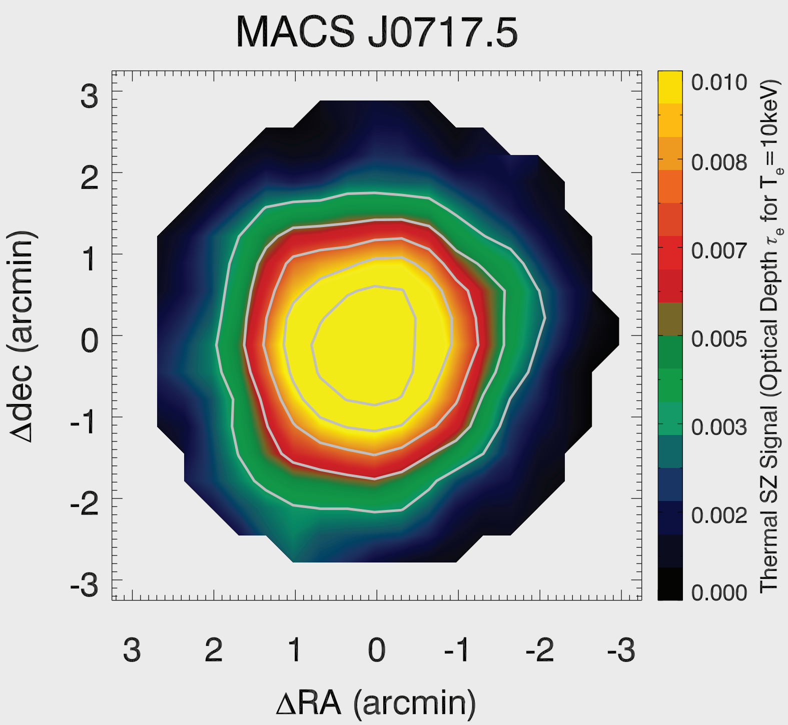
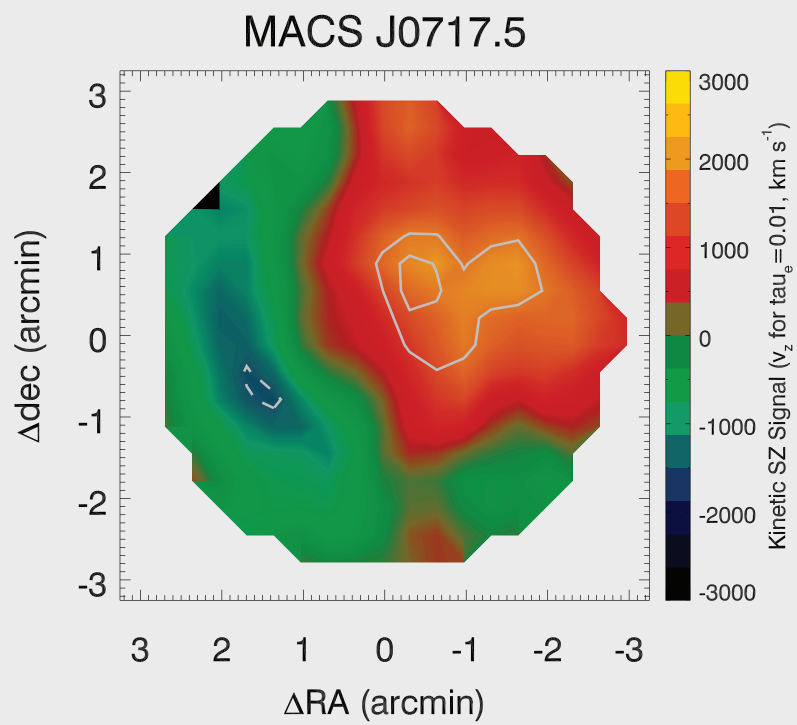
Measuring Large-Scale Velocity Fields with the Kinematic SZ Effect

Jack Sayers

November 08, 2018





Future Potential and (Some) Current Results using the Kinematic SZ Effect

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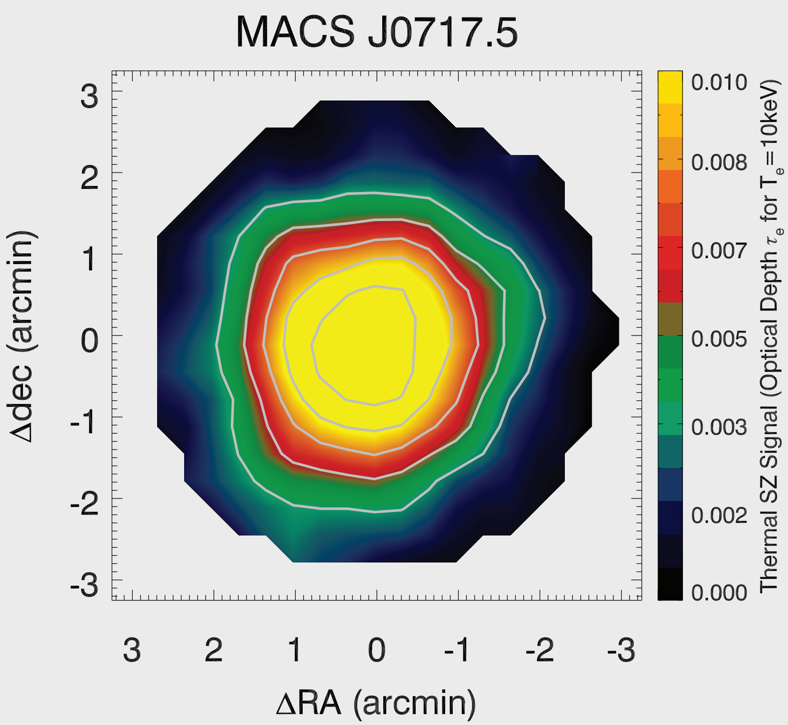
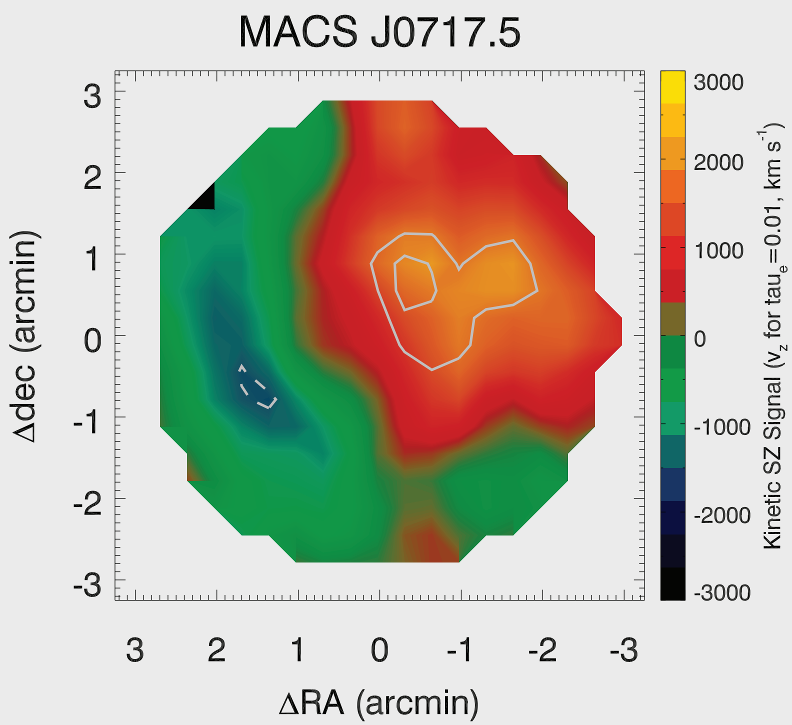
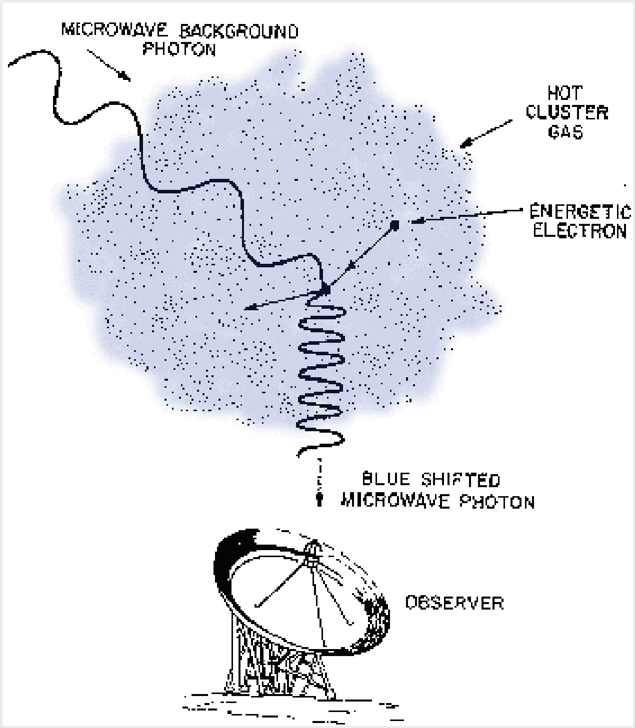
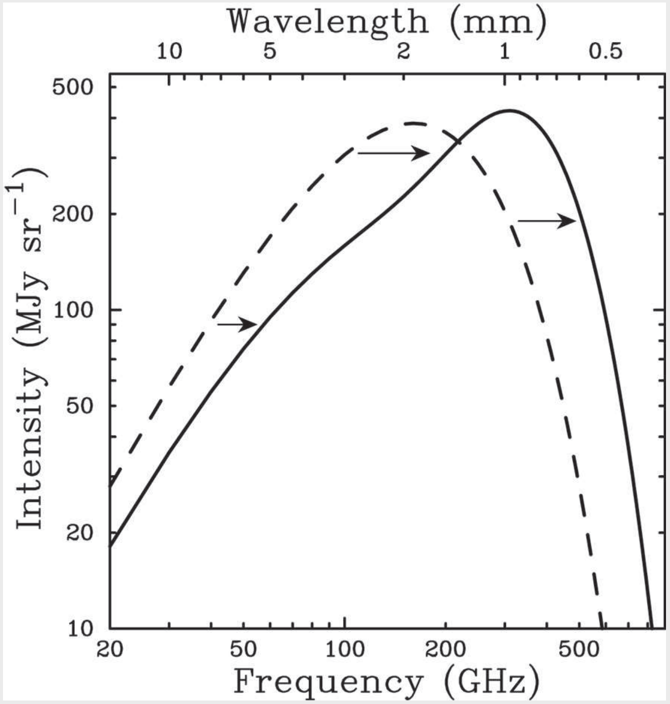




Galaxy Cluster Atmospheres



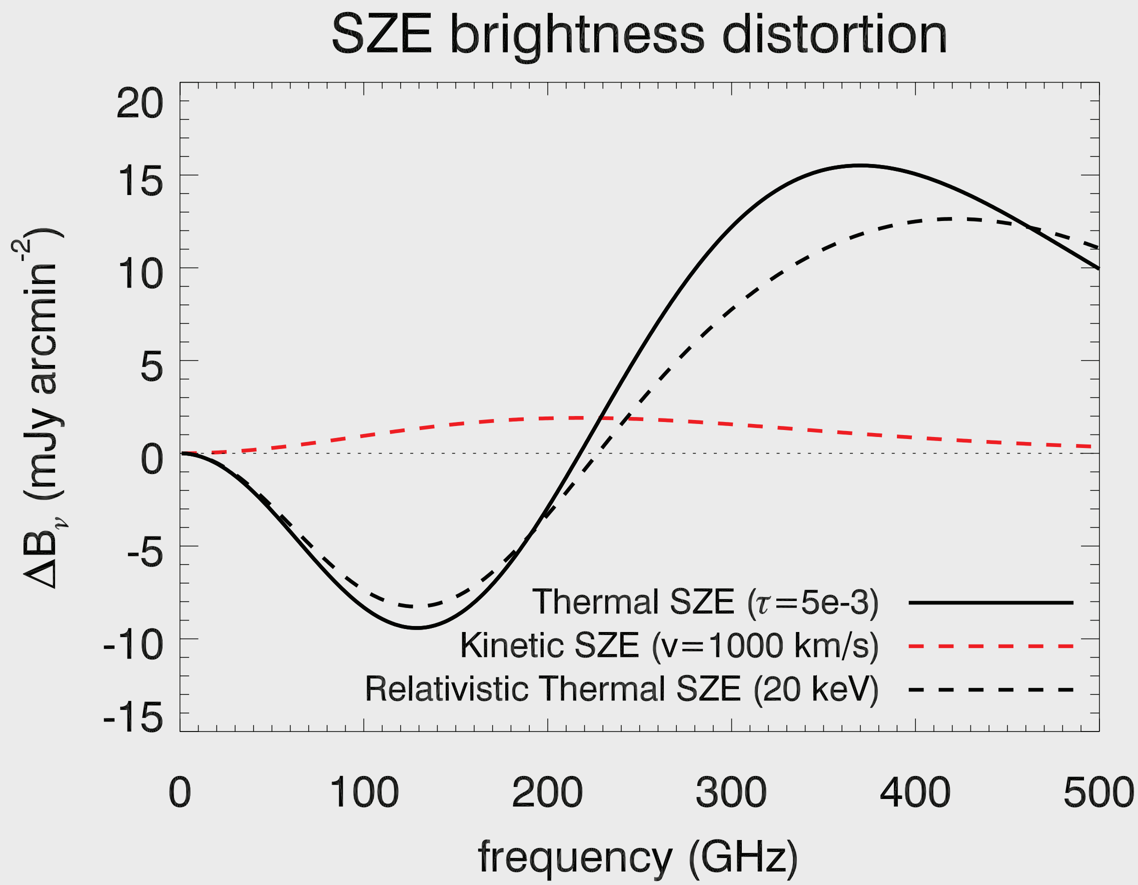


- Intra-cluster medium → 90% of baryons → 10^8 K (few keV)
- Directly emits thermal Bremsstrahlung in X-rays
- Compton scatters CMB photons → Sunyaev-Zel'dovich effect

Figures taken from Carlstrom+2002

The SZ Effects

- Thermal SZ effect
  - $\frac{\Delta T_{CMB}}{T_{CMB}} \sim T_e \tau_e$
- Kinematic SZ effect (Doppler shift)
  - $\frac{\Delta T_{CMB}}{T_{CMB}} \sim v_z \tau_e$
- Relativistic distortions to both
- Can determine τ_e, T_e, and v_z via SZ brightness with $3+$ spectral bands

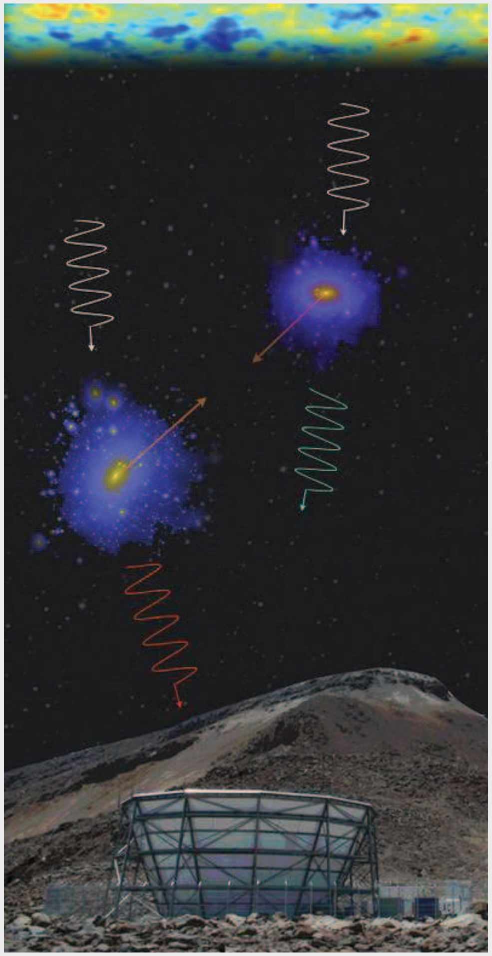


The Kinematic SZ Effect

- The good:
  - The SZ effects are a fractional distortion of the CMB $\rightarrow$ brightness is redshift independent
  - Proportional to density $\rightarrow$ (comparatively) easier to study low density outskirt regions compared to X-rays
  - Measures v_z relative to CMB reference frame $\rightarrow$ absolute velocity measurements
- The bad:
  - Signal is dim, and $\sim \times 10$ dimmer than thermal SZ effect $\rightarrow$ difficult to detect and requires precise calibration
  - Many contaminating signals $\rightarrow$ spectrally degenerate with primary CMB anisotropies, much dimmer than thermal SZ effect and thermal dust emission from background galaxies (CIB)

Large-Scale Velocities with kSZ

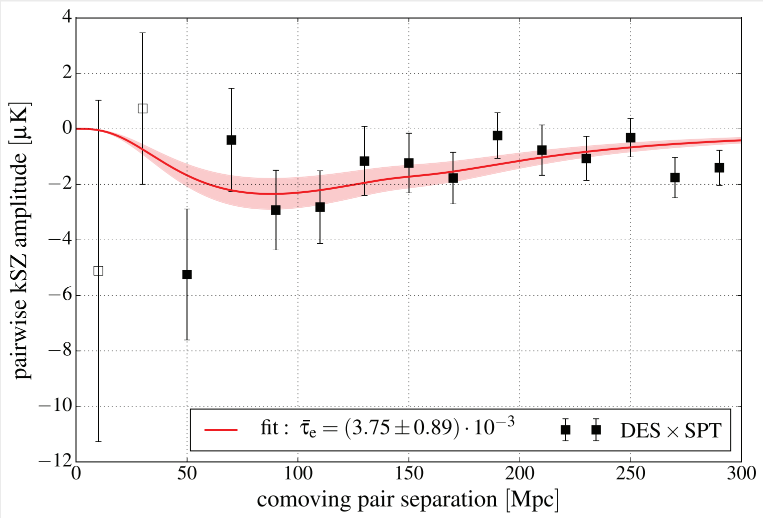
- Can average away contaminating signals by differencing total SZ signal from nearby pairs of objects
- Combine CMB survey data with external catalog (SPT/DES, ACT/BOSS, Planck/SDSS)
- On average, CMB, CIB, and thermal SZ will be the same in both objects, motion towards each other produces kinematic SZ with opposite signs

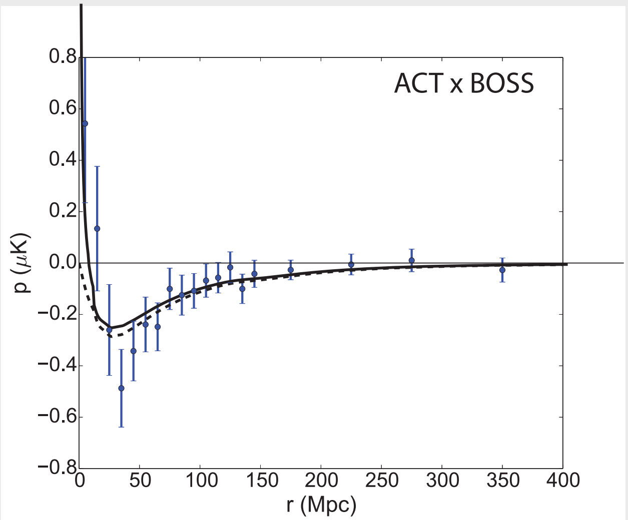


Pairwise kSZ (Das)

Pairwise kSZ Measurements

- Modest significance detections using existing data (SPT w/ DES cluster catalog, ACT w/ BOSS galaxy catalog, Planck w/ SDSS galaxy catalog)

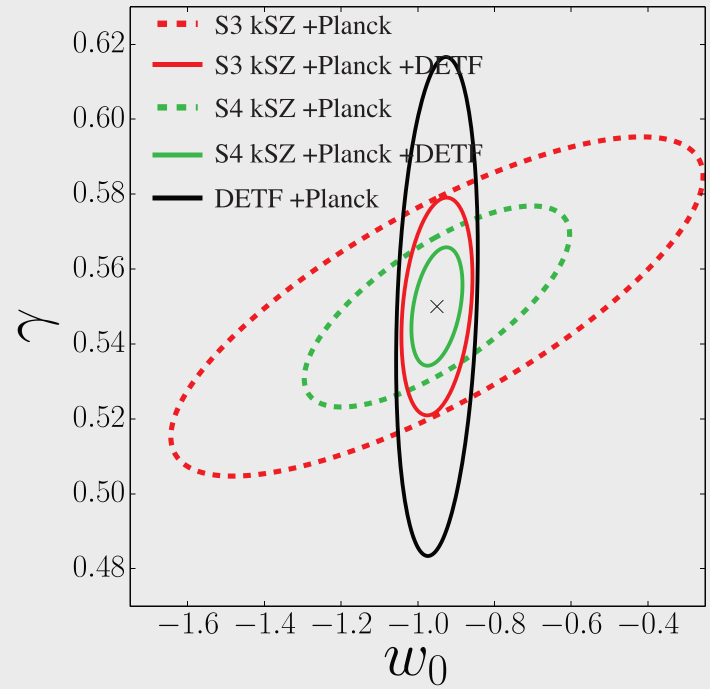




SPT/DES results from Soergel+2016, ACT/BOSS results from de Bernardis+2017

Cosmological Constraints from Pairwise kSZ

- Velocity field measurements are excellent for constraining dark energy and modified gravity
- DETF FOM ~200 for CMB-S4 → in the ballpark of other Stage IV surveys like MS-DESI (~700) and LSST (~800) → combined analysis can be powerful for breaking degeneracies



Adapted from Mueller+2015

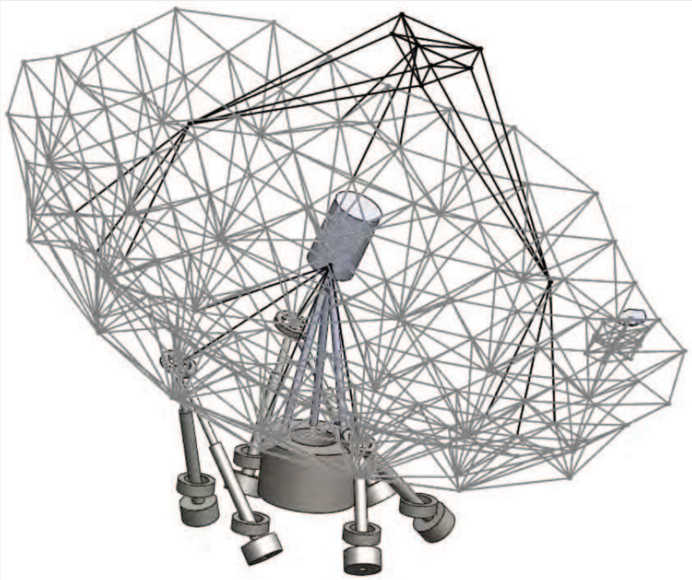
- Modified gravity → $\sigma(\gamma)$ ~0.03 for Stage III CMB and ~0.01 for CMB-S4 → similar to projections for MS-DESI, LSST, WFIRST, Euclid

What About Individual kSZ Detections?

- Pairwise kSZ has some downsides $\rightarrow$ actually measure $v_z \times \tau_e$, so you need an estimate of τ_e $\rightarrow$ also lose absolute v_z
- Individual kSZ detections would allow for direct absolute v_z measurements, but would require excellent signal separation $\rightarrow$ tSZ, CIB and primary CMB (at low-z)
- Probably not possible to the desired sensitivity from 5–10 m CMB survey telescopes, mainly due to CIB
- Need high angular resolution (large aperture) survey telescope with spectral coverage between 90–400 GHz

What About Individual kSZ Detections?

- As a straw-person example, consider the nominal design for the 30 m Chajnantor Sub/millimeter Survey Telescope (CSST)
- Large FOV with 6 photometric channels at 90–405 GHz
- 30k clusters with $\sigma_v \sim$200 km/s

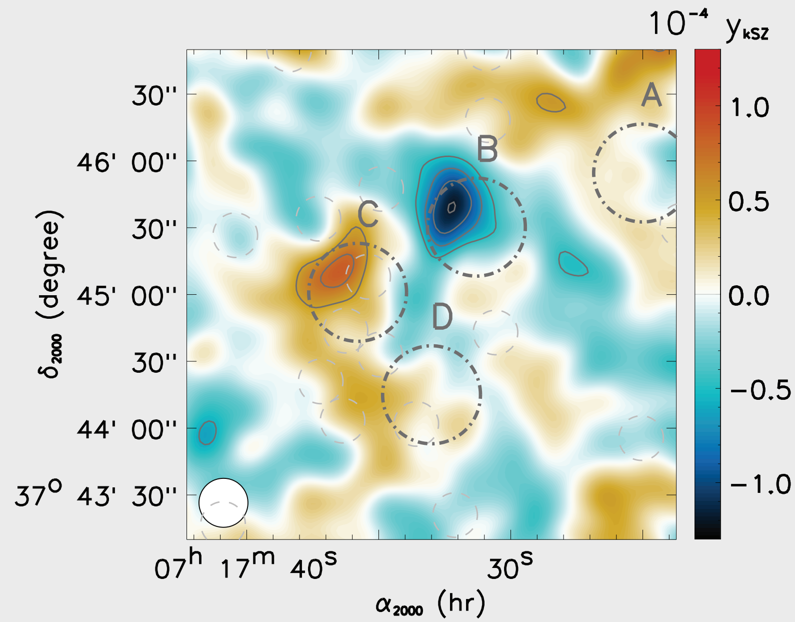


Inexpensive 30 m Telescope (Padin 2014)

- Would provide constraints on dark energy and modified gravity similar to CMB-S4 (and also MS-DESI, LSST, etc.)
- High mass clusters $\rightarrow$ internal ICM motions at $15''$ resolution

Current Status of Individual kSZ Detections?

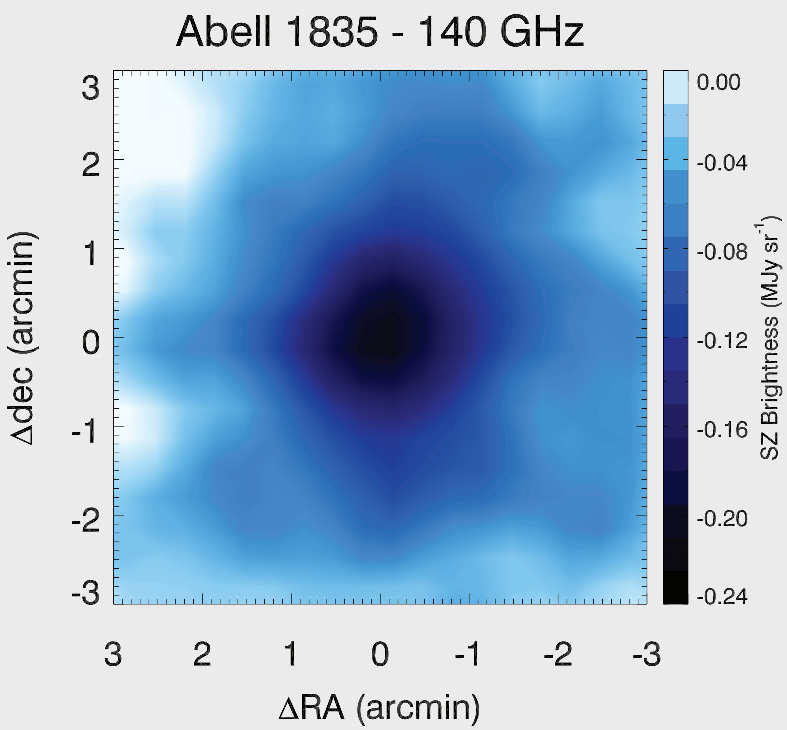
- No detections to date of single cluster bulk velocity
- Best to date is ACT/LABOCA study of 11 clusters with per-cluster σ_v ~1000–2000 km/s (Lindner+2015)
- Two independent detections of velocity substructure in MACS J0717.5 → merging sub-cluster with v_z ~3000 km/s

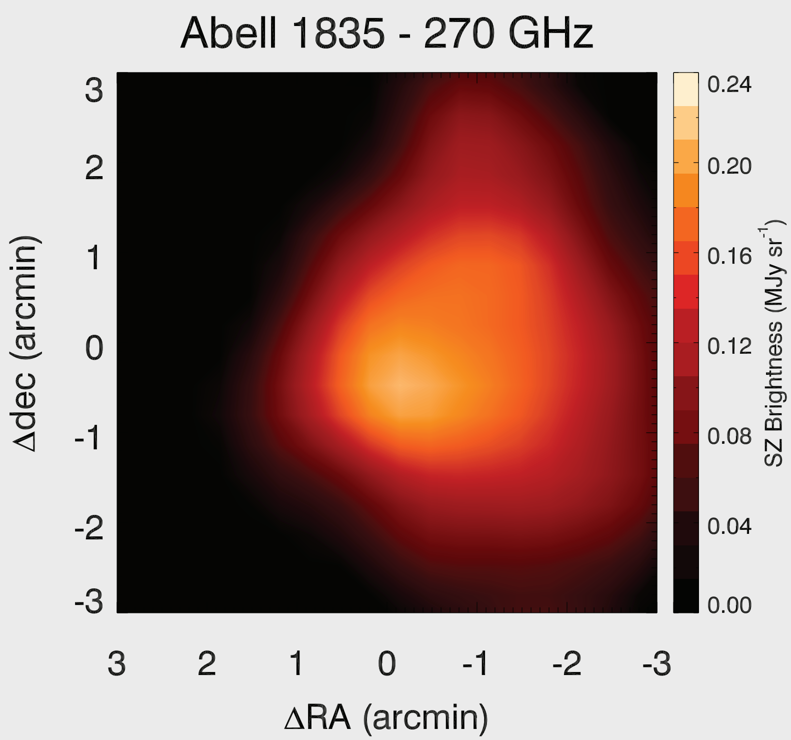


NIKA kSZ map of the exceptional merger velocities in MACS J0717.5 ($z = 0.55$, Adam+2017)

Current Status of Individual kSZ Detections?

- We are just finishing a study of 10 clusters using 10-m class data from Bolocam, AzTEC, *Herschel*-SPIRE, *Planck*, *Chandra*, and *HST* $\rightarrow$ bulk velocities and internal motions



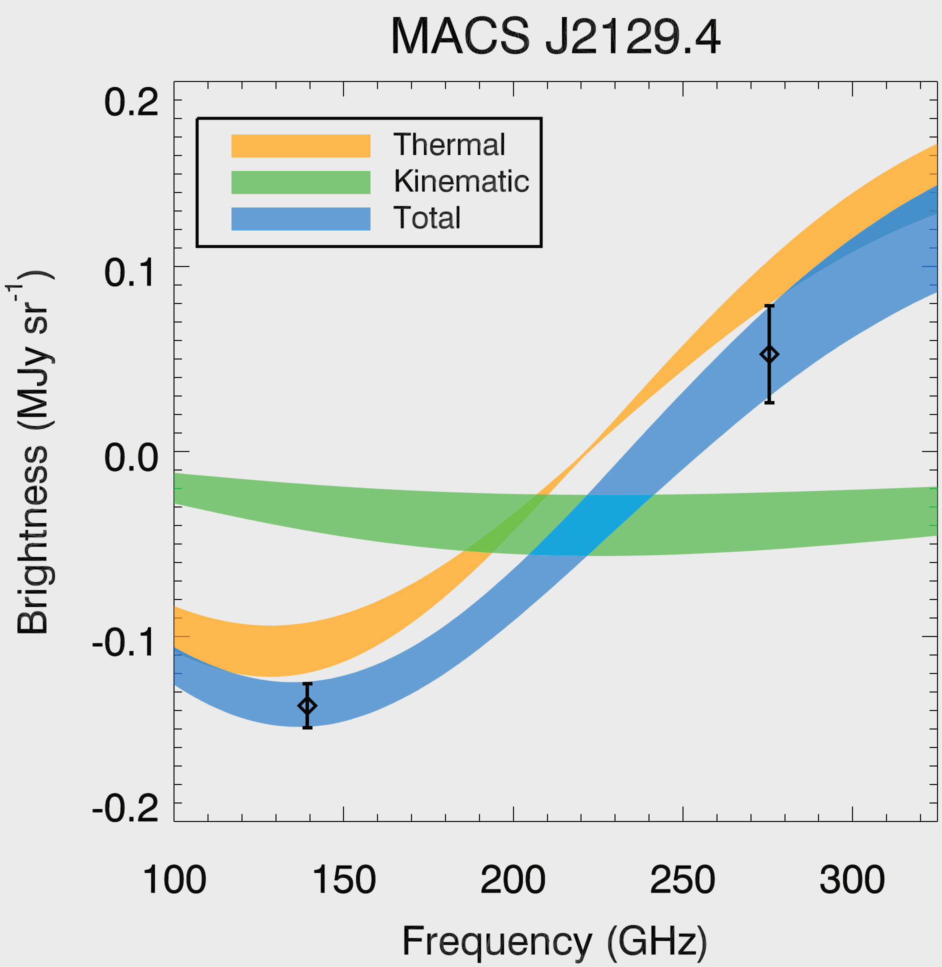


Why So Many Datasets?

- kSZ fit based on 140/270 GHz Bolocam and AzTEC data

- *Chandra* used to constrain T_e

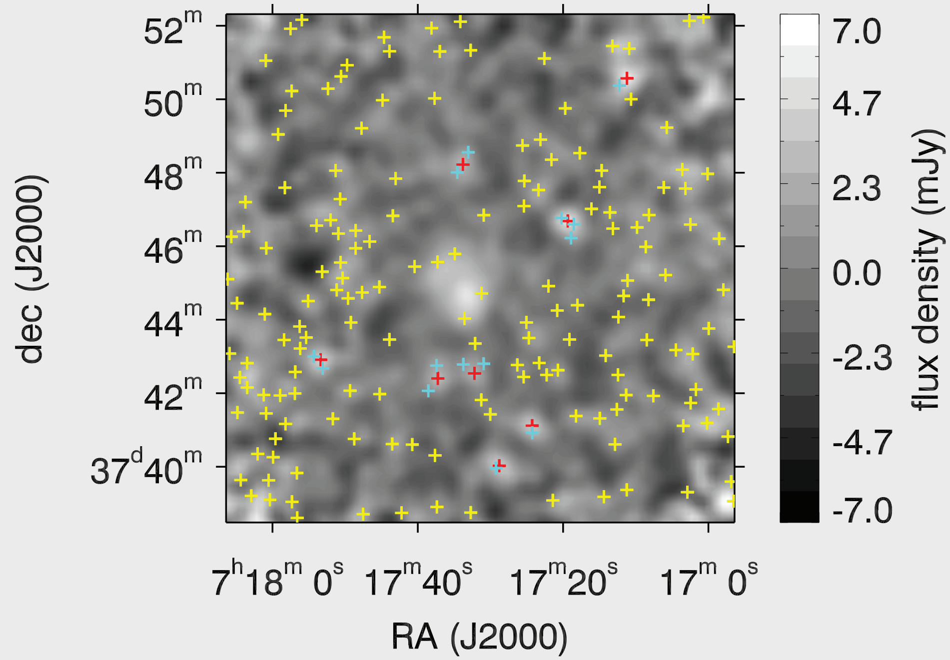
- *Planck* used to constrain large angular scale SZ signal



- *Herschel*-SPIRE used to detect/subtract CIB sources

Dusty Galaxies at 270 GHz

- 270 GHz images limited by variations in background CIB
  - brightest object usually a background galaxy, not SZ cluster
- Detect 10s of galaxies at 270 GHz plus ~ 100 more with SPIRE



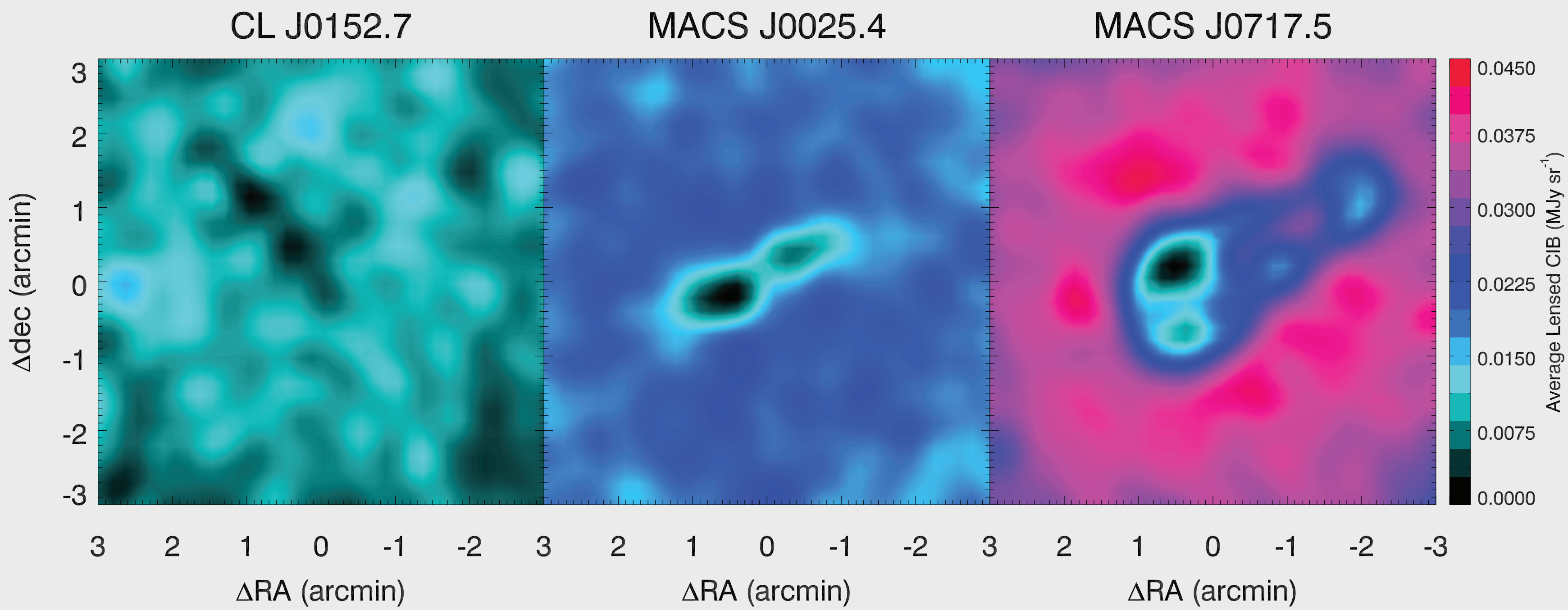
Each cross is a detected galaxy

- Extrapolate SPIRE detections to 270 GHz via greybody fit
  - $S\nu = S_0(1 - e^{-(\nu/\nu_0)^\beta})B(\nu, T_{dust})$
  - Float T_{dust}, set $\beta = 2.15$ based on empirical calibration

Why Do We Need *HST*?

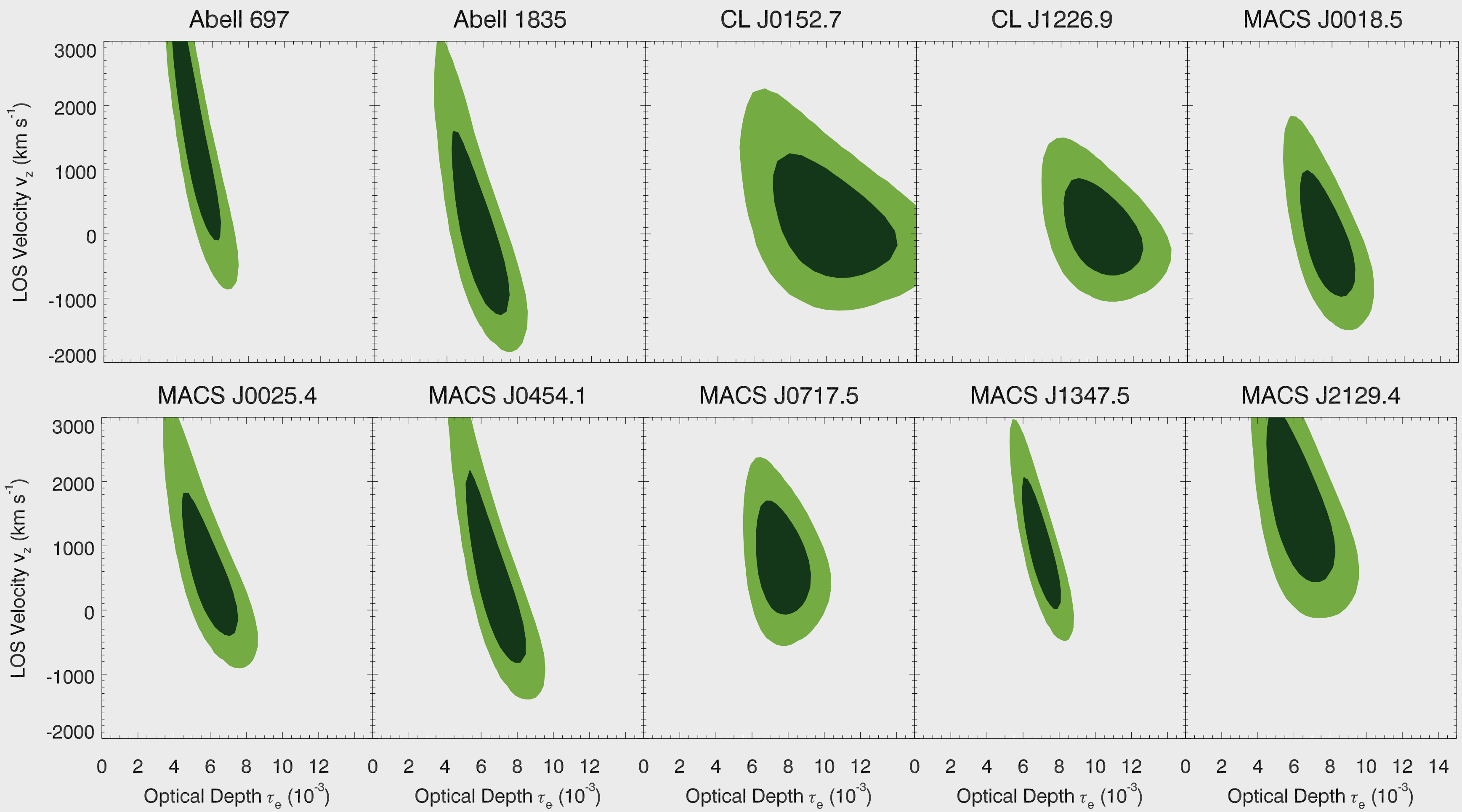
- The combination of gravitational lensing and bright source subtraction produces an on-average decrement in CIB

- In our case, decrement is 10–25% of 270 GHz SZ signal



Bulk Velocity Constraints

- With $Chandra$ prior on T_e, we measure v_z and τ_e

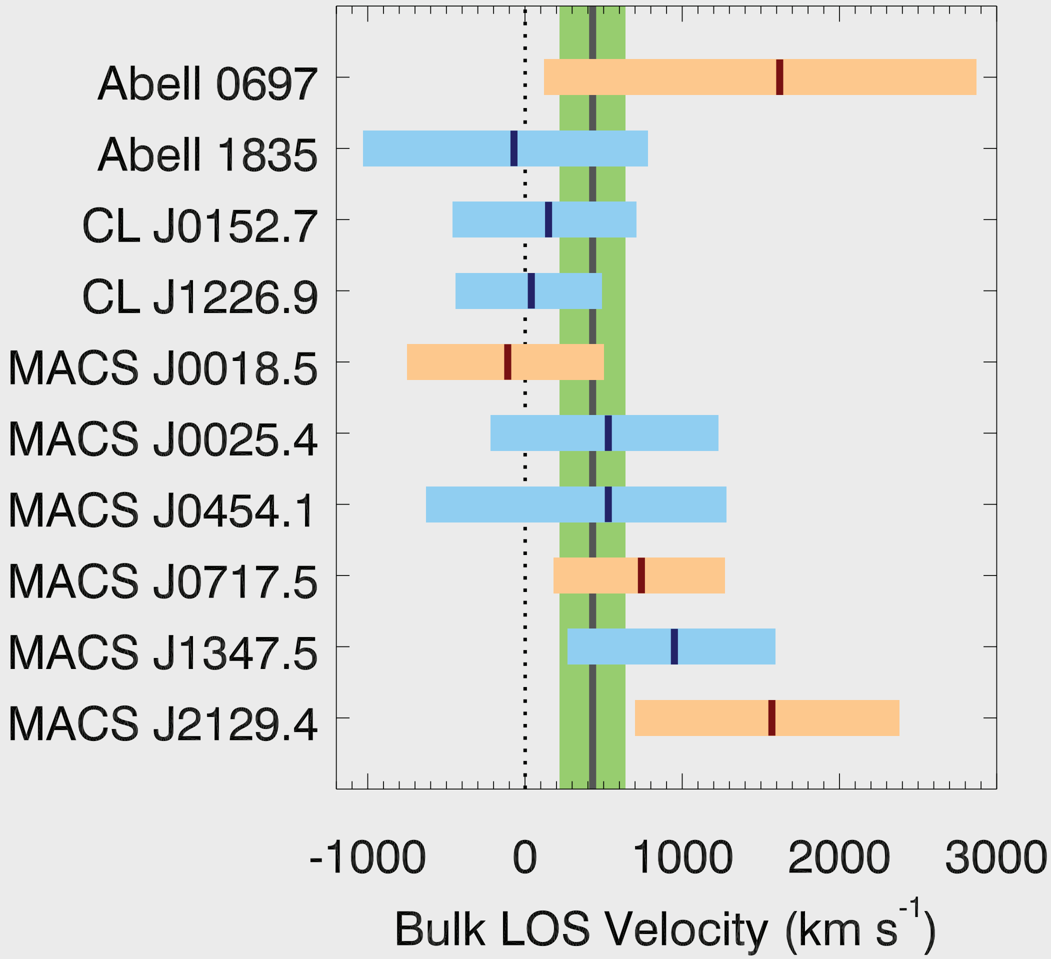


Bulk Velocity Constraints

- Typical per-cluster σ_v ~500–1000 km/s $\rightarrow$ factor of 2 improvement relative to ACT/LABOCA

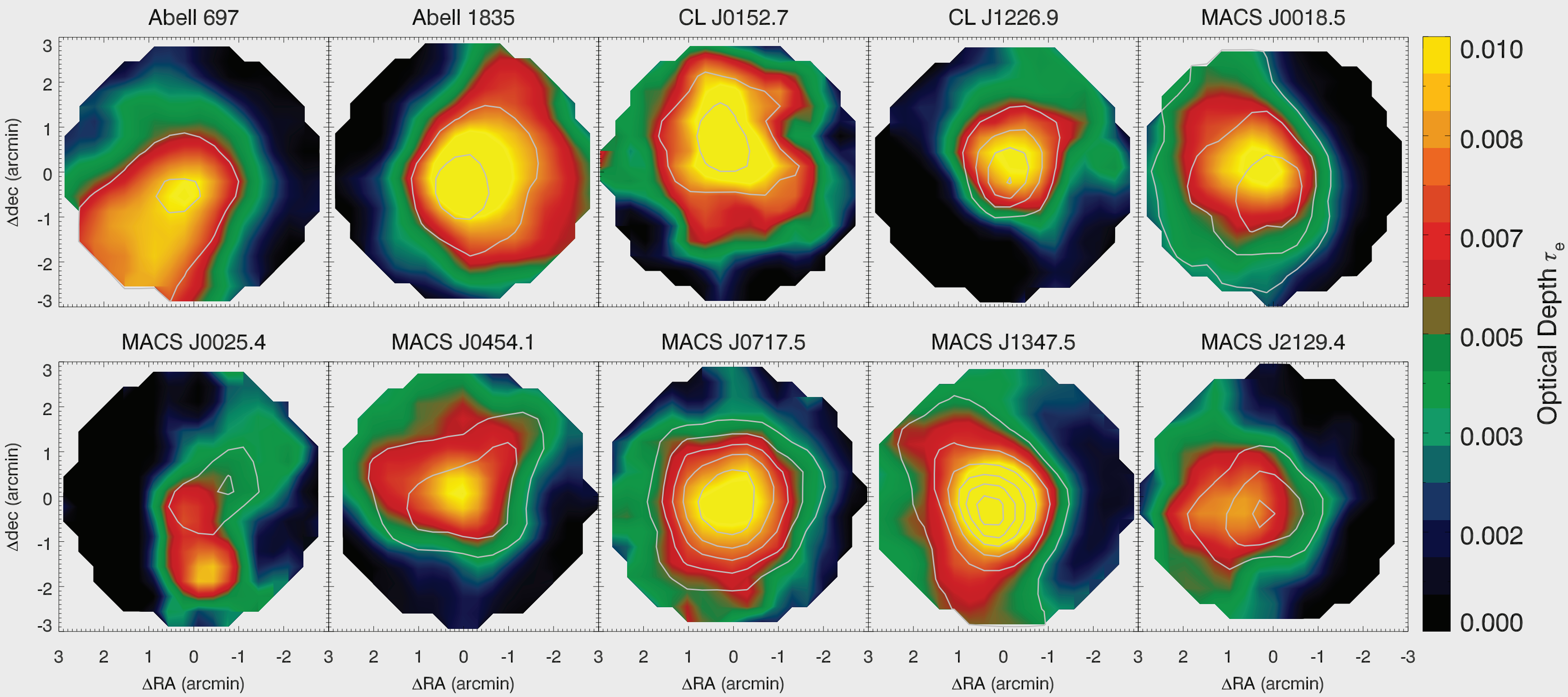
- Ensemble mean $\langle v_z \rangle = 430 \pm 210$ km/s

- Intrinsic scatter $\sigma_{\rm int} = 470 \pm 340$ km/s $\rightarrow$ simulations predict ~250 km/s



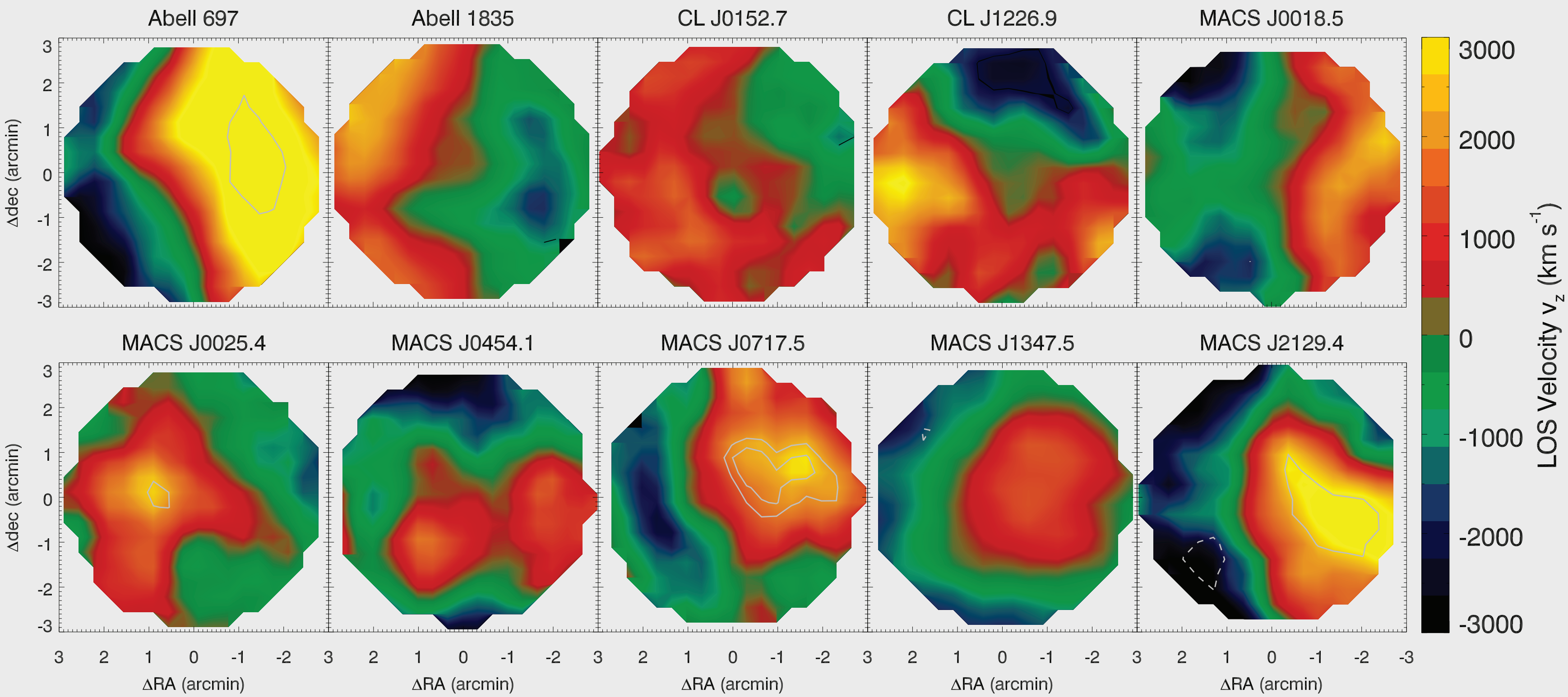
Internal ICM Motions

- Convolve data to a common resolution of $70''$ and fit for τ_e and v_z pixel by pixel
- Optical depth τ_e measured with peak S/N of 5–15



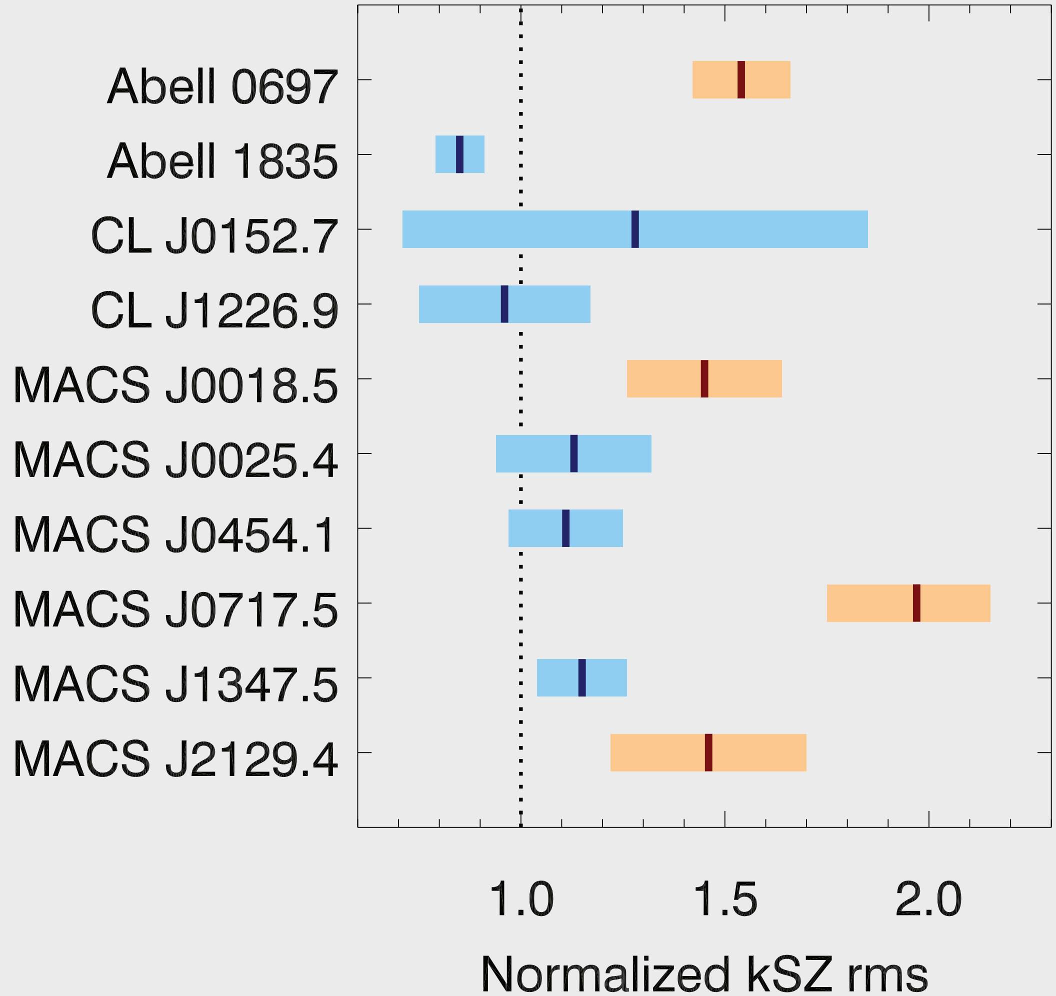
Internal ICM Motions

- Typical $\sigma_v \sim 1000$ km/s for each resolution element
- Only significant detection is the known sub-cluster in MACS J0717.5 (and that's only at 3σ)



Bulk Velocity Constraints

- Can compare rms in kSZ map to expectation based on random noise
- Two clusters, Abell 0697 and MACS J0717.5, show a $\sim 4\sigma$ excess in rms
- LOS mergers (red) all show some excess, corresponds to rms $v_z \sim$1000–2000 km/s



Summary

- The kSZ effect promises to be a powerful tool for constraining dark energy and modified gravity $\rightarrow$ interesting results from pairwise measurements in CMB surveys coming
- Future large-aperture survey telescopes like CSST could provide interesting cosmological constraints from individual kSZ detections $\rightarrow$ also a wealth of information on internal cluster dynamics
- Although the images have modest angular resolution and sensitivity, we have now reached the point of detecting internal cluster motions with the kSZ
- Higher resolution, deeper measurements from IRAM/NIKA2 and LMT/TolTEC will build on these internal motion measurements in the near future