Probing the Dark Matter Density Profile by Galaxy Cluster Gravitational Lensing

Keiichi Umetsu (梅津敬一), ASIAA
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Collaborators (this talk)

Tom Broadhurst (Tel Aviv U., Israel)
Elinor Medezinski (Tel Aviv U., Israel)
Adi Zitrin (Tel Aviv U., Israel)
Yoel Rephaeli (Tel Aviv U., Israel)
Nobuhiro Okabe (ASIAA, Taiwan)
Sandor Molnar (ASIAA, Taiwan)
Bau-Ching Hsieh (ASIAA, Taiwan)
Masahiro Takada (IPMU, Japan)
Toshifumi Futamase (Tohoku U., Japan)
Masamune Oguri (NAOJ, Japan)
Graham P. Smith (Birmingham U., UK)
1. Equilibrium Density Profile of DM Halos
2. Gravitational Lensing Theory (mostly focused on weak lensing)
3. Cluster Lensing Effects
4. Highlights of Cluster Lensing Constraints on the DM Halo Density Profiles
4. Summary
5. Future Work
1. Equilibrium Density Profile of Dark Matter Halos
**Concordance Structure Formation Scenario**

**Standard Lambda Cold Dark Matter (=LCDM) Paradigm:**
- **Initial conditions**, precisely known from linear theory & CMB\(^+\) data (@ \(z = z_{\text{dec}} \sim 1100\))
- >70% of the current energy density is in the form of mysterious DE.
- ~85% of our *material universe* is composed of DM.
- Use an **N-body simulation** (+linear theory) to study hierarchical structure formation (\(0 < z < 1100\))

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**Figure:**
- WMAP5yr+
  - 74% Dark Energy
  - 22% Dark Matter
  - 4% Atoms
- 2dF Redshift Survey
- Millenium simulation (Springel+ 05)
Nature of CDM Structure Formation

1. **Hierarchical growth**: Non-relativistic (cold) nature of DM
   - bottom up formation of structures in the CDM model
   - smaller objects first form, and merge together into larger systems: i.e., galaxies -> groups -> clusters -> superclusters

2. **Anisotropic collapse**: Collisionless nature of DM
   - any small initial deviation from sphericity of a collapsing cloud gets magnified by tidal forces (e.g., Zel’’dovich 1970; Shen et al. 2006)
   - gravitational collapse proceeds along sequence:
     - Collapse along smallest axis -> planar geometry -> wall
     - Collapse along middle axis -> filament
     - Collapse along longest axis -> triaxial (spheroidal) DM halos

   After having collapsed into a clump, “virialization and emergence” of cosmic object

3. **Void formation**: $\delta \sim -1$ nonlinear structure
   - Under-dense regions, corresponding to density troughs in primordial density fields
Observed Matter $P(k)$ vs. LCDM

$P(k) = A k^{n_s}$ with $n_s \sim 1$

($n_s = 1$: Harrison-Zel'dovich spectrum)

@ $k << k_{eq} \sim 0.01h/Mpc$

Turn-over @ $k \sim k_{eq}$

$P(k) = A k^{(n_s-4)}$ @ $k >> k_{eq}$

due to decay of $\Phi(k)$ on sub-horizon scales in the radiation era

Cosmic mean properties on “large scales” ($r >> 1Mpc/h$) are well explained by $\Lambda$CDM.

How about nonlinear scales ($<1-10Mpc/h$)?

Primordial, $P(k) \sim k$

BAO

Small scales, $P(k) \sim k^{-3}$

Tegmark & Zaldarriaga 2002
Gravitational Growth of Structure: Gravitational Instability

Growth of density perturbations

Gas cooling, radiative process, SF etc.

DM halo formation via gravitational collapse

Overdense regions:
- Hubble flow
- Turn around
- Violent relaxation
- Mass accretion, hierarchical mergers
Tiny density perturbations have evolved into “cosmic web” large scale structure (LSS)
Large Scale Structure and Galaxy Clusters

**N-body simulations**

Study “nonlinear” structure formation in an expanding Universe after the cosmic decoupling epoch (z\sim 1100) governed by the gravity

- **Large Scale Structure**: cosmic structure on scales of \sim 10-50 Mpc/h in mildly-nonlinear regime (\delta \sim 1), representing forming superclusters, low-density voids, filaments of galaxies.

- **Clusters of galaxies**: largest self-gravitating systems (aka, DM halos) with \delta \gg 1, composed of \sim 10^{2-3} galaxies.

\[
\begin{align*}
M_{\text{vir}} & \sim 10^{14-15} M_{\odot} / h \\
R_{\text{vir}} & \sim 1-2 \text{Mpc} / h \Rightarrow t_{\text{dyn}} = 3-5 \text{Gyr} < t_{H} \\
k_B T_{\text{gas}} & \sim 5-10 \text{keV}
\end{align*}
\]
Simulated Clusters of Galaxies

**Galaxy Clusters** – identified as dense nodes of “Cosmic Web”, being building blocks of LSS

Distribution of discrete galaxies ($N=10^{2-3}$)  
Distribution of underlying DM ($\sim$mass)

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From Millennium Simulation  
DM distribution around a forming cluster  
Deep HST image of massive cluster
Unresolved Problem: Equilibrium Density Profile of DM Halos?

- **Theoretical interest:** what is the final state of the cosmological self-gravitating system?
  - Forget cosmological initial conditions but reflect the nature of DM (EoS, collisional nature)?
  - Keep initial memory somehow?

- **Practical importance:** testable predictions for galaxies and galaxy clusters
  - can distinguish the underlying cosmological model through comparison with observations: i.e., galactic rotation curve, gravitational lensing, X-ray/Sunyaev-Zel’dovich effects
Theoretical Difficulties

- Nonlinear and N-body gravitational “relaxation” process
  - Needs numerical simulations
- Cosmological initial conditions
  - Background cosmology (Hubble flow, linear growth rate)
  - Shape and normalization of matter power spectrum, $P(k)=T^2(k)k^{ns}$
- Internal and velocity structures
  - Dynamical friction and tidal disruption of substructures in the central high-density region \(\rightarrow\) Needs high mass/force resolution
  - Velocity anisotropy couples with the density profile via the Jean equation
- Cosmological boundary conditions
  - DM halos are NOT isolated systems
    - Turn around \(\rightarrow\) violent virialization \(\rightarrow\) 2ndary infall, mergers
  - Collisions and mergers of DM halo
  - continuous accretion of matter in outskirts from LSS \(\rightarrow\) needs a wide dynamic range
Theoretical Studies (70’-90’)

- **1970**: Peebles; N-body simulation (N=300).
- **1977**: Gott; secondary infall model \( \rho \propto r^{-9/4} \).
- **1985**: Hoffman & Shaham; predict that density profile around density peaks is \( \rho \propto r^{-(n+3)/(n+4)} \).
- **1986**: Quinn, Salmon & Zurek; N-body simulations (N \( \sim \) 10^4), confirmed \( \rho \propto r^{-(n+3)/(n+4)} \).
- **1988**: Frenk, White, Davis & Efstathiou; N-body simulations (N=323), showed that CDM model can reproduce the flat rotation curve out to 100kpc.
- **1990**: Hernquist; proposed an analytic model with a central cusp for elliptical galaxies \( \rho \propto r^{-1}(r+rs)^{-3} \).

\[
n(k) = \frac{d \ln P(k)}{d \ln k}
\]
Concordance Universal CDM Density Profile:
Navarro-Frenk-White 1997 (NFW) Model

Empirical predictions from cosmological N-body simulations of CDM structure formation: “NFW” universal density profile

— The universal profile fits DM halos that span ~9 orders of magnitude in mass (dwarf galaxies to clusters) regardless of the initial conditions and cosmology.

— Not a single power-law but continuously steepening density profile with radius:
  central cusp slope of $n(r) = -rac{d\ln \rho}{d\ln r} = 1 - 1.5$ (cuspy but shallower than the isothermal body, $n=2$), outskirt slope of $n(r) = 3$

\[
\rho(r) = \rho_s \left(\frac{r}{r_s}\right)^{-1} \left(1 + \frac{r}{r_s}\right)^{-2}
\]

\[c_{\text{vir}} := \frac{r_{\text{vir}}}{r_s}\]

\[r\]

\[r_{\text{vir}} / r_s\]
Latest LCDM Prediction: Duffy+2008

Median C-M relation of N-body CDM halos in the WMAP5 cosmology ($\sigma_8=0.8$)

$$\langle c_{\text{vir}} \rangle = c_0 (1+z)^{-\alpha} \left( \frac{M_{\text{vir}}}{10^{15} M_{\odot}/h} \right)^{-\beta}$$

- $c_0 \sim 5.2$
- $\alpha \sim 0.66$
- $\beta \sim 0.084$

Figure 3: Histogram of halo concentrations in the NFW, Einasto, relaxed and Einasto, relaxed cases.

Duffy et al. 2008
My Observational Approach

• **Target:** massive clusters with $M_{\text{vir}} \approx [5-30] \times 10^{14} M_{\text{sun}}/h$
  
  – Curvature in the density profile shape is more pronounced due to their lower mass concentration: $C_{\text{vir}} \propto M_{\text{vir}}^{-0.1}$
  
  – Best observational constraints are available by virtue of their high total mass.
  
  – Gas cooling and relevant baryonic physical processes are only important at $r < 0.01 \ r_{\text{vir}}$ ($\sim 20\text{kpc}/h$), and hot baryons ($\sim 95\%$ of the baryons in high-mass clusters) trace the gravitational potential field dominated by DM.

• **Method:** weak and strong gravitational lensing
  
  – Depends only on gravity.
  
  – No assumption required about the physical/dynamical state of the system (cf. X-ray and dynamical observations).
  
  – Strong lensing provides tight constraints on the inner mass profile at $r = [0.01 − 0.1] \times r_{\text{vir}}$.
  
  – Weak gravitational Lensing probes the cluster mass out to beyond the virial radius, $r > 0.1 \ r_{\text{vir}}$, in a model independent manner.
Clusters as astrophysical probes:

A1689 (z=0.18)

- **Subaru**
  - Suprime-Cam
  - 34'x27'

- **HST ACS**
  - 3.3'x3.3'

- **Chandra ACIS**

- AMiBA

- VLT/VIRMOS

- Suzaku/XIS
My lecture notes on

“Cluster Weak Gravitational Lensing”

from “Enrico-Fermi Summer School 2008, Italy” found @
arXiv:1002.3952

Theoretical backgrounds and basic concepts on cosmological lensing and observational techniques are summarized in these lecture notes.
Gravitationally-lensed images of background galaxies carry the imprint of $\Phi(x)$ of intervening cosmic structures:

Observable weak shape distortions can be used to derive the distribution of matter (i.e., mass) in a model independent way!!
Gravitational Bending of Light Rays

**Gravitational deflection angle** in the weak-field limit (|Φ|/c²<<1)

Light rays propagating in an inhomogeneous universe will undergo small transverse excursions along the photon path: i.e., **light deflections**

\[
\delta \hat{\alpha} \approx \frac{\delta p_\perp}{p_\parallel} = - \frac{2}{c^2} \nabla_\perp \Psi(x_\parallel, x_\perp) \delta x_\parallel
\]

Small transverse excursion of photon momentum

\[
\hat{\alpha}^{GR} = 2 \hat{\alpha}^{\text{Newton}} \rightarrow \frac{4GM}{c^2r} = 1.75 \left( \frac{M}{M_{\text{sun}}} \right) \left( \frac{r}{R_{\text{sun}}} \right)^{-1}
\]
Lens Equation (for cluster lensing)

**Lens equation** (Cosmological lens eq. + single/thin-lens approx.)

- $\beta$: true (but unknown) source position
- $\theta$: apparent image position

\[
\beta - \theta = \frac{D_{LS}}{D_{OS}} \hat{\alpha}(\theta) \equiv -\nabla \psi(\theta)
\]

Cluster (thin lens)  

Background (source)

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

$D_{OL}, D_{LS}, D_{OS} \sim O(c/H_0)$
Gravitational Lensing in Galaxy Clusters

**Strong lensing**
- Multiple Images
- Arclets

**Weak lensing**
- Weak Shear

Observer | Cluster of Galaxies | Background Galaxy

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Optical Path

Wave Front

Multiple Images Area

*Figure by J.P. Kneib*
Quadrupole Weak Lensing

Differential deflection causes a distortion in “area” and “shape” of an image

Deformation of shape/area of an image

For an infinitesimal source:

\[ \delta \beta_i = A_{ij} \delta \theta_j + O(\delta \theta^2) \]

\[ d^2 \vec{\beta} = A \ d^2 \vec{\theta} \]

A: Jacobian matrix of the lens equation
Effects of Convergence and Shear

Local lens mapping by Jacobian matrix, $A_{ij}$

\[ A_{ij} (\theta) = \delta_{ij} - \psi_{ij} \]

\[ A(\theta) = \begin{pmatrix} 1 - \kappa - \gamma_1 & -\gamma_2 \\ -\gamma_2 & 1 - \kappa + \gamma_1 \end{pmatrix} = (1 - \kappa) \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} - \begin{pmatrix} \gamma_1 & \gamma_2 \\ \gamma_2 & -\gamma_1 \end{pmatrix}. \]
**Physical Meaning of $\kappa$**

**Lensing Convergence**: weighted-projection of mass overdensity

$$\kappa(\theta) \equiv \frac{1}{2} \Delta^{(2)} \psi(\theta) = \int dl \, \delta \rho_m \left( \frac{c^2}{4\pi G} \frac{D_{OS}}{D_{OL} D_{LS}} \right)^{-1} \approx \frac{\Sigma_m(\theta)}{\Sigma_{\text{crit}}}$$

**Critical surface mass density** of gravitational lensing

$$\Sigma_{\text{crit}}(z_L, z_S; \Omega_m, \Omega_\Lambda, H_0) = \frac{c^2}{4\pi G} \frac{D_{OS}}{D_{OL} D_{LS}}$$

**Strong lensing**  \(\kappa \sim 1\)  @ high density regions \((r \sim 100\,\text{kpc/h})\)  probability

**Weak lensing**  \(\kappa \sim 0.1\)  @  \(r \sim [100-2000]\,\text{kpc/h}\)

**Cosmic shear**  \(\kappa \sim 0.01\)  @ Large Scale Structure \((\sim 10\,\text{Mpc})\)

*Note, this is only a crude definition, as lensing also depends on the (trace-free) tidal shear field.*
2x2 shear matrix: describes Quadrupole Shape Distortions (2 DoF)
- Coordinate dependent (cf. Stokes Q,U)
- Spin-2 “directional” quantity
- Observable as an image ellipticity in the WL limit (\(|\kappa|,|\gamma| << 1\))

\[
\Gamma_{ij} = \begin{bmatrix} +\gamma_1 & \gamma_2 \\ \gamma_2 & -\gamma_1 \end{bmatrix} \Leftrightarrow \begin{bmatrix} +Q & U \\ U & -Q \end{bmatrix}
\]

Spin-2 complex shear field
\[
\gamma(\theta) = \gamma_1 + i\gamma_2 \equiv |\gamma| e^{2i\phi_\gamma}
\]
How to measure the gravitational distortion?

**Image quadrupoles:**

\[ Q_{ij} = \langle \Delta x_i \Delta x_j \rangle \]

Quadrupole moments of the object surface brightness around the object center.

**Complex ellipticity,** \( e = e_1 + ie_2 \):

\[ e_1 = \frac{Q_{11} - Q_{22}}{Q_{11} + Q_{22}}, \quad e_2 = \frac{2Q_{12}}{Q_{11} + Q_{22}} \]

In the weak limit \((\kappa, |\gamma| << 1)\):

**Mapping from intrinsic \(\rightarrow\) observed ellipticity**

\[ e^{obs} = e^{(s)} + 2\gamma + O(|\gamma|^2) \]

\( e(s) \): source intrinsic ellipticity

Assuming that background sources have random orientations:

\[ \langle e^{obs} \rangle = 2\gamma + O\left( \frac{\sigma_e}{\sqrt{N}} \right) + O(|\gamma|^2) \]
Weak Shear: Tangential Distortion

Simulated 3x3 degree field (Hamana 02)

Cluster z = 0.77; Arc z = 4.89:
Photo from H. Yee (HST/ACS)

Observable tangential alignment of background galaxy images, probing the underlying gravitational field of cosmic structure
3. Cluster Lensing Effects

① Tangential Gravitational Shear
② Einstein Radius Constraint
③ Magnification Bias
(1) Weak Lensing Tangential Distortion

Measure of tangential coherence of distortions around the cluster (Tyson & Fisher 1990)

Mean tangential ellipticity of BG galaxies ($\gamma_+^r(r)$) as a function of cluster radius; uses typically (1-2) x $10^4$ background galaxies per cluster, yielding typically S/N=5-15 per cluster.

(2) Einstein Radius Constraint

Lensing geometry for an Einstein ring

The apparent size of an Einstein ring yields a tight constraint on the interior projected mass enclosed by the arcs:

$$\theta_E = \sqrt{\frac{4GM_{2D}(\leq \theta_E)}{c^2} \frac{D_{LS}}{D_{OL}D_{OS}}}$$

or

$$\overline{\Sigma_{\text{m}}}(\leq \theta_E) = \frac{c^2}{4\pi G} \frac{D_{OS}}{D_{OL}D_{LS}}$$,

i.e., $\overline{\kappa}(\leq \theta_E) = 1$, or $g_+(\theta_E) = 1$
WL Tangential Distortion + Einstein Radius

Tangential distortion + $\theta_E$ constraint in CL0024+1654 ($z=0.395$)

Constraints on DM Structure Parameters

(3) Weak Lensing Magnification Bias

**Magnification bias**: Lensing-induced fluctuations in the background density field (Broadhurst, Taylor, & Peacock 1995)

\[
\frac{\delta n(\theta)}{n_0} \approx -2(1-2.5\alpha)\kappa(\theta)
\]

with unlensed counts of background galaxies

\[n_0(<m) \propto 10^{\alpha m}\]

When the count-slope is <0.4 (=lens invariant slope), a net deficit is expected.
Example of Magnification Bias Measurement

Count depletion of “red” galaxies in CL0024+1654 (z=0.395)

Distortion of “blue+red” sample

4. Highlights of Cluster Lensing Constraints on the DM Halo Density Profiles
[1] Full Weak + Strong Lensing Analysis

Combining WL ($\sim 10^4$ weakly lensed images) and SL ($\sim 30-100$ strongly lensed images)
→ Probing the mass density profile from 10kpc/h to 2000kpc/h

Results for Abell 1689 ($z=0.183$) and CL0024+1654 ($z=0.395$)

The profile shapes are consistent with CDM (NFW) over the entire cluster, but the degree of concentration is much higher than expected for LCDM.

Weak + strong lensing constraints on CL0024+1654 (z=0.395)

Generalized NFW (gNFW) profile w/ 3 free parameters:

\[ \frac{\rho(r)}{\rho_s} = \frac{1}{(r/r_s)^{\alpha}(1+r/r_s)^{(3-\alpha)}} \]

\[ c_{-2} := \frac{r_{\text{vir}}}{(2-\alpha)r_s} \]

- Central cusp slope \( \alpha < 1 \) at 68.3%CL from the combined strong and weak lensing constraints – yet consistent with NFW.
- Cored profile (\( \alpha \sim 0 \)) is preferred (cf. Tyson et al. 1998; CDM crisis)
- Note CL0024 is the result of a line-of-sight collision of 2 similar-mass clusters, viewed approximately 2-3Gyr after impact (see Umetsu et al. 2010, ApJ in press)

“WL distortion + Einstein-radius constraint” (left) vs. “WL magnification bias” (right) in 4 high-mass clusters:

Observed curves are similar in form, well described by CDM-consistent NFW profiles

Taking into account an orientation bias correction of +18\%, discrepancy is still 4σ. With a 50\% bias correction, it represents a 3σ deviation (BUM+2008)


Results and Implications?

**Results:**
- **BUM+2008:** $<C_{\text{vir}}>=10\pm1$ for $<M_{\text{vir}}>=1.25\times10^{15} \text{ M}_{\odot}/h$
- **Oguri+2009:** $<C_{\text{vir}}>\sim8$; larger the $\theta_E$, higher the concentration
- Both found a significant **over-concentration** w.r.t. LCDM, $<C_{\text{vir}}>=5\pm1$, even after correcting for the selection/orientation bias (+50% at most)

$\rightarrow$ **Clusters formed earlier (z>~1) than expected (z<~0.5)?**

**Possible Solutions:**
- Accelerated growth factors of density perturbation for a generalized DE Equation-of-State (e.g., Sadeh & Rephaeli 2008)
- Non Gaussianity in the primordial density perturbation to advance cluster formation (e.g., Matthis, Diego, & Silk 2004)

*Nevertheless, detailed SL modeling (i.e., HST data!!) is needed for accurate determination of halo concentration, and hence for a stringent test of LCDM*
Stacked Cluster Weak Lensing Analysis

Stacking WL distortion profiles of an “unbiased” sample of clusters
→ less sensitive to substructures/asphericity of individual clusters

\[ M < 6 \times 10^{14} M_{\odot}/h \ (N=10) \]

\[ M > 6 \times 10^{14} M_{\odot}/h \ (N=9) \]

SIS rejected @6 and 11 σ levels (Okabe, Takada, Umetsu+ 10, arXiv:0903.1103)
C-M Relation: Observations vs. Theory

Subaru WL (19 clusters)

Steeper trend than LCDM theory

Stacked WL results

Okabe, Takada, Umetsu+2010

LCDM theory

Duffy+08

Duffy+ (2008)

NFW, Einasto

NFW, relaxed

Einasto, relaxed

Relaxed, z = 0.1

Schmidt & Allen (2007)

Buote et al. (2007)
Summary

• To date, detailed full mass profiles $\Sigma_m(r)$ have been measured for several clusters (A1689, CL0024, A1703 by our group) from joint weak + strong lensing analysis, and show a continuously steepening radial trend, consistent with the collisionless CDM model.

• Such a joint measurement is so far limited by the availability of deep, high-resolution space-telescope (HST/ACS) data.

• The exact cusp (1-1.5?) and outer (3-4?) slopes are yet to be determined from a larger sample of clusters.

• Massive clusters with strong-lensing based Einstein-radius measurements (N~10 so far) show higher-than-expected mass concentrations, indicating a tension with the standard LCDM model.

• Statistical stacked weak lensing analysis is very promising and complementary to joint strong+weak lensing analysis, but is yet insensitive to the inner profile. This results in a (noise-induced) correlation between $(M_{\text{vir}}, C_{\text{vir}})$. 
5. Future Work
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.

WFC3 (UVIS + IR) and ACS will be used to image 25 relaxed clusters in 14 passbands from 0.22 - 1.6 microns. Total exposure time per cluster: 20 orbits.

Clusters chosen based on their smooth and symmetric x-ray surface brightness profiles. Minimizes lensing bias. All clusters have $T > 5$ keV with masses ranging from $\sim 5$ to $\sim 30 \times 10^{14} M_\odot$. Redshift range covered: $0.18 < z < 0.90$.

Multiple epochs enable a $z > 1$ SN search in the surrounding field (where lensing magnification is low).

<table>
<thead>
<tr>
<th>Marc Postman (P.I.)</th>
<th>Megan Donahue</th>
<th>Dani Maoz</th>
<th>Stella Seitz</th>
</tr>
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<tr>
<td>Matthias Bartelmann</td>
<td>Rosa Gonzalez-Delgado</td>
<td>Elinor Medezinski</td>
<td>Keiichi Umetsu</td>
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<tr>
<td>Narciso Benitez</td>
<td>Holland Ford</td>
<td>Leonidas Moustakas</td>
<td>Arjen van der Wel</td>
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<td>Larry Bradley</td>
<td>Leopoldo Infante</td>
<td>Eniko Regoes</td>
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<td>Dan Coe</td>
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CLASH: An HST Multi-Cycle Treasury Program

Both strong AND weak lensing measurements are needed to make accurate constraints on the DM profile.

CLASH data will allow us to definitively derive the representative equilibrium mass profile shape and robustly measure the cluster DM mass concentrations and their dispersion as a function of cluster mass and their evolution with redshift.
CLASH: An HST Multi-Cycle Treasury Program

Cutouts of Chandra images of 18 of the 25 CLASH clusters from ACCESS database
CLASH: An HST Multi-Cycle Treasury Program

Why 14 filters?

Will yield photometric redshifts with rms error of \(\sim 2\% \times (1 + z)\) for sources down to \(\sim 26\) AB mag.

With 14 filters, 80\% photo-z completeness is reached at AB \(\sim 26\) mag and useful redshift information is available for \(\sim 5\) times as many lensed objects than would be possible solely from spectroscopically acquired redshifts.
CLASH: An HST Multi-Cycle Treasury Program

The blue and red solid curves show the expected number of $z=8$ and $z=10$ galaxies, respectively, to be discovered behind our 25 clusters as a function of magnitude in the detection band (F110W at $z=8$ and F140W at $z=10$).

A significant advantage of searching for high-$z$ objects behind strongly lensing clusters is that the lens model can also be used to discriminate between highly-reddened objects and truly distant, high-$z$ objects as the projected position of the lensed image is a strong function of the source redshift.

The parallel fields of the cluster survey provide the means to find $\sim 10$ SNe Ia at $z > 1$ and would double the number of known SNe Ia at $z > 1.2$ (and potentially more, the precise number depending on the assumed time delay).
CLASH: An HST Multi-Cycle Treasury Program

Footprint of our 2 ORIENT survey. ACS FOV in green, WFC3/IR FOV in red, WFC3/UVIS in magenta. The area of the complete 14-band coverage in the cluster center is 4.07 square arcminutes (88% of the WFC3/IR FOV).

Limiting SNR=5 AB magnitudes (for flat spectrum point source) for each passband shown above.
Backup Slides
Geometric Scaling of Lensing Signal

Distance ratio as a function of source $z$

Typical $z$ of BG galaxies:
- Low-z cluster: $zd=0.2$
- Med-z cluster: $zd=0.5$
- High-z cluster: $zd=0.8$

Physical mass to signal units

$$\kappa(\theta) \propto \left(\frac{D_{ds}}{D_s}\right) \Sigma_m(\theta)$$
(3) Weak Lensing Mass Reconstruction

Observable shear field into a 2D mass map: “non-local”

Extract E-mode from shear matrix;

Then, invert:

\[
\Delta \kappa(\theta) = \partial^i \partial^j \Gamma_{ij}(\theta)
\]

\[
\kappa(\theta) = \Delta^{-1}(\theta, \theta') * \left( \partial^i \partial^j \Gamma_{ij}(\theta') \right)
\]

Kaiser & Squires (1993) Inversion Method:

\[
\hat{\kappa}(\vec{l}) = \cos(2\phi_l) \gamma_1(\vec{l}) + \sin(2\phi_l) \gamma_2(\vec{l}), \quad \vec{l} \neq 0
\]

Use the Green function for 2D-Poisson equation:

But l=0 mode (DC-component) is “unconstrained”.

Mass-sheet degeneracy (in the weak lensing limit)

\[
\kappa(\theta) \rightarrow \kappa(\theta) + \text{const.}
\]
Example of Mass Reconstruction

Galaxy cluster: CL0024+1654 (z=0.395)

Weak lensing convergence, $\kappa = \Sigma_m / \Sigma_{\text{crit}}$

HST/ACS (3’x3’ FoV)

SUBARU/Suprime-Cam (34’x27’ FoV)

$R_vir \approx 1.8\text{Mpc}/h (~8 \text{arcmin})$

**LCDM Prediction for Halo**

**Mass vs. Concentration Correlation**

Gravity is scale free – but the *formation epoch* of DM halos, which depends on the structure formation scenario, $P(k)$, gives a mass & redshift dependence of the degree of mass concentration, $C_{\text{vir}}$.

**LCDM N-body halo concentration vs. $M_{\text{vir}}$ relation:**

$$c_{\text{vir}} \sim c_0 (1 + z)^{-\alpha} \left( \frac{M_{\text{vir}}}{10^{15} M_{\odot} / h} \right)^{-\beta}$$

- $c_0 \sim 5$
- $\alpha \sim 1$
- $\beta \sim 0.1$

**Spherical collapse model:** $r_{\text{vir}} \sim (1 + z_{\text{vir}})^{-1}$; massive objects formed later in LCDM, so *lower concentrations for massive objects*

**Scaling radius depends on the structure formation, especially on the *formation epoch of the progenitor DM halo***

- Bullock+2001: $\alpha=1$
- Duffy+2008: $\alpha=0.66$
Rotation/Gradient-Free (E/B) Distortions

Shear matrix with 2 degrees-of-freedom can be expressed with 2 scalar potentials (e.g., Crittenden et al. 2002):

\[
\Gamma_{ij} = \left( \partial_i \partial_j - \frac{1}{2} \delta_{ij} \Delta \right) \psi_E + \frac{1}{2} \left( \epsilon_{kj} \partial_i \partial_k + \epsilon_{ki} \partial_j \partial_k \right) \psi_B
\]

Shear matrix in terms of potential:

\[
\psi_E = \psi \quad \text{(lens potential)}
\]

\[
\psi_B = 0
\]

In pure WL, B-mode = 0 (E>>B)

⇒ WL produces a tangential (E-mode) distortion pattern around the positive mass overdensity.

⇒ B-mode “signal” can be used to monitor residual systematics in WL measurements: e.g., PSF anisotropy
A source galaxy at $z=1.675$ has been multiply lensed into 5 apparent images.

CL0024+1654
(z=0.395)
HST/WFPC2
A1689 (z=0.183): One of the most massive clusters known. A total of >100 multiply-lensed images of ~30 background galaxies identified by SL modeling
Strong Lensing: Giant Luminous Arcs

RCS0224, HST/ACS
cluster $z = 0.77$, arc $z = 4.89$
CLASH: An HST Multi-Cycle Treasury Program

RXJ1347-1145 (z = 0.45)

SUPRIME CAM Image

ACS/WFC Image