Mass and Hot Baryons from Cluster Lensing and SZE Observations

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Collaborators

**Lensing collaborators:**
T. Broadhurst (Bilbao), E. Medezinski (JHU), A. Zitrin (Tel Aviv), N. Okabe (ASIAA, Taiwan), M. Sereno (POLITO)

**CLASH lensing collaboration:**

**Bolocam/AMiBA CLASH-SZE collaboration:**
S. Golwala (PI), J. Sayers, N. Czakon et al. (CLASH-Bolocam)
New Era of Multi-\(\lambda\) Cluster Astrophysics and Cosmology

Comparing / combining high-quality multi-\(\lambda\) cluster observations [lensing/SZE/X-ray/optical/dynamics] for Cluster Cosmology and Astrophysics

Cluster Lensing as a Primary Mass Probe

SUBARU wide-field imaging (Suprime-Cam) for weak lensing

High-resolution space imaging with Hubble for strong lensing

A1689 (z=0.183)
Umetsu & Broadhurst (2008)
Full Lensing Analysis in the Cluster Regime

- **Weak Gravitational Lensing (WL)**
  - **Distortion** *(shearing)*
  - **Dilution** *(purity of BG sample)*
  - **Depletion** *(magnification)*
  - **Deprojection** *(2+1D analysis)*
  - **Stacked lensing analysis**

- **Strong Gravitational Lensing (SL)**
Mean tangential ellipticity of galaxies behind massive clusters (A370, Cl0024, RXJ1347) does increase with source redshift.

Model-Independent Single Cluster WL Tomography

COSMOS photo-z distributions of BR$_c$z$'$-selected background samples

Medezinski, Broadhurst, Umetsu, Benitez, & Taylor 2011 (MBU+11)
**Keys: WL Distortion and Dilution**

Tangential Distortion:

\[
\gamma_+(R) \propto \Delta \Sigma_+(R) \equiv \overline{\Sigma(<R)} - \Sigma(R)
\]

The Dilution Effect

**Background (BG):**

WL signal rises all the way to the center.

**Green = Cluster+BG galaxies:**

WL signal is diluted progressively toward the center by unlensed cluster members!

Recovered signal is proportional to BG purity

Broadhurst, Takada, Umetsu+05; Umetsu & Broadhurst 08; Medezinski+07,10
Count Depletion due to Magnification

Sky expands due to gravitational magnification

Source plane

Image plane (lensed)

Leading to a depletion of counts-in-cells

Simulations with glafic (M. Oguri)
Weak Lensing Magnification Bias

Lensing-induced fluctuations in background counts:

$$\frac{\delta n(\theta)}{n_0} = \mu^{s-1}(\theta) - 1 \approx 2(s - 1)\kappa(\theta)$$

with unlensed LF of BG galaxies

$$n_0(> F) \propto F^{-s}$$

When the count-slope is shallow ($s<1$), a net deficit of counts results: the case for **faint red galaxies** (Broadhurst, Taylor, Peacock 1995)

![Graphs and histograms](image)
Combining WL Shear and Magnification

Tangential distortion (shear)

\[ \Delta \Sigma_+ (R) = \bar{\Sigma}(< R) - \Sigma(R) \]

Number counts (magnification bias)

A unique mass profile solution \( \Sigma(R) \) can be obtained from Bayesian analysis of WL shear + mag-bias (Umetsu et al. 2011a)
What we gain by adding magnification?

Marginalized PDFs of $\Sigma(R)$ in N=12 radial bins: A1689

Shear data alone

Shear + mag-bias

Umetsu et al. 2011a

- Mass-sheet degeneracy is fully broken
- ~30% improvement in mass determination
Combining Full Lensing Constraints
(shear, magnification, strong lensing)

Strong and Weak lensing contribute equal logarithmic coverage of radial mass profile for massive clusters:

→ Combined SL + WL probes the full radial range [0.5%, 150%] $R_{\text{vir}}$

4 high-mass clusters characterized by a large Einstein radius, $\theta_{\text{Ein}} \sim 40'' (z=2)$

A Precise Cluster Mass Profile Averaged from the Highest-Quality SL+WL Data


Stacking clusters by

\[
\langle \Sigma \rangle = \left( \sum_n C_n^{-1} \right)^{-1} \left( \sum_n C_n^{-1} \Sigma_n \right)
\]

Total S/N=58σ

A single NFW gives an excellent fit over ~2-decades of radius

SIS model is rejected at >60σ significance

Lensing observations are consistent with that, DM is non-relativistic (cold) and effectively collisionless on the relevant scales.
Constraint on Central Cusp Slope

\[ \rho(r) \propto r^{-\alpha} \]

\[ \alpha = 0.89^{+0.27}_{-0.39} \]

Slightly shallower than, but consistent with, NFW (cf. Merrit+06, Graham+06, Navarro+10)

Umetsu et al. 2011b
Projection Effect by Halo Triaxiality

Spherical
Triaxial (prolate)

Hennawi, Dalal, Bode, Ostriker 2007
Mean Concentrations for SL Clusters ($\theta_{\text{Ein}}=40''$)

Figure 10, Oguri et al. 2011 (arXiv:1109.2594)

**Umetsu+ method**
- SL mass profile +
- WL shear profile +
- WL mag-bias profile

**Oguri+ method**
- Einstein radius +
- WL shear profile
Bayesian Deprojection of 3D Dark-Matter Structure

Full-2+1D SL+WL Bayesian analysis (A1689) by Sereno & Umetsu 2011

C200 vs. major-minor axis ratio, $q_1$

2D mass map in A1689 from shear + magnification

Umetsu & Broadhurst 2008
Umetsu 2011 (in prep)

C200 vs. l.o.s. alignment, $\cos[\theta]$
SZE Multi-scale Multi-frequency Cluster Program

CLASH-SZE collaboration

- Collaboration between CLASH and several SZE groups: Bolocam, MUSTANG/GBT, AMiBA, ... (discussion going on with AMI group)
- Forming an SZE consortium to study the CLASH sample (20 X-ray and 5 lensing selected clusters at 0.18<z<0.9)

Aim: Probing hot cluster baryons from small to large angular scales

- Large angular scale: 1 to 10+ arcmin
  - Bolocam@150GHz (1 to 14 arcmin)
  - AMiBA-13@94GHz (2 to 11 arcmin)
- Small angular scale: 0.1’ to 1’
  - GBT/Mustang@90GHz (9” to 40”
Bolocam/CSO 150GHz

Ongoing Bolocam-CLASH SZE collaboration

- Angular coverage of $\Delta \theta = 1$ to 14 arcmin
- Probing IC-gas structure out to R500+
- 23/25 CLASH clusters observed with Bolocam, with a typical peak S/N=10

CLASH sample will be completed in this October to a peak sensitivity of S/N>10

See N. Czakon’s talk and J. Sayers’s poster
CLASH WL and SZE Collaboration:
Cluster-Cluster Lensing in A383 (z=0.19)

A z=0.9 BG cluster \( (M_{\text{vir}} \sim 2 \times 10^{14} M_{\odot}) \) weakly magnified (~14%) by A383

See Zitrin et al. 2011 (arXiv:1108.4929)

Umetsu, Medezinski, Nonino + CLASH

Sayers, Czakon, Sunil et al.
AMiBA/MLO at 94GHz (ASIAA+NTU, Taiwan)

AMiBA-7 (2006-2008)

AMiBA-13 (2011~)


K.Y. Lin+ in prep.
Combining Lensing w/ SZE+X-ray:

Hot Baryon Fractions in Clusters

Large-scale $f_{\text{gas}}$ constraints ($\sim 0.8r_{\text{vir}}$, $<z>=0.2$) from tSZE+WL+X, independent of dynamical state and level of hydrostatic equilibrium

**AMiBA-7 tSZE + WL + X-ray**

- Komatsu/Seljak model (AMiBA/Subaru)
- Isothermal $\beta$ model (AMiBA/Subaru)
- Afshordi+07 (WMAP3, $>3$keV, $c_{200}=5$)
- Vikhlinin+06 (Chandra, $>5$keV, $c_{500}=3$)
- Allen+04 (Chandra, $>5$keV, $c_{200}=3.5$)

**WMAP7 tSZE and X-ray constraints**

Cosmic Mean Baryon Fraction

$\Omega_b/\Omega_m=0.167$

AMiBA tSZ+WL+X (Umetsu et al. 2009)

Vikhlinin+2009

Komatsu et al. 2010, WMAP-7yr

Summary

• We explored the utility of high-quality lensing data by combining all possible lensing information available in the cluster regime:
  • WL Distortion (shear)
  • WL Dilution (purity of BG sample)
  • WL Depletion (magnification)
  • Strong lensing (SL)
  • Stacking SL+WL (shear + magnification)
  • Deprojection of 2D SL+WL
• Cluster lensing and LCDM come closer:
  • Stacked cluster mass profile shapes are in good agreement with latest N-body simulations.
  • Multi-scale Multi-frequency SZE collaboration is going on along with the CLASH program.