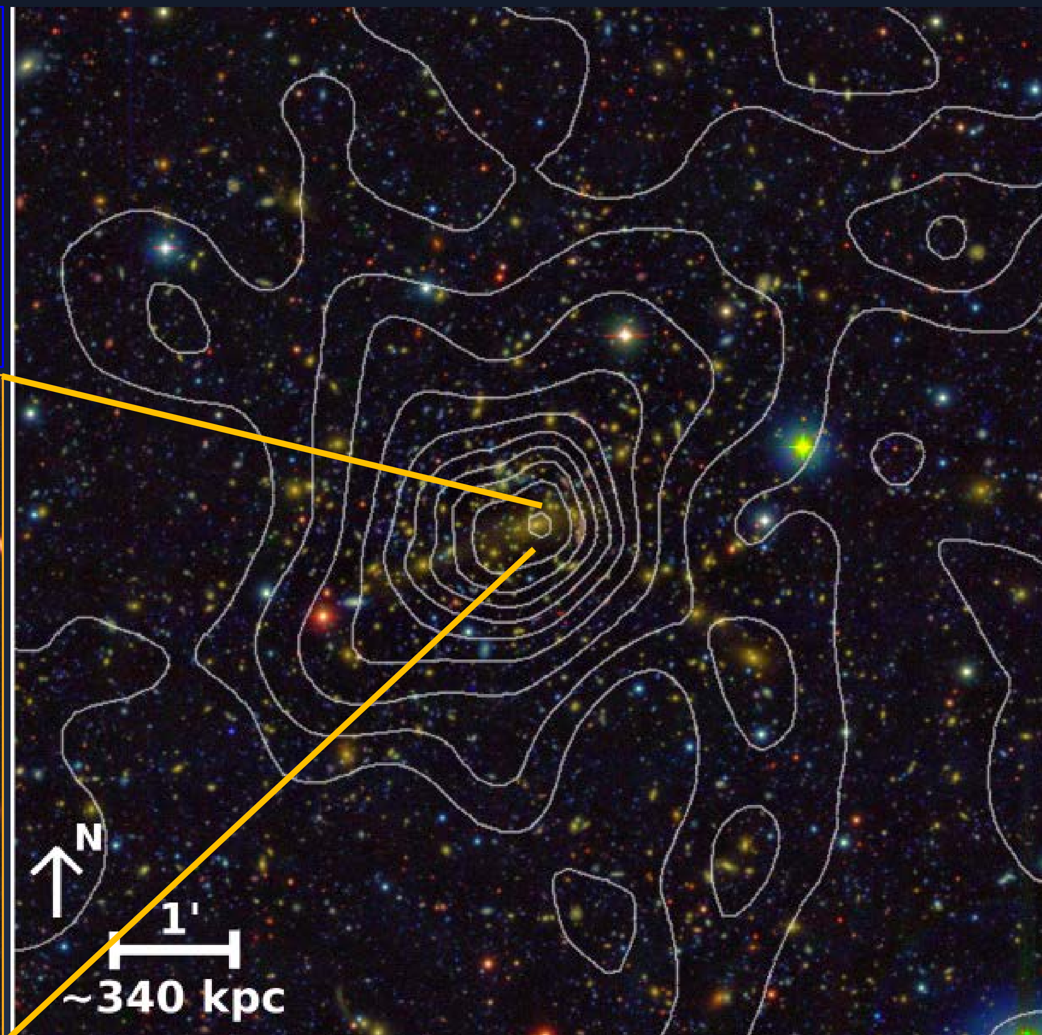
The Full Strength of Cluster Gravitational Lensing:

Matter Distribution in and around Cosmic Giants from the CLASH Survey

Cluster Lensing And Supernova survey with Hubble



Keiichi Umetsu (ASIAA, Taiwan) with the CLASH team

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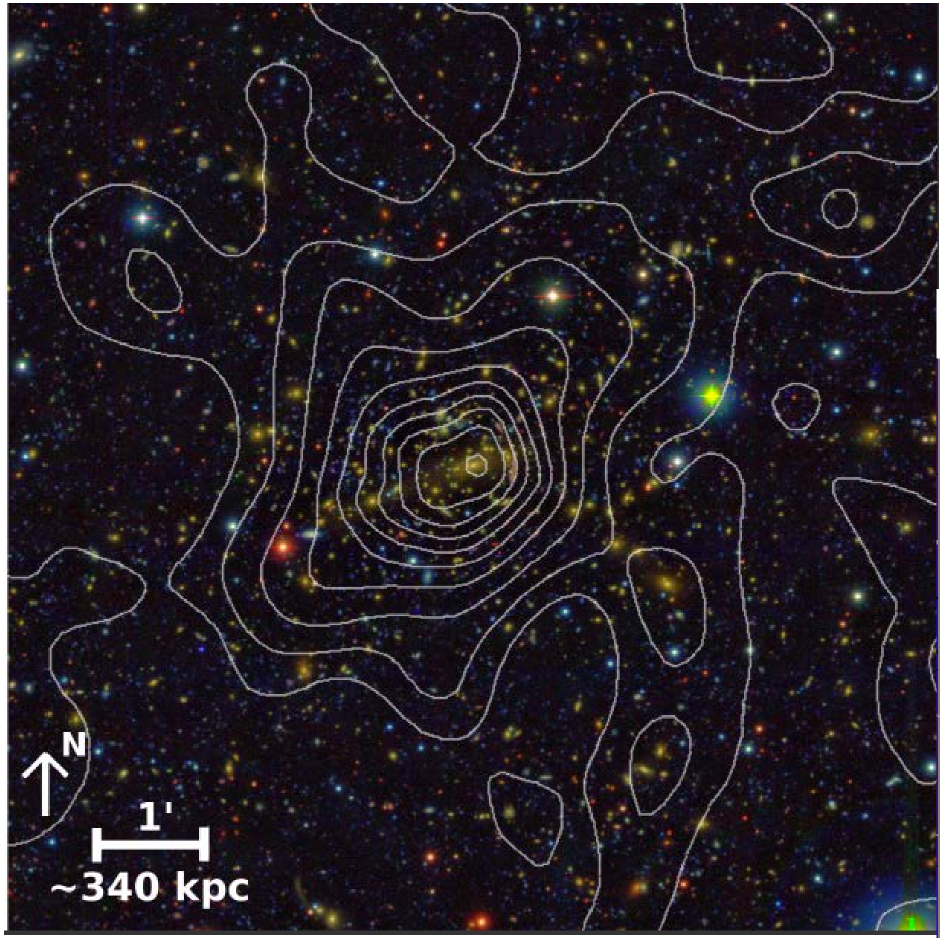
Galaxy Clusters as Cosmological Probe

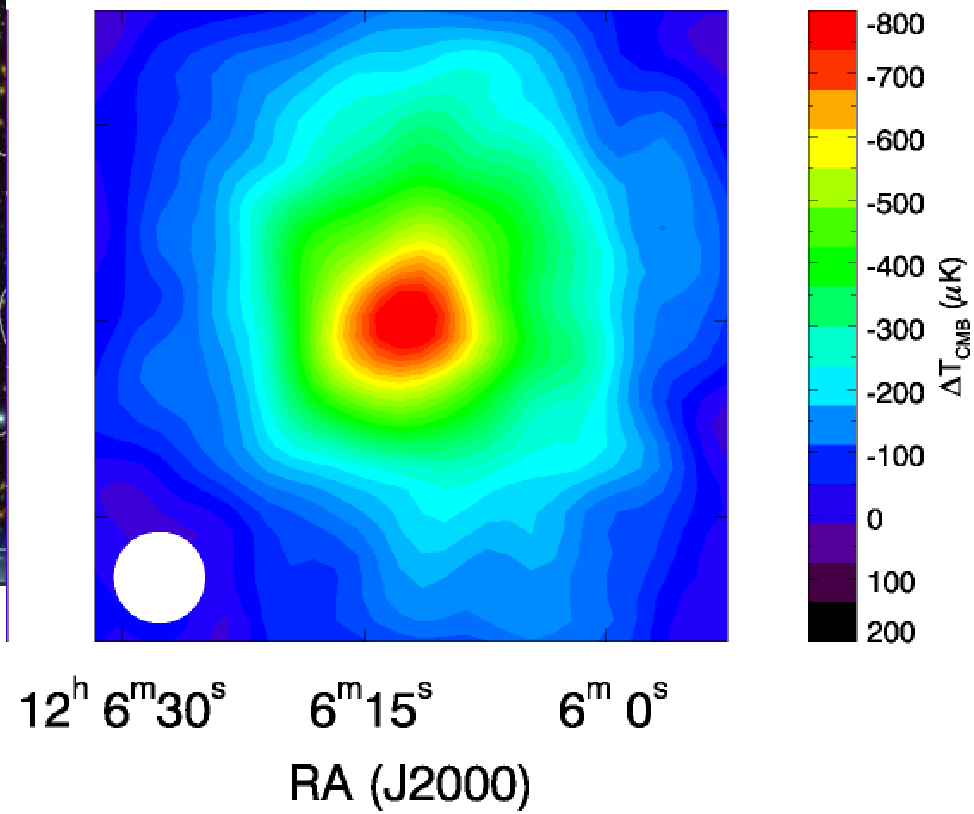
Clusters of Galaxies



MACS1206 cluster at z=0.44
(Umetsu et al. 2012, *ApJ*, 755, 56)

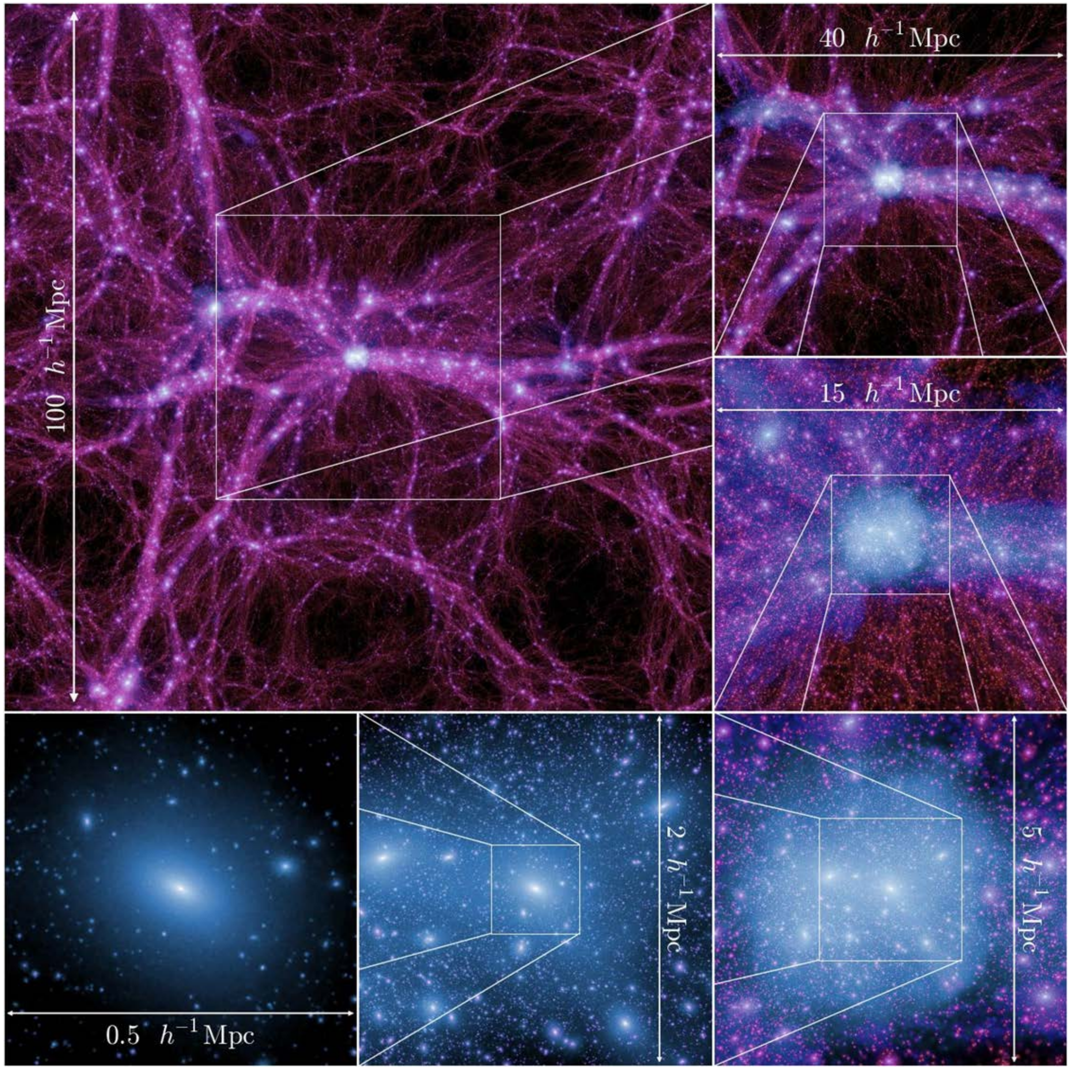
Clusters = composed of 100-1000 galaxies and filled with hot, diffuse intracluster plasmas of $k_B T$=3-10keV, corresponding to $M_{grav}=10^{14\text{-}15} M_{sun}$

Sunyaev-Zel'dovich Effect (SZE)



Clusters: the largest/youngest class of DM halos

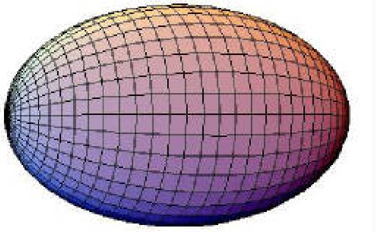
Halos = gravitationally-bound objects $\frac{1}{2}\ddot{I} = 2K + U - E^{(S)} \sim 0$



Clusters formed at the intersection of filaments and sheets

Typical formation epoch: z_f=0.5-0.7

Young halos are prolate (collisionless nature)

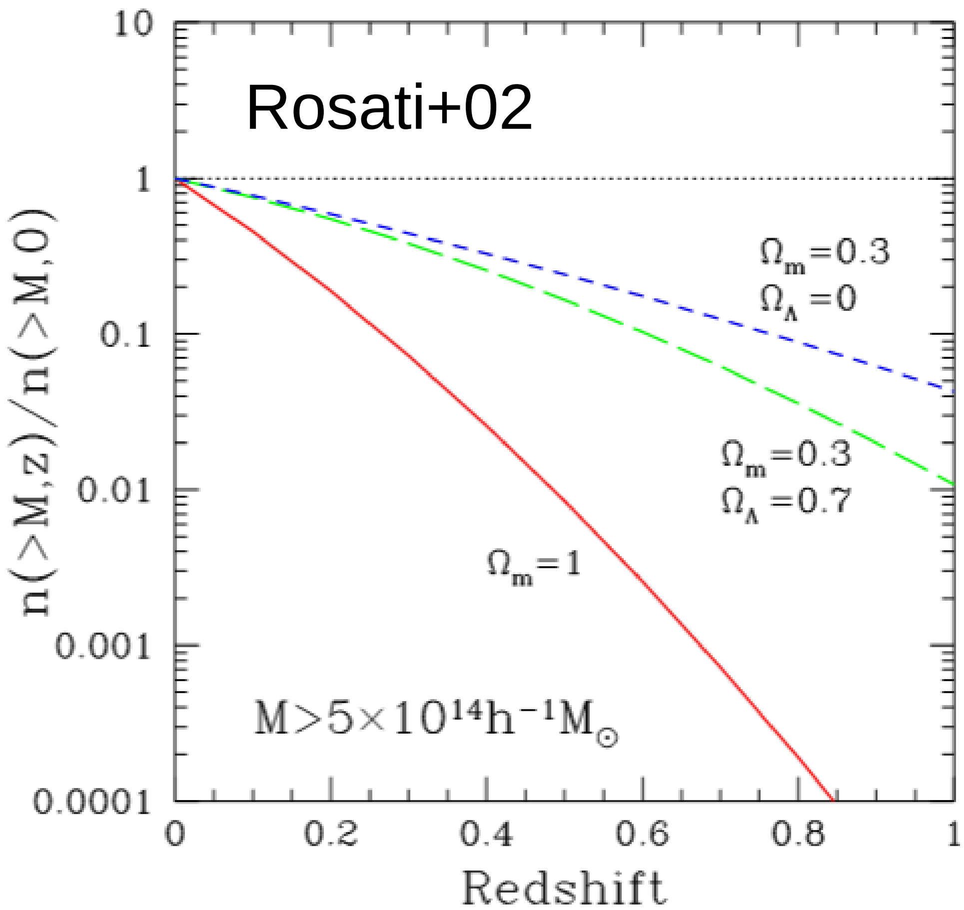


Boylan-Kolchin+09

Clusters as Cosmological Probe

<u>Cluster counts</u>

$$\frac{dN(>M_{\lim},z)}{d\Omega dz} = \int_{M_{\lim}}^{\infty} dM \boxed{\frac{dV(z)}{d\Omega dz}} \boxed{\frac{d^2n}{dVdM}(M,z)}$$



Comoving volume element

$$\frac{d^2V}{dzd\Omega} = \frac{cr^2[\chi(z)]}{H(z)}, \quad \chi(z) = \int_0^z \frac{dz'}{H(z')}$$

Halo mass function

$$\frac{d^2n}{dVdM}(M,z) \propto \exp\left[-\frac{\nu^2}{2}\right]$$

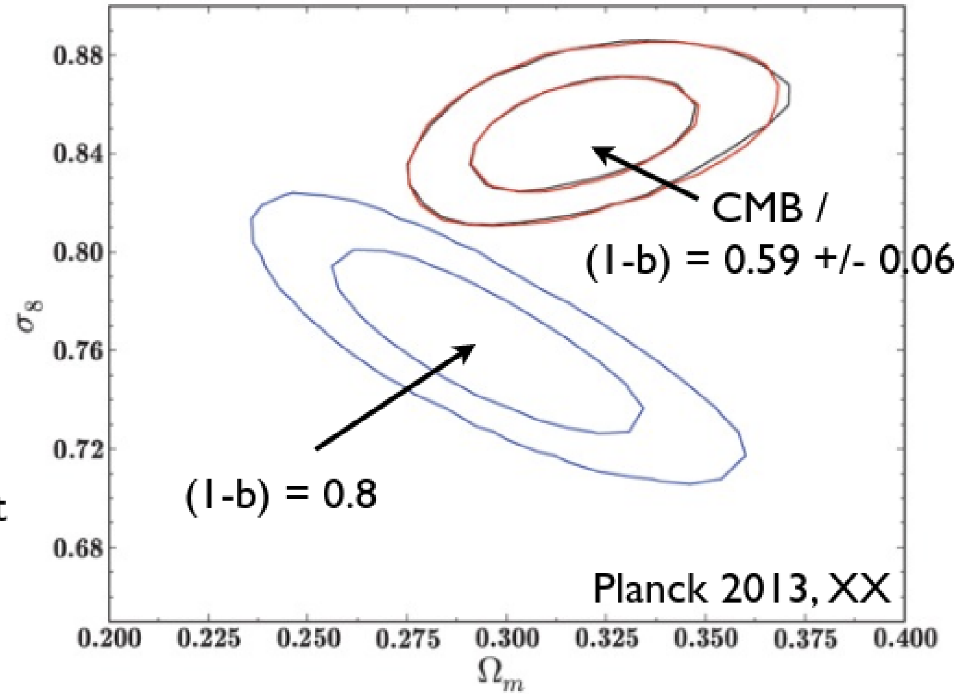
$$\nu \equiv \frac{\delta_c(z)}{\sigma(M,z)} \approx \frac{1.69}{D_+(z)\sigma(M)} \sim 3 \text{ for clusters}$$

Cluster counts are exponentially sensitive to *cosmology* and ***cluster mass calibration***!

Planck13 CMB vs. Cluster Cosmology

b=0.2?? – 0.4??

- Planck: 3σ tension between SZ cluster counts and CMB cosmology
- assumes M_{Planck} / M_{true} = (1-b) = 0.8
- calibrated with XMM hydrostatic masses (Arnaud et al. 2010) + simulations



suggested explanations:

- mass bias underestimated (and no accounting for uncertainties)
- 2.9σ detection of neutrino masses: Σm_ν = (0.58 +/- 0.20) eV (Planck+WMAPpol+ACT+BAO: Σm_ν < 0.23 eV, 95% CL)

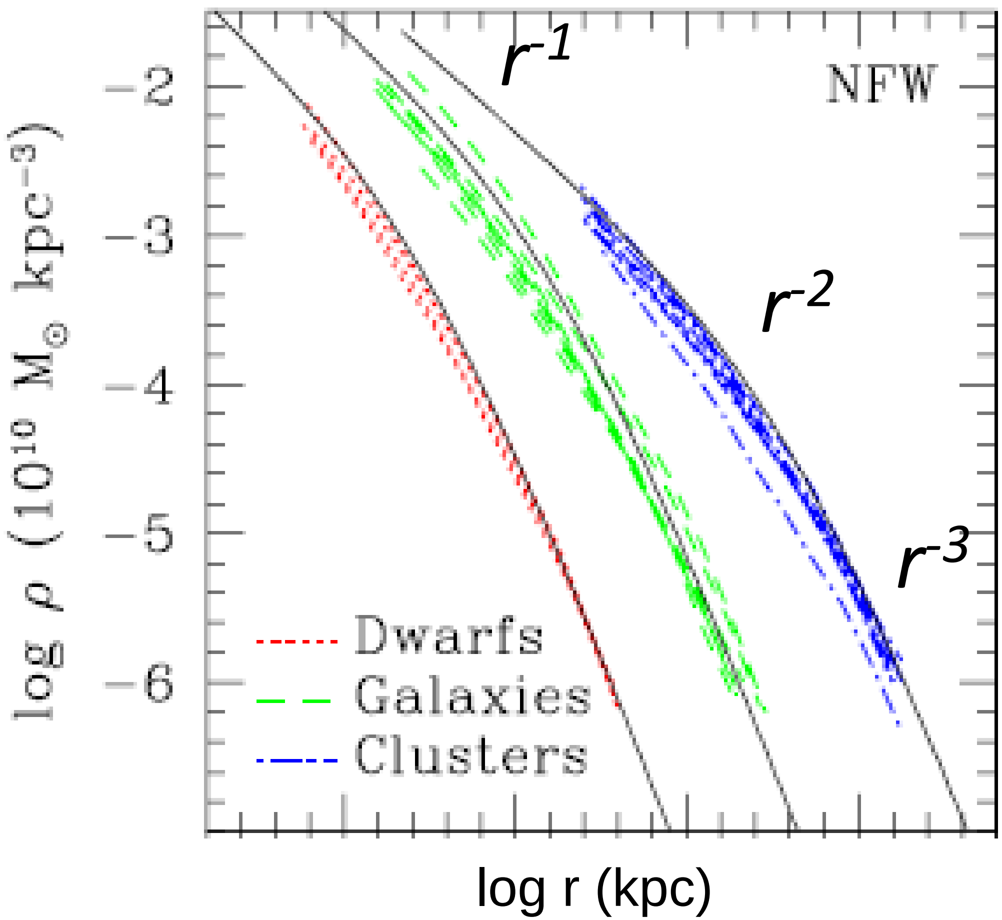
Slide taken from Anja von der Linden's presentation

Key Predictions of nonlinear structure formation models

(1) Quasi self-similar DM-halo density profiles

Quasi Self-similar Halo Density Profile for collisionless CDM

Spherically-averaged DM density profiles ρ(r) from numerical simulations

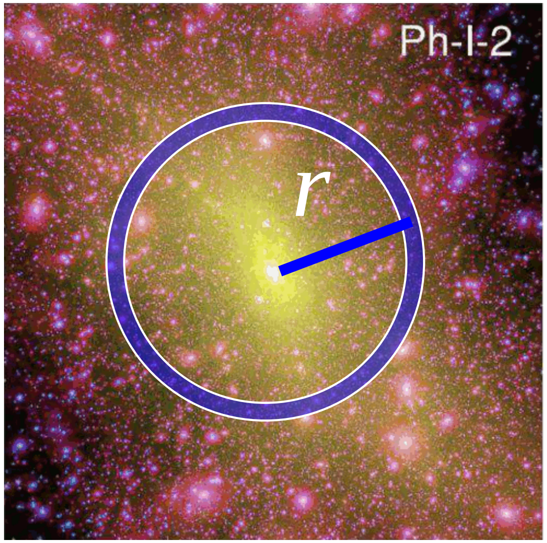


Cuspy, outwardly-steepening density profiles

Empirical fitting formula by Navarro-Frenk-White (NFW)

$$\rho(r) = \rho_s f(r/r_s)$$

$$= \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

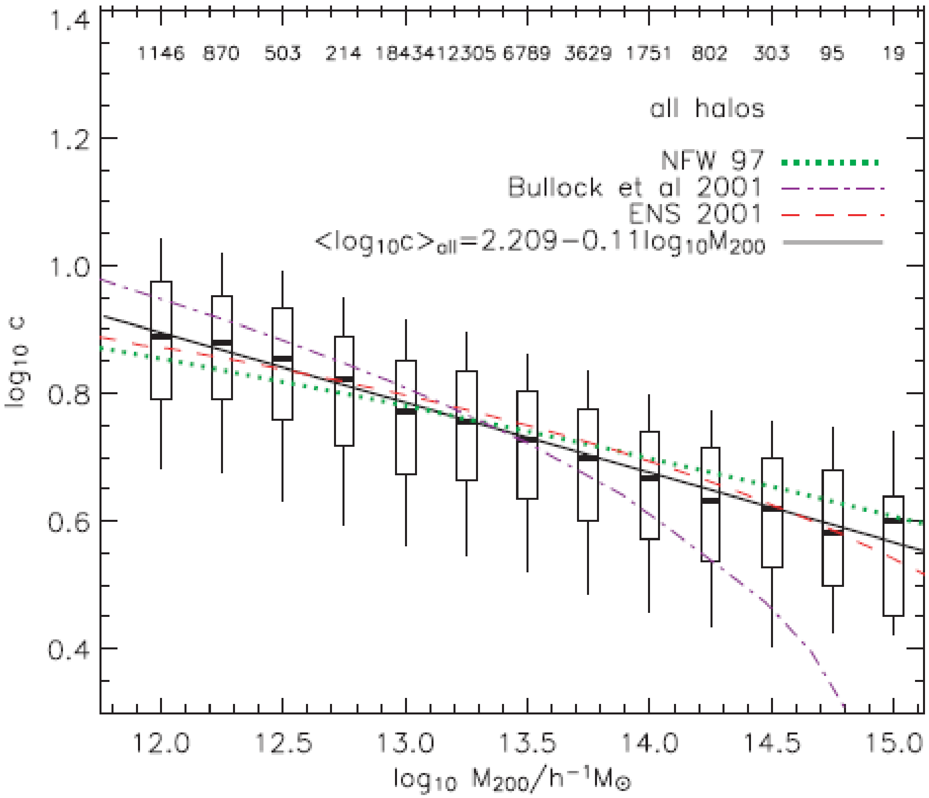


Key Predictions of nonlinear structure formation models

(2) Halo concentration-mass relation

Degree of Mass Concentration

$$c_{200} \equiv \frac{r_{200}}{r_s} = \frac{\text{(Virial radius)}}{\text{(Scale radius)}}$$



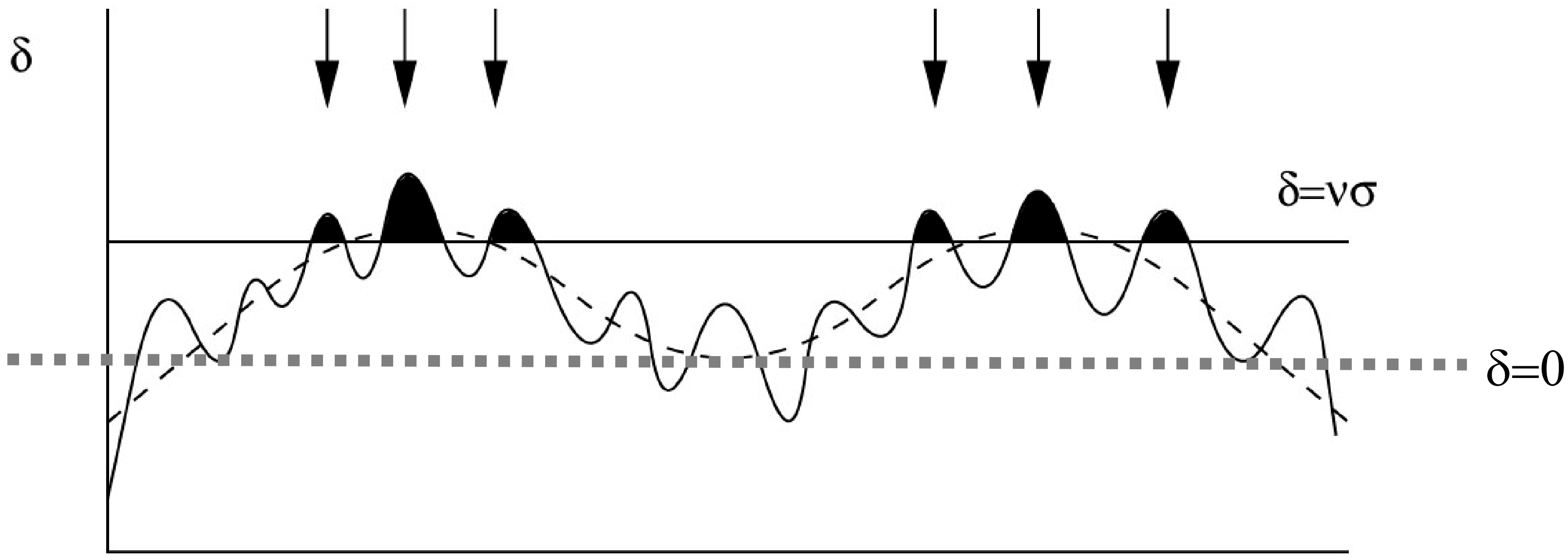
In hierarchical structure formation, <*c*> is predicted to decrease with increasing *M*

DM halos that are more massive collapse later on average, when the mean background density of the universe is correspondingly lower (Bullock+01; Neto+07; Duffy+08; Bhattacharya+13)

Clusters (groups) of galaxies are predicted to have <*c*>=3-4 (5-6)

Key Predictions of nonlinear structure formation models

(3) Halo bias: surrounding large-scale structure



$$\delta(\mathbf{x}) := \frac{\rho - \bar{\rho}}{\bar{\rho}} = \int \frac{d^3k}{(2\pi)^3} \tilde{\delta}(\mathbf{k}) e^{i\mathbf{k}\cdot\mathbf{x}}$$

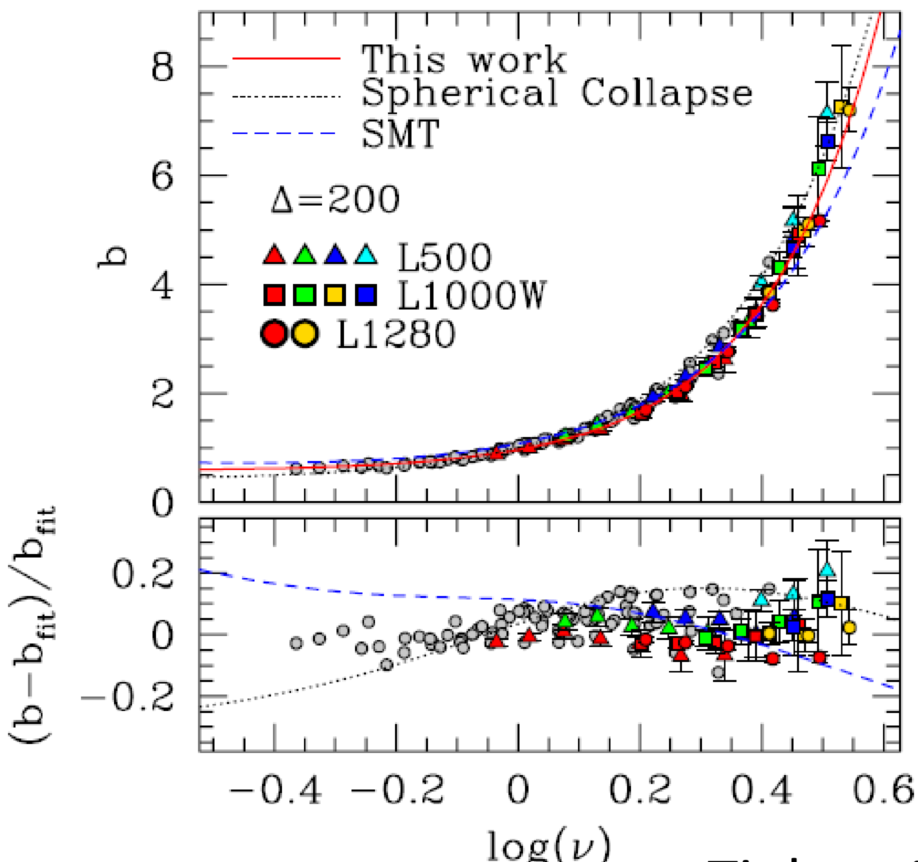
$$\left\langle \tilde{\delta}(\mathbf{k}) \tilde{\delta}(\mathbf{k}') \right\rangle = (2\pi)^3 \delta_D^3(\mathbf{k}+\mathbf{k}') P(k)$$

Halo Bias Factor: b_h

Clustering of matter around halos with *M*:

$$\xi_{\rm hm}(r\,|\,M) \equiv \langle \delta_{\rm h}(\mathbf{x}\,|\,M)\delta_{\rm m}(\mathbf{x}+\mathbf{r})\rangle$$

$$= \frac{\langle \rho_{\rm halo}(r\,|\,M)\rangle}{\bar{\rho}} + \underline{b_{\rm h}(M)\xi_{\rm mm}(r)} \quad \textbf{2h term}$$



Correlated matter distribution (2h term)

Matter correlation function:

$$\xi_{\rm mm}(\mathbf{r}) \equiv \langle \delta_{\rm m}(\mathbf{x})\delta_{\rm m}(\mathbf{x}+\mathbf{r})\rangle = \int \frac{d^3k}{(2\pi)^3} P(k) e^{i\mathbf{k}\cdot\mathbf{r}}$$

$$\propto \sigma_8^2$$

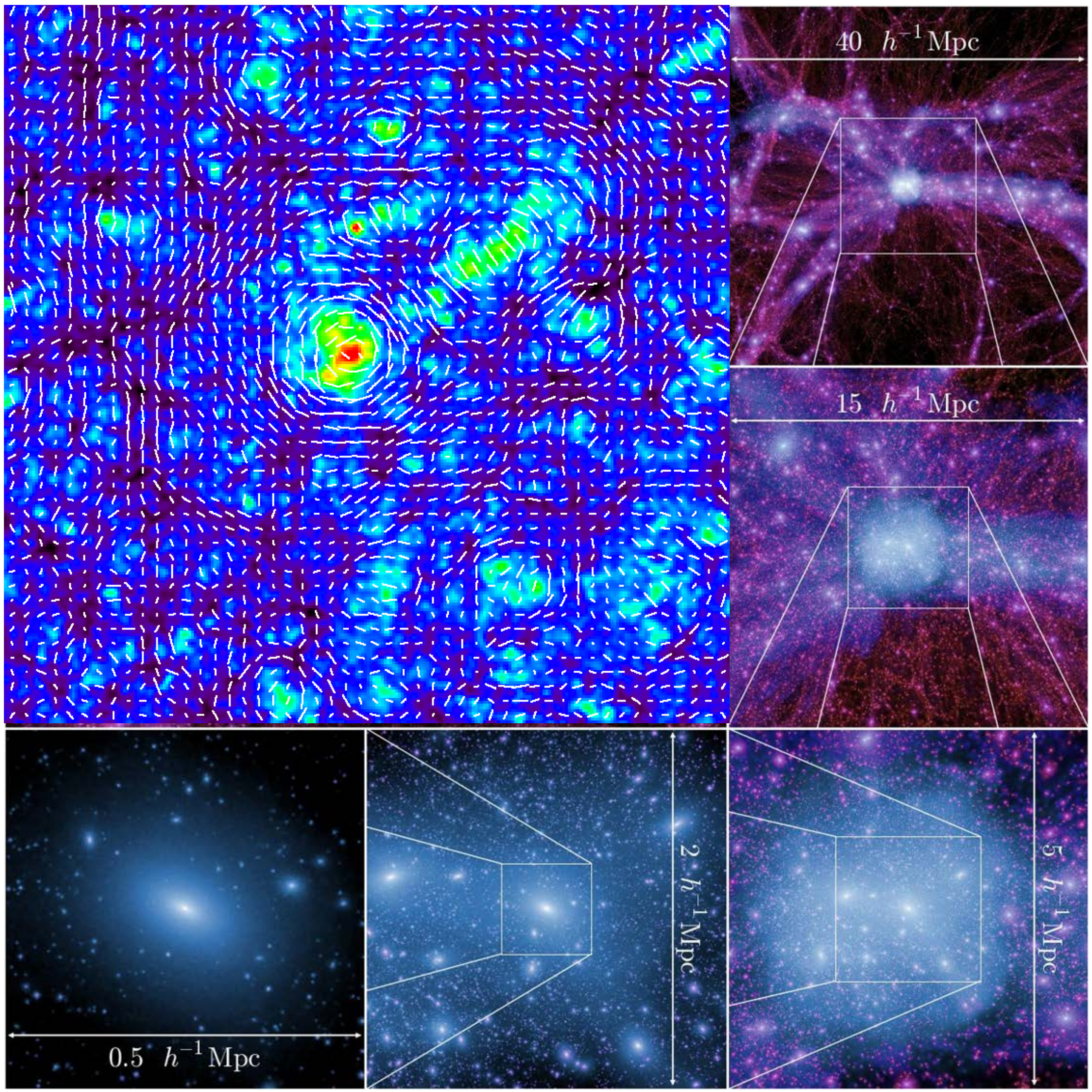
Linear halo bias:

$$b_{\rm h}(\nu) \approx 1 + \frac{\nu^2 - 1}{\delta_c}$$

$$\nu \equiv \frac{\delta_c}{\sigma(M,z)} \sim 3-4 \text{ for clusters}$$

Tinker+10 LCDM simulations

2. Cluster Weak Gravitational Lensing



Key Objectives

Cluster structure (1h)

Halo mass, M_{200}

Halo density profile, $\rho(r)$

c-M relation, $c(M,z)$

Surrounding LSS (2h)

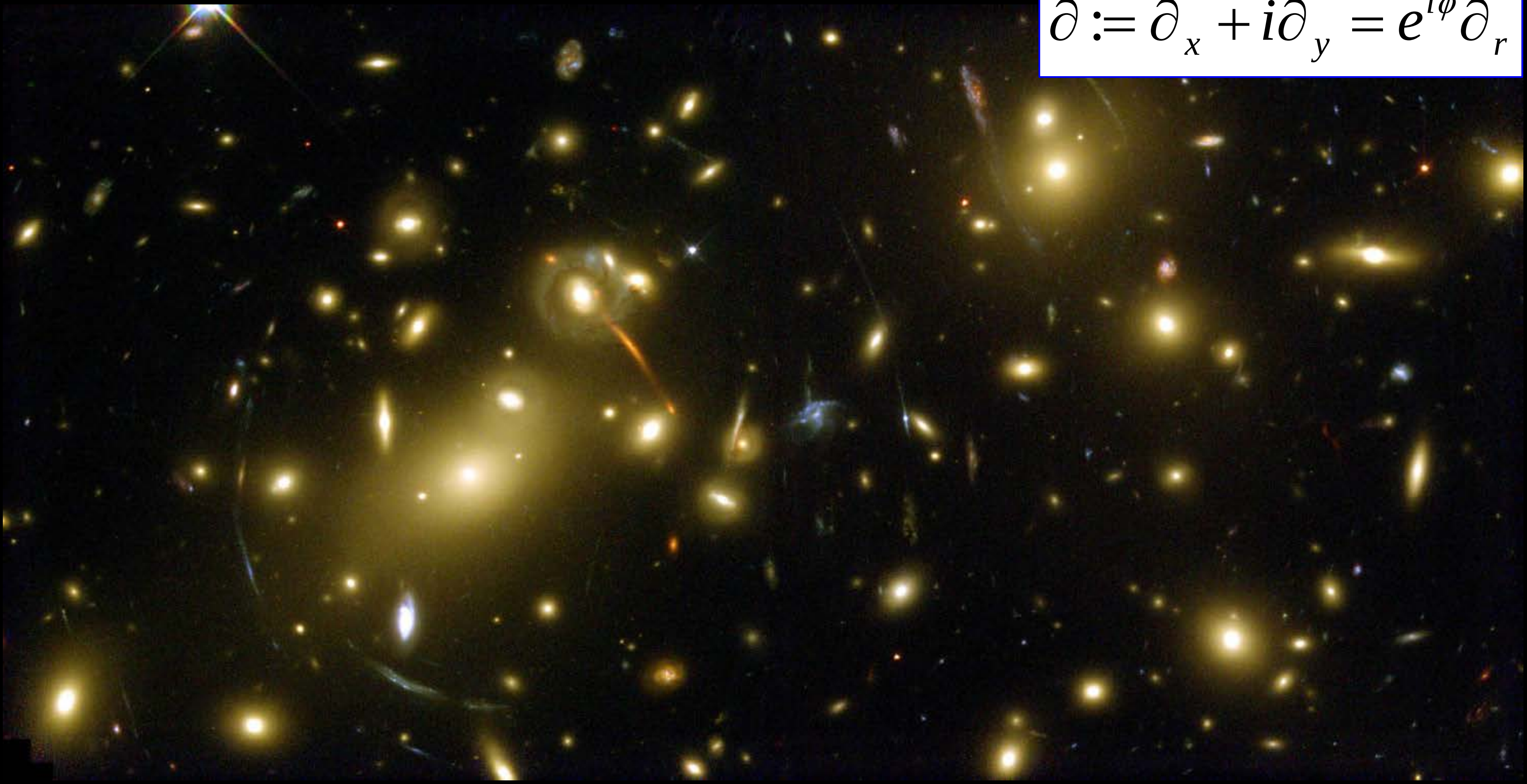
Halo bias $b_h(M,z)$

Clustering strength σ_8

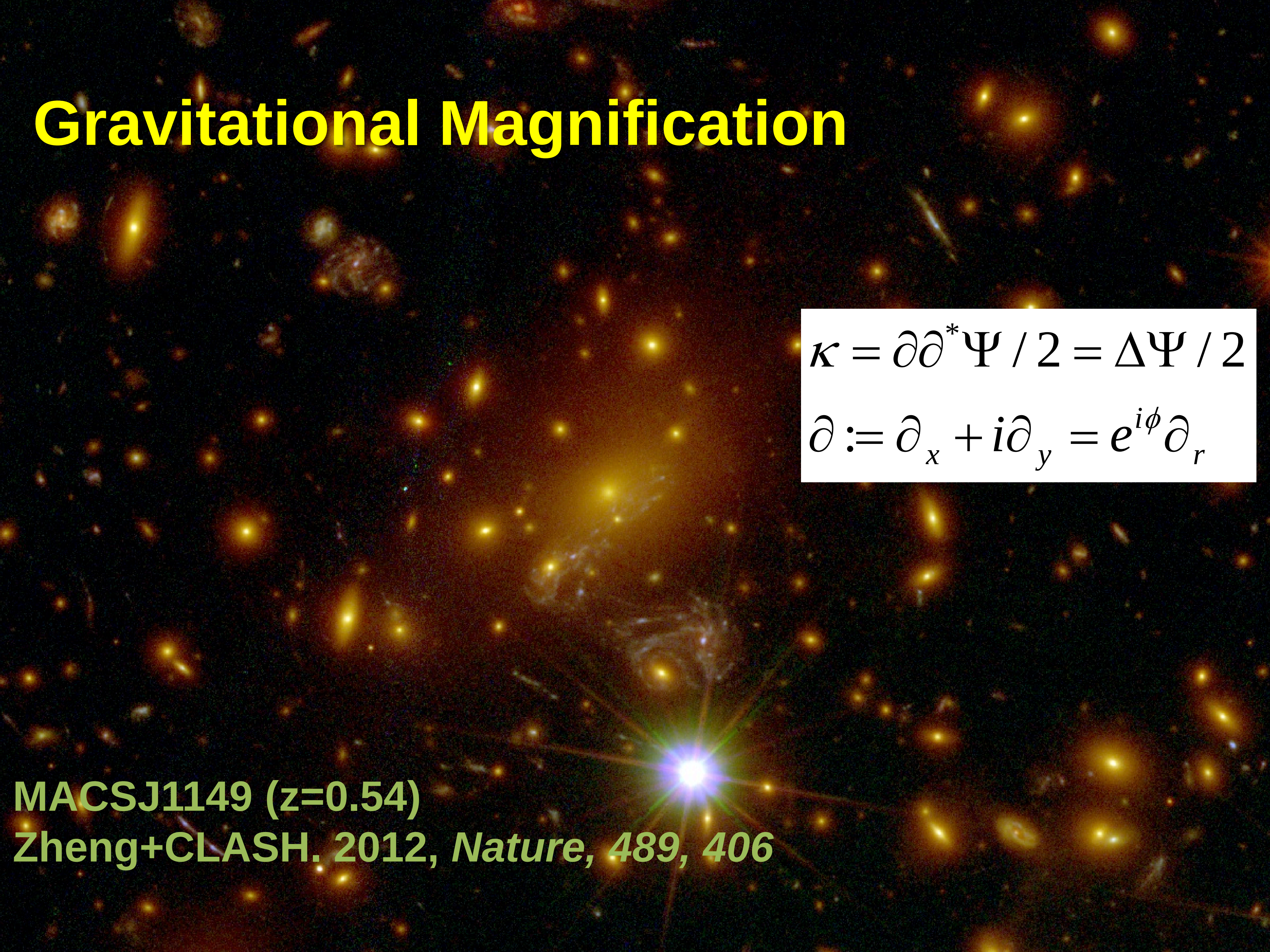
Gravitational Shear

$$\gamma = \partial\partial\Psi / 2$$

$$\partial := \partial_x + i\partial_y = e^{i\phi}\partial_r$$



Gravitational Magnification

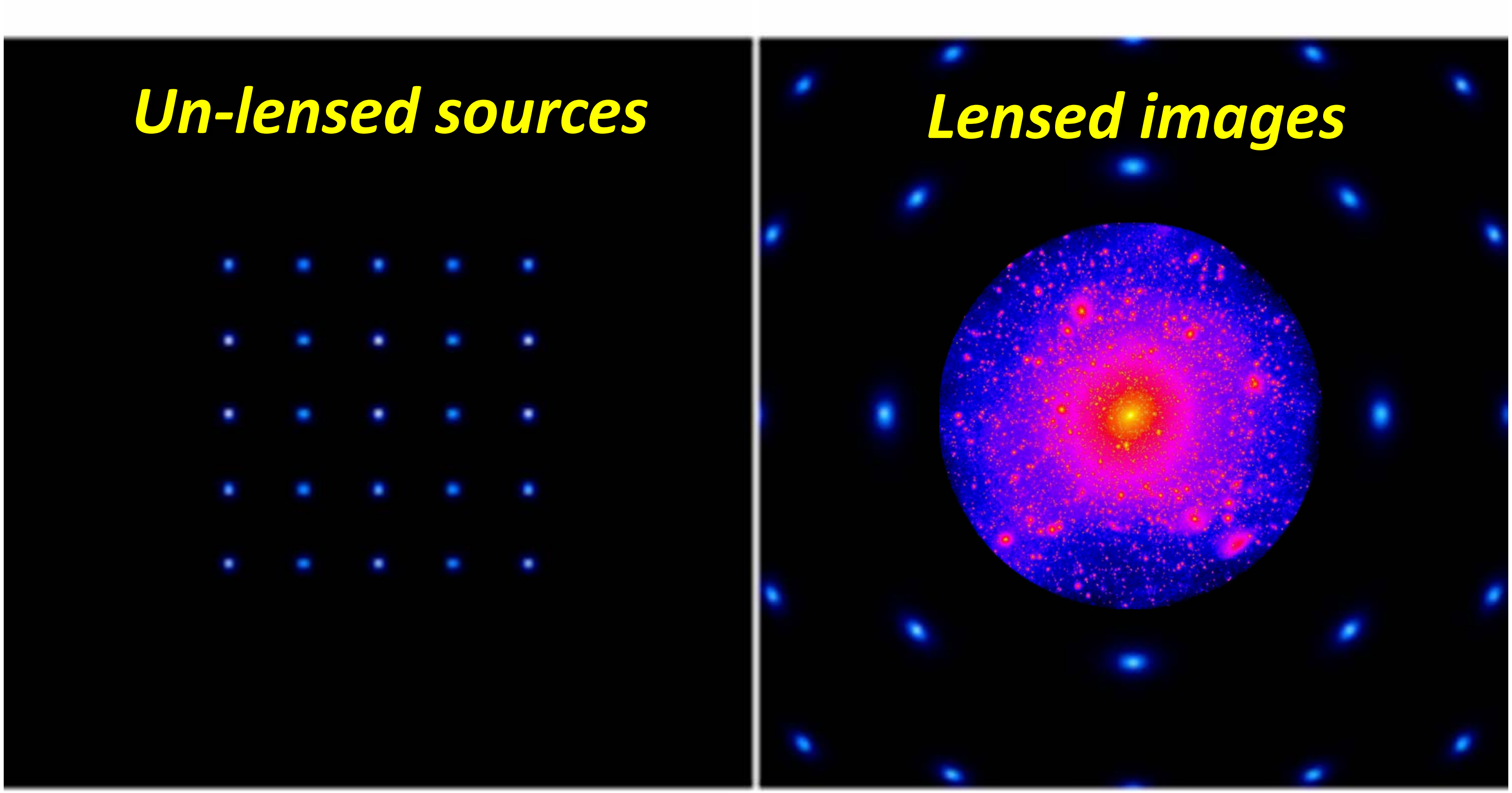


$$\kappa = \partial\partial^* \Psi / 2 = \Delta\Psi / 2$$

$$\partial := \partial_x + i\partial_y = e^{i\phi}\partial_r$$

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

Shear and Magnification Effects



- **Shear**
  - ✓ Shape distortion: $\delta e_+ \sim \gamma_+$
- **Magnification**
  - ✓ Flux amplification: μF
  - ✓ Area distortion: $\mu \Delta \Omega$

Sensitive to "modulated" matter density

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

Sensitive to "total" matter density

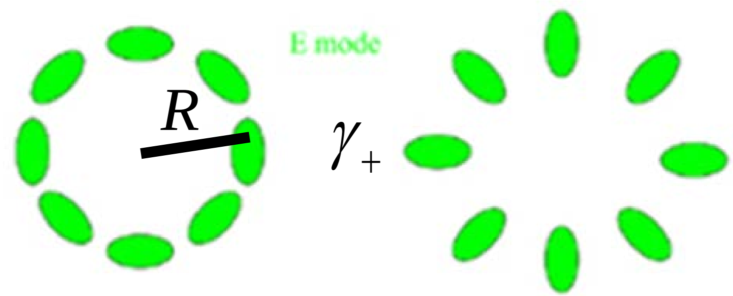
$$\mu \approx 1 + 2\kappa; \quad \Sigma_{\rm crit}\kappa = \Sigma(R)$$

Tangential Shear, γ_+

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

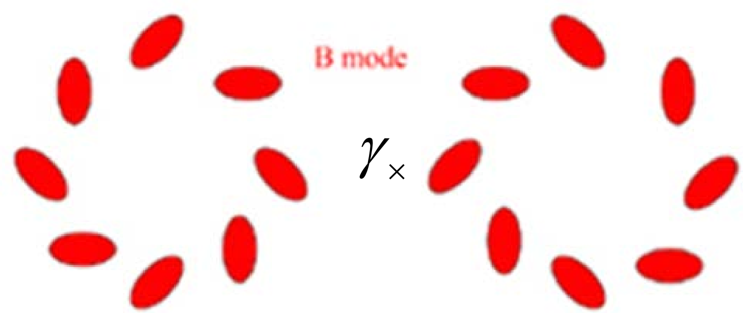
$$\gamma_+(R) = \Delta\Sigma_+(\mathrm{R}) / \Sigma_{\mathrm{crit}}$$

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



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

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



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

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

Sensitive to interior mass

$$\Sigma(\mathbf{R}) = \int \delta\rho_{\mathrm{m}}(\mathbf{r})dx_{\|}$$

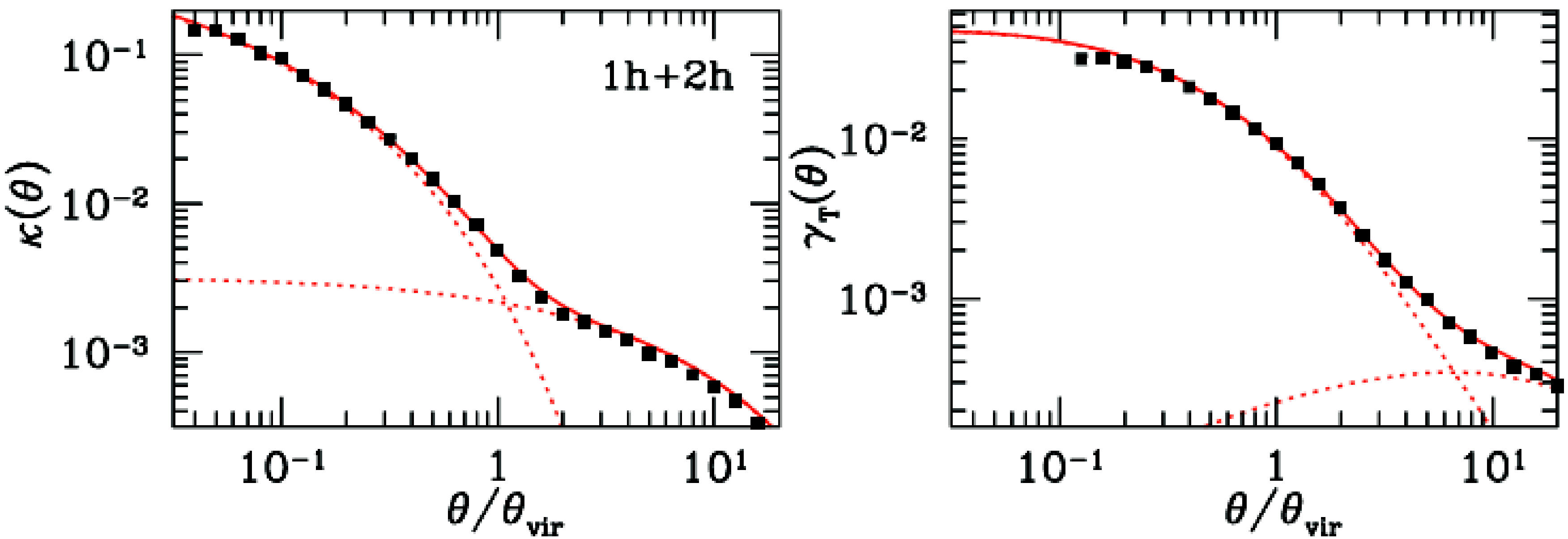
$$\Sigma_{\mathrm{crit}} = \frac{c^2}{4\pi G}\frac{D_{\mathrm{S}}}{D_{\mathrm{L}}D_{\mathrm{LS}}}$$

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:***

γ remains unchanged by $\kappa \to \kappa + \text{const.}$

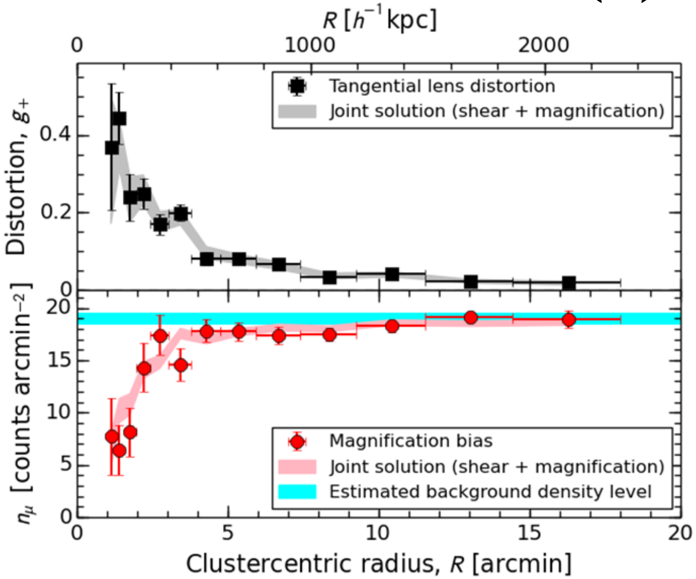
Combining Shear and Magnification

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

Tangential distortion
$$g_+(R) = \frac{\kappa(<R) - \kappa(R)}{1 - \kappa(R)},$$

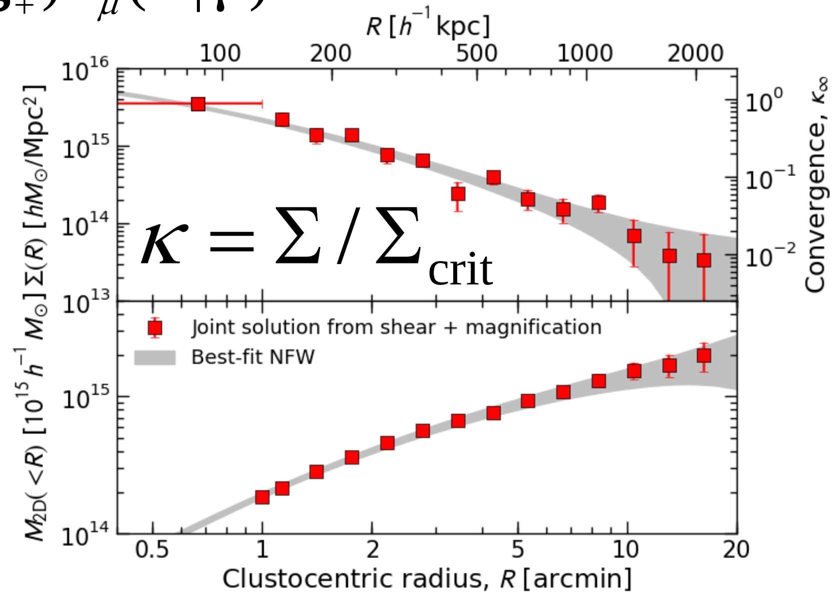
Inverse magnification
$$\mu^{-1}(R) = [1 - \kappa(R)]^2 - [\kappa(<R) - \kappa(R)]^2$$

$$L(\boldsymbol{\kappa}) = L_g(\boldsymbol{\kappa} \mid \mathbf{g}_+) L_\mu(\boldsymbol{\kappa} \mid \boldsymbol{\mu})$$



g_+

μ



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

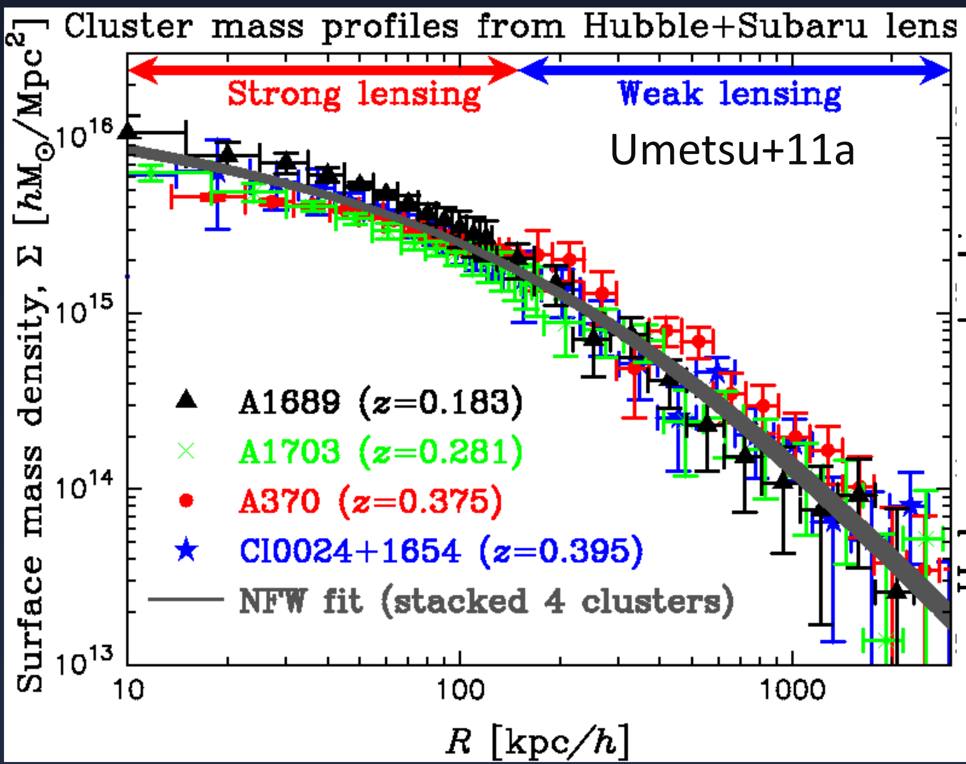
Cluster Lensing And Supernova survey with Hubble

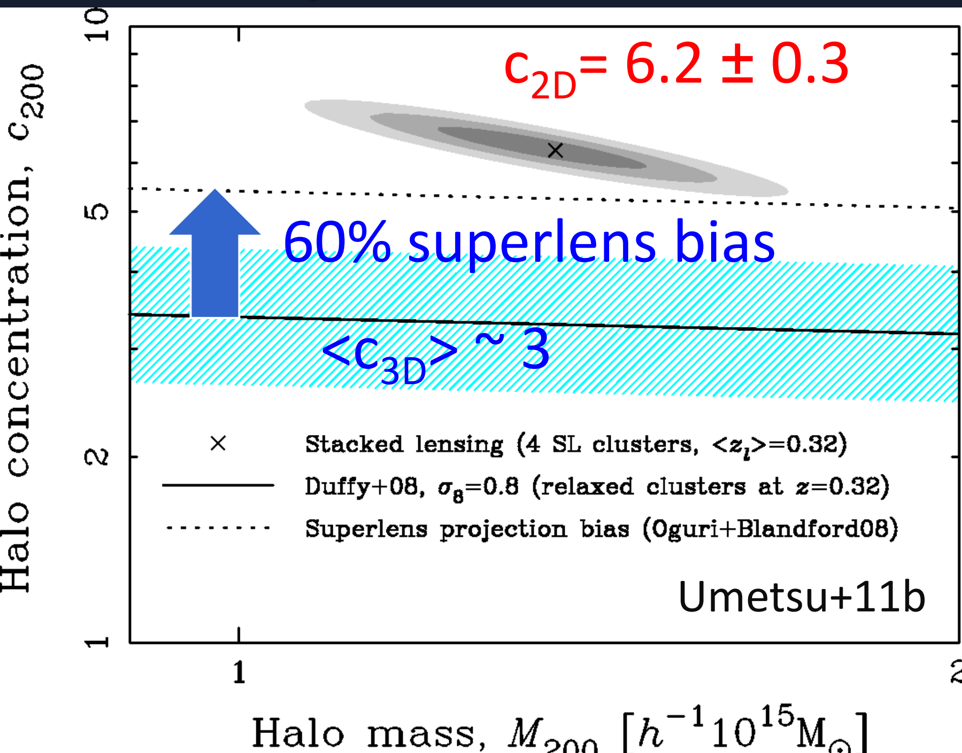
PI. Marc Postman (STScI)

http://www.stsci.edu/~postman/CLASH/Home.html

CLASH Objectives & Motivation

Before CLASH (2010), deep-multicolor Strong (*HST*) + Weak (*Subaru*) lensing data only available for a handful of "**super lens" clusters**

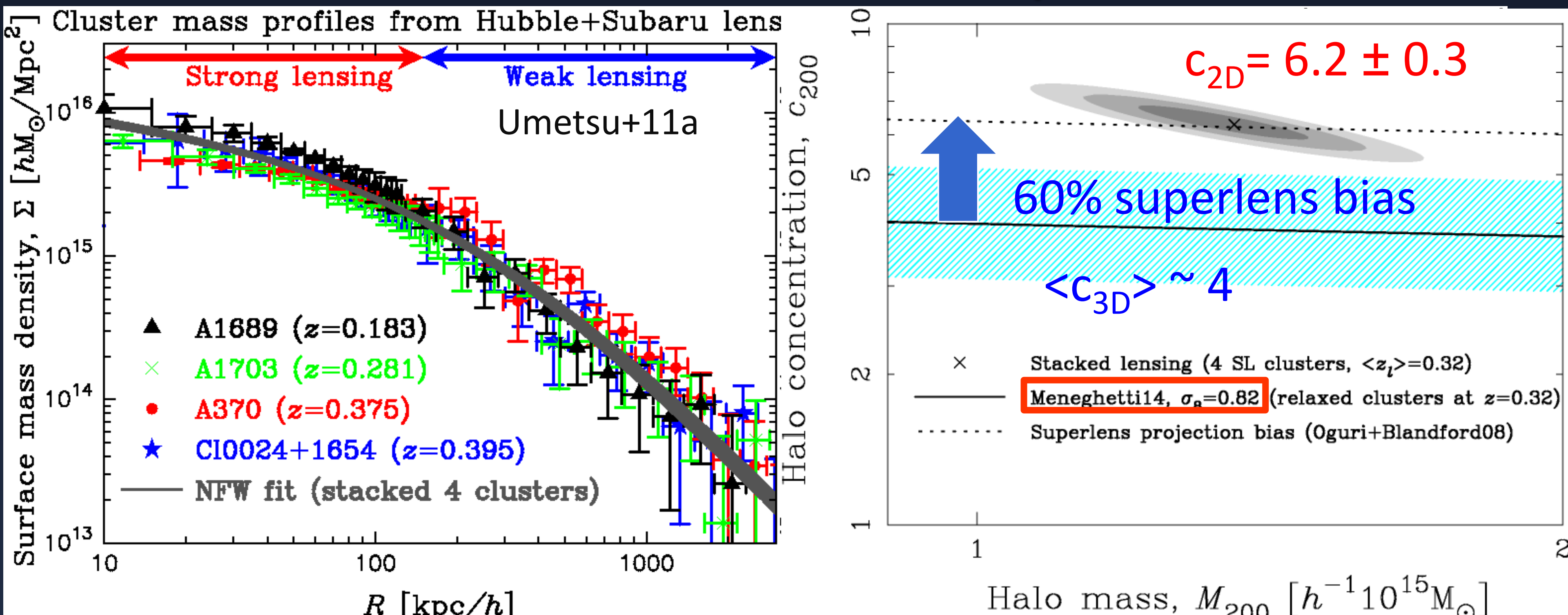




Total mass profile shape: consistent w self-similar NFW (cf. Newman+13; Okabe+13)
Degree of concentration: predicted superlens correction not enough if $<c_{LCDM}>$~3?

CLASH Objectives & Motivation

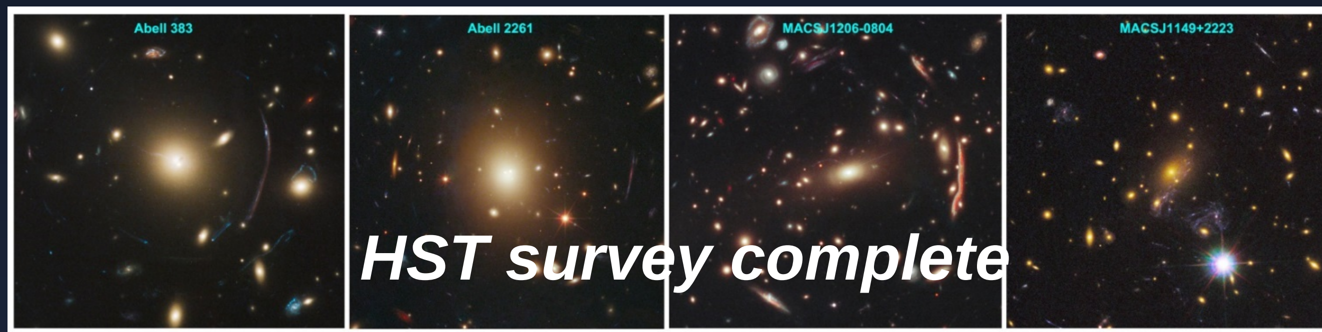
Before CLASH (2010), deep-multicolor Strong (*HST*) + Weak (*Subaru*) lensing data only available for a handful of "**super lens" clusters**



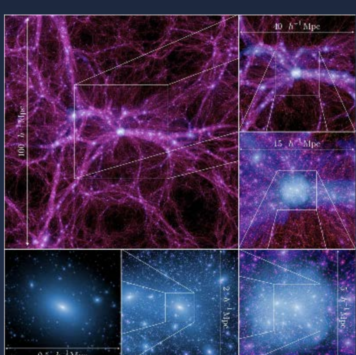
Total mass profile shape: consistent w self-similar NFW (cf. Newman+13; Okabe+13)
Degree of concentration: predicted superlens correction is just enough if <c_{LCDM}>~4

CLASH: Observational + Theory Efforts

A 524-orbit *HST* Treasury Program to observe 25 clusters in 16 filters (0.23-1.6 μm) (Postman+CLASH 12)



Wide-field Subaru imaging (0.4 - 0.9 μm) plays a unique role in complementing deep *HST* imaging of cluster cores (Umetsu et al. 2014, *ApJ*, 795, 163)



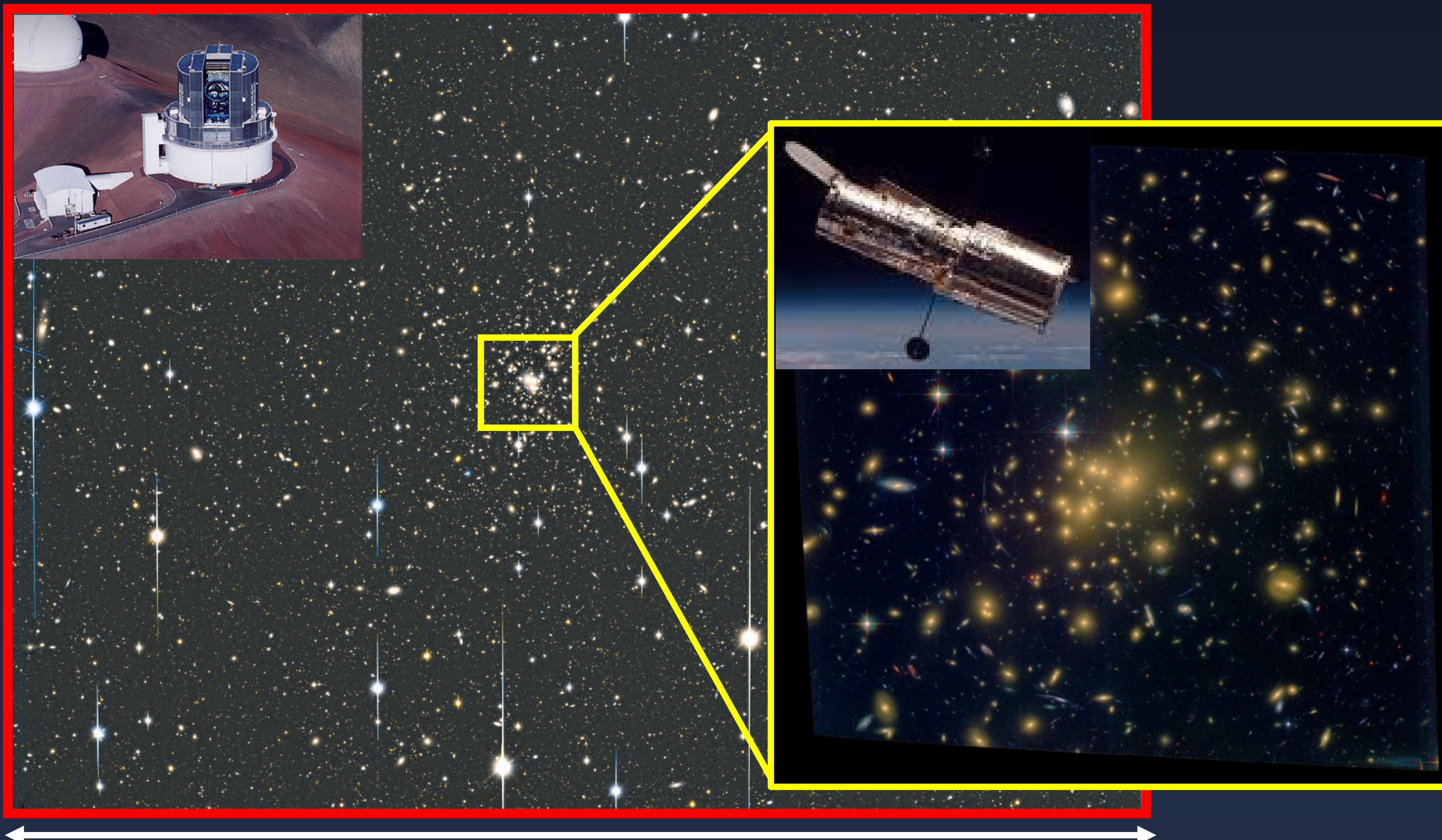
MUSIC-2 (hydro + N-body re-simulation) provides an accurate characterization of CLASH sample with testable predictions (Meneghetti et al. 2014, *ApJ*, 797, 34)

The CLASH Gallery (*HST*)

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

SUBARU (S-Cam) multi-color imaging for wide-field weak

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



34 arcmin

CLASH X-ray-selected Subsample (0.18<z<0.9)

- **X-ray morphology + T_x selection**
  - T_x > 5keV (M_{200} > 5e14M_{sun}/h)
  - Small BCG to X-ray-peak offset, σ_{off} ~ 10kpc/h
  - Smooth regular X-ray morphology

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

- **CLASH theoretical predictions** (Meneghetti+CLASH 14)
  - Composite relaxed (70%) and unrelaxed (30%) clusters
  - Mean $\langle c_{200} \rangle$=3.9, $\sigma(c_{200})$ = 0.6, c_{200}=[3, 6]
  - Negligible orientation bias (~2% in $\langle M_{3D} \rangle$)
  - >90% of CLASH clusters to have strong-lensing features

CLASH Weak-Lensing Results (1)

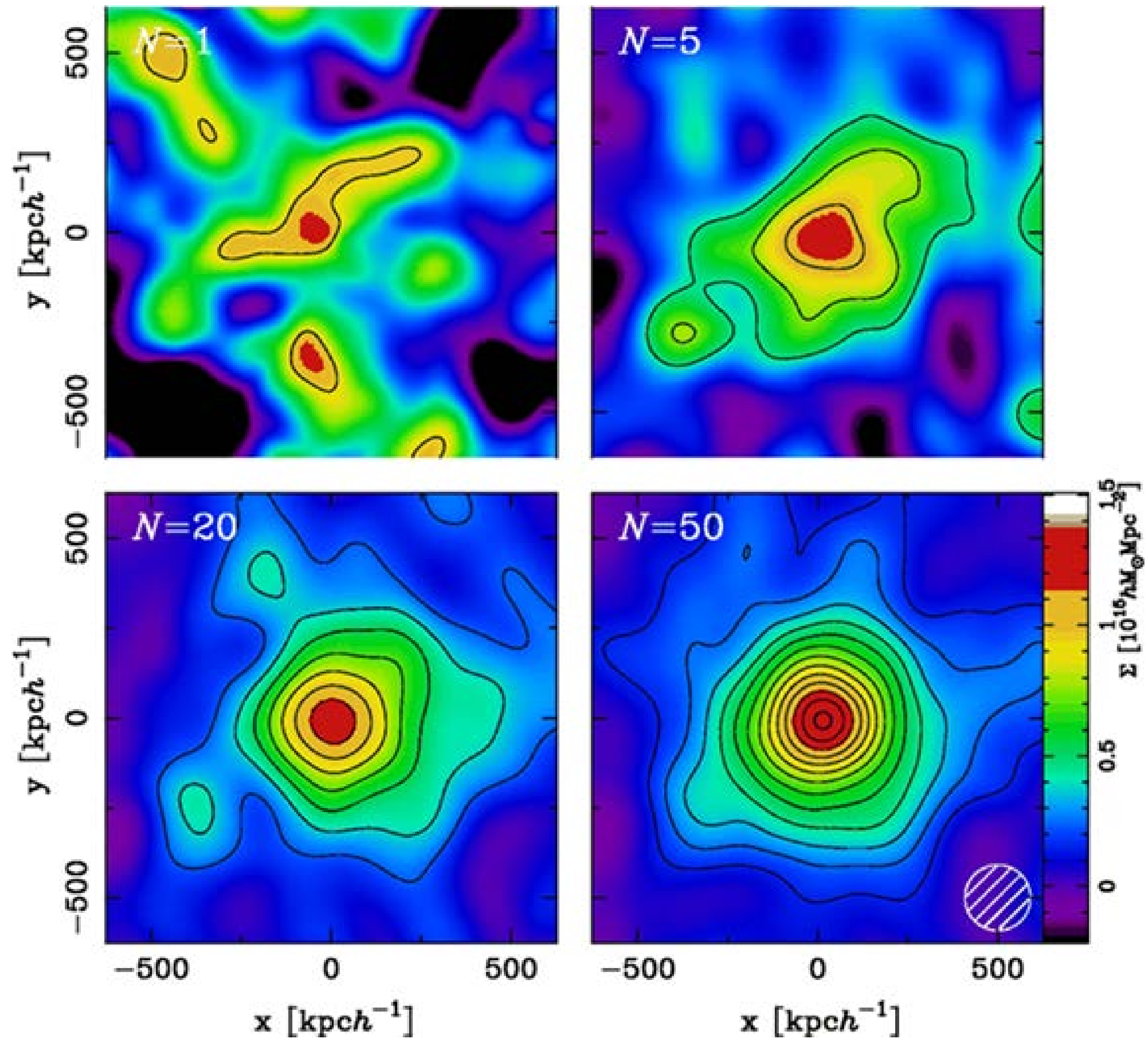
Ensemble-averaged DM halo structure:

- Cluster halo density profile, $\langle \Delta\Sigma_{+}(R) \rangle$
- Degree of halo concentration, $\langle c(M,z) \rangle$

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

Umetsu+CLASH 2014, *ApJ*, 795, 163

Power of Stacked WL Analysis



Okabe, Smith, Umetsu+13, *ApJL*, 769, 35

Averaged Halo Density Profile $\Delta\Sigma_+(R)$

Stacking WL-shear signals of individual clusters by

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

Summing over clusters (n=1, 2, ..)

with individual "sensitivity" matrix

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

defined with total covariance matrix

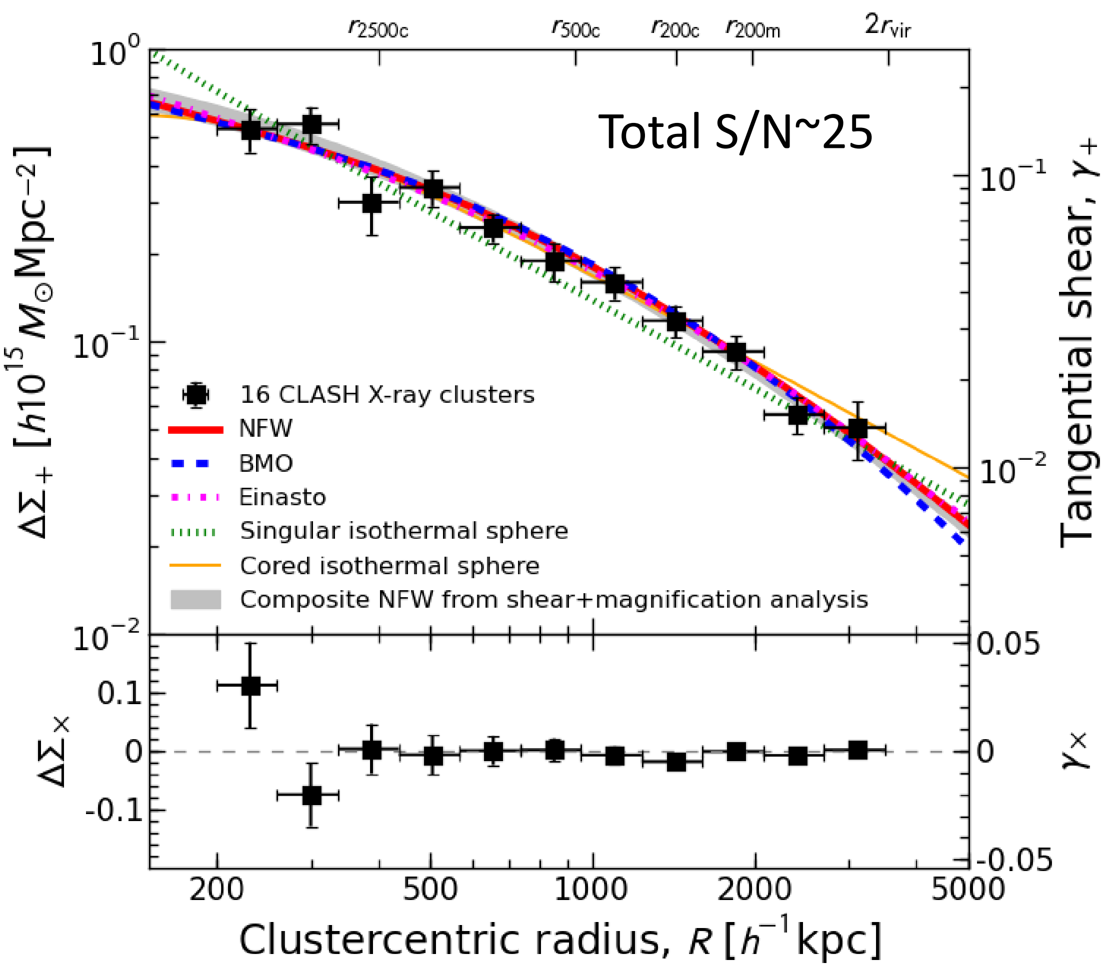
$$C_+ = C_+^{\rm stat} + C_+^{\rm sys} + C_+^{\rm lss}.$$

With "trace-approximation", averaging (stacking) 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 et al. 2014, *ApJ*, 795, 163

CLASH Averaged Halo Density Profile



Stacked-shear-only analysis provides a net 1-halo-only constraint ($\gamma_{+,2h}<10^{-3}$) at <z>=0.35

NFW an excellent fit (PTE = 0.66)

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

Einasto (PTE=0.51)

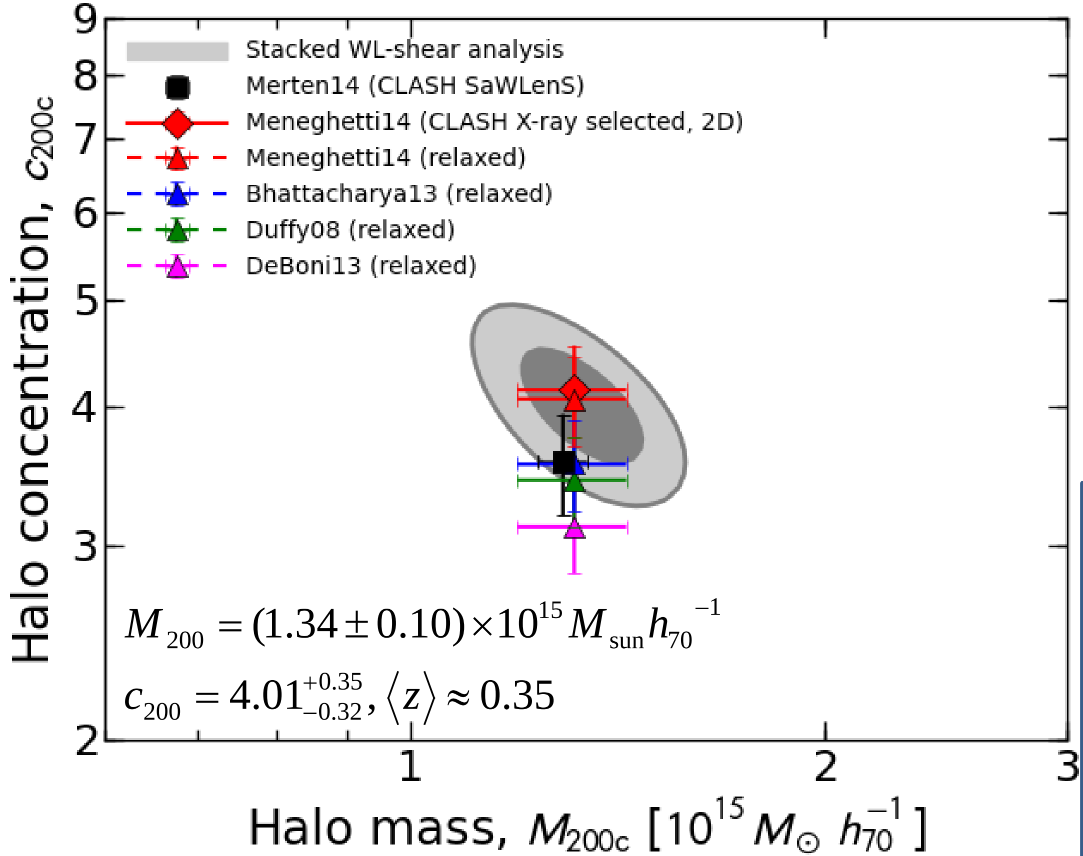
- Einasto shape parameter α_E=0.19+/-0.07, consistent with NFW curvature (α_E~0.18)

Umetsu+CLASH 14, *ApJ*, 795, 163

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

Integrated Constraints on $c(M,z)$

$$\langle c_{200c} \rangle = \frac{\int dM dz N(M,z) \hat{c}_{200c}(M,z)}{\int dM dz N(M,z)} \approx \frac{\sum_n \mathrm{tr}(\mathcal{W}_n) \hat{c}_{200c}(M_n, z_n)}{\sum_n \mathrm{tr}(\mathcal{W}_n)}$$



Umetsu+CLASH 14, *ApJ*, 795, 163

Variance in theory due primarily to different cosmology (σ_8)

Meneghetti14: σ_8=0.82
Bhattacharya13: σ_8=0.8
Duffy08: σ_8=0.796
DeBoni13: σ_8=0.776

- Excellent agreement with LCDM predictions for CLASH (M14), $\langle c_{200} \rangle = 3.9$
- Consistent with Bhatt13, Duffy08 LCDM predictions for relaxed halos @1σ, $\langle c_{200} \rangle$~3.6

CLASH Weak-Lensing Results (2)

Individual cluster mass profiles:

- Cluster mass profile $\Sigma(R)$ reconstruction
- Spherical mass estimates (M_{500}, M_{200}, M_{vir}, …)

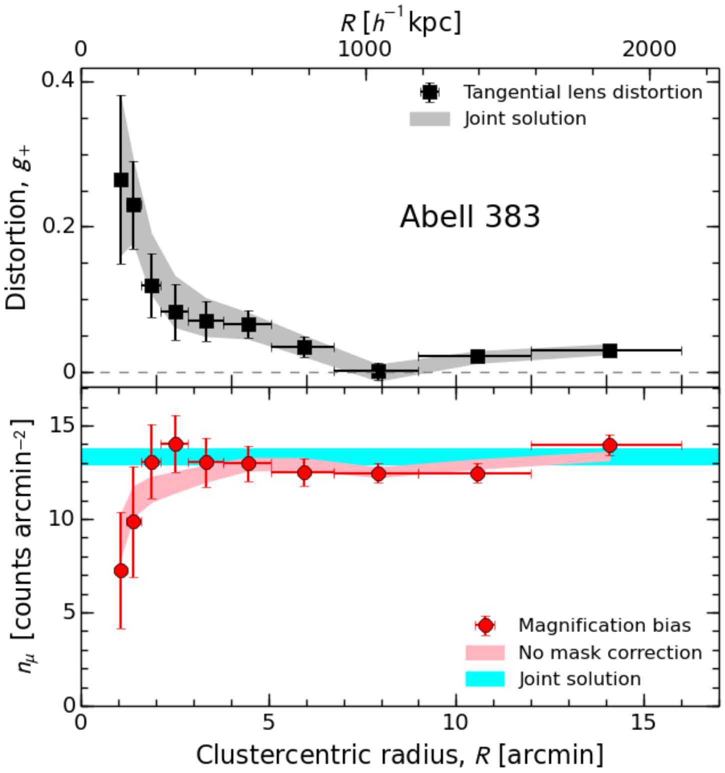
from **joint *shear+magnification* WL analysis** of all CLASH clusters

Umetsu+CLASH 2014, *ApJ*, 795, 163

Joint Shear + Magnification WL Analysis

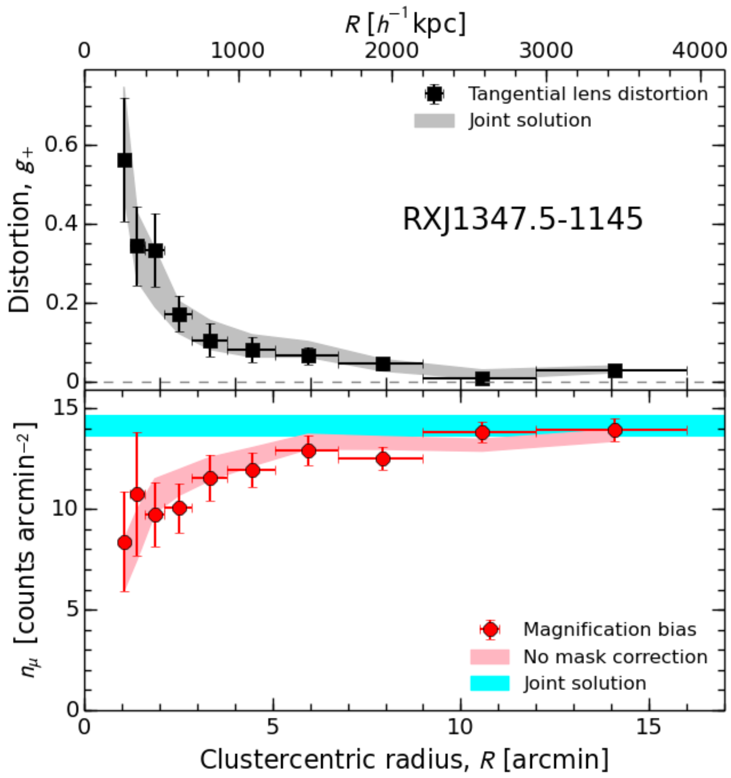
CLASH low mass

M_{200}=6e14*M*sun/*h* (*z*=0.19)



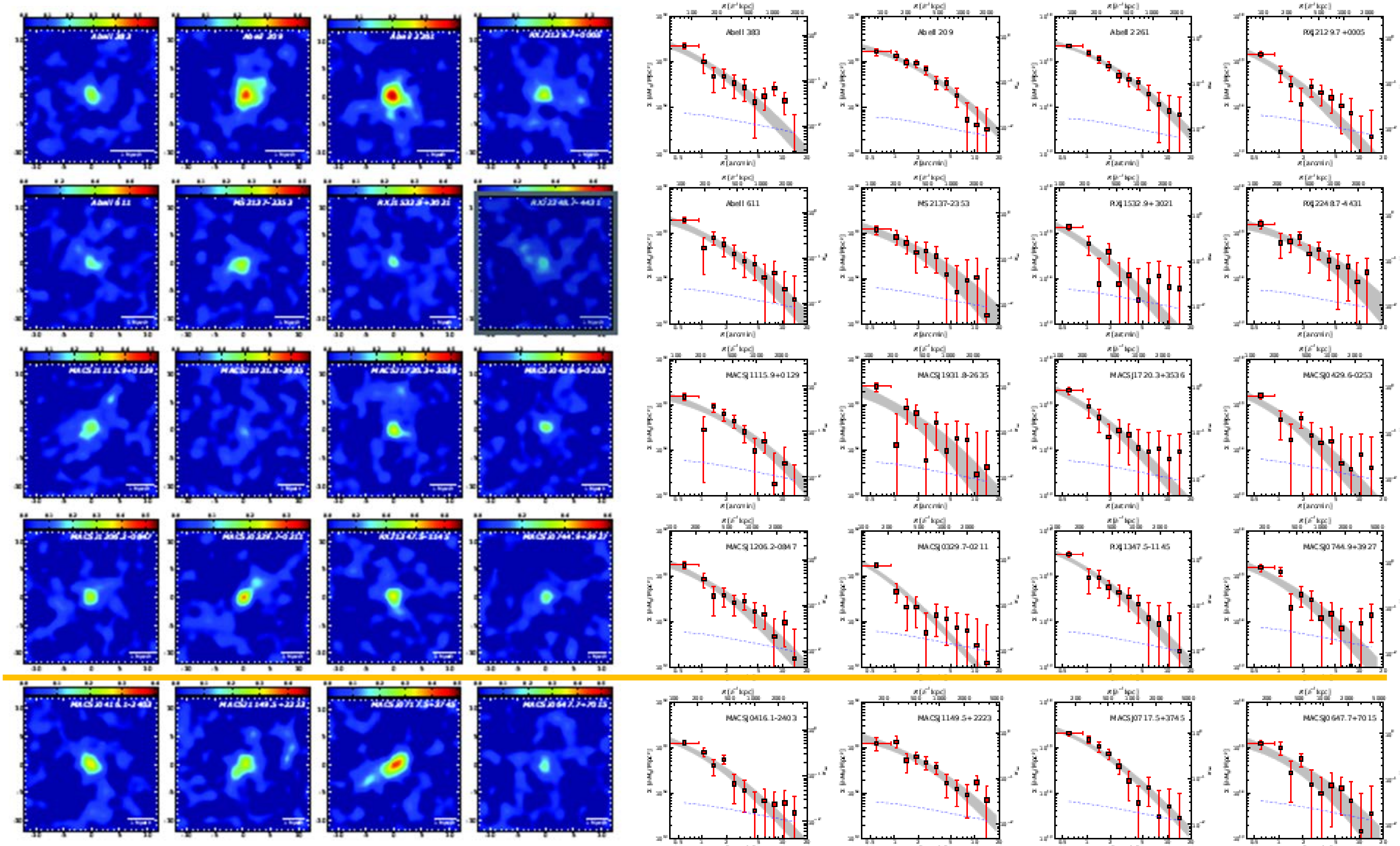
CLASH high mass

M_{200}=20e14*M*sun/*h* (*z*=0.45)



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

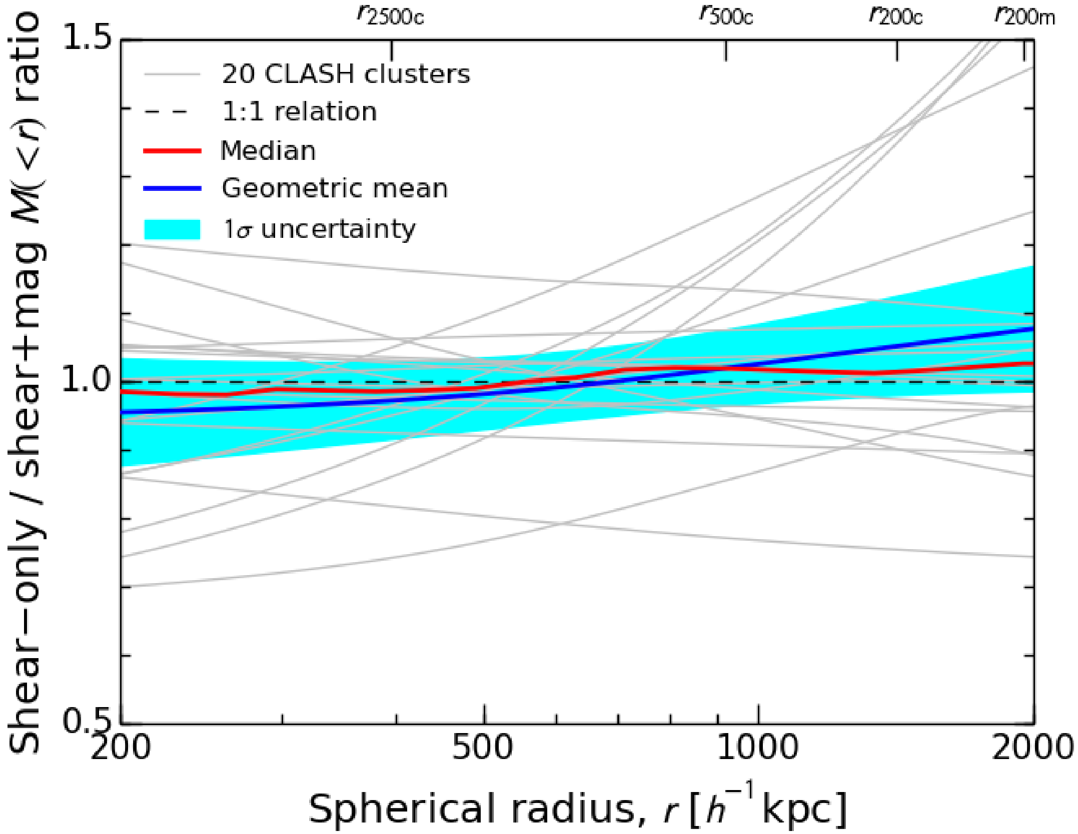
CLASH Mass Density Profile Dataset



Umetsu+CLASH 2014, *ApJ*, 795, 163

Shear-Magnification Consistency

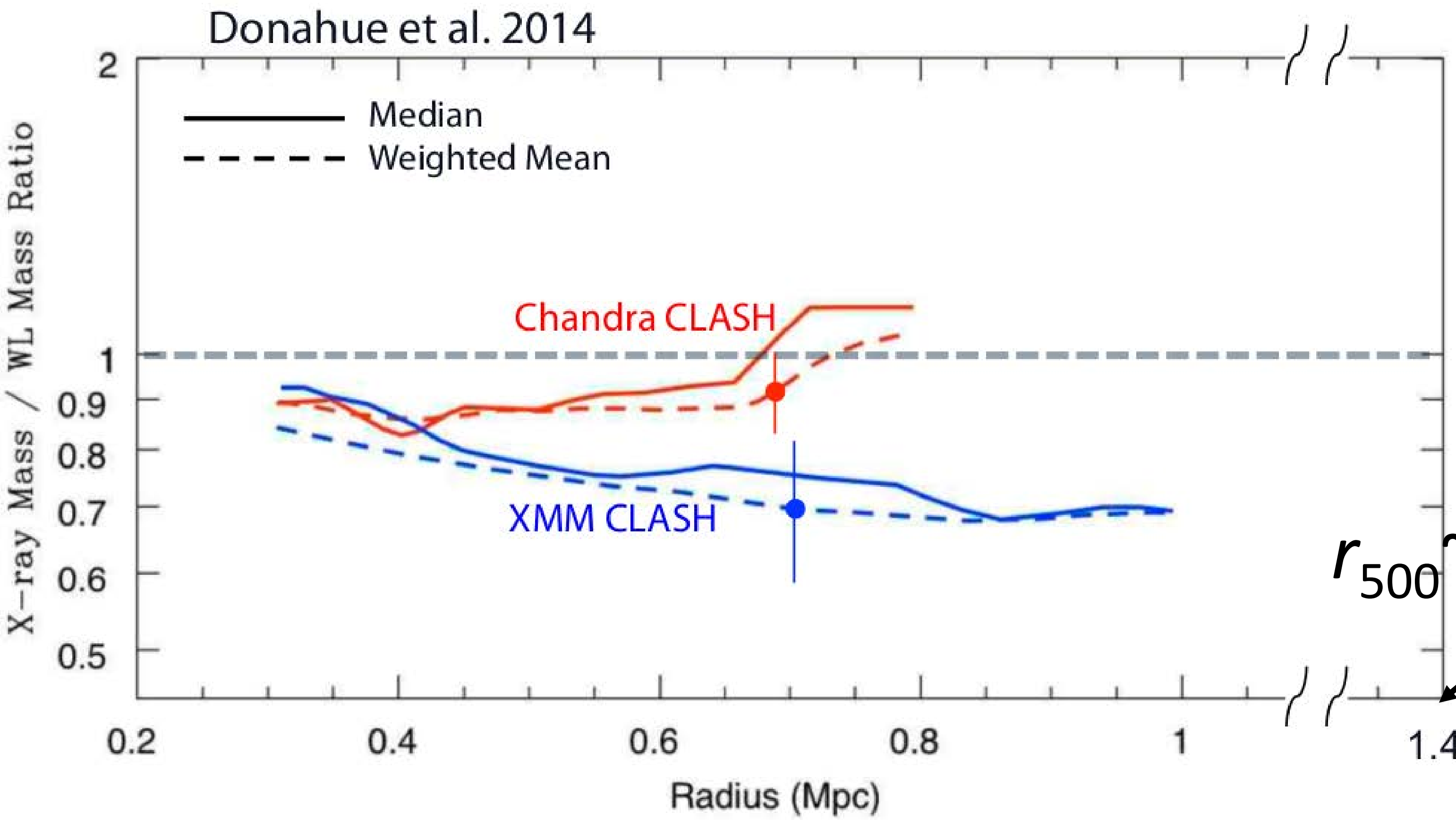
M(<*r*) de-projected assuming spherical NFW density profiles



Umetsu et al. 14, *ApJ*, 795, 163

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

CLASH: WL vs. X-ray Mass Comparison



r_{500}~0.6 r_{200}

Donahue et al. 2014, *ApJ*, 794, 136

X-ray to WL mass comparison at r_{500}

- $b = 1 - \langle M_{Chandra}/M_{WL} \rangle = 0.22 +/- 0.10$
- $b = 1 - \langle M_{XMM}/M_{WL} \rangle = 0.44 +/- 0.06$

Full-Lensing Analysis: Strong-lensing, Weak-lensing Shear and Magnification

Adding "Strong Lensing" to provide tighter constraints on *the inner density profile* (R<200kpc/h)

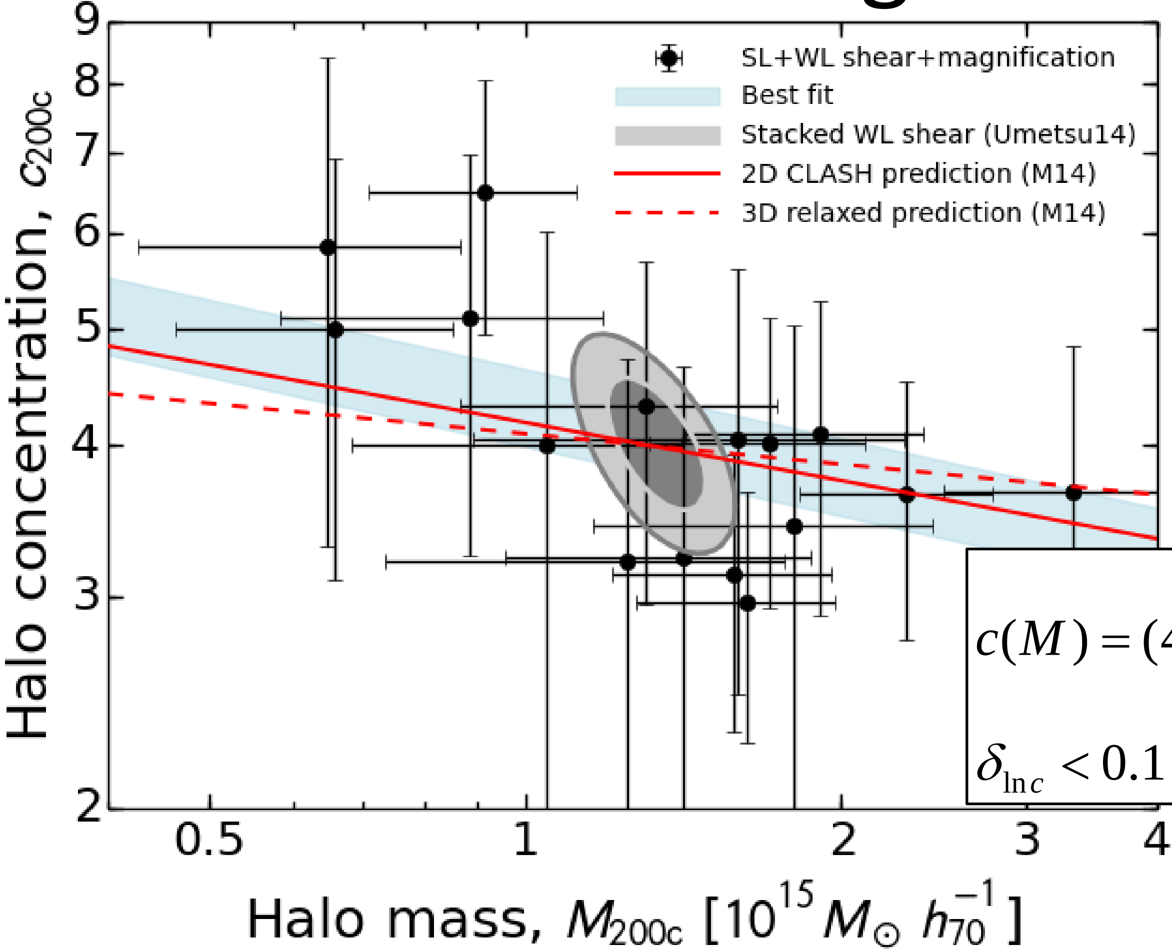
Multi-probe lensing method by Umetsu 2013, *ApJ*, 769, 13

Direct reconstruction of individual mass profiles $\Sigma(R)$ from **full likelihood analysis of *SL, WL shear and magnification*** constraints from the CLASH survey

$$L(\boldsymbol{\kappa}) = L_g(\boldsymbol{\kappa} \,|\, \mathbf{g}_+) L_\mu(\boldsymbol{\kappa} \,|\, \boldsymbol{\mu}) L_{\rm SL}(\boldsymbol{\kappa} \,|\mathbf{M}_{\mathbf{proj}})$$

- CLASH-WL shear & magnification constraints from *Subaru* observations (Umetsu+14, *ApJ*, 795, 163)
- CLASH-SL projected mass constraints $M_{\rm proj}$ from *HST* observations (Zitrin+14, arXiv:1411.1414)

CLASH *c*-*M* relation from SL, WL shear and magnification



Maximum-likelihood inference

$$\ln \hat{c}(M_i) = A \ln M_i + B$$

$$-2\ln L = \sum_{i=1}^{N} \left\{ \frac{[\ln c_i - \ln \hat{c}(M_i)]^2}{\sigma_i^2} + \ln \sigma_i^2 \right\},$$

$$\sigma_i^2 = \sigma_{\ln c_i}^2 + A^2 \sigma_{\ln M_i}^2 - 2\sigma_{\ln c_i}\sigma_{\ln M_i} + \delta_{\ln c,\mathrm{int}}^2$$

$$c(M) = (4.1 \pm 0.3)\left(\frac{M}{1.3 \times 10^{15} M_{\mathrm{sun}}} \right)^{-0.191 \pm 0.075}$$

$$\delta_{\ln c} < 0.1\,(68.3\%\,\mathrm{CL})$$

Umetsu+2015, in prep

Fully consistent with LCDM predictions + CLASH selection function

Average Matter Distribution in and around CLASH Clusters

Total matter density profile @ R=[0.01, 2]r_{vir} averaged over the X-ray-selected CLASH sample:

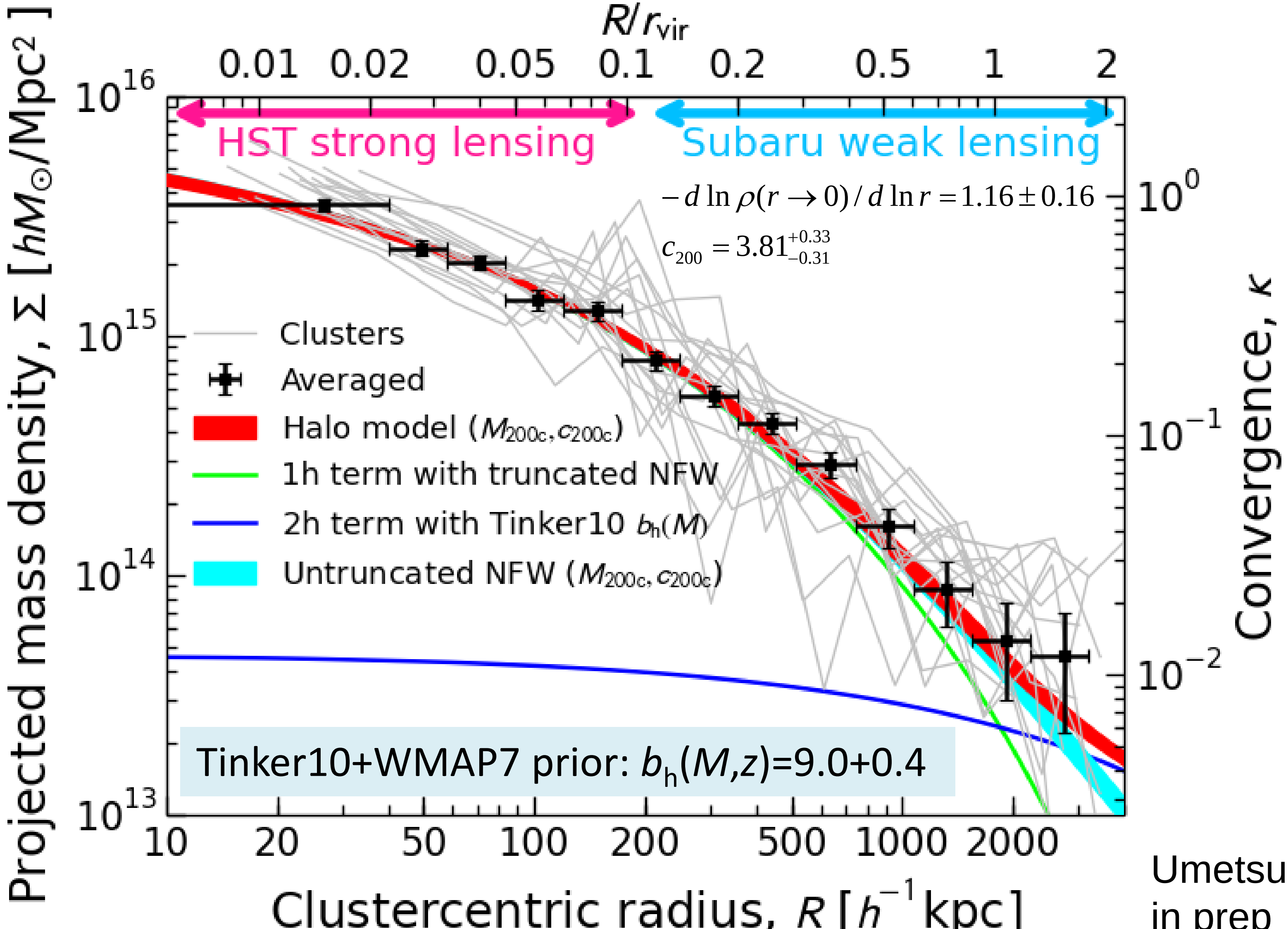
$$\Sigma(R\,|\,M)=\int\bar{\rho}\,\xi_{\mathrm{hm}}(\mathbf{r}\,|\,M)\,dx_{||}$$

Clustering of matter around halos with M:

1h term **2h term**

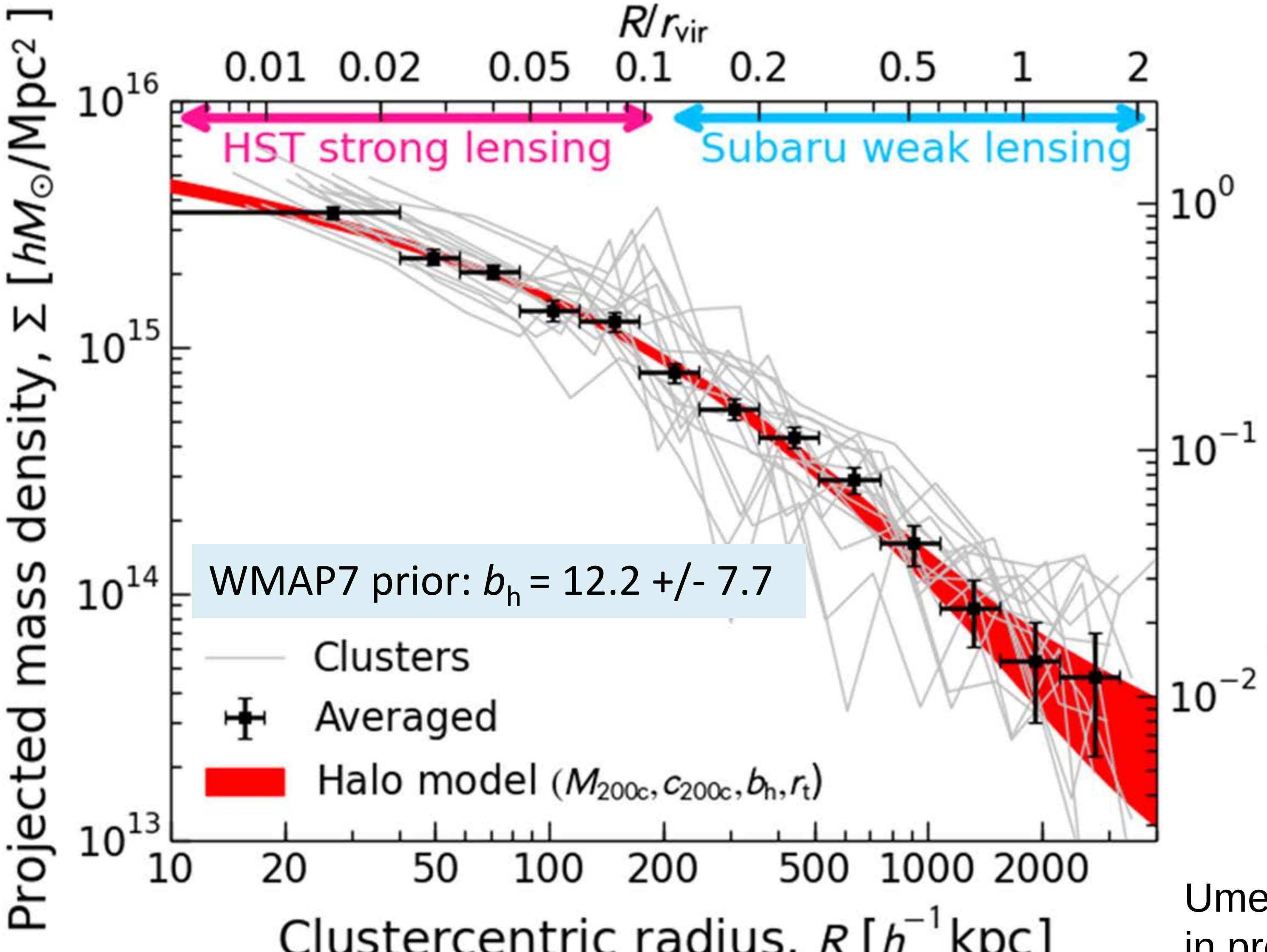
$$\xi_{\mathrm{hm}}(r\,|\,M)=\frac{\langle\rho_{\mathrm{halo}}(r\,|\,M)\rangle}{\bar{\rho}}+b_{\mathrm{h}}(M)\,\xi_{\mathrm{mm}}(r)$$

CLASH Averaged Total Mass Profile vs. LCDM



Umetsu+2015, in prep

CLASH Averaged Total Mass Profile vs. LCDM

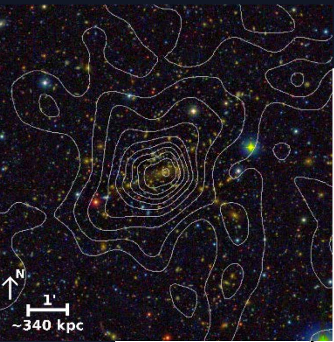


Umetsu+2015, in prep

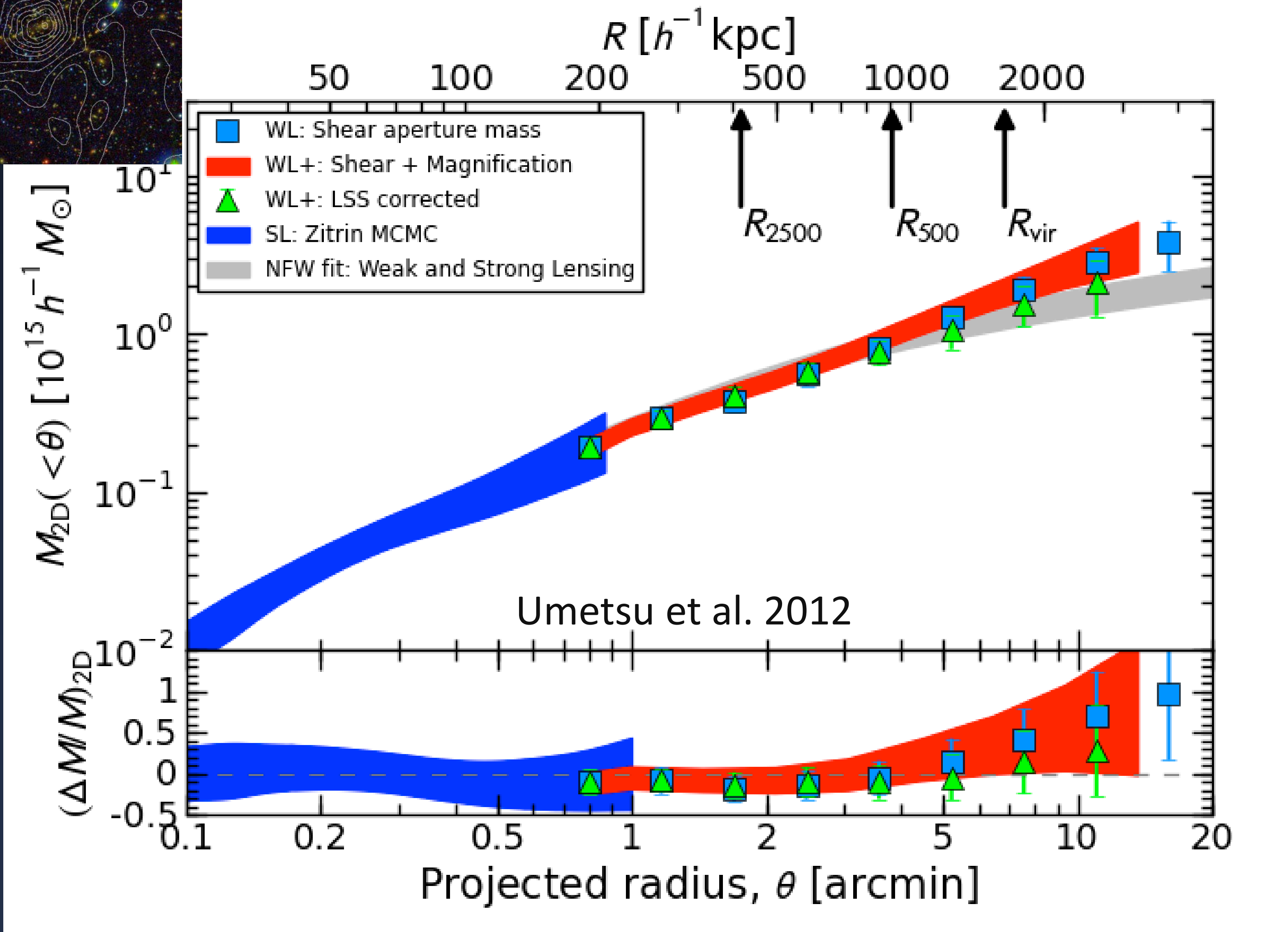
Constraints on the Intracluster Dark-Matter Equation of State

A Case study from the ongoing CLASH-VLT redshift survey (PI: Piero Rosati)

MACS1206 (z=0.44): A relaxed CLASH cluster

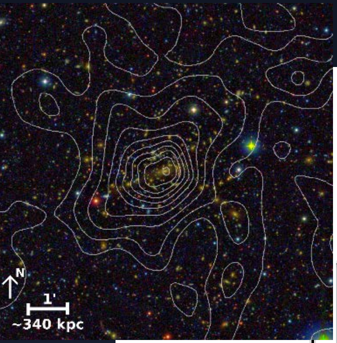


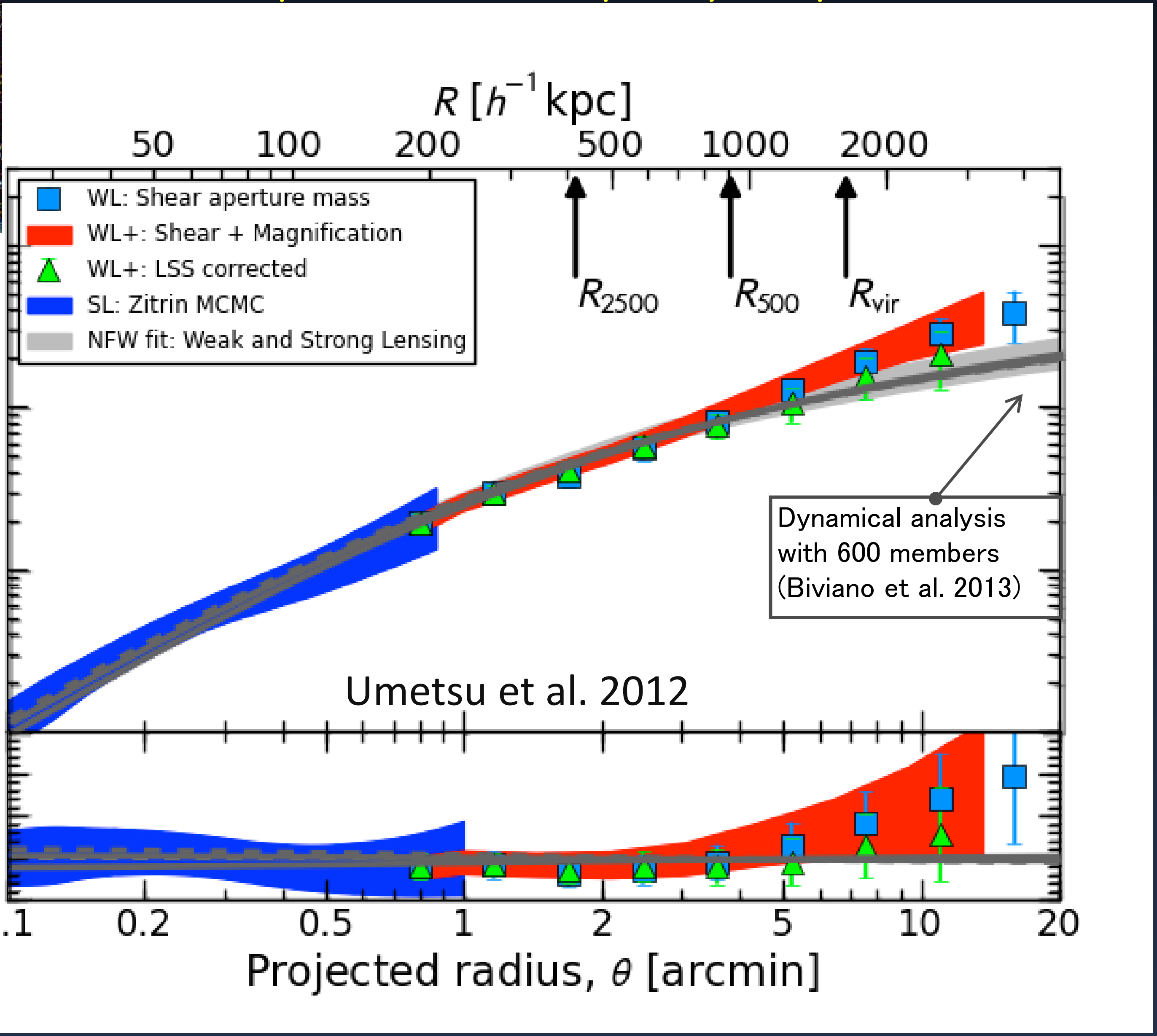
Total mass profiles from completely independent methods agree.



MACS1206 (z=0.44): A relaxed CLASH cluster

Total mass profiles from completely independent methods agree.





Constraining DM Equation of State

- By testing whether 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:

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

Sartoris et al 2014, *ApJL*, 783, 11

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

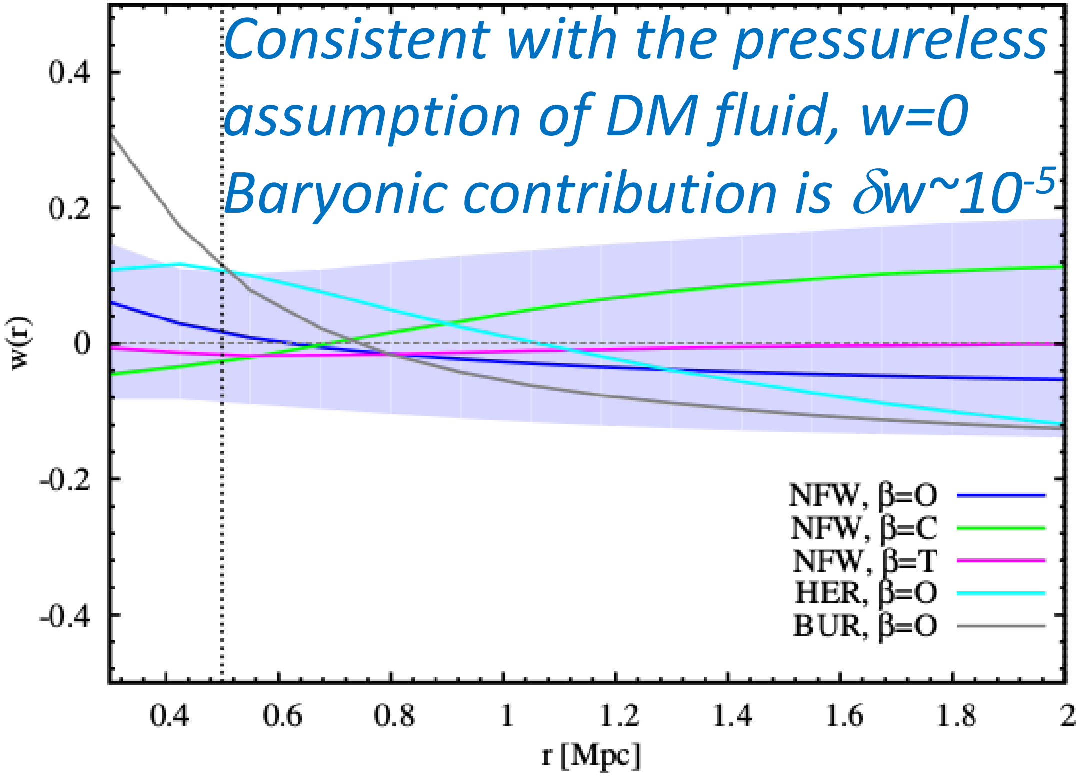
$$2\Phi_l \equiv \Phi + G\int \frac{m(r)}{r^2} dr,$$

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

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

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

First application to a relaxed cluster



$$\langle w \rangle = 0.00 \pm 0.15(stat) + 0.08(syst)$$

In CLASH, we have 11 more clusters with VLT redshift measurements to improve the DM EoS constraint

Sartoris et al 2014, *ApJL*, 783, 11

Summary

- Averaged matter distribution within CLASH clusters is in excellent agreement with standard predictions for collisionless-DM-dominated halos:
  - Outward steepening radial dependence with central cusp slope $\beta = -d\ln\rho/d\ln r(r \rightarrow 0) = 1.16$ +/- 0.16 (NFW: $\beta=1$)
  - Einasto degree of curvature, $\alpha_E = 0.190$ +/- 0.07 ($n_E = 1/\alpha_E \sim 5$)
  - Average concentration, $\langle c_{200} \rangle = 4.01$ (+0.35, -0.32) at $\langle M_{200} \rangle = (1.3 \pm 0.1) 10^{15} M_{sun}$, $\langle z \rangle = 0.35$
  - c-M scaling relation with $d\ln c(M)/d\ln M = -0.191$ +/- 0.075 and intrinsic scatter $\delta_{\ln c} < 0.1$ (68.3%CL)
- Total matter distribution $\langle \Sigma(R) \rangle$ in/around CLASH clusters R=[0.01, 2] r_{vir} is fully consistent with LCDM halo model
  - Total = smoothly-truncated NFW + correlated large-scale structure with $b_h(\sigma_8/0.81)^2 \sim 9.0$
  - Marginal detection of clustering 2h term ($\sim 1.6\sigma$) within $2r_{vir}$

Summary (contd.)

- Consistent WL shear & magnification measurements allow for accurate cluster mass profile measurements for 20 CLASH clusters
  - ~8% residual mass-calibration uncertainty, comparable to other current best WL efforts (~7% by *Weighing the Giants* project)
  - Crucial for cluster cosmology (cf. 20%-40% mass uncertainty in Planck 2013)
- Our lensing+kinematics study of a single cluster found the DM EoS to be <*w*>=0.00 +/- 0.15 +/- 0.08 within *R*=0.5-2Mpc, confirming the standard pressureless assumption of DM fluid. A full CLASH-VLT sample of 12 clusters will further tighten the constraint on DM EoS.

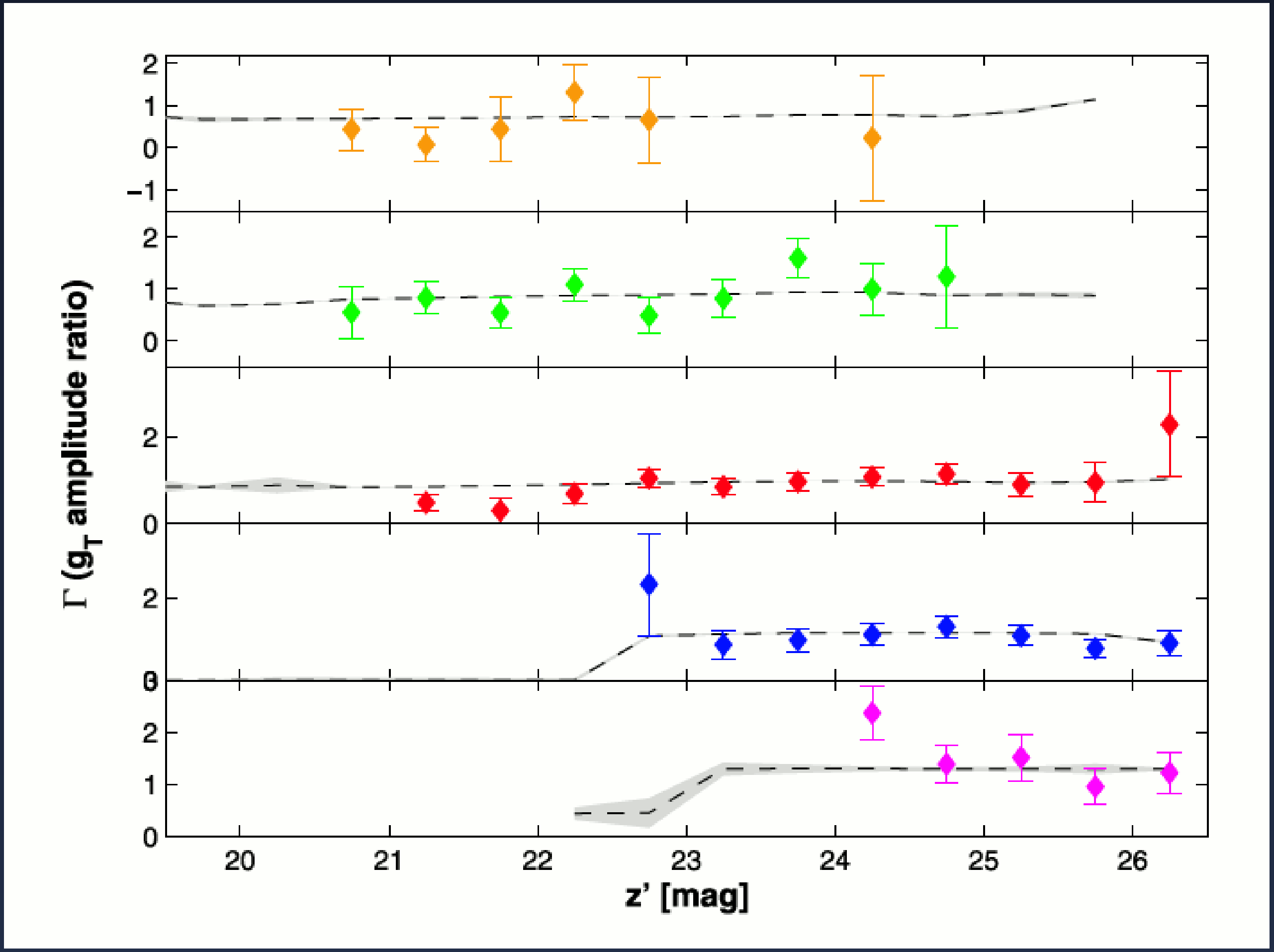
CLASH Products released

http://archive.stsci.edu/prepds/clash/

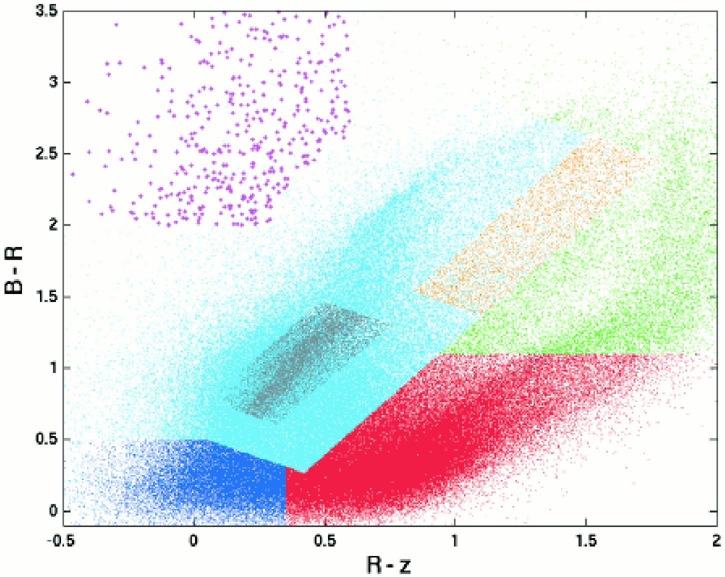
- Calibrated and co-added images [HST, Subaru]
- Object catalogs [HST, Subaru]

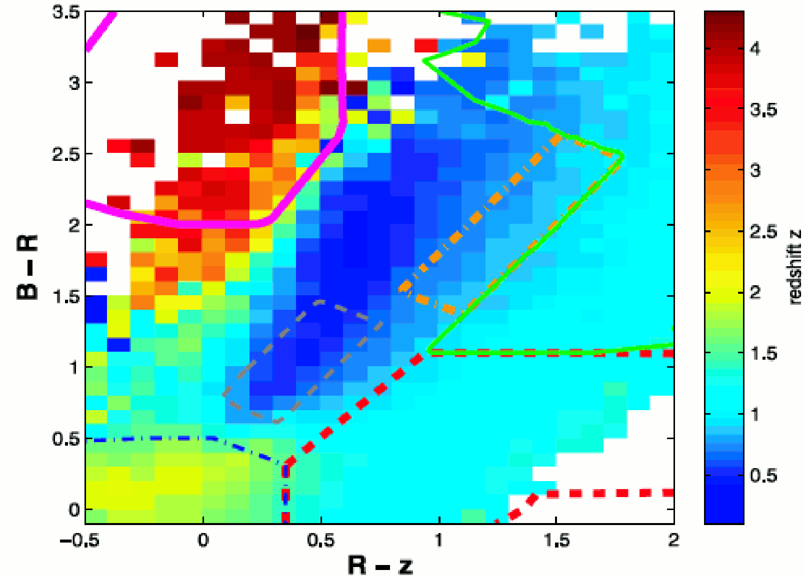
Supplemental Slides

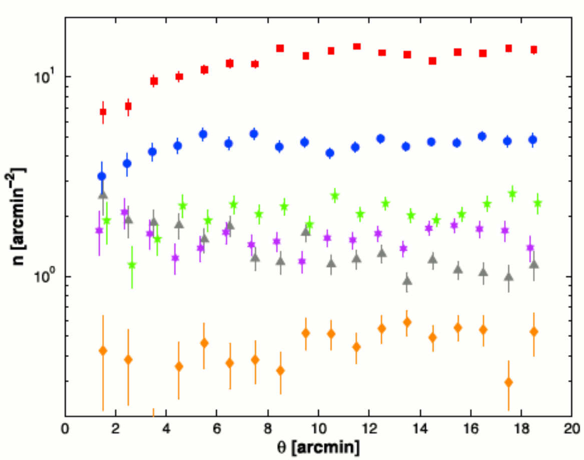
SUBARU shear strength as a function of magnitude

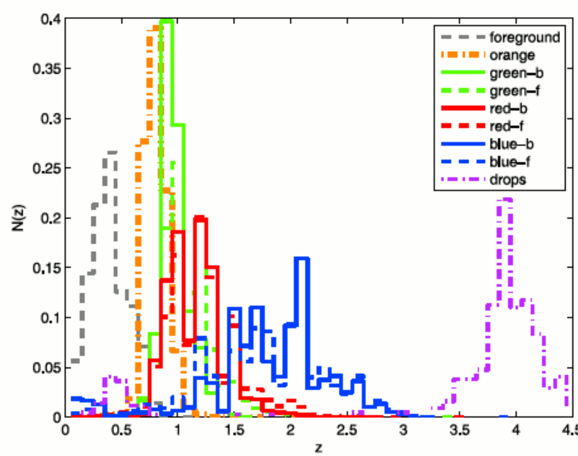


Medezinski, Broadhurst, Umetsu+11

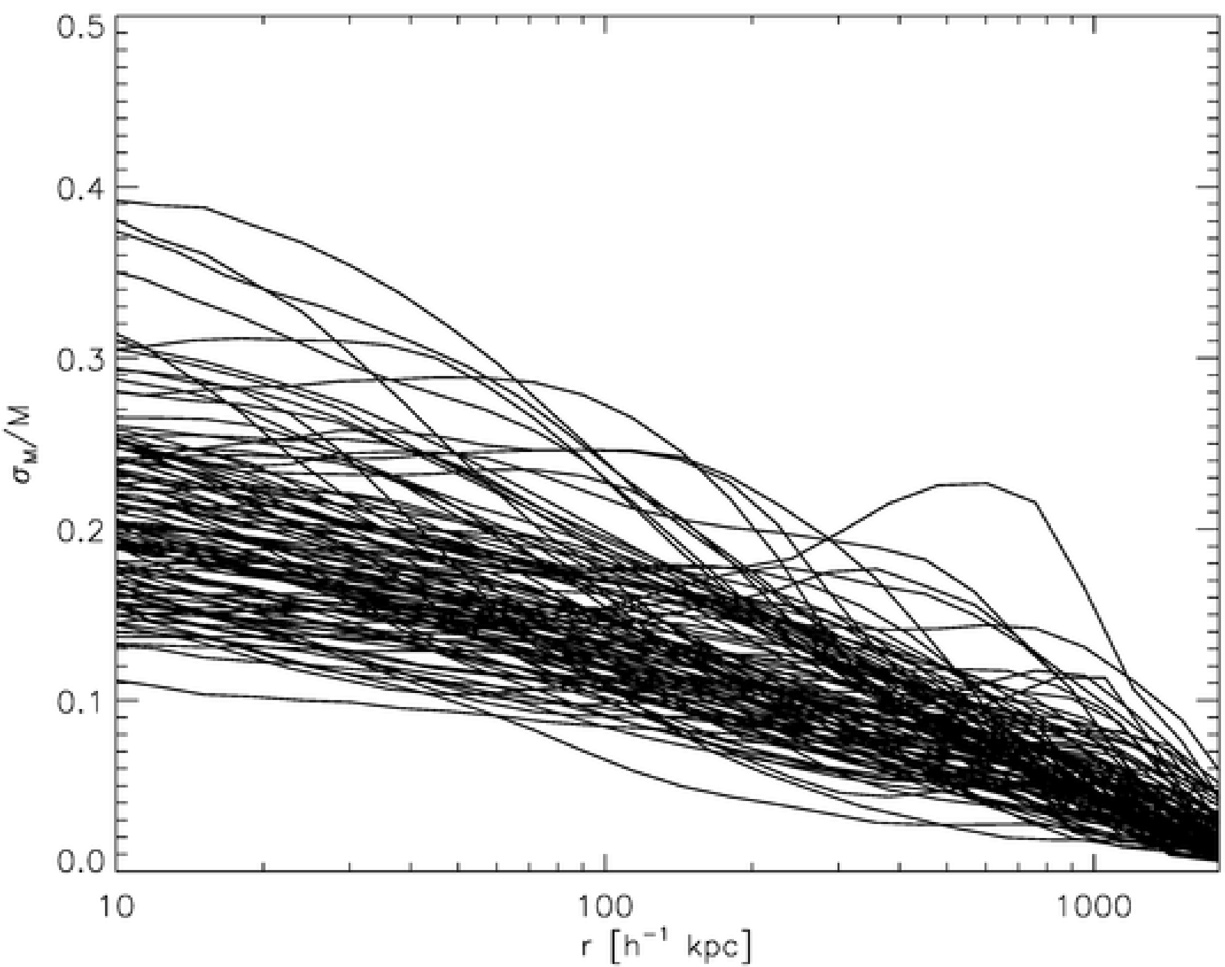

B - R
R - z


B – R
R – z
redshift z


n [arcmin^{-2}]
θ [arcmin]

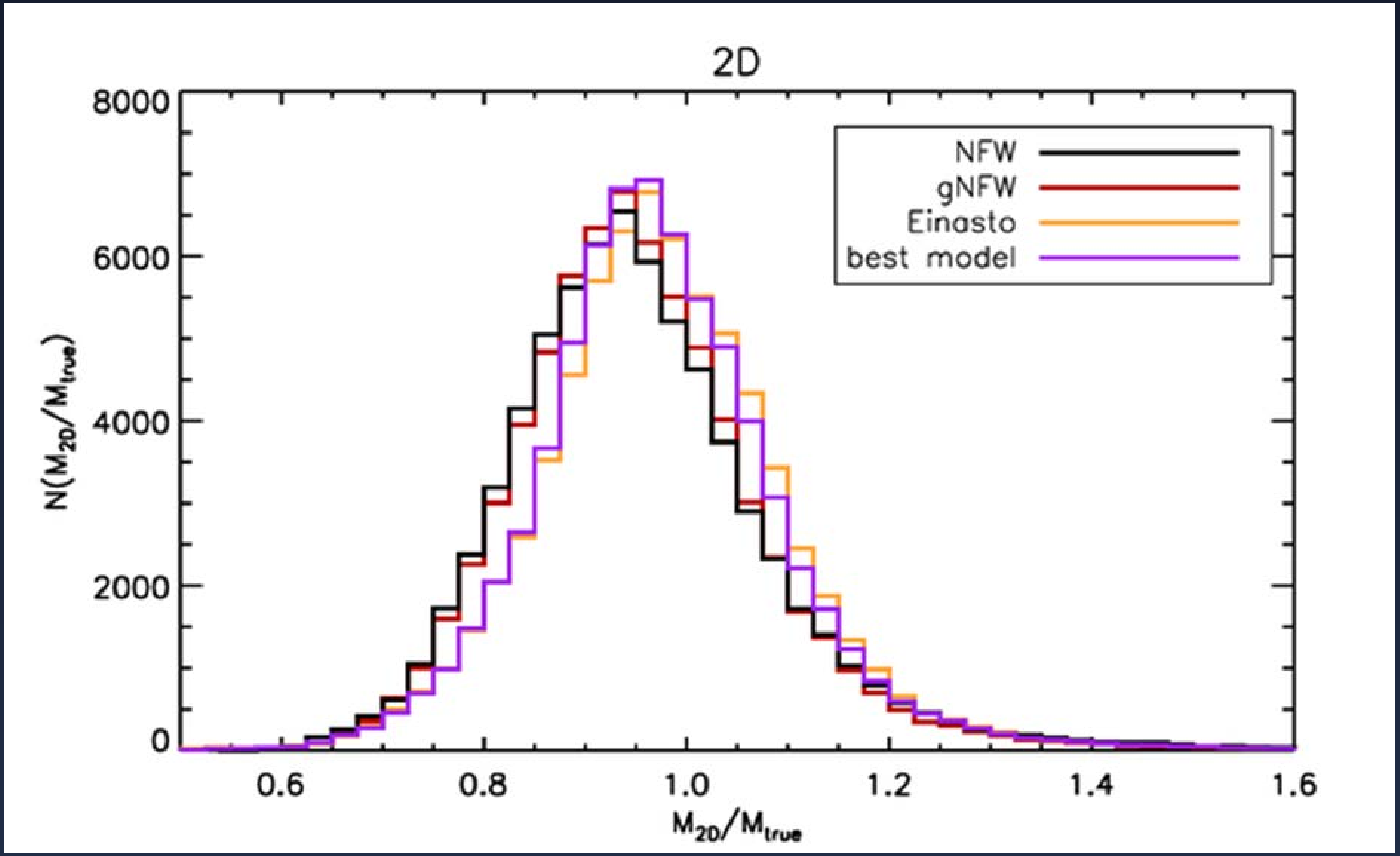

N(z)
z
foreground
orange
green–b
green–f
red–b
red–f
blue–b
blue–f
drops

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



MUSIC-2 simulation by Massimo

Cluster masses recovered from lensing analysis



Meneghetti+CLASH 14

Magnification bias effects

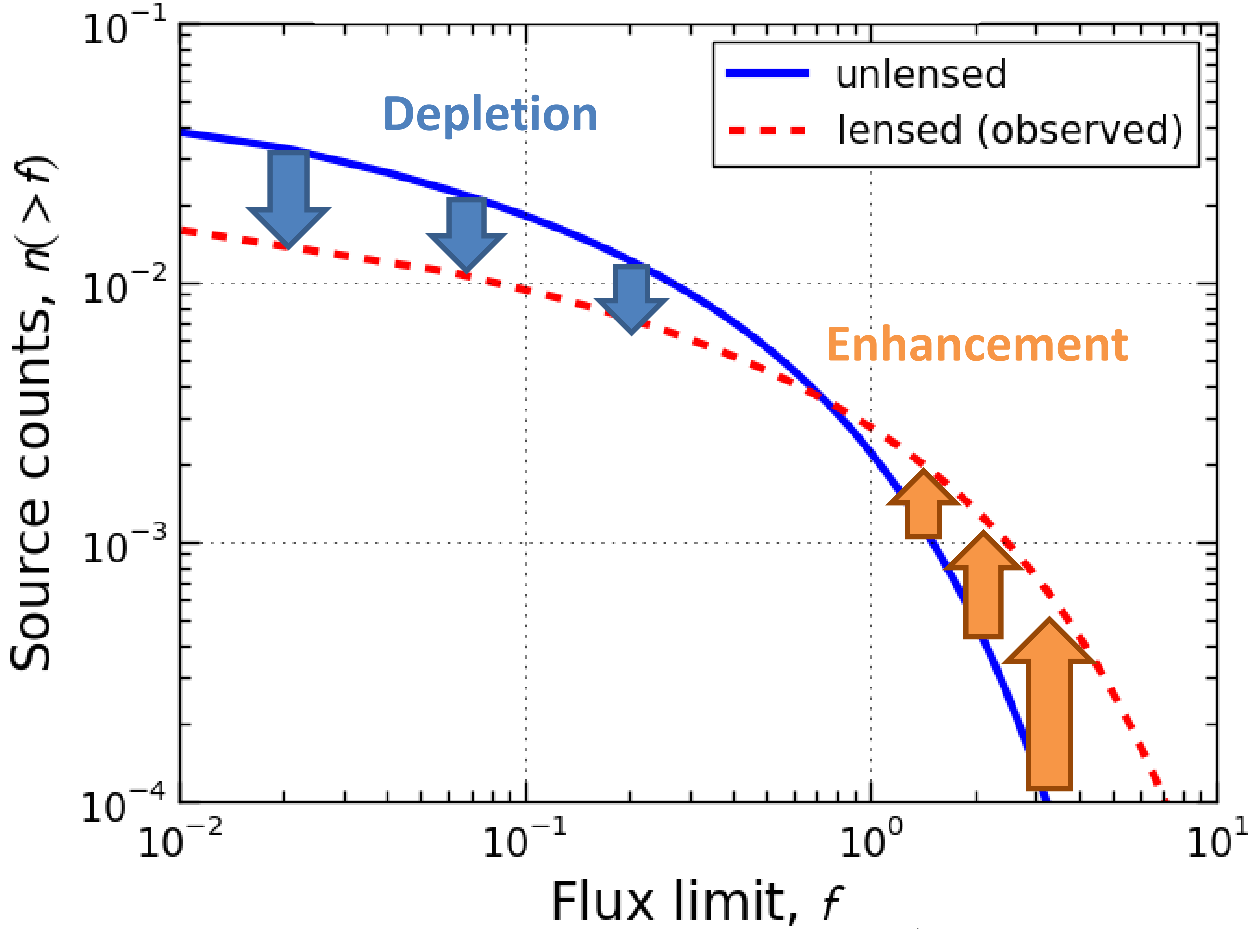
Flux-limited source counts:

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

Broadhurst, Taylor & Peacock 95

Geometric area distortion

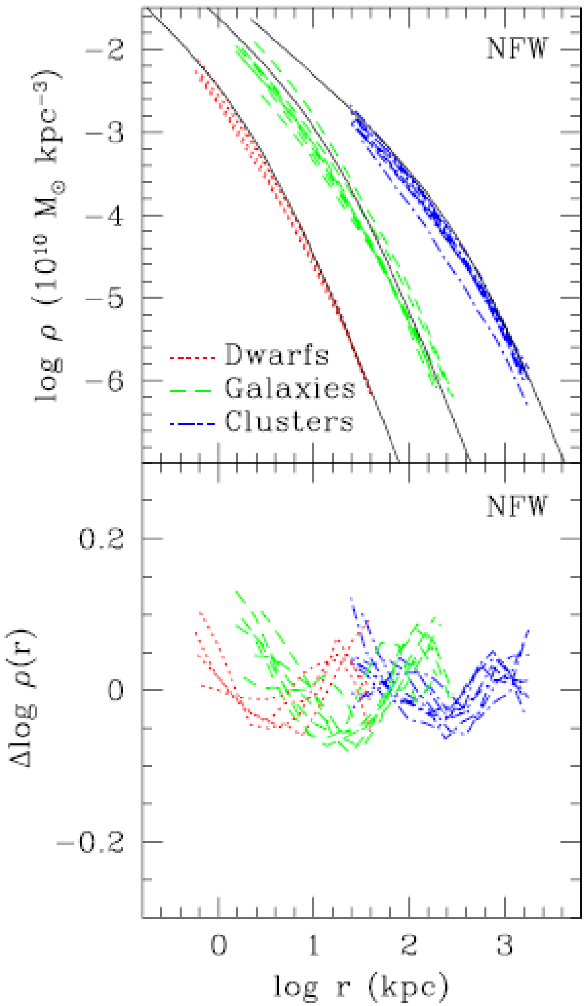
n/μ

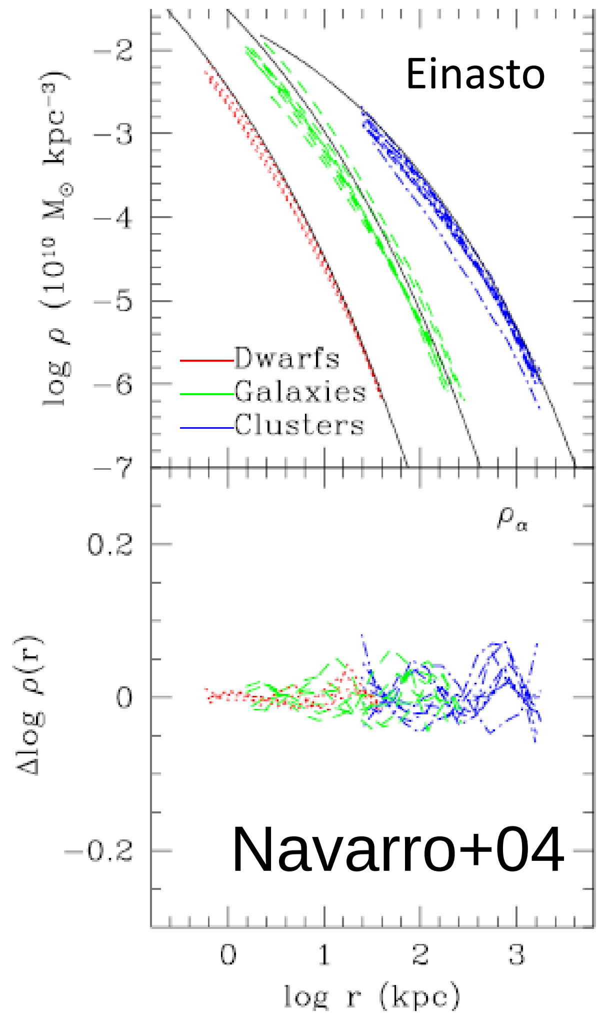


Flux amplification

“Diversity” of halo density profiles

Mass profiles of DM halos are not strictly self-similar:

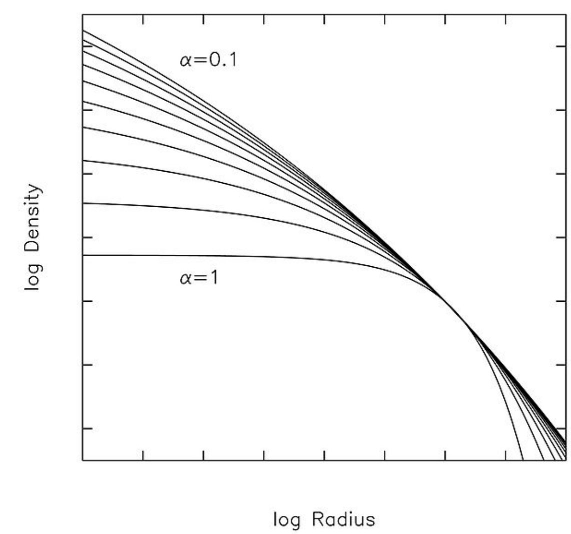




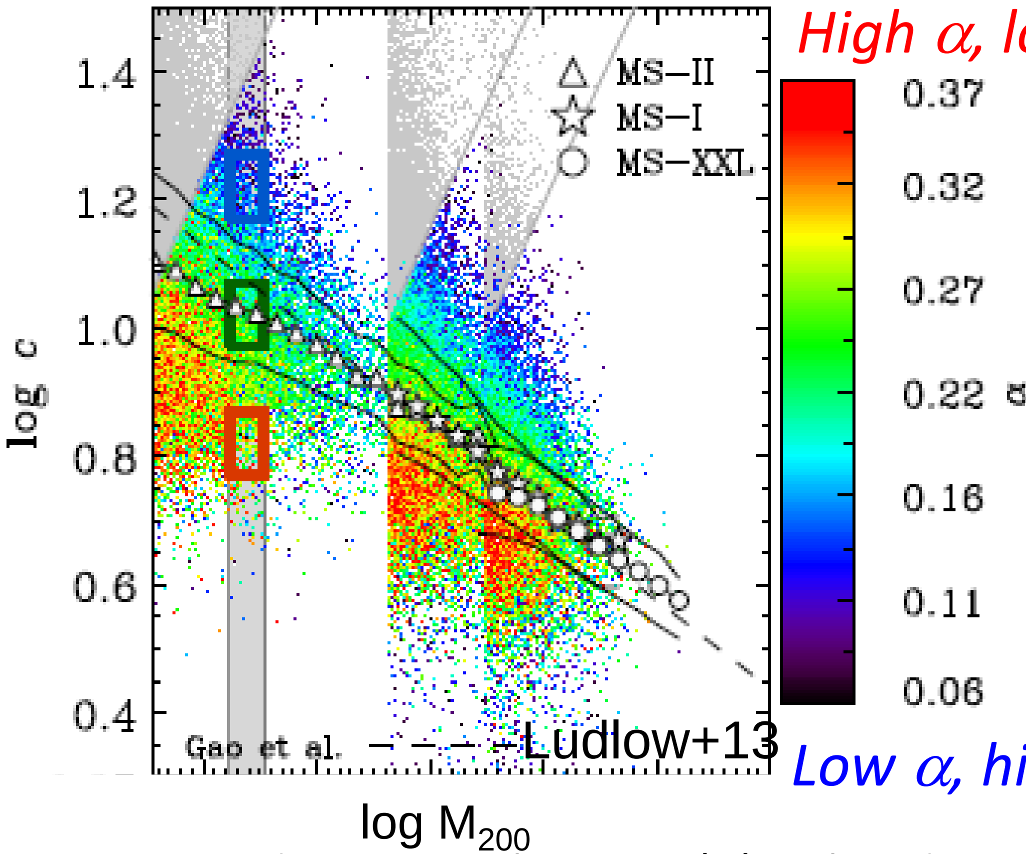
Einasto profile (ρ_s, r_s, α)

$$\frac{d \ln \rho(r)}{d \ln r} = -2\left(\frac{r}{r_s}\right)^{\alpha}$$

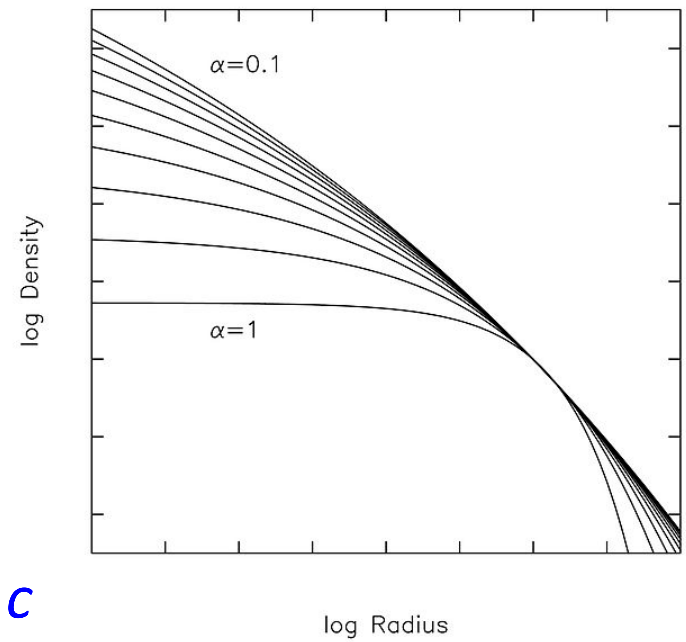
α: degree of curvature



Intrinsic Scatter in c(M): Mass Assembly Histories (MAH)



α: degree of curvature



- Scatter is due to another DoF (α), related to MAH (Ludlow+13)
- Larger or smaller values of α correspond to halos that have been assembled more or less rapidly than the NFW curve
- Clusters with average c_{200} have the NFW-equivalent α ~0.18

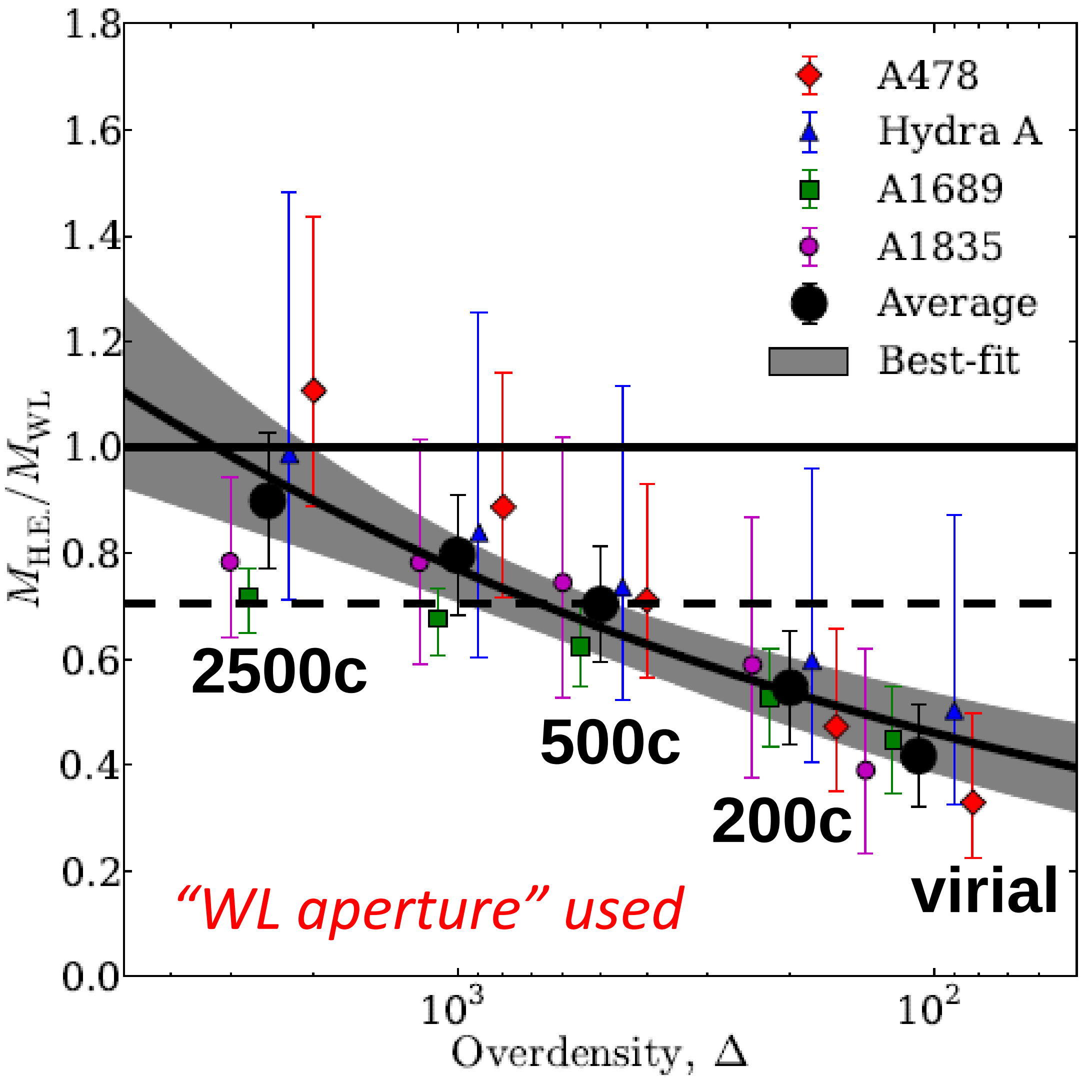
$$\begin{aligned} ds^2 &= a^2(\eta)d\tilde{s}^2 = a^2\tilde{g}_{\mu\nu}dx^\mu dx^\nu \\ &= a^2\left[-(1+2\Psi)d\eta^2 + (1-2\Psi)\left\{d\chi^2 + r^2(\chi)(d\theta^2 + \sin^2\theta d\phi^2)\right\}\right] \end{aligned}$$

$$\delta k^\mu(\lambda) = -\frac{2}{r^2(\lambda)}\int_0^{\lambda_s} d\lambda' \partial^\mu \Psi(\lambda')/c^2 \quad (\mu = \theta, \phi),$$

$$\boldsymbol{\beta} - \boldsymbol{\theta} = \int_{\text{Observer}}^{\text{Source}} d\boldsymbol{\alpha} = \boldsymbol{\alpha}(\chi_s),$$

$$\boldsymbol{\alpha}(\chi_s) = -\frac{2}{c^2}\int_0^{\lambda_s} d\lambda \frac{r(\lambda_s - \lambda)}{r(\lambda_s)} \boldsymbol{\nabla}_\perp \Psi(x(\lambda)); \quad x(\lambda) = x^{(b)}(\lambda) + \delta x(\lambda)$$

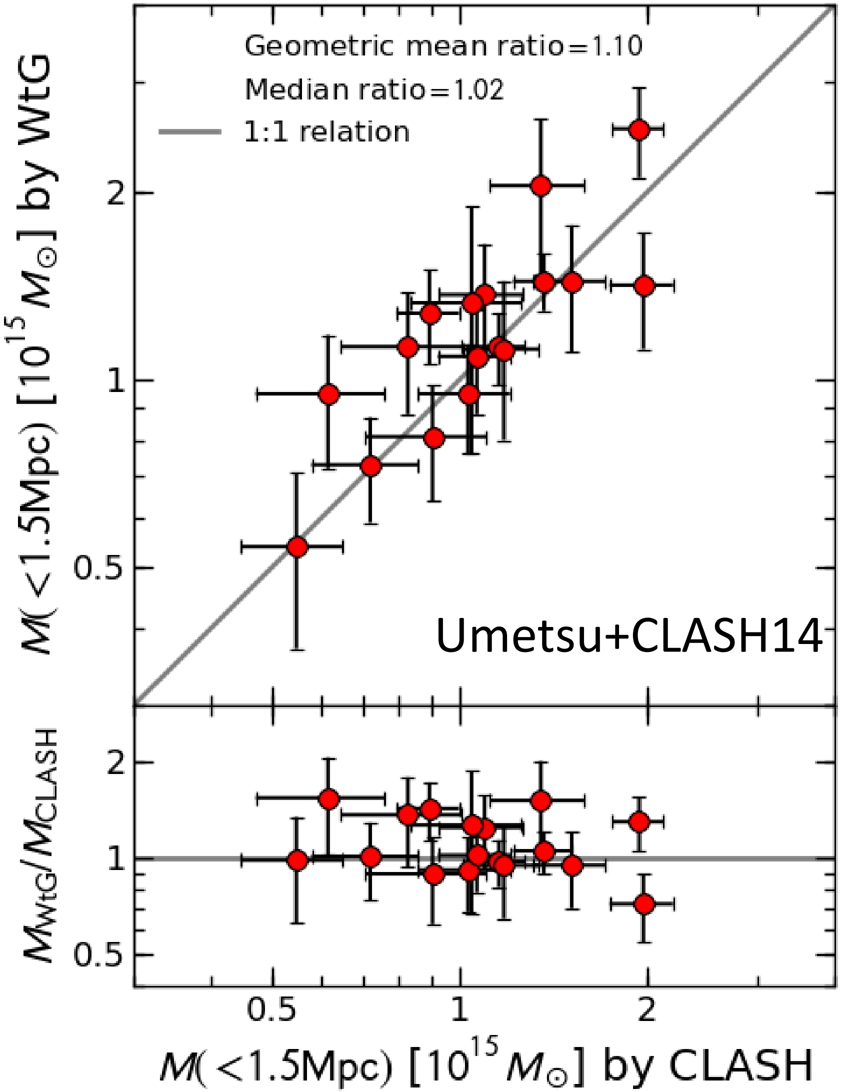
Suzaku-X HSE vs. Subaru WL



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

Okabe, Umetsu et al.14, PASJ, in press (arXiv:1406.3451)

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>)

- $\langle M_{WtG}/M_{CLASH} \rangle = 1.10$
- Median ratio = 1.02

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

No mass dependent bias

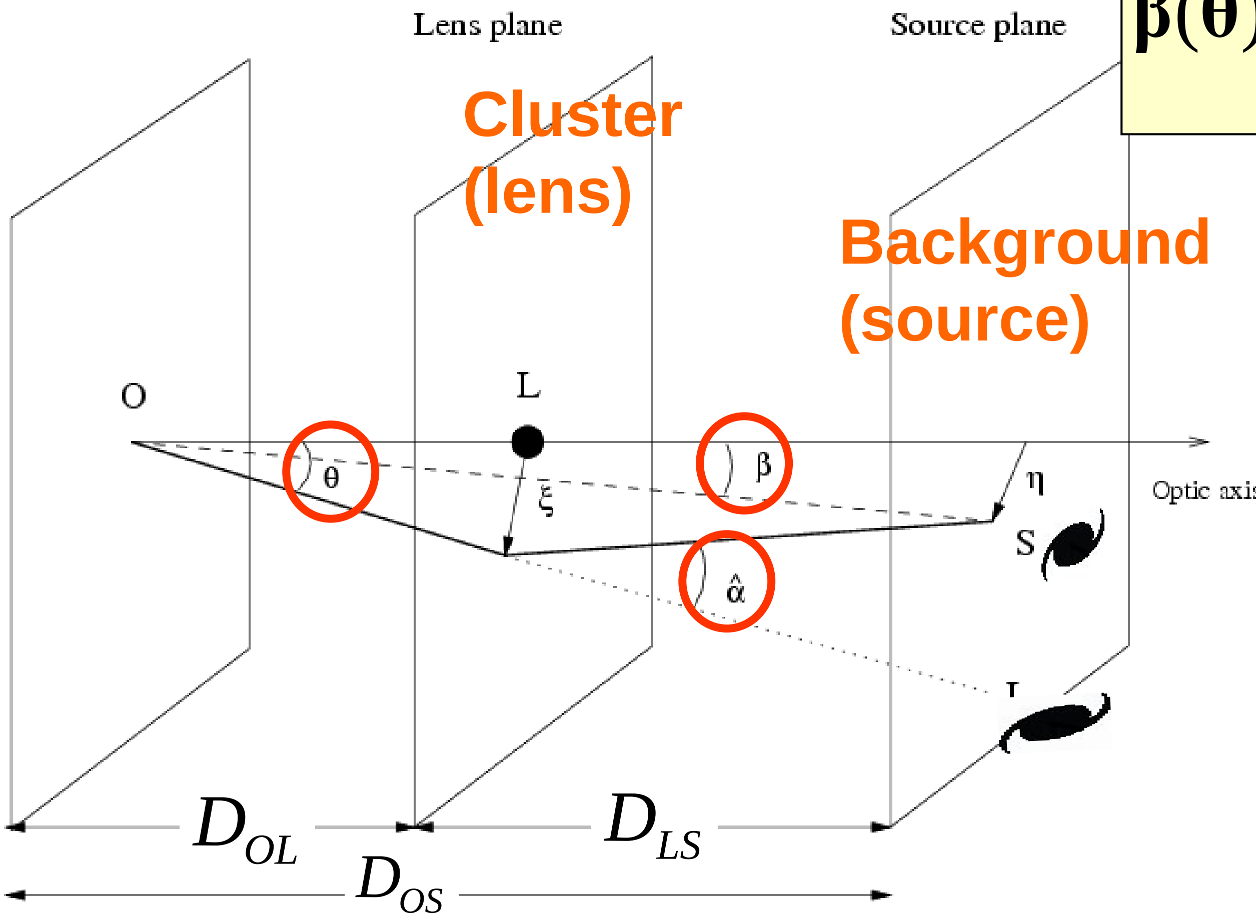
Cluster Lens Equation

Cosmological lens equation + single/thin-lens approximations

β: true (but unknown) source position

θ: apparent image position

$$\boldsymbol{\beta}(\boldsymbol{\theta}) - \boldsymbol{\theta} = \frac{D_{LS}}{D_{OS}} \int \delta\hat{\boldsymbol{\alpha}}(\boldsymbol{\theta})$$

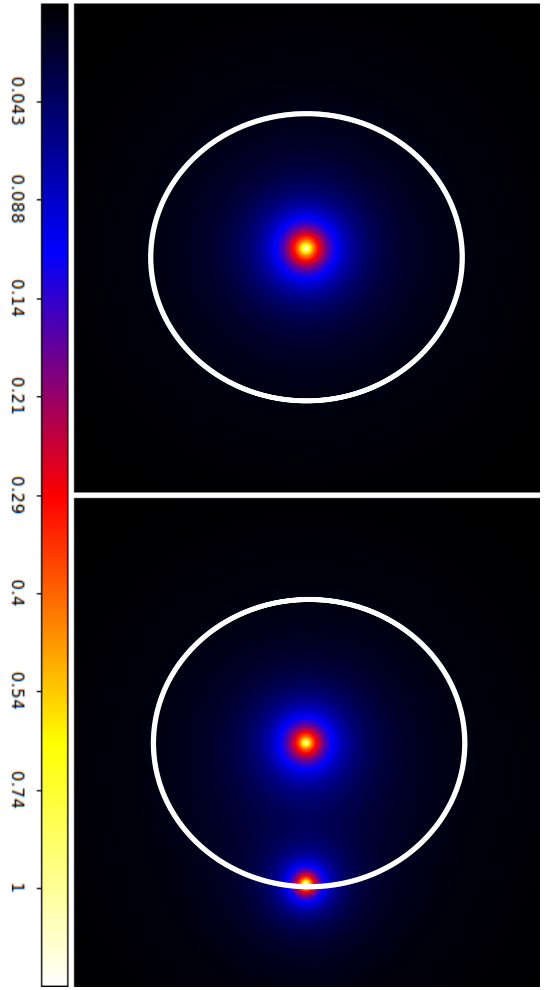


Angular diameter distances:

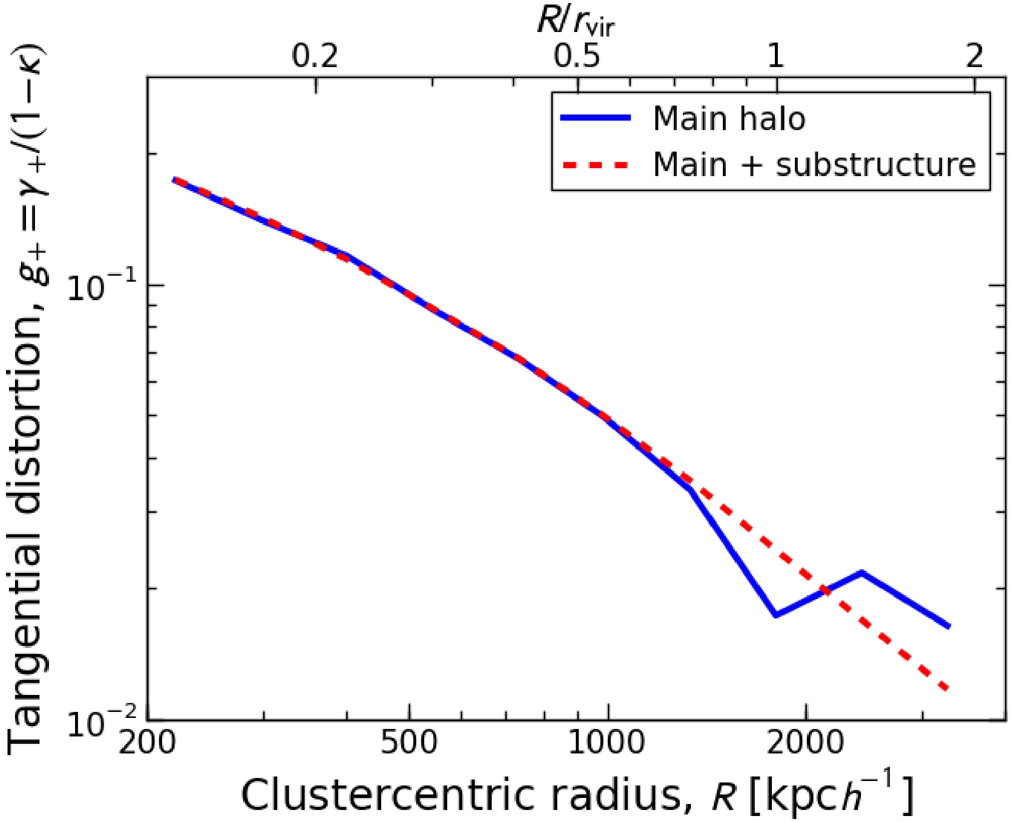
D_{OL}, D_{LS}, D_{OS} ~ $O(c/H_0)$

For a rigid derivation of cosmological lens eq., see, e.g., Futamase 95

Non-local substructure effect



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

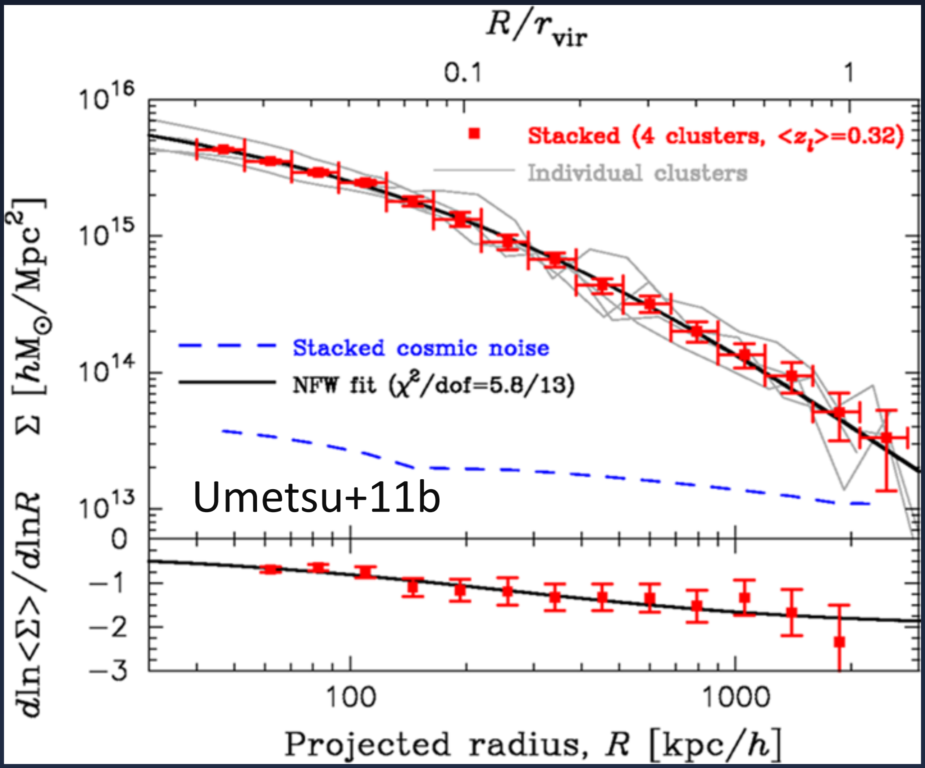


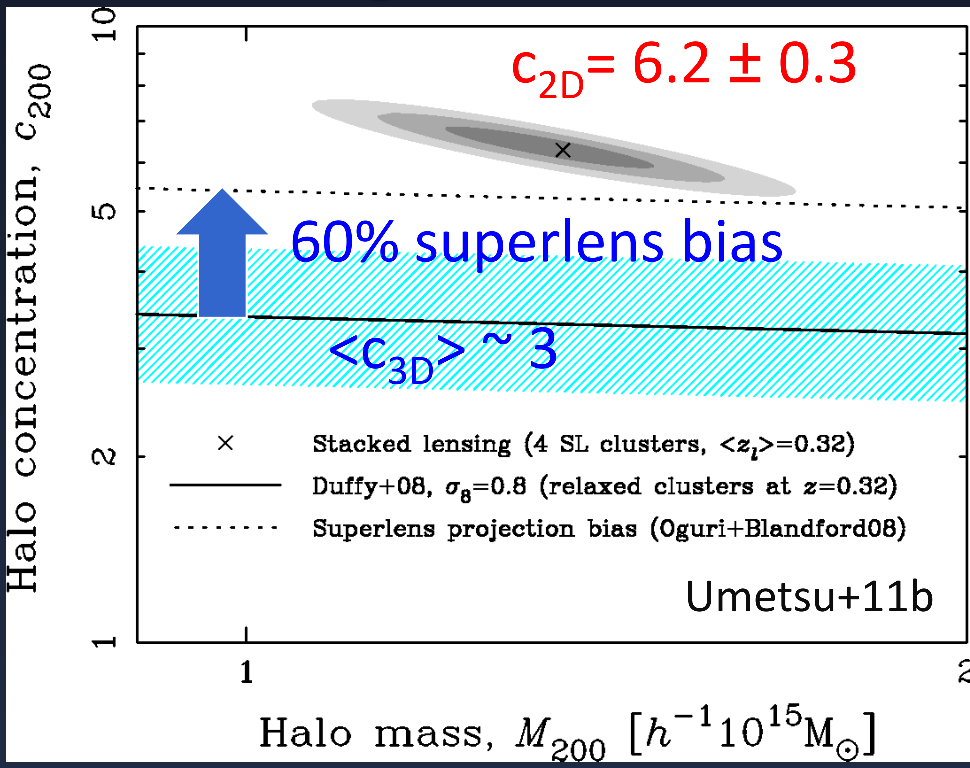
Known ~10% negative bias in mass estimates from tangential-shear fitting, inherent to clusters sitting in substructured field (Rasia+12)

CLASH Objectives & Motivation

$$c_{200c} := r_{200c} / r_s$$

Before CLASH (2010), deep-multicolor Strong (*HST*) + Weak (Subaru) lensing data only available for a handful of **strong-lens clusters**

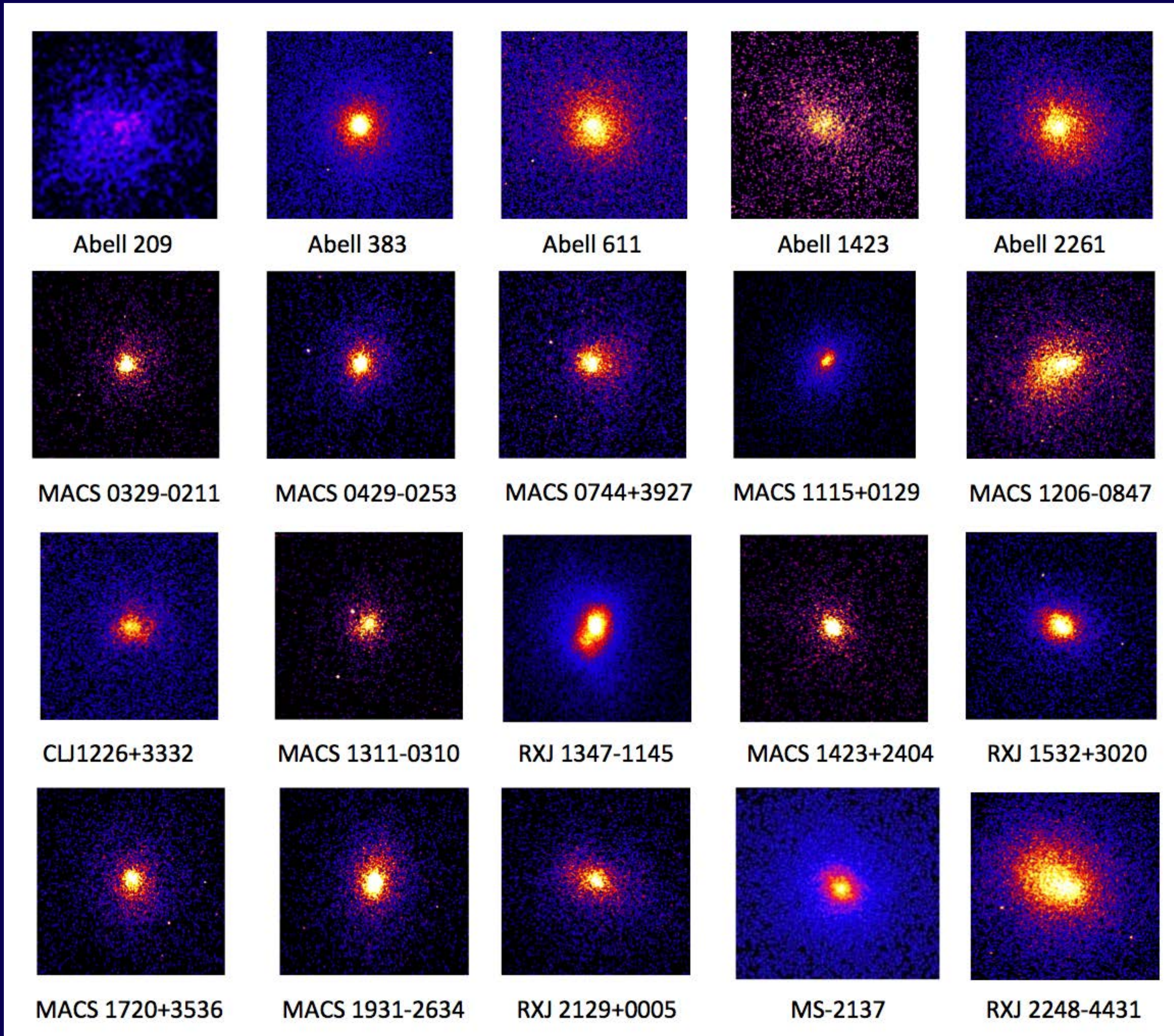


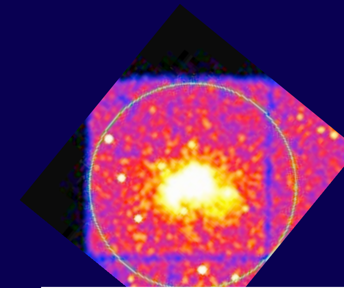


Total mass profile shape: consistent w CDM (self-similar universal profile)

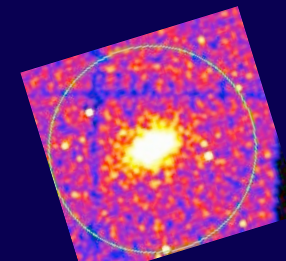
Degree of concentration: maximum superlens correction not enough if $<c_{LCDM}>$~3?

X-ray observations with Chandra and XMM-Newton Satellites

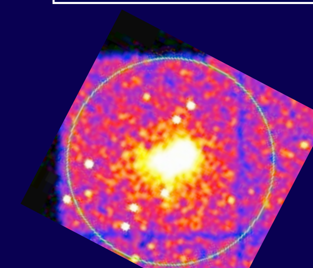




MACS 0717+3745



RXJ 0647+7015

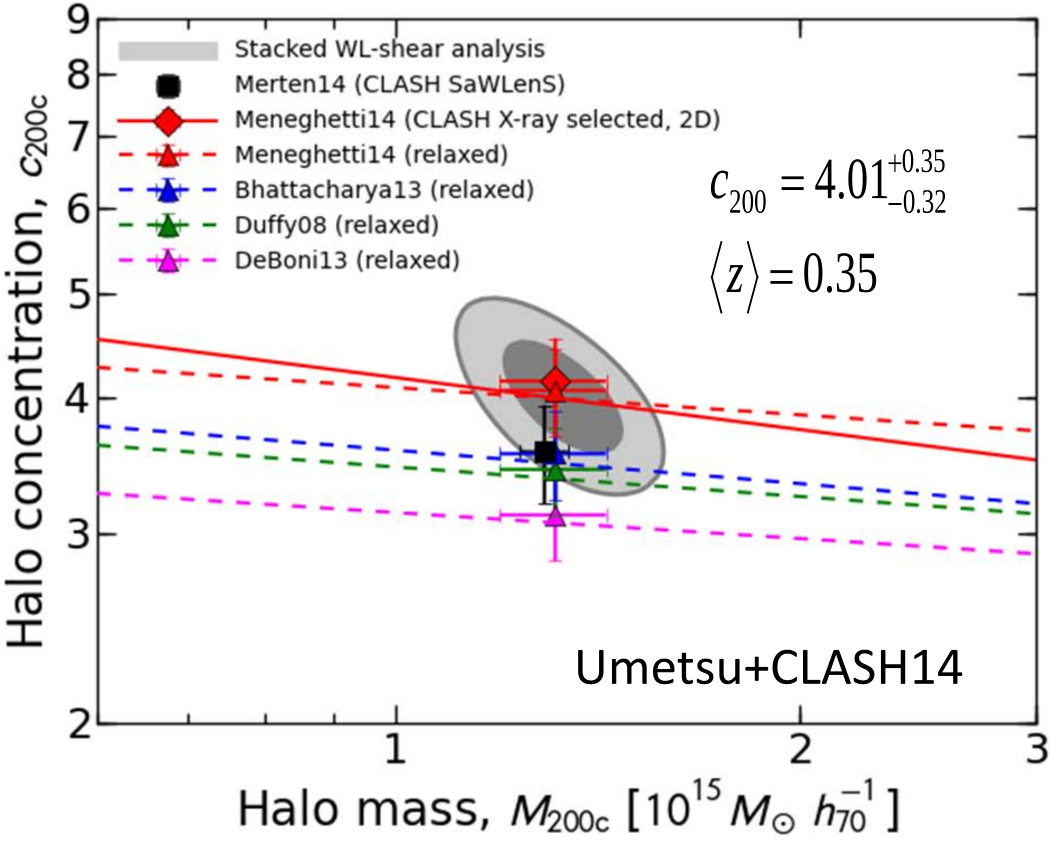


MACS 1149+2223

All have
T_x > 5 keV

X-ray images of 23 of the 25 CLASH clusters. 20 are selected to be “relaxed” clusters (based on their x-ray properties only). 5 are selected specifically because they are strongly lensing $\theta_E > 30''$

CLASH-WL vs. c-M relations



M14 (CLASH): σ_8=0.82

Bhat13: σ_8=0.8

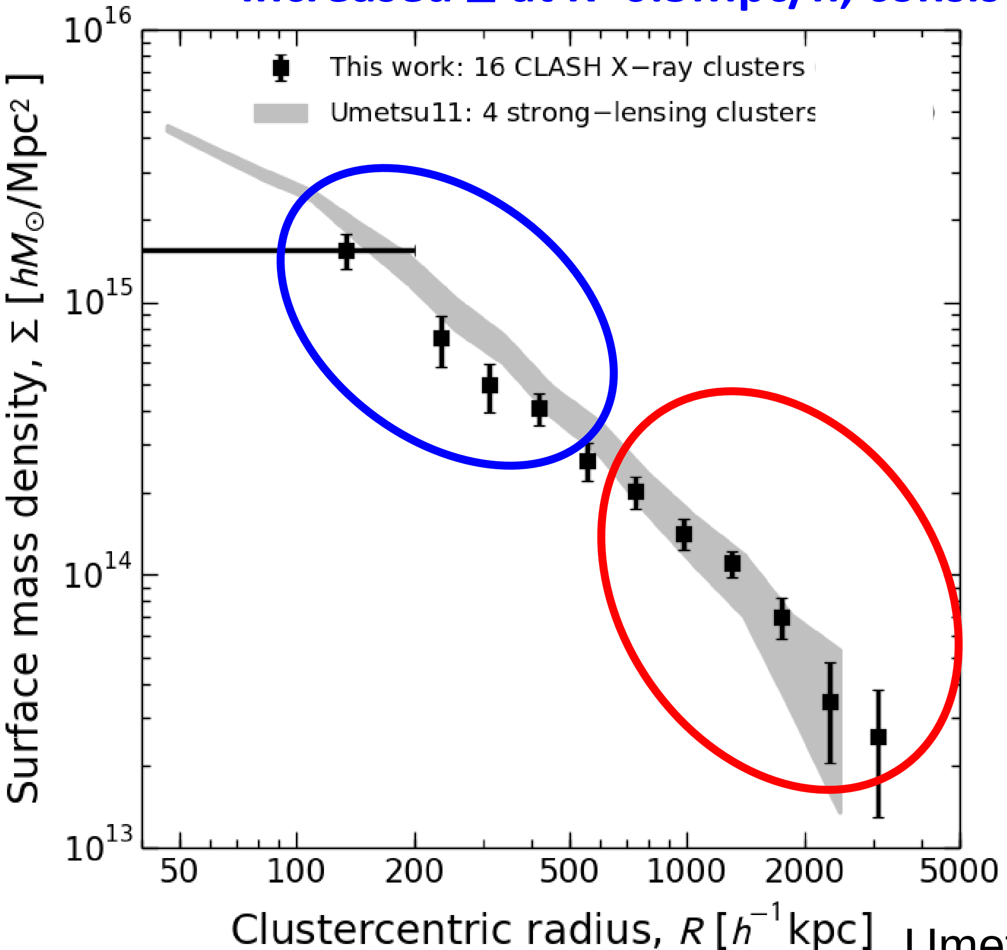
Duffy08: σ_8=0.8

DeBoni13: σ_8=0.78

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

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

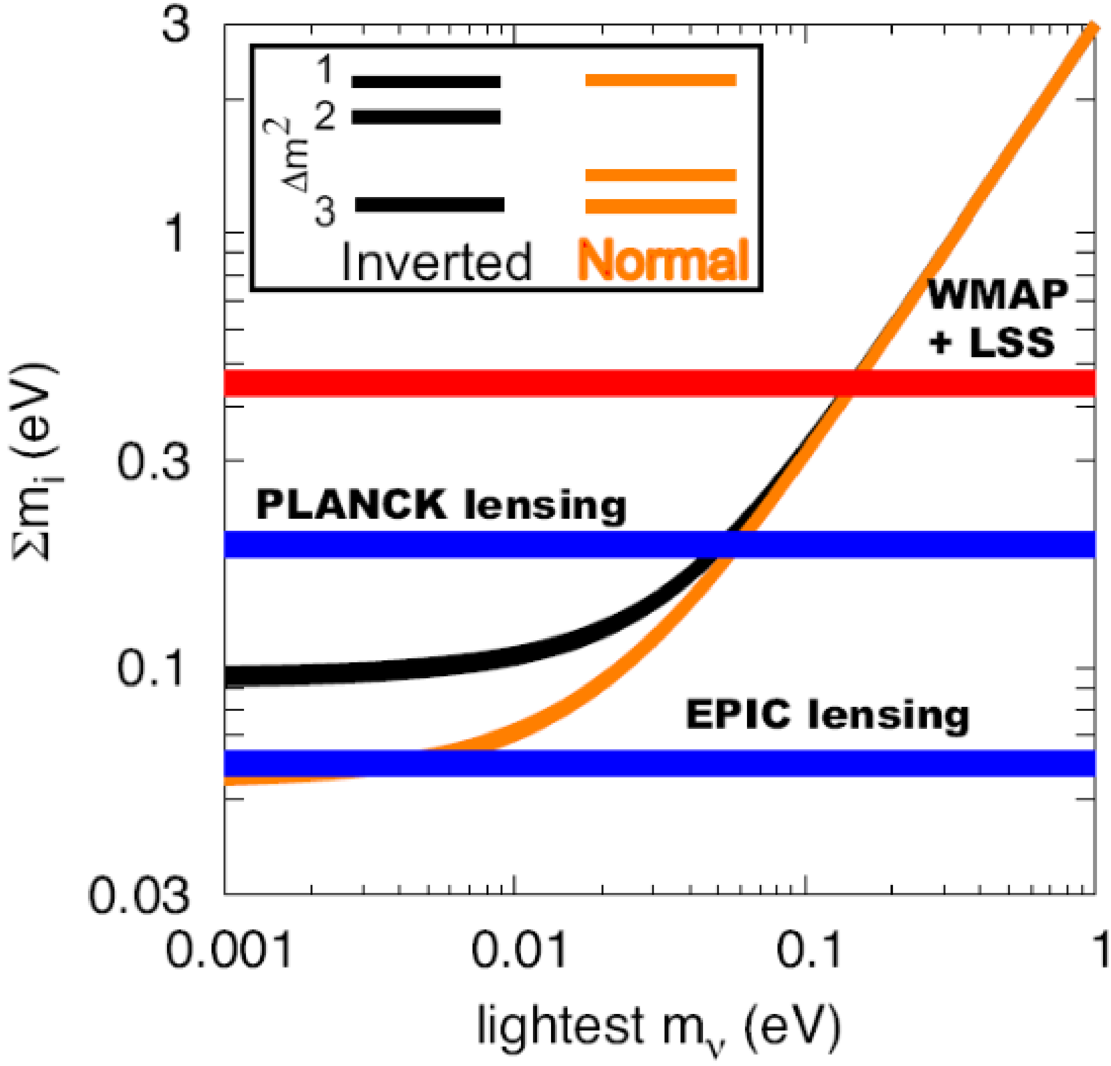
- M_{200} = 1.3e15M_{sun}
- c_{200} = 4.0
- θ_E ~ 15” (z_s=2)
- ν=3.8 (b_h~9)

Umetsu11b sample

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

Umetsu+14, ApJ, accepted (arXiv:1404.1375)

Neutrino Mass Hierarchy from Cosmology



Future Cosmological Constraints on Neutrino Hierarchy

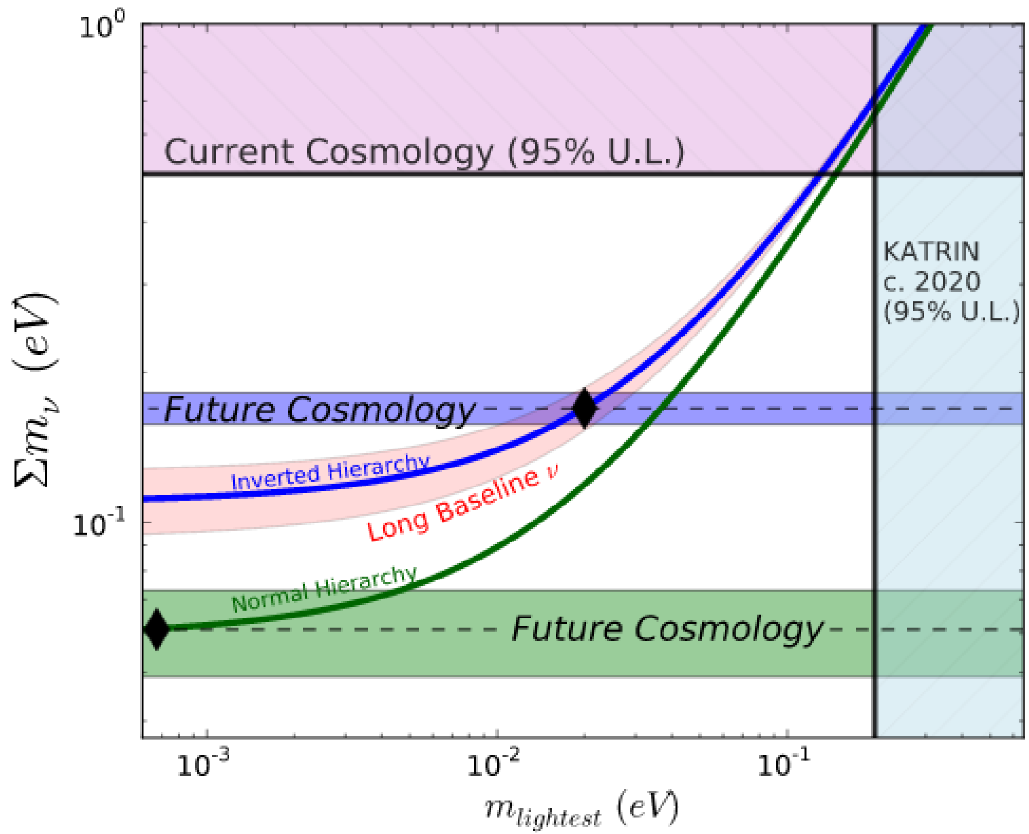
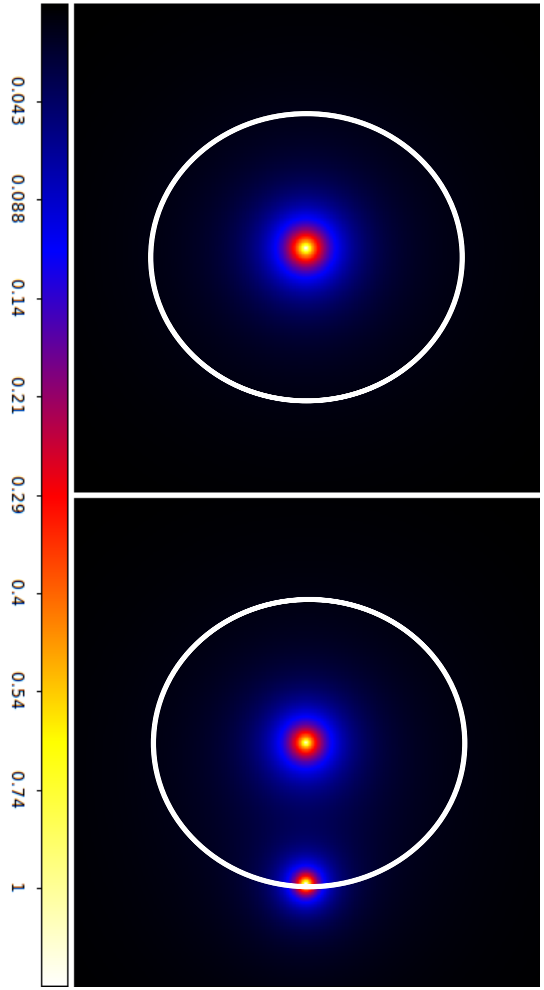
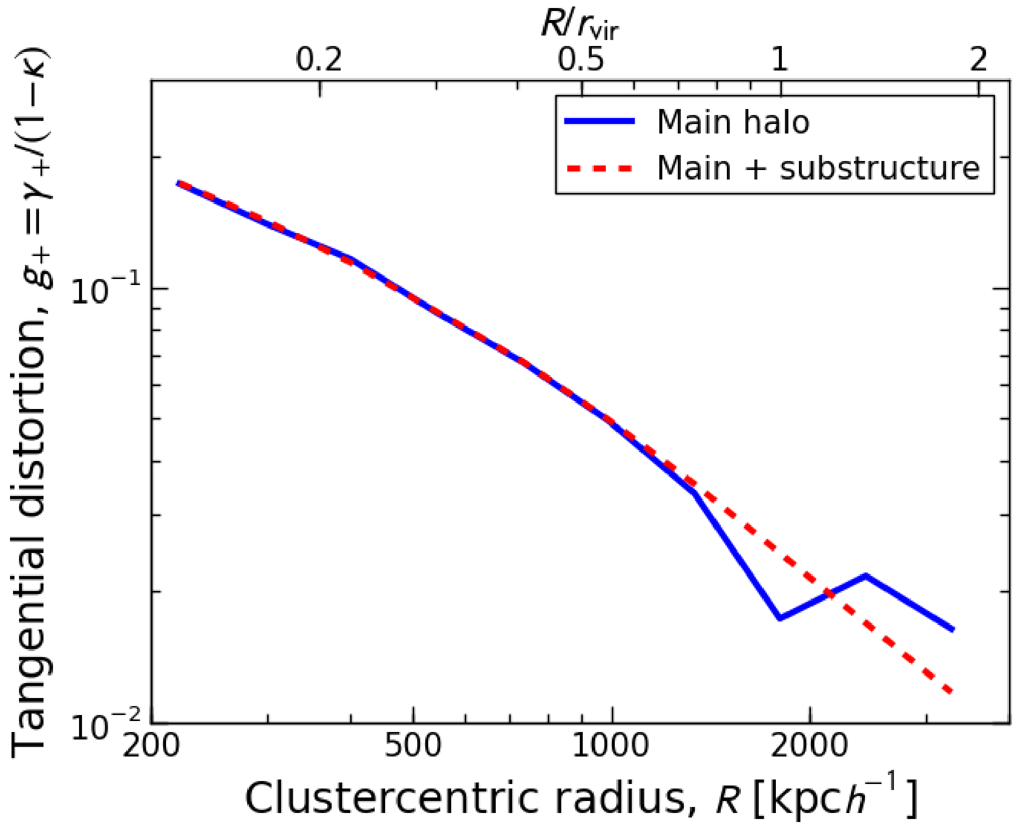


Figure 1-2. *Shown are the current constraints and forecast sensitivity of cosmology to the neutrino mass in relation to the neutrino mass hierarchy. In the case of an "inverted hierarchy," with an example case marked as a diamond in the upper curve, future combined cosmological constraints would have a very high-significance detection, with 1σ error shown as a grey band. In the case of a normal neutrino mass hierarchy with an example case marked as diamond on the lower curve, future cosmology would detect the lowest $\sum m_\nu$ at a level of $> 4\sigma$.*

Shear: non-local substructure effect



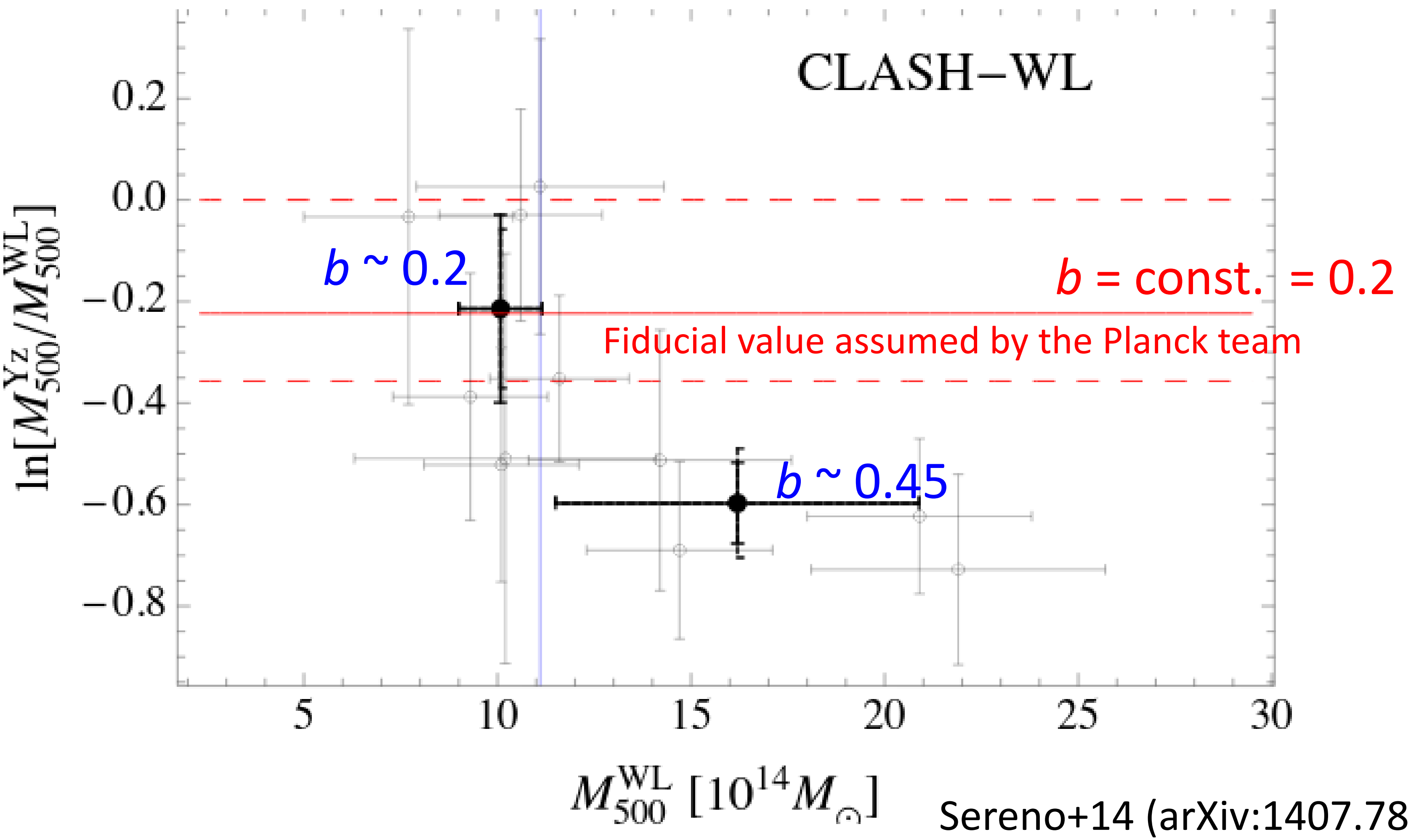
Substructure in outskirts of the main halo, modulating $\Delta\Sigma(R) = \Sigma(< R) - \Sigma(R)$



Known 5-10% negative bias in mass estimates from tangential-shear fitting, inherent to rich clusters (Rasia+12)

Comparison with *Planck* Masses

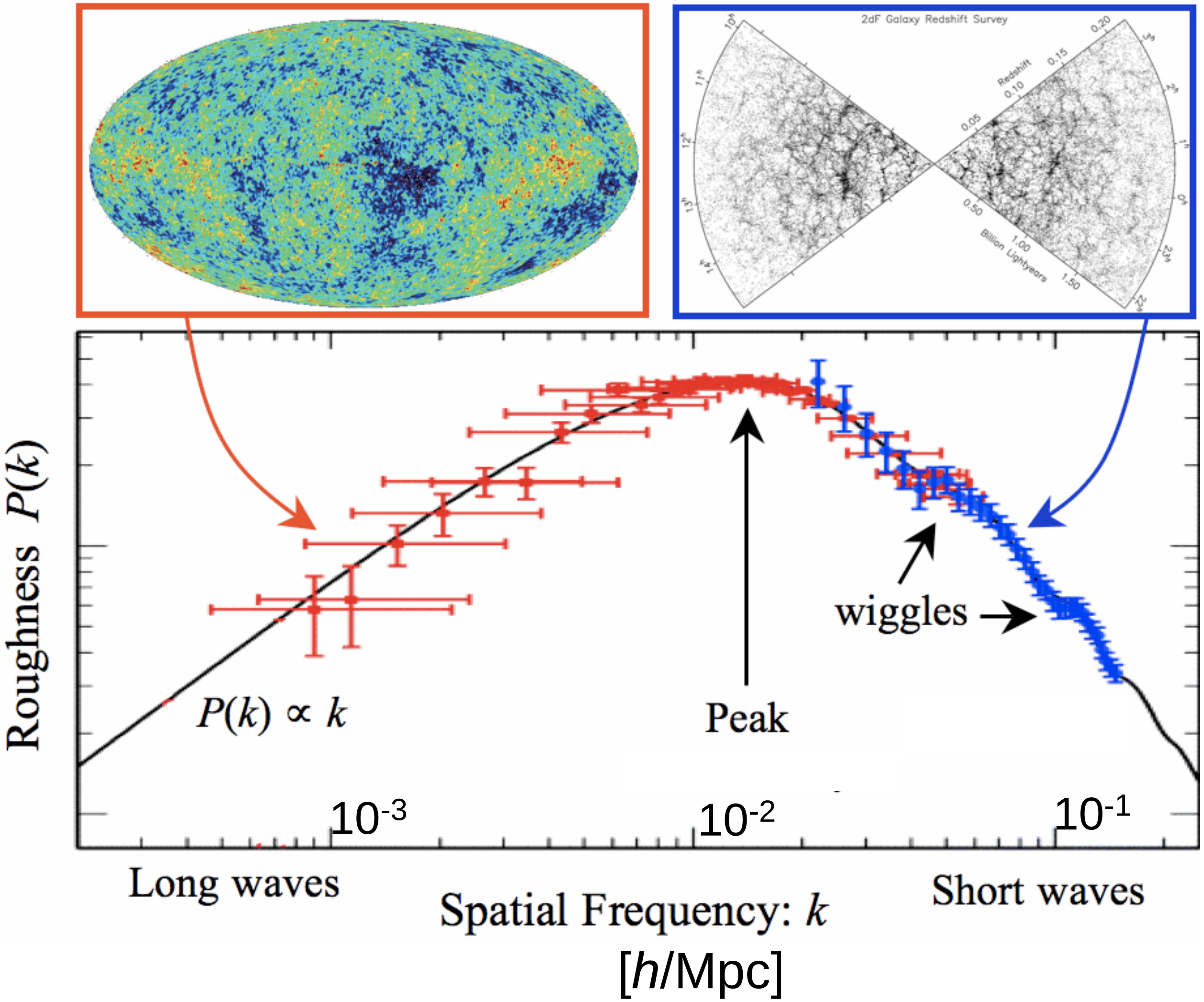
Mass-dependent bias (20-45%) observed for *Planck* mass estimates



Sereno+14 (arXiv:1407.7869)

ΛCDM: Standard Structure Formation Paradigm

Matter power-spectrum density, *P*(*k*)



$$\delta(\mathbf{x}) := \frac{\rho - \bar{\rho}}{\bar{\rho}} = \int \frac{d^3k}{(2\pi)^3} \tilde{\delta}(\mathbf{k}) e^{i\mathbf{k}\cdot\mathbf{x}}$$

$$\left\langle \tilde{\delta}(\mathbf{k}) \tilde{\delta}(\mathbf{k}') \right\rangle = (2\pi)^3 \delta_D^3(\mathbf{k}+\mathbf{k}') P(k)$$

How about nonlinear small scales, λ<10Mpc/*h*?