Multi-wavelength Imaging of the SZ Effect in MACS J0717.5+3745

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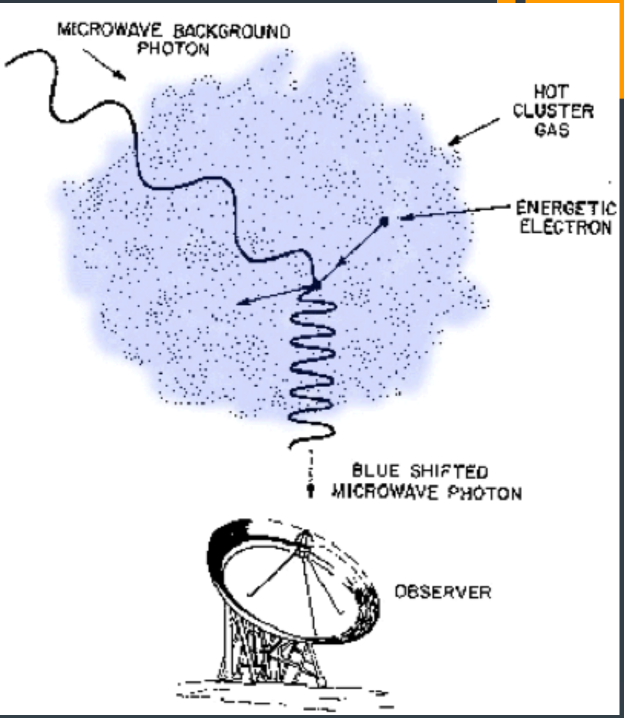
The Sunyaev-Zel'dovich Effect (SZE)

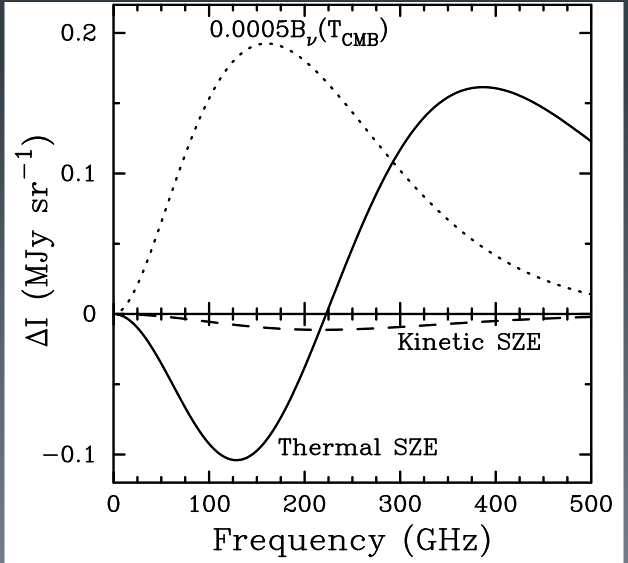
- Cosmic Microwave Background photons are scattered to higher energies by the hot electrons in the intra-cluster medium.
- The SZE has 2 main forms: thermal and kinetic.
- The intensity of the thermal SZE (tSZE) is proportional to Compton-*y*, and is a function of the line of sight integrated pressure:

$$y \equiv \frac{\sigma_{\rm T}}{m_e c^2} \int n_e k_{\rm B} T_e \, d\ell = \frac{\sigma_{\rm T}}{m_e c^2} \int P_e \, d\ell$$

- The kSZE is a Doppler shift of the CMB. It is linearly proportional to the gas velocity along the line of sight v_z and to the electron opacity τ_e as $dT_{kSZE} = -\tau_e(v_z/c)\, T_{CMB}$.
- Both thermal and kinetic require small relativistic corrections (e.g. Itoh et al. 1988, Nozawa et al. 2004/2006).

On the right are example tSZE and kSZE spectra for y=1e-4 and v_z=500 km/s. Figures are from L Van Speybroeck (upper) and Carlstrom, Holder, and Reese 2002 (lower).



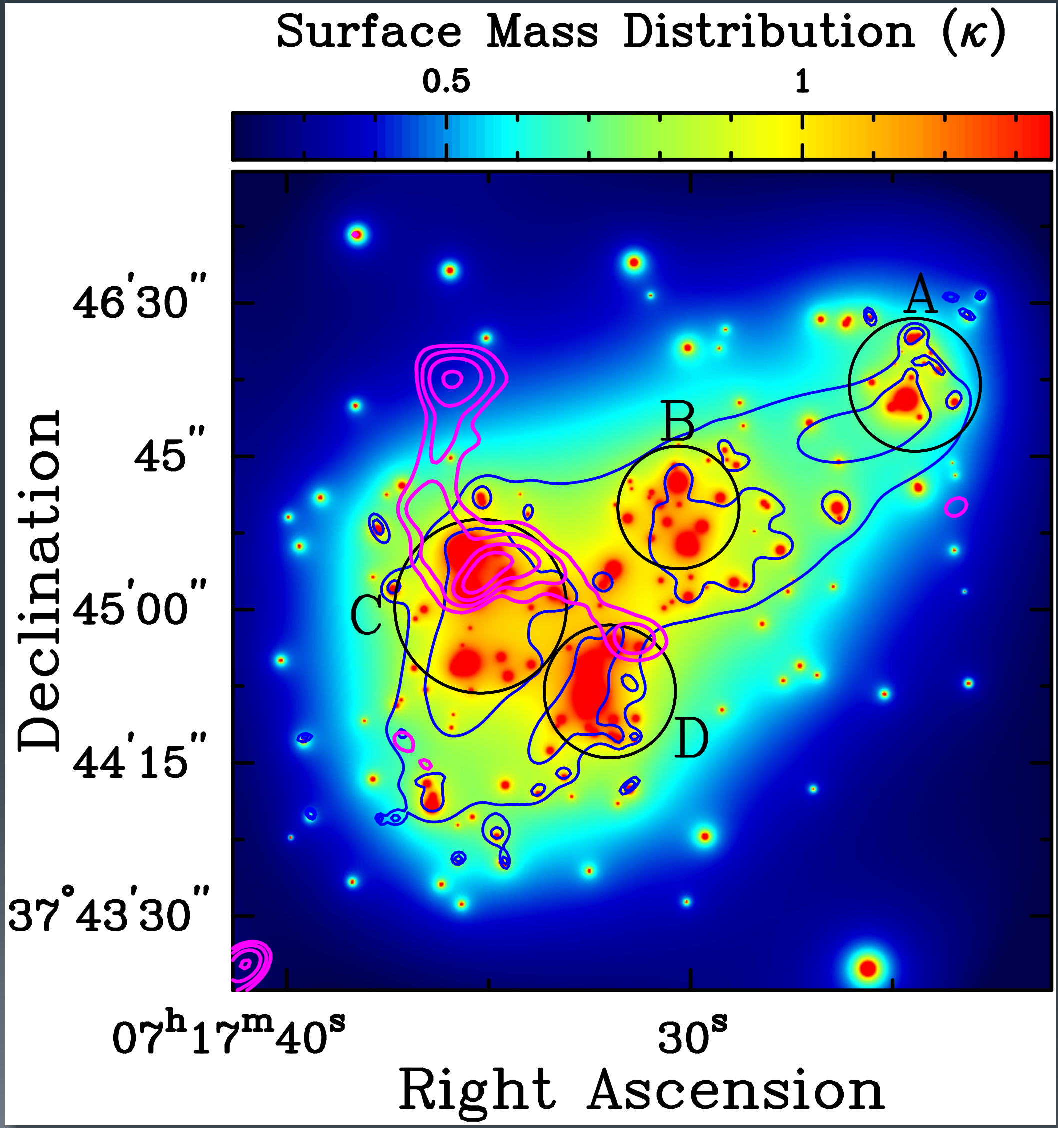


MUSTANG, The **Mu**ltiplexed **S**QUiD-**T**ES **A**rray at **N**inety **G**Hz:

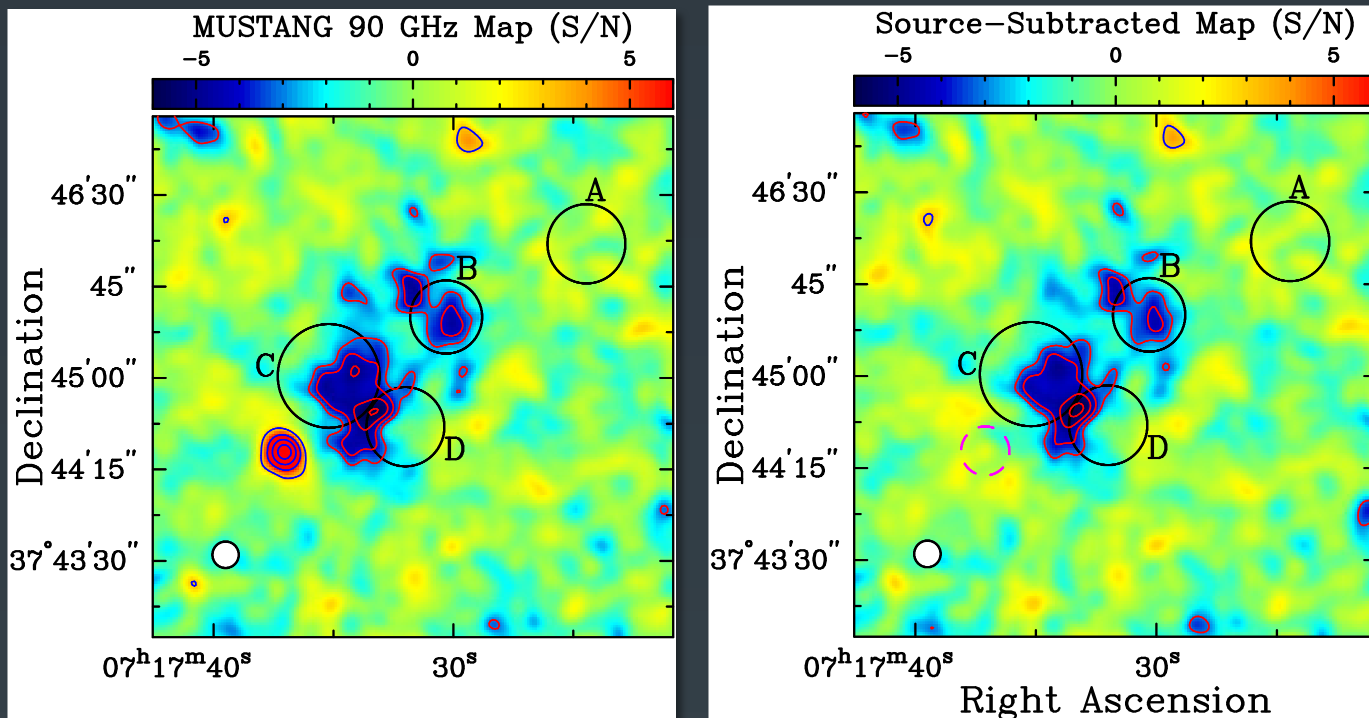
- is a cryogenic, re-imaging focal plane camera with an 8x8 array of Transition Edge Sensor (TES) bolometers.
- the receiver was built at U Penn as a facility instrument for the 100-m Green Bank Telescope.
- has a resolution of ~9” and can image a massive cluster to a peak S/N ~ 6 with about 5 hours of on-source time.
- has a 42" instantaneous field of view on the sky.
- due to common mode subtraction of the atmosphere, scales >1’ are not recovered. MUSTANG SZ observations therefore provide a high-pass filtered view of cluster physics, but don’t recover the bulk SZ flux.

MACS J0717.5+3745

- A massive triple-merger at z=0.55.
- Color map is the strong lensing map from Zitrin et al. 2009.
- Circles locate the optically-identified galaxy subclusters from Ma et al. 2009 (which agree with strong lensing peaks).
- Blue contours are strong lensing from Limousin et al. 2012, using better redshift determinations of the lensed sources.
- Magenta contours are 610 MHz radio emission, from van Weeren et al. 2009, showing relativistic plasma from merger activity.
- See Mroczkowski et al. 2012 (http://arxiv.org/abs/1205.0052)

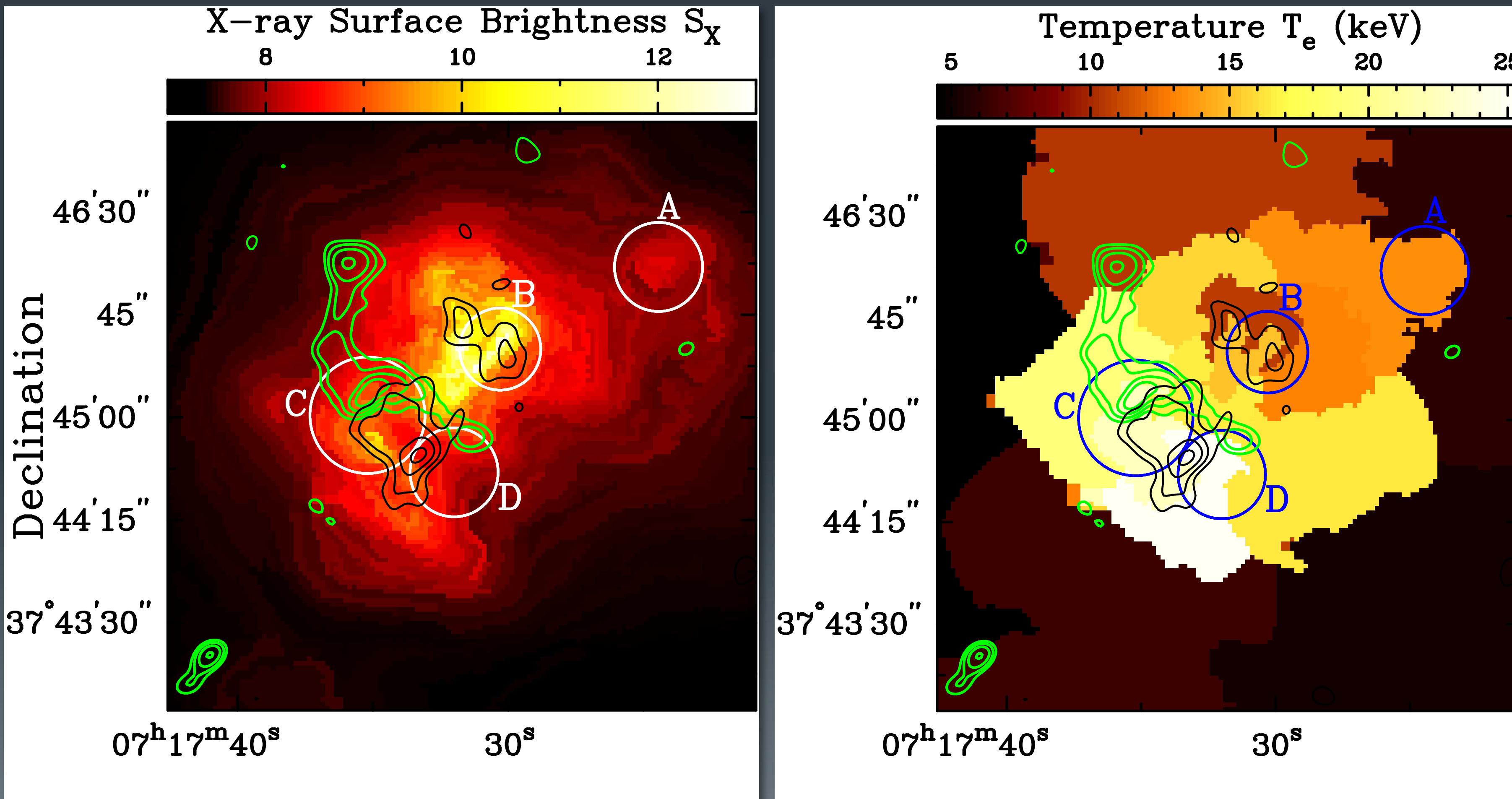


MACS J0717.5+3745 MUSTANG 90 GHz observation

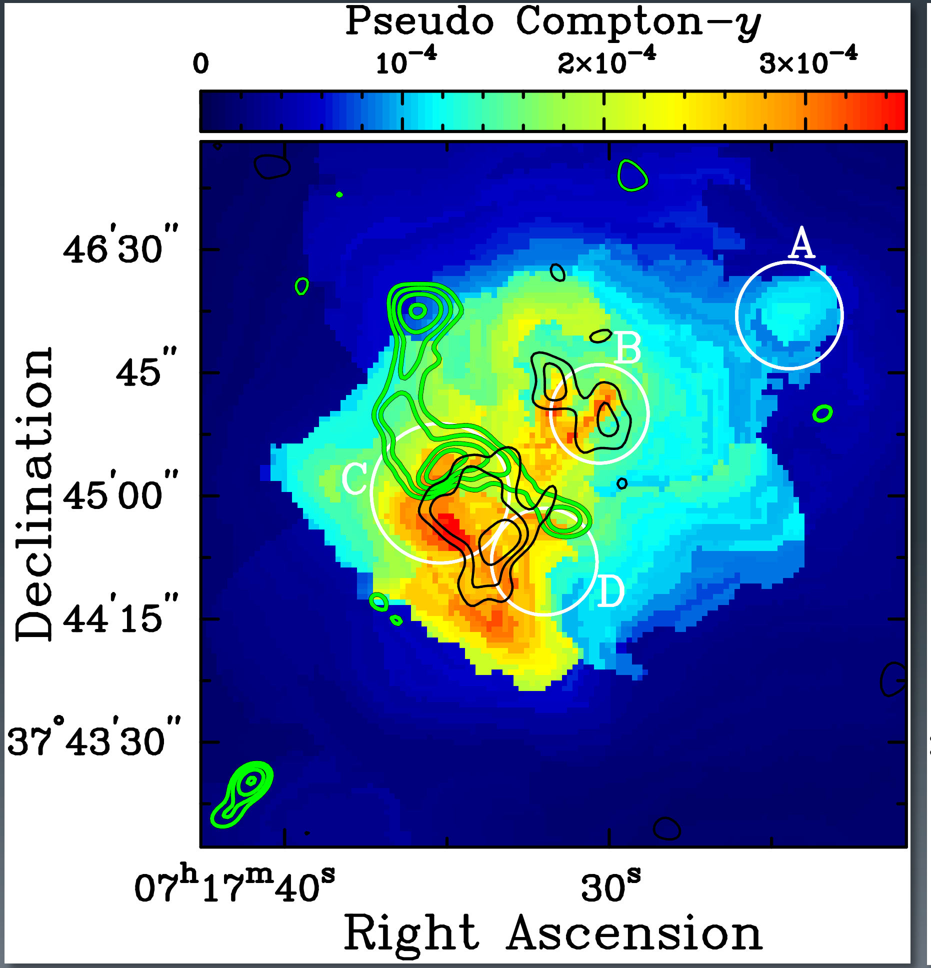


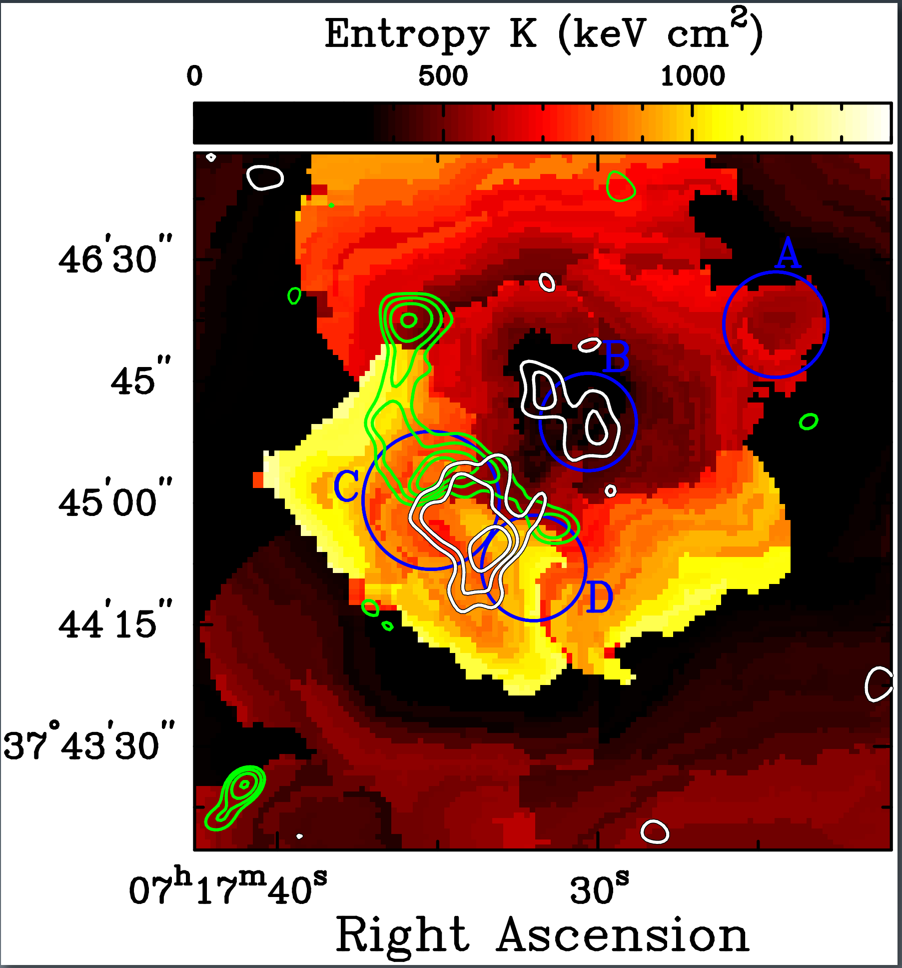
- MUSTANG observation is a high-pass filtered view of the cluster gas pressure. Scales >1' are not recovered.
- There is a z~0.15 foreground galaxy in the SE part of the map.
- One pressure peak is located where C&D are interacting.
- The secondary is associated with subcluster B.
- We can remove the foreground galaxy from the time-ordered data using an iterative procedure.
- This slightly changes the noise estimates, but does not alter the feature shapes.
- (http://arxiv.org/abs/1205.0052)

MACS J0717.5+3745 X-ray properties: Surface brightness and Temperature



MACS J0717.5+3745 X-ray derived properties: pseudo Compton-*y* and entropy ($K=k_B T_e\, n_e^{-2/3}$)



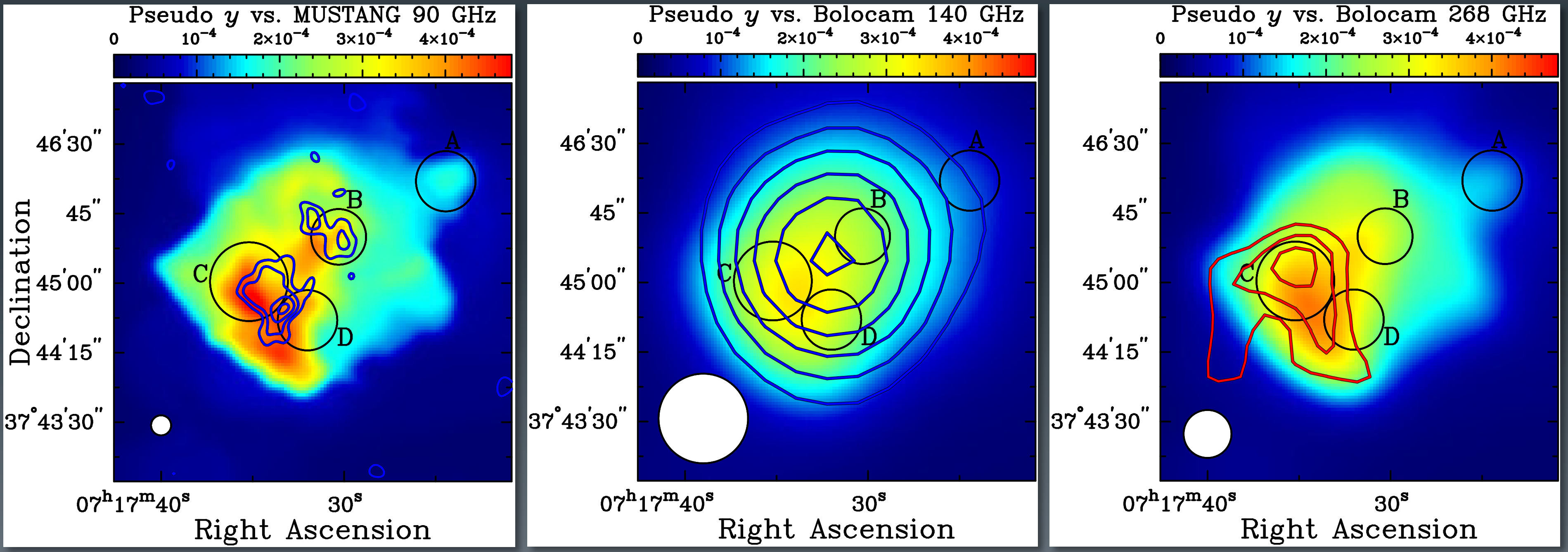


The SZE in MACS J0717.5+3745 on larger scales using Bolocam

- Bolocam is a 144-element bolometric array that operates from the 10-meter Caltech Submillimeter Observatory.
- It can observe at either 140 or 268 GHz, providing resolutions of 58” and 31”, respectively, of the SZE decrement and increment.
- It has an instantaneous field of view of 8’, and recovers scales up to 14’ in a typical cluster observation.
- We use the Bolocam 140 GHz observations to normalize the X-ray pseudo Compton *y* and entropy maps.

Comparison of MUSTANG and Bolocam 140+268 GHz observations with pseudo *y*-maps

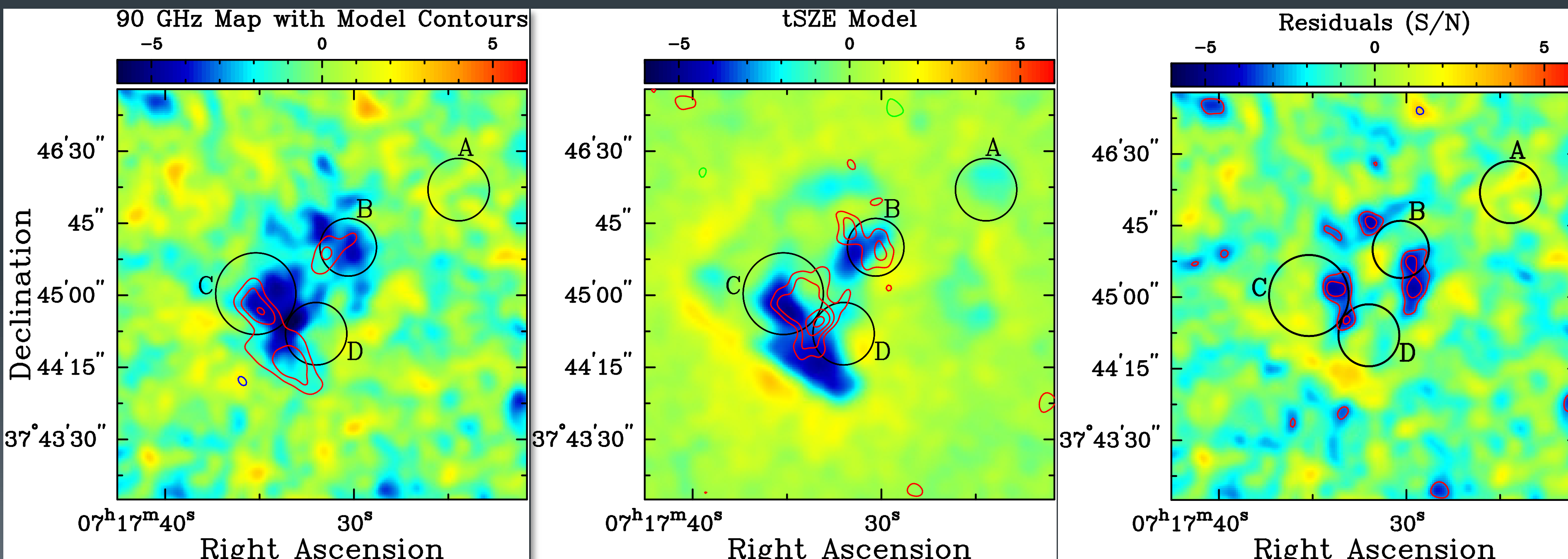
- Bulk properties predicted from X-ray template agree qualitatively at 90 and 140 GHz.
- Subcluster C shows up strongly at 268 GHz, but B is missing.



Mroczkowski et al. 2012 (http://arxiv.org/abs/1205.0052)

Subtracting the *y*-map template from the MUSTANG 90 GHz data

- Subtracting the model from the MUSTANG data reveals pressure substructure in the residuals (on the right) no predicted by the X-ray data (e.g. resolution, hot out of band gas).
- There are also some ringing effects in the model (middle) due to sharp features in the template.



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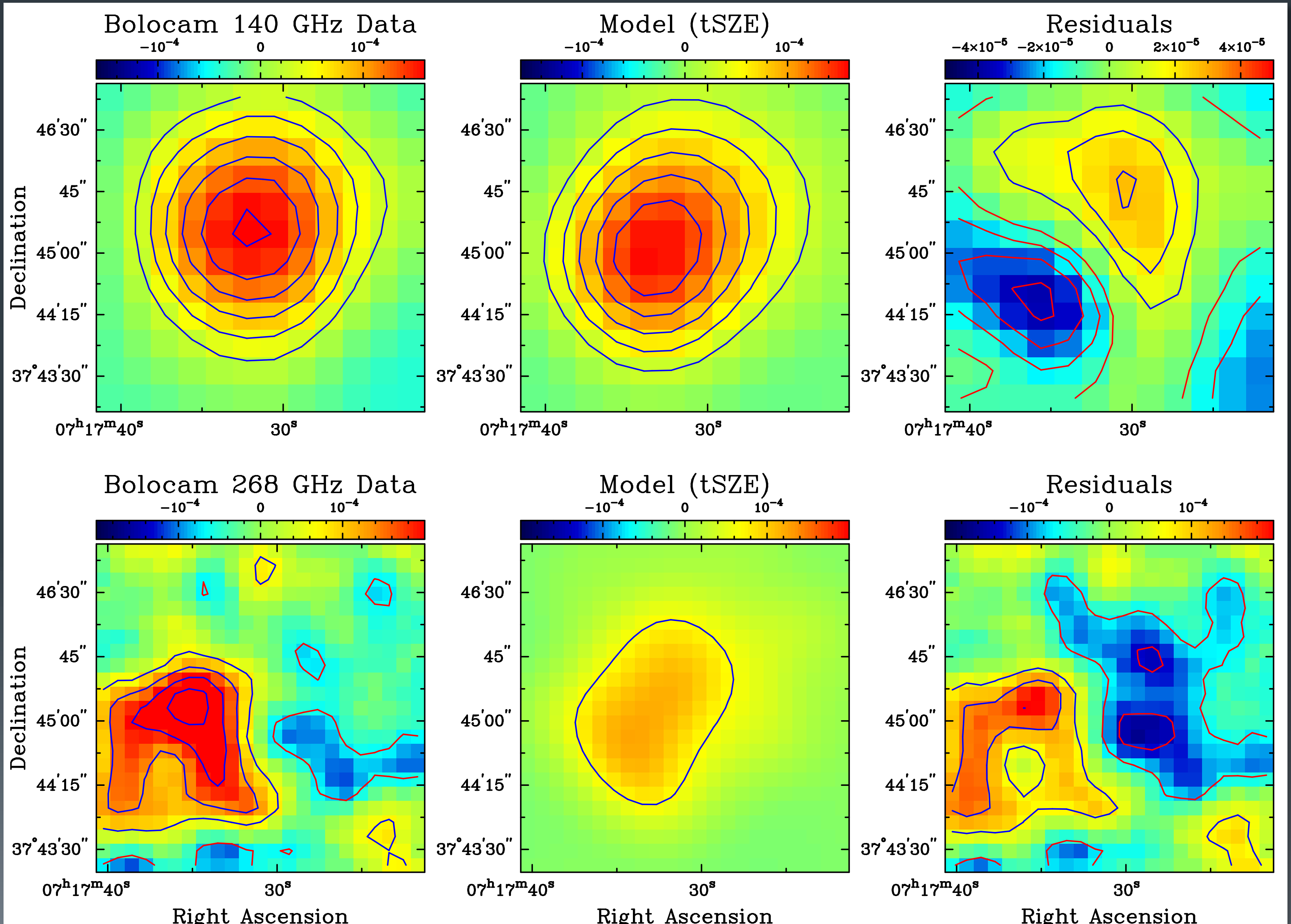
Fitting the Pseudo-*y* Map to the Bolocam 140 and 268 GHz Data



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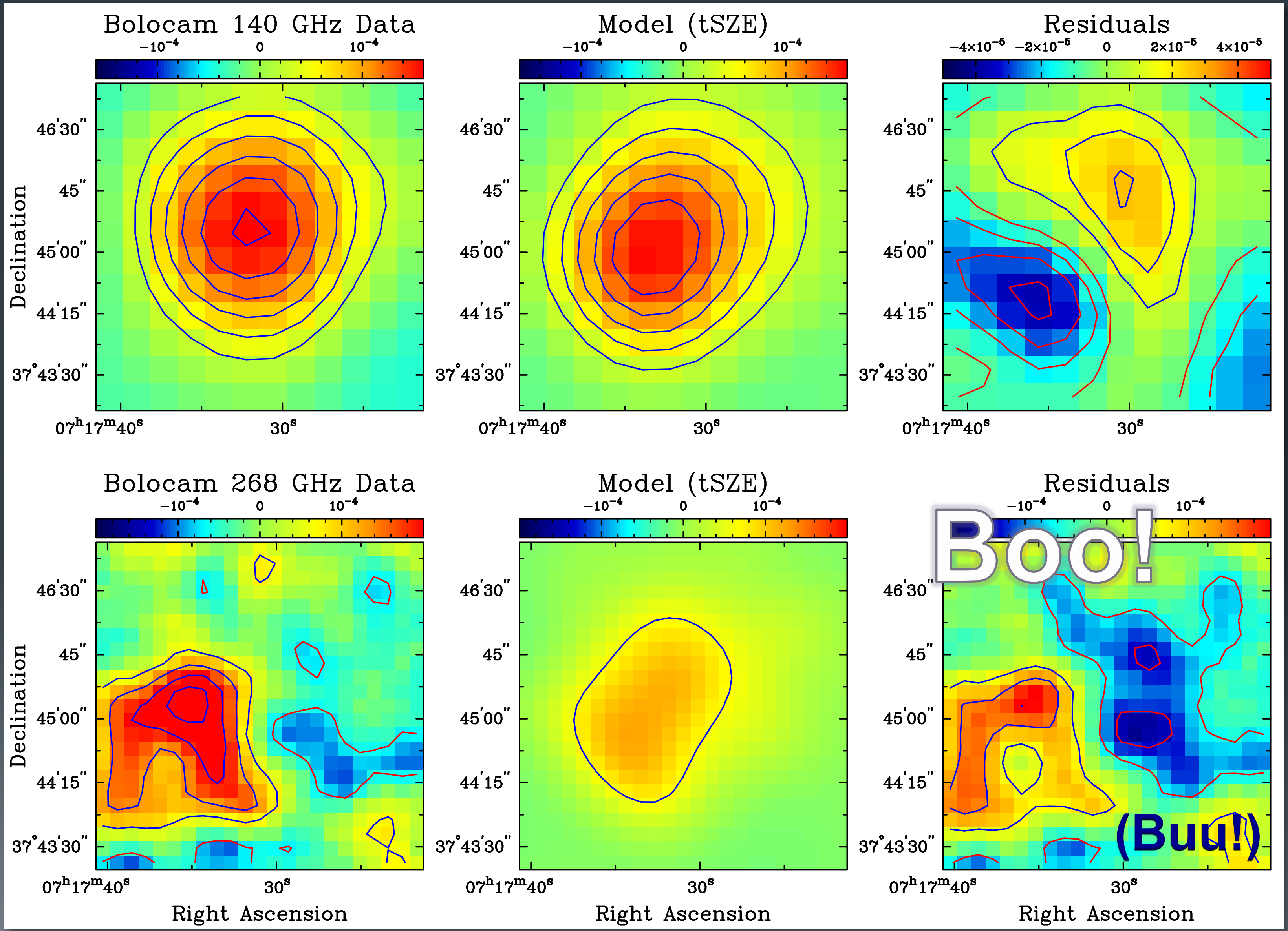
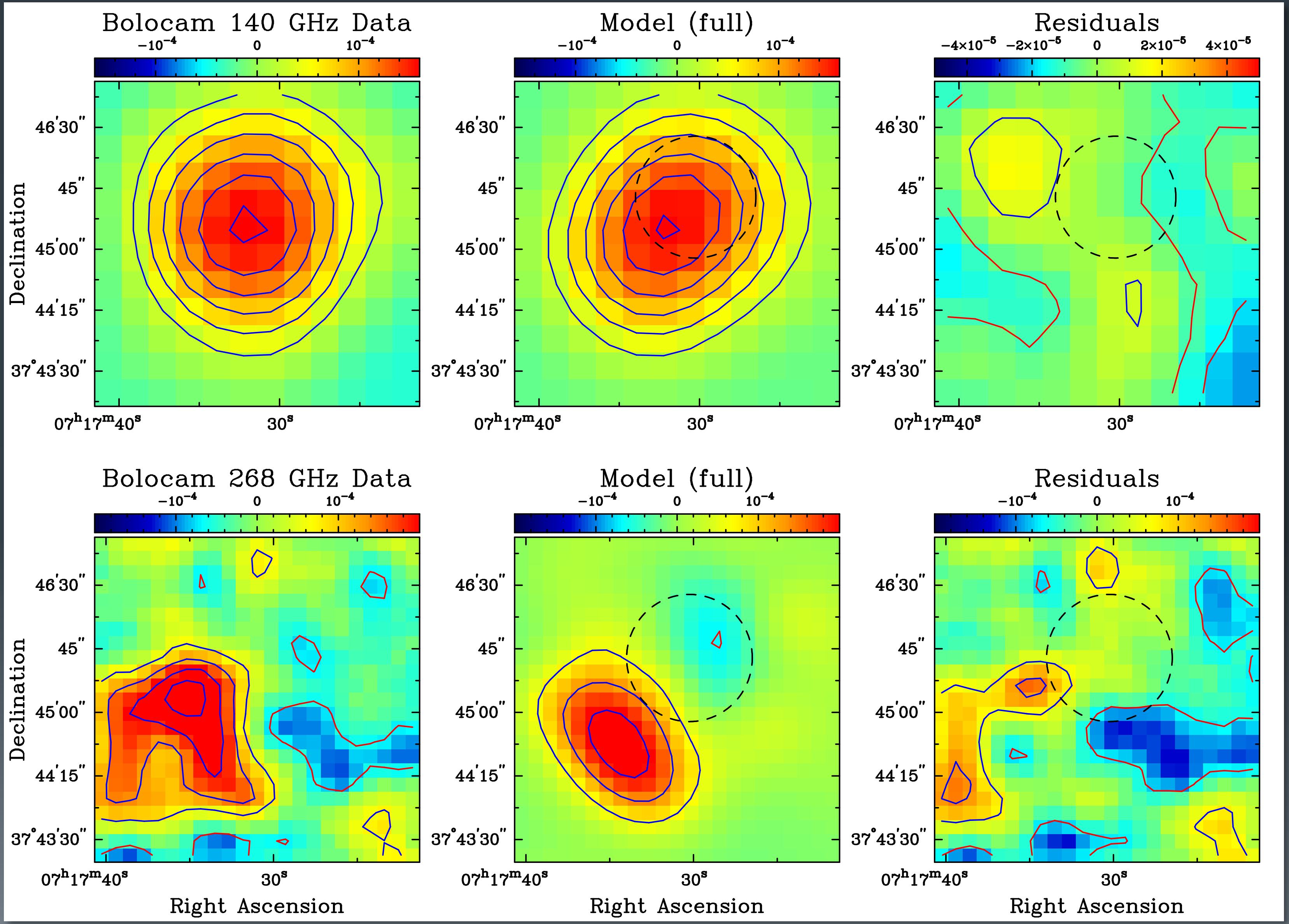
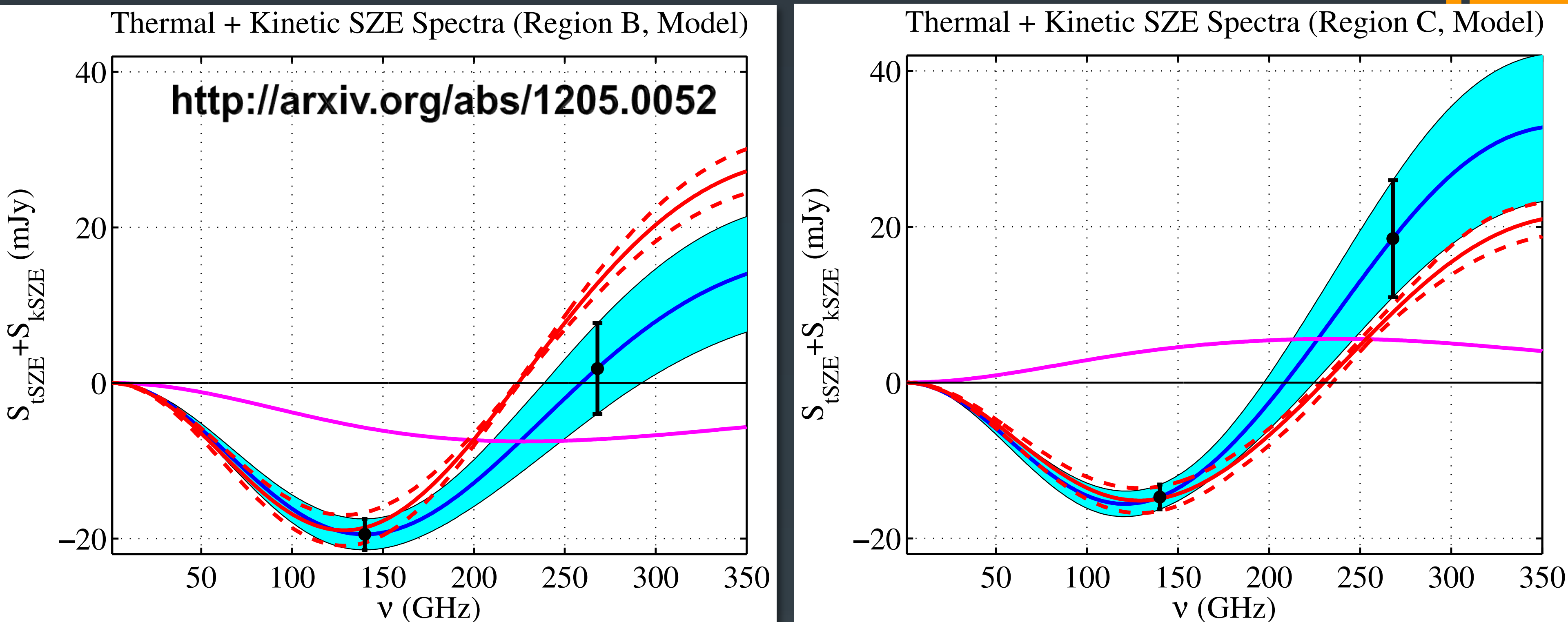


Adding a Gaussian Component at Subcluster B to the Pseudo-*y* Fit

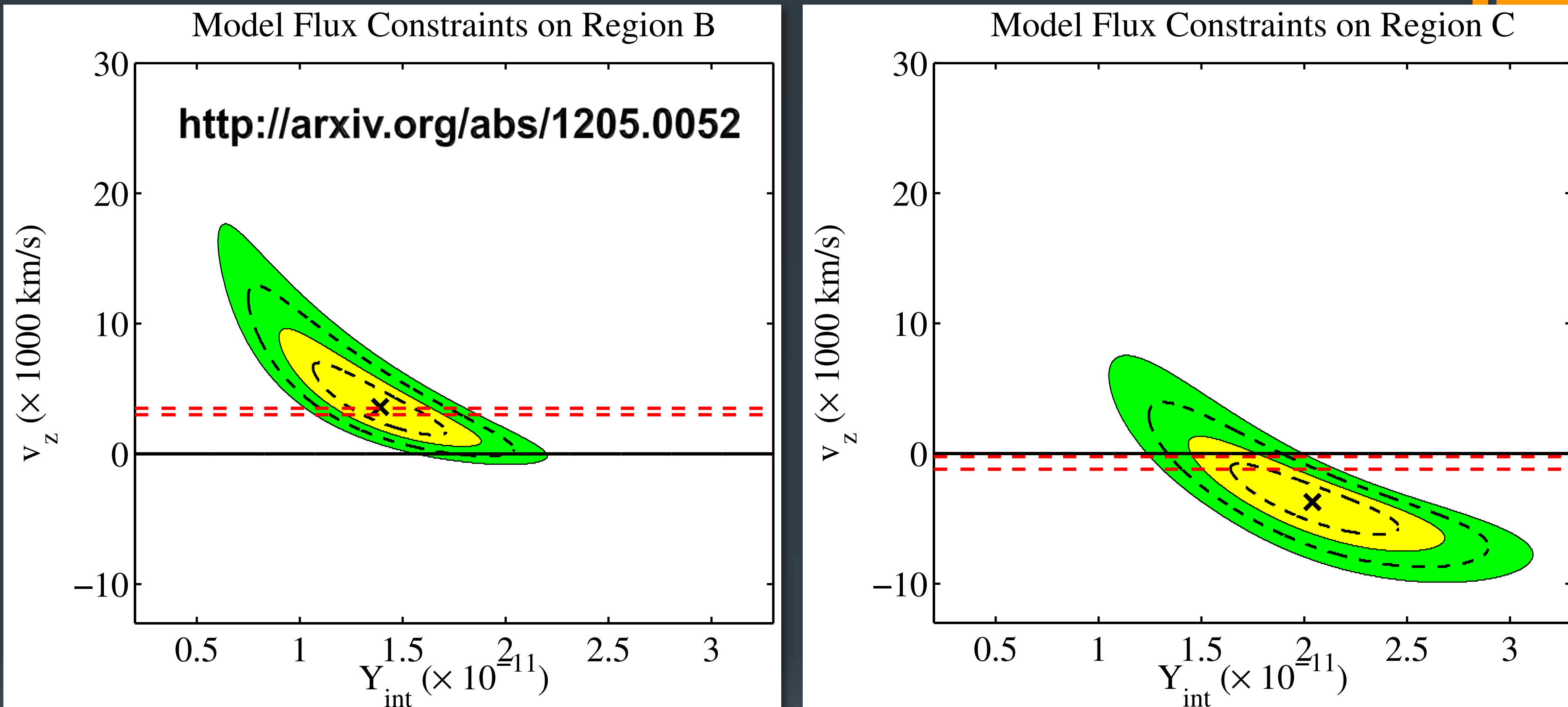


Fitting a thermal + kinetic SZE spectrum to Subclusters B and C



- Marginalizing over the X-ray constraints on temperature, we fit for a thermal + kinetic SZE spectrum to describe the Bolocam 140+268 GHz data.
- B requires a negative flux at both frequencies (decrement and increment), and cannot be explained by any thermal SZE or contamination.
- The best TSZE spectrum (red) is excluded at 98%.
- C also favors a non-thermal SZE spectrum with a kinetic component.

kSZE constraints on proper velocities of Subclusters B & C



- Yellow region shows the 1-σ constraints on both Y and v. Green is for 2-σ.
- Dotted regions are 1 and 2-σ on each parameter (marginalizing over the other).
- We find that $v_z=3600^{+3440}_{-2160}$ km/s for subcluster B, with a probability $v_z<0$ of 2.1%. The optical velocity estimate for this subcluster is 3238^{+252}_{-242} km/s.
- For C, $v_z=-3720^{+2960}_{-2480}$ km/s (optical is -733^{+486}_{-478} km/s).

Conclusions

- with Bolocam, we have made the first detection of a kSZE component to the spectrum of a resolved subcluster. This may even be the strongest kSZE detection in any individual cluster yet.
- with MUSTANG-1, we have again revealed pressure substructure that is poorly constrained by current X-ray observations.
- Look forward to MUSTANG-2, which will bring a larger field of view and the background-limited performance necessary for precision cosmology with the SZE. This will unleash the full potential of the GBT, which has more collecting area than the full ALMA+ACA will.
- MUSTANG-2 will become a facility instrument of the NRAO, so the larger astronomical community will benefit (e.g. follow-up for eROSITA, LSST, EUCLID, Planck, etc.)

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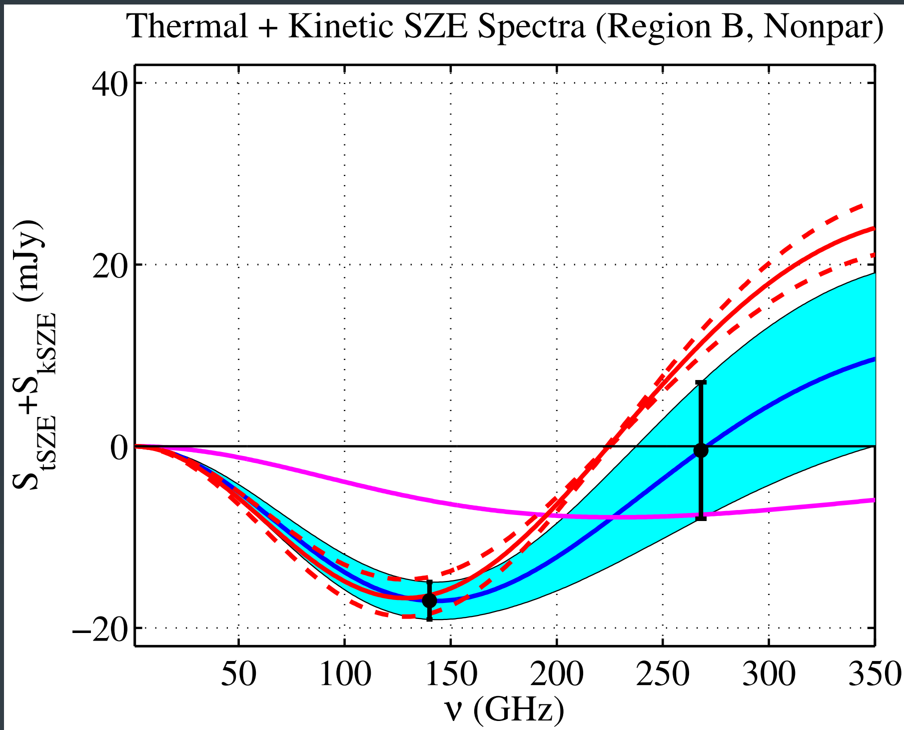
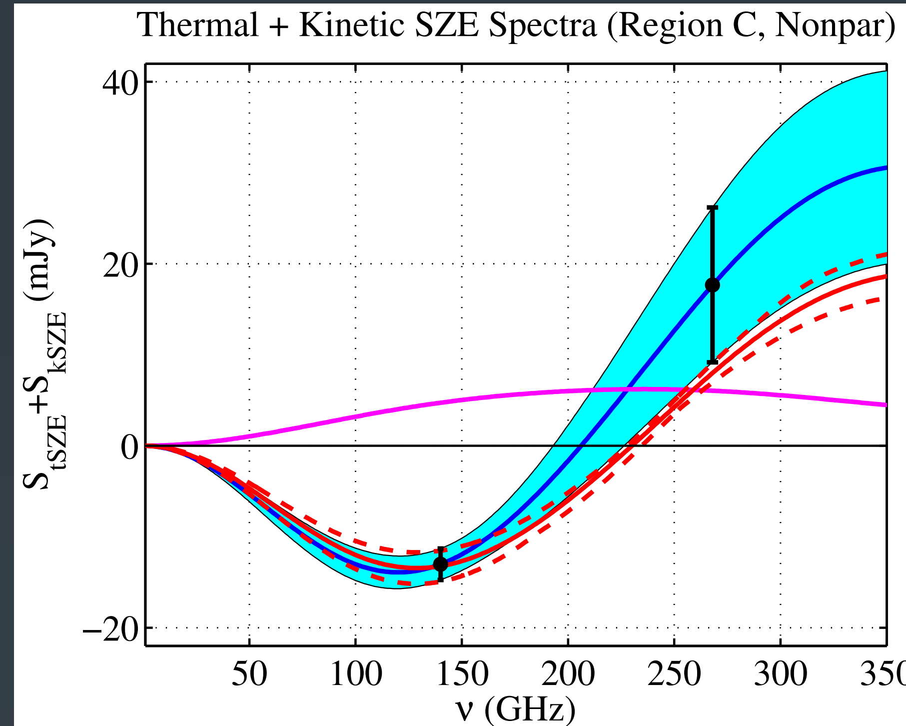
Fitting a KSZ+TSZ Spectrum to Subclusters B and C

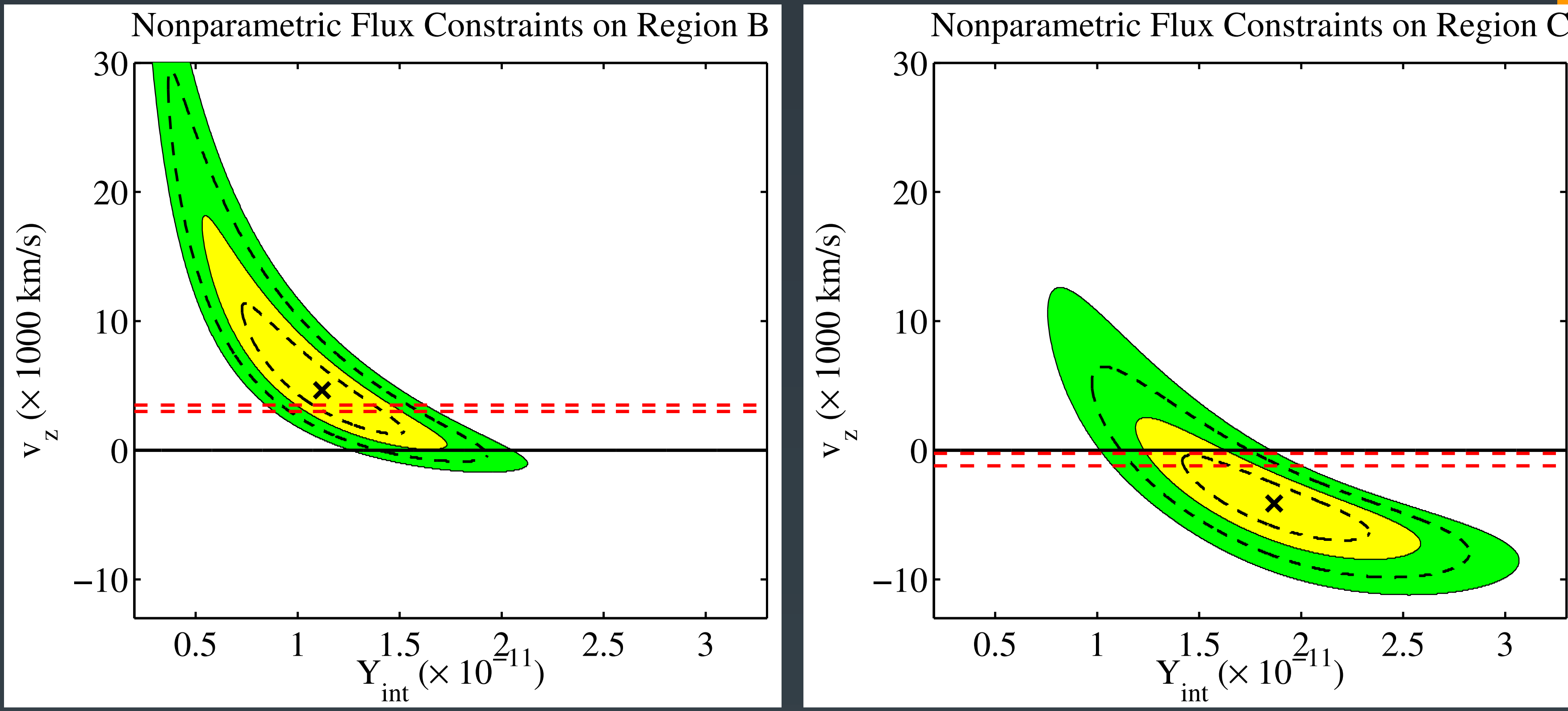




- We also fit the tSZE+kSZE spectrum using model-independent flux estimates from the deconvolved Bolocam maps.
- The error bars are larger, but results are very consistent with those using the model-integrated fluxes.

http://arxiv.org/abs/1205.0052

KSZ constraints on proper velocities of Subclusters B & C



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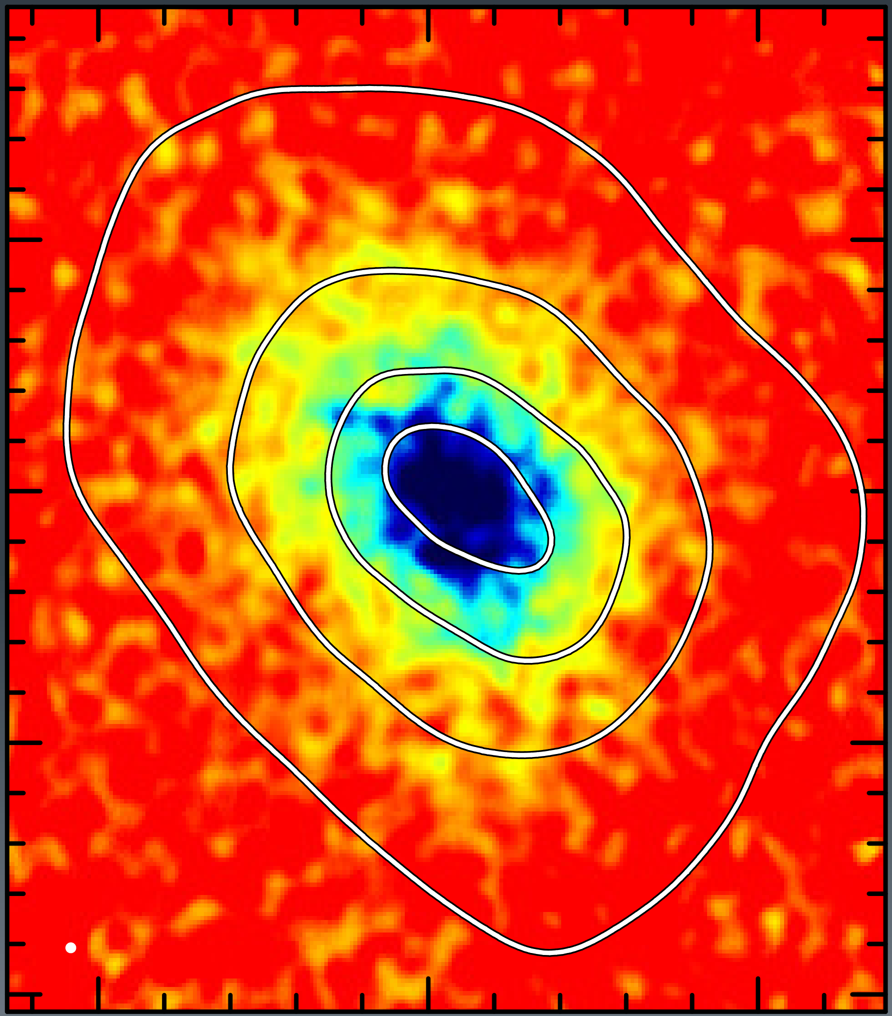
what about the MUSTANG data?

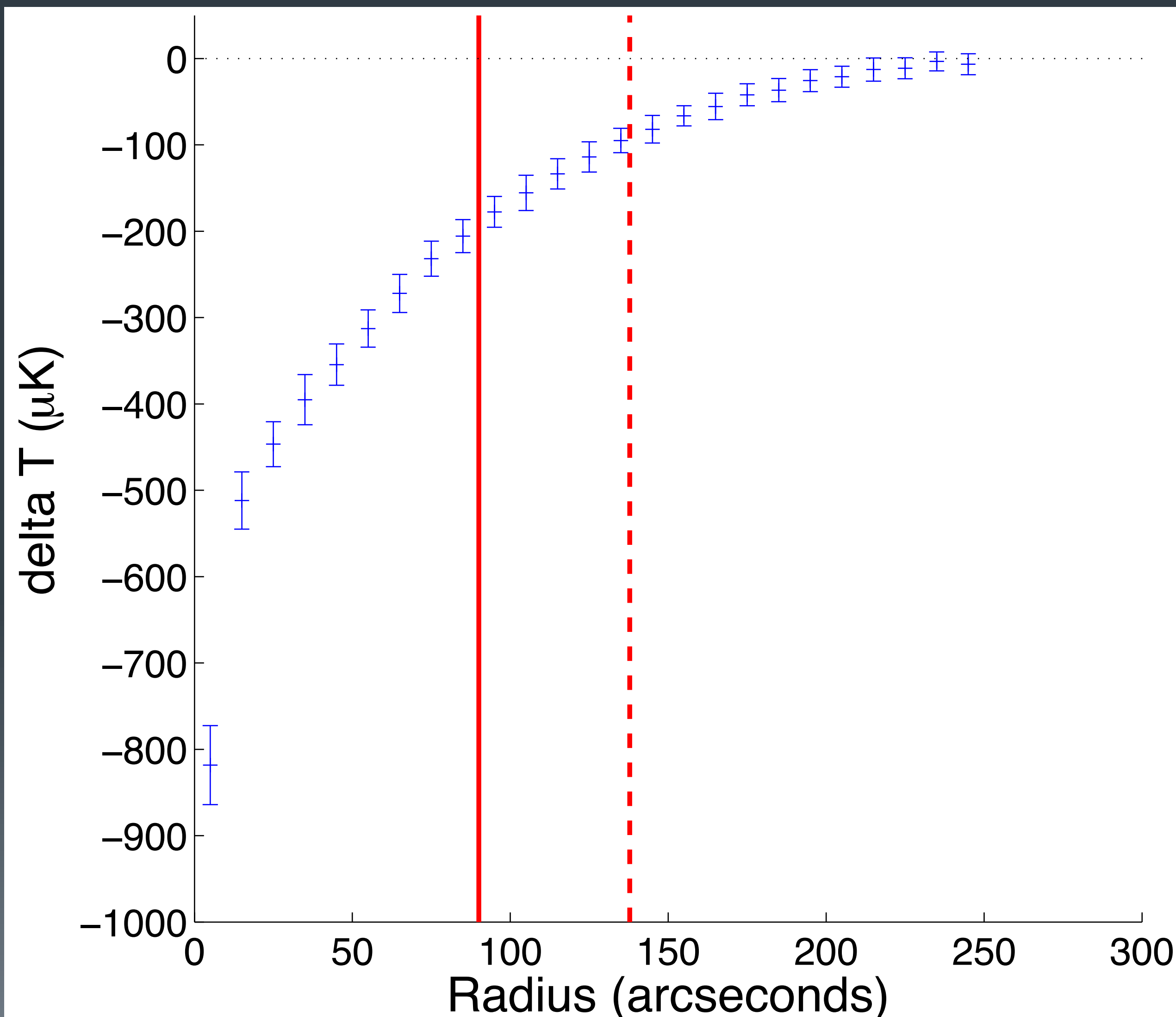
- It's missing from the kSZE analysis because it cannot recover scales larger than ~1 arcmin.
- We have the largest steerable object on land at our disposal, and probably the noisiest TES detectors currently in use.
- the GBT has more collecting area than full ALMA will, and holography has improved its surface efficiency by a factor of 4 since MUSTANG started.
- for a relatively low cost *(x1000 less than any X-ray satellite one can devise),* we could improve MUSTANG's mapping speed by ~250 times using technology already demonstrated.
- MUSTANG observing proposals have been ranked so highly (despite its limitations) that we are now backlogged by hundreds of hours.

Simulated observation with MUSTANG-2



- 4.5×10^{14} M_{solar} cluster at z=0.5 (typical of ACT & SPT discovered clusters).
- Simulations were performed by Nick Battaglia (CITA) using GADGET-2.
- The sims include star formation, stellar feedback, and a model for AGN feedback (all of which reduce the SZE signal.
- Image to left is 1-hour (3.6 ksec) map with contours from input map. The mock observation includes real atmospheric noise from MUSTANG-1 observations.

recovery of cluster profile from a mock MUSTANG-2 1-hour observation



- solid red line is r500 (typical limit of a deep *Chandra* observation).
- the dashed red line is r200 (approx. the virial radius).
- profile is still significant beyond r200!
- this is only 1 hour on a z = 0.5 cluster (to put this in X-ray terms, *MUSTANG-2 will require only 3.6 ksec to probe beyond the virial radius of an intermediate redshift cluster*).