Realistic Mock kSZ Observations to Forecast Constraints on Structure Formation and Cosmic Acceleration

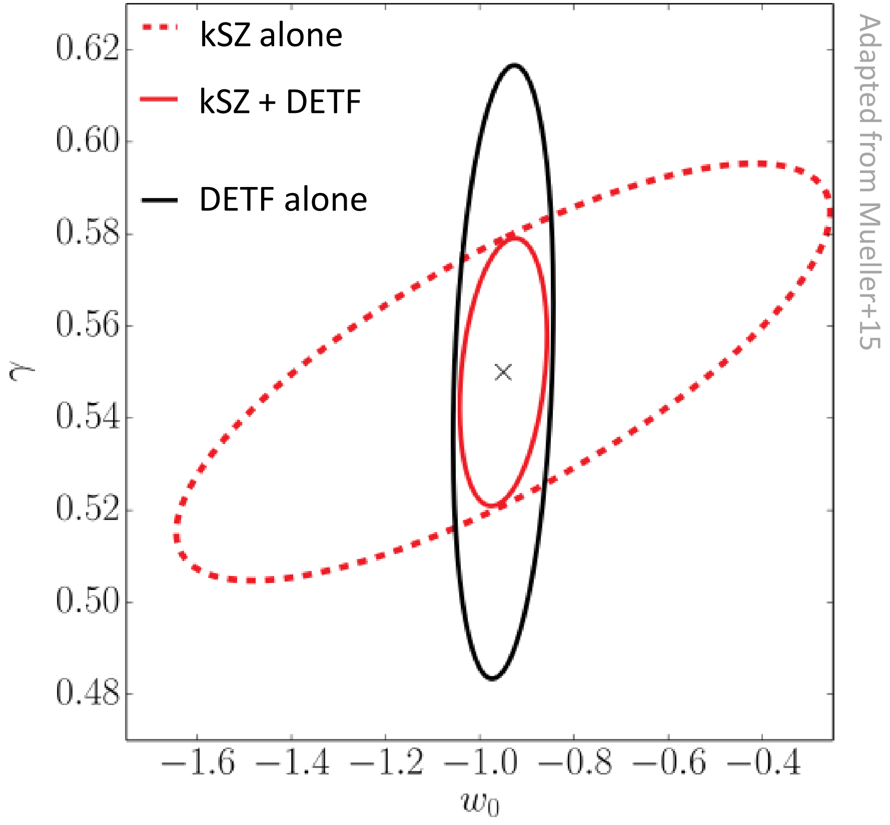
Ted Macioce (tmacioce @ caltech.edu)

Golwala Group, Caltech

Motivation #1: Cosmology With Velocity Field Measurements

- Deviations in velocity arise due to the gravitational pull of matter overdensities
- Can measure cosmic velocity field in different ways:
  - Redshift-space distortions
  - “Pairwise” kSZ (e.g., Hand+ 2012)
  - kSZ in individually detected massive clusters, $> 10^{14}\ M_{\odot}$ (our approach)

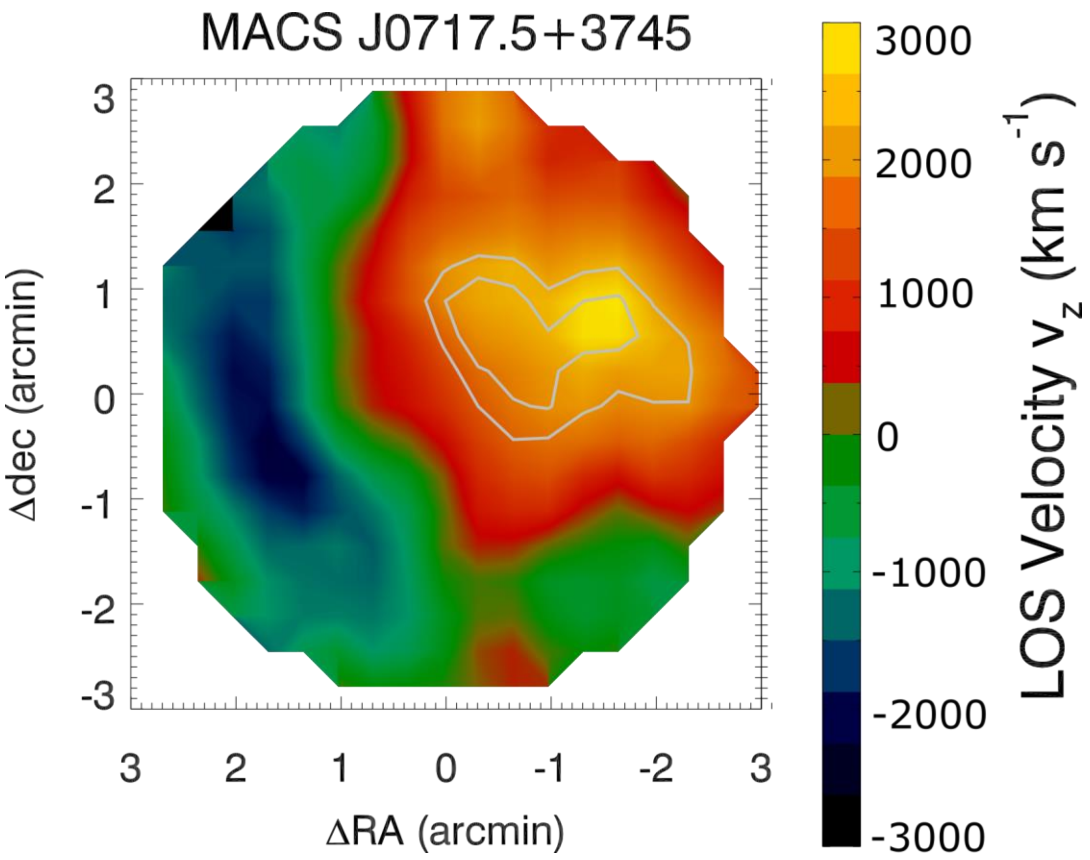
Constraints on the cosmic growth function with pairwise kSZ + DETF



“DETF” is shorthand for a collection of non-kSZ Dark Energy Task Force Stage III observables, including BAO and weak lensing

Motivation #2: Galaxy Cluster Formation Physics

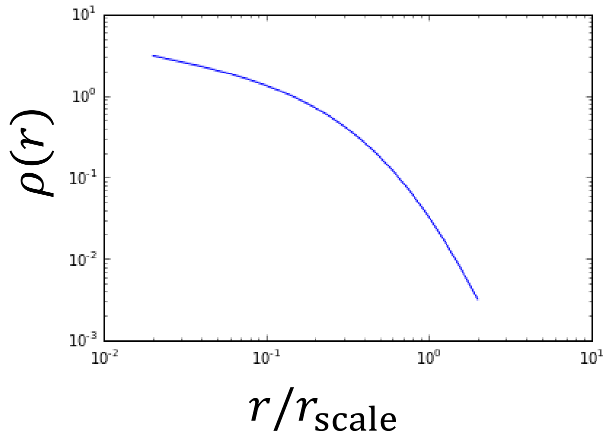
- Hydrodynamical simulations: accreting matter not fully thermalized → bulk motion of intracluster medium (ICM)
- Can measure line-of-sight ICM motion in cluster kSZ maps to test the simulated scenario
- Can also observe velocity in mergers, e.g. MACS J0717.5+3745 subcomponent (right)



Sayers+19

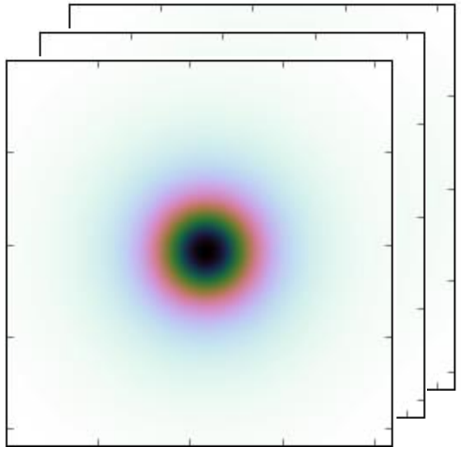
Our Approach: Individual-Cluster Mock SZ Observations

Model of ICM distribution (GNFW profile or simulated cluster)



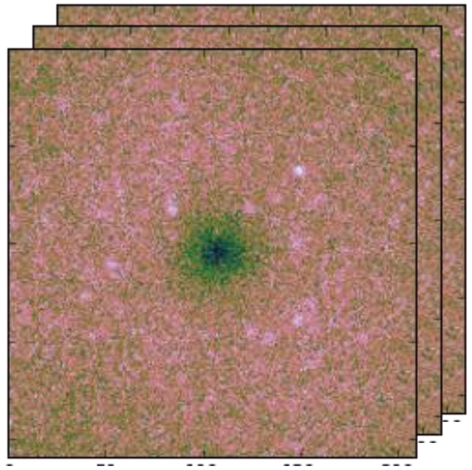
Line-of-sight projection

SZ surface brightness at multiple frequencies



+ Contaminants
+ Instrumental Effects

Mock images



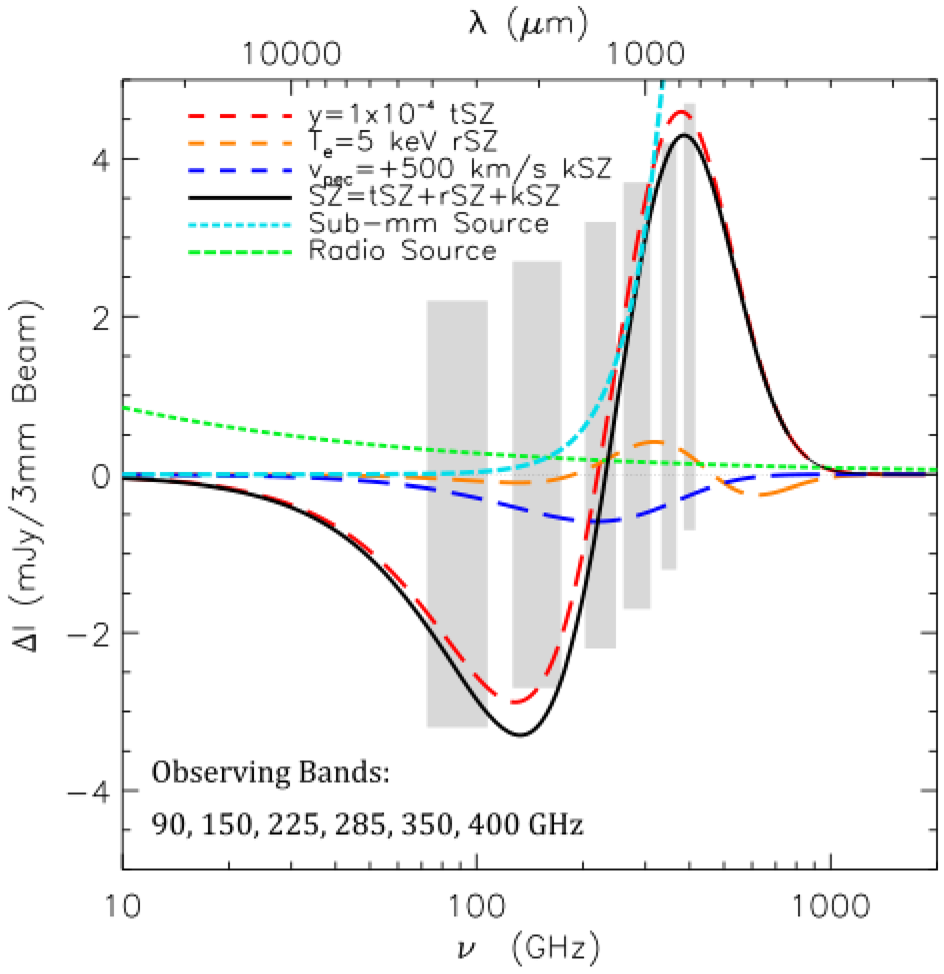
Separate components and fit for the input parameters T_e, v_z, τ (cluster-averaged or resolved)

Get uncertainties with bootstrapping/MCMC (not Fisher matrices)

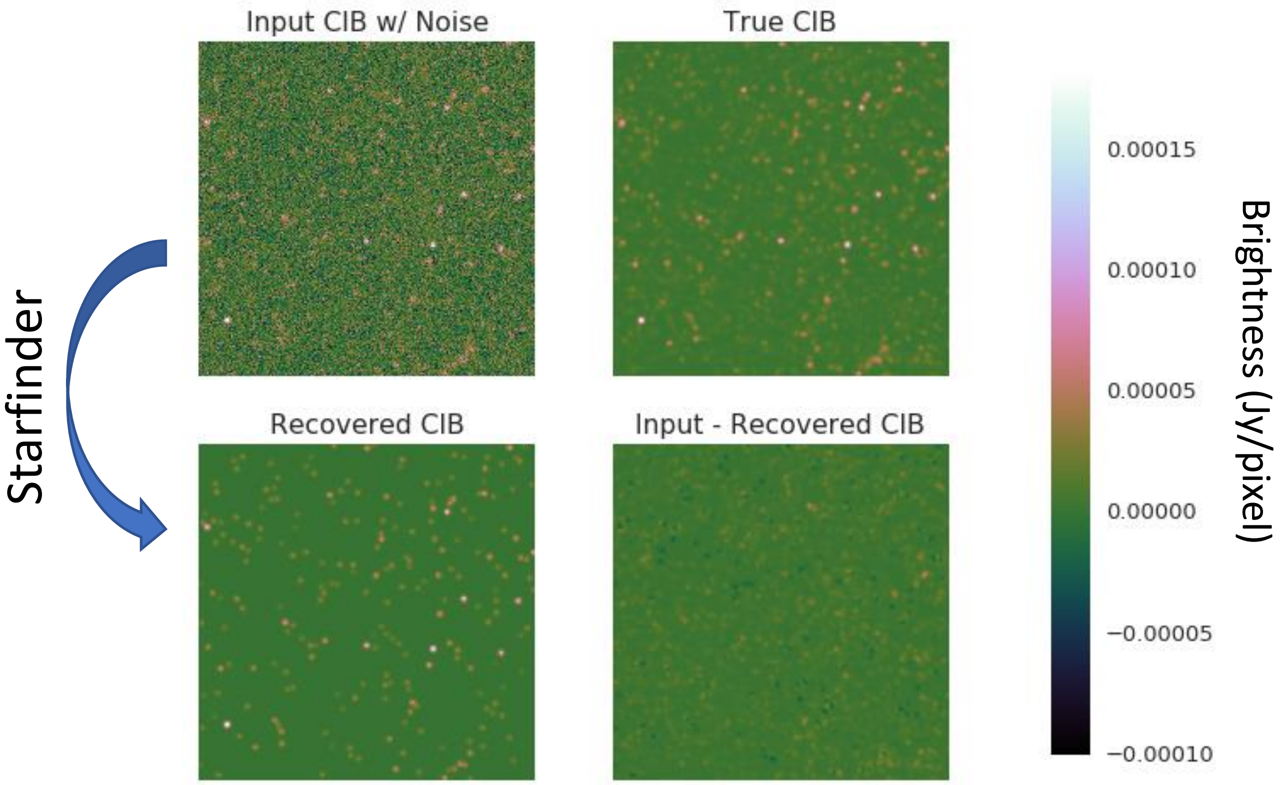
Goal: Generate and analyze a representative sample of clusters with various instrumentation choices, comparing & quantifying v_{pec} & cosmological constraints

Modeling Contaminants of the SZ Signal

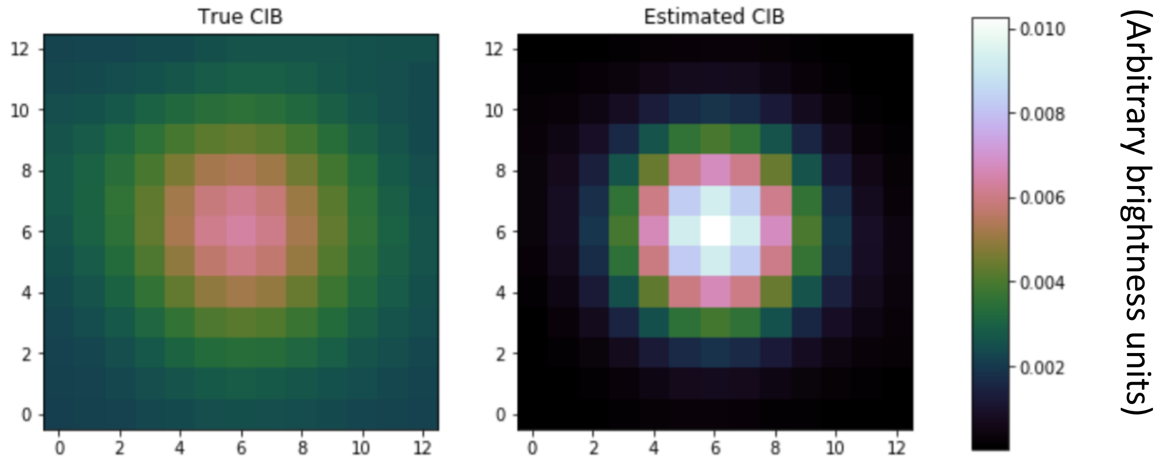
- Cosmic infrared background (CIB)
- Radio galaxies
- Primary CMB anisotropies
- Instrumental noise
- Atmospheric fluctuations
- Gravitational lensing of backgrounds by the cluster
- Other effects that may be important to future measurements: flux calibration, bandpass calibration



CIB Inclusion and Removal

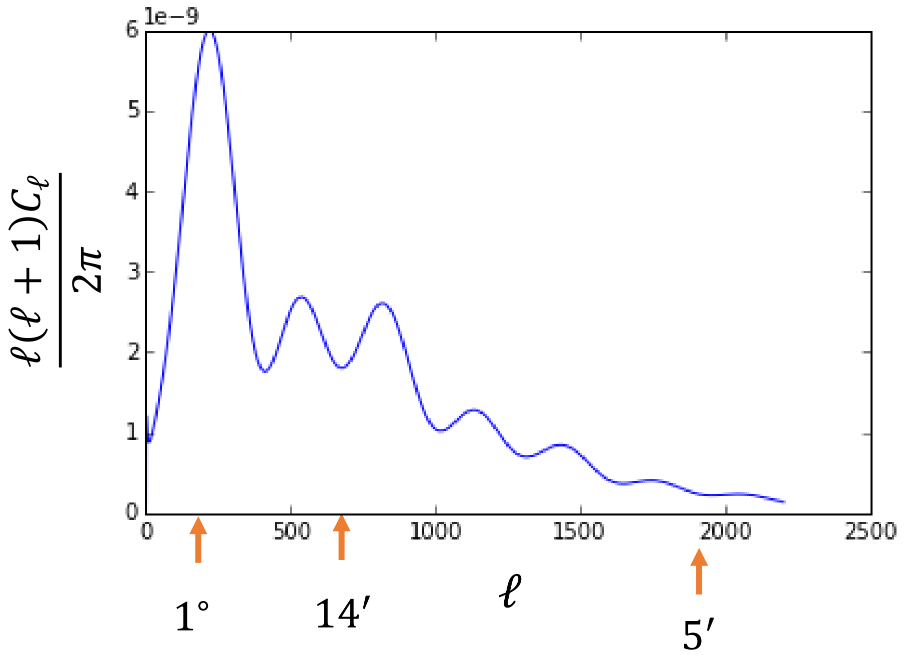


- Start with a realistic CIB model (SIDES, Bethermin+17)
- Remove point sources optimally using multi-band detection and fitting
- Must correct for boosting from noise and dim sources, as in stacks below



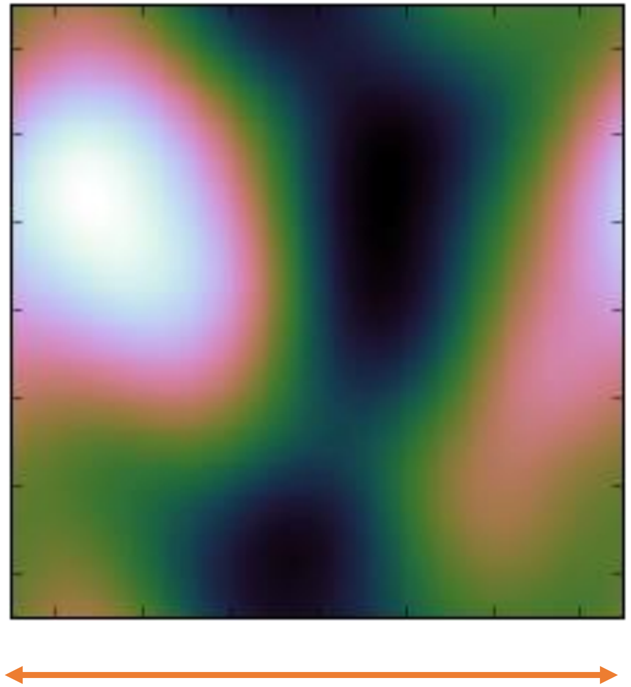
Primary CMB Anisotropies

CMB Power Spectrum



Fourier Transform

CMB Realization



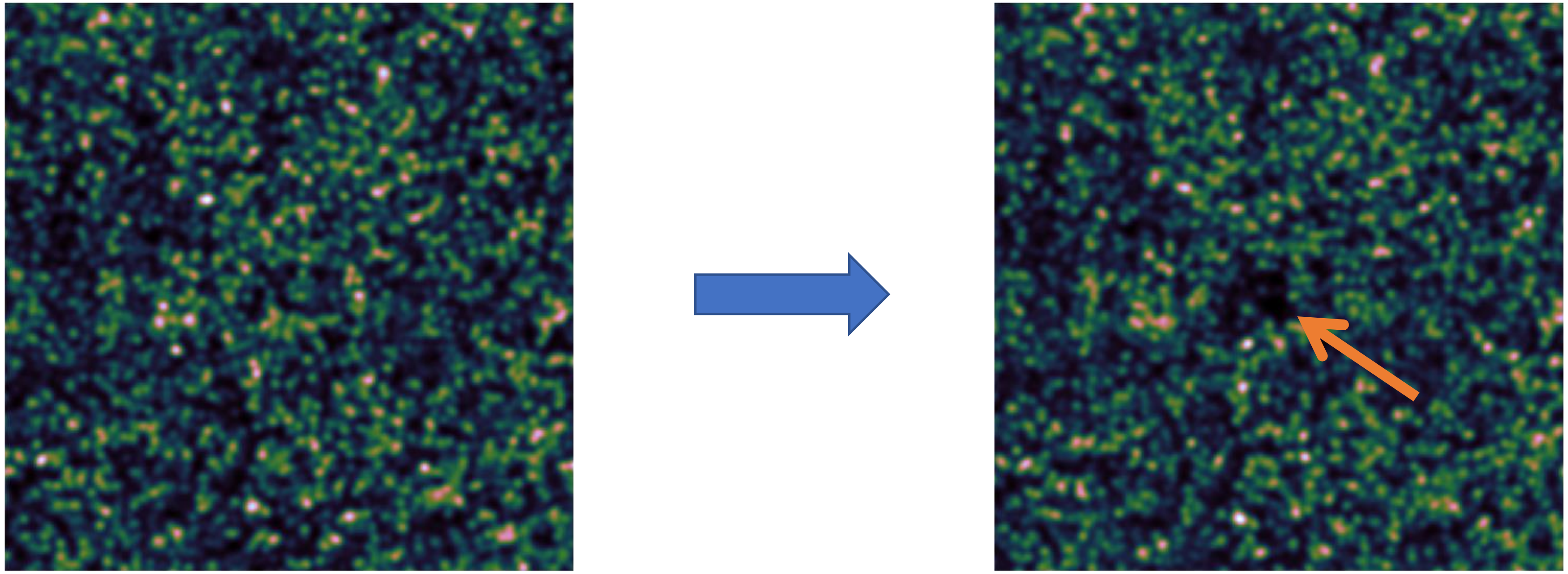
- Scale noise by CMB power spectrum (from CAMB)
- Considered how to disentangle from kSZ. This gets harder (as expected) when cluster angular scale approaches feature size of primary anisotropies
- Junhan Kim developing technique to estimate and remove CMB from CMB/kSZ internal linear combination map, treating kSZ as noise for the purpose of CMB estimation

Gravitational Lensing of CIB and CMB

- Can see a deficit in point-source-cleaned CIB towards a massive cluster (see, e.g., Zemcov+13). Could bias recovered SZ signal for single-cluster analyses
- Has two calculation modes: deflections and magnifications (fast) and a ray tracer (accurate)

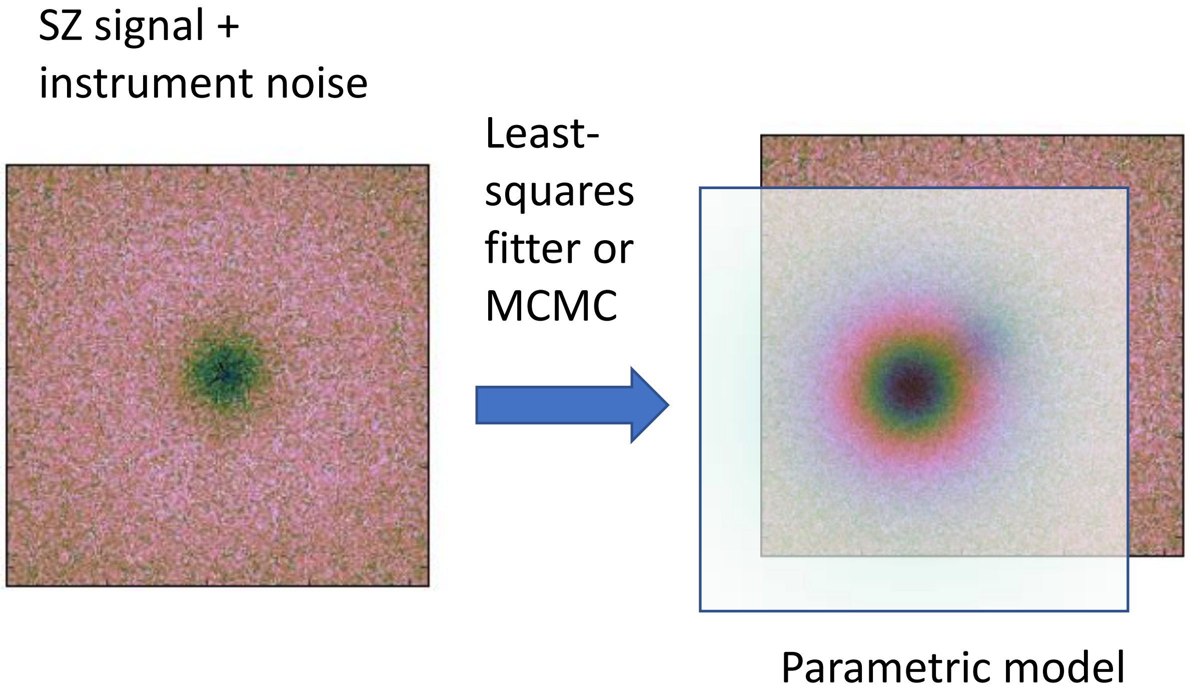
Unlensed CIB

Lensed CIB (no SZ effect)



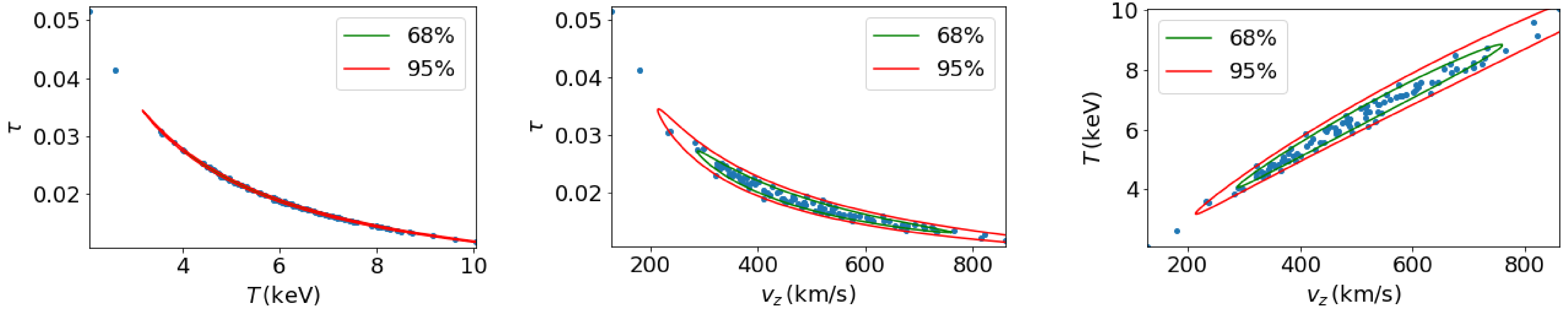
Fitting Mock Cluster Observations

- Still working to treat contaminants. Meanwhile, have developed fitting machinery based on instrument noise only
- Want to recover cluster-averaged peculiar velocity v_z with uncertainties
- Use a least-squares fitter to vary SZ parameters T_e, τ, v_z (+ position & shape) and minimize the residual
- Can also use Markov-Chain Monte Carlo (MCMC) sim. to robustly quantify uncertainties



SZ Parameter Degeneracies: v_z, T_e, τ

$M_{500} = 7.8 \times 10^{14} M_{\odot}$
30m instrument observing at
[90, 150, 220, 270, 350, 400] GHz



- Simultaneous v_z, T_e, τ constraint possible by including relativistic SZ signal, but still have degeneracy
- Problem: covariance (Fisher) matrix describes local curvature; inaccurate for complicated degeneracy shapes
- Developed a way to quantify constraint quality that is not driven by the degeneracy shape
- Metric for quality of constraint: geometric mean of areas of 68% confidence regions

Parameter constraints with a 10% prior on T_e

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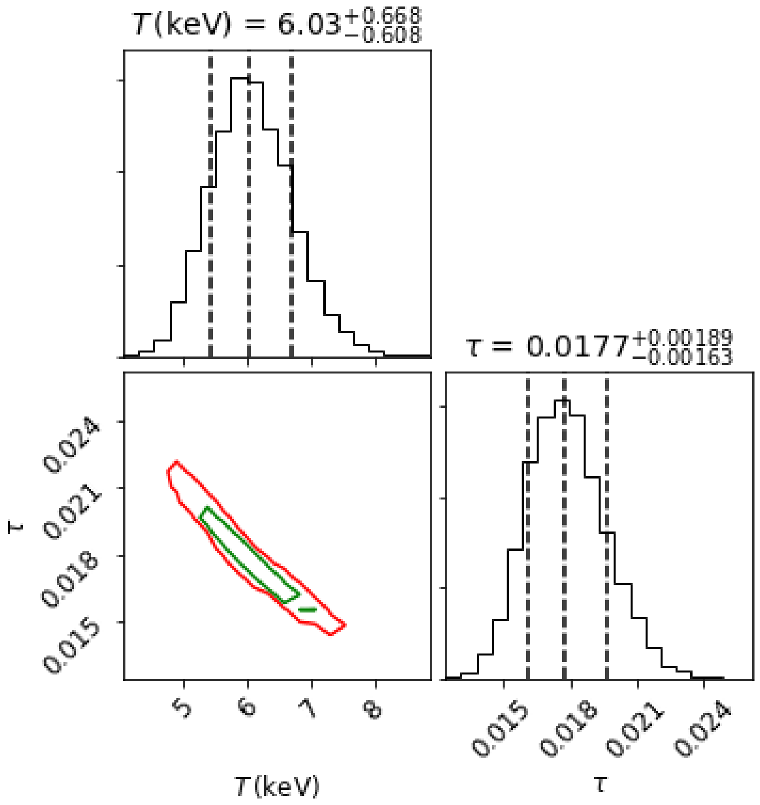
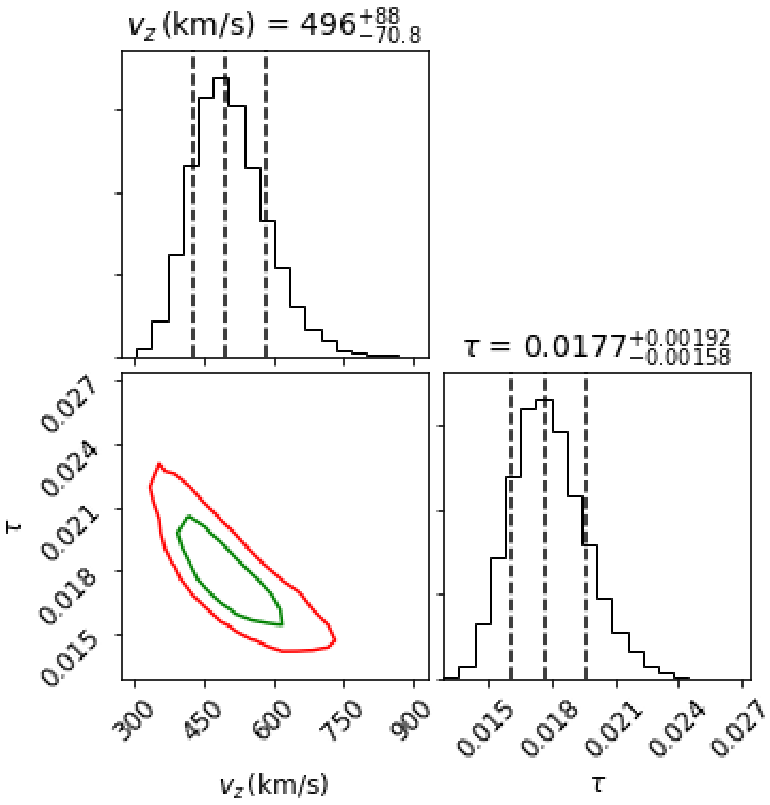
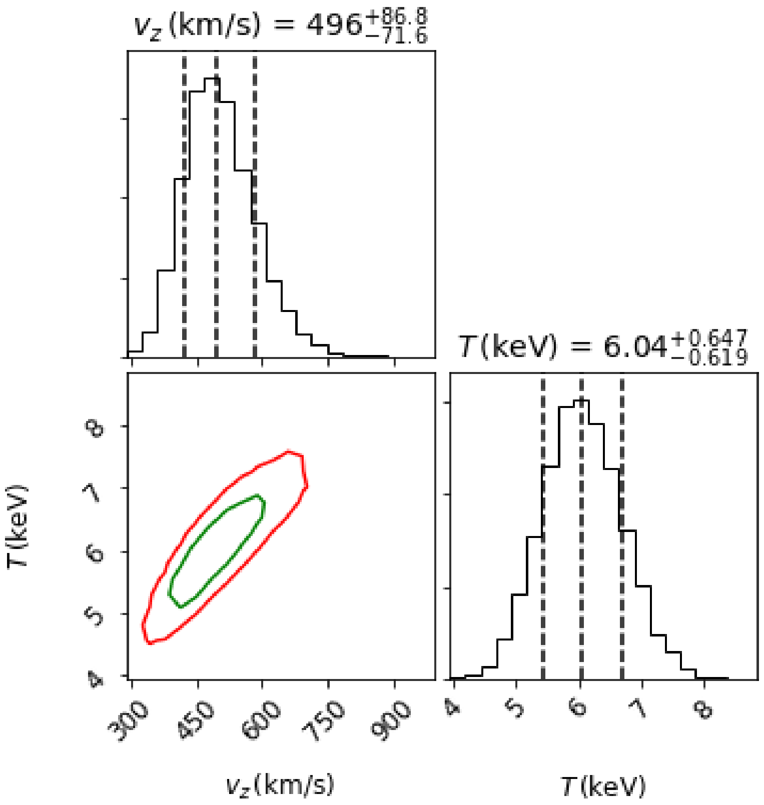






$T = 6.0^{+0.7}_{-0.6}$ keV
(10%)

$v_z = 500^{+90}_{-70}$ km/s
(~20%)

$\tau = 0.018^{+0.002}_{-0.002}$
(10%)

Can This Pipeline Be Applied to CMB-S4?

- Yes, though it is not optimized for surveys like S4:
  - Targets single-cluster observations, while S4 kSZ measurements are best made as stacks
  - Originally developed to study science potential of large (30-50m) scale dishes with high frequency coverage (>300 GHz) for deep point source cleaning
- Dish diameter and frequency coverage are flexible, so can be adapted to CMB-S4
- Could be useful to forecast tSZ (pressure structure) and rSZ (temperature structure) constraints
- Promising possibility: low-z cluster studies? ~Arcminute resolution, ~μK_{CMB}-arcmin sensitivity, and large field of view of S4 could be a good match

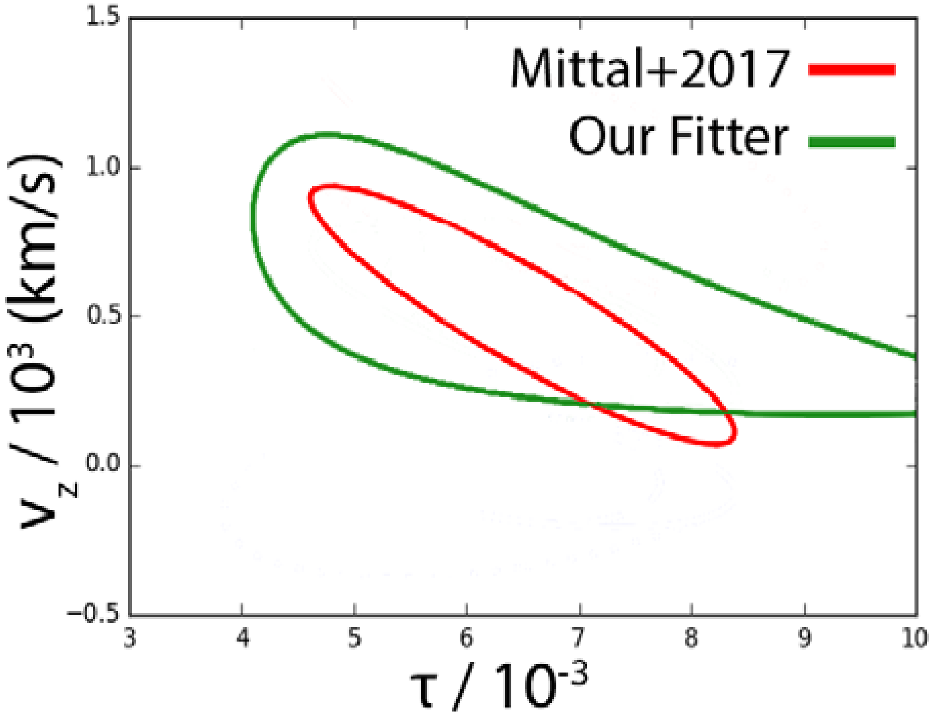
Thanks!

Extra Slides

Comparison with a Fisher Matrix Approach (Mittal+2018)

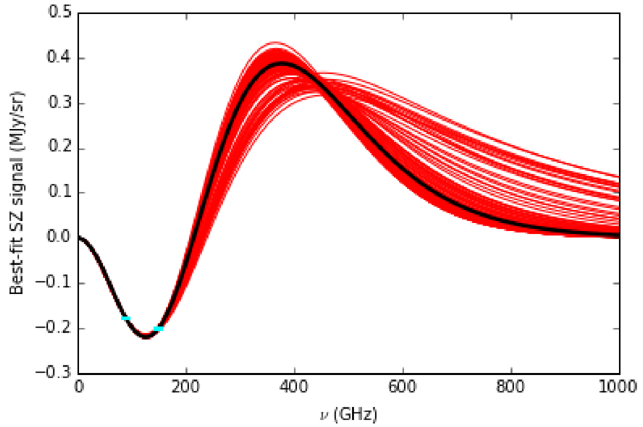
Fisher Matrices: most straightforward way to forecast uncertainties, but cannot fully describe degeneracies

z=0.5, $M_{500} = 10^{15} M_{\odot}$

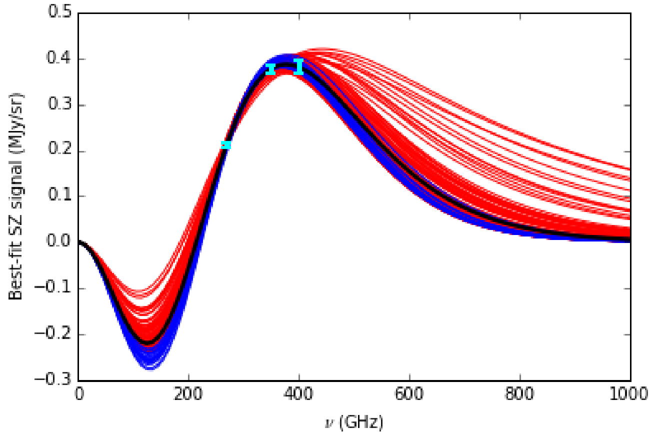


Ensembles of 100 Recovered SZ Spectra

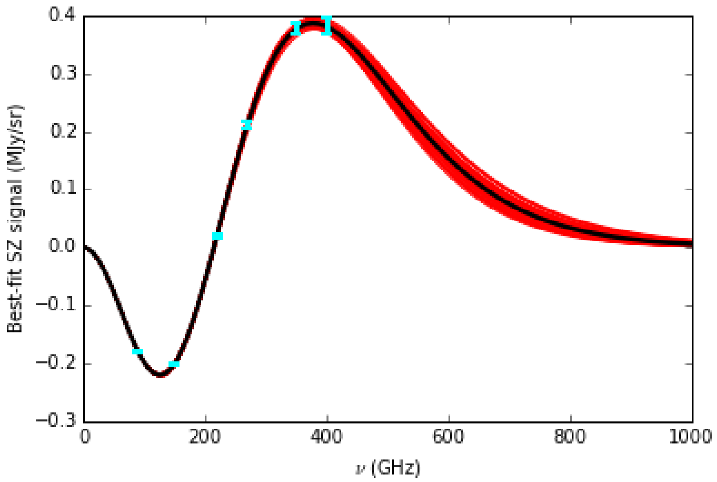
Observing bands (GHz):
90, 150



Observing bands (GHz):
270, 350, 400



Observing bands (GHz):
90, 150, 220, 270, 350, 400



True SZ signal (has $v_z > 0$)
Recovered SZ signal with $v_z > 0$
Recovered SZ signal with $v_z < 0$

- 2-3 bands are unable to constrain the spectral shape well
- Better fit from 6 bands