Galaxy Clusters and Sunyaev-Zeldovich Effect Instrumentation

Sunil Golwala/Jack Sayers    Ay111   Nov 19, 2021
$z = 20.0$

50 Mpc/h
Millennium Simulation
10,077,696,000 particles
Galaxy Cluster Primer

Most massive collapsed objects, formed at $z < 2$

Characteristics:

- $R \sim 1-3$ Mpc ($10^{25}$ cm), collapsed from $\sim 10$ Mpc region
  
  ($1$ Mpc = $[9, 5, 3, 2]$’ at $z = [0.1, 0.2, 0.5, 1]$)

- $M \sim 10^{14}$ $M_\odot$ to few $\times 10^{15}$ $M_\odot$, mostly dark matter, follows generalized Navarro, Frenk, White (NFW) profile

- Hot baryonic plasma $\sim 15$-20% of mass
  
  - $T \sim 10^8$ K = few keV
  - $L_x = 10^{43}$-$10^{45}$ erg/sec
  - density $= 0.001$-$0.1$/cm$^3$
  - sound crossing time $\sim 0.5$ Gyr $\ll$ age $\rightarrow$ close to hydrostatic equilibrium
  
  - gas somewhere between isothermal ($P \propto \rho$) and adiabatic ($P \propto \rho^{5/3}$)
  
  - thermal conduction substantial but not perfect
  
  - metallicity $\sim 1/3$-$1/2$ solar

- $10$s to $100$s of galaxies, $\sim 2$-$3$% of mass

- magnetic field $\sim 1$ $\mu$G

- Observable in O/IR via detection of member galaxies

- Lensing of background galaxies in O/IR maps dark matter

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Young et al 2014

Galaxy Cluster Structure and Cosmology and SZ Instrumentation

2021/11/19 — Golwala — Ay111
Galaxy Cluster Primer

Intracluster medium “emission” mechanisms:

X-ray emission from thermal bremsstrahlung

\[ S_X = \frac{1}{4\pi(1+z)^4} \int n_e^2 \Lambda_{ee} \, dl \]

\[ \Lambda_{ee} = \text{cooling function} \propto T_e^{1/2} \]

Thermal Sunyaev-Zeldovich (tSZ) effect:
Compton scattering of CMB photons

\[ \Delta T_{\text{CMB}} = f_{(x,T_e)} T_{\text{CMB}} \int \sigma_T n_e \frac{k_B T_e}{m_e c^2} \, dl \]

\[ \sigma_T = \text{Thomson cross-section} \]

Relativistic SZ (rSZ) effect:
dependence of \( f \) on \( T_e \)

Kinetic SZ (kSZ) effect:
Compton scattering due to Doppler shift
(line-of-sight peculiar velocity)

Note the different dependences on \( n_e \) and \( T_e \)!
Self-Similar, Universal Cluster Model

Assume gravity dominates, not baryonic physics

A spherical overdensity breaks away from expansion, collapses, and virializes; density at virialization is cosmology-dependent $\Delta_v \approx 180$. Defines virial radius ("edge of cluster"), total mass $M_{tot}$

$$\frac{4}{3} \pi \rho_c(z) \Delta_v(z) r_{vir}^3 = M_{tot}$$

$\rho_c(z) =$ critical density at redshift $z$

$$\alpha E^2(z) = \Omega_M(1 + z)^3 + \Omega_\Lambda + \Omega_k(1 + z)^2$$

Assume isothermality of gas (virialization to logical extreme) in non-singular isothermal sphere with gas temperature related to galaxy velocities

$$n_e(r) = n_{e0} \left(1 + \frac{r^2}{r_c^2}\right)^{-3\beta/2} \frac{\mu m_p \sigma^2}{kT_e}$$

$\beta = 1$ for ideal gas in equipartition, no gravity

Require hydrostatic equilibrium (gas pressure provides support against gravity): relates total mass sourcing gravity to gas temperature and density profile

$$M(r) = \frac{3\beta kT_e}{\mu m_p} \frac{r^3}{r_c^2 + r^2}$$
It’s really more complicated than that...

\[ z = 20.0 \]

- Dark matter density
- Gas density
- Gas temperature

- Kinetic SZ
- Thermal SZ
- Gas shocks

\[ 4 \text{ Mpc/h} = [25', 14', 7.6', 5.8'] \text{ at } z = [0.1, 0.2, 0.5, 1.0] \]
Questions, Questions, Questions

Underlying structure

Does the dark matter profile evolve with time? Is it reflective of the redshift of formation? How much dark matter substructure is preserved? How do scaling relation parameters depend on formation history and current morphology?

Composition

What is the baryon fraction as a function of radius and redshift? How are the baryons divided among stars, cold gas, and hot gas? What is the metallicity as a function of radius and redshift? Is there segregation of different elements? How did cluster magnetic fields come into existence and evolve?

Formation and Virialization

How is the kinetic energy of infalling gas thermalized? What are the bulk motions in the ICM? What do they tell us about the cluster assembly history? How much does the ICM deviate from hydrostatic equilibrium? What is the size and cause of temperature gradients in the ICM?

Energy Input and Loss Mechanisms

What is the role of radiative cooling? What is the form and effect of feedback from galaxies (AGN, winds, cosmic rays)? What is the cosmic ray content of the ICM? What impact does it have on the thermodynamics?

Physics of the ICM Plasma

What is the microscopic plasma physics of the ICM: thermal conductivity, viscosity, electron-ion equilibration time? What is the level of turbulence in the ICM? How is it created? Is the ICM stable against convective instability? What is the magnetohydrodynamics of the ICM, and how does it affect the plasma’s properties?

What are the systematic limits on our ability to constrain cosmology with clusters?
Example Science Project: What is the distribution of galaxy cluster shapes?

Motivation

Shapes depend on how/when galaxy clusters form;

\[ \longrightarrow \text{sensitive to} \]

underlying cosmology
detailed properties of gravit non-gravitational physical processes the ICM

Clusters \( \sim \) triaxial ellipses

\( \text{SZ brightness} \sim n_e T_e \Delta l, \text{X-ray brightness} \sim n_e^2 \Delta l \)

\[ \longrightarrow \text{can constrain LOS cluster length} \Delta l \sim (\text{SZ})^2/(XR) \]

CLASH triaxial shape analysis w/SZ + XR

more robust concentration-mass relation than lensing alon suggests recently formed halos less spherical

XMM-Heritage Triaxial Shape program

3 Msec for 118 SZ-selected clusters SZ WG, obs done weak lensing via Caltech Subaru exchange time

\( \times 5 \) more clusters than CLASH \[ \longrightarrow \text{definitive analysis} \]

1 yr demo project underway, multi-year analysis afterward
Non-Thermal Pressure $\rightarrow$ tSZ Deficit

Weak-lensing + X-ray + Bolocam tSZ analysis of CLASH clusters

CLASH selected based on X-ray regularity (relaxed)

This analysis of subsample that appear spherical on the sky

Analysis assumes

- spherical symmetry
- non-thermal pressure follows shape from simulations

Exclude clusters that seem to show evidence of LOS extension (non-sphericity)

Find no evidence for non-thermal pressure in this biased sample

Siegel et al 2018

Figure 2.

Constraints on the concentration and total mass at $r_{500}$ for the six galaxy clusters in our sample. Contours denote 68% and 95% credible regions. The colors denote fits to different combinations of data sets. Blue denotes a fit to the lensing data only (GL), green the X-ray data only (XR), red the X-ray and SZ data (XR+SZ), and gold the full multiwavelength dataset using the maximally restricted model (XR+SZ+GL). Note that the range of the y-axis is different for each row.
Non-Thermal Pressure $\rightarrow$ tSZ Deficit

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Non-Thermal Pressure → tSZ Deficit

Weak-lensing + X-ray + Bolocam tSZ analysis of CLASH clusters

Full triaxial analysis recently completed

Greater consistency with simulations observed at large radius than in spherical analysis

But observed much less non-thermal pressure at small radius than simulations

⟹ There are thermalization processes not accounted for in simulations
Example Science Project: ICM Velocity Structure in Mergers

**Question:**

What are the dynamics and associated physics processes in cluster mergers?

**Motivation:**

~ half of a typical cluster’s mass is acquired from mergers
Merger velocities are sensitive to cosmology
Interesting merger-driven physics — shocks, sloshing cores, etc.

**Approach**

Most studies use plane-of-sky morphology (e.g., Bullet cluster)
Line-of-sight ICM velocity is now become accessible:

- X-ray spectroscopy in the future: Hitomi, XRISM, Athena
- Doppler shift via kinetic SZ

**First demonstration:**

<table>
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<th>Sub-cluster C (Model)</th>
<th>Data 140 GHz</th>
<th>Data 268 GHz</th>
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</thead>
<tbody>
<tr>
<td>RA (J2000)</td>
<td>7°17′36″</td>
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<td>dec (J2000)</td>
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**Fig. 4.—**

- The green circles show the 1σ confidence regions for the sub-clusters B, C, and D. This fit produces contour lines that are consistent with the data.

**Fig. 6.—**

- The contour plots show the integrated surface brightness for sub-cluster C, with contours spaced by 1σ. The green circles indicate the 1σ confidence regions, and the best-fit thermal plus kinetic SZ spectrum is shown in blue.

**Table 2.**

- The table lists the maximum likelihood parameters for the model fit, including the electron temperature and pressure, along with their uncertainties.

**Systematic Uncertainties**

- The uncertainties on the mean integrated surface brightness are dominated by the convolution of the aperture and PSF.

**Example Science Project: ICM Velocity Structure in Mergers**

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Example Science Project: ICM Velocity Structure in Mergers

Expanded project:

- Consistent detection of $v_z$ rms in excess of noise for mergers, none for relaxed clusters
- Pursuing cluster member $v_z$ via spectroscopy w/Keck
- Plan detailed merger modeling

![Image of galaxy cluster maps and diagrams]

Upcoming Science Project: ICM Velocity Structure in Mergers

Prior kSZ with 10-m telescopes

\[ \sigma_v \sim 1000 \text{ km/s per 1'} \]

Barely resolve typical velocity structure, S/N \( \sim 1 \)

New observations soon with 50-m Large Millimeter Telescope (LMT)

\[ \sigma_v \sim 100 \text{ km/s per 10''} \]

Highly spatially resolved ICM velocity maps, S/N \( \sim 5 \)

Now identifying \( z \sim 1 \) LMT targets using Keck

LMT online in 2021?
Systematics Limits to kSZ Precision

Multi-band coverage necessary for teasing apart SZ effects and contaminating galaxies, degeneracy between $v_{\text{pec}}$ and $T_e$

Ongoing project to simulate ultimate limits to kSZ sensitivity for bulk (cosmological) and internal ICM velocities
Summary of Observational and Forecasting Projects

Triaxial shapes
  1 yr demonstration and/or multi-yr full analysis using the XMM-Heritage sample

ICM pressure shapes
  open-ended opportunities to build on existing results w/ available larger samples

Non-thermal pressure
  1 yr demonstration and/or multi-yr full analysis using the XMM-Heritage sample

Merger studies
  1 yr opportunities using existing data, longer-term based on future LMT observations

AGN studies
  1 yr opportunity to lead Abell 2052 study, although analysis will be technical and complicated

$H_0$ measurement
  multi-yr collaborative rSZ measurement, open-ended opportunities w/ larger sample

kSZ forecasting
  multi-yr project to incorporate instrumental/calibration effects
Instrumentation

Ongoing developments to enable multi-band studies of galaxy clusters

- Multi-scale phased-array antennas to enable measurement of 6 spectral bands in a single focal plane
- Background-limited microstrip-coupled kinetic inductance detectors (KIDs) to provide excellent sensitivity in all spectral bands
- Microstripline and parallel-plate capacitors using 1 µm thick crystalline silicon to minimize KID two-level-system noise and antenna microstripline loss
- Broadband, antireflection-structured, gradient-index silicon optics

Ample opportunities for instrumentation work with a range of levels of time commitment
Kinetic Inductance Detectors

Superconductors have an AC inductance due to inertia of Cooper pairs alternately, due to magnetic energy stored in screening supercurrent

Changes when Cooper pairs are broken by energy input from light

Sense the change by monitoring a resonant circuit

Key point: superconductors provide very high Q \( (Q_i > 10^7 \text{ achieved}) \), so thousands of such resonators can be monitored with a single feedline enormous cryogenic multiplex technology relative to existing ones very simple cryogenic readout components
Antenna Coupling

Provides a way to couple incoming light to detectors without feedhorns and in a planar format fully consistent with photolithographic fabrication.
Multi-band Antenna-Coupled KIDs

- 6 x 6 spatial pixel array
- x16 to make full focal plane

- KIDs (four, one per band)
- recent change: reduce length of Al section

- single pixel

- phased array antenna

- bandpass filters for 2 bands
  - B0 (150 GHz)
  - B1 (225 GHz)
  - B2 (290 GHz)
  - B3 (350 GHz)

Galaxy Cluster Structure and Cosmology and SZ Instrumentation
Wide-Band Multi-Scale Antenna

Same focal plane area can be used for multiple spectral bands
Pixel size scales with wavelength to ensure good matching to Airy function
Multi-Scale Antennas

Coherently combine light from adjacent pixels after band-filtering

- Same focal plane area can be used for multiple spectral bands
- Pixel size scales with wavelength to ensure good matching to Airy function

Scalable technique provides natural match to the foregrounds challenges

Three-scale: 90/150, 220/290, 350/405 GHz: ideal SZ bands
Four-scale: 40, 60, 90/150, 220/290 GHz: ideal CMB polarization bands

![Diagram](image-url)
Performance

(a) reasonable KID response to temperature
(b) Dark noise below photon noise for the given spectral bands
(c) See generation-recombination noise at 290 mK
(d) Optical efficiency scales w/band in reasonable way
   AR tuned for B3, B4
   B4 need to be understood
Broadband Anti-Reflection-Structured Silicon Optics

Motivation

**Crystalline silicon is excellent optical material:**
- High index
- High conductivity
- Low loss

**But high index necessitates ARC**

**Need wide bandwidth ARC for applications**
- CMB pol: 40-300 GHz (7:1)
- SZ: 90-405 GHz (6:1)
- Origins Space Telescope: 25-500 µm (20:1)

![Diagram showing etching process](image)

Each equivalent SiO₂ thickness is calculated for every step of the etching process. The bottom diagram visually shows how a thicker mask is needed for shallower etches. Between etches, SiO₂ is uniformly removed over the wafer to expose each silicon etch pattern sequentially.

![Antireflection structure](image)

Parabolic index variation = parabolic lens
Fabrication: 2-Layer

Etch Pattern

<table>
<thead>
<tr>
<th>Layer</th>
<th>Top</th>
<th>Bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geom.</td>
<td>Post</td>
<td>Hole</td>
</tr>
<tr>
<td>depth</td>
<td>T1: 216</td>
<td>T2: 122</td>
</tr>
<tr>
<td>size [μm]</td>
<td>C: 72</td>
<td>B: 77</td>
</tr>
</tbody>
</table>

Grid: A = 125 μm
Wafer thickness: 1000 ± 25 μm

Block 2 wafer layout
S. Radford
corrected 2015-12-14

Etched Identification
P-72-216-H-77-122
4 mm height

mounting surface, 5 mm wide

Ø100.0 wafer

CZ silicon

Stacked Wafer Gradient Index Silicon Optics with Integral Antireflection Layers

Fabrication: 2-Layer

Top view

Zoom of top view
Can see layer of holes
Fabrication: 2-Layer

Isometric view

Top view

Zoom of top view
Can see layer of holes
Fabrication: 2-Layer

Side view of cleaved wafer
Two-Layer Results: Excellent!

Results from a wafer with the two-layer AR structure fabricated on both sides

> 10 kΩ·cm → negligible loss

Did one set of test wafers to determine mapping from mask dimensions to fabricated dimension

Tweaked the HFSS sim to use the measured dimensions from a cleaved sample; slightly off from design

Likely can reliably hit desired dimensions with more fab practice

sub-unity transmission due to measurement systematics, not loss

< 1% reflection from two parallel faces!

covers entire 1-1.4 mm window!

Power (%) vs Frequency (GHz)

Reflection HFSS
Transmission HFSS
Reflection data
Transmission data
Increased Bandwidth via More Layers

4-layer: > 3.2:1 bandwidth

6-layer: ~5.5:1 bandwidth!
Gradient Index Lenses

Hexagonal hole pattern
Size varying with radius to vary index
1 mm thickness wafers
Clamp many together
Fab in process
A couple clever tricks needed…

\[ \text{\sim 74 \mu m} \]
\[ \text{\sim 26 \mu m} \]
Gradient Index Lenses

First results — very good!

Clearly, they work as lenses
AR structure reduces sidelobes

Properties:
  focal length: 175 mm measured, 220 mm expected
  beam waist: 3.4-3.9 mm measured, 3.5 mm expected
Conclusion

Many exciting topics in cluster studies and instrumentation with SZ:

- Analyses using in-hand and in-process data sets for various cluster science topics, also bearing on galaxy evolution via AGN feedback studies

- Simulations of ultimate kSZ sensitivity: can we do cosmology with cluster peculiar velocities?

- Development of detectors and optics for multiple spectral bands: ultimate kSZ search

- Instrumentation upgrade, redeployment, and searches for kSZ

- Many graduate opportunities, ranging from pure instrumentation to pure analysis (though a mix is typical and preferred)