Intensity Mapping with CCAT-prime

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Representing the CCAT consortium

Who is CCAT-Prime?

CCAT-p

- **Cornell University**
- **German consortium led by University of Cologne**
  - Cologne, Bonn, 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

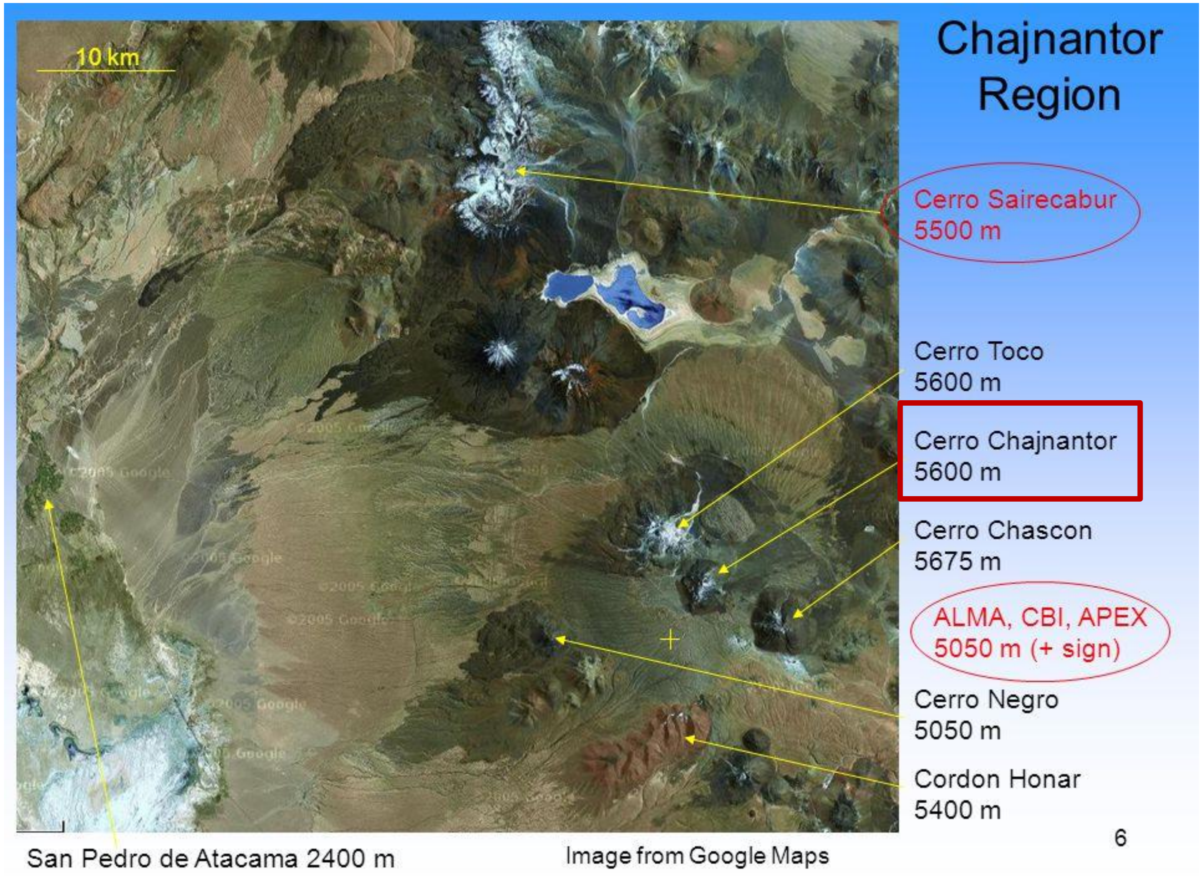
What is CCAT-Prime?

A 6 m submm-mm wave telescope
with – a very large field of view
and – very high surface accuracy
at – an extremely good site

CCAT-Prime Science

- Trace star formation in the Milky Way, the Magellanic clouds and other nearby galaxies through submm spectroscopy and photometry
- Constrain feedback mechanisms and test cosmological parameters by measuring the thermodynamic properties of galaxy clusters through the SZ effects on the CMB.
- Trace the evolution of DSFG through submm-mm wave surveys.
- Measure CMB Rayleigh scattering providing constraints on new particle species and characterizing polarized dust foregrounds that limit CMB constraints on inflation.
- **Trace the formation of the first star-forming galaxies that re-ionize the Universe through wide-field spectral line surveys focusing on [CII] at z ~ 3.5 to 8.1.**

Where is CCAT-prime?

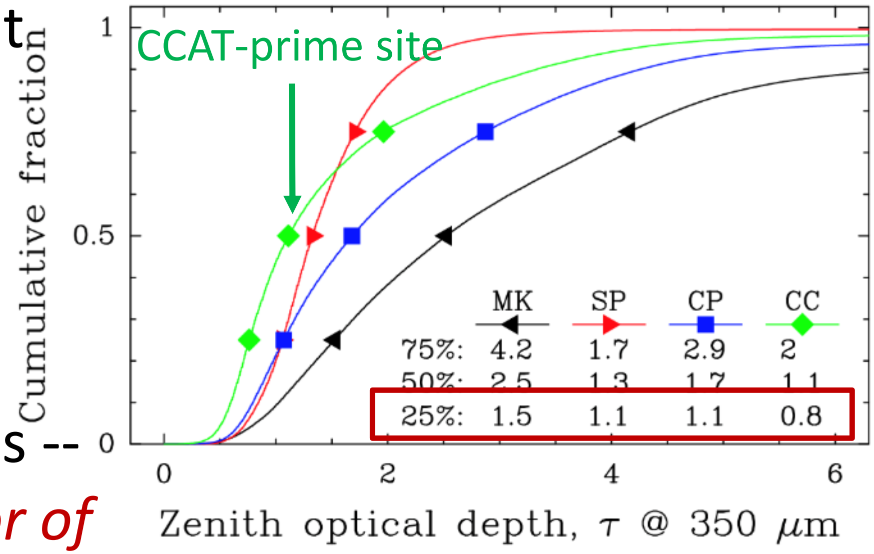


Cerro Chajnantor at 5600 m

The Site

5000 meters is very good, but 5600 meters is even better…

- Submillimeter sensitivity is all about telluric transmission
- Simon Radford: 350 μm ran tipping radiometers at MK, SP, Chajnantor plain and peak > than a decade –
- Simultaneous at CCAT & ALMA sites -- median H_2O - 0.6 vs. 1 mm ⇒ *factor of 1.8 in sensitivity at 45° elevation*



Radford & Peterson 2016PASP..128g5001R

Water Vapor Scale Height

	τ(350 μm) Chaj. plateau	τ(350 μm) Cerro Chaj.	PWV [mm] Chaj. plateau	PWV [mm] 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

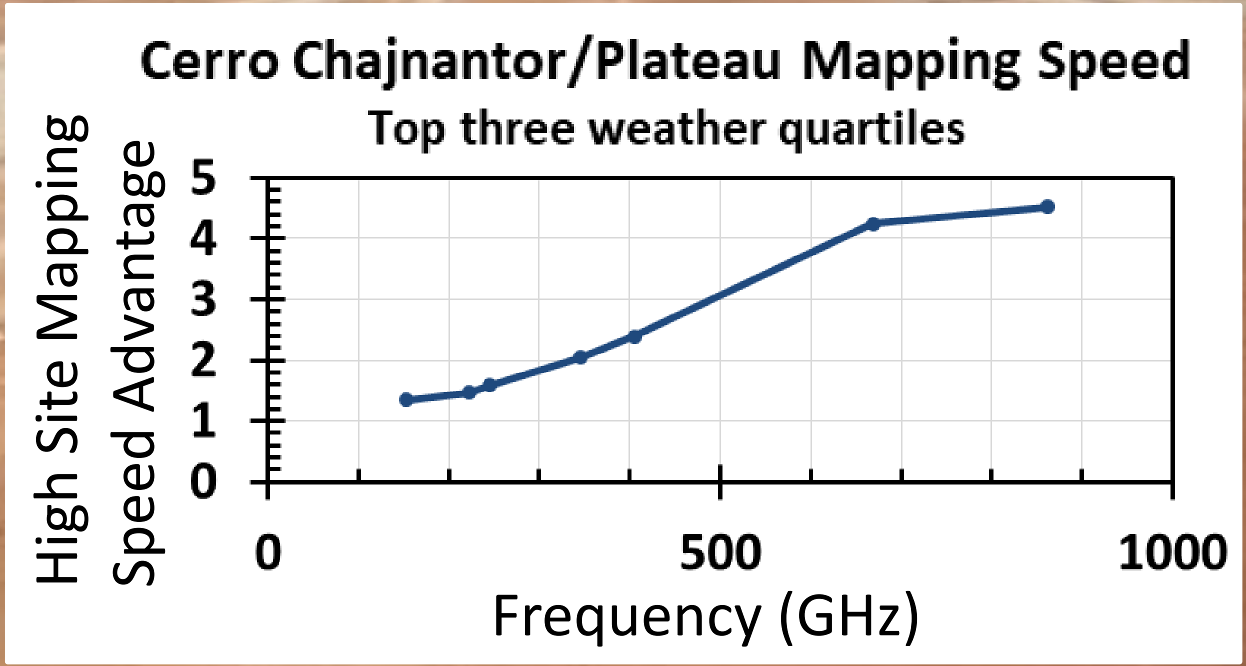
* WV scale height = $550\,\mathrm{m}/\ln(\mathrm{PWV_{cp}}/\mathrm{PWV_{cc}})$

Cerro Chajnantor

CCAT-p site at 5600 m

Chajnantor plateau
ALMA site at 5000 m

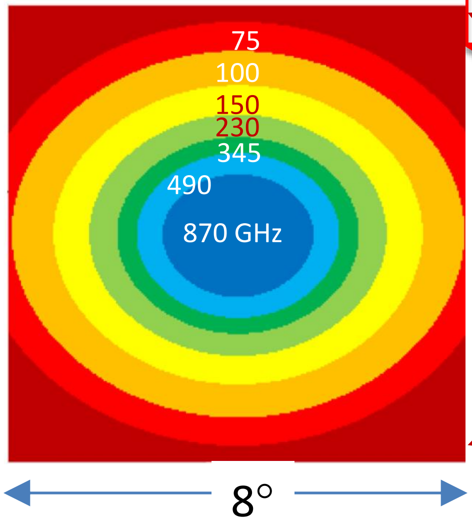
Significant gains in mapping speed even at lower frequencies



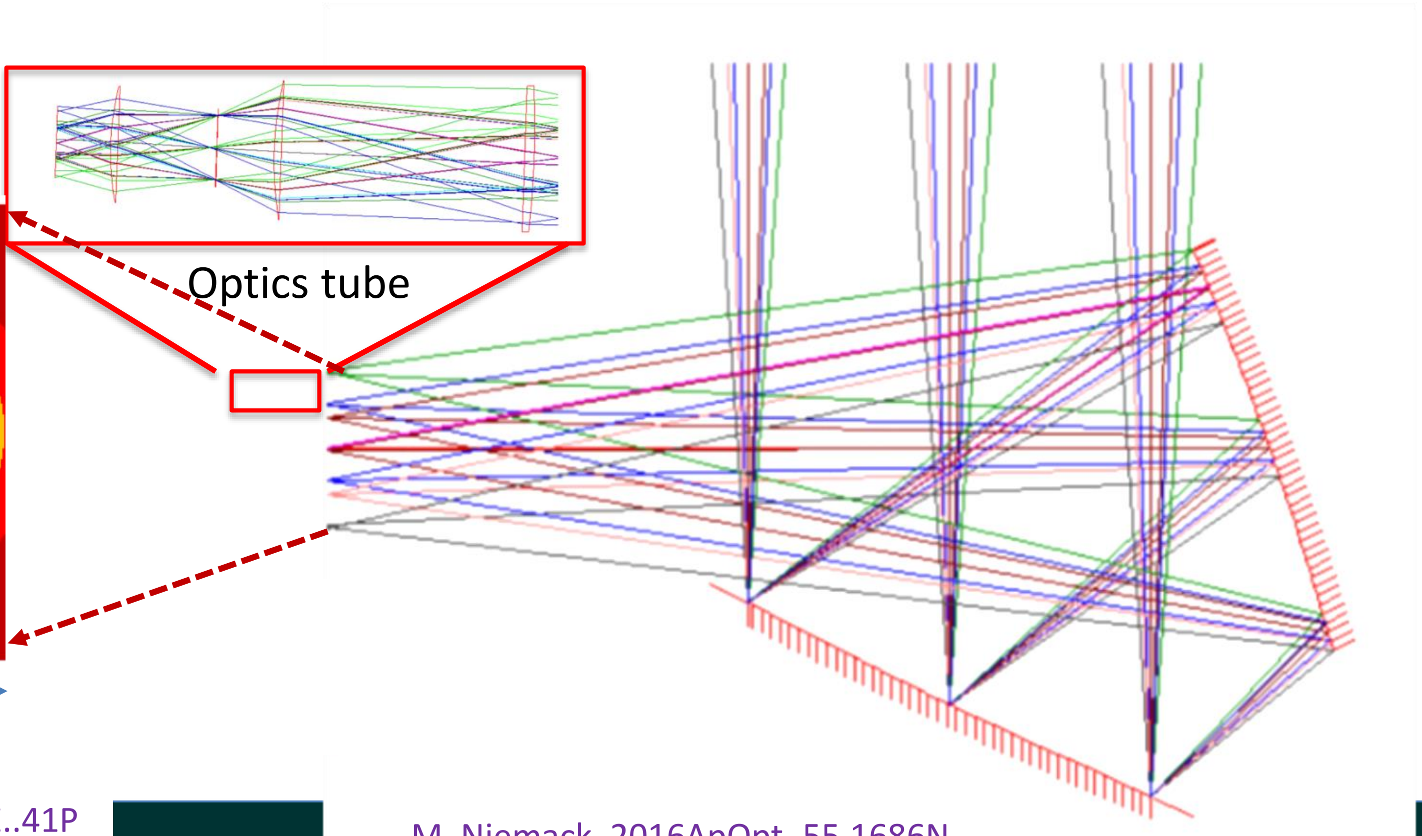
The Telescope and Instrument

Crossed Dragone Design

- Original concept published in 1978: C. Dragone AT&T Tech. Mem. 57, 2663
- Used in 2 <2 m CMB experiments (QUIET, C. Bischoff. et al. 2013) and the Atacama B-Mode Search, T. Essinger-Hileman et al. 2009



Parshley et al. 2018SPIE10700E..41P

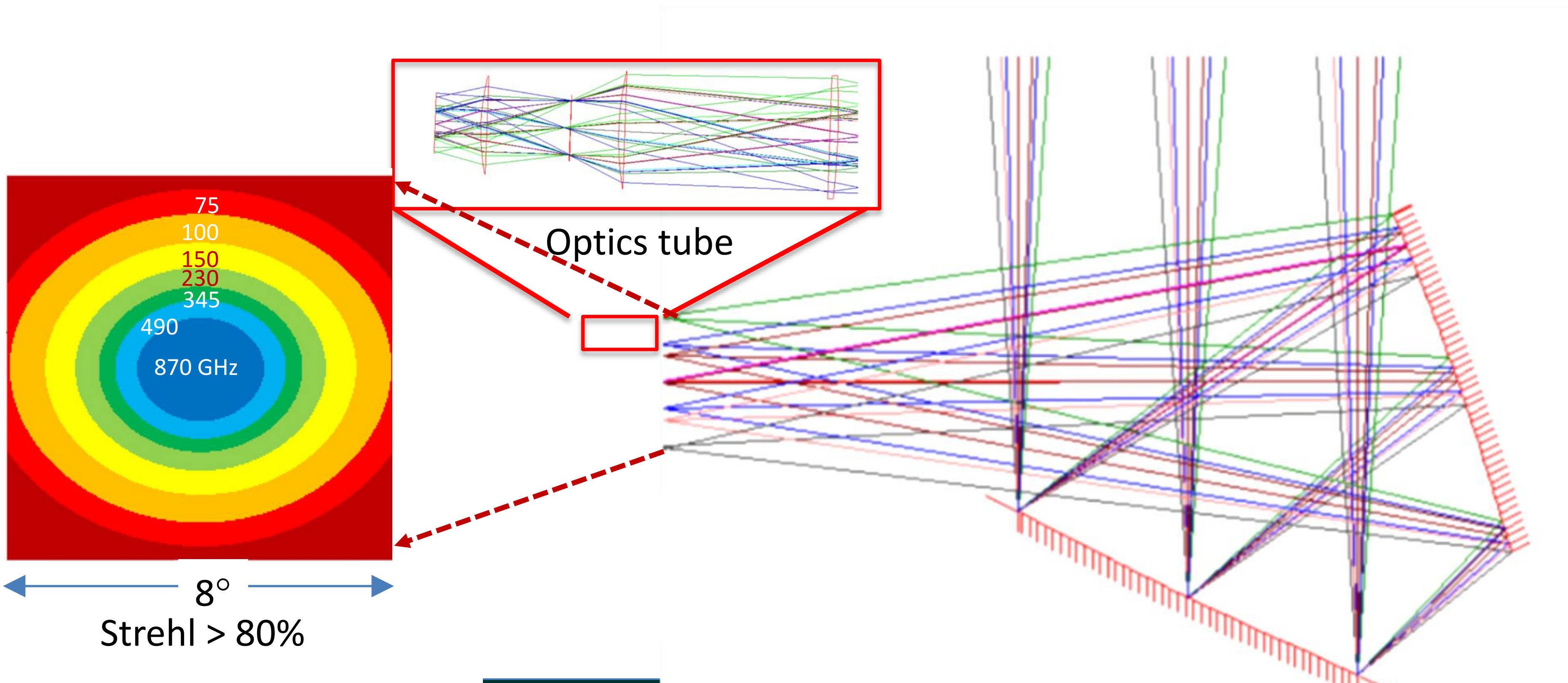


M. Niemack, 2016ApOpt..55.1686N

Crossed Dragone Design

- Field is split into “instrument modules”
- Each module can have entirely different configurations

3 mm	58,000 f·λ pixels
2 mm	98,000 f·λ pixels
1 mm	150,000 f·λ pixels
0.35 mm	400,000 f·λ pixels



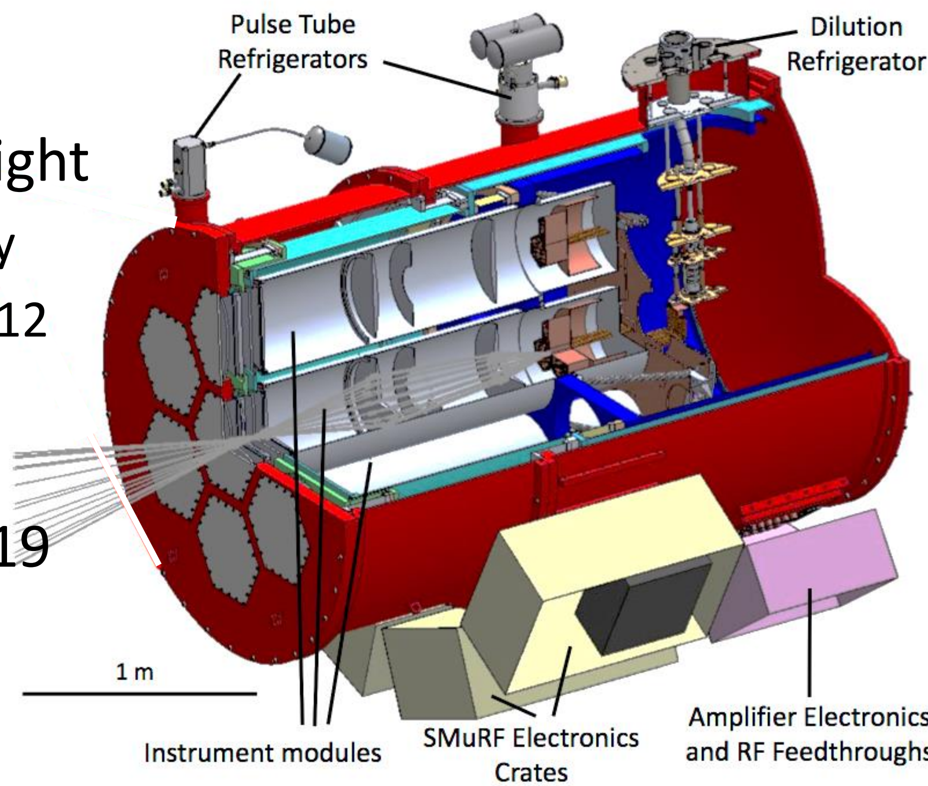
Parshley et al. 2018SPIE10700E..41P

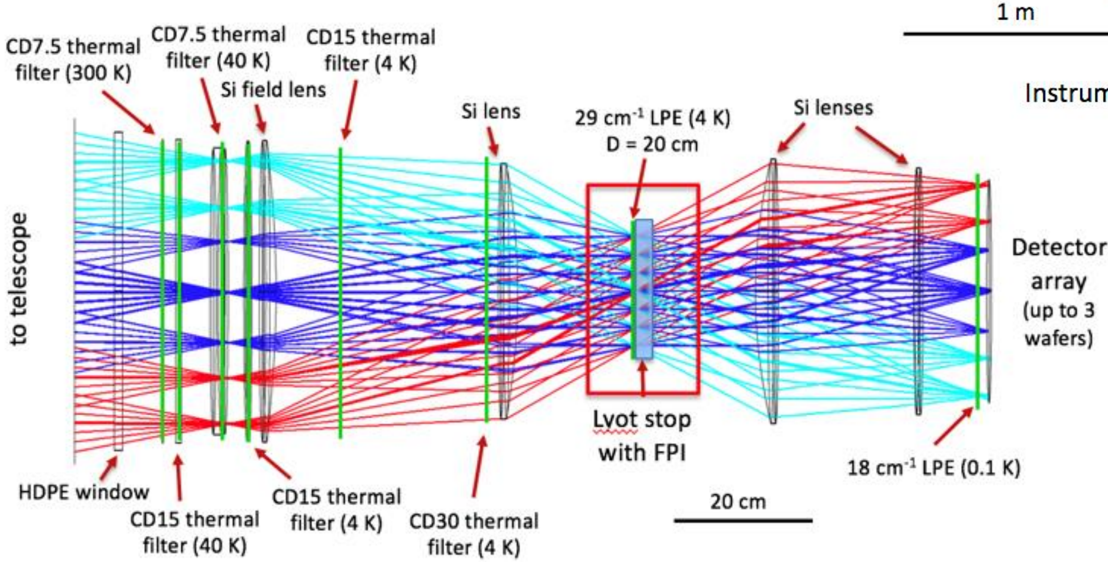
M. Niemack, 2016ApOpt..55.1686N

Vavagiakis et al. 2018SPIE10708E..1UV

PrimeCam Design

- 7- 1.3° **Instrument Modules**: first light
  - (1) 860 GHz camera 20 K-pix. KID array
  - (2) 220, **270, 350,** 405 GHz camera 1512 pol-sensitive multichroic TES each
  - (2) EoR-Spec 3024 dichroic TES each
- Growth potential in focal plane to 19 instrument modules





Epoch of Reionization Spectrometer (**EoR-Spec**) instrument module

The Telescope Specifications

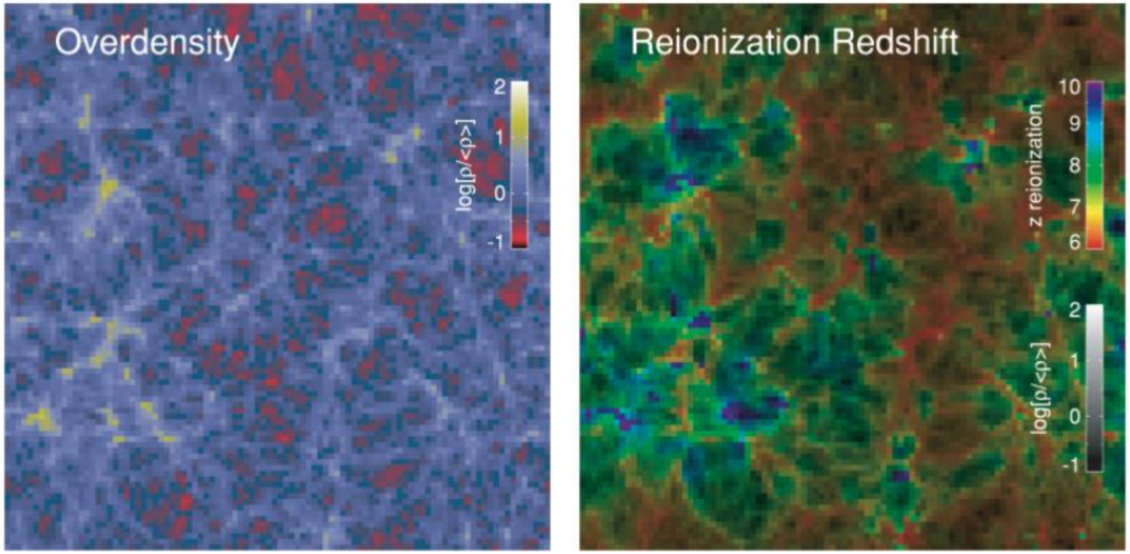
- 6 m diameter - 5.8 m illumination
- 10.7 μm rms wfe
- Up to 8° FoV
- No blockage, small gaps (<1%) $\Rightarrow$ emissivity < 2.8%
- 3°/sec scanning
- 1/10 beam reconstruction
- El: 0 to 170 degrees
  - Systematics and sun avoidance

Manufactured by Vertex Antennentechnik gmbh

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

- Aggregate [CII] signal from star forming galaxies at z ~ 3.5 to 8.1 ⇒ 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.

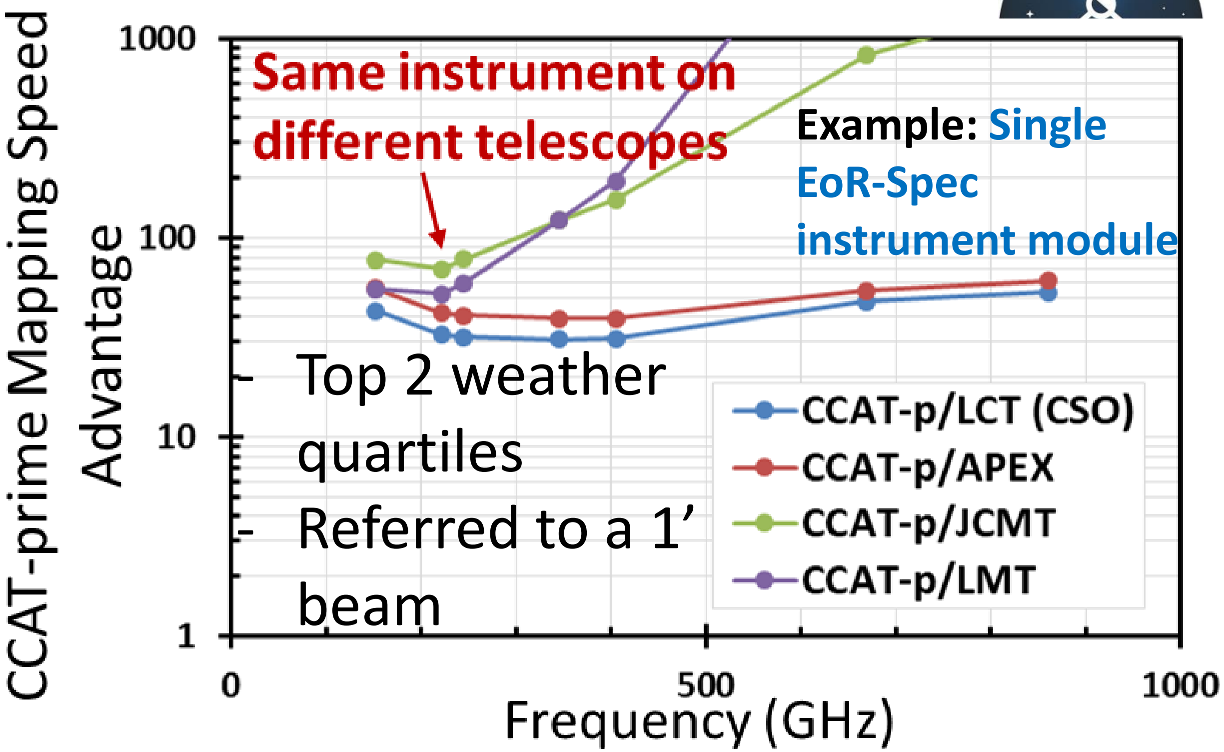
Intensity Mapping Requirements

CCAT-p

- Resolution into individual galaxies not required
  - Clustering scale 0.5 to 1 Mpc or ~1-2’ at z = 3.5-8.1, - good match for 6-m aperture (40”@ 1mm)
  - Need wide (~8°²) survey areas: spectral/spatial mapping speed critical
  - Ideally would like FoV ~ > 1° matches 40 Mpc void size-scale: systematics
  - Need moderate spectral resolution R ~ 100 for line detection and constraints along z direction, and…
  - Large enough spectral BW to identify interloper lower z CO by line multiplicity
  - *Sensitivity is at a premium: high site, very low emissivity telescope is essential!*

CCAT-prime Intensity Mapping Advantage

- Referred to a 1’ beam
- Site advantage (pwv)
  - Take top 2 quartiles
- Surface accuracy (wfe)
- Emissivity (ε_{tel})
- Field of View
- *CCAT-prime has >30 × the mapping speed*
- *Advantage grows if we employ > 1 EoR-Spec instrument module*



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	18→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’

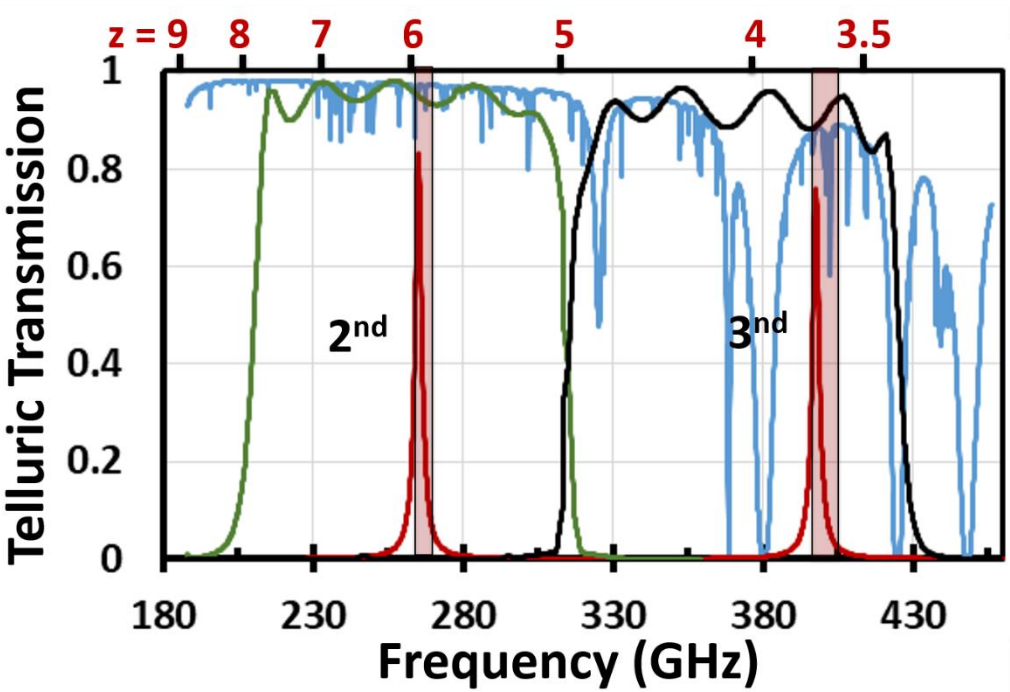
Top two quartiles

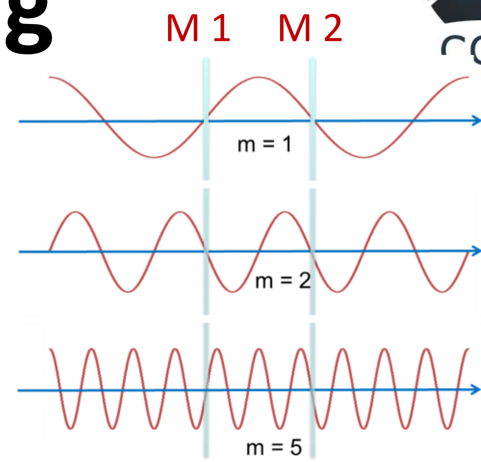
Large BW × FoV Spectrometer

CCAT-p

- Trans-mm wave from ~ 0.71 to 1.4 mm (420-210 GHz)
- Direct detection for optimal sensitivity
- Need a spectral × spatial product of pixels > 10-20,000 to complete an $8^{(\circ)2}$ survey in 4000 hours.
- Pixel costs limit the experiment
  - Can invest pixels spectrally, e.g. grating spectrometers
  - Can invest pixels spatially, e.g. Fabry-Perot interferometers (FPI)
- A FPI can take both polarizations, and more than one spatial mode ⇒ can be twice as sensitive per pixel
- *CCAT-prime is optimized for wide-fields with planar large format arrays, technologies are mature ⇒ we chose the FPI.*

Fabry-Perot Fringe Selection and Spectral Multiplexing



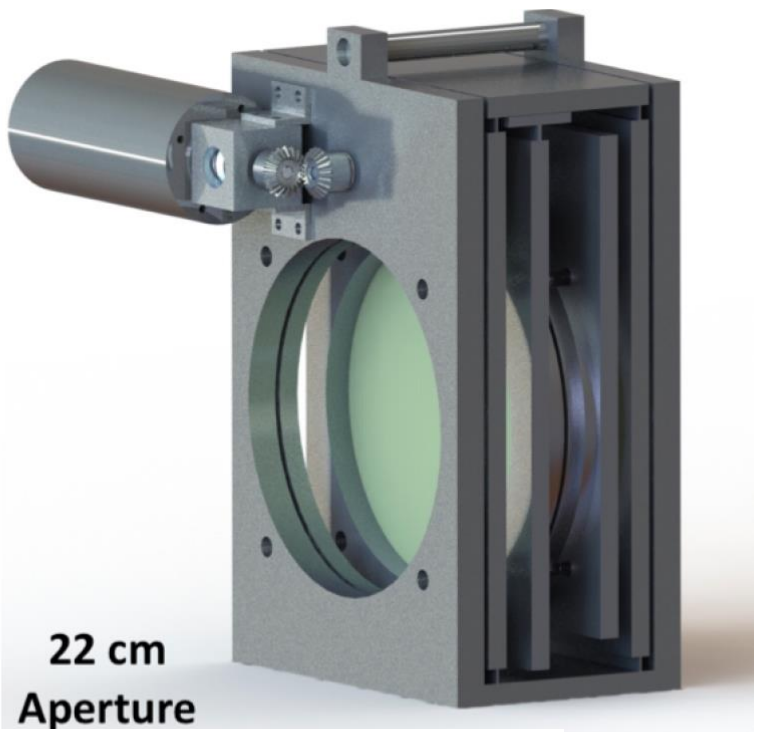


Dichroic bolometer BP set to sort the 2nd and 3rd orders of the FPI

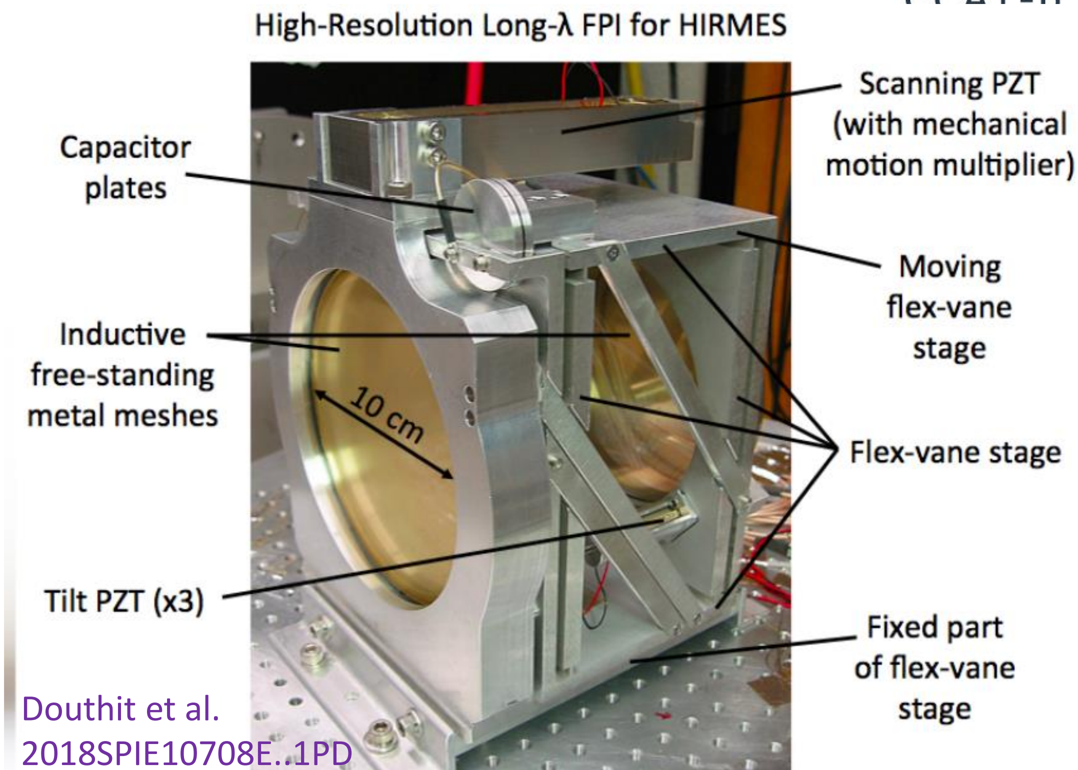
- Start with 2nd order at 210 GHz – 3rd at 315
- Natural spectral multiplex of ~ 15 GHz, or 7% of total BW
- Spatially scan on sky
- Move FPI – scan again – need about 14 spectral positions for full coverage

Stacey et al. 2018SPIE10700E..1MS

EoR-Spec Implementation

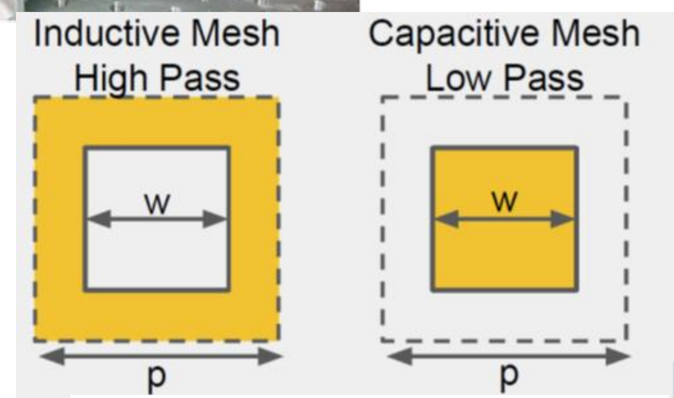


Stacey et al. 2018SPIE10700E..1MS



Douthit et al. 2018SPIE10708E..1PD

- Step through octave of bandwidth
  - Possible with free-standing inductive metal mesh mirrors
  - Better with the silicon substrate based inductive/ capacitive mirror technologies that we are developing



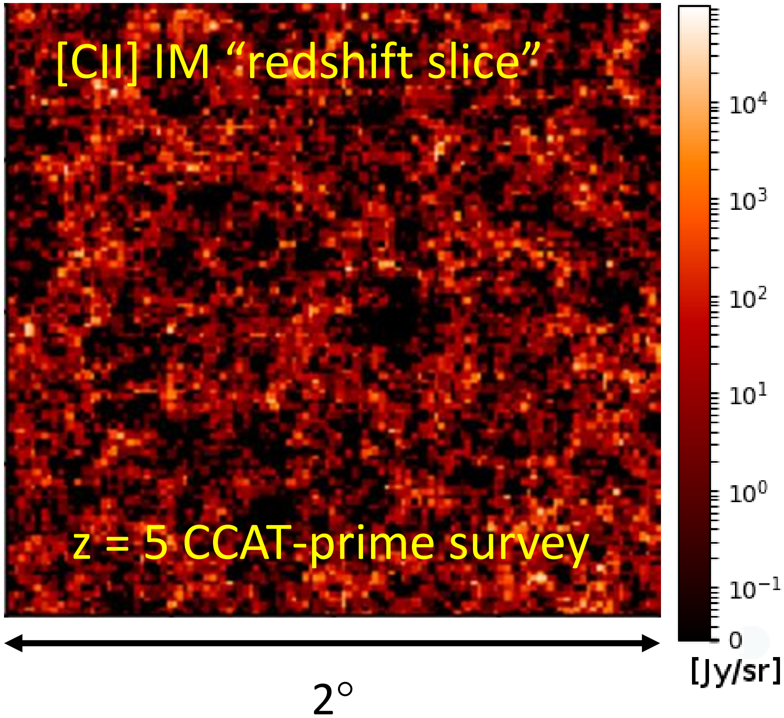
Cothard et al. 2018SPIE10706E..5BC

Quick summary of EoR Spec

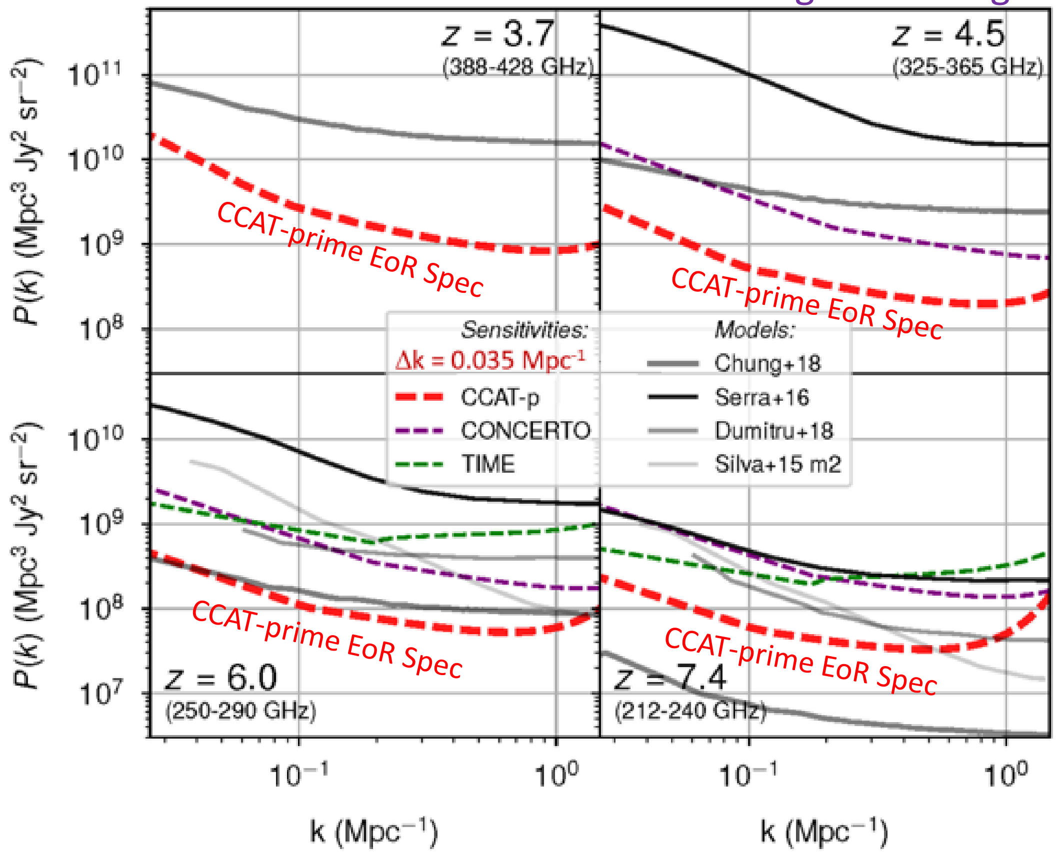
- **Frequency Coverage:** 420 to 210 GHz (z ~ 3.5 to 8.1 in [CII]) with 2 FPI fringes
  - Complementary to other surveys/techniques to follow
  - More or less orthogonal systematics to spectral multiplexers
- **Beamsize:** ~ 52 to 35” at 420 to 210 GHz
- **Instantaneous Field of View:** 1.3° diameter
- **Numbers of Pixels**: 3024 spatial positions sampling 10 spectral channels simultaneously *per instrument module*
- **# Modules:** First light 2 deployed, up to 7 modules possible.
- **Sensitivity:** Photon noise limited at RP ~ 100 ~ 0.66 to 3 MJy/sr-$s^{1/2}$ RP of 100 is sufficient to:
  - Sufficiently resolve the IM signal in redshift space for model tests
  - Facilitate removal of foreground CO rotational line emission
- **Versatility:**
  - Resolving power can be tuned higher if signal comes in fast…
  - Scan range can be shortened to focus on lower z if signal comes in slowly…

Intensity Mapping Signal

Christos Karoumpis

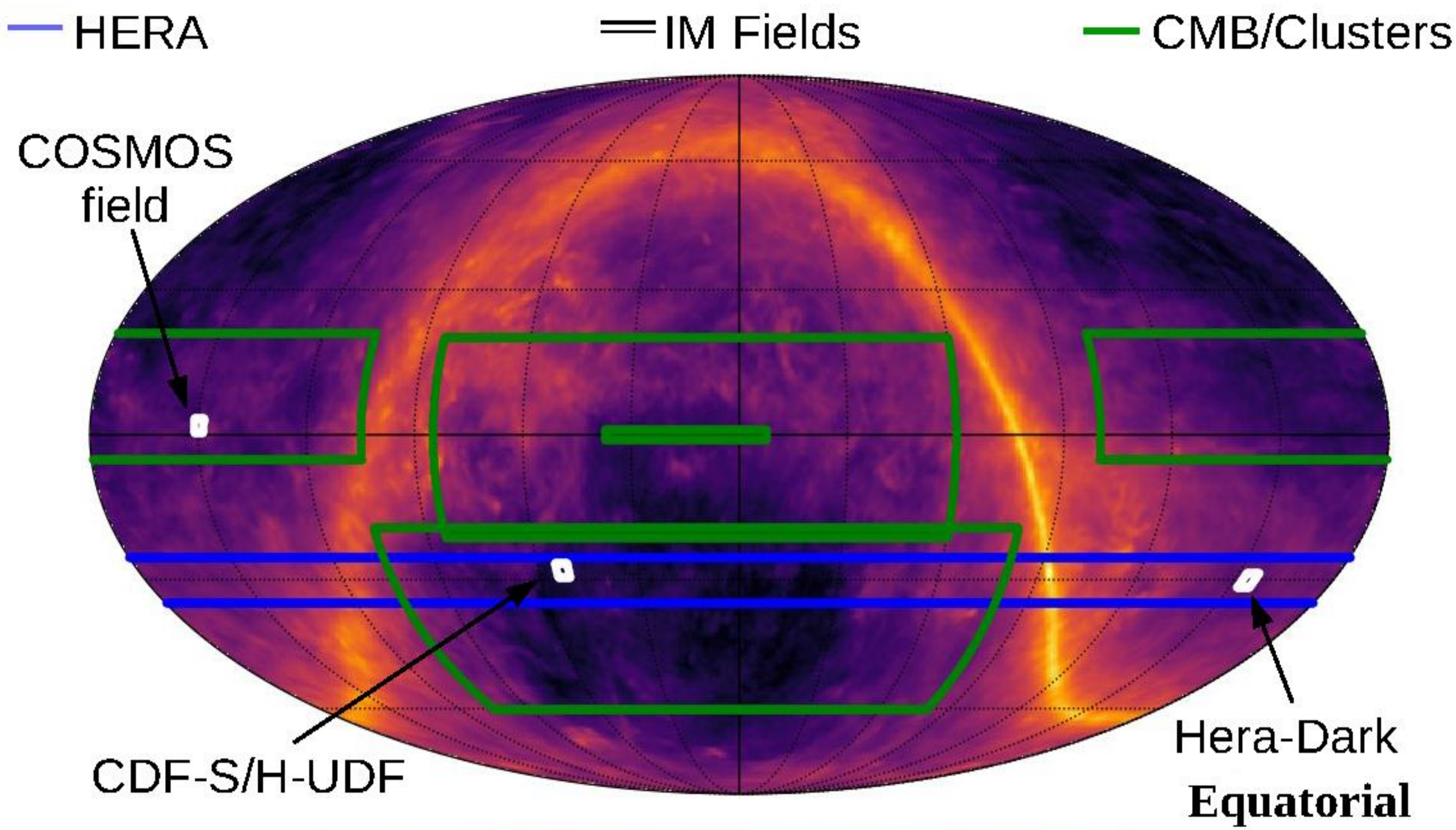


Dongwoo Chung



- $2 \times 4^{(\circ)2}$ surveys; total integration time 4000 hrs; top 2 weather quartiles
- The EoR Spec/CCAT-prime combination detects the [CII] IM signal all spatial frequencies and for all models to z ~ 6, and most models at higher redshifts

Survey Strategy



- Science fields coordinated with other (CMB/cluster) surveys to maximize efficiency

Telescope Schedule

Four year project (July 2017 to June 2021)

- Detailed Design CDR passed Oct. 2019
- Road upgrade in process (TAO)
- FDR in June 2019
- Concrete pads late 2019
- 13 months Fabrication which includes a trial assembly in Europe before shipping to Chanjnantor
- June 2020 parts starts arriving at the site
- 12 months Assembly/Checkout
  - Incl. 3 months unpacking/inspection and sequenced transport to summit

Telescope Schedule

Four year project (July 2017 to June 2021)

- Detailed Design CDR passed Oct. 2019
- Road upgrade in process (TAO)
- FDR in June 2019

First light spring 2021!

assembly in Europe before shipping to Chajnantor

Still looking for additional partners!

- 12 months Assembly/Checkout
  - Incl. 3 months unpacking/inspection and sequenced transport to summit

CCAT-p