Institute for Astro- and Particle Physics Extragalactic Astrophysics

Weak Gravitational Lensing by Galaxy Clusters

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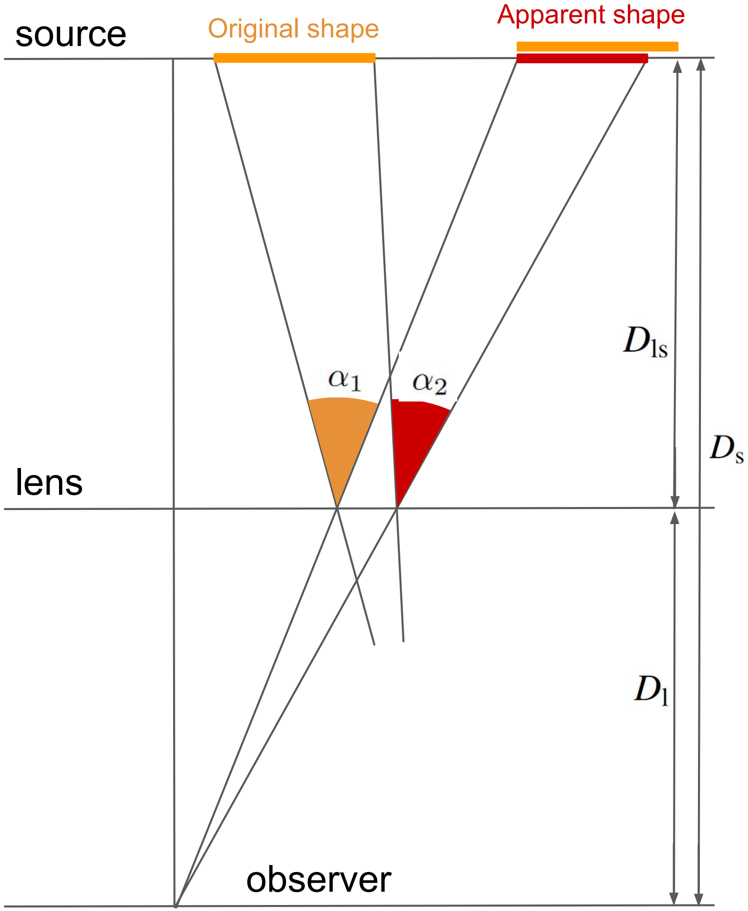
eROSITA-DE: WL work package, Cluster & Cosmology Group
DES Collaboration, KiDS Collaboration, HSC Collaboration

Weak lensing by massive halos

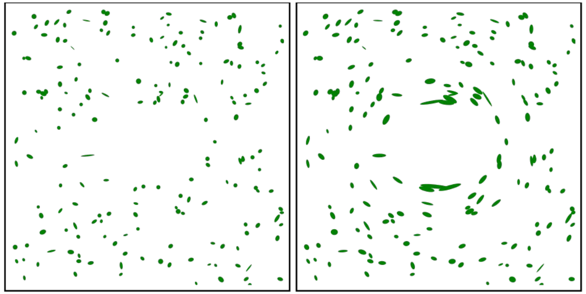


Gravitational potentials bend space time, and therefore *deflect light*, $\vec{\alpha} = -\vec{\nabla}\phi$

Differential deflection, $\alpha_2 < \alpha_1$, leads to a *tangential distortion* of background images

Background source are randomly oriented, hence averaging many such sources reveals the coherent tangential distortion

Source: Wikipedia



The strength of the distortion is modulated by the geometrical configuration

$$\Sigma^{-1}_{\rm crit,ls} = \frac{4\pi G}{c^2}\frac{D_{\rm l}}{D_{\rm s}}\max\left[0, D_{\rm ls}\right]$$

<u>Lenses</u>: massive halos with redshift → eRASS:1 clusters&groups

<u>Sources</u>: galaxies from Dark Energy Survey (DES) with shape and photo-z measurement (also from HSC, KiDS)

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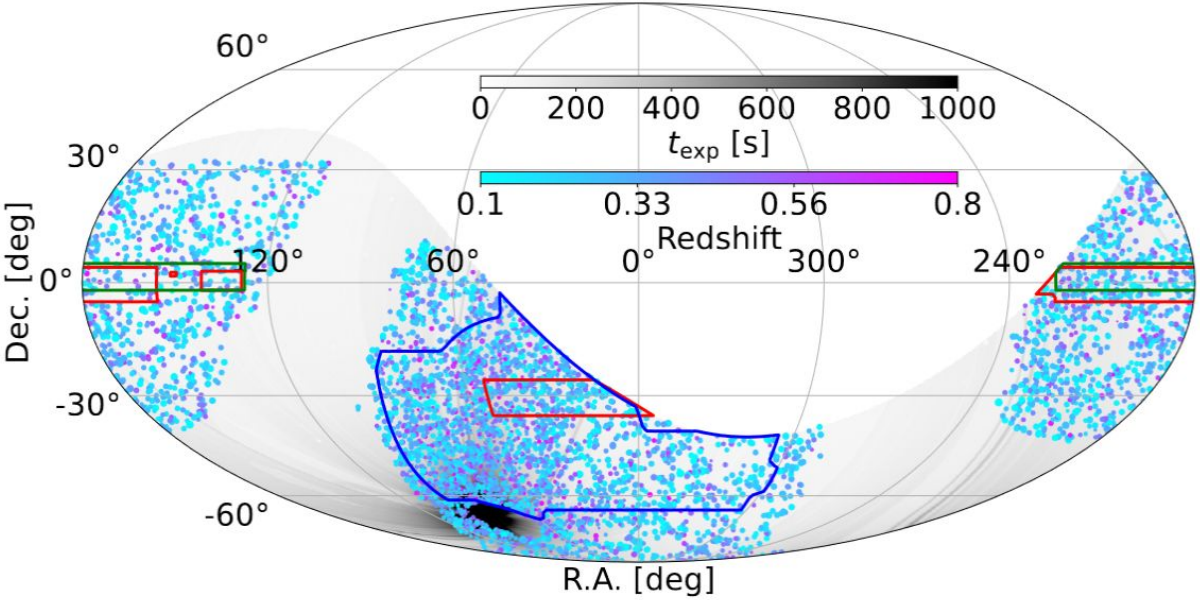
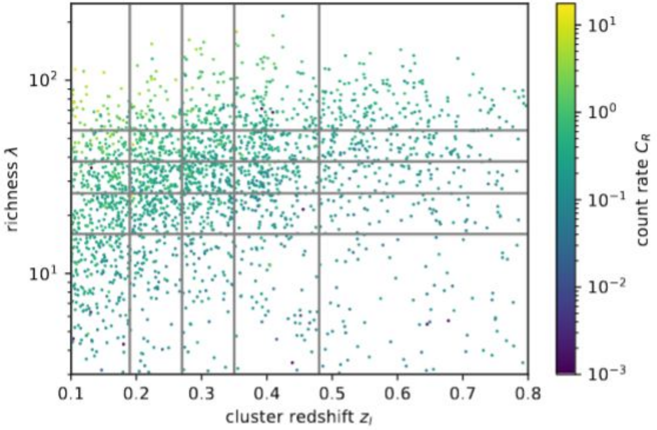
Lens sample: eRASS1 clusters



First eROSITA All Sky Survey (eRASS1)

Selection of clusters & groups as extended X-ray sources (Bulbul+24)

Targeted redmapper in DECaLs DR 10 data for redshifts and confirmation (Kluge+24)



Overlap with all 3 stage III WL surveys DES Y3, KiDS, HSC S19A

2201 clusters in DES Y3, with z_med ~ 0.3
(ideal for WL with higher z DES tomo bins)

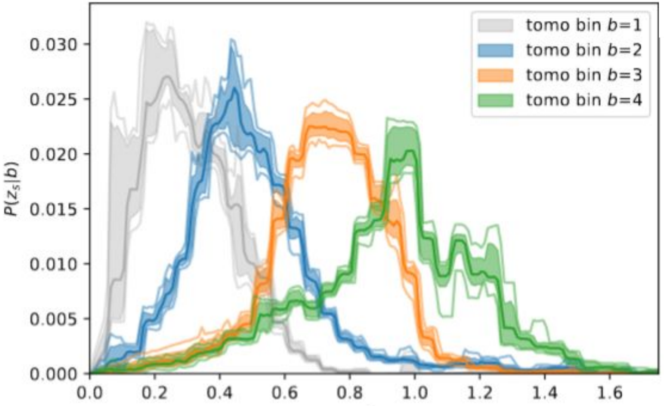
Source sample: DES Y3 shapes

For each lens, select background source by weighting the DES tomographic redshift bins

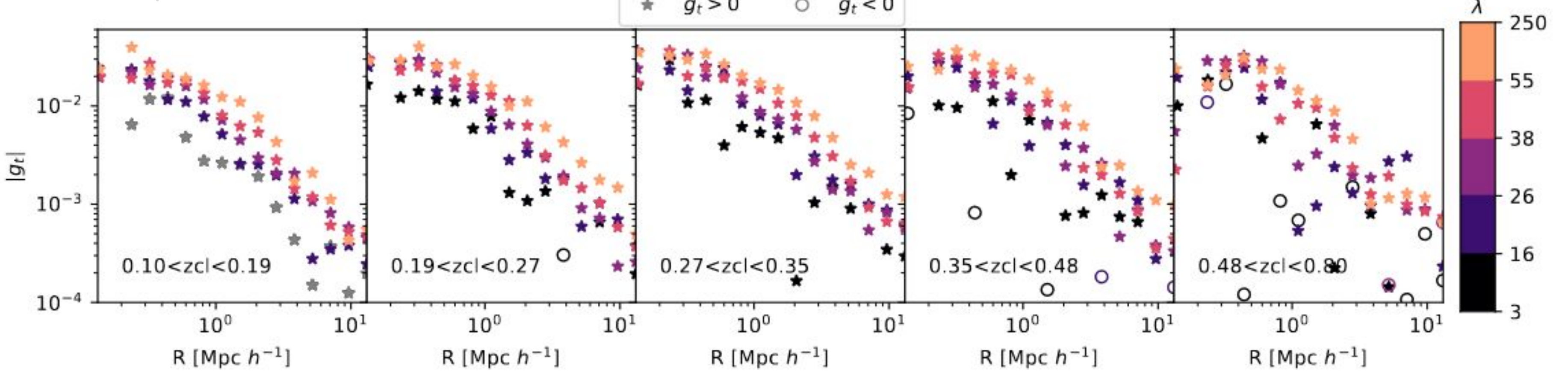
$$w_b = \begin{cases} \langle \Sigma_{\mathrm{crit,ls}}^{-1} \rangle_b & \text{for } z_l < z_{\mathrm{med},b} \\ 0. & \text{otherwise} \end{cases}$$

Estimate the tangential shear by binning the tangential ellipticities of the sources

Total S/N on 2.2k object = 92



Raw tangential shear in richness redshift bins



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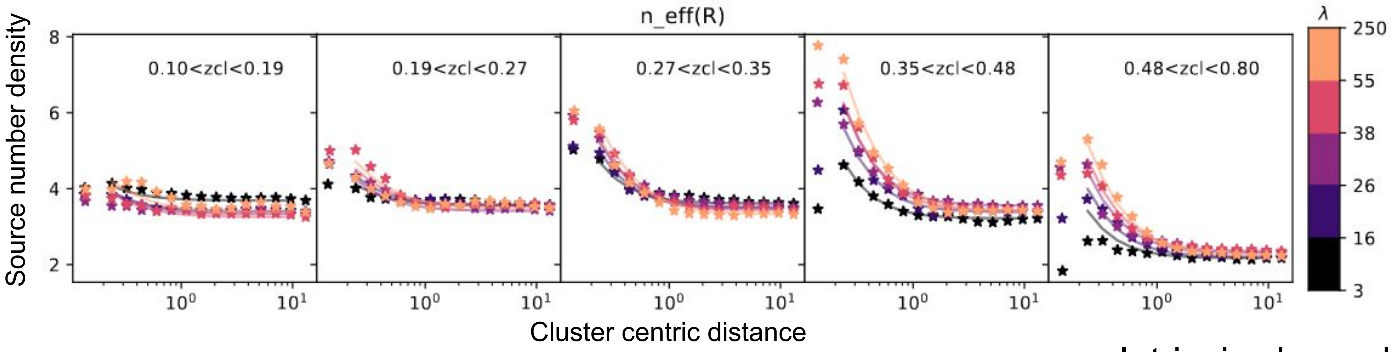
eROSITA

Stats and Sys for WL measurement

Some (unlensed) cluster galaxies leak into the background selection → fit for cluster member contamination

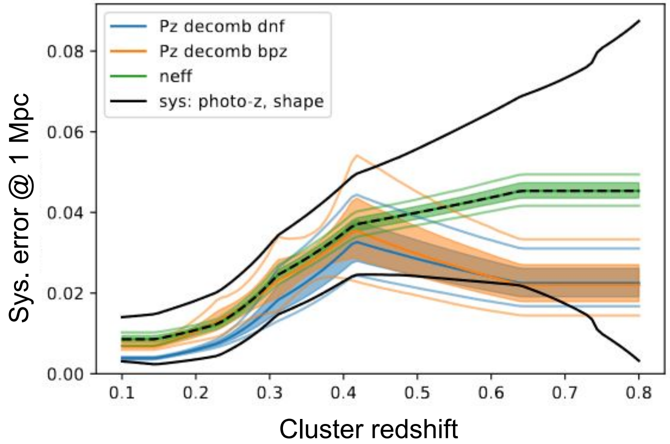


Increase in source number density density towards cluster center due to cluster member contamination

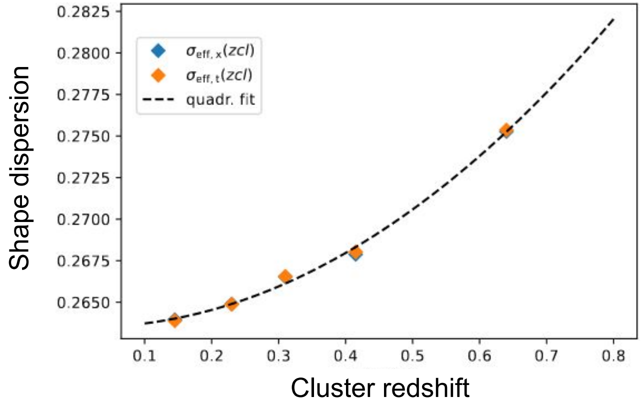
Stars: data
Solid lines: our fit to calibrate this effect

DES team has extensively calibrated photo-z and shape measurements (proprietary access thx to GEC)

<1 % sys. uncertainty for z<0.4

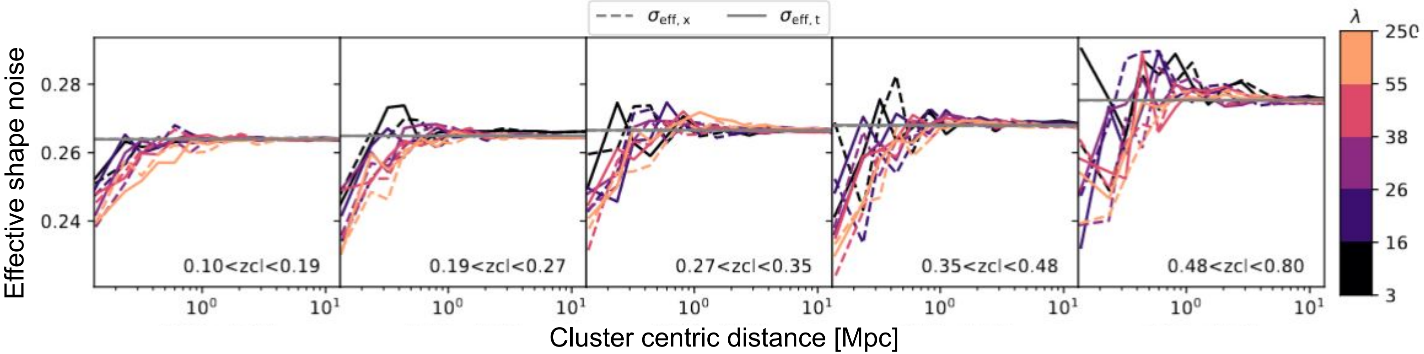


Intrinsic shape dispersion for each background selection → empirically estimate



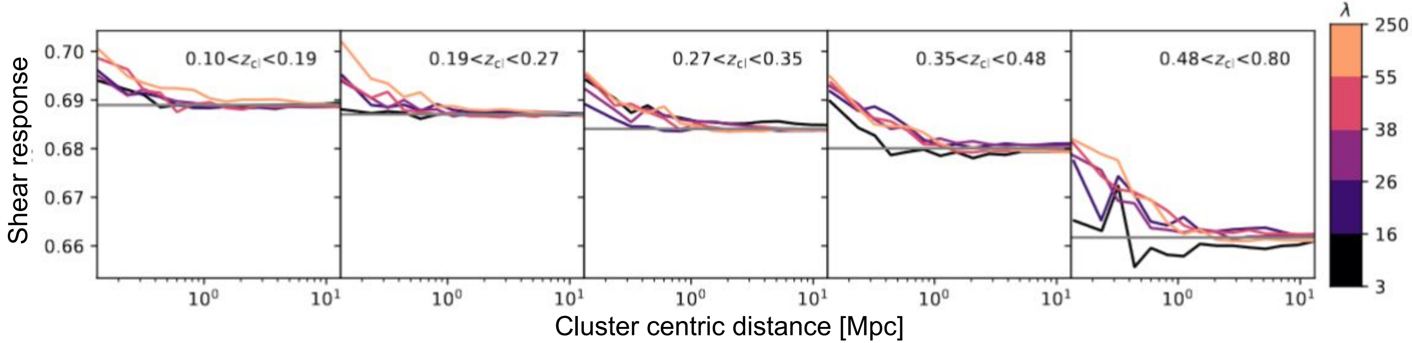
Cluster LoS anomalies detected!

Galaxy clusters are over-densities in the galaxy field, cluster members are brighter and redder than field



Reduced shape noise towards cluster center, with richness trend

Cluster members are preferentially elliptical galaxies → rounder



Increased response towards cluster center, also with richness trend

– cluster members are brighter and rounder → higher response

– field galaxies are magnified, and thus brighter → higher response

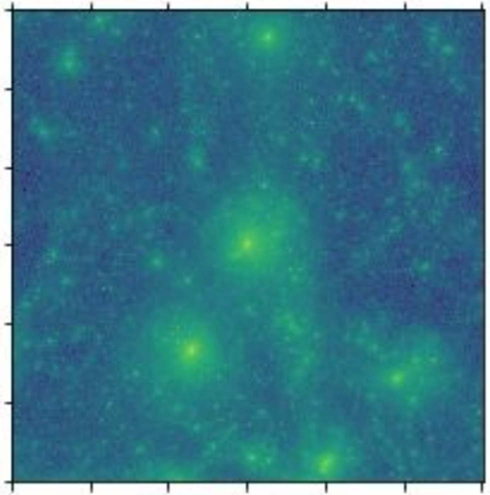
We exclude cluster centers Rmin>0.5 Mpc/h → sub percent effects

“Luckily” we understand baryon feedback impact on massive WL profiles “only” to 2 % (Grandis+21)

Calibrating halo mass → WL

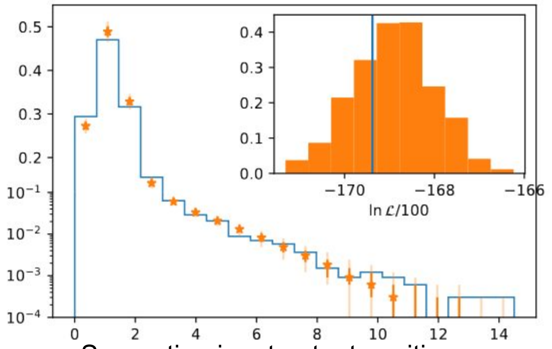
Synthetic shear profiles
– 2d surface mass densities from hydro sims
– source redshift and shape measurement uncertainties from WL surveys
– cluster member contaminations from WL tasks
– mis-centering from digital twin + hydro sims

⇒ halo catalogs with realistic shear profiles

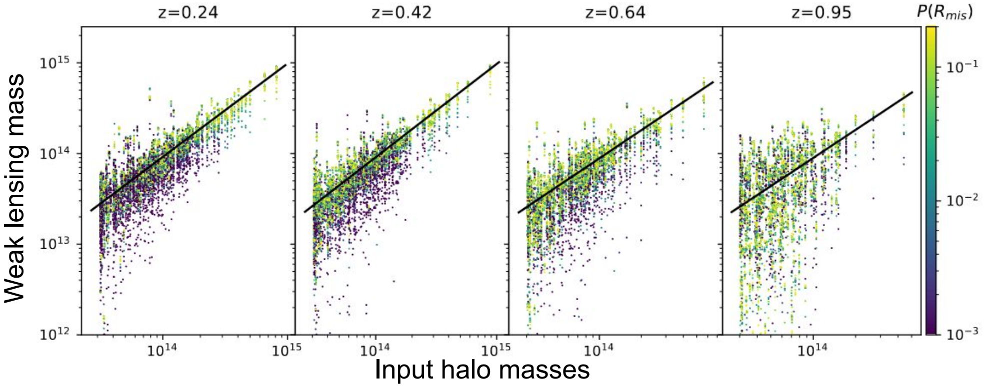


2d projected density map of a massive halo in the TNG300 simulation, box size 10 Mpc/h

Mis-centering in eROSITA digital twin



Shear profile model for cosmology pipeline
– analyse the synthetic shear profiles with same model as used in cosmology pipeline



⇒ output mass (called *WL mass*) for each simulated halo

⇒ difference and scatter to halo mass captured in WL bias and scatter

$$\left\langle \log \frac{M_{\rm WL}}{M_0} \right\rangle = b(z) + b_M \log\left(\frac{M}{M_0}\right)$$

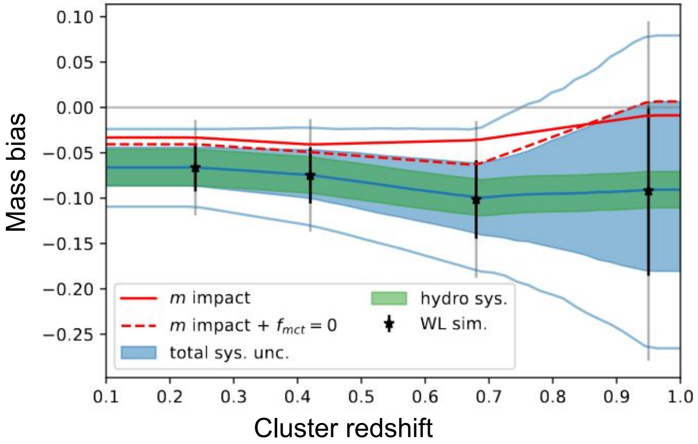
$$\log \sigma^2_{\rm WL} = s(z) + s_M \log\left(\frac{M}{M_0}\right)$$

Mass calibration

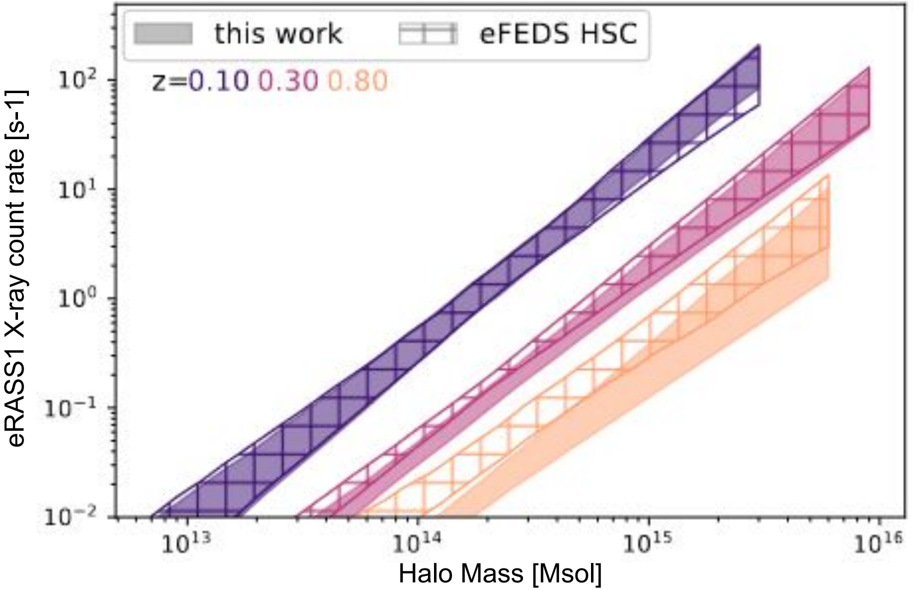
Determining Systematics

(known) Systematic uncertainty = uncertainty on bWL

– draw ~1000 synthetic cluster catalogs with WL shear, measure their WL masses, fit the WL bias and scatter
While varying all the input parameters like:
– photo-z and shape measurement uncertainty
– mis-centering distribution params
– cluster member contamination fits
– add 2% extra error due to hydro modelling

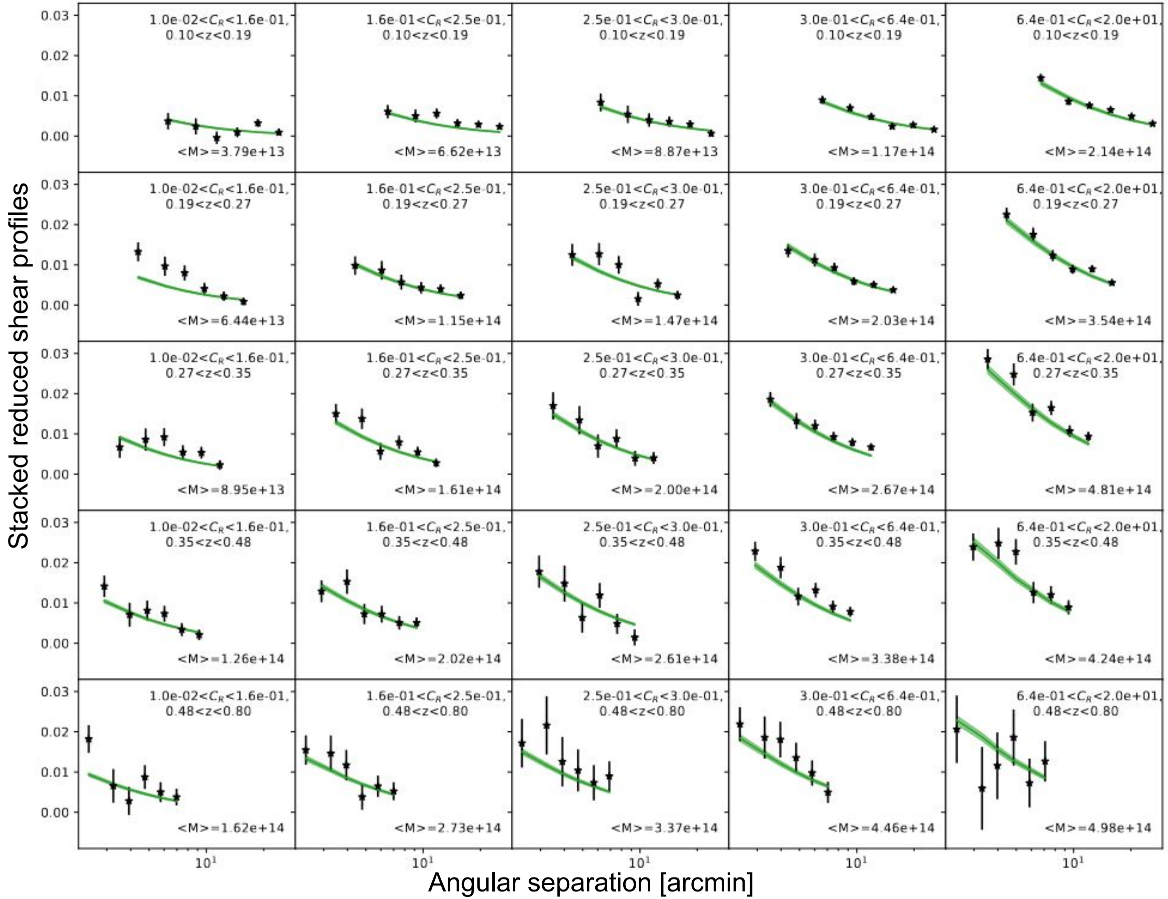


Done for DES, KiDS and HSC



Use part of the eROSITA cosmology pipeline (Ghirardini+24) to constrain the X-ray count rate relation to halo mass and redshift

Goodness of Fit



Mass calibration performed on individual cluster WL profiles (simplifies selection effects modelling)

Goodness of fit validation on stacks in X-ray count rate – redshift bins

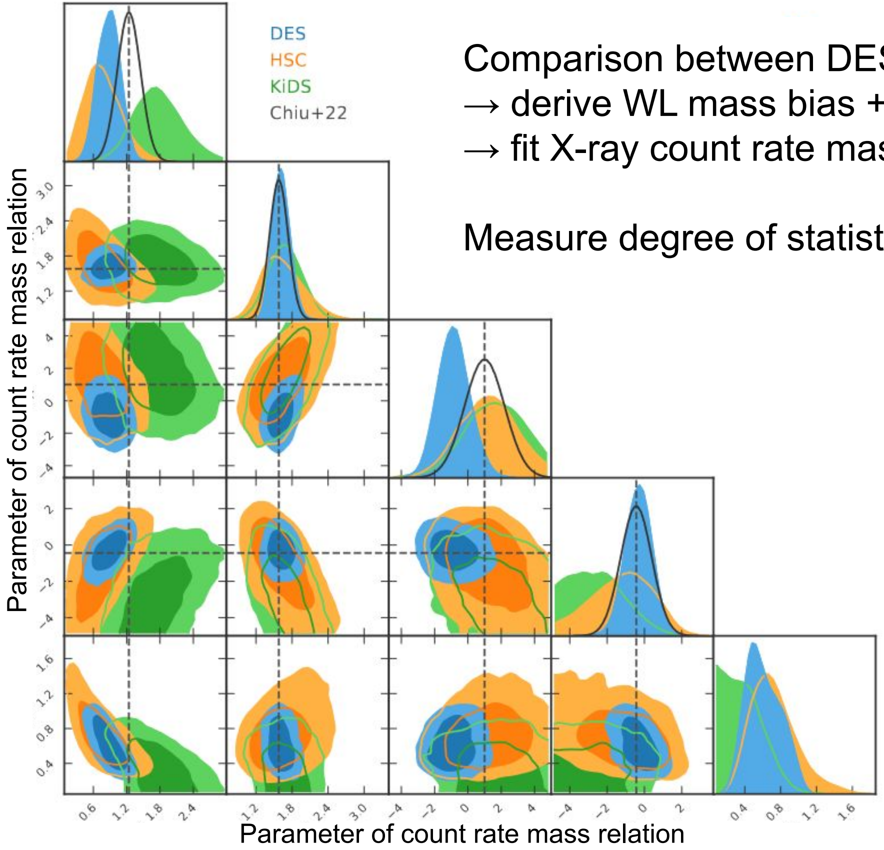
Total signal to noise after scale cuts: 62

Goodness of fit

$$\chi^2 = 180.0^{+45.8}_{-30.4} \text{ for 150 data points}$$

Cross survey comparison

How consistent is the WL signal we measure in the 3 stage III surveys? (Kleinebreil&SG+24)



Comparison between DES, KiDS & HSC at population level
→ derive WL mass bias + uncertainties for each survey
→ fit X-ray count rate mass relation for each survey

Using Raveri&Doux21 method

Measure degree of statistical agreement between posteriors (a.k.a tension)

HSC–KiDS 1.3 sigma
KiDS–DES 2.7 sigma
DES–HSC 0.23 sigma

Some potential tension between KiDS and DES WL

Goodness of fit of cosmological population model

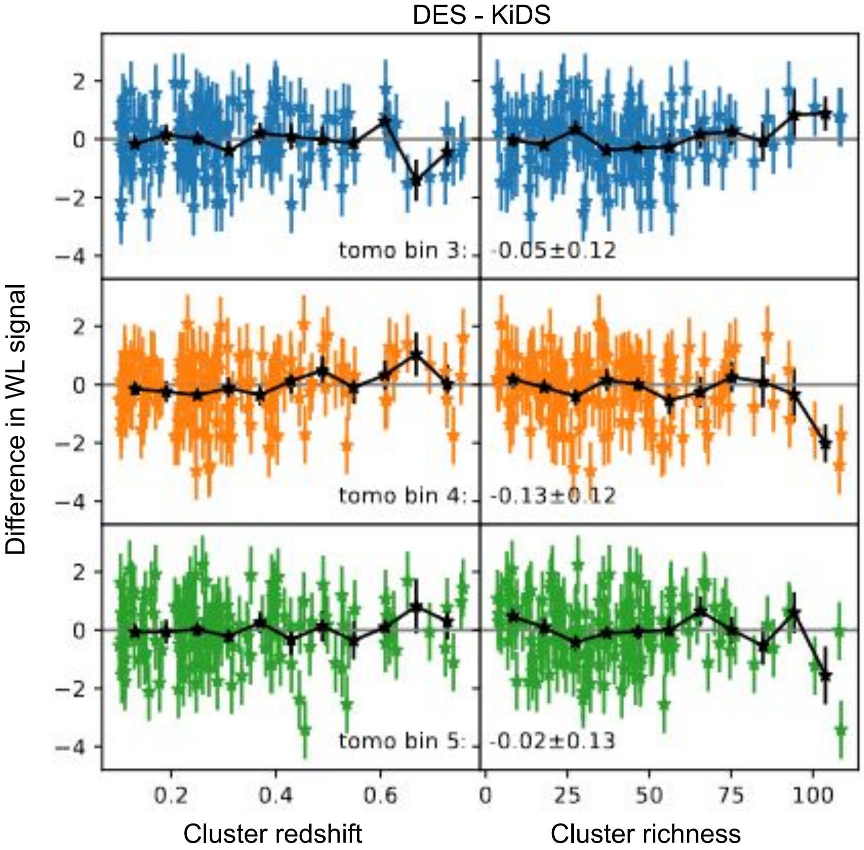
$$\chi^2_{\rm DES} = 173.2^{+43.2}_{-27.6}\ (150\ \text{d.o.f.})$$
$$\chi^2_{\rm HSC} = 140.0^{+3.2}_{-6.2}\ (70\ \text{d.o.f.})$$
$$\chi^2_{\rm KiDS} = 60.2^{+9.7}_{-5.6}\ (63\ \text{d.o.f})$$

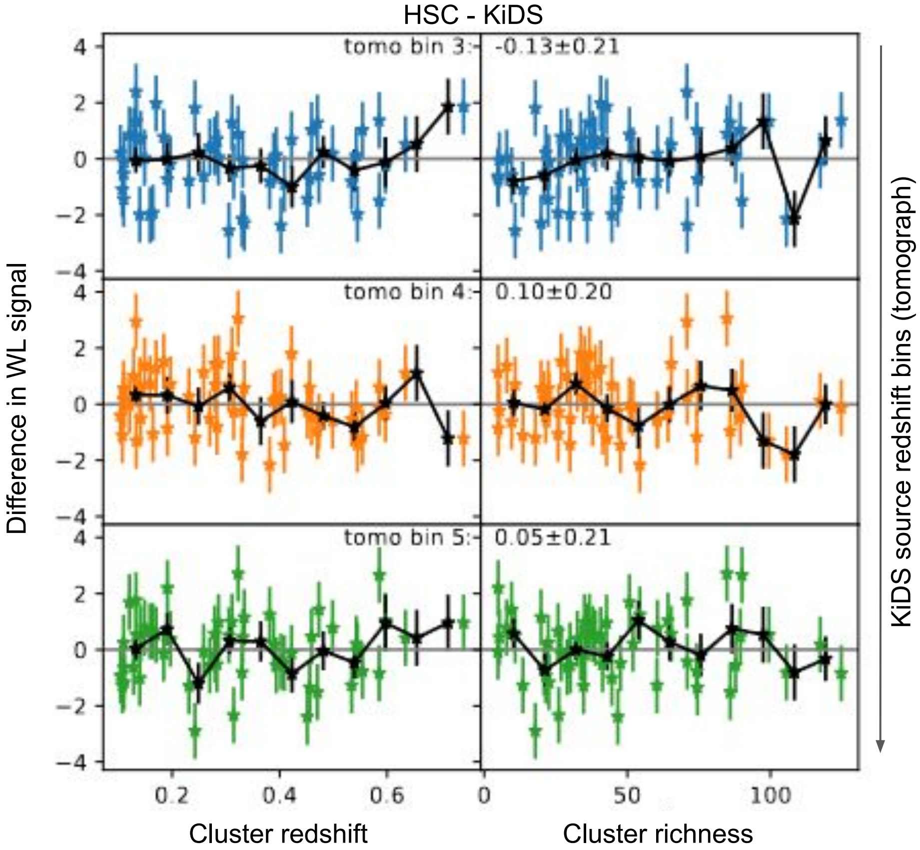
Ghirardini+24

Bad fit to HSC WL, does not impact final cosmology constraints

Cross survey comparison

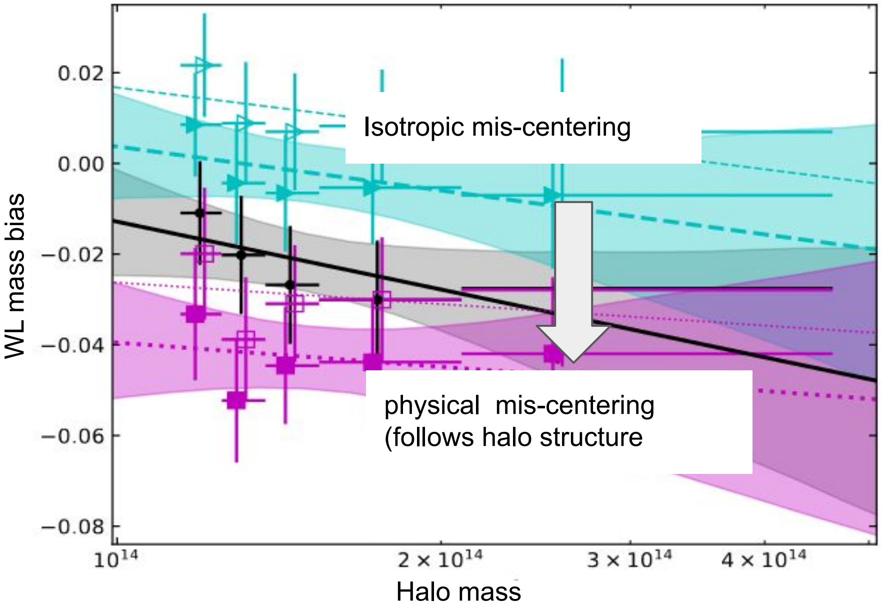
Some eRASS1 clusters fall in the footprints of DES&KiDS or KiDS&HSC → compare WL signals





Future improvements

Sommer+23

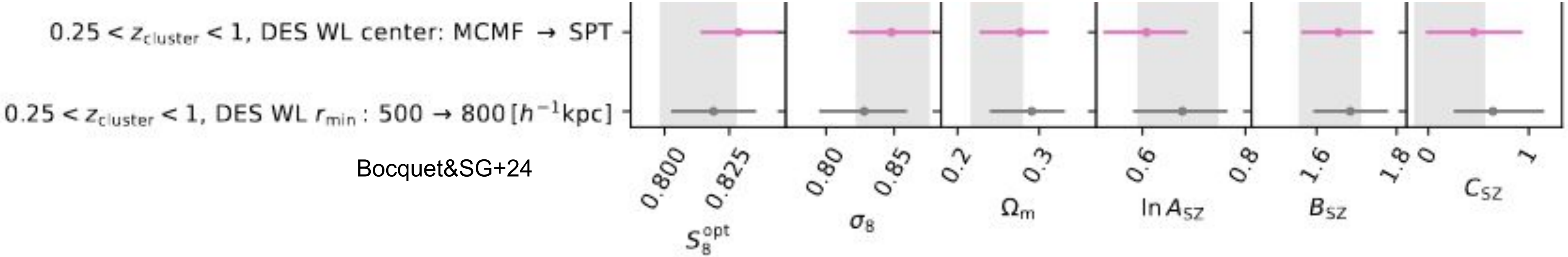


understand the impact using X-ray centers (instead of true halo centers) better

→ need to understand correlation between X-ray surface brightness peak and projected halo ellipticity

→ another cross check is to use the centers provided by the optical follow-up for comparison to the results based on X-ray centers
(leads to 1 sigma shifts in number counts of South Pole Telescope selected clusters with DES Y3 WL)

→ modify the minimal fitting radius

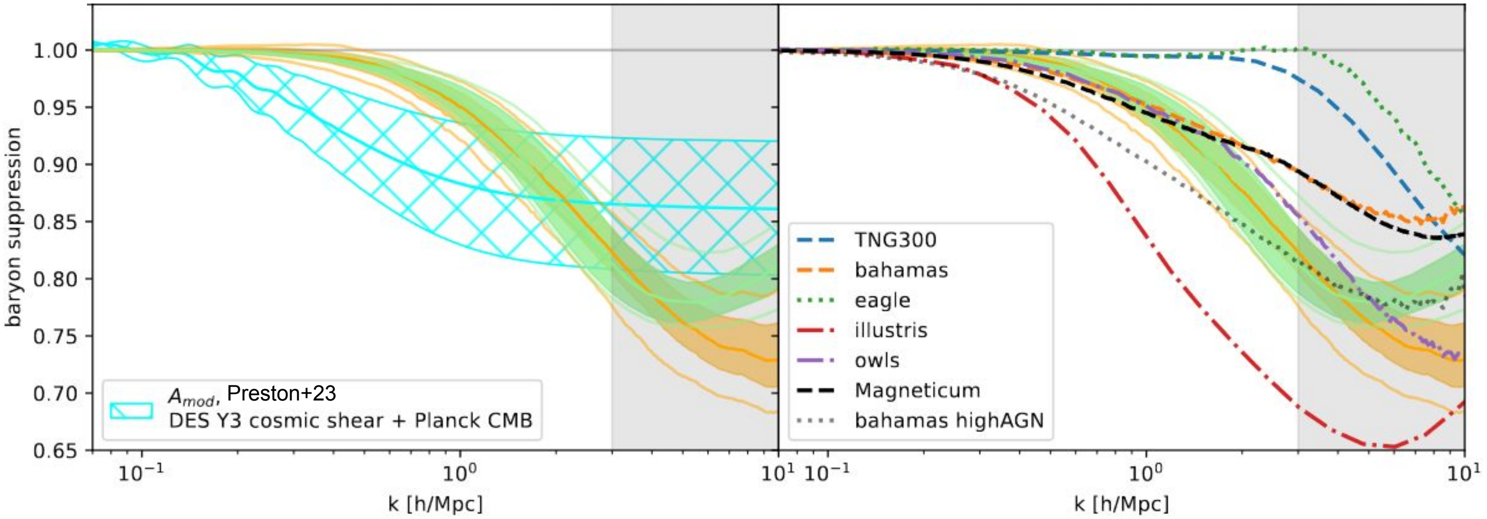


Bocquet&SG+24

Helping out cosmic shear

Cluster X-ray and WL observations tightly constrain Baryon feedback in halos

→ pre eRASS1 pilot study with gas/stellar mass fractions and 8 X-ray surface brightness profiles



using 2 baryonification models (bacco, Schneider19)

Grandis+24a
(submitted to MNRAS)

Cluster X-ray and WL already provide % precision on the matter power spectrum suppression due to baryons

Posterior predictive from data independent on cosmic shear

Baryon Feedback in halos likely not the source of S8-tension (→ pin this down with eRASS1 + DES)

Confirmed by the Flamingo Team McCarthy+23 (subm.)

→ WL + X-ray observations of cluster and group constrain astrophysical uncertainties on cosmic shear

→ relevance for and complementarity with cosmic shear experiment

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Thank you for your attention