The Fred Young Submillimeter Telescope (FYST): Nearing First Light

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Cornell University

Canadian Consortium

CCAT Presentation at SPIE 2026

Telescope

Parshley et al. Poster **14147-144**
CCAT: Final Assembly of the Fred Young Submillimeter Telescope (FYST)

Higgins et al. Poster **14154-211**
CCAT: Using a laser metrology system for mirror panel alignment

Prime-Cam

Vavagiakis et al. Talk **14156-3**
CCAT: The Prime-Cam Instrument for the Fred Young Submilliometer Telescope: Overview and Status

Keller et al. **14156-4**
CCAT: Design and characterization of the 350 GHz Instrument Module

Austermann et al. **14156-5**
CCAT: The focal plane arrays of the Prime-Cam submillimeter receiver

Freundt et al. **14156-6**
CCAT: In-lab characterization of the EoR-Spec instrument module

Patel et al. Poster **14156-97**
CCAT: Optical design of the 410 GHz Prime-Cam module

Burgoyne et al. Poster **14156-99**
CCAT: LED mapping the first science array at 850 GHz

Xie et al. Poster **14156-101**
CCAT: A two-octave 1.024 GHz KID readout … on RFSoC

Chapman et al. Poster **14156-156**
CCAT: Development of an MKID array for a 410 GHz module

Chapman et al. Talk **14156-54**
7/10 9:10 Room B5-M3
CCAT: Characterization of the first KID array for the Prime-Cam 850 GHz module

Patel et al. Talk **14156-62**
7/10 13:20 Room B5-M3
CCAT: Readout power and frequency optimization of the 280 GHz instrument module Al and TiN KID arrays

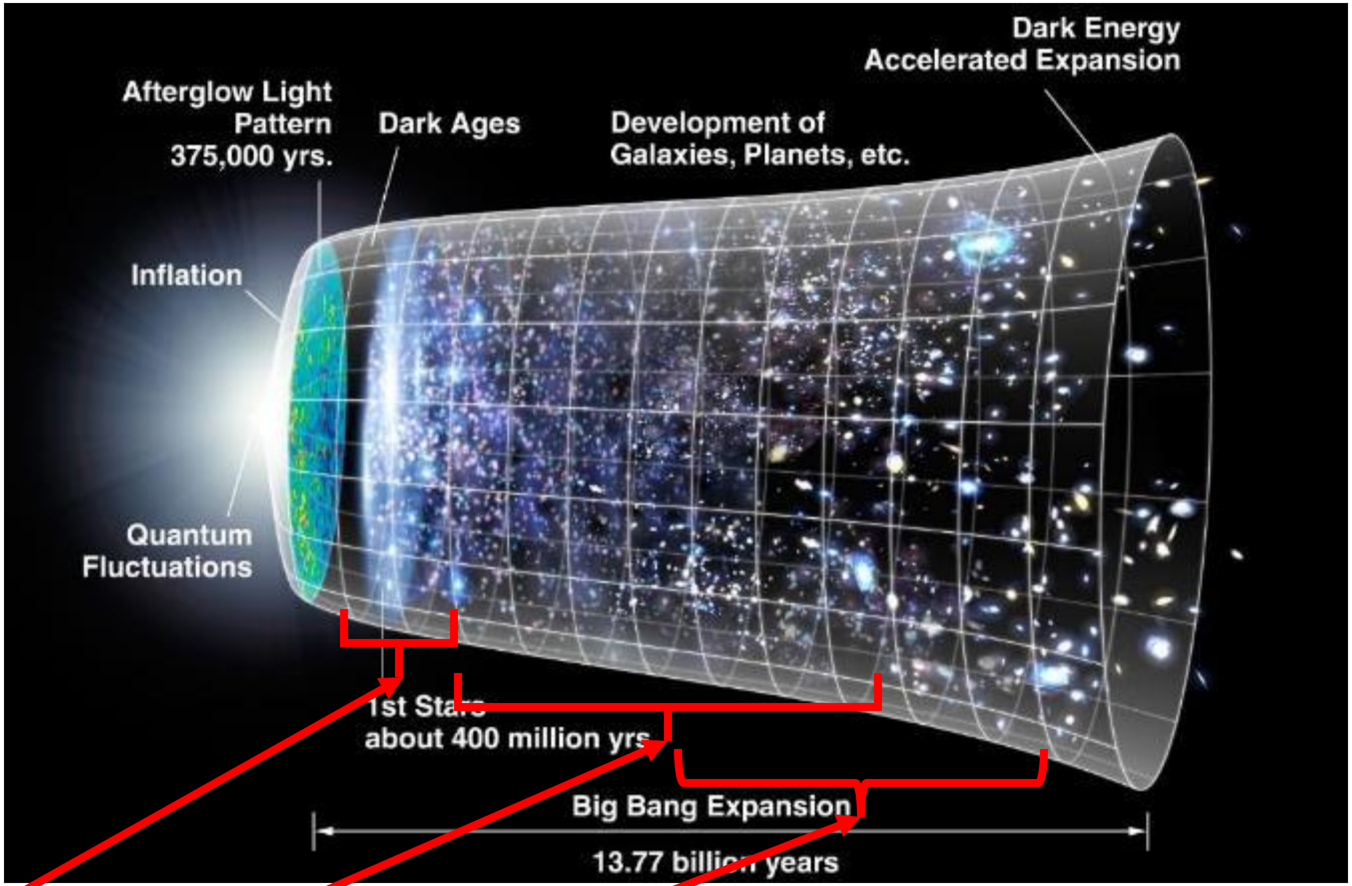
What is FYST?

The **Fred Young Submillimeter Telescope** (FYST) is a 6-meter diameter, high precision telescope located at 5600 m elevation on Cerro Chajnantor in the Atacama desert region of northern Chile:

- Novel telescope design, large field of view telescope
- Exceptional site gives access to short submillimeter wavelength astrophysics that is not possible from lower elevations:
  "The highest observatory site to which you can drive a truck."*
- Coordinated legacy surveys will yield answers to fundamental questions in cosmology and astrophysics.

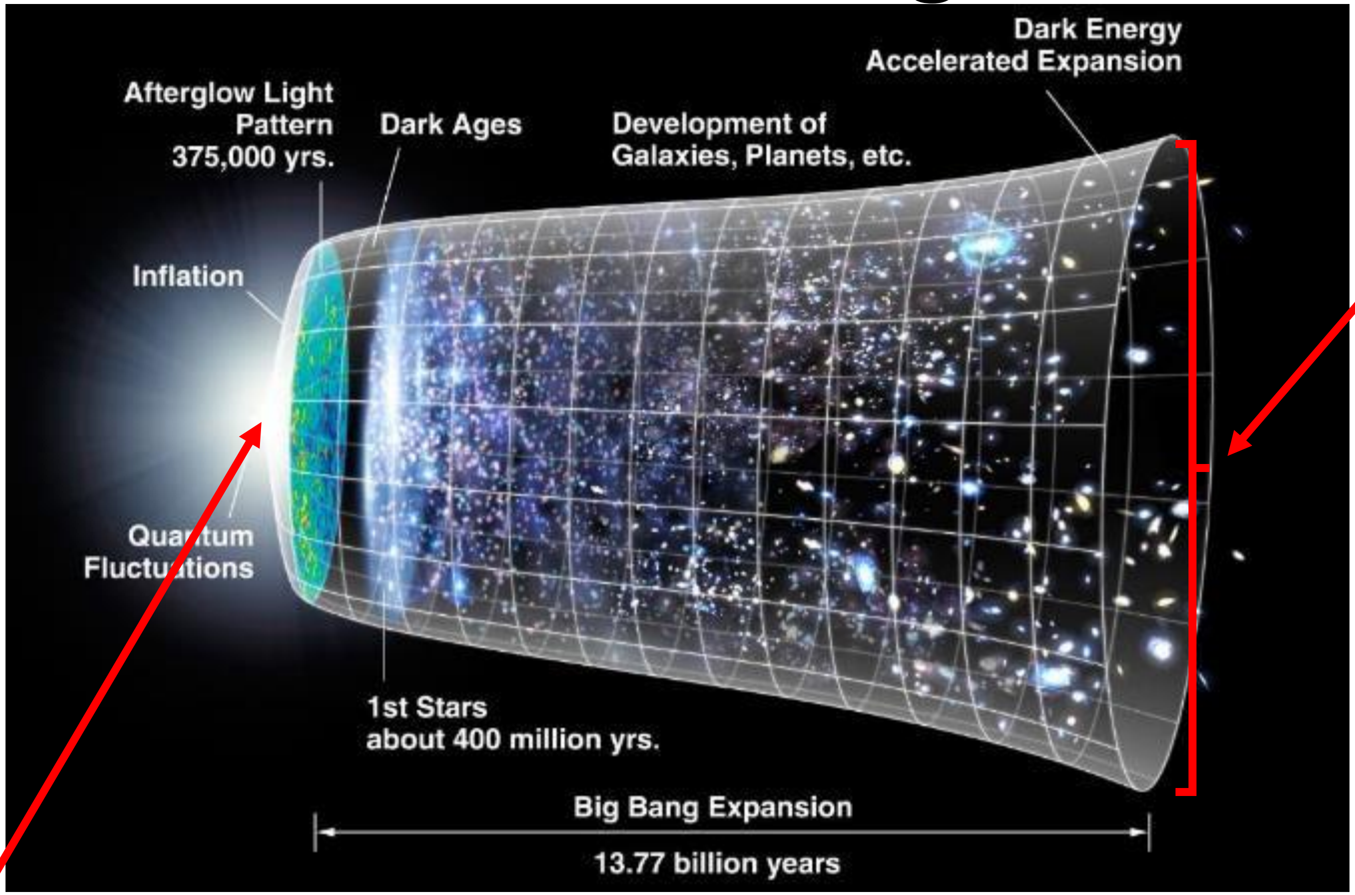
*TAO is 40 meters higher!

CCAT Science: Evolution of the Universe



- Trace reionization process and galaxy evolution through line intensity mapping (LIM)
- Trace the history of dusty star formation across cosmic time with submillimeter continuum surveys
- Trace the growth of large-scale structure and fundamental physics through SZ studies of massive galaxy clusters

The CCAT Science: Origin of the U.



- Reveal the processes of star formation in the Galaxy and nearby galaxies through spectroscopy and polarization studies

- Greatly improve searches for primordial gravity waves from the inflationary epoch through deep submm polarization measurements of the CMB

CCAT's Forte

This is mostly large-scale mapping and low surface brightness science *enabled by:*

- A large field of view (FoV) telescope
- Sensitive, large FoV instrumentation
- A high surface accuracy, low emissivity telescope
- An extraordinary submillimeter site

The Fred Young Submillimeter Telescope (FYST)

6 m off-axis submm telescope

- Exceptionally wide field of view: up to 8° @ 3mm wavelength
- Exceptionally high surface accuracy: <10.7 μm rms
- No blockage: ε < 2.8% which optimizes system sensivity
- Fast scanning: 3°/sec minimizing sky/detector noise
- Exceptional site on Cerro Chajnantor at 5600 m elevation
- State of the art wide-field instrumentation

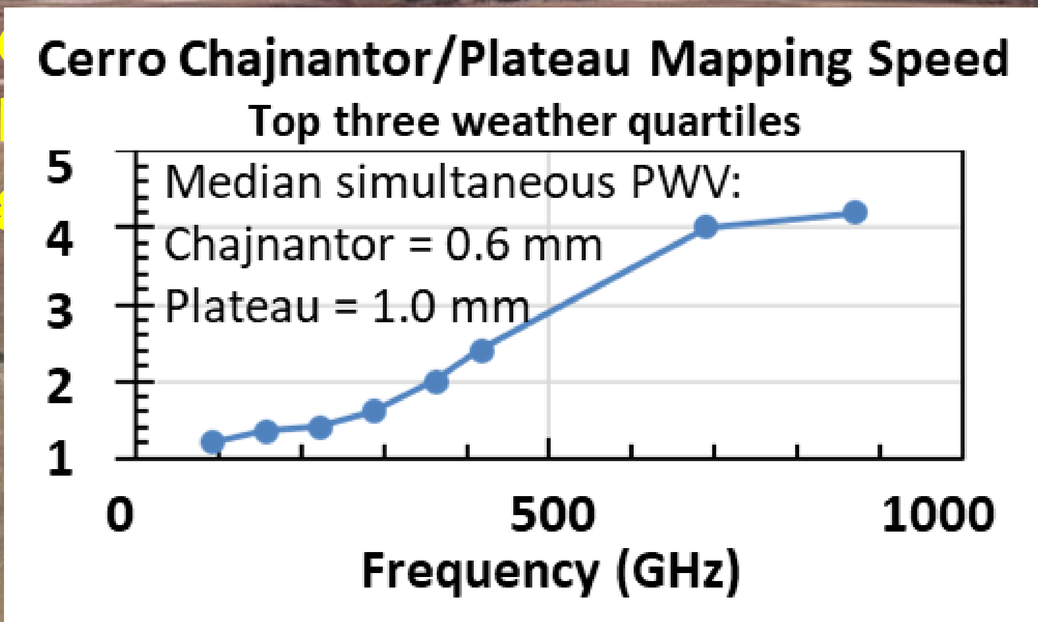
Manufactured by Vertex Antennentechnik gmbh

Unsurpassed performance for wide-field low surface brightness science

Is the extra 600 meters worth it?

FYST site at 5600 m

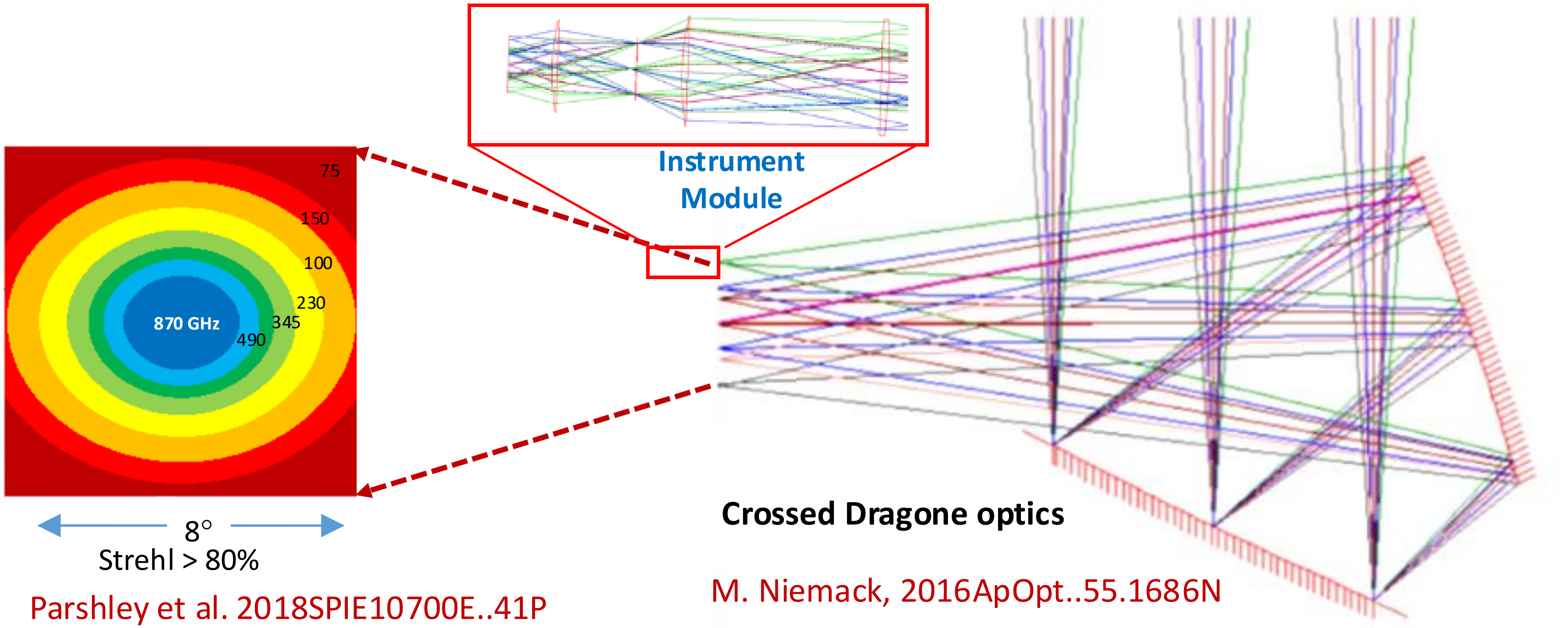
Cerro Chajnantor



Chajnantor plateau ALMA site at 5000 m

Giovanelli et al. 2001 PASP 113, 803G
Radford and Peterson 2016. *Pub. Astron. Soc. Pacific*, 128: 965.

FYST Optics: Field of View



Parshley et al. 2018SPIE10700E..41P

M. Niemack, 2016ApOpt..55.1686N

- Field is split into **"instrument modules"** ⇒ reasonable 45 cm diameter windows ⇔ **1.3° FoV**
- Each module can have entirely different configurations: e.g., **cameras/spectrometers**

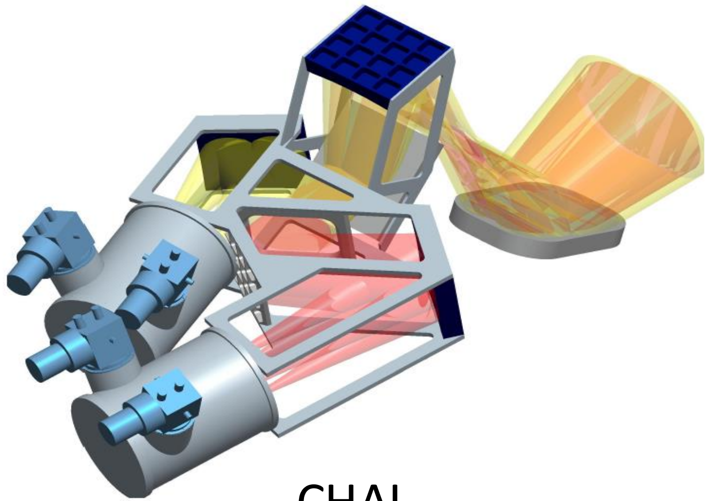
A "filled focal plane" has:

3 mm	1,300 1.2f·λ beams
2 mm	3,000 1.2f·λ beams
1 mm	12,000 1.2f·λ beams
0.35 mm	98,000 1.2f·λ beams

Or well over 100,000 beams!

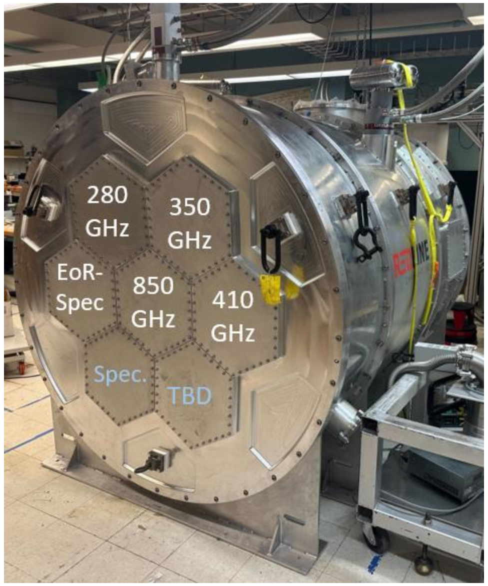
Instrumentation Enables the Science

Name	Driver Science	Frequency Range	FoV	No. Pixels
CHAI [CHAI (THz)]	Galactic Ecology Mini-CHAI	455-495, 800-820 GHz 1.4-1.5 THz	17’ x 8.5’ 1 beam	2×64 2×1
Prime-Cam Cameras	kSZ, Galactic Evolution	280, 350, 410, 850 GHz	3^0 diameter	$>5.9 \times 10^4$
Prime-Cam Spectrometers	LIM/EoR-Spec	210-420 GHz	$2 \times 1.3°$	1.2×10^4

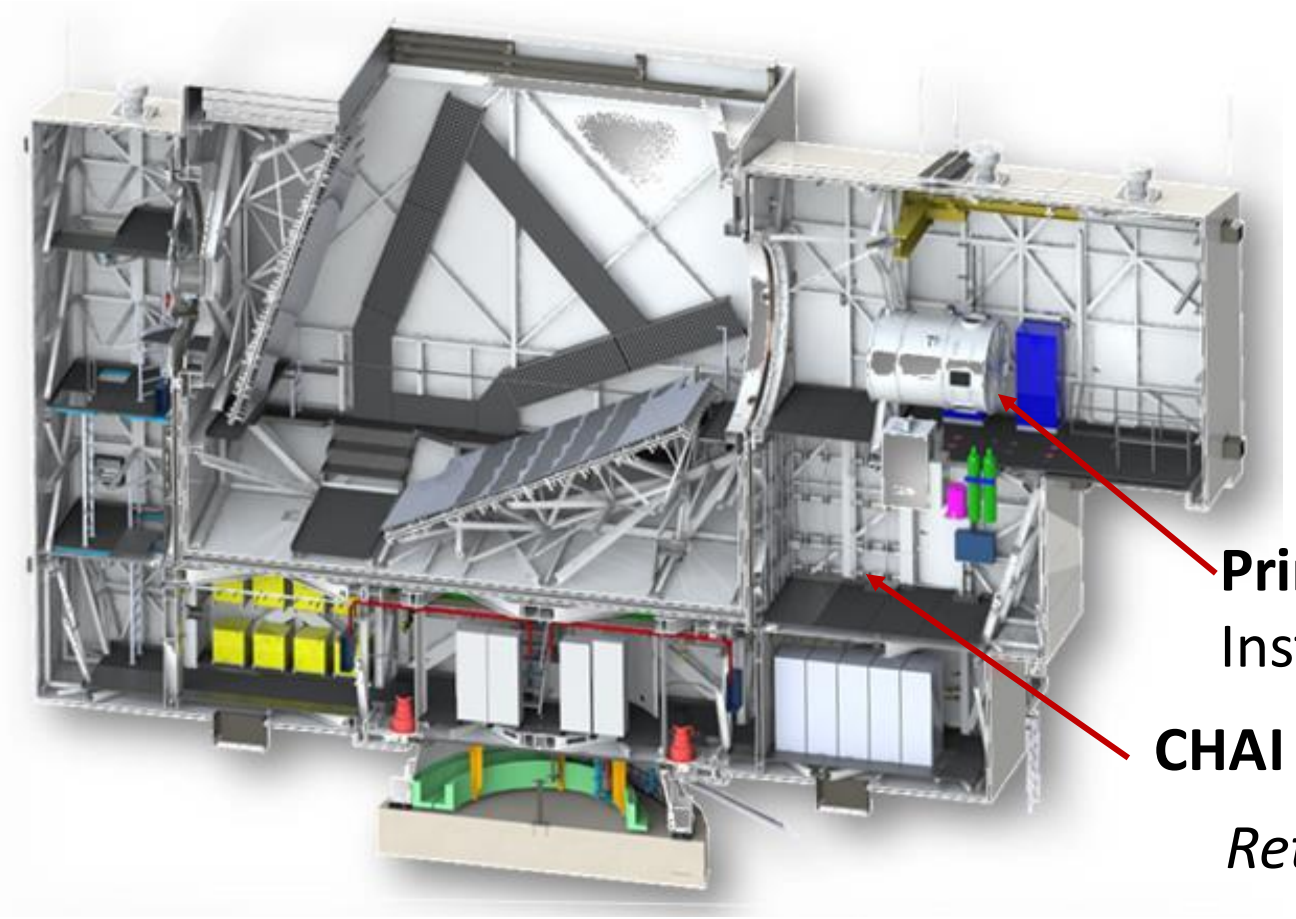


CHAI

Prime-Cam



Co-mounted Instruments



FYST
Cutaway

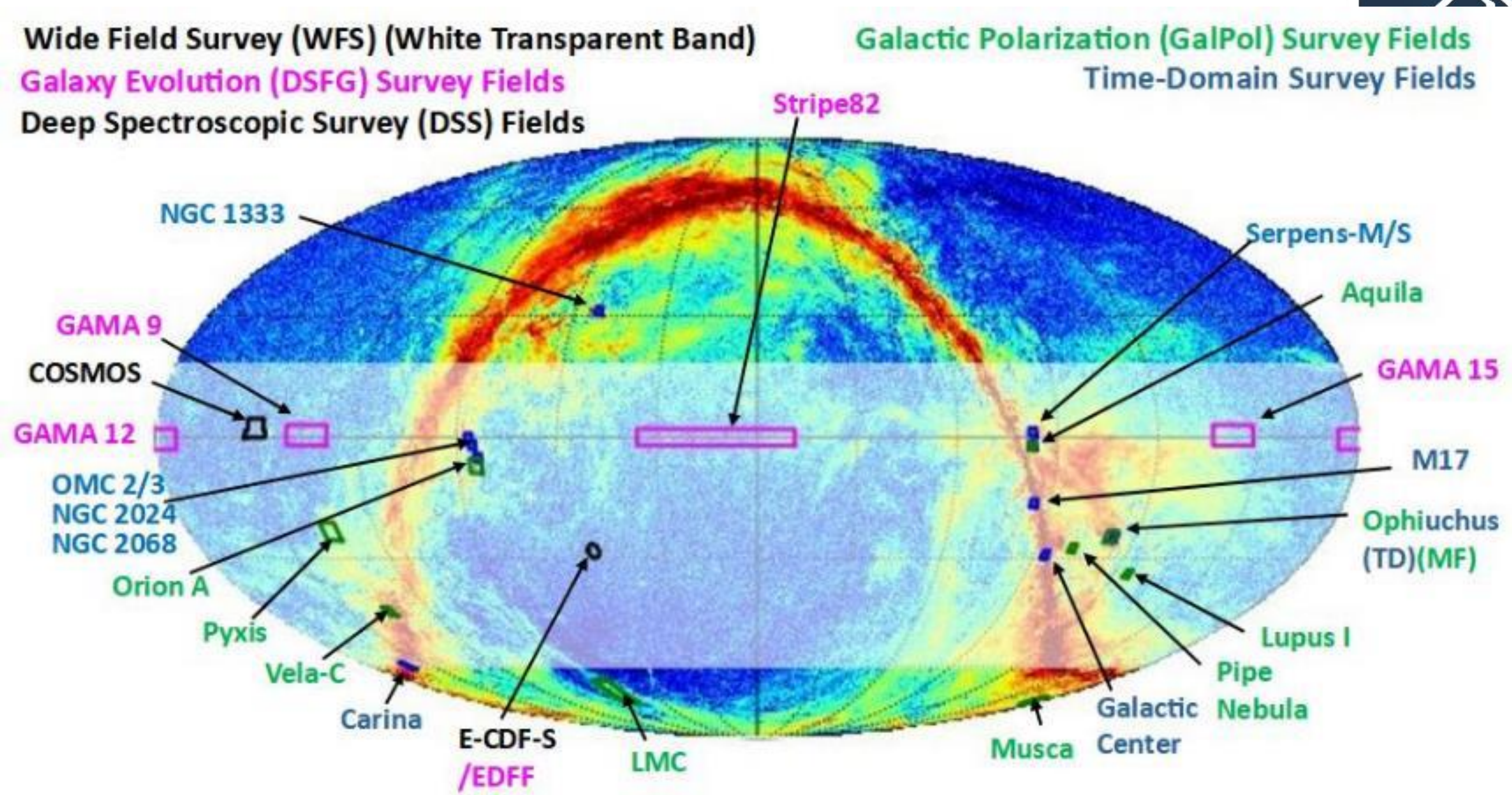
Prime-Cam Instrument Station -1

CHAI Instrument Station-2

Retractable tertiary

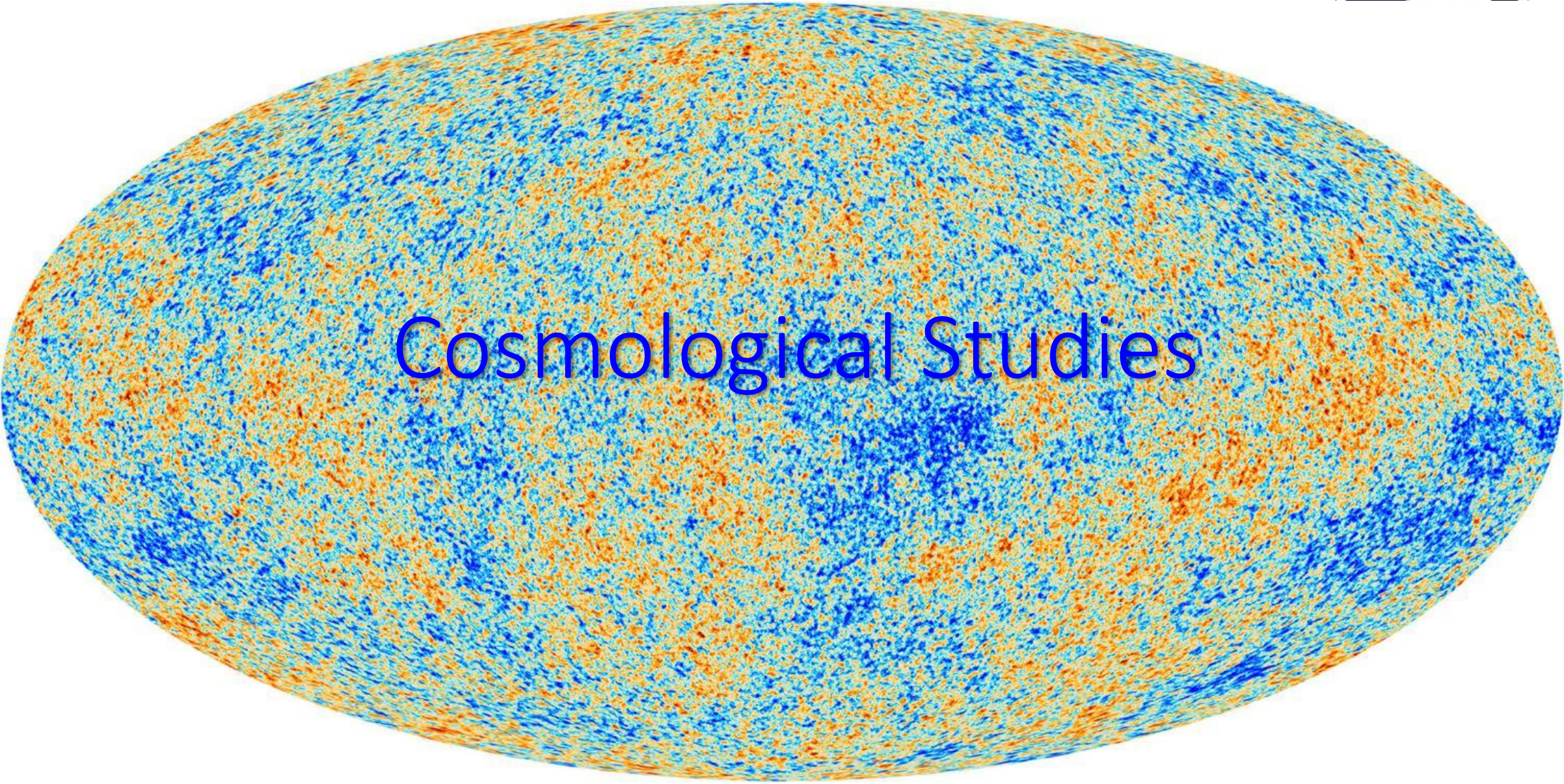
One instrument at a time, in campaign mode: limited by power requirements

Prime-Cam Survey Fields



- **Wide Field Survey** (20,000□°)– CMB & SZ **4000 hours in 5 years**
- **Deep Spec. Survey** (2×4□°)– LIM
  4000 hours total in 5 years
- **Selected Fields** – CIB, Galactic, & Transient science
  ~ 2000 hours total in 5 years

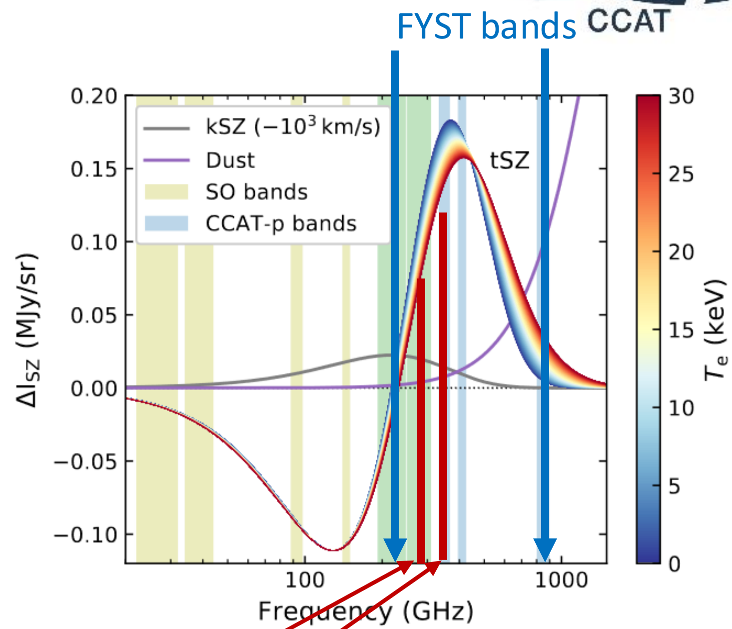
Science Plans



Cosmological Studies

S-Z Science

- Galaxy clusters affect the CMB through the Sunyaev-Zeldovich effect:
  - Thermal – tSZ total cluster thermal energy
  - Kinetic – kSZ movement w.r.t. CMB
  - Relativistic – rSZ mean T of scattering electrons
- Focus on 280-850 GHz bands complementing AdvACT and planned SO 30 to 280 GHz surveys



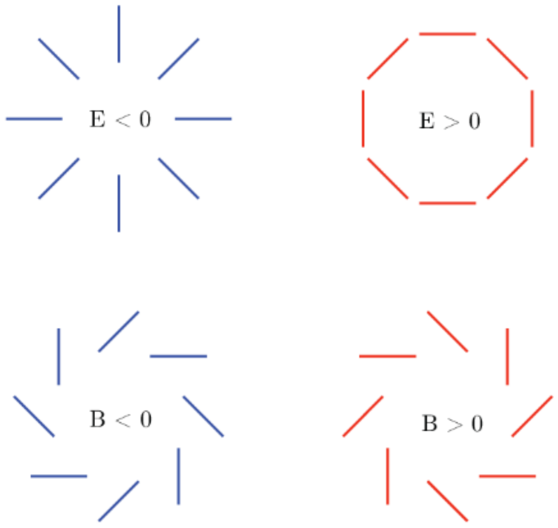
- High frequency FYST observations are critical for separate SZ components *and* for removing dust foregrounds. ***Both 280/350 modules for 1st light!***
- Yield constraints on:

  - Parameters that govern the growth of structure in the Universe, e.g. H_0, dark energy equation of state, dark matter, sum of the neutrino masses…

  - Role of AGN in heating intra-cluster and AGN/SF feedback

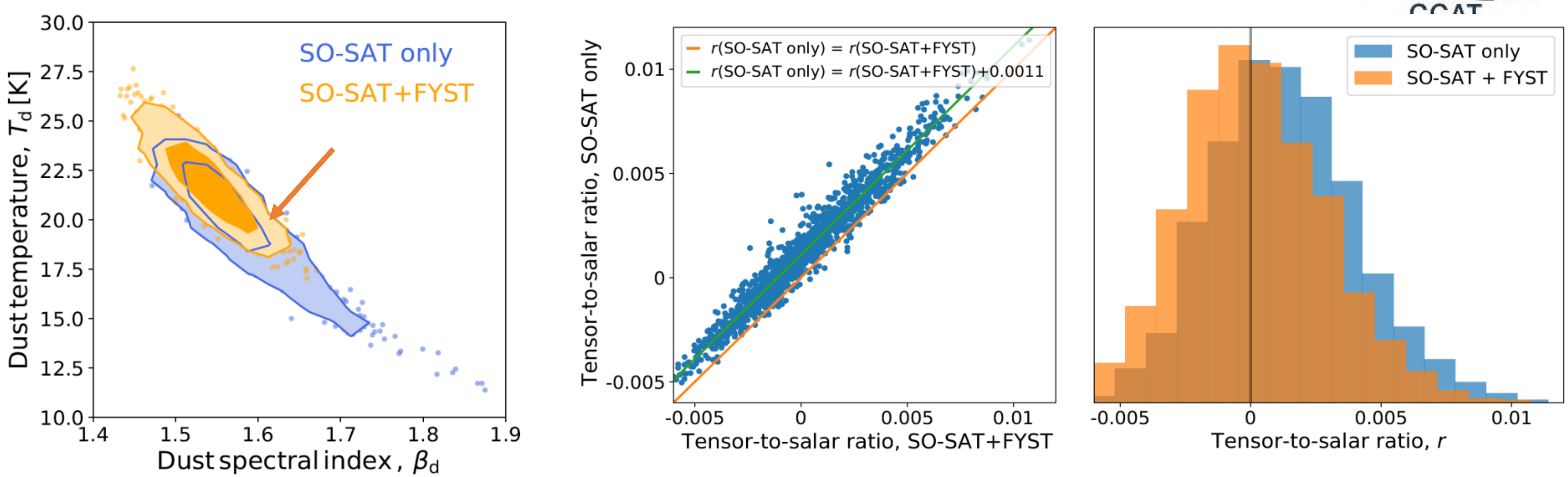
Search for Gravitational Waves

- Detailed CMB observations of temperature and polarization constrain cosmological parameters that determine large scale structure– e.g. H_0, $\Omega_b h^2$, Ω_m, Ω_Λ, age…
- Prime-Cam on FYST will improve constraints on the amplitude of *primordial gravitational waves* that are imprinted on CMB 'B-mode' polarization
- B-modes are predicted by inflationary theories – critical to understanding of "puzzles" of large-scale structure including horizon and flatness problems, etc.
- Detection of primordial B-modes would be fundamentally important!



Note that E-modes will stay the same on reflection, while a negative B-mode will look like a positive B-mode on reflection, and vice-versa.

Better constraints on cosmological “r”



Eiichiro Komatsu

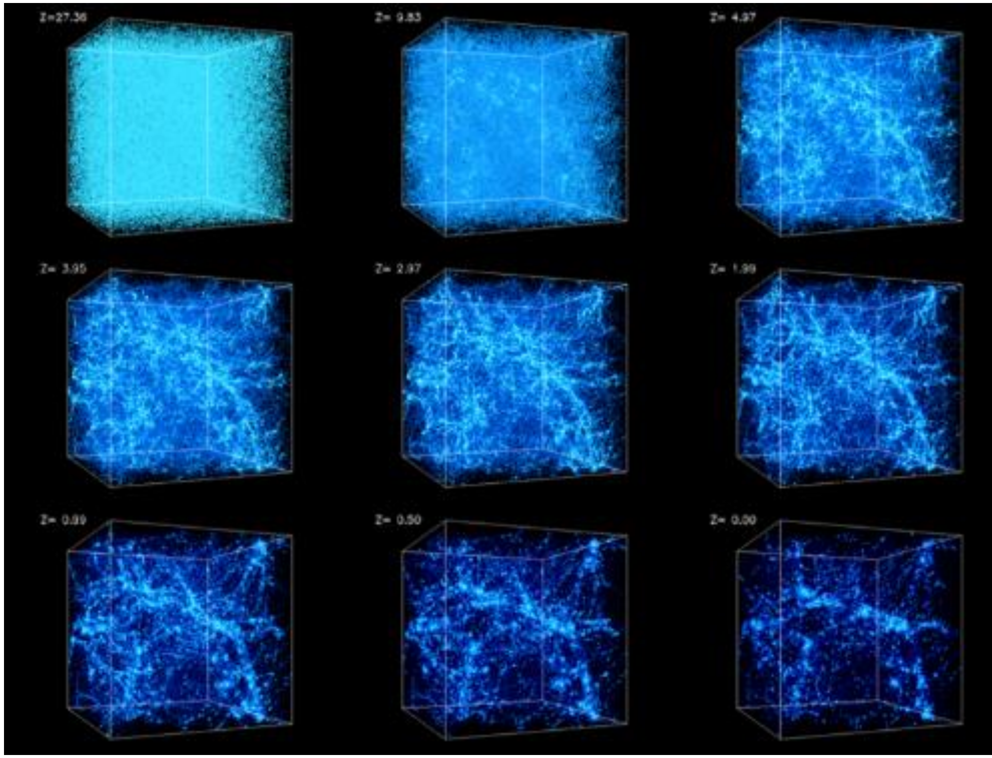
- Dust foregrounds complicate measurements the cosmological tensor-to-scalar ratio, “r”
- Dust parameters (β_d, T_d) constrained with muli-λ observations, enabling effective removal of Galactic polarization.
- A non-zero tensor-to-scalar ratio, $r \sim 0.001$ is expected in inflationary models
- Without FYST the bias in the r is ~ the expect signal $r_{SO\text{-}SAT} = (1.3 \pm 2.8) \times 10^{-3}$
- With Prime-Cam the bias essentially zero! $r_{SO\text{-}SAT+FYST} = (0.2 \pm 2.7) \times 10^{-3}$

Line Intensity Mapping
HII
bubble
neutral H
ionized HII
Loeb 06

Overall Goal

- Trace the evolution of star and galaxy formation as linked to underlying structure, the "**cosmic web**" from the epoch of reionization through cosmic noon

- Need large scale tracers of the:
  - Star "stuff": hydrogen: CO/ HI 21 cm
  - Star formation: Hα 656 nm, [CII] 158 μm
  - Structure: from the galaxy sizes to that of cosmic web over-densities
  - *Need 3-d maps: X, Y, and "z"*



- A variety of tracers over < Mpc to > 30 Mpc scales ⇔ < arcminute to degree scales

Deep Surveys, Large Fields

- To map individual galaxies (arcseconds) over degree scales is impractical
- Largest telescopes have small fields of view, and to use them it would be prohibitively expensive time wise

*We need a $2^{\circ} \times 2^{\circ}$ field for our science: **2500 ×** larger than the SMACS 0723 field!*

JWST
SMACS 0723

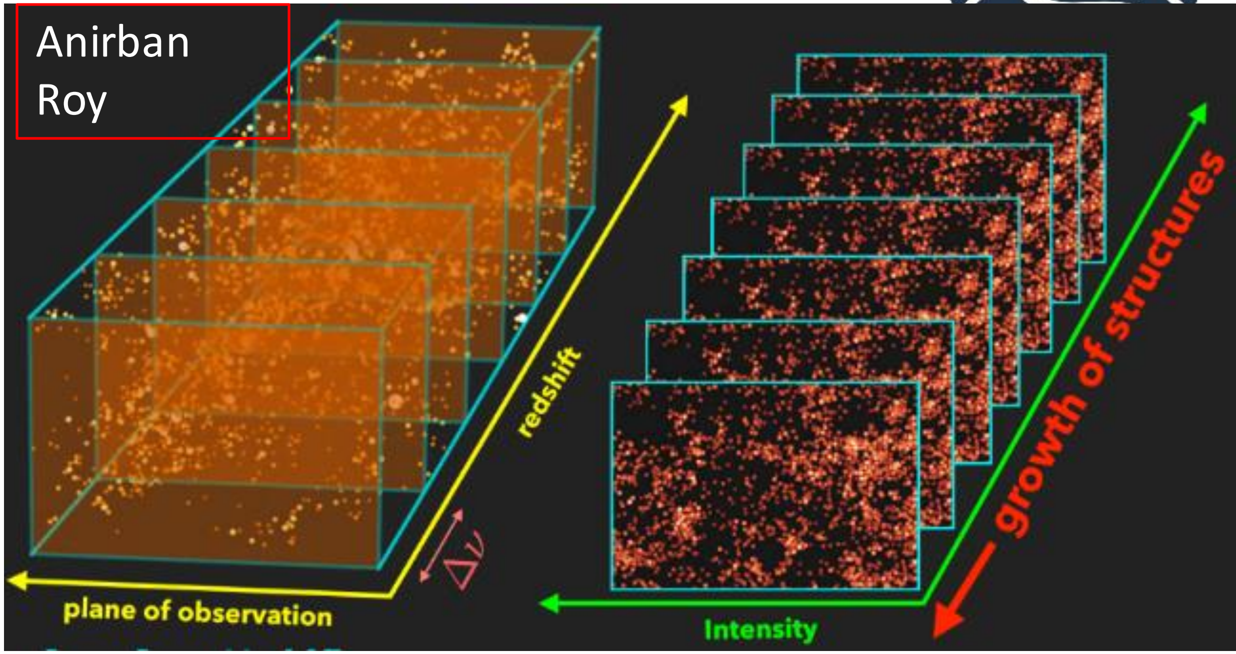
2.4'

A Practical Approach

- Fortunately, the predominant sources of reionization are smaller systems that are quite faint but very numerous
- A practical approach emerges. *Map the aggregate signals from these faint sources.*
- This Line Intensity Mapping (LIM) technique is easier to effect:
  - Dedicated highly multiplexed spectral/spatial systems tuned to spectral lines at appropriate redshifts
- A variety of tracers (e.g. HI, CO, Hα) over 0.3 Mpc to > 20 Mpc scales ⇔ arcminute to degree scales
- We chose to focus on [CII] – with [OIII] and CO as well…
- ***For [CII], FYST is ideal:*** the beam @ 1 mm ~ 45” ⇔ 0.25 Mpc at z ~ 8 (210 GHz) & modules with 1.3° fields of view ⇔ 25 Mpc
- Our fields (E-COSMOS, and E-CDF-S) are the most extensively studied deep extra-galactic fields

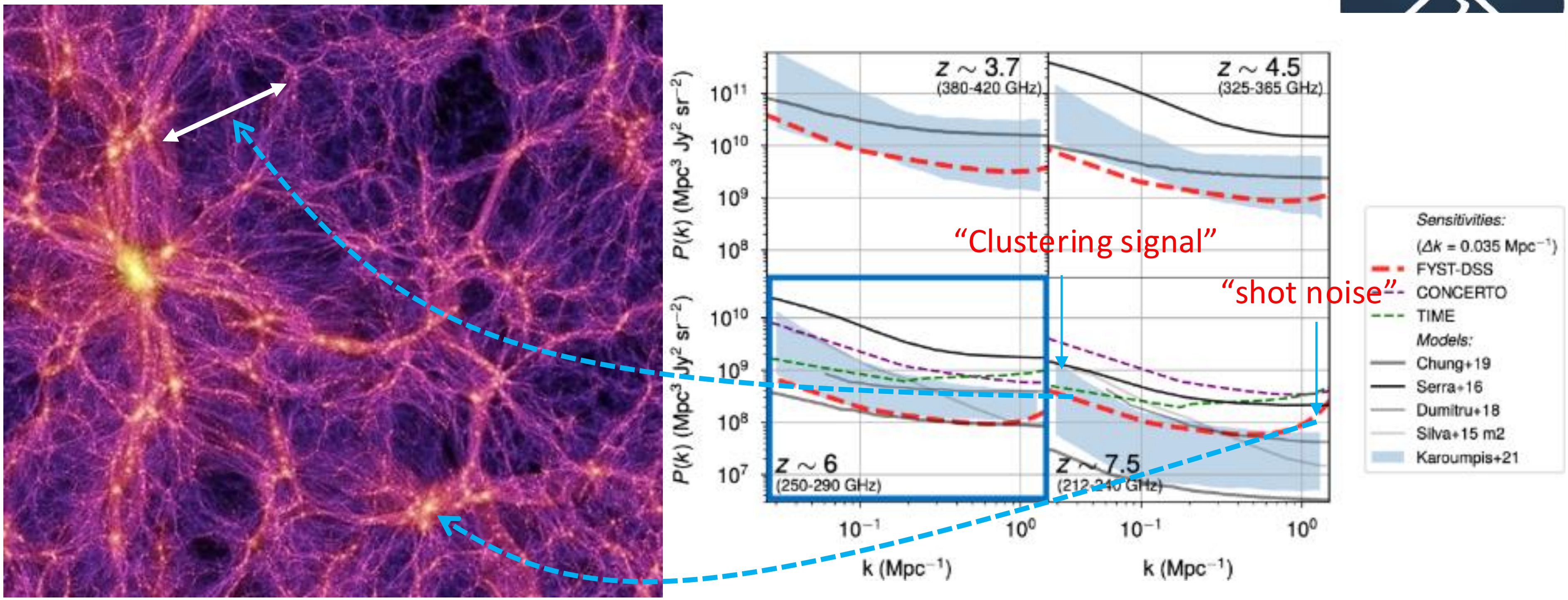
A Visualization of the Data

- **EoR-Spec Fabry Perot Interferometer**
  - RP ~ 100,
  - ν: 210 – 420 GHz
  - 3.5 < z < 8 in [CII]
  - 2 x 4 sq. deg. field
- Translating:
  - 2° field is 36 Mpc on a side at z ~ 8
  - Beam = 0.25 Mpc in x & y
  - Vel Res. 1% ⇔ 24 Mpc in z or 9 million years



- Reveal the growth of galaxies and large-scale structure over cosmic time
  - 3-d measurements of the of evolution of star/galaxy formation from redshift 8 to 3.5 – the *Epoch of Reionization through to Cosmic Noon*
  - [CII] tracks star formation tracing both the *reionization process* and the underlying and evolving Cosmic Web ⇒ *traces the growth of structure: reflecting the fundamental physics of* dark matter, GR, dark energy…

A Difficult Measurement



- ❑ Not likely to directly image structures ⇒ detect structure size-scales in the Fourier domain

- ❑ A very challenging program need to maximize sensitivity and pixel counts (spectral × spatial) in the system ⇒ we chose an imaging FPI – EoR-Spec:
  - ➢ Instrument predictions in dashed lines: no current competition at z< 5

- ❑ EoR-Spec on FYST promises to be a very competitive system at all targeted redshifts

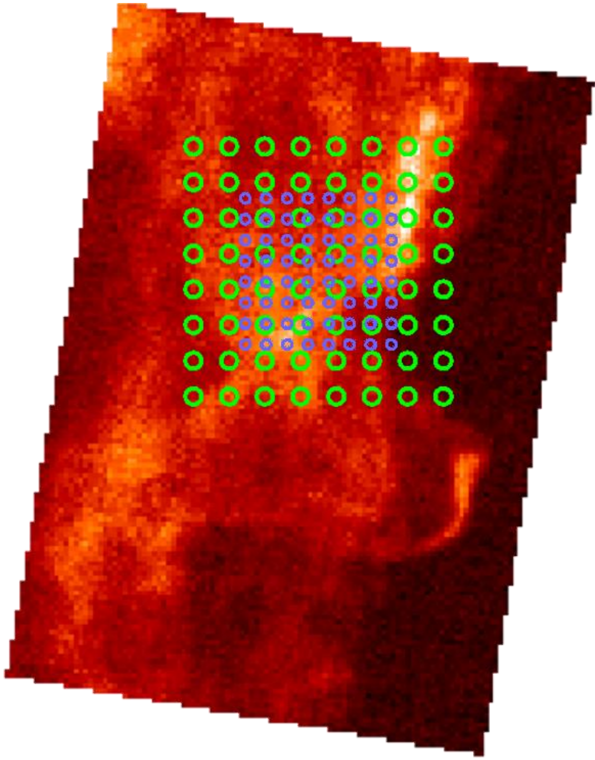

Galactic Ecosytems with CHAI

CHAI: 64 pixel, 2 frequencies

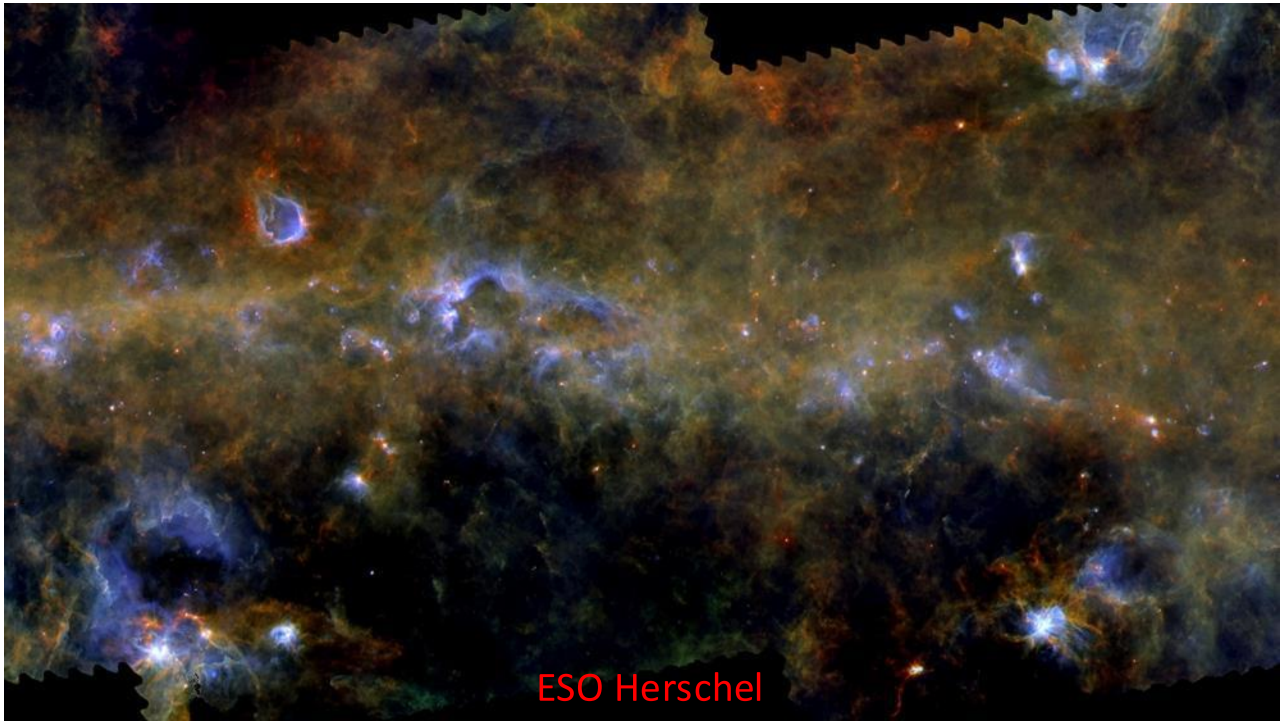
- **LFA:** 455-495 GHz and **HFA:** 800-820 GHz
- **Targeting:**
  - CO 4-3 and [CI] 1-0 and
  - CO 7-6 and [CI] 2-1
- **DSB noise temperature:** < 100K @490GHz and < 200 K @810 GHz
- **Velocity coverage:** 2500 and 1500 km/s

Designed for large scale mapping of velocity resolved spectral lines

CHAI's 8x8 pixels overlaid on [CII] map of horse head nebula



Galactic Science with CHAI



- Velocity resolved imaging of the Galaxy in submm [CI] and mid-J CO lines
- 15” imaging over 200 $(^\circ)^2$ scales (*50,000:1*) of the Milky Way, LMC, SMC:
  - [CI] tracing gas temperature and mass $\Rightarrow$ tracking “CO dark” gas
  - Mid and high-J CO & ^{13}CO tracing gas excitation, shocks, density and mass
- Tracing accumulation and flows of gas into cores and young stars.

First Light Science Goals

- Prime-Cam
  - Test mapping strategies
  - SZ-Science, CIB galaxy evolution in Deep56 patch and selected Herschel deep fields
  - Polarization studies of Galactic molecular clouds and star formation regions – overlap with SOFIA/HAWc+ (far-IR) fields
  - React to targets of opportunity ’s and monitor known variable protostars
- Mini-CHAI
  - Test mapping strategies/measure high frequency performance
  - [CI]/CO mapping of Galactic starformation regions – address CO-dark molecular cloud science
  - Demonstrate sensitivity and stability with extragalactic measurements including redshift 1.3 [CII] observations

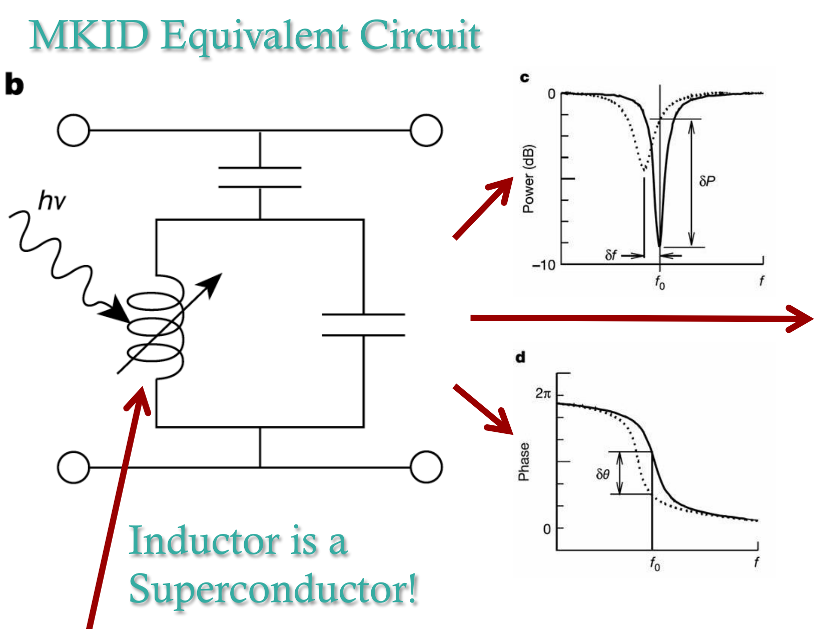
Instrumentation with Status

Prime-Cam overview

- Design drivers
  - Uses the 4.5° heart of 8° FYST FOV
  - Modular approach ⇒ path for next generation technologies
- Initial module configuration
  - 4 polarization modules funded:
    280, 350, 410, 850 GHz
    - Mike Niemack (280, 350 GHz) lead
    - Scott Chapman (850 GHz) lead
    - Eve Vavagiakis & Chapman (410 GHz leads)
  - R=100 spectrometer module 210 – 420 GHz funded (possibly 2):
    - Gordon Stacey lead
- Future on-chip spect. (90 – 180 GHz)
    - Abby Crites lead

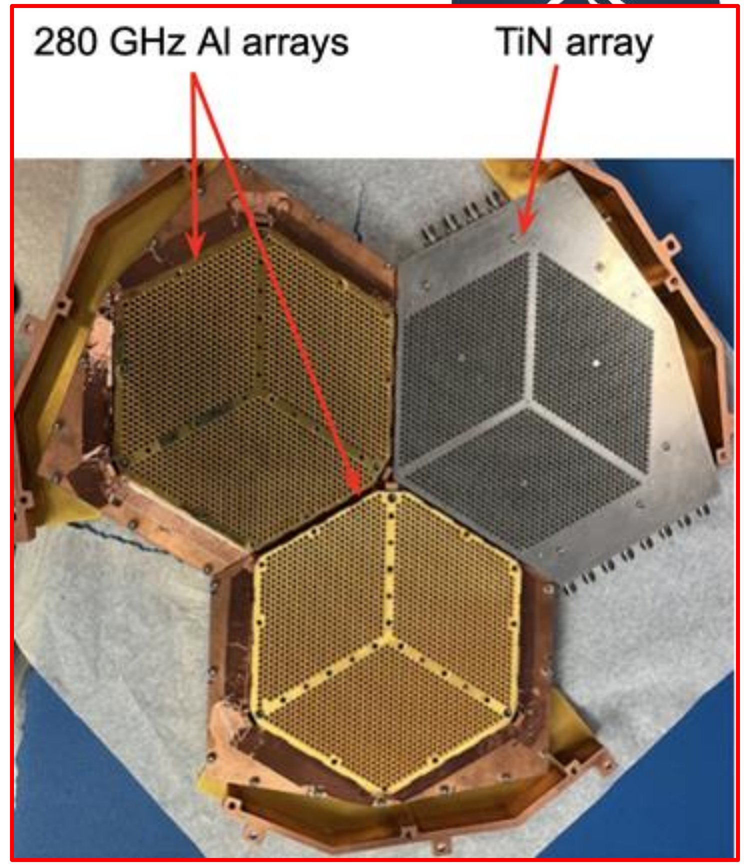
Prime-Cam: Detectors

- ❑Kinetic Inductance Detector (KID) arrays (NIST)



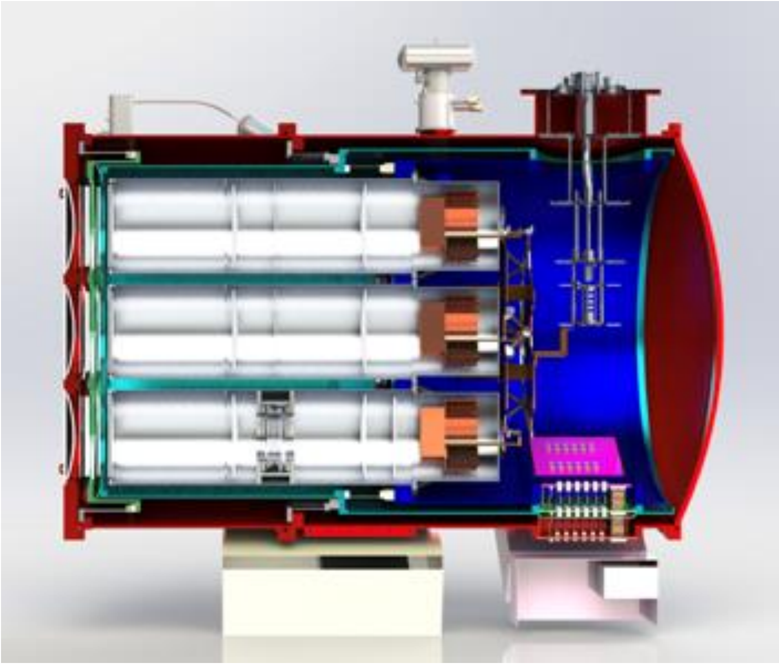
- ❑3,500 – 20,000 detectors per camera
- ❑Arrays tested within Prime-Cam and ModCam in Niemack lab

280 GHz array for PrimeCam

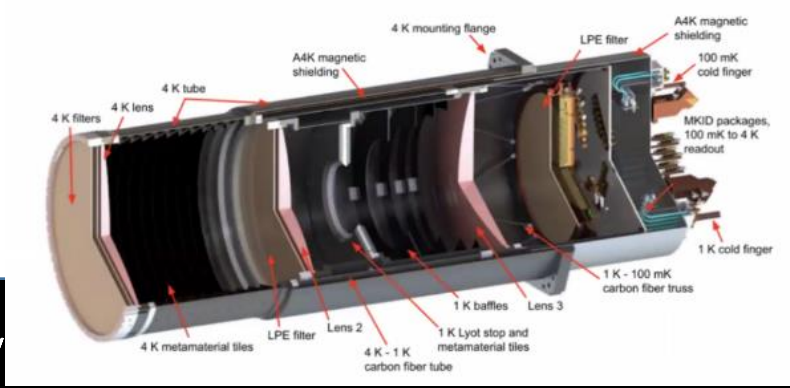


Prime-Cam: Cryostat

- Manufacture: Redline Technologies



Cross section of Prime-Cam design



Thomas Nikola, Yuhan Wang, Lawrence Lin and Mike Niemack

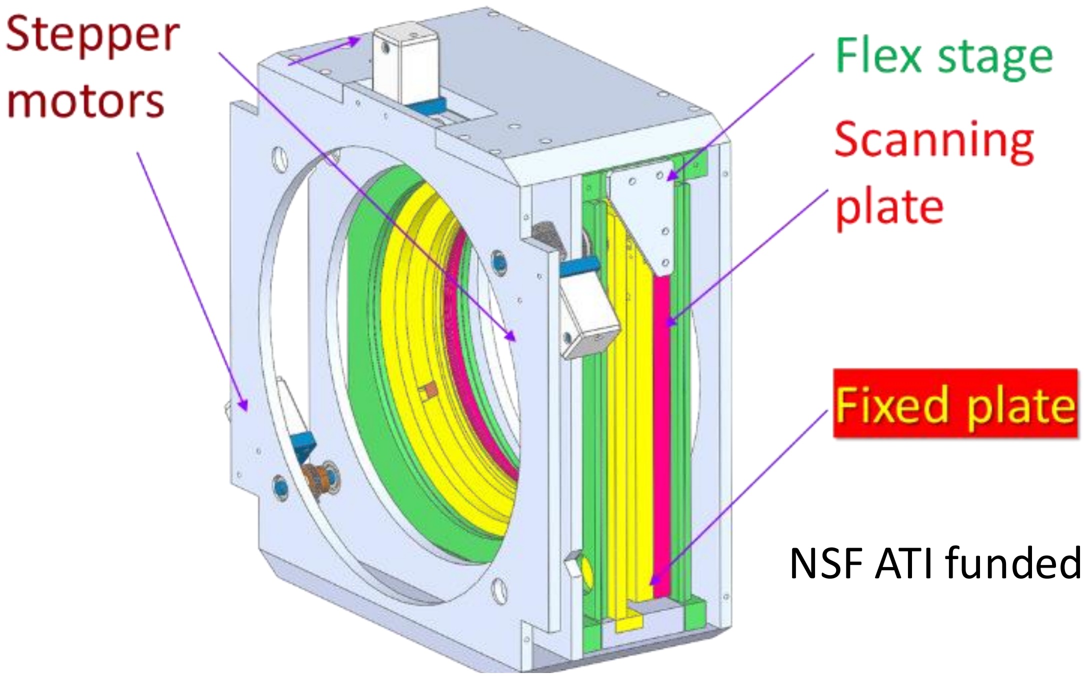
Arrived January 2025 shipped to CCAT in < 1.5 years!

Prime Cam: Arrival in Late July

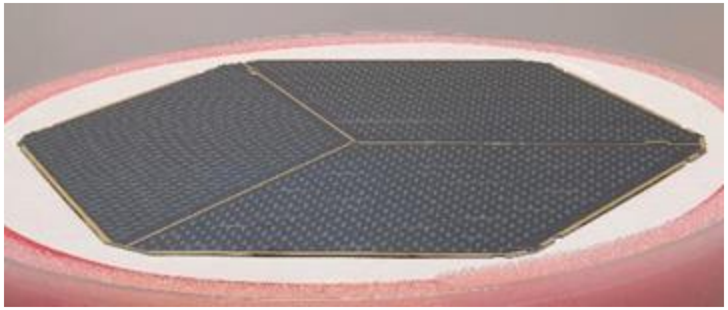
- Shipped and on its way to FYST
- Now in the Pacific Ocean

- Expected at site in late July

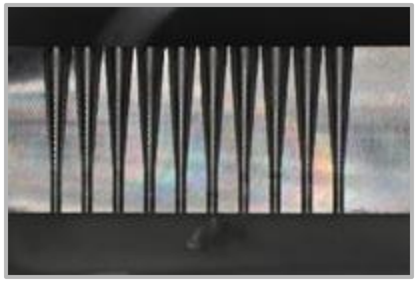
FPI Imager Called “EoR-Spec”



NSF ATI funded



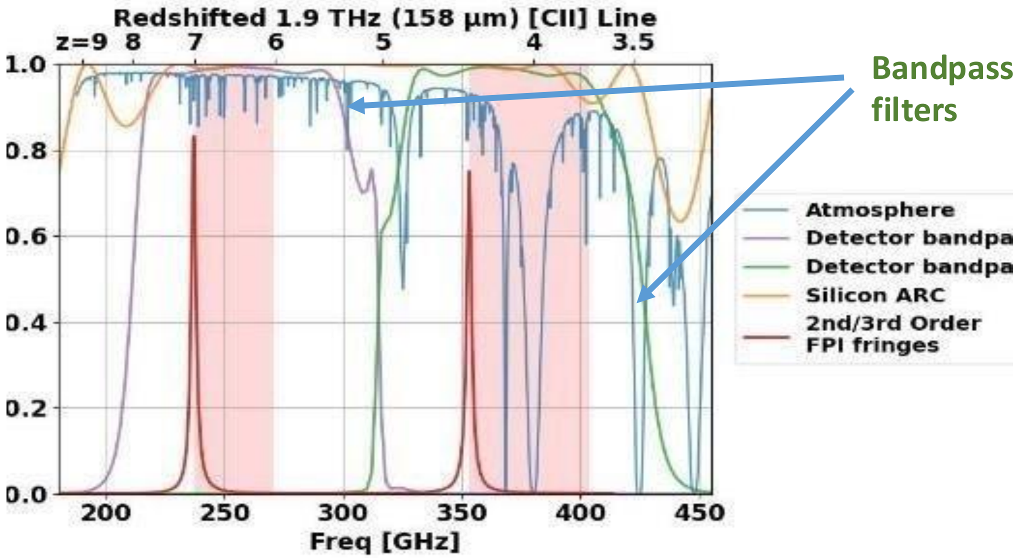
210-315 GHz Array

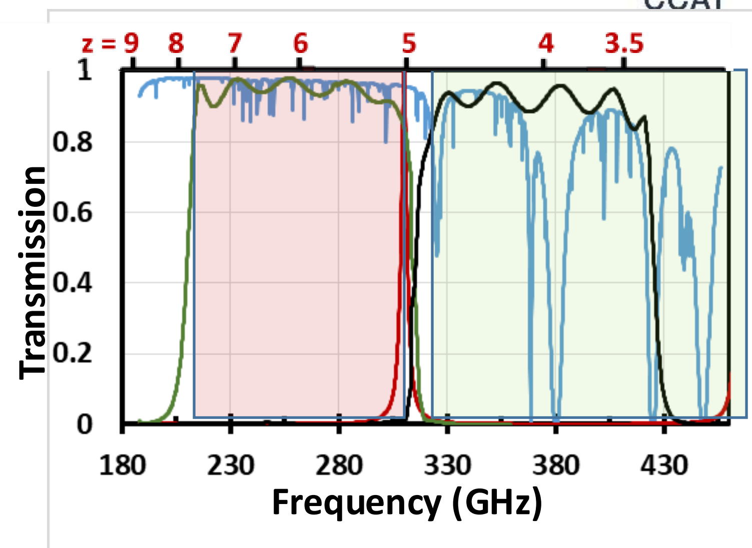


Al feedhorn array

- ***Known, high efficiency technologies***
- Array similar to cameras: but polarizations tied together and a somewhat lower NEP requirement
- Designed to have finesse $\propto \lambda$ to achieve near uniform resolving power using silicon-substrate-based mirrors

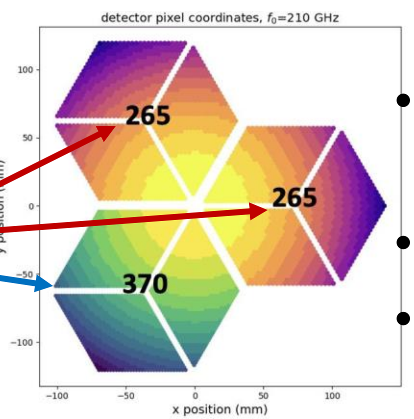
Fabry-Perot Fringe Selection, Spectral Multiplexing, and Scanning





Features

- Natural spectral multiplex of ‘
40 GHz, or 35% of total BW
- 2 (1) KID array (2nd and 3rd) orders sorted w/ BP filters
- Beams (2) modules is: 6912 (6144) @ 280 (350) GHz

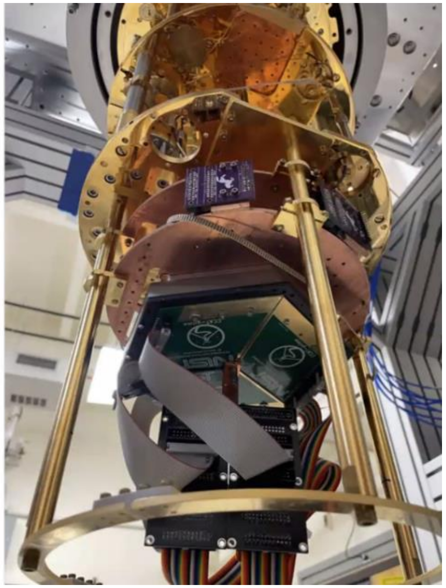
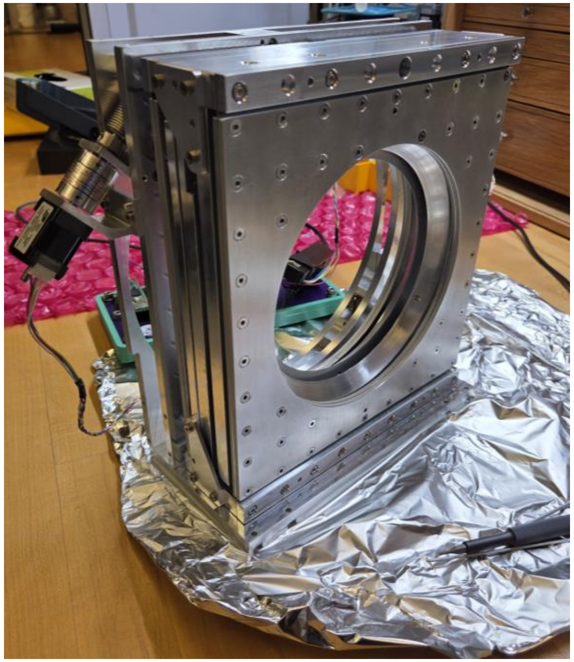


Observing Technique

- Start @ 210 and 315 GHz (2nd & 3rdorder)
- Spatially scan on sky
- Move FPI – spatially scan again – need ~ 10 spectral steps for full

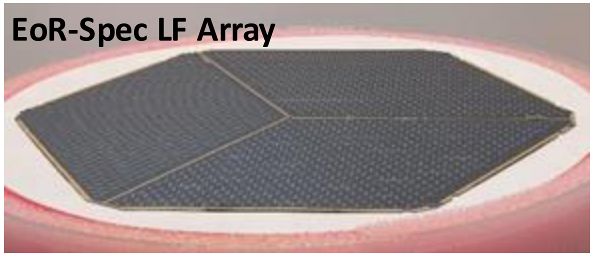
EoR-Spec Status: Expected First Light in 2nd Quarter 2027



- First low frequency array LED-mapped at NIST
  - Reveals/checks tone-pixel IDs
  - Tone "collisions" make pixels not viable
- Capacitor trimming increases pixel yield to > 95%

Rodrigo Freund



FYST timeline

- Celebrated "completion" in April 2024 in Germany
- Shipped major components beginning in September 2024
  - Mirror shipment delayed
- Major telescope parts arrived in the spring of 2025
  - Mirrors begin their journey in the summer
- Assembly at site in the fall of 2025

April 20, 2025

Reconstruction begins!

Yoke Arm Assembled: June 6, 2025

Azimuth motion demonstrated!

Installation of the FYST yoke arms on 10 Nov (top) and 15 Nov (bottom). Notice the yoke traverse was rotated 180º between the two dates. Nov 2025

February 22, 2026

With alignment of the yoke arms completed, construction of the upper sections of the elevation housing proceeded.

March 5, 2026

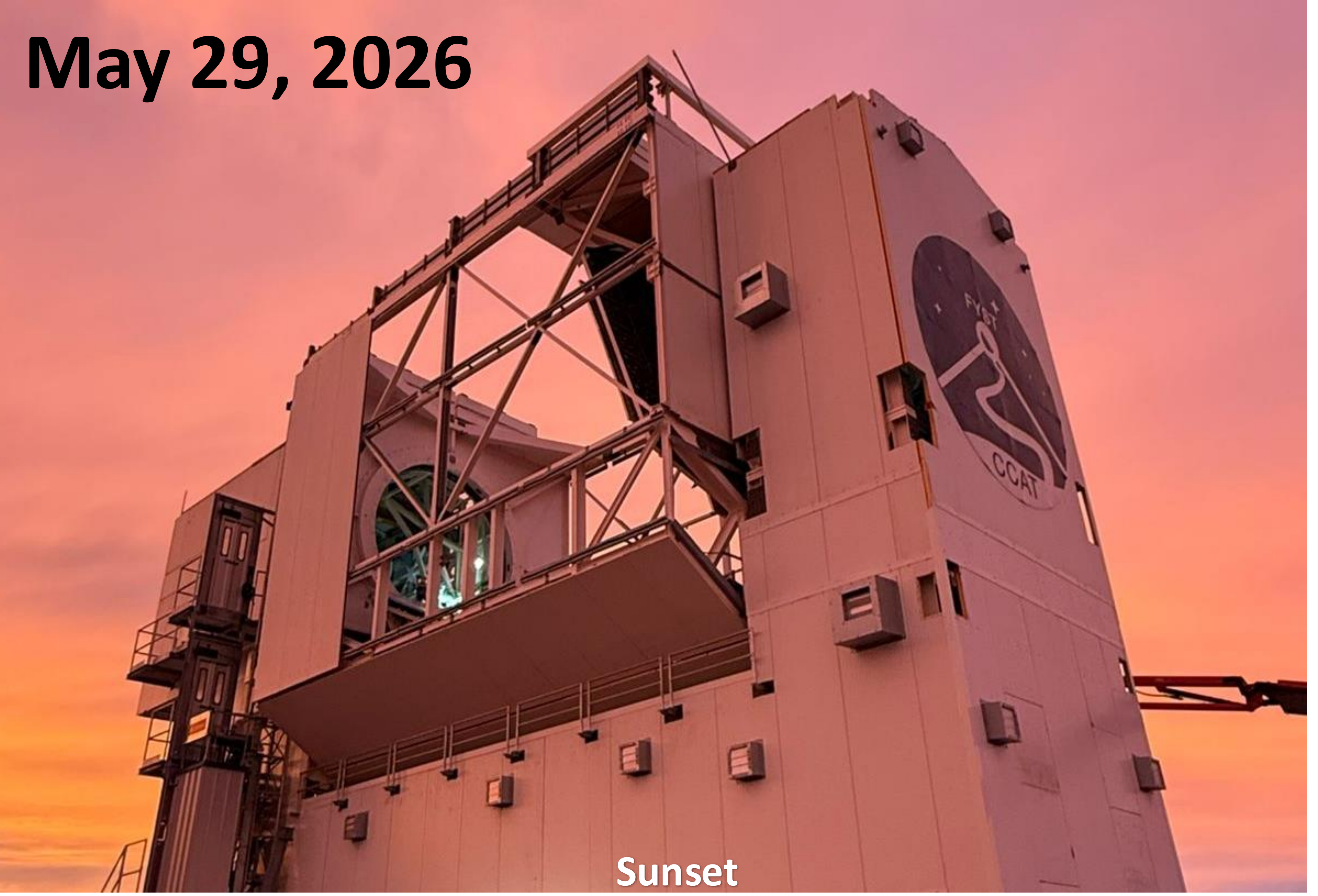
View of the CCAT Observatory summit site with the FYST under construction.

April 9, 2026

Inaugural Event: Attendees at the Summit

Elevation zero

May 29, 2026



Sunset

The Near Future

- Q4 2026:
  - Mirror alignment (holography) in the fall
  - First light with “Mini-CHAI”
- Q3-4 Installation of Prime-Cam
  - First light with Prime-Cam
- Q1 2027
  - Installation of EoR-Spec
  - Installation of the 850 GHz camera
- Q2 2027: Beginning of routine operations

Inviting partners at all levels…