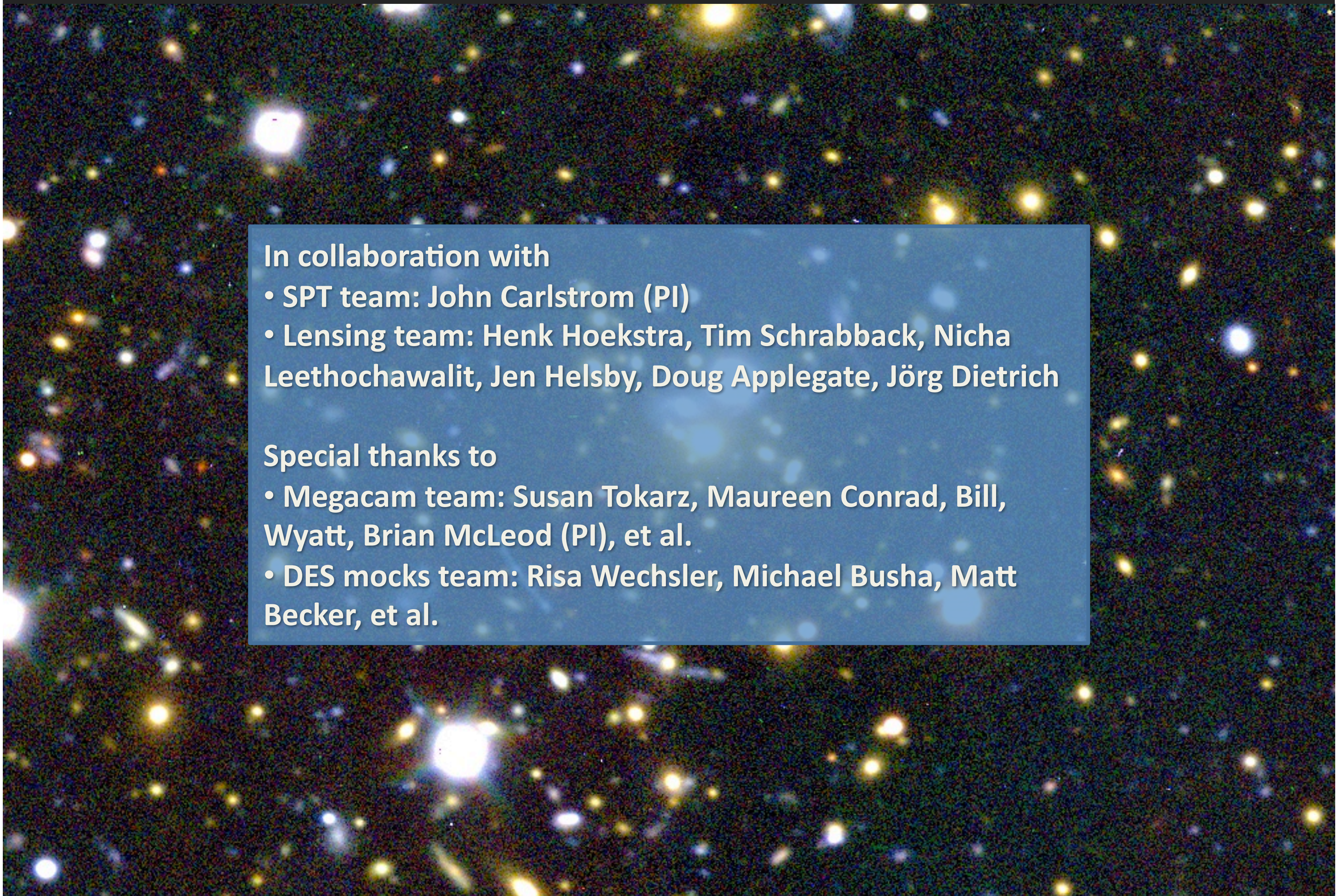
Weak lensing masses of SZ selected clusters from the South Pole Telescope survey

Will High
U. Chicago and KICP

Fall 2012



In collaboration with

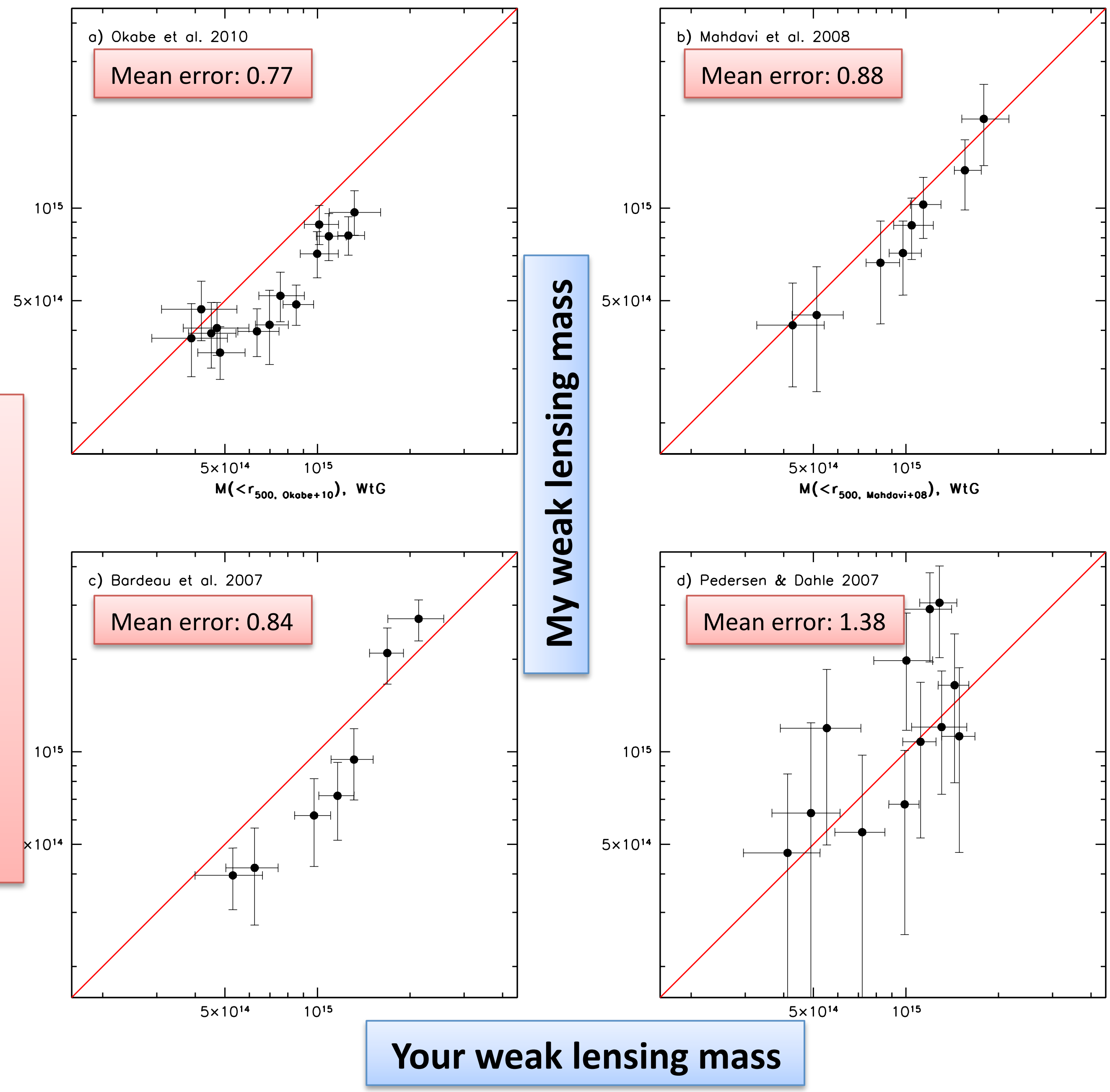
- SPT team: John Carlstrom (PI)
- Lensing team: Henk Hoekstra, Tim Schrabback, Nicha Leethochawalit, Jen Helsby, Doug Applegate, Jörg Dietrich

Special thanks to

- Megacam team: Susan Tokarz, Maureen Conrad, Bill, Wyatt, Brian McLeod (PI), et al.
- DES mocks team: Risa Wechsler, Michael Busha, Matt Becker, et al.

Weak lensing cluster masses are in flux

Applegate et al. (2012)



What causes this?

- Choice of cluster center
- Cluster galaxy (de)contamination
- Shear calibration
- NFW concentration
- Source redshift distribution
- N-body calibration
- …

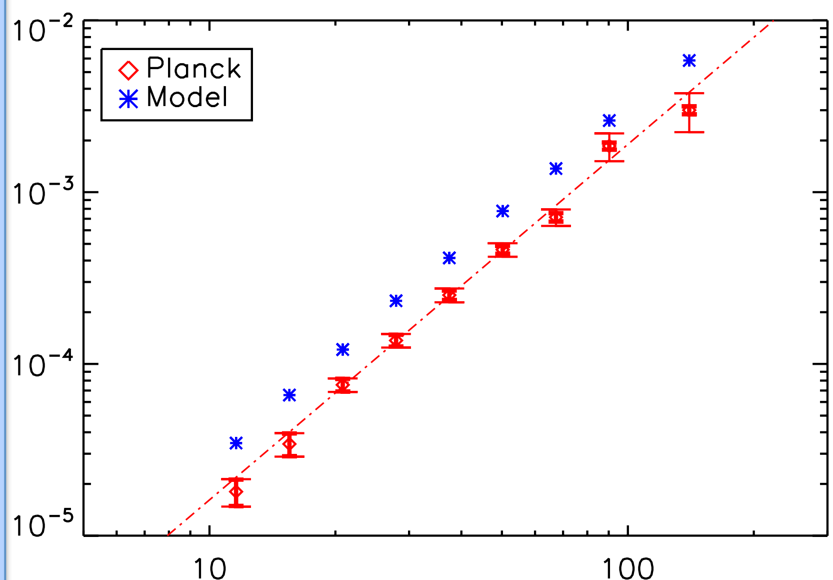
Weak lensing cluster masses are in flux

What causes this?

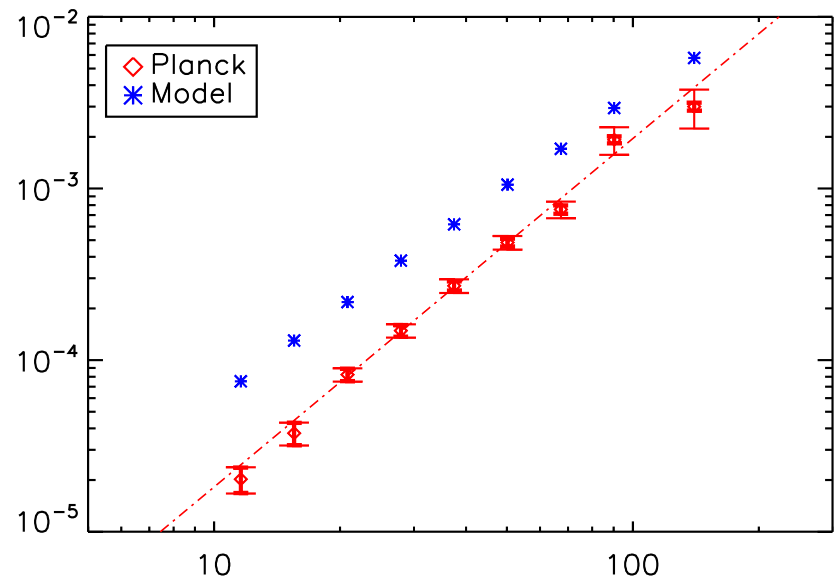
It's not just weak lensing. Systematic errors in X-ray, SZ, and O/IR mass-observables propagate through the system to create (or hide) discrepancies. *Lesson: calibrate mass-observables jointly in fully self-consistent way.* ***If you do this, you find the field is in a significantly worse state than stated systematic errors in previous published works would have you believe.***

Planck Early Results XII (2011)

An observable that scales with mass



Your mass calibrated to weak lensing

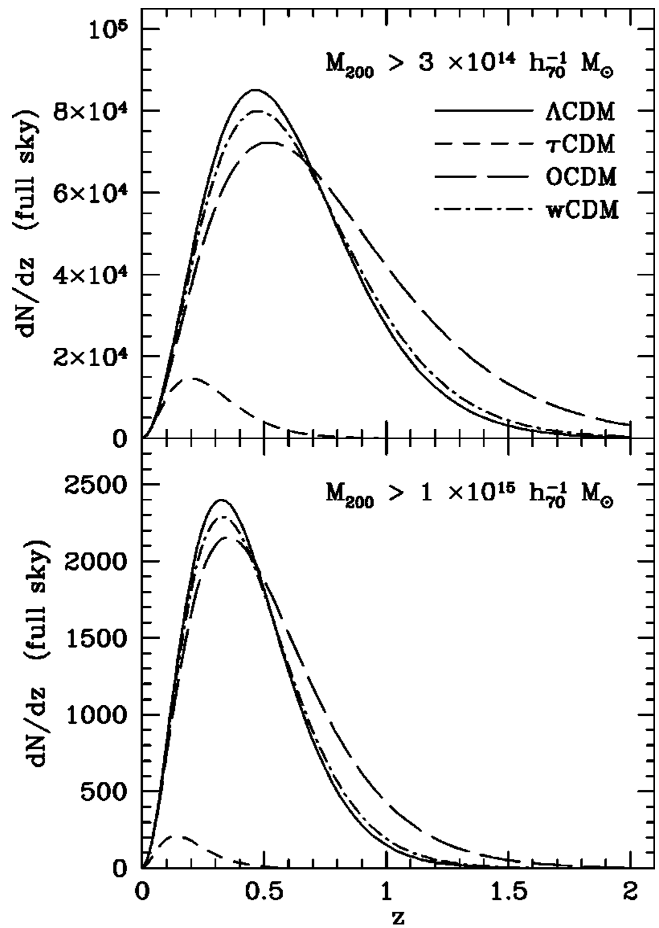


My mass calibrated to weak lensing

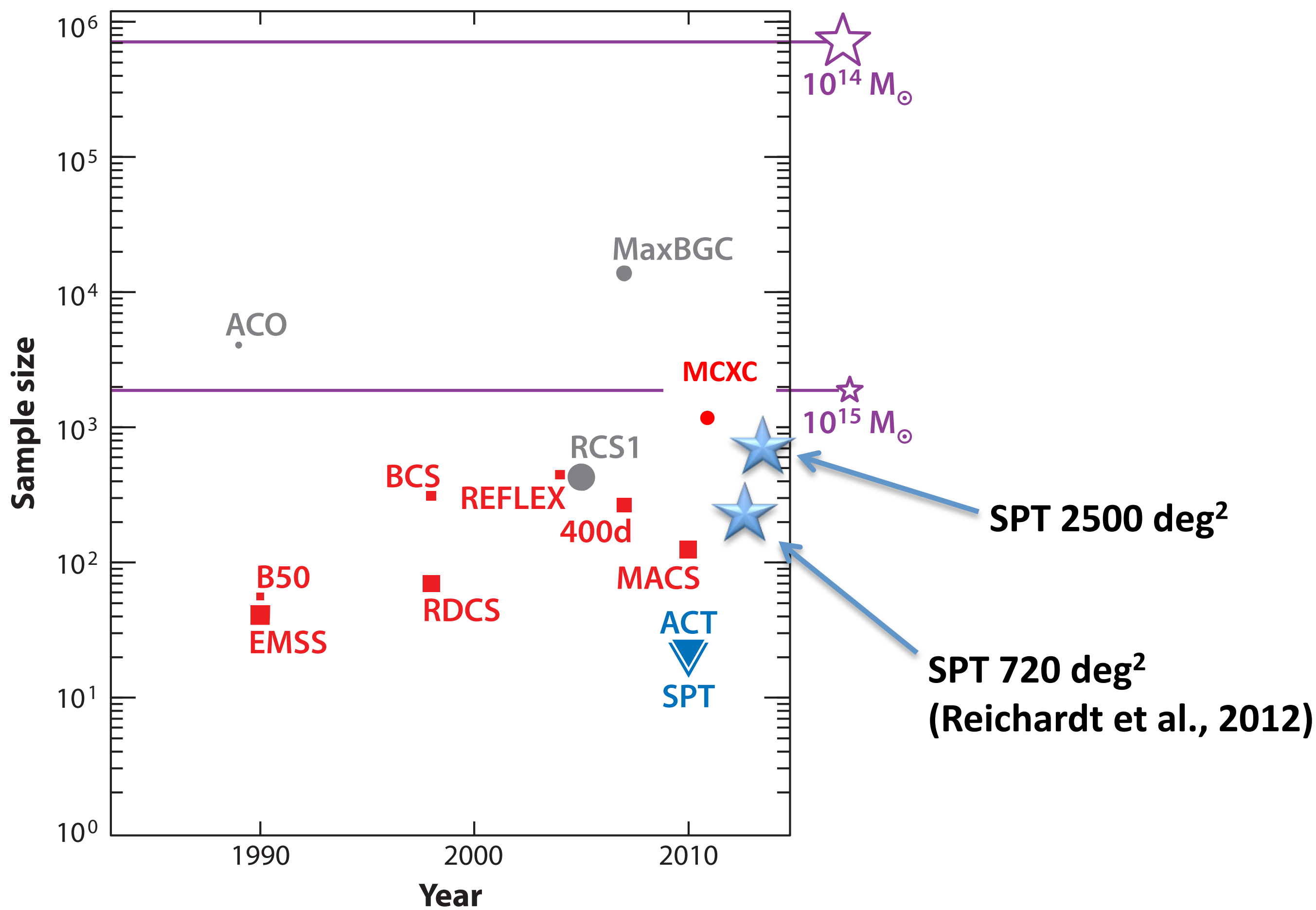
Cluster-abundance cosmology

- Cosmological parameters:
  - Dark energy equation of state: $w = P/\rho$
  - Other ΛCDM extensions: f_{NL}, Σm_ν
- Dominant systematic uncertainty in w constraints is cluster mass
- <u>Absolutely critical</u> to have empirical measurements of total mass:
  - Must not rely entirely on N-body sims
  - Weak lensing is one of only a few direct measures of total mass
  - *Close the loop: tie to N-body simulations with realism, because that's where the mass function comes from*

Voit (2005)

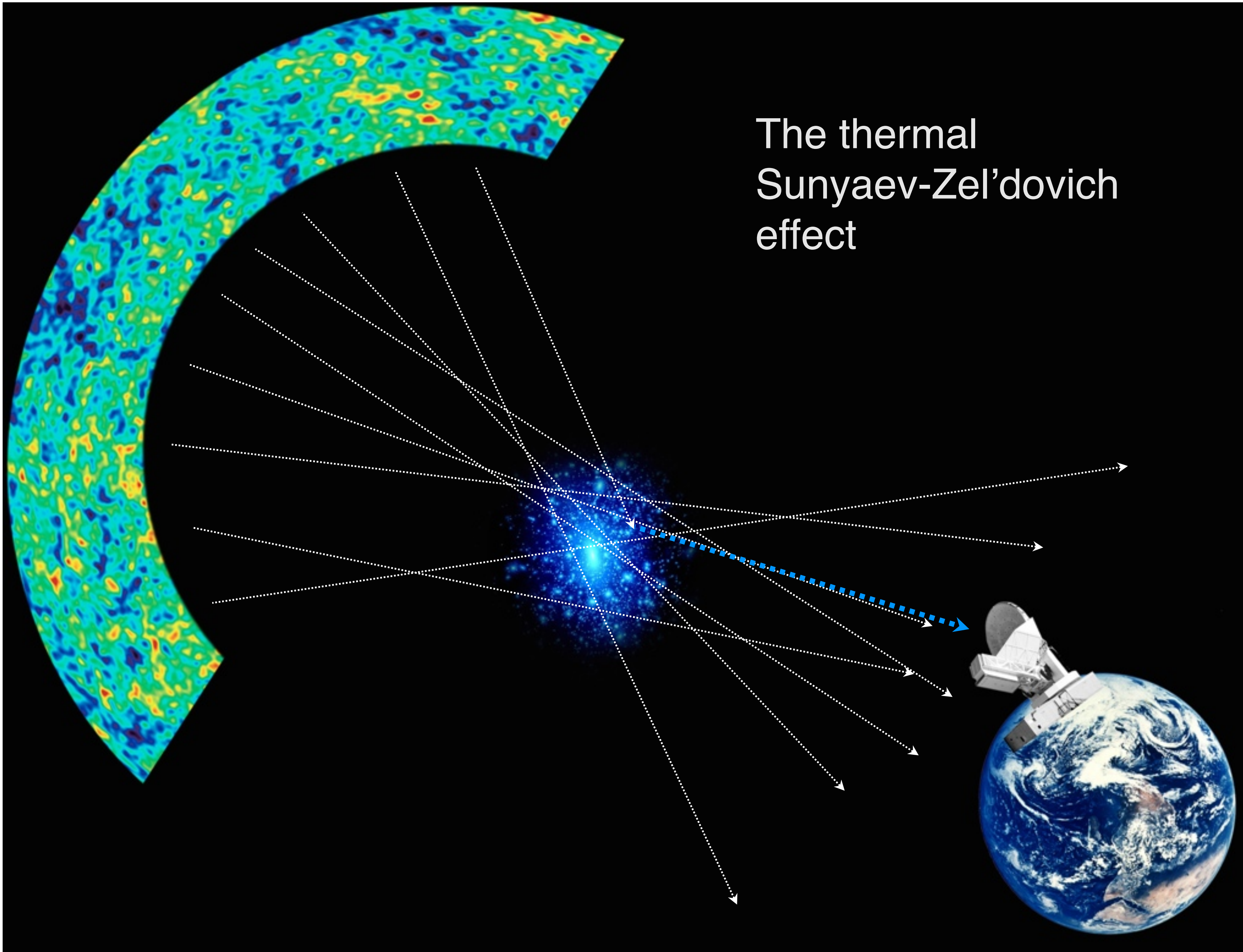


Cluster surveys

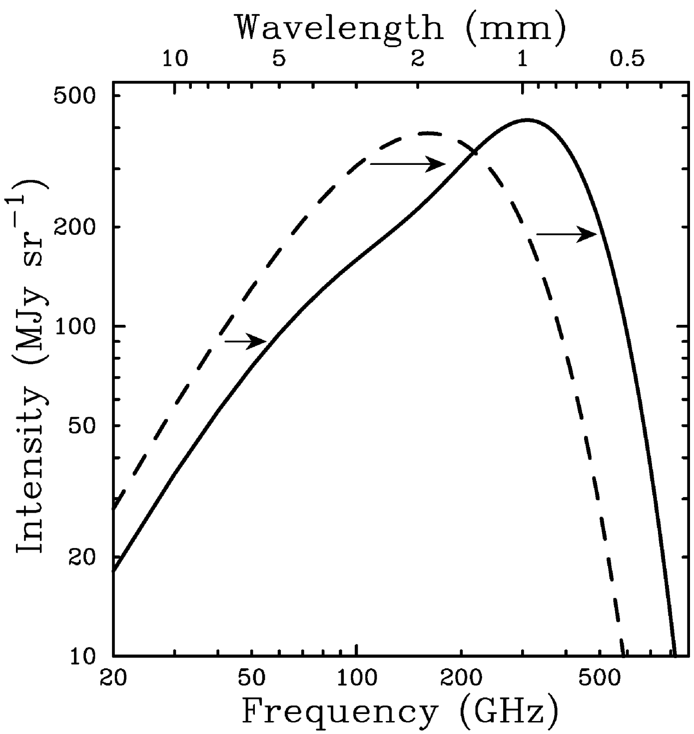


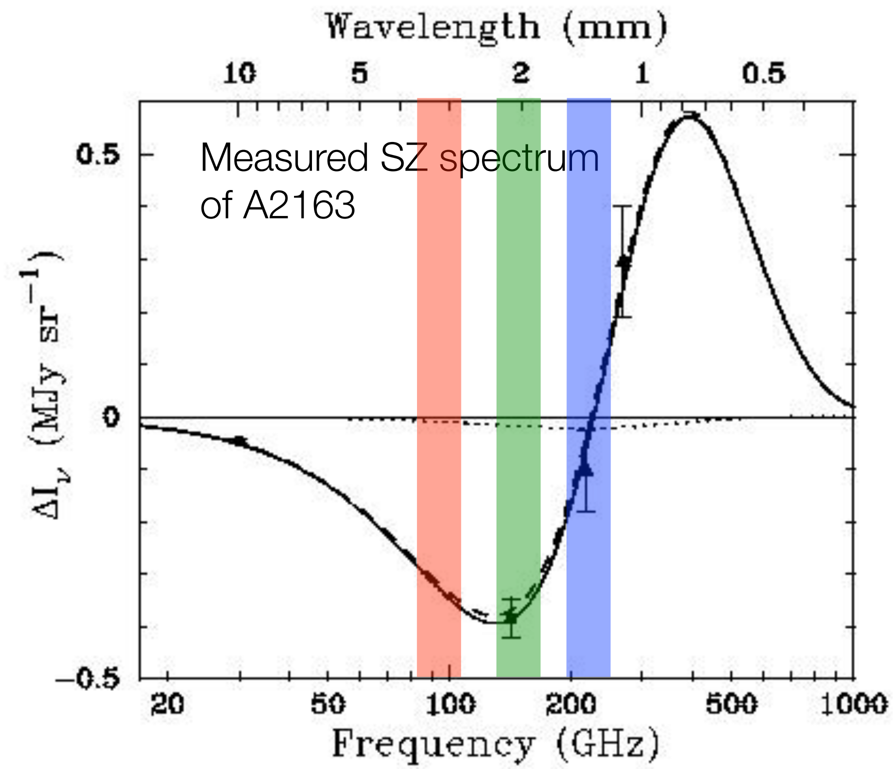
Adapted from Allen, Evrard, & Mantz (2012)

The thermal Sunyaev-Zel'dovich effect



The Sunyaev-Zel'dovich effect





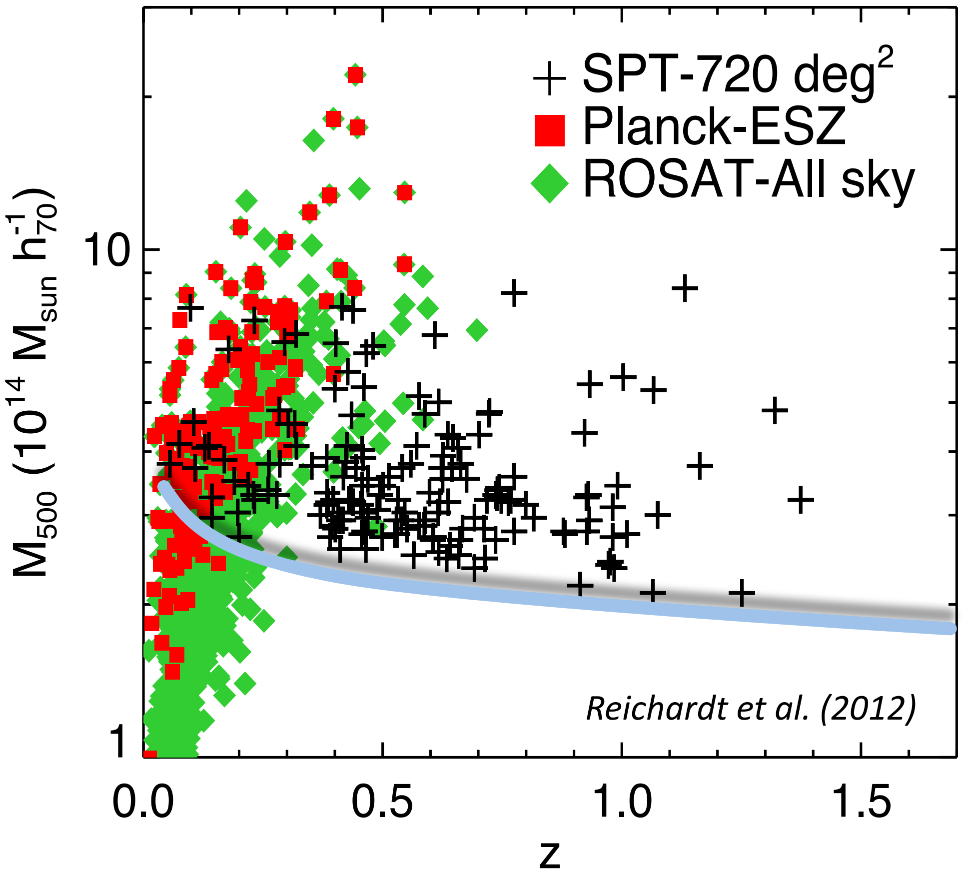
Take-home message #1

SZ signal is not an emissive process but a spectral disortion, so with beam well matched to the size of clusters, it's nearly redshift independent.

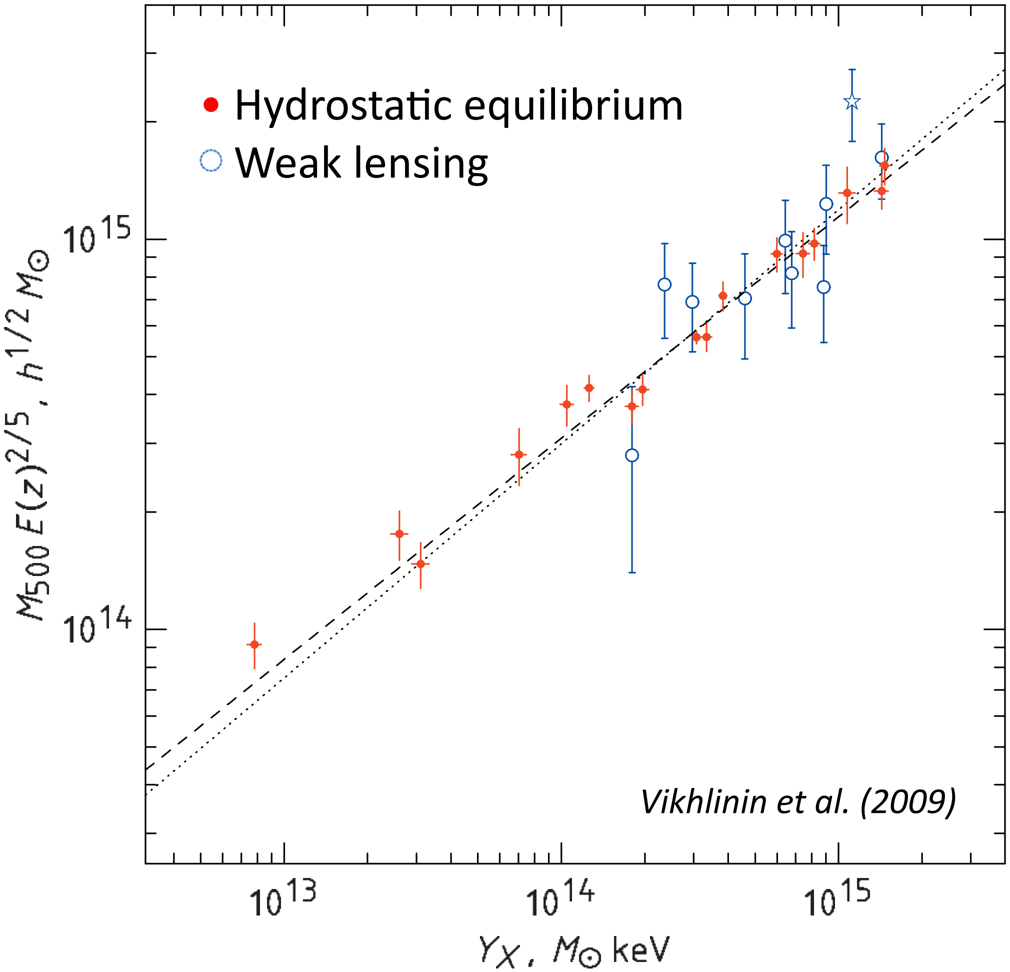
Take-home message #2

SZ signal is a direct probe of total thermal energy, and so is a good proxy for cluster mass.

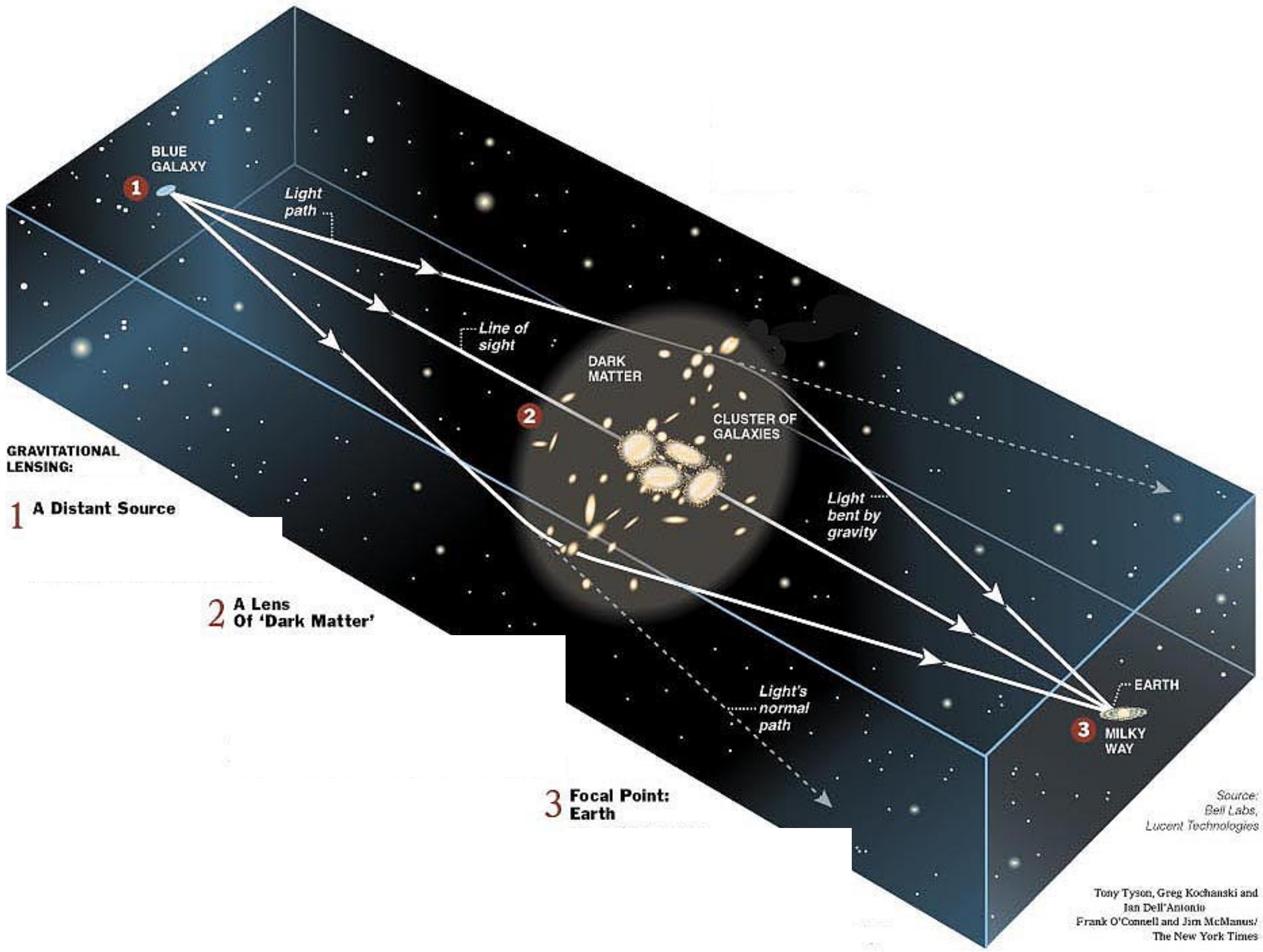
South Pole Telescope detected clusters



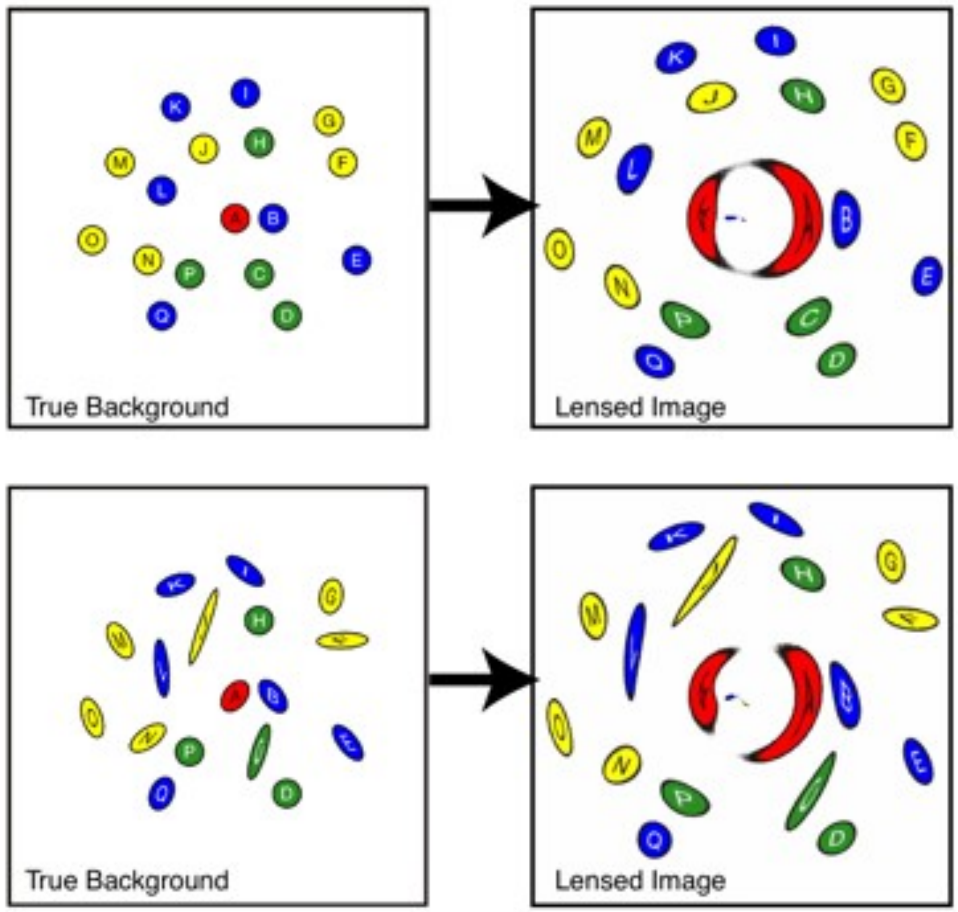
Calibrating mass-observables with weak lensing



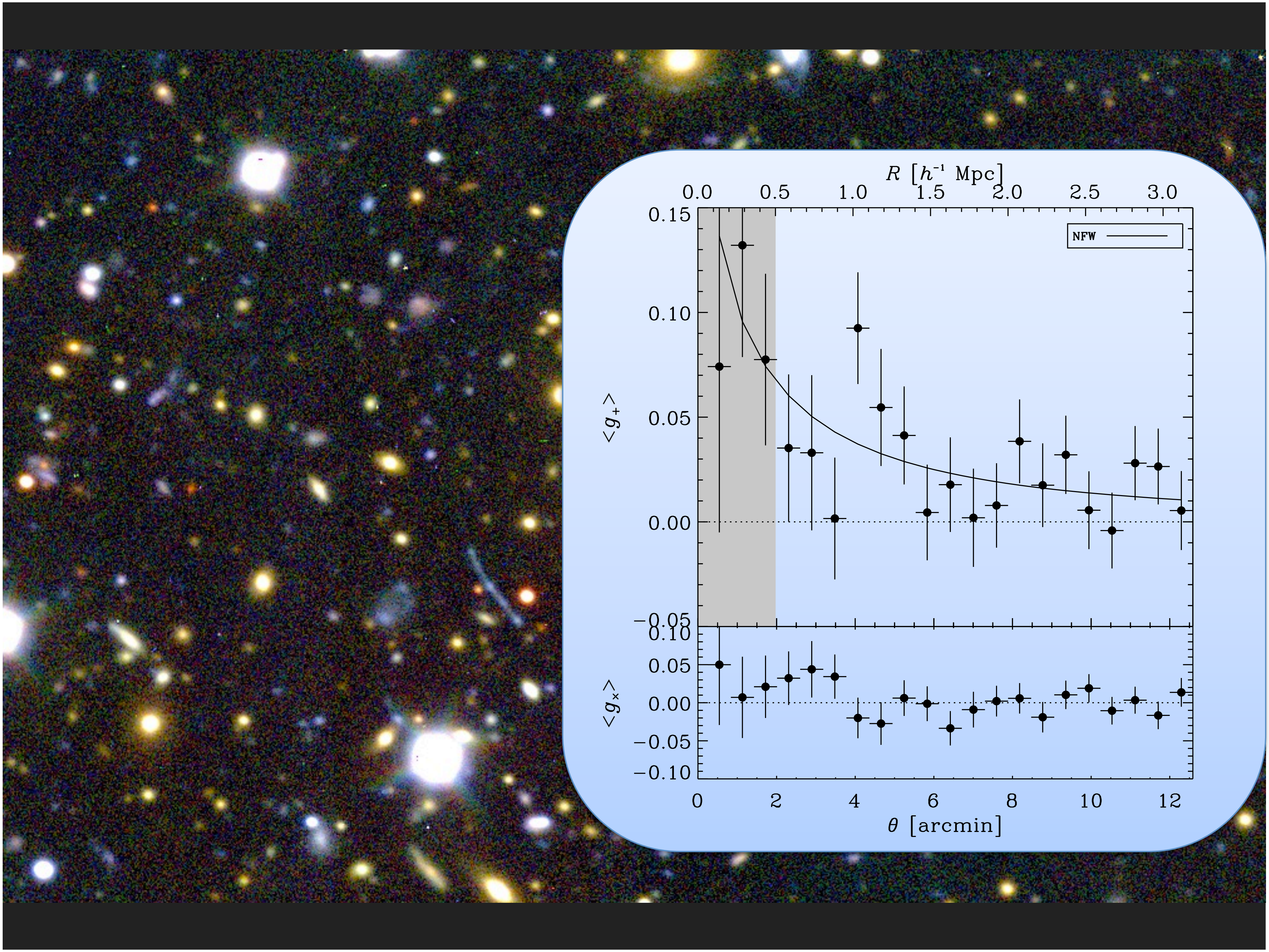
Weak lensing



Weak lensing



Williamson, Oluseyi, & Roe (2007)



R [h⁻¹ Mpc]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0.15
0.10
0.05
0.00
−0.05
NFW
<g+>
0.10
0.05
0.00
−0.05
−0.10
<g×>
0
2
4
6
8
10
12
θ [arcmin]

SPT targeted weak lensing sample

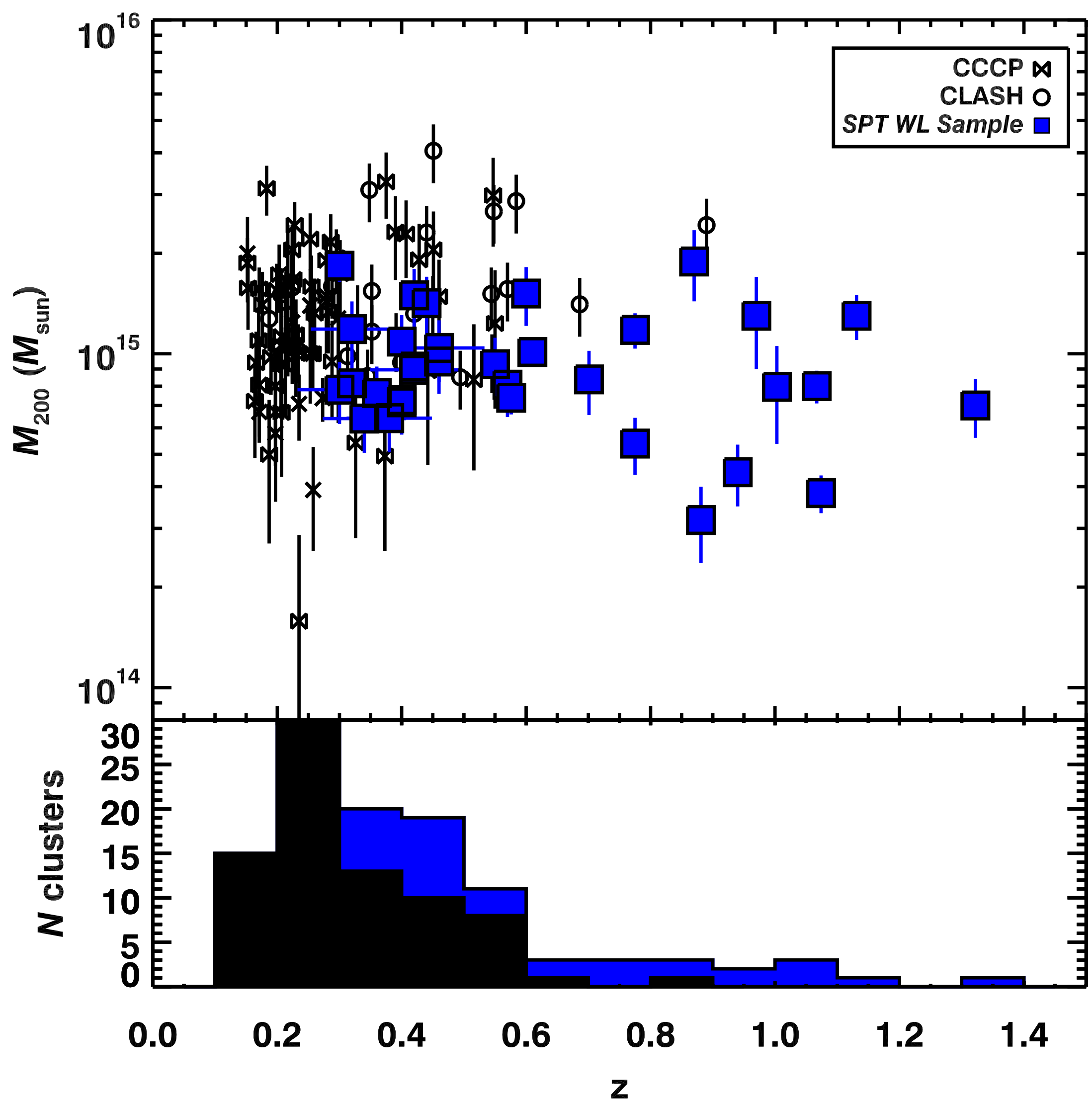
○ 33 clusters at 0.3 < z < 1.3
○ Complete SZ, X-ray coverage
○ Spectroscopy, Spitzer NIR, and multiband OIR from the ground

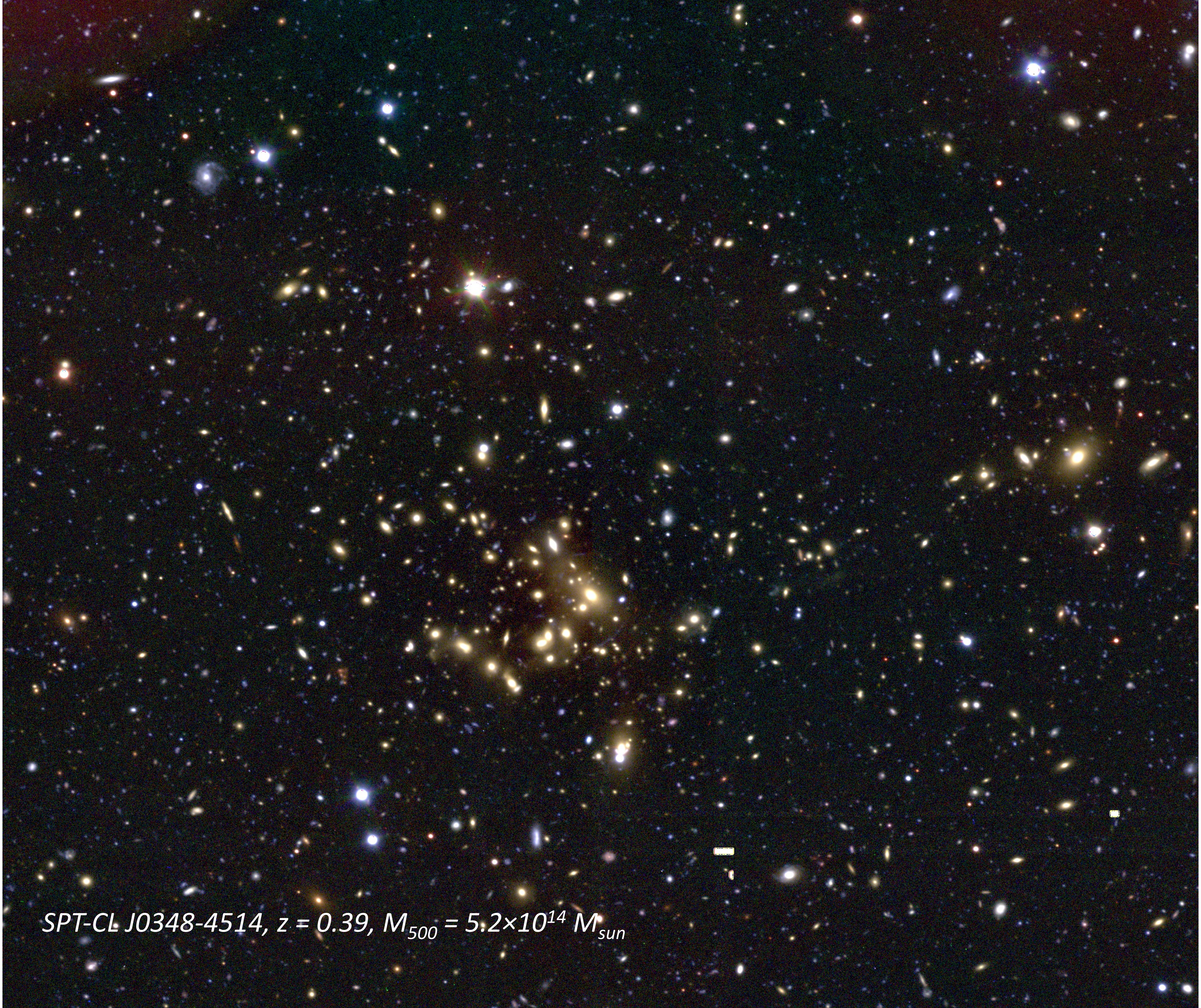
Ground WL sample

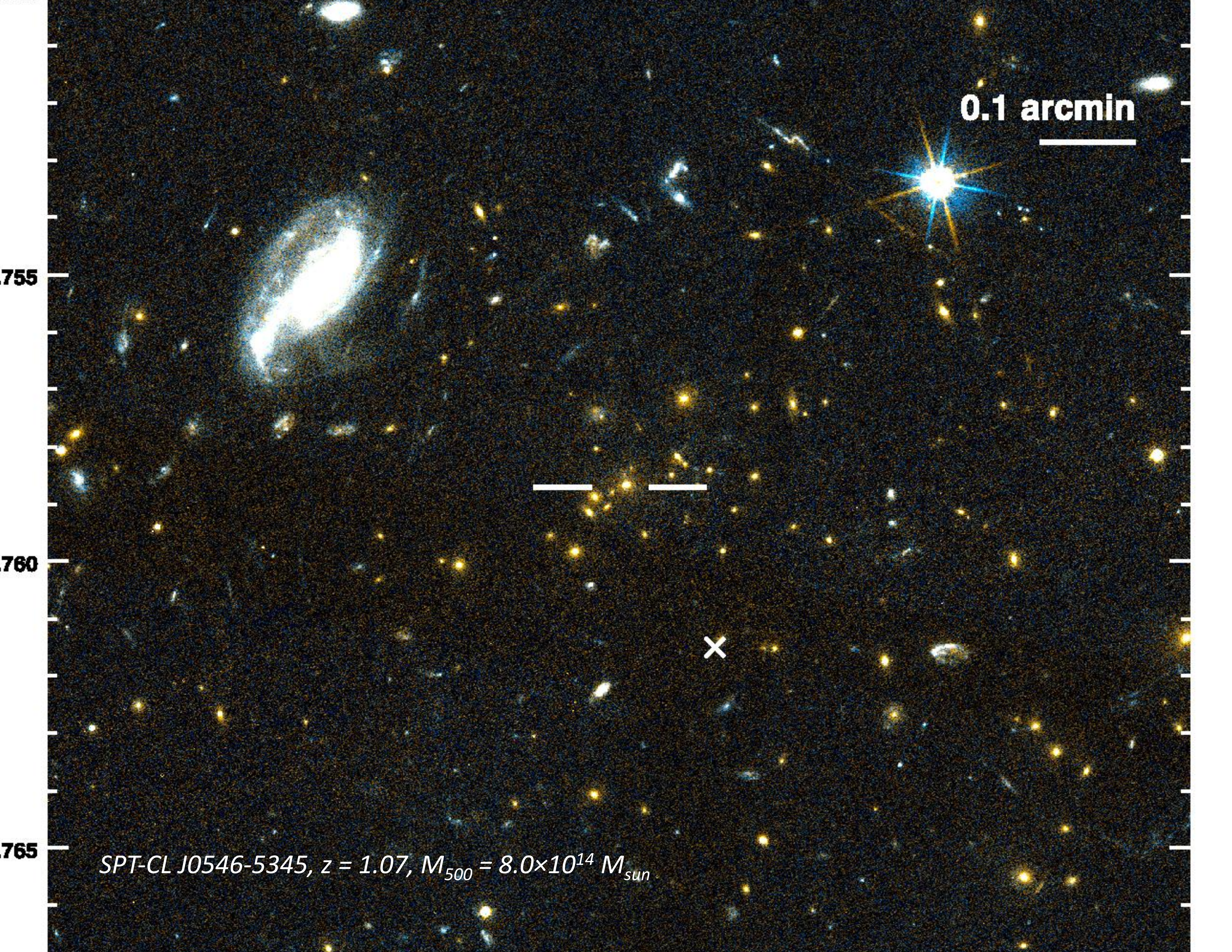
- Magellan/Megacam camera
- 19 clusters at 0.3 < z < 0.6
- Imaging in (*u*)*gri* in 2011A+B

Space WL sample

- HST/ACS camera
- 14 clusters at 0.6 < z < 1.3
- Imaging in *F606W* and *F814W* in Cycle 18 and Cycle 19
- Added deep imaging with VLT
- Observations ongoing



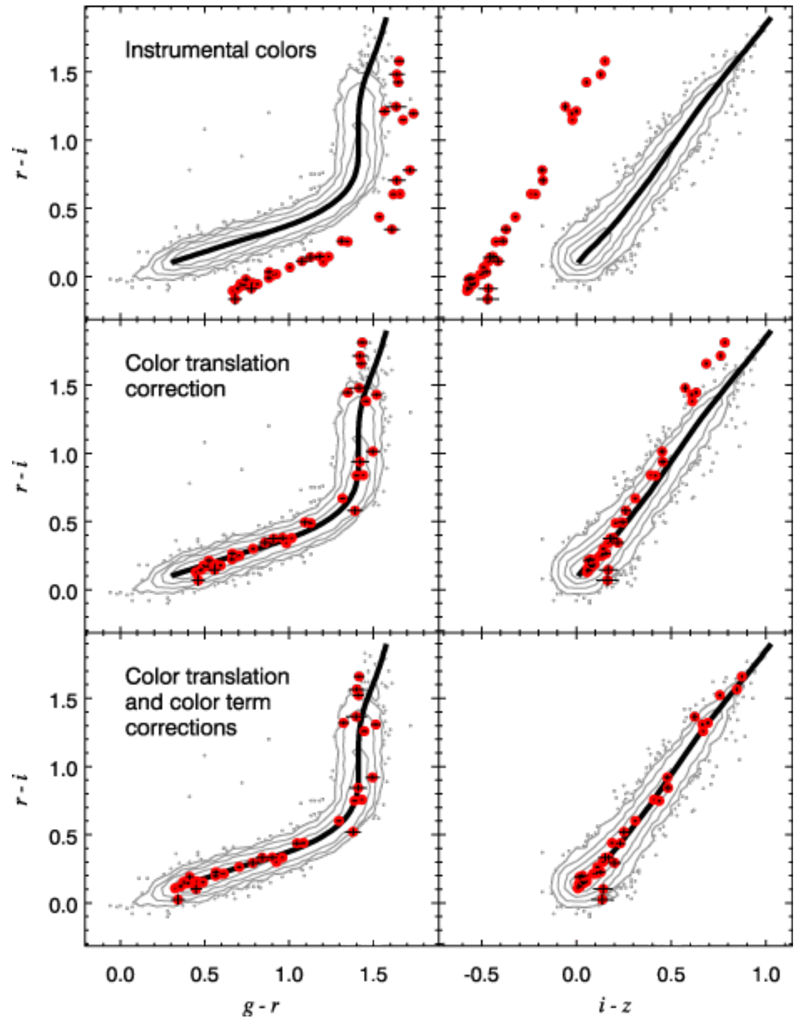

SPT-CL J0348-4514, z = 0.39, M500 = 5.2×1014 Msun



.755
.760
.765
0.1 arcmin
SPT-CL J0546-5345, z = 1.07, M500 = 8.0×10^14 Msun

Stellar locus photometric calibration

Magellan/IMACS stellar locus



SLR: Stellar Locus Regression

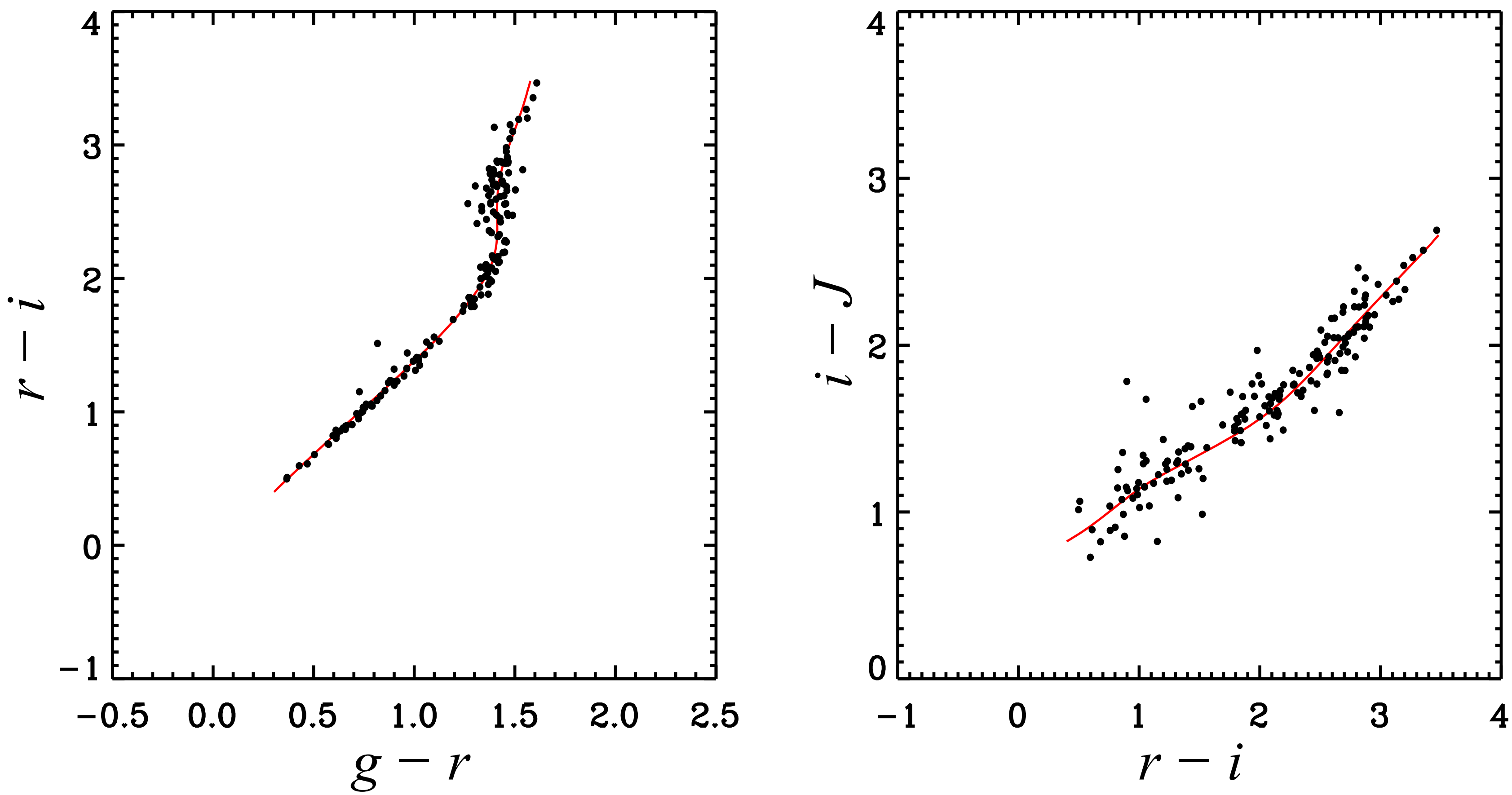
- Allows for calibration of colors and magnitudes without the traditional use of standard star fields
- Successfully used by Weighing the Giants to obtain photo-*z*'s

Adapted from High et al. (2009)

SLR gives dereddened colors to 0.01–0.03 mag (SDSS) and magnitudes to 0.05 mag (2MASS).

Stellar locus photometric calibration

Magellan/Megacam stellar locus



SLR gives dereddened colors to 0.01–0.03 mag (SDSS) and magnitudes to 0.05 mag (2MASS).

Estimating shear

Massey et al. (2007)

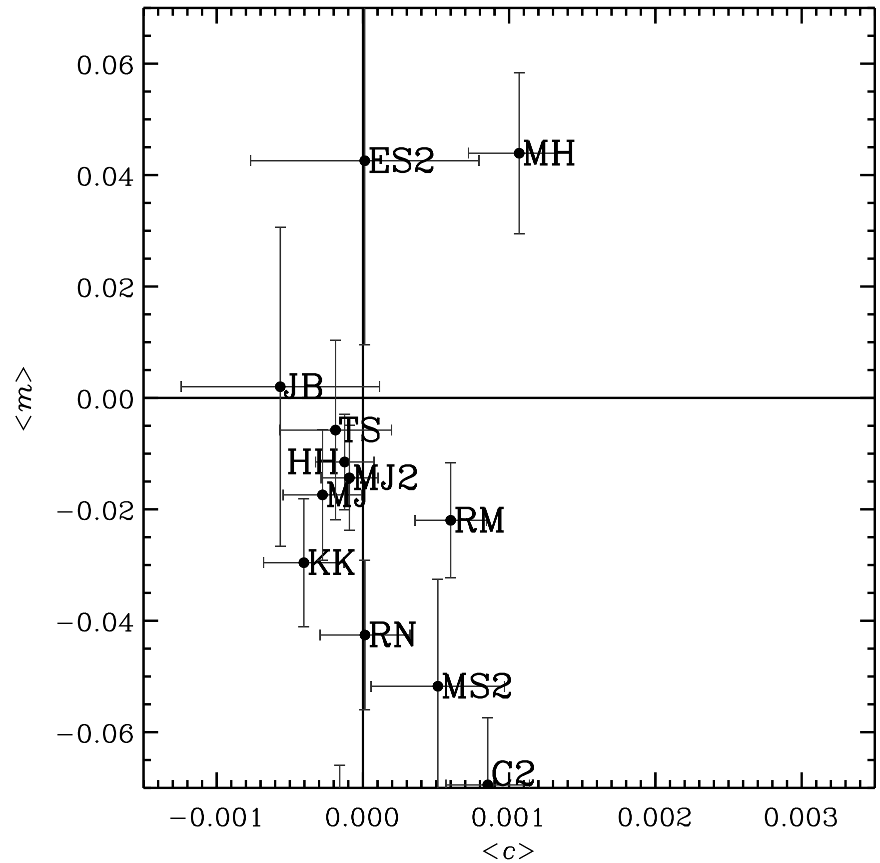
Shear pipelines that we use:

- ground data: Henk Hoekstra (HH)
- space data: Tim Schrabback (TS)

Full pipelines blind-tested by the **Shear Testing Program** (STEP: Heymans et al. 2006; Massey et al. 2007). Includes realistic point-spread functions.

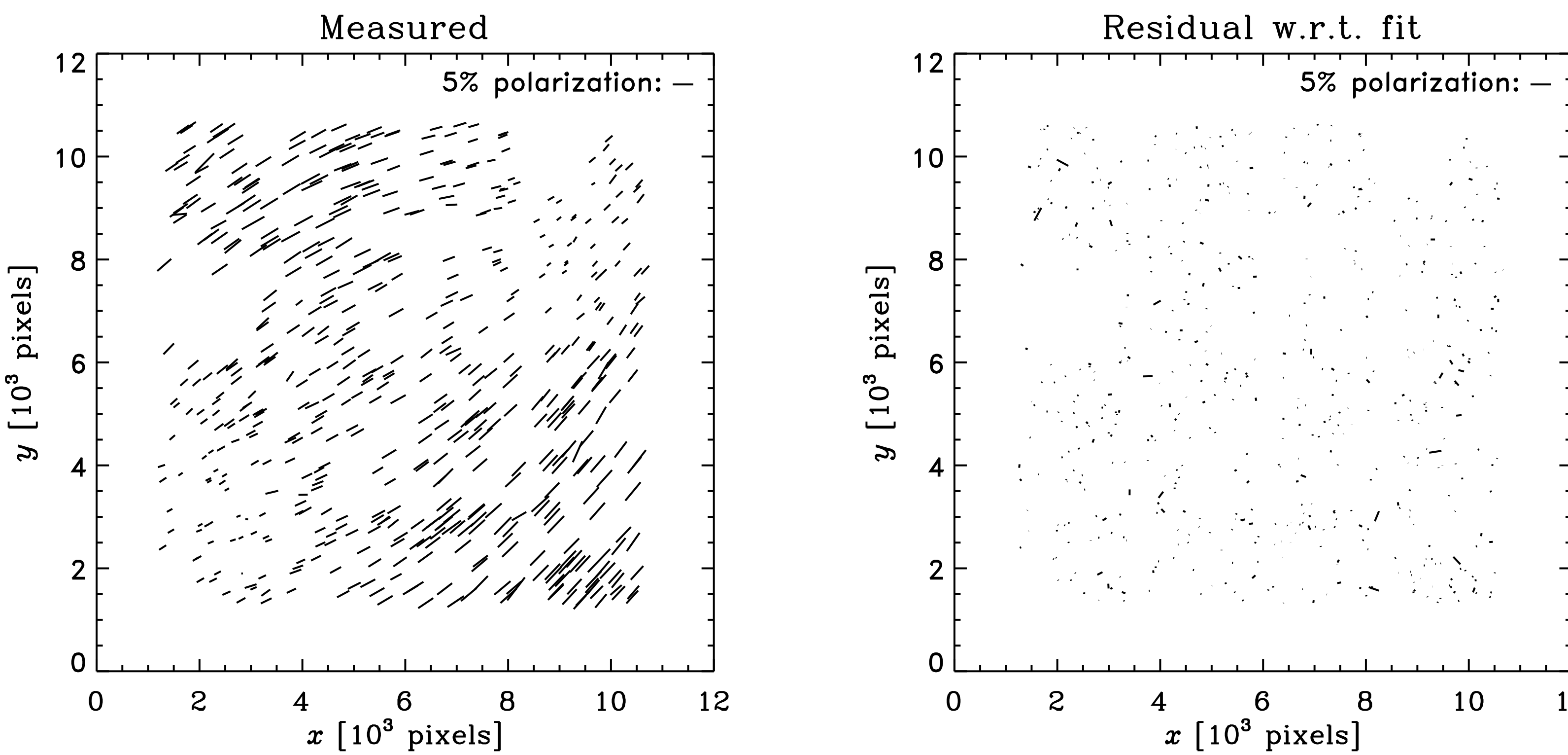
STEP bias statistics:

$$\langle \tilde{\gamma}_1 \rangle - \gamma_1^{\mathrm{input}} = m_1 \gamma_1^{\mathrm{input}} + c_1$$
$$\langle \tilde{\gamma}_2 \rangle - \gamma_2^{\mathrm{input}} = m_2 \gamma_2^{\mathrm{input}} + c_2.$$



Shear code recovers truth with no measurable additive bias (c) and with multiplicative bias (m) of 2% or better.

Magellan/Megacam PSF performance

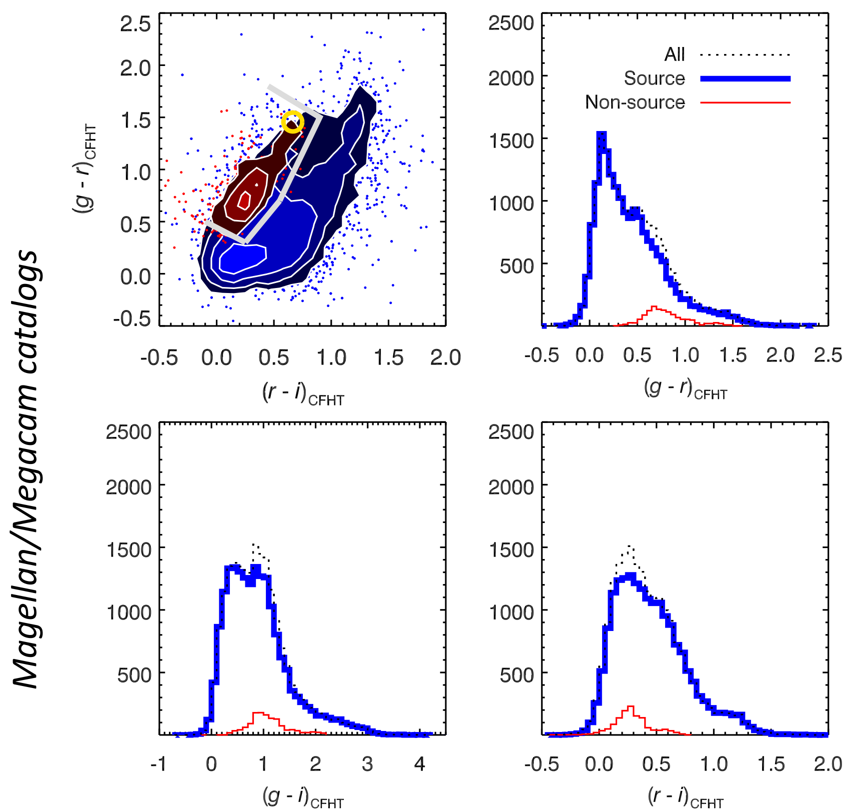


High et al. (2012)

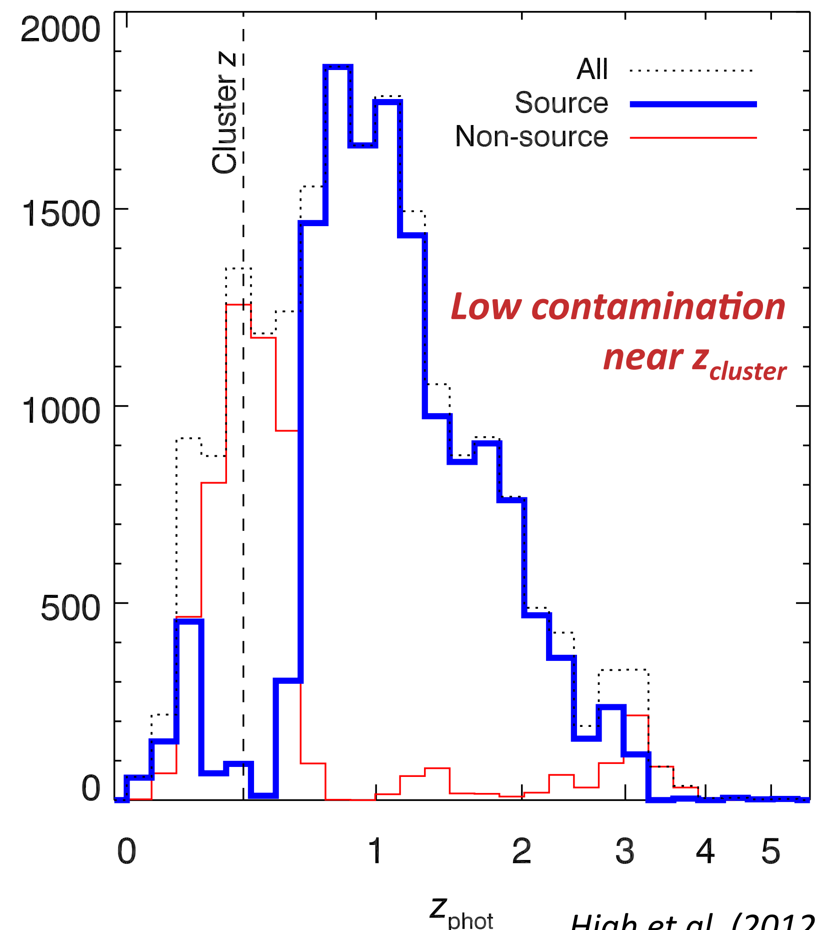
PSF polarization residuals are 0.003 to 0.005 rms, no appreciable residual in radial bins.

Source redshift distribution and cluster-galaxy decontamination

Procedure for ground sample:
- ○ Cut out $i >$ ~~25~~ 24
- ○ Cut out $|z_{phot} - z_{cluster}| < 0.05$ region in color-color space
- ○ Estimate mean and variance of β from reference photo-*z* catalogs using the same cuts



CFHTLS Deep field photo-z catalogs
Coupon et al. 2009



High et al. (2012)

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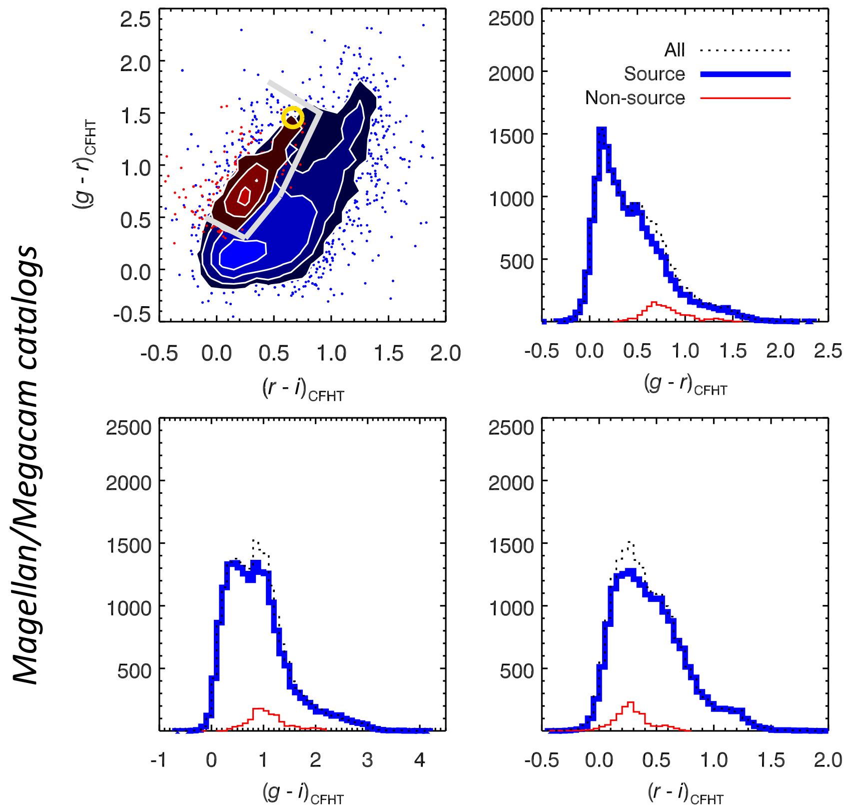
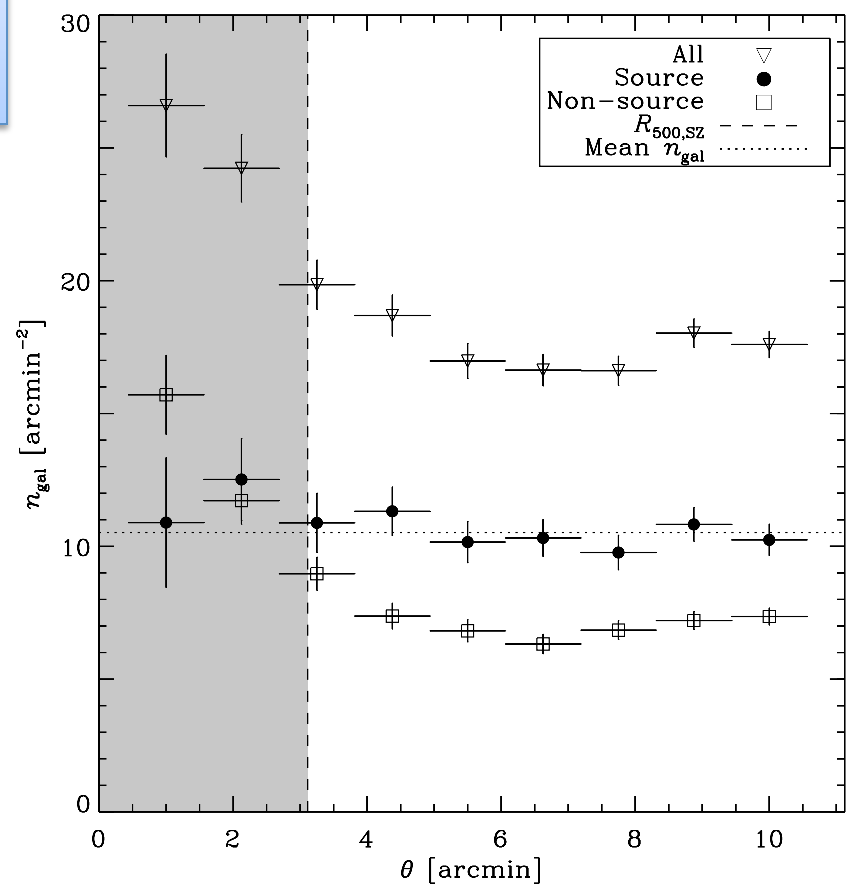


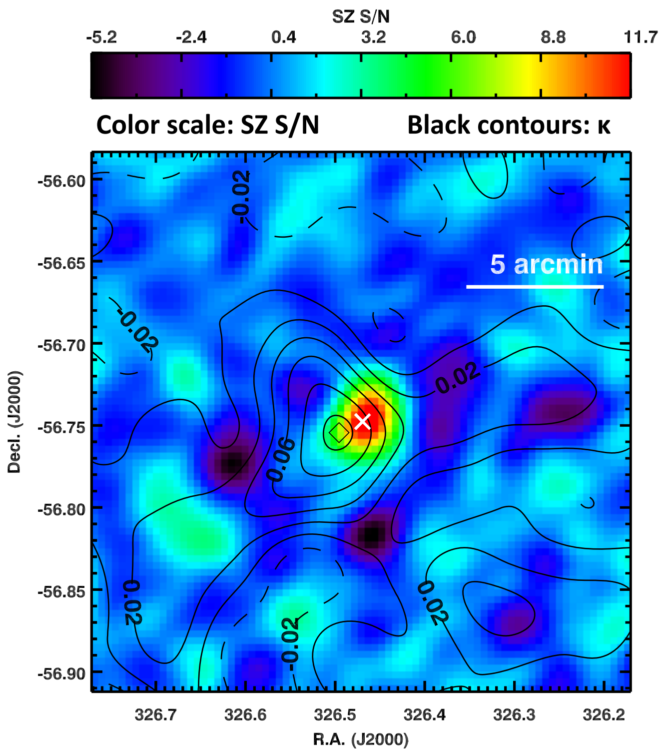
Magellan/Megacam catalogs

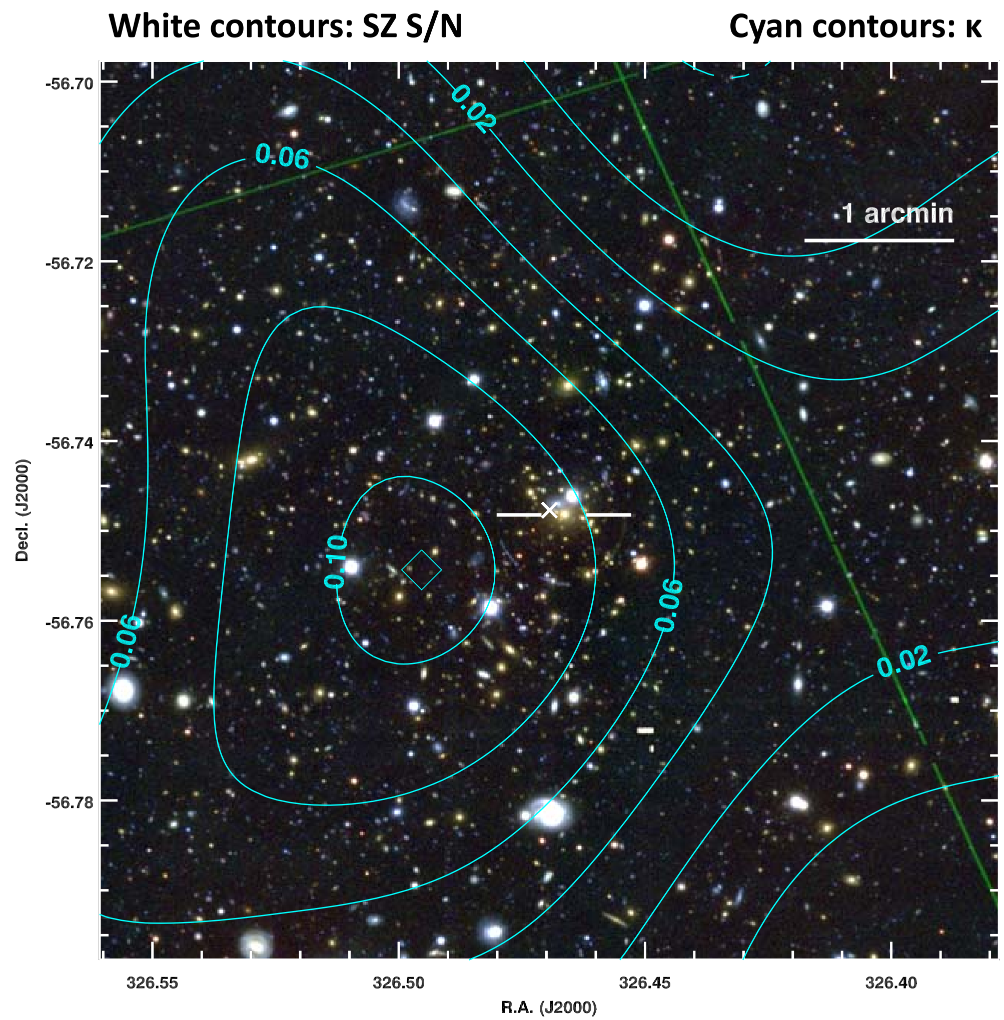


High et al. (2012)

The results

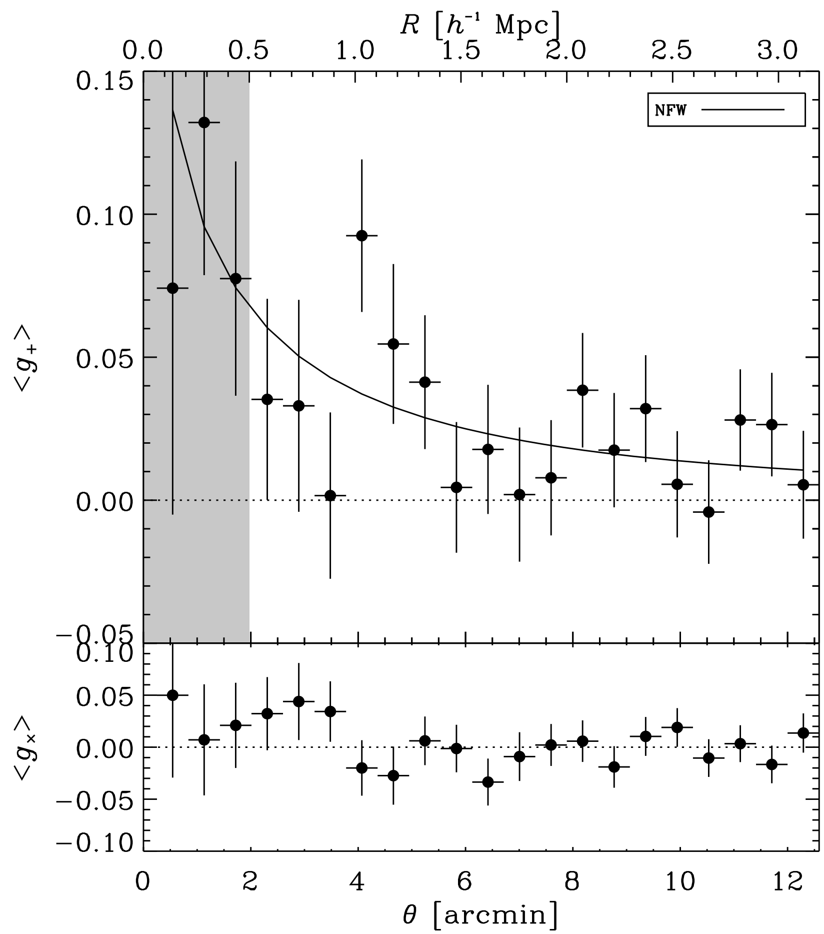
O/NIR: Magellan/Megacam
SZ: SPT S/N
κ: Kaiser Squires reconstruction





SPT-CL J2145-5644, z = 0.48, $M_{500} = 6.5\times10^{14}\ M_{sun}$

The results



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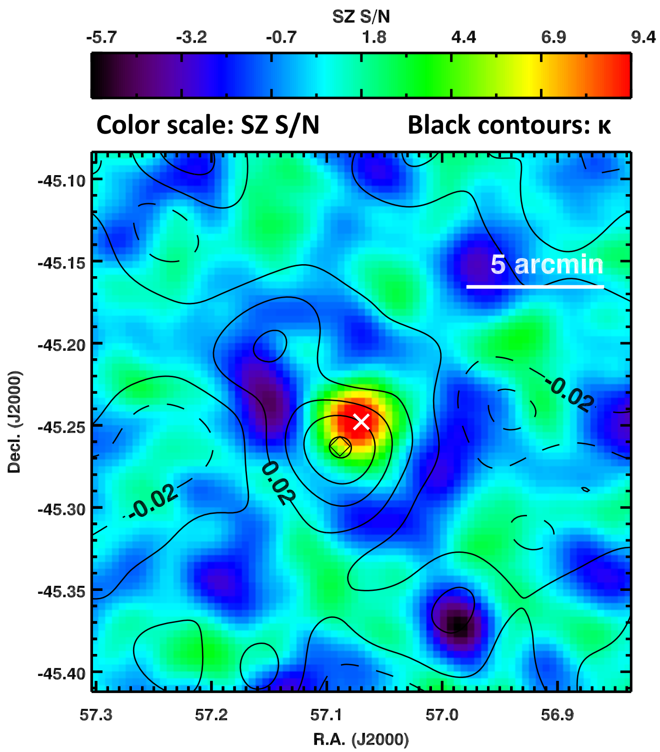
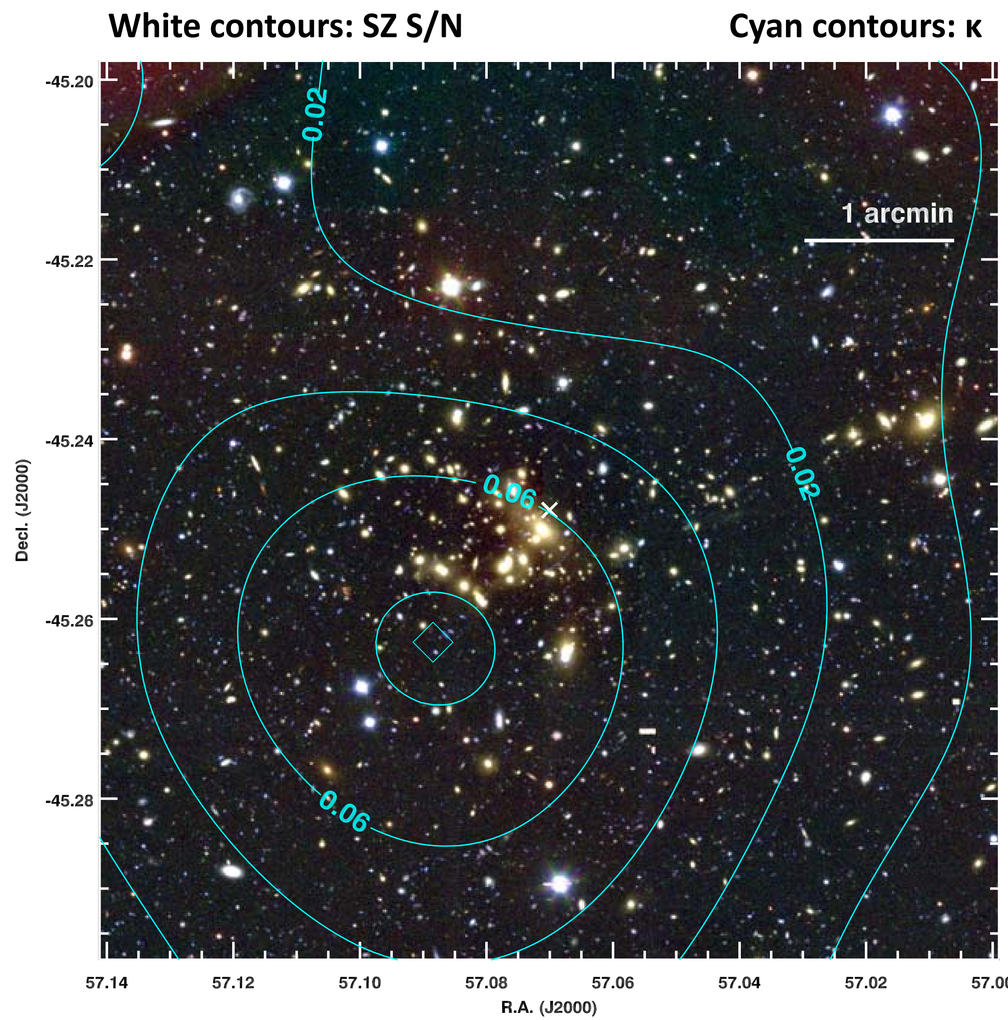
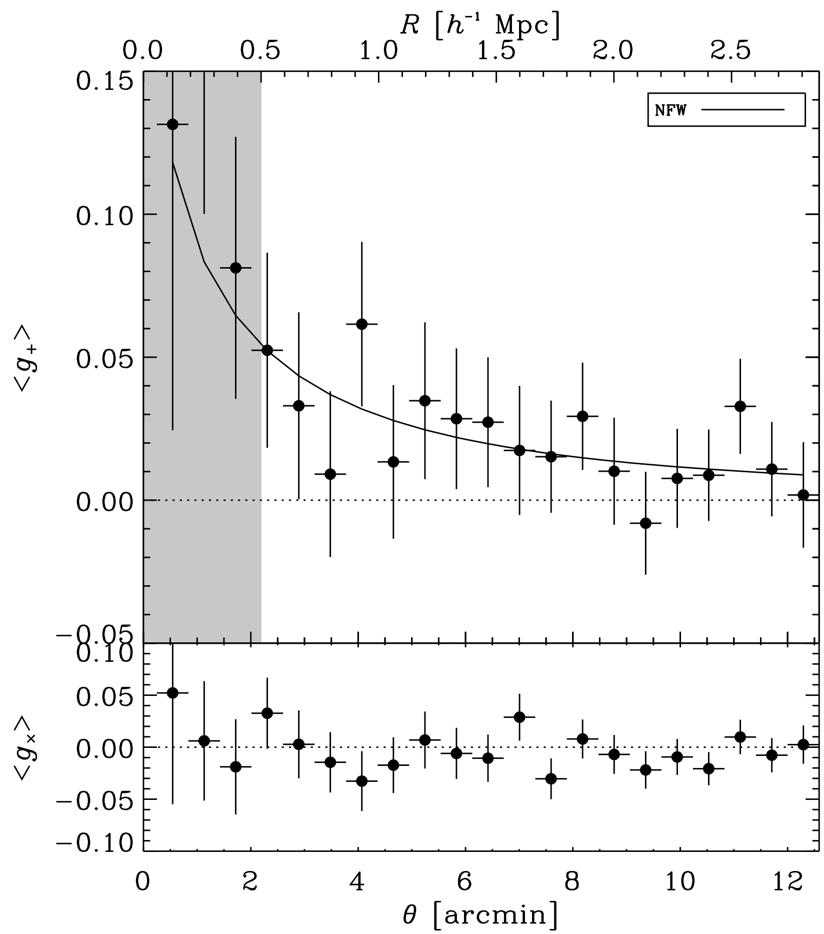




SPT-CL J0348-4514, z = 0.39, $M_{500} = 5.2\times10^{14}\ M_{sun}$

The results

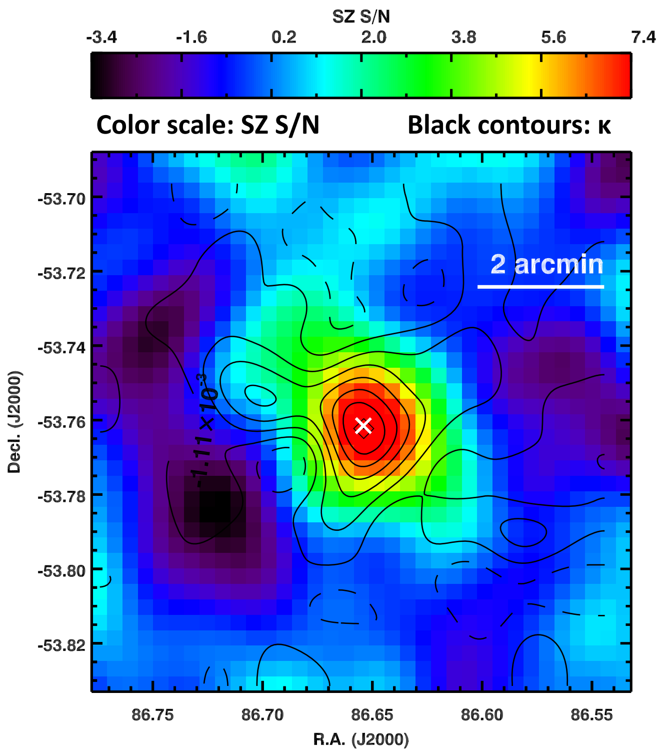


SPT-CL J0348-4514, z = 0.39, $M_{500} = 5.2\times10^{14}\ M_{sun}$

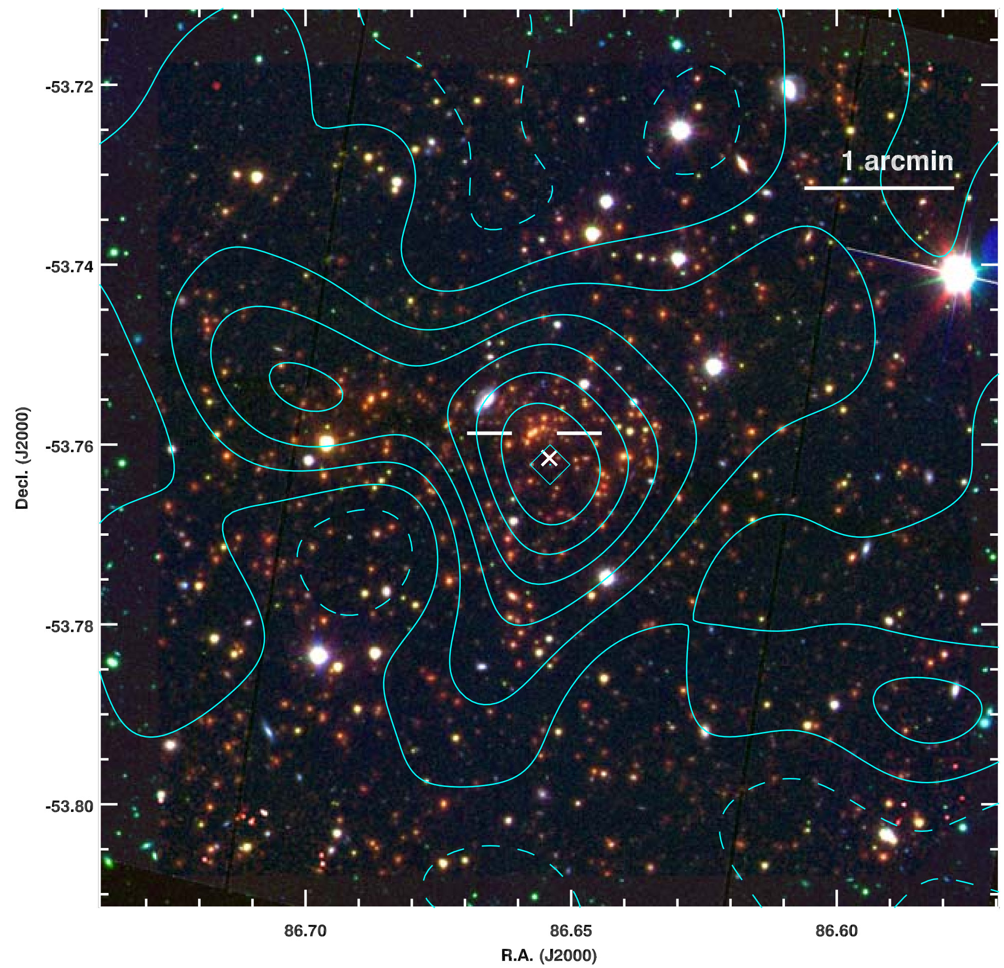
The results

O/NIR: VLT/FORS2 & Spitzer
SZ: SPT S/N
κ: Kaiser Squires reconstruction

Color scale: SZ S/N Black contours: κ

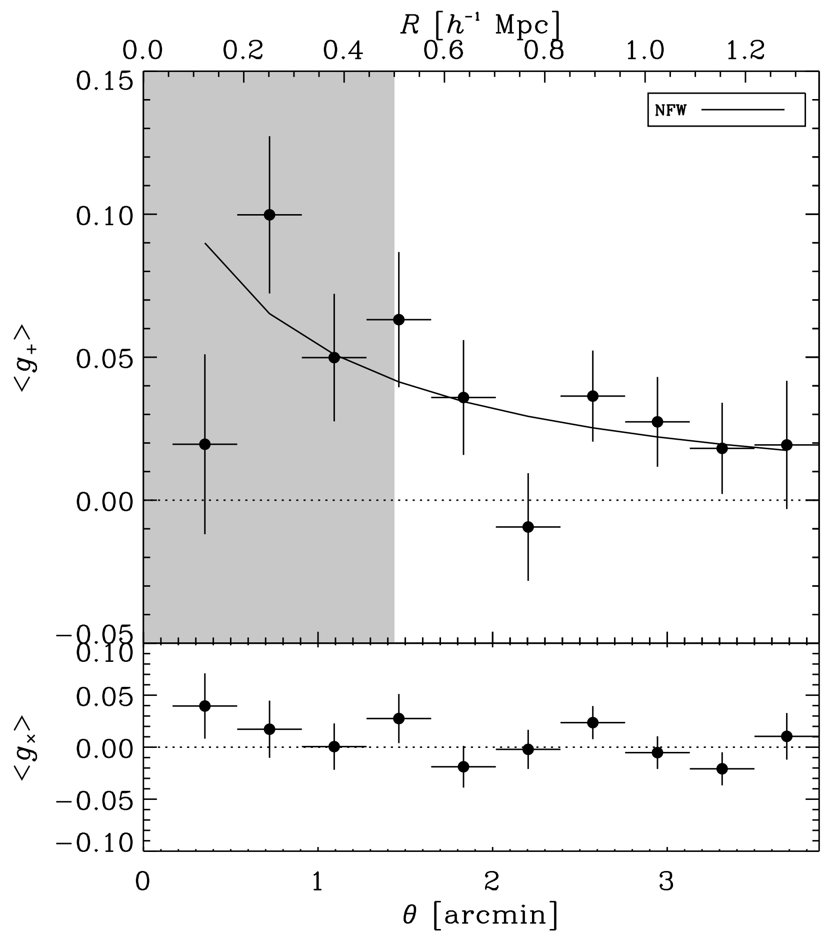


Cyan contours: κ



SPT-CL J0546-5345, z = 1.07, $M_{500} = 8.0 \times 10^{14}\ M_{sun}$

The results



SPT-CL J0546-5345, z = 1.07, $M_{500} = 8.0\times10^{14}\ M_{sun}$

The results

O/NIR: VLT/FORS2
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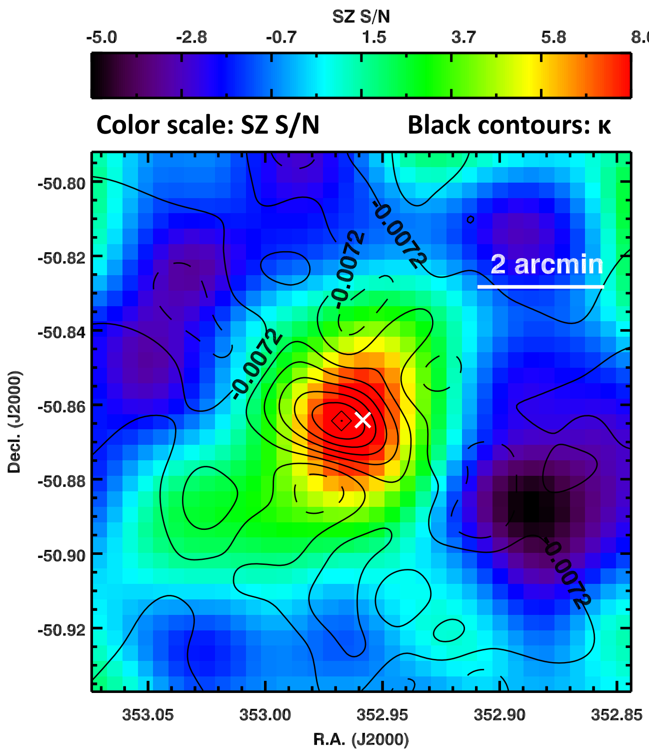
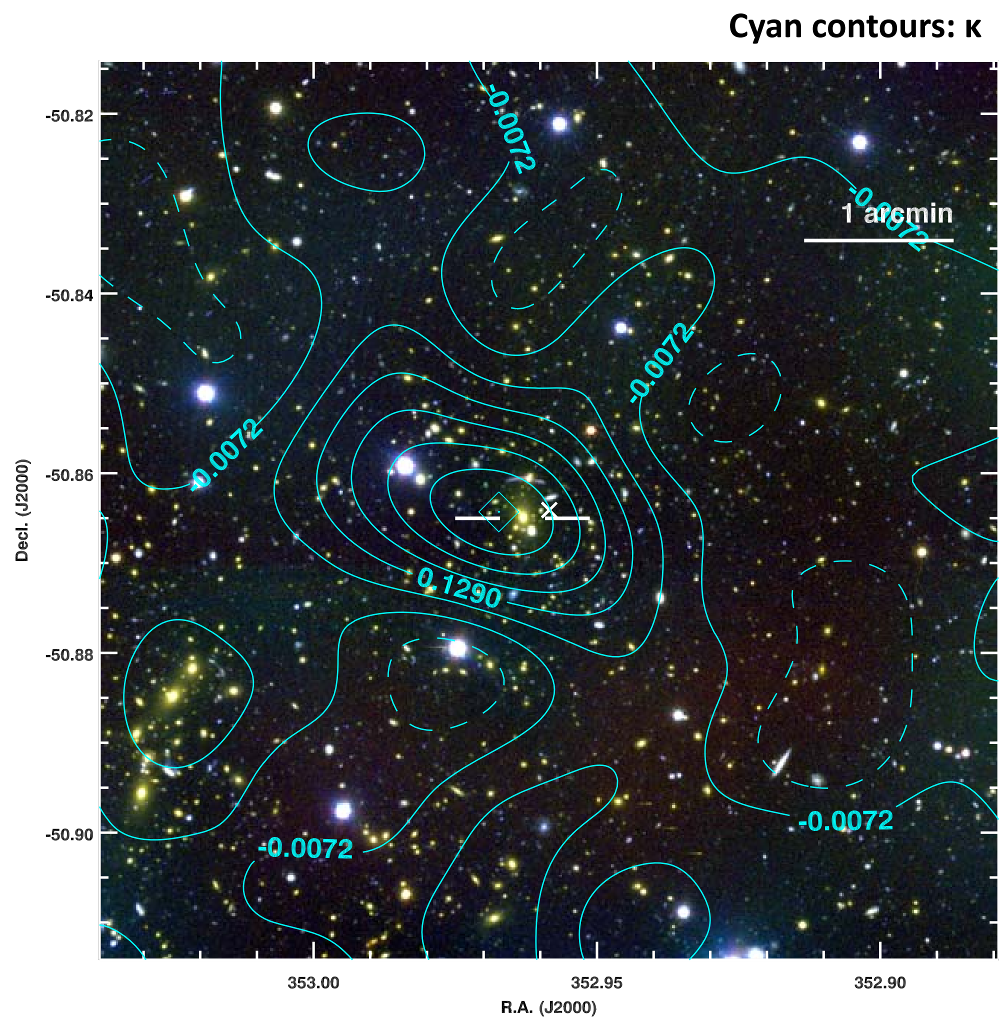
κ: Kaiser Squires reconstruction

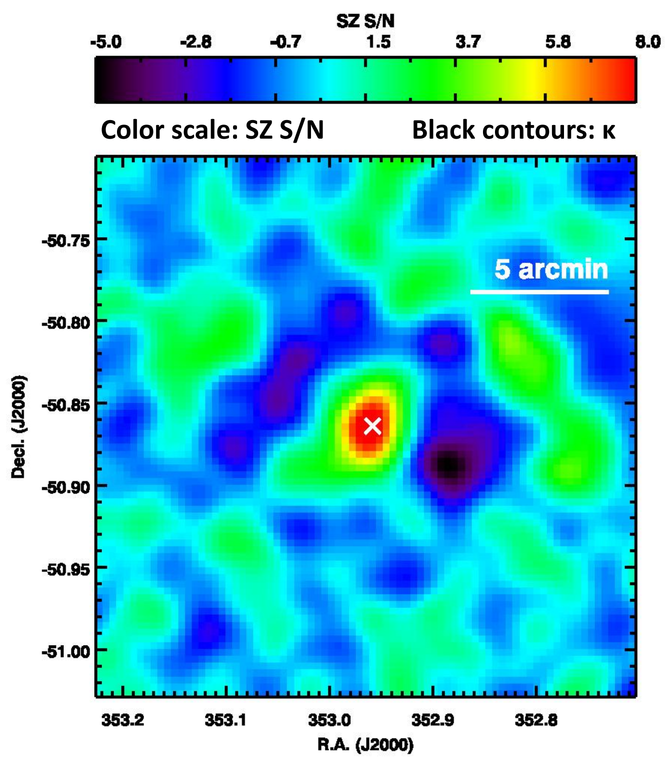


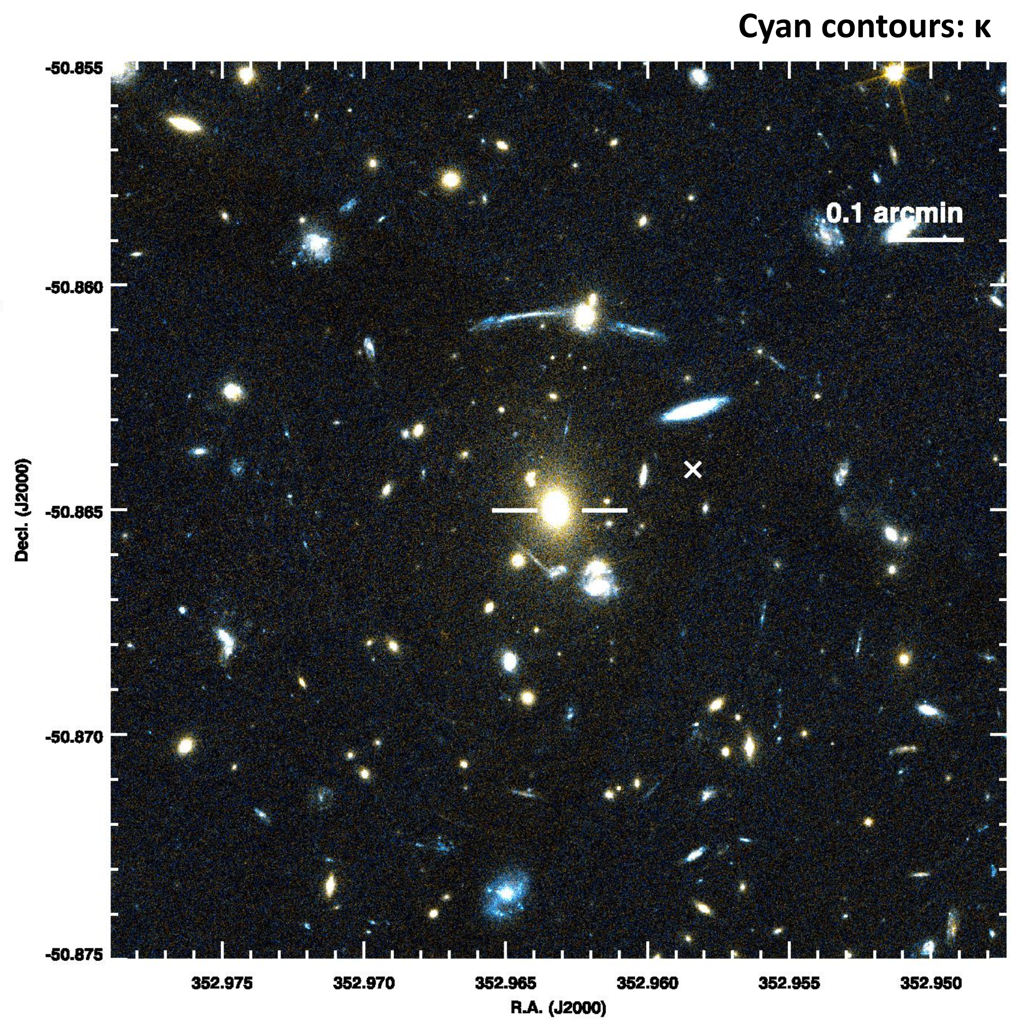


SPT-CL J2331-5051, z = 0.58, $M_{500} = 5.1 \times 10^{14}\ M_{sun}$

The results

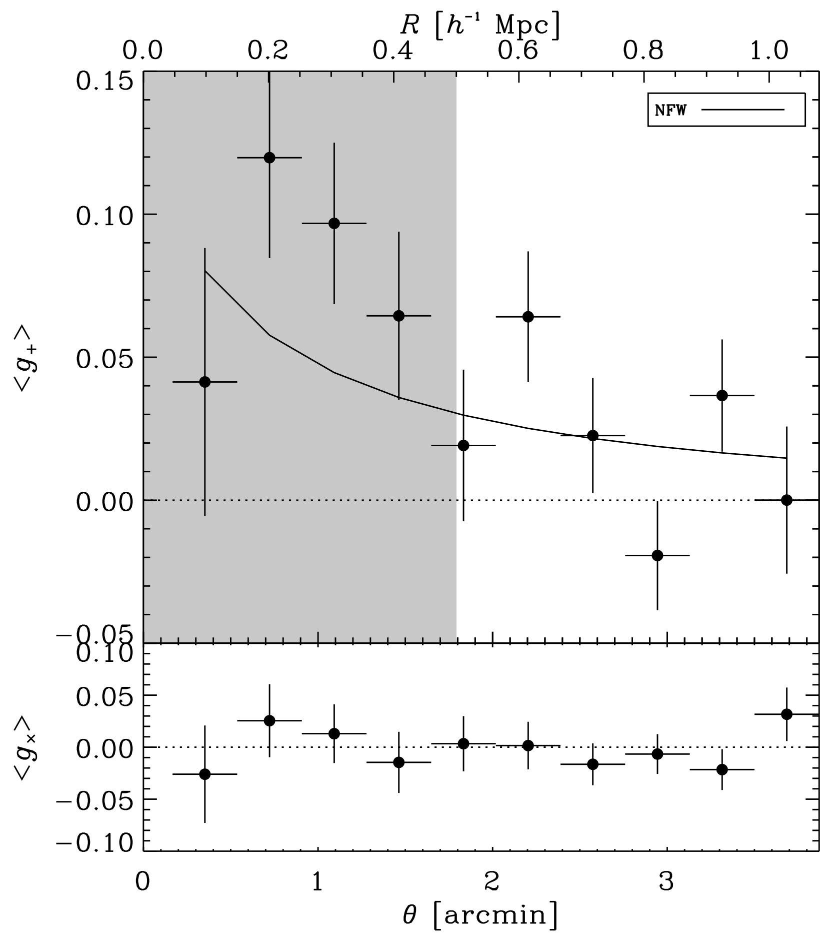
O/NIR: HST/ACS
_SZ:_ SPT S/N
_κ:_ Kaiser Squires reconstruction





SPT-CL J2331-5051, z = 0.58, $M_{500} = 5.1\times10^{14}\ M_{sun}$

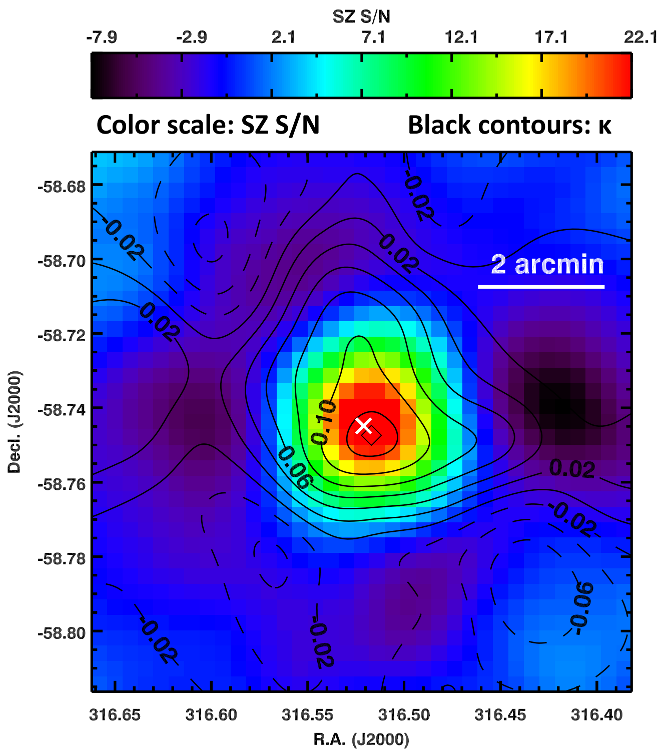
The results

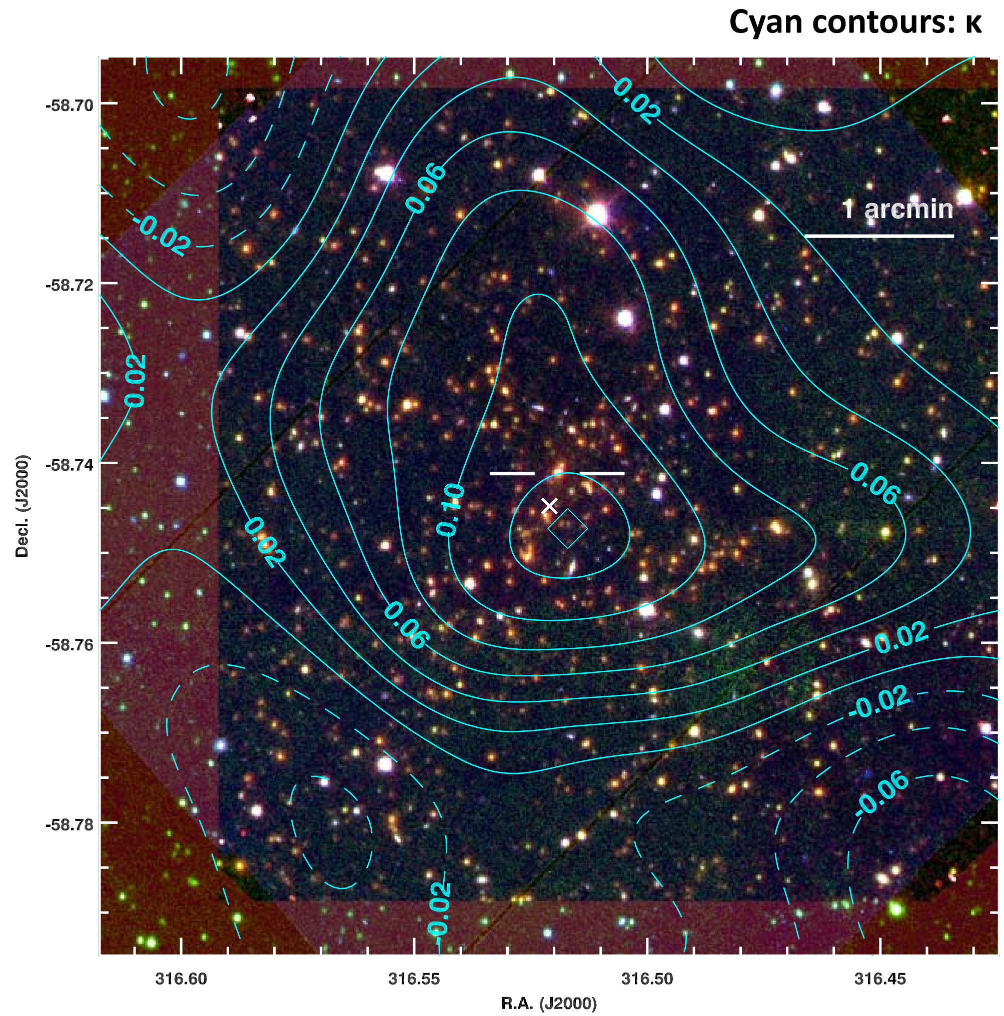


SPT-CL J2331-5051, z = 0.58, $M_{500} = 5.1\times10^{14}\ M_{sun}$

The results

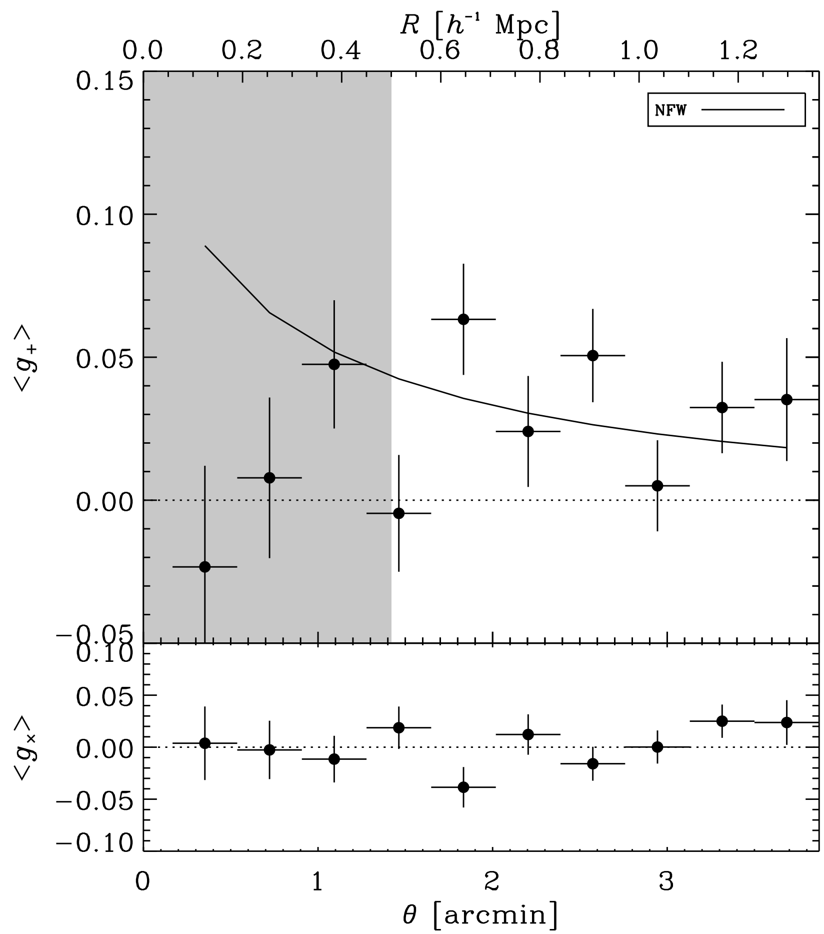
O/NIR: HST/ACS & Spitzer
SZ: SPT S/N
κ: Kaiser Squires reconstruction





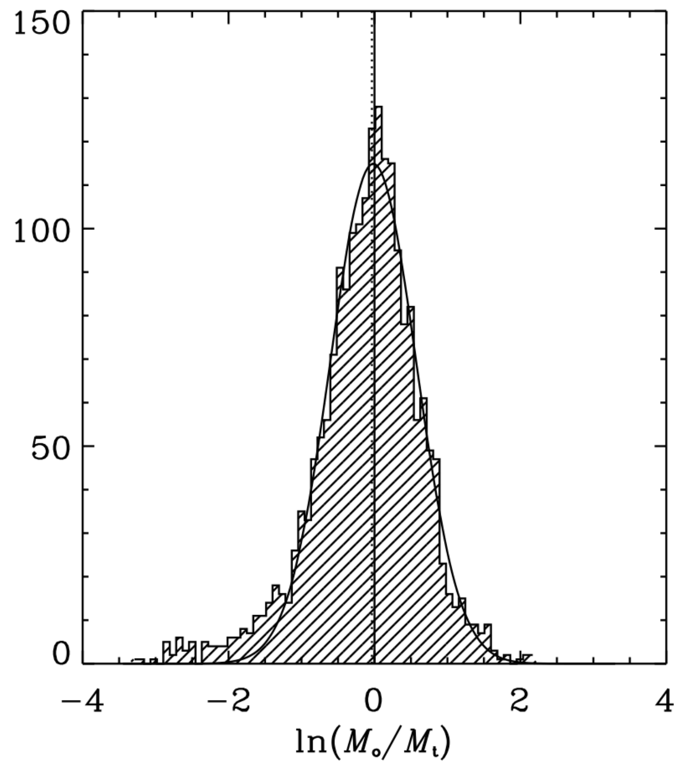
SPT-CL J2106-5844, z = 1.13, $M_{500} = 8.4{\times}10^{14}\ M_{sun}$

The results



SPT-CL J2106-5844, z = 1.13, $M_{500} = 8.4\times10^{14}\ M_{sun}$

Calibration to *N*-body simulations



Article	NFW WL mass bias
Becker & Kravtsov 2012	-5% to -10%
Rasia et al. 2012	-5% to -10%
Bahe et al. 2012	-5%
High et al. 2012	-5% to -10%

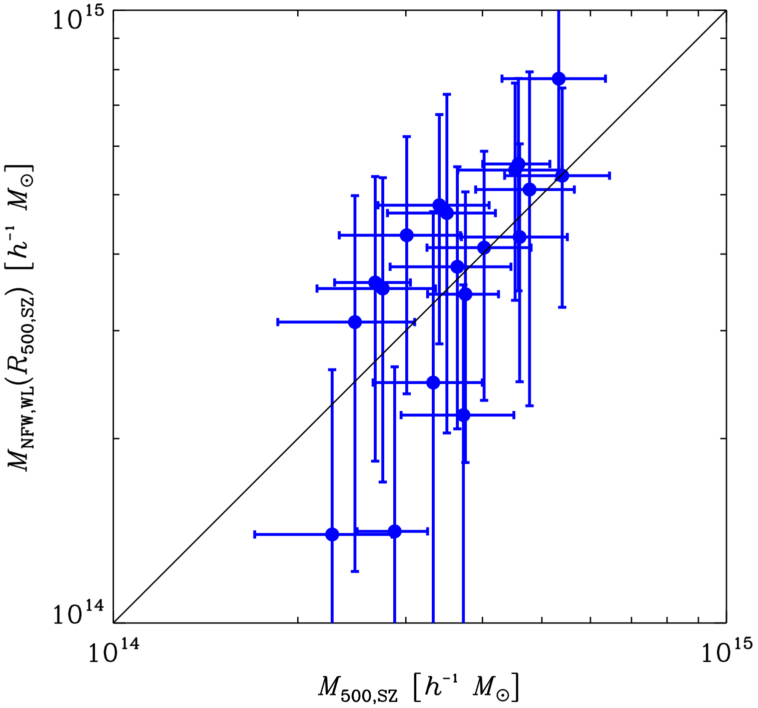
Our tests:

- Use two flavors of Dark Energy Survey mocks at 220 deg^2 and 5k deg^2; fake galaxies with realistic color, magnitude, and clustering properties (ADDGALS, R. Wechsler et al.)
- Replicate our color and magnitude selection for all massive $0.25 < z < 0.65$ halos
- Also geared up on simulations from Becker & Kravtsov (2012)

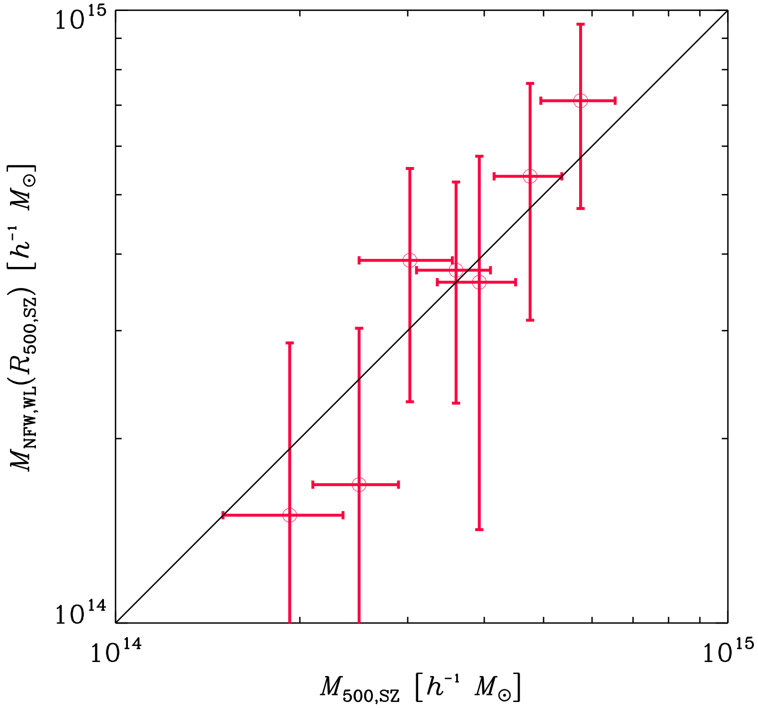
WL NFW masses recover truth with overall bias of -5% to -10%.

WL test of joint SZ/X-ray masses

Mean calibration from <u>ground</u> sample: *1.26 ± 0.16*



Mean calibration from <u>space</u> sample: *1.16 ± 0.26*



High et al. (in prep.)

WL calibration of M – Y_{SZ}:
A first look at the SPT data

Y_{SZ} measured with Rapid Gridded Likelihood Estimator (T. Montroy et al. in prep.).

Assume self-similar scaling with free normalization parameter,

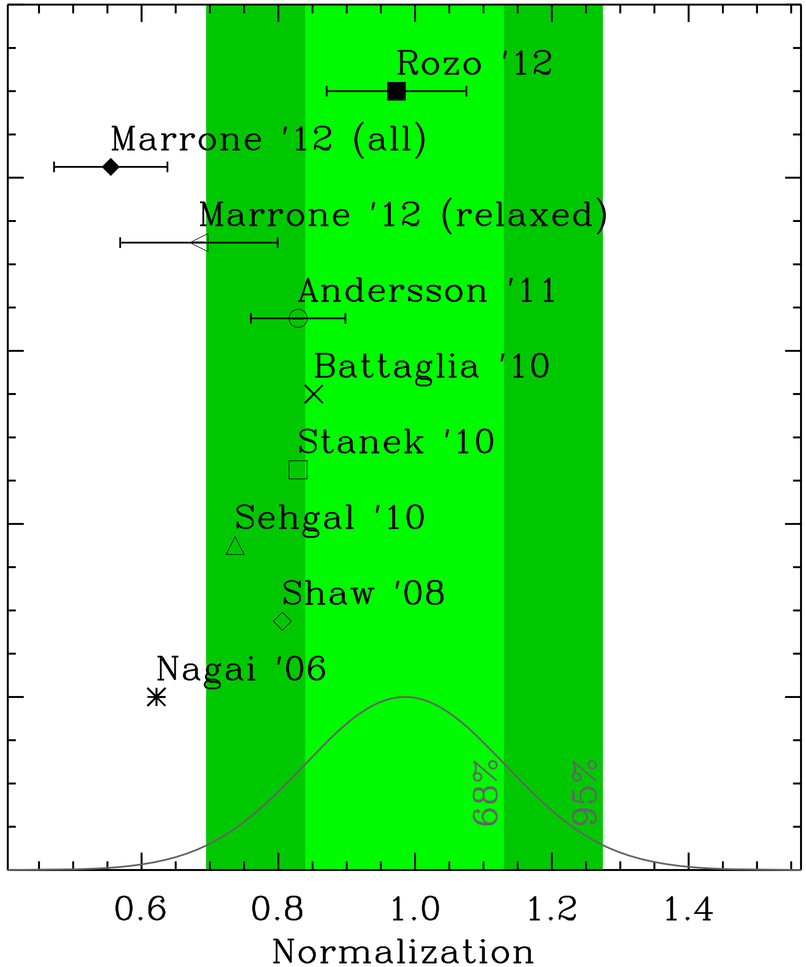
$$\frac{M_{500}}{10^{14}\,M_\odot} = e^A \left(\frac{Y_{\rm sph} D_A^2 E(z)^{-2/3}}{10^{-5}\,{\rm Mpc}^2}\right)^{3/5}$$

19 SPT-detected clusters used here:

- 7 from space sample
- 12 from ground sample

Aghanim et al. (2012) and Applegate et al. (2012) have also given evidence for -30% WL biases in LoCuSS results (Okabe et al. 2010; Marrone et al. 2012).

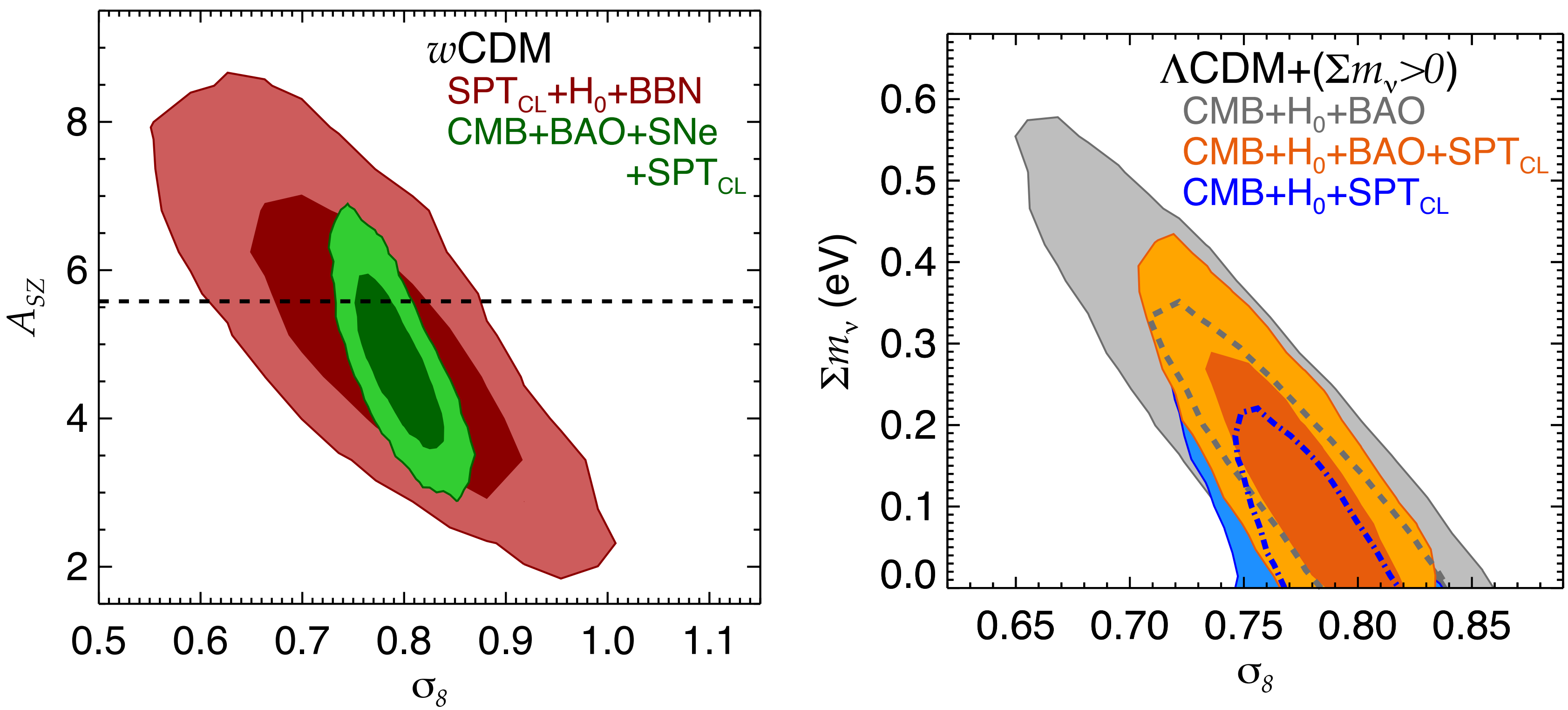
These results are preliminary.



High et al. (in prep.)

Implication for cosmology

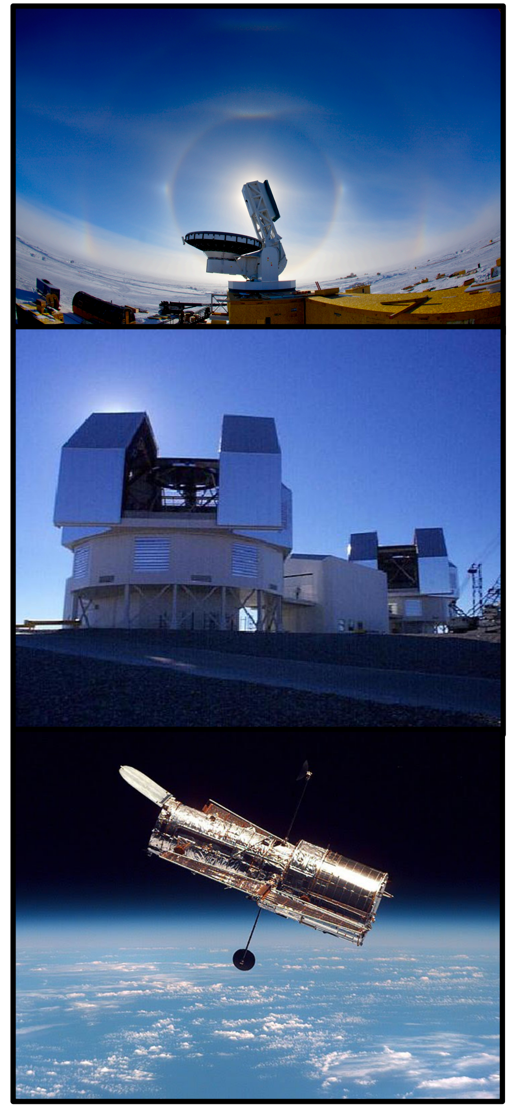
$$\zeta = A_{SZ}\left(\frac{M_{500}}{3\times10^{14}M_\odot h^{-1}}\right)^{B_{SZ}}\left(\frac{E(z)}{E(0.6)}\right)^{C_{SZ}}$$



Benson et al. (2011)

Summary

- Weak lensing quality data obtained for 33 clusters
  - 19 clusters at $0.3 < z < 0.6$ with Magellan/Megacam
  - 14 clusters at $0.6 < z < 1.3$ with HST/ACS
  - full SZ, X-ray, and spectroscopic overlap
- First look at 28 clusters
  - provides 14% direct mass calibration
  - shows weak evidence for low mass estimates
- Analysis now undergoing refinement and scrutiny
- ***First***
  - WL detections using Megacam at Magellan
  - direct calibration of code used on real data to N-body simulations
- *Matching the statistical power of the SPT_{CL} data set will require a sub-3% calibration of mass. SPT_{CL} poised to achieve $\delta w = 0.035$*
- Ancillary science



SPT

Magellan

HST

EXTRA SLIDES

Weak lensing

Observable quantity: reduced shear, *g*. $\gamma = (1 - \kappa) g$

Shear relates to mass via: $\langle \gamma_+ \rangle (R) = \frac{\langle \Sigma \rangle (< R) - \Sigma(R)}{\Sigma_{\rm crit}}.$

The signal is a function of lens and source redshifts through:

$$\Sigma_{\rm crit} = \frac{c^2}{4\pi G} \frac{1}{D_{\rm l} \beta},$$ where $$\beta \equiv D_{\rm ls} / D_s$$

A model for the project mass density, $\mathbf{\Sigma}$, determines both the shear and convergence, and therefore the reduced shear.

The key ingredients to weak lensing analyses are

1. estimating *reduced shear* and
2. estimating *source redshifts*.

Weak lensing

Advantages

1. Extremely simple theoretical relationship between *total mass* and observables
   - A key piece of evidence for the existence of dark matter
   - Independent of matter's dynamical state or history
2. Relatively straightforward to realistically simulate in the same *N*-body simulations that cosmological fitting functions are tuned to
   - Ray tracing
   - Source selection

Challenges

1. Accurately estimating reduced shear
   - Correct for the smearing and shearing by anisotropic point-spread functions
   - Cluster galaxies contaminate shear profiles
2. Accurately estimating source redshift distribution
   - Photo-z's are hard!
   - Availability of photo-z's at very faint magnitudes or very high redshift is scant

South Pole Telescope

- (Sub)millimeter wavelength telescope:
  - 10 meter aperture
  - 1’ FWHM beam at 150 GHz
  - Off-axis Gregorian optics design
  - 20 micron RMS surface accuracy
  - 1 arc-second pointing
  - Fast scanning, up to 4 deg/sec in azimuth
- SZ receiver:
  - 1 sq. deg FOV
  - ~960 background limited pixels
  - Observe in 3+ bands between 95-220 GHz simultaneously
  - Modular focal plane
- Polarimeters are currently deployed for CMB polarization and deep-SZ studies (SPTpol)