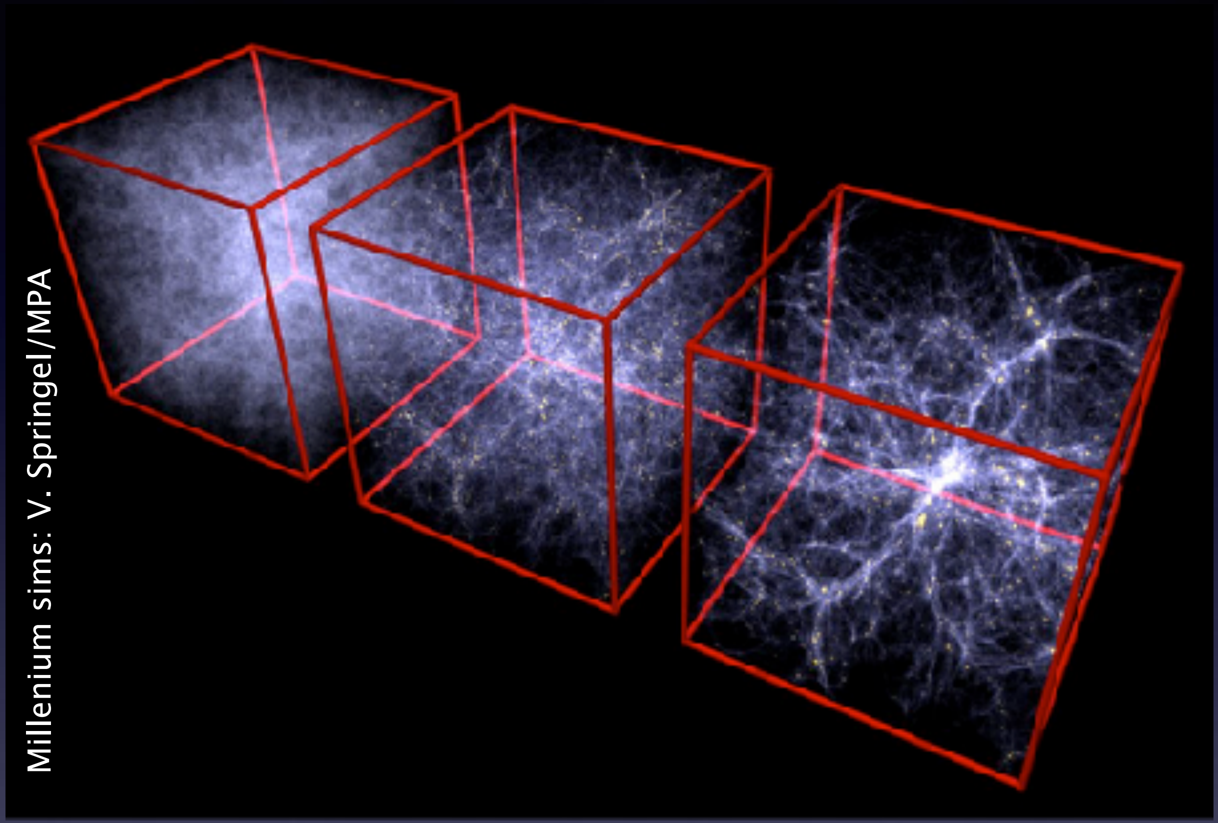
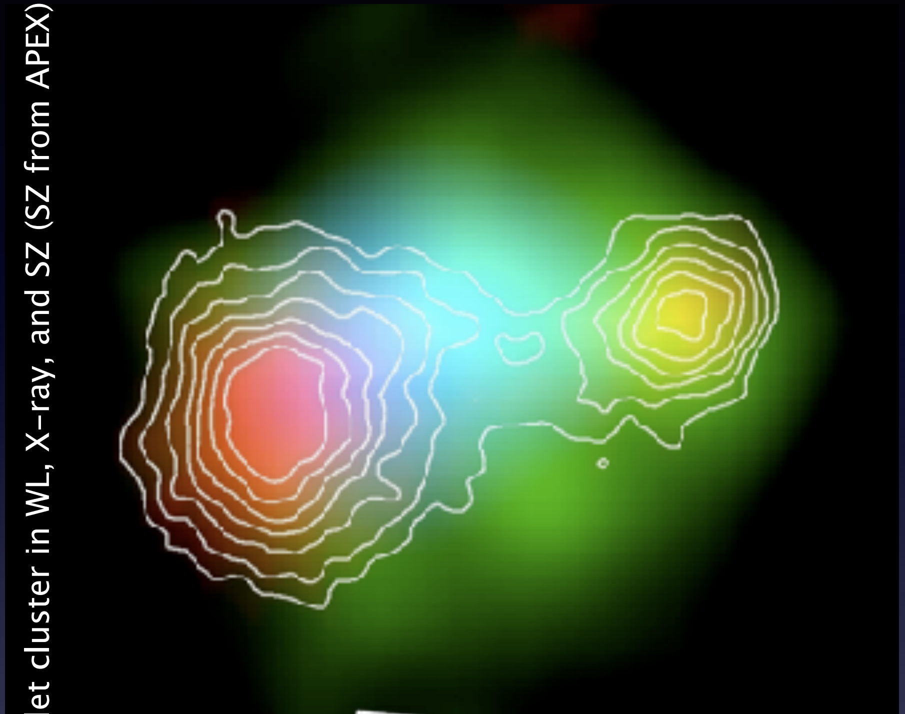
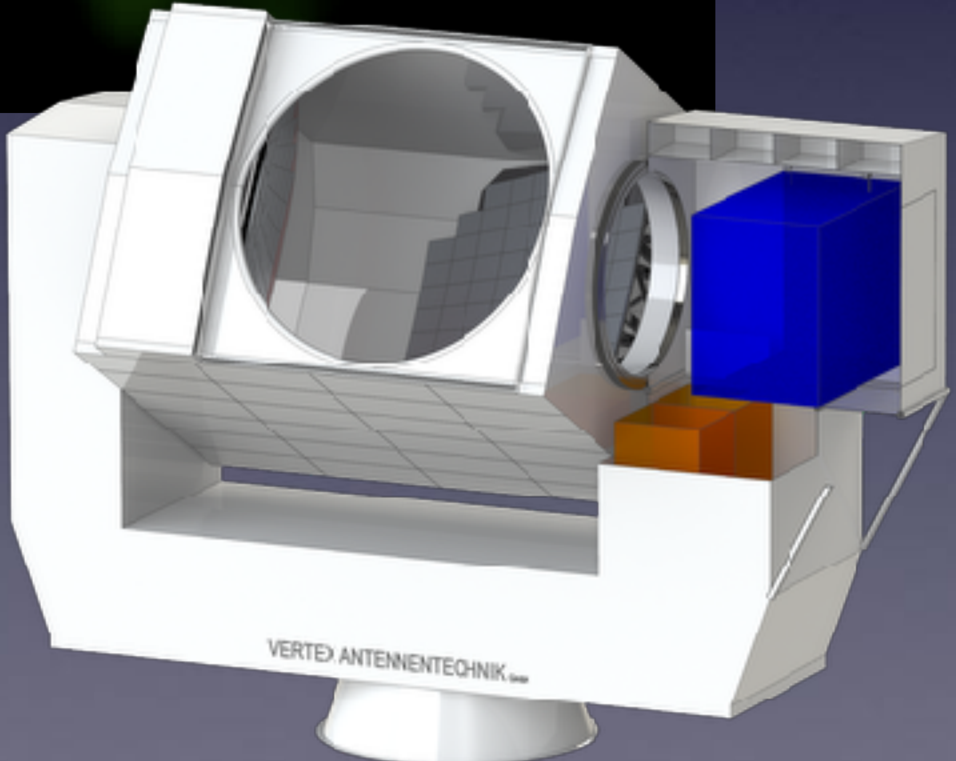
SZ science: from **APEX-SZ** to **CCAT-prime** and beyond



Millenium sims: V. Springel/MPA



Bullet cluster in WL, X-ray, and SZ (SZ from APEX)

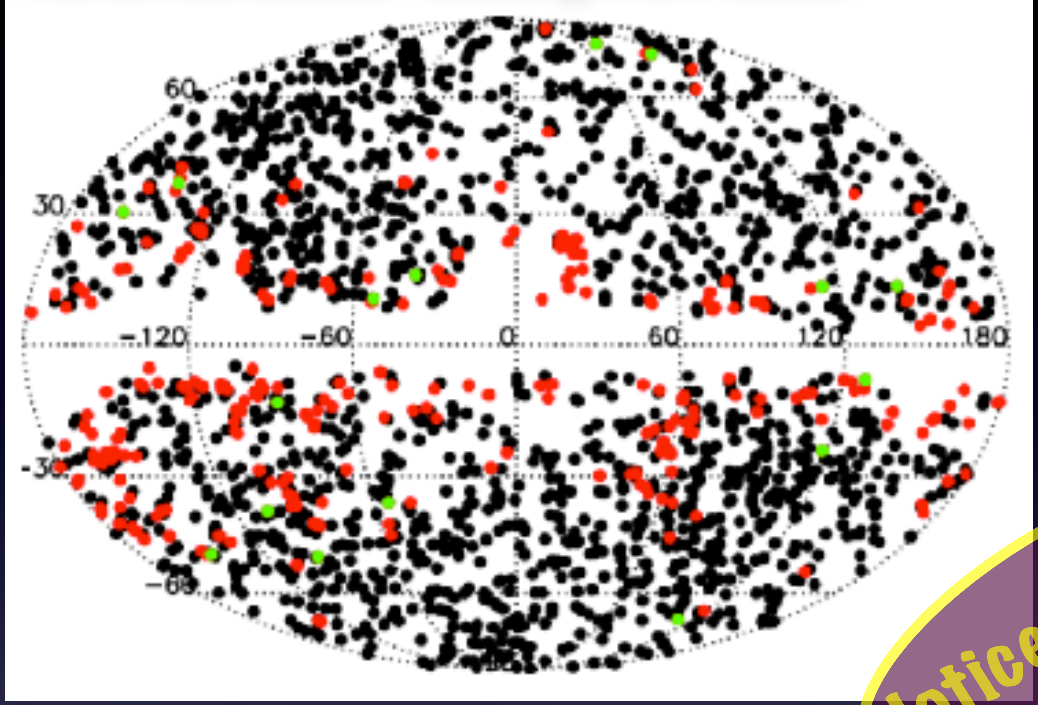


Kaustuv Basu (Universität Bonn)

With inputs from J. Erler, M. Ramos-Ceja, A. Mikler, and members of the APEX-SZ and CCAT-prime collaborations

Galaxy cluster cosmology

Planck SZ cluster catalog from 2015

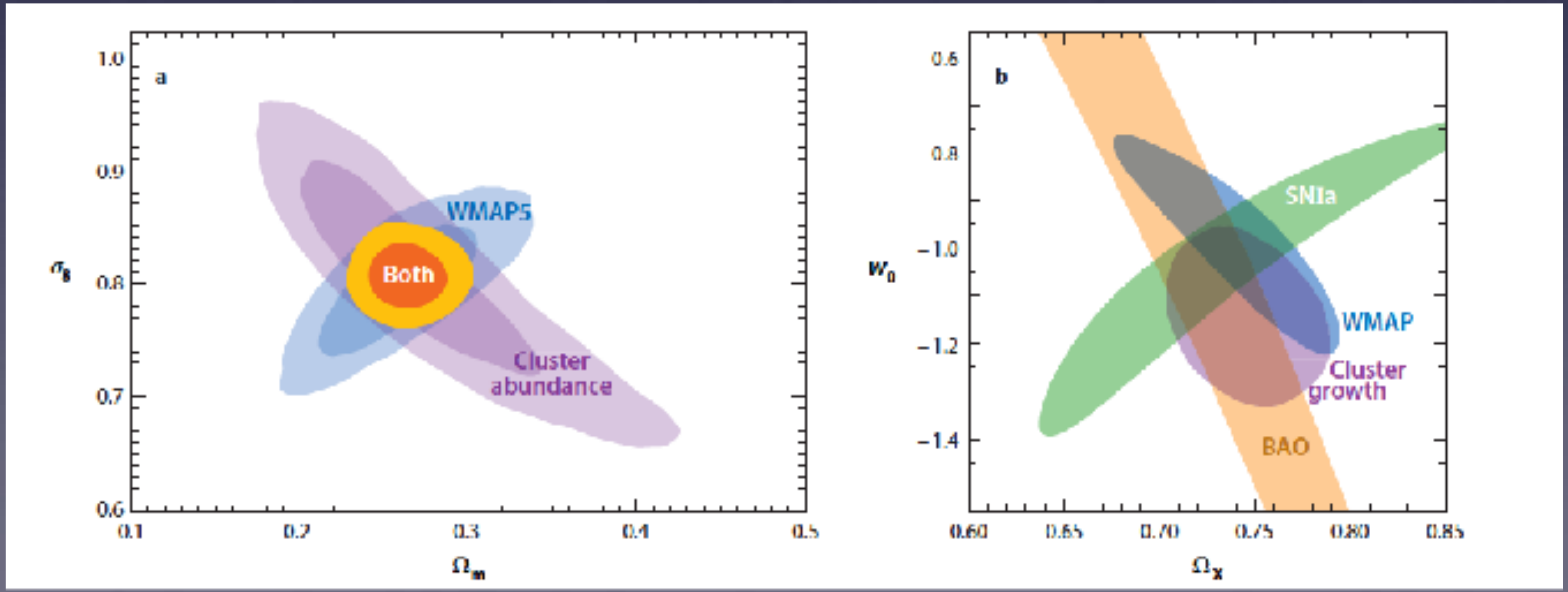


Notice SZ bias

Galaxy clusters provide precise knowledge of several cosmological parameters in many independent ways, for example:

- ☑ number counts and angular clustering
- ☑ velocity measurements (direct and pairwise)
- ☑ baryon fraction, D_A from XSZ, triaxiality, etc
- ☑ high-res CMB power spectrum/bispectrum

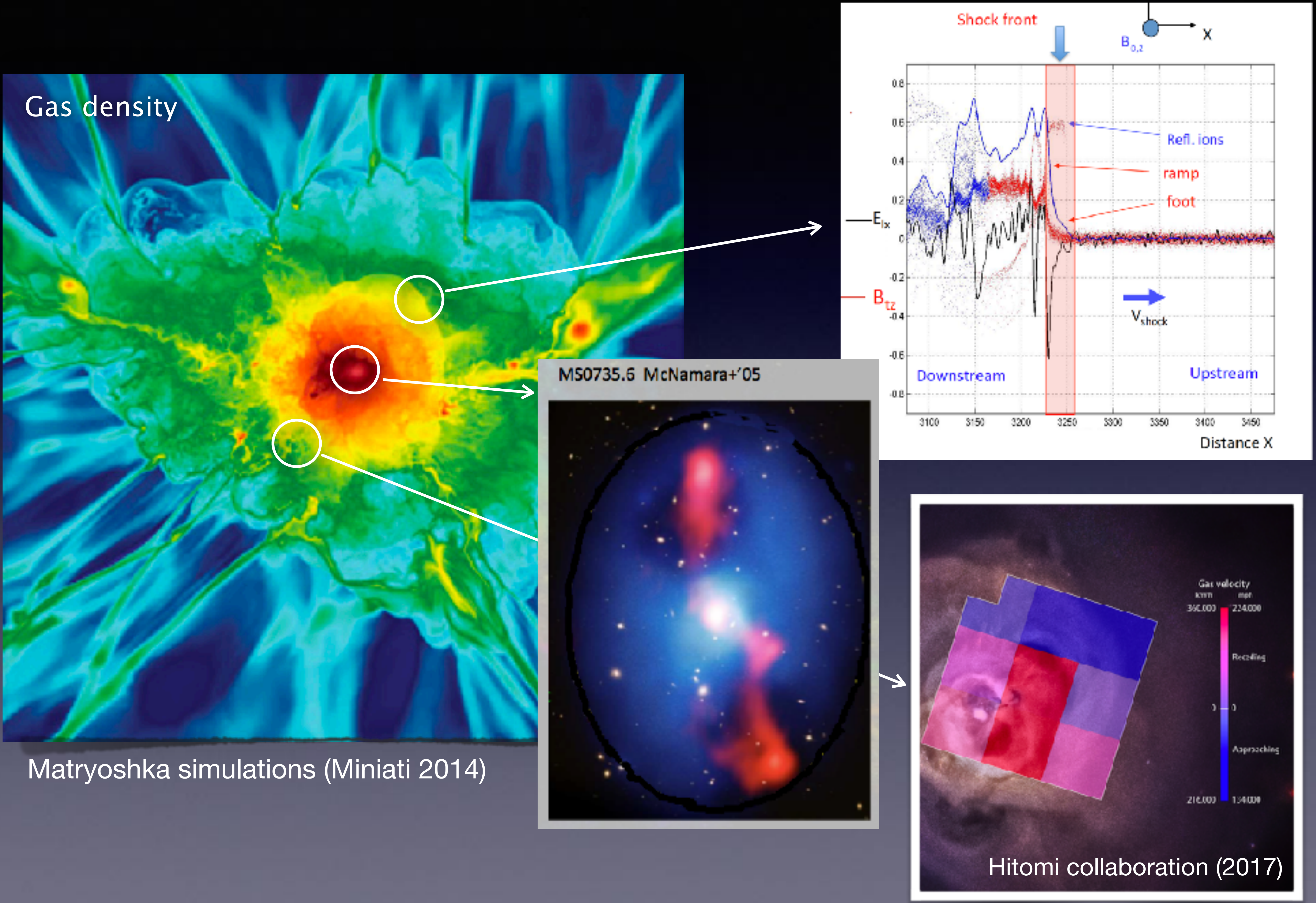
Review by Allen, Evrard & Mantz (2011)



Current constraints mainly come from cluster number counts, where the errors are dominated by **mass calibration uncertainties**

Huge potential for future improvements

Galaxy clusters for astrophysics



Marcowith et al. (2012)

Matryoshka simulations (Miniati 2014)

Hitomi collaboration (2017)

Our toolbox: 3 favours of the SZ effect

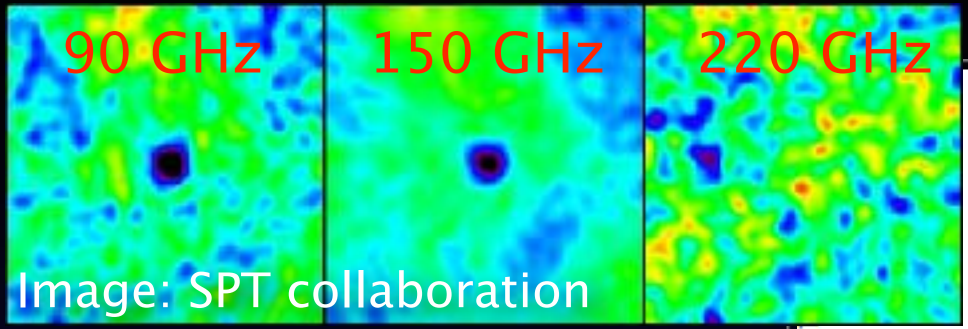
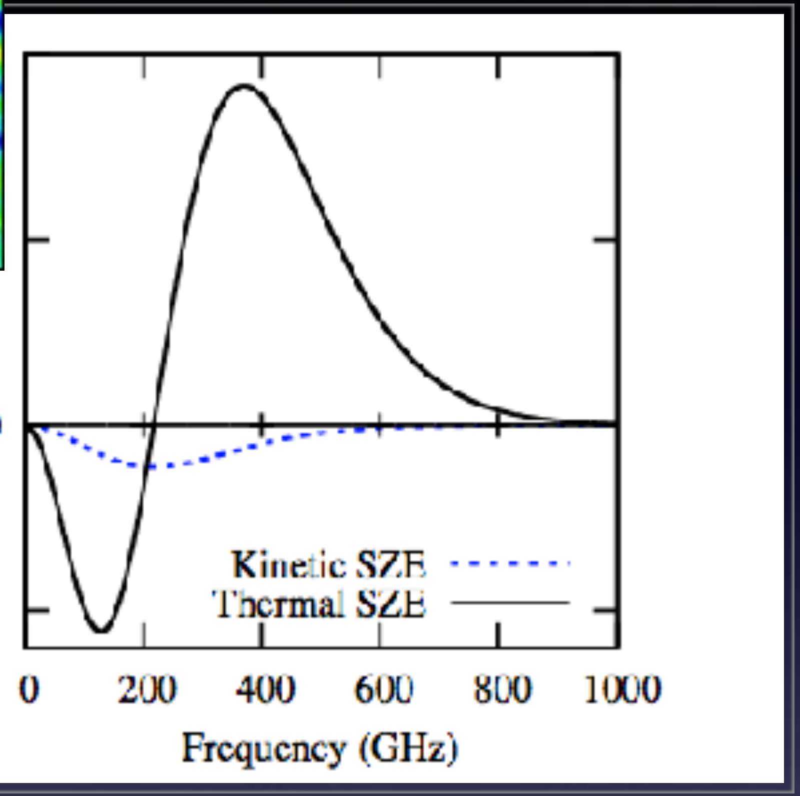


Image: SPT collaboration

tSZ effect for cluster detection and primary characterization



kSZ effect to measure the cluster peculiar motion (pairwise or individually)

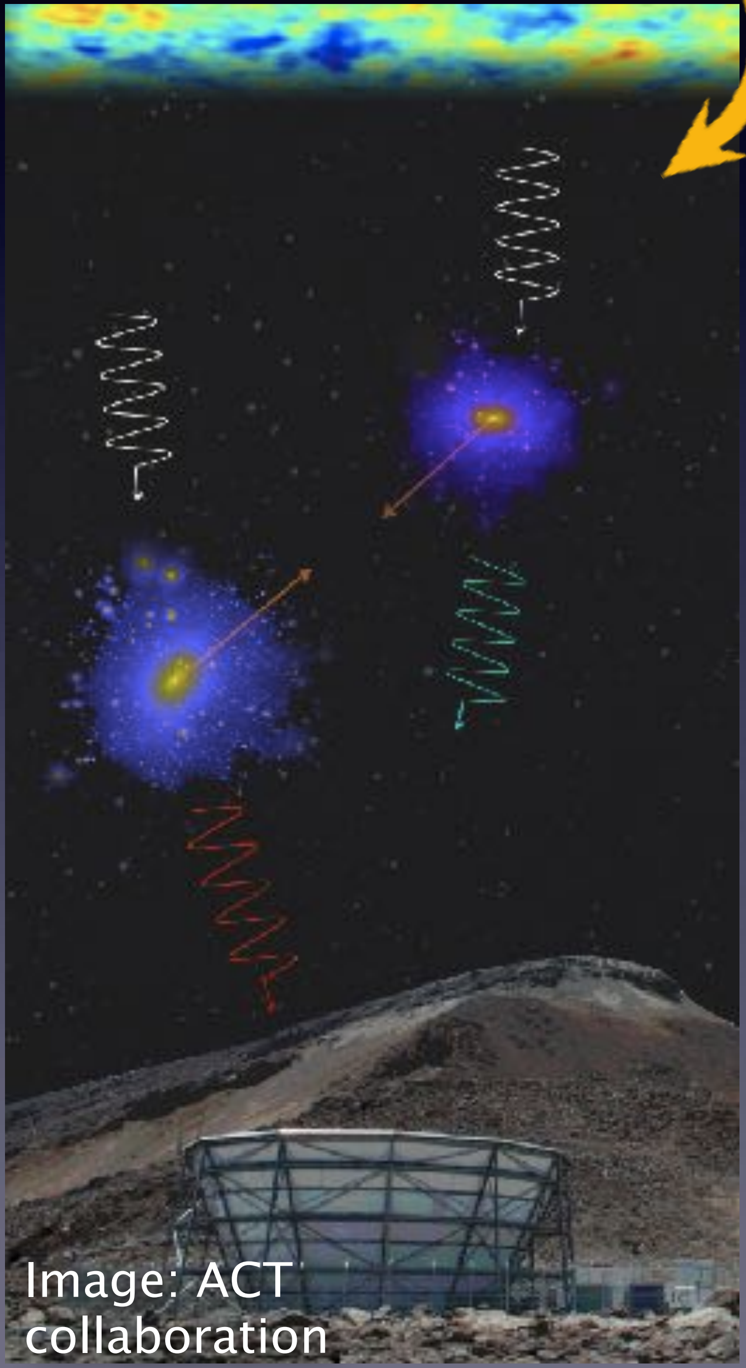
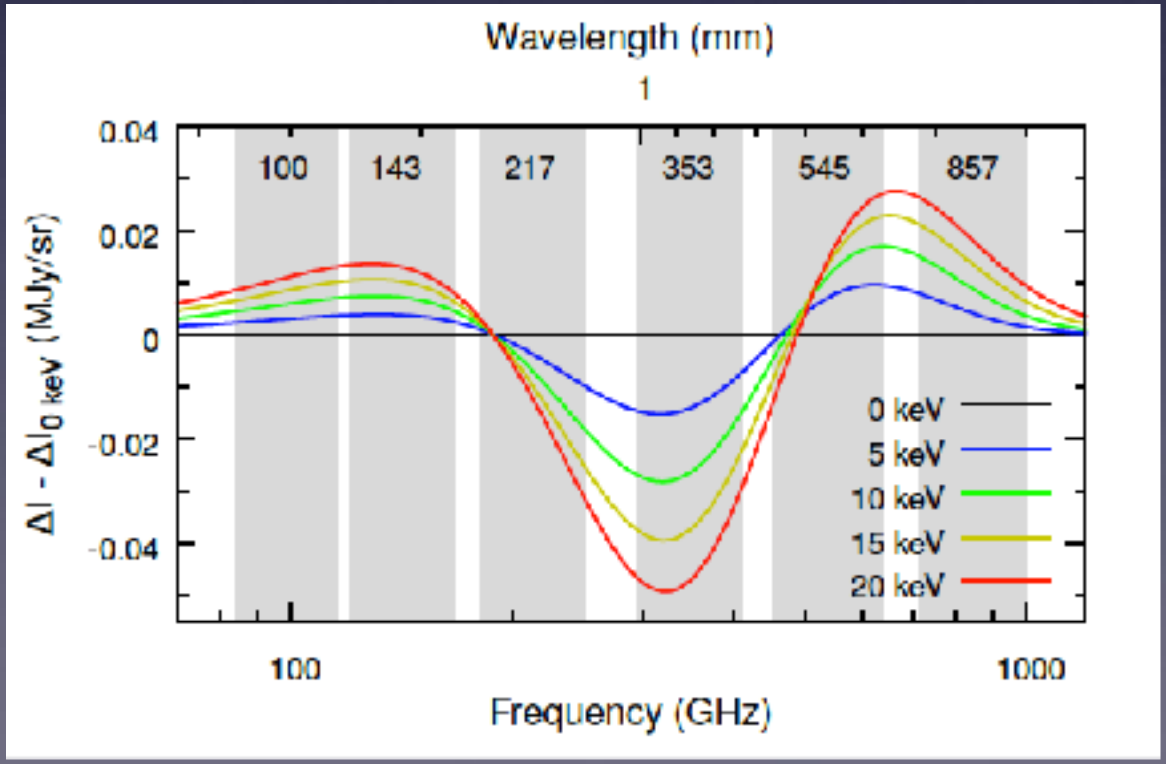


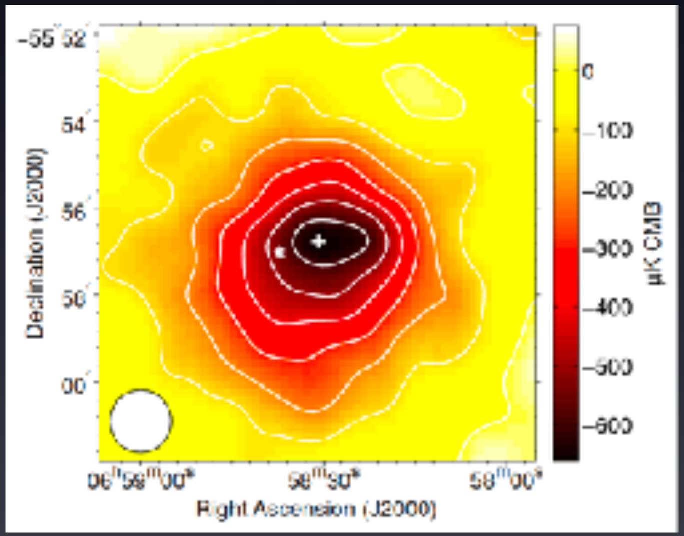
Image: ACT collaboration

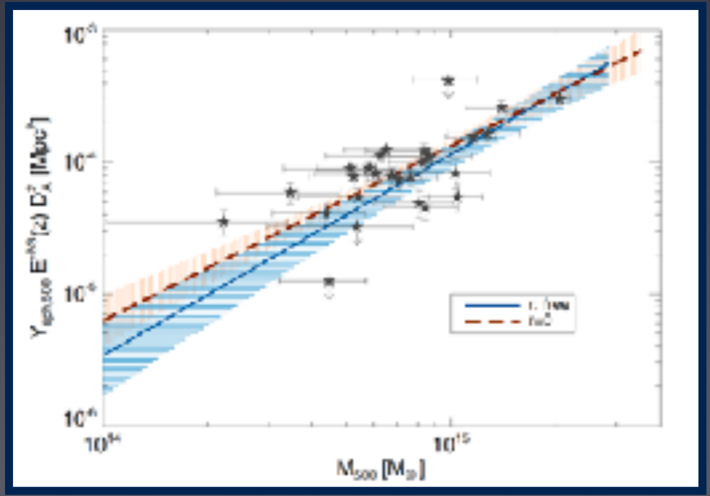
rSZ effect (or, the relativistic tSZ effect) to measure cluster temperatures



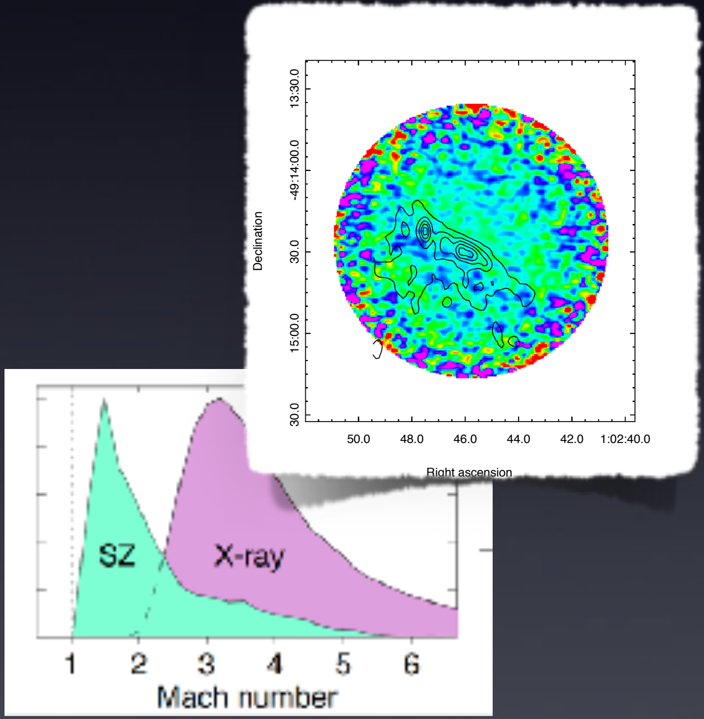
Outline: from APEX-SZ to CMB-S4

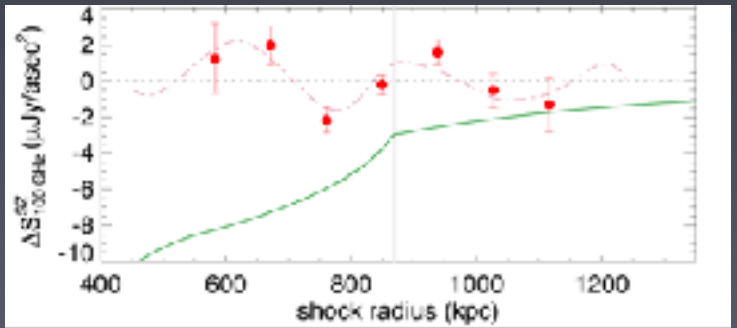
APEX-SZ: *past result highlights and what's new?*



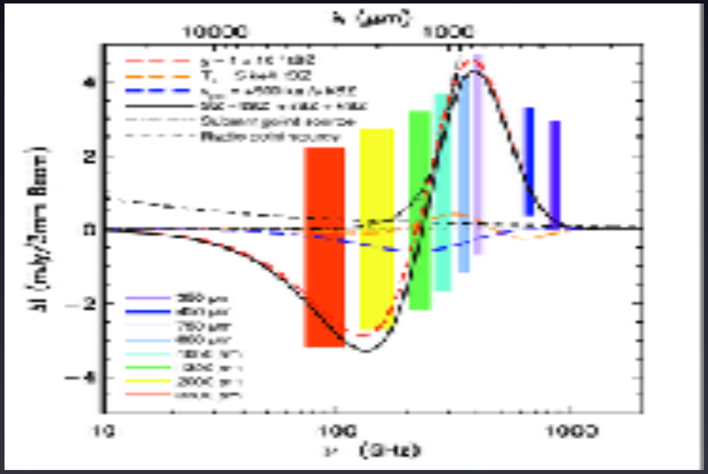


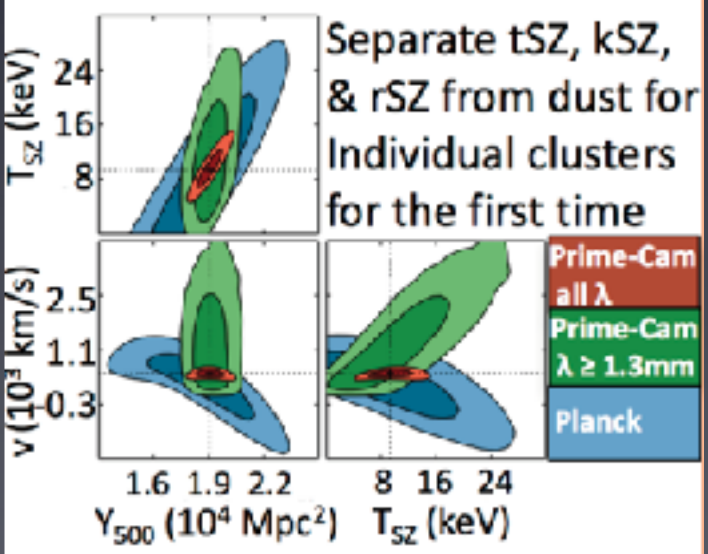
High-resolution SZ: *astrophysics from ALMA to AtLAST*





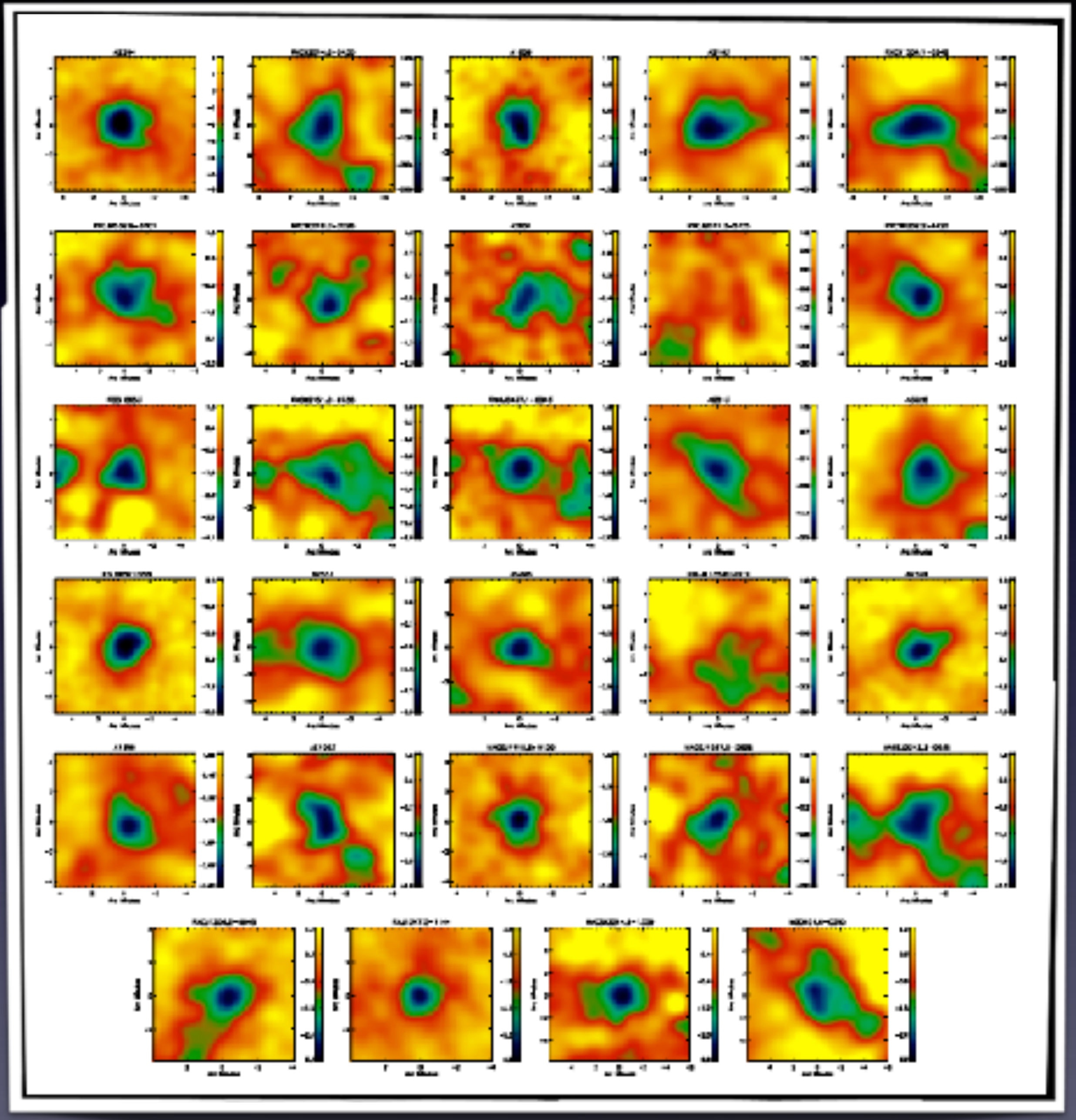
Our current focus: *CCAT-prime and its* ***unique*** *SZ science*

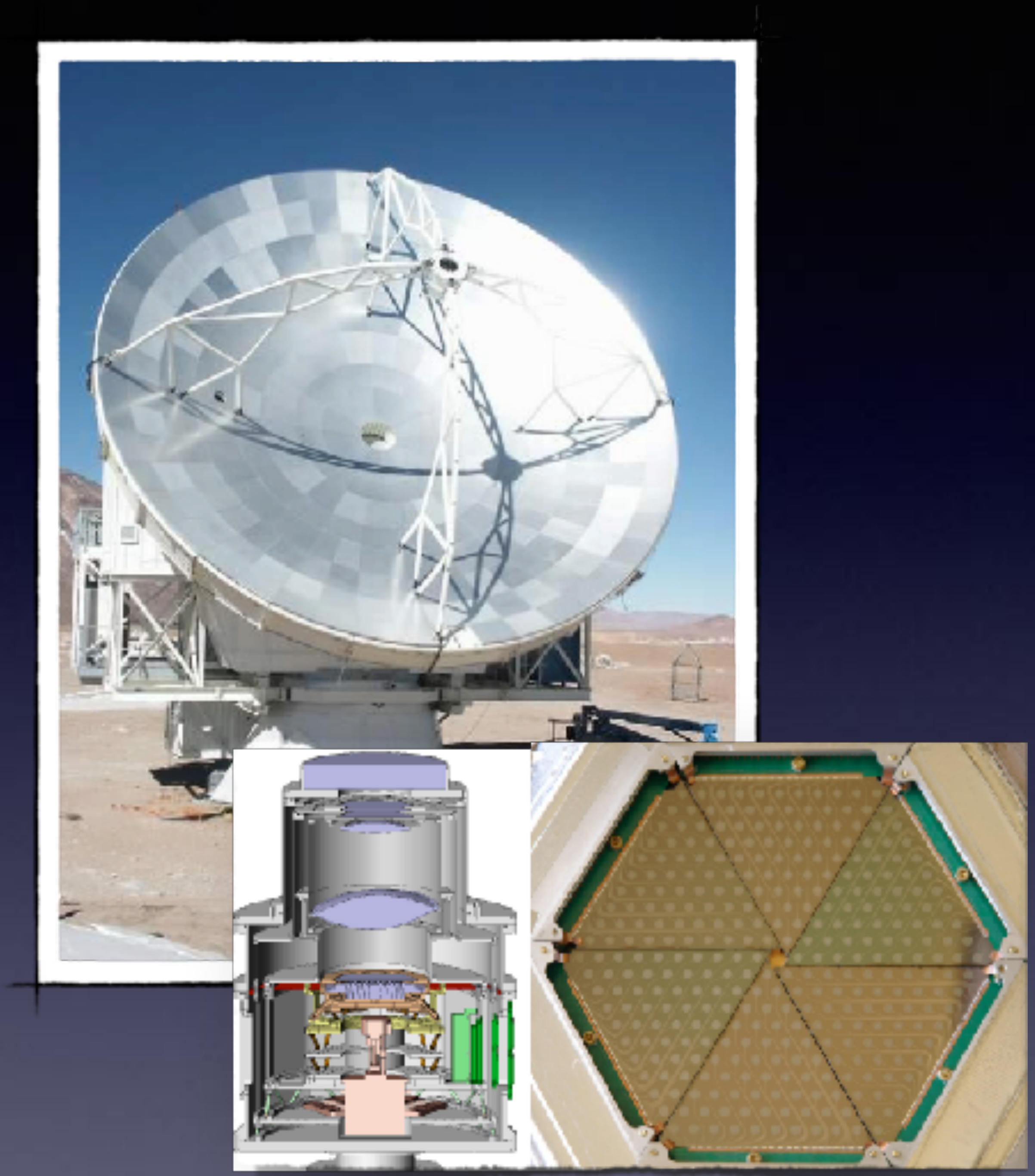



Separate tSZ, kSZ, & rSZ from dust for Individual clusters for the first time

The APEX-SZ camera and its results

Targeted observation of 40+ clusters and some ~1 deg^2 fields





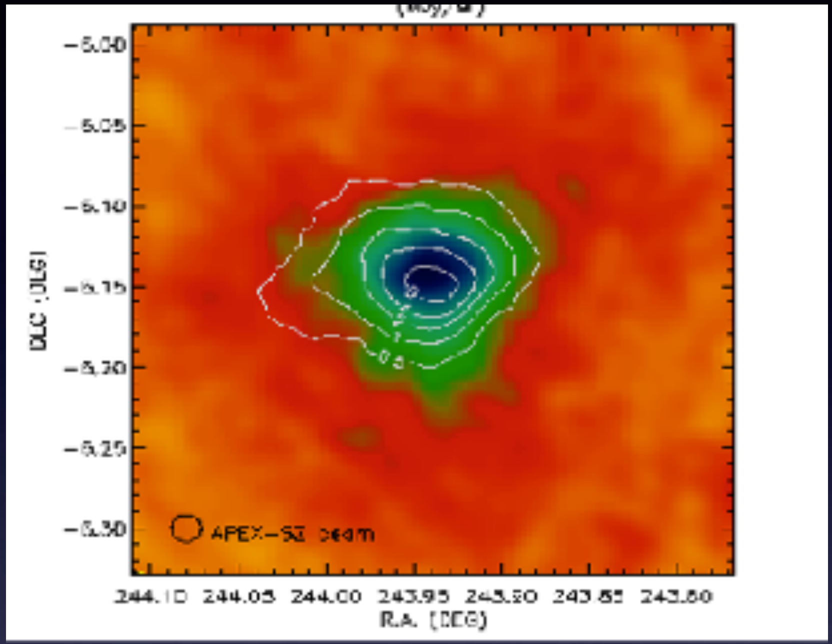
~200 element TES array with roughly 0.5° FoV **(operational between 2007-2010)**

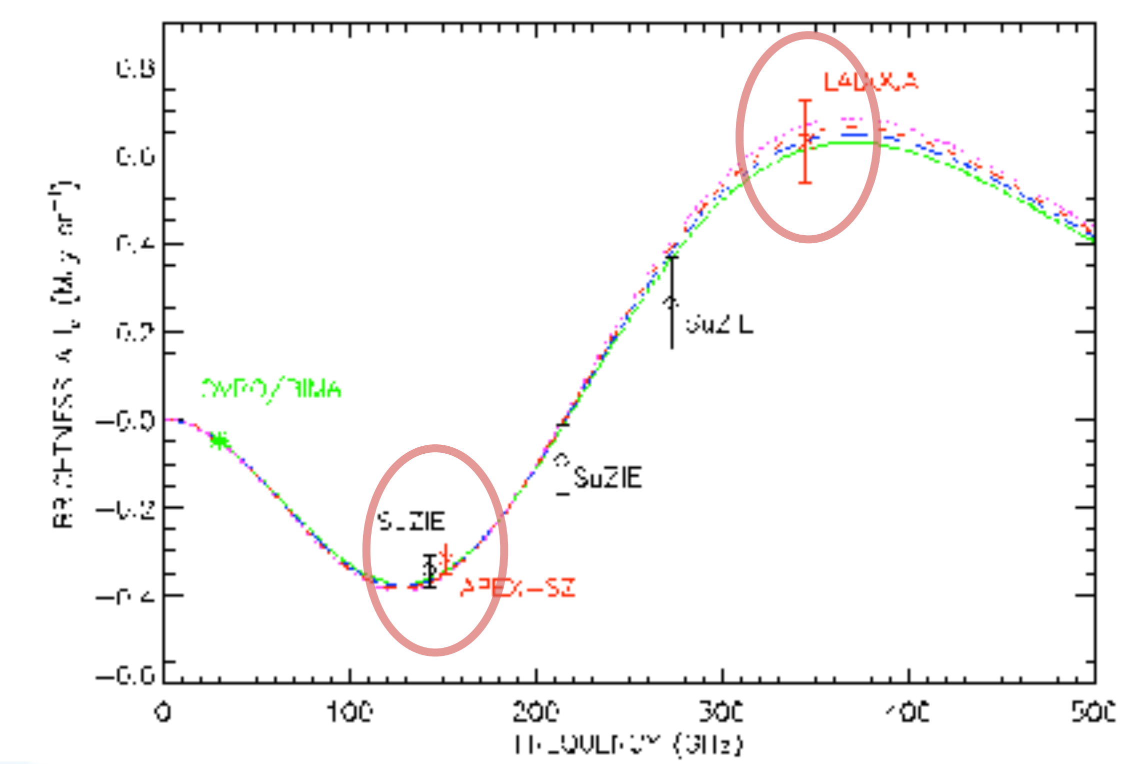
See: Halverson et al. (2009), Nord et al. (2009), Reichardt et al. (2009), Basu et al. (2010), **Bender et al. (2016)**

Multi-frequency SZ imaging from APEX

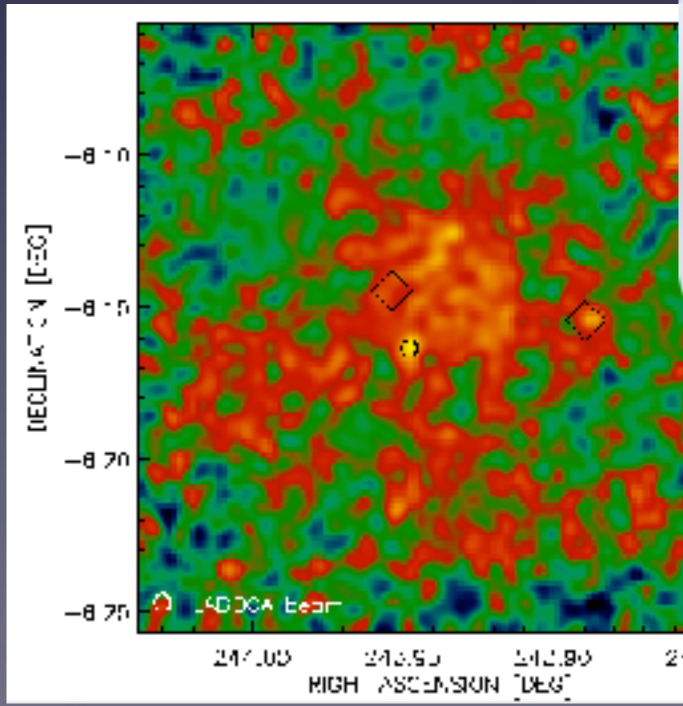
Measurements on Abell 2163 (**Nord**, Basu, et al. 2009)

APEX-SZ (150 GHz)

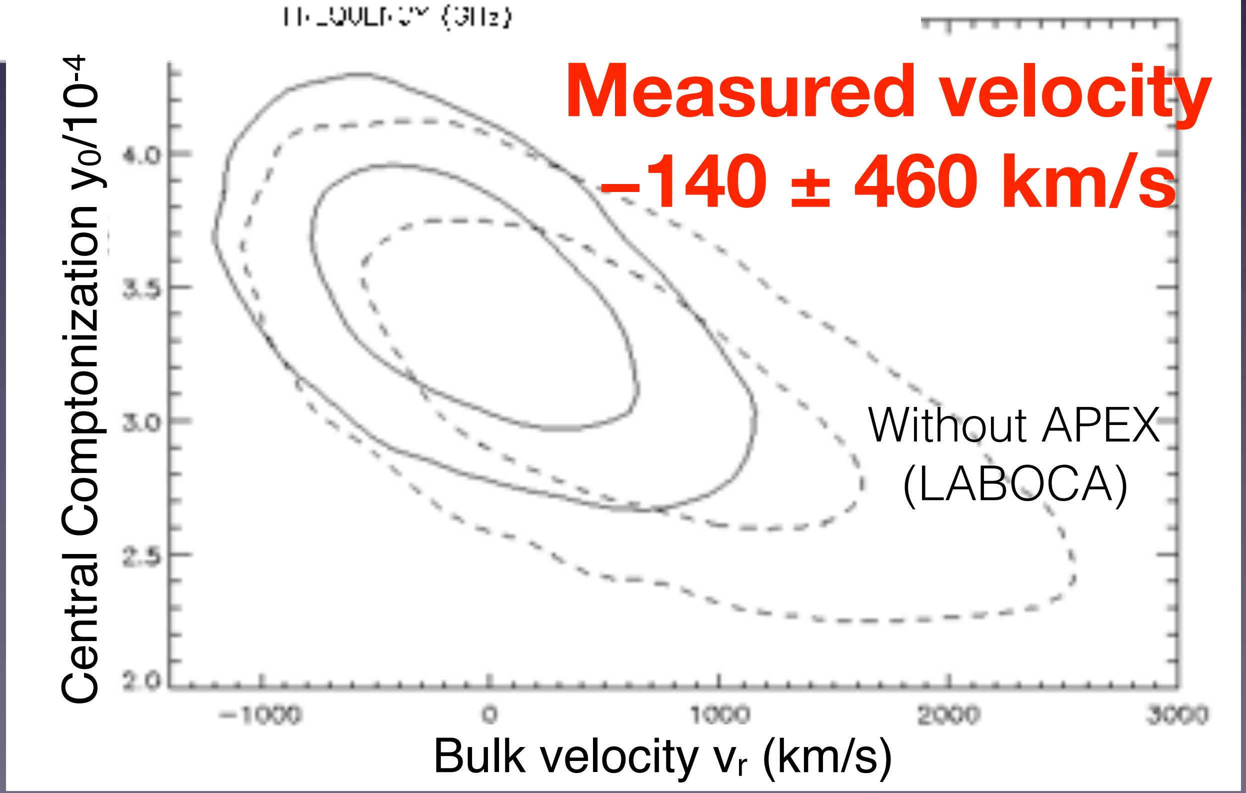




LABOCA (350 GHz)



The only SZ imaging done by LABOCA



Measured velocity –140 ± 460 km/s

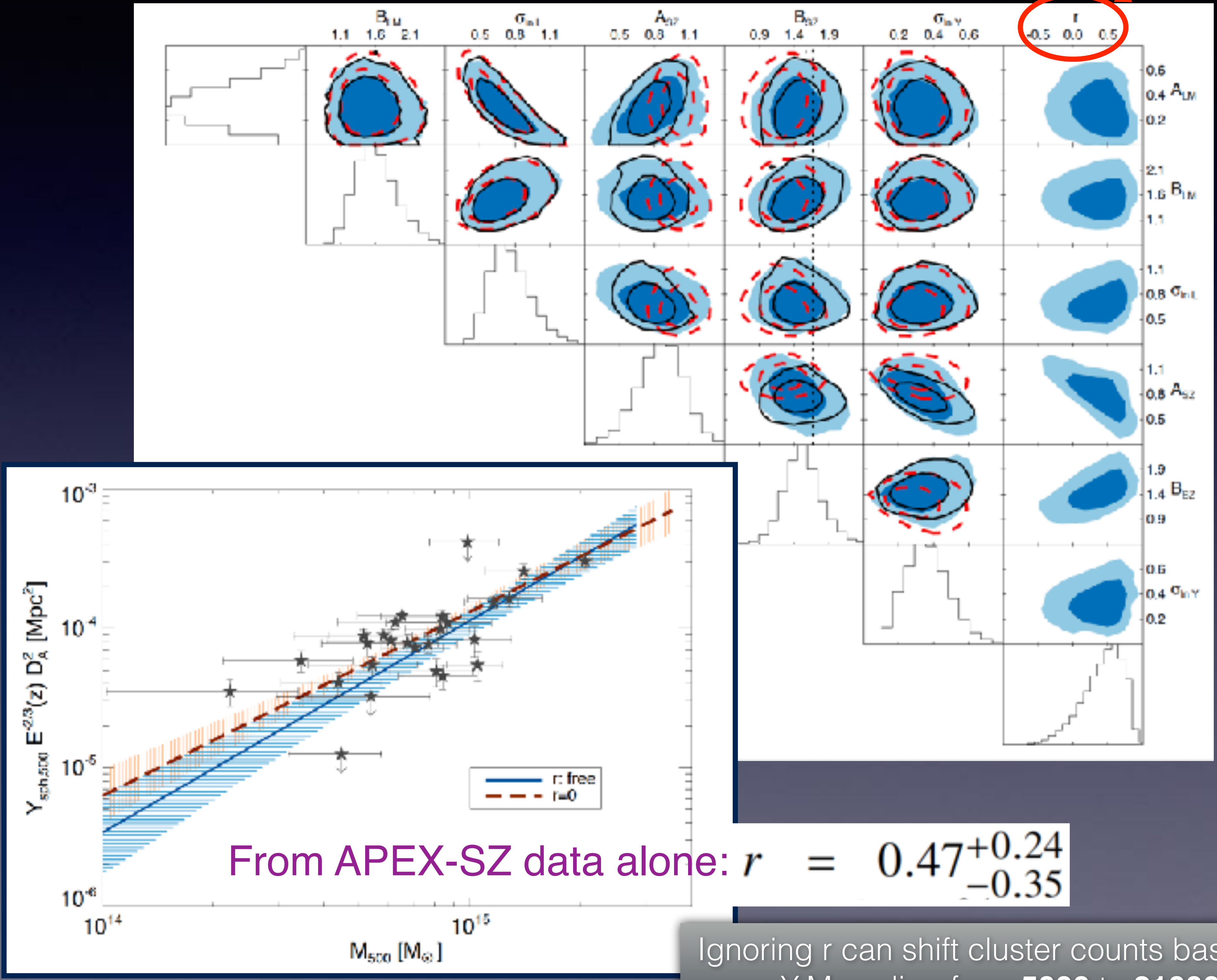
Without APEX (LABOCA)

APEX-SZ new: *Y-M* scaling relations

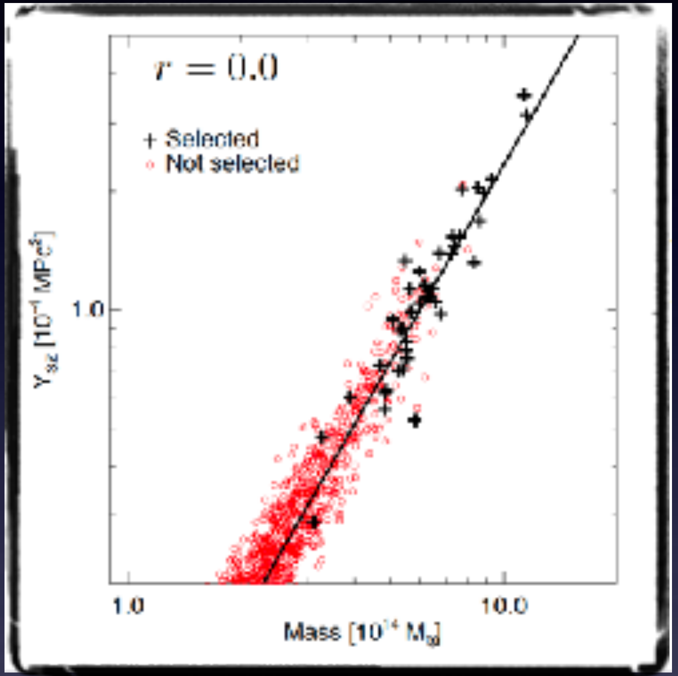
- A *complete* (30 clusters) sample from ROSAT
- WL masses from WFI data (Klein et al. in prep.)

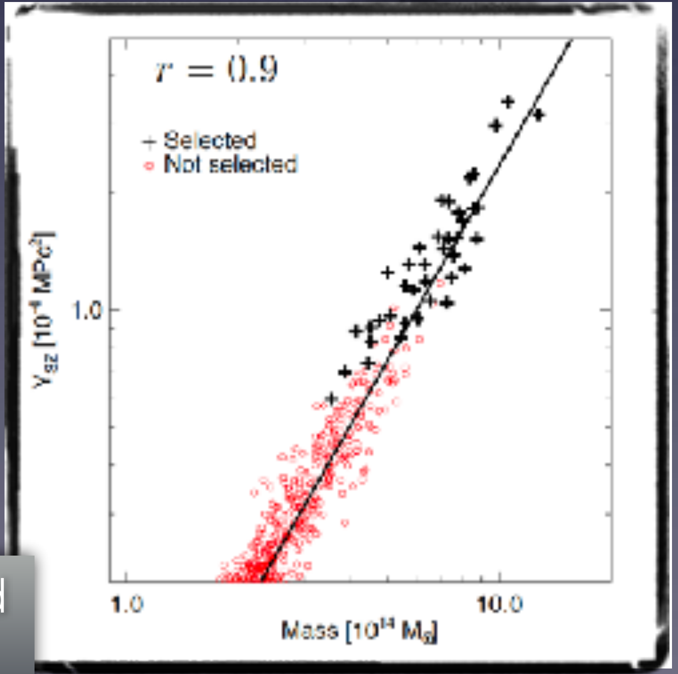
(Positive) correlation in the intrinsic scatter of L_X and Y_{SZ}

A. Nagarajan,.. KB.. et al.
(submitted, in arXiv soon!)



From APEX-SZ data alone: $r = 0.47^{+0.24}_{-0.35}$



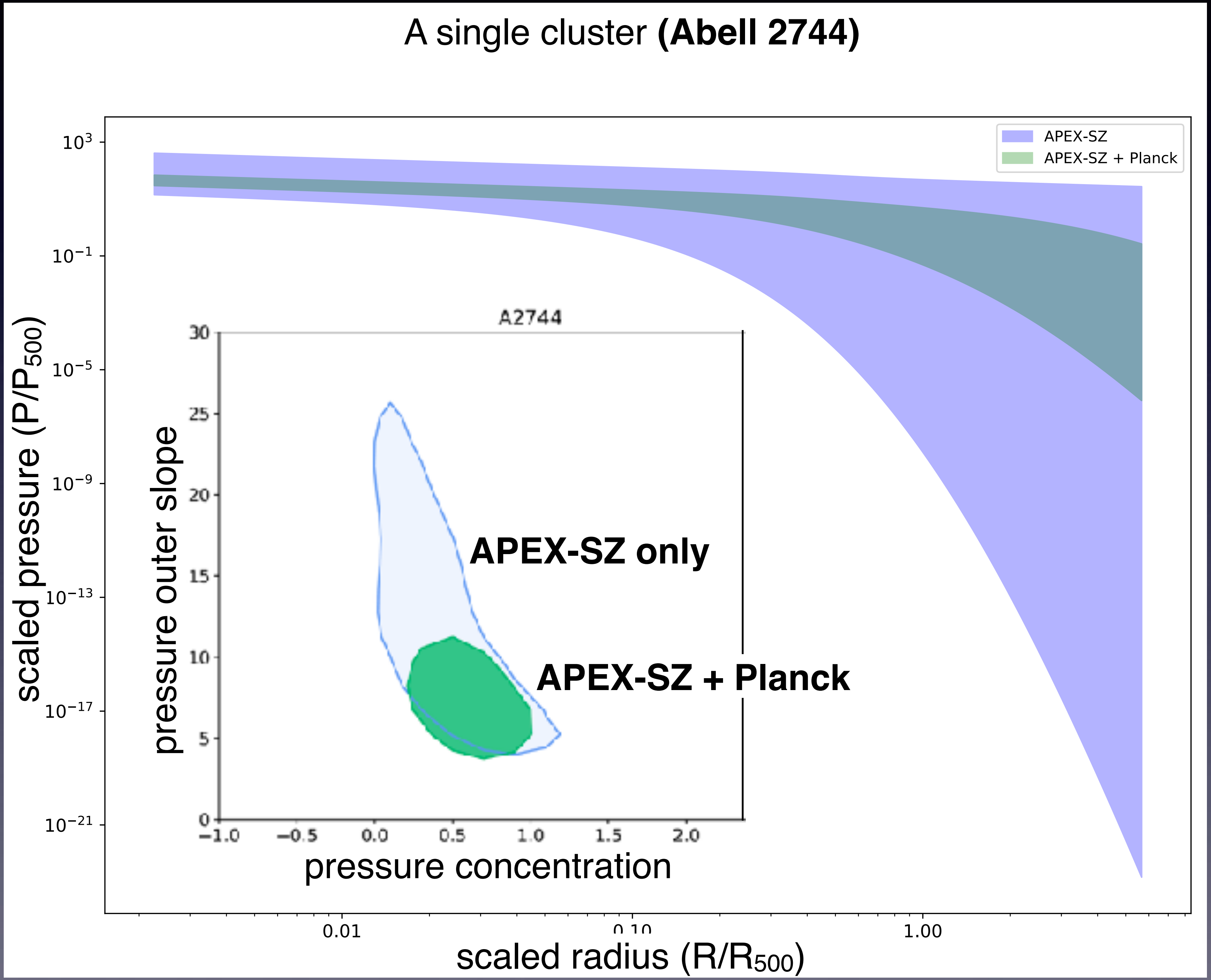


Ignoring r can shift cluster counts based on Y-M scaling from **5000** to **21000**

APEX-SZ new: *Pressure profiles*

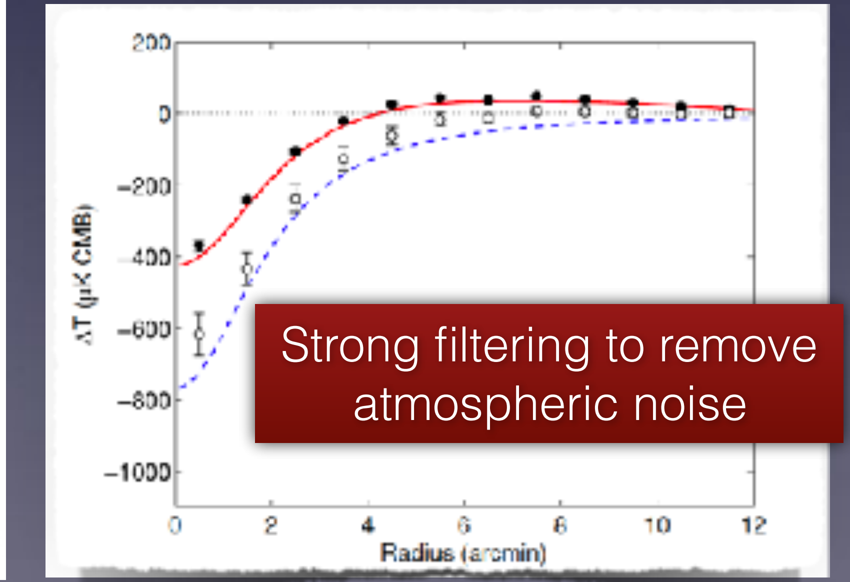
A. Mikler et al. (in preparation)

Constraining the shape of the outer pressure profile



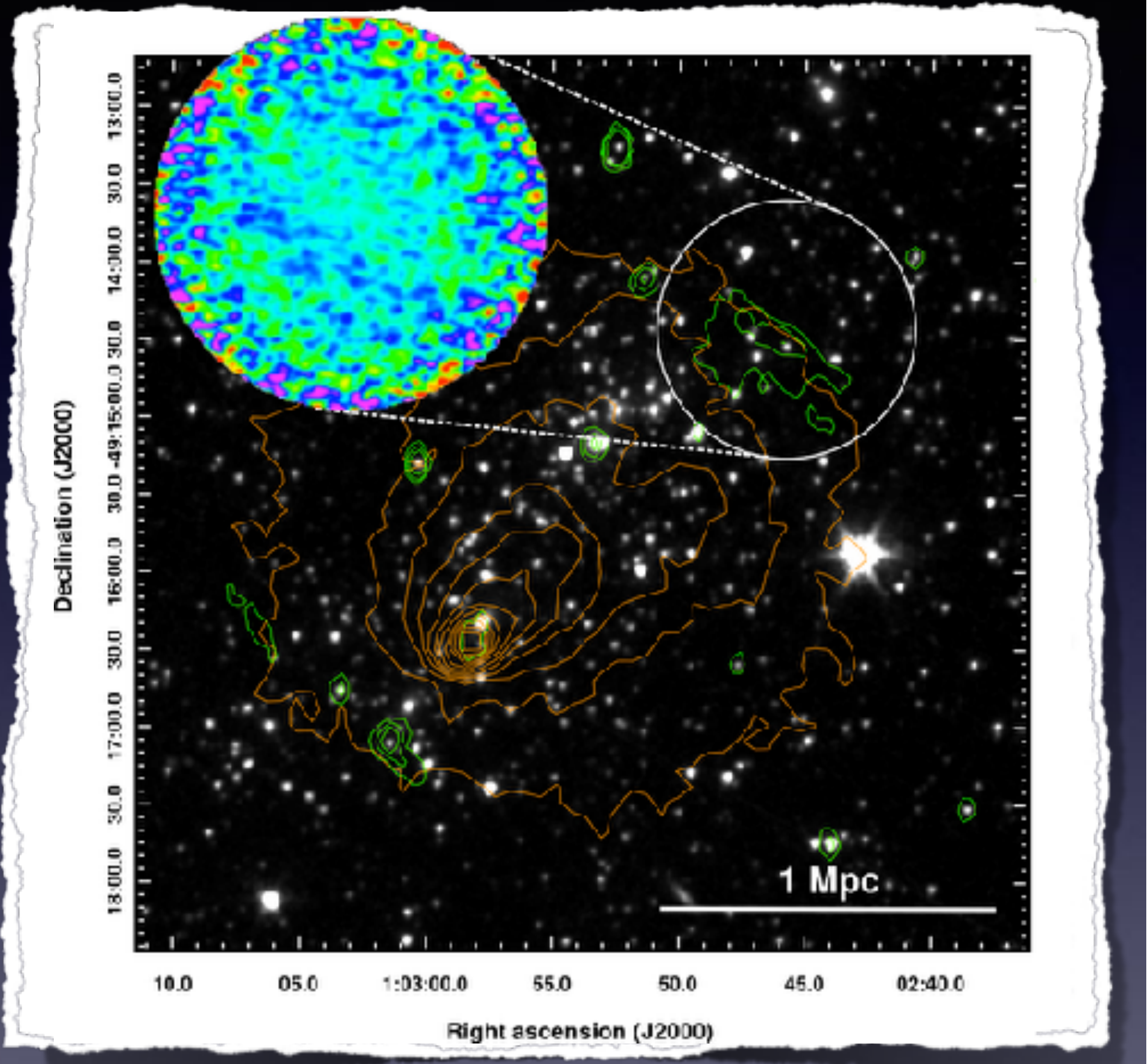
A single cluster **(Abell 2744)**

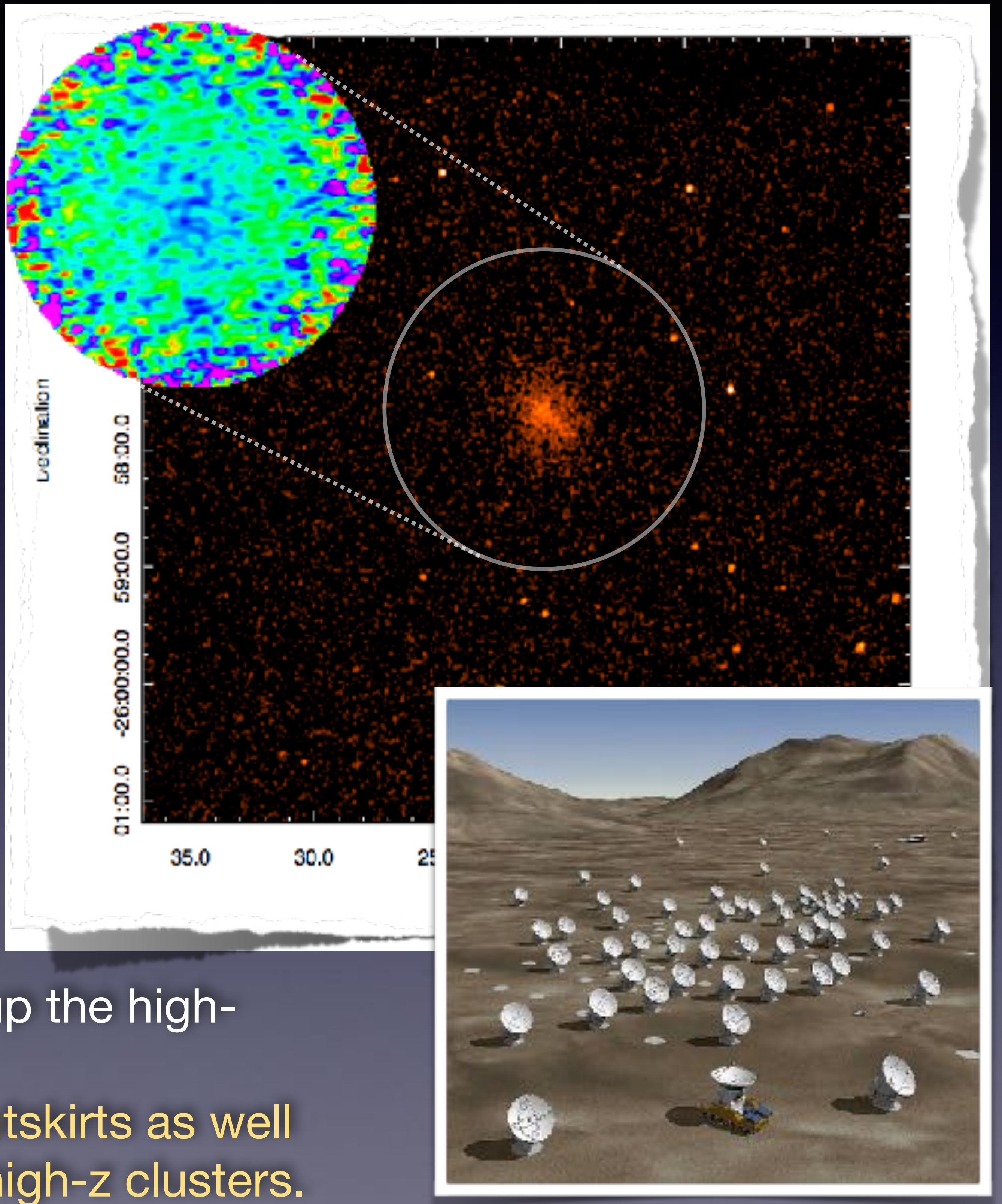
Applying *Planck* priors on APEX-SZ



Strong filtering to remove atmospheric noise

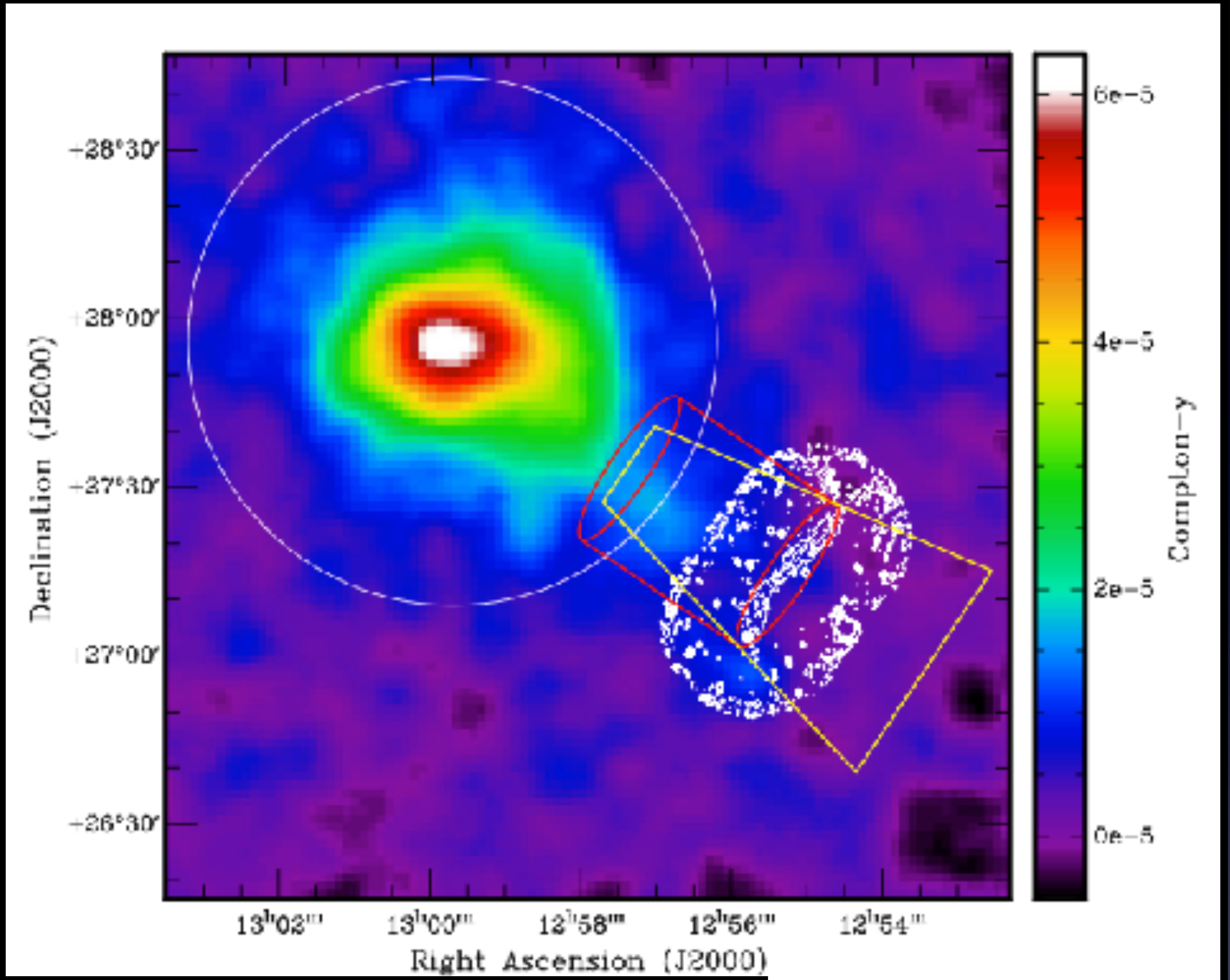
High-resolution SZ: shocks & cool-cores





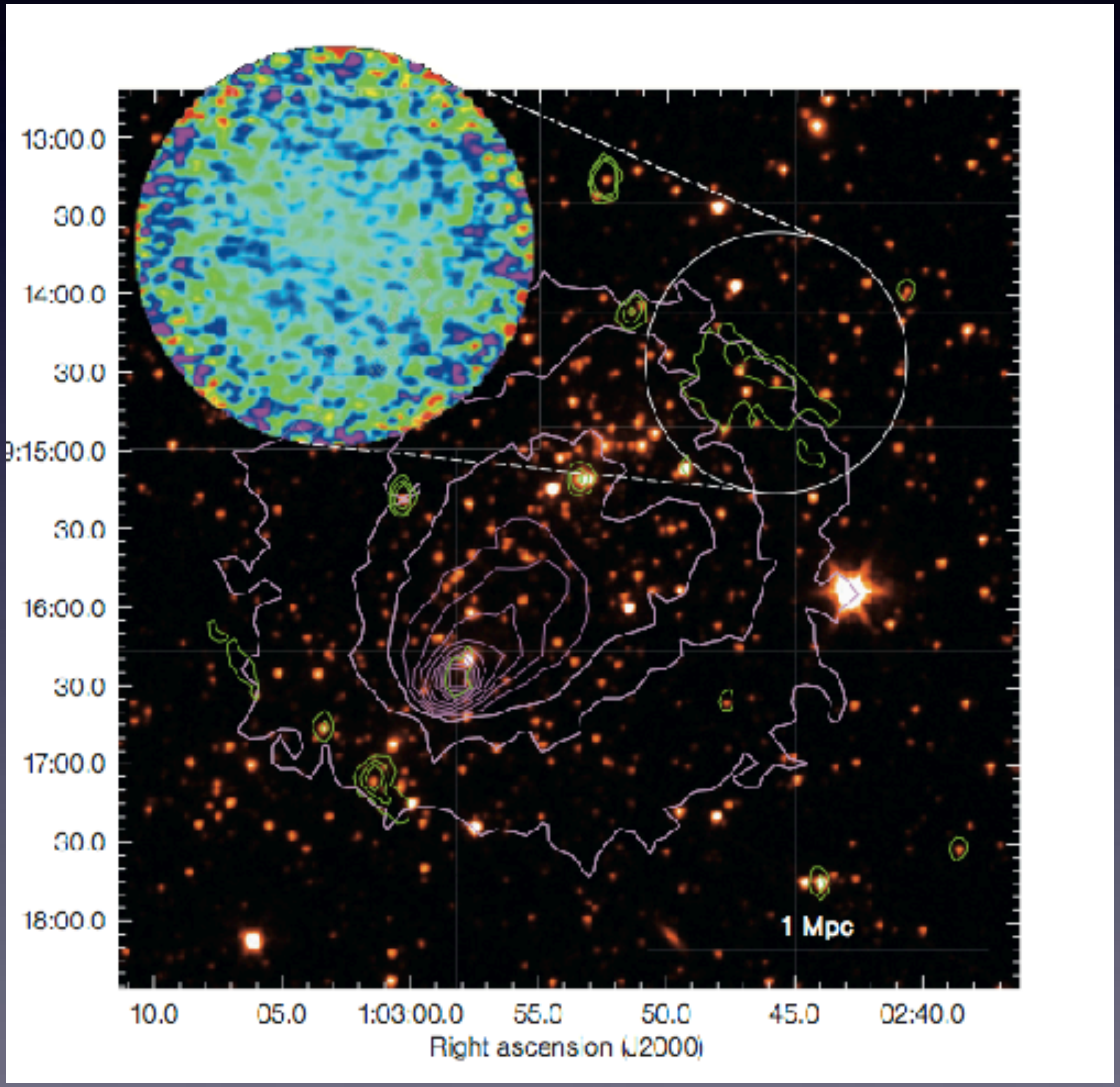
- ALMA and other instruments are opening up the high-resolution frontier of SZ (see Tony's talk).
- We measured with ALMA a shock in the outskirts as well as gas cuspiness at the central region for high-z clusters.

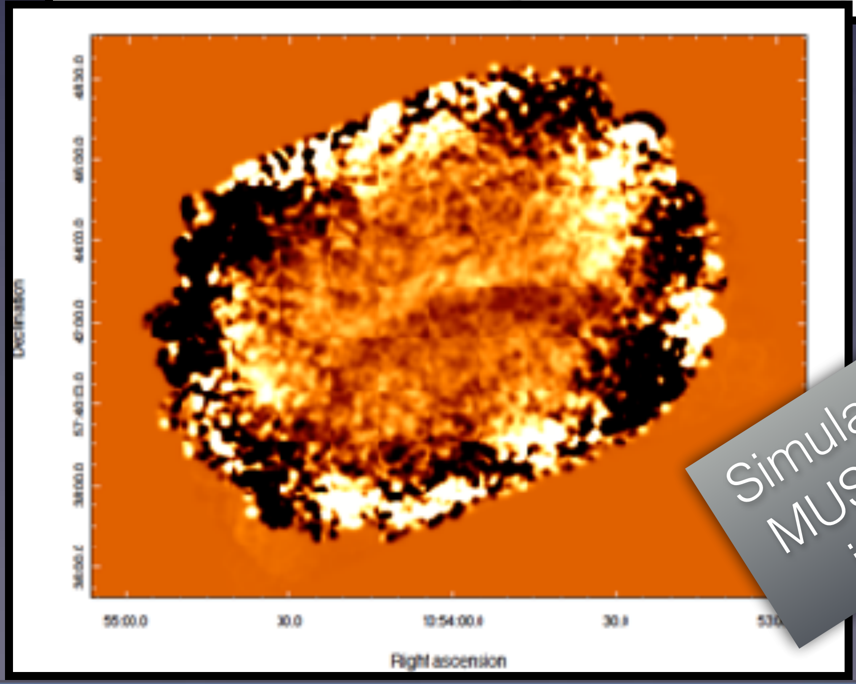
SZ shocks by *ALMA* and *others*



The first radio relic shock in SZ (with Planck): Erler et al. (2015)

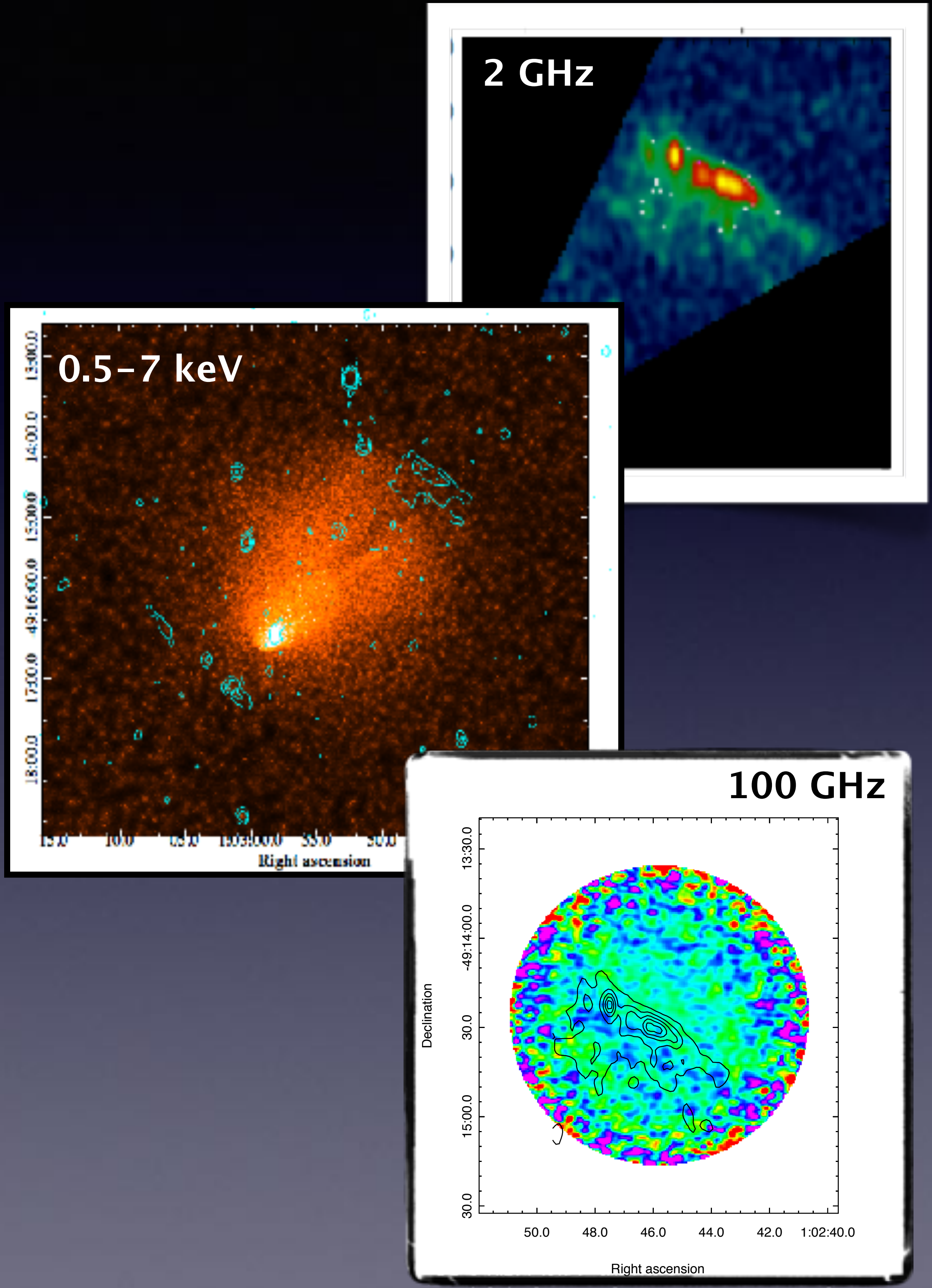
Relic shock in El Gordo: Basu et al. (2016)

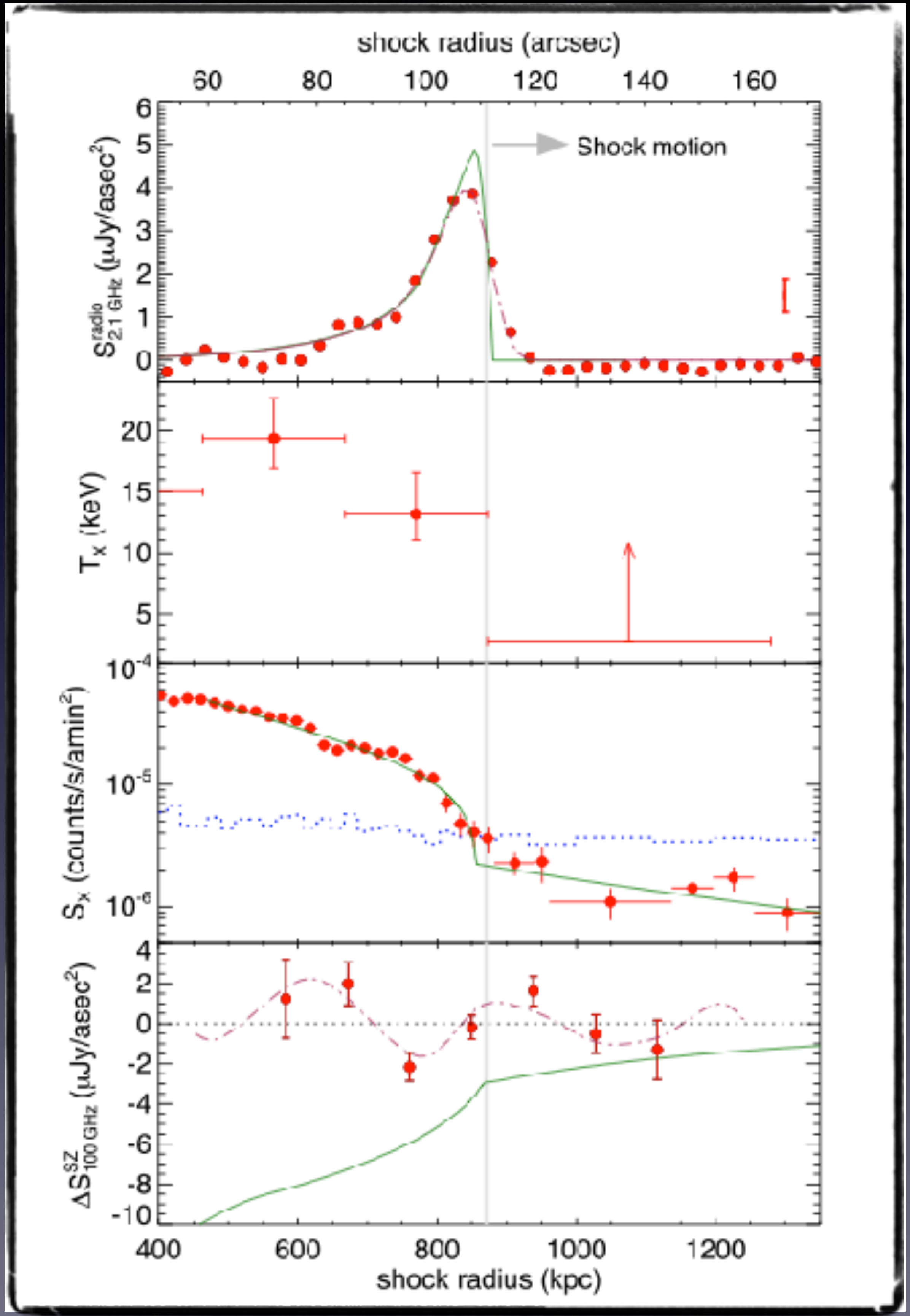




Simulation for MUSTANG-2 imaging

SZ shock in *El Gordo* (z=0.9)



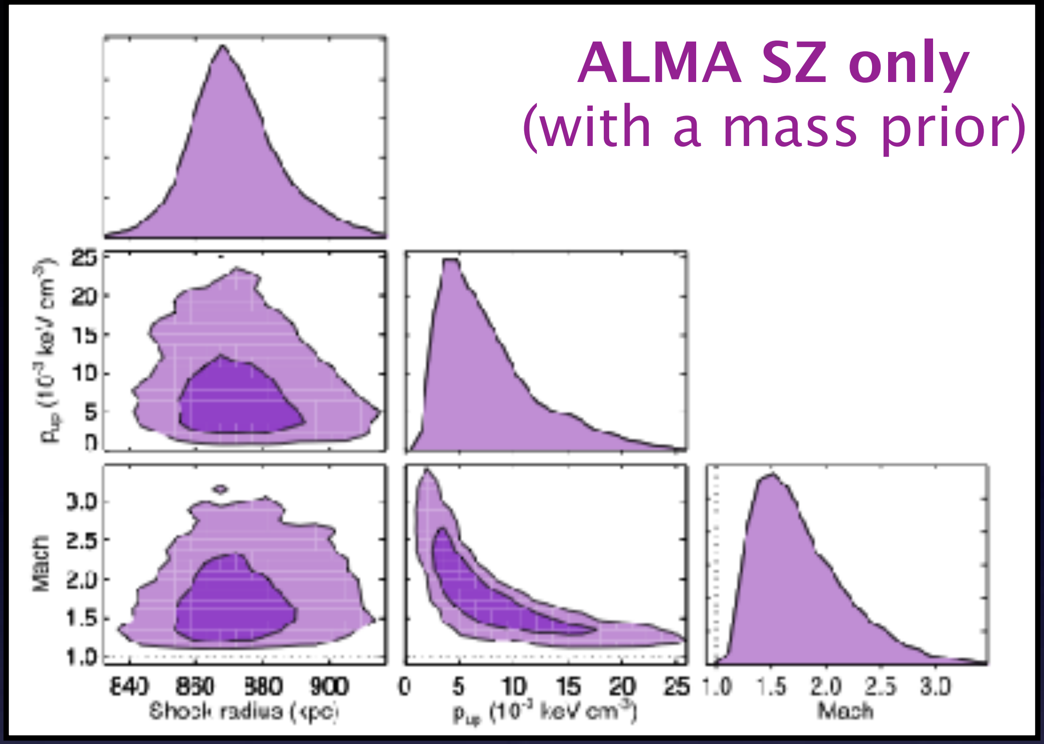


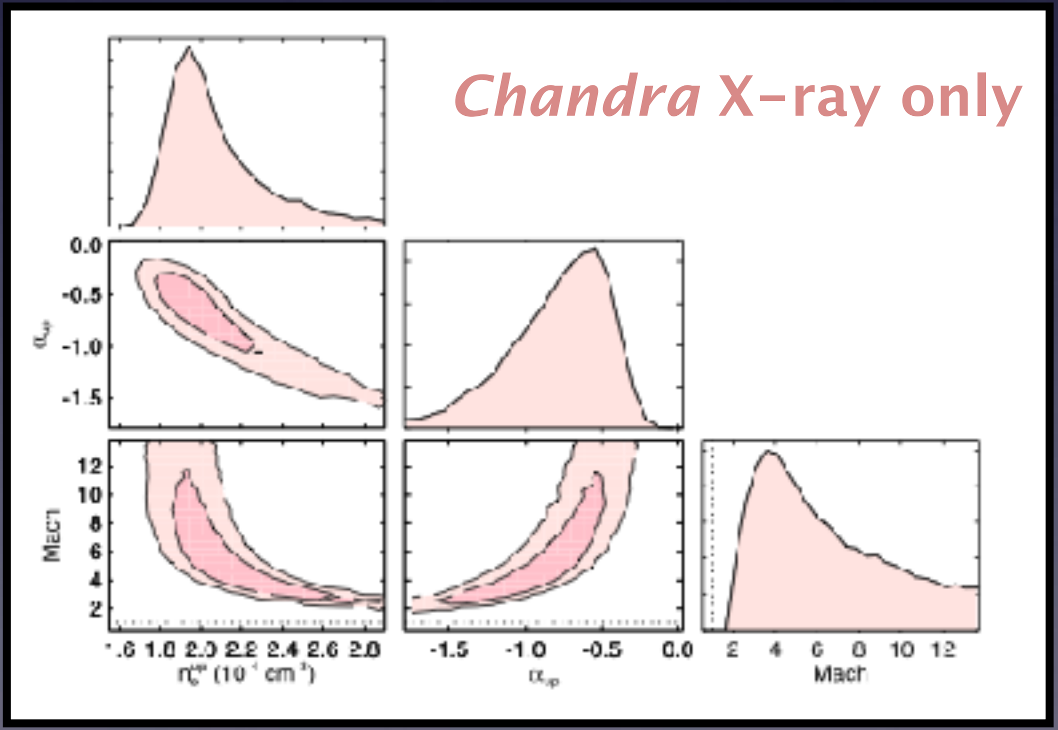
Basu et al. (2016)

SZ shock in *El Gordo (z=0.9)*

ALMA SZ data alone points to a weak shock: $\mathcal{M} = 1.4^{+1.2}_{-0.2}$

X-ray brightness jump suggests stronger: $\mathcal{M} = 3.5^{+6.4}_{-1.3}$

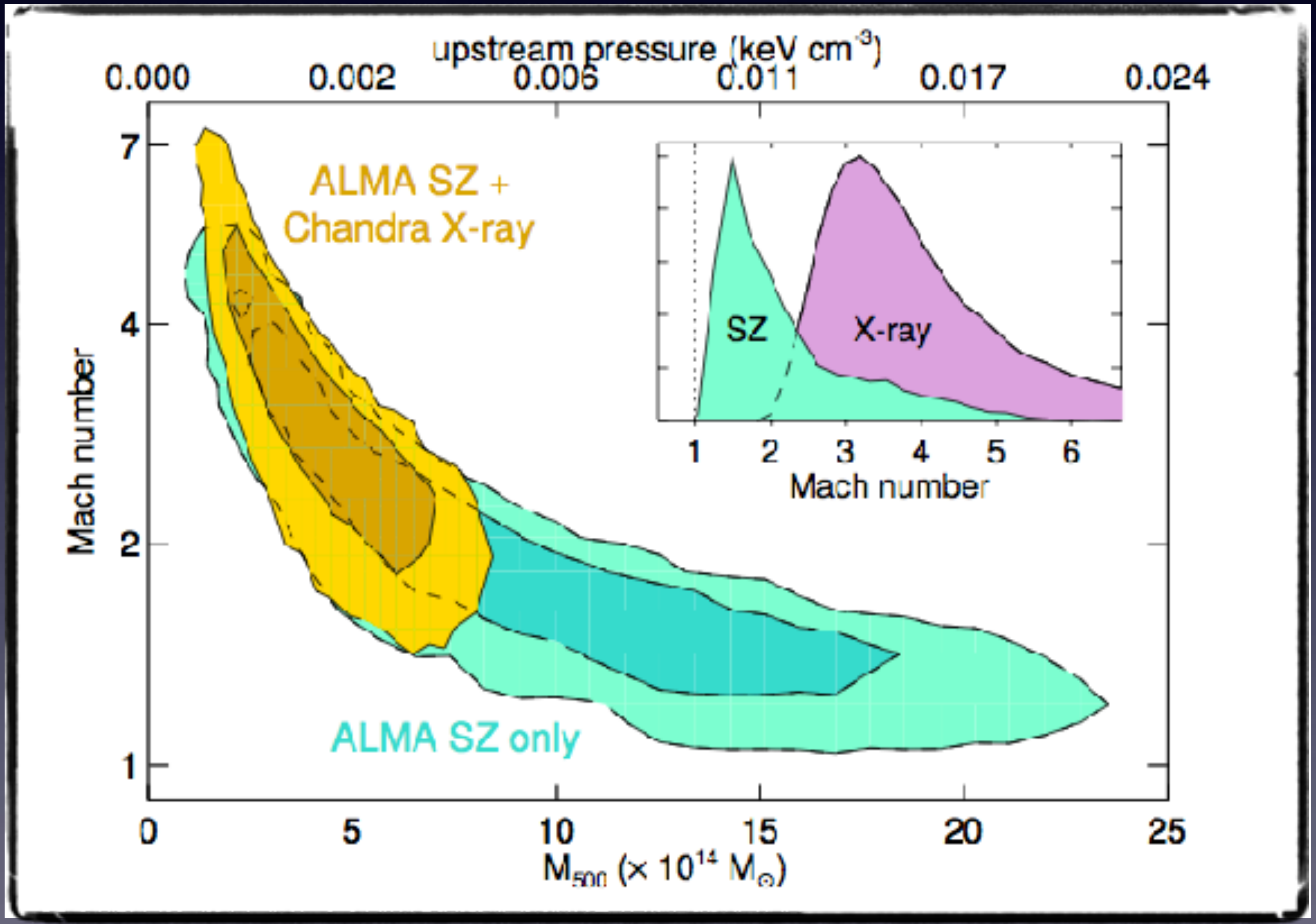




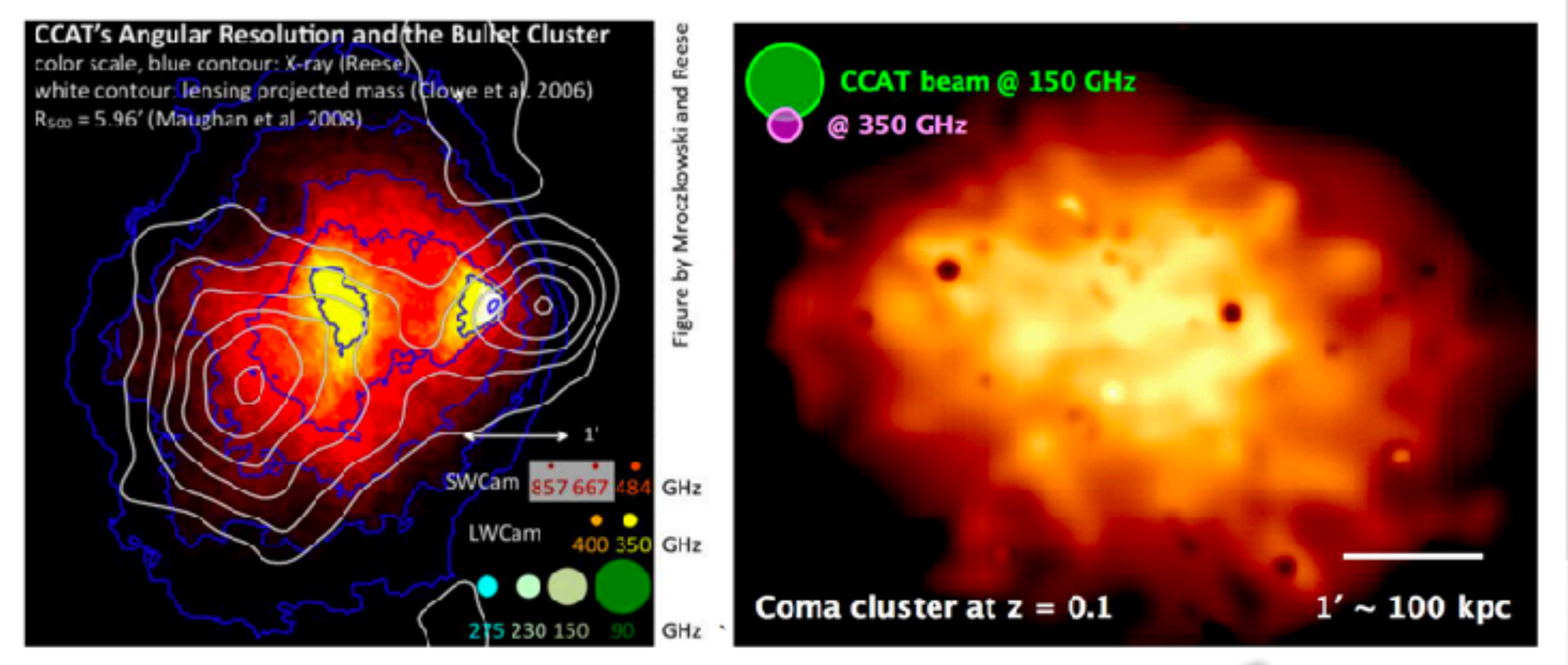
Basu et al. (2016)

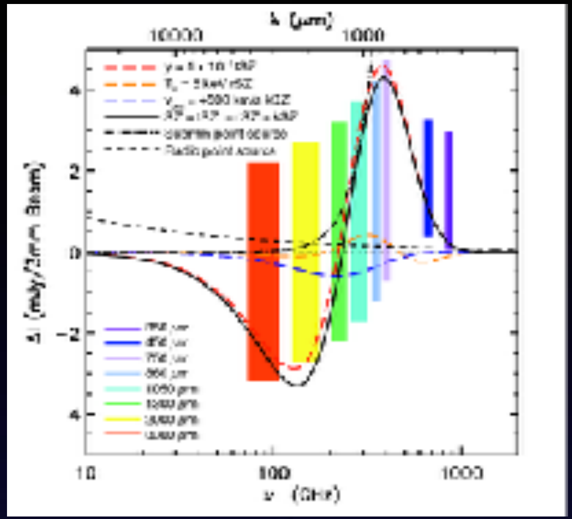
For El Gordo the discrepancy is likely due to IC emission

For Bullet a similar discrepancy points towards e-/ion non-equilibrium!

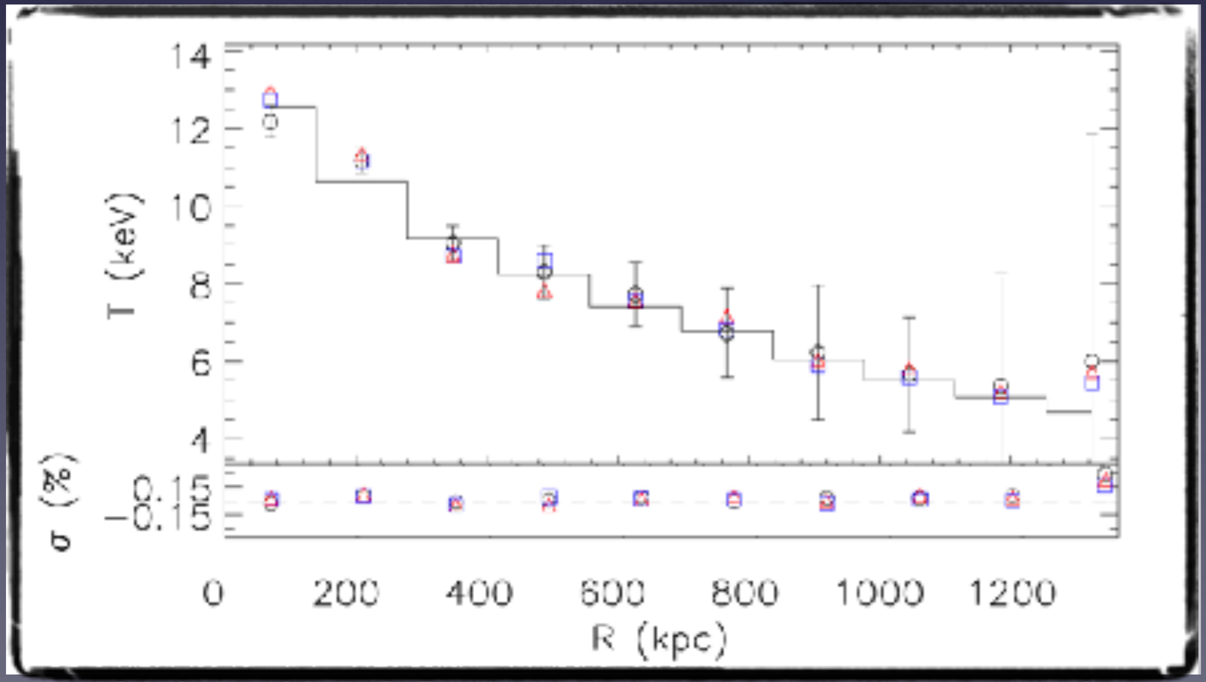


Large aperture single dish: ~~CCAT (25 m)~~ AtLAST



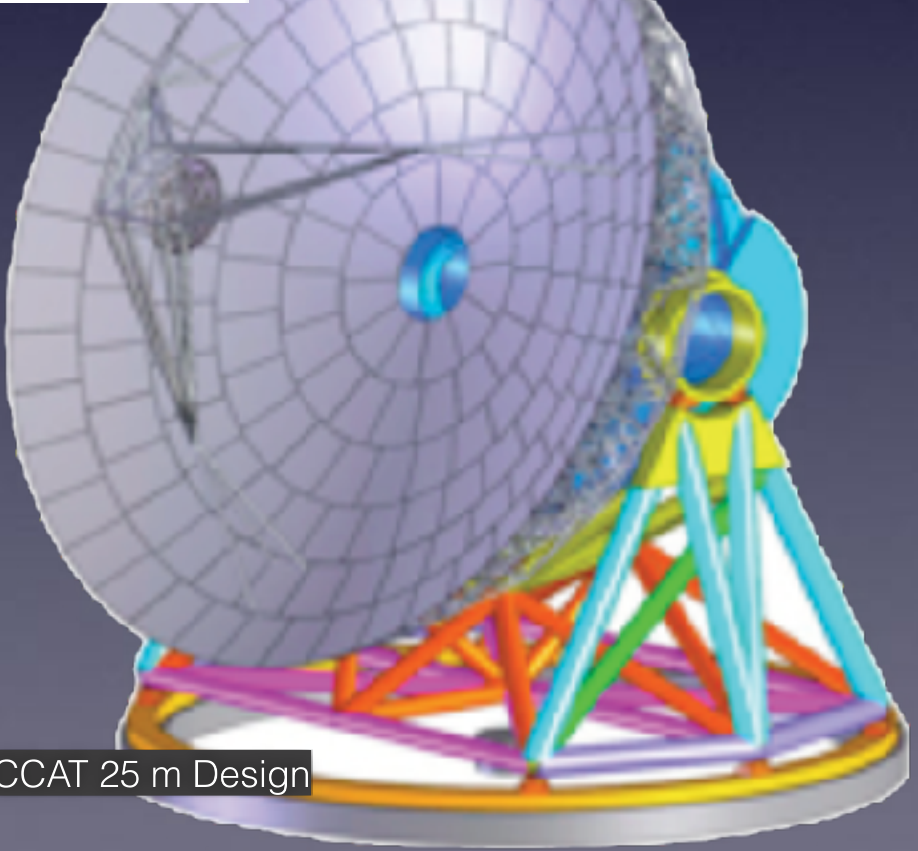


LWCam + SWCam



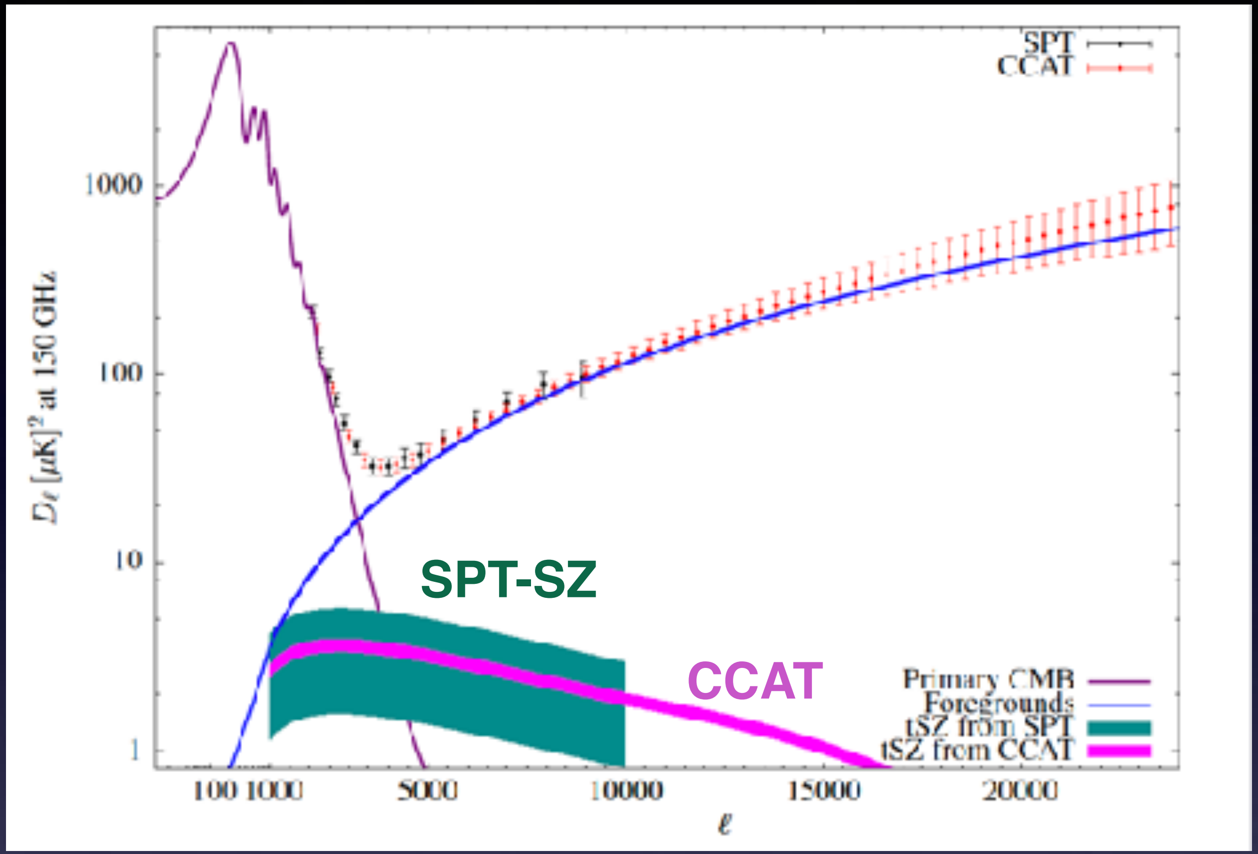
Temp profile predictions by Morandi, Cui, Nagai, and Sayers

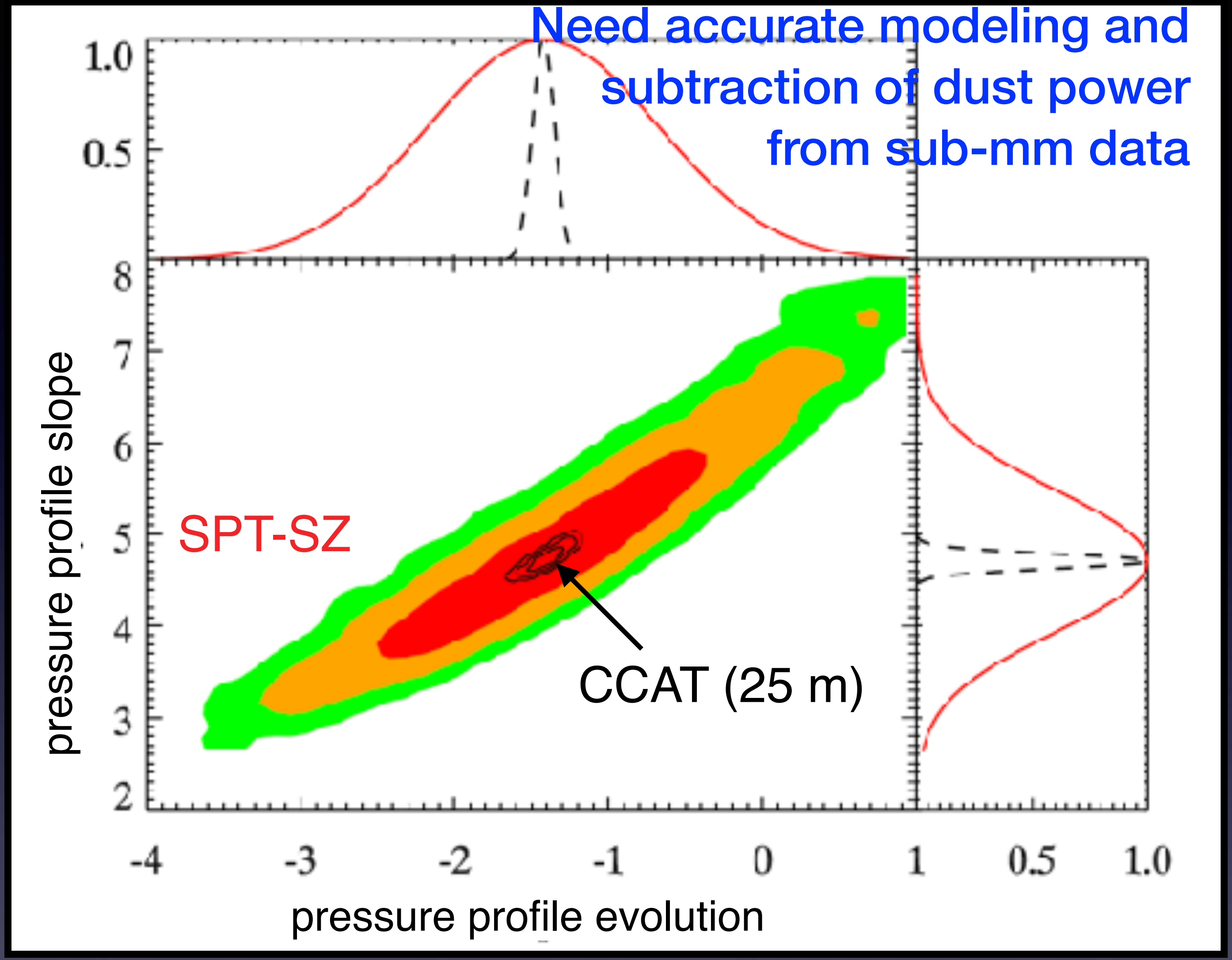
Source: CCAT White Paper



CCAT 25 m Design

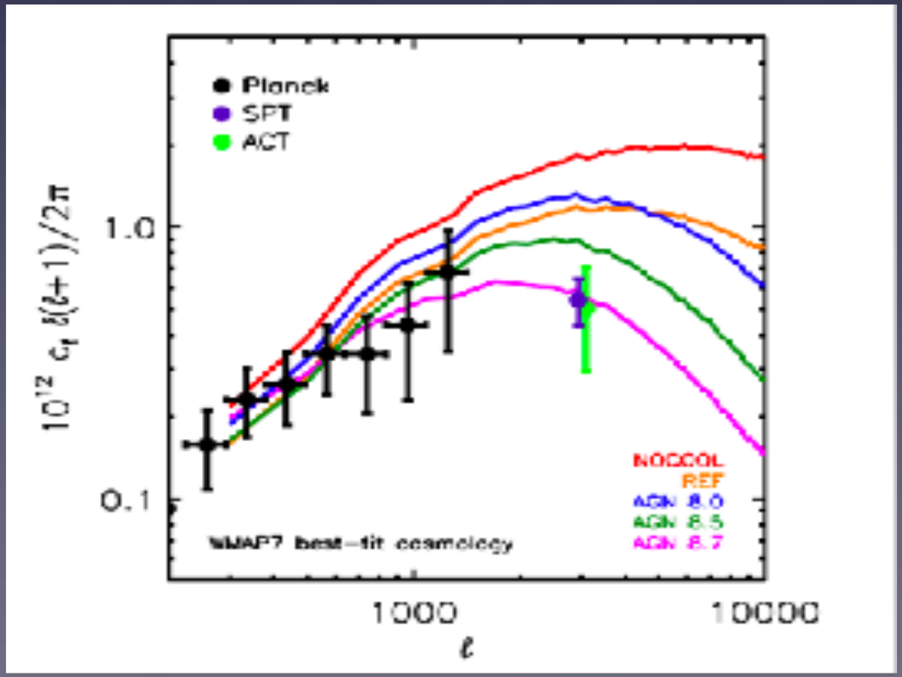
tSZ power spectrum





Need accurate modeling and subtraction of dust power from sub-mm data

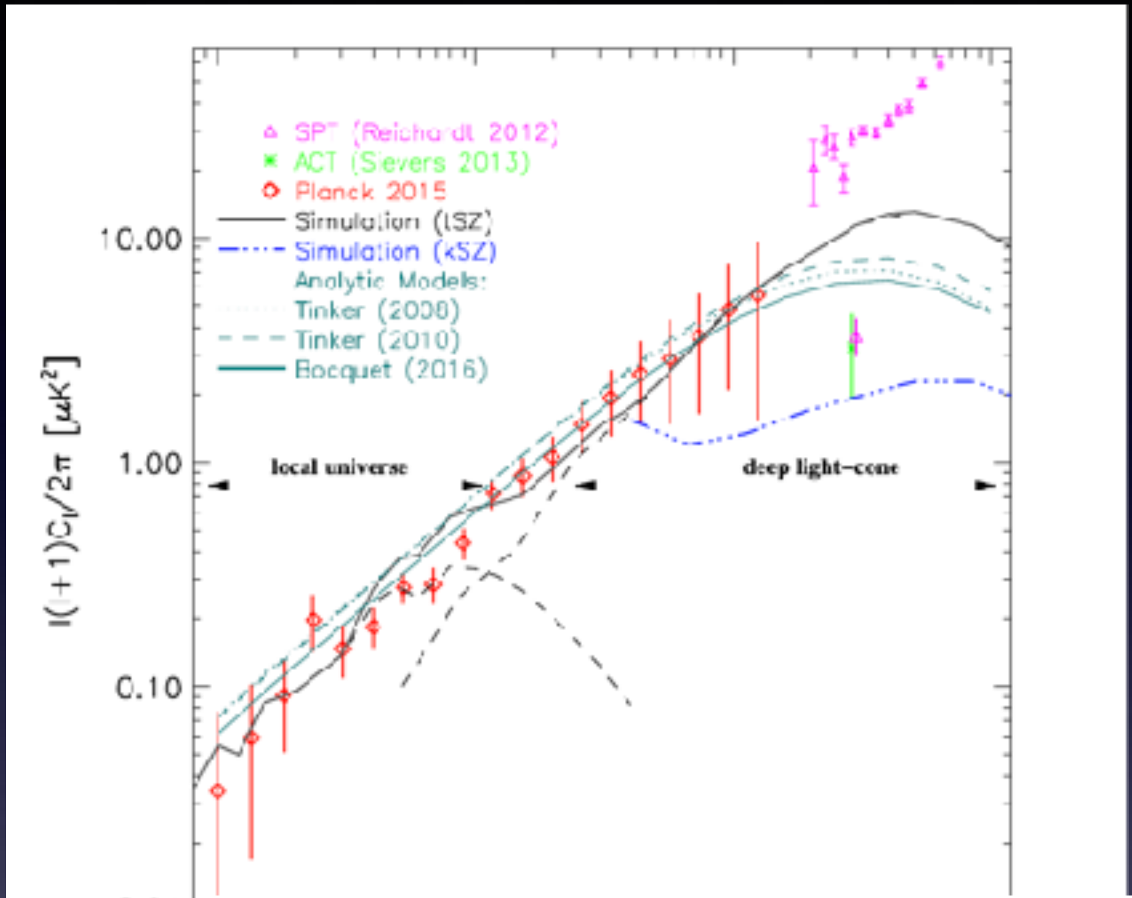
Ramos-Ceja, Basu et al. (2015)



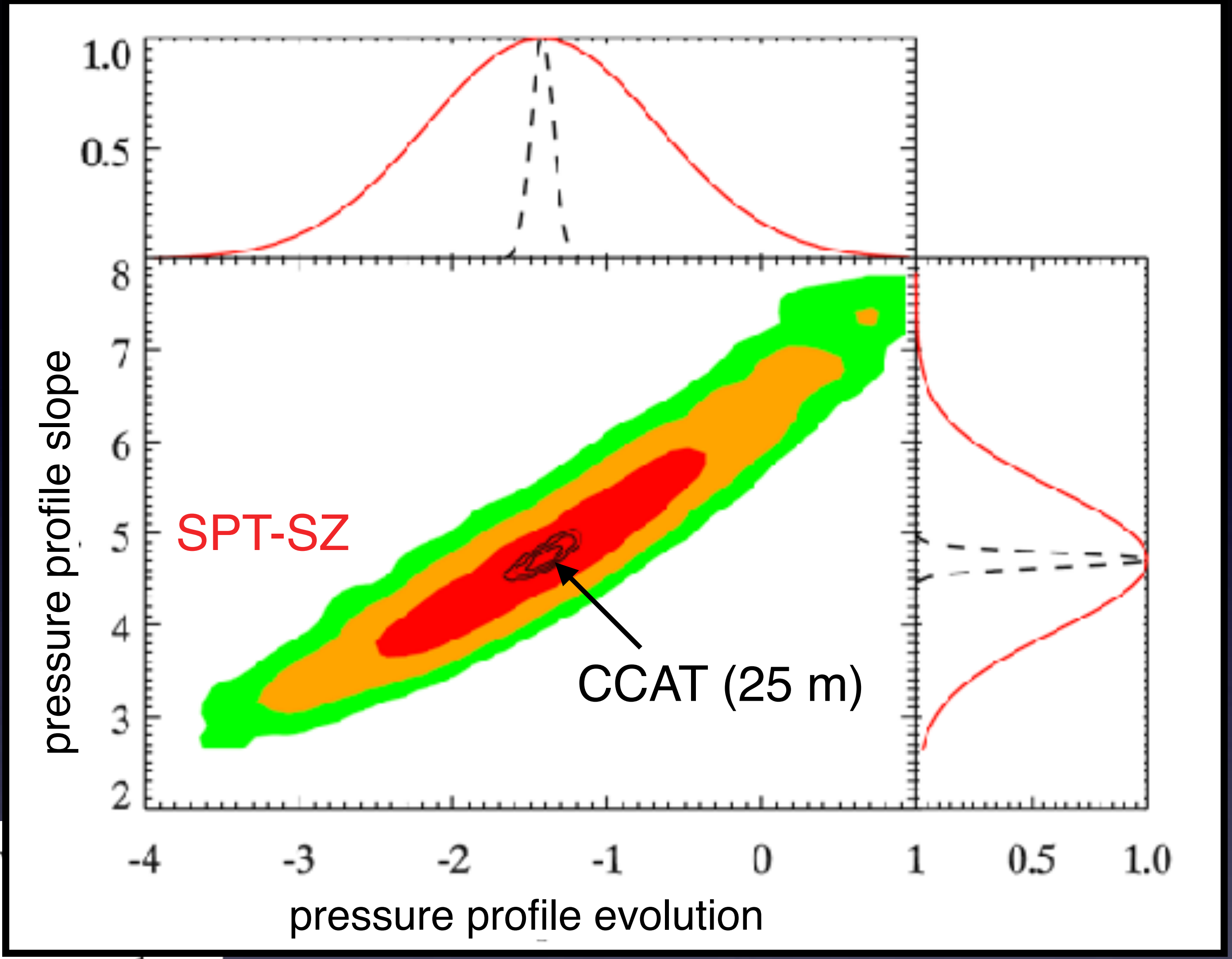
Hydro sims: McCarthy et al. (2014)
Different AGN feedback models

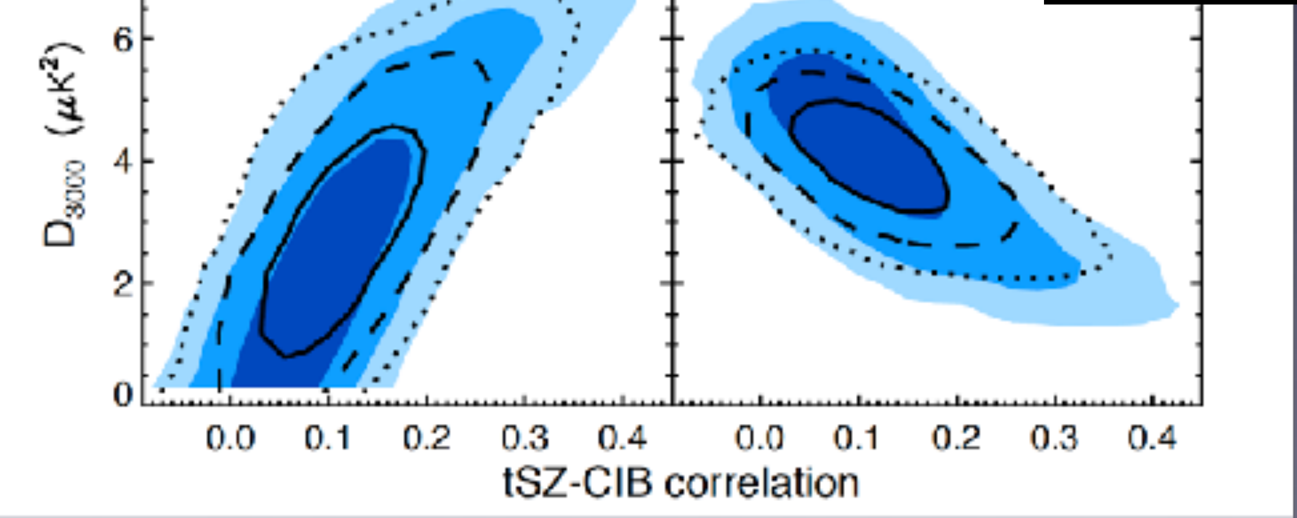
tSZ power spectrum

Dolag, Komatsu & Sunyaev (2016)



Ramos-Ceja, Basu et al. (2015)



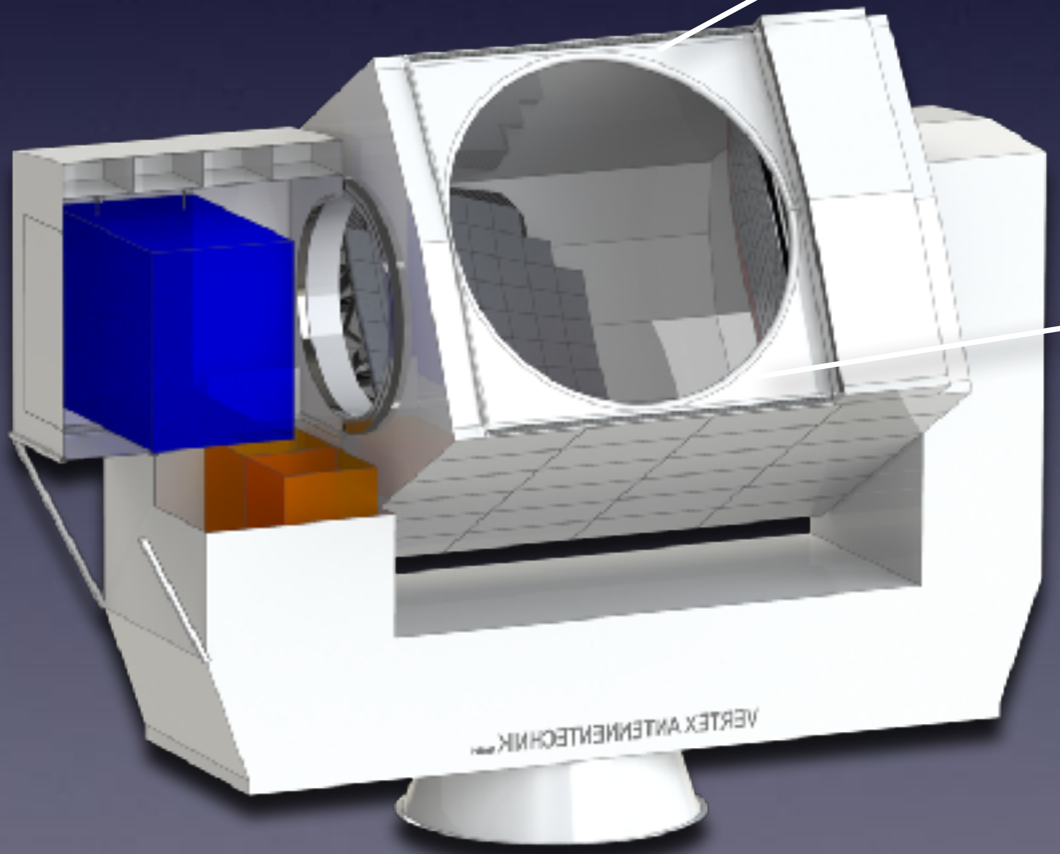


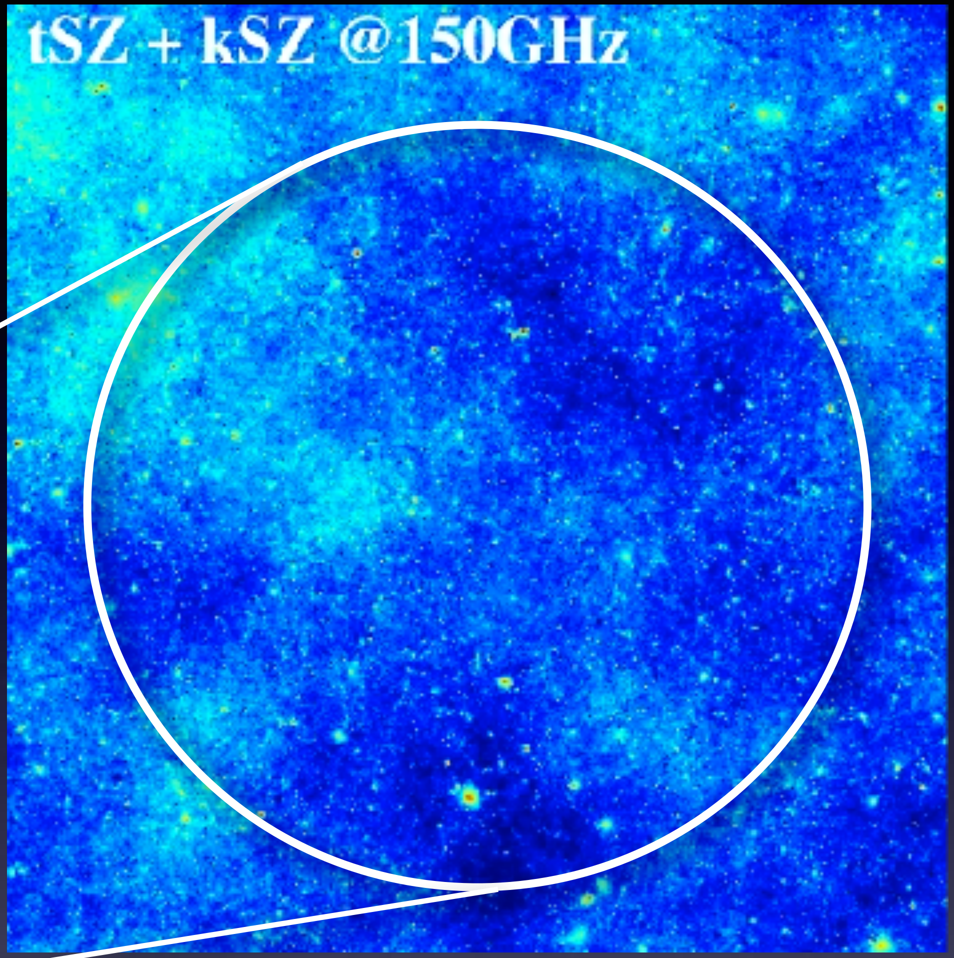
tSZ-CIB correlation is degenerate with the tSZ (and kSZ) power – external data/model is required

George et al. (2014)

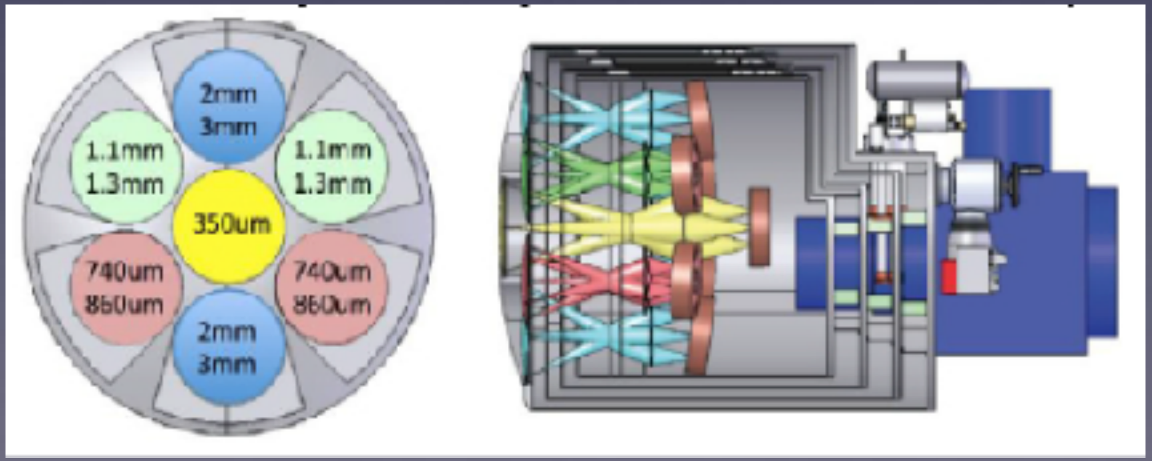
CCAT-prime

- 6 m diameter sub-mm telescope
- Wavelength range 3 mm up to 0.2 mm
- FoV at 3 mm *up to 8 degrees*
- Key cosmology/LSS science: wide area cluster SZ survey + a deep C+ IM survey



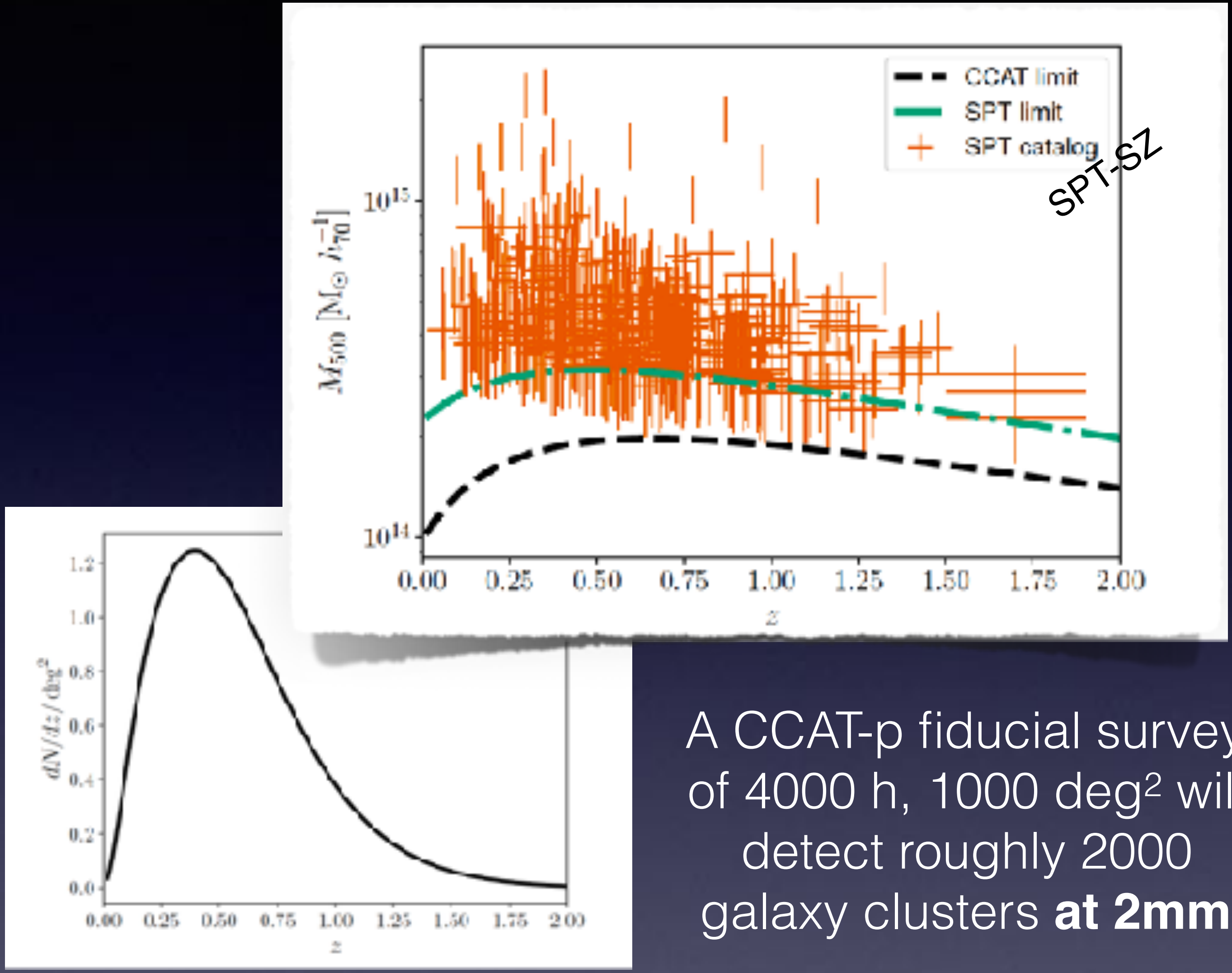


8.8°×8.8° sky area simulation
(Credit: K.Dolag/Magneticum sims)

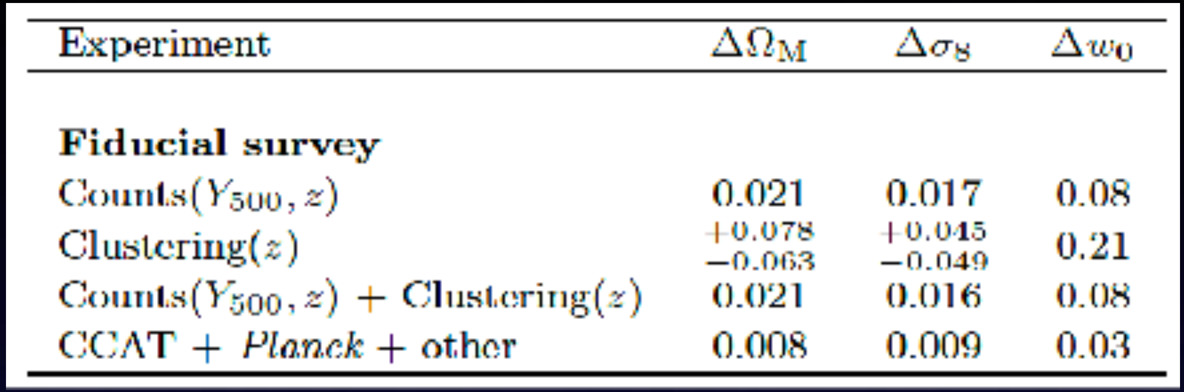


CCAT-prime tSZ survey predictions

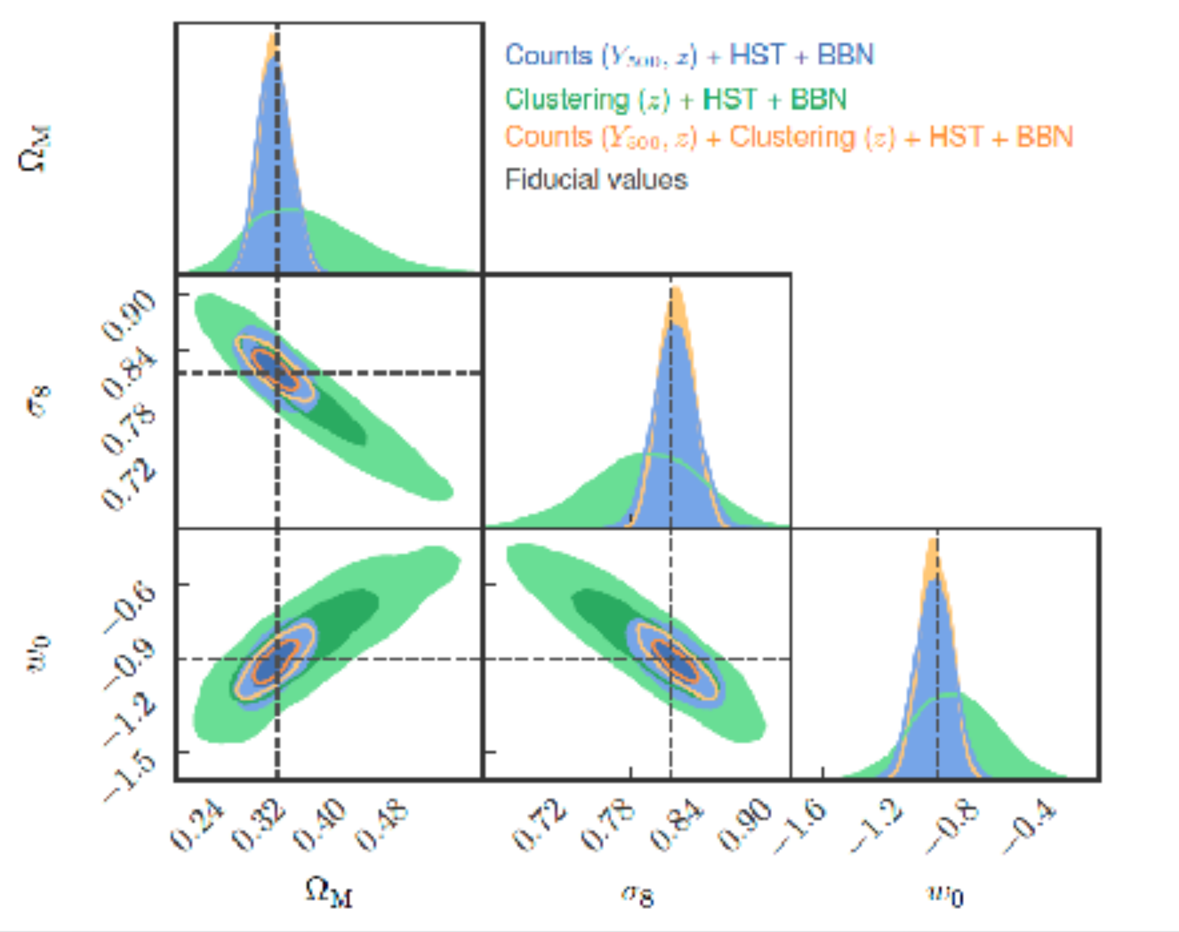
Figures from N. Gupta, Masters thesis (Gupta, Basu & Porciani, in prep.)



A CCAT-p fiducial survey of 4000 h, 1000 deg^2 will detect roughly 2000 galaxy clusters **at 2mm**

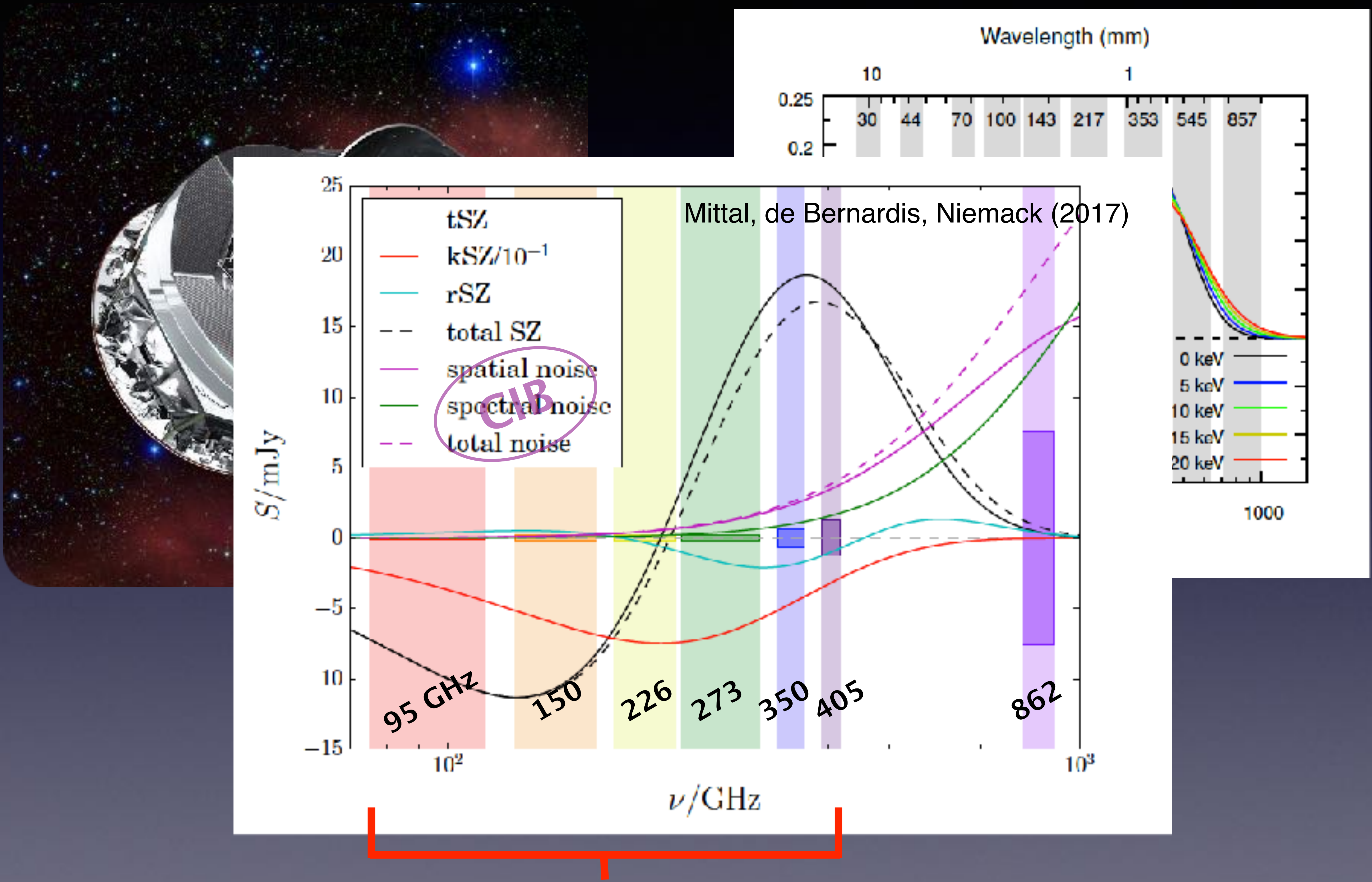


Experiment	$\Delta\Omega_M$	$\Delta\sigma_8$	Δw_0
Fiducial survey			
Counts(Y_{500}, z)	0.021	0.017	0.08
Clustering(z)	$^{+0.078}_{-0.063}$	$^{+0.045}_{-0.049}$	0.21
Counts(Y_{500}, z) + Clustering(z)	0.021	0.016	0.08
CCAT + *Planck* + other	0.008	0.009	0.03



- CCAT-p survey, without Planck CMB priors, will constrain σ_8 to 0.6% and 0.7% accuracy for constant and varying DE. ω_0 is constrained with 7% accuracy.
- Even for a 1000 deg^2 survey, some cosmological parameters will be better constrained than by eROSITA thanks to the low scatter *Y-M* scaling.

Requirement for SZ spectral analysis



Mittal, de Bernardis, Niemack (2017)

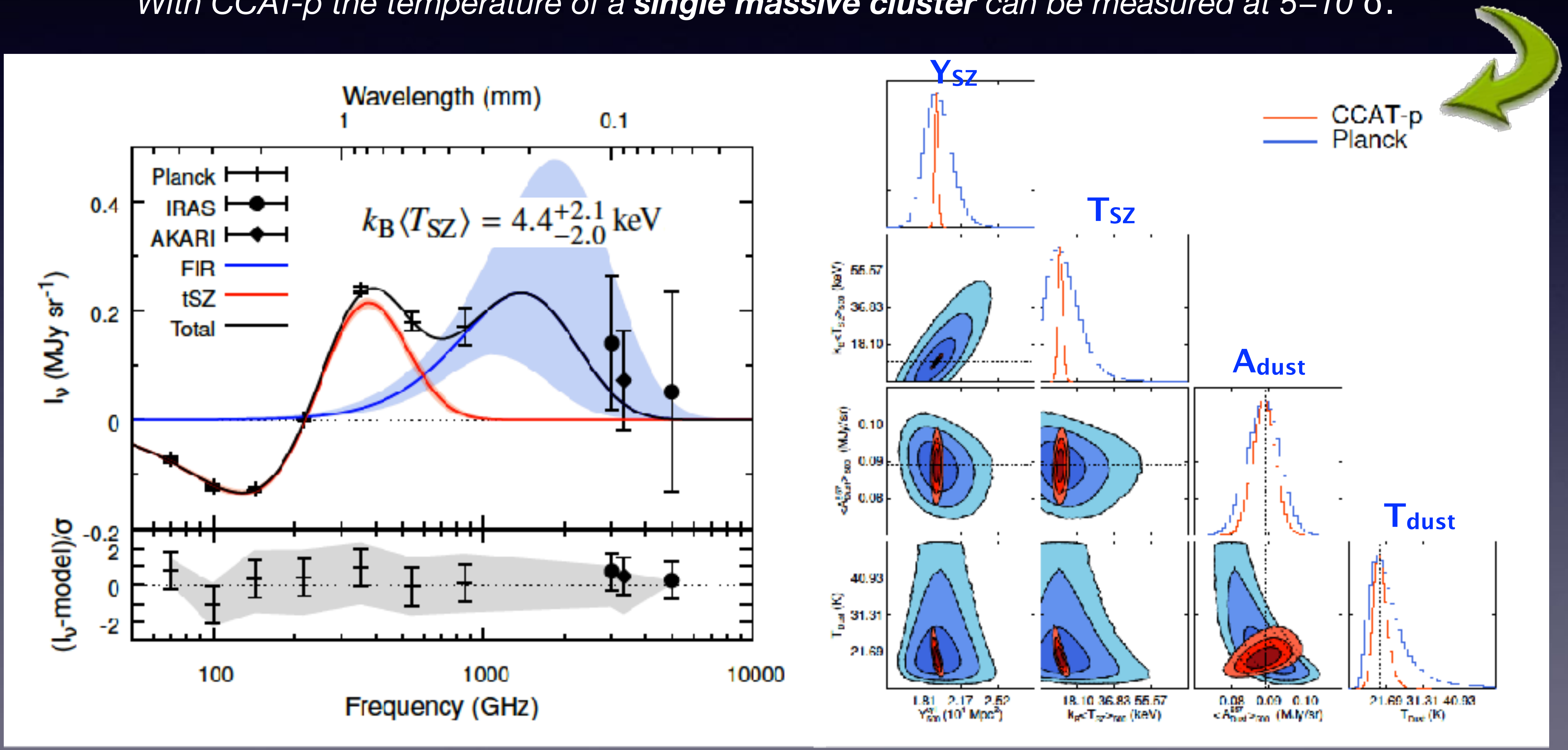
CCAT-p sensitivity is on average 5 to 15 times better than Planck (angular resolution ~6 times better)

rSZ: State-of-the-art and CCAT-prime

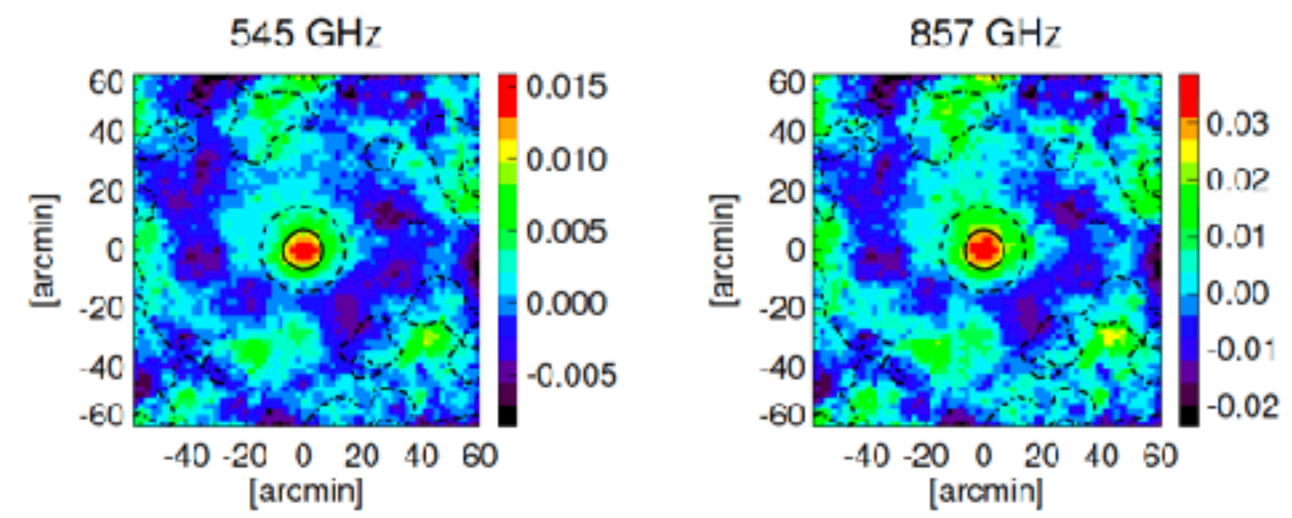
Erler, Basu et al. (arXiv:1709.01187)

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

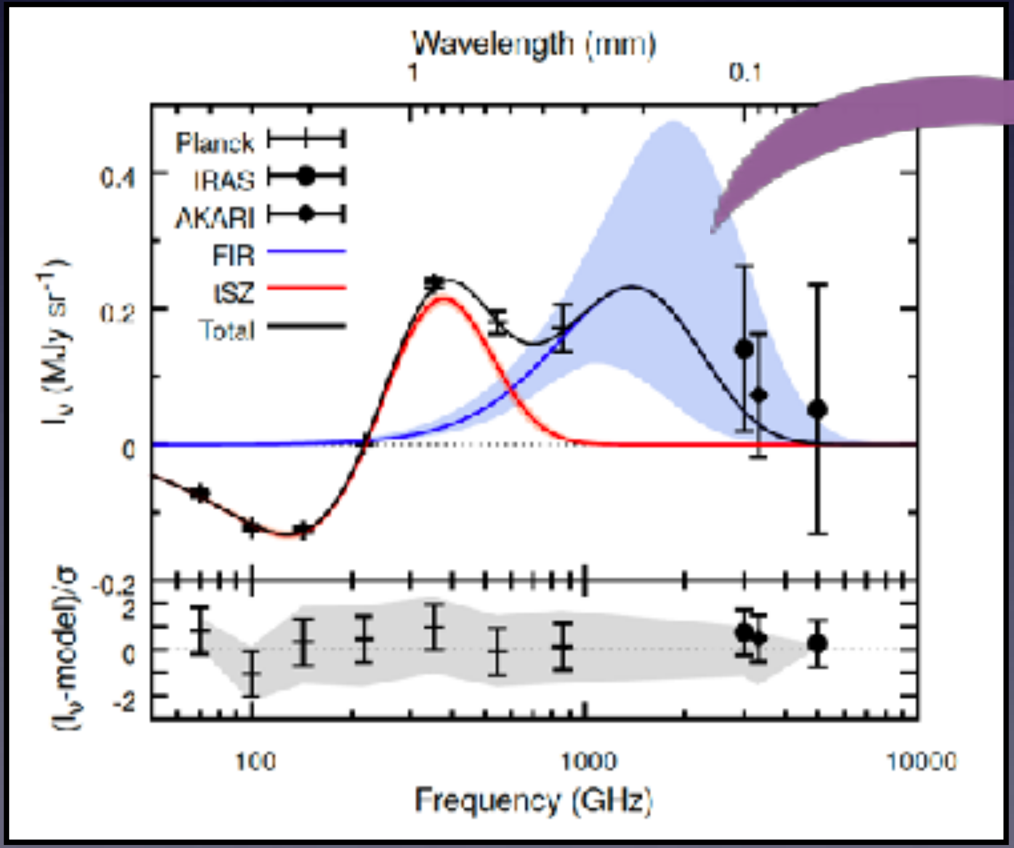
*With CCAT-p the temperature of a **single massive cluster** can be measured at 5–10 σ.*



More to consider: dust in galaxy clusters

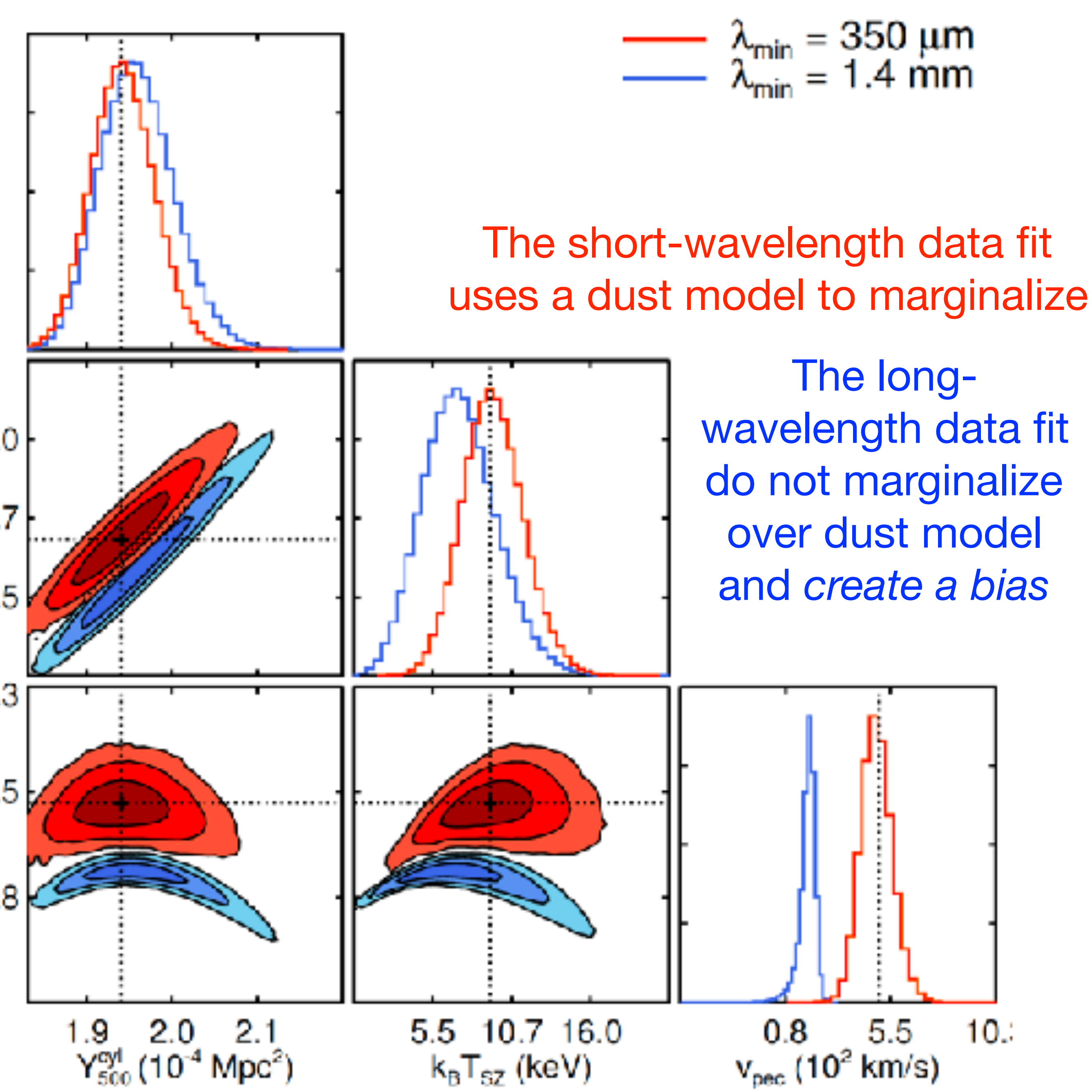


Planck collaboration (2016)



Erler et al. (2017)

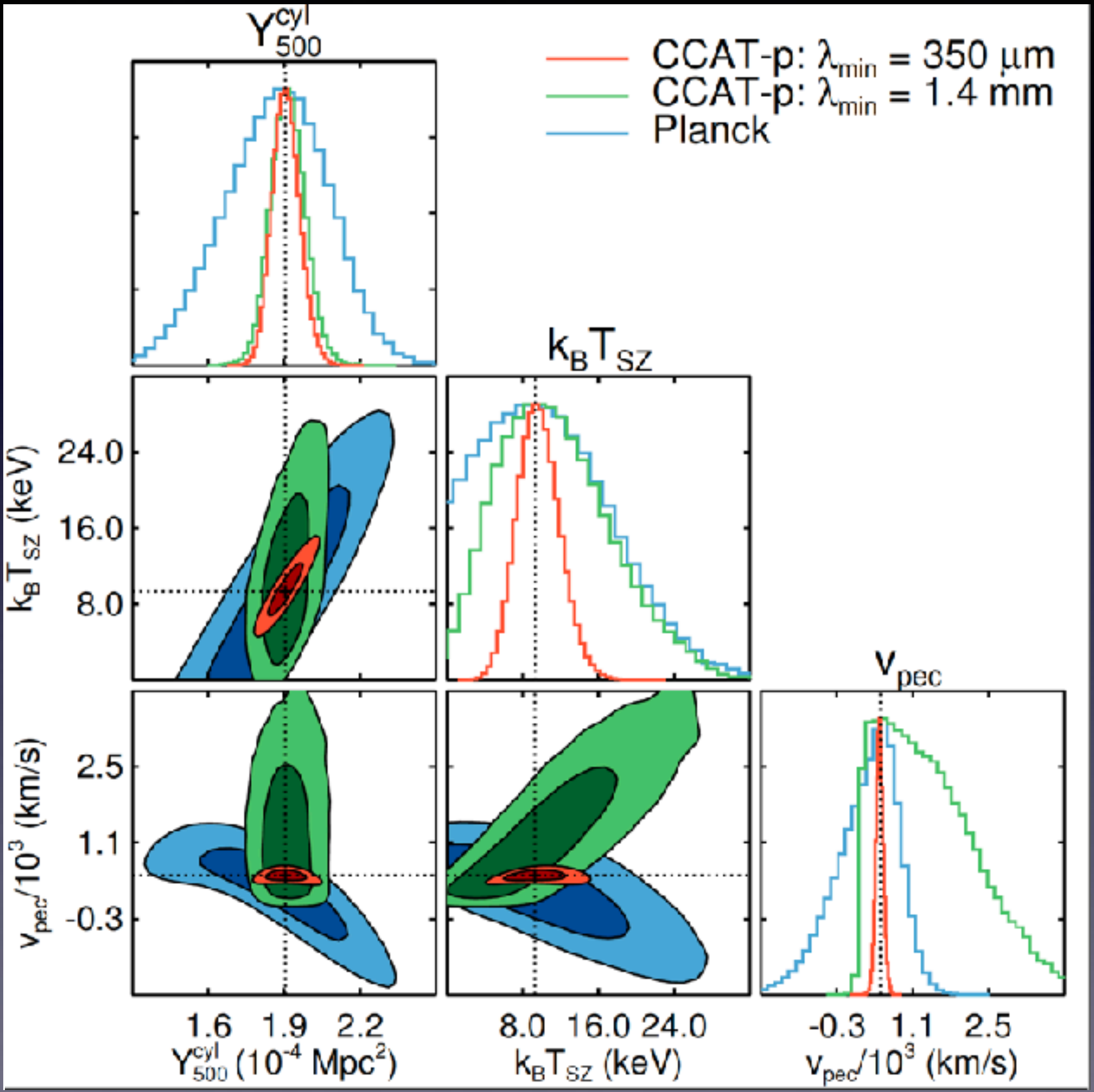
Figure from Jens Erler



The short-wavelength data fit uses a dust model to marginalize

The long-wavelength data fit do not marginalize over dust model and *create a bias*

More on *cluster dust*



Applying X-ray temperature priors

Temperature prior from eROSITA (at 30%-40% level)

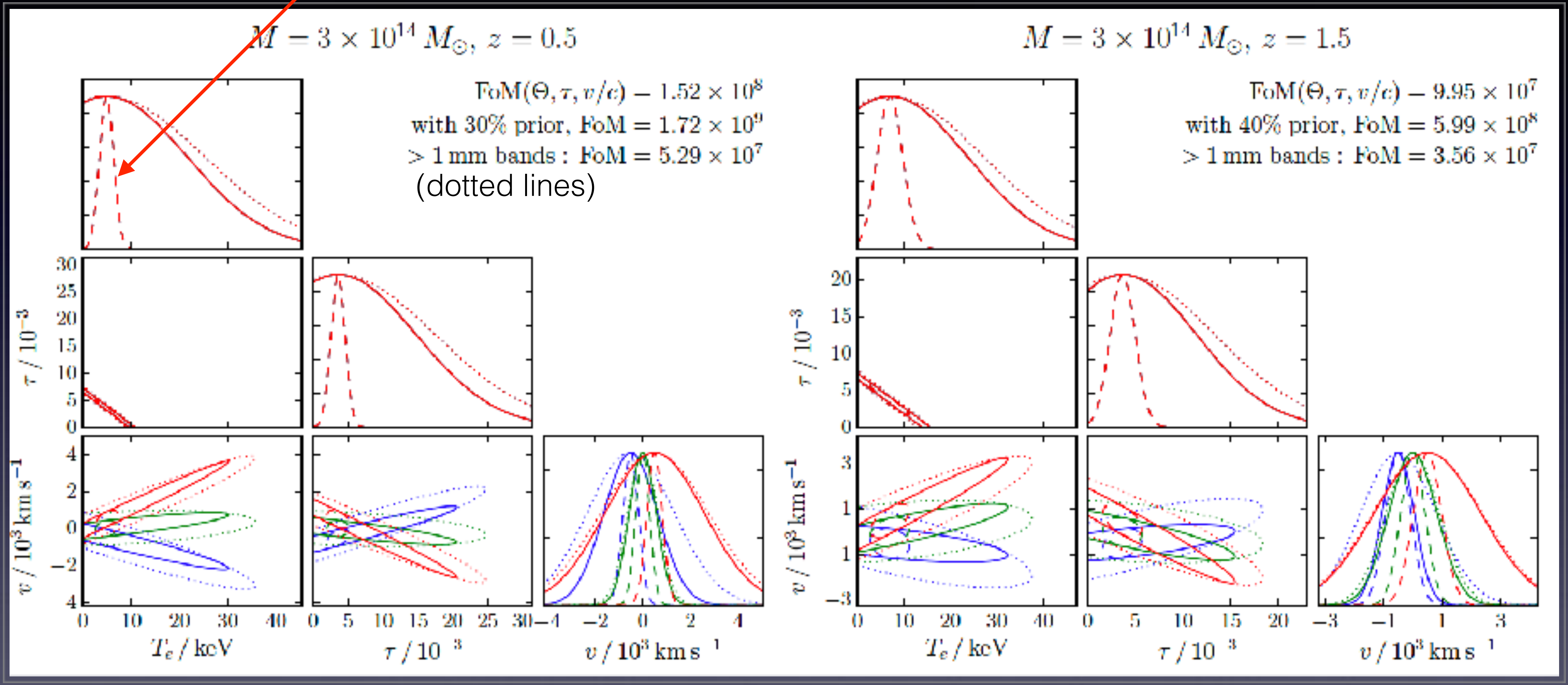
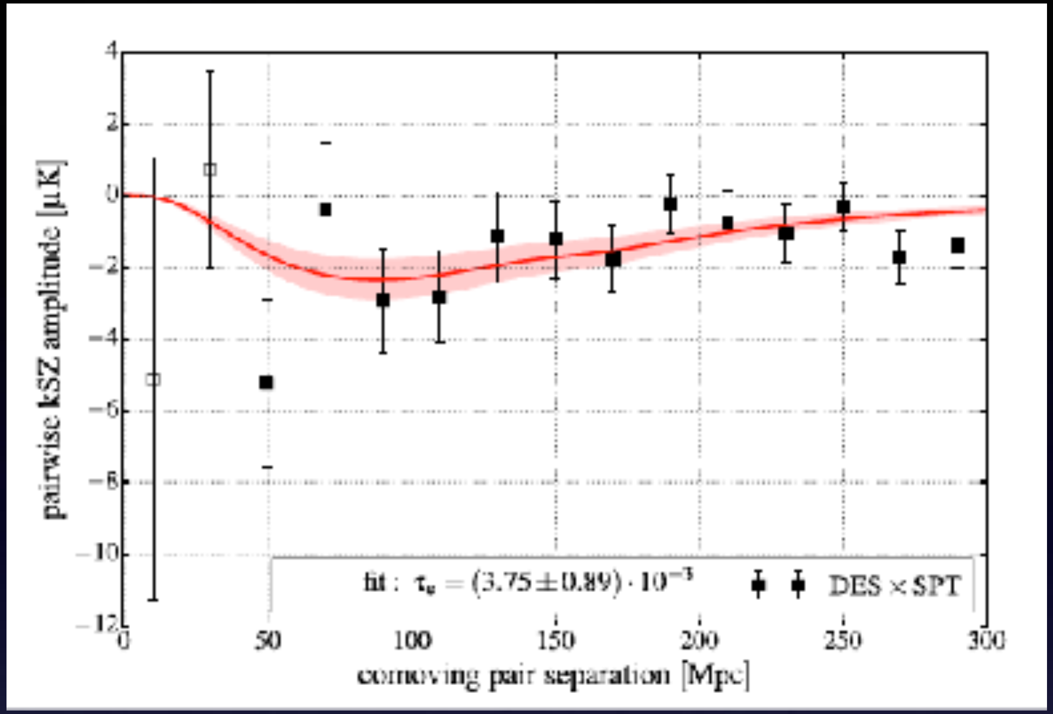


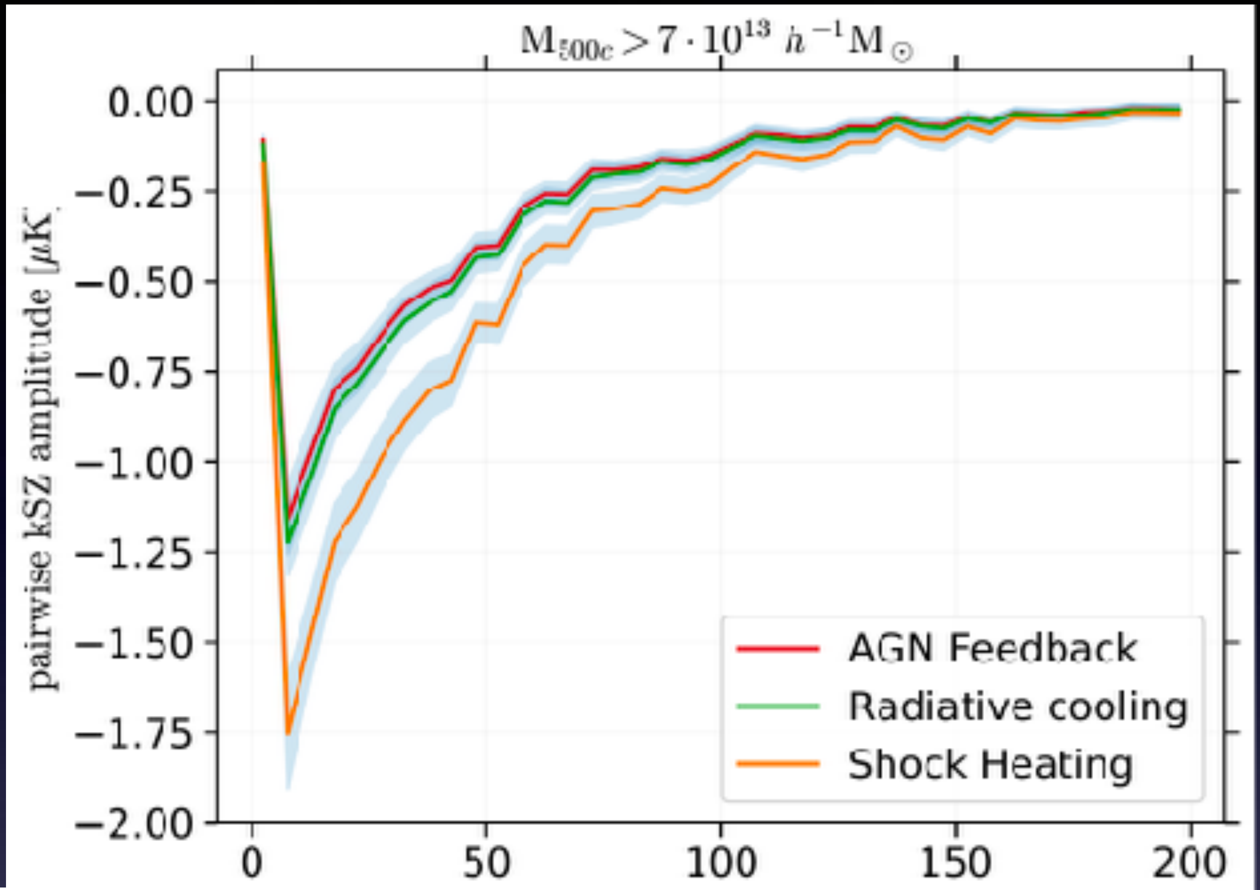
Figure from Mittal, de Bernardis & Niemack (2017)

X-ray temperature priors will significantly improve the velocity and tau constraints (though mostly effective for lower-redshift systems, until *Athena* arrives)

kSZ: cluster τ and pairwise momentum



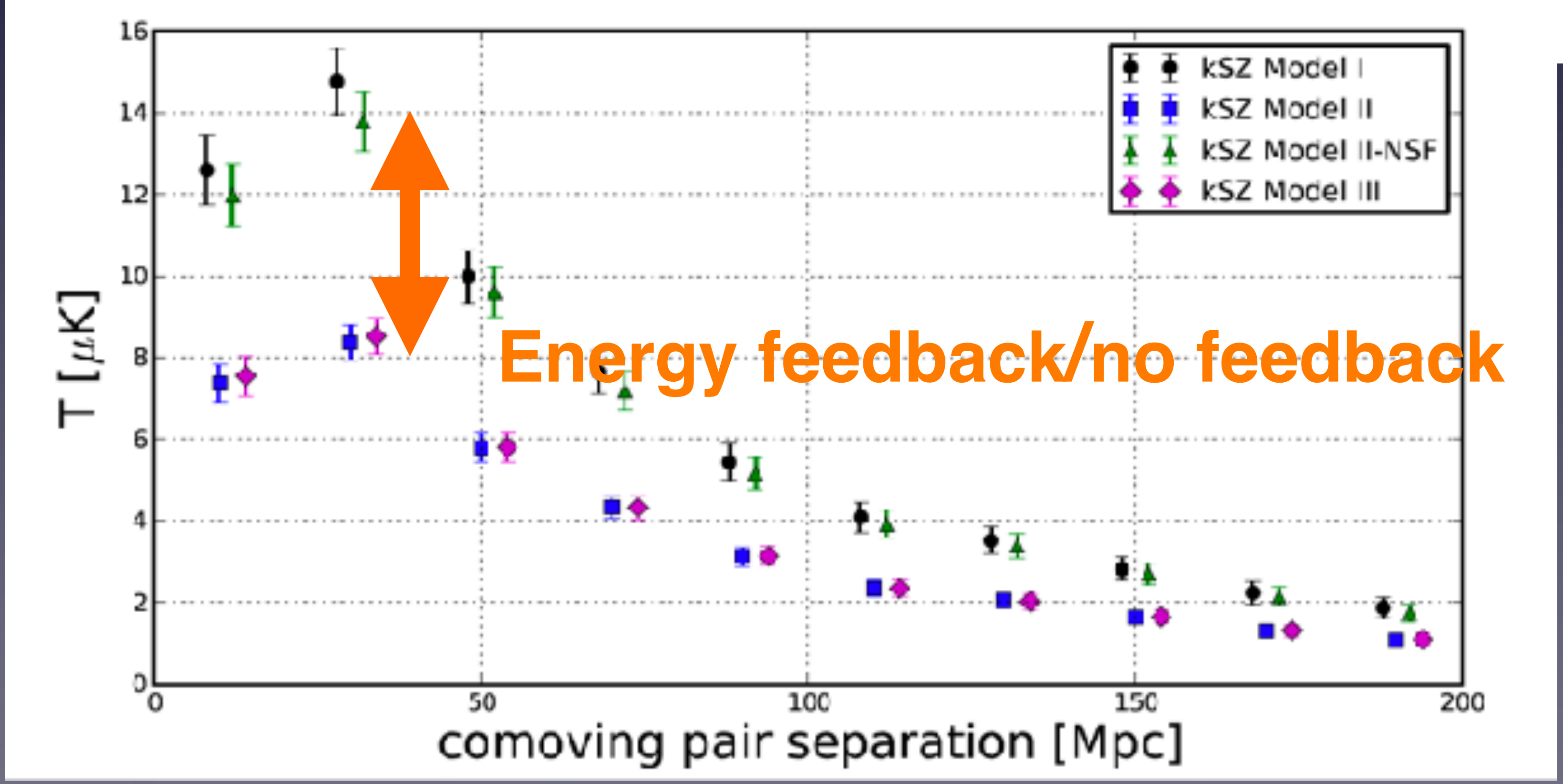
Pairwise kSZ measurement (Soergel et al. 2016)



J. Kuruvilla et al. (preliminary)

τ-M scaling relation parameters
from Battaglia et al. (2017)
hydro simulations

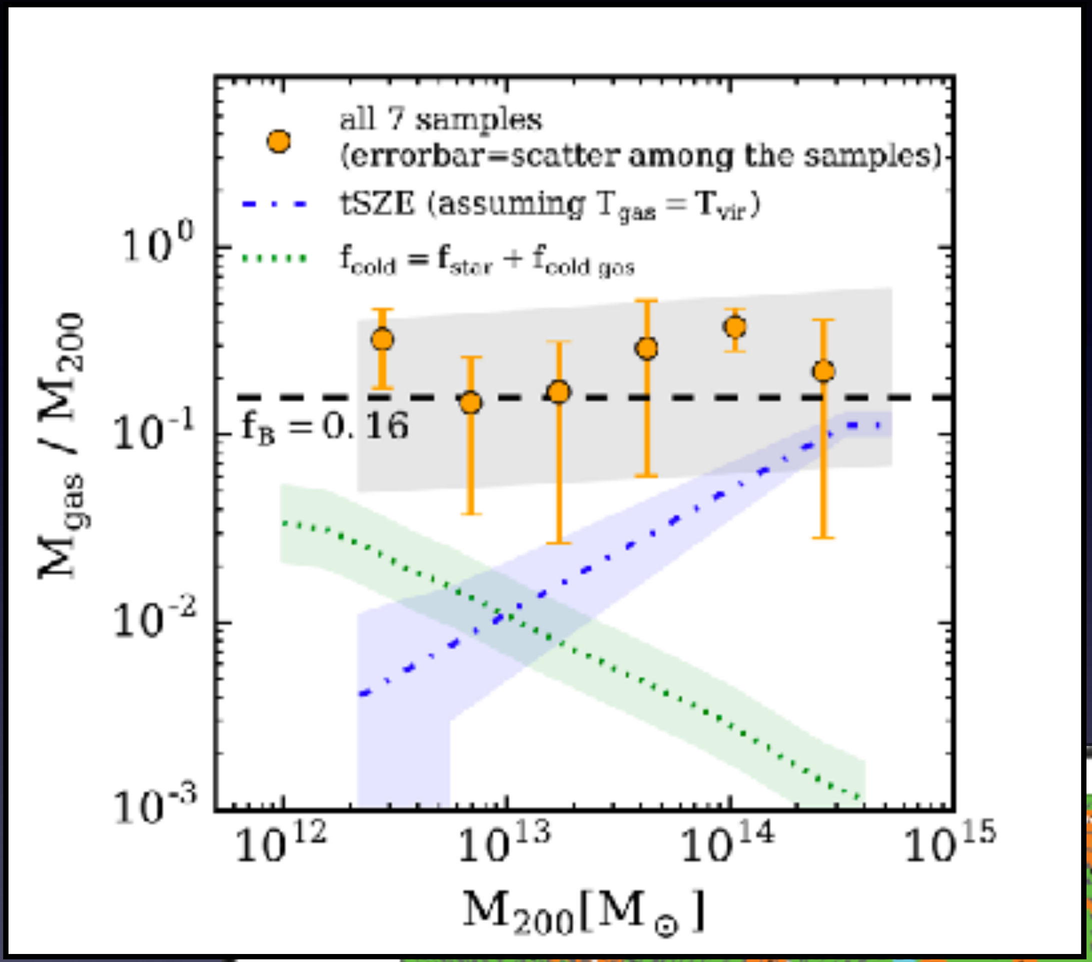
Pairwise kSZ simulation (Flender et al. 2016)



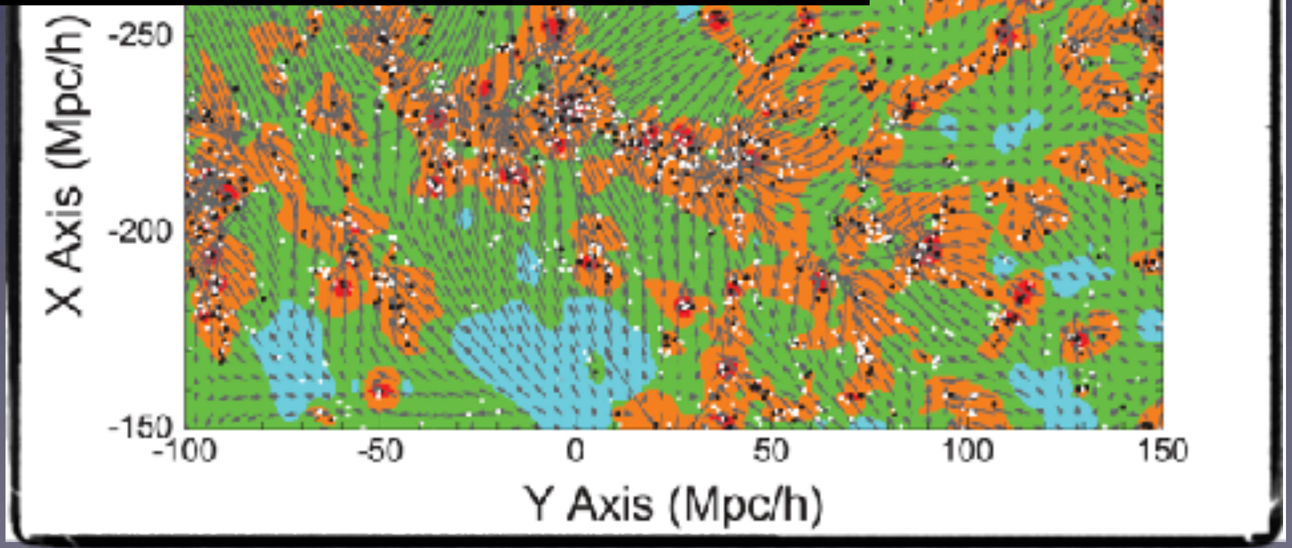
Energy feedback/no feedback

kSZ: f_{gas} and feedback in clusters/groups/galaxies

Lim et al. (2018), kSZ stacking
on catalogs based on SDSS data

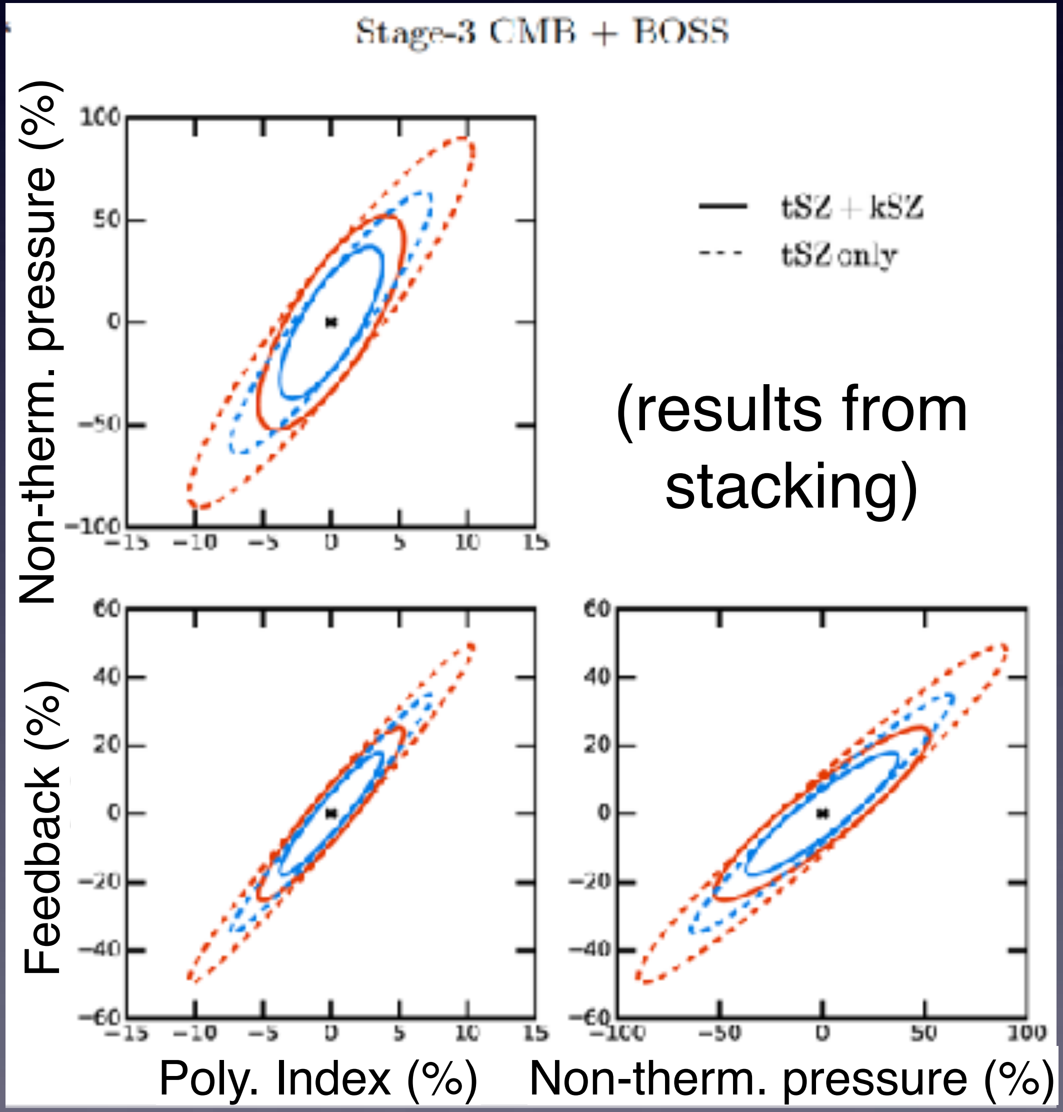


Velocity field modelled from linear theory and smoothed density field Reconstruction (Wang et al. 2012)



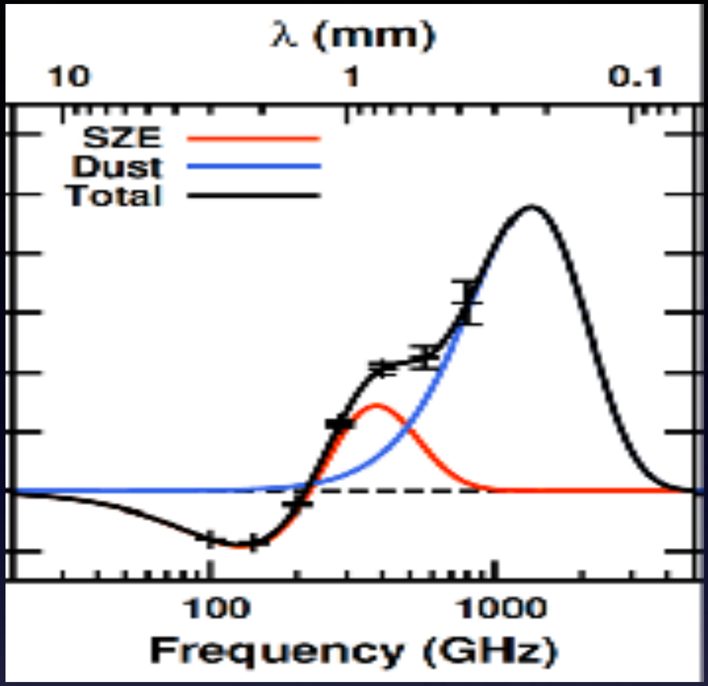
Combined **tSZ + kSZ + optical** data can put tight constraints on baryonic physics of DM halos: *not only clusters but galaxies, QSOs,..*

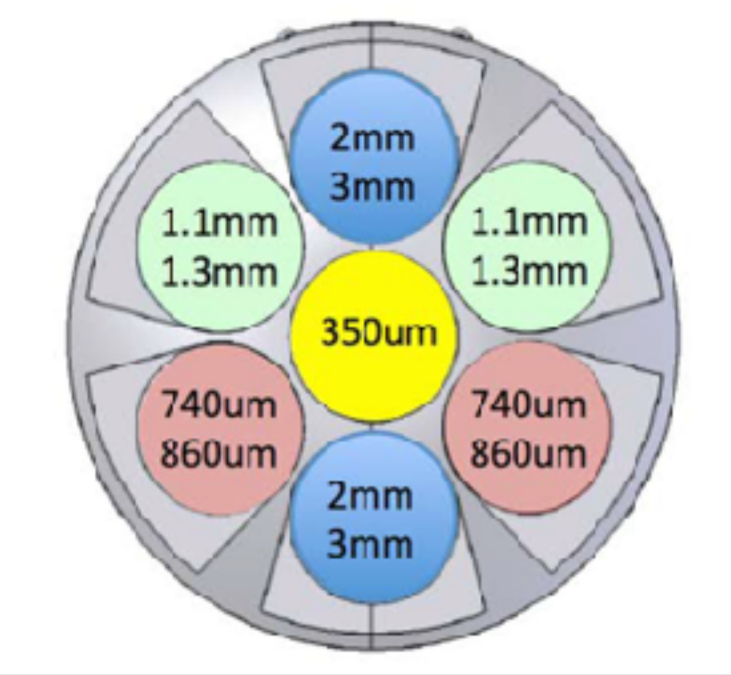
(Battaglia et al. 2017)

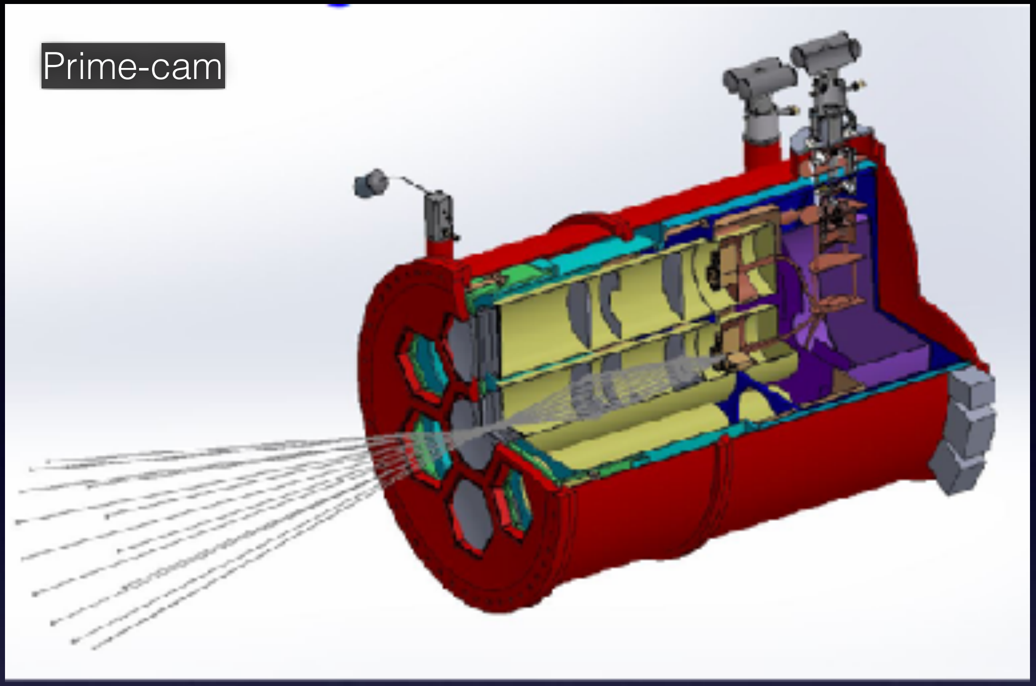


(results from stacking)

A German contribution for the CCAT-p CMB science?

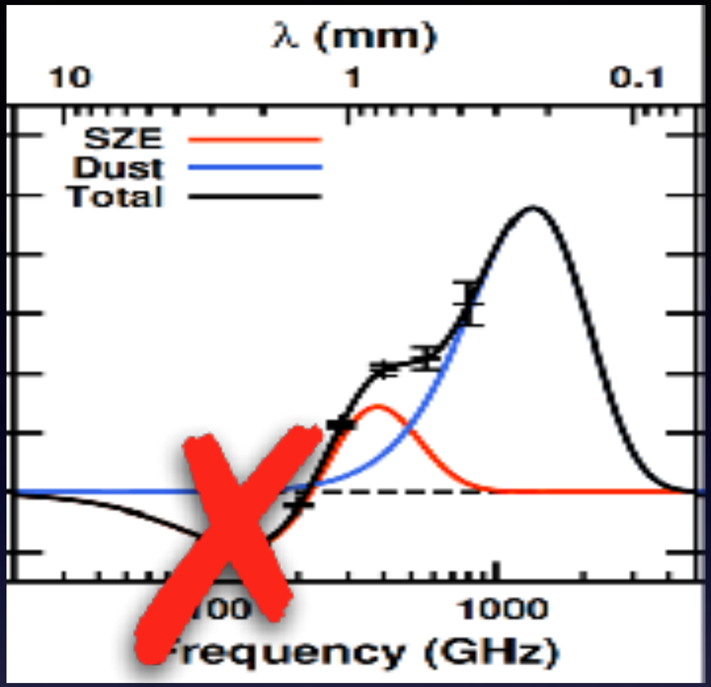


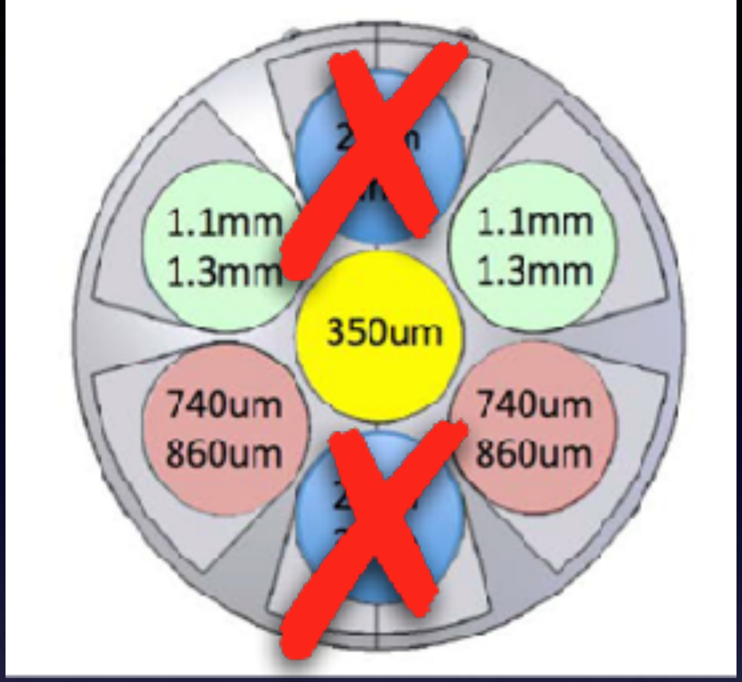


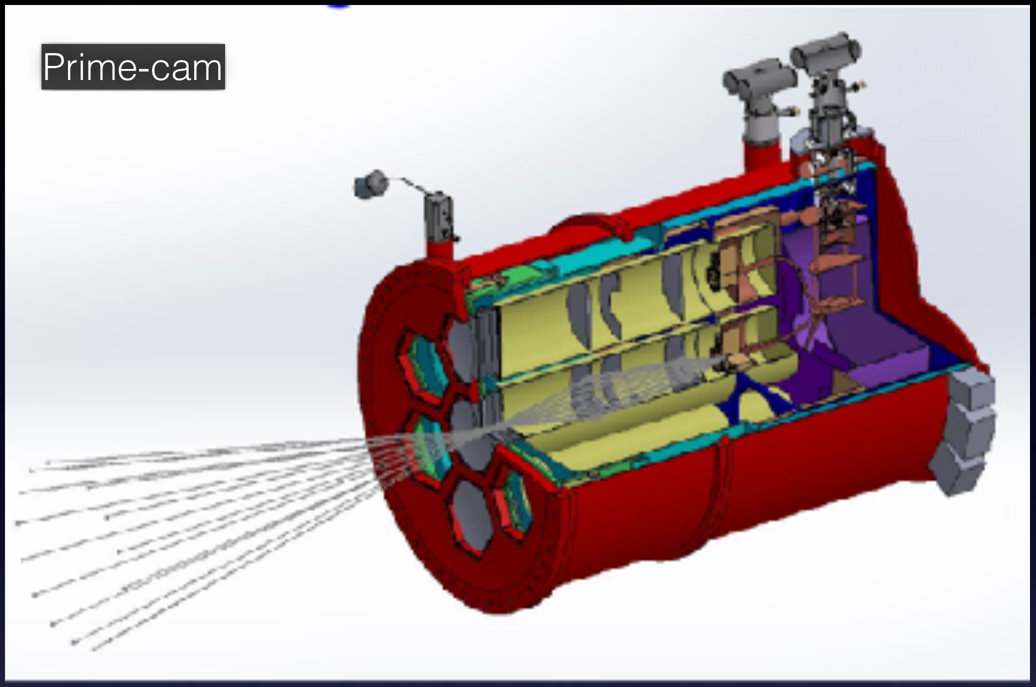


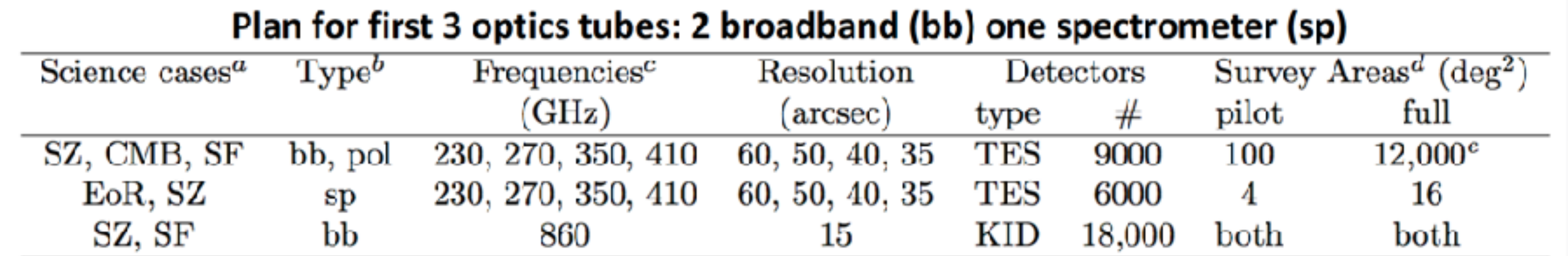
The original 7-frequency SZ camera design

A German contribution for the CCAT-p CMB science?









Plan for first 3 optics tubes: 2 broadband (bb) one spectrometer (sp)

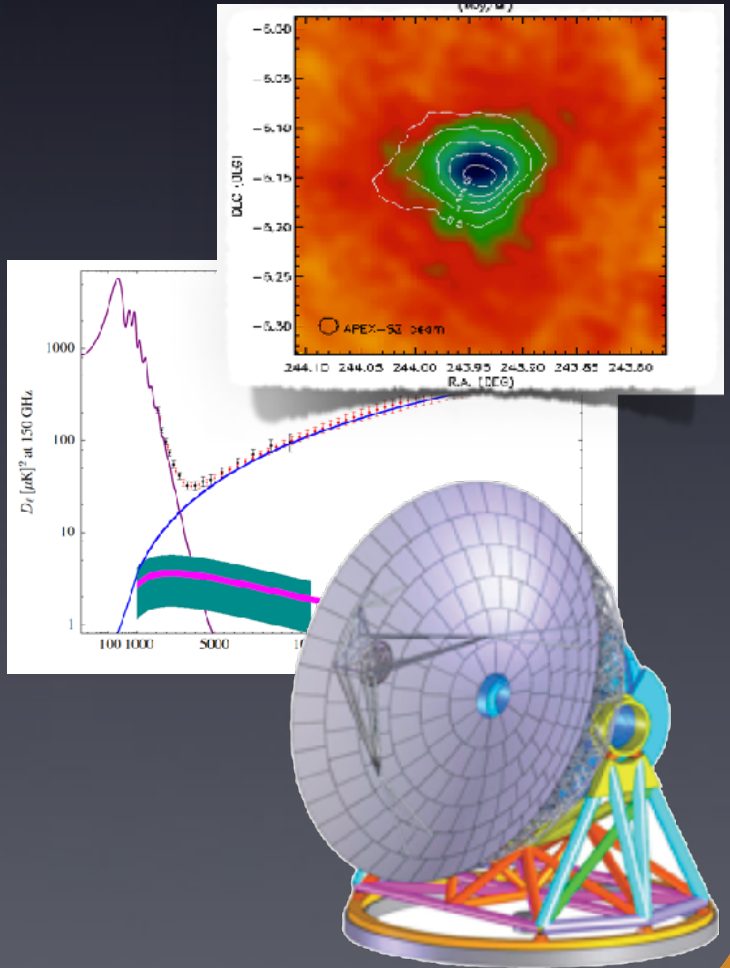
Science cases[a]	Type[b]	Frequencies[c] (GHz)	Resolution (arcsec)	Detectors type	#	Survey Areas[d] (deg^2) pilot	full
SZ, CMB, SF	bb, pol	230, 270, 350, 410	60, 50, 40, 35	TES	9000	100	12,000[e]
EoR, SZ	sp	230, 270, 350, 410	60, 50, 40, 35	TES	6000	4	16
SZ, SF	bb	860	15	KID	18,000	both	both

Unknown systematics from cross-telescope data combination

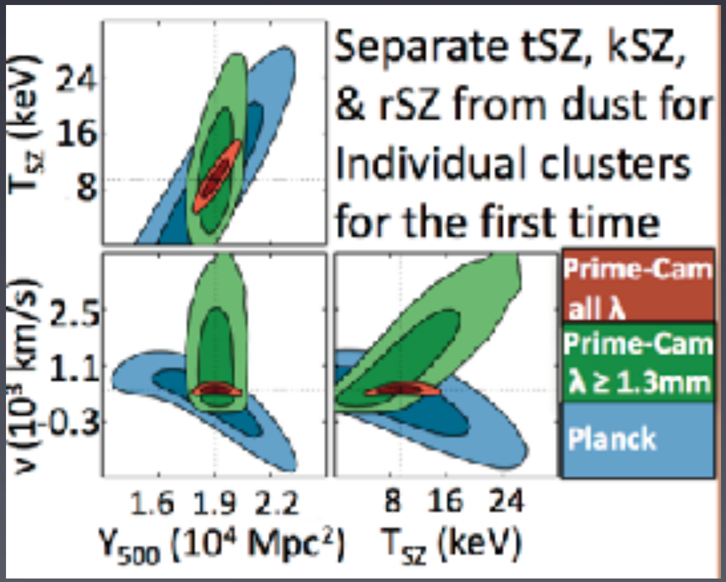
(and possibly reduced sensitivity) ➡ ***Ideal to have in-built mm bands***

Take home points

A broad-spectrum of SZ science leading to our work on the CCAT-prime



CCAT-prime's unique ability is accurate modelling of multiple SZ components in presence of foregrounds – particularly cluster dust



Separate tSZ, kSZ, & rSZ from dust for Individual clusters for the first time

Losing the 2 & 3 mm bands from the survey camera may not be the best option – German contribution?