CONSTRAINING $f(R)$ MODIFICATIONS TO GRAVITY

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$f(R)$ GRAVITY

- Introduced to explain cosmic-acceleration without a cosmological constant
- Avoid cosmological constant problems… 55 orders of magnitude too large

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Change gravity ($f(R) + \ldots$)

Change matter content (Λ + dark energy + ….)

$$S = \int d^4x \sqrt{-g} \left[\frac{R + f(R)}{2(8\pi G)^2} + \mathscr{L} \right]$$

$$f_{R_0} = \frac{df}{dR}\Big|_{z=0}$$

$f(R)$ GRAVITY

- The expansion history $H(z)$ is almost identical to Λ (for certain model choices)
  - No chance to observe this with Supernovae sadly
- **The growth of structure can change**

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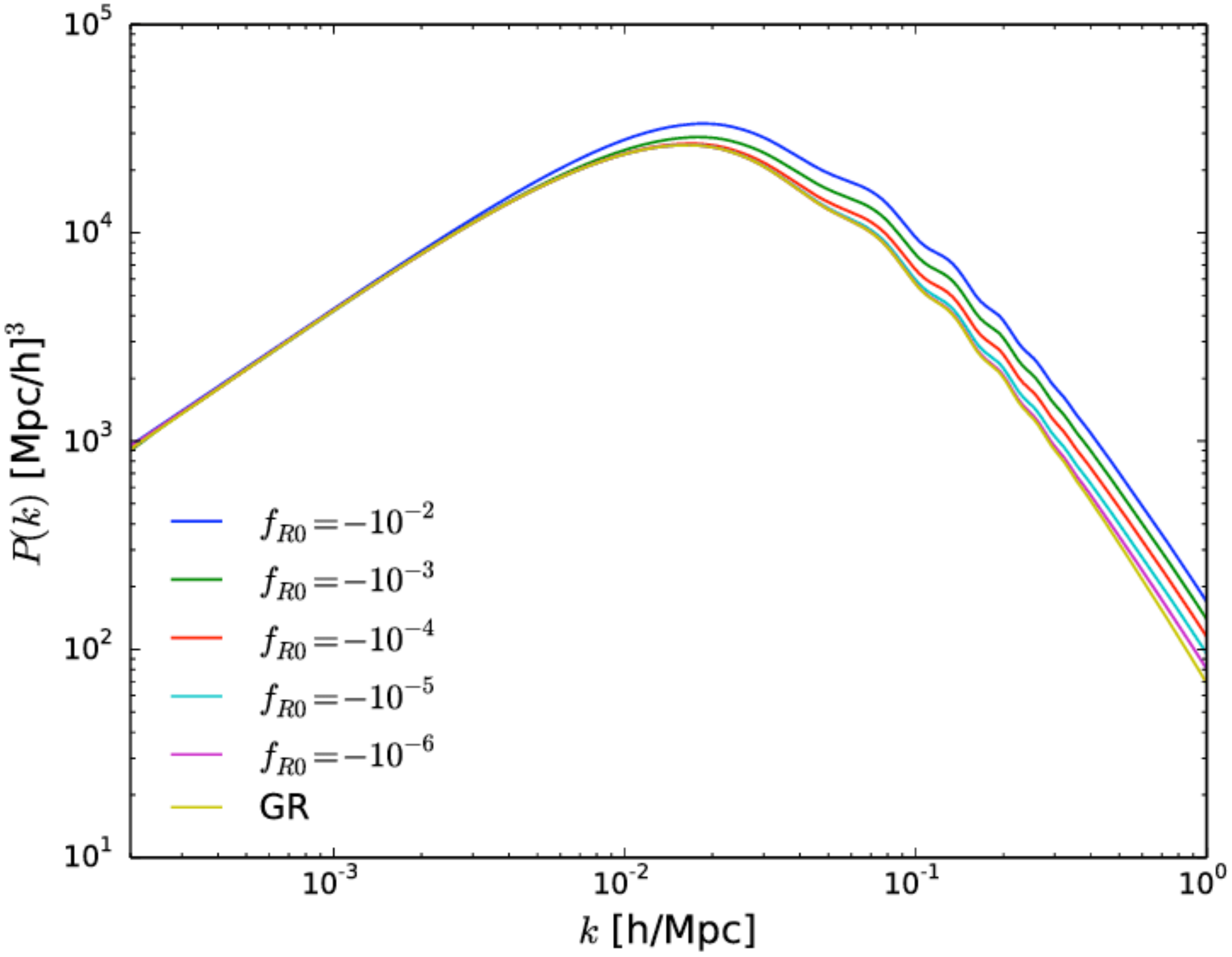
MATTER POWER SPECTRUM

- How can we measure the growth of structure?
  - Look at matter fluctuations
- $P(k) \sim \langle \delta(r')\delta(r) \rangle$
- $f(R)$ enhances the growth of structure

$$C_{gg}(\ell) \approx \int dz W_g^2(z) P(k = \ell/\chi, z)$$

$$C_{\kappa\kappa}(\ell) \approx \int dz W_\kappa^2(z) P(k = \ell/\chi, z)$$



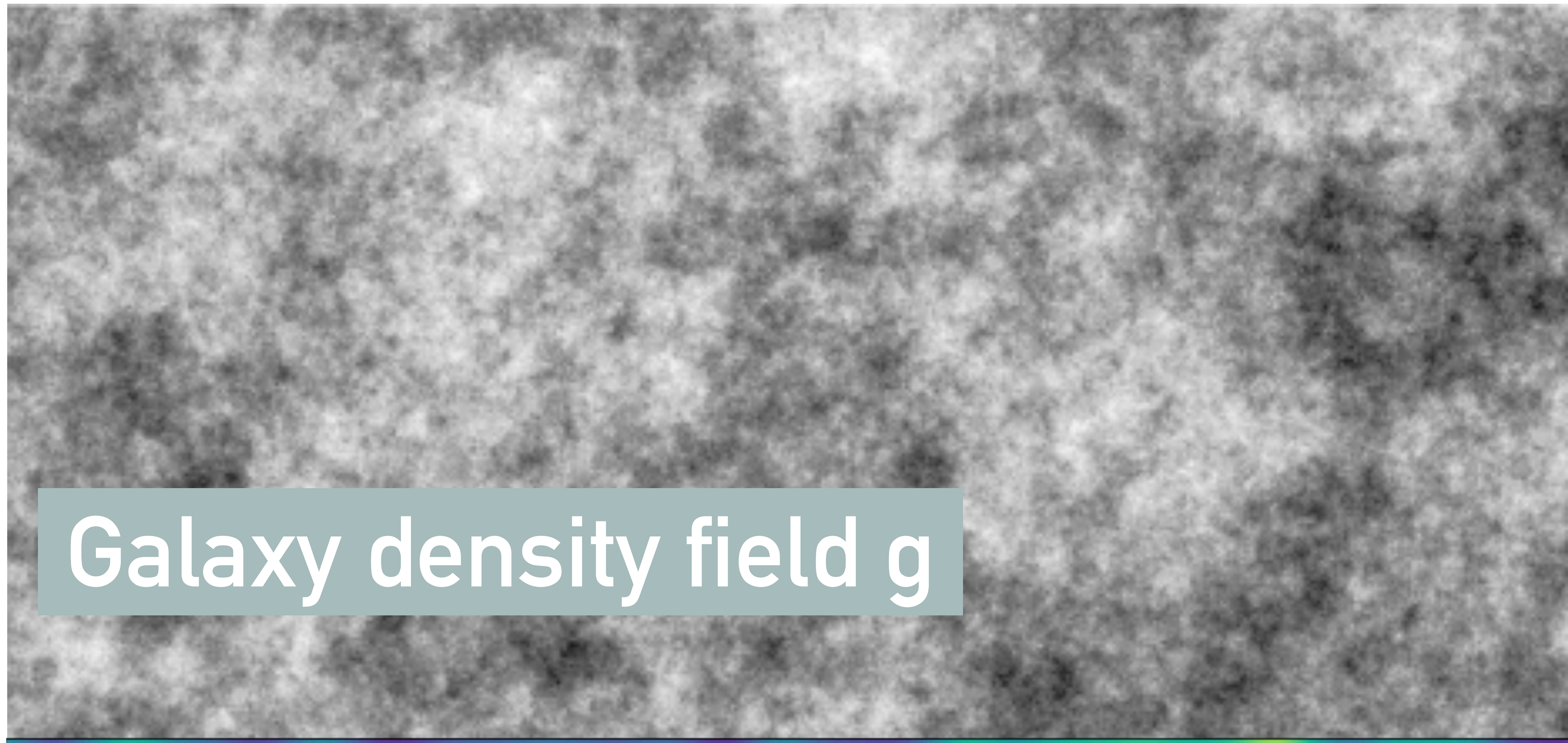
3X2PT: CROSS-CORRELATION FUNCTIONS

- We can get more information with cross correlations of fields
- Removes systematics
- Helps us to constrain the galaxy bias (difficult/impossible to predict from theory)

$$C_{gg}(\ell) \propto b^2 C_{\delta\delta}(\ell)$$

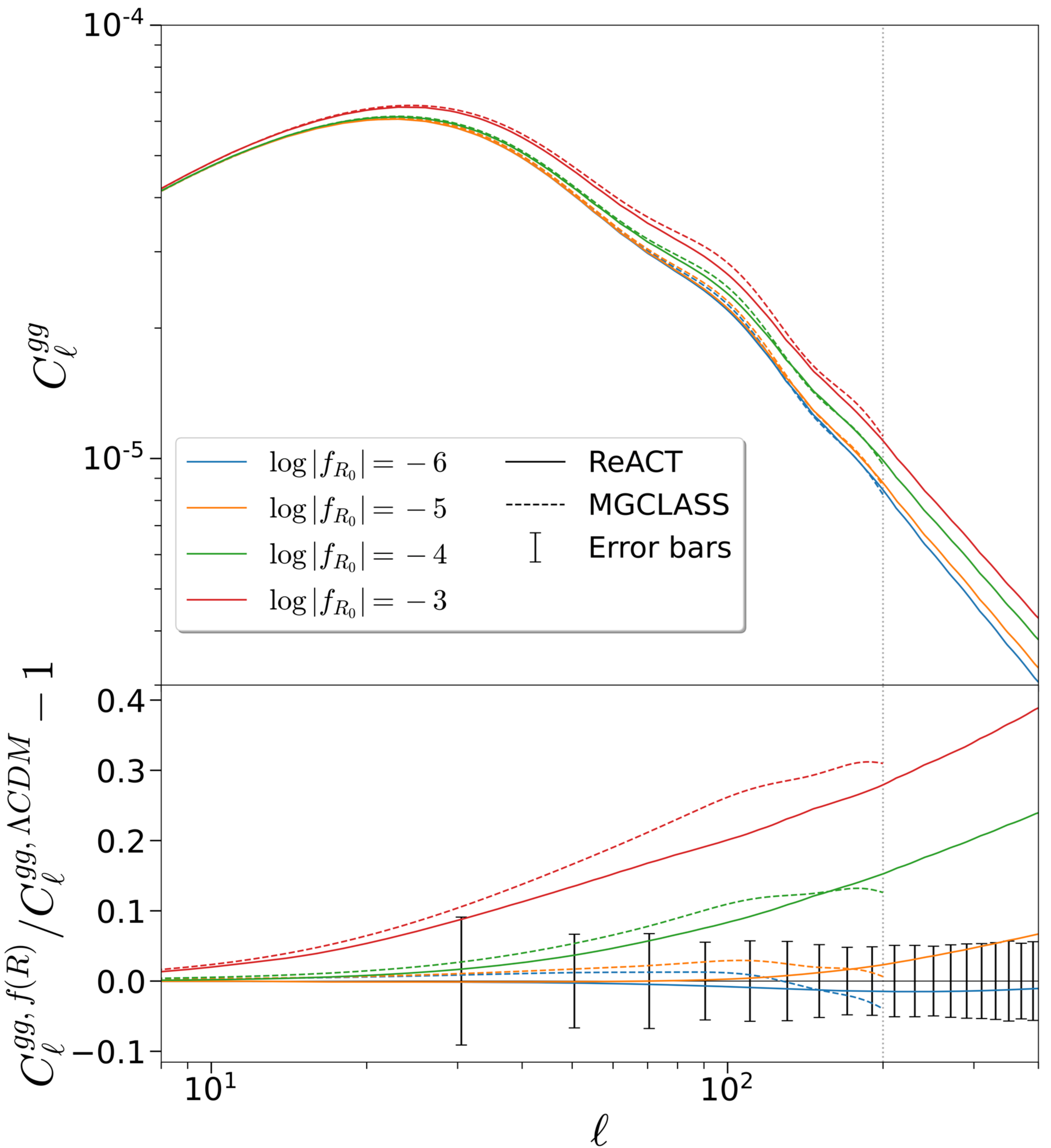
$$C_{\kappa\kappa}(\ell) \propto C_{\delta\delta}(\ell)$$

$$C_{\kappa g}(\ell) \propto b C_{\kappa\delta}(\ell)$$



THEORETICAL MODELLING

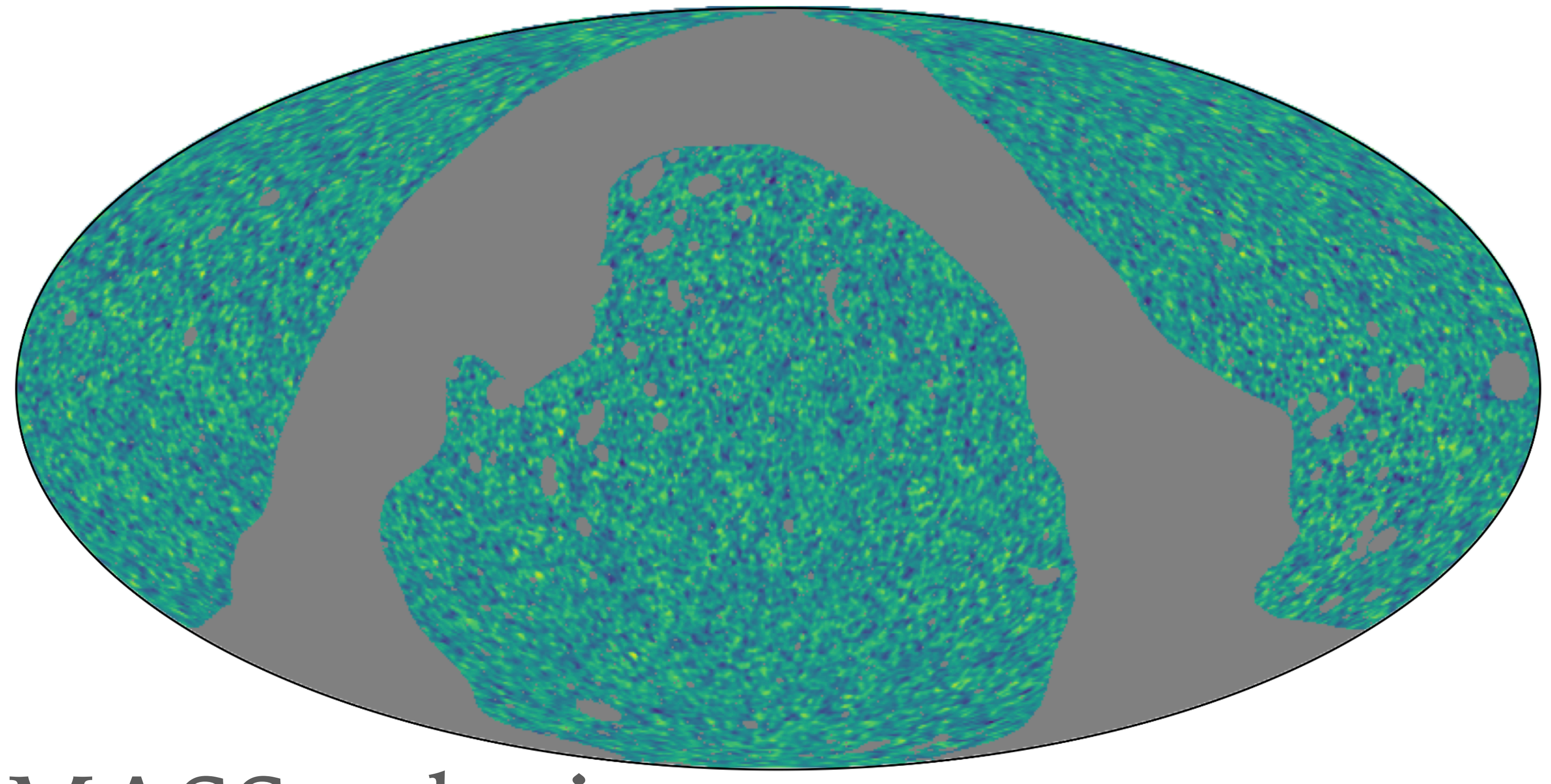
- How to calculate $f(R)$ modifications to the growth of structure
- Two codes
  - Mgclass (linear)
  - ReACT (non-linear)
- Agreement is not excellent



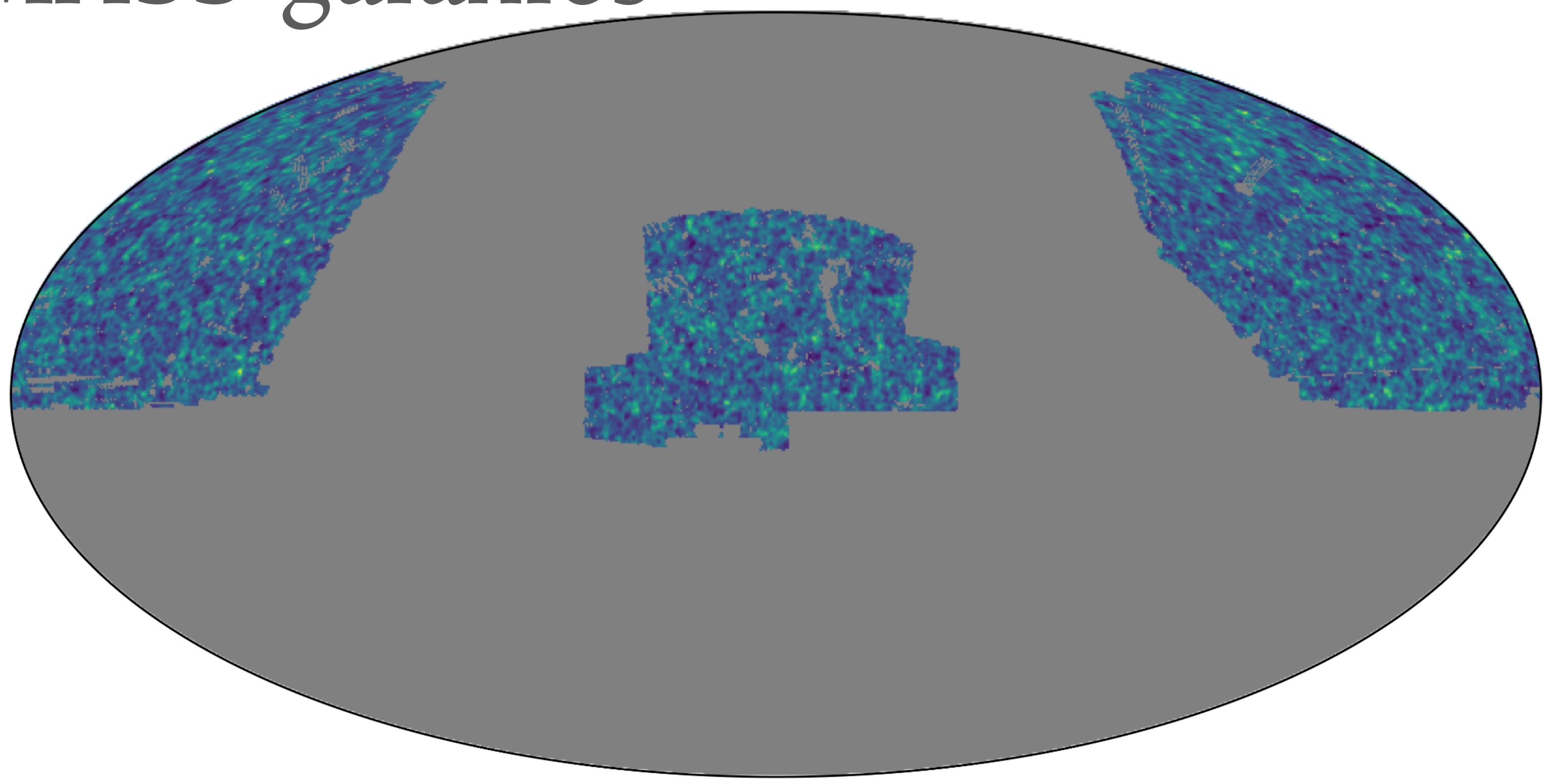
DATA WE USED

- Planck lensing
  - Quick explanation of CMB lensing on the next slide!
- SDSS/BOSS galaxies
  - LOWz: 350,000 galaxies $0.15 < z < 0.45$
  - CMASS: 750,000 galaxies $0.45 < z < 0.8$
- Also we use Planck temperature and polarisation spectra

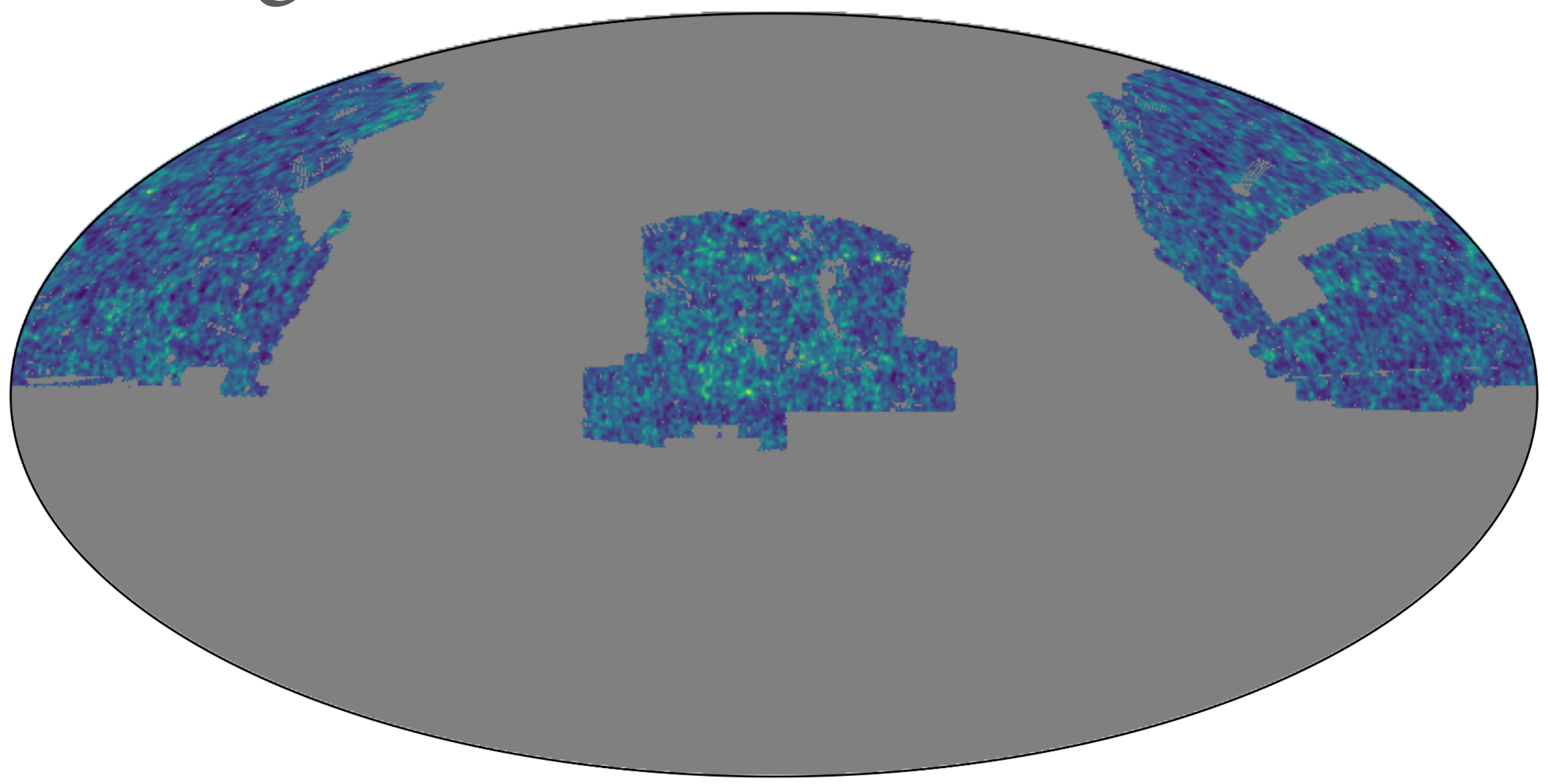
Planck lensing



CMASS galaxies

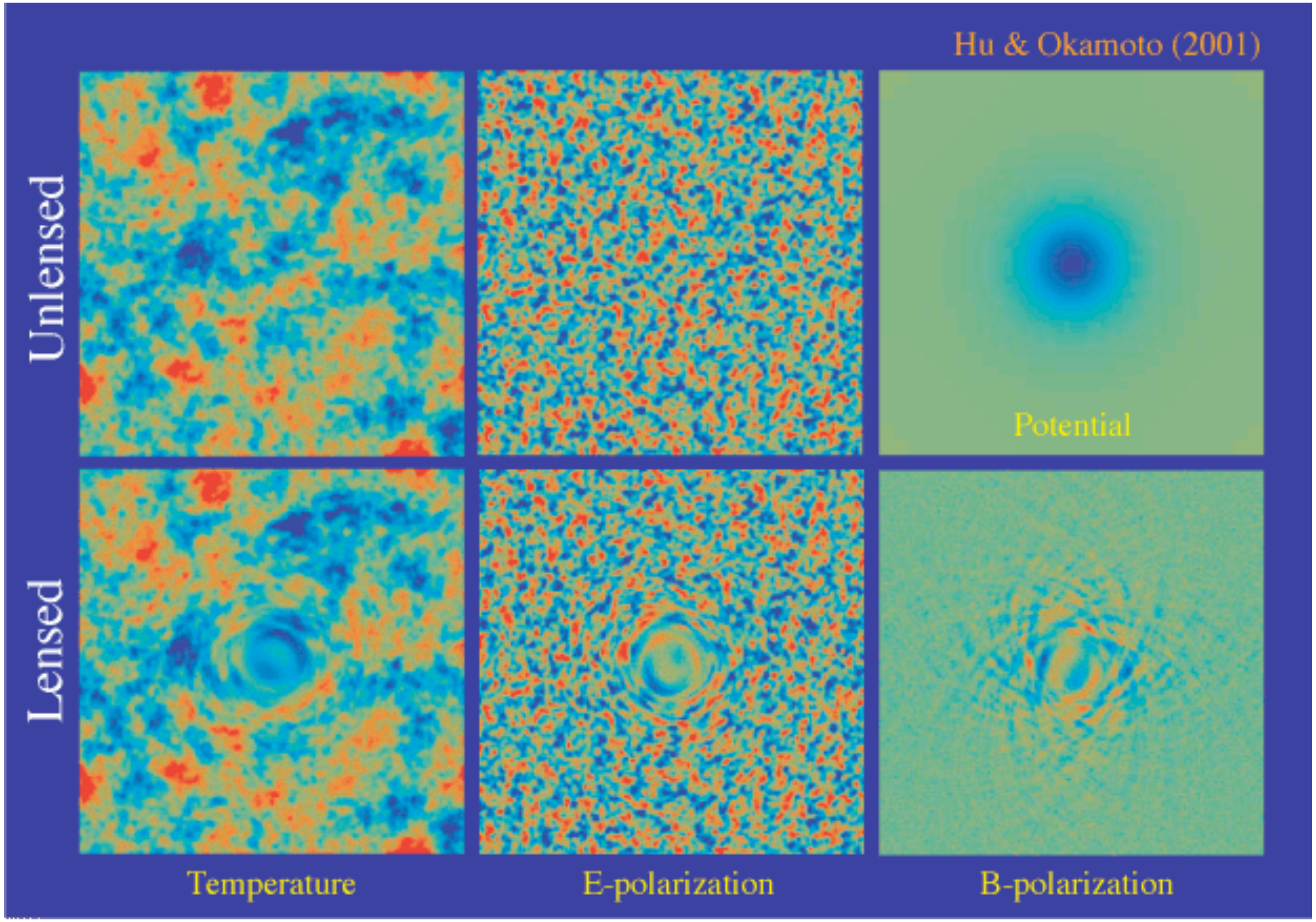


LOWz galaxies



CMB LENSING

- Amplifies/diminishes angles on the sky
- Induces CMB correlations where there should not be!
- We can use this to reconstruct the lensing signal



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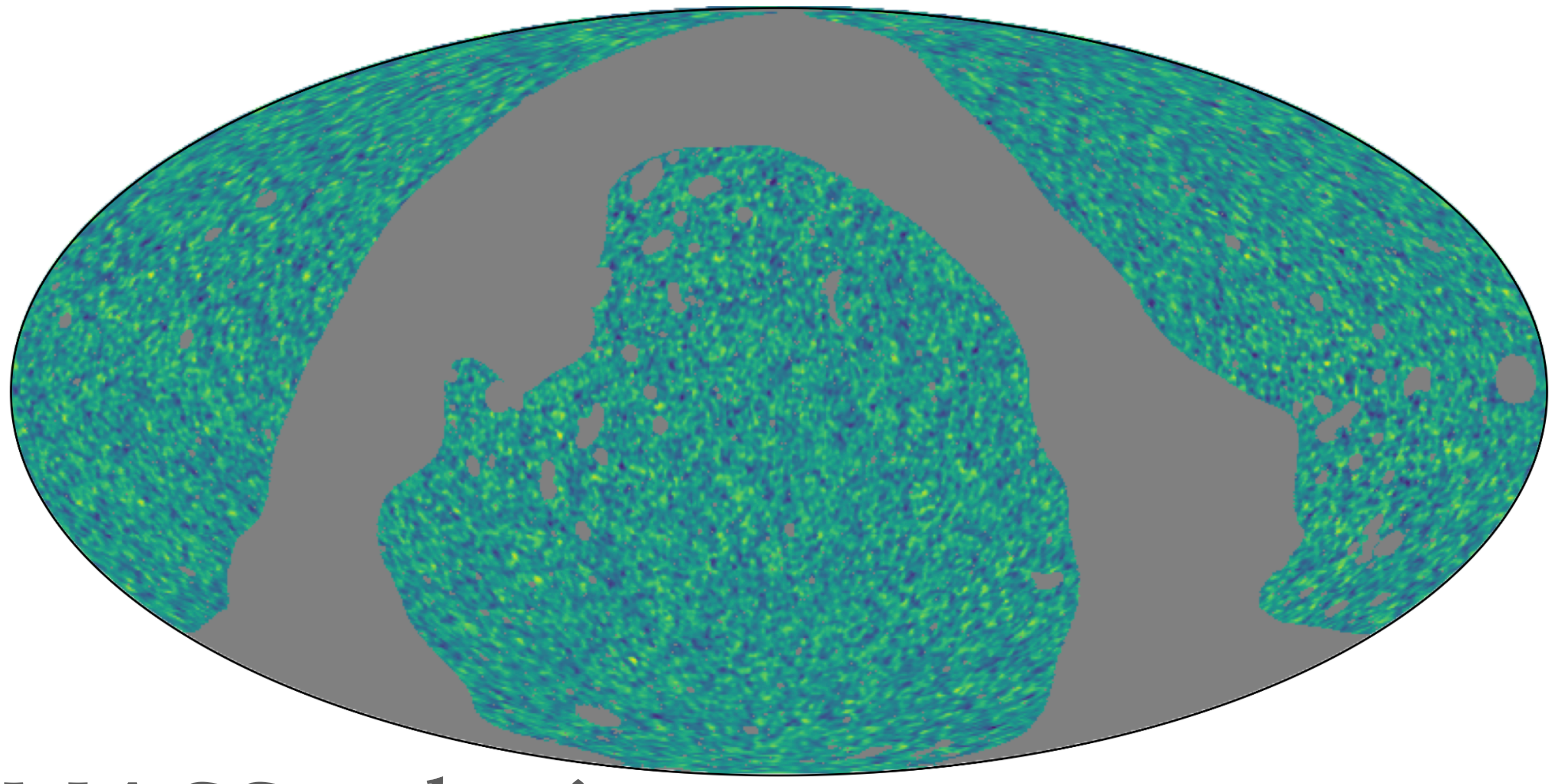
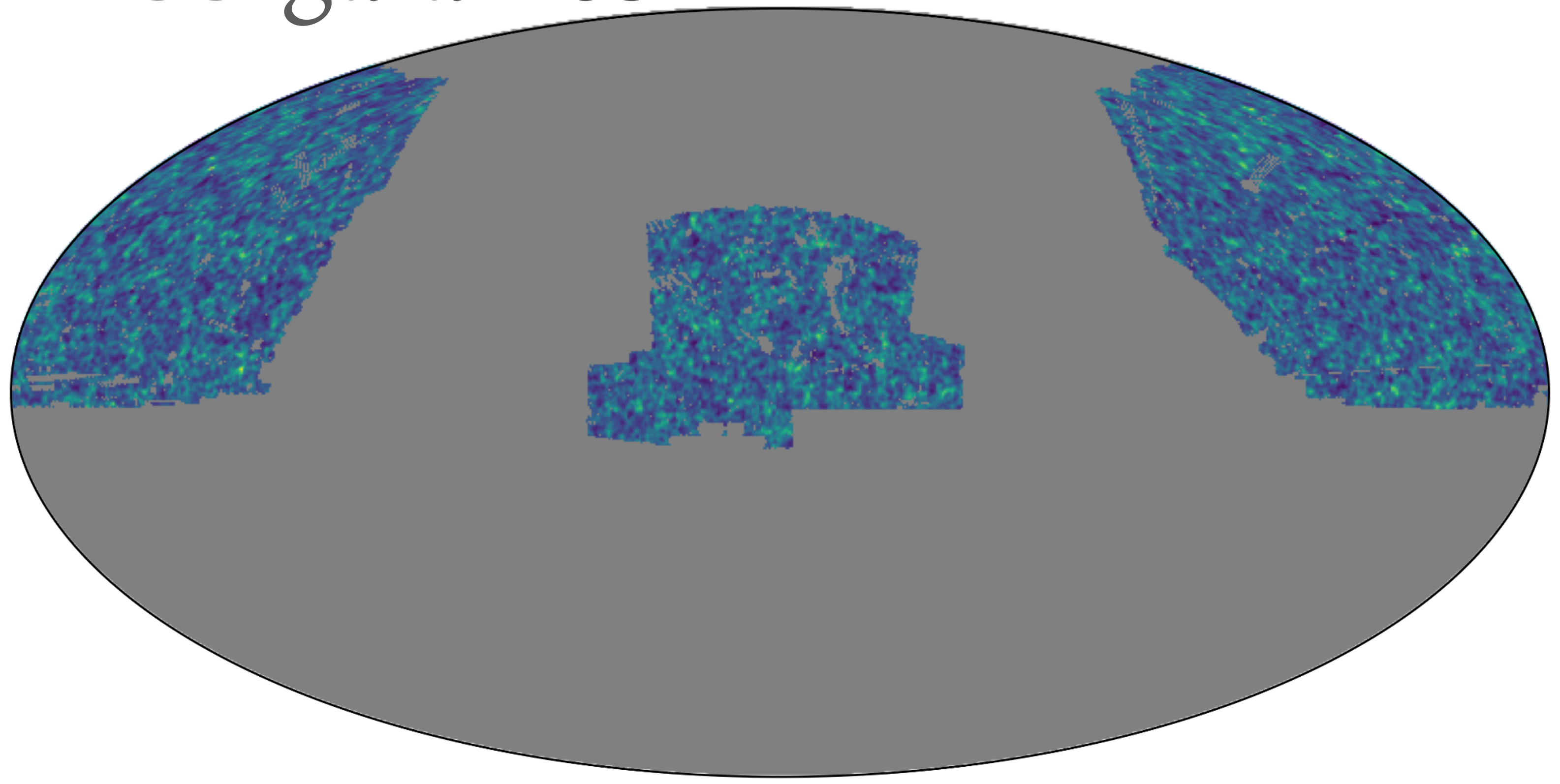
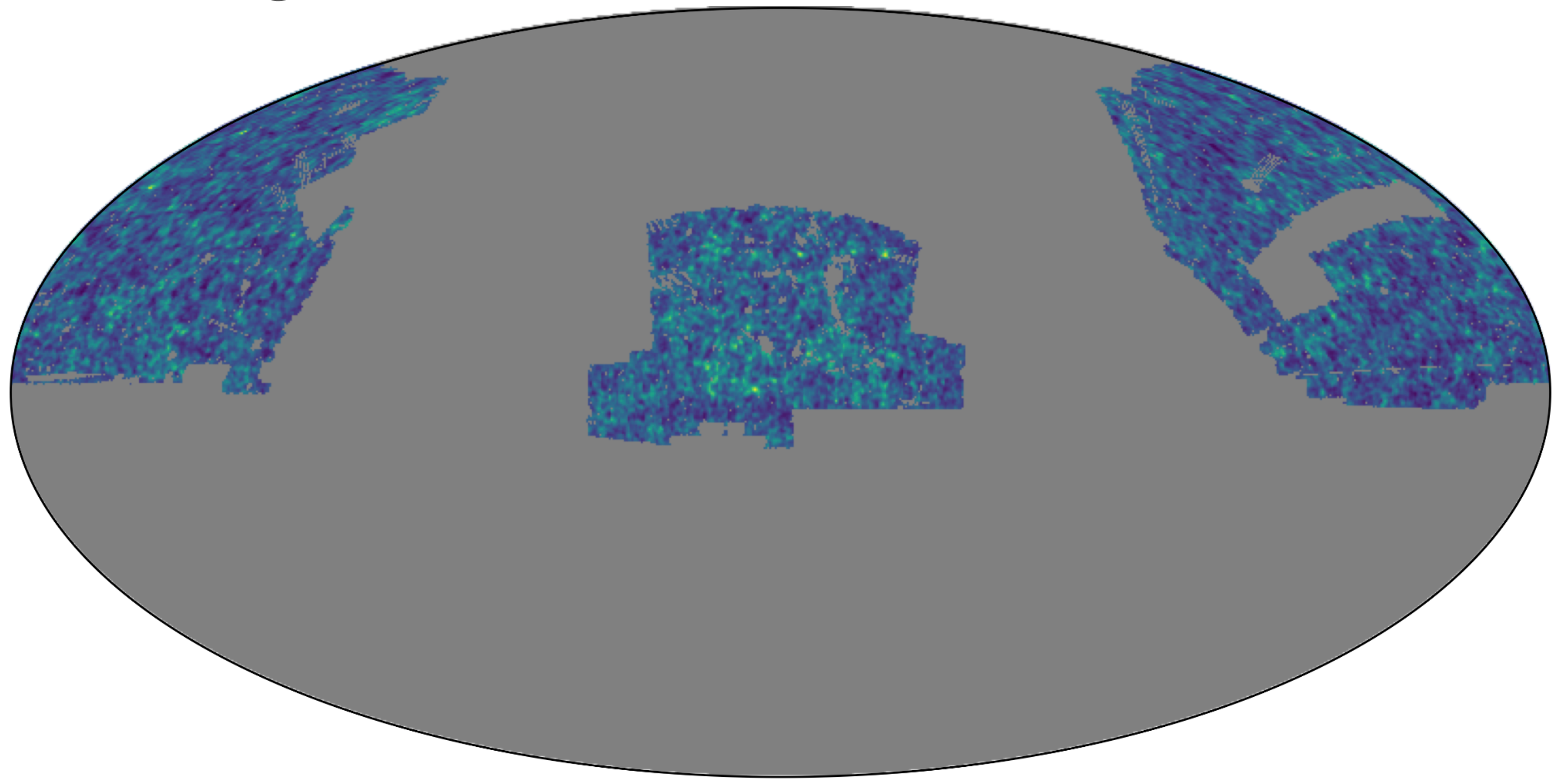


CMASS galaxies



LOWz galaxies



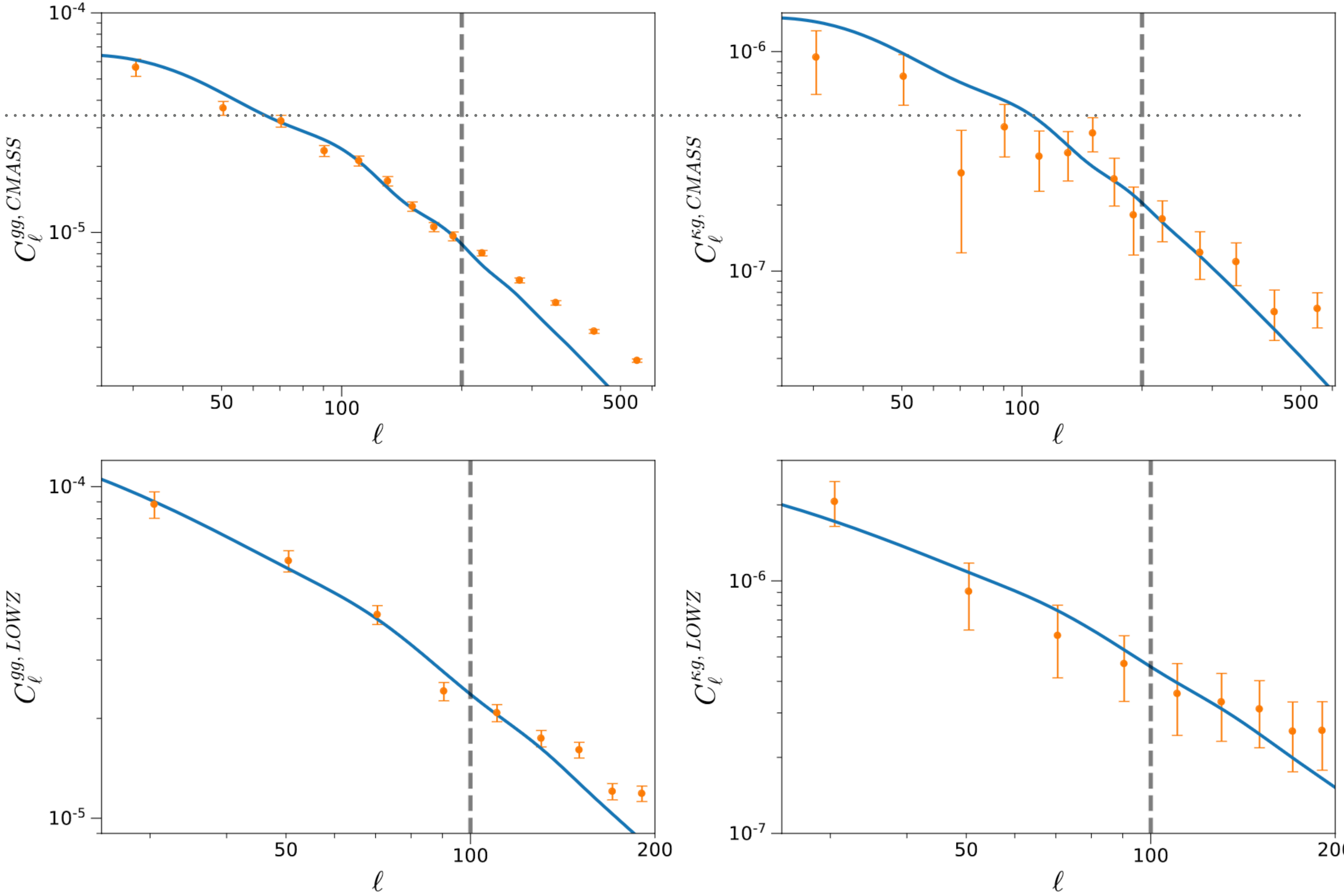
OBSERVATIONS

- Orange points are our measurements
- Blue line is the best-fit model
- We stick to the linear regime due to insufficiency of theoretical modelling

$$C_{gg}(\ell) \propto b^2 C_{\delta\delta}(\ell)$$

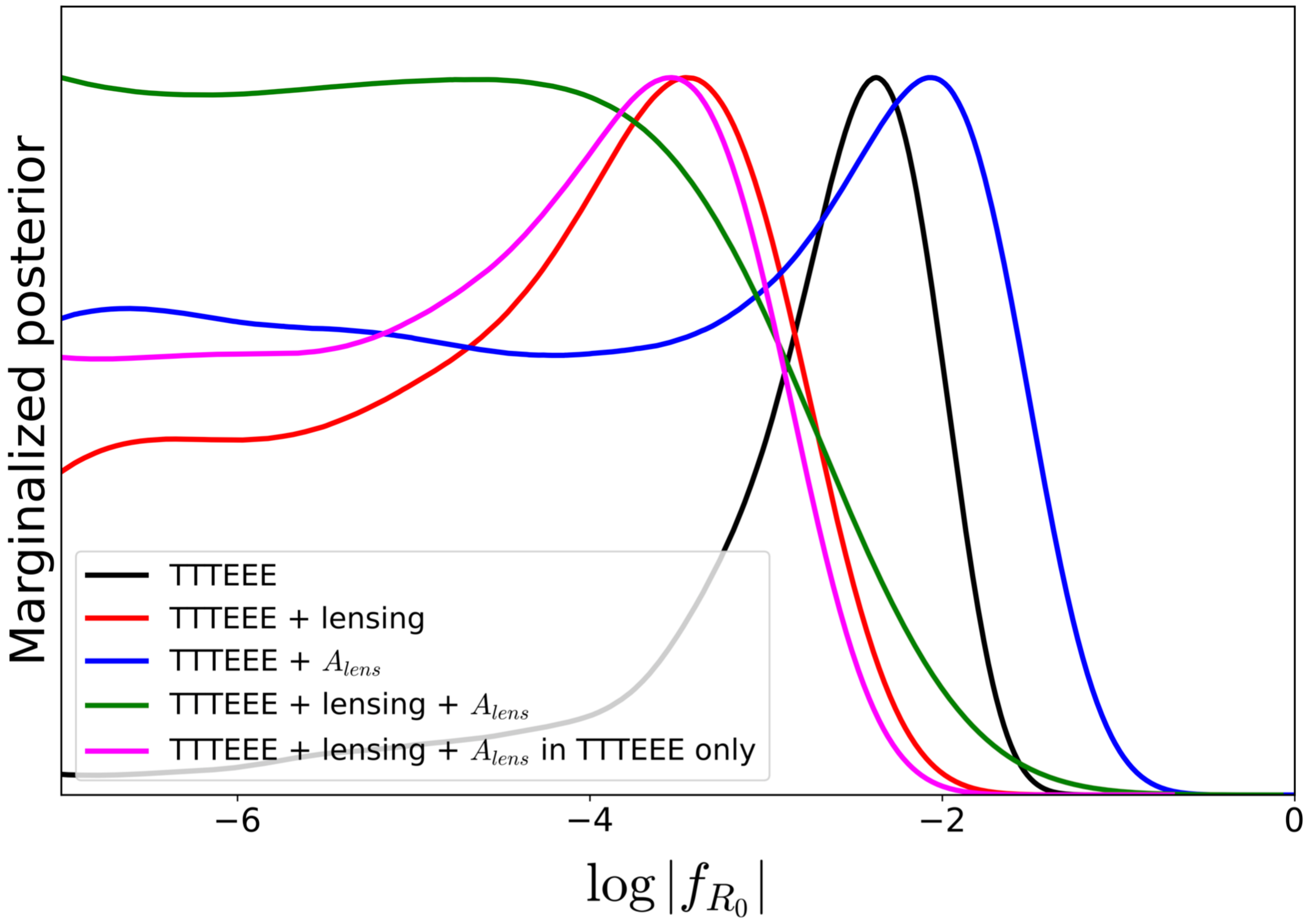
$$C_{\kappa\kappa}(\ell) \propto C_{\delta\delta}(\ell)$$

$$C_{\kappa g}(\ell) \propto b C_{\kappa\delta}(\ell)$$



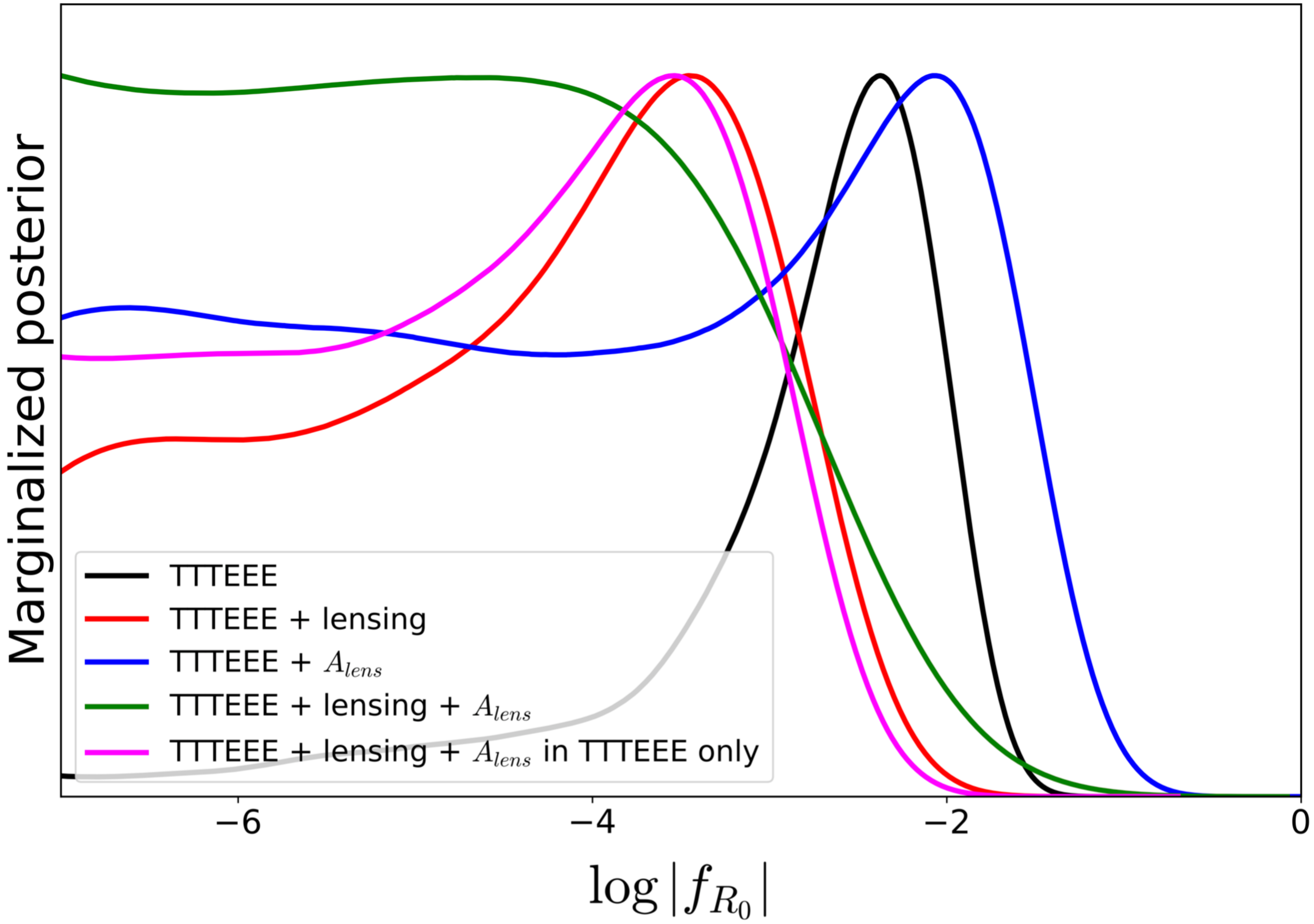
POSTERIORS

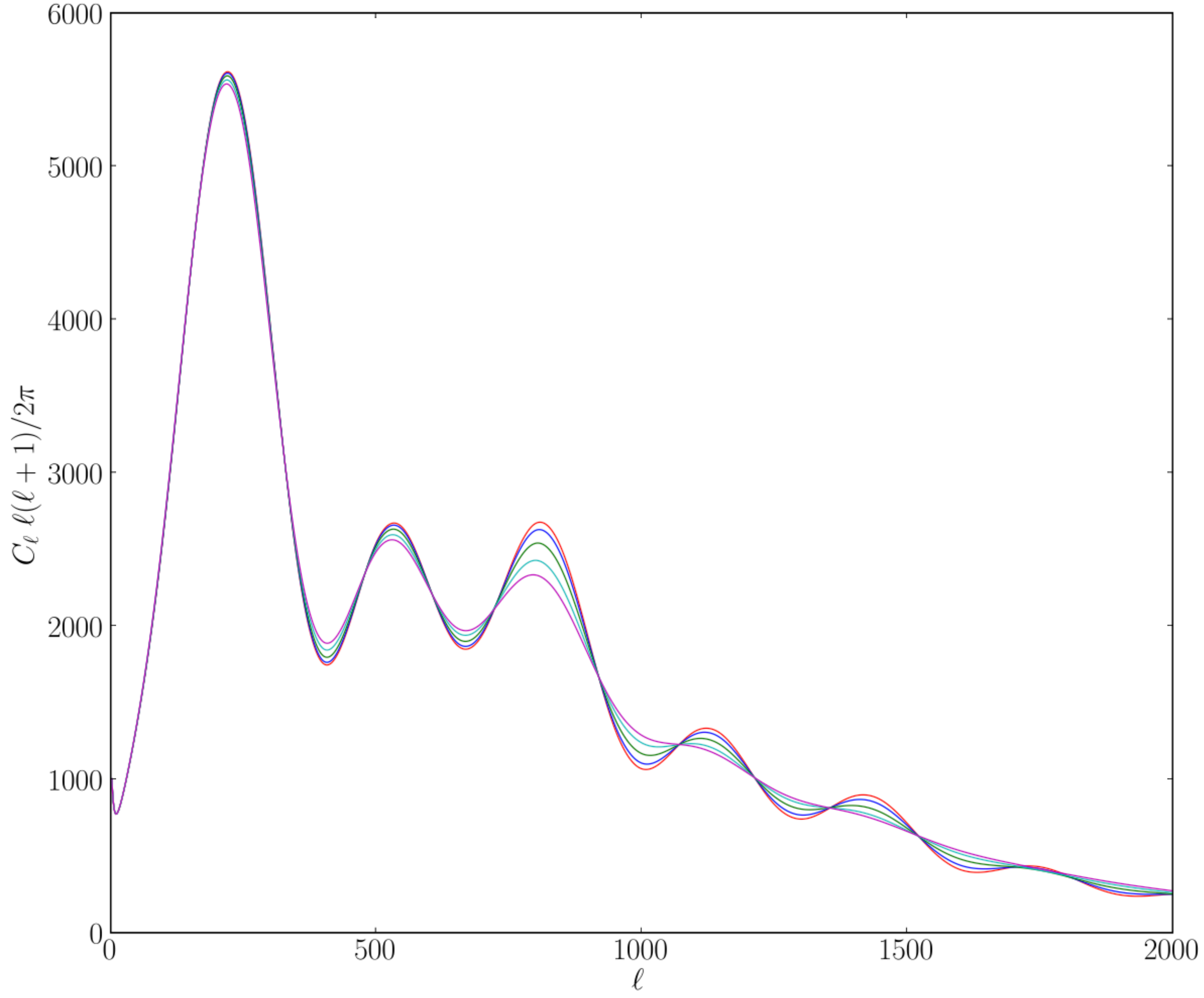
➤ We run MCMCs with a Gaussian likelihood, to infer constraints on modifications to gravity



POSTERIORS

- We measure $f(R)$ at many σ… this is a known problem: A_{lens}, Planck appears to smooth

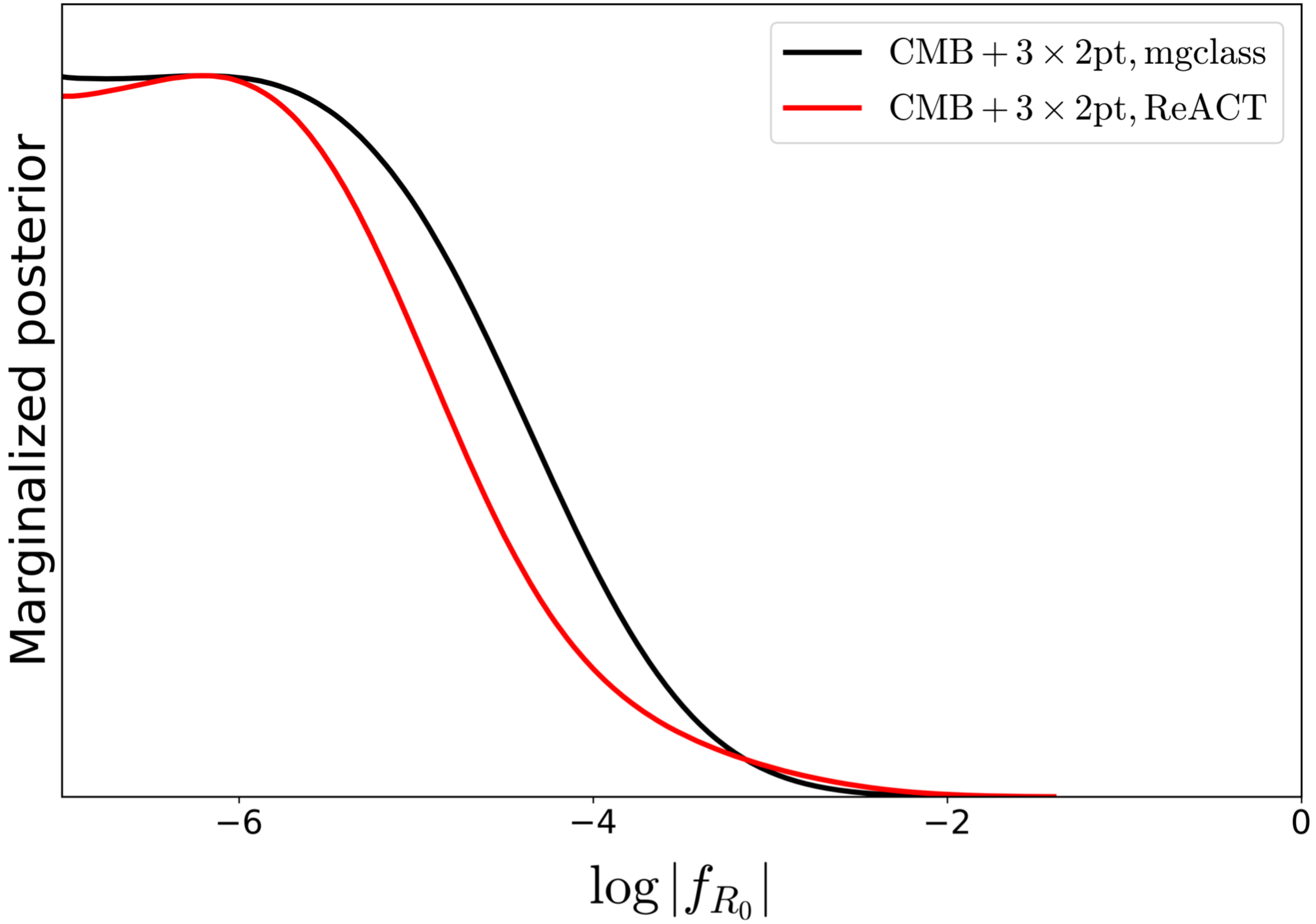




$$C^{\Psi}(\ell) \to A_{lens} C^{\Psi}(\ell)$$

POSTERIORS

- Adding 3x2pt, clearly no signs of $f(R)$



- Upper limits at 95% confidence
  - MGclass: $\log|f_{R_0}| < -4.12$
  - ReACT: $\log|f_{R_0}| < -4.61$

POWER OF CROSS-CORRELATIONS

- Upper limits at 95% confidence
  - With cross-correlation: $\log|f_{R_0}| < -4.12$
  - Without the cross-correlation ReACT: $\log|f_{R_0}| < -2.95$

$$C_{gg}(\ell) \propto b^2 C_{\delta\delta}(\ell)$$

$$C_{\kappa\kappa}(\ell) \propto C_{\delta\delta}(\ell)$$

$$C_{\kappa g}(\ell) \propto b C_{\kappa\delta}(\ell)$$