# Accurate cluster masses from weak lensing

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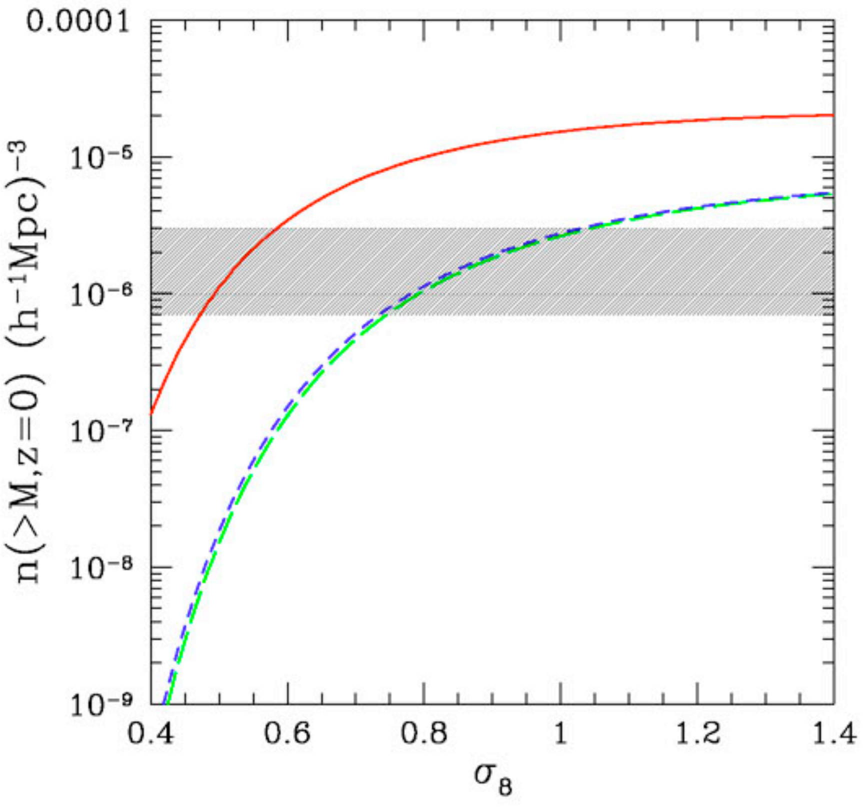
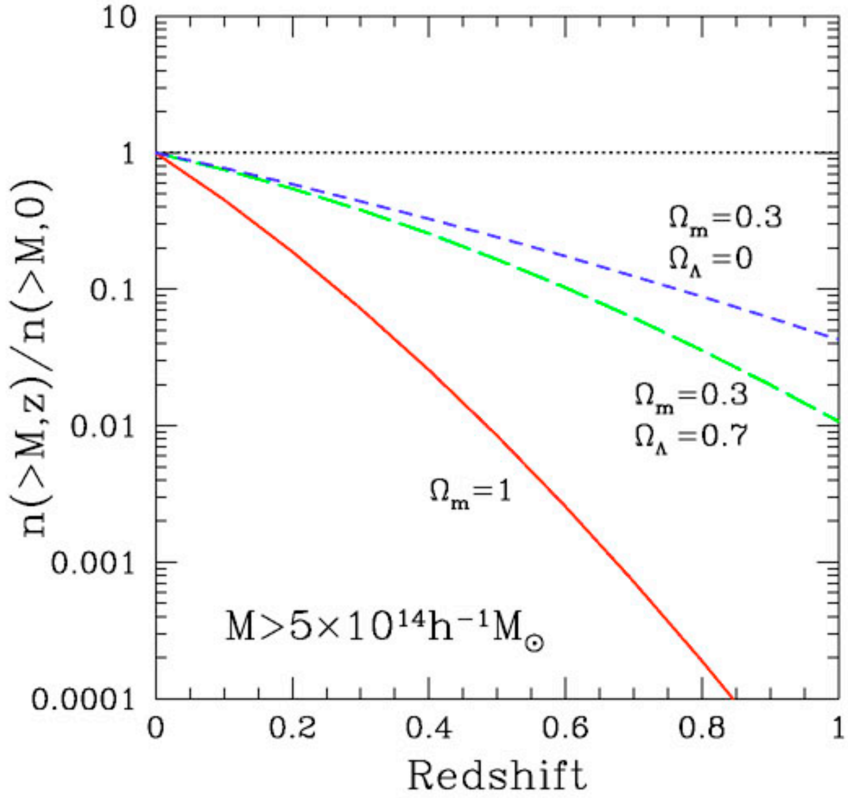
# One reason to *find* clusters of galaxies

The number density of clusters as a function of mass and redshift is a sensitive probe of cosmology.

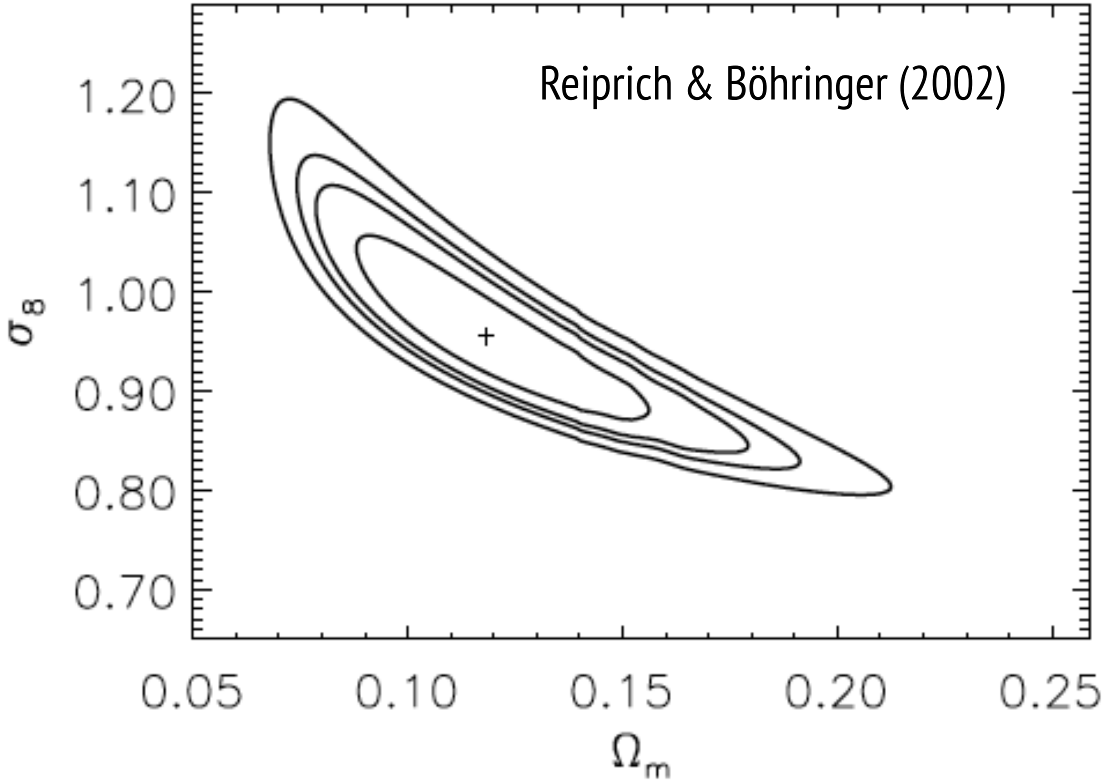




# One reason to *count* clusters of galaxies

Precise measurements of cosmological parameters can therefore be obtained, even with modest samples of low-z clusters:

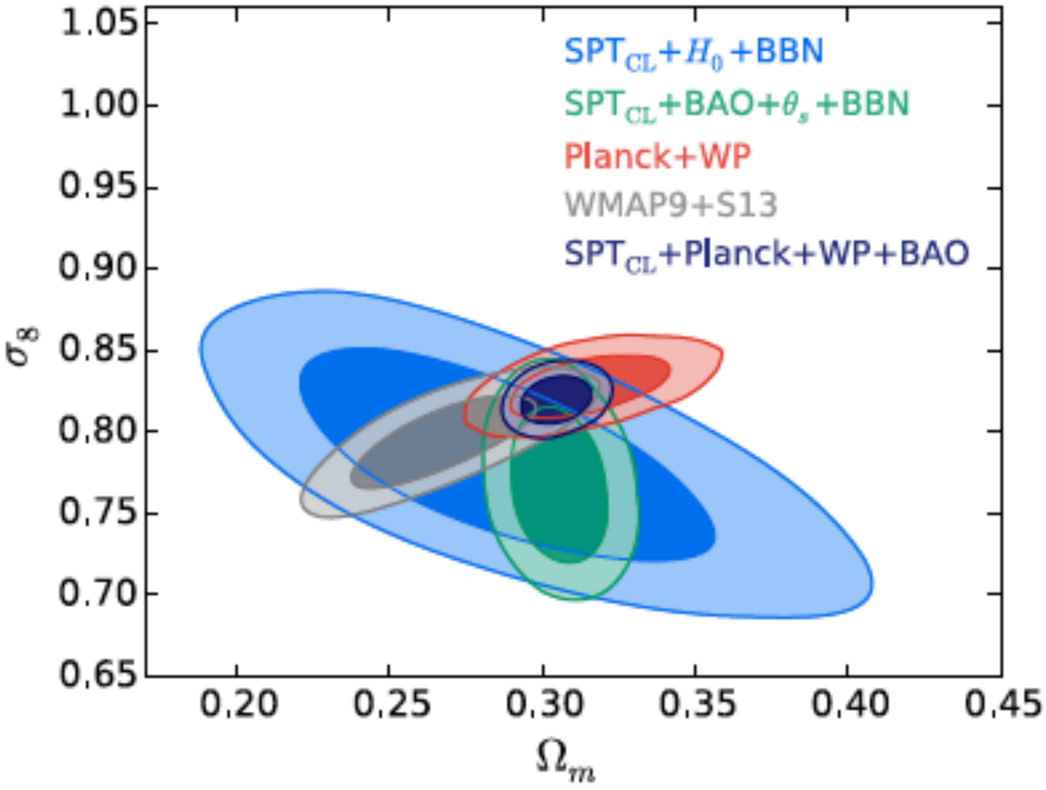
HIGLUGCS studied only 63 of the X-ray brightest systems.



# One reason to *count* clusters of galaxies

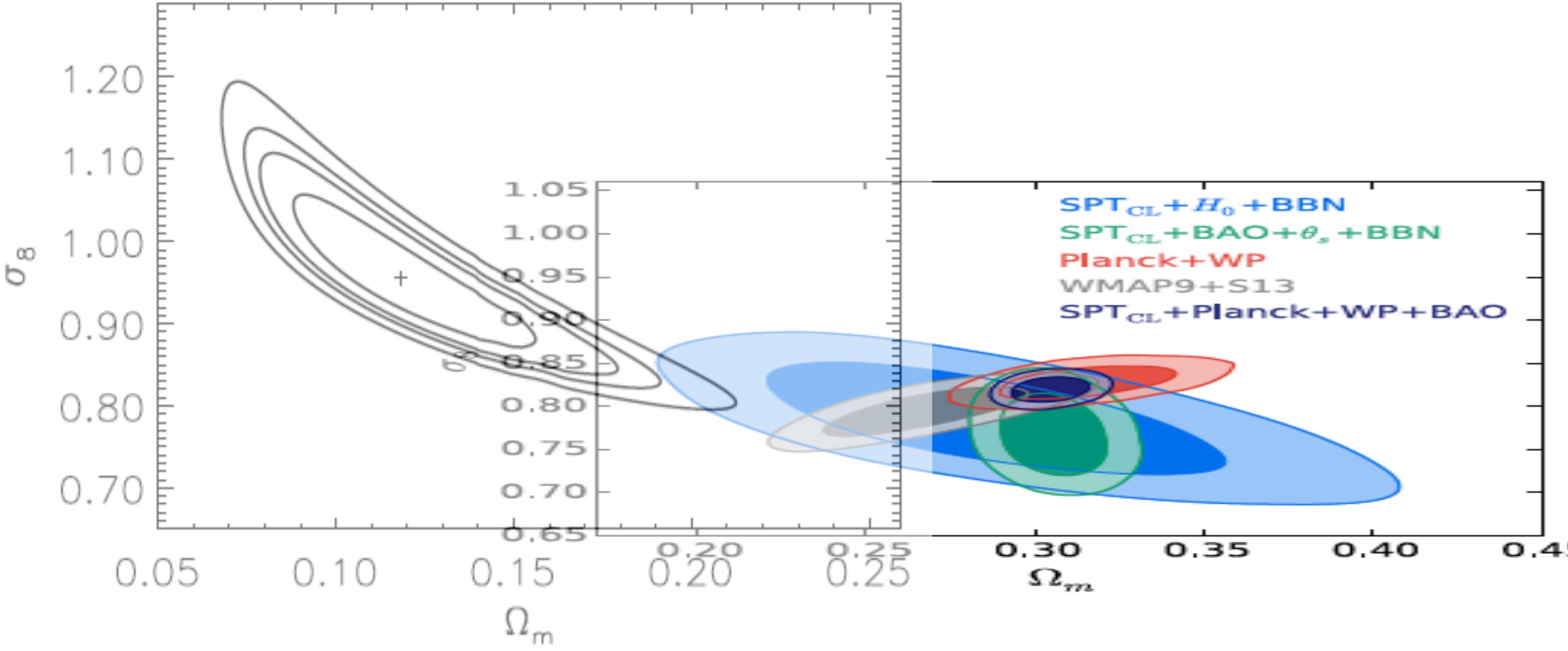
Going to higher redshift should help tremendously. So the most recent constraints should be much better!?

De Haan et al. (2016): 377 z>0.25 massive clusters discovered by SPT.



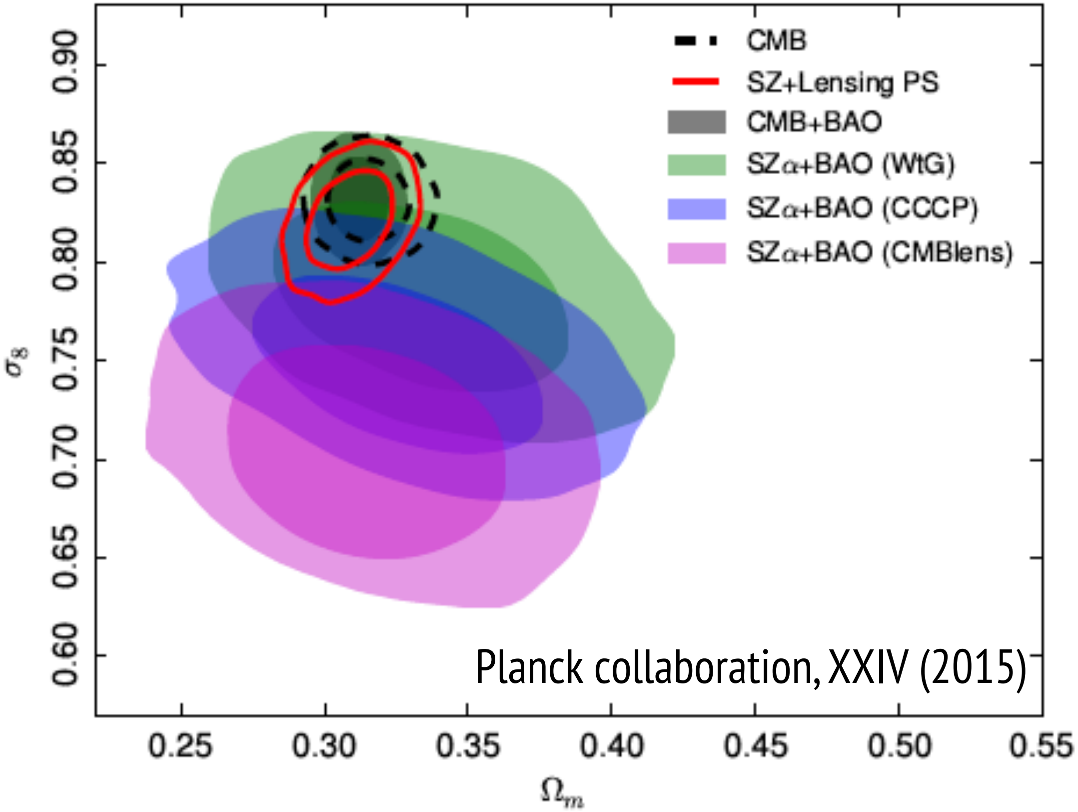
# One reason to *study* clusters of galaxies

Cluster counts may be good tools for precision cosmology, but are they useful for accurate cosmology?



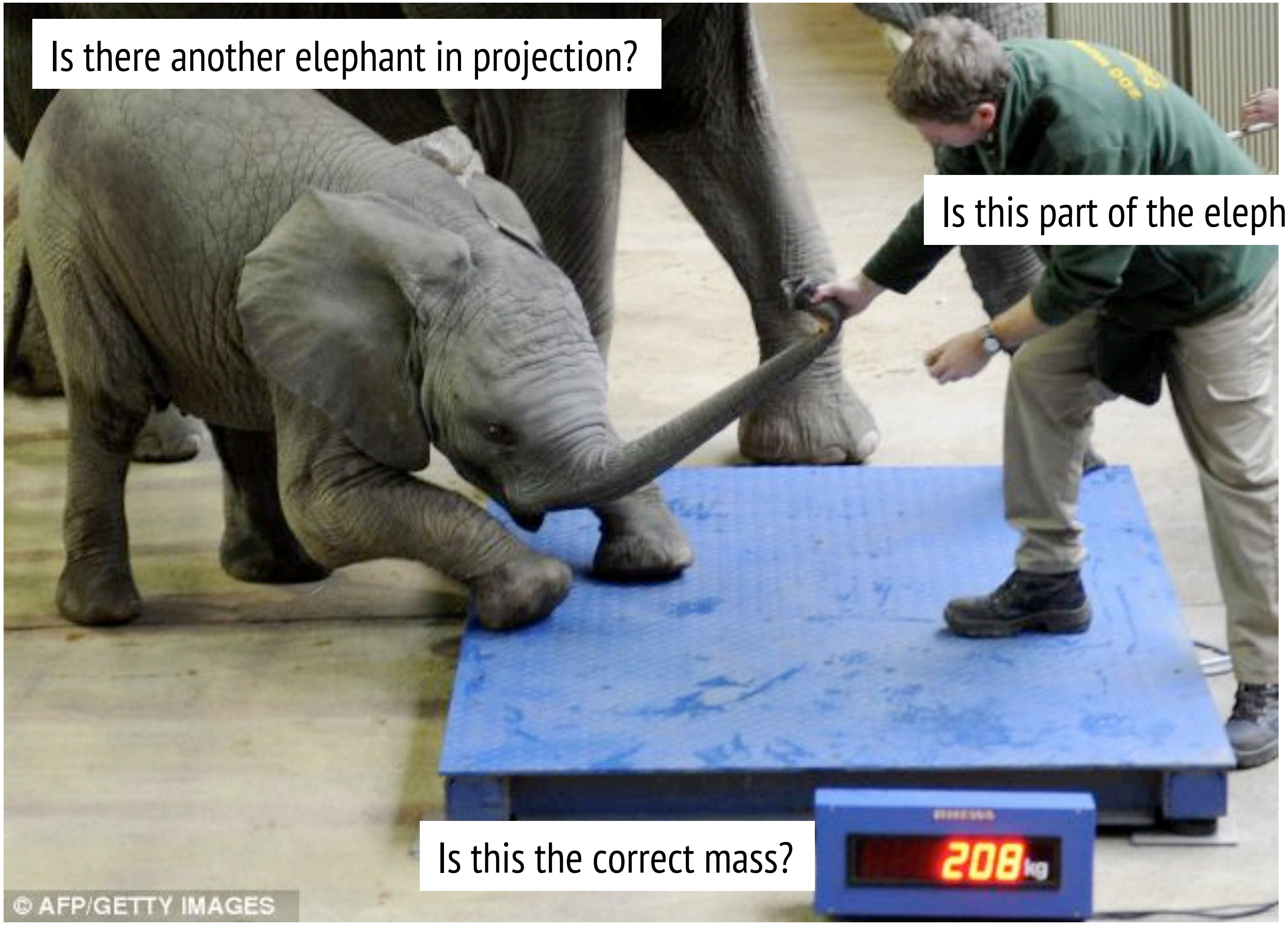
# We have the samples, but we need the masses

Planck cluster counts vs Planck primary CMB results: is the difference real? Or is it the result of biases in the masses?



Planck collaboration, XXIV (2015)

# Accurate cosmology with clusters of galaxies?

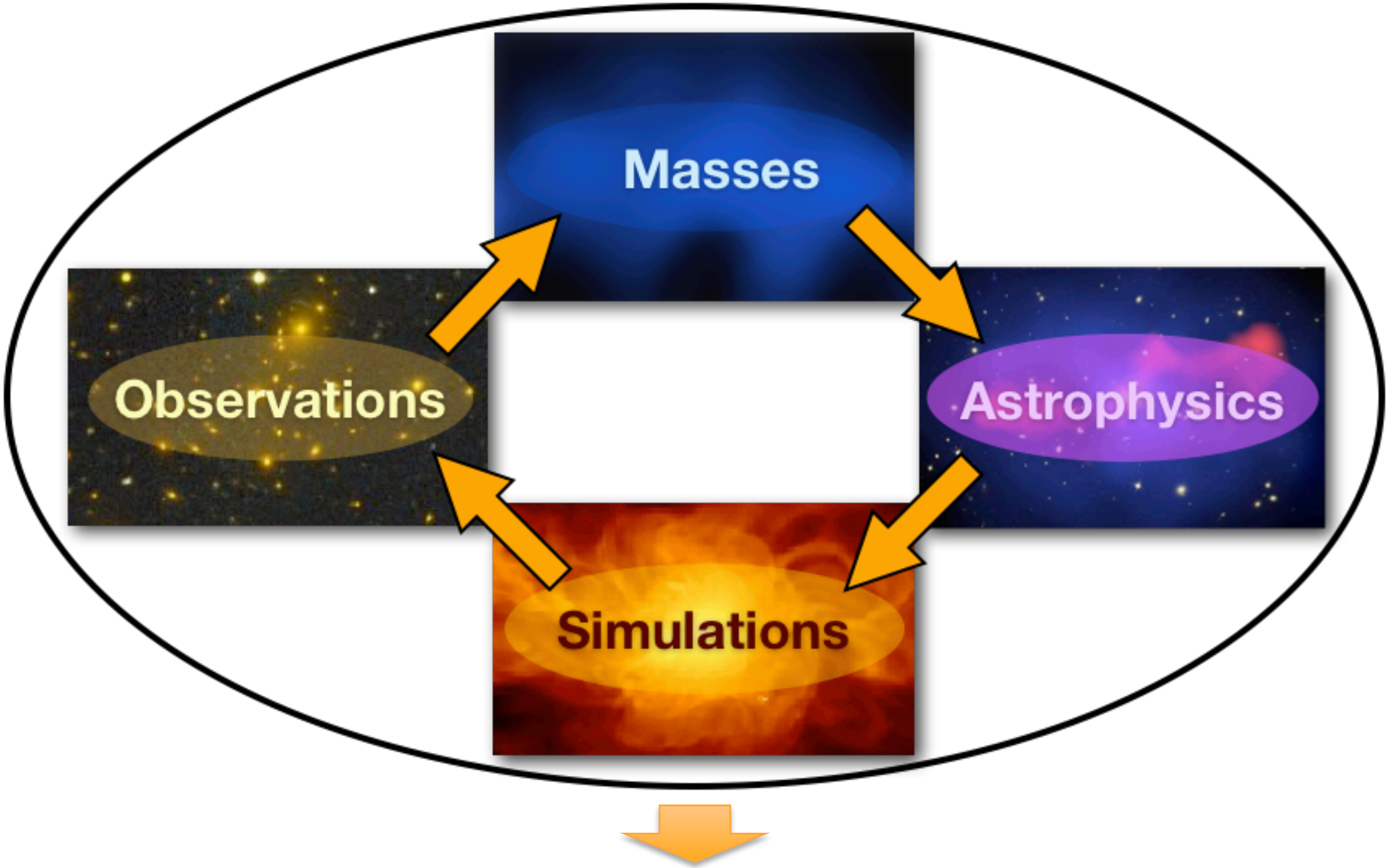


Is there another elephant in projection?

Is this part of the elephant?

Is this the correct mass?

# We need to *understand* clusters of galaxies



Masses

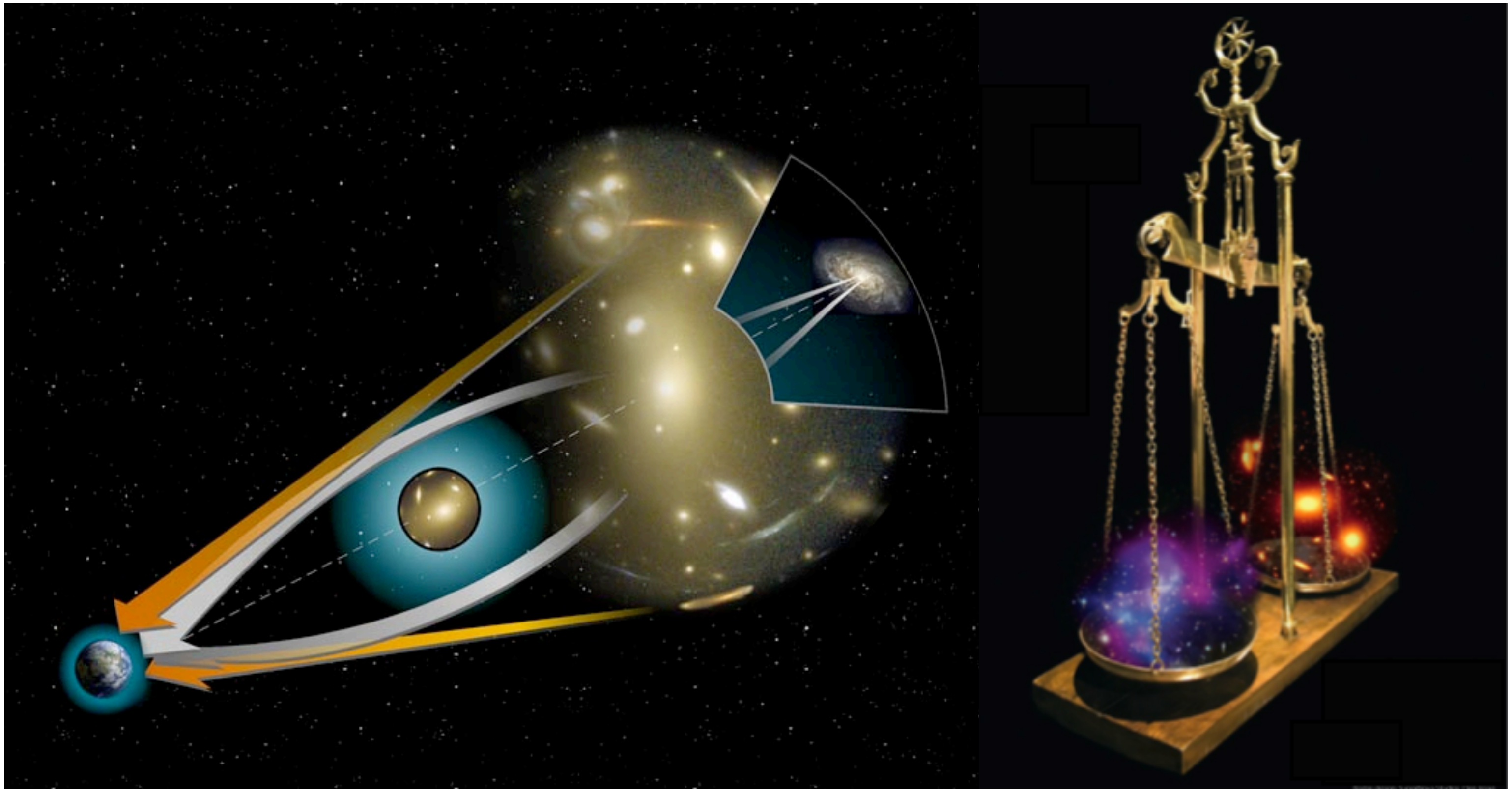
Astrophysics

Simulations

Observations

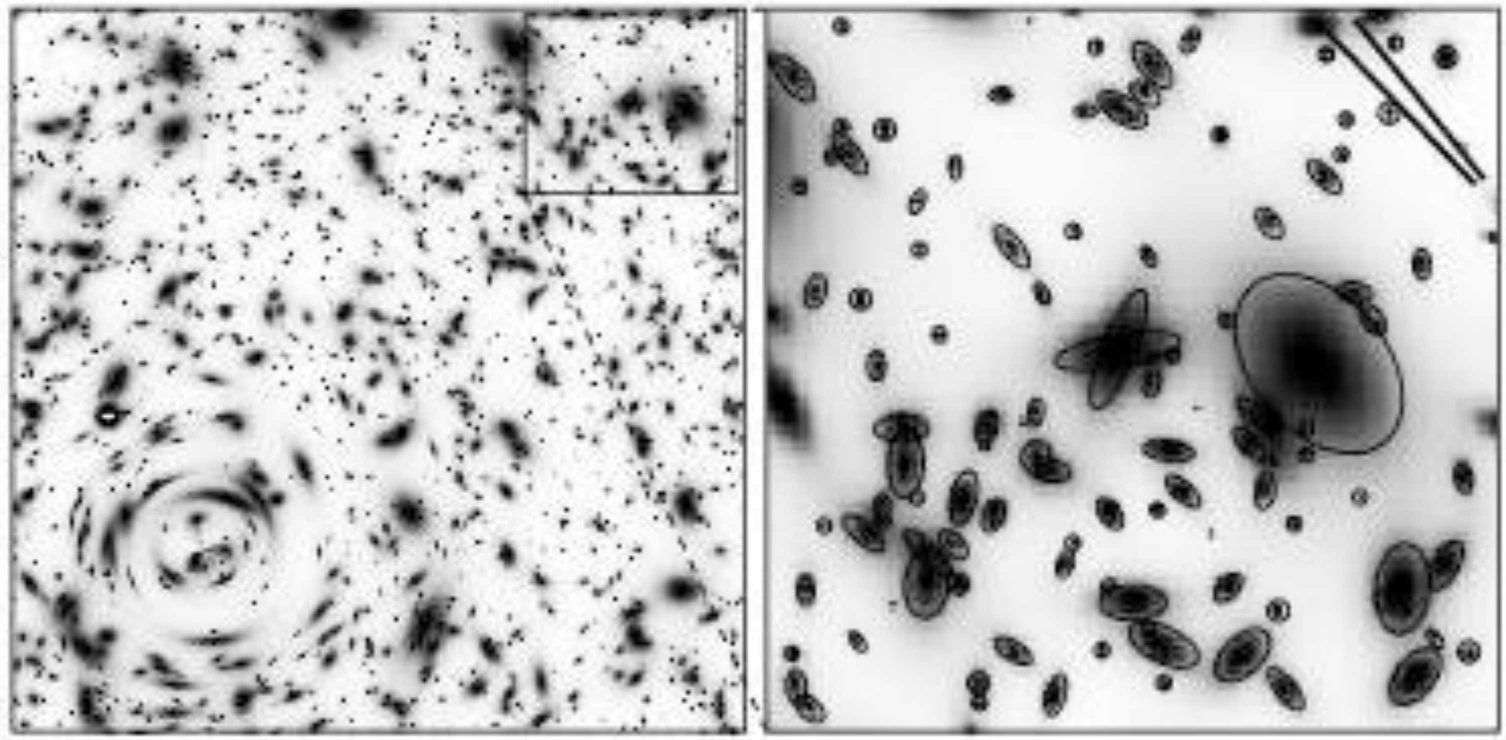
Cosmology/Galaxy Formation

# Weak gravitational lensing



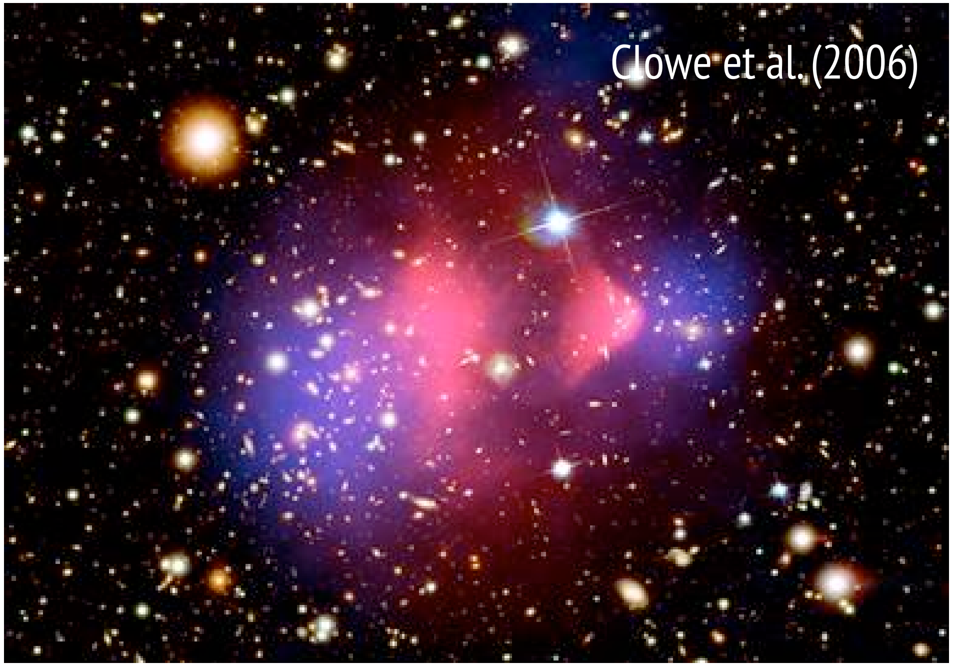
Density fluctuations in the universe affect the propagation of light rays, leading to correlations in the the *observable* shapes of galaxies.

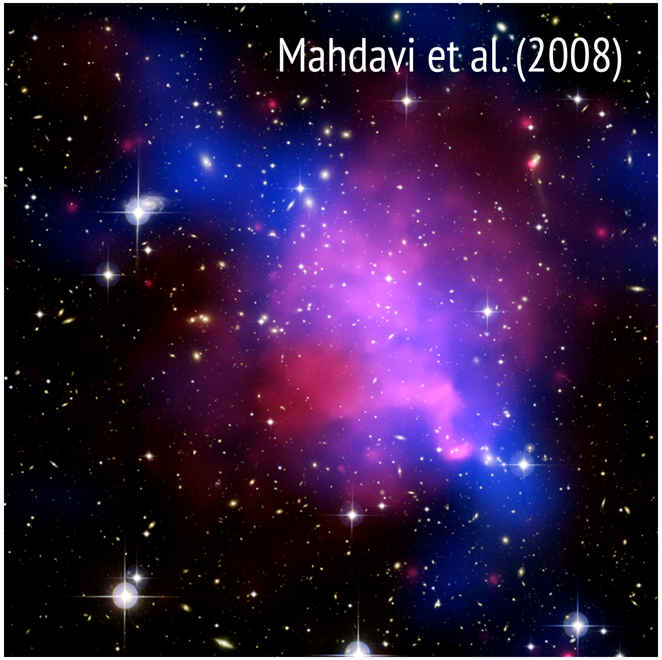
# Weak gravitational lensing



No astrophysics involved: a measurement of the ellipticity of a galaxy provides an unbiased but very noisy estimate of the shear.

# We can “see” dark matter!

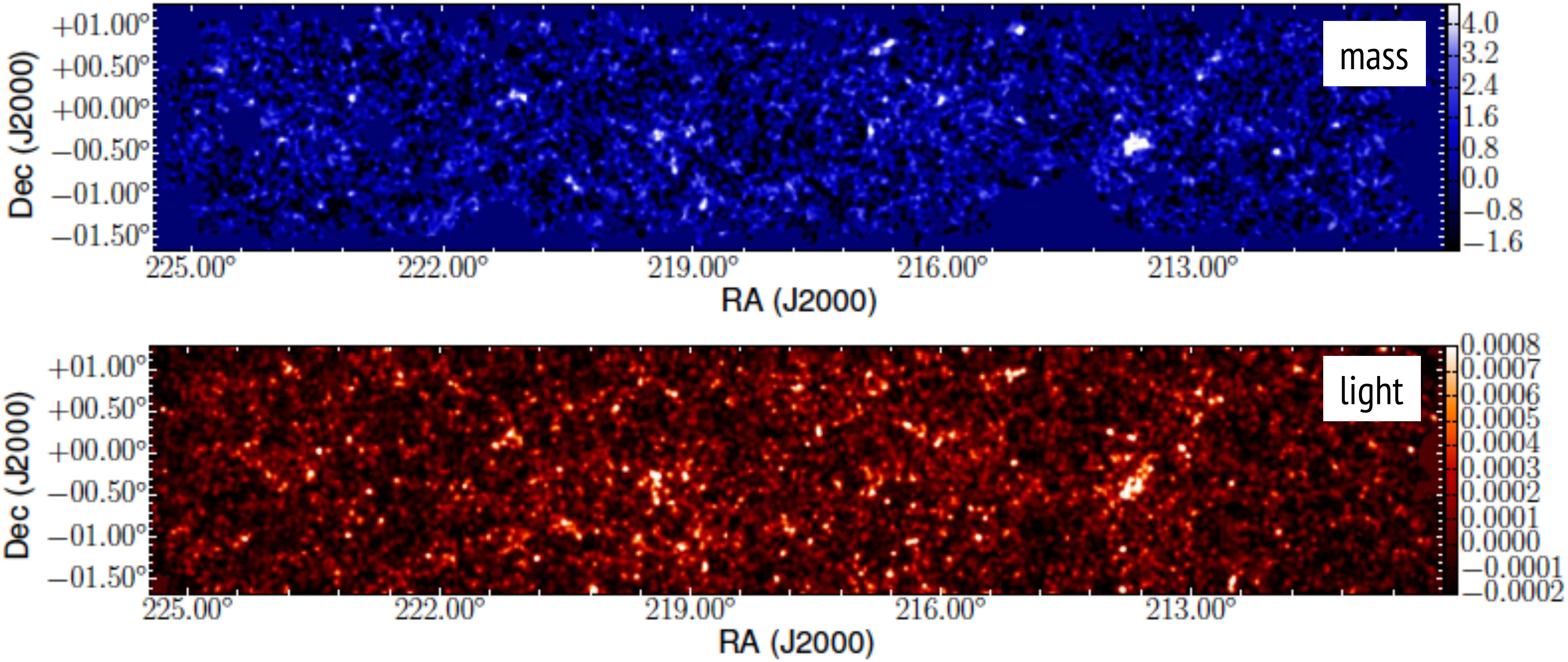

Clowe et al. (2006)


Mahdavi et al. (2008)

By averaging the shapes of many galaxies it is possible to reconstruct the (projected) matter distribution, independent of the dynamical state of the object of interest (e.g. a cluster of galaxies)

# Peaks in the matter distribution

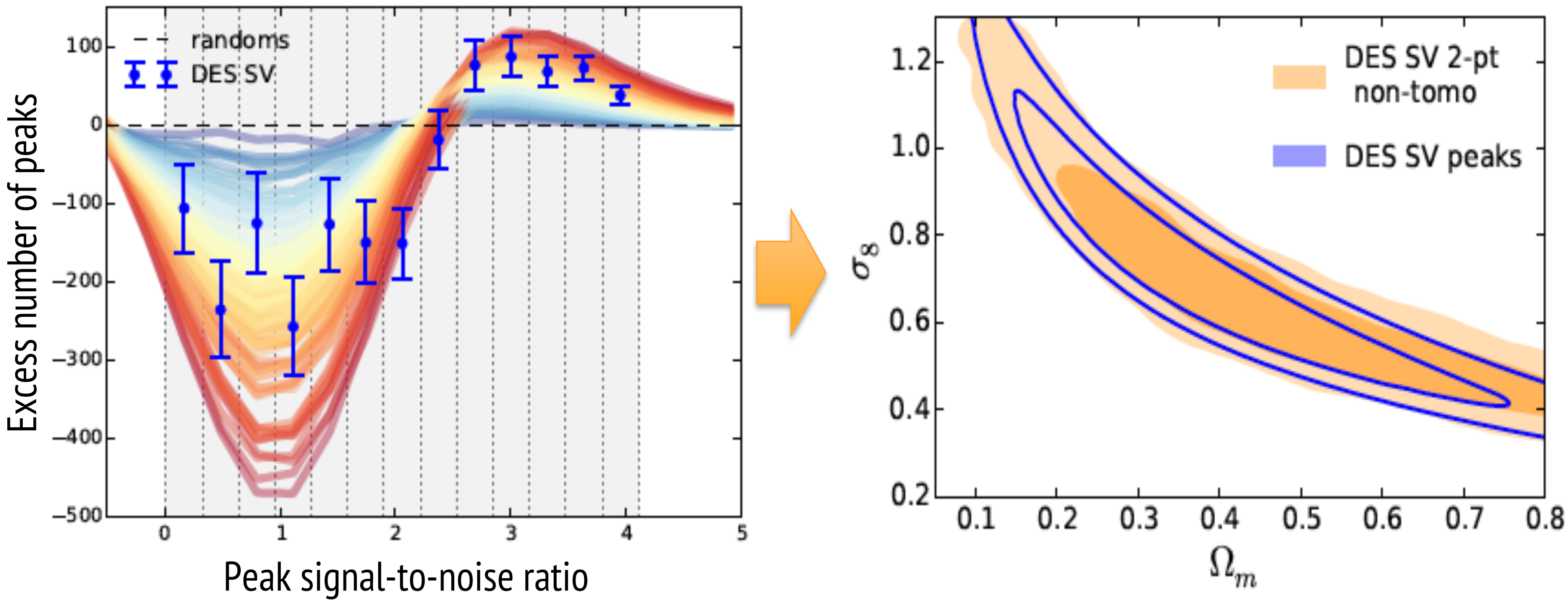
We can also instead identify peaks in the mass distribution thanks to deep imaging surveys: Oguri et al. (2017) compare the mass and light distributions in deep HSC observations.



# Peaks in the matter distribution

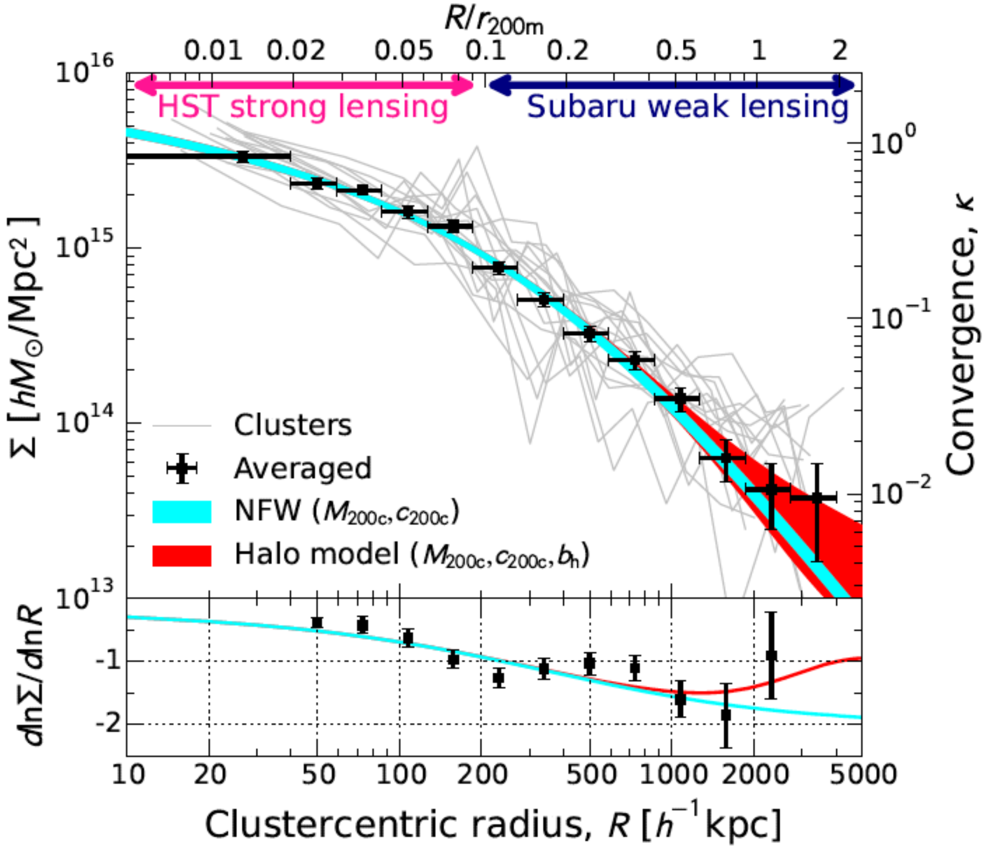
Peak statistics can complement traditional 2-point constraints, although some sources of bias need to be studied in more detail.

Constraints from DES SV data: Kacprzak et al. (2016)



# Matter distribution in clusters of galaxies

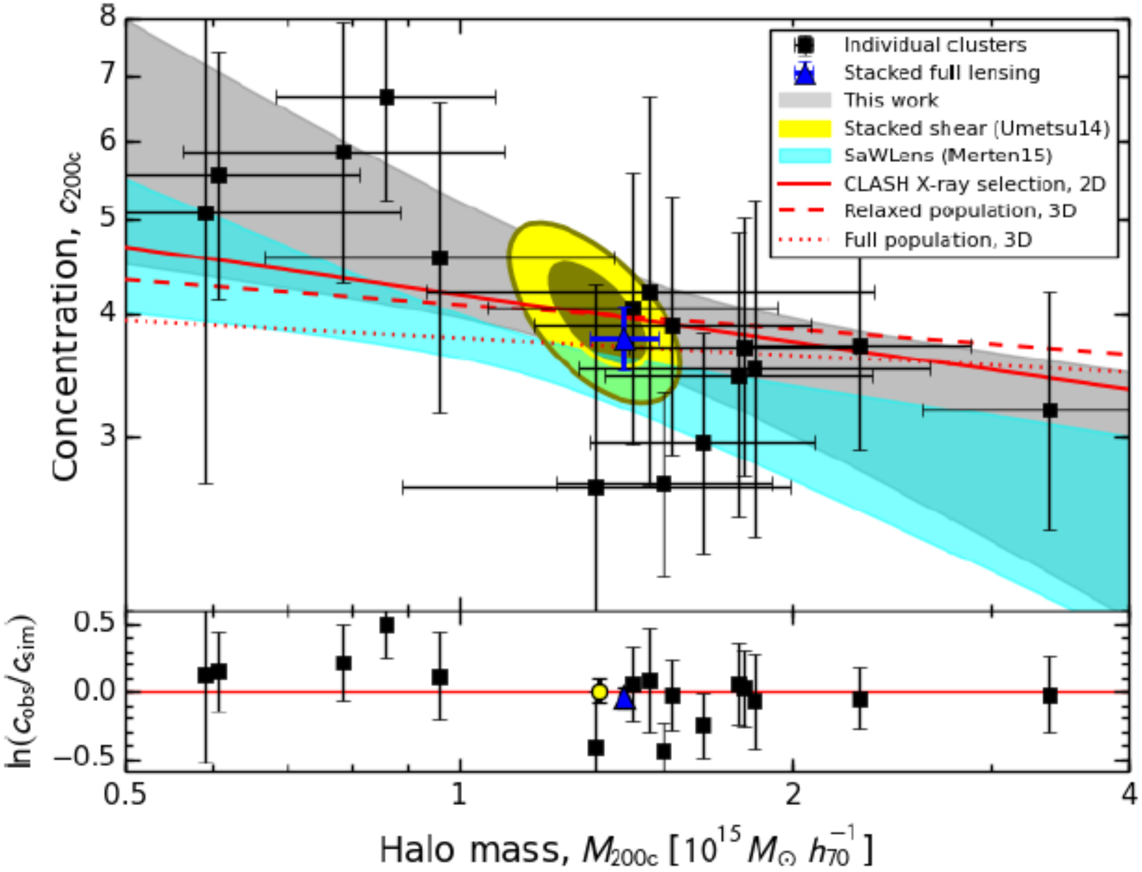
Gravitational lensing can also be used to measure the radial density profile of clusters of galaxies over a wide range in scales.



Umetsu et al. (2016): 16 clusters from CLASH

# Matter distribution in clusters of galaxies

Mass and concentration can be determined for individual massive clusters and compared to predictions from cosmological simulations.



Umetsu et al. (2016)

# What to do if the profile is not NFW?

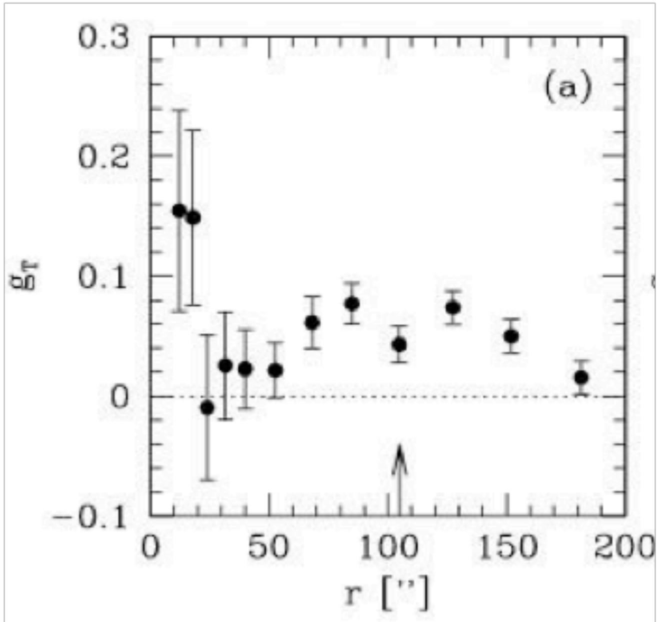
The density profile may not be described well by an NFW profile, or there may be significant substructure. This would lead to biased masses.

Lensing measures a "mass contrast": $g_T(r) \propto \langle \Sigma(<r) \rangle - \langle \Sigma(r) \rangle$

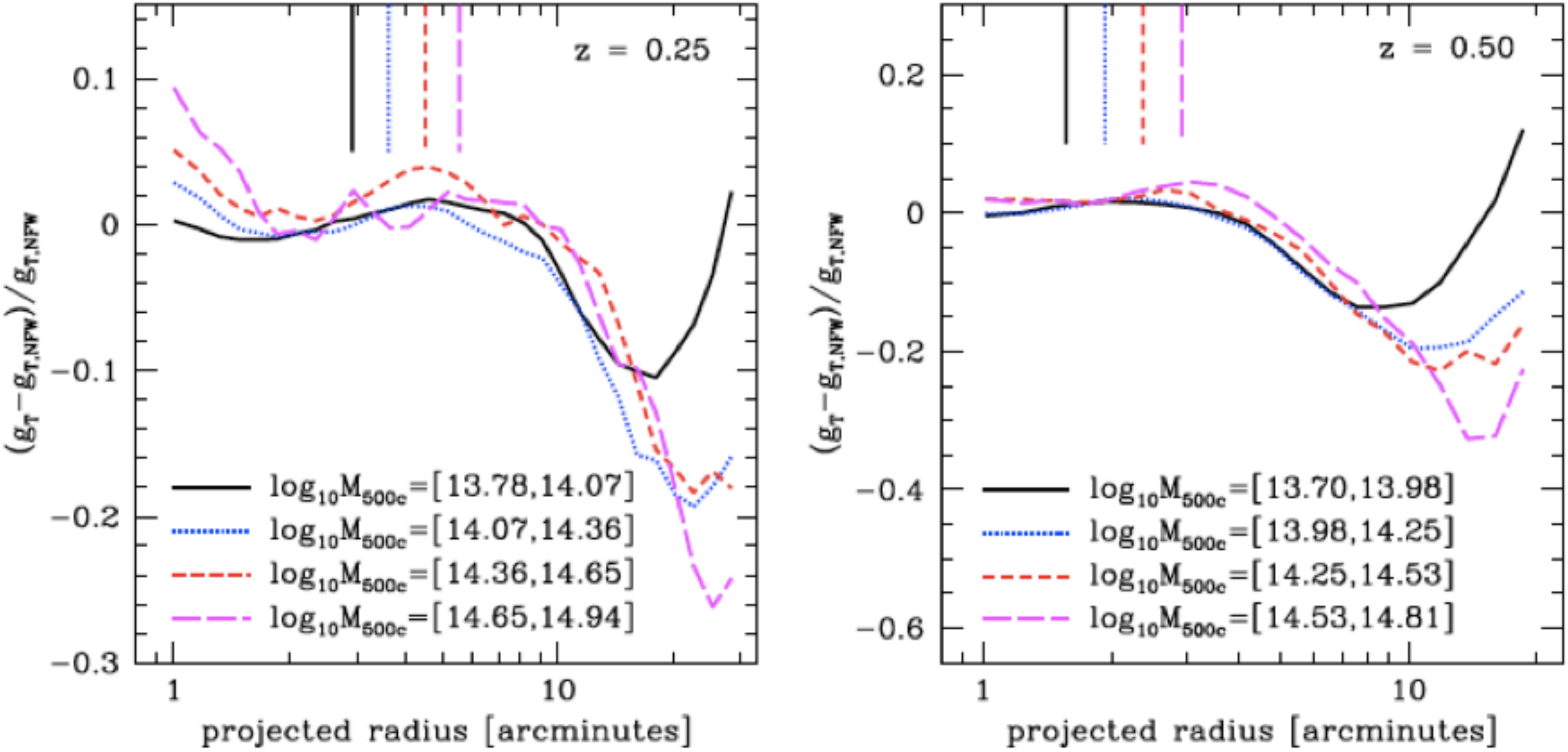
One solution is to use aperture masses (1-d mass reconstructions)

- This can minimize the model dependence
- This reduces the sensitivity to the centroid
- Reduced contamination by cluster members

***But with a reduction in precision…***



# How to interpret the signal?



Becker & Kravtsov (2011): simulations are useful to correctly *interpret* the lensing signal, especially when parametric models are fitted.

# Stacked cluster analyses

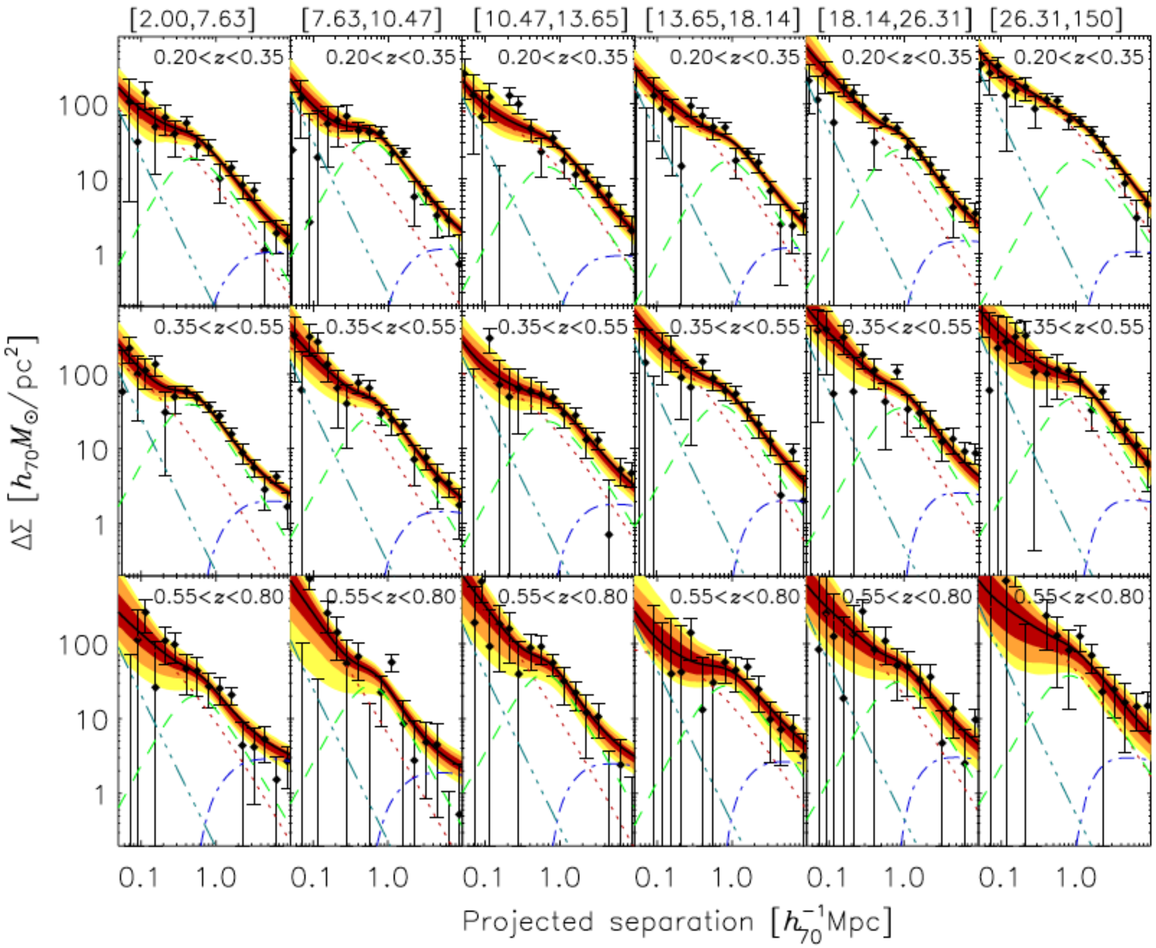
The statistical uncertainty in the weak lensing measurement does not depend on the cluster mass, but on the number density of background galaxies: the intrinsic shapes are the dominant source of uncertainty

To improve constraints for individual massive clusters we need deep HST observations (see talk by Schrabback).

Alternatively we can combine the signals of large samples of clusters, binned by an observable of interest (richness, luminosity, etc.). This allows us to extend the mass and/or redshift range.

# Ensemble averages of large samples

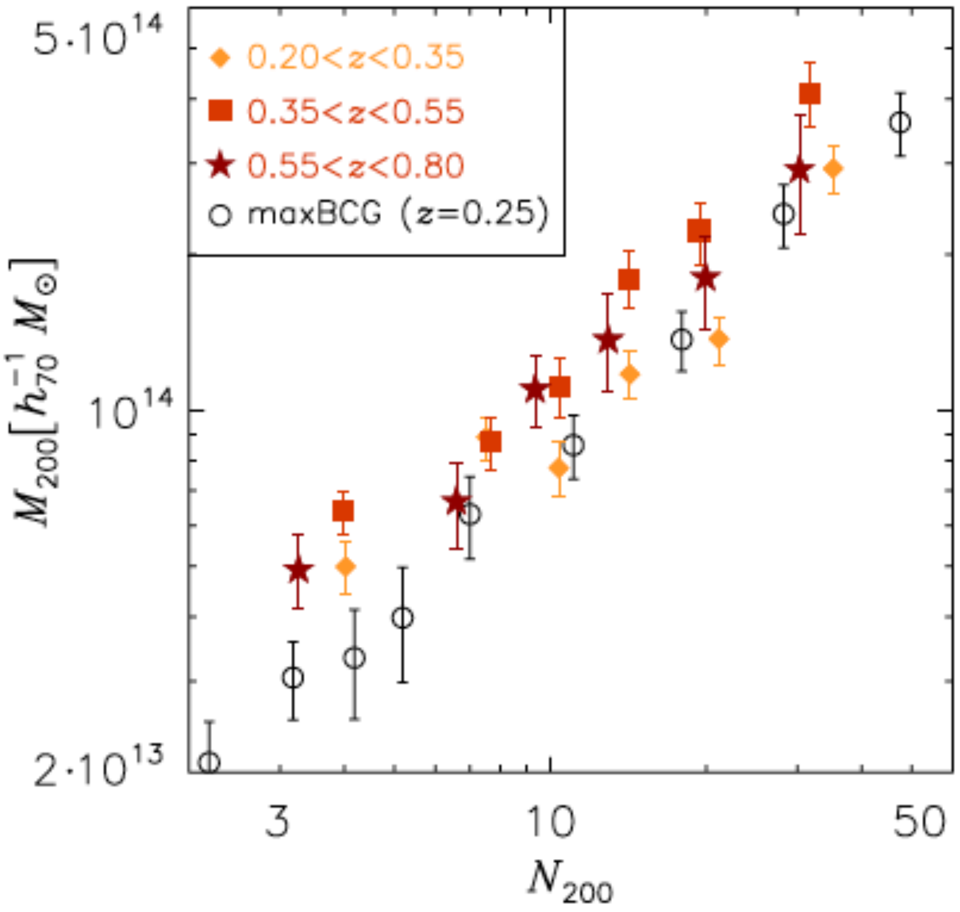
Lensing signal of $10^4$ optically selected clusters from RCS2 as a function of richness and redshift.



Van Uitert et al. (2016)

# Evolution in the mass-richness relation?

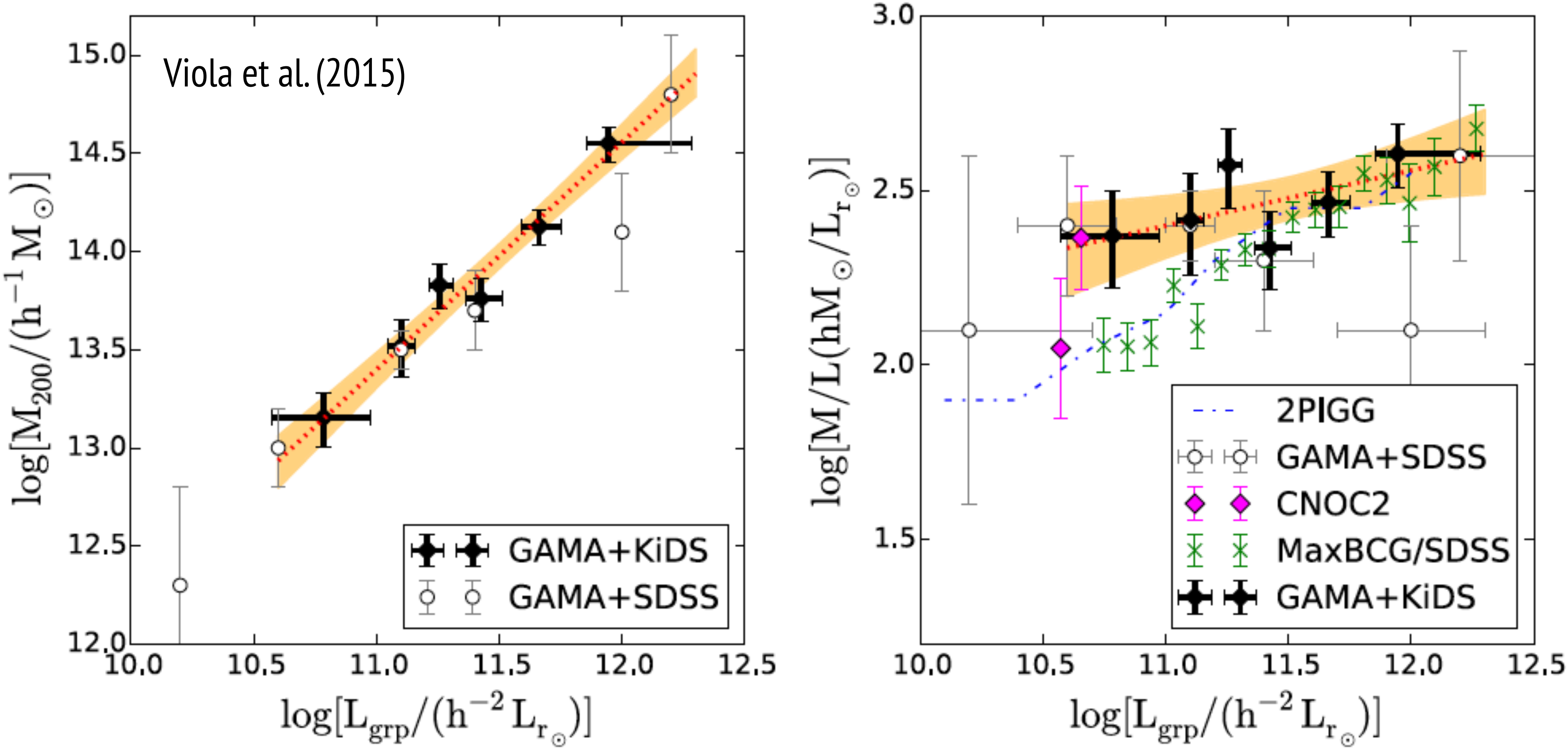
This enables studies of average scaling relations.



Van Uitert et al. (2016)

# Scaling relations for galaxy groups

It is also possible to extend studies to lower mass systems.



# Interpretation of stacked scaling relations

To interpret the stacked signal we need to understand the underlying population: correlations between parameters of interest can bias the result.

The best strategy is to define samples using an (independent) indicator and stack the observables of interest.

Realistic cosmological simulations can also be very helpful in interpreting scaling relations and in identifying various selection biases. The simulations themselves benefit from comparisons to the observations as well.

# Studies of individual massive clusters

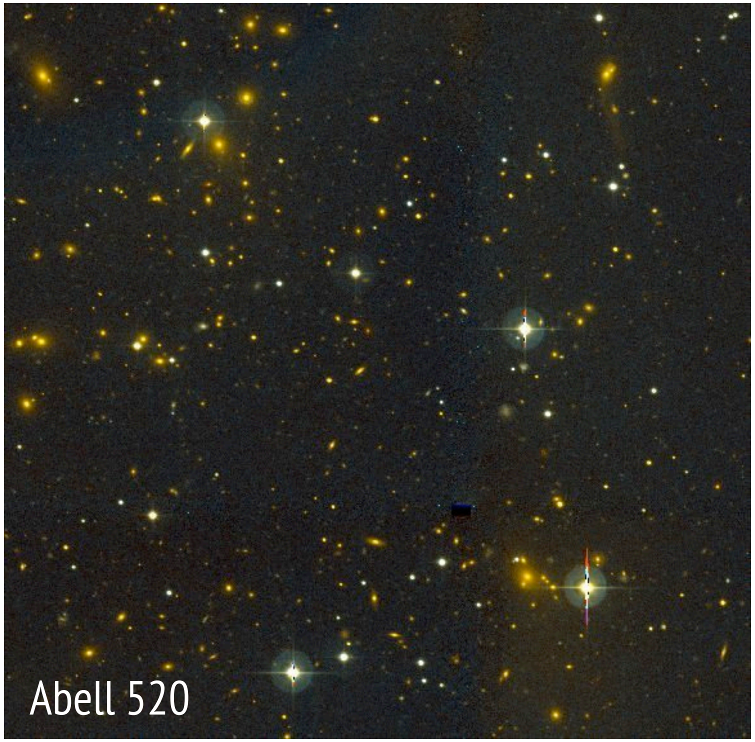
Thanks to wide-field imagers on 4-8m class telescopes it is possible to study significant samples of massive clusters of galaxies.

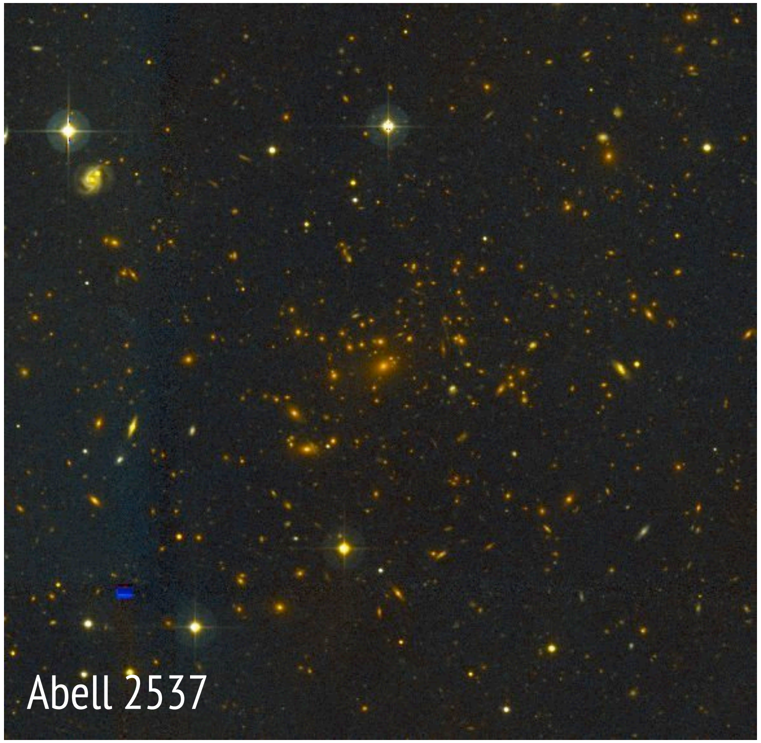
**Canadian Cluster Comparison Project (CCCP):**
50 clusters with $0.15<z<0.55$
**Multi-Epoch Nearby Cluster Survey (MENeaCS):**
48 clusters with $0.05<z<0.15$
**Weighing the Giants (WtG):**
51 clusters with $0.15<z<0.7$
**Local Cluster Substructure Survey (LoCuSS):**
50 clusters with $0.15<z<0.3$
**Cluster Lensing And Supernova survey with Hubble (CLASH):**
20 clusters with $0.2<z<0.55$

With such large samples, systematic uncertainties are comparable to the statistical uncertainties.

# Canadian Cluster Comparison Project

Our motto: *CCCP is good for the masses!*

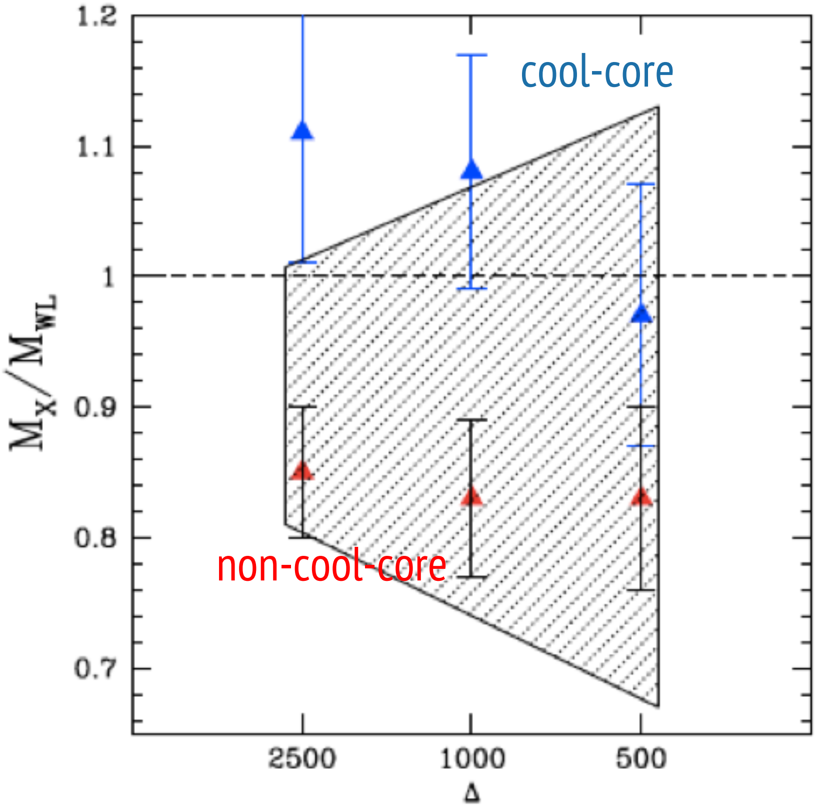




The Canadian Cluster Comparison Project is a comprehensive study of 50 massive clusters with $0.2<z<0.55$ with the aim to compare accurate lensing masses to X-ray observations.

# Calibrating other mass proxies

Mahdavi et al. (2013) studied how the weak lensing masses compare to estimates based on X-ray observations, assuming hydrostatic equilibrium: $M_{HSE}(r_{500})=(0.88\pm0.05)\times M_{WL}(r_{500})$.



Mahdavi et al. (2013)

# How accurate are cluster lensing masses?

So far we implicitly assumed that the lensing masses are accurate. Is this a reasonable assumption?

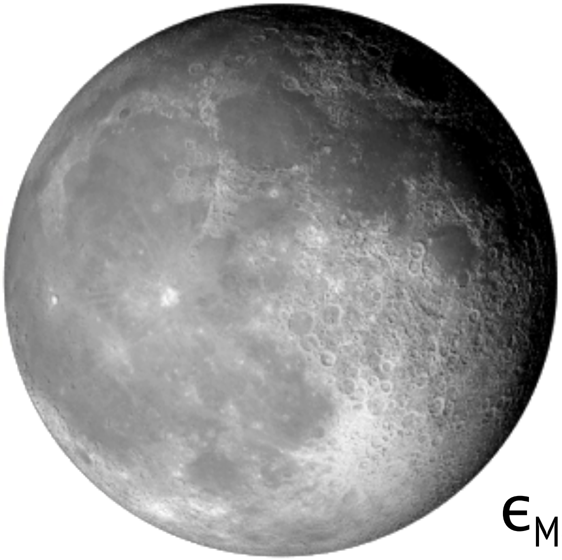
**Key ingredients:**

- Accurate shapes (corrected for instrumental effects)
- Accurate knowledge of the source redshift distribution
- Accurate removal/accounting of cluster members
- Need to account for cluster geometry

# The very slightly distorted Universe

To infer unbiased cluster masses, we need to ensure that the measurement of the galaxy ellipticities is sufficiently accurate. In the case of future projects, such as *Euclid*, this means that the bias in the shear is <0.2%.

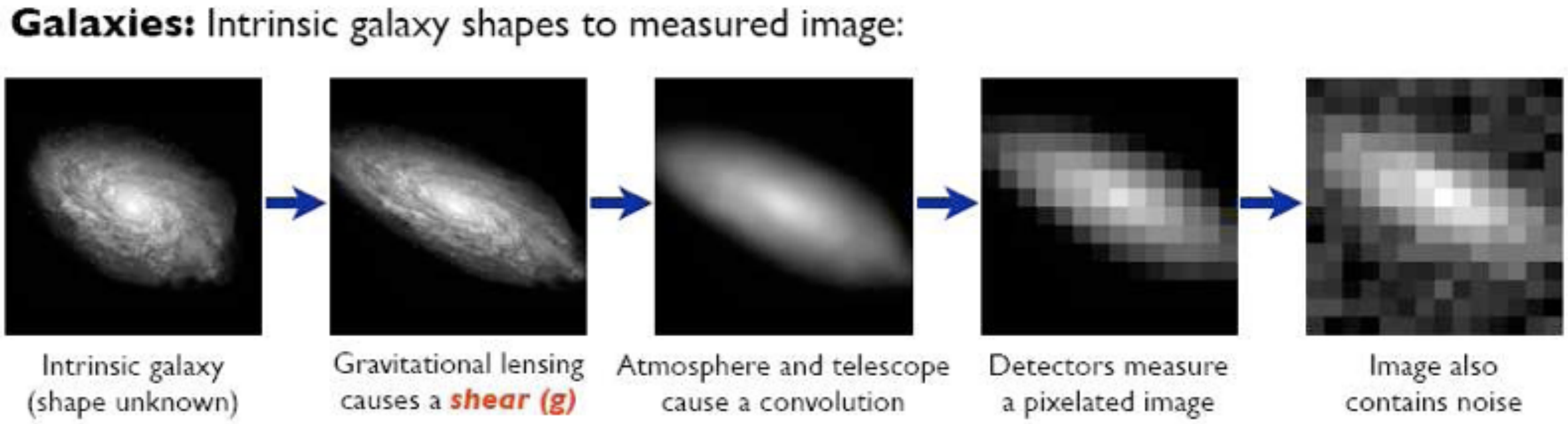
$\epsilon_{\mathrm{Earth}}=0.00335$



$\epsilon_{\mathrm{Moon}}=0.00125$

# The importance of image simulations

The observed images are “corrupted” by the PSF which needs to be corrected for with high accuracy, but also by detector effects.

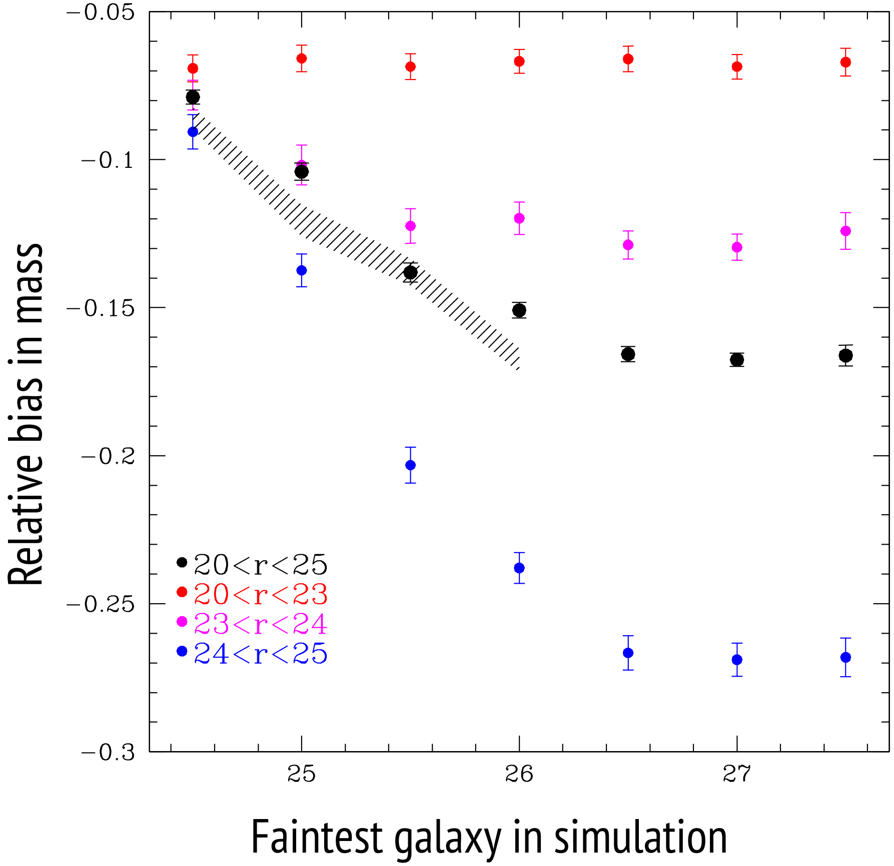


GREAT'08 challenge

The accuracy of weak lensing measurements can be determined using image simulations. However, the results are only meaningful if the simulations match the data!

# The importance of realistic image simulations

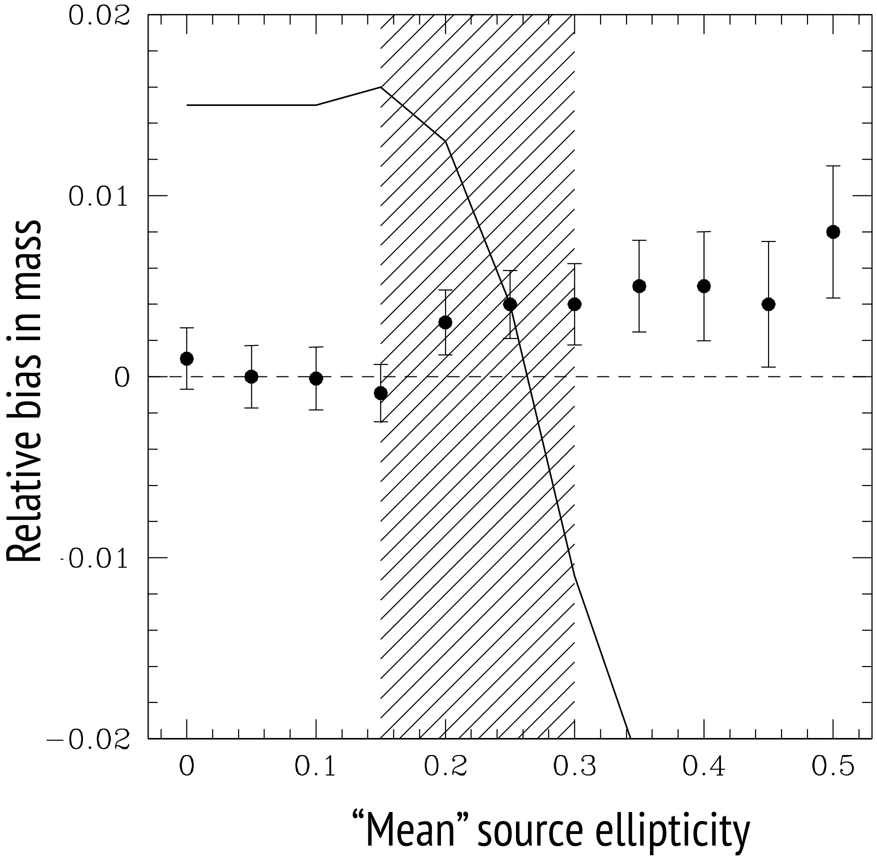
For instance we cannot ignore the impact of faint (undetected) galaxies that affect the background determination. Or the impact of blending, stars, etc.



Hoekstra et al. (2015)

# Calibration of the algorithm

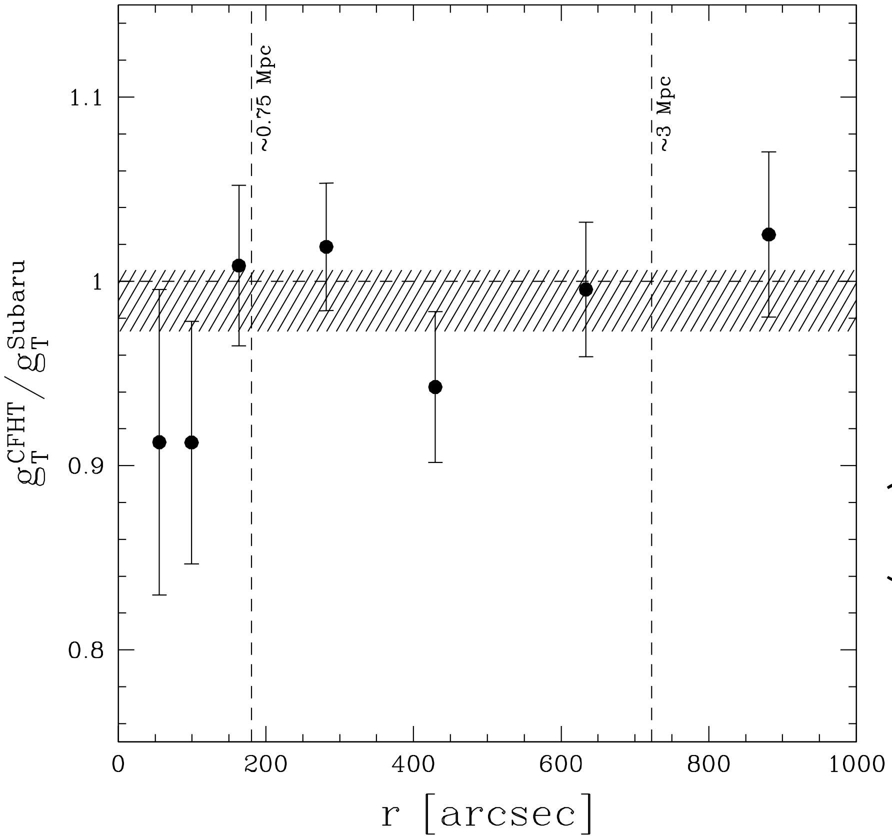
Using extensive image simulations we obtained an empirical correction that is accurate to ~1%. Improving this further requires significant work.



Hoekstra et al. (2015)

# Comparison with Subaru data

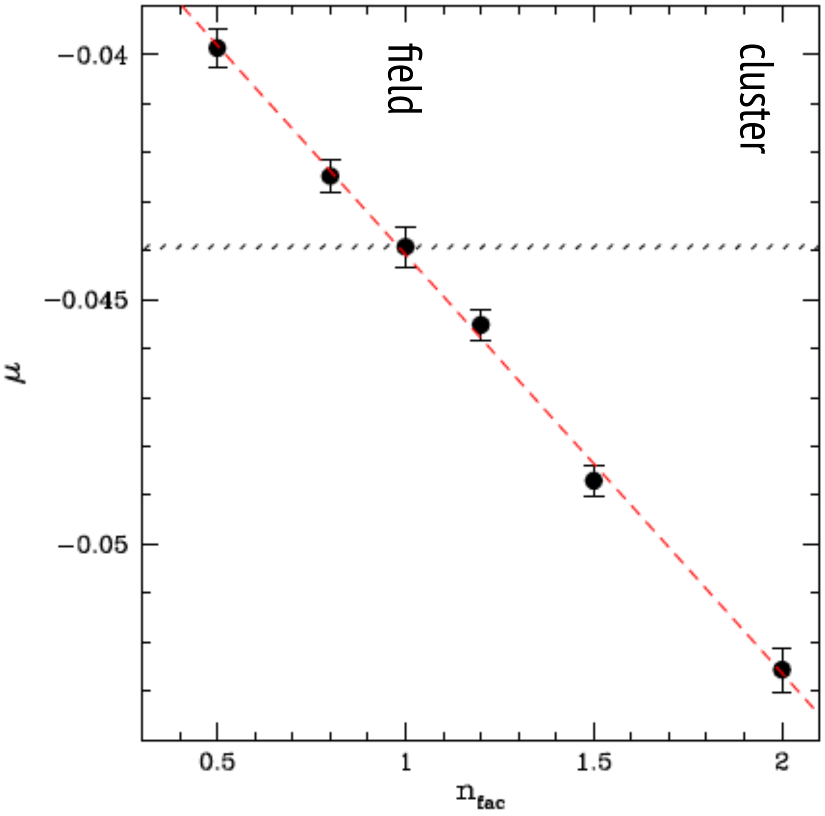
When we match the catalogs the difference is 1±2%. We find a similar result when we compare to the Weighing the Giants catalog provided by Anja von der Linden.



Hoekstra et al. (2015)

# To do much better requires a lot of work

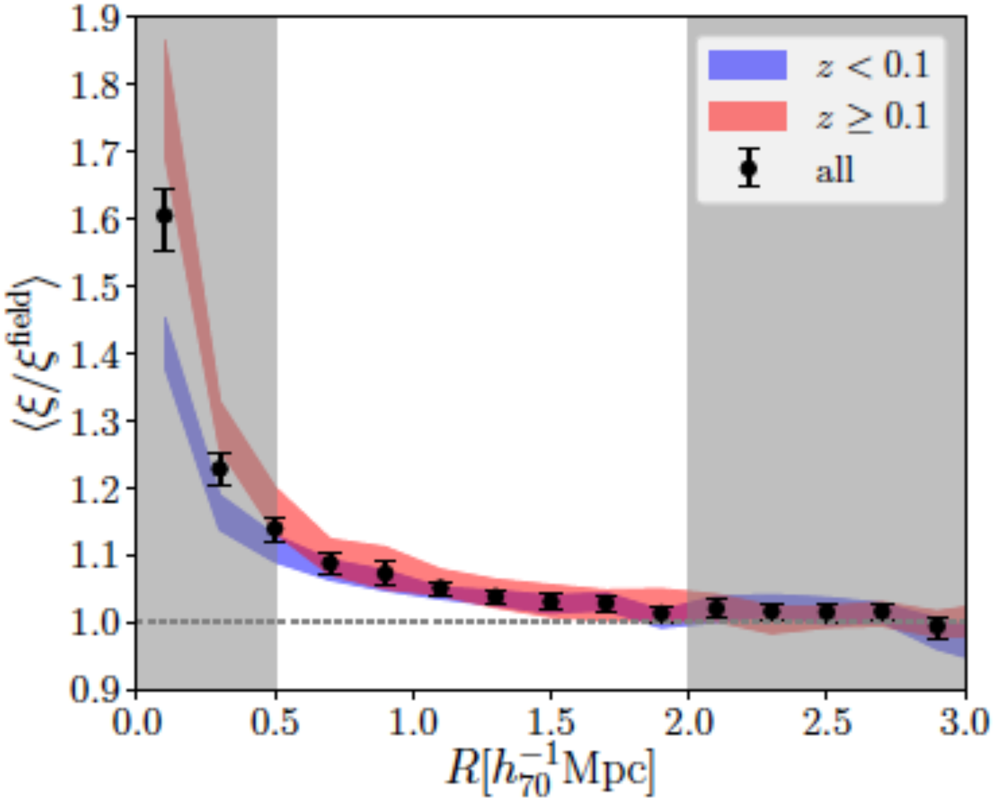
At the sub-percent level the bias depends on many additional factors, such as local galaxy density. This needs to be accounted for in future cluster studies (but also for cosmic shear).



Hoekstra et al. (2017)

# Contamination by cluster members

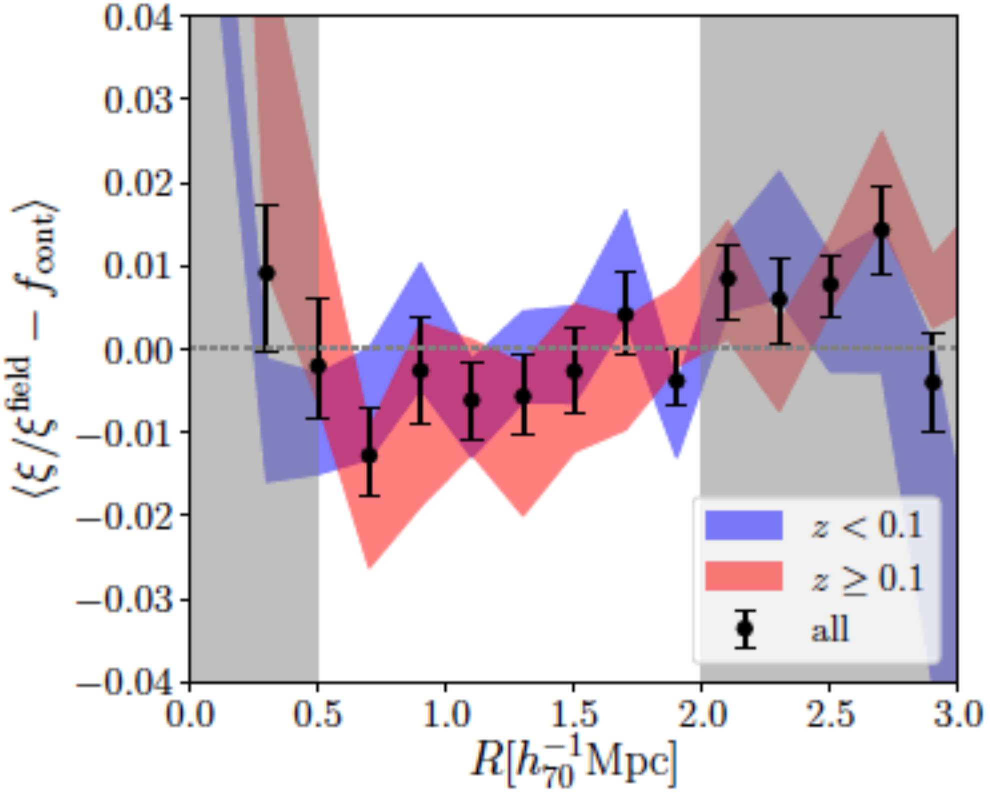
Galaxy clusters are full of galaxies. Without individual photometric redshifts (which is the case for CCCP and MENeaCS) these galaxies contaminate the source sample.



Herbonnet et al. (in prep.)

# Contamination by cluster members

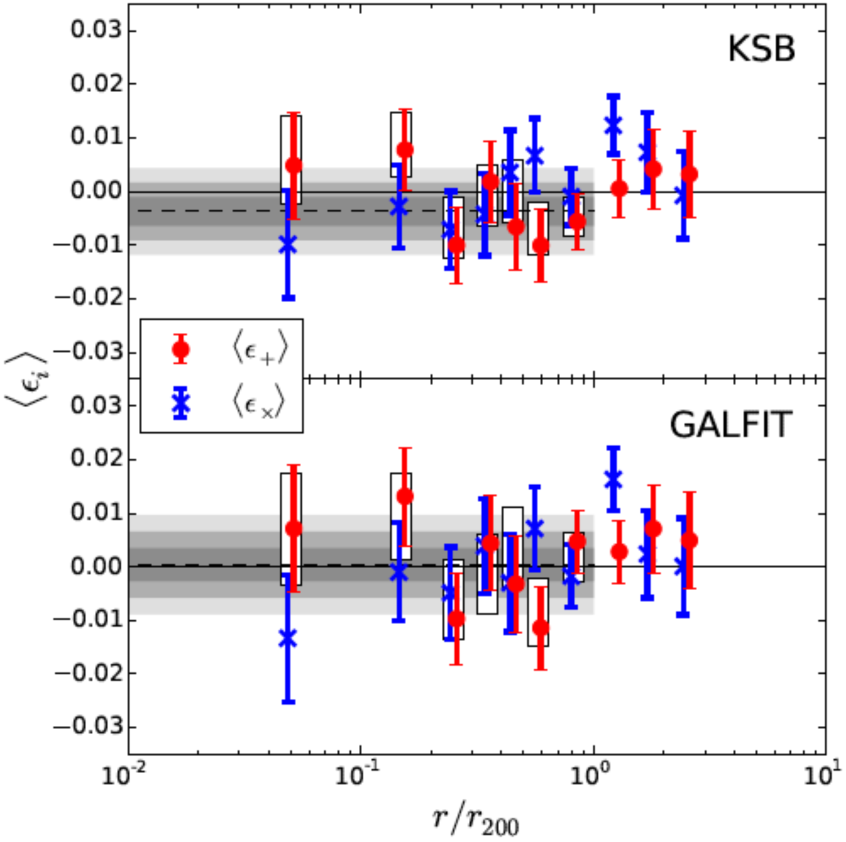
But we can model this, at least in an ensemble averaged sense. For larger cluster samples photometric redshifts for the sources are necessary, unless cleverly chosen filter combinations are used (e.g. Schrabback et al. 2016).



Herbonnet et al. (in prep.)

# (no) alignments of cluster members

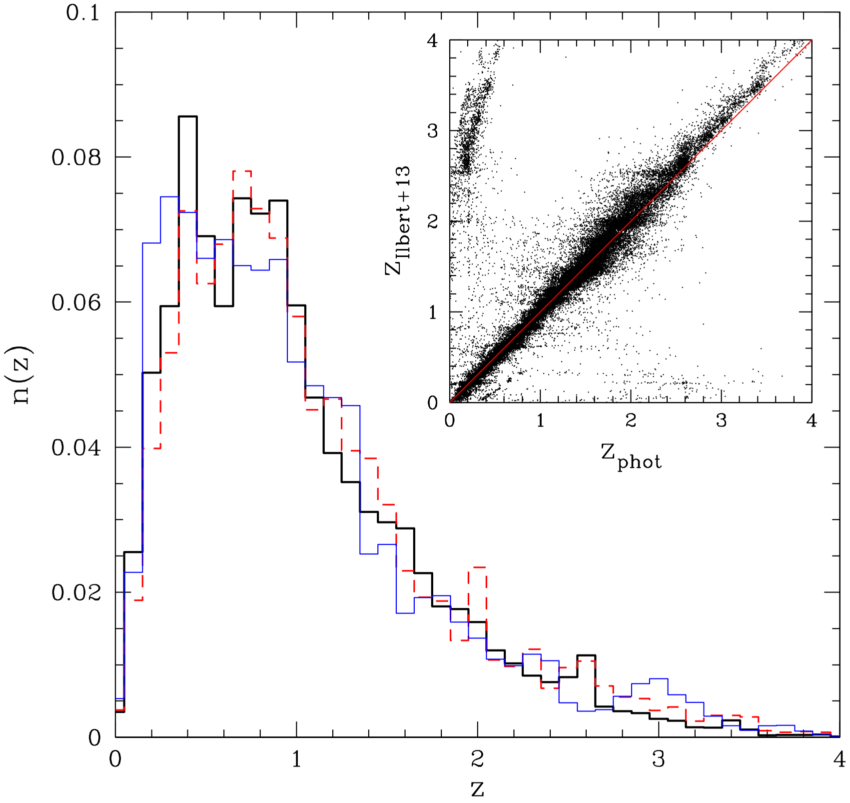
This correction does assume that cluster galaxies are not aligned radially (or tangentially): no evidence for such alignments.



Sifon et al. (2015)

# The importance of source redshifts

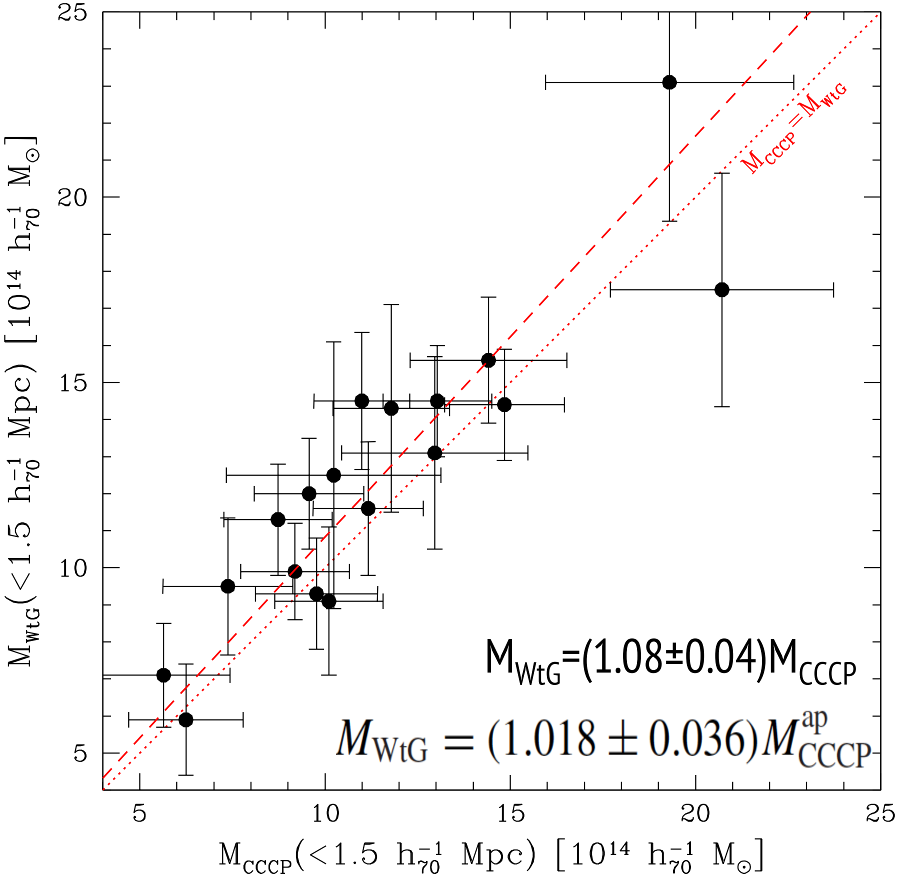
Thanks to deep NIR data from UltraVISTA the COSMOS-30 photometric redshifts are now more reliable. However, the uncertainty in the n(z) of the sources remains a dominant source of systematic uncertainty.



Hoekstra et al. (2015)

# Comparison with WtG

We follow the fitting approach of Applegate et al. (2014) and measure the corresponding masses, which agree fairly well.

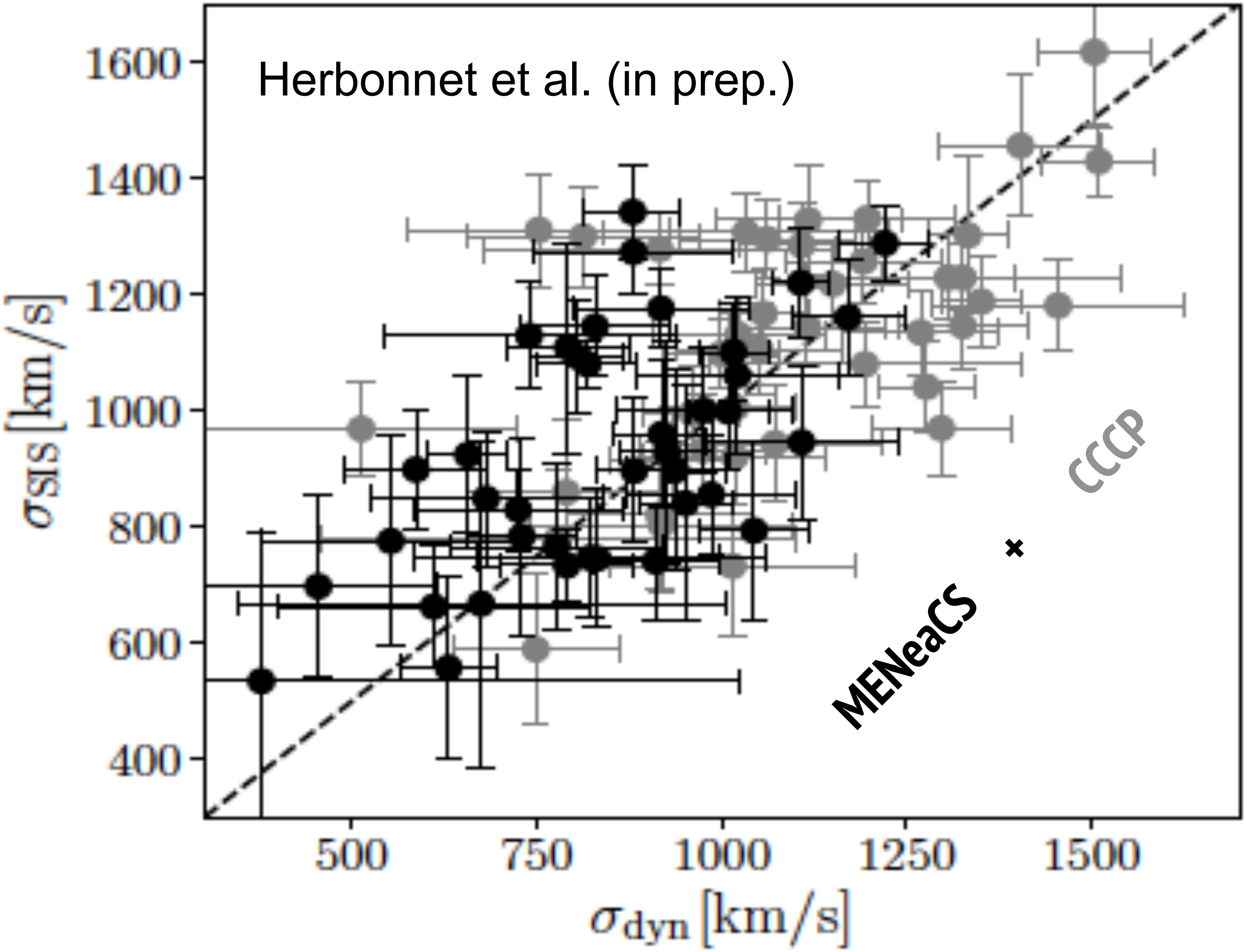


$M_{WtG}=(1.08±0.04)M_{CCCP}$

$$M_{\mathrm{WtG}} = (1.018 \pm 0.036) M^{\mathrm{ap}}_{\mathrm{CCCP}}$$

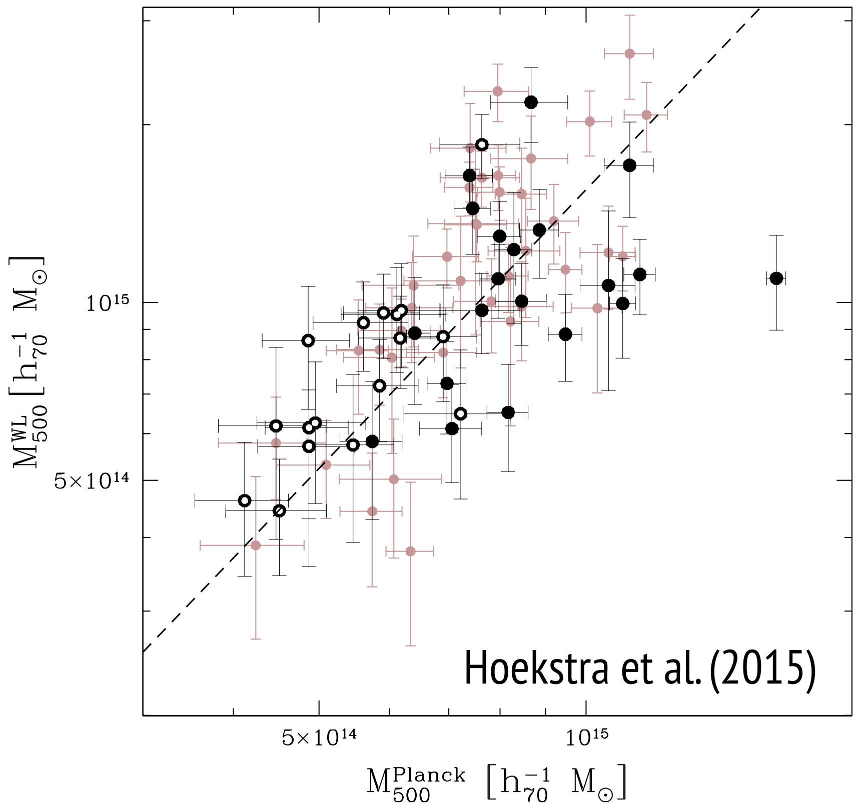
Hoekstra et al. (2015)

# Comparison to dynamical estimates

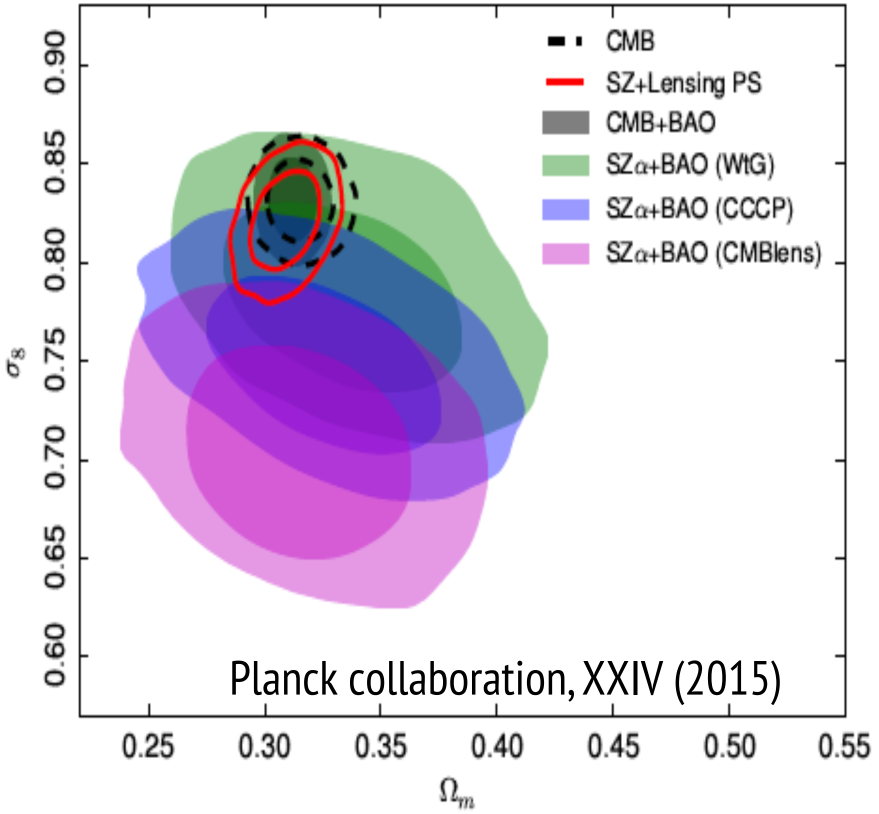


Herbonnet et al. (in prep.)

# Comparison to Planck masses



Hoekstra et al. (2015)

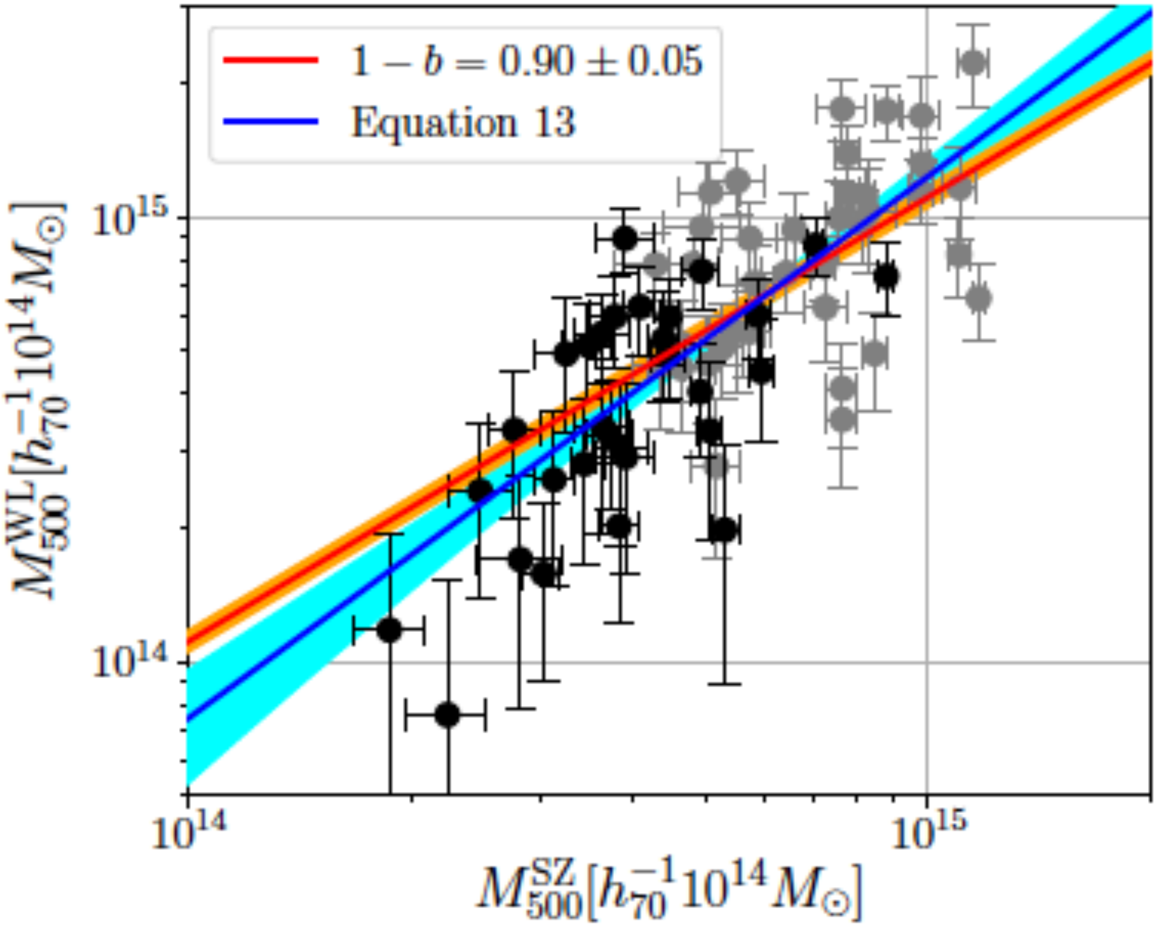


Planck collaboration, XXIV (2015)

CCCP: $M_{Planck} = (0.76\pm0.05)\ M_{WL}$

# Scaling relations with extended sample

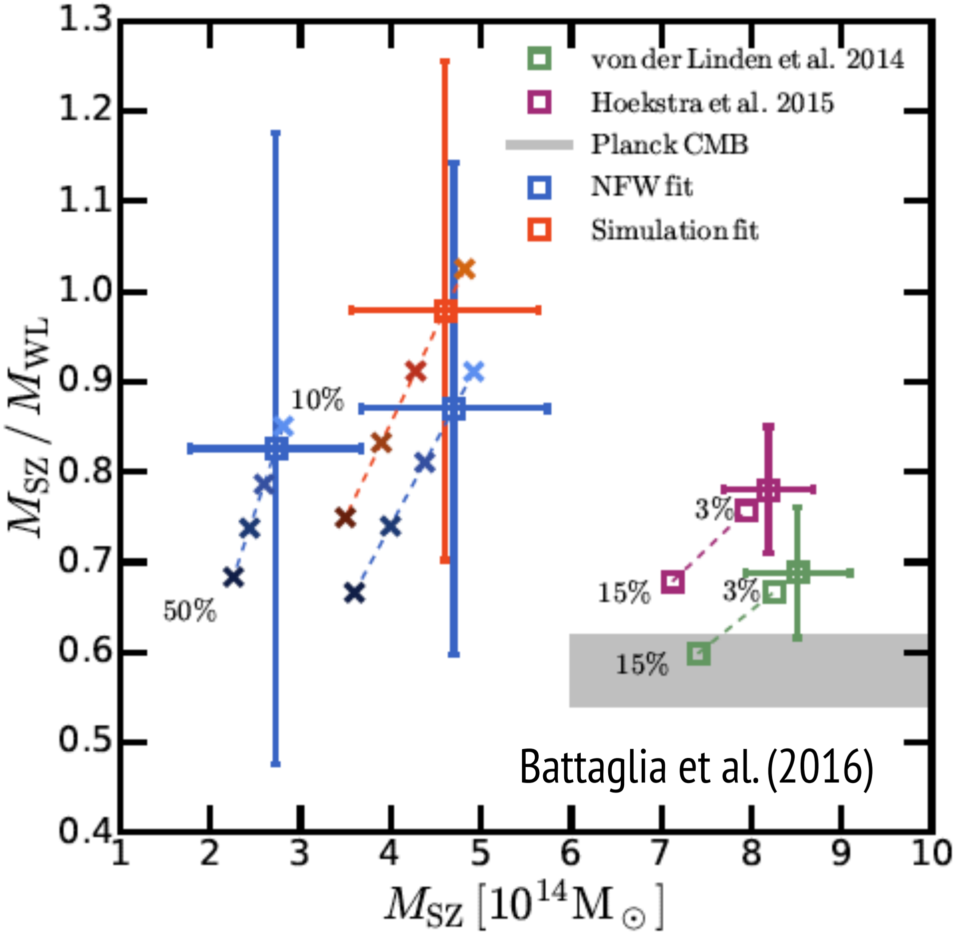
$$\frac{M_{500}^{\mathrm{SZ}}}{10^{15} M_\odot} = (0.84 \pm 0.07) \left( \frac{M_{500}^{\mathrm{WL}}}{10^{15} M_\odot} \right)^{(0.82 \pm 0.08)} \qquad (13)$$



Herbonnet et al. (in prep.)

# Eddington bias correction

Scaling relations should account for the sample selection: Eddington bias is expected to be relevant at the low mass end.



Battaglia et al. (2016)

# Systematic error budget

Shape measurement: ~1%
Contamination by members: ~2%
Photometric redshifts: 2-8% (depending on cluster redshift)

Density profile: <1% (projected mass)
7-9% (spherical overdensity)

We need better redshift knowledge, not necessarily better images
The use of masses in apertures defined with respect to a density introduces additional uncertainties, which can easily be avoided...

To improve further we need to “observe” realistic cluster simulations.

# What is next?

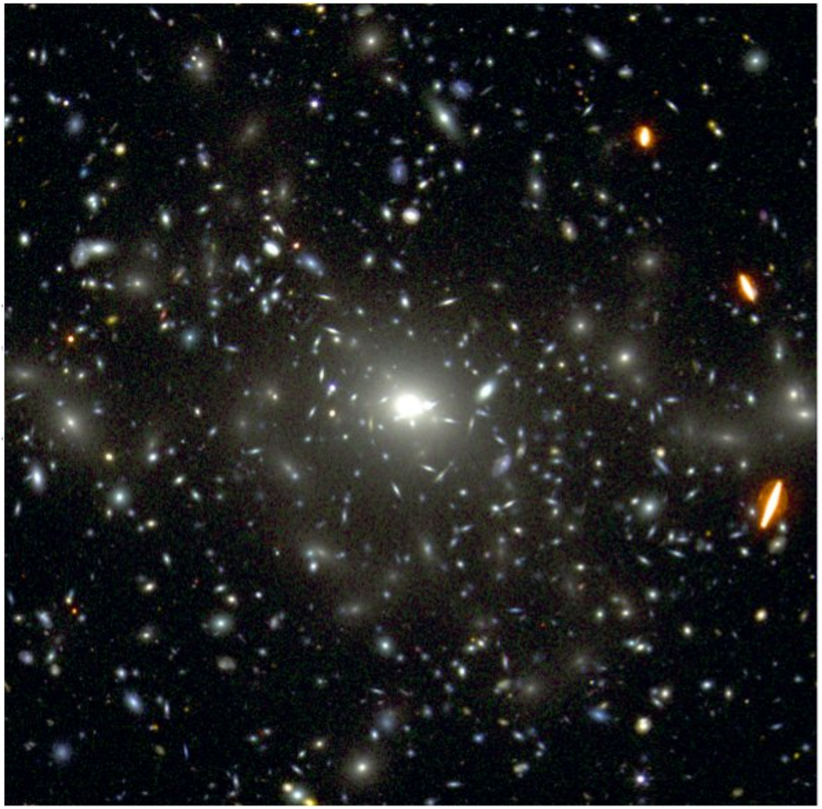
# Euclid: a satellite designed to do weak lensing

Euclid will survey 15000 $deg^2$

Optical (VIS) data: excellent for WL shape measurements.

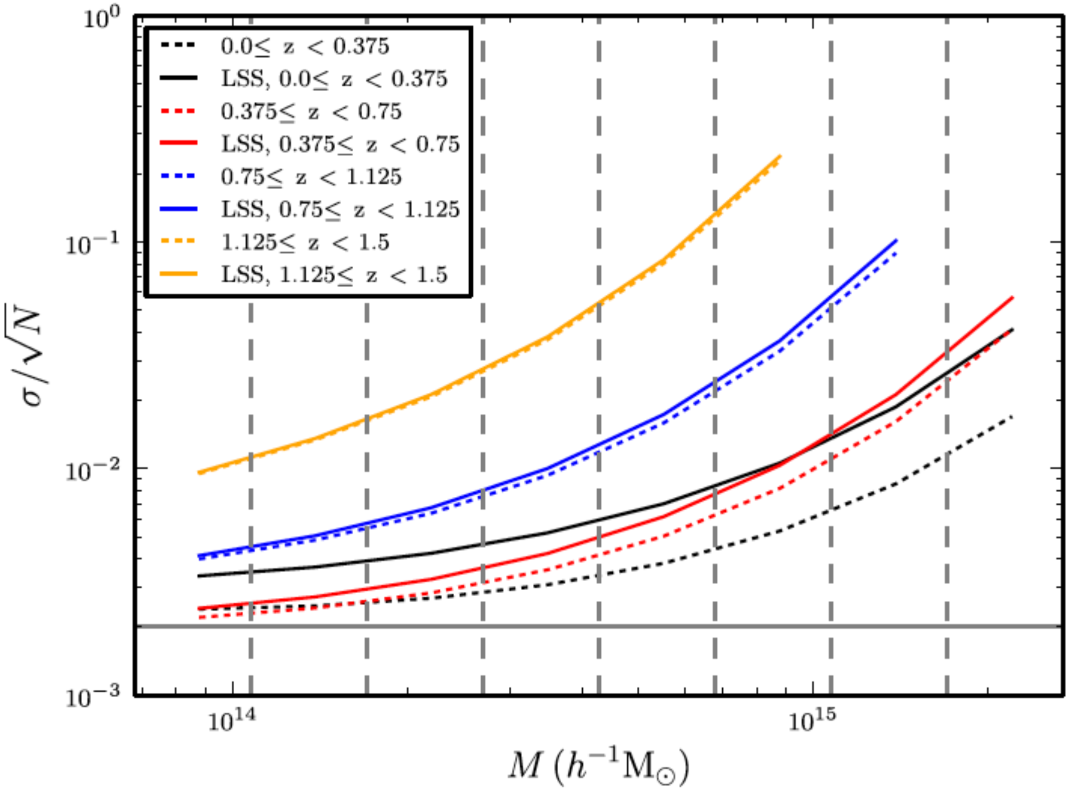
NIR (YJH) imaging down to $m_{AB}$~24 will be great to find high-z clusters.

Euclid is expected to find 5000 cluster strong lenses.



Cosmic shear studies drive the requirements for the weak lensing measurements: are these sufficient for cluster studies?

# Euclid will be limited by shape noise



Köhlinger et al. (2015): the statistical uncertainties are larger than the systematic errors. But we do need to account for cluster members scattering into the source sample and the mis-centring distribution.

# We can get the masses right...

# Conclusions

Weak gravitational lensing has become the prime calibration of cluster masses. This is a major shift from ~15 years ago!

For current samples the systematic uncertainties are subdominant. To achieve (sub)percent accuracy requires significant effort, including careful comparison to realistic cluster simulations.

Many of the improvements will come naturally thanks to future cosmic shear surveys.