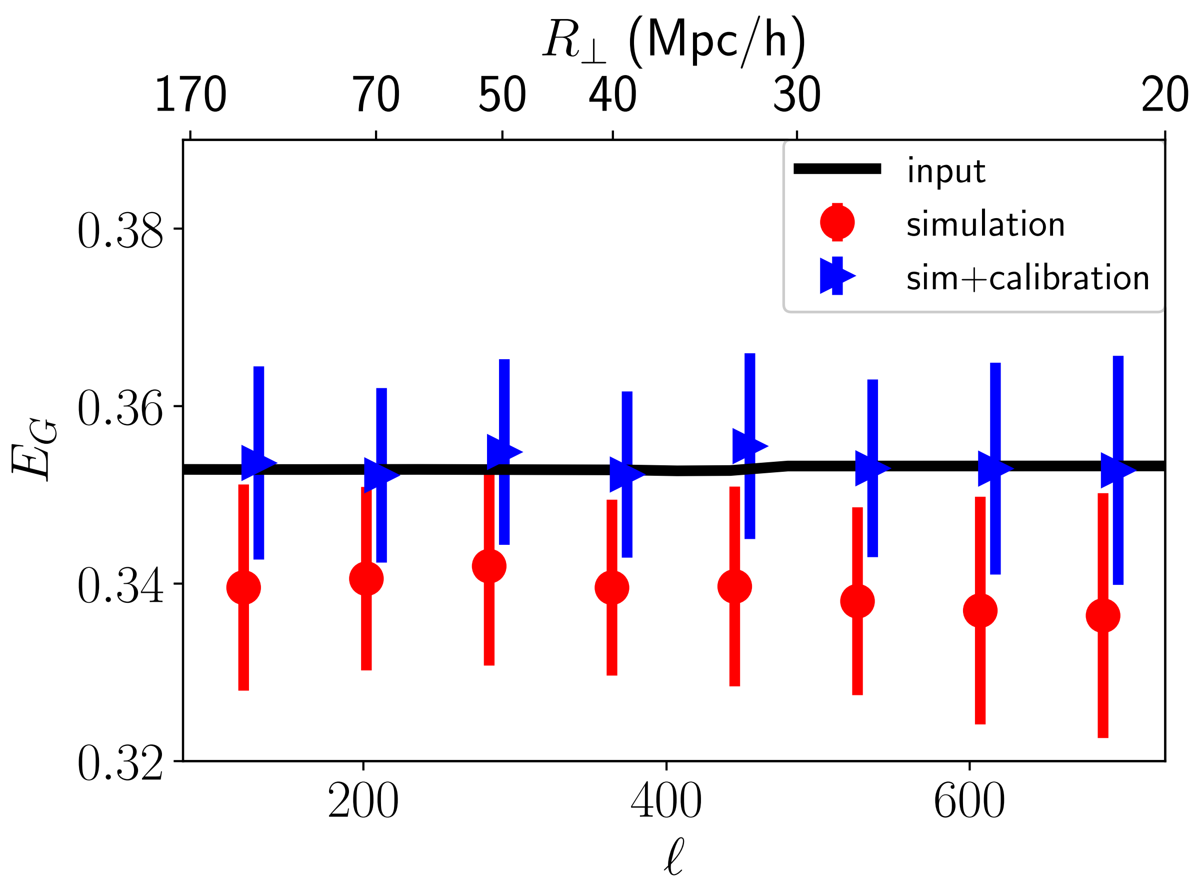
$$\widehat{\Delta C_\ell}^{\kappa_{\rm CMB}\,g} = \left( \frac{\Delta C_\ell^{\kappa_{\rm CMB}\,g}}{C_\ell^{\kappa_{\rm CMB}\,\kappa_{\rm CMB}}} \right) \hat{C}_\ell^{\kappa_{\rm CMB}\,\kappa_{\rm CMB}}$$

- Calibration method: Use $C_\ell^{\kappa\kappa}$ to calibrate $C_\ell^{\kappa g}$ and $C_\ell^{gg}$.
- $E_G$ remains independent of clustering bias
- Simulate correlated $\kappa$ and galaxy maps with galaxies under magnification bias.
- ***Compute $E_G$ difference with and w/o calibrations.***
- 100 sims, various upcoming CMB and galaxy surveys

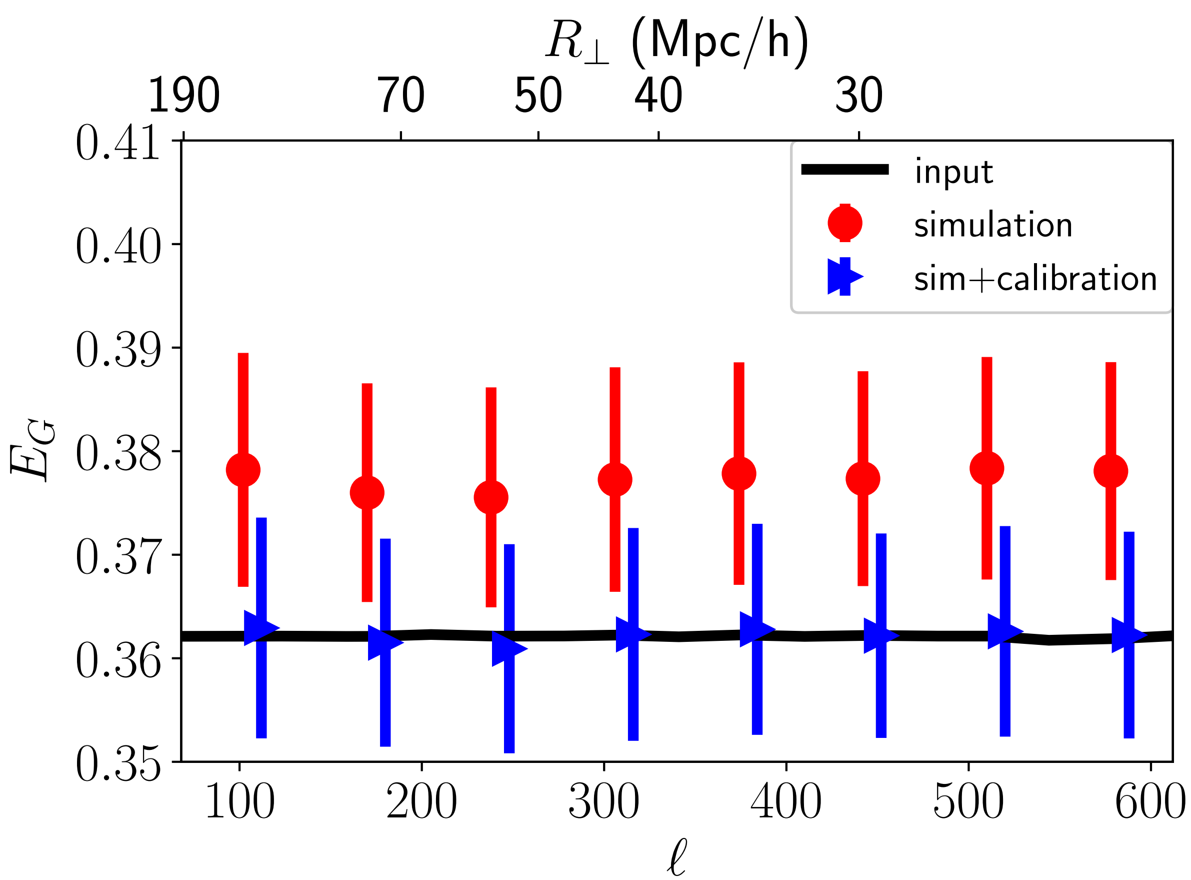
Yang & **Pullen** (2018)

# Calibration method removes bias

DESI ELGs x Adv. ACT

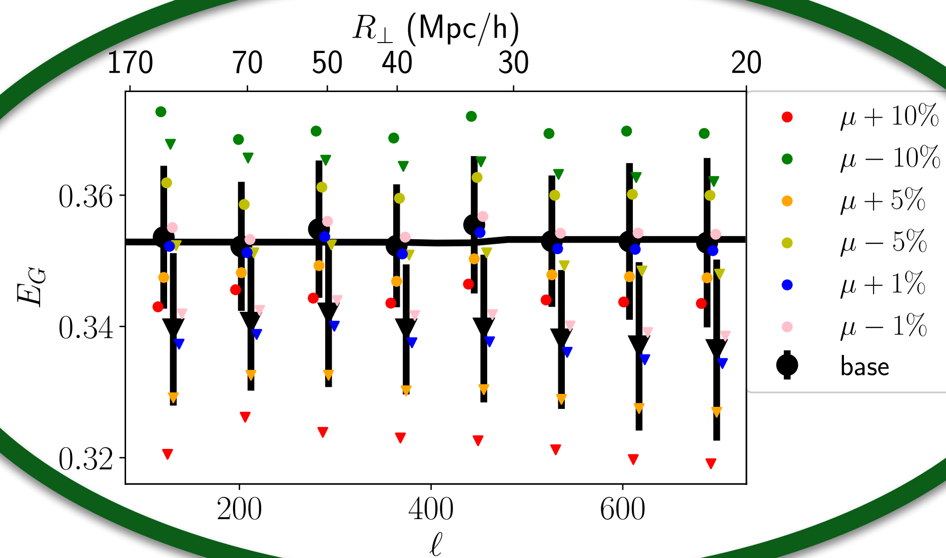


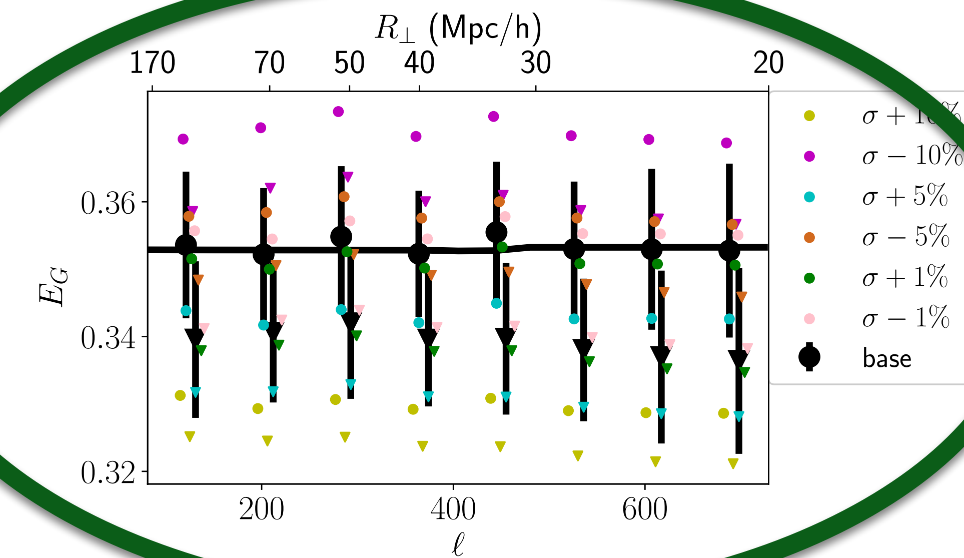

LSST x Adv. ACT



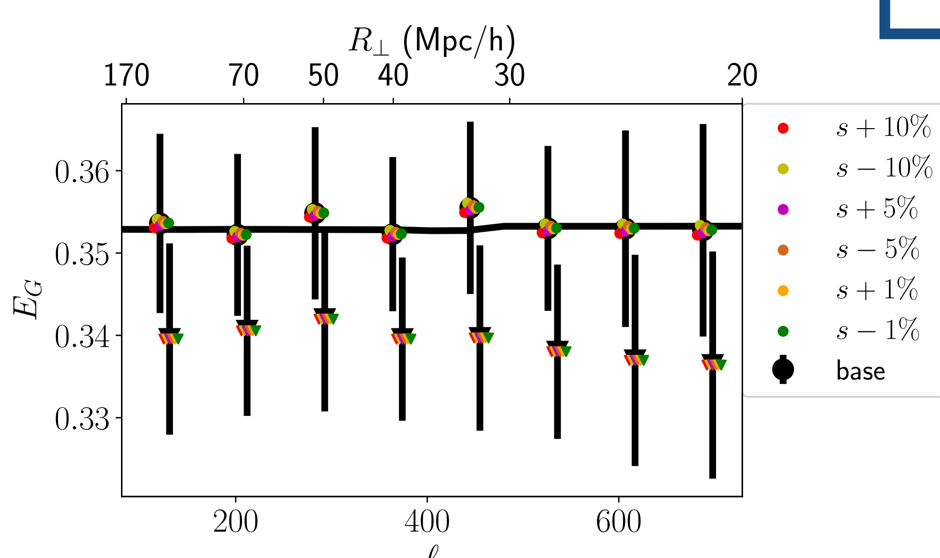

Yang & **Pullen** (2018)

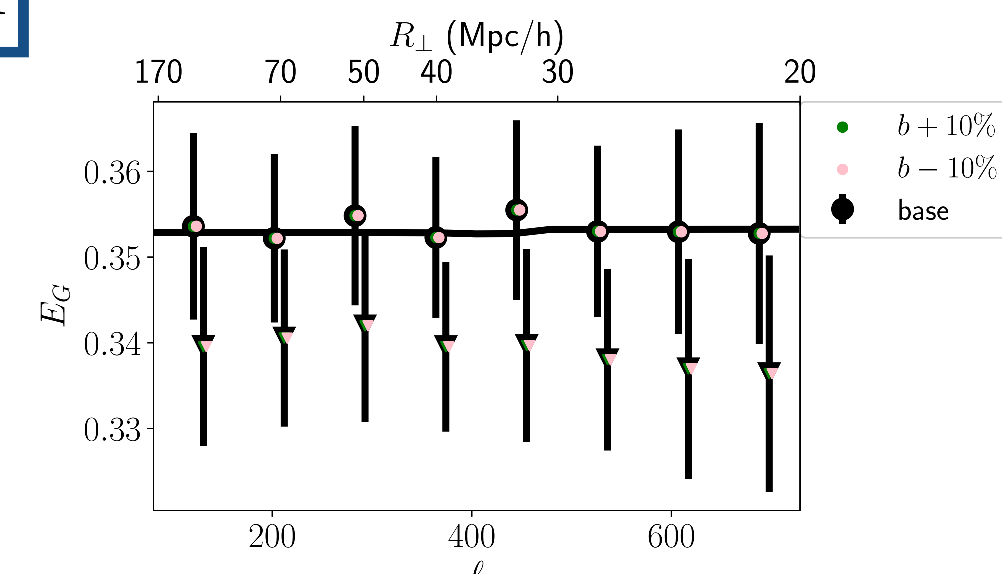
# Calibration method is stable




DESI ELG
x Adv. ACTPol




Is sensitive to mis-identified redshift distributions

Yang & **Pullen** (2018)

# Next Steps for $E_G$

- LSS predictions for alternative models - massive gravity?

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

- Improve $E_G$ statistics using joint lensing-clustering mocks

- Non-projected $E_G$ estimator - 3D lensing?

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

# Summary

- $E_G$ is a promising method for testing ΛCDM and gravity on large scales.
- Surveys with lensed galaxies can bias $E_G$ measurements using galaxy-lensing cross-correlations
- This bias is more significant for higher redshift surveys with lower clustering bias
- Our calibration method can remove magnification bias to below statistical levels
- More work is needed to analyze the effects of other $E_G$ systematics and design mitigation techniques.