Scatter and bias in cluster mass estimates

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2015/3/25 Astroparticle View of Galaxy Clusters @ Hiroshima

Scatter and bias in lensing cluster mass estimates

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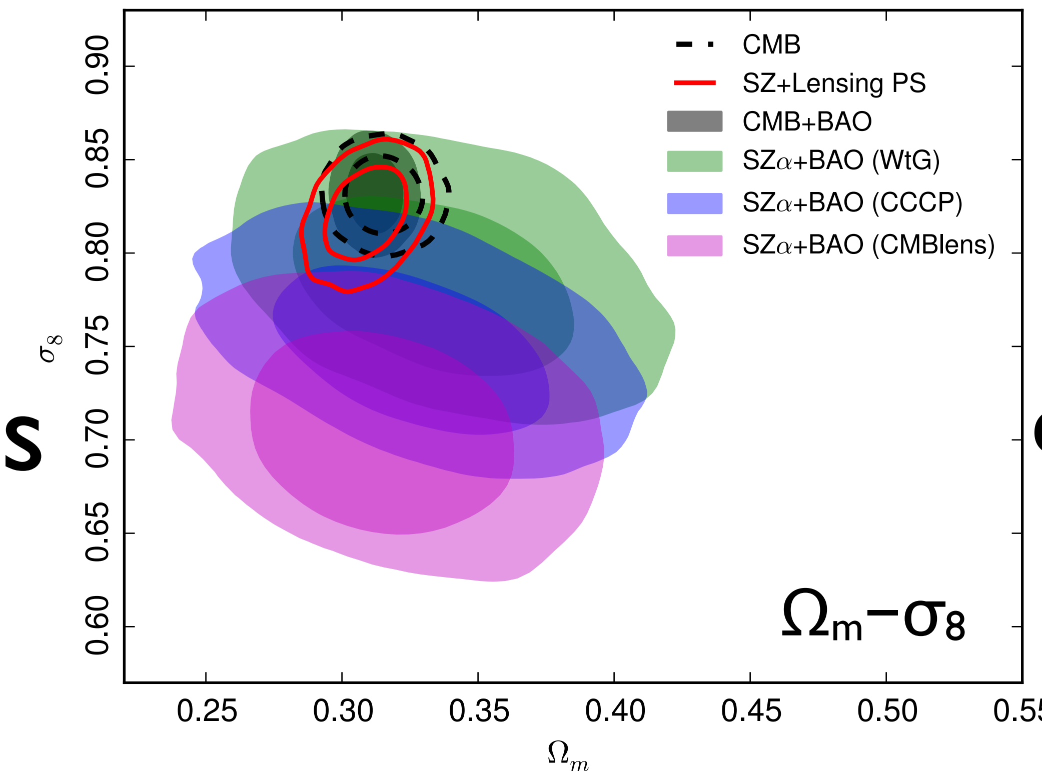
Cluster mass

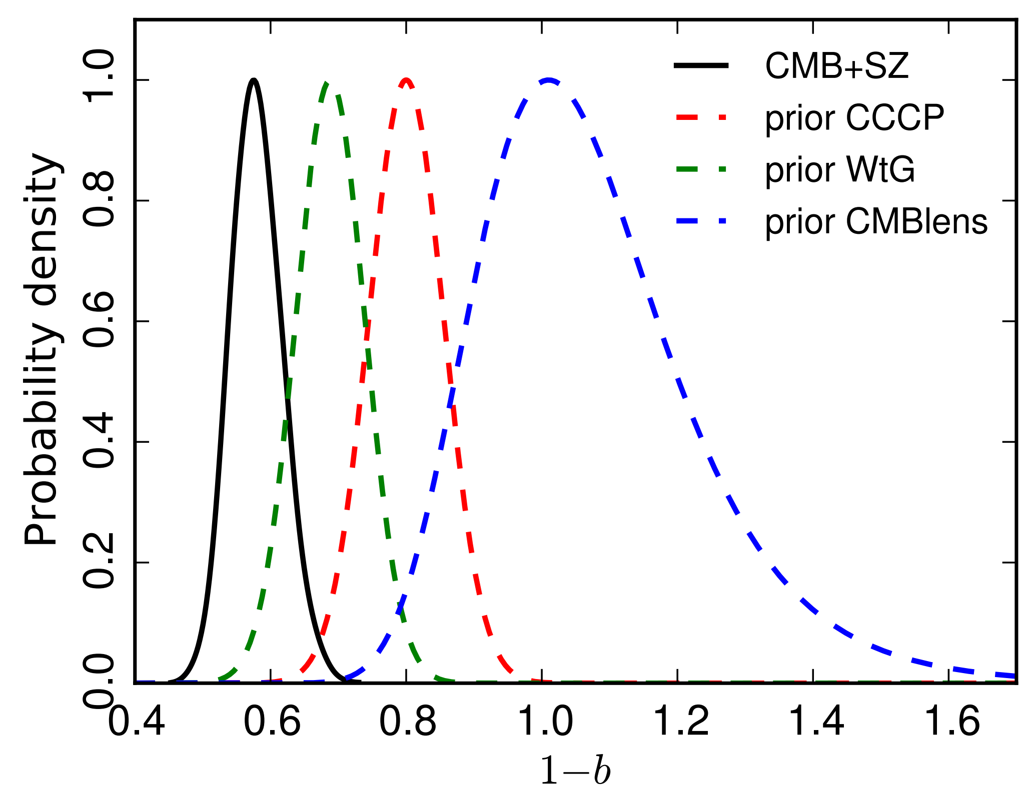
- one of the most fundamental parameters that characterize clusters
- not easy to measure because it is dominated by the mass of dark matter
- critically important for cluster cosmology

Planck 2015

- cosmology with Planck SZ cluster counts
- different mass estimates yield quite different cosmology results
- uncertainty in cluster mass estimates is the most outstanding issue in cluster cosmology!



different cosmo. constraints



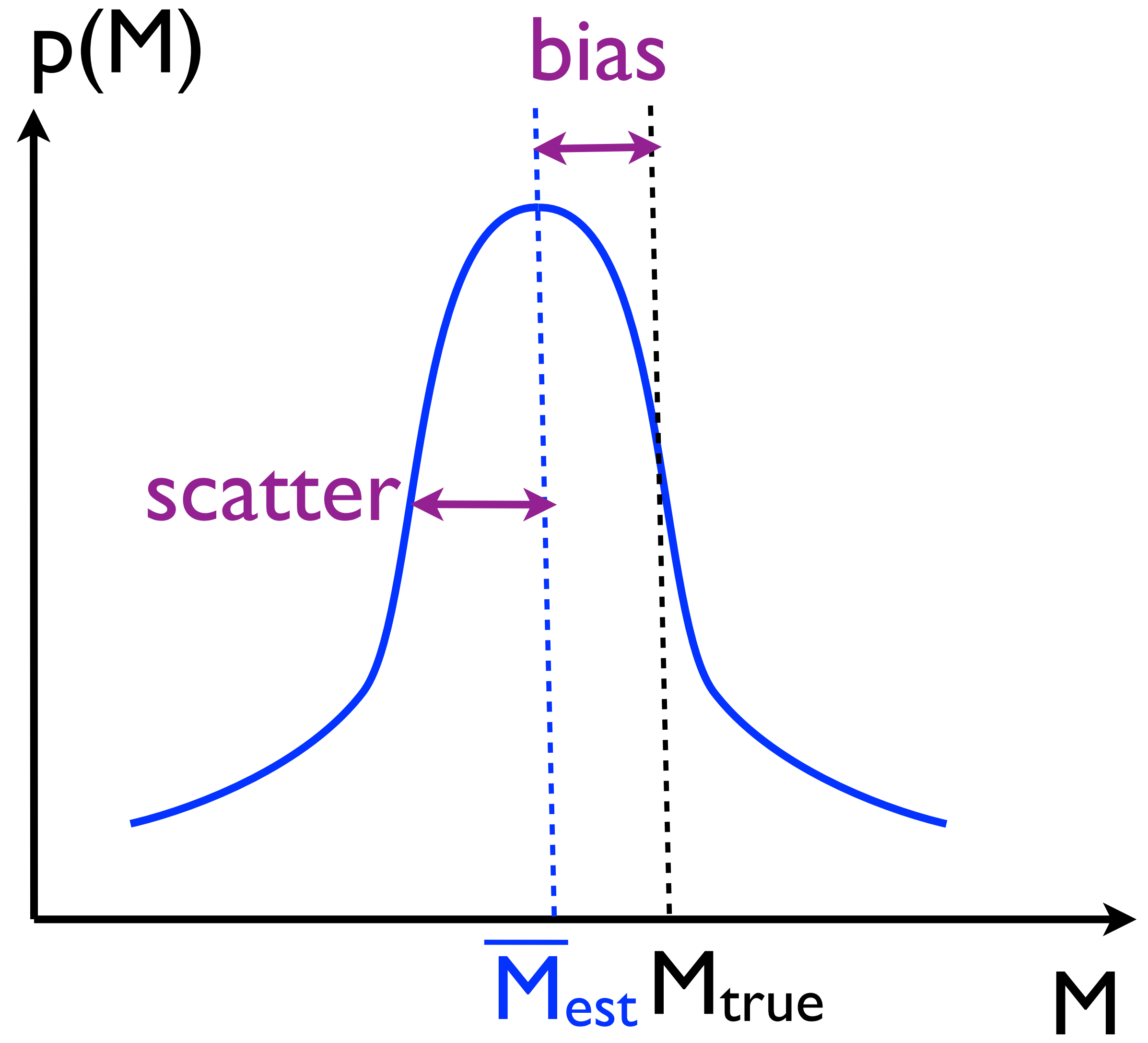
different mass estimates

Planck collaboration, arXiv:1502.01597

Mass estimates: scatter and bias

"accuracy" of mass estimates?

- scatter
  important for analysis of individual clusters
- bias
  important for statistical analysis *even for the case* scatter ≫ bias

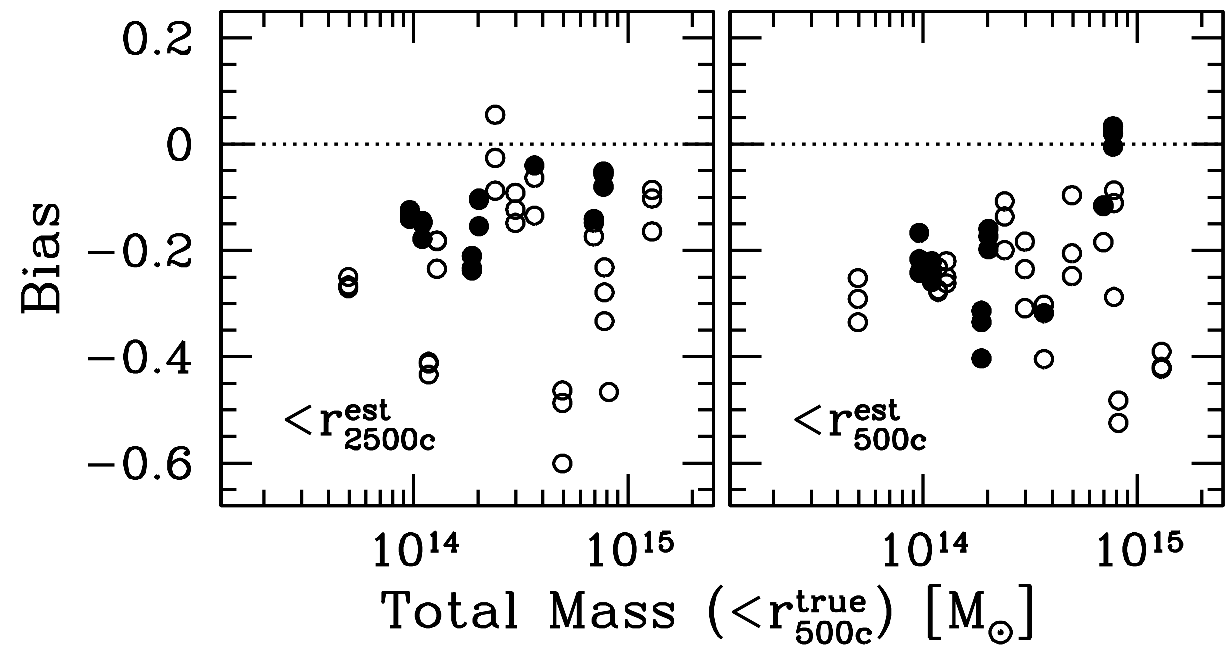


Cluster mass estimates

- X-ray hydrostatic equilibrium
  small scatter, large bias
- weak gravitational lensing
  large scatter, small bias

X-ray hydrostatic equilibrium

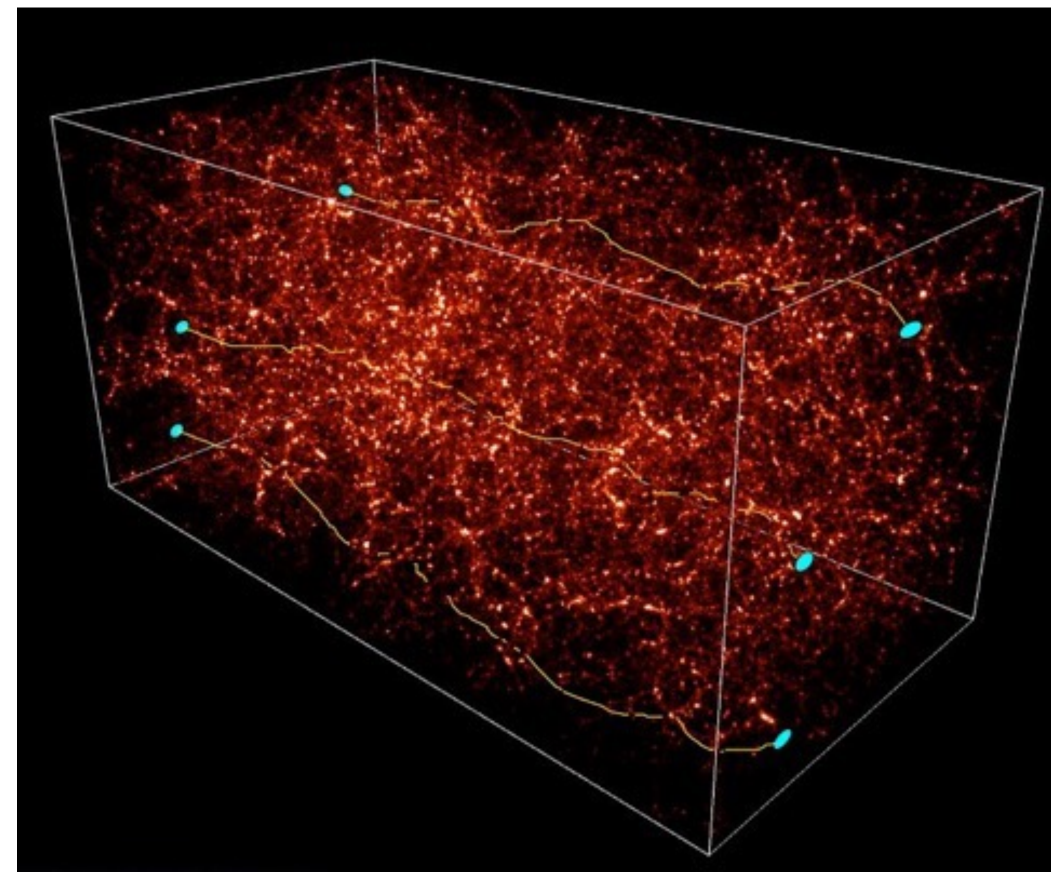
- X-ray mass derived w/ hydrostatic equilibrium is known to be biased low by ~10−40%
- need independent mass estimates to quantify the X-ray mass bias



Nagai et al. (2007)

Weak lensing

- purely gravitational effect
- direct measurements of total mass, including dark matter!



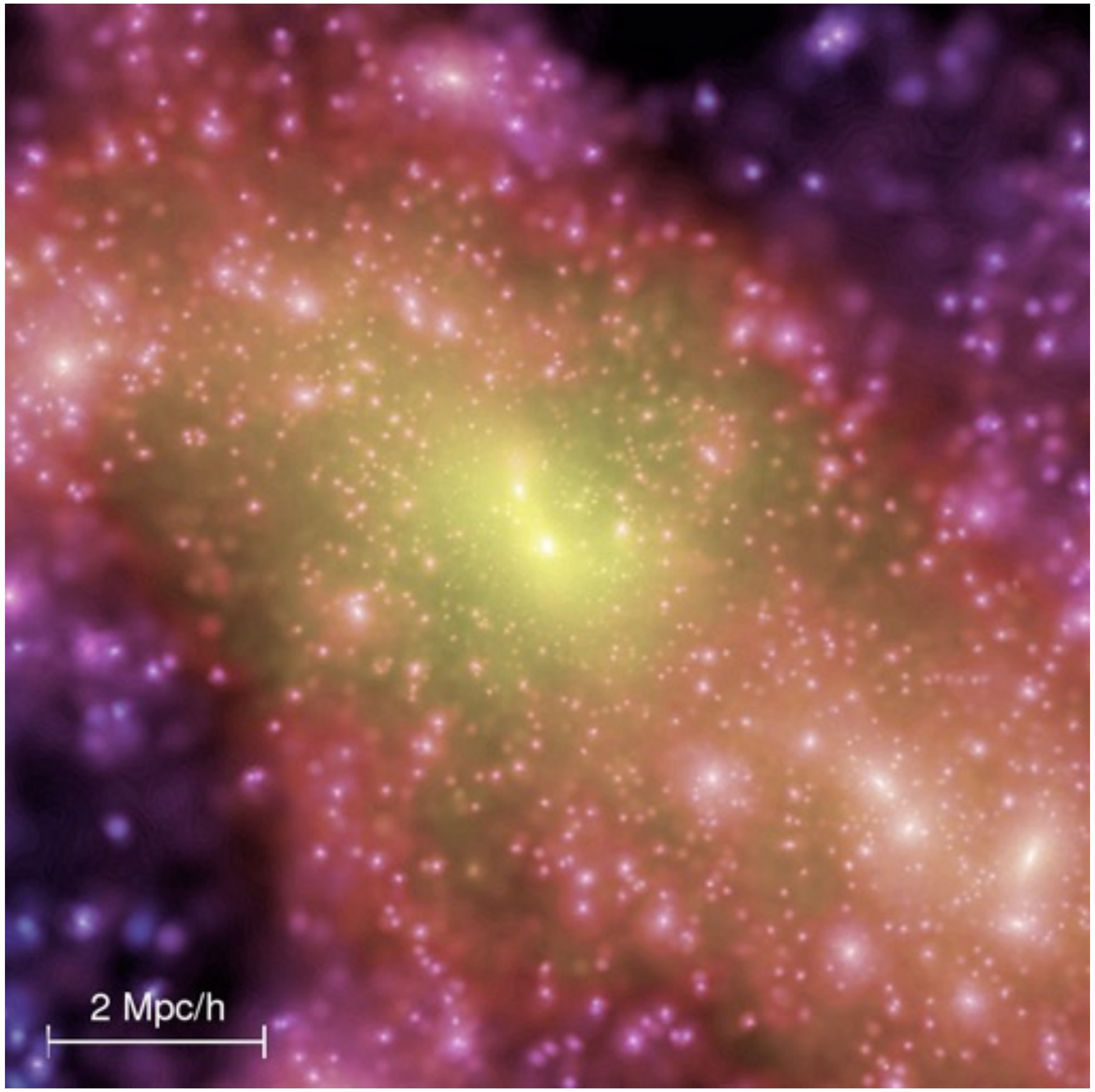
S. Colombi

Scatter and bias in lensing mass

- scatter
  statistical error − shot noise, LSS
  halo triaxiality
- bias
  profile mismatch
  substructure? (not in this talk)
  photo-z, dilution, ... (not in this talk)

Halo triaxiality

- ΛCDM model predicts highly non-spherical halo shape
- typical major-to-minor axis ratio 2:1



http://www.mpa-garching.mpg.de/galform/millennium/

Observational evidence

- direct measurements of halo shapes w/ WL
- non-sphericity detected at ≳ 5σ

  $\langle e_{2D} \rangle = 0.46 \pm 0.04$

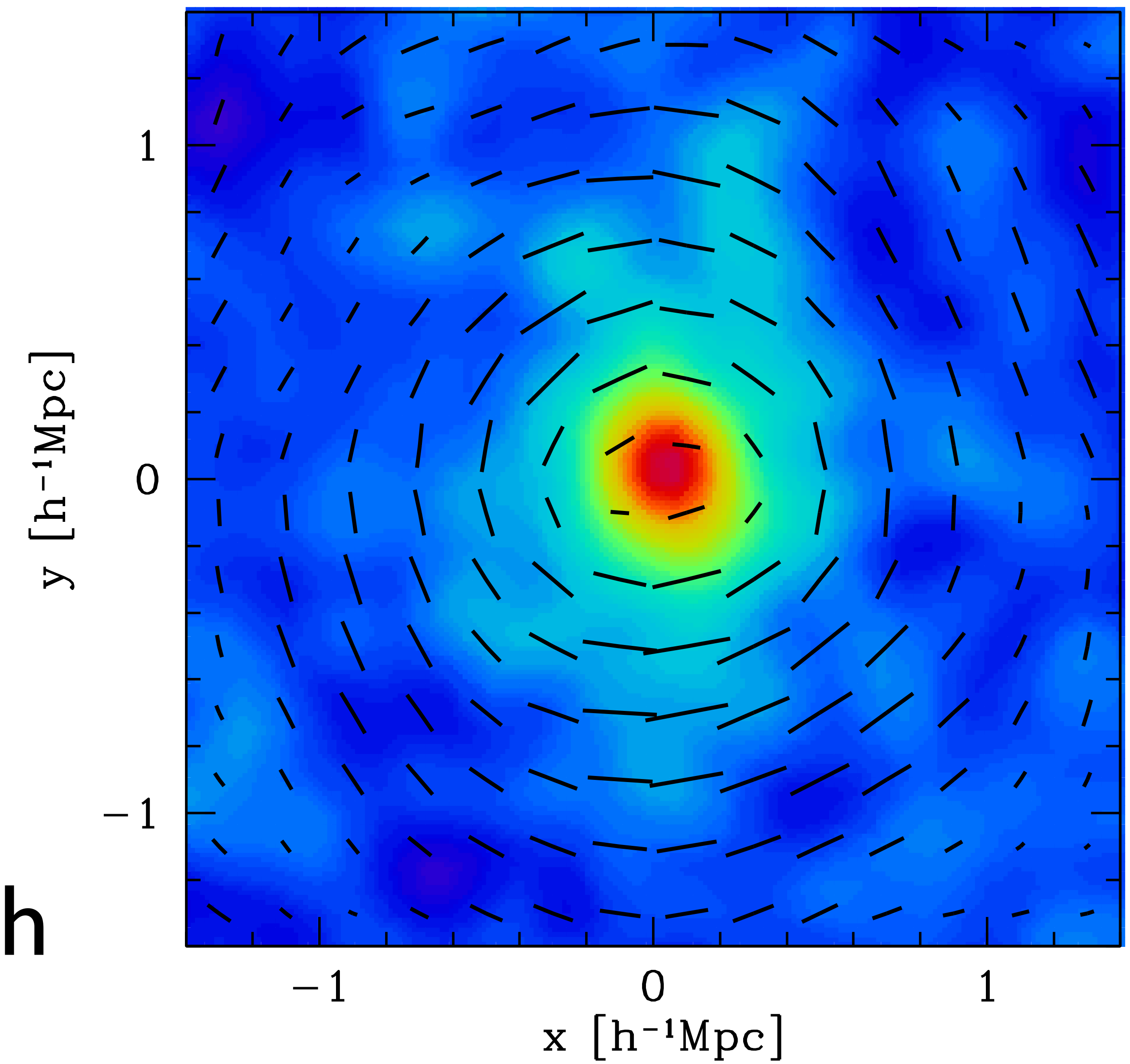
  (Oguri et al. 2010 w/ LoCuSS)

  $\langle e_{2D} \rangle = 0.47 \pm 0.06$

  (Oguri et al. 2012 w/ SGAS)

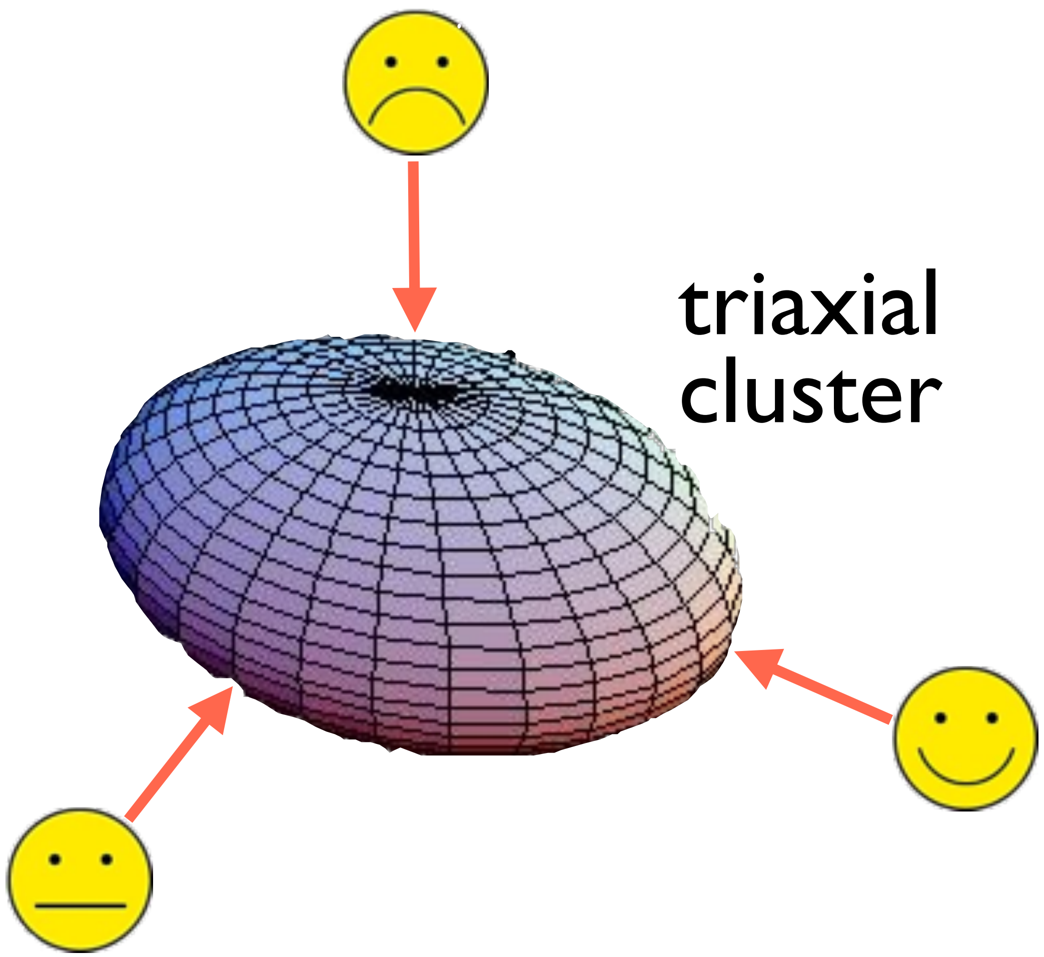
- e_{2D} quite consistent with ΛCDM predictions!

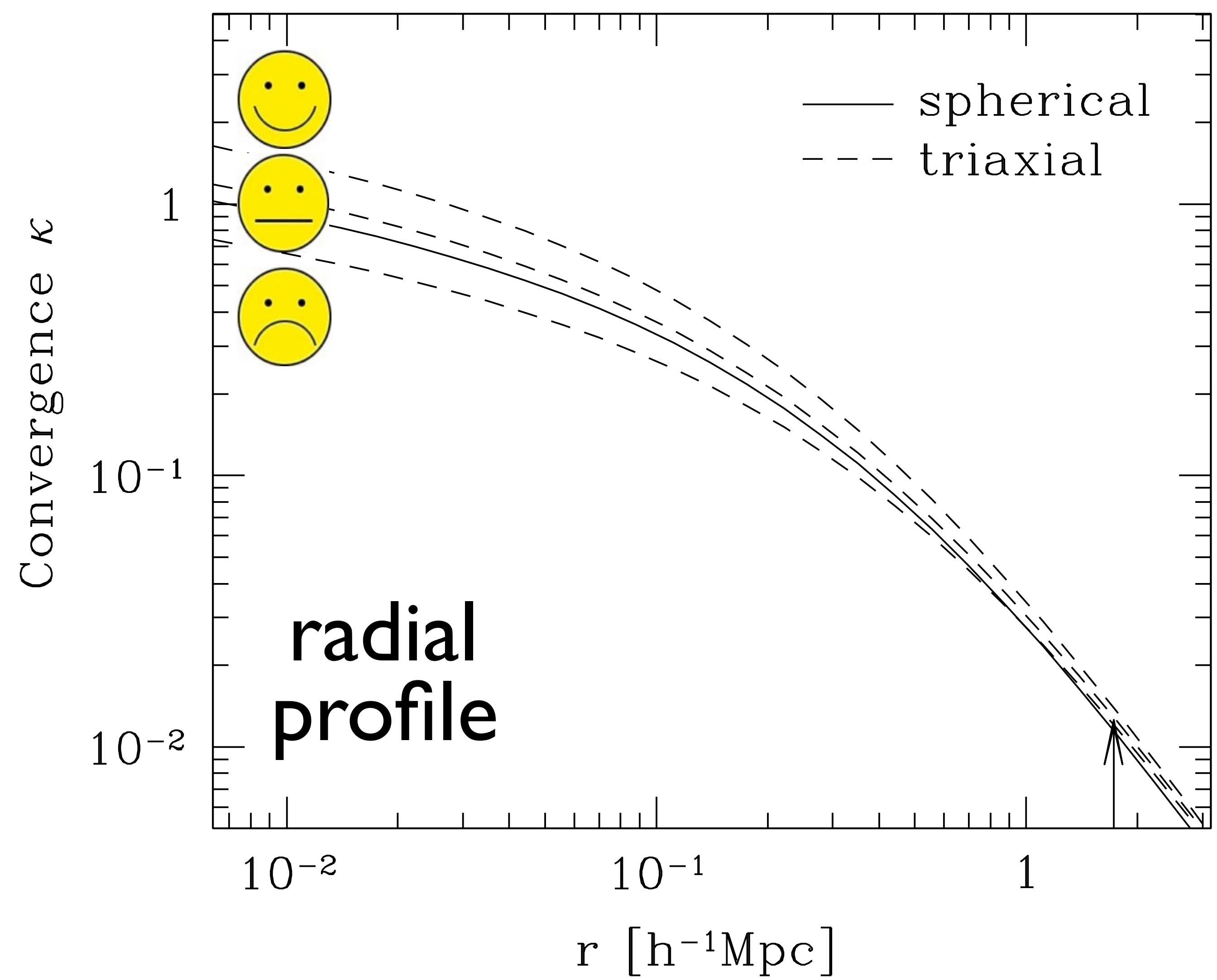
Oguri et al. (2012)



Oguri, Takada, Umetsu, Broadhurst ApJ **632**(2005)841

Projection effect

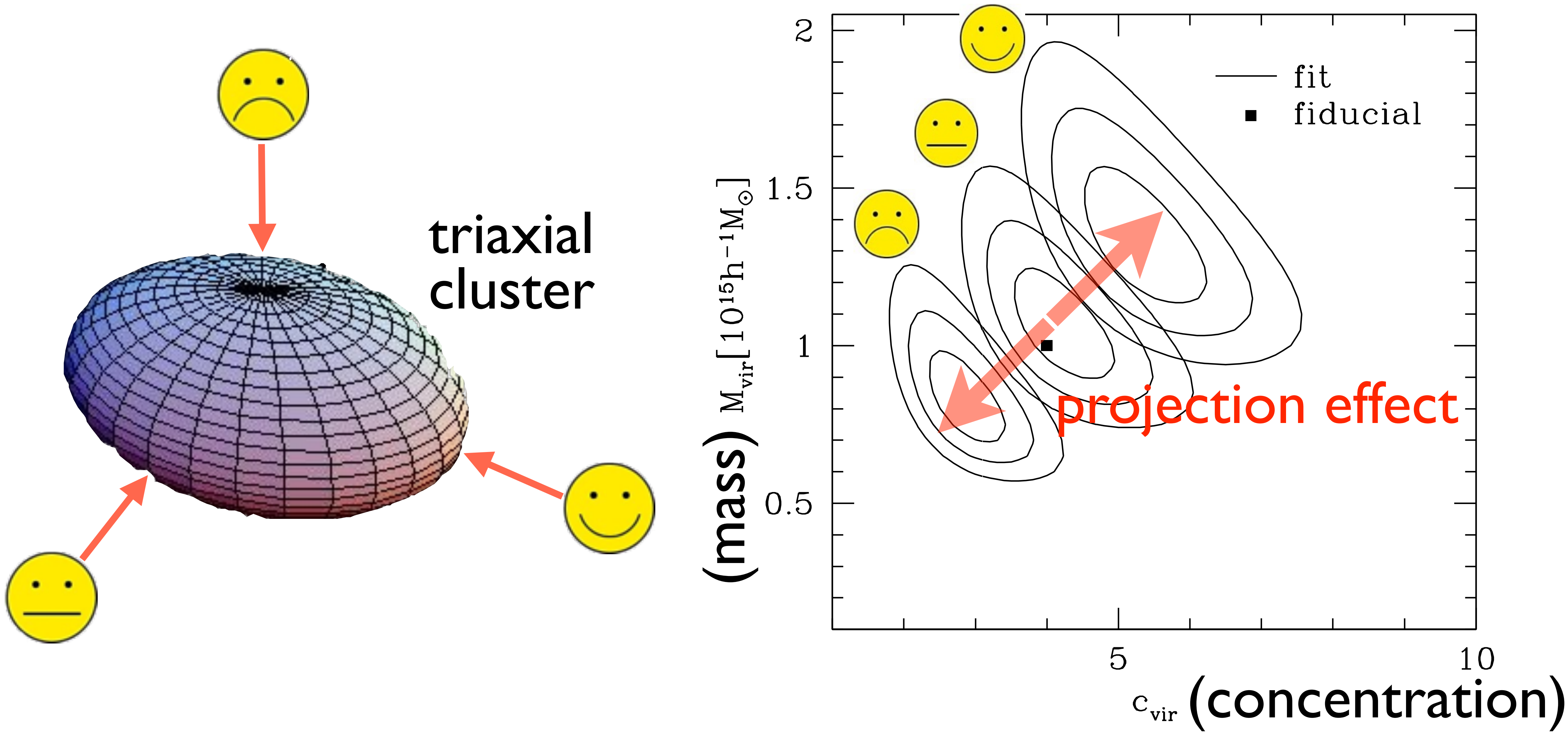




- projected mass profile depends sensitively on the projection direction

Oguri, Takada, Umetsu, Broadhurst ApJ **632**(2005)841

Projection effect

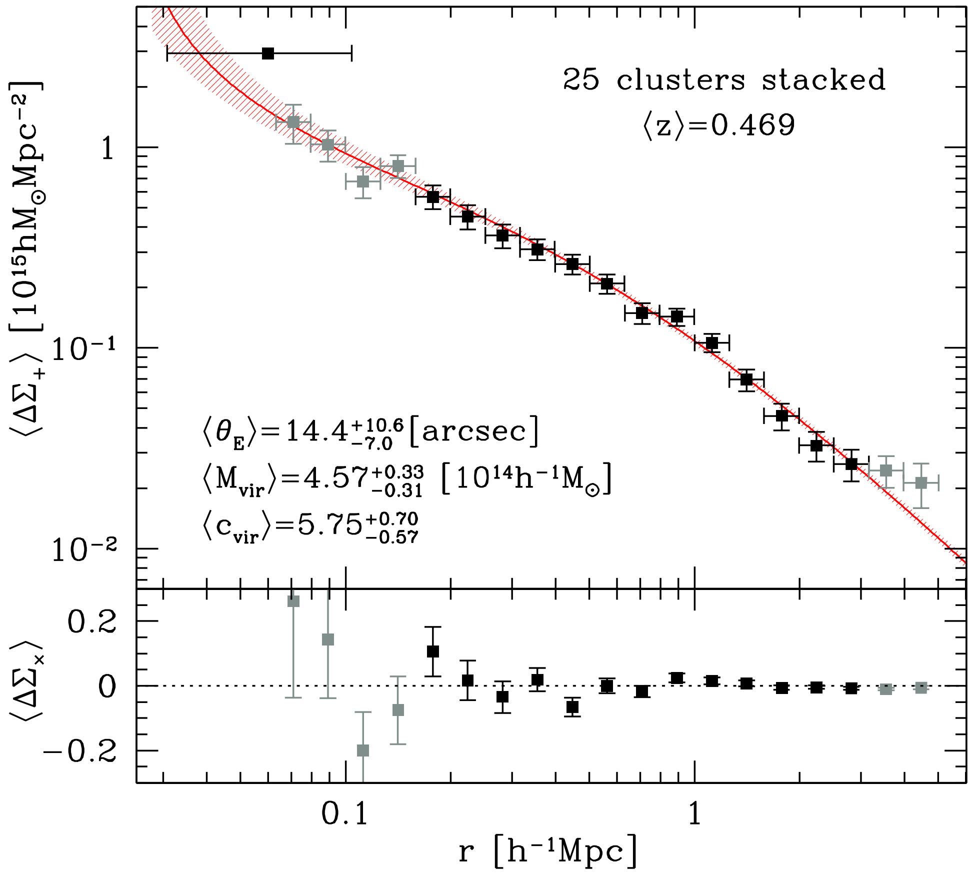


- lensing-derived mass and concentration are significantly affected by the cluster orientation → ~20-30% scatter in lensing mass

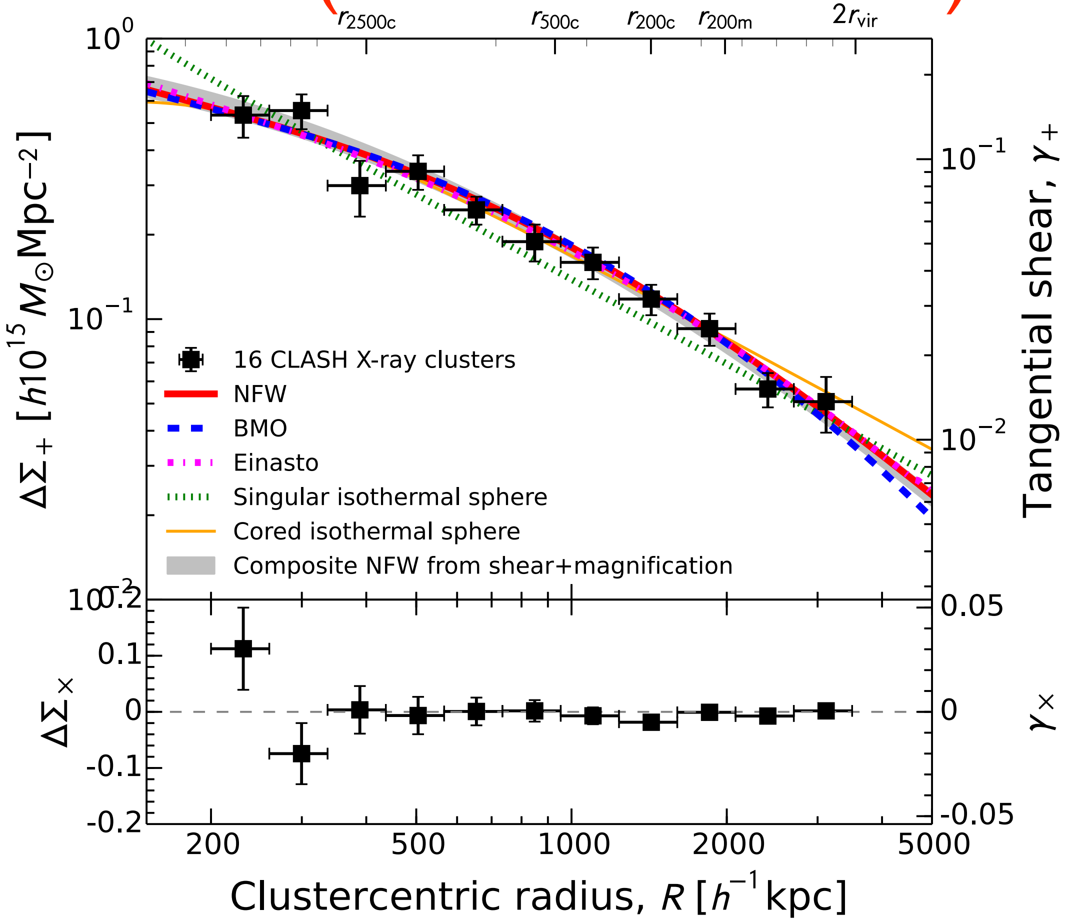
Bias from radial mass profile

- data have often been analyzed assuming a simple NFW profile
- any mismatch between assumed and true mass profiles can cause bias

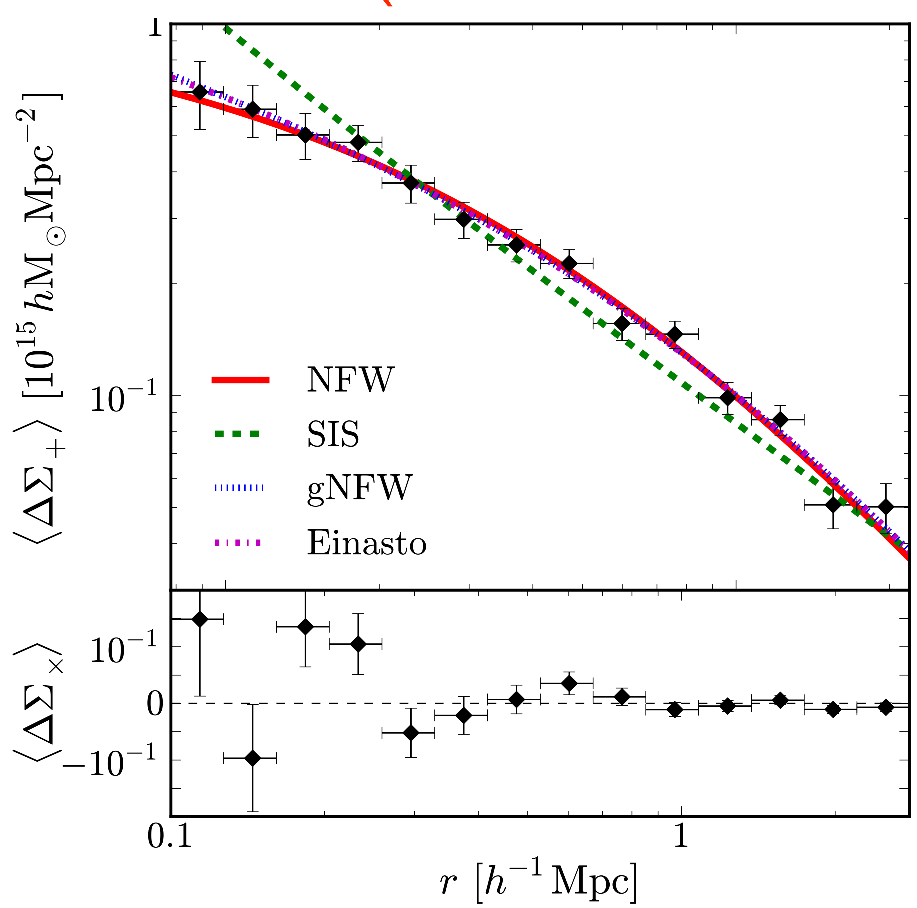
SGAS (Oguri et al. 2012)



CLASH (Umetsu et al. 2014)



LoCuSS (Okabe et al. 2013)

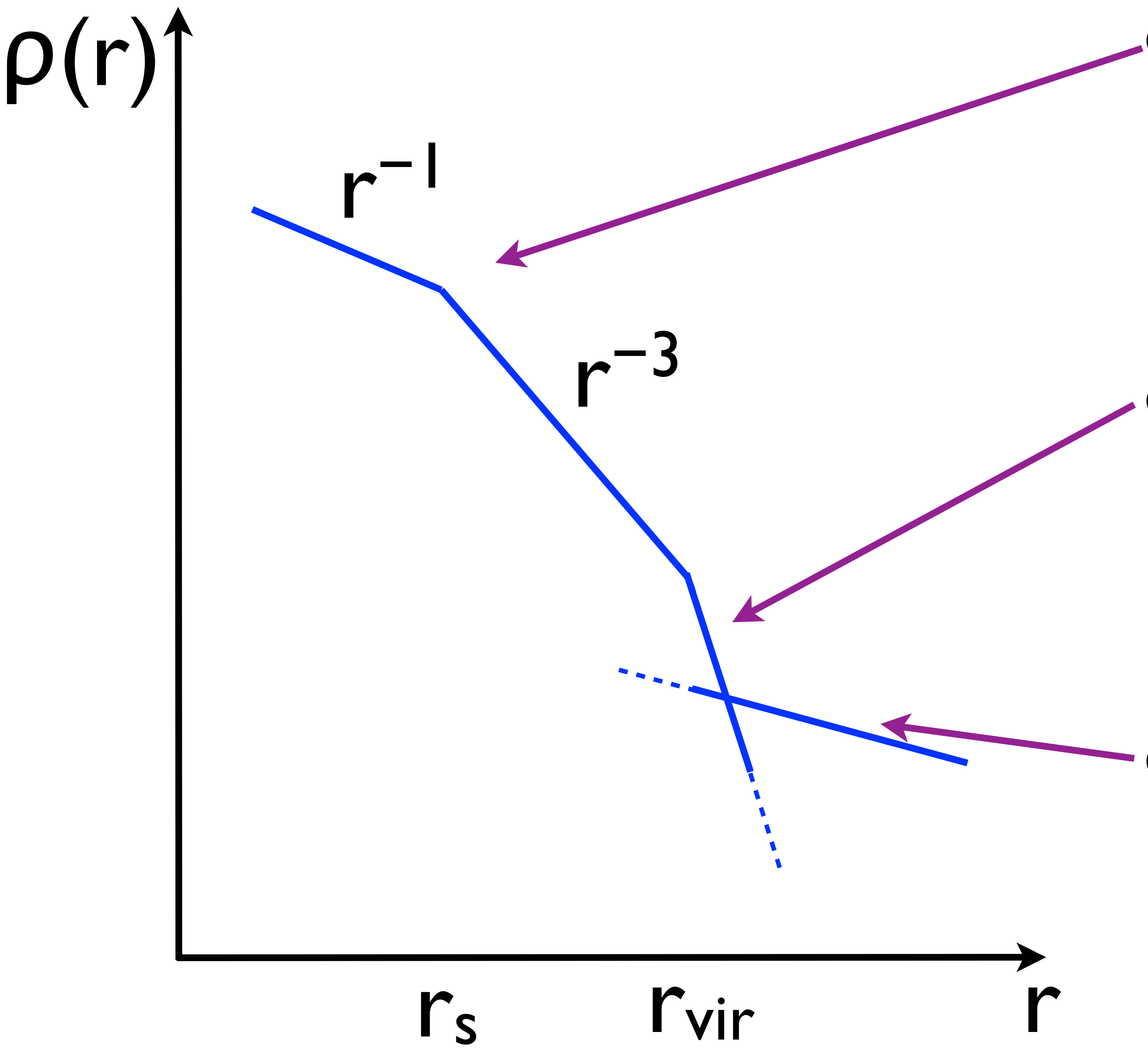


all data from Subaru S-cam

observed density profiles are consistent with the NFW profile!

(←see talk by N. Okabe)

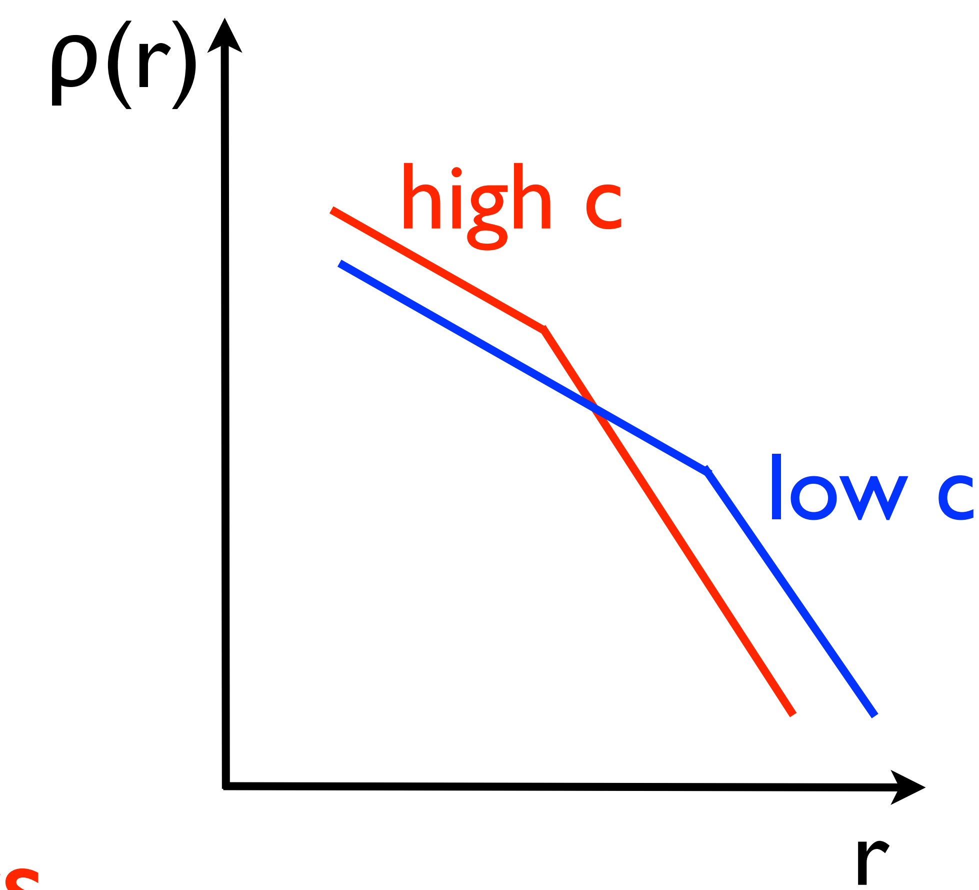
Possible origins of bias



- concentration $c=r_{vir}/r_s$
  central concentration of radial profile
- steepening
  cutoff of radial density profile beyond $\sim r_{vir}$
- 2-halo term
  correlated matter fluctuations around the cluster

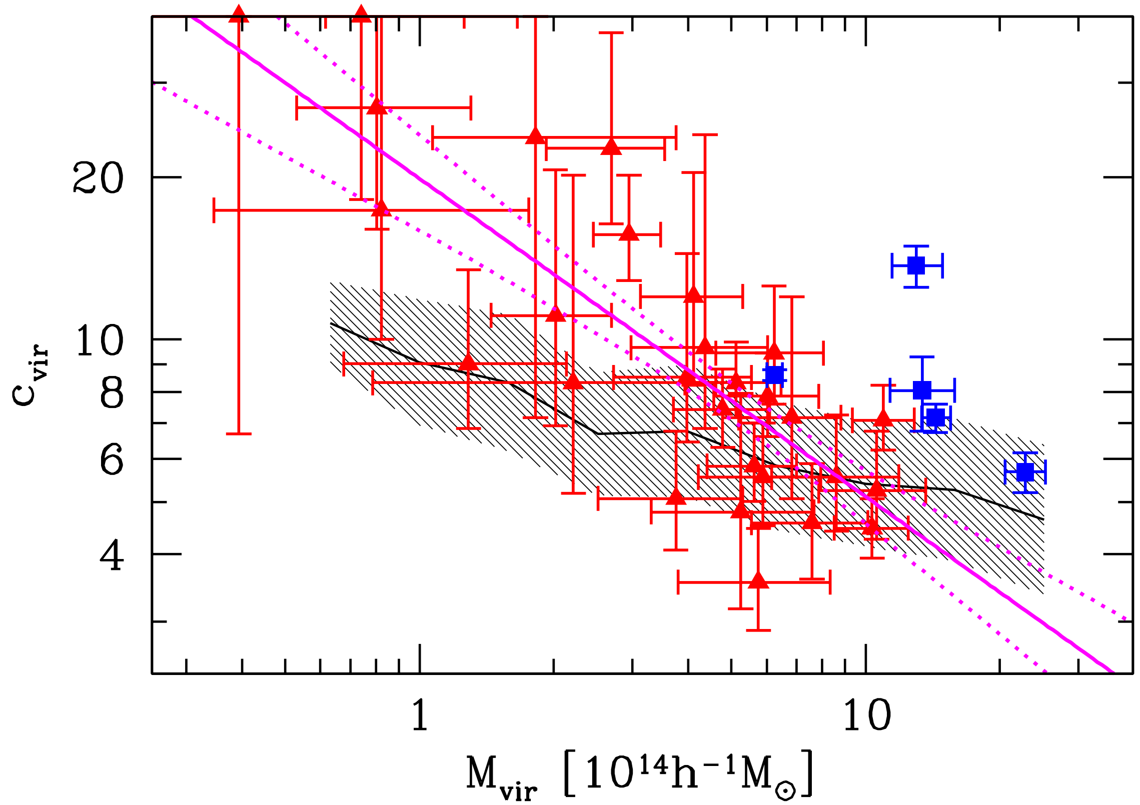
Halo concentration

- in some work, specific values or forms of concentrations are assumed to get mass
- the mass would be biased if the assumed concentration is wrong
- concentrations in real clusters consistent with ΛCDM predictions?

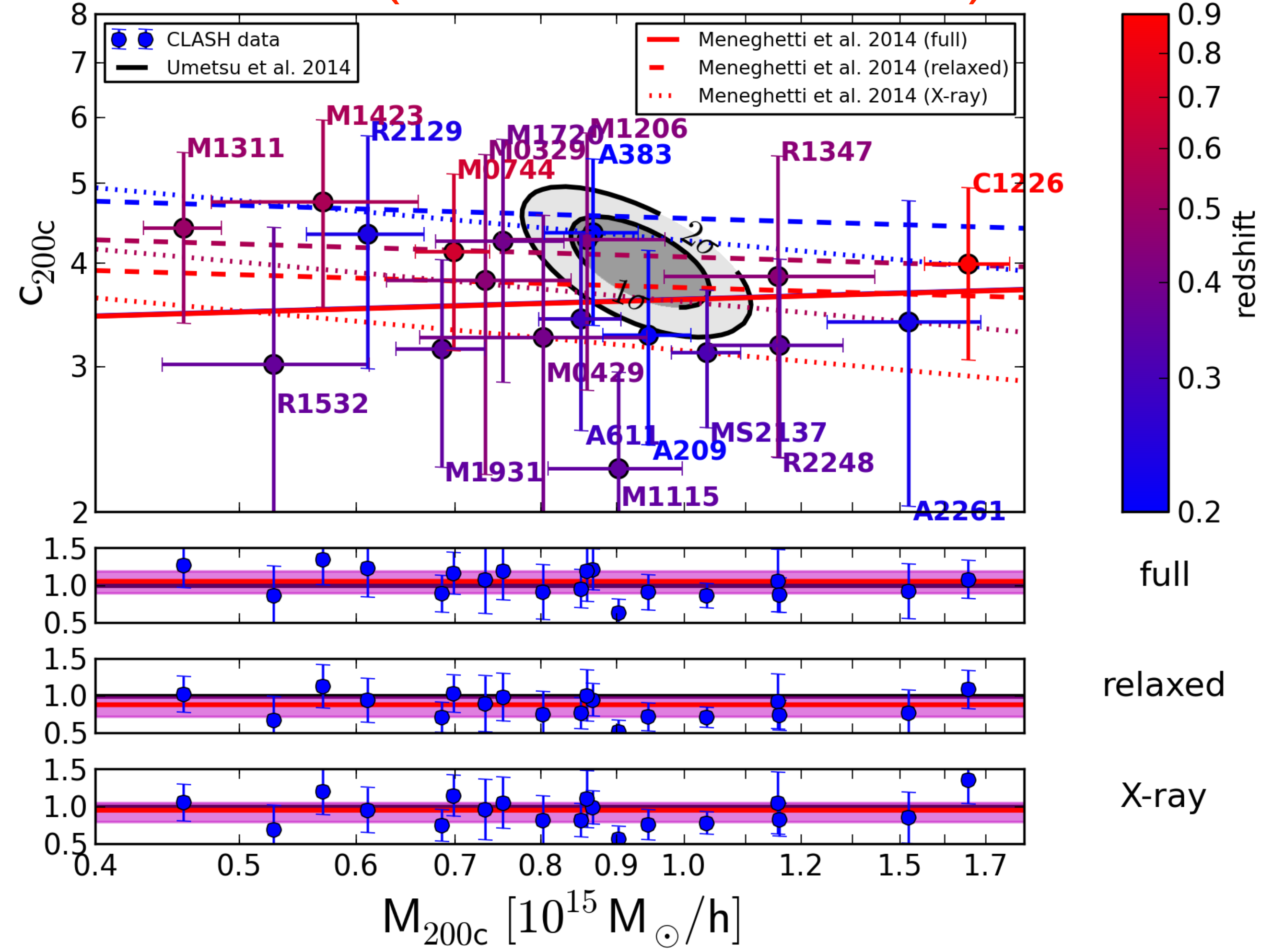


(cf. anomalously high concentrations claimed by Broadhurst et al.)

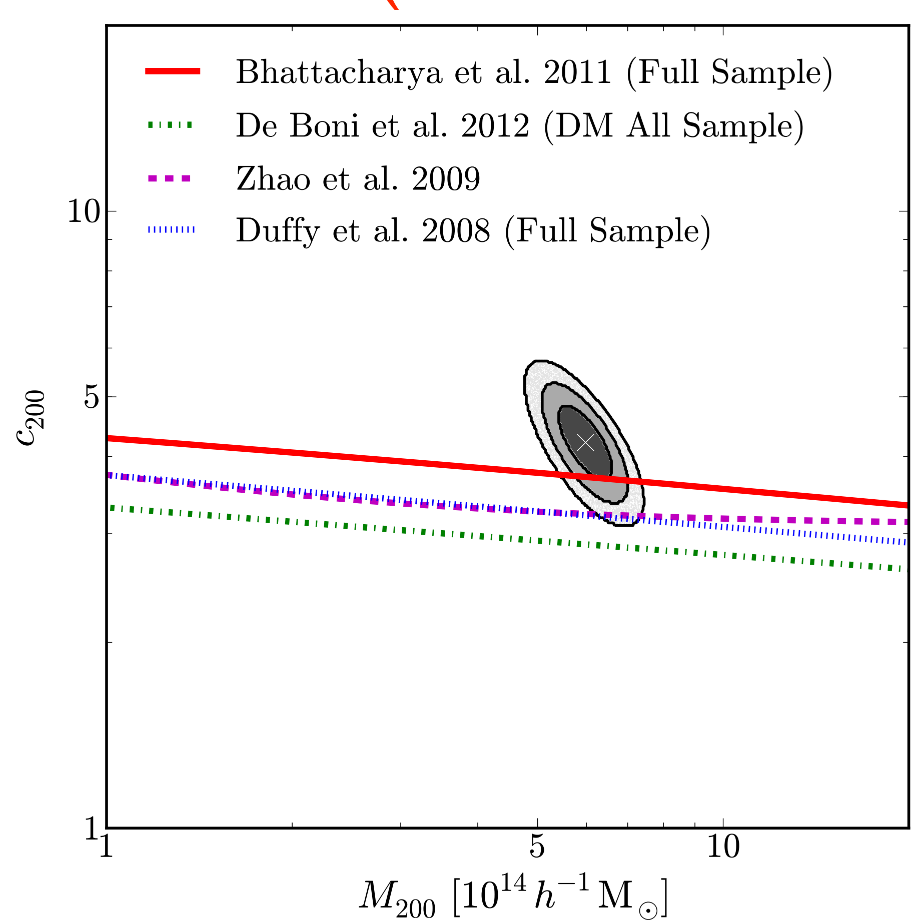
SGAS (Oguri et al. 2012)



CLASH (Merten et al. 2014)



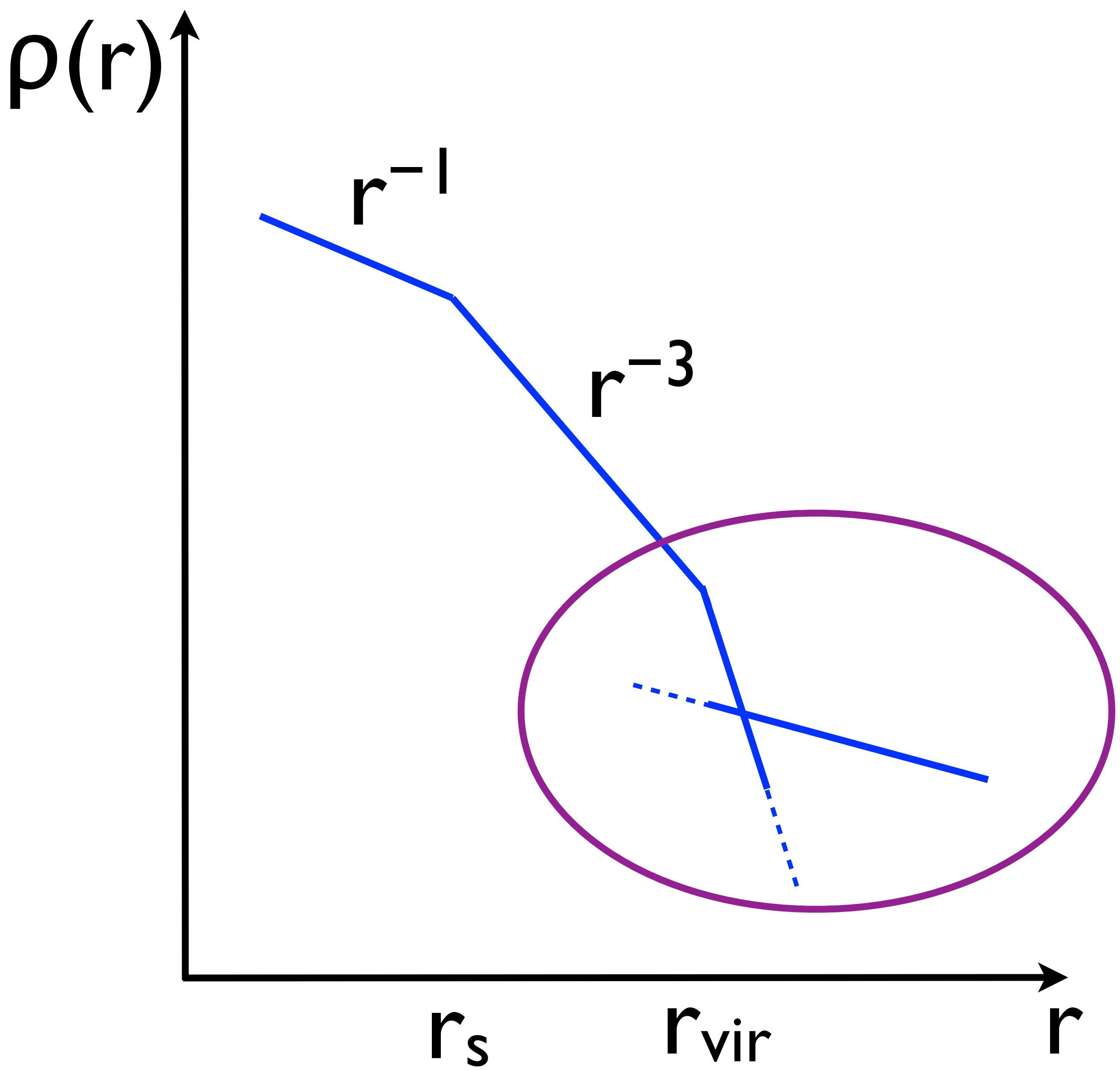
LoCuSS (Okabe et al. 2013)



concentration values also consistent with ΛCDM prediction!

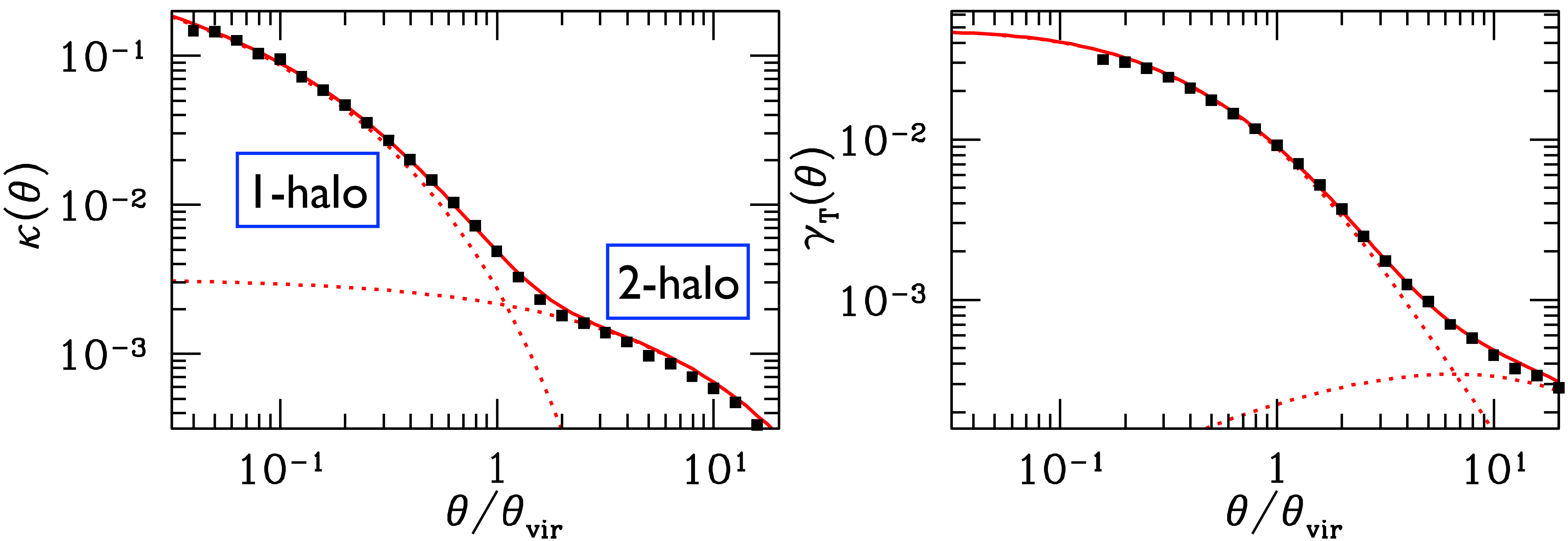
(←see talk by N. Okabe)

Outer density profile of clusters



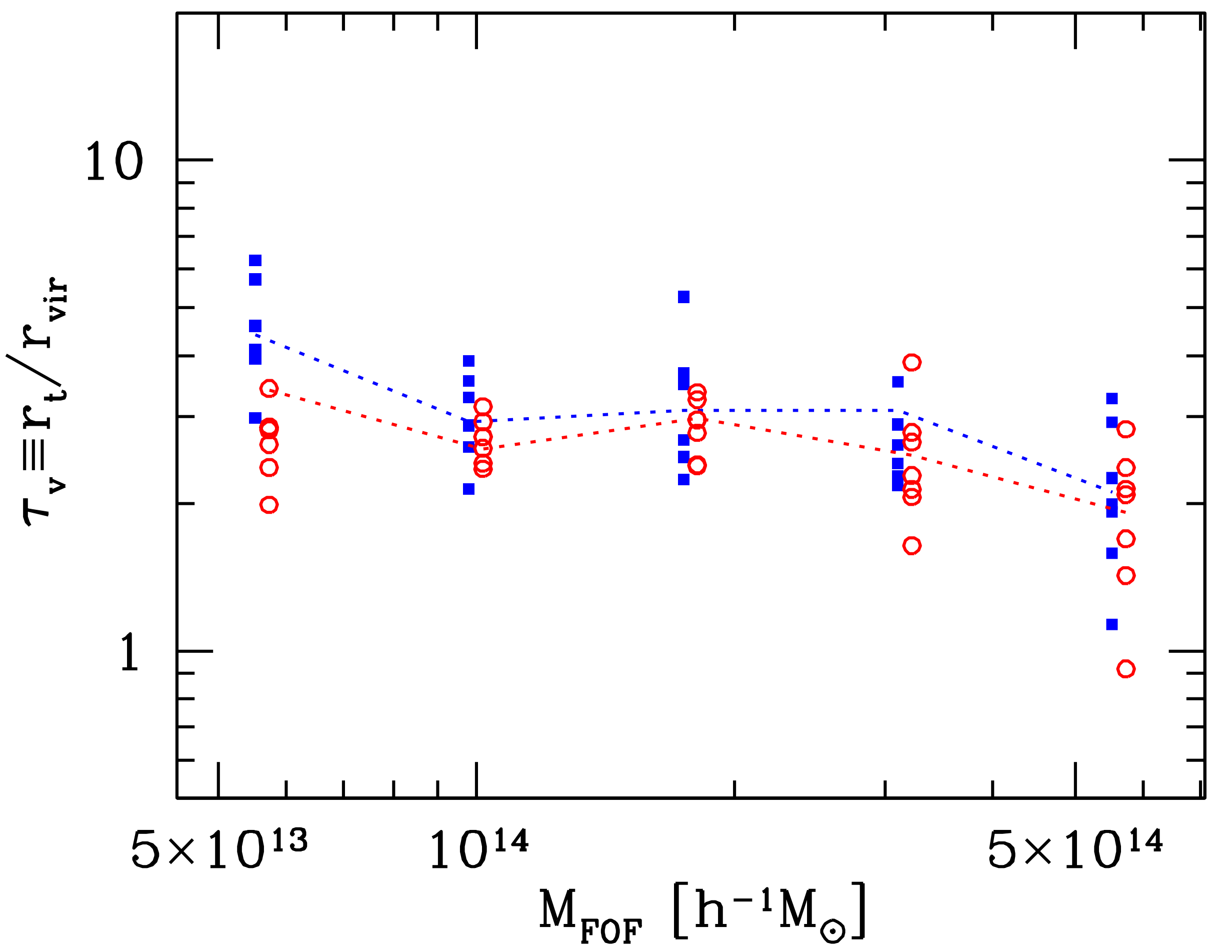
- has not attracted much attention until recently
- turned out to be quite important for accurate mass measurements

Outer lensing profiles



- detailed lensing profiles from ray-tracing in N-body simulations
- *truncated* NFW profile + 2-halo term can fit the profile in the simulation well

Truncation radius



- profiles in simulations are fitted with a smoothly truncated NFW profile (Baltz, Marshall & Oguri 2009)

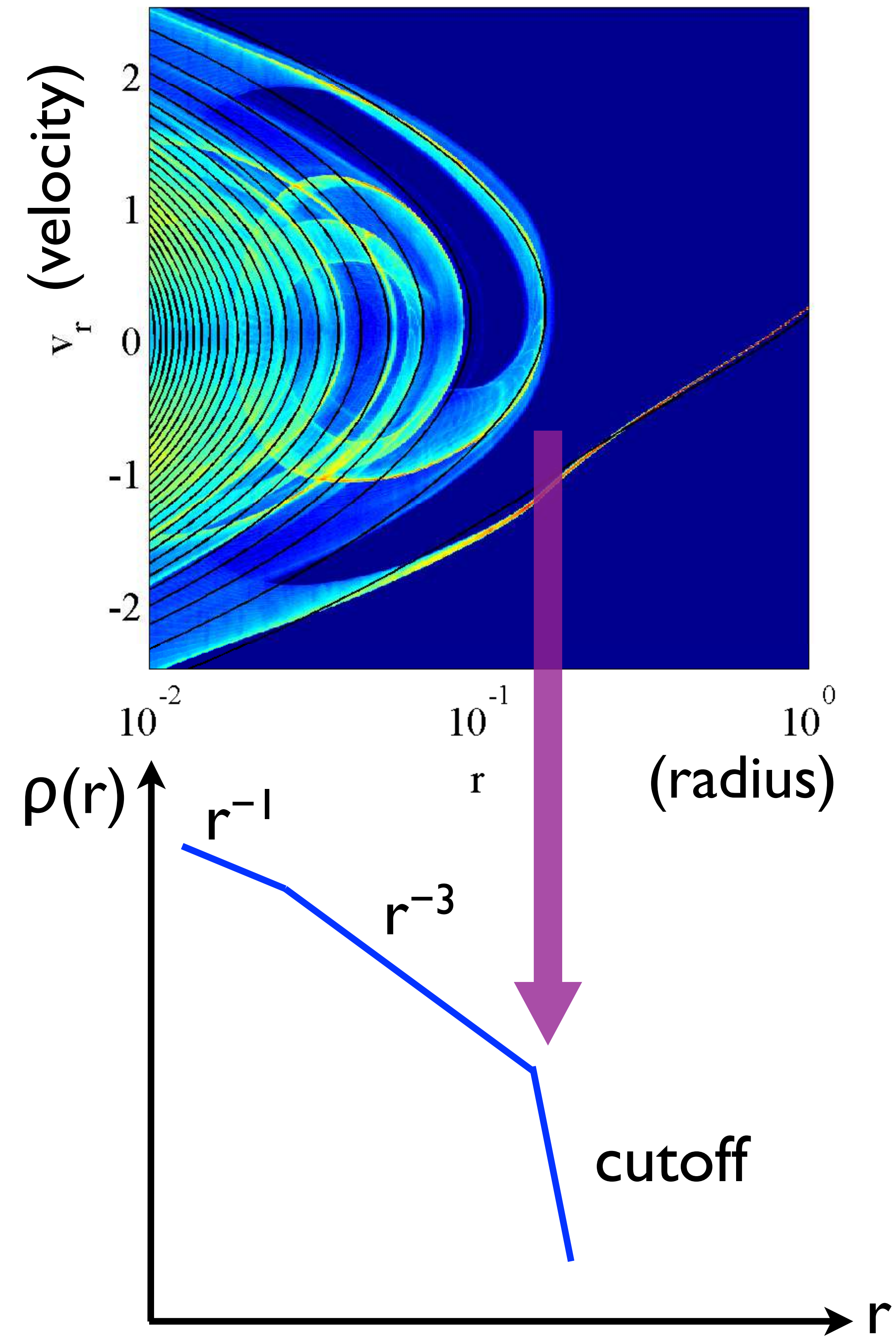
$$\rho_{\rm BMO}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}\left(\frac{r_t^2}{r^2+r_t^2}\right)^n$$

- truncation radius weakly depends on halo masses, more massive halos have smaller truncation radius

Adhikari, Dalal & Chamberlain (2014)

Physical origin of steepening?

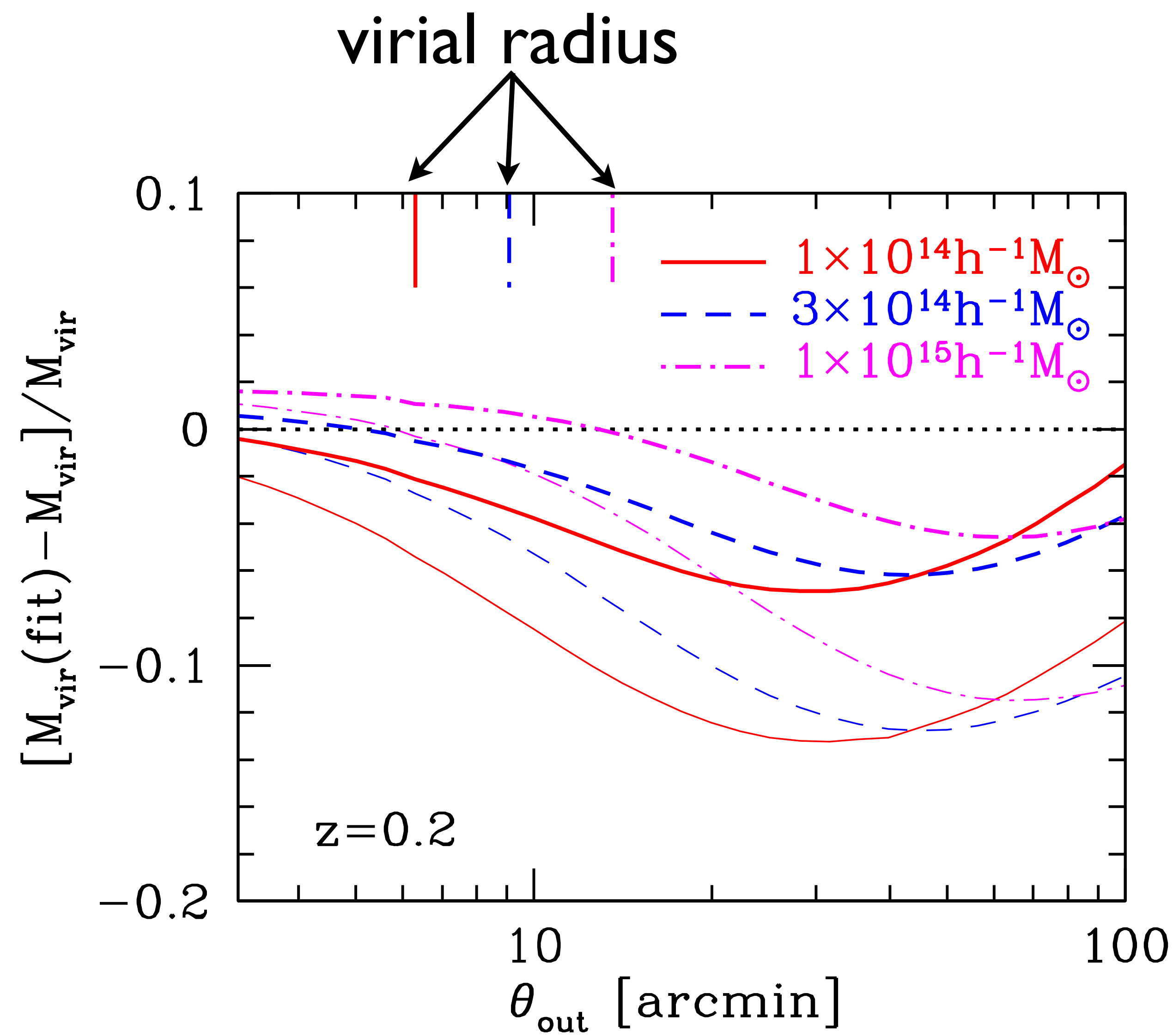
- steepening can be explained by "turn-around" of infalling material
- this suggests that the cutoff radius is partly determined by the accretion rate



Oguri & Hamana MNRAS **414**(2011)1851

Mass bias and outer density profile

- fitting shear profiles assuming traditional NFW without 2-halo
- best-fit mass can be biased low up to ~10%
- bias can be reduced by restricting fitting region to $\lesssim r_{vir}$
  (or including steepening and 2-halo in profile fitting)



thick: r_t=2.6r_{vir}
thin: r_t=2.0r_{vir}

Scatter and bias in lensing mass

- scatter
  statistical error – shot noise, LSS
  halo triaxiality

- bias
  profile mismatch
  substructure? (not in this talk)

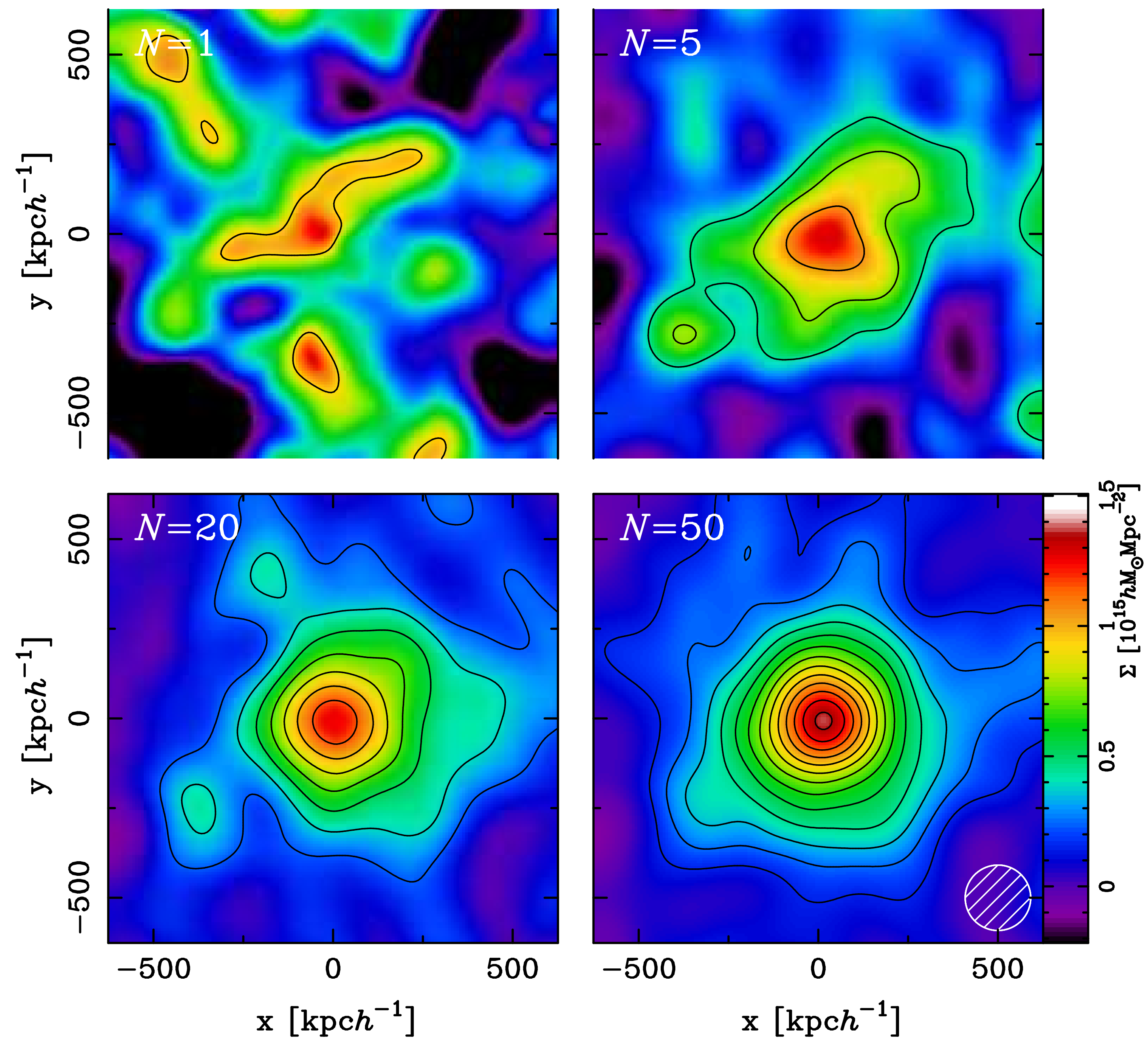
getting more and more understood by
ray-tracing simulations and observations

Statistical lensing mass estimate

- weak lensing mass estimates have large scatter
- one way to beat down scatter is to combine many measurements → stacked weak lensing
- very powerful approach in the era of wide-field surveys

Power of stacking

- stacking significantly enhances S/N
- one can get average properties very well
- particularly powerful when applied to wide -field survey data

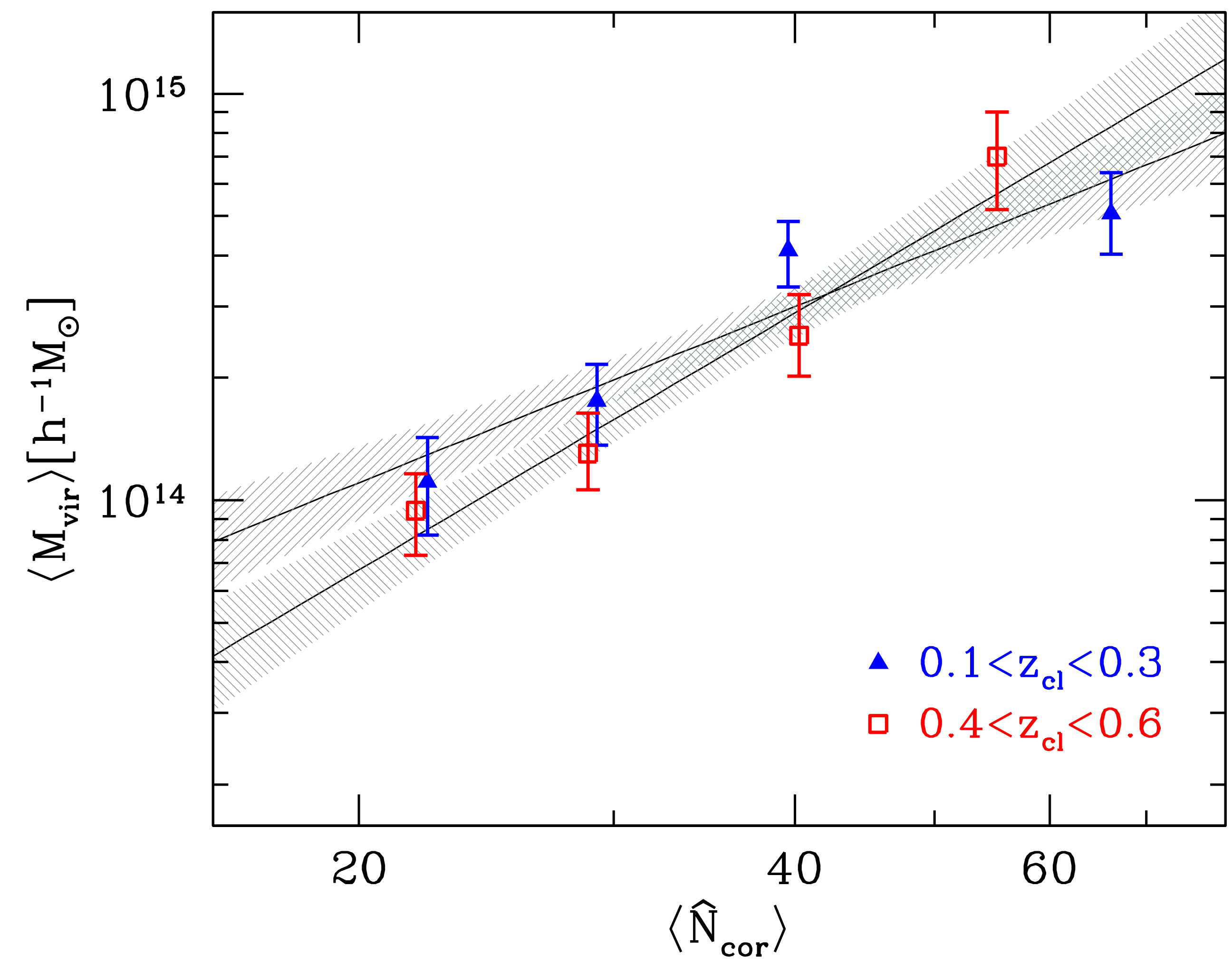


Okabe et al. (2013)

Oguri MNRAS **444**(2014)147

Scaling relation

- stacking of CFHTLenS data for SDSS clusters
- calibrate richness-mass relation well from ~120 deg^2 lensing data, down to ~$10^{14} M_{Sun}$



Bias in stacking analysis

- you need to understand your sample very well for proper understanding of stacking results
- if you take the interpretation of the sample wrong, stacking analysis results will be biased
- selection function is critically important!

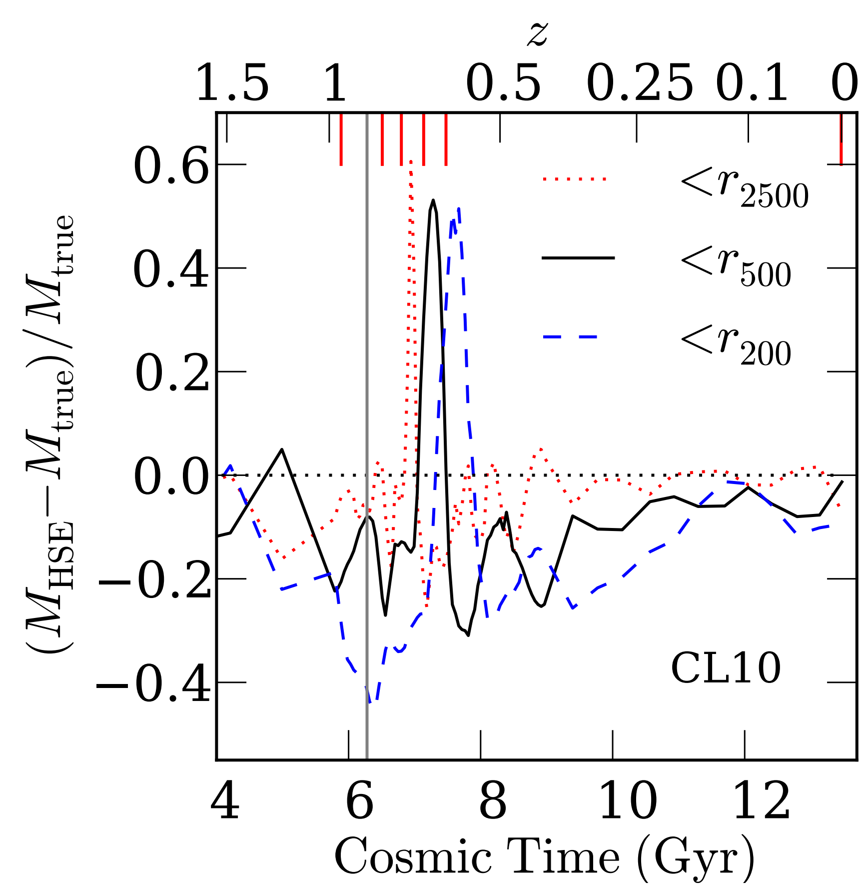
Possible cluster selection effects

- concentration/formation history
- merger
- orientation bias

Effects of merger

- merger can have large impact on observables
- change X-ray properties drastically
- strong lensing cross section also enhanced

Clowe et al. (2006)

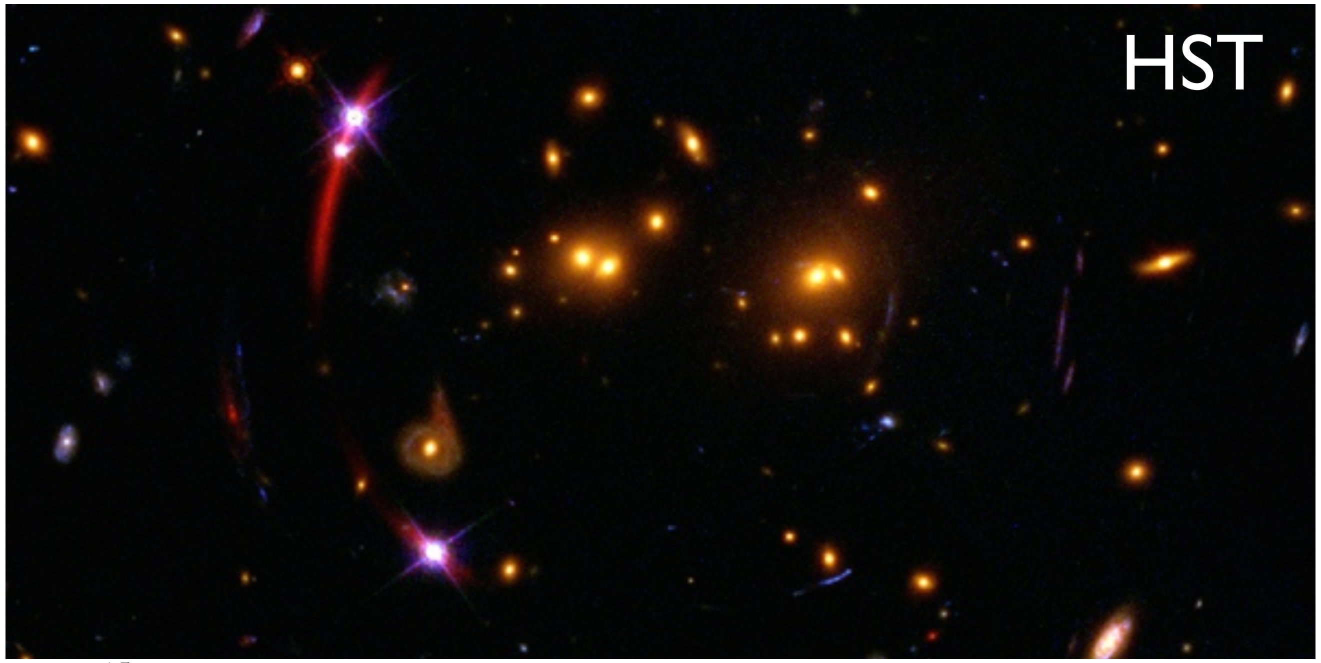


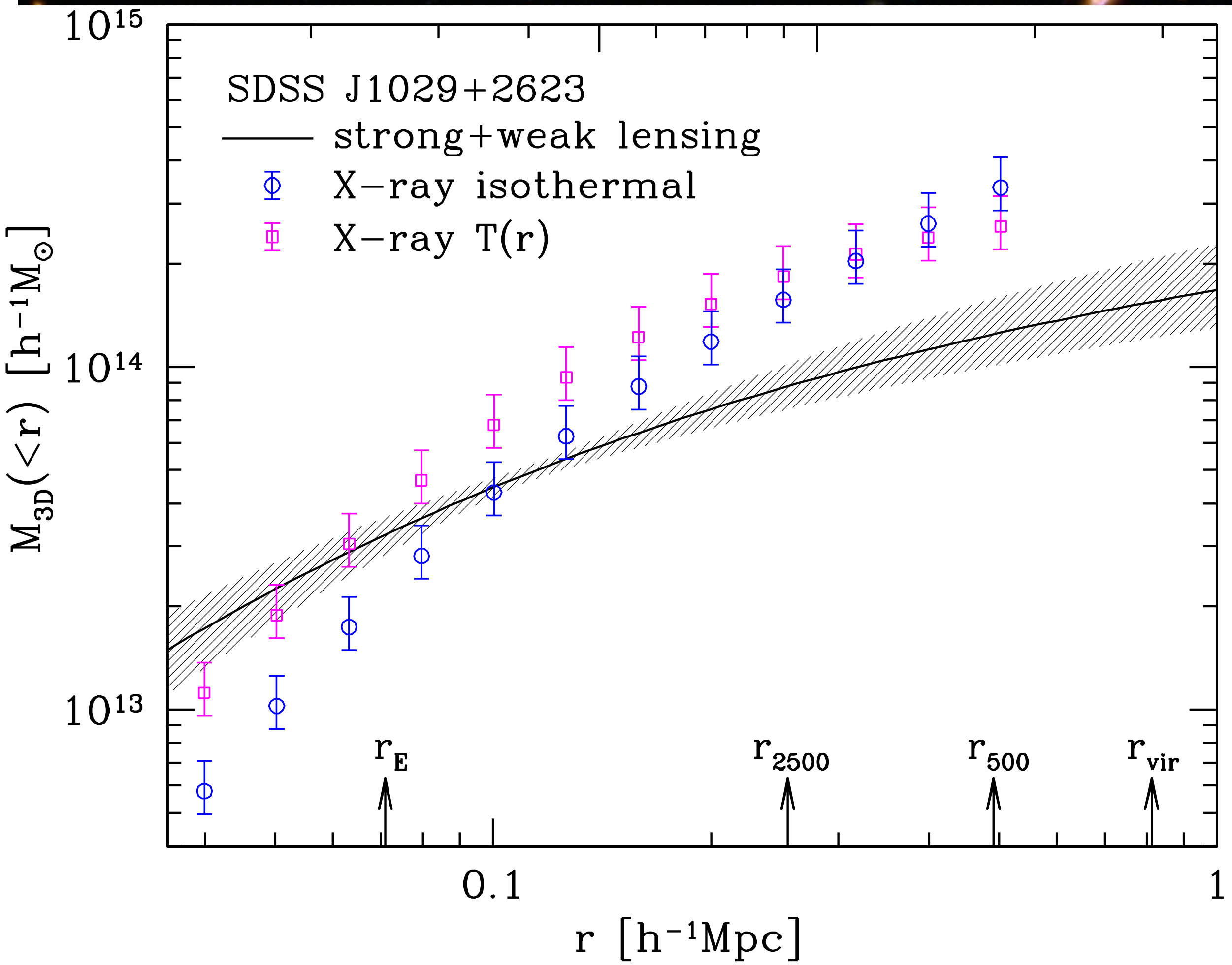
Simulation (Nelson et al. 2011)

Ota, Oguri et al. ApJ **758**(2012)26
Oguri et al. MNRAS **429**(2013)482

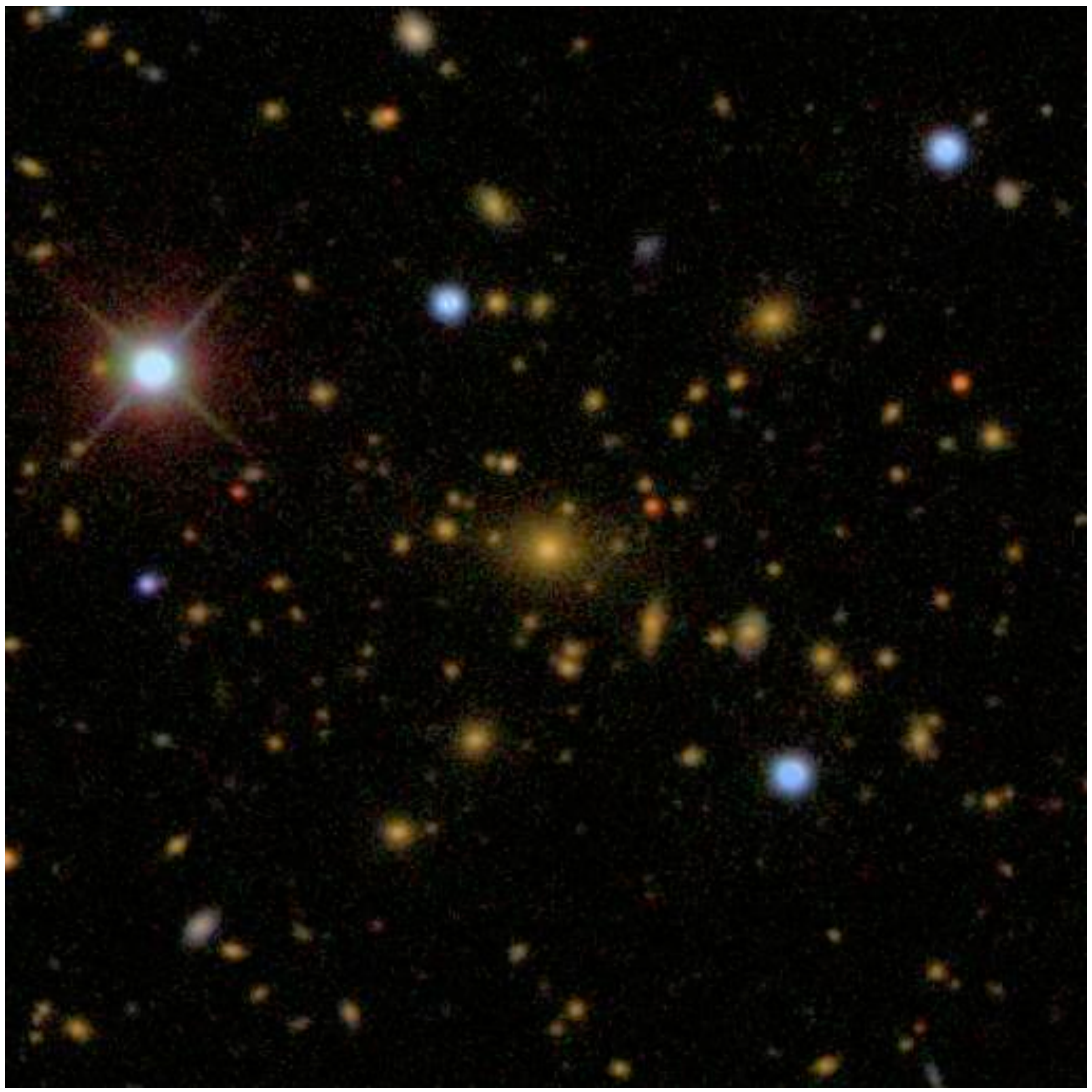
An extreme example?

- SDSS J1029+2623 ("the Hidden Fortress")
- mass distribution very concentrated
- mass discrepancy M_X/M_{lens}~2−3 (!)
- interpretation: line-of-sight merger

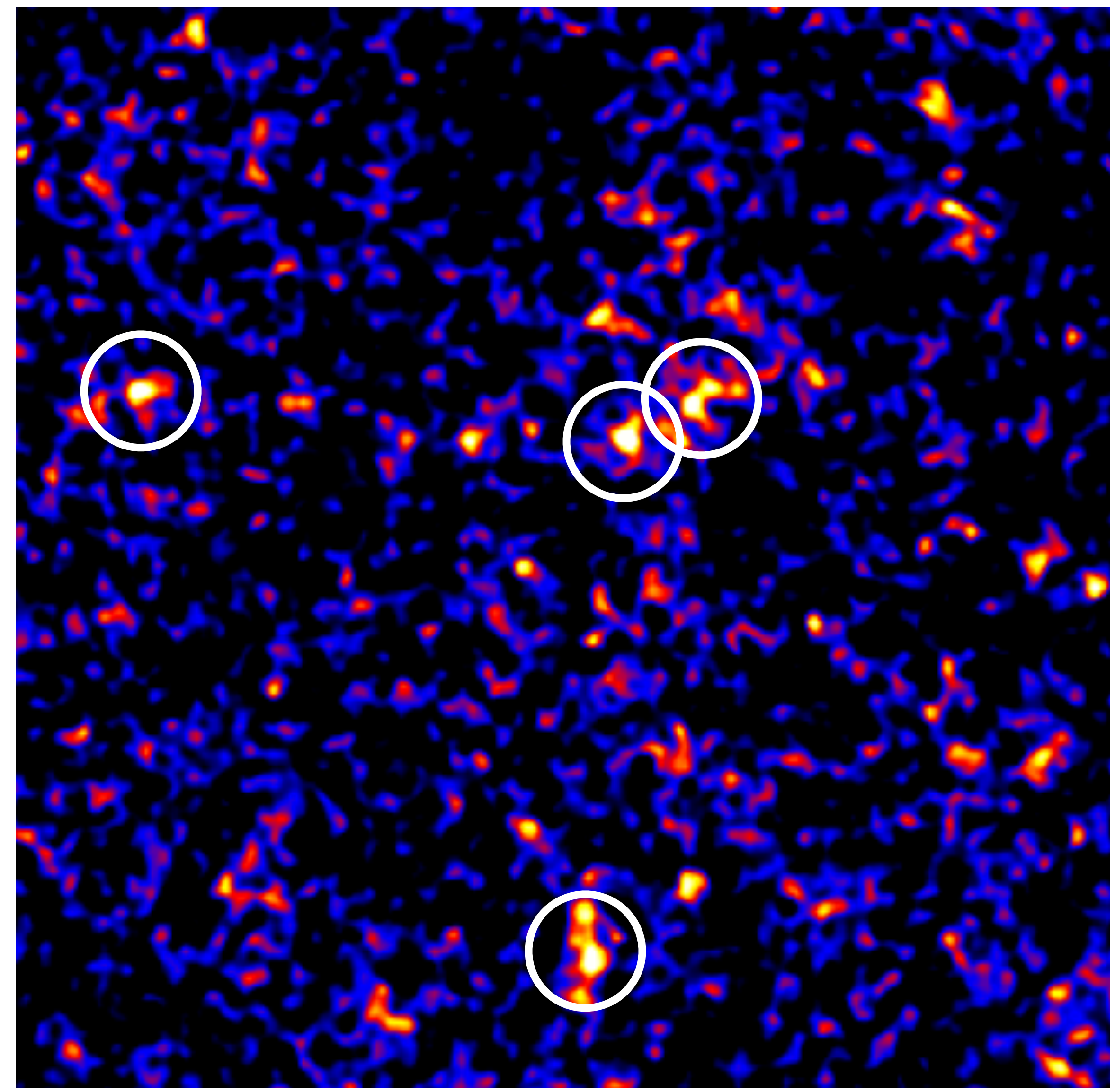




Cluster selection in optical surveys



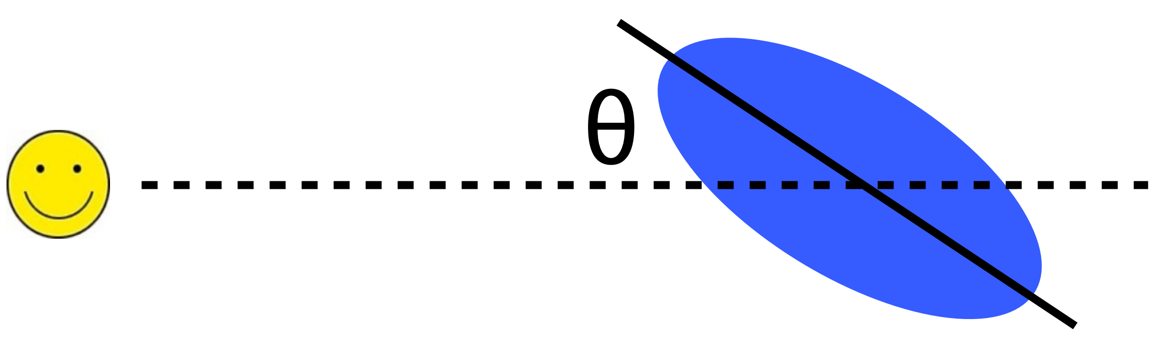
optical (galaxy)



weak lensing
(see talk by S. Miyazaki)

Orientation bias

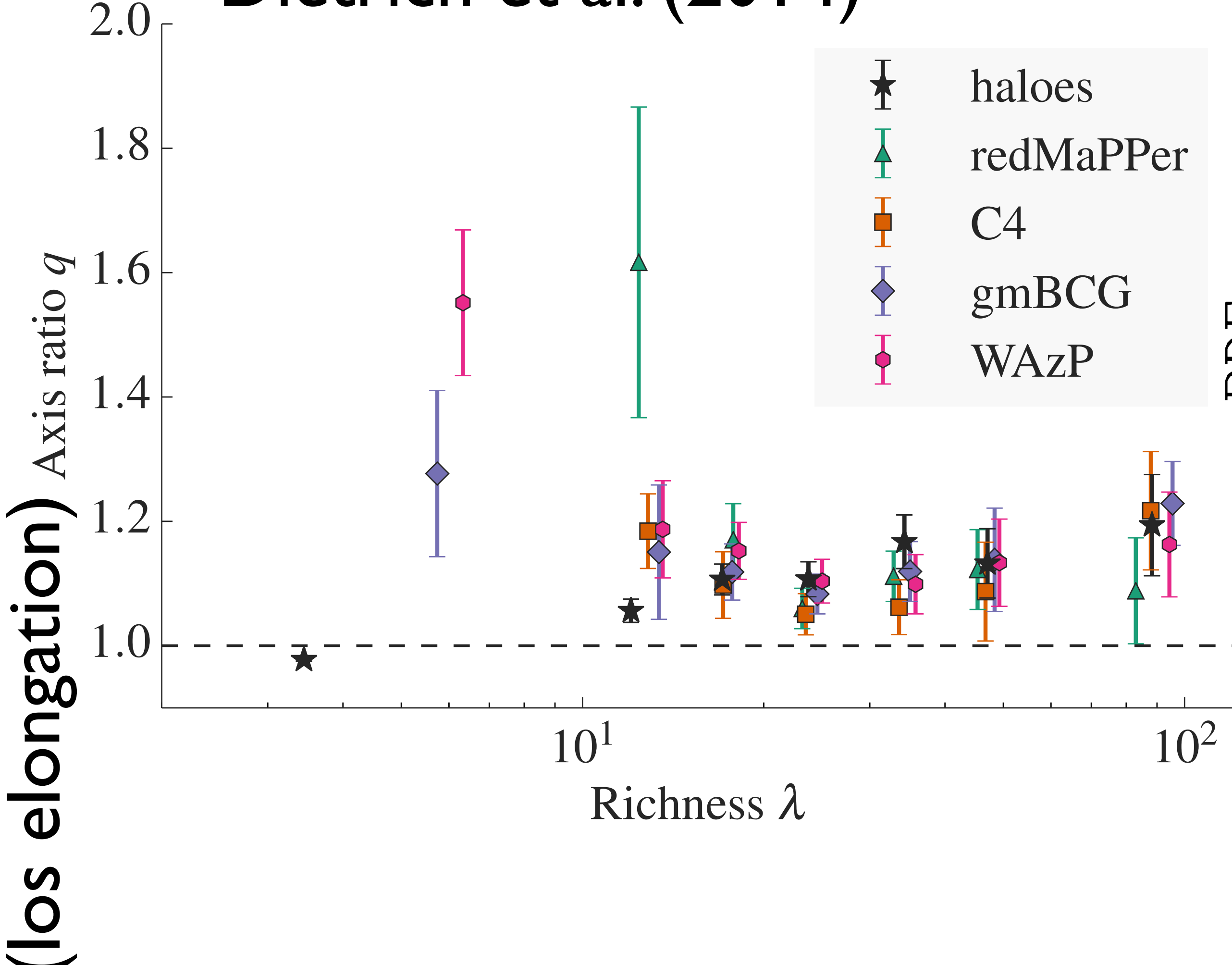
- triaxiality affects some cluster selection methods
- then resulting cluster sample has orientation bias, i.e., cluster orientations w.r.t line-of-sight direction is *not* random
- since lensing properties are sensitive to cluster orientations, the orientation bias can have large impact on stacked lensing analysis



Estimated orientation bias

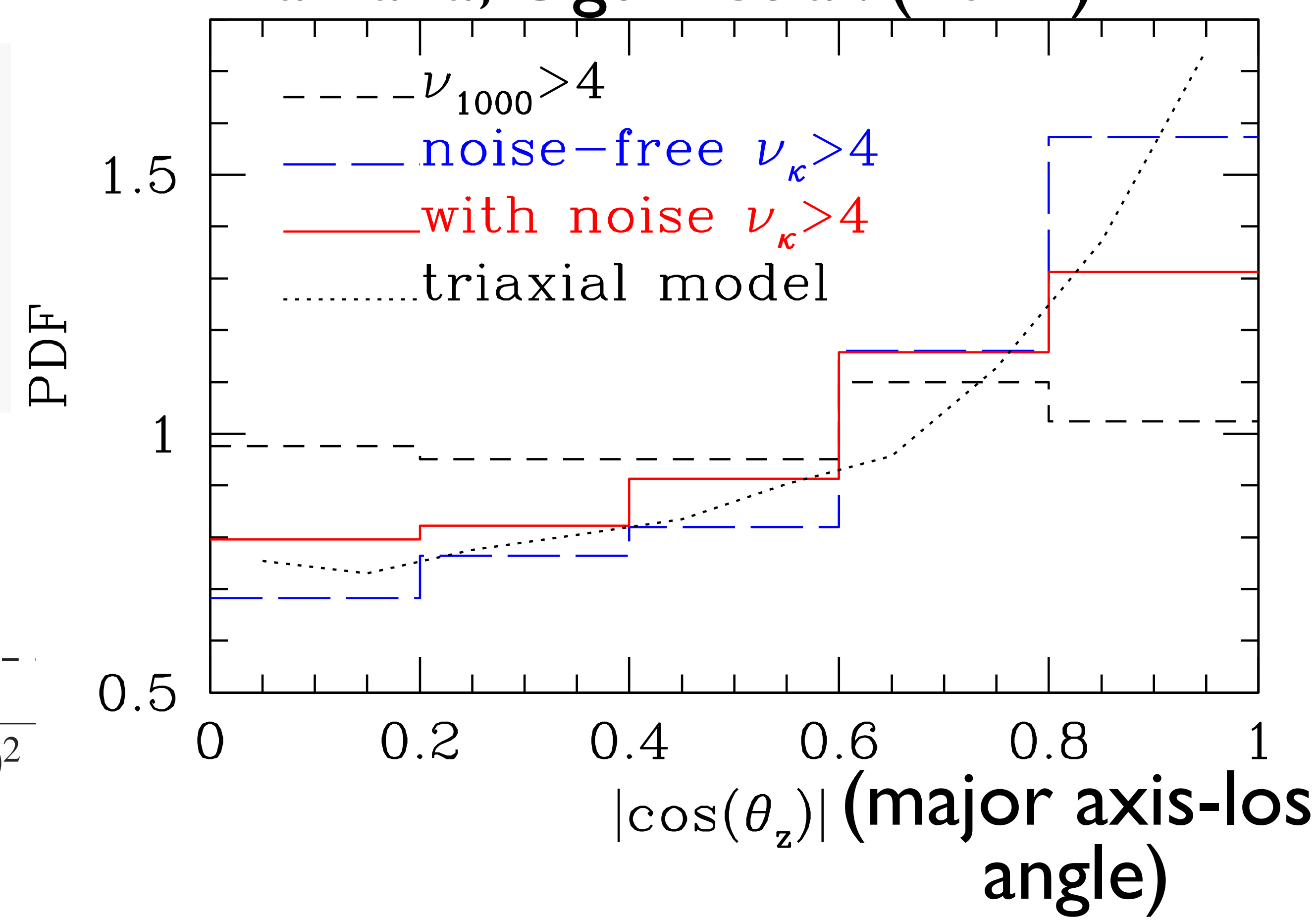
optical (galaxy)

Dietrich et al. (2014)



weak lensing

Hamana, Oguri et al. (2012)



- optical and weak lensing selected clusters are preferentially aligned with line-of-sight direction!

Summary

- origins of scatter and bias in cluster (lensing) mass estimates are getting more and more understood − triaxiality, outer profile, ...
- stacking analysis is powerful in reducing scatter, but understanding of the selection function is critically important (e.g., orientation bias)