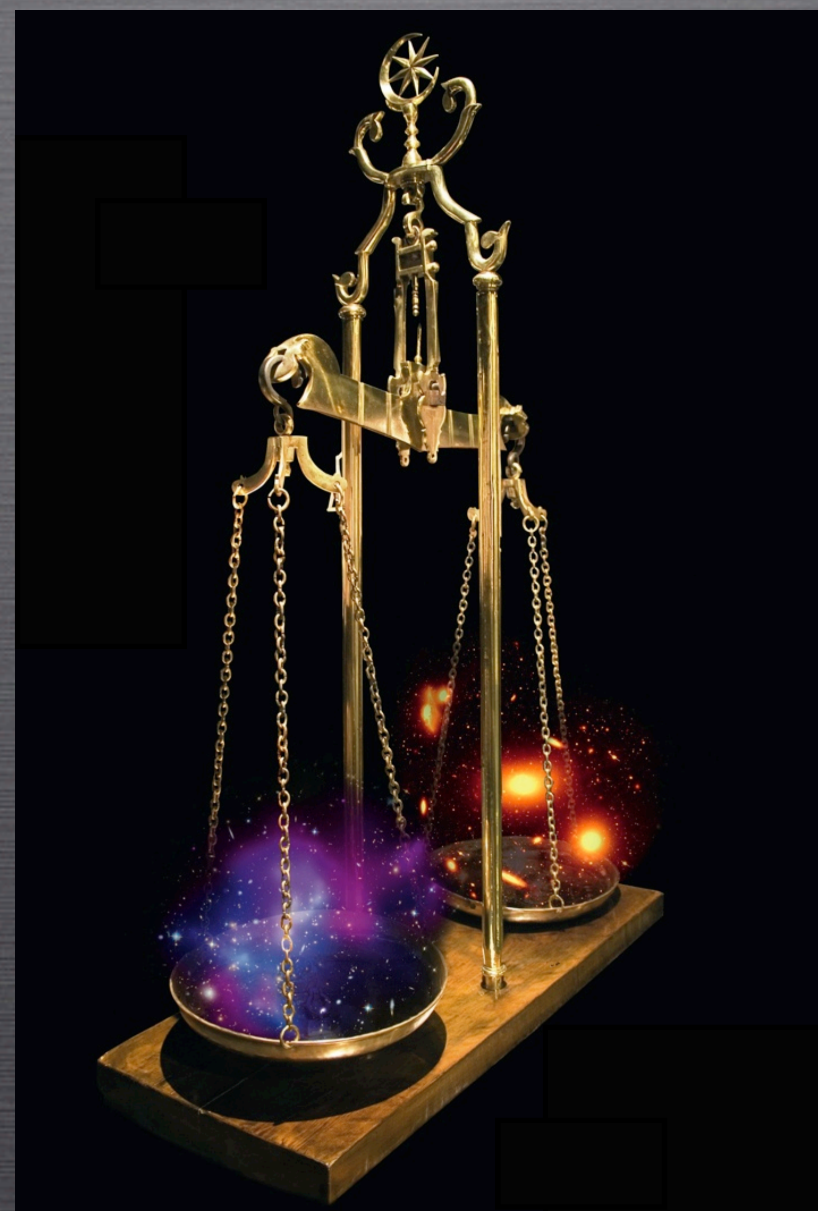
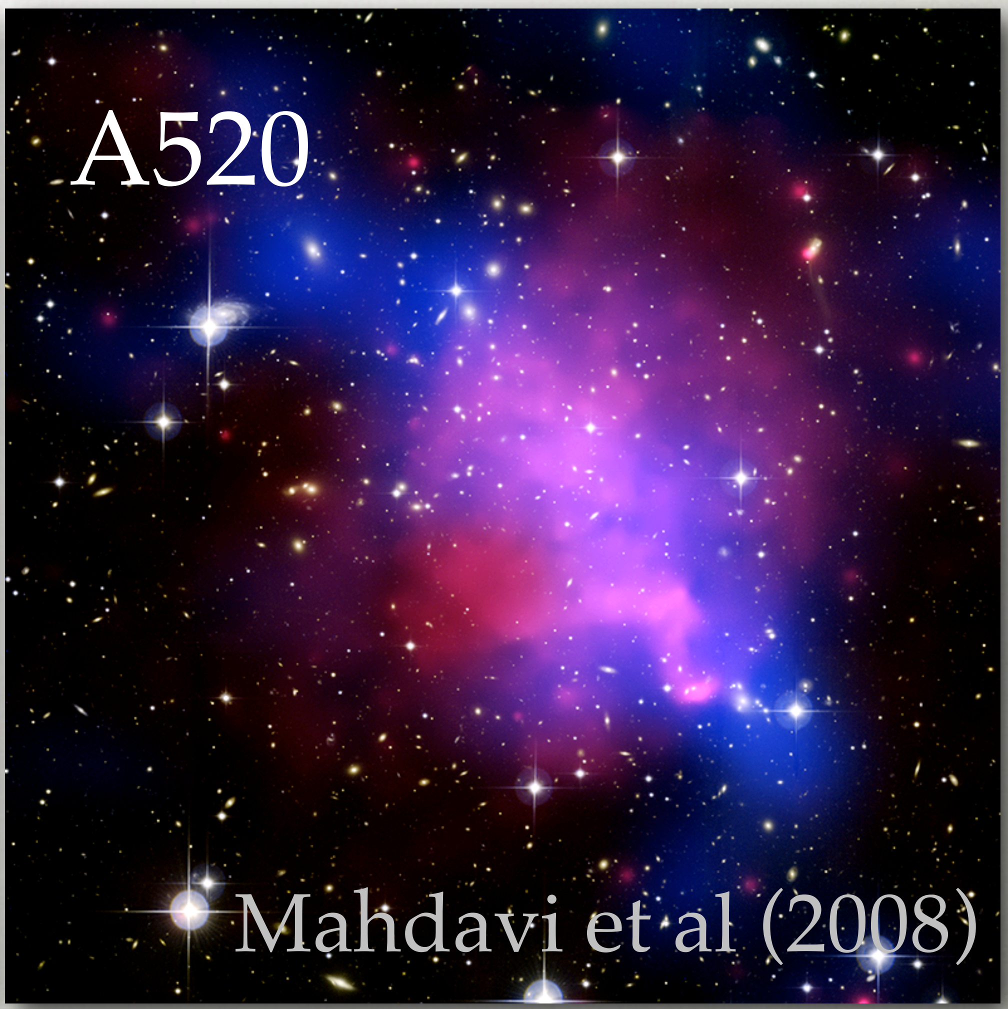
Measuring masses

using weak gravitational lensing



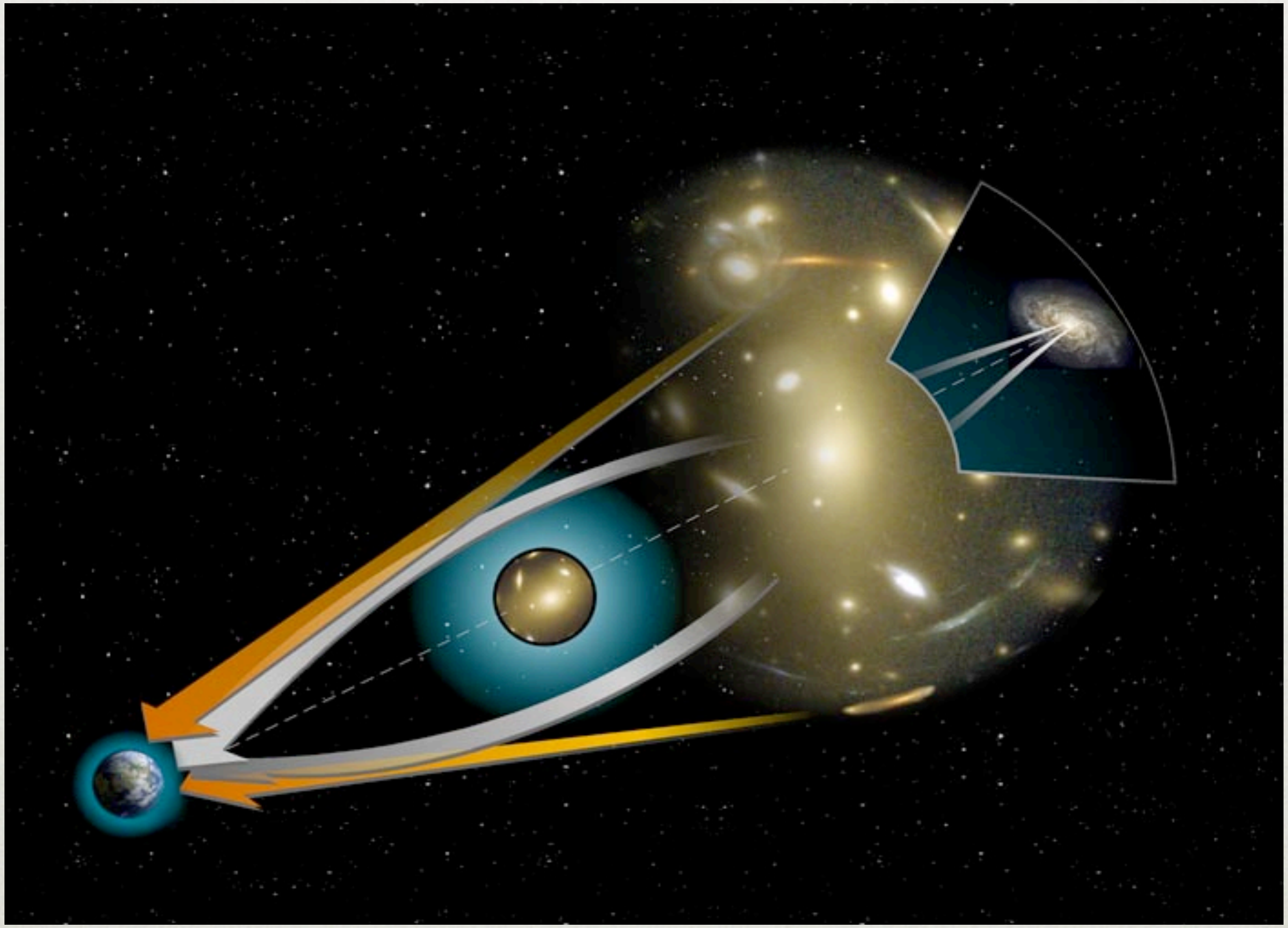
Henk Hoekstra
Leiden Observatory

How to measure the mass of ...



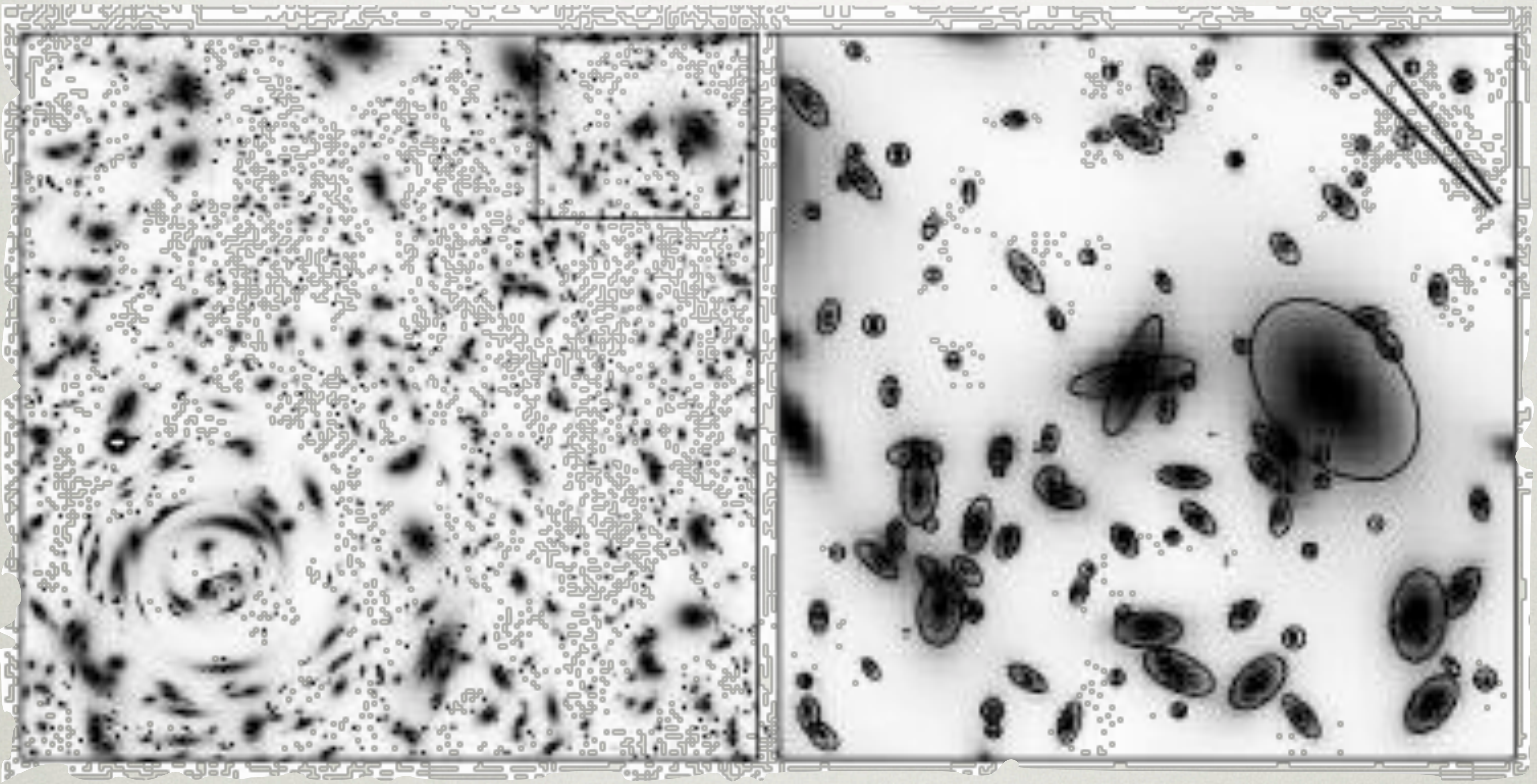
Clusters have a complicated history of multiple mergers resulting in complicated geometries with a lot of substructure. This is particularly important at high redshifts.

Gravitational lensing



Inhomogeneities in the matter distribution deflect light rays and cause coherent distortions in the shapes of distant galaxies.

Weak gravitational lensing



A measurement of the ellipticity of a *single* galaxy provides an unbiased but noisy measurement of the gravitational lensing shear

What do we measure?

Underlying assumption: *the source position angles are uncorrelated in the absence of lensing.*

- Measure the galaxy shapes from the images
- Correct for observational distortions
- Select a sample of background galaxies

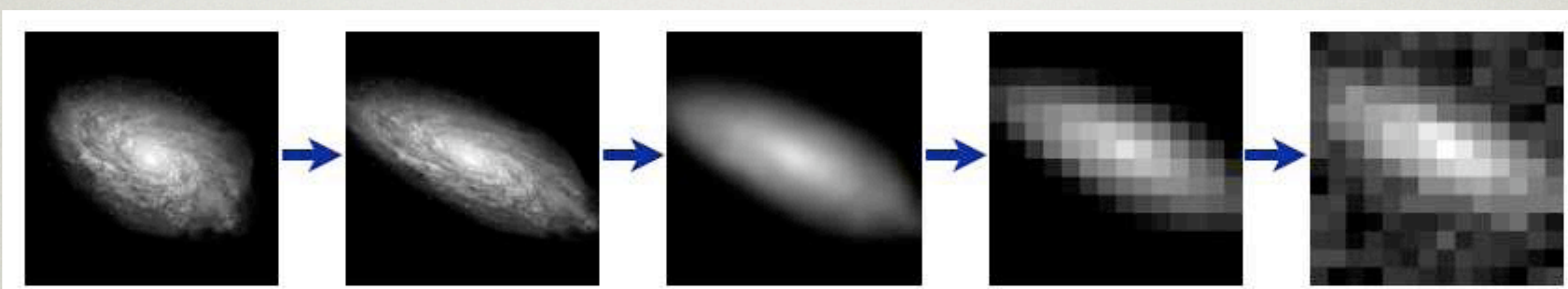
Lensing signal

The conversion of the lensing signal into a mass requires knowledge of the source redshift distribution

PSF correction

It is relatively easy to create simulated data to test the measurement techniques.

The Shear TEsting Programme is an international collaboration to provide a means to benchmark the various methods. This has evolved into a challenge to involve computer scientists: GREAT'08 & GREAT'10.

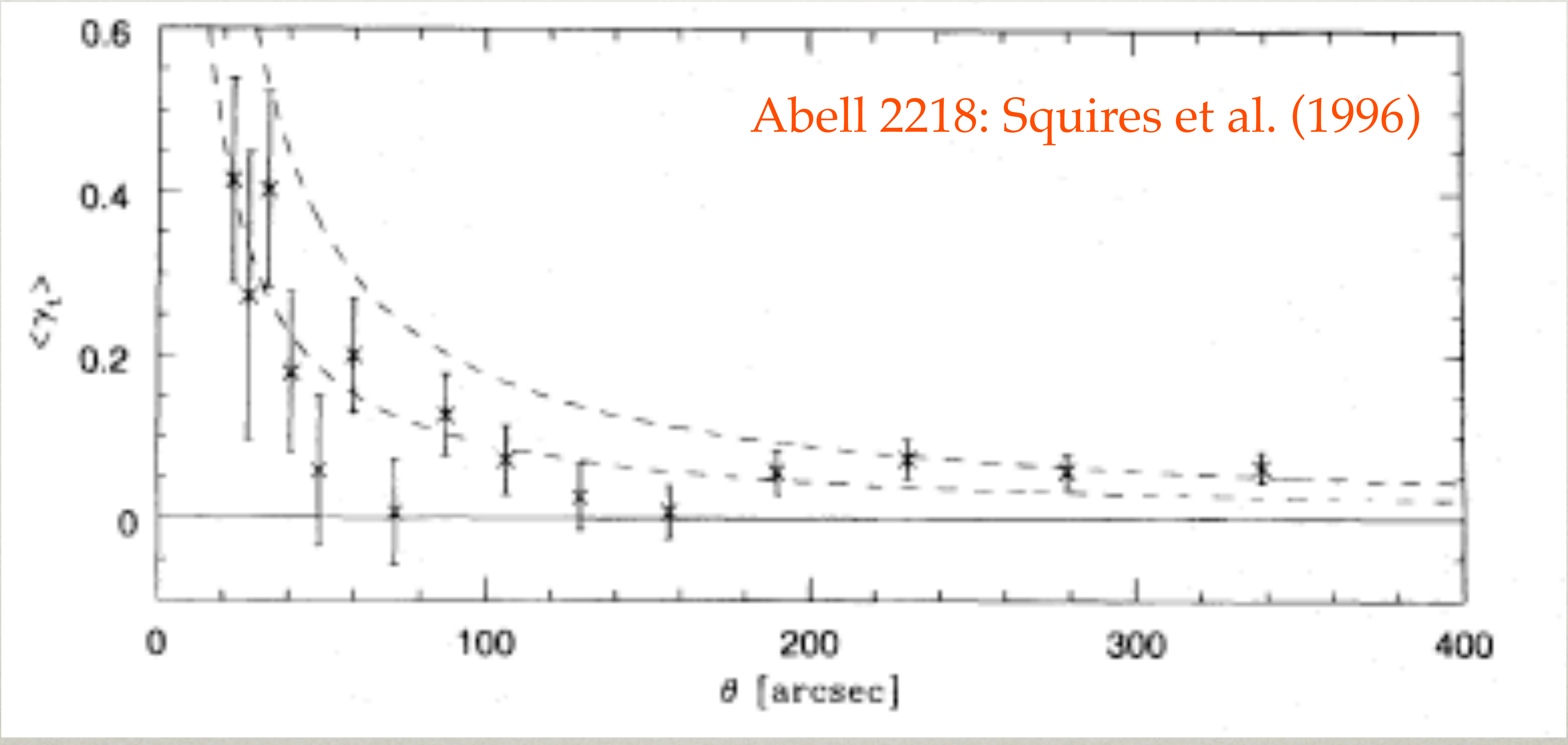


?

We can currently reach an accuracy of 1-2% in the shear measurement.

In the beginning...

A handful of clusters were studied in the ’90s using cameras with relatively small fields of view and little knowledge of the source redshift distribution.



Modern cluster lensing

Improvements since the early days:

- measure signal out to larger radii
- better knowledge of the source redshift distribution
- better corrections for systematic effects

As the sample sizes increase, the lensing analysis needs to become more advanced: deal with contamination by cluster galaxies, centroid errors, contributions from local and distant large scale structure, etc.

Limitations of weak lensing

- Weak lensing yields the projected mass distribution.
- The signal depends on all matter along the line of sight.
- We require good knowledge of the source redshifts.
- Need to account for contamination by cluster members.
- What to pick as the cluster centre?

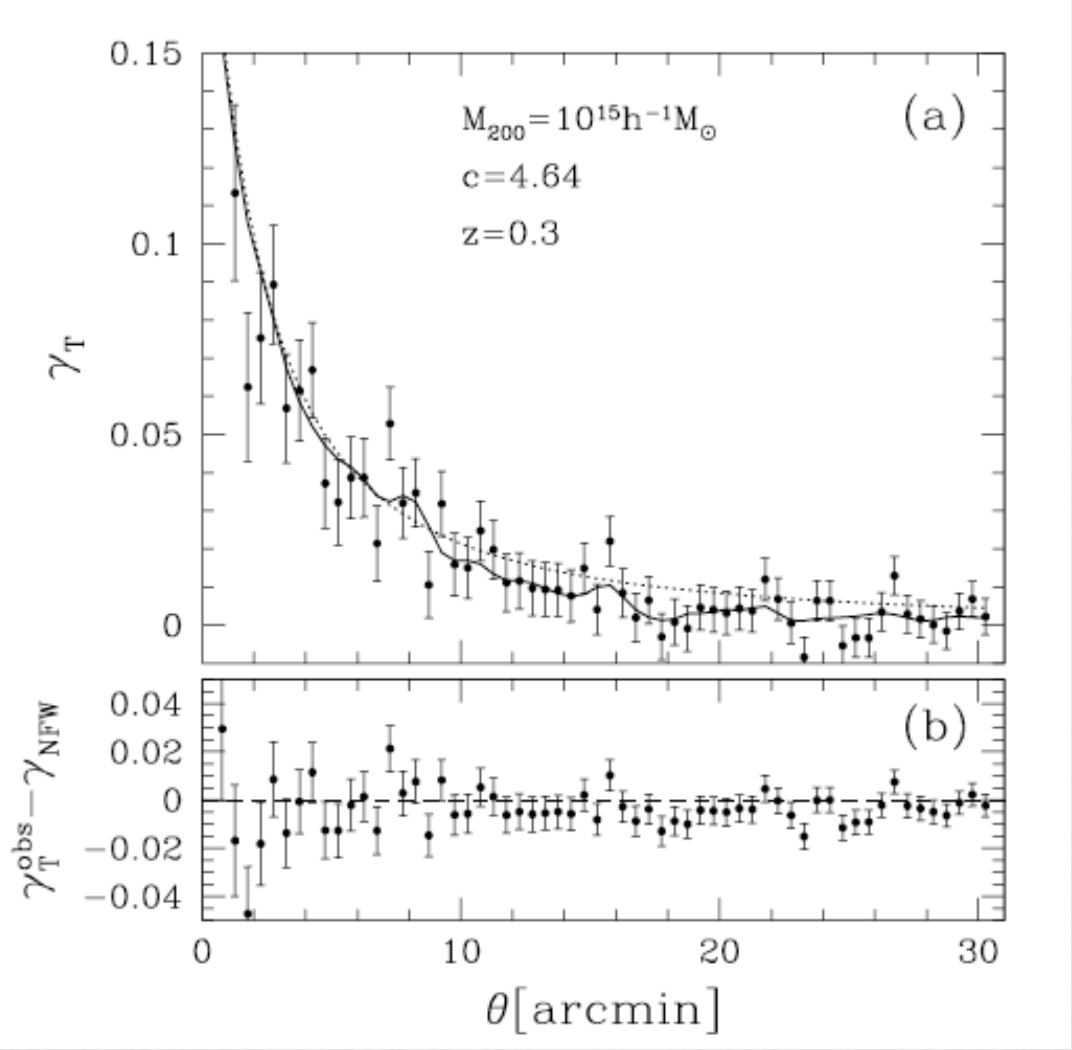
The last point is particularly problematic if we fit a simple parametric model and is made worse if there is substructure!

Use aperture masses (1-d masses):

- ❑ This can minimize the model dependence
- ❑ This reduces the sensitivity to the centroid
- ❑ Also reduces contamination by cluster members
- ❑ Small bias (Becker & Kravtsov 2011)

Effects of 'cosmic noise'

Hoekstra (2003)

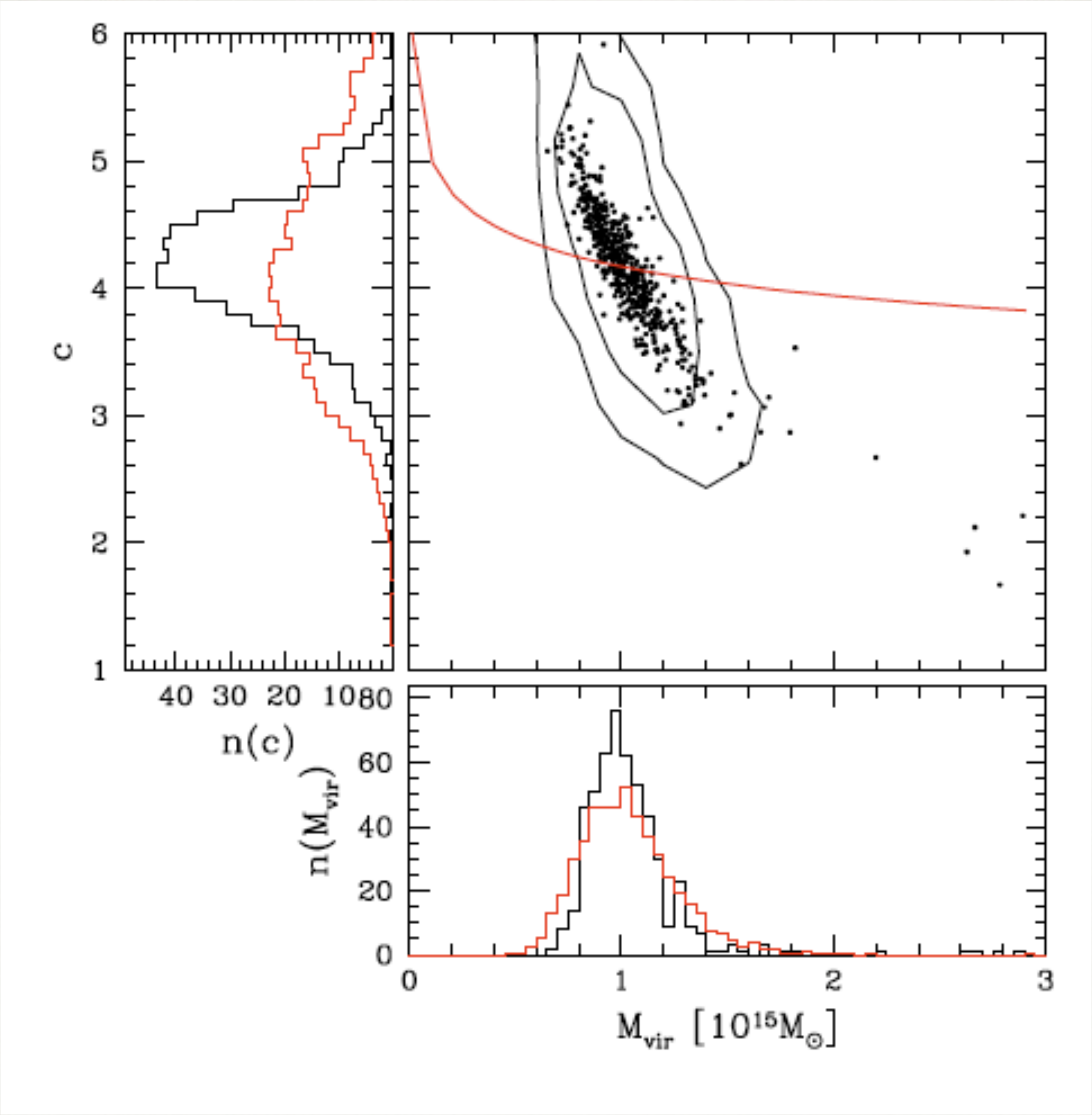


Uncorrelated large scale structure is an additional source of noise

- Limits the accuracy with which masses can be determined
- Lowers the true significance of peaks in a mass reconstruction

Effects of 'cosmic noise'

Hoekstra et al. (2011)



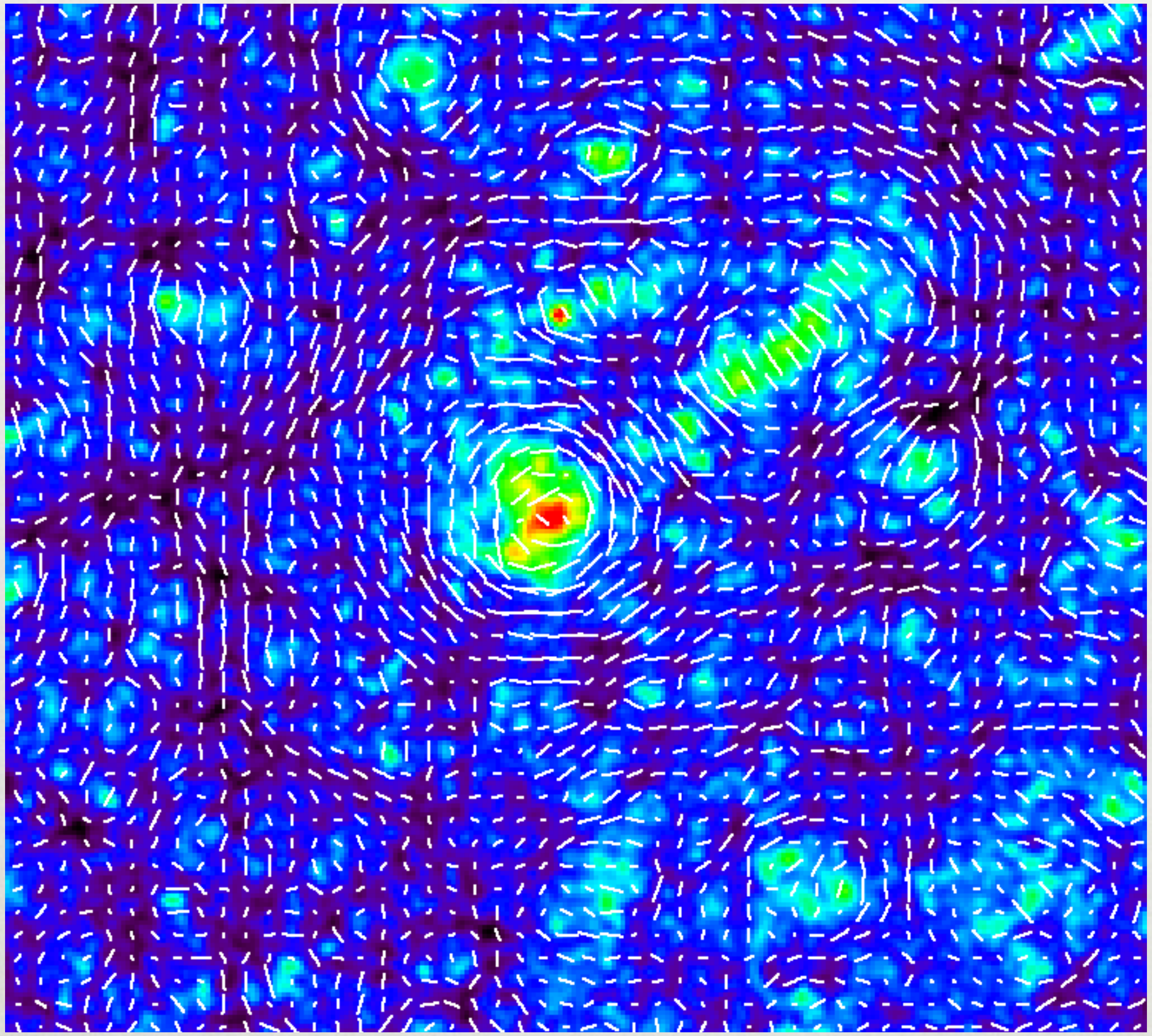
Cosmic noise is very important for studies of the mass profile.

Applications

- Map the matter distribution
- Calibrate scaling relations
- Study cluster physics

We can 'see' dark matter

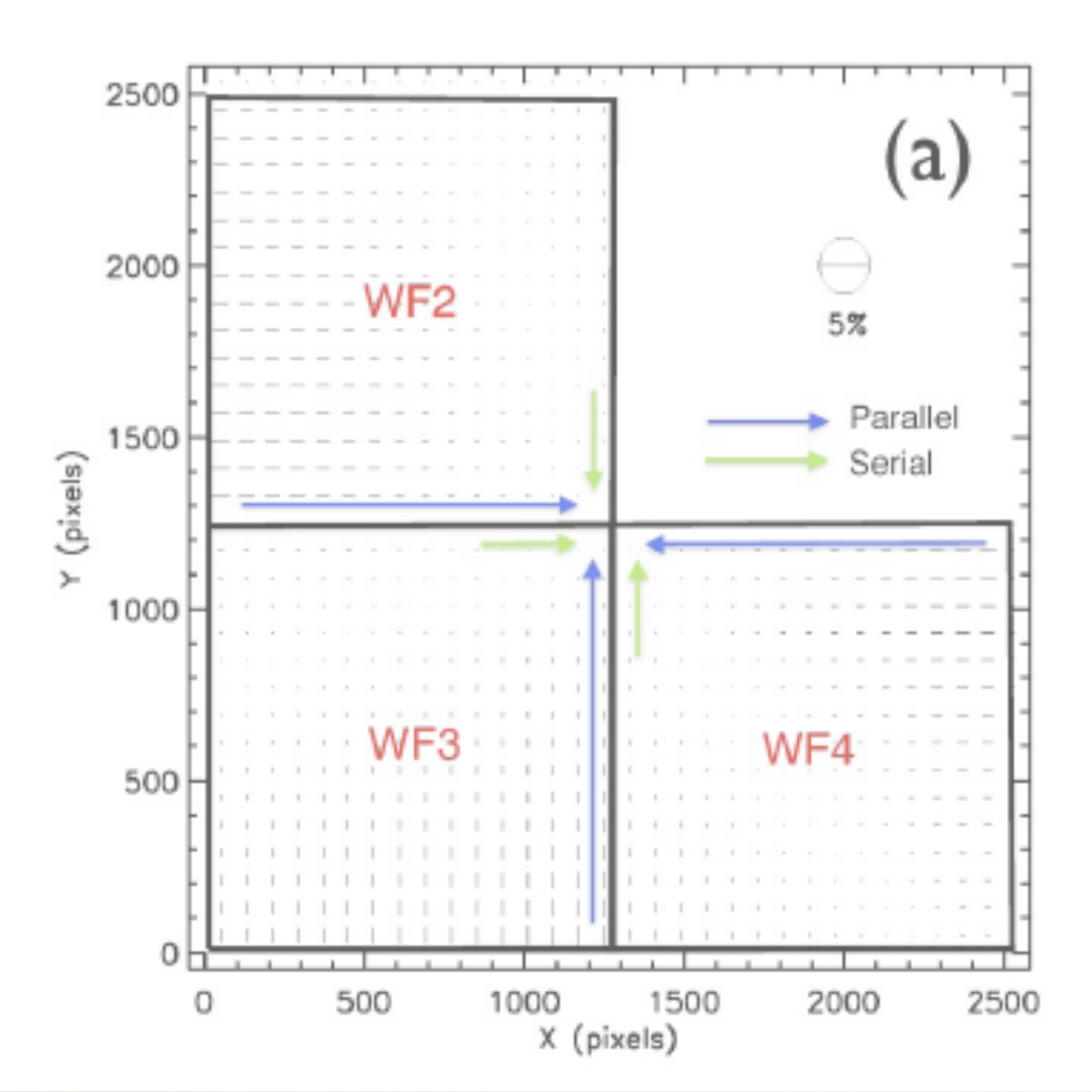
Courtesy B. Jain

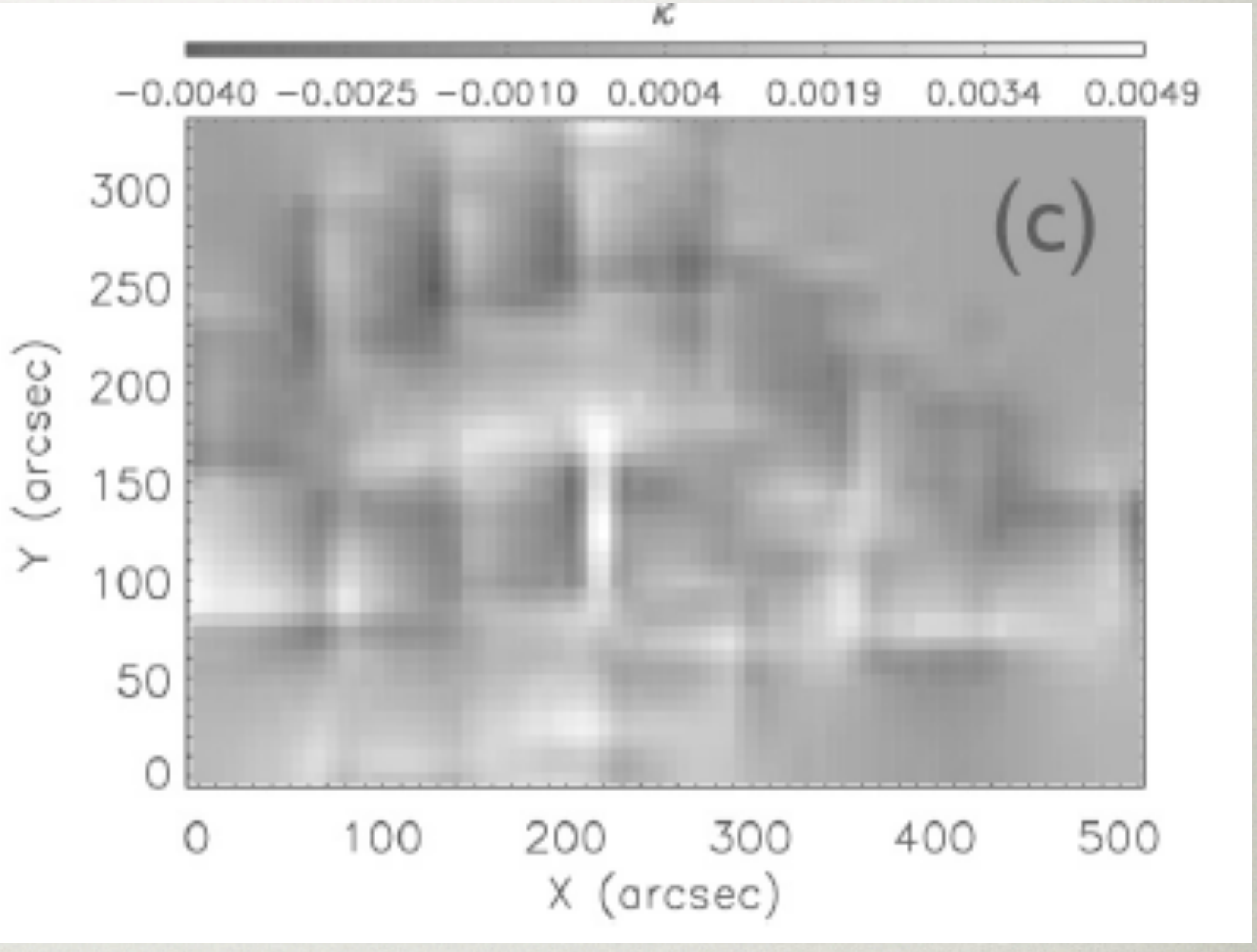


In the absence of noise we would be able to map the matter distribution in the universe (even "dark" clusters).

We need high source densities: best using HST data

Issues with HST data



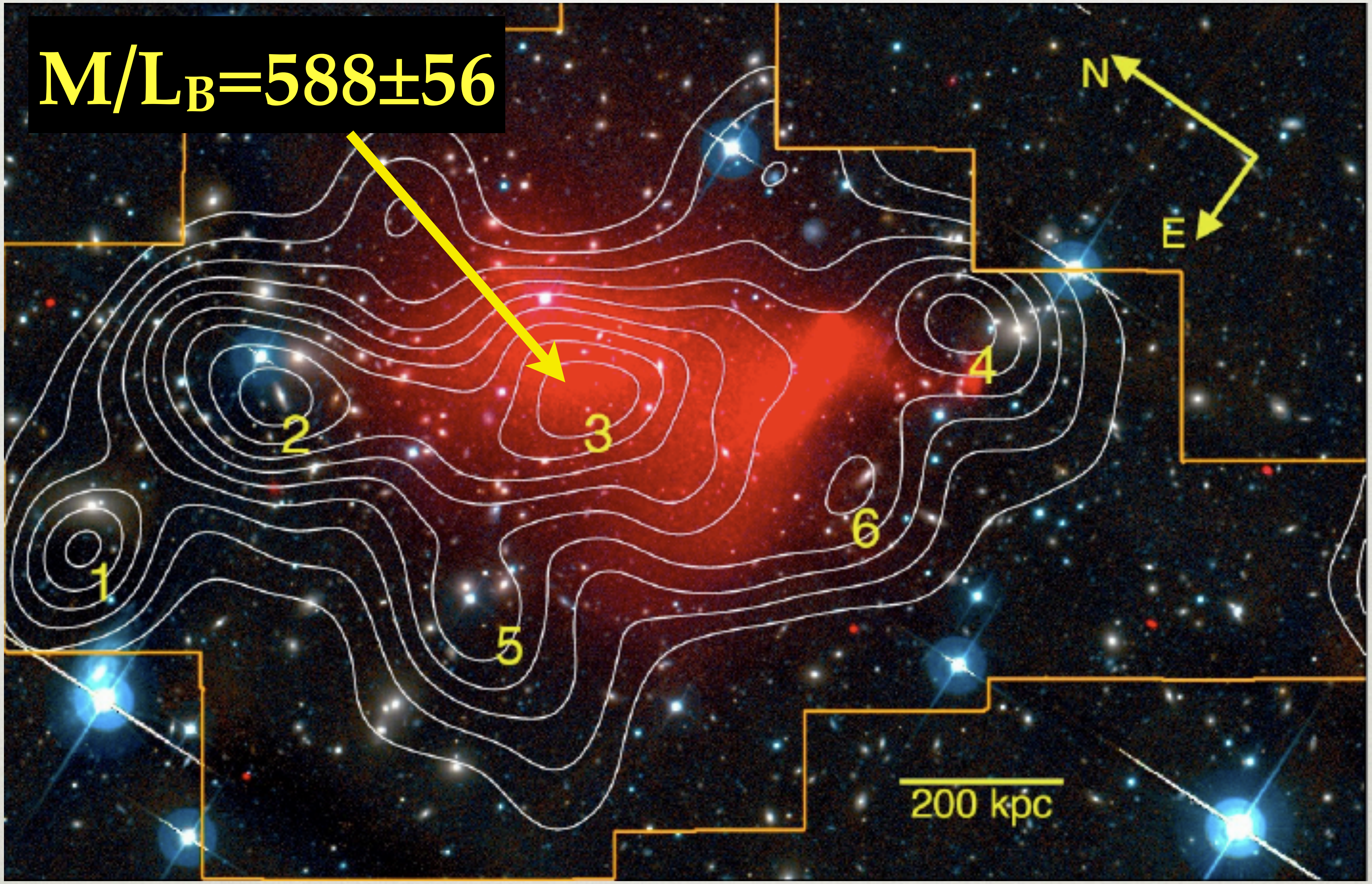


Jee et al. (2012)

CCDs in space degrade due to radiation damage. Charge Transfer Inefficiency (CTI) introduces spurious signal.

A520: THE MYSTERY DEEPENS

Jee et al. (2012)



A recent analysis using WFPC2 data is in excellent agreement with our puzzling ground based results...

Large cluster samples

We have two options to study cluster samples:

Masses for individual clusters:

- study scatter
- expensive
- only massive clusters

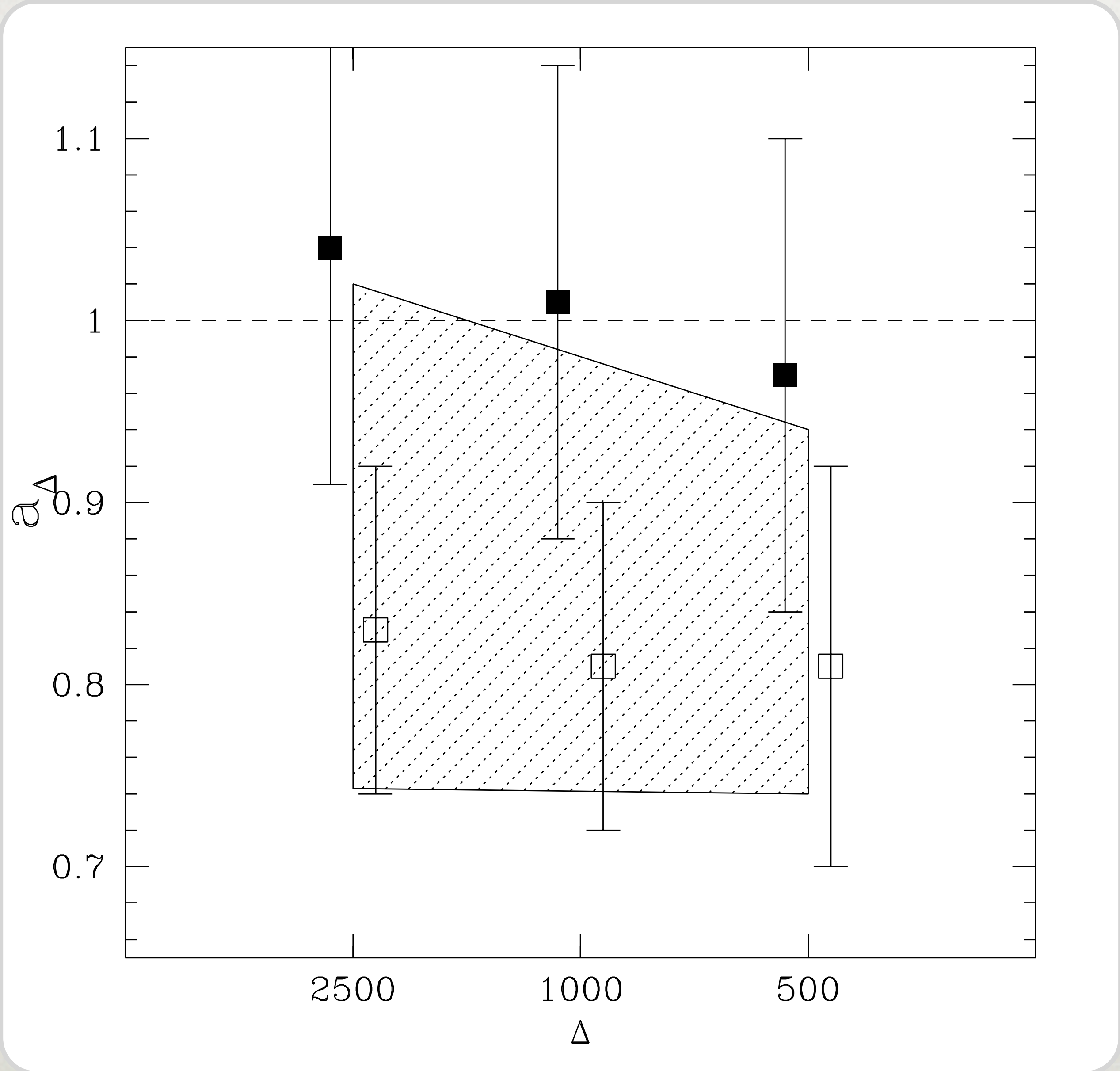
Masses for ensembles of clusters:

- cheap
- large range in mass (and redshift)
- but how to bin?
- what about intrinsic scatter?

Lensing by individual clusters

Testing X-ray masses

X-ray / WL mass



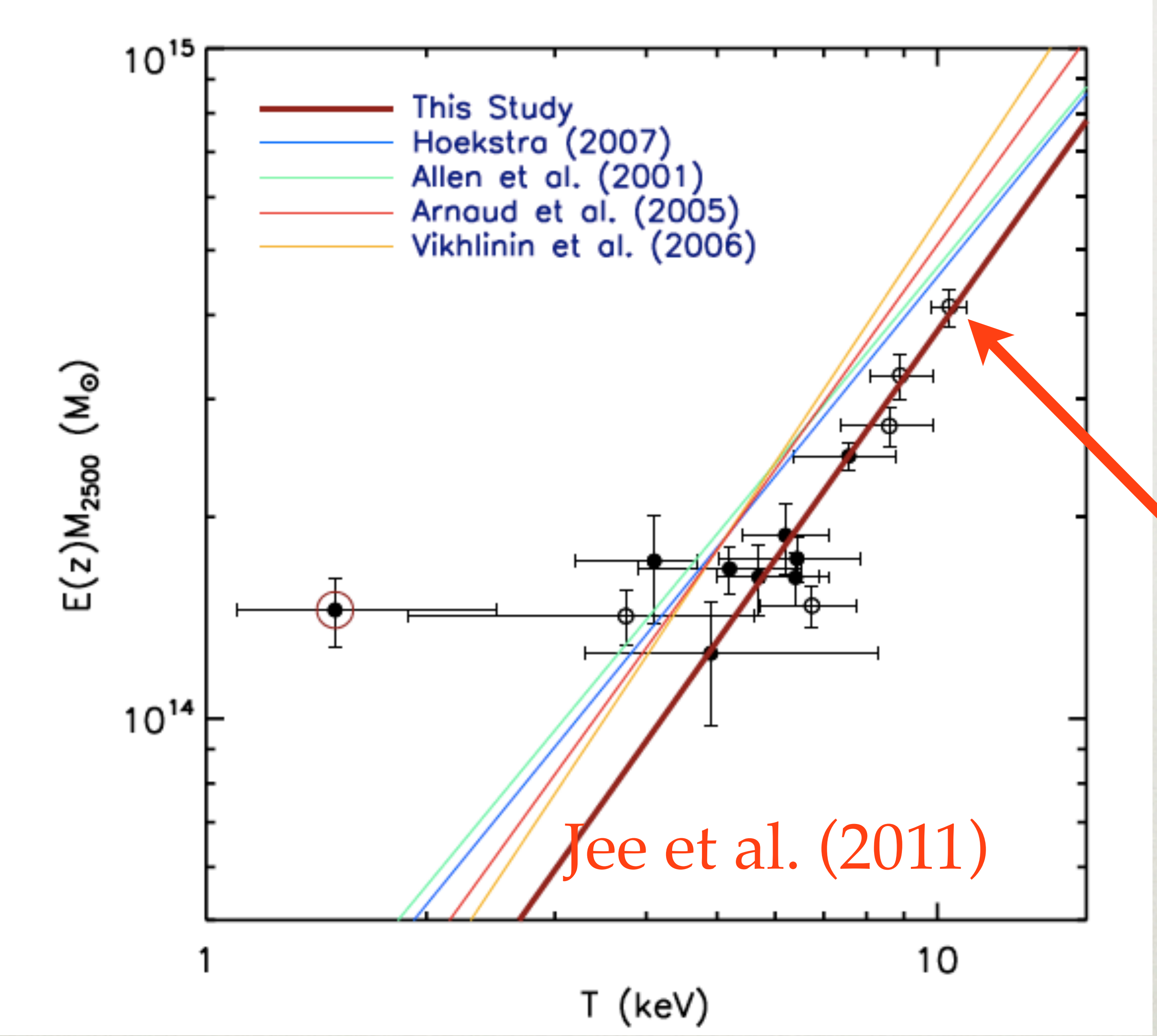
“cool core”

“disturbed”

Mahdavi et al. (in prep):

gas is not always in hydrostatic equilibrium.

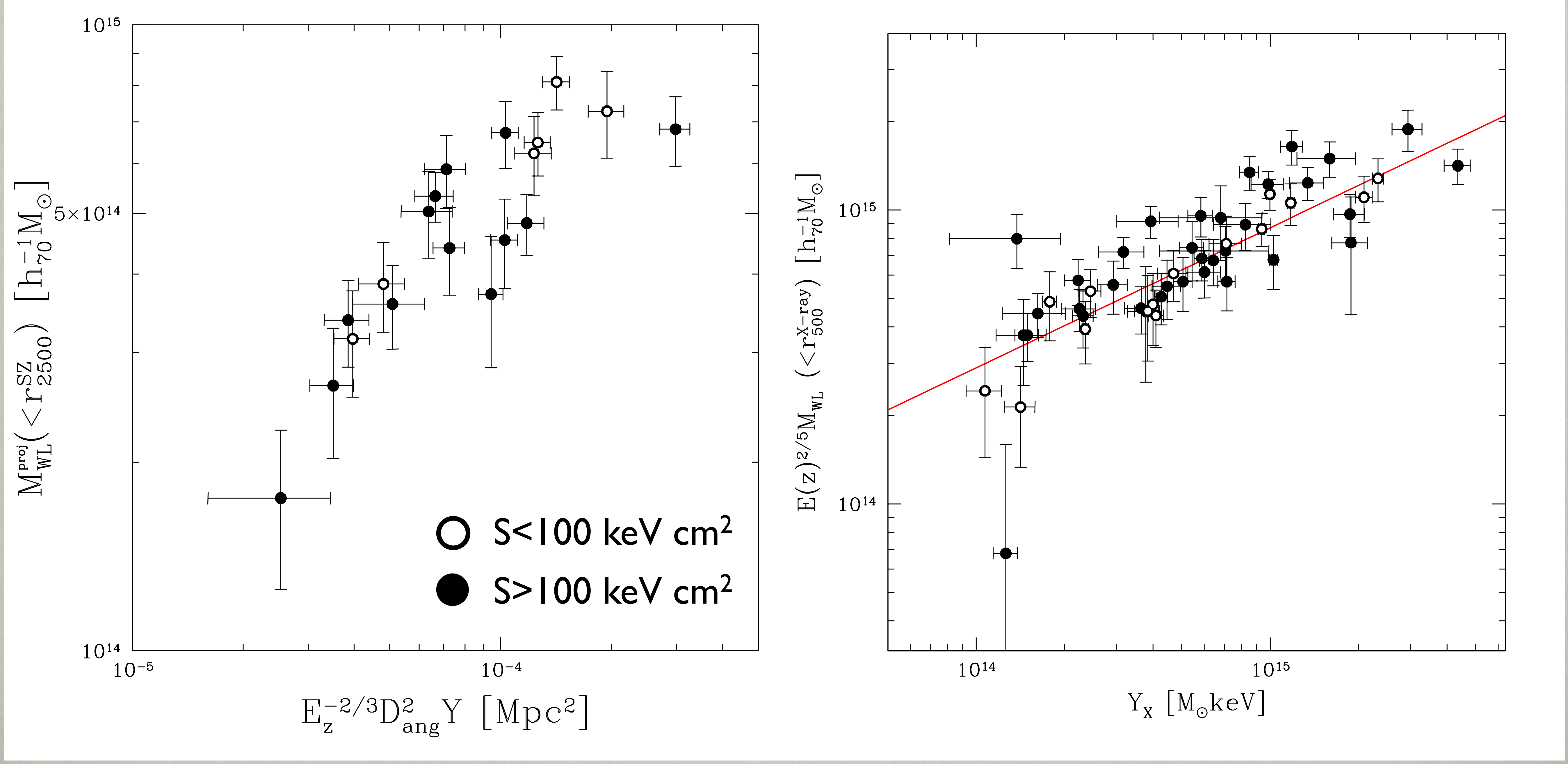
Evolution of M-T relation



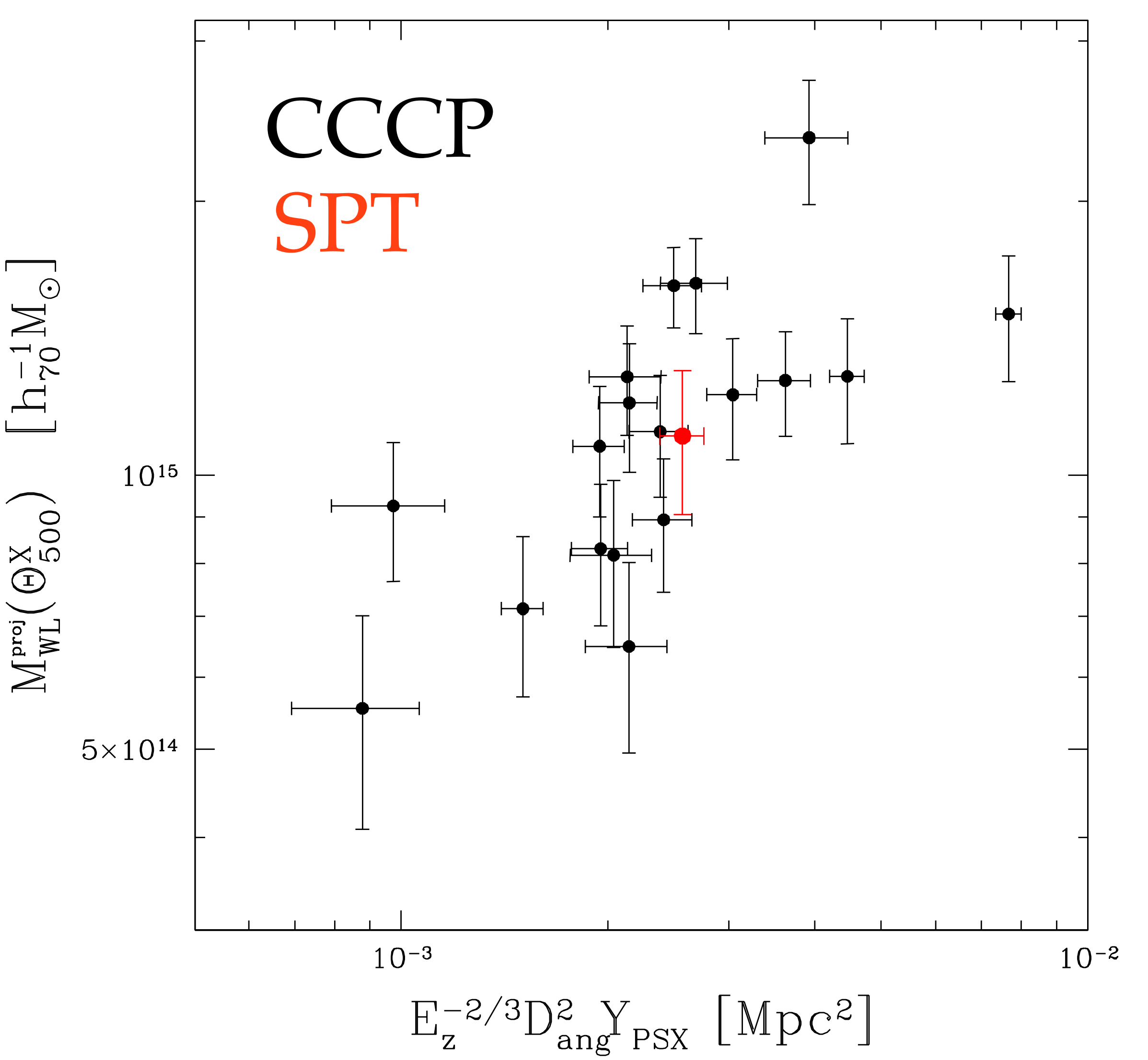
Normalization 20-30% lower at z~1

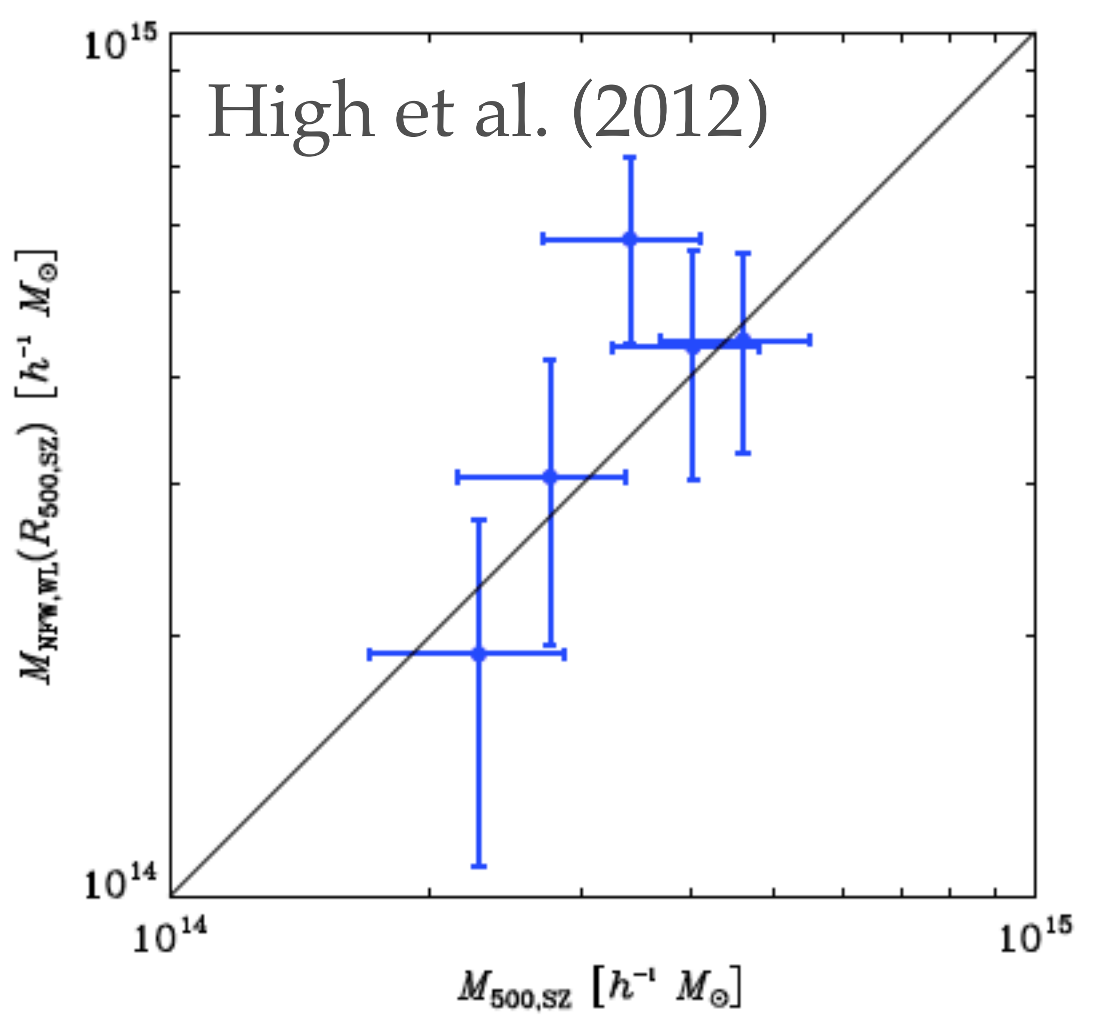
More CCCP results

“real” SZ (Bonamente et al.)　　　　“X-ray” SZ (CCCP)



Planck & SPT observations





Samples with WL and SZ measurements are increasing rapidly.

Stacking clusters

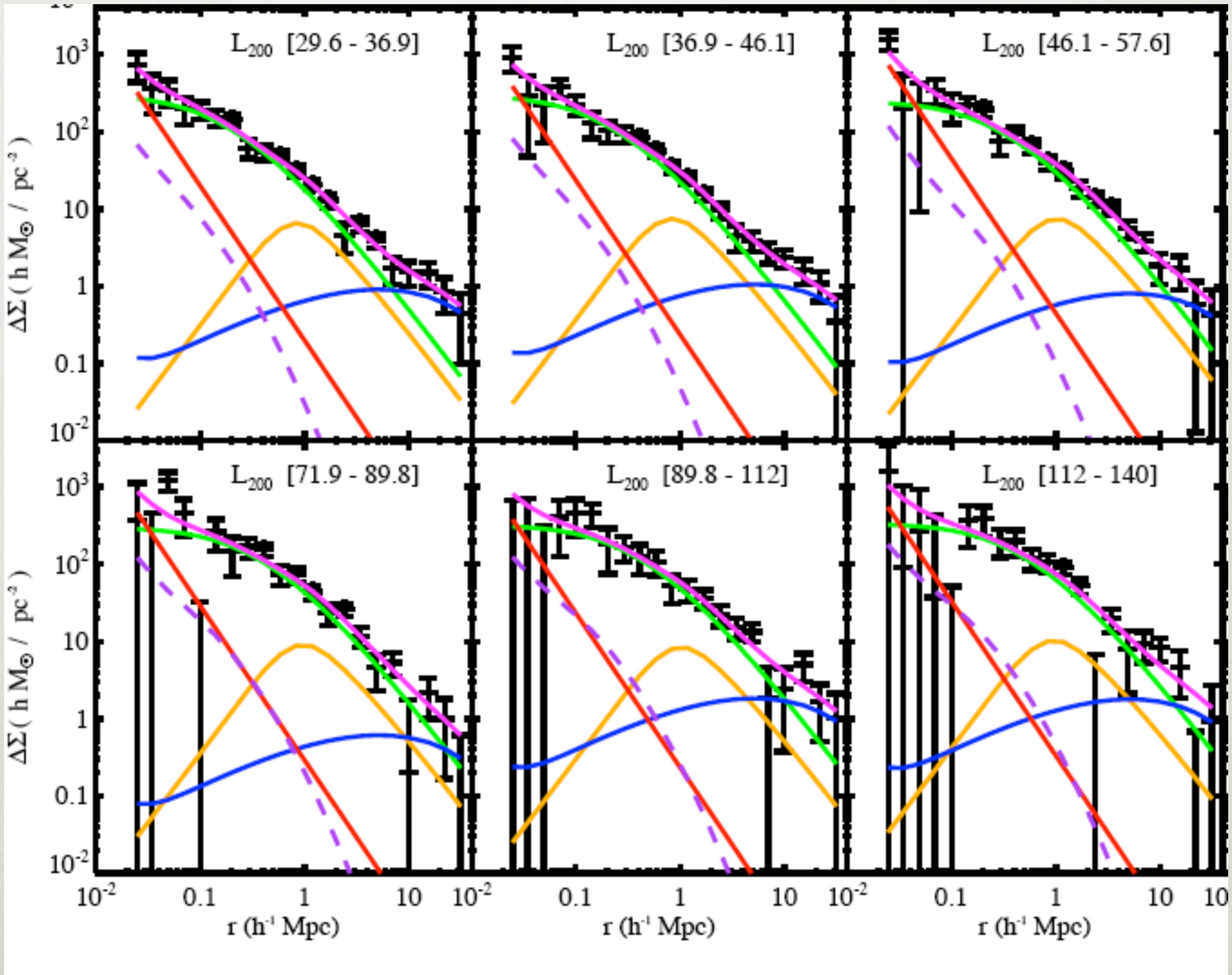
If the masses are too low, one can still learn about the cluster properties by stacking the signal of many systems. This is for instance done for galaxy groups (Hoekstra et al. 2001; Parker et al. 2006). **See also talk by Giodini**

Similarly, although the SDSS imaging is not deep enough to study the masses of individual clusters, the signals of similar systems can be combined.

For instance this allows studies of the cluster mass profile out to large radii

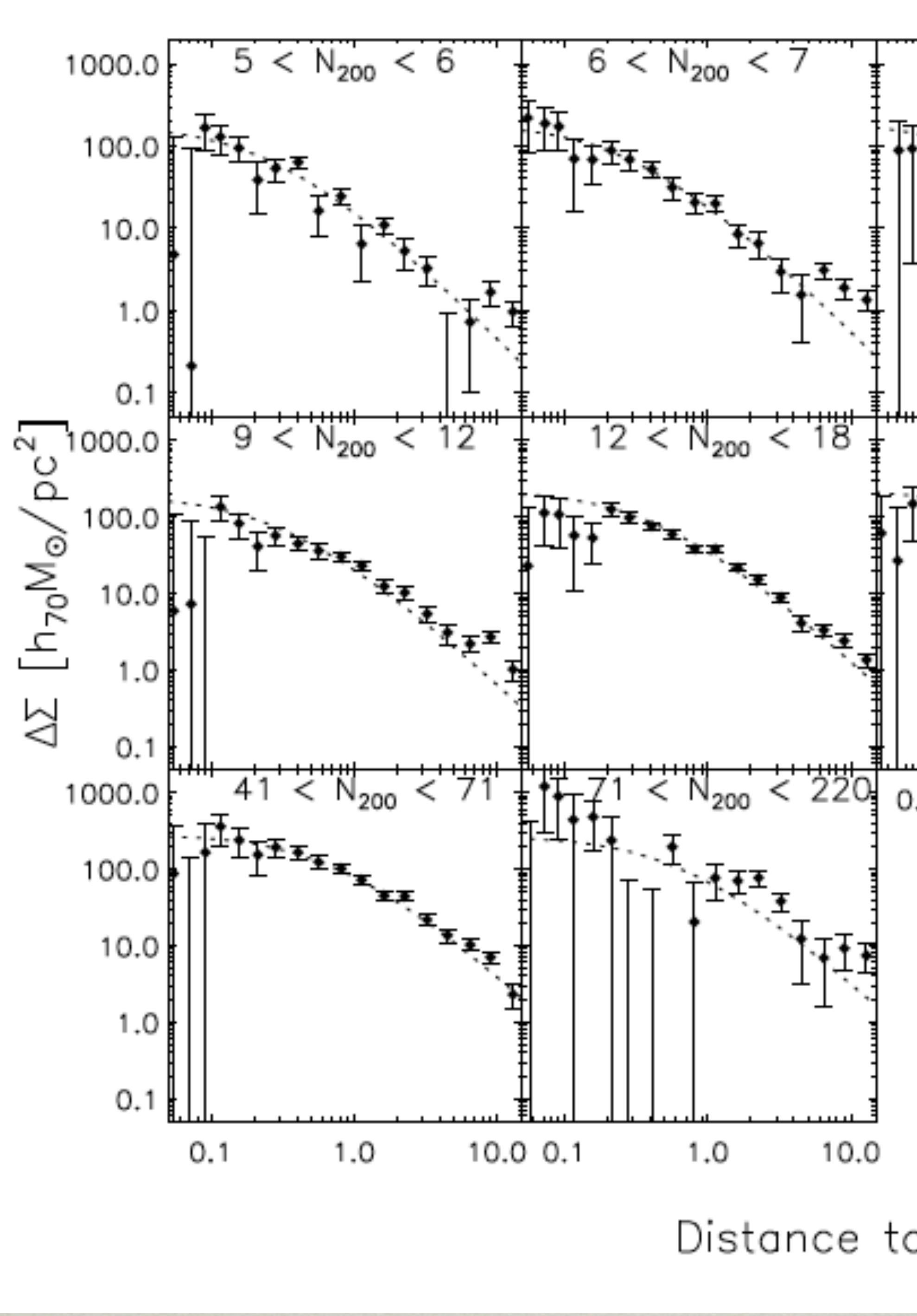
Cluster density profiles

SDSS



Johnston et al. (2007)

RCS2 - 28,000 clusters



van Uitert et al. (in prep)

RCS2 - 28,000 clusters

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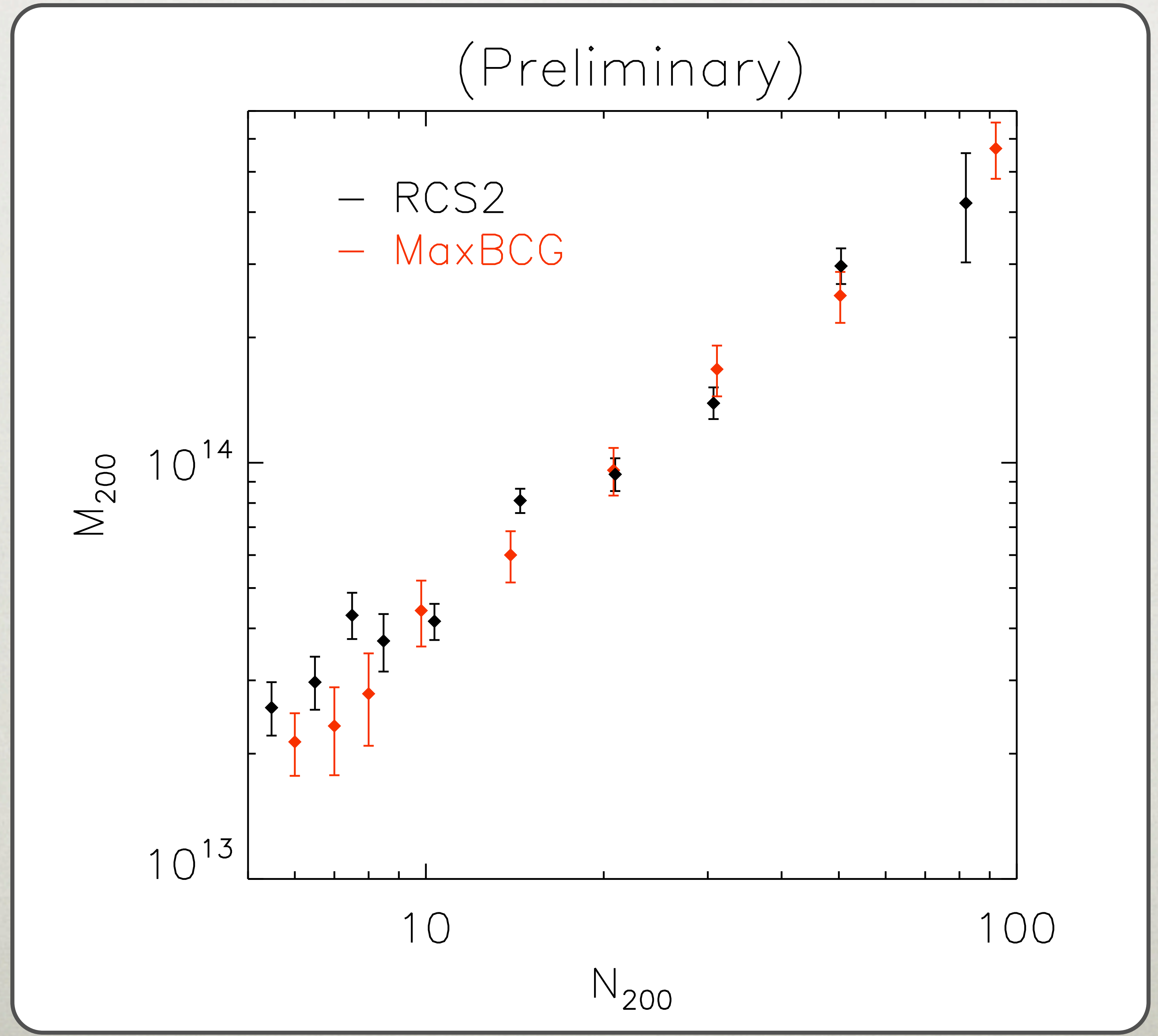

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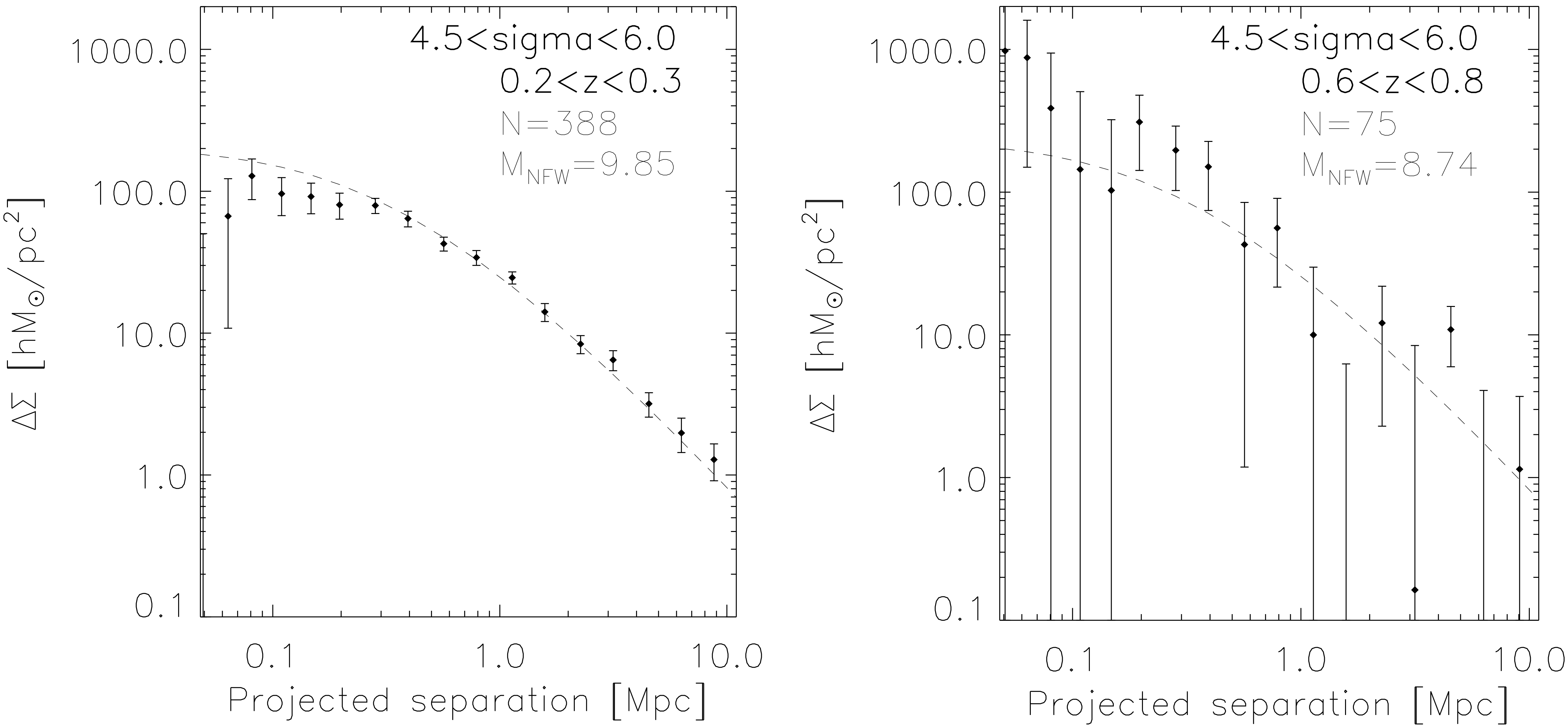

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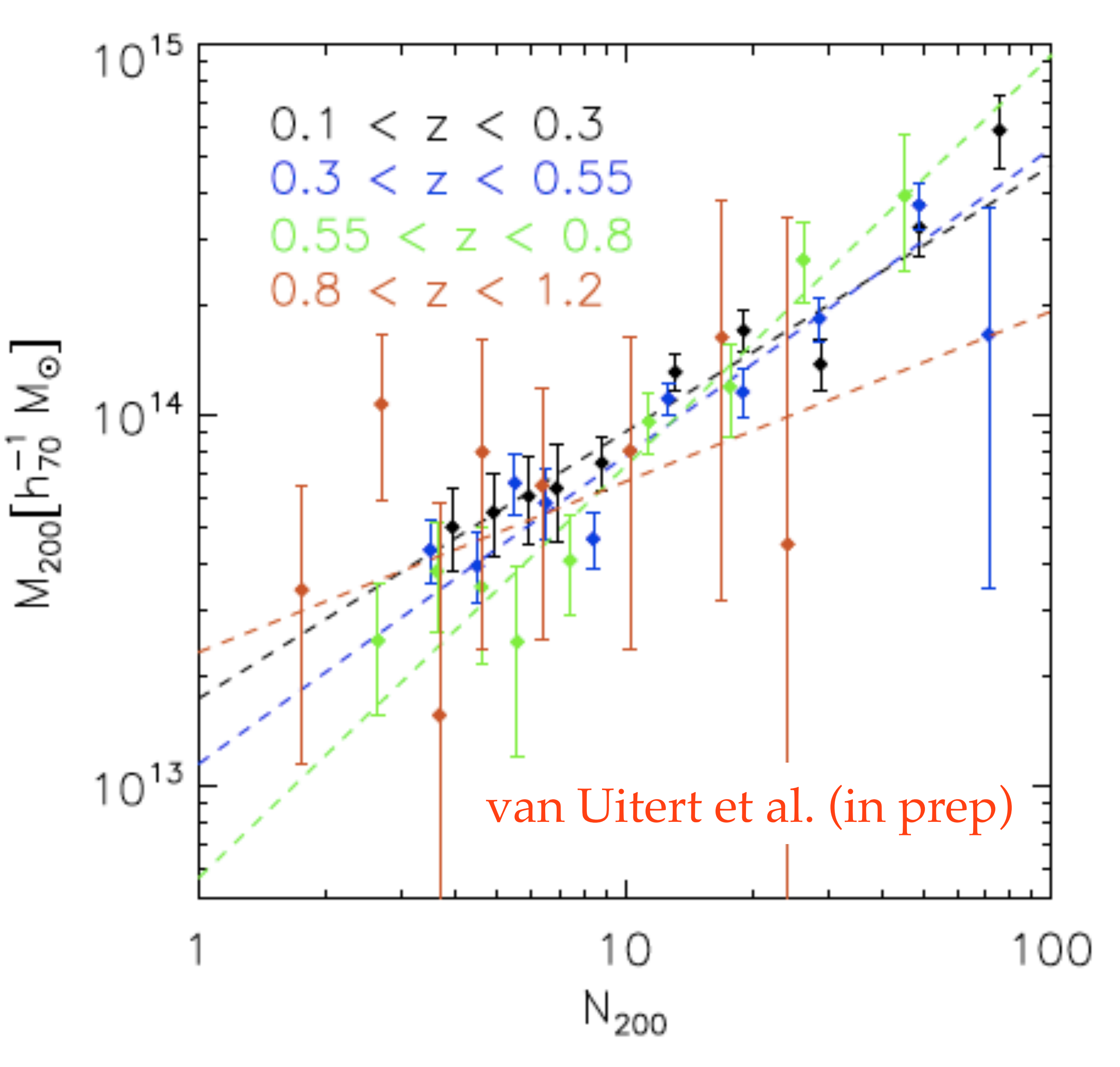
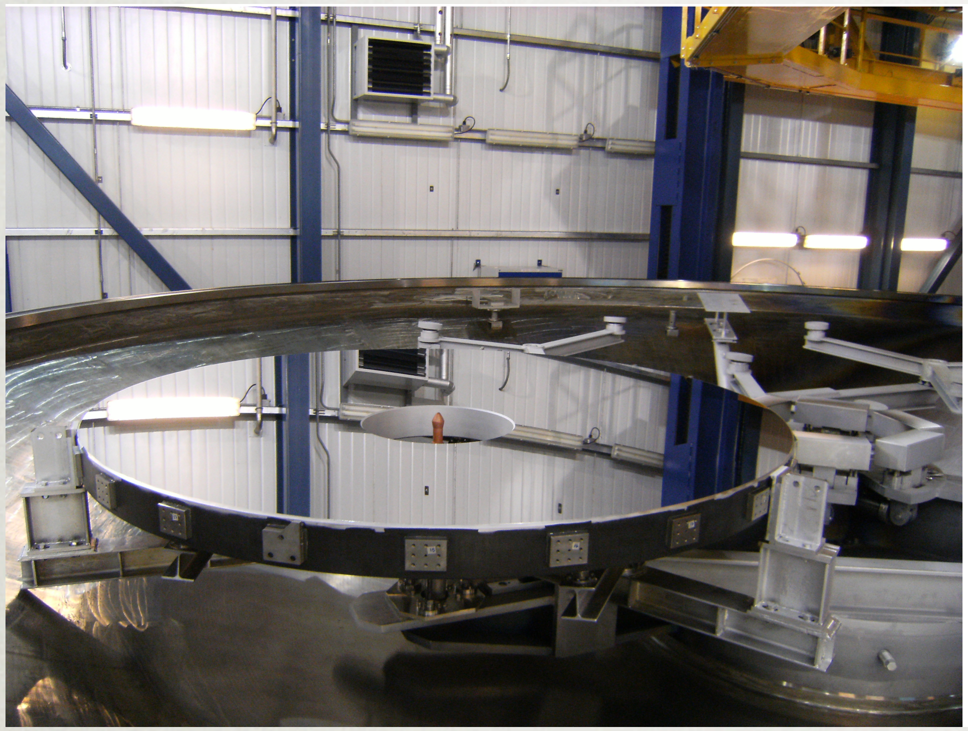


We can start to study the evolution of the mass-richness relation

More data coming!



KiDS + VIKING: (1500 deg^2,ugriZYJHK)
- has started fall 2011
- goal is completion in ~3 years

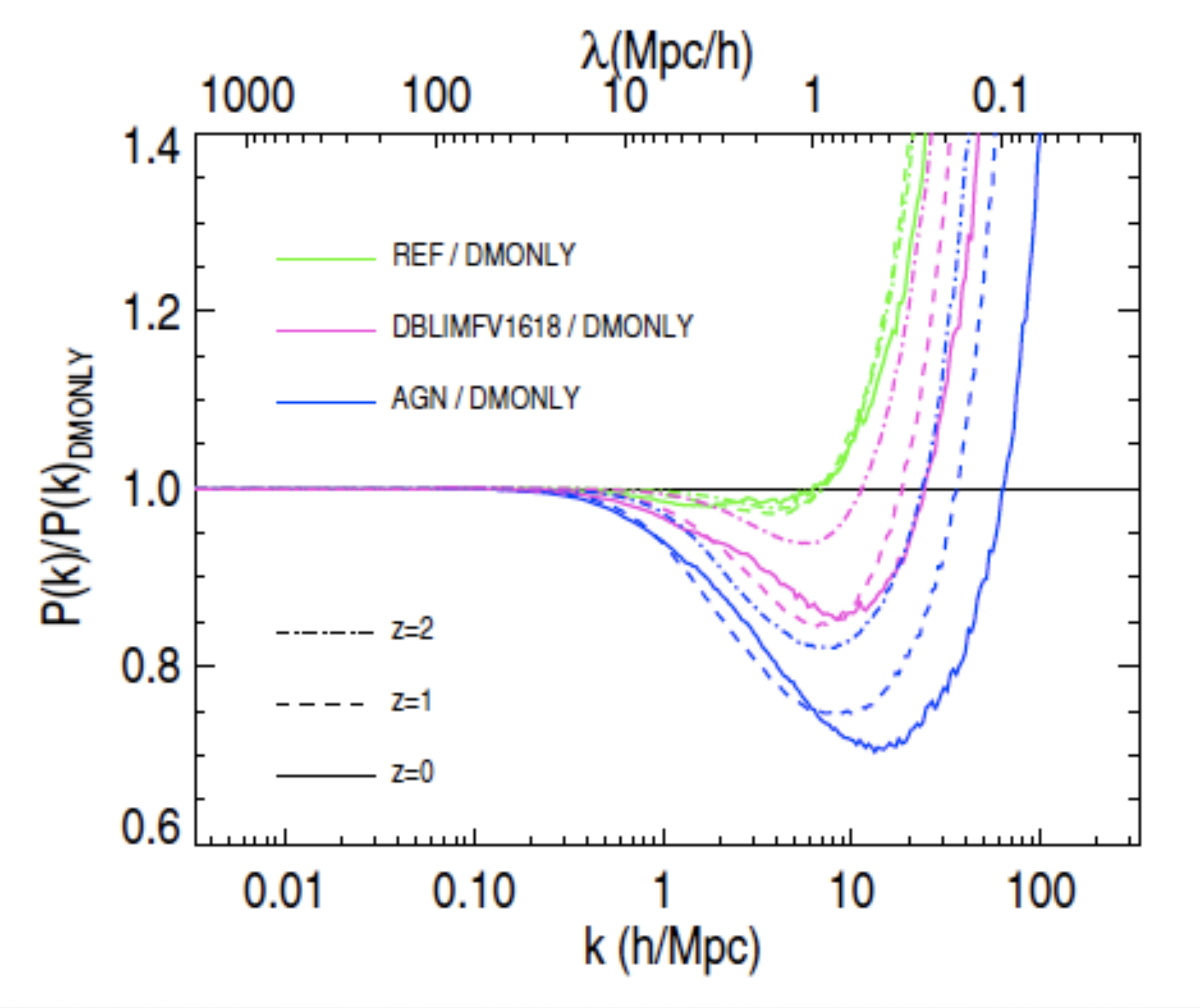
>2019: *Euclid* will improve S/N per cluster by a factor ~2-3

One more reason to care

Weak lensing by large scale structure (cosmic shear) is one of the most powerful probes of dark energy.

But... the correct interpretation of the signal from future projects, such as *Euclid,* requires an improved understanding of the baryon feedback processes in groups and clusters of galaxies.

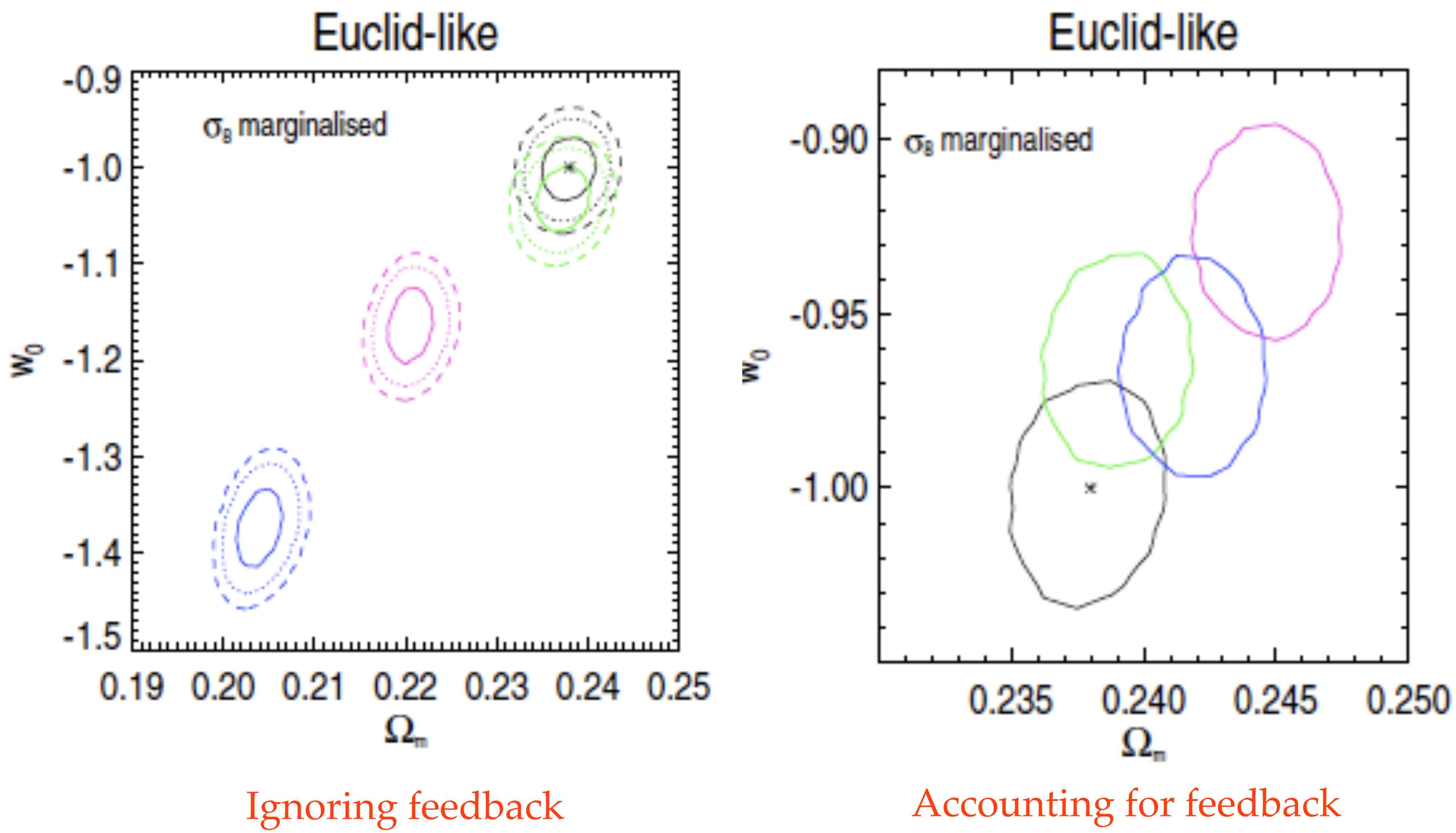
Matter power spectrum



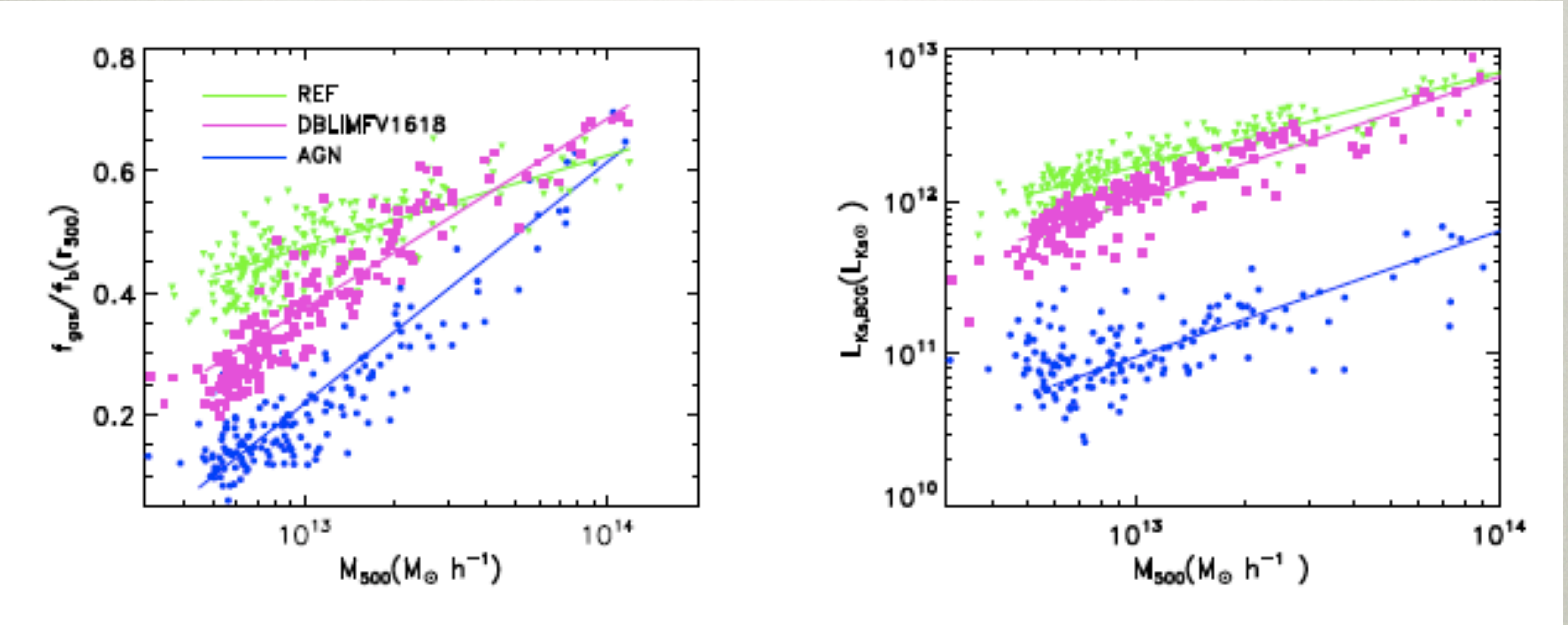
van Daalen et al. (2011): feedback can modify the matter power spectrum significantly

We cannot ignore (g)astrophysics

Semboloni et al. (2012)



Halo model with baryons



Current simple model:

- galaxies are point masses with a luminosity
- gas follows beta-model with some fraction removed

REDUCED BIASES

Despite its simplicity the model already reduces the biases in cosmological parameters to a level comparable to the statistical error.

Constraints from SZ and X-ray observations should provide important additional constraints, reducing biases even further.

Conclusions

Weak lensing studies of clusters, groups and galaxies provide important information to link observations to simulations, which in turn leads to a better understanding of baryon physics.

Sample sizes are increasing rapidly (KiDS, DES, Euclid). Therefore it is important that the analyses become more sophisticated.