Measuring masses

from galaxy clusters down to galaxies

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Why do we care?

Together with distance and luminosity, the mass is a key parameter in astronomy. Without masses, it becomes impossible to compare objects.

The problem with masses on scales of galaxies and larger is that most of the matter is invisible...

Is the light not enough?

In the case of main-sequence stars, the luminosity gives an excellent mass estimate. Can we not do the same for galaxies and clusters?

Indeed more massive systems are also more luminous, but the spatial distributions of dark matter and baryonic matter differ. Furthermore, various processes can expel gas, but not dark matter.

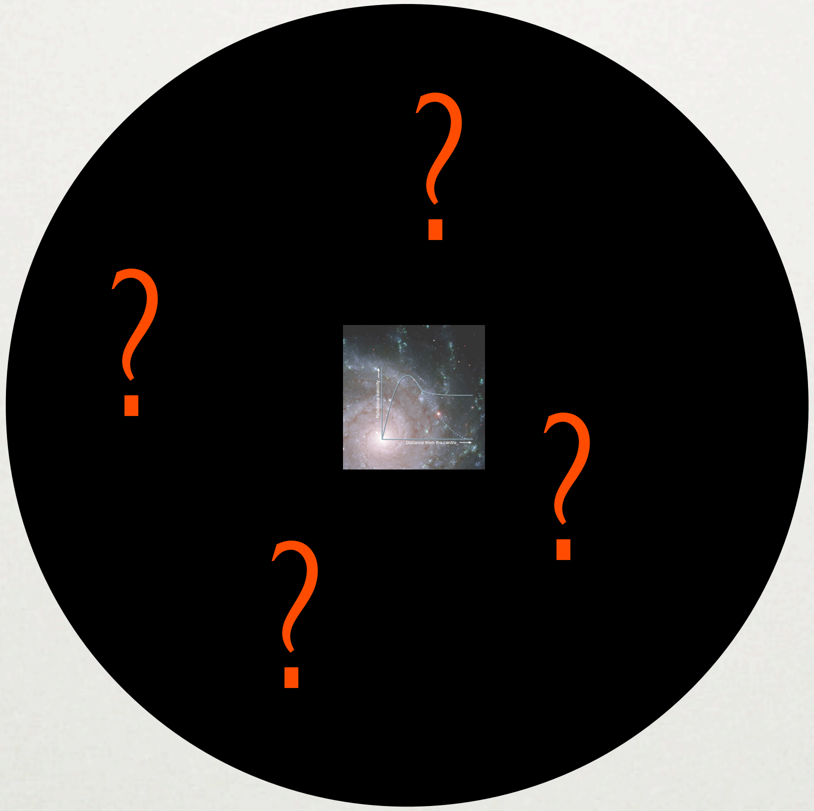
How to weigh objects?

Masses can be determined through a number of different techniques. The most commonly used methods provide dynamical masses. These assume

- the system is in equilibrium (relaxed).
- the system has a specific geometry (spherical).

Examples: motion of galaxies or gas particles

Dark matter around galaxies



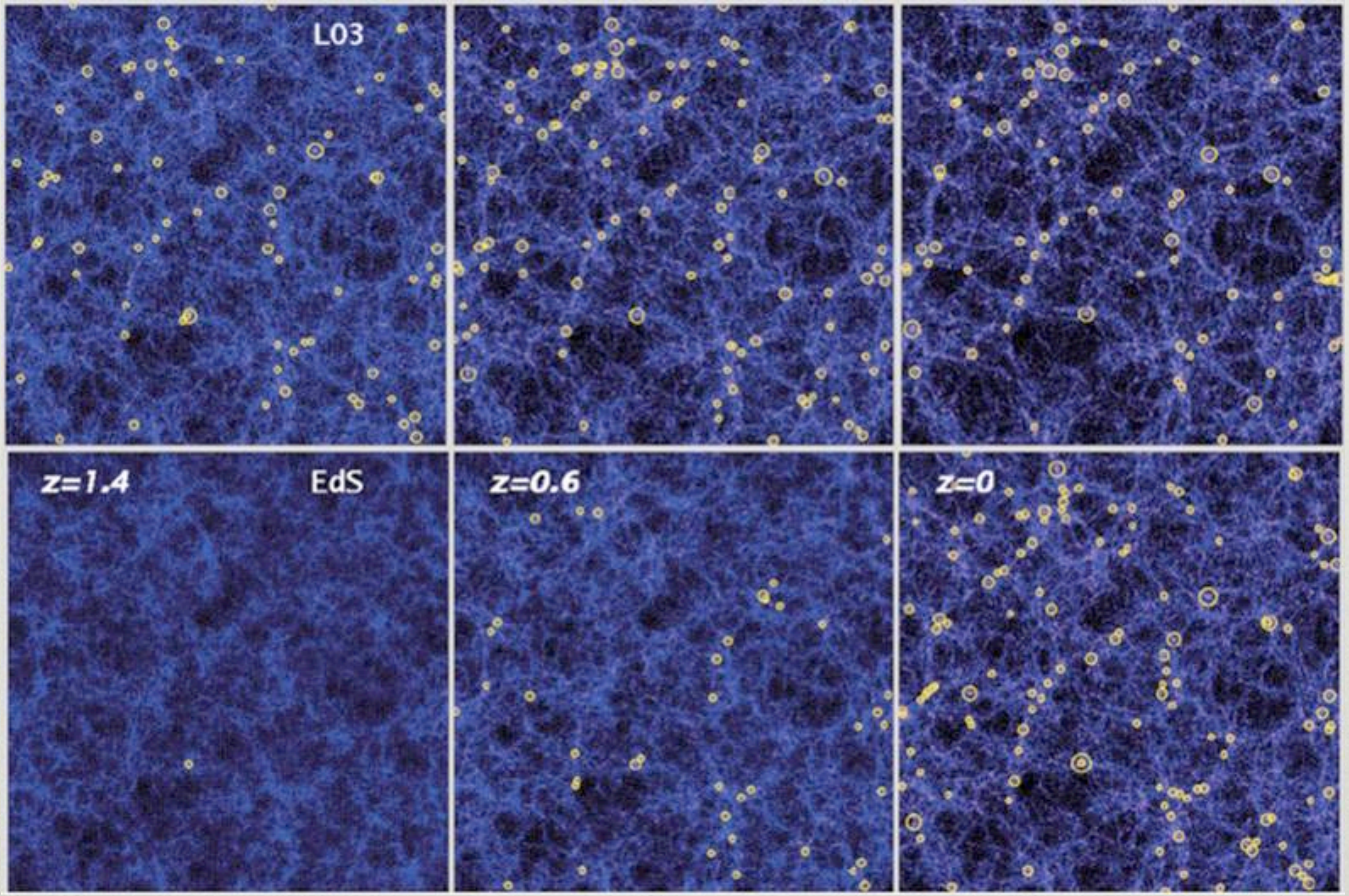
Dynamical studies have provided important constraints on the mass distribution on scales of a few tens of kpc.

But what do we know about the mass distribution on scales larger than 100kpc? How can we study this (as a function of redshift)?

How to measure the mass of ...

Bullet Cluster

Abundance of clusters



The growth of structure is a sensitive probe of cosmology

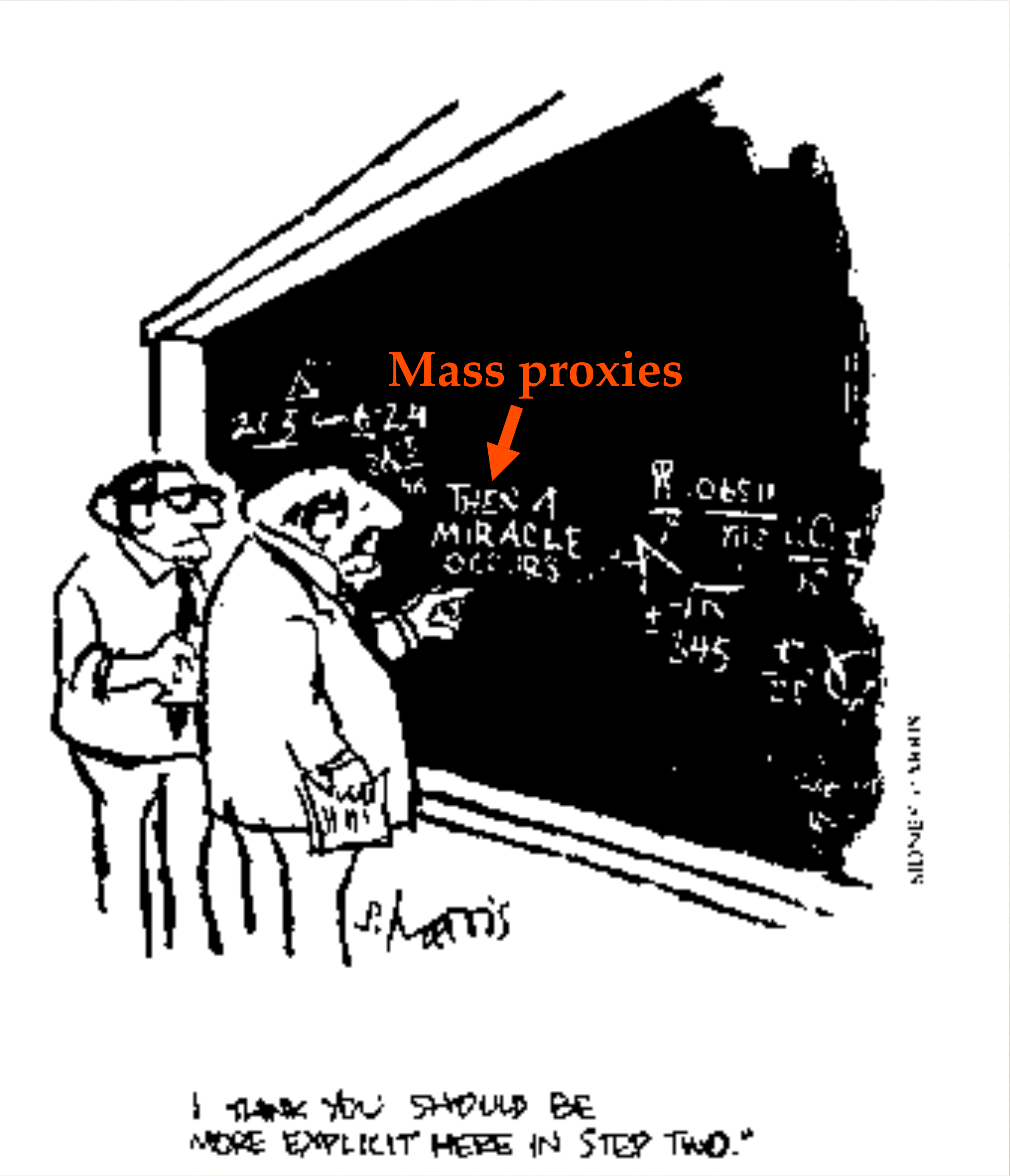
The current situation?

Mass proxies

Cluster survey → → Cosmology?

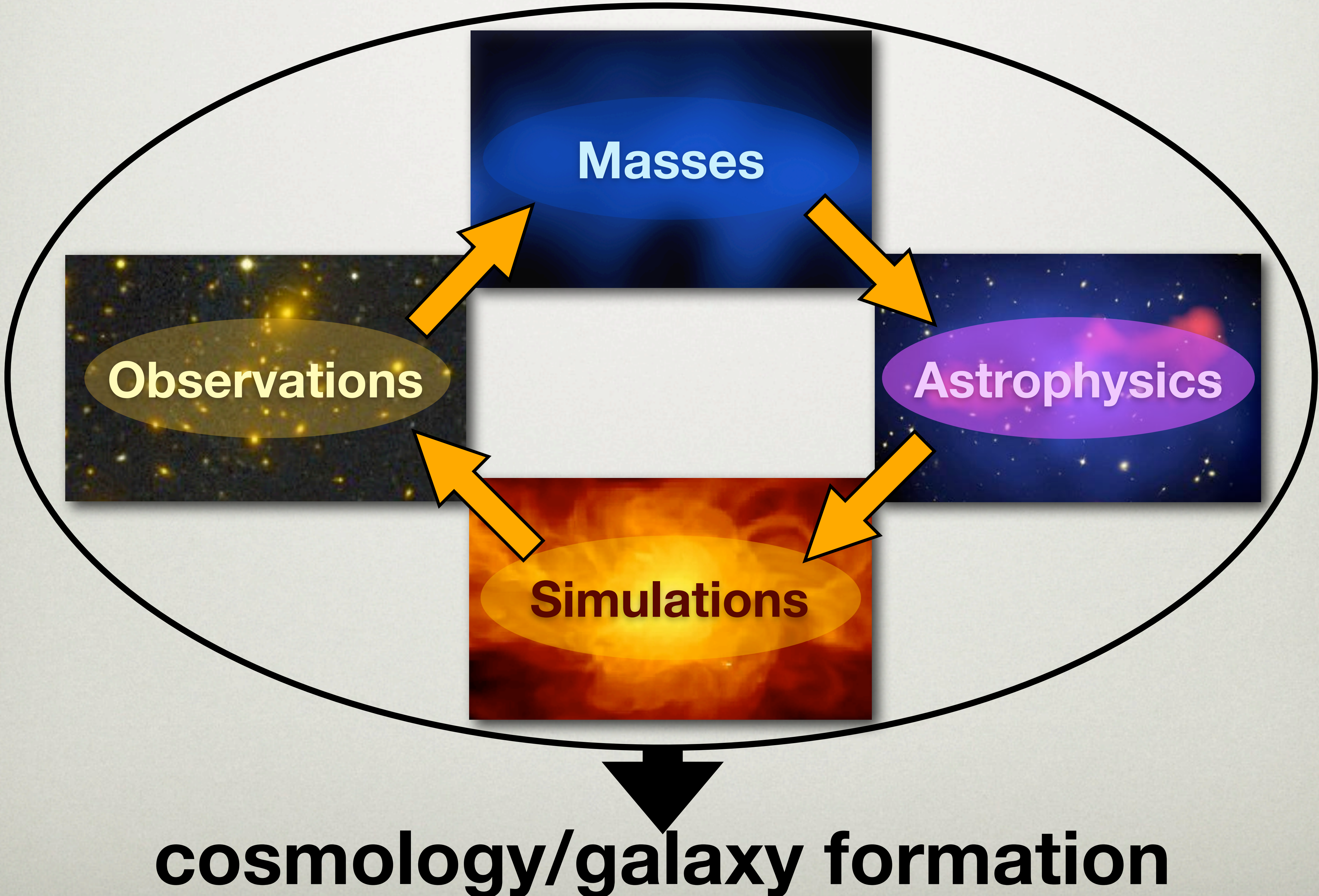
The current situation?

Cluster survey →



→ Cosmology?

Closing the loop



This is not easy

The mass estimates depend on

- dynamical state
- 3-d geometry
- adopted centre
- outer radius for the measurement

BUT...

Clusters are not...

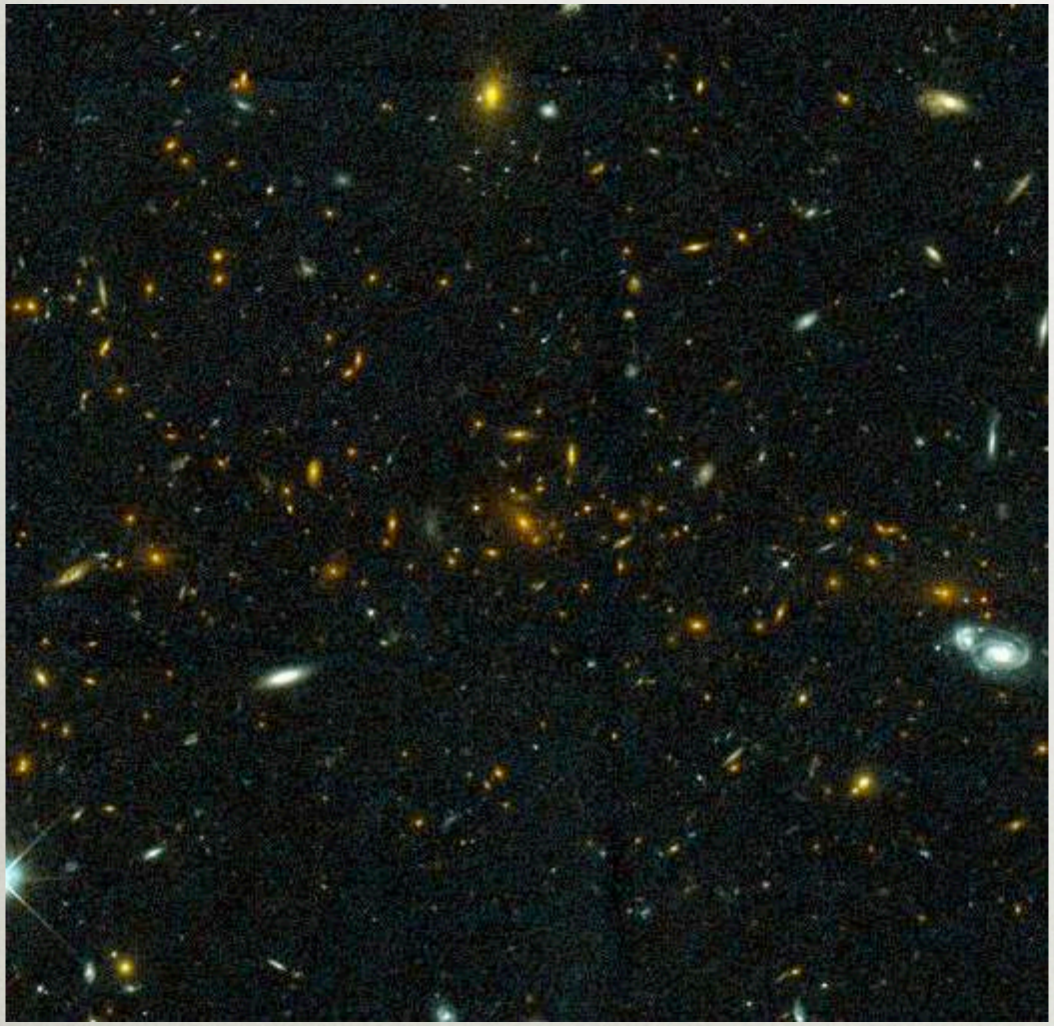
- Simple
- Spherical
- Relaxed

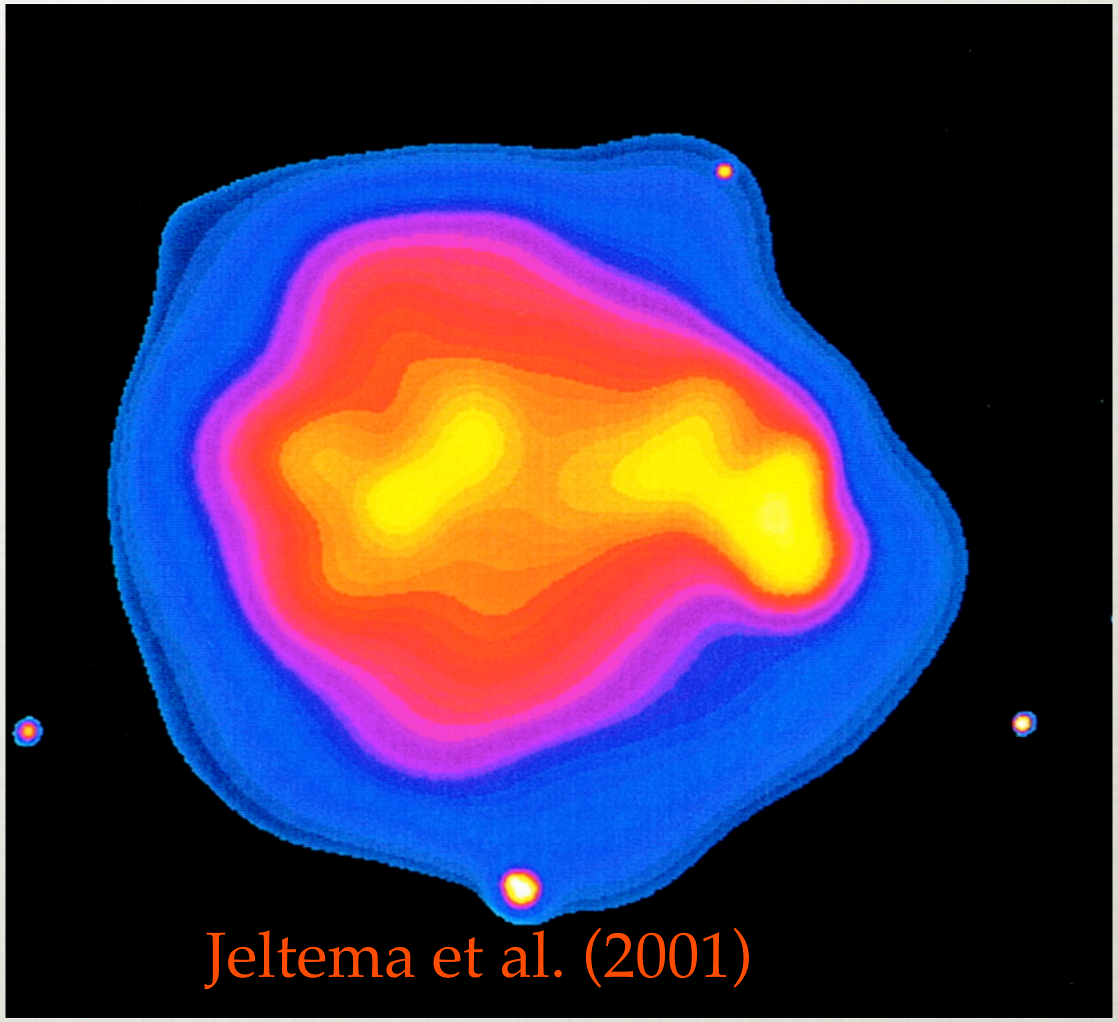
Clusters have a complicated history of multiple mergers resulting in complicated geometries with a lot of substructure.

Clusters become particularly messy at high redshift. For attempts to measure the equation of state of the dark energy this is a key redshift range…

A massive high-z cluster

MS1054-03 (z=0.83)





The light distribution consists of multiple clumps

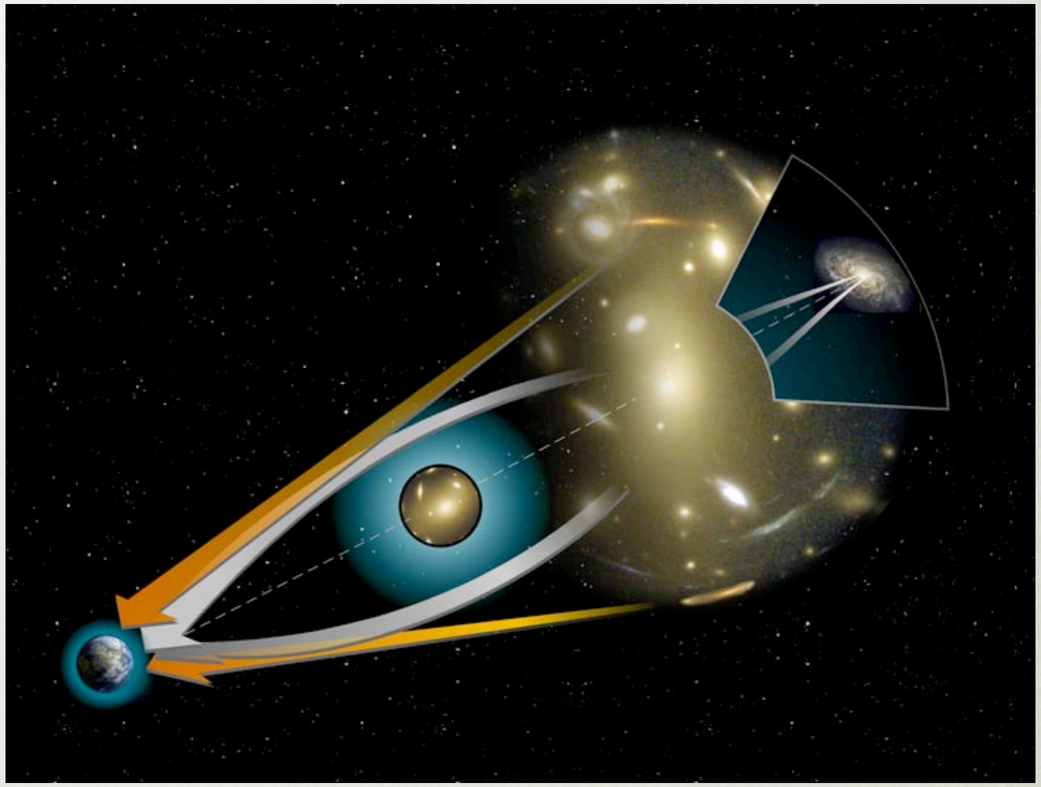
Nature's own weighing scales

Gravitational lensing

Zwicky (1937): "… The gravitational fields of a number of "foreground" nebulae may therefore be expected to deflect light coming to us from certain background nebulae. The observations of such gravitational lens effects promises to furnish us with the simplest and most accurate determination of nebular masses. *No thorough search for these effects has as yet been undertaken*."

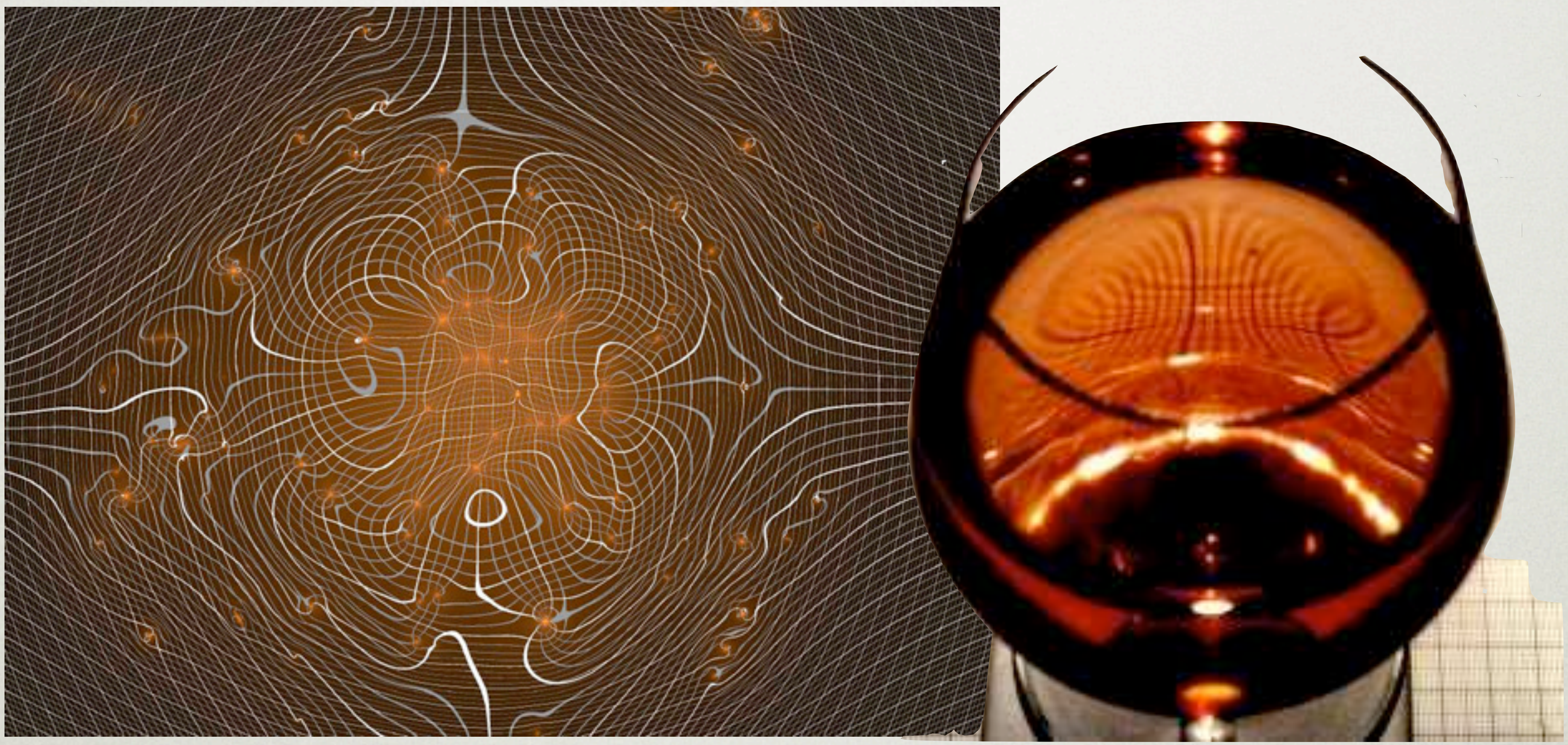
Gravitational lensing

Observations of the gravitational lensing signal provide a powerful way to study the dark matter distribution in the universe.



- It does not require assumptions about the dynamical state of the system under investigation.
- It can probe the dark matter on scales where other methods fail, as it does not require visible tracers of the gravitational potential.

Gravitational lensing



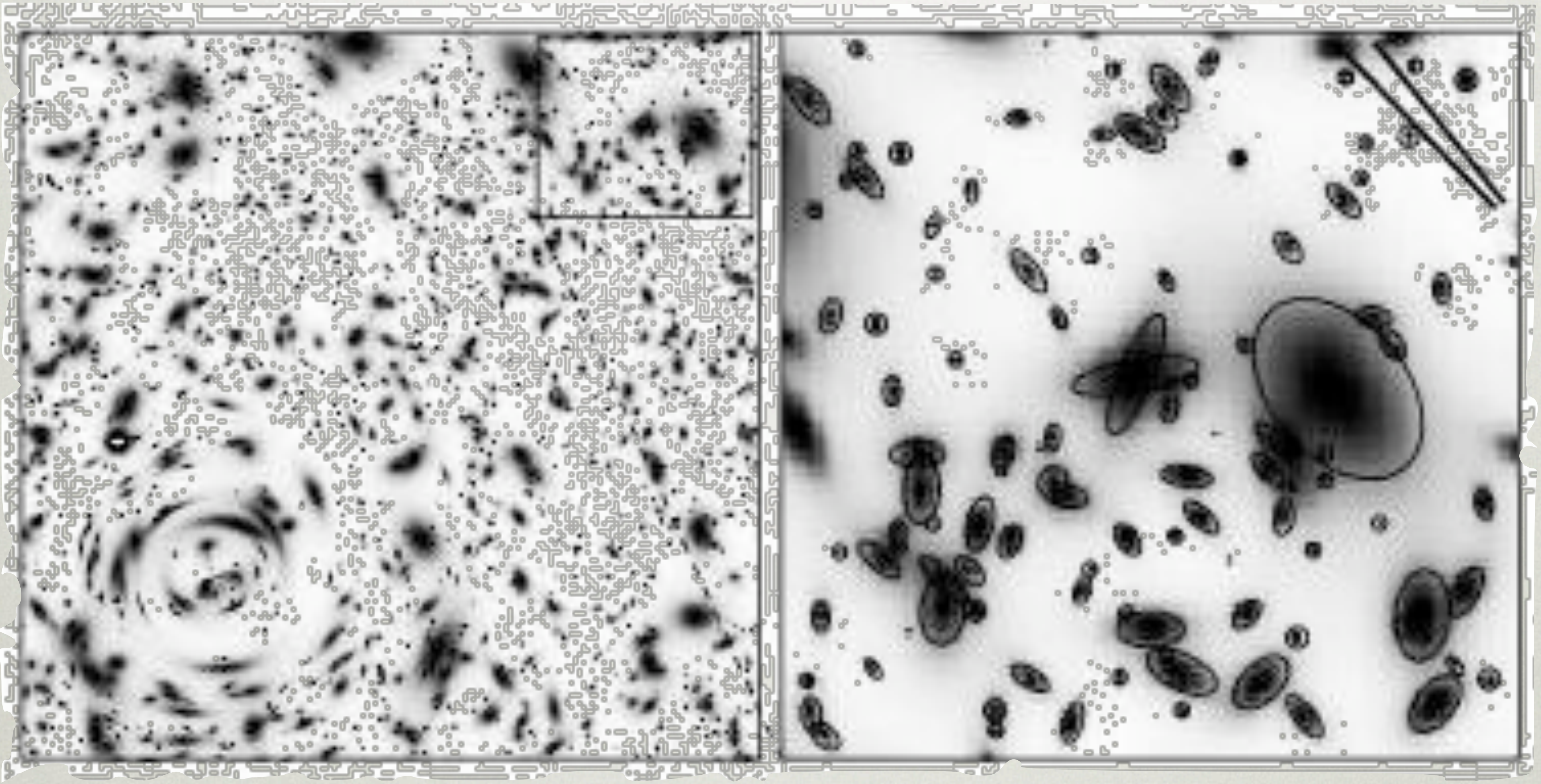
The cluster mass distribution causes a distortion in the shapes of background galaxies. The leads to spectacular lensing examples.

Gravitational lensing

Galaxy Cluster Abell 2218 **HST • WFPC2**

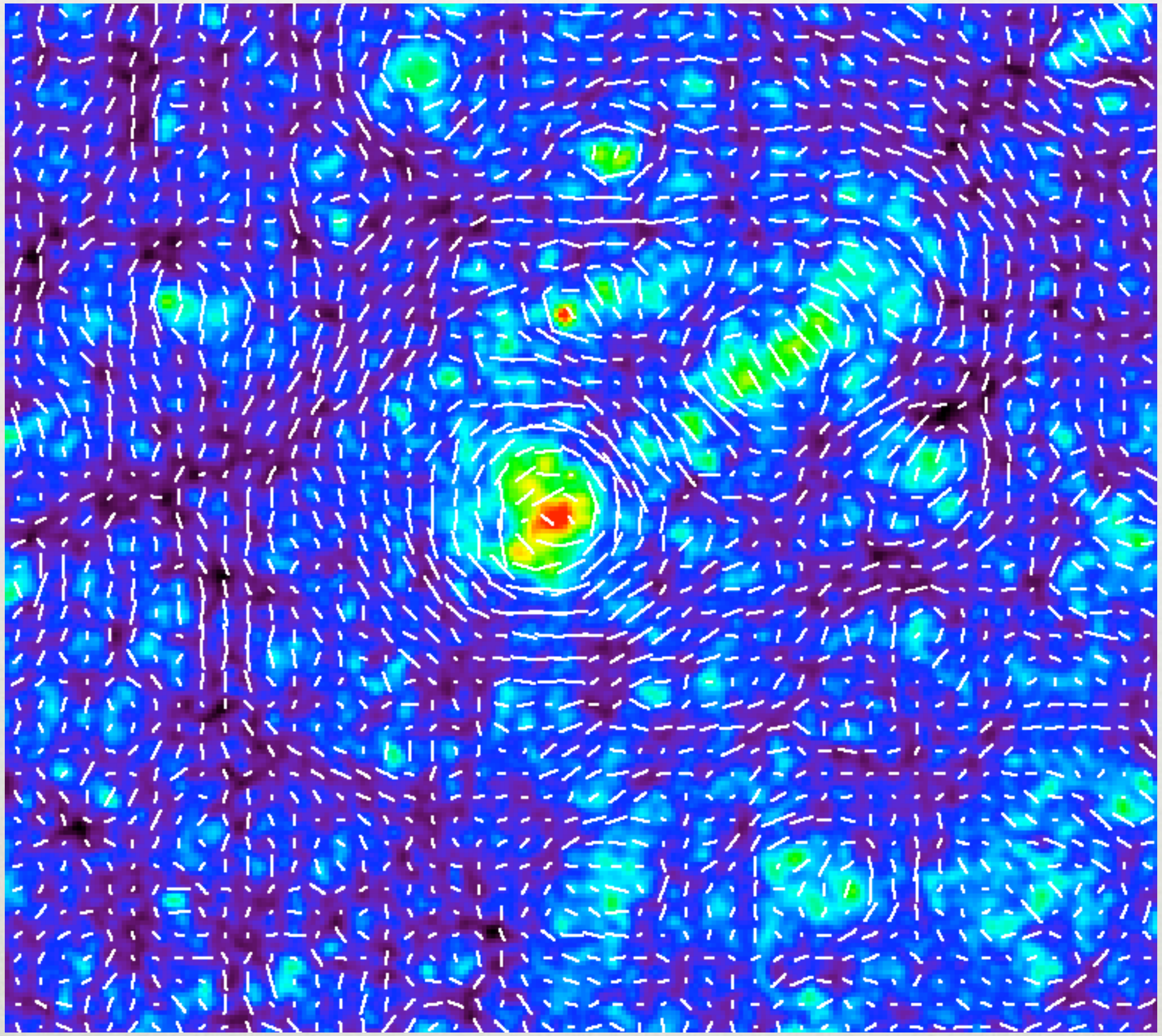
NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

Weak gravitational lensing



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

We can 'see' dark matter

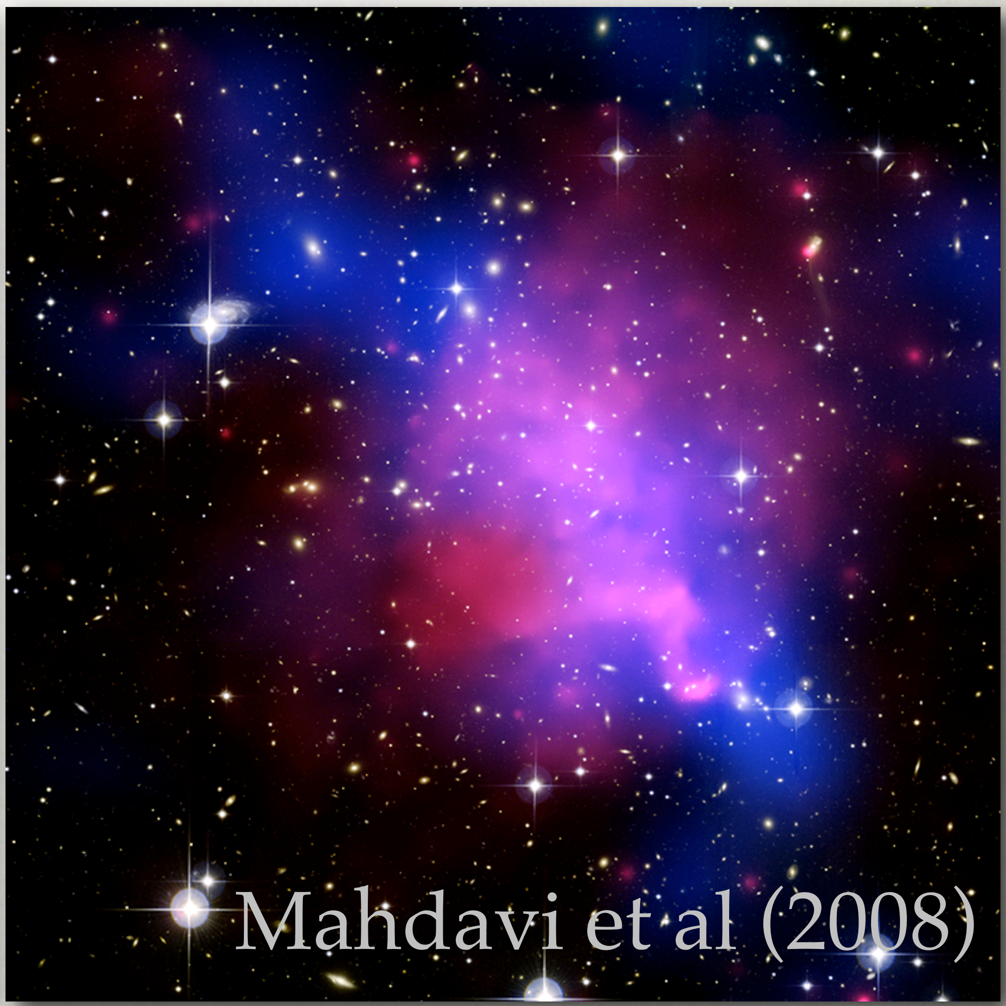


Courtesy B. Jain

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

We can 'see' dark matter

and it is blue...



Weak gravitational lensing provides an important link between the observable universe and numerical simulations.

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

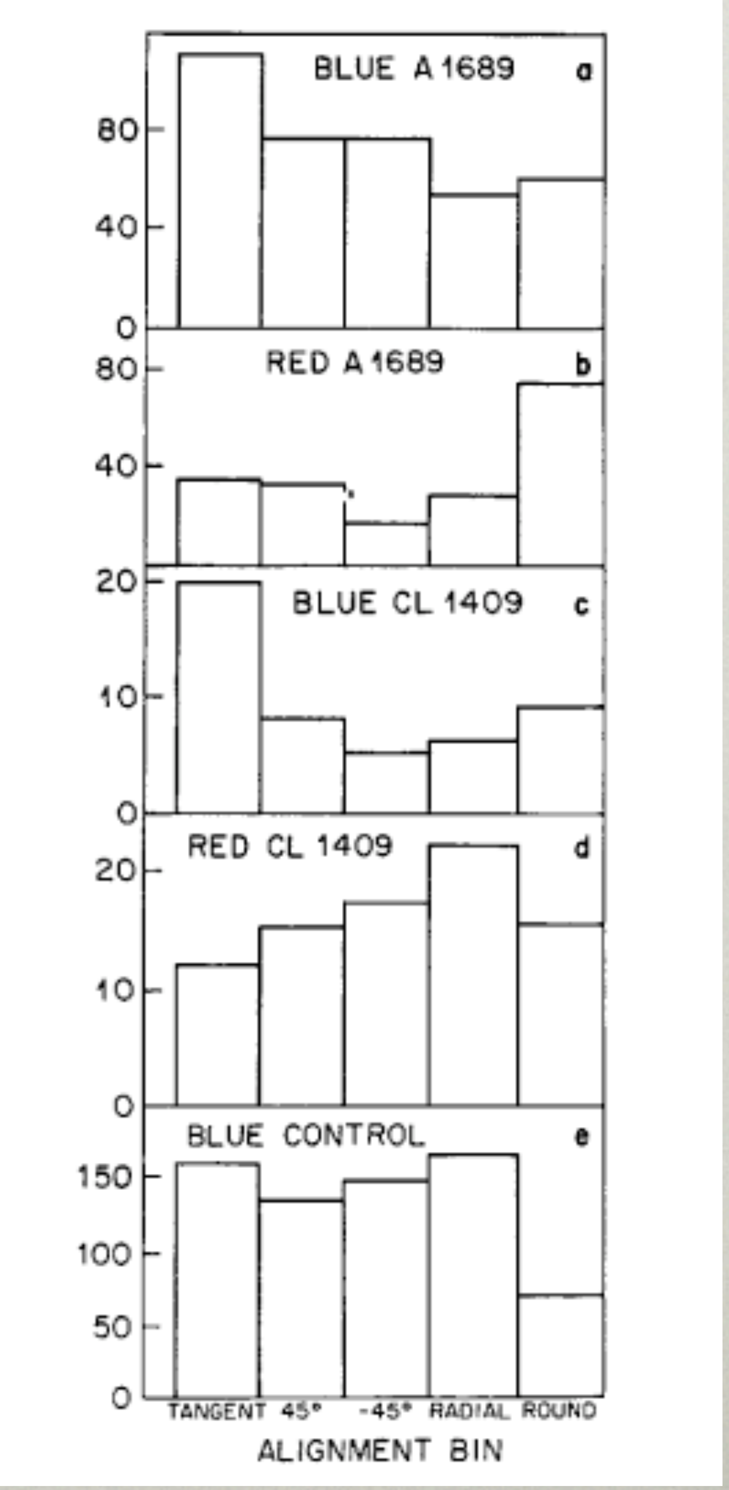
Lensing signal

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

A brief history

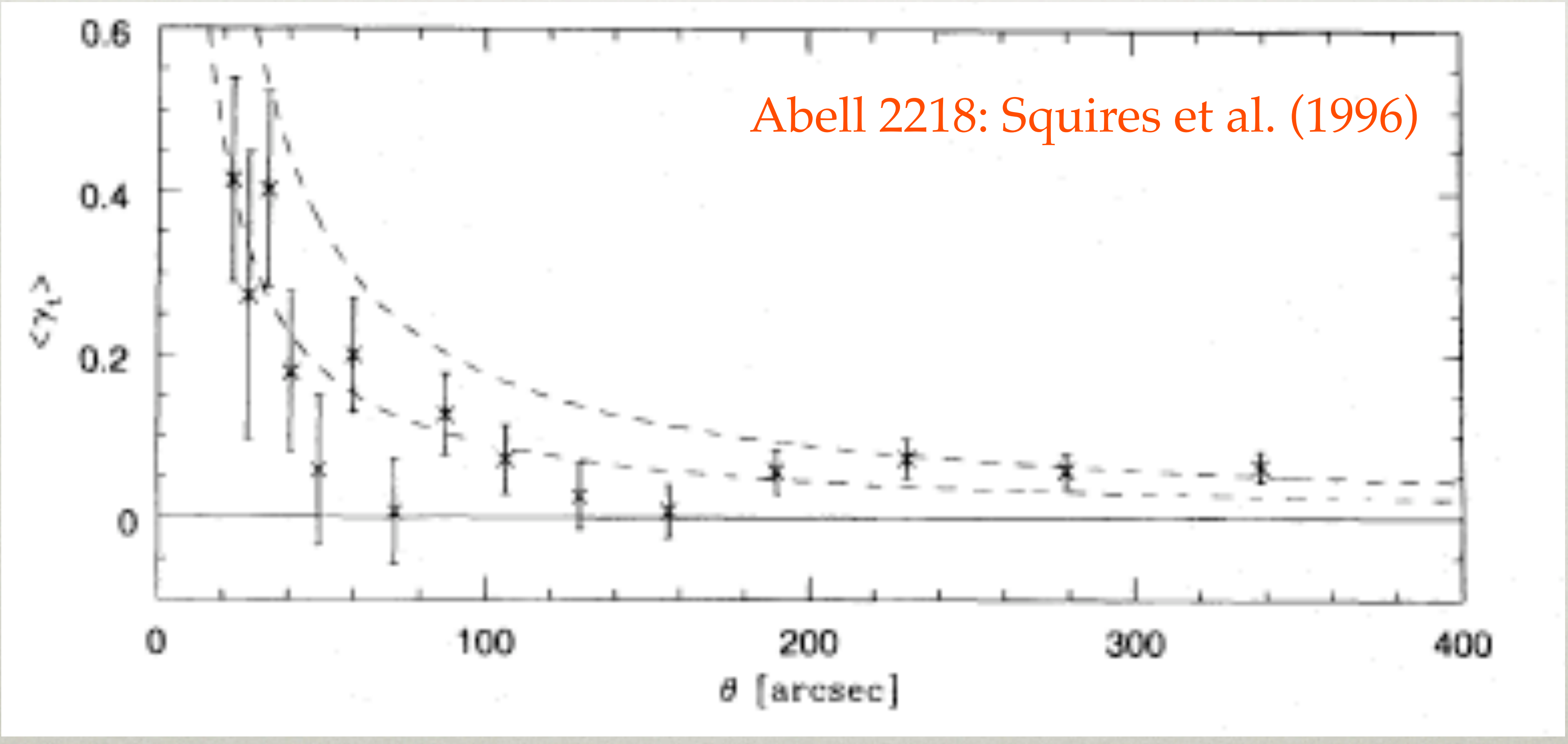
Most structures in the universe are not massive enough and need to be studied in a statistical sense by stacking their signals.

Massive clusters are the only objects for which weak lensing can give masses on an individual basis. The induced shears are a few percent, which explains why the first weak lensing detection was made for the cluster Abell 1689 (Tyson et al. 1990)



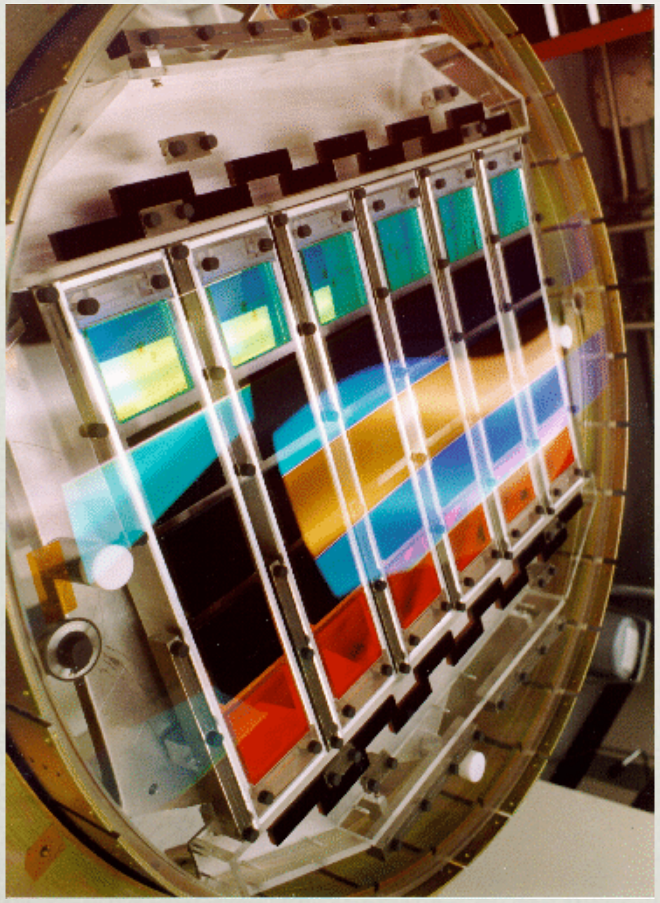
A brief history

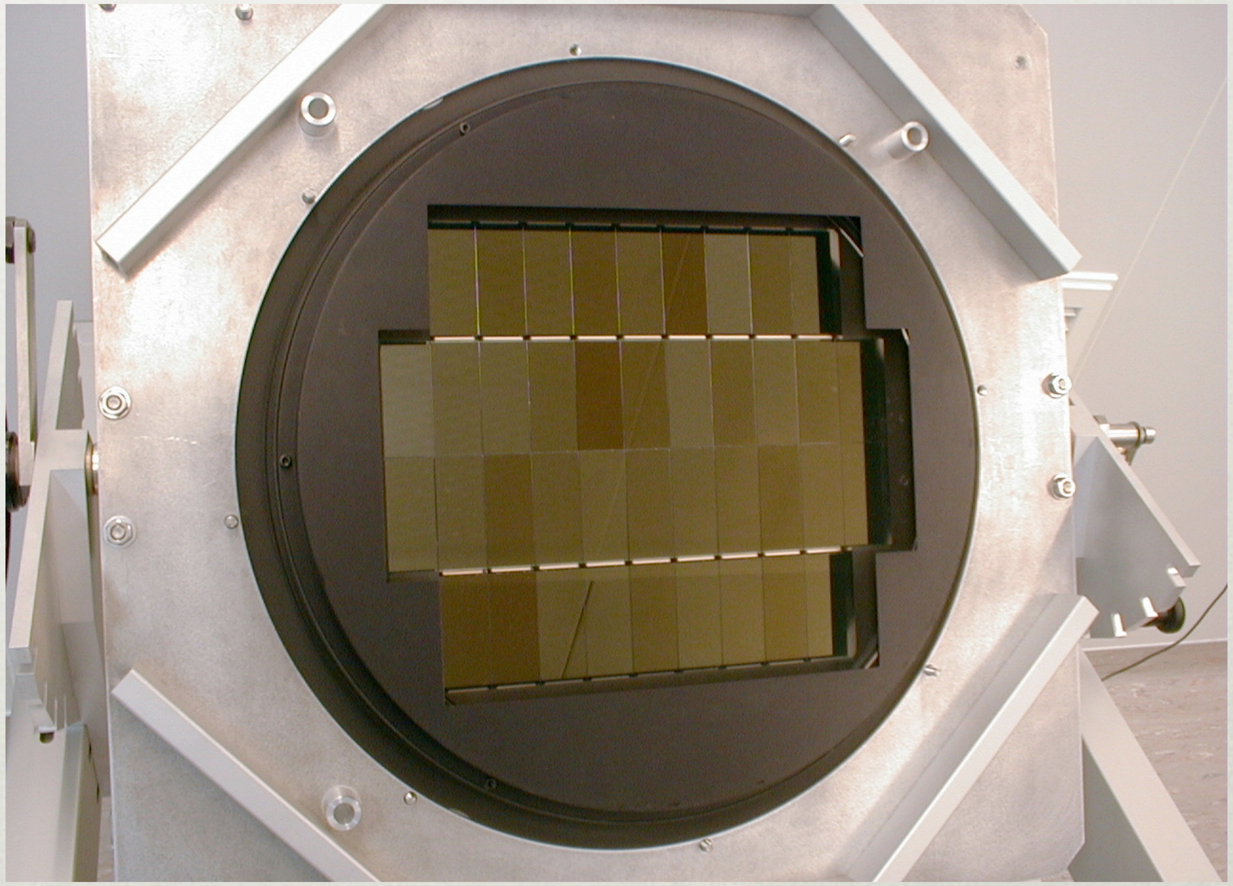
A handful of clusters were studied in the ’90s using cameras with relatively small fields of view and little knowledge of the source redshift distribution.



A NEW MILLENNIUM...

In 2000 the first cosmic shear detections we published, and cluster weak lensing was no longer "fashionable" (if it ever was…)





But the wide field imagers developed for cosmic shear are great for cluster work as well, as we can image large samples of clusters out to large radii!

Modern cluster lensing

Compared to earlier work we now have a better understanding of the source redshift distribution and can correct better for systematic effects.

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

Limitations

Fig. 5.—Zoom-in of one of our convergence maps showing two clusters that lie almost on top of each other in projection. *Left*: Full κ map. *Middle*: Portion coming from the 100 h^{-1} Mpc slice at low redshift. *Right*: Portion coming from the 100 h^{-1} Mpc slice at higher redshift. The regions shown are $0^\circ.3$ on a side.

Projections are important when studying peaks in large scale weak lensing maps.

Limitations of weak lensing

The mass depends on the adopted centre!

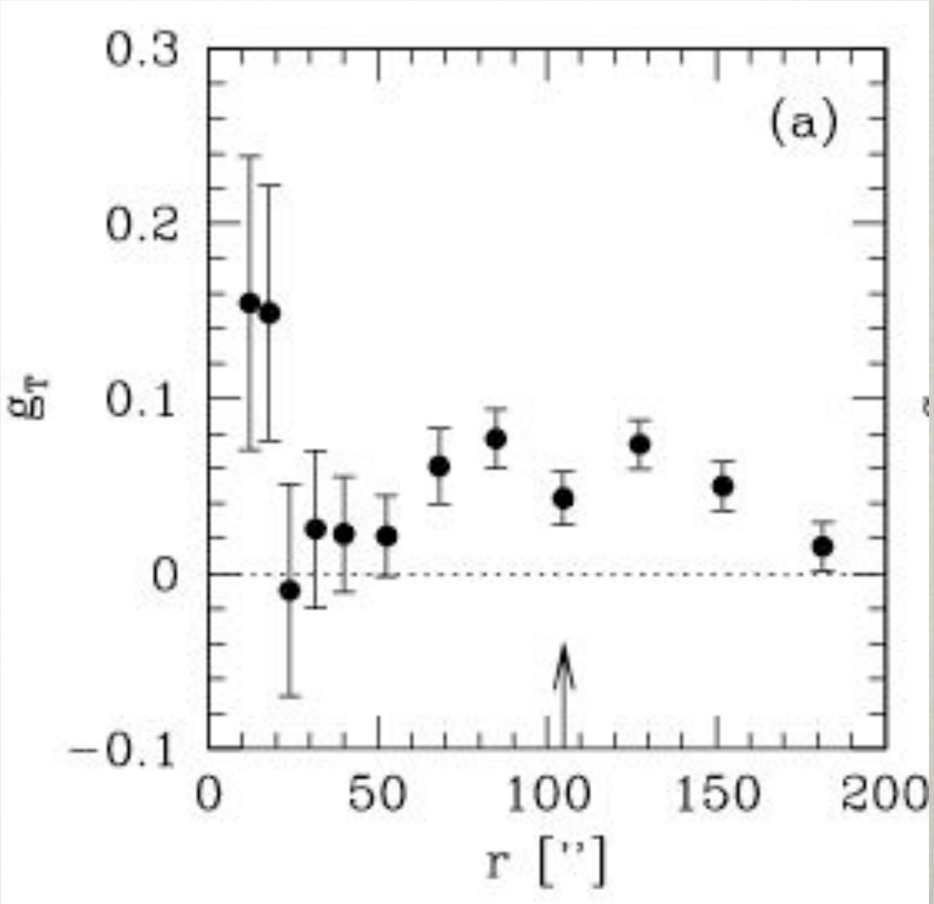
This is particularly problematic if we fit a simple parametric model and is made worse if there is substructure!

Use aperture masses (1-d masses):

- This can minimize the model dependence
- This reduces the sensitivity to the centroid

"mass contrast"

$$g_T(r) \propto \langle \Sigma(<r) \rangle - \langle \Sigma(r) \rangle$$



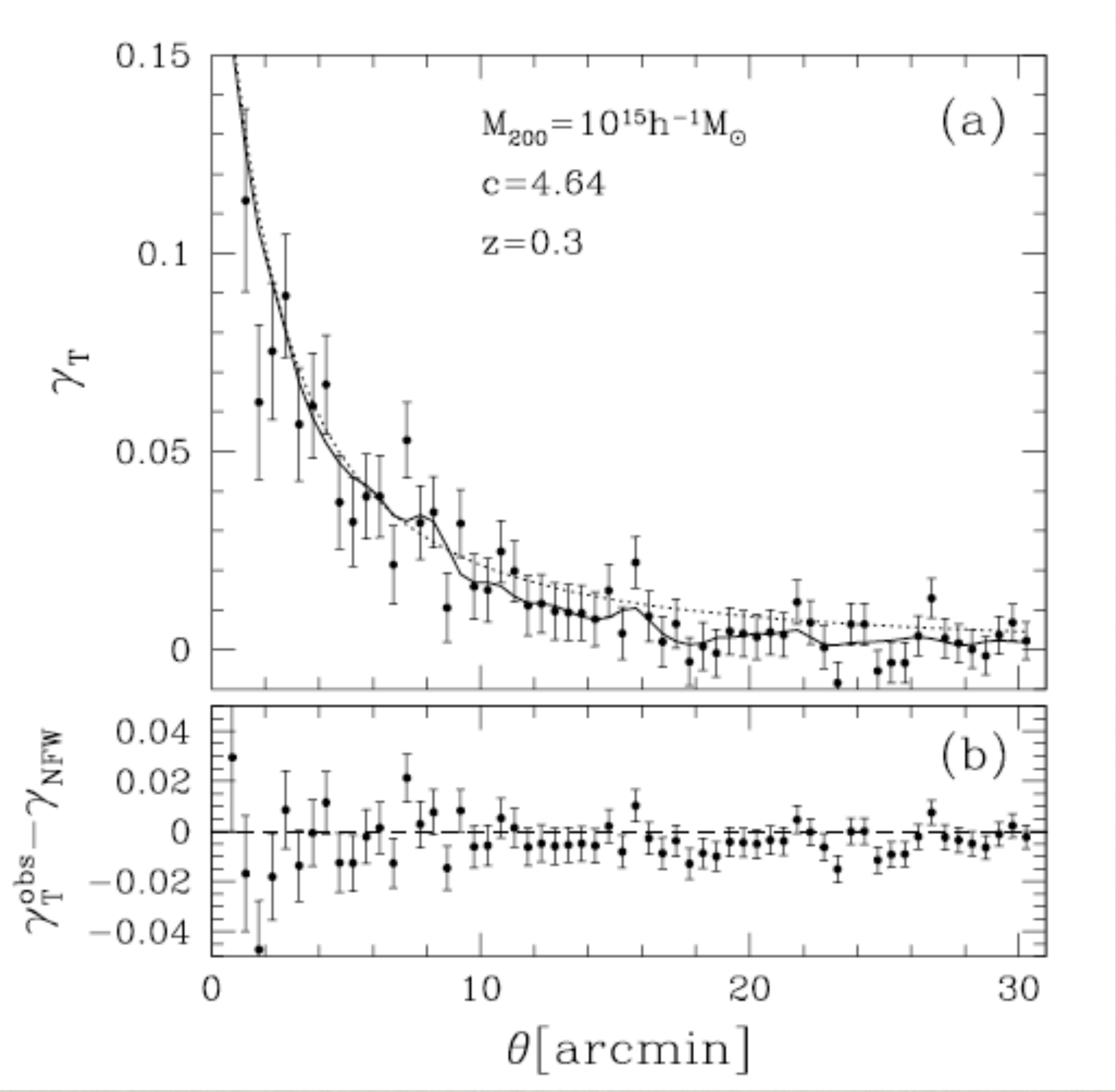
Limitations of weak lensing

- Weak lensing gives the projected mass distribution
- The signal depends on all matter along the line of sight
- We require good knowledge of the source redshifts

Uncorrelated large scale structure is an additional source of noise

Limits the accuracy with which masses can be determined

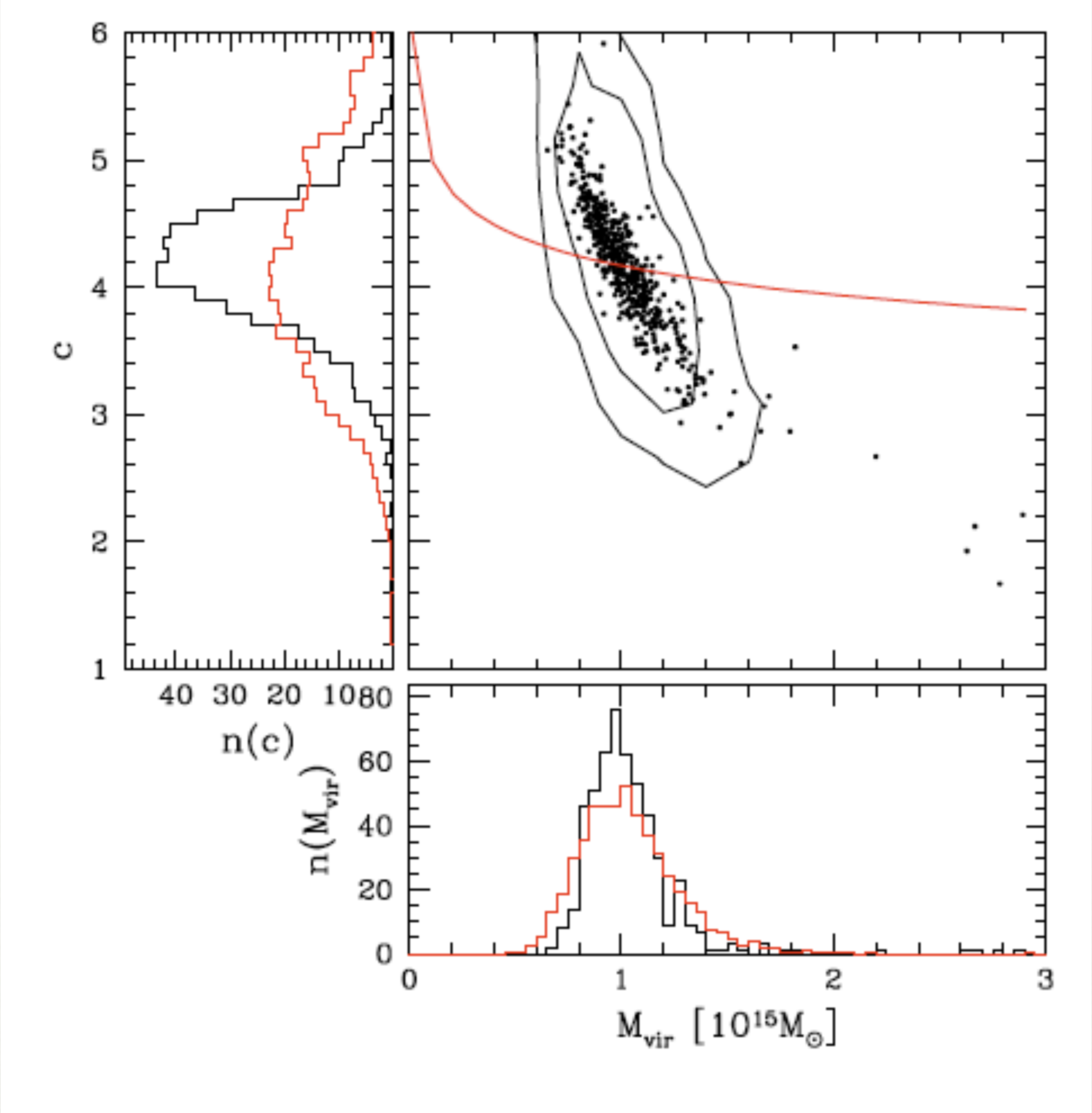
Effects of 'cosmic noise'



Hoekstra (2003)

Effects of 'cosmic noise'

Hoekstra et al. (2011)



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

Large cluster samples

Observations ⟷ **Masses** ⟷ **Simulations**

↑

Weak lensing masses

A large sample of clusters with accurate weak lensing masses is important for the success of cluster abundance studies.

Large cluster samples

We want to study the scaling relations between *mass* and *observables* as a function of *redshift*.

This requires large range in mass/redshift

Comparison of mass-proxies can help identify which ones work best, but also provides insights in the relevant cluster physics.

Such large multi-wavelength surveys are starting to yield 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

CCCP: Good for the masses

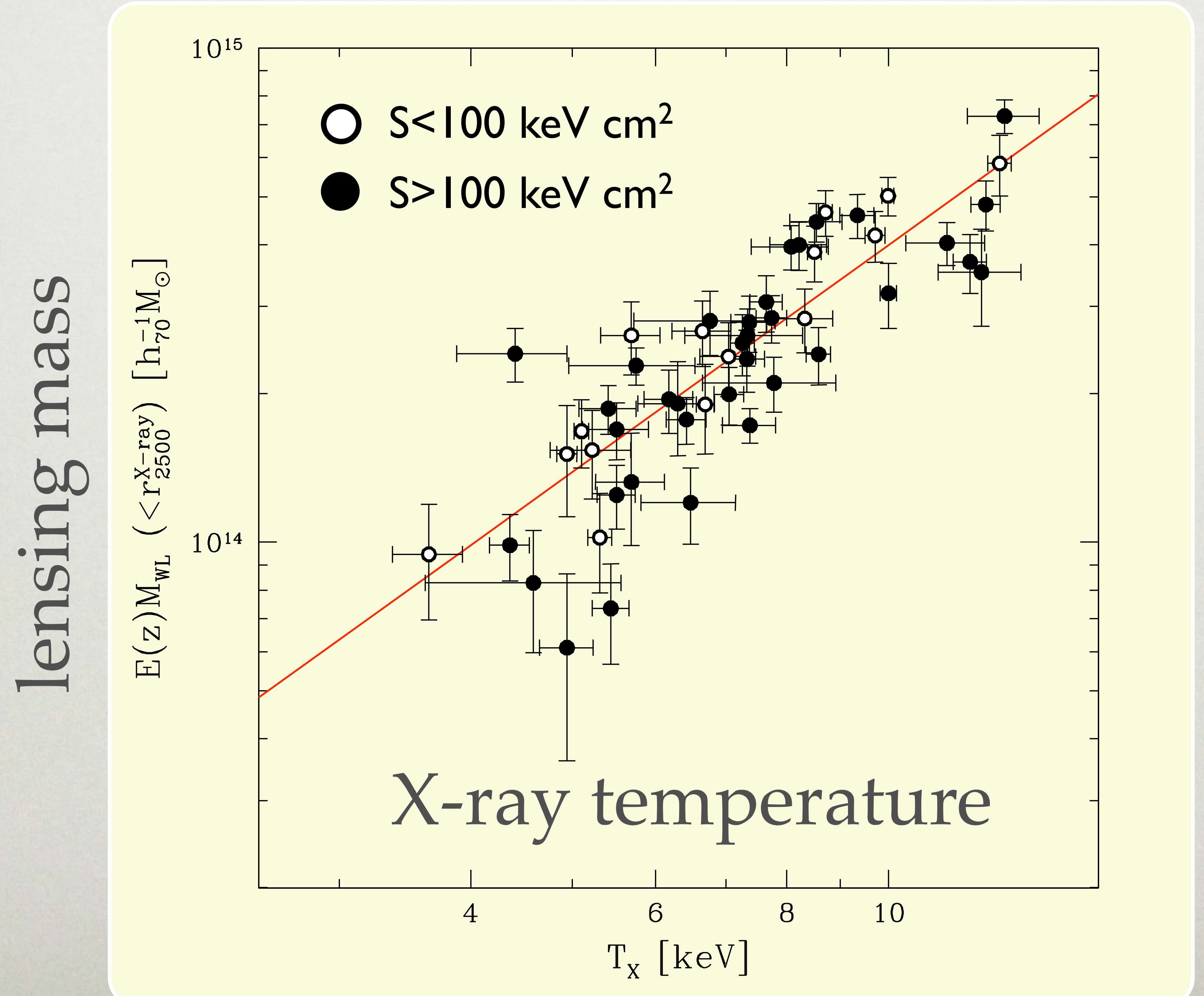
Andisheh Mahdavi, Arif Babul, Pat Henry, Chris Bildfell

The Canadian Cluster Comparison Project is a study of 50 X-ray luminous clusters of galaxies with $0.15<z<0.55$ and $T_x>5$ keV.

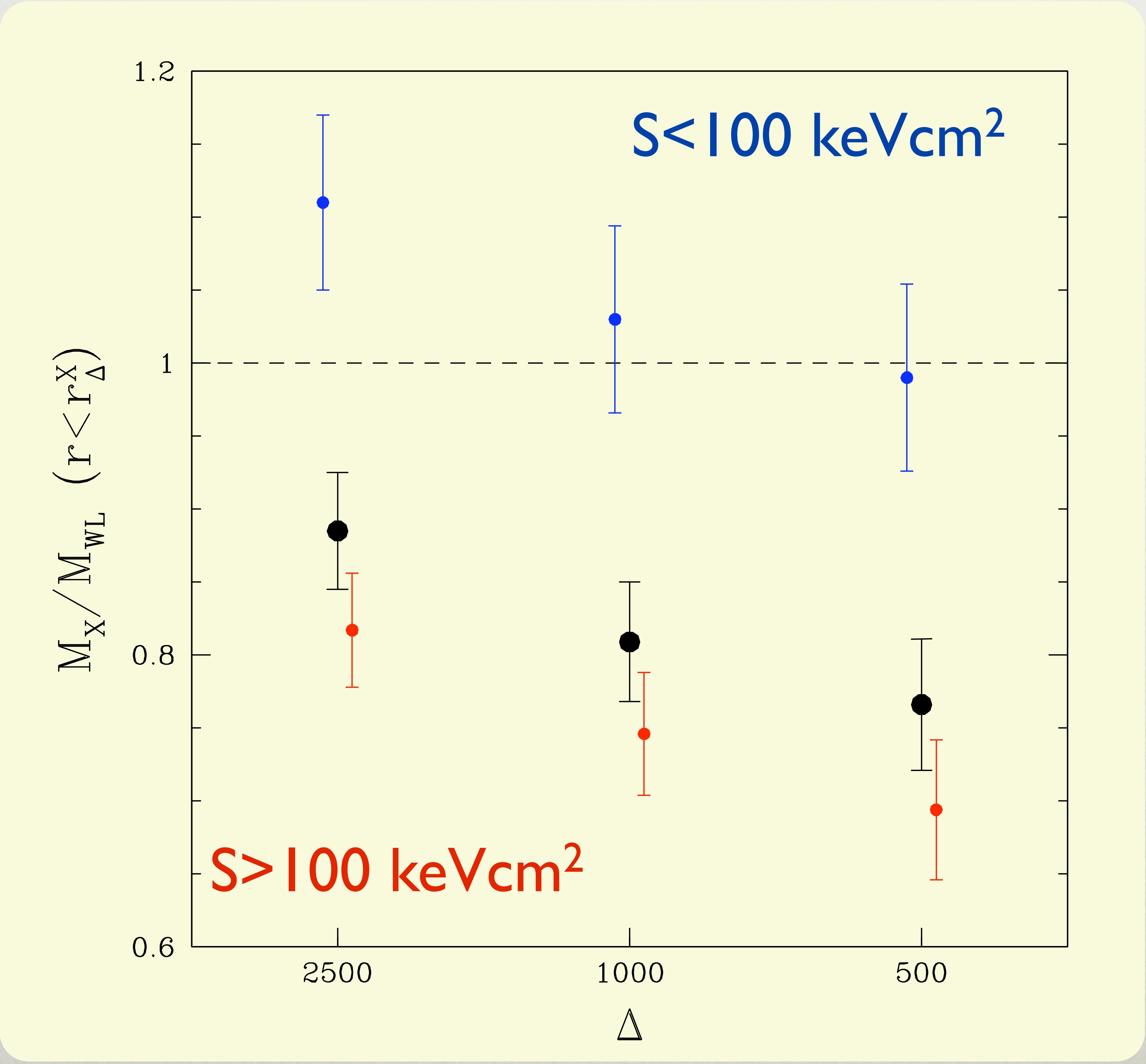
- study properties of the ICM
- calibration for cluster abundance studies

We recently completed the Multi-Epoch Nearby Cluster Survey (MENeaCS), which is a survey of 60 clusters with $0.05<z<0.15$

Mass-X-ray properties

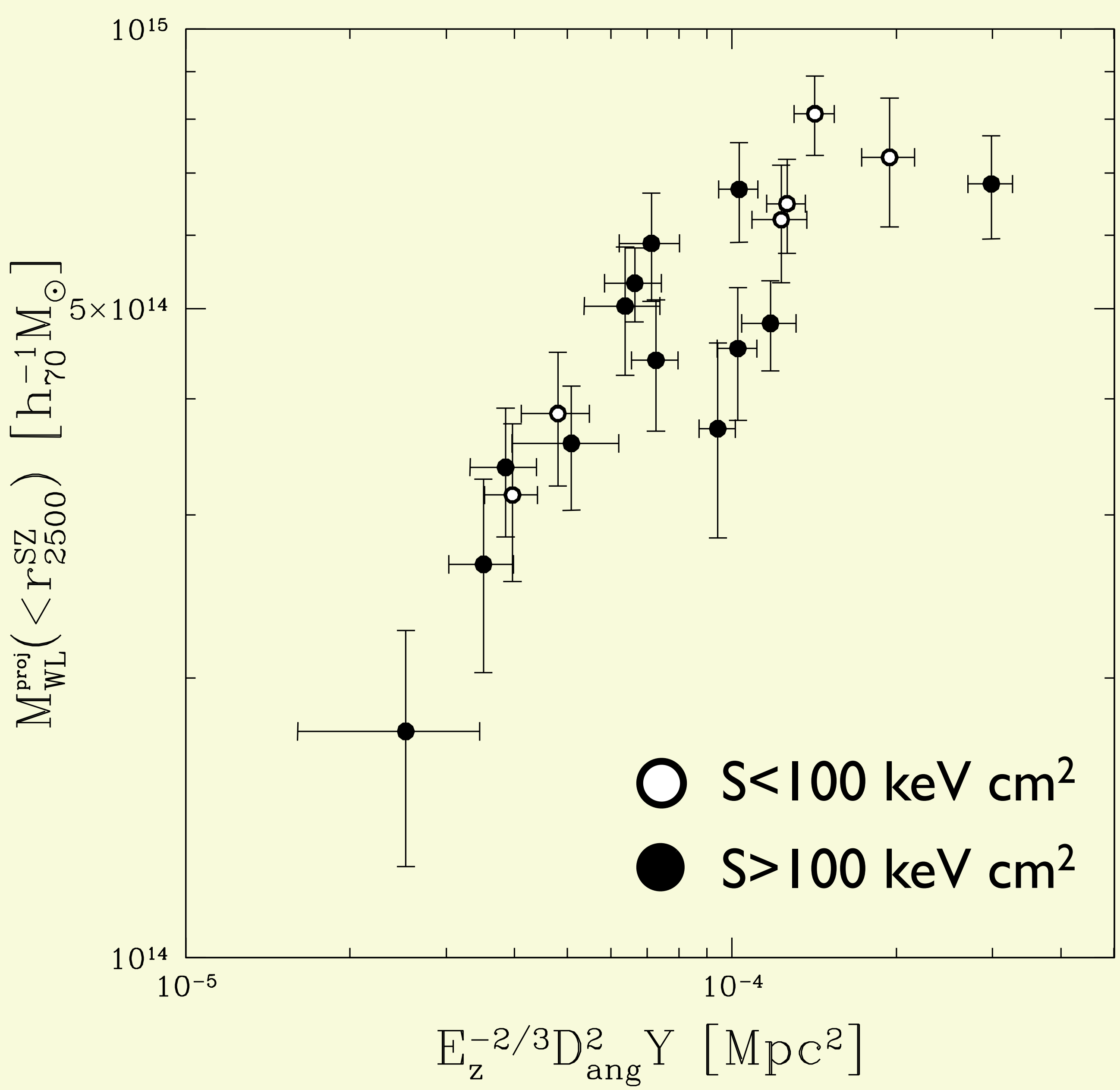


Lensing vs X-ray masses

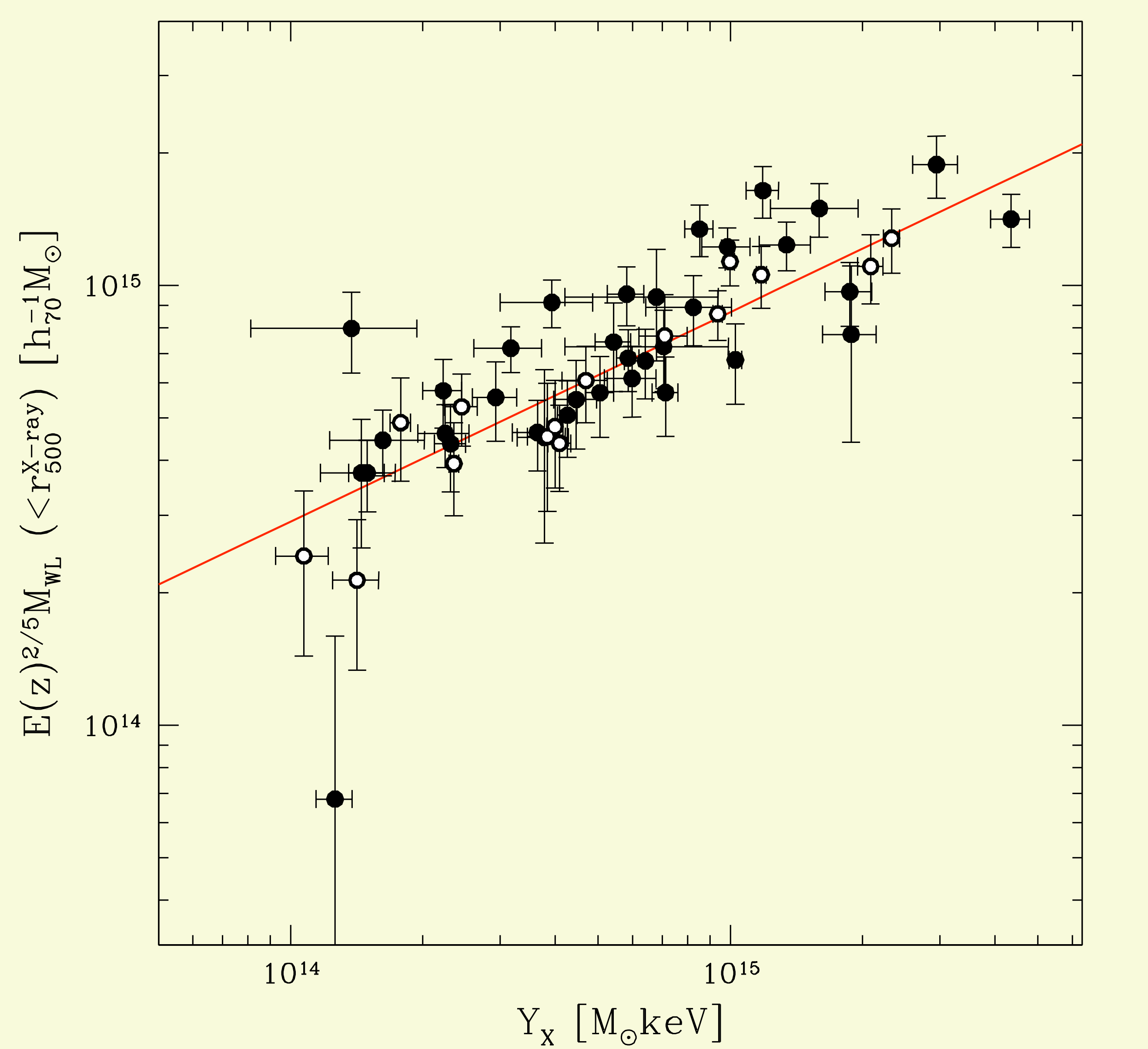


Comparison of proxies

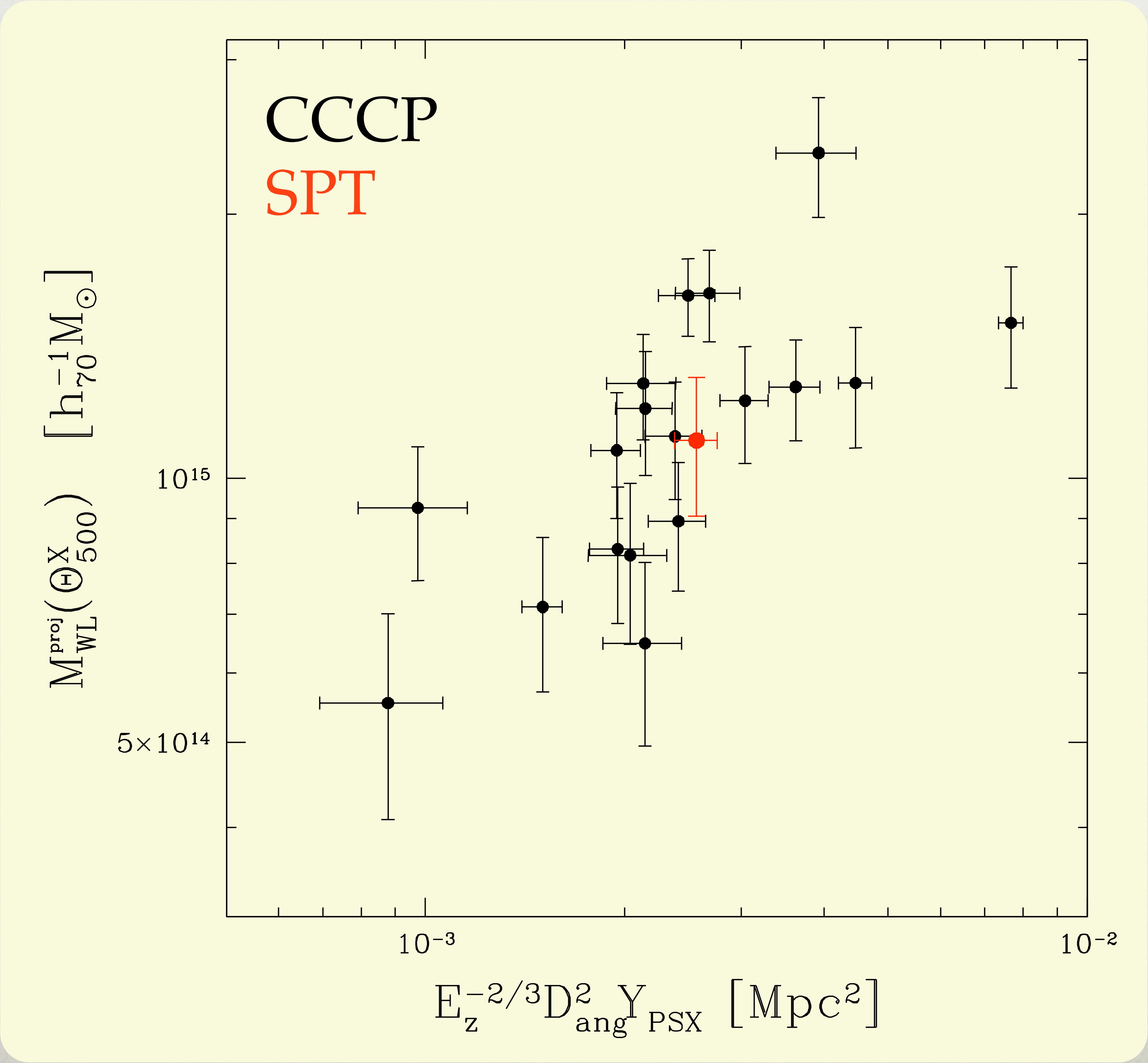
“real” SZ (Bonamente et al.)



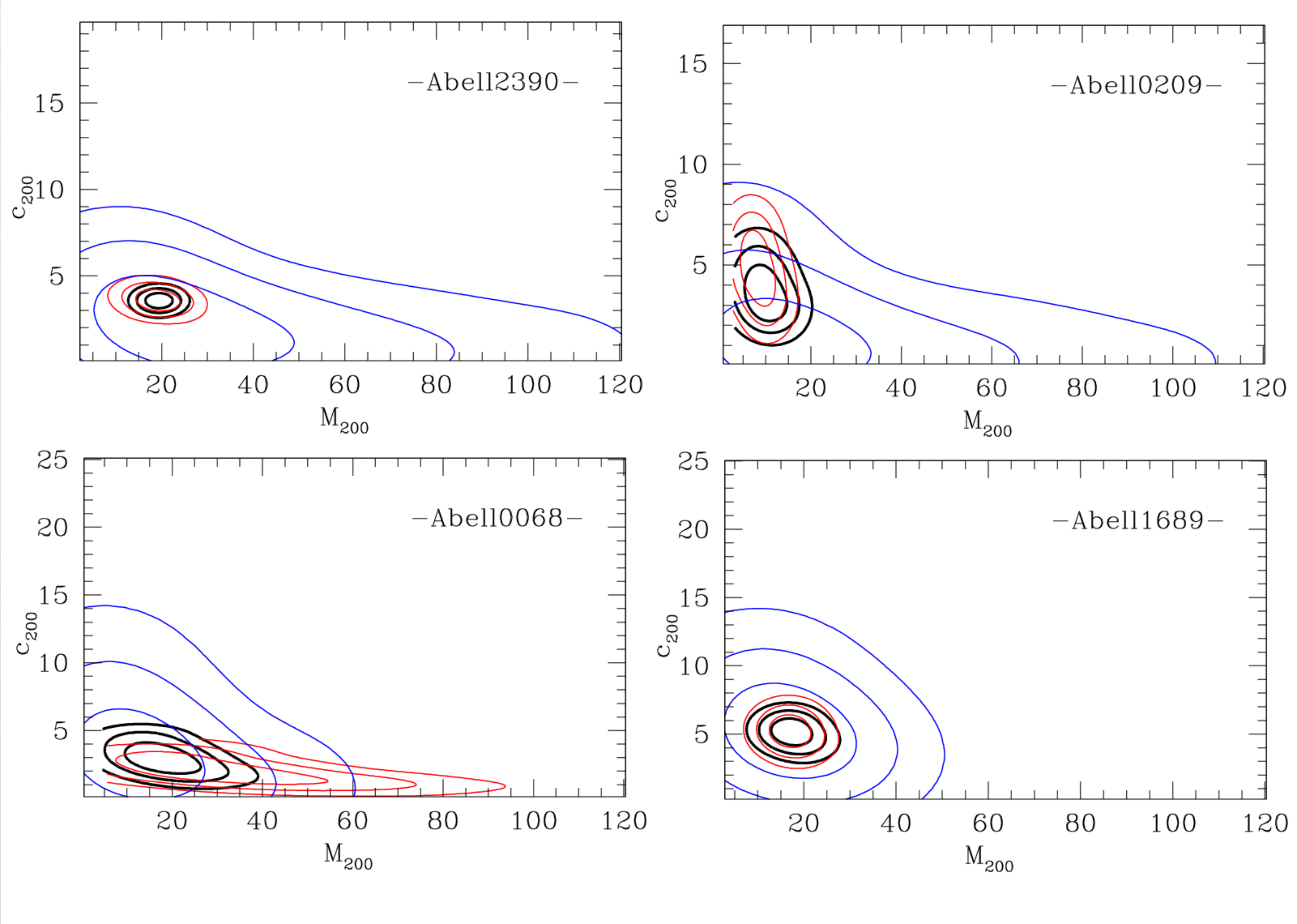
“X-ray” SZ (CCCP)



Planck SZ observations



Density profiles

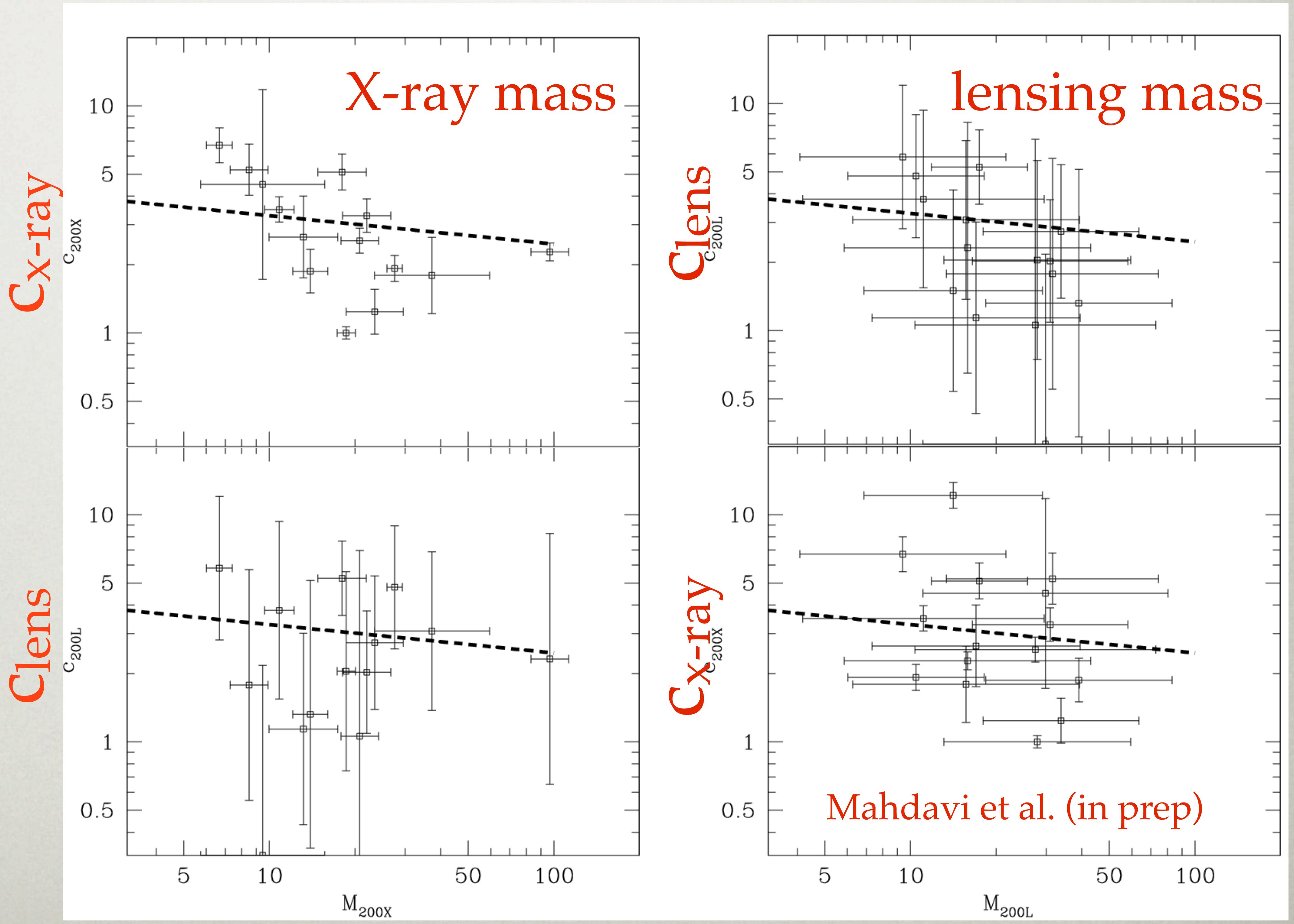


Joint X-ray + lensing model can help constrain profile parameters (Mahdavi et al., in prep)

Density profiles

Correlated
(X-ray)

Uncorrelated
(X-ray + lensing)



Stacking clusters

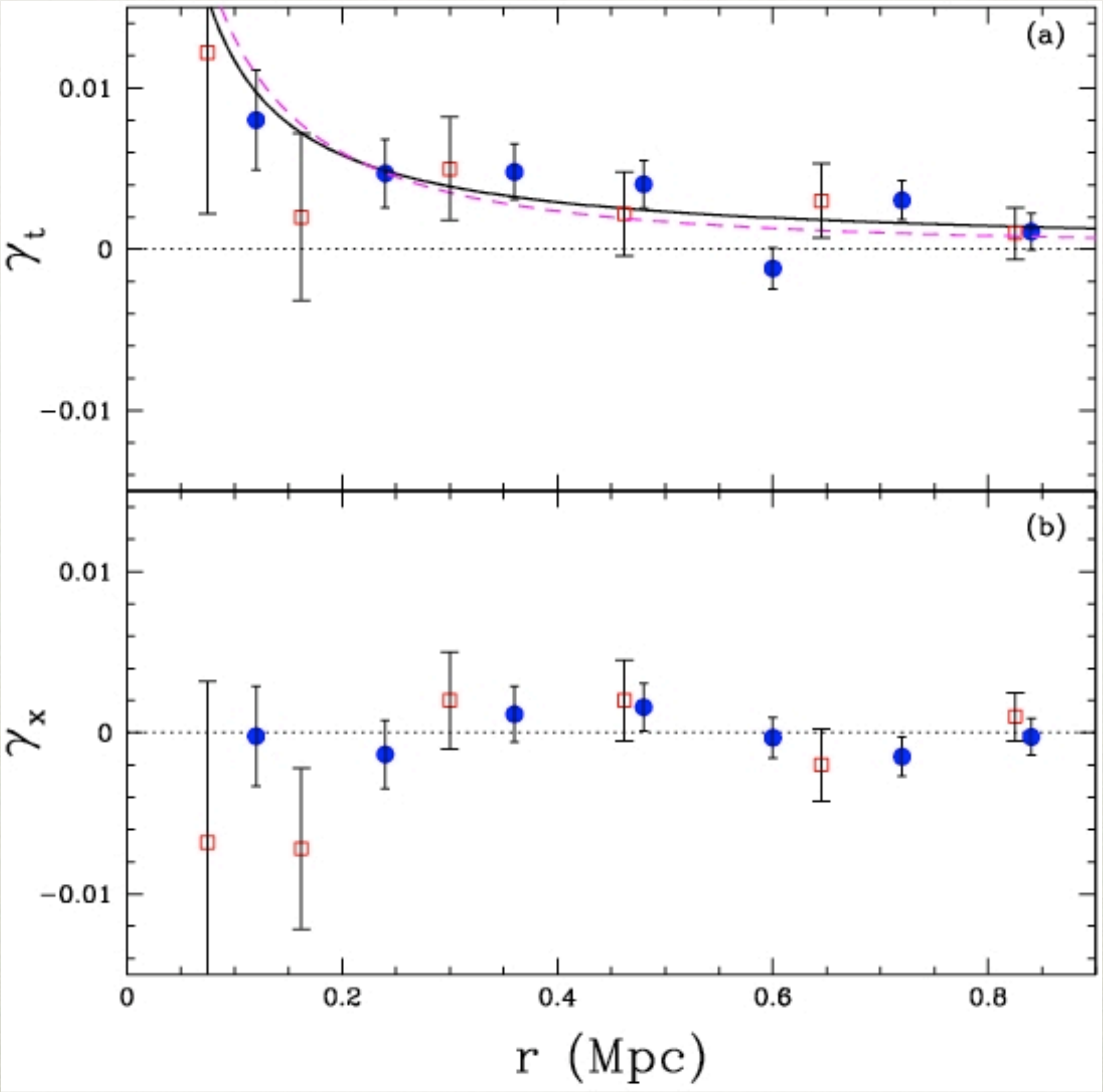
If the masses are too low, one can still learn about the cluster properties by stacking the signal of many systems. This is for instance done for galaxy groups (Hoekstra et al. 2001; Parker et al. 2006).

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

Lensing by groups

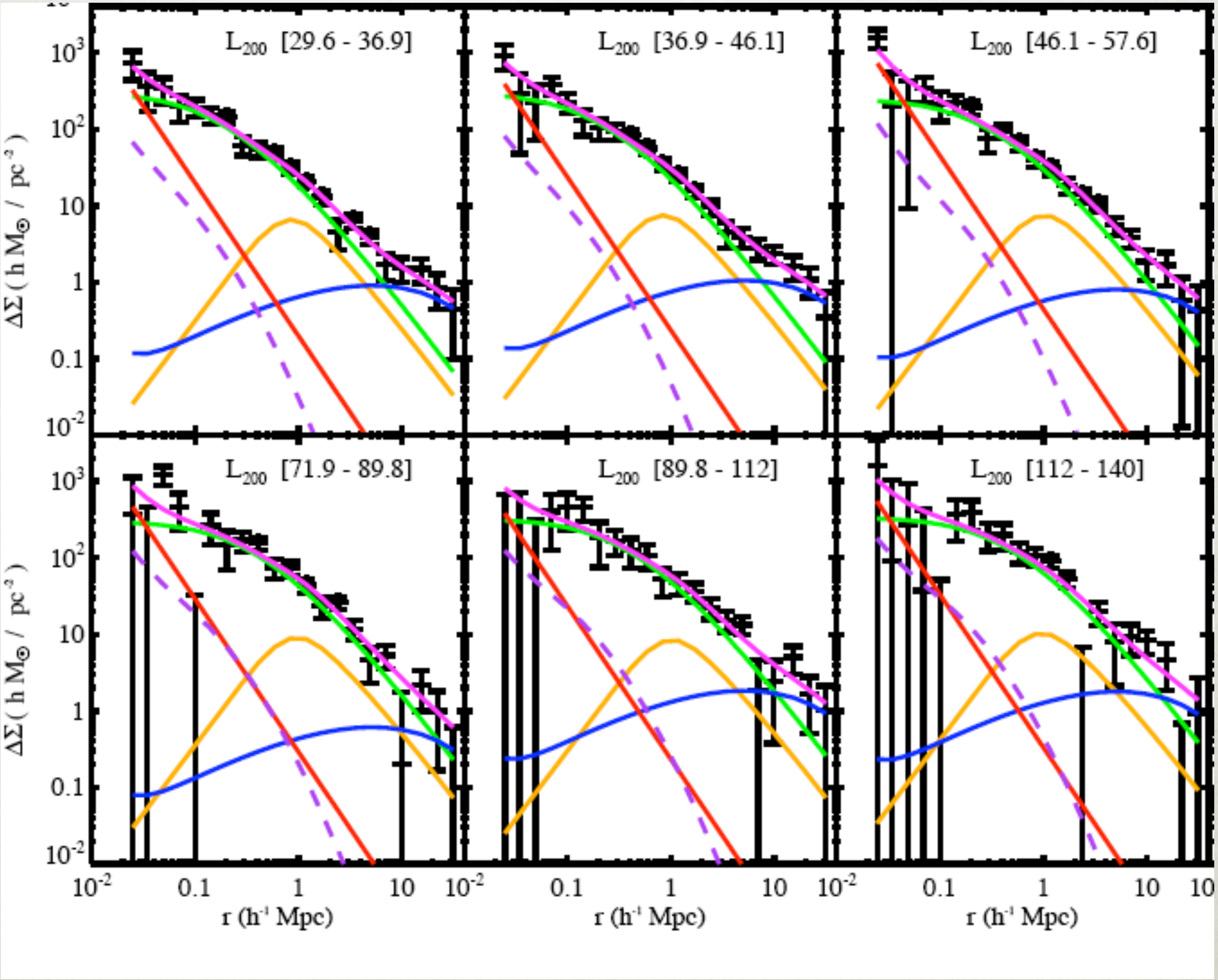
CNOC2



Hoekstra et al. (2001); Parker et al. (2005)

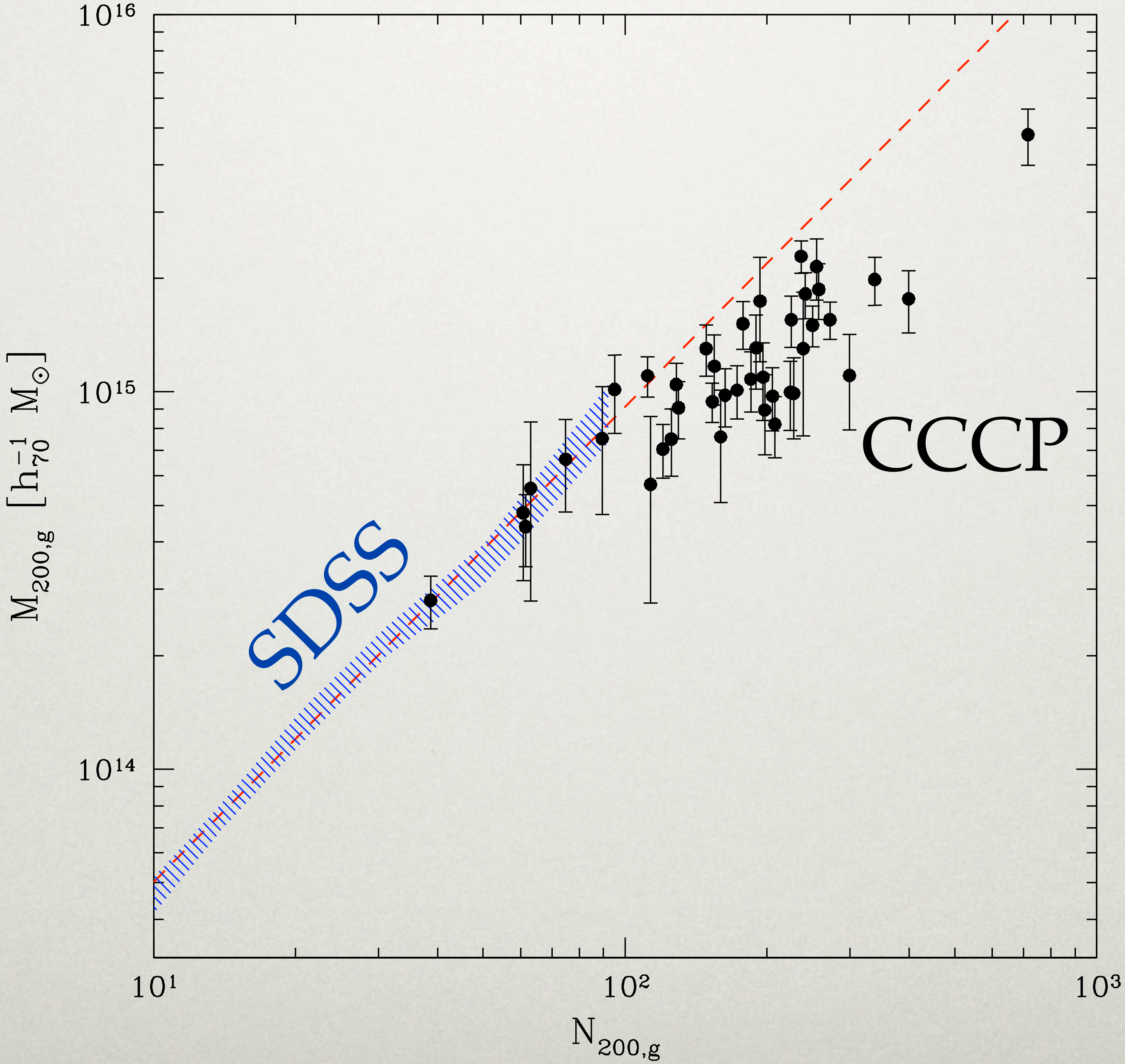
Cluster density profiles

SDSS



Johnston et al. (2007)

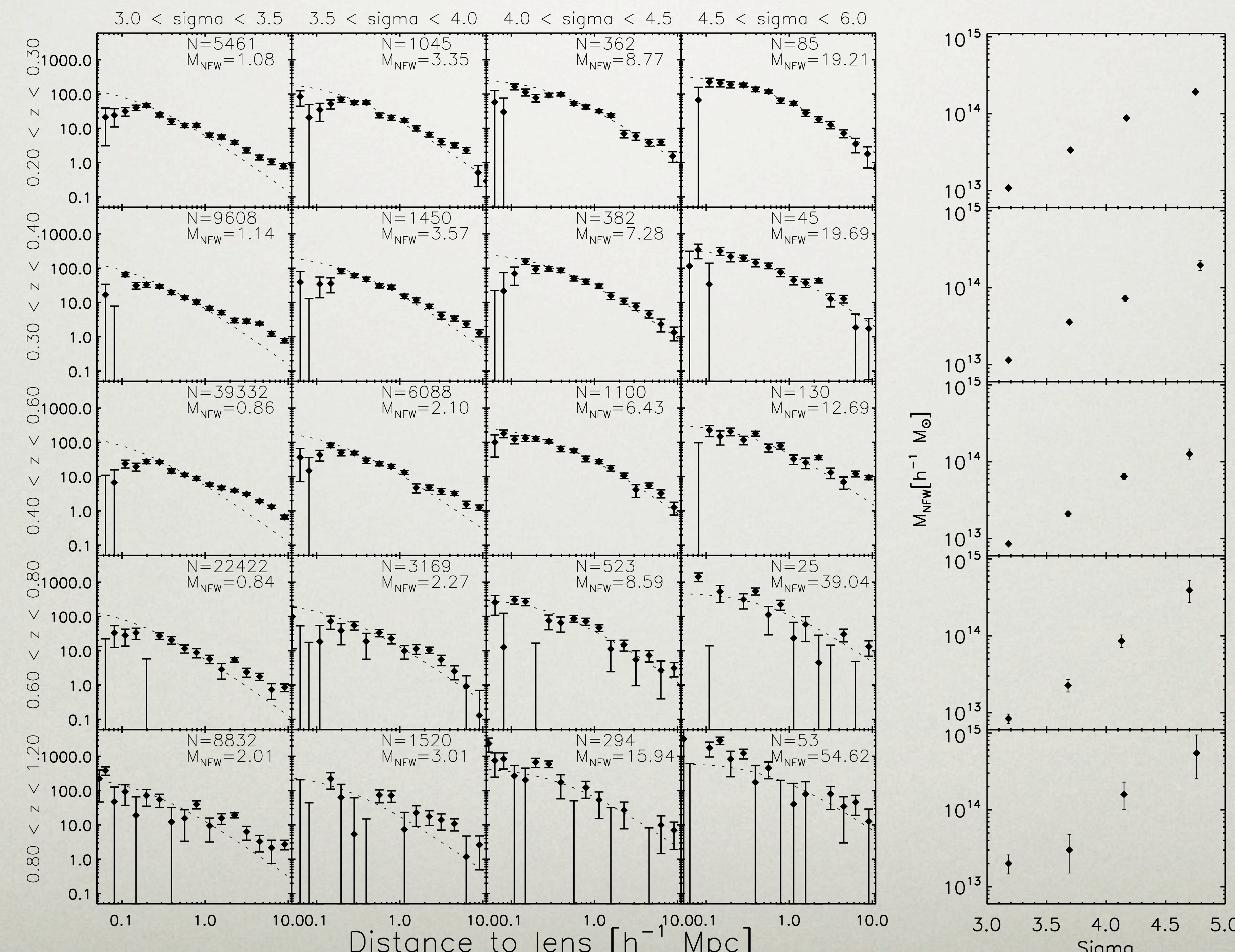
Combined with CCCP



RCS2 - 100,000 clusters

van Uitert et al. (in prep)

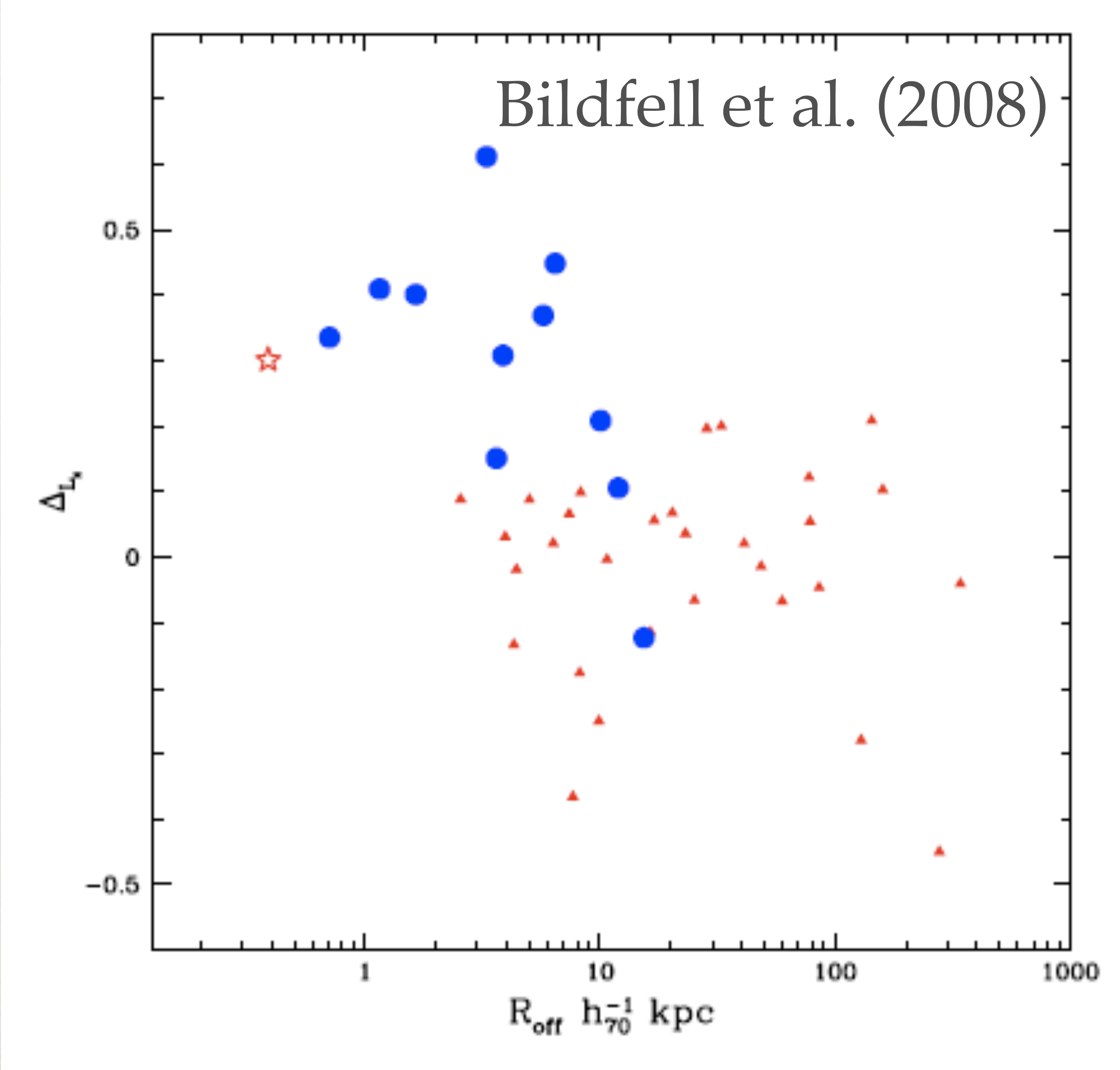
lensing signal



mass

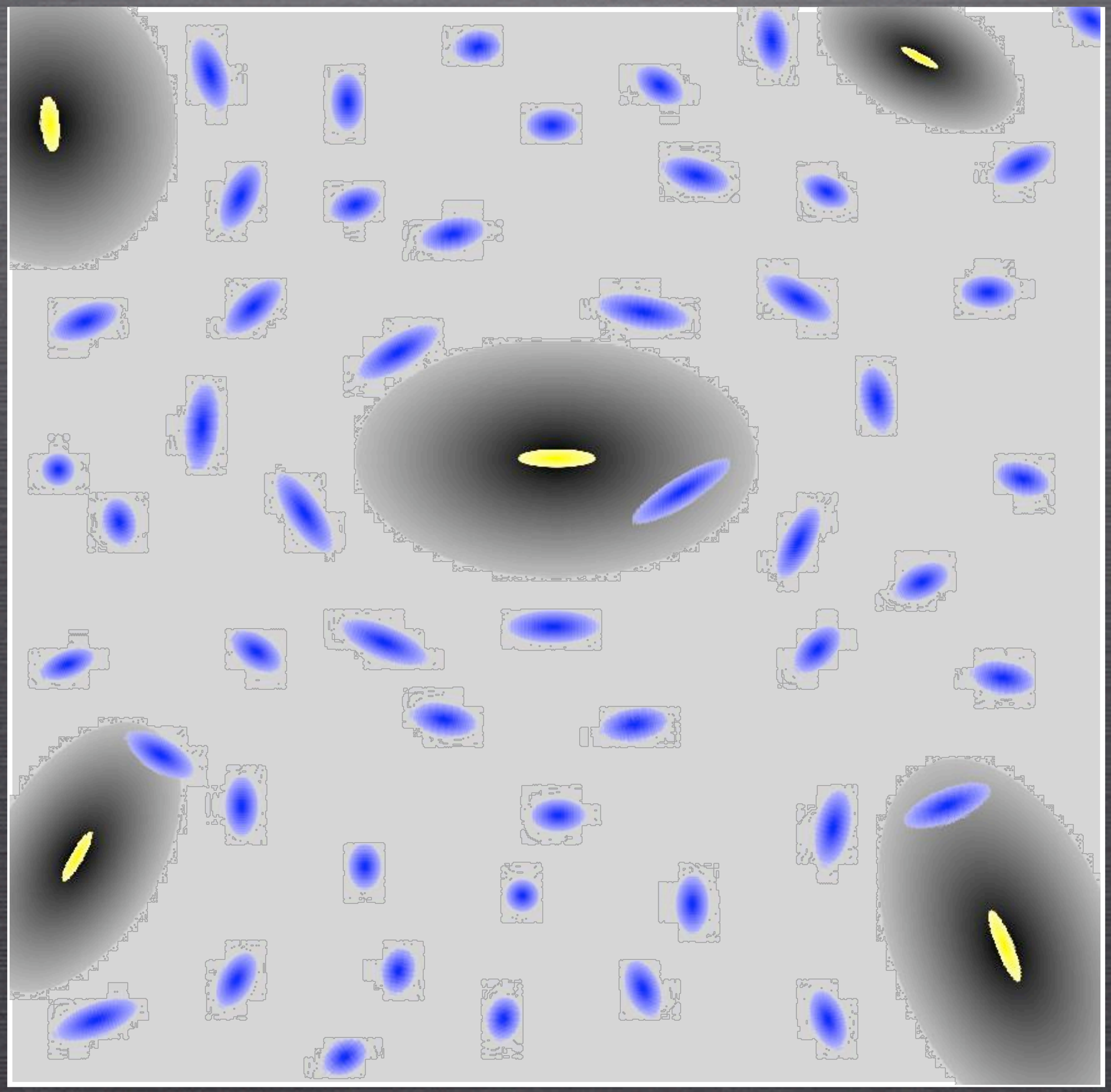
z~0.9

Centroiding issues

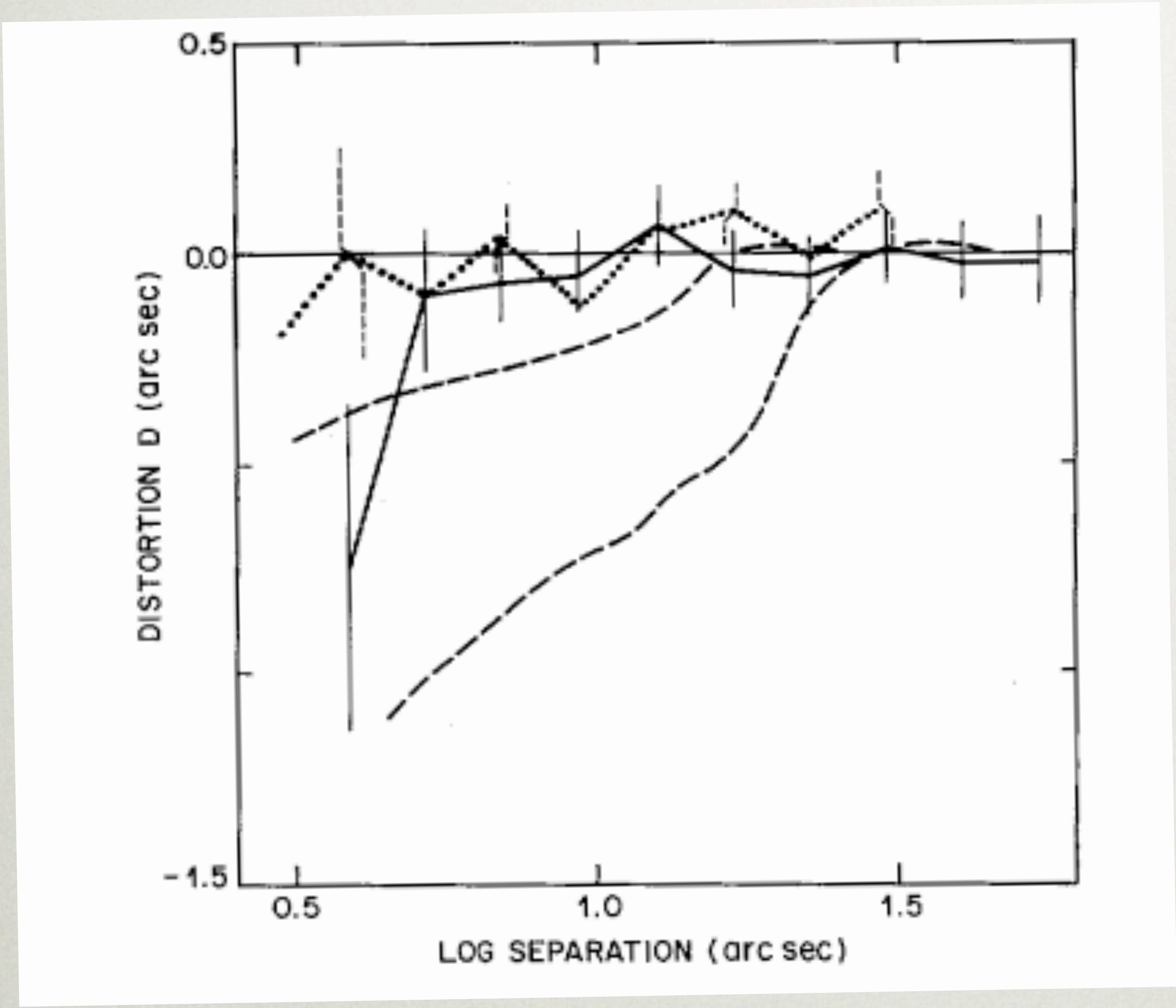


The central galaxies is not always 'red and dead'

Lensing by galaxies



A brief history



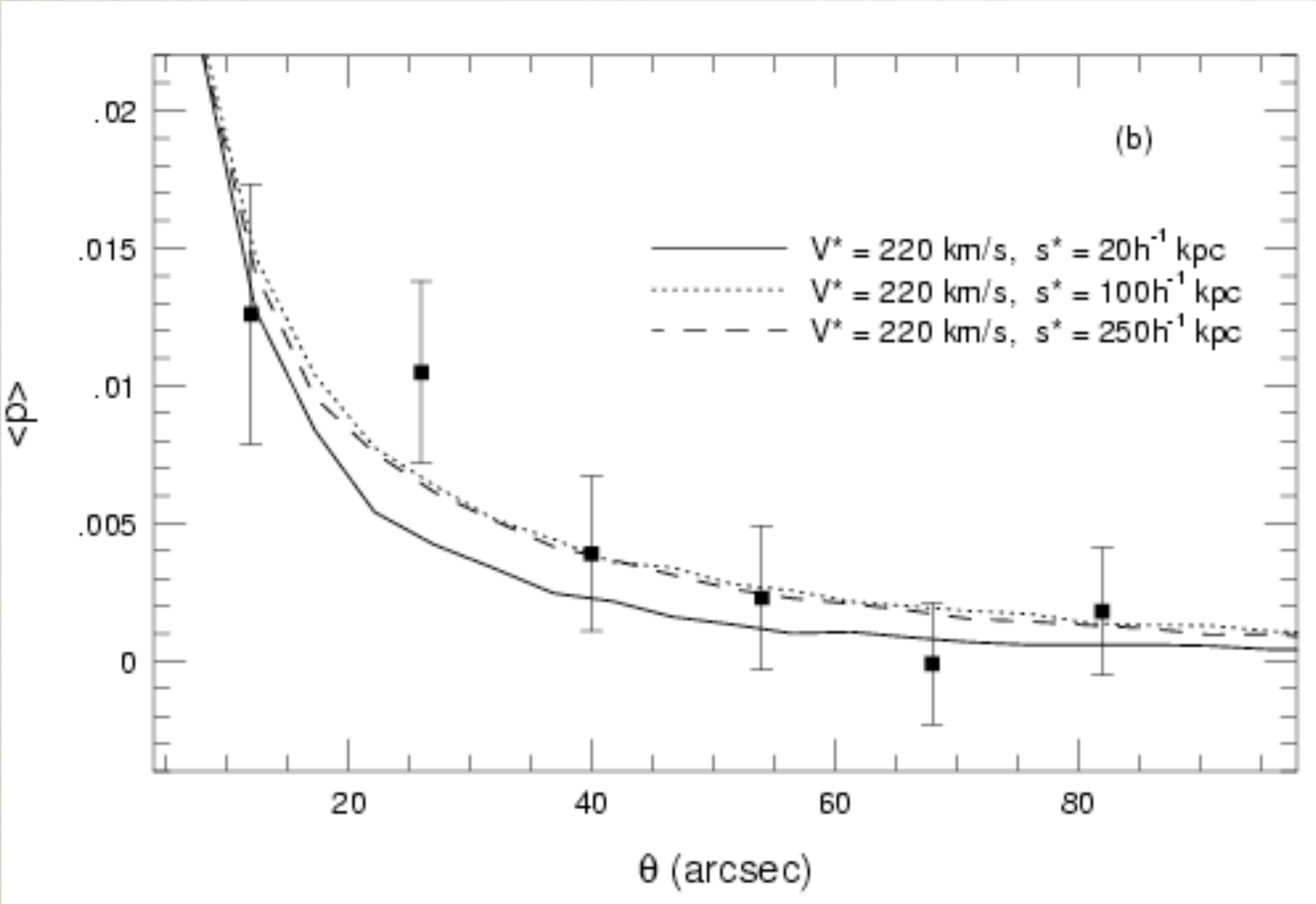
Tyson et al. (1984)

Photographic plates
~12000 lenses
~47000 sources

Circular velocity <170km/s

off to the loonie bin…?

14 YEARS AGO

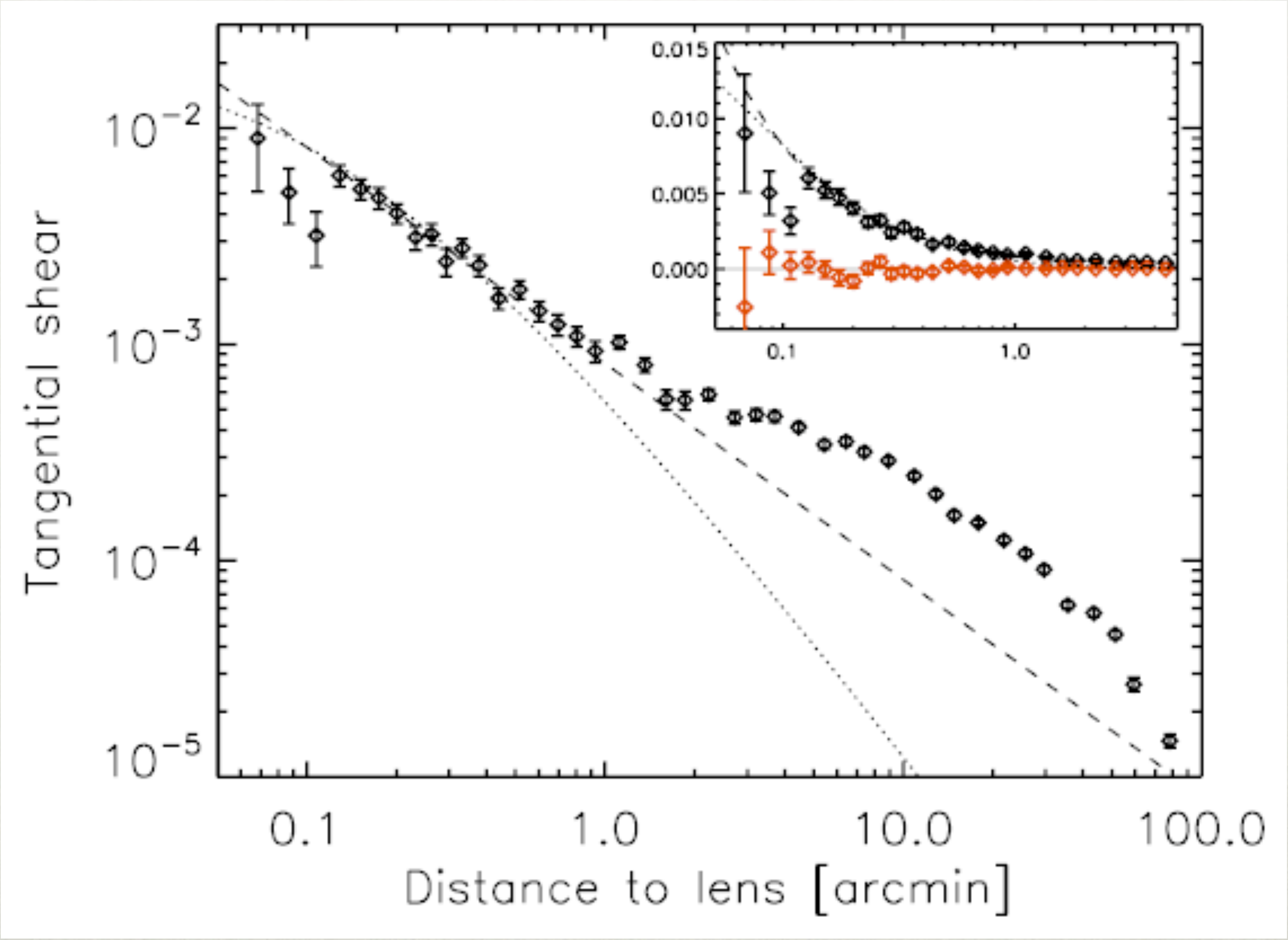


Brainerd et al. (1996)

CCD imaging
~439 lenses
~511 sources

not so crazy after all…?

Present day...



RCS2: 800 square degrees (van Uitert, in prep.)

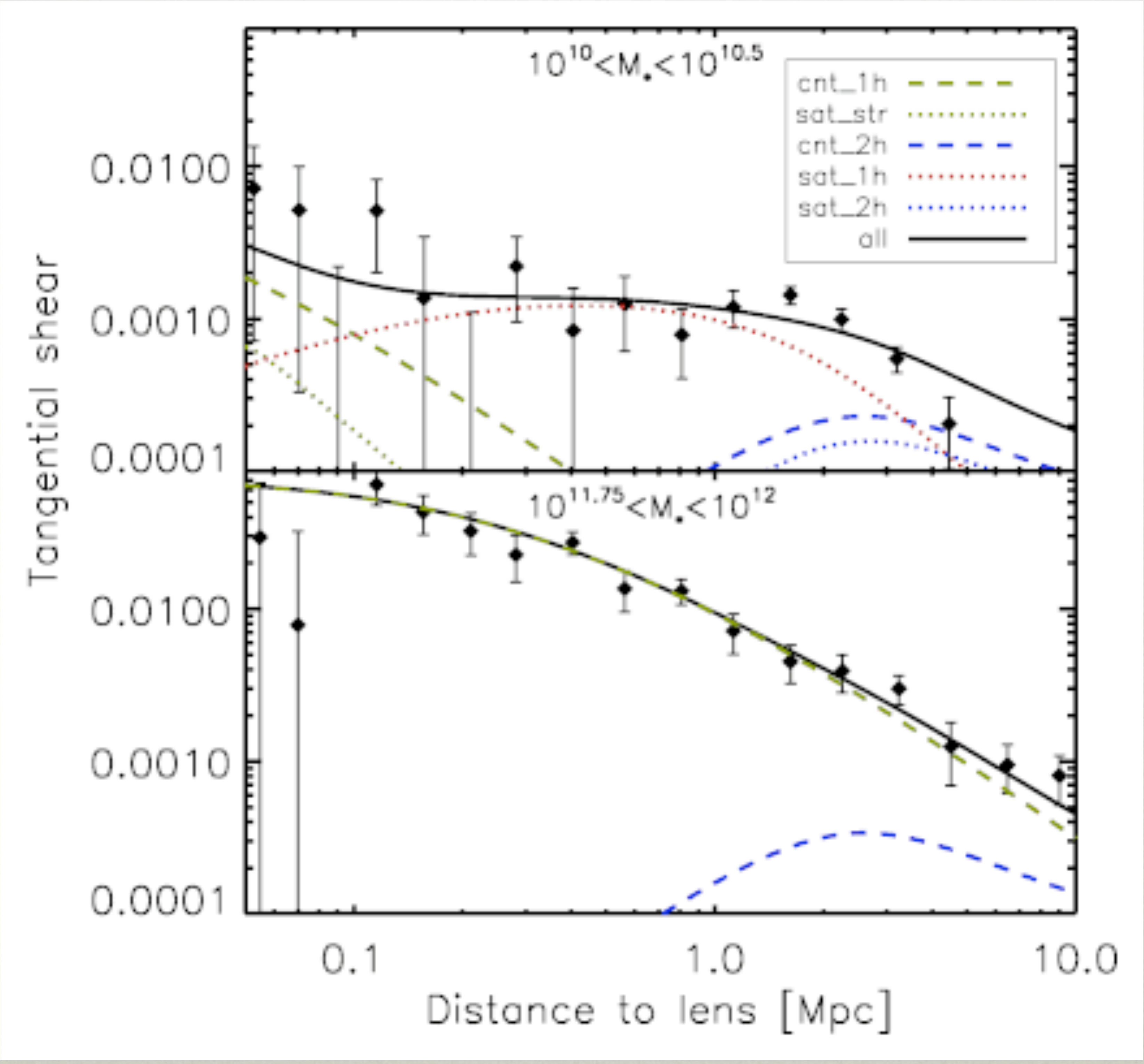
How to interpret the signal?

The signal *(the galaxy-mass cross-correlation function)* is the convolution of the dark matter distribution around galaxies and the clustering properties of the lenses.

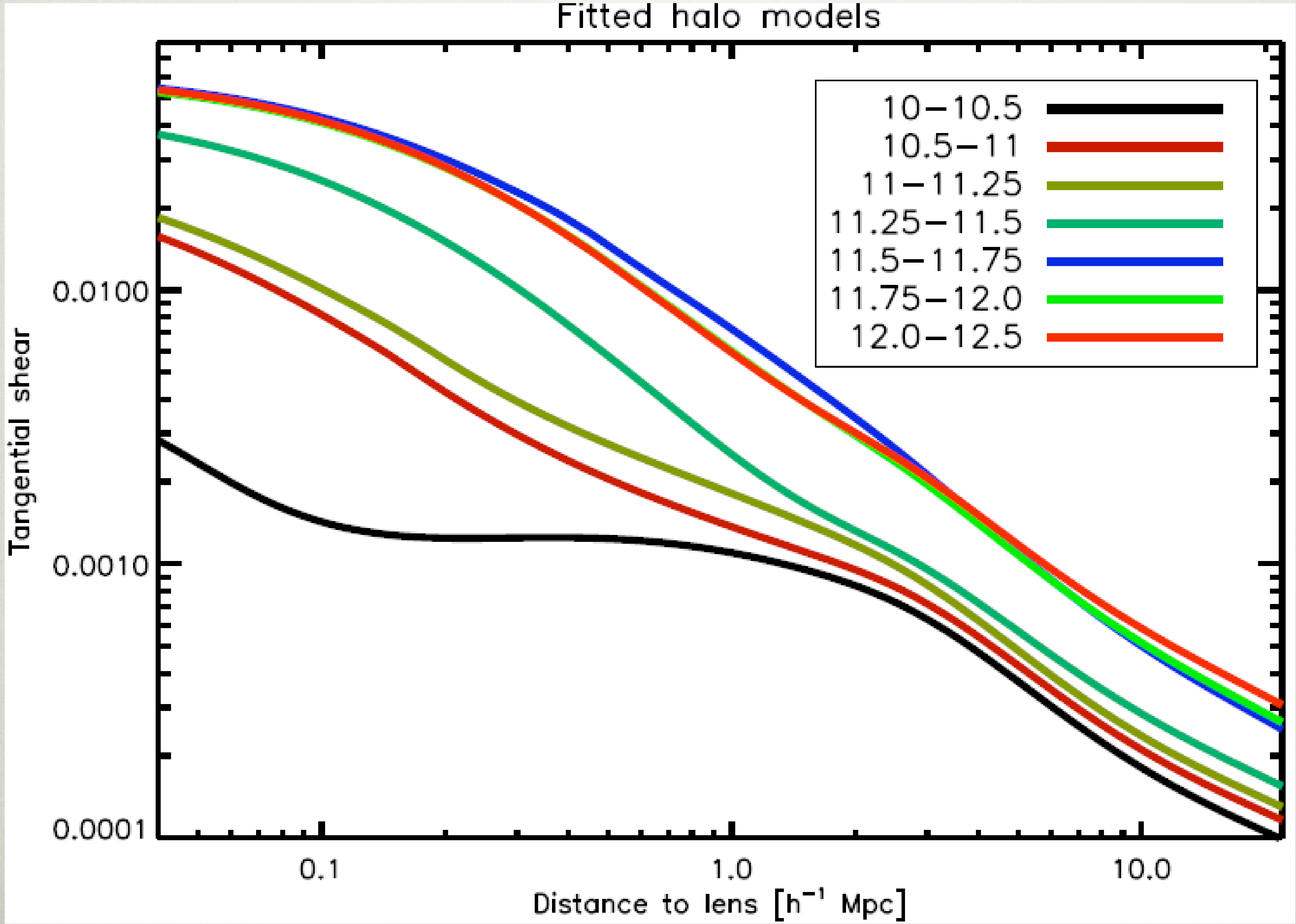
We have some options to infer information about the properties of the dark matter halos around galaxies:

- interpret the data in the context of a model (simulations/analytical)
- deconvolve the correlation function
- look at isolated halos

Halo-model interpretation



Halo-model interpretation



RCS2 + SDSS

Comparison of RCS2 overlap with SDSS

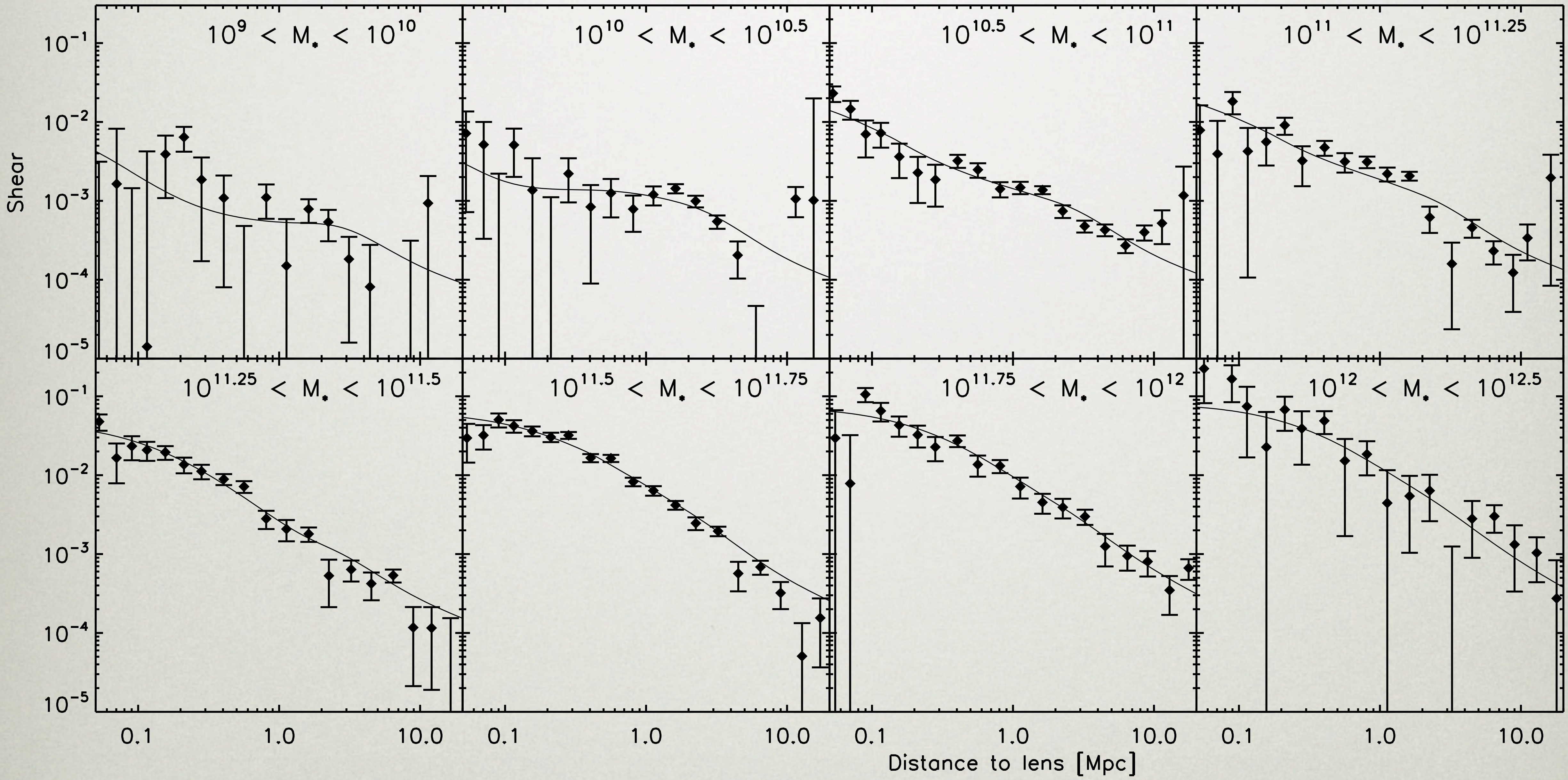
Used area [sqd]	~300	~10 000
Galaxy density [arcmin^{-2}]	8	1.5
D_{LS}/D_S (z_L=0.1)	0.79	0.61
D_{LS}/D_S (z_L=0.4)	0.34	0.07

Effective SDSS area:

z_L=0.1: ~2700 deg^2

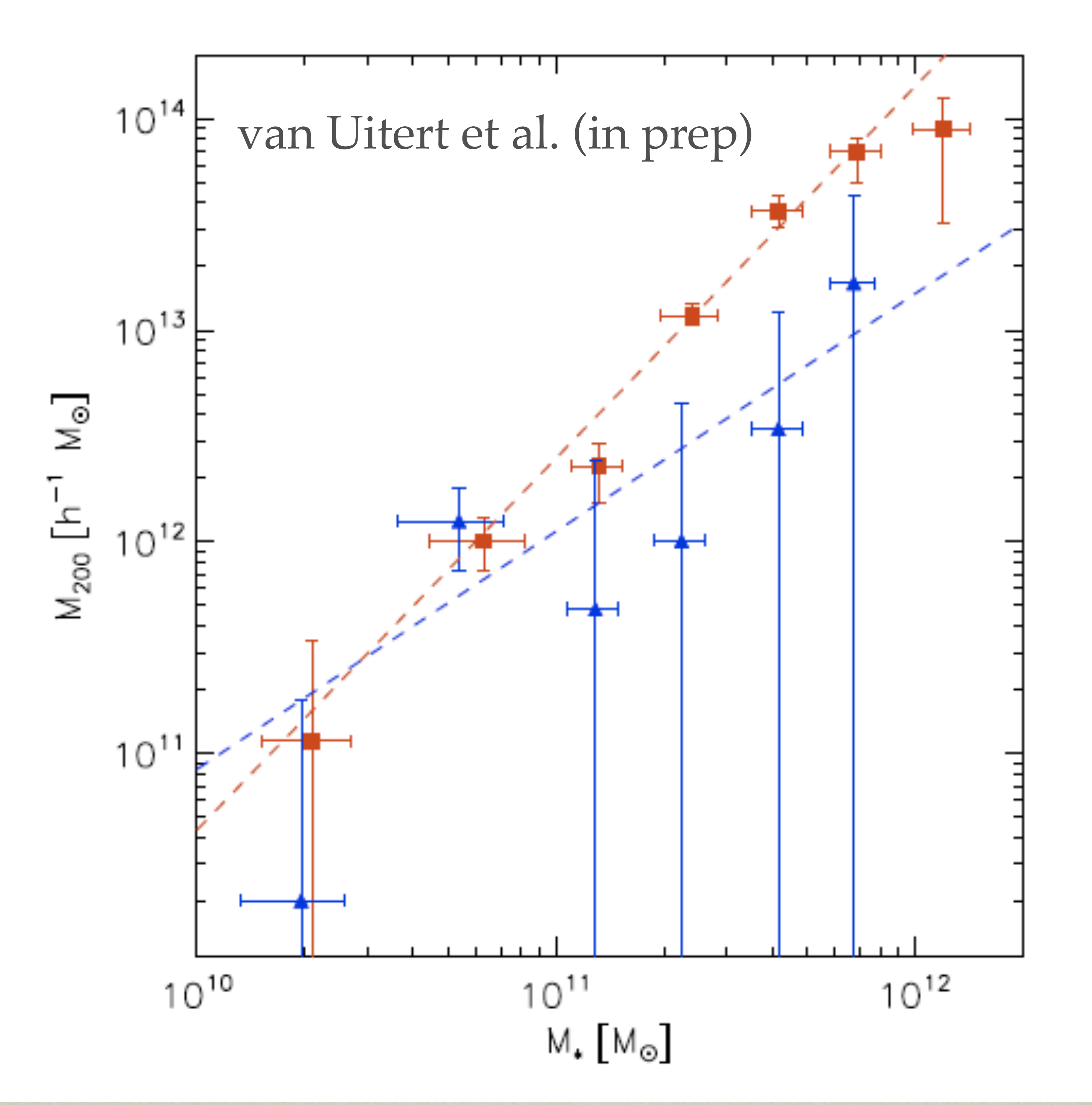
z_L=0.4: ~41000 deg^2 large improvement!

Signal vs stellar mass

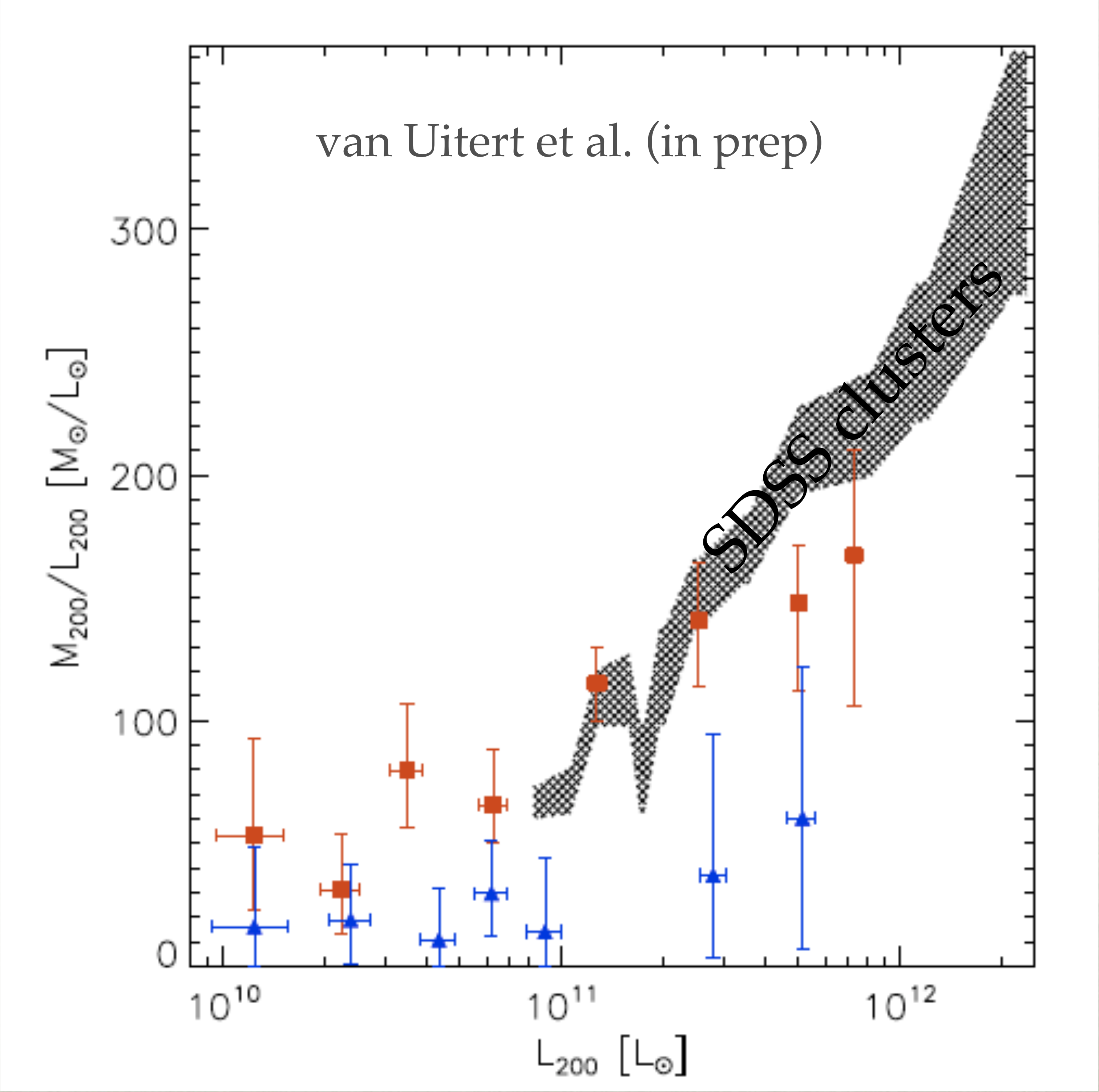


overlap of RCS2 with SDSS

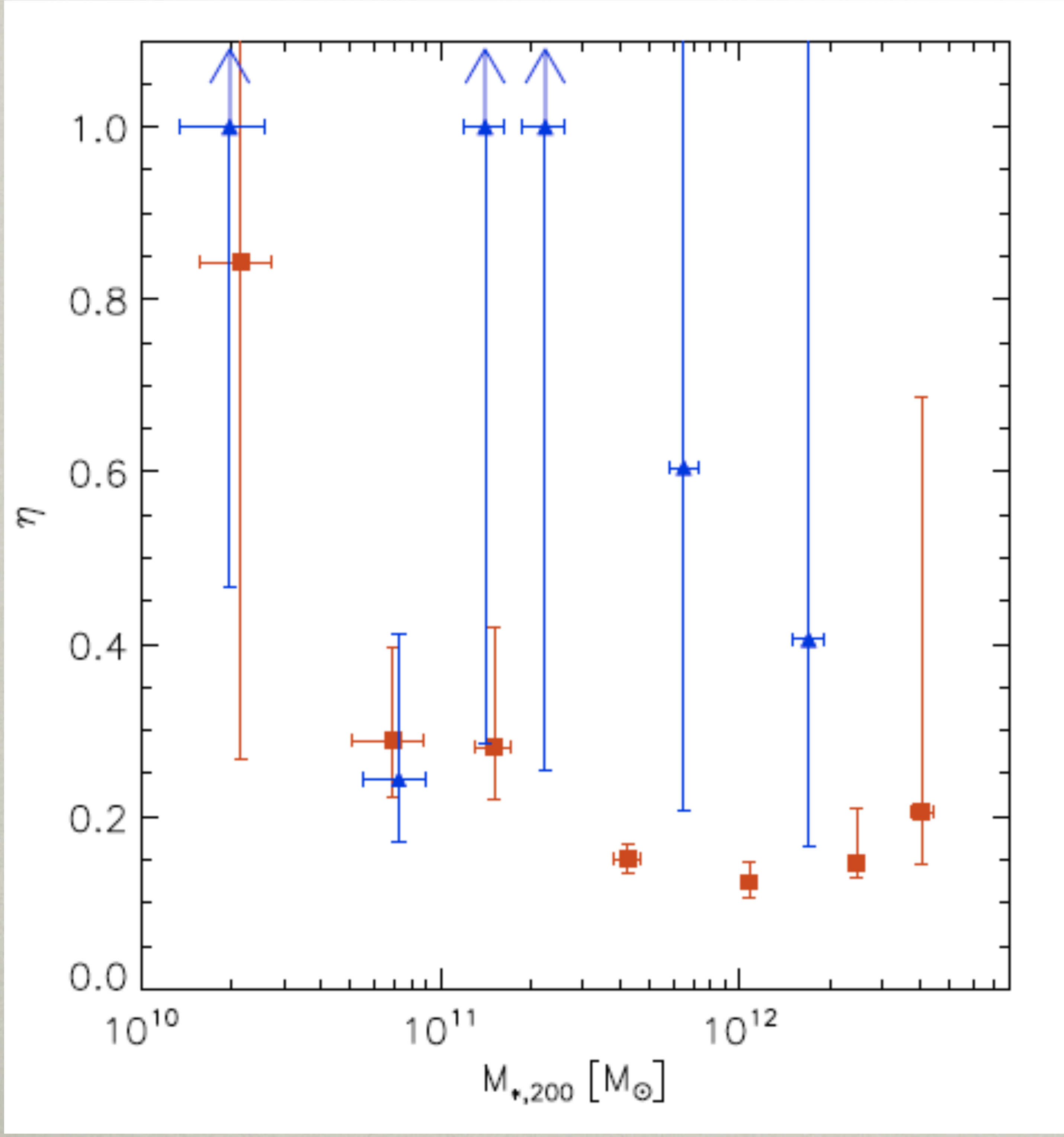
M_{200}-M_{STAR} RELATION



M_{200}-L_{200} RELATION



Baryon conversion



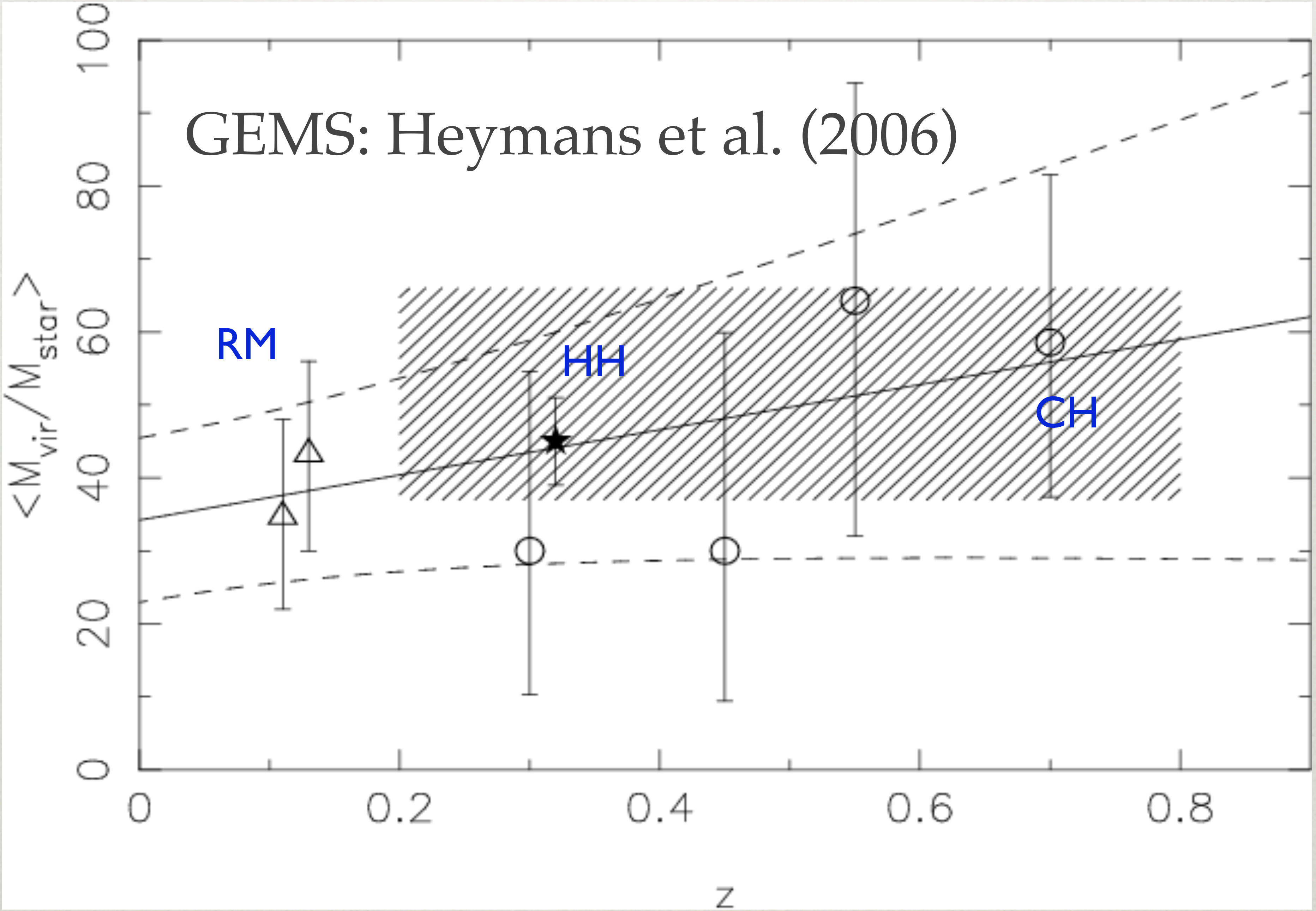
Fraction of baryons converted into stars:

Early type galaxies: ~14%

Late type galaxies: ~40%

van Uitert et al. (in prep)

Stellar mass fraction



RCS2 will improve this for early type galaxies

Conclusions

Weak lensing studies of clusters, groups and galaxies provide important information to link observations to simulations.

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