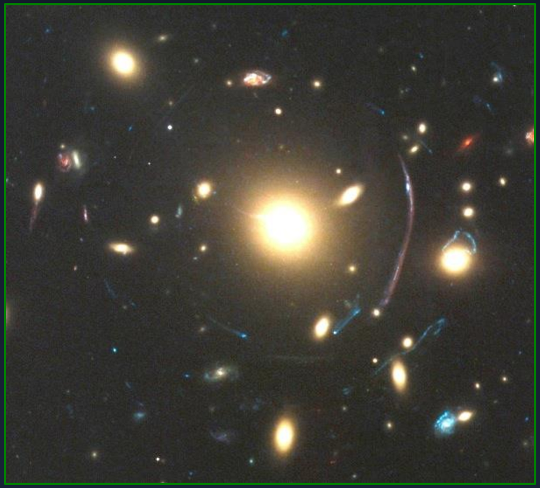
Mass Distribution in and around Galaxy Clusters from Gravitational Lensing:

Cluster Lensing And Supernova survey with Hubble

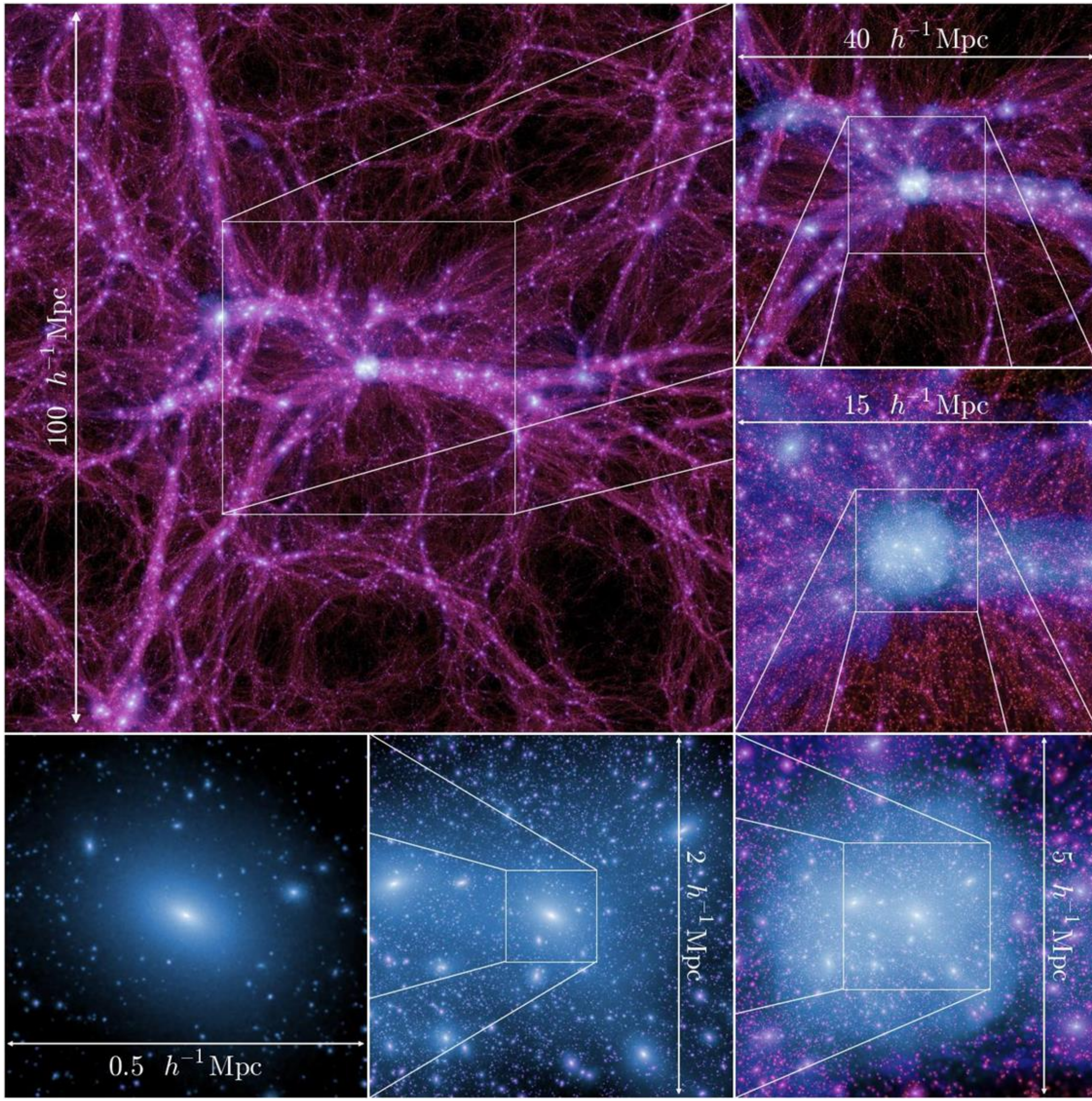
CLASH



Keiichi Umetsu (ASIAA, Taiwan) with the CLASH team

Galaxy Clusters as Cosmological Probes

Boylan-Kolchin+09



Surrounding LSS (2h)

- ✓ Halo bias $b(M,z)$
- ✓ Primordial matter $P(k)$

Halo structure (1h)

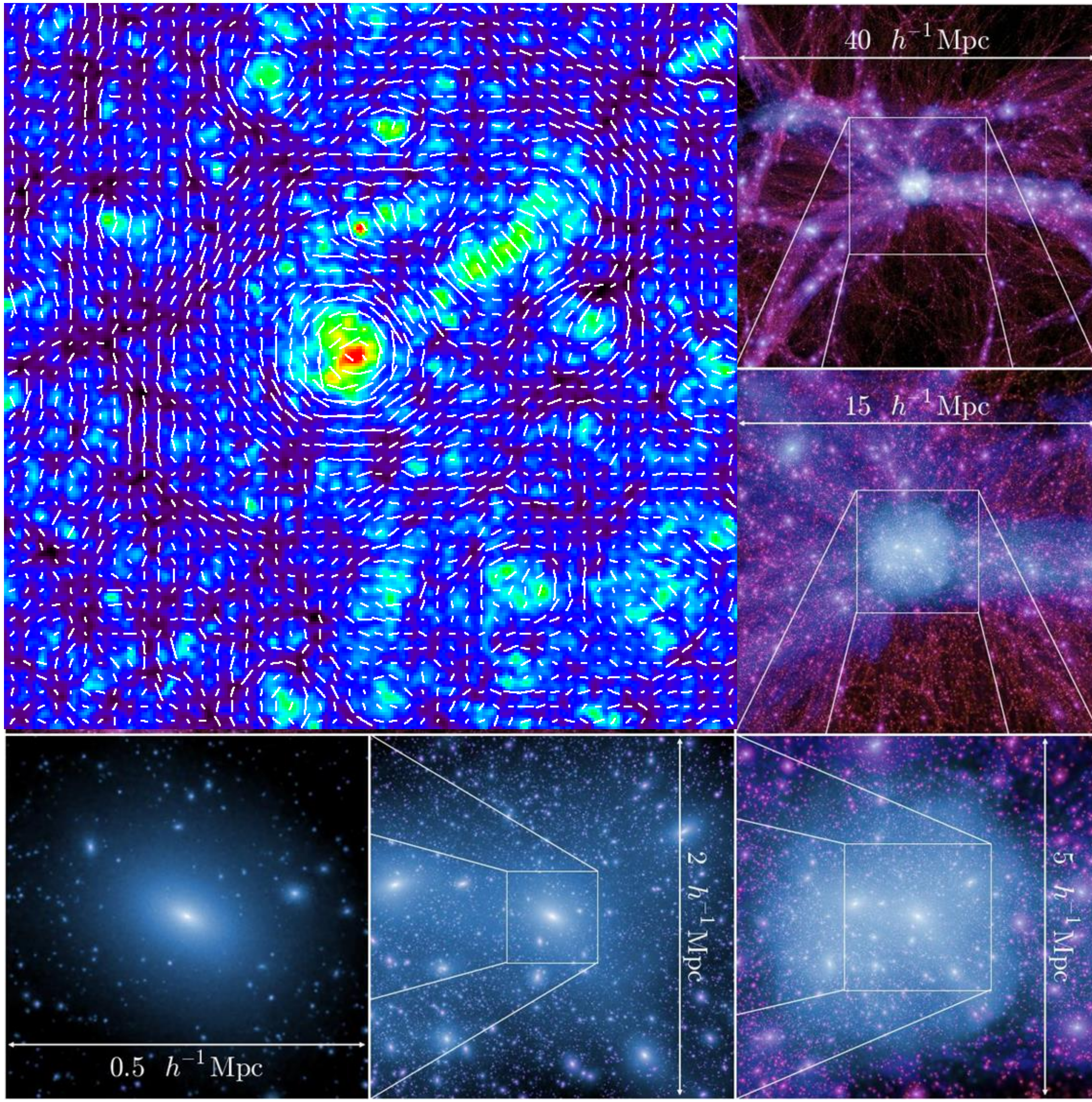
- ✓ *Mass, M*(r):
  Cluster cosmology
- ✓ *Concentration, c*(M,z):
  Halo mass assembly
- ✓ *Central cusp*:
  DM nature

Substructure

- ✓ Mass accretion history
- ✓ Subhalo mass function

Galaxy Clusters as Cosmological Probes

Boylan-Kolchin+09



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Tangential Shear

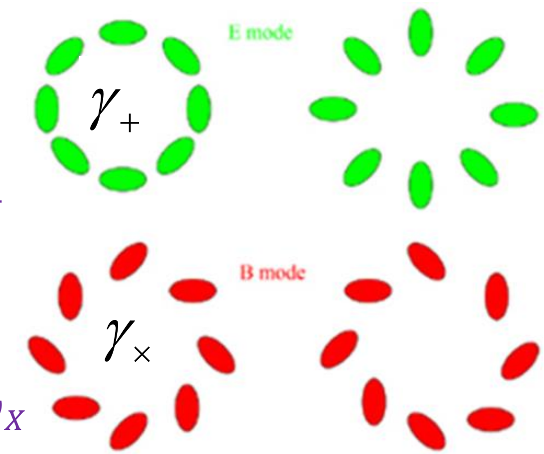
Measure of azimuthally-averaged tangential coherence of elliptical distortions around a given point (Kaiser 95):

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

$$(\boldsymbol{\Gamma}_+)_{ij} = \left(\boldsymbol{\delta}_i\boldsymbol{\delta}_j - \frac{\mathbf{1}}{\mathbf{2}}\Delta^{(2)}\boldsymbol{\delta}_{ij}\right)\boldsymbol{\psi}_+$$

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

$$(\boldsymbol{\Gamma}_X)_{ij} = (\boldsymbol{\epsilon}_{kj}\boldsymbol{\partial}_i\boldsymbol{\partial}_k - \boldsymbol{\epsilon}_{ki}\boldsymbol{\partial}_j\boldsymbol{\partial}_k)\boldsymbol{\psi}_X$$



$\Delta\Sigma$(R) is the radially-*modulated* surface mass density:

$$\Delta\Sigma(R) = \underline{\Sigma(< R)} - \Sigma(R)$$

Sensitive to interior mass

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

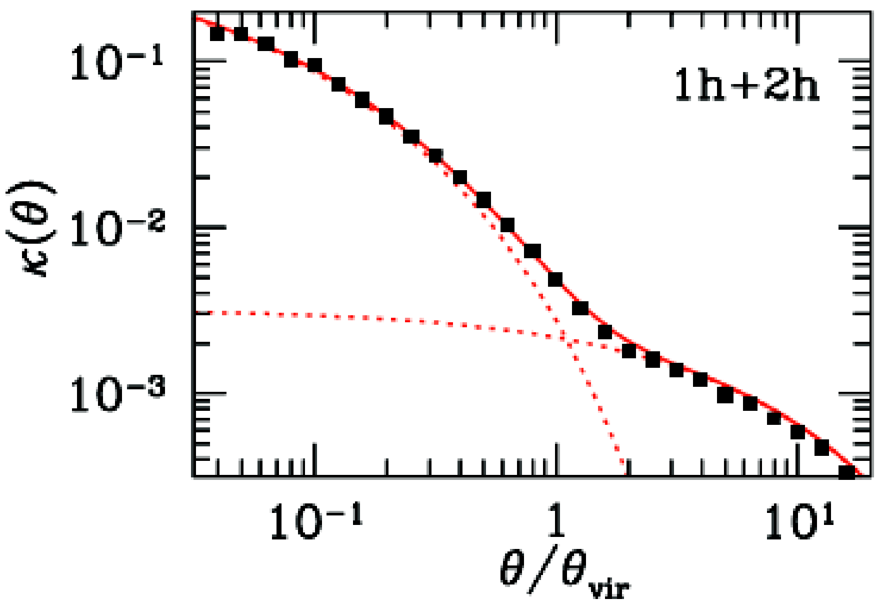
$\Sigma_{\mathrm{crit}}(z_l,z_s)$ is the *critical surface mass density of lensing*

Shear doesn't see mass sheet

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

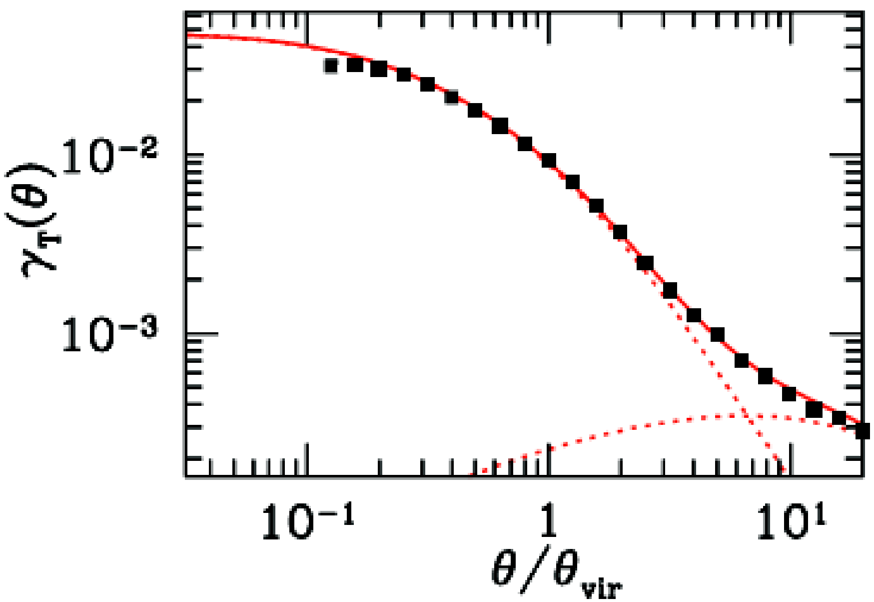
Total

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



Modulated

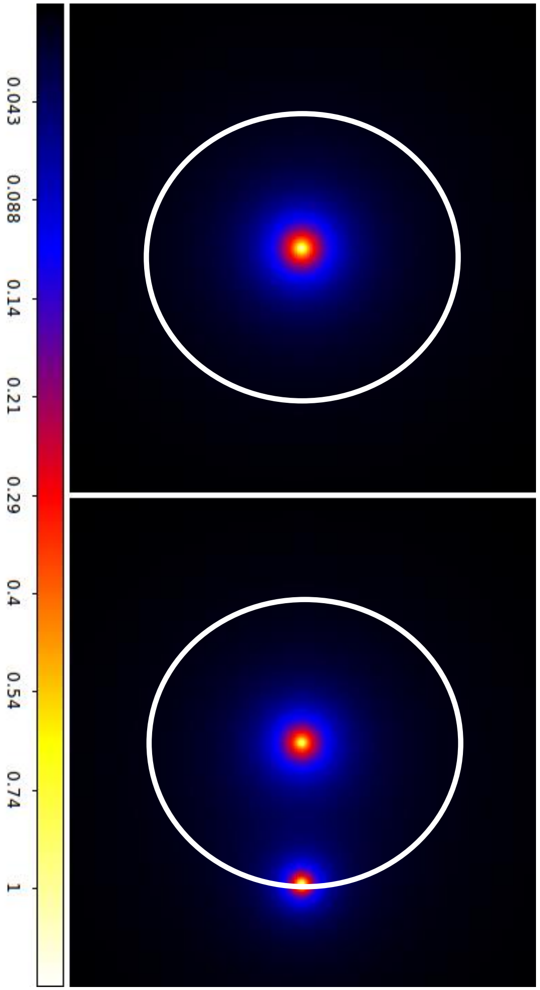
$$\gamma_+ = \Delta\Sigma(R) / \Sigma_{\rm crit}$$

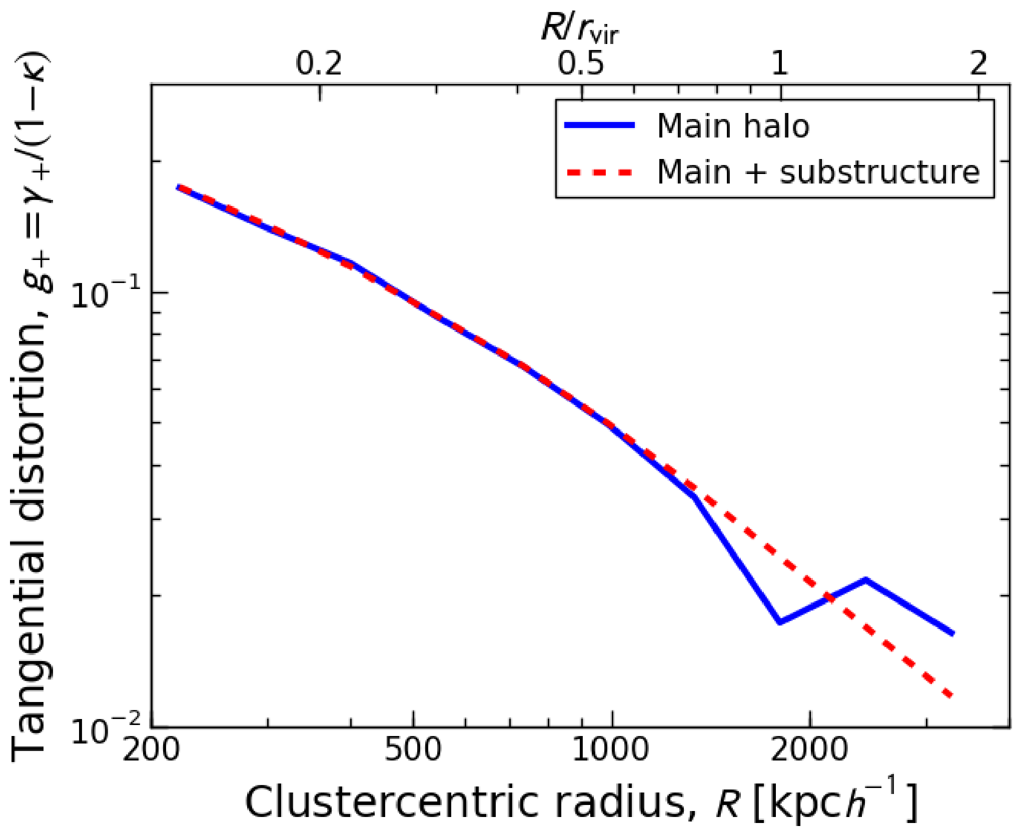


- **Tangential shear is a powerful probe of 1-halo term, or internal halo structure.**
- **Shear alone cannot recover absolute mass, known as *mass-sheet degeneracy***

Non-local substructure effect

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



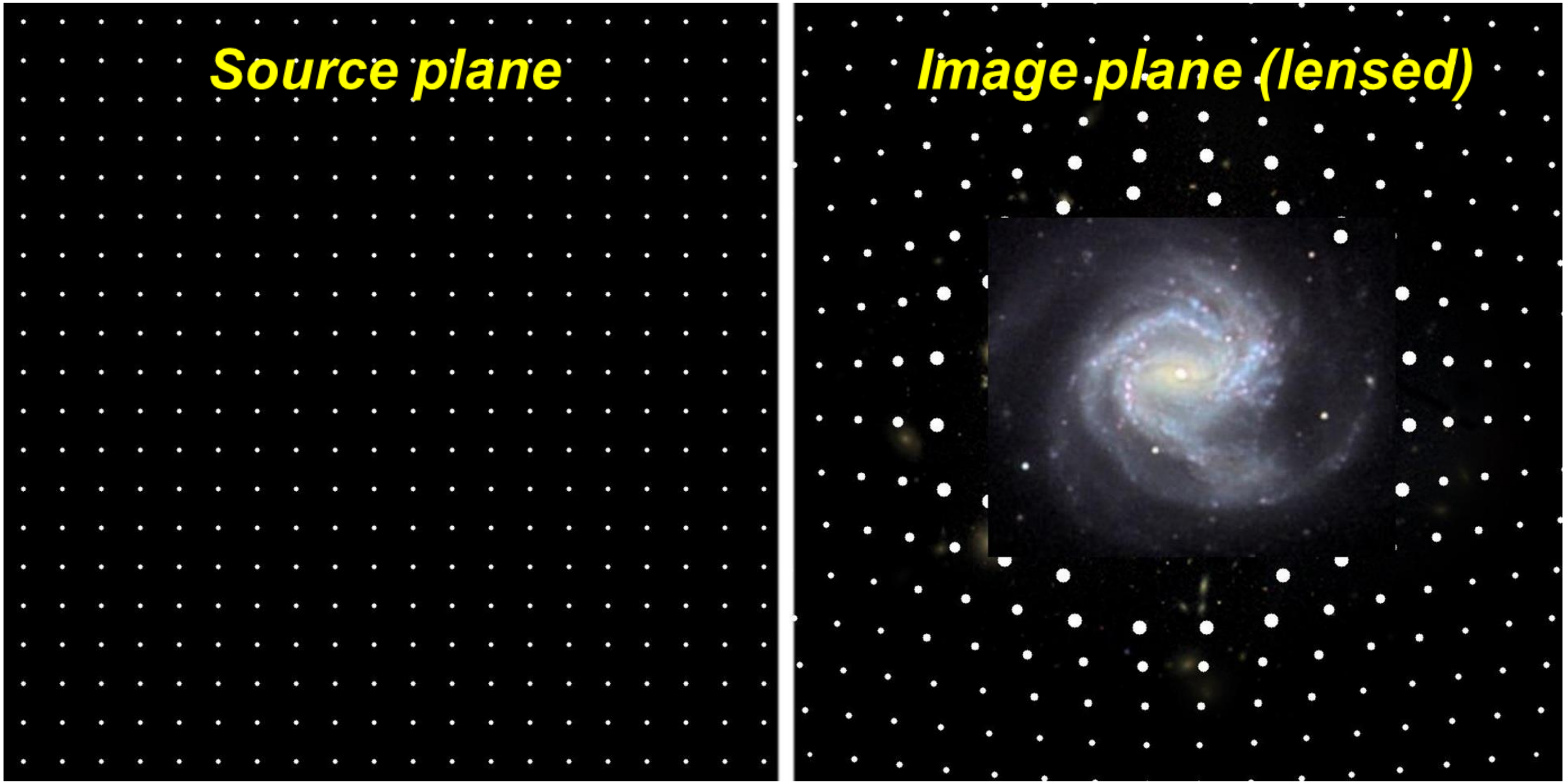


Known ~10% negative bias in mass estimates from tangential-shear fitting, inherent to clusters sitting in substructured field (Rasia+12)

Cluster Lensing Magnification

MACSJ1149 (z=0.54)
Zheng+CLASH. 2012, *Nature, 489, 406*

Magnification Effects



- Image flux, *F*: $\mu \sim 1+2\kappa$
- Image size, *r*: $\mu^{1/2} \sim 1+\kappa$
- Sky area, $\Delta\Omega$: $\mu \sim 1+2\kappa$

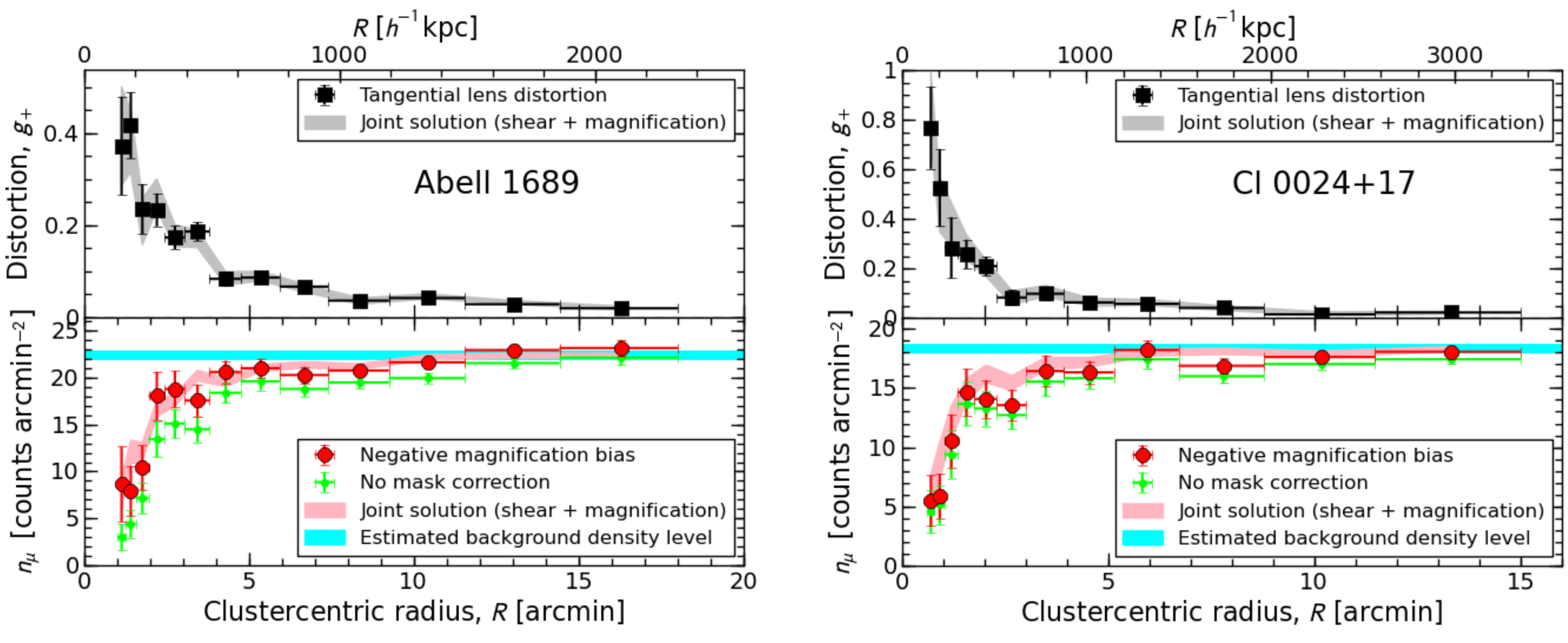
Sensitive to "local" matter density

$$\kappa = \Sigma / \Sigma_{\rm crit}$$

Negative Magnification Bias: Count Depletion

Geometric shear-magnification consistency

Number counts of red galaxies at <z>~1 highly depleted



Umetsu+11a, ApJ, 729, 127

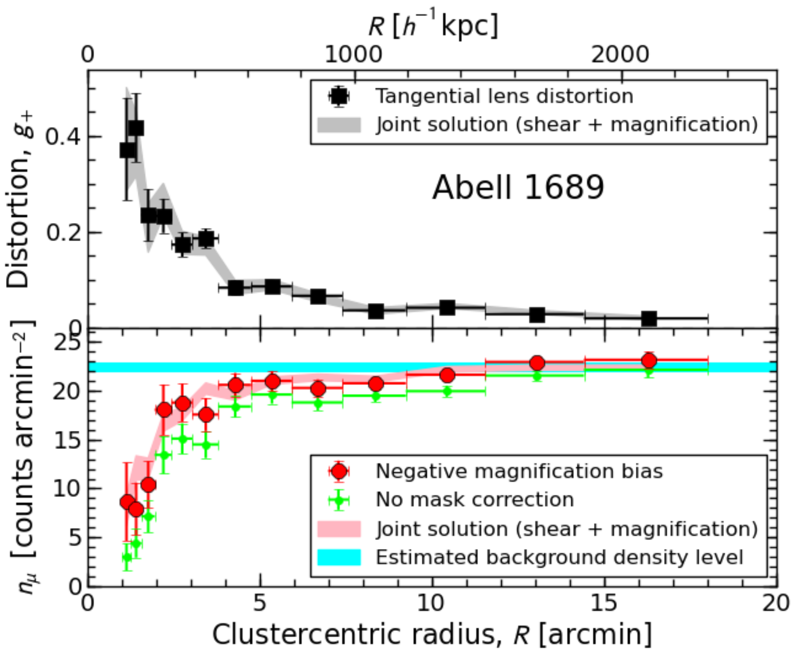
Subaru telescope data

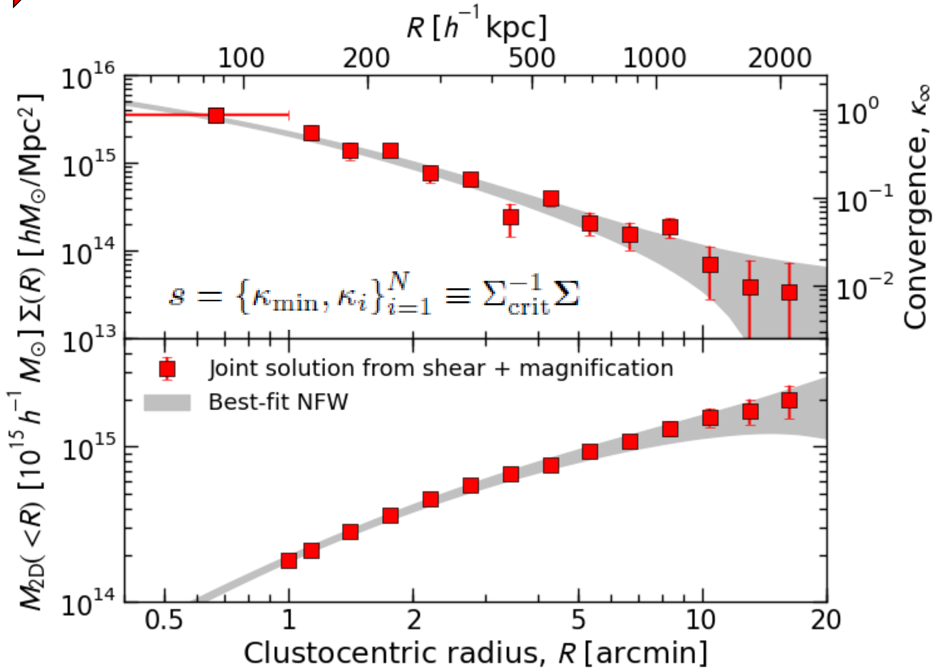
Combining Shear and Magnification

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

Shear + magnification

Non-parametric Σ(R) solution



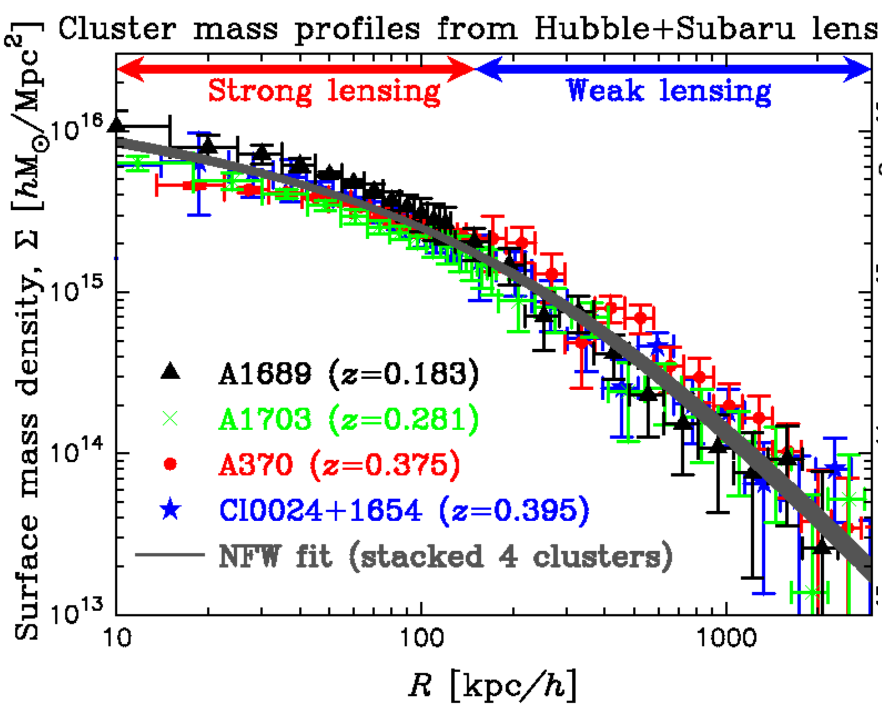


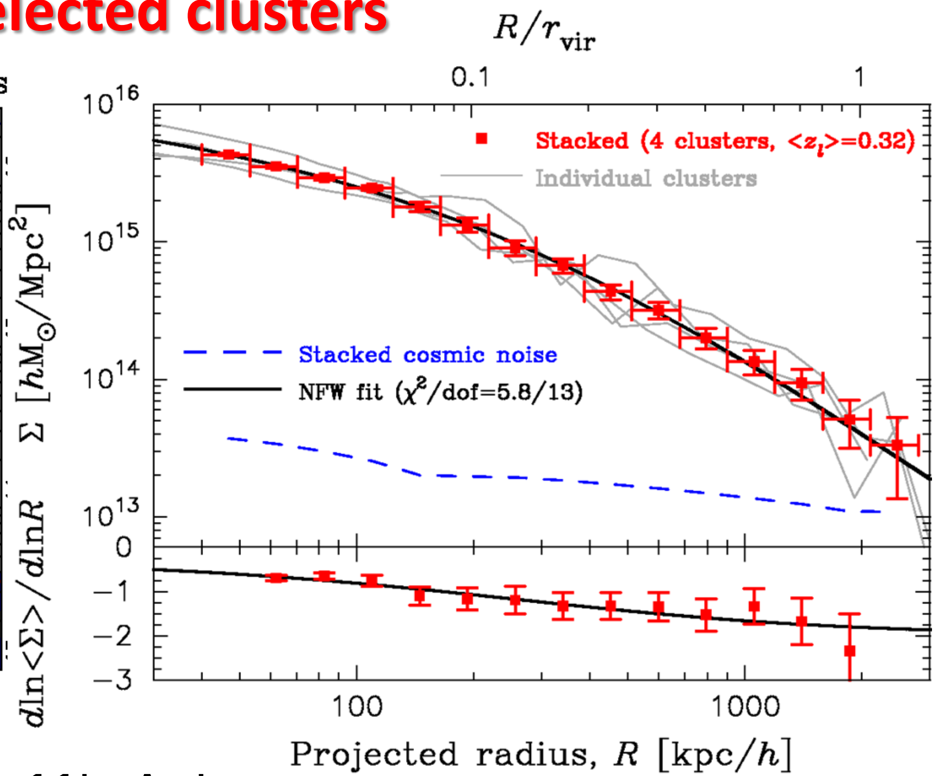
- Mass-sheet degeneracy broken
- Total statistical precision improved by ~20-30%
- Calibration uncertainties marginalized over: $c = \{\langle W\rangle_s, f_{W,s}, \langle W\rangle_\mu, \overline{n}_\mu, s_{\rm eff}\}$.

Mass profiles from full-lensing analysis

Multi-scale, multi-probe lensing approach (**strong-lensing** + **shear** + **magnification**) with ***HST*+Subaru**, probing > 2 decades in cluster-centric radius, R= [5x10^{-3}, 1.5] R_{vir}

"pre"-CLASH work on 4 lensing-selected clusters





Umetsu+11a. 11b, ApJ

CLASH:

Cluster Lensing And Supernova survey with Hubble

An HST Multi-Cycle Treasury Program designed to place new constraints on the fundamental components of the cosmos: dark matter, dark energy, and baryons.

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

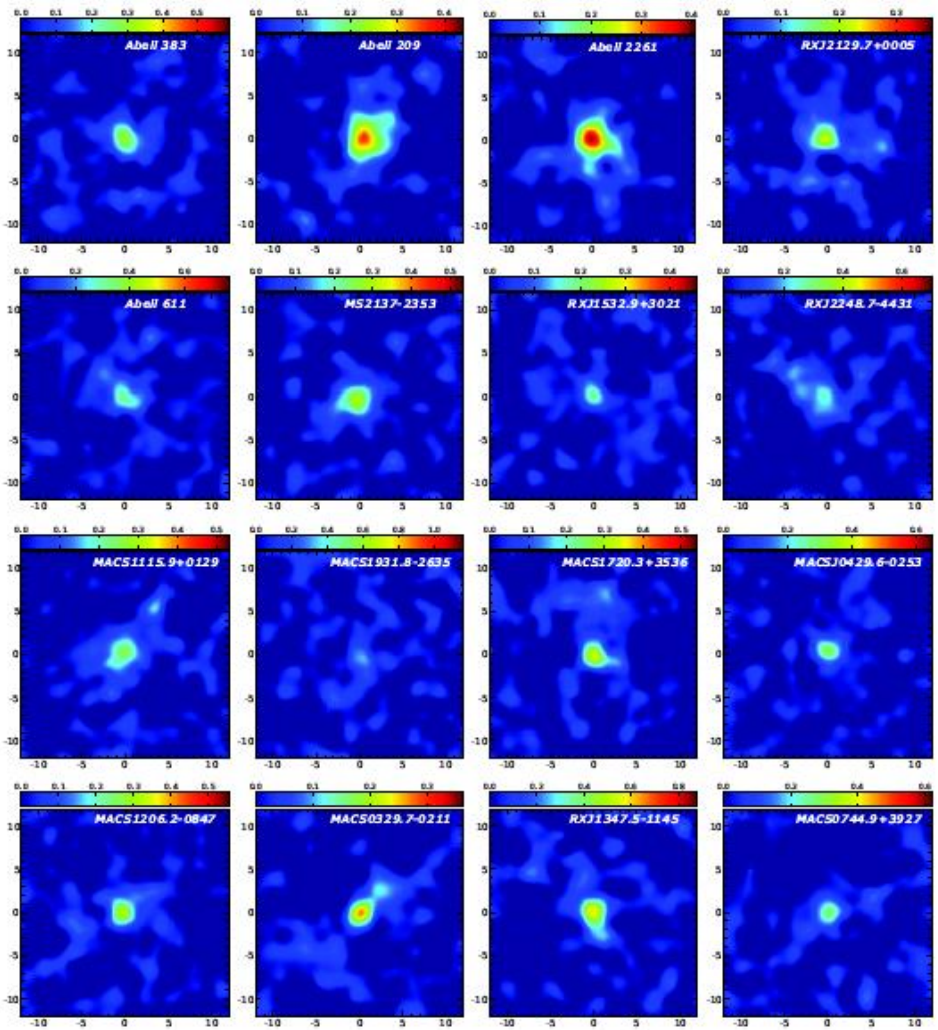
My talk will focus on CLASH-WL results based primarily on Subaru data

The CLASH Gallery (HST)

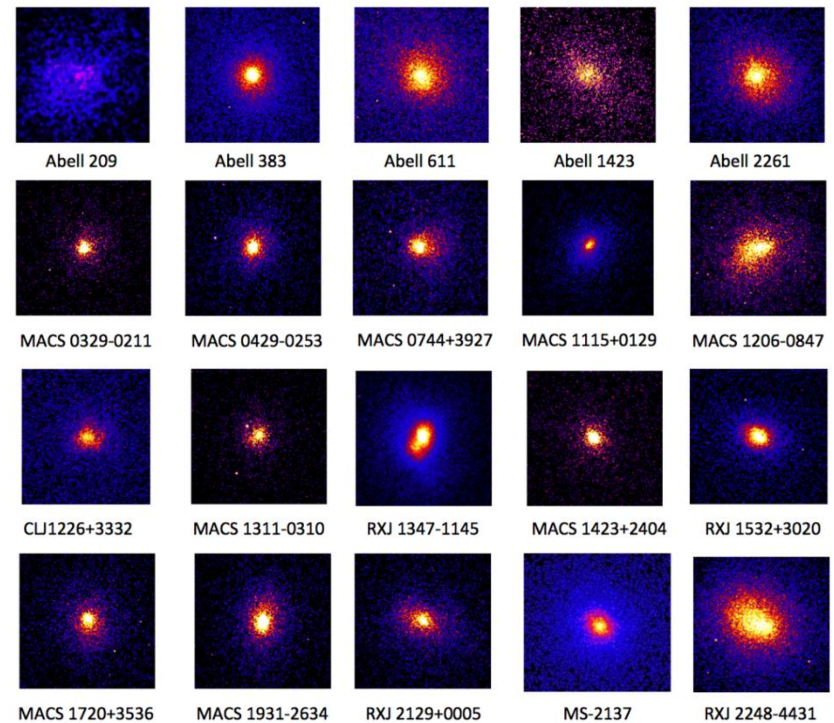
The final HST observation for CLASH was on 9-July-2013 … 963 days, 15 hrs, 31 min after first obs.

CLASH X-ray-selected subsample

WL mass maps: 16 clusters completed



X-ray maps: 20 CLASH clusters are purely X-ray selected to be massive and relaxed



Umetsu+CLASH 14, in prep (Subaru, 24’x24’)

Postman+CLASH 12, ApJS

Ensemble-averaged DM halo 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

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

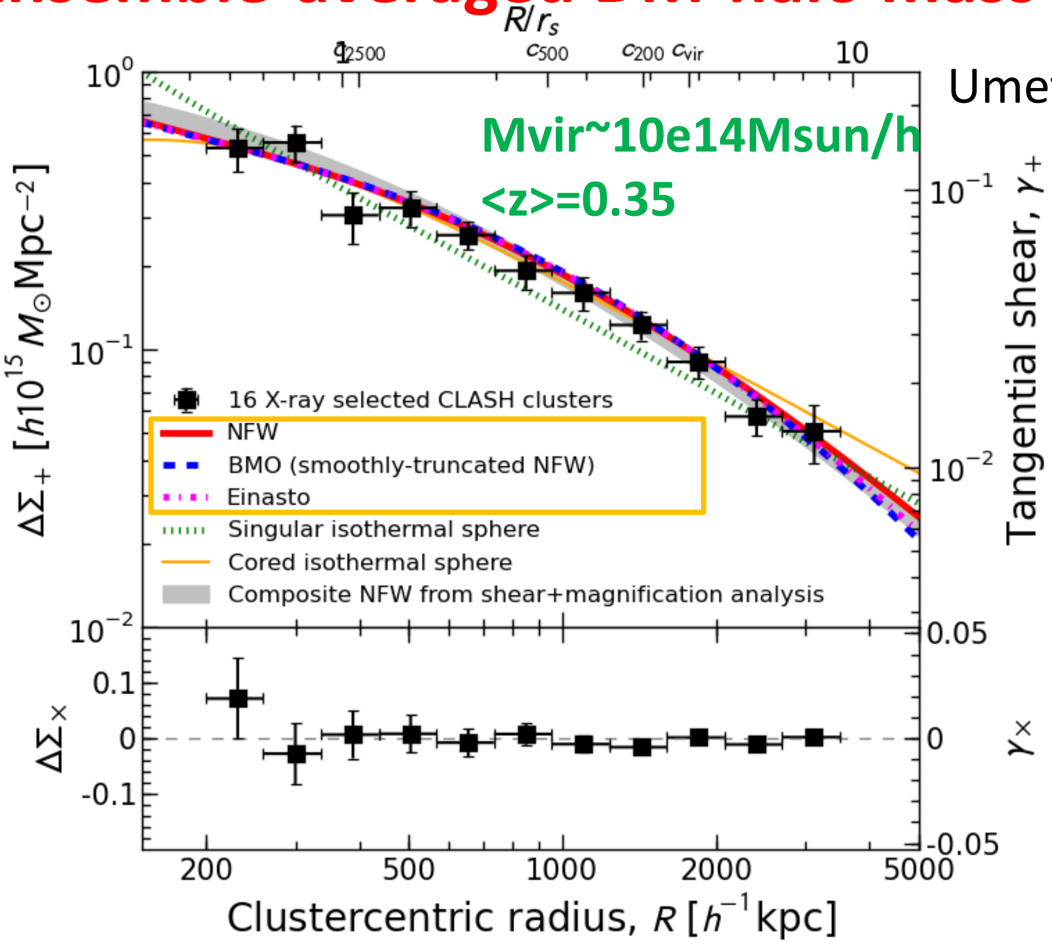
With "trace-approximation", averaging is interpreted as

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

CLASH-WL: Stacked Shear-only Analysis

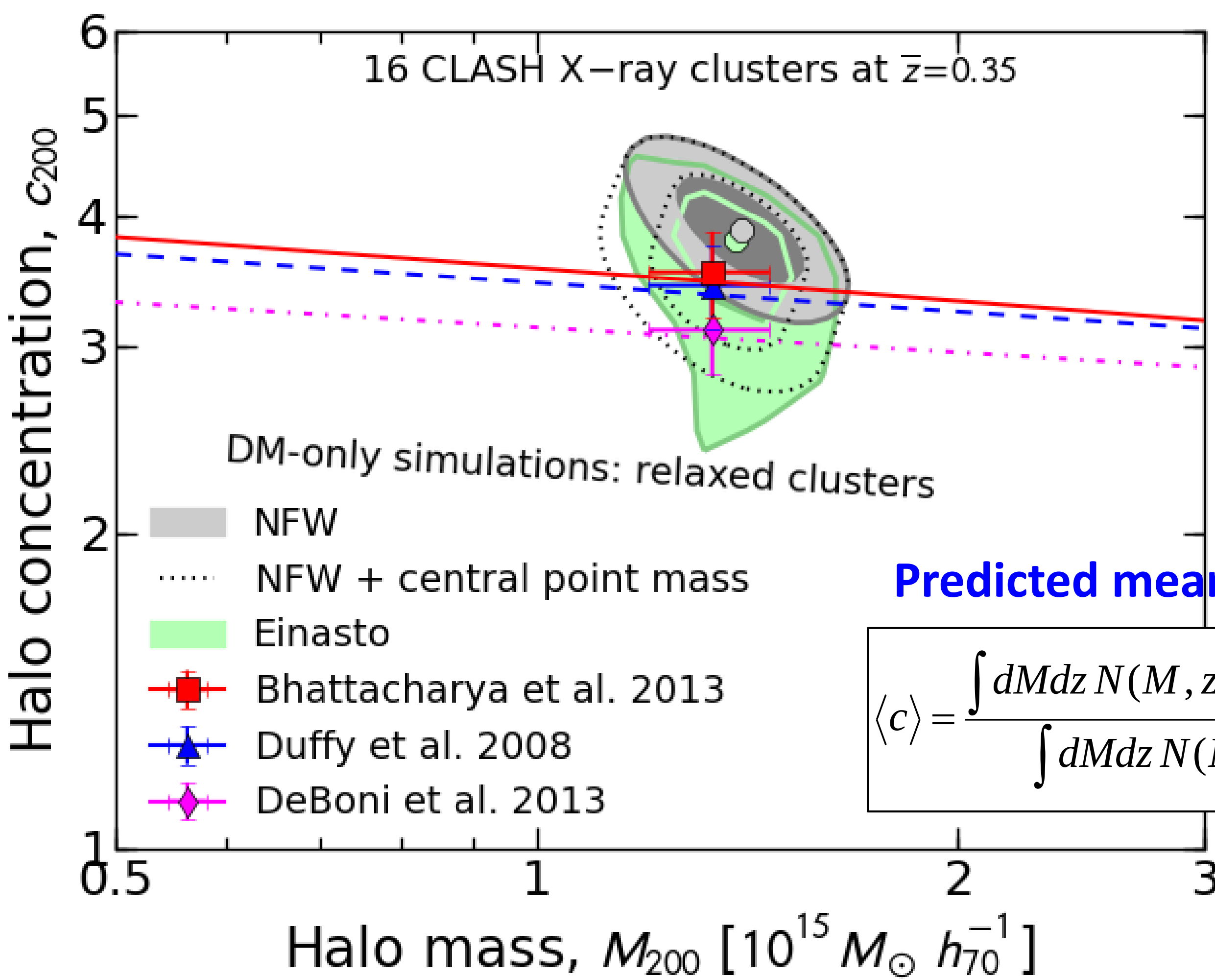
Ensemble-averaged DM-halo mass profile

Umetsu+CLASH14, in prep



Consistent with a family of density profiles for collisionless-DM halos in gravitational equilibrium (NFW, BMO, Einasto)

CLASH-WL: Mass-concentration relation



Predicted mean concentration

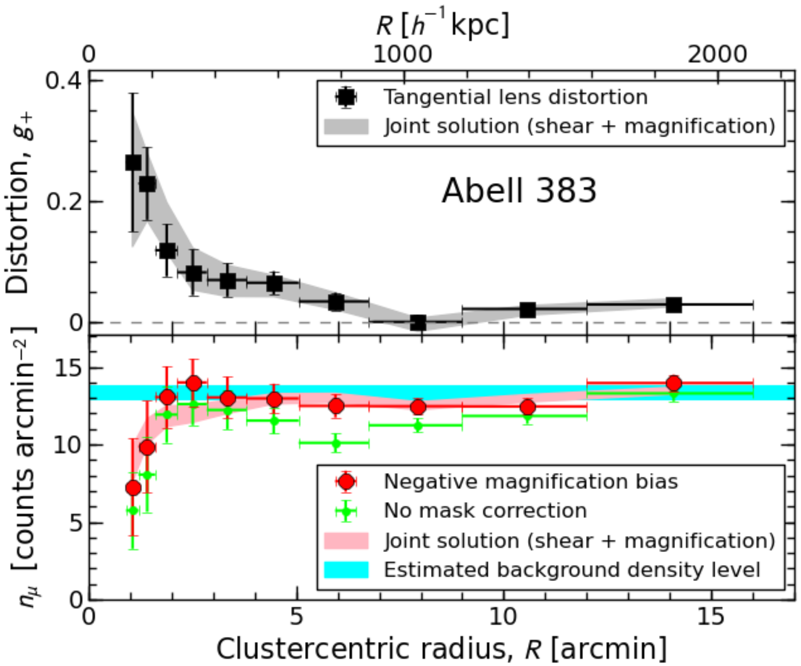
$$\langle c\rangle = \frac{\int dMdz\,N(M,z)\,\hat{c}(M,z)}{\int dMdz\,N(M,z)} \approx \frac{\sum_n \mathrm{tr}(W_n)\,\hat{c}(M_n,z_n)}{\sum_n \mathrm{tr}(W_n)}$$

Umetsu+CLASH14 in prep

CLASH-WL: Shear+Magnification measurements of 16 X-ray clusters

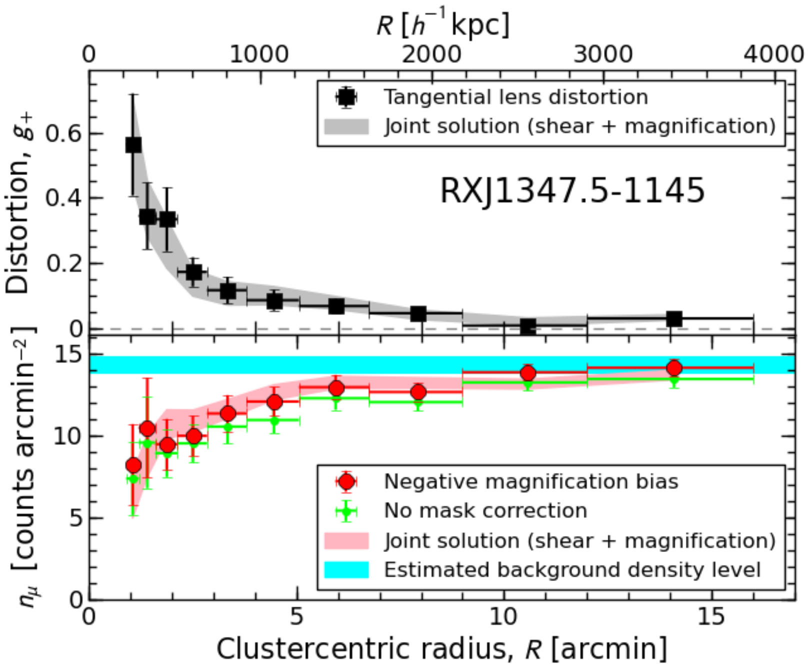
CLASH low mass

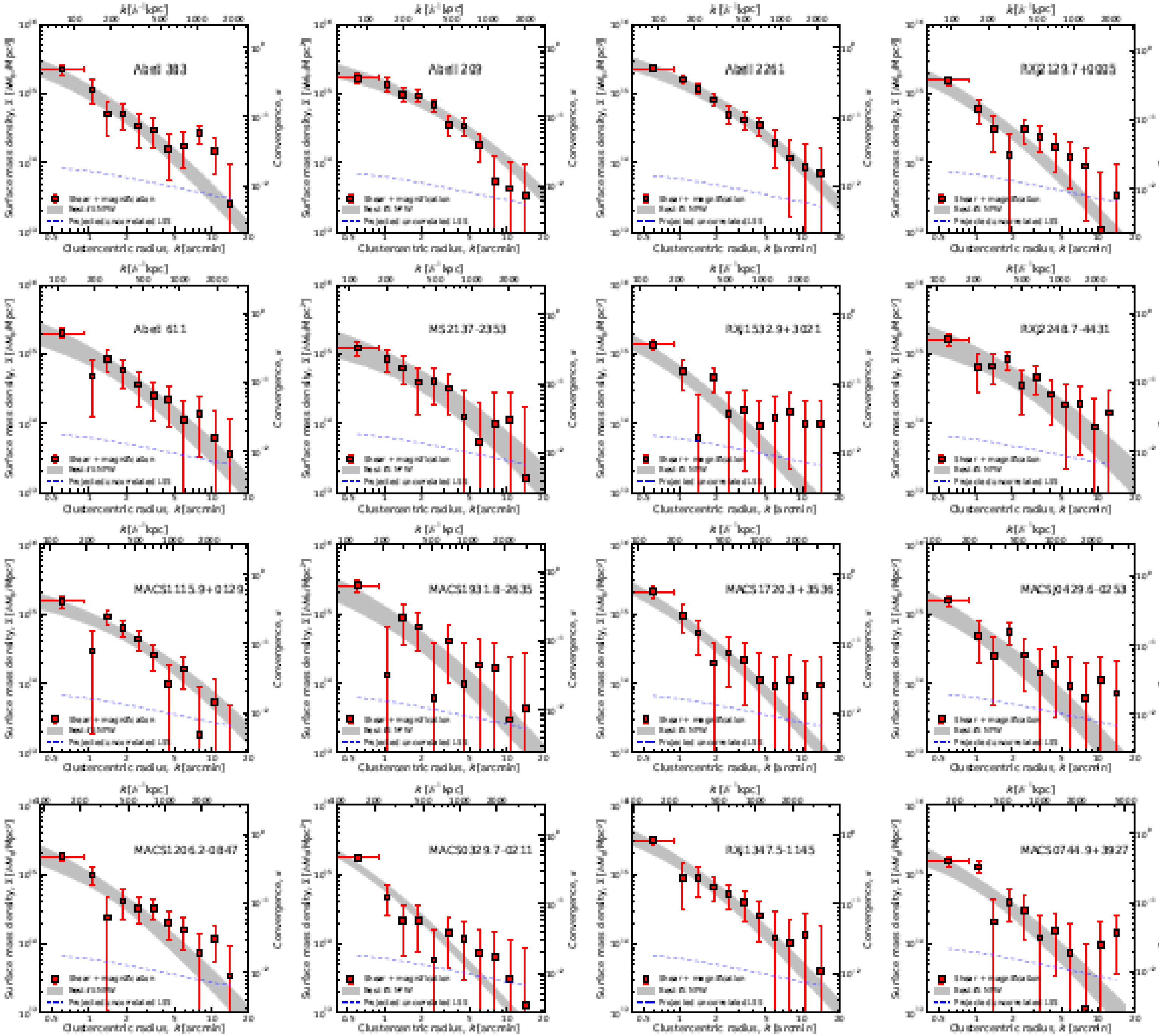
M_{vir}=6e14Msun/h (z=0.19)



CLASH high mass

M_{vir}=23e14Msun/h (z=0.45)




Abell 383
Abell 209
Abell 2261
RXJ2129.7+0005
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MS2137-2353
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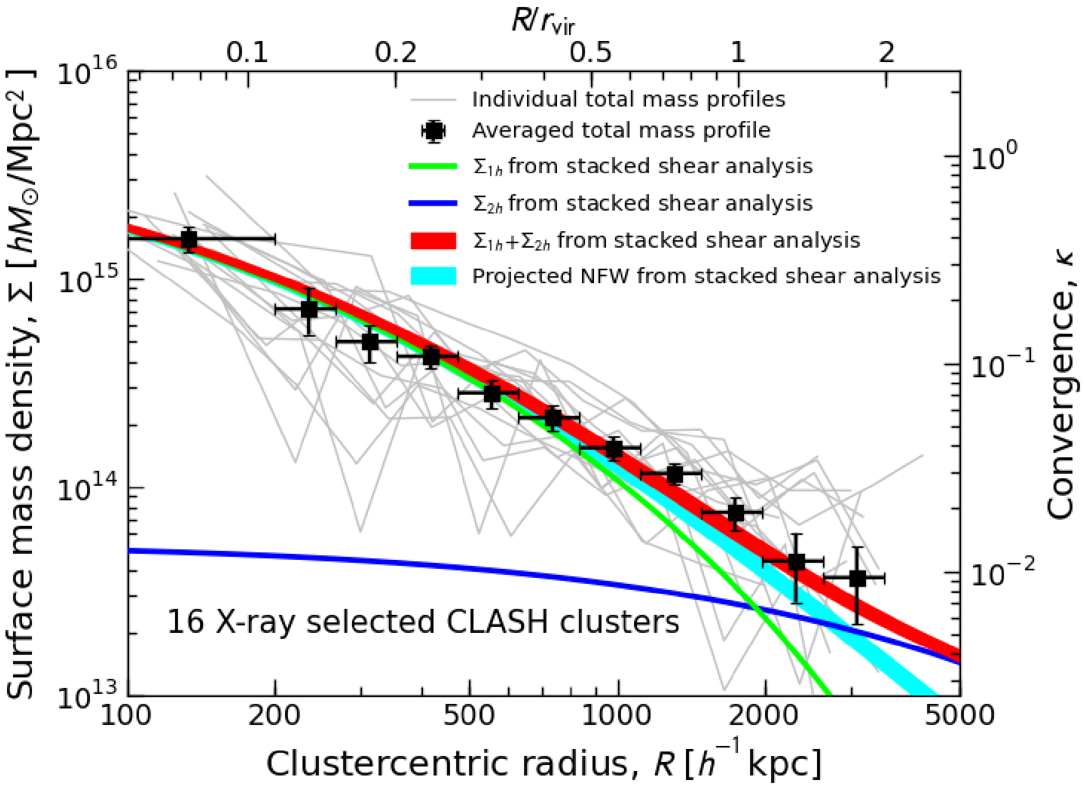
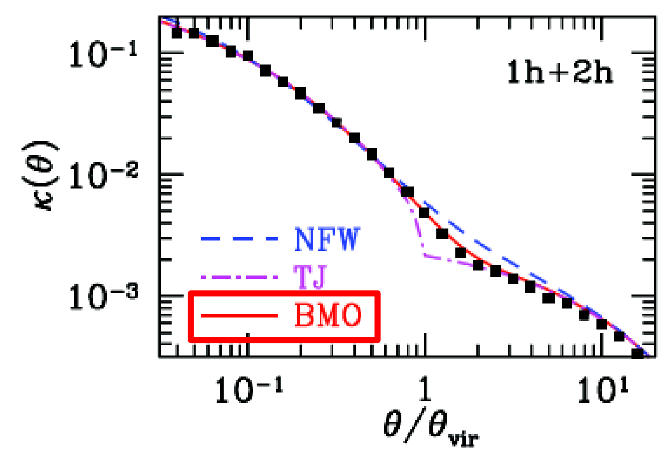
MACS1115.9+0129
MACS1931.8-2635
MACS1720.3+3536
MACSJ0429.6-0253
MACS1206.2-0847
MACS0329.7-0211
RXJ1347.5-1145
MACS0744.9+3927
Clustercentric radius, R [arcmin]
Convergence, κ

CLASH-WL: Stacked total mass profile from combined shear + magnification

- Measuring 1h+2h term out to $R=2r_{vir}$ around 16 X-ray clusters with $<M_{vir}>$=10e14Msun/h at $<z>$=0.35 → halo bias b^L_h= 9 (Tinker+10)
- Testing shear vs. magnification consistency in the context of LCDM



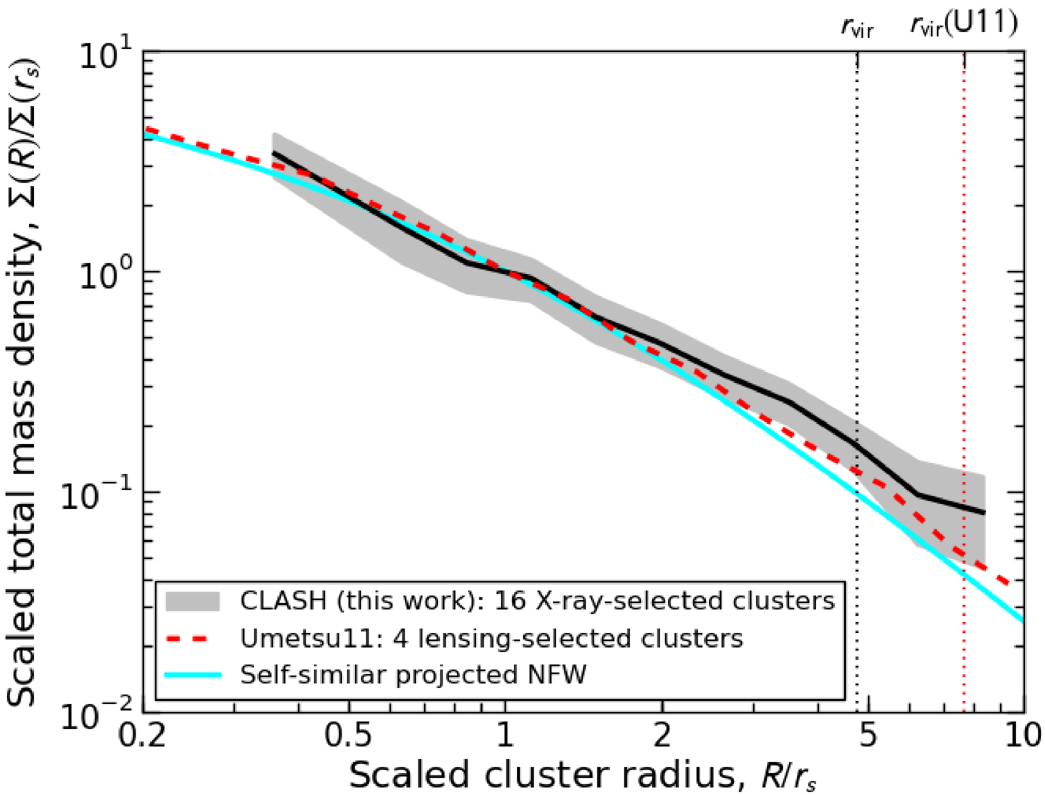
2D halo model decomposition:
smoothly-truncated NFW (BMO) + LCDM 2h-term



Umetsu+CLASH14 in prep

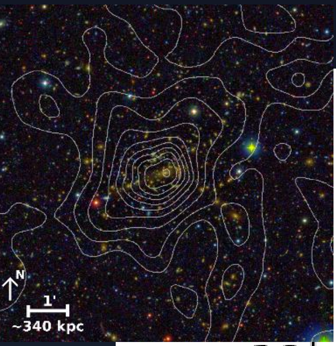
“Scaled” Mass Profile Shape

Strong-lensing (SL) vs. X-ray selected cluster samples

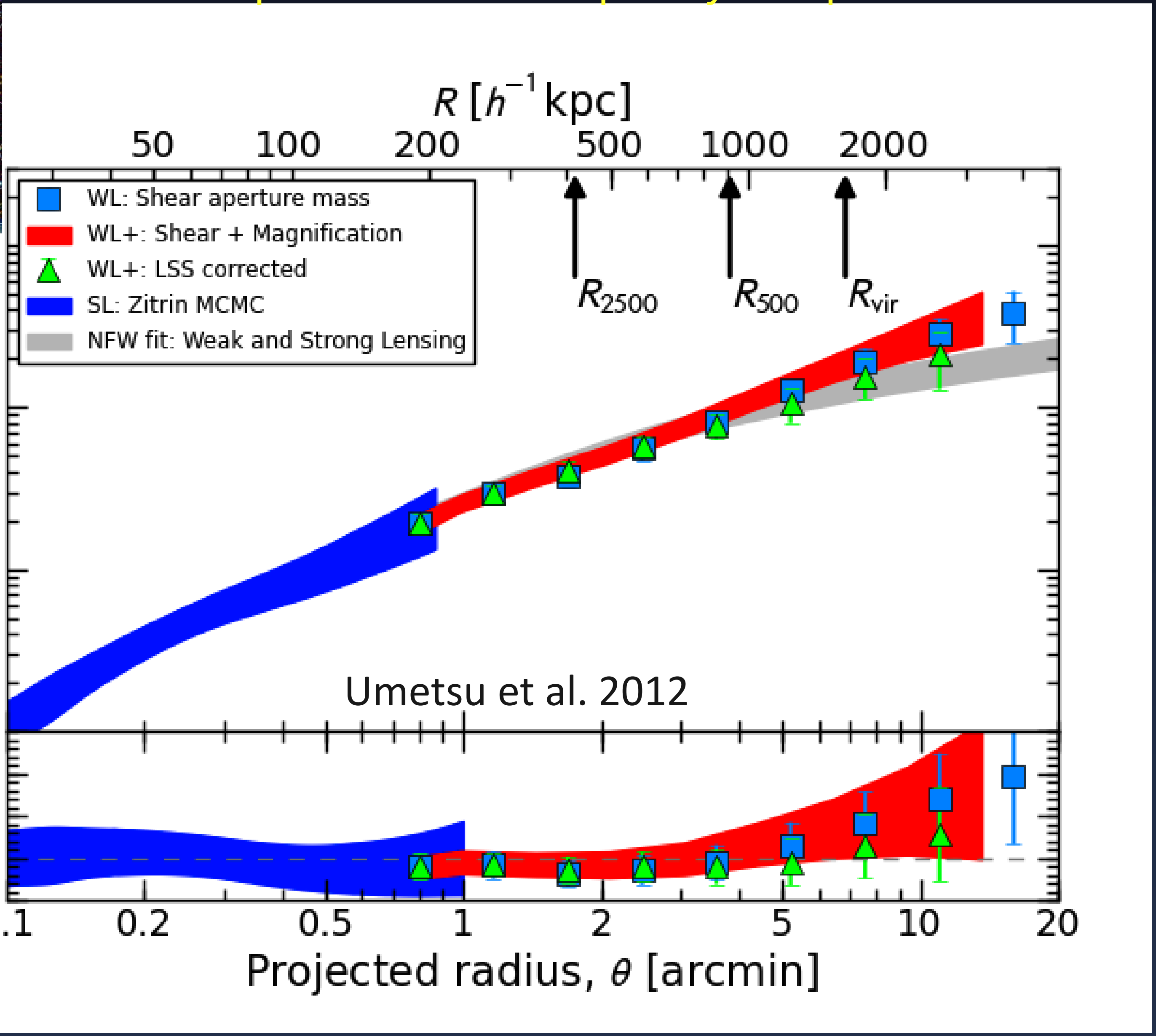


- When scaled, their ensemble-averaged mass profiles are consistent within errors.
- The SL clusters appear to have a steeper outer profile: i.e., less significant 2h-term in projection space.

MACS1206 (z=0.44): A cluster with a high degree of dynamical relaxation



Total mass profiles from completely independent methods agree.



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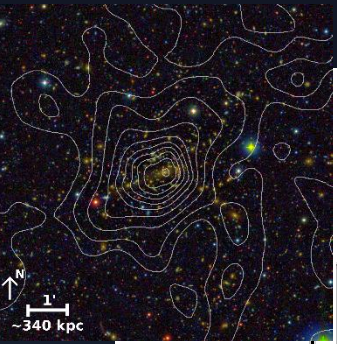
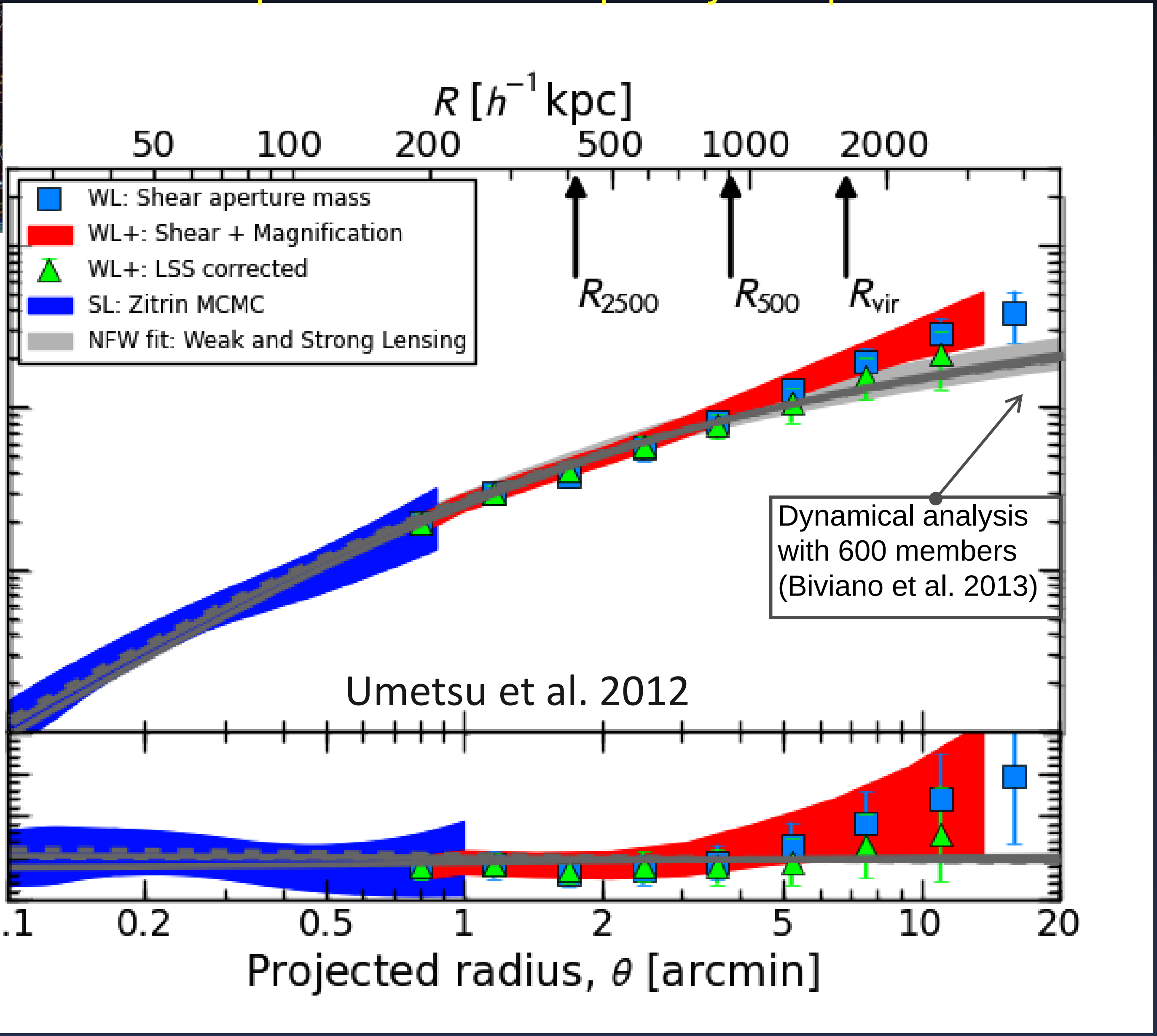




Constraining the DM Equation of State

B. Sartoris et al., submitted to ApJ Letters

- By testing whether the intracluster DM is pressureless (w=0) using cluster mass profiles M(<r) of MACS1206 determined from 2-independent ways:
  - **Gravitational lensing with HST+Subaru** (Umetsu+2012)
  - **Galaxy kinematics with VLT/VIMOS** (Biviano+2013)
- Test made possible by our high-quality CLASH data for an equilibrium cluster:

$$w(r) = \frac{p_r(r) + 2p_t(r)}{c^2 3\rho(r)}$$

Framework

Consider the static, spherically-symmetric metric within a DM halo of the form:

$$ds^2 = -e^{-2\Phi(r)}dt^2 + \left[1 - \frac{2Gm(r)}{r}\right]^{-1} dr^2 + r^2 d\Omega^2.$$

Consider an intracluster DM fluid with anisotropic pressure. In this metric, the Einstein field equations read:

$$\rho(r) = \frac{1}{8\pi G}\frac{m'}{r^2},$$
$$p_r(r) = -\frac{1}{8\pi G}\frac{2}{r^2}\left[\frac{m}{r} - r\Phi'\left(1 - \frac{2m}{r}\right)\right],$$
$$p_t(r) = \frac{1}{8\pi G}\left\{\left(1 - \frac{2m}{r}\right)\left[\frac{\Phi'}{r} + \Phi'^2 + \Phi''\right] - \left(\frac{m}{r}\right)'\left(\frac{1}{r} + \Phi'\right)\right\}.$$

The equation of state of this DM fluid is defined as

$$w(r) = \frac{p_r + 2p_t}{3\rho}.$$

Consider the weak-field limit, $|\Phi| \ll 1$, $Gm/r \ll 1$.

DM EoS from kinematics+lensing

The Jeans equation provides a way to measure the cluster mass profile from cluster galaxy kinematics

$$m_K(r) = -\frac{r\sigma_r^2}{G}\left[\frac{d\ln n_g}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right],$$

where galaxies as the probe particles are non-relativistic, $\sigma_r, \sigma_t \ll 1$ with $\beta = 1 - \sigma_t^2/(2\sigma_r^2)$. In our metric, the kinematic mass profile is related to the potential by

$$m_K(r) = \frac{r^2}{G}\Phi' \approx 4\pi \int [1 + 3w(r)]\, r^2 \rho(r) dr.$$

Gravitational lensing is sensitive to g_{00} and g_{rr}. Hence, its potential and associated mass profile are defined by

$$2\Phi_l \equiv \Phi + G\int \frac{m(r)}{r^2} dr,$$

$$m_L(r) \equiv \frac{r^2}{G}\Phi_l' = \frac{1}{2}\left[m_K(r) + m(r)\right].$$

To first order, the DM equation of state is sensitive to the derivatives of the lensing and kinematic mass profiles:

$$w(r) \approx \frac{2}{3}\frac{m_K'(r) - m_L'(r)}{2m_L'(r) - m_K'(r)}.$$

$$\langle w \rangle = 0.00 \pm 0.14(stat) + 0.03(syst)$$

Consistent with w=0

Negligible baryonic contribution

averaged in R=0.5-2Mpc

Summary

- Ensemble-averaged internal halo structure $\Delta\Sigma$ (1h) of relaxed CLASH clusters in good agreement with a family of standard (collisionless) DM predictions:
  - Halo mass: M_{200}=(1.4 +/- 0.1) $10^{15} M_{sun}$ at z=0.35
  - Degree of curvature: α=0.25 +/- 0.07 (Einasto)
  - Degree of concentration: $3.3<c_{200}<4.2$ at 1σ
- Total matter distribution Σ (1h+2h) around clusters determined from shear+magnification, being consistent with the shear-only prediction (b_h~9), thus establishing consistency in the context of LCDM.

Summary (contd)

- CLASH HST (SL) + Subaru (WL) + VLT (kinematics), providing high-quality data to test DM models:
  - 20 CLASH clusters X-ray-selected to be relaxed
  - 5 CLASH clusters lensing-selected (merging clusters)
- For a relaxed cluster with no orientation bias (for lensing), lensing+kinematics (HST+Subaru+VLT) can be used to test the pressureless assumption of DM.
  - CLASH-VLT redshift survey is in progress (12 southern CLASH clusters at $0.3<z<0.6$), providing 500 members/cluster out to >3Mpc.

Supplemental Slides

Magnification bias effects

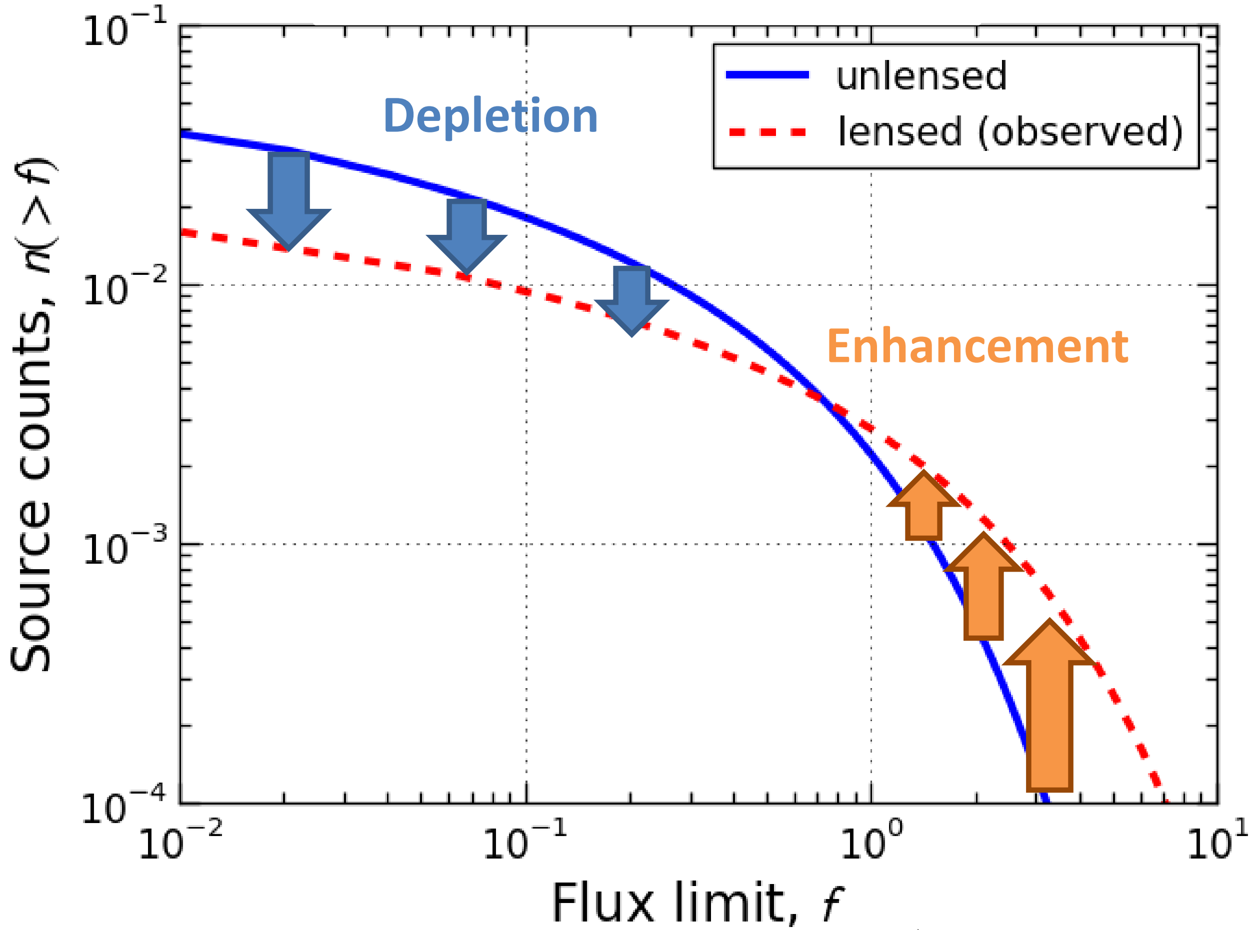
Flux-limited source counts:

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

Broadhurst, Taylor & Peacock 95

Geometric area distortion

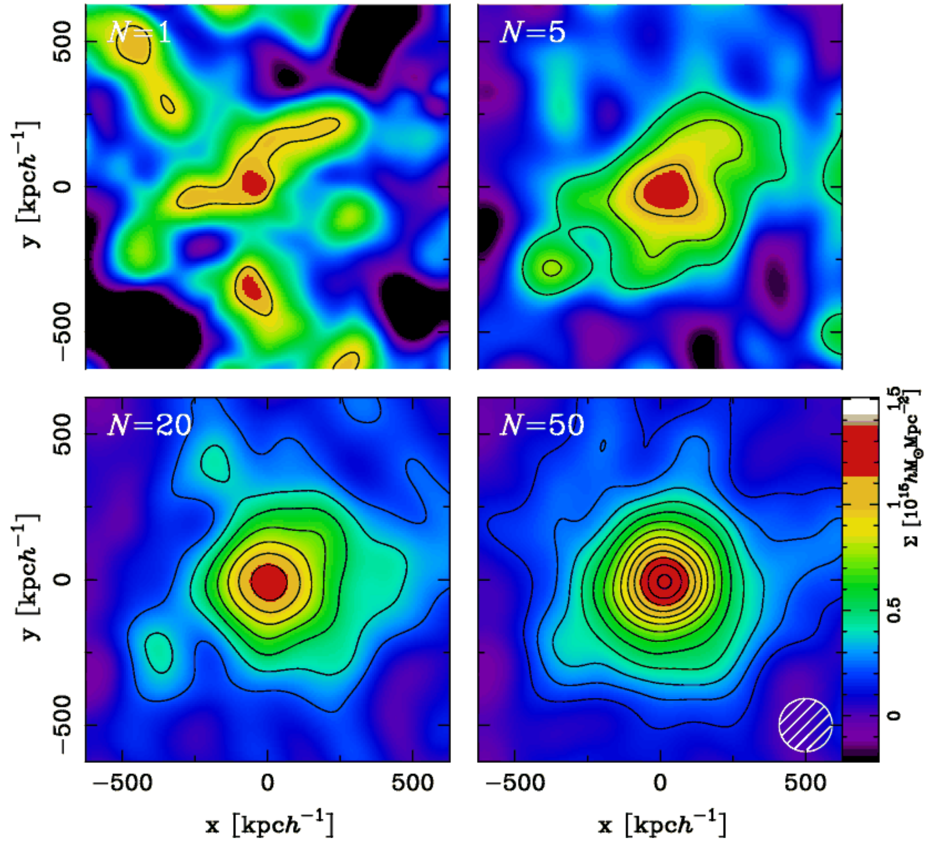
n/μ



Flux amplification

Power of Stacking Analysis

Stacking lensing signals around a sample of clusters to average out projection effects due to halo asphericity, substructure, and uncorrelated LSS



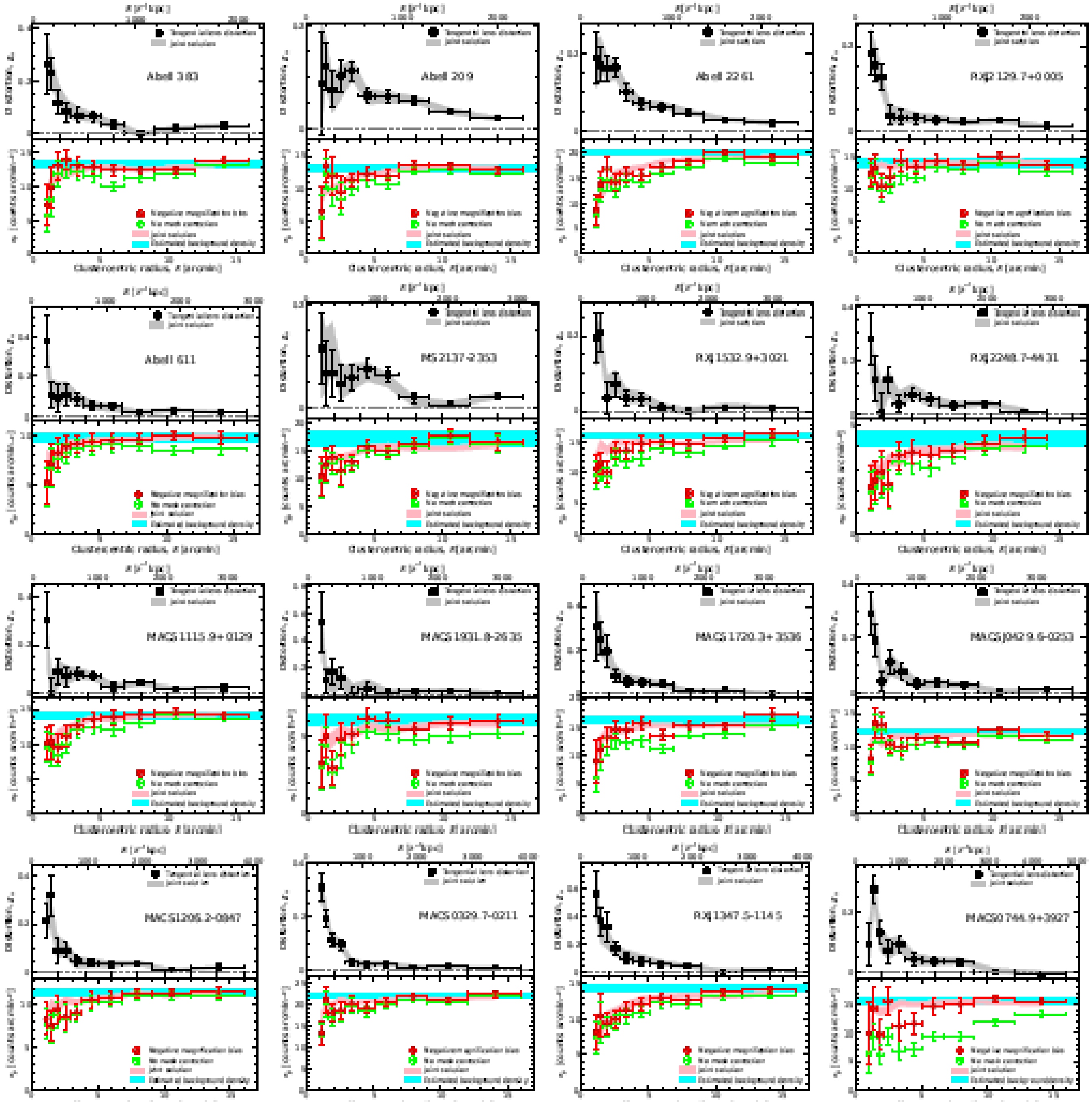
Okabe, Smith, Umetsu+13

November 25, 2013

PASCOS 2013

Mas Distribution in and around Galaxy Clusters from Strong-Lensing, Weak-Lensing Shear and Magnification

Keiichi Umetsu (ASIAA, Taiwan)
with the CLASH team



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MACSJ0429.6-0253
MACS1206.2-0847
MACS0329.7-0211
RXJ1347.5-1145
MACS0744.9+3927
Tangential lens distortion
Joint solution
Negative magnification bias
No mask correction
Estimated background density
Clustercentric radius, R [arcmin]
Distortion, g_+