# CCAT-p^rime

**a high throughput, high sensitivity telescope to study star & galaxy formation and cosmology**


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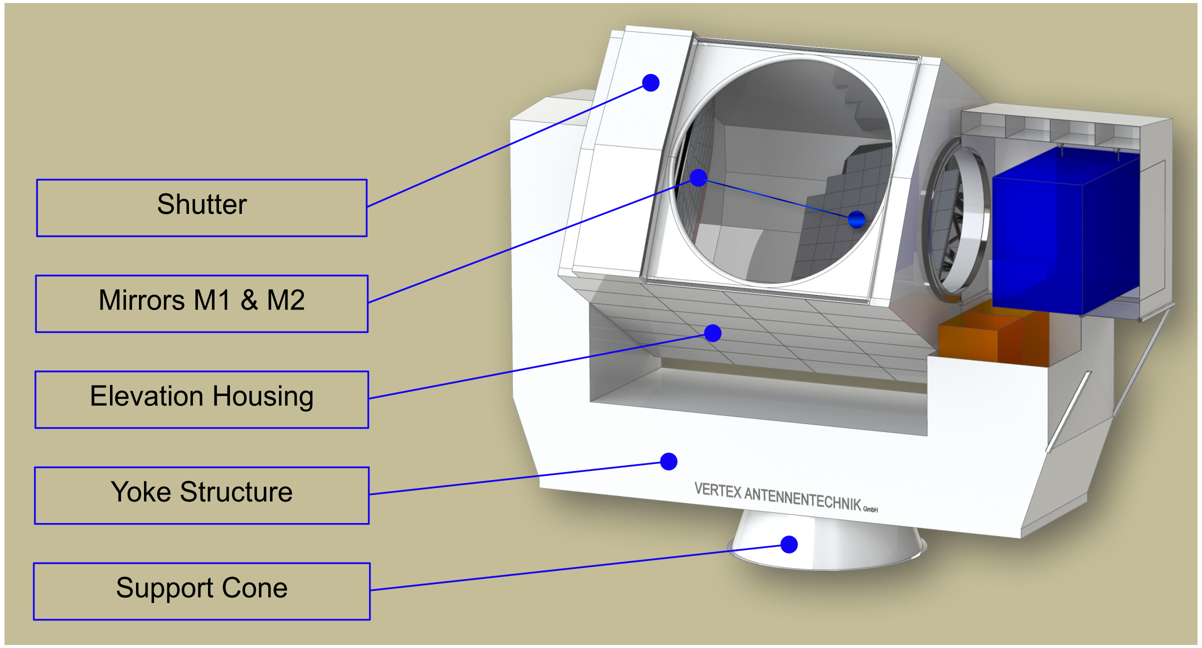
Representing the CCAT-p consortium

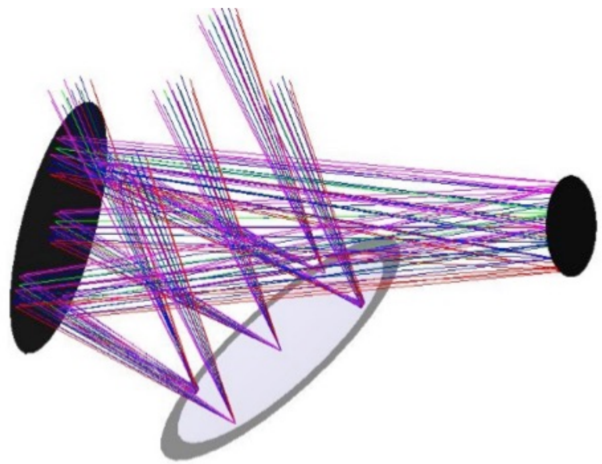
# Who is CCAT-p ?

- **Cornell University**
- **German consortium Univ. Cologne & Univ. Bonn**
  - joining: Ludwig Maximilian Univ. (Mohr), Max-Planck Inst. for Astrophysics (Komatsu, White)
- **Canadian university consortium**
  - **Waterloo**, Toronto, British Columbia, Calgary, Dalhousie, McGill, McMaster, Western Ontario

# What is CCAT-p?

CCAT-prime is a high surface accuracy / throughput 6 m submm (0.3-3mm) telescope



# Where is CCAT-p?

## Cerro Chajnantor at 5600 m w/ TAO

# Opportunity

CCAT-p

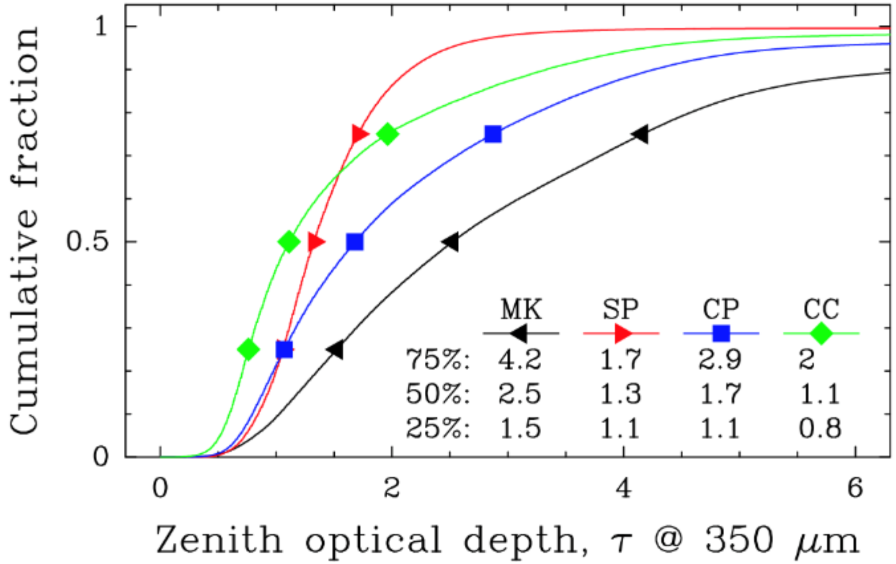
- Unique **site** enables unique science
- High accuracy (< 11 μm rms), low blockage (< 1%) **telescope design** (emissivity < 2%) maximizes surface brightness sensitivity
- Extraordinary **throughput** optimal for large-area survey science
- **Paving the road** / lowering risk for a large-aperture submm telescope (at the same site)

see talk by Chao-Lin Kuo

# 5000 meter is good, but 5600 meters is better

CCAT-p

- Submillimeter sensitivity is all about telluric transmission
- Simon Radford ran tipping radiometers at primary sites for more than a decade (Radford & Peterson, arXiv:1602.08795)
- Simultaneous for CCAT & ALMA sites: median is 0.6 vs. 1 mm $H_2O$
  $\Rightarrow$ *factor of 1.7 in sensitivity*

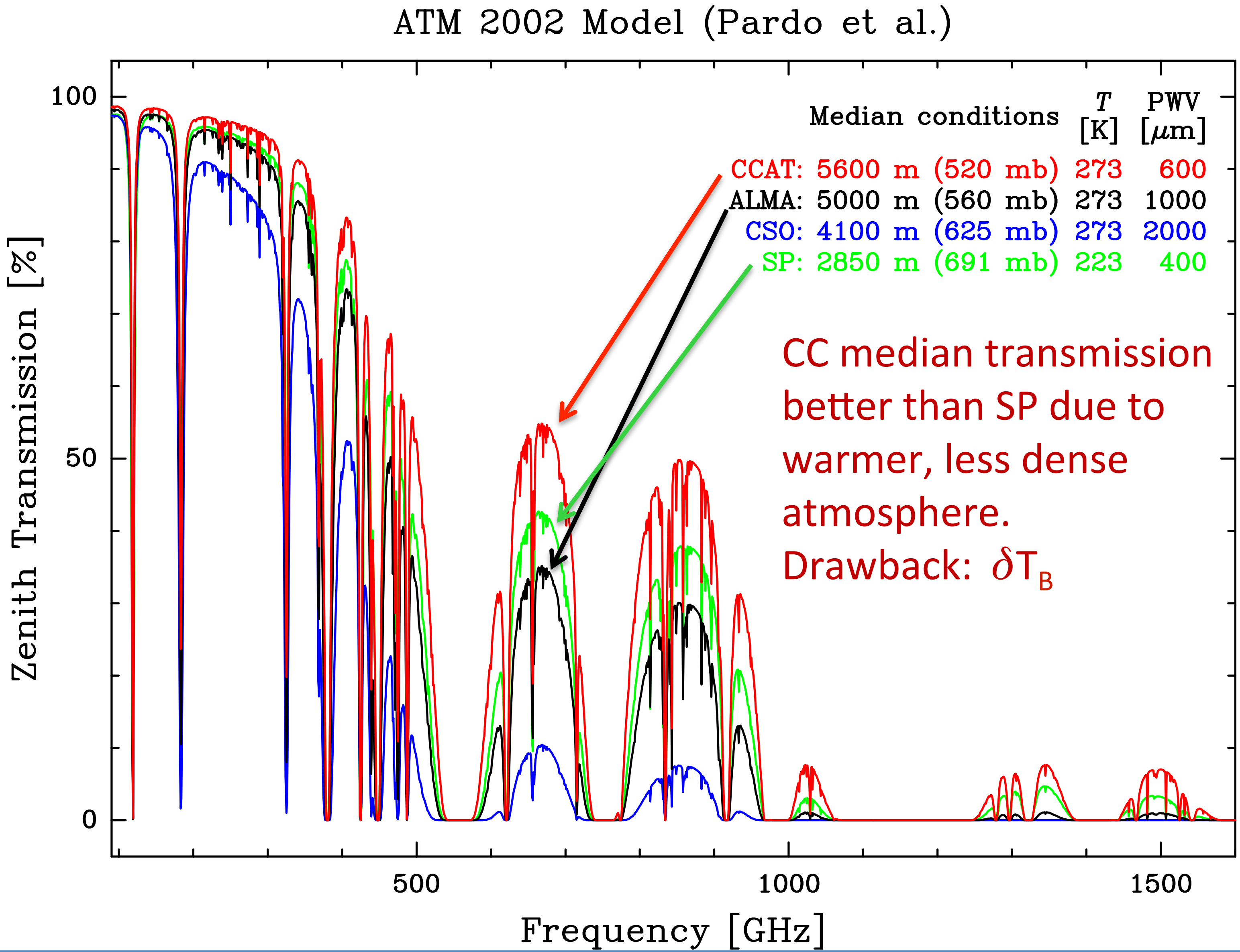



Water Vapor Scale Height

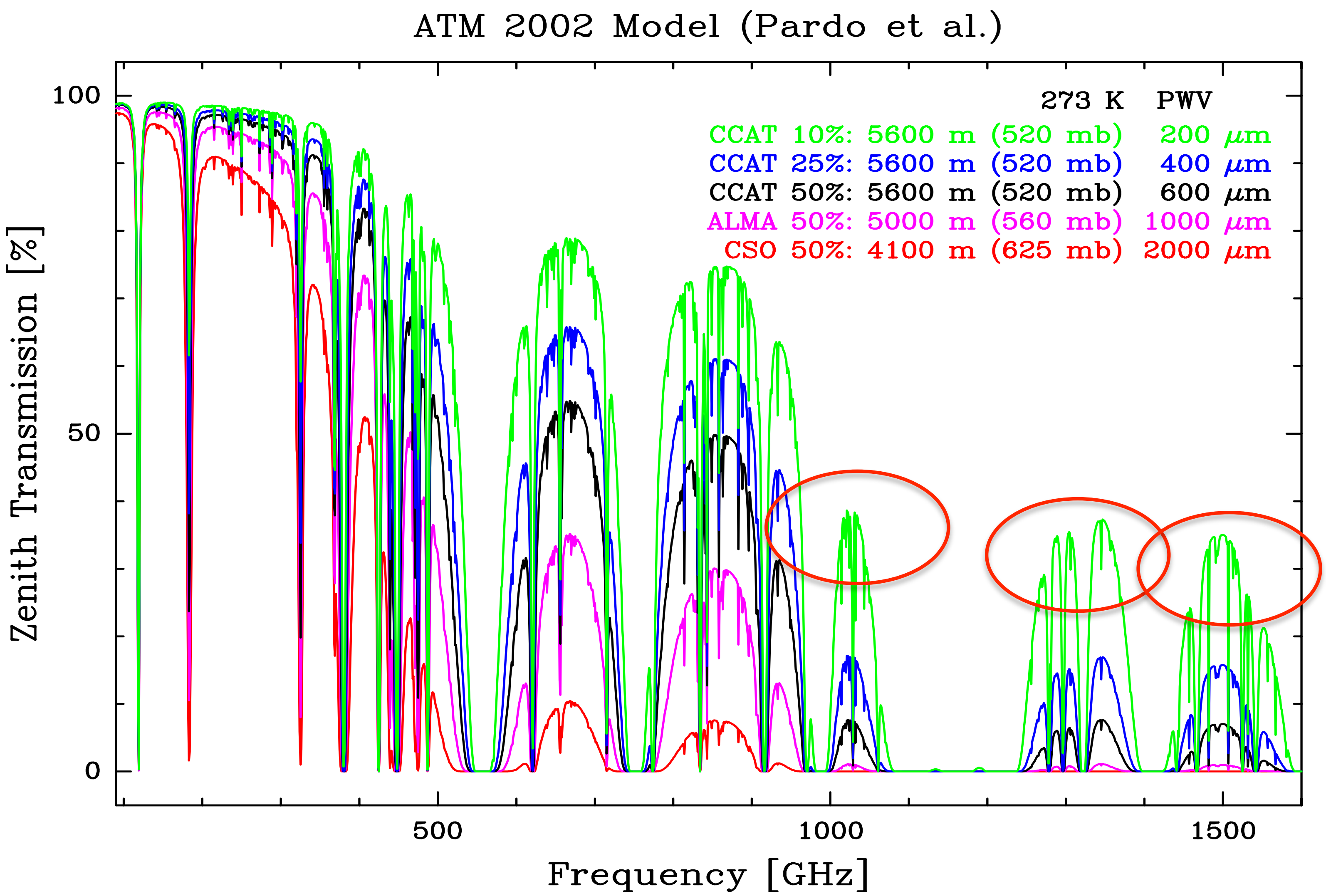
| | $\tau$(350 $\mu$m) Chaj. plateau | Cerro Chaj. | PWV [mm] Chaj. plateau | Cerro Chaj. | WV scl. ht. [m] * |
|---|---|---|---|---|---|
| 75 % | 2.7 | 1.9 | 2.0 | 1.3 | 1280 |
| 50 % | 1.5 | 1.1 | 1.0 | 0.6 | 1080 |
| 25 % | 1.0 | 0.7 | 0.53 | 0.28 | 860 |

* WV scale height = 550 m/ ln($PWV_{cp}$/$PWV_{cc}$)

# Median *Zenith* Transmission

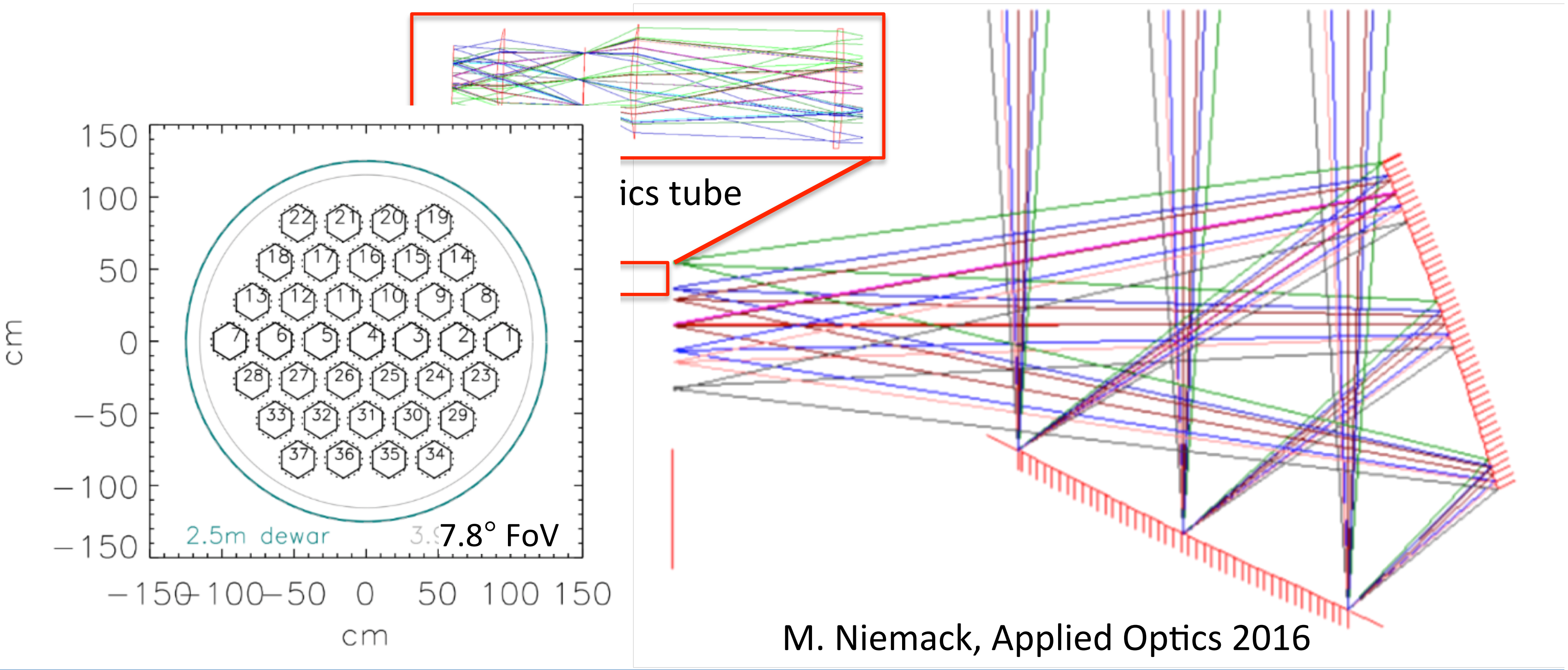


# Chajnantor Site opens up THz Windows



# Crossed-Dragone Design

- Original concept published in 1978 by Corrado Dragone AT&T Tech. Mem. 57, 2663
- Used in <2 m CMB experiments (QUIET, C. Bischoff. et al. 2013), Atacama B-Mode Search (Essingger-Hileman et al. 2009), LSPE/STRIP

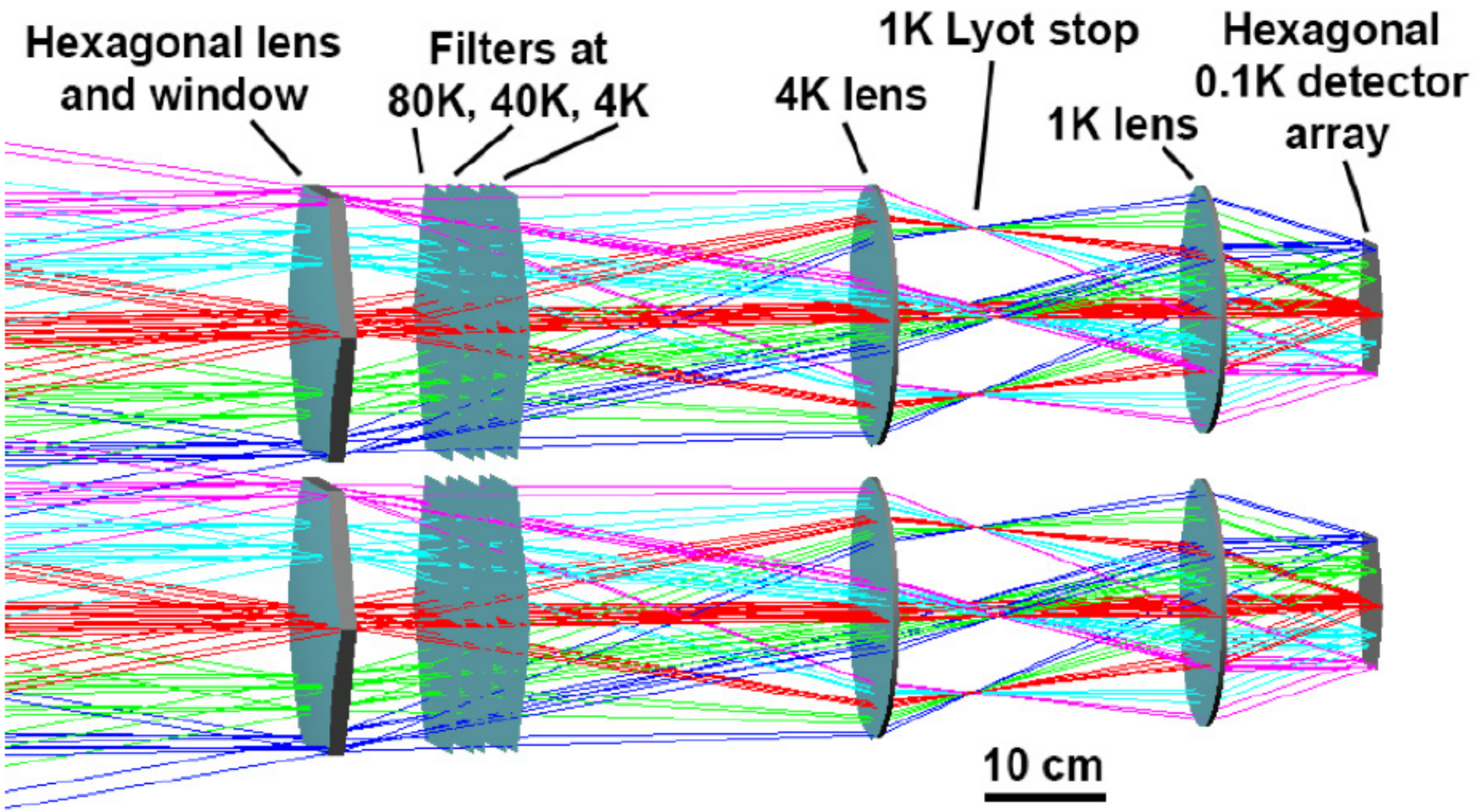



M. Niemack, Applied Optics 2016

# Sub-camera "Tubes" building blocks

CCAT-p

Close-packed reimaging optics with ~30 cm, 0.9 deg FoV diameter, well matched to 6'/15cm superconducting detector fabrication capabilities.

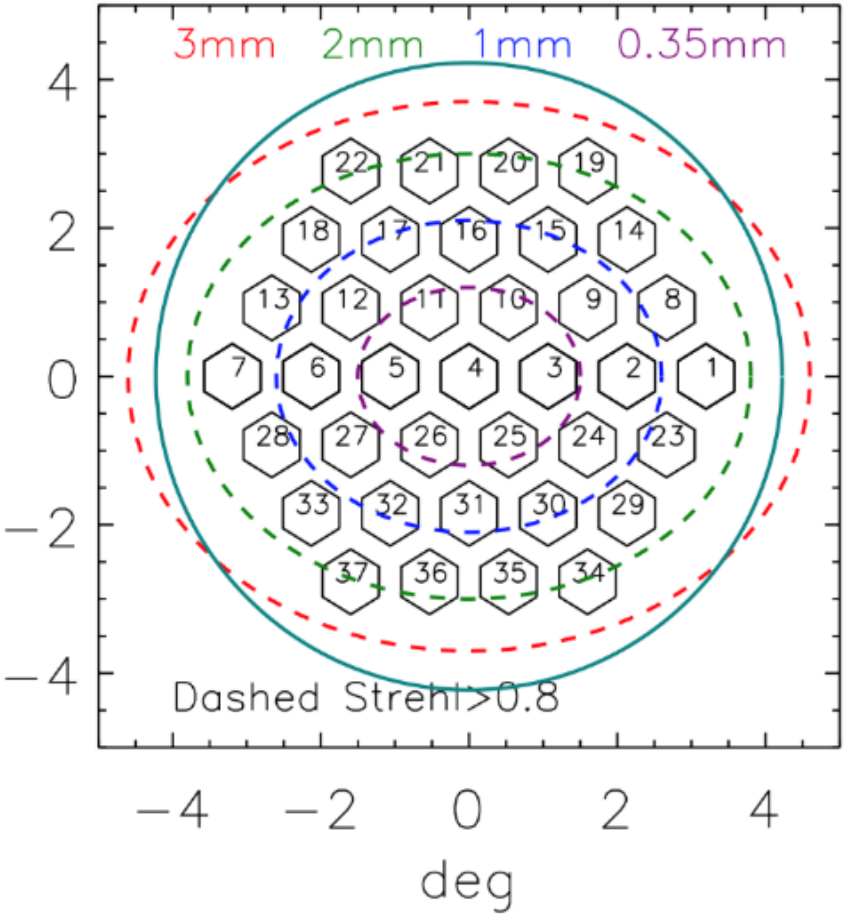



feedhorn-fed
1.5 $\lambda$/D
multichroic
polarimeter TES
bolometers

# Bolometer Camera Design

f/3 coma-corrected

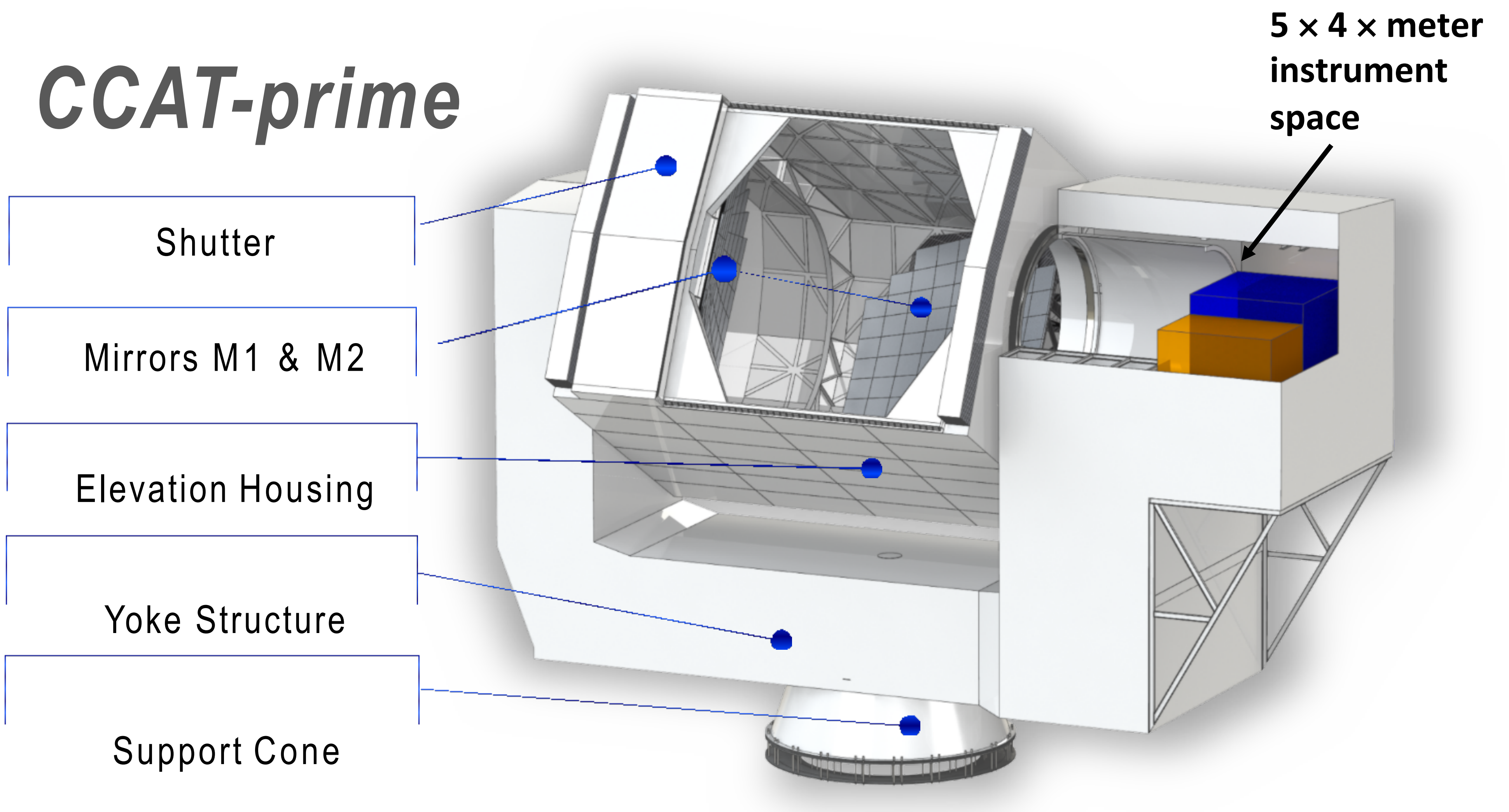
7.8° FoV




| | |
|---|---|
| 3 mm = 37 OT | 26,000 pixels |
| 2 mm = 33 OT | 58,000 pixels |
| 1 mm = 19 OT | 110,000 pixels |
| 0.35 mm = 7 OT | 400,000 pixels |

0.9° diameter optics tubes are mostly enclosed in Strehl>0.8 (diffraction-limited)

# CCAT-prime

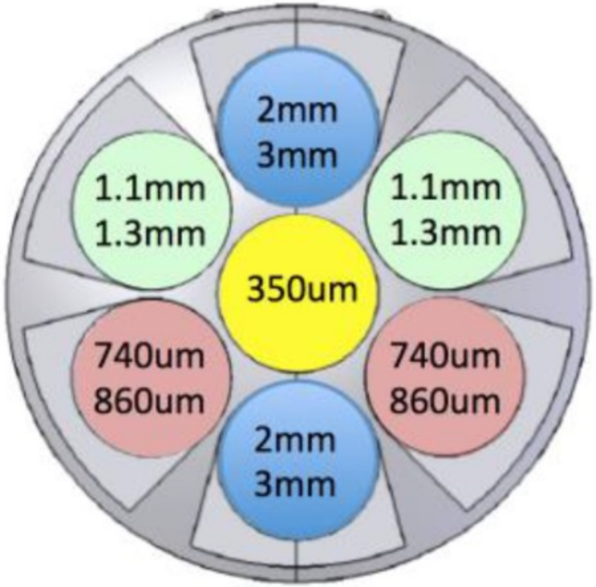


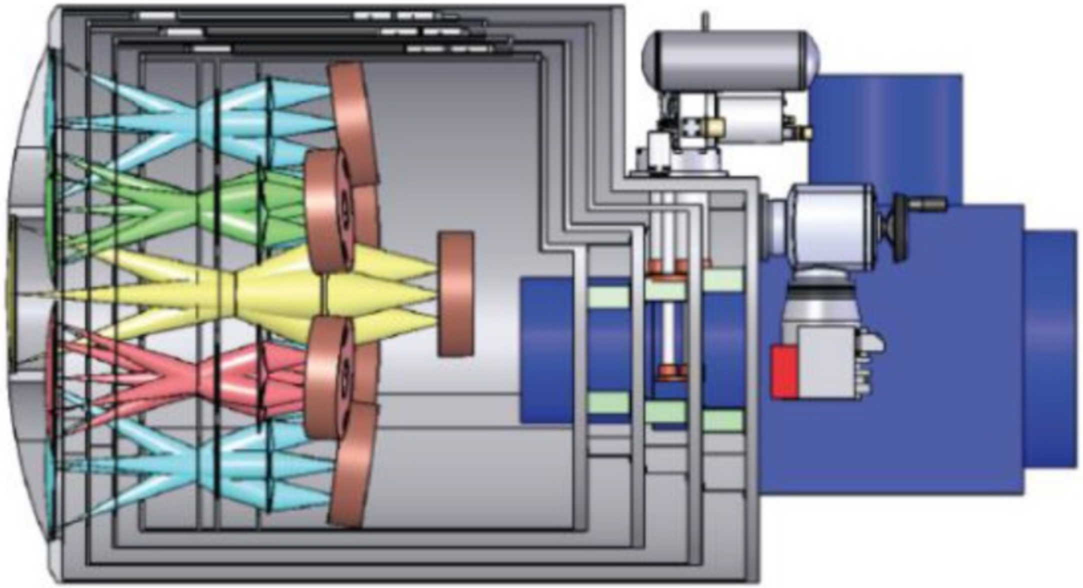

Being designed and built by Vertex Antennentechnik GmbH



Simons Observatory adopting similar design

# P-Cam: initial design

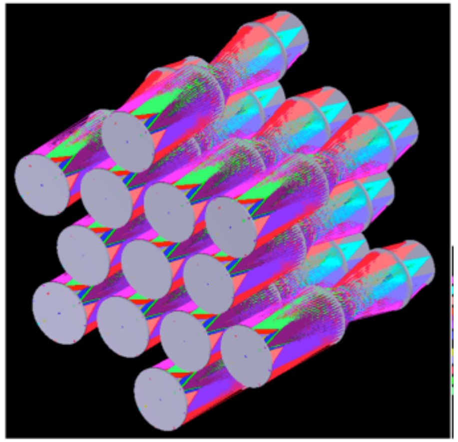


- Seven subcamera "tubes" populated with TES bolometers
- each FoV ~ 0.9 degree with feedhorn fed 1.5 $\lambda$/D pixels
  - 20,000 (first light) to 60,000 (fully populated) pixels per subcamera @ 350 $\mu$m
  - For other wavelengths, numbers scale from 60,000 as $1/\lambda^2$
  - dichroic polarization sensitive bolometers at longer wavelengths
- Cameras are modular (size, optics, filtration), easily exchanged
- Start with very modest numbers of pixels and growth to fill out camera, then entire CCAT-Prime FoV if so desired

# Instrument concept for CCAT and Simons Observatory

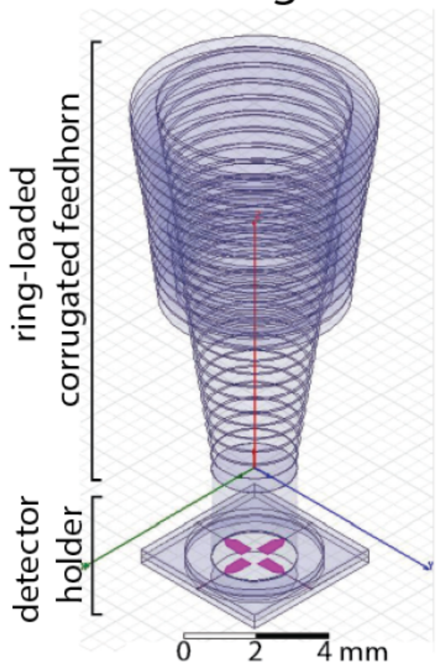
- Currently looking at a system with 13 optics tubes designed for SO. 7 central tubes good for submm bands.
- Feedhorn-coupled multichroic polarimeter arrays with 4 bands per feedhorn: 740, 860, 1100, 1300$\mu$m (NIST, McMahon et al.)
- 3-4 15cm 400 feed detector arrays tiled in each optics tube.
- Add FP on two tubes for intensity mapping.
- Cryogenics arranged such that tubes can be exchanged on the telescope from the back.



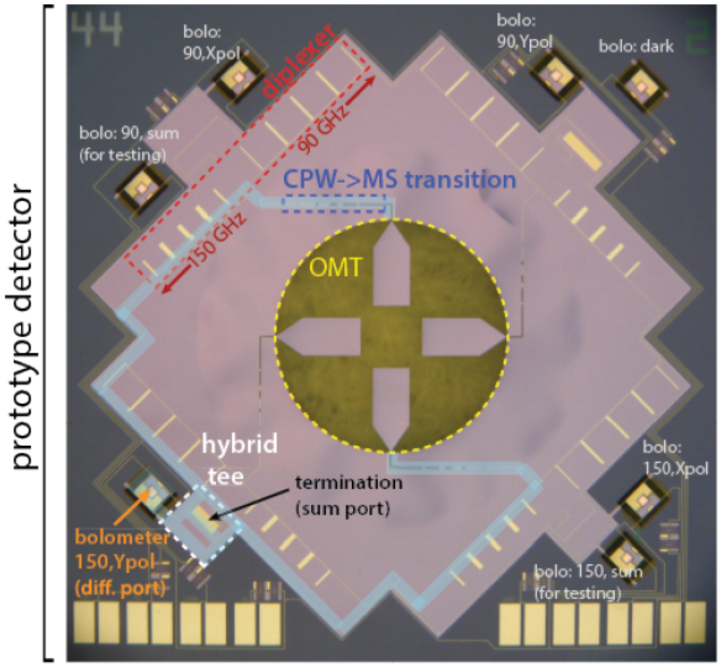
P. Mauskopf , SO

Cost-effective, low-risk technology for CCAT-p first light science

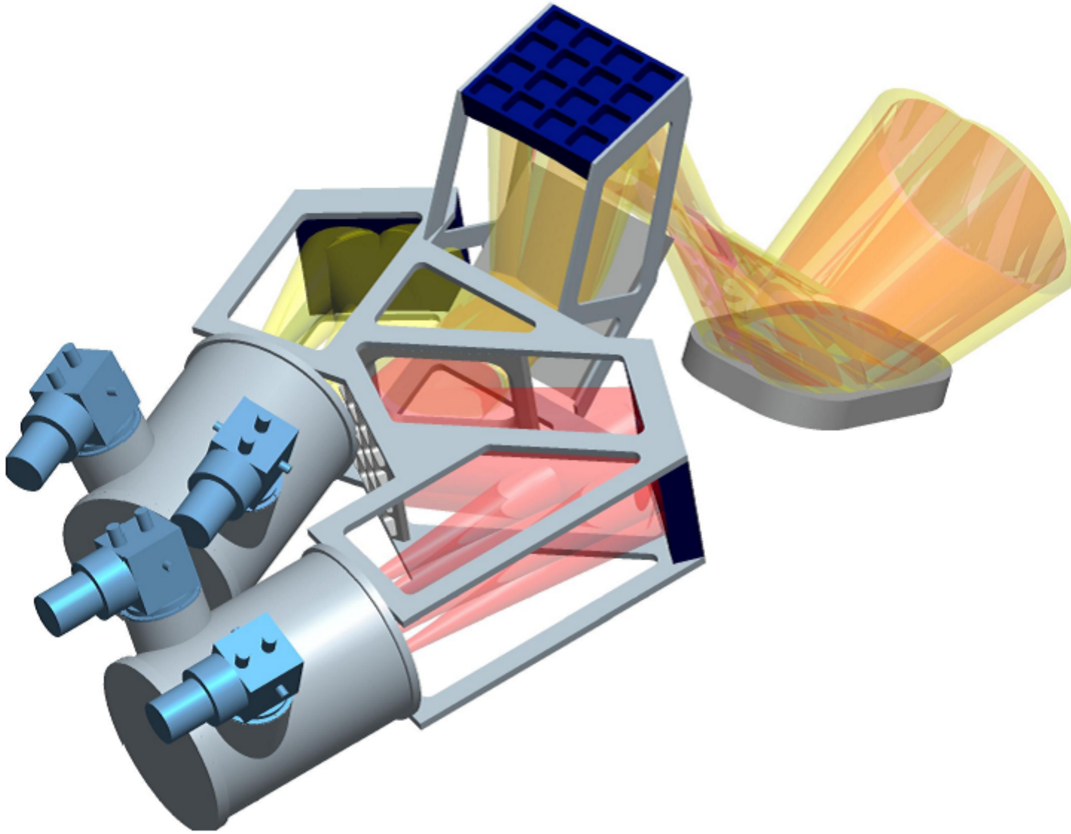
Design




Datta et al. 2016. J Low Temp Phys.



# CCAT Heterodyne Array Instrument "CHAI"



- Heterodyne, dual frequency array
- 500 GHz (600 μm) and 850 GHz (350 μm): CO(4-3), CO(7-6) [CI] × 2
- 64 (baseline), 128 (goal) pixels in each band

# Schedule

**Telescope: 4 year construction (6/2017 to 6/2021)**

- 20 months Detailed Design [PDR @ 4 months; CDR @ 10 months, FDR @ 18 months.]
- 13 months fabrication incl. trial assembly in Duisburg
- 3 months Shipping & Receiving
- 12 months Assembly/Checkout

**Cameras** under design & construction, $€ still being raised.

***Project has started, but still welcomes new partners.***

# CCAT-p Science

- Star formation in the **Milky Way,** the **Magellanic clouds** and other **nearby galaxies** through submm spectroscopy and photometry
- Measurement of **the velocities, temperatures and optical depth of galaxy clusters** via the SZ effects to place new constraints on models of dark energy and modified gravity and the sum of the neutrino masses;
  - **Polarization foregrounds**: Galactic dust science & CMB poln corrections
- Evolution of **DSFG** through submm-mm wave surveys.
- EoR **intensity mapping in [CII]** at redshifts from 5 to 9.
- Stage 4 CMB: **CMB polarization** at 10 times the speed of current facilities $\Rightarrow$ inflationary gravity waves and the sum of the neutrino masses.

# Cluster cosmology: tSZ, kSZ, rSZ

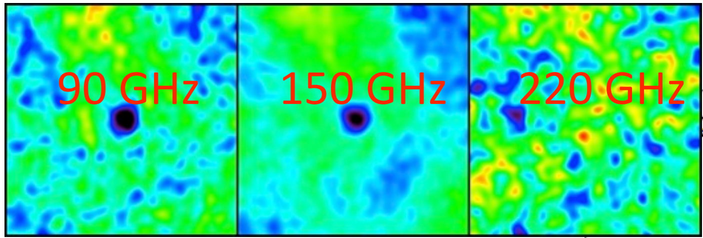
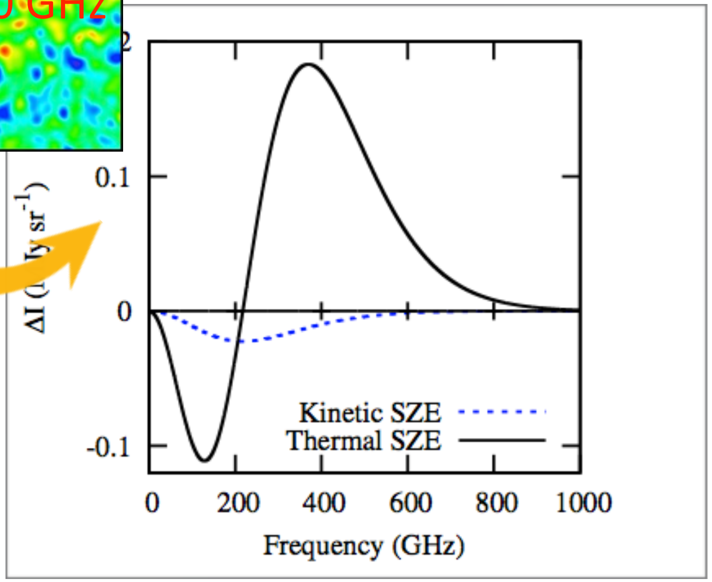
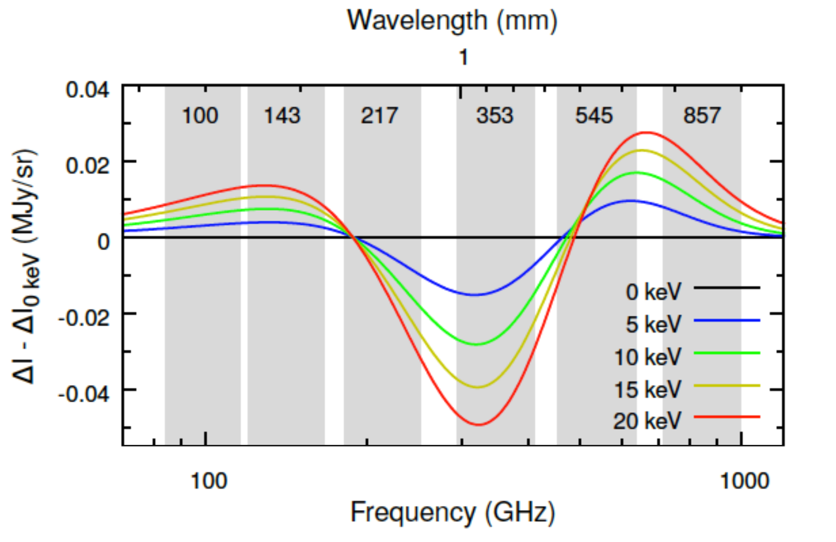


Image: SPT collaboration




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

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




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

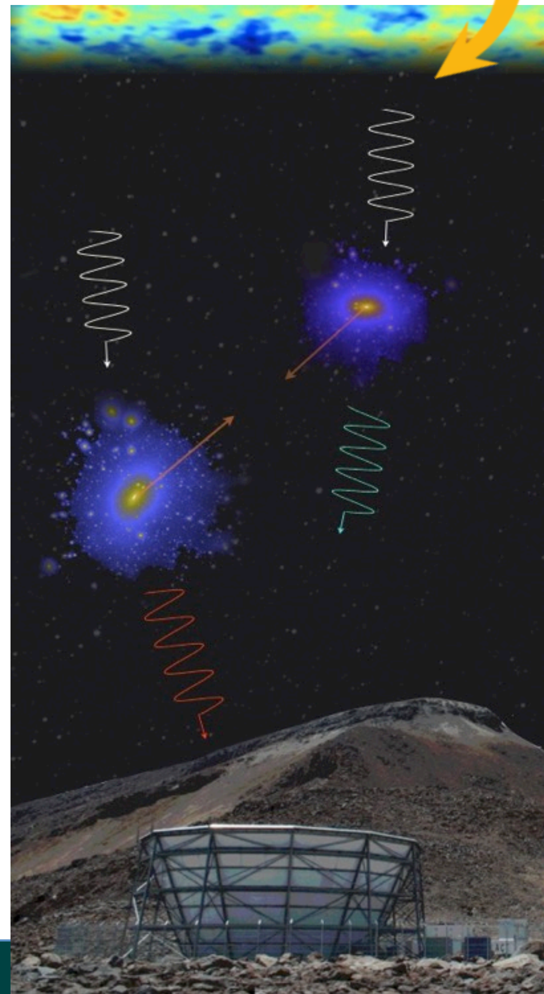


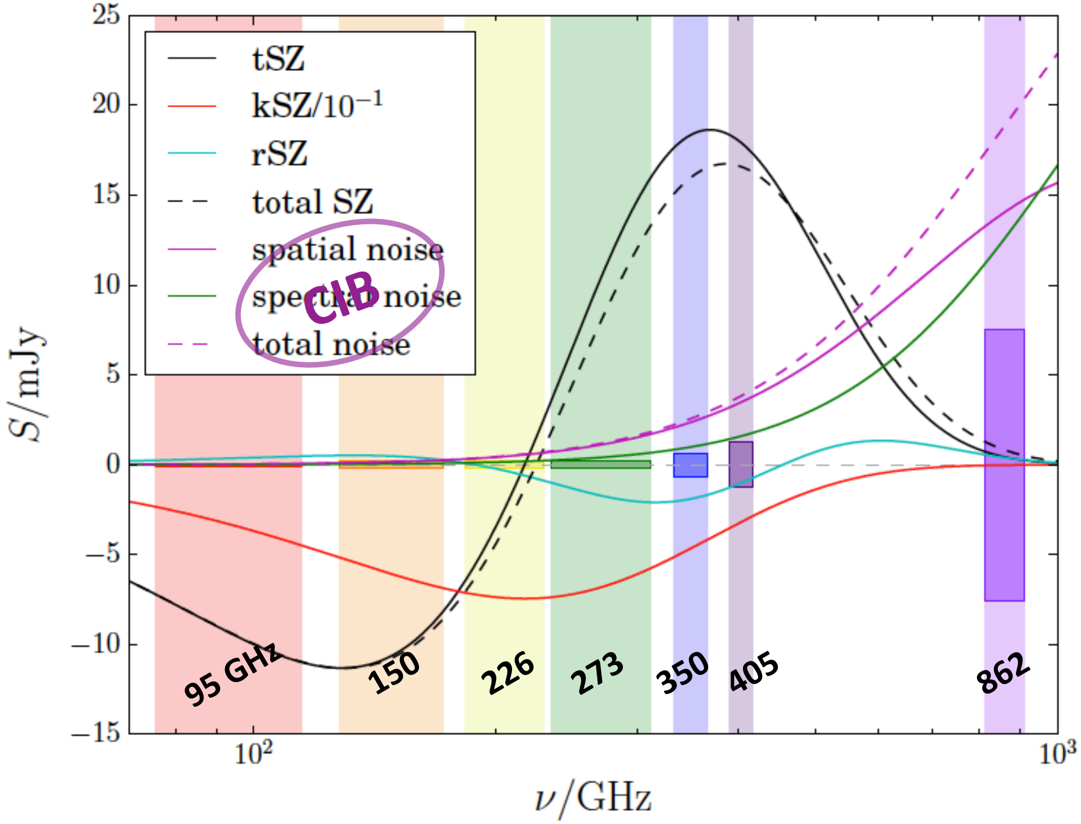
Image: ACT collaboration

# CCAT-p view of SZ spectrum

CCAT-p

Vast improvement in sensitivity and resolution compared to Planck, except 350um

Figure: Mittal, de Bernardis & Niemack 2017




| ν GHz | FWHM arcmin | $\Delta T$ $mK_{RJ}$-arcmin | $\Delta T$ $mK_{CMB}$-arcmin | $\Delta I$ 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 | $1.92 \times 10^4$ | 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 | $6.9 \times 10^4$ | 109 |

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

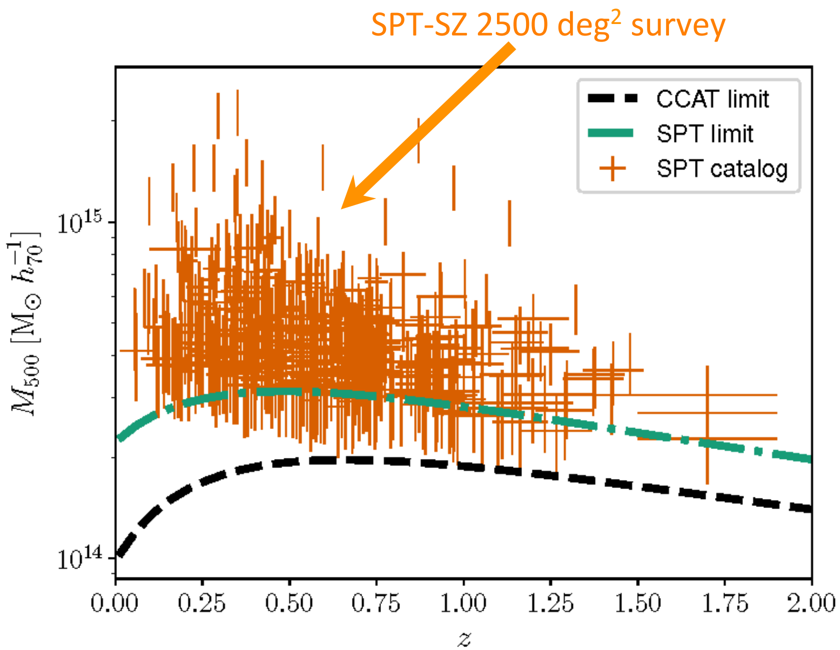
Gupta, Basu & Porciani, t.b.subm.

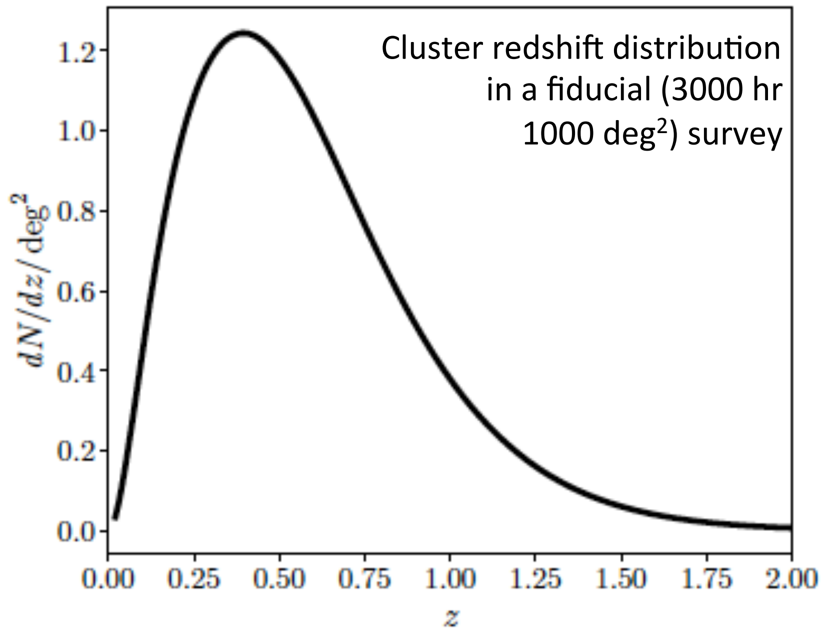
# tSZ survey predictions

CCAT-p

Survey options:

| Survey | $T_{\rm int}$ (Kh) | $A$ ($\deg^2$) | $\sigma_T$ ($\mu$K) | $N$ ($z \leq$ |
|---|---|---|---|---|
| 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 |




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.

Gupta, Basu & Porciani, t.b.subm.

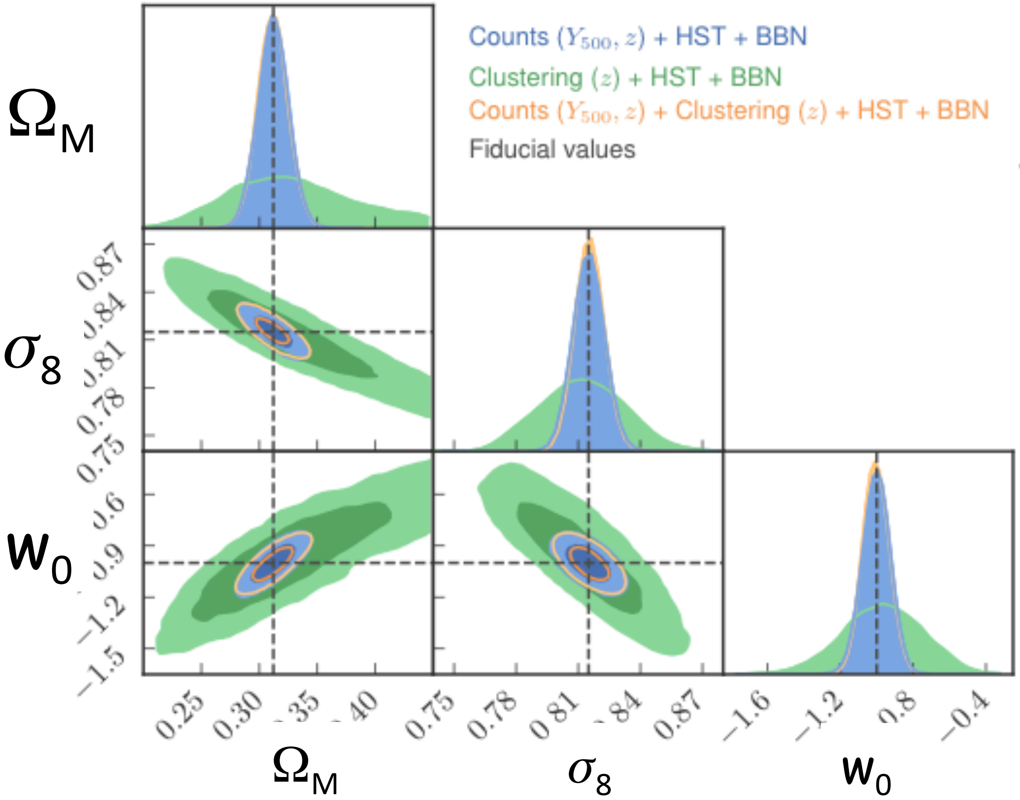
# tSZ survey predictions

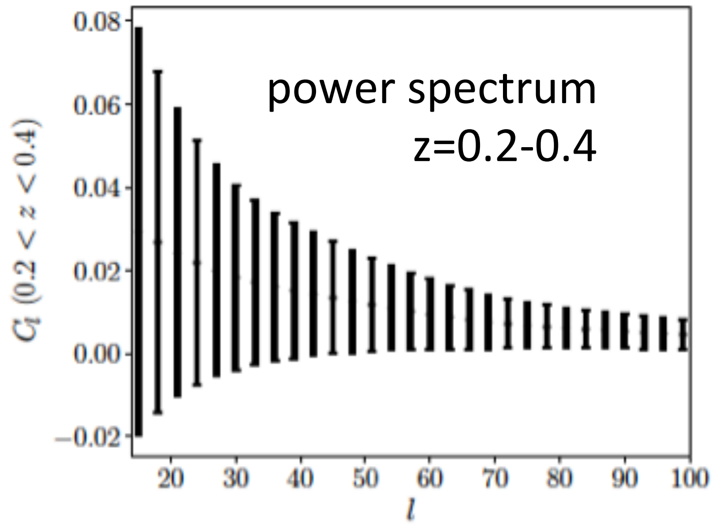
CCAT-p

CCAT-p tSZ data alone will constrain $\boldsymbol{\Omega}_m$, $\boldsymbol{\sigma}_8$ and $\boldsymbol{w}_0$ to roughly 4%, 0.7% and 7% accuracies, respectively. In ~1000 $deg^2$ survey area, **angular clustering** data will not bring improvements.

Better than the all-sky eROSITA, thanks to lower scatter Y-M scaling relation.

| Experiment | $\Delta\Omega_M$ | $\Delta\sigma_8$ | $\Delta w_0$ |
|---|---|---|---|
| **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 |






For given survey time, wider surveys will do better than deep, narrow surveys.

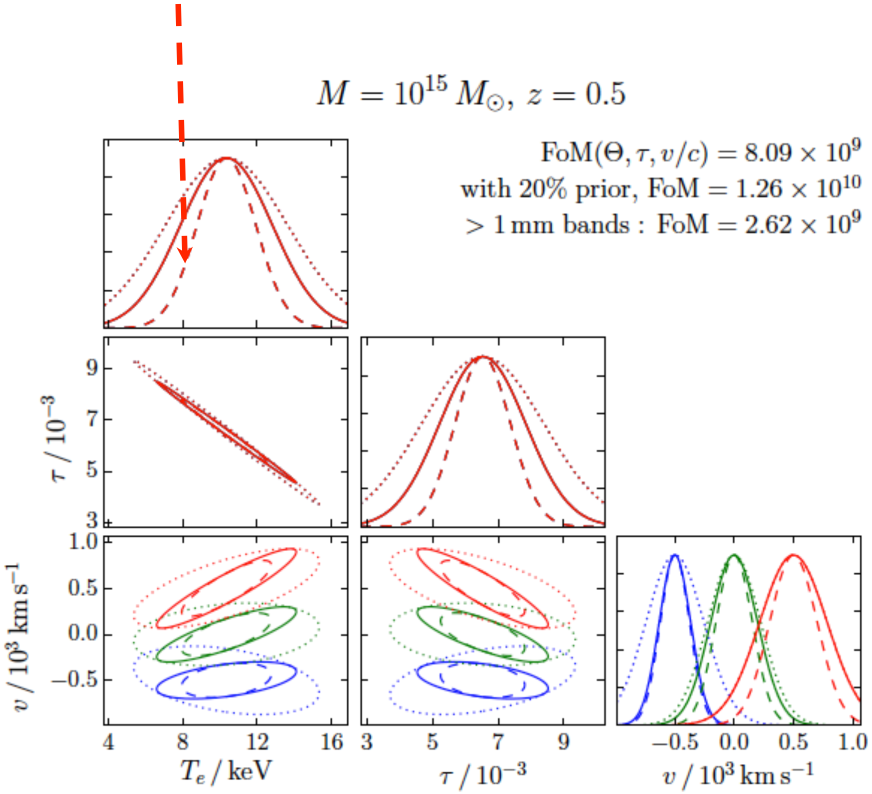
Mittal, de Bernardis & Niemack, subm. (1708.06365)

# kSZ predictions

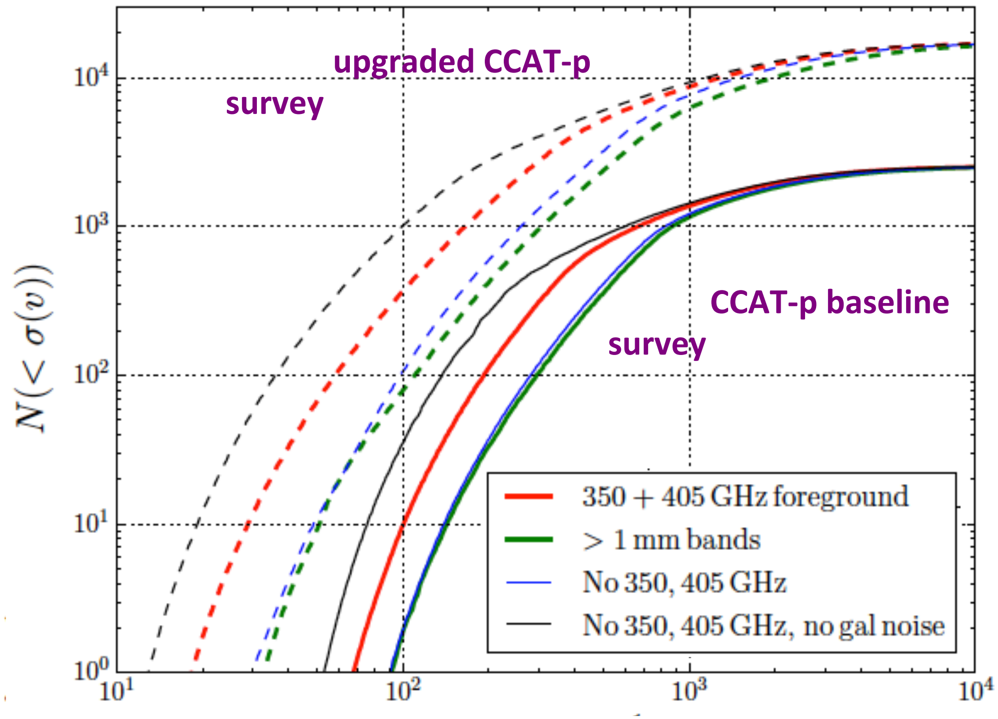
**CCATp is ideally suited for individual cluster kSZ measurement**

kSZ modeling results for a single high-mass cluster.

Employ eROSITA temperature priors for improved precision.




CCAT-p baseline survey will provide kSZ measurements for few hundred clusters



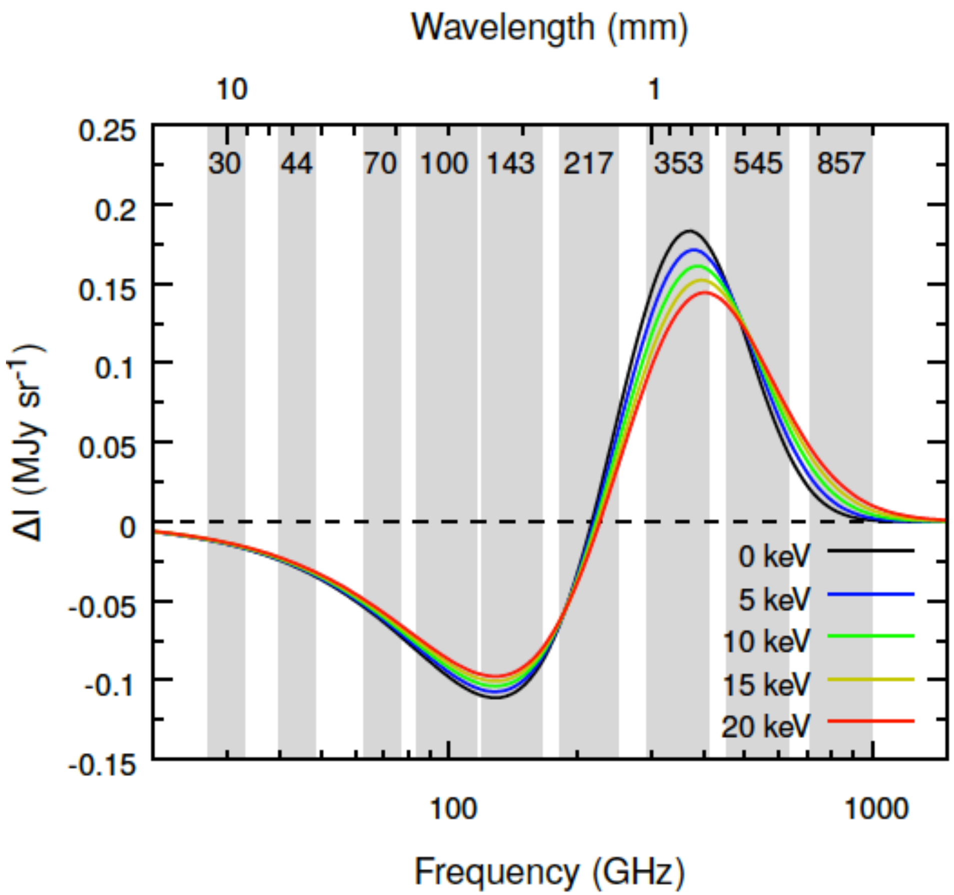

velocity dispersion $\sigma(v)$ [km s$^{-1}$]

# rSZ predictions

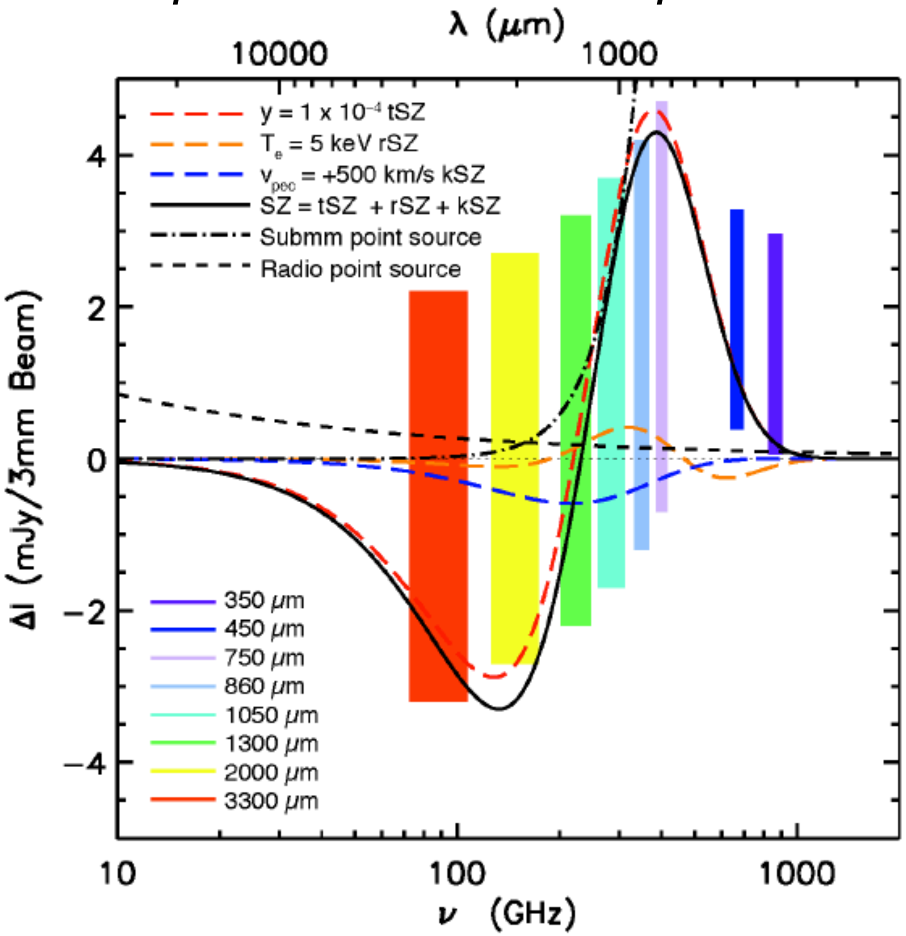
With the rSZ signal the electron temperature of the intracluster medium can be measured directly.

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

*SZ spectrum with Planck bands*




*SZ spectrum with CCAT-p bands*






Source: Erler et al. (arXiv:**1709.01187**)

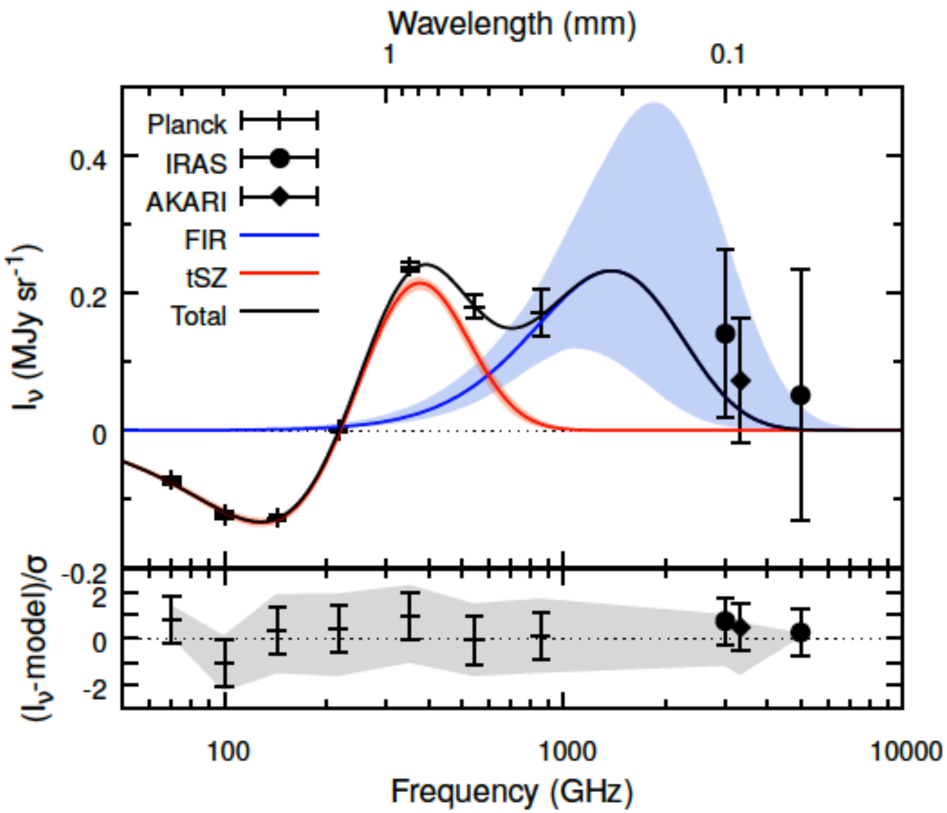
Source: CCAT-p SZ white paper

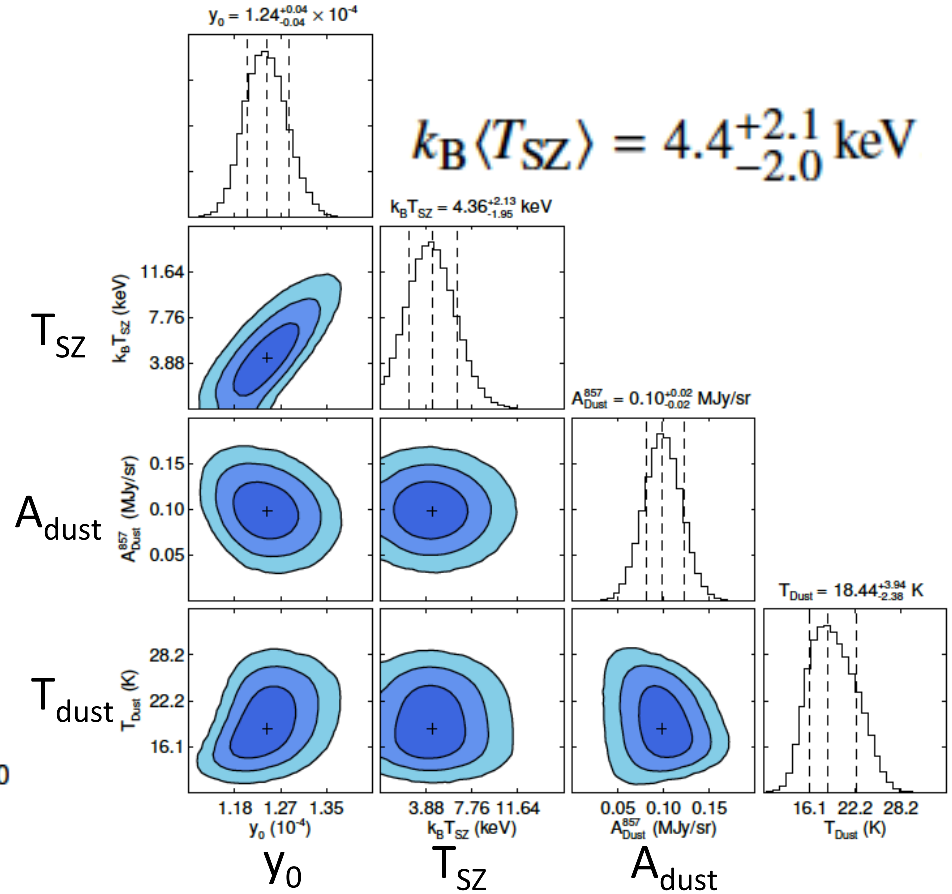
# Relativistic SZ from *Planck*

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

With current *Planck* data, modelling rSZ with cluster CIB, matched filtering and stacking 772 clusters: 2.3σ significance detection of cluster temperature.

Dust modeling crucial for correct kSZ, disentangle to go to next level.



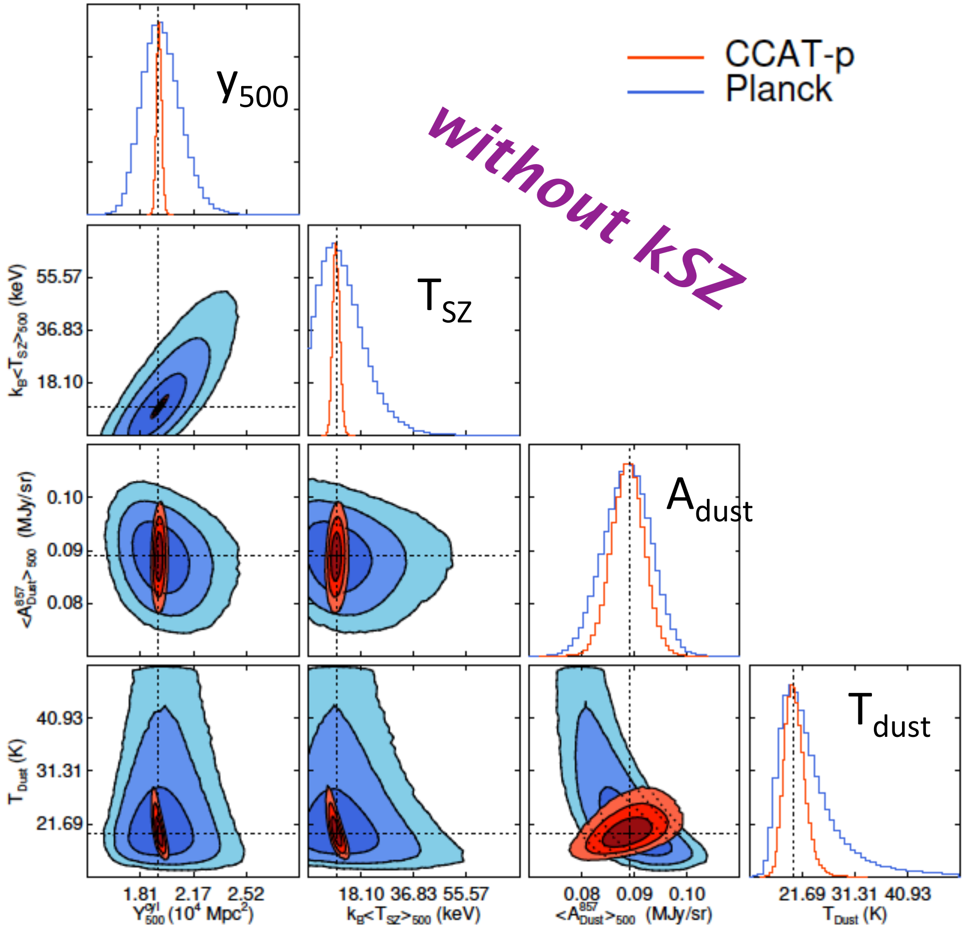



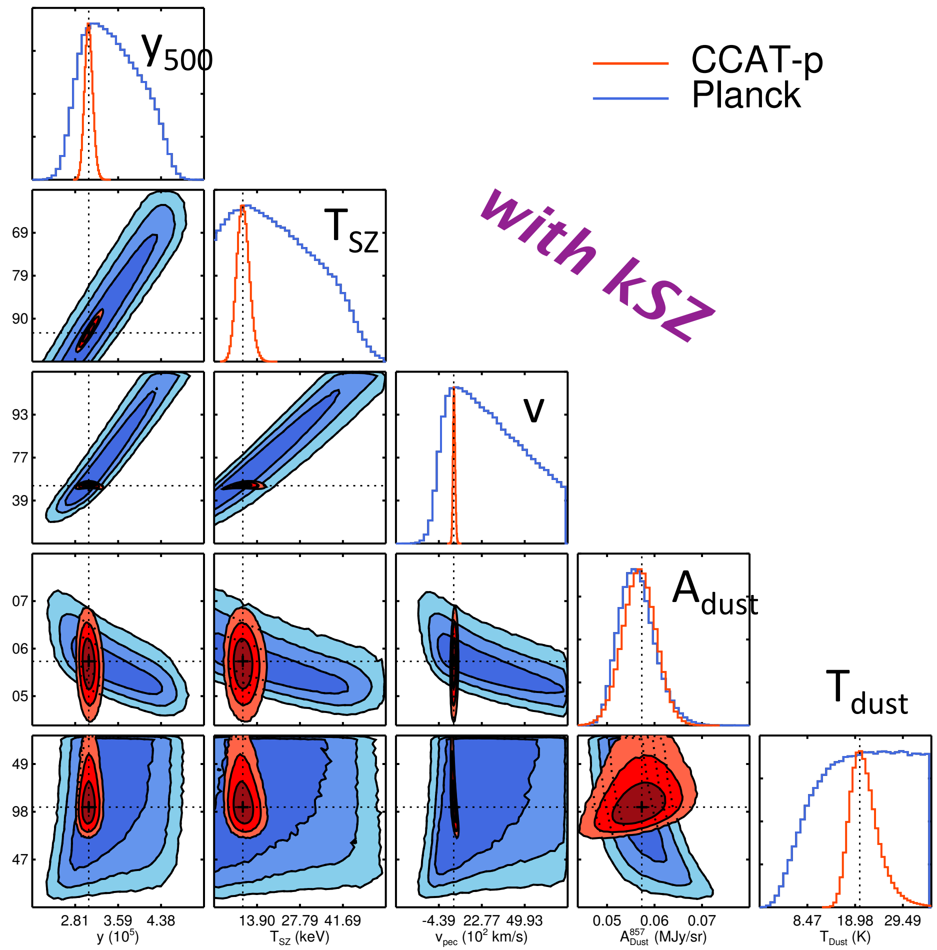

 *With CCAT-p the temperature of a single massive cluster can be measured at 5—10 σ.*

# CCAT-p and *Planck* comparison

Need x10 better sensitivity for individual cluster detection:
Predictions for a single cluster with $M_{500}$ = 8 x$10^{14}$ $M_\odot$ at z=0.2
Joint modelling

Erler et al.



# Polarized CMB and Dust Emission

- Polarized galactic dust foregrounds limit current constraints on Inflationary Gravity Waves (e.g. BICEP2)

- Planck measurements suggest several polarized dust bands are needed to detect B-modes with $r \leq 0.01$

( Planck intermediate results. XXII and XXXVIII 2015 )

- CCAT-prime SZ instrument with polarization detectors
  - ➢ Unique niche in CMB community
  - ➢ Improve constraints on inflation via foregrounds
  - ➢ Understand galactic dust turbulent energy cascade

( e.g. Caldwell, Hirata, Kamionkowski, arXiv:1608.08138 )

# CCAT-p cluster SZ 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.

- 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.

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

- Polarization measurements will help constrain foreground dust properties, assisting B-mode detection efforts.

## Atacama Large-Aperture Submm/mm Telescope (AtLAST)

https://www.eso.org/sci/meetings/2018/AtLAST2018.html

A workshop to discuss science/technical aspects of

the **At**acama **L**arge-**A**perture **S**ubmm/mm **T**elescope (AtLAST)

ESO-HQ, Garching b. München, Germany

January 17-19, 2018

The Atacama Large Millimeter/Submillimeter Array (ALMA) is currently the world's most sensitive telescope operating at 0.3 to 3 mm (and will soon be extended to 10 mm). However, as an interferometer, its mapping speed for large areas is limited, while the largest angular scales it can access are limited to < 1 arcminute at 3 mm. This limit is even more stringent at shorter wavelengths. Further, existing submm/mm single dish facilities are not expected to remain competitive beyond 2030.[1]

We have therefore begun a two-year effort concerning the scientific merit for – and technical implementation of – an **At**acama **L**arge **A**perture **S**ubmm/mm **T**elescope (AtLAST). We now invite to community to join in establishing working groups on science and technology aspects of AtLAST, and are holding a 3-day workshop at ESO Headquarters in Garching on January 17-19, 2018. The science and technology working groups will conclude the study in early 2019 with a public report including recommendations for organisational and financial paths to building an international collaboration. The workshop will be a crucial forum to collect insights and feedback, and commit to a single vision for producing a single dish facility.

The science case, role and prospects for a large single dish submm/mm telescope will also be discussed in the context of existing and planned major single dish (sub)mm observatories. As an outcome of the workshop, our study will collect and critically review the existing science cases, identify possible technical designs and their instrument / development options, assess operational and technological ties with ALMA and explore science synergies with both ALMA and future survey missions at other wavelengths, such as Athena, the ELT, Subaru, eROSITA, the Origins Space Telescope, SPICA, and the SKA, to name a few. One possible synergy for ALMA, in particular, is to use this facility in long baseline and/or VLBI campaigns. Roughly half of the workshop will be dedicated for discussion and planning of study reports.

The workshop will take place at the ESO Headquarters in Garching (Germany) January 17-19, 2018, and is supported and coordinated by ESO, the University of Bonn, and RadioNet. This event has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730562 [RadioNet].

Workshop email: AtLAST@eso.org