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

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Cornell University

Canadian Consortium

What is FYST?

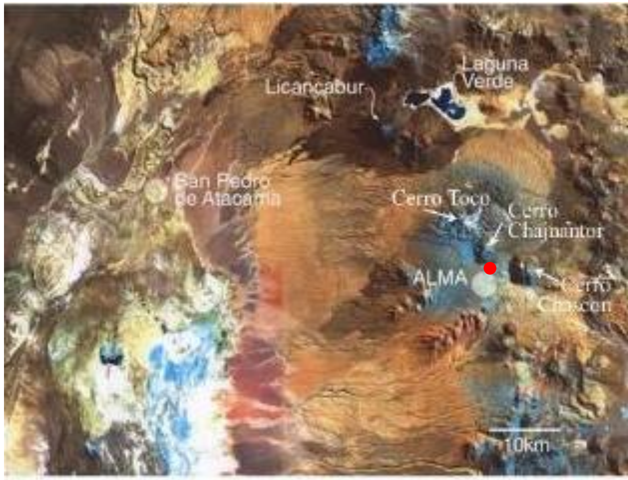
The **Fred Young Submillimeter Telescope** (FYST) is a 6-meter diameter, high precision telescope located at 5600 m elevation on Cerro Chajnantor in the Atacama desert region of northern Chile:

- 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.

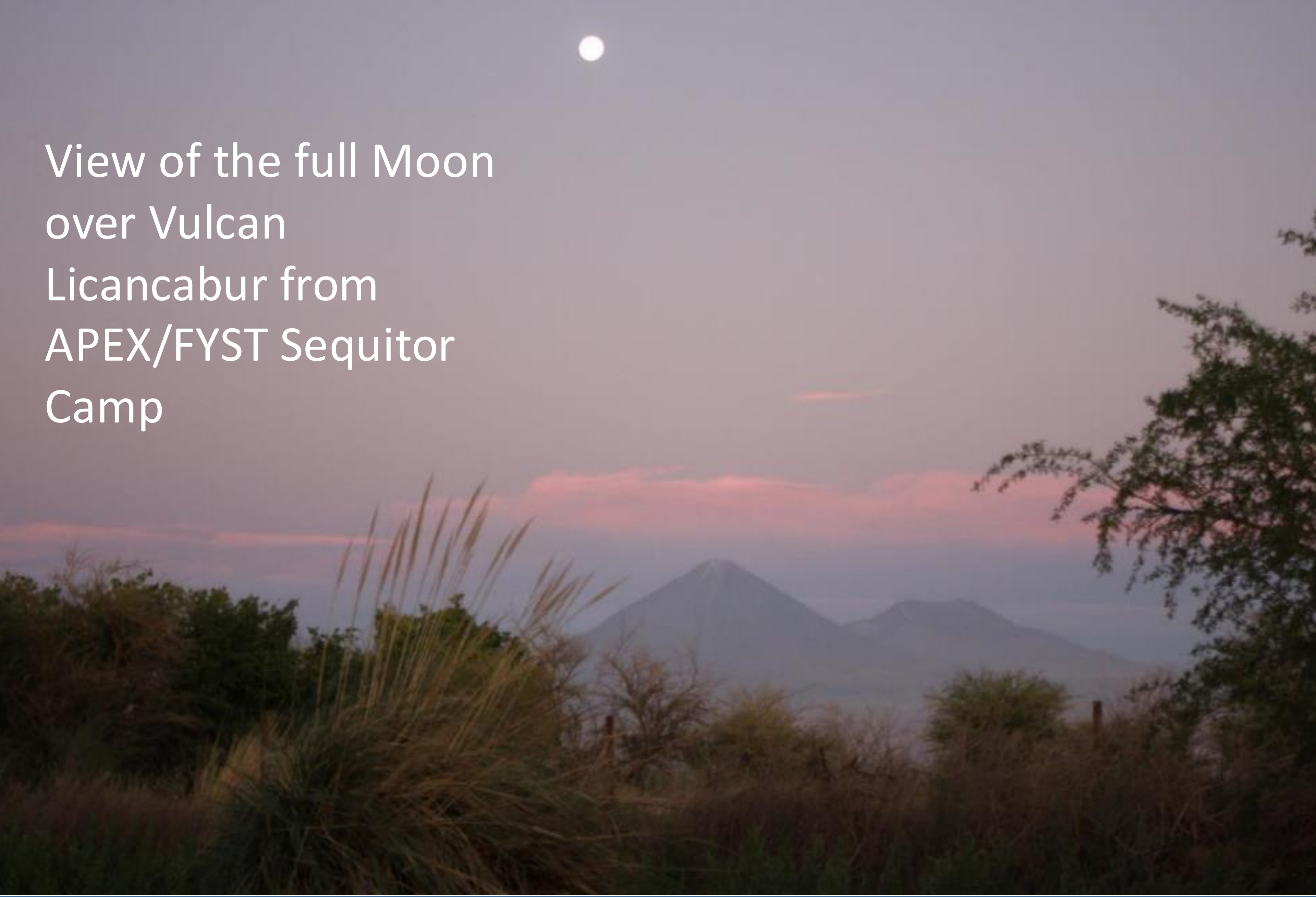
*TAO is 40 meters higher!

Why Chile?

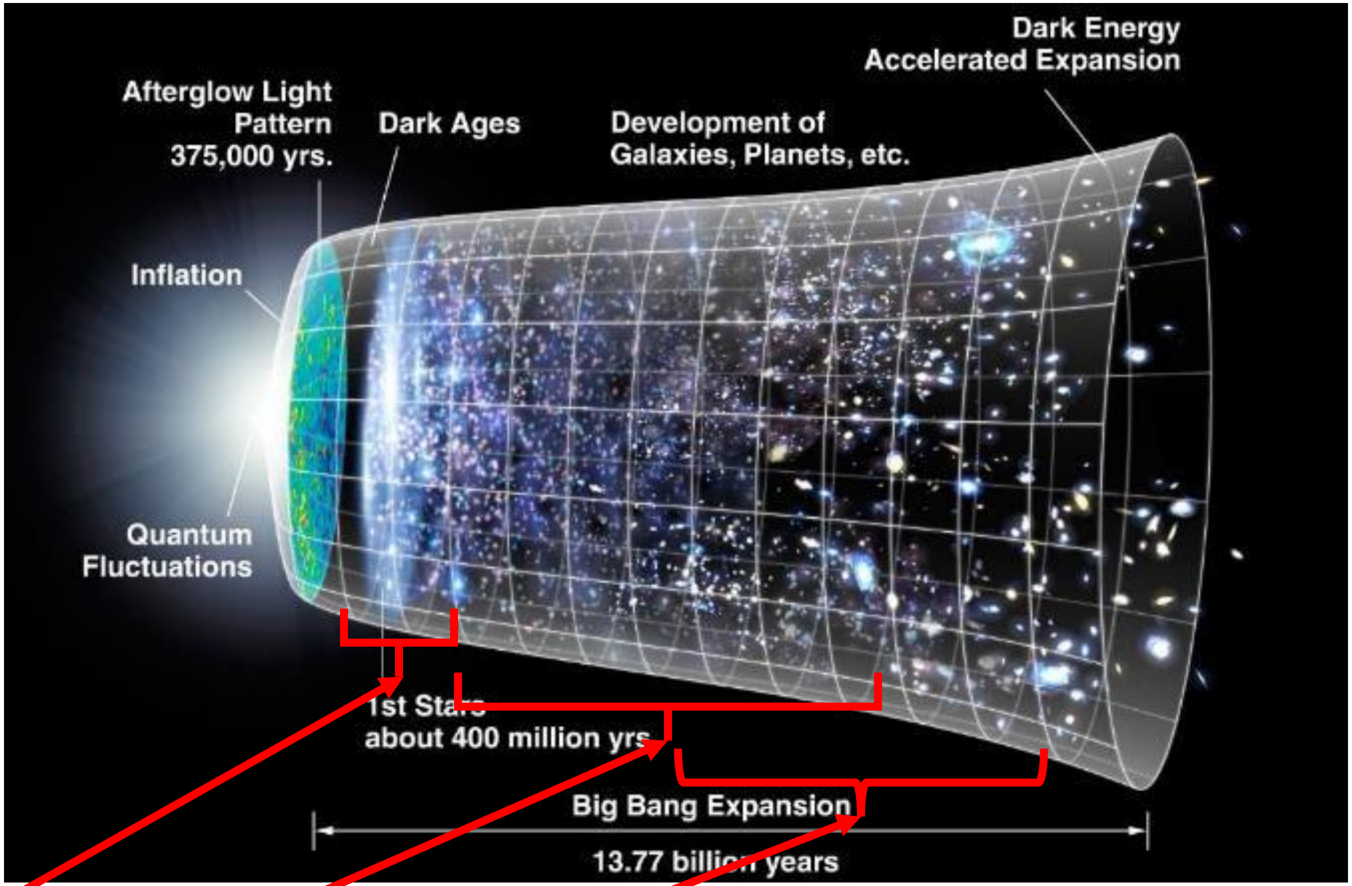
- ❑The high dry locations in Chile are arguably the best astronomical sites on Earth.
- ❑Chile has hosted major telescopes since the 1950s.
- ❑The CCAT site is adjacent to both the Atacama Large Millimeter Array (ALMA) and the 12 m APEX telescope



Driving into San Pedro de Atacama

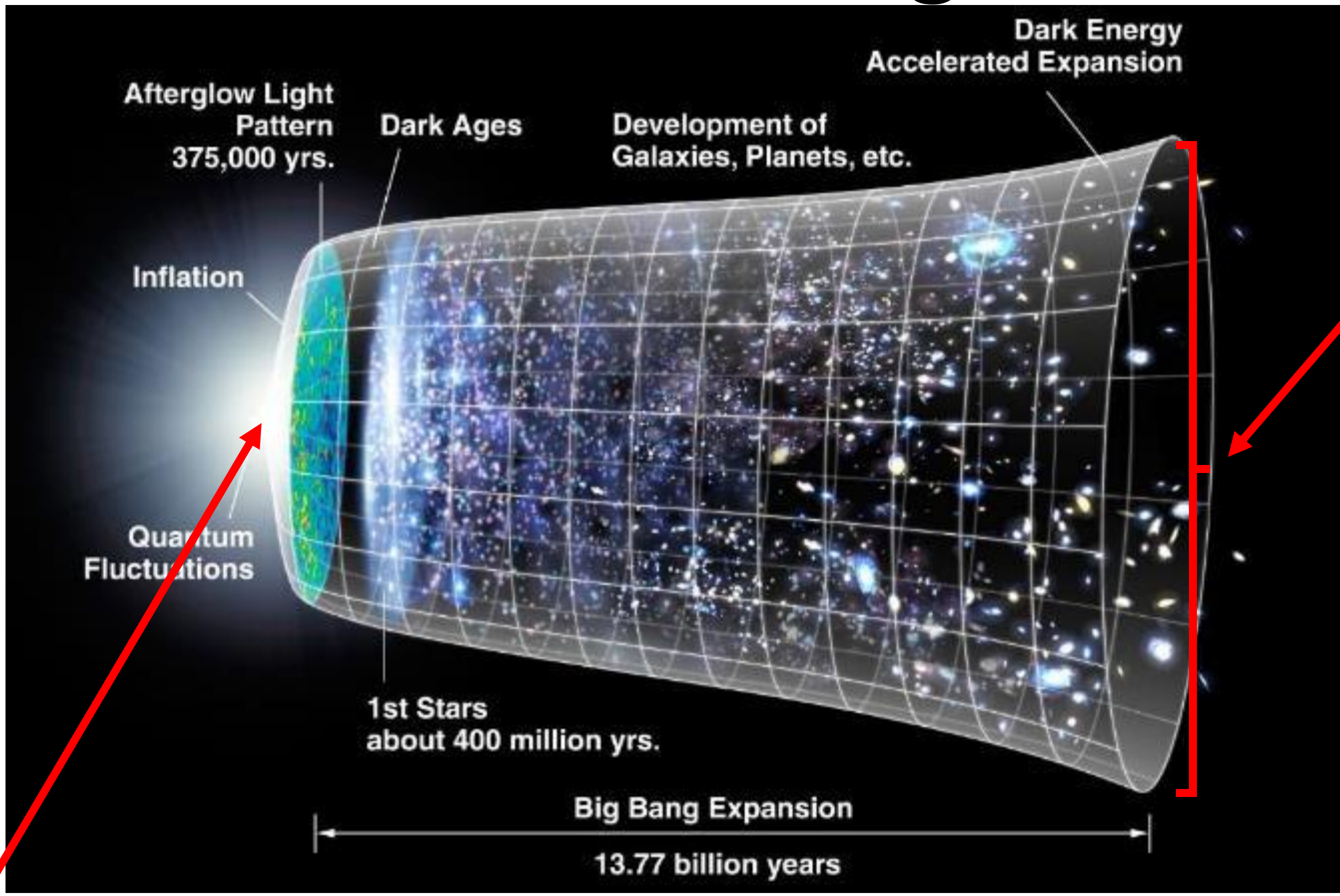

View of the full Moon over Vulcan Licancabur from APEX/FYST Sequitor Camp

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?

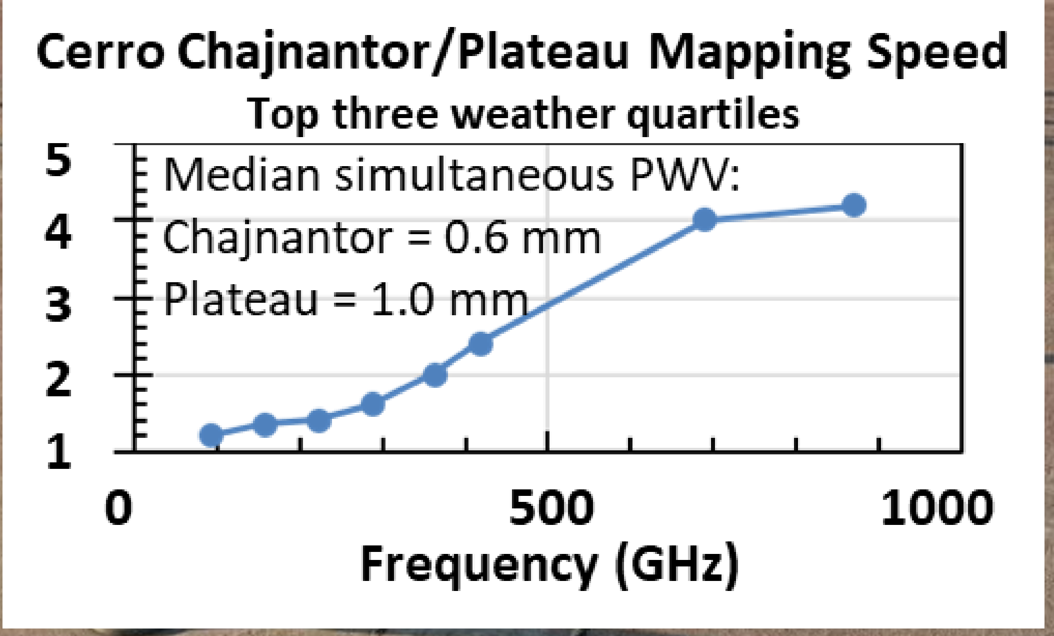
FYST site at 5600 m

Cerro Chajnantor

Great telescope: lets put it at a great site!

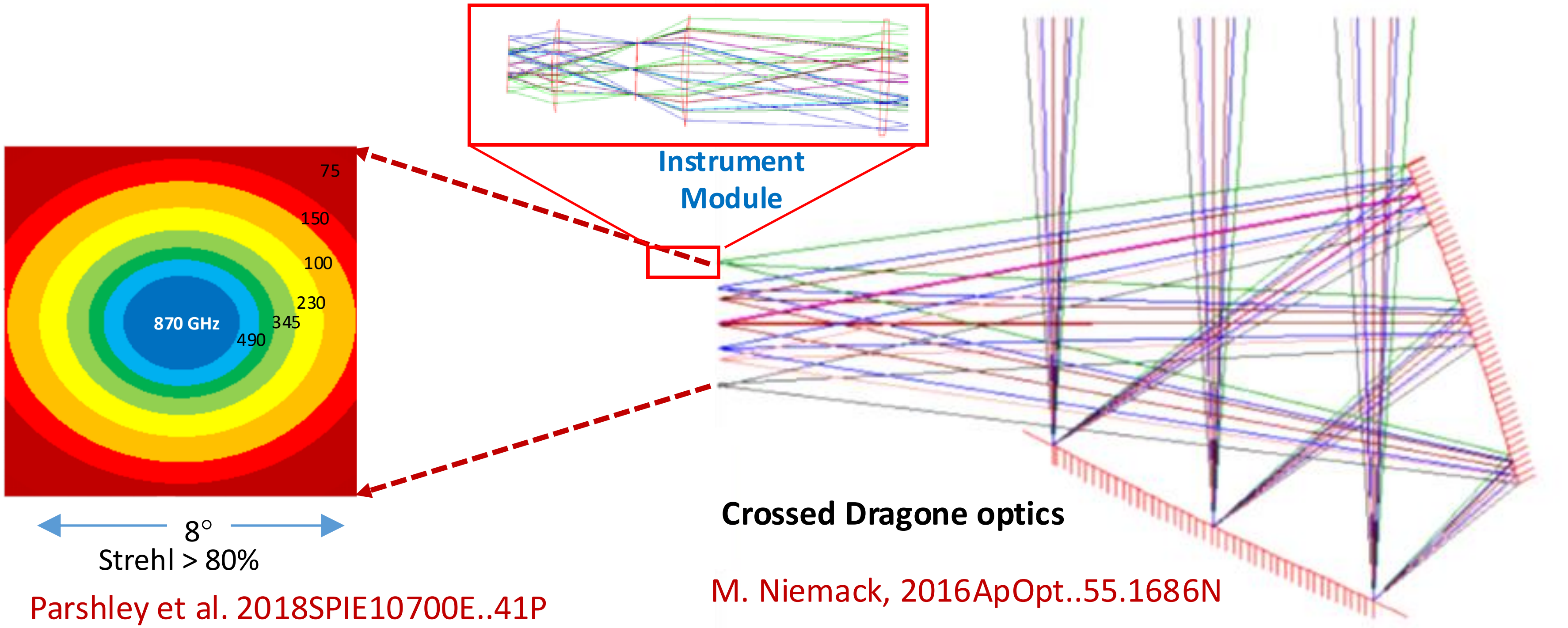
Chajnantor plateau ALMA site at 5000 m

Summit of Chajnantor is even better!



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

FYST Optics: Field of View



- 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**

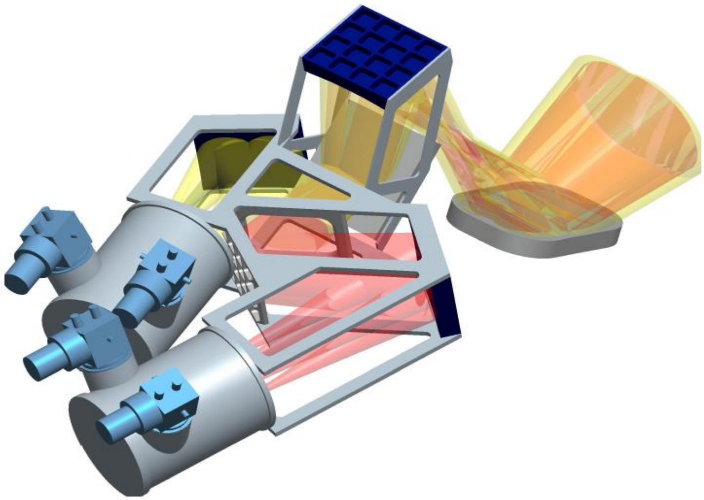
A "filled focal plane" has:

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

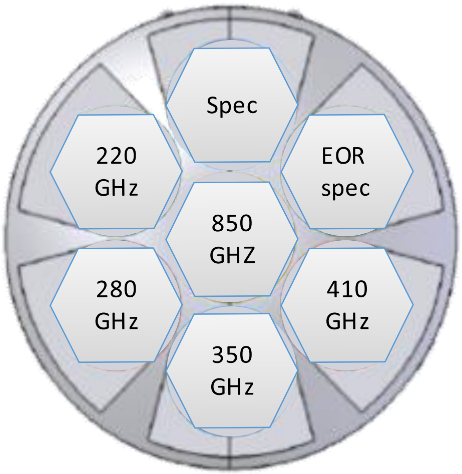
Or well over 100,000 beams!

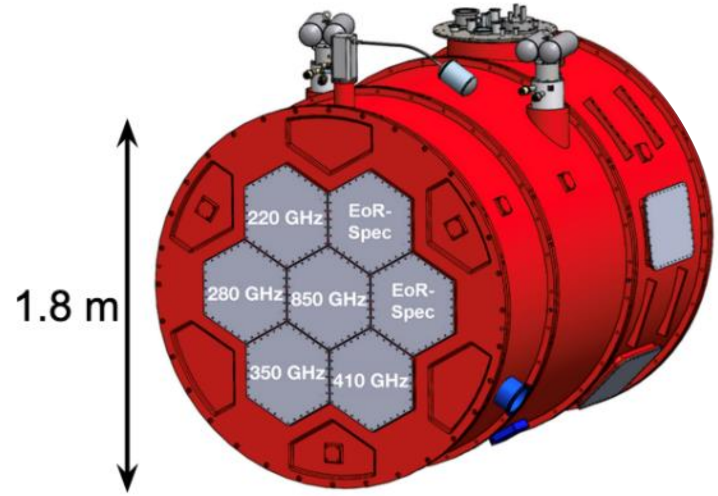
Instrumentation Enables the Science

Name	Driver Science	Frequency Range	FoV	No. Pixels
CHAI [CHAI (THz)]	Galactic Ecology	455-495, 800-820 GHz 1.4-1.5 THz	17' x 8.5'	2 × 64
PCam/Cameras	kSZ, Galactic Evolution	220, 280, 350, 410, 850 GHz	3^{0} diameter	>5.9x10^{4}
P-Cam/Spectrom	LIM/EoR-Spec	210-420 GHz	2 × 1.3°	1.2x10^{4}



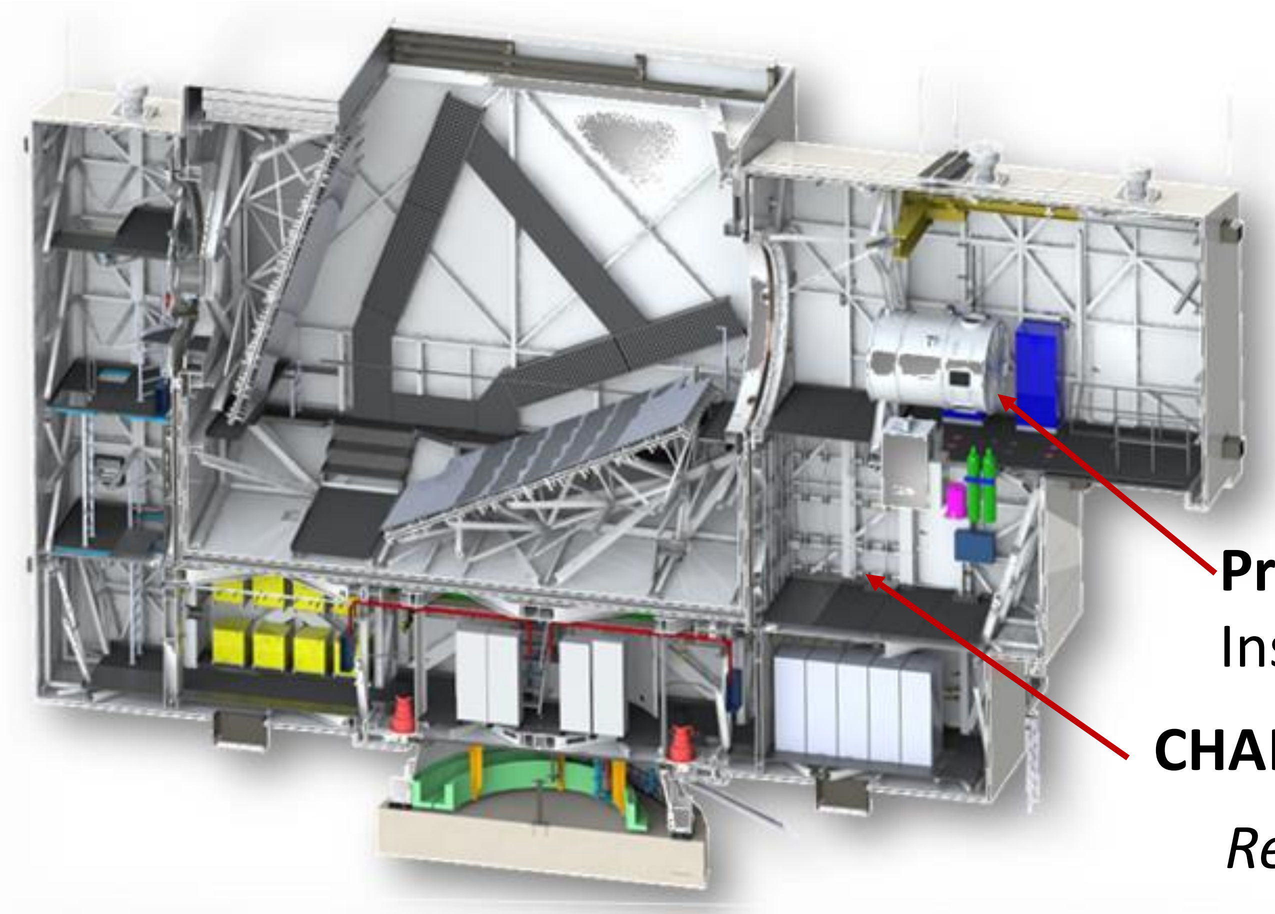
CHAI





Prime-Cam

Co-mounted Instruments



FYST
Cutaway

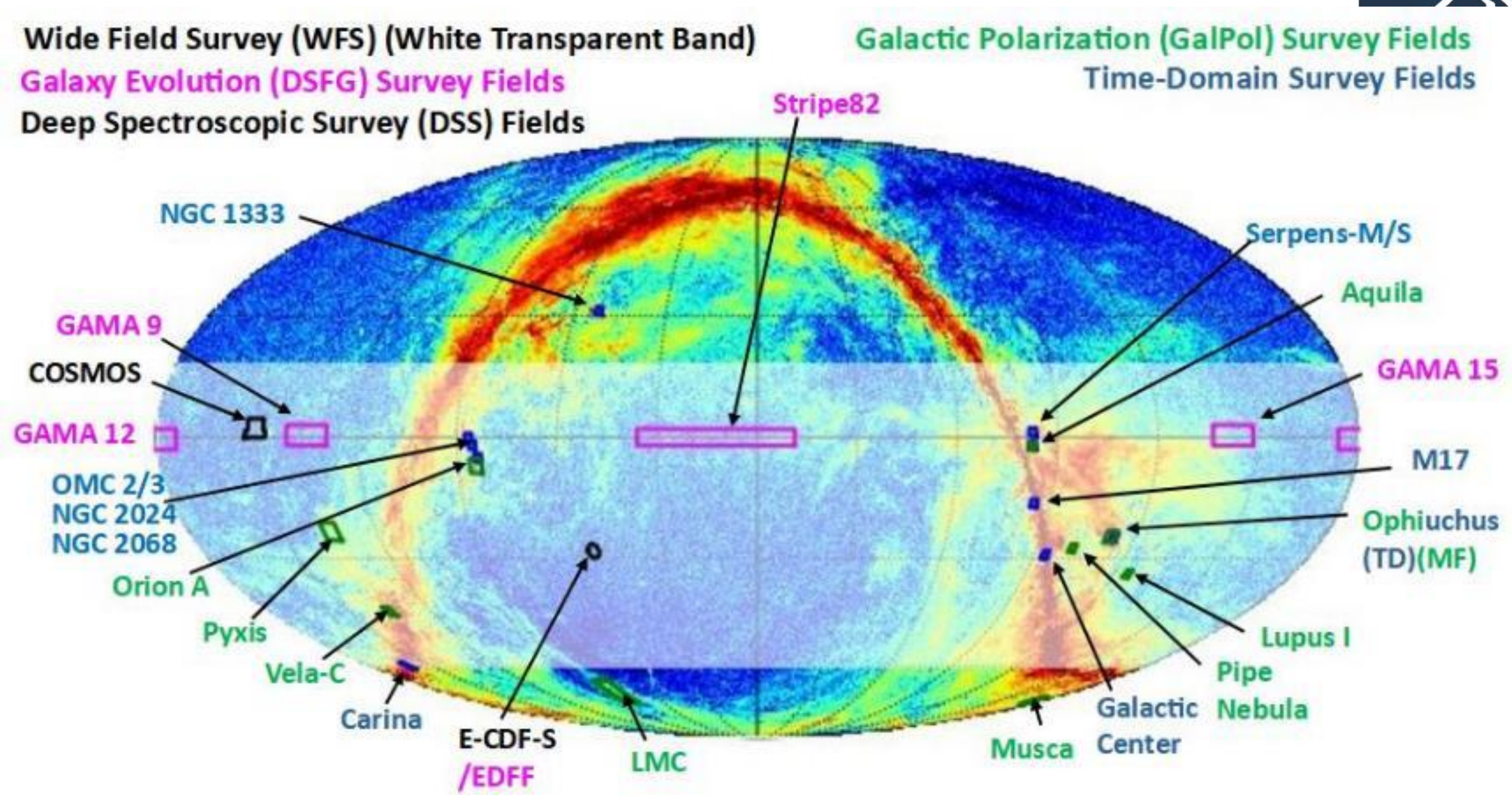
Prime-Cam
Instrument Station -1

CHAI Instrument Station-2

Retractable tertiary

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

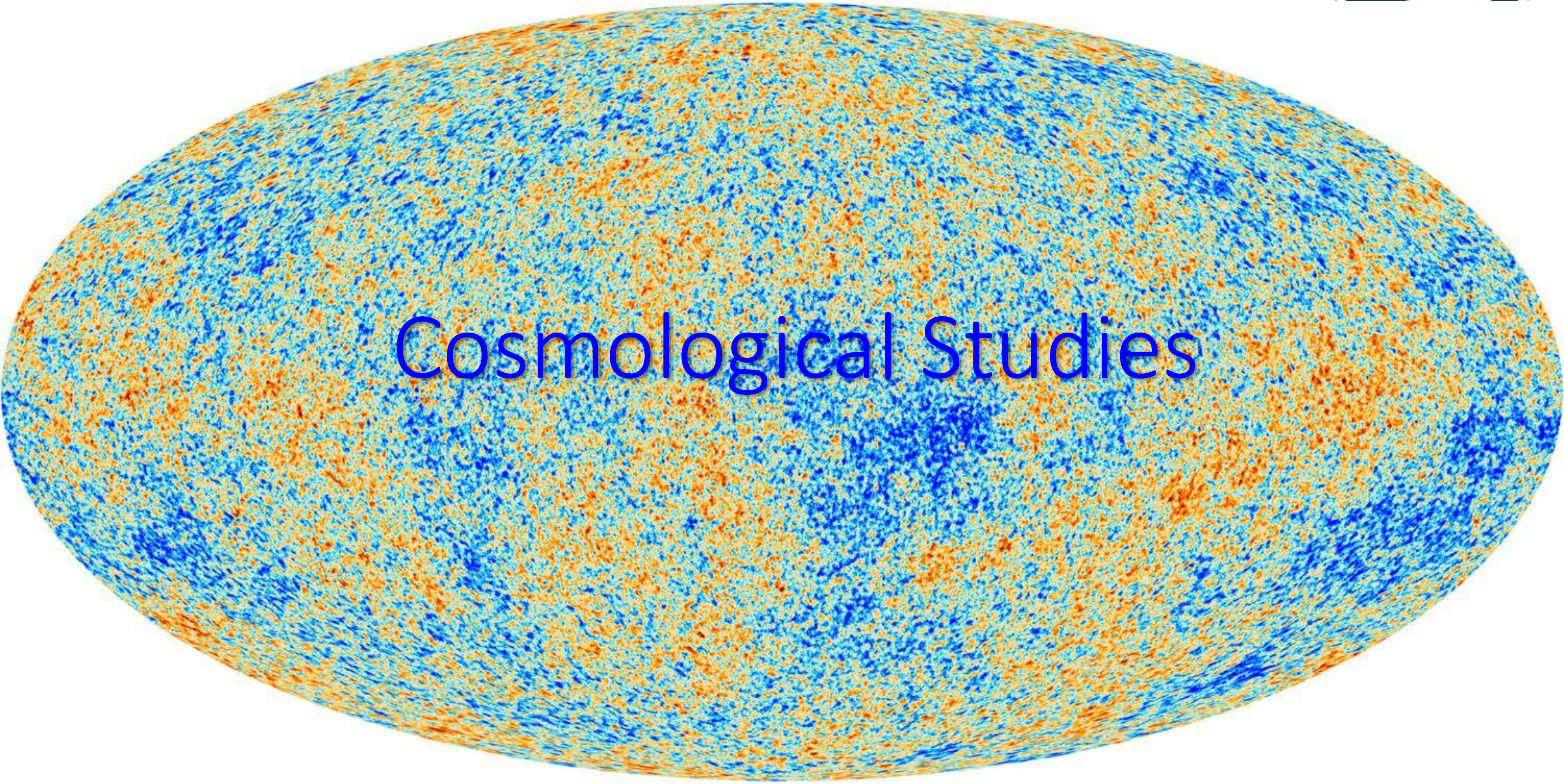
Prime-Cam Survey Fields



- **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**

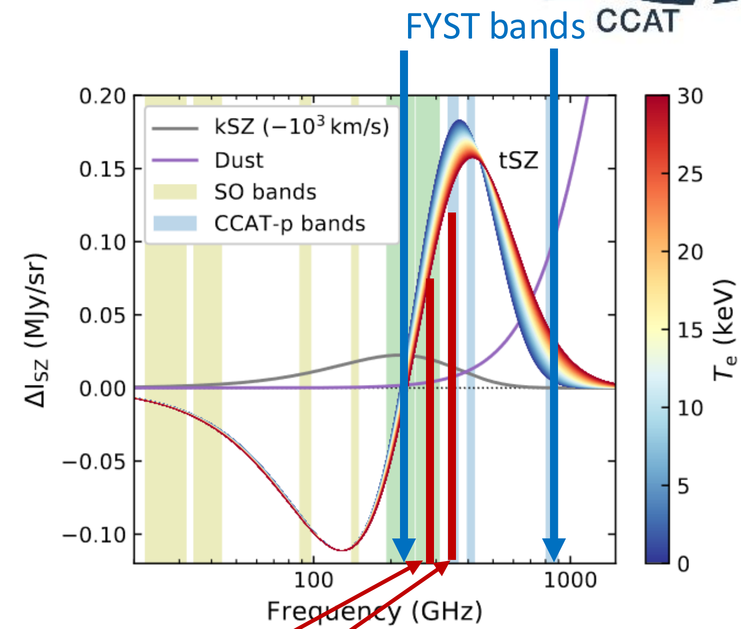
Science Plans

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



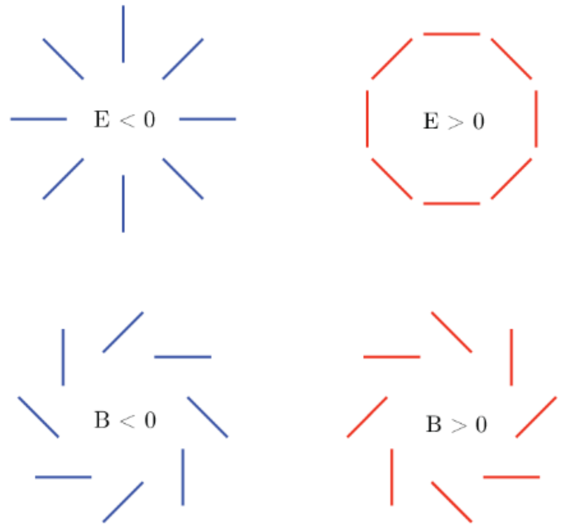
- High frequency FYST observations are critical for separate SZ components *and* for removing dust foregrounds. ***Both 280/350 modules for 1st light!***
- Yield constraints on:

  - 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

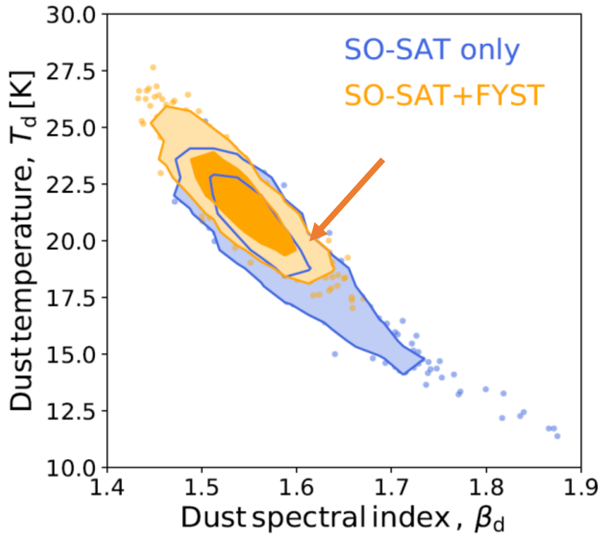
Search for Gravitational Waves

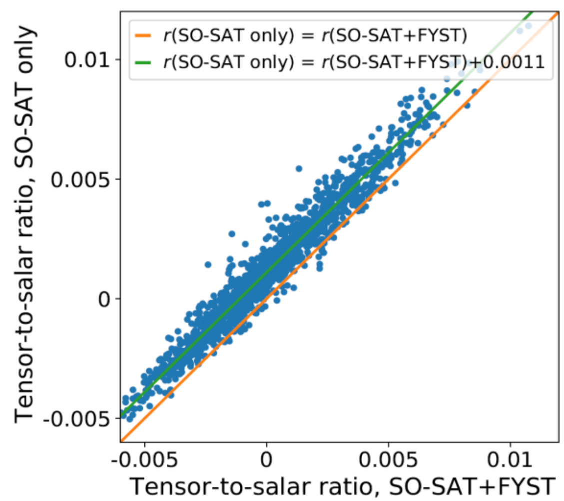
- Detailed CMB observations of temperature and polarization constrain cosmological parameters that determine large scale structure– e.g. H_0, $\Omega_b h^2$, Ω_m, Ω_Λ, age…
- Prime-Cam on FYST will improve constraints on the amplitude of *primordial gravitational waves* that are imprinted on CMB ‘B-mode’ 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!

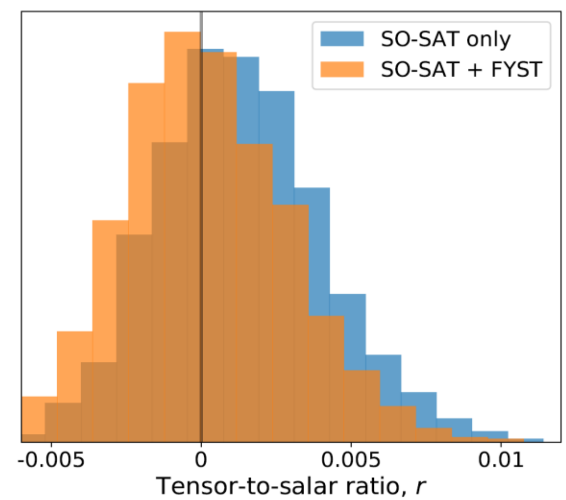


Note that E-modes will stay the same on reflection, while a negative B-mode will look like a positive B-mode on reflection, and vice-versa.

Better constraints on cosmological "r"







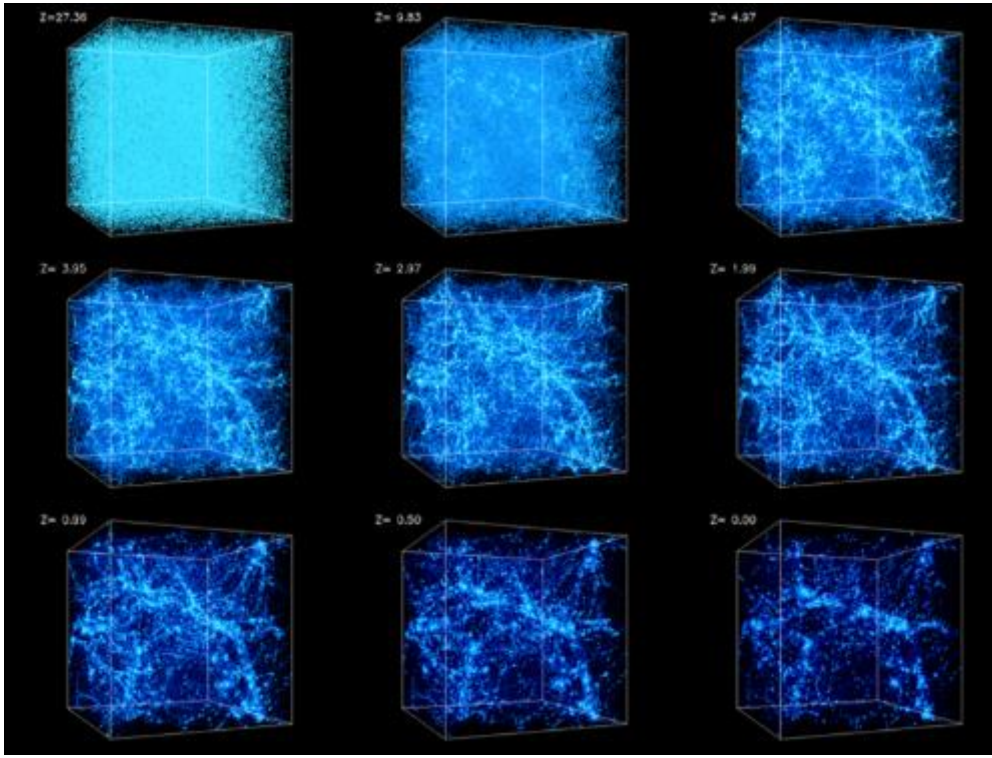
Eiichiro Komatsu

- 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! $r_{SO\text{-}SAT+FYST} = (0.2 \pm 2.7) \times 10^{-3}$


HII
bubble
Line Intensity Mapping
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 X** larger than the SMACS 0723 field!*

JWST
SMACS 0723

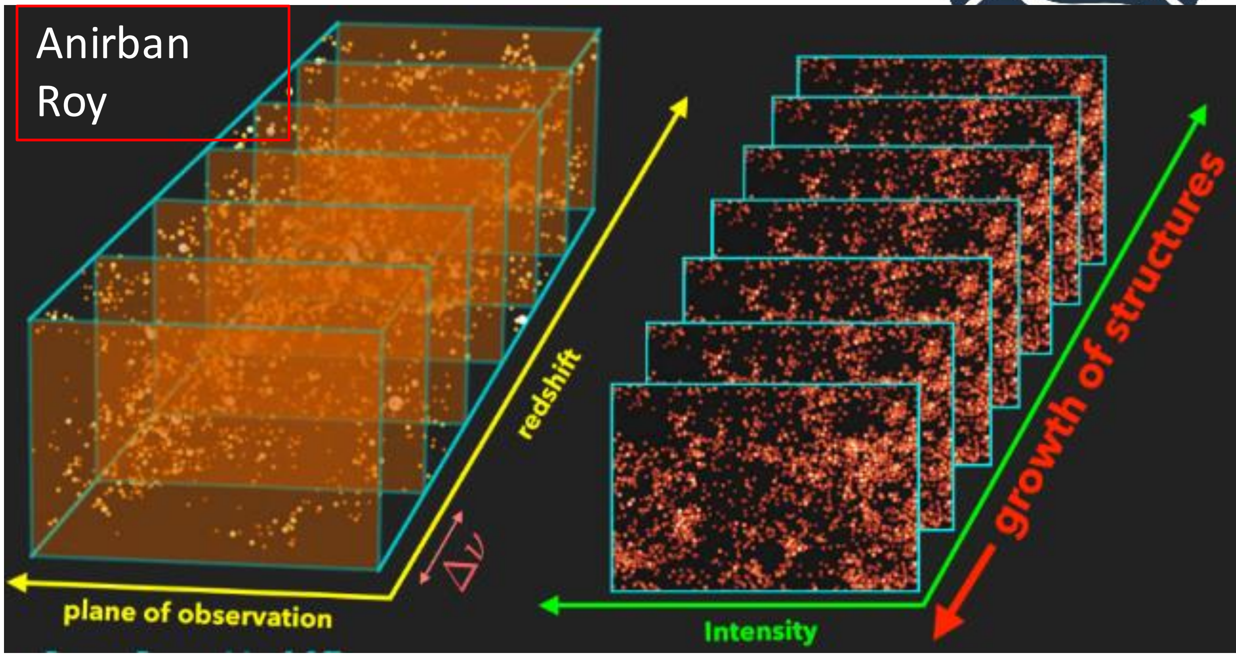
2.4’

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 $\Leftrightarrow$ 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" $\Leftrightarrow$ 0.25 Mpc at z ~ 8 (210 GHz) & modules with 1.3° fields of view $\Leftrightarrow$ 25 Mpc
- Our fields (E-COSMOS, and E-CDF-S) are the most extensively studied deep extra-galactic fields

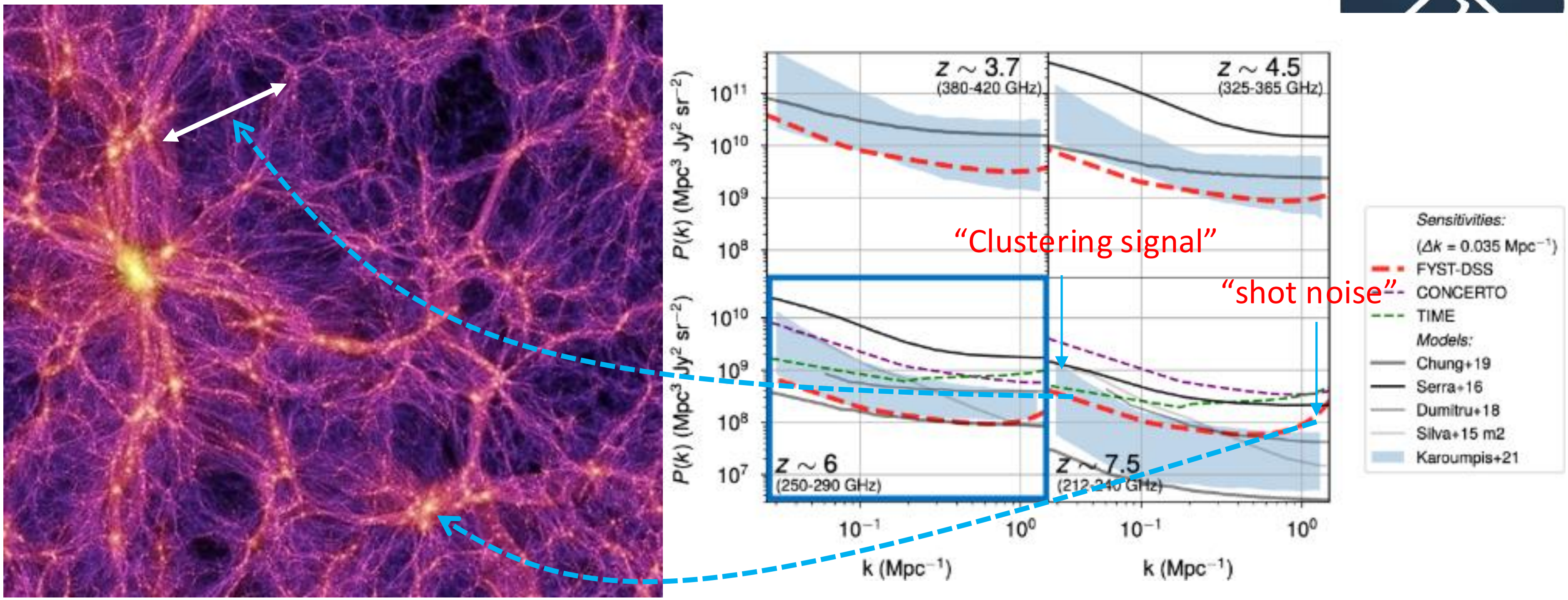
A Visualization of the Data

- ❑ **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…

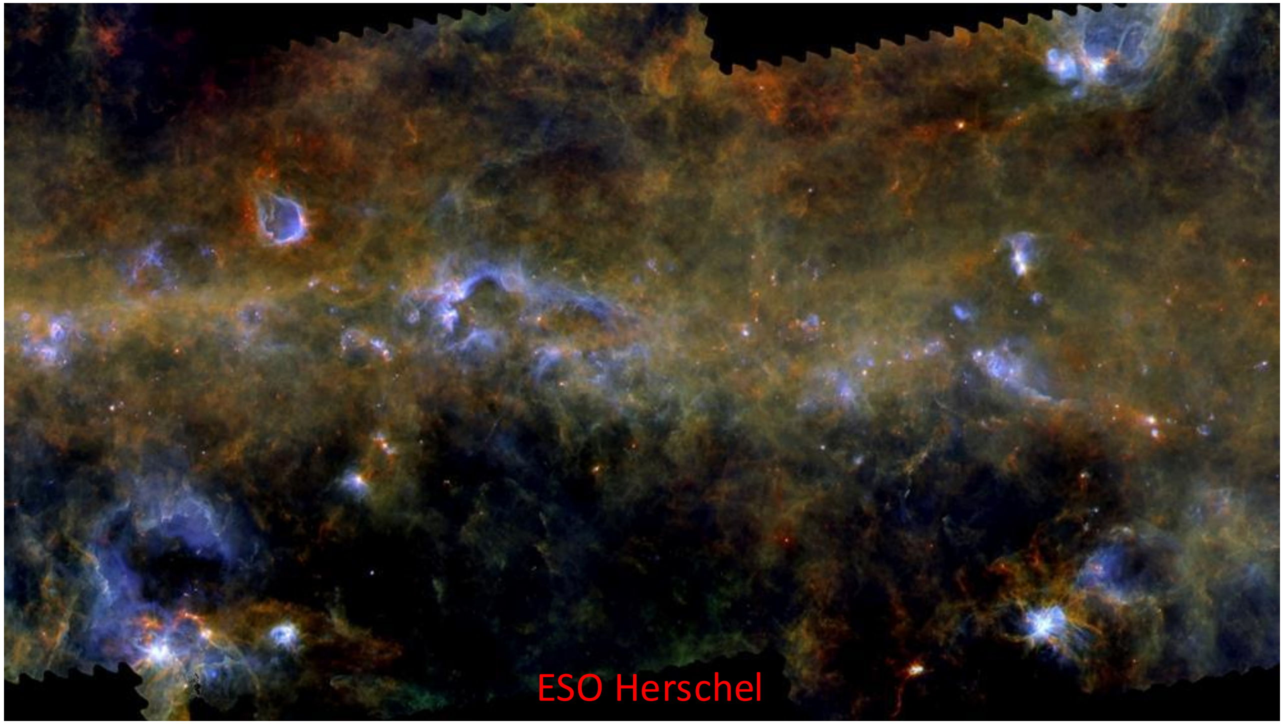
A Difficult Measurement



- ❑ 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

Galactic Science with CHAI



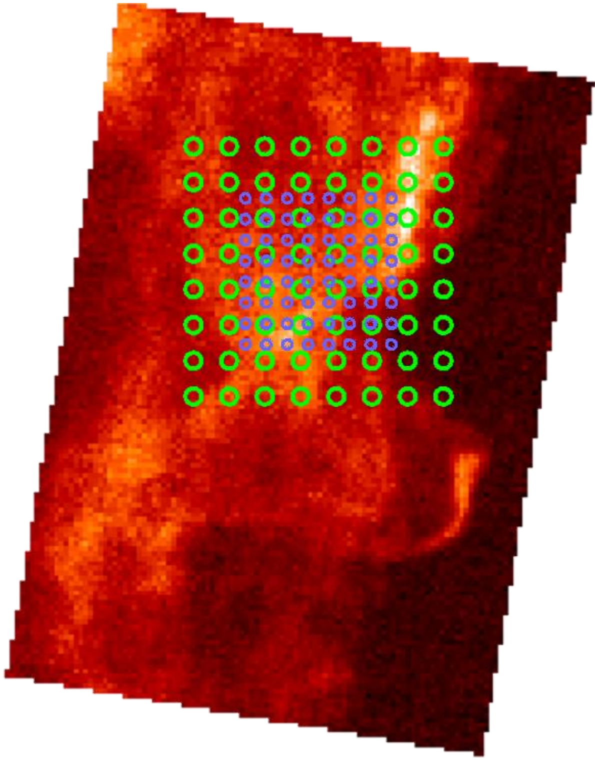
- Velocity resolved imaging of the Galaxy in submm [CI] and mid-J CO lines
- 15” imaging over 200 $(^\circ)^2$ scales (*50,000:1*) of the Milky Way, LMC, SMC:
  - [CI] tracing gas temperature and mass $\Rightarrow$ tracking “CO dark” gas
  - Mid and high-J CO & ^{13}CO tracing gas excitation, shocks,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

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

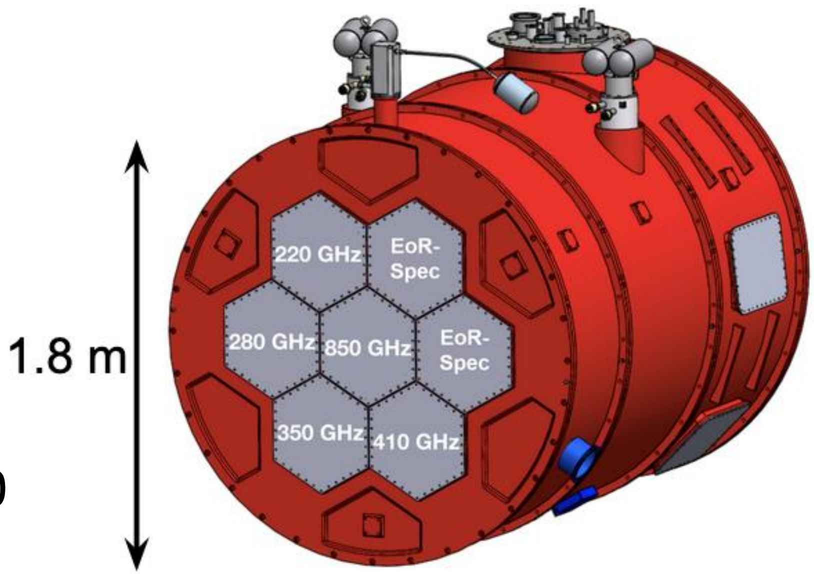
CHAI's 8x8 pixels overlaid on [CII] map of horse head nebula



Instrumentation with Status

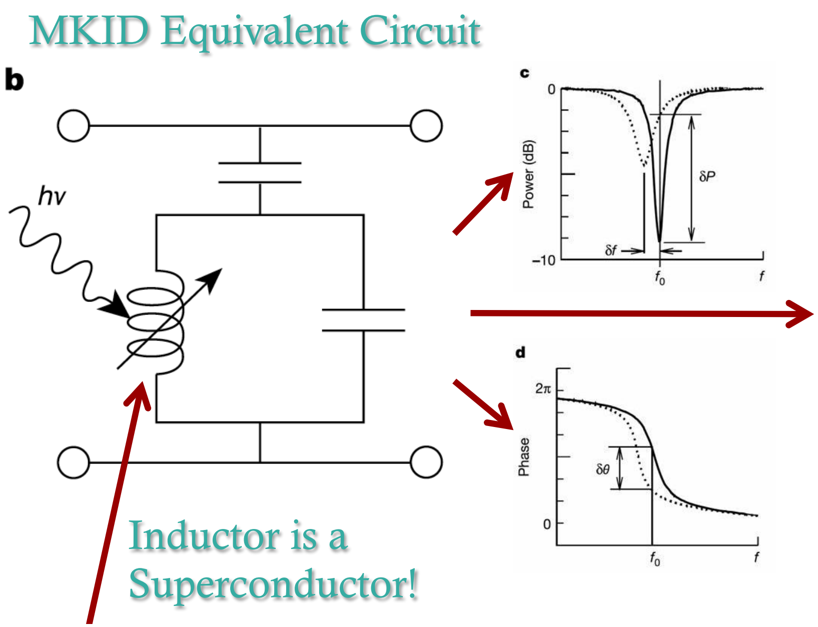
Prime-Cam overview

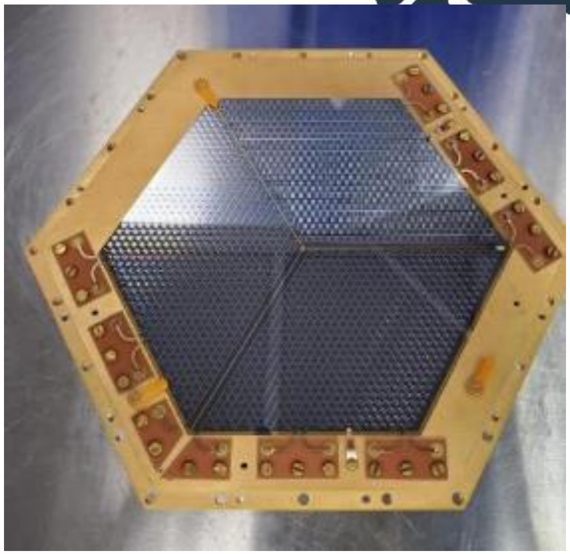
- Design drivers
  - Uses 4.5° heart of 8° FYST FOV
  - Modular approach ⇒ path for next generation technologies
- Initial module configuration
  - 3 polarization modules funded: 280, 350, 850 GHz
    - Mike Niemack (280, 350 GHz) lead
    - Scott Chapman (850 GHz) lead
  - R=100 spectrometer module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



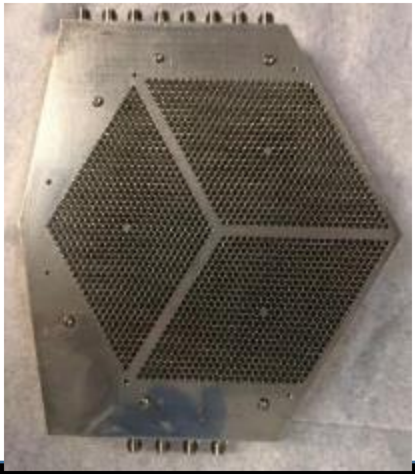
Prime-Cam: Detectors

- Kinetic Inductance Detector (KID) arrays (NIST)





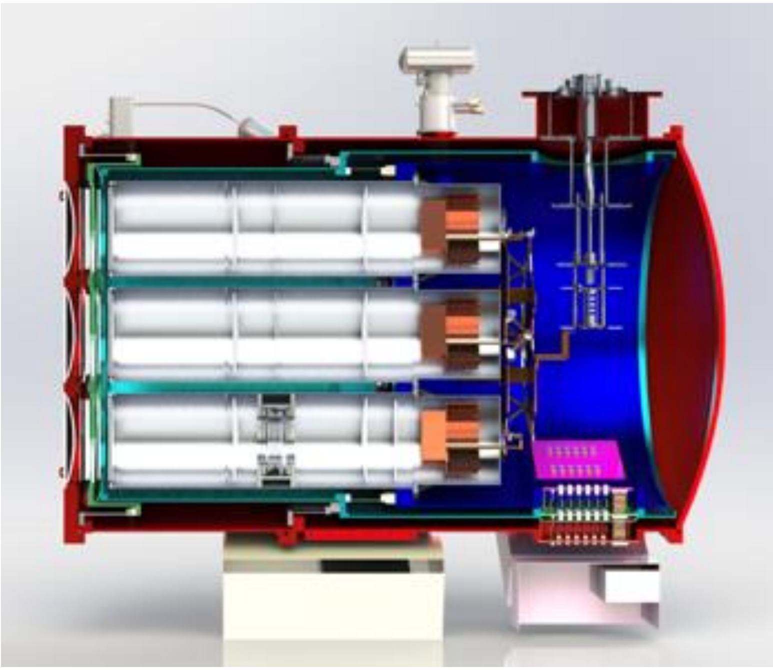
280 GHz array for PrimeCam



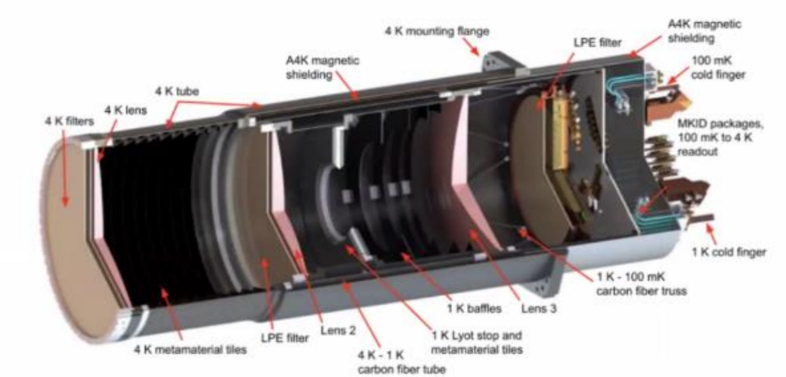
- 3,500 – 20,000 detectors per wafer,
- Arrays tested within ModCam in Niemack lab

Prime-Cam: Cryostat

- Manufacture: Redline Technologies

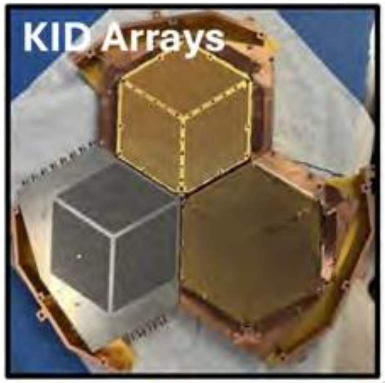


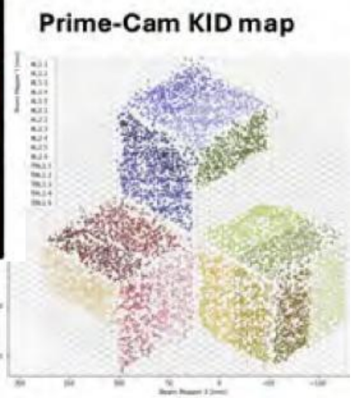
Cross section of Prime-Cam design



Thomas Nikola, Yuhan Wang, Lawrence Lin and Mike Niemack January 2025

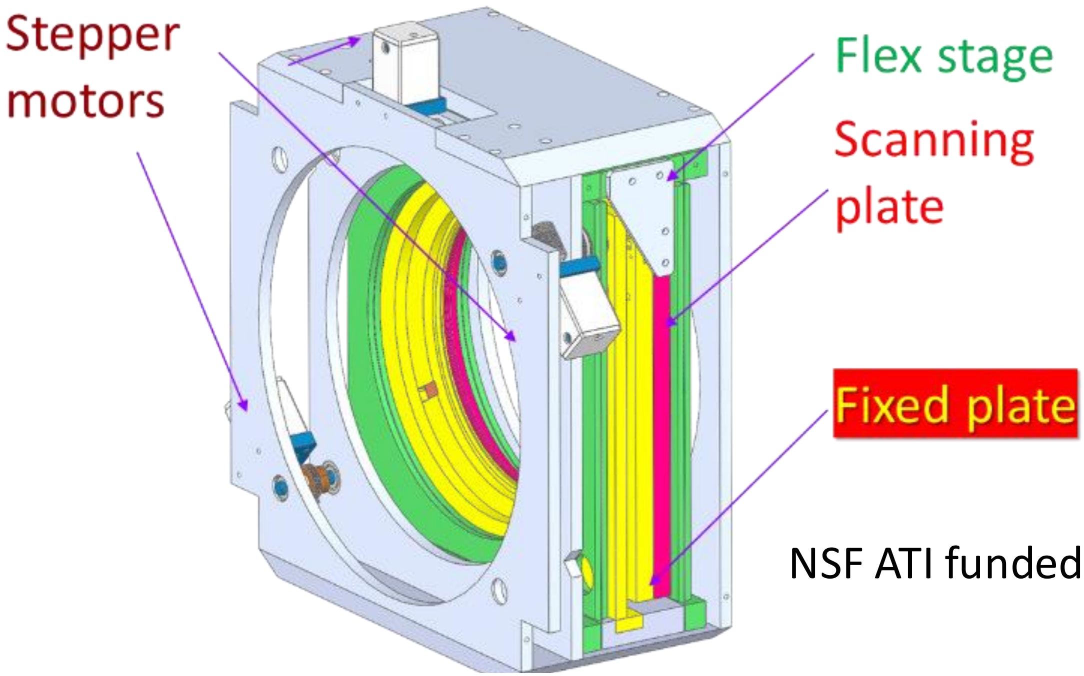
Prime-Cam Status



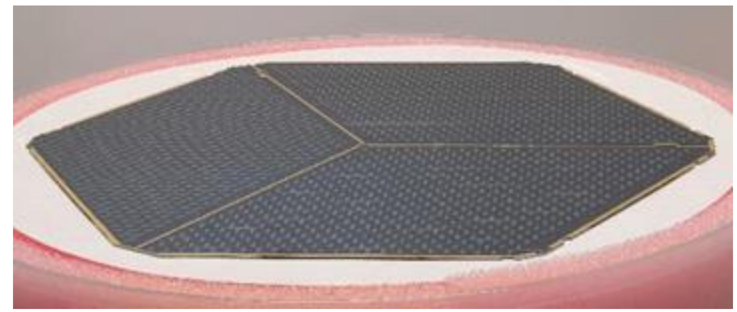


Prime-Cam w/ 280 GHz module on its way and 350 GHz module to follow to FYST for first light in Oct/Nov time frame!

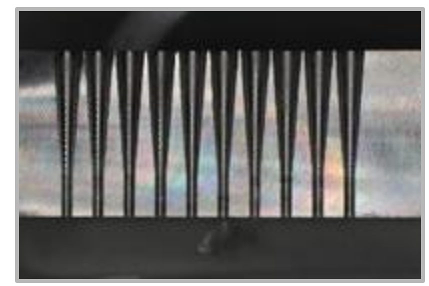
FPI Imager Called “EoR-Spec”



NSF ATI funded



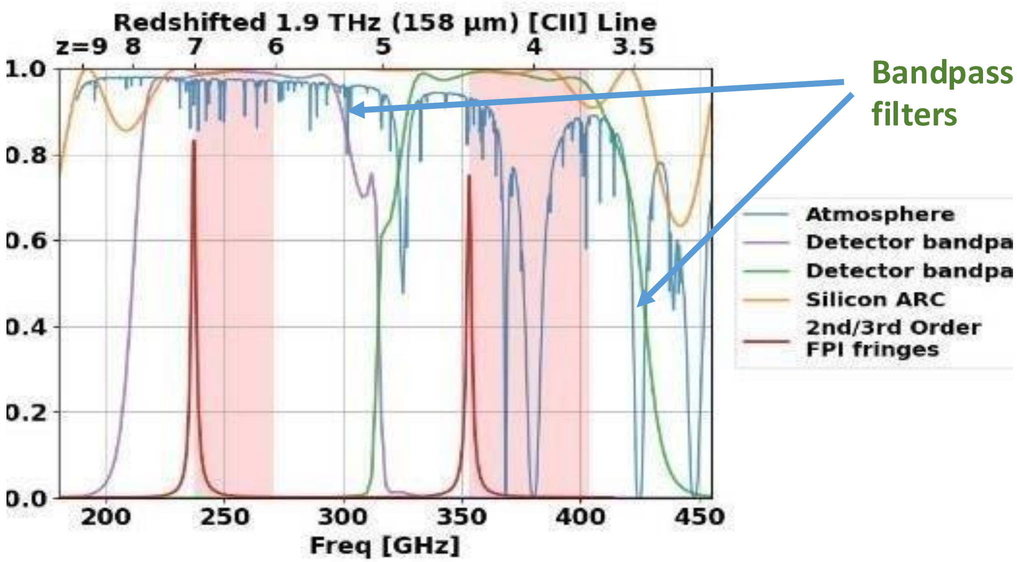
210-315 GHz Array

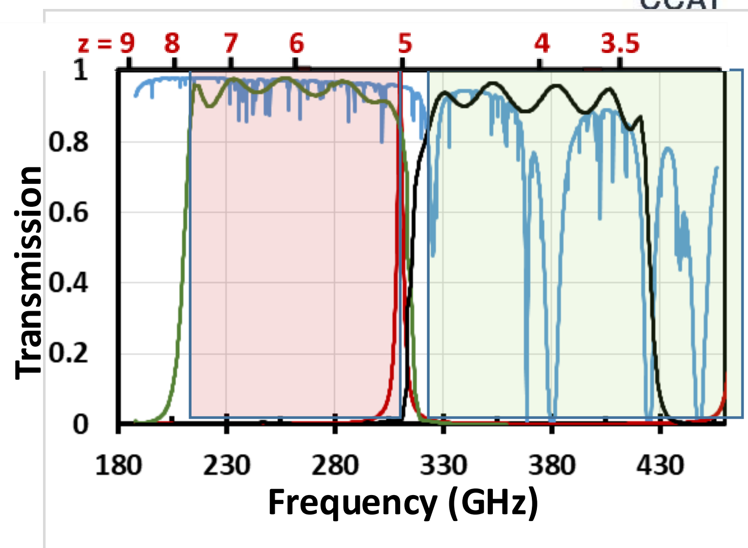


Al feedhorn array

- ***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

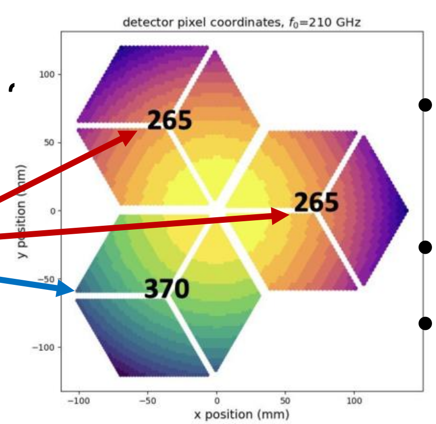
Fabry-Perot Fringe Selection, Spectral Multiplexing, and Scanning





Features

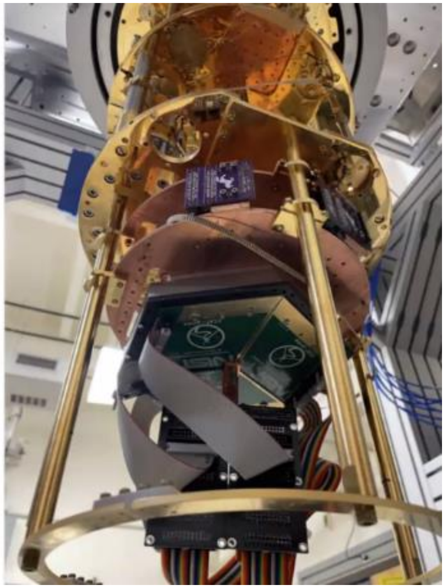
- Natural spectral multiplex of '
40 GHz, or 35% of total BW
- 2 (1) KID array (2nd and 3rd) orders sorted w/ BP filters
- Beams (2) modules is: 6912 (6144) @ 280 (350) GHz

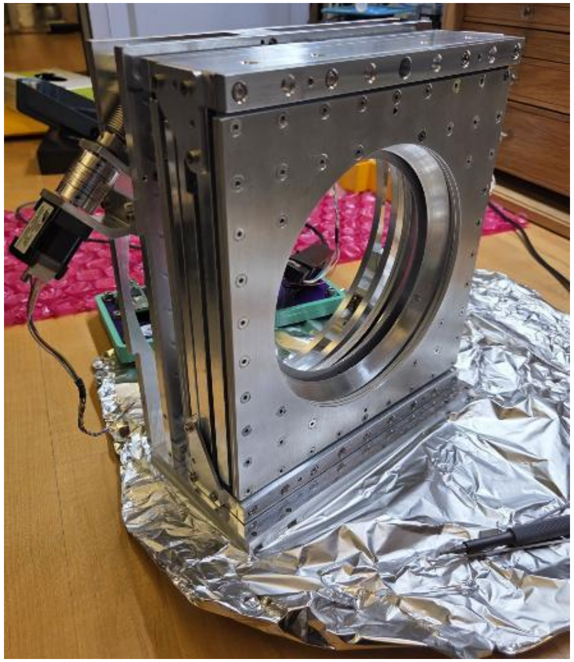


Observing Technique

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

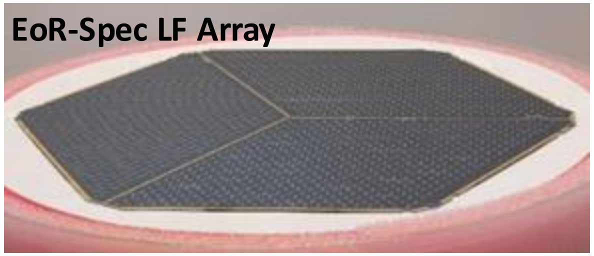
EoR-Spec Status





Rodrigo Freund

- 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%



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 in the fall of 2025

Voyage of the Sloman Discoverer

3/11/2025 CCAT/FYST History 14

First Parts Arrive March 22

FYST
CCAT

Day 30: April 20, 2025

Reconstruction begins!

Yoke Arm Assembled: June 6, 2025

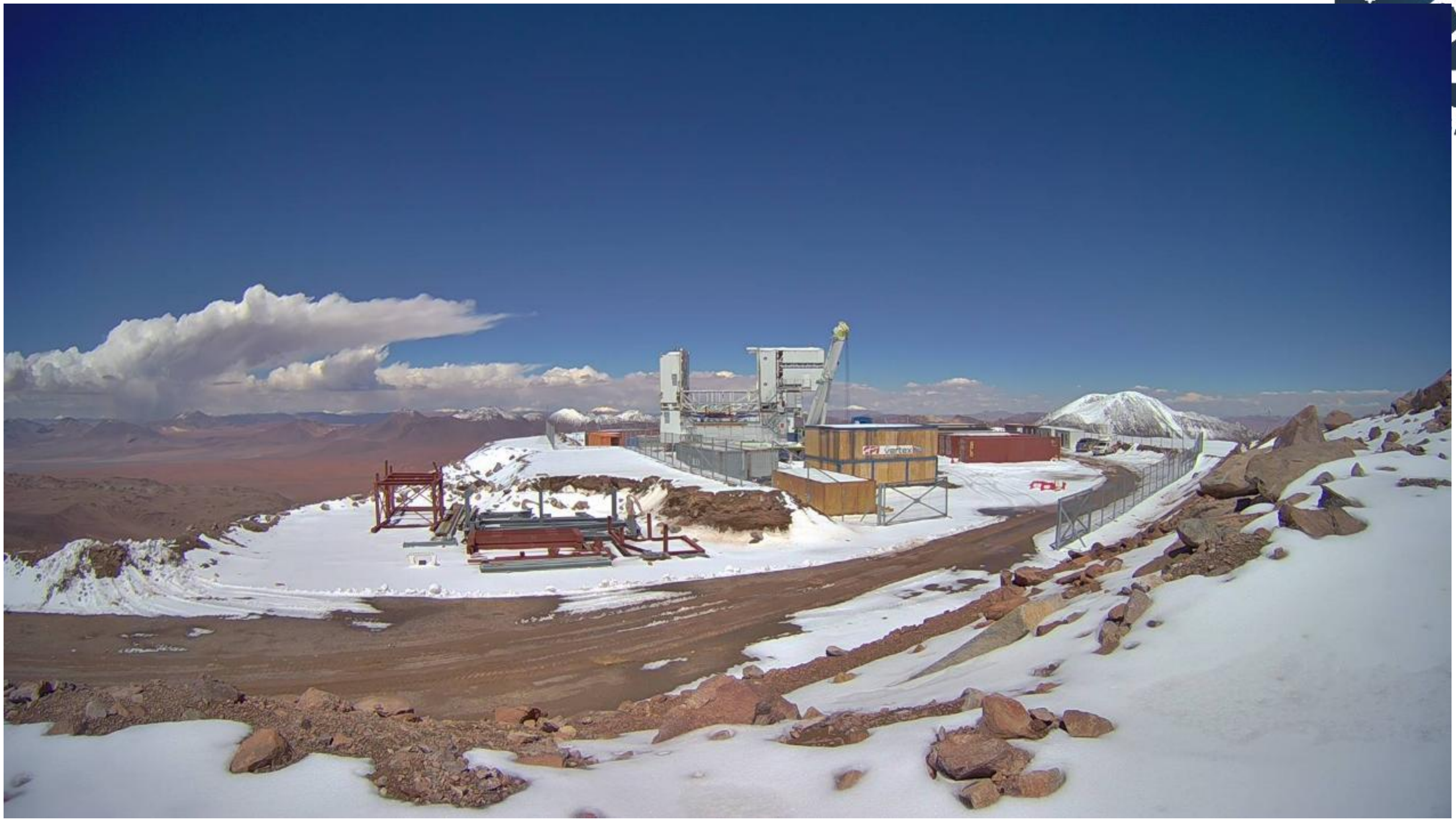
Azimuth motion demonstrated!

Summit Camera View, Oct. 22

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

November 18, 2025

January 27, 2026



Summer in Chile brings winds from the east and sometimes snow at the summit

January 28, 2026

The summit at night during laser measurement of the yoke arm alignment

February 28, 2026

A view of the summit with the elevation housing tilted.alignment

February 22, 2026

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

February 24, 2026

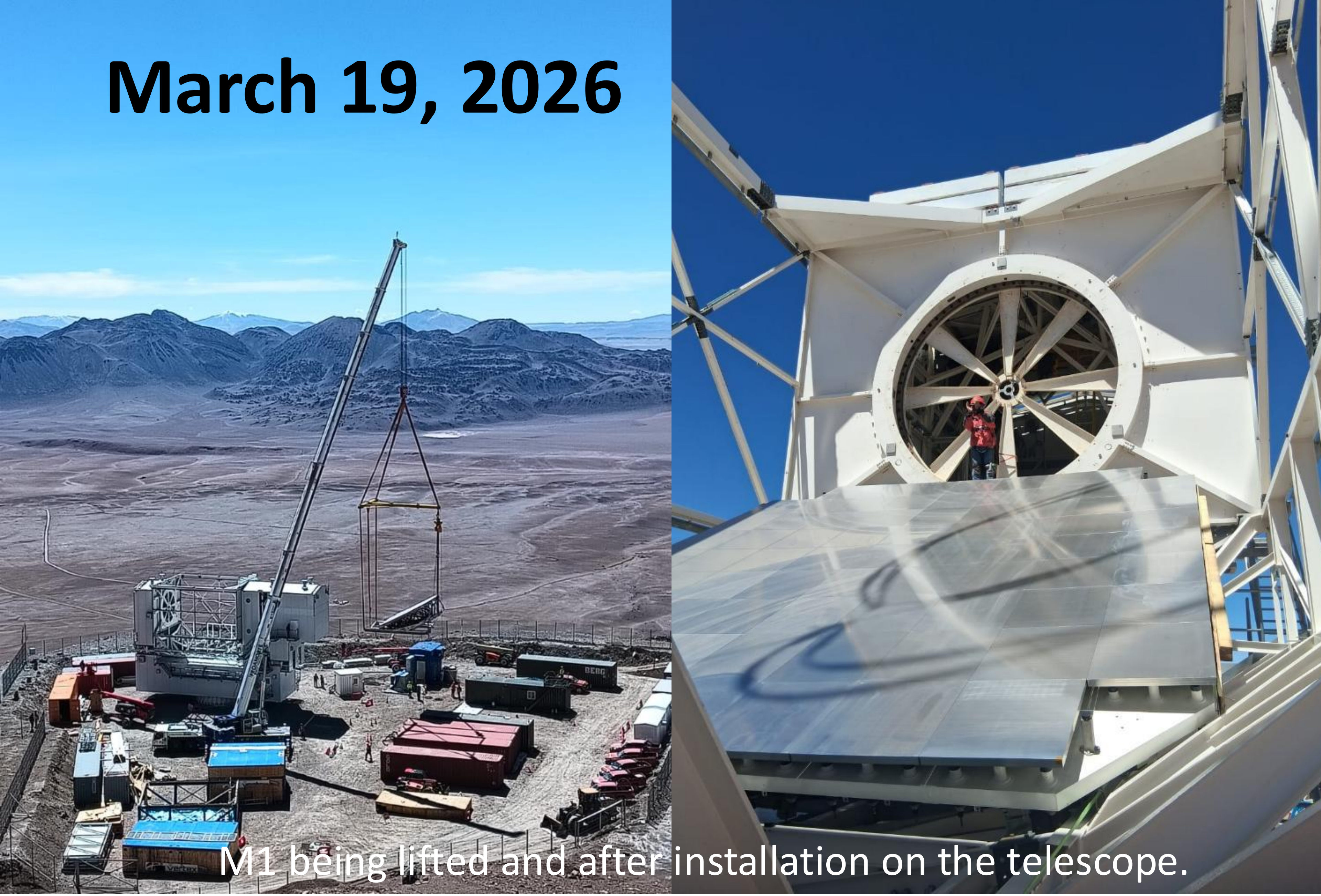
View of the summit from above after an overnight snowfall .

March 5, 2026

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

Installation of the Primary Mirror, M1: March 19, 2026

March 19, 2026



M1 being lifted and after installation on the telescope.

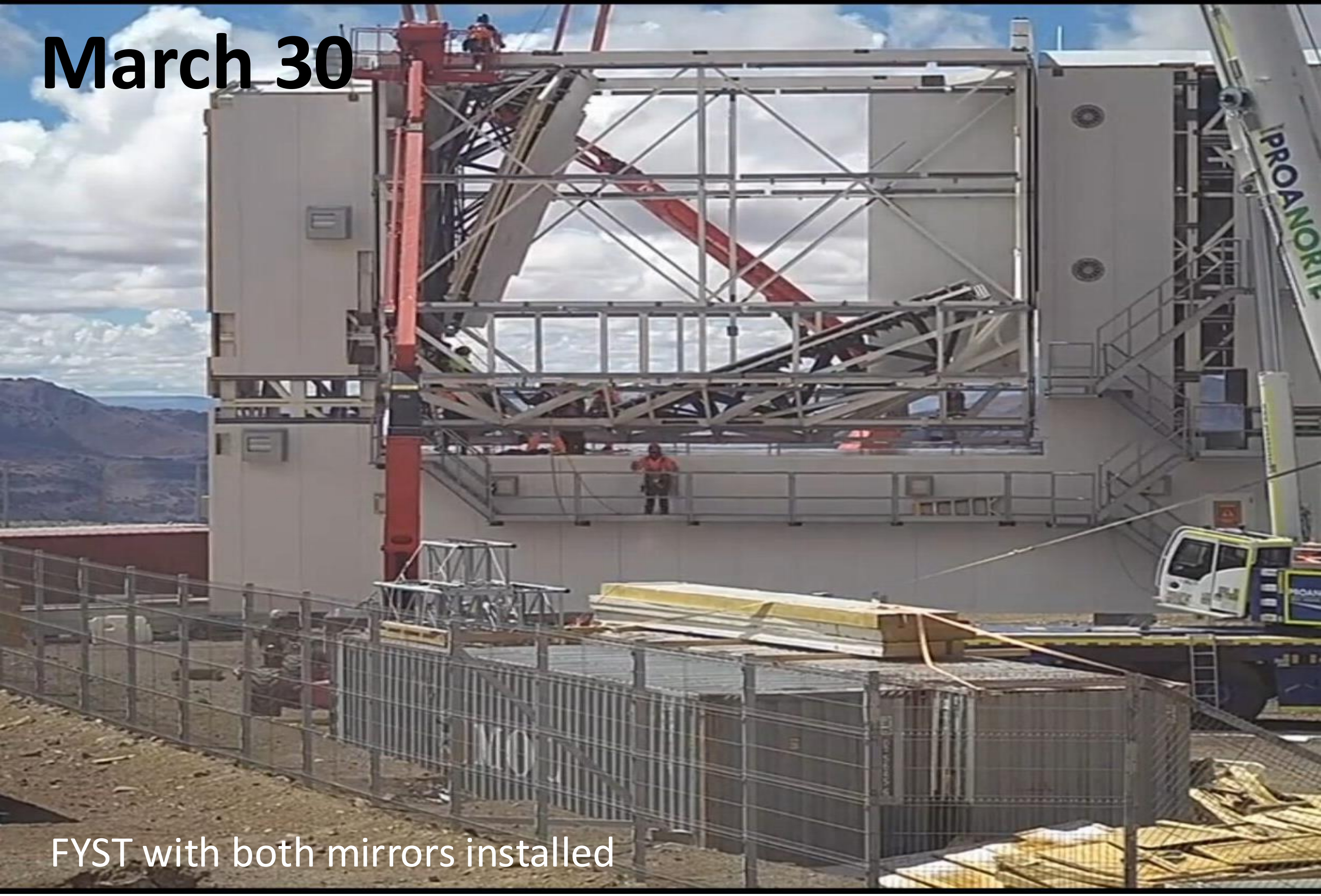
March 19, 2026

The CCAT team and construction crew celebrate the successful installation of the primary mirror.

March 30, 2026

The secondary mirror M2 lifted and positioned in the telescope

March 30



FYST with both mirrors installed

April 1, 2026

View of the summit

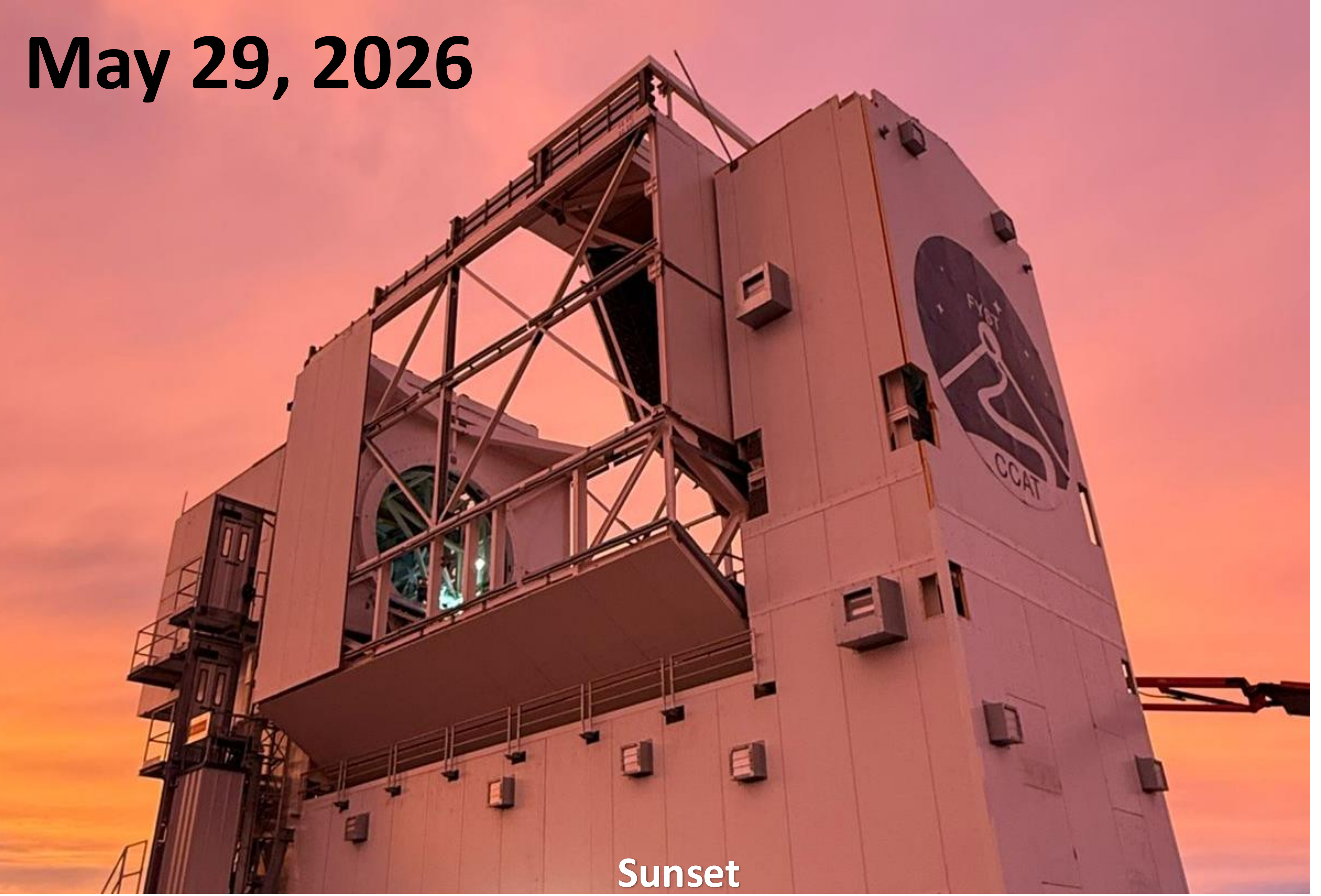
April 9, 2026

Inaugural Event: Attendees at the Summit

April 9, 2026

Better view!

May 29, 2026



Sunset

The 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…

Fred Young Submillimeter Telescope

ccatobservatory.org


CORNELL
BIG RED

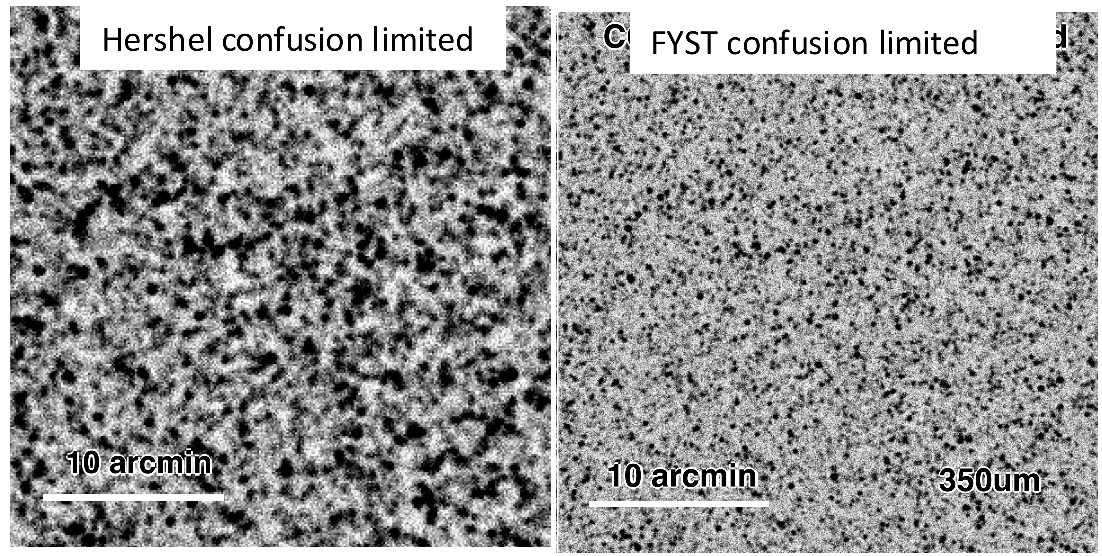
SLOW

ZIM


Dusty Star Forming Galaxies

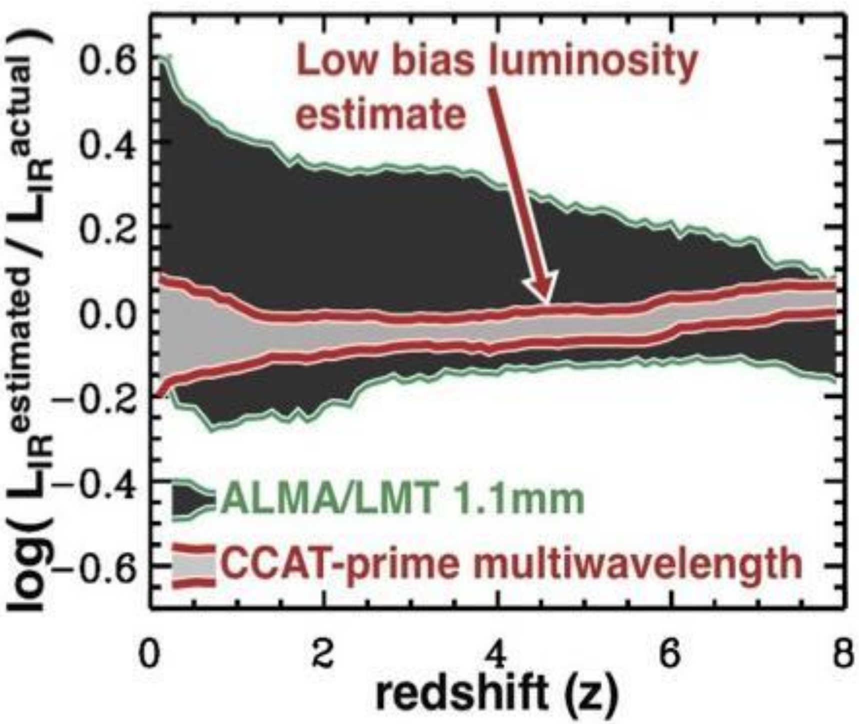
- Half of star formation over cosmic time is obscured by dust
- Much of this emission was resolved by Spitzer and Herschel at $z < 1.7$, but only 10% resolved at higher z
- Critical to understand this epoch of maximum SF rate per unit volume and the epoch at which most the galaxies, including our own assembled
  - Trace the dusty star forming history of the Universe
  - 20,000 $(^\circ)^2$ survey will reveal the extreme luminosity systems

Simulated 850 GHz 350 μm images illustrating the confusion limit



FYST/SF Cam goes ~ 2.6 × deeper into the confusion

Dusty Star Forming Galaxy Luminosity Estimates



- If only have a long wavelength estimator, source luminosity estimates will be poor
- Multi-wavelength aspect $\Rightarrow$ tight (<10%) estimates of luminosity over wider range of redshifts