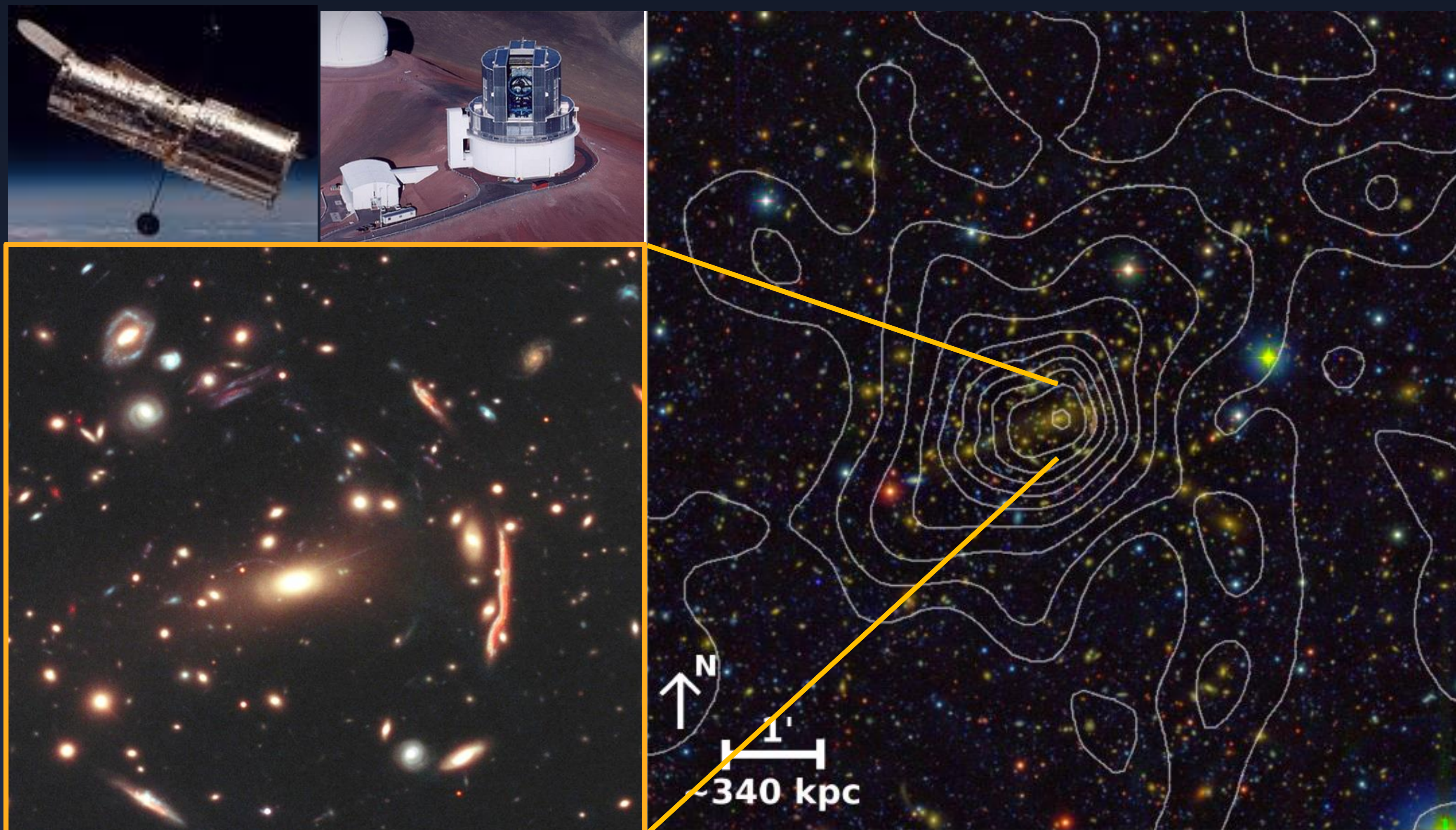
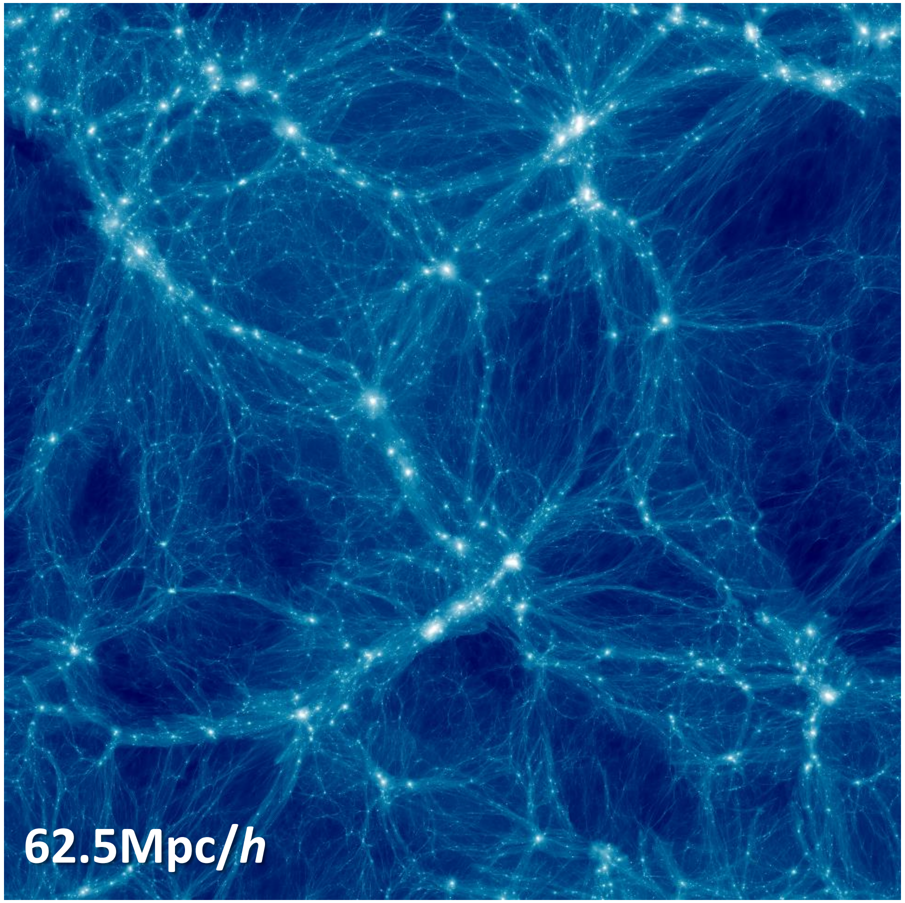
Characterizing Galaxy Clusters with Gravitational Lensing: Halo Shape and Splashback Radius

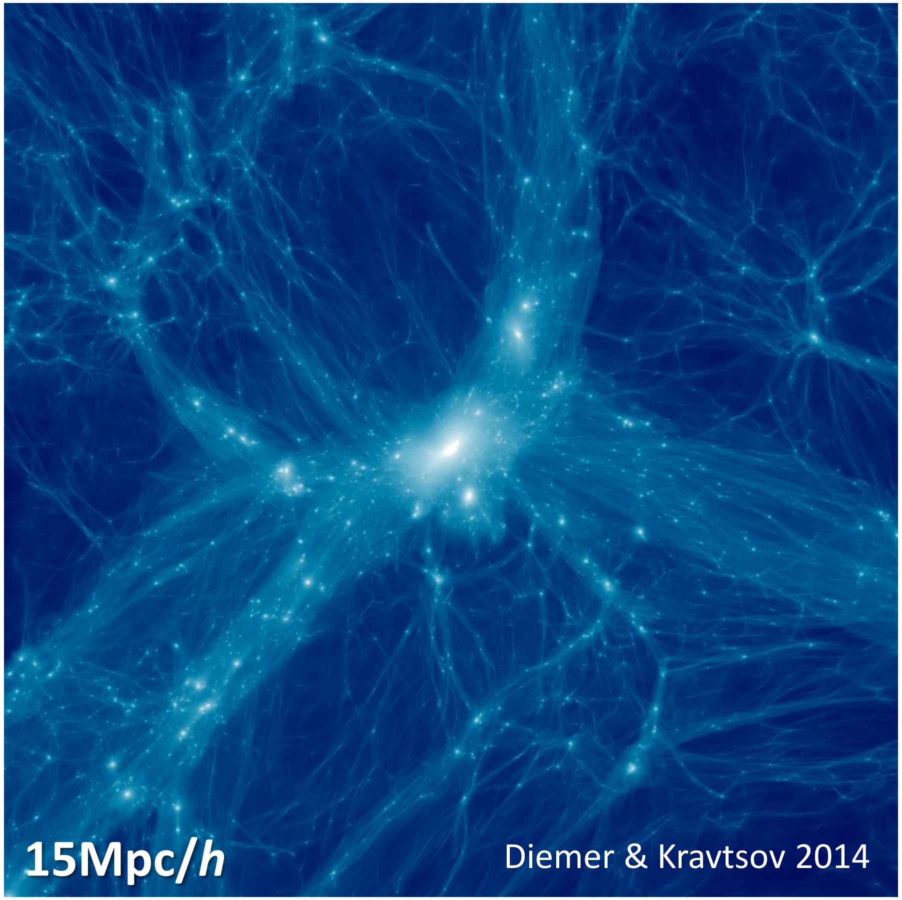


Keiichi Umetsu (ASIAA)

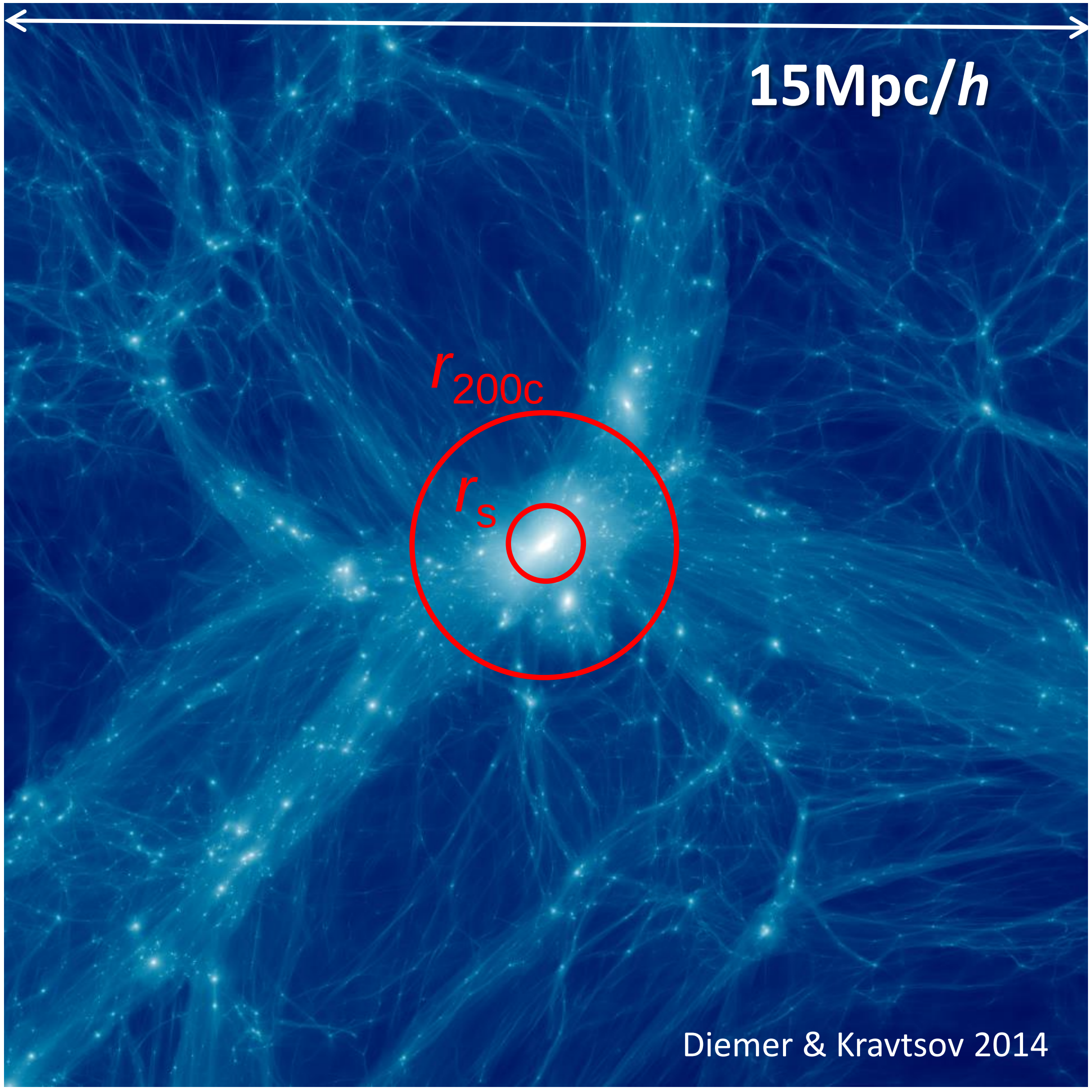
Galaxy clusters: Largest class of dark-matter halos

Space-time abundance of rare massive clusters is "exponentially" sensitive to cosmology AND their mass calibration





Cluster gravitational lensing



Key Objectives

Intra-halo structure

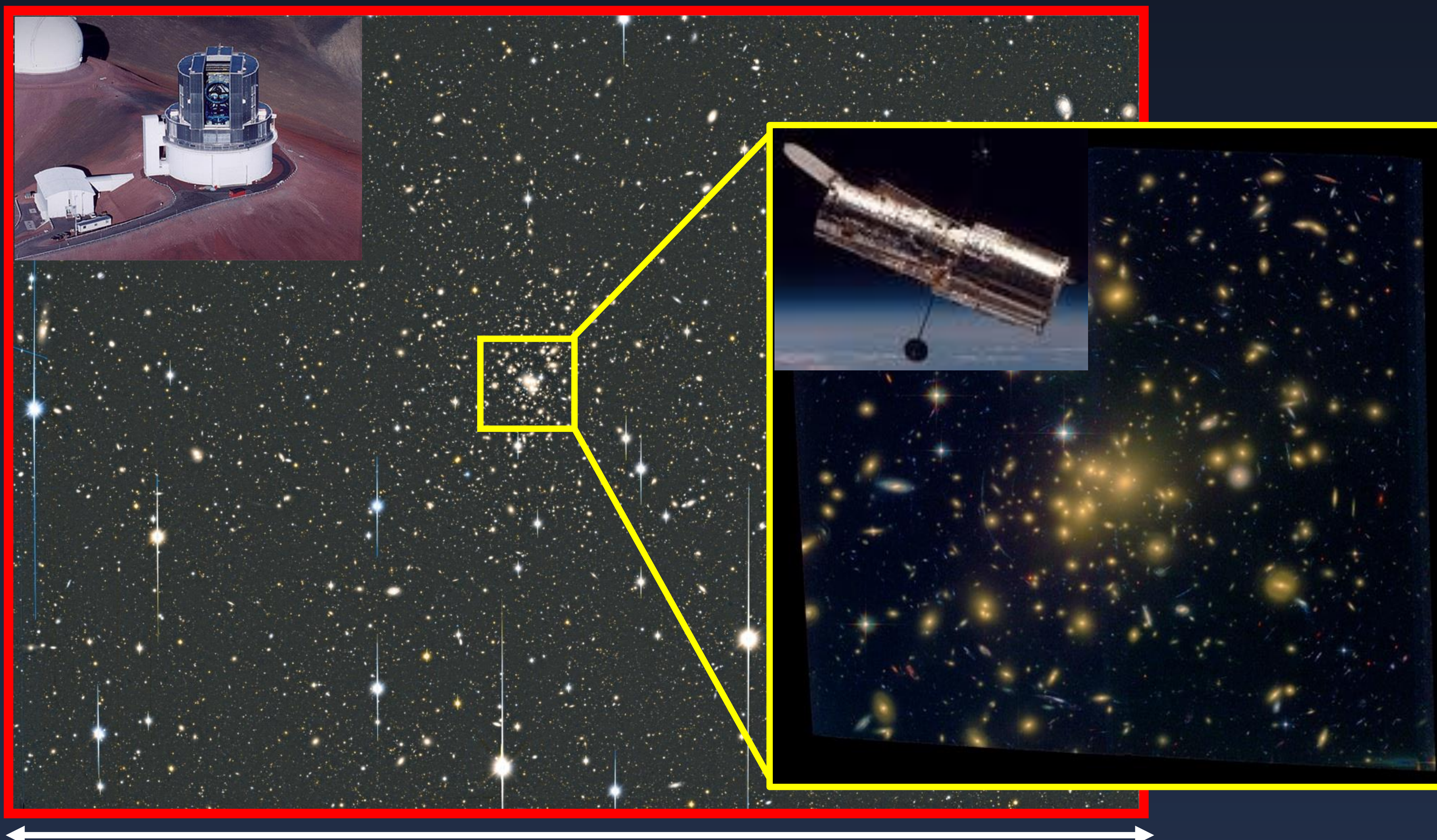
Density profile, $\rho(r)$
Halo mass, M_Δ
Concentration, $c_\Delta = R_\Delta / r_s$
Splashback radius, R_{sp}
Halo shape

Surrounding LSS

Halo bias $b_h(M)$
DM clustering strength, σ_8
Assembly bias

Subaru/Suprime-Cam multi-color imaging for wide-field weak lensing

High-resolution space imaging with *HST* (ACS/WFC3) for strong lensing



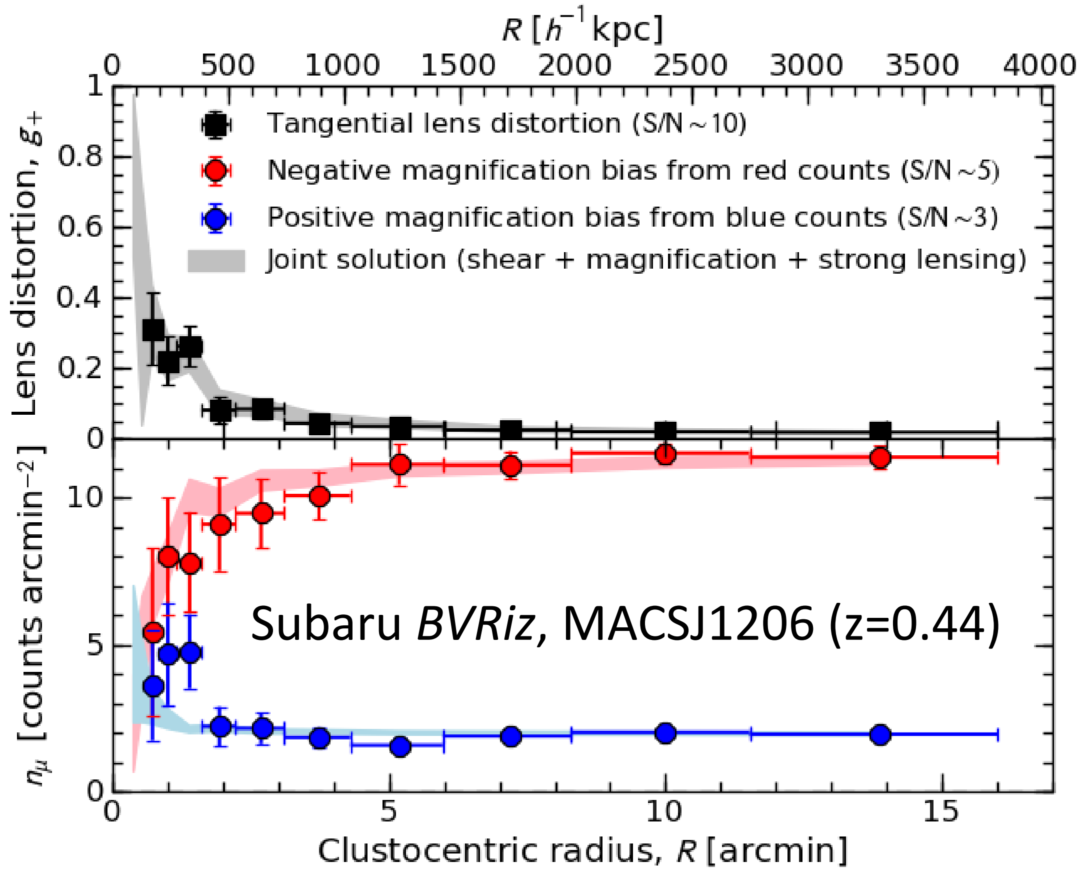
34 arcmin

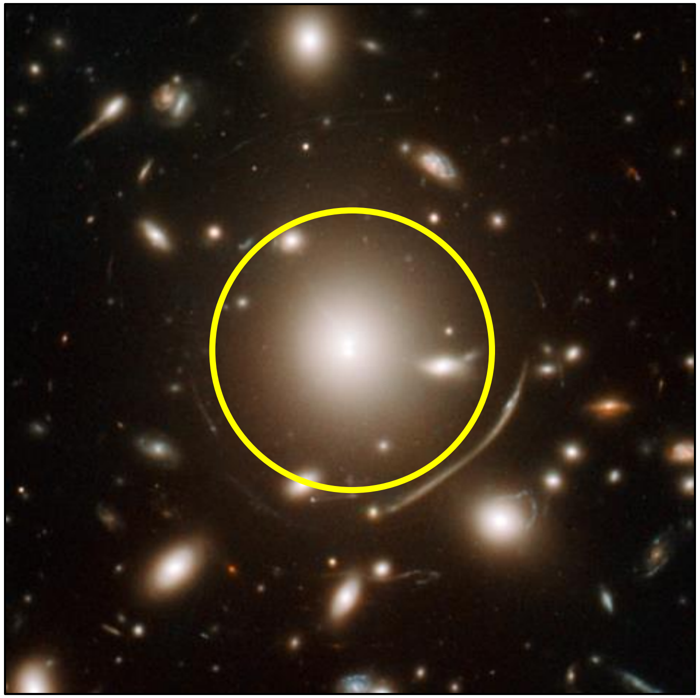
CLUMI (CLUster lensing Mass Inversion): Multi-probe lensing analysis

Combining strong-lensing, weak-lensing shear and magnification

$$\{M_{2\mathrm{D},i}\}_{i=1}^{N_{\mathrm{SL}}}, \{\langle g_{+,i}\rangle\}_{i=1}^{N_{\mathrm{WL}}}, \{\langle n_{\mu,i}\rangle\}_{i=1}^{N_{\mathrm{WL}}}.$$

$$P(\boldsymbol{\Sigma}|\mathrm{WL},\mathrm{SL}) \propto P(\mathrm{WL},\mathrm{SL}|\boldsymbol{\Sigma})P(\boldsymbol{\Sigma}) = P(\boldsymbol{n}_\mu|\boldsymbol{\Sigma})P(\boldsymbol{g}_+|\boldsymbol{\Sigma})P(\boldsymbol{M}_{2D}|\boldsymbol{\Sigma})P(\boldsymbol{\Sigma})$$

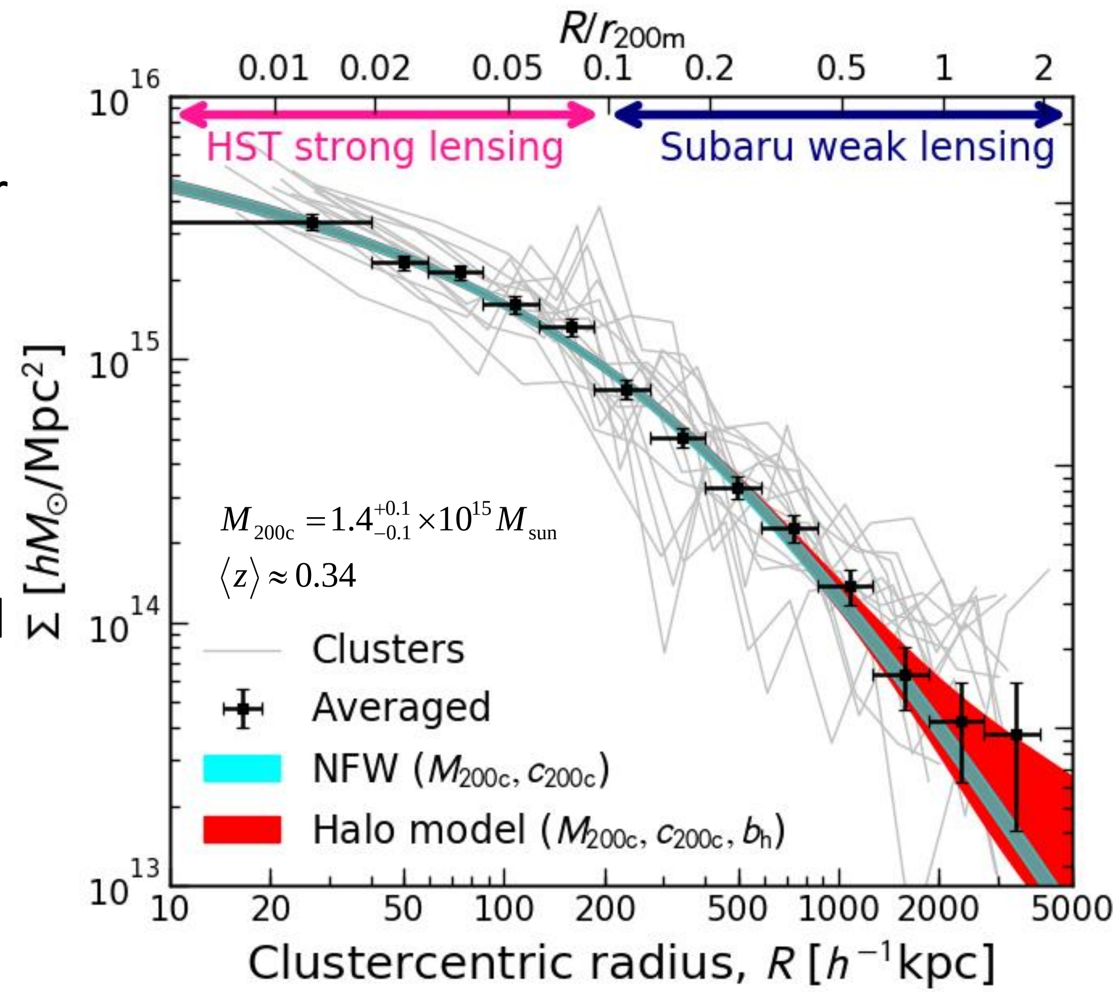




Umetsu 2013, *ApJ*, 769, 13

Ensemble Cluster Mass Profile (CLASH)

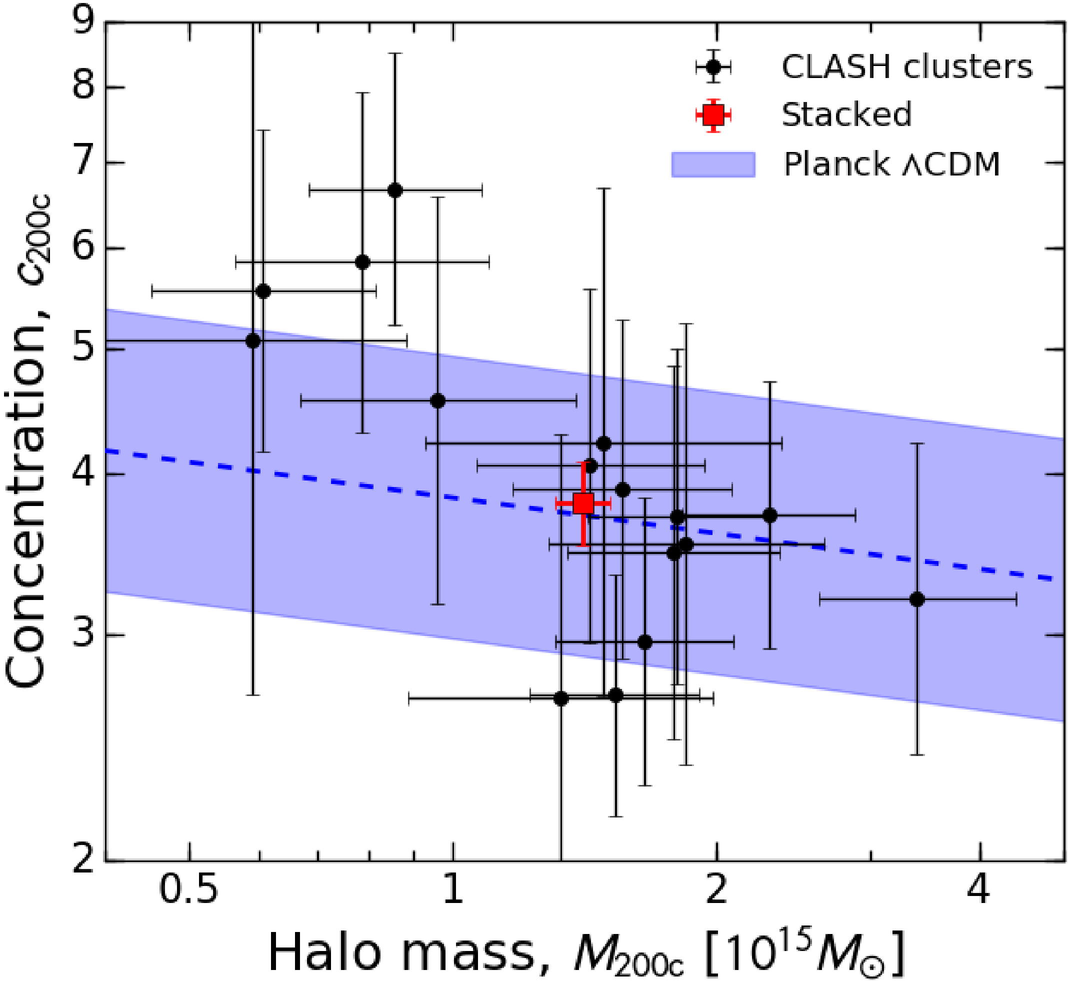
- Combining strong and weak lensing allows measurements of cluster density profiles over a wide dynamic range.
- The stacked profile is well described by cuspy, outward-steepening density profiles as predicted for CDM-dominated halos.
- Cored profiles (e.g., Burkert) are disfavored by the data.
- Both strong and weak lensing are needed!!!



Umetsu+16, *ApJ*, 821, 116
Merten+15, *ApJ*, 806, 4

Concentration vs. Mass (CLASH)

The $c(M)$ relation is sensitive to the shape and normalization of $P(k)$



Data consistent with *c*-*M* relations calibrated for recent ΛCDM cosmologies

Low mass excess is due to X-ray cluster selection

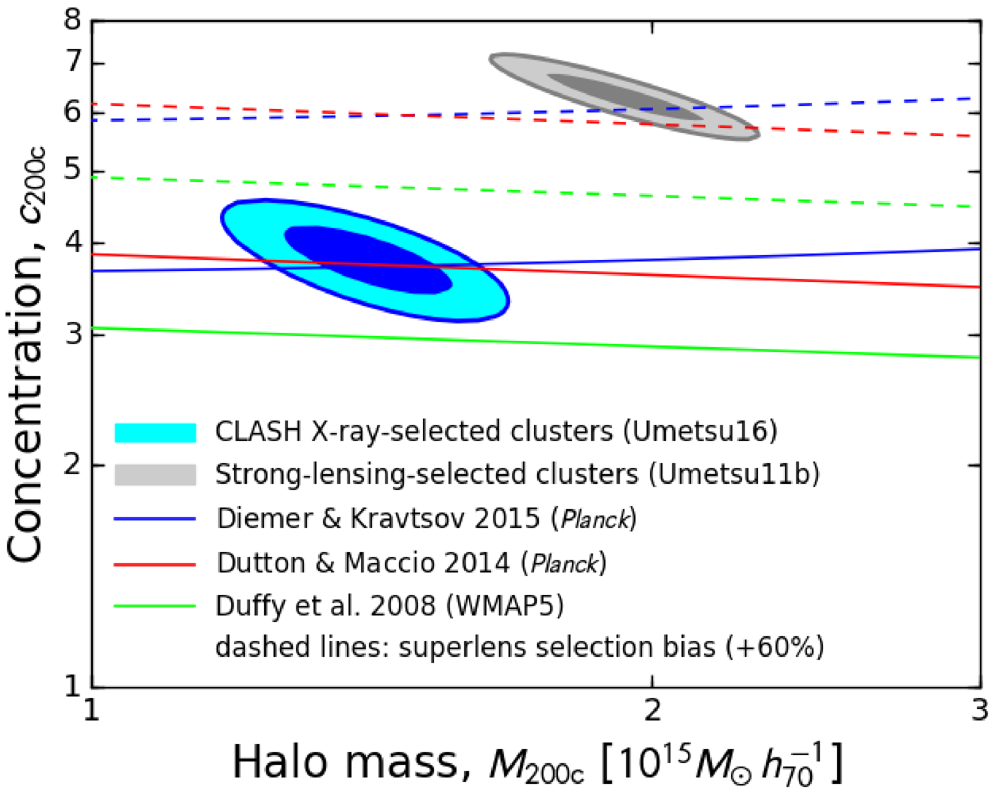
$$c_{200c} = 3.79^{+0.30}_{-0.28}$$

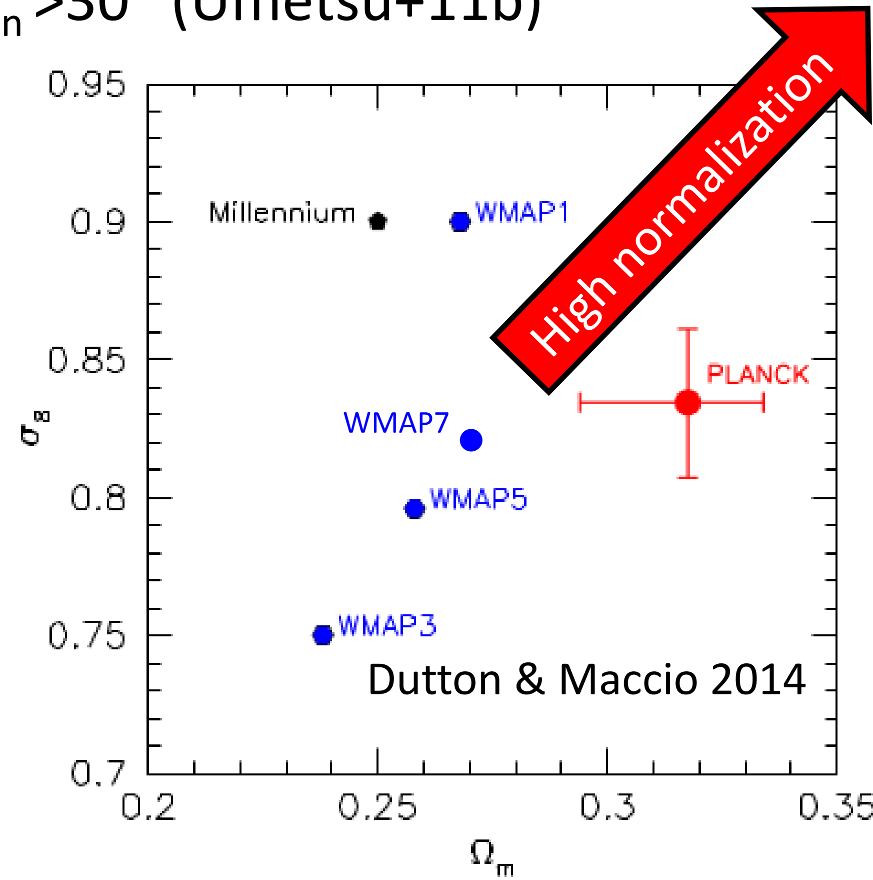
$$\text{at } M_{200c} = 1.4^{+0.1}_{-0.1} \times 10^{15} M_{sun}$$

Umetsu+16, *ApJ*, 821, 116
Merten+15, *ApJ*, 806, 4C

CLASH vs. Superlens Clusters

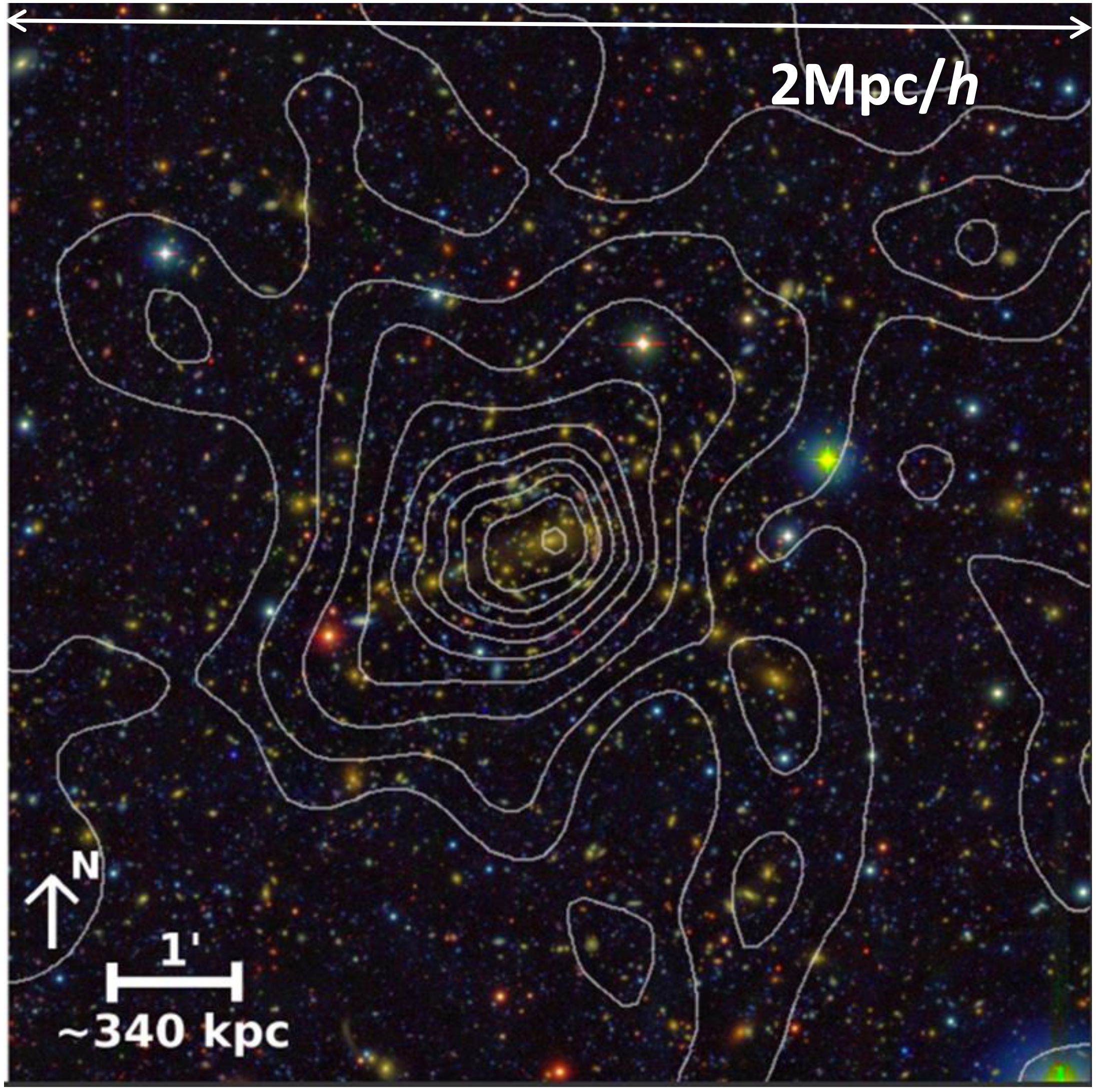
- **X-ray selected** CLASH clusters (Umetsu+16)
- **Superlens** clusters with $R_{\rm Ein}$ >30" (Umetsu+11b)





Umetsu+16, *ApJ*, 821, 116

Cluster gravitational lensing



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DM clustering strength, σ_8
Assembly bias

J. Merten's SaWLens reconstruction of MACS1206 (Umetsu+12, *ApJ*, 755, 56)

Splashback Radius of Galaxy Clusters

Umetsu & Diemer 2017, *ApJ*, 836, 231

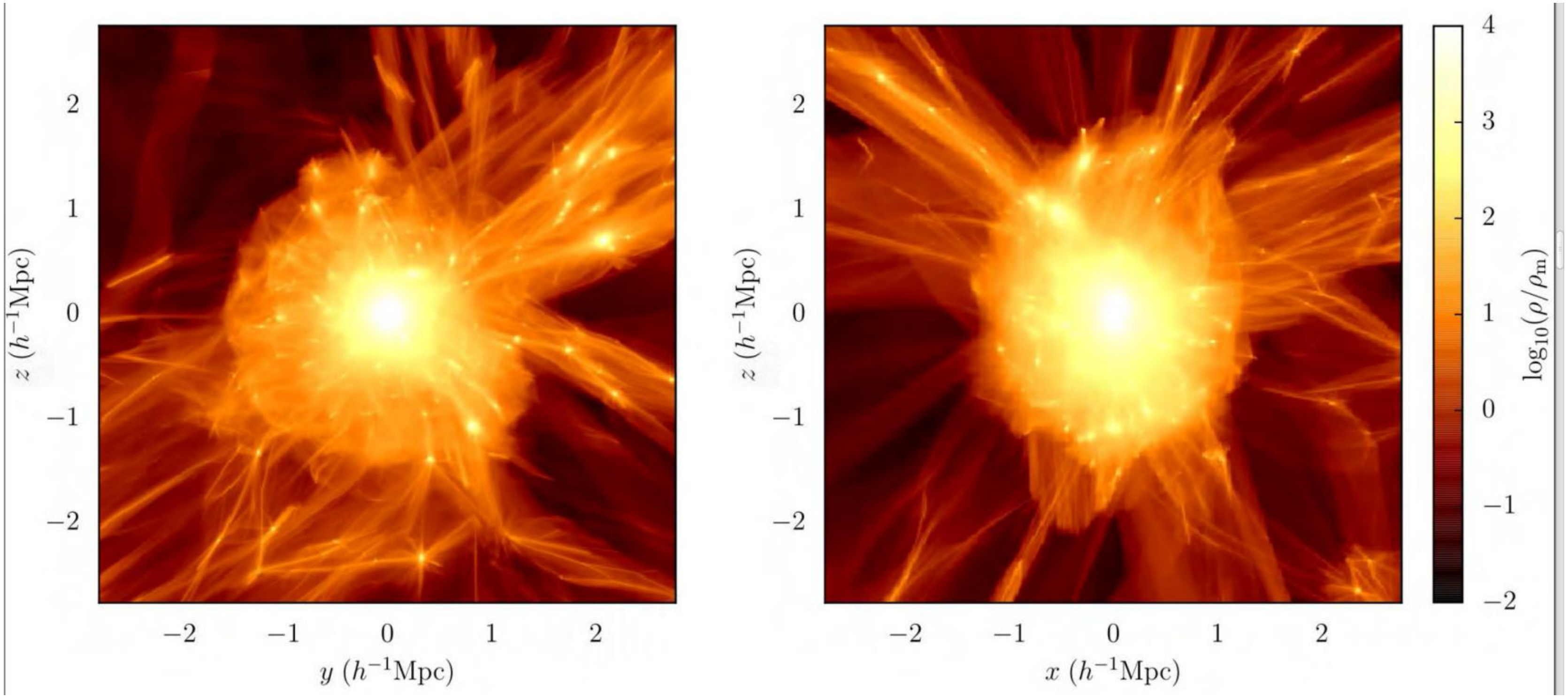
Okumura, Nishimichi, Umetsu, & Osato 2017, arXiv:1706.08860 (submitted to PRL)

Splashback radius, R_{sp}: Physical halo boundary

$r > R_{sp}$: outer infall region
$r < R_{sp}$: multi-stream intra-halo region

Slow accreting halos — $R_{sp} >> R_{200m}$

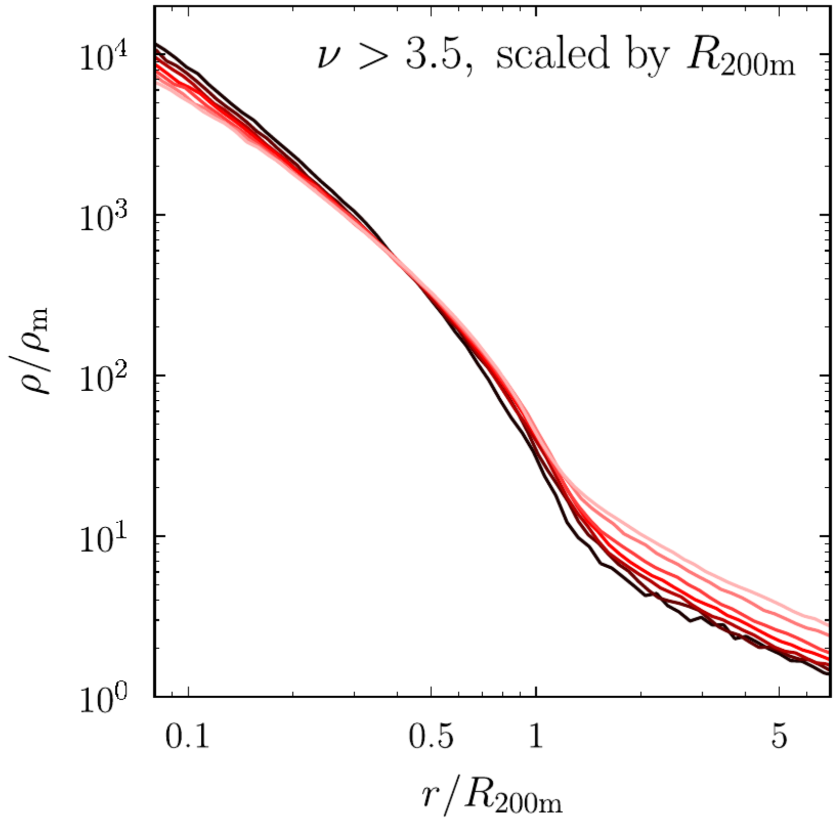
Fast accreting halos — $R_{sp} \sim R_{200m}$

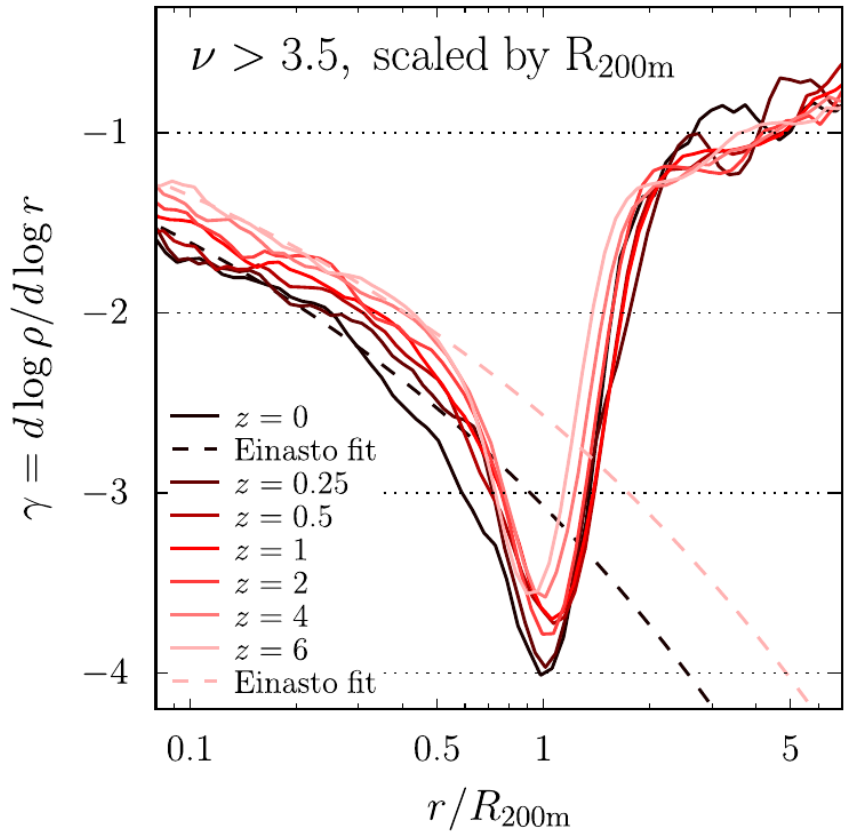


More, Diemer, & Kravtsov 2015

Splashback feature in real space

Steepest "3D" gradient point as splashback radius R_{sp}





N-body simulations (Diemer & Kravtsov 14, DK14)

Splashback feature in real and velocity space

Intrinsic Alignments and Splashback Radius of Dark Matter Halos from Cosmic Density and Velocity Fields

Teppei Okumura,[1,*] Takahiro Nishimichi,[2,3] Keiichi Umetsu,[1] and Ken Osato[4]

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[2] *Kavli Institute for the Physics and Mathematics of the Universe (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba 277-8583, Japan*
[3] *CREST, JST, 4-1-8 Honcho, Kawaguchi, Saitama, 332-0012, Japan*
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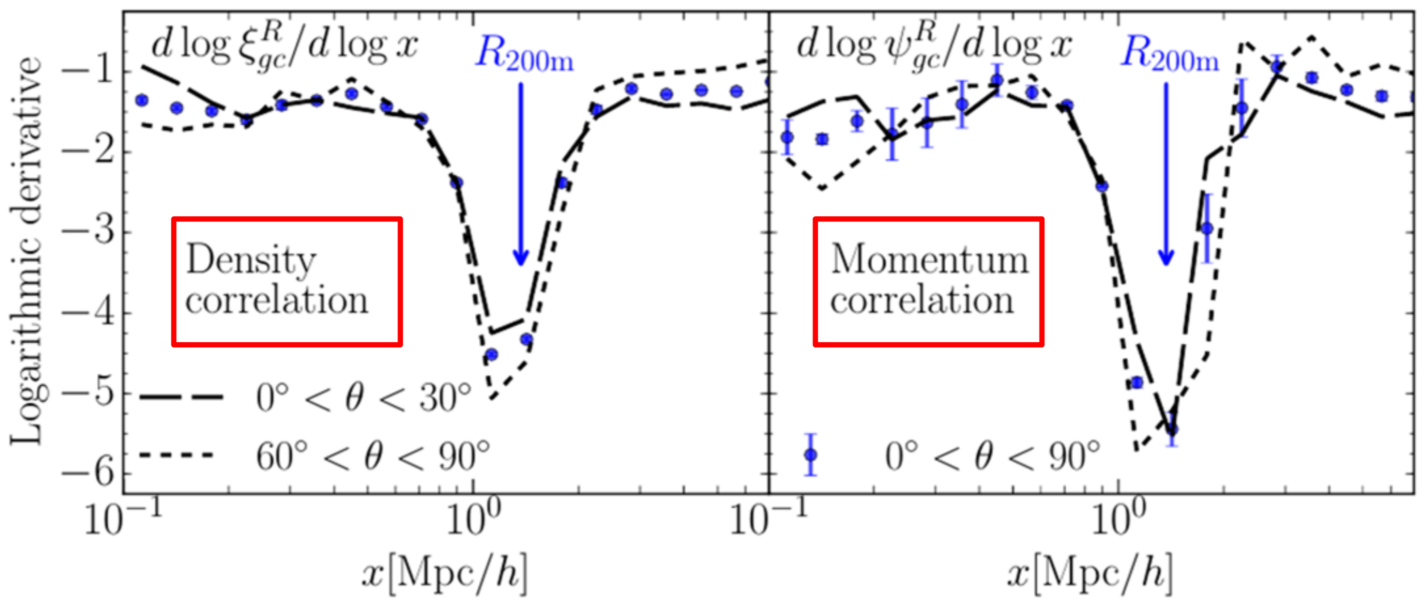
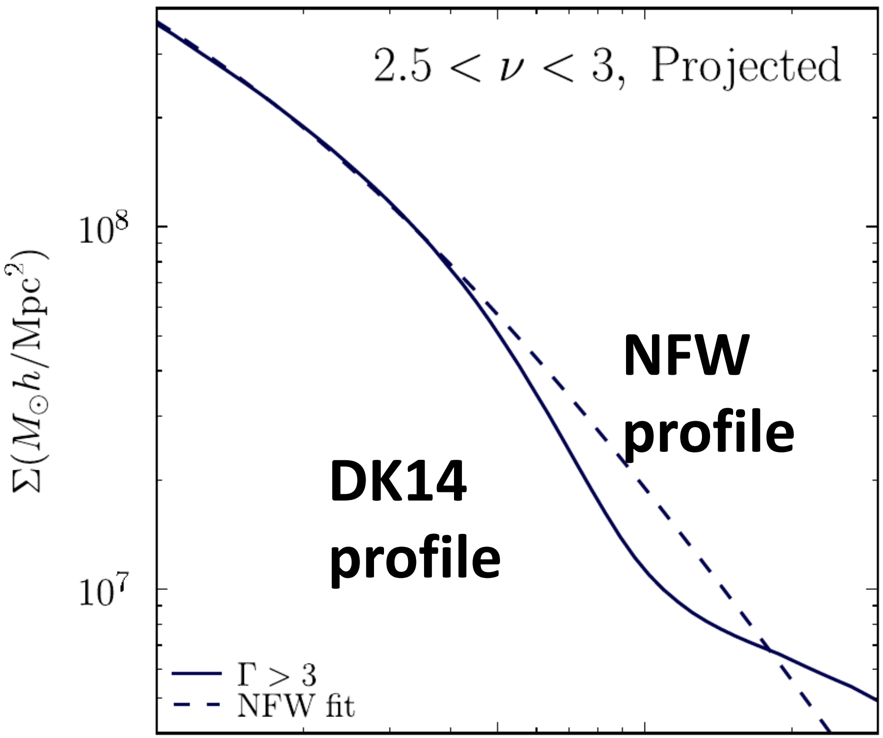
(Dated: July 4, 2017)

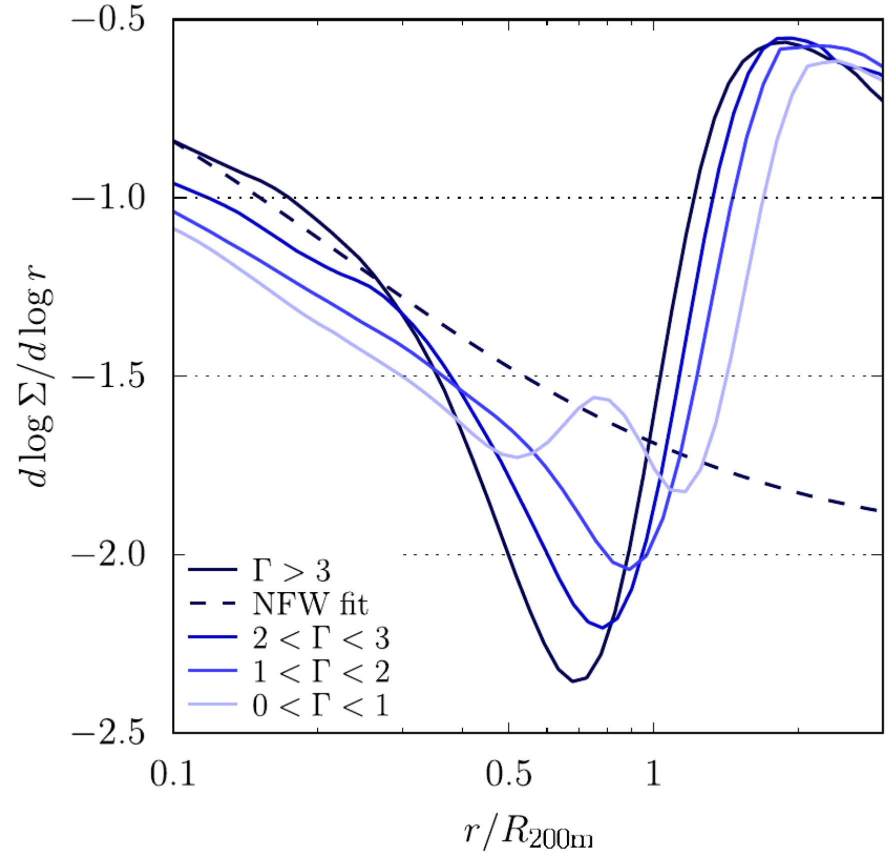
arXiv:1706.08860

Cluster-galaxy correlations from *N*-body simulations



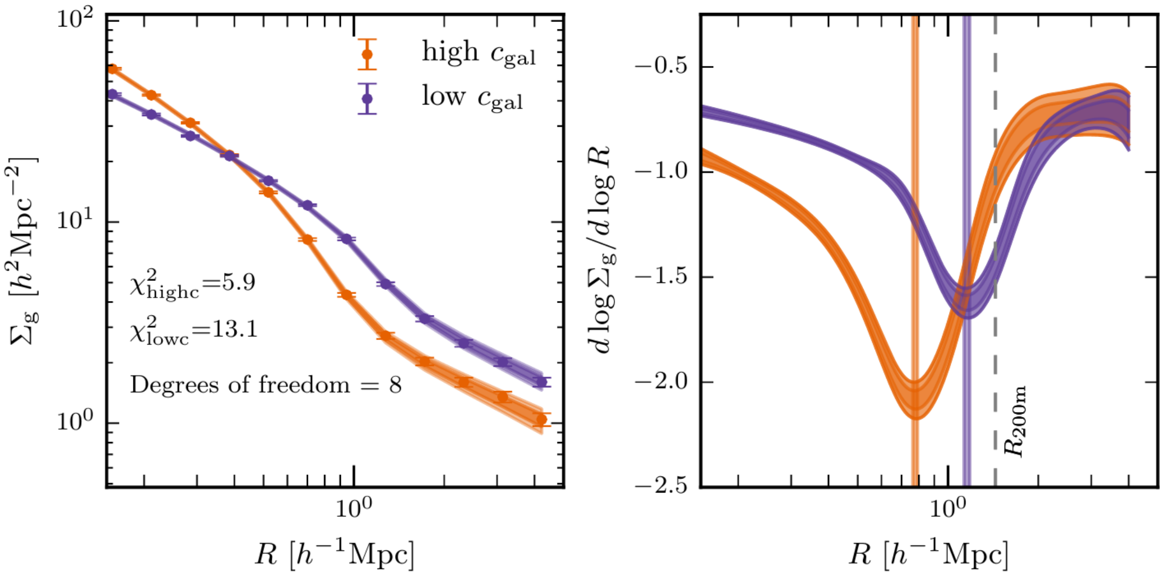
Splashback feature in projected density



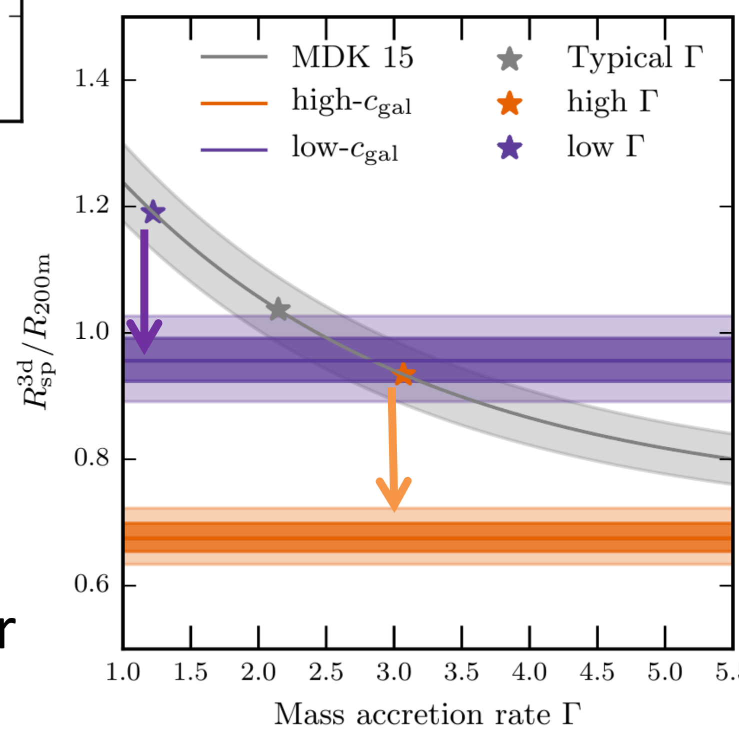


N-body simulations (DK14)

Splashback in surface number density profiles of cluster galaxies?

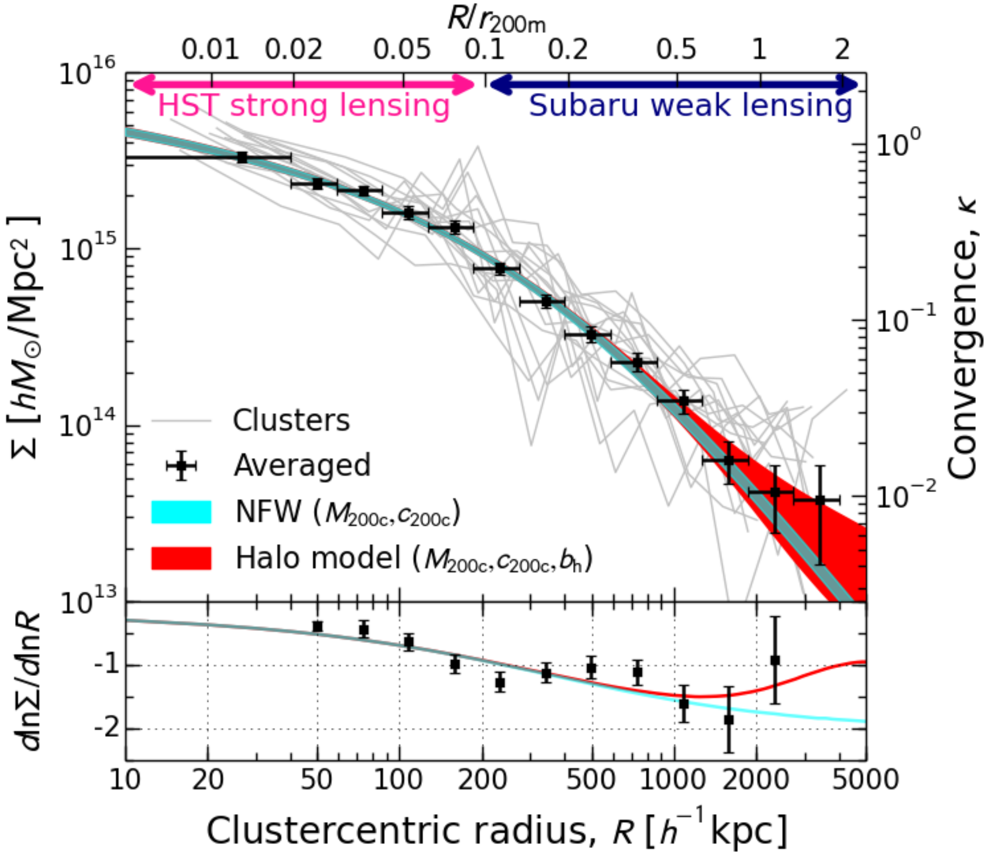


Projected galaxy distribution around SDSS/DR8 redMaPPer clusters (More+16, *ApJ*, 825, 39)



- Splashback feature detected using "galaxies", instead of "mass"
- However, observed $R_{\rm sp}$(gal)/$R_{\rm 200m}$(WL) values are *significantly smaller* than predicted!
- Likely due to projection effects in cluster membership identification (Zu et al. 16)

Splashback in CLASH lensing data?



CLASH X-ray regular subsample prevalently composed of relaxed clusters (70%; Meneghetti+14)

$$\langle M_{200\mathrm{m}} \rangle = (1.3 \pm 0.1) \times 10^{15} h^{-1} M_{\mathrm{sun}}$$

$$\langle \nu_{200\mathrm{m}} \rangle = 4.0 \pm 0.1$$

16 clusters with $\langle z \rangle \cong 0.34$

Umetsu+16, *ApJ*, 821, 116

- CLASH spans a factor of 5 (1.7) in mass (radius), so that sharp gradient feature is washed out when stacked in physical units.
- How to extract R_{sp} from coarsely binned ensemble profiles?

Solution: Parametric forward modeling of “scaled” cluster lensing profiles

Mass distribution around halos in ΛCDM (DK14)

$$\Delta\rho(r) = \rho(r) - \rho_{\rm m} = \rho_{\rm inner} \times f_{\rm trans} + \rho_{\rm outer}$$

A scaled version of DK14 density profile:

$$\begin{aligned}\Delta\rho(r = r_\Delta x) &= \mathcal{N}\left\{\exp\left[-\frac{2}{\alpha}c_\Delta^\alpha(x^\alpha - 1)\right]\left[1 + \left(\frac{x}{\tau_\Delta}\right)^\beta\right]^{-\gamma/\beta} + \frac{B_\Delta}{\epsilon_\Delta + x^{s_{\rm e}}}\right\} \\ &\propto f_{\rm inner}(x) f_{\rm trans}(x) + f_{\rm outer}(x),\end{aligned}$$

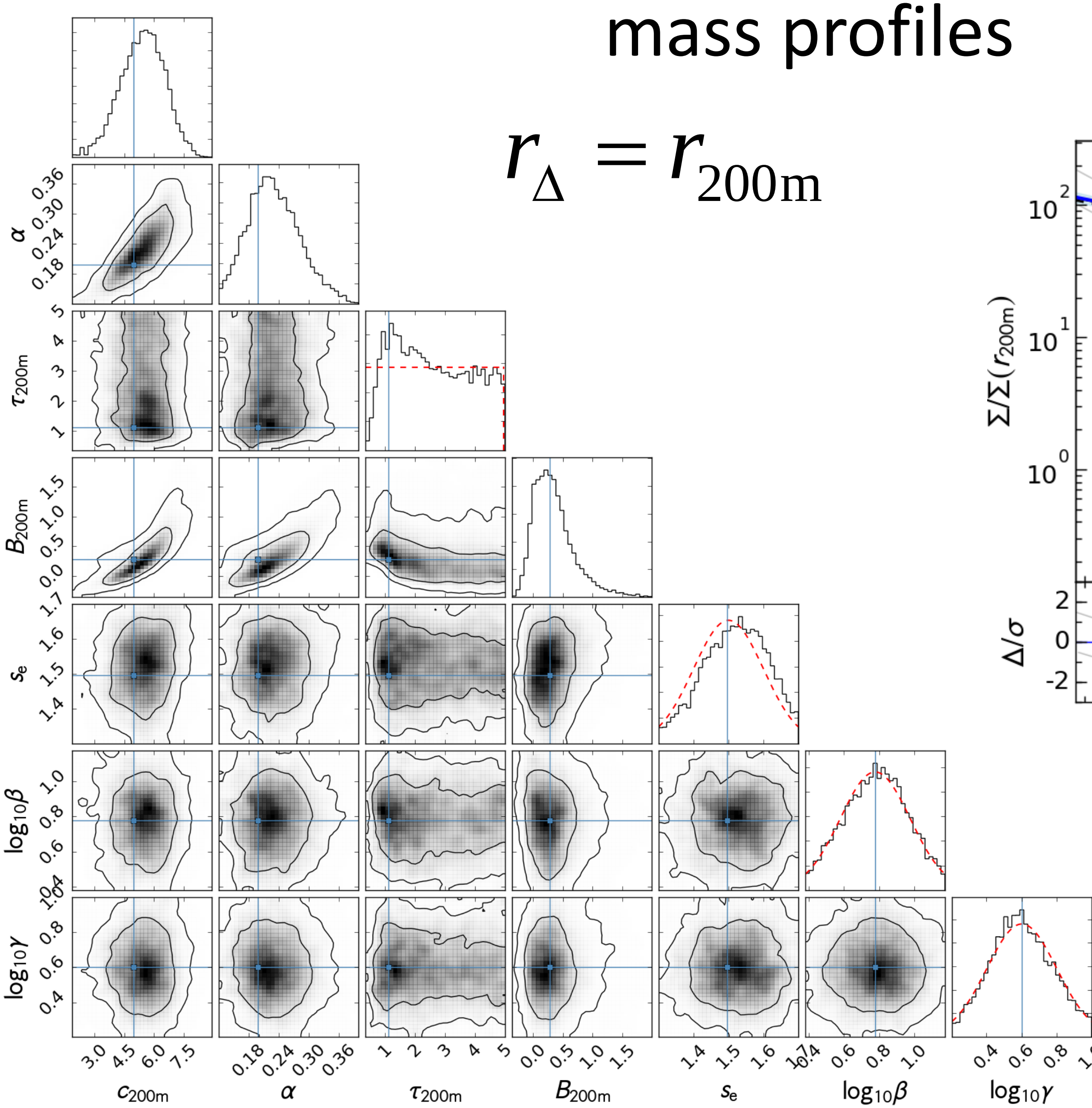
$$y(x) := \frac{\Sigma(R = r_\Delta x)}{\Sigma(r_\Delta)}$$

specified by $\boldsymbol{p} = \{c_\Delta, \alpha, \tau_\Delta, B_\Delta, s_{\rm e}, \beta, \gamma\}$

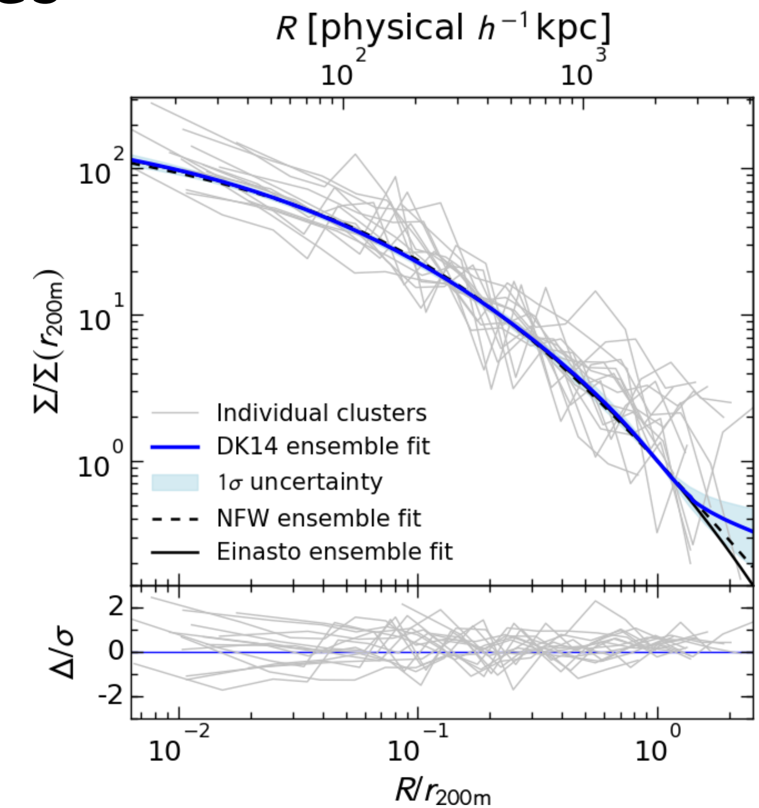
We marginalize over nuisance shape parameters ($s_{\rm e}$, β, γ) using “generic” priors found from *N*-body simulations of DK14

Umetsu & Diemer 17, *ApJ*, 836, 231

Application to CLASH: Universality of cluster mass profiles



$$r_\Delta = r_{200m}$$

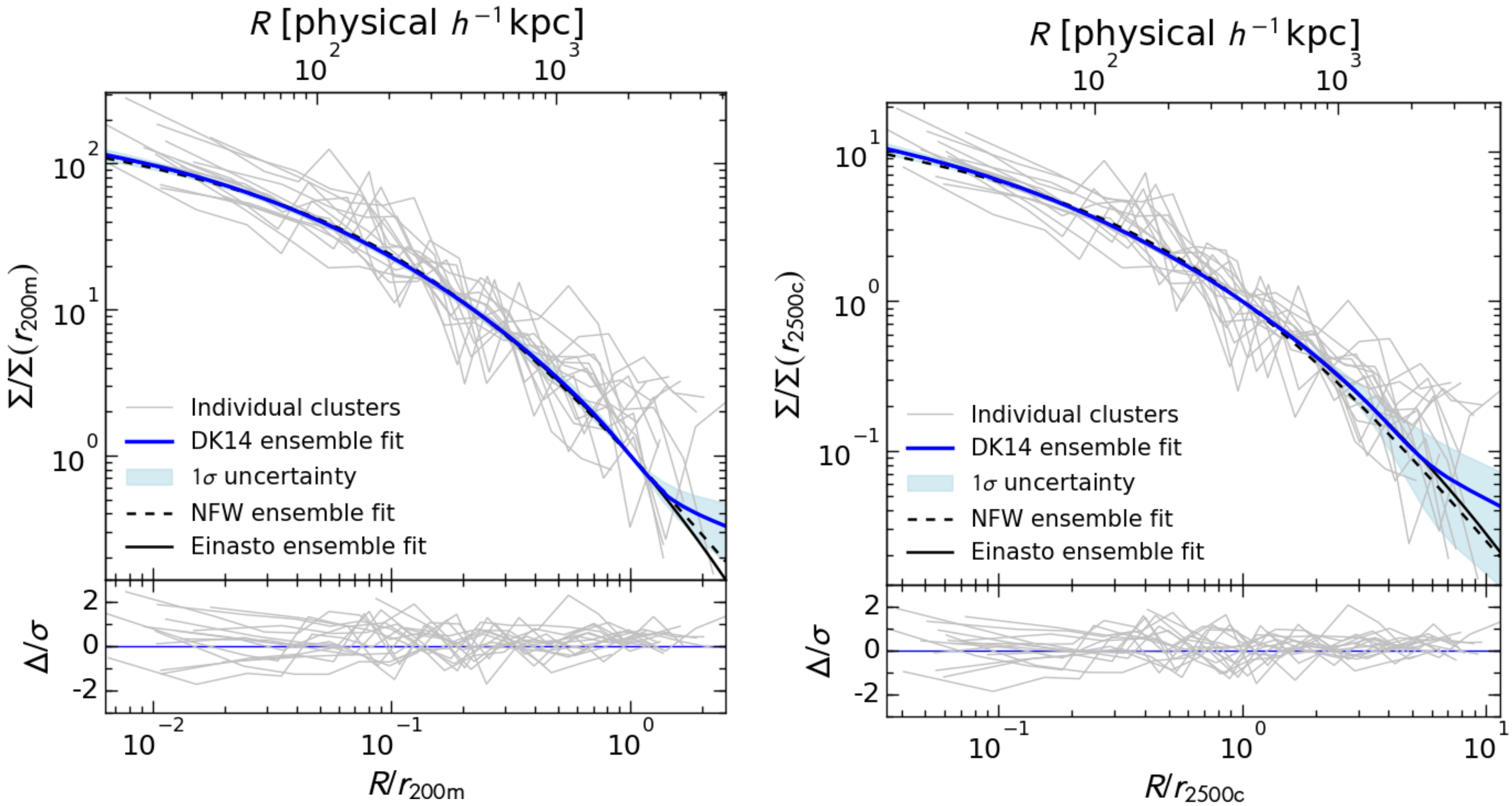


Umetsu & Diemer 17

Results: CLASH scaled density profiles

$r_\Delta = r_{200\mathrm{m}}$

$r_\Delta = r_{2500\mathrm{c}} \sim 0.2 r_{200\mathrm{m}}$

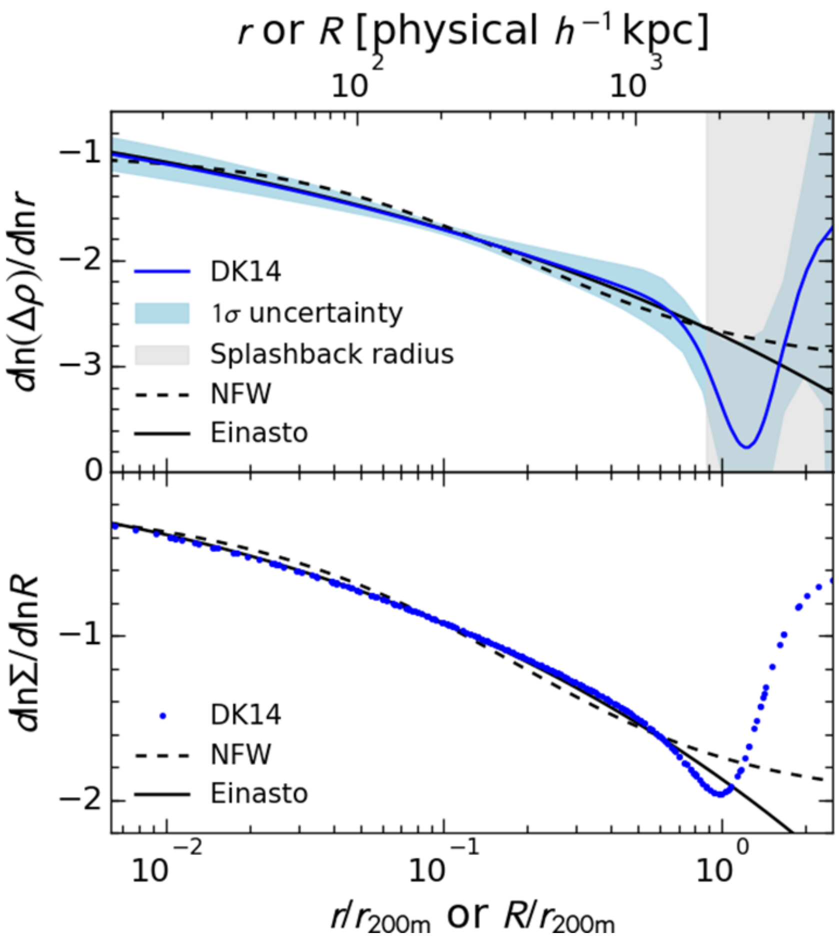


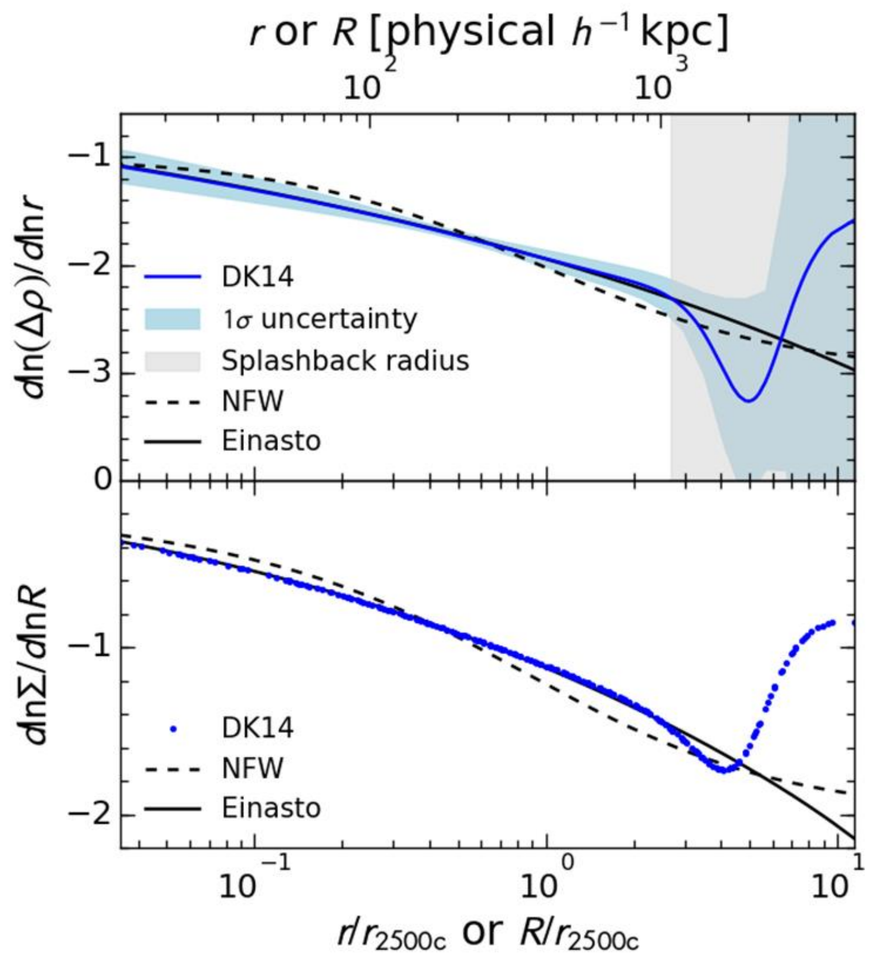
Umetsu & Diemer 17

Results: CLASH logarithmic density gradient

$r_\Delta = r_{200\mathrm{m}}$

$r_\Delta = r_{2500\mathrm{c}} \sim 0.2 r_{200\mathrm{m}}$





Umetsu & Diemer 17

Constraints on Splashback R_{sp} & M_{sp}

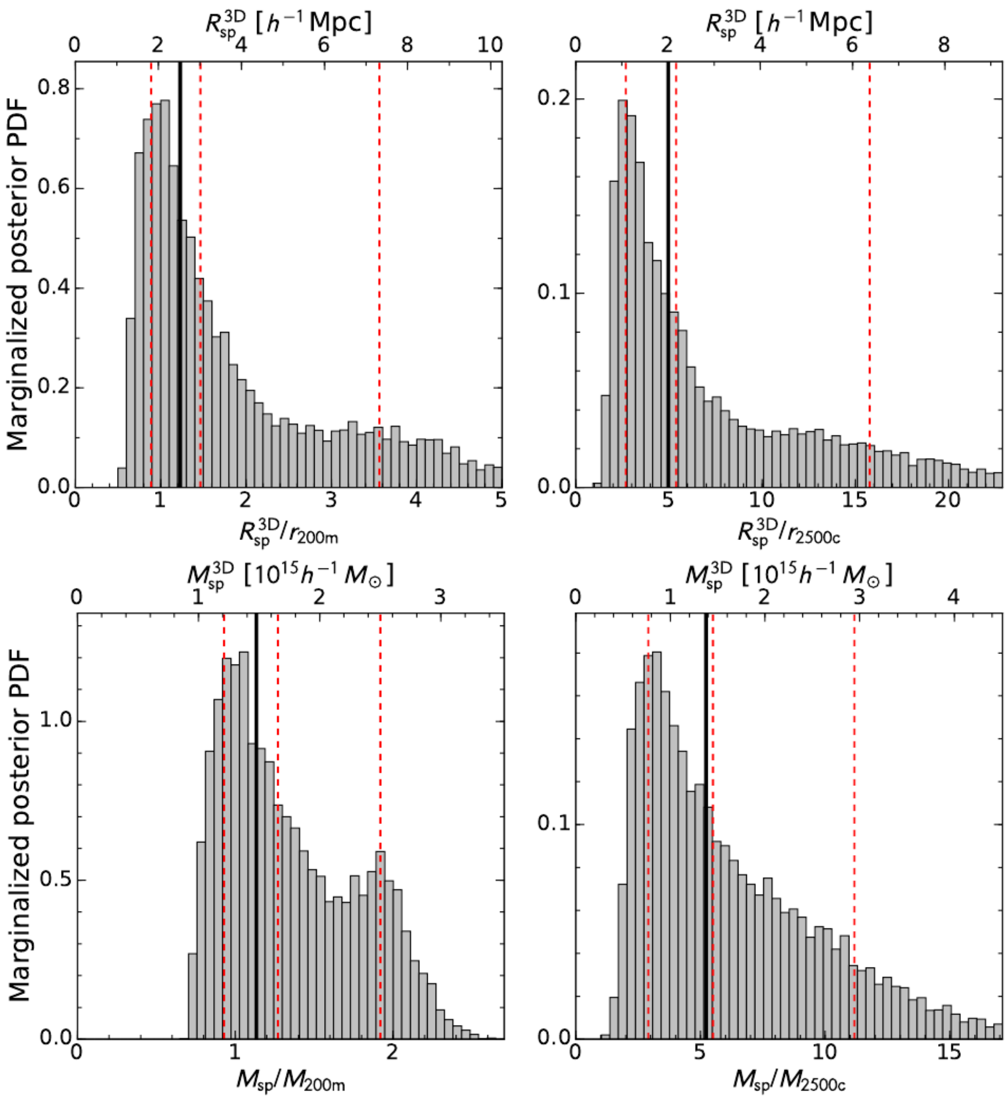


Table 3
Constraints on the Splashback Radius and Mass

Δ	R_{sp}^{3D}/r_{Δ}	R_{sp}^{3D} (Mpc/h)	M_{sp}/M_{Δ}	M_{sp} ($10^{15} M_{\odot}/h$)
200m	> 0.89 (1.23)	> 1.83 (2.52)	> 0.93 (1.13)	> 1.21 (1.48)
virial	> 0.91 (1.52)	> 1.67 (2.78)	> 0.94 (1.30)	> 1.13 (1.56)
200c	> 1.04 (1.90)	> 1.52 (2.79)	> 1.03 (1.55)	> 1.04 (1.57)
500c	> 1.37 (3.09)	> 1.30 (2.94)	> 1.31 (2.39)	> 0.90 (1.64)
2500c	> 2.69 (4.96)	> 1.09 (2.00)	> 2.91 (5.22)	> 0.77 (1.38)

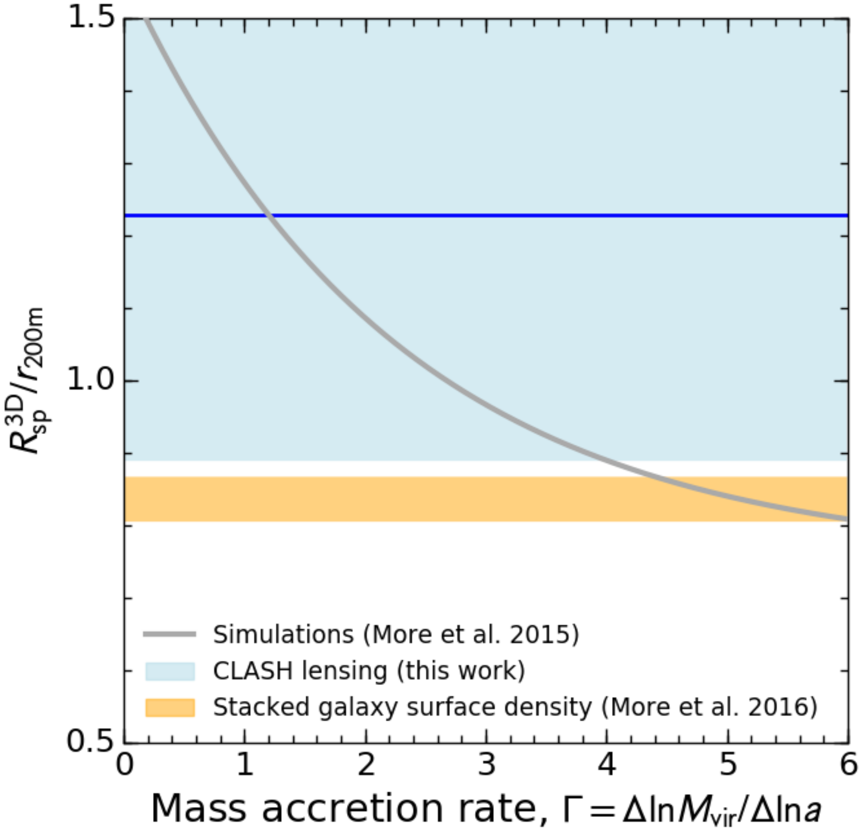
Note. — Lower limits (68% CL) and best-fit model values (in parentheses) for the three-dimensional splashback radius and mass. The splashback radius and mass in physical length units were converted using the effective overdensity radius $r_{\Delta}^{\rm eff}$ and mass $M_{\Delta}^{\rm eff}$ of the sample, respectively.

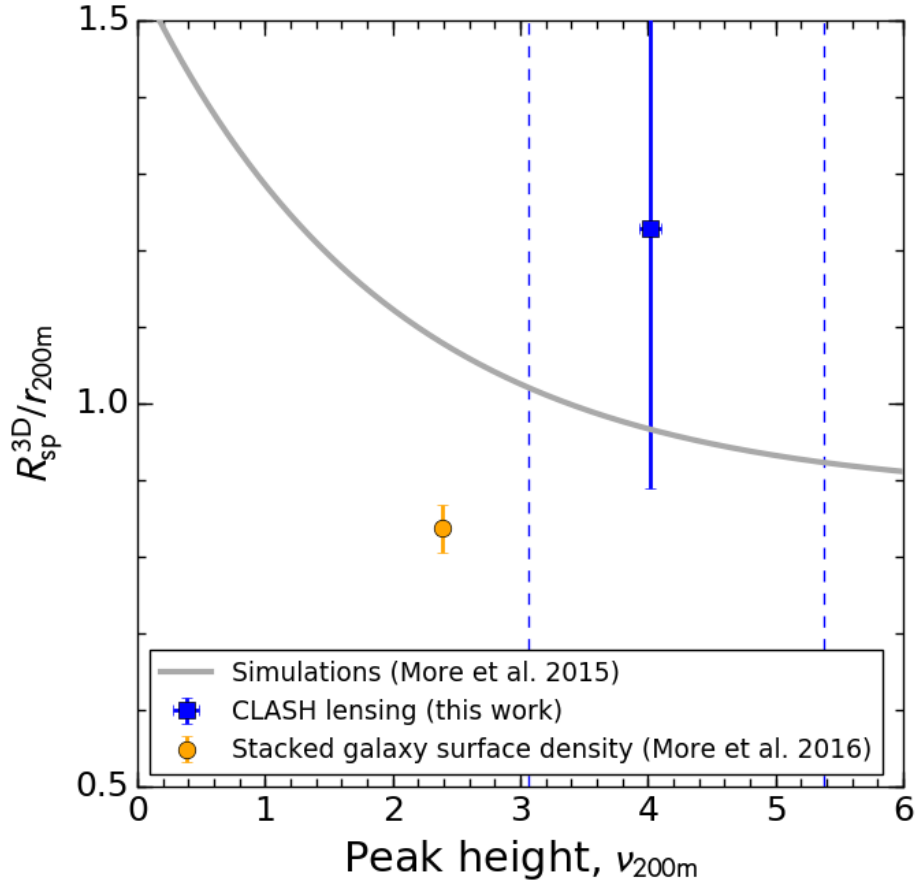
Tighter lower bounds on (R_{sp}, M_{sp}) obtained when cluster profiles are normalized to outer halo radii (r_{200m})

Umetsu & Diemer 17

First lensing constraints on $R_{\rm sp}$

$$R_{\rm sp}^{\rm 3D}/r_{\rm 200m} > 0.89\,(1\sigma) \Rightarrow \quad \Gamma := \frac{\Delta \ln M_{\rm vir}}{\Delta \ln a} < 4.0\,(1\sigma)$$





CLASH data consistent with a representative range of MAR

Cluster Halo Shape from Weak Lensing

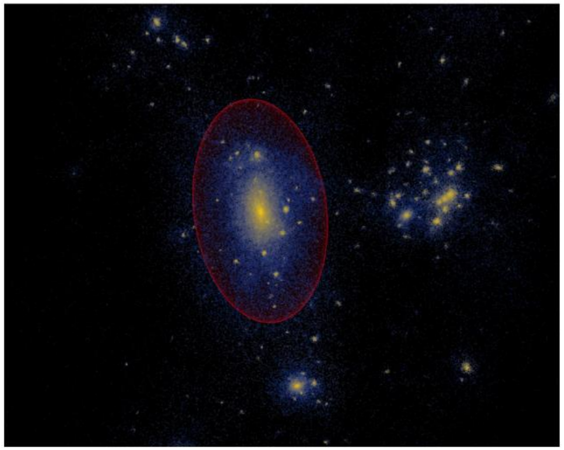
In collaboration with CLASH and CLUMP-3D: Mauro Sereno, I-Non Chiu, Stefano Ettori, Julian Merten, Jack Sayers et al.

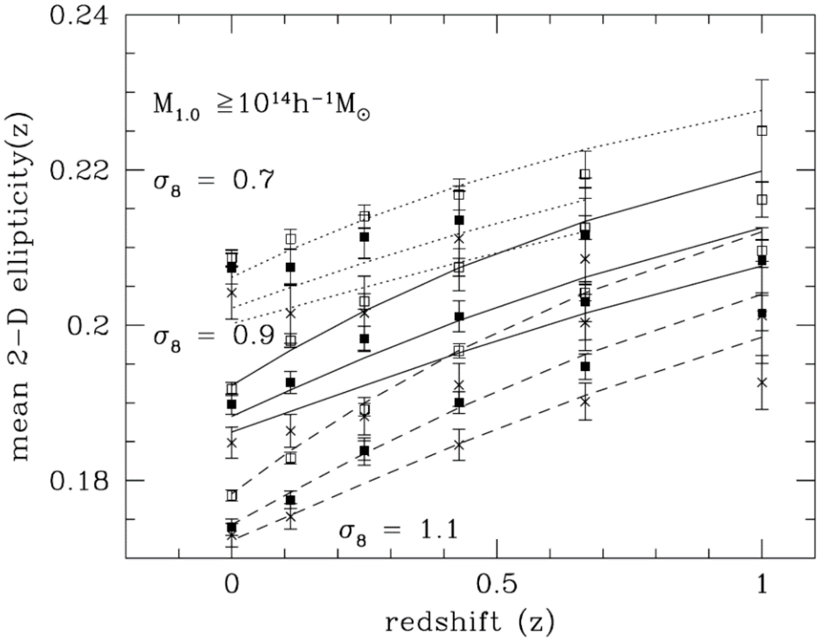
For SaWLens-2, see Julian's talk

See I-Non Chiu and Mario Bonamigo's talks on Thursday

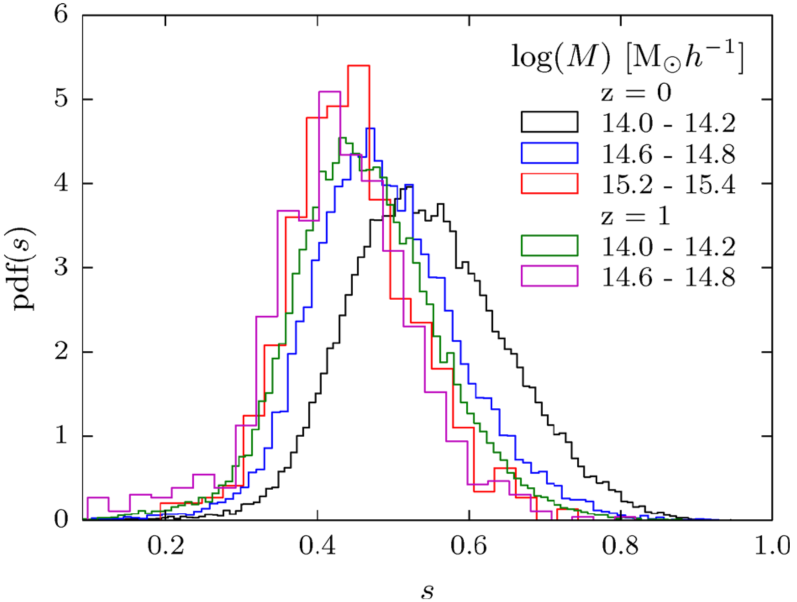
Halo shape as a cosmological probe

- Aspherical halo shape due to collisionless DM nature
- Halo shape depends on σ8 and halo mass
- Dynamically young halos tend to be more prolate



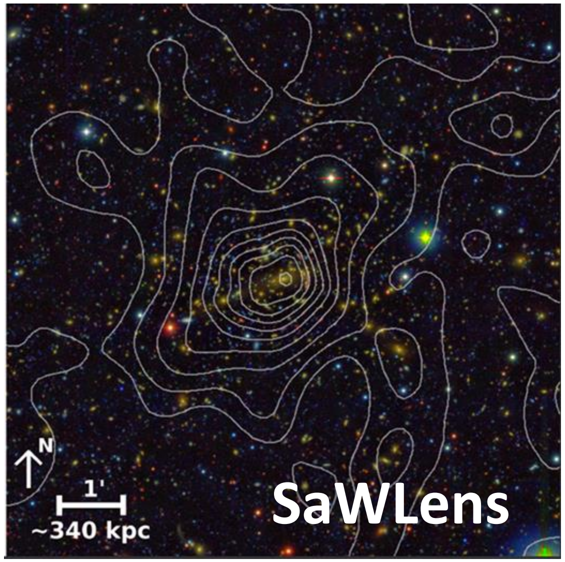


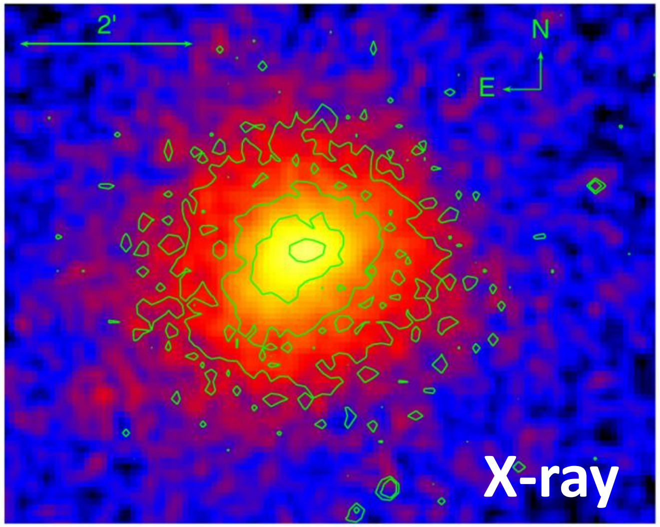
Ho+06



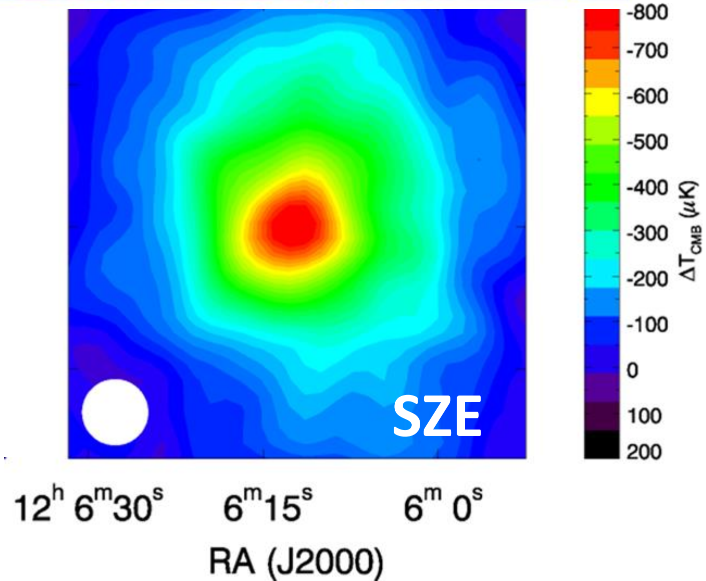
Bonamigo+!5

2D halo shape in lensing, optical (BCG), X-ray, and SZE



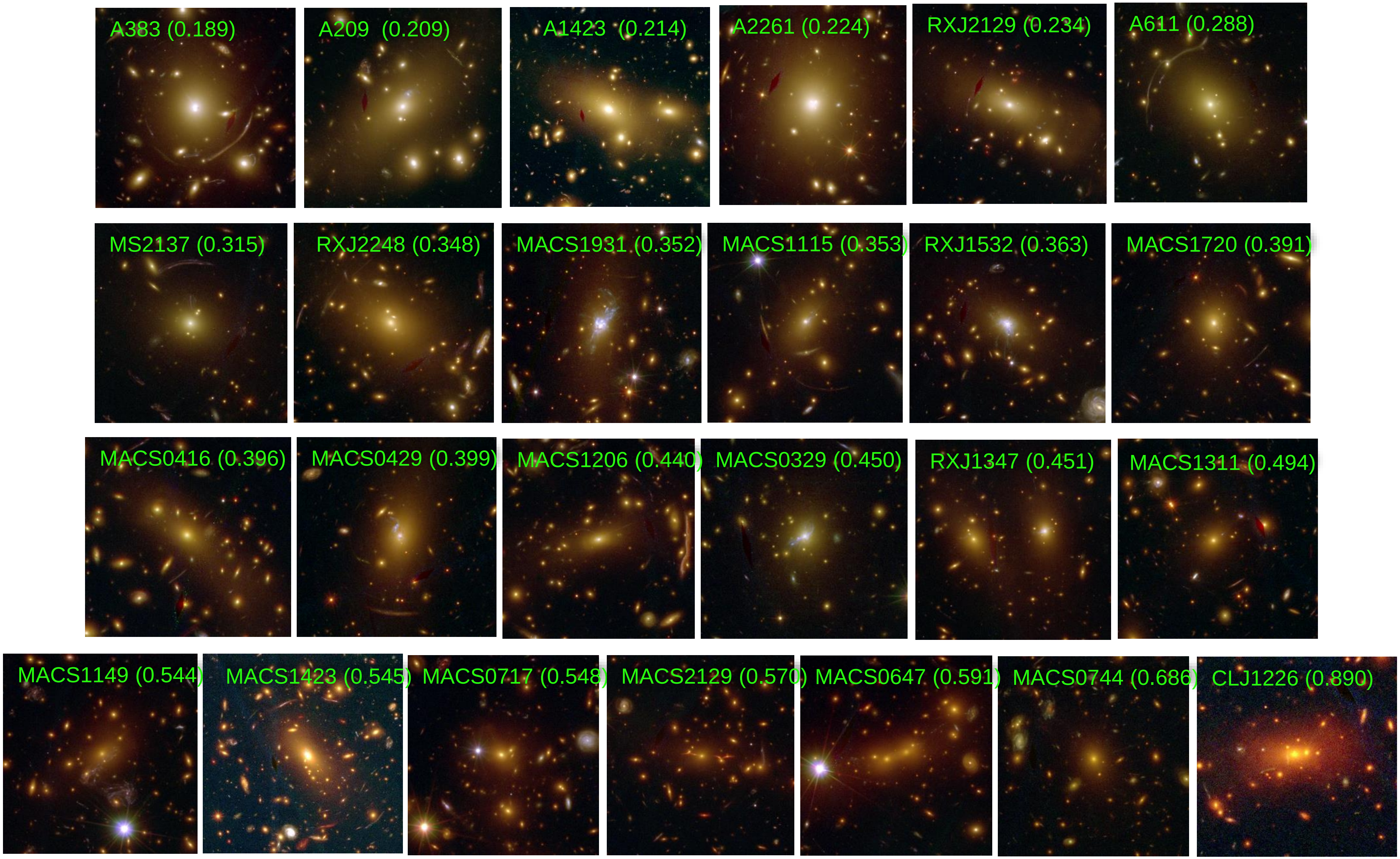


IC-gas in HSE is rounder than the DM distribution: $e^{ICM}/e^{DM} \sim 0.7$ (Lee & Suto 03)



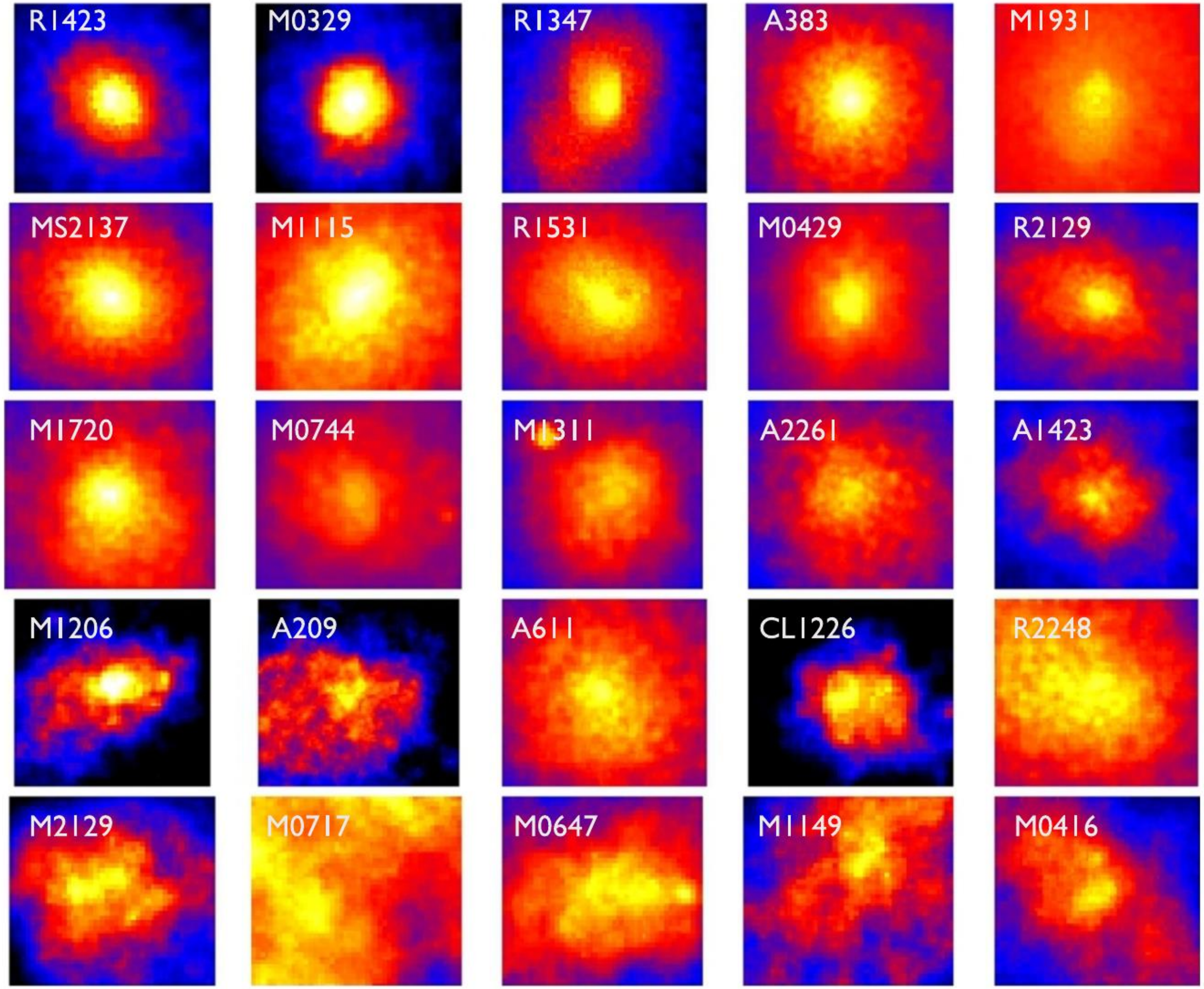
MACS1206 (Umetsu+12)

CLASH *HST* dataset



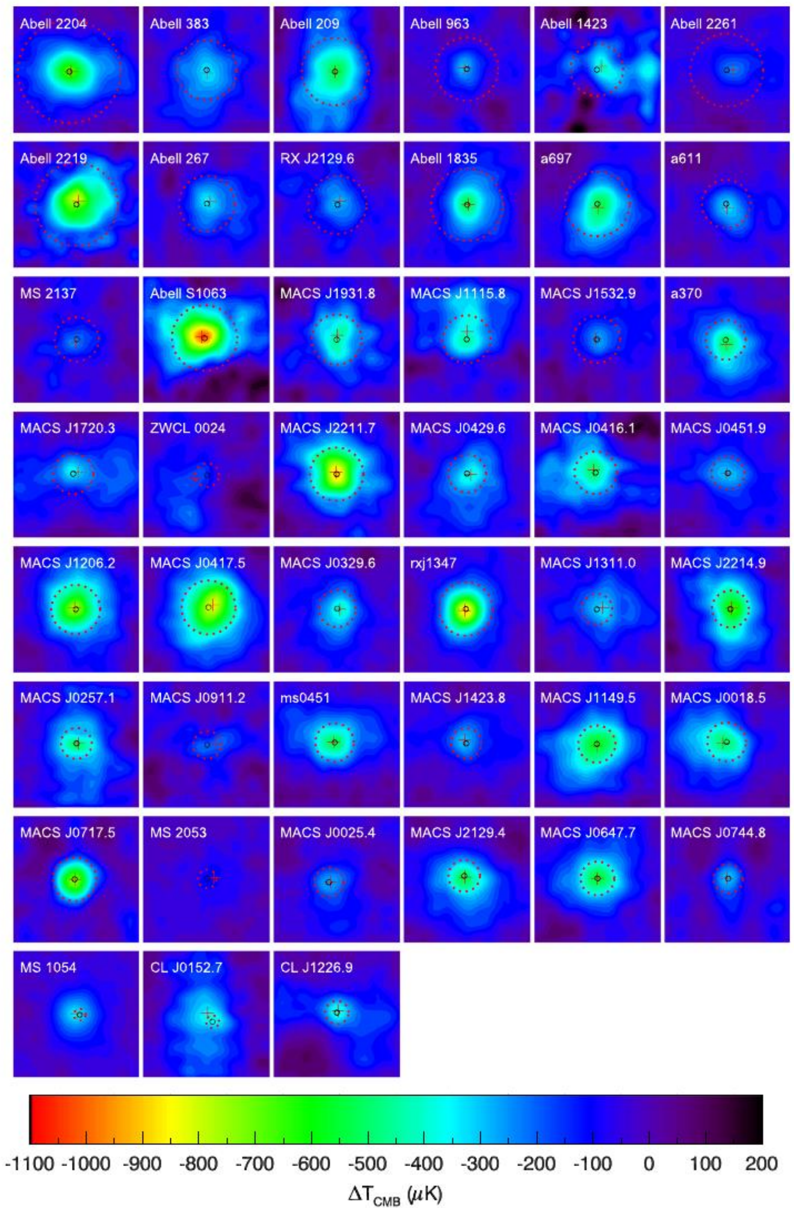
Zitrin et al. 2015, *ApJ*, 801, 44

CLASH X-ray dataset



Donahue et al. 2016, *ApJ*, 819, 36

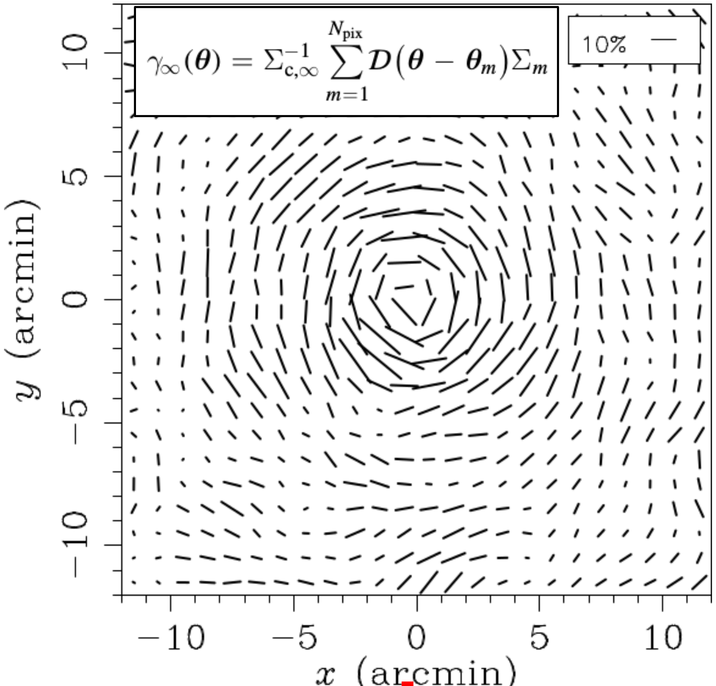
CLASH+ SZE dataset



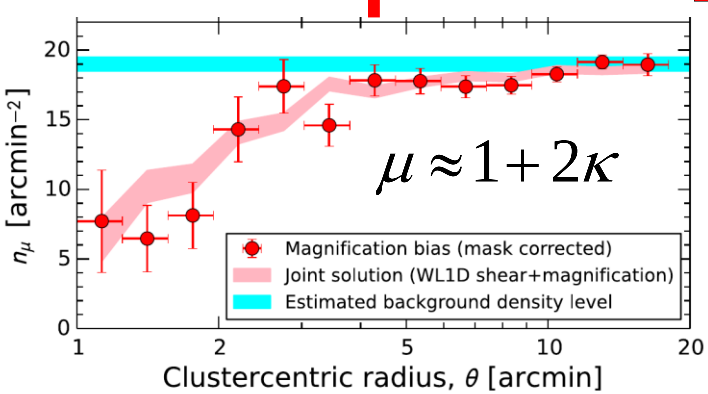
Czakon et al. 2015, *ApJ*, 806, 18

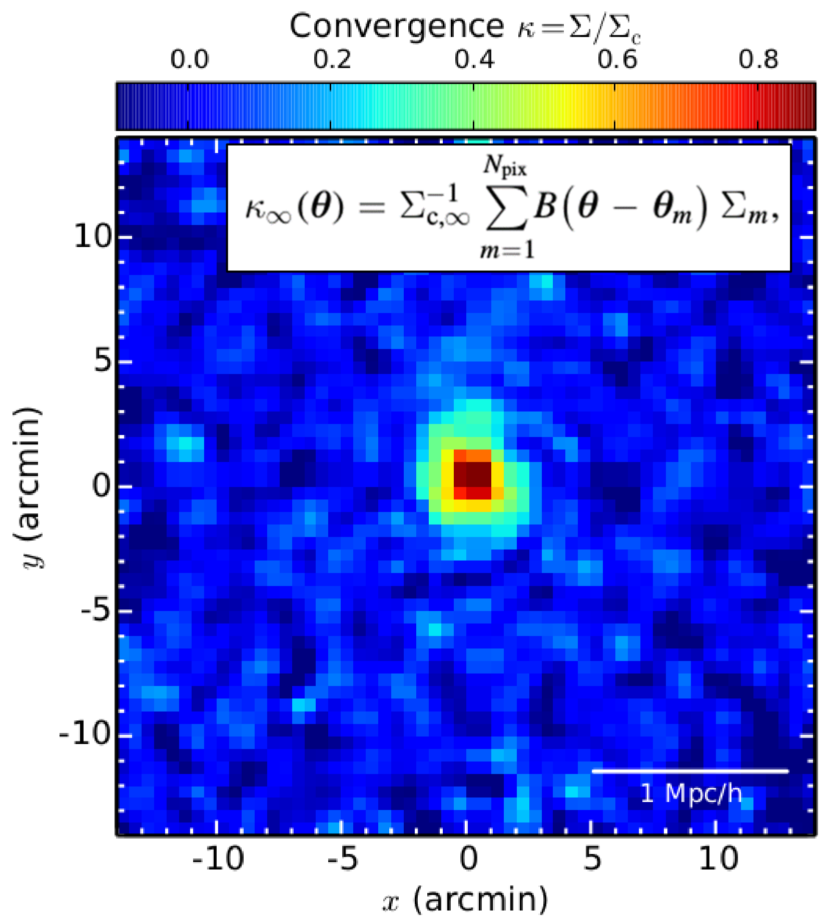
CLUMI-2D: Combining 2D shear and magnification

Subaru/S-Cam data: A1689



+





+ covariance matrix

Umetsu+15, *ApJ*, 806, 207

Joint-likelihood mass reconstruction

Joint 2D-shear + magnification likelidhood

$$l(\mathbf{m}) = l_g(\mathbf{m}) + l_\mu(\mathbf{m})$$

parameter vector

$$\mathbf{m} = (\{\Sigma_i\}_{i=1}^{N_{\rm pix}}, \mathbf{c})$$

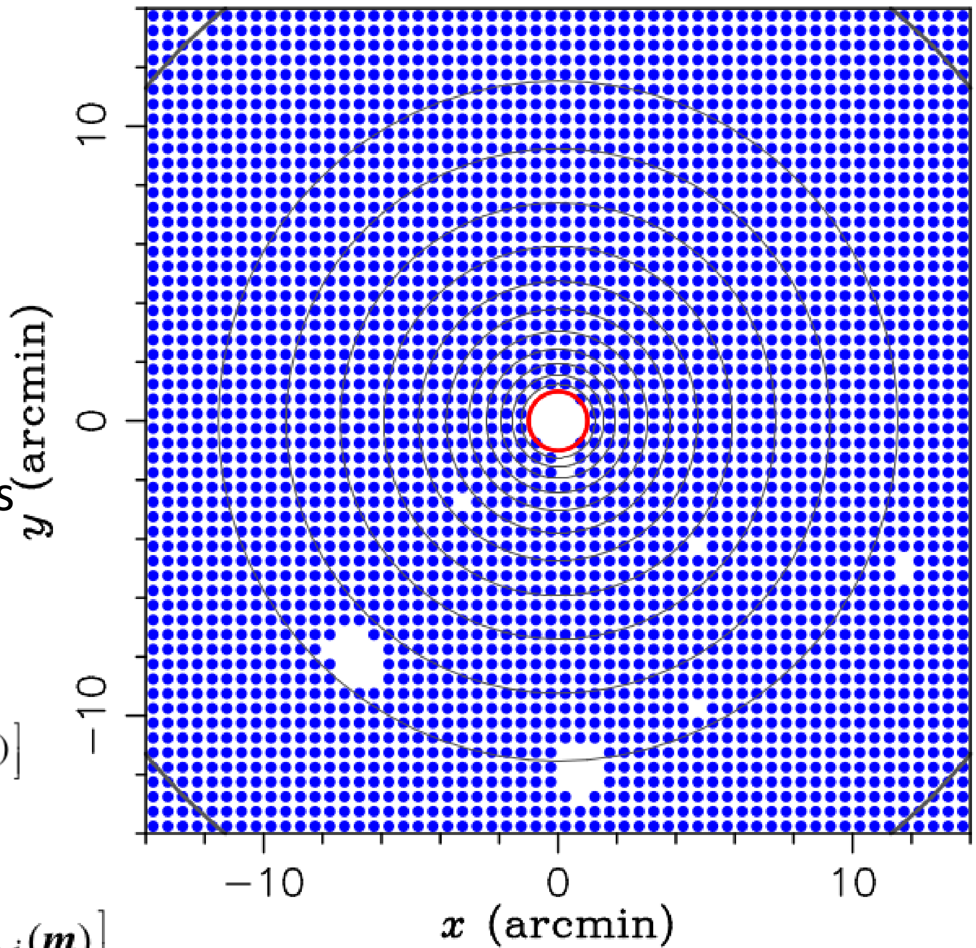
with calibration (nuisance) parameters

$$\boldsymbol{c} = \left(\langle W \rangle_g, f_{W,g}, \langle W \rangle_\mu, \bar{n}_\mu, \alpha \right).$$

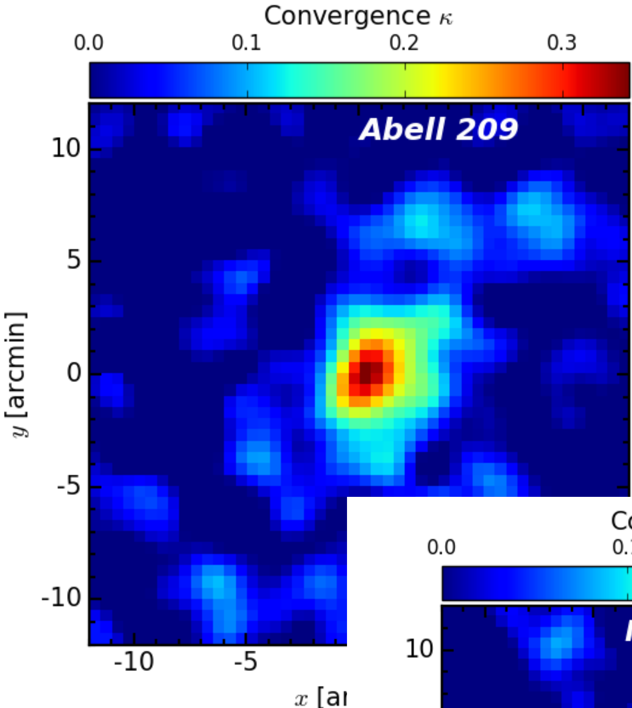
$$l_g = \frac{1}{2} \sum_{m,n=1}^{N_{\rm pix}} \sum_{\alpha=1}^{2} \left[g_{\alpha,m} - \hat{g}_{\alpha,m}(\boldsymbol{m}) \right] \left(\mathcal{W}_g \right)_{mn} \left[g_{\alpha,n} - \hat{g}_{\alpha,n}(\boldsymbol{m}) \right]$$

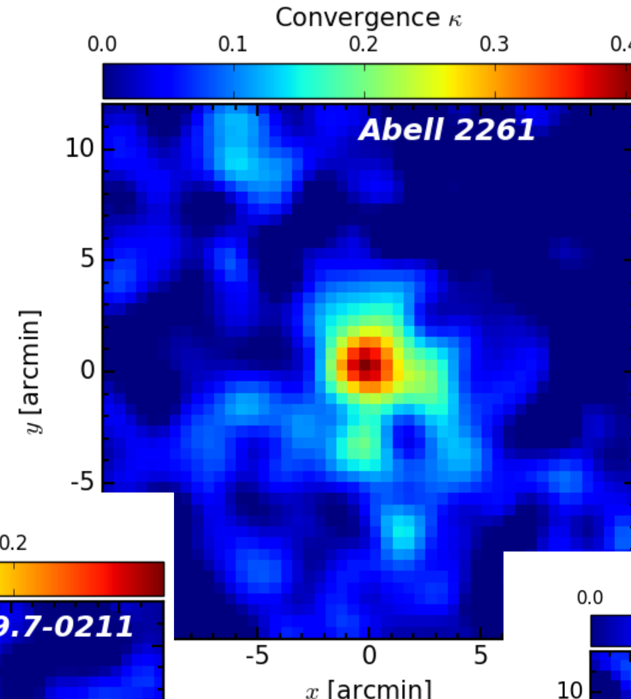
$$l_\mu = \frac{1}{2} \sum_{i=1}^{N_{\rm bin}} \left[n_{\mu,i} - \hat{n}_{\mu,i}(\boldsymbol{m}) \right] \left(\mathcal{W}_\mu \right)_{ij} \left[n_{\mu,j} - \hat{n}_{\mu,j}(\boldsymbol{m}) \right],$$

Distribution of constraints (A1689)

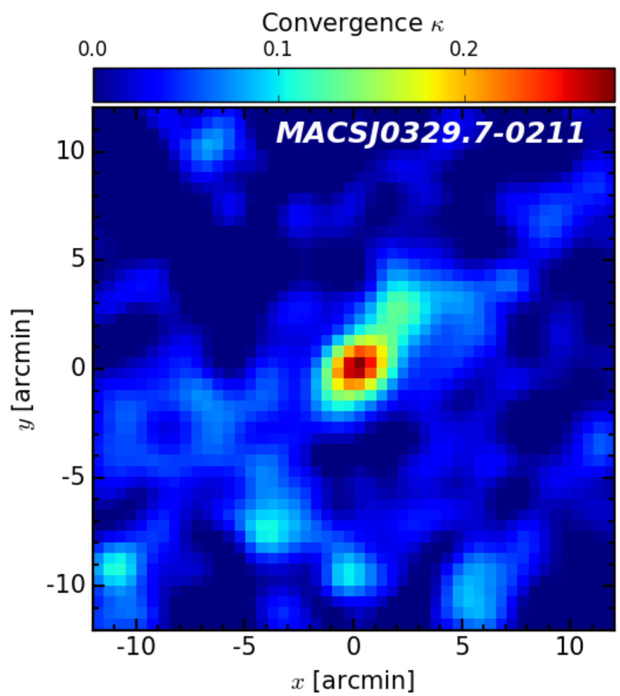


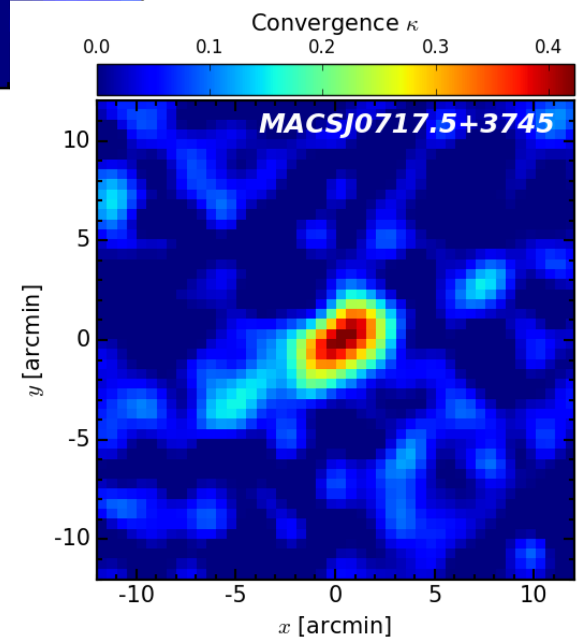
CLASH-WL2D: Reconstruction examples





Smoothed by 1.8’ FWHM Gaussian for visualization purposes

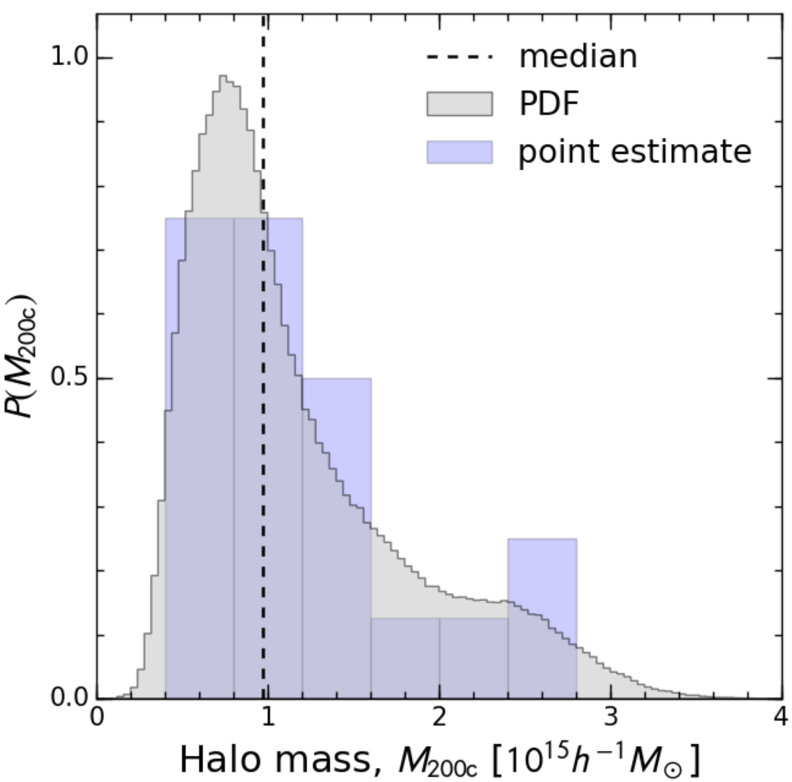


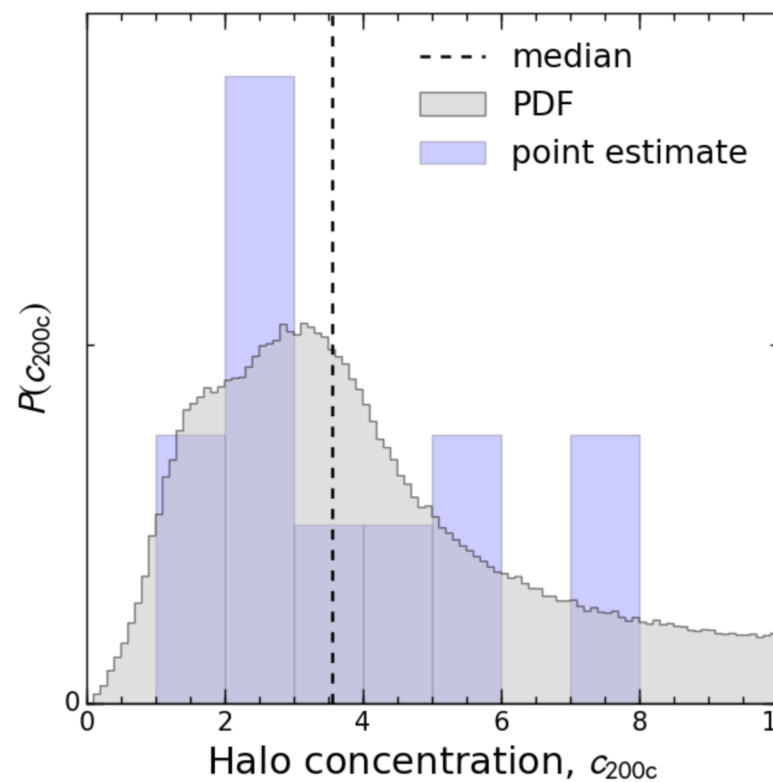


Stacked CLASH PDF (eNFW): M_{200c}, c_{200c}

20 CLASH clusters (16 X-ray-selected + 4 magnification selected) from Umetsu+14

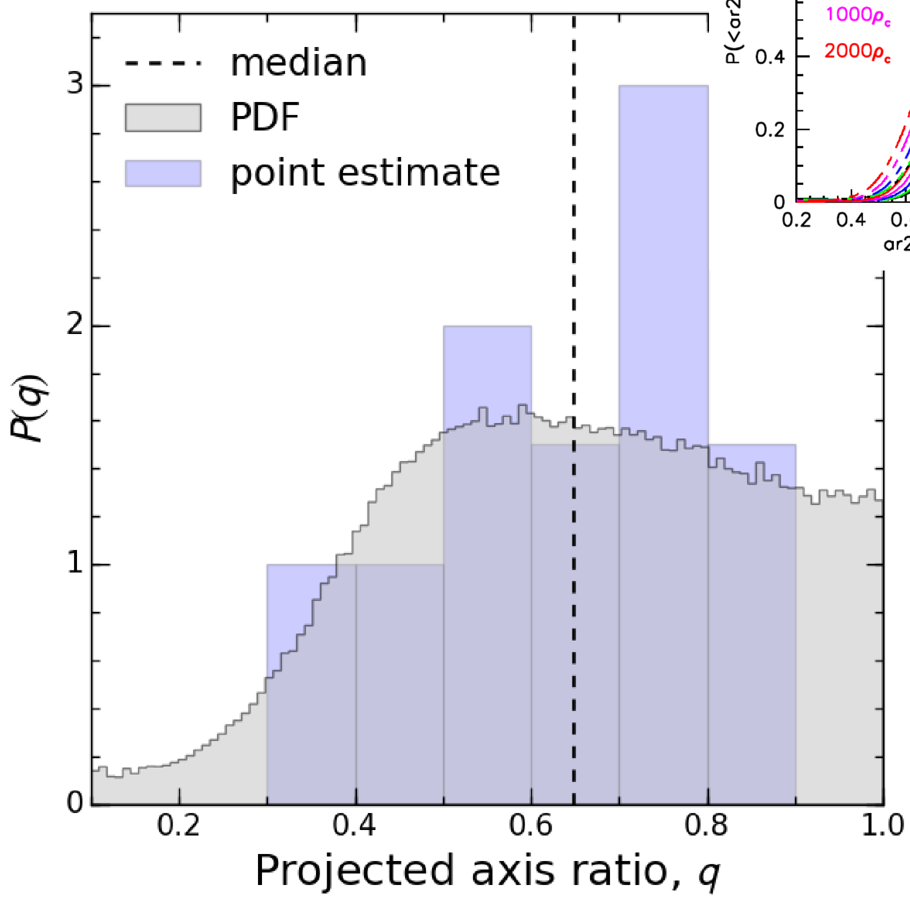
$\langle c \rangle = 3.75 \pm 0.27$

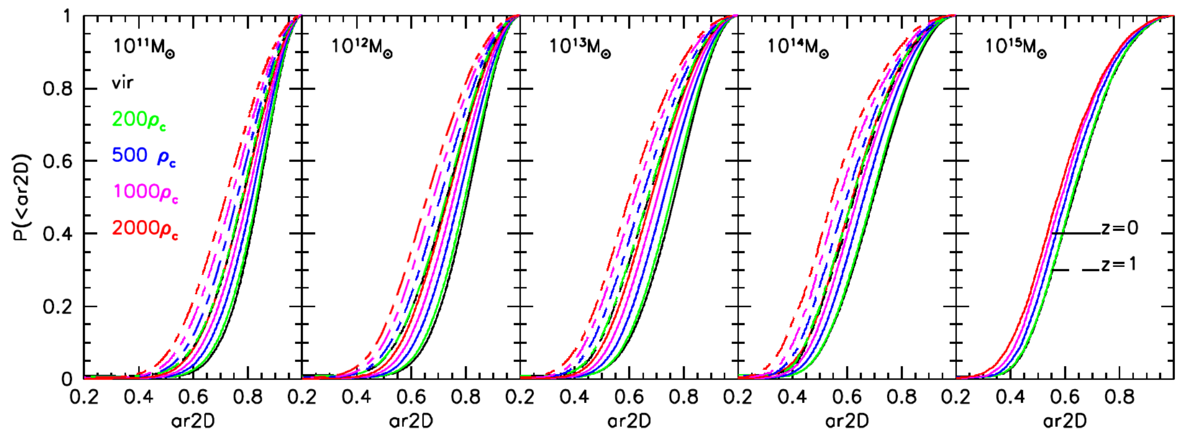




Stacked CLASH PDF (eNFW): 2D axis ratio

$\langle q \rangle = 0.64 +/- 0.03$

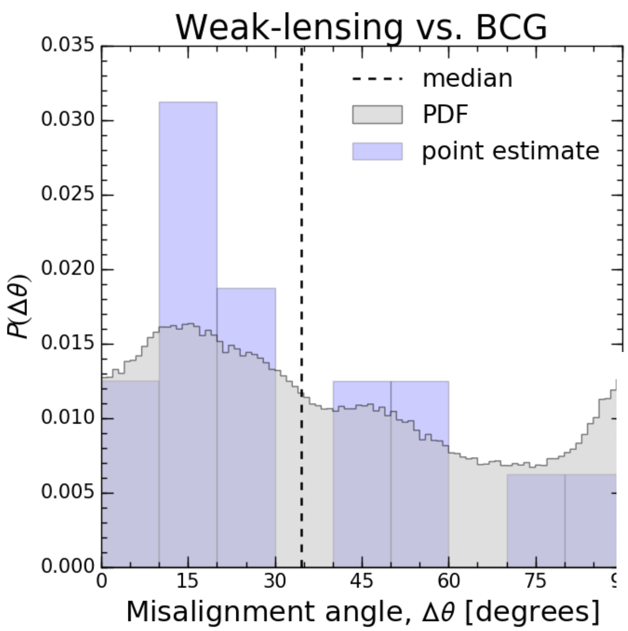


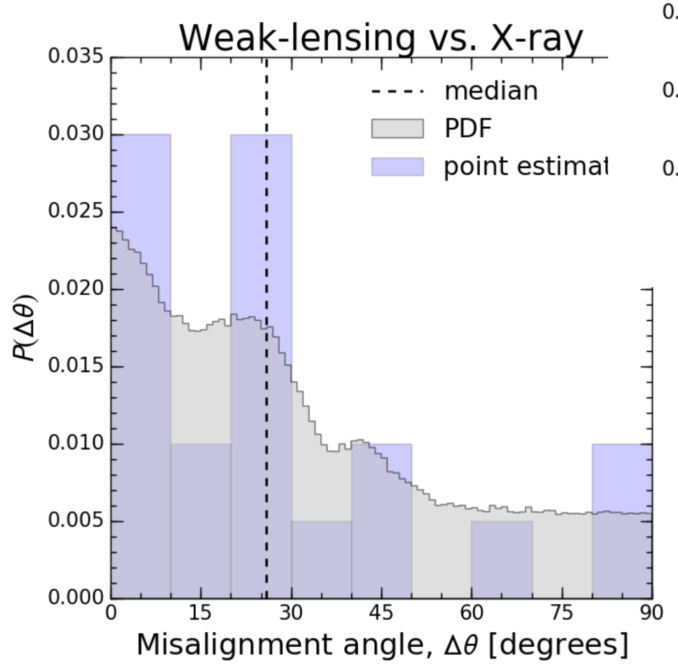


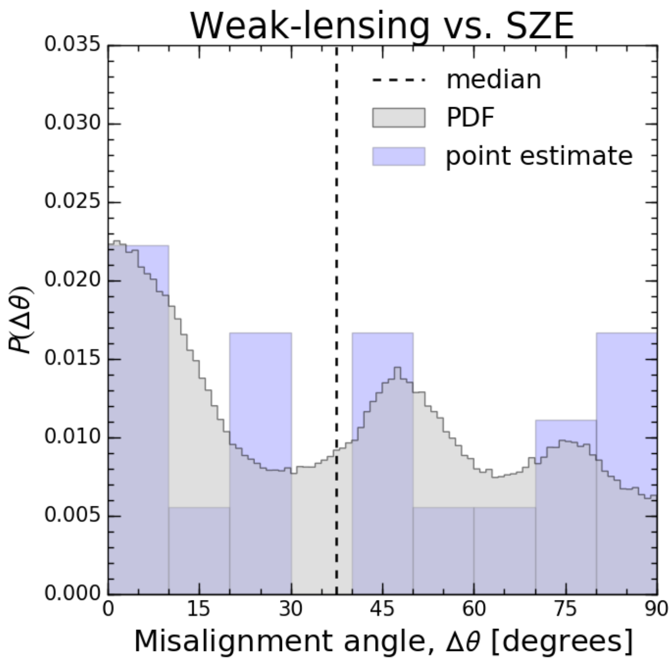
N-body simulations
(Despali+15)

Preliminary Results

WL vs. BCG, X-ray, SZE alignments







Preliminary Results

Summary

- No statistically significant detection of the splashback radius from CLASH lensing. NFW/Einasto gives very good fits!!!
- Assuming the DK14 profile with generic priors, first lensing constraints on the splashback feature obtained. No tension with LCDM.
- Larger statistics needed for "detection" of R_{sp} by lensing → Subaru HSC SSP-Wide survey (1400 degrees^2)

More+16, *ApJ*, 825, 39 (SDSS galaxies)