SPT SMGs: High-redshift star formation under the cosmic microscope

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SPT
The South Pole Telescope

**Telescope**
- 10 meter off-axis sub/mm telescope
- located at the geographic south pole
- 1 deg$^2$ field of view
- ~1' beams
- optimized for fine scale anisotropy measurements

**SPT-SZ Camera (1st Generation):**
- 2007 – 2011
- 960 pixel mm camera, 1 deg$^2$ FOV
- 1.4, 2.0, and 3.0 mm
- completed 2500 deg$^2$
- 18 $\mu$K-arcmin depth, ~1 mJy

**SPT-pol Camera (2nd Generation):**
- 2012 – 2016
- 1600 detector mm camera, 1 deg$^2$ FOV
- 2 and 3 mm + polarization
- currently surveying 500 deg$^2$
- 4.5 $\mu$K-arcmin depth

**SPT-3G Camera (3rd Generation):**
- 2017 – 2020
- 15k detector mm camera, 2.4 deg$^2$ FOV
- 1.4, 2, 3 mm + polarization
- planned 2500 deg$^2$ x5 deeper
- 2.5 $\mu$K-arcmin depth
SPT Science

Cosmic Microwave Background:

- CMB Polarization: Hanson et al. 2013 PRL

Galaxy Clusters:


Galaxy Evolution:

- Catalog of mm sources: Mocanu et al. 2013 ApJ
- High-z strongly-lensed starforming galaxies: Vieira et al. 2013 Nature
South Pole Telescope
2 mm data
South Pole Telescope
2 mm data

Galaxy Clusters detected with the Sunyaev-Zeldovich effect

“Shadows” in the cosmic microwave background from inverse compton scattering

Use ‘em to measure Dark Energy

Probes the 2nd half of the history of the universe
South Pole Telescope
2 mm data

Majority of the SPT sources are high redshift AGN with the jets pointed at us. They have radio, x-ray, and sometimes gamma-ray counterparts.
South Pole Telescope
2 mm data

high redshift
strongly lensed
dusty starforming
galaxies

Use gravitational lensing as a cosmic telescope to study the first galaxies and directly image dark matter
mm-wave source counts

Vieira et al 2010
Mocanu et al 2013
Everett et al in prep

![Graph showing mm-wave source counts with data points and curves for different categories such as Total, Strongly Lensed SMGs, Unlensed SMGs, Blazars, and SPT Total Source Counts. The graph has a logarithmic scale for both axes, with the x-axis representing 220 GHz $S_V$ in mJy and the y-axis representing $N(>S)$ in degrees$^{-2}$. The graph also includes a confusion limit and SPT-3G and SPT-SZ marks.]
2500 deg$^2$ SPT survey
81 strongly lensed SMGs at $S_{870\mu m} > 25$ mJy
The SPT sources are rare and bright (~1/30 deg$^2$)
The SPT selection is independent of lensing configuration (e.g. $r_E$, $z_{lens}$, $z_{source}$)
Majority are galaxy-galaxy lenses with $r_E \sim 0.5''$ and magnification $\mu \sim 8$
4 cluster lenses (~5%)
4 unlensed sources (~5%)

When the system is unresolved, we save $\mu^2$ time on the telescope —> great for line surveys. (20 min instead of 20 hours)
When we resolve the system we gain in angular resolution by $\sqrt{\mu}$ —> we can resolve kpc scales.
Excellent complement to deep submm surveys.

Gravitational Lensing = cosmic microscope
Spectroscopic redshift survey with ALMA

ALMA Cycle 0 Band 3
100 GHz compact configuration
26 sources
5 tunings in the 3 mm band
~20 minutes per source

Vieira et al. 2013 Nature
Composite CO spectrum

\[ T_{\text{EX,CO}} < 50\text{K} \]
\[ 1 < \tau_{\text{CO}(1-0)} < 10 \]

• 100+ sources total from 2500 deg$^2$ SPT-SZ survey

• 81 with $S_{870\mu m}>25$ mJy —> this is our sample

• ALL have ALMA 3mm spectra

• 69 with confirmed spectroscopic redshifts (>85% complete so far)

• 1.9<z<6.9; median < z > = 4.1; 36 at z>4, 12 at z>5

• of these, 42 have ALMA imaging. (call it half)
• 82 with S_{870um}>25 mJy from 2500 deg^2 SPT-SZ survey —> All have ALMA 3mm spectra. This is among the largest samples of lensed galaxies in the literature.
• 69 with confirmed and unambiguous spectroscopic redshifts (>85% complete so far). This is among the highest spectroscopic completeness of any sample of high redshift galaxies
• 1.9<z<6.9; median < z > = 4.1; 36 at z>4, 12 at z>5
• Of these, 42 have ALMA imaging. (call it half)
• SPT has discovered 70% of dusty star forming galaxies at z>4
submm-selection

\[ L_{\text{FIR}} = \varepsilon 4\pi r^2 \sigma T_d^4 \]

- SMG z > 1
- Lensed SPT

\( \mu L_{\text{FIR}} \) vs. \( T_d [\text{K}] \), \( z \) vs. \( \mu L_{\text{FIR}} \)
ALMA Cycle 0 Band 7 350 GHz
2 minute snapshots with 16 antennas

8'' x 8'' boxes

= 1 orbit HST/WFC3 imaging
= 2 minute ALMA 350 GHz snapshot
ALMA
SDP 81
z=3.042

Data like this coming for 3 SPT sources soon!
Dark Matter Sub-Structure detection with ALMA

- We can use these background sources as backlights to image the foreground lensing halo.
- Dark matter substructure is an interesting and powerful probe of LCDM on small scales
- ALMA SDP81- like data for 3 SPT sources was completed in Cy4

SPT0346-52 at z=5.7
The most intensely star forming galaxy

well above the MS

50ks with Chandra
AGN = no

Ma et al. 2016
Ma et al. 2015
$\text{H}_2\text{O}$ as a resolved SFR indicator

- $\text{H}_2\text{O}$ is bright!
- Best tracer of $L_{\text{IR}}$
- We want to calibrate this line as a resolved SFR indicator
- We have three sources with 10-20$\sigma$ resolved detections of $\text{H}_2\text{O}$ 988 GHz
- B9 continuum coming in cycle 5

<table>
<thead>
<tr>
<th>source</th>
<th>$z$</th>
<th>magnification</th>
<th>$r_{\text{Einstein}}$ [arcsec]</th>
<th>$L_{\text{IR}}$ [$10^{12}L_\odot$]</th>
<th>$T_{\text{dust}}$ [K]</th>
<th>$L_{\text{H}<em>2\text{O}}$ [$10^8L</em>\odot$]</th>
<th>$L_{\text{H}<em>2\text{O}}/L</em>{\text{IR}}$ [$10^{-5}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPT0529-54</td>
<td>3.369</td>
<td>13.2 ± 0.85</td>
<td>1.536</td>
<td>3.9 ± 0.7</td>
<td>33.3 ± 0.9</td>
<td>3.8 ± 0.3</td>
<td>0.5 ± 0.2</td>
</tr>
<tr>
<td>SPT0532-50</td>
<td>3.399</td>
<td>10.0 ± 0.57</td>
<td>0.55</td>
<td>9.0 ± 1.8</td>
<td>39.2 ± 1.0</td>
<td>21.7 ± 0.4</td>
<td>1.9 ± 0.2</td>
</tr>
<tr>
<td>SPT0538-50</td>
<td>2.782</td>
<td>20.0 ± 1.8</td>
<td>1.987</td>
<td>3.8 ± 0.9</td>
<td>38.5 ± 1.1</td>
<td>11.9 ± 0.7</td>
<td>1.2 ± 0.2</td>
</tr>
</tbody>
</table>
Future line line studies:

- This high redshift sample opens up a new window onto the ISM
- $z > 4$ brings [CII]158μm from B10 to B7 —> high resolution spatially resolved spectroscopy
- redshift makes FSL [OI]63μm and [OIII]52μm possible
- now: CO, $\text{H}_2\text{O}$, HCN, OH, …
- Fute: HD: CH … ?
We will finally be able to do good, old-fashioned optical astronomy with the SPT sources:

- stellar masses
- calibrating obscured+unobscured SFR indicators
- Resolved Hα, Paα
- metallicities
- AGN diagnostics
- 3.3 um PAH line
- etc
Origins Space Telescope
2030—2040
9 meter
7—300 μm
4 K

Hubble Space Telescope
1990—2018
2.4 meter
0.1—2.4 μm
260 K

James Webb Space Telescope
2018—2028
6.5 meter
0.6—27 μm
50 K

James Webb Space Telescope
2018—2028
6.5 meter
0.6—27 μm
50 K
OST provides the crucial link in wavelength coverage between JWST and ALMA to complete our view of the evolution of the universe.

https://asd.gsfc.nasa.gov/firs/
assuming:
20'x20' FOV @ 60 um
$T_d \sim 35$K $z \sim 4$
SPTpol
500 deg$^2$ survey at 150 GHz with arcminute resolution

- SPTpol = 2nd generation survey
- x2 as deep as SPT-SZ
- SPT-3G has deployed
Open Questions:

- When was the first dust formed?
- When were the first massive galaxies formed?
- How are these extreme galaxies forming? Inside-out ? Outside-in ?
- What regulates and shuts down the most intense SF?
- Can we develop FIR lines as a robust metallicity indicator for dusty galaxies?
- What are the roles of BHs and accretion in this evolution?
- Does the structure in the subhalo structure of the foreground lenses jive with LCDM ?
Conclusions:

- CMB experiments have made huge impacts in the fields of cosmology and astrophysics and will continue to do so into the next decade.
- SPT has constructed one of the most unique samples of high redshift galaxies and possibly the best sample for molecular studies.
- SPT+ALMA redshift survey is complete
- This is THE sample for detailed high-redshift studies of SMGs
- SPT-3G has deployed and is in commissioning.
- Many exciting years ahead with ALMA and JWST.