Weak lensing shear multipole analysis of galaxy clusters

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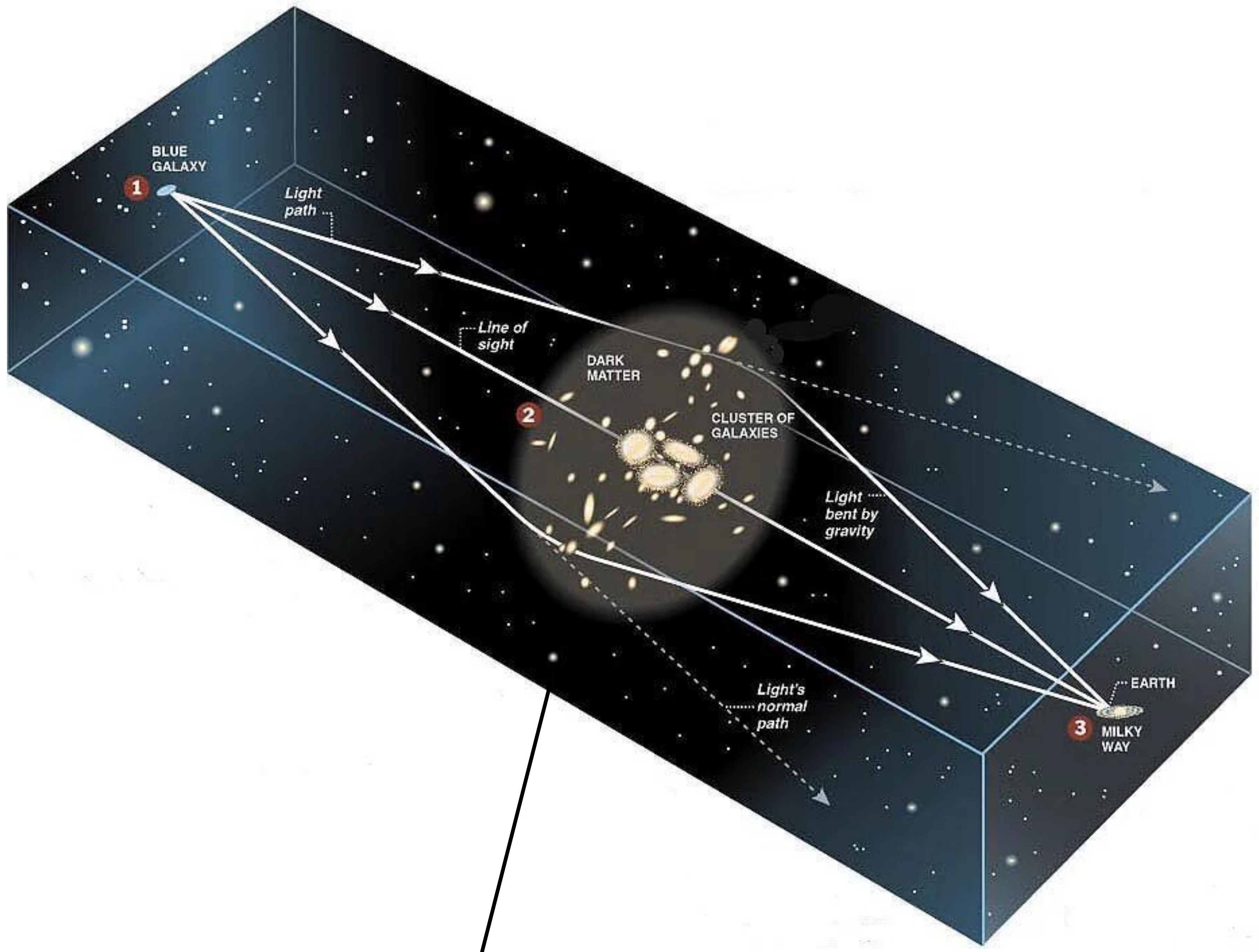
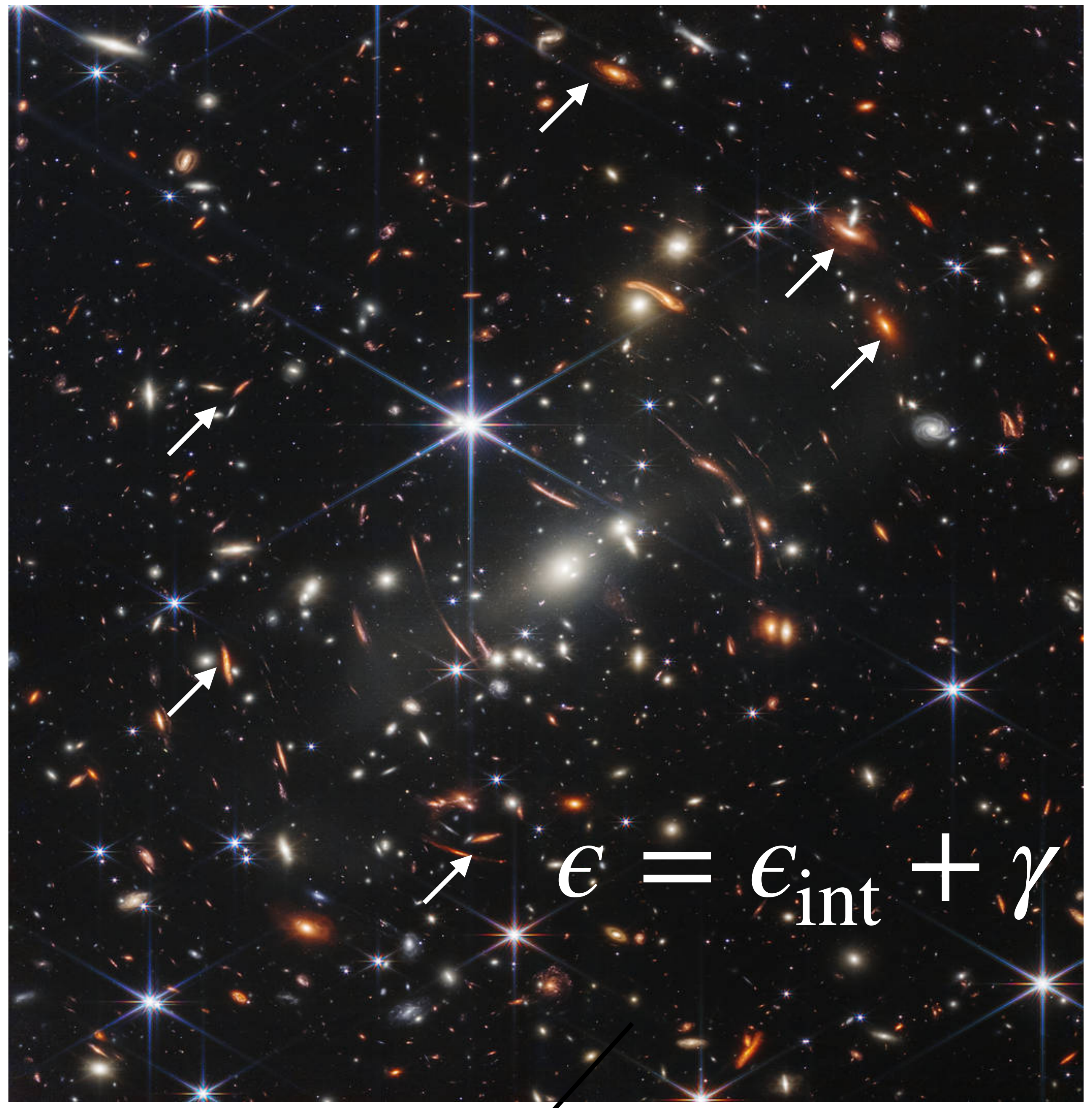
Weak gravitational lensing



Bending of light coming from distant galaxies

Deformation of galaxy shapes



JWST, SMACS J0723

Inducing a coherent deformation of observed galaxy shapes

Probe of the local shear field

$$\langle \epsilon \rangle = \underbrace{\langle \epsilon_{\text{int}} \rangle}_{\approx 0} + \gamma$$

The shear can be deduced locally by averaging galaxy shapes

Relies on accurate galaxy shape measurement, see Manon Ramel's talk

Shear analysis - In practice

Tangential/cross reference frame

$$\gamma_+ + i\gamma_\times = -\gamma e^{-2i\varphi}$$

- Can be fully described by its multipole moments

$$\gamma_+(R,\varphi) = \underbrace{\gamma_+^{(0)}(R)}_{\text{monopole}} + \underbrace{\gamma_+^{(1)}(R)e^{i\varphi} + \gamma_+^{(2)}(R)e^{i2\varphi} + \dots}_{\text{multipoles}}$$

- Each moment $\gamma_{+/\times}^{(m)}$ can be estimated from background galaxies

$$\gamma^{(m)} \propto \int_0^{2\pi} \gamma(R,\varphi)e^{-im\varphi}d\varphi$$

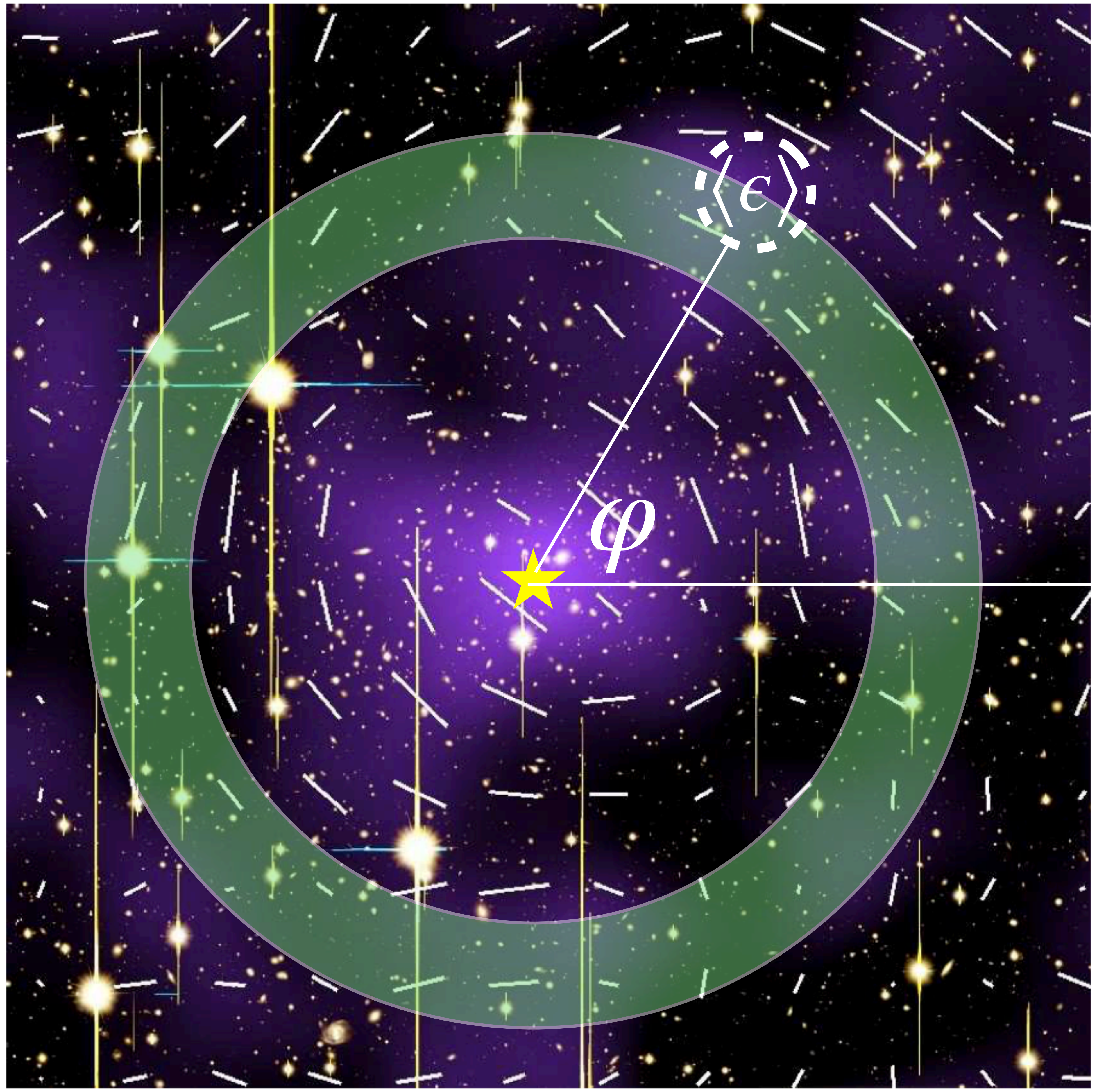
Observable

$$\boxed{\hat{\gamma}_{+/\times}^{(m)}(R) = \langle \hat{\epsilon}_{+/\times} e^{-im\varphi} \rangle |_R}$$

Prediction

$$\boxed{\gamma_{+/\times}^{(m)} \text{ depends on } \kappa^{(m)}}$$

linked to cluster mass



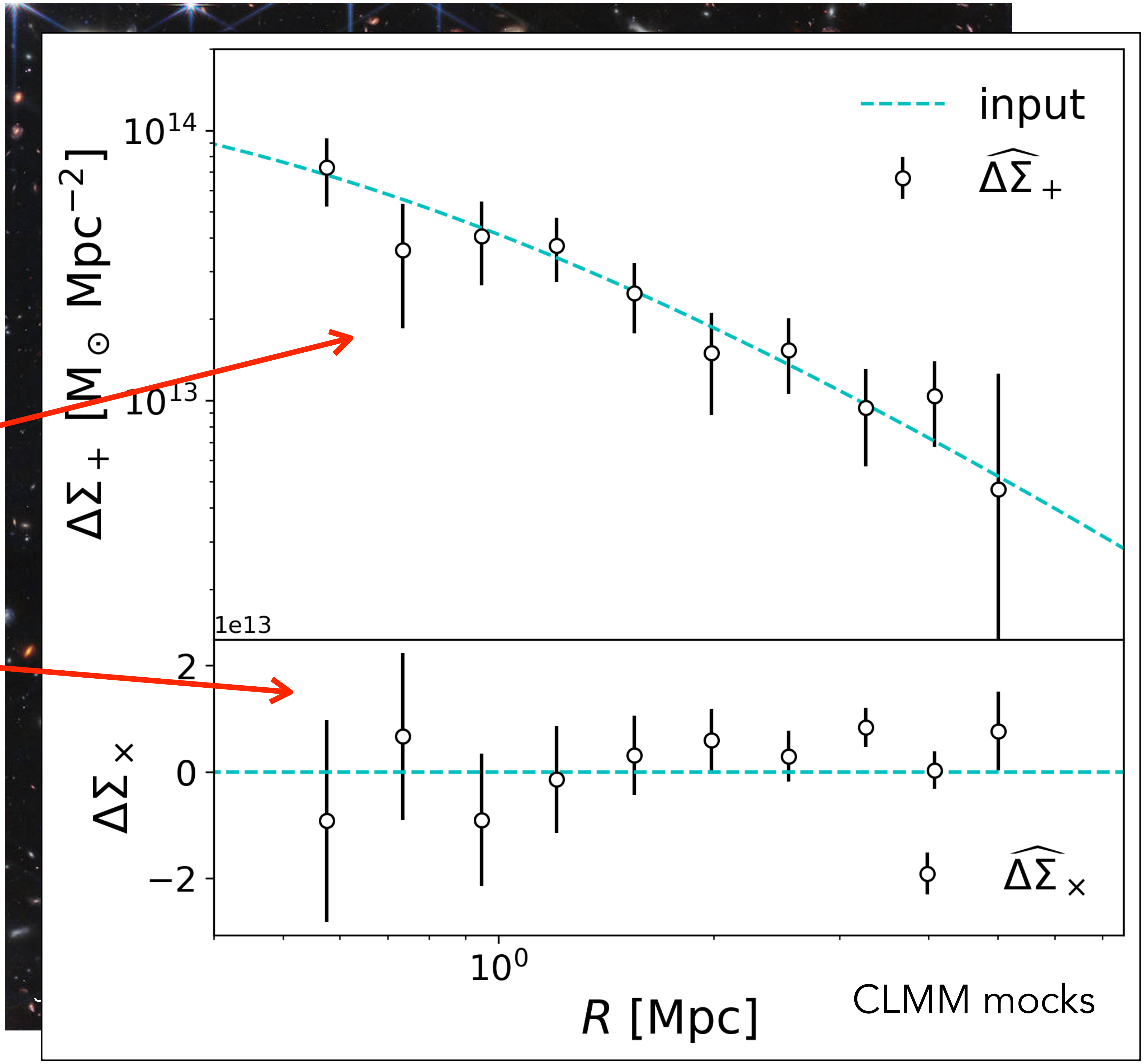
Oguri et al. 2010, A2390

Standard WL mass reconstruction

- Assume the halo is spherical
  - $\kappa^{(m\neq0)} = 0 \rightarrow \gamma^{(m\neq0)} = 0$
- Only the monopole

average tangential shear $\boxed{\widehat{\gamma}_+^{(0)} = \frac{1}{N}\sum_{s=1} \widehat{\epsilon}_{+,s}}$

average cross shear = 0 $\boxed{\widehat{\gamma}_\times^{(0)} = \frac{1}{N}\sum_{s=1} \widehat{\epsilon}_{\times,s}}$

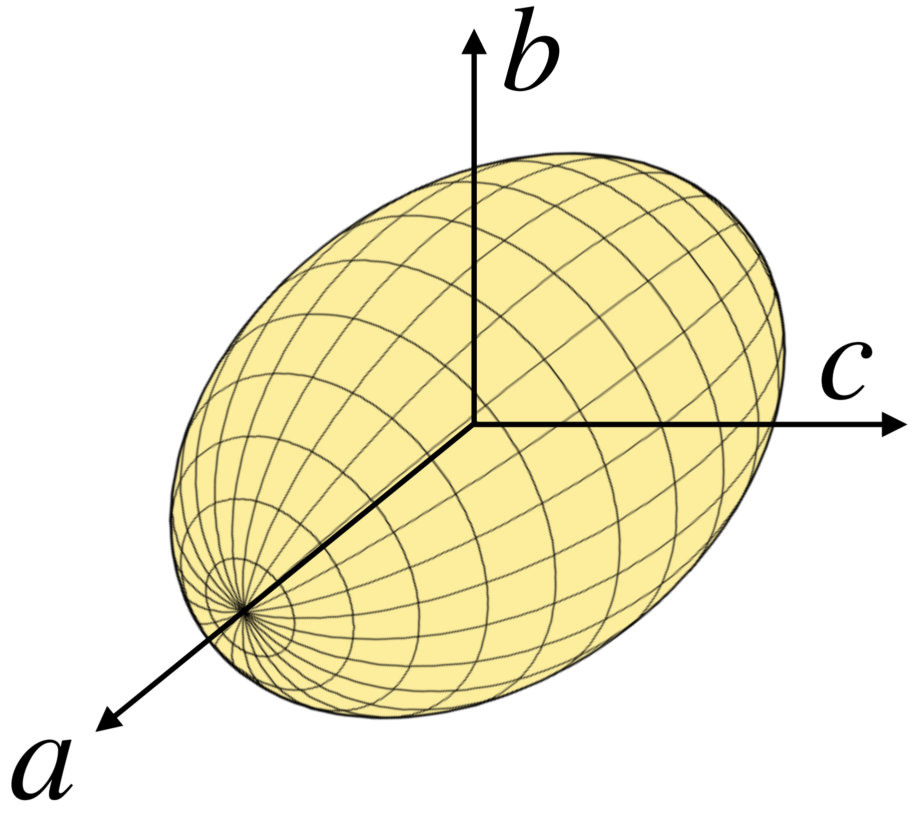


- *Halo mass fitted on the average tangential shear profile*
- *Cross shear = used as a null test (systematic residual)*

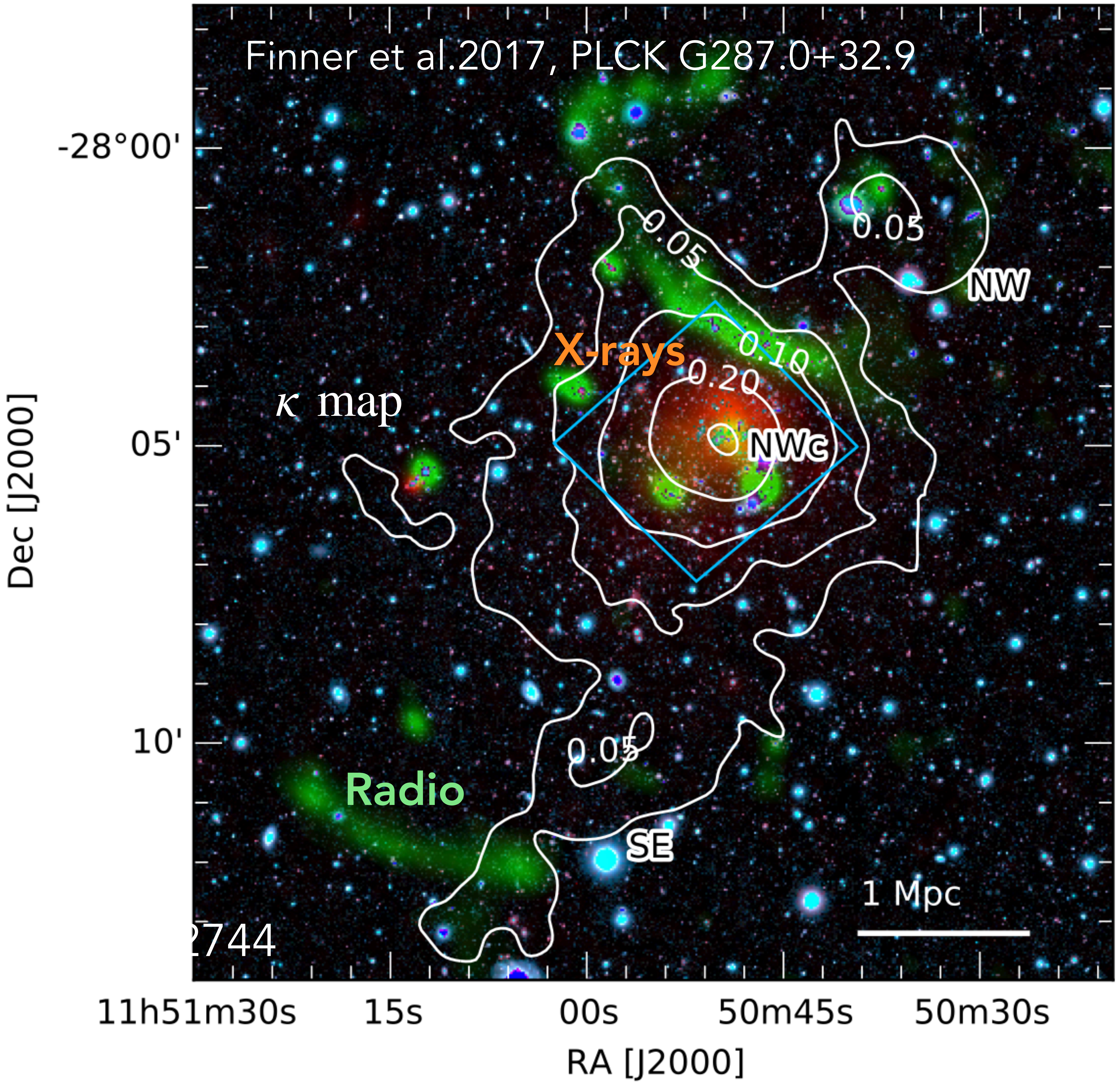
Lensing shear field around real clusters

Halos are not spherical (at all)

- Complex merging history, non-spherical initial over-densities, connected to neighbouring halos, etc.
- Multi-wavelength probes of the non-sphericity
- Simulations: Triaxial spheroids, halos are found to be prolate shaped (Schneider et al, 2012)



$$b \sim c < a$$



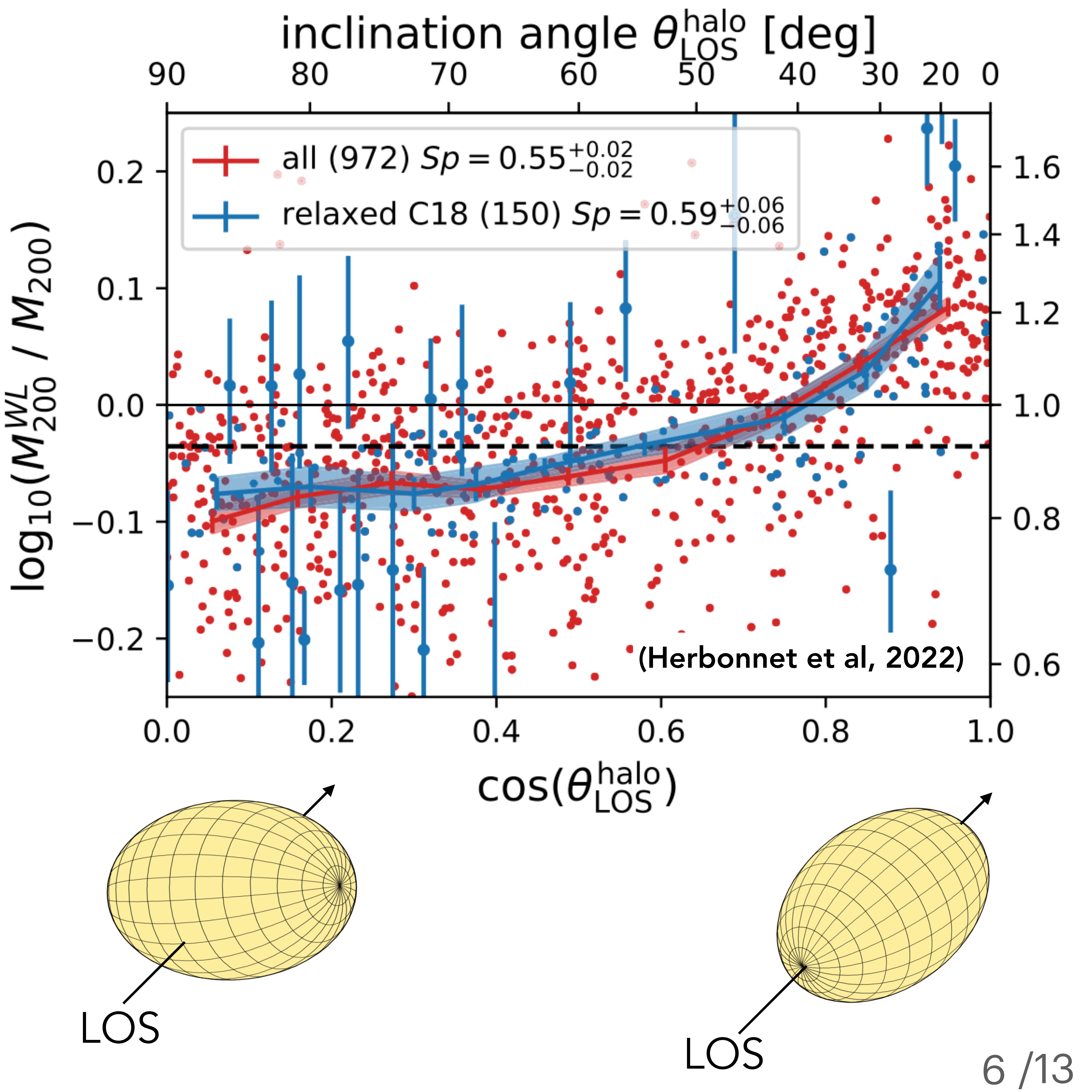
Standard WL mass reconstruction

Spherical halo modeling

- Assuming halos to be spherical may induce a bias
- Trend between WL mass and dark matter halo orientation = strong effect of projection
- Triaxiality contributes to the scatter in WL mass

Concerns for cosmology

- Stat. power of future large surveys can be not fully exploited if the mass calibration is not accurate
- Issue for optically selected clusters (selection bias, Wu et al, 2022)



Shear multipoles

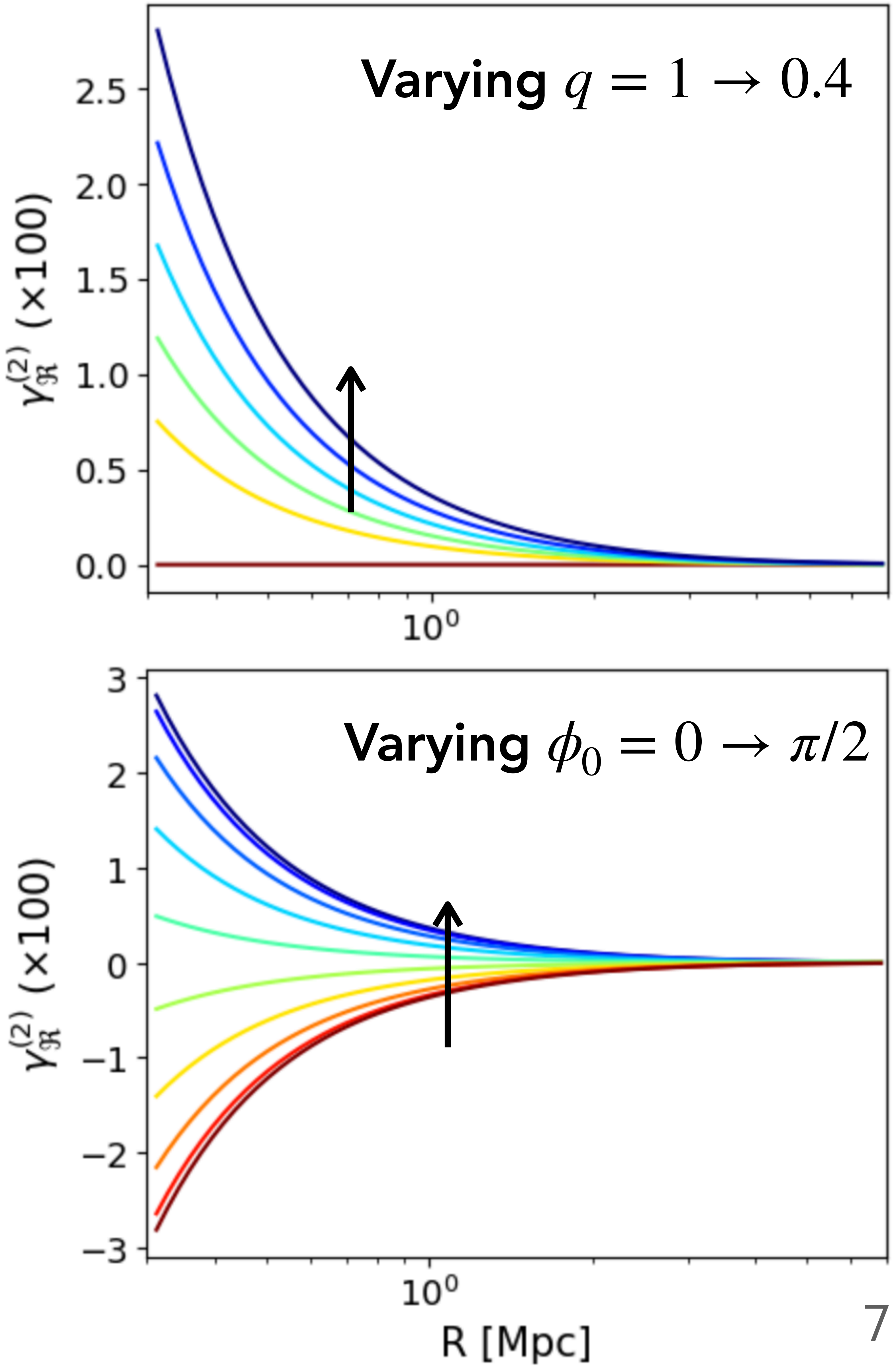
Beyond sphericity

$$\kappa = \kappa_{\rm sph}\left(R\sqrt{\frac{\cos^2(\phi-\phi_0)}{q^2} + q^2\sin^2(\phi-\phi_0)}\right) \quad \begin{array}{l} \to \kappa^{(m\neq 0)}(R) \neq 0 \\ \to \gamma^{(m\neq 0)}(R) \neq 0 \end{array}$$

- Shear multipole moments sensitive to halo shape (Adhikari, 2014)
- Use them to probe projected halo ellipticity + orientation
- Does it improve the lensing mass calibration ?

Shear multipole analyses

- Stacked analyses
    - Gonzalez et al. (2020), Shin et al. (2017), Van Uitert et al. (2017)
    - Stack on preferred axis (e.g. BCG, member galaxies)
    - Lower in amplitude, low SNR
- Individual clusters ?
- Feasible in the context of Rubin LSST/Euclid ?



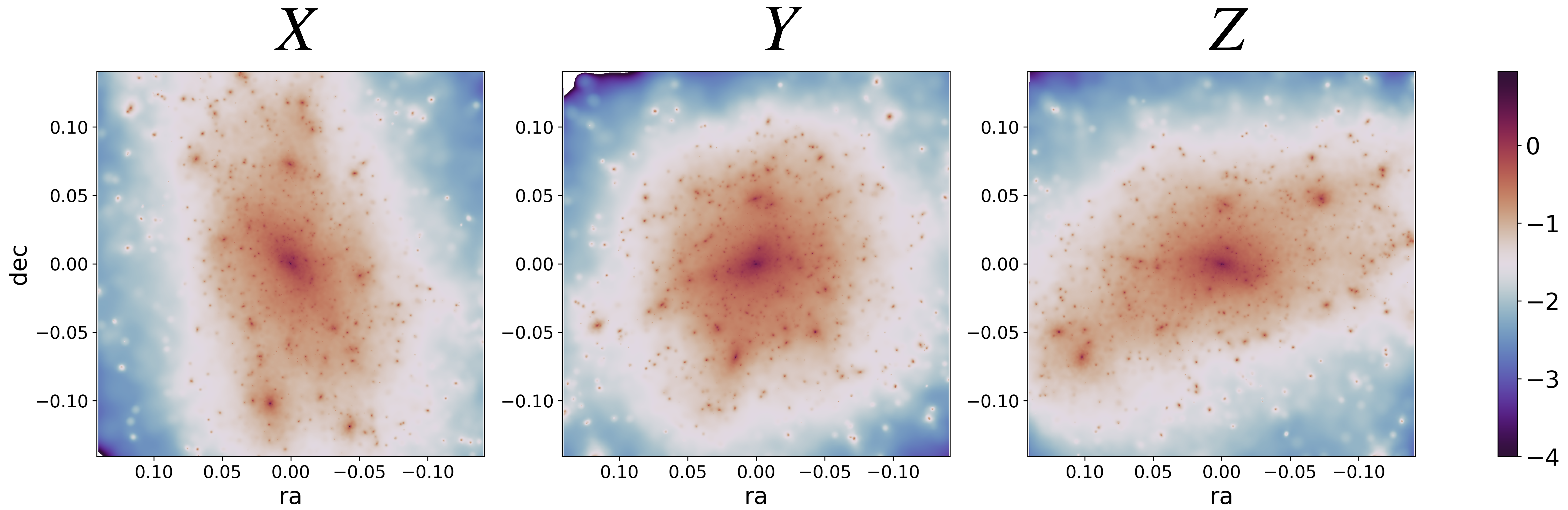
Lensing with the **The Three Hundred** Project

The Three Hundred (Cui et al., 2018)

- Study galaxy cluster formation history
- High resolution simulations of 300 halos $> 6.4 \times 10^{14} M_\odot$ (N-body + hydro.)
- Mock observations in X-rays, SZ, optical
- + Weak lensing maps (Meneghetti et al. 2023 (in prep), Giocoli et al. 2023, and Herbonnet et al. 2022)

"3D" view of matter distribution

- Derived for 3 orthogonal projections along the LOS



THE300:
MODELLING GALAXY CLUSTERS AND THEIR ENVIRONMENT

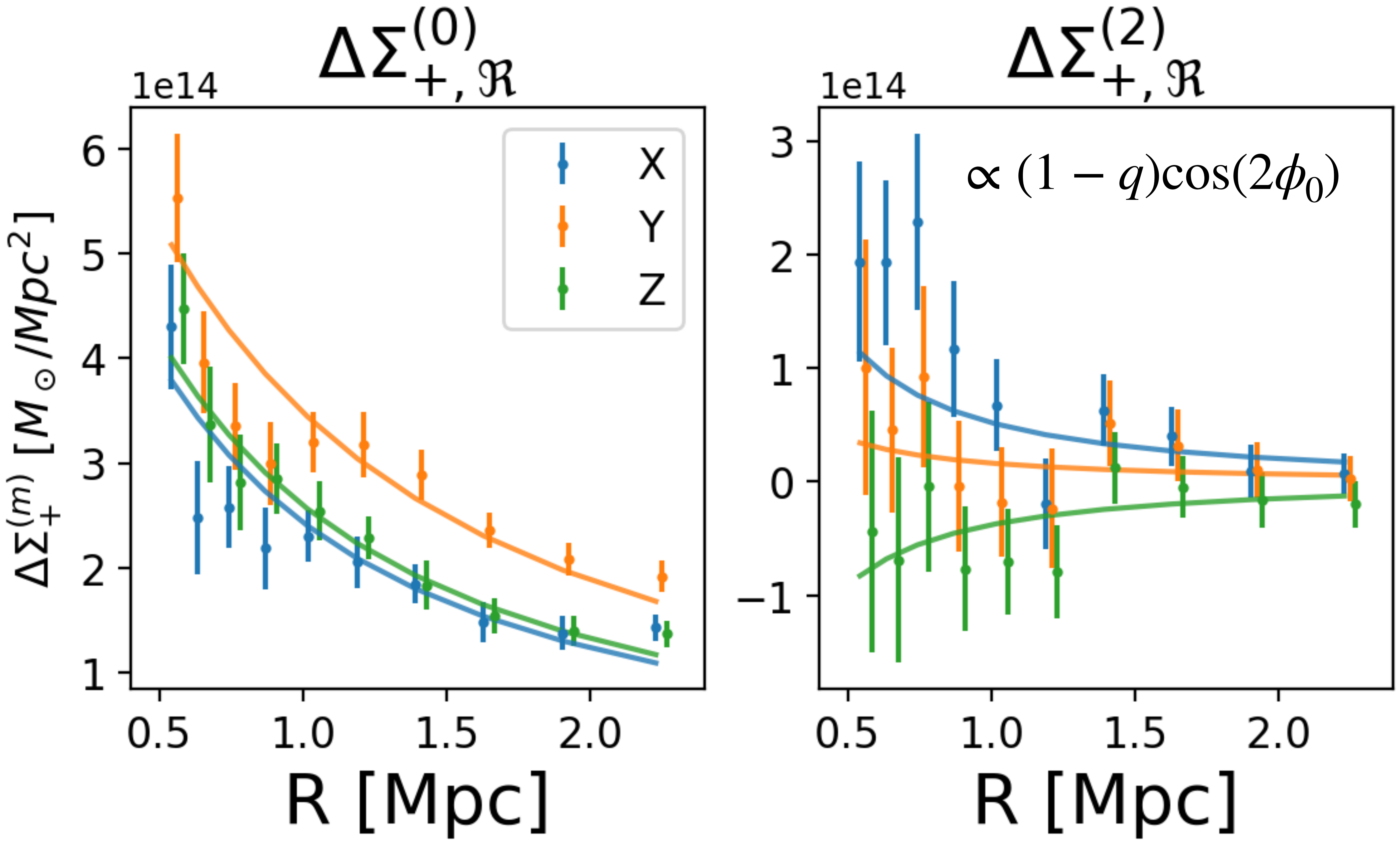
Methodology

Weak lensing analysis per LOS

- Estimate the shear multipoles for each LOS projection (LSST-like source catalog)
- Fit elliptical model to the lensing profiles

Test elliptical mass model

- Compare the recovered lensing masses between them
- Are the masses compatible ?
- Overlap of mass posteriors !



Single cluster analysis - elliptical modelling

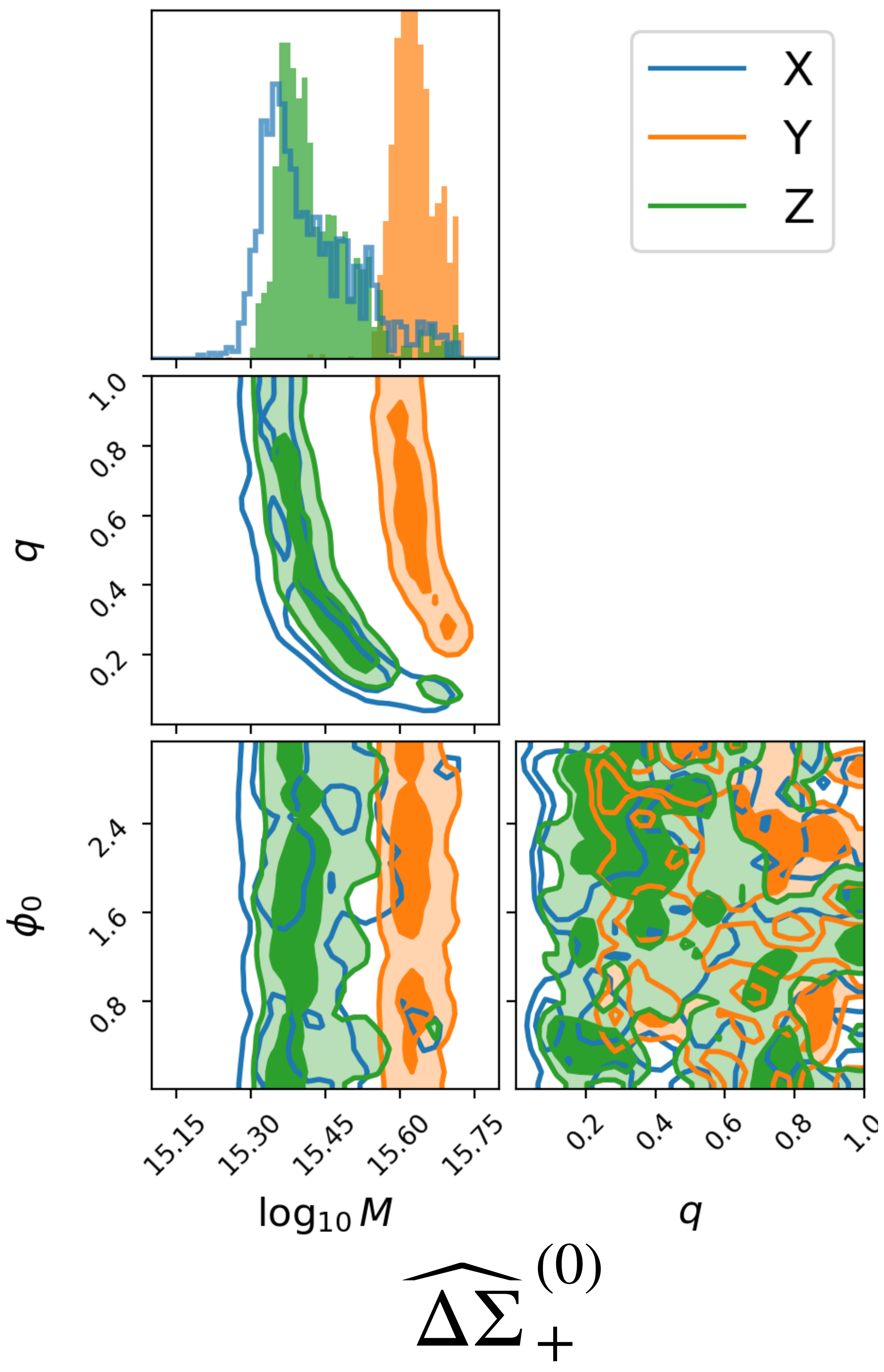
$$\kappa = \kappa_{\rm sph}\left(R\sqrt{\frac{\cos^2(\phi-\phi_0)}{q^2}+q^2\sin^2(\phi-\phi_0)}\right)$$

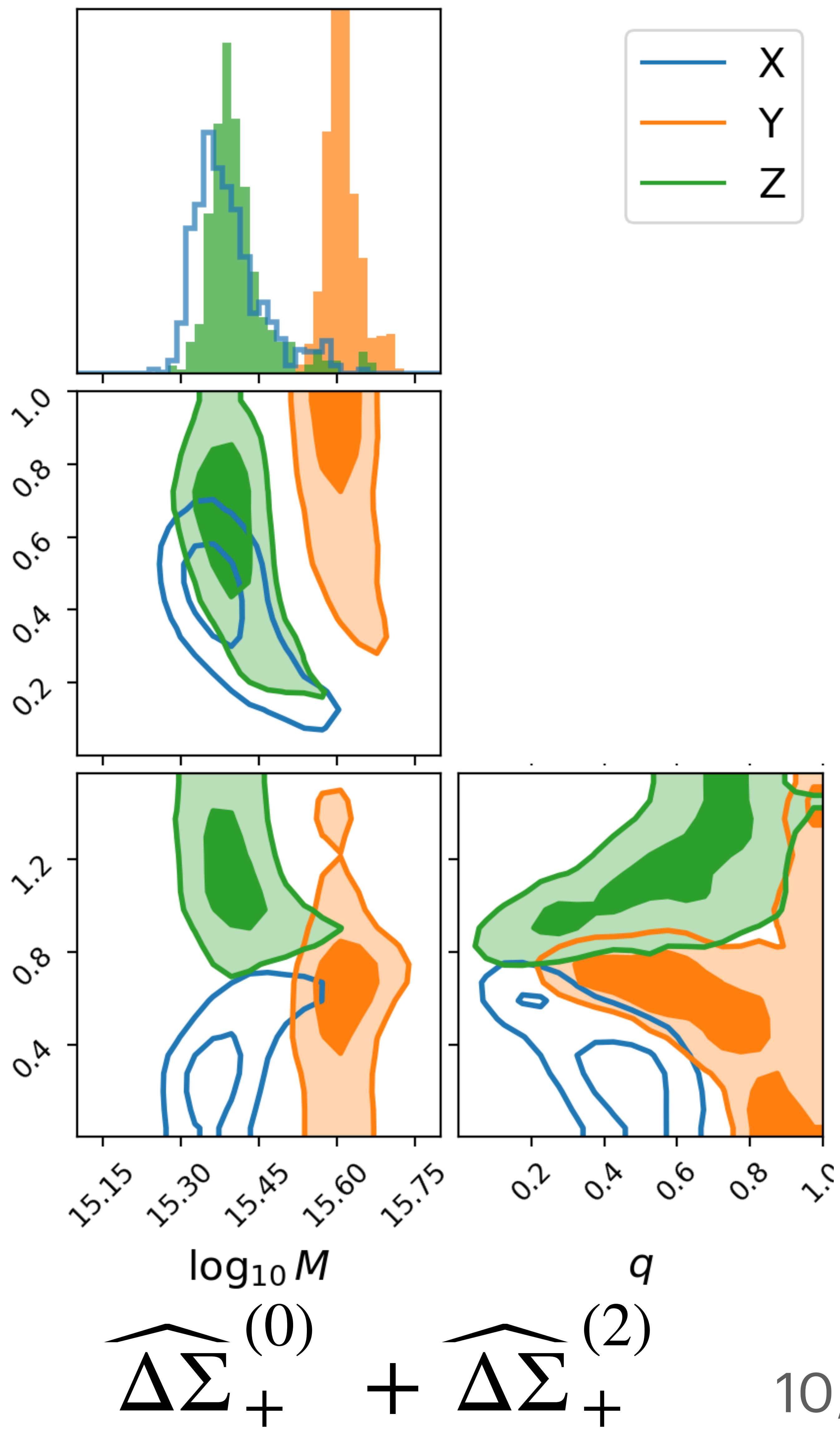
Using only monopole

- $\Delta\Sigma_+^{(0)}$ invariant under ϕ_0, thus difficult to fit axis ratio
- The Y projection gives higher mass

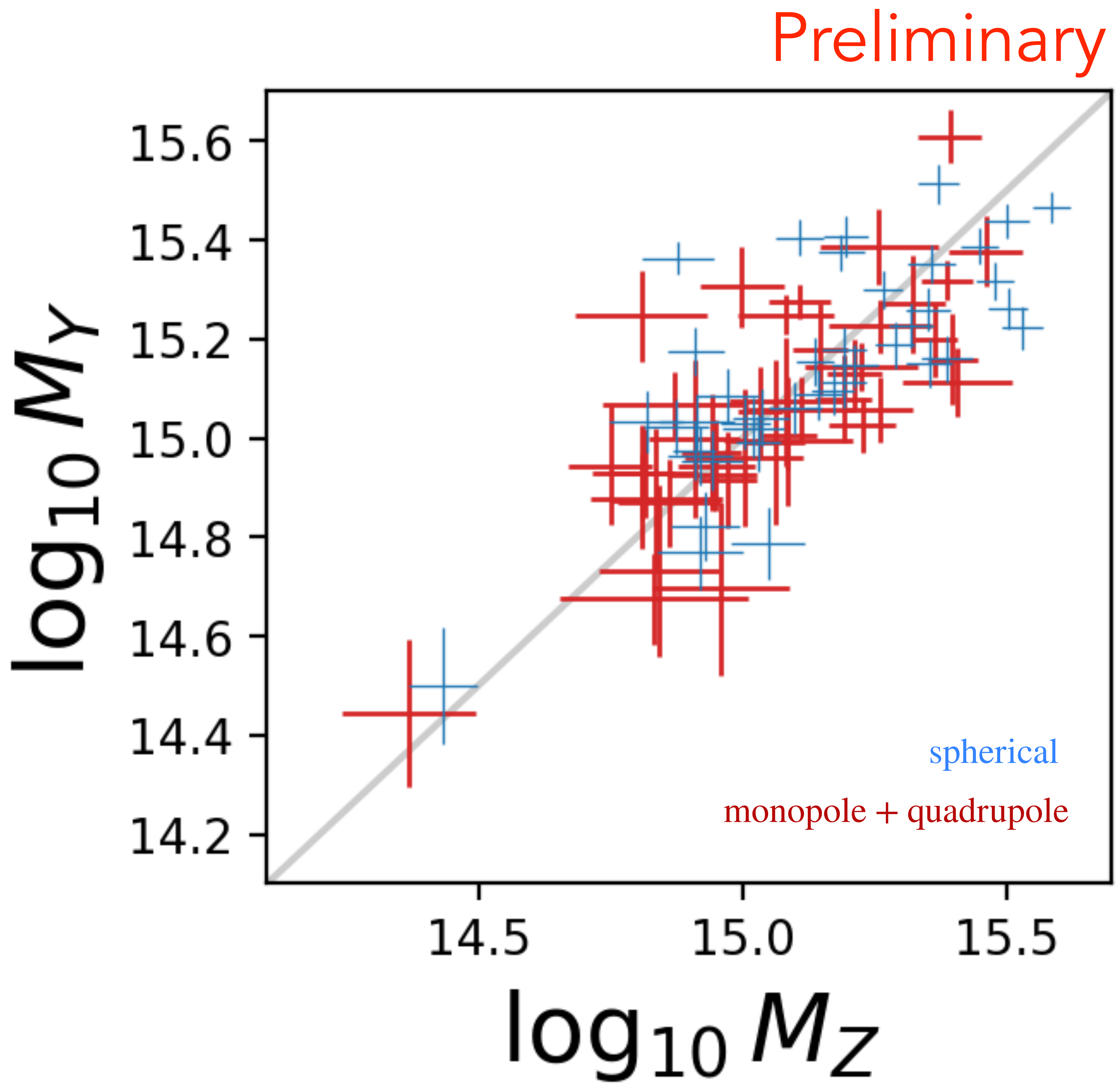
Using monopole + quadrupole

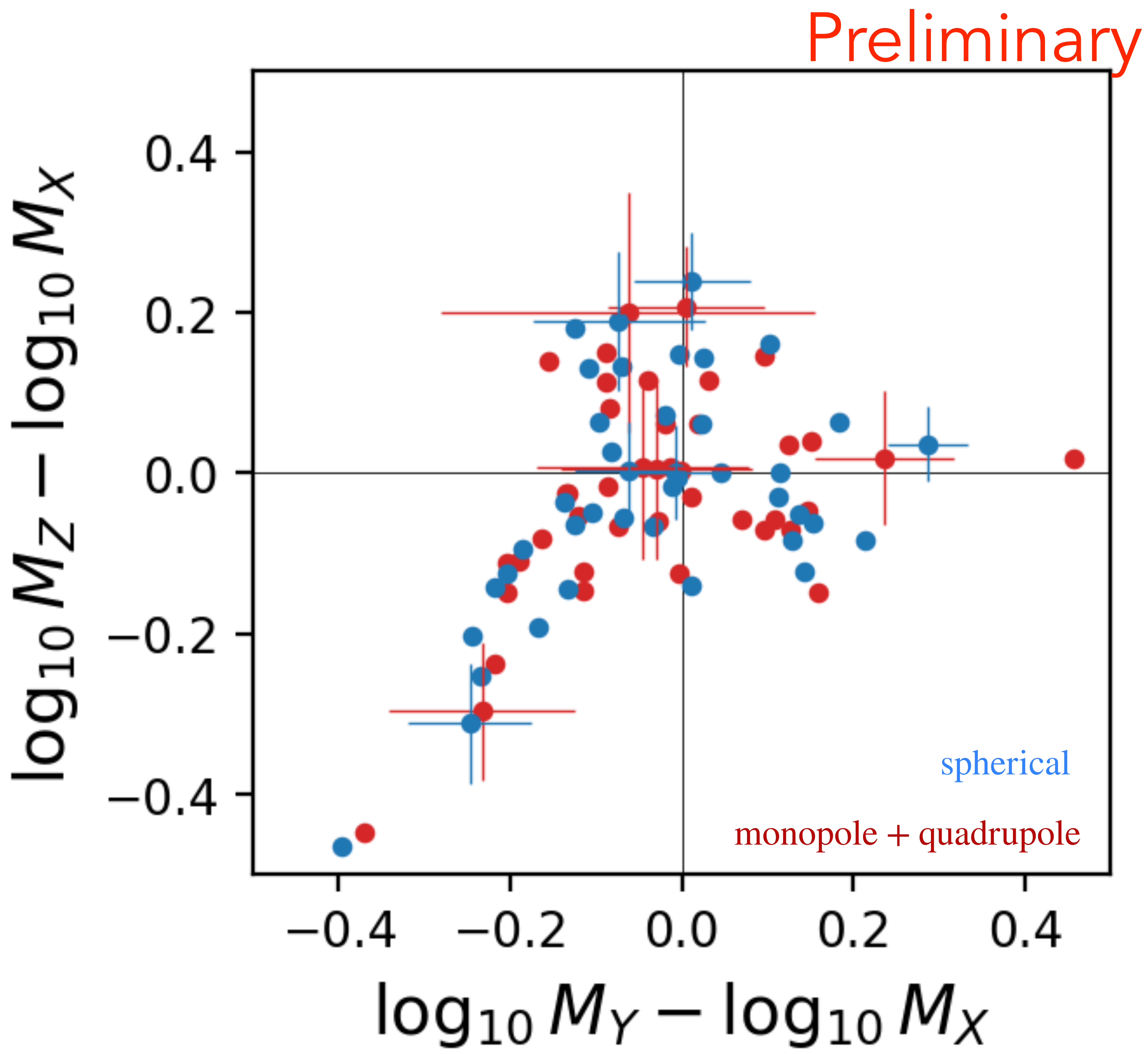
- Probes $\varepsilon\cos(2\phi_0)$
- $q \approx 1$:
  - Spherical along LOS, no large quadrupole
  - The analysis gives higher mass, which indicates the halo is elongated and aligned along the Y-axis





Impact on cluster mass (40 clusters)





Mass versus Mass

- Ideally, $M_X = M_Y$
- The "quadrupole" masses have larger error bars, more representative to the scatter
- They are compatible at 1-2 σ with *spherical* masses

ΔMass versus ΔMass

- Ideally, ΔMass ≈ 0
- Monopole + quadrupole = no significant improvement

Ellipticities

$$\varepsilon_{\mathrm{proj}} = \frac{1-q}{1+q}$$

- Fitting monopole and quadrupole
- Per projection

$$\langle \varepsilon_{\mathrm{proj,X}} \rangle \approx 0.24 \pm 0.08$$

$$\langle \varepsilon_{\mathrm{proj,Y}} \rangle \approx 0.25 \pm 0.10$$

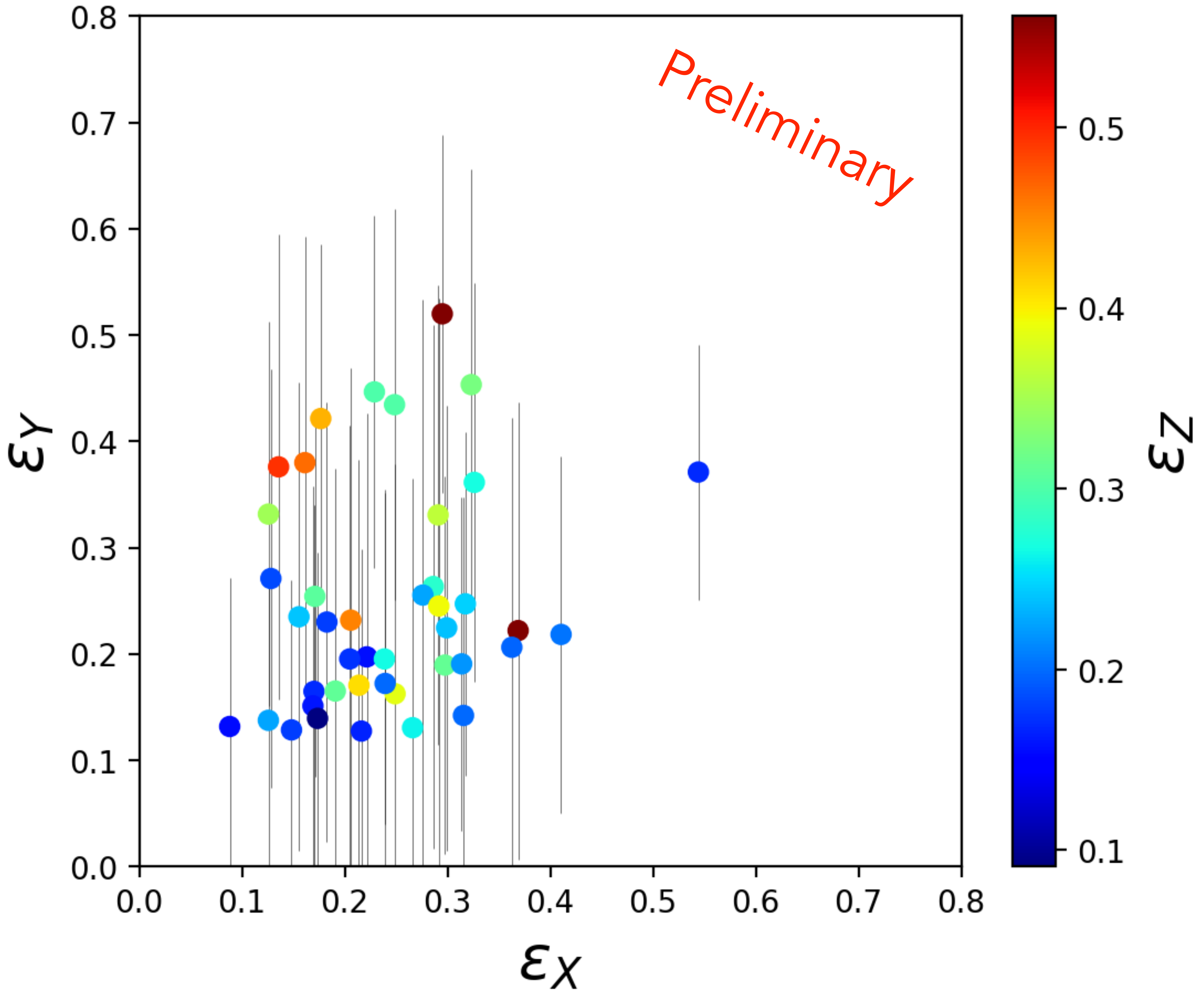
$$\langle \varepsilon_{\mathrm{proj,Z}} \rangle \approx 0.28 \pm 0.11$$

- Compatible with previous stacked estimates

(Shin et al., 2017) $\langle \varepsilon_{\mathrm{proj}} \rangle = 0.21 \pm 0.04$

(Gonzalez et al., 2020) $\langle \varepsilon_{\mathrm{proj}} \rangle = 0.27 \pm 0.03$

- Need to check how ellipticity and mass correlate with simulation quantities



Conclusions

- **Weak lensing study of galaxy clusters**
    - Crucial for precise cosmological constraints
    - The lensing can be used to probe cluster mass density
    - Multipoles are used to trace the halo ellipticity + orientation

- **Methodology**
    - Lensing analyses of the same cluster for several LOS projections
    - Direct test of projection effects

- **The Three Hundred**
    - Multipoles do not correct mass compared to *standard* spherical approach
    - But increases error bars (need to apply to the full The300 sample)
    - Ongoing:
        - Plan to use higher order multipoles
        - Combining tangential and cross shear (pipeline still under construction)
    - Measuring non-zero multipole moment on individual clusters can be a rapid test for sphericity
    - We find average $\langle \varepsilon_{\rm proj} \rangle$ compatible with other shear multipole studies

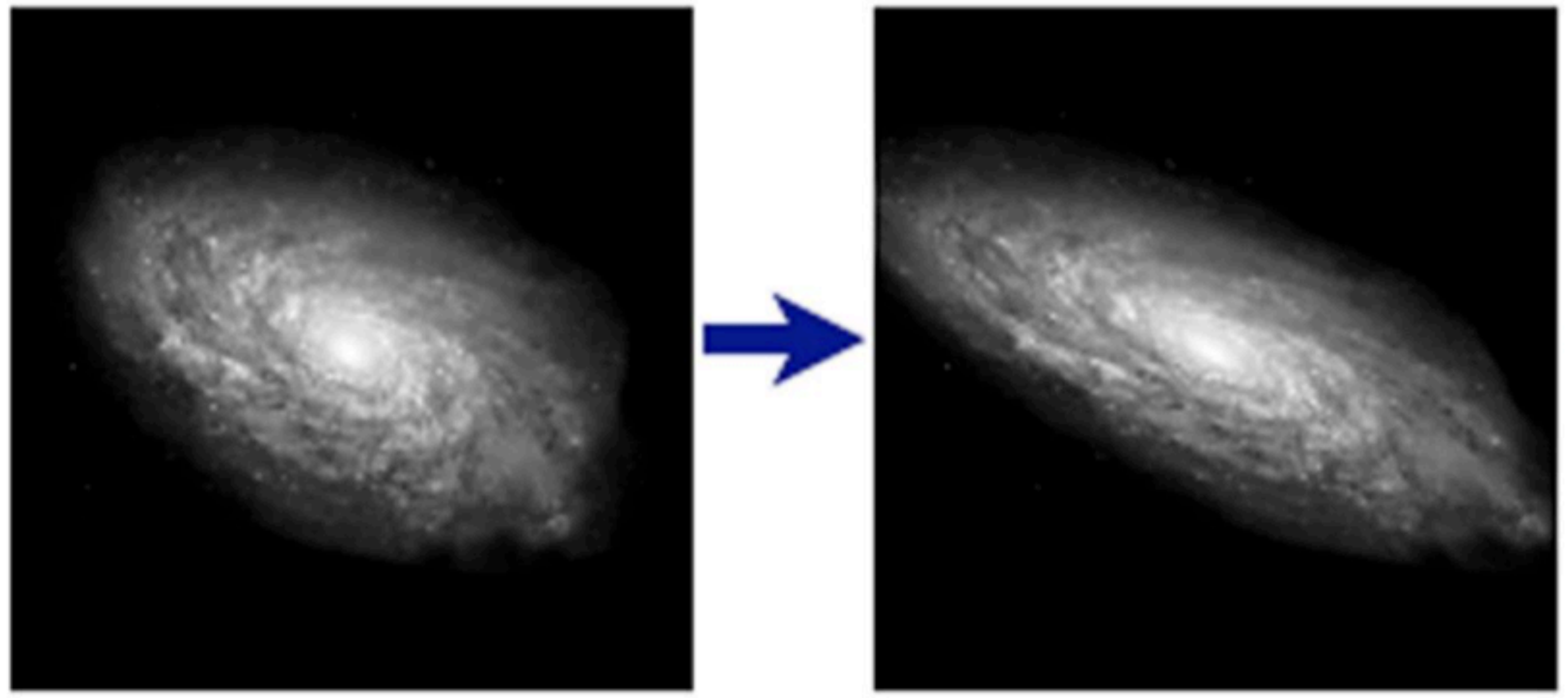
Realistic background galaxy sample

Unlensed source sample

- We created source galaxy mocks
- Shape noise/per component $\sigma_{\epsilon_{1,2}} = 0.25$
- Un-lensed source sample $n(z)$ Chang et al. (2013)
- $n_{\rm gal} = 30\ \mathrm{gal\,.\,arcmin}^{-2}$ (LSST-like density)
- Following the methodology in Herbonnet et al. (2022)

Lensed source sample

- Create $\kappa(z_{\rm src})$ and $\gamma(z_{\rm src})$ maps for each source redshifts (redshift rescaling of theThe300 lensing maps)
- Galaxies are individually sheared from the map interpolation
- We do not account for the "shift" of galaxies on the sky plane (magnification)



Intrinsic galaxy (shape unknown)

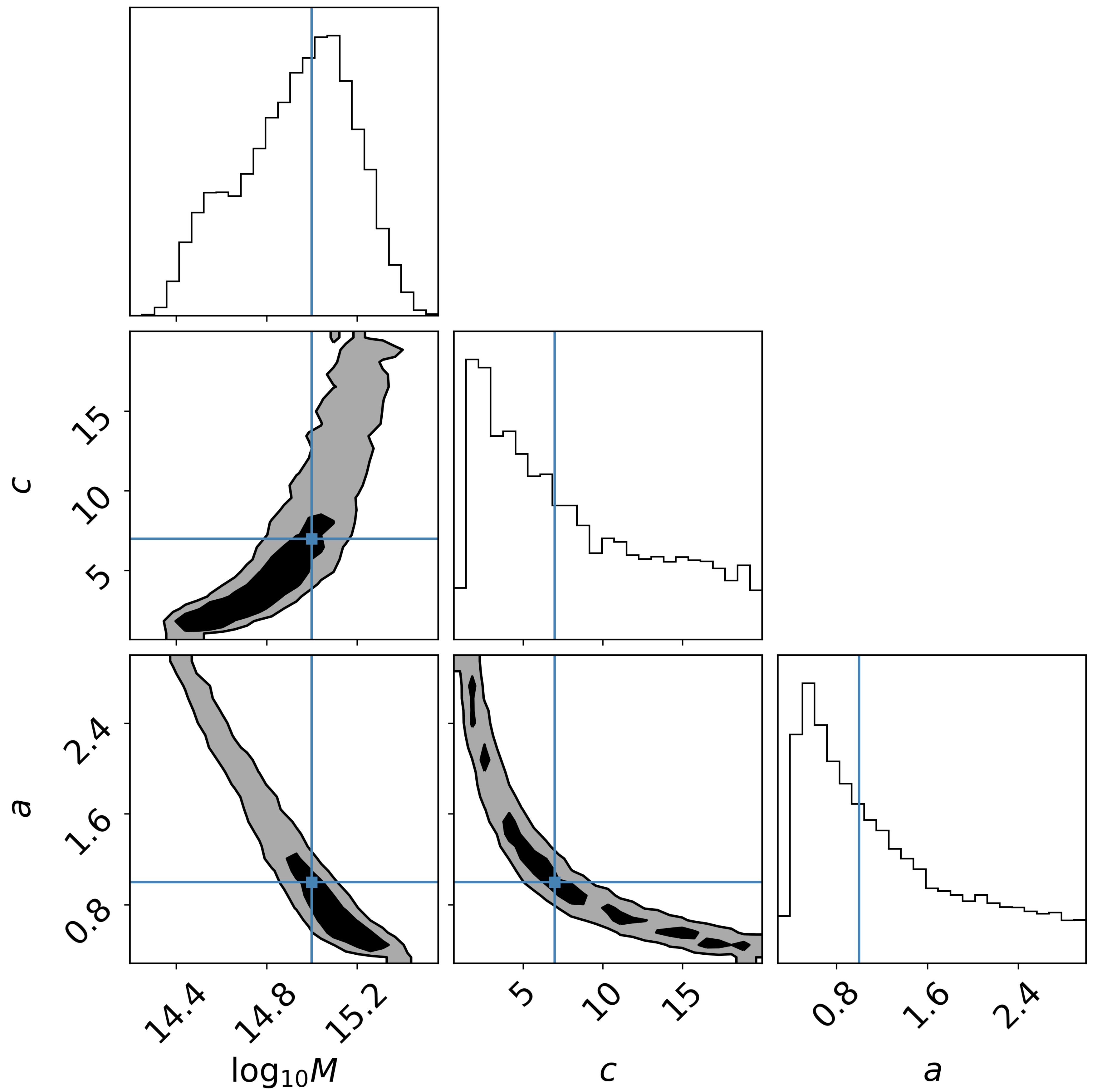
Gravitational lensing causes a ***shear (g)***

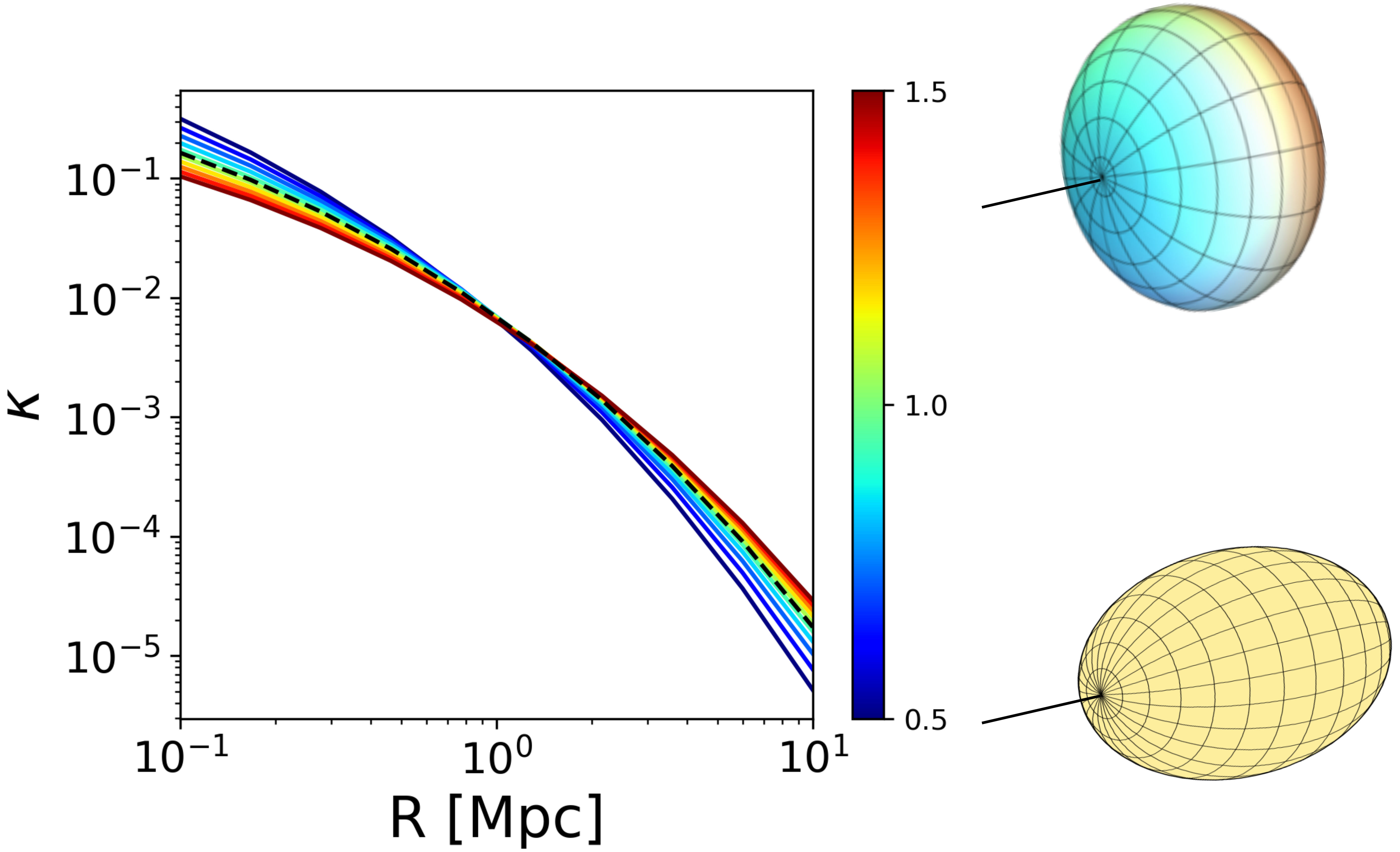
$$\epsilon^{\rm obs} = \frac{\boxed{\epsilon^{\rm int}} + \boxed{g}}{1 + g * \epsilon^{\rm int}}$$

$$g(z_{\rm src}) = \frac{\gamma(z_{\rm src})}{1 - \kappa(z_{\rm src})}$$

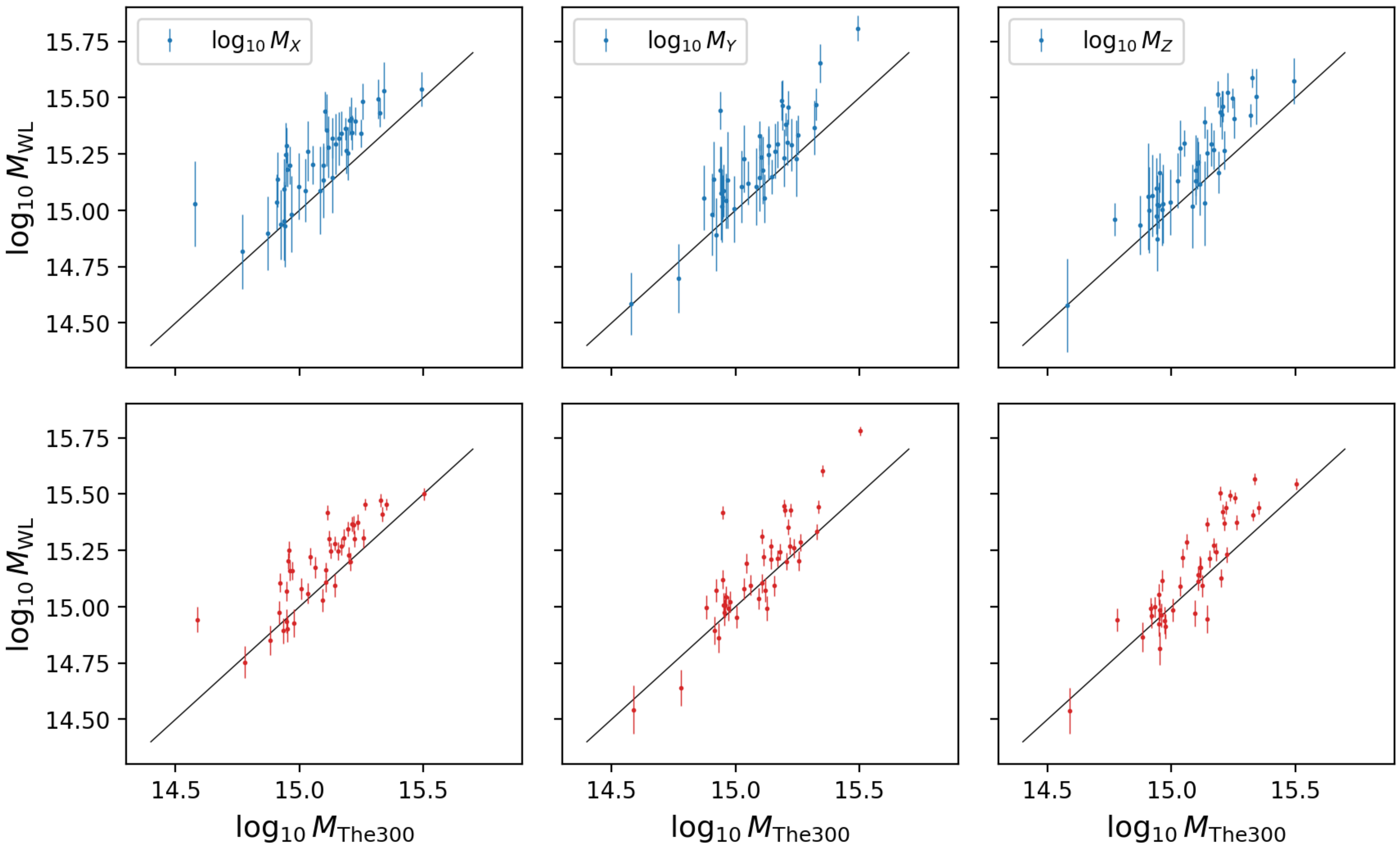
Correlation between mass and prolate index

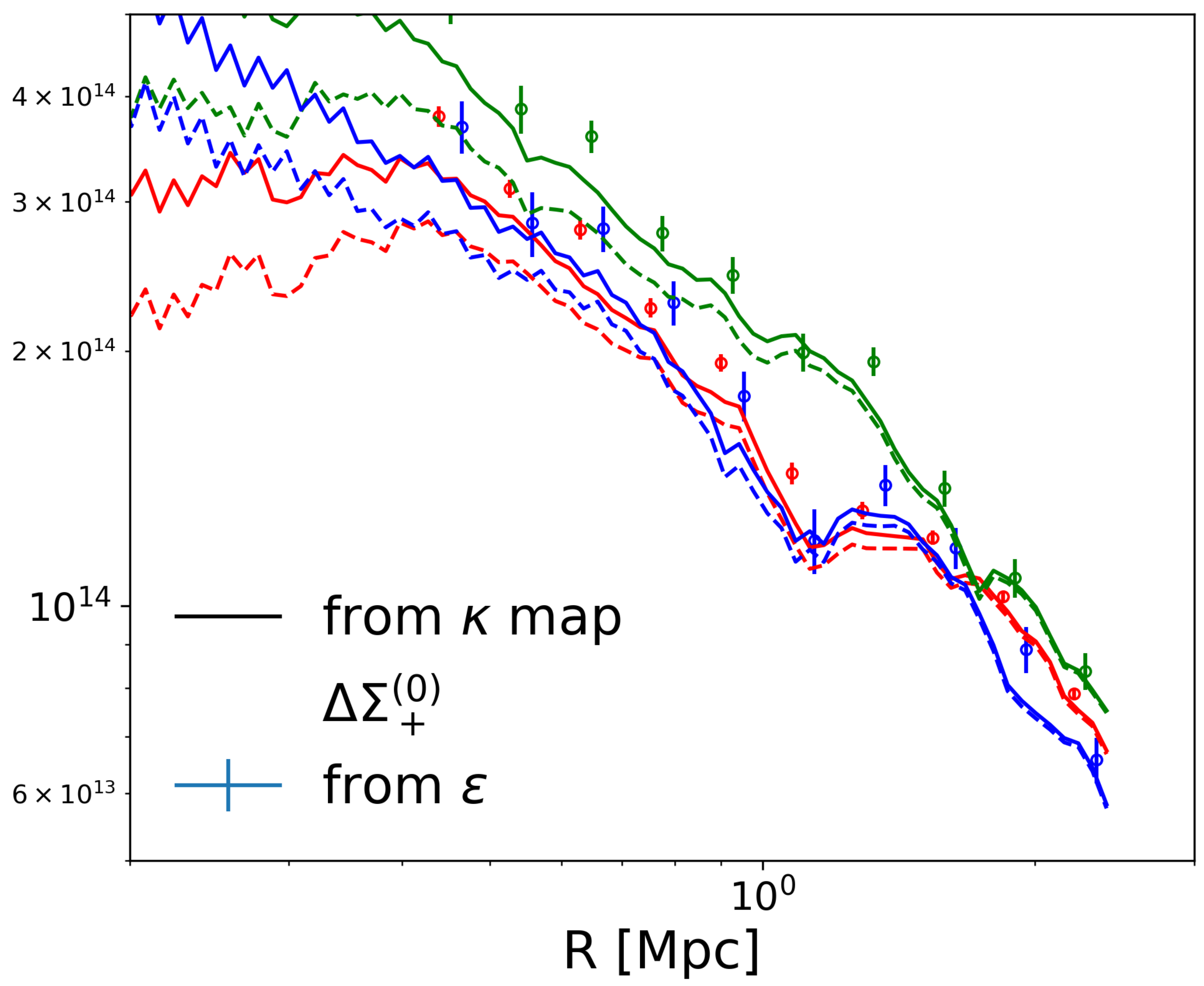
- We consider spherical halo
- Fit prolate/oblate modeling $\epsilon_{\rm proj}$
- Strong correlation between a and mass





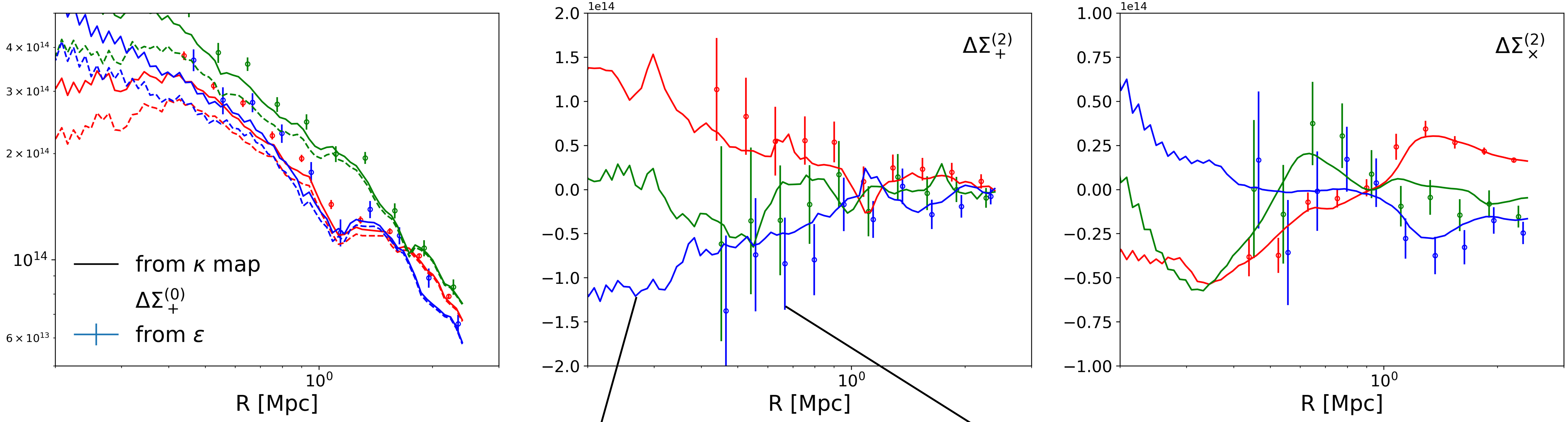
Comparison to The300 masses





- Persistent positive bias (weak lensing corrections, that may be important for massive clusters, not taken in account here)

Data vs maps



From sheared background sources

$$\gamma^{(m)}_{\mathrm{The300}} = \mathscr{F}(\kappa^{(m)}_{\mathrm{The300}})$$

From the lensing maps