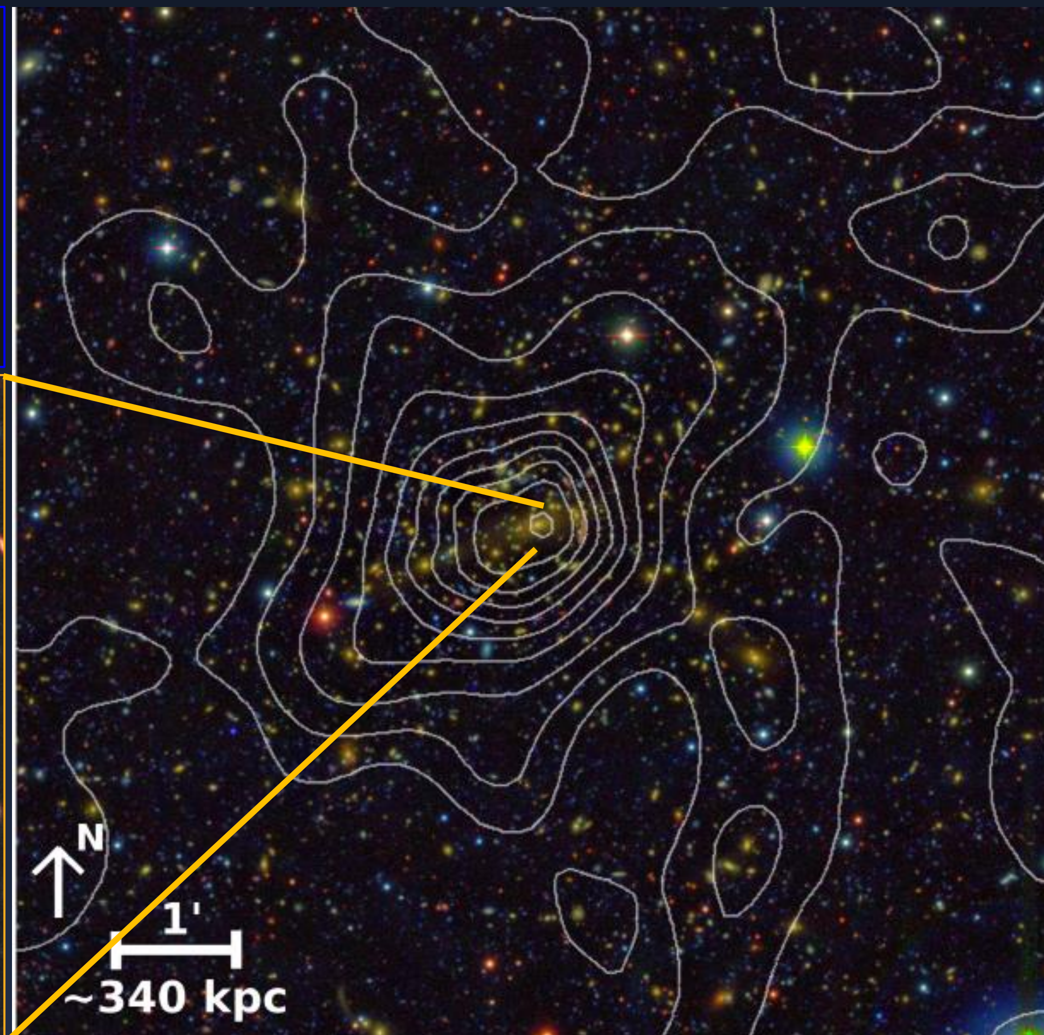
CLASH: Subaru Weak-Lensing Results

Cluster Lensing And Supernova survey with Hubble

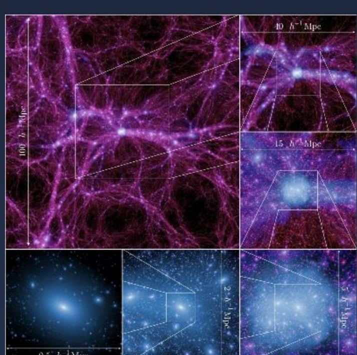


Keiichi Umetsu (ASIAA, Taiwan) with the CLASH team

CLASH: Observational + Theory Efforts

A 524-orbit *HST* Multi-Cycle Treasury Program designed to place new constraints on the fundamental components of the cosmos: dark matter, dark energy, and baryons (Postman+CLASH 2012)

Wide-field Subaru imaging (0.4 - 0.9 μm) plays a unique role in complementing deep HST imaging of cluster cores.



MUSIC-2 (hydro + N-body re-simulation) provides an accurate characterization of CLASH sample with testable predictions (Meneghetti+14, arXiv:1404.1384)

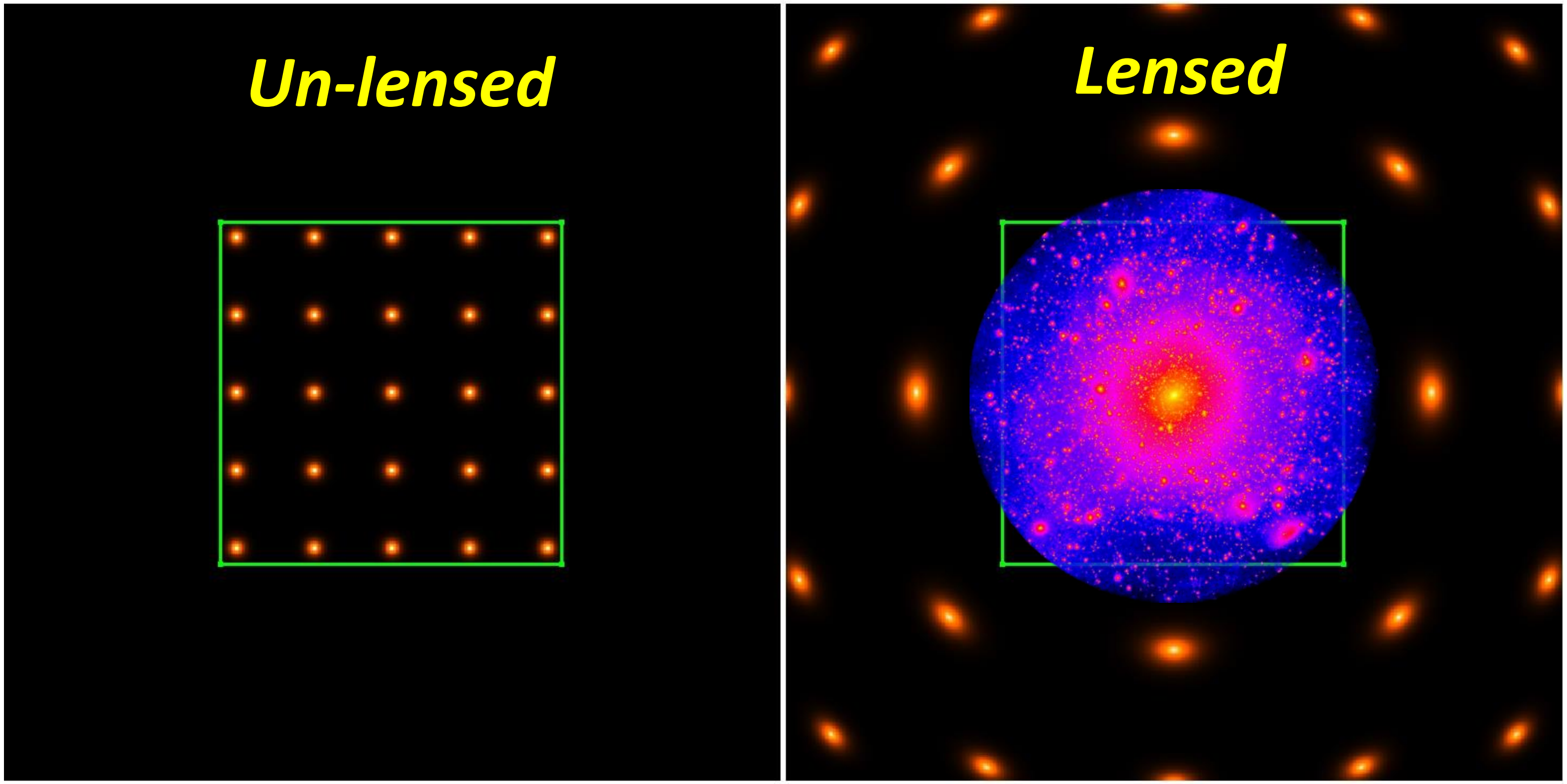
CLASH X-ray-selected subsample

- Redshift coverage
  - $0.18 < z < 0.90$
- X-ray morphology + T_x selection
  - $T_x > 5$keV
  - Small BCG to X-ray-peak offset, σ_{off} ~ 10kpc/h
  - Smooth regular X-ray morphology

→ ***Optimized for radial-profile analysis (R>2 σ_{off} ~ 20kpc/h)***

- CLASH theoretical predictions (Meneghetti+CLASH 14)
  - Composite relaxed (70%) and unrelaxed (30%) clusters
  - Mean $\langle c_{200c} \rangle$=3.9, $\sigma(c_{200c})$ = 0.6, c_{200c}=[3, 6]

Lensing Shear and Magnification



- **Shear**
  - ✓ Geometric shape dist: $\delta e_+ \sim \gamma_+$

Sensitive to "modulated" matter density

$$\Sigma_{crit}\gamma_+ = \Delta\Sigma(R) \equiv \Sigma(<R) - \Sigma(R)$$

- **Magnification**
  - ✓ Flux amplification: μF
  - ✓ Geometric area dist: $\mu\Delta\Omega$

Sensitive to "total" matter density

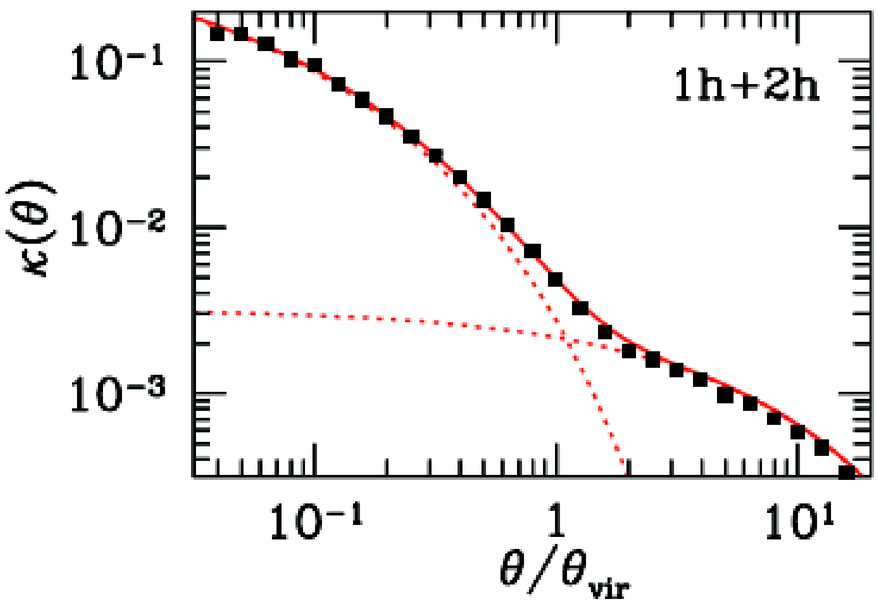
$$\mu \approx 1 + 2\kappa; \quad \Sigma_{crit}\kappa = \Sigma(R)$$

Shear doesn't see mass sheet

Averaged lensing profiles in/around LCDM halos (Oguri+Hamana 11)

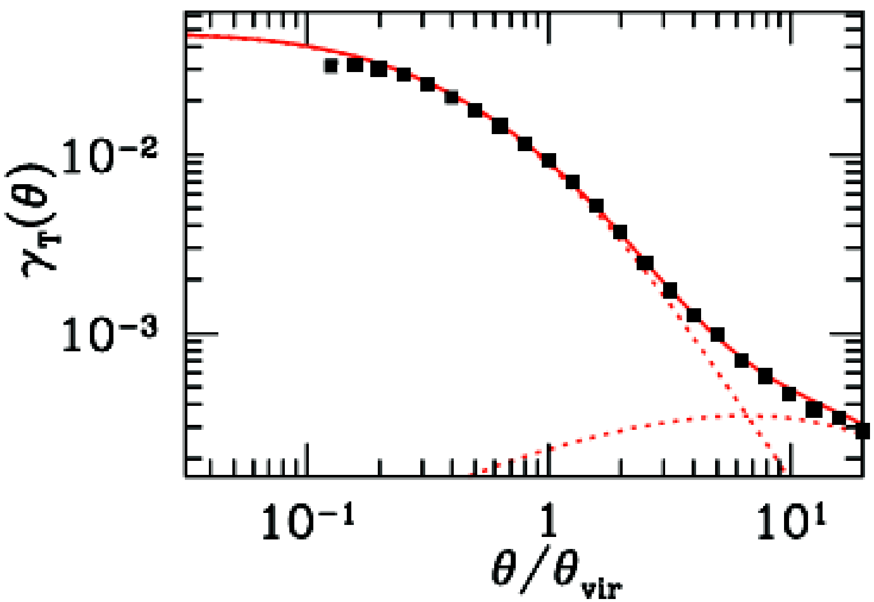
Total

$$\kappa = \Sigma(R) / \Sigma_{\rm crit}$$



Modulated

$$\gamma_{+} = \Delta\Sigma(R) / \Sigma_{\rm crit}$$



- **Tangential shear is a powerful probe of 1-halo term, or internal halo structure.**
- **Shear alone cannot recover absolute mass, known as *mass-sheet degeneracy***

CLASH-WL Results (1)

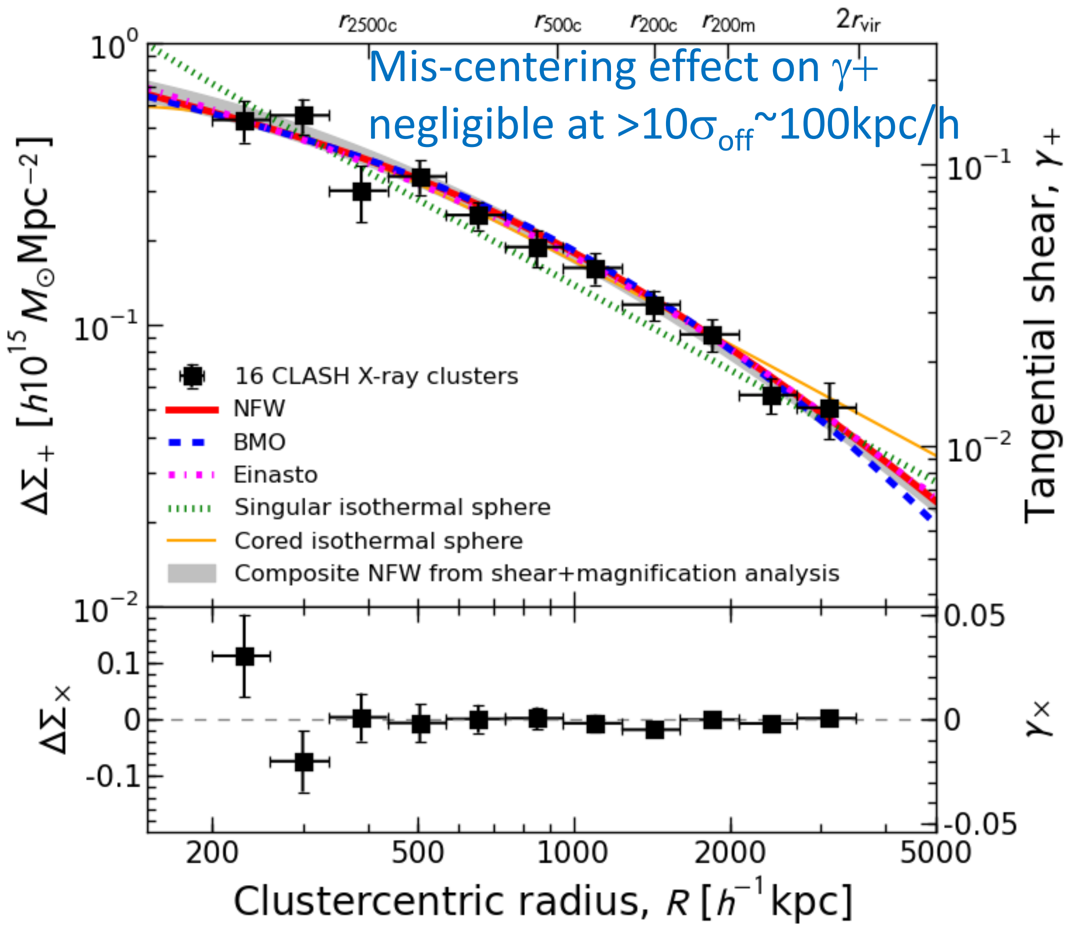
Ensemble-averaged internal halo structure:

- Halo mass density profile, $<\Delta\Sigma(R)>$
- Degree of mass concentration, $<c_{200}>$

from ***stacked WL-shear-only*** analysis of CLASH X-ray-selected sample (16 clusters)

Umetsu, Medezinski, Nonino+CLASH 14, arXiv:1404.1375

Stacked halo density profile ΔΣ(R)



Stacked shear-only analysis provides a net 1-halo-only constraint ($\gamma_{+,2h}$<1e-3)

NFW an excellent fit (PTE = 0.66)

- M_{200c} = (1.3+/-0.1) $10^{15}M_{sun}$
- c_{200c} = 4.01 (+0.35, -0.32)

at <z>=0.35

- b_h= 9 +/- 2 (WMAP7+Tinker10)

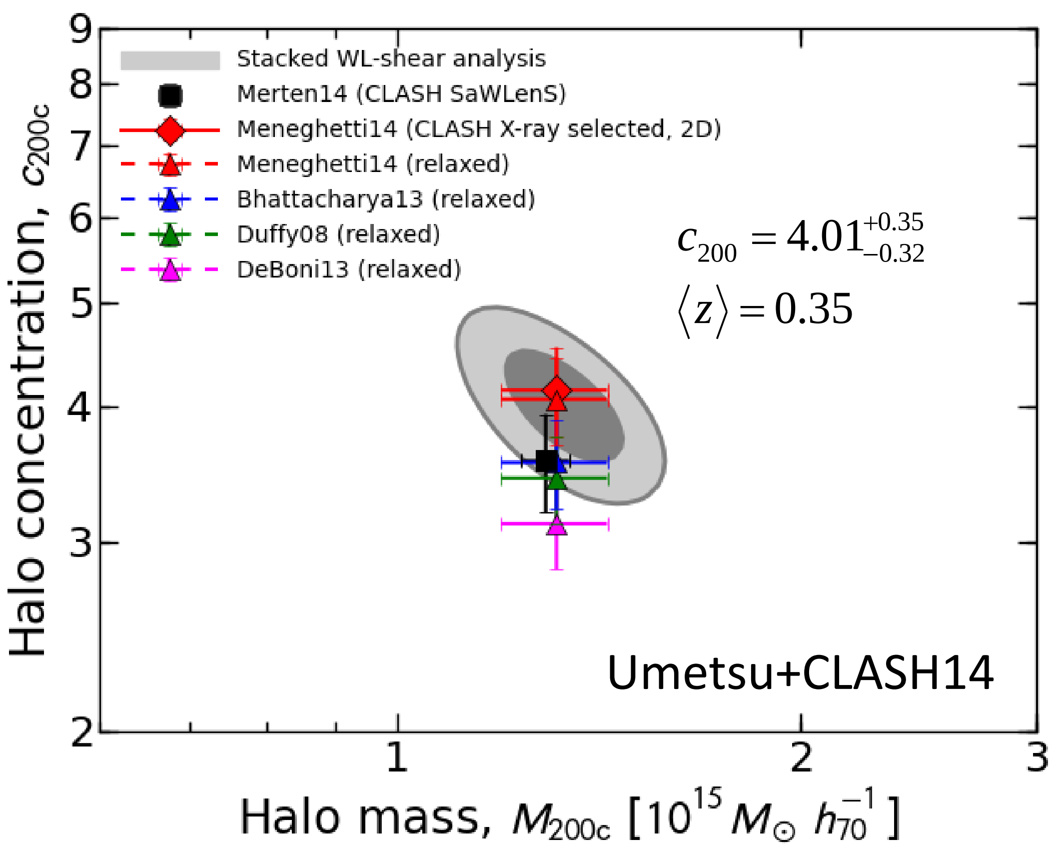
Corresponding to θ_{Ein}=(15” +/- 4”) at z_s=2, consistent w SL analysis, <θ_{Ein}>~20” (Zitrin+14, in prep)

Consistent w a family of density profiles for collisionless DM halos (NFW, variants of NFW, Einasto)

Integrated constraints on $c(M_{200},z)$

Theoretical predictions for stacked c(M,z)

$$< c >= \frac{\int dM \int dz\, N(M,z)\,\hat{c}(M,z)}{\int dM \int dz\, N(M,z)} \approx \frac{\sum_n \mathrm{tr}(W_n)\,\hat{c}(M_n, z_n)}{\sum_n \mathrm{tr}(W_n)}$$



Variance in theory due to different cosmology and mass resolution

M14 (MUSIC-2): σ_8=0.82

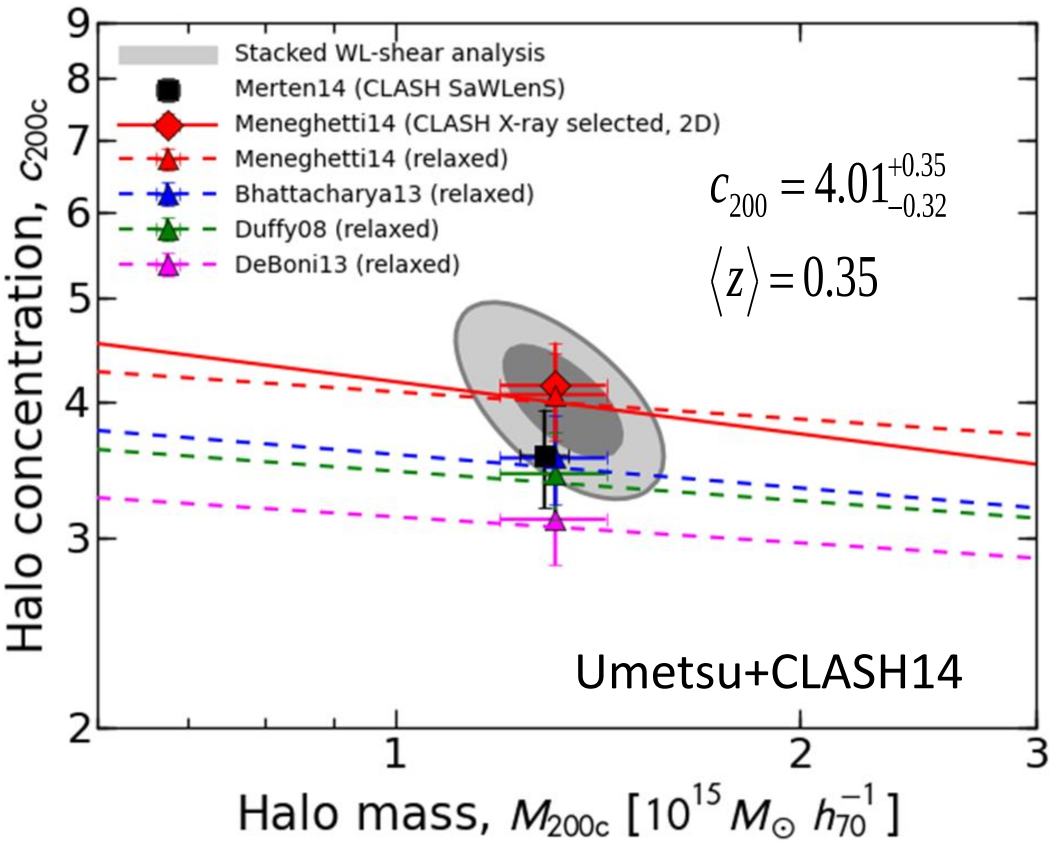
Bhat13: σ_8=0.8

Duffy08: σ_8=0.8

DeBoni13: σ_8=0.78

- Excellent agreement w CLASH predictions (M14), c_{200c}~4
- Consistent w Bhatt13, Duffy08 (relaxed) predictions at 1σ, c_{200c}~3.6

CLASH-WL vs. c-M relations



M14 (MUSIC-2): σ_8=0.82

Bhat13: σ_8=0.8

Duffy08: σ_8=0.8

DeBoni13: σ_8=0.78

At low M_{200}, X-ray selection picks up clusters with higher concentrations (Meneghetti+14)

CLASH-WL Results (2)

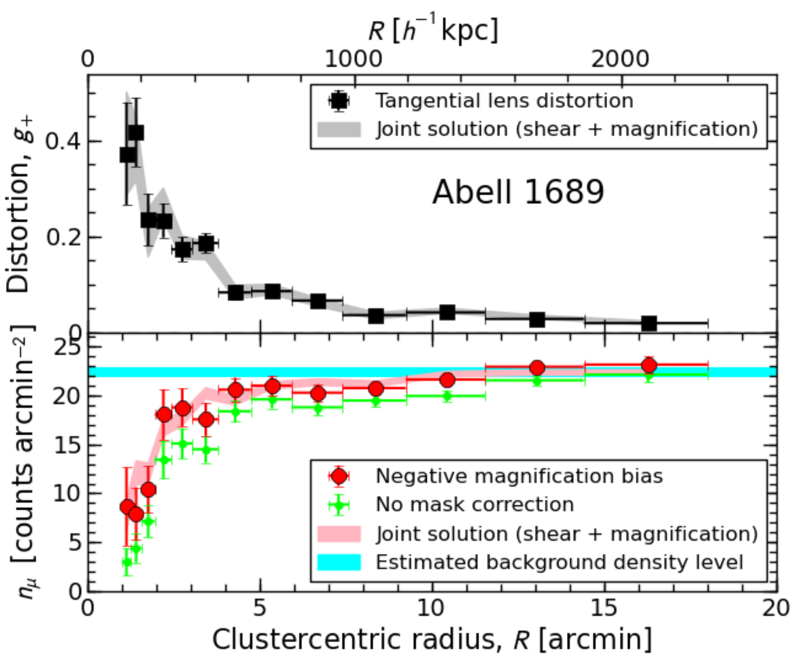
- Individual mass profile reconstruction of 20 CLASH clusters from joint Shear+Magnification analysis (16 X-ray + 4 lensing clusters)

Umetsu, Medezinski, Nonino+CLASH 14, arXiv:1404.1375

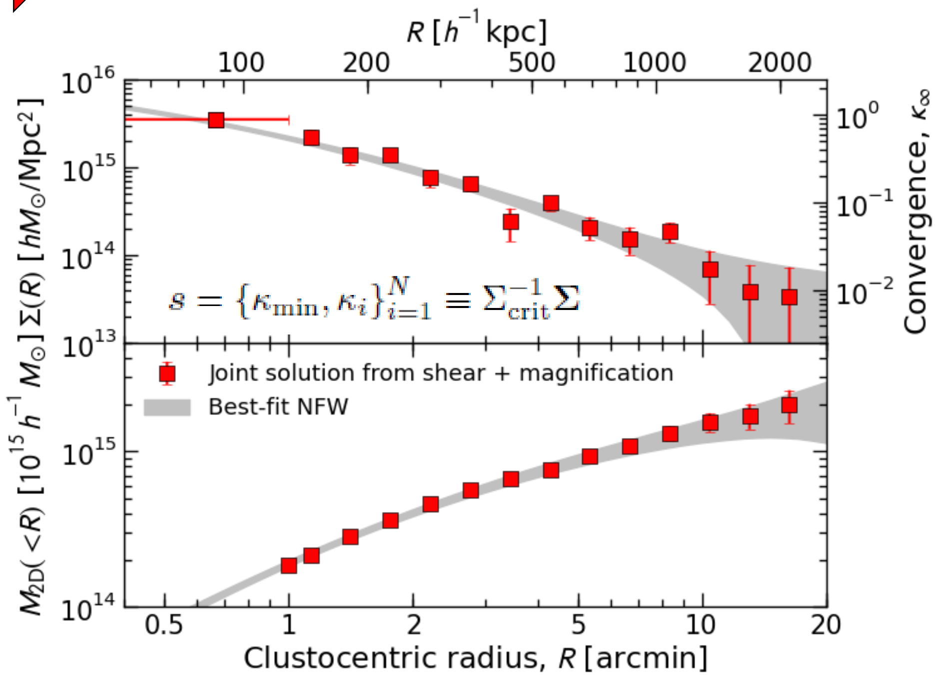
Method: Combining Shear & Magnification

Bayesian joint-likelihood approach (Umetsu+11a; Umetsu 13)

Shear + magnification



Non-parametric Σ(R) solution

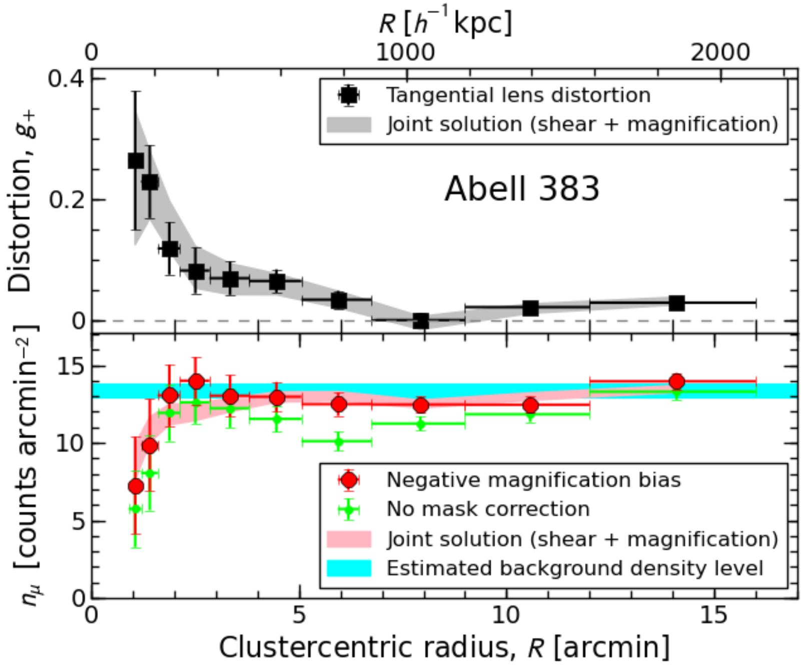


- Mass-sheet degeneracy broken
- Total statistical precision improved by ~20-30%
- Calibration uncertainties marginalized over: $c = \{\langle W\rangle_s, f_{W,s}, \langle W\rangle_\mu, \overline{n}_\mu, s_{\rm eff}\}.$

CLASH-WL: Joint Shear + Magnification Analysis

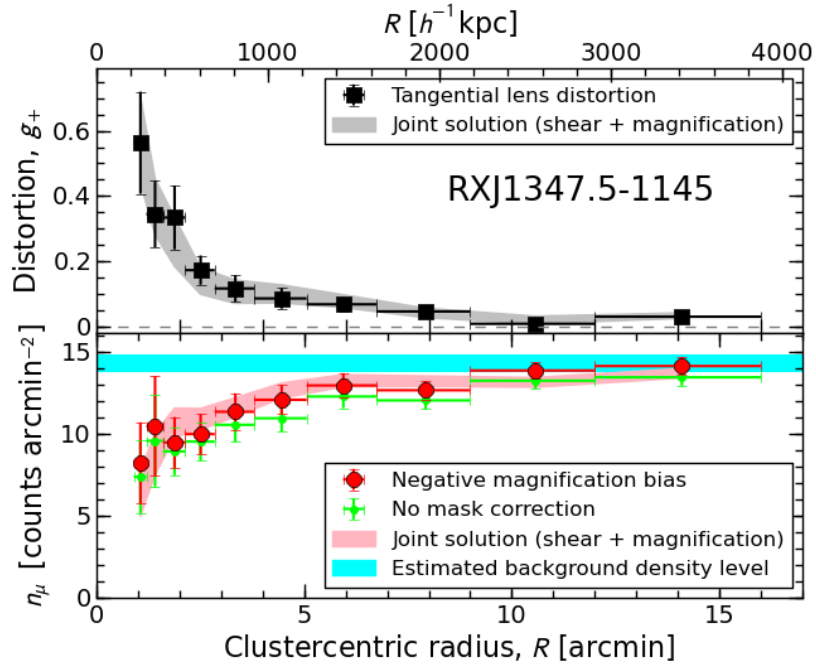
CLASH low mass

M_{200c}=6e14Msun/h (z=0.19)



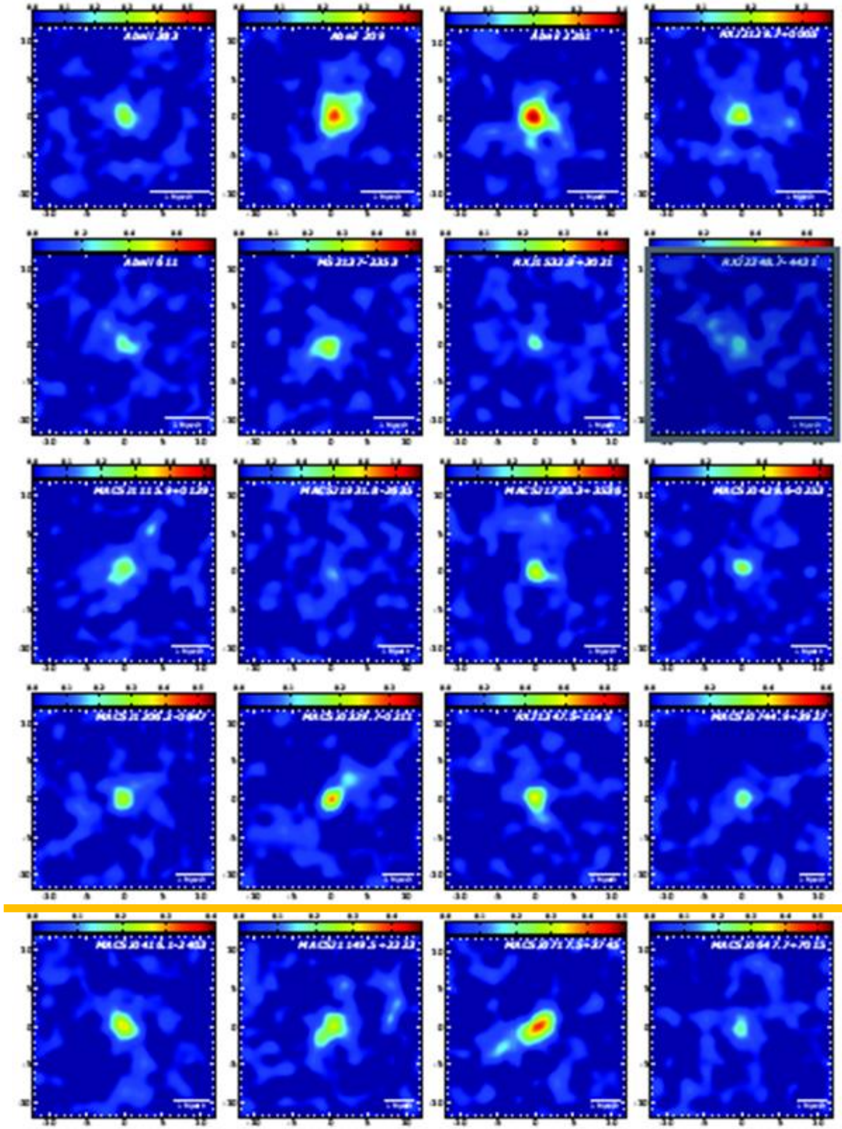
CLASH high mass

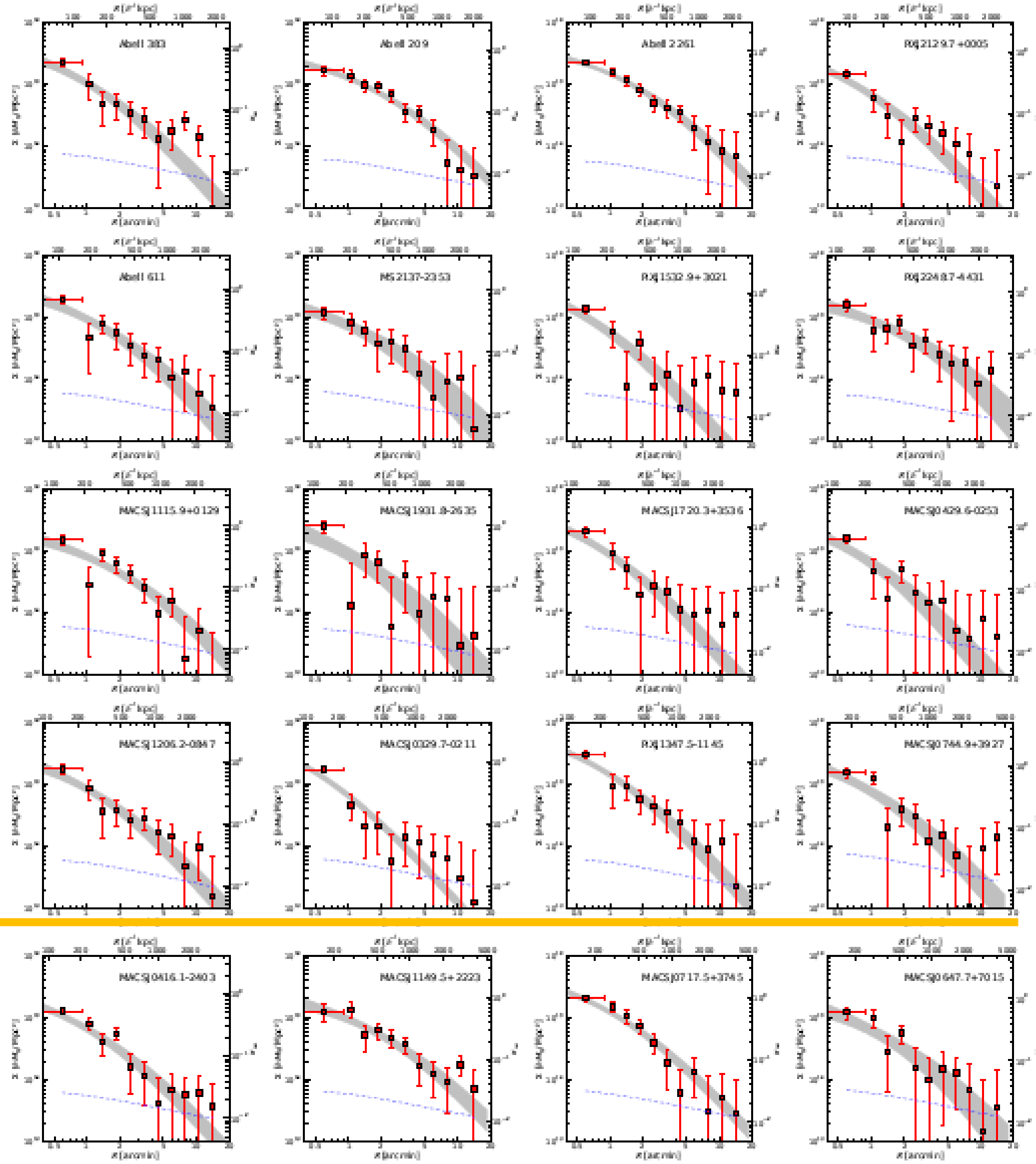
M_{200c}=20e14Msun/h (z=0.45)



Shear-magnification consistency: $<\chi^2/dof>$ = 0.92 for 20 CLASH clusters

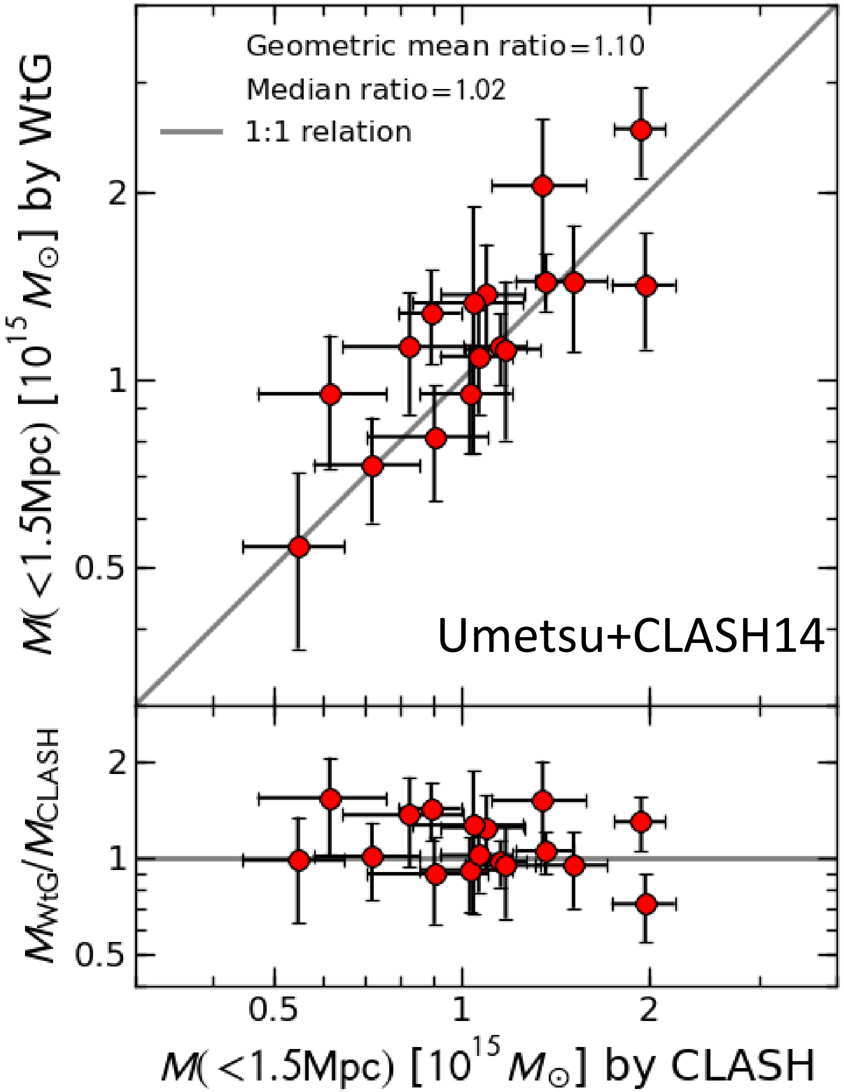
Mass Density Profile Dataset





Umetsu, Medezinski, Nonino+CLASH 14, arXiv:1404.1375

Comparison with WtG @R=1.5Mpc



17 clusters in common (Subaru):

- **WtG**: shear-only (Applegate+14), NFW c_{200c}=4 prior
- **CLASH**: shear + magnification, NFW log-uniform: $0.1<c_{200c}<10$

Un-weighted geometric mean mass ratio (<Y/X> = 1/<X/Y>)

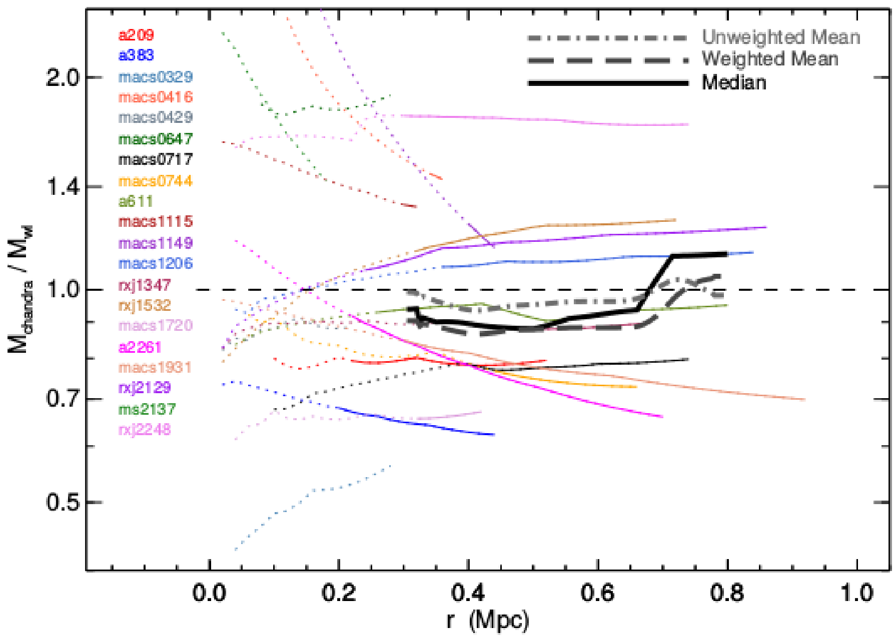
- <M_WtG/M_CLASH> = 1.10
- Median ratio = 1.02

Systematic uncertainty in the overall mass calibration of 8% from shear-magnification consistency (Umetsu+14)

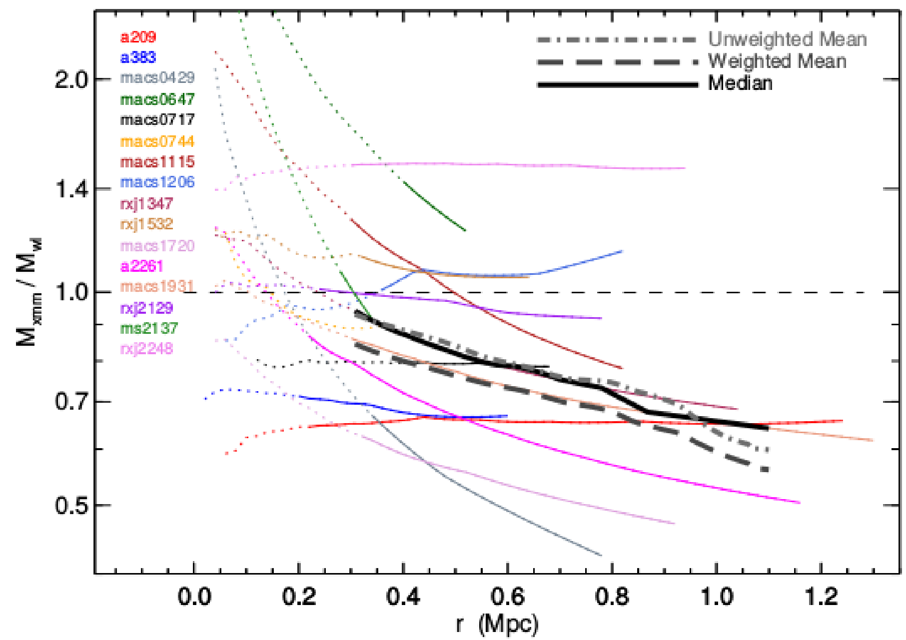
No mass dependent bias
No tension

CLASH Comparisons with X-ray masses

Chandra HSE / Subaru-WL



XMM HSE / Subaru-WL



X-ray to WL comparison at R=0.5Mpc

- bias = 1 - $\langle M_{chandra}/M_{wl} \rangle$ = 0.05 +/- 0.07 (11 clusters)
- bias = 1 - $\langle M_{xmm}/M_{wl} \rangle$ = 0.16 +/- 0.06 (14 clusters)

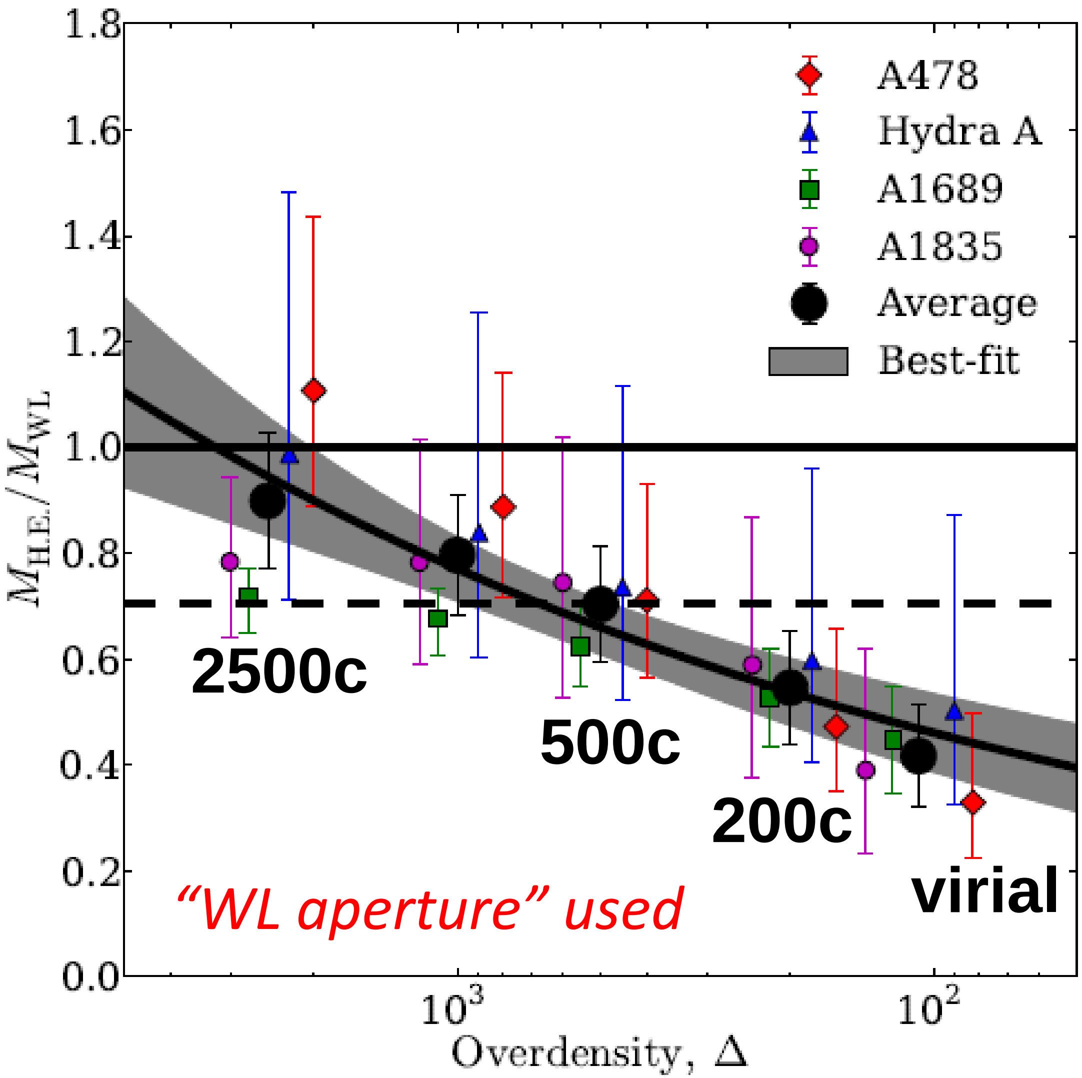
X-ray to WL comparison at r_{500} [no aperture correction]

- bias = 1 - $\langle M_{chandra}/M_{wl} \rangle$ = 0.09 +/- 0.12 (20 clusters)
- bias = 1 - $\langle M_{xmm}/M_{wl} \rangle$ = 0.41 +/- 0.07 (16 clusters)

Un-weighted means quoted

Donahue+CLASH 14 (arXiv:1405.7876)

Suzaku-X HSE vs. Subaru WL



Independent *Suzaku*-HSE vs. Subaru-WL results, consistent with XMM-HSE vs. Subaru-WL of CLASH collaboration

Okabe, Umetsu, .. Matsushita+14 (arXiv:1406.3451)

Shear + Magnification + “Zitrin-SL”

Total mass density profile

$$\Sigma(R) = \Sigma_{1h}(R) + \Sigma_{2h}(R)$$

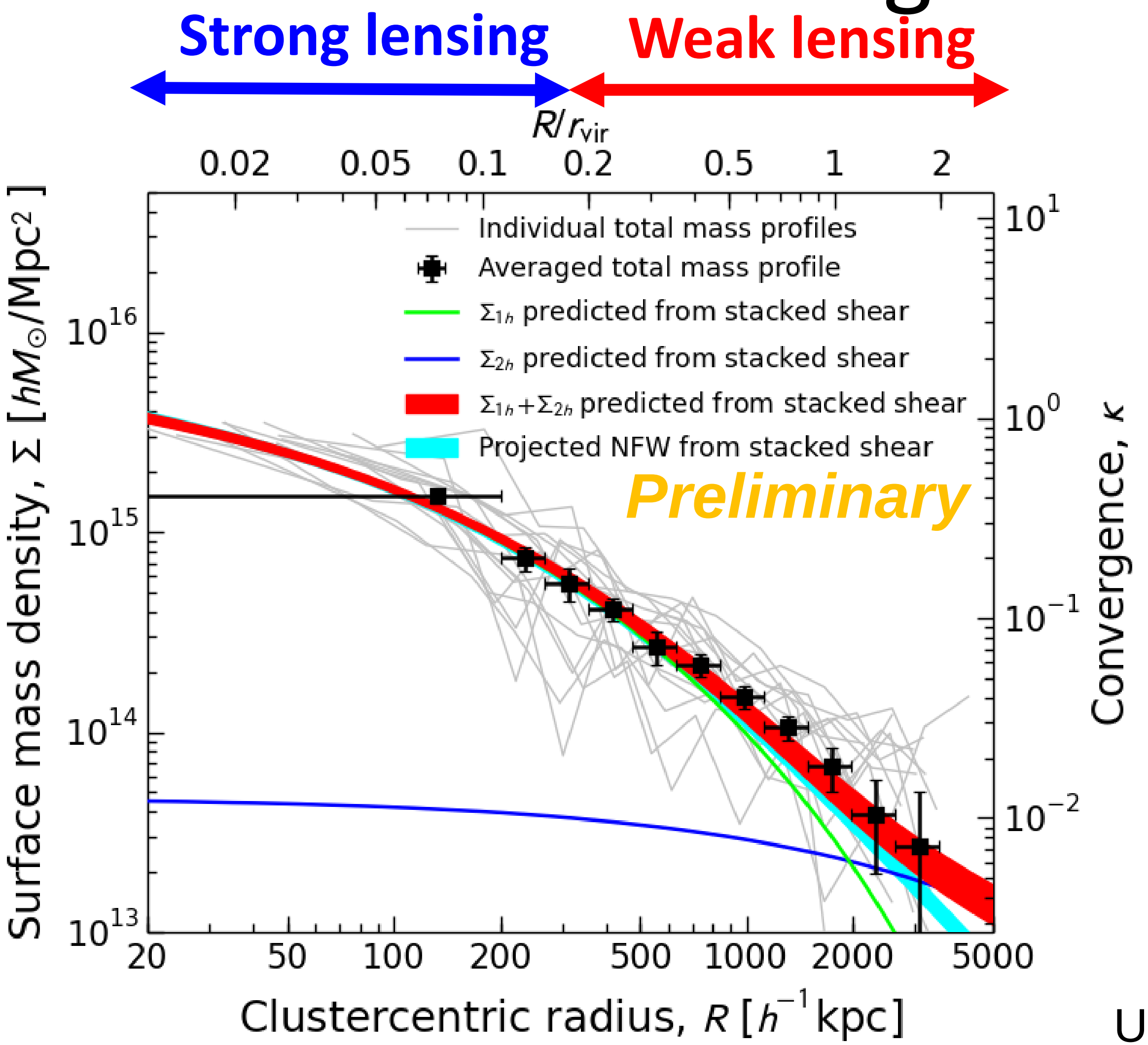
around the CLASH “X-ray-selected” sample

1h term **2h term**

Clustering of matter around halos with M:

$$\xi_{\rm hm}(r\,|\,M) = \frac{\langle \rho_{\rm 1h}(r\,|\,M)\rangle}{\bar{\rho}} + b_{\rm h}(M)\,\xi_{\rm mm}(r)$$

Averaged cluster (1h) + LSS (2h) from WL shear + magnification + SL



Adding *HST* SL tightly constrains the inner density profile (R<100kpc/h)

Inner mass profiles from SL follow 1h prediction from outer WL-shear information

Recovered mass-sheet (LSS), consistent w the shear-based halo model prediction, b_h=9 +/- 2 (WMAP7+Tinker10)

Umetsu+2014b, in prep

CLASH-WL Summary

- Ensemble-averaged halo structure $\Delta\Sigma$ (1h) of X-ray-regular CLASH clusters is consistent with a family of standard (collisionless) DM predictions:
  - M_{200c}= (1.3 +/- 0.1) $10^{15} M_{sun}$, $\langle z \rangle$=0.35
  - NFW (PTE=0.66): c_{200c}=4.01 (+0.35, -0.32)
  - Einasto (PTE=0.51): degree of curvature, α_E=0.19 +/- 0.07
- The stacked-mean concentration agrees with:
  - theoretical expectation, $\langle c_{200c} \rangle$ ~ 3.9, which takes into account CLASH selection function and projection effects (Meneghetti+14)
  - Measured effective Einstein radius, $\langle \theta_{Ein} \rangle$=20" ($z_s$=2), from independent HST-SL analysis (Zitrin+CLASH 14, in prep)

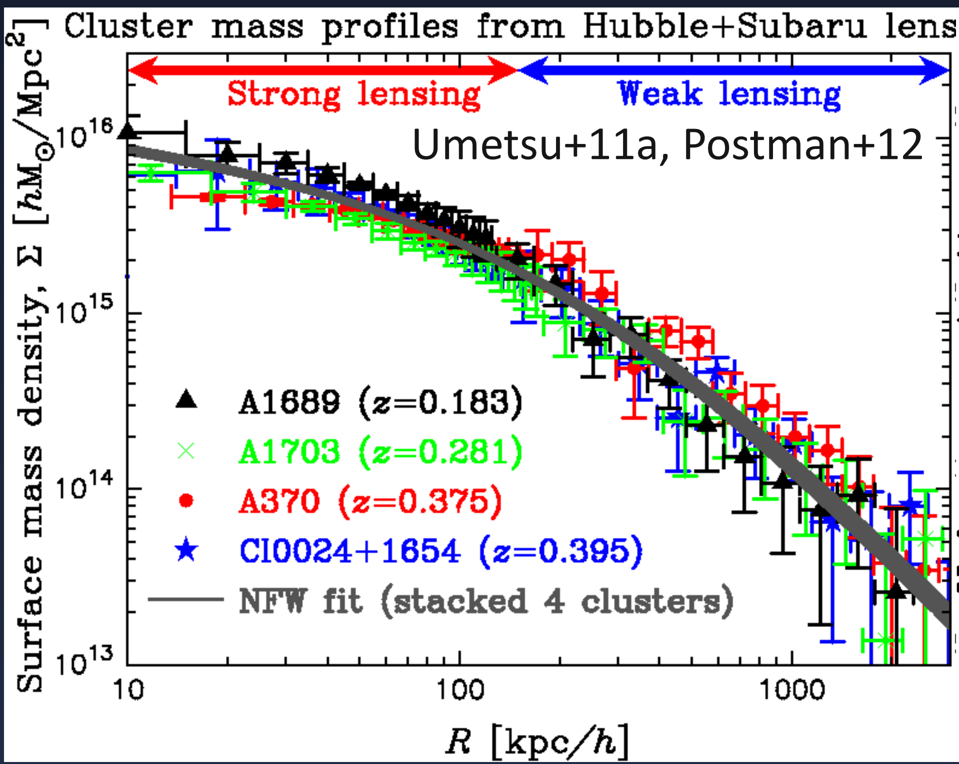
CLASH-WL Summary (contd.)

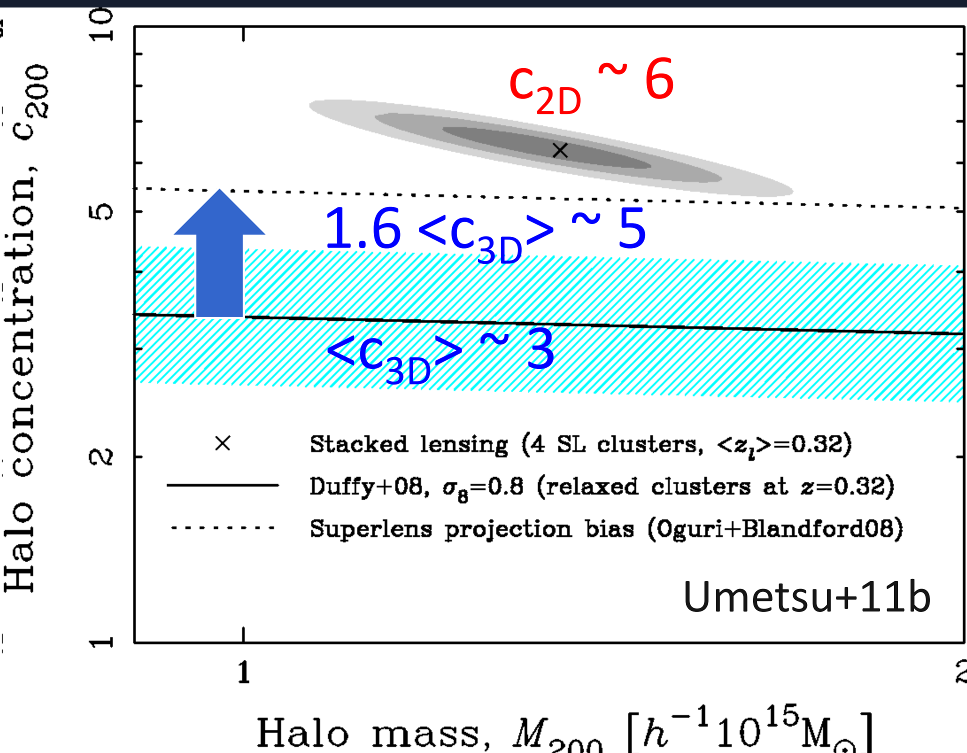
- Consistent geometric shear vs. magnification measurements allow for accurate cluster mass profile measurements for 20 CLASH clusters with +/-8% systematic mass-calibration uncertainty.
- Total matter distribution Σ (1h+2h) recovered from full-lensing analysis (SL + shear + magnification) is consistent with shear-based halo model predictions (b_h=9+/2 at M_{200}=1.3e15M_{sun}, z=0.35), establishing further consistency in the context of LCDM.

Supplemental Slides

CLASH Motivation

Before CLASH, deep-multicolor Strong (*HST*) + Weak (Subaru) lensing data only available for a handful of **strong-lens clusters** (θ_E > 30”, z_s=2)



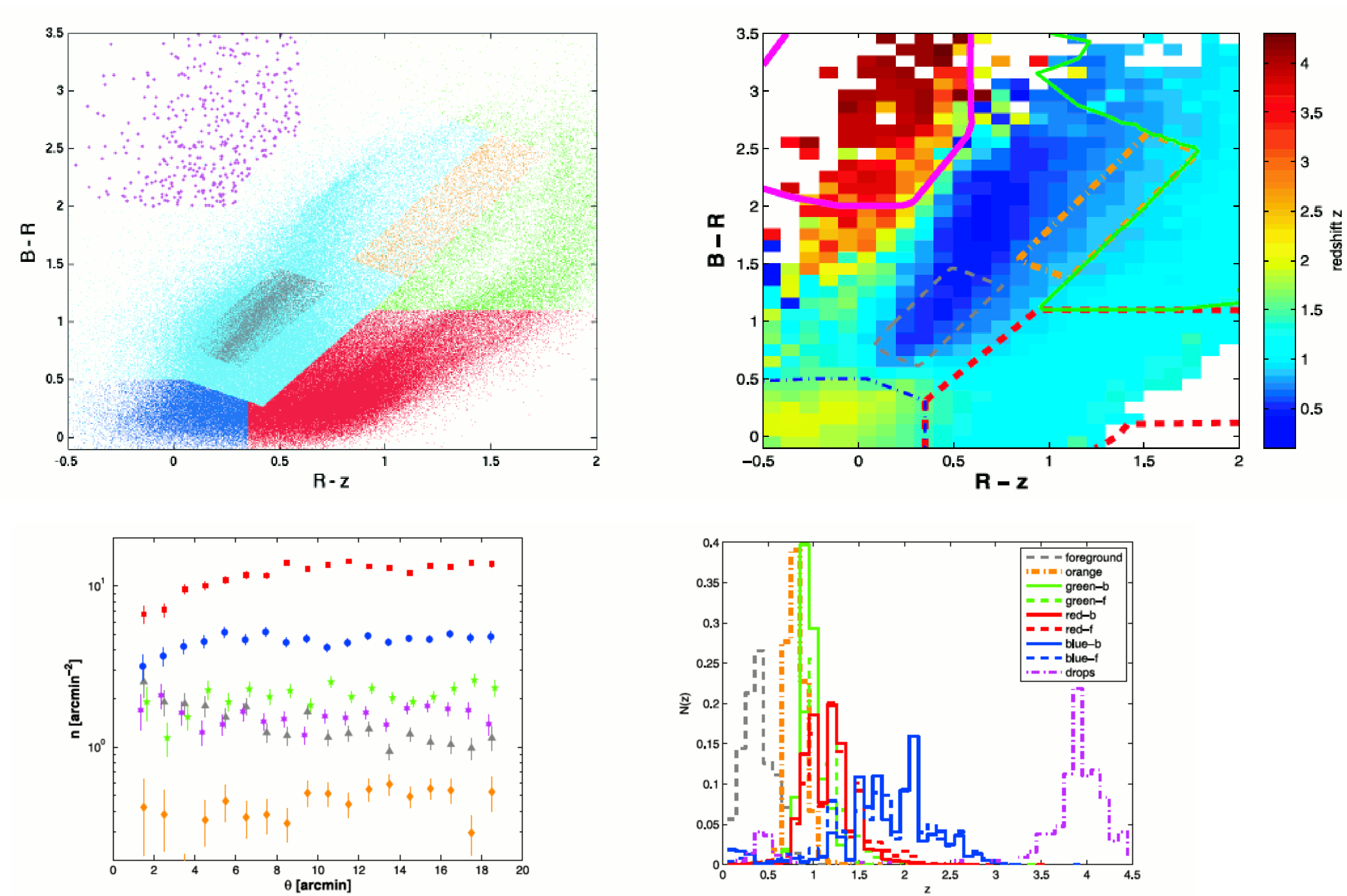


Total mass profile shape: consistent w self-similar NFW (cf. Newman+13; Okabe+13)

Over concentration?: maximum superlens correction (<60%) not enough if $\langle c_{LCDM}\rangle$~3?

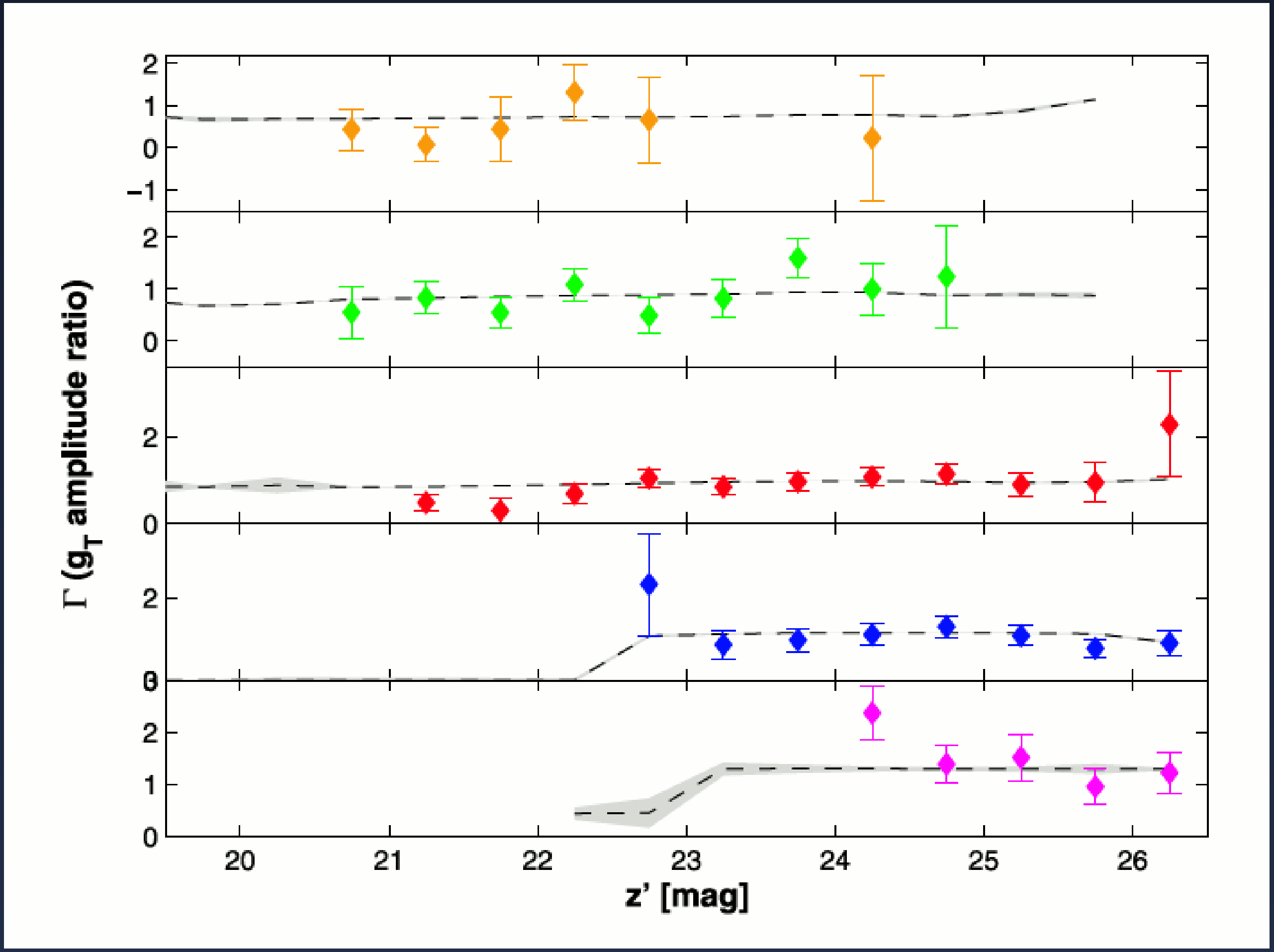
SUBARU multi-color maging for wide-field weak lensing

High-resolution space imaging with *Hubble* for strong lensing



B - R
R - z
B – R
R – z
redshift z
n [arcmin^{-2}]
θ [arcmin]
N(z)
z
foreground
orange
green–b
green–f
red–b
red–f
blue–b
blue–f
drops

SUBARU shear strength as a function of magnitude



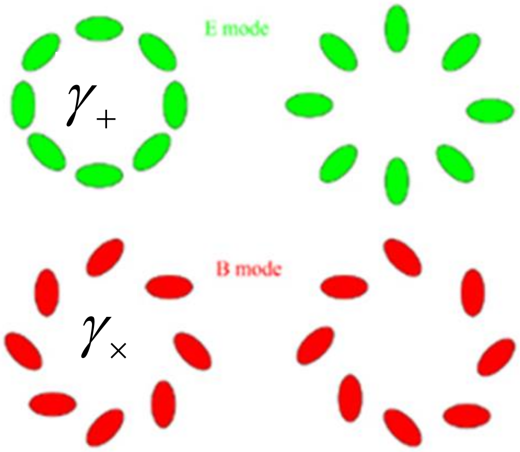
Medezinski, Broadhurst, Umetsu+11

Tangential Shear

Azimuthally-averaged tangential coherence of elliptical distortions around a given point (Kaiser 95):

$$\gamma_{+}(R) = \Delta\Sigma(\mathrm{R}) / \Sigma_{\mathrm{crit}}$$

$$\gamma_{\times}(R) = 0$$



ΔΣ(R) is the radially-*modulated* surface mass density:

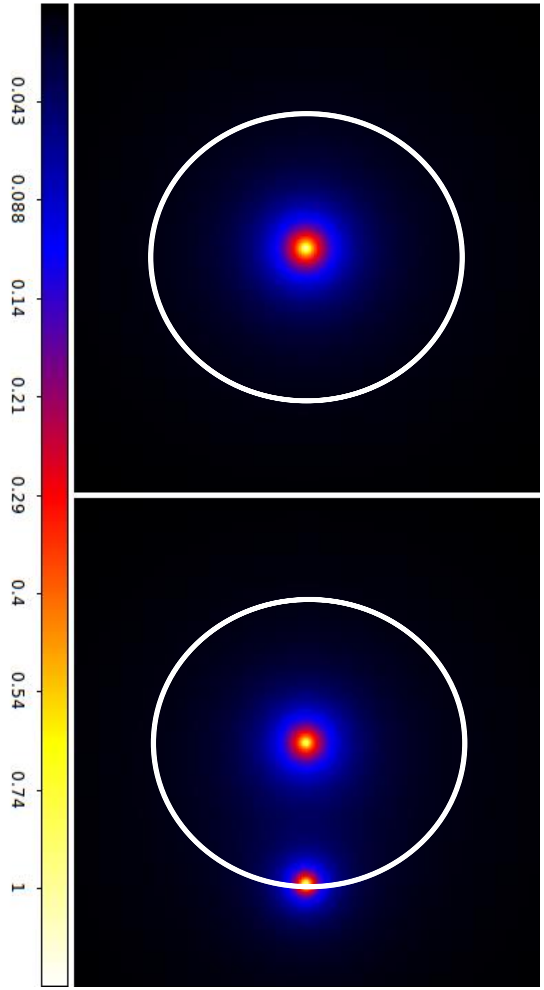
$$\Delta\Sigma(R) = \Sigma(< R) - \Sigma(R)$$

Sensitive to interior mass

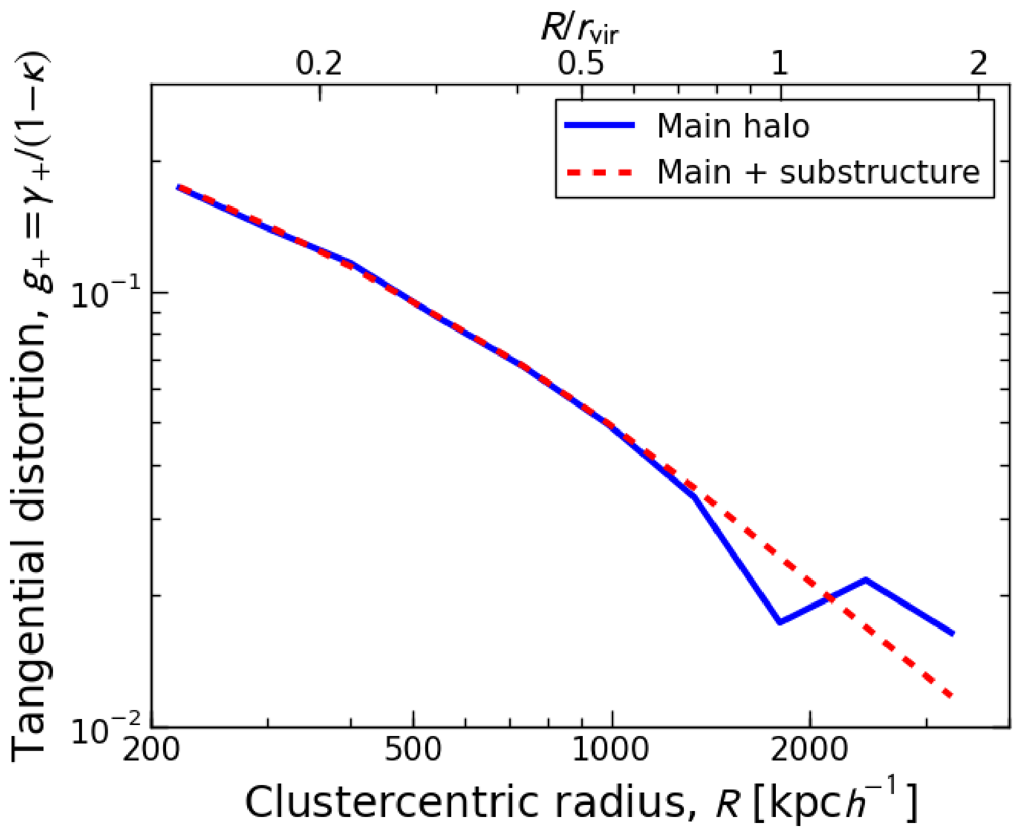
$$\Sigma = \int dl\,\delta\rho$$

$\Sigma_{crit}(z_l,z_s)$ is the *critical surface mass density of lensing*

Non-local substructure effect



A substructure at R ~ r_{vir} of the main halo, modulating $\Delta\Sigma(R) = \Sigma(<R) - \Sigma(R)$



Known ~10% negative bias in mass estimates from tangential-shear fitting, inherent to clusters sitting in substructured field (Rasia+12)

Magnification bias effects

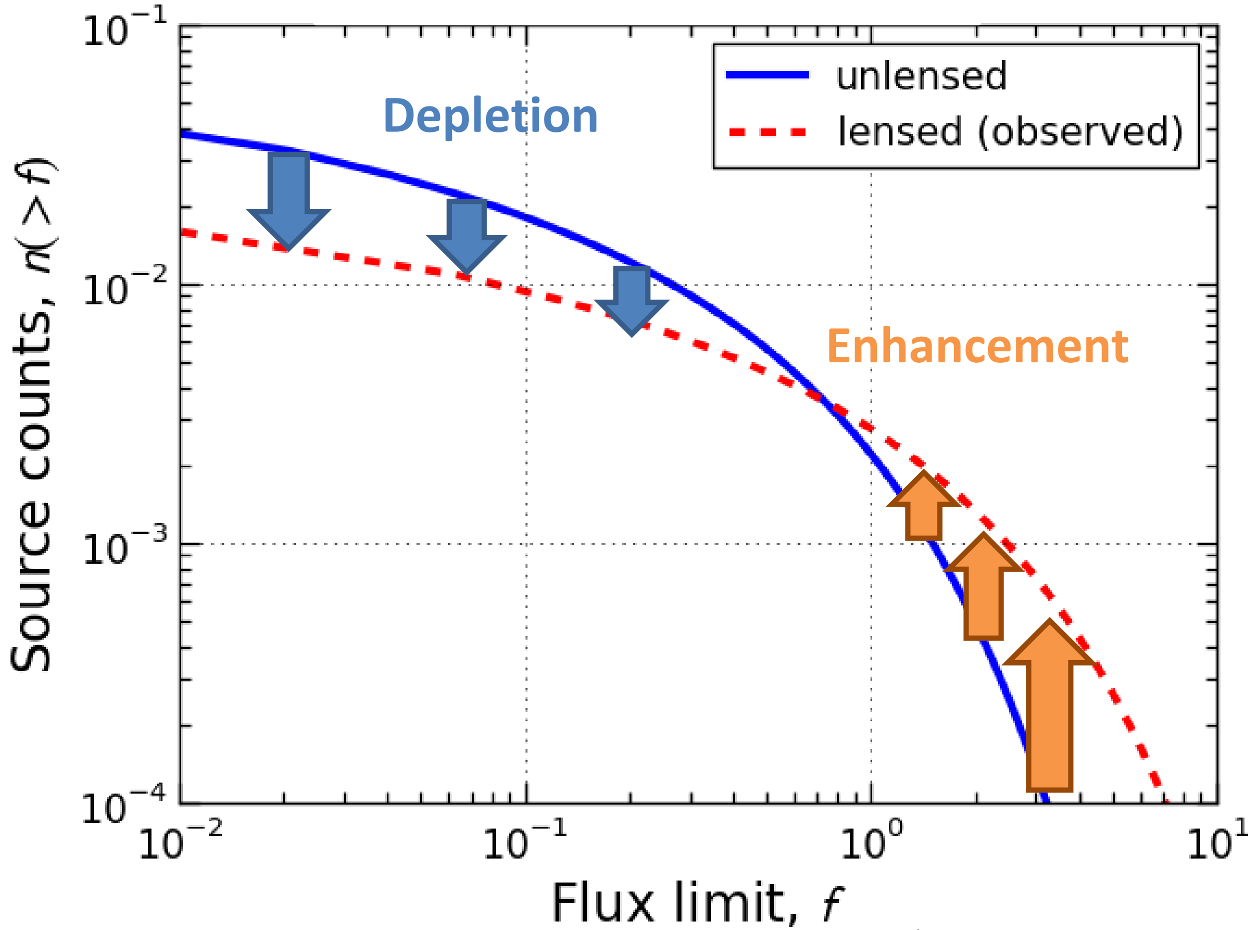
Flux-limited source counts:

$$n_{\rm obs}(>f) = \mu^{-1} n(>\mu^{-1} f)$$

Broadhurst, Taylor & Peacock 95

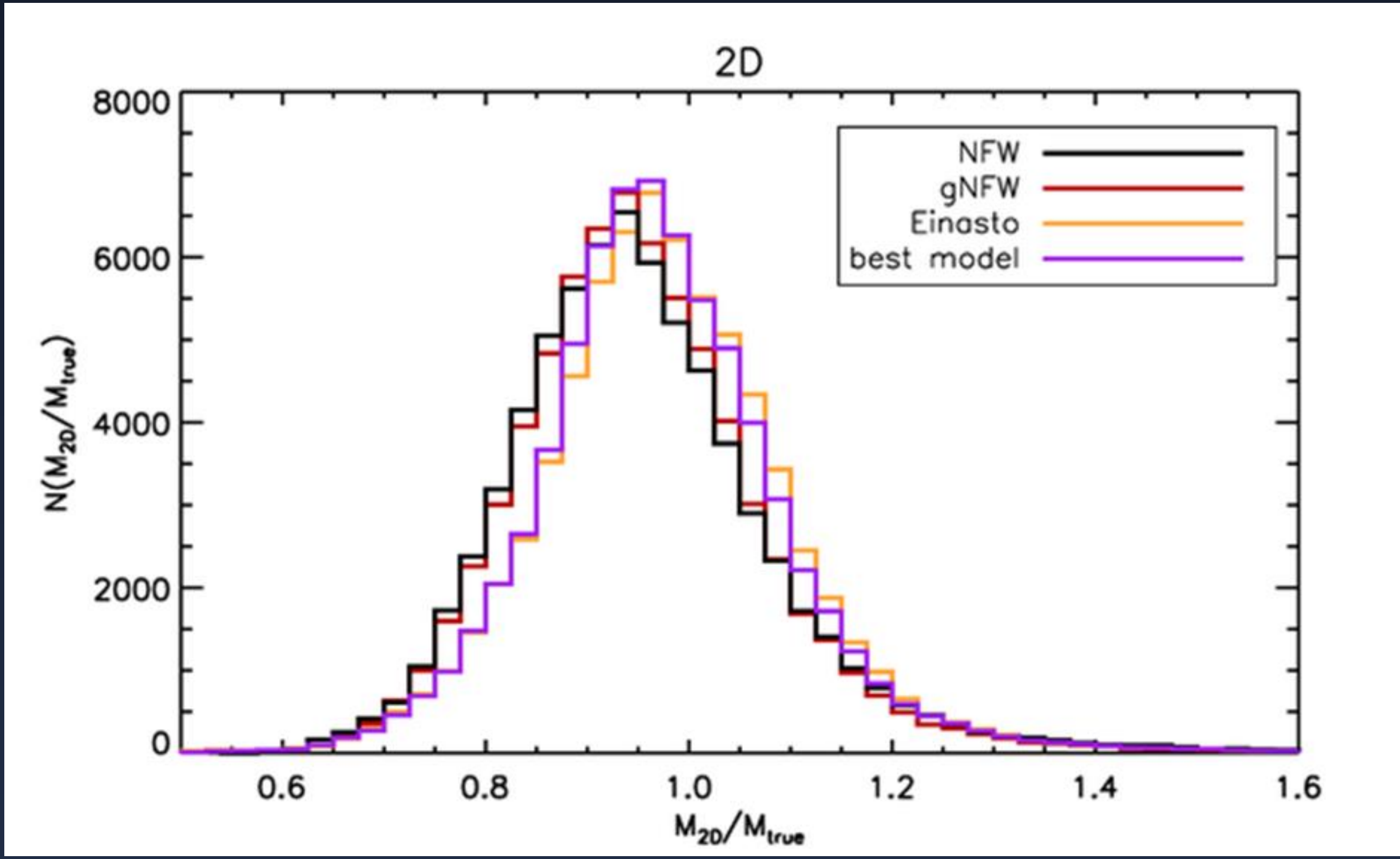
Geometric area distortion

n/μ



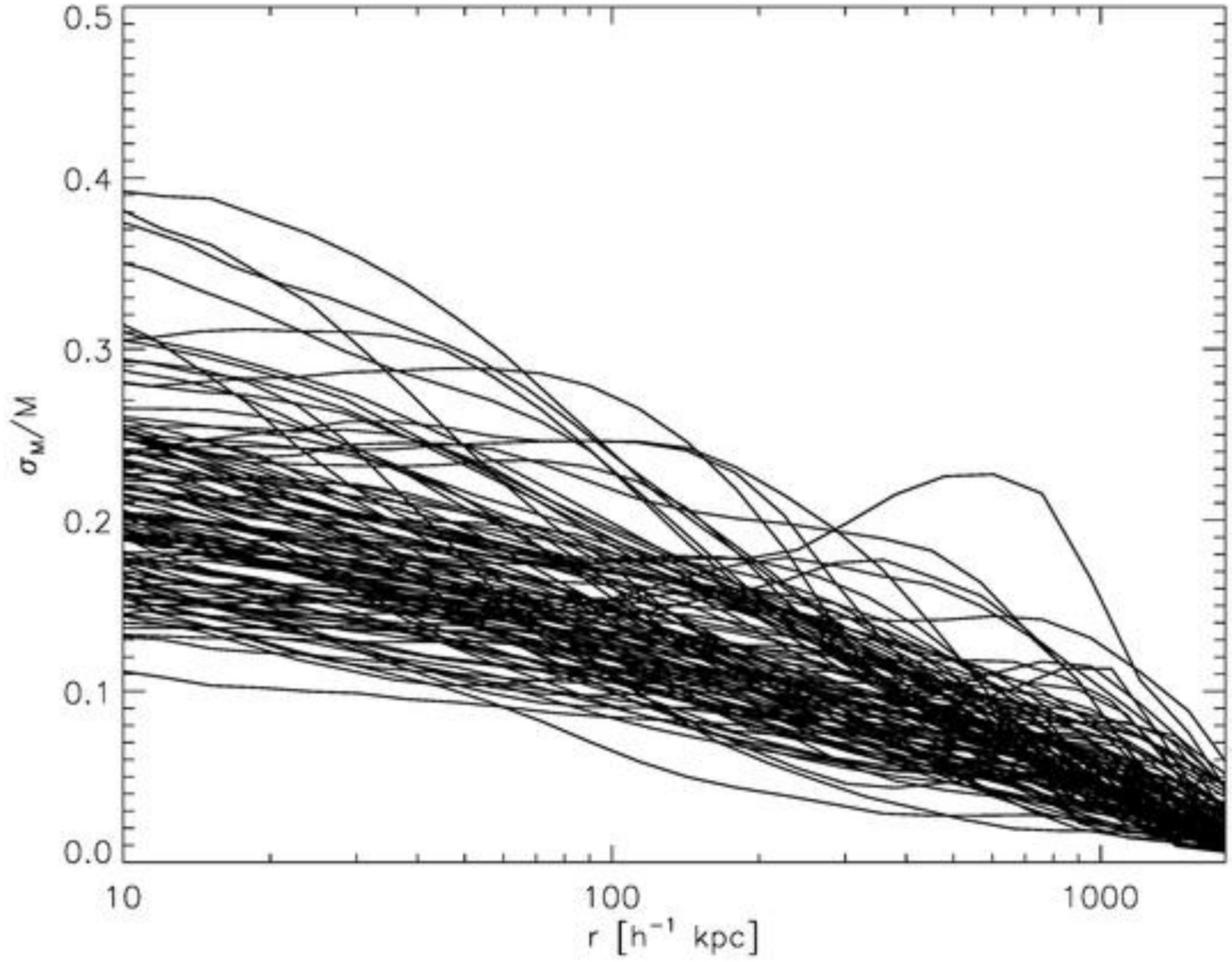
Flux amplification

Cluster masses recovered from lensing analysis



Meneghetti+CLASH 14

Scatter in $M_{2D}(R)$ by halo triaxiality



MUSIC-2 simulation by Massimo

Ensemble-averaged DM halo (1h) density profile

Stacking of weak-lensing signals by weighting individual clusters according to the sensitivity kernel matrix:

$$\langle\langle \widehat{\Delta\Sigma_+} \rangle\rangle = \left(\sum_n \mathcal{W}_{+n}\right)^{-1} \left(\sum_n \mathcal{W}_{+n} \widehat{\Delta\Sigma}_{+n}\right),$$

with the individual sensitivity matrix

$$(\mathcal{W}_{+n})_{ij} \equiv \Sigma_{c,n}^{-2} \left(\mathcal{C}_{+n}^{-1}\right)_{ij}$$

defined with the total covariance matrix

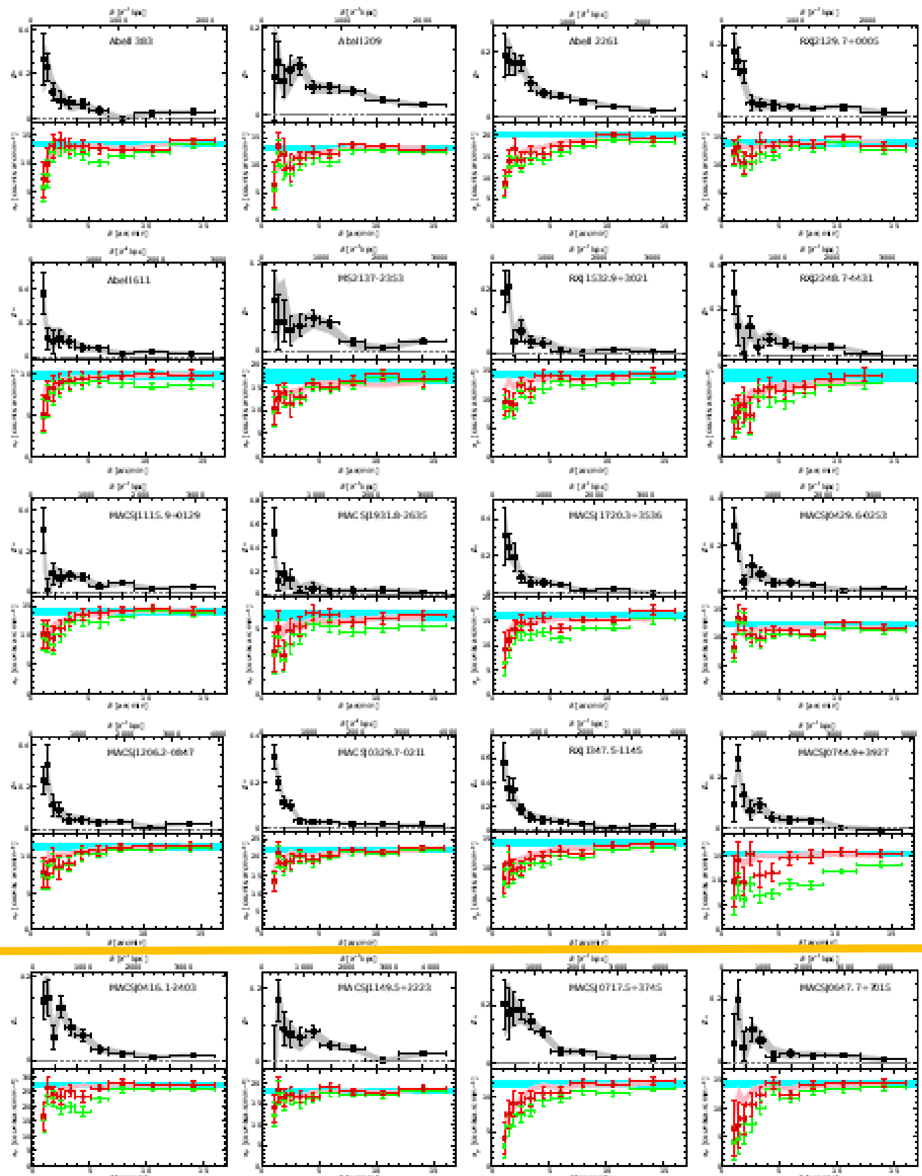
$$\mathcal{C}_+ = \mathcal{C}_+^{\rm stat} + \mathcal{C}_+^{\rm sys} + \mathcal{C}_+^{\rm lss}.$$

With "trace-approximation", averaging is interpreted as

$$\langle\langle \Sigma_c^{-1} \rangle\rangle = \frac{\sum_n {\rm tr}(\mathcal{W}_{+n}) \Sigma_{c,n}^{-1}}{\sum_n {\rm tr}(\mathcal{W}_{+n})},$$

Umetsu+CLASH 14, arXiv:1404.1375

20 CLASH clusters in Umetsu+14



16 X-ray-selected clusters

- 15 clusters from 8.3m Subaru Telescope
- 1 southernmost cluster (RXJ2248) from 2.2m ESO/MPG
- 0.18 < z < 0.69

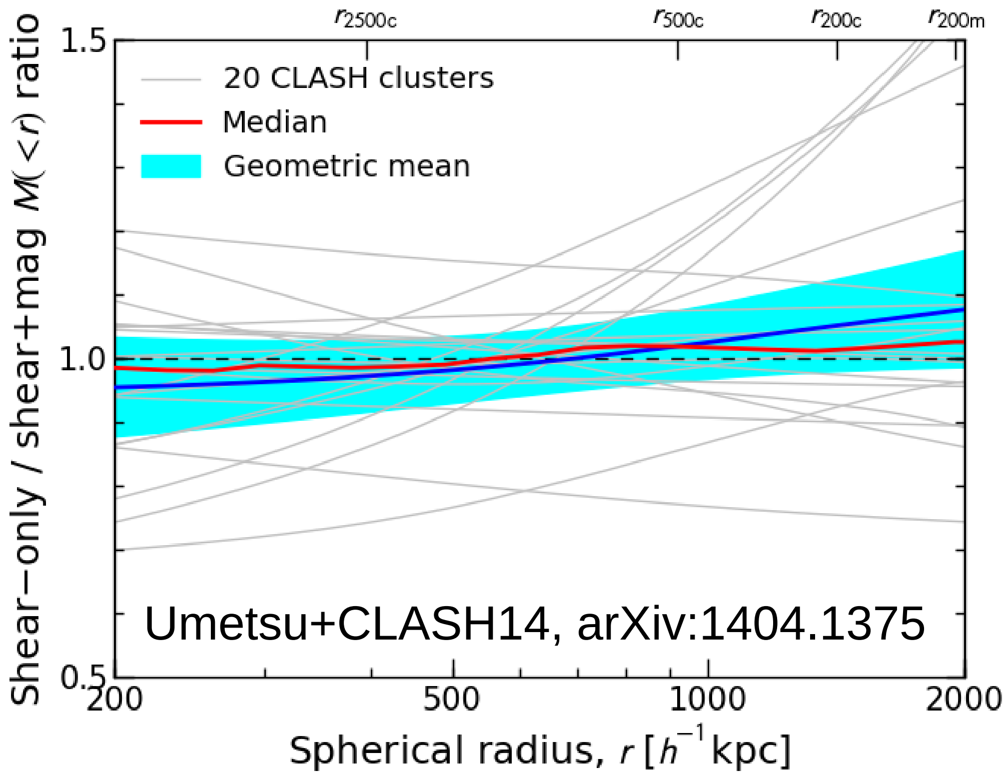
$\langle\chi^2/\text{dof}\rangle$ = 0.92 for 20 CLASH clusters

4 high-magnification clusters

- All 4 clusters from 8.3m Subaru Telescope

Shear-Magnification Consistency

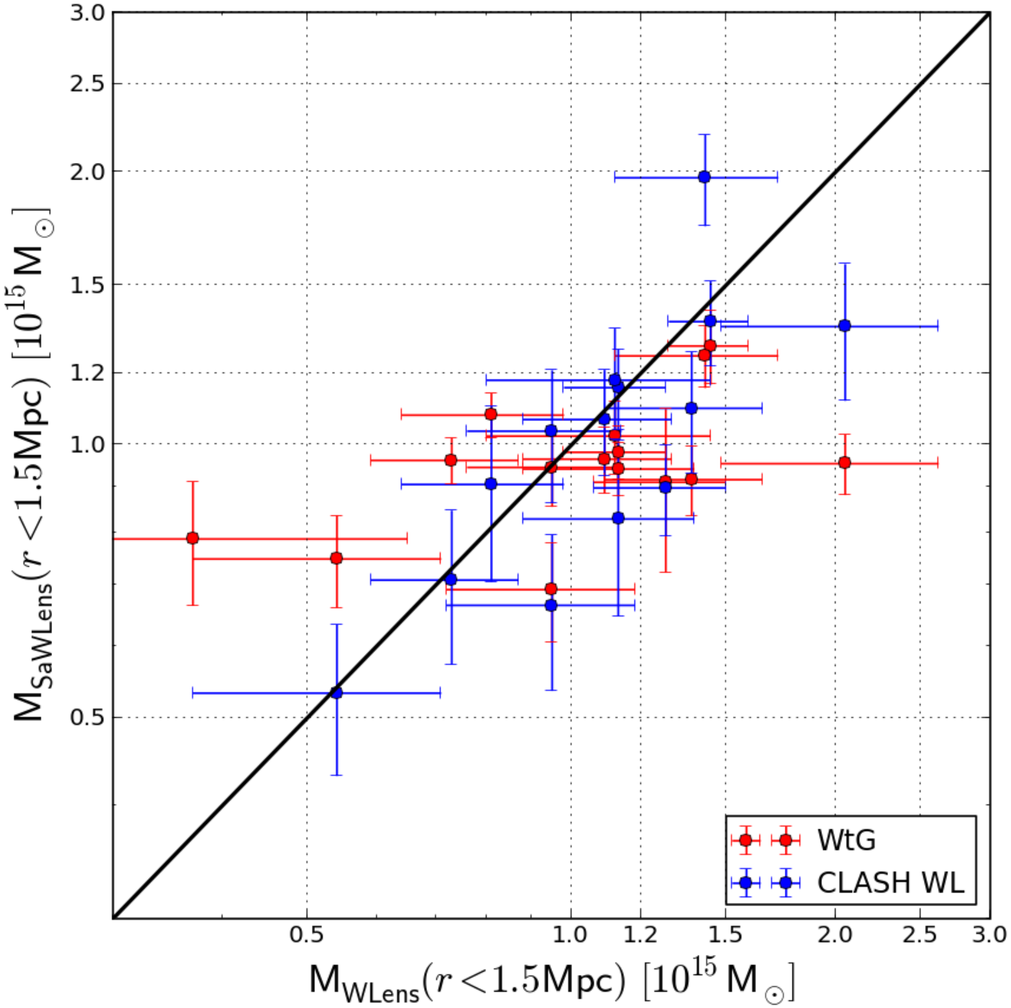
M(<r) de-projected assuming spherical NFW (20 CLASH clusters)



Internal systematic uncertainty in the overall mass calibration, empirically derived to be about +/- 8%

Mass Comparisons @ R=1.5Mpc

Merten+CLASH 14



Un-weighted geometric mean mass ratios (<Y/X>=1/<X/Y>)

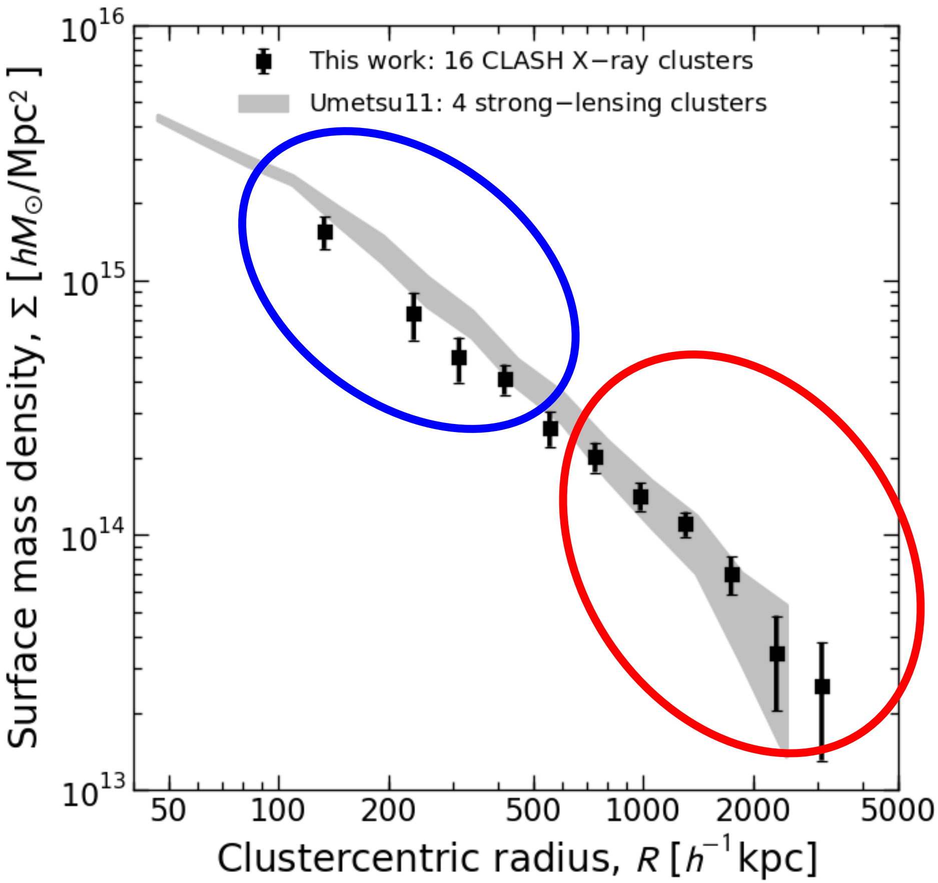
- <SaWLenS / WL> = 0.96
- <WL / WtG> = 0.91
- <SaWLenS / WtG> = 0.88

WL (Umetsu+14)
→ shear+mag (Subaru)
SaWLenS (Merten+14)
→ SL + shear (HST+Subaru)
WtG (Applegate+14)
→ shear (Subaru)

Note: WL mass calibration uncertainty of 8 percent

Comparison with pre-CLASH results

- **C_{200} vs θ_E relation, consistent with triaxial CDM halos (Oguri+12)**
- **Similar ν (MAH), similar Σ in outskirts (Diemer & Kravtsov 14)**
- **Increased Σ at R<0.5Mpc/h, consistent w orientation bias (Gao+12)**



CLASH X-ray-selected sample

- M_{200} = 1.3e15M_{sun}
- c_{200} = 4.0
- θ_E ~ 15” (z_s=2)
- ν=3.8 (b_h~9)

Umetsu11b sample

- M_{200} = 1.7e15M_{sun}
- c_{200} = 6.1
- θ_E ~ 36” (z_s=2)
- ν=4.1 (b_h~11)

Umetsu+CLASH 2014, arXiv:1404.1375