High Resolution SZ Instrumentation

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Future Instruments Session
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Why should you care about high-resolution/multi-wavelength SZ?

1. Just look at the great results coming out from MUSTANG2, NIKA2, ALMA+ACA, and even CARMA (3 years after being decommissioned).

2. We can get a ground-based view of the same ICM you see in the X-ray at few to 10’s of arcsec resolutions.

3. Ground-based instrumentation develops much more quickly and is much less expensive (e.g. a 40-meter mm/submm telescope in the Atacama desert might cost about the same as NuSTAR, and essentially no temperature is “out of band” for SZ if you have enough frequency channels).

4. mm-wave facilities don’t just do SZ. Look at all the great results coming out of ALMA (e.g. the molecular filaments many here at SnowCluster talked about).
Chandra/VLA/HST (left) + MUSTANG1 (right)

Image Credits:
Left: van Weeren NRAO press release, 11 June 2014
https://public.nrao.edu/news/pressreleases/colliding-galaxy-clusters

Right: van Weeren + MUSTANG Collaboration
MUSTANG2 vs. Chandra

>15-sigma peak in a couple hours (< 10 ksec) on-source. Much more extended emission shows up than original MUSTANG1 observation. Hints of a NW sub-cluster pressure enhancement?

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MUSTANG2 vs. VLA

Magenta contours are VLA 1.8 GHz data, courtesy of Reinout van Weeren

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MUSTANG-2 compared to NIKA1 (right)

From R. Adam et al. 2017

Preliminary!
SZ instrument overview

* Bolometers offer larger fields of view (currently ~4-6 arcminutes for ~10-20” resolution imagers)

* Multiple beams on the sky means a faster mapping speed.

* Currently the main facilities are MUSTANG2 on the 100-meter GBT and NIKA2 on the IRAM 30-meter.

* Soon TolTEC on the 50-meter Large Millimeter Telescope (next year?).

* AtLAST: a 40-meter with >1 deg² field of view to be build in the Atacama desert in Chile, where the transmission is much better than IRAM, LMT, or GBT sites.

* CSST: 30-meter Chajnantor Submm Survey Telescope, also in the Atacama desert. This would likely be a private facility of Caltech.

* Interferometers provide even higher spatial resolution and give you spectral resolution “for free”.

* ALMA: fifty 12-meter antennas currently operating > 84 GHz.

* Large collecting area.

* ~0.9’ field of view. Largest scale it recovers is ~0.4’.

* ACA: 12 7-meter antennas, same frequencies as ALMA but more compact configuration, yielding the ability to recover more extended scales (~0.7’)

* Smaller apertures give ~1.4’ field of view, but much less collecting area, so the imaging speed is ~250 times slower.
Interferometer vs Single Dish Sensitivity

\[ S_{\text{rms}} \propto \frac{T_{\text{sys}}}{A_e \sqrt{N t \Delta \nu}} \]

- \( T_{\text{sys}} \) is the noise temperature, with contributions from the sky noise (\( T_{\text{sky}} \sim \) ambient temperature times opacity) and the instrument/receiver (\( T_{\text{rx}} \)). For a direct detection element (bolometer/KID), which does not preserve phase, \( T_{\text{rx}} \) can be much lower than for heterodyne receivers (interferometer), which are fundamentally limited by quantum noise (but in practice are typically 4-6 times higher).

- \( A_e \) is the effective aperture size of the telescope.

- \( N \) – for a bolometer camera is the number of independent detectors, and for an interferometer the number of baselines. For \( M \) interferometric elements, \( M = N^* (N-1) \).

- \( t \) is the integration time.

- \( \Delta \nu \) is the bandwidth. Bolometers typically have more bandwidth, but provide (essentially) no spectral information.
The Atacama Large Millimeter/Submillimeter Array (ALMA)

- 66 antennas: fifty in the 12-meter array, twelve in the 7-meter ALMA Compact Array (ACA), and four 12-meter telescopes in the Total Power Array (TPA).

- 12-meter array has a 56” primary beam (field of view) at 90 GHz. 7-meter ACA has 1.4’ primary beam at 90 GHz.

- 8 GHz of bandwidth for continuum observations. This will likely double in ~5 years.

- Typically recover scales as large as 0.6 times the primary beam, depending on observing strategy (i.e. the $uv$-space sampling of the sky, better if you can observe down to the shadowing limit to obtain shortest projected baselines).

Credit: ALMA (ESO/NAOJ/NRAO), O. Dessibourg
SZ sensitivity of ALMA

- Thermal SZ magnitude is plotted on right (top, blue curve), with ALMA bands shown in color. Typical radio and submm source spectra are shown in green and red.

- SZ decrement peaks at ~130 GHz, but one must account for the receiver and atmospheric noise (2nd plot).

- Band 1 (35-51 GHz, purple) will access scales as large as 3.6’ at the shadowing limit of the ALMA 7-meter Morita array (ACA).

- For a feature of fixed scale and Compton $y$, ALMA’s sensitivity to the thermal SZ will peak in Band 2 (67-116 GHz), a new receiver we (the EU, led by ESO) hope to build soon for ALMA.

- Notably, the Band 2 Receiver will be forward compatible with the expected 16-GHz wideband upgrade to the ALMA correlator and digitizer electronics. Continuum/SZ sensitivity will improve by a factor of $\sqrt{2}$.

- The Band 1 and original Band 3 receivers will still be limited to 8 GHz (even after upgrades to the ALMA correlator and digitizers).
MUSTANG-2 on the 100-meter GBT

* The 100-meter Green Bank Telescope (GBT) has a resolution of 8.5” at 90 GHz

* This is over half the collecting area of the ALMA 12-meter array (after accounting for the ~35% aperture efficiency of the GBT at 90 GHz).

* MUSTANG-2 is now observing, and has 215 detectors spanning a ~4.5 arcminute field of view.

* The current mapping speed of 0.056 mJy hr^{1/2} in the central 2’ diameter of 6.5’ diameter maps. This corresponds to dy ~ 3e-5 when considering the 9” beam size.

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NIKA2 on the IRAM 30-meter Telescope

• NIKA2 operates at 150 GHz and 260 GHz from the IRAM 30-meter, located at 2850 meters elevation, in the Sierra Nevada mountains above Granada, Spain. Replaced NIKA1.

• NIKA2 has 616 pixels at 150 GHz and 2 arrays (for polarization) of 1140 detectors each at 260 GHz, covering a 6.5’ diameter field of view.

• NIKA1 and NIKA2 have been trailblazers for lumped-element kinetic inductance detectors (LEKIDs, see Zmuidzinas 2012 review), and made the first SZ detections using KIDs.

• See Florian Ruppin’s talk.
NIKA2 2 mm map (left) vs. MUSTANG(1) 3.3 mm map (right). NIKA2’s 6.5-arcminute FoV recovers much larger scales than MUSTANG’s 42”. NIKA2 also offers a 1-mm channel simultaneously, though this still needs instrumental improvements.

Images are from Ruppin et al. 2018 (see Florian Ruppin’s talk for reference)
Large Millimeter Telescope / Gran Telescopio Milimétrico (LMT/GTM)

* Is a 50-meter telescope, now observing with the full optical surfaces, and is located at 4600 meters above sea level in Puebla, Mexico.

* Is built at a great sight for mm-wave astronomy, with an average of ~2 mm PWV (precipitable water vapour) over the year. For comparison, good weather at the IRAM 30-meter is ~4 mm PWV, and for the GBT 100-meter is 4-10 mm PWV.
TolTEC on the LMT/GTM

× 3-color kinetic inductance detector (KID) imaging polarimeter camera spanning tSZ null (~218 GHz). Bands are centered at 150, 220, and 280 GHz.

× Fully samples the 4’ field of view of the LMT.

× Planned commissioning in early 2019.

× The numbers below imply a thermal SZ mapping speed at 2.1 mm (150 GHz) achieving $\delta y = 4-10 \times 10^{-6}$ in 1 hour assuming a map 6.5’ in diameter.

Note: All detectors are polarization-sensitive. Mapping speed values are for opacity of $\tau_{225\text{GHz}}=0.1$.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Beamsize (FWHM)</th>
<th>Number of Pixels</th>
<th>Number of Detectors</th>
<th>Maximum Mapping Speed Prediction</th>
<th>Minimum Mapping Speed Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 mm</td>
<td>9.5 arcseconds</td>
<td>450</td>
<td>900</td>
<td>69 deg$^2$/mJy$^2$/hr</td>
<td>10 deg$^2$/mJy$^2$/hr</td>
</tr>
<tr>
<td>1.4 mm</td>
<td>6.3 arcseconds</td>
<td>900</td>
<td>1800</td>
<td>20 deg$^2$/mJy$^2$/hr</td>
<td>3 deg$^2$/mJy$^2$/hr</td>
</tr>
<tr>
<td>1.1 mm</td>
<td>5 arcseconds</td>
<td>1800</td>
<td>3600</td>
<td>12 deg$^2$/mJy$^2$/hr</td>
<td>2 deg$^2$/mJy$^2$/hr</td>
</tr>
</tbody>
</table>

× Source: [http://toltec.astro.umass.edu/about.php](http://toltec.astro.umass.edu/about.php)

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# High Resolution SZ instrument mapping speeds

<table>
<thead>
<tr>
<th>Instrument/Telescope</th>
<th>$\nu$ (GHz)</th>
<th>D (m)</th>
<th>$\theta$ (&quot;)</th>
<th>FoV (’)</th>
<th>S (µJy) in 1 hr$^1$</th>
<th>Compton $y$ (10$^{-6}$)</th>
<th>$\delta T$(µK) in 1 hr</th>
<th>Map size (sq. armin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MUSTANG-2 on the 100-m GBT</td>
<td>90</td>
<td>100</td>
<td>10</td>
<td>4.5’</td>
<td>56</td>
<td>19.7</td>
<td>85.7</td>
<td>33</td>
</tr>
<tr>
<td>NIKA2 on the IRAM 30-m</td>
<td>150</td>
<td>30</td>
<td>18</td>
<td>6.5’</td>
<td>444</td>
<td>74</td>
<td>192</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>220</td>
<td>-</td>
<td>12</td>
<td>-</td>
<td>2350</td>
<td>1211</td>
<td>2221</td>
<td>-</td>
</tr>
<tr>
<td>ALMA 12-m</td>
<td>95</td>
<td>12</td>
<td>~5</td>
<td>0.9’</td>
<td>11.3</td>
<td>19.2</td>
<td>84</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>-</td>
<td>~13</td>
<td>2’</td>
<td>7.2</td>
<td>17.5</td>
<td>92</td>
<td>3.2</td>
</tr>
<tr>
<td>ACA 7-m</td>
<td>95</td>
<td>7</td>
<td>~13</td>
<td>1.4’</td>
<td>148</td>
<td>37.2</td>
<td>162</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>-</td>
<td>~33</td>
<td>3.2’</td>
<td>95</td>
<td>34.2</td>
<td>179</td>
<td>7.8</td>
</tr>
<tr>
<td>TolTEC on the LMT/GTM 50-m</td>
<td>150</td>
<td>50</td>
<td>10.0</td>
<td>4’</td>
<td>11.1-29.6</td>
<td>4-10.6</td>
<td>10.3-27.5</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>220</td>
<td>-</td>
<td>6.9</td>
<td>-</td>
<td>20.4-54.4</td>
<td>330-870</td>
<td>33.7-89.7</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>280</td>
<td>-</td>
<td>5.4</td>
<td>-</td>
<td>26.2-69.5</td>
<td>29-77</td>
<td>78.8-209</td>
<td>-</td>
</tr>
</tbody>
</table>

1. For the X-ray astronomers: 1 hr = 3.6 ksec.
2. Estimates for NIKA2 were performed using version 7 of the NIKA2 time estimator 2018.JAN.20 (http://www.iram.es/IRAMES/mainWiki/Continuum/TimeEstimatorScript_summer).
3. The TolTEC imaging speeds are just projections at this point, assuming background-limited performance. The values here were computed with the help of Sean Bryan’s mapping speed projection memo written for the TolTEC group. As with any instrument, the actual on-sky performance remains to be demonstrated.
Future High-resolution SZ mapping

* All the large (>12-meter) single dish mm/submm observatories are northern hemisphere facilities.

* Upgrades to SPT and ACT, Simons Observatory (which ACT is part of), CCAT-prime (6.5 meter), CMB-S4, etc. will improve sensitivity and frequency coverage, but not the resolution (~1 arcminute).

* However, a number of large (25-50 meter) single dish telescopes are being studied. I would like to unite the community behind the “Atacama Large Aperture Submm/mm Telescope” (AtLAST) project.

* AtLAST would be a publically accessible 40-meter class telescope with a field of view > 1 square degree, and would be built high in the Atacama desert (roughly 5100-5600 meters). A filled focal plane at the same mm-wave frequencies as the LMT would conservatively be at least 225 times faster (1 deg vs. 4’ FoV), while the lower atmospheric noise would further improve the mm-wave mapping speed by another factor >2 times.

* With a mapping speed ~500 times faster than LMT and 4-5 orders of magnitude higher than ALMA, AtLAST would therefore be transformative for mm-wave observations, including resolved SZ studies.

* Find out more and get involved by going to http://atlast-telescope.org/ and emailing atlast@eso.org to join a working group. Get involved or AtLAST will never happen!

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## Future mapping speed forecasts

<table>
<thead>
<tr>
<th>Instrument</th>
<th>$\nu$ (GHz)</th>
<th>$\theta$ (&quot;)</th>
<th>FoV (')</th>
<th>$S$ ((\mu)Jy) in 1 hr$^1$</th>
<th>Compton $y$ ($10^{-6}$)</th>
<th>$\delta T$ ((\mu)K) in 1 hr</th>
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<td>5.4</td>
<td>-</td>
<td>26.2-69.5</td>
<td>29-77</td>
<td>78.8-209</td>
<td>-</td>
</tr>
<tr>
<td>7-band camera$^1$ on the AtLAST 40-m</td>
<td>93</td>
<td>20.4</td>
<td>165</td>
<td>5.2</td>
<td>0.5</td>
<td>2.2</td>
<td>3600</td>
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<tr>
<td></td>
<td>150</td>
<td>12.6</td>
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<td>5.0</td>
<td>1.1</td>
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<td>220</td>
<td>8.6</td>
<td>165</td>
<td>6.0</td>
<td>61.6</td>
<td>6.3</td>
<td>-</td>
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<tr>
<td></td>
<td>278</td>
<td>6.8</td>
<td>233</td>
<td>6.6</td>
<td>4.7</td>
<td>12.3</td>
<td>-</td>
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<tr>
<td></td>
<td>350</td>
<td>5.4</td>
<td>261</td>
<td>17.2</td>
<td>12.3</td>
<td>73.4</td>
<td>-</td>
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<tr>
<td></td>
<td>405</td>
<td>4.7</td>
<td>261</td>
<td>30.0</td>
<td>29.5</td>
<td>252</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>463</td>
<td>4.1</td>
<td>261</td>
<td>91.2</td>
<td>143.6</td>
<td>1620</td>
<td>-</td>
</tr>
</tbody>
</table>

1. Assuming FoV for AtLAST first generation instrumentation will be determined by evolving NIKA2 and TolTEC detector counts a few (~5) years, and will not fill the >1 deg$^2$ field of view of the telescope.
2. These AtLAST forecasts assume top 50% weather in June-August (i.e. best 3 months in Atacama), and do not account for imperfect subtraction of the atmosphere on extended scales.
3. The 30-meter Chajnantor Submm Survey Telescope (CSST) would have similar performance as AtLAST in terms of $\delta T$ or $y$, but $\frac{3}{4}$ the resolution, and lower point source sensitivity in Jy by a factor of $(40/30)^2\sim1.8$. See Sunil Golwala’s talk from the AtLAST workshop at ESO (https://www.eso.org/sci/meetings/2018/AtLAST2018/program.html).

Again: find out more and get involved by going to [http://atlast-telescope.org/](http://atlast-telescope.org/) and emailing [atlast@eso.org](mailto:atlast@eso.org) to join a working group. *Get involved or AtLAST will never happen!*