Lensing and AMiBA Studies of Galaxy Clusters

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1. Introduction: Galaxy Clusters?
Concordance Structure Formation Scenario

Standard Lambda Cold DM (=ΛCDM) Paradigm:

- **Initial conditions**, precisely known from linear theory & CMB+ data (@ z = z_dec ~ 1100)
- 80% of our *material universe* is composed of dark matter
- Use an N-body simulation (+linear theory) to study hierarchical structure formation (0 < z < 1100)
- **Bottom-up nature**: smaller objects first formed, then larger ones form via mergers and mass-accretions
Observed Matter $P(k)$ vs. $\Lambda$CDM

- $P(k) = Ak^n$ with $n \approx 1$
- $@ k << k_{eq} \approx 0.01h/Mpc$
- Turn-over $@ k \approx k_{eq}$
- $P(k) = Ak^{n-4}$ at $k >> k_{eq}$
- due to the decay of $\Phi(k)$ on sub-horizon scales in the radiation era
- Baryon acoustic oscillation features ($\lambda_s < k_{s.h.} = 150Mpc/h$)
- Non-linear at high-$k$ modes, $k > k_{NL} \approx 0.2h/Mpc$

"Average" properties of the Universe on "large scales" are well explained by $\Lambda$CDM

Tegmark & Zaldarriaga 2002
Large Scale Structure in the Universe

N-body simulations

Studying “non-linear” structure formation in an expanding Universe after the cosmic decoupling epoch (z~1100) governed by the gravity

- Large Scale Structure (LSS): cosmic structure on scales of ~10-50 Mpc/h, representing forming super-clusters, low-density voids, filaments of galaxies
- Clusters of galaxies: non-linear, most massive gravitationally bound structure of R=(1-2) Mpc/h, which serve as building blocks of LSS
Galaxy Clusters — Building Blocks of LSS

**Galaxy Clusters** — identified as dense nodes of “Cosmic Web”

Typical mass: $M_{\text{vir}} \sim 10^{14-15} \, M_{\odot} / h$

Distribution of discrete galaxies

Distribution of underlying DM (\(\sim\)mass)

From Millennium Simulation
Clusters as astrophysical probes

A1689 (z=0.183)

- **Subaru**
  Suprime-Cam
  34’x27’
- **HST ACS**
  3.3’x3.3’
- **Chandra ACIS**
- **AMiBA**
- **VLT/VIRMOS**
- **Suzaku/XIS**

Dynamics

Strong-lensing

Weak-lensing

S-Z effect
My lecture notes on

“Cluster Weak Gravitational Lensing”

from “Enrico-Fermi Summer School 2008, Italy” found at
http://www.asiaa.sinica.edu.tw/~keiichi/upfiles/umetsu_fermi08.pdf

Theoretical backgrounds and basic concepts on cosmological lensing and observational techniques are summarized in these lecture notes.
Importance of Gravitational Lensing

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 \(|\Phi/c^2|<<1\)

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**

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

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

- $\beta$: true source position
- $\theta$: apparent image position

$$\beta - \theta = \frac{D_{ds}}{D_s} \hat{\alpha}(\theta) \equiv -\nabla \psi(\theta)$$

For a rigid derivation of cosmological lens eq., see, e.g., Futamase 95
3. Cluster Weak Lensing
3.1 Quadrupole Weak Lensing

Differential deflection causes a distortion in "area" and "shape" of an image.

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

For an infinitesimal source:

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

\( A \): Jacobian matrix of the lens equation.
Effects of Convergence and Shear

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

\[ A^{-1}(\theta) \]

Convergence alone

Gravitational Lensing

Source

Image

Convergence + Shear

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

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

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

**Critical surface mass density of gravitational lensing**

$$\Sigma_{\text{crit}} (z_d, z_s ; \Omega_m, \Omega_\Lambda, H_0) = \frac{c^2}{4\pi G} \frac{D_s}{D_d D_{ds}}$$

- **Strong lensing** $\kappa \sim 1$ @ high density regions ($r=10\text{kpc-100kpc}$)
- **Weak lensing** $\kappa \sim 0.1$ @ $r = 100\text{kpc} – \text{a few Mpc in clusters}$
- **Cosmic shear** $\kappa \sim 1\%$ @ Large Scale Structure (~10Mpc)

*Note, this is only a crude definition, as lensing also depends on the (trace-free) tidal shear field.*
Geometric Scaling of Lensing Signal

Distance ratio as a function of source $z$

Physical mass to signal units

$$\kappa(\theta) \propto \left(\frac{D_{ds}}{D_s}\right)\Sigma_m(\theta)$$

Low-z cluster:
- $z_d = 0.2$

Med-z cluster:
- $z_d = 0.5$

High-z cluster:
- $z_d = 0.8$
Gravitational Shear Field

**2x2 shear matrix:** Quadrupole shape distortions (2 DoF)

- Coordinate dependent (cf. Stokes Q,U)
- Spin-2 “directional” quantity
- **Observable as an image ellipticity in the WL limit (|κ|,|γ|<<1)**

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

**Spin-2 complex shear field**

\[
\gamma(\theta) = \gamma_1 + i\gamma_2 \equiv |\gamma| e^{2i\phi_\gamma}
\]
Measurement of the Shear: Moment Method

Image quadrupoles:

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

Quadrupole moments of the object surface brightness

Complex ellipticity, \( e = e_1 + i e_2 \):

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

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

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

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

e(s): source intrinsic ellipticity

Assuming that background sources have random orientations:

\[ \langle e^{\text{obs}} \rangle = 2\gamma + O\left(\frac{\sigma_e}{\sqrt{N}}\right) + O(|\gamma|^2) \]
E and B Mode Distortion Patterns

Shear matrix with 2-DoF 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:

\[
\begin{align*}
\psi_E &= \psi \text{ (lens potential)} \\
\psi_B &= 0
\end{align*}
\]

In a pure weak lensing signal,

- B-mode = 0 (E>>B)

\[\Rightarrow\] B-mode “signal” can be used to monitor residual systematic effects in lensing measurements:

- e.g., residual PSF anisotropies
Shear-to-Mass Inversion: 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:

\[
\hat{\kappa}(\vec{l}) = \cos(2\phi_1) \hat{\gamma}_1(\vec{l}) + \sin(2\phi_1) \hat{\gamma}_2(\vec{l}), \quad \vec{l} \neq 0
\]

Use the Green function for 2D-Poisson equation:

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

Mass-sheet degeneracy (in the weak lensing limit)

\[
\kappa(\theta) \rightarrow \kappa(\theta) + \text{const.}
\]
Weak Shear Field vs. 2D Mass Map

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
3.2 Cluster Weak Lensing Profiles
Cluster Tangential Distortion

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

\[ \gamma_+ (r) \propto \Delta \Sigma_m (r) \equiv \overline{\Sigma_m}(<r) - \Sigma_m (r) \]

**Higher concentration**

A1689  
(z=0.183)

**Low-z**

A2142  
(z=0.09)


Full Lensing Analysis: Weak + Strong Lensing

Galaxy cluster: CL0024+1654 (z=0.395)

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

HST/ACS (2’x2’ region)

SUBARU/Suprime-Cam

$R_{\text{vir}}=\sim 1.8\text{Mpc}/h$ ($\sim 8$ arcmin)

Umetsu et al. 2010
Combining Weak and Strong lensing data

→ Probing the mass density profile from 10kpc/h to 2000kpc/h

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

Umetsu et al. 2010, arXiv:0908.0069 (CL0024+1654)
Stacked Cluster Weak Lensing Analysis

Stacking cluster WL distortion profiles from Subaru data
→ less sensitive to substructures/asphericity of individual clusters

M<6e14M_{sun}/h

\[ \chi^2/\text{d.o.f.}=44.6/14 \]

\[ c_{\text{vir}} = 4.06^{+0.55}_{-0.60}, M_{\text{vir}} = 4.79^{+0.48}_{-0.42} \times 10^{14} h^{-1} M_{\odot} \]

M>6e14M_{sun}/h

\[ \chi^2/\text{d.o.f.}=136/14 \]

\[ c_{\text{vir}} = 3.59^{+0.34}_{-0.32}, M_{\text{vir}} = 9.68^{+0.86}_{-0.74} \times 10^{14} h^{-1} M_{\odot} \]

SIS rejected @6 and 11 \( \sigma \) levels (Okabe,Takada,Umetsu+ 10, arXiv:0903.1103)
3.3 Magnification Bias (Count Depletion)

**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

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

When the count-slope is <0.4 (=lens invariant slope), a net deficit is expected.
Cluster Depletion Profile in CL0024

Count depletion of “red” galaxies in CL0024

$\text{Number counts, } n(\theta) \text{ [arcmin}^{-2}]$

$\theta \text{ [arcmin]}$

$8\sigma$ detection

$3-25\%$ masking correction

Umetsu et al. 2010, arXiv:0908.0069
Count Depletion in Other Clusters

Lens distortion (left) vs. depletion (right) in high-mass clusters

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

NFW model predictions from g+ profiles consistent with the depletion curves

Other Interesting Topics on Cluster Lensing

- **Weak Lensing Flexion and HOLICs**
  - Next higher-order weak lensing distortions, responsible for weakly-skewed arc-like images, or *arclets* (Goldberg & Bacon 2005; Bacon et al. 2006)
  - Can be used to measure directly the mass of giant elliptical galaxies
  - Moment-based HOLICs (Higher Order Lensing Image Characteristics) formalism given by Okura, Umetsu, Futamase 2007, 2008

- **Cluster-Galaxy Galaxy Lensing**
  - Stack the tangential distortion signal around cluster member galaxies to measure the averaged mass profile of cluster galaxies (e.g., Natarajan et al. 2009).
  - Can be used to study the cluster galaxy masses as a function of cluster environments, which may reveal imprints of cluster internal dynamics, such as tidal stripping

- **Weak Lensing Dilution**
  - Use dilution of the weak lensing signal to measure the number fraction of cluster galaxies, which can be then used to measure the cluster luminosity and the cluster luminosity function (Medezinski, Broadhurst, Umetsu et al. 2007, 2010)
4. The Y.T. Lee AMiBA Project

Academia Sinica IAA

National Taiwan University, Physics and Electrical-Engineering Dept.
4.1 CMB Interferometers
CMB vs. Interferometer

How to weigh a frog that is attached to a Jumbo-Jet?

How to weigh a frog that is attached to a Jumbo-Jet?

Single dish observations compare two measurements:

\[(M + m) - M' = m\]

- \(M\) : weight of Jumbo with the frog
- \(M'\) : weight of Jumbo without a frog

Measurement of CMB anisotropy:

\[\frac{m}{M'} < 10^{-5}\]

Credit: Prof. Atsuto Suzuki, Tohoku U.

Figure by Prof. Makoto Hattori
Observable: **Complex Visibility, \( V(u,v) \)**

E-field measured by a pair of receivers, being cross-correlated to form a complex visibility

\[
V(\vec{u}) = \int d^2 x \ A(\vec{x}) I(\vec{x}) \exp[2\pi i \vec{u} \cdot \vec{x}]
\]

\[
\vec{u} = \frac{\vec{d}}{\lambda} \quad \text{baseline vector}
\]

\( I(x) \): intensity map on the sky

\( A(x) \): antenna primary beam pattern

Visibility is Fourier Transform of intensity pattern \( I(x) \) attenuated by \( A(x) \)

\[
V(\vec{u}) = \text{FT}[A(\vec{x}) I(\vec{x})]
\]

Angular power spectrum directly measured by interferometer!!

\[
C_l \big|_{l=2\pi \nu} \approx \langle V(\vec{u}) V^*(\vec{u}) \rangle
\]
Fringes

Moon fringes measured in drift-scanning observations with the 2-element AMiBA prototype (2002-2004)
CMB Interferometers

- Typical angular sizes ~ 1 degree – 10 arcmin
  - small antennas, and/or, low frequency (10-100 GHz)
- CMB anisotropy = diffuse, weak signal (10-100 μK)
  - close-packed, or compact array to maximize sensitivity
- Observing strategies, different from traditional ones
  e.g., NO geometrical delay to create fringes while tracking

\[
\Delta \theta = \frac{1}{\Delta u} \approx 20' \left( \frac{d}{60 \text{ cm}} \right)^{-1} \left( \frac{\lambda}{3 \text{ mm}} \right)
\]

CBI @ 26-36 GHz, 13 elements, Chile (1999~)

DASI @ 26-36 GHz, 13 elements, South Pole (1999~)
Uniform UV-Coverage

Traditional interferometer
[2-axes: Azimuth, Elevation]

AMiBA with active platform rotations
[3-rotation DoF: Az, El, Pol]

Synthesized beam (PSF) is an Inverse FT of the UV-sampling function:

\[ B(\tilde{x}) = \text{FT}^{-1}[S(\tilde{u})] \]

UV-track due to earth rotation while tracking a target

12 sky-pol rotations done for Jupiter observations
4.2 The AMiBA Project
Science Goal (I)

Power Spectra $C_l$ of CMB Anisotropies

Wu 2004
Science Goal (II)

Study and Search for Clusters via SZE

Abell 1914 z=0.17

CL0016+16 z=0.54

MS1054−0321 z=0.83

Brightness of Sunyaev-Zel’dovich effects (SZE), z-independent:

Free from cosmological brightness dimming,

\[
(D_A / D_L)^2 \propto (1 + z)^{-4}
\]

Signal strength of thermal SZE

\[
y = \int_0^{\lambda_{\text{LSS}}} d\tau \frac{k_B(T_\tau - T_{\text{CMB}})}{m_e c^2} \approx \int \frac{k_B T_\tau}{m_e c^2} \sigma_T n_e d\tau \alpha \int d\ell P_\ell
\]

What we seek for is a 10-100 \( \mu \text{K} \) weak signal!!
What is the AMiBA Project?

AMiBA is:

- a platform-mounted *interferometer* operating at 3mm, specifically designed to study the structure of CMB at $l=800-8000$ (20 to 2 arc-minutes)
  - The 7-element AMiBA (AMiBA-7) focused on SZE observations for galaxy cluster physics and cosmology
- the first major astronomical project designed, constructed, operated, and led by Taiwan
- *so far the first & only* CMB/SZE telescope for Asia
- *one of few SZE instruments operating at 3mm* (where foreground/CMB contamination is minimized) with published scientific results: cf. SPT bolometer array, SZA interferometer at 1cm ($1'-10'$) and 3mm ($<1'$)
AMiBA will target angular scales smaller than WMAP to study cluster-sized structures (R~1Mpc) via the SZ Effects.

Umetsu, Chiueh, Lin+ 2004
AMiBA-7 Science Highlights

Seven 0.6m reflectors close-packed on the 6m platform
AMiBA-7 SZE Maps


Obtained AMiBA images of SZE decrement towards 6 Abell clusters in 2007

CLEANed images (z=0.1-0.3)
**Power of AMiBA/SZE for Cluster Physics**


**A2142 – merging cluster with X-ray cold fronts**

- **Large scale** NW-SE structure consistent between AMiBA SZE (color-coded) and Subaru weak lensing (white contours)

- **Extended SZE excess** associated with the NW mass clump is detected, which may be indicating a pressure increase in the IC gas.

- **Power of AMiBA SZE** to probe the ICM in low-density outskirts where X-ray emission is not sensitive.

- **AMiBA-13** will sharpen the SZE map, probing the merger physics in clusters.
Cluster Gas Fractions from Subaru/S-Cam WL + AMiBA SZE

First “Lensing+SZE” based cluster gas fraction measurement out to large radii ($r_{200}$), without assuming hydrostatic equilibrium

- (22 +/- 16)% of the baryons are missing from the hot plasma phase in X-ray hot clusters >8keV
- ~5% can be accounted for by “cool” baryons (stars in galaxies, diffuse IC-light): cf. Gonzalez+05

SZE Observations with AMiBA-13

- Science operation with the 13-element AMiBA has started.
- Coordinated Subaru weak lensing observations being conducted (March 2009 and 2010)
Summary

- Galaxy clusters, the largest bound astrophysical objects in the Universe, serve as astrophysical laboratories as well as cosmological probes.
- Gravitational Lensing offers the most direct route to the total mass distribution (dominated by invisible DM) in clusters, regardless of their physical/dynamical state or matter contents.
- Gravitational lensing thus provides an important basis for cluster studies via multi-wavelength observations, such as the internal dynamics of relaxed clusters, the dynamics of merging clusters, and the physical interplay between DM and ICM in forming clusters, etc.
Cluster Lensing: Strong/Weak Regimes

**Strong lensing**
- Multiple Images
- Arclets

**Weak lensing**
- Weak Shear

Non-Linear

Observer
Cluster of Galaxies
Background Galaxy

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Optical Path
Wave Front
Multiple Images Area
Lens Distortion + “Einstein Radius”

CL0024+1654 \((z=0.395)\)

Constraints on DM Structure Parameters

Umetsu, Medezinski, Broadhurst+ (2010)
Importance of AMiBA Frequency

SZE Frequency Spectrum and Coverage

Red: Interferometer
Blue: Multi-pixel bolometer

- At 90-100GHz, relative SZE strength w.r.t. CMB and foreground emission is maximized: optimal window
- AMiBA is one of few leading SZE instruments operating at 3mm.
- AMiBA@3mm@Hawaii serves as a very unique SZE instrument for multi-wavelength SZE studies.

Fig from Zhang et al. 02
Why at 3mm?
Dust/Synchrotron foreground minimized

Typical SEDs of Galaxies

Other CMB interferometers:
CBI (@30GHz)
AMI (@15GHz)
SZA (@30/90GHz)

Fig. 1.—Data points show the radio through infrared spectral energy distributions of four representative galaxies from our sample of 17 listed in Table 1. The data are obtained from NED (JRA data points), the NRAO VLA Sky Survey (Condon et al. 1998), the Westerbork Northern Sky Survey (Rengelink et al. 1997), and from Rigopoulou et al. (1996), Renford (1999), and Lisenfeld et al. (1999). The solid curves show polynomial fits to the data. For the M82 spectrum, the straight lines indicate the spectral index that would be derived for the source at $z = 0$ and $z = 3$ between observing frequencies of 1.4 and 350 GHz.