A technical summary: Heterodyne

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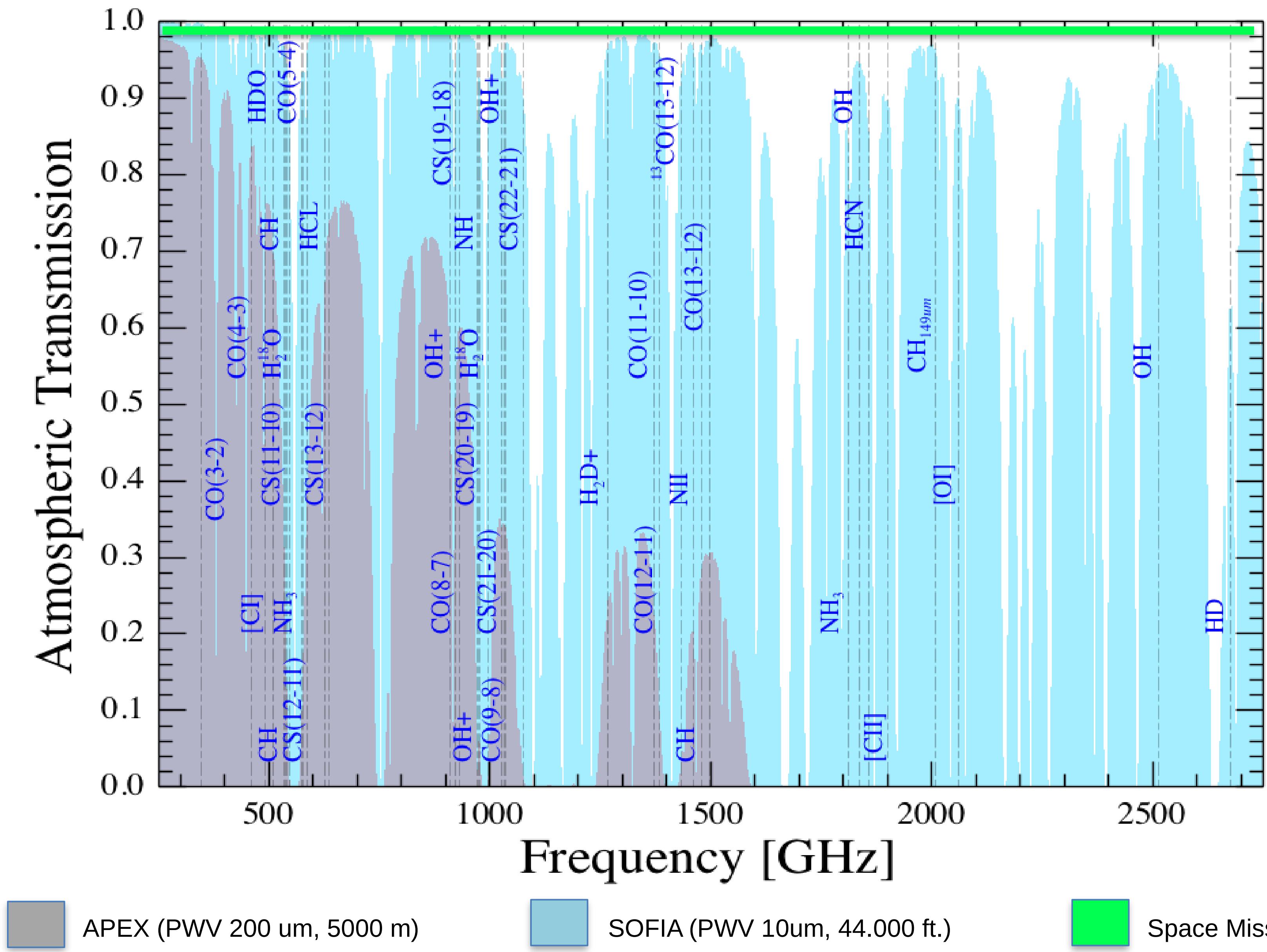
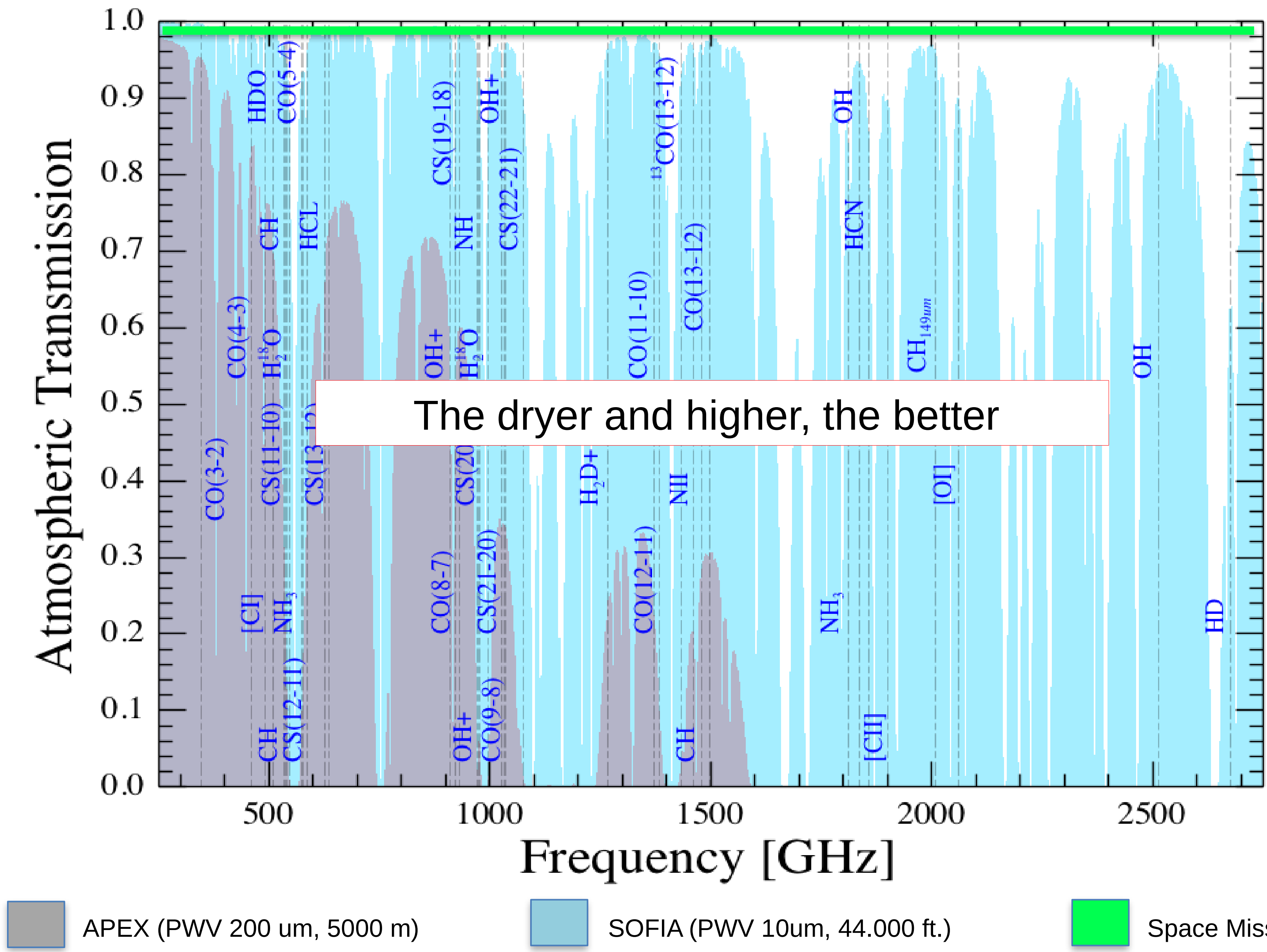
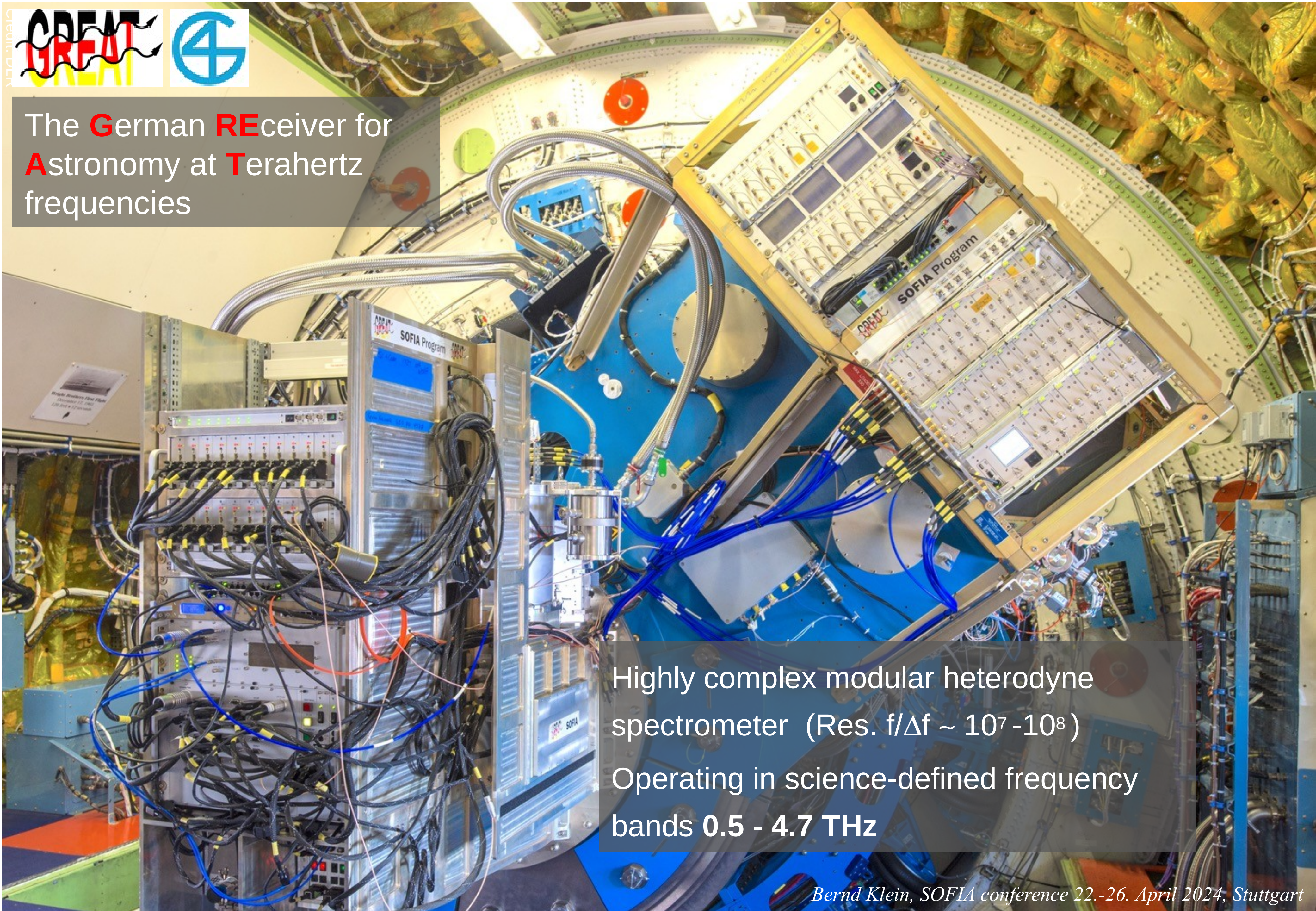
Role of the atmosphere



Bernd Klein, SOFIA conference 22.-26. April 2024, Stuttgart

Role of the atmosphere



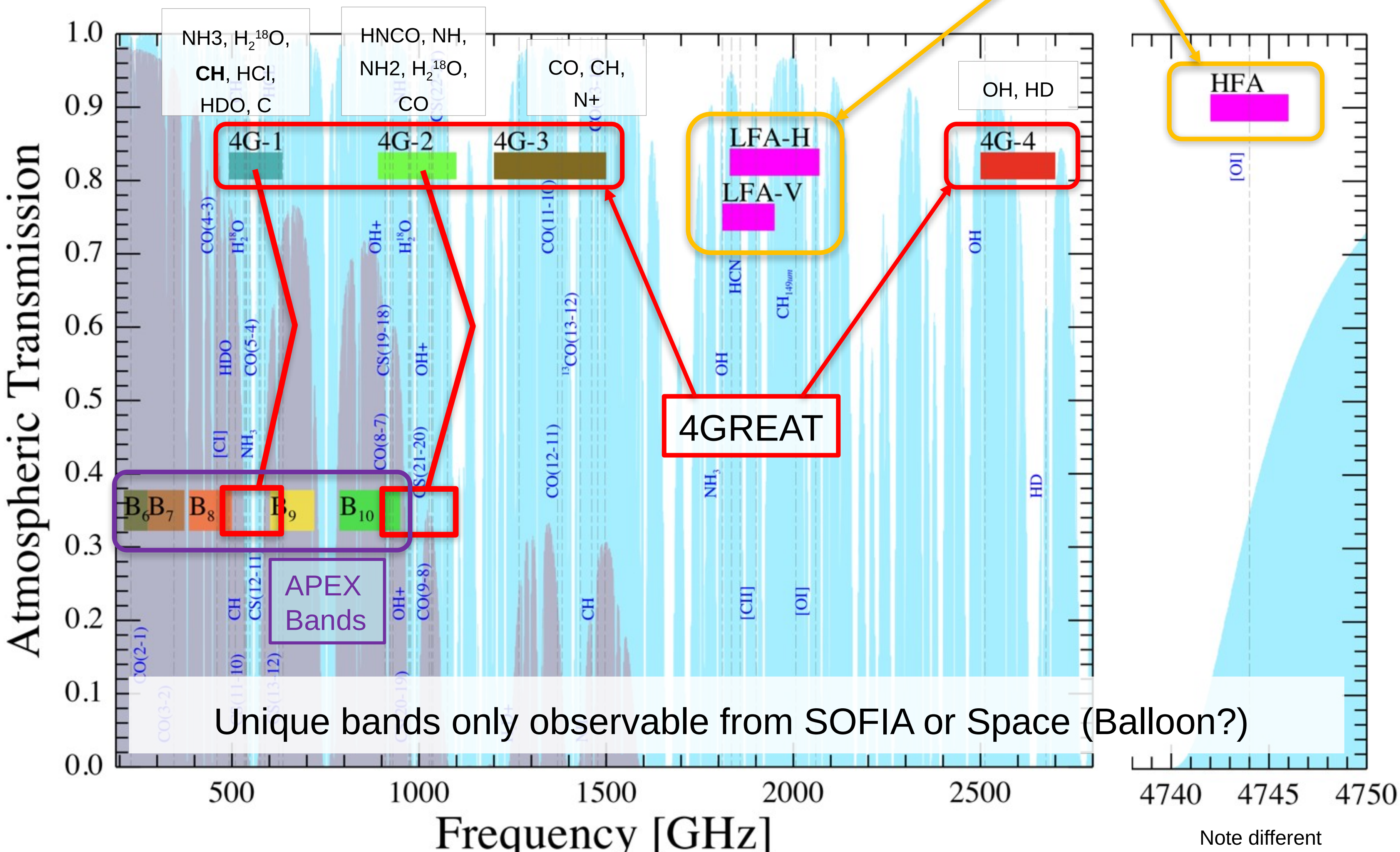


The **G**erman **RE**ceiver for **A**stronomy at **T**erahertz frequencies

Highly complex modular heterodyne spectrometer (Res. f/Δf ~ 10^7 - 10^8)

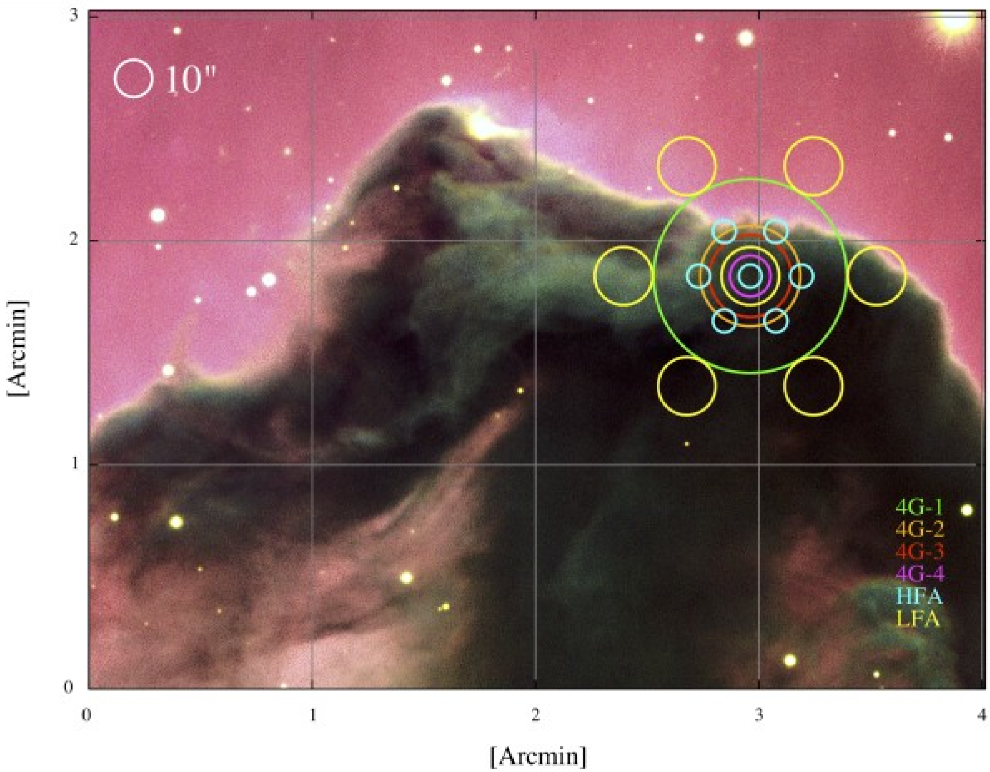
Operating in science-defined frequency bands **0.5 - 4.7 THz**

GREAT & APEX frequency bands



Atmospheric transmission for SOFIA (43.000 ft, 10 um) and ALMA (5000 m, 200 um).

GREAT Configurations Overview



- 3 cryostat (4G, LFA, HFA)
- 2 combinations
- Up to 5 simultaneous bands

Channel		Frequencies [THz]	Lines of interest	T_{rx}[K] / BW_{3dB} [GHz]
upGREAT	LFA	2x7 [1.8– 2.1]	NH_3, OH, CO series, [CII], [OI]	750 / 3.3
upGREAT	HFA	7x [4.74]	[OI]	900 / 3.3
4GREAT	4G1	0.49 - 0.63	[CI], CH, NH_3, $H_2{}^{18}O$, CO	150 / 4.0
	4G-2	0.89 – 1.10	CO, CH^+, OH^+, NH	300 / 4.0
	4G-3	1.25 – 1.52	[NII], CO series, OD, SH, H_2D^+	600 / 3.3
	4G-4	2.49 – 2.60	$^{(18)}OH(^2\Pi_{3/2})$	1500 / 2.0

Far-IR Spectroscopy Space Telescope (FIRSST) and its Heterodyne Spectrometer Instrument (HSI)

Martina Wiedner,
Andrey Baryshev,
Paul Grimes,
HSI team,
FIRSST team

FIRSST
FAR-INFRARED SPECTROSCOPY
SPACE TELESCOPE

An Astrophysics Probe Explorer Proposal
in response to NASA AO **NNH23ZDA021O**

From University of California, Irvine, with
The Johns Hopkins University Applied Physics Laboratory

16 November 2023

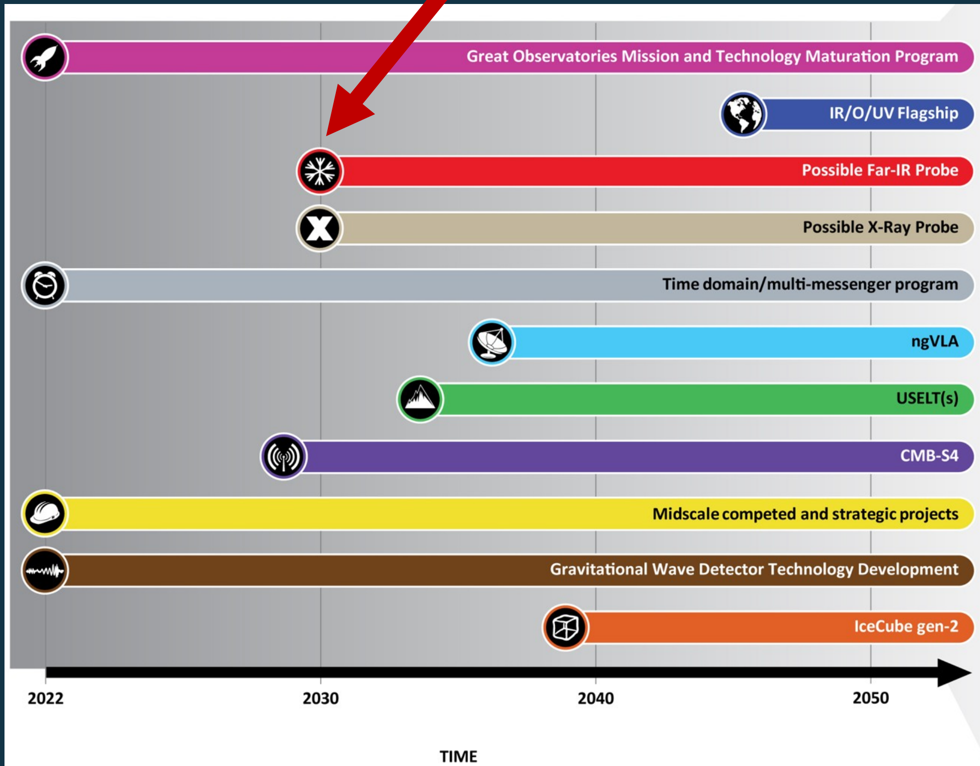
Dr. Asantha Cooray
Principal Investigator
University of California, Irvine

Dr. Pramod Khargonekar
Vice Chancellor for Research
University of California, Irvine

Partnering with
Ball Aerospace
Goddard Space Flight Center
Infrared Processing and Analysis Center
Observatoire de Paris
Smithsonian Astrophysical Observatory

This proposal contains JHU/APL and Ball Aerospace proprietary information.

NASA Apex call for Probe mission



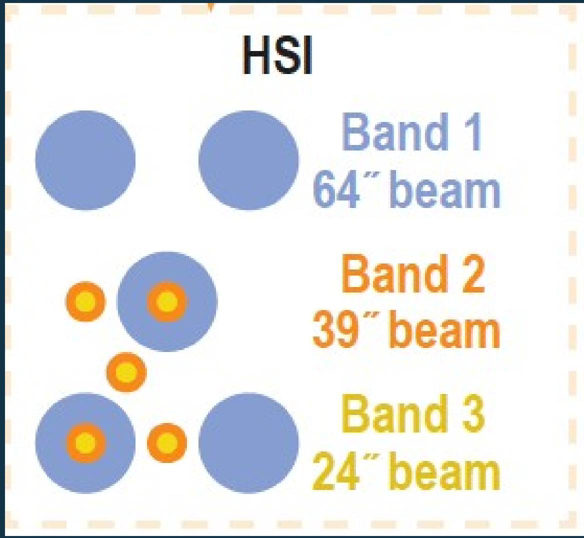
5 X-ray and 3 Far-IR proposals submitted:

- PRIMA: imaging, spectroscopy 1.8m @ 4.5K,
  24 – 235 microns, R = 10, >85, < 4 400
  PI Glenn, Meixner
- **FIRSST**: spectroscopy, 1.8m @ 4.8K
  35 – 600 microns, R = 100, 10^5 , 10^7
  PI Cooray, McGregor
- Saltus: spectro and imaging, 14m @ 45K
  34 – 660 microns, R= 300, 10^7
  PI Walker

Schematic drawn by Paul Grimes

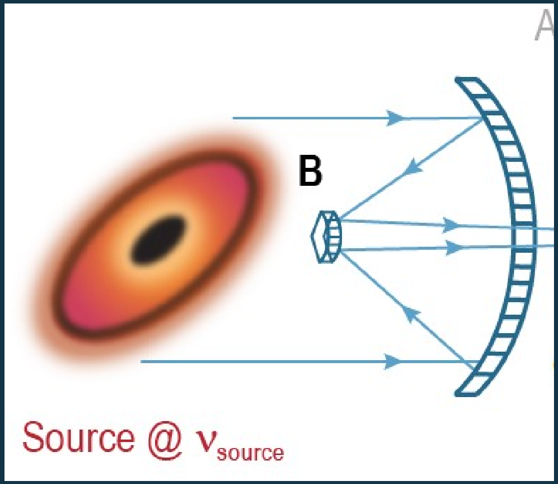
HSI PARAMETERS

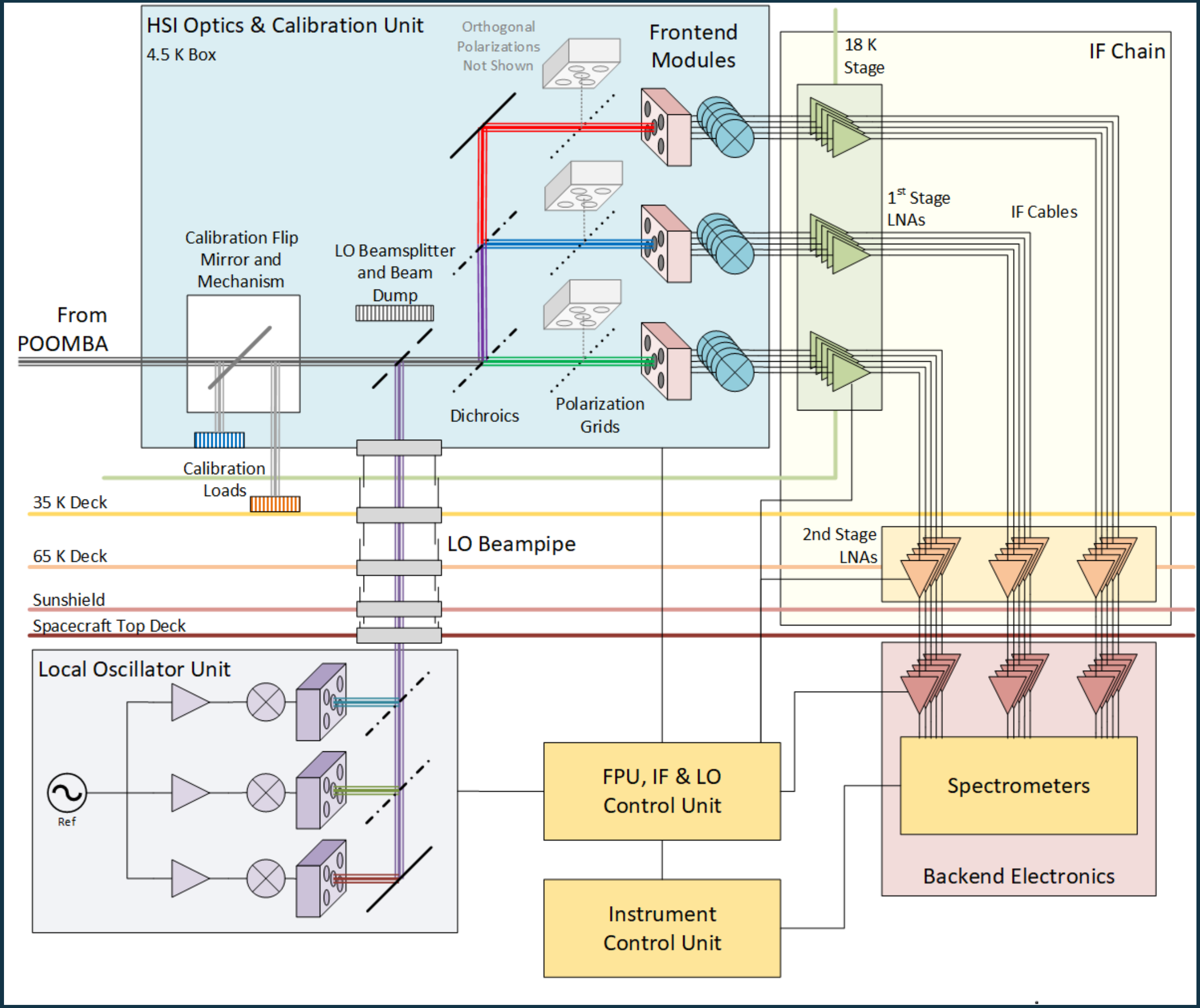
PARAMETER		BAND 1	BAND 2	BAND 3
Wavelength (µm)		380 - 600	240 - 340	150 - 200
Frequency (GHz)		790 - 500	1250 - 882	2000 - 1500
Resolving power (λ/Δλ)*		10^6 to 10^7		
Beam size		52″ - 83″	33″ - 47″	21″ - 28″
Instantaneous FoV		300″×200″	150″×100″	150″×100″
Spectral channels*		1024 or 10,000		
Array size		5 pixels × 2 polarizations		
Aperture efficiency		80%		
Mixer Type		SIS	HEB	HEB
Receiver noise temperature (DSB)	CBE	60K	300K	400K
	MEV	72K	400K	500K
	Sci. Reqt.	80K	430K	525K
IF bandwidth		4GHz		
Optical bench temperature		4.7K with ±0.1K stability (not critical)		
LNA temperature (1st stage)		18K with ±0.1K stability during Allan time		
Mixer temperature		4.7K with ±10mK stability during Allan time		
RMS WFE budget (nm)	Requirement	<7500		
	Allocated	3000		
	Margin	250%		



Schematic drawn by Paul Grimes

HSI Schematics





Schematic drawn by Paul Grimes

HSI Hardware Partners

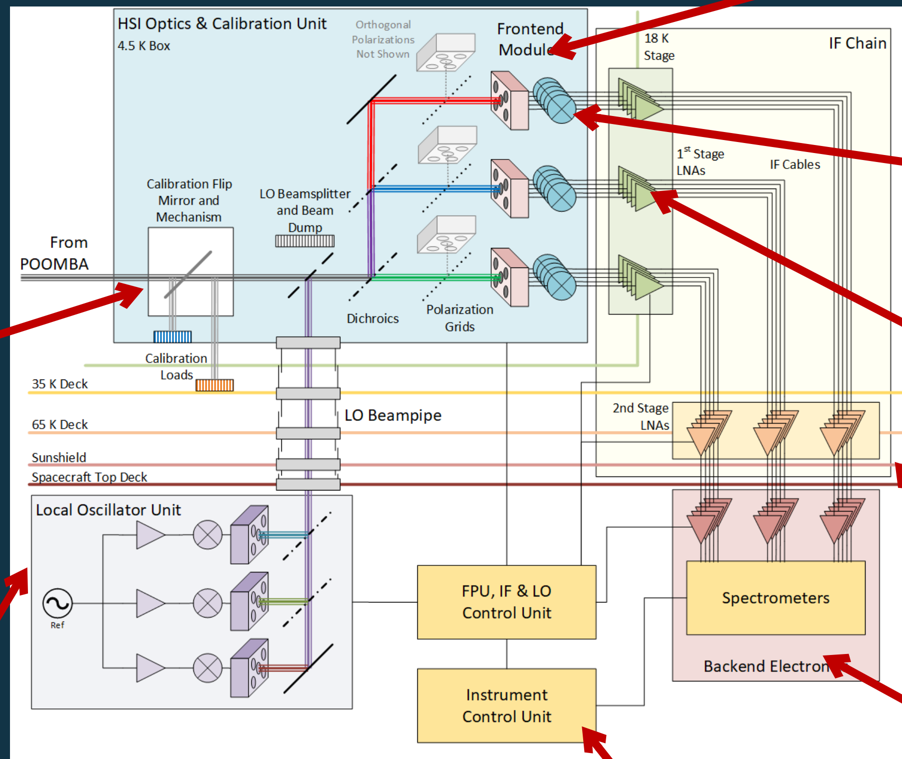
Focal plane arrays & Mixers
- SIS – IRAM/LERMA, France
- HEB – Chalmers, Sweden
- SIS – Uni Köln, Ger
- Feedhorn arrays and mixer– Oxford, UK

Smithsonian Astrophysical Observatory
- Integration and Testing
- Ground support equipment
- LO Beampipe

Subsystem level system I&T
- NOVA, NL

Ground system support
- STFC, UK

Optics
- NOVA,



Low noise amplifiers
- InP – Yebes, Spain
- SiGe – Yebes, COTS
- Bckup LNA

IF system
- Yebes, Spain
- U of Calgary (TBC)

Local Oscillators
- LERMA, France
- RPG or similar (commercial),Germany

Control Electronics
- INAF - IAPS, Turin, Italy

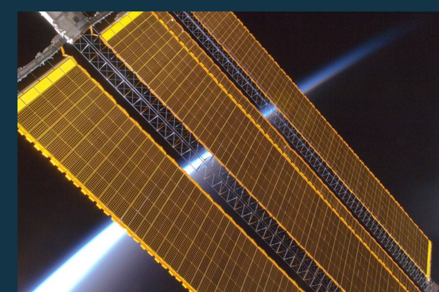
Backend
- MPIfR Bonn, or MPS and/or Omnisys

Schematic drawn by Paul Grimes

Challenges

Heat load: @ 4.5K   only 53 mW cooling capacity for all instruments and telescope!
→ Only essential components on 4.5K stage
→ Low heat load --> LNAs 5mW to 1 mW

Electrical Power: 260 W for HSI
→ For array require low power components
→ In particular backend
→ LO



Mass (80 kg) and Volume (0.123 m^3)
→ Few, wide channels
→ Compact designs

Timeline : 2026/27 PDR (TRL 6), 28/29 component delivery
→ High TRL, proven concepts

Schematic drawn by Paul Grimes

ASTHROS

ASTHROS (short for Astrophysics Stratospheric Telescope for High Spectral Resolution Observations at Submillimeter-wavelengths) is a high-altitude balloon mission for studying astrophysical phenomena.

ASTHROS

- ASTHROS is a **2.5-m** telescope on a long-duration flight balloon that will produce high spectral resolution

- ASTHROS will produce the first high-spectral resolution images of the [NII] 122µm line, which is obscured by the atmosphere even at SOFIA altitudes and can only be observed at balloon altitudes or from space.

- ASTHROS will have the capability to observe numerous other lines, for example, the HD line at 2.67 THz

- The ASTHROS instrument consist of **4-pixel receivers in the 1.5 THz & 2.5 THz** range based on room-temperature frequency multiplied local oscillator sources and cryogenically cooled HEB mixers.

- ASTHROS will aim to fly for **21 to 28 days** an altitude of about **130,000 feet** (40 kilometers) above **Antarctica**.

- First launch is planned for **December 2024**

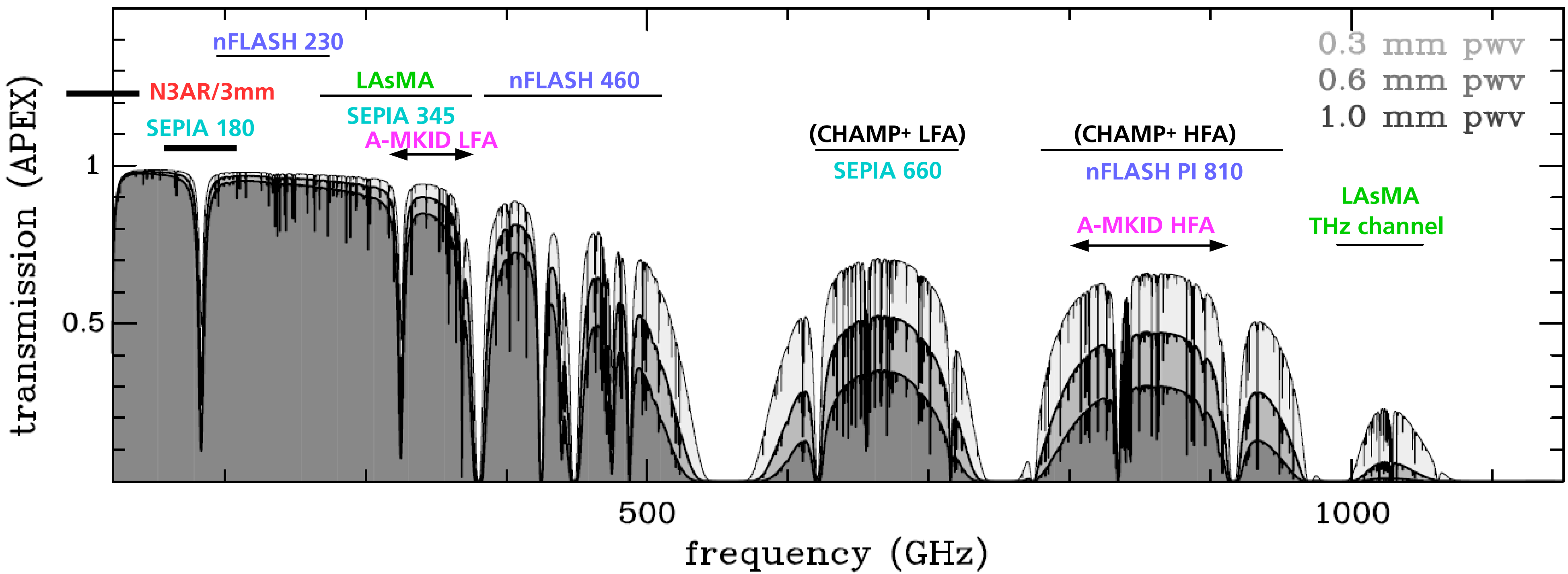
More information on ASTHROS:

https://www.jpl.nasa.gov/missions/asthros

APEX Instrumentation Overview

APEX instrumentation

Overview of all current and future APEX instruments



APEX instrumentation

Single-beam heterodyne receivers at APEX

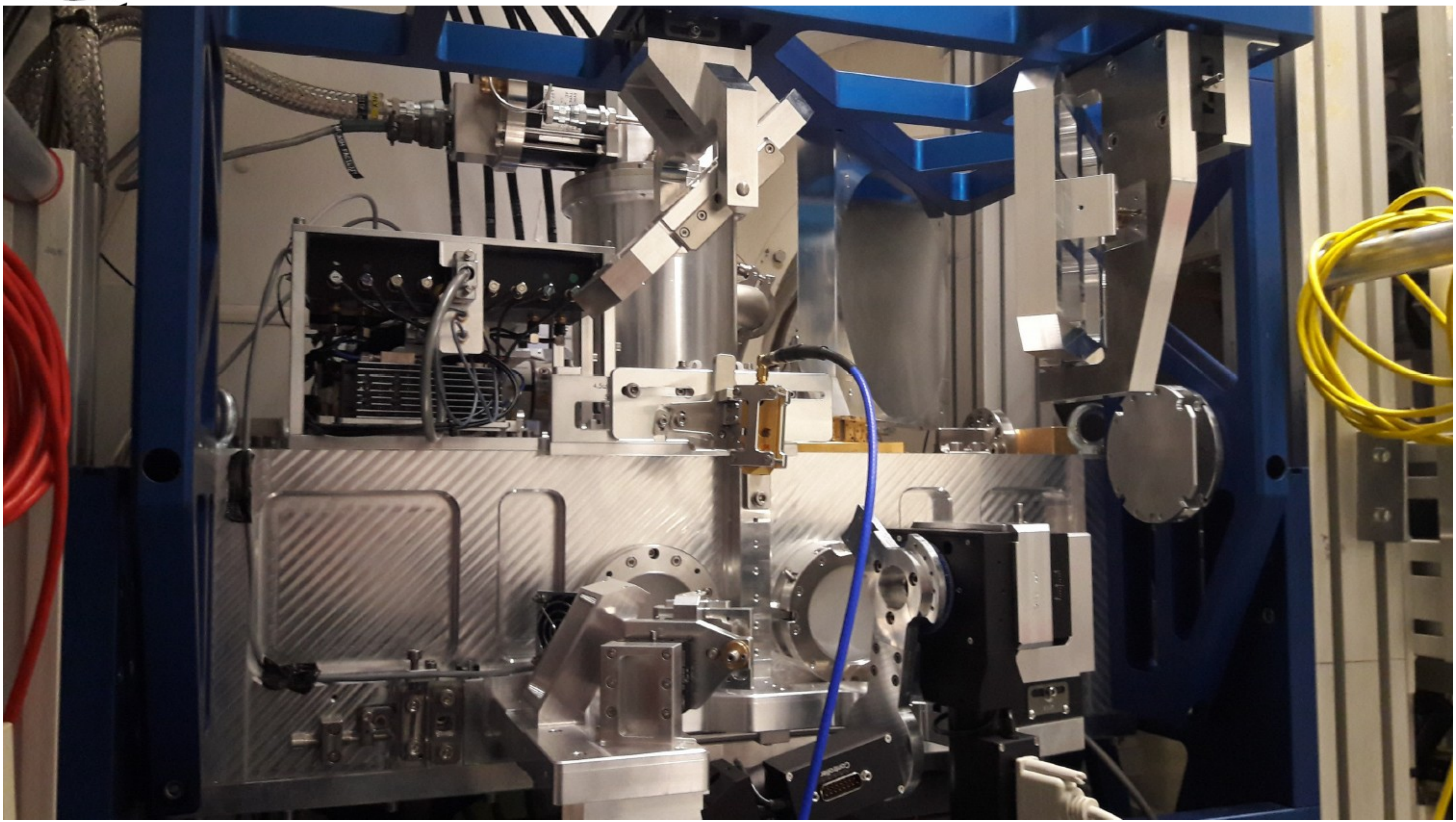
ALMA bands	#5	#6	#7	#8	#9	#10
RF bandwidth [GHz]	158-211	200-280	262-374	374-510	600-720	780-950
host receiver	SEPIA180	(PI230) NFLASH	SEPIA345	NFLASH	SEPIA660	NFLASH (PI)
mixers	2× 2SB	2× 2SB	2× 2SB	2× 2SB	2× 2SB	2× 2SB
IF response [GHz]	4 – 8	4 – 12	4 – 12	4 – 8	4 – 12	4 – 12
responsible party	OSO/ESO	MPIfR	OSO/ESO	MPIfR	OSO/ESO	MPIfR
operational by	2018	2016/18	2020	2020	2018	2024

Multi-beam heterodyne receiver at APEX

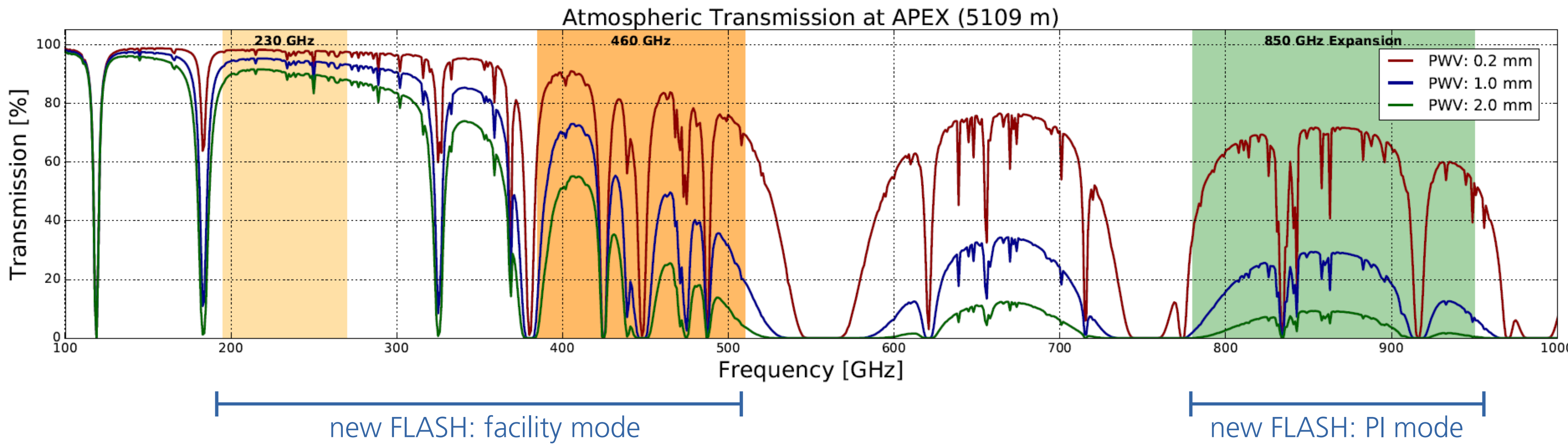
Instrument	RF range [GHz]	IF band [GHz]	T_{Rx} [K][a]	type of mixer	in operation since	in operation until	instrument status	notes
LAsMA	268 – 375	7×2× 4 – 8 7×2× 4 – 10	80 – 100	2SB	09/16 01/22		PI	7 pixel heterodyne array

Incoherent Array						
Instrument	λ_{cc}[μm]	number of pixels	FoV [arcmin]	NEFD [mJy √s]	Instrument status	Notes
A-MKID	865	3520	15 × 15	50	shipped to APEX; installation 08/2023	cooperation between MPIfR with SRON
	353	21600		160		

The new FLASH receiver: NFLASH



The new FLASH receiver: NFLASH



230 GHz band:

- VDI LO unit,
  tuning range: 200–270 GHz
- dual-polarization setup
- IRAM SIS 2SB mixer (PI230),
  IF bandwidth 4 – 12 GHz
  total IF bw: 2x 2x 8 GHz = 32 GHz
- T_{RX}: 60 – 80 K

460 GHz band:

- VDI LO unit,
  tuning range: 385–510 GHz
- dual-polarization setup
- ALMA band 8 SIS 2SB mixer,
  IF bandwidth 4 – 8 GHz
  total IF bw: 2x 2x 4 GHz = 16 GHz
- T_{RX}: 100–150 K

810 GHz band:

- broadband VDI hybrid LO,
  tuning range: 780–950 GHz
- dual-polarization setup
- ALMA band 10 mixer
  (SRON cooperation) 2SB
  IF bandwidth 4 – 12 GHz
  total IF bandwidth: 32 GHz
- Receiver temperature: 600–1000 K

SEPIA: Swedish-ESO PI receiver for APEX

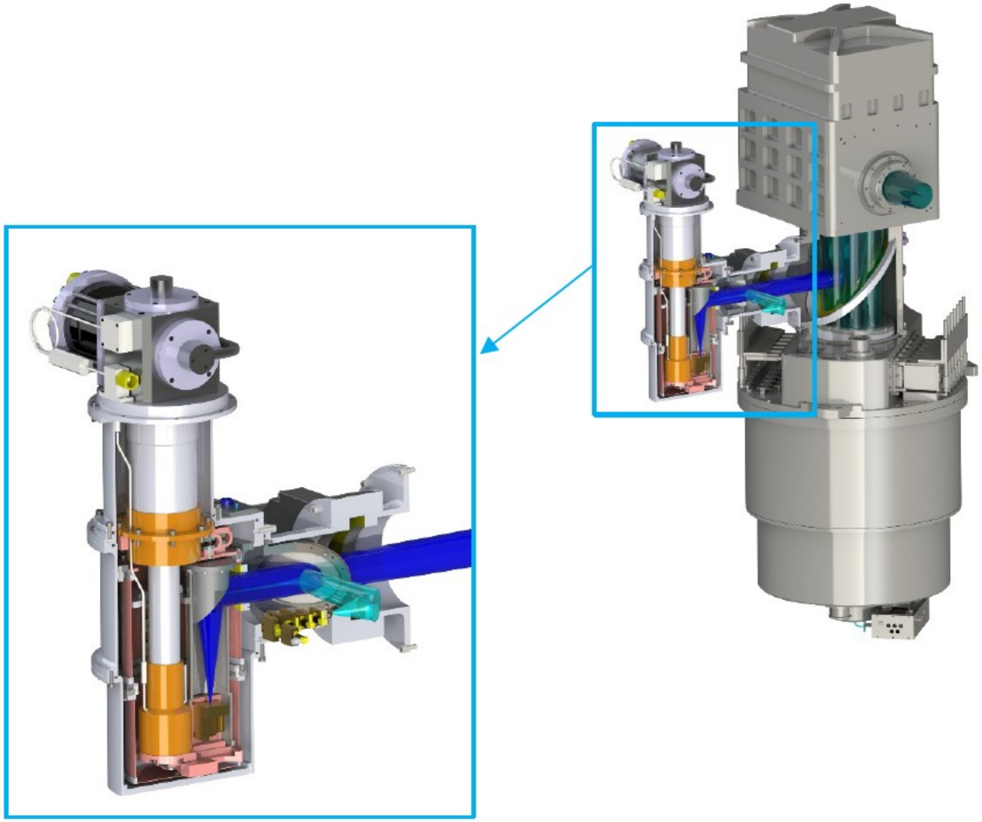
OSO / MPIfR agreement to use SEPIA for 2023 – 2025

- **BAND 5**
  - Frequency range: 159 – 211 GHz
  - Dual polarization, dual sideband (2SB mixers)
  - Receiver noise temperature: ~ 55 K (SSB)
  - IF bandwidth: 4 – 8 GHz

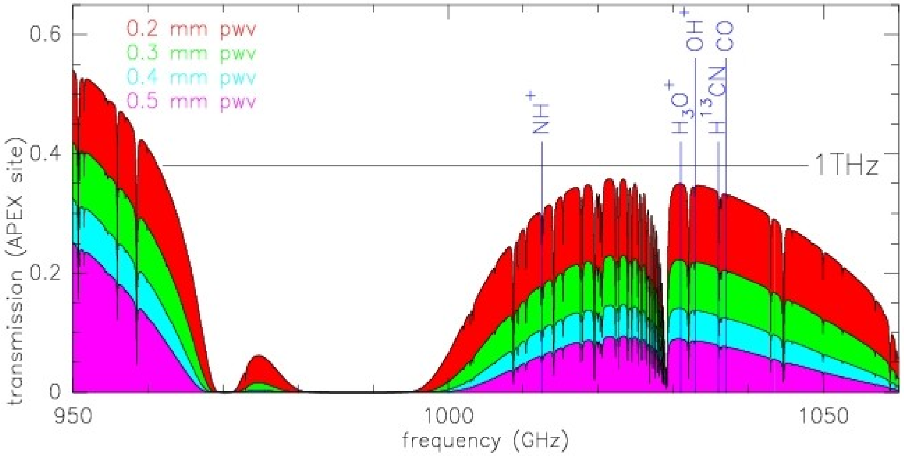
- **BAND 7**
  - Frequency range: 272 – 376 GHz
  - Dual polarization, dual sideband (2SB mixers)
  - Receiver noise temperature: 60 – 120 K (SSB)
  - IF bandwidth: 4 – 12 GHz

- **BAND 9**
  - Frequency range: 597 – 725 GHz
  - Dual polarization, dual sideband (2 SB mixers)
  - Receiver noise temperature: 225 – 375 K (SSB)
  - IF bandwidth: 4 – 12 GHz

LAsMA – the new THz channel



3D model of the planned THz receiver



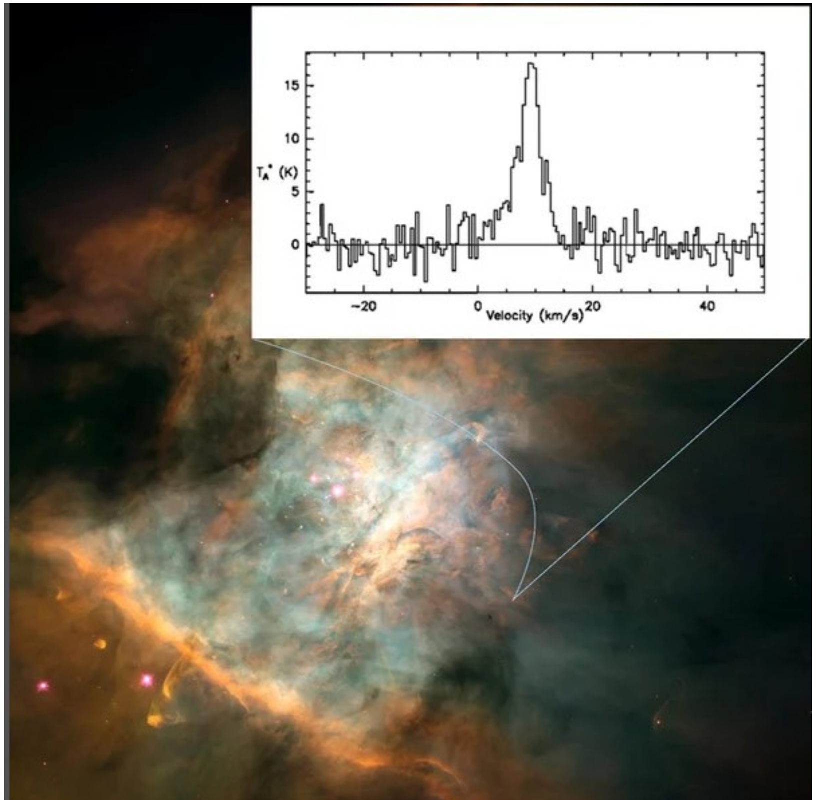
Technical specifications:

- Spin-off from our Herschel involvement (HIFI band 5 mixer, DSB)
- Co-aligned to the central pixel of LAsMA for pointing reference
- RF range: 990 – 1050 GHz
- Receiver noise temperature (DSB): 400 – 550 K
- VDI solid-state LO source
- IF bandwidth: 4 – 8 GHz
- Parallel use of the LAsMA IF processor and FFT spectrometer

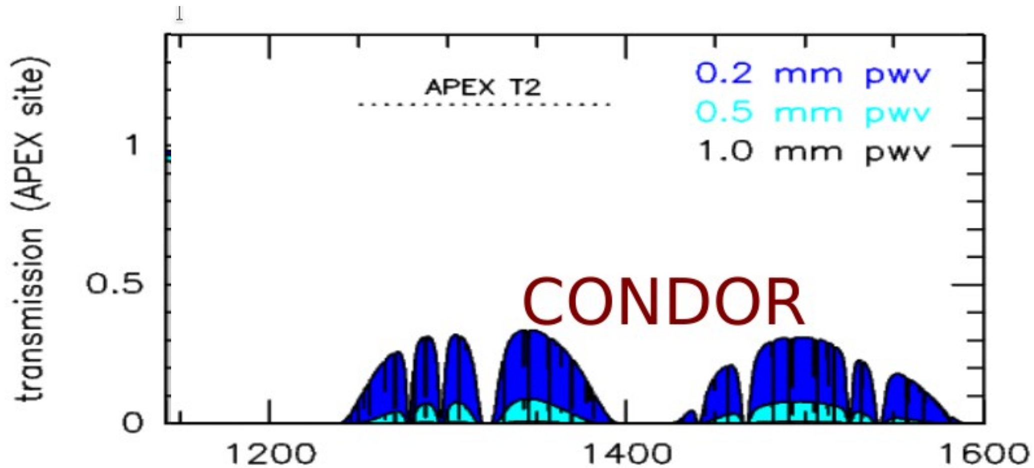
- Strong operation boundaries:
  - requires best weather conditions (PWV < 0.3 mm)
  - pointing requirements are demanding (main beam: 6'' only)
  - telescope surface must be very good (surface rms < 15 μm)

CONDOR: The CO N+ Deuterium Observation Receiver

November 2005



Star formation in the Orion Nebula. The plot in the upper right corner shows the first CONDOR detection of highly excited carbon monoxide (CO J = 13 → 12) from the massive star formation region FIR4 in Orion. The line is a clear indicator of hot gas. In the background is an optical image from the Hubble Space Telescope, which shows a larger region of stars and glowing dust. FIR 4 is not visible at optical frequencies because it is hidden behind a thick layer of dust and gas.



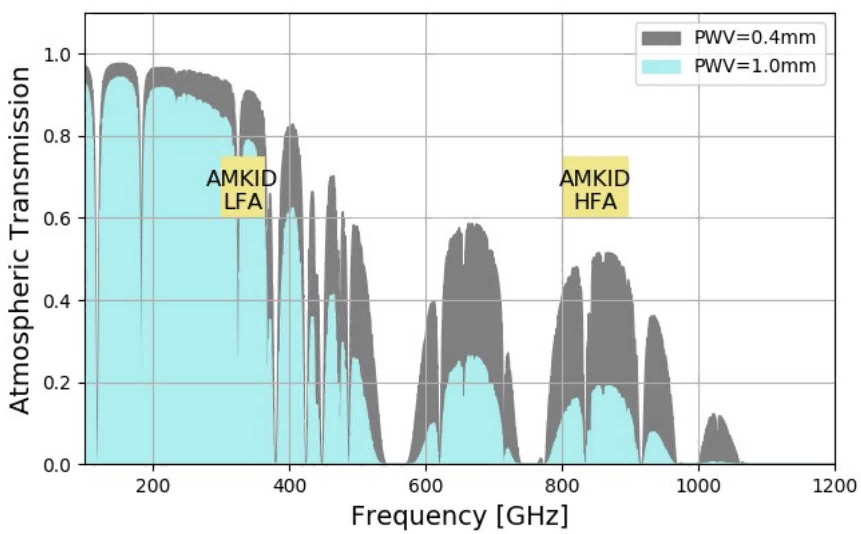
The CONDOR project

The CONDOR project is carried out at the First Physical Institute of the University of Cologne in an Independent Junior Research Group of the Collaborative Research Center 494.

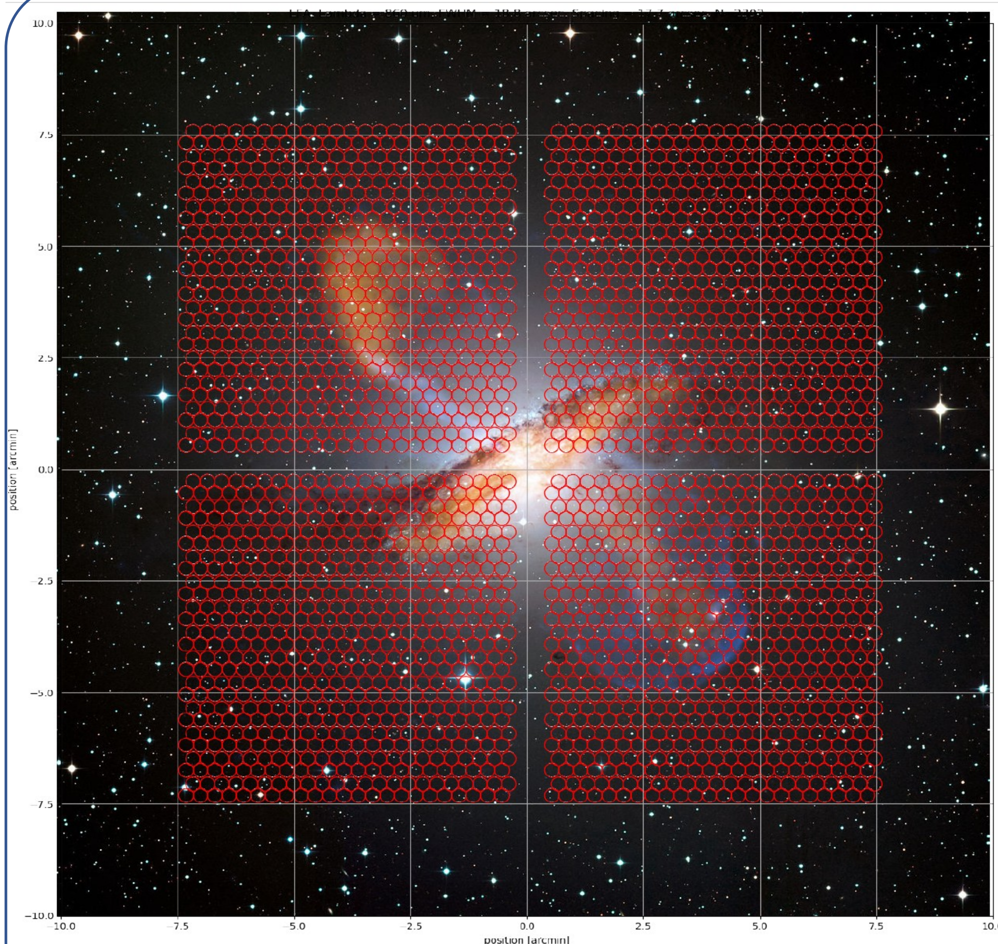
More information on CONDOR:

https://www.mpg.de/514249/pressRelease20051222

A-MKID: Microwave Kinetic Inductor Detector Camera for APEX

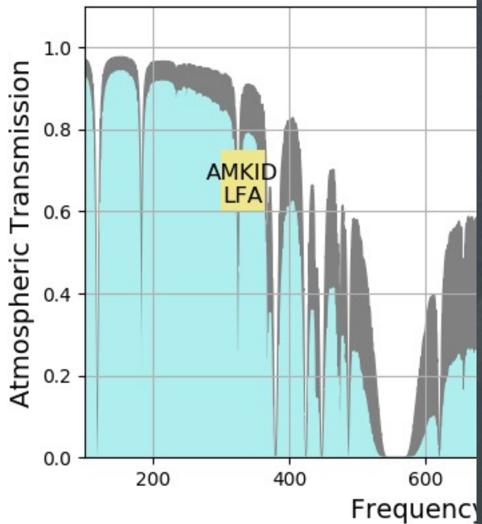


- Incoherent receiver for APEX (5.000masl)
- Dual Band: 330-364 GHz & 800-900 GHz
- Field of view: 15X15 arcmin^2
- Beam size:
  - Low Band 17’’
  - High Band 8’’
- Technology: Kinetic Inductance Detectors
- Pixel spacing, Number of detectors:
  - Low Band (1.1Fλ, 2800 pixels)
  - High Band (1.3Fλ, 13800 pixels)
- Number of pixels:
  3520 pixels at LFA and 13952 pixels at HFA

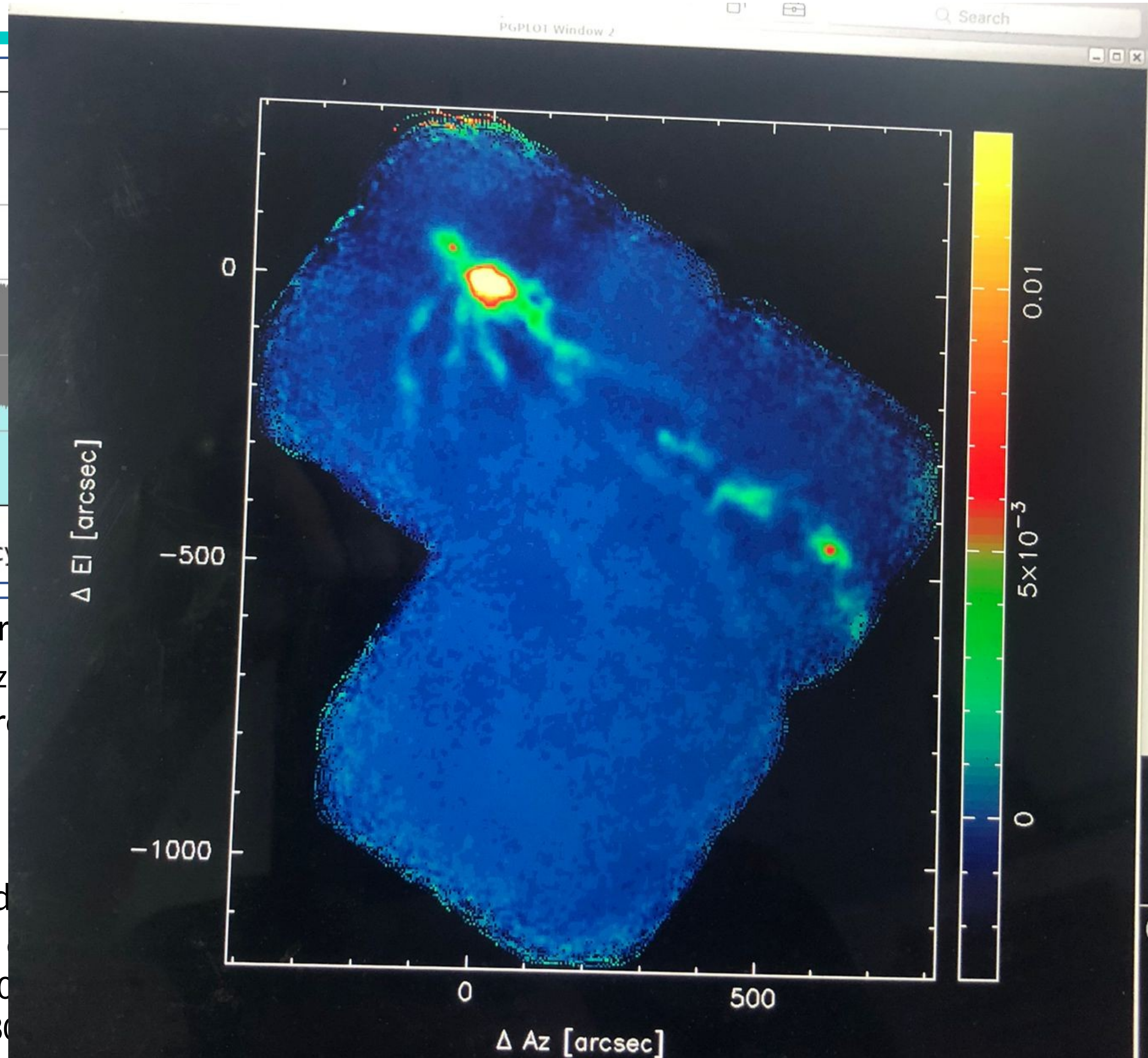


Colour composite image of Centaurus A (©ESO), and layout of the LFA AMKID camera. HFA array cover the same field of View of LFA but with 5 time more pixel density.

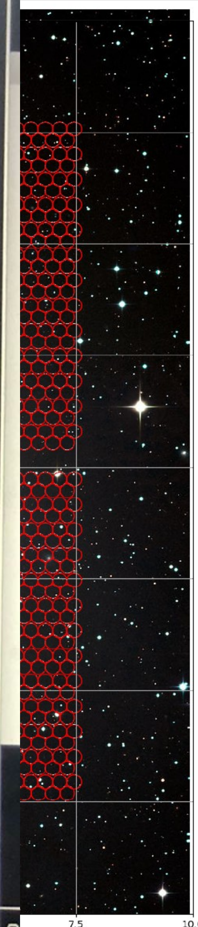
A-MKID: Microwave Kinetic Inductor Detector Camera for APEX



- Incoherent receiver for
- Dual Band: 330-364 GHz
- Field of view: 15X15 ar
- Beam size:
  - Low Band 17''
  - High Band 8''
- Technology: Kinetic Ind
- Pixel spacing, Number
  - Low Band (1.1Fλ, 2800
  - High Band (1.3Fλ, 138
- Number of pixels:
  3520 pixels at LFA and



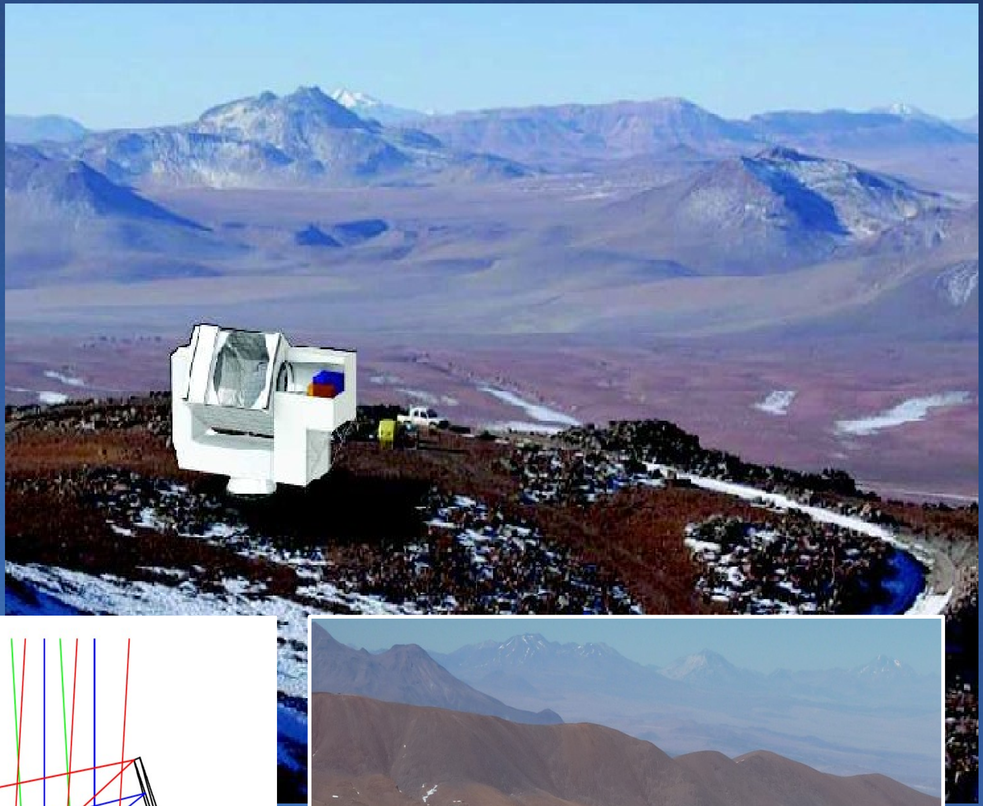
140sec integration on Orion IRC2 (LFA)

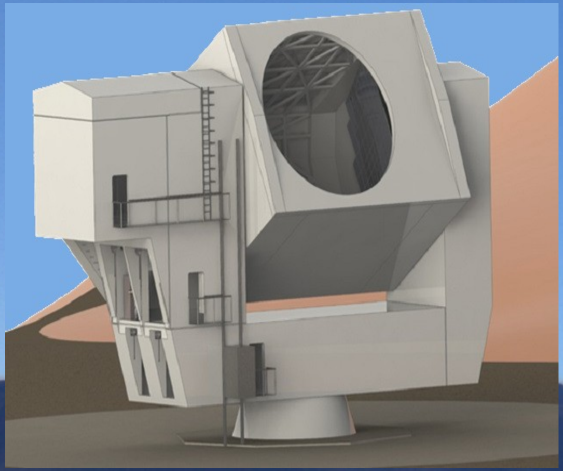


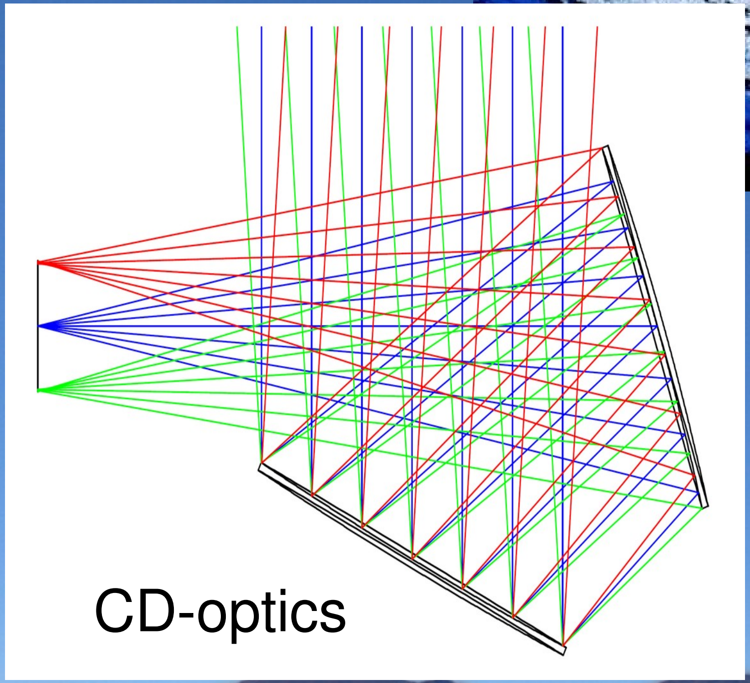
out of the
ew of LFA

CCAT Observatory

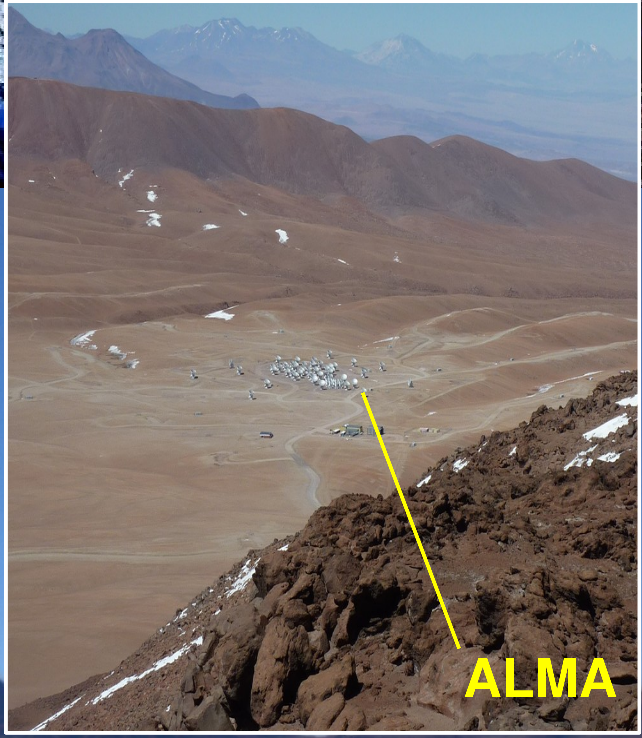
- FYST telescope: 6 m diameter
- crossed Dragone (CD)
- flat FOV ~8° at 100 GHz
- 10 (goal: 7) μm surface
- Cerro Chajnantor / Chile (5600m)
- first light: 2025
- two instruments:
  - PrimeCam
  - CHAI





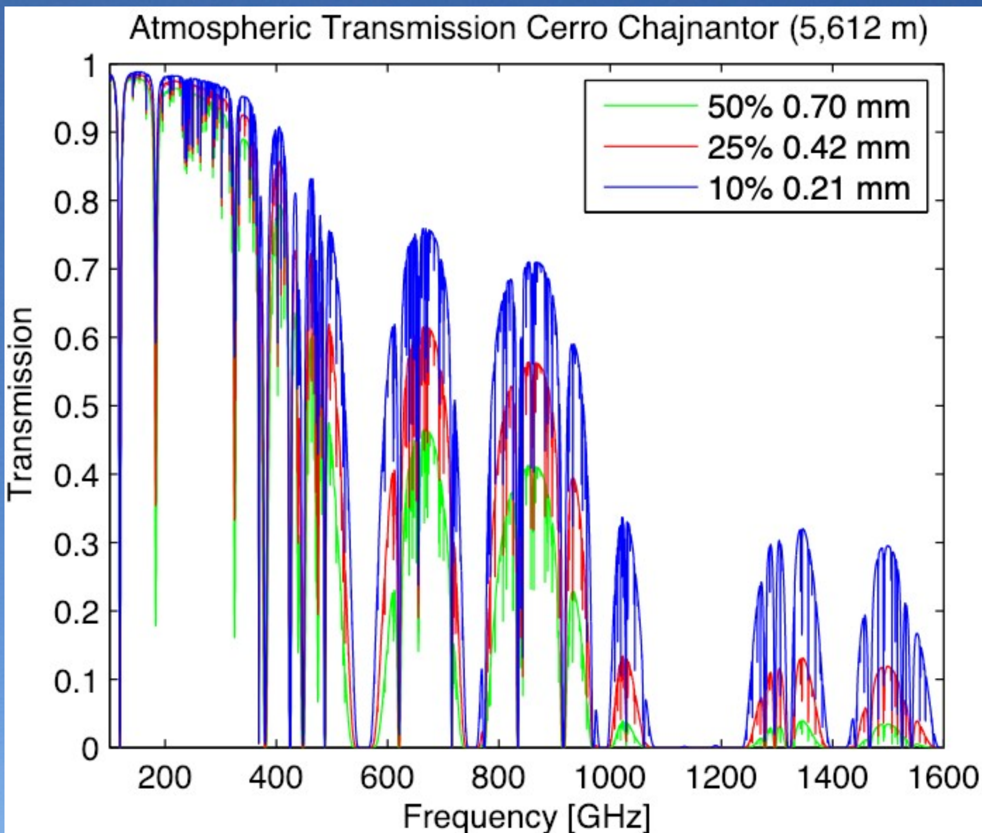


Dragone 1982
Niemack 2015

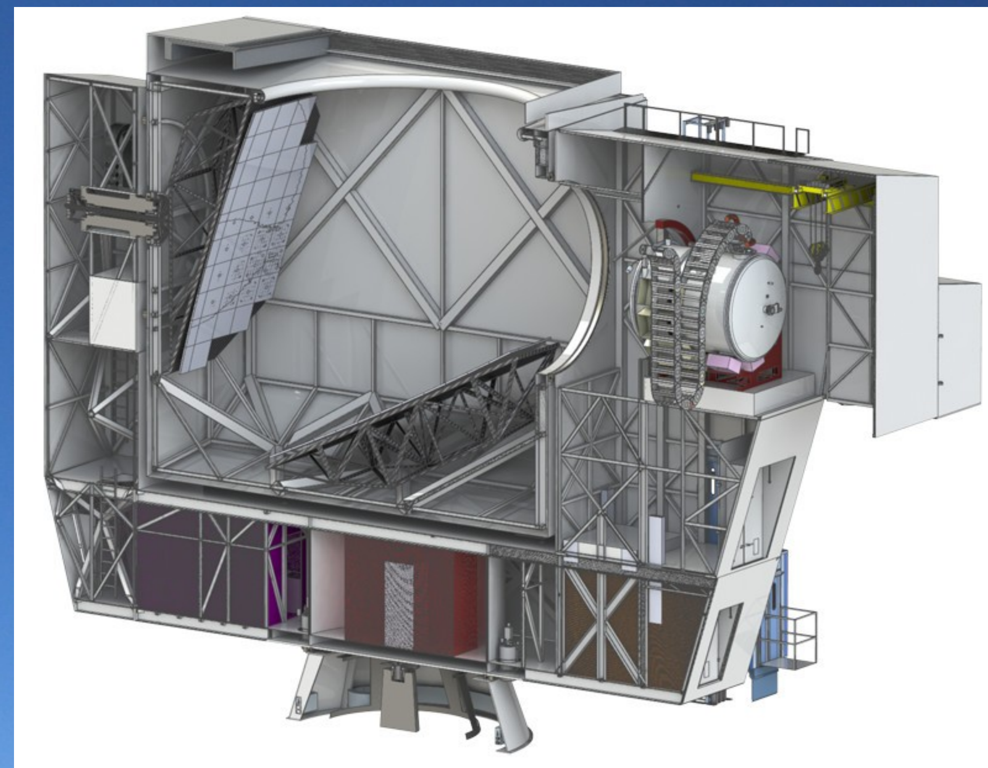


Cerro Chajnantor Site Testing

Excellent site for submm and possibly THz astronomy



Bustos+ 2014



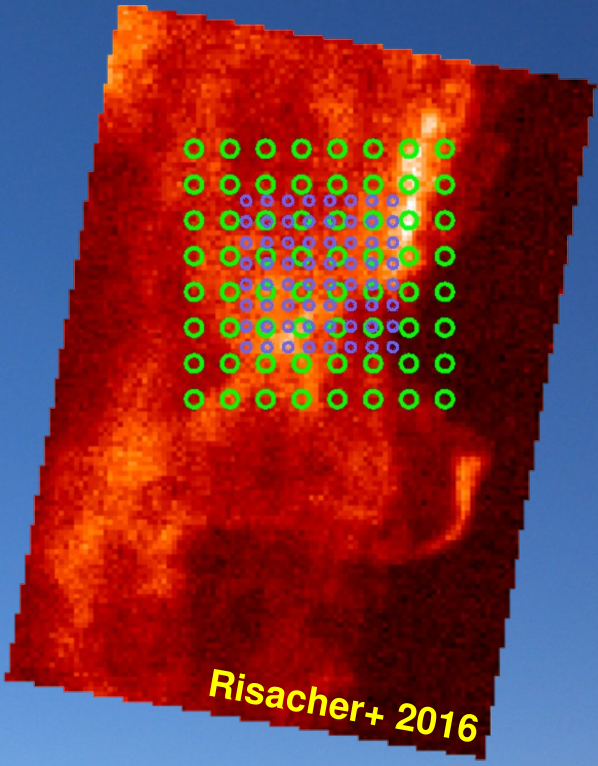
3D model of the Fred Young Submm Telescope (FYST)

CHAI: CCAT Heterodyne Array Instrument

	LFA	HFA
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

- ideal for large scale mapping ([CI], CO 4→3, 7→6)
- 800 GHz beam fits SOFIA at 2000 GHz ([CII], [OI])

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




SOFIA is no longer flying - but wonderful
memories of a GREAT time remain.