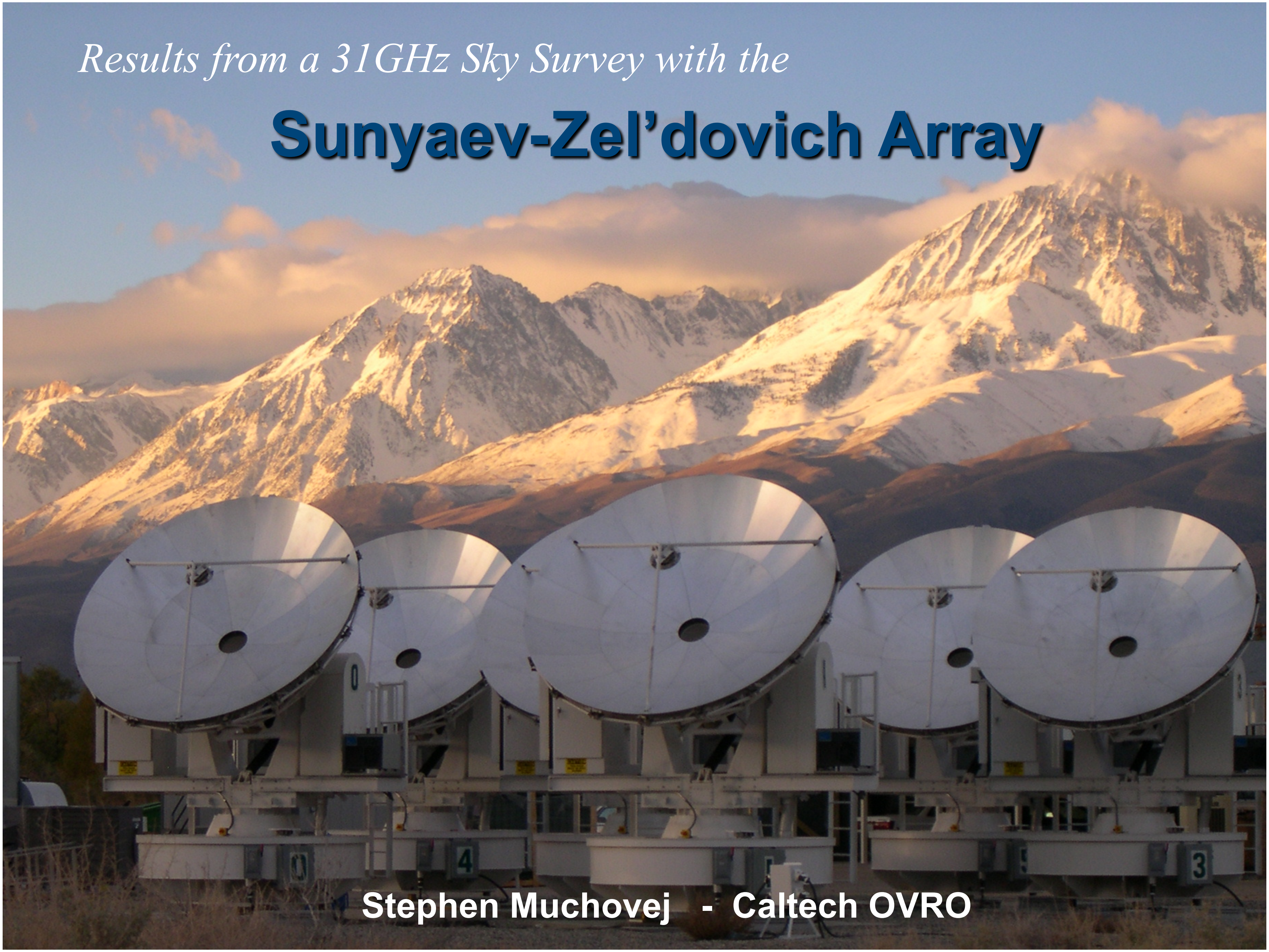

Results from a 31GHz Sky Survey with the
Sunyaev-Zel'dovich Array
Stephen Muchovej - Caltech OVRO

The Sunyaev-Zel'dovich Array (SZA)

Chicago:

John Carlstrom (P.I), Erik Leitch, Clem Pryke, John Cartwright, Adam Mantz, Dan Marrone, Tom Plagge, Marcus Runyan, Chris Greer, Ryan Hennessy, Michael Loh, Matthew Sharp

Columbia:

Amber Miller, Tony Mroczkowski, Stephen Muchovej

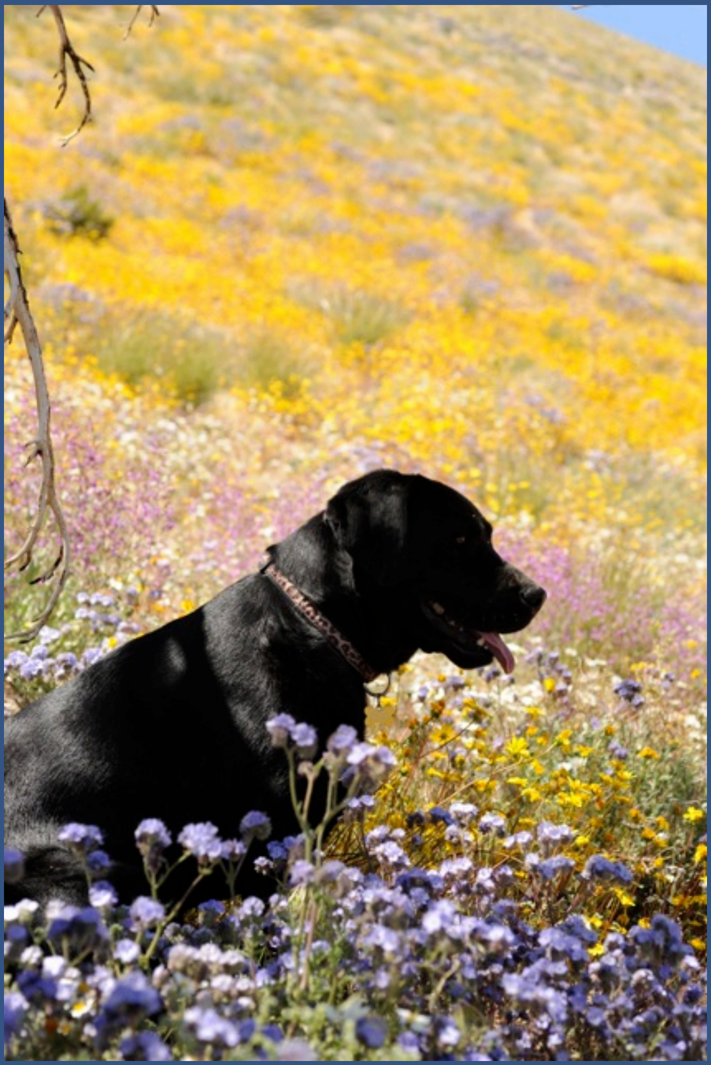
Caltech (OVRO):

David Hawkins, James Lamb, David Woody

NASA/MSFC: Marshall Joy

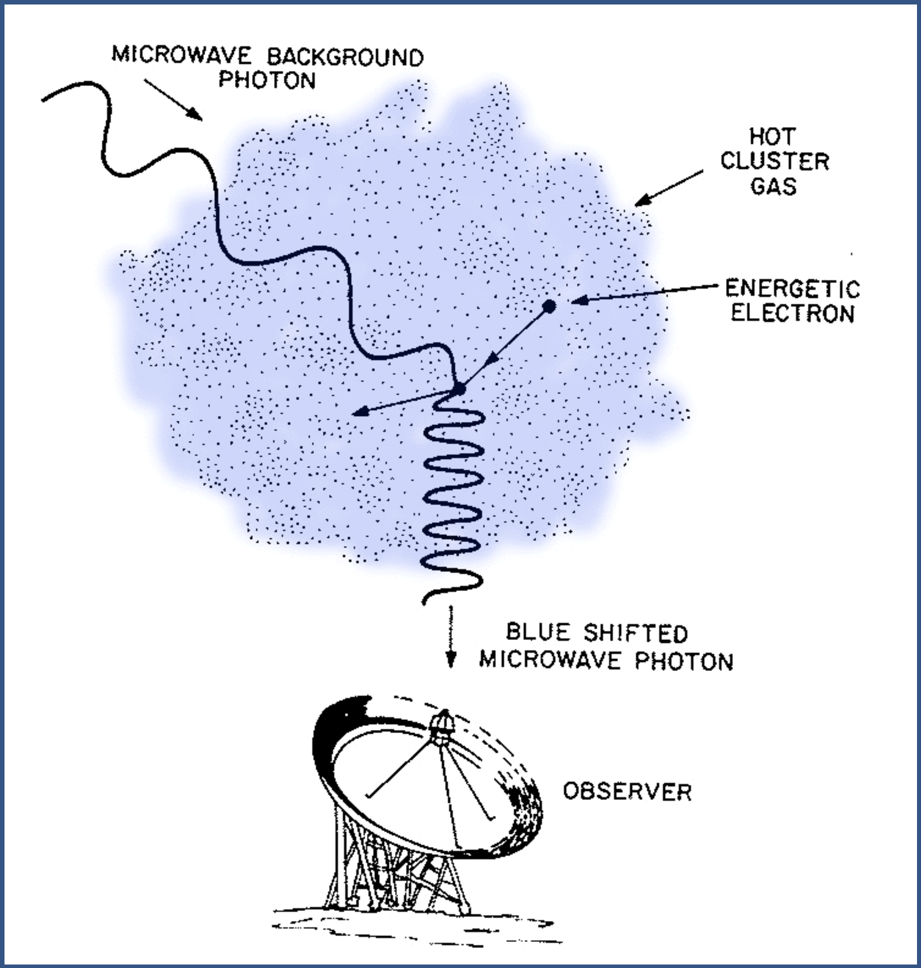
Photo: Leitch

OUTLINE

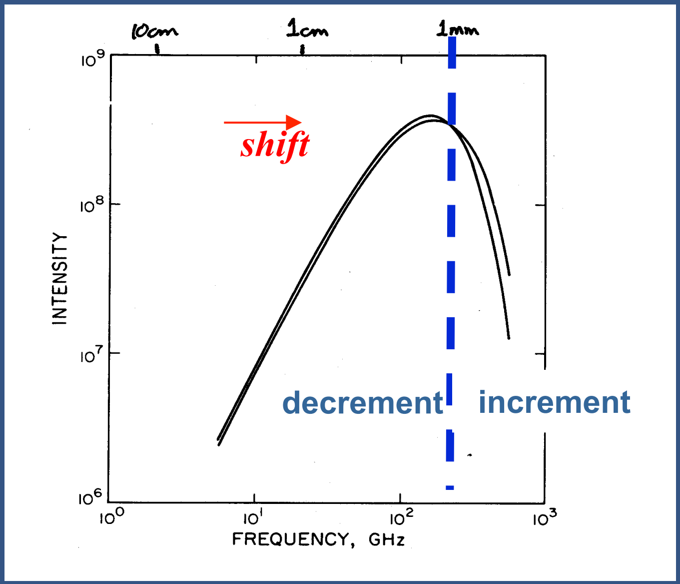


I. Introduction to the Instrument
II. SZA Cluster Observations
III. The SZA survey
IV. Survey Results
    I. Source Populations
    II. CMB Anisotropy
    III. Cosmology with the Cluster Survey
V. A very *Anomalous* Field

The Sunyaev-Zel'dovich Effect from Clusters



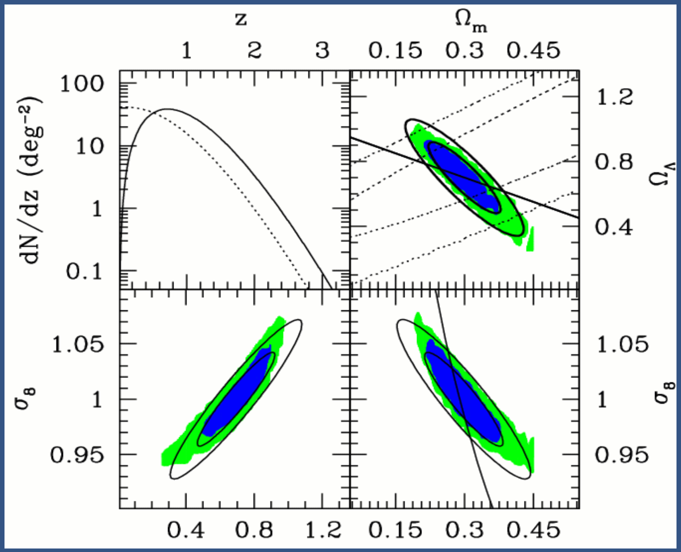
L. Van Speybroeck



- Measure of Integrated Pressure (Total Thermal Energy)
- Clean Measure of Baryon Gas Mass
- Redshift independent

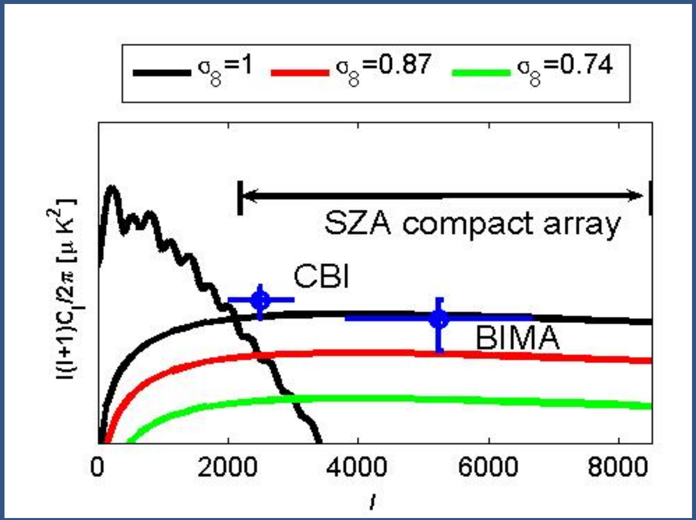
SZA Science Goals

- Several Square Degree Survey
  (Stephen Muchovej thesis)
  - *Cluster Abundance dN/dz*
  - *Measure σ_8 (rms linear fluctuations in the mass distribution on scales of 8 Mpc)*
  - *Tests of Non-Gaussianity*



Carlstrom, Holder, Reese, 2002, ARAA V40

- Pointed Observations
  - Scaling Relations
  - Better Estimates of Cluster Observables/Scaling Relations
    (Tony Mroczkowski thesis)

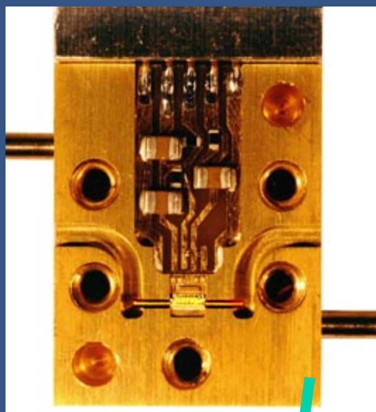


- Detailed Imaging of Clusters at 90GHz
- CMB Anisotropy Measurements
  (Matthew Sharp thesis)

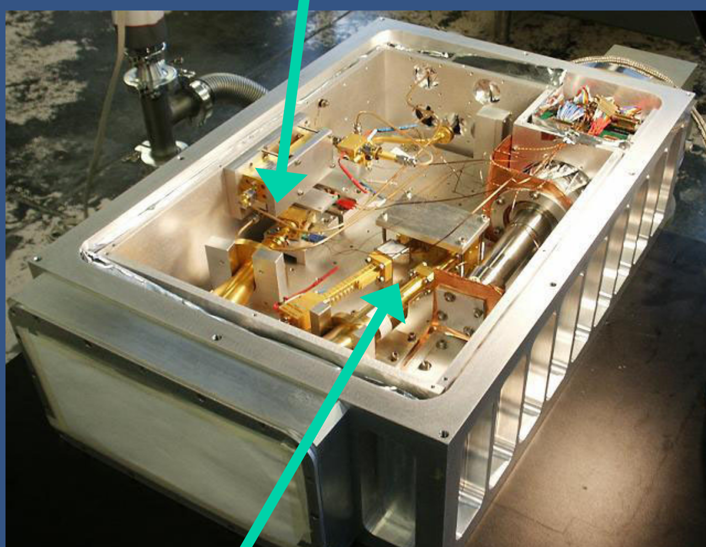
The SZA: Eight 3.5m telescopes

- Stand alone array
- Allow close pack configurations for high brightness sensitivity
  - 1.2 diameter minimum spacing
- Two bands 26-36, 85-115 GHz for survey & follow-up
- High accuracy telescopes permit observations to 300 GHz
  - 30 um RMS surface
  - 1 arcsec rms pointing spec
- 8 GHz correlation bandwidth for sensitivity
  - 10 times BIMA bandwidth
- SZA + CARMA: 23-element heterogeneous array
  - Sensitive, high resolution, 5 - 10” SZE imaging

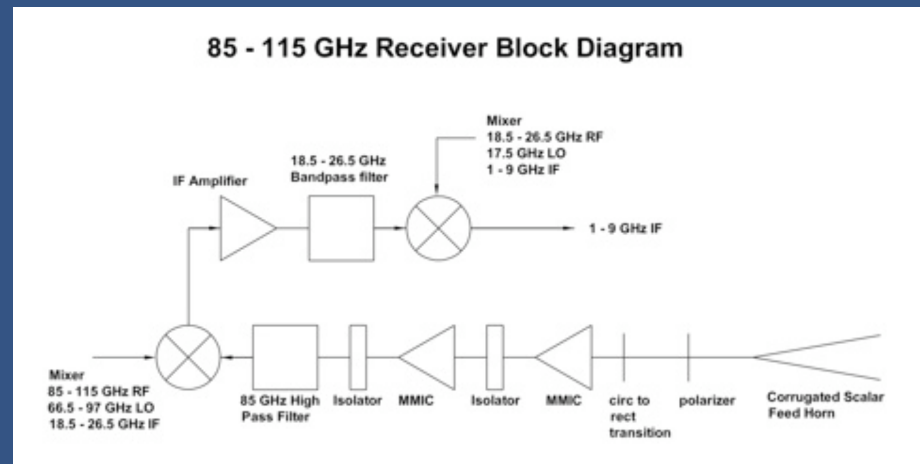
SZA Receiver



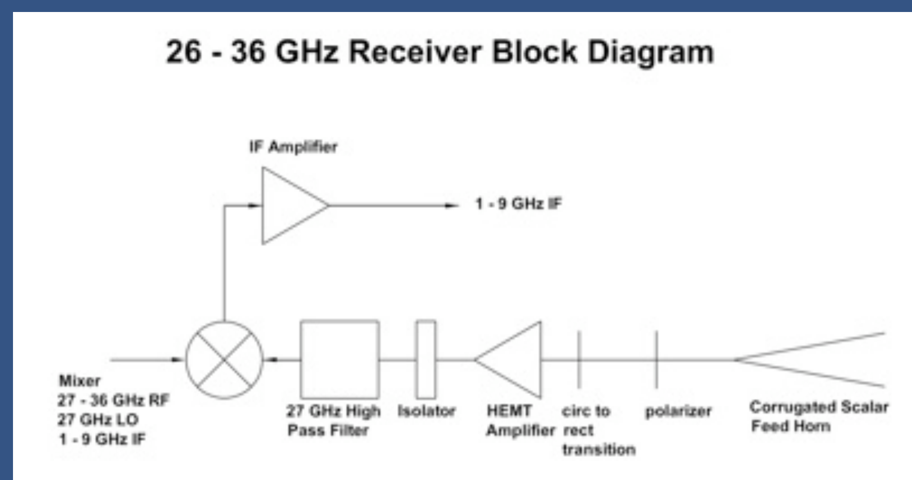
85 - 115 GHz SZA MMIC Amplifier. Design from UMASS Amherst, blocks built in Chicago, Receivers built and tested Columbia University



26-36GHz HEMT Amplifier recycled from DASI

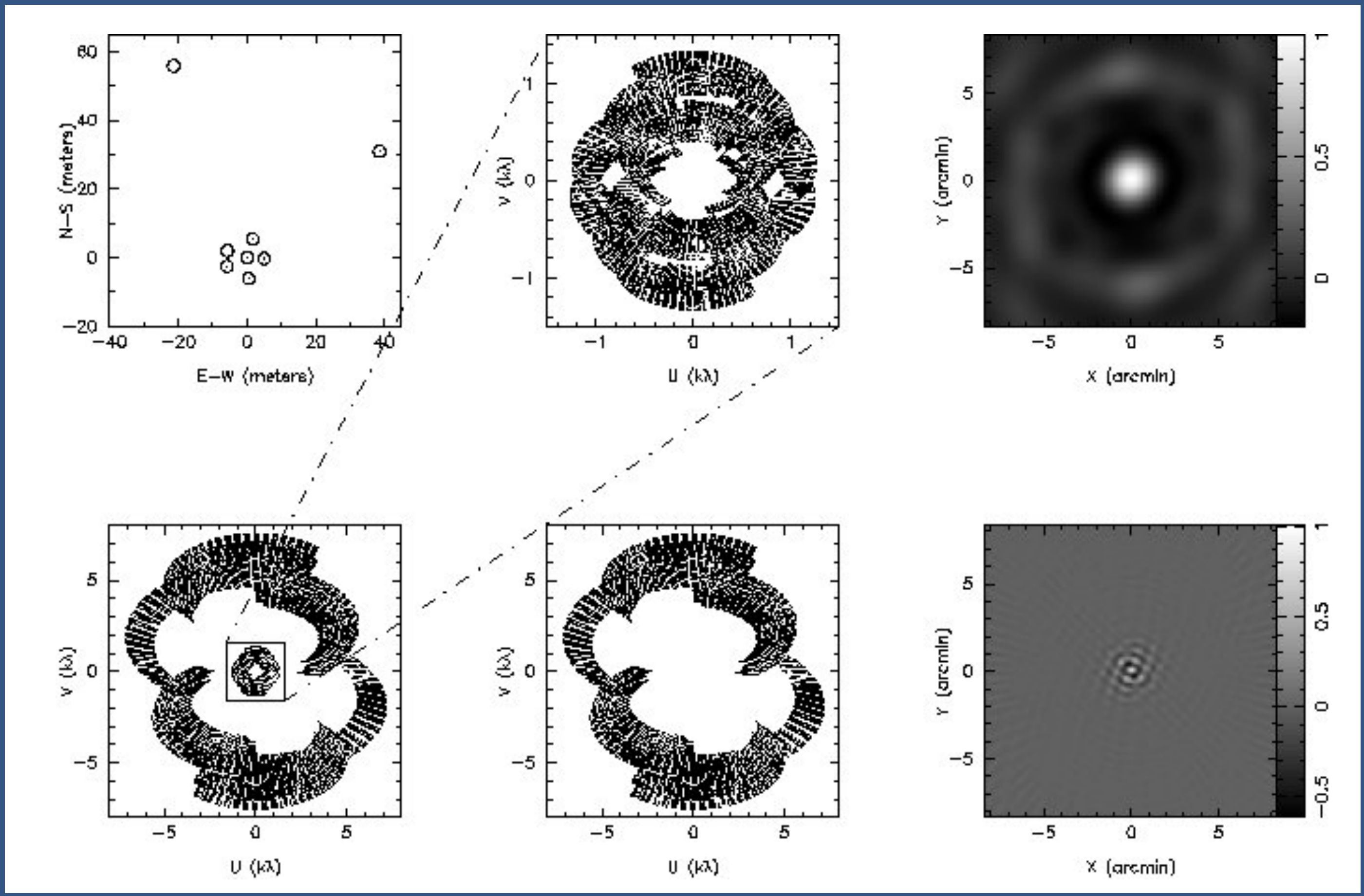


Heterodyne Systems with HEMT amplifiers



SZA *uv* coverage and synthesized beams

SZA configuration

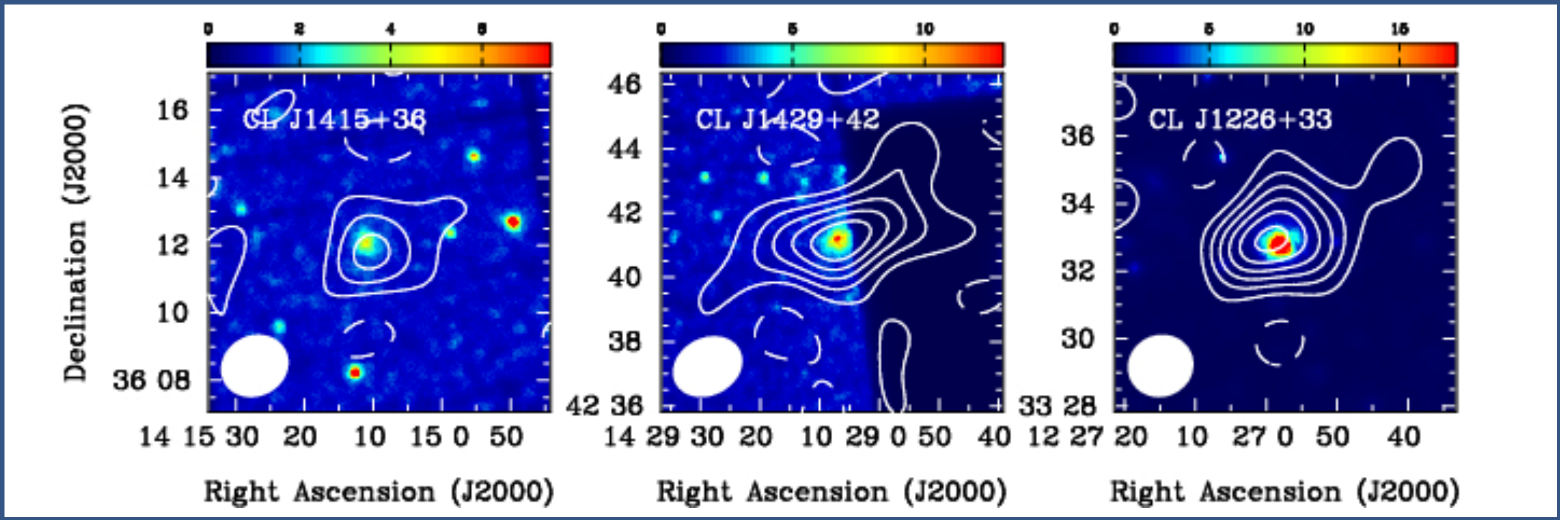


u-v coverage for entire array

u-v coverage
short baselines (top)
Long baselines (bottom)

"Dirty beams"
Short baselines (top)
Long baselines (bottom)

High-z clusters observed during Commissioning of SZA



ClJ1415.1+3612
- z ~ 1.03
- 1.9x10^14 M_solar
- 34.1 hours
- rms 0.16mJy/beam

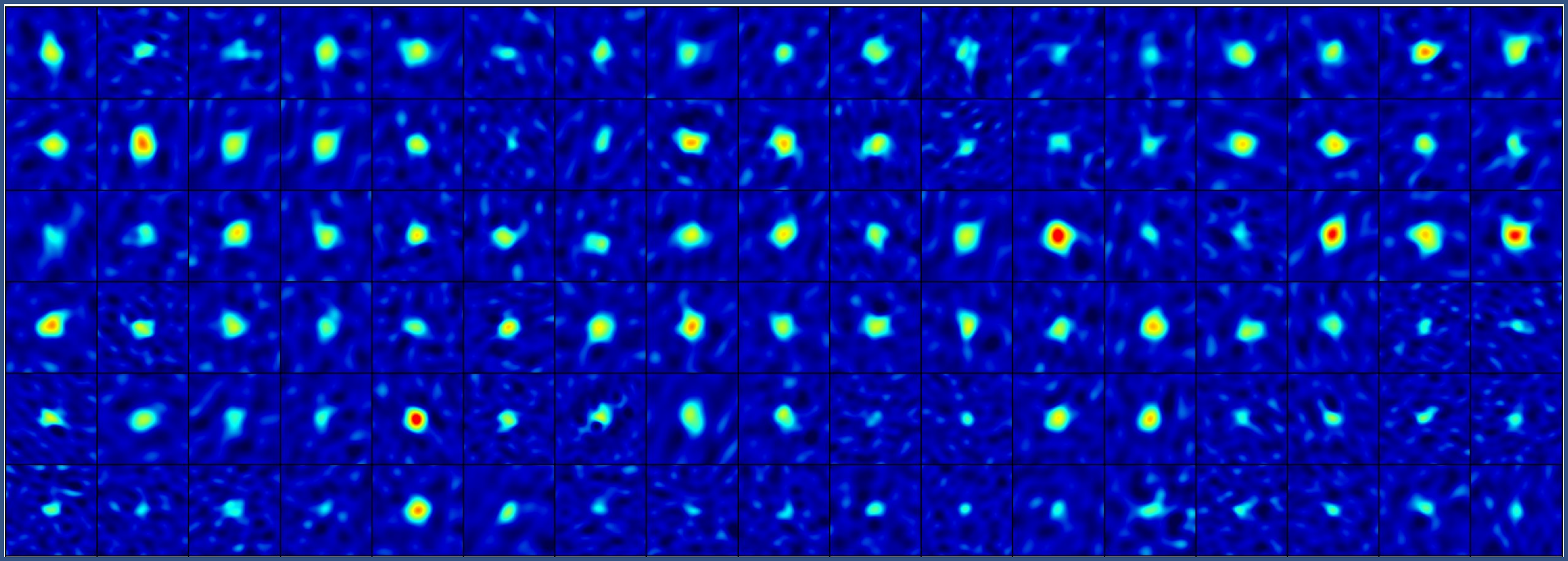
ClJ1429.0+4241
- z ~ 0.92
- 3.4x10^14 M_solar
- 32.1 hours
- rms 0.17mJy/beam

ClJ1226+3332
- z ~ 0.89
- 7.2x10^14 M_solar
- 7.6 hours
- rms 0.38mJy/beam

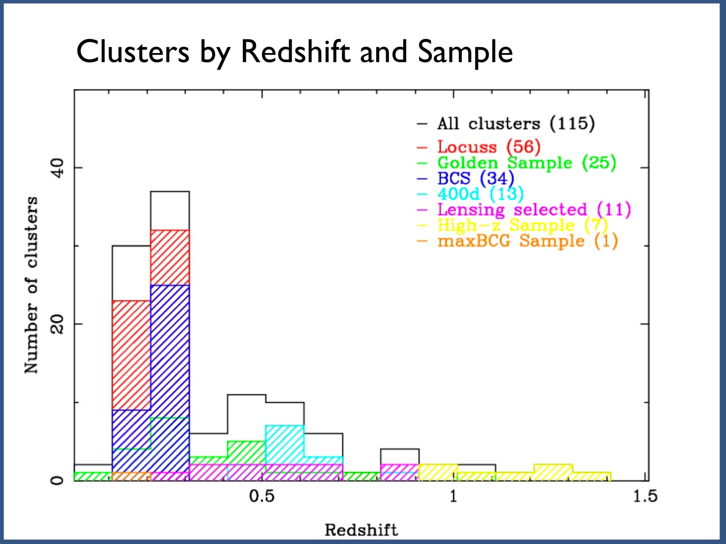
- Extended redshift range of reported SZ measurements
  - Until recently, Cl1415 was the highest redshift cluster yet seen in SZE
- Extend the low-mass range
  - Cl1415 is one of lowest mass clusters observed in the SZE
- SZA observations sensitive to angular scales out to ~ 7' (beyond “virial radius” of clusters)
- Good Agreement with X-ray cluster mass and temperature
- Good News for this and future SZ surveys

Muchovej et. al 2007. ApJ 663, 708

Many clusters have been observed

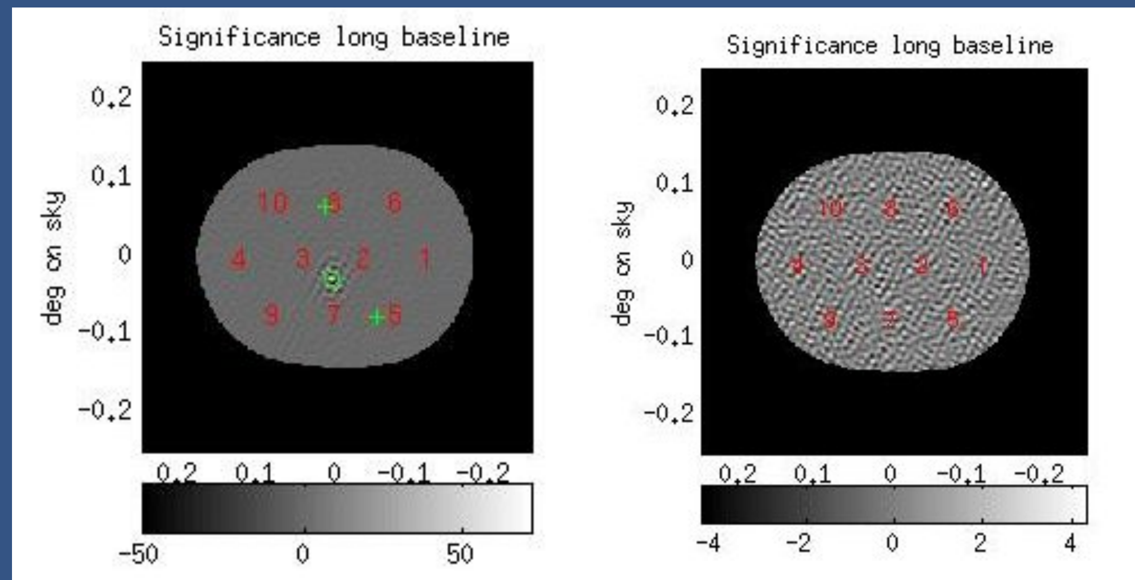


- Detected over 250 clusters up to a redshift of 1.4
- Detected clusters with masses down to ~ 10^14 $M_\odot$
- Various on-going projects quantifying scaling relations given different selection effects (e.g., X-ray, Weak Lensing)
- Current projects focusing on statistical properties of the full sample.



Test of Survey on Cl0016+0016

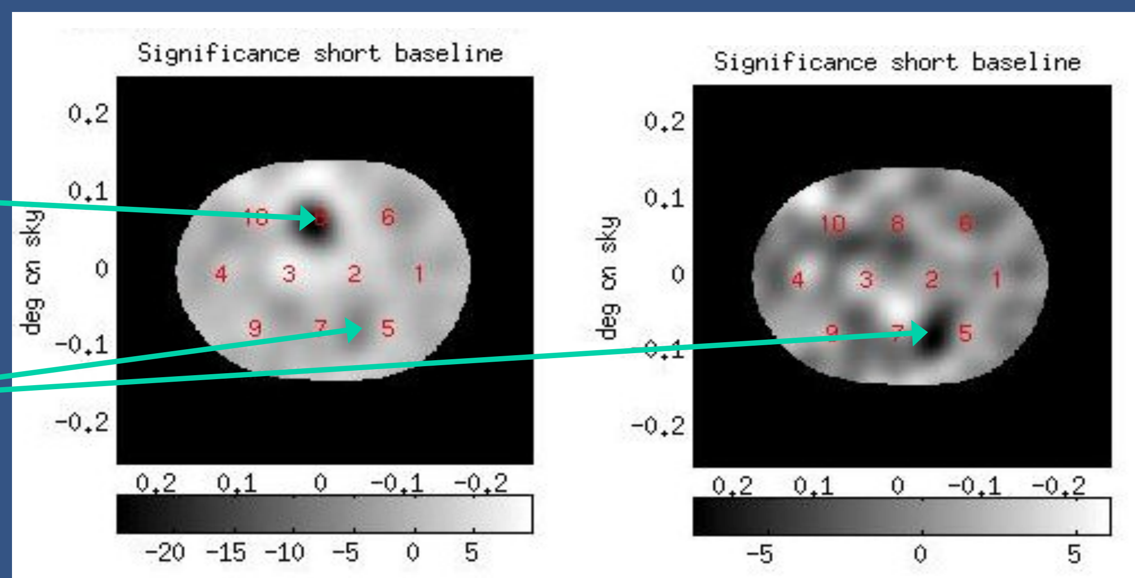
- 10 pointing Mosaic in 3-4-3 Hex Pattern
- 4.8 arcminute Separation
- Median rms 0.31mJy/beam
- Bright Point Source at > 60 sigma



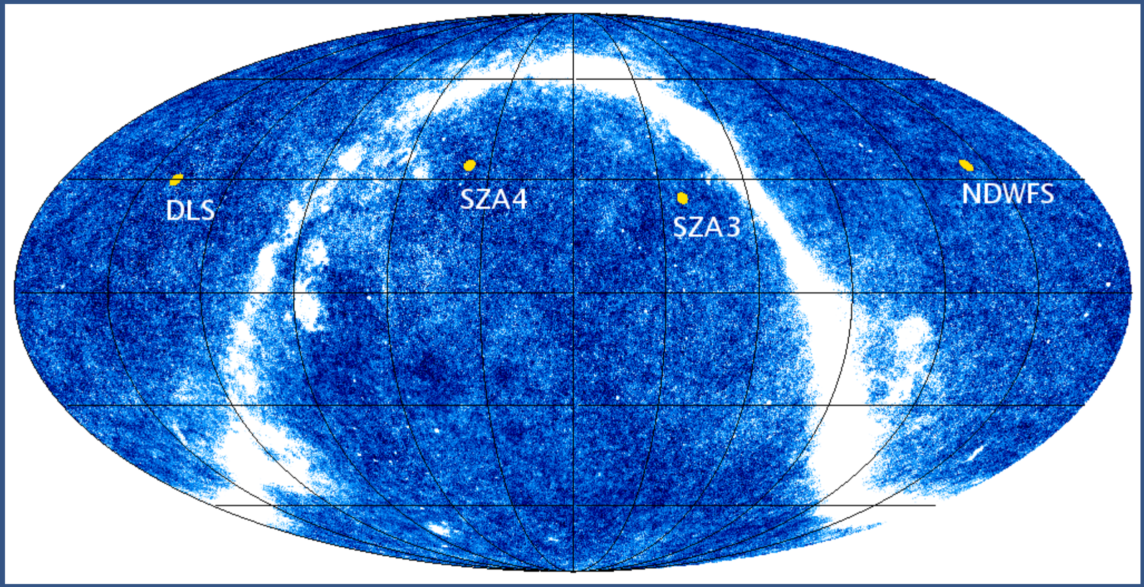
Two Clusters Detected

Cl0016+0016
M ~ 1.3 x 10^15 M_solar
(Hughes et al., 1995, ApJ448:L93)

RXJ0018.3+1618
M ~ 5 x 10^14 M_solar
(Hughes & Birkinshaw, 1998, ApJ 497:645)



SZA survey



Fields need to be selected to:

- Be properly spaced in RA to allow **survey observations 24 hours/day** (four fields each roughly 1.5 square degrees equally spaced in RA)

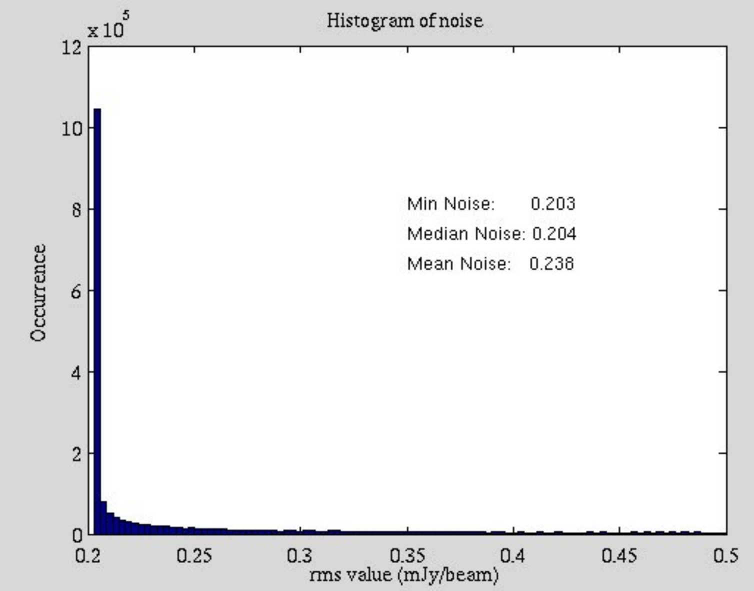
- Be properly positioned in declination (near zenith at transit) so as to **minimize atmospheric contamination and to optimize imaging**

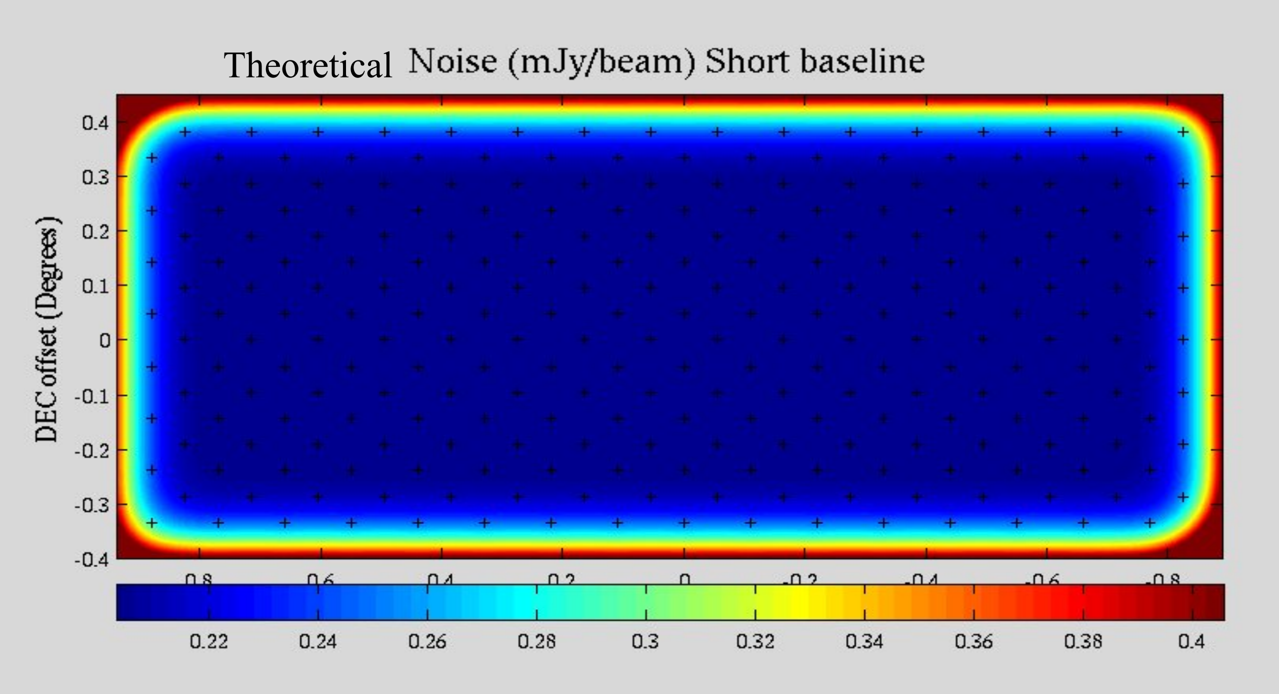
- **Minimize foregrounds** (WMAP Ka band map)

- To take advantage of as much **publicly available optical data** as possible for for **redshift information** - two fields overlap with existing optical - science requires photometric redshifts (need imaging in several bands including near IR)

Survey Strategy

- 16 Rows of 16 Pointings
  - 6.6' separation in Right Ascention
  - 2.9' separation in Declination
  - Uniform coverage
  - ~1.5 sq degrees at rms 0.5mJy/beam
- 4 pointings observed each track
  - Simultaneous CMB Anisotropy Analysis





Data Collection Completed in 2008

Found many sources of emission (~40 per field)…

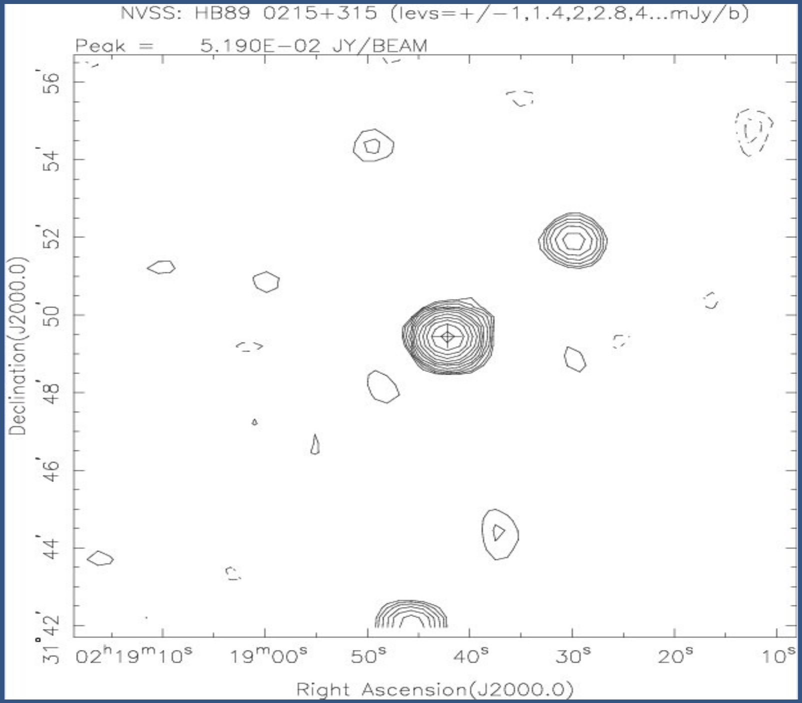
Source Extraction Algorithm

- Multi-pointing fitting done directly in *uv*-space to SZA data

- Sources fall into 3 categories
  - Unresolved Sources (<22")
  - Extended Emission
  - Bright Unresolved Sources

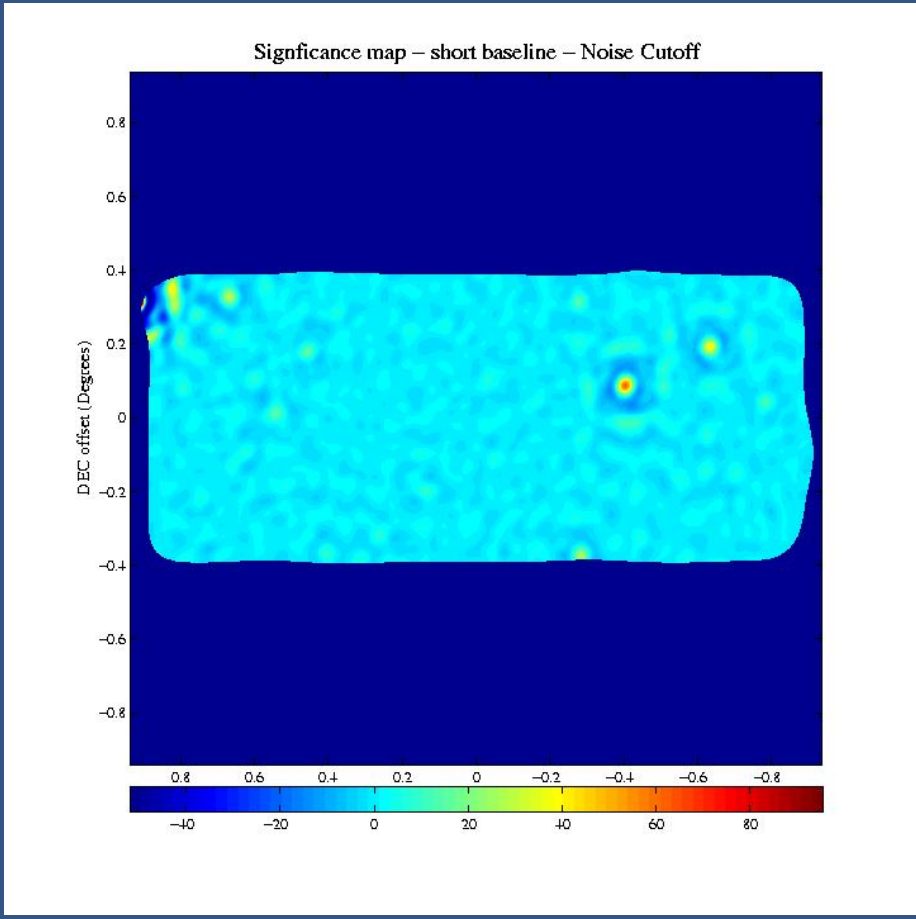
- Use of VLA Data as Priors (5GHz observations/NVSS/FIRST).

- Two Stages: Iterative and using a Template

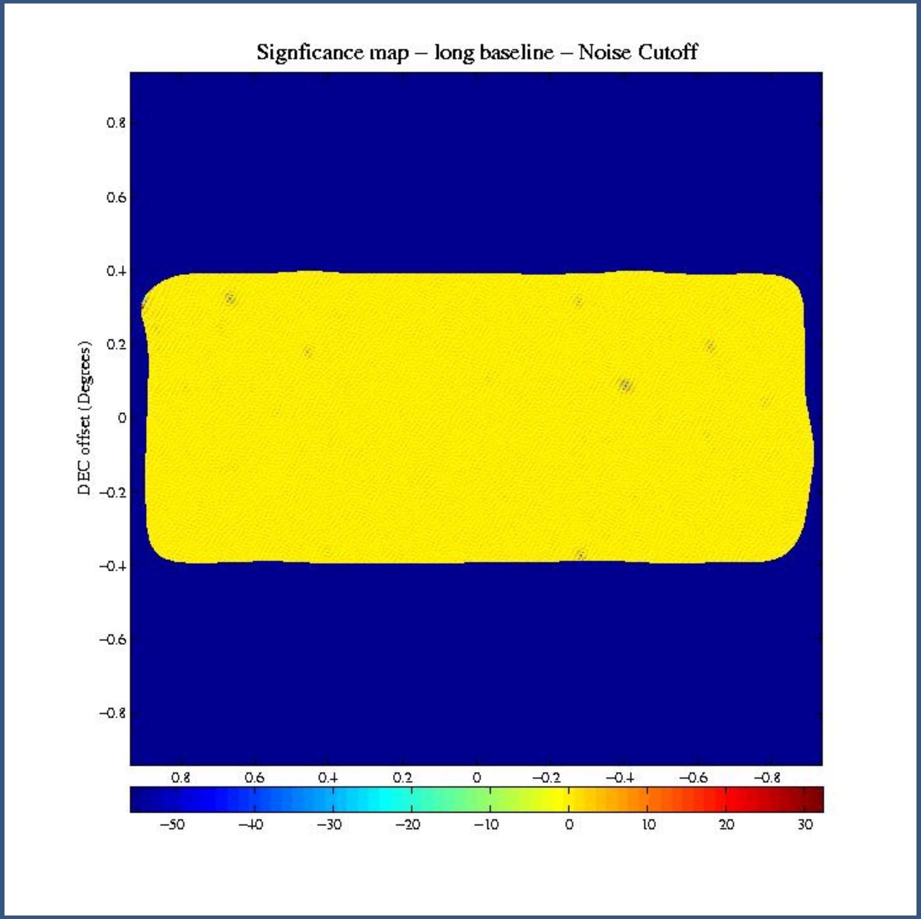


Iterative Removal of Sources

Significance Maps for SZA3 field - Dynamic scale as bright sources are removed



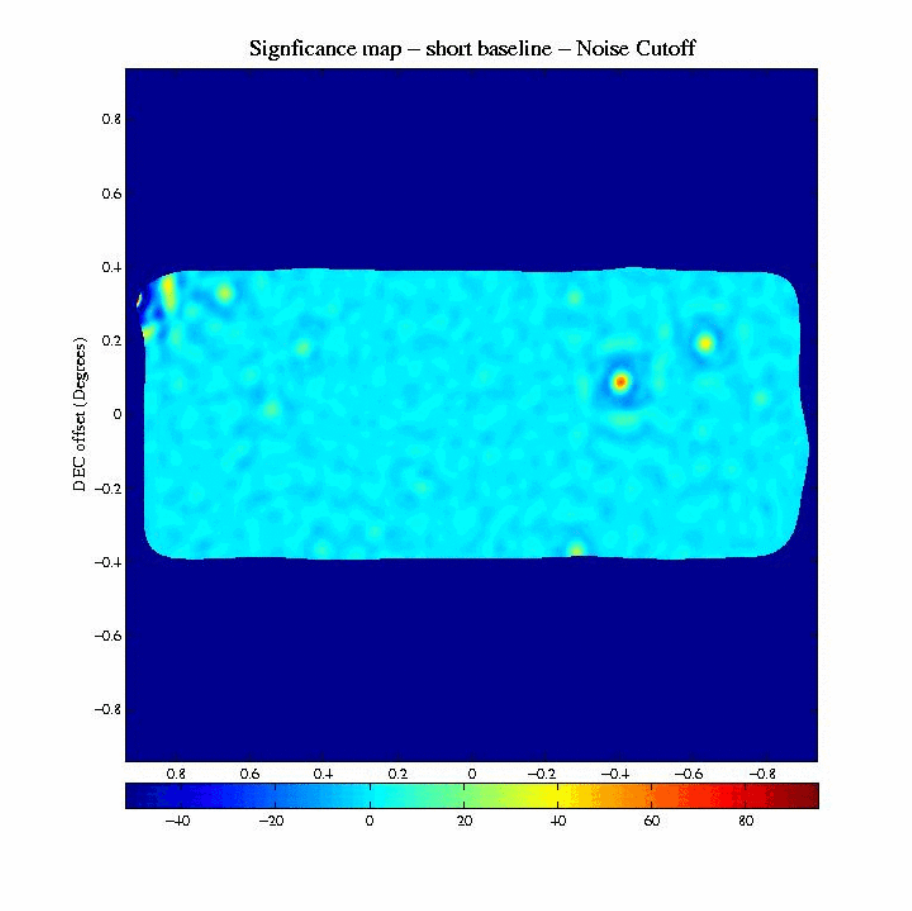
Short Baselines



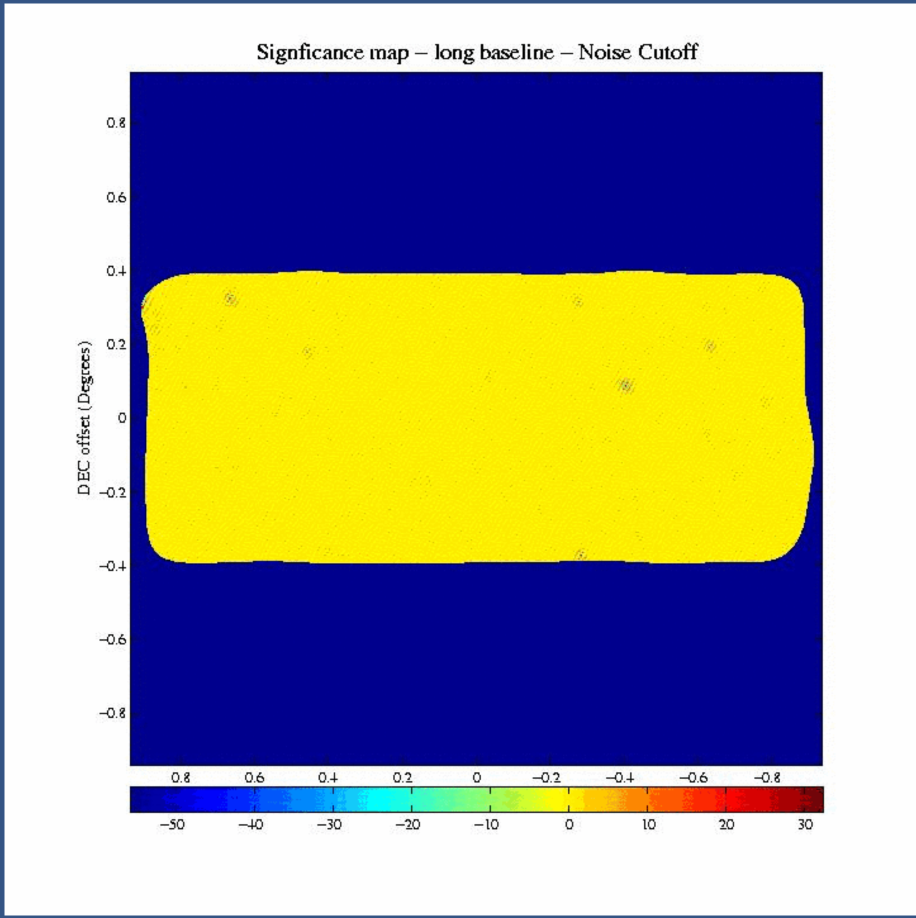
Long Baselines

Iterative Removal of Sources

Significance Maps for SZA3 field - Dynamic scale as bright sources are removed



Short Baselines



Long Baselines

30 GHz Source Characteristics

• Analysis includes all data (including those reserved for anisotropy measurements)

• 209 Sources found at >5σ at 30GHz over 7.7 square degrees

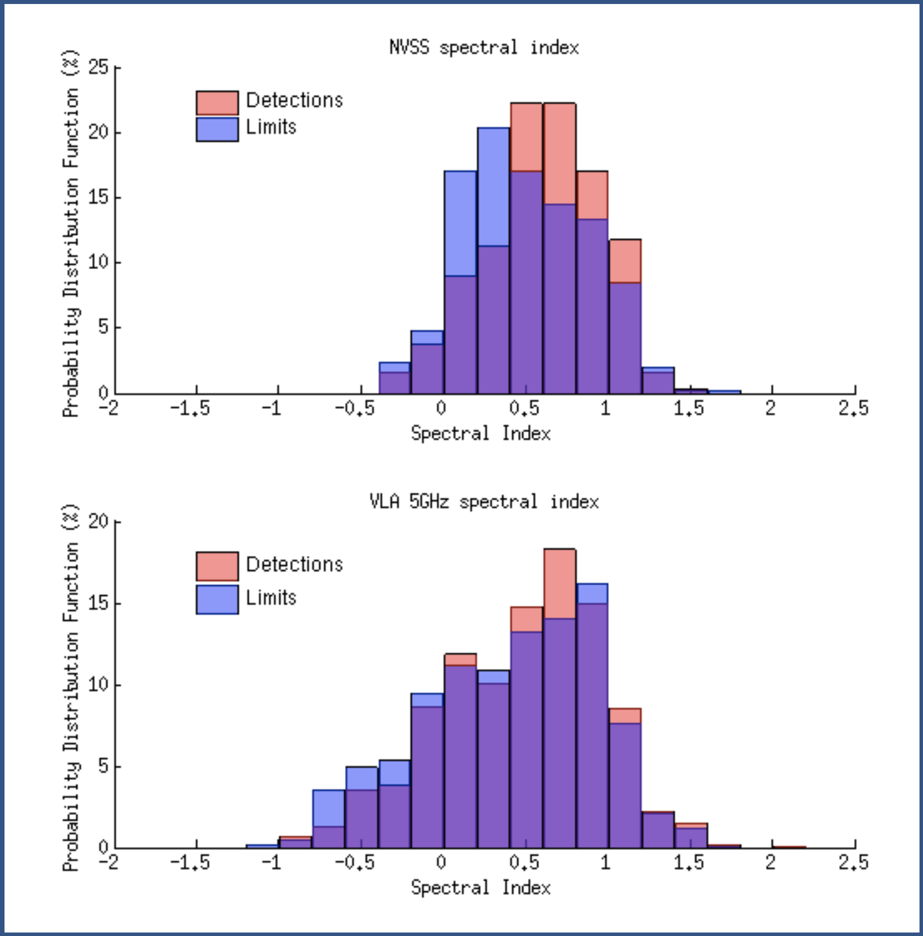
• Min flux ~0.7mJy to brightest of ~204mJy.

• ~95% with counterparts at 5GHz (~14% inverted), 75% in NVSS (~5% inverted)

• Spectral Index defined as $I \propto \nu^{-\alpha}$. Consistent with synchrotron emission

• First un-biased sample of sources at 30GHz at the mJy level

• Spectral index distributions are messy - be cautious when comparing to other experiments.



Muchovej et. al 2010. ApJ 716, 521

Source Characteristics

- Source counts calculated as a power law:

$$\frac{dN}{dS} = N_0 \left(\frac{S}{S_0}\right)^{-\gamma}$$

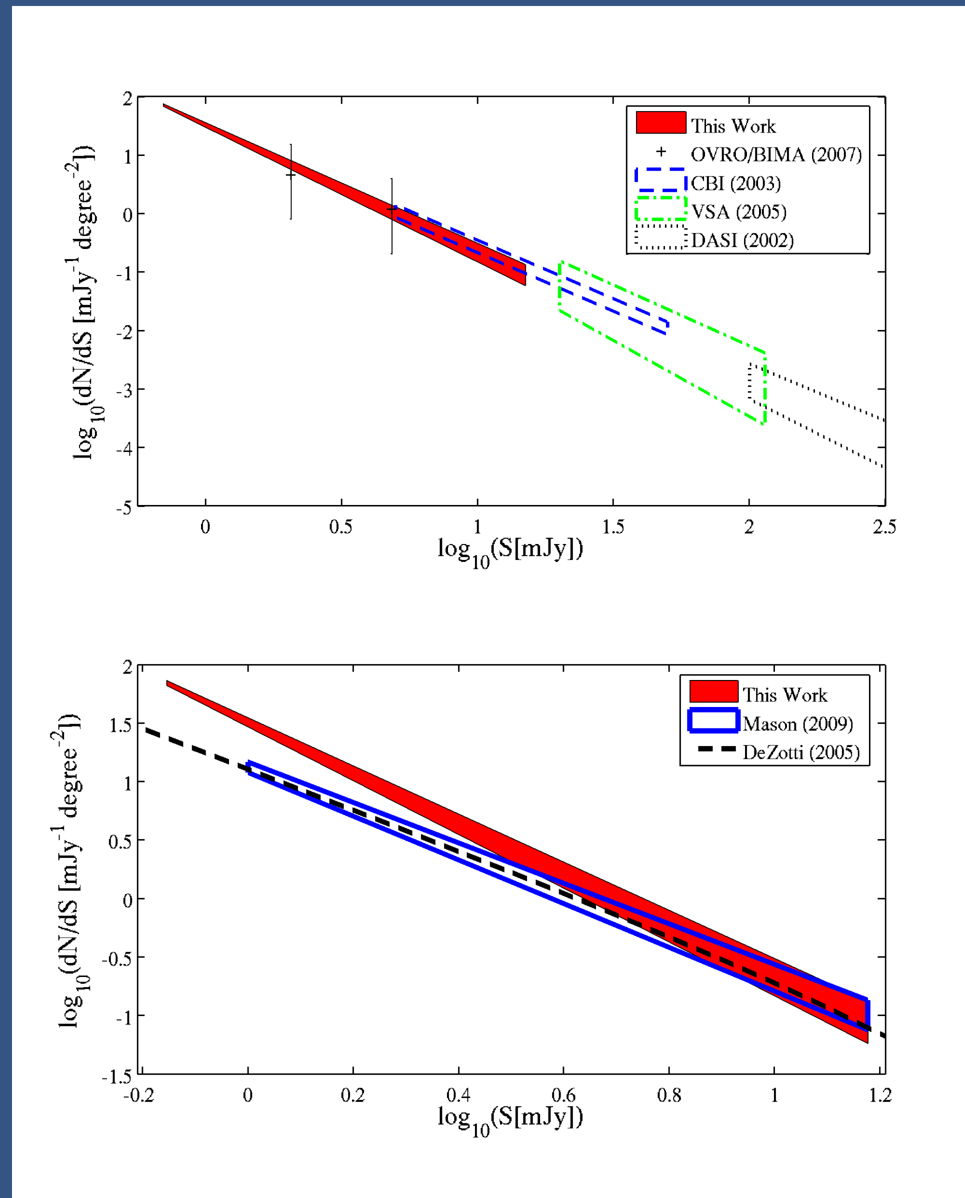
- Calculation done in significance bins, not flux bins.

$$N(>S) = (27.2 \pm 2.5)\,\mathrm{deg}^{-2} \times (S_{mJy})^{-1.18 \pm 0.12}$$

- Results agree well with previous experiments at higher flux values, as well as field source observations by Coble et al. (2007)

- Confirms overdensity of sources towards the center of massive clusters

- Results disagree with predictions from Mason et al. (2009) - best explained by a slight shift in spectral index distribution at lower fluxes.



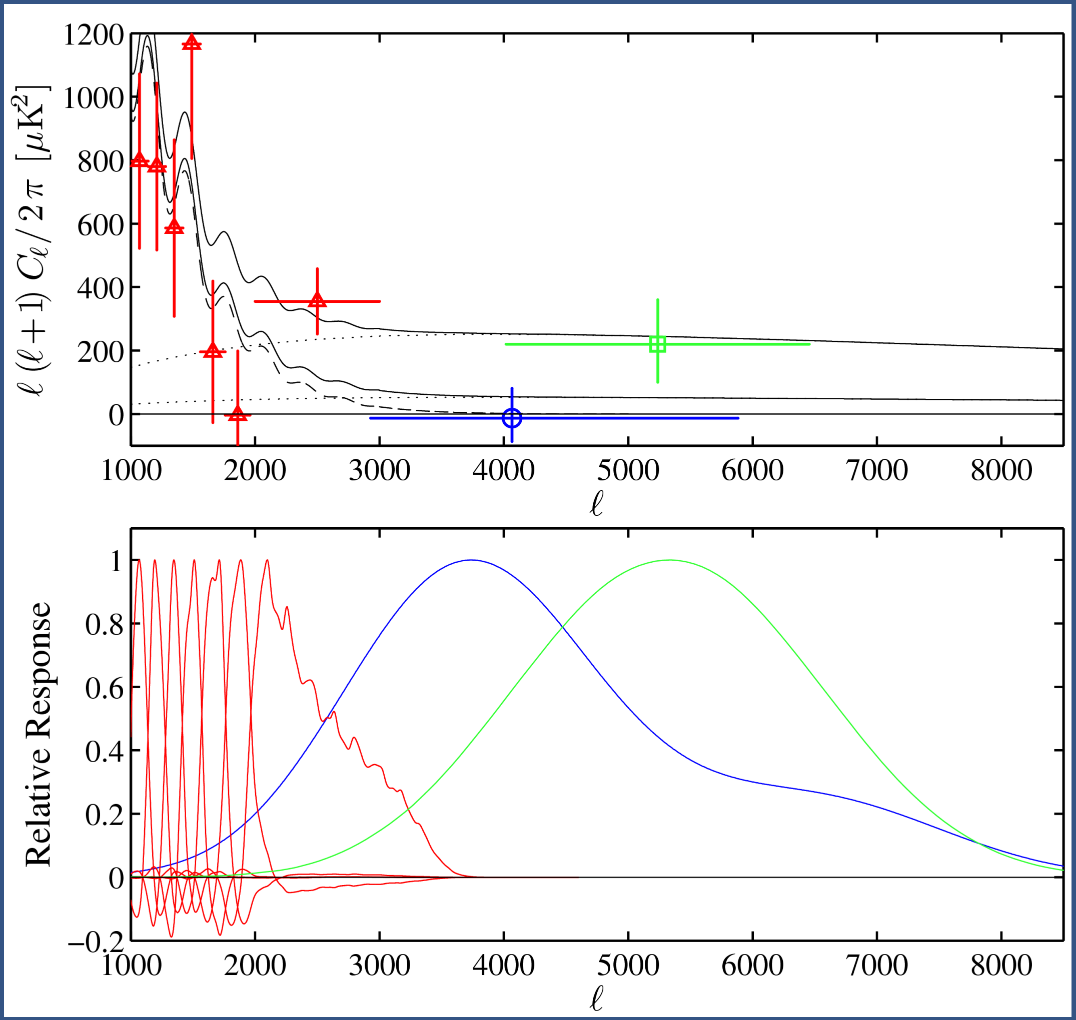
Muchovej et. al 2010. ApJ 716, 521

CMB Anisotropy Measurement

- Calculated using 1340 hours of observations on 44 fields, comprising about 2 square degrees

- RED – CBI
  GREEN – BIMA
  BLUE -- SZA

- Once unresolved radio sources are accounted for, consistent with $\sigma_8 \sim 0.8$.

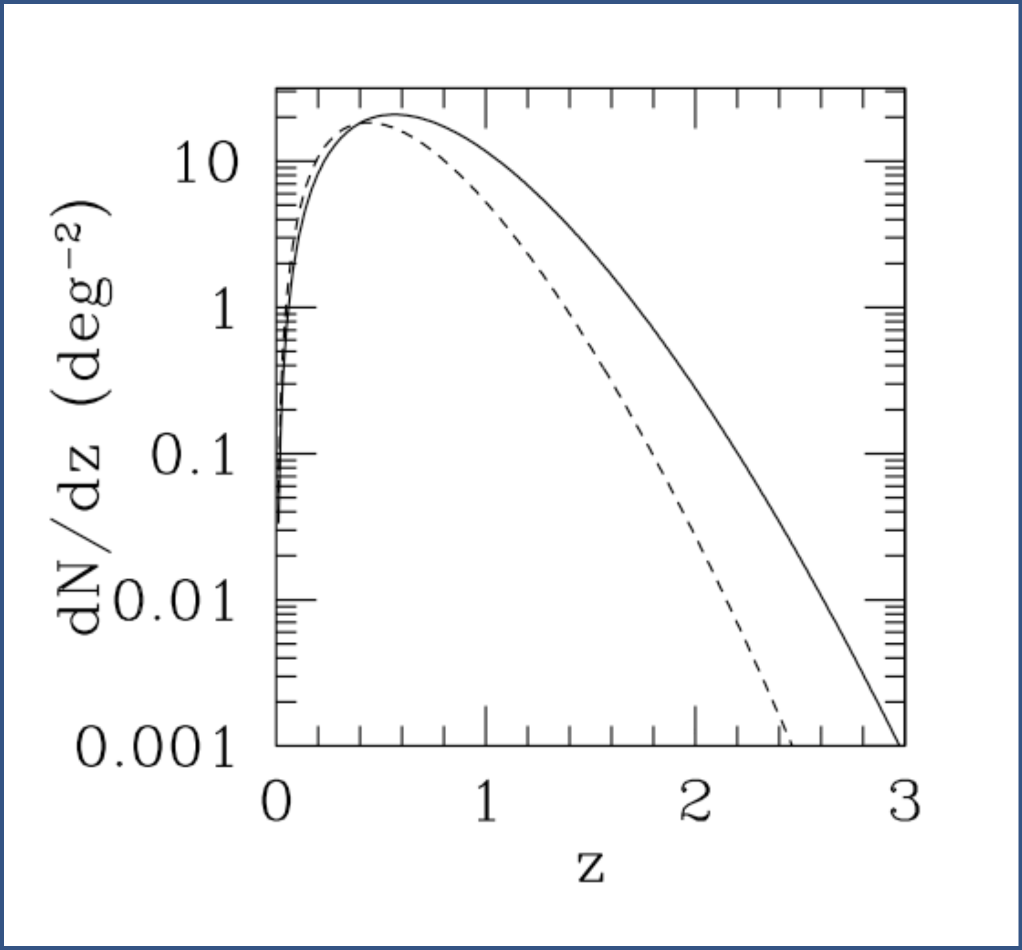


Sharp et. al 2010. ApJ 713, 82

Cosmology from Galaxy Cluster Surveys

- Massive clusters are rare (exponential in the mass function)

- Number density of rich clusters depends strongly on the amplitude of mass density fluctuations on a scale of $8h^{-1}$ Mpc, σ_8



Carlstrom et al. (2002)

Towards a Limit on σ_8

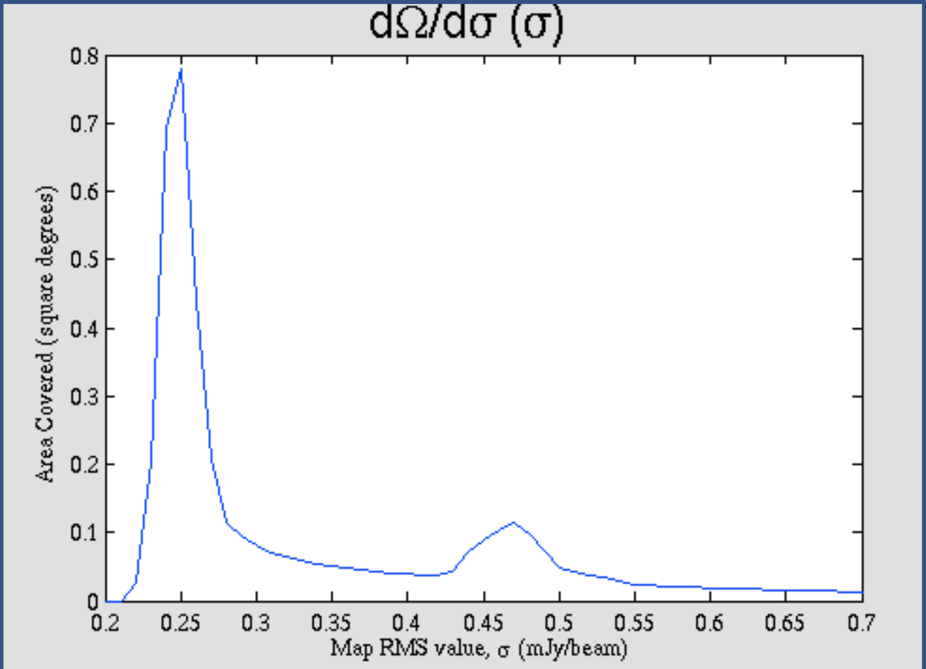
Number of Clusters we expect to see is given by

$$N = \int d\sigma \int p(D|M,\sigma) \times \frac{dN}{dM\, d\Omega}(M,\sigma_8) \times \frac{d\Omega}{d\sigma}(\sigma)\; dM$$

• Total survey area of 4.3 square degrees with noise less than 0.75mJy/beam (excludes SZA3 field)

• Most of our coverage comes has noise of roughly 0.27 mJy/beam

•dN/dMdΩ from Tinker et al (2008)



$Completeness - p(D|M, z, \sigma)$

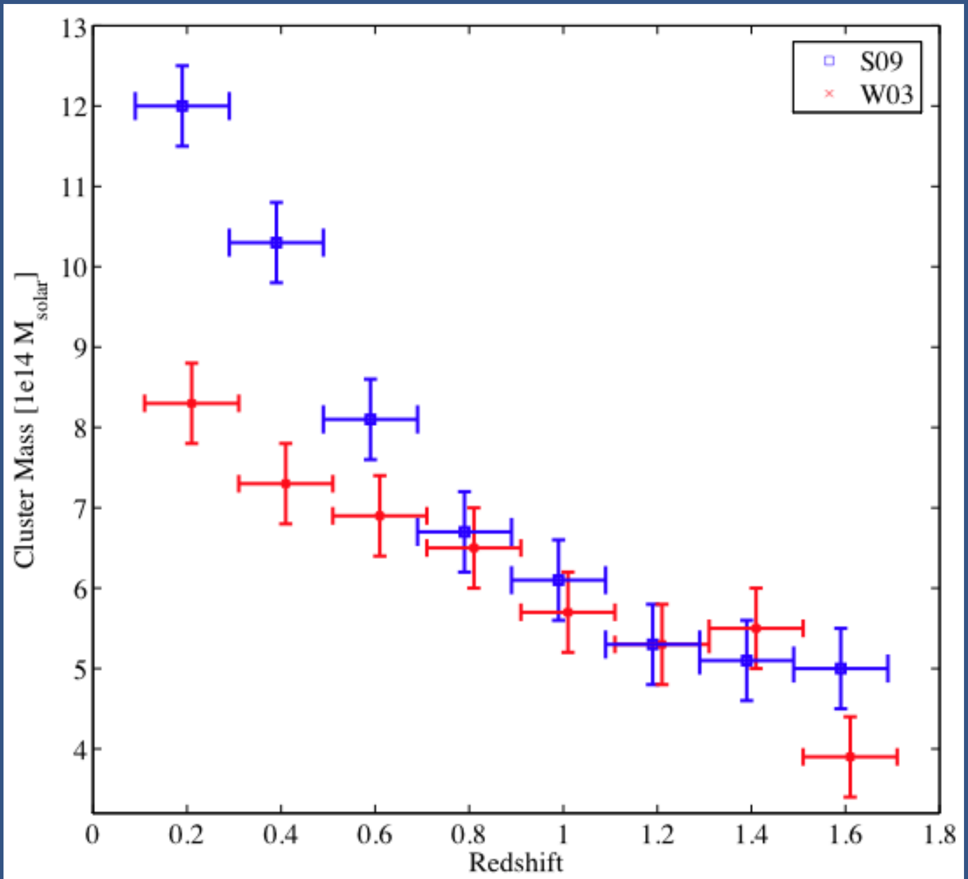
•To calculate Completeness, use Shaw et al. (2009) simulations to relate SZ flux to cluster mass.

• N-body simulation of dark matter; gas included in semi-analytic method, including significant feedback.

• Mass ranges range from from 1.5e14 to 12e14 $M_{solar,}$, redshifts from 0.1 to 2.

• 200 Realizations of noise/point source combinations using SZA dNdS for field, and Coble for clusters for each mass/redshift range.

• Combine this with the are covered and we can get an estimate of the mass limit of our survey.



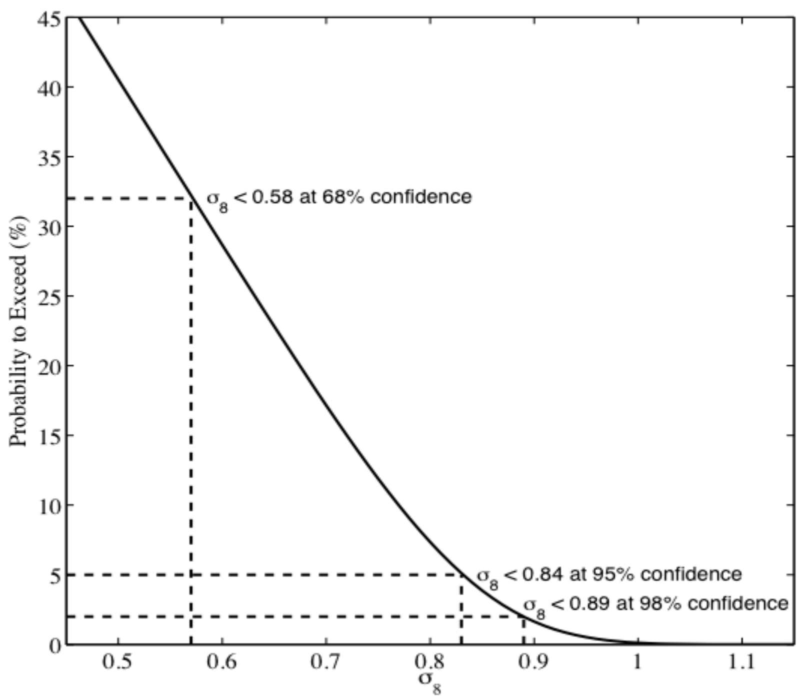
Muchovej et. al 2011, ApJ 732, 28

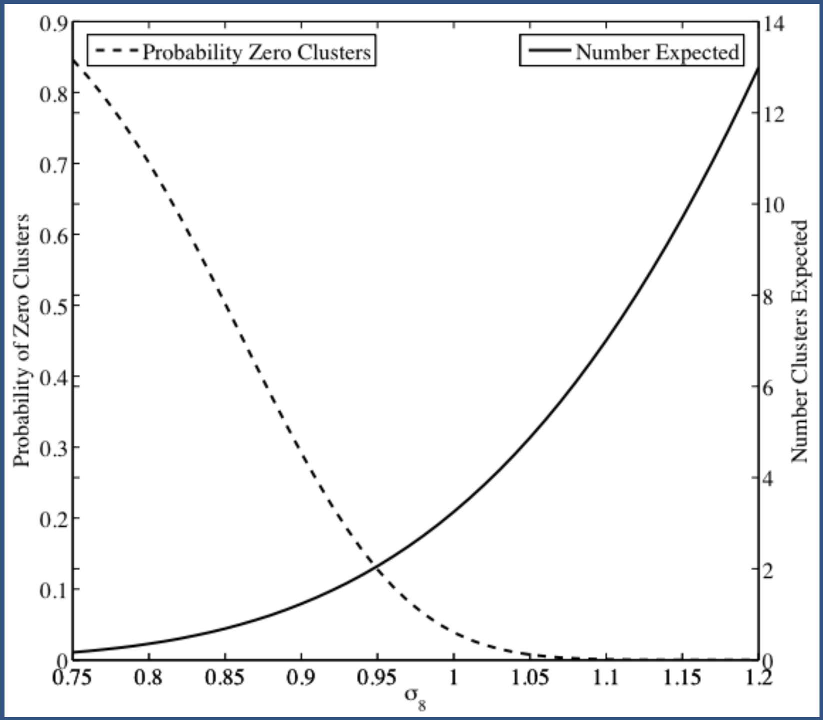
• Good agreement between simulations with differing gas physics (Shaw et al., 2009 and White, 2003)

Limit on σ_8

- From the expected number of clusters, use Bayesian statistics to calculate a probability of a given value of σ_8.

- We expect a non-detection 5% of the time for values of 0.97.





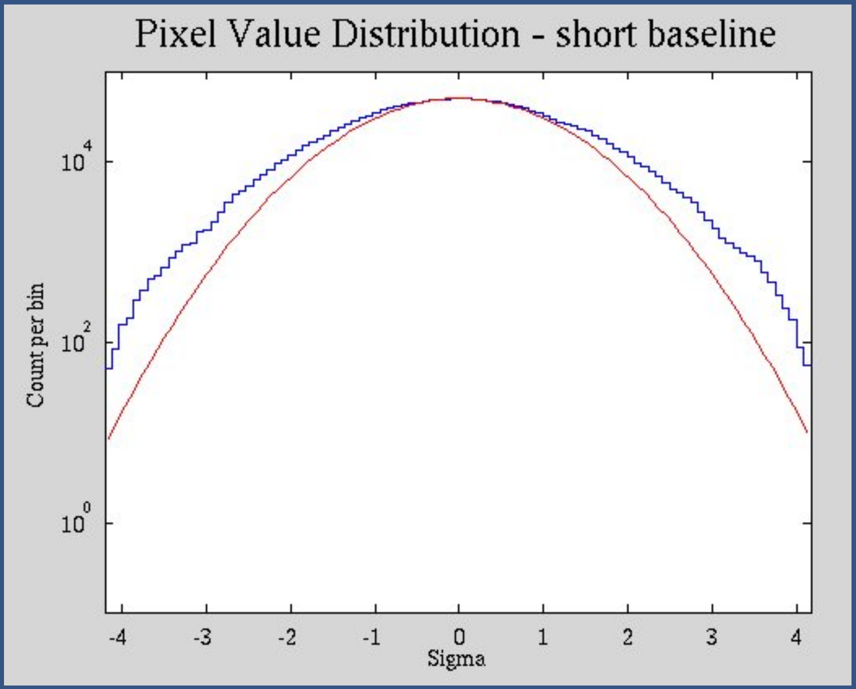
Muchovej et. al 2011, ApJ 732, 28

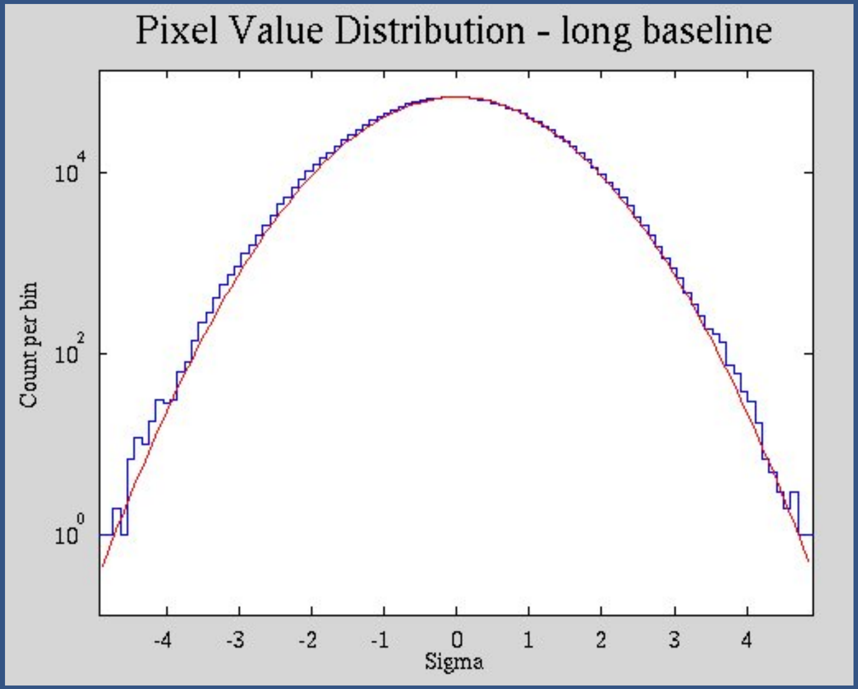
- σ_8 **< 0.84 + 0.07** at 98% confidence, where uncertainties include an estimate due to differing gas physics of simulations; source-cluster correlation; flux calibration; source modelling; and clustering of clusters.

- Agrees with recent WMAP, SPT, and ACT results.

Evidence for Anomalous emission?

- Once all sources are removed, resulting map noise distribution in image plane matches theoretical for the long baselines on all fields.





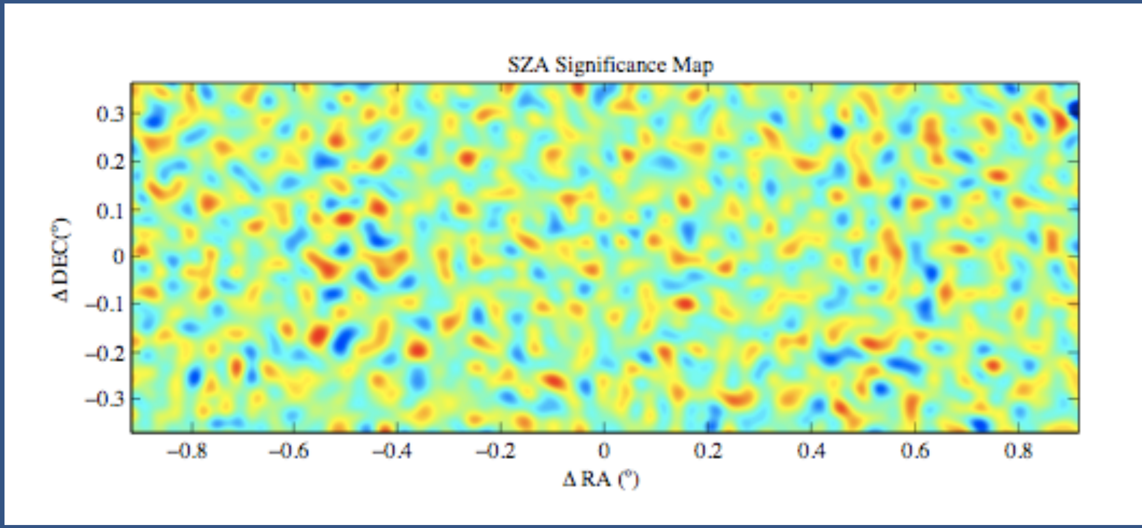
- Not the case for the short baseline images, as the image plane noise in has discrepancies of roughly 18% in the SZA3 field

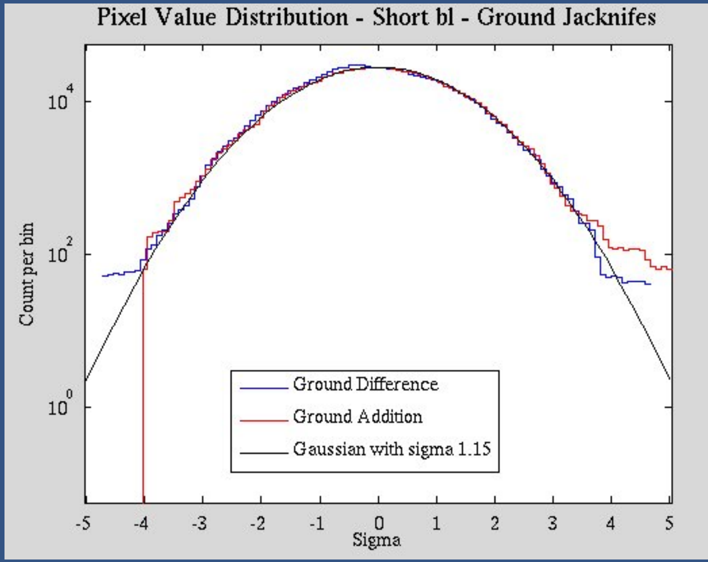
- Discrepancy of roughly 3-5% on the other fields

Anomalous Signal in SZA3 Field

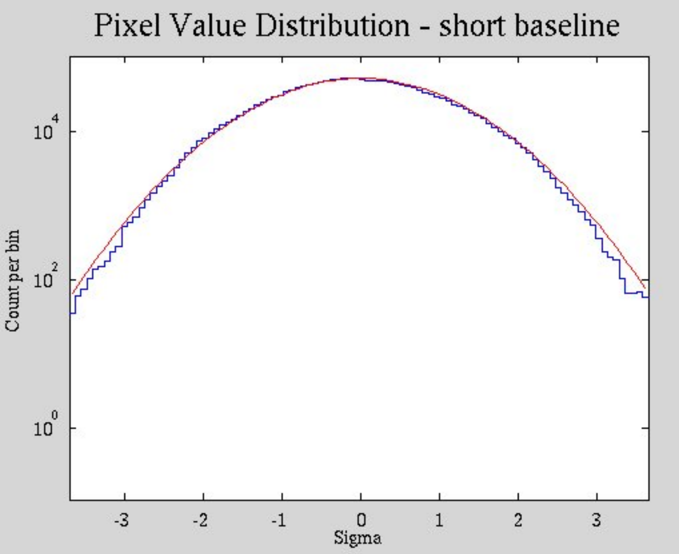
- Jacknife tests indicate the signal is real.

•Ground Jacknife Test indicate the signal is inconsistent with ground





- Data Halves Jacknife test indicate signal is coming from the sky

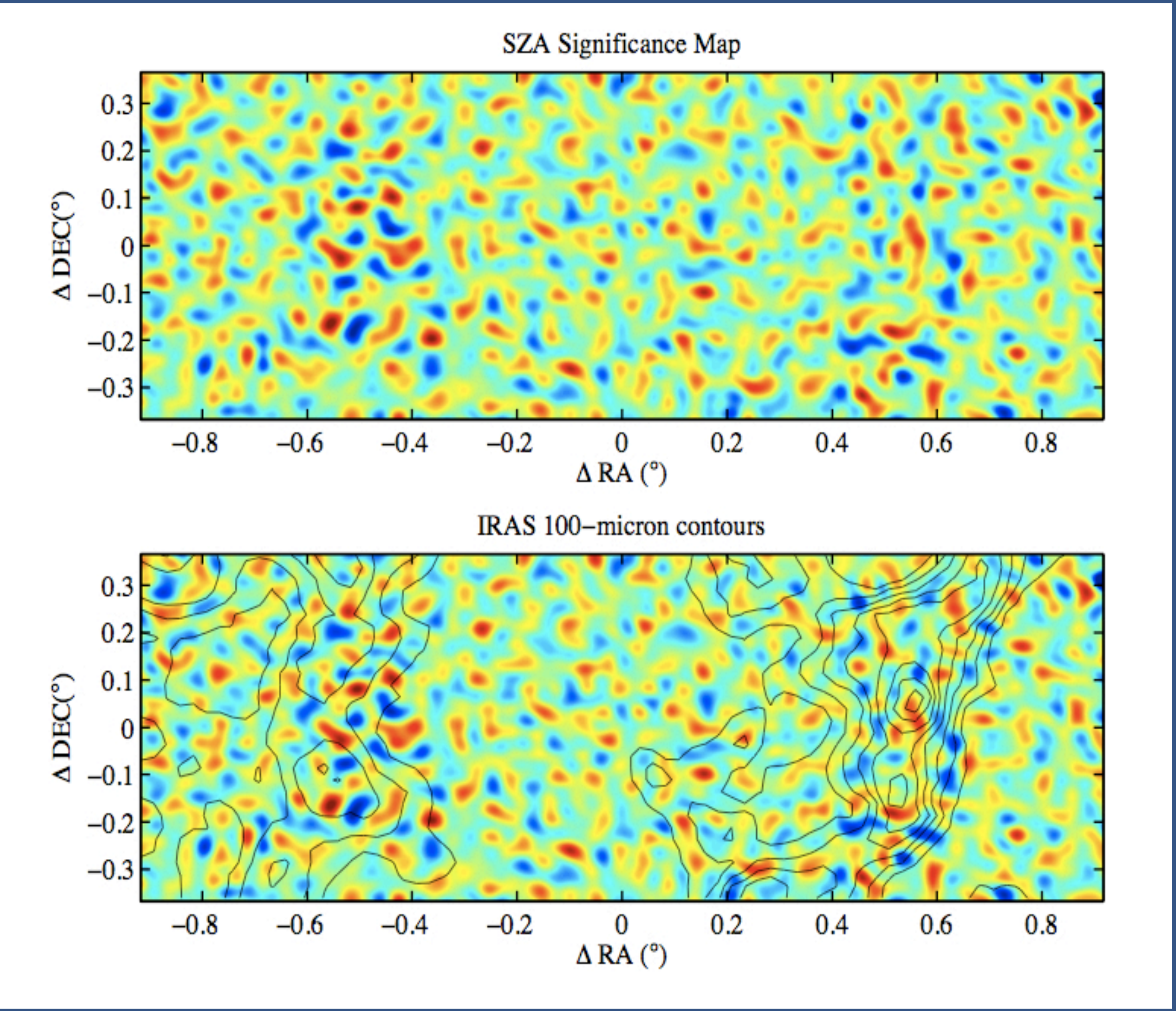


Excess Signal in SZA3 Field

• Strongest regions of emission spatially associated with ridges of dust in the IRAS 100 μm

• IRAS resolution (5') presents challenges when making a quantitative foreground analysis.

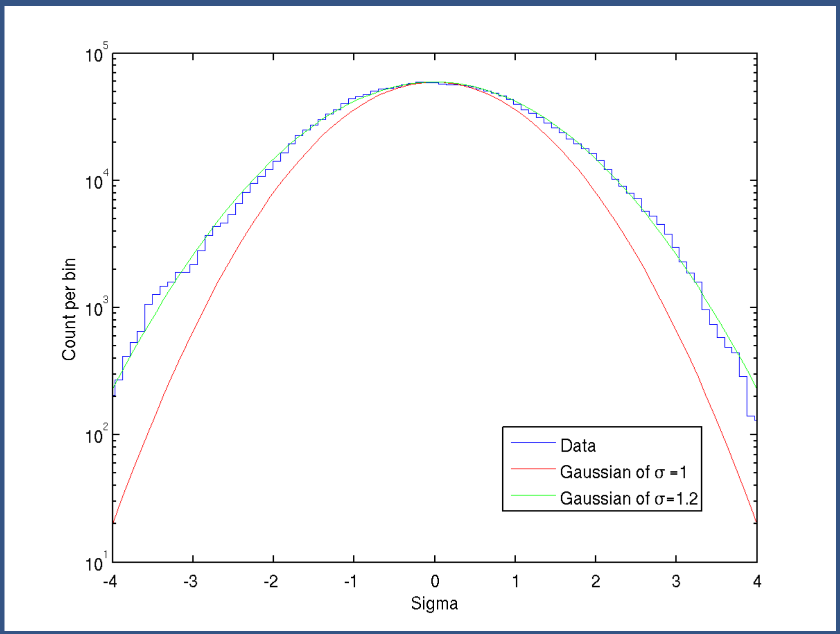
• SZA data which are sensitive to scales larger than 5' make up only 35% of the short baseline data (roughly 18% of the full data set).

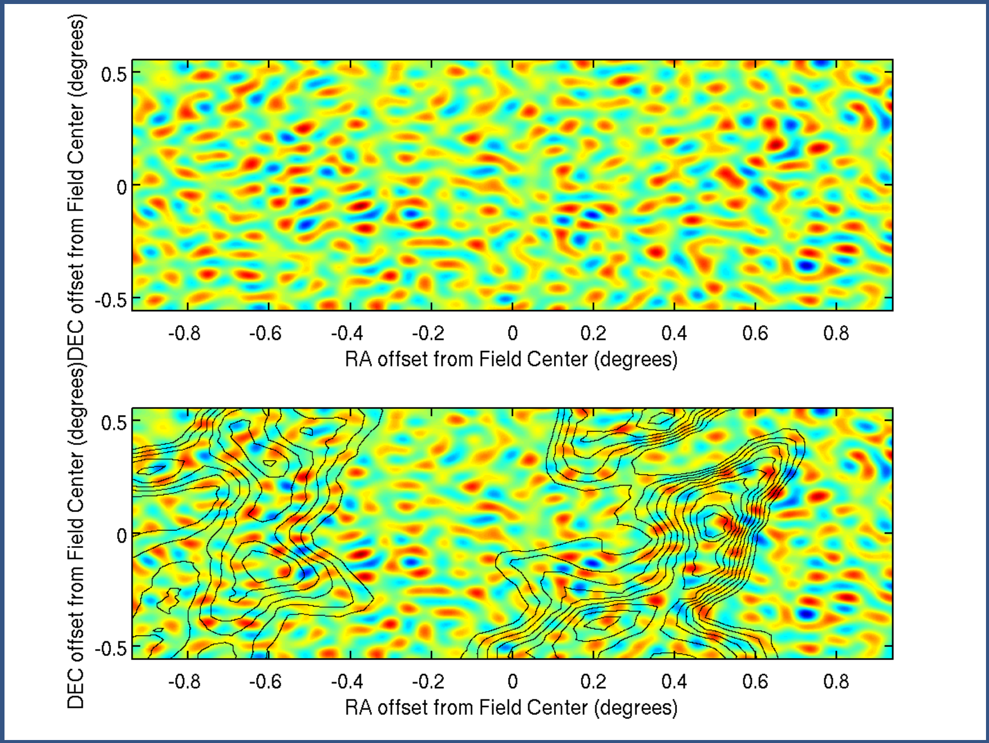


Quantitative Analysis?

- Excess signal is present even in the smaller dataset.

- Excess noise still detected at 20% level.





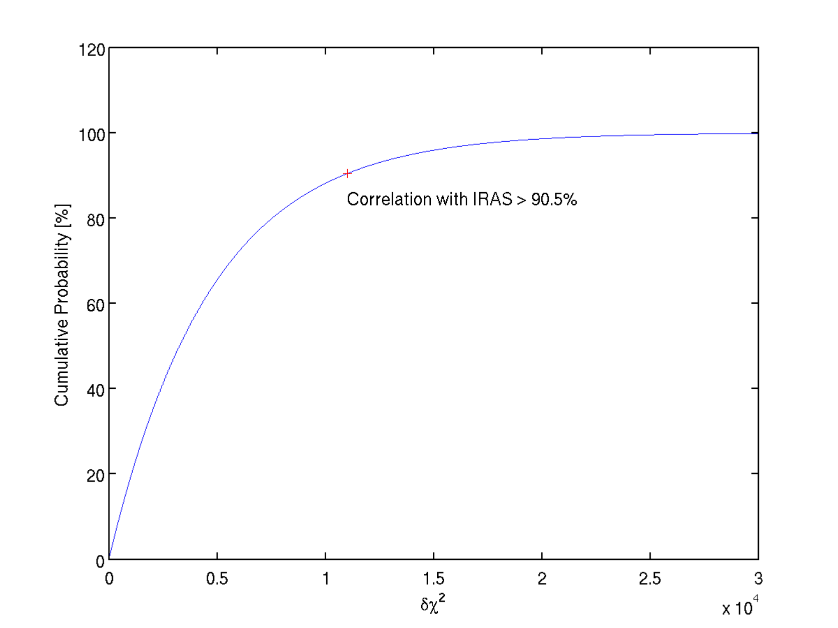
- How significant is the correlation?

Significance of Correlation

- Equipped with a foreground template, can use the deprojection technique to determine the amount of power left once those modes are excised from the data.

- In the unaltered data, the reduction in χ^2 from projecting out the IRAS map is 1.1e4.

- To determine how significant this is, we calculate a distribution of this χ^2 by deprojecting IRAS templates randomly selected.



- Compared to this distribution, our association with IRAS is better than 90.5%. (low limit due to intrinsic assumptions in this calculation)

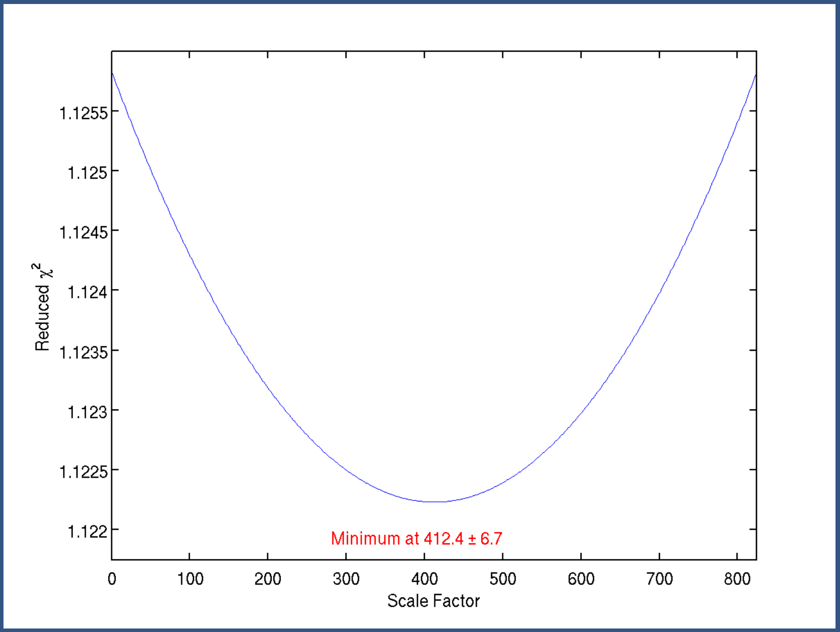
- This is diffuse, not compact excess! There's nothing special about this region in the galaxy.

Consistent with Thermal dust?

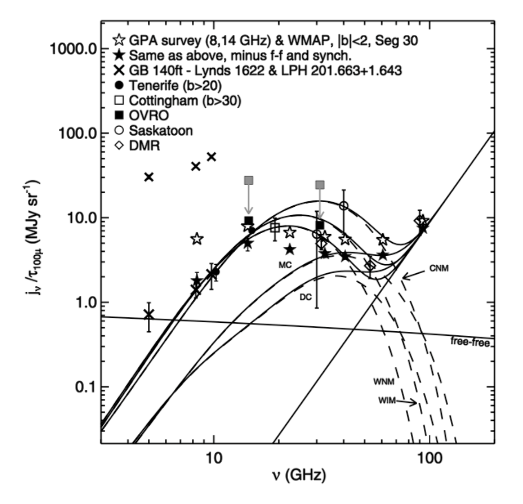
- To determine if it's consistent with thermal dust, we calculate the expected emission using the SFD model.

- We then sample this onto our uv-coverage, and determine the scale factor that minimizes the χ^2 between data and model.

- Our best fit scaling indicates that the amplitude of the IRAS correlated emission in our field is 412 ± 6.7 times what is predicted by thermal dust.

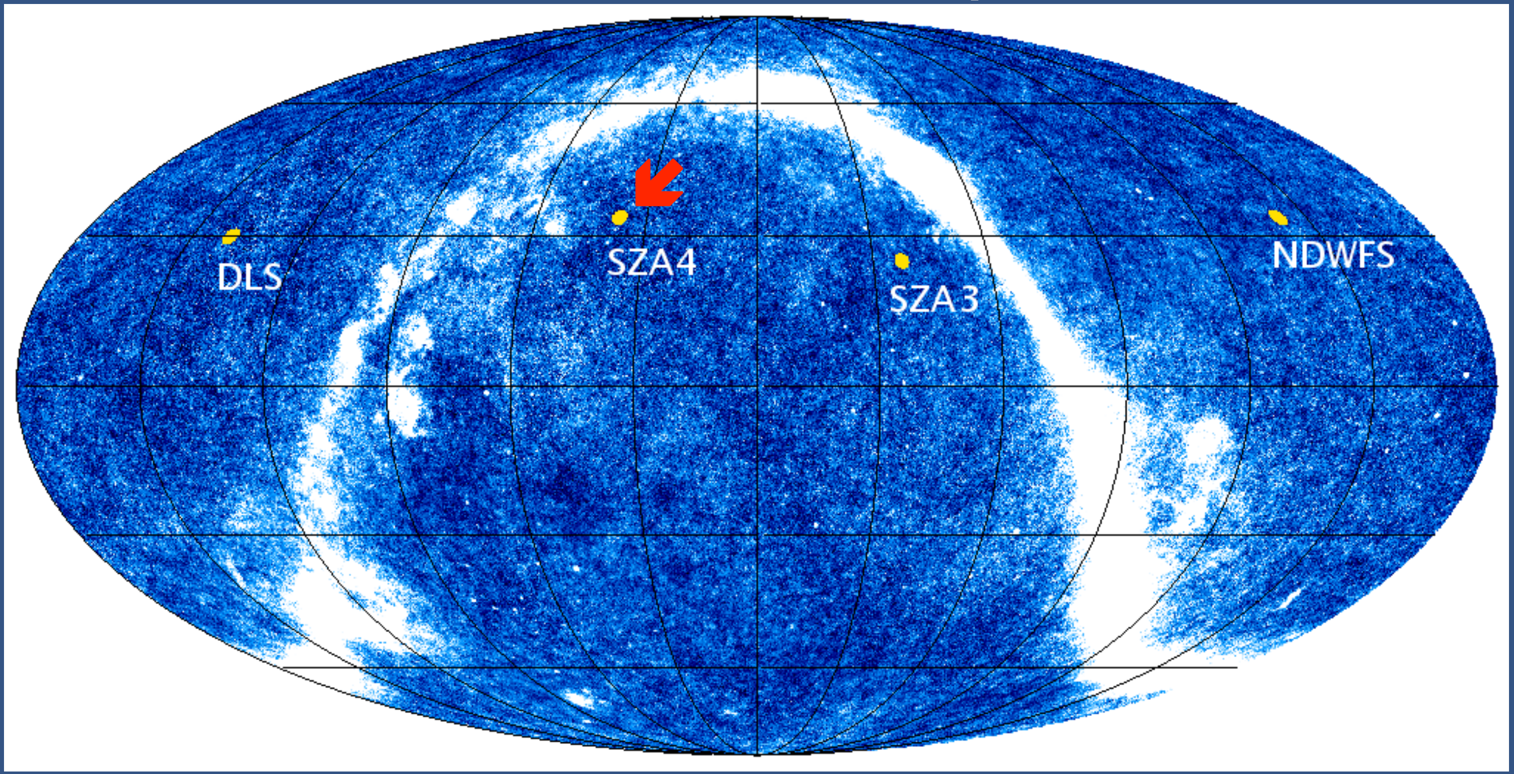


- Are there environments in which spinning dust emission is two orders of magnitude greater than thermal dust (in flux)?



Finkbeiner et. al (2004)

Further Analysis



- Robustly quantify the correlation with dust by using the best fit IRAS maps to our data.

- Quantify the correlation with other templates. *NEED HIGH RESOLUTION IR DATA* -- anyone know of some for this field? RA~21:30, DEC +25. *WISE?*

- Check the correlation with other templates.

- Determine if the grain size and temperatures in that region would produce spinning dust emission in agreement with the level we see.

Conclusions

• SZA is a powerful instrument for SZ science, AME observations.

• Analysis of 7.7 square degrees of the sky at 30GHz determined, for the first time, the number density of sources of emission at a high frequency.

    • Indicates excess power in some CMB observations is a result of under-predicting the contribution due to dim sources.

• CMB anisotropy measurements at high-ell consistent with $\sigma_8 < 0.8$.

•Our small survey (4.3 square degrees) for clusters of galaxies predicts $\sigma_8 = 0.84 + 0.07$, consistent with WMAP, SPT , and ACT results.

•We have detected a component of large-scale diffuse emission in the SZA3.

    • Data jack-knife tests indicate it is real
    • It is at least 91% spatially correlated with IRAS dust emission
    • Its level is two orders of magnitude greater than what is predicted by SFD for thermal dust

•SZA is now a part of CARMA – apply for your own observations!

Thank you.

Results from a 31GHz Sky Survey with the Sunyaev-Zel'dovich Array

Stephen Muchovej
Caltech

sjcm@astro.caltech.edu