A Measurement of the Velocity Sub-Structure in MACS J0717.5 using the Kinetic Sunyaev-Zel’dovich Effect
A Measurement of the Velocity Sub-Structure in MACS J0717.5 using the Kinetic Sunyaev-Zel’dovich Effect

Jack Sayers, Tony Mroczkowski, Mike Zemcov, Phil Korngut, Jamie Bock, Sunil Golwala, Seth Siegel (Caltech), Esra Bulbul (Harvard), Nicole Czakon, Patrick Koch, Kai-Yang Lin, Keiichi Umetsu (SINICA), Eiichi Egami, Tim Rawle, Marie Rex (Arizona), Adam Mantz (Chicago), Sandor Molnar (Taiwan), Leonidas Moustakas (JPL), Elena Pierpaoli, Jennifer Shitanishi (USC), Erik Reese (Penn), ApJ, 778, 52 (2013)
The SZ Effect

- SZ effect describes the Compton scattering of the CMB with hot electrons in the intra-cluster medium (ICM)

- Fractional shift of CMB → redshift independent

- Thermal SZ effect
  \[
  \frac{\Delta T_{CMB}}{T_{CMB}} = f(\nu, T_e) y
  \]
  \[
  y = \int n_e \sigma_T \frac{k_B T_e}{m_e c^2} dl
  \]

- Kinetic SZ effect - Doppler shift
  \[
  \frac{\Delta T_{CMB}}{T_{CMB}} = -\frac{v_z}{c} \tau_e
  \]
  \[
  \tau_e = \int n_e \sigma_T dl
  \]
What is the Kinetic Sunyaev-Zel’dovich Effect?

- kSZ brightness is independent of redshift and directly proportional to the line of sight velocity relative to CMB
  - Enables **absolute** velocity measurements at any redshift

- Enables direct measurements of both the overall cluster peculiar velocity and of velocity structure within the ICM
  - Measurable kSZ signal also sourced by patchy reionization (e.g., Zahn+12)

- kSZ signal is dim → order of magnitude below thermal SZ
  - Also significant contamination from: primary CMB fluctuations, background dusty galaxies, radio galaxies, atmospheric brightness fluctuations

- kSZ is difficult to measure!
MACS J0717.5+3745

- Galaxy distribution, X-ray, and mass modeling all show four distinct peaks → C is the main cluster, A has already passed through along the plane of the sky, B and D are infalling along the line of sight (Ma+2009)

- Cherry-picked for our kSZ study based on \( \approx 3000 \text{ km/s} \) spectroscopic LOS velocity measured for sub-cluster B
Bolocam Overview

- 144-pixel spiderweb bolometer array (NTD-Ge, e.g., Planck-HFI, SPIRE)
- Two non-simultaneous observing bands, 140 GHz and 268 GHz (well positioned for kSZ studies)
- 10.4 m Caltech Submm Observatory → angular resolution 58 and 31 arcsec at 140 and 268 GHz
**Bolocam Data Reduction**

- I’ll skip the specifics, but two things...
- Removing atmospheric fluctuations also removes a lot of cluster signal
  
  - Option 1: identically filter a model of the SZ signal prior to fitting
  - Option 2: deconvolve the effects of the filtering
  - This talk focuses on option 1 → although we also performed the analysis using option 2 and obtained consistent results

- background galaxies are very bright at 268 GHz → remove using *Herschel*-SPIRE

Top shows actual cluster, bottom shows cluster after processed with Bolocam pipeline
SZ Model

- Use *Chandra* combined density and temperature to create thermal SZ model

- This model is **not** a good fit to Bolocam → require an additional model component towards sub-cluster B
  - In other words, spectrum towards B is not consistent with thermal SZ
Peculiar Velocity Constraints

- Compute 140/268 GHz brightness within 1’ aperture centered on sub-cluster B (also for the sub-cluster C)

- Total SZ brightness is equal to $f(\nu, T_e) y - (v_z/c) \tau_e$ → depends on ICM $y$, $\tau_e$, $T_e$, and $v_z$
  - Use X-ray spectroscopic data from XMM/Chandra to constrain $T_e$
  - Assume isothermality so that $y \propto T_e \tau_e$
  - Then constrain $y$ and $v_z$ using our two-band SZ data

- For sub-cluster B we get $v_z = +3450 \pm 900$ km/s

- PDF is not Gaussian → likelihoods show that model-fit is 4.2σ away from 0

- sub-cluster C has $v_z \simeq -500$ km/s (consistent with $v_z = 0$)
SZ Fits and Peculiar Velocity Constraints

- Red: best-fit tSZ-only
- Green: best-fit kSZ
- Blue: best-fit total SZ
- Good agreement with Ma+2009 spectroscopy
  - Is it too good?
Cosmological Implications

- 3000 km/s is quite large, is this compatible with $\Lambda$CDM?

- Back of the envelope $\rightarrow M = 1.5 \times 10^{15} \text{ M}_\odot$, infall from infinity reaches 3000 km/s at a separation of 1.5 Mpc (roughly 2/3 of the cluster virial radius)

- $N$-body simulations, e.g., Lee & Komatsu (2010), at $z = 0.5$ such velocities have a non-negligible probability for a merging sub-cluster within the virial radius of the main cluster

- $\Lambda$CDM is fine...
Possible Systematics

• *Chandra* and *XMM* don’t agree on temperatures, especially high temperatures like MACS J0717.5
  - In our case, the two instruments disagree at the $\approx 2\sigma$ level
  - Our best-fit $v_z$ using the *Chandra*-only or *XMM*-only temperature differ by $\approx 500$ km/s ($0.5\sigma$) $\rightarrow$ significance from 0 effectively unchanged due to covariances between $T_e$, $y$, and $v_z$

• Does our aperture contain SZ signal from more than one sub-cluster? Are we measuring an intact ICM moving with a single velocity?
  - X-ray temperature towards sub-cluster B is relatively cold, indicating that it is likely still intact
  - Ruan+13 studied exactly this type of scenario using simulated clusters $\rightarrow$ interactions between the merging ICMs tend to behave in a way that leaves the kinetic SZ signal relatively unchanged ($\approx 10\%$)
Summary

• We have made a resolved measurement of the kinetic SZ signal towards MACS J0717.5

• Our absolute kSZ velocities are consistent with the spectroscopic velocities determined by Ma+2009, strengthening the evidence for their proposed merger scenario

• Have similar data for a sample of 9 additional clusters
Bolocam HFF Field SZ Data

- Bolocam has observed all 6 Frontier Fields at 140 GHz, with high significance resolved images of the SZ signal towards each cluster
  - Abell 370 S/N = 13
  - Abell 2744 S/N = 16
  - Abell S1063 S/N = 15
  - MACS J0416 S/N = 9
  - MACS J0717 S/N = 21
  - MACS J1149 S/N = 17

- All of these data will become public very soon (before the end of the year) via the NASA/IPAC Infrared Science Archive (IRSA)
  - Bolocam data for 40+ clusters will also become public
Bolocam HFF Field SZ Data

Abell 370
Abell 2744
Abell S1063

MACS J0416
MACS J0717
MACS J1149
Additional Slides
Dusty Galaxies at 268 GHz

- Dusty galaxies are bright at 268 GHz
  - brightest object in the Bolocam image is a background galaxy
  - *Herschel*-SPIRE (600/850/1200 GHz) detects 200 galaxies!
  - Bolocam image limited by spatial fluctuations in background galaxies → confusion-limited

![Bolocam Image](image_url)

**Blue:** S/N starting at +4
**Cross:** dusty galaxy
**Green:** sub-clusters B and C
Dusty Galaxies at 268 GHz

- Need to subtract these galaxies!
- 8 sources are individually resolved and detected with Bolocam
- SPIRE detects at total of 200 source candidates → 162 remain after discarding the counterparts to the Bolocam detections along with low significance objects
- For those 162 sources, extrapolate greybody to 268 GHz
  - Extrapolated source template describes 268 GHz data very well → subtracting template results in $\Delta \chi^2 = 166$ (max 240)
  - Consistency check → best-fit Bolocam amplitude of template is $0.84 \pm 0.09$ → on average, greybody works for extrapolation
Dusty Galaxies at 268 GHz

- Bolocam+SPIRE detect all galaxies above 1 mJy at 268 GHz → hints of an excess at bright end (probably lensing)

- Residual pixel histogram consistent with Bethermin+11 → predicted broadening of 12.3%, observed 11.9 ± 0.9%
Measuring the SZ Spectrum - Systematics

• We were forced to make several arbitrary choices in order to determine the SZ brightness of sub-cluster B → how do our results depend on those choices?

• Examined the effects of:
  - Varying the pseudo Compton-\(y\) map within the X-ray uncertainties
  - Varying the SZ map region used for the fit
  - Discarding the pseudo Compton-\(y\) map entirely, and using only profiles centered on the various sub-clusters
  - Changing the F-test decision threshold, which results in a pseudo Compton-\(y\) map plus profiles at B and A
  - Varying the profile shape used for sub-cluster B

• None of these change our results by more than 1.0\(\sigma\) for the model-derived (0.6\(\sigma\) for the direct integration of deconvolved maps) → conservatively add these factors to error budget
Measuring the SZ Spectrum - Systematics

- Our choice of aperture size (140 GHz PSF) and location (Ma+2009 estimated positions) was also arbitrary

- Other reasonable choices for the aperture position are: 1) projected mass peak from Limousin+12 and 2) the X-ray centroid → re-fit at both locations

- Also tried varying the aperture diameter by ±50%

- Difference in SZ brightness from all of these variations is consistent with measurement noise → therefore our results are not sensitive to the exact choice of aperture
## Measuring the SZ Spectrum - Results

<table>
<thead>
<tr>
<th>Frequency GHz</th>
<th>Best Fit Measurement Err. MJy sr⁻¹</th>
<th>Flux Err. MJy sr⁻¹</th>
<th>Modeling Err. MJy sr⁻¹</th>
<th>Total Err. MJy sr⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sub-Cluster B</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model 140</td>
<td>-0.344 0.028 0.017 0.028 0.043</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model 268</td>
<td>0.052 0.029 0.005 0.029 0.041</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deconv. 140</td>
<td>-0.341 0.027 0.017 0.016 0.036</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deconv. 268</td>
<td>0.095 0.049 0.010 0.029 0.058</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Sub-Cluster C</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model 140</td>
<td>-0.262 0.026 0.013 0.028 0.040</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model 268</td>
<td>0.217 0.039 0.022 0.029 0.053</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deconv. 140</td>
<td>-0.270 0.026 0.014 0.016 0.034</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deconv. 268</td>
<td>0.220 0.059 0.022 0.029 0.069</td>
<td></td>
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</tr>
</tbody>
</table>

- Also fit the brightness of sub-cluster C since it’s the most massive sub-cluster
- In all cases we find consistent results from both analysis methods (the model fit and the deconvolved data)
What Limited our $v_z$ Constraints?

- Uncertainty on X-ray temperature $\rightarrow$ inflating the uncertainty by a factor of 5 our constraint on $v_z$ only degrades by 10%

- Noise from unsubtracted galaxies $\rightarrow$ eliminating this noise improves our $v_z$ constraint by $\approx 20\%$ (note that the approximate bias we would have obtained if we had not subtracted the brightest galaxies is $\approx 10\%$)

- Noise from primary CMB fluctuations $\rightarrow$ eliminating this noise improves our $v_z$ constraint by $\approx 5\%$

- Flux calibration $\rightarrow$ assuming perfect calibration improves our $v_z$ constraint by $10 - 15\%$

- Limited by SZ measurement noise (but not for long...)
Future Prospects for kSZ Measurements

- Bolocam already starting to be limited by dusty galaxies → these will be a significant contaminant for deeper data
- Disentangling thermal SZ is also a challenge → ≃ 10 times brighter than kSZ for more typical \( v_z \simeq 500 \) km/s
- Must constrain \( T_e \) → either need deep X-ray (100s of clusters) or enough spectral coverage to measure relativistic corrections to thermal SZ spectrum
- Primary CMB fluctuations → another significant contaminant, particularly at low–\( z \)
- Likely will need 6+ trans-mm bands
Future Prospects for kSZ Measurements

- As a strawman for a future kSZ instrument, consider a 6-band 90–400 GHz instrument with 50k detectors operating on the 25 m CCAT.

- Such an instrument could reach $\sigma_v \simeq 300$ km/s in $\lesssim 1$ hour per cluster or $\sigma_v \simeq 150$ km/s in $\simeq 5$ hours.

- Constraints from SZ survey
  - Blue = counts, 4000 clusters
  - Red = kSZ, $\pm 100$ km/s, 1000 clusters
  - Figure: Suman Bhattacharyya
Future Prospects for kSZ Measurements

- What about kSZ in the context of all cosmological probes?

- Consider a next-generation spectroscopic RSD measurement like MS-DESI

- kSZ can provide competitive constraints that are highly complementary (different systematics, mass scale, etc.)
  - requires large sample ($\gtrsim 10k$)
  - $\gamma_0$ constraint $\sim \sqrt{\sigma_v}$
  - Figure from Rachel Bean
Future Prospects for kSZ Measurements

- Deep observations → dedicated program could detect ICM velocity substructure in a large sample of clusters (≈ 100)

- Morandi+12 estimated $v_z$ recovered for a 16 hour 6-band CCAT integration
  - Unbiased recovery in relaxed clusters, limited by intrinsic $v_z$ dispersion of ≈ 50 – 100 km/s

Solid line: true $v_z$
Points w/ error: kSZ recovered $v_z$