SZ Effect Science with CCAT

Sunil Golwala/Caltech on behalf of CCAT Consortium

AAS Anchorage Special Session

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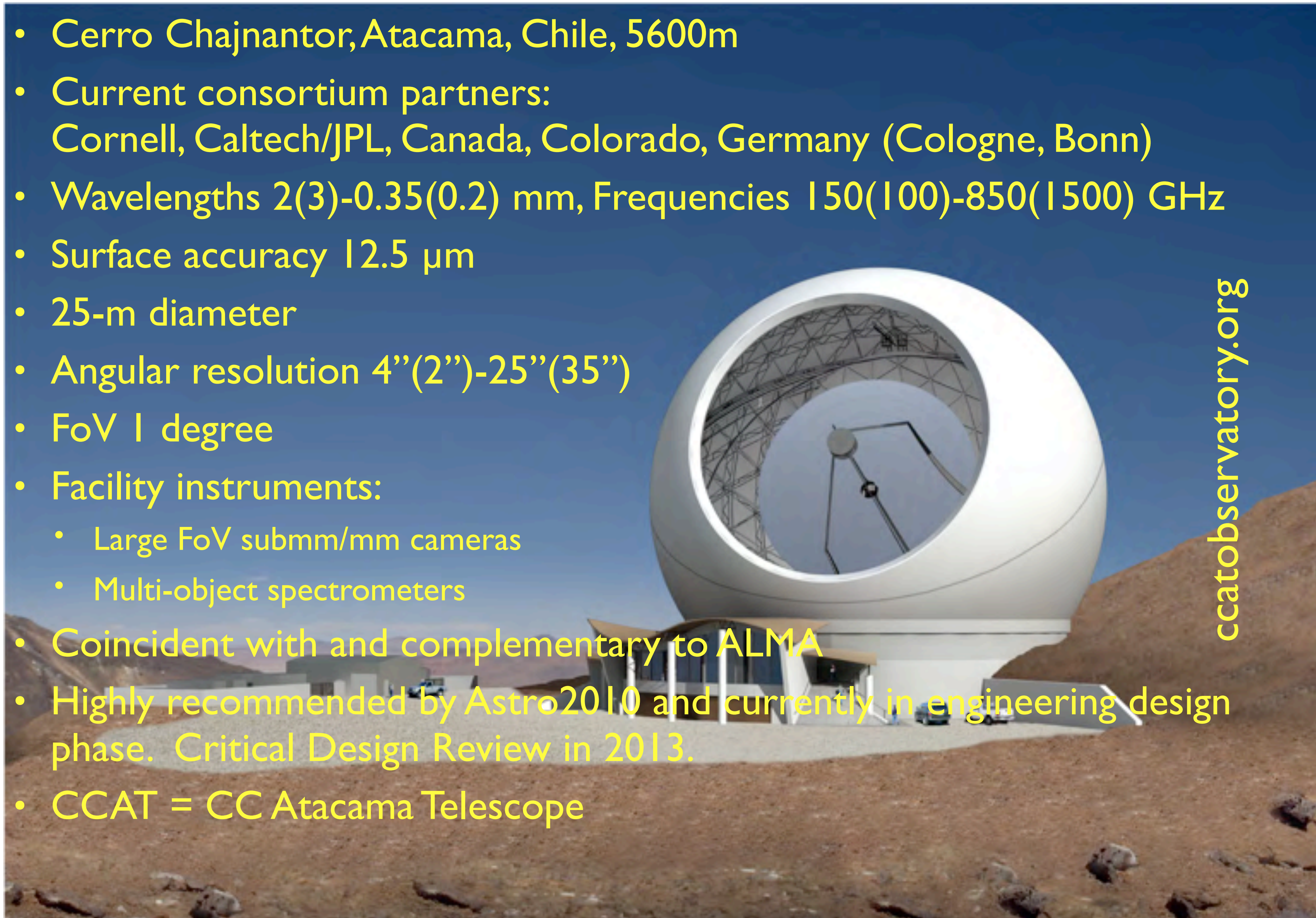
What is CCAT?

- Cerro Chajnantor, Atacama, Chile, 5600m
- Current consortium partners:
  Cornell, Caltech/JPL, Canada, Colorado, Germany (Cologne, Bonn)
- Wavelengths 2(3)-0.35(0.2) mm, Frequencies 150(100)-850(1500) GHz
- Surface accuracy 12.5 μm
- 25-m diameter
- Angular resolution 4”(2”)-25”(35”)
- FoV 1 degree
- Facility instruments:
  - Large FoV submm/mm cameras
  - Multi-object spectrometers
- Coincident with and complementary to ALMA
- Highly recommended by Astro2010 and currently in engineering design phase. Critical Design Review in 2013.
- CCAT = CC Atacama Telescope



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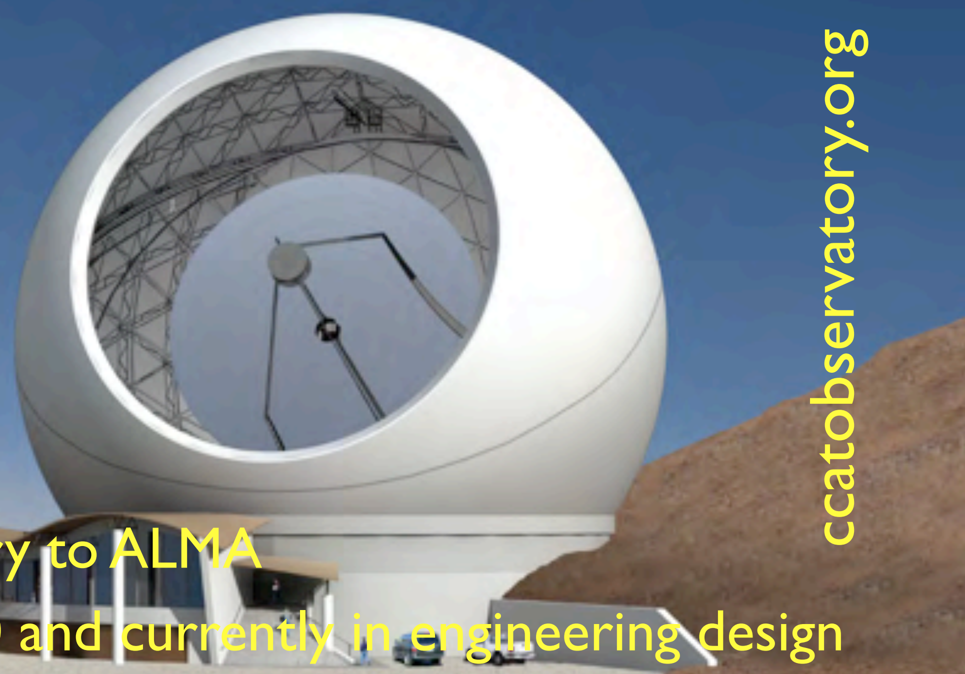
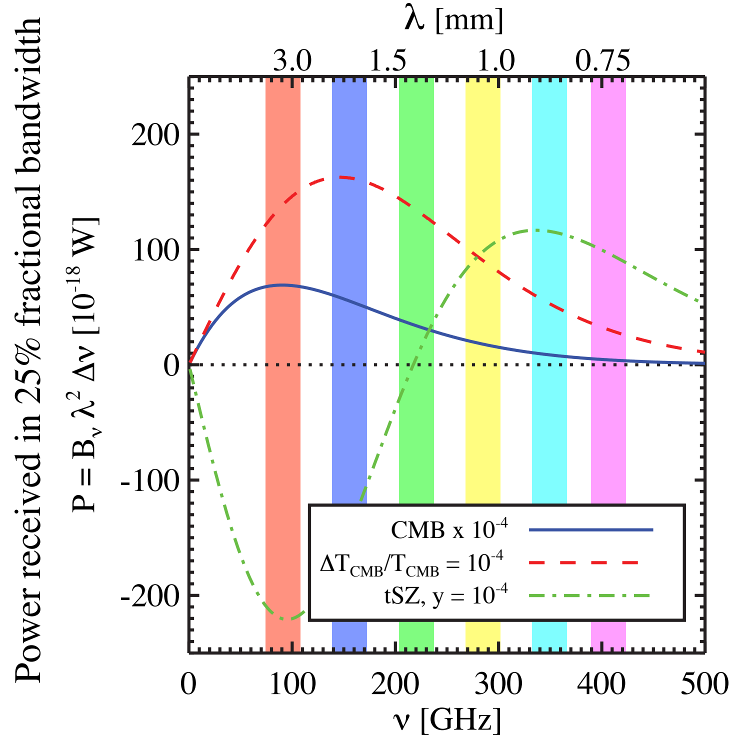
  <u>No, CC = Cluster Cosmology!</u>



How will CCAT enable SZ measurements?

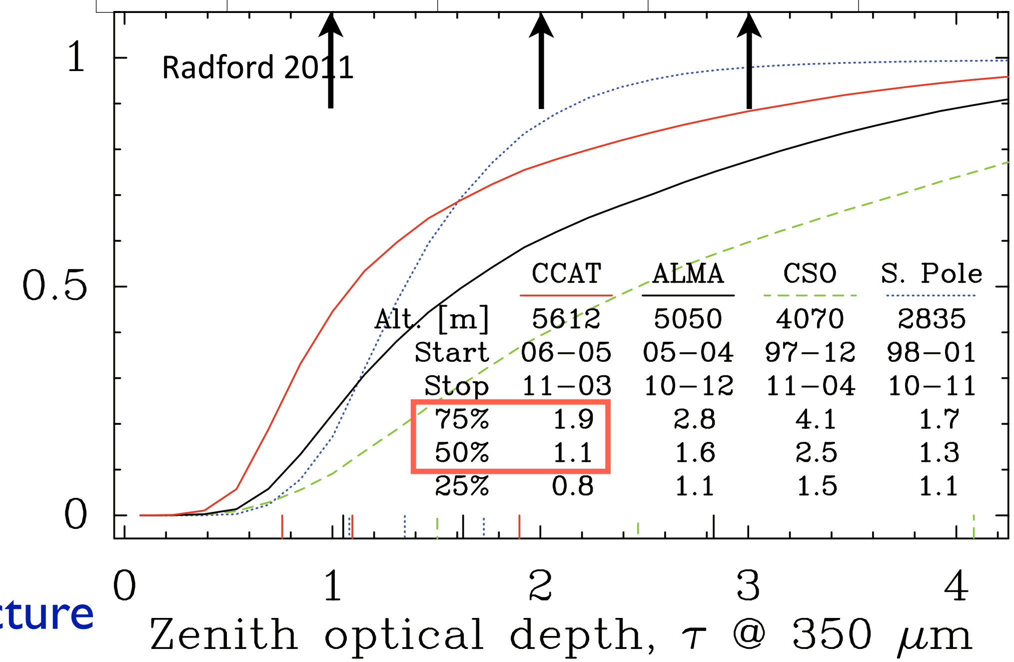


$\tau = 10^{-2}$
$y = 10^{-4}$,
kT_e = 5 keV
v_{pec} = 3000 km/s

up to 6 spectral bands

expected CCAT long-wavelength bands

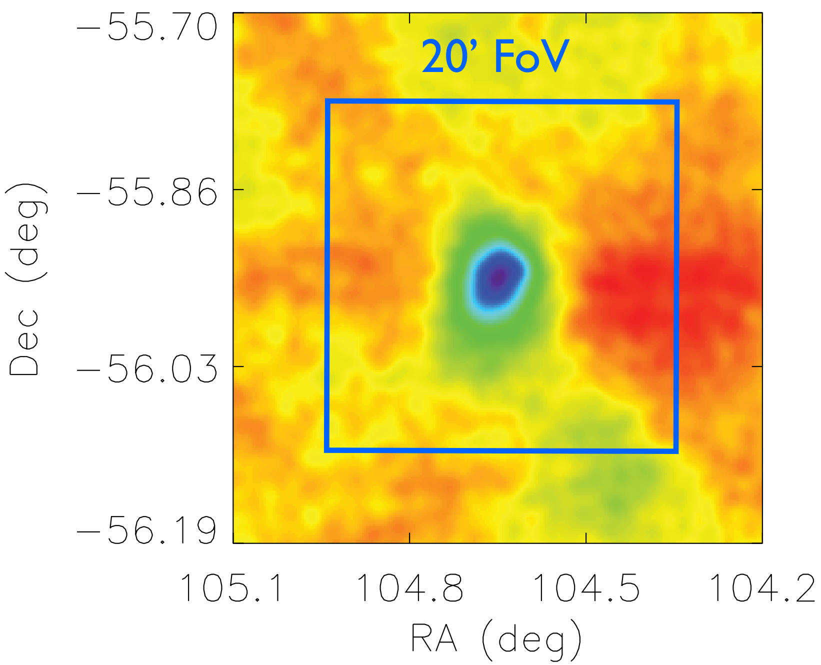
λ [mm]	τ_λ at $\tau_{350\,\mu m}$ = 1	2	3
0.87	0.15	0.3	0.5
1.1	0.07	0.12	0.18
1.4	0.040	0.078	0.12
2.0	0.024	0.041	0.06
3.0	0.021	0.026	0.031

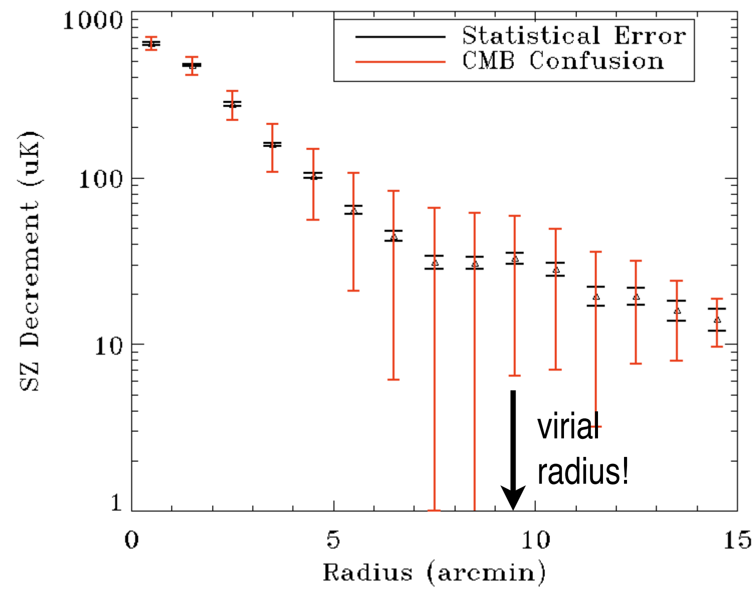


- Excellent mm/submm site
  - mm opacity generally ≲ 10%,
    → high instantaneous sensitivity
  - Atmospheric opacity fluctuations low:
    x 2/3 relative to Chajnantor,
    x1/2 relative to Mauna Kea
    → better recovery of large-scale structure

How will CCAT enable SZ measurements?

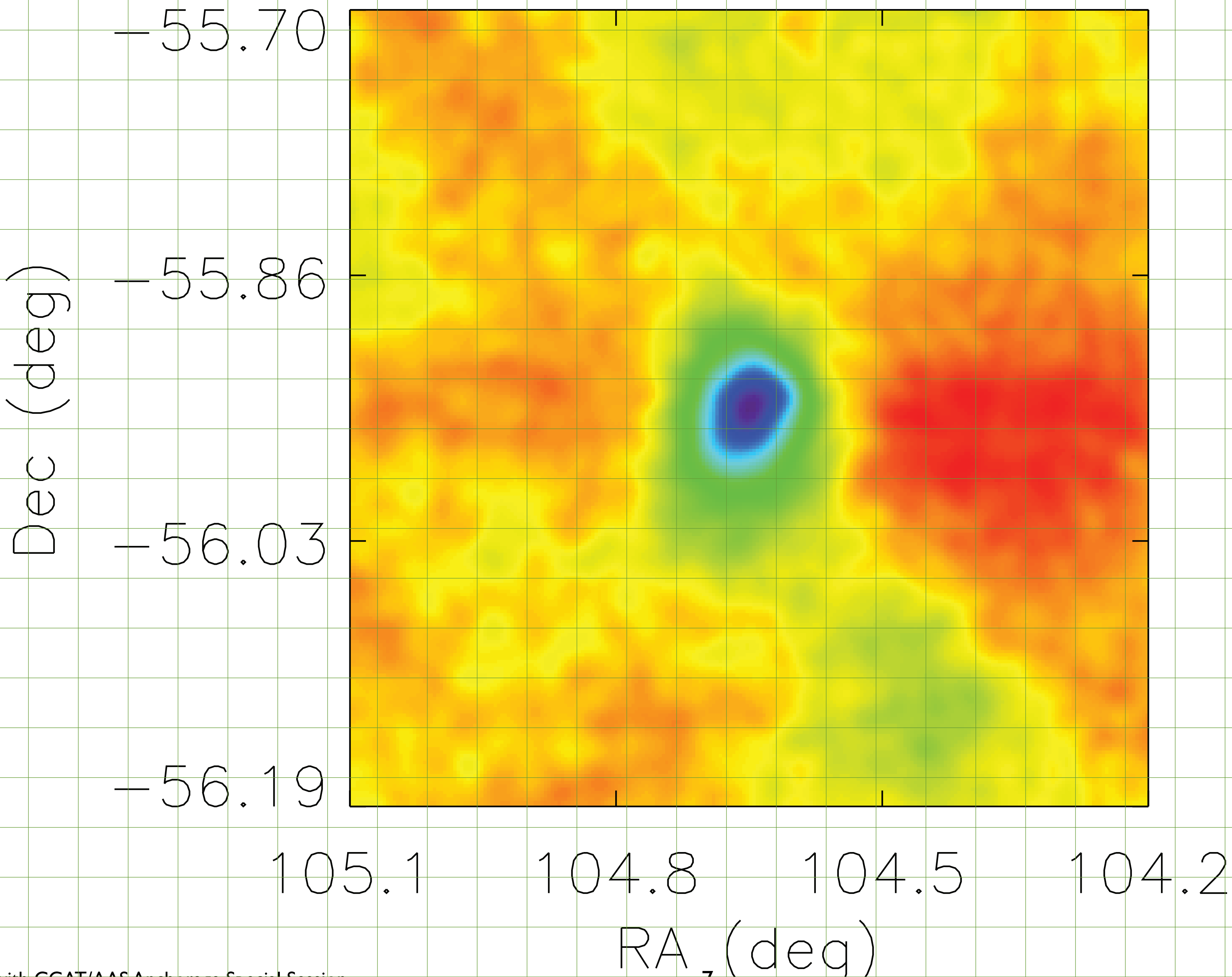
- Fast scanning
  - speed = 1 deg/s
  - accel = 1 deg/s^2
  - Moves bulk of cluster signal above atmospheric fluctuation 1/f noise
- Wide field of view
  - capable of 1 degree,
    20' expected at first light for mm
    → entire cluster viewed instantaneously
- High angular resolution and well-filled focal plane
  - $\Delta\theta$ = 12" at 1 mm, 4000 pixels in 20'
  - $\Delta\theta$ = 25" at 2 mm, 1000 pixels in 20'
  - Above for 2 f λ pixels (2 x FWHM); more pixels possible!
  - Raw mapping speed of the focal plane will be enormous



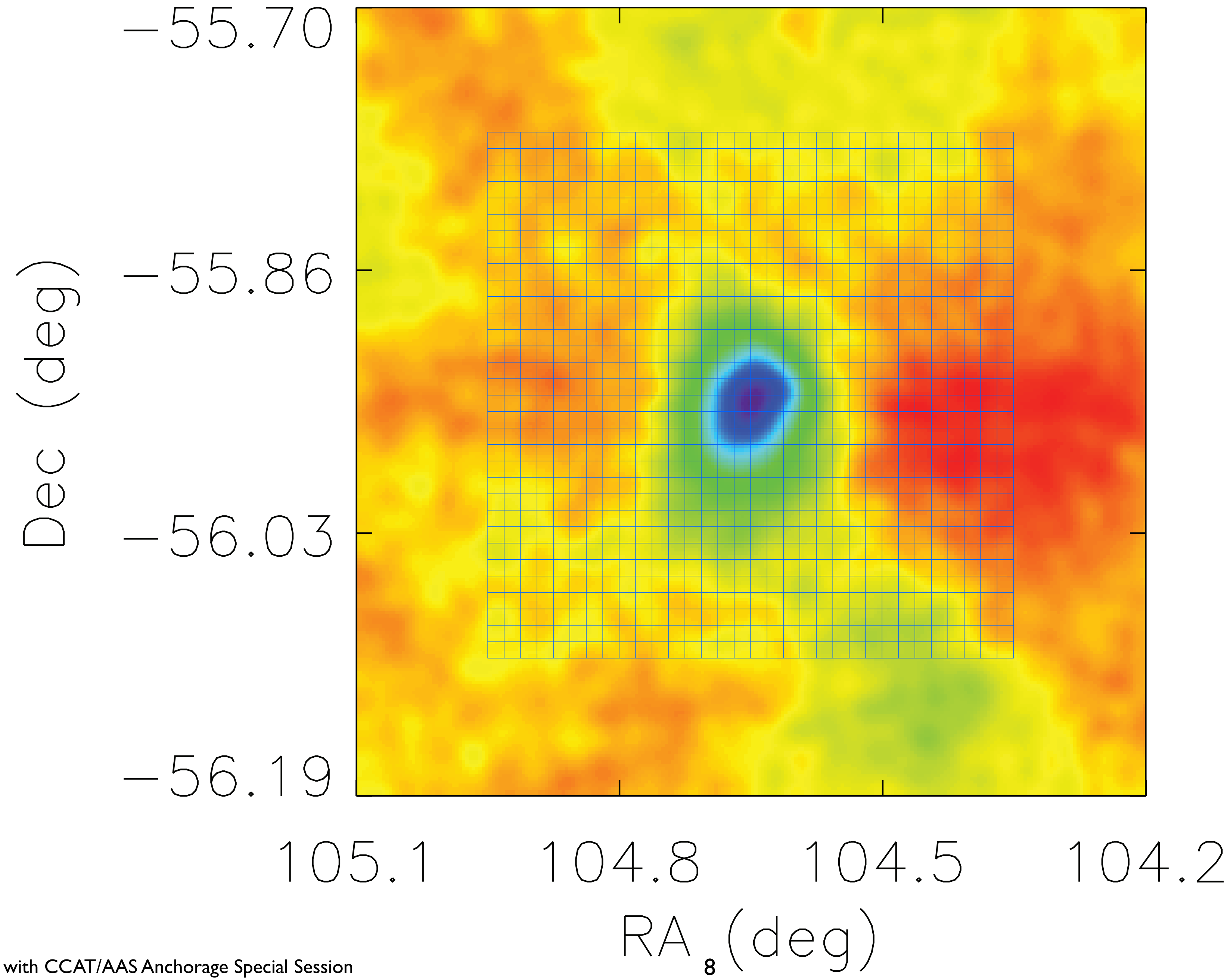


Bullet cluster w/SPT, Benson 2009 Bonn SZ and Plagge et al (2010)

1 deg FoV, 1 arcminute resolution

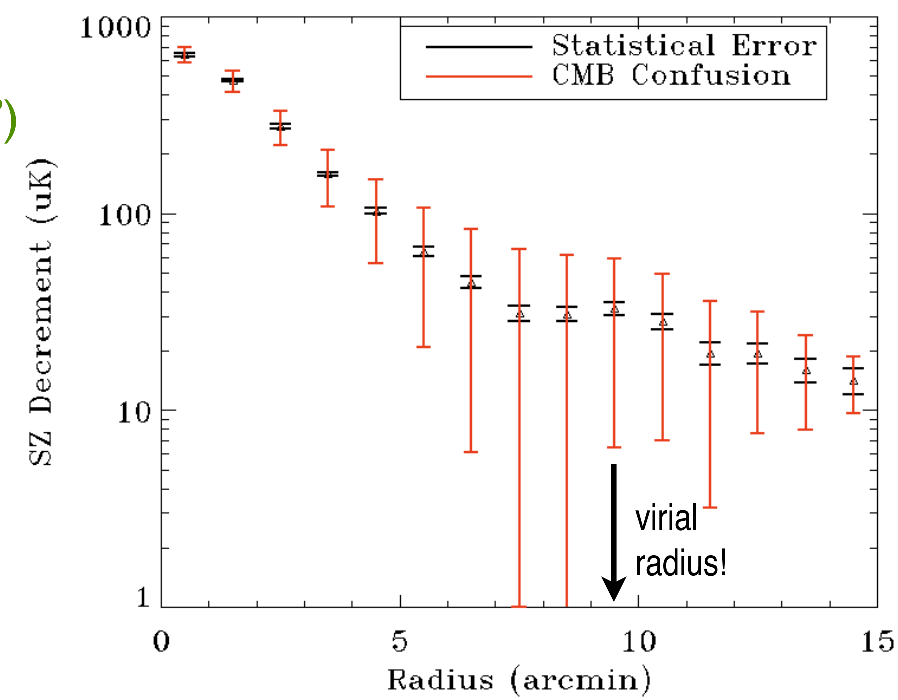


20' FoV, 25" resolution

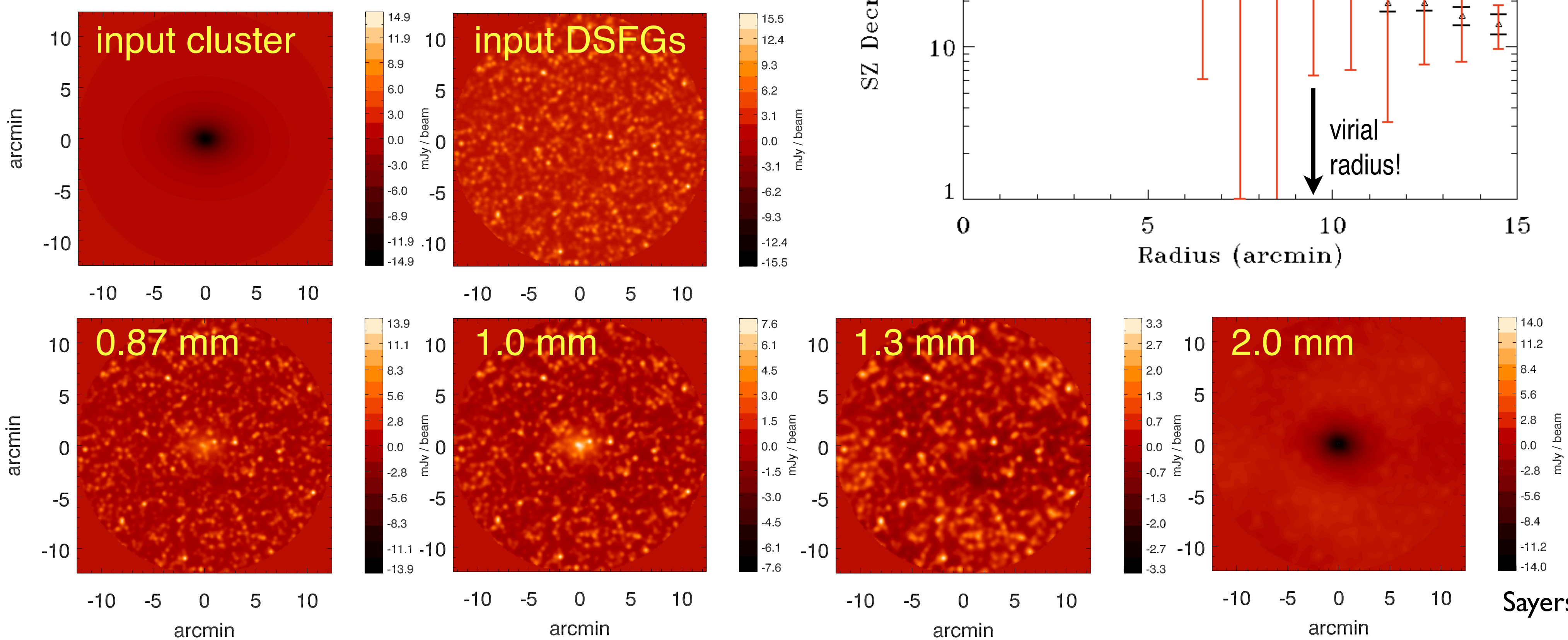


How will CCAT enable SZ measurements?

- Require multiple bands simultaneously for removal of contamination
  - CMB confusion on large scales
  - dusty star-forming galaxies (DSFGs)
    - Low opacity, high angular resolution (9”) at 870 μm → deep DSFG information
  - Eventually: imaging spectrometers



Bullet cluster w/SPT, Benson 2009 Bonn SZ



Sayers

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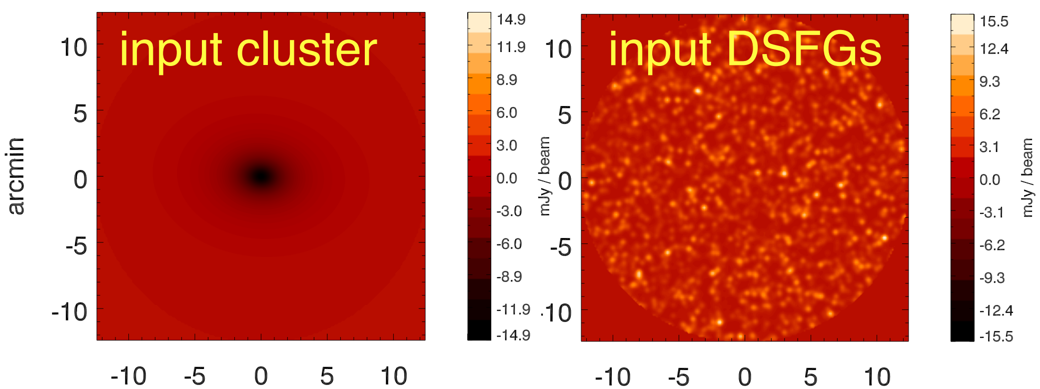
Depth at 1 source per beam based on Blain DSFG models

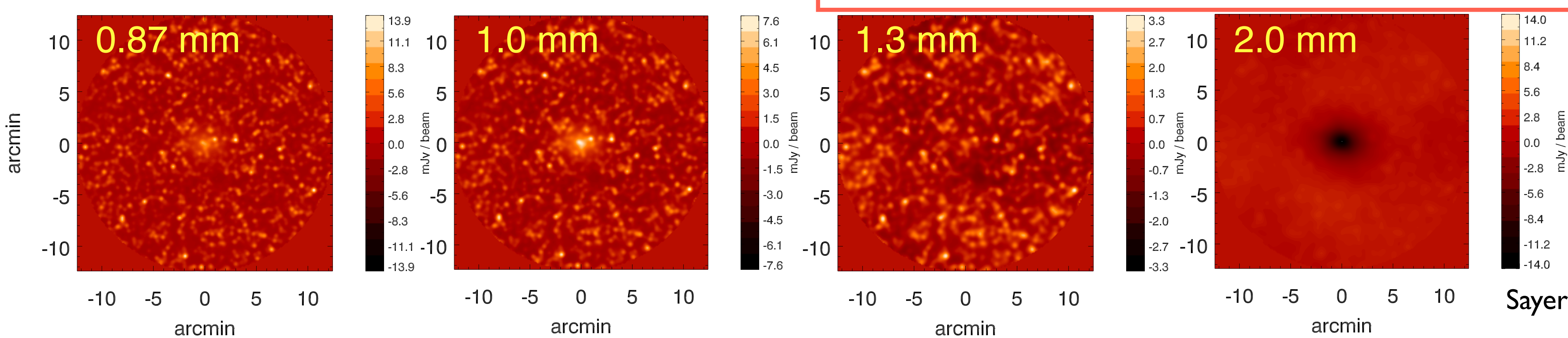
frequency	flux density	temperature	y parameter
275 GHz	66 μJy	27 μK_{CMB}	1.1×10^{-5}
220 GHz	89 μJy	21 μK_{CMB}	N/A
150 GHz	44 μJy	6 μK_{CMB}	2.3×10^{-6}
100 GHz	21 μJy	2.1 μK_{CMB}	5.1×10^{-7}

Projection of long-submm detection limits into SZ bands, assumes flux $\propto \nu^{3.7}$

	350 GHz		490 GHz	
frequency	1 src per 30 beams	1 src per 10 beams	1 src per 30 beams	1 src per 10 beams
275 GHz	340 μJy	160 μJy	140 μJy	59 μJy
220 GHz	150 μJy	70 μJy	62 μJy	26 μJy
150 GHz	36 μJy	17 μJy	15 μJy	6.3 μJy
100 GHz	8.1 μJy	3.8 μJy	3.4 μJy	1.4 μJy



$\Delta T \sim 10\ \mu K_{CMB}$, $\Delta y \sim 3 \times 10^{-6}$ in cluster outskirts. DSFGs must be removed, but removal is nontrivial!



Sayers

What can we learn about clusters with CCAT?

Based on input from CCAT SZ/cosmology science working group

- Precise information about baryons out to the virial radius and beyond
  - How does the baryon fraction, temperature, and pressure behave as one moves from the core through the virialized region and out to the infall region?
- Pressure in the ICM
  - Characterize deviations from hydrostatic equilibrium and understand causes.
  - Pressure power spectrum can test for turbulence in ICM.
  - Nonthermal pressure due to relativistic electrons; correlate with gamma-ray, radio
- Bulk flows inside the ICM via kinetic SZ (kSZ) effect
  - Remnants of cluster mergers?
- SZ-based cluster temperatures via relativistic SZ (rSZ) effect
- SZ substructure and its relation to gas substructure, galaxies
- Scaling relations and intrinsic scatter as a probe of non-self-similar effects

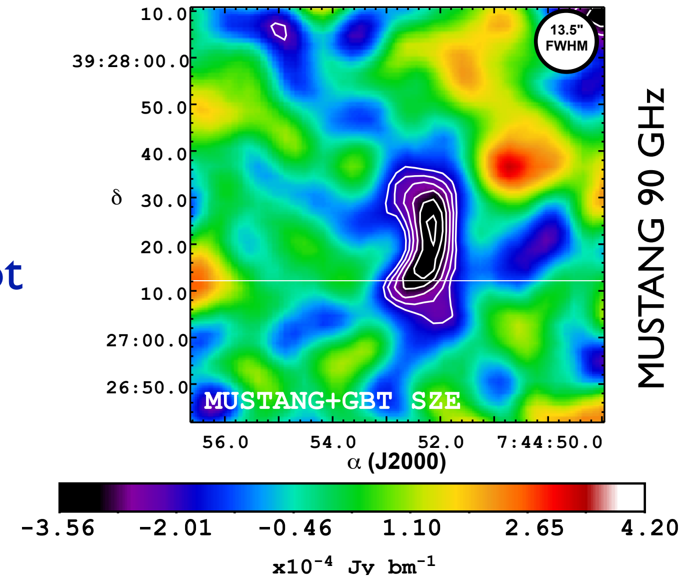
What cosmology can we do with CCAT?

Based on input from CCAT SZ/cosmology science working group

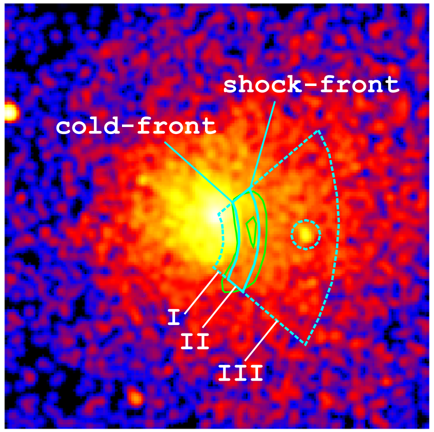
- Detailed study of clusters near detection limit in large-area surveys
  - Cosmological interpretation currently limited by calibration of SZ flux to mass
  - Modeling of relation between cluster flux and mass may be substantially improved with better S/N, higher-resolution measurements
  - SZ surveys provide an archival data set with well-defined selection function, v. orthogonal to expected X-ray (eROSITA) or optical (DES) selection functions
- Deeper surveys to lower mass threshold
  - Characterize the behavior of cluster counts vs. z at lower mass; probes higher z range, different regime of structure formation
- Thermal and kinetic SZ power spectra
  - Both measurements currently limited by DSFG removal; CCAT multiple colors and high angular resolution can improve substantially
  - Can test ICM models that predict tSZ power spectrum
  - Use bispectrum to separate cosmology and cluster astrophysics
- Measurement of the cluster peculiar velocity field using kSZ
- Cluster angular power spectrum

High-Resolution SZ with CCAT

- Δθ = 12" at 1 mm, 25" at 2 mm: fine-scale imaging of SZ effect a la MUSTANG/GBT and CARMA+SZA
  - Search for shocks
    - merger shocks
    - accretion shock in outskirts
  - search for hot gas not noticed in X-ray
    - use rSZ spectral information to measure T; need the high-frequency bands



MUSTANG 90 GHz

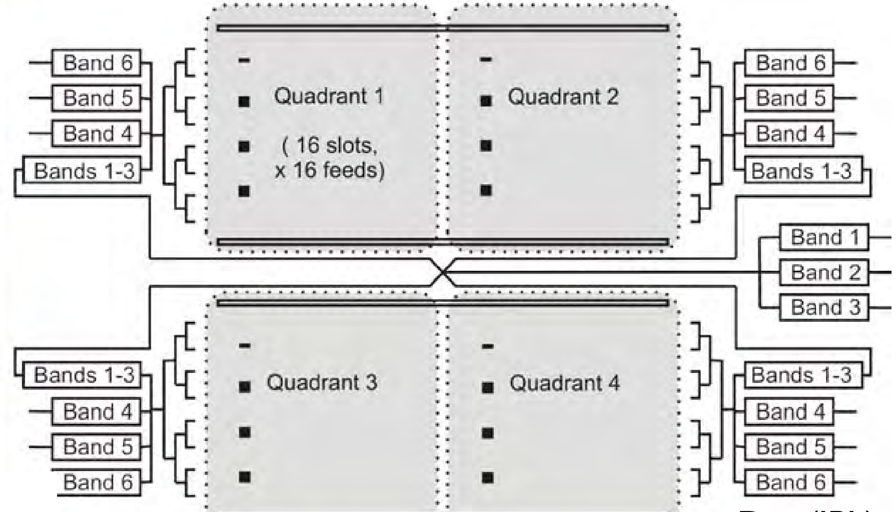


Chandra X-ray
MACSJ0744, Korngut et al 2011

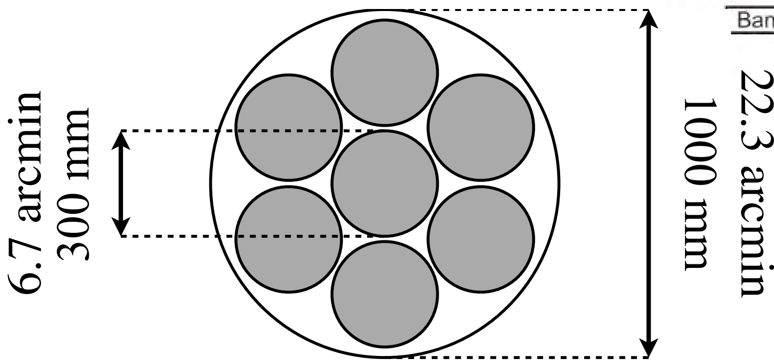
  - Measure pressure in low-density regions w/low X-ray flux (e.g., radio bubbles)
  - Search for non-thermal electrons in correlation w/radio, gamma-ray
  - Search for bulk motions using kSZ
    - Mroczkowski et al 2012 showed how important multi-band data was to see hints of kSZ signal from 3000 km/s subclump in MACSJ0717.5
  - High-frequency bands remove DSFGs to reveal structure at high resolution

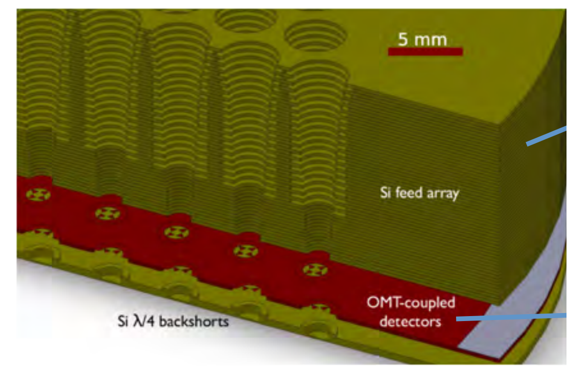
CCAT SZ Instrumentation

- Near-term: Camera using multiscale, multiband phased-array antennae or corrugated feeds would provide "transformational" impact
  - covers 5-6 colors in each pixel, 740 μm to 2 or 3.3 mm
  - matches pixel size to Airy function



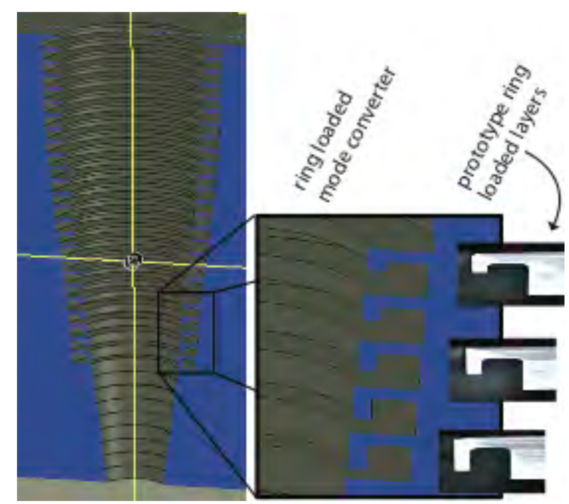
Day (JPL)





Irwin, Niemack et al (NIST)

λ [μm]	ν [GHz]	$\Delta\nu$ [GHz]	Per-Pixel Sensitivity [mJy s$^{1/2}$]	Number of Pixels total	Number of Pixels in FoV	Pixel Size (F/#) $\times\lambda$	Pixel Size mm at F/2	Beam FWHM [′]	Mapping Speed $\square^\circ$/mJy^2/hr in band	Mapping Speed at 1 mm
750	400	30	5.9	21952	17241	1.16	1.7	0.10	5.5	41
850	350	34	3.7	29152	17241	1.02	1.7	0.12	21	61
1100	275	95	1.6	5488	4310	1.58	3.5	0.15	45	25
1300	230	62	1.8	5488	4310	1.34	3.5	0.18	51	5.8
2000	150	47	1.7	1372	1077	1.74	7.0	0.28	33	0.26
3300	90	35	1.8	1372	1077	1.05	7.0	0.45	79	0.036



McMahon (U Michigan)

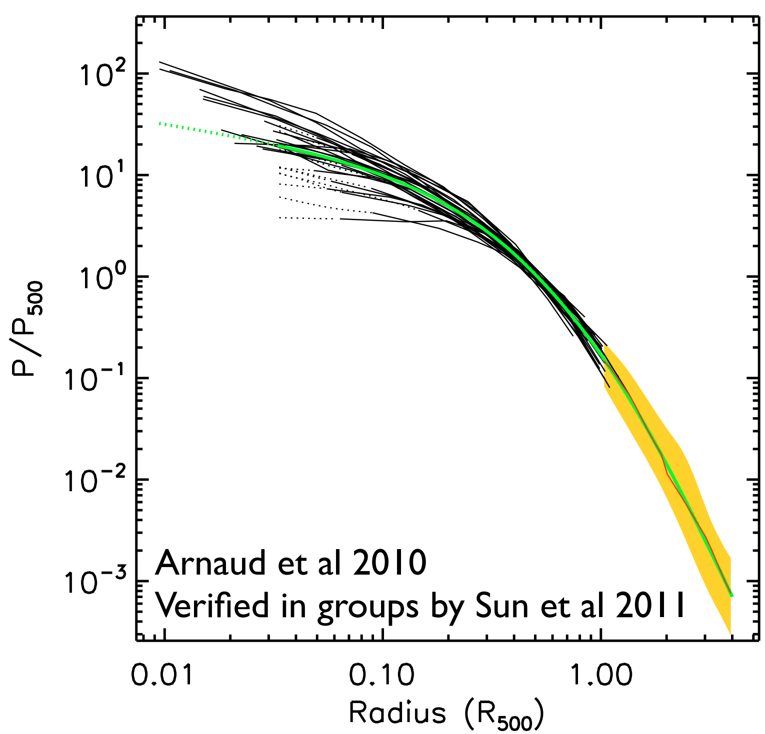
- Long-term: New channelizer concept could provide O(100-1000) spectral channels per spatial pixel
  - Enormous spectral information for separation of components

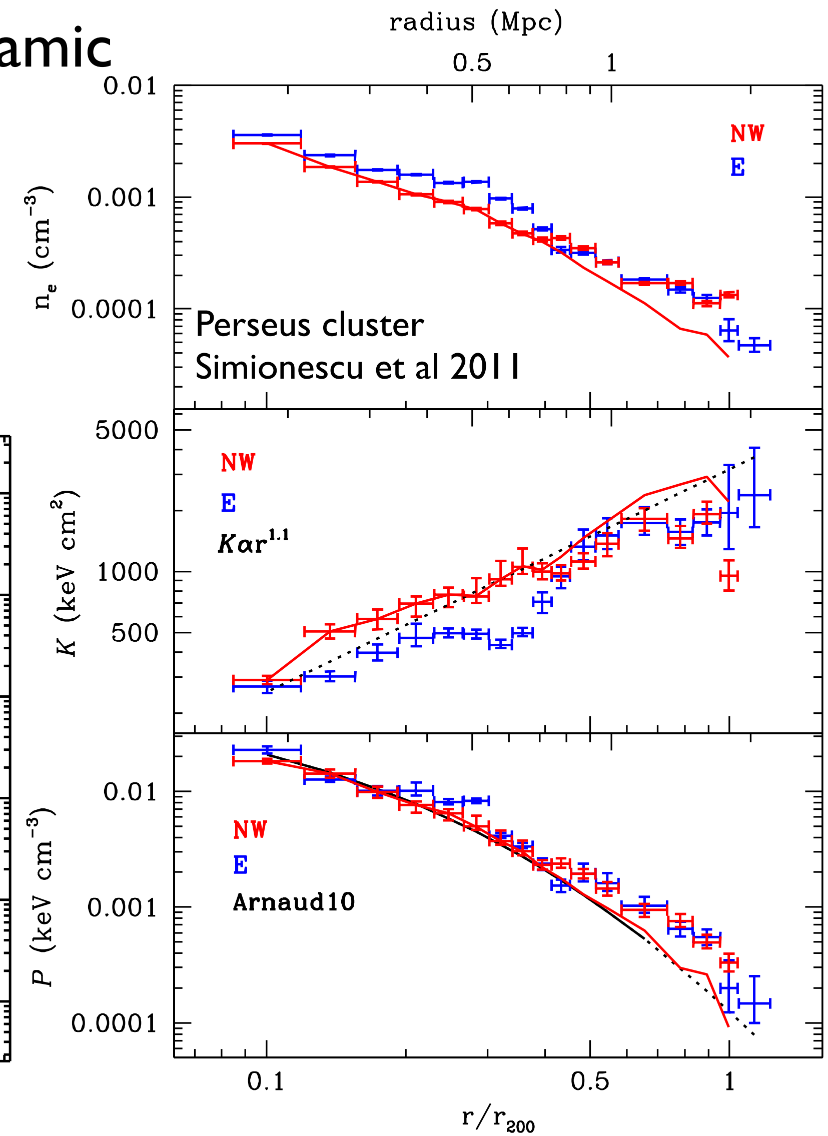
CCAT Organization and Status

- Management team reports to CCAT Board
  - Partner institutions and AUI
  - project director: R. Giovanelli, Cornell; project manager: J. Zivick, Cornell; project engineer: S. Padin, Caltech; project scientist: J. Glenn, Colorado
- Critical Design Review: June, 2013
  - $4.5M from NSF in 2011-2013, matching partner contributions, to prepare CDR
  - Instrument studies for LWCam, SWCam, X-Spec, and CHAI funded ($3.8M total)
  - Construction 2014-2017(8?), science soon after
- The project is formalizing the science case
  - Must be ready to prioritize instrument choices at CDR
  - Led by project scientist, many subcommittees working in many areas (including SZ and cosmology)
- Expecting major NSF contribution
  - Only medium-scale ground-based project specifically recommended by Astro2010
  - 1/3 NSF contribution ($37M) + operations funding ($7.5M/yr)

Studying the ICM out to the virial radius

- ICM has not been systematically studied out to r_{vir} with X-ray due to low photon rate and high particle bgnd (though Suzaku now has a few)
- Self-similar accretion predicts thermodynamic variables, baryon fraction, etc.
  - Suzaku observations beginning to suggest deviations (e.g., Simionescu et al 2011), but have to be careful with Suzaku backgrounds (Eckert et al 2011)
- Deviations from self-similarity may explain low tSZ power
- CCAT will enable high S/N at r_{vir}

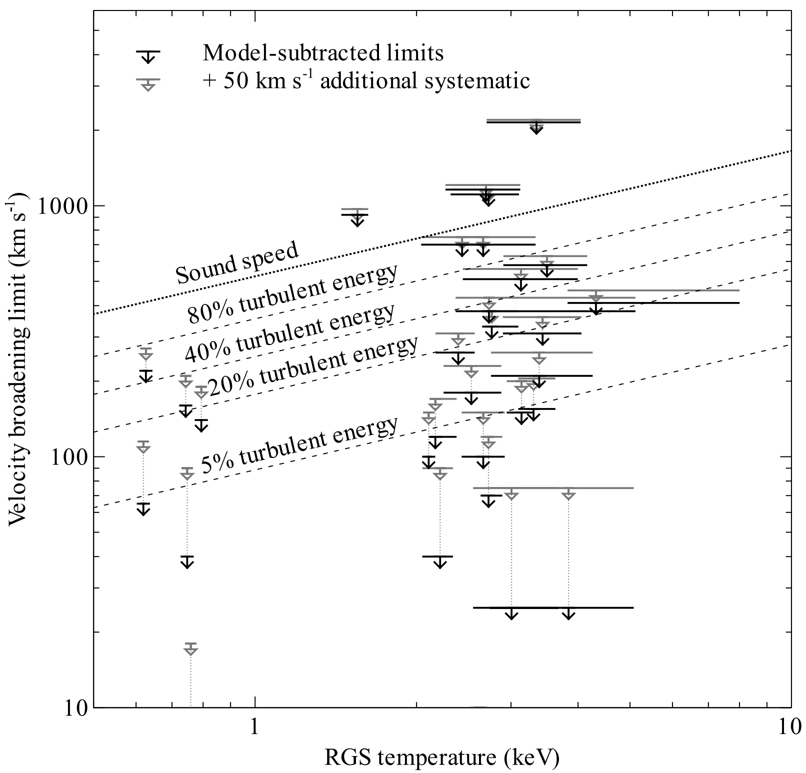




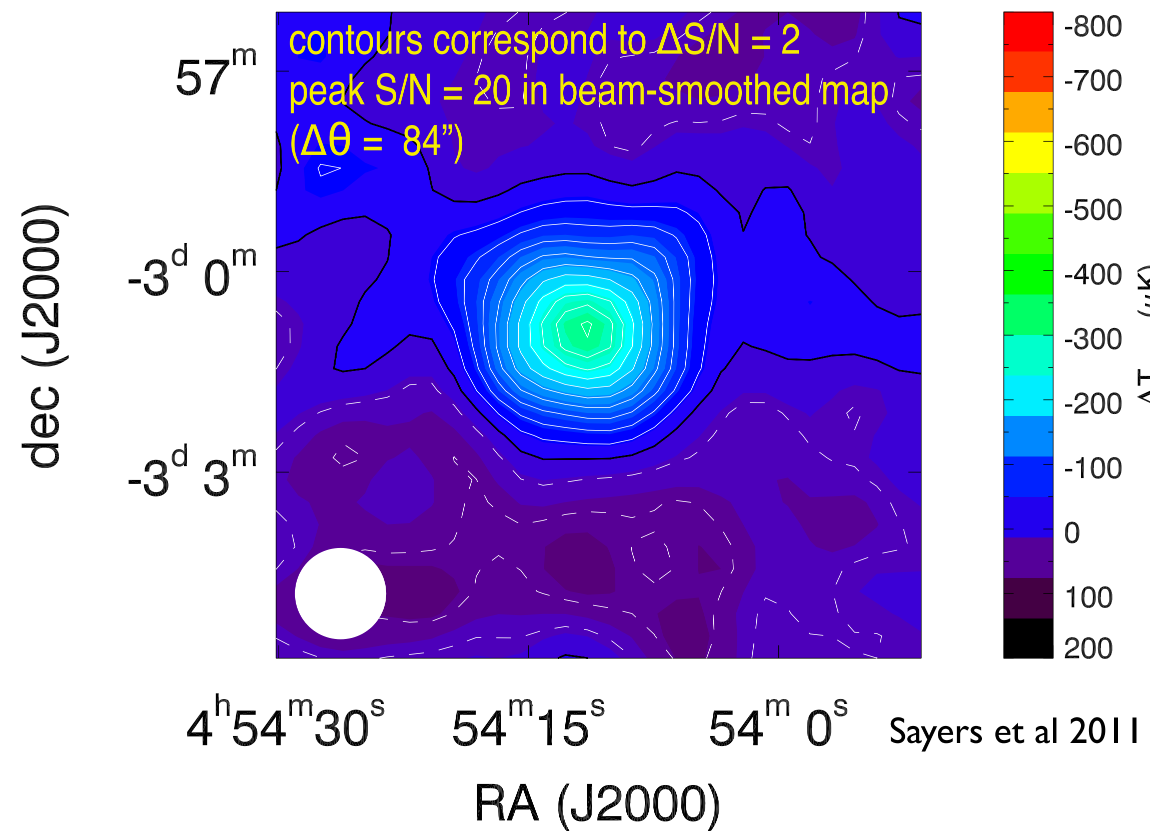
Turbulence in the ICM

- Prior attempts via X-ray spectral line broadening
  - Will improve with Astro-H spectrometer
- Expect ~10% pressure fluctuations at CCAT beam (40-400 kpc)
  → Can study if have S/N = 50 per beam.
  Plausible: S/N = 20-100 achieved for massive clusters

Sanders et al 2011



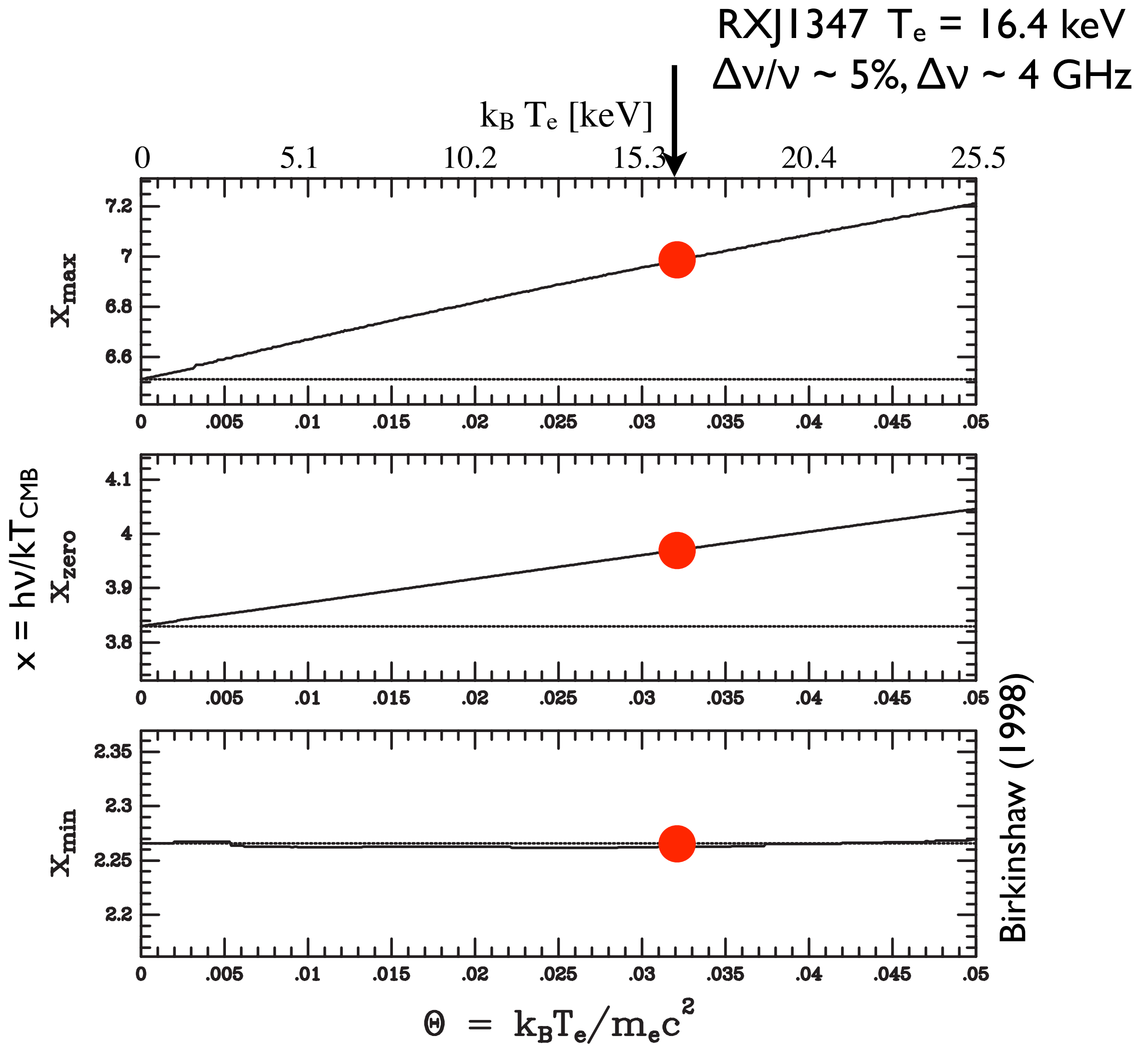
MS0451 50 ksec Bolocam 2 mm



Sayers et al 2011

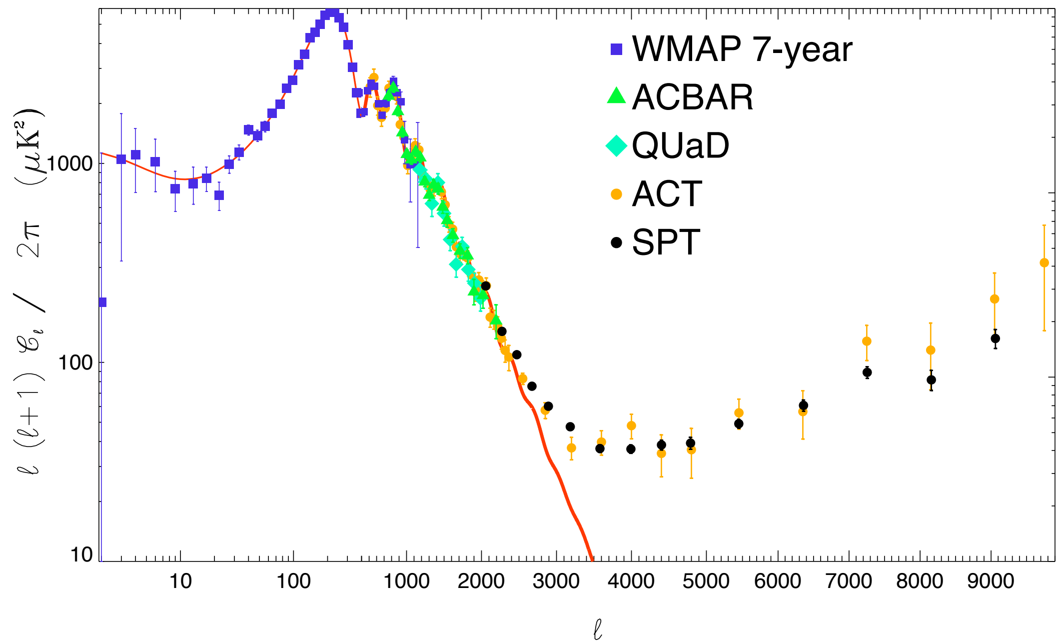
Measuring Cluster Temperatures with SZ

- Relativistic shift in tSZ null proportional to electron temperature
- Early science: multicolor imaging, multiobject spectroscopy
- Long-term: imaging spectroscopy

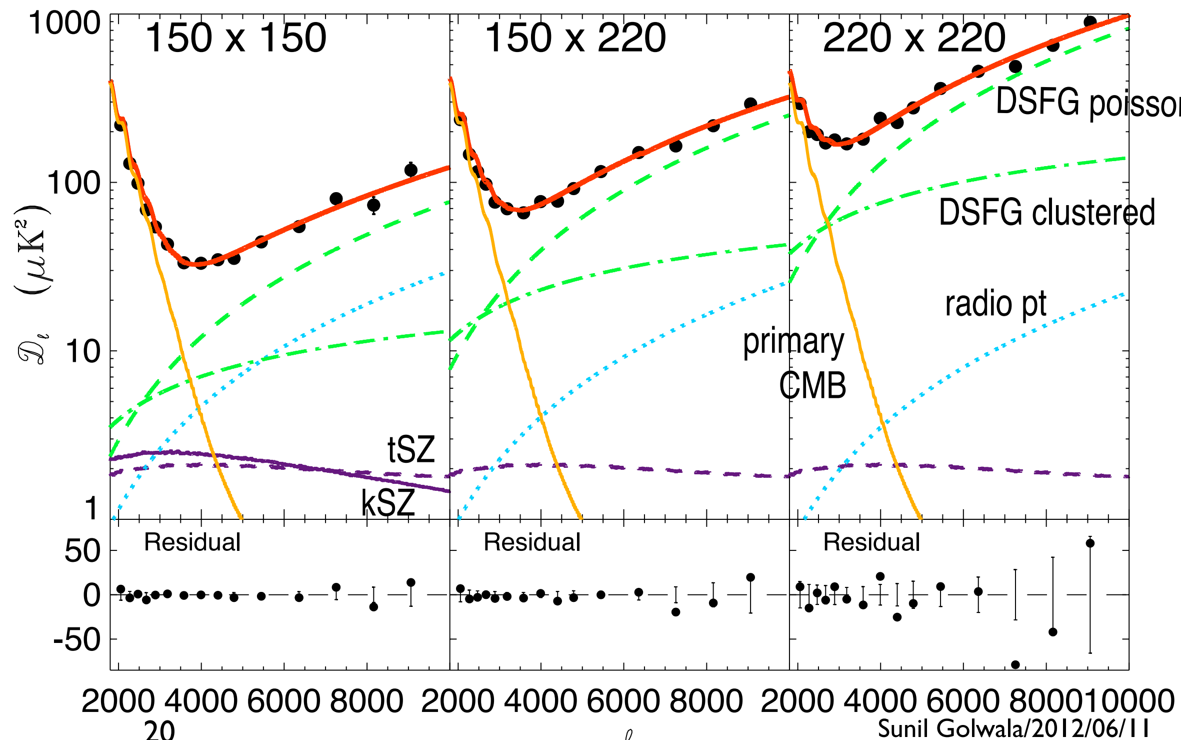


SZ Power Spectra

- V. precise measurements of angular power spectra at high ℓ by SPT and ACT
  - tSZ contribution probes σ_8 and ICM physics
  - kSZ due to Ostriker-Vishniac effect (Doppler effect of moving haloes) and patchy reionization
- But severely dominated by DSFGs, even at 150 GHz; detection of SZ requires tSZ, kSZ templates

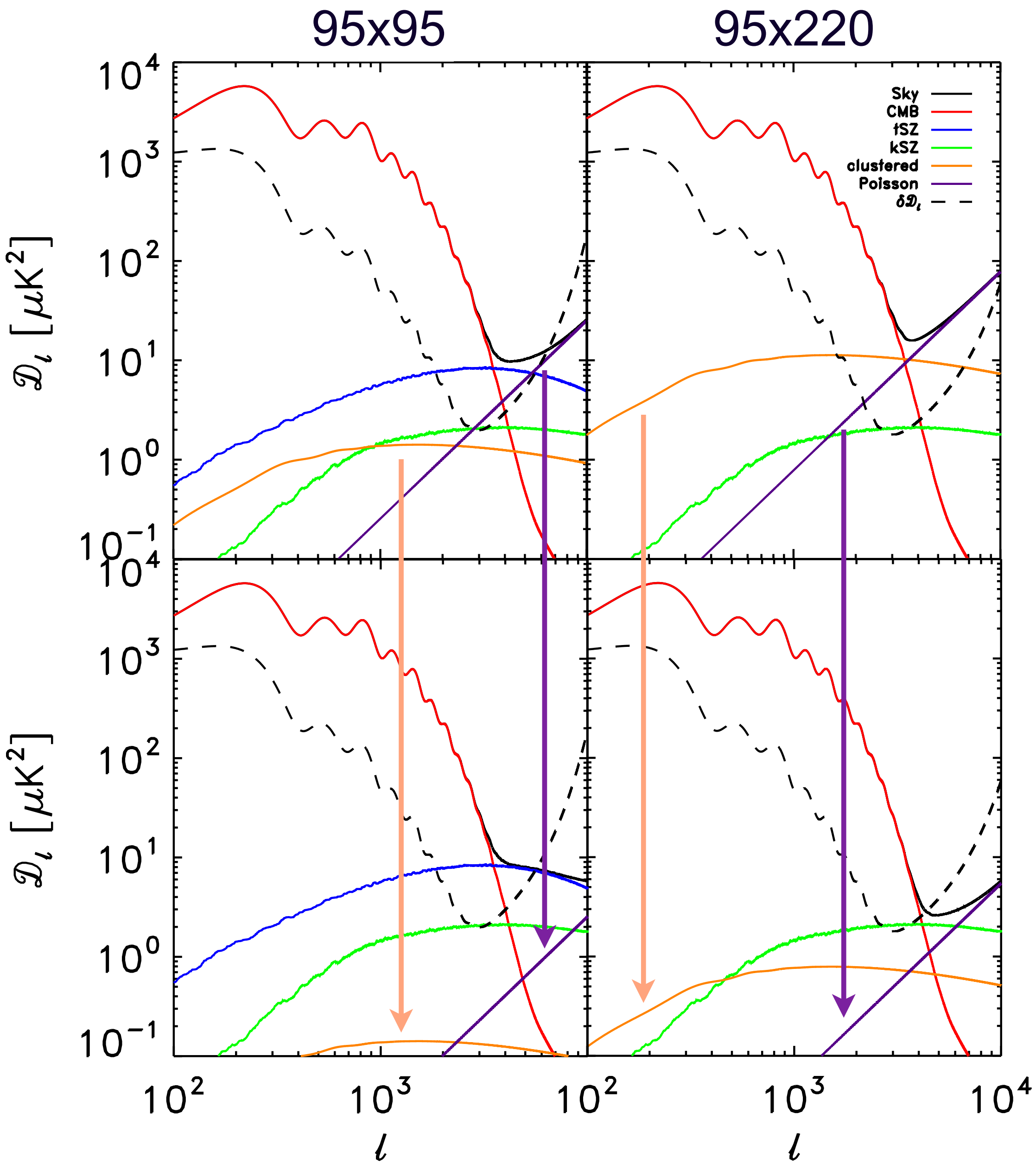


Shirokoff et al 2011



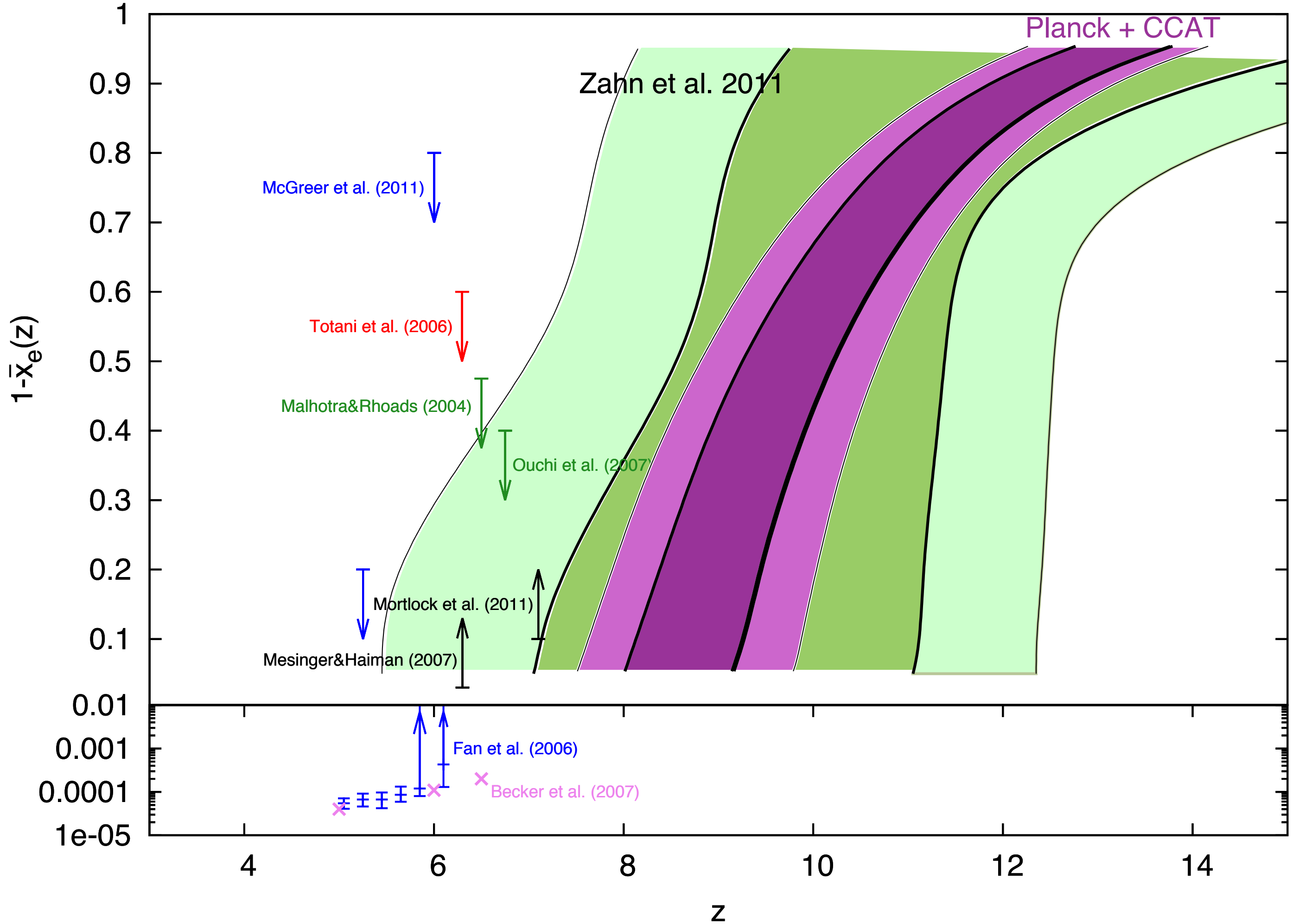
SZ Power Spectra

- With DSFG detection, can reduce contamination
  - c.f. predictions for cleaning SPT 100 deg2 w/500 μm SPIRE (Δθ=37"): massive reduction in DSFG signals
  - CCAT:
    - 2.5x smaller mm beams → $\delta\mathcal{D}_\ell$ flat to 2.5x higher ℓ
    - in-band DSFG detection at Δθ=25"
    - DSFG detection at 0.87 mm with Δθ=9" and smaller extrapolation in λ
    - Much better DSFG removal, not running into beam-scale noise



Reichardt, Princeton Planck Worksop

Studying Reionization with CCAT



Measure the kSZ power spectrum at high angular multipoles, $\ell > 3000$

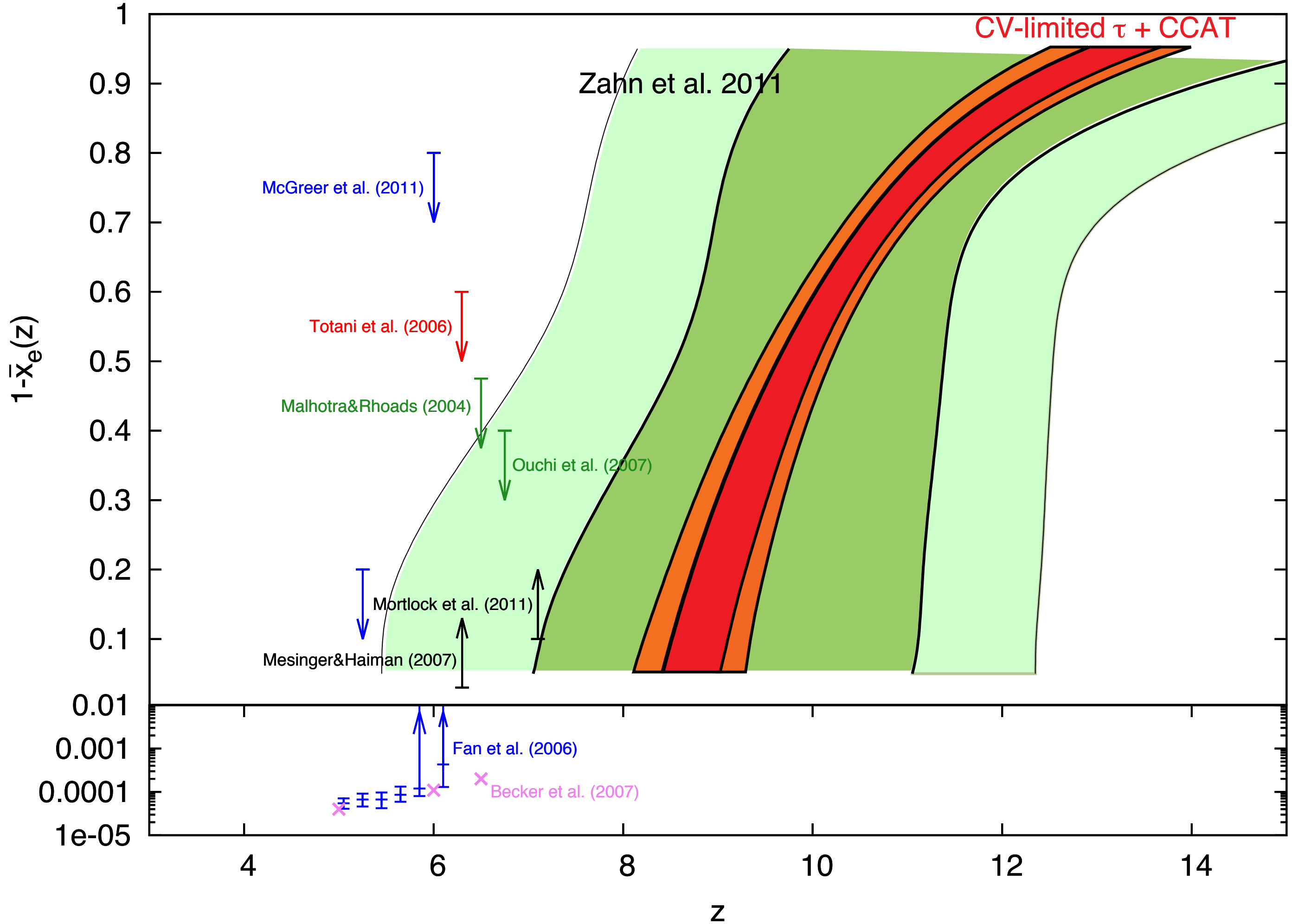
calculations by Zahn and Reichardt based on techniques developed for SPT in Zahn et al 2012 and Reichardt et al 2012

Amplitude of kSZ power spectrum proportional to duration of reionization.

CCAT high-frequency bands and angular resolution enable removal of DSFG contamination

Measurement becomes limited by the precision on reionization optical depth τ measurement

Studying Reionization with CCAT



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Conclusions

- CCAT will enable the next major leap forward in SZ work after the current generation of large-area surveys and follow-up instruments
  - Studies of the intracluster medium and the formation of galaxy clusters.
  - Measurement of the SZ anisotropy power spectra.
  - Cosmological parameter estimation.
  - Probes of the epoch of reionization.
- The case for SZ with CCAT is promising but needs to be elaborated.
  - Please contact FB or SG to express interest!
- Thanks to many for discussions and ideas!