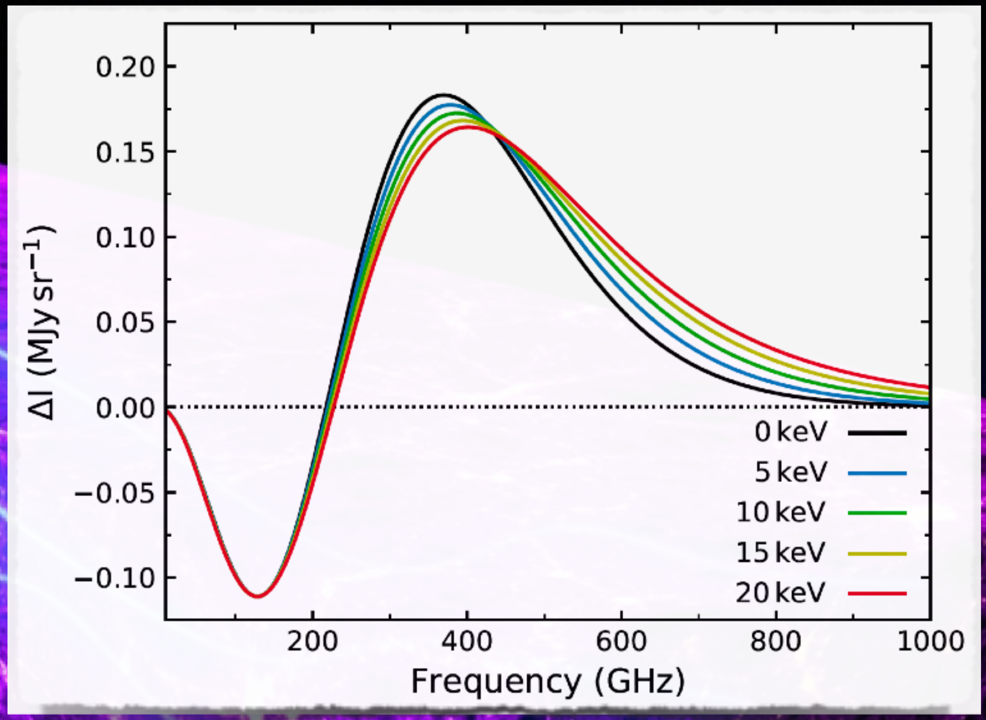
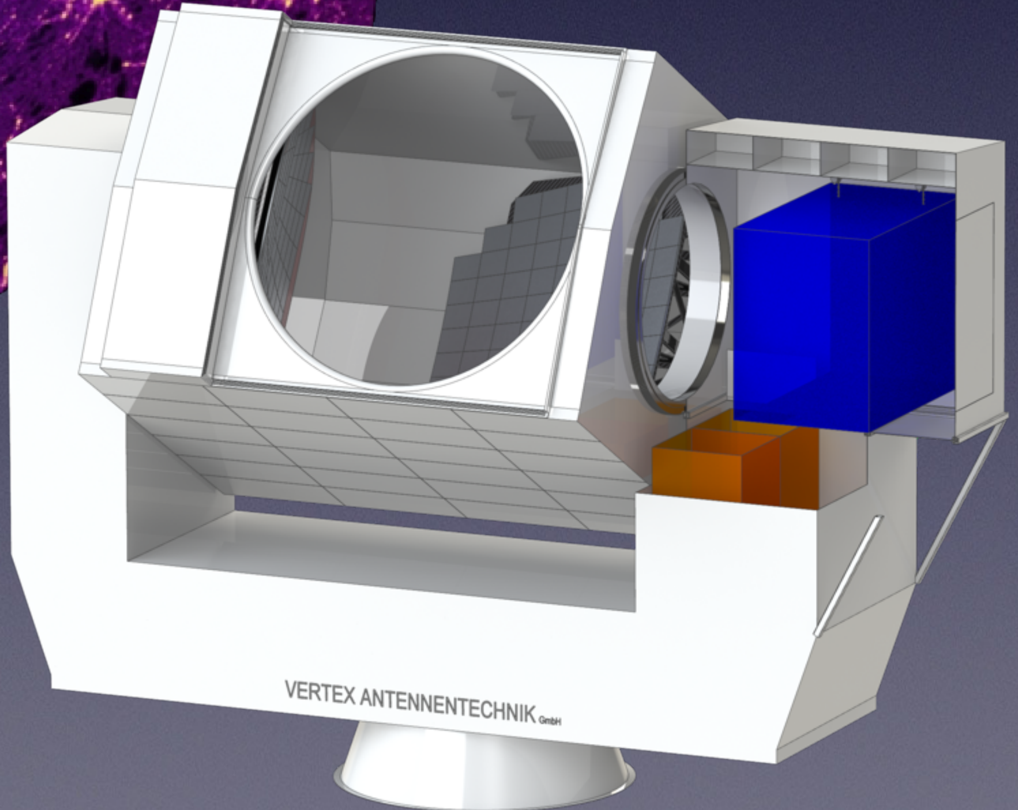
SZ Effect Spectral Studies from Ground & Space



Credit: ESA/Planck



Kaustuv Basu (AIfA, Universität Bonn)

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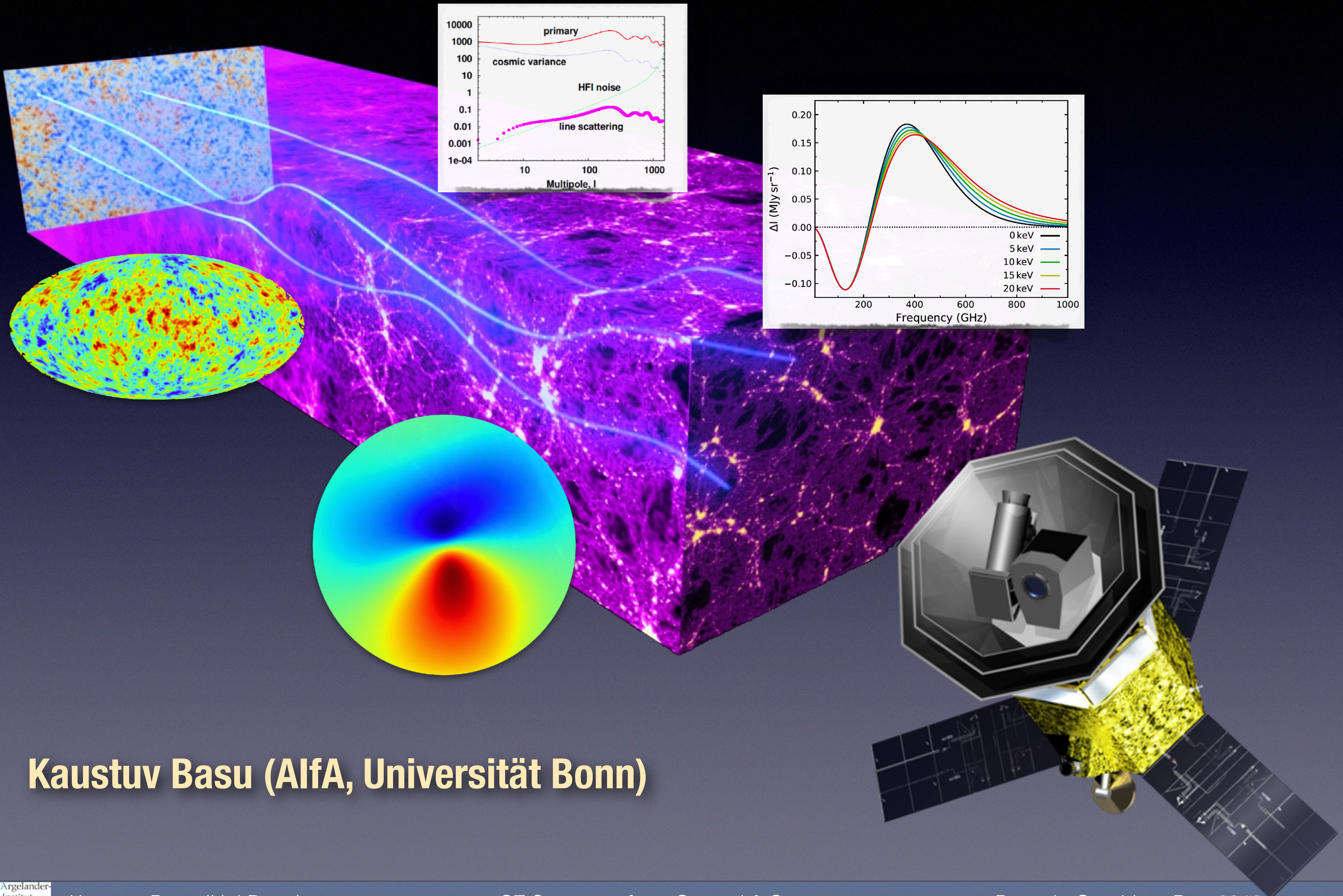

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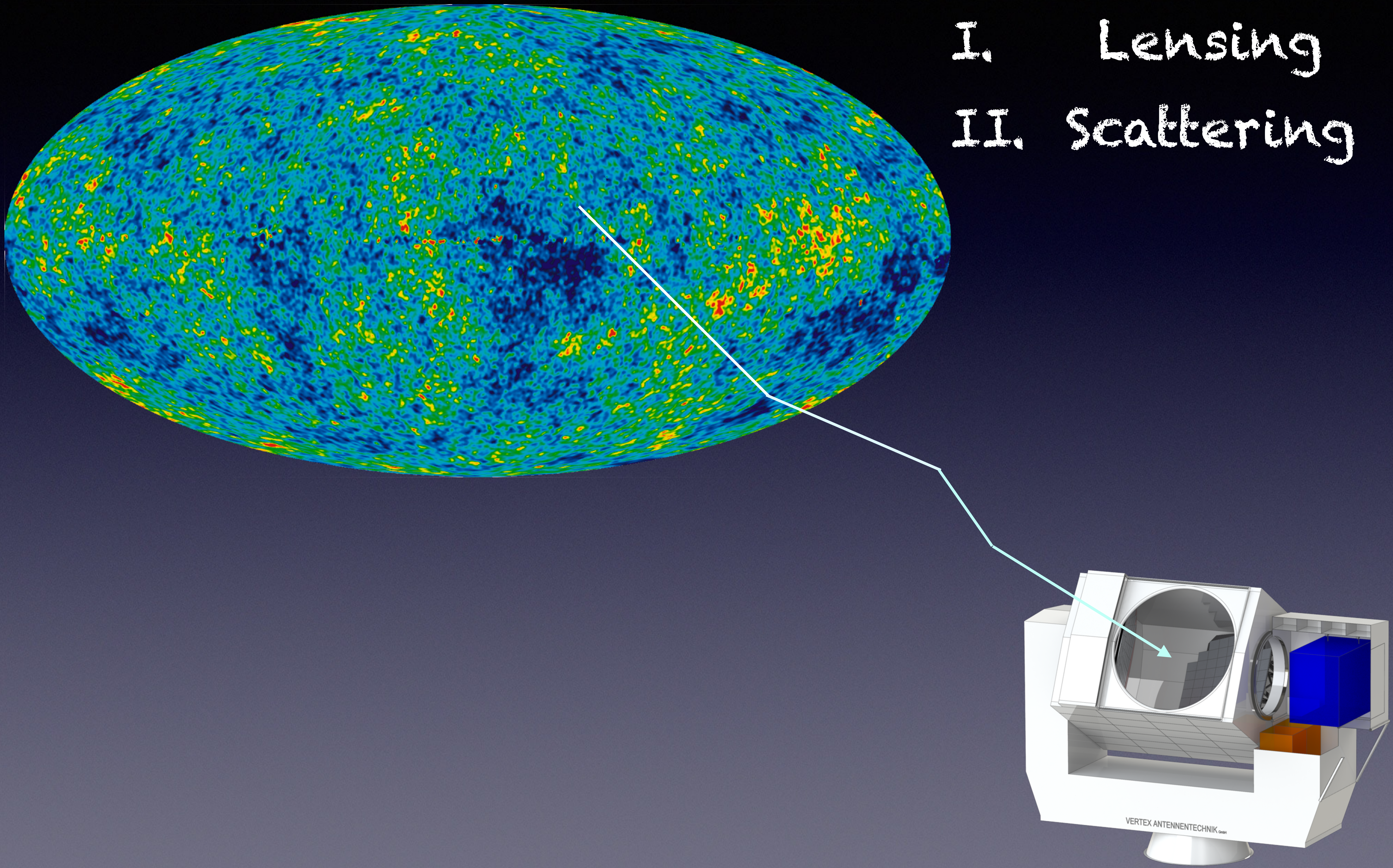
The CMB as a Backlight



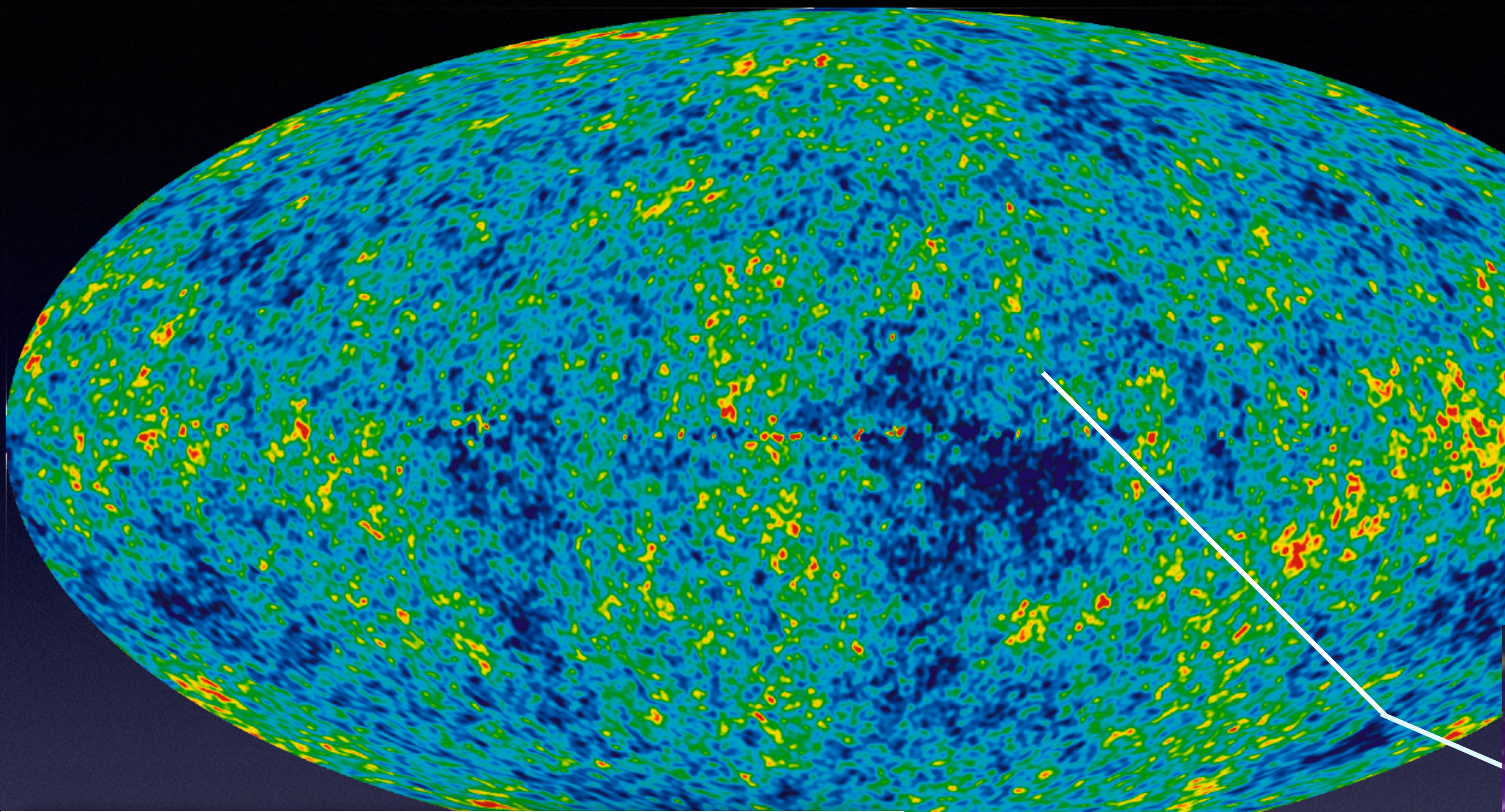
I. Lensing

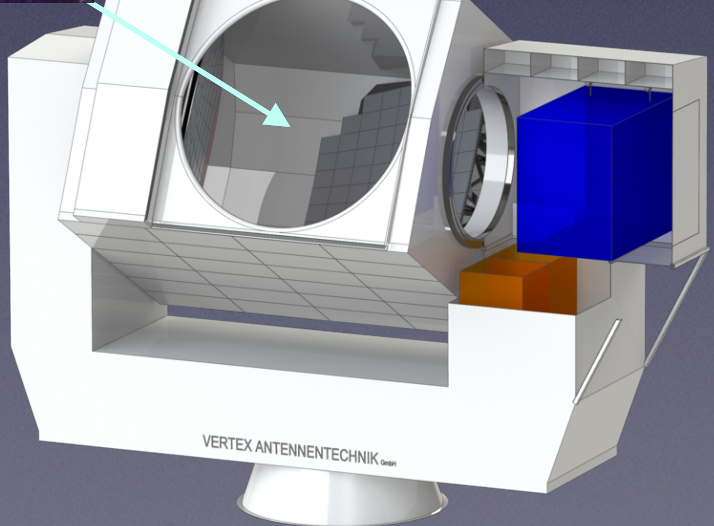
II. Scattering

CMB as a backlight: SZ effect

I. Lensing

II. Scattering





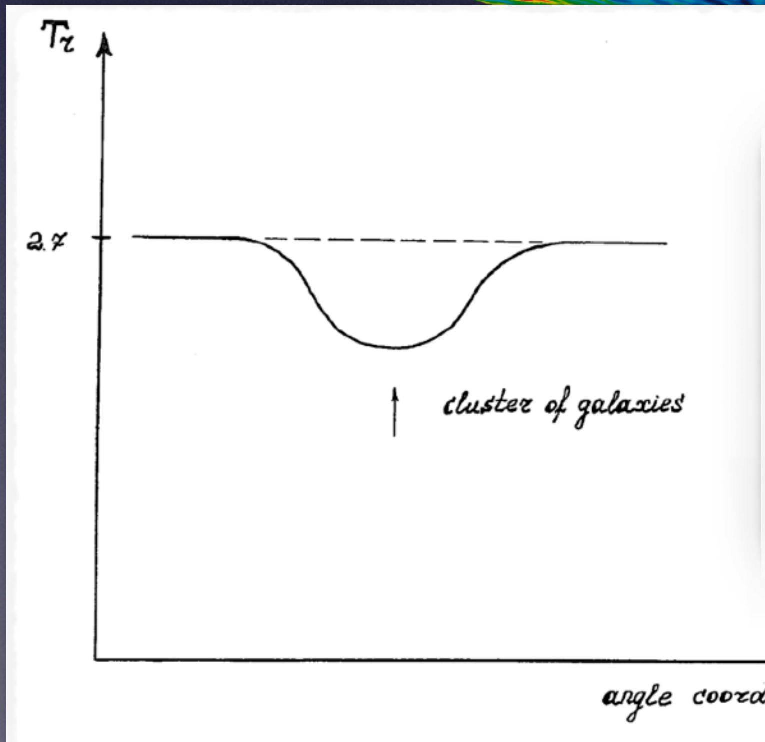


FIG. 1. The “hole” in the microwave background.

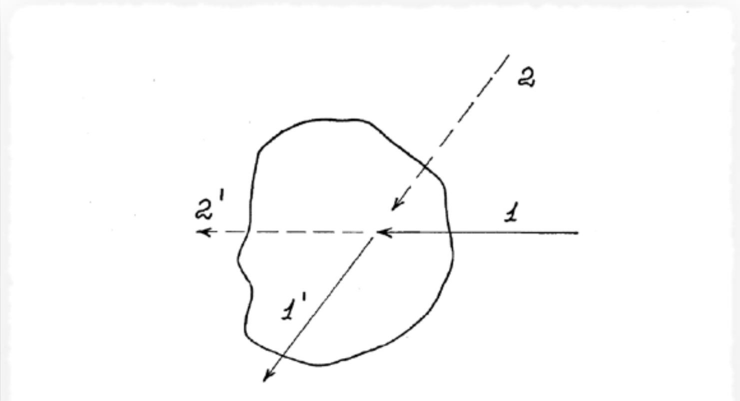


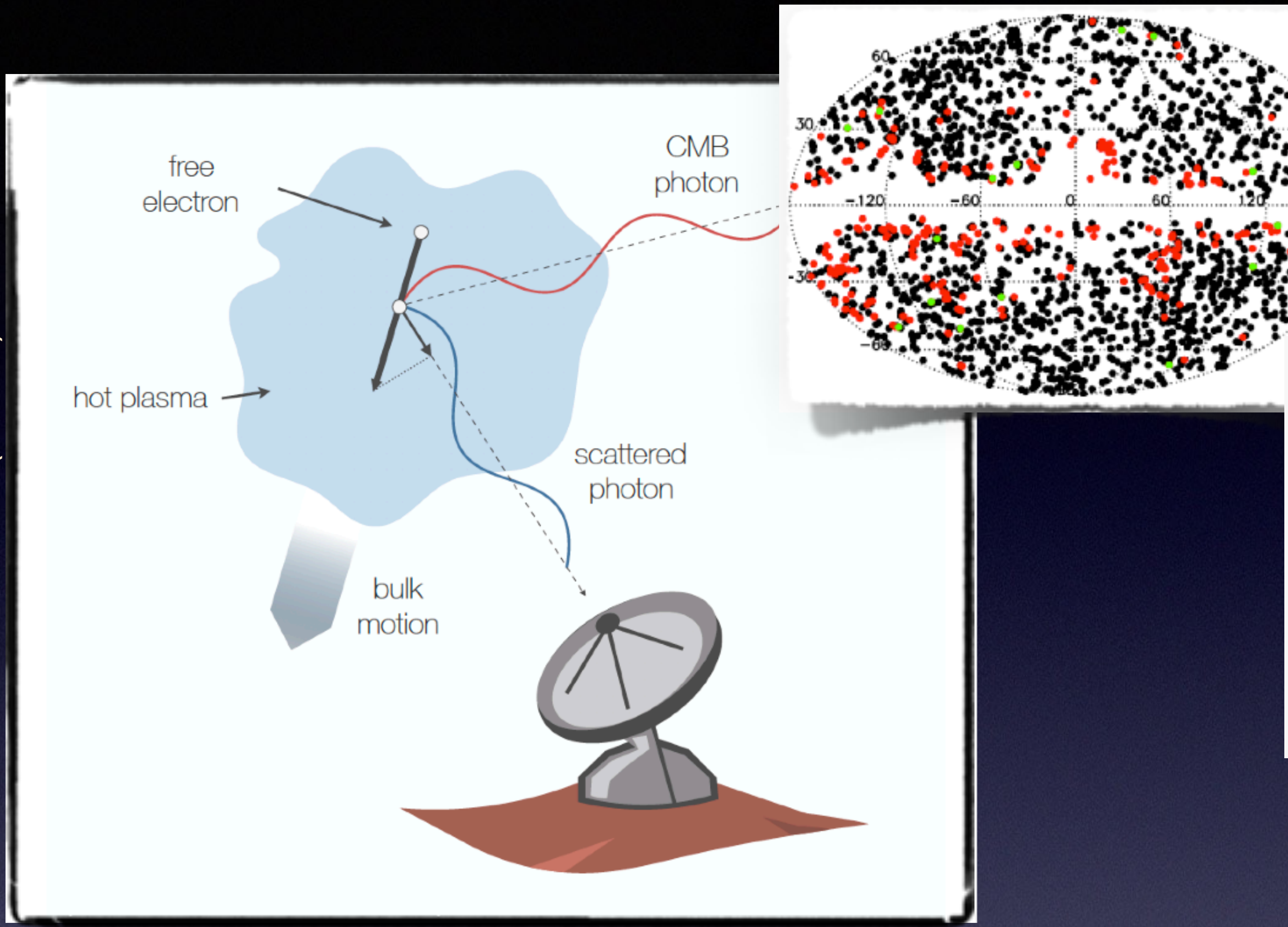
FIG. 2. The scattering of isotropic radiation field by the cloud of electrons.

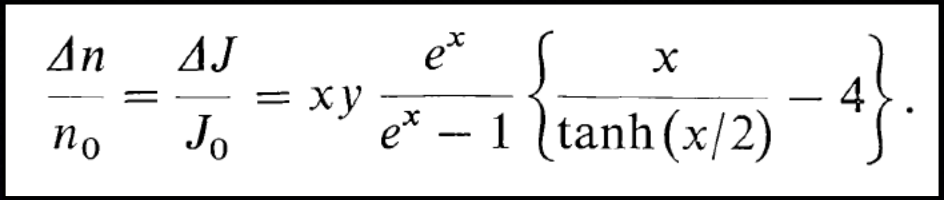
R. A. Sunyaev & Ya. B. Zeldovich

Comments on Astroph. & Space Ph., 1972

Flavours of the SZ effect: tSZ, kSZ

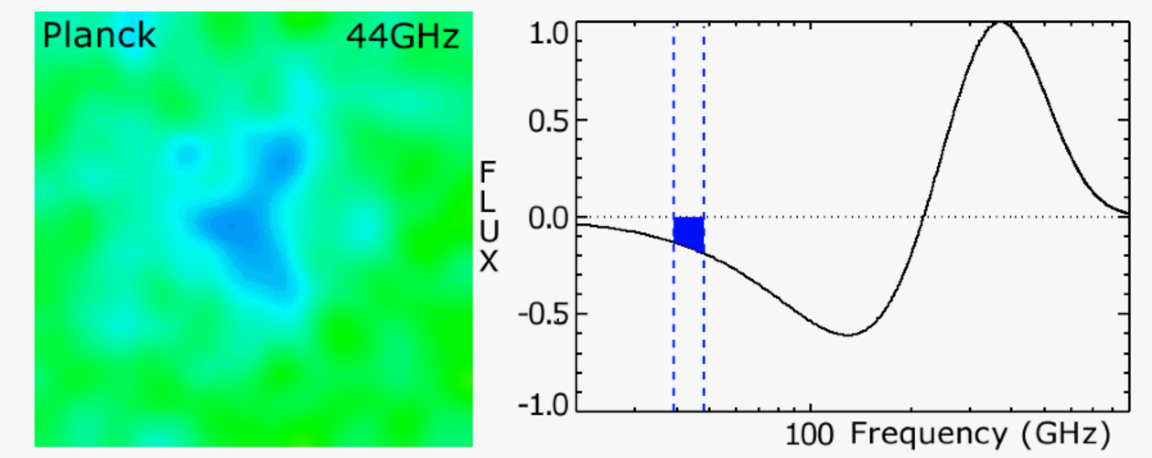
Mroczkowski et al. (2019)



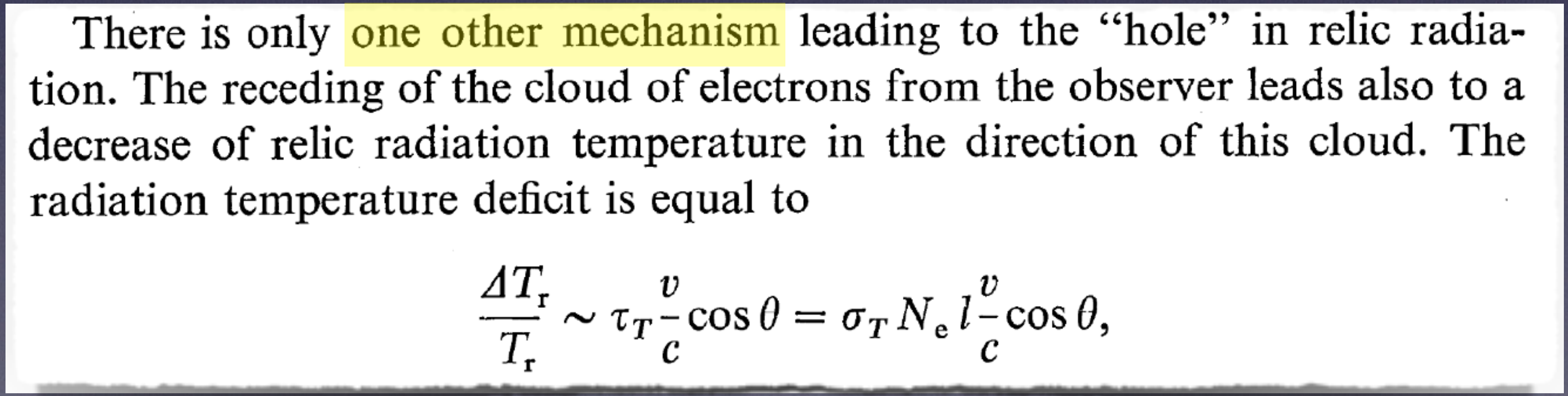


$$\frac{\Delta n}{n_0} = \frac{\Delta J}{J_0} = xy\,\frac{e^x}{e^x - 1}\left\{\frac{x}{\tanh(x/2)} - 4\right\}.$$

Zeldovich & Sunyaev 1969, Ap.Sp.Science



Credit: Planck collaboration (2015)



There is only one other mechanism leading to the "hole" in relic radiation. The receding of the cloud of electrons from the observer leads also to a decrease of relic radiation temperature in the direction of this cloud. The radiation temperature deficit is equal to

$$\frac{\Delta T_r}{T_r} \sim \tau_T \frac{v}{c} \cos\theta = \sigma_T N_e l \frac{v}{c} \cos\theta,$$

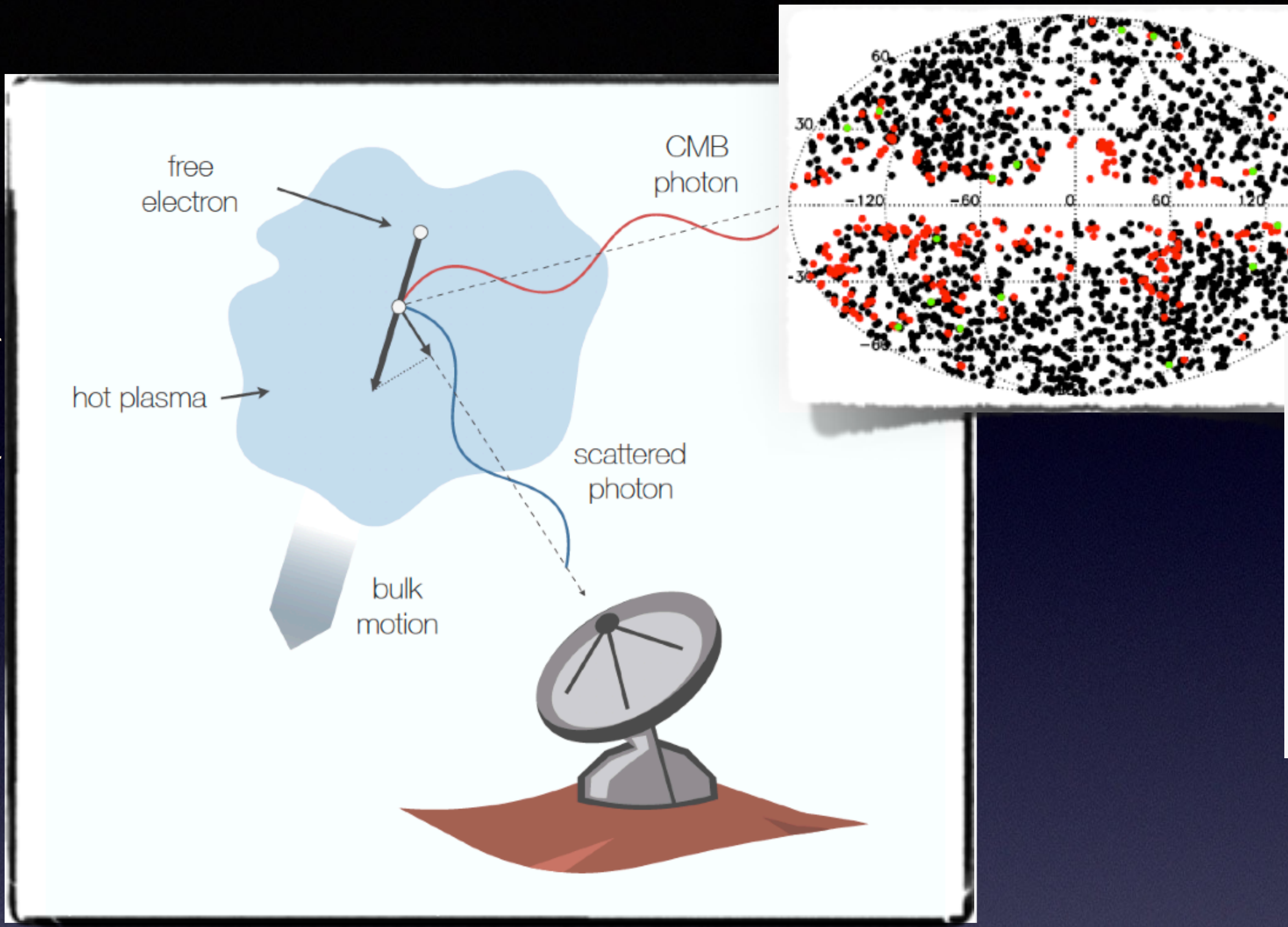
R. A. Sunyaev & Ya. B. Zeldovich
Comments on Astrophysics & Space Physics, 1972

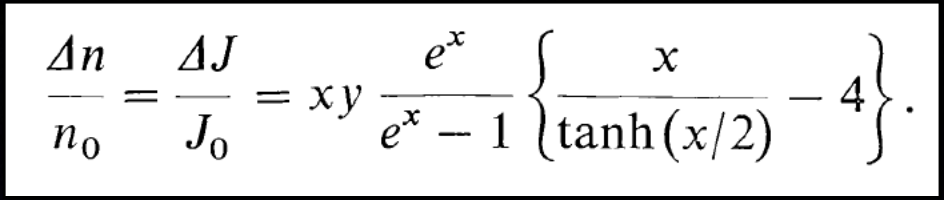
kSZ measures the peculiar velocities, and in the limit of the linear perturbation theory, directly the growth rate

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

Flavours of the SZ effect: tSZ, kSZ

Mroczkowski et al. (2019)





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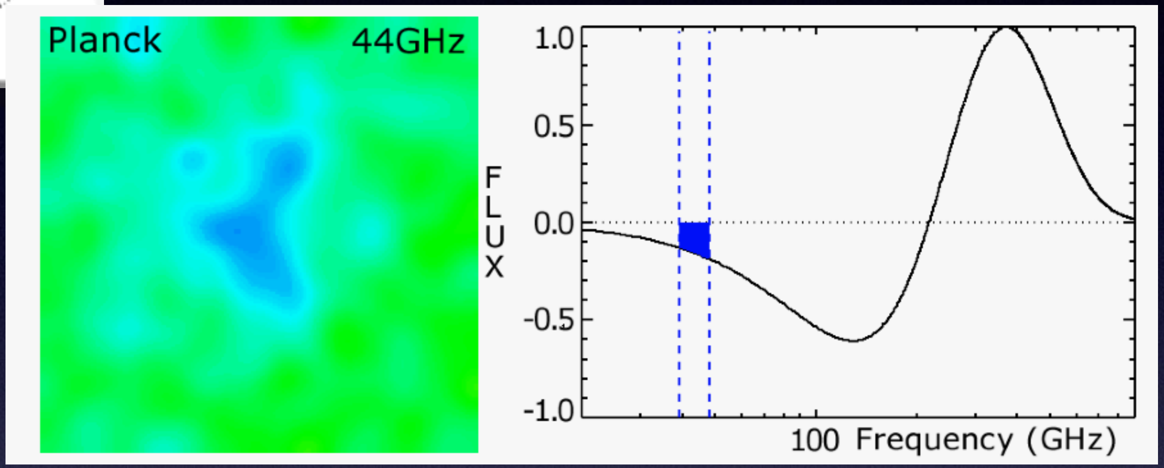
Zeldovich & Sunyaev 1969, Ap.Sp.Science



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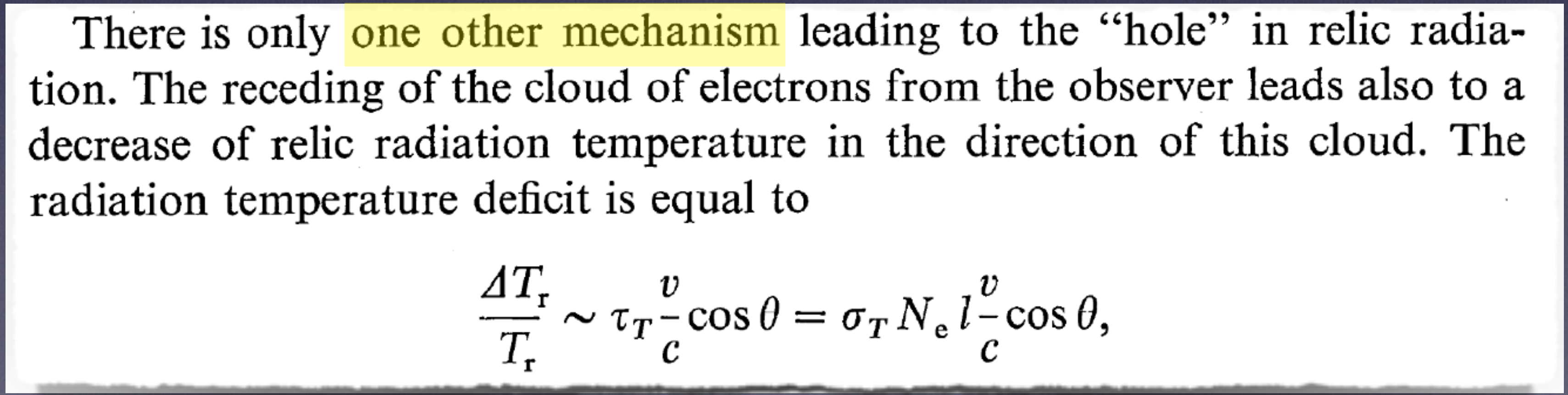

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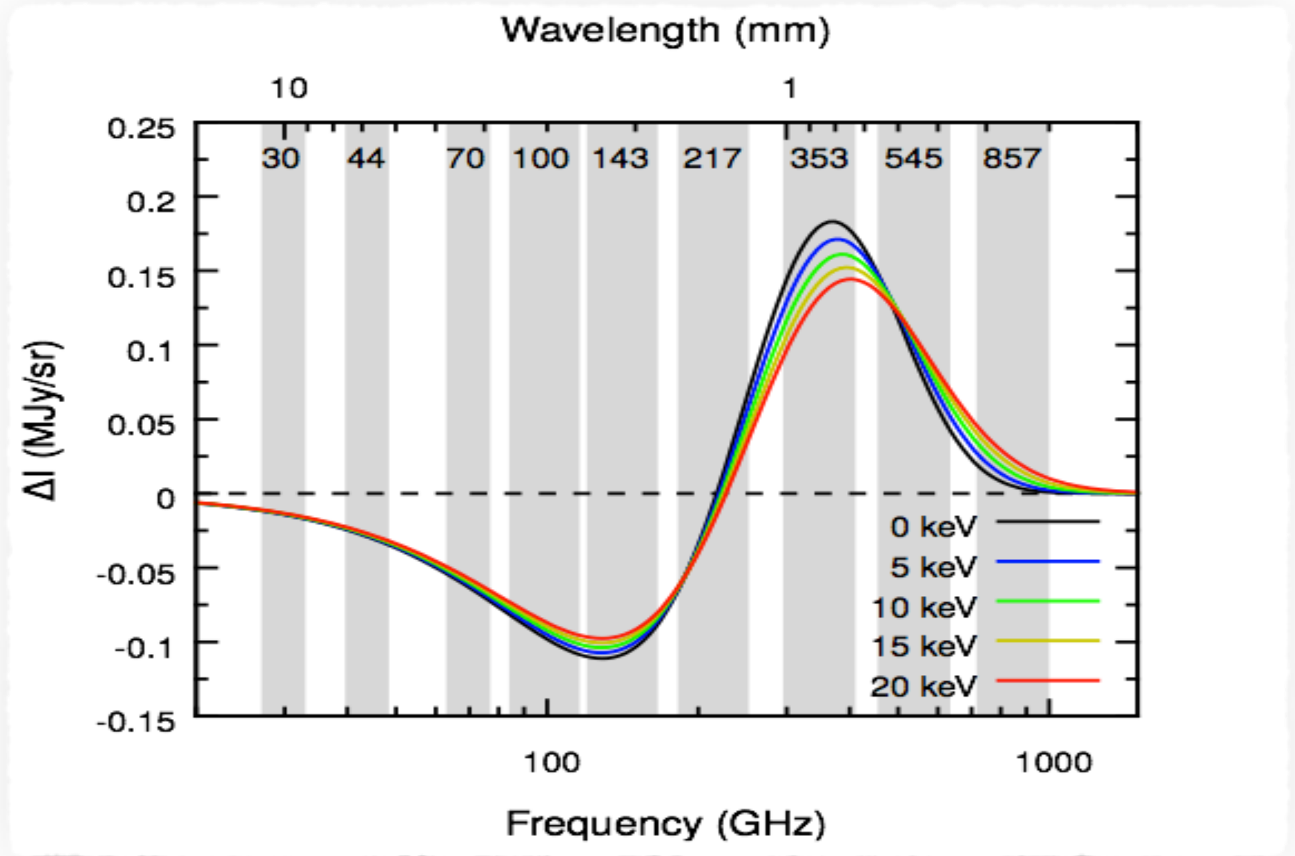
Flavours of the SZ effect: rSZ, ntSZ



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

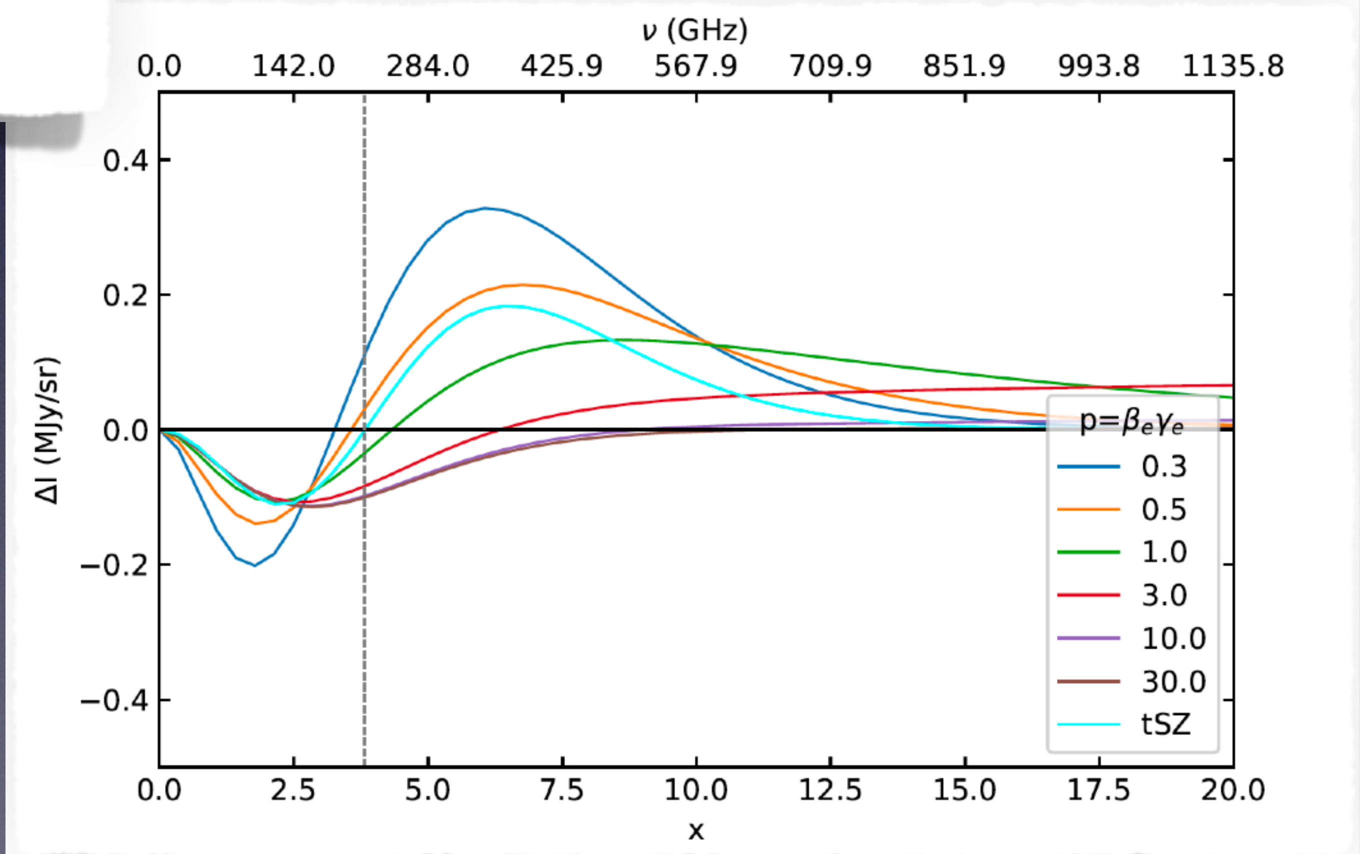
$\beta = (3k_BT_e / m_ec^2)^{1/2} \approx 0.1$–$0.2$ for 5 keV plasma

$$\left\langle \frac{\Delta\nu}{\nu} \right\rangle \approx 4\Theta_e + 10\Theta_e^2 + \frac{15}{2}\Theta_e^3 - \frac{15}{2}\Theta_e^4 + O(\Theta_e^5)$$

Relativistic corrections occur both on tSZ (k_BT_e / m_ec^2) and kSZ (v_p/c) effects.

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

IC emission is routinely observed in hard X-ray band, from AGN lobes!

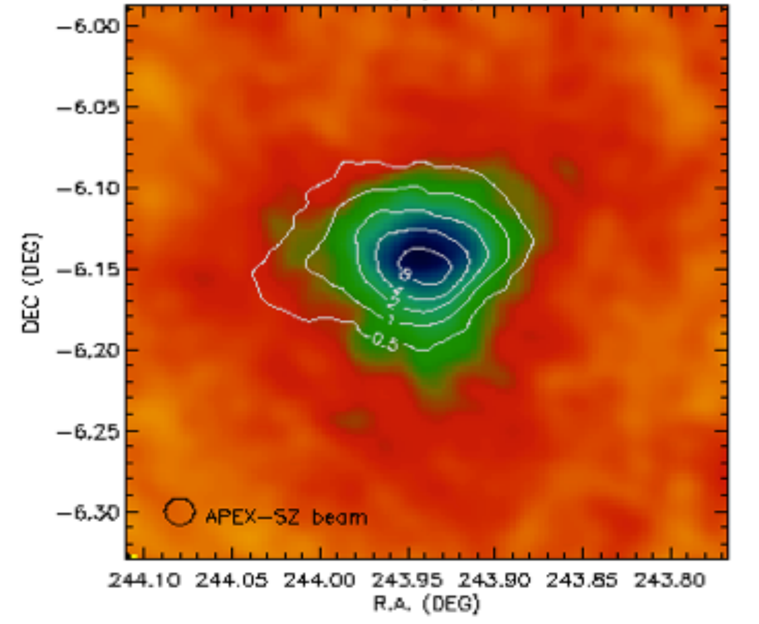


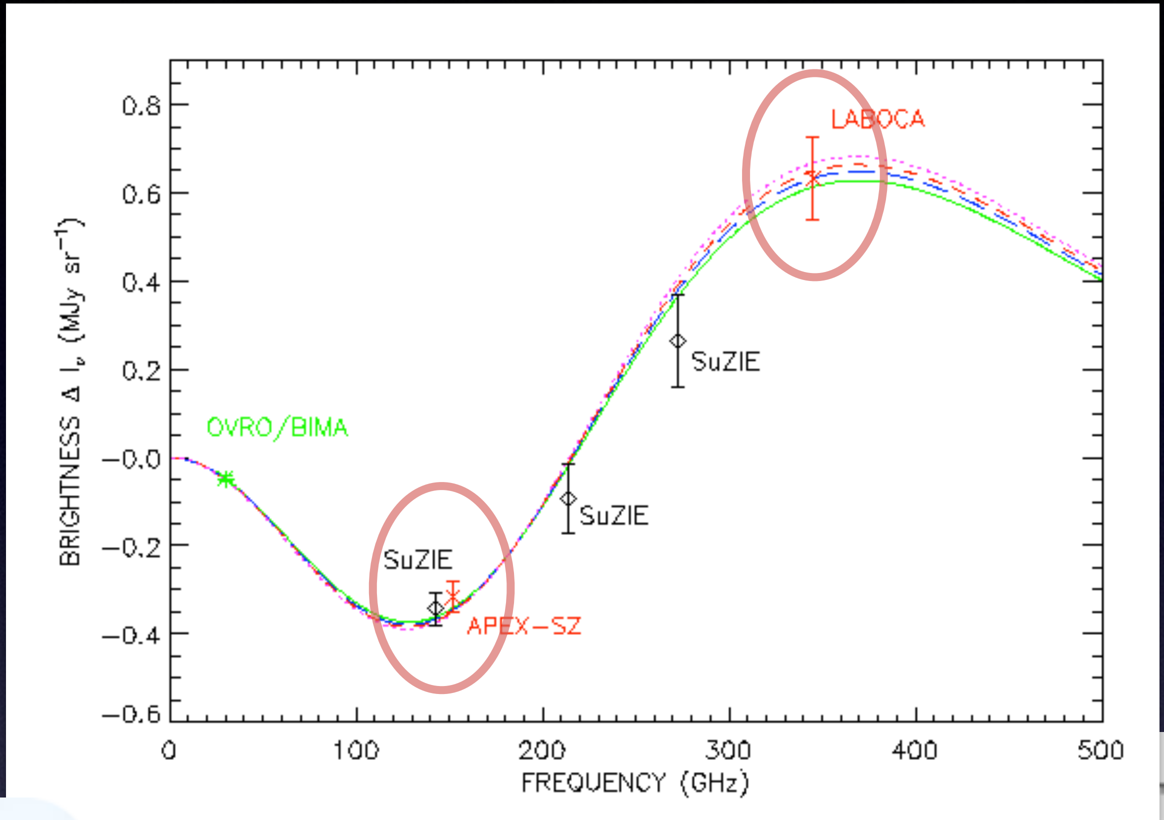
+ Polarized SZ and Multiple-Scattering SZ

A bit of history..

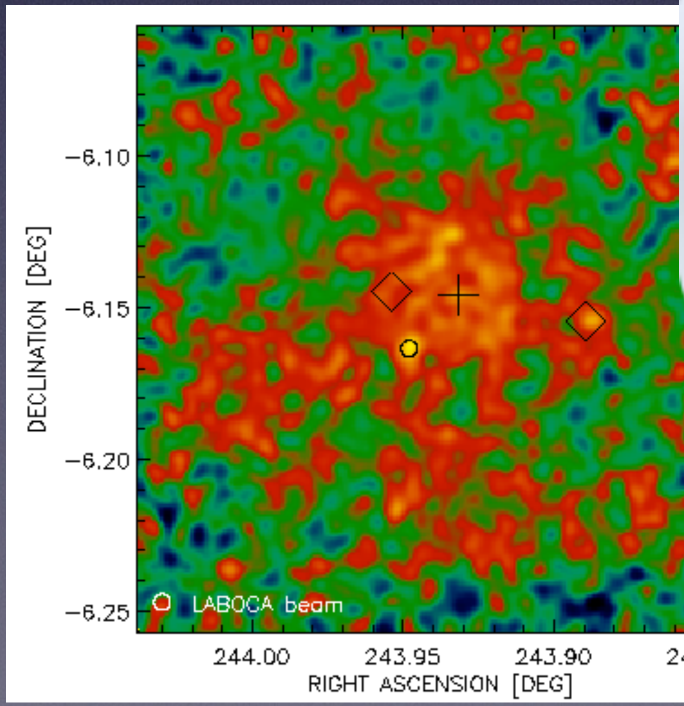
Nord, Basu et al. (2009) — first large-format SZ increment imaging

APEX-SZ (150 GHz)

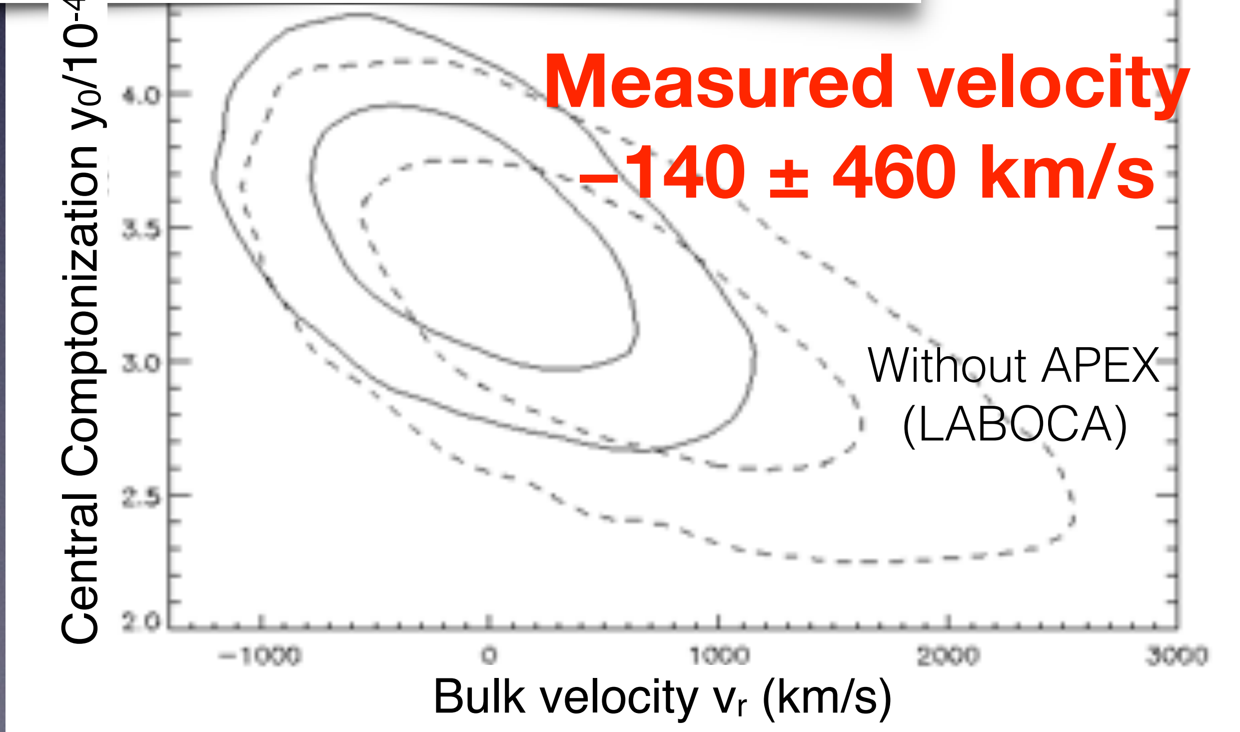




LABOCA (350 GHz)



The only SZ imaging done by LABOCA



Measured velocity –140 ± 460 km/s

Relativistic SZ effect

Relativistic corrections occur both on tSZ and kSZ spectra and can inform us about both temperature and velocities of galaxy clusters.

We focus only on the relativistic tSZ, which is a ~few percent effect, and find constraints on T_{SZ}.

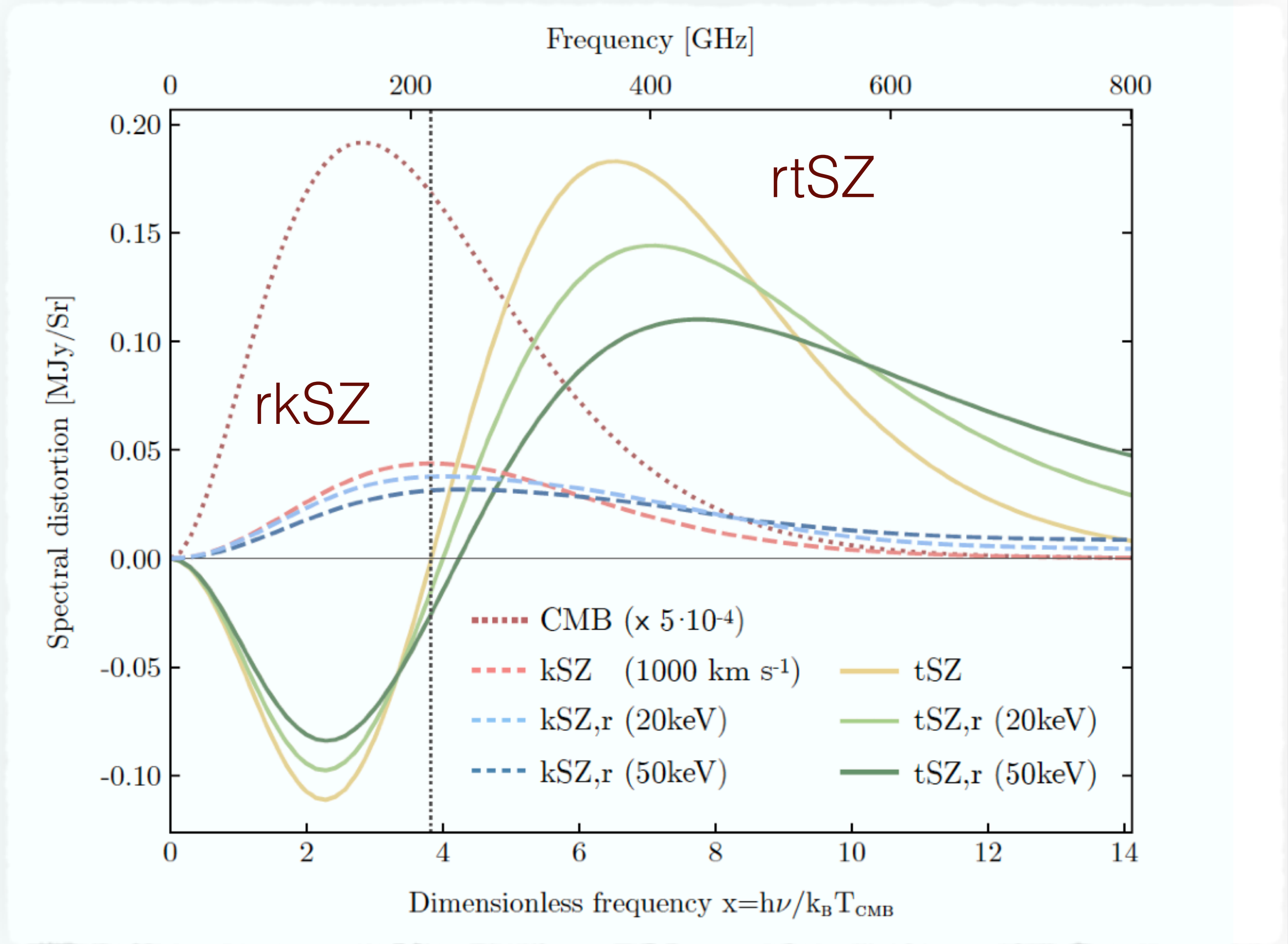
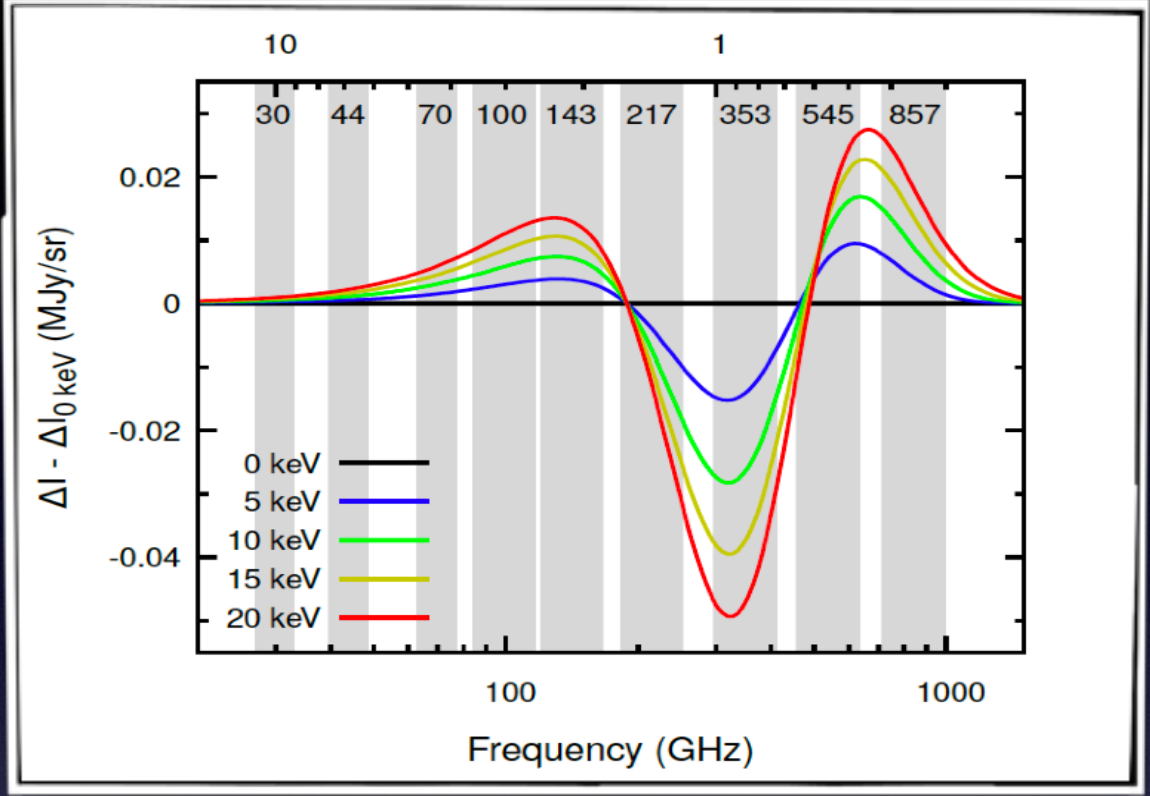
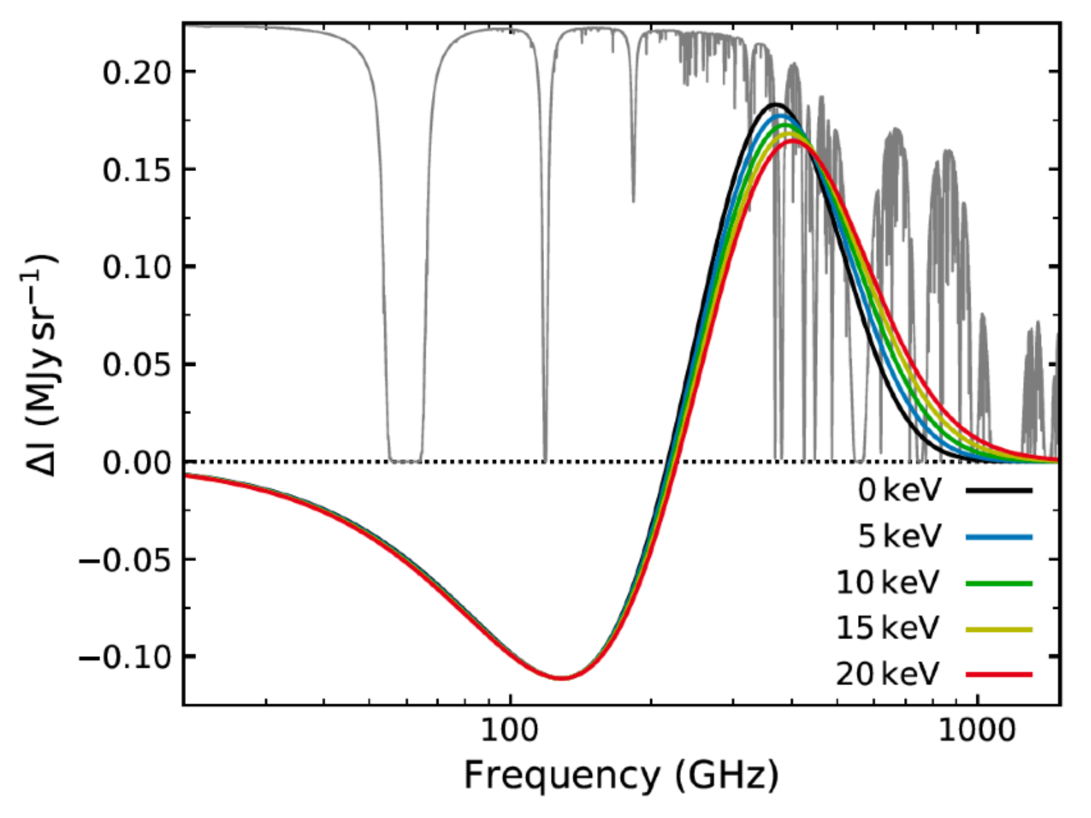
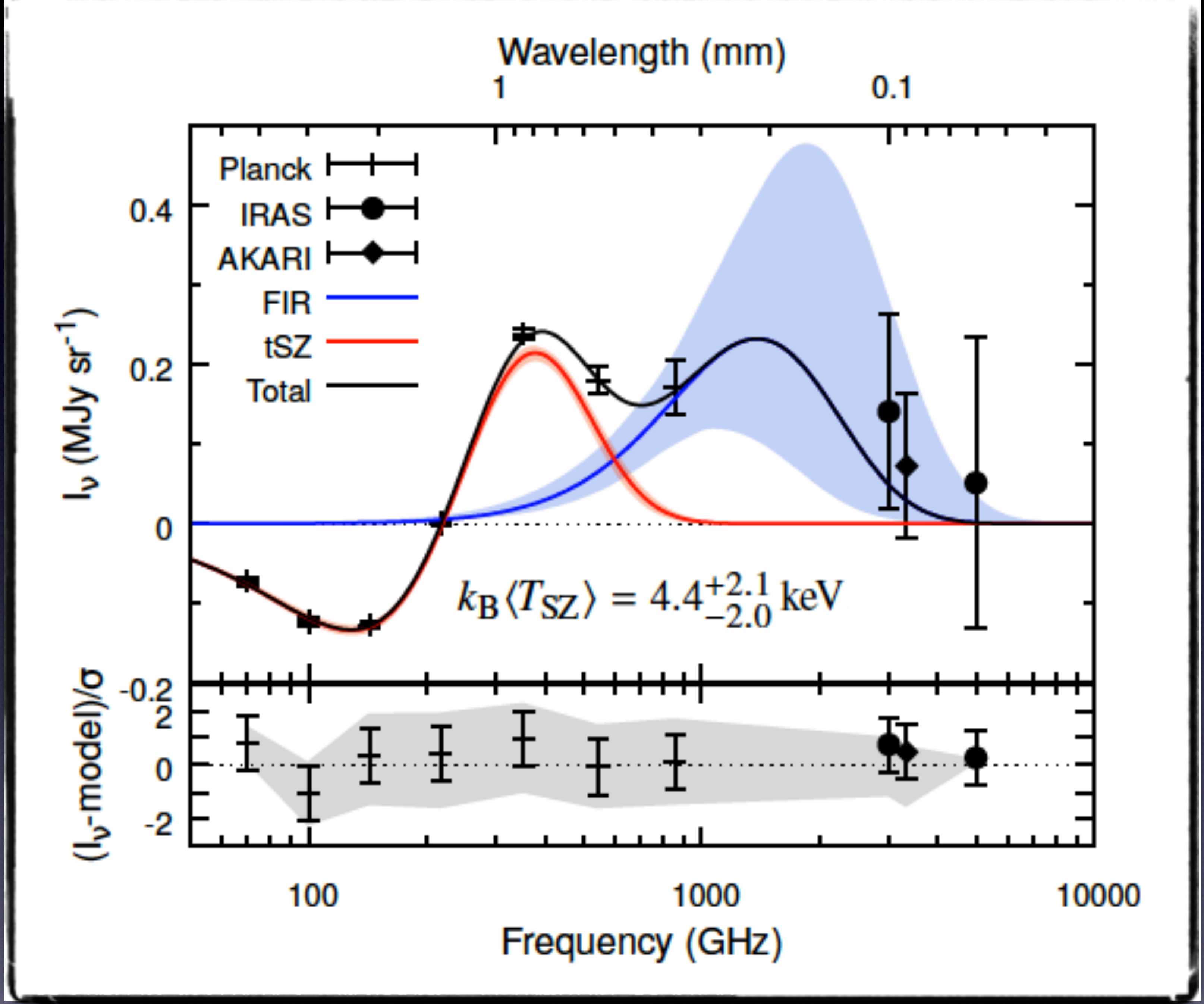


Fig. From Mroczkowski et al. (2019)





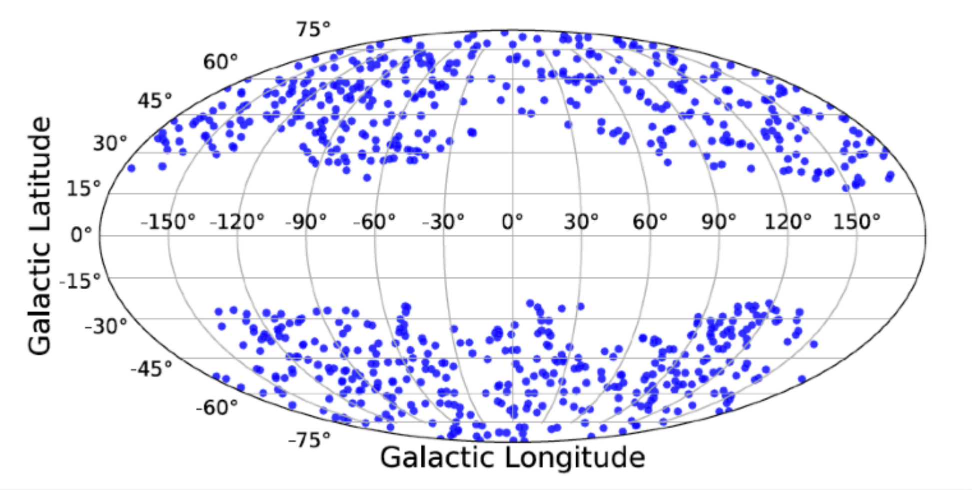
First tentative rSZ detection

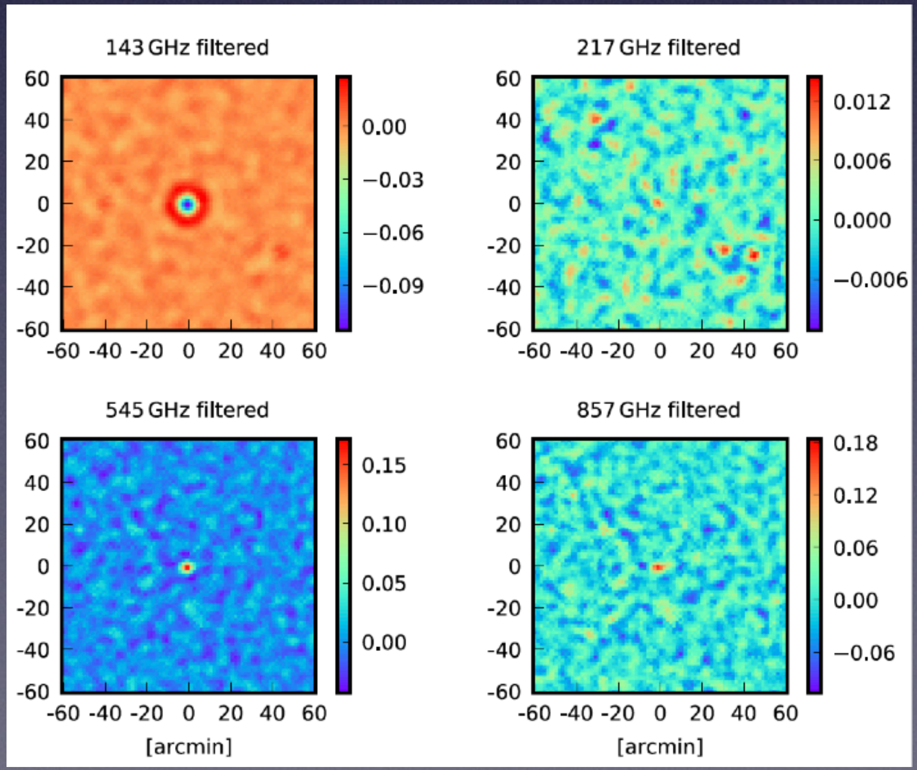


Erler, Basu et al. (2018)

772 *Planck* clusters, **matched-filtered and stacked**

(IRAS and AKARI for the far-infrared)



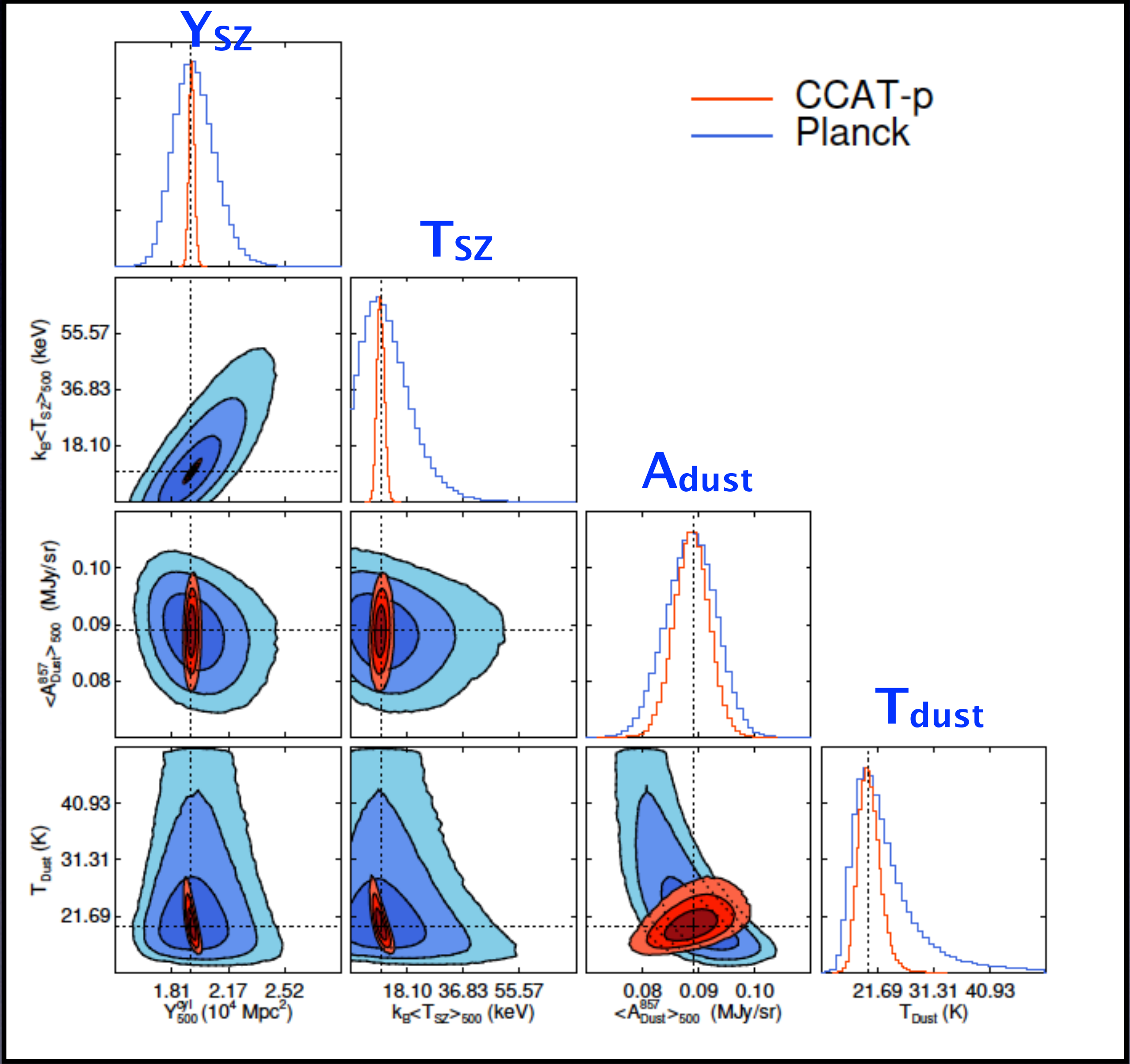


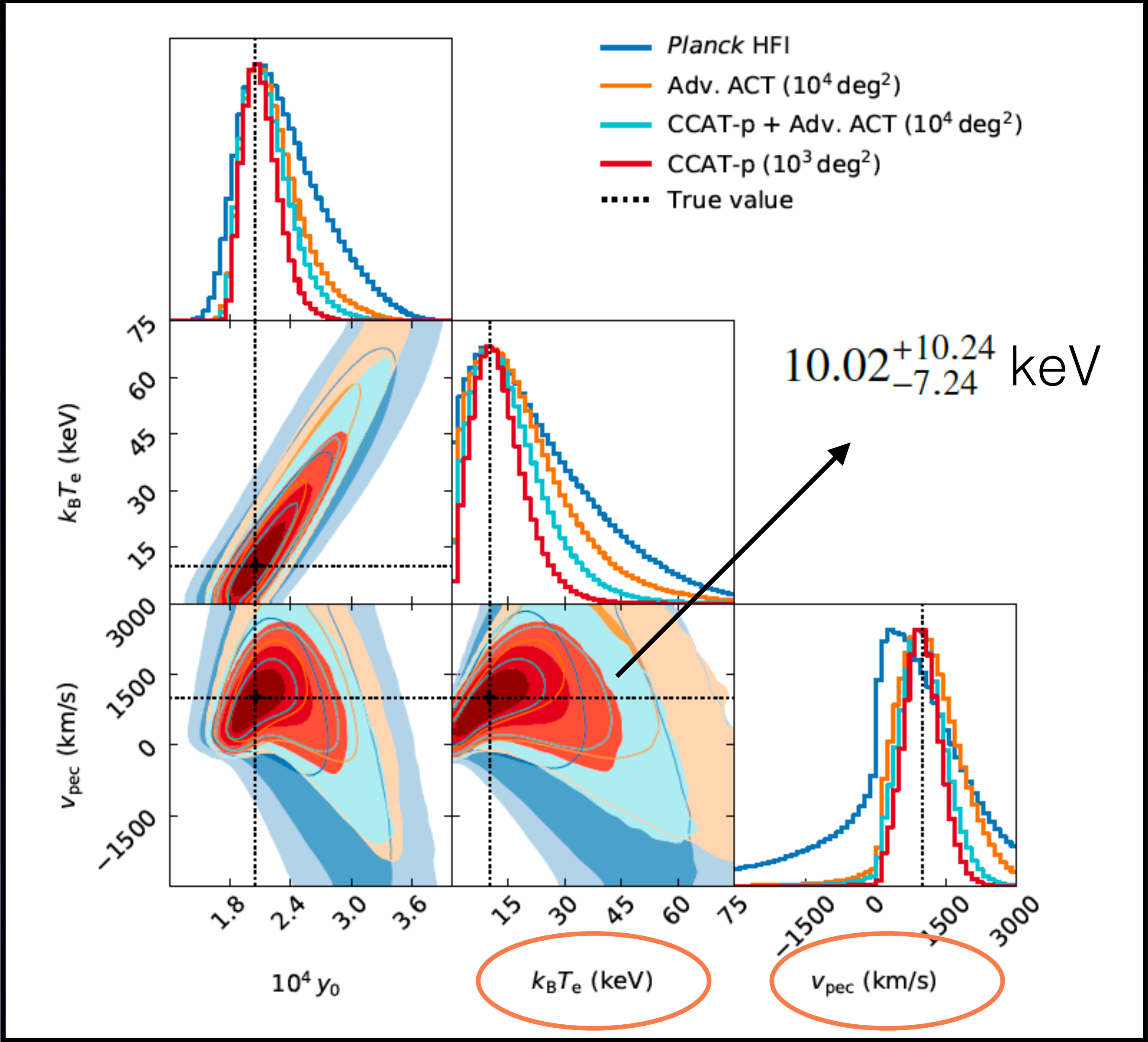
rSZ in the near future

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





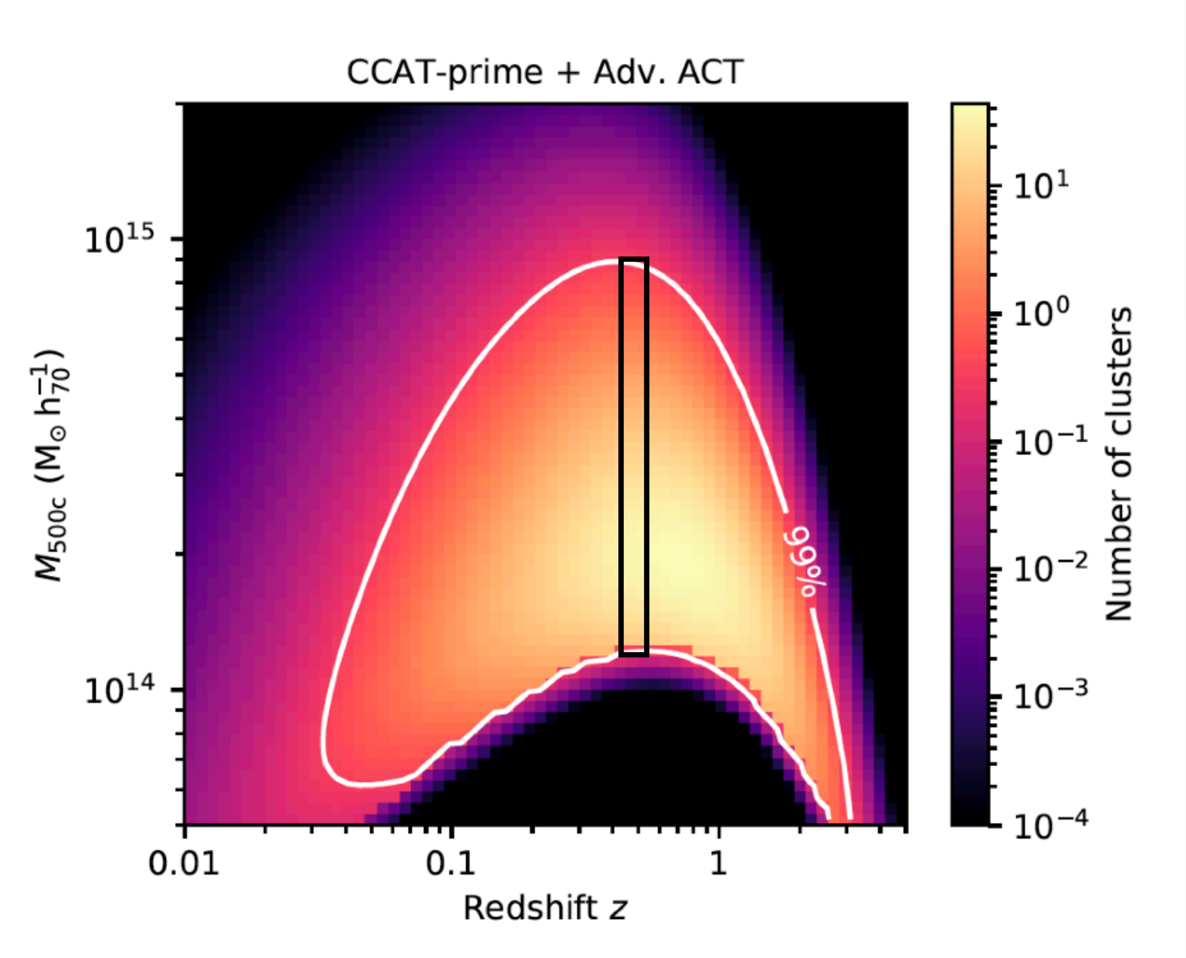
$10.02^{+10.24}_{-7.24}$ keV

Erler, Basu et al. (2018)

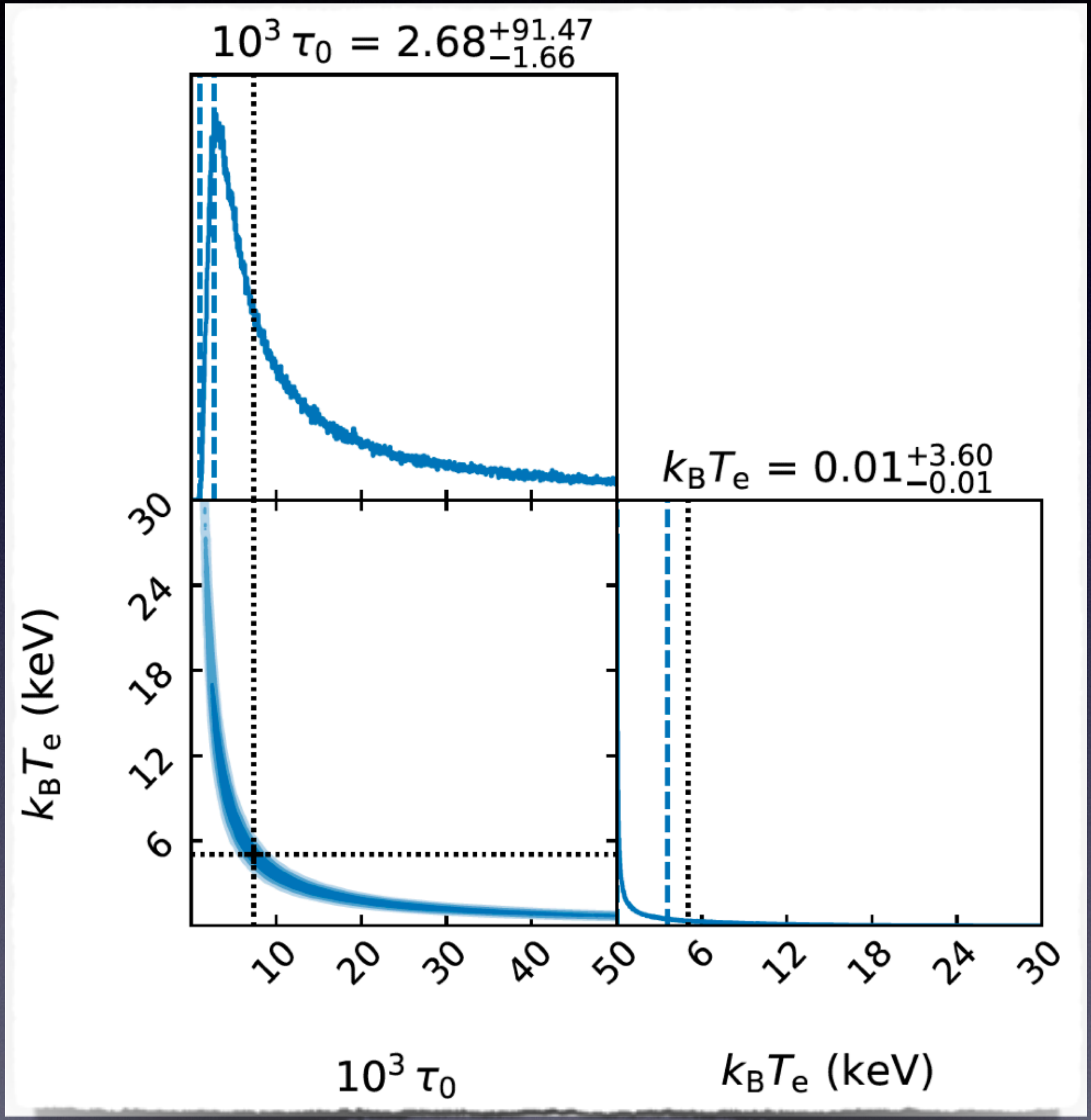
Jens Erler Ph.D. Thesis

Taking T_{SZ} measurements further

Cluster sample expected from a 10^4 deg^2 survey with advACT + CCAT-prime



Erler, Basu+ in prep.



Stacking ~200 of clusters in narrow redshift bins. Full foreground model & no worry about velocities!

Taking T_{SZ} measurements further

Erler, Basu+ in prep.

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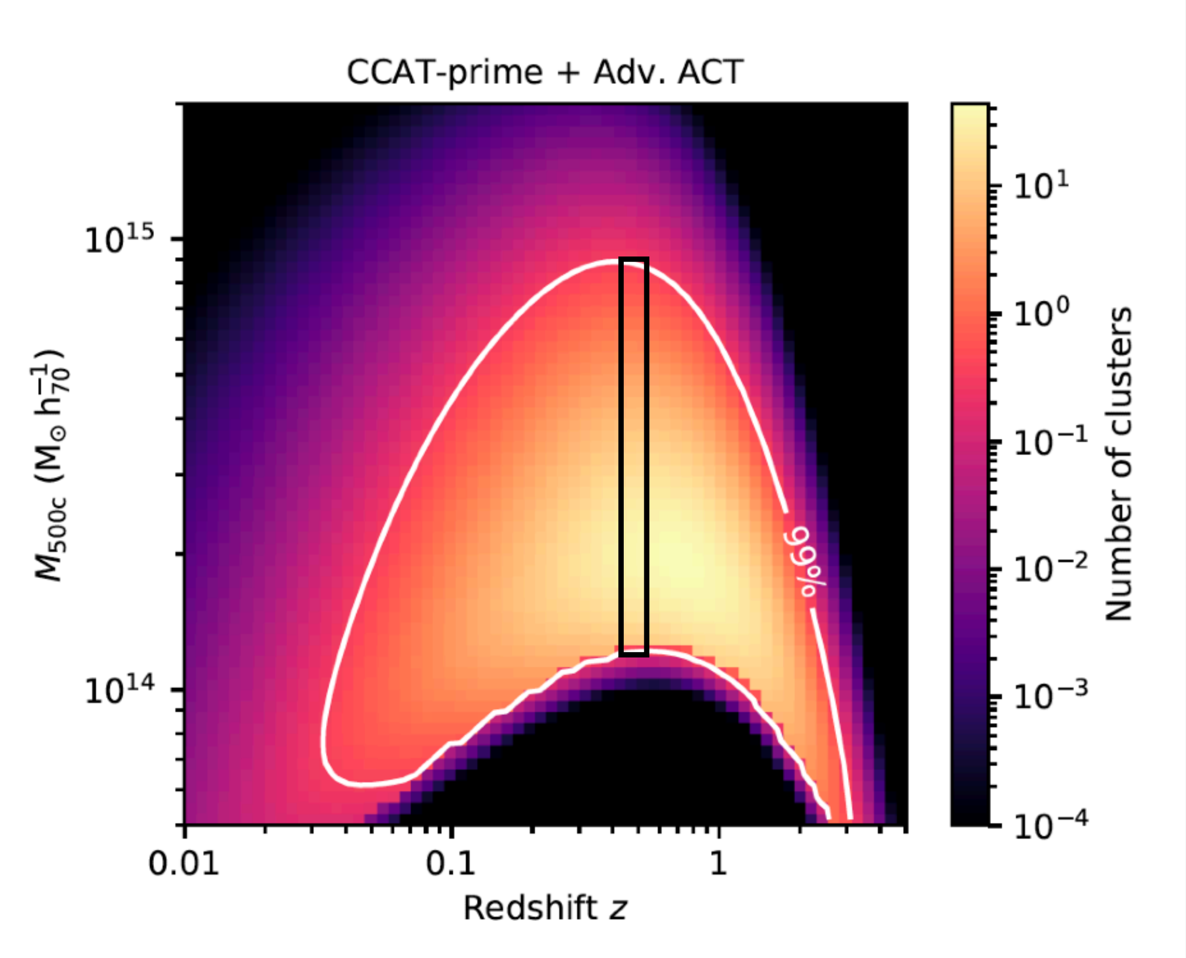

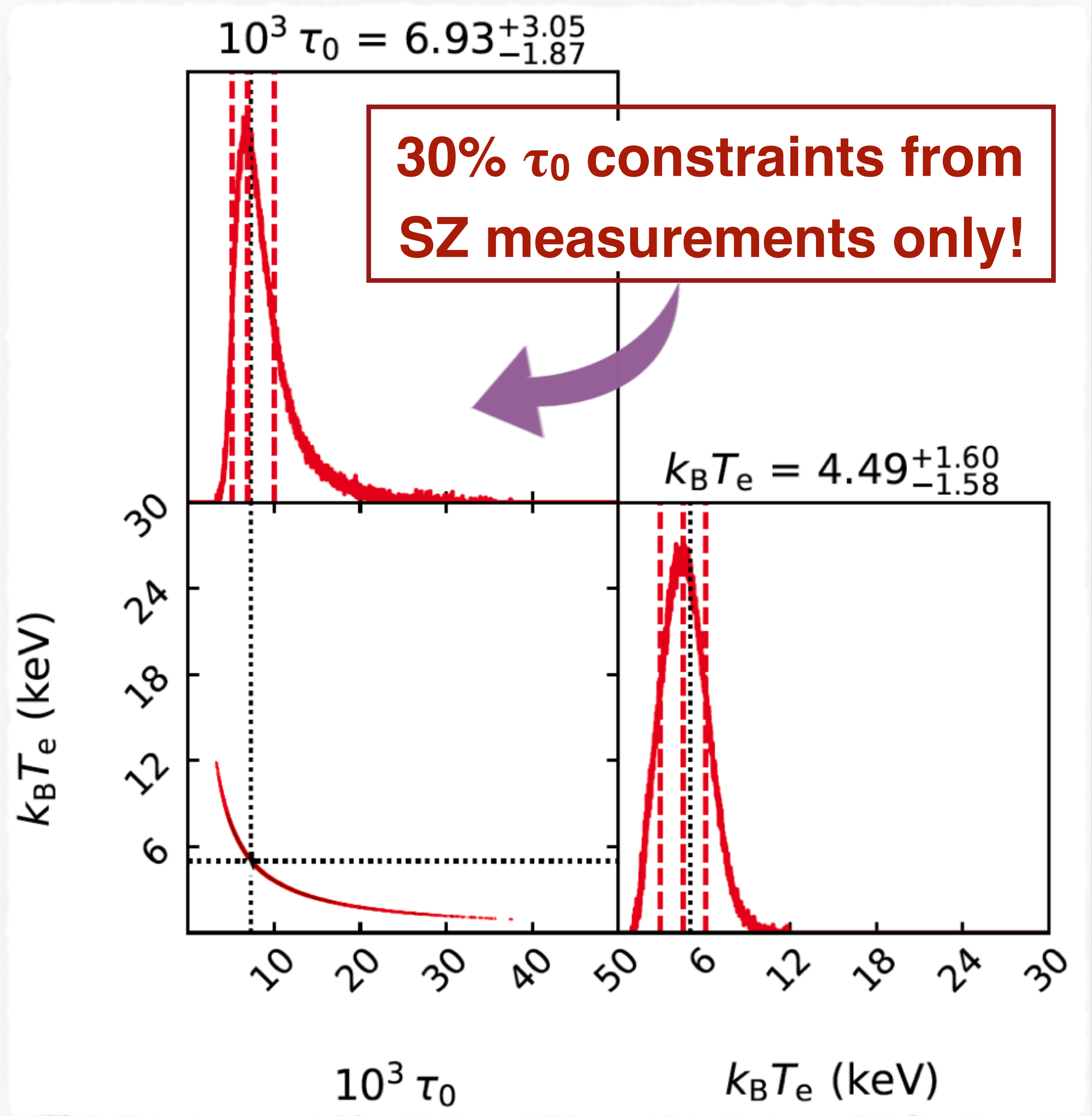

30% τ_0 constraints from SZ measurements only!

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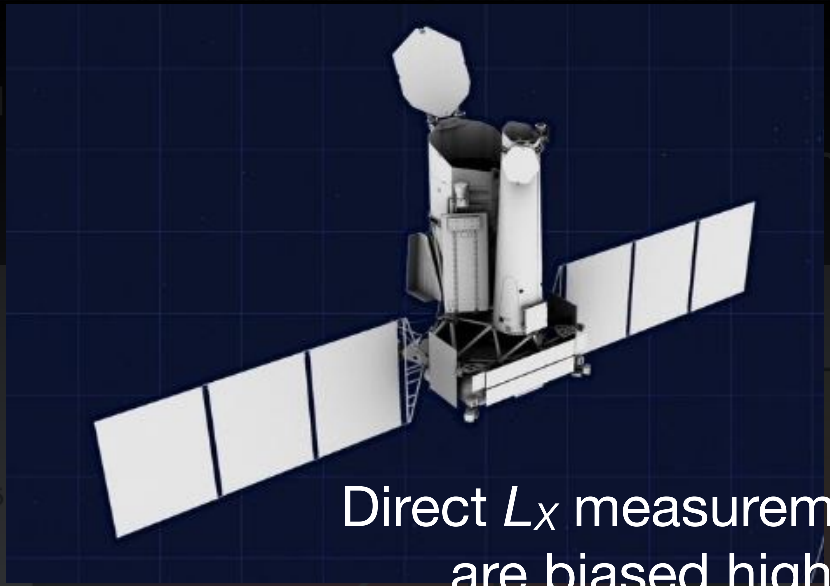
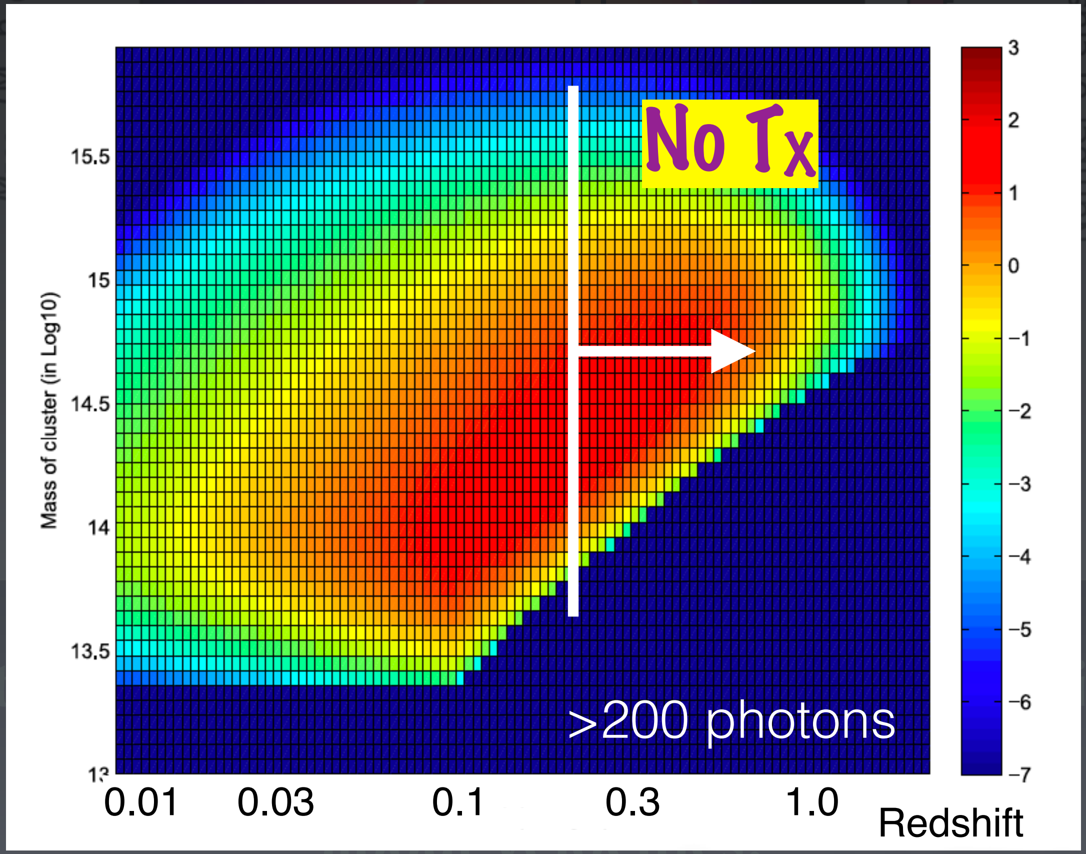
Taking T_{SZ} measurements further

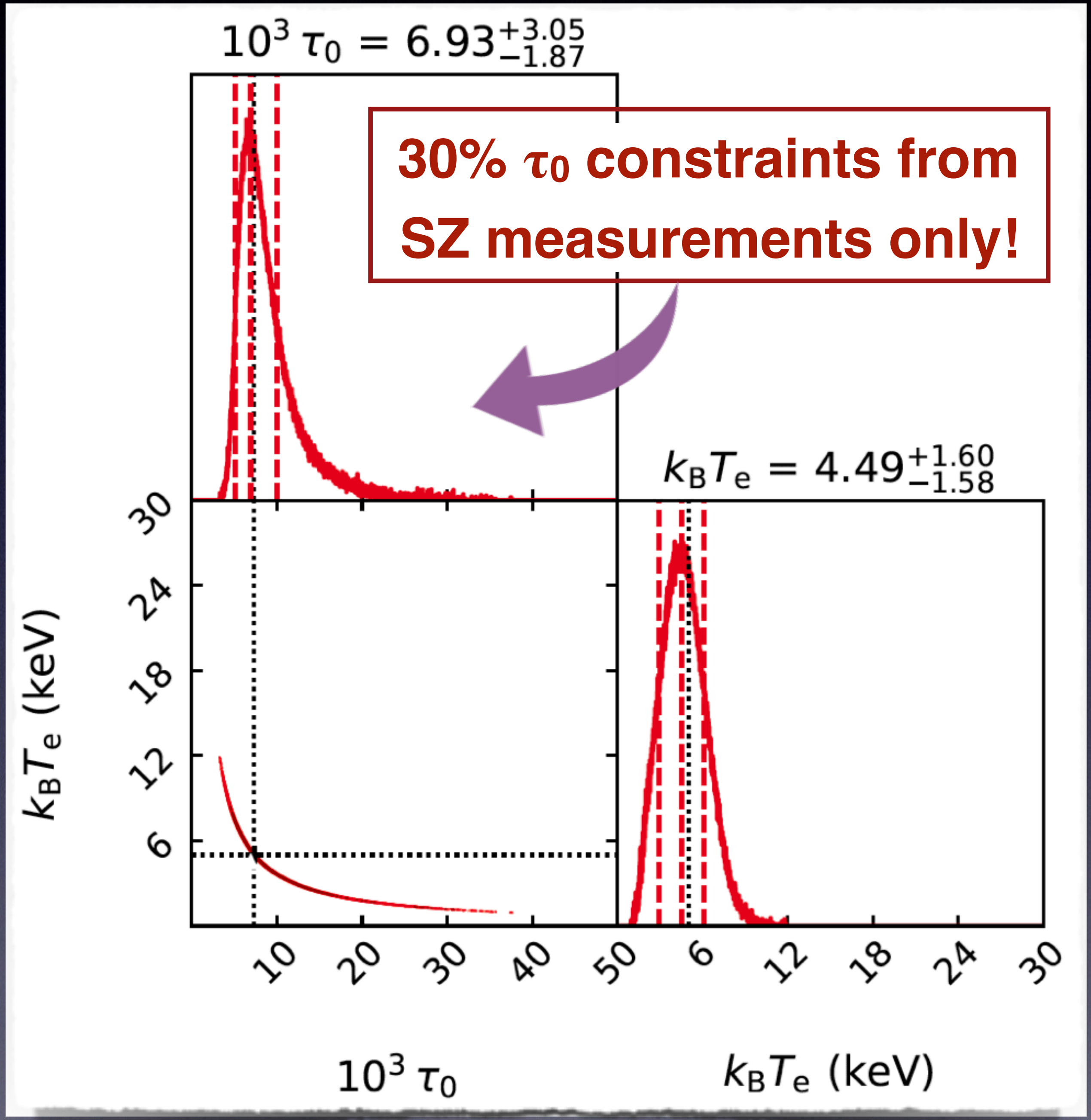


Direct L_X measurements are biased high



Borm et al. (2014)

Erler, Basu+ in prep.



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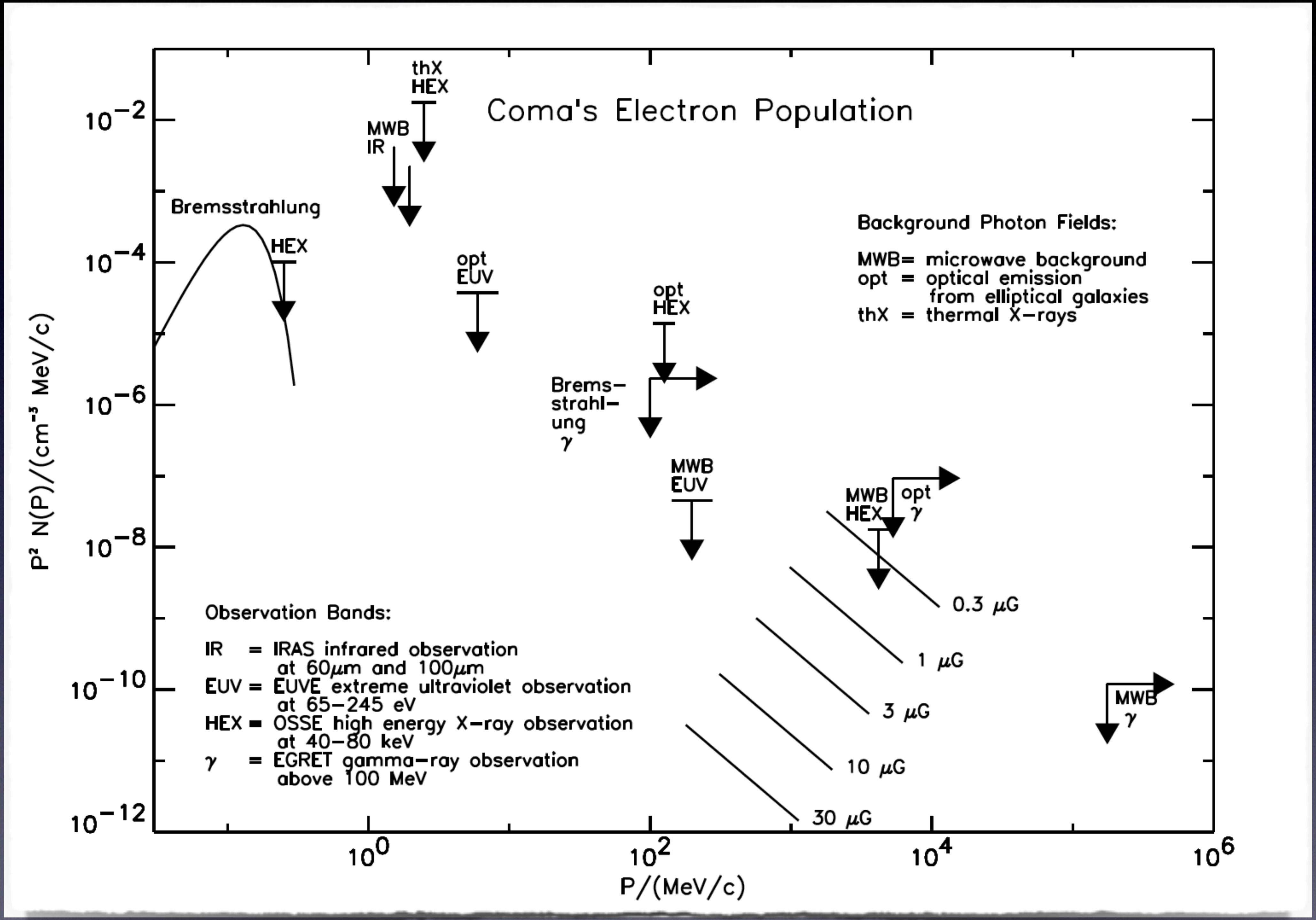
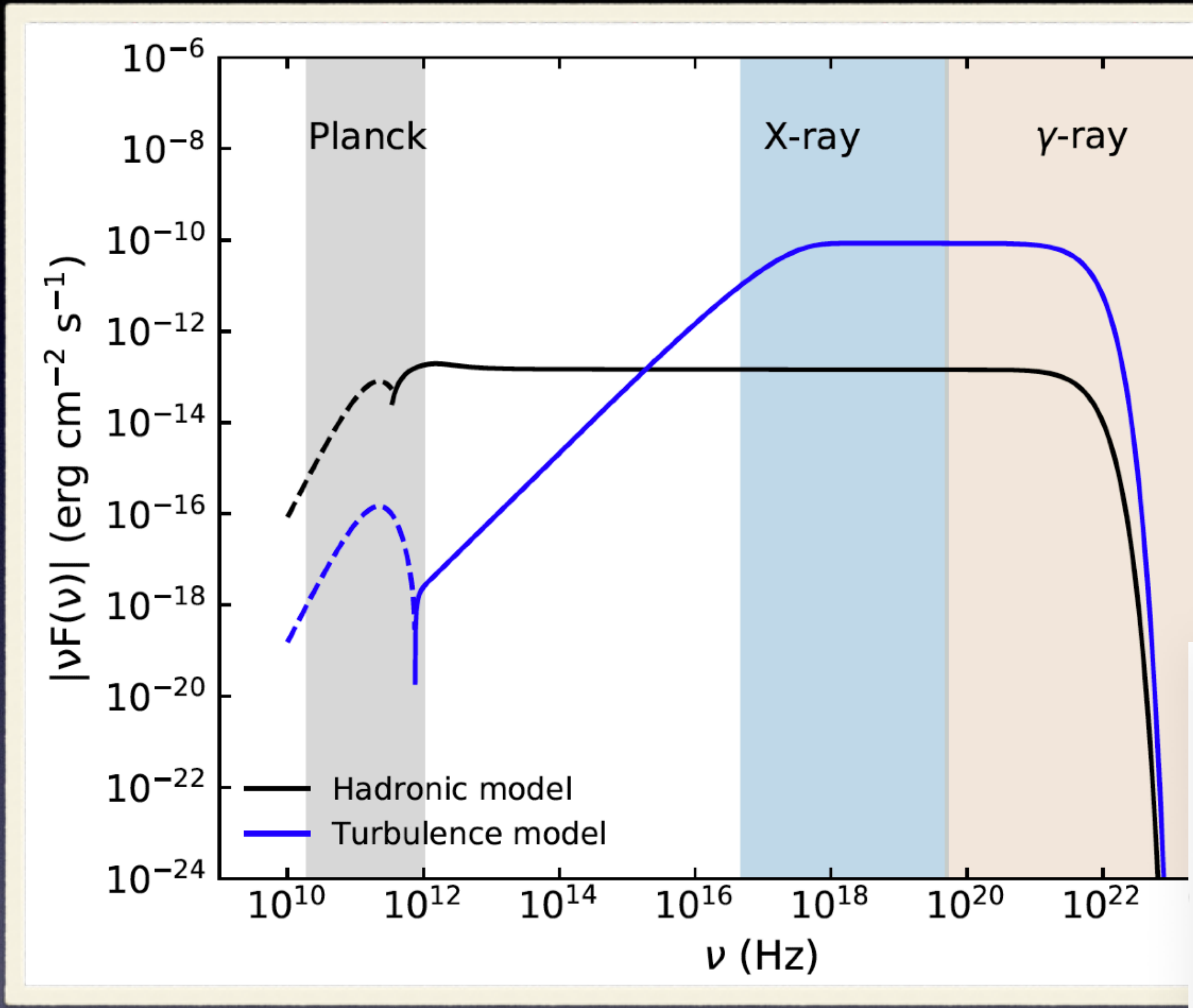
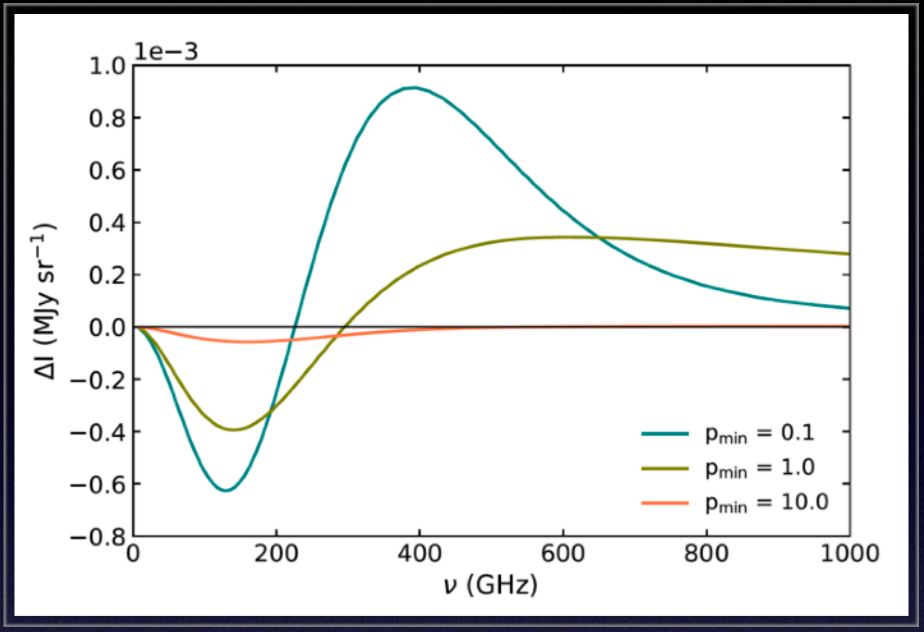
Nonthermal electrons in galaxy clusters



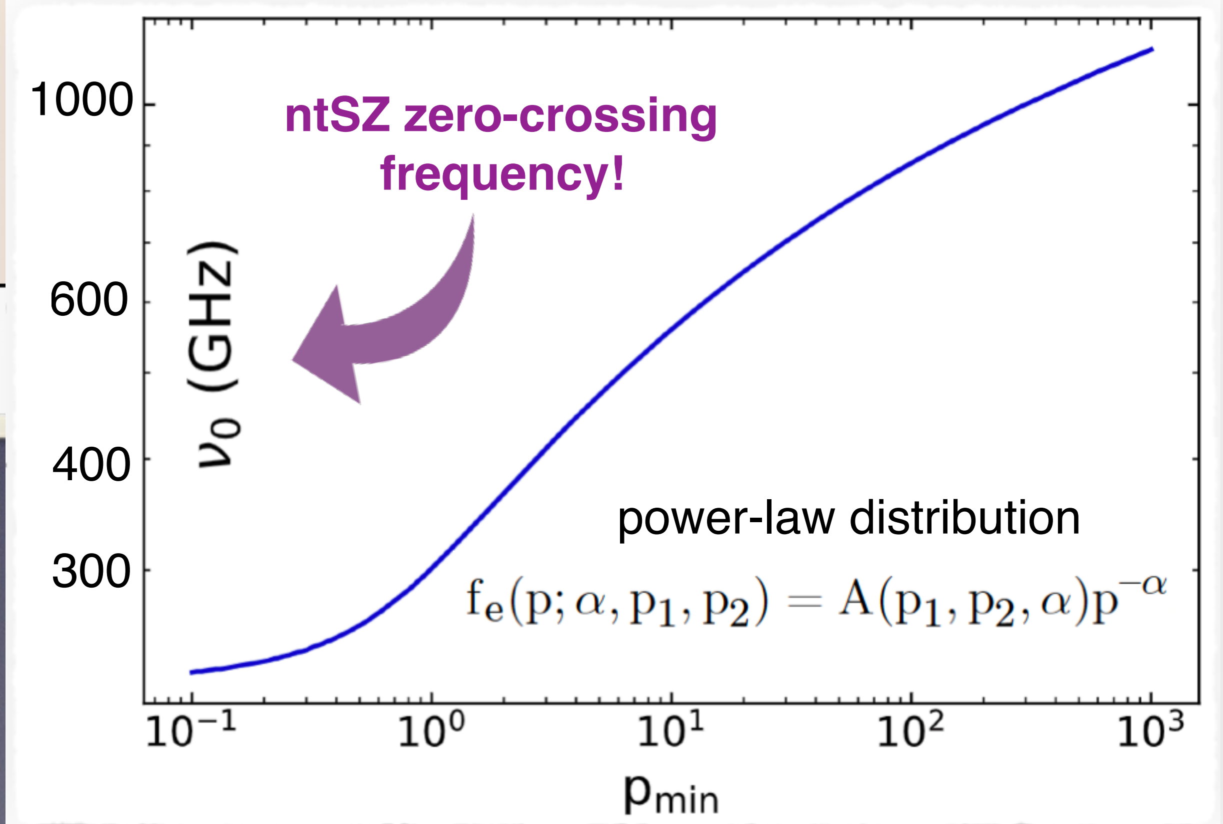
Enßlin & Biermann (1998)

Nonthermal SZ in galaxy clusters





Muralidhara+ in prep.



ntSZ zero-crossing frequency!

power-law distribution

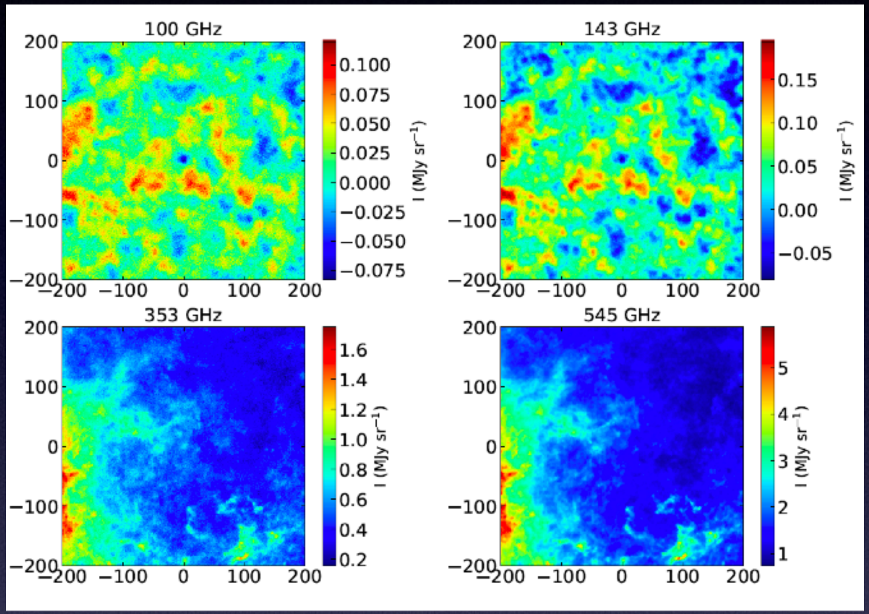
$$f_e(p;\alpha,p_1,p_2) = A(p_1,p_2,\alpha)p^{-\alpha}$$

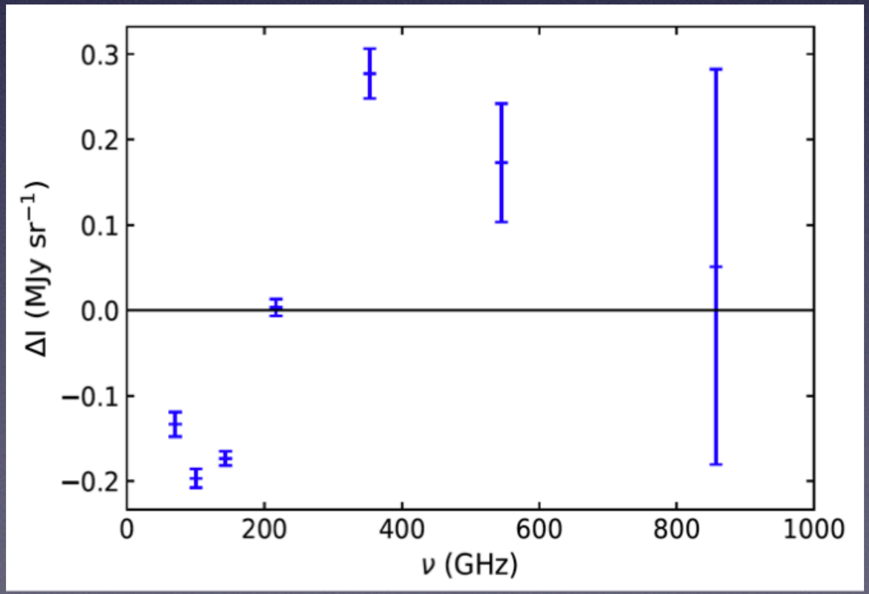
For the observed diffuse radio emissions in galaxy clusters (radio halos), ~GeV energy electrons are responsible. The effective p_{min} can be a ~few hundreds to ~1000.

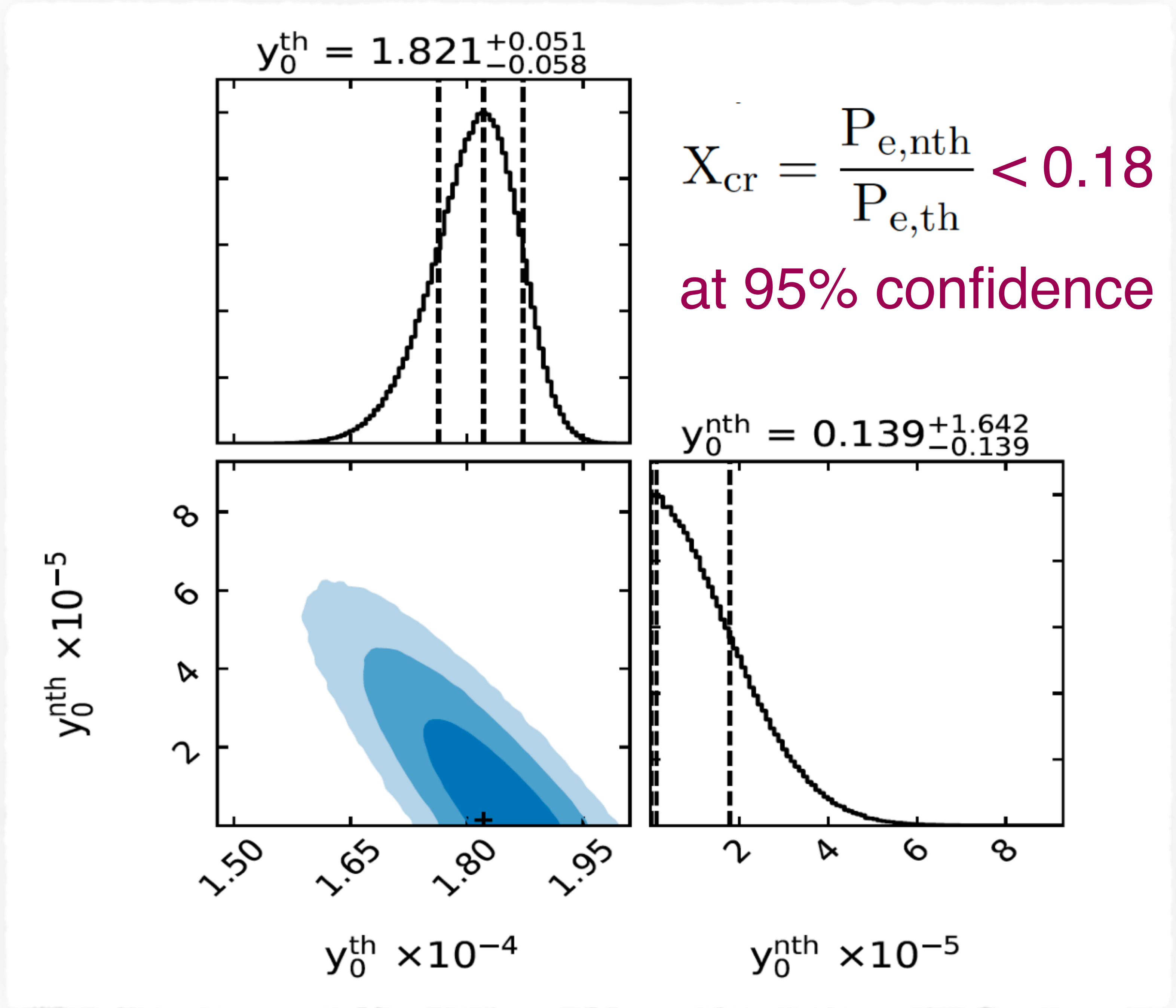
CRe energy constraints from Planck(!)

62 radio halo clusters extracted from Planck data — a simple 2-component spectral fit

Muralidhara+ in prep.







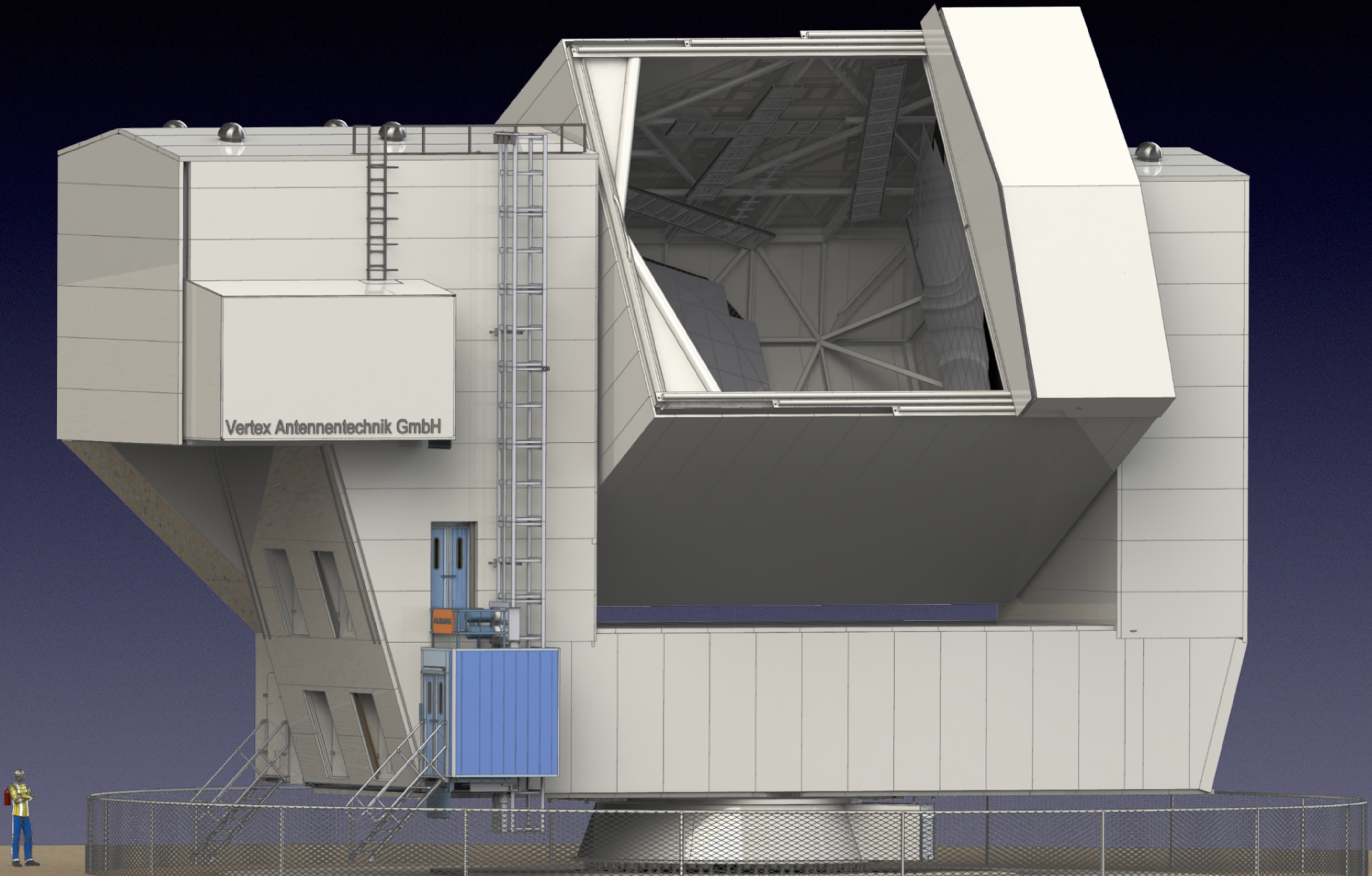
$$X_{cr} = \frac{P_{e,nth}}{P_{e,th}} < 0.18$$

at 95% confidence

There is a strong chance ntSZ can nail this down, before γ-ray or IC-Xray

CCAT-prime

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



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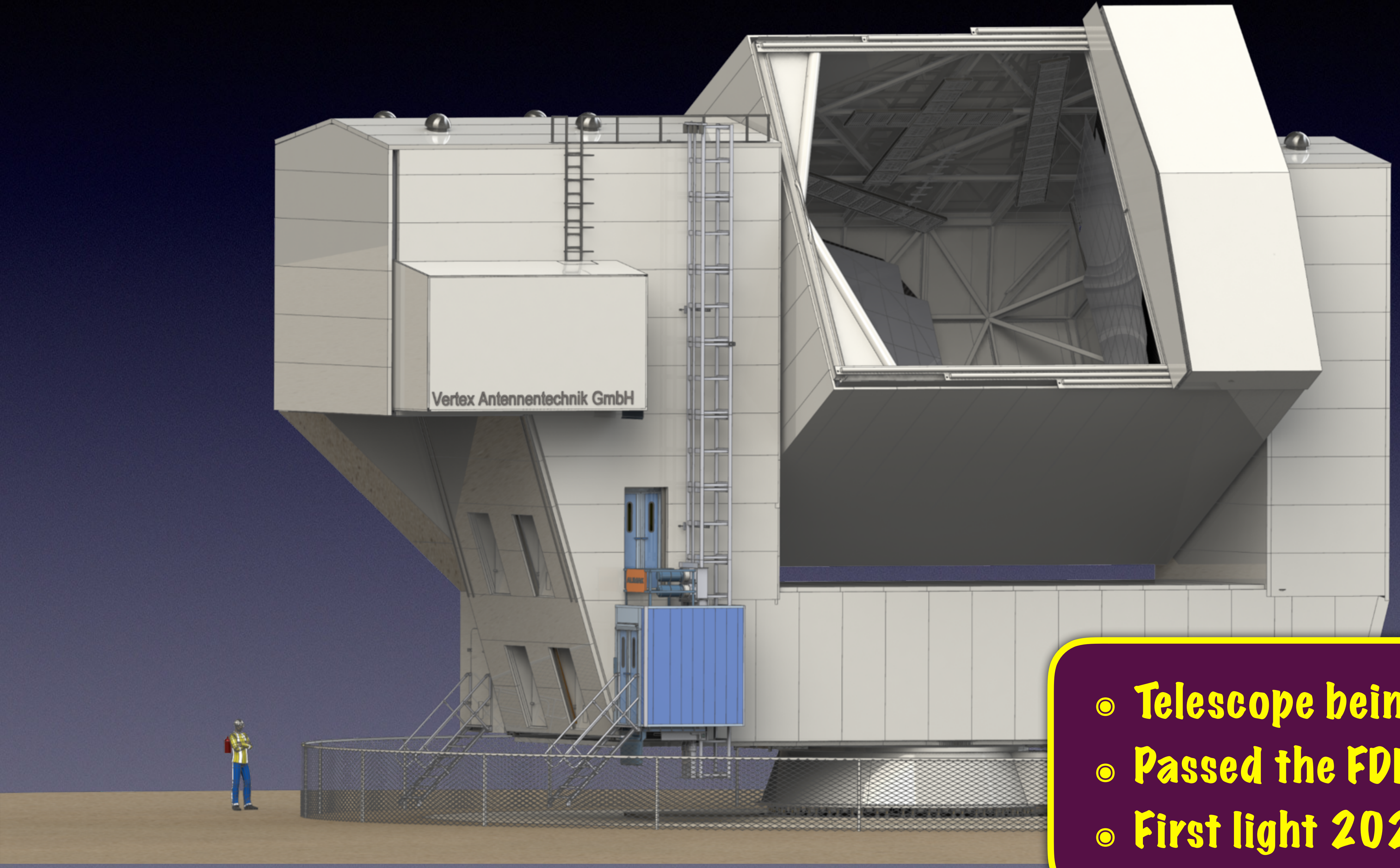
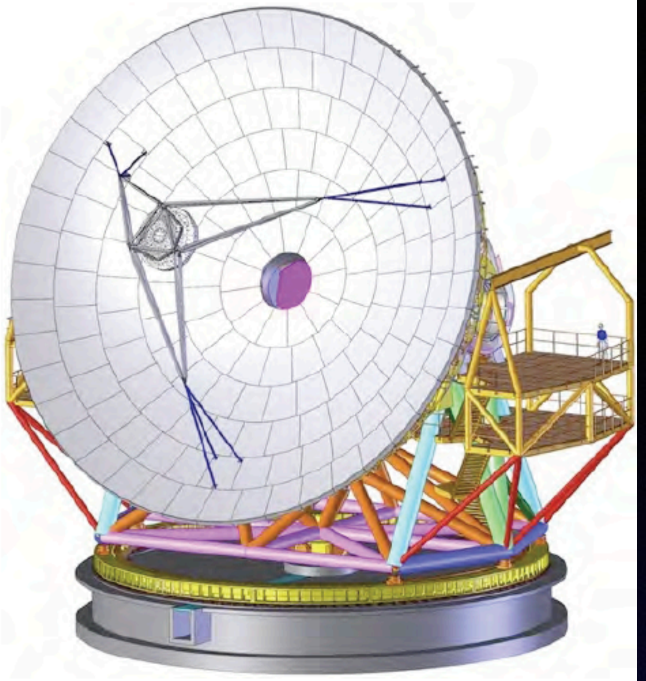


- Telescope being built
- Passed the FDR in Nov
- First light 2021-2022

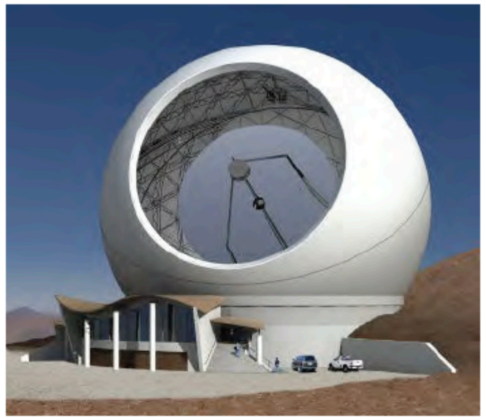
Backstory:

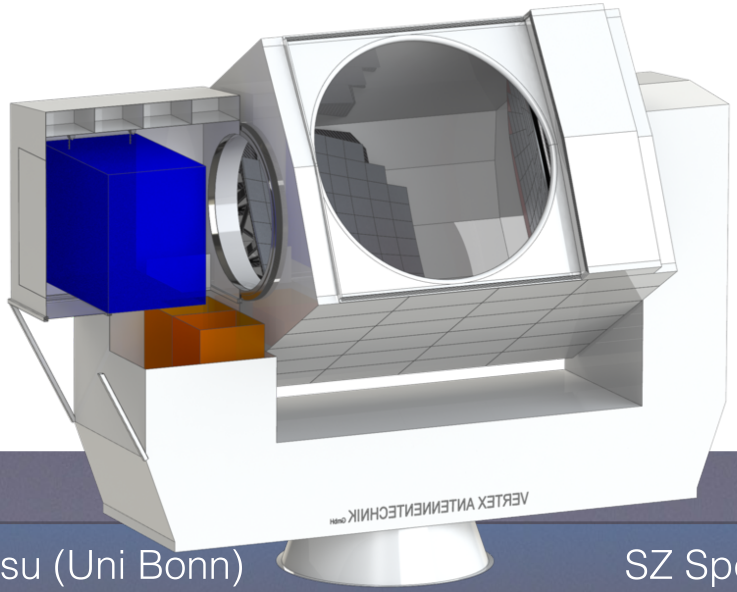
Cerro Chajnantor Atacama Telescope

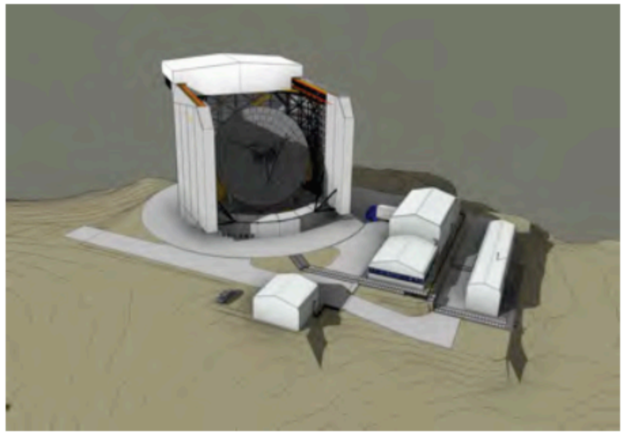


25 m
FoV 30'
<15 μm surface

2003	Partnership workshop Pasadena
2004	MoU Caltech, JPL, Cornell
2005	project office
2006	feasibility study review
2007-9	site selection, joining Colorado, Cologne/Bonn, AUI, Canada
2010	astro2010 recommendation
2011-14	Engineering Design Phase (NSF-supported): reference design
2013	EDP external review
2013-15	NSF MSIP proposals fail; Caltech, Colorado leave
2015	MTM, Vertex provided turn-key design studies & pricing
2016	CCAT terminated, CCAT-prime born

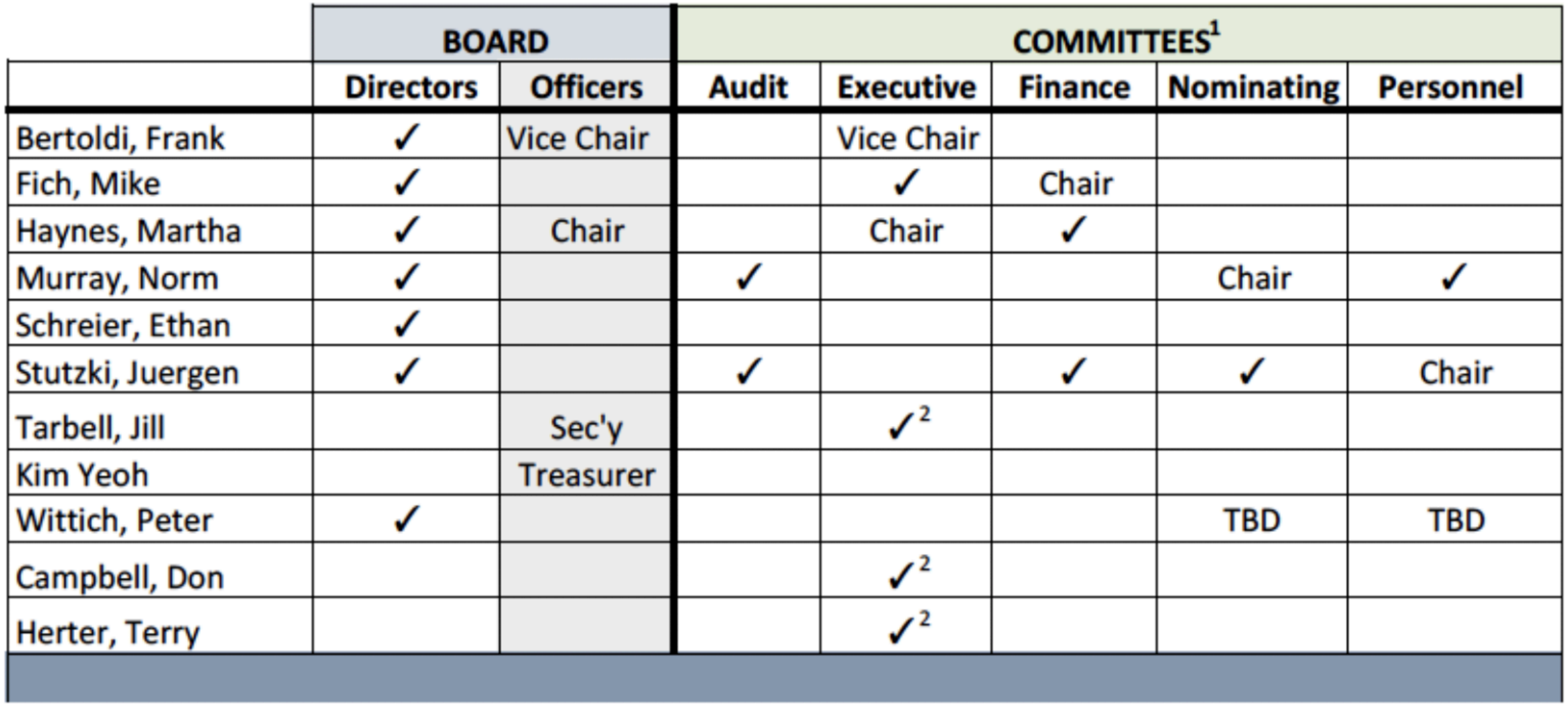






Who is CCAT-prime ?

Terry Herter : P-Director
Jim Blair : P-Manager
Gordon Stacey : P-Scientist
Stephen Parshley : P-Engineer



	BOARD		COMMITTEES[1]				
	Directors	Officers	Audit	Executive	Finance	Nominating	Personnel
Bertoldi, Frank	✓	Vice Chair		Vice Chair			
Fich, Mike	✓			✓	Chair		
Haynes, Martha	✓	Chair		Chair	✓		
Murray, Norm	✓		✓			Chair	✓
Schreier, Ethan	✓						
Stutzki, Juergen	✓		✓		✓	✓	Chair
Tarbell, Jill		Sec'y		✓[2]			
Kim Yeoh		Treasurer					
Wittich, Peter	✓					TBD	TBD
Campbell, Don				✓[2]			
Herter, Terry				✓[2]			

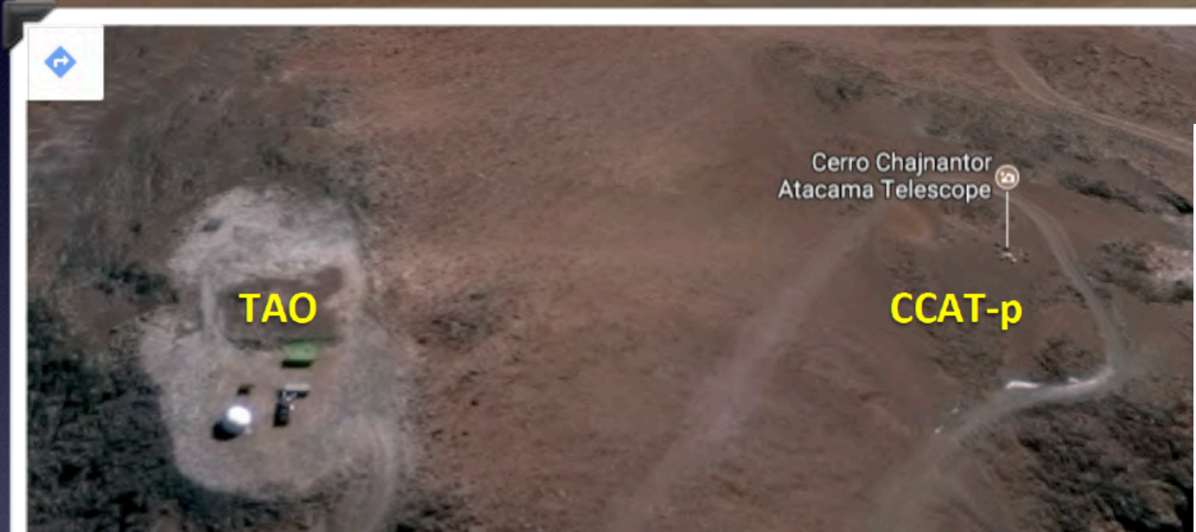
Funded by: private donor and Cornell university

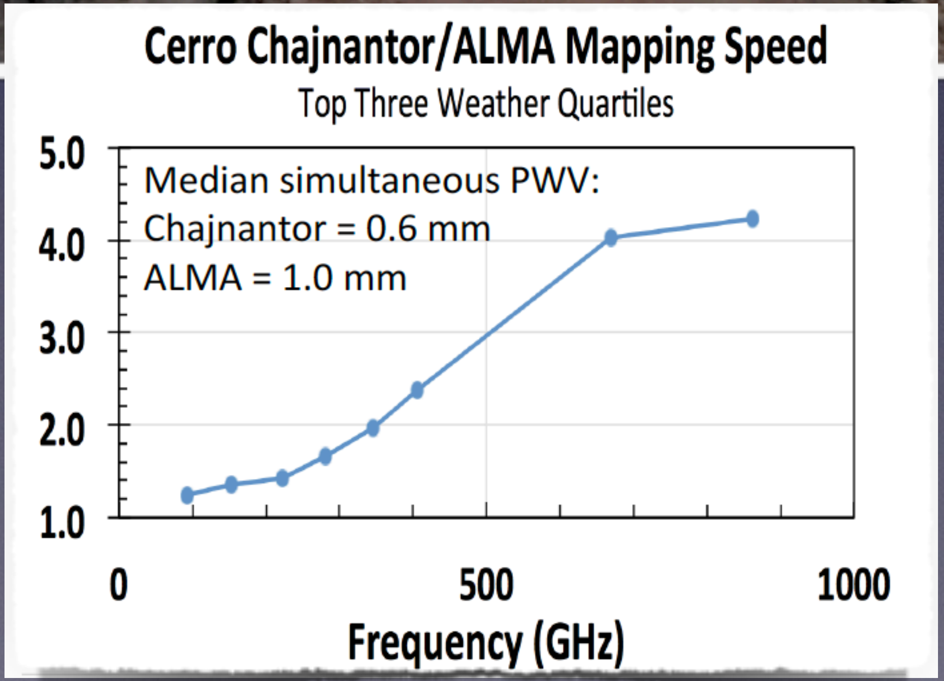
DFG Großgeräte, Univ. Köln & Bonn, SFB956 (CHAI)

Where is CCAT-p?

Cerro Chajnantor at 5600 m w/ TAO

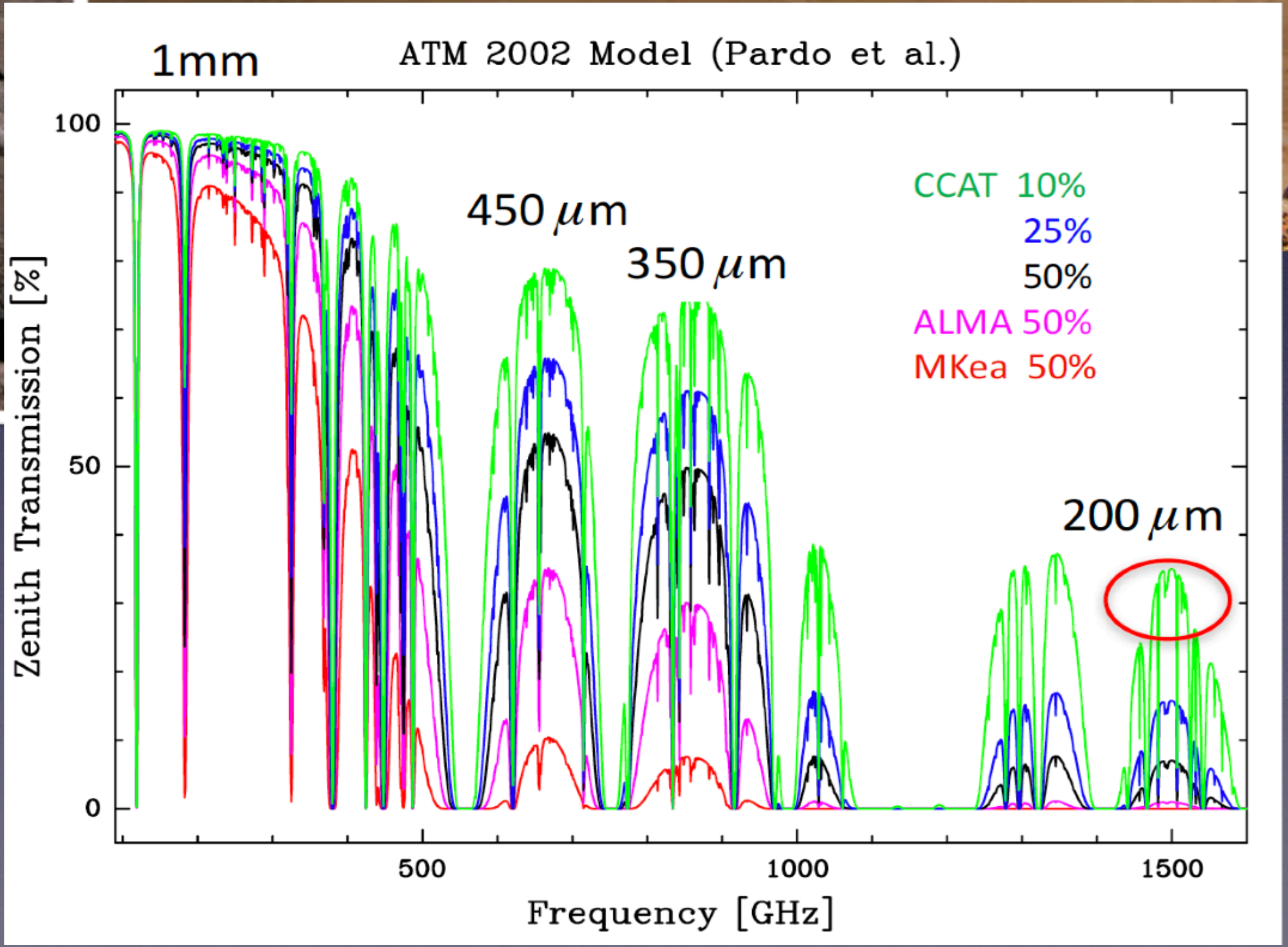
Location! Location! Location!




Cerro Chajnantor/ALMA Mapping Speed

Top Three Weather Quartiles

Median simultaneous PWV:
Chajnantor = 0.6 mm
ALMA = 1.0 mm


ATM 2002 Model (Pardo et al.)

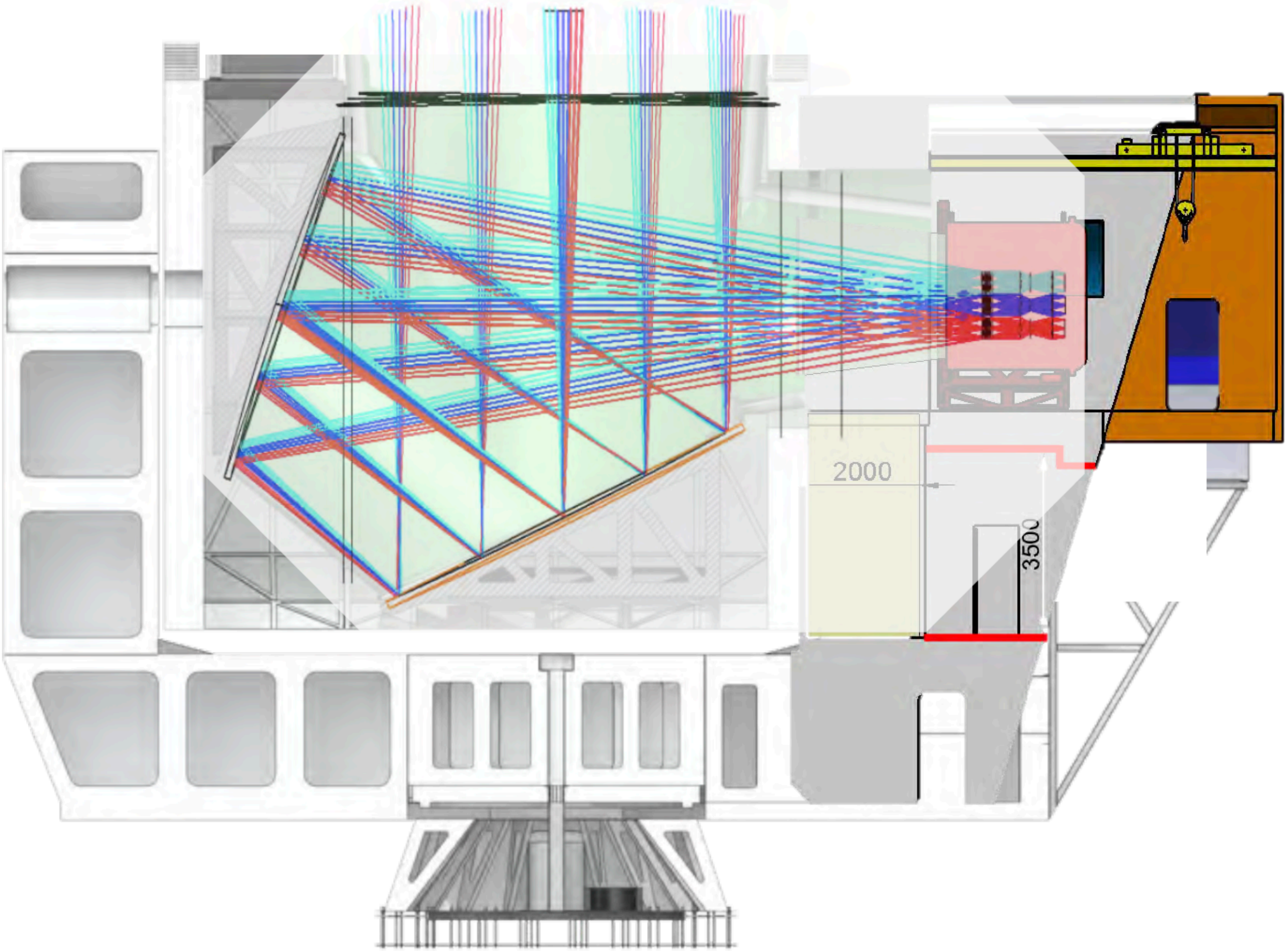
Crossed-Dragone Optics Design

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%

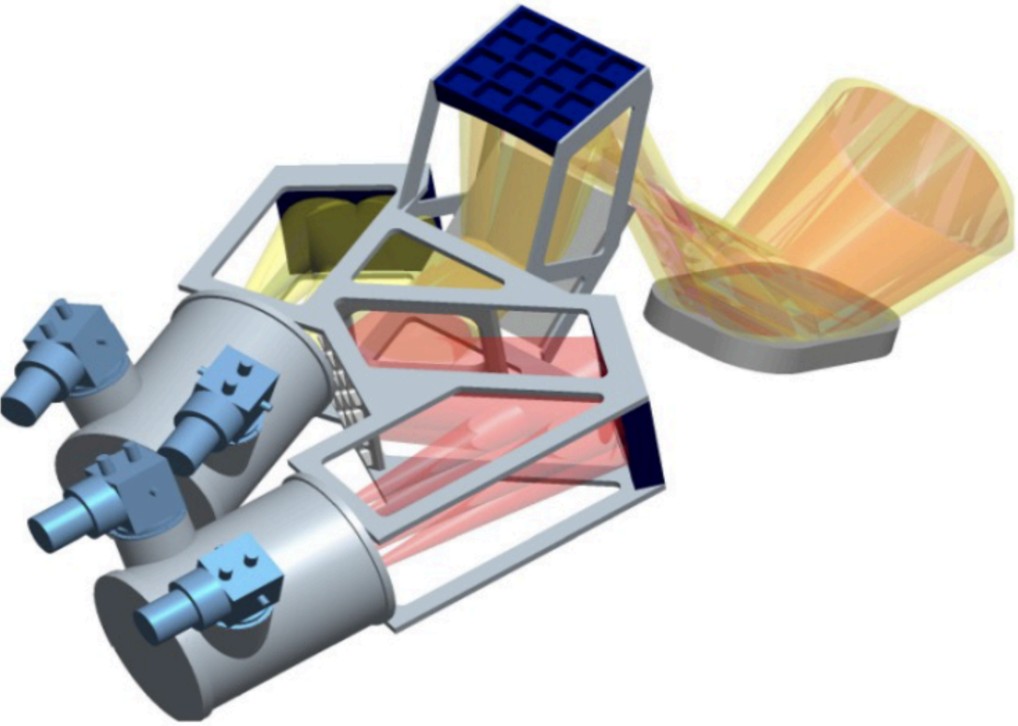
CCAT-p



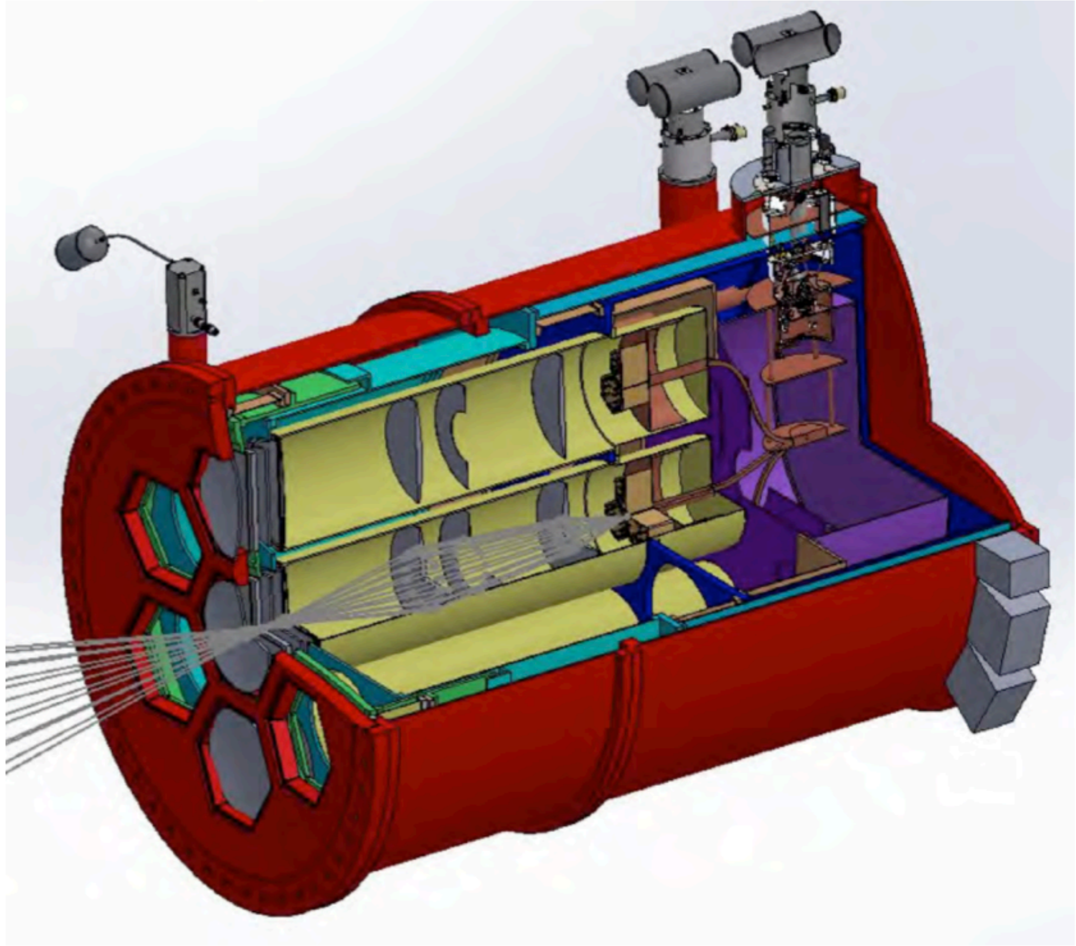
CCAT-prime's first-light

Instrumentation

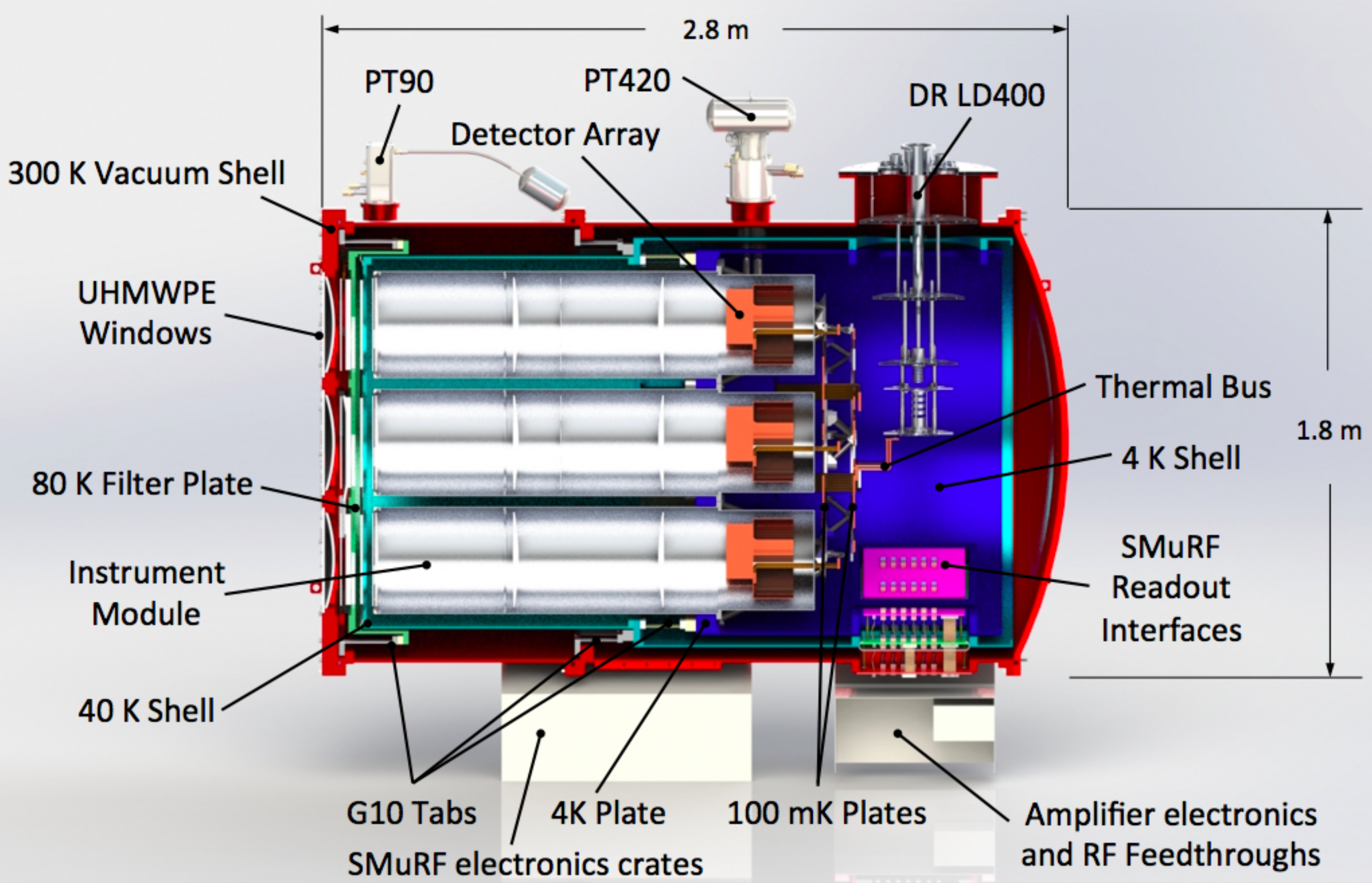
Name	Primary Science	λ range	FoV	No. Pixels	1st Light?
CHAI	GEco	200 – 700 um	17' x 8.5'	64 (256 goal)	yes
P-Cam	kSZ, GEvo	350 – 1300 um	3° diameter	5.9×10^4	yes
P-Cam	IM/EOR	740 – 1300 um	--	2.0×10^4	yes

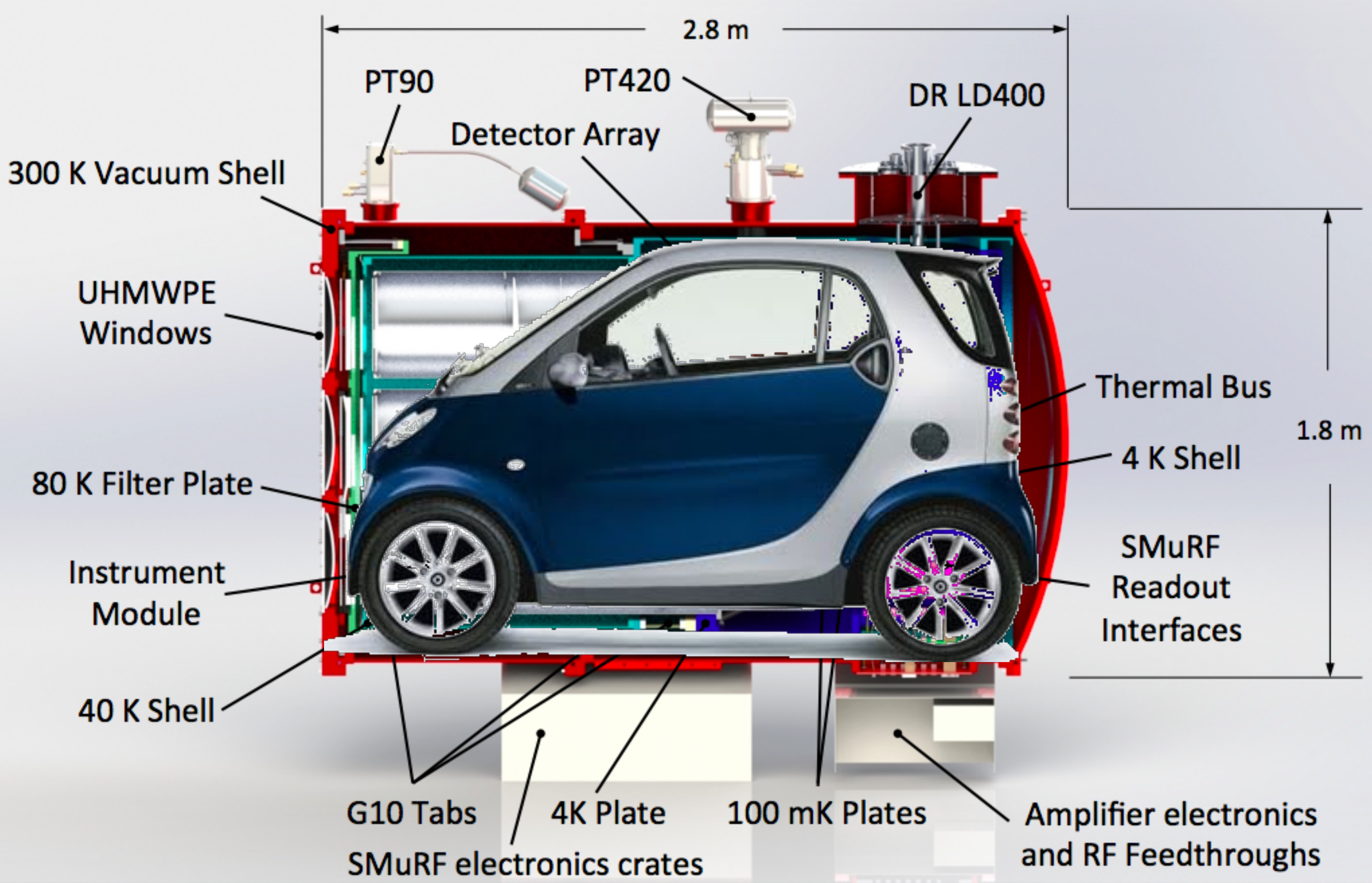


CHAI

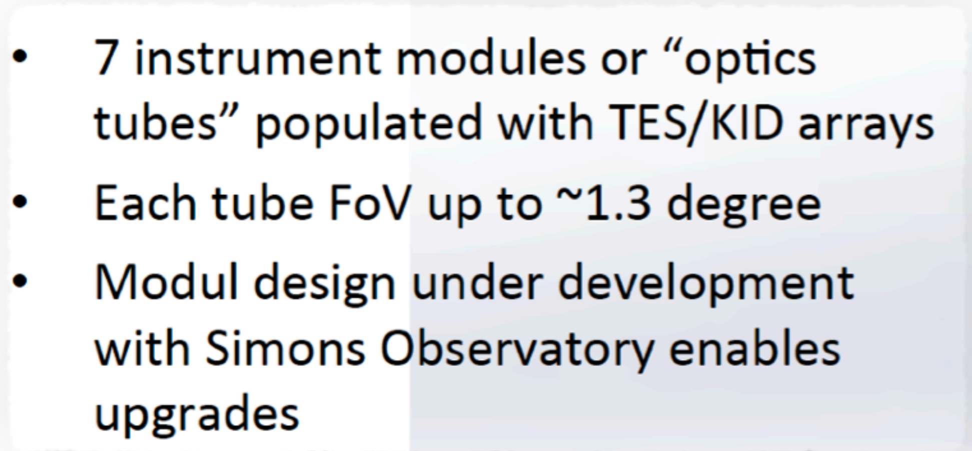


Prime-Cam

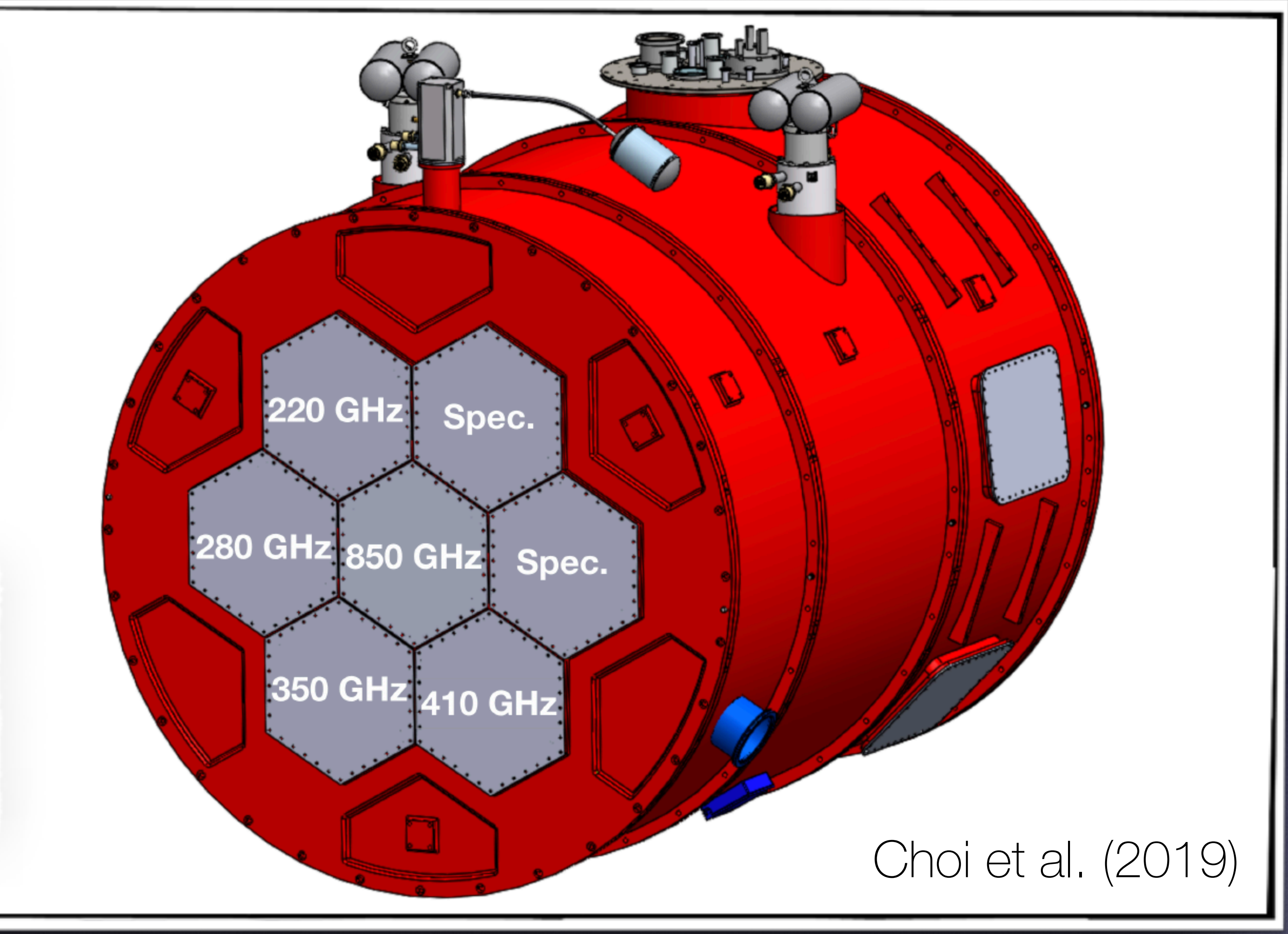

2.8 m
PT90
PT420
DR LD400
Detector Array
300 K Vacuum Shell
UHMWPE Windows
Thermal Bus
1.8 m
4 K Shell
80 K Filter Plate
SMuRF Readout Interfaces
Instrument Module
40 K Shell
G10 Tabs
4K Plate
100 mK Plates
Amplifier electronics and RF Feedthroughs
SMuRF electronics crates


2.8 m
PT90
PT420
DR LD400
Detector Array
300 K Vacuum Shell
UHMWPE Windows
Thermal Bus
1.8 m
4 K Shell
80 K Filter Plate
SMuRF Readout Interfaces
Instrument Module
40 K Shell
G10 Tabs
4K Plate
100 mK Plates
Amplifier electronics and RF Feedthroughs
SMuRF electronics crates

Prime-Cam current configuration

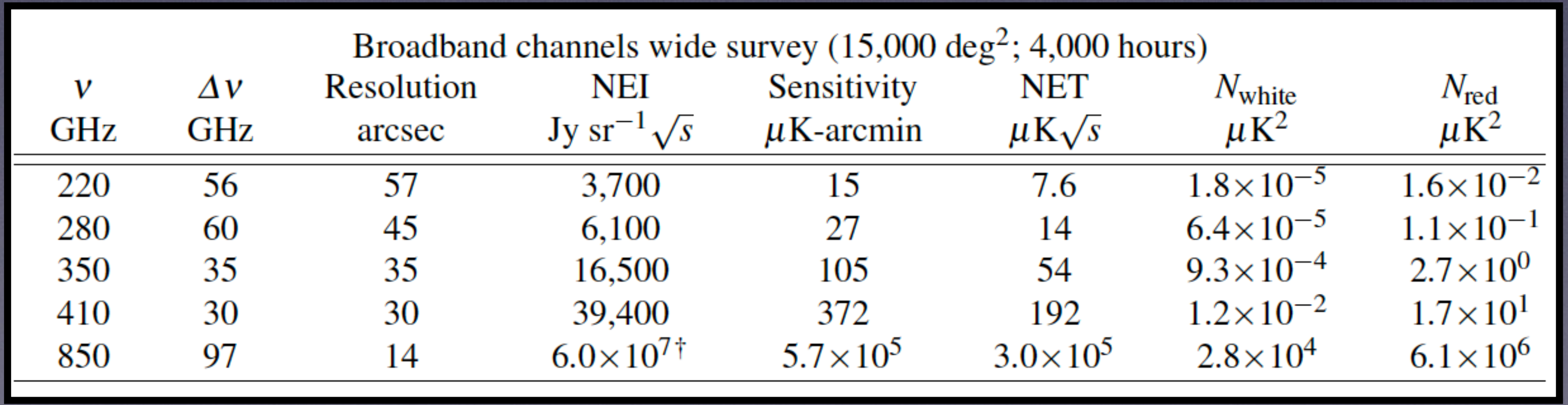


- 7 instrument modules or "optics tubes" populated with TES/KID arrays
- Each tube FoV up to ~1.3 degree
- Modul design under development with Simons Observatory enables upgrades



Choi et al. (2019)

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.

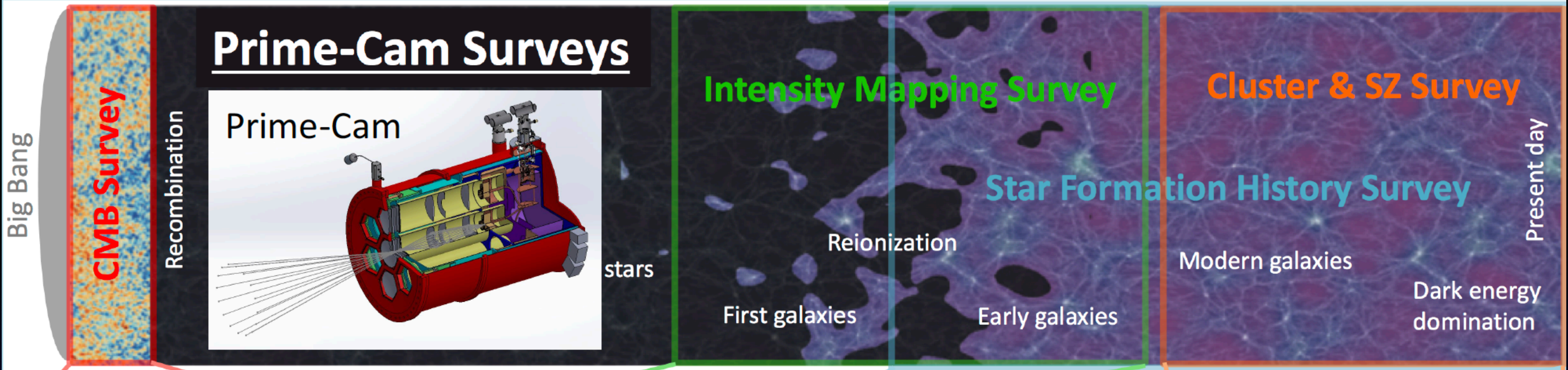


Broadband channels wide survey (15,000 deg^2; 4,000 hours)

ν GHz	$\Delta\nu$ GHz	Resolution arcsec	NEI Jy sr$^{-1}\sqrt{s}$	Sensitivity μK-arcmin	NET μK$\sqrt{s}$	$N_{\rm white}$ μK^2	$N_{\rm red}$ μK^2
220	56	57	3,700	15	7.6	1.8×10^{-5}	1.6×10^{-2}
280	60	45	6,100	27	14	6.4×10^{-5}	1.1×10^{-1}
350	35	35	16,500	105	54	9.3×10^{-4}	2.7×10^{0}
410	30	30	39,400	372	192	1.2×10^{-2}	1.7×10^{1}
850	97	14	$6.0\times10^{7\dagger}$	5.7×10^{5}	3.0×10^{5}	2.8×10^{4}	6.1×10^{6}

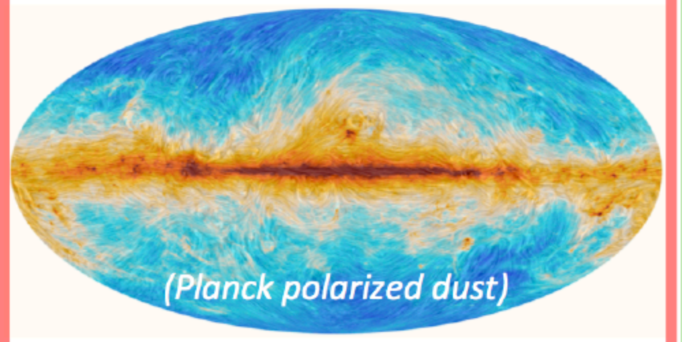
1. See Choi et al. (2019) for Prime-cam description and survey sensitivities
2. APC White Paper by Herter et al. for general CCAT-p overview and science goals

Prime-Cam Surveys

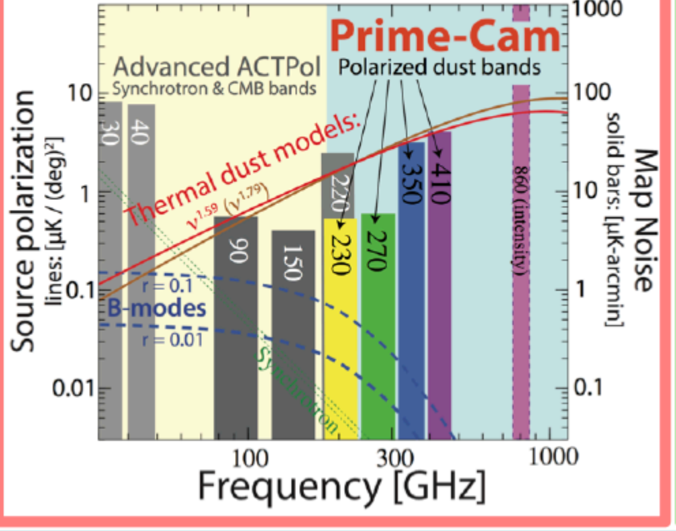


CMB Polarization

Galactic dust contaminates CMB polarization

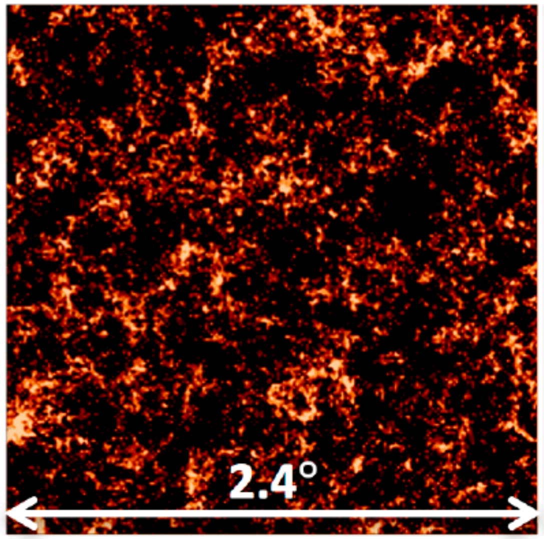


Determine the CMB foreground dust complexity and probe the galactic turbulent energy cascade

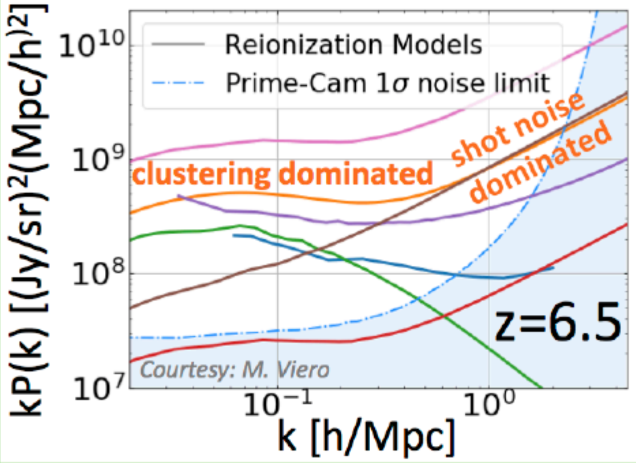


Reionization

Simulated [CII] redshift slice

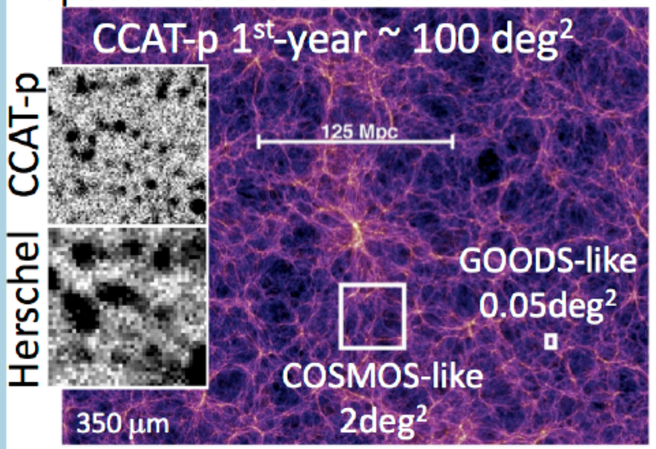


Unique spectrometer to characterize Reionization through galaxy clustering

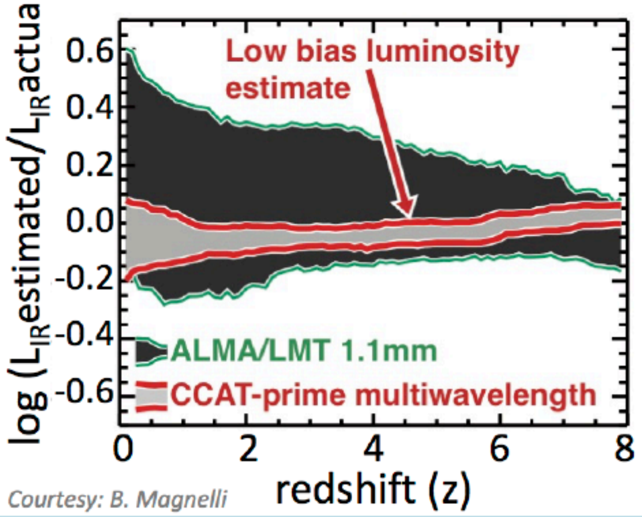


Star Formation

Prime-Cam survey probes all cosmic environments at significantly higher spatial resolution than Herschel

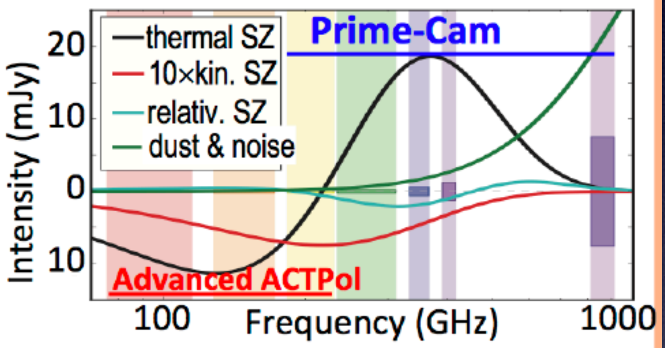


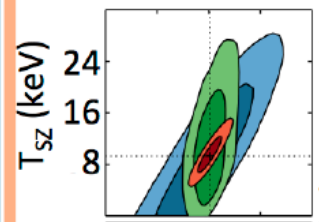
Characterize environments and physical parameters for >10^5 early galaxies



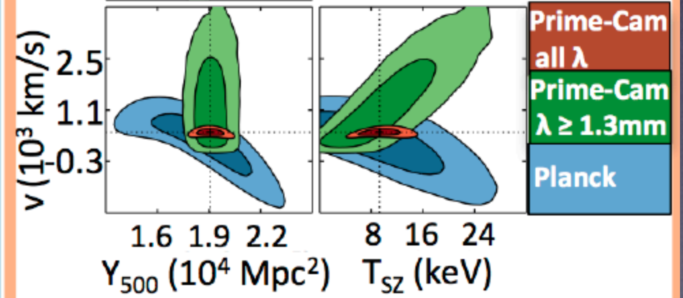
Clusters & Cosmology

Clean SZ component separation

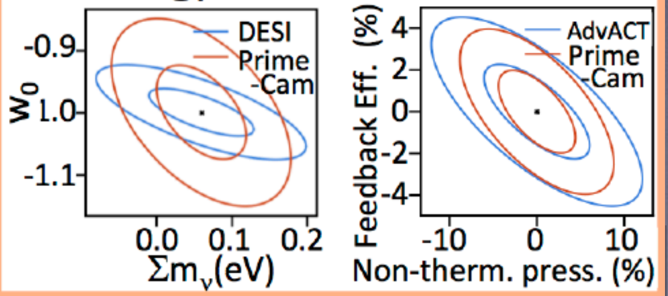




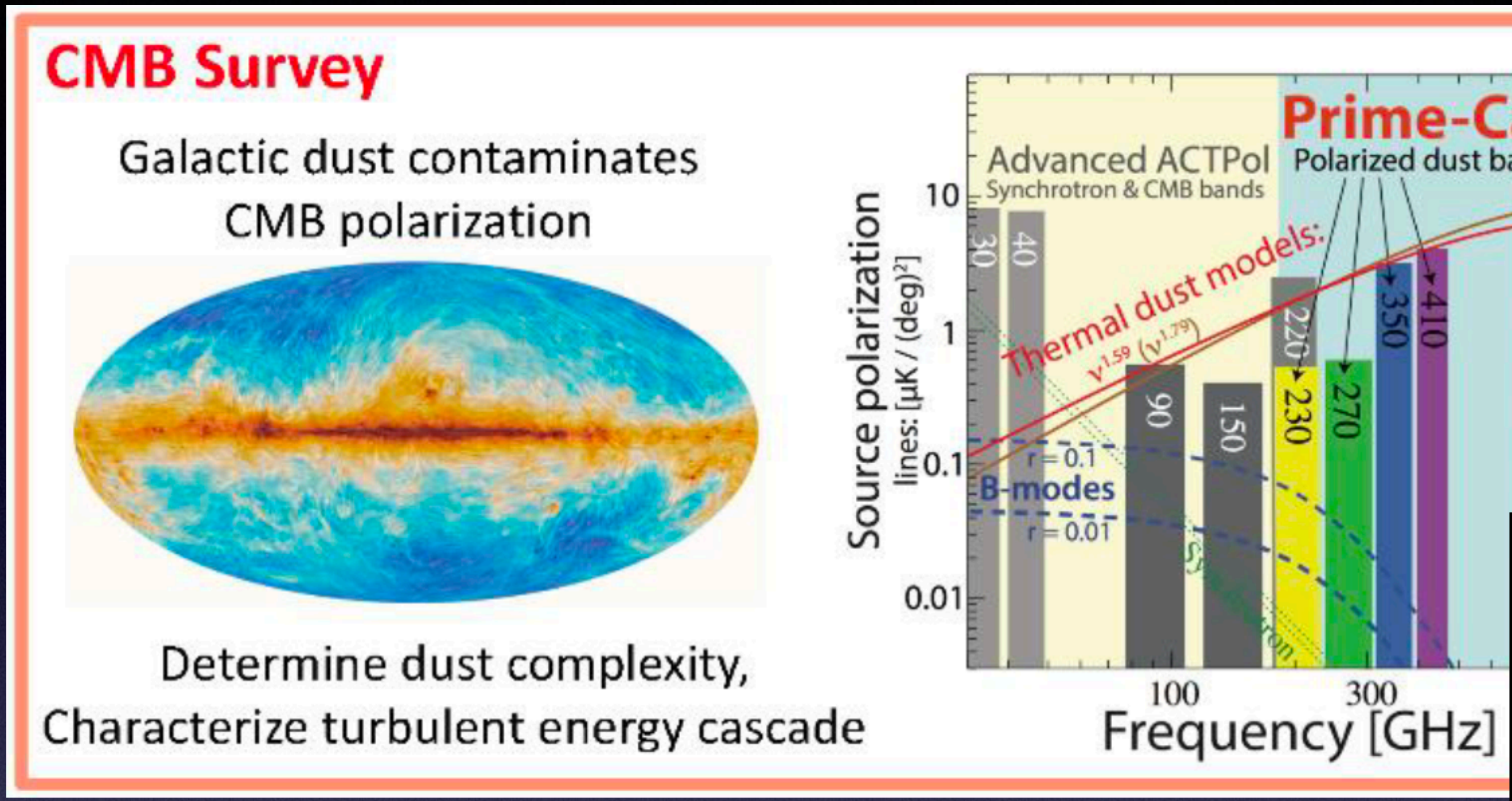
Separate tSZ, kSZ, & rSZ from dust for Individual clusters for the first time



Cosmology & Feedback constraints



CCAT-prime CMB science goals



CMB Survey

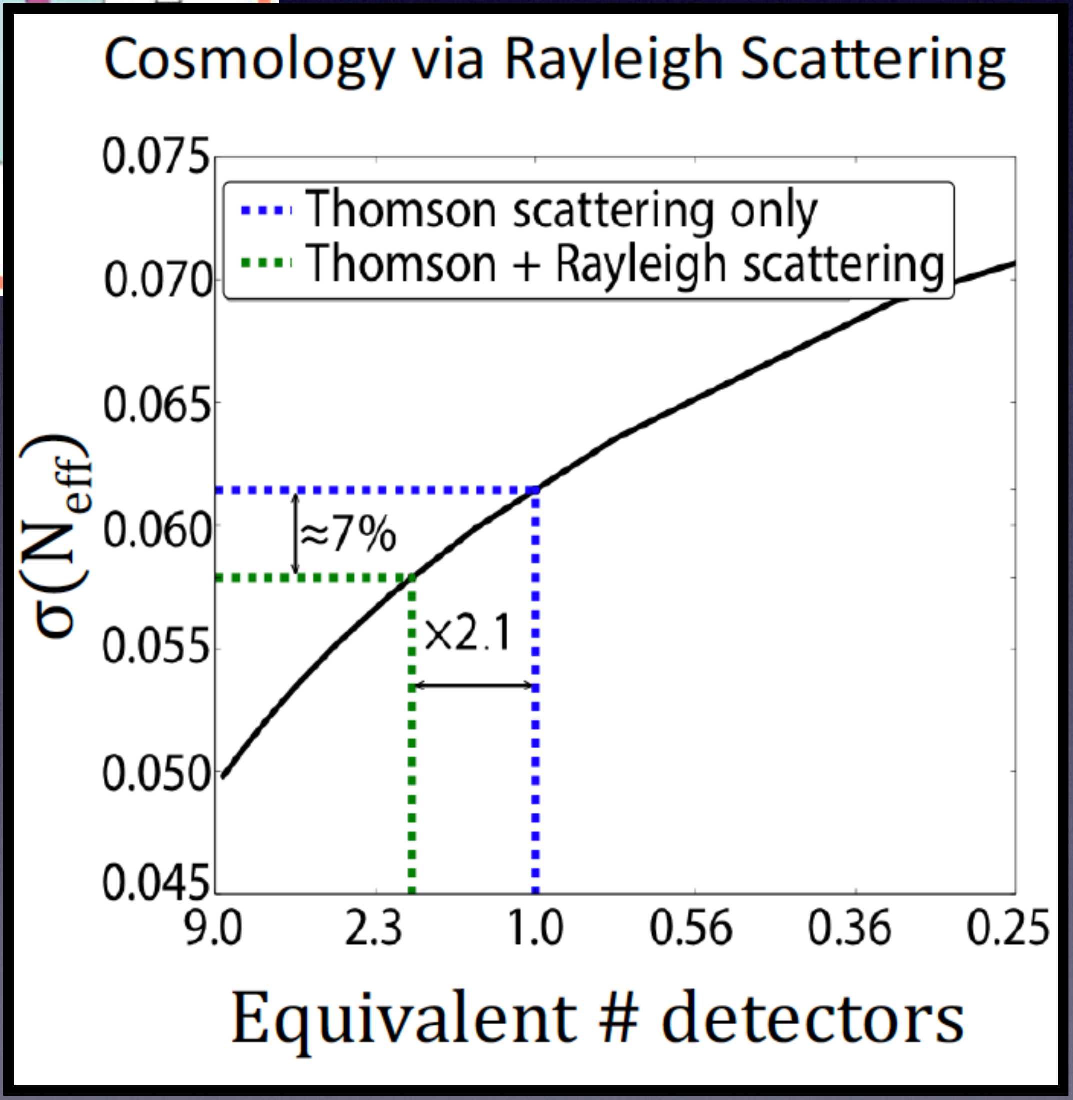
Galactic dust contaminates CMB polarization

Determine dust complexity, Characterize turbulent energy cascade

CCAT-prime can provide accurate dust SED and polarization measurements at sub arcminute-scale above 250 GHz.

Rayleigh scattering: Due to the (frequency)^4 dependence, high frequencies are critical. Its measurement will offer on average ~10% improvement on cosmological parameter errors.

This modest improvement can be translated into a significant improvement in the number of detectors needed to make similar progress.



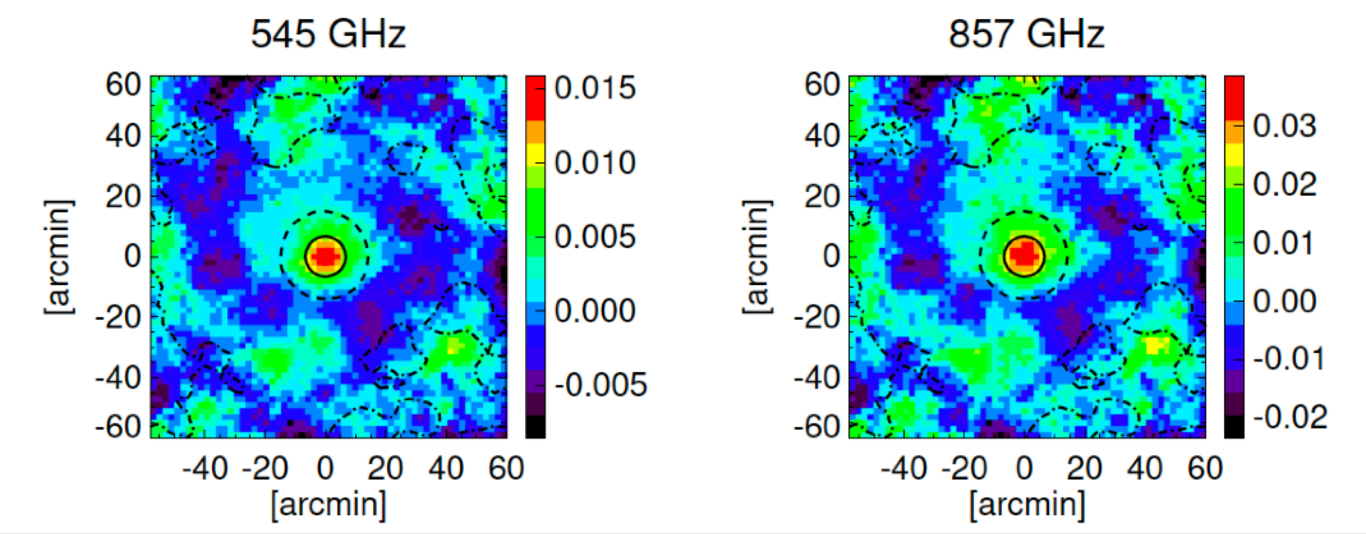
Cosmology via Rayleigh Scattering

Credit: Mike Niemack, CCAT-p MSIP proposal

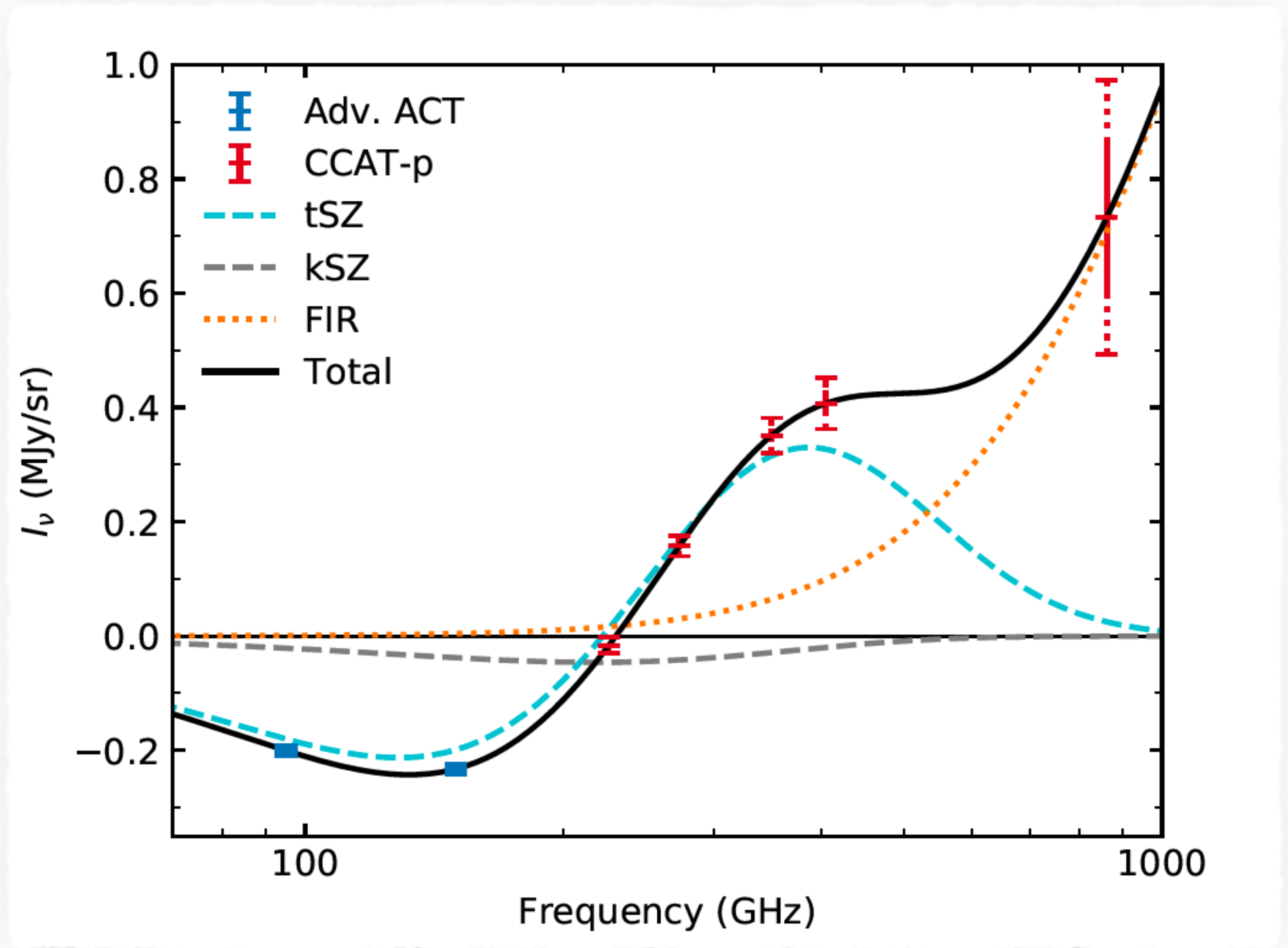
Cluster science at high frequencies

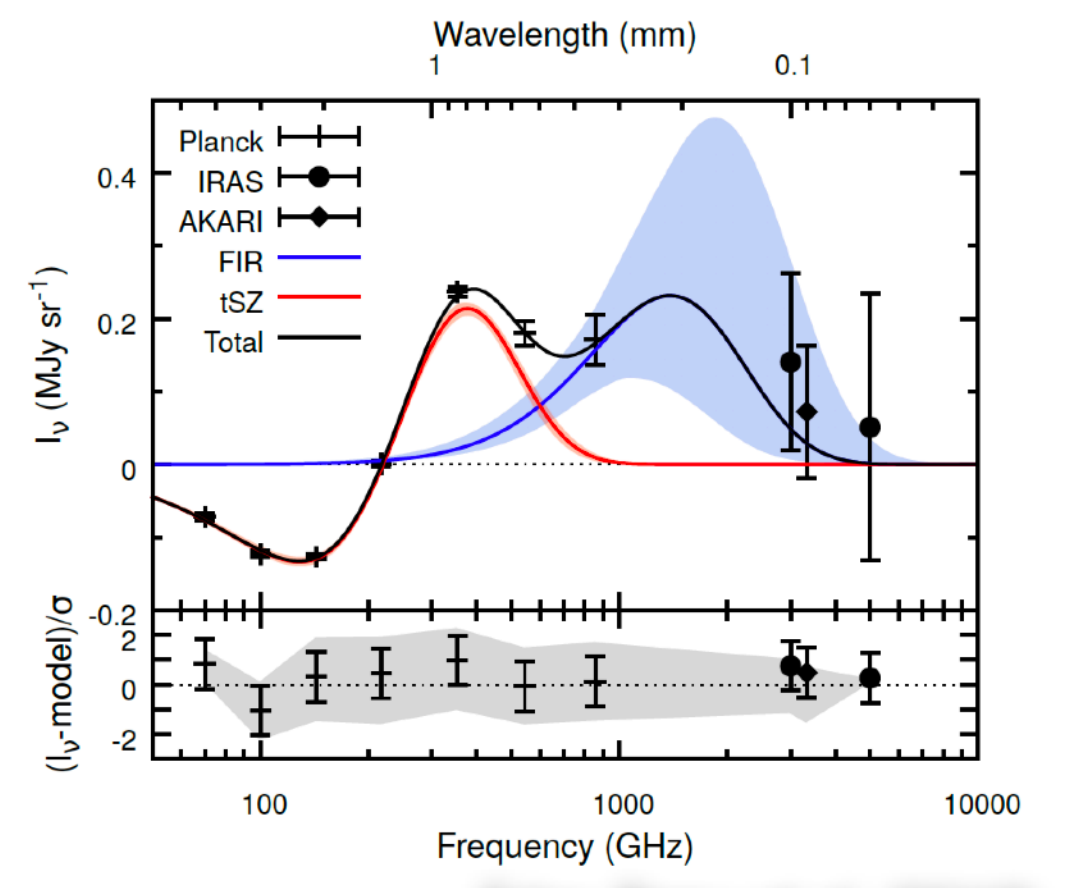
Adding CCAT-prime data to SO (93—280 GHz) does not make any significant difference in the **cluster number counts** (although it may help with sample purity).

So what is the most immediate advantage of CCAT-p in cluster studies? Answer: **Dust!**



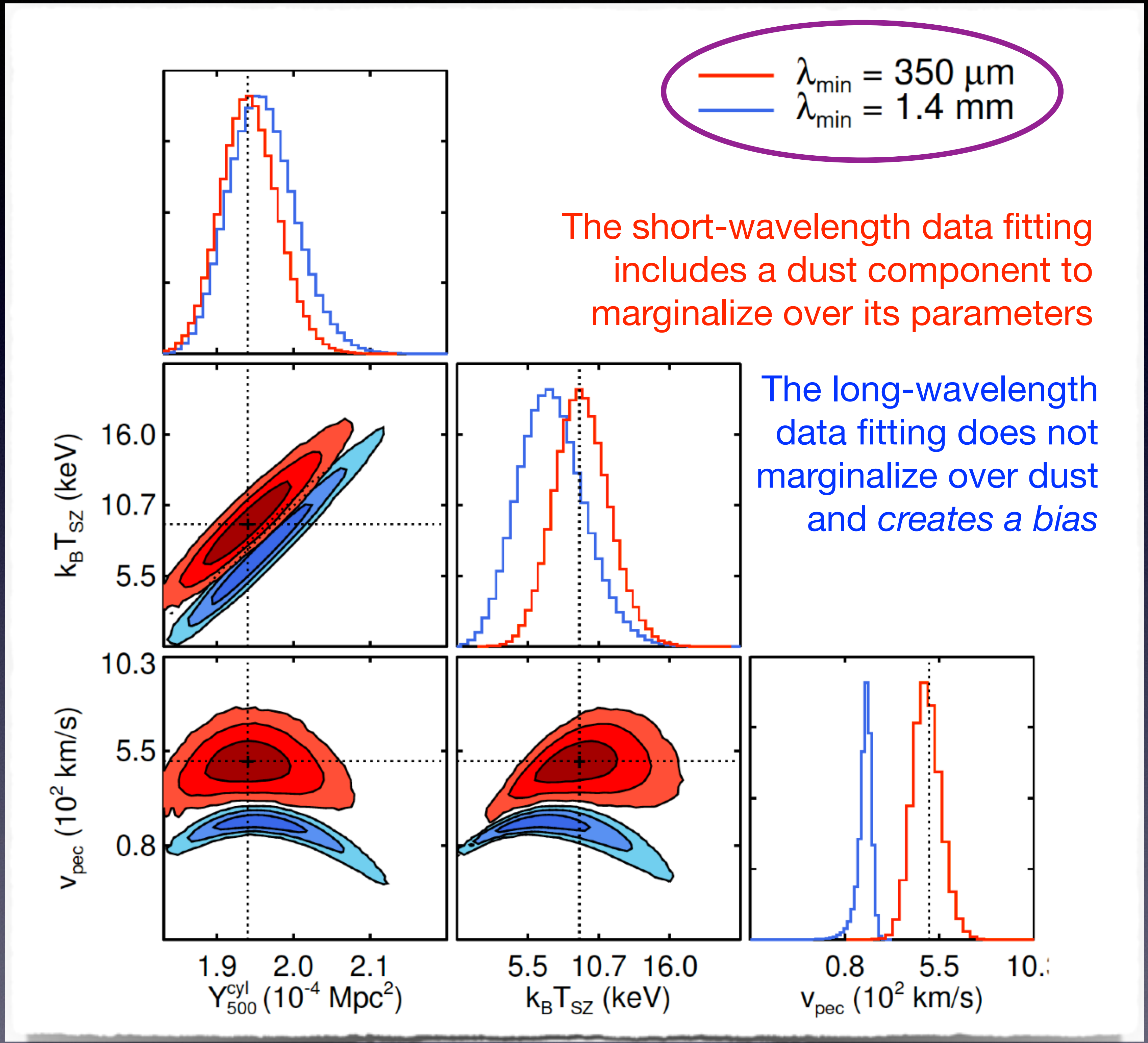
Planck collaboration (2016)





Erler, Basu et al. (2018)

Impact of dust on SZ parameters



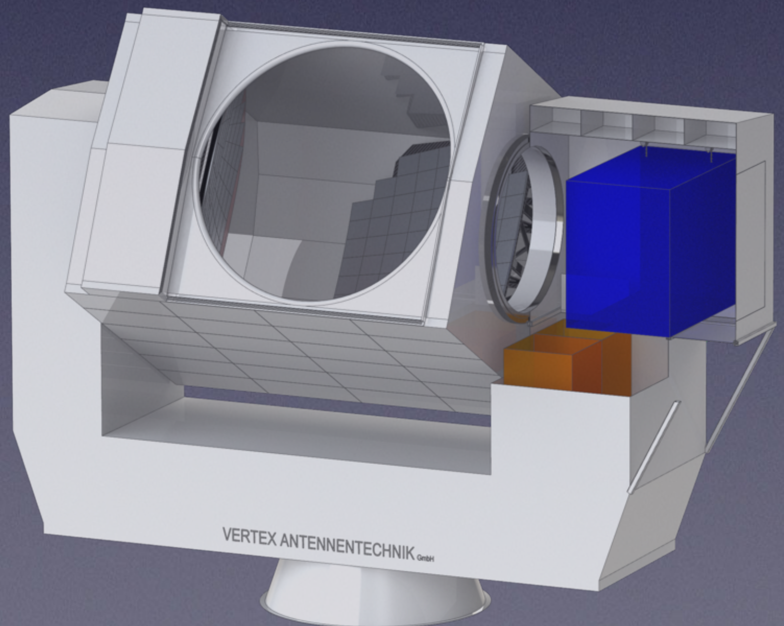
The short-wavelength data fitting includes a dust component to marginalize over its parameters

The long-wavelength data fitting does not marginalize over dust and *creates a bias*

We build a dust model from the difference between the matched filtering and aperture photometry results.

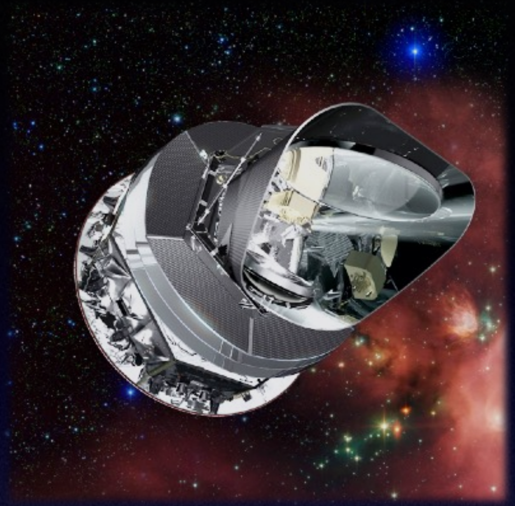
The A_{dust} shown here lies at the upper limit of the allowed range. :-)

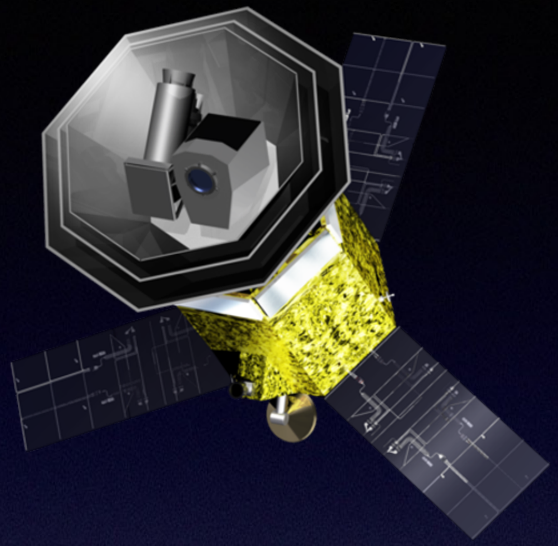
Also, only white noise is used here to illustrate the biases.

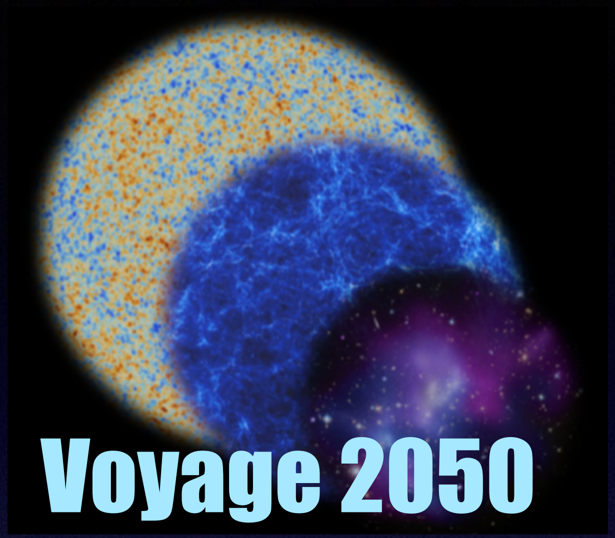


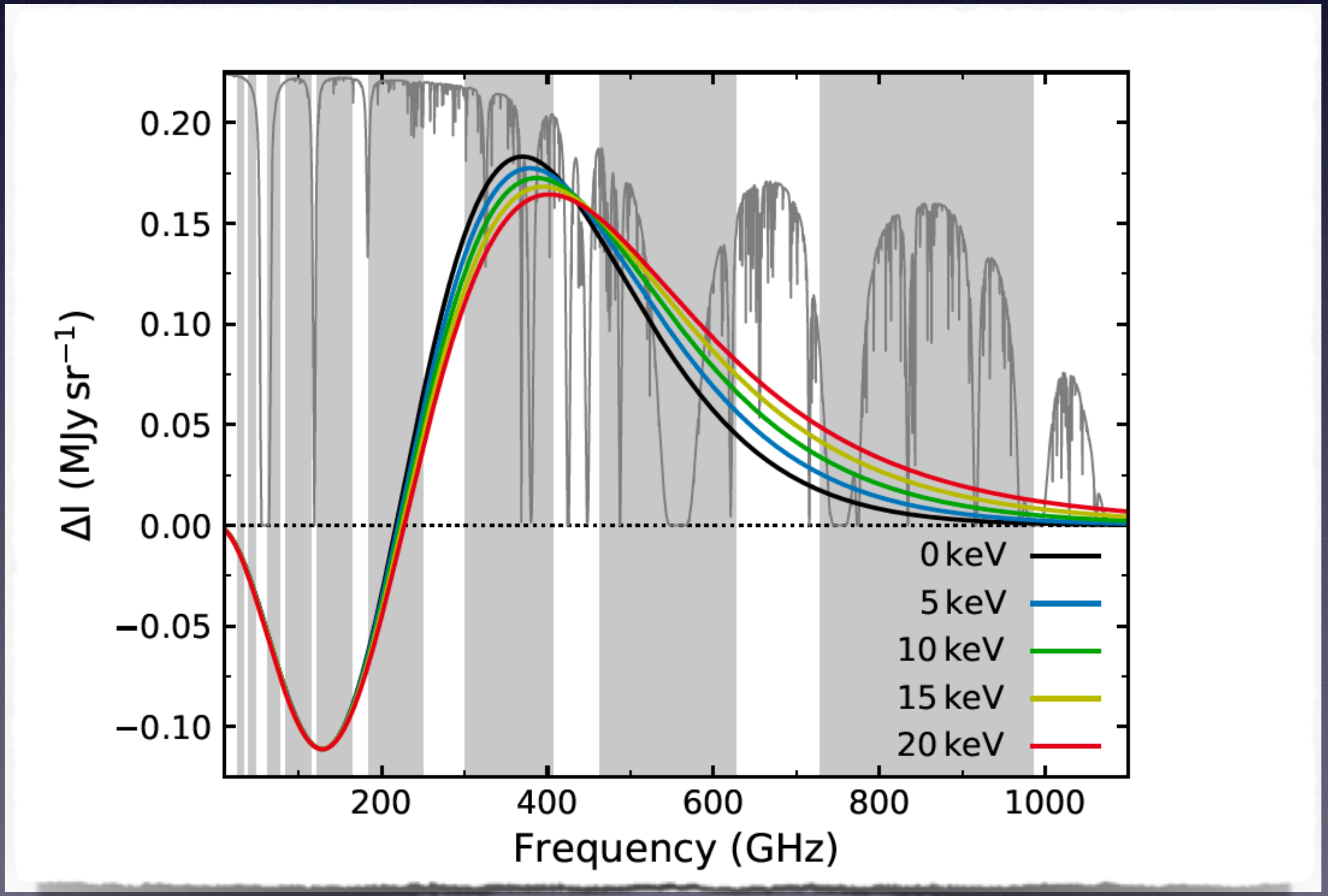
Basu, Erler+ in prep.
See also **Astro2020 White Paper, 1903.04944**

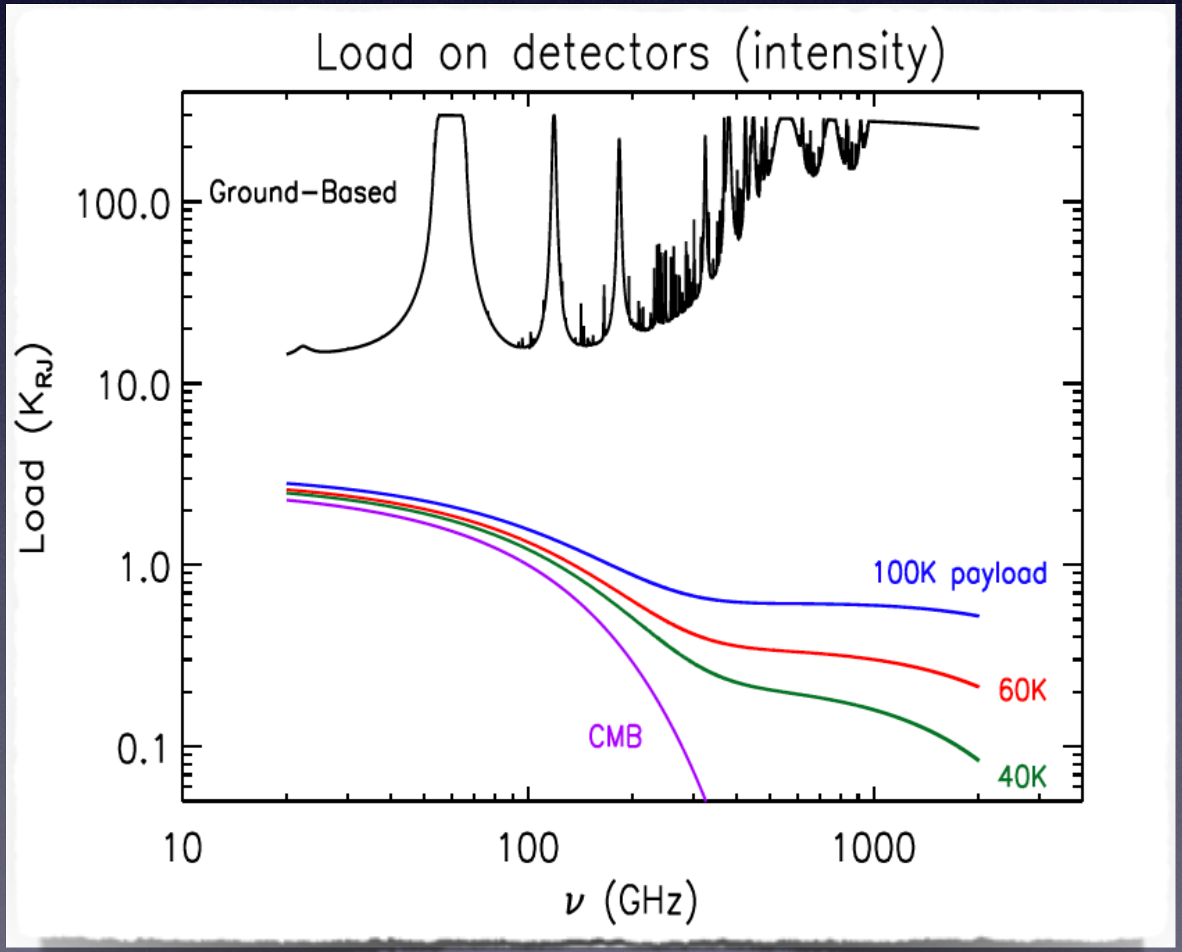
The Future: SZ Spectroscopy from Space



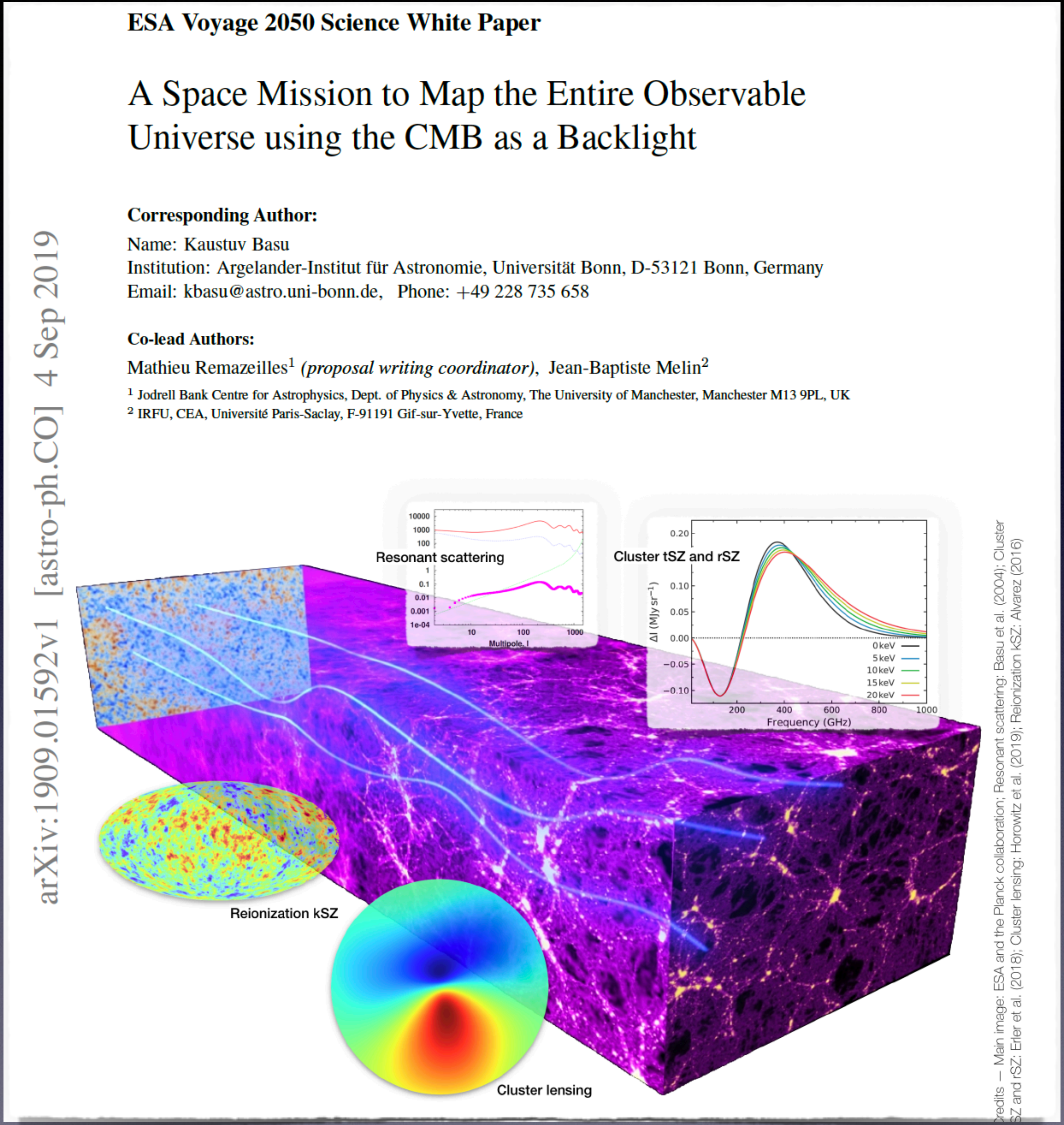








Delabrouille et al. (2018)



ESA Voyage 2050 Science White Paper

A Space Mission to Map the Entire Observable Universe using the CMB as a Backlight

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Co-lead Authors:

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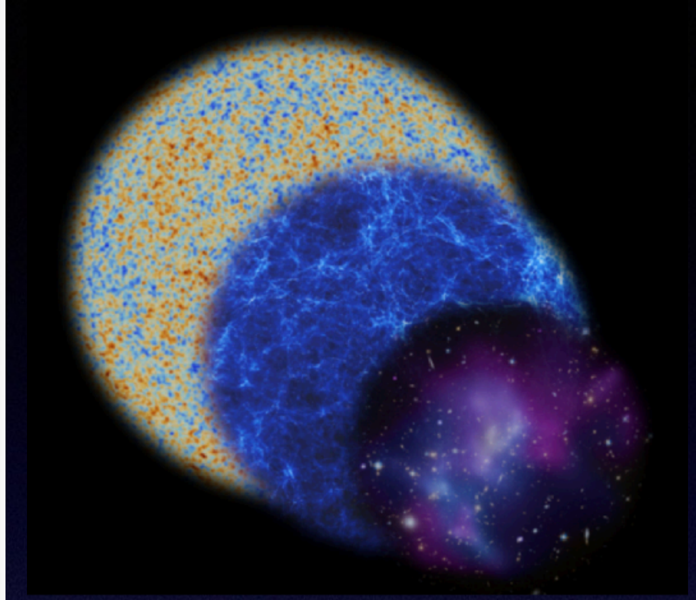
arXiv:1909.01592v1 [astro-ph.CO] 4 Sep 2019

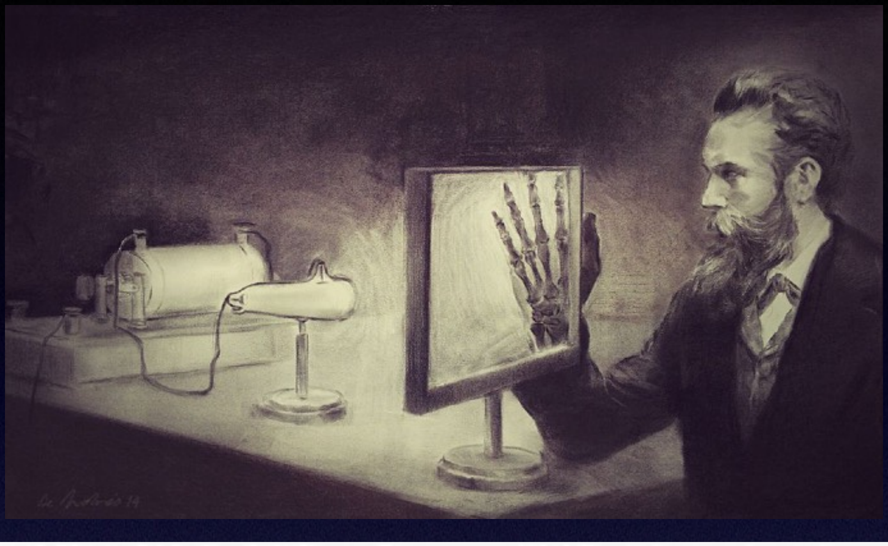
redits — Main image: ESA and the Planck collaboration; Resonant scattering: Basu et al. (2004); Cluster
SZ and rSZ: Erler et al. (2018); Cluster lensing: Horowitz et al. (2019); Reionization kSZ: Alvarez (2016)

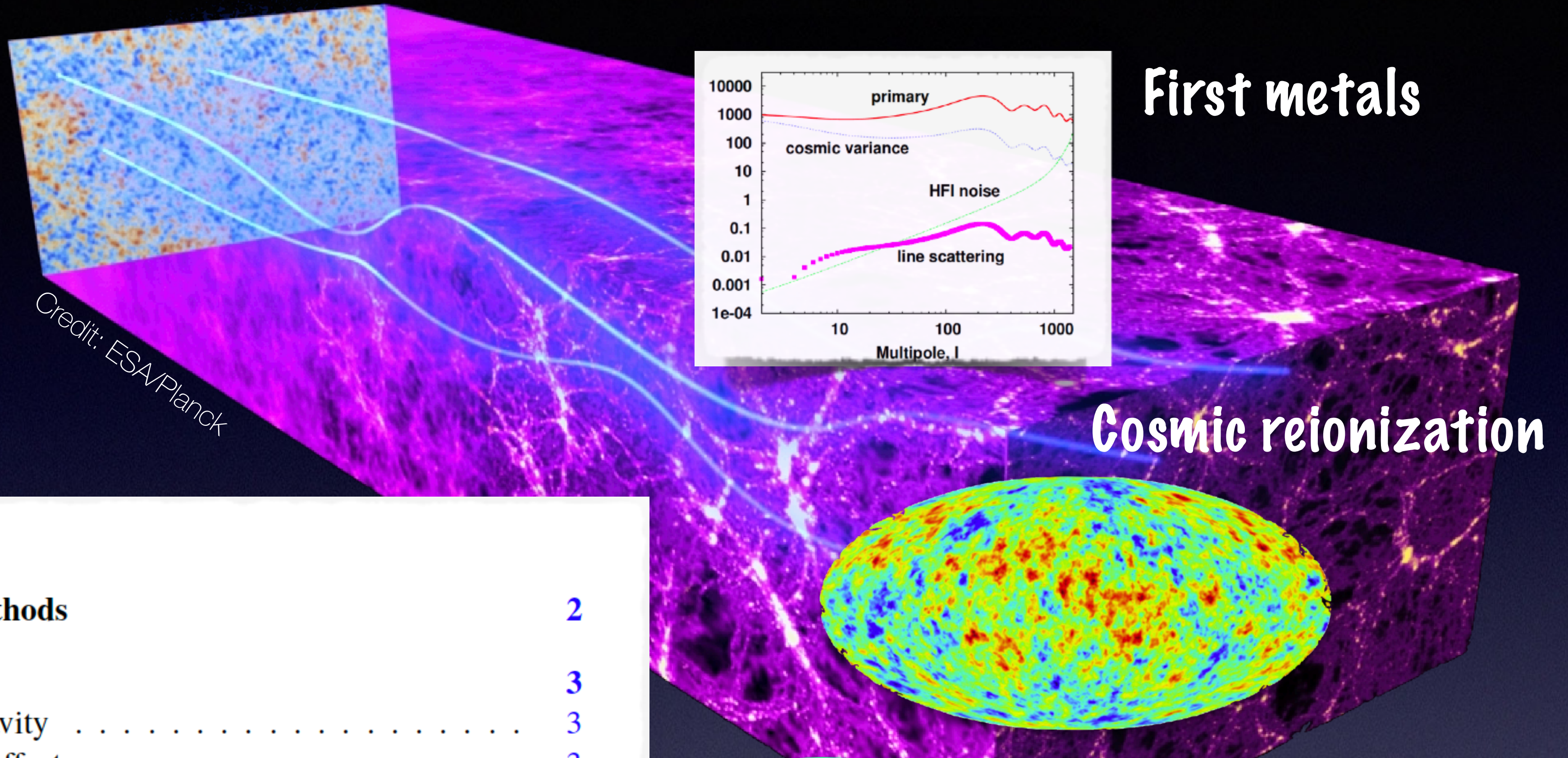
MICROWAVE SPECTRO-POLARIMETRY
OF MATTER AND RADIATION
ACROSS SPACE AND TIME



Kaustuv Basu (Bonn), Mathieu Remazeilles (Manchester), Jean-Baptiste Melin (IRFU Saclay), David Alonso (Oxford), James G. Bartlett (APC - Univ. Paris), Nick Battaglia (Cornell), Jens Chluba (Manchester), Eugene Churazov (MPA, IKI), Jacques Delabrouille (APC Paris & IRFU, Saclay), Jens Erler (Bonn), Simone Ferraro (LBNL), Carlos Hernandez-Monteagudo (CEFCA), J. Colin Hill (IAS), Selim C. Hotinli (Imperial College), Ildar Khabibullin (MPA, IKI), Mathew Madhavacheril (Perimeter Institute), Tony Mroczkowski (ESO), Daisuke Nagai (Yale), Srinivasan Raghunathan (UCLA), Jose Alberto Rubino Martin (IAC), Jack Sayers (Caltech), Douglas Scott (UBC), Naonori Sugiyama (NAOJ), Rashid Sunyaev (MPA, IKI), Inigo Zubeldia (Cambridge)

A wish list for SZ & lensing science

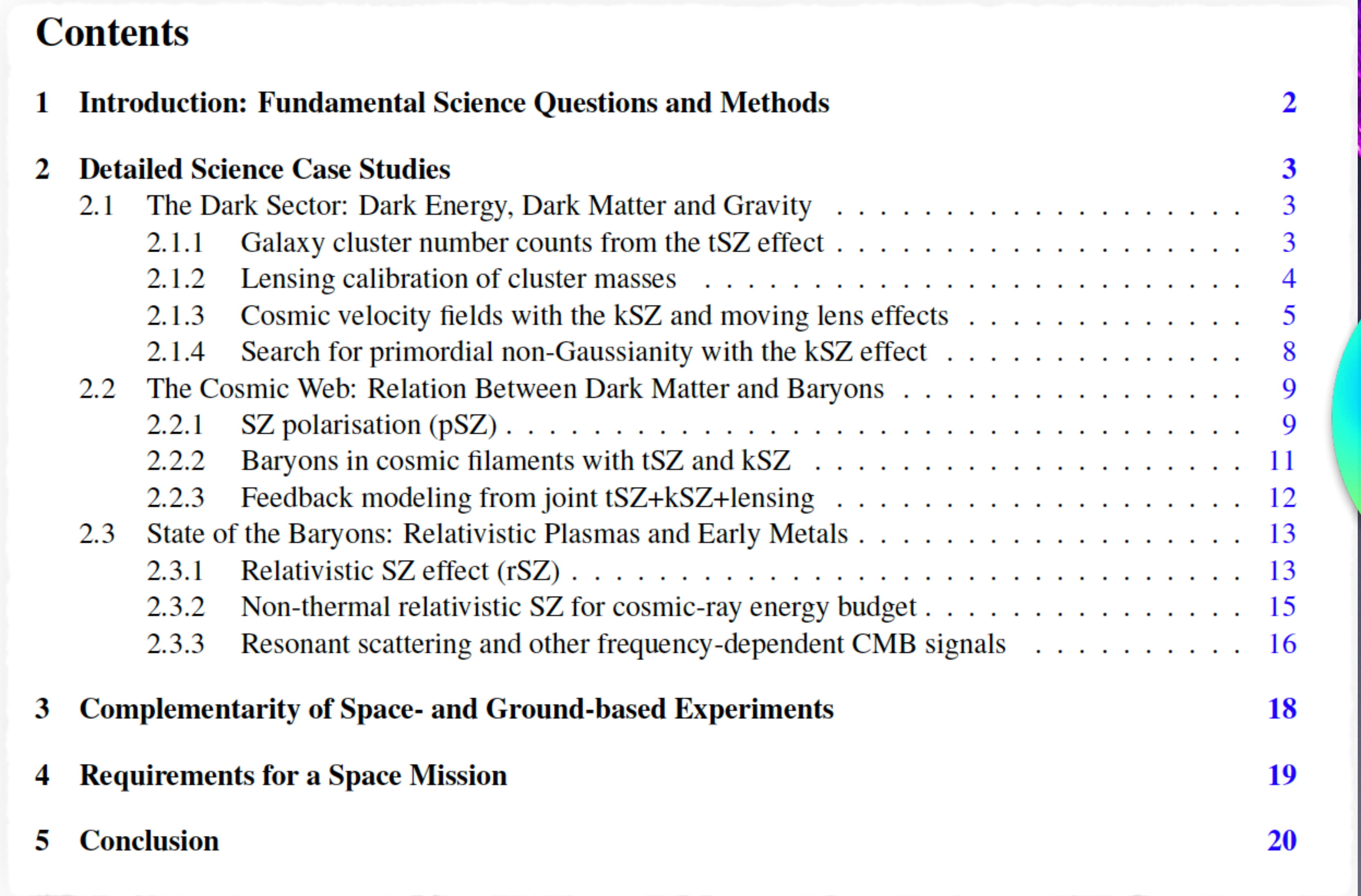




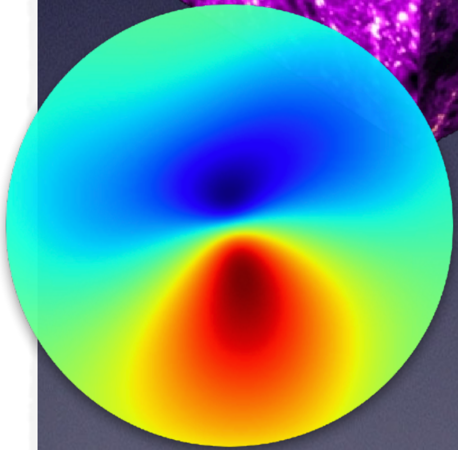
Credit: ESA/Planck

First metals

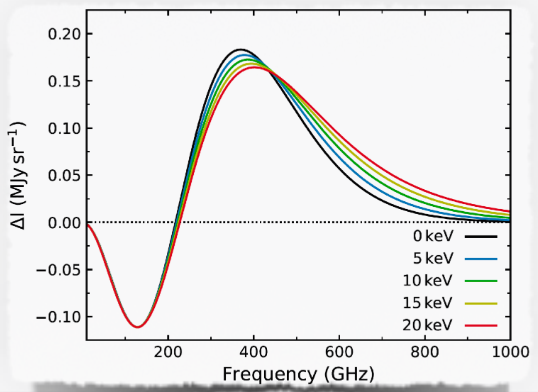
Cosmic reionization



Contents



Lensing mass
of galaxy clusters



Plasma at extreme
temperatures

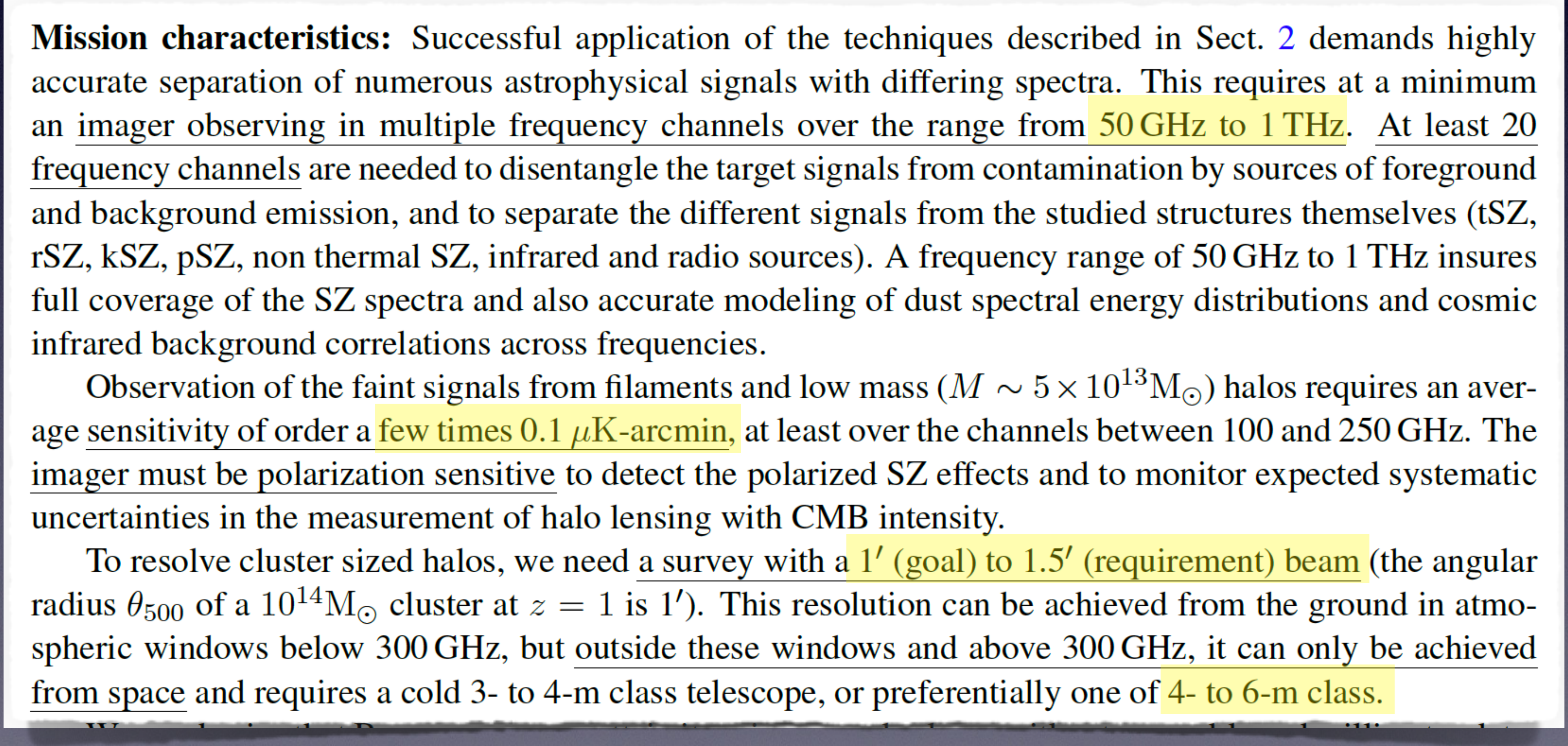
A wish list for mission requirements

Complete frequency coverage from ~50 GHz up to 1 THz

Polarization sensitive **imager** with sensitivity ~few × 0.1 μK-arcmin

Angular resolution 1.5′–1′ to resolve 10^{14} $M_\odot$ at z=1

4m–6m class telescope, cold primary



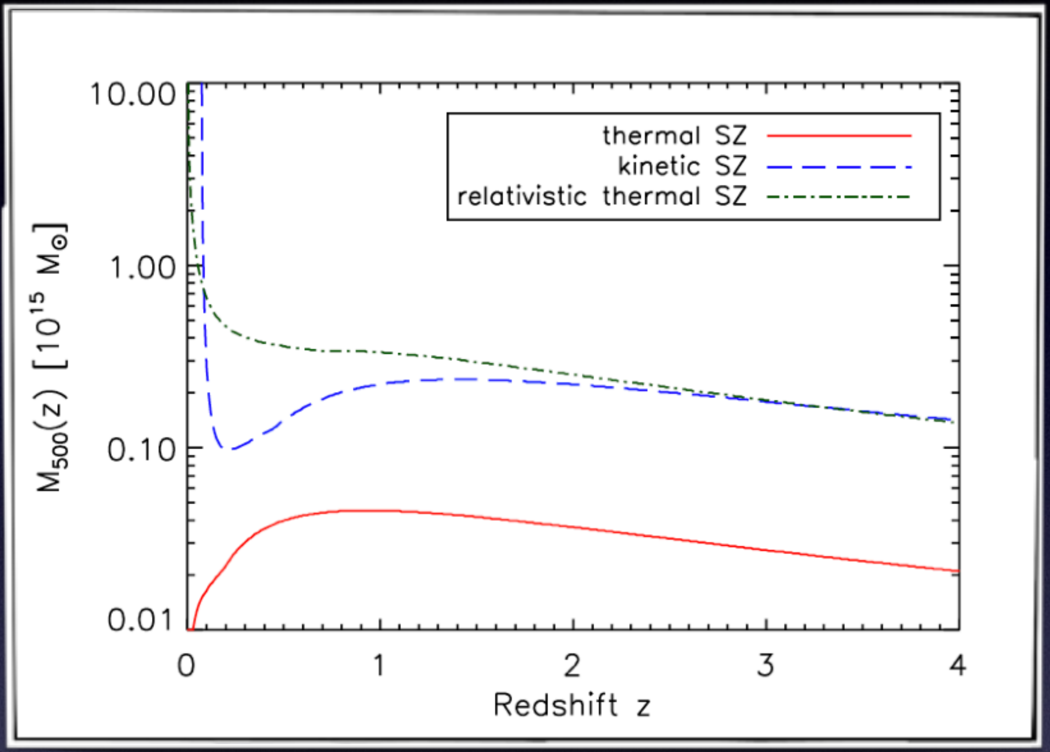
Mission characteristics: Successful application of the techniques described in Sect. 2 demands highly accurate separation of numerous astrophysical signals with differing spectra. This requires at a minimum an imager observing in multiple frequency channels over the range from 50 GHz to 1 THz. At least 20 frequency channels are needed to disentangle the target signals from contamination by sources of foreground and background emission, and to separate the different signals from the studied structures themselves (tSZ, rSZ, kSZ, pSZ, non thermal SZ, infrared and radio sources). A frequency range of 50 GHz to 1 THz insures full coverage of the SZ spectra and also accurate modeling of dust spectral energy distributions and cosmic infrared background correlations across frequencies.

Observation of the faint signals from filaments and low mass ($M \sim 5 \times 10^{13} \mathrm{M}_\odot$) halos requires an average sensitivity of order a few times 0.1 μK-arcmin, at least over the channels between 100 and 250 GHz. The imager must be polarization sensitive to detect the polarized SZ effects and to monitor expected systematic uncertainties in the measurement of halo lensing with CMB intensity.

To resolve cluster sized halos, we need a survey with a 1′ (goal) to 1.5′ (requirement) beam (the angular radius θ_{500} of a $10^{14}\mathrm{M}_\odot$ cluster at $z = 1$ is 1′). This resolution can be achieved from the ground in atmospheric windows below 300 GHz, but outside these windows and above 300 GHz, it can only be achieved from space and requires a cold 3- to 4-m class telescope, or preferentially one of 4- to 6-m class.

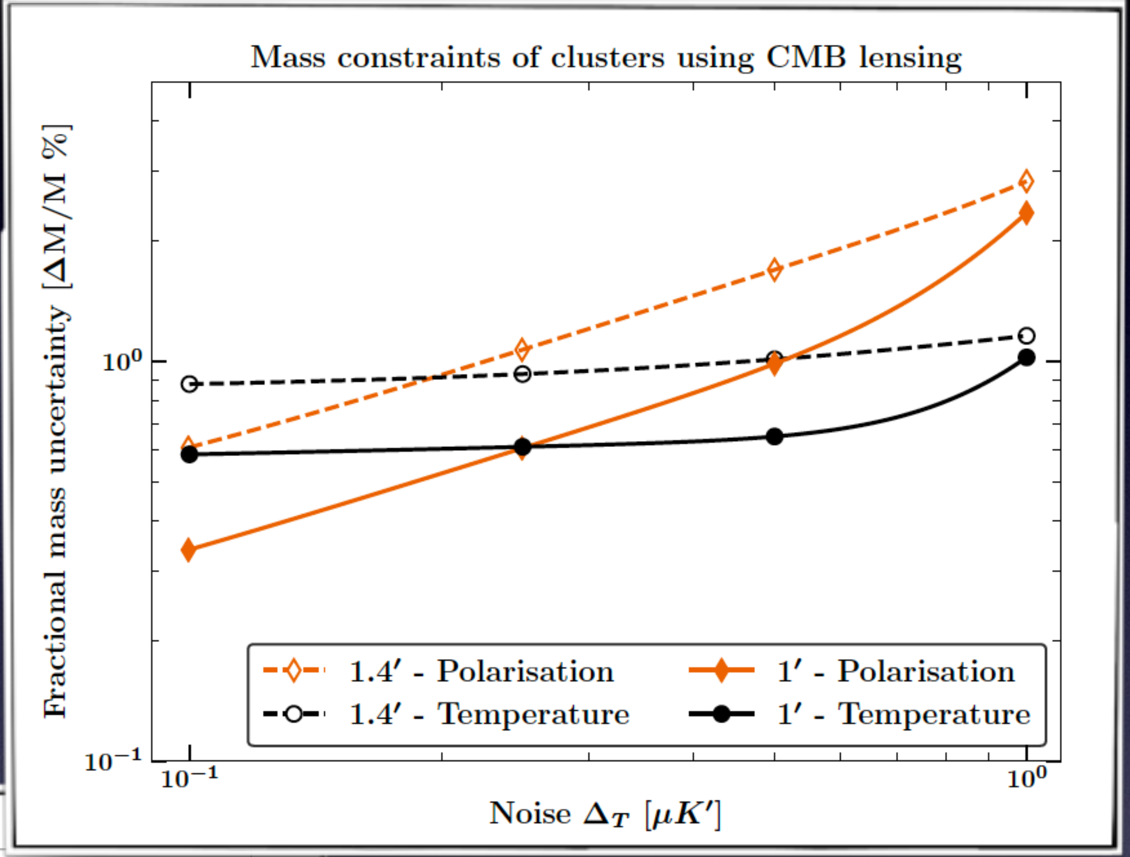
Science highlights for the Backlight mission

A million galaxy clusters and groups
above mass 5×10^{13} M$_\odot$



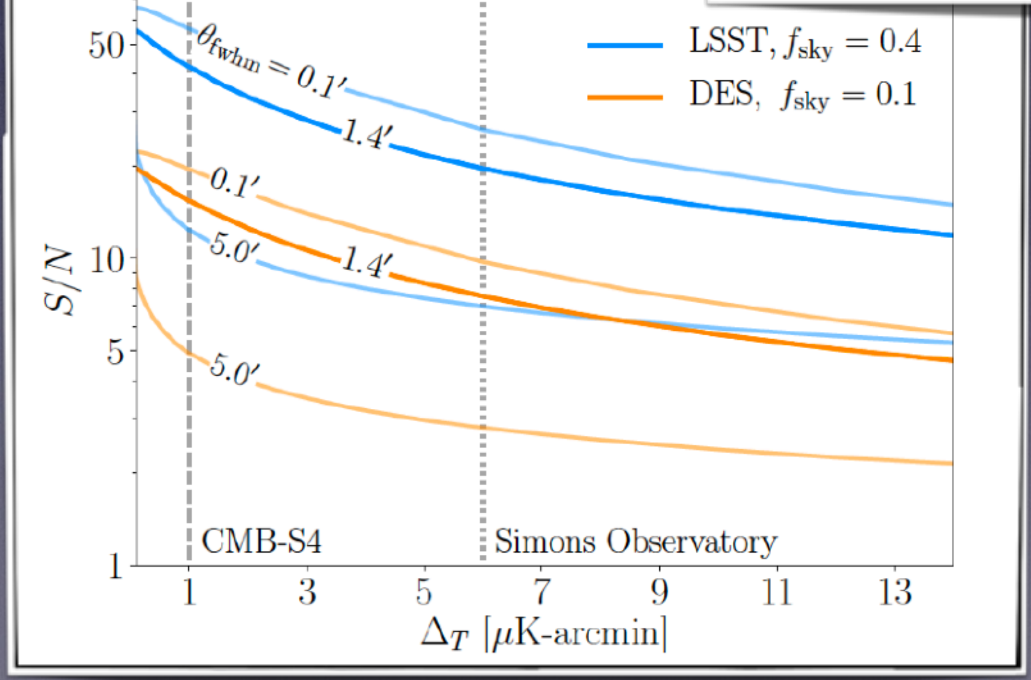
J.-B. Melin et al.

Cluster masses directly from CMB
lensing (both temp & polarization)



S. Raghunathan et al.

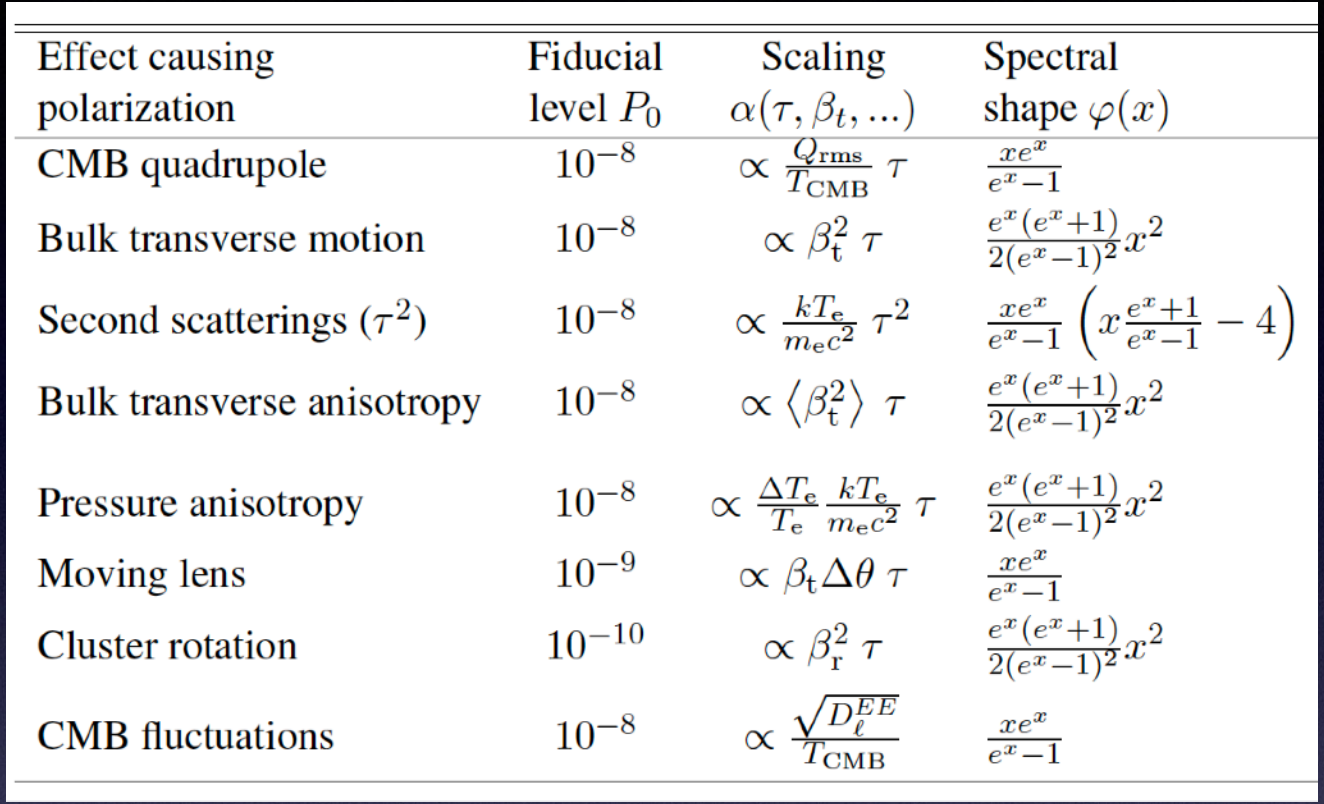
Transverse velocity
measurements from
the moving-lens effect



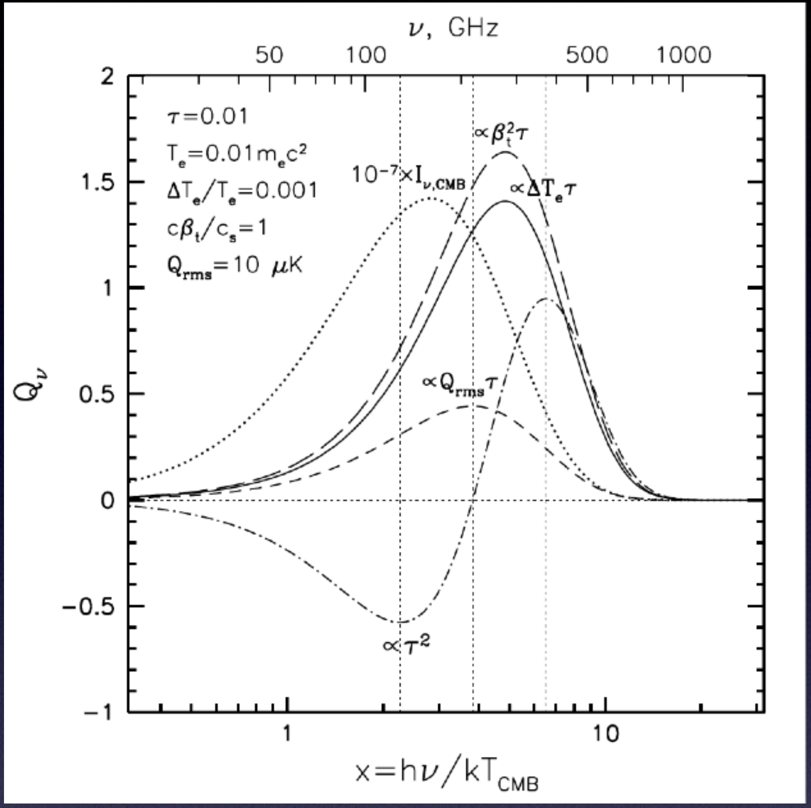
S. Hotinli et al.

Science highlights for the Backlight mission

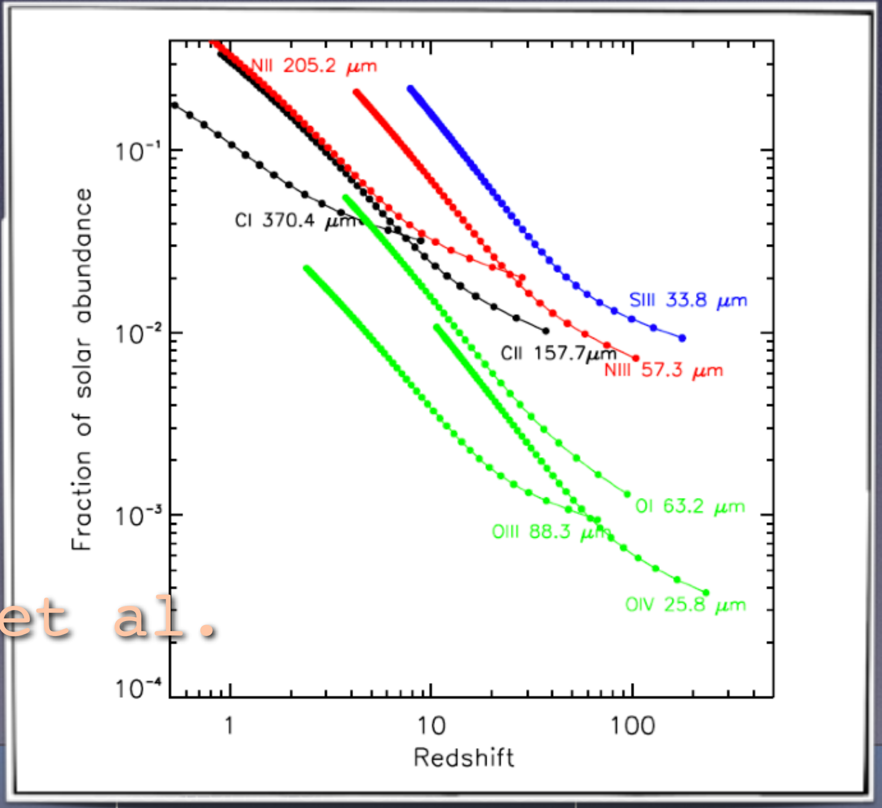
A wide range of science from SZ polarization measurements



Effect causing polarization	Fiducial level P_0	Scaling $\alpha(\tau, \beta_t, ...)$	Spectral shape $\varphi(x)$
CMB quadrupole	10^{-8}	$\propto \frac{Q_{\rm rms}}{T_{\rm CMB}}\,\tau$	$\frac{xe^x}{e^x-1}$
Bulk transverse motion	10^{-8}	$\propto \beta_{\rm t}^2\,\tau$	$\frac{e^x(e^x+1)}{2(e^x-1)^2}x^2$
Second scatterings (τ^2)	10^{-8}	$\propto \frac{kT_{\rm e}}{m_{\rm e}c^2}\,\tau^2$	$\frac{xe^x}{e^x-1}\left(x\frac{e^x+1}{e^x-1}-4\right)$
Bulk transverse anisotropy	10^{-8}	$\propto \langle\beta_{\rm t}^2\rangle\,\tau$	$\frac{e^x(e^x+1)}{2(e^x-1)^2}x^2$
Pressure anisotropy	10^{-8}	$\propto \frac{\Delta T_{\rm e}}{T_{\rm e}}\frac{kT_{\rm e}}{m_{\rm e}c^2}\,\tau$	$\frac{e^x(e^x+1)}{2(e^x-1)^2}x^2$
Moving lens	10^{-9}	$\propto \beta_{\rm t}\Delta\theta\,\tau$	$\frac{xe^x}{e^x-1}$
Cluster rotation	10^{-10}	$\propto \beta_{\rm r}^2\,\tau$	$\frac{e^x(e^x+1)}{2(e^x-1)^2}x^2$
CMB fluctuations	10^{-8}	$\propto \frac{\sqrt{D_\ell^{EE}}}{T_{\rm CMB}}$	$\frac{xe^x}{e^x-1}$



E. Churazov et al.

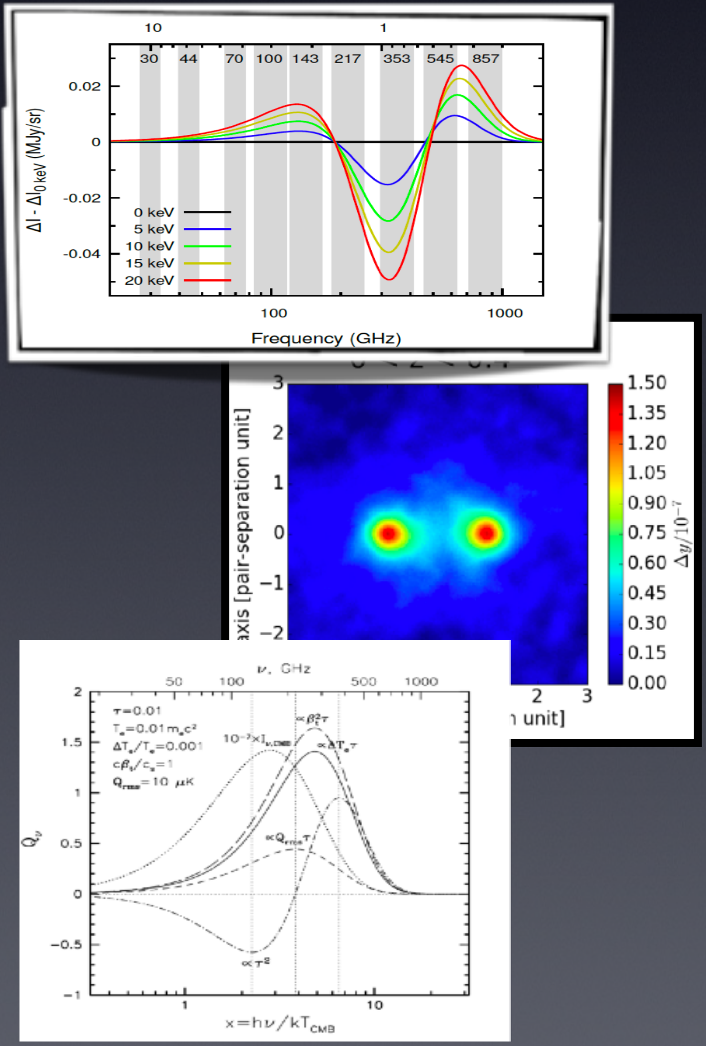


First metals in the Universe via CMB resonant scattering

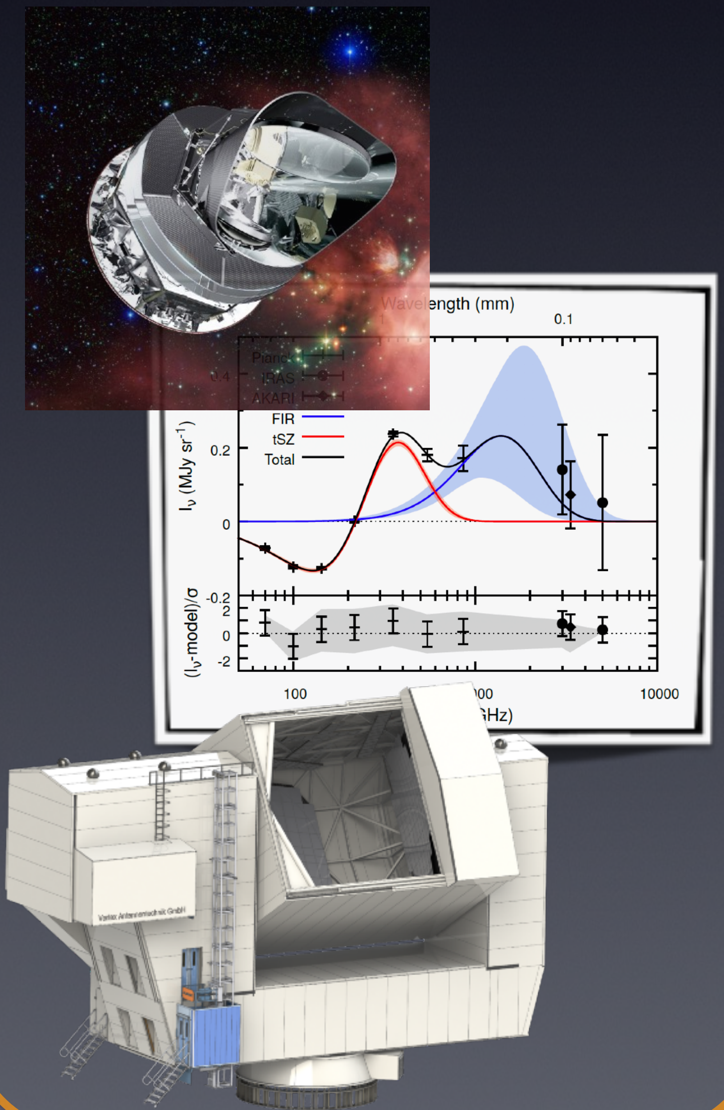
C. Hernandez-Monteagudo et al.

Take home points

A rich variety of SZ spectral science is coming online. This is in addition to the high-resolution SZ studies.



Planck data have been absolutely critical to start this effort. Next steps with advACT, SPT-3G, SO, CCAT-p.



It is absolutely critical to have access to submm (>220 GHz) wavebands. Ultimate frontier: Space!