4×2 Hot electron bolometer mixer arrays for detection at 1.4, 1.9 and 4.7 THz for a balloon borne terahertz observatory

Dr. Jose R. G. Silva, on behalf GUSTO team

Yokohama, 20 June 2024

SRON
Netherlands Institute for Space Research

GUSTO

Outline

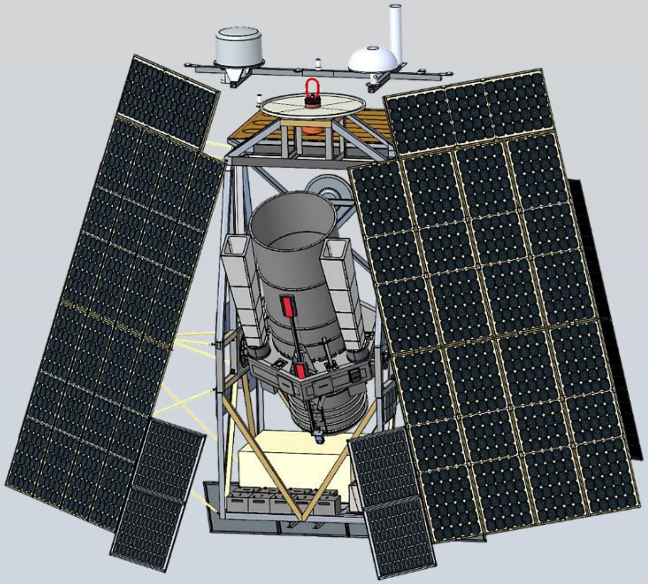
- GUSTO overview
- Initial Science Results
- 4 × 2 HEB Arrays
- Optimization of Lens antenna system
- RF performance
- Conclusions

Mission Overview

GUSTO Highlights

Instrument
- 0.90-m telescope
- Terahertz heterodyne array receivers
- Cryostat cooled 4 K detectors

Launch site
- McMurdo Stn. Antarctica



Key Mission Requirements

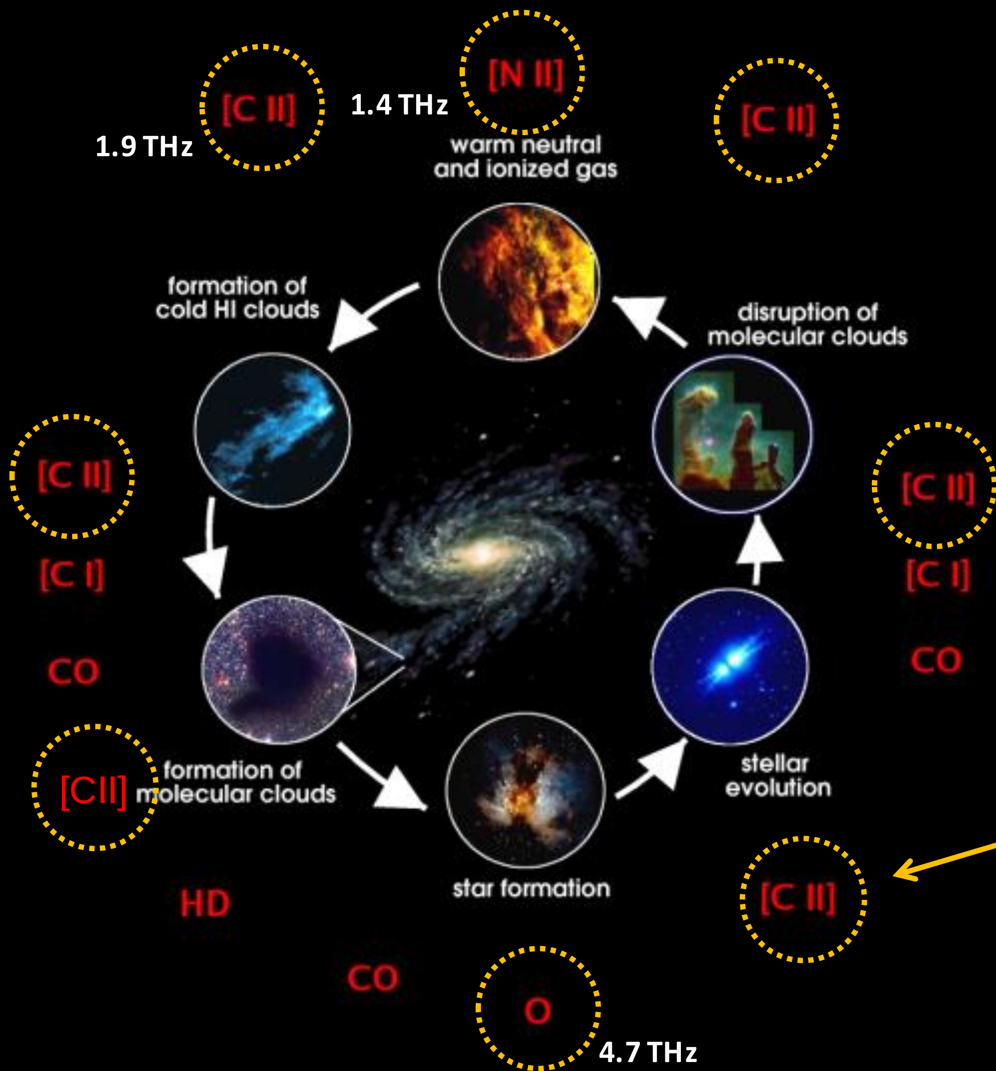
Mission Design Life	**75 day Baseline, 55 day Threshold**
Altitude	**Sub-orbital, 33 km**
Launch Vehicle	**Zero Pressure Balloon (ZPB)**
Mass	**1,600 kg maximum**
Power Usage	**850 W minimum average**
Data Downlink	**300 kbps minimum average**
Storage	**1.6 Tb**

Mission Programmatics

$48 M Cost Cap
31 December 2023, launch readiness date
Sponsored by NASA Explorers Program

Instrument: University of Arizona (UA)
Gondola: Johns Hopkins Applied Physics Lab (APL)
Mission Operations: APL
Science Operations: UA

Life Cycle of ISM

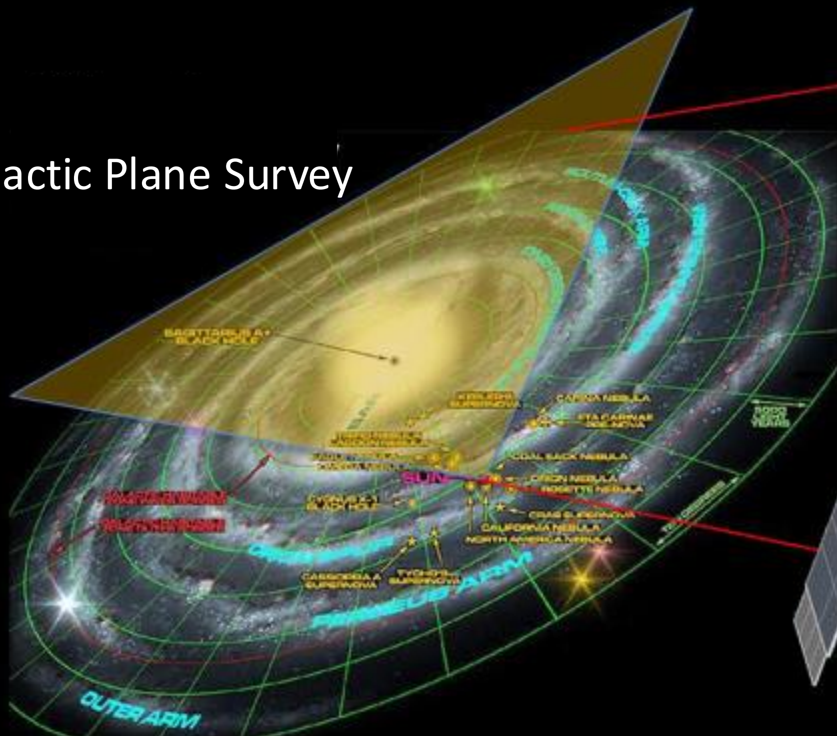


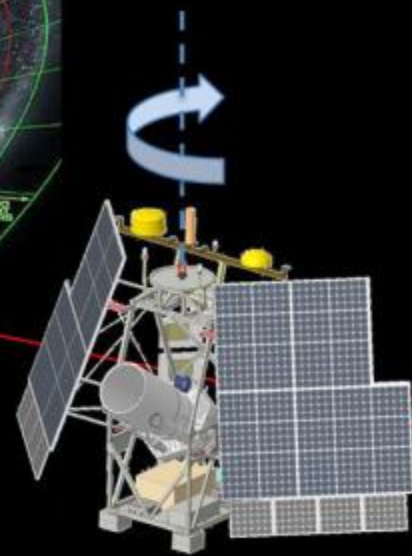
Fine structure lines, Carbon, Oxygen, and Nitrogen, to probe **all relevant** phases of the interstellar medium from dense, warm, molecular interfaces to ionized gas

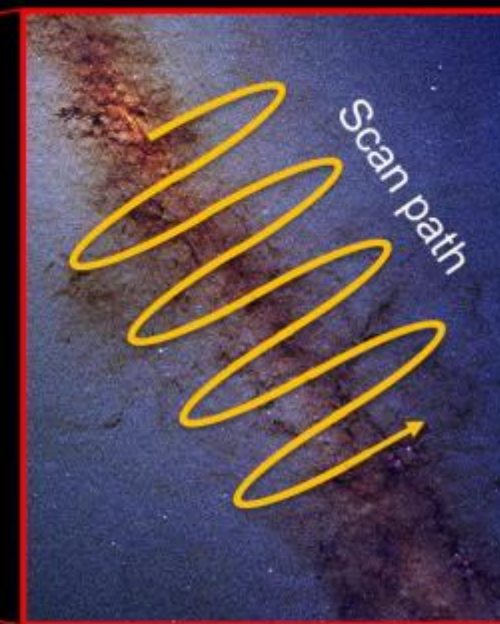
Brightest Line in *the FIR over cosmic time*

GUSTO Observational Objectives

Galactic Plane Survey

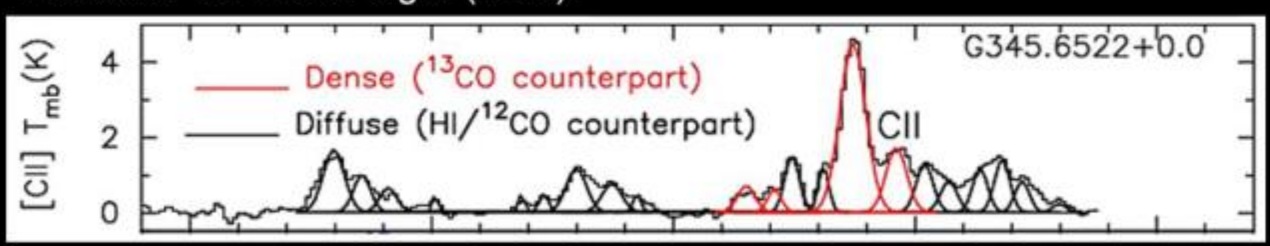






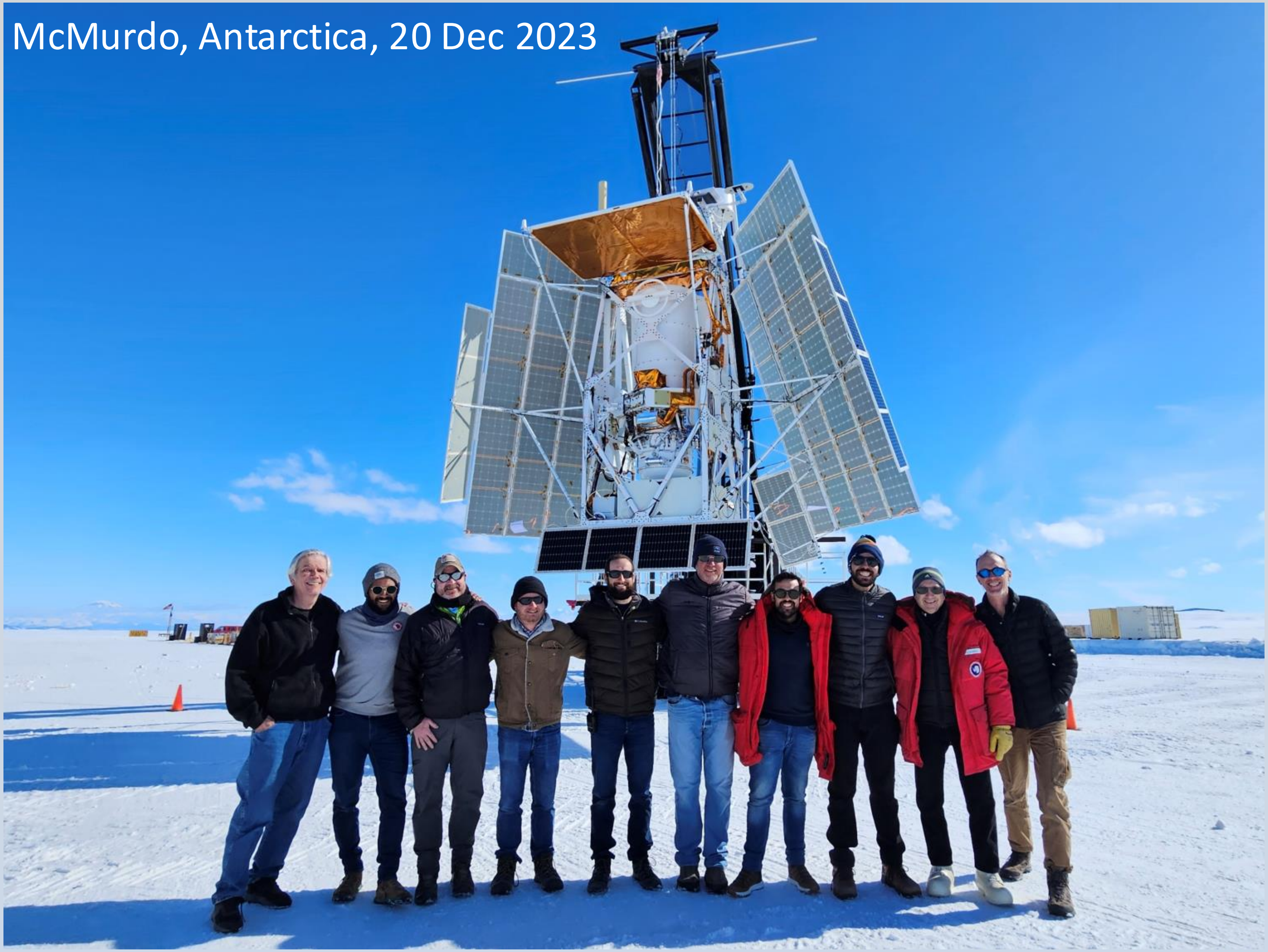
On-the-Fly Mapping

Herschel CII line of sight (LOS):



LMC Survey
Dist: 158,000 ly

GUSTO Hang-test

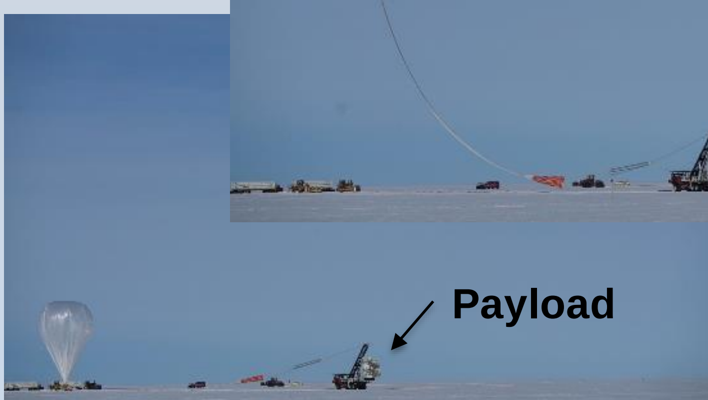


GUSTO

Launch on December 31, 2023

CSBF Website

Balloon Release



Balloon Inflation

GUSTO Trajectory

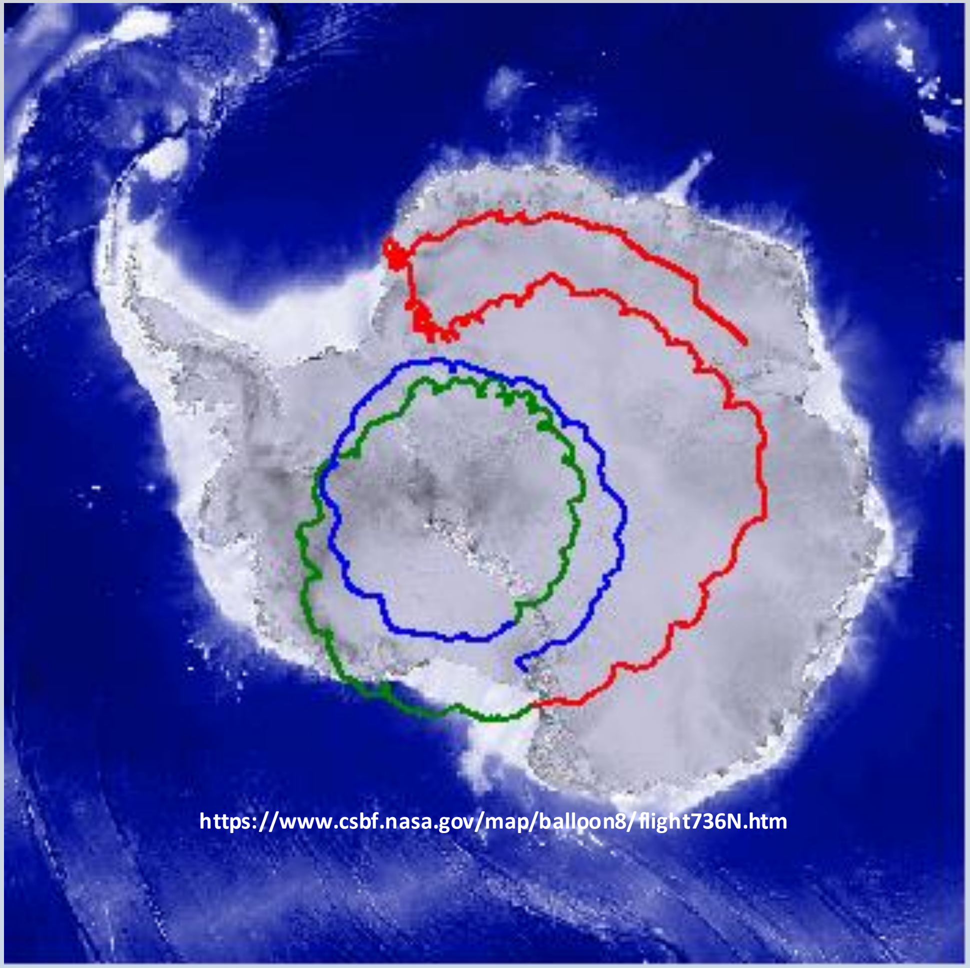
Flight Duration:
57 days, 7 hours

New NASA record for longest duration

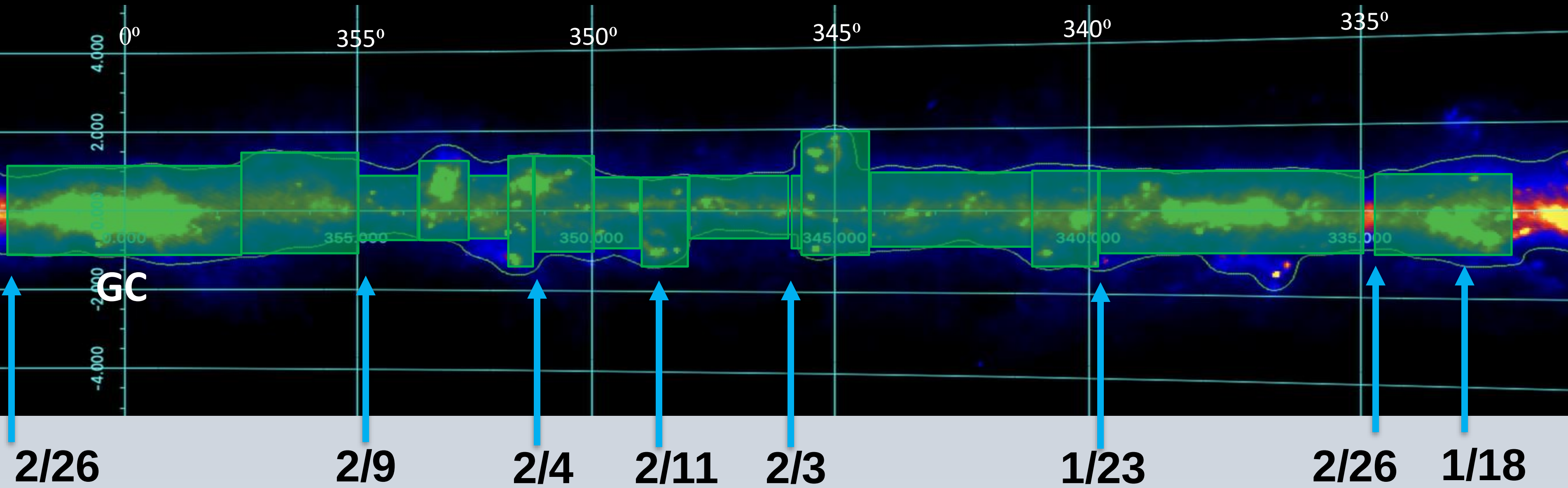
Payload position as of:
20:31:07Z 02/27/24

Latitude: 71˚ 12.54 S
Longitude: 61˚ 59.47 E

~~Recovery to be assessed in October~~



Galactic Plane Survey status

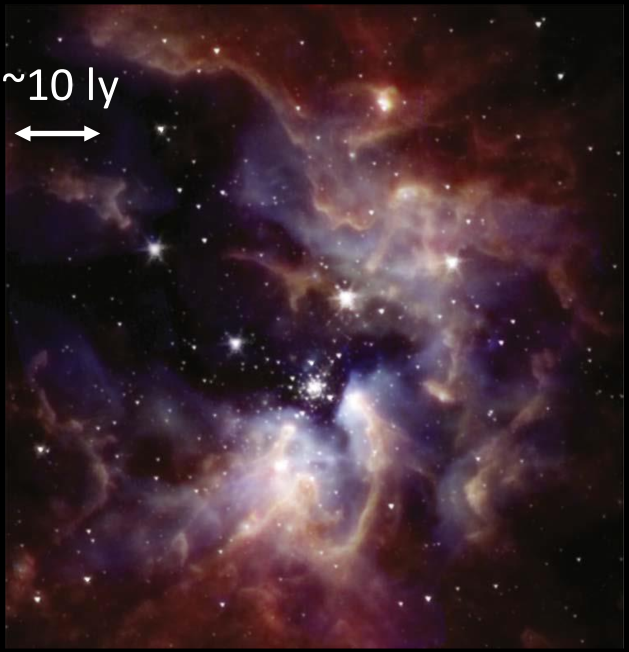


- **Data products on track to meet or exceed Threshold Requirements**
  - Angular resolution & coverage, spectral resolution & coverage, sensitivity
- **62 square degrees of Galactic Plane mapped in Bands 1 and 2**
  - Easily exceeds mission success criteria, and 100% of Threshold mission!
  - ***> 1 Million Lines of Sight through the Milky Way!***
  - *Data processing ongoing*

Band	SSB Tsys (K)
B1 [NII]	2200-2500 K
B2 [CII]	2500-2800 K

Receivers' performance
Incl. Trec, optics, telescope forward efficiency

Targeted Deep Sky Survey: NGC 3603



Buizer et al. 2024
(Dust: SOFIA + Herschel)

Massive Star Forming Region (100x Orion)

Dist: ~20,000 ly
Mass: ~4x10^5 M_{sun}
Luminosity: ~3x10^6 L;$_{sun}$

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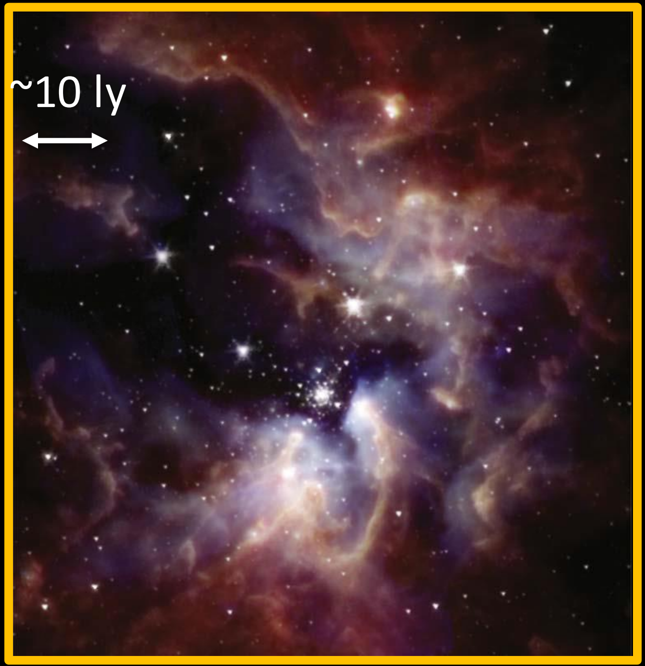

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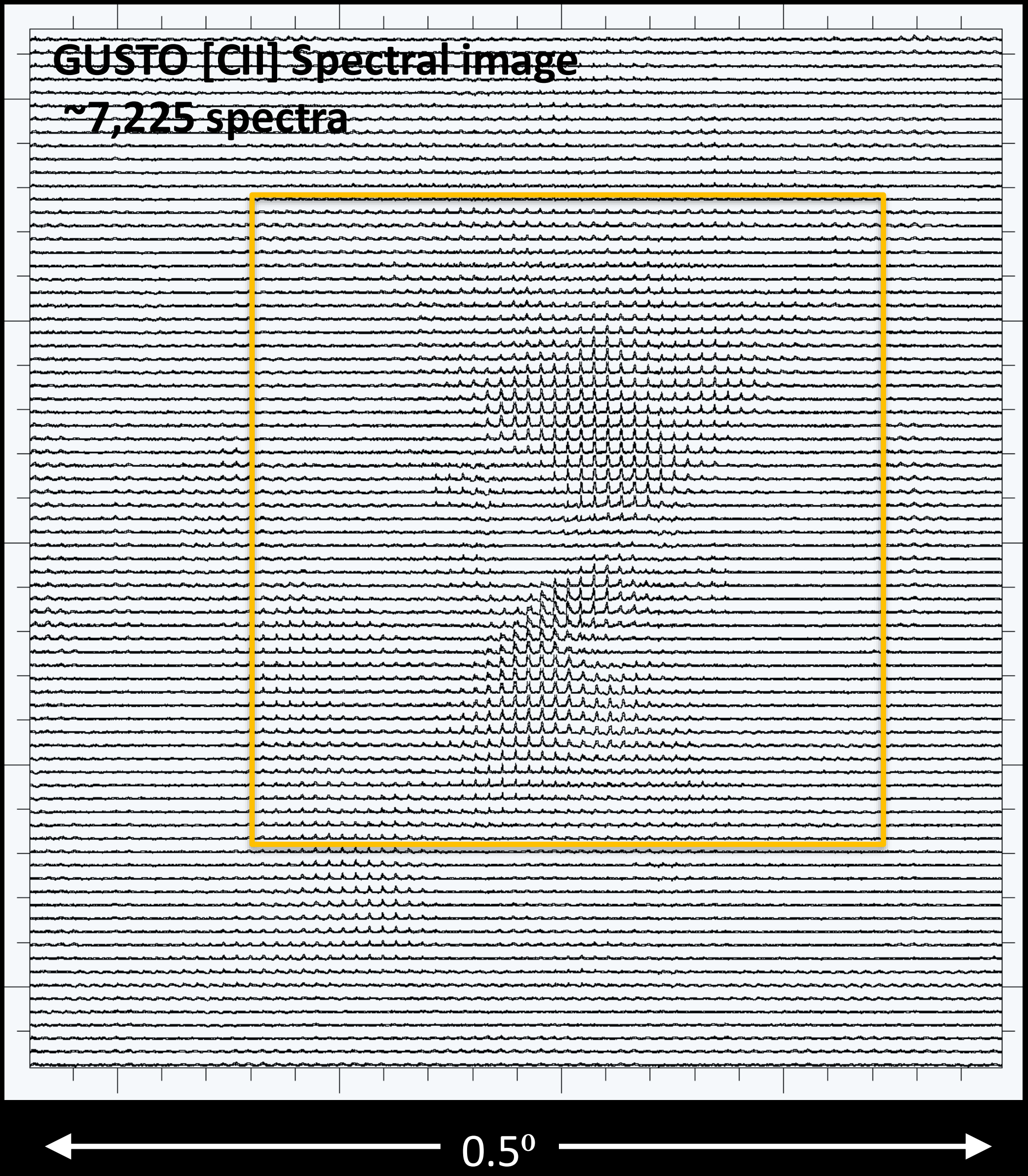

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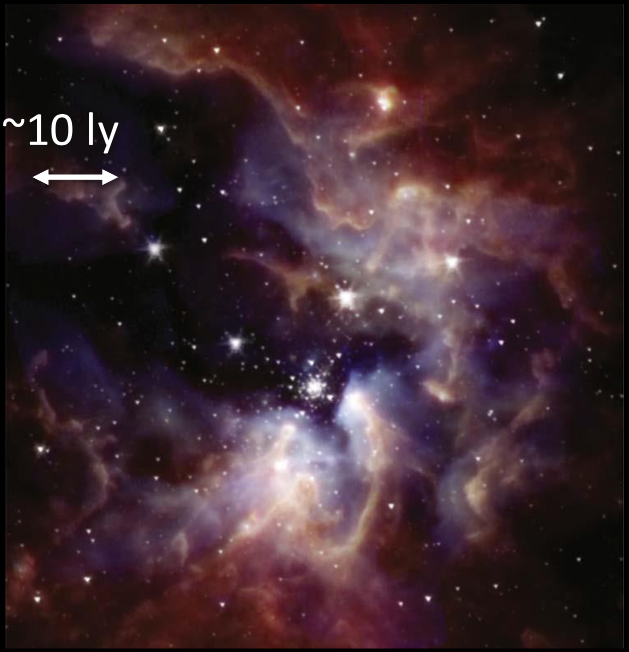

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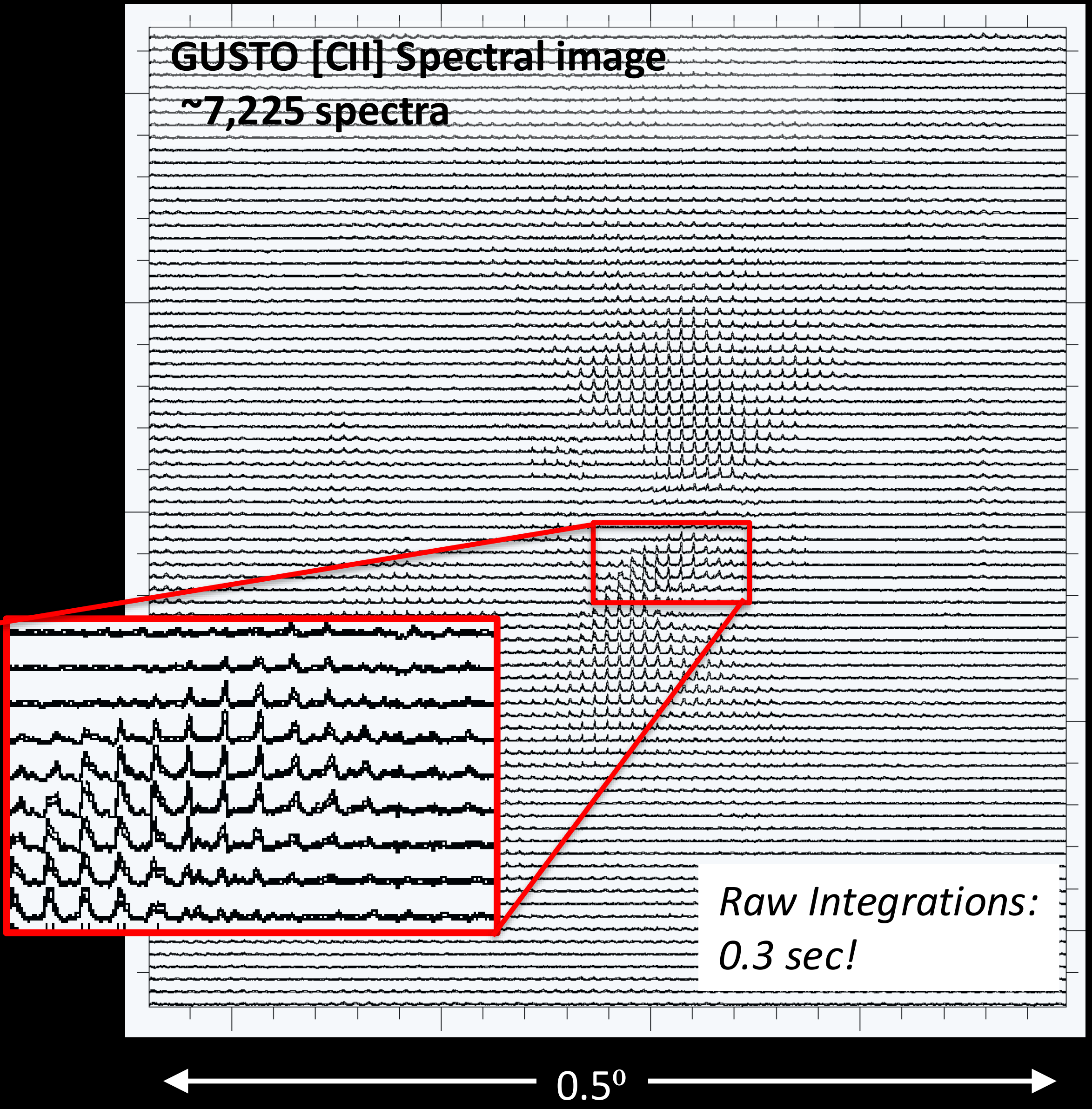

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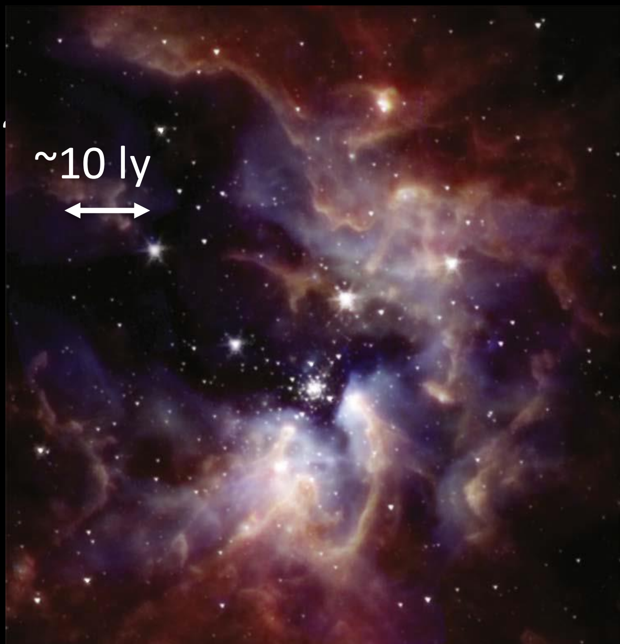

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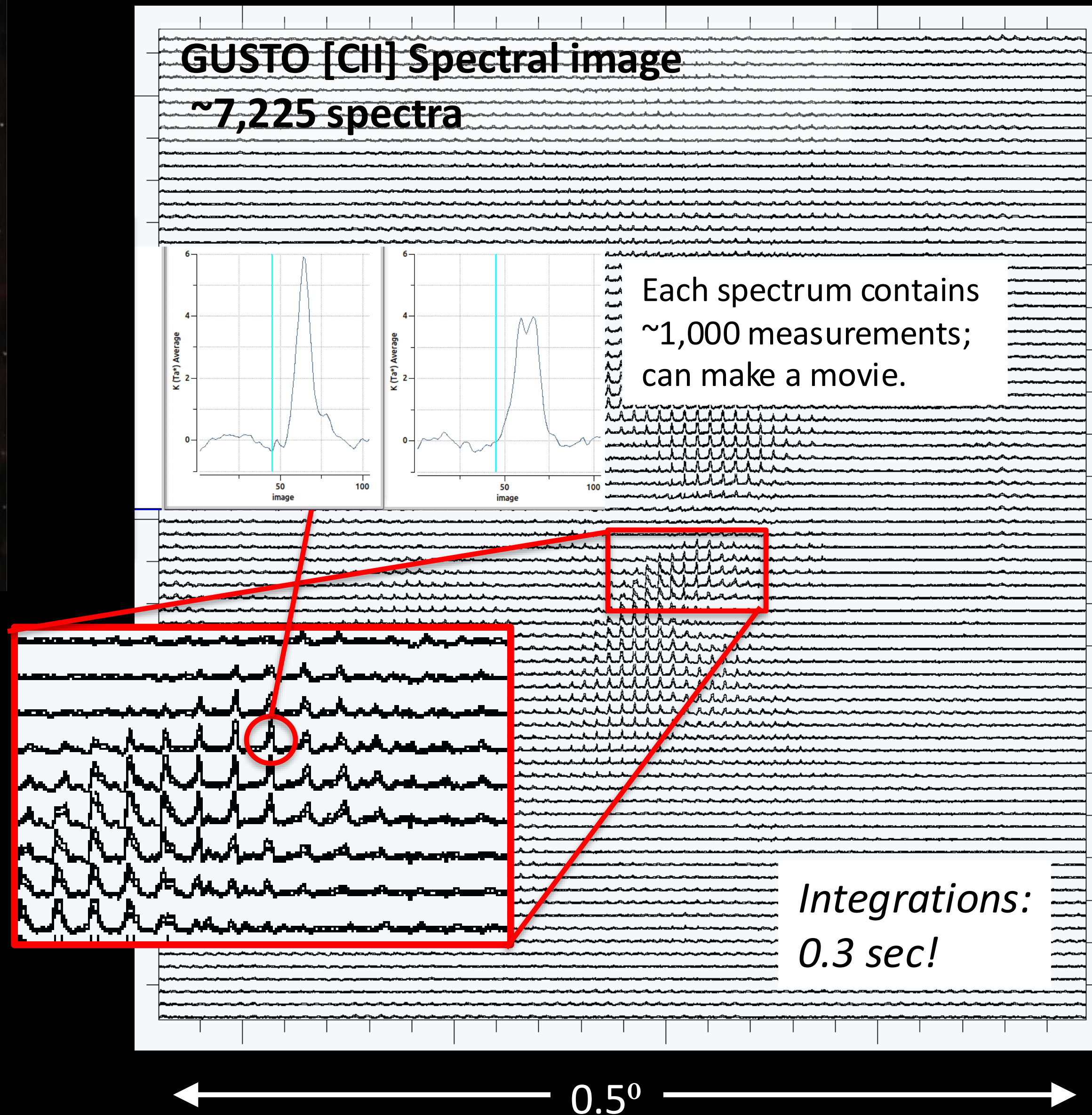
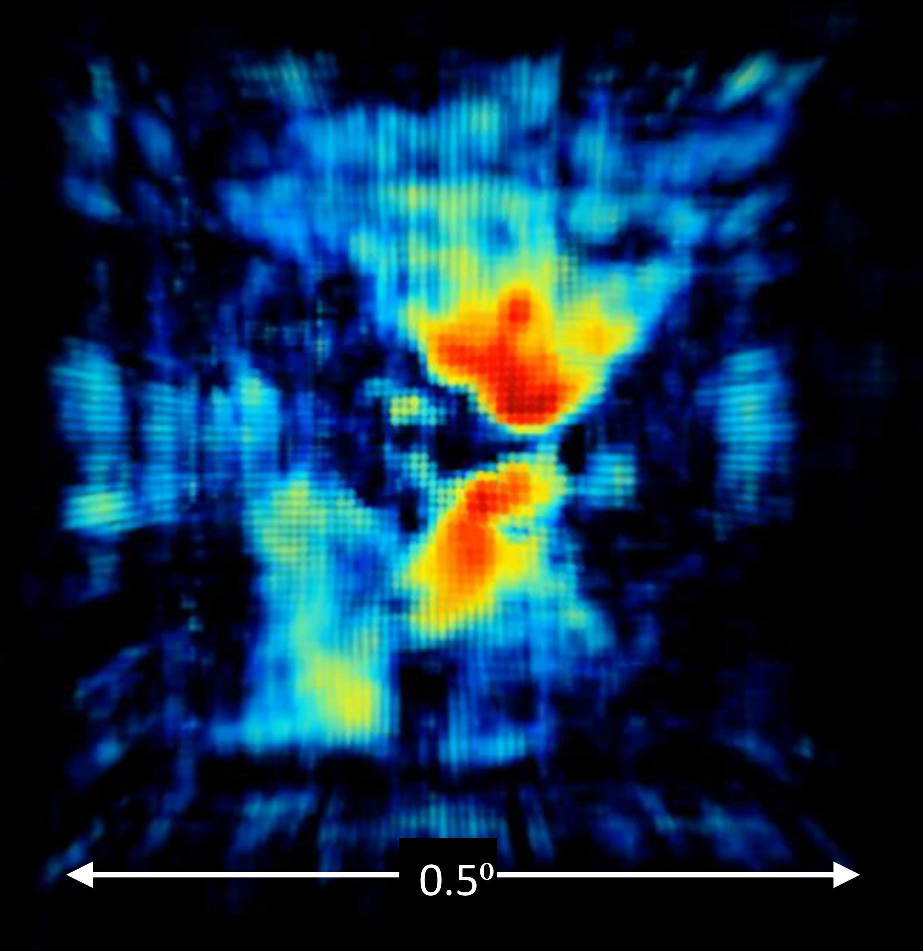


Targeted Deep Sky Survey: NGC 3603

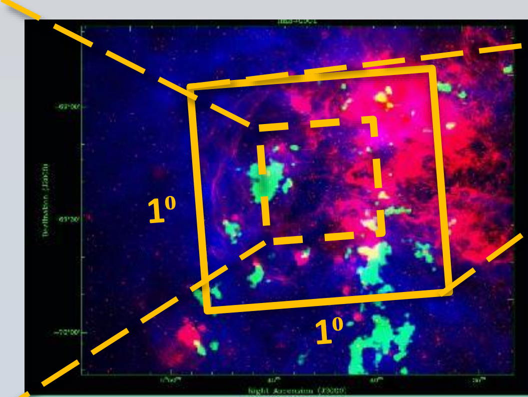
[CII] 3D Movie



Initial Science Results: LMC

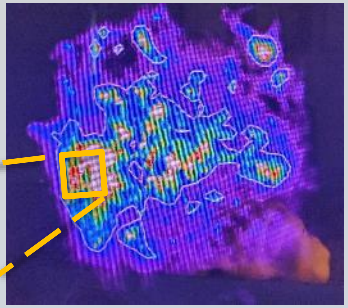
JWST NIRCam Image

Fully Surveyed in [CII] & [NII]



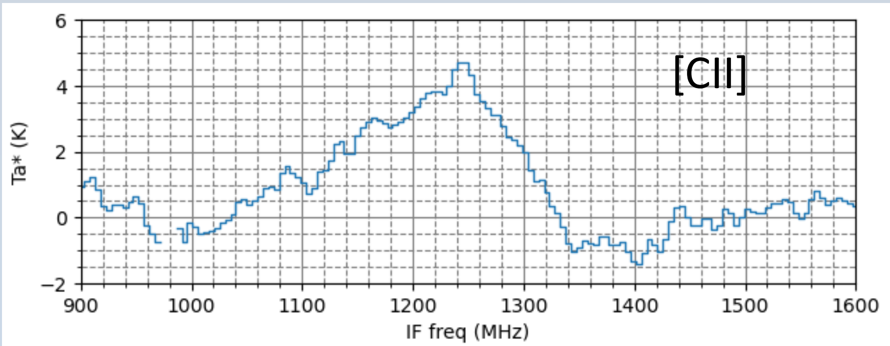
(Red Hα, Blue HI, and Green CO)

LMC Survey



LMC Survey in Bands 1 and 2

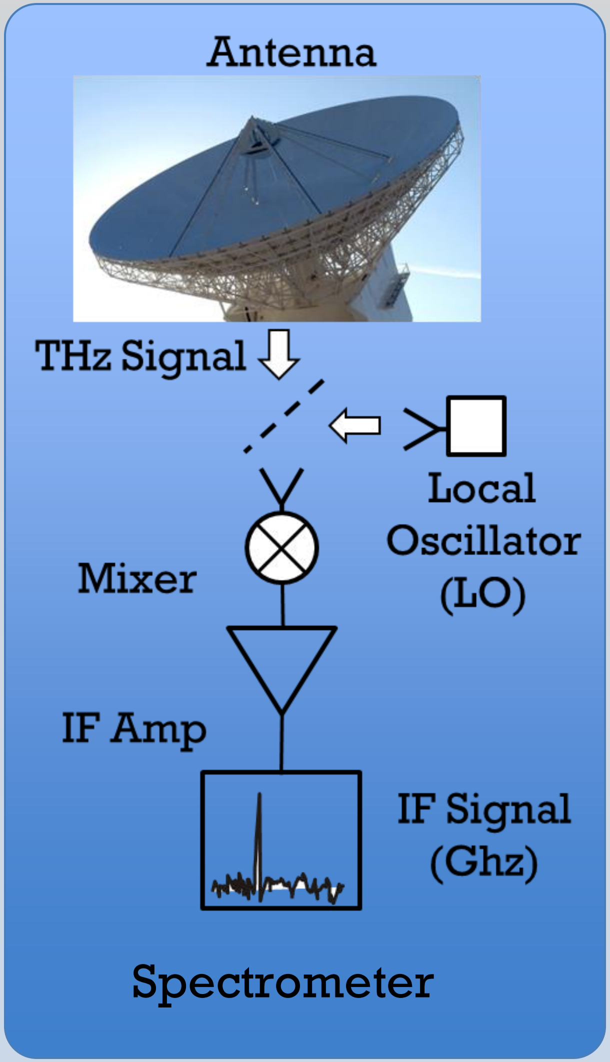
- 1.1 deg^2 map of 30 Dor region (100% complete)
- 0.6^{o}x0.5^o map around N11 (100% complete)
- 0.9 deg^2 map, molecular ridge south of 30 Dor



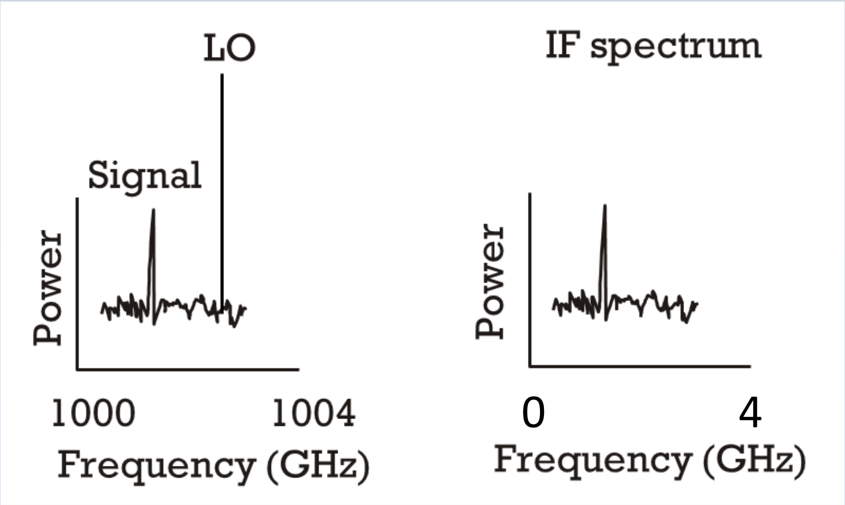
First Extragalactic GUSTO spectrum (30 Dor in LMC)

A total of 12,750 LoS were observed for the LMC

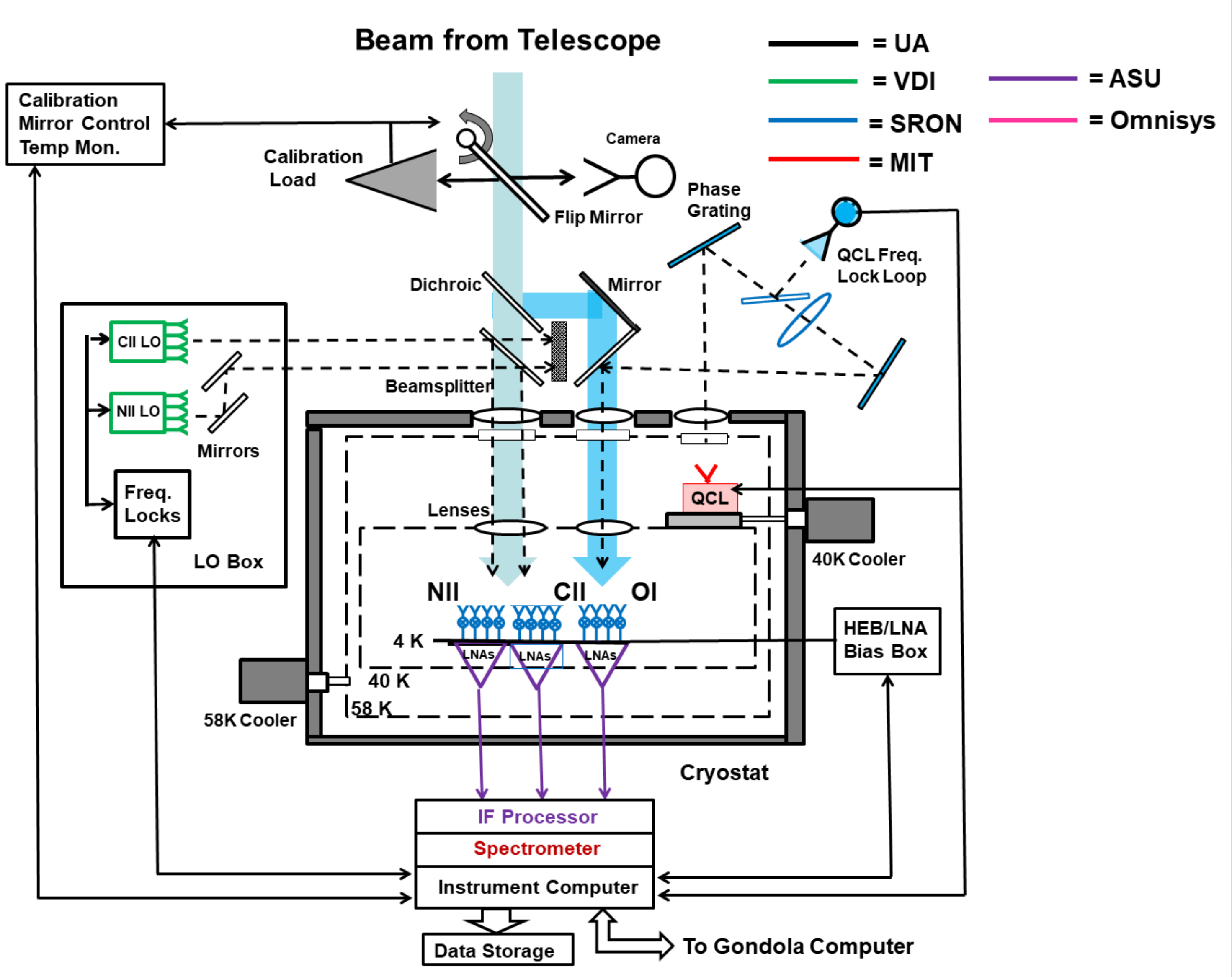
Heterodyne detection



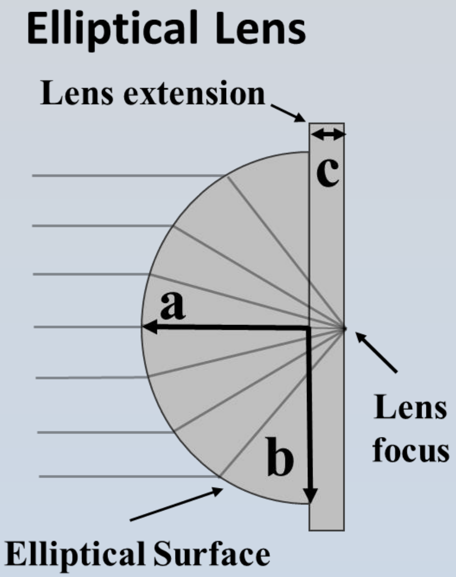
- Extremely high spectral resolution: $10^{6\text{-}7}$ ($\lambda/\Delta\lambda$)
- For each pixel we need one mixer and one LO
- Each pixel is a spectrometer

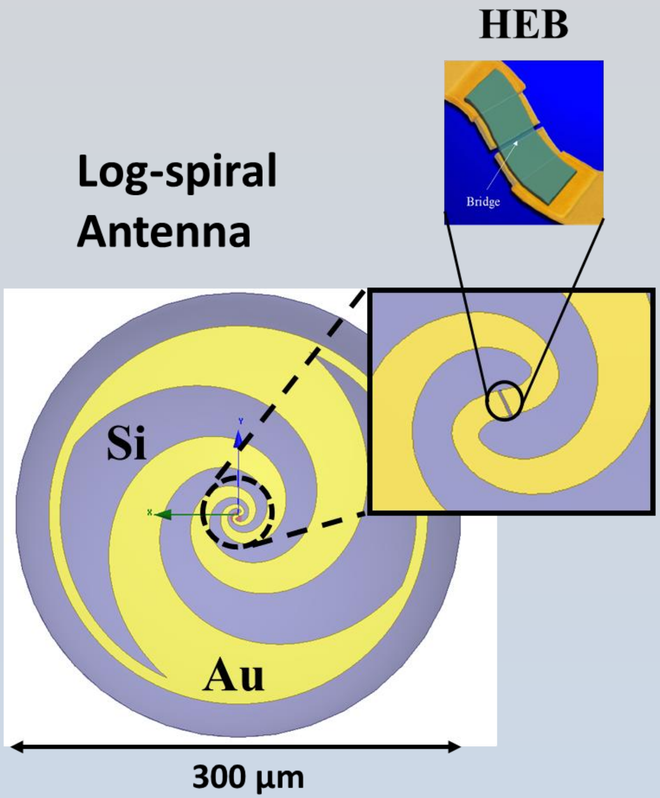


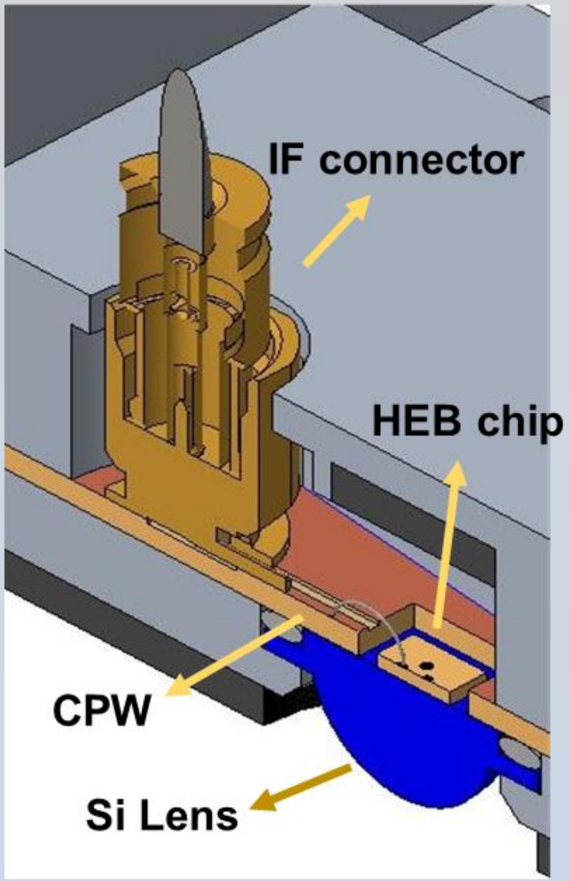
GUSTO instrument Block diagram



HEB Mixer Arrays – Single Pixel Architecture

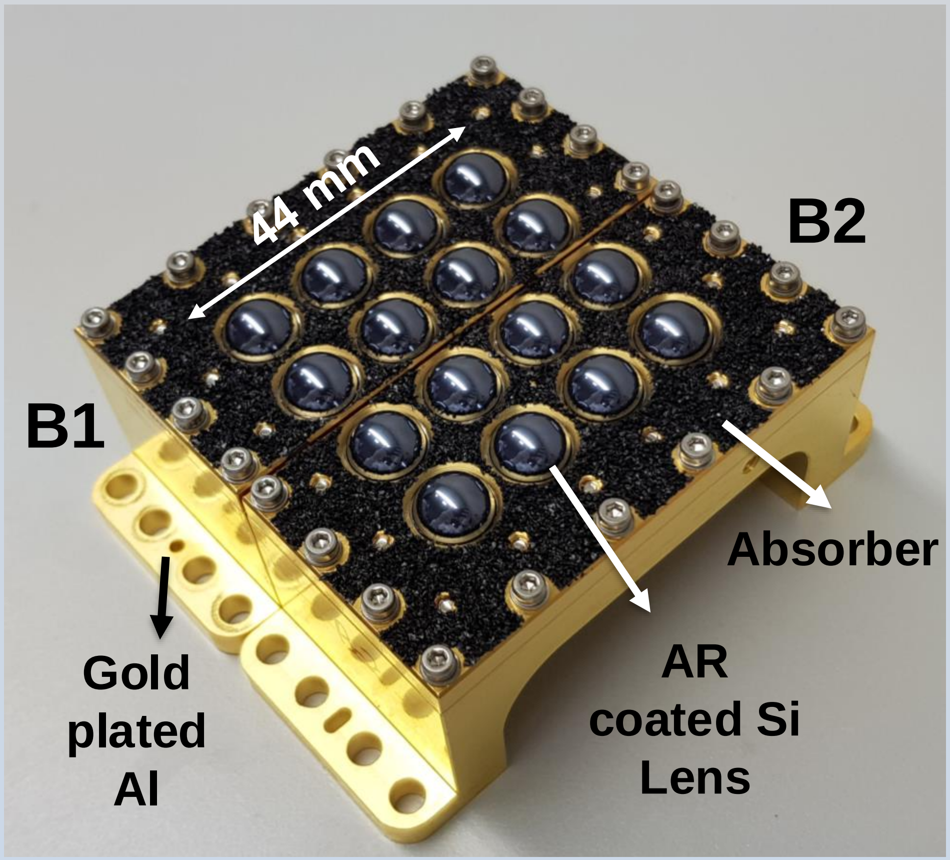




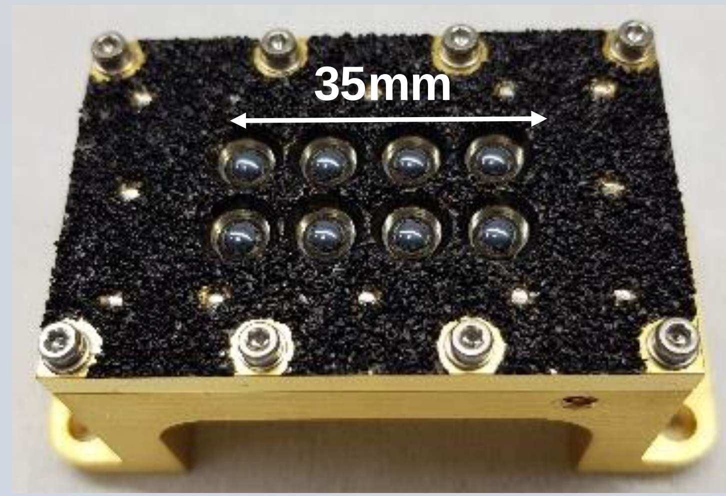


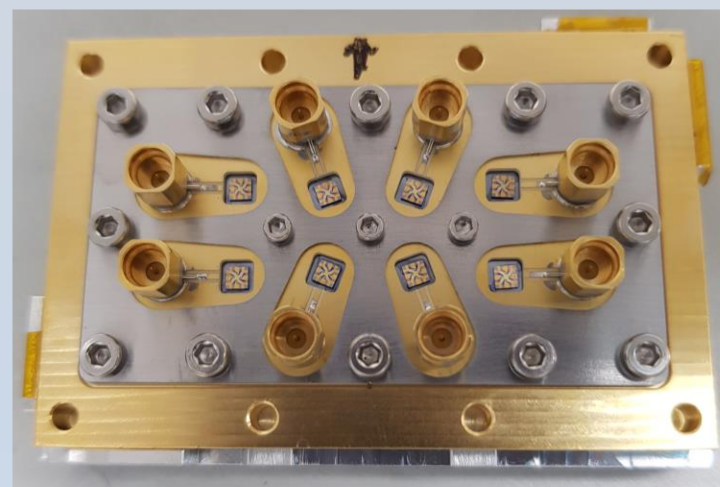
4×2 HEB mixer Arrays

B1 & B2

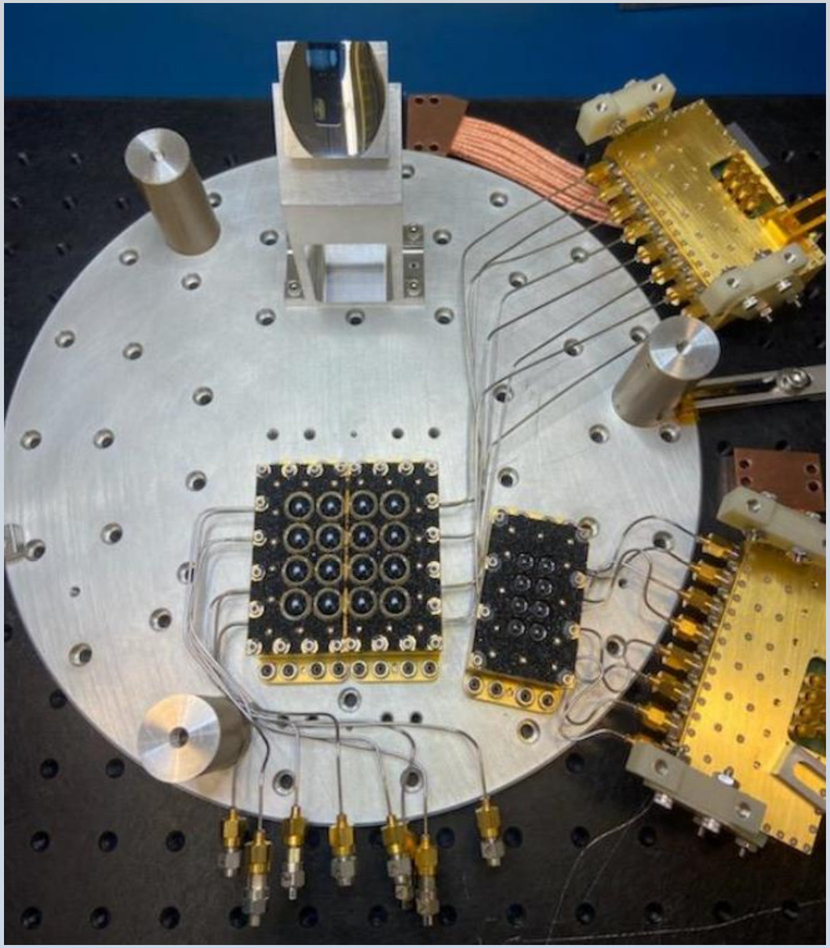


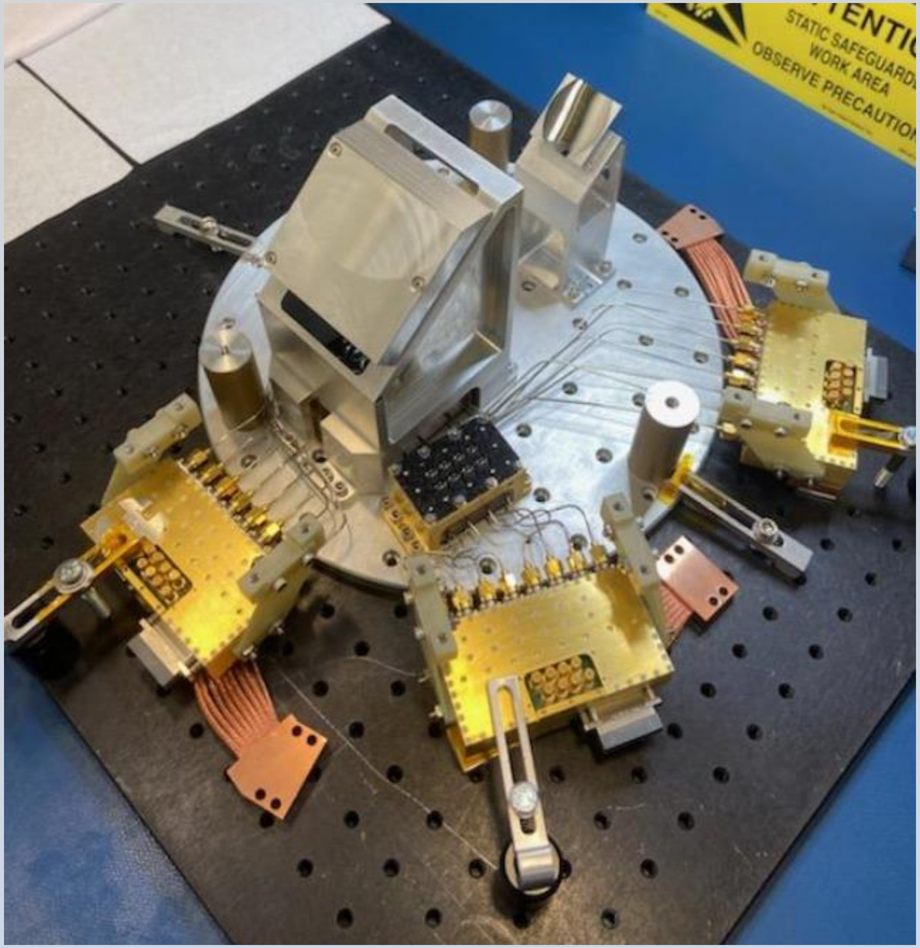
B3





Integration on GUSTO Cold Plate



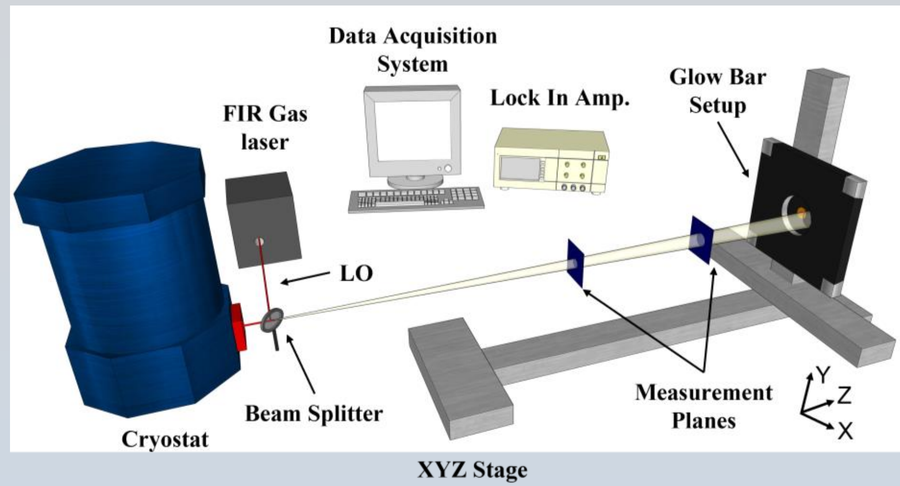


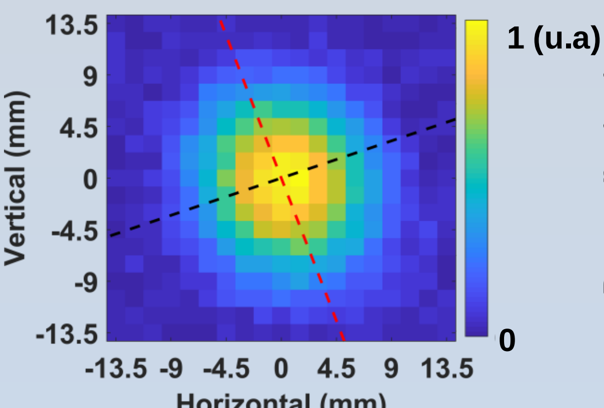
Lens-Antenna Beam pattern

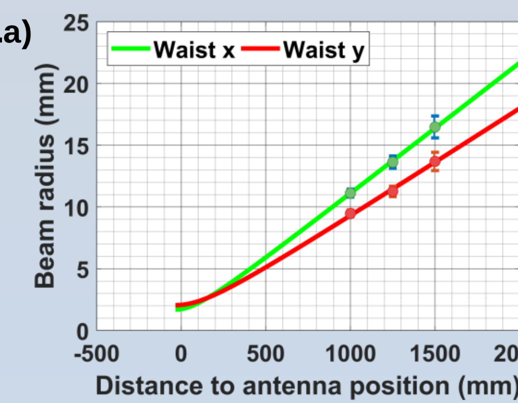
Simulated Antenna far field using HFSS, propagated using Geometric Optics and Physical Optics

Experimental verification:

Amplitude only Heterodyne beam pattern at multiple planes in far field







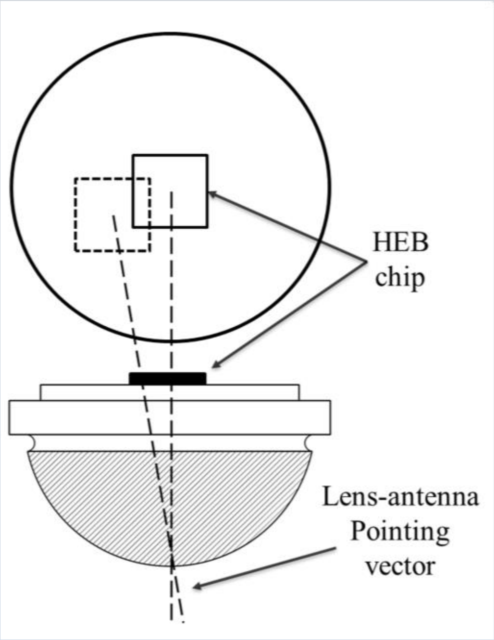
Band	Beam waist radius ±0.1 (mm)	Phase Center ±75 (mm)
B1 (1.4 THz)	4.0	-40
B2 (1.9 THz)	3.6	30
B3 (4.7 THz)	1.9	-100

J.R. Silva et al, " Beam Waist Properties of Spiral Antenna Coupled HEB Mixers at Supra-THz Frequencies", IEEE TST, 2020

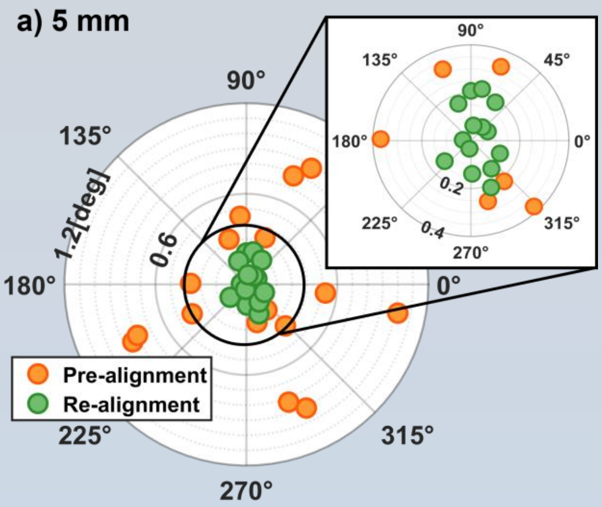
Pointing accuracy

Fabrication/assembly tolerances cannot constrain steering

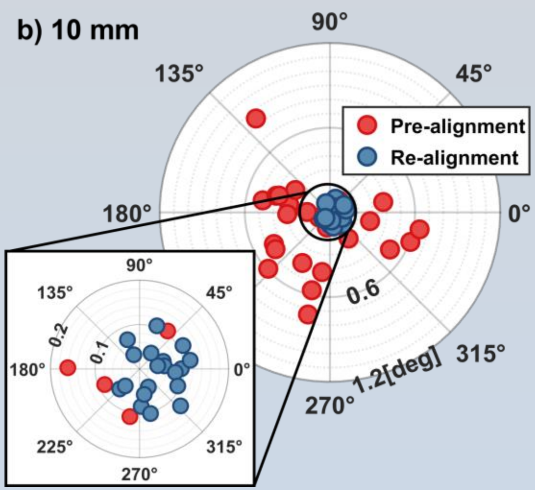
Solution: Align, measure, re-align to correct , verify



Small (S)



Large (L)

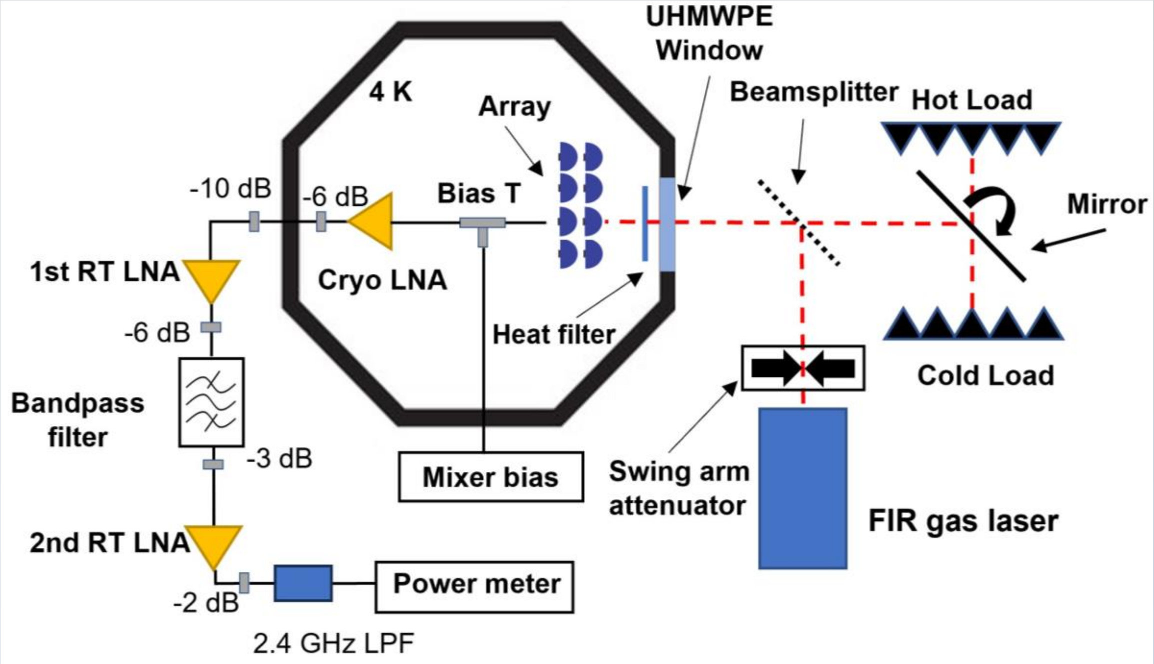


Dramatic improvement in both magnitude and variation.
Critical for coupling to LO and avoid vignetting on telescope optical path

J.R. Silva et al, ", High accuracy pointing for quasi-optical THz mixer arrays" IEEE TSTT 2022

RF performance

Experimental Setup



Key parameters:

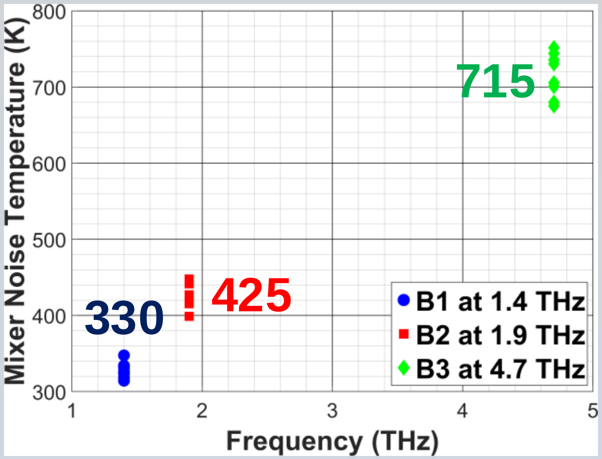
- DSB Mixer noise temperature
- DBS Mixer conversion Loss
- LO power requirements
- IF bandwidth

Removing contribution from optics in front of Lens and IF defines the performance at the interface with GUSTO

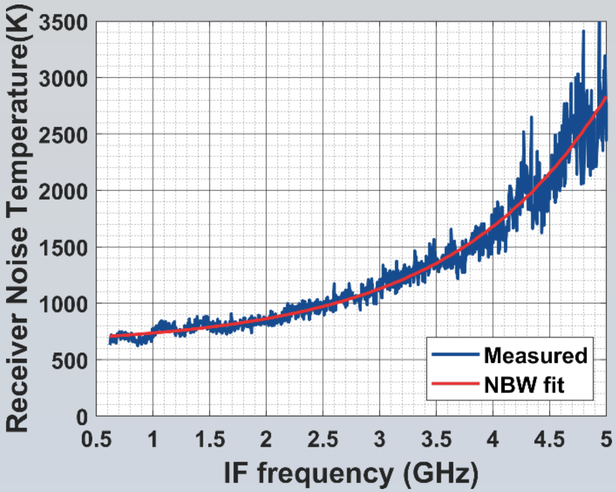
$$T_{mixer}^{DSB} = \frac{T_{rec}^{DSB} - T_{Opt} - T_{IF} \times L_{rec}^{DSB}}{L_{Opt}}$$

Lab characterization

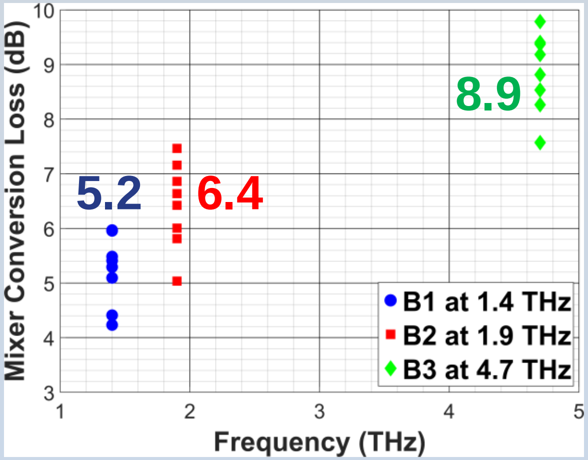
State of the art performance and good uniformity



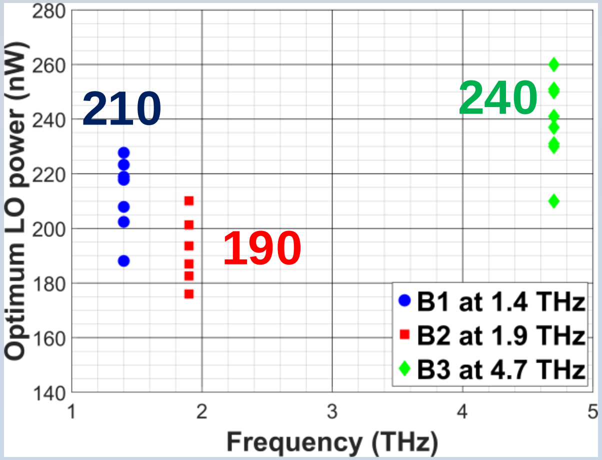
Noise Temperature



IF bandwidth ≈3.5 GHz



Conversion Loss



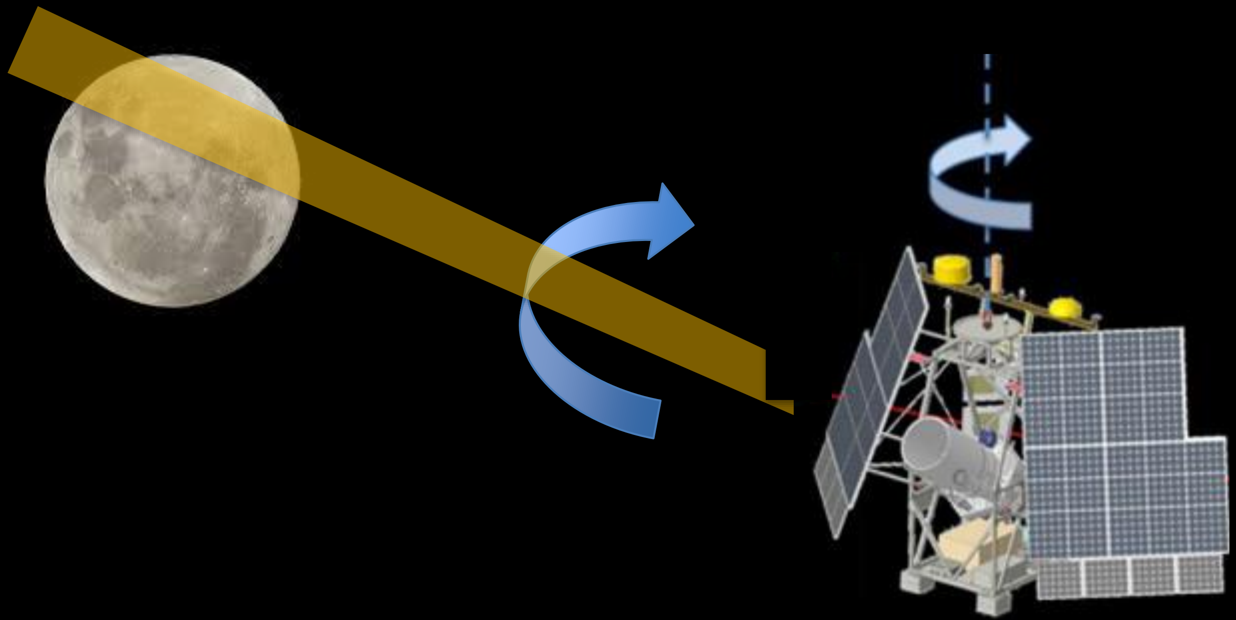
LO Power

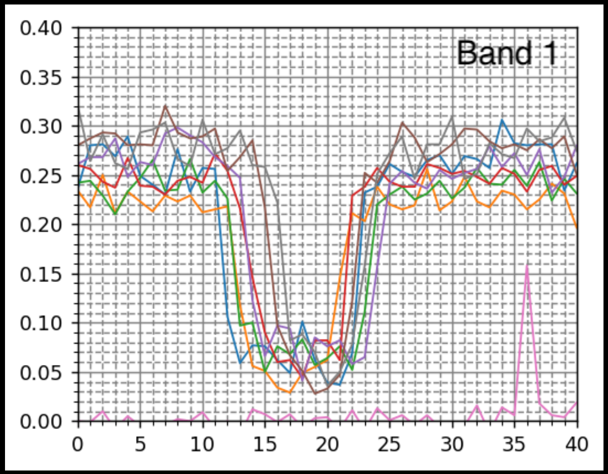
Conclusions

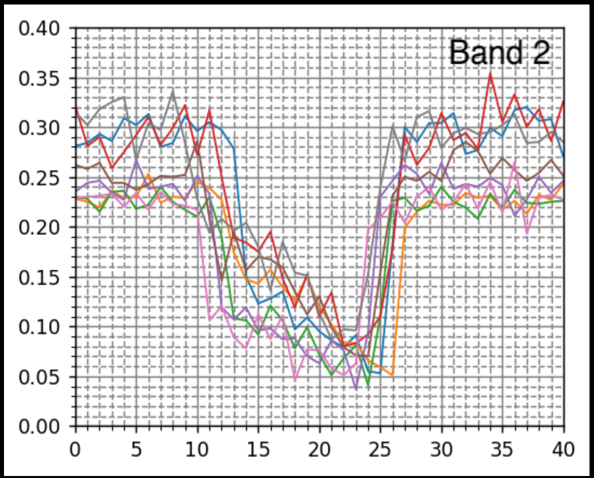
- GUSTO successfully launched from McMurdo Stn. Antarctica in 2023, making a new NASA record for duration balloon mission of +57 Days
- 4x2 HEB mixer arrays demonstrated – higher pixel count at THz frequencies
- GUSTO performance met or exceeded mission success criteria. A follow-on GUSTO II mission is being planned
- Demonstrate heterodyne array receiver technology for HiRX instrument for SALTUS

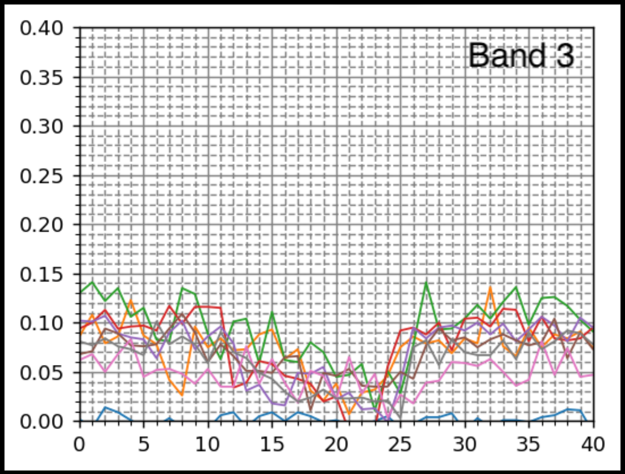
Backup Slides

Moon scans









Moon scans in bolometer mode show all detectors propagated through observatory

Science Objectives

1. Determine the constituents and the life cycle of interstellar gas in the Milky Way
2. Witness the formation and destruction of star-forming clouds
3. Understand the dynamics and gas flow into and within the Galactic Center
4. Understand the interplay among star formation, stellar winds and radiation, and the structure of the interstellar medium in the Large Magellanic Cloud (LMC)
5. Construct Milky Way and LMC templates for comparison to distant galaxies.