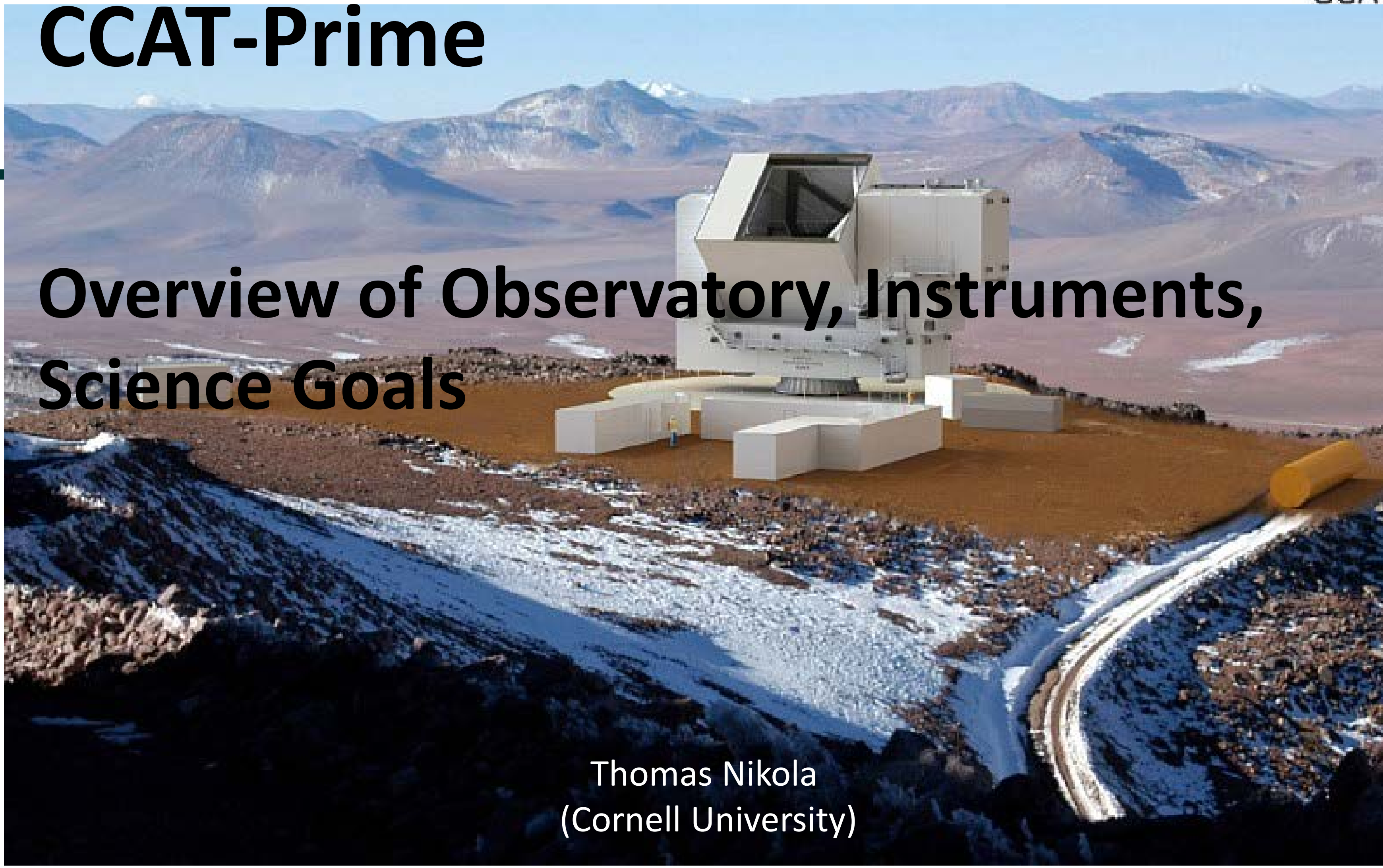
CCAT-Prime



Overview of Observatory, Instruments, Science Goals

Thomas Nikola
(Cornell University)

- Following slides and information was mostly taken from a recent “remote” CCAT-prime workshop hosted by Mike Fich in Waterloo.

CCAT Partnership

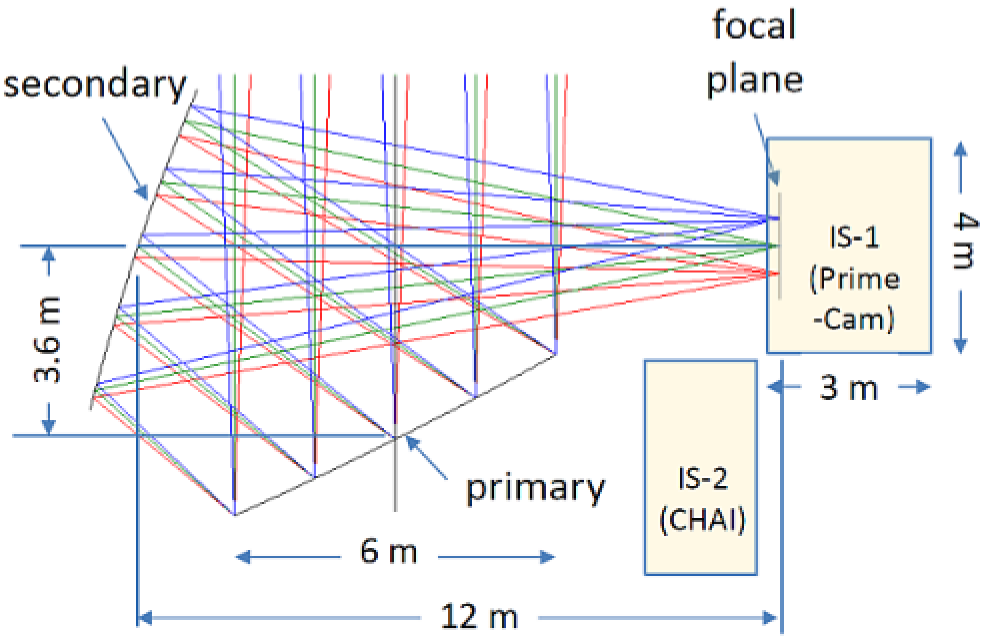
- CCAT Observatory, Inc.
  - Cornell University
  - German consortium led by University of Cologne
    - Cologne, Bonn, Max Planck Inst. for Astrophysics
  - CATC, membership in CCAT Observatory, Inc through Venture Agreement
- CATC (Canadian Atacama Telescope Corp.)
  - Canadian consortium led by University of Waterloo
  - Waterloo, Toronto, British Columbia, Calgary, Dalhousie, McGill, McMaster, Western Ontario
  - CATC "Observers"/partners: St. Mary's, Manitoba, Lethbridge, Alberta, National Research Council
- TAO – Tokyo Atacama Observatory
  - Share mountain top – constructing road
  - Draft agreement to share common costs (road maintenance, power, …)

Project Personnel

- Director
  - Terry Herter
- Project Manager
  - Jim Blair
- Project Engineer
  - Steve Parshley
- Deputy Project Engineer
  - Ronan Higgins
- Software Manager
  - Mike Nolta
- Power Consultant
  - John Kiefer
- Construction Manager & TAO Liaison
  - Pedro Correa
- Project Scientist
  - Gordon Stacey
- CHAI Instrument Scientist
  - Urs Graf
- Prime-Cam Instrument Scientist & Simons Observatory Liaison
  - Mike Niemack

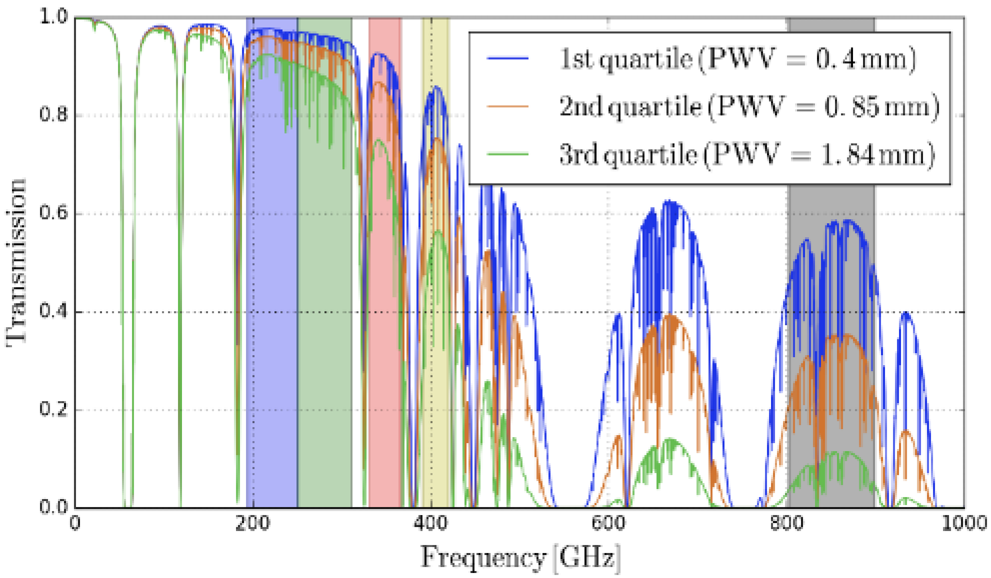
CCAT-Prime Telescope

- Aperture: 6 m
- Optimized for submillimeter/millimeter wavelengths
- Coma-corrected, cross-Dragone telescope design
- Surface half-wavefront error: <11 μm
- Low emissivity optical design: <2.8% (goal <1%)
- Large field of view
  - ~7.3° x 6.5° at 3 mm
  - ~2.5° x 2° at 350 μm
- Pointing Error: <1.4"
- Scan Speed:
  - $> 0.33° \, s^{-1} \cdot (\lambda / 350 \mu m)$ (in azimuth; half in elevation)



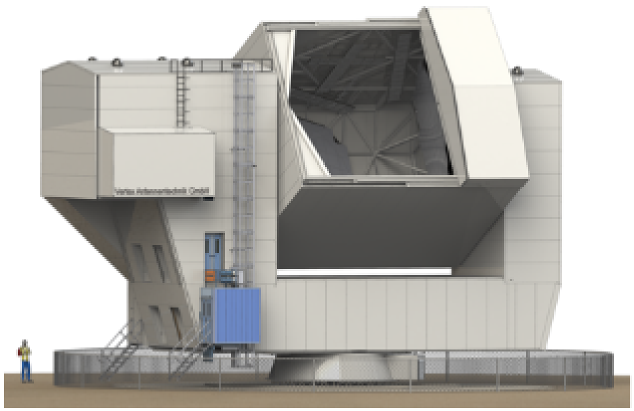
CCAT-prime Site

- Location:
  - Cerro Chajnantor
  - 5600 m
  - Above ALMA plateau

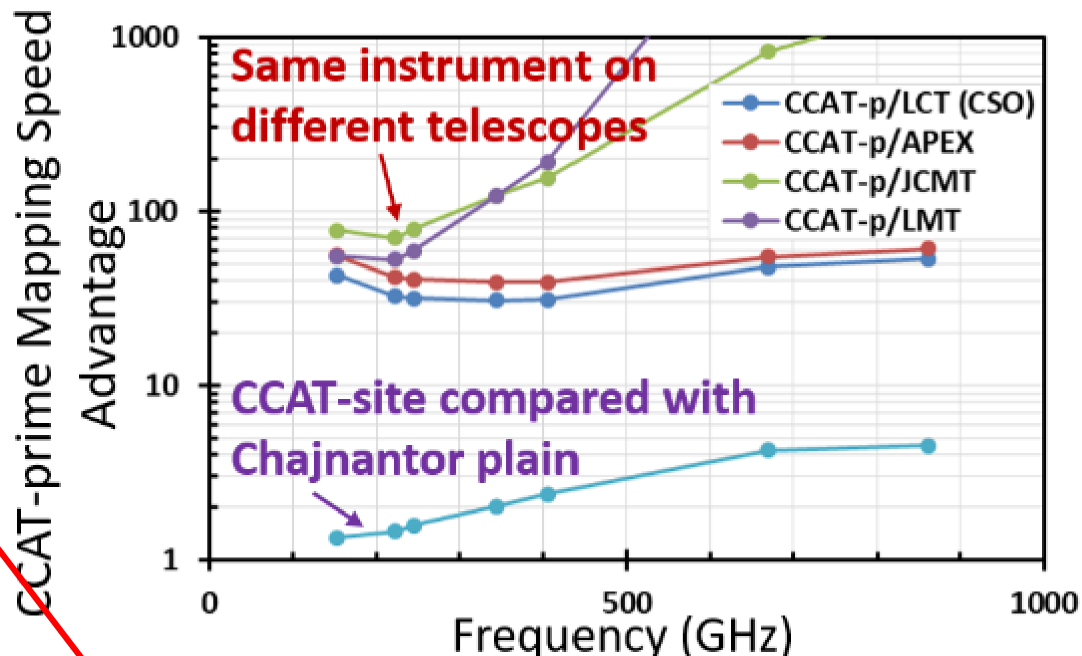


CCAT-prime Site

- The extra ~600 m above ALMA plateau make a big difference

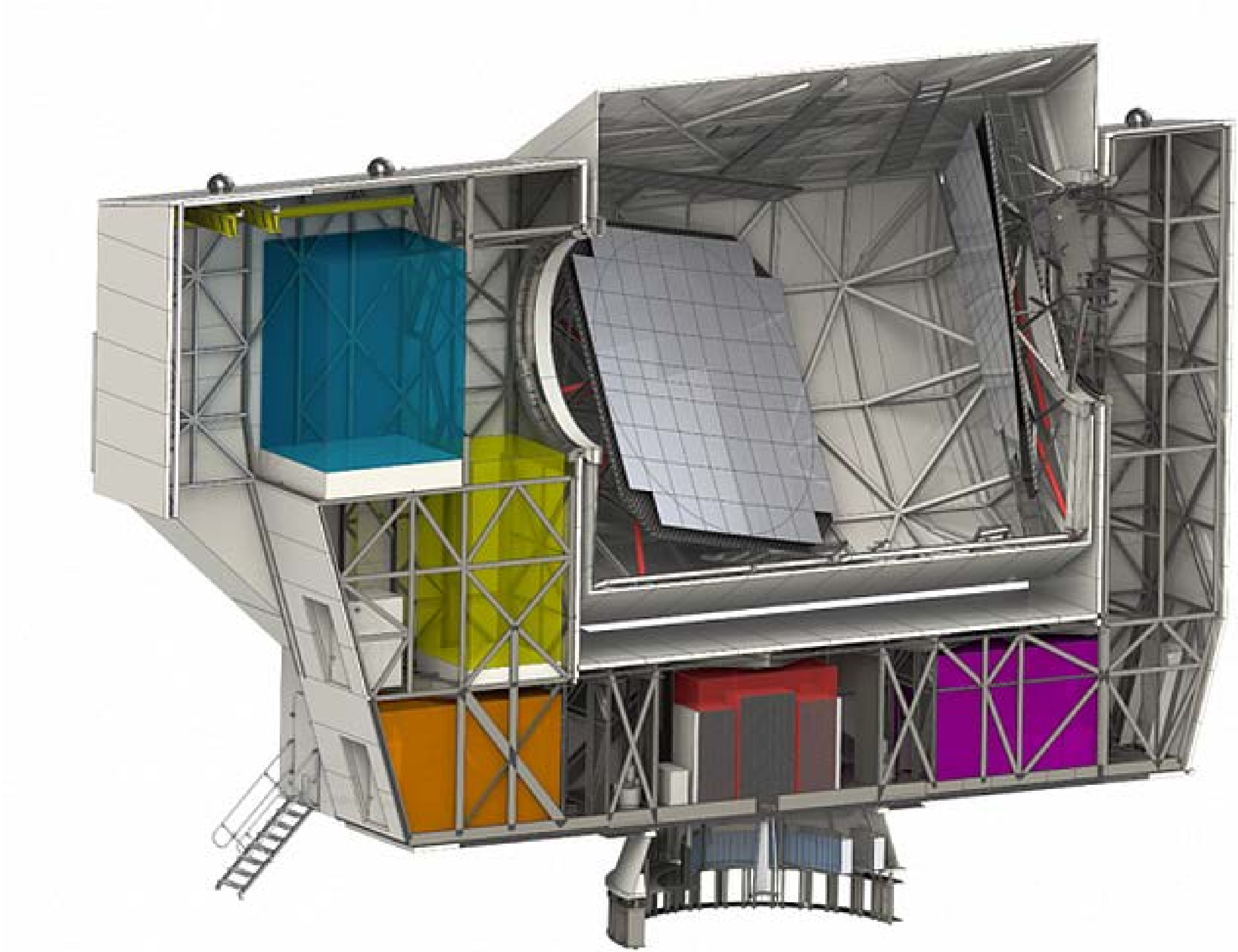


Telescope	pwv(mm)	wfe (μm)	ε_{tel}	FoV (dia.)
CCAT-p: 6 m	0.28; 0.60	10.7	2.8%	78′
LCT (CSO): 10.4	0.53; 1.0	13	10%	15′
APEX: 12 m	0.53: 1.0	11	10%	11.4′
JCMT: 15 m	1.0; 2.0	25	10%	9.0′
LMT: 50 m	1.0: 2.0	50	15%	8.0′

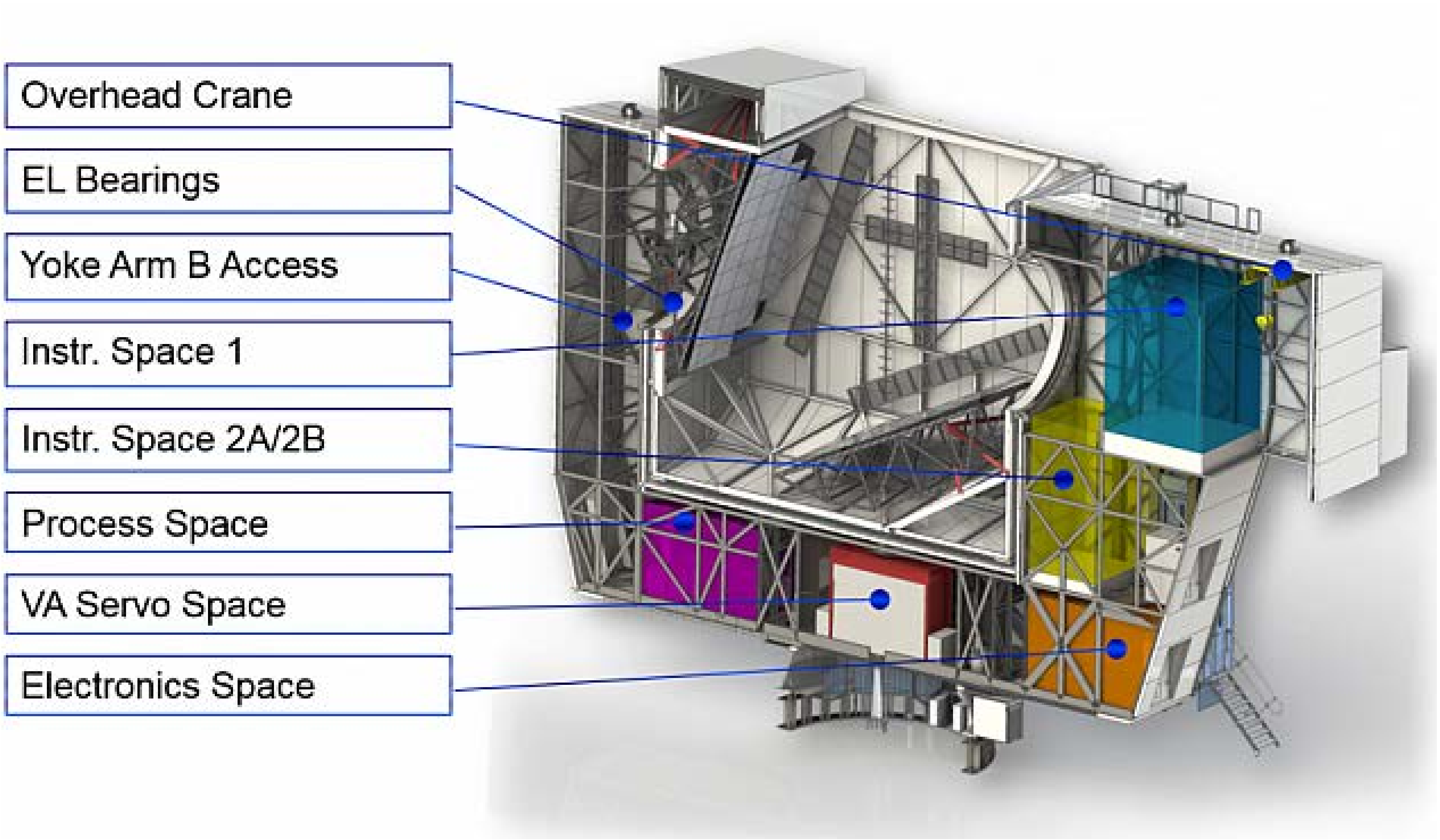


Single Prime-Cam
Instrument Module (1/7)

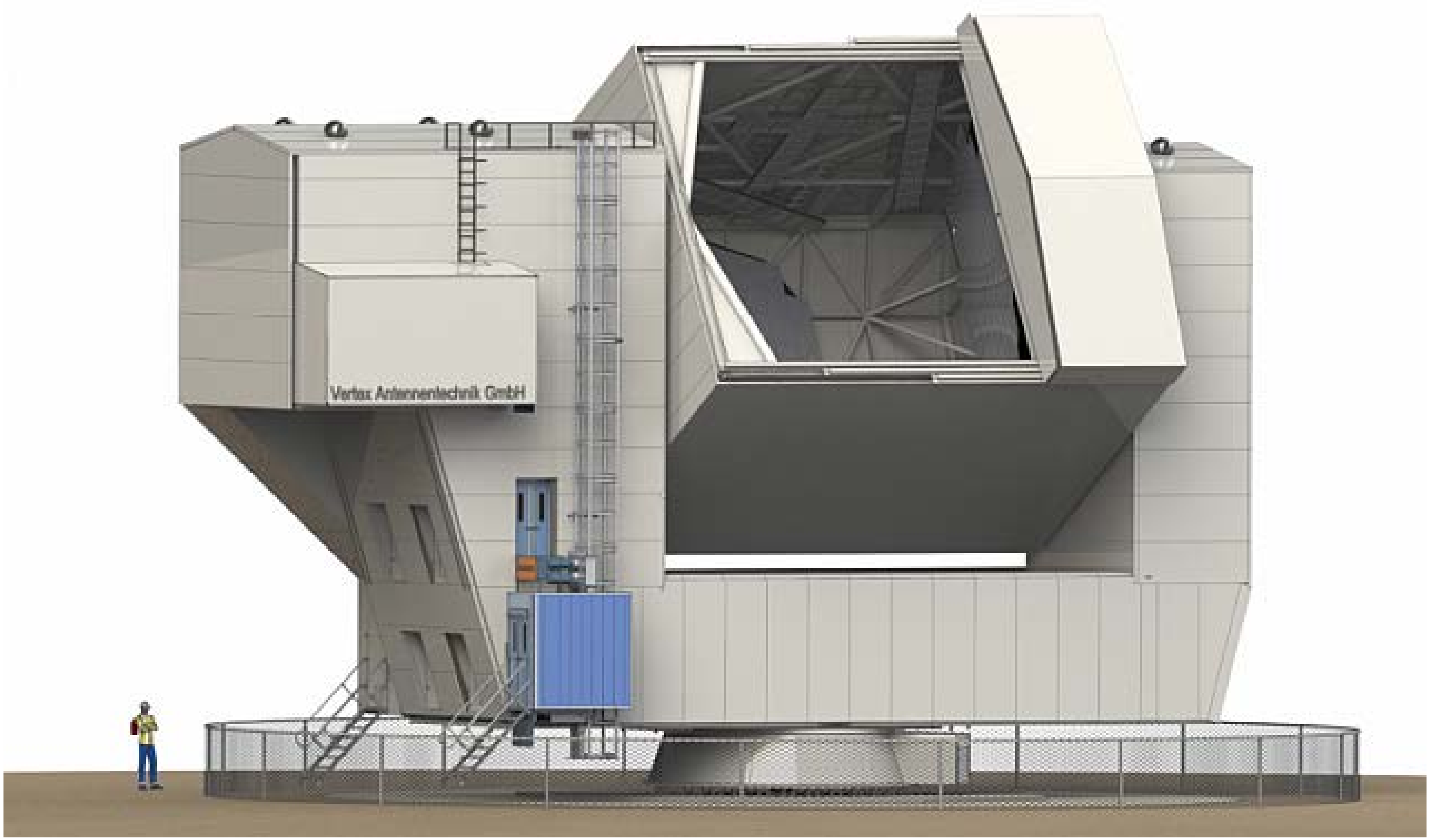
CCAT-prime Observatory



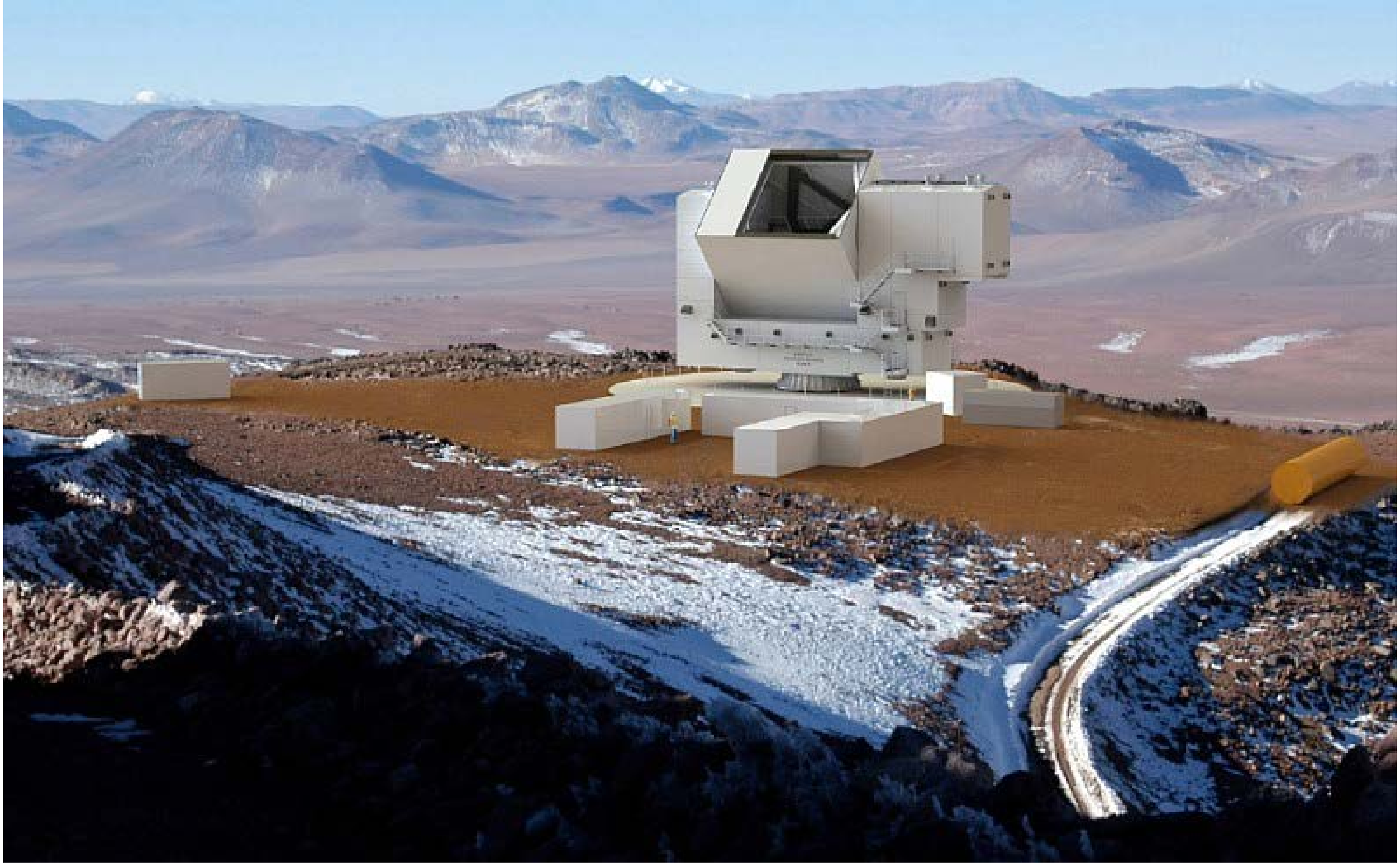
CCAT-prime Observatory



CCAT-prime Observatory



CCAT-prime Observatory



CCAT-prime Observatory

CCAT-p

- Telescope is fully funded
  - Mostly by private donor, but also University funds
- Prime-Cam Instrument:
  - Cryostat & some closed cycle cooling systems are also funded by University and start-up funds
  - Seeking funds for detectors and individual instrument modules
- Construction has started
- First light expected end of 2021/start of 2022

CCAT-prime Construction

Base-ring for telescope

Preparation of site for test-assembly in Germany 2020

Telescope Site: Road construction

Telescope Site: Road construction

CCAT-p

Science goals

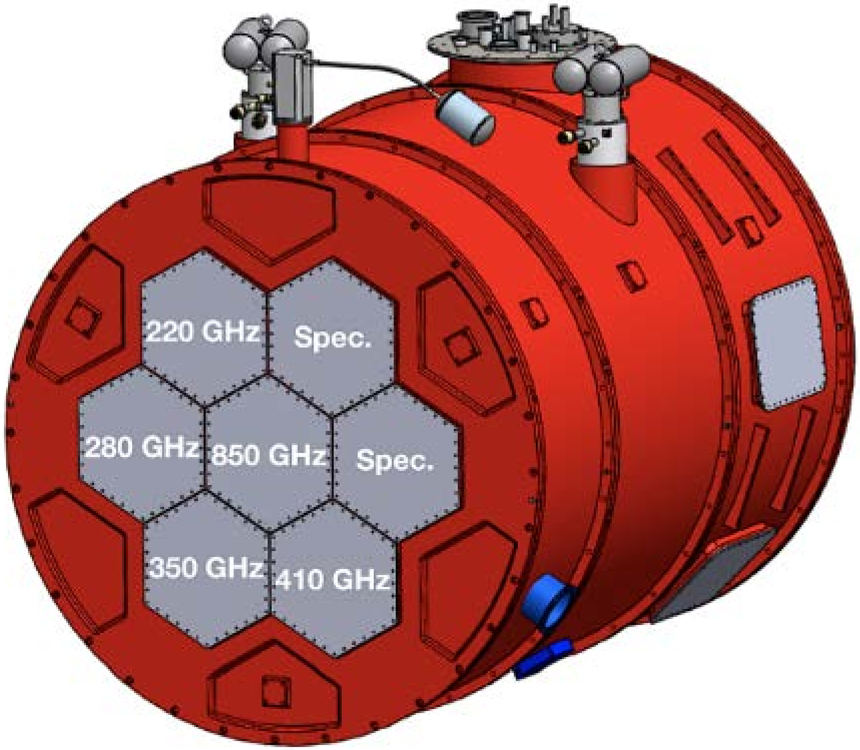
- Probing the Epoch of Reionization (EoR) using redshifted [CII] 158 μm line emission
- Tracing galaxy evolution and galaxy cluster formation via Sunyaev-Zeldovich effect
- Measuring CMB foregrounds to constrain inflation
- Studying the physics of star formation in the Milky Way and nearby galaxies.
- Probing galaxy evolution from the first billion years to Cosmic Noon through observations of the infrared background
- Improving constraints on new particle species through observation of Rayleigh Scattering

Instruments

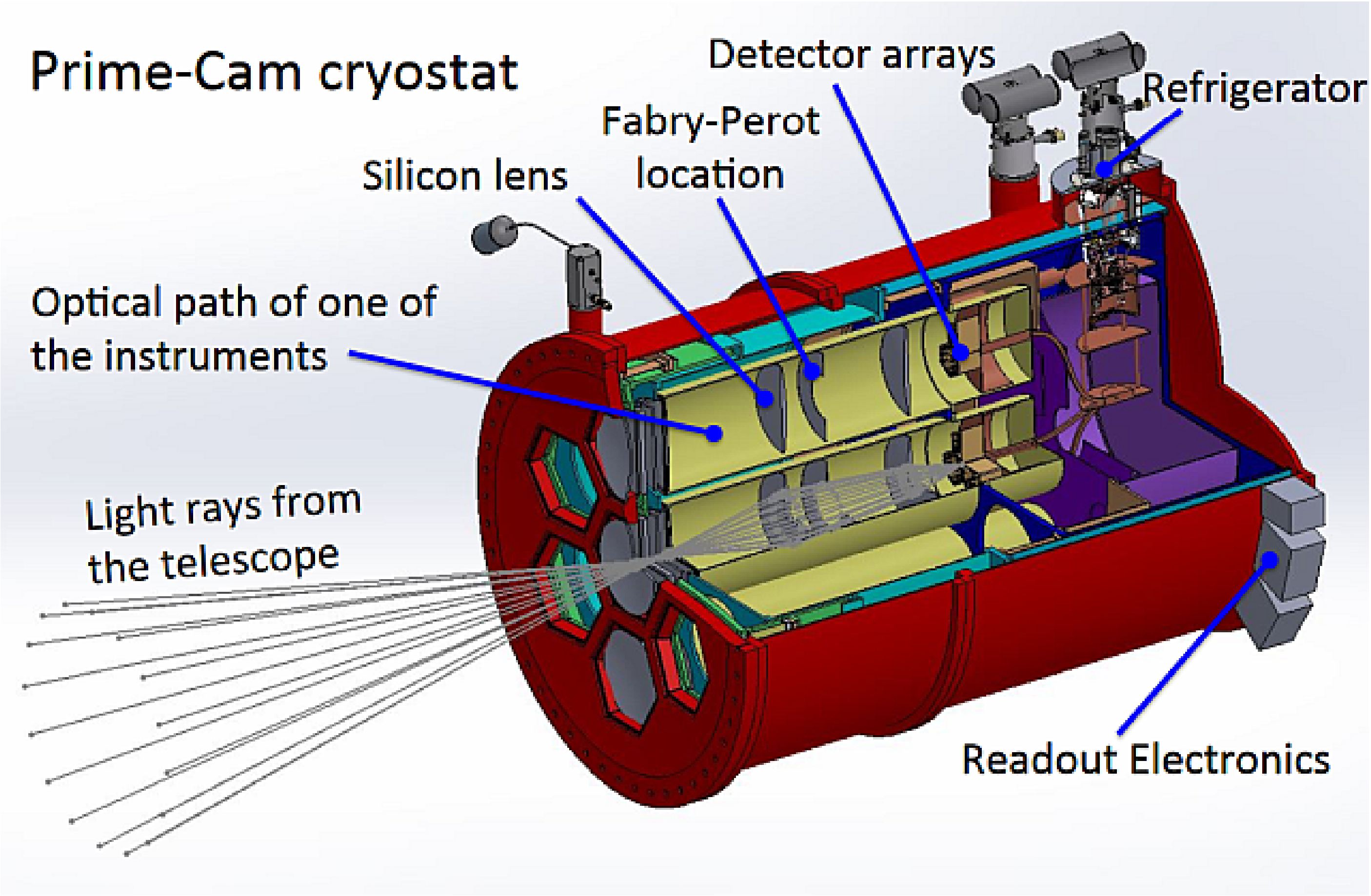
- Prime-Cam
  - Direct detection instrument
  - Modular camera/spectrometer instrument
  - Covering ~8 degree field of view
- CHAI
  - Heterodyne spectrometer
  - High-spectral resolution

Prime-Cam

- A modular instrument
  - 7 independent instrument modules
  - Each module has a FoV ~ 1.3°
  - Instrument size:
    - ~1.8 m diameter
    - ~2.5 m long
- Angular resolution on CCAT-prime:
  - 57” at 220 GHz
  - 14” at 850 GHz



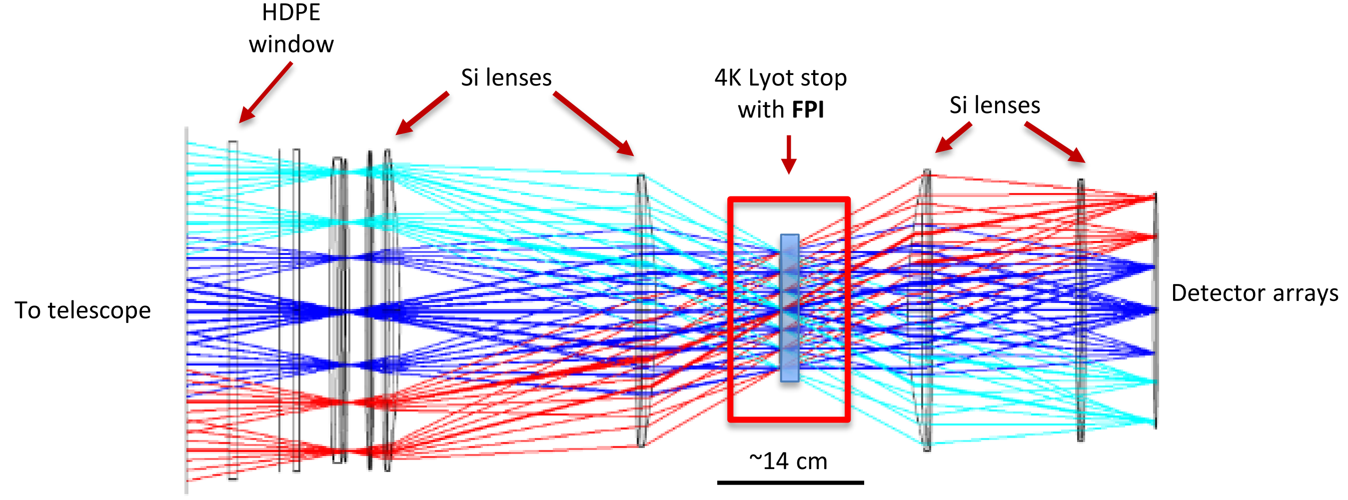
Prime-Cam



Eve Vavagiakis

Prime-Cam Optics

- Optical design of each instrument module is similar
  - Slight differences due to off-axis locations
  - Number of lenses and optimization for camera modules differ slightly from spectrometer module

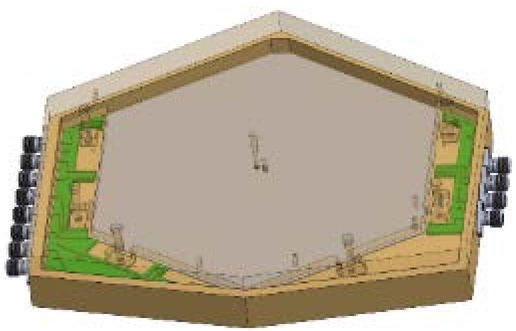


Optical design of spectrometer module

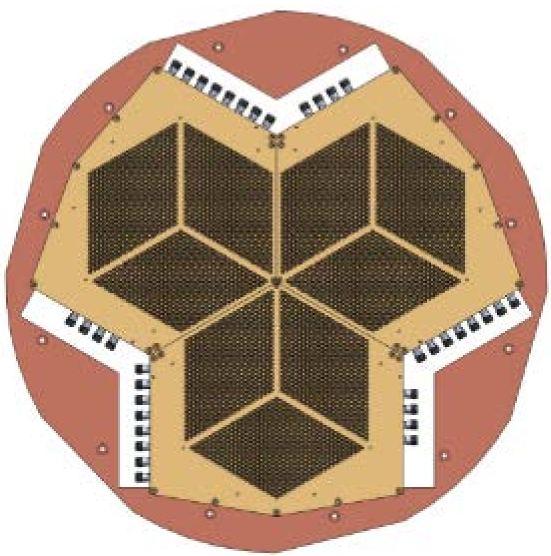
Prime-Cam Detectors

CCAT-p

- Large format MKID detectors from NIST (Hubmayr, Wheeler)
  - “spin-offs” from BLAST-TNG and TolTEC
  - Feedhorn coupled



Mechanical designs of a single array mount



Focal plane layout of a single instr. module with 3 arrays

Cody Duell (Cornell)

Prime-Cam Detector Readout

- Readout for first-light detectors: ROACH-2
  - One ROACH-2 is limited to readout ~500 – 1000 detectors
- Planning to use Xilinx RFSoC- based readout for full Prime-Cam
  - 1 RFSoC based readout system reads ~5000 detectors
  - RFSoC readout has reduced power consumption

RFSoC

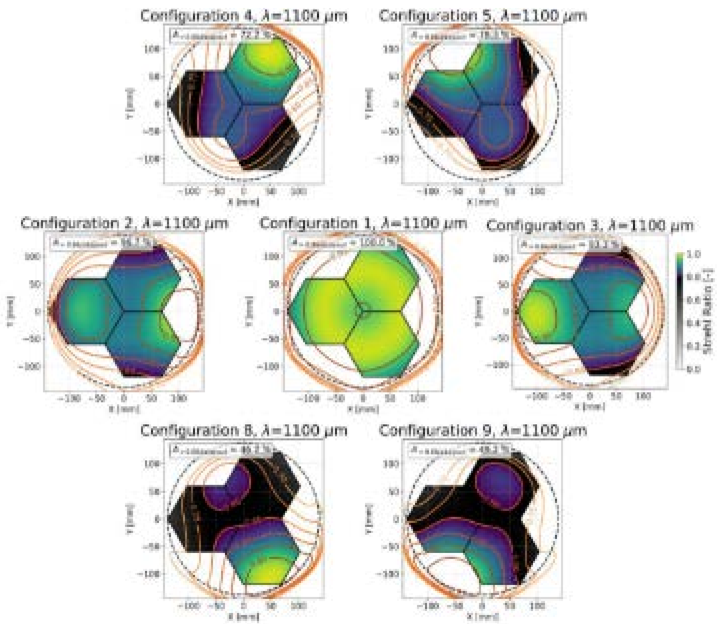
Roach-2

Cody Duell (Cornell)

Prime-Cam Detectors

Camera Module	Detectors
220 GHz	~8,000
280 GHz	~10,000
350, 410, 850 GHz	~21,000
Spectrometer Module	
250 GHz	~10,000
360 GHz	~21,000

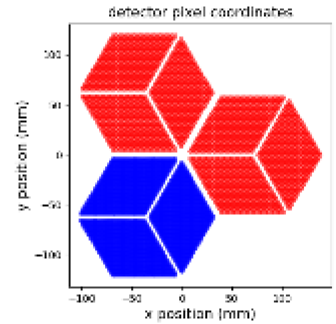
Choi+ 2020JLPT

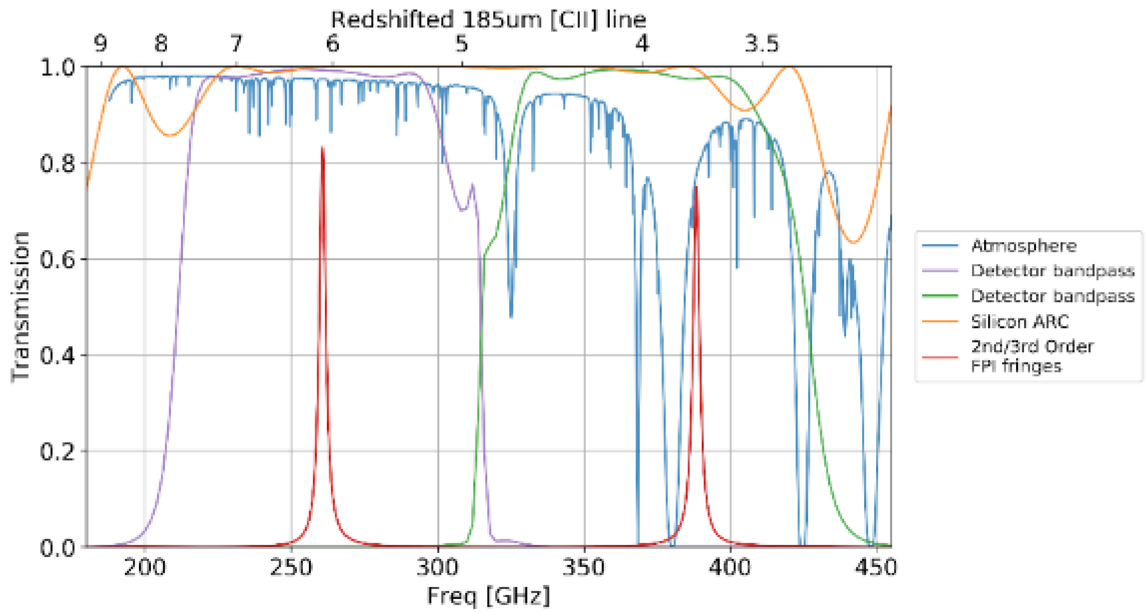


Gallardo+ 2018SPIE

EoR-Spectrometer Module

- Scanning Fabry-Perot Interferometer (FPI)
  - Spectral resolution $R \approx 100$
  - 210 - 420 GHz
  - Second and third orders in-band
- Focal plane detector arrays
  - Low and high band KID arrays
  - Spectrally multiplex observations





Cothard et al. 2019 arXiv:1911.11687

Prime Cam Sensitivity

Table 2: Overview of baseline Prime-Cam survey performance [52]

Survey	Field ID	LST range [h]	Area [deg^2]	Time [hr]	Sensitivity^c (@ representative ν_{obs}[GHz])	Supporting Surveys^b
EoR^a	E-COSMOS	7.0-13.0	8	2000	0.02 MJy sr^{-1} bin^{-1} @ 220	1
	E-CDFS	23.5-7.0	8	2000	0.02 MJy sr^{-1} bin^{-1} @ 220	2
	HERA-Dark	13.0-23.5	8	*(filler)*	0.02 MJy sr^{-1} bin^{-1} @ 220	3
DSFG	Stripe 82	20.0-5.5	300	500	2.5 mJy beam^{-1} @ 860	4
	GAMA9/12/15	5.5-20.0	110	180	2.5 mJy beam^{-1} @ 860	5
SZ/CMB	AdvACT/SO	all	12,000	4000	11 μK/arcmin^2 (CMB) @ 270	6

^{a}Spectroscopy; sensitivities provided for R=100. ^{b}(1) Deep Subaru HSC+PSF spectroscopy & COSMOS X-Ray-to-meter-wave multiwavelength survey; (2) deep Euclid grism spectroscopy (upcoming), HERA HI 21 cm (upcoming), & H-UDF/CDF-S multiwavelength surveys (incl. JWST GTO); (3) HERA HI 21 cm (upcoming), VLASS; (4) SDSS, HeLMS/HeRS Herschel/SPIRE, VLASS; (5) GAMA, H-ATLAS Herschel/SPIRE, ACT, VLASS; (6) Planck, SDSS, DES, ACT, SO, DESI, LSST, eROSITA (upcoming). ^{c}Preliminary model; an enhanced noise model will be presented by Choi, S. et al. (2019), in prep.

Herter+ ASTRO2020 (arXiv:1909.02587)

Prime-Cam Survey Sensitivity

CCAT-p

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_{white} μK^2	N_{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	6.0×10^{7} †	5.7×10^{5}	3.0×10^{5}	2.8×10^{4}	6.1×10^{6}

Broadband channels star formation survey in 1st quartile PWV (410 deg^2; 680 hours)

ν GHz	$\Delta\nu$ GHz	Resolution arcsec	NEI Jy sr$^{-1}\sqrt{s}$	Sensitivity μK-arcmin	NET μK$\sqrt{s}$	N_{white} μK^2	N_{red} μK^2
220	56	57	3,000	6	6.3	2.9×10^{-6}	2.5×10^{-3}
280	60	45	4,900	11	11	1.0×10^{-5}	1.7×10^{-2}
350	35	35	12,300	42	40	1.5×10^{-4}	4.3×10^{-1}
410	30	30	27,400	149	134	1.9×10^{-3}	2.7×10^{0}
850	97	14	3.8×10^{7} †	2.3×10^{5}	1.9×10^{5}	4.5×10^{3}	9.8×10^{5}

Selected spectrometer channels targeted survey (8 deg^2; 4,000 hours)

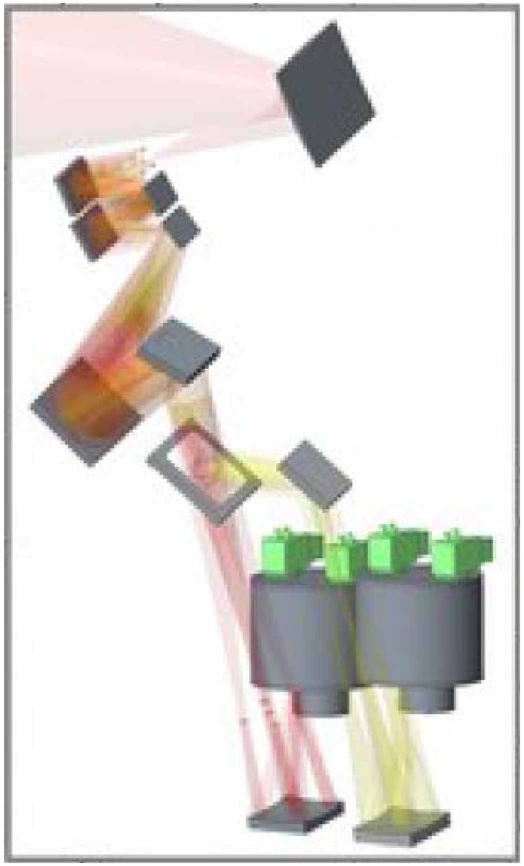
ν GHz	$\Delta\nu^*$ GHz	Resolution arcsec	[CII] redshift	NEI Jy sr$^{-1}\sqrt{s}$	N_{white} Mpc^3 Jy^2 sr^{-2}
220	2.2	57	7.5	12,900	1.2×10^{9}
280	2.8	45	5.8	16,600	2.0×10^{9}
350	3.5	35	4.4	30,600	6.3×10^{9}
410	4.1	30	3.7	61,500	2.3×10^{10}

Choi+ 2020JLPT

CHAI
CCAT-prime Heterodyne Array

	LowFrqArray	HighFrqArray
RF range [GHz]	455 – 495	800 – 820
Noise temp. (DSB) [K]	<100	<200
IF band [GHz]	4 – 8	4 - 8
Resolution [kHz]/[km/s]	100 / 0.06	100 / 0.04
Velocity coverage [km/s]	2500	1500
Beam size [“]	26	15
Field of view [‘ x ‘]	7.5 x 7.5	4.5 x 4.5

University of Cologne, Germany

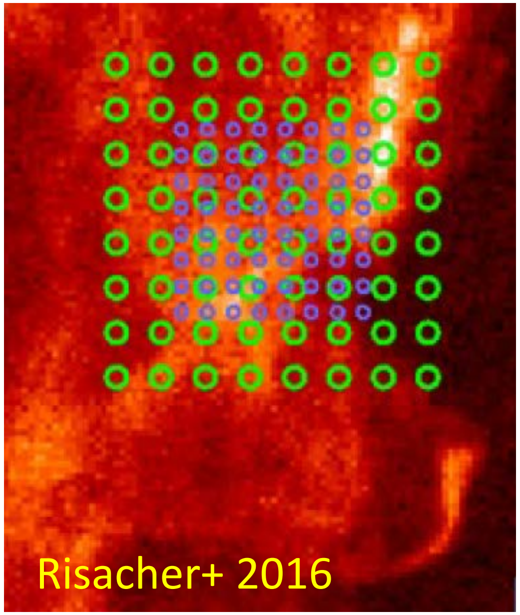


Graf+ 2020

CHAI
CCAT-prime Heterodyne Array

	LowFrqArray	HighFrqArray
RF range [GHz]	455 – 495	800 – 820
Noise temp. (DSB) [K]	<100	<200
IF band [GHz]	4 – 8	4 - 8
Resolution [kHz]/[km/s]	100 / 0.06	100 / 0.04
Velocity coverage [km/s]	2500	1500
Beam size [“]	26	15
Field of view [‘ x ‘]	7.5 x 7.5	4.5 x 4.5

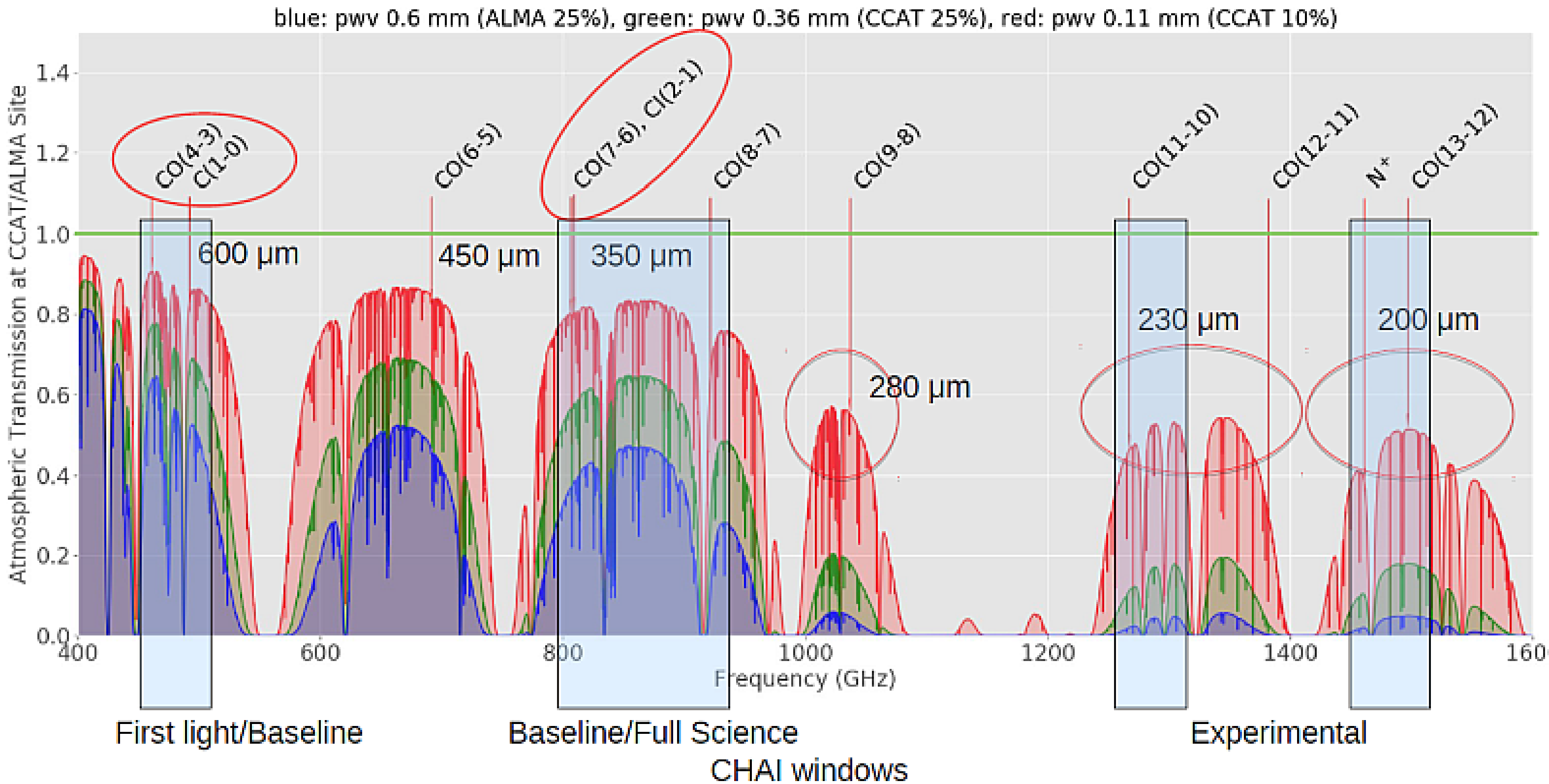
University of Cologne, Germany



CHAI 8x8 detector array footprint overlaid on SOFIA [CII] map of the horse head nebula

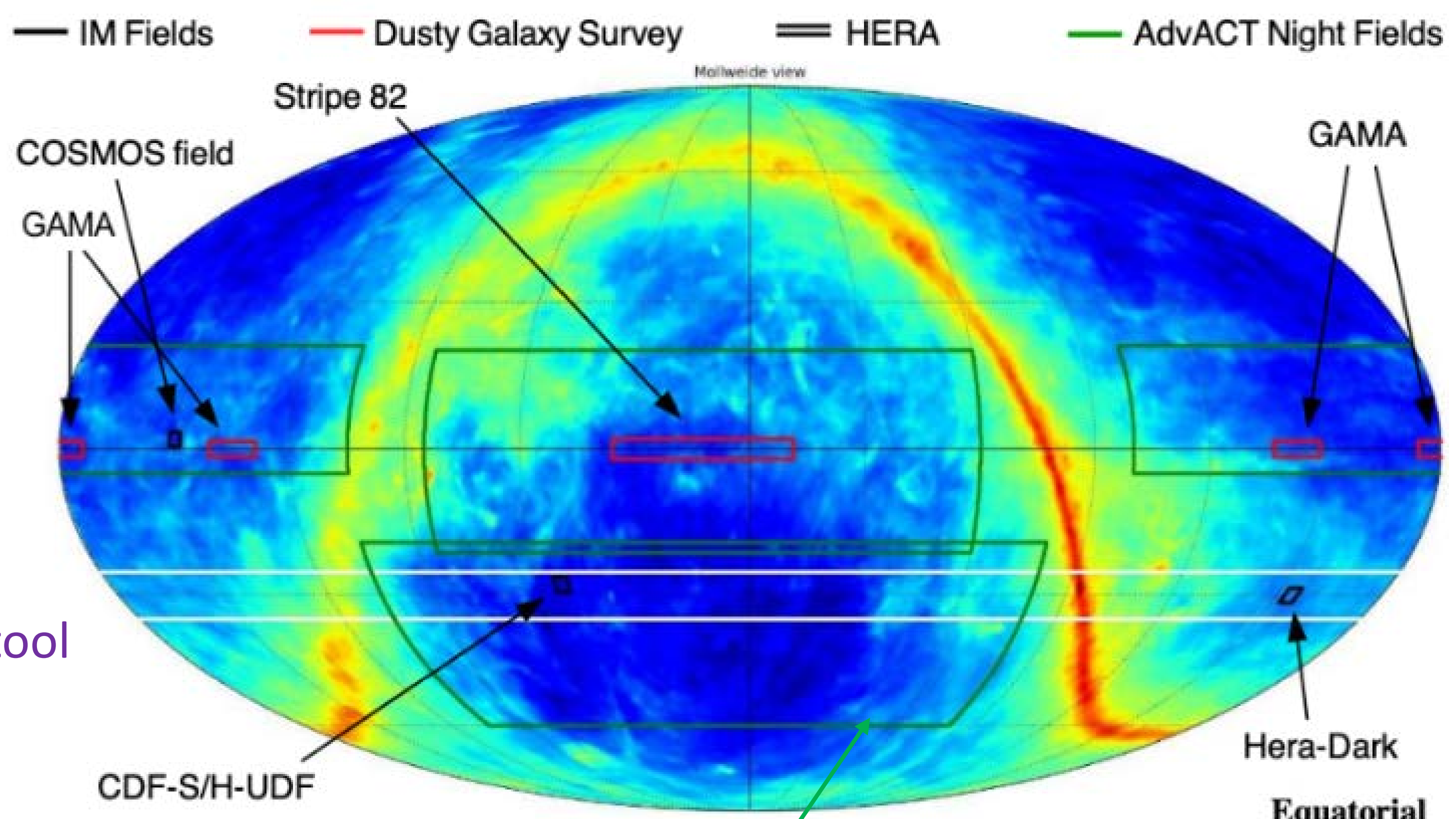
At 800 GHz CCAT-prime resolution is similar to SOFIA at 2 THz ([CII], [OI])

CHAI
CCAT-prime Heterodyne Array



R. Simon; University of Cologne, Germany

Survey Observing Strategy



ACT-Pol planning tool

Figure by Jason Stevens

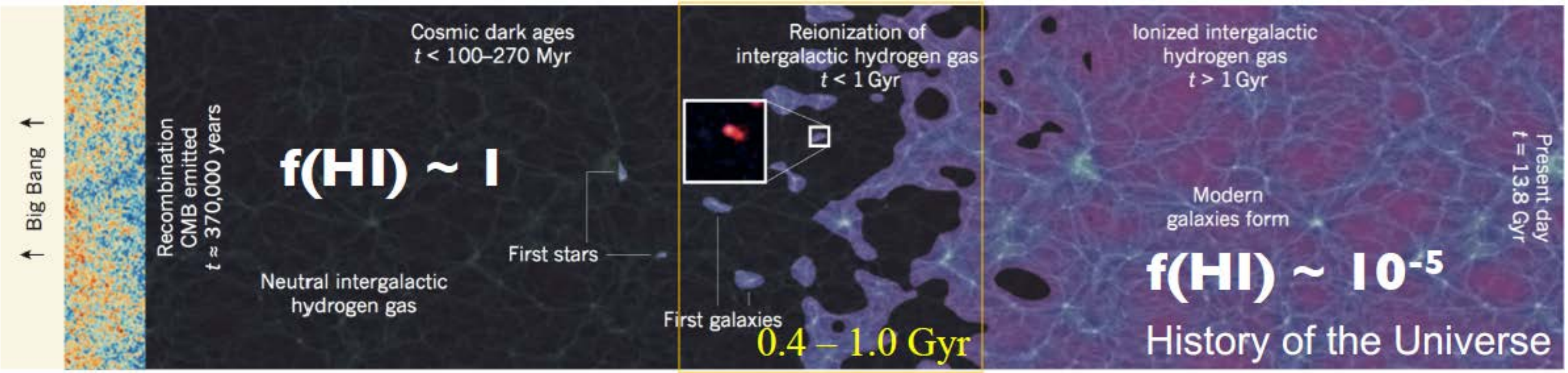
"cosmology" survey (green boxes) expandable to include Galactic regions

Stacey et al. 2018 (arXiv:1807.04354)

CCAT-prime: Science Working Groups

- Tracing the Epoch of Ionization through Line Intensity Mapping (Coordinators: *Stacey, Riechers*)
- Galaxy and Cluster Formation (Coordinators: *Battaglia, Basu*)
- Tracing Dusty Star Formation over Cosmic Time (Coordinators: *Chapman, Aravena*)
- Characterizing foregrounds for CMB observations (Coordinators: Niemack, Choi)
- CMB Constraints on cosmological Rayleigh Scattering (Coordinator: *Meerburg*)
- New Windows into Time Domain Astrophysics (Coordinator: *Johnstone*)
- Tracing Star Formation in the Galaxy and Nearby Galaxies (Coordinators: *Simon, Stutz, Nikola*)
- Magnetic Fields and Galactic Science (Coordinator: *Fissel*)

Epoch of Reionization



Robertson et al. (2010); Riechers (2013)

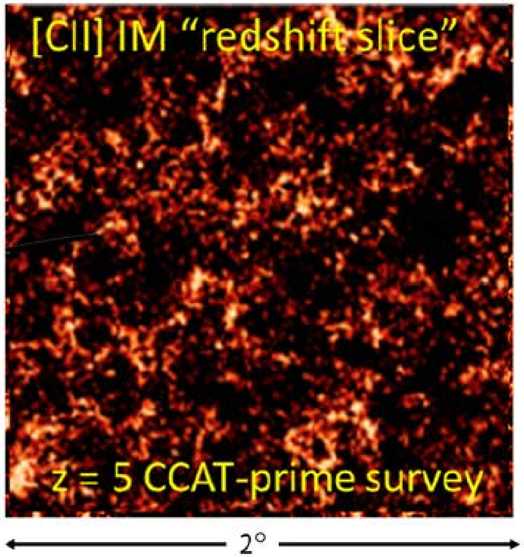
- Science goal:
  - Determine the topology and timescale of cosmic reionization

- [CII] line intensity mapping between redshifts 3.5-8
  - Measure aggregate emission from star forming galaxies, hence process of re-ionization
  - Trace evolution of structure during early galaxy formation

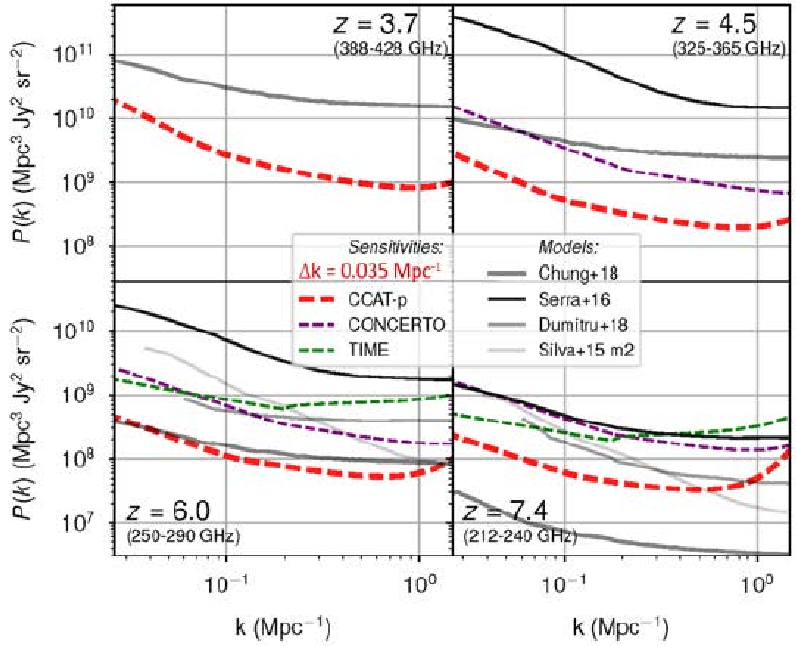
Riechers +

Epoch of Reionzation

- CCAT-prime survey:
  - early: 1 deg^2/400h
  - baseline: 2.25 deg^2/2500h
  - full: 9 deg^2/6000h w/2 tubes



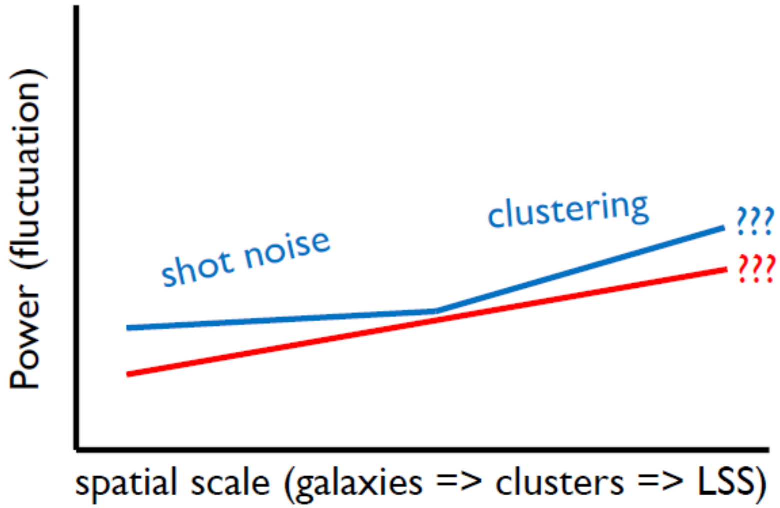
[CII] Intensity Mapping



Chung+ 2020 (arXiv:1812.08135)

Epoch of Reionization

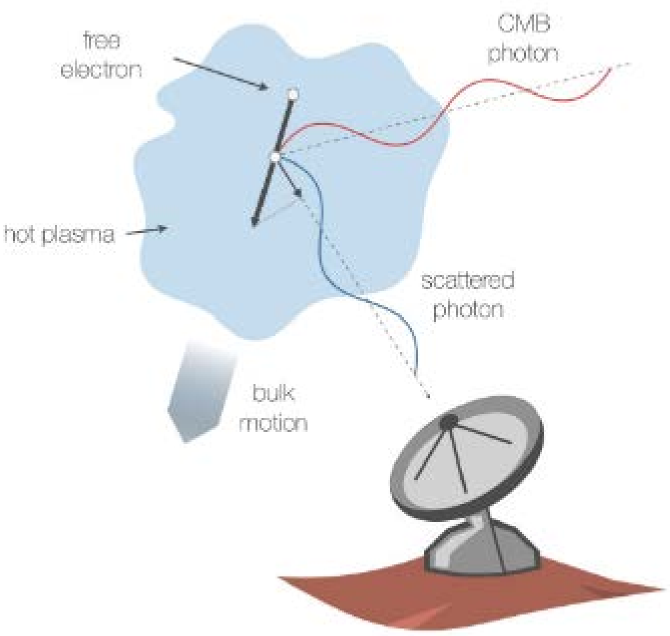
- Reionization timescale depends on the free mean path of the ionizing photons traveling in the Intergalactic Medium (IGM) and its density structure:
  - Overdense region ionize first
  - Galaxy clustering drive the evolution
  - Large-scale [CII] intensity/fluctuations due to clustering
  - Small-scale [CII] intensity/fluctuations measures galaxies



- CCAT-prime/Prime-Cam will also measure [OIII] 88 µm emission

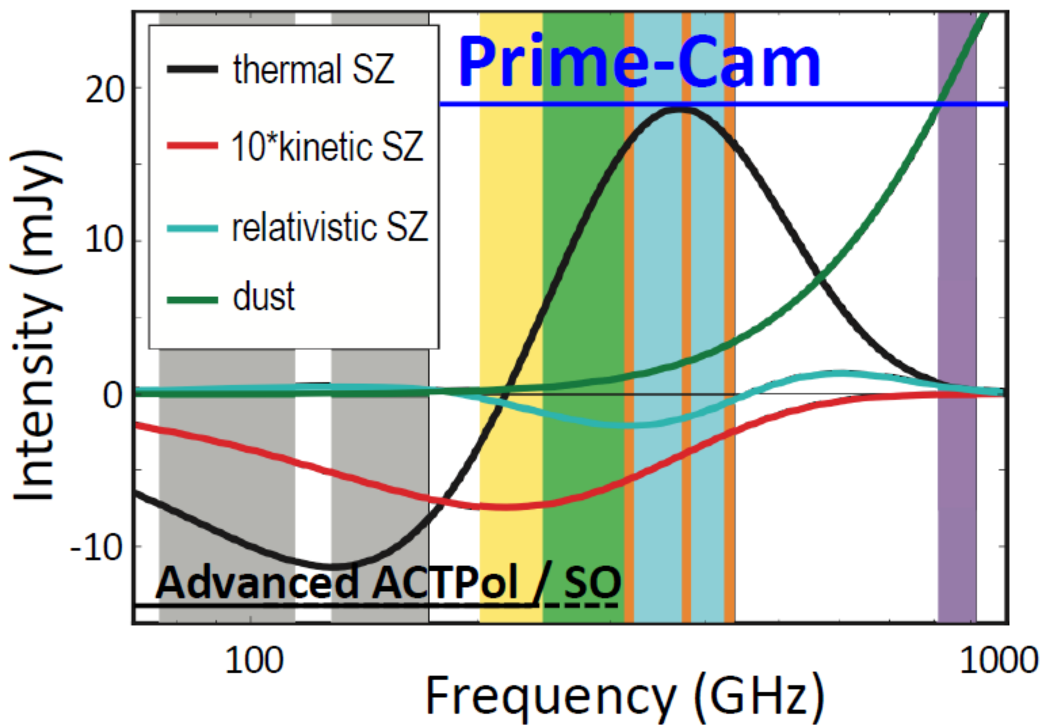
Riechers +

Galaxy and Galaxy Cluster Formation: using Sunyaev-Zeldovich Effect



Mroczkowski+ 2019

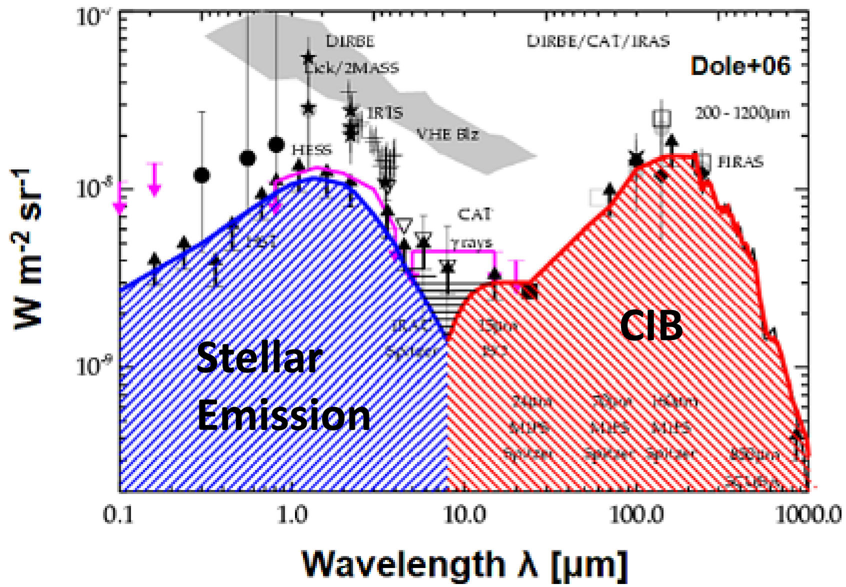
Observing bands and SZ spectra



Herter+ ASTRO2020 (arXiv:1909.02587)

Tracing Dusty Star Formation over Cosmic Time

- About ½ of all energy radiated from galaxies is emitted in the Cosmic Infrared Background (CIB)

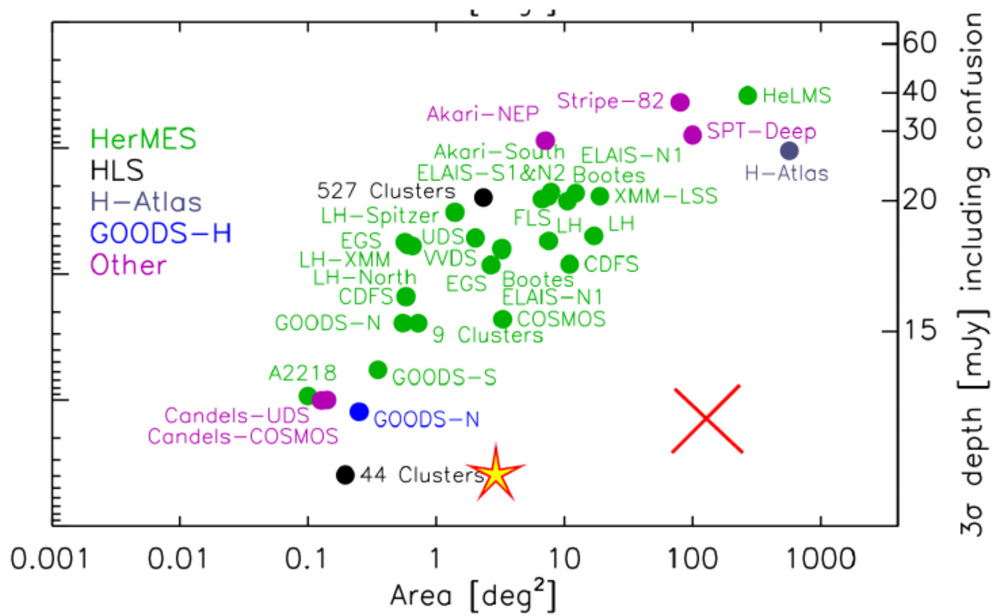


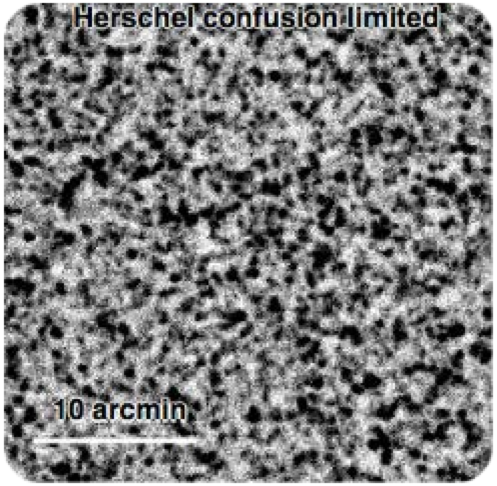
- At λ> 250 μm, only about 15% of CIB has been resolved into individual galaxies

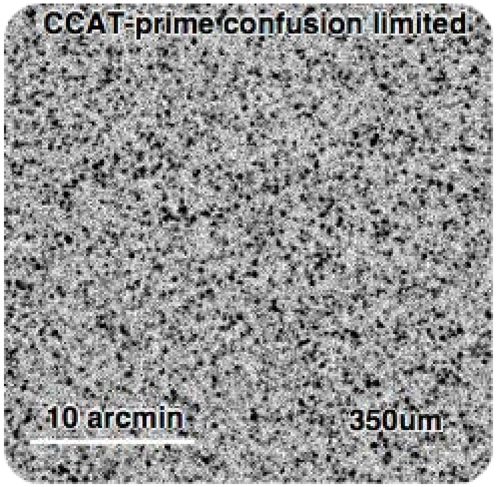
Scott Chapman+

Tracing Dusty Star Formation over Cosmic Time

- Science goals:
  - Resolve up to 40% of CIB at 350 μm (confusion limit: 2.5 mJy at 350 μm)
  - Robust constrain of bright-end of Luminosity function
  - Impact on environment
  - Role of dusty SF galaxies in galaxy evolution
  - Study of “exotic” galaxies



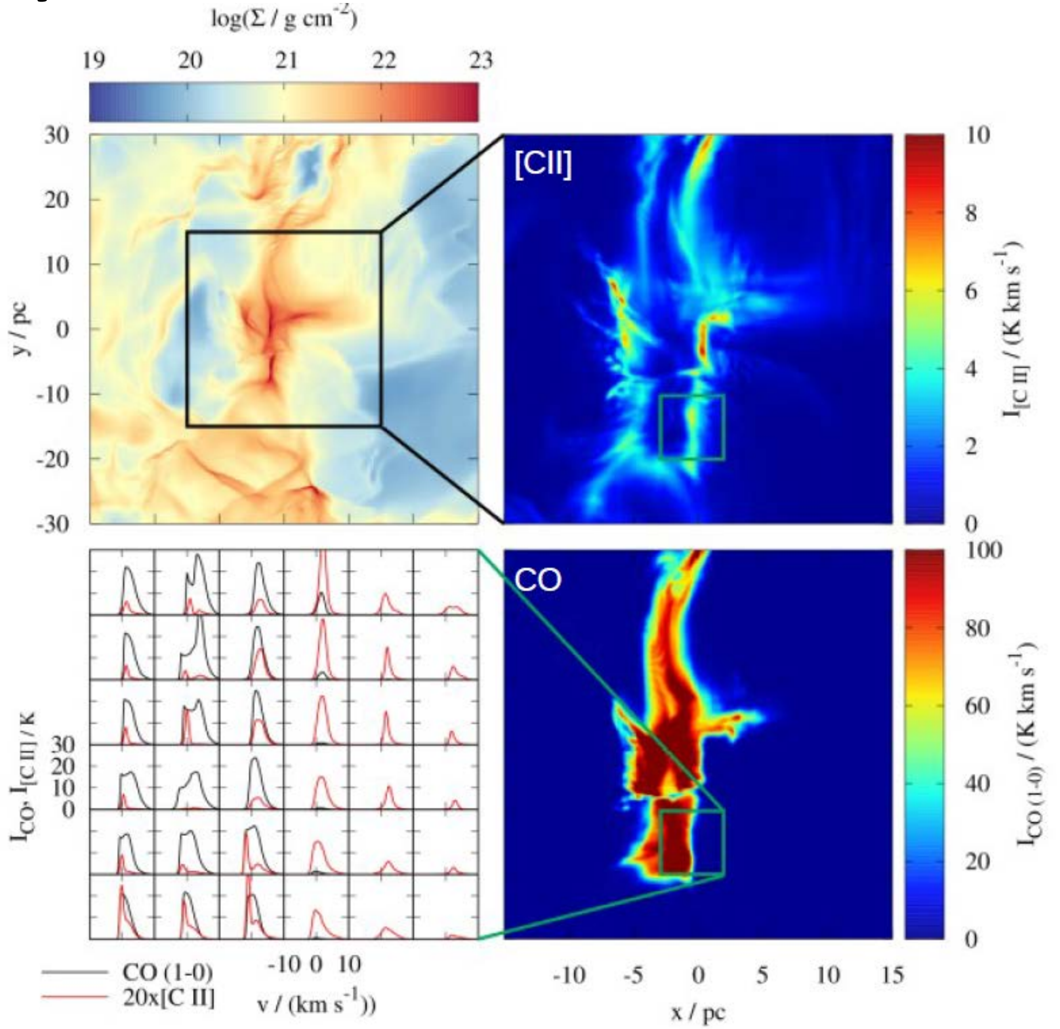




Aravena+; Scott Chapman+

Galactic and Nearby Galaxies: “Ecosystem”

- CHAI observations
- Resolve structures within clouds (filaments)
- Dynamics of ISM (turbulence, mass flows, …)
- CO (4-3) and (7-6), and both [CI] fine-structure lines observations



Comparing observations with synthetic maps:
Example:
continuum and spectra → SILCC-Zoom
Seifried et al. 2017, Walch et al. 2015

Simon+

Other CCAT-prime Science Drivers

- Measuring CMB foregrounds to constrain inflation
- Improving constraints on new particle species through observation of Rayleigh Scattering

Summary

- CCAT-prime construction is under way
- Cryostat for Prime-Cam instrument is being fabricated
  - Seeking funding for detectors
- Team is working on refining the observing strategies to optimize the science return

CCAT-p