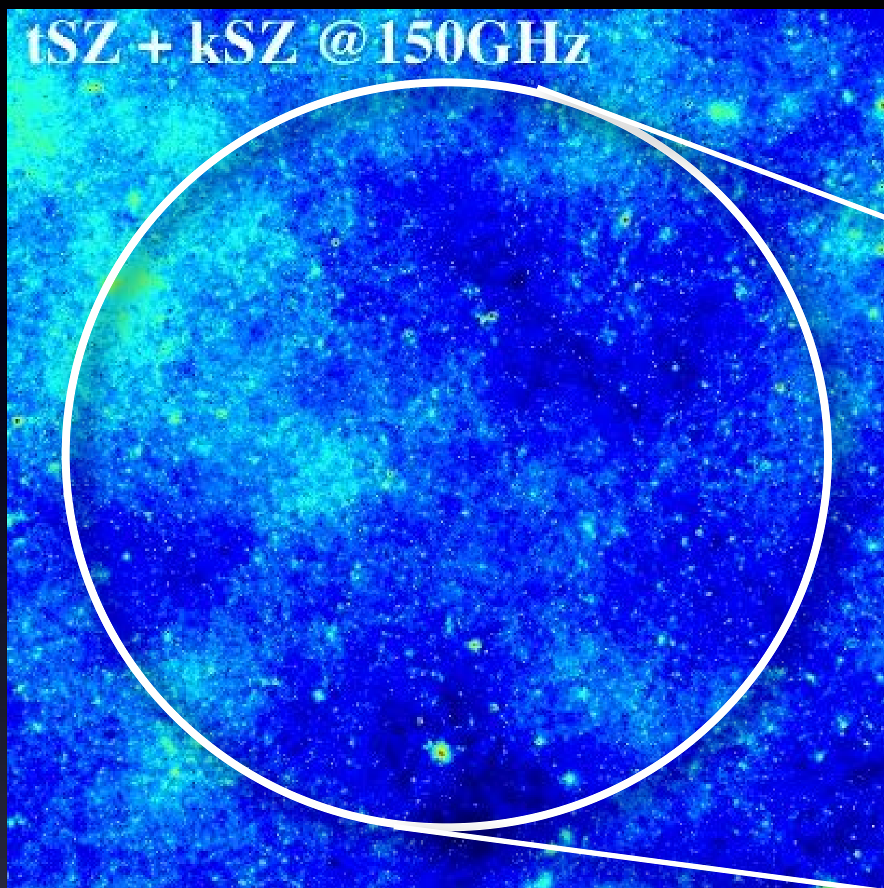
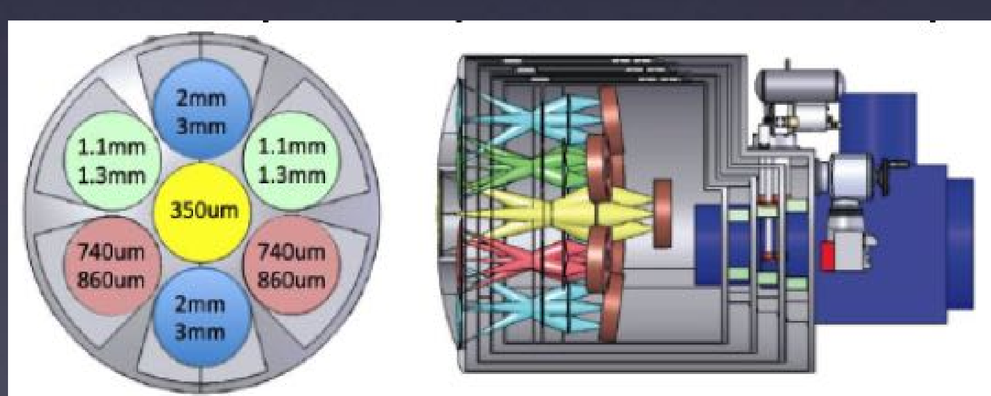
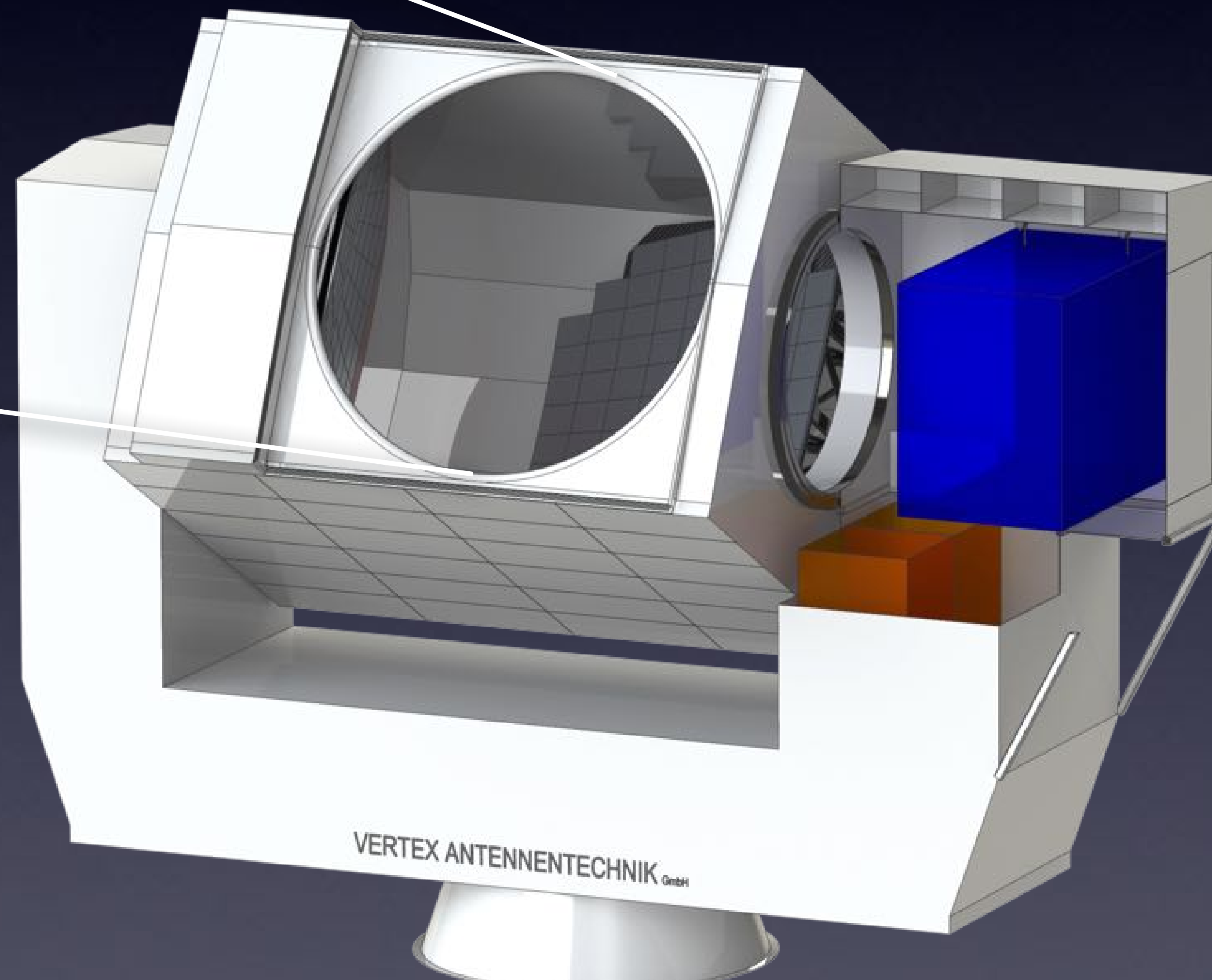
Galaxy Cluster Cosmology with *CCAT-prime*



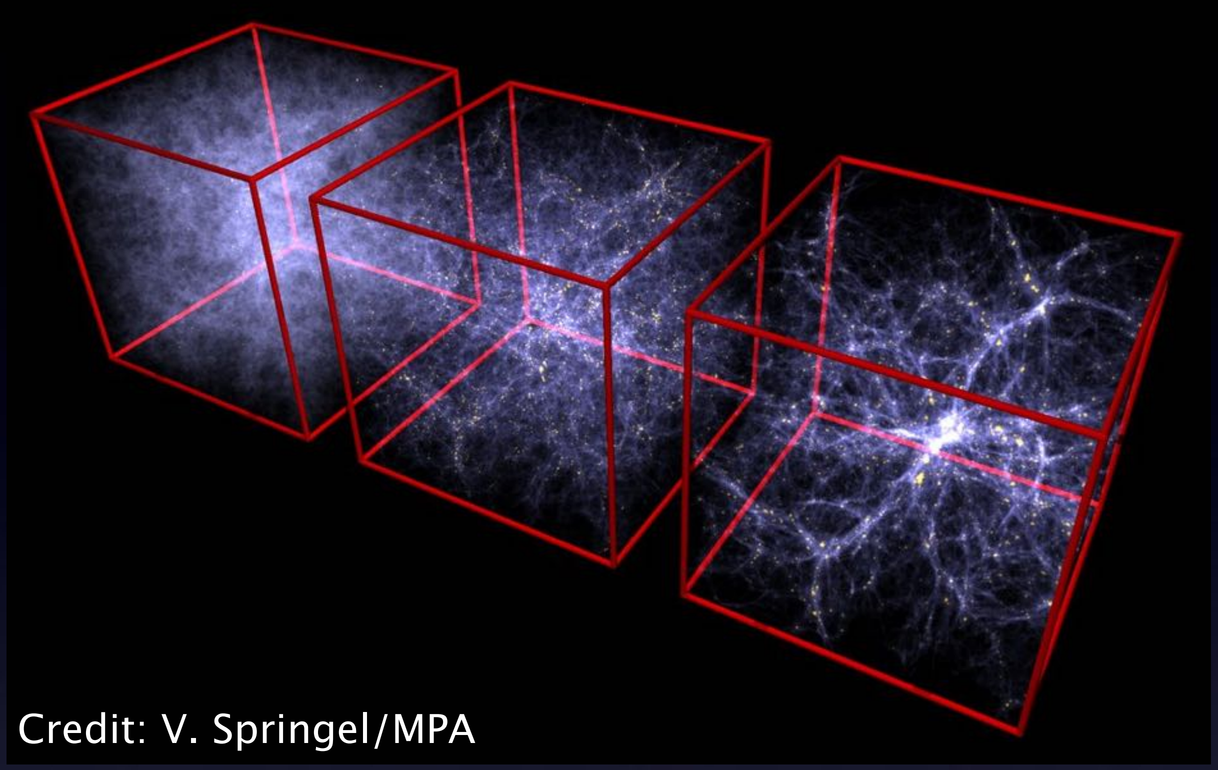
8.8°×8.8° sky area simulation
(Credit: K.Dolag/Magneticum sims)

Kaustuv Basu (Uni Bonn)
and
Members of the CCAT-p collaboration





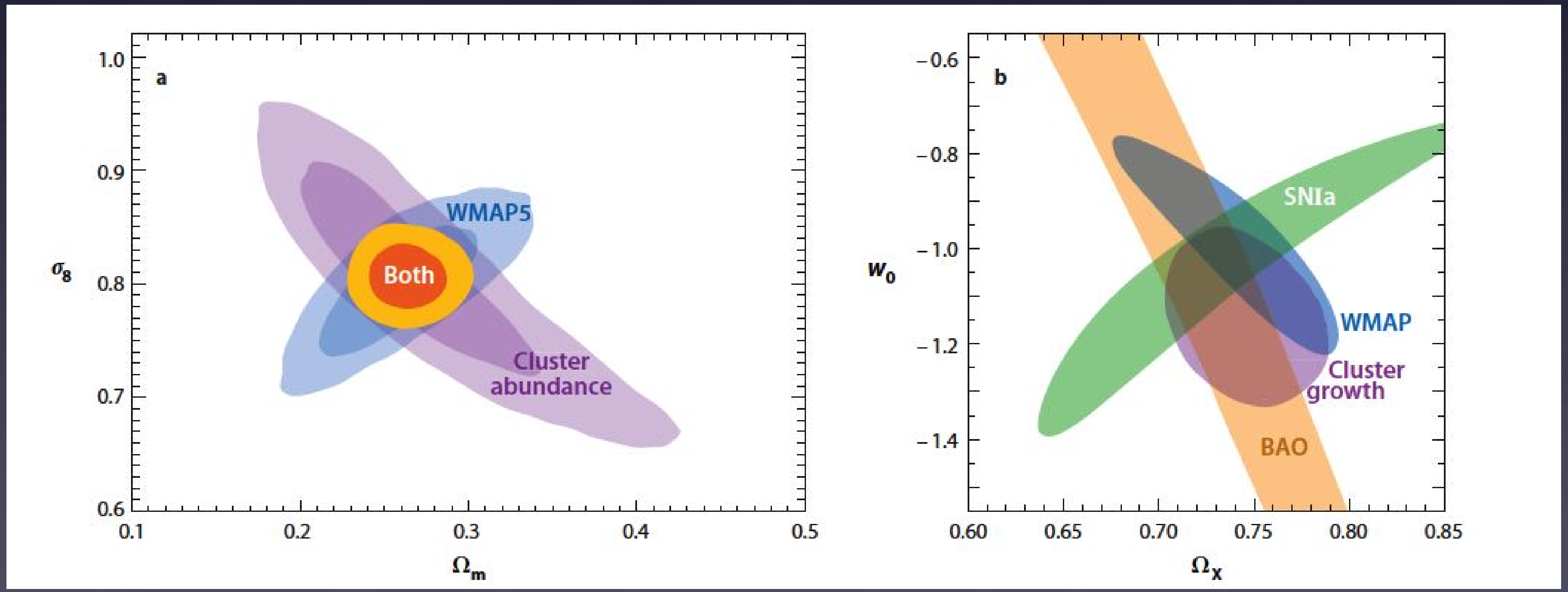
Galaxy clusters for cosmology



Galaxy clusters are extremely versatile tools for cosmology. Precise knowledge of cosmological parameters can be obtained in many different (and independent) ways.

- number counts and angular clustering
- velocity measurements (direct and pairwise)
- gas mass fraction, direct D_A from X/SZ, etc.
- microwave power spectrum/bispectrum etc.

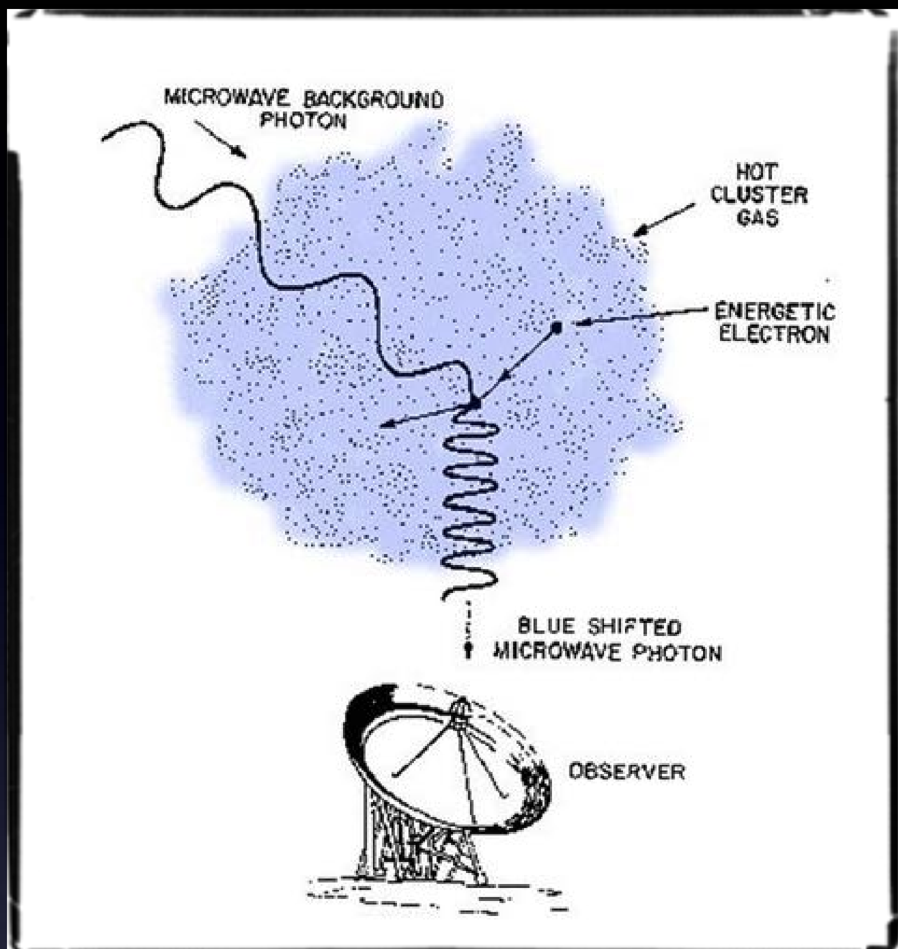
Review by Allen, Evrard & Mantz (2011)



Current constraints mostly come from measuring the *cluster number counts*, and the errors are dominated by *mass modeling uncertainties*

⇨ huge potential for future improvements!

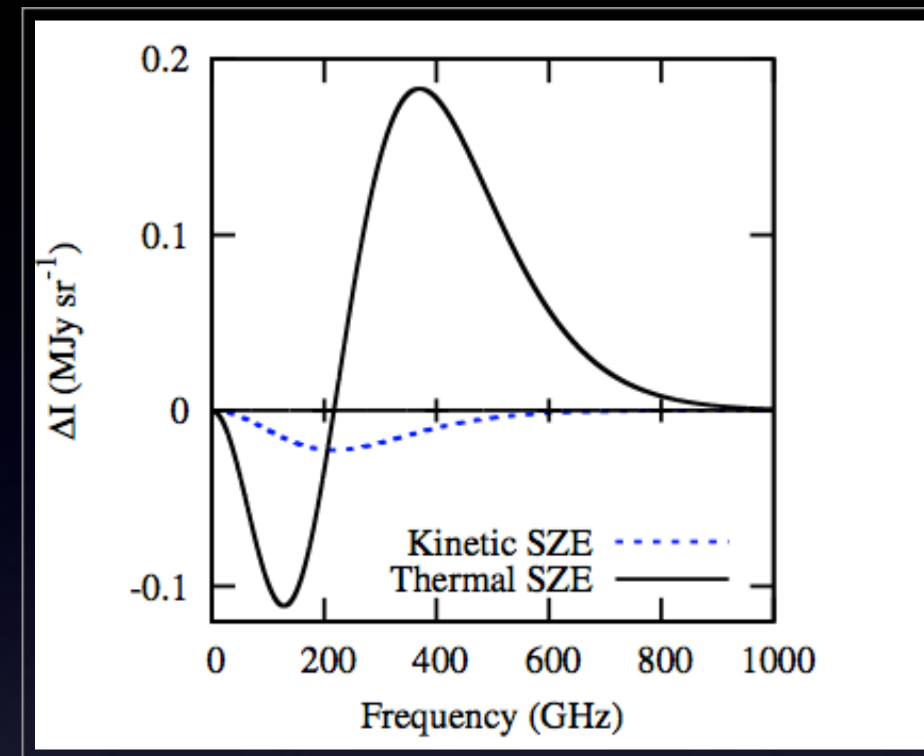
Sunyaev-Zel'dovich effect(s)



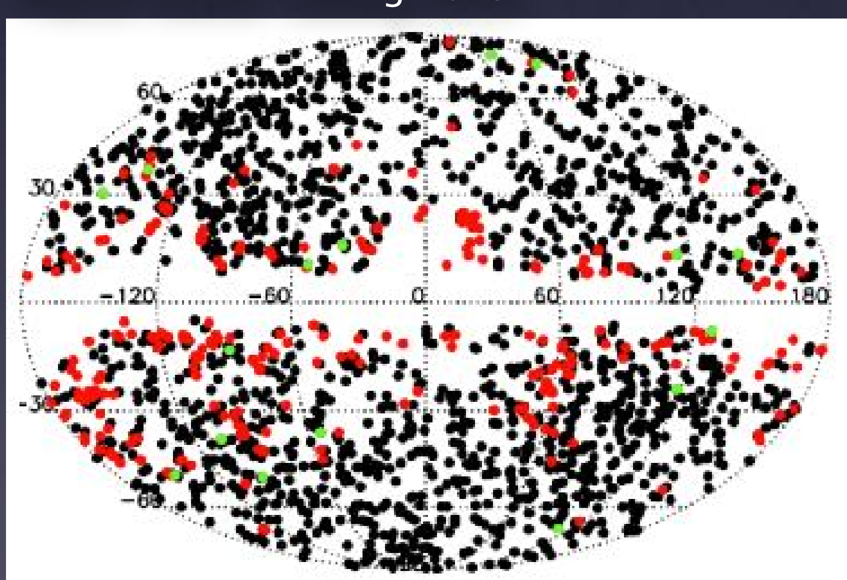
Inverse Compton scattering producing unique spectral distortion on the background CMB.

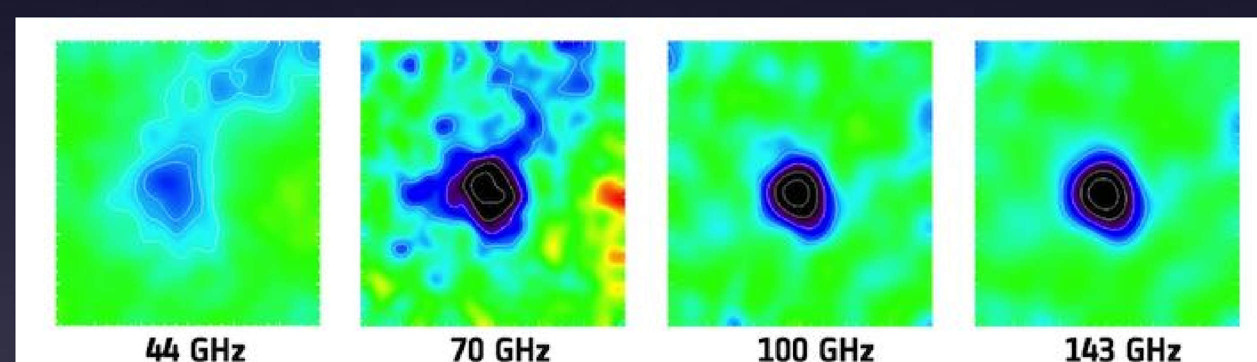
An ideal tool for finding and characterizing galaxy clusters.

Well over 1000 galaxy clusters have been identified from SZ.

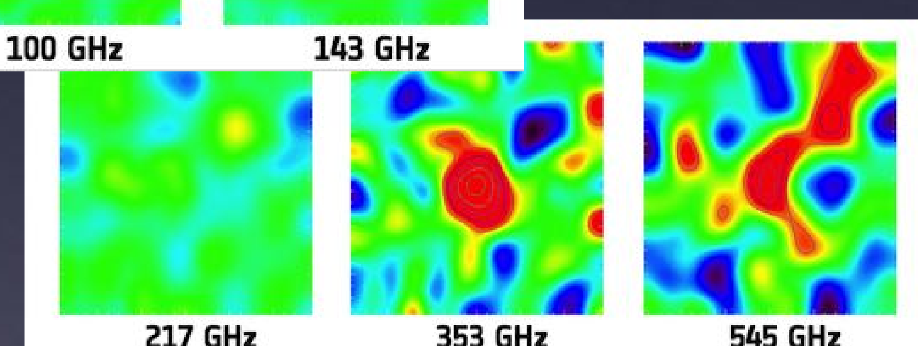


Planck cluster catalog 2015



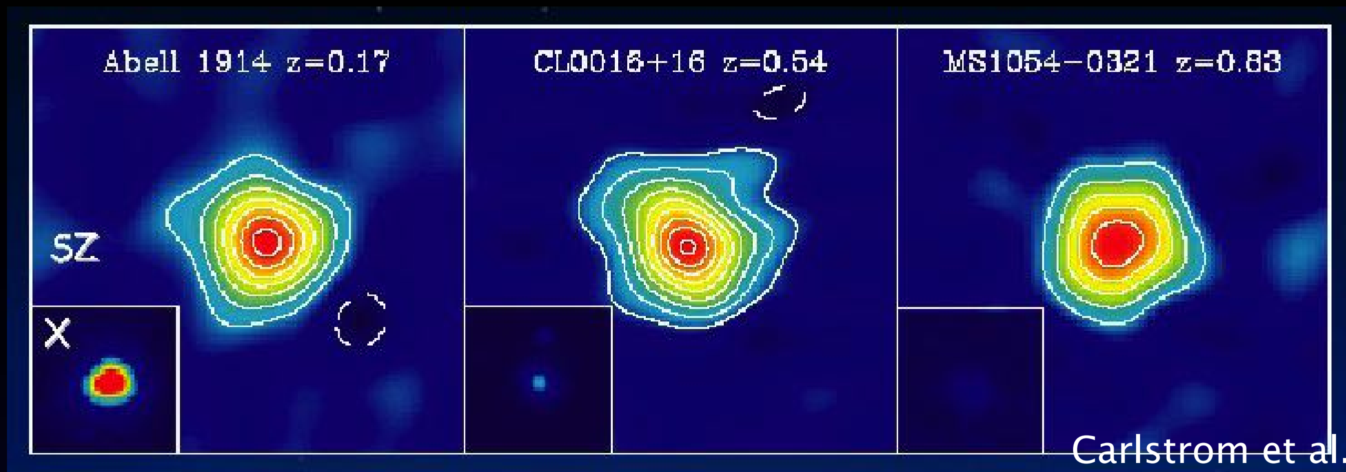


Credit: Planck collaboration



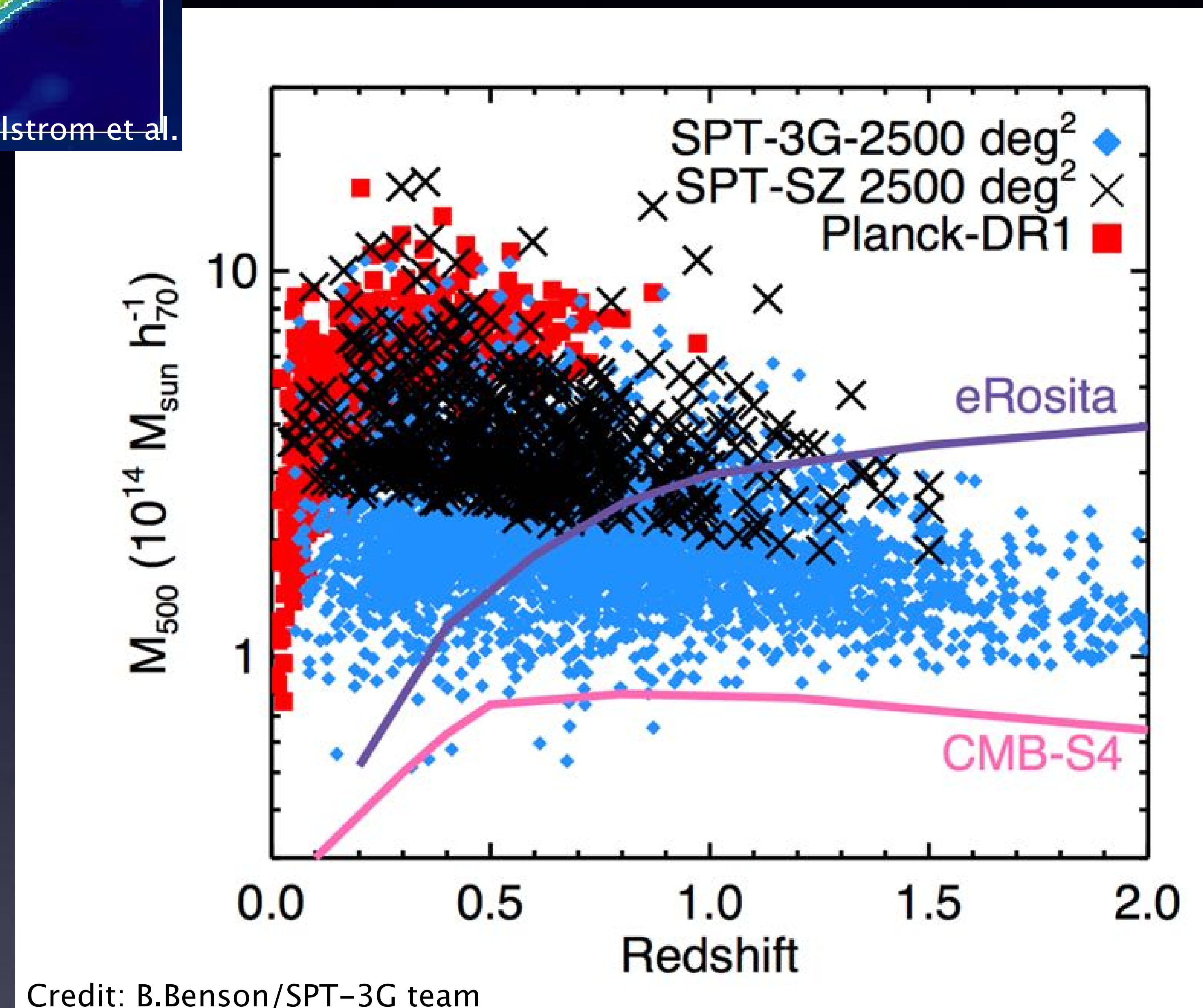
Next generation experiments will move from *photometric* to *spectroscopic* SZ measurements.

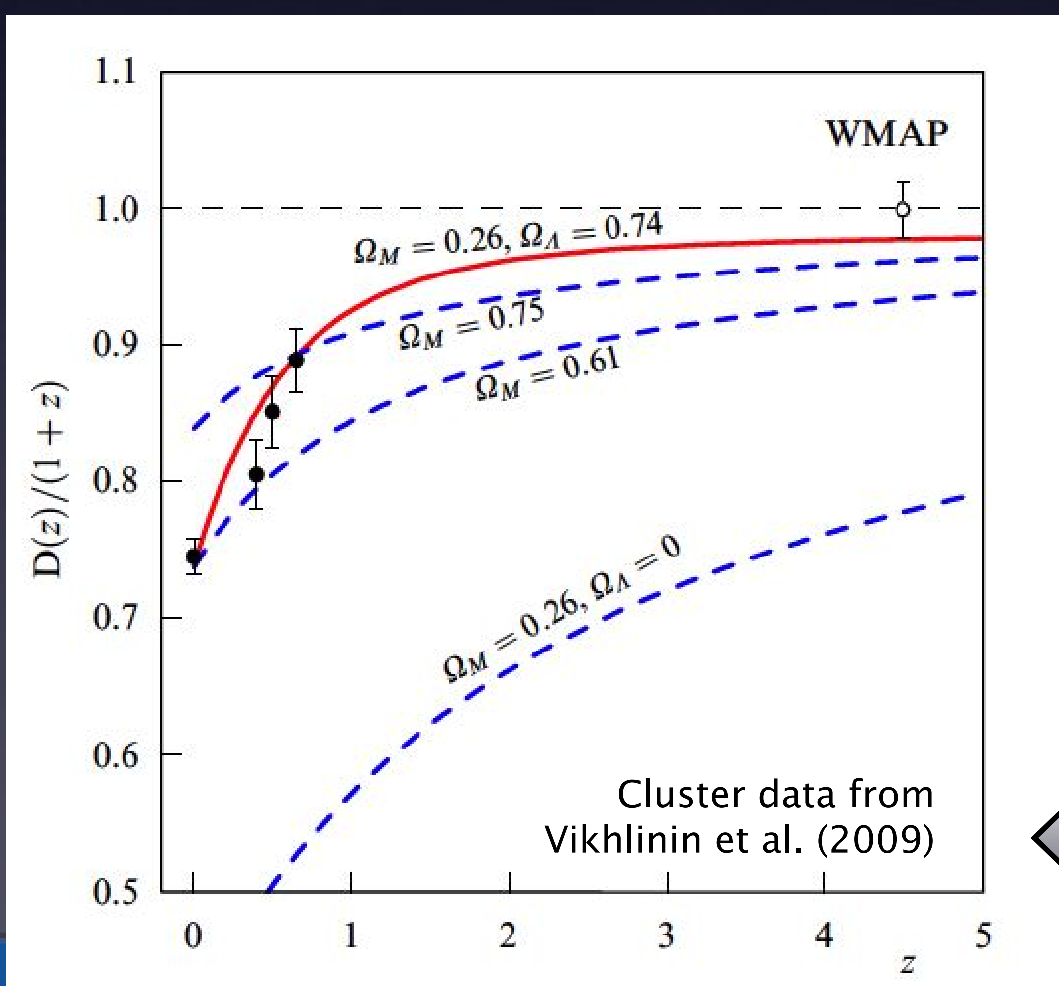
Advantages of SZ measurement



$$\frac{\Delta T}{T_{\rm CMB}} = g(x) \int n_e(l) \, \frac{k_B T_e(l)}{m_e c^2} \, dl$$

SZ signal is a scattering of the CMB: its brightness is *redshift independent!* The integrated signal correlates with total cluster mass.





SZ surveys are the ideal probe for finding galaxy clusters at redshift z ~ 1-2 **and** robustly constrain their masses

CCAT-p SZ itineray: tSZ ➔ kSZ ➔ rSZ

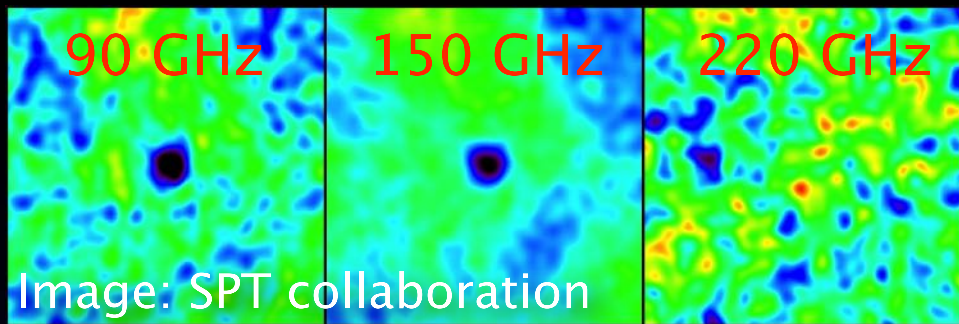
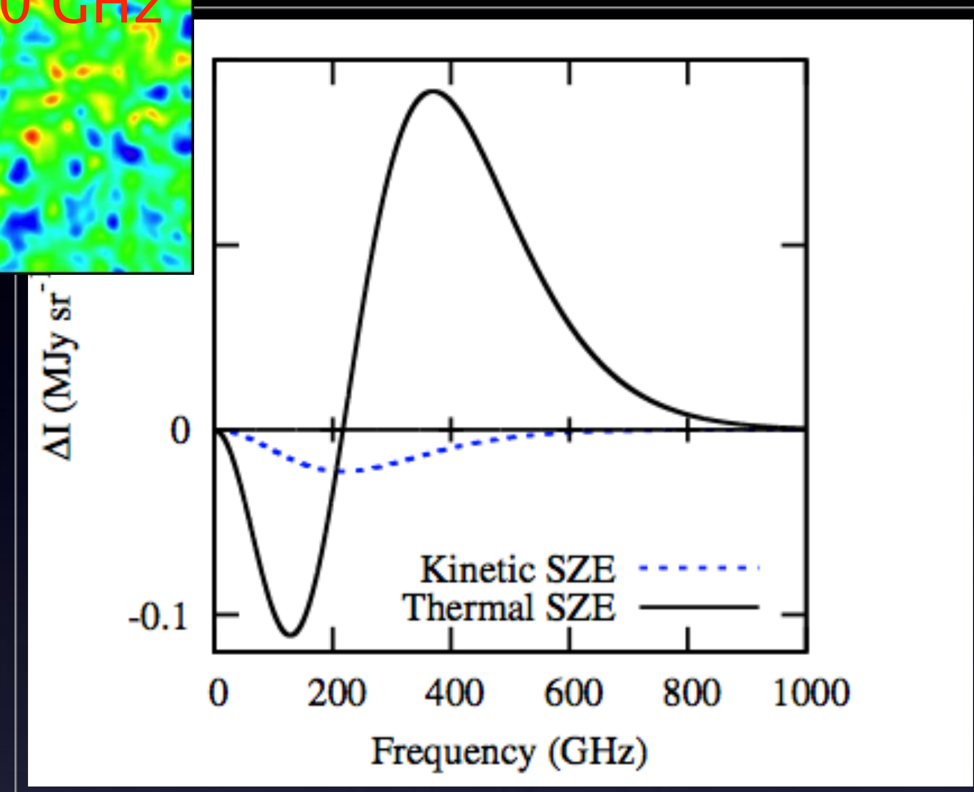


Image: SPT collaboration

First, **tSZ effect** for cluster selection and basic characterization



Second, **kSZ effect** to measure cluster peculiar motions (both pairwise and individual)

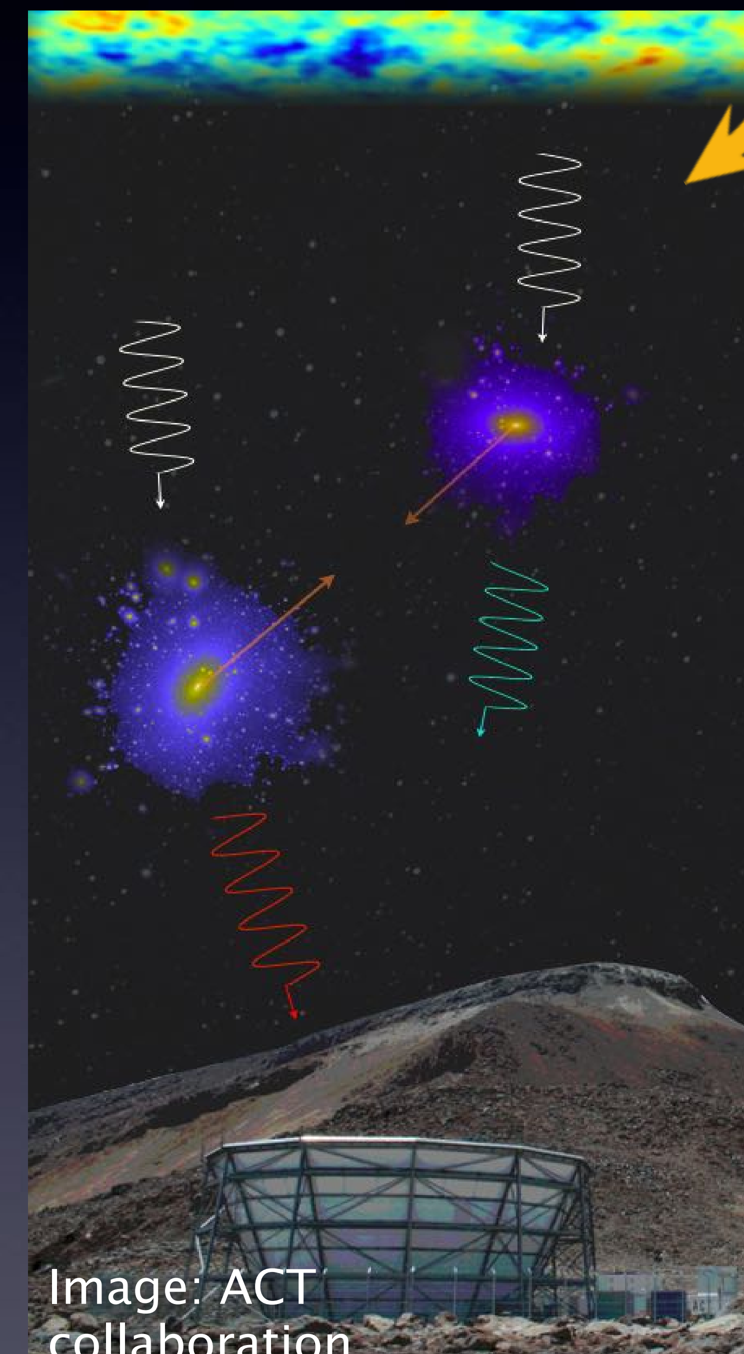
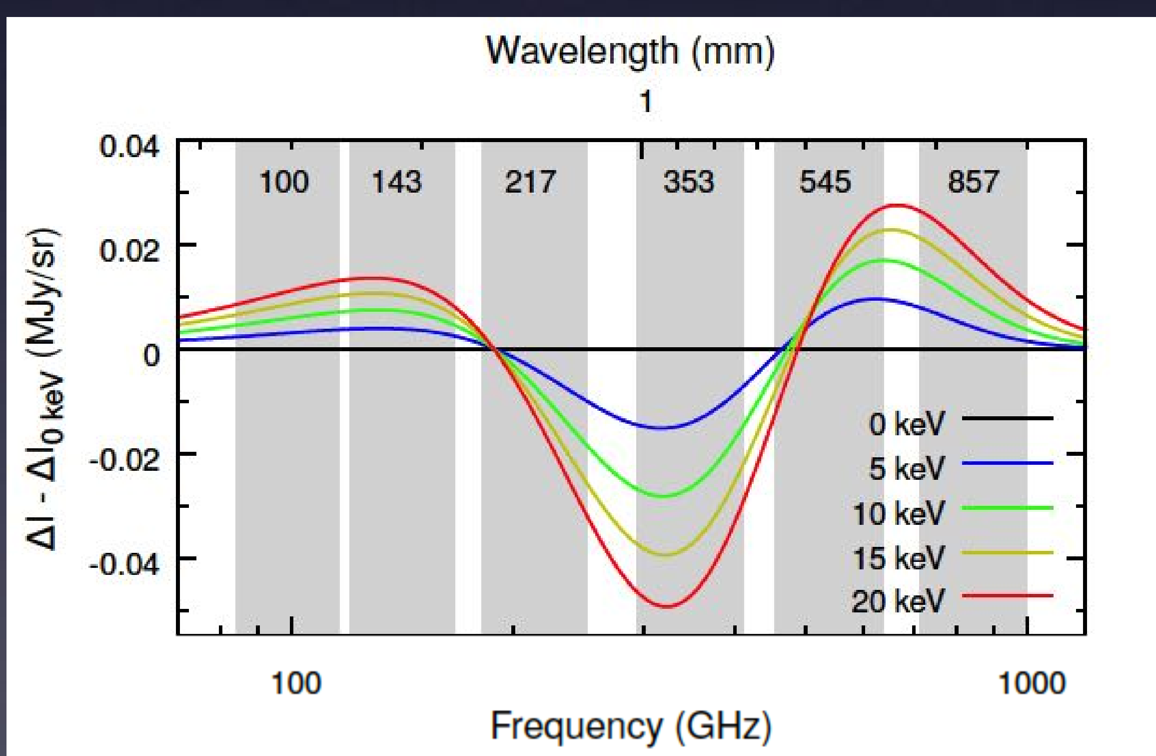


Image: ACT collaboration

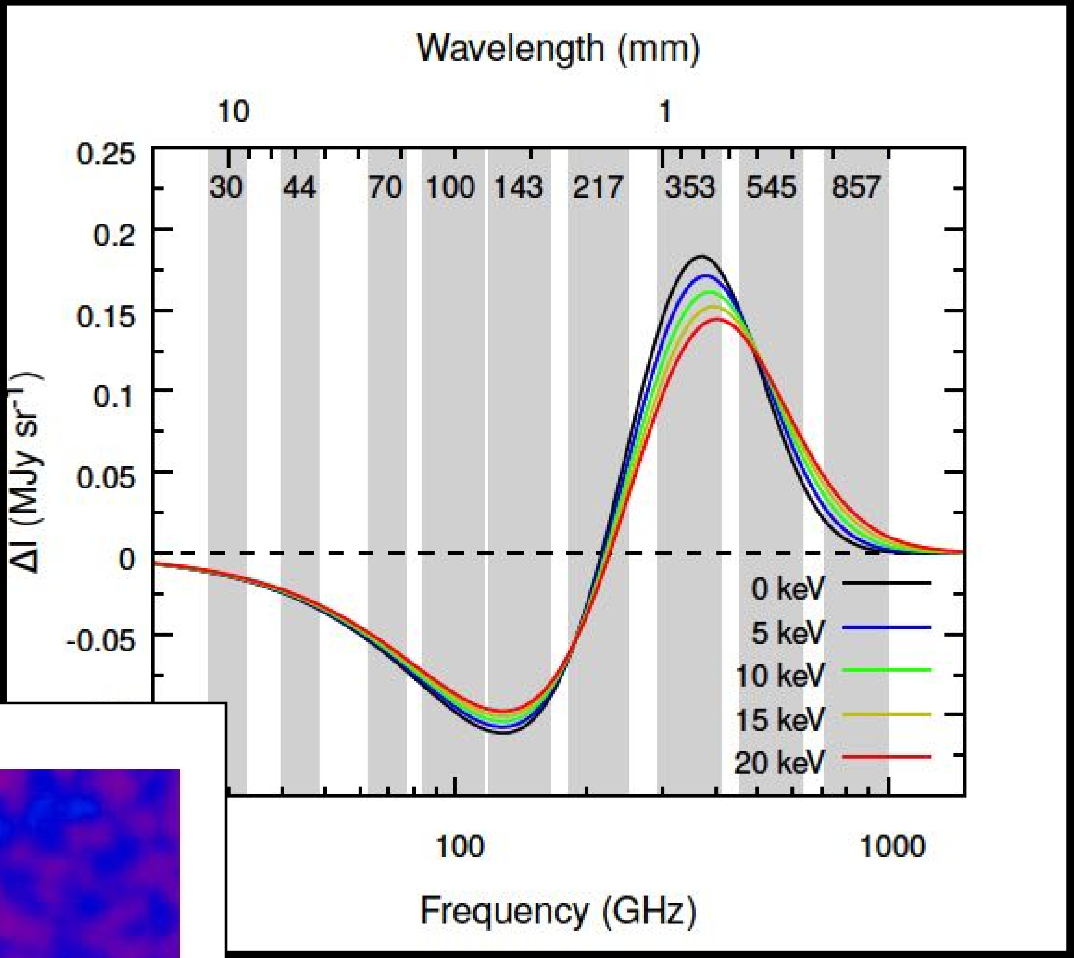
Finally, **rSZ effect** (or the relativistic tSZ effect) for cluster temperatures



Full spectral coverage for SZ science

Ideal for component separation (Galactic/ extragalactic **foregrounds** as well as **kSZ/tSZ**), and absolutely necessary for SZ spectral distortion measurements (i.e. the rSZ).

After the end of the *Planck* mission, there is currently no other space- or ground-based experiment with a similar spectral coverage.



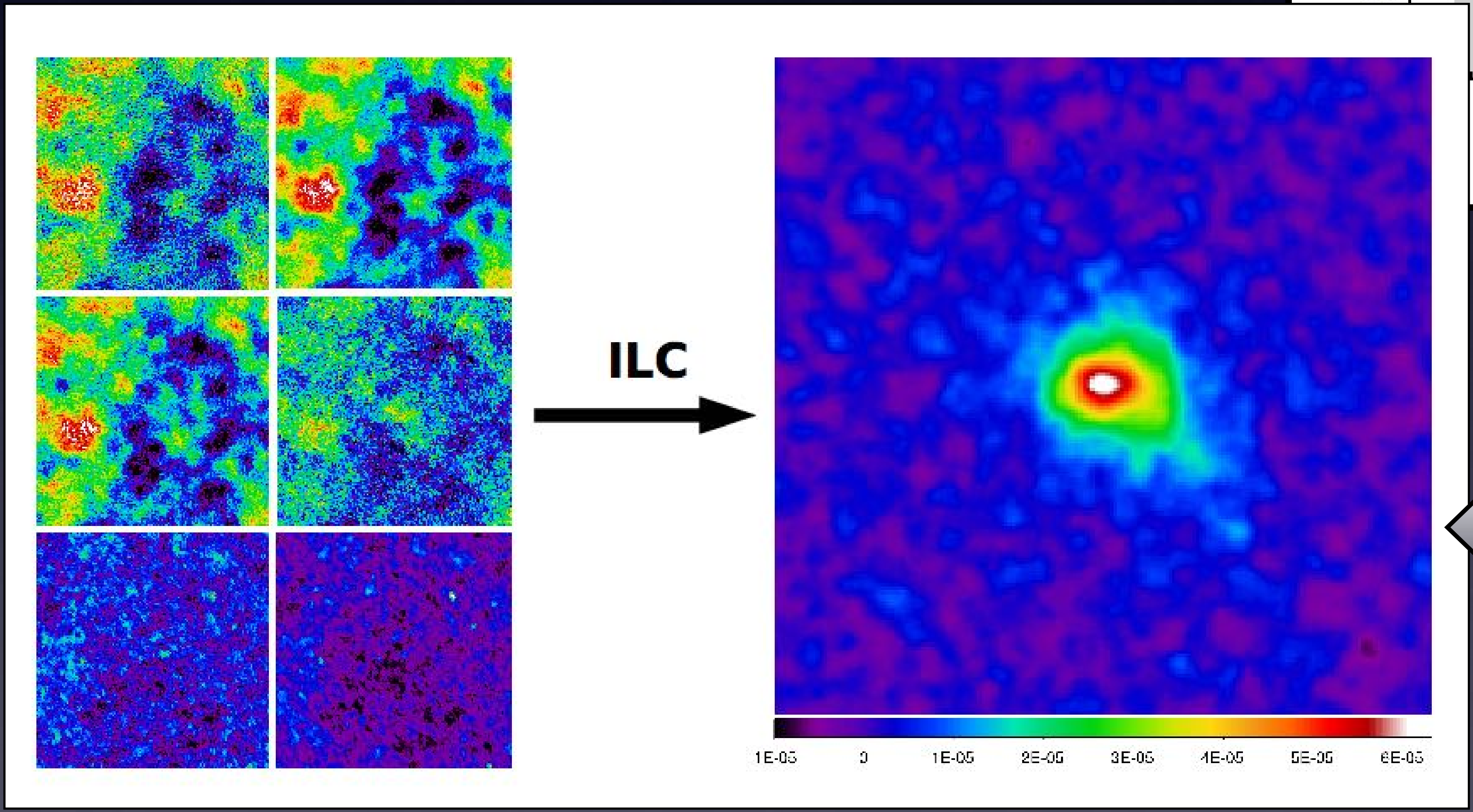
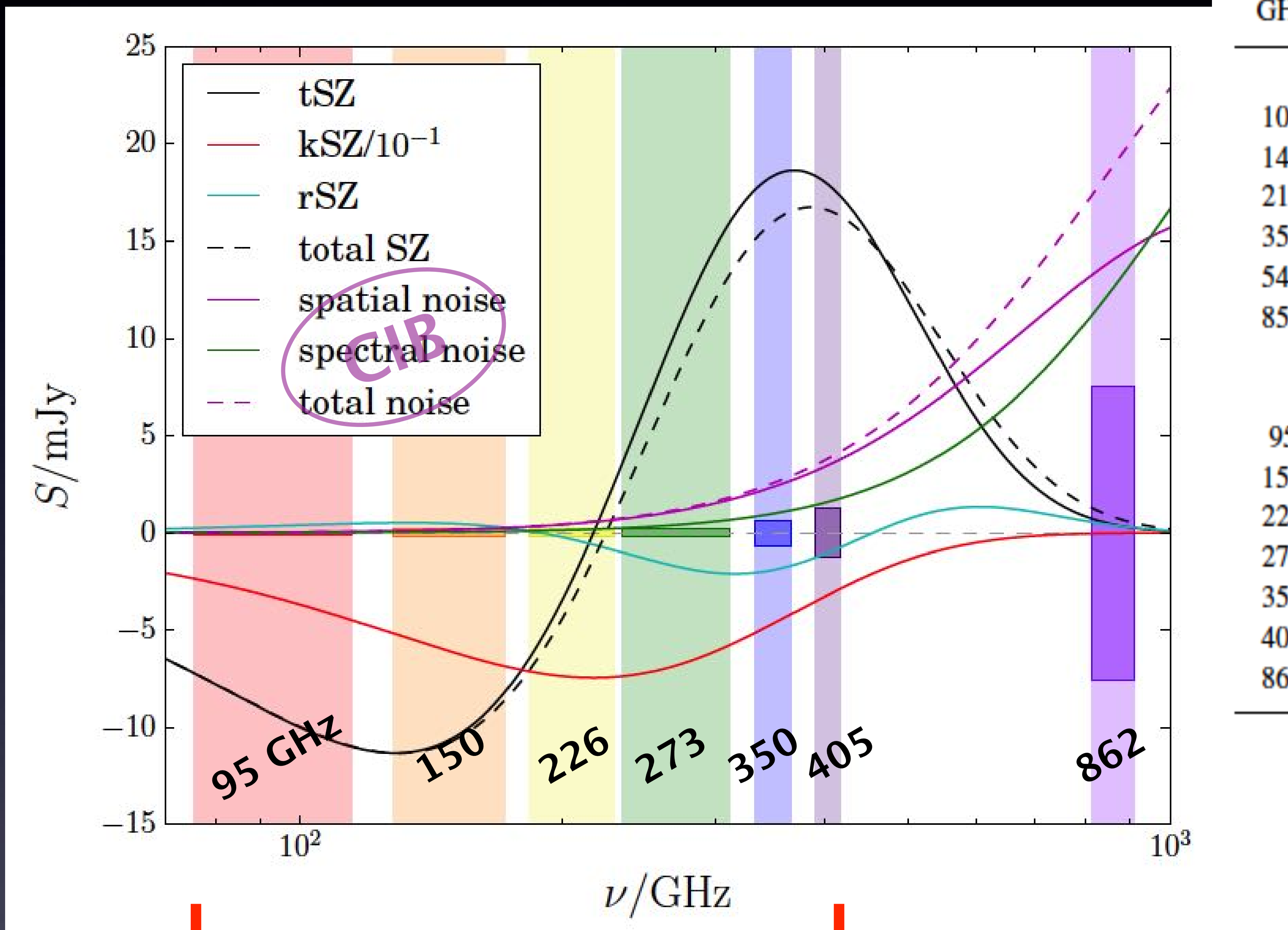


Illustration of foreground separation by ILC (Internal Linear Combination) method. Through a linear combination of multi-wavelength Planck data, Galactic foregrounds are effectively removed **(J. Erler Master's thesis)**

CCAT-p view of the SZ spectra

Figure: Mittal, de Bernardis & Niemack (arXiv:1708.06365)



ν GHz	FWHM arcmin	ΔT mK_{RJ}-arcmin	ΔT mK_{CMB}-arcmin	ΔI kJy/sr-arcmin
Planck (all-sky-average full mission data)				
100	9.68	61.4	77.3	18.9
143	7.30	19.8	33.4	12.4
217	5.02	15.5	46.5	22.5
353	4.94	11.7	156	44.9
545	4.83	5.10	806	46.8
857	4.64	1.90	1.92×10^4	43.5
CCAT-p (4000 h, 1000 deg^2 survey)				
95	2.2	3.9	4.9	1.1
150	1.4	3.7	6.4	2.6
226	0.9	1.5	4.9	2.4
273	0.8	1.2	6.2	2.7
350	0.6	2.1	25	7.9
405	0.5	3.1	72	16
862	0.2	4.7	6.9×10^4	109

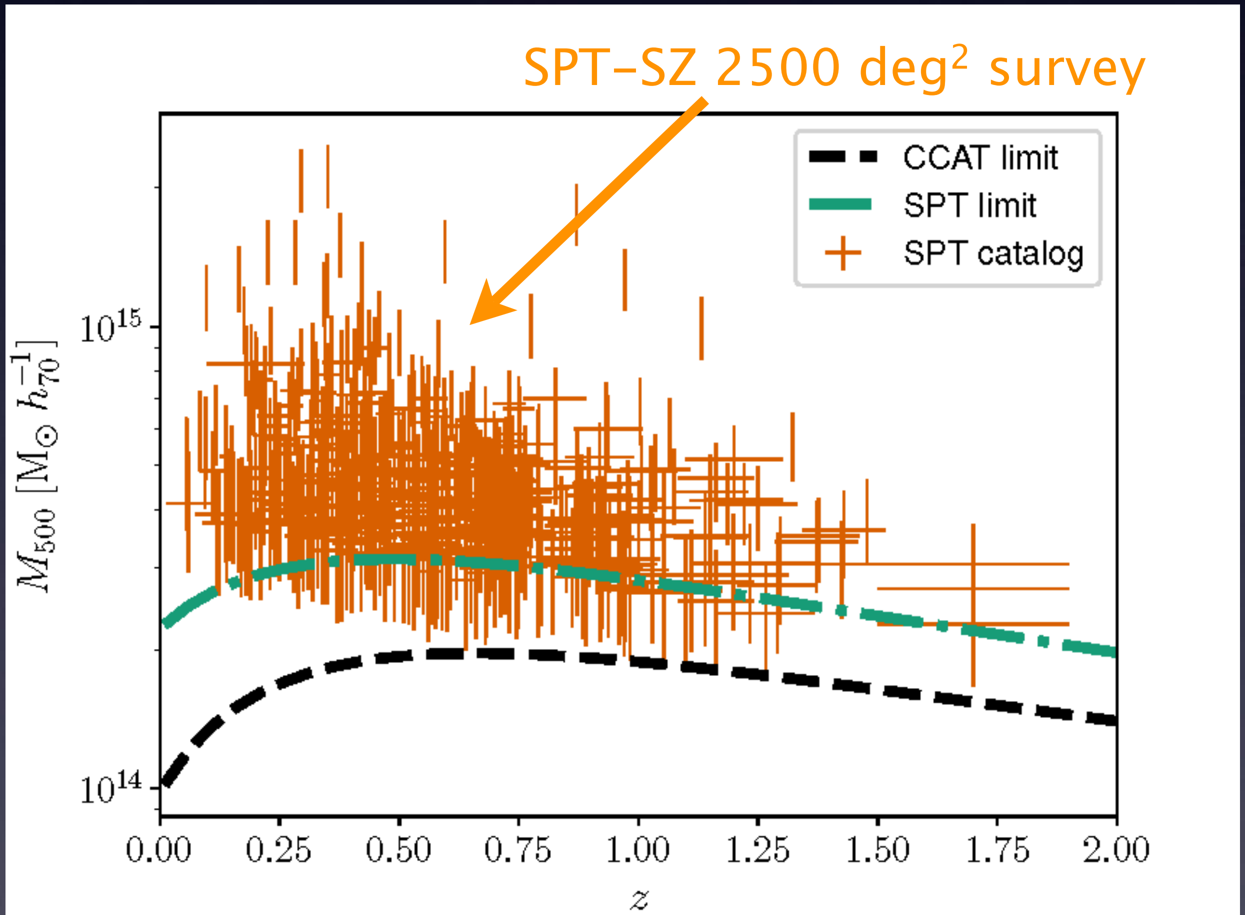
Erler et al. (arXiv:1709.01187)

In these frequencies CCAT-p sensitivity is on average 5 to 15 times better than *Planck*'s (and angular resolution is ~6 times better)

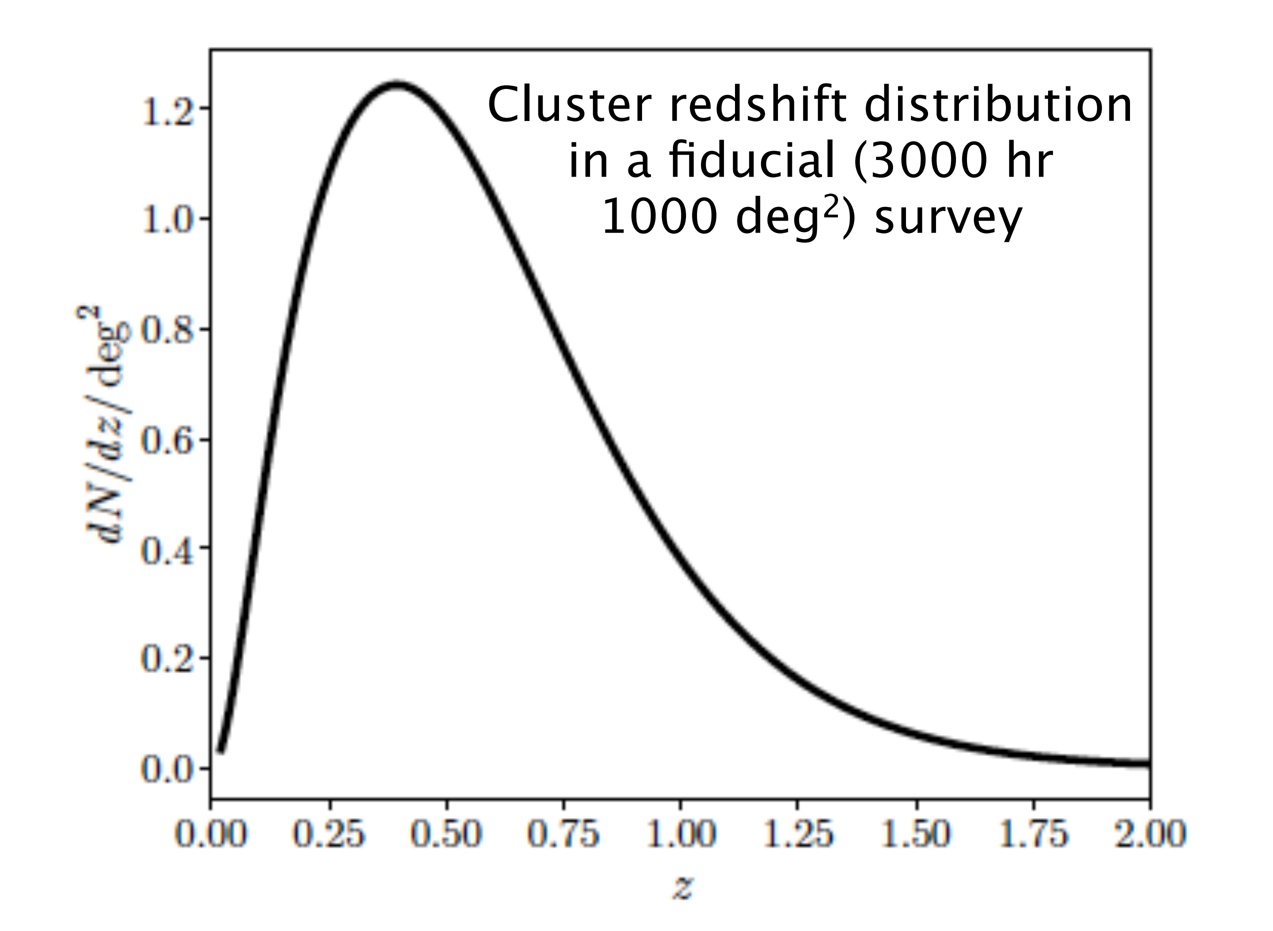
tSZ survey predictions

Some survey options:

Survey	$T_{\rm int}$ (Kh)	A (deg^2)	σ_T (μK)	N ($z \leq 2$)
Fiducial	3	1000	6.4	2095
Deep-I	3	500	4.5	1921
Deep-II	10	1000	3.5	5843
Wide-I	3	2000	9.1	2172
Wide-II	10	10000	11.1	7200



Gupta, Basu & Porciani (to be submitted)



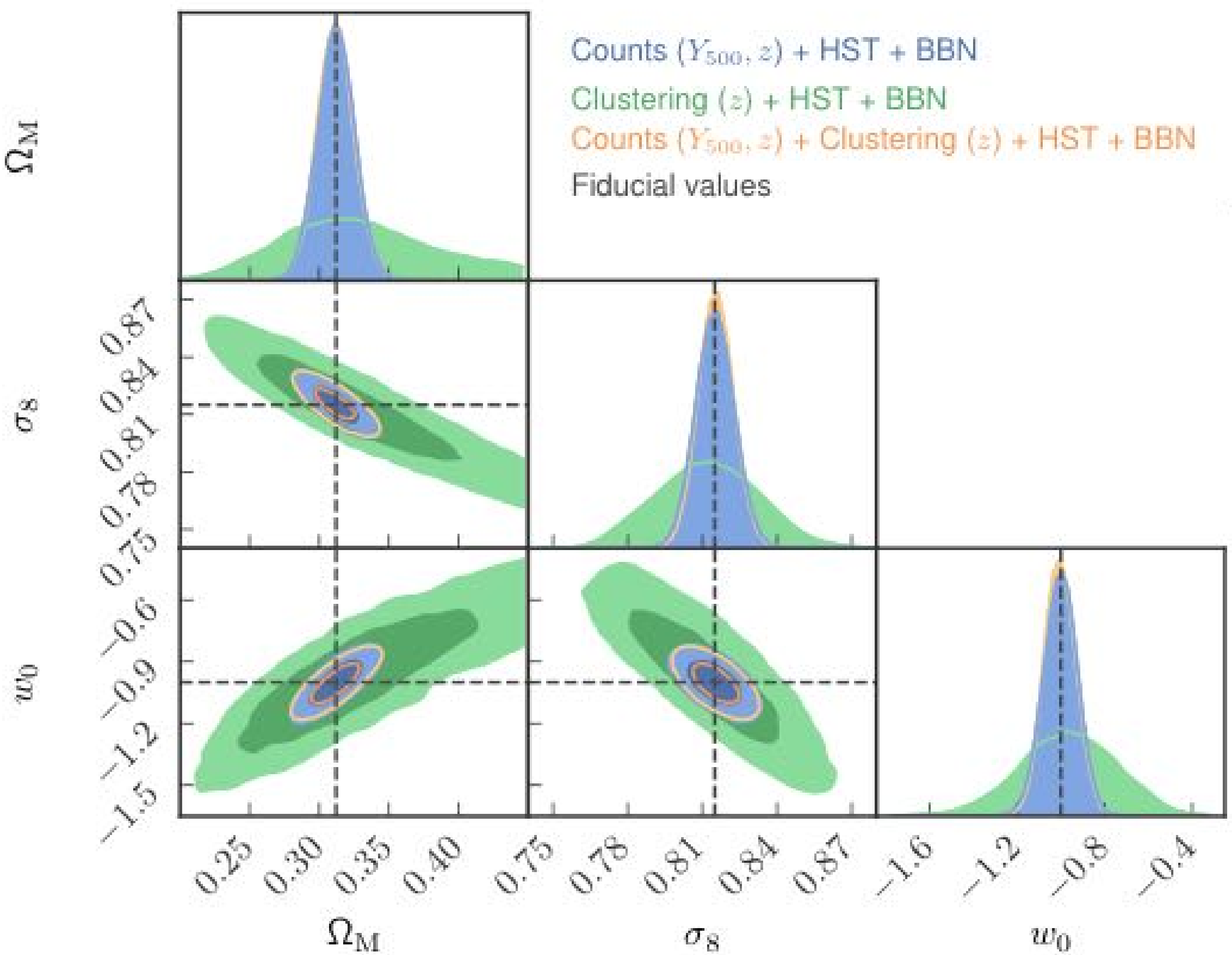
CCAT-prime sensitivity will be similar to that of SPT-3G (with 20% worse resolution).

In a fiducial survey of 3000 hours in 1000 deg^2 (first 2-4 years) it can detect **over 2000 galaxy clusters** with S/N ≥ 5.

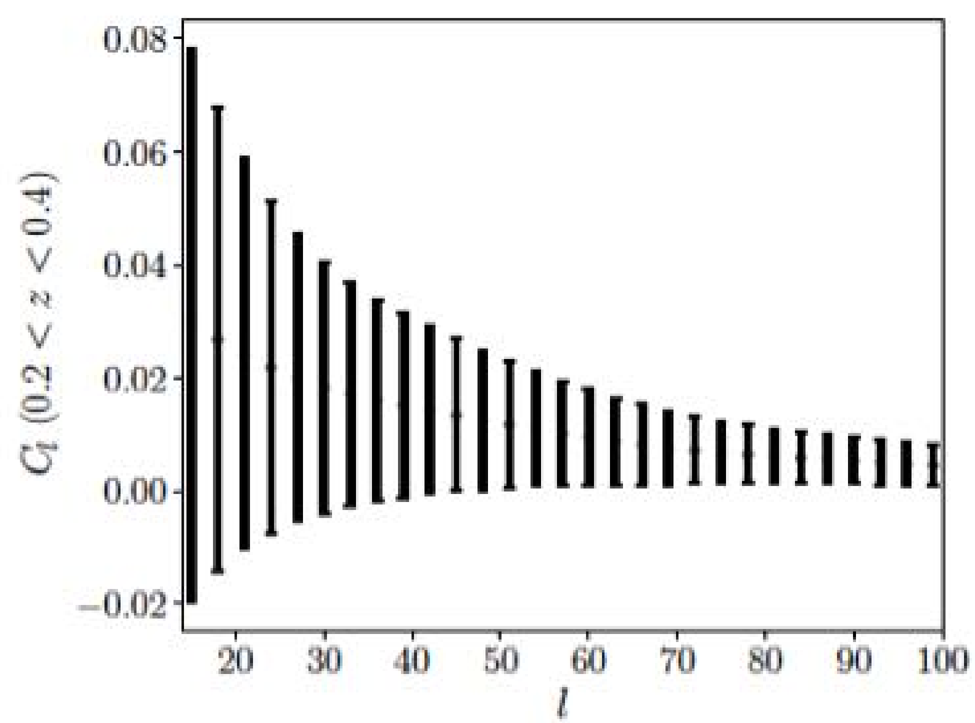
tSZ survey predictions

CCAT-p tSZ survey of 1000 deg^2 will constrain Ω_m, σ_8 and w_0 to roughly 4%, 0.7% and 7% accuracies, respectively.

For the same survey time, wider surveys do better than deep, narrow surveys.



Experiment	$\Delta\Omega_M$	$\Delta\sigma_8$	Δw_0
Fiducial survey			
Counts(Y_{500}, z)	0.013	0.007	0.07
Clustering(z)	$^{+0.061}_{-0.050}$	0.020	0.15
Counts(Y_{500}, z) + Clustering(z)	0.013	0.007	0.07



Gupta, Basu & Porciani (to be submitted)

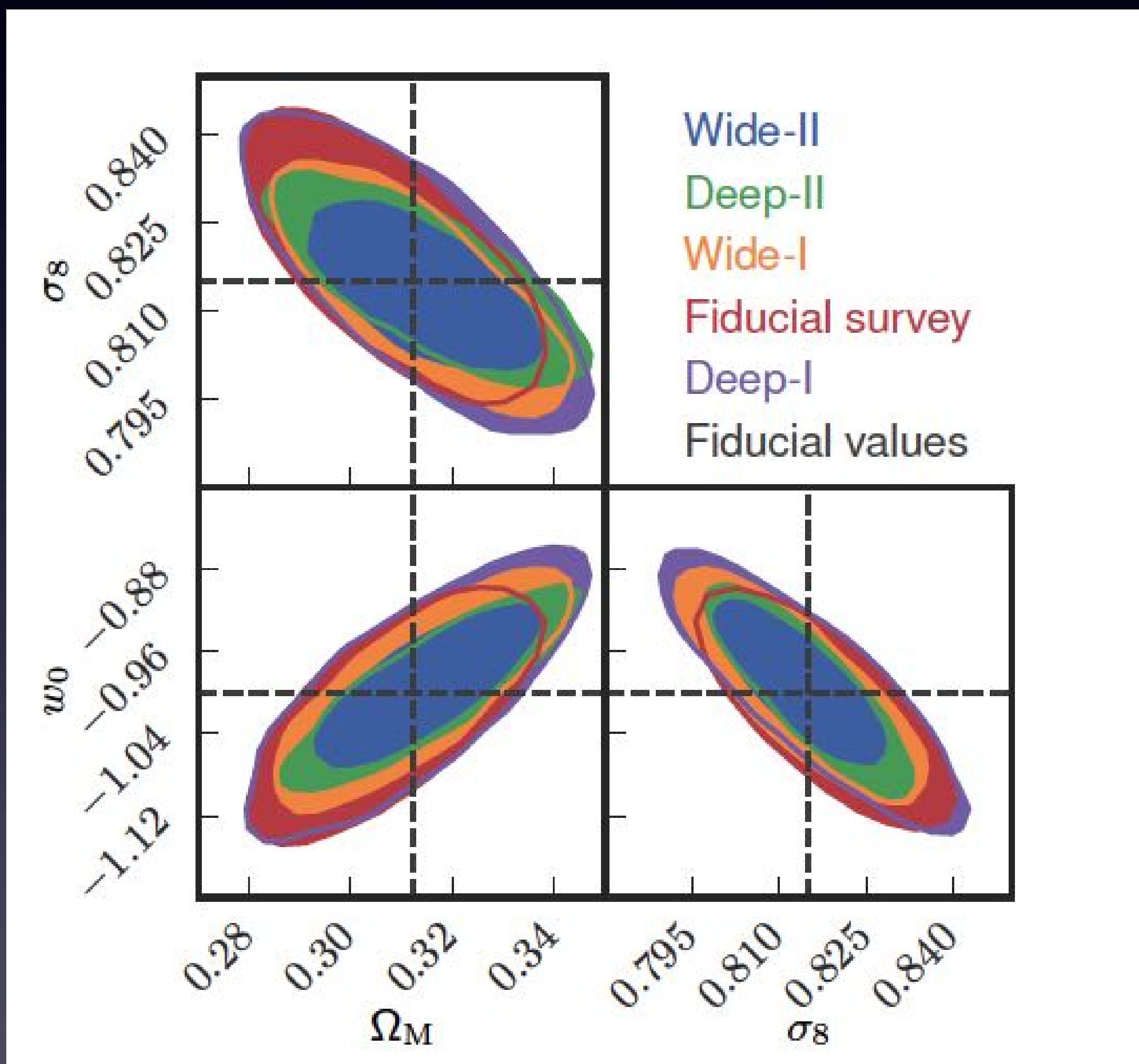
tSZ survey predictions

CCAT-p first light instrument might leave the 2mm/3mm channels out for future upgrades.

eROSITA

Parameter set	# parameters	$\Delta\sigma_8$ ($\Delta\sigma_8/\sigma_8$)
σ_8	1	0.0005 (0.06 per cent)
$\sigma_8 + \Omega_m + n_s + h + \Omega_b = \Lambda$CDM	5	0.003 (0.4 per cent)
ΛCDM + f_{NL}^{local}	6	0.017 (2.1 per cent)
ΛCDM + LM sector	9	0.113 (14 per cent)

eROSITA prediction, Pillepich et al. (2012)

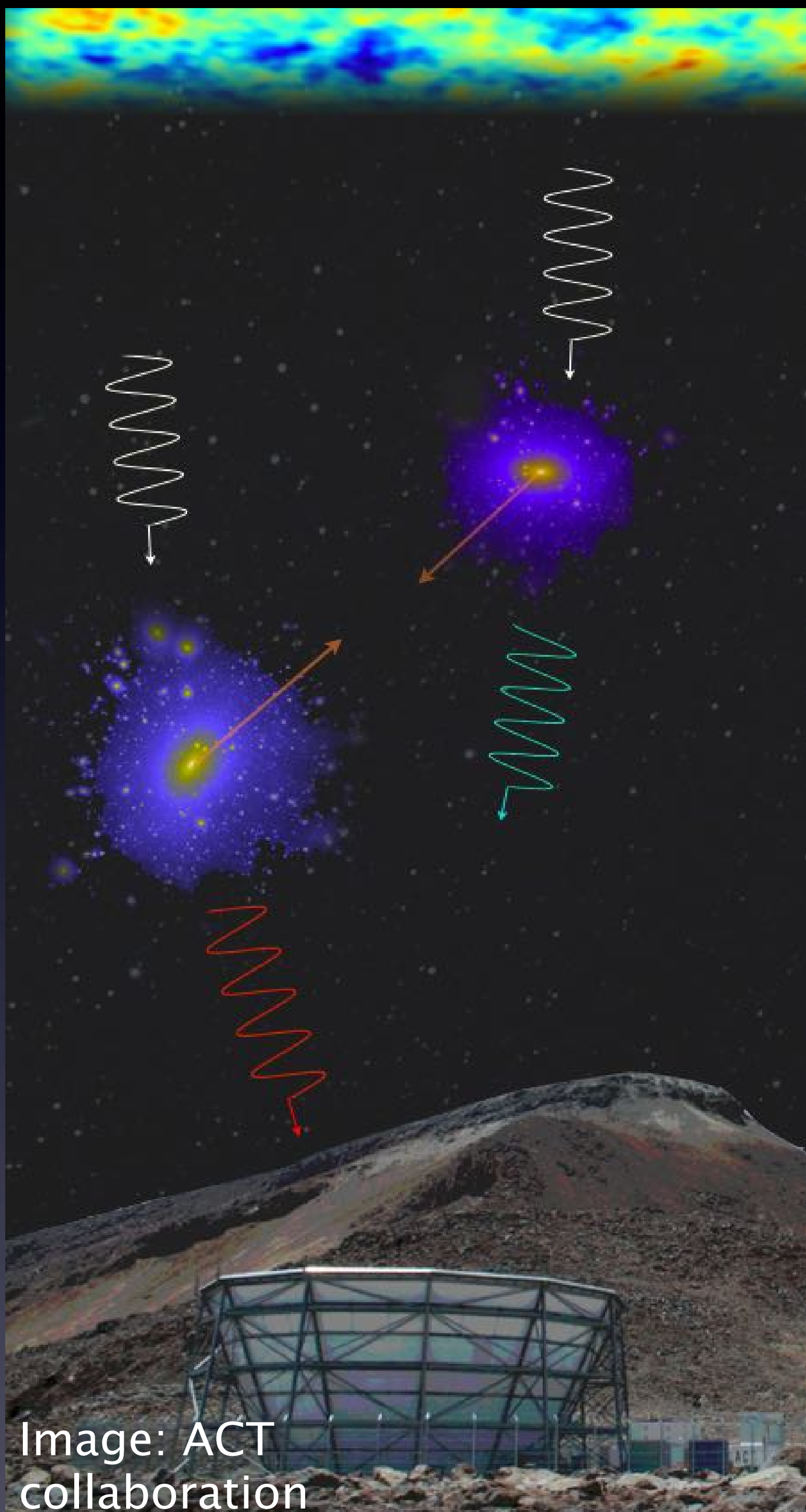


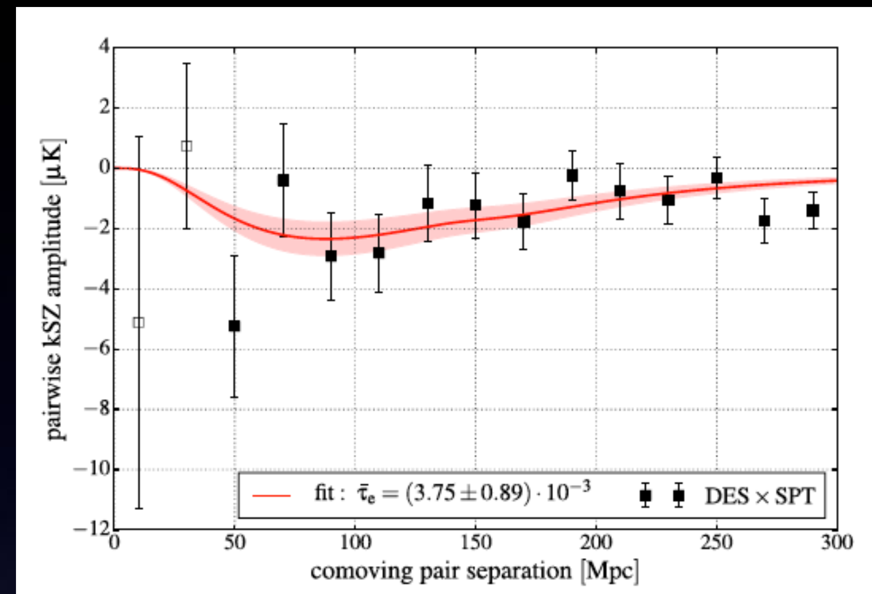
Even with a 1000 deg^2 CCAT-p survey, the cosmological constraints will be **better than the all-sky eROSITA**, thanks mainly to the low-scatter *Y-M* scaling relation.

Experiment	$\Delta\Omega_M$	$\Delta\sigma_8$	Δw_0
Fiducial survey			
Counts(Y_{500}, z)	0.021	0.017	0.08
Clustering(z)	$^{+0.078}_{-0.063}$	$^{+0.045}_{-0.049}$	0.21
Counts(Y_{500}, z) + Clustering(z)	0.021	0.016	0.08
CCAT + *Planck* + other	0.008	0.009	0.03

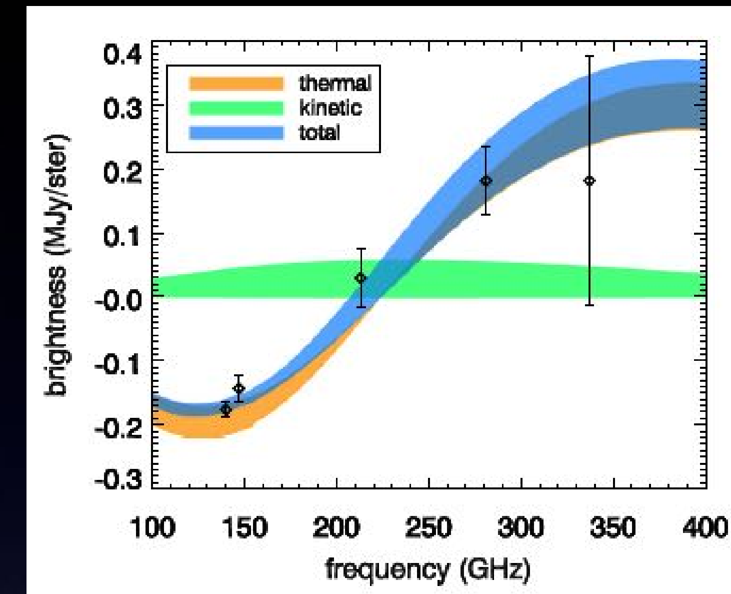
Gupta, Basu & Porciani (to be submitted)

kSZ state-of-the-art





Pairwise kSZ measurement
(Soergel et al. 2016)



Individual kSZ measurement
(Sayers et al. 2016)

kSZ measures the bulk motion of galaxy clusters and hence directly probe the growth of matter overdensity

$$\sigma_v^2(z) = f^2(z) \int dk \, \frac{P_m(k)}{2\pi^2} |W(kR)|^2,$$

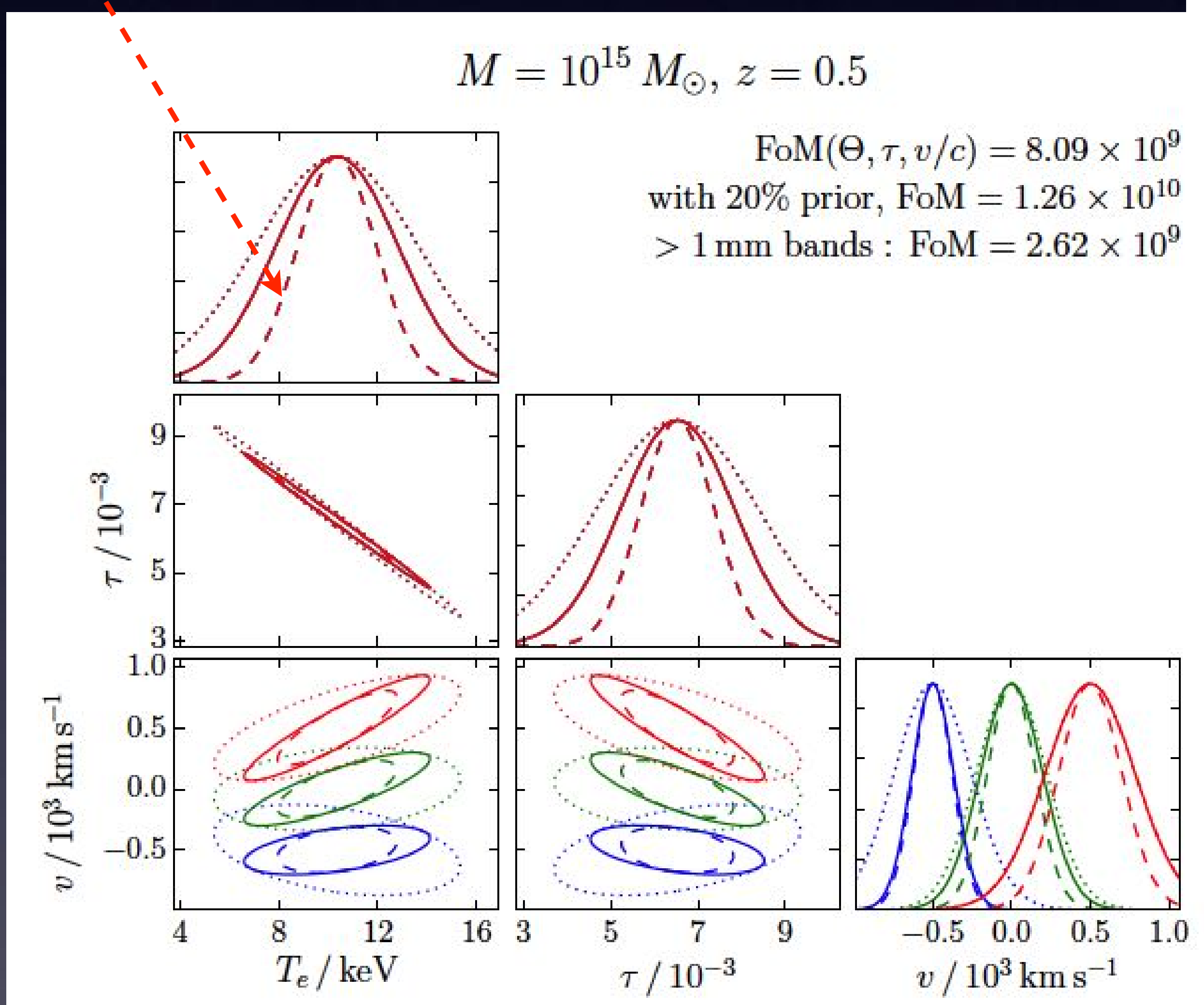
Current kSZ measurements are limited to "pairwise" stacking results and low-significance detections of internal gas motions in clusters.

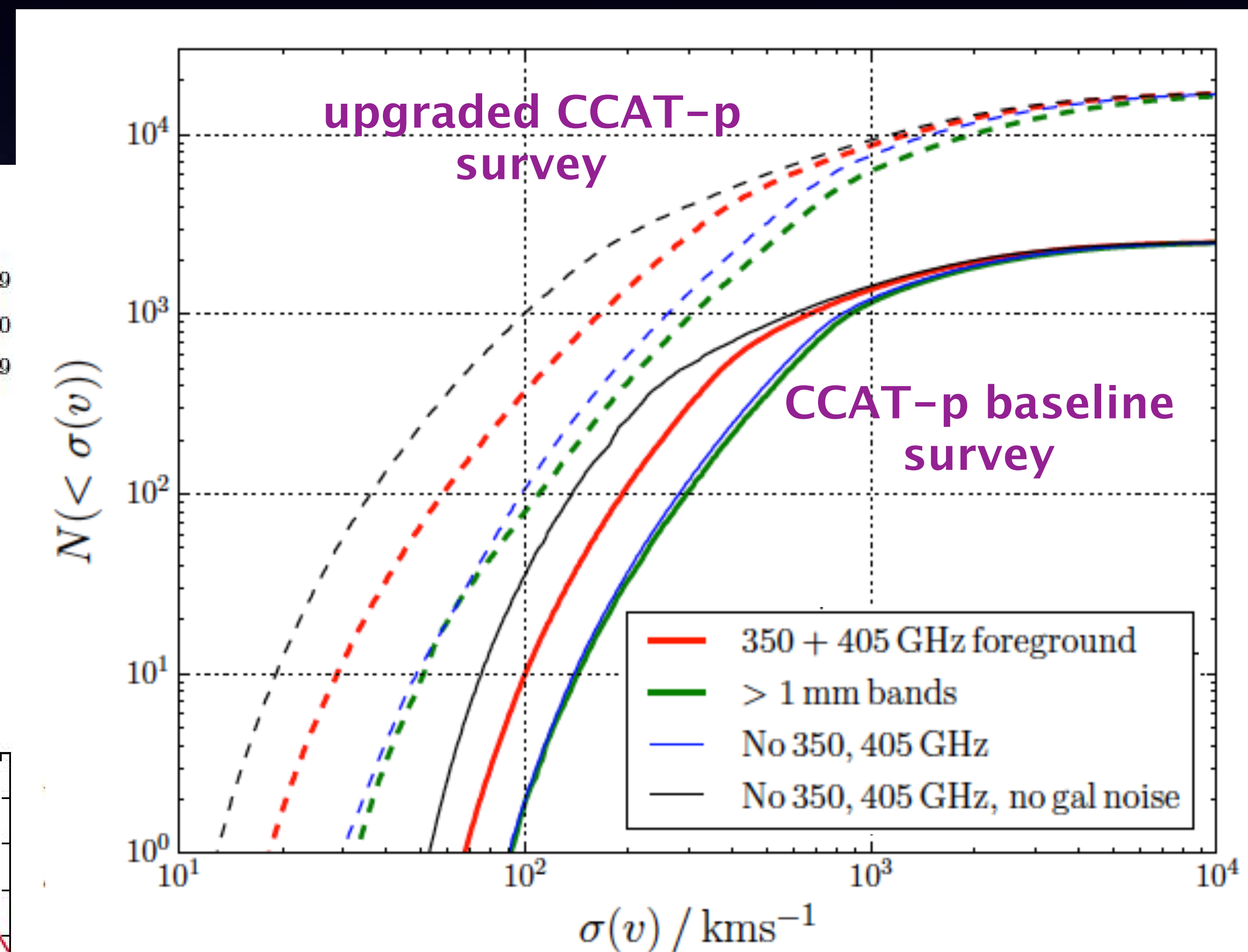
kSZ predictions

Mittal, de Bernardis & Niemack (arXiv:1708.06365)

CCAT-p baseline survey will provide kSZ measurements for up to 100-200 galaxy clusters

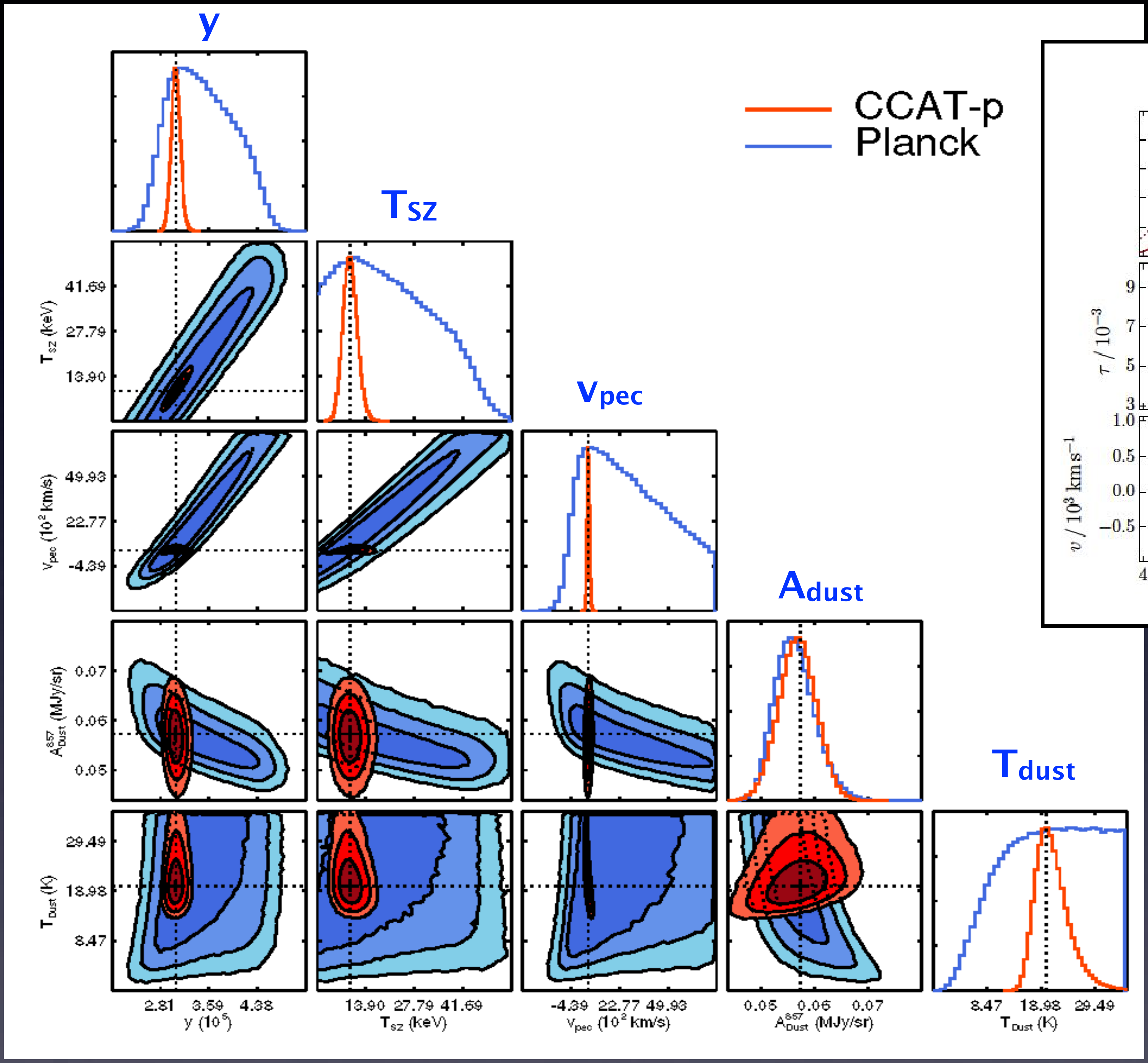
kSZ modeling results for a single high-mass cluster. One can employ eROSITA temperature priors for improved precision.

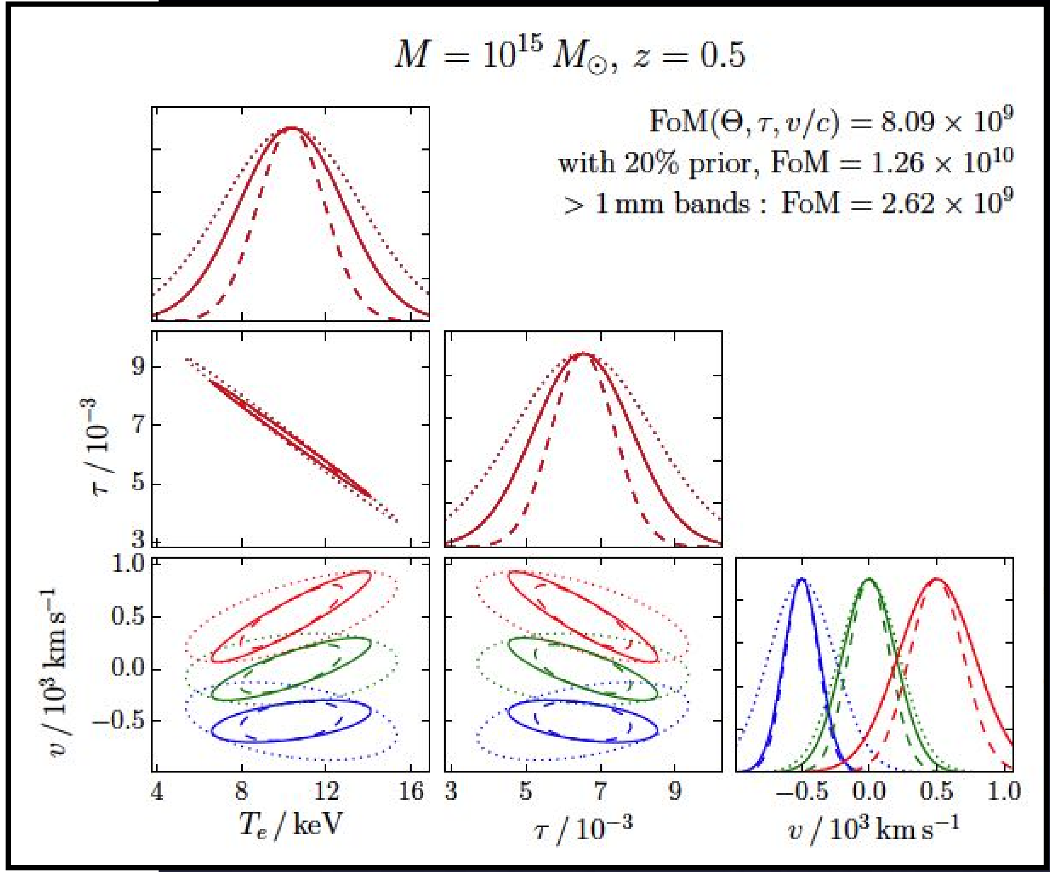




kSZ predictions

Result for a **single cluster with M_{500} = 8 x10^{14} M$_\odot$ at z=0.2** (foregrounds-free simulation)





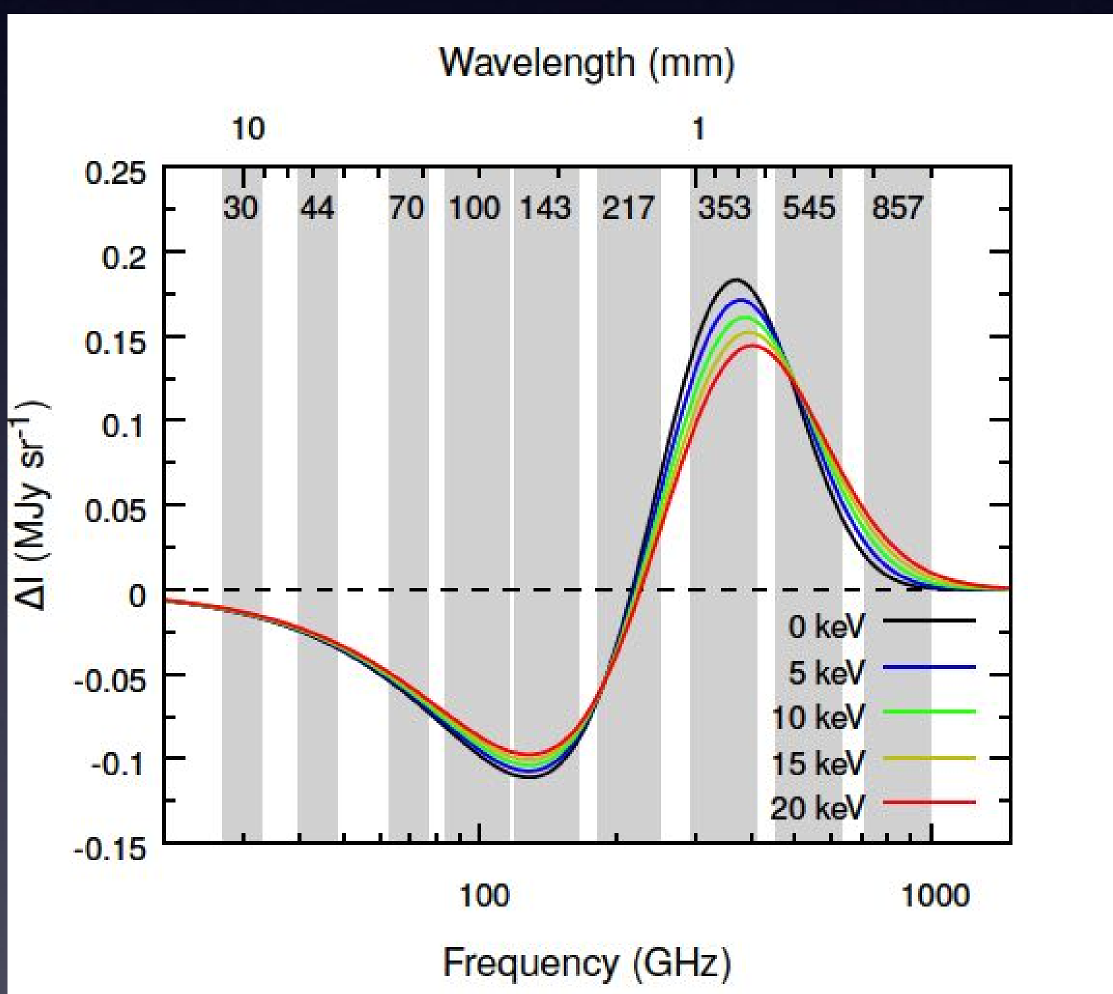
With 100s of individual kSZ measurements, new & exciting science possibilities will become doable (e.g. velocity correlation measurements without mean optical-depth assumptions)

rSZ (or relativistic tSZ) effect

With the rSZ signal the electron temperature of the intracluster medium can be measured directly.

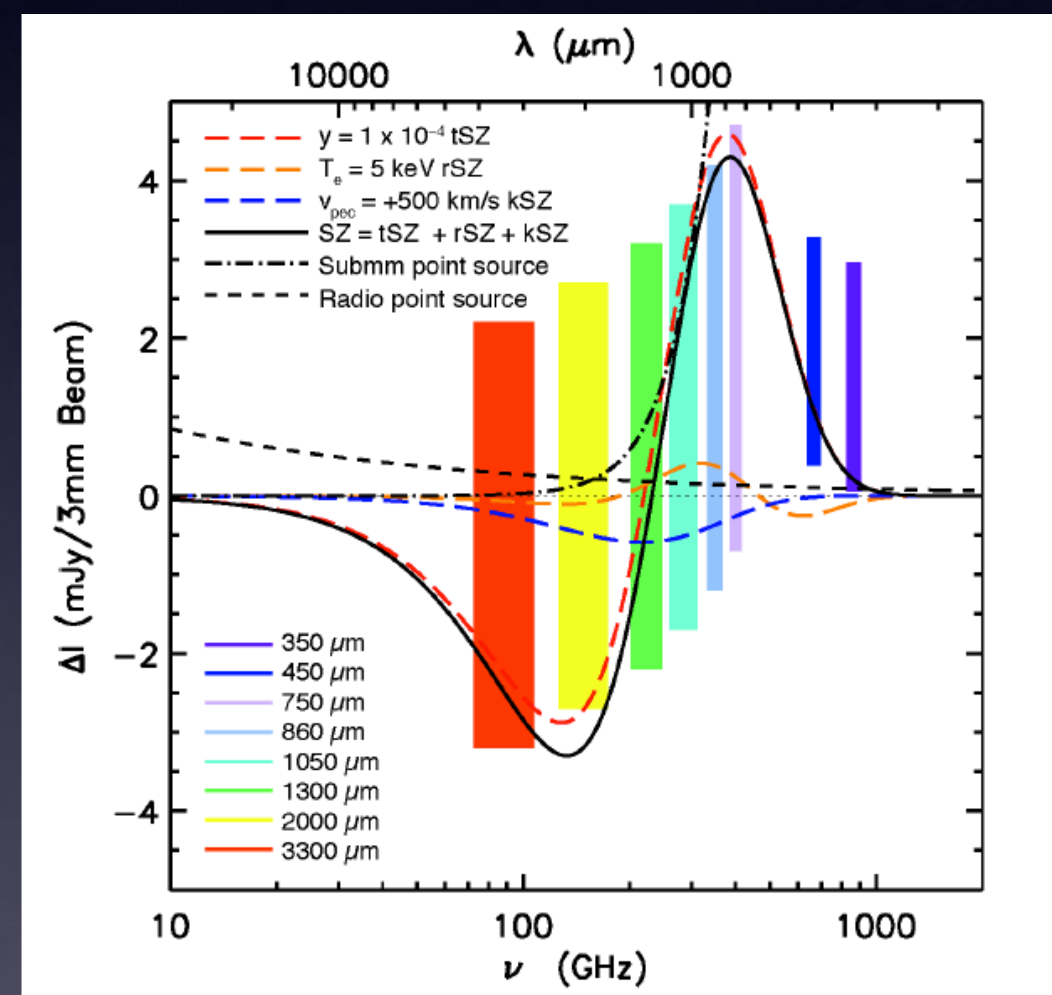
This breaks the degeneracy between the density and temperature estimates from standard photometric tSZ measurements and provide a more complete thermodynamic description of the ICM (like X-ray data)

SZ spectrum with Planck bands



Erler et al. (arXiv:1709.01187)

SZ spectrum with CCAT-p bands



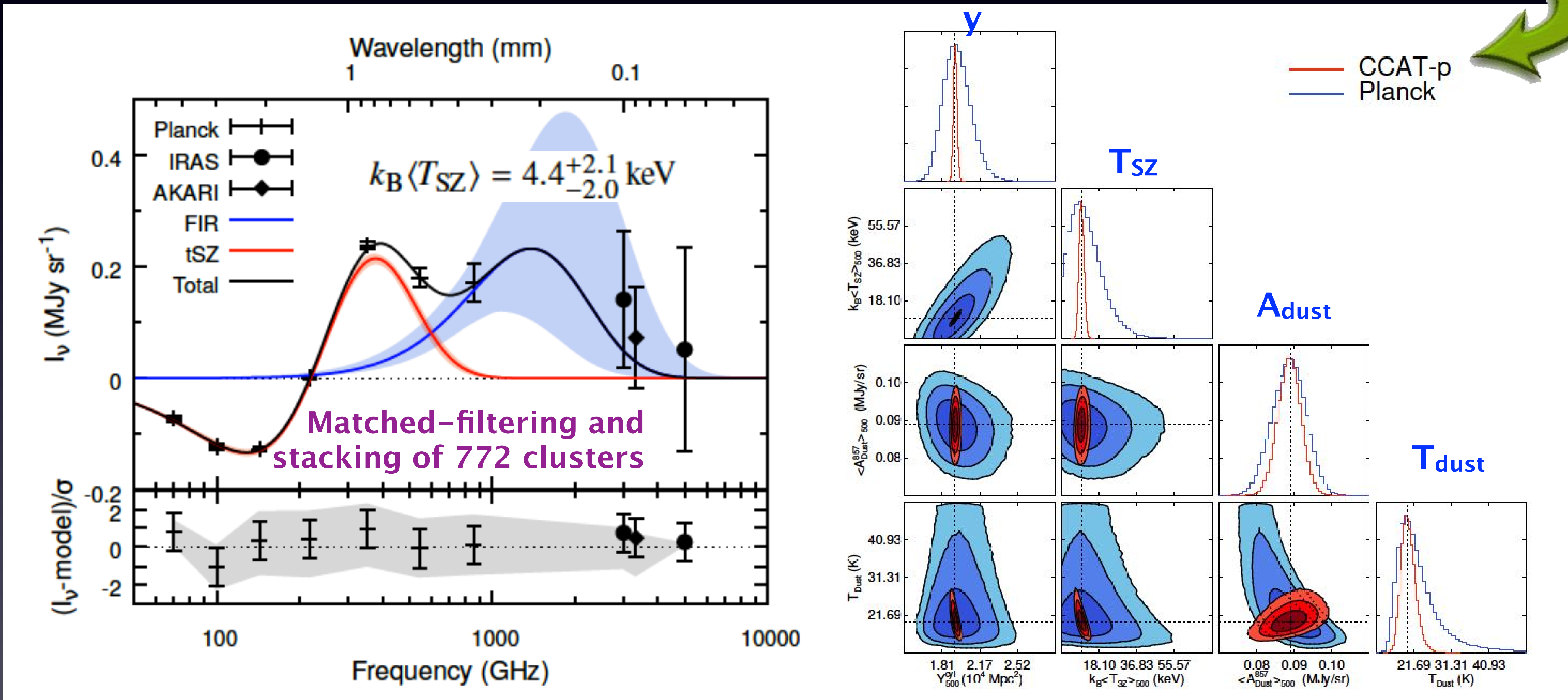
Source: CCAT-p SZ white paper

rSZ from *Planck* & CCAT-p

Erler, Basu, Chluba & Bertoldi **(arXiv:1709.01187)**

With current *Planck* data, roughly 2.3σ significance detection of cluster temperature is obtained after stacking 772 clusters.

*With CCAT-p the temperature of a **single massive cluster** can be measured at 5–10 σ.*



CCAT-p **SZ survey** outlook

- **CCAT-prime will be the first tSZ survey experiment to provide kSZ and rSZ measurements in large samples (>100) of clusters**

- The spectral coverage of of CCAT-p will be similar to Planck HFI, with roughly 5-15 times better sensitivity (apart from the 860 GHz channel where atmospheric emission is significant even in the best weather)

- The better sensitivity and angular resolution will be excellent for foreground characterization and removal (e.g. cluster CIB emission, Galactic dust polarization for B-mode studies, etc.)

- There will be a significant number of high S/N kSZ detections to enable cosmological modeling with direct kSZ number counts (rather than pairwise kSZ) or from kSZ angular correlation function

- The rSZ temperature measurements will provide independent mass calibration of clusters, a crucial ingredient for cosmology