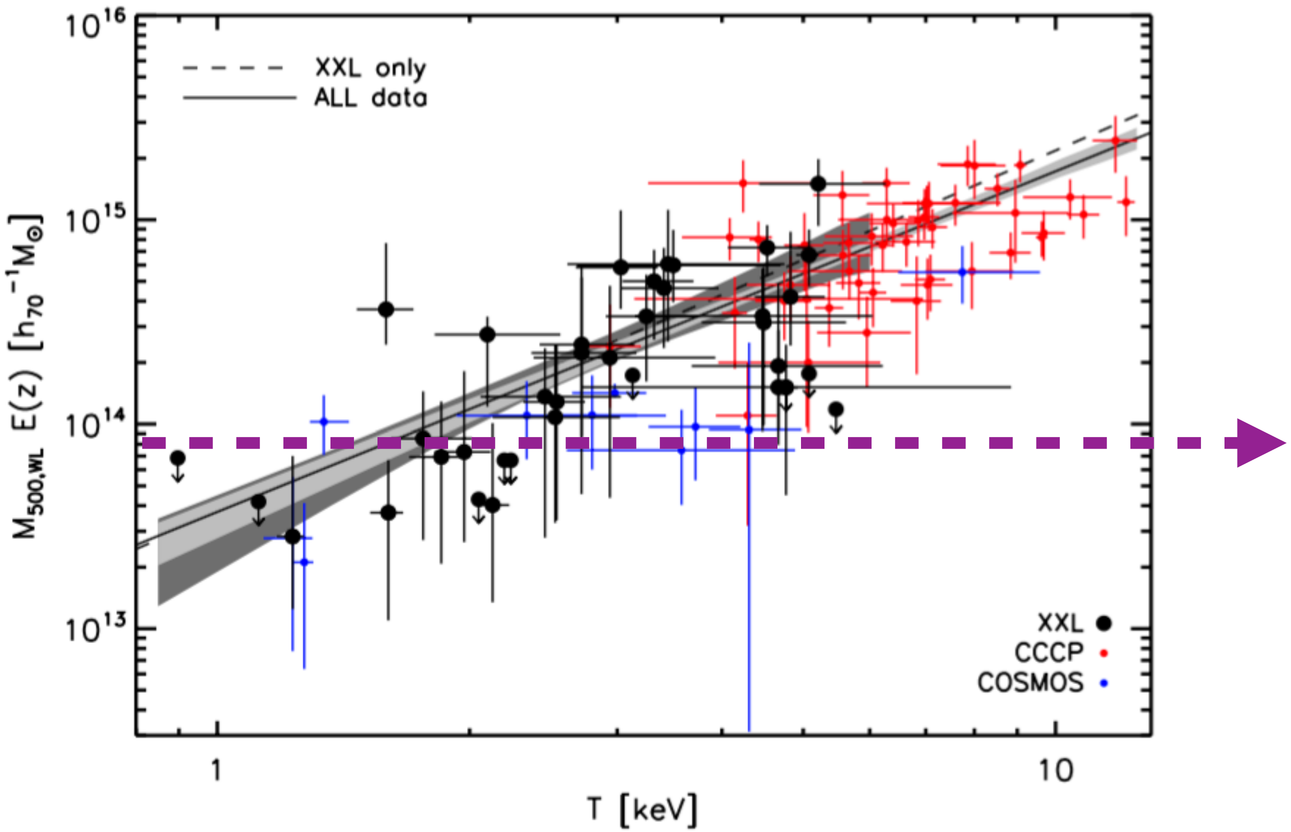
The masses of galaxy groups

Graham P. Smith, University of Birmingham

Chris Haines, Alexis Finoguenov, Maggie Lieu (unpublished work at end of talk)

Many colleagues in LoCuSS, and XXL, including some at this meeting:
Arif Babul, Jessica Democles, Gus Evrard, Marguerite Pierre, Trevor Ponman, Tatyana Sadibekova

What do we mean by a "galaxy group"?



Lieu, et al., 2016, A&A, 592, A4

galaxy clusters

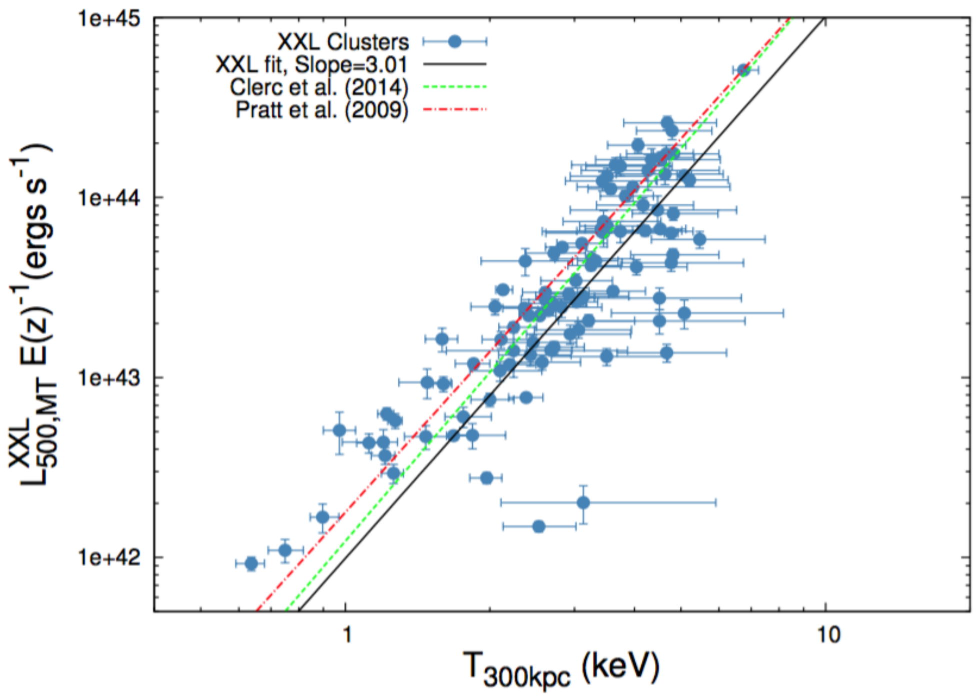
$M_{200}E(z)/h_{70} \approx 10^{14} M_{\odot}$

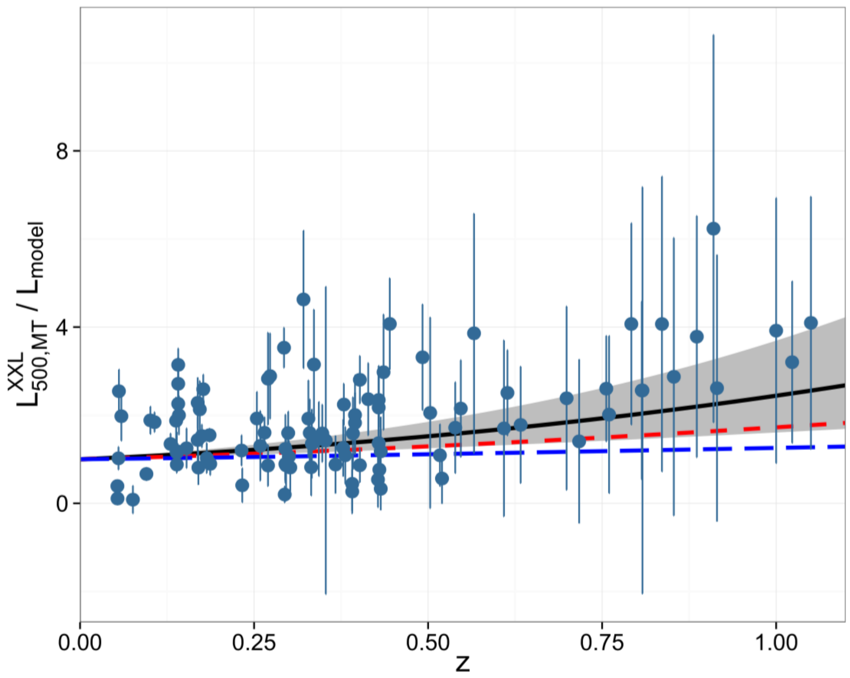
galaxy groups

Why measure group masses? — connect to halo mass function

- "Weak" connection to the halo mass function:
  - Unbiased estimates of r_Δ to measure physical properties of groups in a self-consistent manner
- "Strong" connection to the halo mass function:
  - Forward modelling of cluster/group population from a halo mass function
  - Allows self-consistent treatment of nuisance parameters (e.g. halo concentration), modelling of covariance (see Gus's talk)
  - Ultimately, simultaneous modeling of cluster/group physics and cosmology
- Accuracy of the connection to the halo mass function:
  - $r_\Delta \propto M_\Delta^{1/3} \Rightarrow \delta r_\Delta / r_\Delta = (\delta M_\Delta / M_\Delta)/3$
  - $\langle \delta r_{500}/r_{500} \rangle \approx 0.03$ at $M_{200} > 5 \times 10^{14} M_\odot$, $z<0.3$ (Okabe & GPS, 2016, MNRAS, 461, 3794)
  - Cluster cosmology aim: $\langle \delta M_\Delta / M_\Delta \rangle \approx 0.01$ for $M_{200} > 10^{14} M_\odot$ at $z<1$ next decade
  - Motivated by group/cluster physics, how accurately do we need to calibrate group/cluster masses out to (say) $z=1$ and down to (say) $M_{200} = 10^{13} M_\odot$?

Example weak connection to the halo mass function: L_X-T_X relation

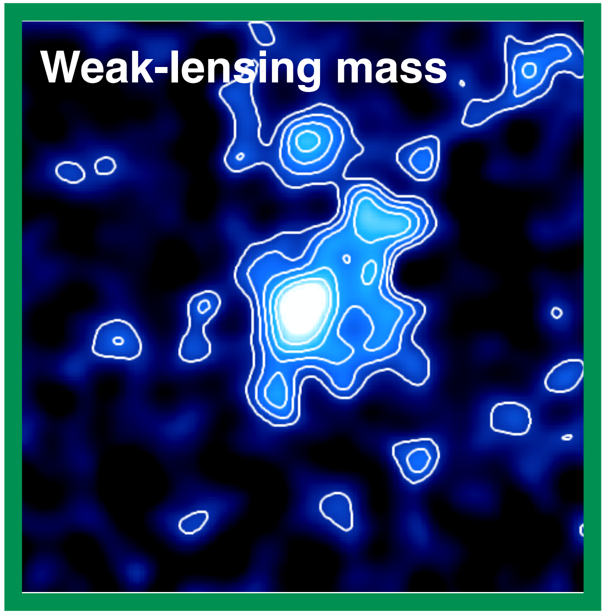


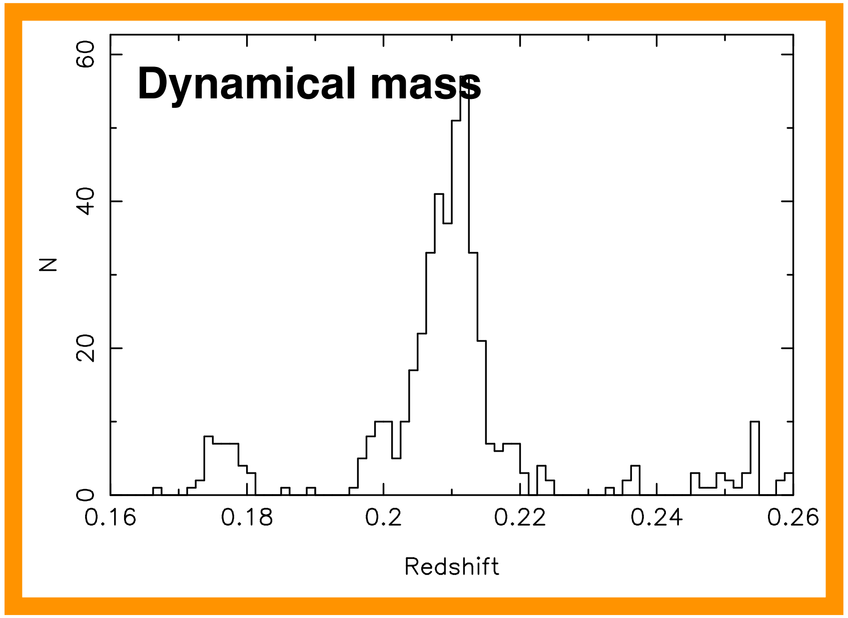


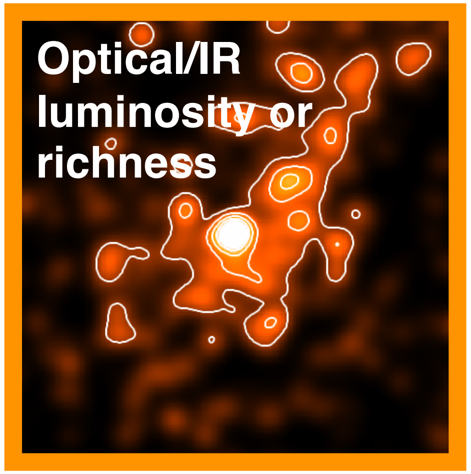
The measured positive evolution of the XXL L_X-T_X relation is sensitive to the choice of M-T relation used for mass calibration, choice of local reference sample, and details of the selection function.

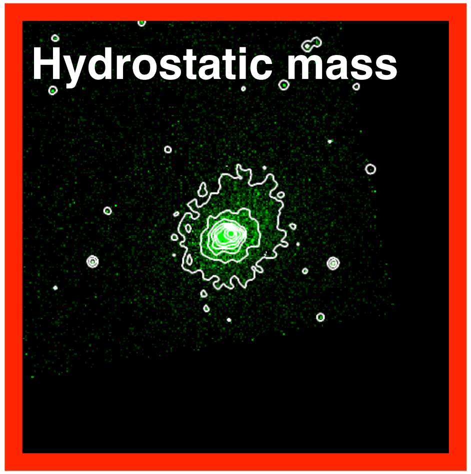
Giles, et al., 2016, A&A, 592, A3

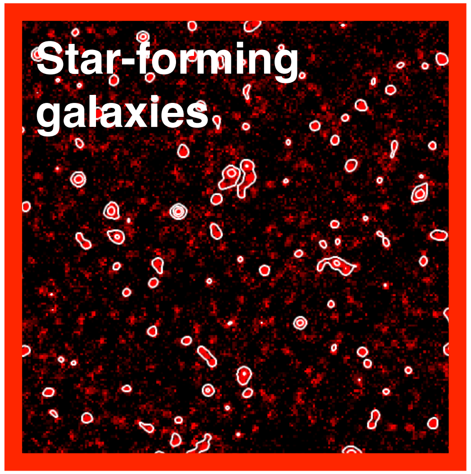
Q: what do we mean by the "mass" of a galaxy group?











A: a quantity that can be calibrated against underlying halo mass from numerical numerical simulations with **minimal/no reliance on the accuracy of the physics in the simulations** across a broad redshift range

Hydrostatic mass R.I.P.?

Differences between the hydrostatic mass measurements by leading cluster cosmology groups can be ~50%!

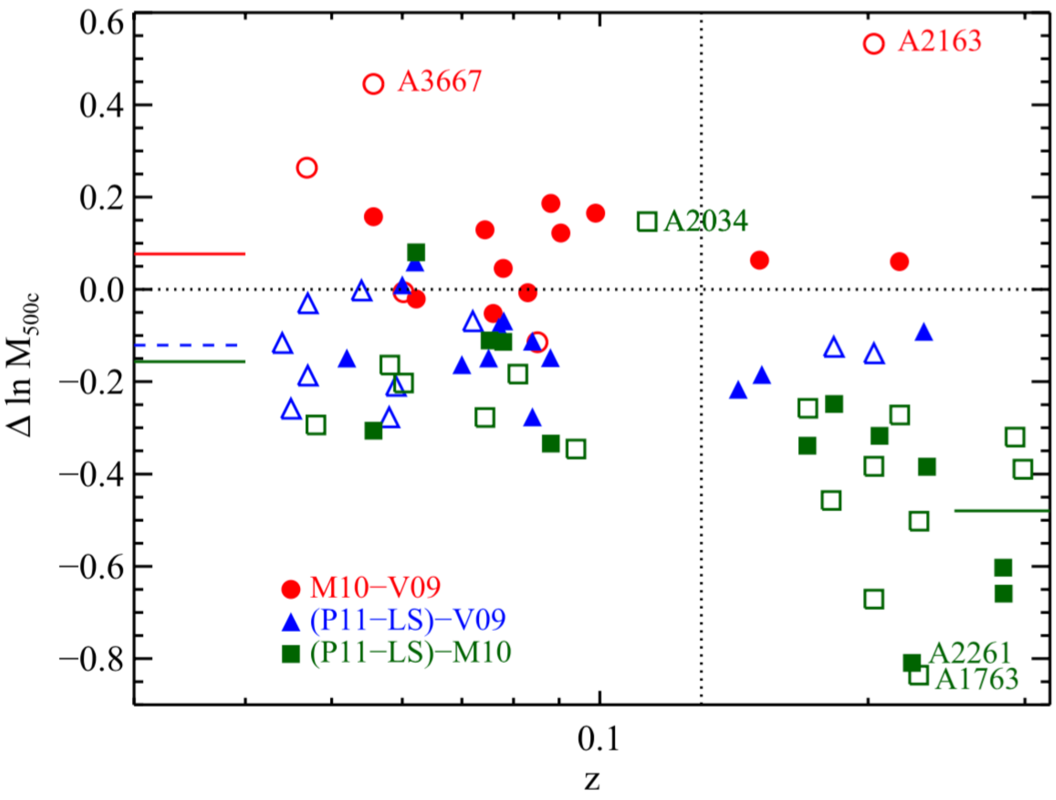
If the X-ray emitting gas in a galaxy cluster is in hydrostatic equilibrium with the gravitational potential:

$$\frac{dP_{\rm gas}}{dr} = -\frac{G\,M_{\rm cl}(\leq r)\rho_{\rm gas}}{r^2}$$

then the mass of the galaxy cluster can be obtained from the density and temperature profiles of the cluster gas:

$$M_{\rm cl}(\leq r) = -\frac{kT}{\mu m_{\rm p} G}\left(\frac{d\ln\rho_{\rm gas}(r)}{d\ln r} + \frac{d\ln T}{d\ln r}\right) r$$

Rozo, et al., 2014, MNRAS, 438, 49

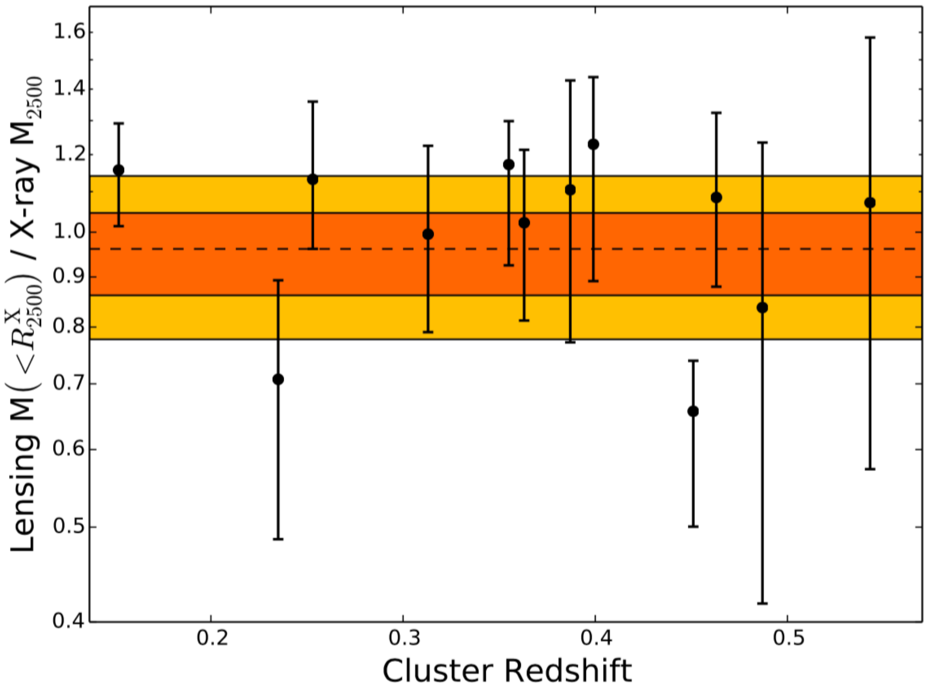


Hydrostatic mass R.I.P.?

"Yes" for putting groups/clusters on absolute mass scale

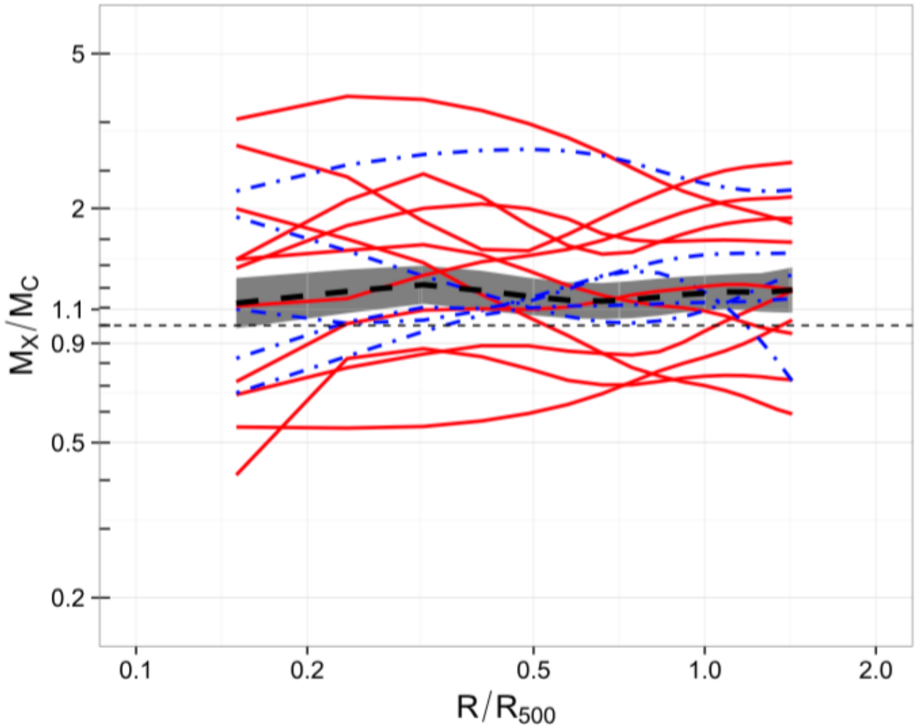
"No" for exploring cluster physics

$M_{WL}/M_{HSE} = 0.96 \pm 0.13$



Applegate, et al., 2016, MNRAS, 457, 1522

$M_{HSE}/M_{Dyn} = 1.2 \pm 0.1$



Maughan, et al., 2016, MNRAS, 461, 4182

Local Cluster Substructure Survey

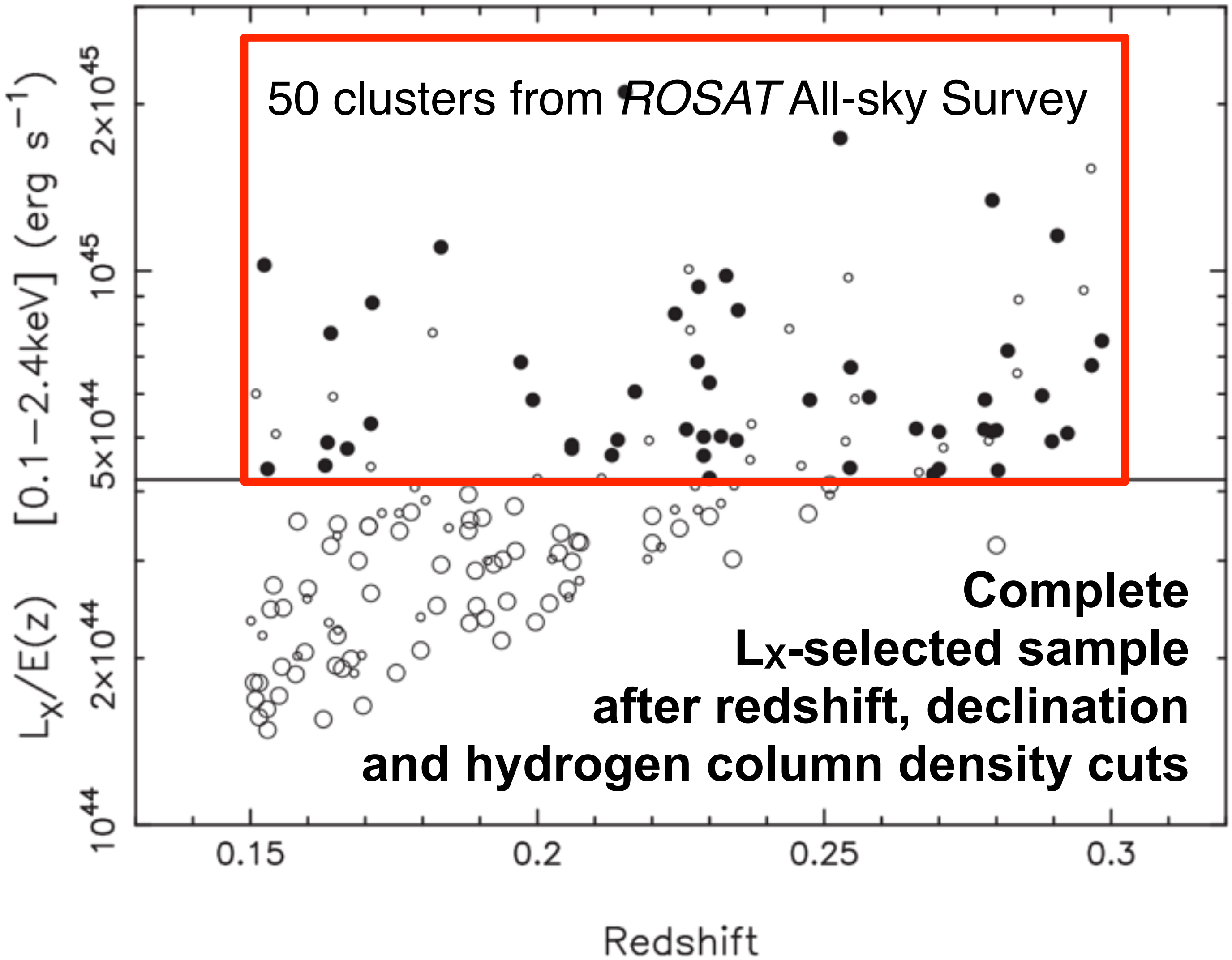
A low redshift baseline study of massive galaxy clusters as a cosmological probe and a laboratory for galaxy evolution

$L_X/E(z) > 4.1 \times 10^{44}$ erg/s

$-25° < \delta < +65°$

$0.15 < z < 0.3$

$n_H < 7 \times 10^{20} cm^2$



A rich multi-wavelength dataset

- Subaru (mainly Gemini exchange time) 50/50, plus 30 more
  - Okabe et al., 2010; Okabe, GPS, et al., 2013; Okabe & GPS, 2016
- X-ray: Chandra ACIS-I for 44/50 and XMM-Newton for 39/50
  - Zhang et al., 2008, 2010; Okabe et al., 2010; Martino et al., 2014
- Sunyaev-Zeldovich Array: 50/50, plus 30 more
  - Marrone, GPS, et al., 2009; Marrone, GPS, et al., 2012
- [Planck: 44/50; all 50 clusters in LoCuSS re-analysis]
  - GPS, et al., 2016, MNRAS, 456, L74; Mulroy, Farahi, et al., in prep.
- HST: WFPC2 and/or ACS observations of 25/50+ that are strong lenses
  - Richard, GPS, et al., 2010; GPS et al., 2010; May et al., in prep.
- Hectospec: 25/50+, and UKIRT/WFCAM, KPNO/NEWFIRM: 50/50+
  - Mulroy, GPS, et al., 2013; Haines et al. 2012, 2013, 2015
- Spitzer/MIPS, Herschel/PACS+SPIRE, GALEX: 25/50+
  - Haines et al. 2009a,b, 2010, 2012, 2013, 2015; GPS et al. 2010a,b

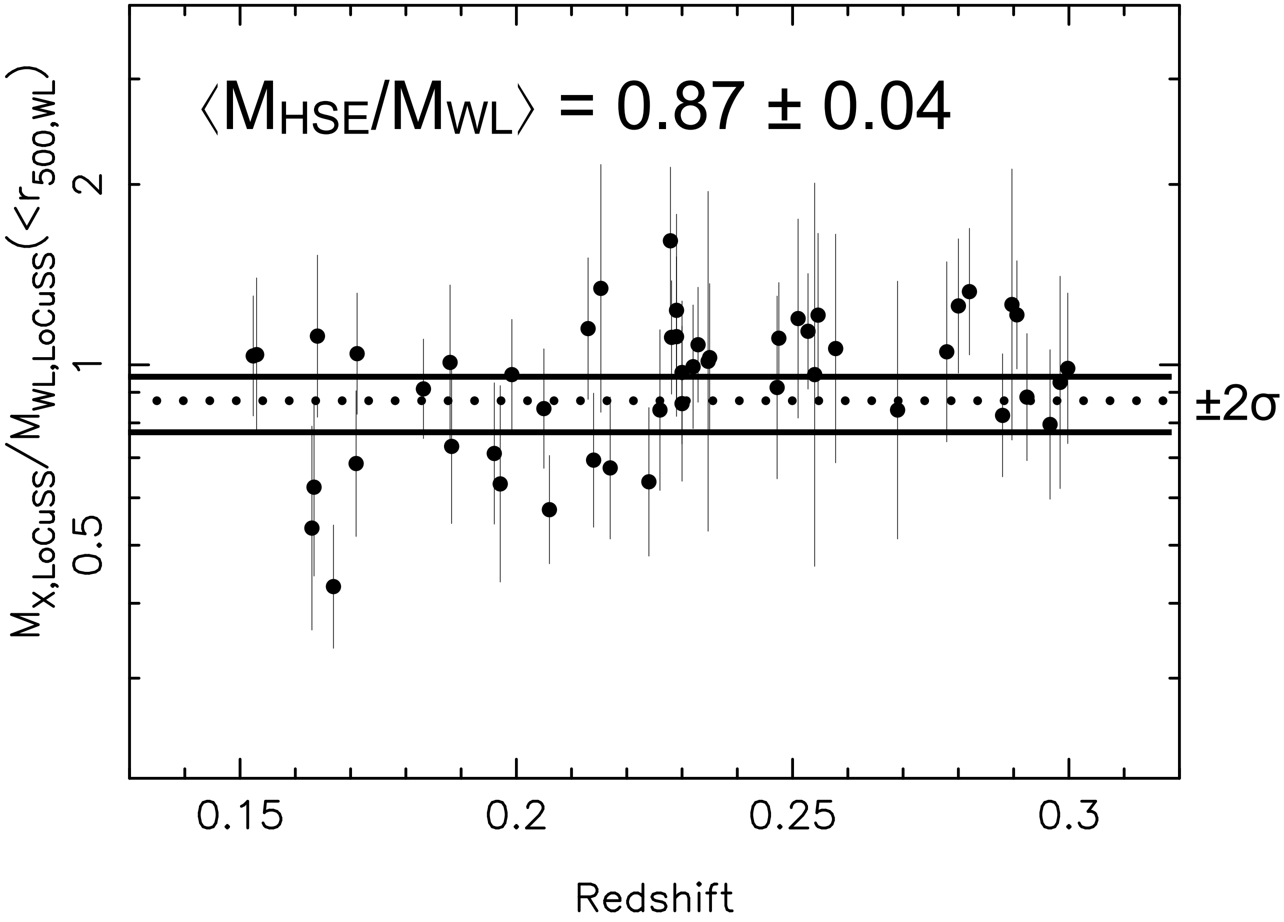
Testing hydrostatic equilibrium with Subaru, XMM, and Chandra

M_{WL} suffer ~4% systematic bias:

- 3% galaxy shape bias
- 1% contamination bias
- <1% modeling bias
- Okabe & GPS, 2016

M_{HSE} suffer ~8% systematic error:

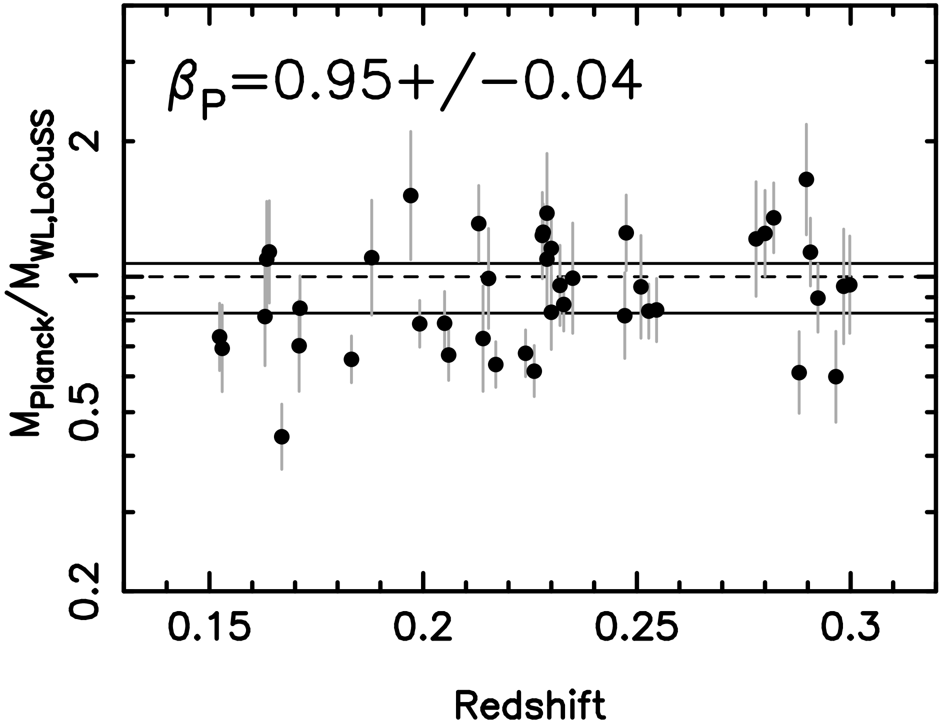
- **M_{CXO}/M_{XMM}=1.02±0.05**
- 8% intrinsic scatter
- Martino et al., 2014, MNRAS, 443, 2342
- Based on the background model of Bartalucci et al., 2014, A&A, 566, A25

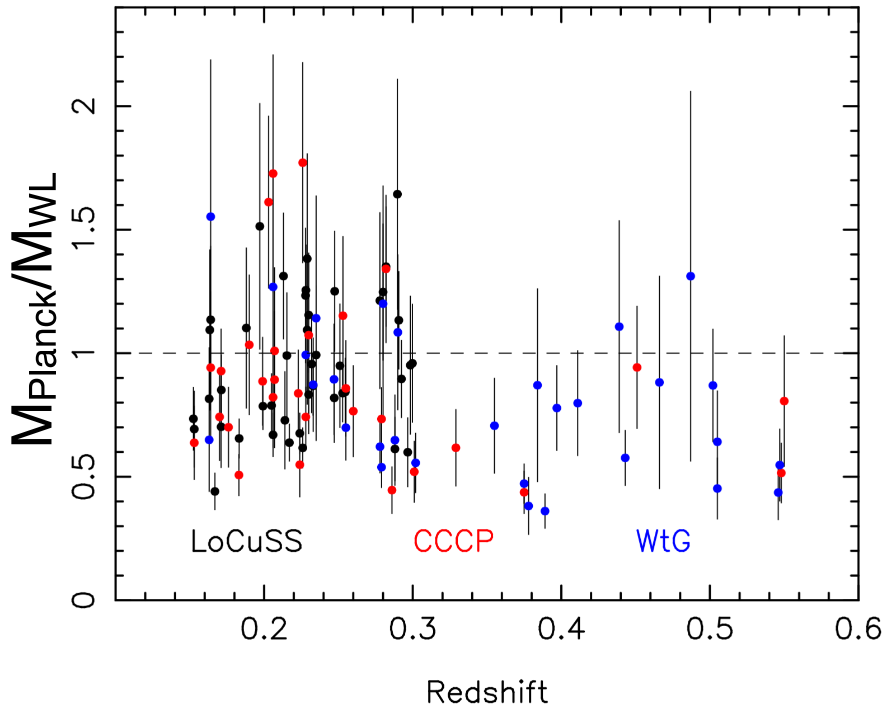


Local Cluster Substructure Survey

GPS, et al., 2016, MNRAS, 456, L74

An aside on the reliability of Planck cluster mass estimates





Previous results from WtG and CCCP (after updating to Planck 2015 analysis) are dominated by clusters at z>0.3:

CCCP: $\beta_{\rm P}\ (z < 0.3) = 0.96 \pm 0.09 \quad \beta_{\rm P}\ (z > 0.3) = 0.61 \pm 0.09$

WtG: $\beta_{\rm P}\ (z < 0.3) = 0.90 \pm 0.09 \quad \beta_{\rm P}\ (z > 0.3) = 0.71 \pm 0.07.$

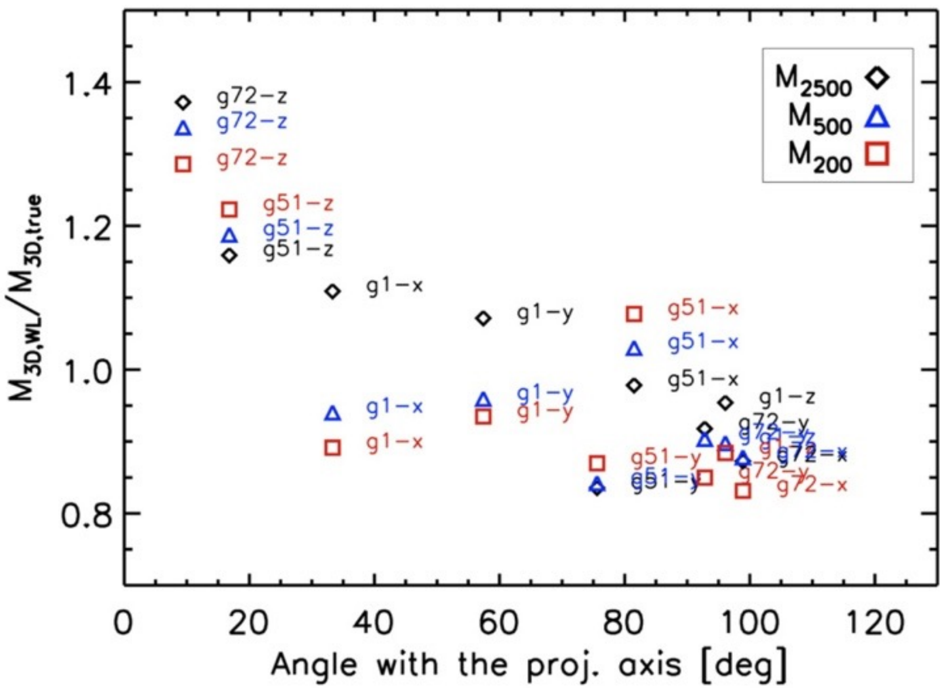
~30-40% bias at z>0.3

Local Cluster Substructure Survey

GPS, et al., 2016, MNRAS, 456, L74

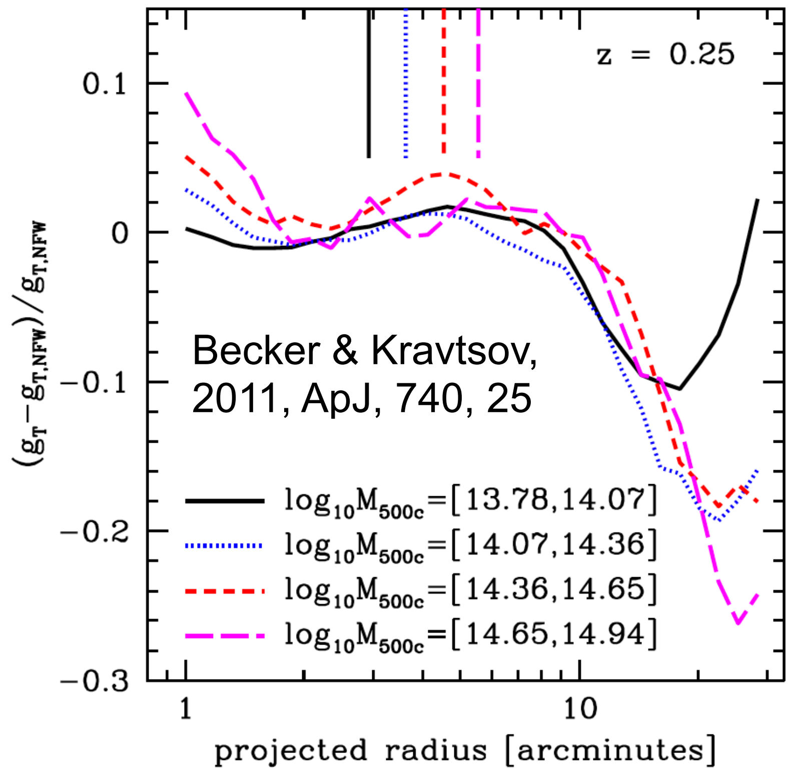
WL is intrinsically a <~5% bias, ~20% intrinsic scatter mass proxy

Fitting a spherical model to a shear profile biases the cluster mass depending on viewing angle through the (intrinsically triaxial) cluster



Meneghetti et al., 2010, A&A, 514, 93

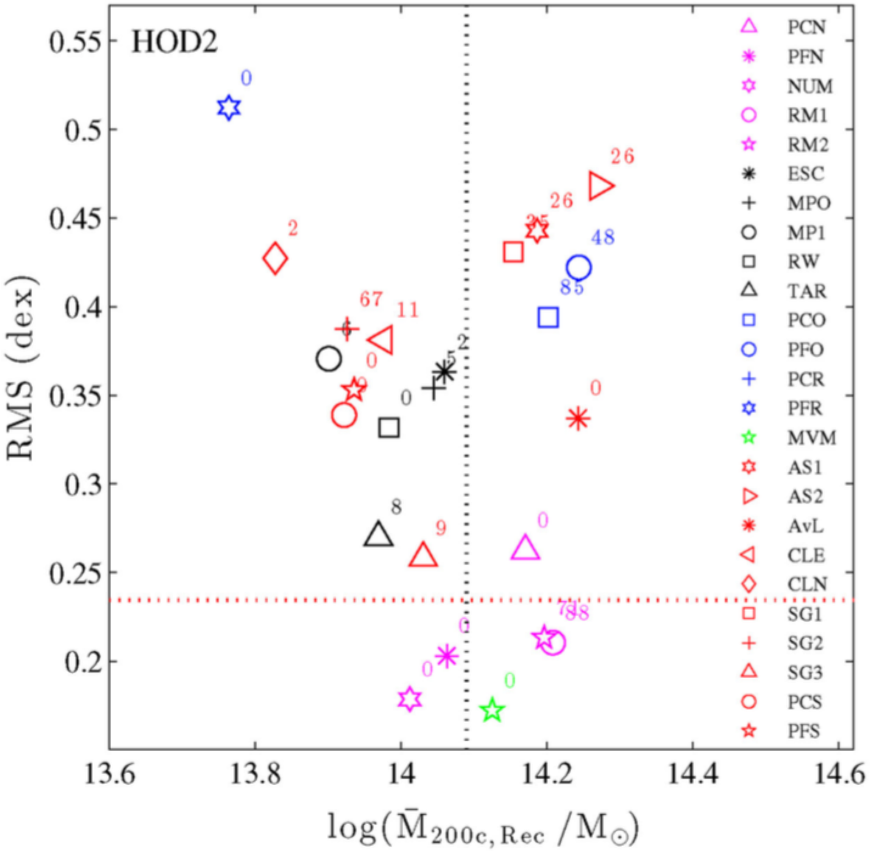
Careful choice of fitting radius and method can reduce the bias in a sample of clusters

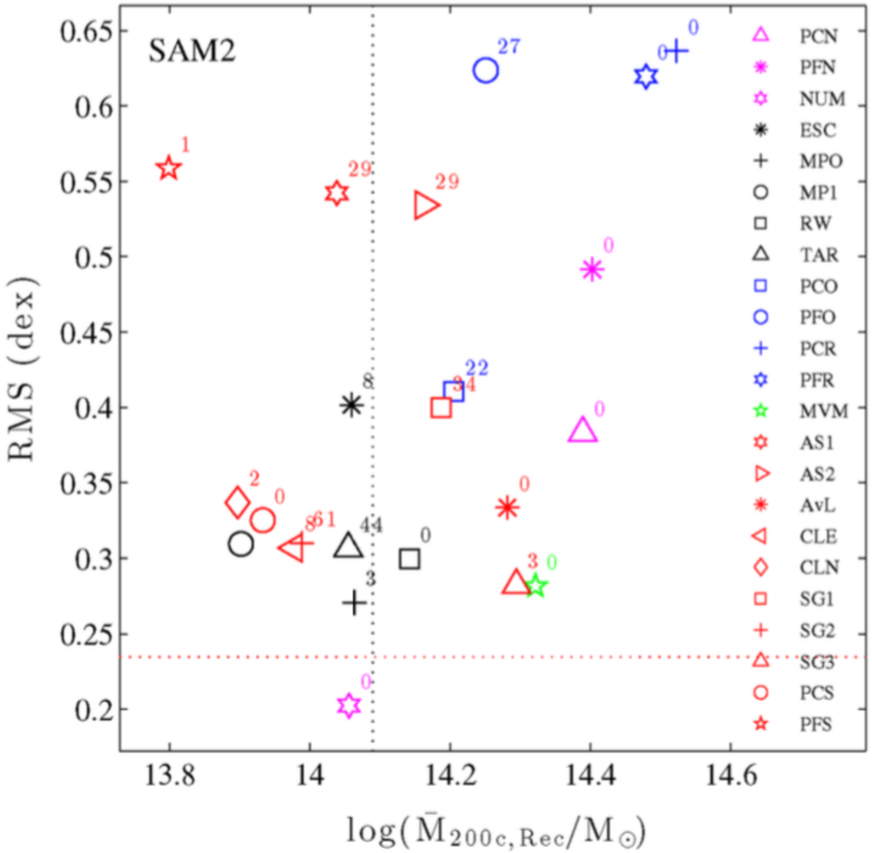


See also:

- Bahé et al., 2012, MNRAS, 421, 1073
- Okabe & GPS, 2016, MNRAS, 461, 3794

Dynamical methods are a ~60-100% scatter mass proxy

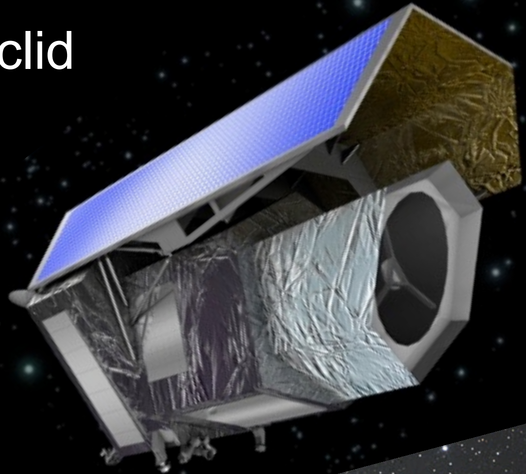




Old et al., 2015, MNRAS, 1897, 920

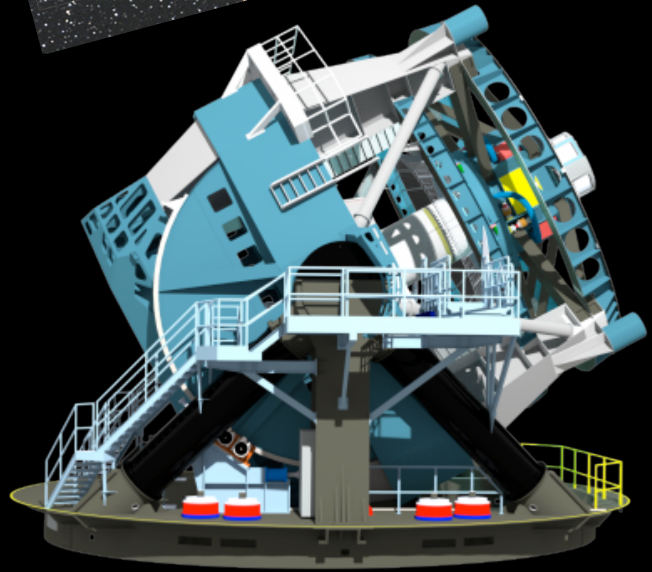
see also: Munari, **Biviano**, et al., 2013, MNRAS, 430, 2638; Caldwell, **McCarthy**, et al., 2016, MNRAS, 462, 4117; Farahi, **Evrard**, et al., 2016, MNRAS, 460, 3900

Euclid



e-ROSITA

LSST



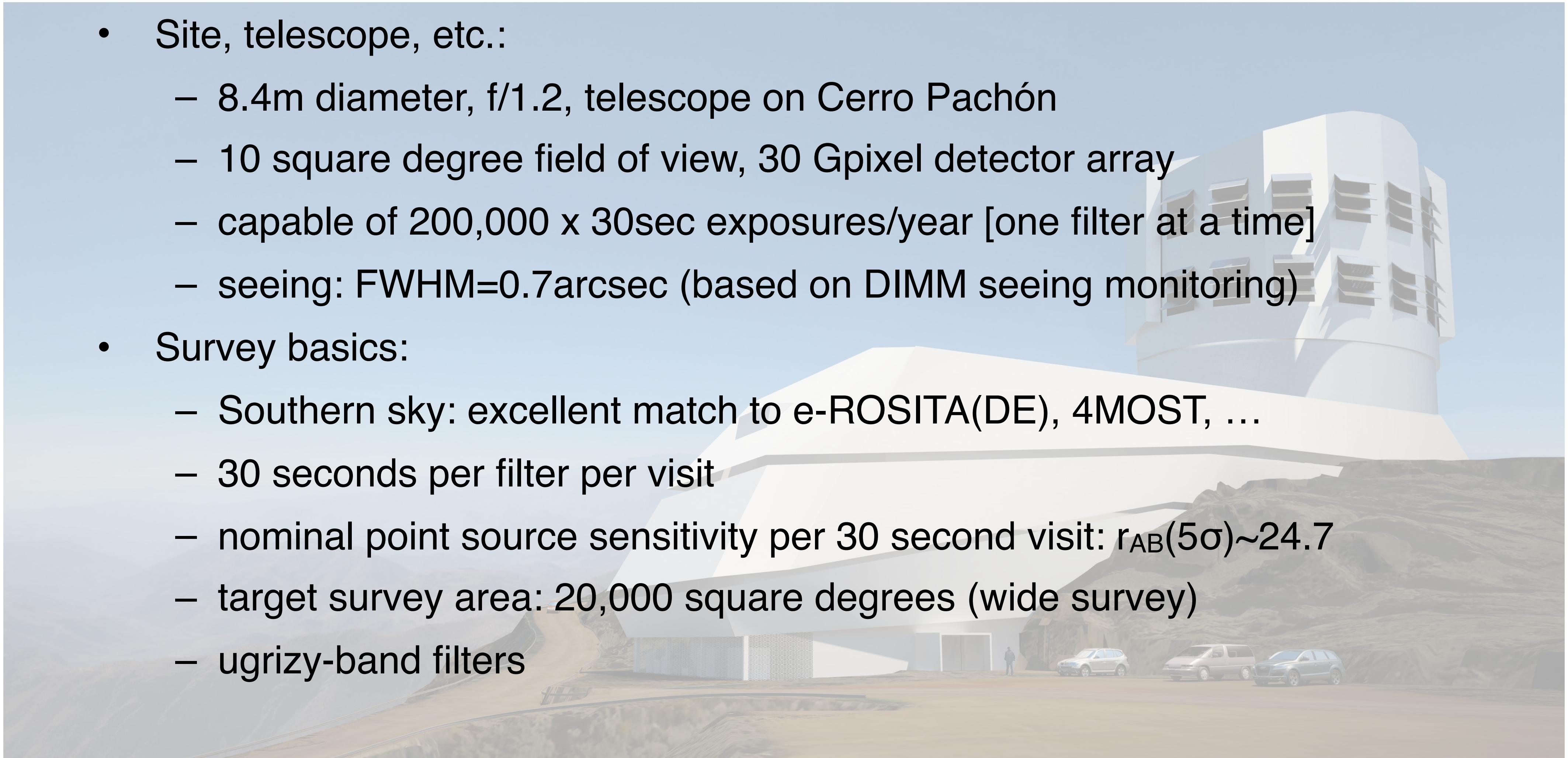
High quality optical data required for accurate mass calibration of “all-sky” cluster/group samples will come from **directly** from LSST and Euclid

X-ray data for testing hydrostatic equilibrium in groups and high-z clusters will rely on pointed follow-up observations

LSST Overview

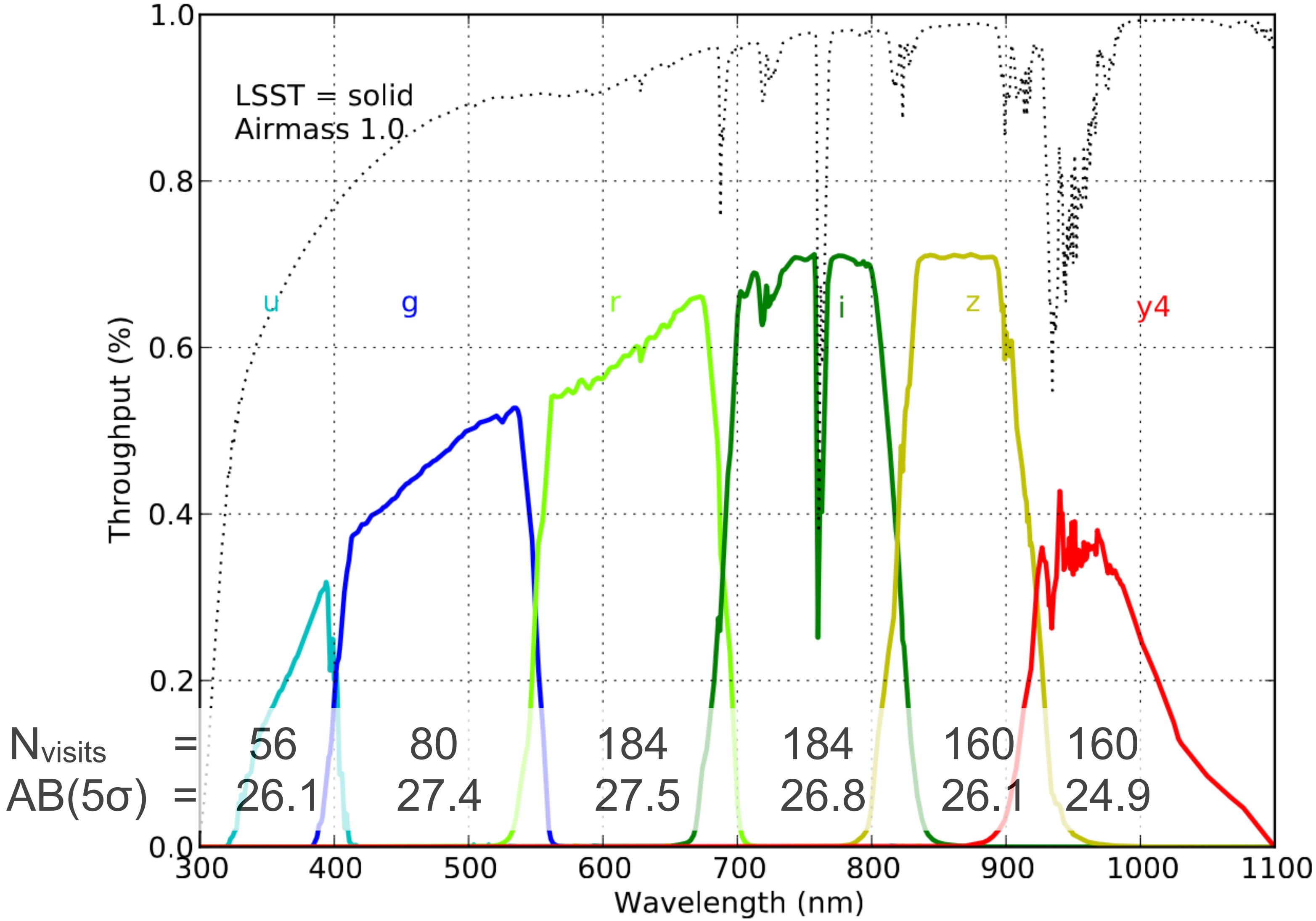
[based on Science Requirements Document July 2011]

- US-led project with growing list of international partners:
  - France, UK, China, Chile, Czech Republic, (South Africa?)
- Site, telescope, etc.:
  - 8.4m diameter, f/1.2, telescope on Cerro Pachón
  - 10 square degree field of view, 30 Gpixel detector array
  - capable of 200,000 x 30sec exposures/year [one filter at a time]
  - seeing: FWHM=0.7arcsec (based on DIMM seeing monitoring)
- Survey basics:
  - Southern sky: excellent match to e-ROSITA(DE), 4MOST, …
  - 30 seconds per filter per visit
  - nominal point source sensitivity per 30 second visit: $r_{AB}(5\sigma)\sim 24.7$
  - target survey area: 20,000 square degrees (wide survey)
  - ugrizy-band filters

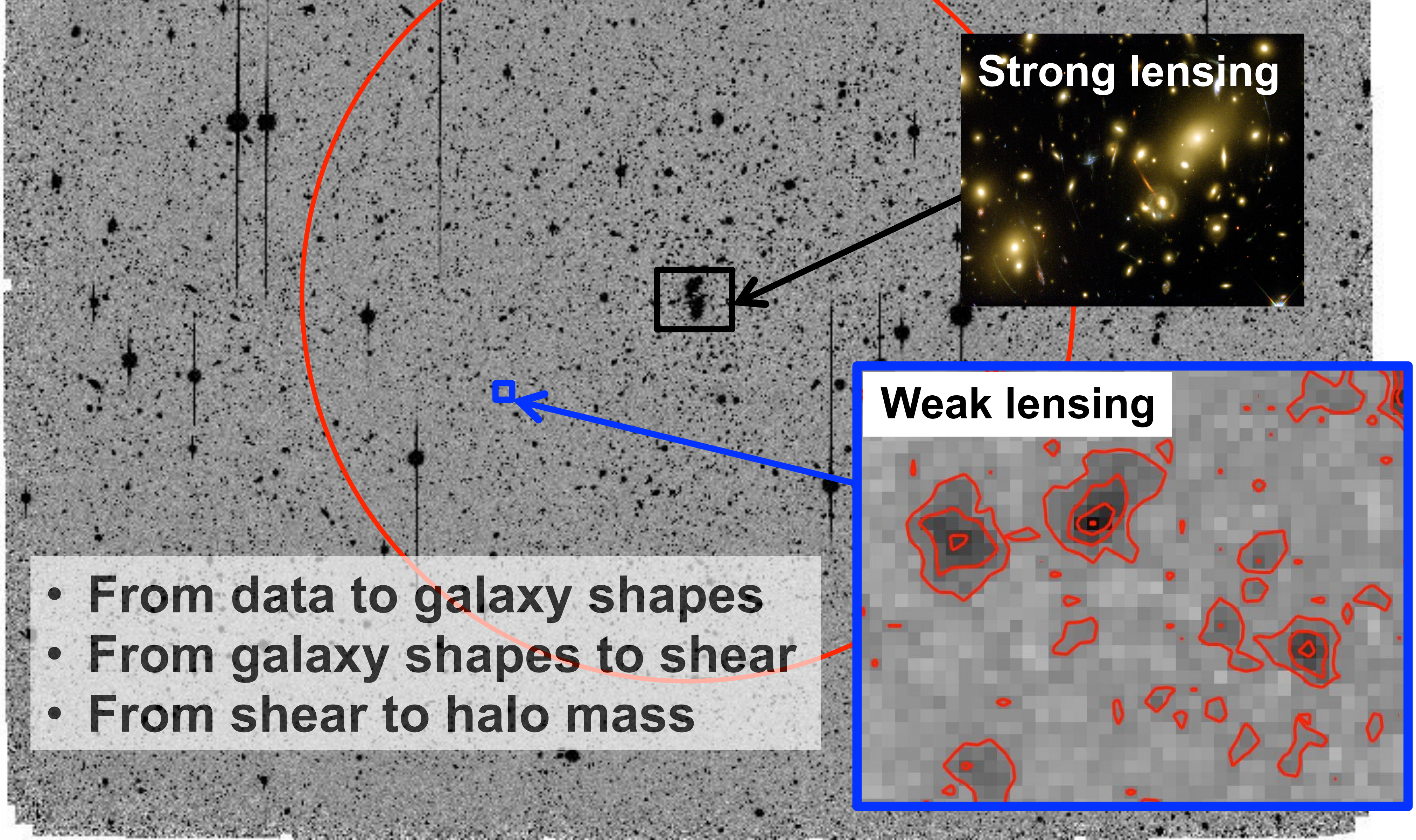


LSST Overview

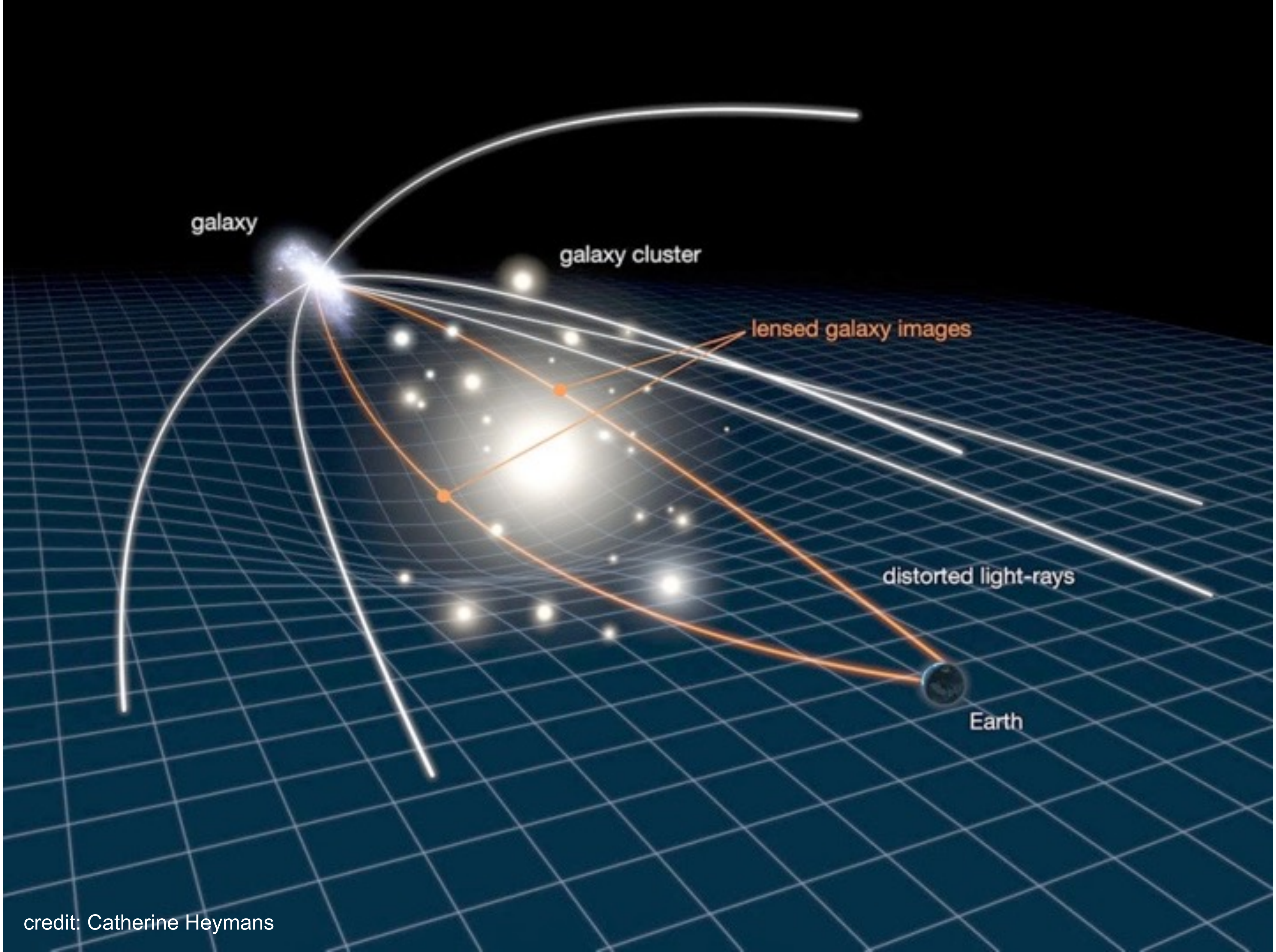
[based on Science Requirements Document July 2011]



Steps towards weak-lensing measurements of halo mass



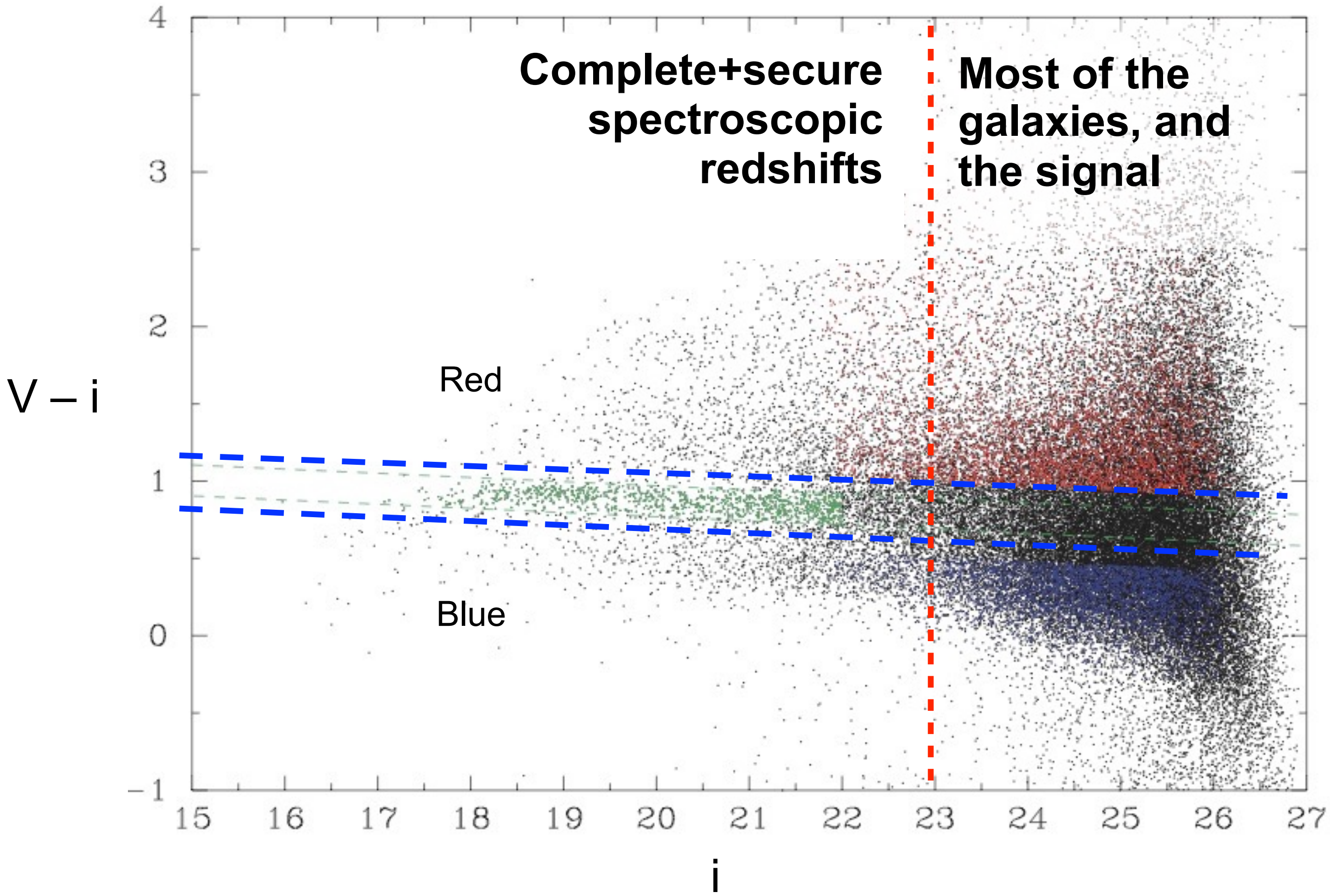
- From data to galaxy shapes
- From galaxy shapes to shear
- From shear to halo mass



credit: Catherine Heymans

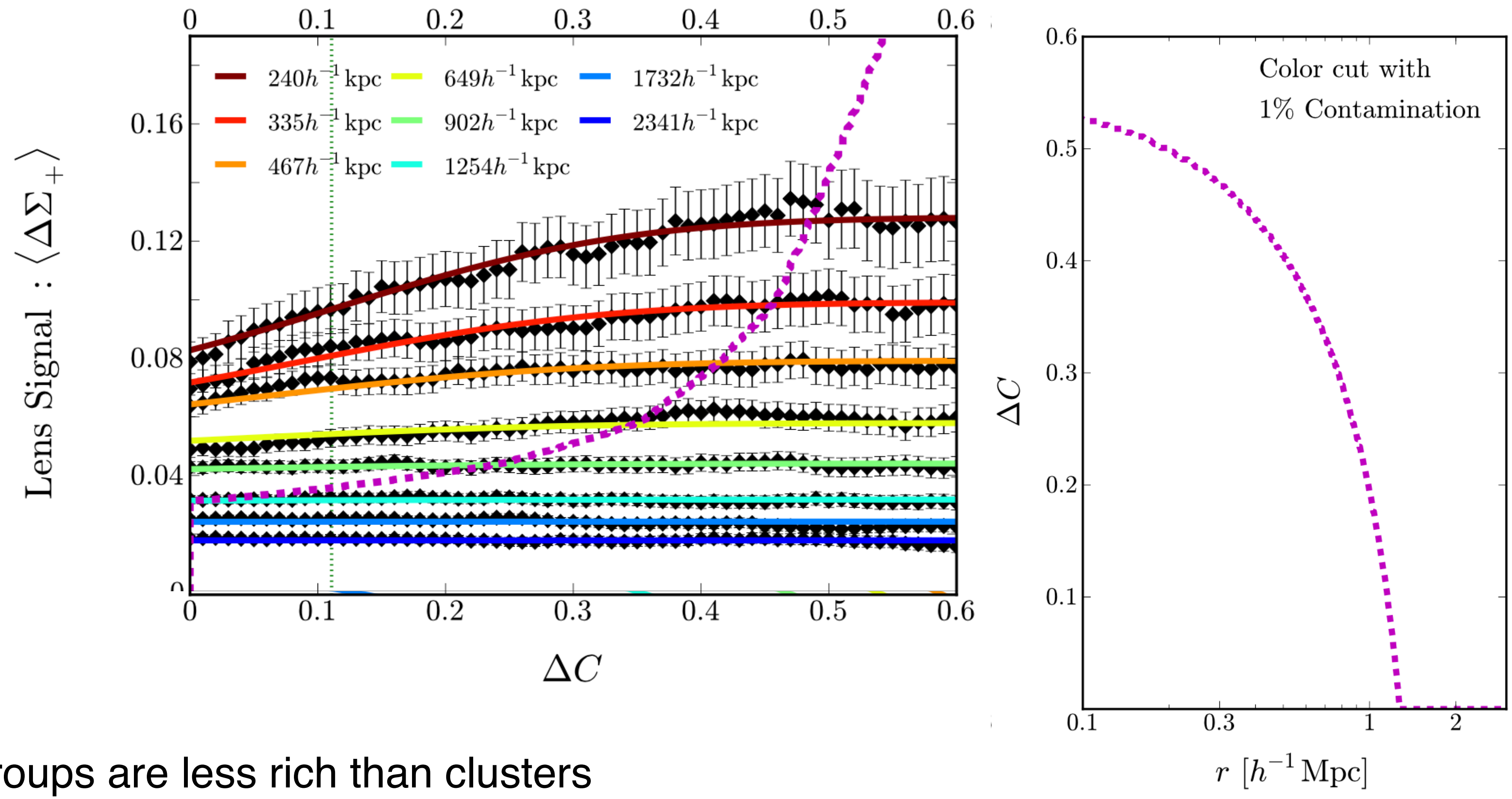
The achilles heal of weak-lensing for halo mass measurement…

It is a formidable challenge to estimate reliably the redshift of ~10^4 galaxies per cluster that are ~10x fainter than the spectroscopic completeness limit.



adapted from Okabe et al., (2010)

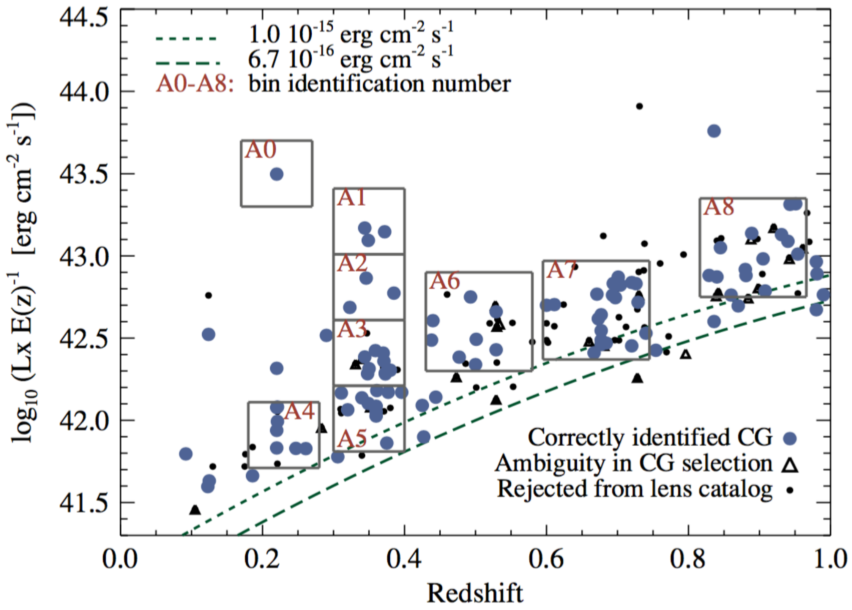
Using shear signal and richness to select background galaxies

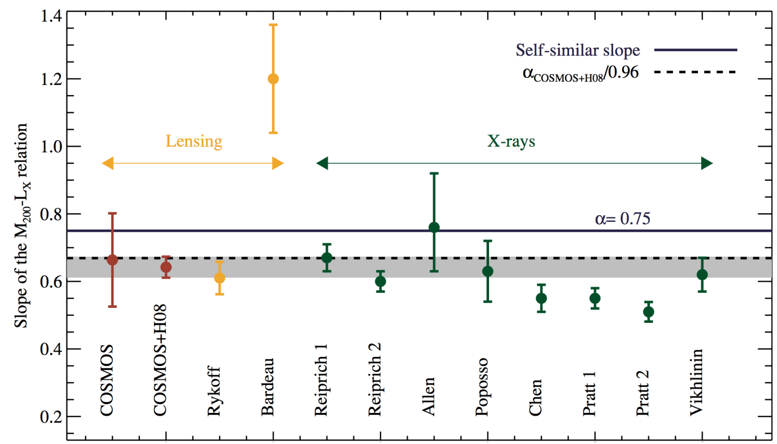


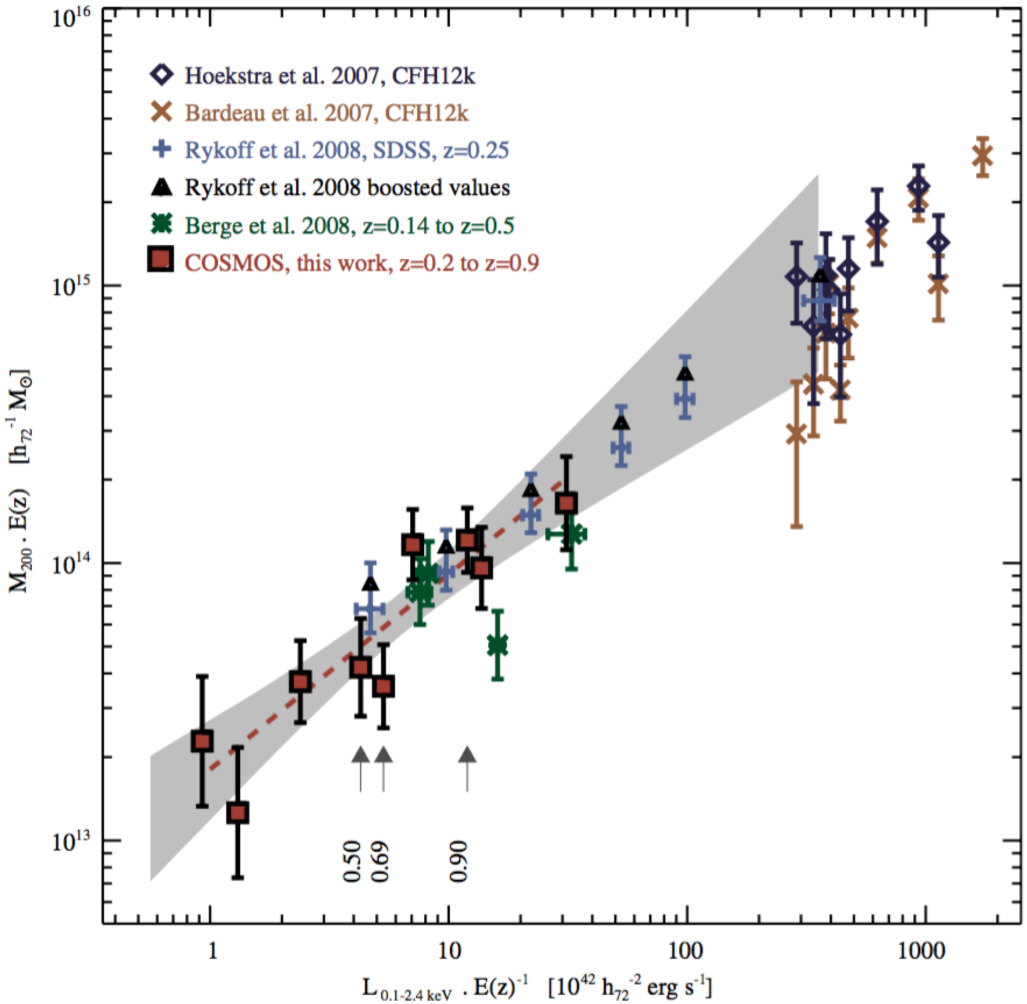
Groups are less rich than clusters
⇒ richness-based background galaxy selection could be promising for group WL studies

Okabe & GPS, 2016, MNRAS, 461, 3794

The first weak-lensing mass calibration of galaxy groups

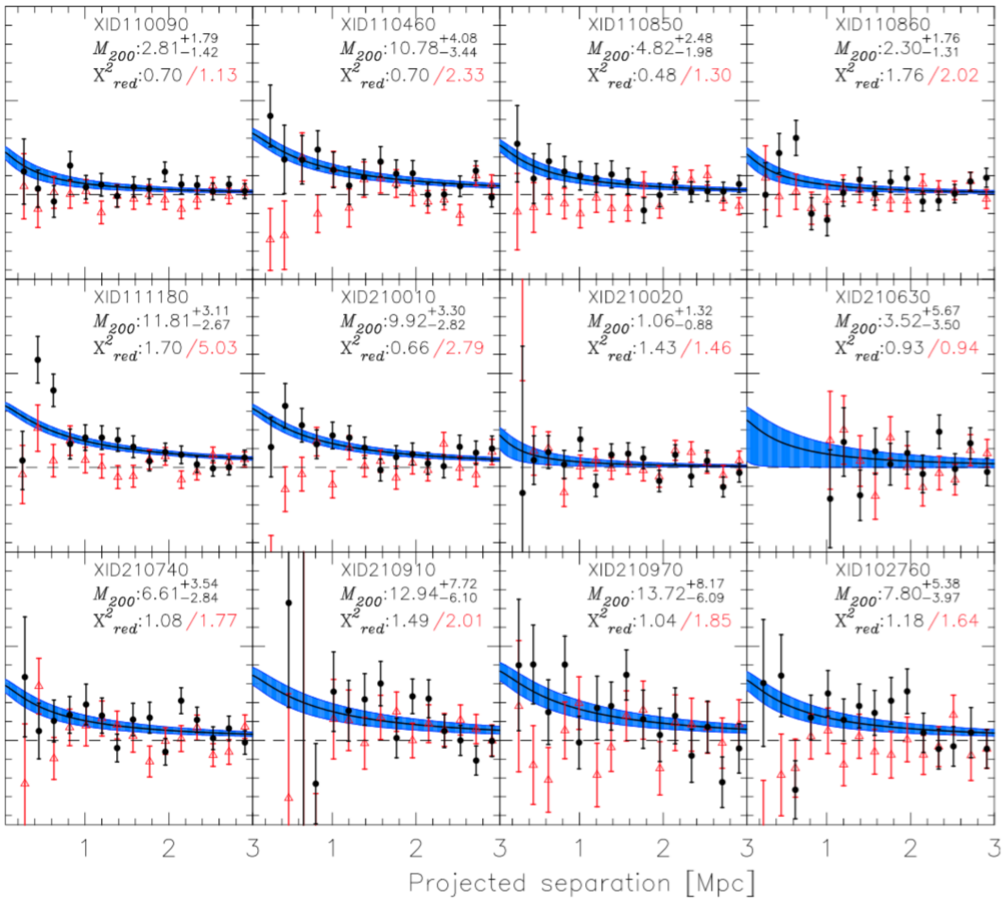


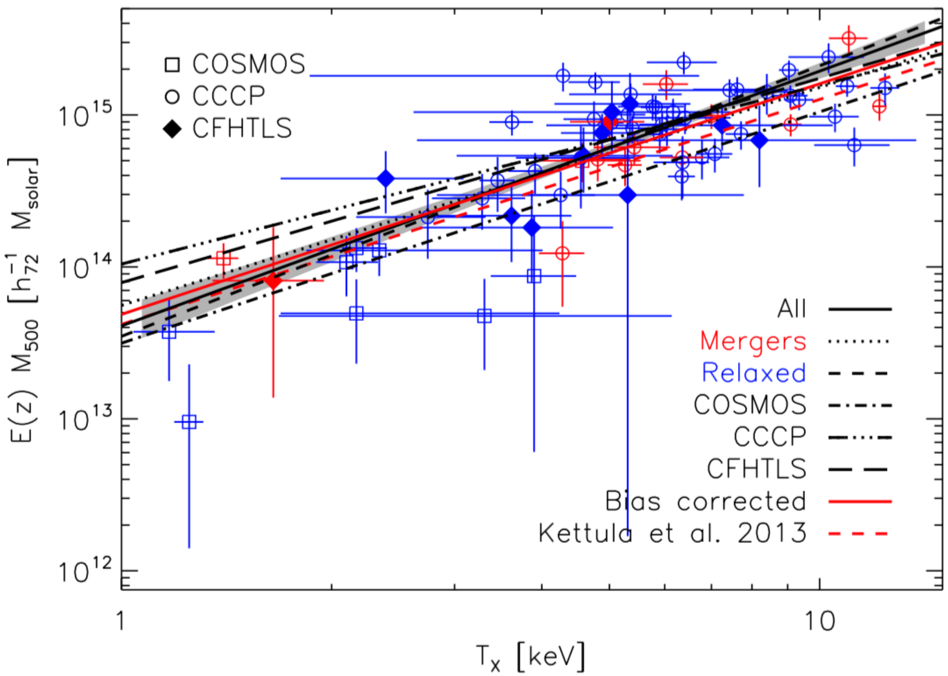




Leauthaud et al., 2010, ApJ, 709, 97

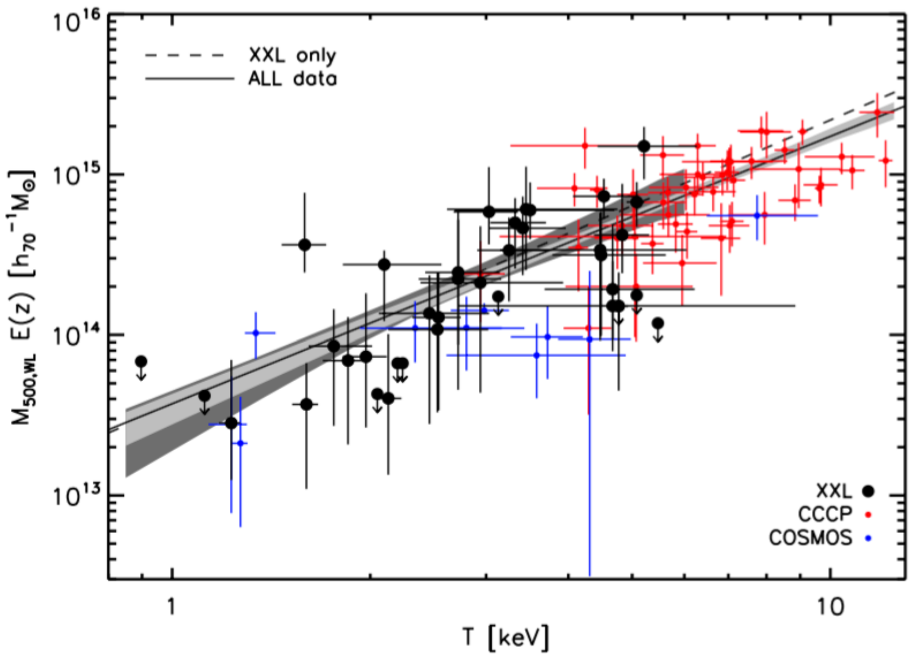
The (first and) second weak-lensing M-T relation of groups



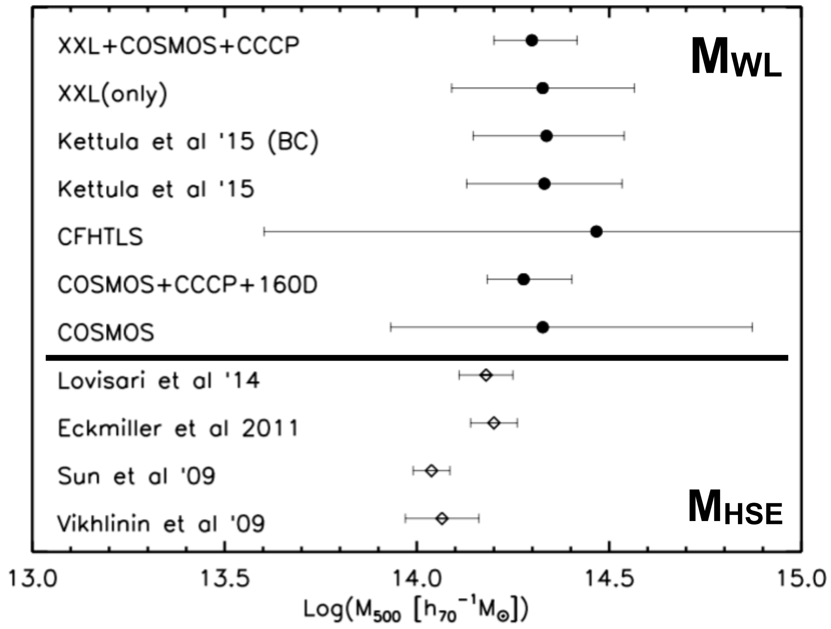


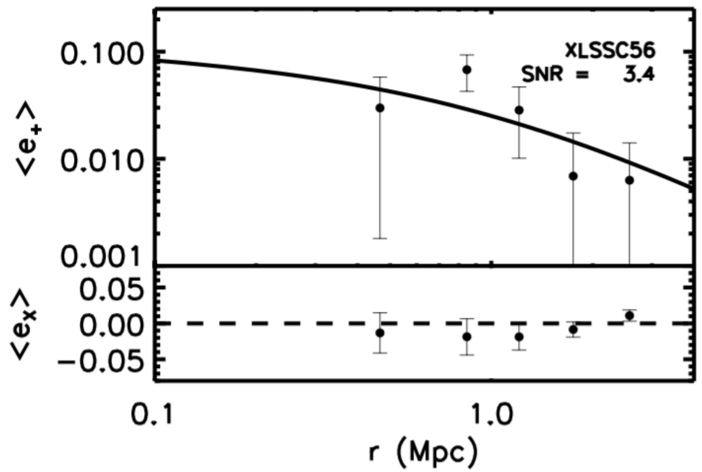
Kettula et al., 2015, MNRAS, 451, 1460
see also Kettula et al., 2013, ApJ, 778, 74

Largest weak-lensing calibrated sample of groups and clusters



Mass of a 3keV "group"

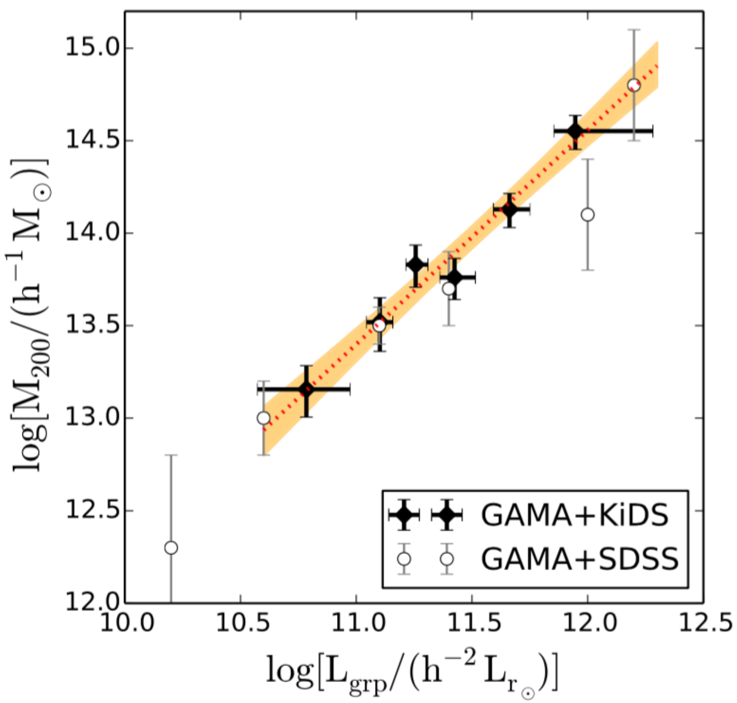


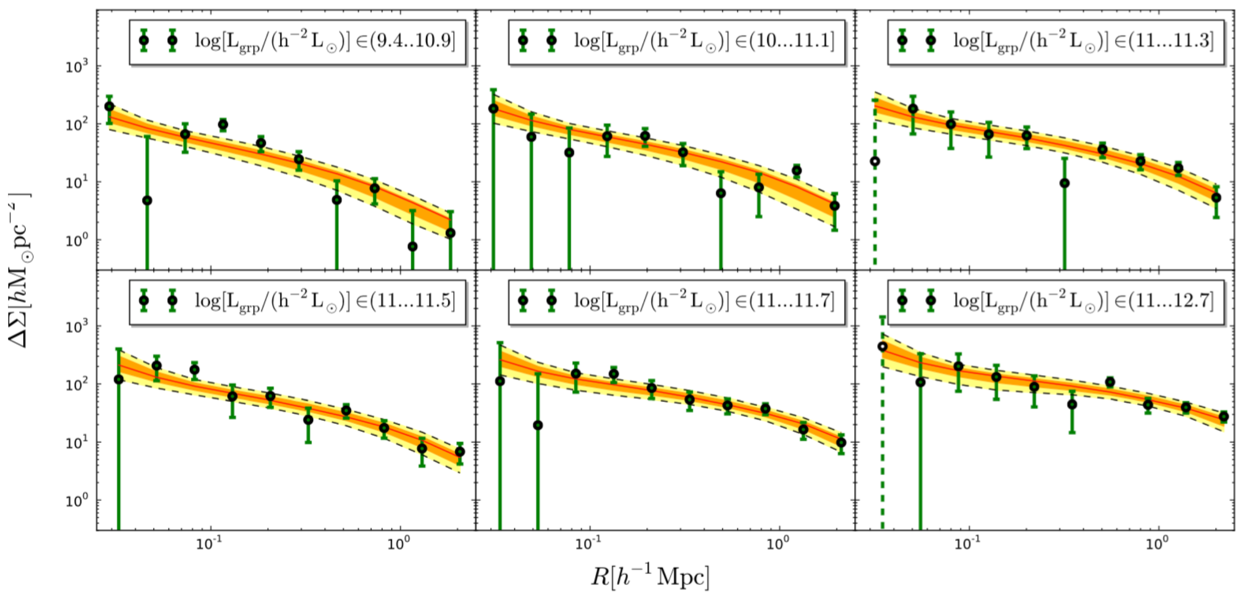


Difference in mass of a 3keV "group" between X-ray and WL studies suggests hydrostatic bias of ~30%

Lieu, GPS, et al., 2016, A&A, 592, A4
see also Eckert et al., 2016, A&A, 592, A12

A forerunner of LSST science from KiDS…





Kilo Degree Survey (KIDS)

750 degree^2 in ugri-bands with OmegaCAM on VST

http://kids.strw.leidenuniv.nl/index.php

Stacked weak-lensing density profiles and masses of 1400 optically-selected groups

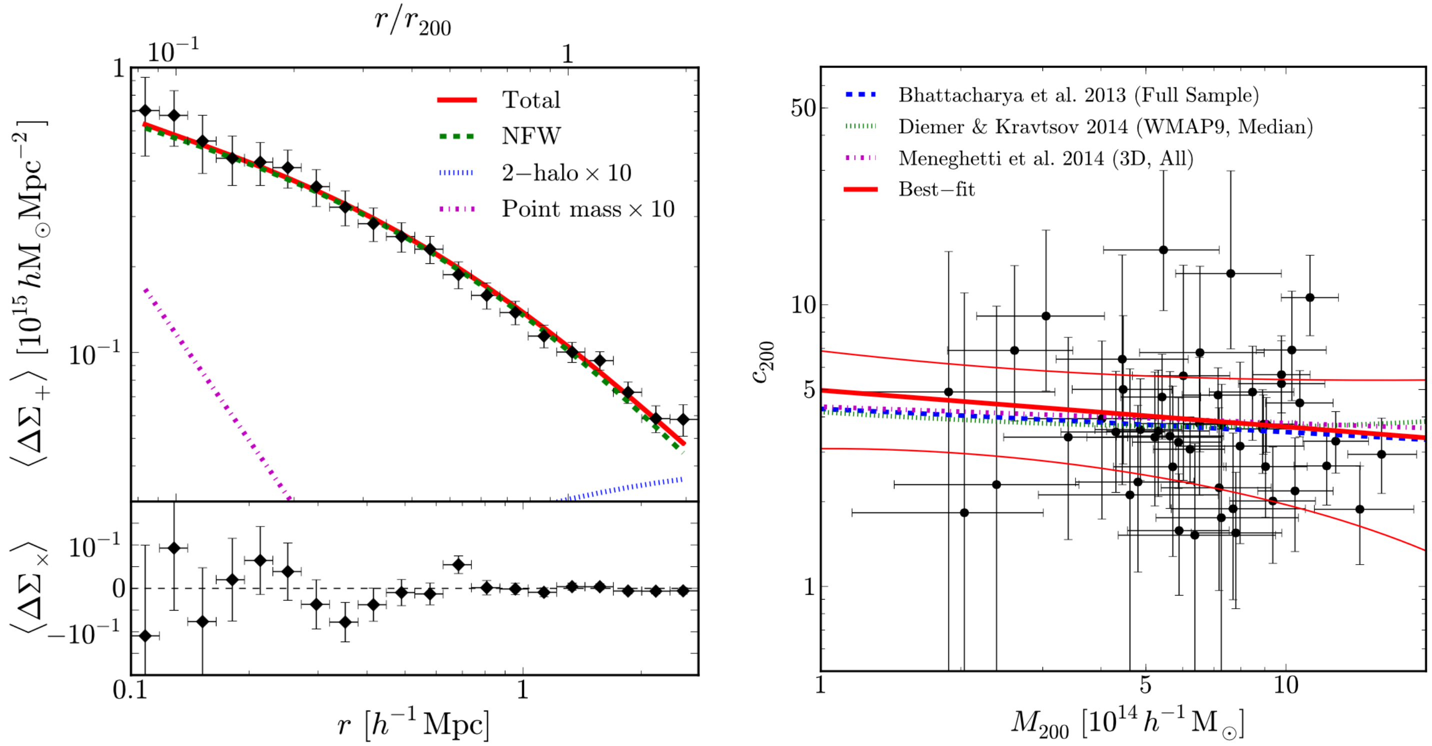
Groups from GAMA; WL data from KiDS

Density profiles agree with NFW and M-L relation is consistent with linear

Viola et al., 2015, MNRAS, 452, 3529

see also van Uitert et al., arXiv:161004226

WL studies rarely break the mass-concentration degeneracy with data



LoCuSS:

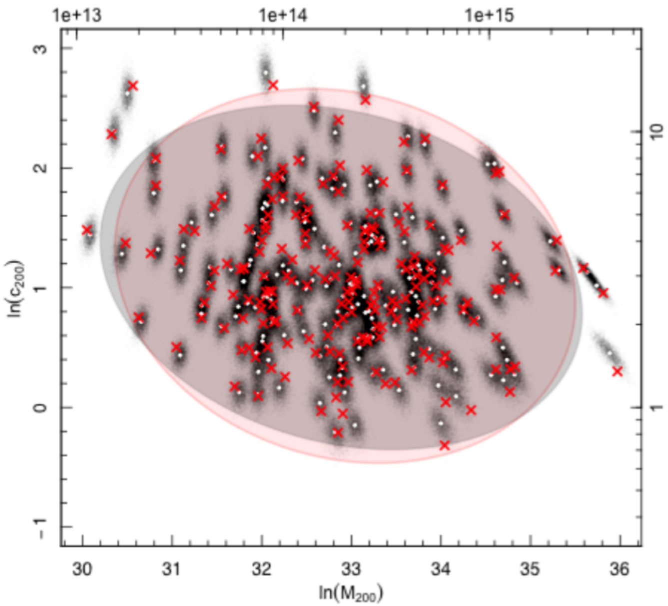
- WL-based mass-concentration relation with 13 background galaxies arcmin^{-2} (Okabe & GPS, 2016, MNRAS, 461, 3794) [see also CLASH papers]

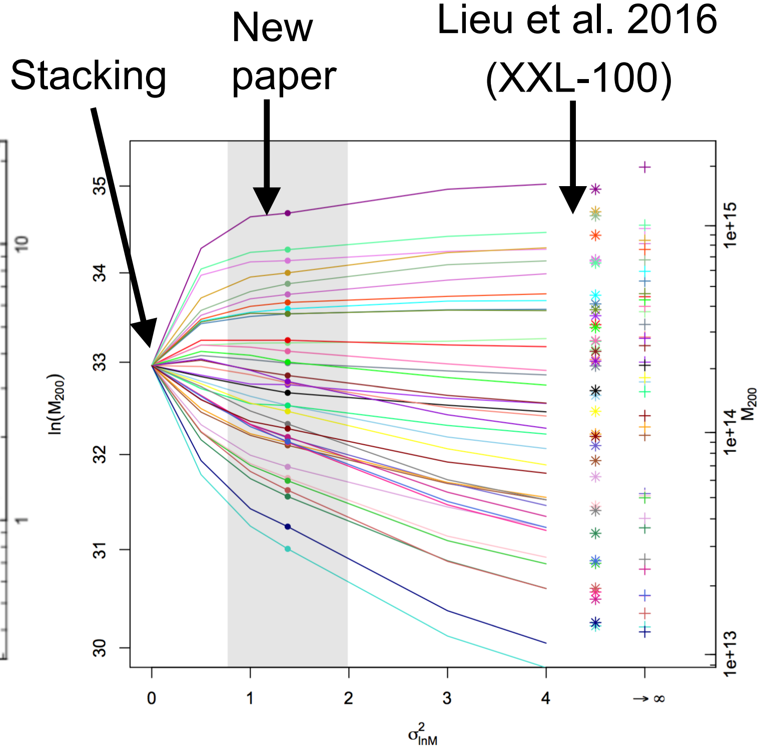
Typical cluster/group weak-lensing studies:

- 5-10 galaxies arcmin^{-2}, assume concentration is constant (WtG), adopt a (zero scatter) mass-c relation (CCCP, XXL, CFHTLS), stack the signal (KIDS, COSMOS)

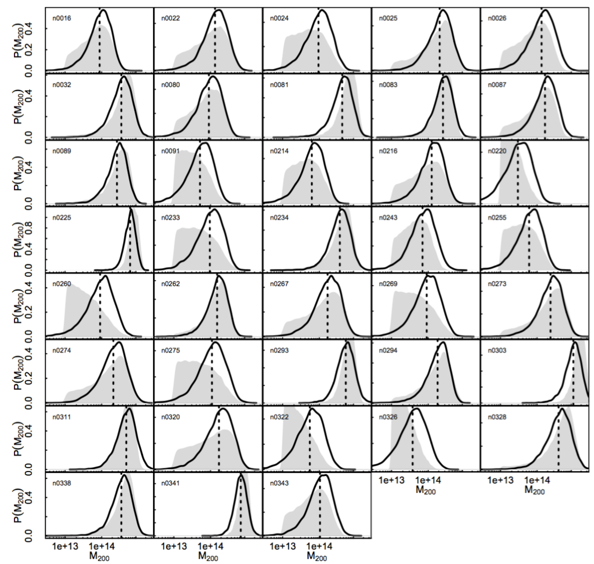
Simultaneous fitting of shear profiles and mass-c relation

Performs well on simulated data: red vs black





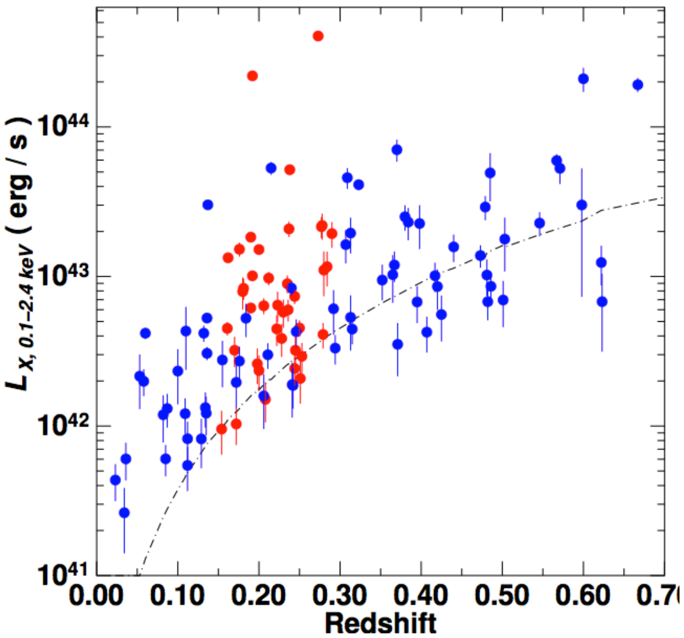
Simultaneous fitting of population improve posteriors on mass for low-SNR groups

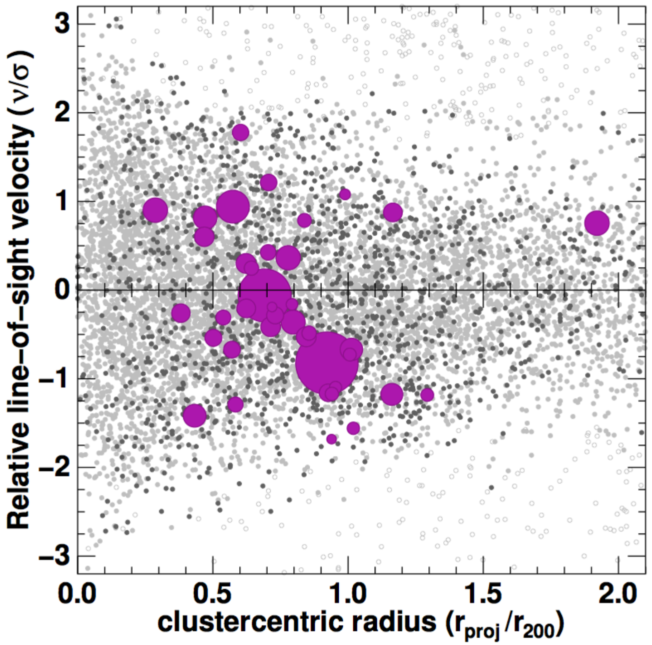


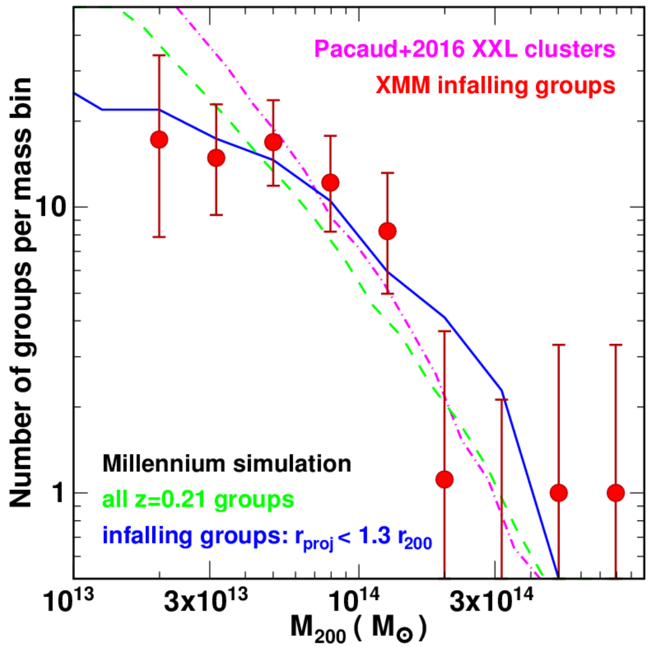
- Forward hierarchical modeling of individual shear profiles, and mass-c relation of the population from a mass function at fixed cosmology
- Avoids strong assumptions on mass-concentration relation
- Avoids stacking: $\sigma_{\ln M}^2$ controls level of reliance on the population

Lieu, Farr, Betancourt, GPS, McCarthy, Sereno, in prep.

The LoCuSS Groups Sample

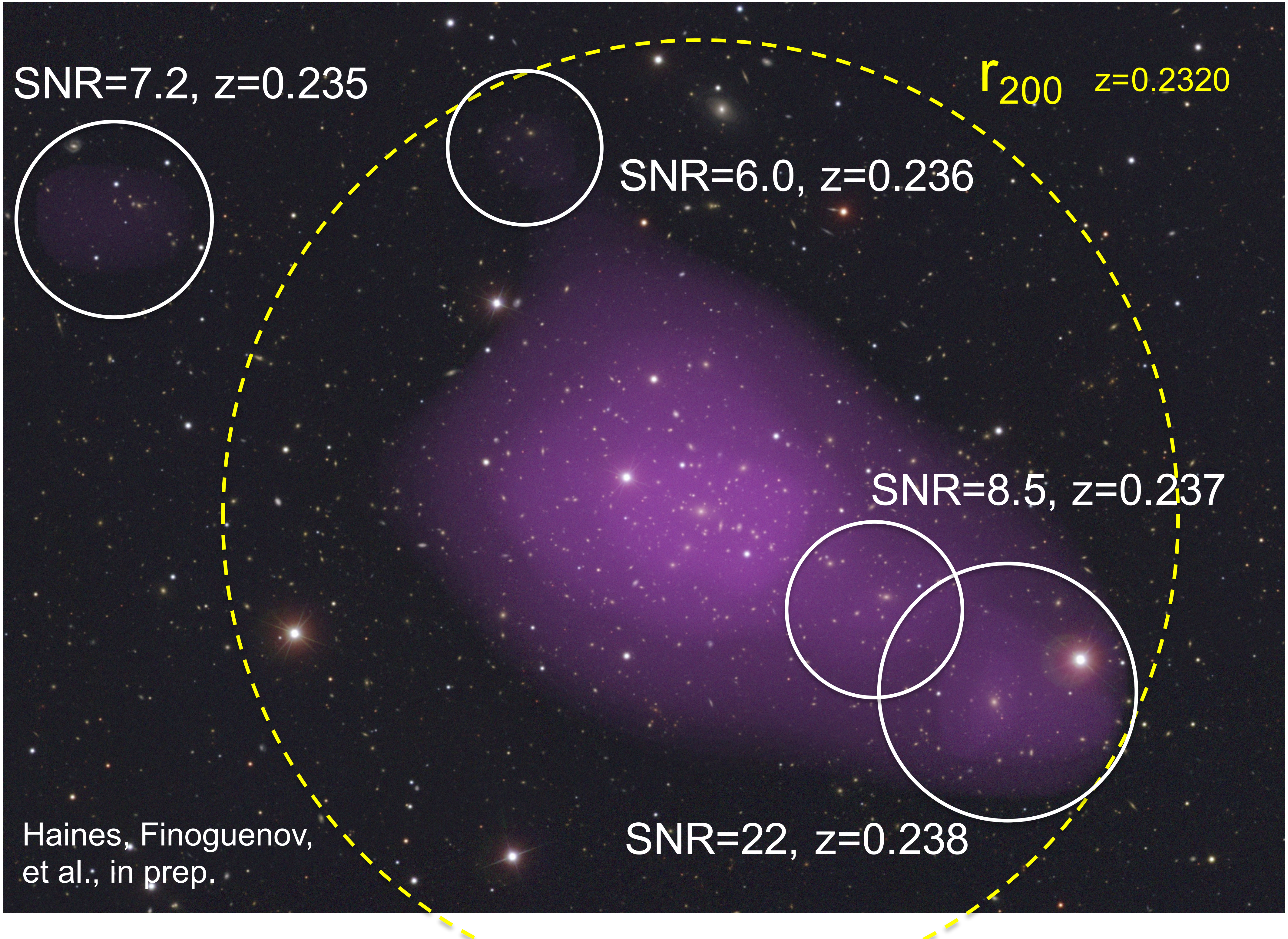






- 23 clusters at 0.15<z<0.3 from the LoCuSS sample with deep XMM data (and rich dataset from Hectospec, Subaru, Herschel, Spitzer, GALEX)
- 39 spectroscopically confirmed, X-ray selected, infalling groups
- preliminary mass function consistent with infalling groups from Millennium
- lots of potential to investigate galaxy evolution and physics of infalling groups

Haines, Finoguenov, et al., in prep.


SNR=7.2, z=0.235
SNR=6.0, z=0.236
r200
z=0.2320
SNR=8.5, z=0.237
SNR=22, z=0.238
Haines, Finoguenov,
et al., in prep.

- Absolute mass calibration of groups and clusters must place minimum reliance on physics in simulations
  - weak-lensing delivers a low bias and ~20% scatter absolute calibration of clusters; looks promising for groups!
  - in principle dynamical masses are promising, but scatter is very large (see Gary and Lindsay's talks)
  - X-ray masses only useful for testing HSE
- Large solid angle optical/near-IR surveys (ongoing, and LSST, Euclid) will provide the weak-lensing data "for free"
- Promising avenues to explore:
  - test weak-lensing mass measurement on numerical simulations down to $10^{13}M_{\odot}$
  - richness-based background galaxy selection methods for groups
  - deep pointed X-ray observations of groups with existing high quality weak-lensing data
  - forward modelling of shear profiles and scaling relations including mass-concentration relation


The end