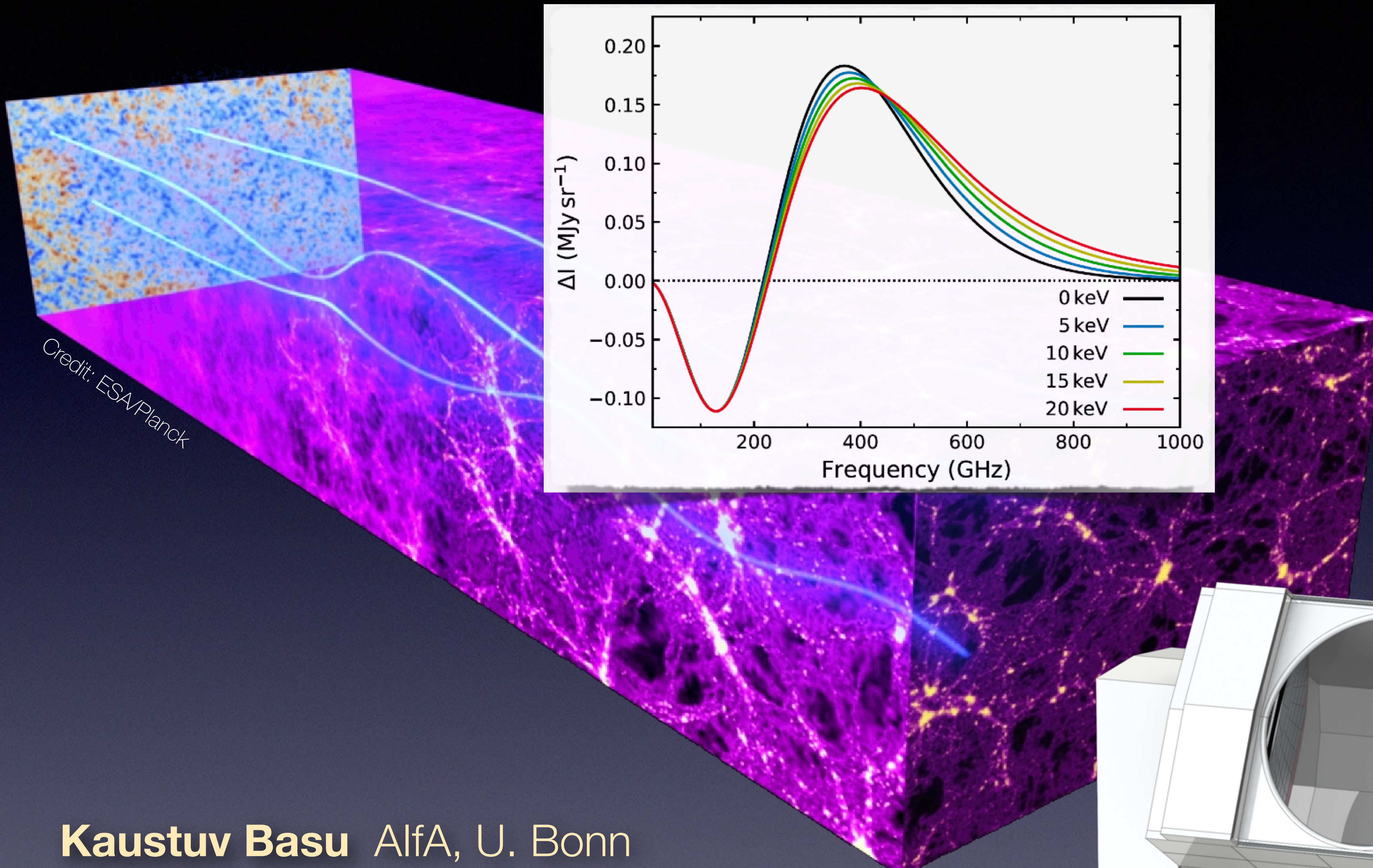
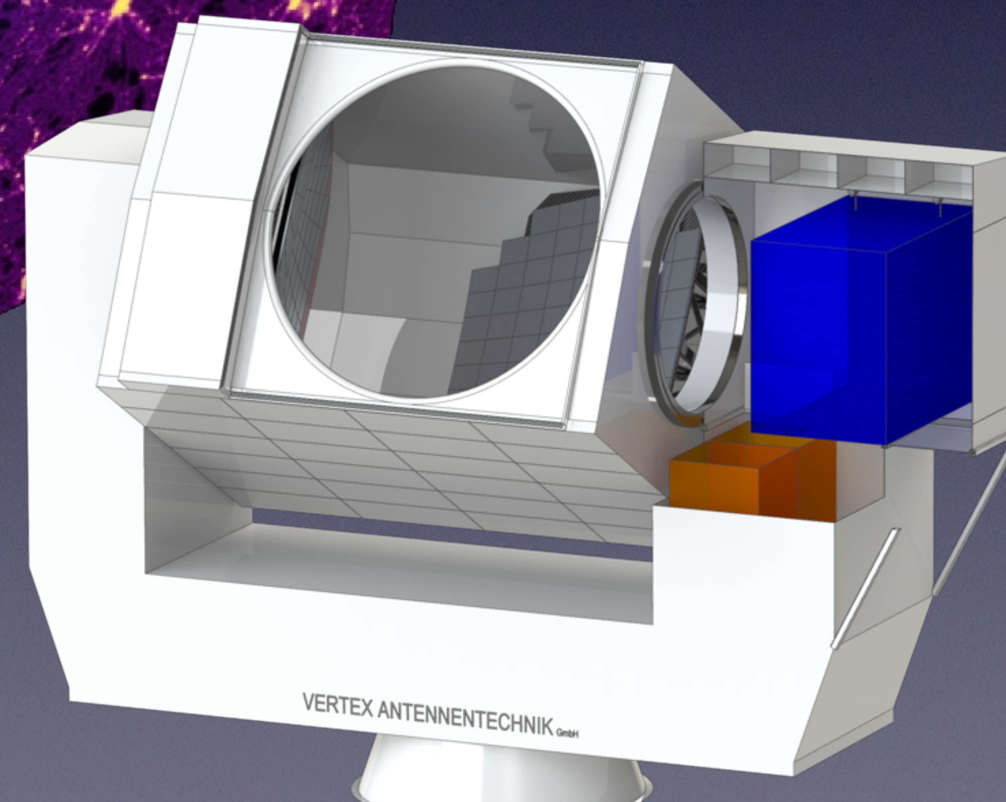
New Frontiers of SZ Effect Observations





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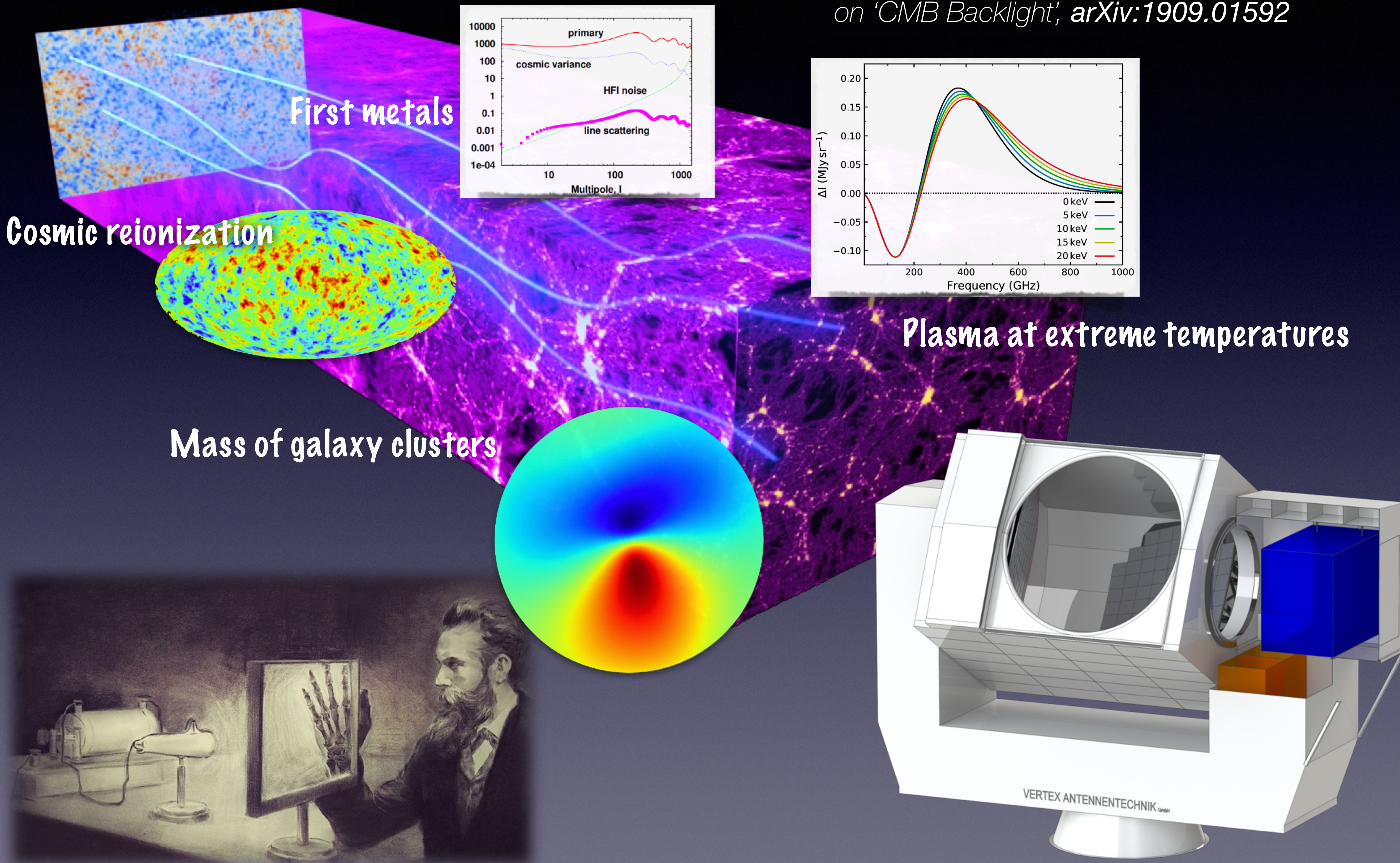
This talk in two parts

- Current status of SZ effect observation, featuring the upcoming CCAT-prime (renamed FYST)
- SZ take on modelling radio halos and relics

Omitting many other potential SZ applications relevant for low-frequency surveys, e.g., kSZ-21 cm correlation

The CMB as a Backlight

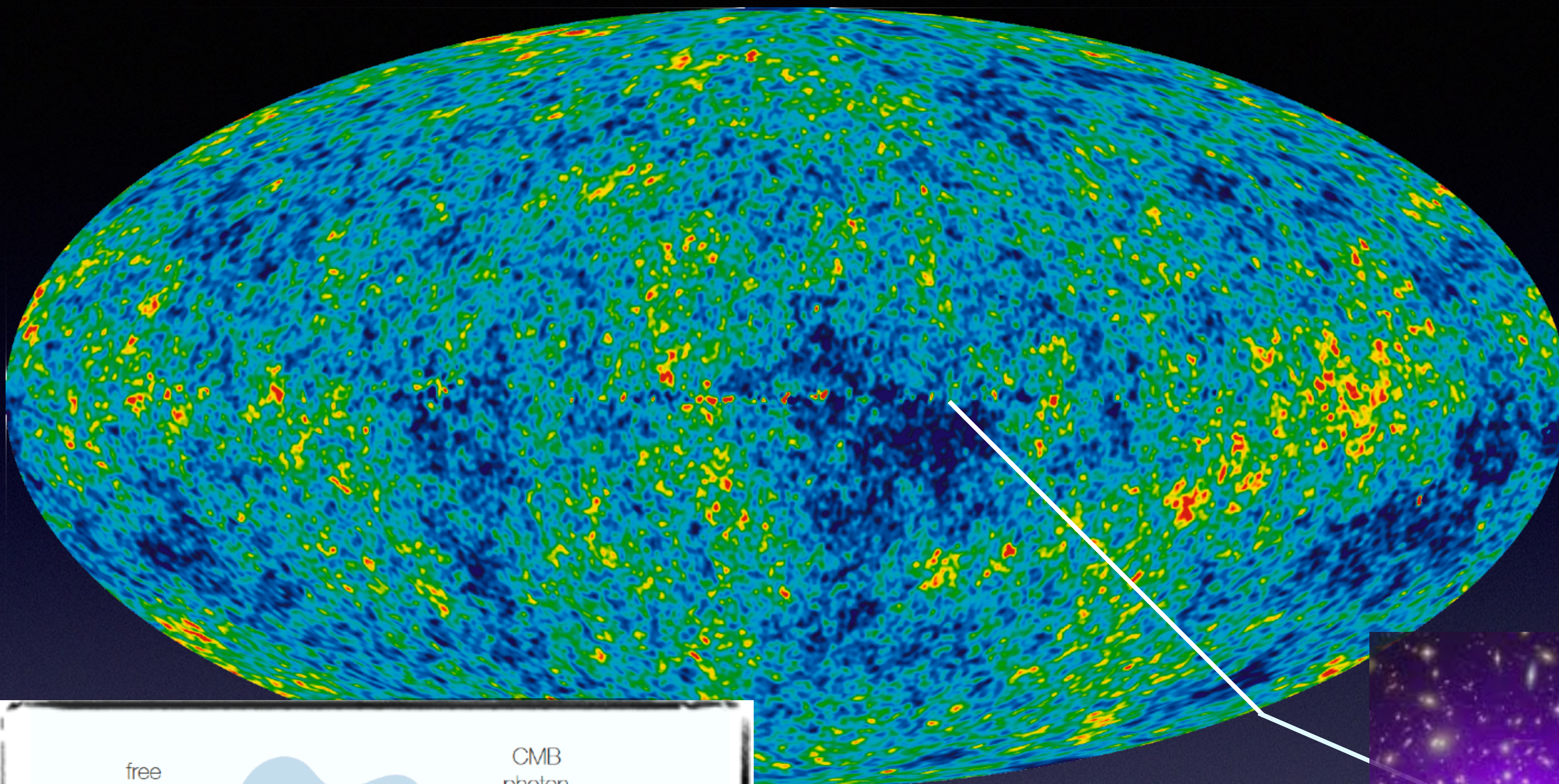
*See, e.g., ESA Voyage 2050 science paper on 'CMB Backlight', **arXiv:1909.01592***

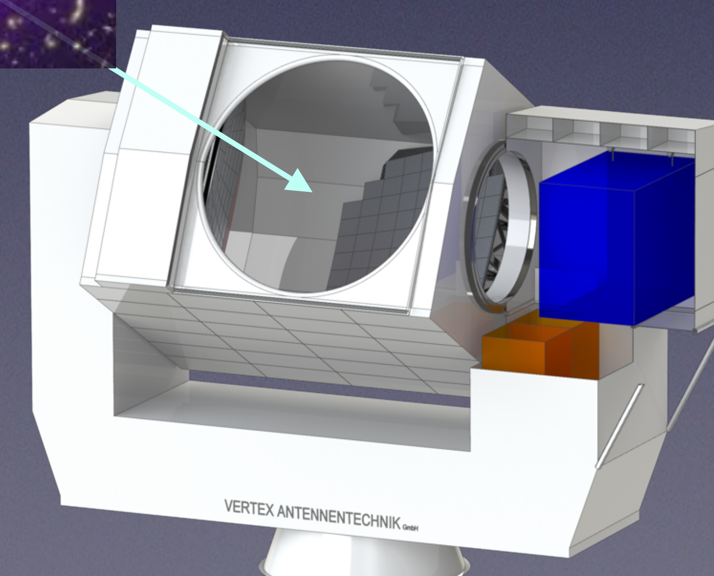


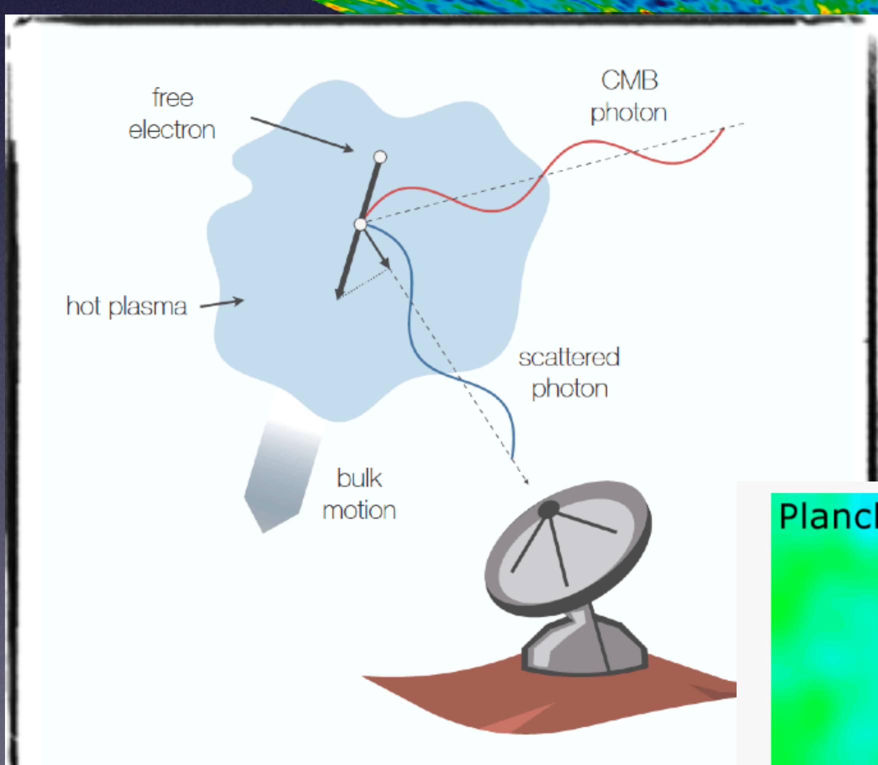
Scattering & the SZ effect

I. Lensing

II. Scattering

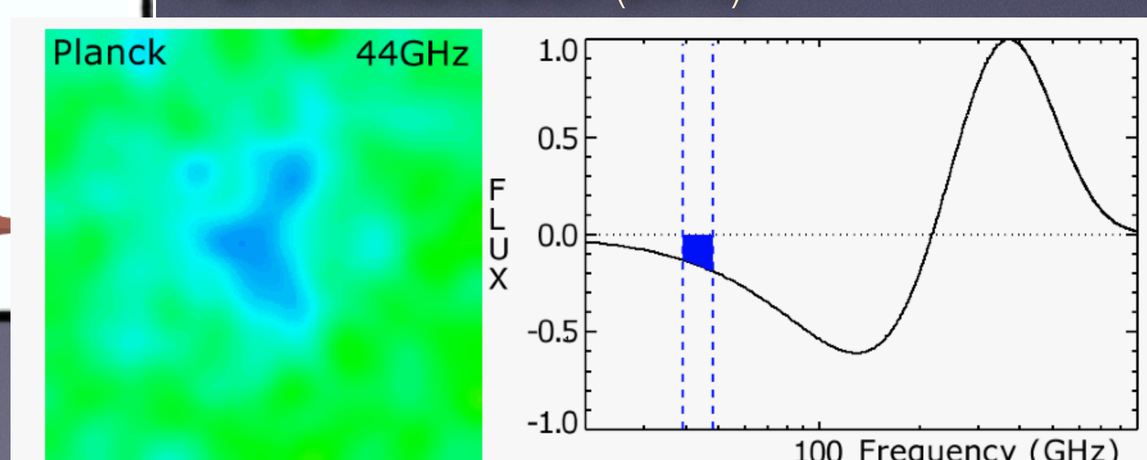




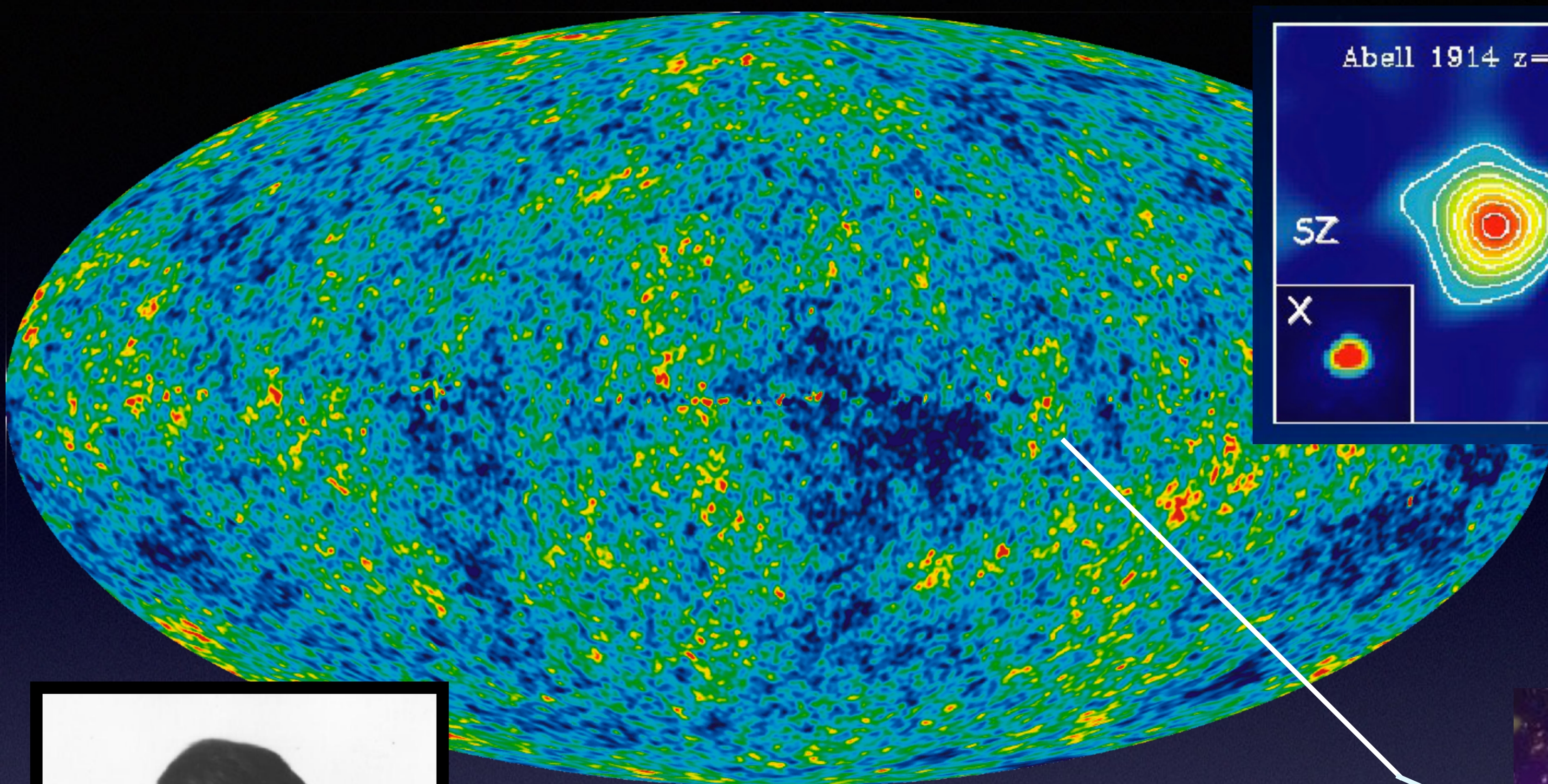


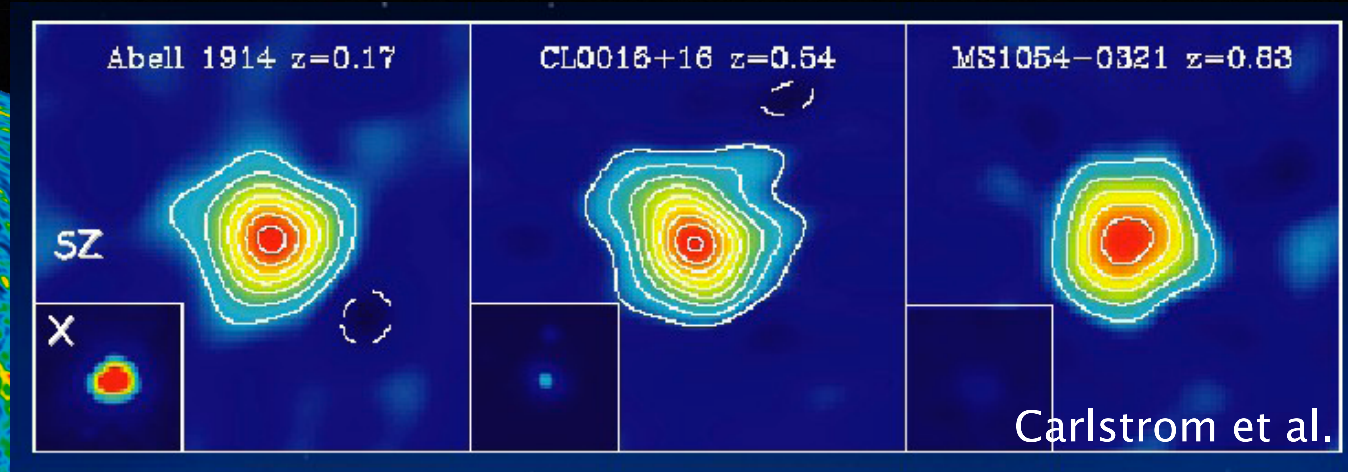
Mroczkowski, Nagai, Basu+ 2019

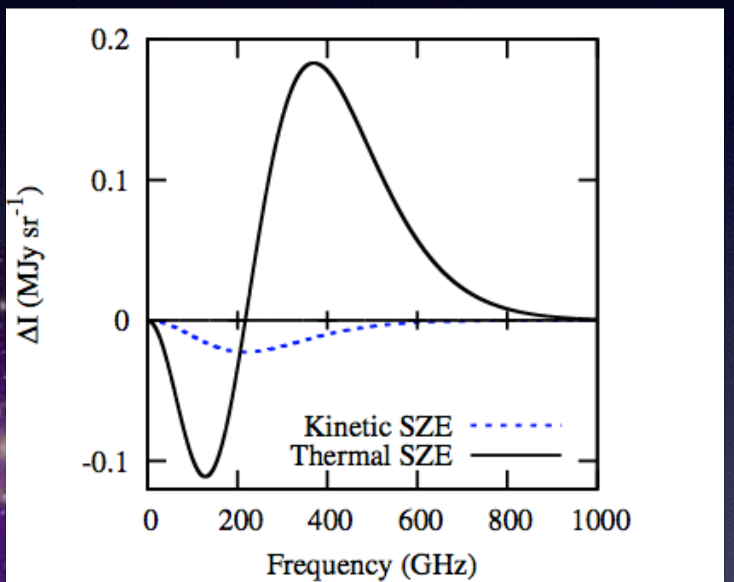
Planck collaboration (2015)



The thermal SZ (tSZ) effect

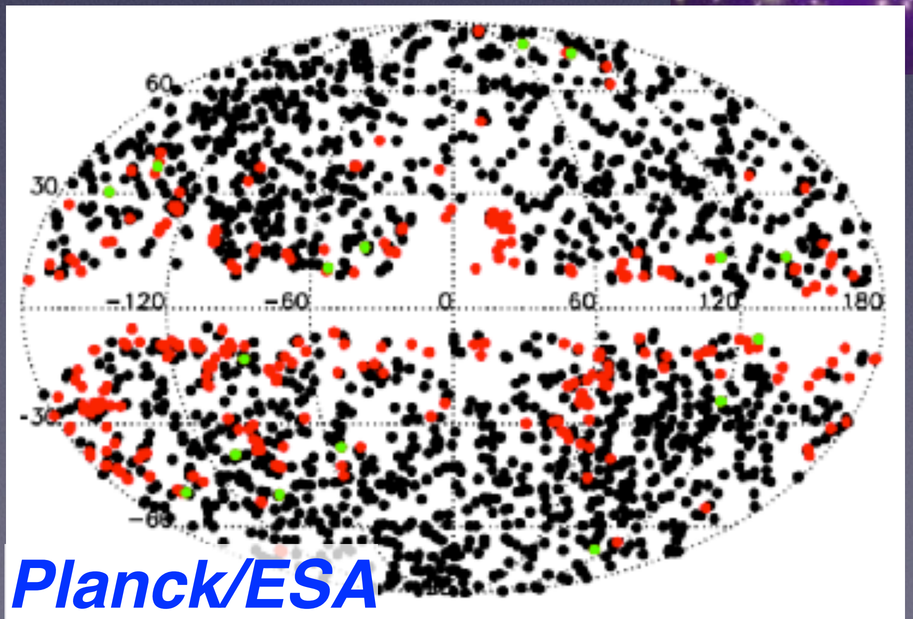




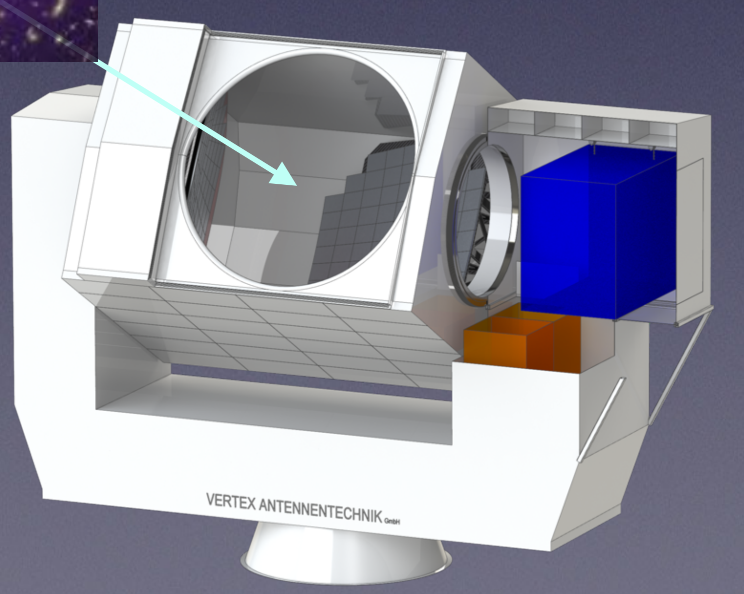


$$\frac{\Delta n}{n_0} = \frac{\Delta J}{J_0} = xy\,\frac{e^x}{e^x - 1}\left\{\frac{x}{\tanh(x/2)} - 4\right\}.$$

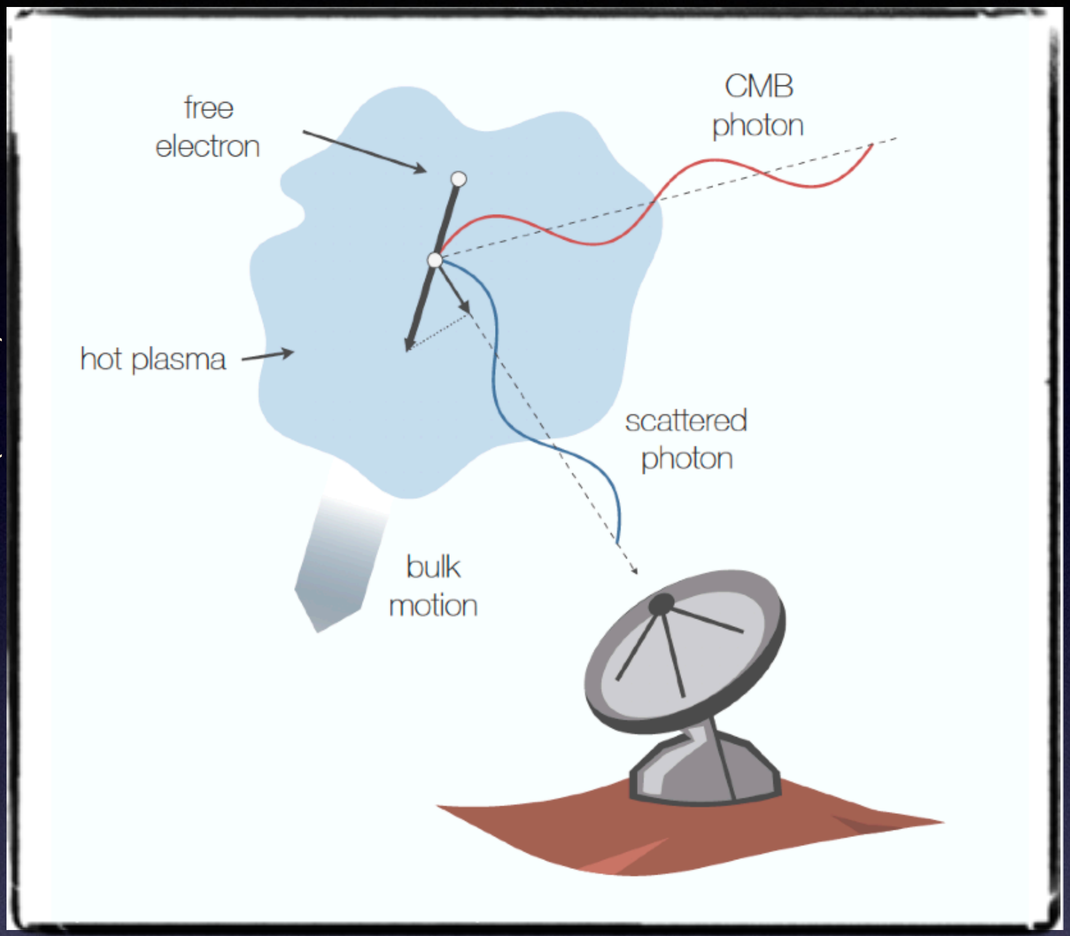
Sunyaev & Zeldovich, 1972



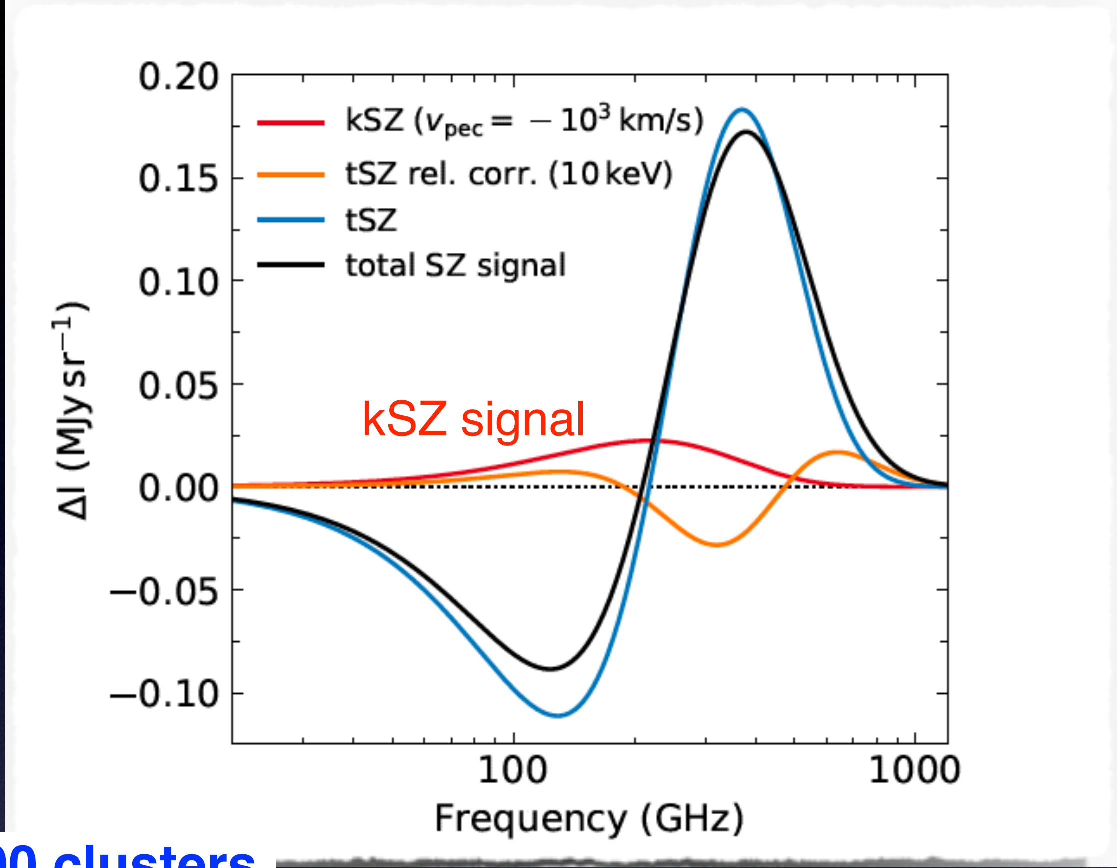
Planck/ESA



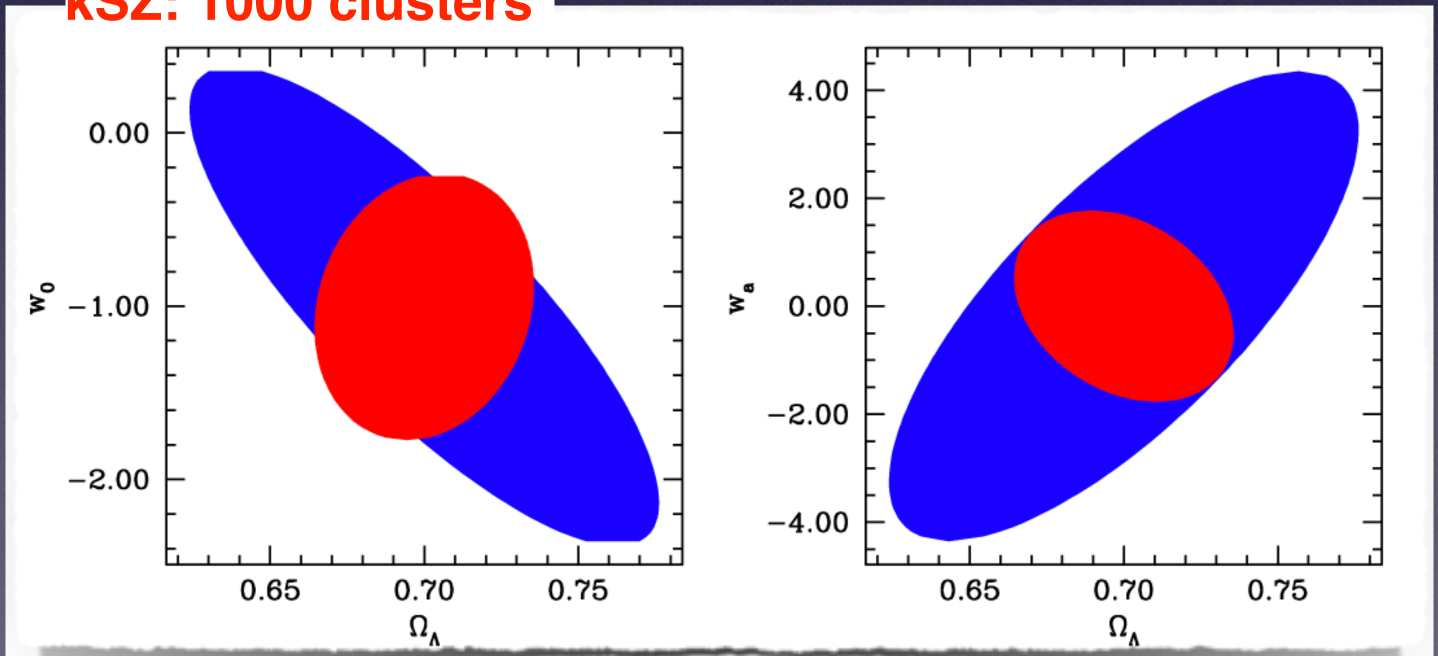
The kinematic SZ (kSZ) effect



Mroczkowski et al. (2019)



tSZ : 4000 clusters
kSZ: 1000 clusters

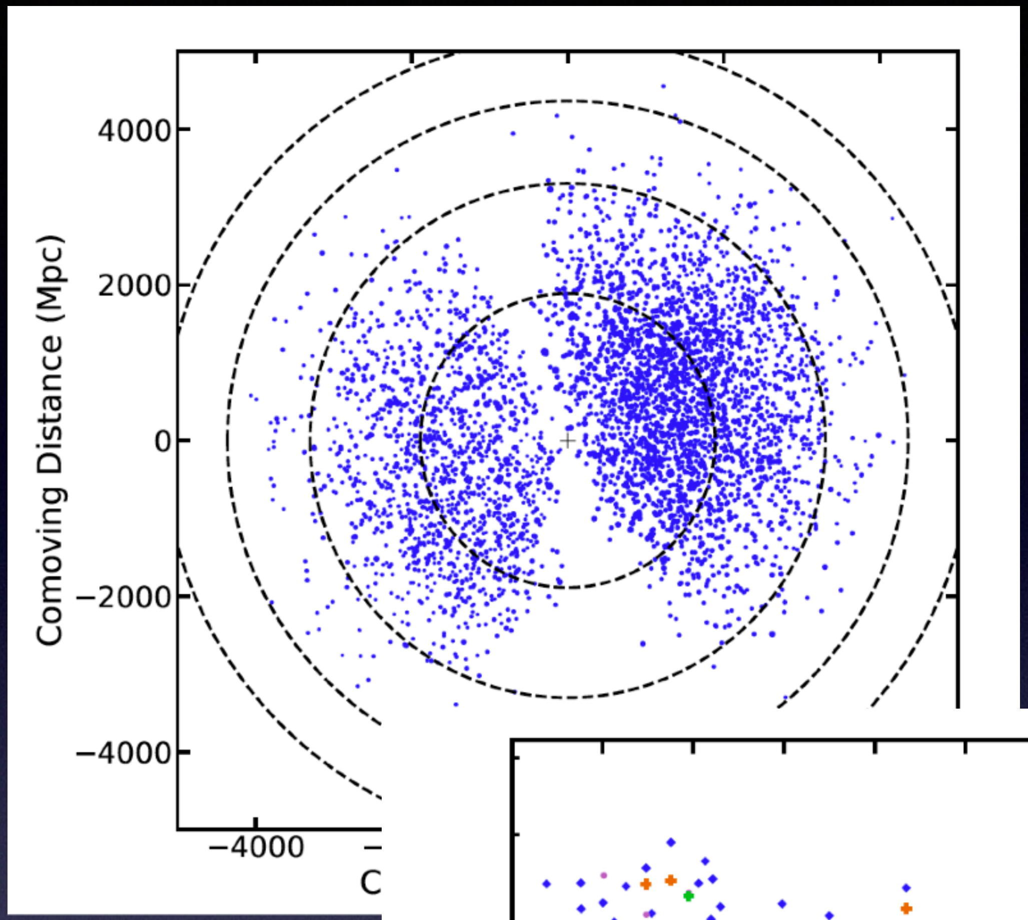


Dark energy parameter constraints from a CCAT 25m-like survey, with σ_v=100 km/s (adapted from Bhattacharya & Kosowsky 2008)

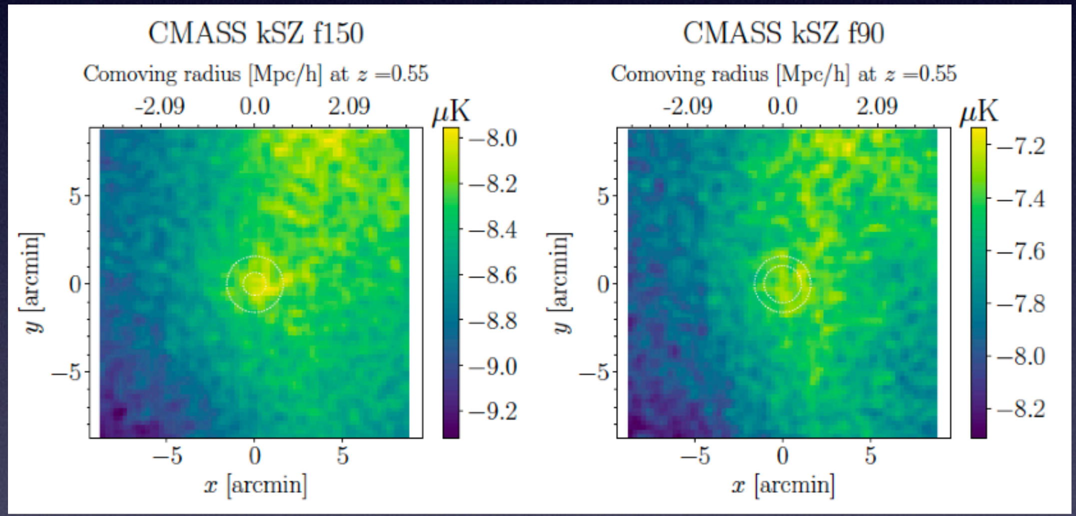
kSZ provides estimates for the **peculiar velocities**, and in the limit of the linear perturbation theory, directly the **growth rate**

$$\vec{v}(\vec{k}) = i\frac{d\ln D}{d\ln a}\frac{aH\delta(\vec{k})\vec{k}}{k^2}$$

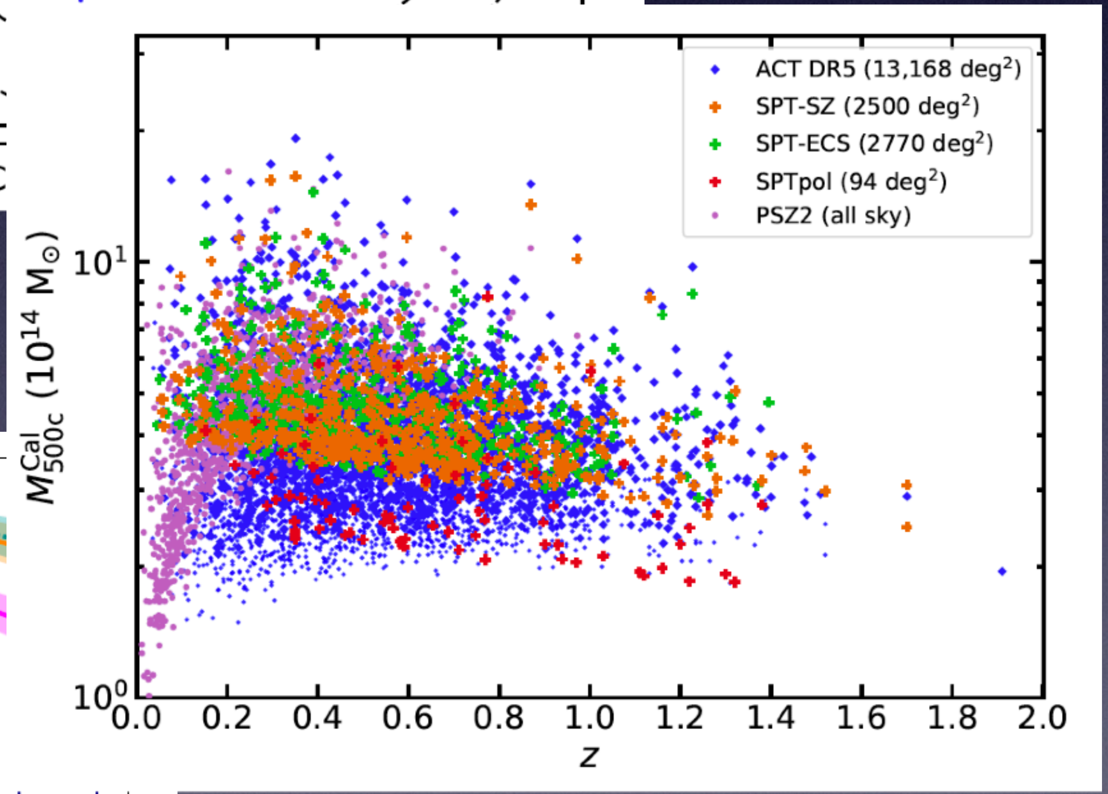
SZ state-of-the-art: ACT 2020 results

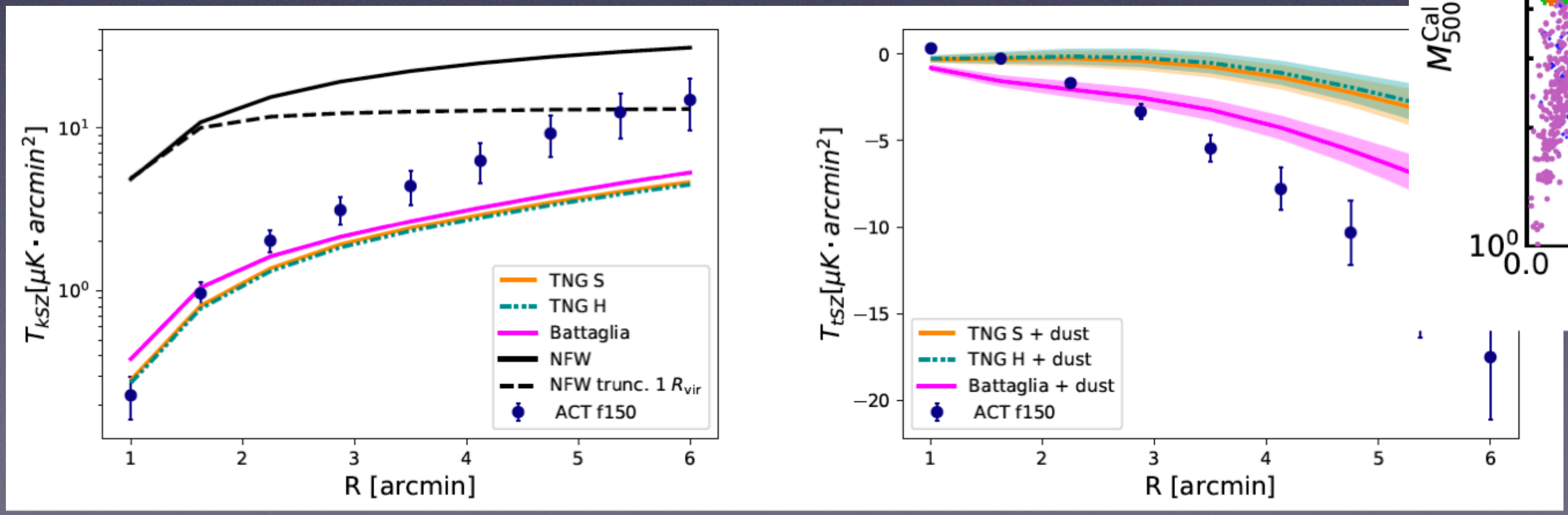


4000+ clusters
(Hilton+ 2020)



kSZ ~ tSZ
($v_r/c \sim kT/mc^2$)

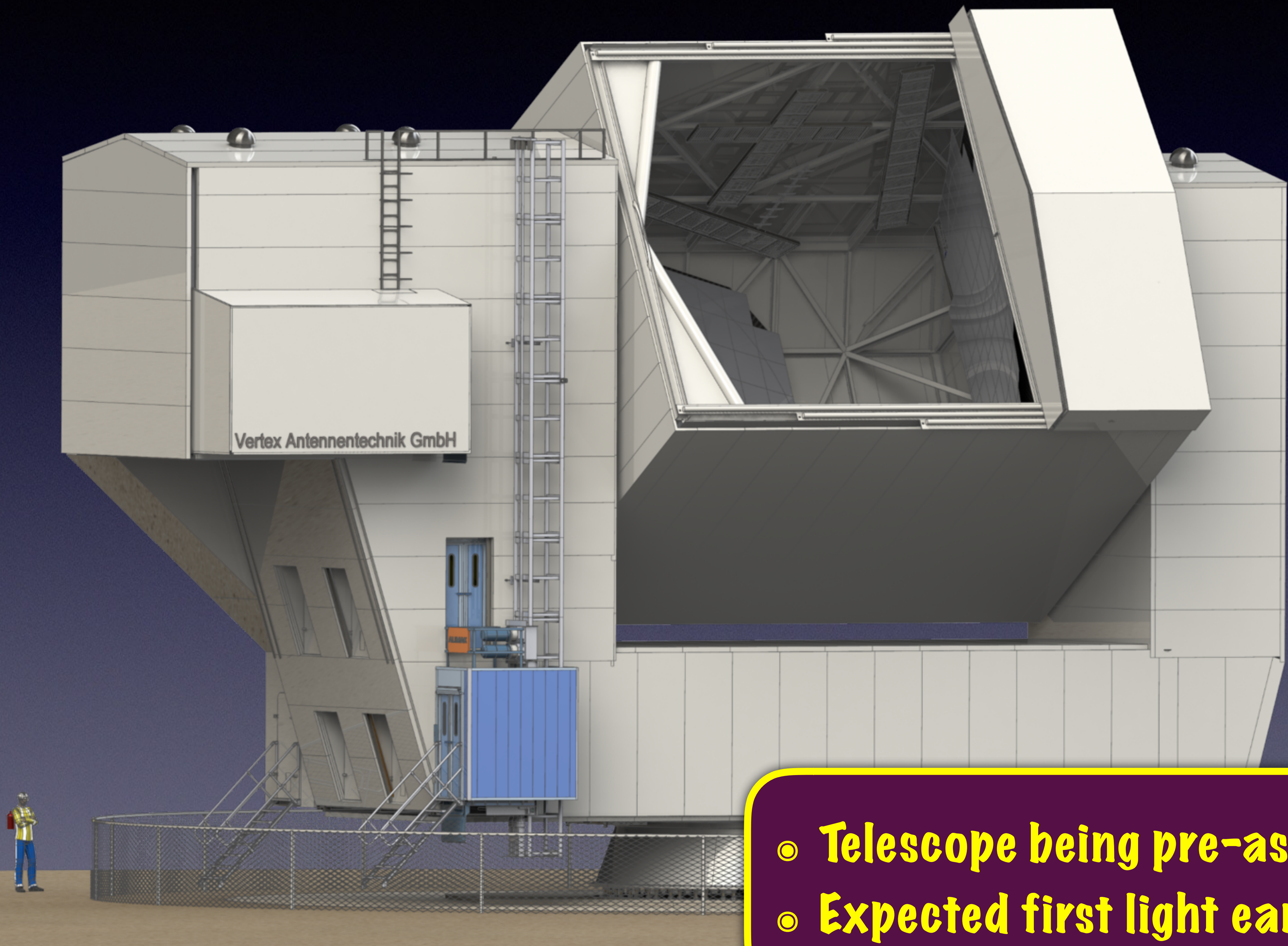




Halo thermodynamic modelling
(Schaan+, Amodeo+ 2020)

FYST (formerly CCAT-prime)

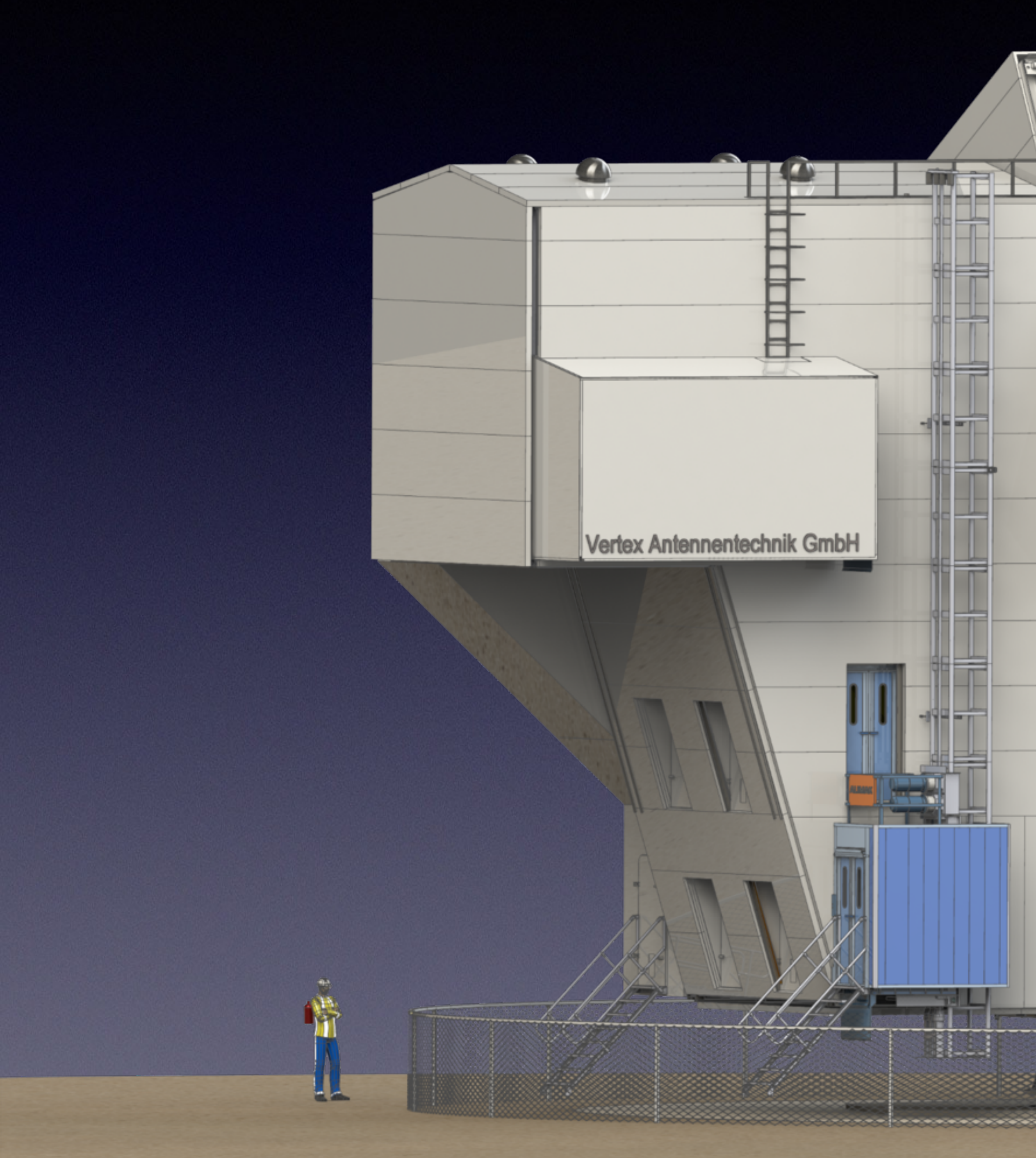
A high throughput, high surface accuracy, 6 m aperture submillimeter (λ = 0.2–3 mm) telescope for dedicated surveys

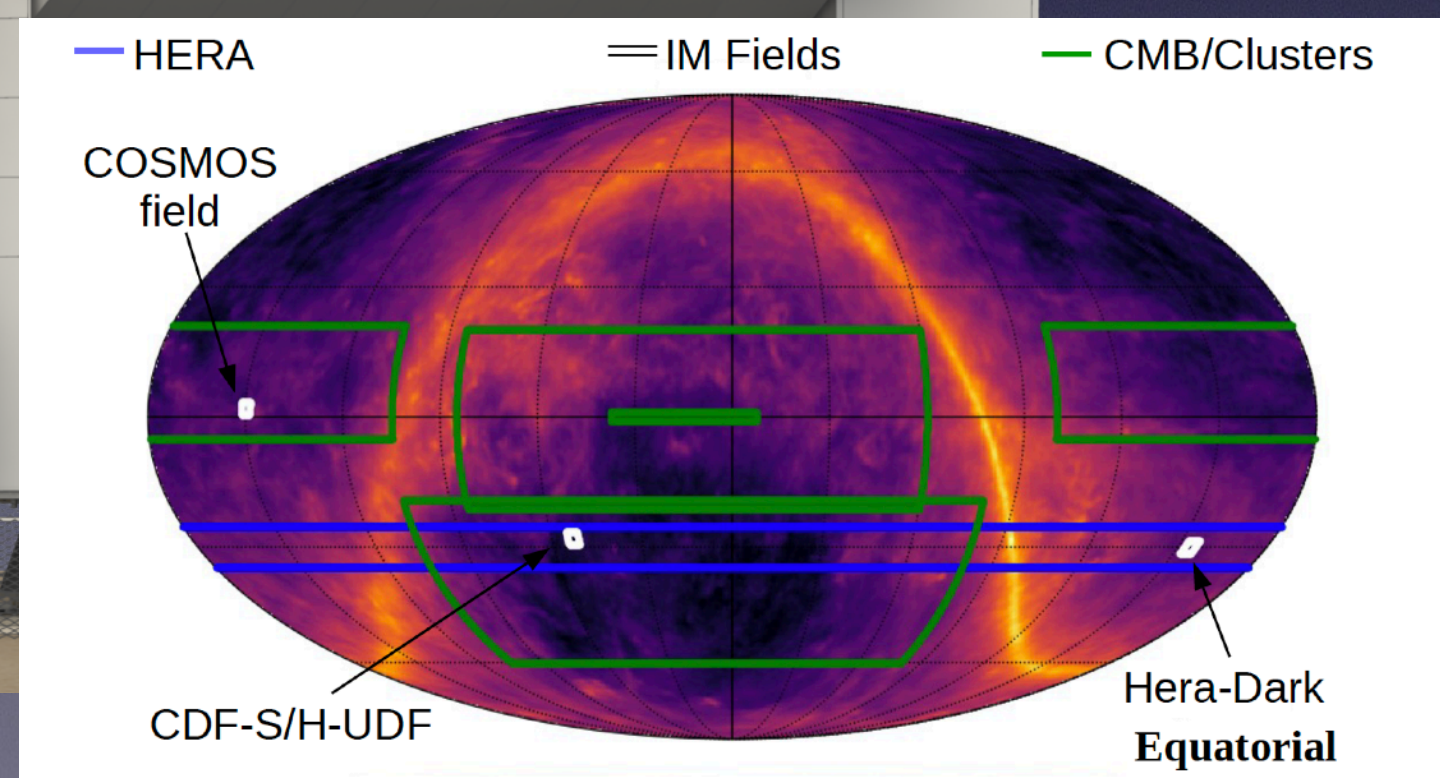


- Telescope being pre-assembled
- Expected first light early-2022

FYST (formerly CCAT-prime)

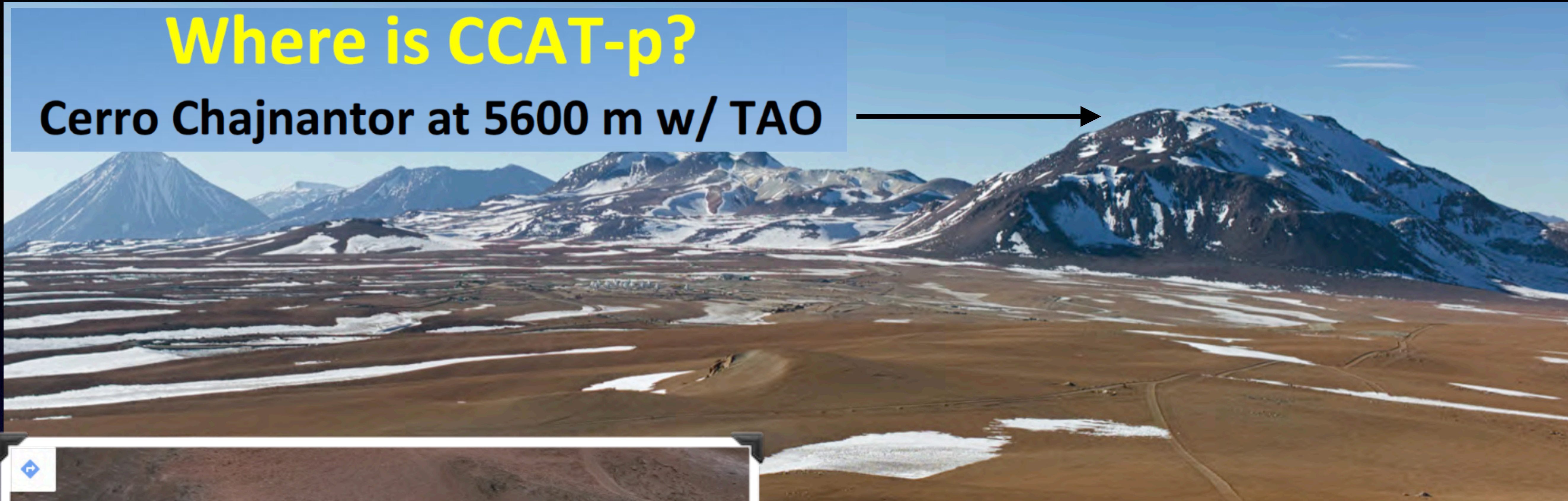
A high throughput, high surface accuracy, 6 m aperture submillimeter (λ = 0.2–3 mm) telescope for dedicated surveys

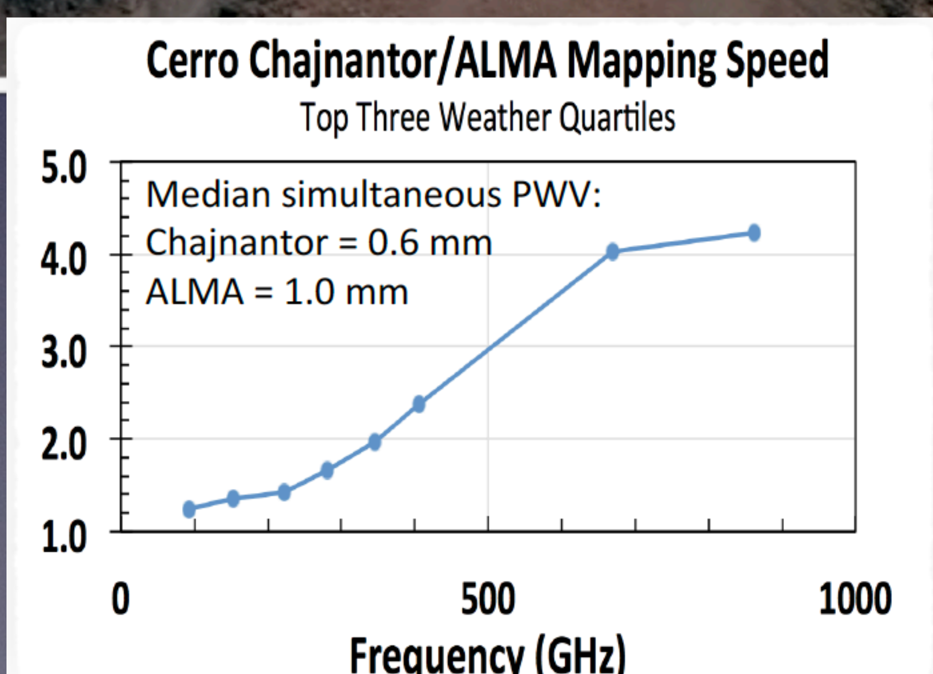


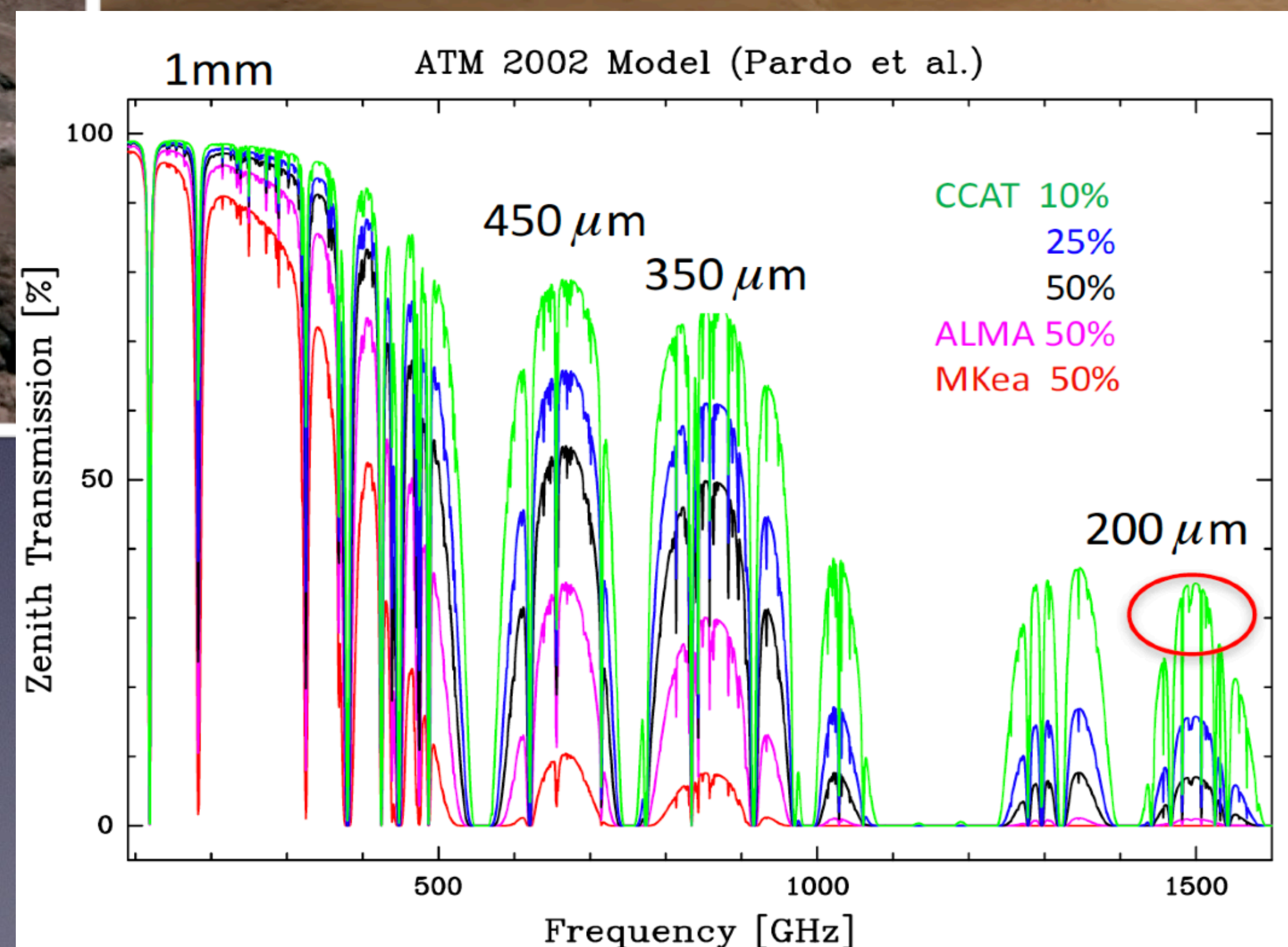


Where is CCAT-p?

Cerro Chajnantor at 5600 m w/ TAO







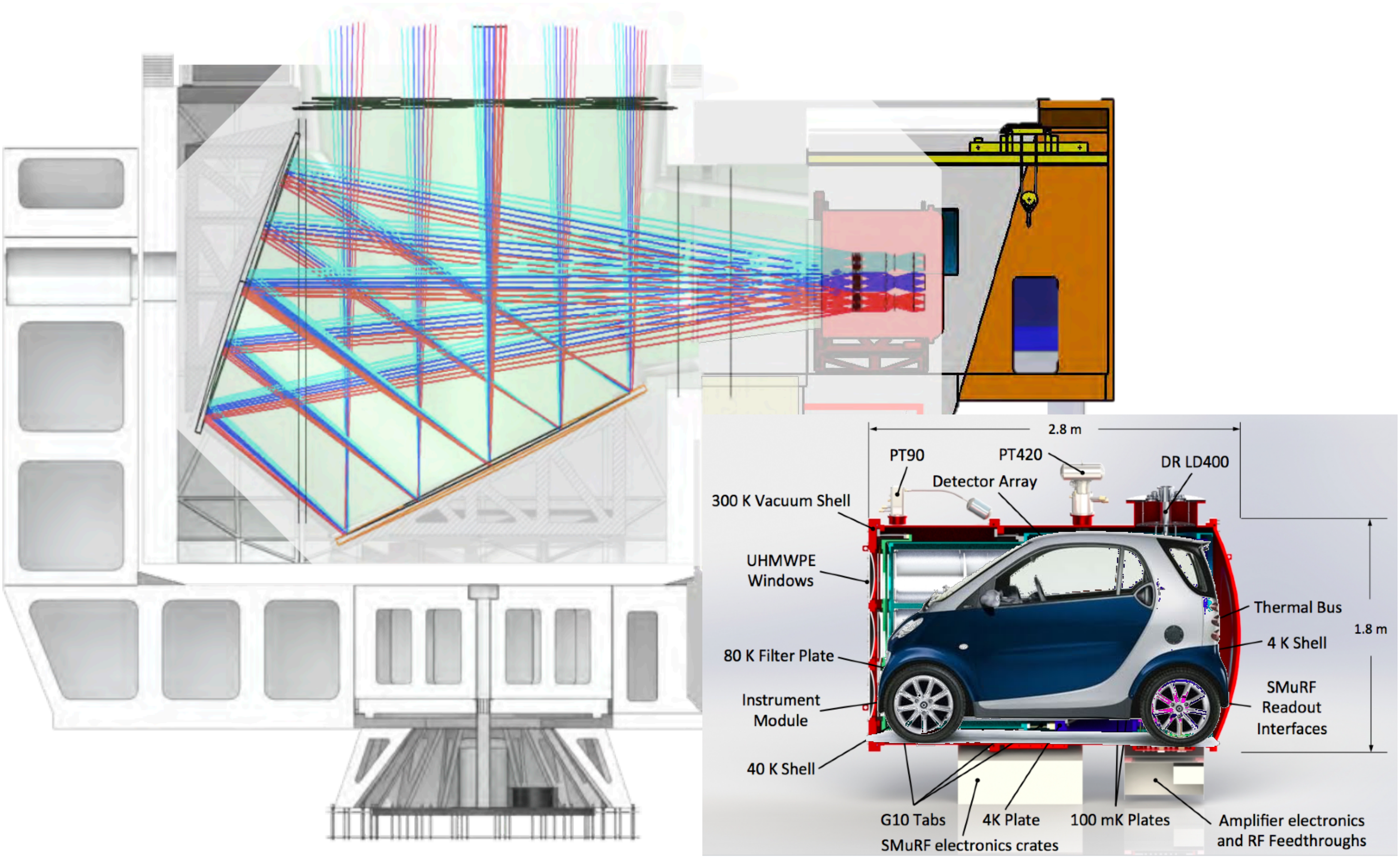
Crossed-Dragone Optics Design

coma-corrected f/2.6 with 5.5m free aperture

high throughput, 8 deg field-of-view, flat focal plane, zero geometric blockage

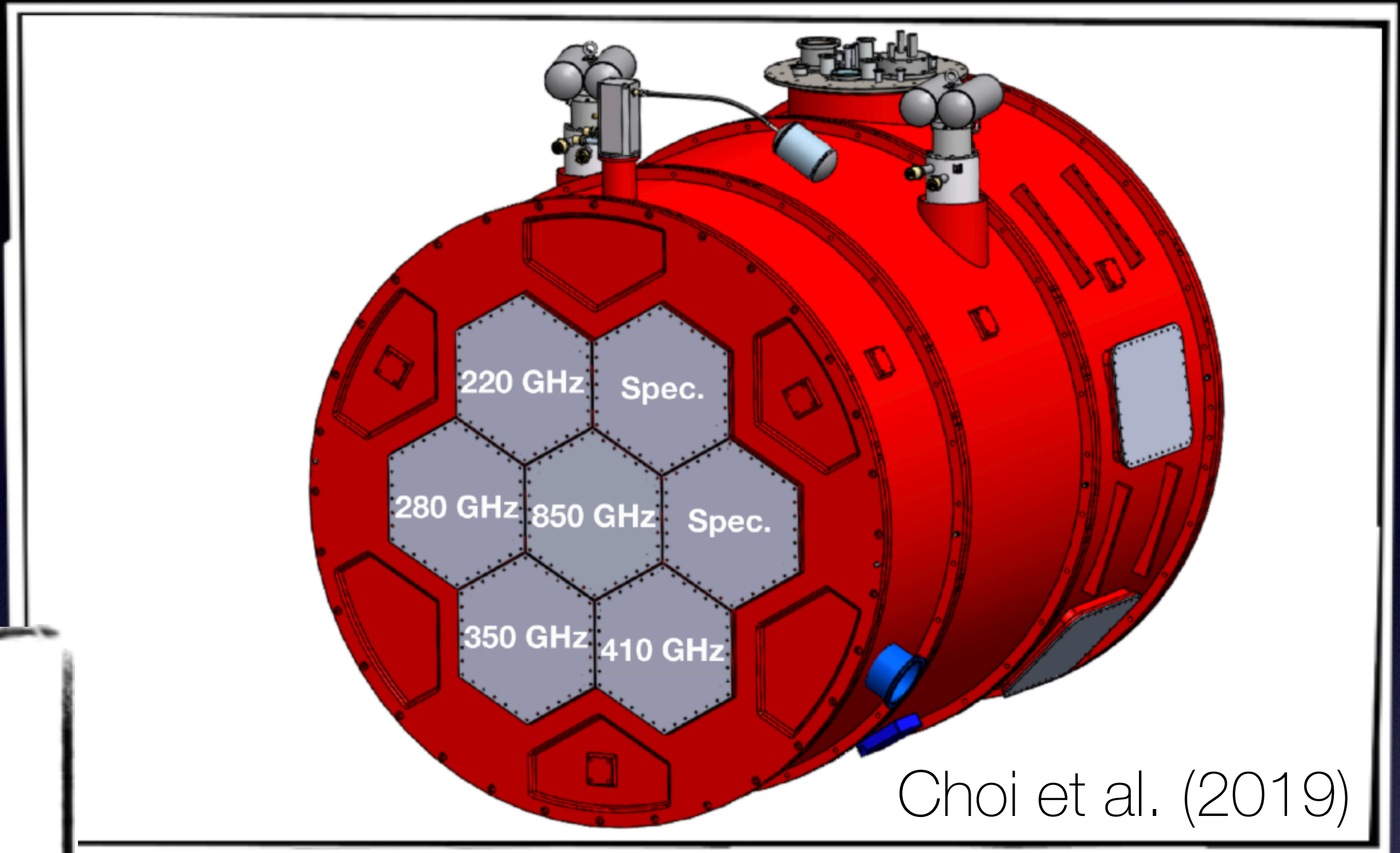
telescope emissivity < 2%, total system emissivity < 7%

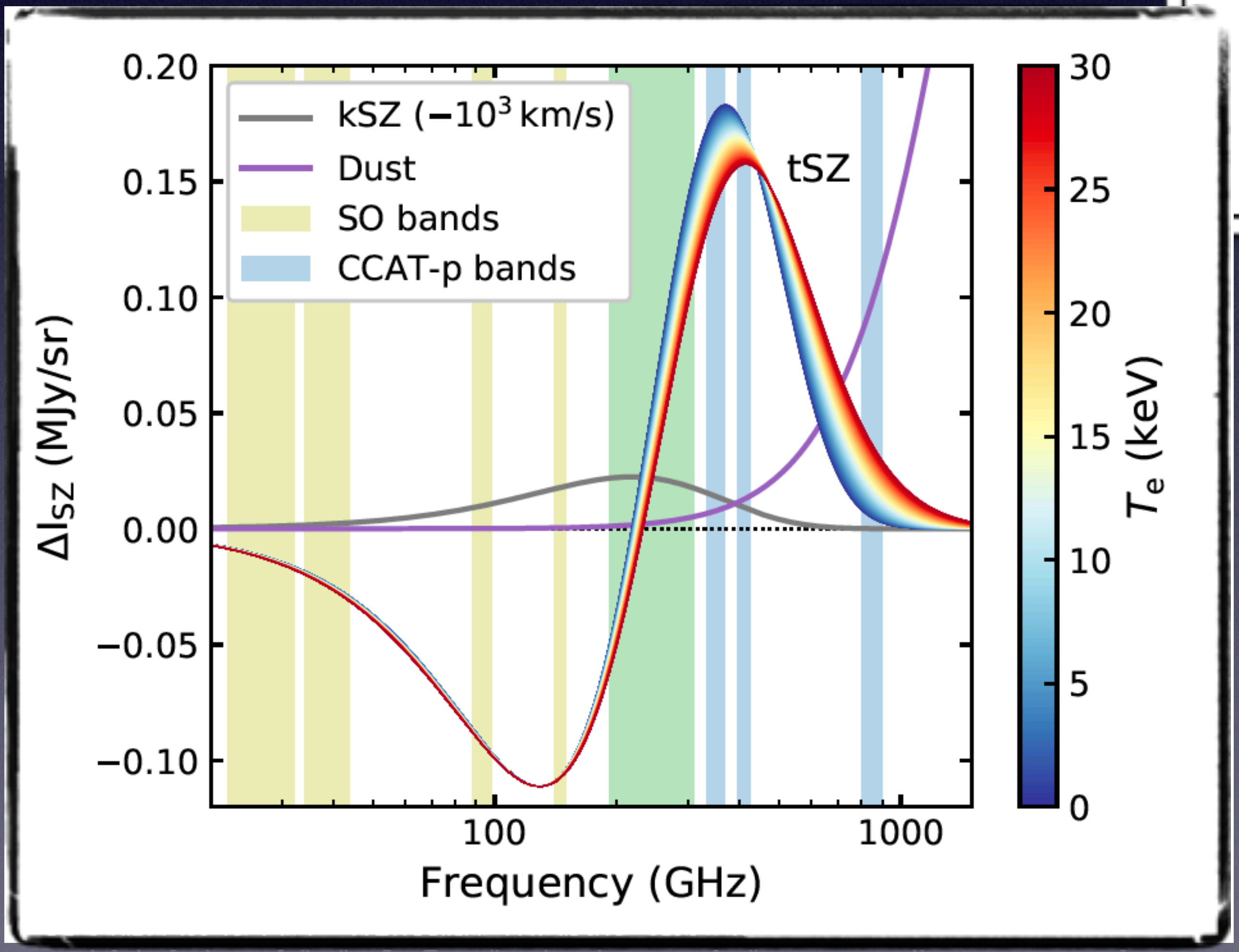
CCAT-p

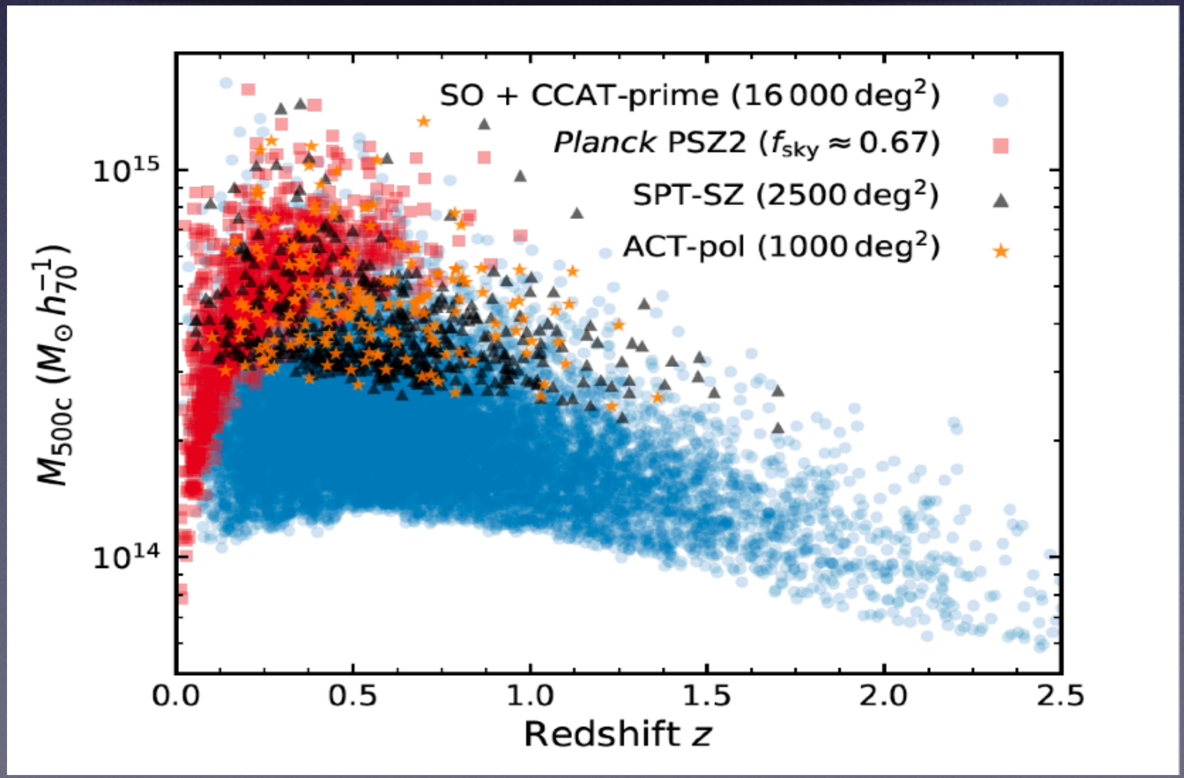


FYST Prime-Cam SZ survey

Prime-Cam will have ∼8,000 KIDs at 220 GHz, ∼10,000 KIDs at 280 GHz, and ∼21,000 KIDs each at 350, 410, and 850 GHz.



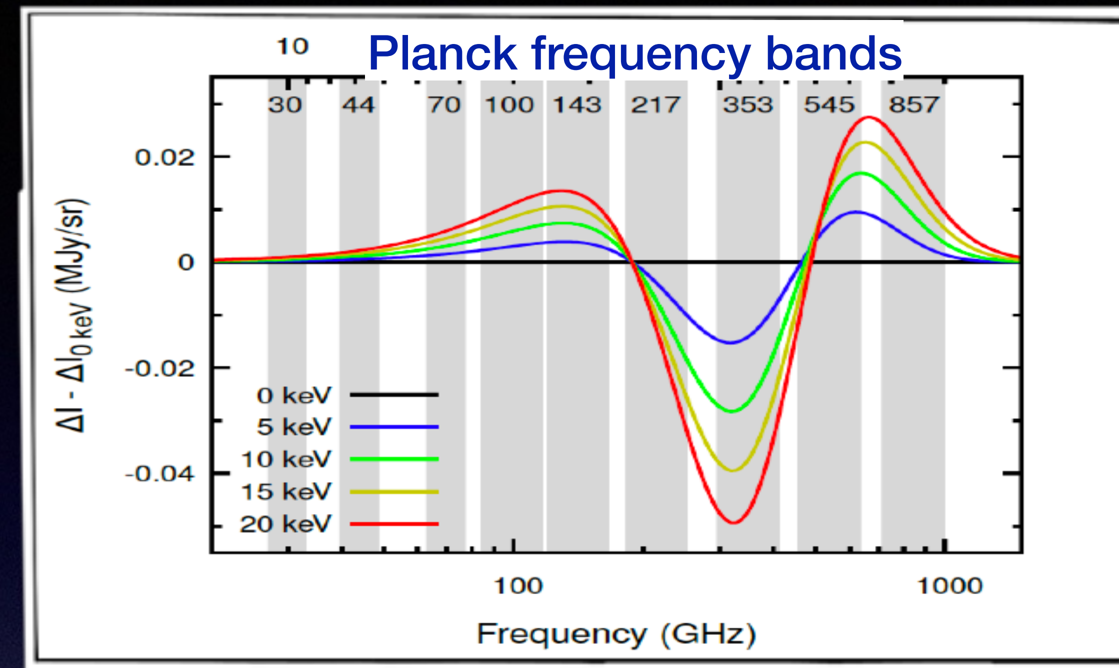


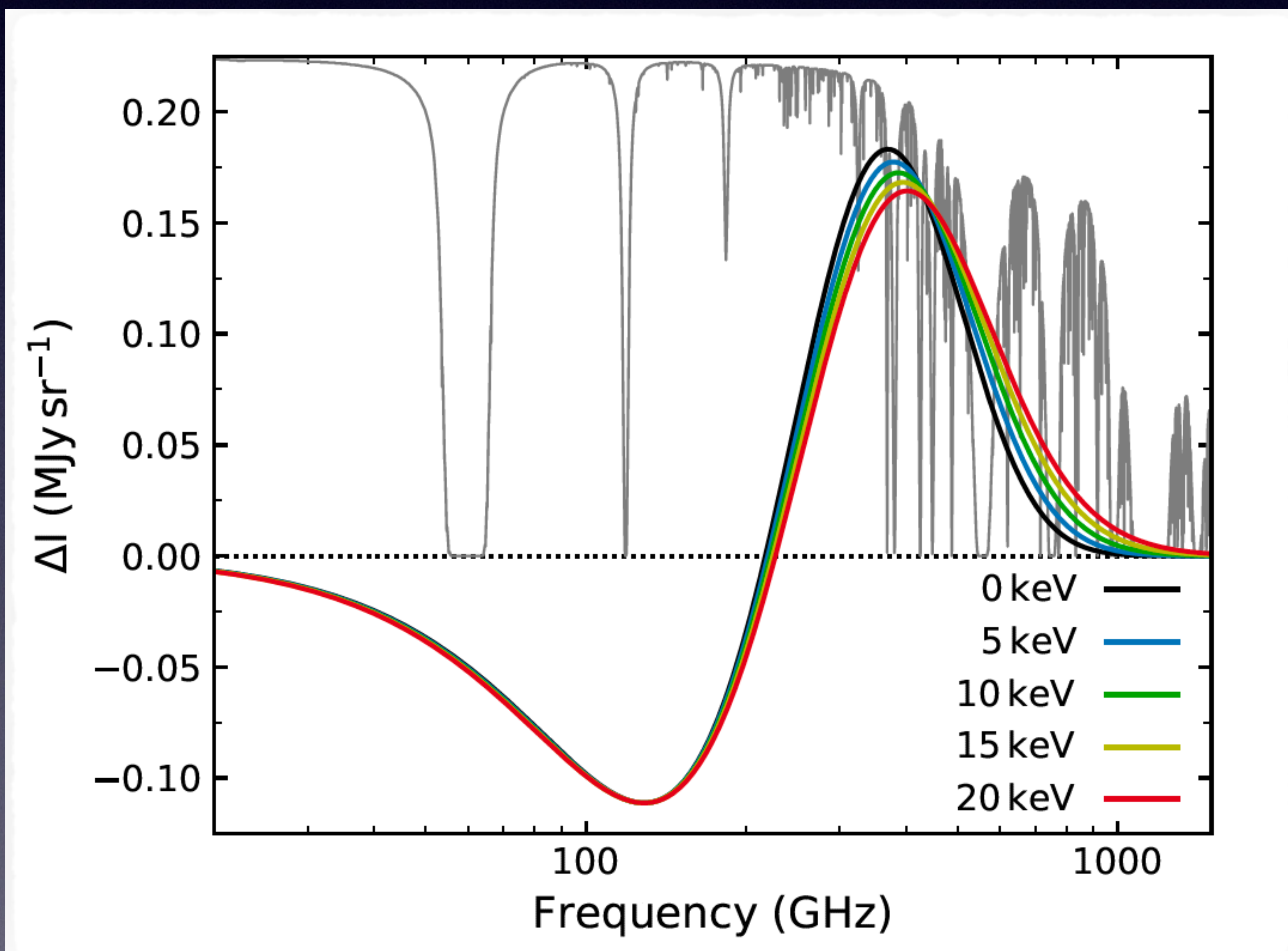


Relativistic SZ (rSZ) effect

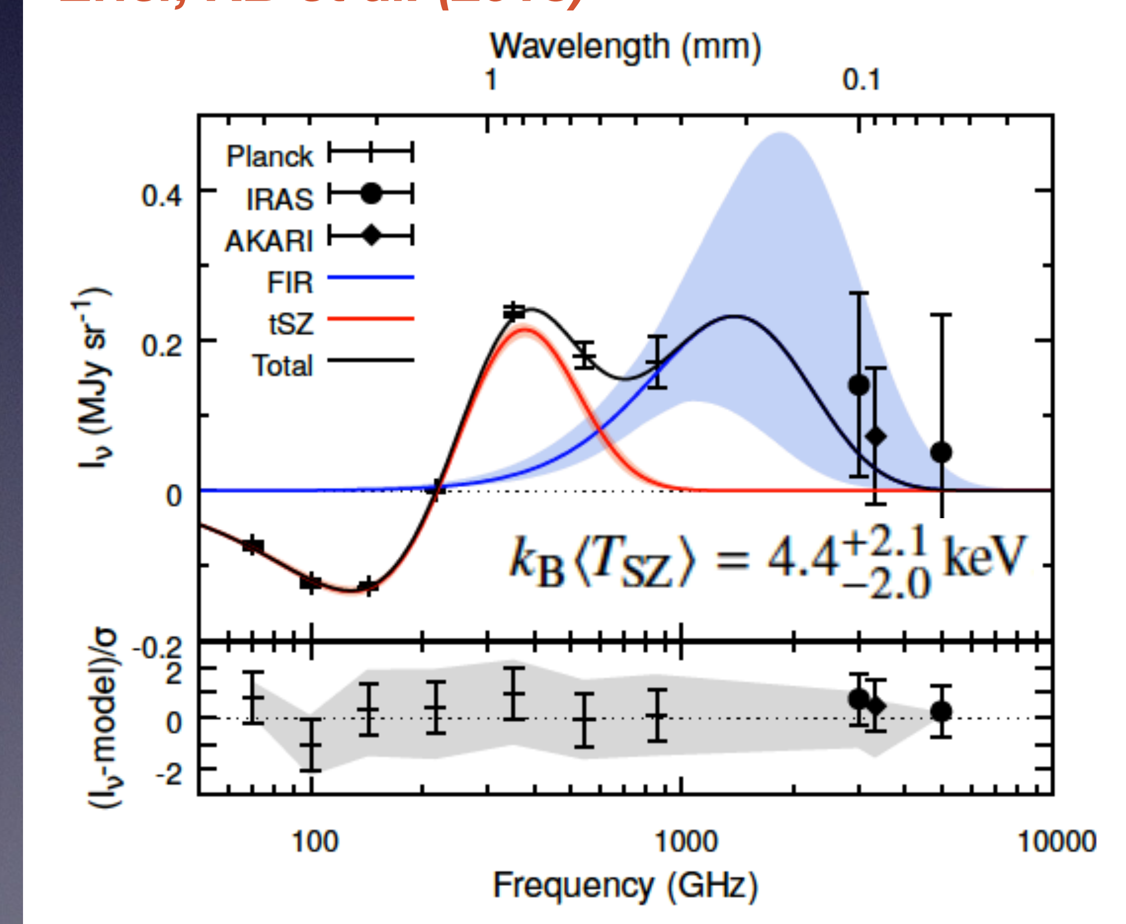
For hot clusters with typical electron energy $kT_e \approx 5$ keV, the relativistic corrections to the SZ spectrum become significant.

$$f(x, T_\mathrm{e}) = \left(x \frac{\exp(x)+1}{\exp(x)-1} - 4 \right) \left(1 + \delta_\mathrm{SZE}(x, T_\mathrm{e})\right)$$





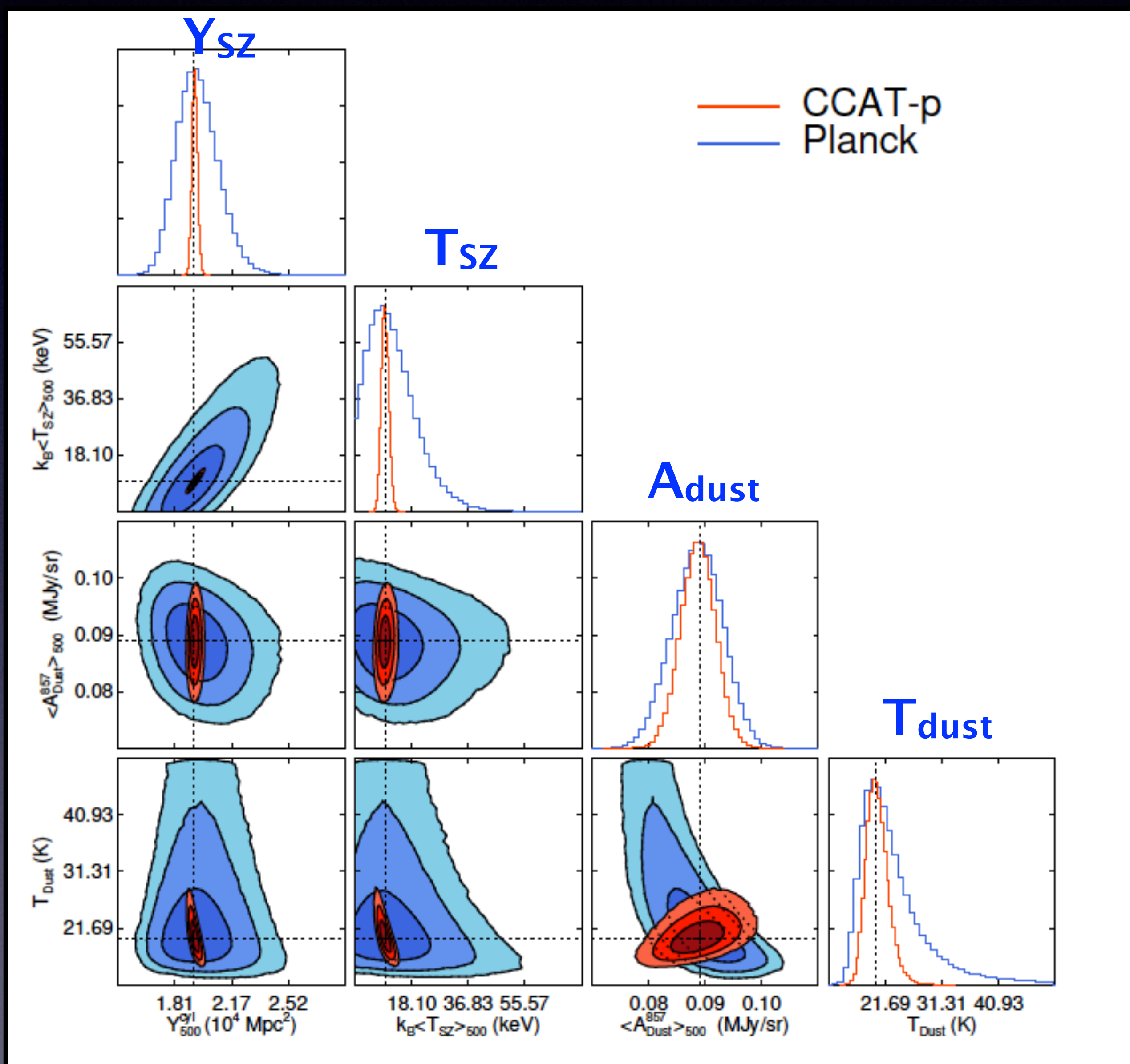
Erler, KB et al. (2018)



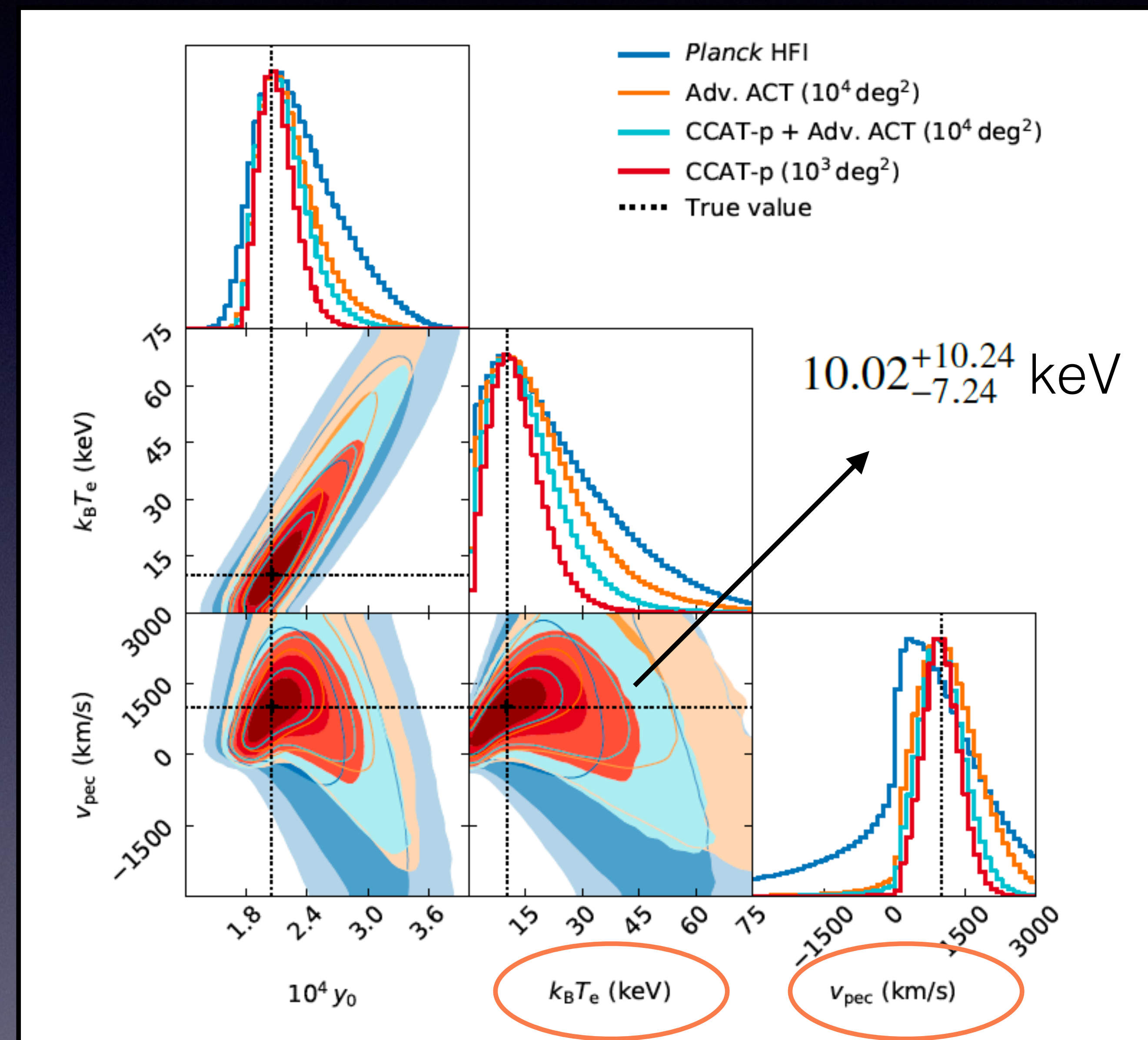
rSZ with CCAT-prime/FYST

Results for a very massive $10^{15}\,M_\odot$ cluster at z=0.25

Early predictions with white noise only ..



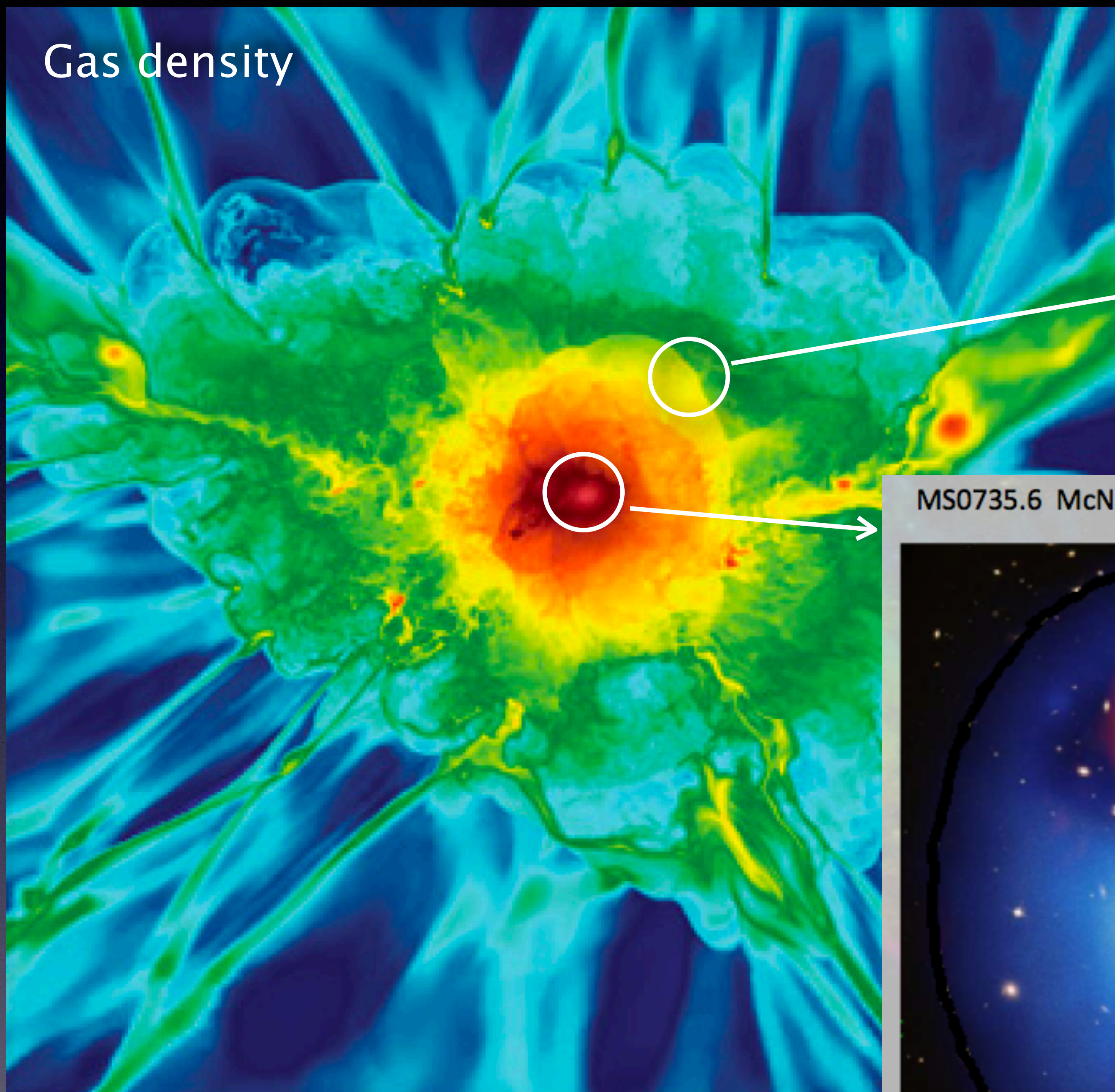
.. then with full foreground realizations



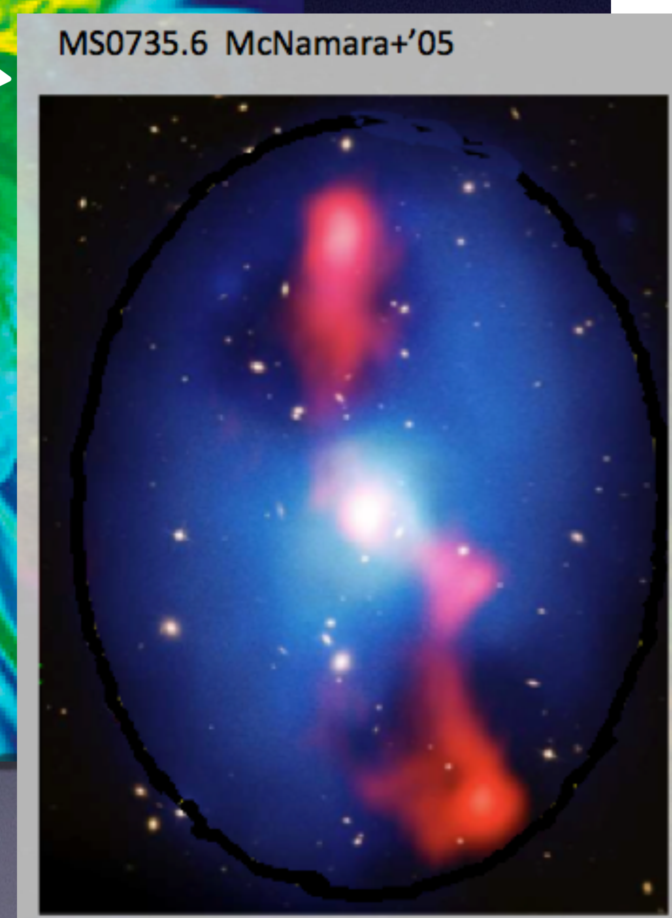
Erler, Basu et al. (2018)

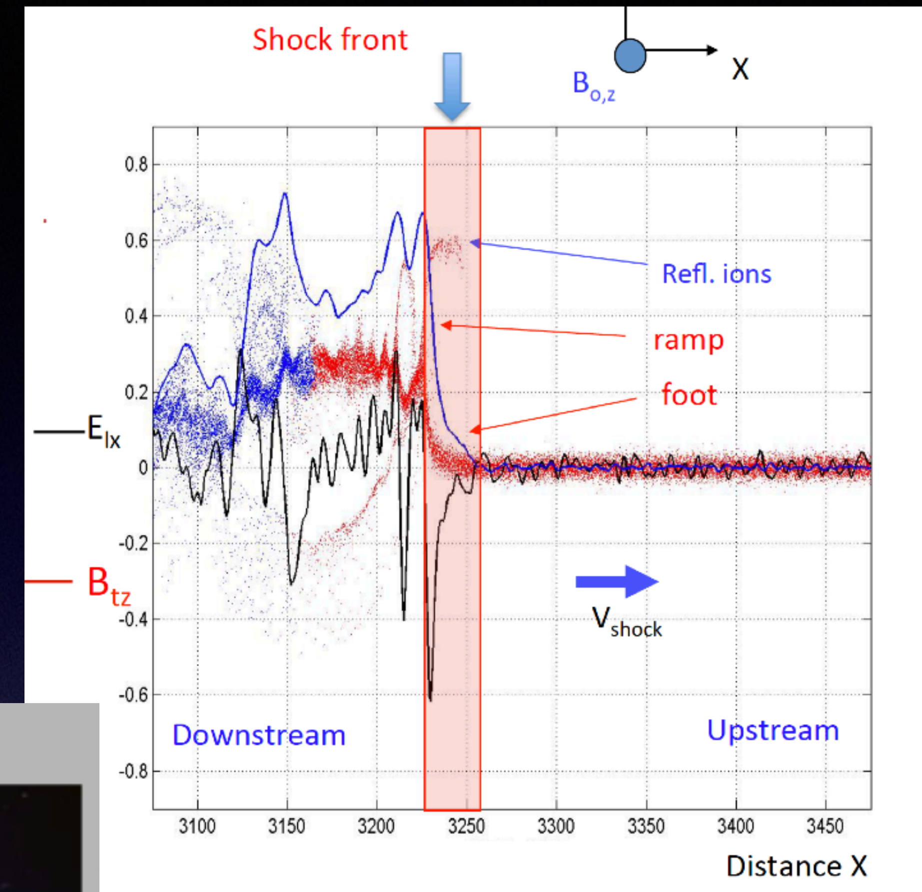
Jens Erler Ph.D. Thesis

Galaxy cluster astrophysics



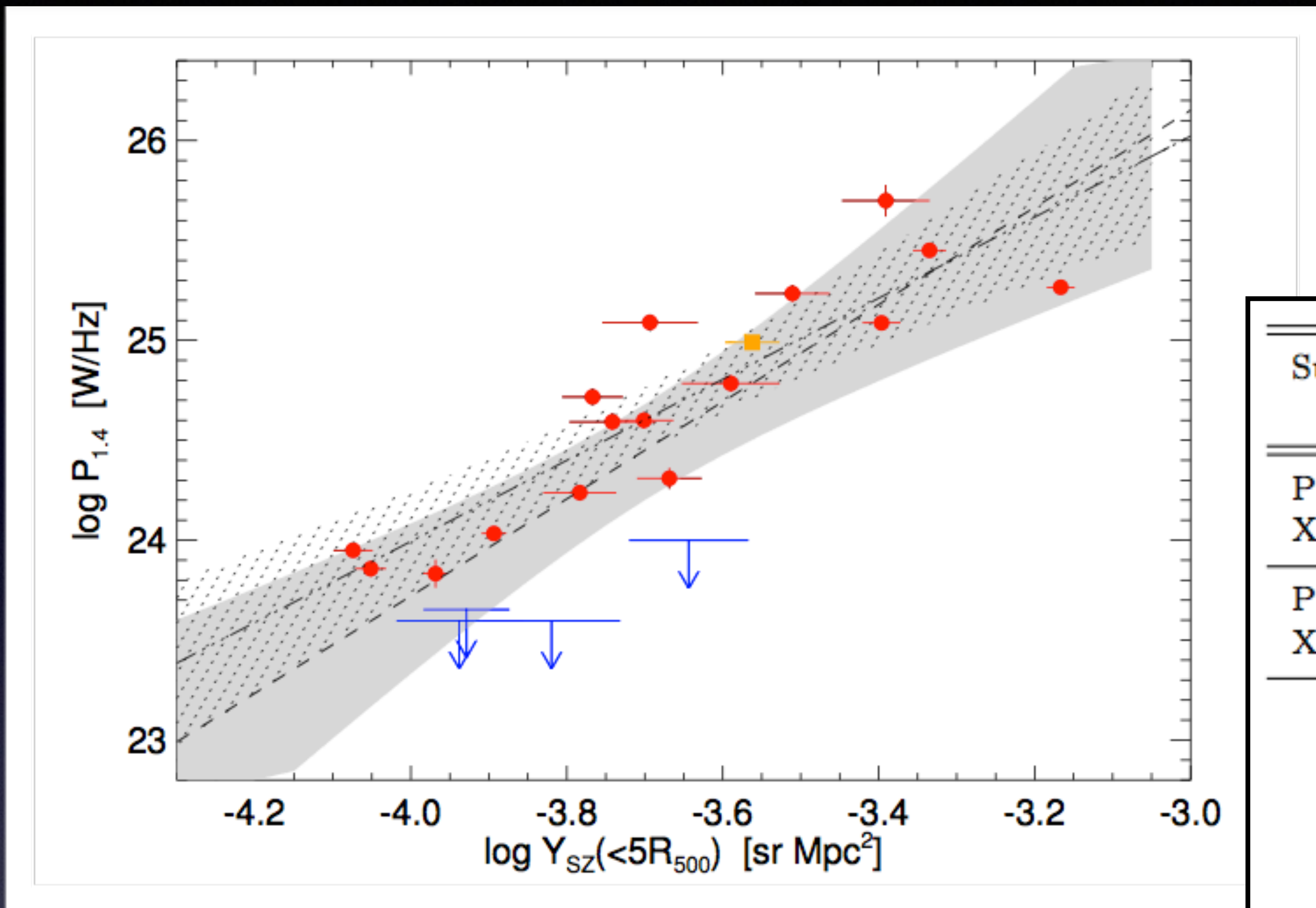
Matryoshka simulations (Miniati 2014)





Marcowith et al. (2012)

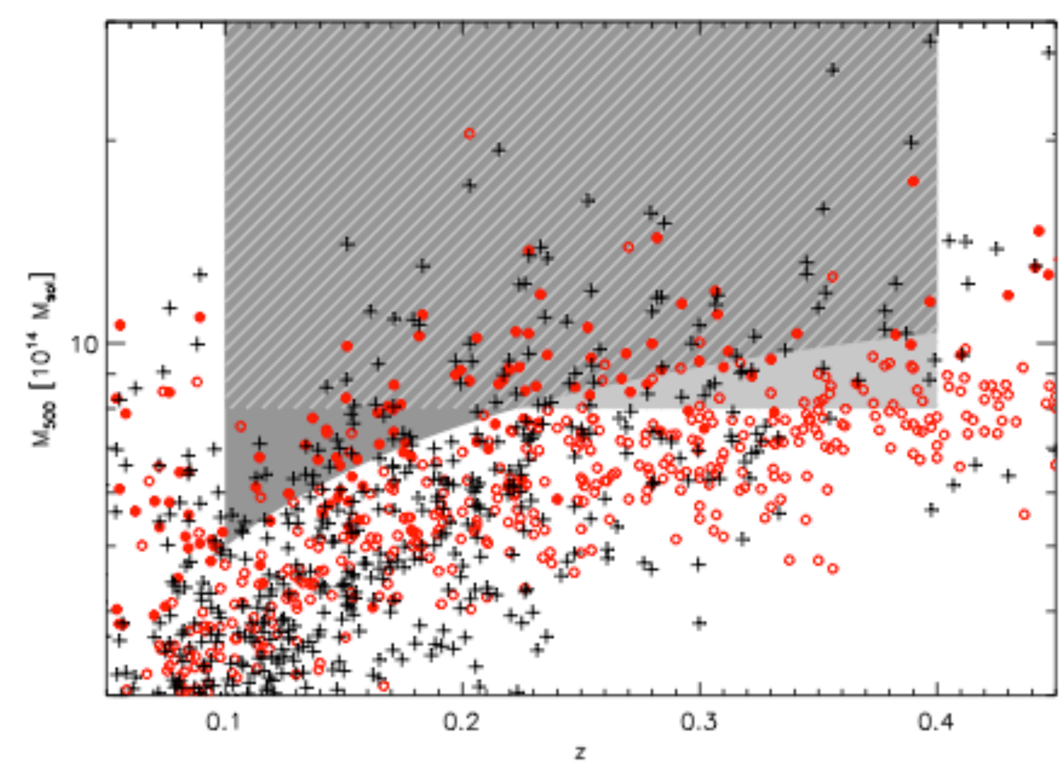
SZ selection for radio halos

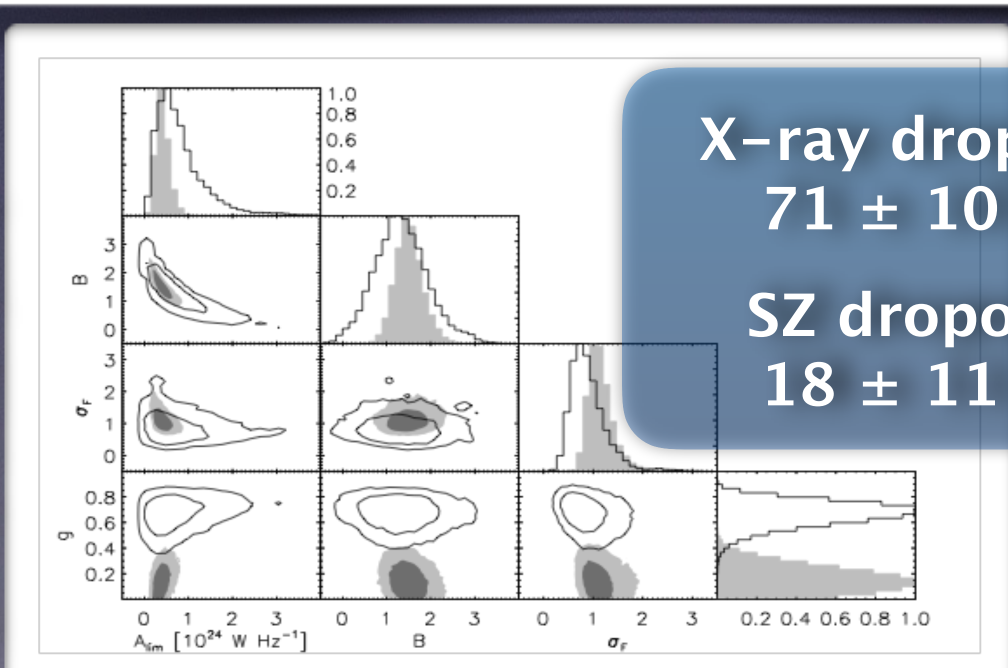


Basu (2012)

Sommer & Basu (2014)

Sub-sample	Mass limit	Primary selection	Flagged due to bad data	Final sample
PSZ(V)	z-dependent	90	1	89
X(V)	z-dependent	86	1	85
PSZ(C)	$8 \times 10^{14} M_{\odot}$	79	0	79
X(C)	$8 \times 10^{14} M_{\odot}$	78	1	77



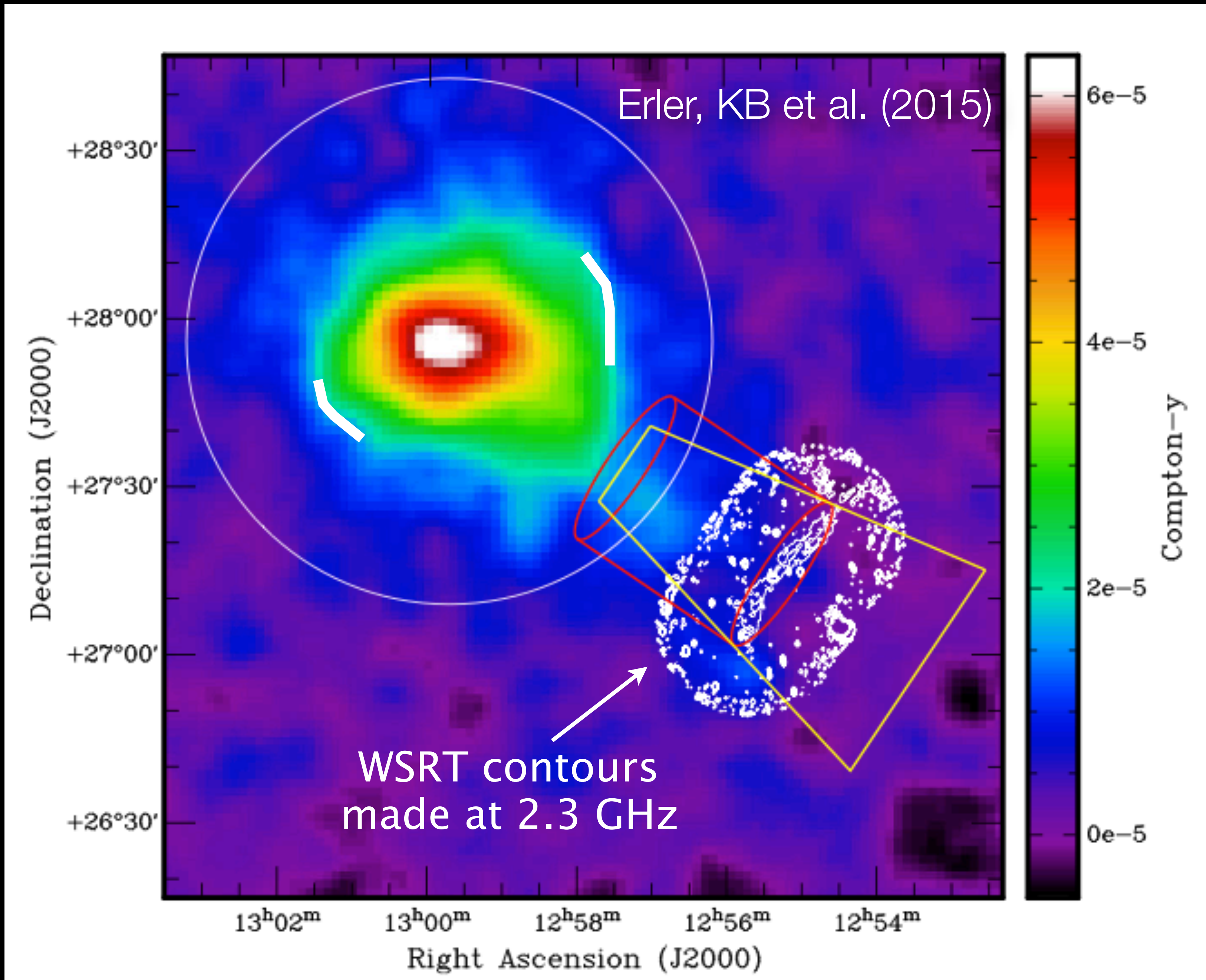


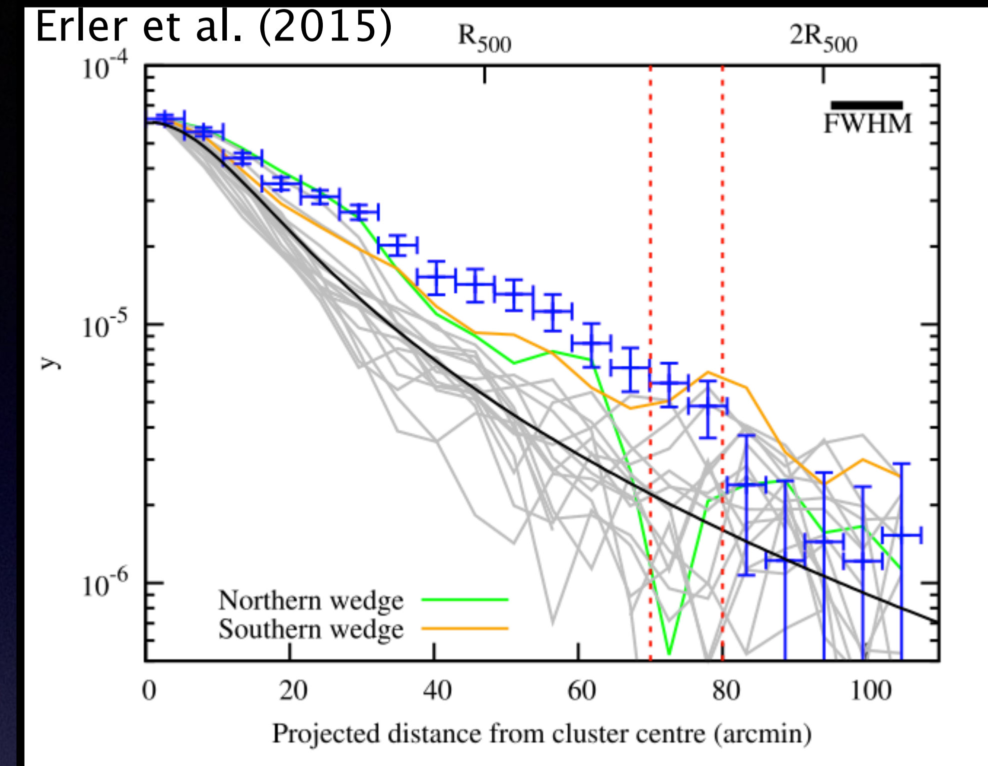
Sommer & Basu (2014)

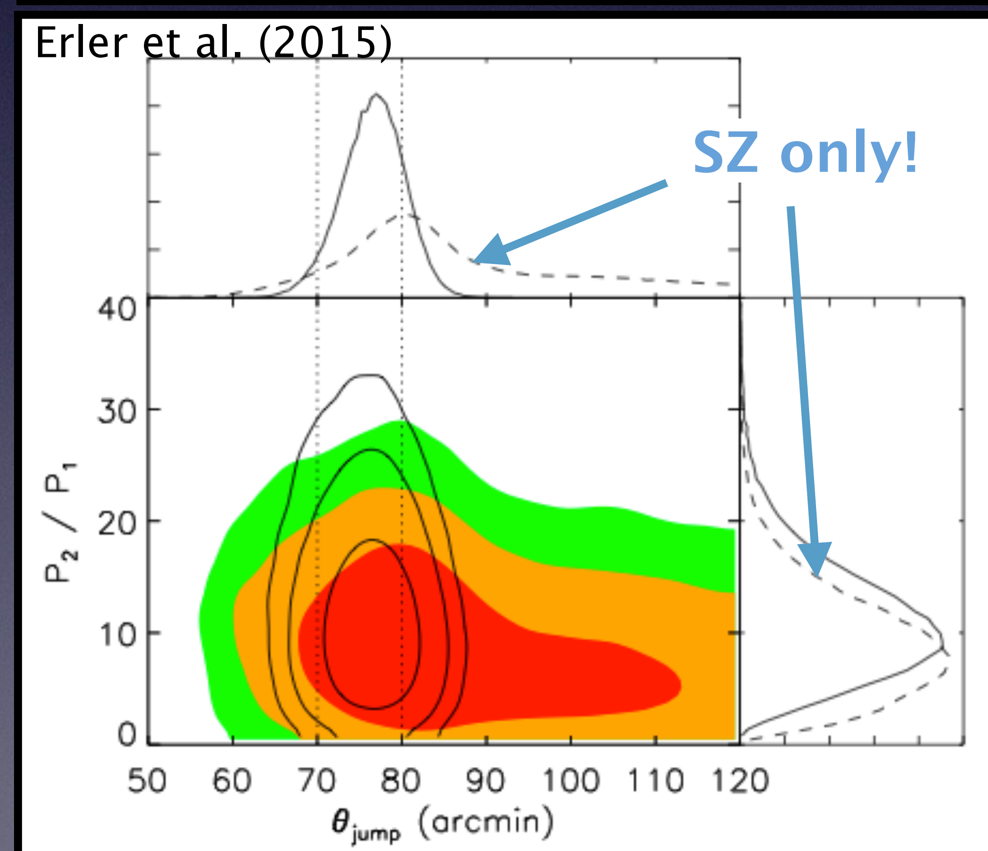
X-ray dropout
71 ± 10 %

SZ dropout
18 ± 11 %

Coma's relic in SZ, with Planck



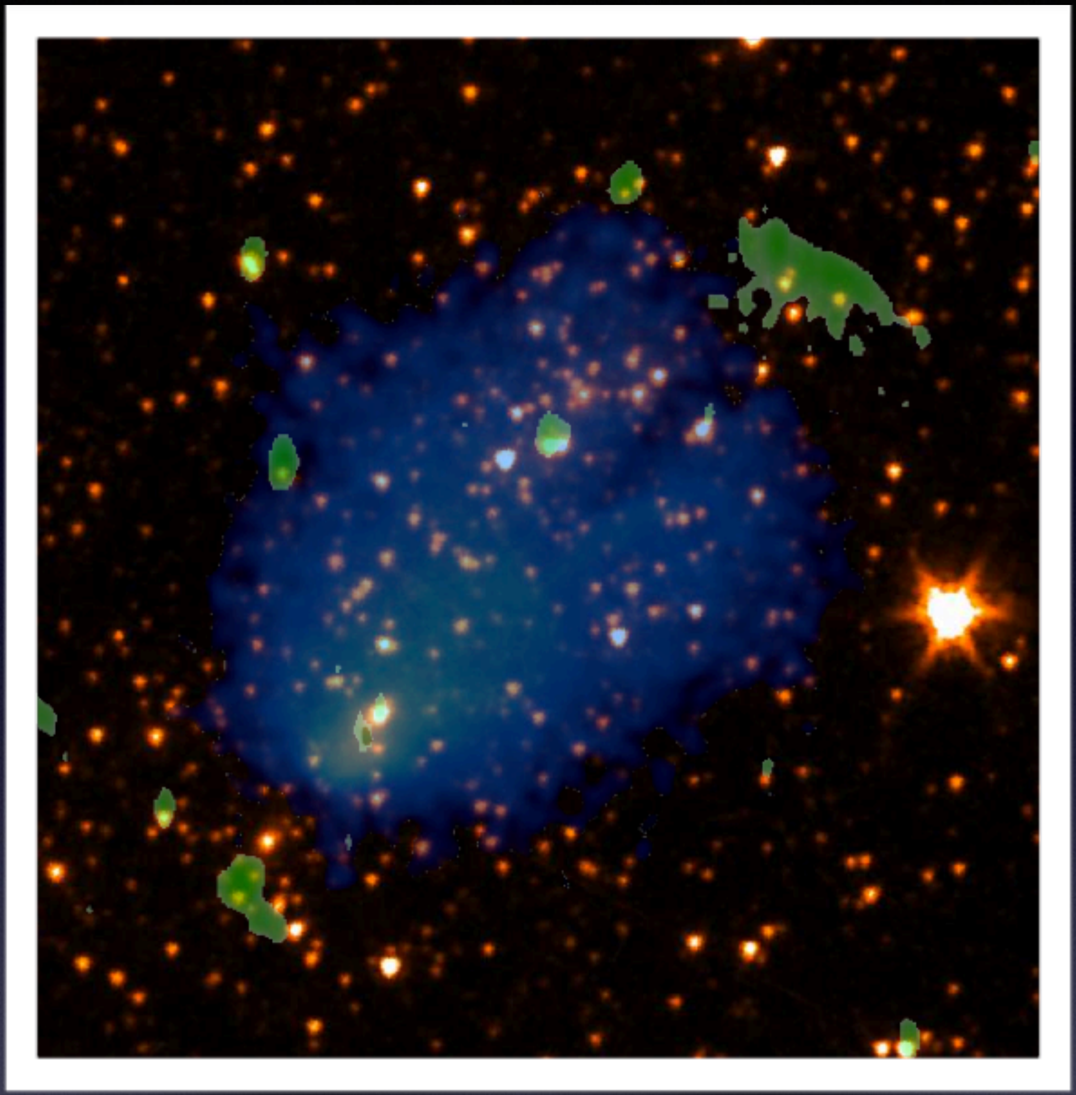




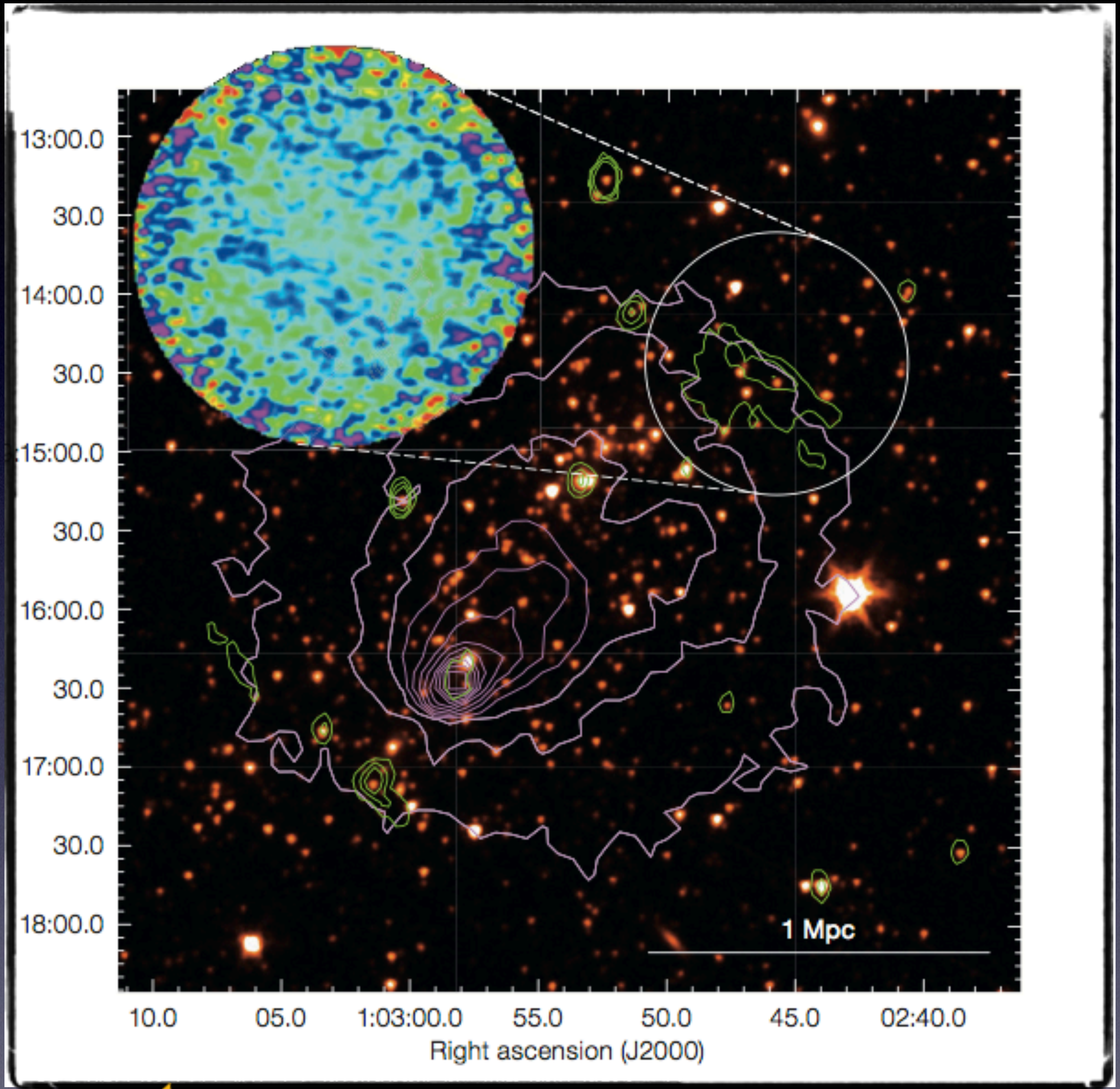
The first measurement of a relic shock in SZ

Mach number derived from the y-jump: $\mathcal{M} = 2.9^{+0.8}_{-0.6}$

SZ shock at El Gordo relic (z=0.9)



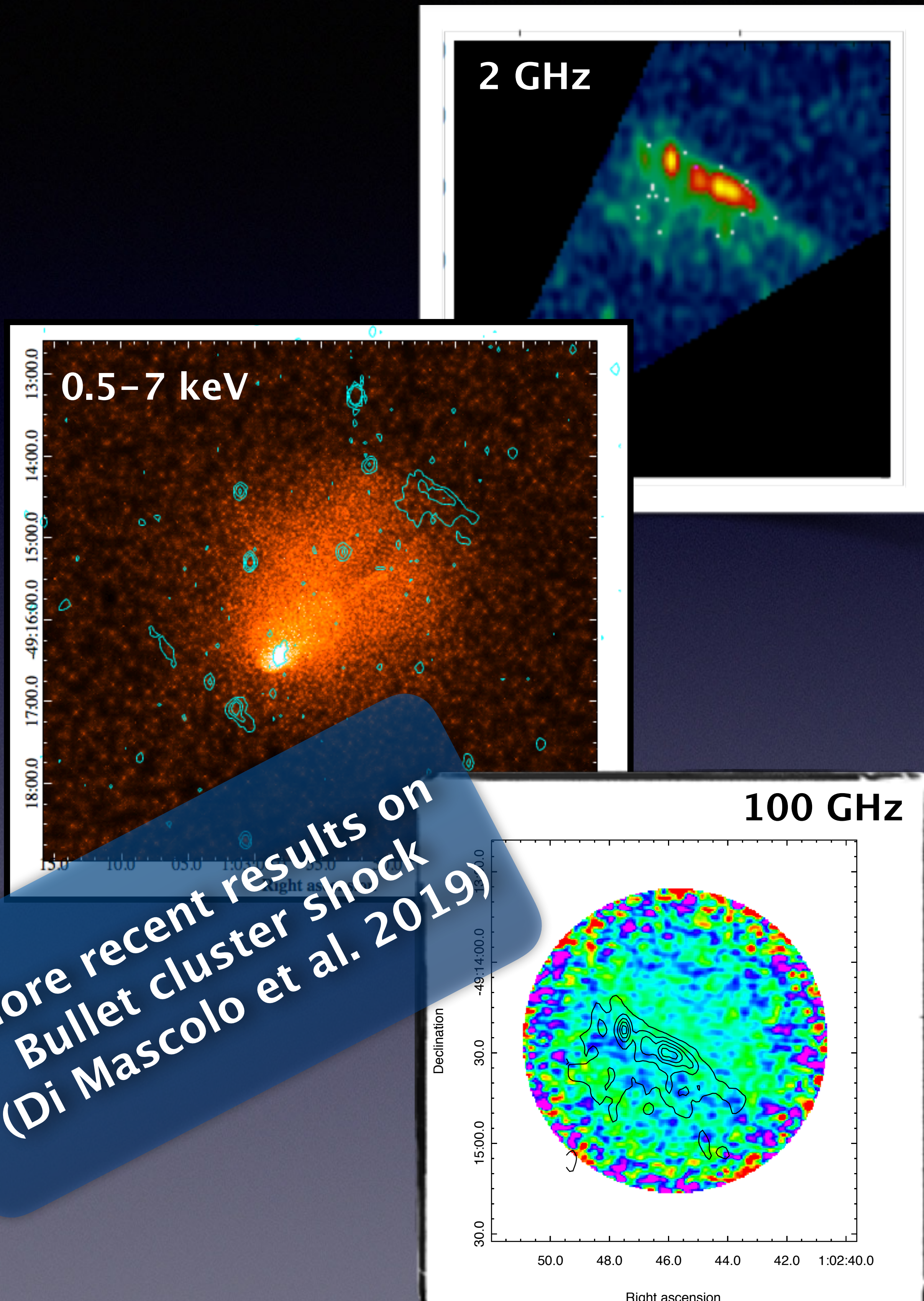
360 ks Chandra (PI: J. Hughes) + ATCA 2.1 GHz radio (Lindner et al. 2014)



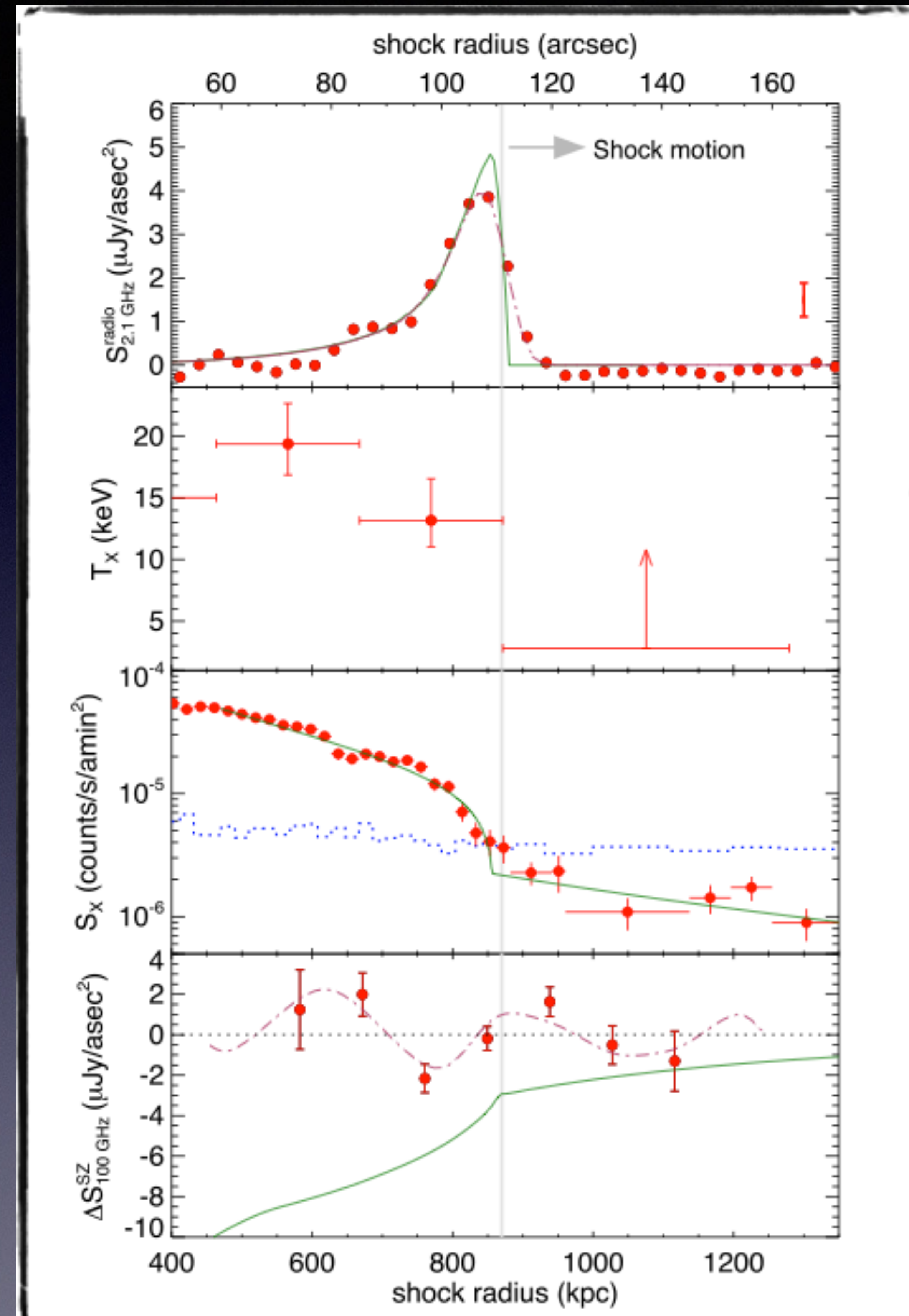
Basu et al. (2016), ApJ, 829

ALMA data ~ 2h on-source
ALMA noise rms ~ 6 μJy/3" beam
(enough to detect M~2 shock with >5σ)

Multi-wavelength view of a radio relic



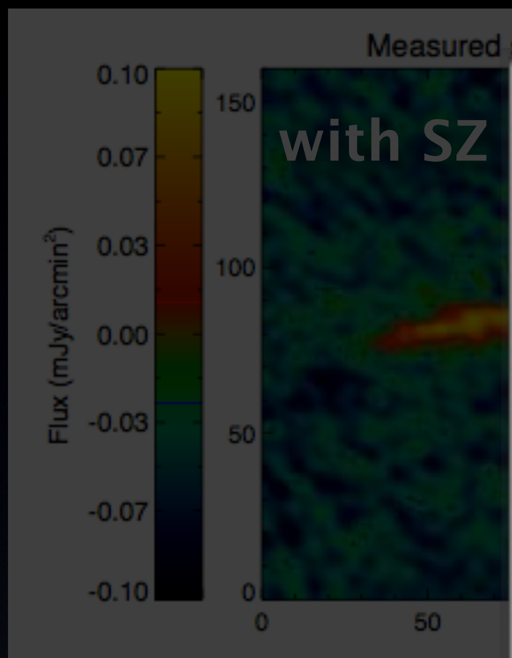
More recent results on Bullet cluster shock (Di Mascolo et al. 2019)



Basu et al. (2016), ApJ, 829

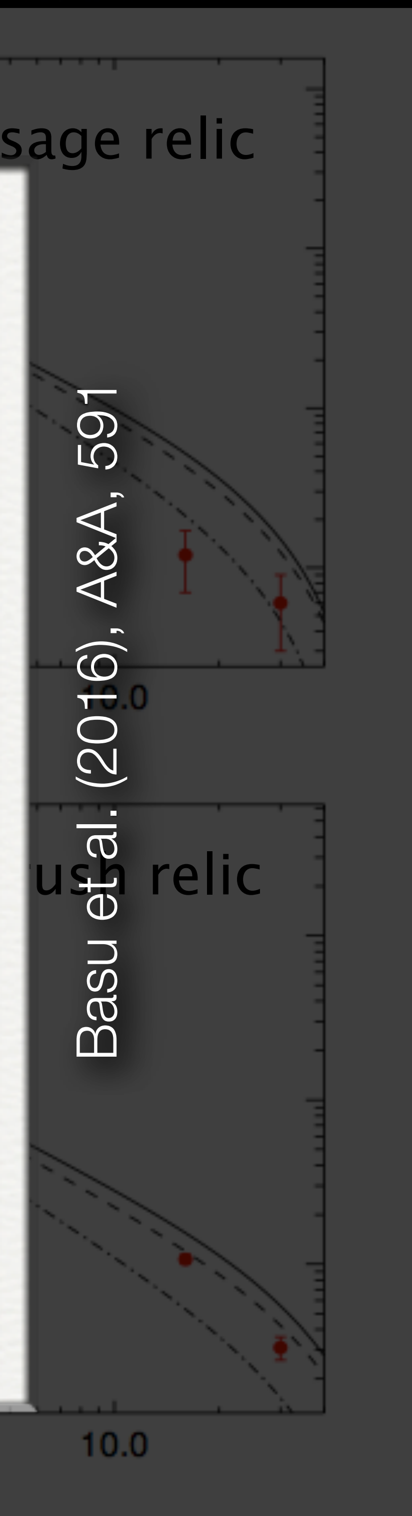
SZ-contamination for radio relics

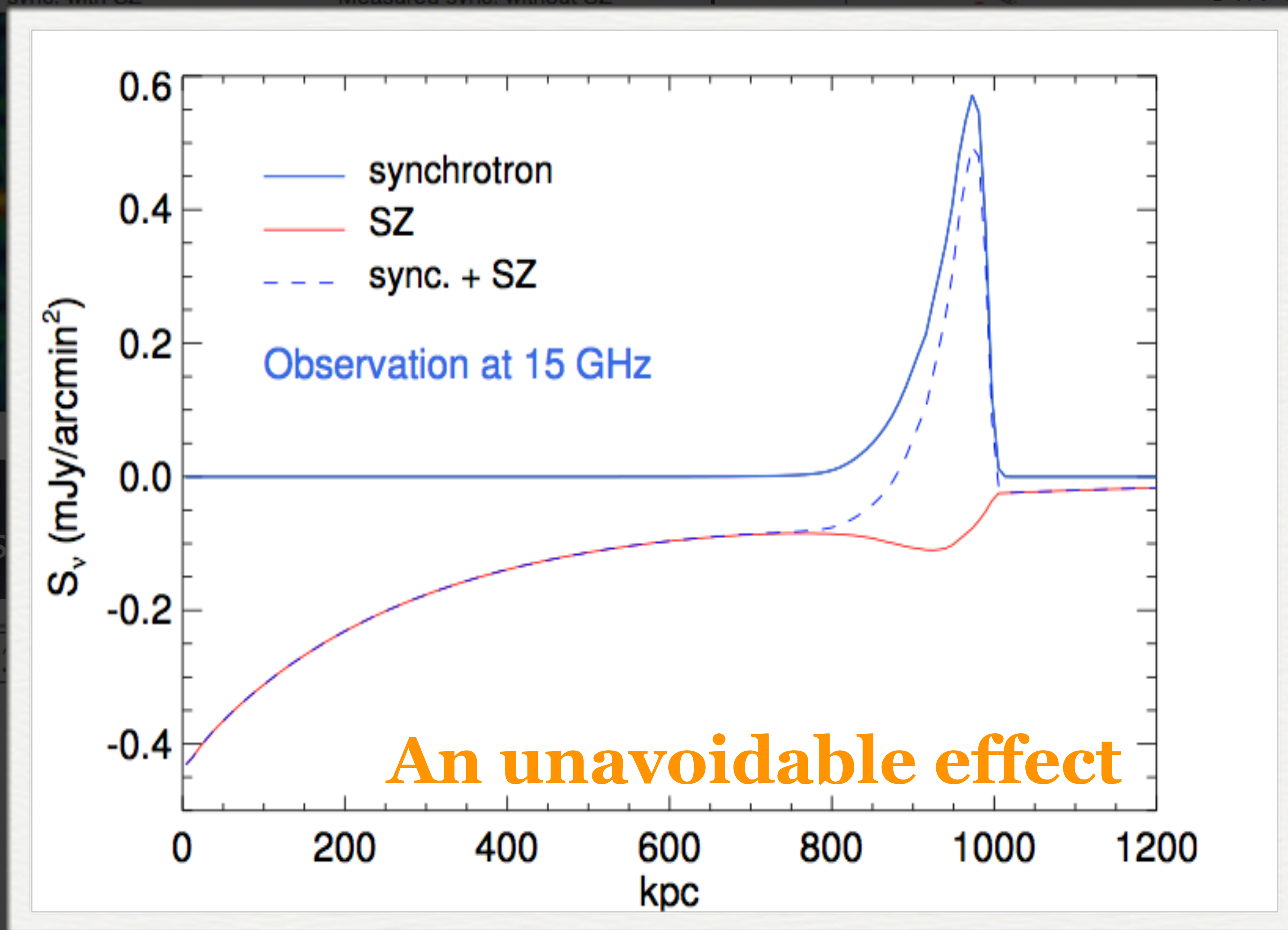
Simulated interferometric observation at 10 GHz



10%–50% flux los

Sausage relic ($\mathcal{M}$ = 2.5)						
($\mathcal{M}$ = 3.5)						
($\mathcal{M}$ = 4.5)						
Toothbrush relic ($\mathcal{M}$ = 3.5)						
($\mathcal{M}$ = 4.5)						
El Gordo relic ($\mathcal{M}$ = 2.5)	<1%	3%	23%	53%	81%	>100%
A2256 relic ($\mathcal{M}$ = 2.0)	1%	3%	28%	66%	96%	>100%





Basu et al. (2016), A&A, 591

Basu et al. (2016), A&A, 591

SZ-contamination for radio relics

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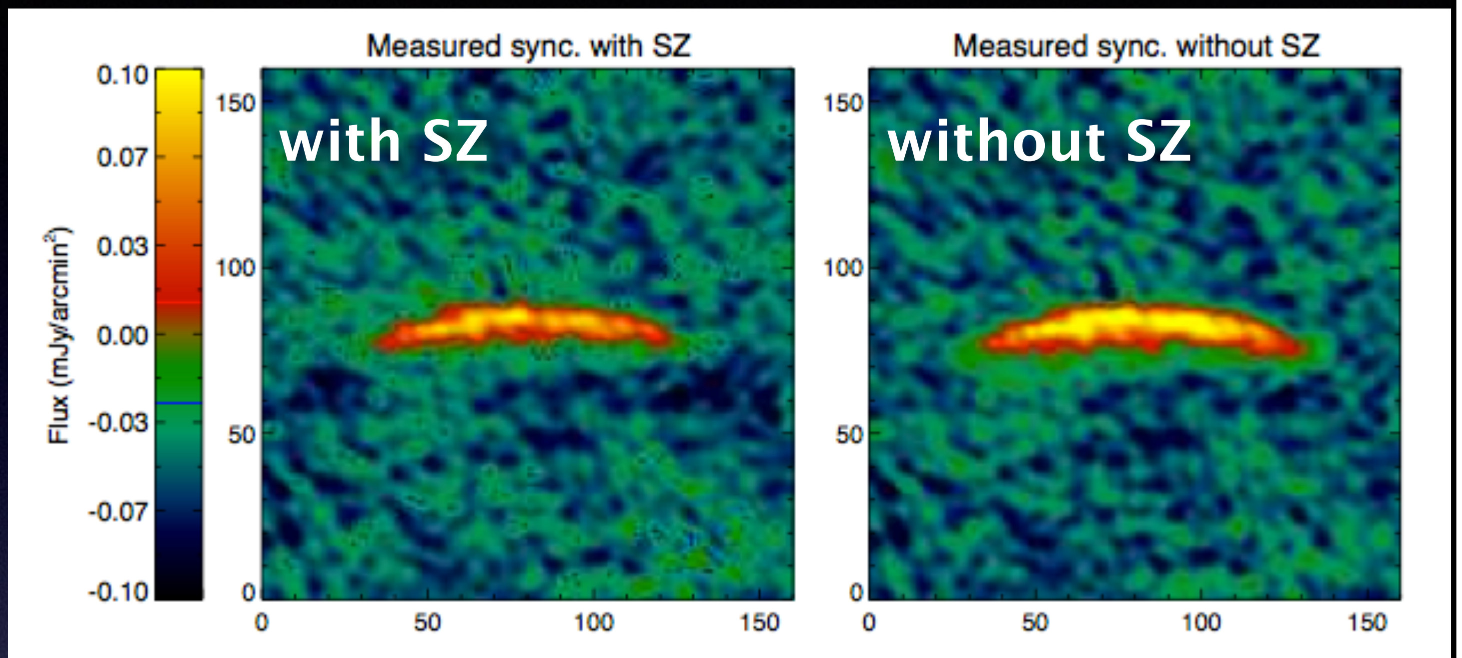
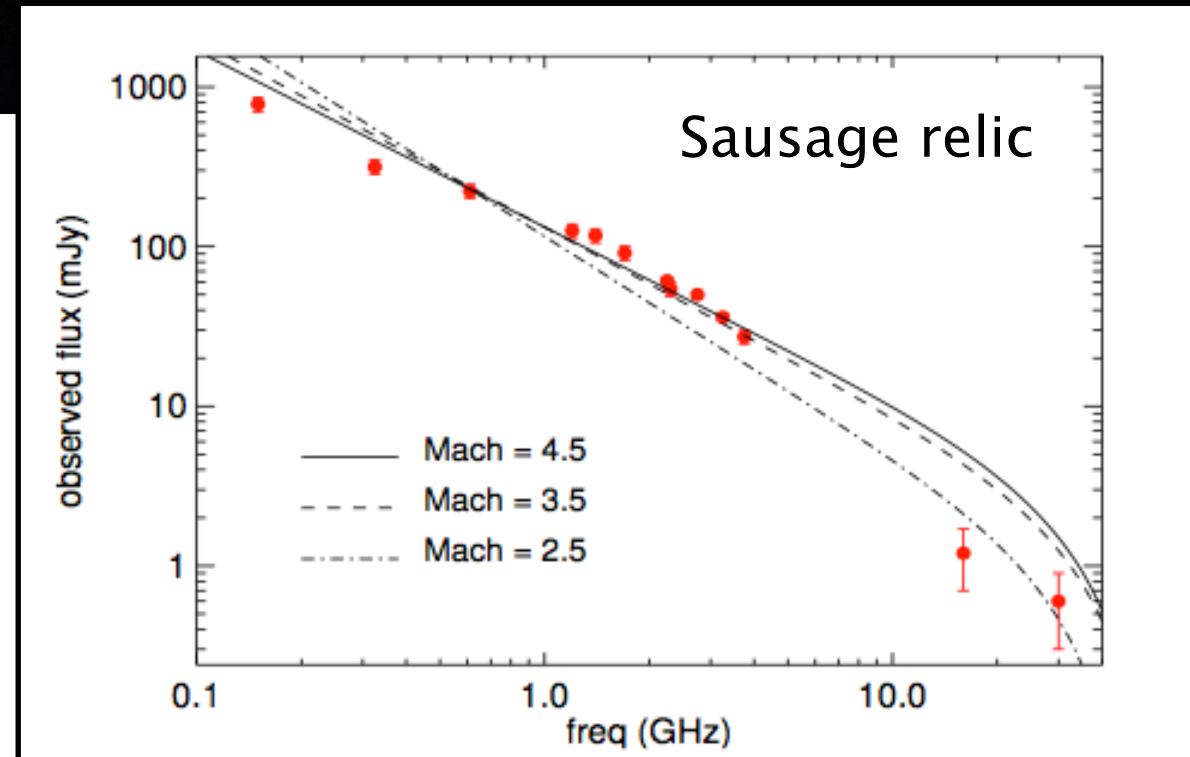
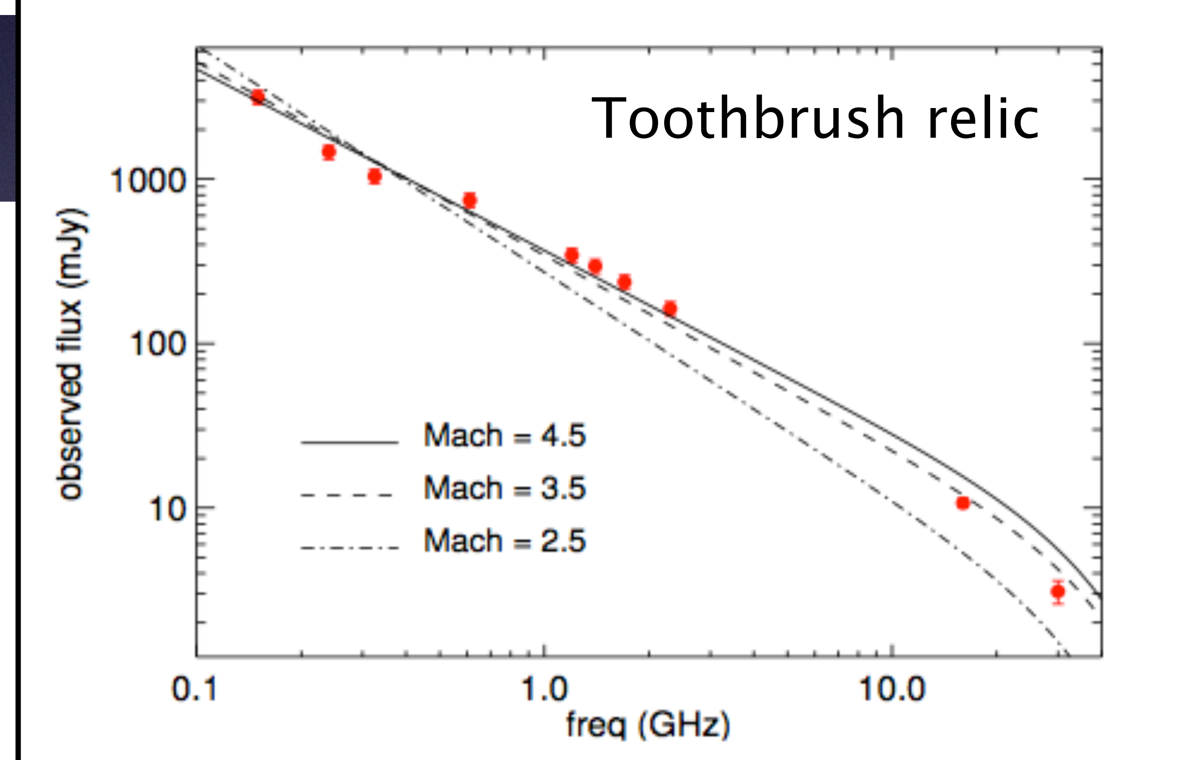




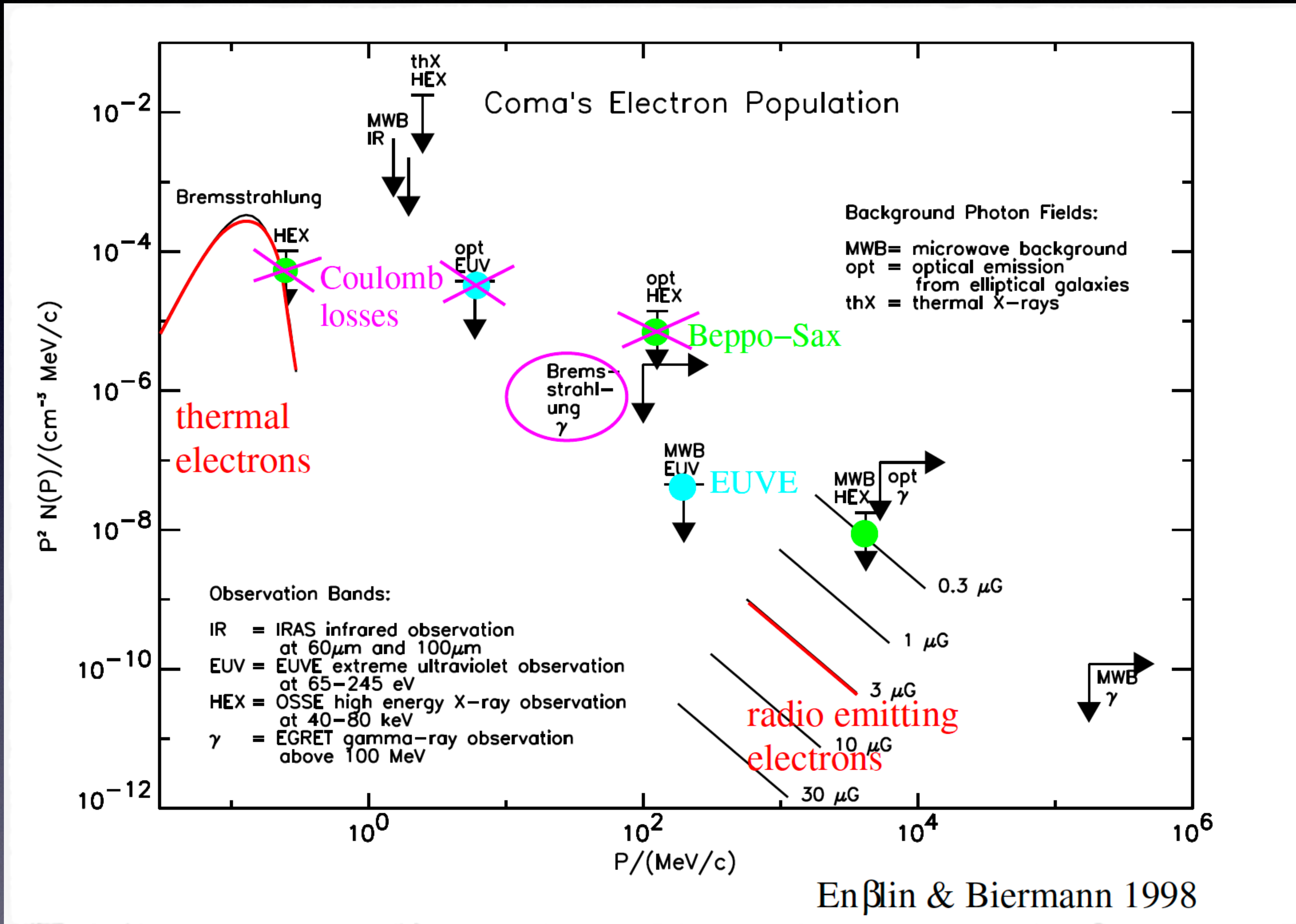


10%–50% flux loss at 10 GHz

	3 GHz	5 GHz	10 GHz	15 GHz	20 GHz	30 GHz
Sausage relic ($\mathcal{M}$ = 2.5)	<1%	<1%	4%	11%	24%	58%
($\mathcal{M}$ = 3.5)	<1%	<1%	3%	10%	21%	49%
($\mathcal{M}$ = 4.5)	<1%	<1%	4%	12%	24%	52%
Toothbrush relic ($\mathcal{M}$ = 3.5)	<1%	<1%	3%	9%	18%	43%
($\mathcal{M}$ = 4.5)	<1%	<1%	3%	10%	20%	46%
El Gordo relic ($\mathcal{M}$ = 2.5)	<1%	3%	23%	53%	81%	>100%
A2256 relic ($\mathcal{M}$ = 2.0)	1%	3%	28%	66%	96%	>100%

Basu et al. (2016), A&A, 591

Nonthermal electrons in galaxy clusters

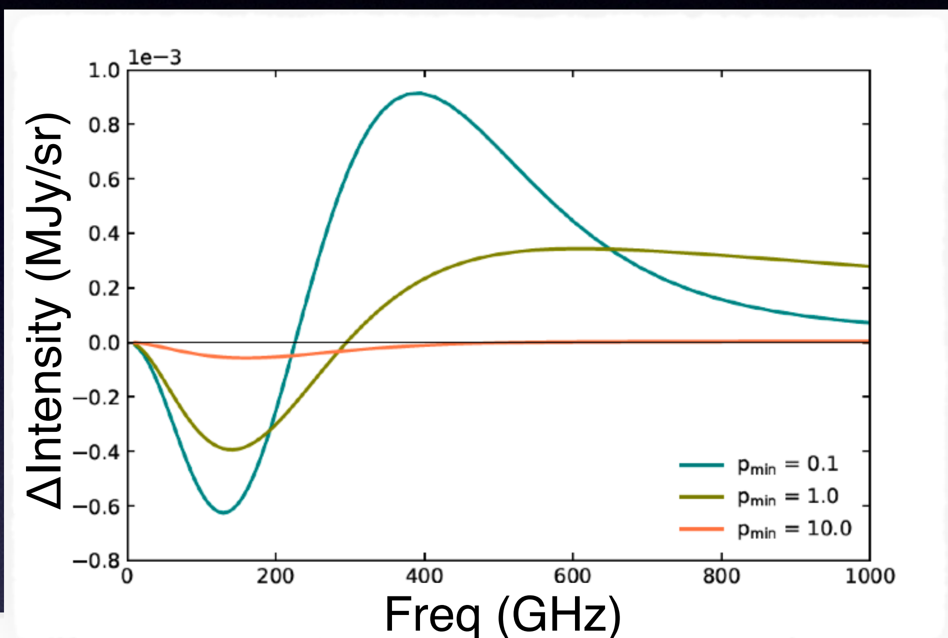


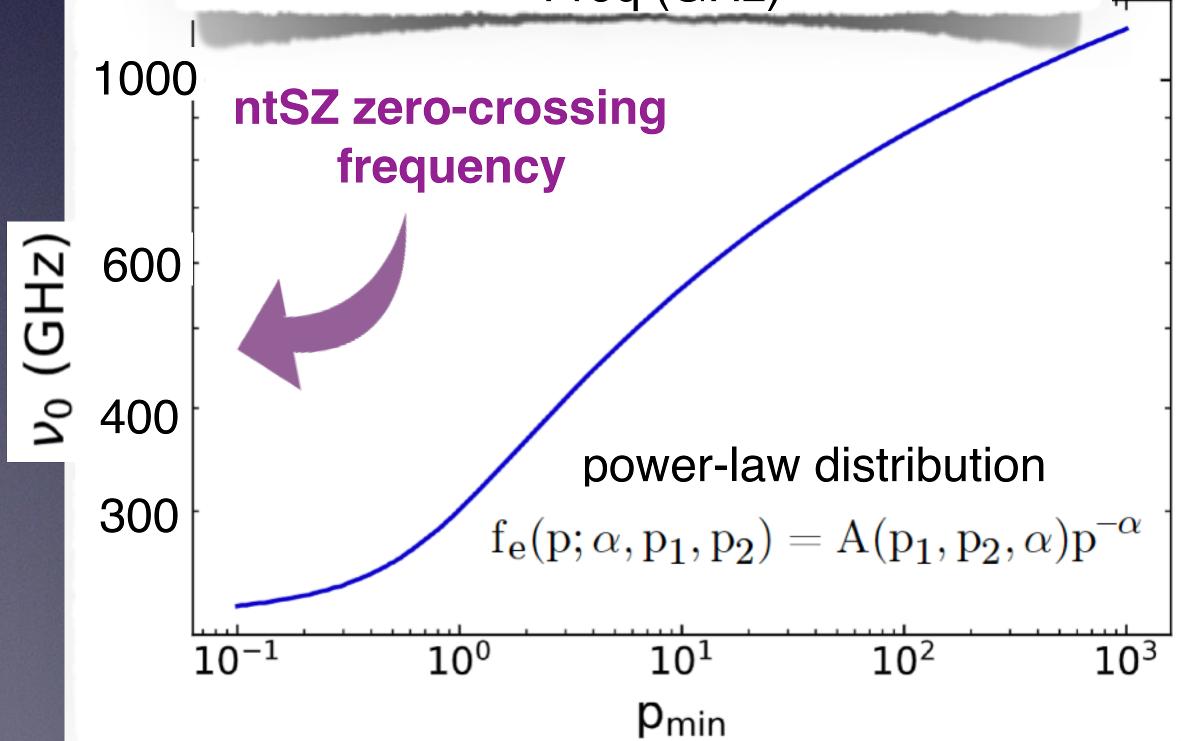
(reproduced in Enßlin 2004, with annotations)

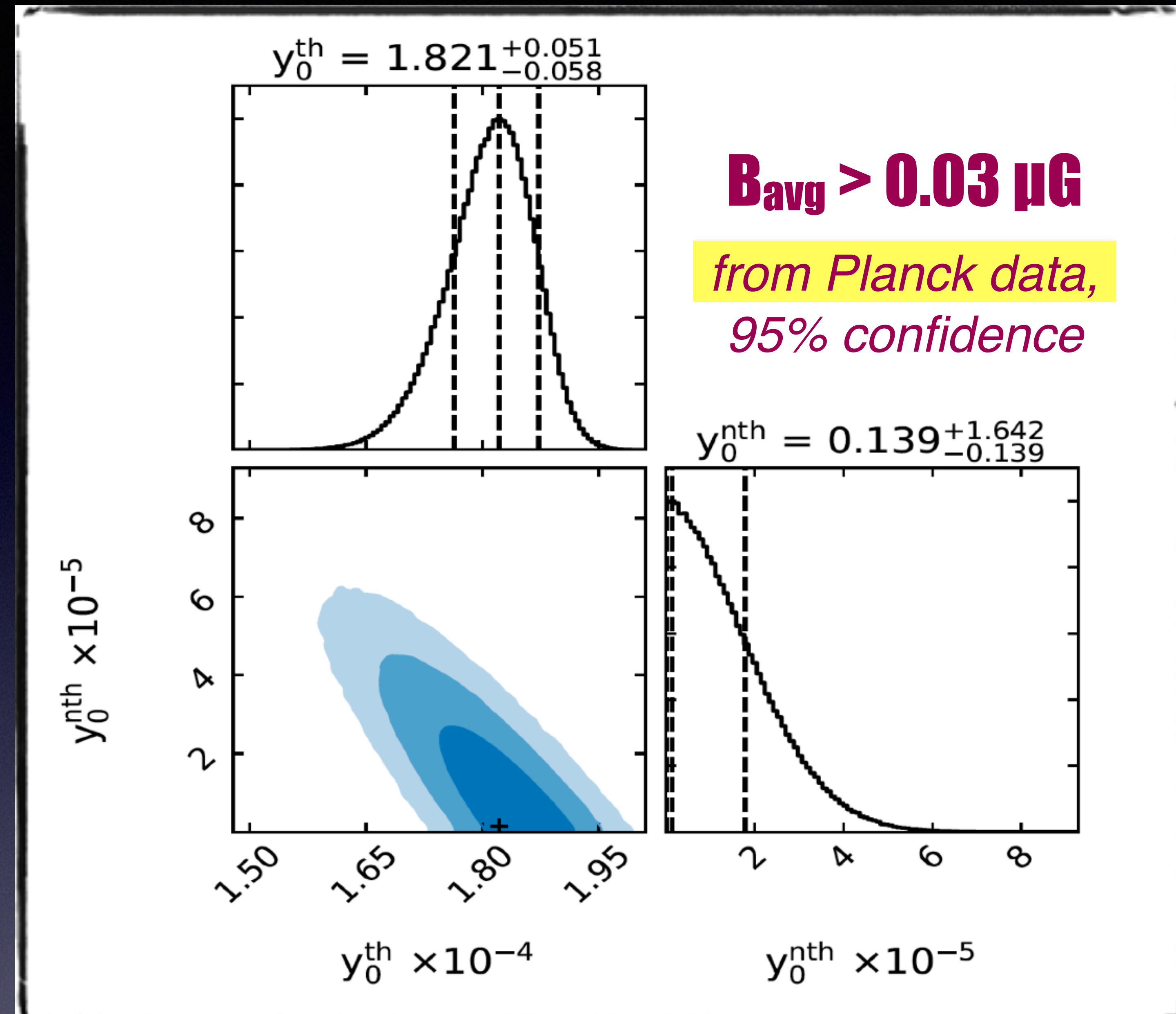
Nonthermal SZ in cluster radio halos

CMB photons will also scatter off other sources of free electrons, e.g. power-law distribution with a high-energy tail

but in clusters it is ≲1% of the tSZ signal 🙁







B_{avg} > 0.03 μG

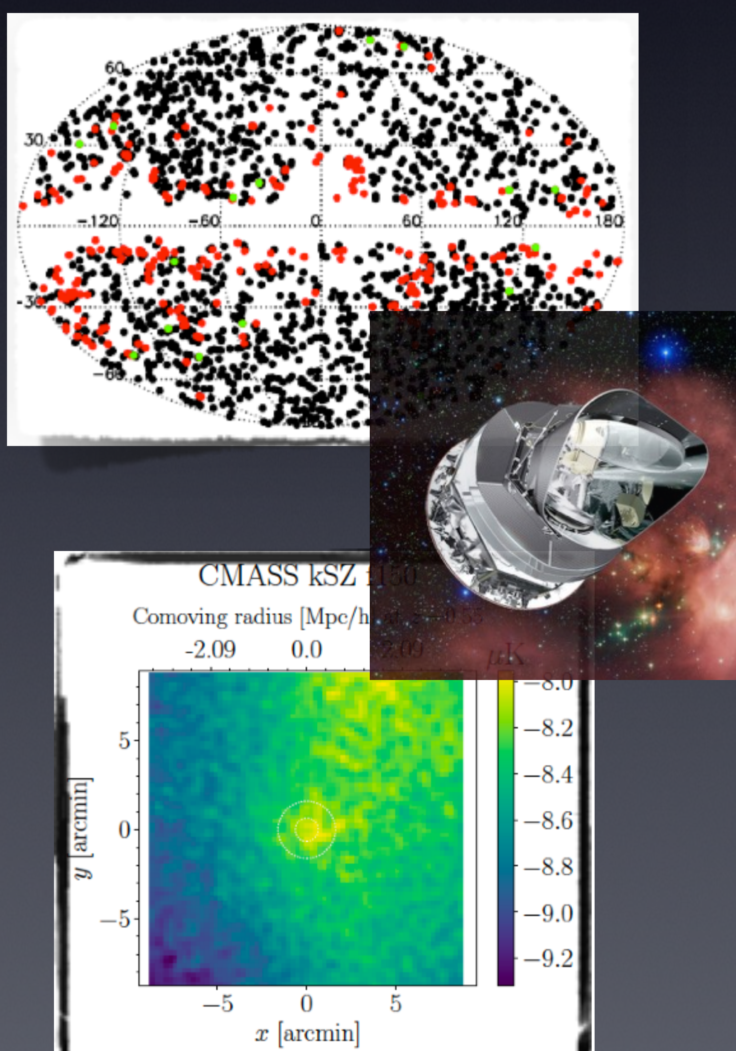
from Planck data, 95% confidence

Muralidhara et al. (in prep)

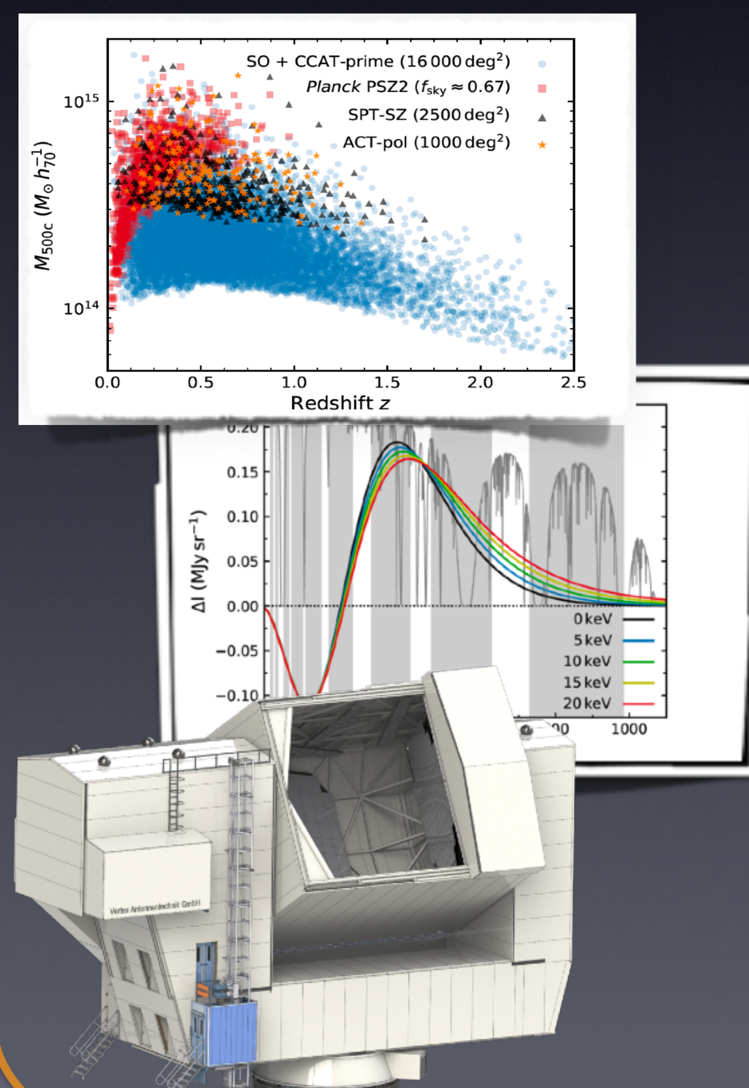
With CCAT-prime and SO, order-of-magnitude better constraints on ntSZ-based B-field limits can be expected in the next ~5 years

Take home points

SZ observation are now well-established for cosmology + astrophys. kSZ is catching up (with tSZ) rapidly.



CCAT-prime (now renamed FYST) will be ground-breaking for SZ science. Strong German involvement.



SZ can play strong complementary role in modelling cluster diffuse synchrotron emissions (+others)