1. **Introduction**: Galaxy Clusters
2. **Cluster Weak Lensing**: Shear & Magnification
3. **Cluster Lensing Results from CLASH**
4. **Intracluster Dark Matter Equation of State**
5. **Summary**
1. Introduction

Galaxy Clusters as Cosmological Probe
Clusters of Galaxies

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

Sunyaev-Zel’dovich Effect (SZE)

Clusters: the largest/youngest class of DM halos

Halos = gravitationally-bound objects

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

Cluster counts
\[ \frac{dN(> M_{\text{lim}}, z)}{d\Omega dz} = \int_{M_{\text{lim}}}^{\infty} \frac{dM}{d\Omega dz} \frac{d^2n}{dVdM}(M, z) \]

Rosati+02

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

Halo mass function
\[ \frac{d^2n}{dVdM}(M, z) \propto \exp\left[-\frac{v^2}{2}\right] \]
\[ v \equiv \frac{\delta_c(z)}{\sigma(M, z)} \approx \frac{1.69}{D_+(z)\sigma(M)} \sim 3 \text{ for clusters} \]

Clustering counts are exponentially sensitive to cosmology and cluster mass calibration!
Planck13 CMB vs. Cluster Cosmology

- Planck: $3\sigma$ tension between SZ cluster counts and CMB cosmology
- Assumes $M_{\text{Planck}} / M_{\text{true}} = (1-b) = 0.8$
- Calibrated with XMM hydrostatic masses (Arnaud et al. 2010) + simulations

Suggested explanations:
- **mass bias underestimated** (and no accounting for uncertainties)
- $2.9\sigma$ detection of neutrino masses: $\Sigma m_\nu = (0.58 +/- 0.20)$ eV
  (Planck+WMAPpol+ACT+BAO: $\Sigma m_\nu < 0.23$ 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 $\rho(r)$ from numerical simulations

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

$$\rho(r) = \rho_s f \left( \frac{r}{r_s} \right)$$

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

Cuspy, outwardly-steepening density profiles
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

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

\[
\langle \tilde{\delta}(k) \tilde{\delta}(k') \rangle = (2\pi)^3 \delta^3_D(k + k') P(k)
\]
Halo Bias Factor: $b_h$

Clustering of matter around halos with $M$:

$$
\xi_{hm}(r | M) \equiv \langle \delta_h(x | M)\delta_m(x + r) \rangle
= \frac{\langle \rho_{halo}(r | M) \rangle}{\bar{\rho}} + b_h(M)\xi_{mm}(r)
$$

2h term

Correlated matter distribution (2h term)

Matter correlation function:

$$
\xi_{mm}(r) \equiv \langle \delta_m(x)\delta_m(x + r) \rangle = \int \frac{d^3k}{(2\pi)^3} P(k)e^{ik\cdot r}
$$

$$
\propto \sigma_8^2
$$

Linear halo bias:

$$
b_h(\nu) \approx 1 + \frac{\nu^2 - 1}{\delta_c}
$$

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

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 $\sigma_8$
Gravitational Shear

\[
\gamma = \frac{\partial \partial \Psi}{2}
\]

\[
\partial := \partial_x + i \partial_y = e^{i \phi} \partial_r
\]
Gravitational Magnification

MACSJ1149 (z=0.54)

\[ \kappa = \partial \partial^* \Psi / 2 = \Delta \Psi / 2 \]

\[ \partial := \partial_x + i \partial_y = e^{i\phi} \partial_r \]
Shear and Magnification Effects

**Shear**
- Shape distortion: $\delta e_+ \sim \gamma_+$

**Magnification**
- Flux amplification: $\mu F$
- Area distortion: $\mu \Delta \Omega$

Sensitive to “modulated” matter density

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

Sensitive to “total” matter density

$\mu \approx 1 + 2\kappa; \quad \Sigma_{\text{crit}} \kappa = \Sigma(R)$
Tangential Shear, $\gamma_+$

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

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

$$\Gamma_+_{ij} = (\delta_i \delta_j - \frac{1}{2} \Delta^{(2)} \delta_{ij}) \psi_+$$

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

$$\Gamma_\times_{ij} = (\epsilon_{kj} \partial_i \partial_k - \epsilon_{ki} \partial_j \partial_k) \psi_\times$$

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

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

Sensitive to interior mass

$$\Sigma(R) = \int \delta \rho_m(r) dx_{\parallel}$$

$$\Sigma_{\text{crit}} = \frac{c^2}{4\pi G} \frac{D_S}{D_L D_{LS}}$$
Shear doesn’t see mass sheet

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

\[ \kappa = \Sigma(R) / \Sigma_{\text{crit}} \]

\[ \gamma_+ = \Delta \Sigma_+(R) / \Sigma_{\text{crit}} \]

- 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:

\[ \gamma \] remains unchanged by \[ \kappa \rightarrow \kappa + \text{const.} \]
Combining Shear and Magnification

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

Tangential distortion
Inverse magnification

\[
\kappa = \frac{\kappa(< R) - \kappa(R)}{1 - \kappa(R)},
\]

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

\[
L(\kappa) = L_g(\kappa | g_+) L_\mu(\kappa | \mu)
\]

- Mass-sheet degeneracy broken
- Total statistical precision improved by \(\sim 20-30\%\)
- Calibration uncertainties marginalized over:

\[
c = \{ \langle W \rangle_s, f_{W,s}, \langle W \rangle_\mu, \bar{\mu}, s_{\text{eff}} \}.
\]
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

Umetsu+11a $c_{2D} = 6.2 \pm 0.3$

Umetsu+11b 60% superlens bias $<c_{3D}> \sim 3$

Total mass profile shape: consistent w self-similar NFW (cf. Newman+13; Okabe+13)
Degree of concentration: predicted superlens correction not enough if $<c_{\Lambda CDM}>\sim 3$?
CLASH Objectives & Motivation

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

Cluster mass profiles from Hubble+Subaru lensing

- Strong lensing
- Weak lensing

Surface mass density, \( \Sigma \) [\( h M_\odot / \text{Mpc}^2 \)]

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Redshift</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1689</td>
<td>0.183</td>
</tr>
<tr>
<td>A1703</td>
<td>0.281</td>
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<tr>
<td>A370</td>
<td>0.375</td>
</tr>
<tr>
<td>Cl0024+1654</td>
<td>0.395</td>
</tr>
</tbody>
</table>

Halo concentration, \( c_{200} \)

Halo mass, \( M_{200} [h^{-1} 10^{15} M_\odot] \)

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

Degree of concentration: predicted superlens correction is just enough if \( <c_{\text{LCDM}}>>4 \)

\( c_{2D} = 6.2 \pm 0.3 \)

60% superlens bias

\( <c_{3D}>>4 \)

Stacked lensing (4 SL clusters, \( z_s=0.32 \))

Meneghetti14, \( \sigma_s=0.82 \) (relaxed clusters at \( z_s=0.32 \))

Superlens projection bias (Oguri+Blandford08)
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)

The final HST observation for CLASH was on 9–July–2013 ... 963 days, 15 hrs, 31 min after first obs.
High-resolution space imaging with *HST (ACS/WFC3)* for strong lensing

*SUBARU (S-Cam)* multi-color imaging for wide-field weak
CLASH X-ray-selected Subsample (0.18<z<0.9)

• **X-ray morphology + $T_x$ selection**
  - $T_x > 5$keV ($M_{200} > 5 \times 10^{14} M_{\odot}/h$)
  - Small BCG to X-ray-peak offset, $\sigma_{\text{off}} \sim 10$kpc/$h$
  - Smooth regular X-ray morphology

→ Optimized for radial-profile analysis ($R > 2\sigma_{\text{off}} \sim 20$kpc/$h$)

• **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 ($\sim 2\%$ 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, $<\Delta \Sigma_+(R)>$
- Degree of halo concentration, $<c(M,z)>$

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

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

$$\langle \Delta \Sigma_+ \rangle = \left( \sum_n W_{+n} \right)^{-1} \left( \sum_n W_{+n} \Delta \Sigma_{+n} \right) ,$$

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

with individual “sensitivity” matrix

$$(W_{+n})_{ij} \equiv \Sigma_{c,n}^{-2} (C_{+n}^{-1})_{ij}$$

defined with total covariance matrix

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

With “trace-approximation”, averaging (stacking) is interpreted as

$$\langle \Sigma_{c}^{-1} \rangle = \frac{\sum_n \text{tr}(W_{+n}) \Sigma_{c,n}^{-1}}{\sum_n \text{tr}(W_{+n})} ,$$

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

- **Einasto** (PTE=0.51)
  - Einasto shape parameter $\alpha_E = 0.19+/-0.07$, consistent with NFW curvature ($\alpha_E \sim 0.18$)


Consistent w a family of density profiles for collisionless DM halos
(NFW, truncated variants of NFW, Einasto)
Integrated Constraints on $c(M, z)$

$$\langle c_{200c} \rangle = \frac{\int \! dM \, dz \, N(M, z) \, \hat{c}_{200c}(M, z)}{\int \! dM \, dz \, N(M, z)} \approx \frac{\sum_n \text{tr}(W_n) \, \hat{c}_{200c}(M_n, z_n)}{\sum_n \text{tr}(W_n)}$$

Variance in theory due primarily to different cosmology ($\sigma_8$)

- Meneghetti14: $\sigma_8=0.82$
- Bhattacharya13: $\sigma_8=0.8$
- Duffy08: $\sigma_8=0.796$
- DeBoni13: $\sigma_8=0.776$

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

$M_{200} = (1.34 \pm 0.10) \times 10^{15} M_{\odot} \, h_{70}^{-1}$

$c_{200} = 4.01^{+0.35}_{-0.32}, \langle z \rangle \approx 0.35$

CLASH Weak-Lensing Results (2)

Individual cluster mass profiles:

• Cluster mass profile $\Sigma(R)$ reconstruction
• Spherical mass estimates ($M_{500}$, $M_{200}$, $M_{\text{vir}}$, ...)

from joint shear+magnification WL analysis of all CLASH clusters

Joint Shear + Magnification WL Analysis

**CLASH low mass**

$M_{200} = 6 \times 10^{14} M_{\text{Sun}} / h \ (z = 0.19)$

**CLASH high mass**

$M_{200} = 20 \times 10^{14} M_{\text{Sun}} / h \ (z = 0.45)$

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

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


Internal systematic uncertainty in the overall mass calibration, empirically derived to be about +/- 8%
CLASH: WL vs. X-ray Mass Comparison

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

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

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

Adding “Strong Lensing” to provide tighter constraints on the inner density profile ($R<200\text{kpc}/h$)


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

\[ L(\kappa) = L_g(\kappa \mid g_+)L_\mu(\kappa \mid \mu)L_{\text{SL}}(\kappa \mid M_{\text{proj}}) \]

- CLASH-SL projected mass constraints $M_{\text{proj}}$ from *HST* observations (Zitrin+14, arXiv:1411.1414)
CLASH \( c-M \) relation from SL, WL shear and magnification

**Maximum-likelihood inference**

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

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

\[
\sigma_i^2 = \sigma_{\ln c_i}^2 + A^2 \sigma_{\ln M_i}^2 - 2 \sigma_{\ln c_i} \sigma_{\ln M_i} + \delta_{\ln c,\text{int}}^2
\]

\[
c(M) = (4.1 \pm 0.3) \left( \frac{M}{1.3 \times 10^{15} M_{\odot}} \right)^{-0.191 \pm 0.075}
\]

\[
\delta_{\ln c} < 0.1 \ (68.3\% \ CL)
\]

Fully consistent with LCDM predictions + CLASH selection function

Umetsu+2015, in prep
Average Matter Distribution in and around CLASH Clusters

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

$$\Sigma(R \mid M) = \int \bar{\rho} \xi_{\text{hm}}(r \mid M) dx_{||}$$

Clustering of matter around halos with $M$:

$$\xi_{\text{hm}}(r \mid M) = \frac{\langle \rho_{\text{halo}}(r \mid M) \rangle}{\bar{\rho}} + b_{h}(M) \xi_{\text{mm}}(r)$$
CLASH Averaged Total Mass Profile vs. LCDM

Tinker10+WMAP7 prior: $b_h(M,z) = 9.0 \pm 0.4$

$-d \ln \rho(r \rightarrow 0)/d \ln r = 1.16 \pm 0.16$

$c_{200} = 3.81^{+0.33}_{-0.31}$
CLASH Averaged Total Mass Profile vs. LCDM

Projected mass density, $\Sigma \left[ hM_\odot/Mpc^2 \right]$

$R/r_{\text{vir}}$

HST strong lensing

Subaru weak lensing

WMAP7 prior: $b_h = 12.2 \pm 7.7$

Clusters

Averaged

Halo model ($M_{200c}, c_{200c}, b_h, r_t$)

Convergence, $\kappa$

Clustercentric radius, $R \left[ h^{-1} \text{kpc} \right]$

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.

Dynamical analysis with 600 members (Biviano et al. 2013)
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 \textit{HST+Subaru} (Umetsu+2012)
  – Galaxy kinematics with VLT/VIMOS (Biviano+2013)
• Test made possible by our high-quality CLASH data for an equilibrium cluster:

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

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

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

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

\[
\rho(r) = \frac{1}{8\pi G} \frac{m'}{r^2},
\]

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

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

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|.

Framework
DM EoS from Kinematics+Lensing

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

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

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

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

\[ m_L(r) \equiv \frac{r^2}{G} \Phi'_l = \frac{1}{2} [m_K(r) + m(r)]. \]

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

Consistent with the pressureless assumption of DM fluid, $w=0$

Baryonic contribution is $\delta w \sim 10^{-5}$

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

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

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 \( \beta=-d\ln \rho/d\ln r \rightarrow 0 = 1.16 \pm 0.16 \) (NFW: \( \beta=1 \))
  – Einasto degree of curvature, \( \alpha_E=0.190 \pm 0.07 \) (\( n_E=1/\alpha_E \approx 5 \))
  – Average concentration, \( <c_{200}> = 4.01 (+0.35, -0.32) \) at \( <M_{200}>= (1.3+/0.1)10^{15}M_{\odot}, <z>=0.35 \)
  – \( c-M \) scaling relation with \( d\ln c(M)/d\ln M = -0.191 +/- 0.075 \) and intrinsic scatter \( \delta_{inc} < 0.1 \) (68.3%CL)

• Total matter distribution \( <\Sigma(R)> \) 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 \( b_h(\sigma_8/0.81)^2 \approx 9.0 \)
  – Marginal detection of clustering 2h term (\( \approx 1.6\sigma \)) within 2\( r_{vir} \)
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 $<w>=0.00 \pm 0.15 \pm 0.08$ within $R=0.5-2\text{Mpc}$, 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

\[ \Gamma (\sigma_T \text{ amplitude ratio}) \]

\[ z' [\text{mag}] \]

Medezinski, Broadhurst, Umetsu+11
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:

\[ n_{\text{obs}}(>f) = \mu^{-1} n(>\mu^{-1}f) \]

Geometric area distortion

\( n/\mu \)

Broadhurst, Taylor & Peacock 95

Source counts, \( n(>f) \)

Flux limit, \( f \)

Flux amplification

Depletion

Enhancement
“Diversity” of halo density profiles

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

Einasto profile \((\rho_s, r_s, \alpha)\)

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

\(\alpha\): degree of curvature
Intrinsic Scatter in $c(M)$: Mass Assembly Histories (MAH)

- Scatter is due to another DoF ($\alpha$), related to MAH (Ludlow+13)
- Larger or smaller values of $\alpha$ correspond to halos that have been assembled more or less rapidly than the NFW curve
- Clusters with average $c_{200}$ have the NFW-equivalent $\alpha \sim 0.18$
\[ ds^2 = a^2(\eta) d\tilde{s}^2 = a^2 \tilde{g}_{\mu\nu} dx^\mu dx^\nu = a^2 \left[ -(1 + 2\Psi) d\eta^2 + (1 - 2\Psi) \left\{ d\chi^2 + r^2(\chi)(d\theta^2 + \sin^2 \theta d\phi^2) \right\} \right] \]

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

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

\[ \alpha(\chi_s) = -\frac{2}{c^2} \int_0^{\lambda_s} d\lambda \frac{r(\lambda_s - \lambda)}{r(\lambda_s)} \nabla_\perp \Psi(x(\lambda)); \quad x(\lambda) = x^{(b)}(\lambda) + \delta x(\lambda) \]
Suzaku-X HSE vs. Subaru WL

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

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 ($<Y/X> = 1/<X/Y>$)
- $<M_{\text{WtG}}/M_{\text{CLASH}}> = 1.10$
- Median ratio = 1.02

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

No mass dependent bias
Cluster Lens Equation

Cosmological lens equation + single/thin-lens approximations

\[ \beta(\theta) - \theta = \frac{D_{LS}}{D_{OS}} \int \delta\alpha(\theta) \]

\( \beta \): true (but unknown) source position

\( \theta \): apparent image position

Angular diameter distances:

\( D_{OL}, D_{LS}, D_{OS} \sim O(c/H_0) \)

For a rigid derivation of cosmological lens eq., see, e.g., Futamase 95
Non-local substructure effect

A substructure at $R \sim r_{\text{vir}}$ of the main halo, modulating

\[ \Delta \Sigma(R) = \Sigma(< R) - \Sigma(R) \]

Known $\sim 10\%$ negative bias in mass estimates from tangential-shear fitting, inherent to clusters sitting in substructured field (Rasia+12)
CLASH Objectives & Motivation

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

![Graphs showing mass profiles and concentration ratios](image)

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

**Degree of concentration:** maximum superlens correction not enough if $\langle c_{\text{LCDM}} \rangle \sim 3$?
X-ray observations with Chandra and XMM-Newton Satellites

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abell 209</td>
<td><img src="image1" alt="Abell 209" /></td>
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<tr>
<td>Abell 383</td>
<td><img src="image2" alt="Abell 383" /></td>
</tr>
<tr>
<td>Abell 611</td>
<td><img src="image3" alt="Abell 611" /></td>
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<tr>
<td>Abell 1423</td>
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<tr>
<td>Abell 2261</td>
<td><img src="image5" alt="Abell 2261" /></td>
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<tr>
<td>MACS 0329-0211</td>
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<td>MACS 0429-0253</td>
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</tr>
<tr>
<td>MACS 0744+3927</td>
<td><img src="image8" alt="MACS 0744+3927" /></td>
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<td>MACS 1720+3536</td>
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<td>MACS 1931-2634</td>
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<td>MS-2137</td>
<td><img src="image19" alt="MS-2137" /></td>
</tr>
<tr>
<td>RXJ 2248-4431</td>
<td><img src="image20" alt="RXJ 2248-4431" /></td>
</tr>
</tbody>
</table>

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 $\theta_E > 30''$. All have $T_x > 5$ keV.
At low $M_{200c}$, X-ray selection picks up clusters with higher concentrations (Meneghetti+14)
Comparison with pre-CLASH results

- $c_{200}$ vs $\theta_E$ relation, consistent with triaxial CDM halos (Oguri+12)
- Similar $\nu$ (MAH), similar $\Sigma$ in outskirts (Diemer & Kravtsov 14)
- Increased $\Sigma$ at $R<0.5\text{Mpc/h}$, consistent with orientation bias (Gao+12)

CLASH X-ray-selected sample
- $M_{200} = 1.3\times 10^{15}\,M_{\odot}$
- $c_{200} = 4.0$
- $\theta_E \sim 15''$ ($z_s = 2$)
- $\nu = 3.8$ ($b_h \sim 9$)

Umetsu11b sample
- $M_{200} = 1.7\times 10^{15}\,M_{\odot}$
- $c_{200} = 6.1$
- $\theta_E \sim 36''$ ($z_s = 2$)
- $\nu = 4.1$ ($b_h \sim 11$)
Neutrino Mass Hierarchy from Cosmology
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 $1\sigma$ 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

Fiducial value assumed by the Planck team
$$\Lambda \text{CDM: Standard Structure Formation Paradigm}$$

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

How about nonlinear small scales, \( \lambda < 10 \text{Mpc}/h \)?

\[
\delta(x) := \frac{\rho - \bar{\rho}}{\bar{\rho}} = \int \frac{d^3k}{(2\pi)^3} \tilde{\delta}(k) e^{ik \cdot x} \\
\langle \tilde{\delta}(k) \tilde{\delta}(k') \rangle = (2\pi)^3 \delta_D^3(k + k') P(k)
\]