CALSH Subaru Weak-Lensing and Sunyaev-Zel’dovich Effect Analyses

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1. Keys for High-Accuracy Cluster Lensing

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

- **Strong Gravitational Lensing (SL)**
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, $\theta_{\text{Ein}} \sim 40'' (z_s=2)$

See Umetsu+2011a, 2011b (figures taken from Postman+11)
First Application of Stacked Strong + Weak Cluster Lensing

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=58\sigma

Exclude R<2d_{\text{offset}}=40\text{kpc}/h to avoid smoothing from miscentering!!

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

SIS model is rejected at >60\sigma significance

Utility of Magnification Information

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)

Gain by Adding Magnification in WL

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

Mass-sheet degeneracy is fully broken

$\sim$30% improvement in mass determination

Umetsu et al. 2011a
Mock Observations

Simulation with *glafic* software

Number count profiles (20 realizations)

Sources:
- $n=20$ arcmin$^{-2}$
- $z_s=1$
- $s=0$ (maximally depleted)
- $\sigma_g=0.4$

1D Bayesian (shear + mag-bias) inversion

**Background counts, $n_g$ (arcmin$^{-2}$)**

- Input NFW: $M_{\text{vir}}=1.5\times10^{15} M_{\odot}/h$, $c_{\text{vir}}=4.0$, $z_i=0.2$

**Convergence, $\kappa$**

- Input NFW: $M_{\text{vir}}=1.0\times10^{15} M_{\odot}/h$, $c_{\text{vir}}=4.2$, $z_i=0.2$

**Umemoto+11 inversion method**

- Input NFW: $M_{\text{vir}}=1.0\times10^{15} M_{\odot}/h$, $c_{\text{vir}}=4.2$, $z_i=0.2$
2. Various Projection Effects

1. Unresolved, uncorrelated LSS: cosmic noise
   - Produces covariance, increases uncertainty in (M,C): 
     $\sim +20\%$ increase in error for CC-selected BG samples.

2. Resolved clusters in LOS (Remember Dan’s talk)
   - Can bias “individual cluster” parameter estimation if they’re not taken into account
   - Seen as a dip (↓) in $g_T(R)$, as a bump (↑) in $\kappa(R)$
   - Can be improved with 2D-WL (Massimo’s talk)

3. Halo triaxiality
   - Can bias low or high “individual cluster” (M,C)
   - 2D structure info can be used to constrain parameter space of triaxial model (Morandi+11, Sereno+Umetsu 11 on A1689)
Projection Effect by Halo Triaxiality

Hennawi, Dalal, Bode, Ostriker 2007
Remarks on the Triaxiality Modeling (I)

Triaxial Potential Approach

- Triaxial perturbation theory (Lee & Suto 03,04)
- Spherical averaging triaxial potential (Buote & Humphrey 11)
- Lensing+ applications: Morandi+ on A1689, A383

- **Pros**
  - Easy to describe IC-gas in HE with DM
  - Analytic modeling and fast computation

- **Cons**
  - Unphysical negative densities and non-elliptical isodensity contours can occur when ellipticity is large
  - How to compare with N-body simulations?
Ellipsoidal Halo Approach

- Ellipsoidal generalization of spherical “density” profiles (e.g., NFW)
- Lensing applications: Oguri, Takada, Umetsu+05; Sereno & Umetsu 11; Sereno & Zitrin 11

- Pros
  - Direct comparison with N-body results (e.g., Jing & Suto 02 N-body priors on axis-ratios)
  - Entire parameter space can be explored (no approx)

- Cons
  - Slow computation
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

C200 vs. l.o.s. alignment, $\cos[\theta]$

Fig taken from Sereno, Ettori, Baldi 11

Umetsu & Broadhurst 2008
SZE Multi-scale Multi-frequency Cluster Program

**CLASH-SZE collaboration**

- Collaboration between CLASH and several SZE groups: Bolocam, MUSTANG/GBT, AMiBA?, SZA? ... (discussion needs to be resumed 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), typically out to R500+
  - AMiBA-13@94GHz (2 to 11 arcmin)
- **Small angular scale:** 0.1’ to 1’
  - GBT/Mustang@90GHz (9” to 40”)

[Image of CLASH-SZE collaboration]
Objective (1): Stacked SZE Profiles

Stacked Bolocam-SZE pressure profile from 40 clusters

Figures by Jack Sayers and the Bolocam team
Objectives (2): Gas Fractions

Large-scale $f_{\text{gas}}$ constraints from tSZ+WL+X, independent of dynamical state and level of hydrostatic equilibrium

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

![Graph of Cosmic Baryon Fraction](image)

**WMAP7 tSZ and X-ray constraints**

- Cosmic Mean Baryon Fraction: $\Omega_b/\Omega_m = 0.167$
- AMiBA tSZ+WL+X (Umetsu et al. 2009)
- Vikhlinin+2009

**Large-scale constraints from tSZ+WL+X, independent of dynamical state and level of hydrostatic equilibrium**

Summary

• We explored the utility of high-quality Hubble + Subaru data by combining all possible lensing information available in the cluster regime:
  • WL Distortion (shear)
  • WL Dilution (purity of BG sample)
  • WL Depletion (magnification)
  • Flexion?
  • Strong lensing (SL)
  • Stacking SL+WL
  • Deprojection of 2D SL + 2D WL
• Implementations and tests of independent lensing dprojection methods are needed
• Joint SL+WL+X+SZE analyses
Spin-1 PSF Anisotropy Correction: Application to Subaru A1689 data

Spin-1 PSF anisotropy from stellar shape moments

$$\zeta_\alpha^* = (C^q)^*_{\alpha\beta}(\zeta_q^*)_\beta$$
Mass Map of A1689 from Spin-1 Flexion

Mass reconstruction in the 4’×4’ core region of A1689 (z=0.18)

E-mode (lensing)

B-mode (noise)

Okura, Umetsu, Futamase 2008

\( n_g = 8 \text{ arcmin}^{-2} \)

0.3FWHM Gaussian

530kpc/h
Mass and Light in A1689 (Subaru)

Mass + Light contours from Shear+Magbias data (Umetsu & Broadhurst 08)

Mass map from Fleixon in a 4’x4’ region using ng=8 gal/arcmin^2 !!! (Okura, Umetsu, & Futamase 2008)