Institute for Astro- and Particle Physics
Extragalactic Astrophysics

Weak lensing calibrated Cluster Number Counts

eROSITA clusters
[Ghirardini,...,SG,FK,TS+24]

Calibrated with DES Y3, KiDS and HSC weak lensing

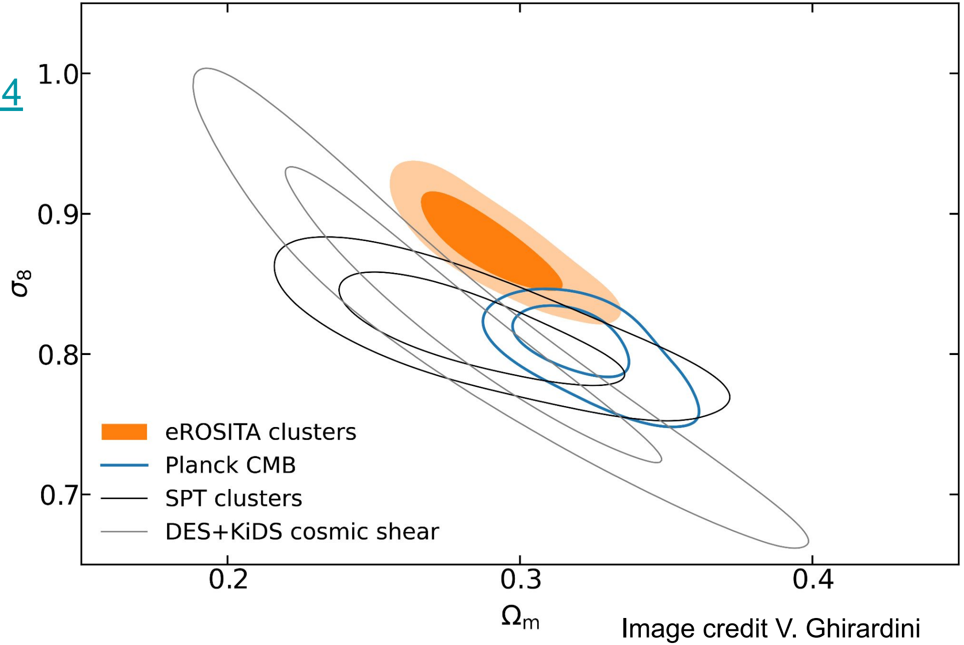


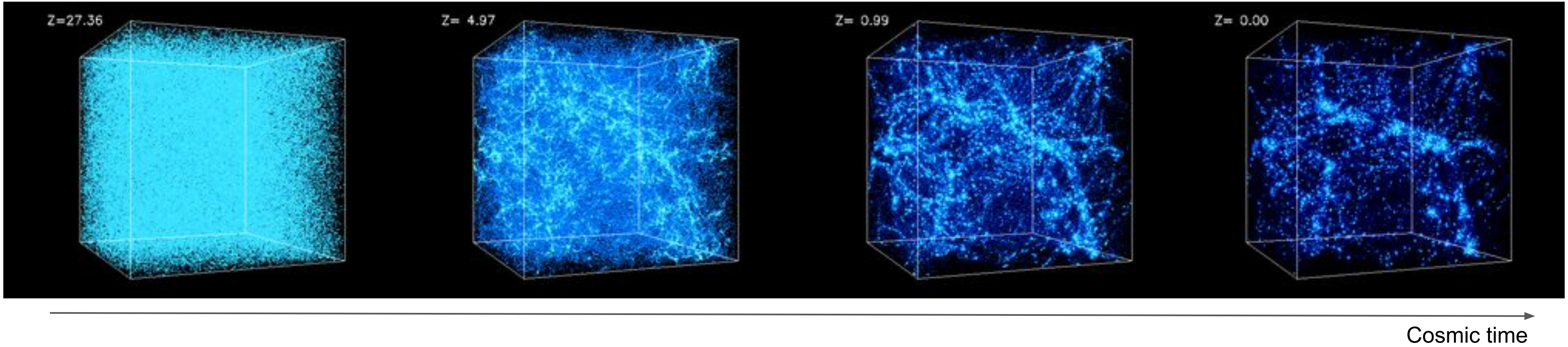
Image credit V. Ghirardini

SPT clusters
[Bocquet,SG,...TS+24]

Calibrated with DES Y3 weak lensing

Halo Formation

simulations were performed at the National Center for Supercomputer Applications by Andrey Kravtsov (The University of Chicago) and Anatoly Klypin (New Mexico State University). Visualizations by Andrey Kravtsov.



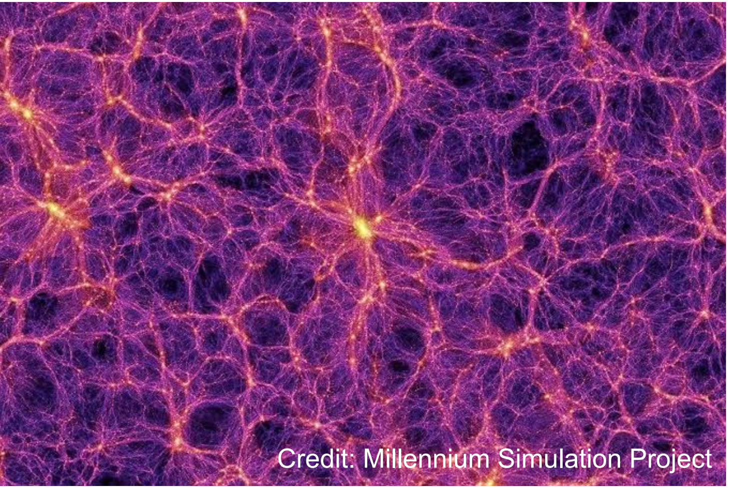
– initial density field is homogeneous with small fluctuations

– such a configuration is gravitationally unstable → over-density become more dense / contract, under-densities become less dense / expand → Cosmic Web

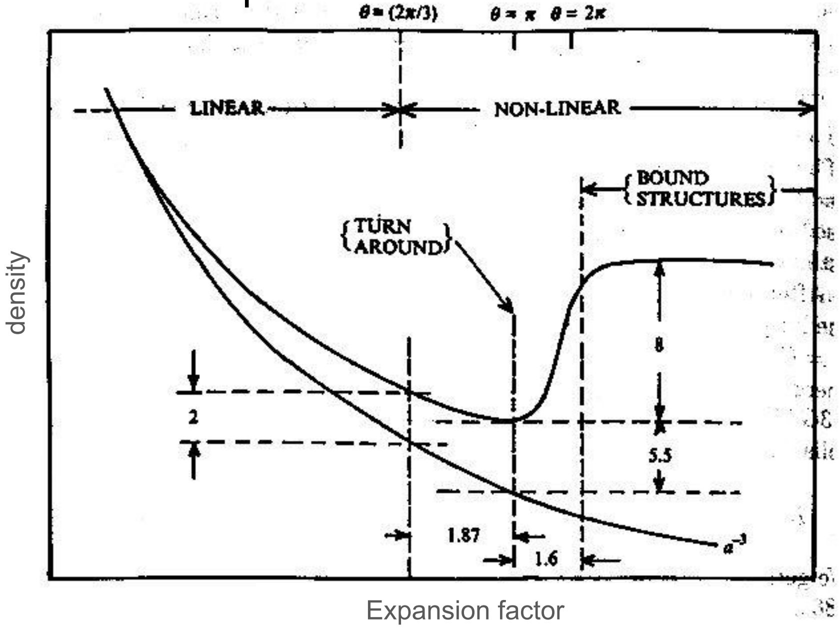
– tracing its dynamics is a multi-scale problem → can be solved in absence of pressure terms: collisionless fluid, drag term (expansion), Poisson equation

→ gravity-only simulations

Halo Formation

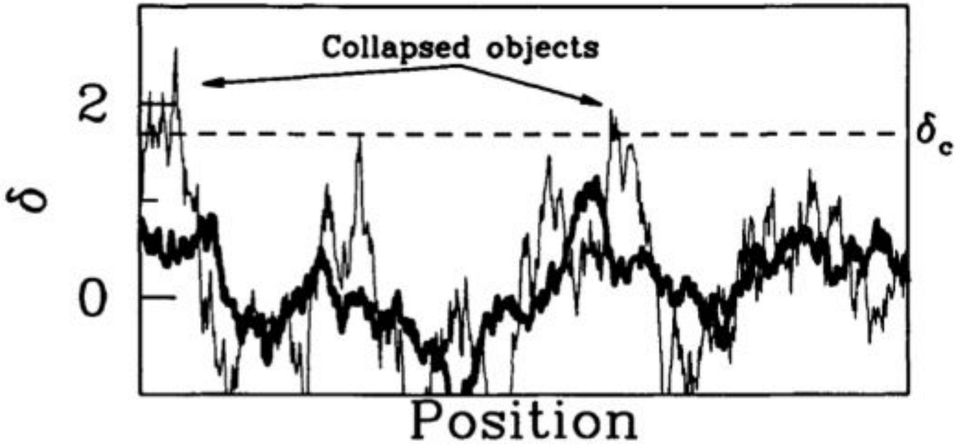


Halos form when the densest regions of the cosmic web:
— exceed a density contrast threshold,
— decouple from the background expansion, and
— undergo gravitational collapse



(1) An overdensity expands slower than the background
(2) ‘Turn around’: the overdensity starts contracting
(3) It collapses
(4) Until it reaches virial equilibrium
(5) An object with constant overdensity forms

Halo Formation



Collapse starts when linear density contrasts exceed a given threshold.

The number density of collapsed objects is the number density of peaks that exceed the threshold

The number density of halos as a function of redshift and halo mass (called *halo mass function*)
— captures information on the non-linear growth of structure
— depends strongly on the cosmological model

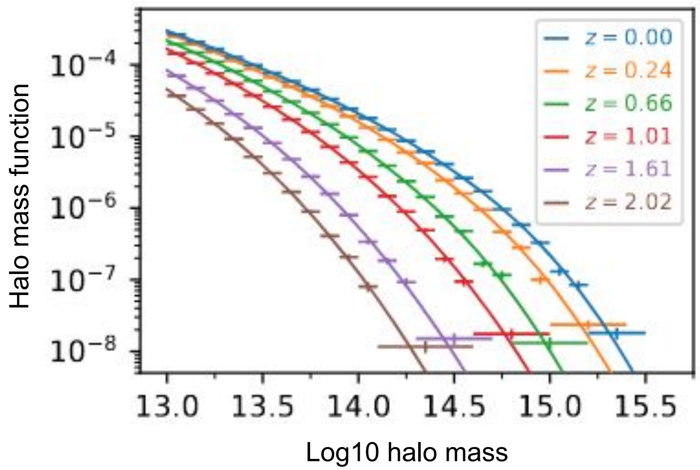
The number of halos as a function of redshift and halo mass

$$\frac{d^2N}{dM\,dz} = \frac{dn}{dM}\frac{dV}{dz}$$

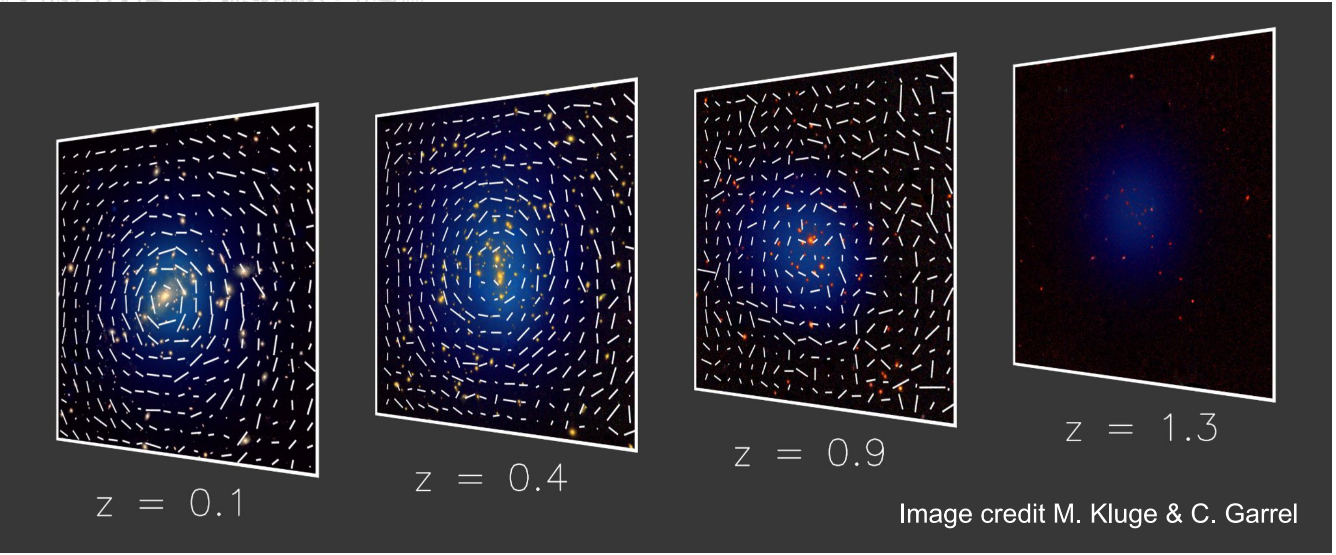
Structure growth: $\frac{dn}{dM}$

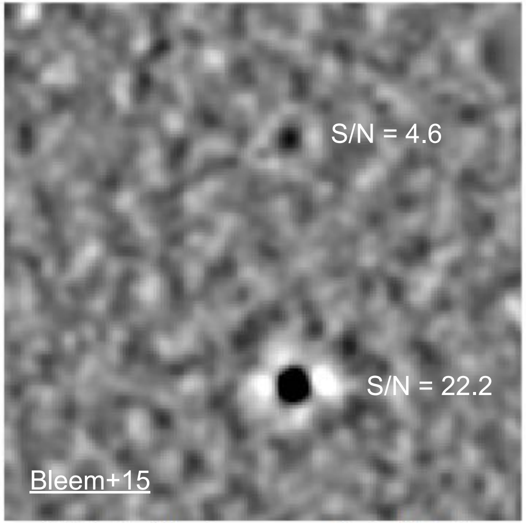
Expansion history: $\frac{dV}{dz}$

Bocquet+20



Galaxy Clusters: observationally



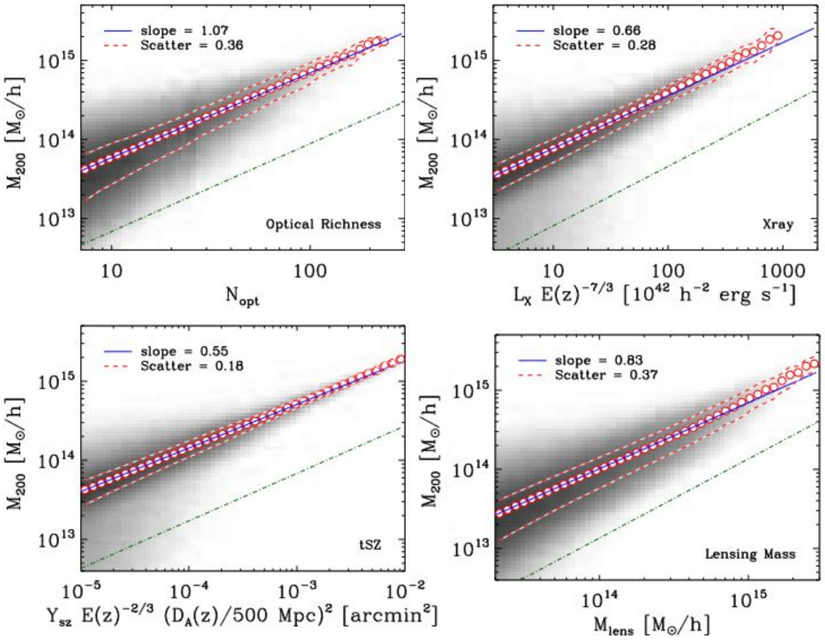


(d) Cluster-filtered map, zoomed in to 1°-by-1°

Galaxy clusters live in the most massive halos (M>10^14 Msol) → gravity dominated objects

Stand out via multiwavelength features:
- extended >1 keV Bremsstrahlung in X-rays
- overdensity of early type galaxies with gigantic central galaxy
- shadow in the CMB at <230 GHz
- gravitational lensing of background galaxies
- and others

Observable Mass relation



Simulation: Angulo+12

To 0th order, clusters are 'self-similar'

Mulroy+19

$$M_\Delta = \frac{4}{3}\pi r_\Delta^3 \Delta \rho_c(z) \propto E^2(z) r_\Delta^3.$$

Using the mass definition, and the virial theorem

$$\langle U \rangle = -2\langle K \rangle$$

We can derive different scalings of observables with halo mass, e.g.

$$T_X \propto [M_\Delta E(z)]^{2/3}$$

Hydrodynamical simulation indicate that the mass and redshift slope might deviate from self-similar behaviour → introduce 'scaling relation' parameters

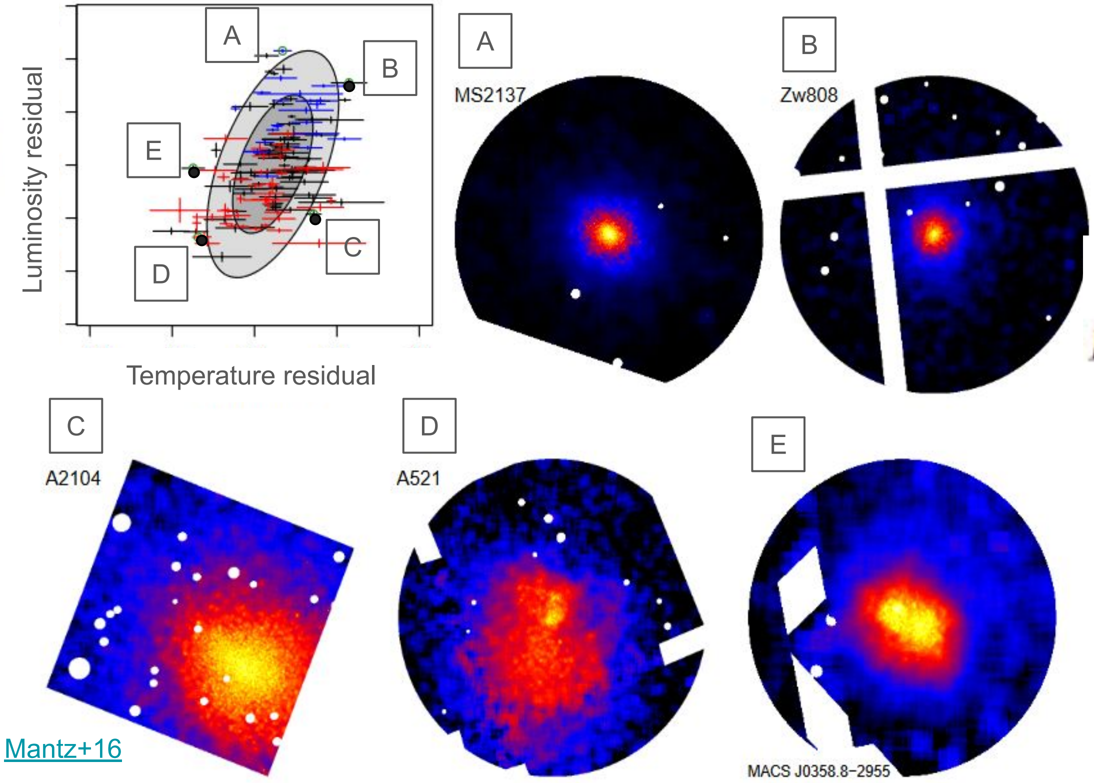
Relation between X-ray count rate and halo mass – 5 unknown params.

$$\left\langle \log \frac{C_R}{C_{R,p}} \middle| M, z \right\rangle = \log A_X + b_X(z) \log \frac{M}{M_p} + e_x(z) \qquad b_X(z) = B_X + F_X \log \frac{1+z}{1+z_p}.$$

Mean observable at mass and redshift

$$e_x(z) = D_X \log \frac{d_L(z)}{d_L(z_p)} + E_X \log \frac{E(z)}{E(z_p)} + G_X \log \frac{1+z}{1+z_p}$$

Observable Mass relation



Mantz+16

Not all halos at given mass and redshift have exactly the same observable

→ scatter around observable mass relation

$$P\left(\begin{bmatrix}\ln\zeta \\ \ln M_{\mathrm{WL}} \\ \ln\lambda\end{bmatrix} \middle| M, z, \boldsymbol{p}\right) = $$

$$= \mathcal{N}\left(\begin{bmatrix}\langle\ln\zeta\rangle(M, z, \boldsymbol{p}) \\ \langle\ln M_{\mathrm{WL}}\rangle(M, z, \boldsymbol{p}) \\ \langle\ln\lambda\rangle(M, z, \boldsymbol{p})\end{bmatrix}, \boldsymbol{\Sigma}_{\text{multi-obs}}\right)$$

Introduce multivariate scaling relation

Correlated scatter is crucial to account for astrophysical effects (like cool core bias)

Bayesian Population modeling

Bocquet,SG,...TS+23

Bayesian approach:
- postulate a stochastic model with free parameters that **generates** your data
- evaluate pdf of the **actual** data as function of model parameters (*likelihood function*)

Generative model

$$\left.\frac{\mathrm{d}N}{\mathrm{d}M}\right|_{M,z} \longrightarrow \{M_i,\ z_i\} \longrightarrow \{\zeta_i,\ \lambda_i,\ M_{\mathrm{WL},i},\ z_i\} \longrightarrow \{\xi_i,\ \lambda_i,\ \mathbf{g}_{\mathrm{t},i},\ z_i\}$$

- halo mass function x volume
- Poisson draw (+ sample var.) → mass selected sample
- Observable mass relation, w/ scatter → ICM-signal, richness, WL mass: intrinsic, noise-free observables
- instrumental noise → ICM signal, richness, tangential shear: measured observables

Resulting multi-observable number density

$$\frac{\mathrm{d}^4N(\boldsymbol{p})}{\mathrm{d}\xi\,\mathrm{d}\lambda\,\mathrm{d}\boldsymbol{g}_\mathrm{t}\,\mathrm{d}z} = \int\cdots\int \mathrm{d}\Omega_\mathrm{s}\,\mathrm{d}M\,\mathrm{d}\zeta\,\mathrm{d}M_\mathrm{WL}\,P(\boldsymbol{g}_\mathrm{t}|M_\mathrm{WL},\boldsymbol{p})P(\xi|\zeta)P(\zeta,\lambda,M_\mathrm{WL}|M,z,\boldsymbol{p})\frac{\mathrm{d}^3N(\boldsymbol{p})}{\mathrm{d}M\,\mathrm{d}z\,\mathrm{d}V}\frac{\mathrm{d}V(z,\boldsymbol{p})}{\mathrm{d}\Omega_\mathrm{s}}$$

← reading direction

marginalizes over latent variables

Our summary statistic is the cluster catalog!

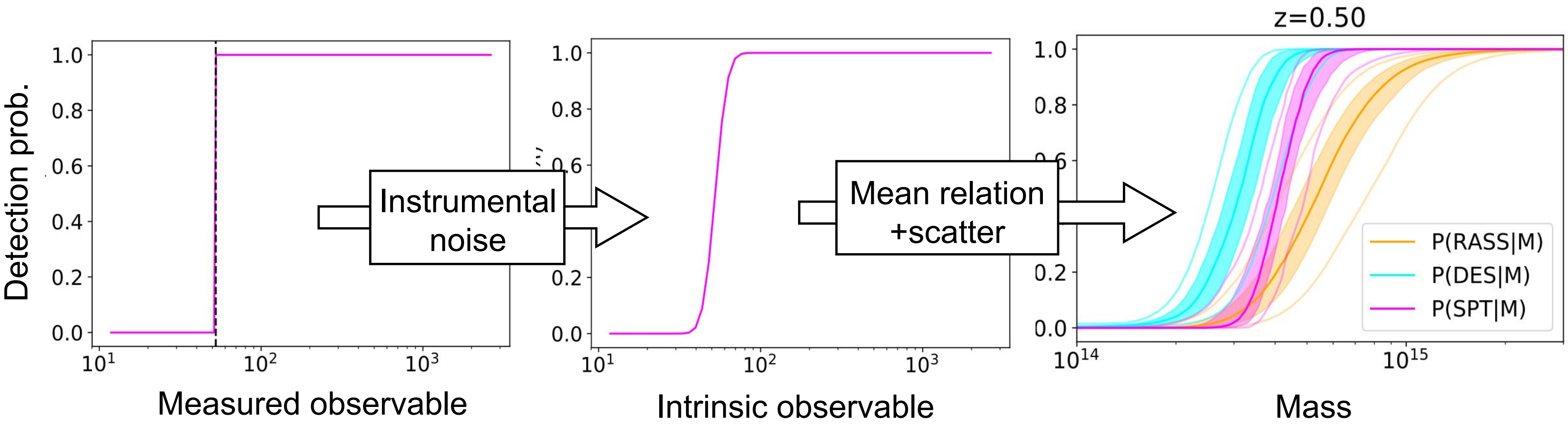
Poisson Likelihood (in limit of infinitesimally small bins, Mantz+14)

$$\ln\mathcal{L}(\boldsymbol{p}) = \sum_i \ln\left.\frac{\mathrm{d}^4N(\boldsymbol{p})}{\mathrm{d}\xi\,\mathrm{d}\lambda\,\mathrm{d}\boldsymbol{g}_\mathrm{t}\,\mathrm{d}z}\right|_{\xi_i,\lambda_i,g_{\mathrm{t},i},z_i} - \int\cdots\int \mathrm{d}\xi\,\mathrm{d}\lambda\,\mathrm{d}\boldsymbol{g}_\mathrm{t}\,\mathrm{d}z\,\frac{\mathrm{d}^4N(\boldsymbol{p})}{\mathrm{d}\xi\,\mathrm{d}\lambda\,\mathrm{d}\boldsymbol{g}_\mathrm{t}\,\mathrm{d}z}\Theta_\mathrm{s}(\xi,\lambda,z)$$

Bayesian Population modeling

Mean scaling between observable and mass + its scatter directly predict incompleteness as function of mass

A.k.a "Selection Function"



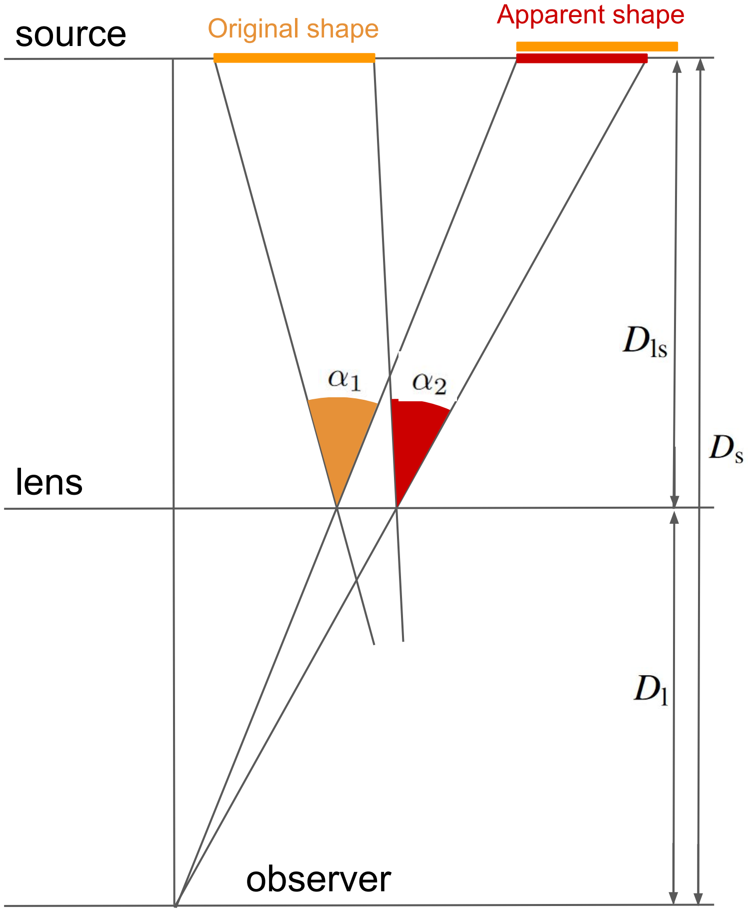
Clusters are selected by imposing a cut in the selection observable(s)

Applying scatter sources and mean observable mass relation gives the mass incompleteness
Crucially with systematic uncertainty!!

Need to empirically constrain the mean relation between selection observable and halo mass

This problem is called *mass calibration*

Weak lensing by massive halos

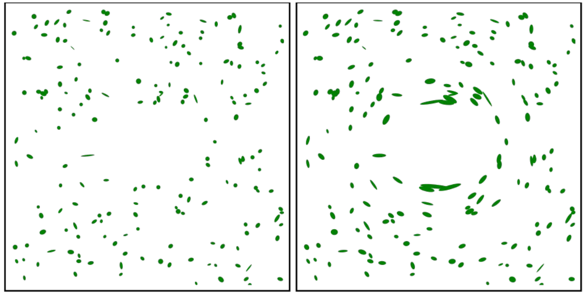


Gravitational potentials bend space time, and therefore *deflect light*, $\vec{\alpha} = -\vec{\nabla}\phi$

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



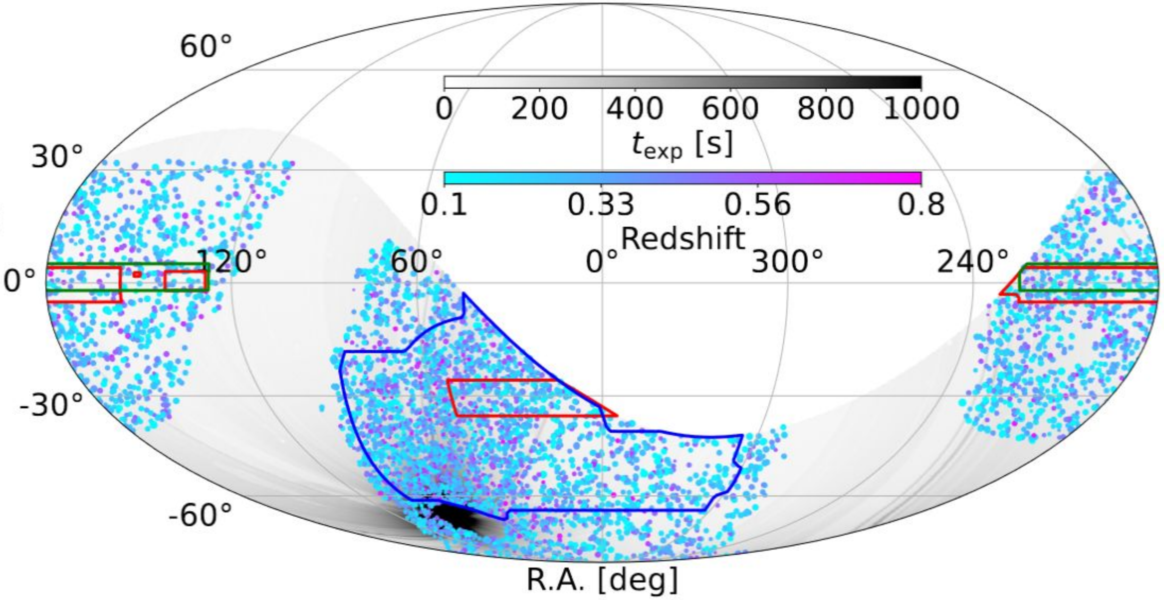
The strength of the distortion is modulated by the geometrical configuration

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

Lenses: massive halos with redshift → eRASS:1 clusters&groups

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

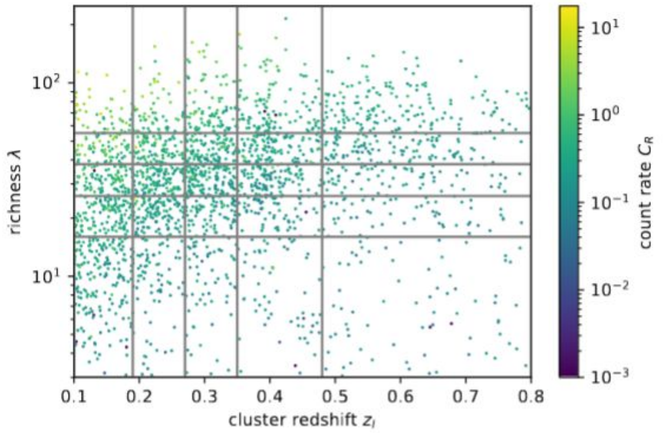
Lens sample: eRASS1 clusters



First eROSITA All Sky Survey (eRASS1)

Selection of clusters & groups as extended X-ray sources (Bulbul,...,SG,FK,TS+24)

Targeted redmapper in DECaLs DR 10 data for redshifts and confirmation (Kluge,...,SG,FK,TS+24)

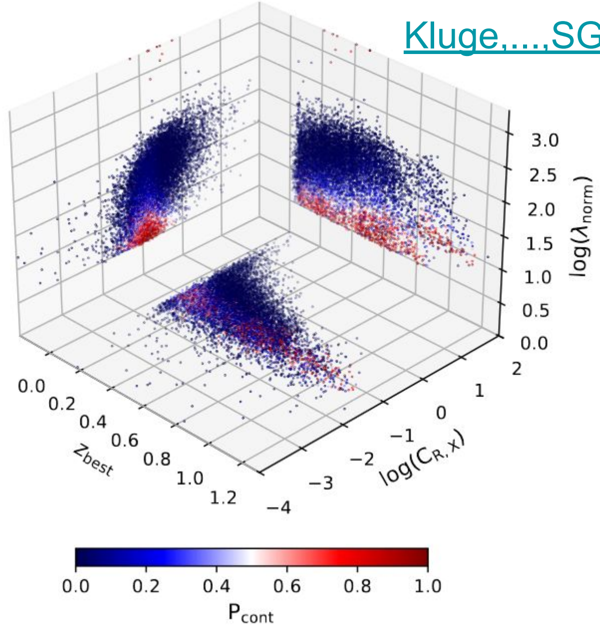


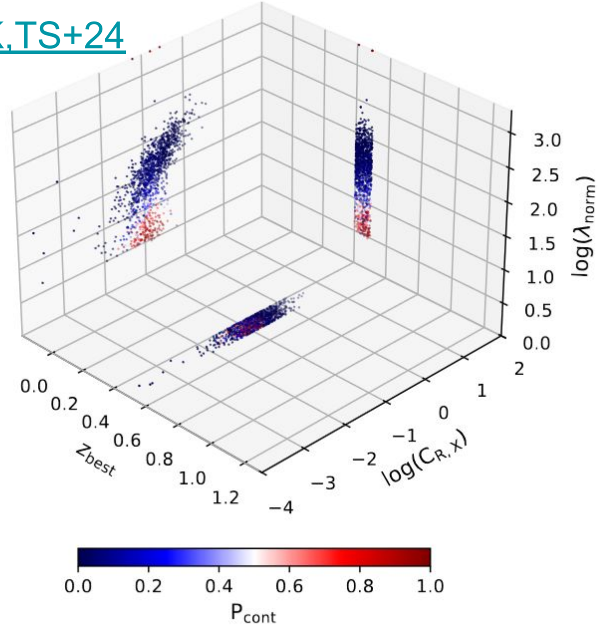
Overlap with all 3 stage III WL surveys DES Y3, KiDS, HSC S19A

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

Lens sample: Contamination

[Kluge,...,SG,FK,TS+24](#)





Richness distribution at given count rate and redshift is modelled as three components
(1) clusters
(2) mis-classified AGN
(3) Background fluctuation

X-ray distribution of (2) & (3) is taken from image simulations

Richness, redshift distribution from
(2) optical follow up of point source
(3) optical follow up of randoms

Resulting contamination from full optical follow up likelihood

$$f_{RS} = 0.0061 \pm 0.0023$$
$$f_{AGN} = 0.0462 \pm 0.0038$$

0.6% of background fluctuations
4.6% of mis-classified AGN

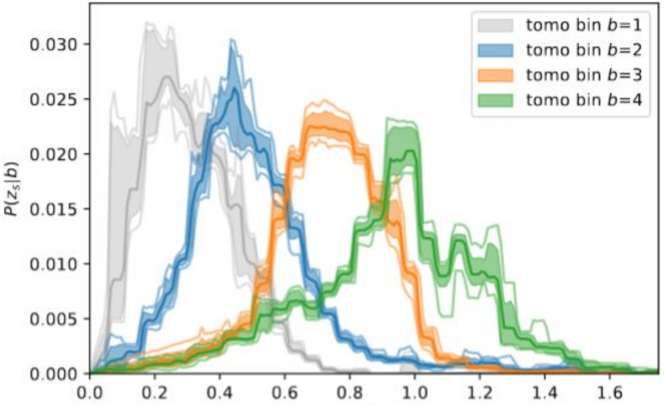
Source sample: DES Y3 shapes

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

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

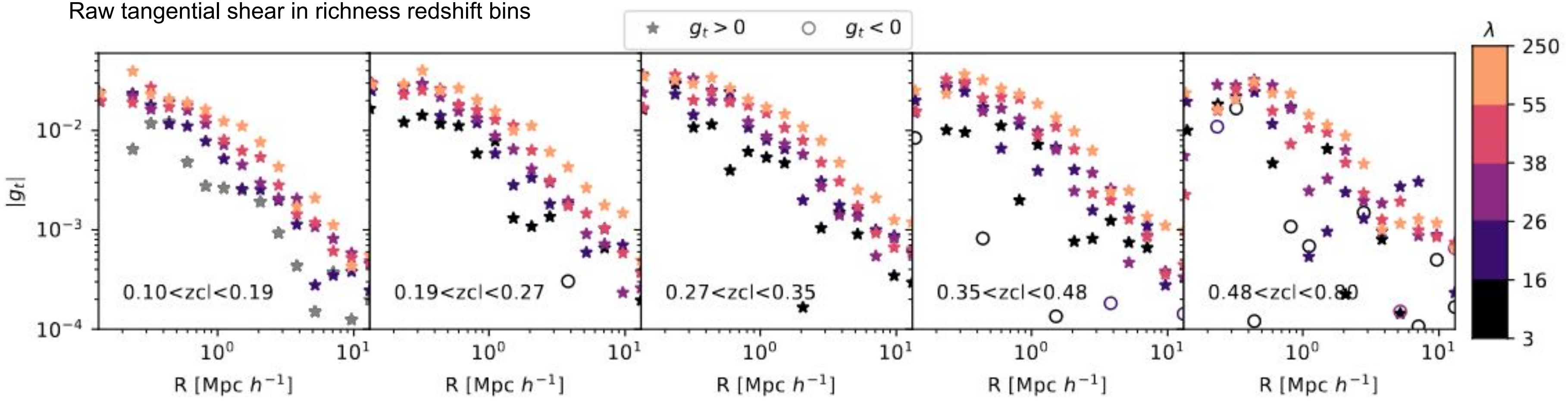
Estimate the tangential shear by binning the tangential ellipticities of the sources

Total S/N on 2.2k objects = 92



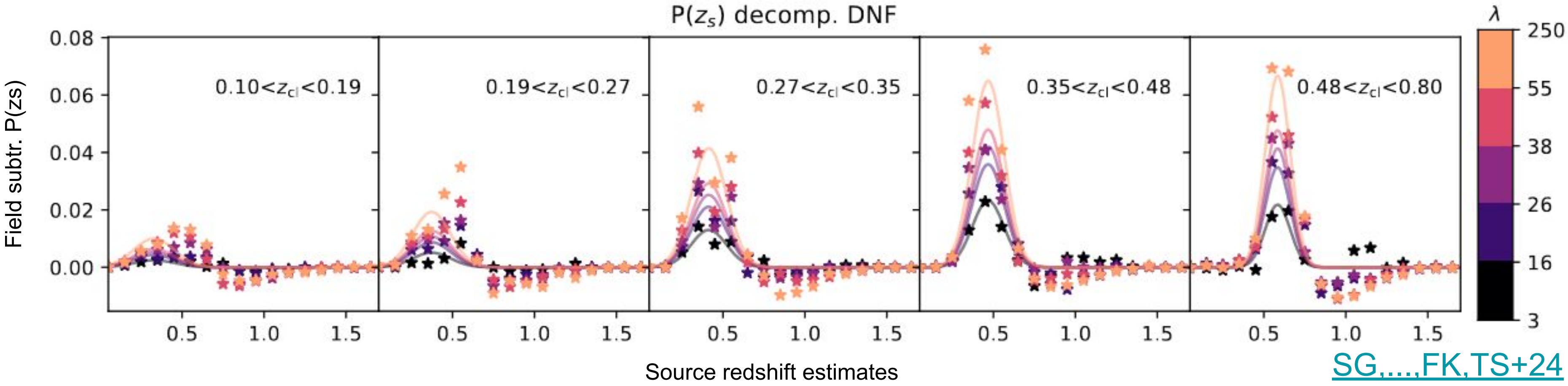
SG,...,FK,TS+24

Raw tangential shear in richness redshift bins



P(z)-decomposition

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



SG,...,FK,TS+24

Cluster centric distance dependent mixture of local field P(zs) and cluster member contribution

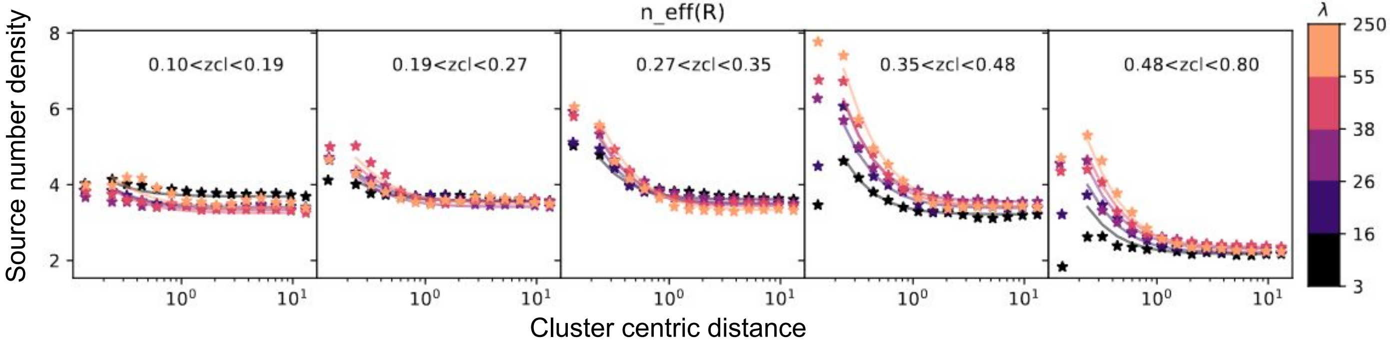
$$P(z_s|R,\lambda,z) = (1 - f_{cl}(R|\lambda,z))\hat{P}_{field}(z_s|z) + f_{cl}(R|\lambda,z)P_{cl}(z_s|z)$$

Fitted to source redshift distribution measured in richness, redshift, cluster centric distance bins

$$\ln \mathcal{L}_\beta = \sum N_{eff}\hat{P}_\beta(z_s)\ln P(z_s|R,\lambda,z) \text{ for } \beta \in (\text{BPZ}, \text{DNF}),$$

Stats and Sys for WL measurement

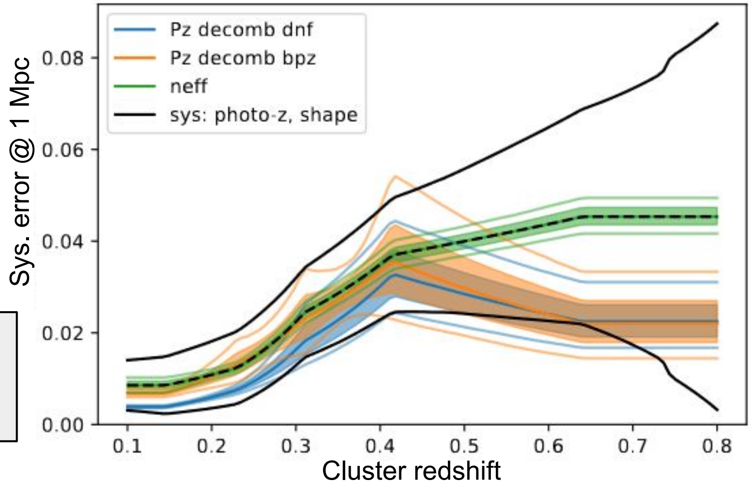
Some (unlensed) cluster galaxies leak into the background selection → fit for cluster member contamination



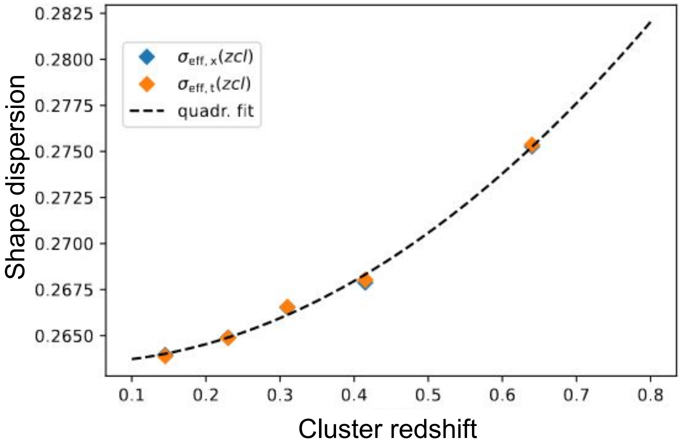
Increase in source number density density towards cluster center due to cluster member contamination

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

DES team has extensively calibrated photo-z and shape measurements



Intrinsic shape dispersion → empirically estimate



<1 % sys. uncertainty for z<0.4

Calibrating halo mass → WL

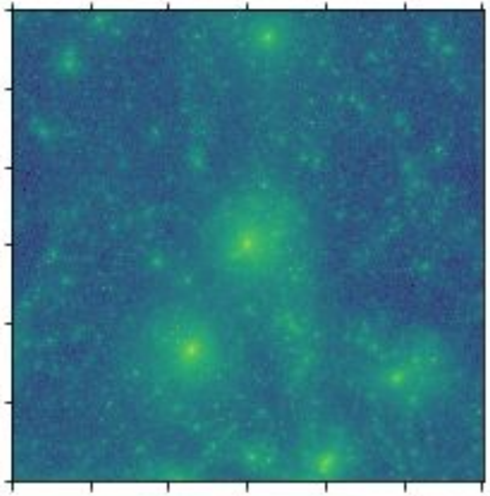
Synthetic shear profiles

– 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

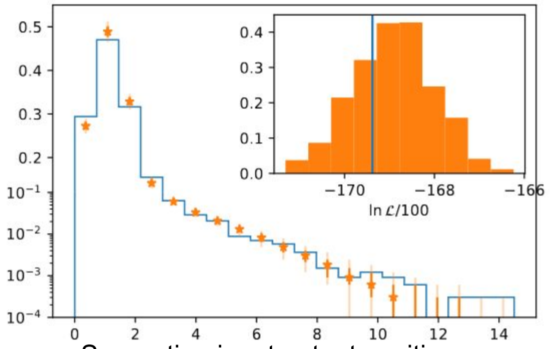
Shear profile model for cosmology pipeline

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

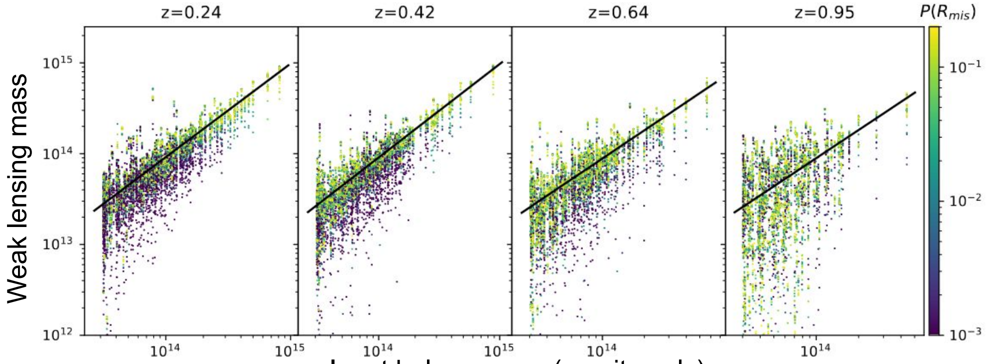


2d projected density map of a massive halo in the TNG300 simulation, box size 10 Mpc/h

Mis-centering in eROSITA digital twin



Separation input output position



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

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

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

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

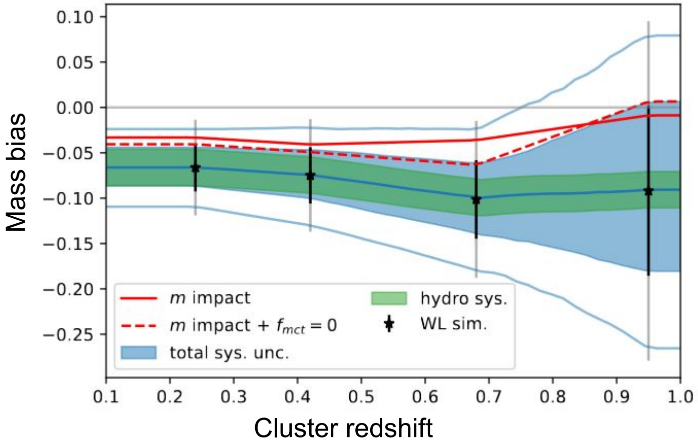
SG,...,FK,TS+24

Mass calibration

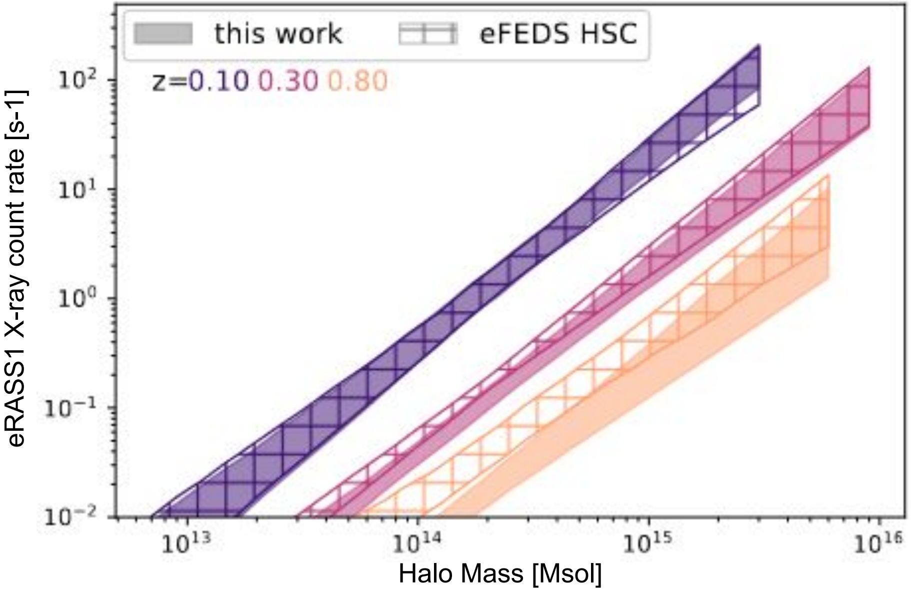
Determining Systematics

(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

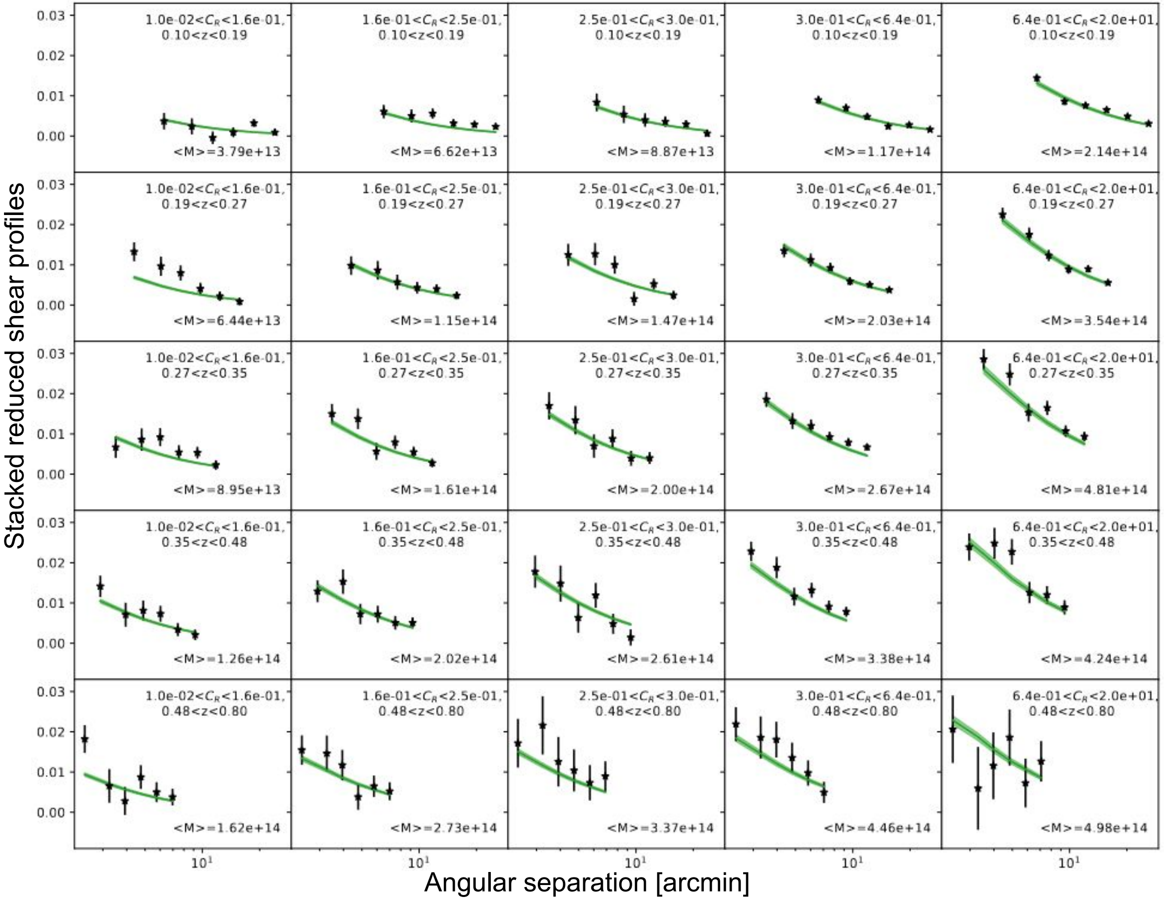


Done for DES, KiDS and HSC



Use part of the eROSITA cosmology pipeline (Ghirardini,...,SG,FK,TS+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

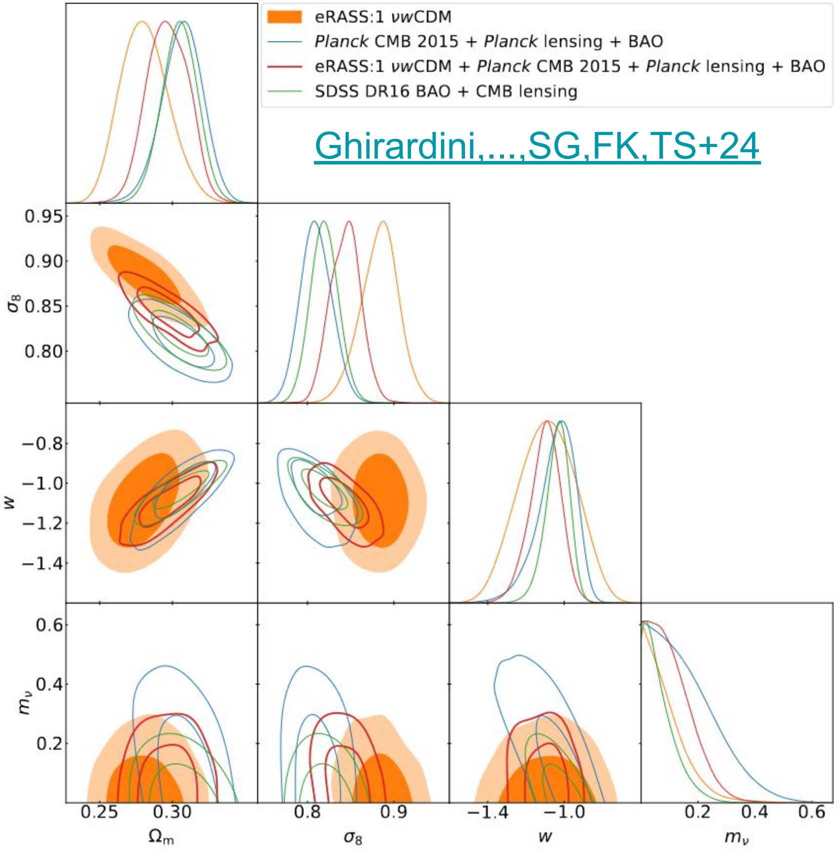
> Total signal to noise after scale cuts: 62

Goodness of fit

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

Cosmological results

Fit catalog containing ICM-signal, richness, redshift and shear with population model

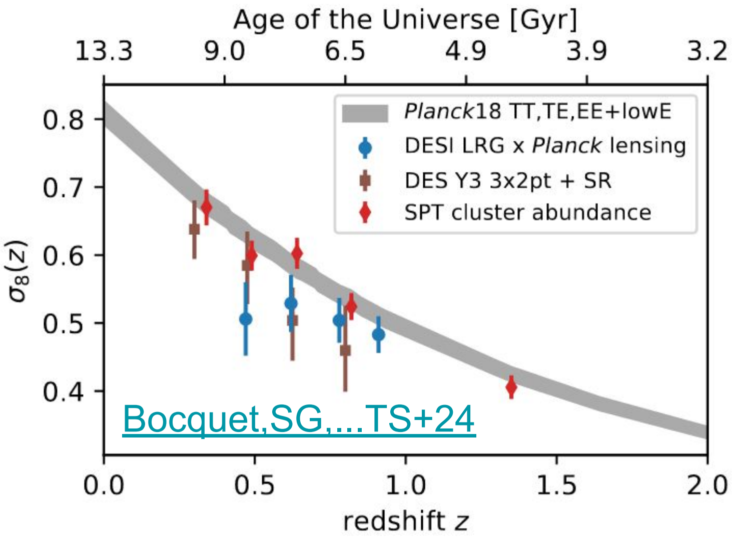


Ghirardini,...,SG,FK,TS+24

Joint constraint on scaling relation parameters + cosmology parameters

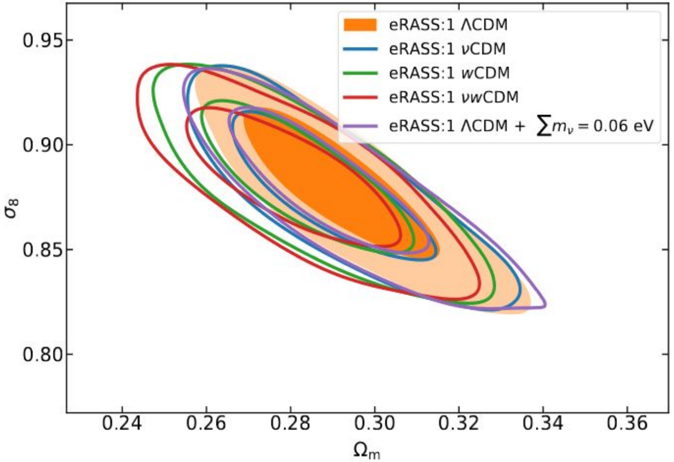
WL calibrated eROSITA clusters measure OmegaM, sigma8, w AND m_nu simultaneously!

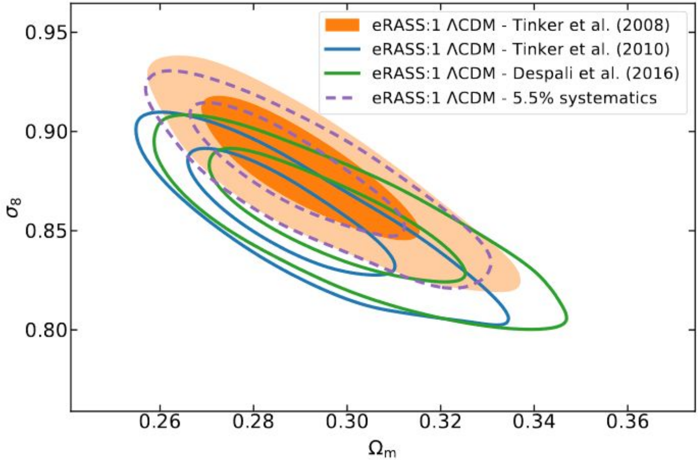
WL calibrated SPT clusters map growth of structure



Bocquet,SG,...TS+24

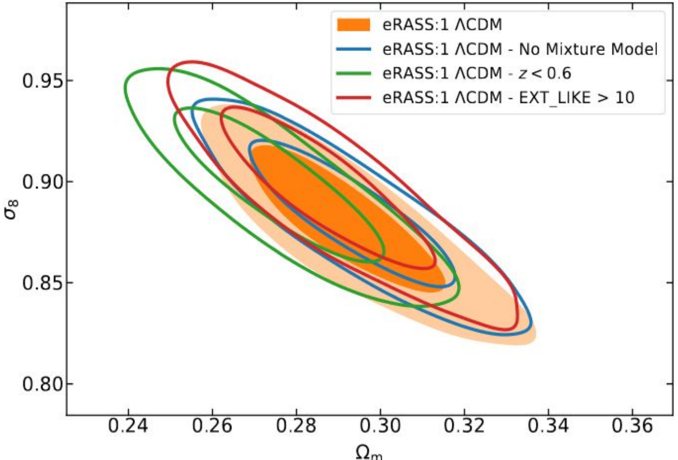
Post Blinding lessons





Halo mass function calibration starts to matter

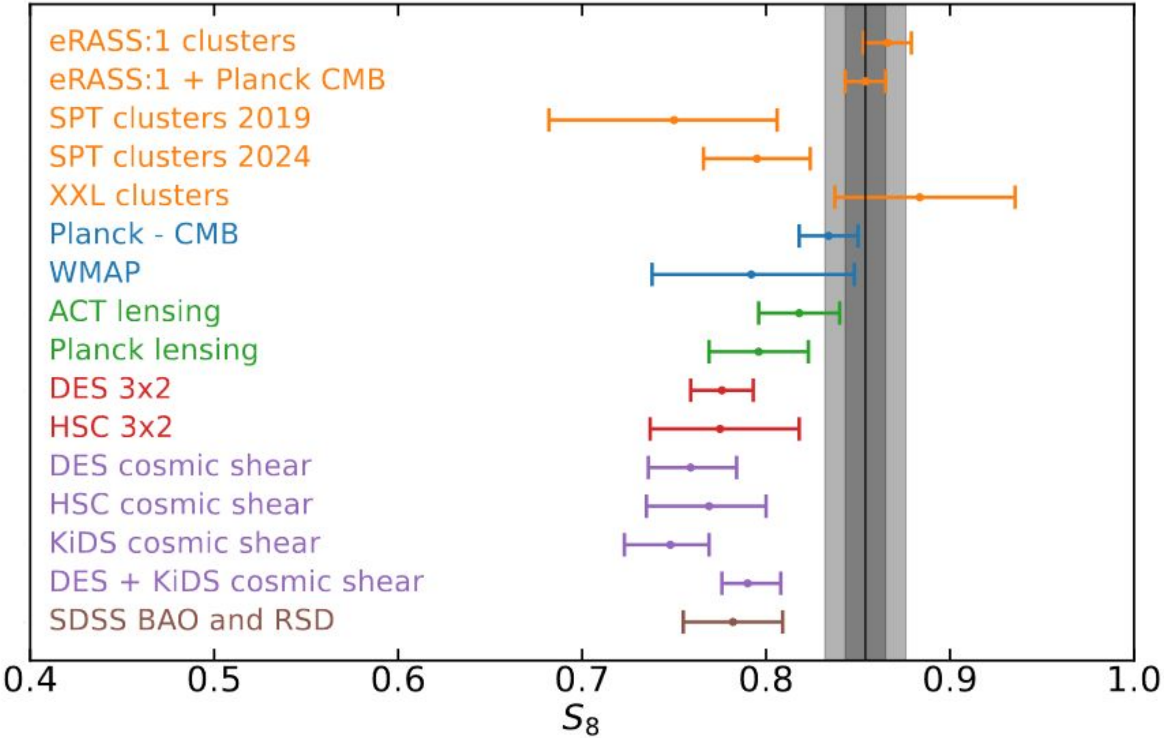
In hindsight: should have tested this while blinded



S8 very stable against model expansion and sample selection

Pyccl feature request: allow for the Costanzi+13 massive neutrino modelling, i.e. using the only P(k) of cdm and baryons, but with the transfer function impacted by massive neutrinos

Comparison to 3x2pt



Very complementary to 3x2pt

Densest points of matter field vs
Average properties of matter field

→ different response to baryon feedback (perturbs mass definition vs suppress small scale signal)
→ CL not affected by intrinsic alignment (Sifon+15)
→ assembly bias / selection effects accounted for in forward model
→ actively avoiding 1- to 2-halo term transition region

We are moving into the age of LSS cosmology :D
– ultimately, it is surprising that all these experiments are quite close

Conclusions

Galaxy clusters inhabit the most massive halos, their number as a function of mass and redshift is a potent cosmological probe

The relation between the observed cluster properties and mass follows tight relations, but has to be calibrated empirically

Using a Bayesian Population model, we can fit for the mass calibration, the selection function and the cosmology simultaneously

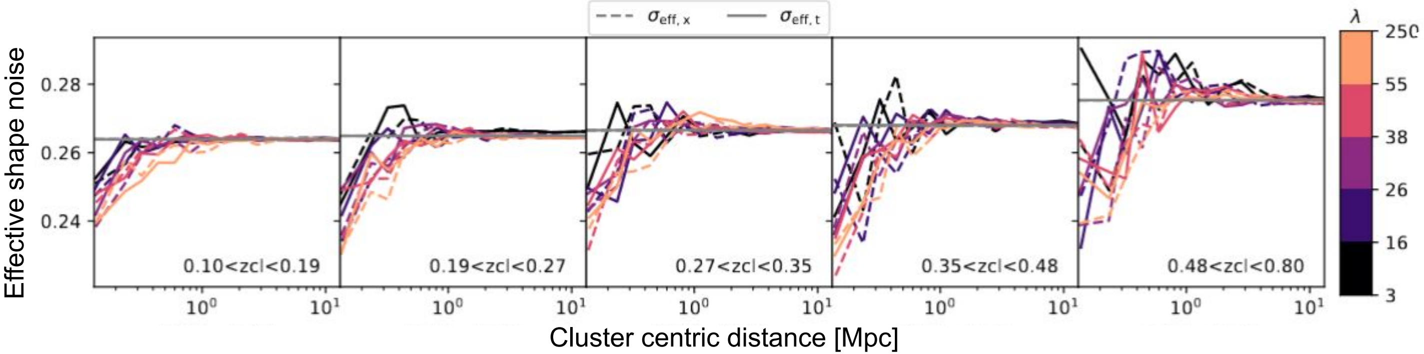
Direct mass information is provided by the weak lensing signature measured from wide photometric surveys

Cluster number counts are sensitive to all later time parameters, can map the growth of structure and are complementary to shear and galaxy auto- and cross-correlations function

Thank you for the attention

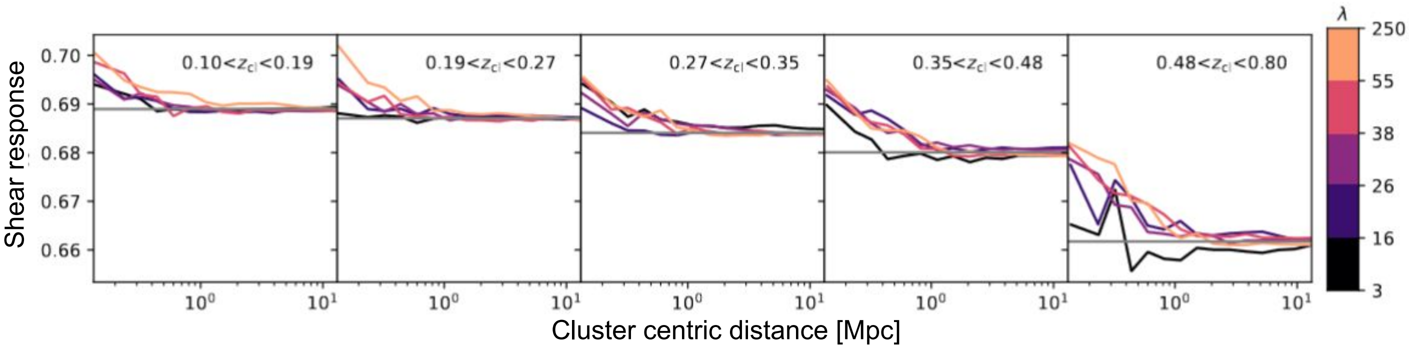
Cluster LoS anomalies detected!

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

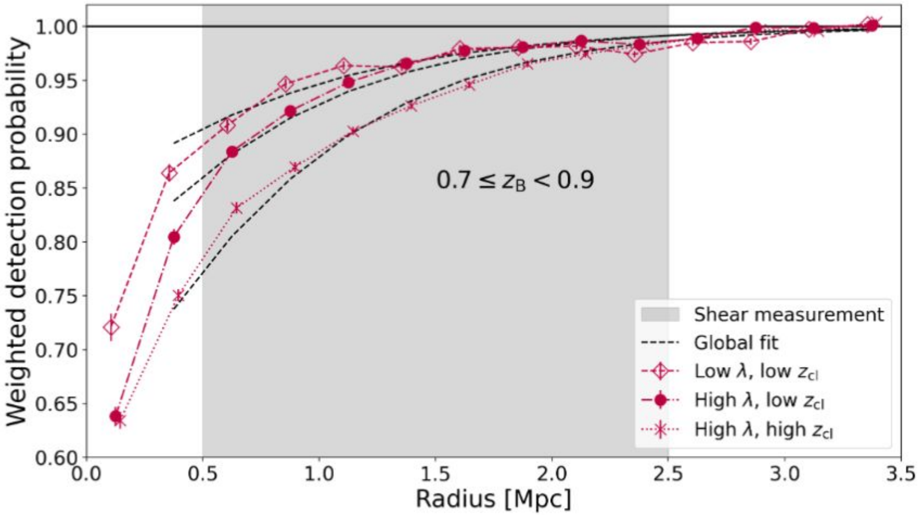
– cluster members are brighter and rounder → higher response

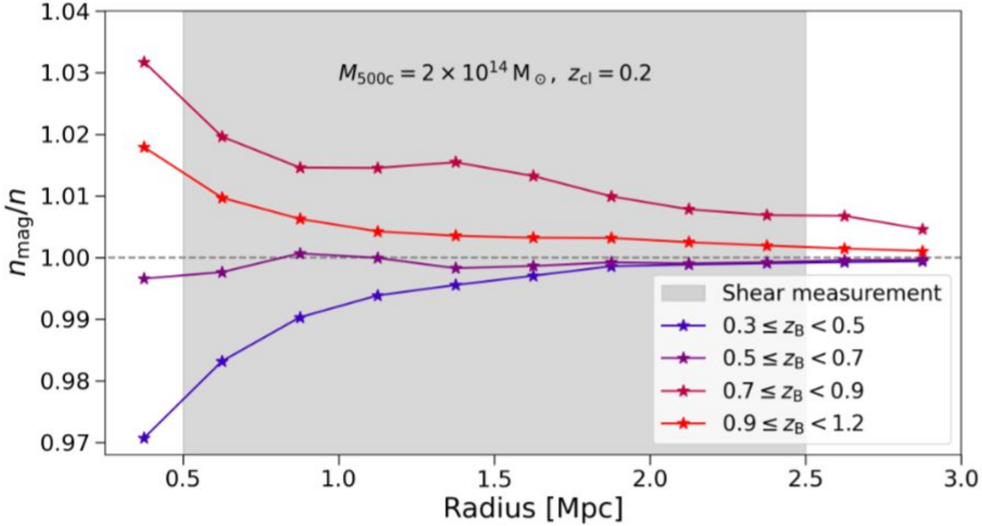
– field galaxies are magnified, and thus brighter → higher response

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 % (SG+21)

Cluster LoS anomalies detected!

Galaxy clusters are over-densities in the galaxy field – effects that might matter for Euclid





Only a fraction of sources injected into KiDS behind eRASS1 clusters is recovered FK,SG,TS+24

– Need to correct effective source density profiles
– P(zs) decomb unaffected?

Work is starting now on understanding cluster specific WL calibrations for Euclid

– shear bias due to increased blending and strong shear in cluster LoS
– synthetic cluster lines of sight
– impact of magnification

Cluster potential also leads to magnification of background sample FK,SG,TS+24

– implication on magnitude, color, morphology distribution of sources