CCAT-prime: a high throughput, high sensitivity telescope for star and galaxy formation and cosmology

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Representing the CCAT consortium

Who is CCAT-prime?

- Cornell University
- German consortium led by University of Cologne
  - Cologne, Bonn, Ludwig Maximilian, Max Planck Inst. for Astrophysics
    - ❖ Formed CCAT Observatory, Inc.
- Canadian consortium led by University of Waterloo
  - Waterloo, Toronto, British Columbia, Calgary, Dalhousie, McGill, McMaster, Western Ontario
    - ❖ Formed Canadian Atacama Telescope Corp (CATC)

❖ CCAT is a Joint Venture between CCAT Corp & CATC

What is CCAT-Prime?

CCAT-Prime is a high surface accuracy 6 m submm telescope

Where is CCAT-prime?

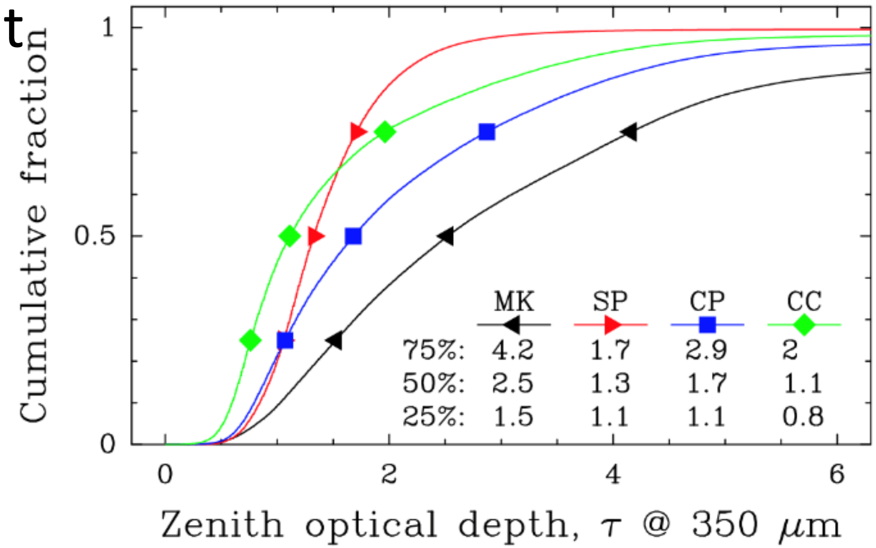
CCAT-p

6 meters? Why are we doing this?

- Unique site enables unique science
- High accuracy (< 11 μm rms), low blockage telescope (< 1%) maximizes surface brightness sensitivity
- Extraordinary throughput optimizes for science enabled by large scale surveys
- CCAT-prime paves the way for a large (25 meter) aperture at the site

5000 meter is good, but 5600 meters is better

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



Radford & Peterson, arXiv:1602.08795

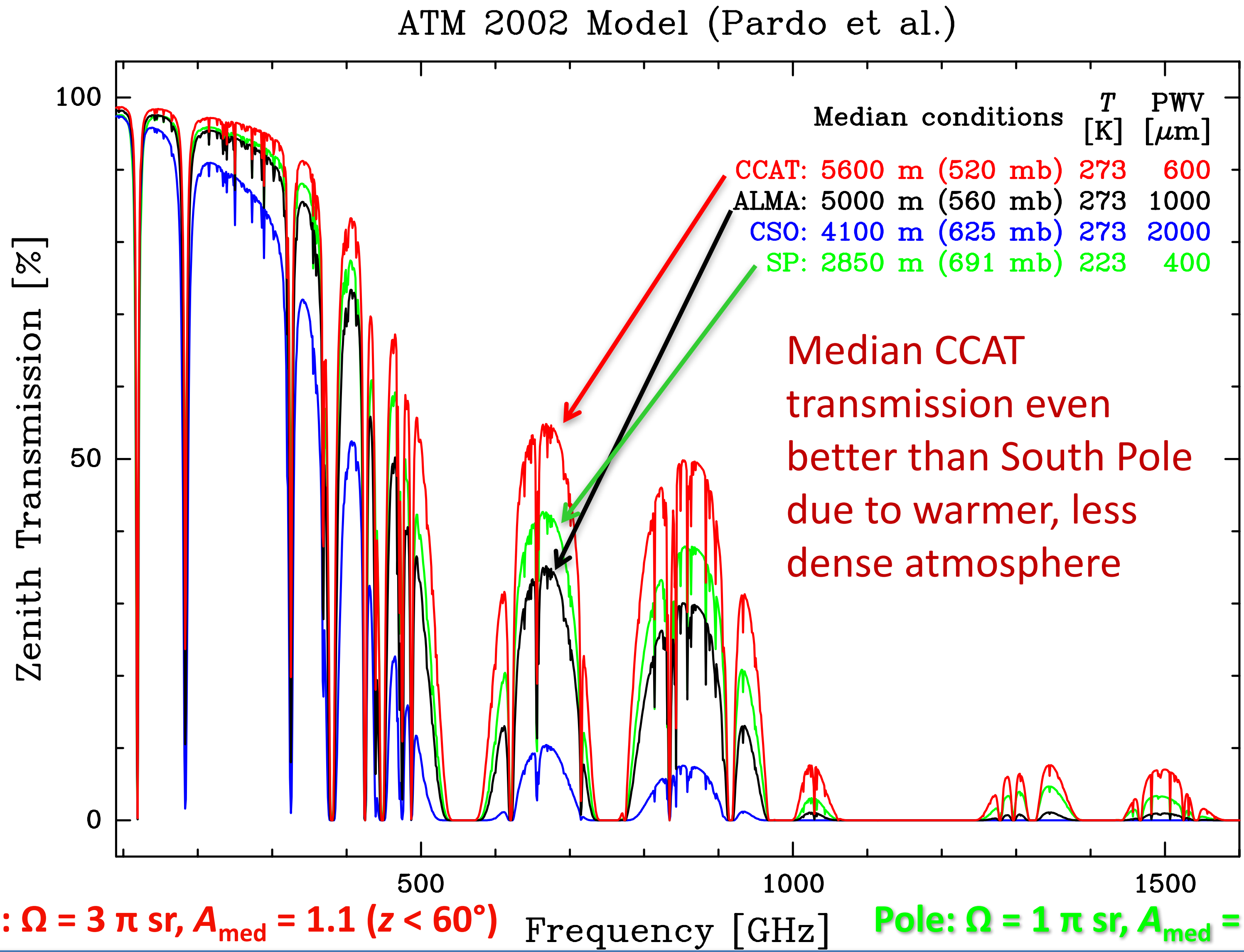
Water Vapor Scale Height

	$\tau(350\ \mu m)$ 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 $= 550\,\mathrm{m}/\ln(\mathrm{PWV_{cp}}/\mathrm{PWV_{cc}})$

Median *Zenith* Transmission

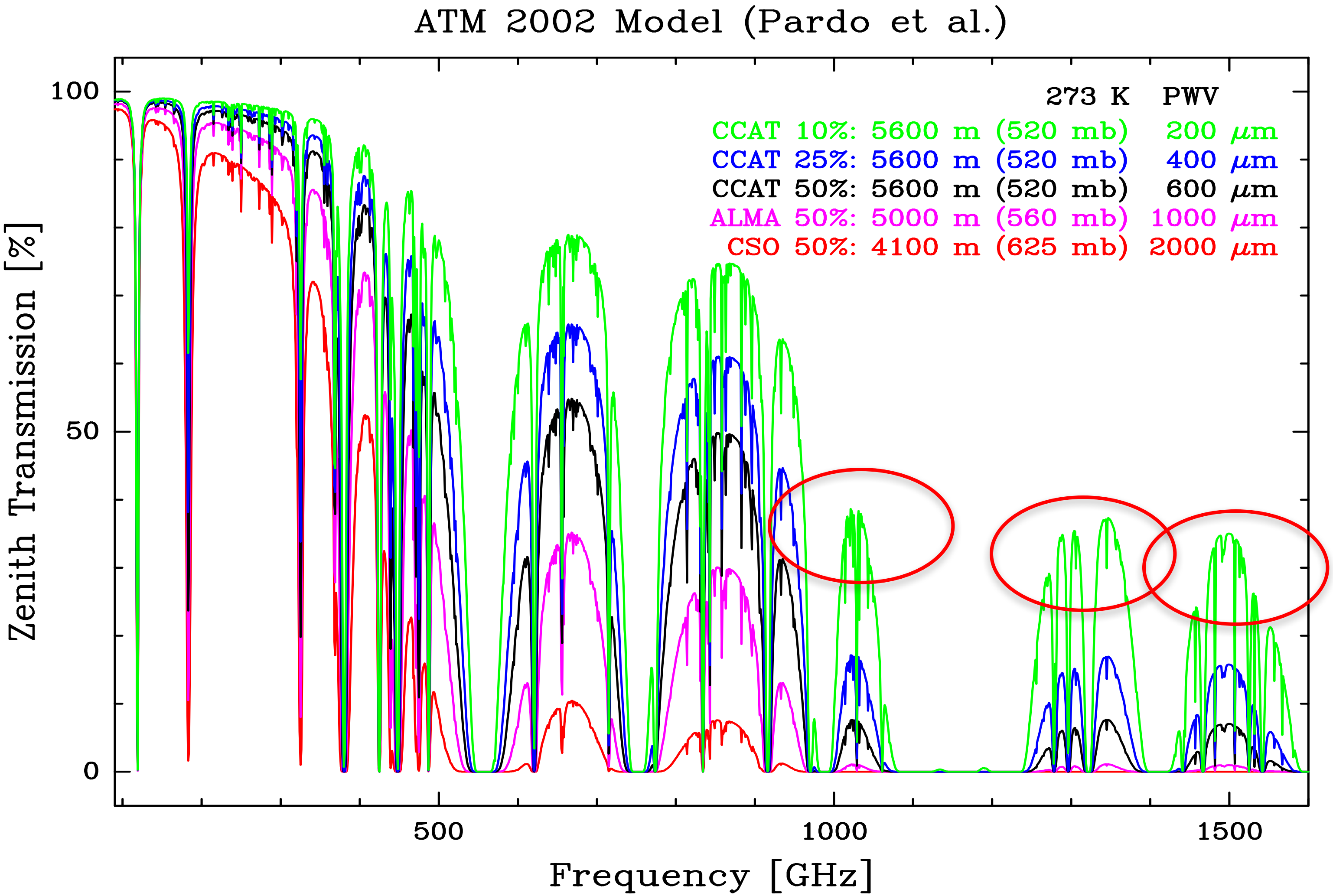
CCAT-p



Tropics: $\Omega = 3\,\pi$ sr, $A_{med} = 1.1$ ($z < 60°$)

Pole: $\Omega = 1\,\pi$ sr, $A_{med} = 1.4$ ($z < 60°$)

Chajnantor Site opens up the THz Windows



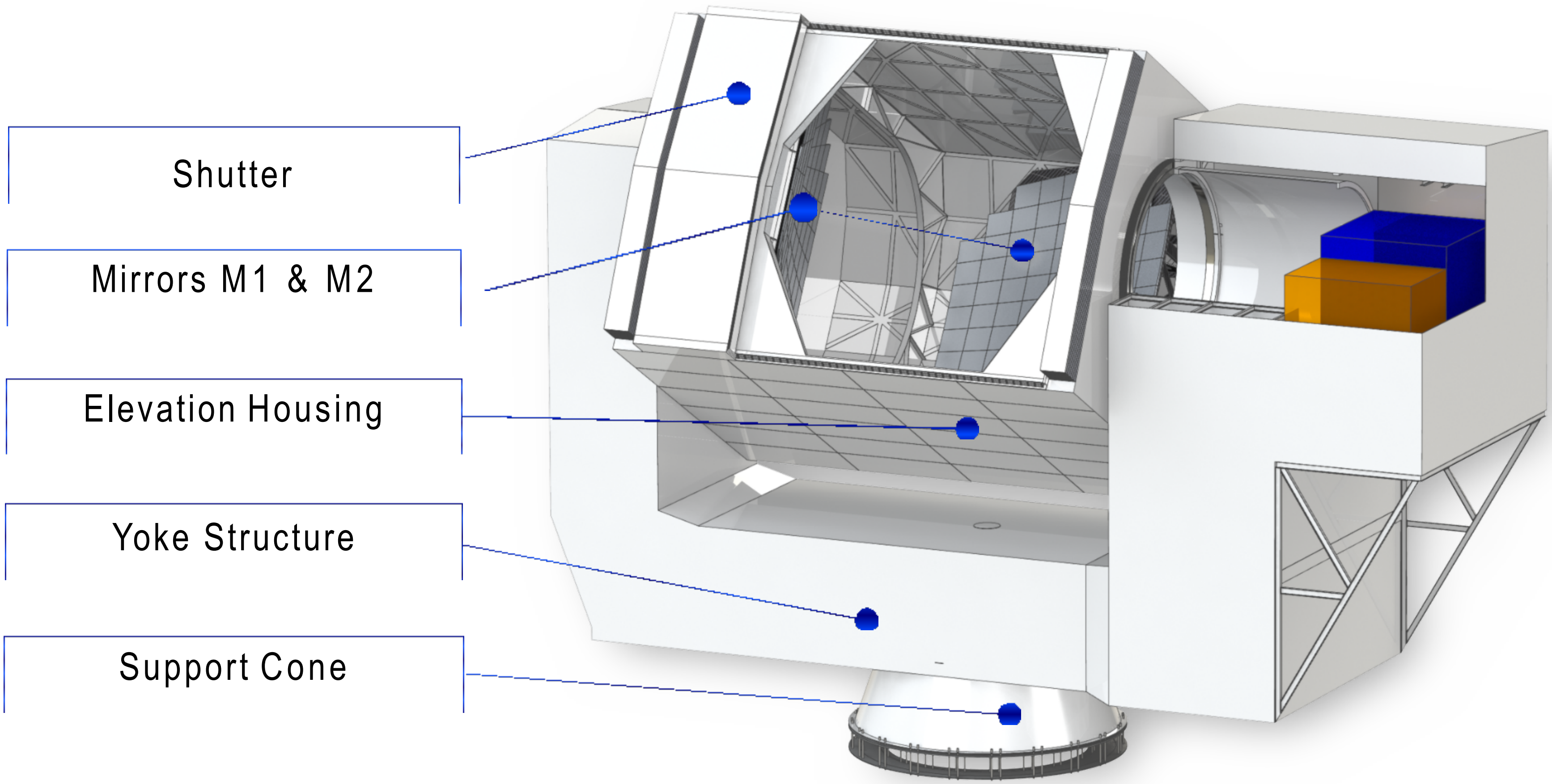
The CCAT-P Concept

6-meter off-axis submm telescope located at CCAT site at 5600 meters on Cerro Chajnantor

- Surface accuracy of <10 μm (7 μm goal)
- High site gives routine access to 350 μm, 10% best weather to 200 μm, advantage at longer λs
- Novel off-axis crossed-Dragone design yielding ⇒ wide, flat field-of-view for Galactic, Cluster, and EoR science
- Optimized throughput ⇒ platform for as Stage 4 CMB observatory
- Plan targeted "campaign-mode" science: aperture size, throughput, mapping speed, superb site

General Layout

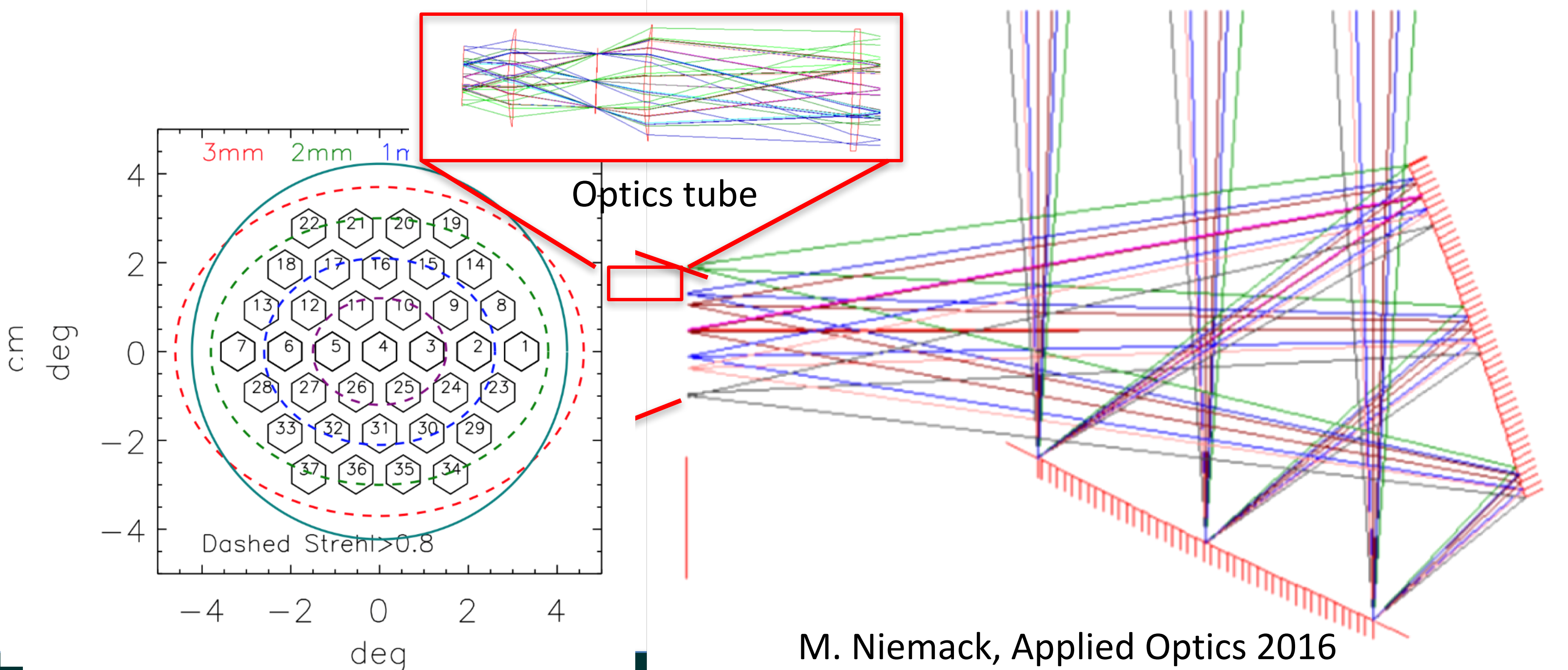
CCAT-prime



Being designed and built by Vertex Antennentechnik GmbH

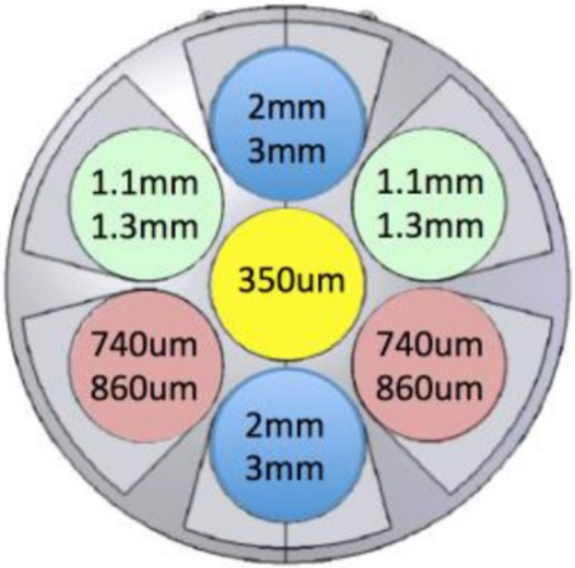
Crossed Dragone Design

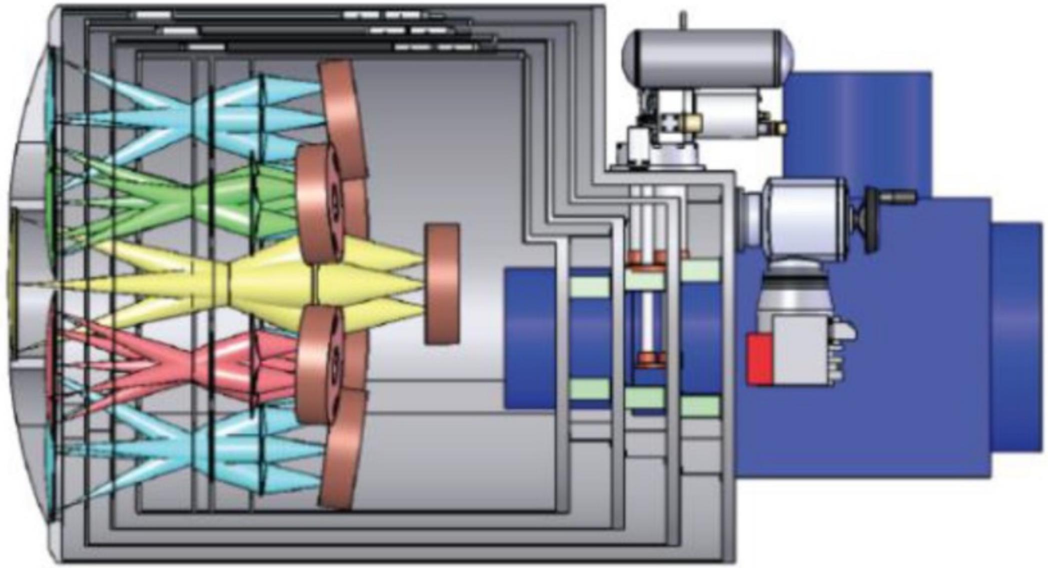
Optics tubes are mostly enclosed in Strehl>0.8 (diffraction-limited)	3 mm = 37 OT	26,000 pixels
	2 mm = 33 OT	58,000 pixels
	1 mm = 19 OT	110,000 pixels
	0.35 mm = 7 OT	400,000 pixels



M. Niemack, Applied Optics 2016

P-Cam



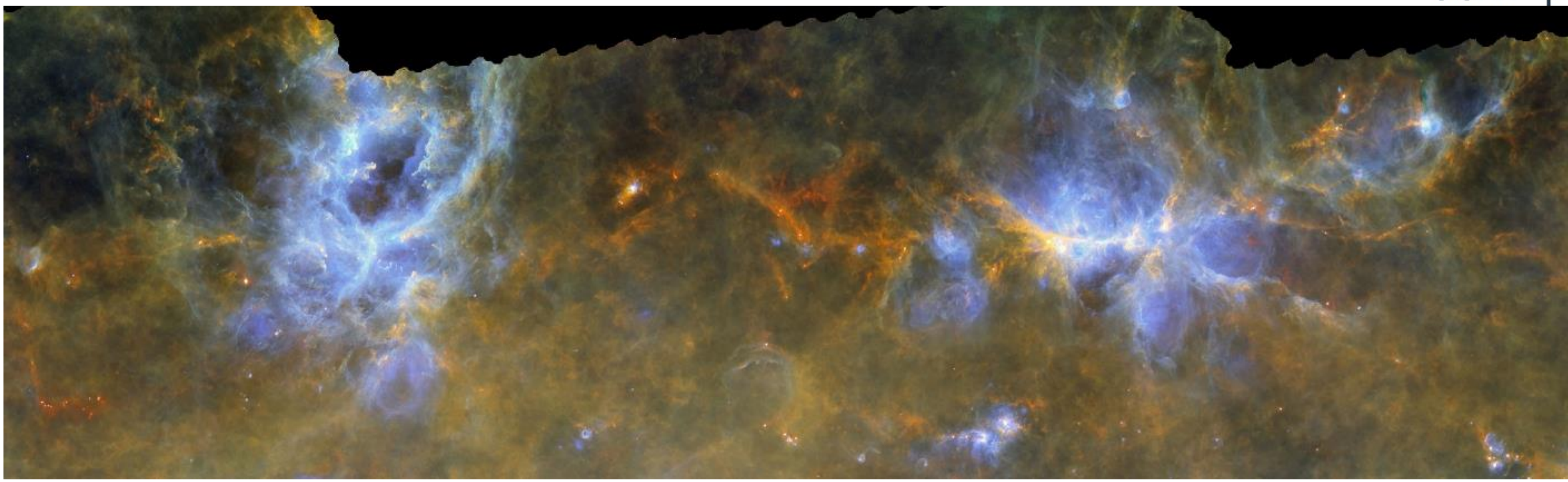


- Seven subcamera “tubes” populated with TES bolometers
- FoV ~ 0.9 degree with feedhorn fed 1.5 λ/D pixels
  - 20,000 to 60,000 pixels per subcamera @ 350 μm; numbers scale from 60,000 as $1/\lambda^2$
  - dichroic polarization sensitive bolometers at longer wavelengths
- Cameras are modular (size, 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

CCAT-Prime Science

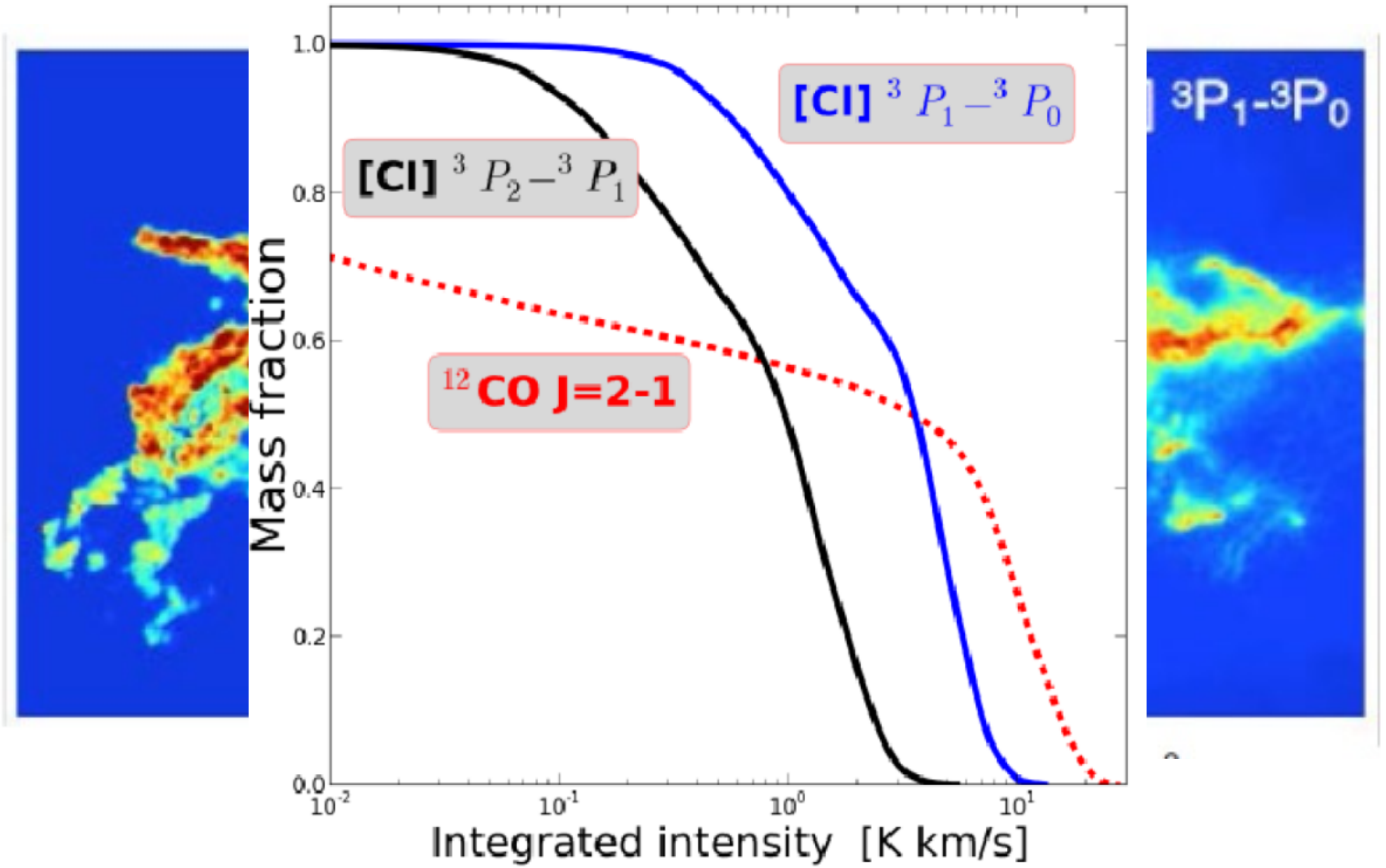
- **GEco:** Star formation in the Milky Way, the Magellanic clouds and other nearby galaxies through submm spectroscopy and photometry
- **kSZ:** Probing of the nature of dark energy, gravity on large scales and neutrino mass sum through kinetic SZ effect
  - Polarization foregrounds: Galactic dust science & CMB poln corrections
- **GEvo:** Evolution of DSFG through submm-mm wave surveys.
- **IM-EoR:** EoR intensity mapping in [CII] at redshifts from 5 to 9.
- **Stage 4 CMB:** CMBR polarization at 10 times the speed of current facilities $\Rightarrow$ inflationary gravity waves and the sum of the neutrino masses.

GEco: Galactic Ecology Science



- 15” imaging over 200 $(^\circ)^2$ scales of the Milky Way, LMC, SMC in:
  - [CI] tracing gas temperature and mass
  - Mid and high-J CO & ^{13}CO tracing gas excitation, shocks, density and mass
  - Also: [NII] tracing embedded SF regions and numbers of ionizing photons
- Tracing accumulation and flows of gas into cores and young stars
- Requires high site for short submm (200 μm, or 1.5 THz) studies

“CO dark” Gas



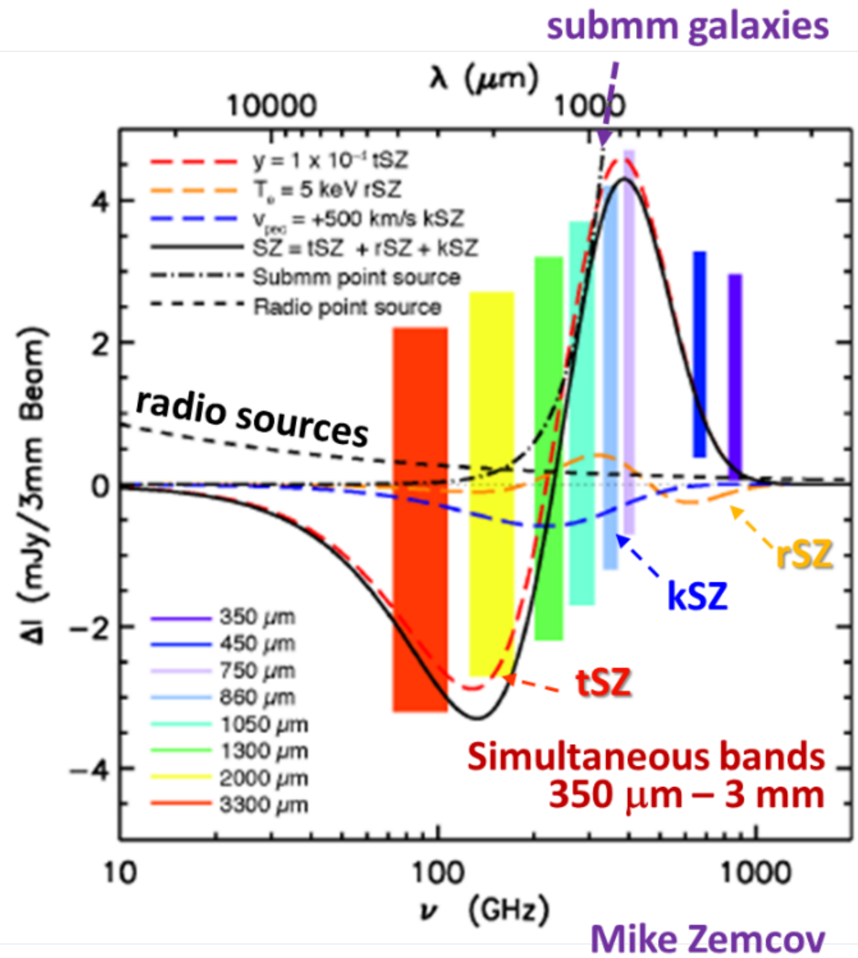
Mass fraction
1.0
0.8
0.6
0.4
0.2
0.0
10^{-2}
10^{-1}
10^{0}
10^{1}
Integrated intensity [K km/s]
[CI] $^3P_1-^3P_0$
[CI] $^3P_2-^3P_1$
^{12}CO J=2-1
$^3P_1$-$^3P_0$

kSZ: Cluster Science through the Sunyaev-Zel’dovich Effects

CCAT-p

Direct observations of the most massive bound entities in the Universe through Sunyaev-Zel’dovich effects

- **7 colors:** 0.35 to 3 mm spectral coverage separates out the **tSZ**, **rSZ,** radio galaxies and submm galaxies from **kSZ**
- **Constraints:** optical depth, velocity, and electron temperature



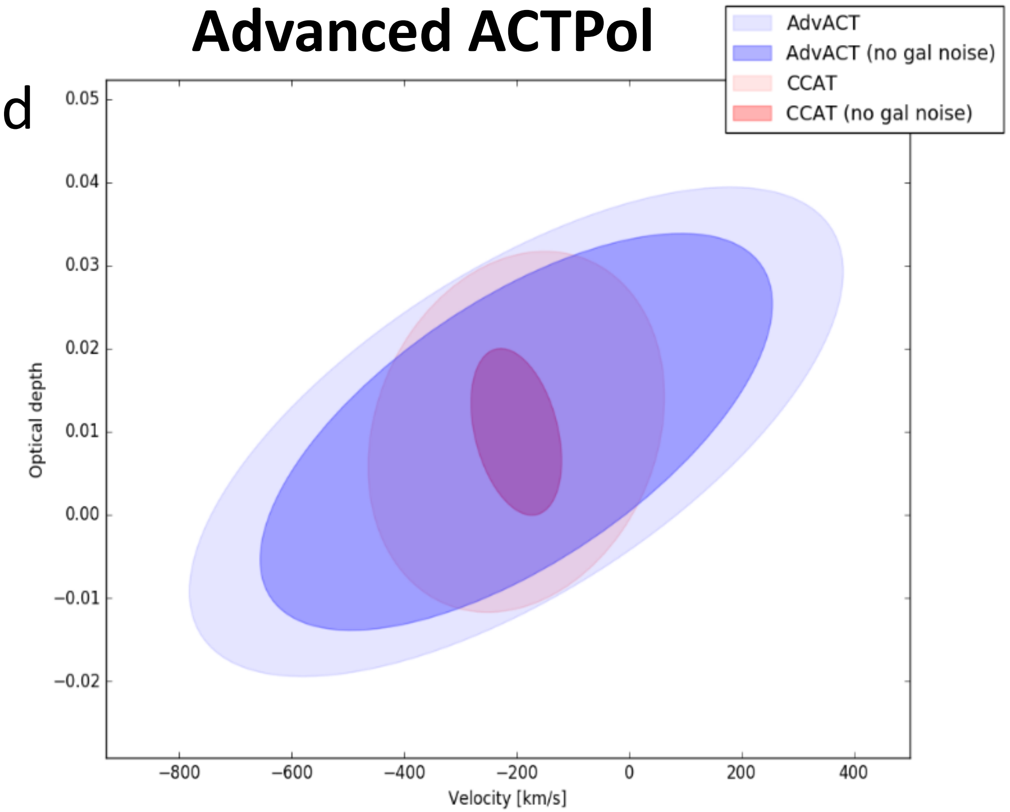
Fundamental Physics Probes

CCAT-p

Directly measure velocities of 1000's of clusters

- **Constrains and/or eliminate models** about dark energy and modified gravity.
- **Improve constraints** on the measurements of the sum of the neutrino masses.
- **Cluster characterization** to inform cosmology
- **Example Survey** 1000 $(°)^2$ measuring 3000 clusters with $M > 2.7 \times 10^{14}\ M_{\odot}$ in 3000 hrs

CCAT-prime velocities appear much better than Advanced ACTPol



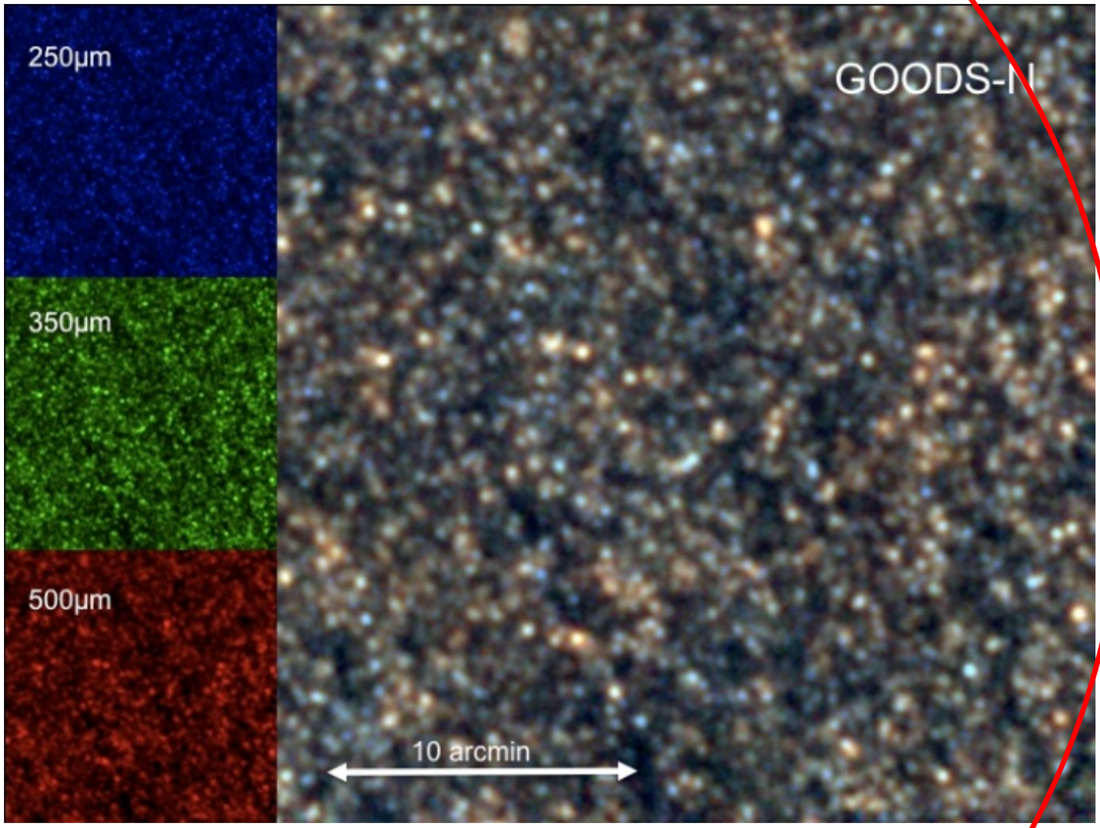
F. de Bernardis and A. Mittal

Obscured SF over Cosmic Time

- CCAT-p aperture lowers 3.5m Herschel confusion limits
- Herschel surveys limited to ~ 6.3 mJy (1σ) confusion limit
- 5.5 m CCAT-p goes a factor of ~ 2.6 deeper into the confusion
  - 2.4 mJy (1σ) in 3 hrs @350 μm
- One camera, using best 50% weather→ $100^{(\circ)2}$ (or 300 $^{(\circ)2}$!) survey @ 350 μm) per year
- Pushes down the luminosity function in the most active epoch star formation in the Universe

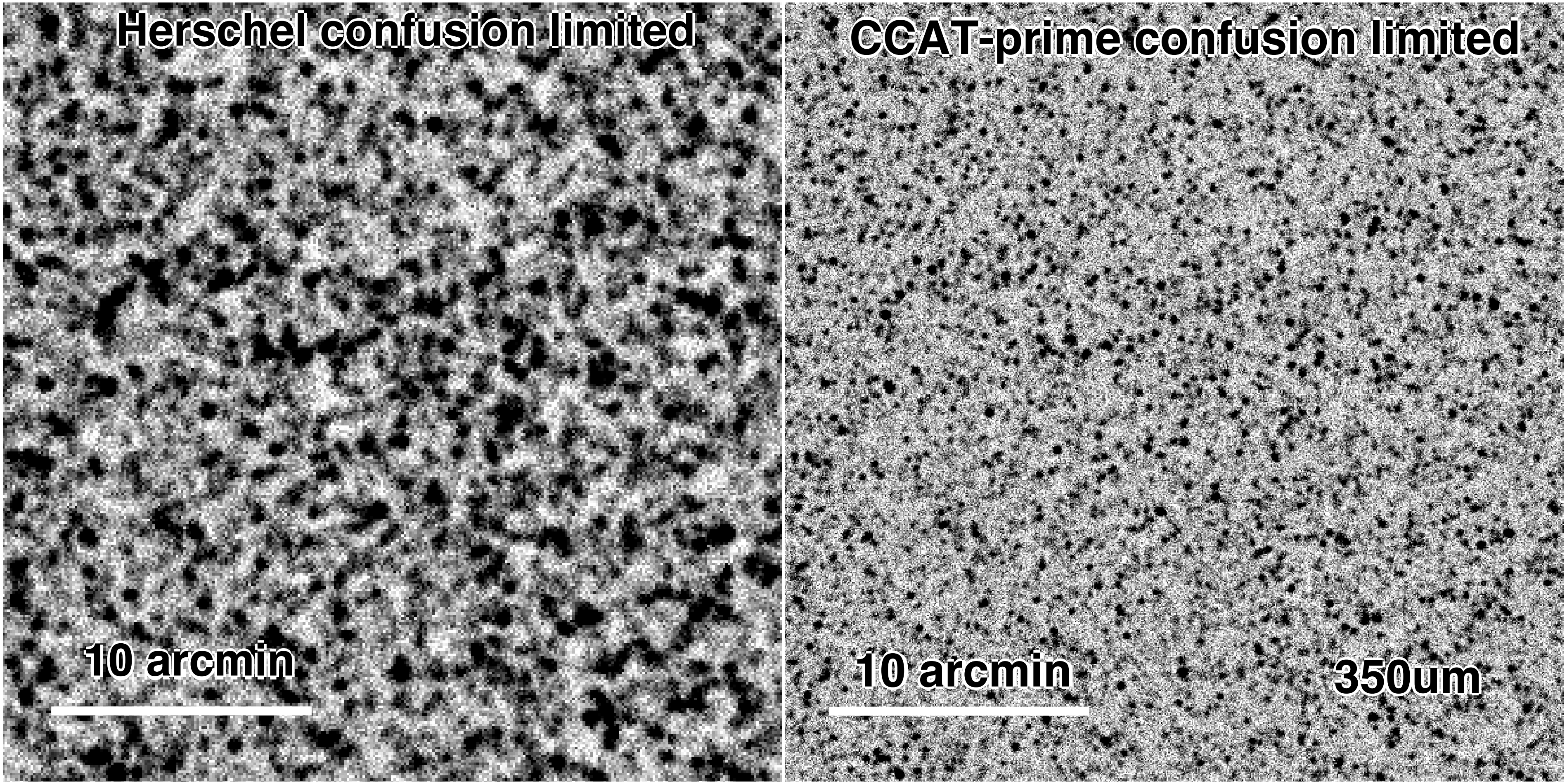
P-Cam 350 um pixel

P-Cam Subcamera FoV = 0.9°



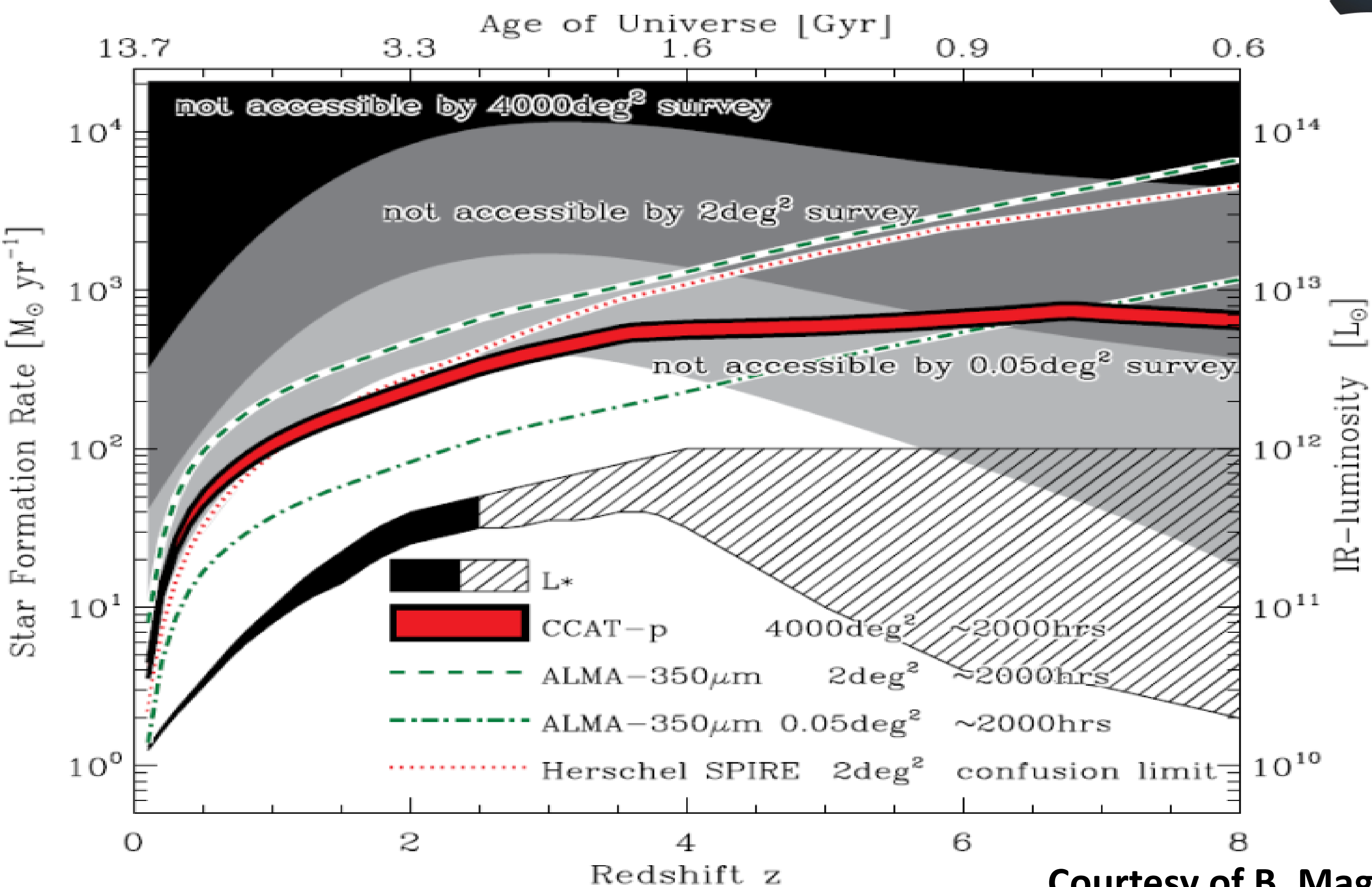
HerMES Lockman Hole North; Oliver et al. (2010, 2011)

CCAT-prime and Herschel



Courtesy of B. Magnelli

CCAT-p Explores FIR Luminosity Function



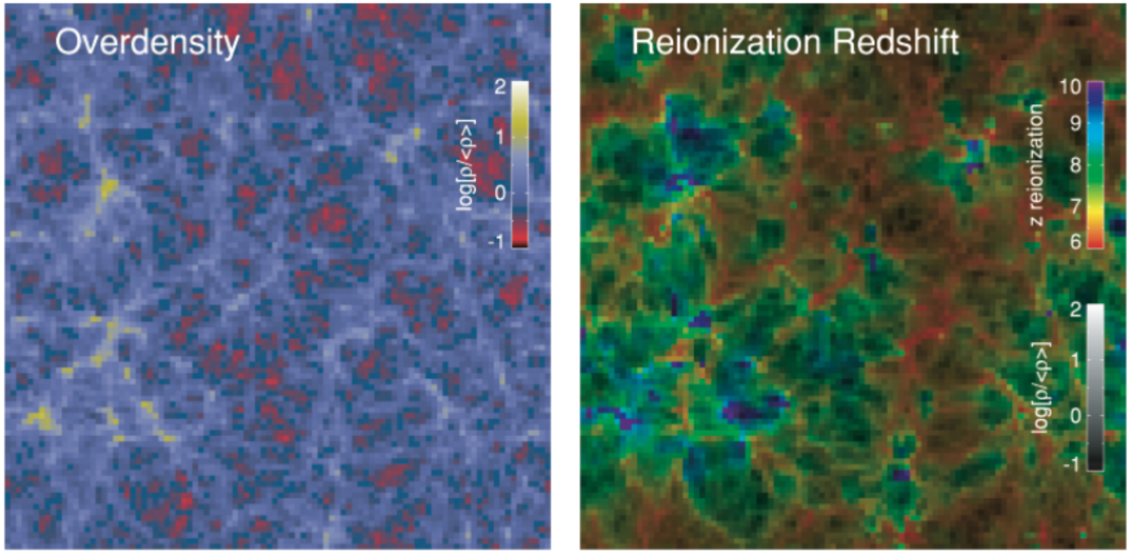
Courtesy of B. Magnelli

EoR-IM: Intensity Mapping of [CII] in the Epoch of Reionization

CCAT-p

- Aggregate [CII] signal from star forming galaxies at z ~ 5 to 9 $\Rightarrow$ 3-D information:
  - Reveals the ***process of reionization*** and the ***underlying dark matter distribution over the cosmic time when the first galaxies formed***
- Combine with SKA 21 cm HI line tracing neutral ISM concentrations

Simulating Reionization



(a) Overdensity $\rho/\bar{\rho}$ at $z = 6.49$.

(b) Redshift of reionization, defined as the redshift at which the hydrogen neutral fraction first dips below 10^{-3}.

Reionization appears not to occur instantaneously, but rather depends on local density (see Finlator et al. 2009). First things to reionize are overdense regions, then voids, then moderate-density structures.

Intensity Mapping of [CII] from the EOR

CCAT-p

- Measure large scale spatial fluctuations of collective aggregate of faint galaxies via redshifted [CII] 158 μm line (+possibly other lines at other z's)
  - Resolution into individual galaxies not required
    - Clustering scale 0.5 to 1 Mpc or ~1-2' at z = 5-9, - good match for 6-m aperture (40"@ 1mm)
    - $16^{\circ 2}$ surveys: spectral/spatial mapping speed critical
    - FoV ~ > 1° matches 40 Mpc void size-scale: systematics
    - Need moderate spectral resolution R ~ 300-500
  - Bandwidth of z ~ 5-9 signal is 0.95-1.6 mm (190-315 GHz)
    - Identify interloper lower z CO by line multiplicity – complete at z > 0.8
    - Sensitivity is at a premium: high site, very low emissivity telescope is essential!

Prediction of the [CII] Signal Strength

Gong et al 2012

CCAT-p

TABLE 1
EXPERIMENTAL PARAMETERS FOR A POSSIBLE CII MAPPING INSTRUMENT.

Aperture diameter (m)	1	3	10
Survey Area (A_S; deg^2)	16	16	16
Total integration time (hours)	4000	4000	4000
Free spectr	[illegible]	[illegible]	185−310
Freq. resol	[illegible]	[illegible]	0.4
Number of bolometers	20,000	20,000	20,000
Number of spectral channels	312	312	312
Number of spatial pixels	64	64	64
Beam size[a] ($\theta_{\rm beam}$; FWHM, arcmin)	4.4	1.5	0.4
Beams per survey area[a]	2.6×10^3	2.3×10^4	2.6×10^5
$\sigma_{\rm pix}$: Noise per detector sensitivity[a] (Jy$\sqrt{\rm s}$/sr)	2.5×10^6	2.5×10^6	2.5×10^6
$t^{\rm obs}_{\rm pix}$: Integration time per beam[a] (hours)	100	11	1.0
$z = 6$ $V_{\rm pix}$ (Mpc/h)^3	217.1	24.1	2.2
$z = 7$ $V_{\rm pix}$ (Mpc/h)^3	332.9	37.0	3.3
$z = 8$ $V_{\rm pix}$ (Mpc/h)^3	481.3	53.5	4.8
$z = 6$ $P^{\rm CII}_N$ (Jy/sr)^2 (Mpc/h)^3	5.4×10^9	5.4×10^9	5.3×10^9
$z = 7$ $P^{\rm CII}_N$ (Jy/sr)^2 (Mpc/h)^3	4.8×10^9	4.9×10^9	4.8×10^9
$z = 8$ $P^{\rm CII}_N$ (Jy/sr)^2 (Mpc/h)^3	4.4×10^9	4.4×10^9	4.3×10^9

[a] values computed at 238 GHz, corresponding to CII at $z = 7$.

Noise requirement = 8×10^{-14} W/m^2/sr

RP = 500

Large BW × FoV Spectrometer

CCAT-p

- Trans-mm wave from ~ 0.95 to 1.6 mm (315-188 GHz)
- Direct detection for optimal sensitivity
- Resolving power requirement is modest, ~ 500 or 600 km/sec
- Need a spectral × spatial product > 20,000 to complete a $16^{\circ 2}$ survey in 4000 hours.
- Spectrometer extremes:
  - 312 spectral positions, 64 spatial positions w/ grating
  - 1 spectral sample, 20,000 spatial positions w/ FPI

EoR IM Science Program

- The spectral multiplexer is challenging at present
- The spatial multiplexer is very straight-forward
- Requiremen ...000 hours

Predictions: 9 ... es of weather:

Using 3.2 car ... to 1.1 and 1.4 mm wavel... ^{2} field to the required a... W/m^2/sr in

One third (or even 1/6th) the number of pixels of grating because we accepted 4 spatial modes

4000 hours integration time

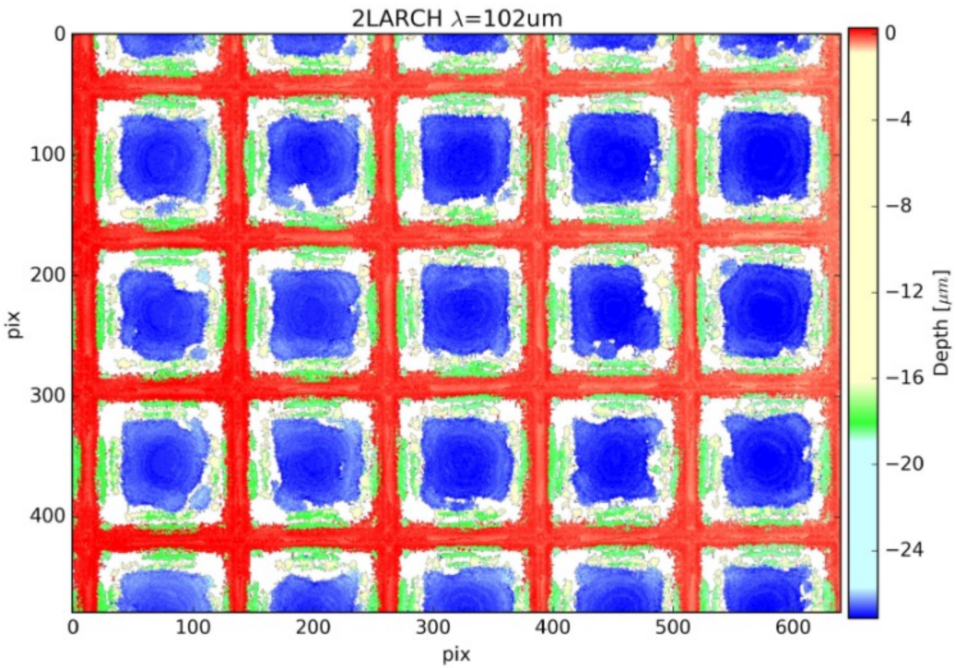
Total number of pixels: 3.2 × 1050 (dichroic) or 6.4 × 1050 single color

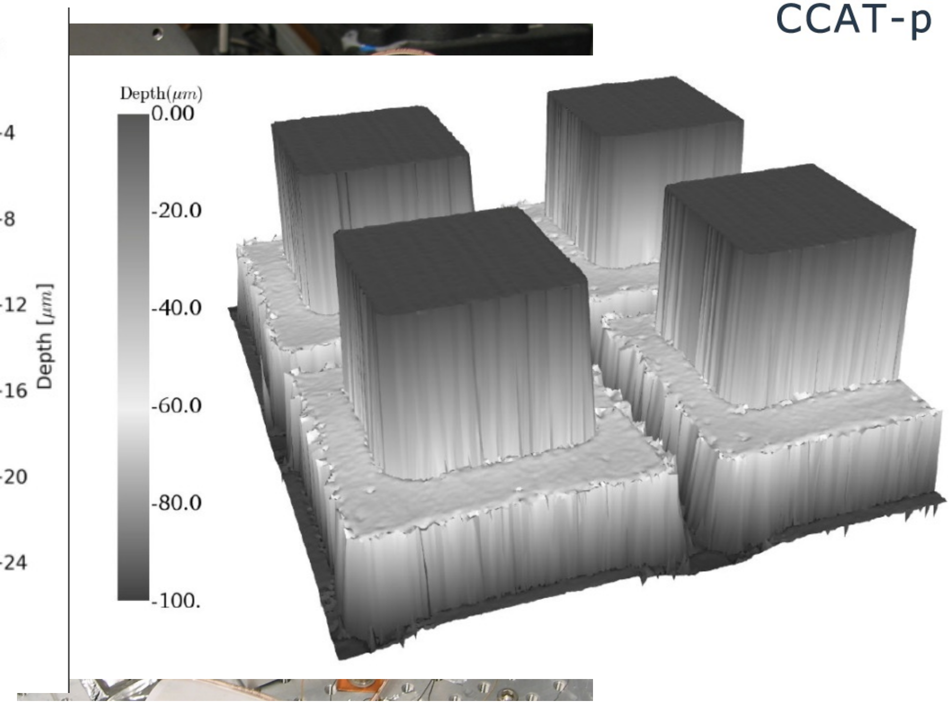
A Tough Experiment!

- The zenith transmission is:
  - 97.9 to 96.6% at our site
  - 96.9 and 95.1% at ALMA site
- Telescope emissivity is 2%
  - Going off-axis makes a difference!
- System emissivity is ~ 5.9%
  - Going to 5600 m makes a difference!
    - Would need 4.1 compared with 3.2 tubes
  - Window emissivity makes a difference (2%)
- Spectrometer transmission is 40% including DQE of 80%

Note that the same stringent requirements hold for the grating spectrometer

Fabry-Perots in Development





R = 10^6 FPI at 112 um for HIRMES on SOFIA

- These are based on free-standing metal mesh
- Developing silicon substrate-based FPI:
  - Silicon AR coatings (dual layer) with microstructures
  - Metalized (superconducting) broad-band reflectors
-

Comparisons to other Coeval Facilities

CCAT-p

- **EoR IM:** surface brightness: WFE, emissivity, site, and FoV:
  - Sensitivity (Jy/beam) $\propto$
    - 1/Ruze Efficiency
    - ~ (System Emissivity)$^{1/2}$ – telescope, warm optics and sky
    - 1/(warm transmission) – includes telescope efficiency, sky transparency
  - Mapping Speed $\propto$
    - (Sensitivity referred to EOR beam)^2
    - Field of view accepted/field of view of P-Cam subcamera

Teles.	WFE (rms), Ruze eff.	Med. PWV	η_{sky} (245 GHz)	tel. emis.	Raw Sens.[2]	P-Cam FoV	FoV (dia.)	Mapping Speed
APEX	17 μm, 97%	1.0	0.945	10%	0.86	24.8’	11.4’	1/16
JCMT	25 μm, 93%	2.0	0.901	10%	0.93	19.8’	9.0’	1/28
LMT	70 μm, 58%	2.0[1]	0.901	15%	0.51	5.9’	8.0’	1/77
CCAT-p	10.5 μm, 99%	0.60	0.962	2.8%	1	54’	143	1→7

[1]This weather is only 4 months/year; [2]Refers to a 65” beam and source elevation of 50°

Comparisons to other Coeval Facilities

CCAT-p

- **kSZ; GEvo:** short submm bands: WFE, emissivity, site, and FoV:

Point source foregrounds

Teles.	WFE (rms), Ruze eff.	1st Q PWV	η_{sky} (860 GHz)	tel. emis.	Raw Sens.[2]	P-Cam FoV	FoV (dia.)	Mapping Speed
APEX	17 μm, 69%	0.6	0.25	10%	0.54	24.8’	11.4’	1/1.4[3]-1/5.9[4]
JCMT	25 μm, 44%	1.0	0.12	10%	1.31	19.8’	9.0’	1/8.3[3]-1/56[4]
LMT	50 μm, 4%	1.0[1]	0.12	15%	1.47	5.9’	8.0’	1/8.6[3]-1/640[4]
CCAT-p	10.5 μm, 87%	0.4	0.39	2.8%	1	54’		1→7

[1]This weather is only 4 months/yr; [2] *Point source –* el. = 50°; [3]beams, [4]areal coverage

1’-scale kSZ Science

Teles.	WFE (rms), Ruze eff.	Med. PWV	η_{sky} (245 GHz)	tel. emis.	Raw Sens.[2]	P-Cam FoV	FoV (dia.)	Mapping Speed
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Schedule

Four (4) year project (July 2017 to June 2021)

- 20 months Detailed Design [PDR @ 4 mths; CDR @ 10 months, FDR @ 18 months.]
- 13 months Fabrication which includes a Trial Assembly in Germany
- 3 months Shipping & Receiving
- 12 months Assembly/Checkout
  - Incl. 3 months unpacking/inspection and sequenced transport to Summit

CCAT-p