SZ/X-ray Joint Analysis of the ICM with APEX-SZ Data

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Collaboration

APEX–SZ collaboration: (PI Adrian Lee)

- UC Berkeley
- MPIfR Bonn
- University of Bonn
- Onsala
- MPE
- ESO
The APEX-SZ Experiment

**Telescope**
- 12 m ALMA prototype, located at 5100 m altitude in the Chilean Altiplano

**Receiver**
- 300 pixel TES bolometer, PI instrument on APEX, **de-commissioned in Dec 2010**
- 1′ resolution, 0.4 deg FoV @ 150 GHz
- About 7% sky time compared to SPT/ACT (often in bad weather!)
## APEX-SZ Observations

<table>
<thead>
<tr>
<th>Name</th>
<th>R.A.</th>
<th>Dec.</th>
<th>z</th>
<th>$M_{200}$</th>
<th>APEX</th>
<th>X-ray</th>
<th>Cont.</th>
<th>Dist.</th>
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<tbody>
<tr>
<td></td>
<td>J2000</td>
<td>J2000</td>
<td></td>
<td>10^{14} M_{\odot}</td>
<td>h</td>
<td>X/Ch</td>
<td>mJy</td>
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<tr>
<td>** Complete X-ray selected sample **</td>
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<td>A2204</td>
<td>16:32:45.7</td>
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<td>0.152</td>
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<td>25/20</td>
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<td>-</td>
<td>17.8</td>
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<td>0.66</td>
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<td>A2163</td>
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<td>-</td>
<td>12.7</td>
<td>25/80</td>
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<td>40/50</td>
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<td>0.05</td>
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<td>** Low-z sub-sample **</td>
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<td>0.2708</td>
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<td>21.4</td>
<td>8.2/0</td>
<td>9.8</td>
<td>0.42</td>
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<td>0.2773</td>
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<td>0/24</td>
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<td>3.65</td>
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<td>0.49</td>
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<td>9.7/10</td>
<td>N/A</td>
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<td>Bullet</td>
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<td>11.5</td>
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<td>17.4</td>
<td>9.7/14</td>
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<td>** Intermediate z sub-sample **</td>
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<td>5/26</td>
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<td>-</td>
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<td>+01:29:53</td>
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<td>0/40</td>
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<td>8.3</td>
<td>45/60</td>
<td>14.4</td>
<td>3.62</td>
</tr>
</tbody>
</table>

Over 900 hours of science data.
APEX-SZ Observations
APEX-SZ past & future results

Halverson, Lanting et al. 2009


Temp profile

Kennedy, Basu et al. (in prep.)

Bender et al. (in prep.)

Kaustuv Basu (AlfA, Univ. Bonn)

ICM modeling with APEX–SZ data (KITP 2011)
Physics at the Cluster Outskirts

Departure from thermodynamic equilibrium in the cluster outskirts ($T_e < T_{\text{gas}}$)

Rudd & Nagai 2009

Gas clumping creates opposite biases for the X-ray spectroscopic and SZ temperatures

RXC J2228.6: Jia, Boehringer et al. 2008

over-prediction of density

under-prediction of temperature
Physics at the Cluster Outskirts

Gas clumping creates opposite biases for the X-ray spectroscopic and SZ temperatures.

RXC J2228.6: Jia, Boehringer et al. 2008

SZ measurement with NRO (From Pointecouteau et al. 2002)

R$_{500}$

over-prediction of density

C

C*R (⇒SZ)

R

under-prediction of temperature

distribution width ($\varepsilon / <T>$)
Modeling the cluster outskirts

Measured $Y_{SZ}$ in a cylinder

$Y_{SZ} / Y_{X}$ comparison in $R_{500}$ sphere

Arnaud et al. 2010

Planck collaboration 2011

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ICM modeling with APEX–SZ data (KITP 2011)
De-projecting without parametric models

De-projection of the SZ map = the radial pressure profile

Fit here

$P_r (\beta)$

GNFW

A2204: Basu et al. 2010

SPT measurement (Plagge et al. 2010)
“True” SZ map/profile

Filtered (observed) map

De-convolved map

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ICM modeling with APEX–SZ data (KITP 2011)
“True” SZ map/profile

Direct de-projection with MCMC method

(see Ameglio, Borgani et al. 2007)
ICM Temperature De-projection

\[ X\text{-ray} \propto n_e^2 \Lambda(T_e) \]

\[ \text{SZE} \propto n_e T_e \]

\[ (\text{SZE}) \text{ observed } \Delta T(\theta) \]

\[ (\text{SZE}) \ n_e(r) \ T_e(r) \]

\[ f(\theta) = \int_{-\infty}^{\infty} g(r)dl = 2 \int_{d_A}^{\infty} g(r) \frac{rdr}{\sqrt{r^2 - d_A^2 \theta^2}} \]

\[ g(r) = \frac{1}{\pi d_A} \int_{\infty}^{r/d_A} \frac{df(\theta)}{d\theta} \frac{d\theta}{\sqrt{\theta^2 - r^2/d_A^2}}. \]
ICM Temperature De-projection

Abell 2204
Archetypal relaxed cluster
Basu, Zhang at el. 2010

X-ray (XMM)

SZE (Apex)
ICM Temperature De-projection

Abell 2204
Archetypal relaxed cluster
Basu, Zhang et al. 2010

Density

Temperature

Kaustuv Basu (AIfA, Univ. Bonn)
ICM modeling with APEX–SZ data (KITP 2011)
SZ/X and X-ray spec. systematic errors

Projected ("spectroscopic-like") temperature and re-calibrated Chandra (88 ks) measurement

XMM temperature profile of ~50 clusters, including systematic errors

(Leccardi & Molendi 2008)
**Biases in SZ/X-ray joint modeling**

Since density profile is almost fully constrained by X-ray, the SZ-derived temperature will carry the opposite bias.

In the soft X-ray band (0.5–2 keV) the surface brightness is almost independent of gas temperature.
APEX-SZ pressure profiles

A907

A1689

A3404

Kaustuv Basu (AlfA, Univ. Bonn)

ICM modeling with APEX–SZ data (KITP 2011)
APEX-SZ pressure profiles

APEX-SZ measurement (Basu et al., in prep.)

SPT measurement (Plagge et al. 2010)
ICM Entropy profiles

\[ K = T_e n_e^{-2/3} \]

Entropy is a fundamental indicator of heating/cooling in the ICM (it remains unchanged during adiabatic processes)

Entropy at the cluster outskirts with **Suzaku**: George et al. 2009, Bautz et al. 2009, Kawaharada et al. 2010, ...

**Chandra** (Sanders et al. 2008)

**Entropy profile in A2204**
Basu, Zhang et al. 2010
**SZ confirmation of “Entropy Floor”**

Entropy comparison from SZ/X–ray imaging data

- **Central entropies from Chandra data**, taken from K. Cavagnolo’s ACCEPT site
- **Difference of entropy in the central ~200 kpc**

Basu, Zhang et al. 2010

Cavagnolo et al. 2009

Kaustuv Basu (AlfA, Univ. Bonn)  
ICM modeling with APEX–SZ data (KITP 2011)
High-Res SZ Imaging with ALMA

XMM J2235.3–2557 (z=1.39)  
Rosati et al. 2009

J. Santos’ talk
(apparently you can get temperature profile at $z=1$ with ~400 ks Chandra time!)
High-Res SZ Imaging with ALMA

Simulated ALMA observation at 90 GHz, Band 3 (Basu & Salomé, in prep)
Analysis of the intra-cluster medium (ICM) with resolved SZE maps have become a reality (some way to catch up with the sophistication and depth of the X-ray spectral analysis).

We have performed non-parametric X-ray/SZE modeling of ICM properties in two clusters out to $r_{200}$. Stacking analysis in progress.

Using APEX-SZ and XMM imaging data we were able to verify the existence of “entropy floors” in clusters, and also measure the decreasing gas temperature at the cluster outskirts (independently of X-ray spectroscopy).