Velocity-Resolved Fine Structure Line Observations and Star Formation:

New Results and New Capabilities

Paul Goldsmith
Jet Propulsion Laboratory, California Institute of Technology
Pasadena CA 91109

Collaborators: William Langer, Youngmin Seo, Jorge Pineda, Juergen Stutzki, Rebeca Aladro, Matthias Justen

GUSTO and ASTHROS teams

Legacy of SOFIA conference – Stuttgart, Germany
25 April 2024

The Interstellar Medium is complex but plays a critical role in the evolution of galaxies

What Controls the Rate of Star Formation?

- **Reservoir** of material – gravitationally bound molecular gas
- **Impediments** to cloud collapse and star formation – turbulence, magnetic fields
- **Limitation** of star formation by effects of young stars

We would like to understand the relationship between ISM and young stars to quantify roles of above processes

This requires tracing the different phases of the ISM

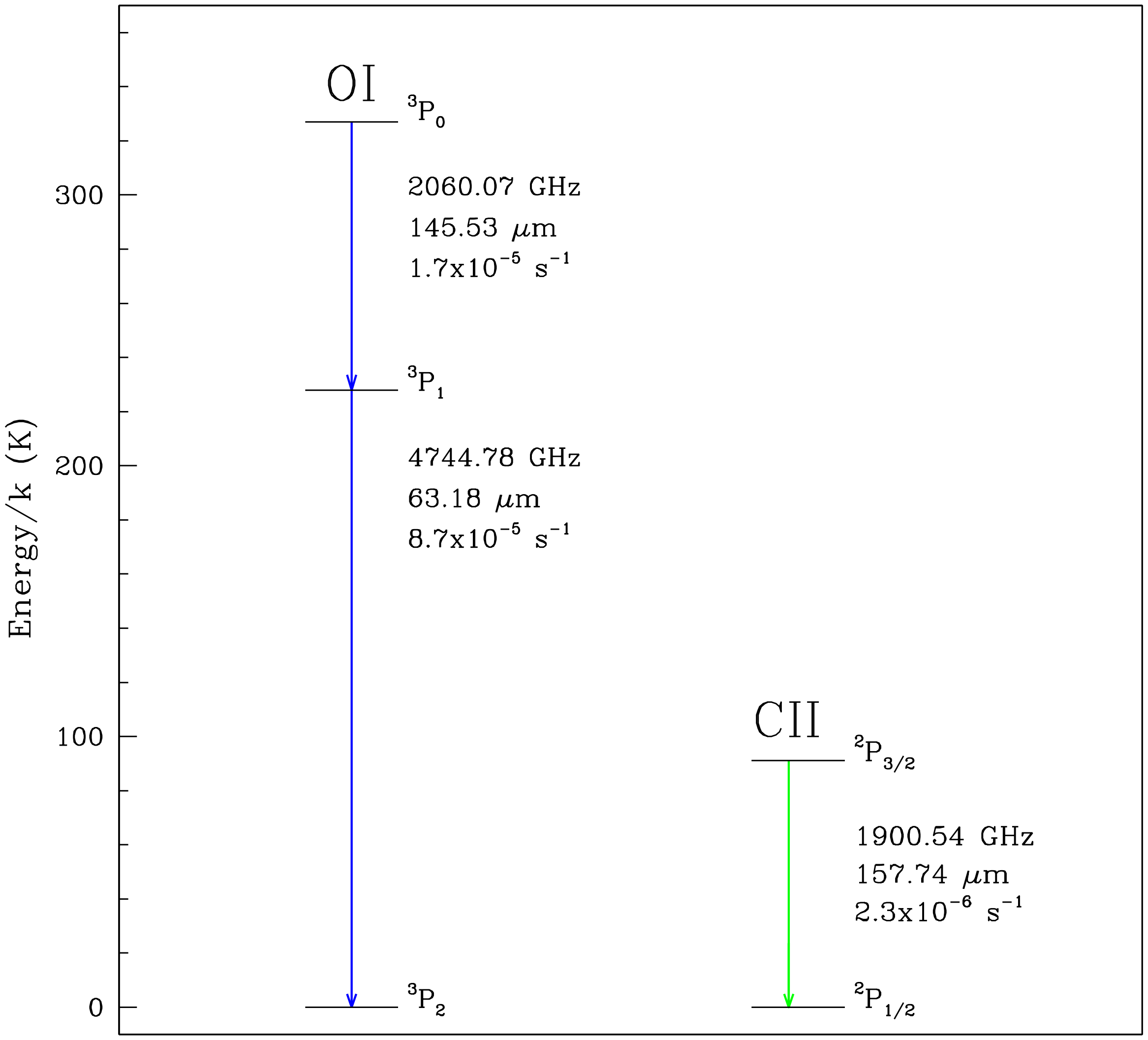
The challenge is the huge variation in physical conditions, particularly n and T, as well as chemical composition

How do we Measure the Rate of Star Formation?

Atomic Oxygen (O^0)

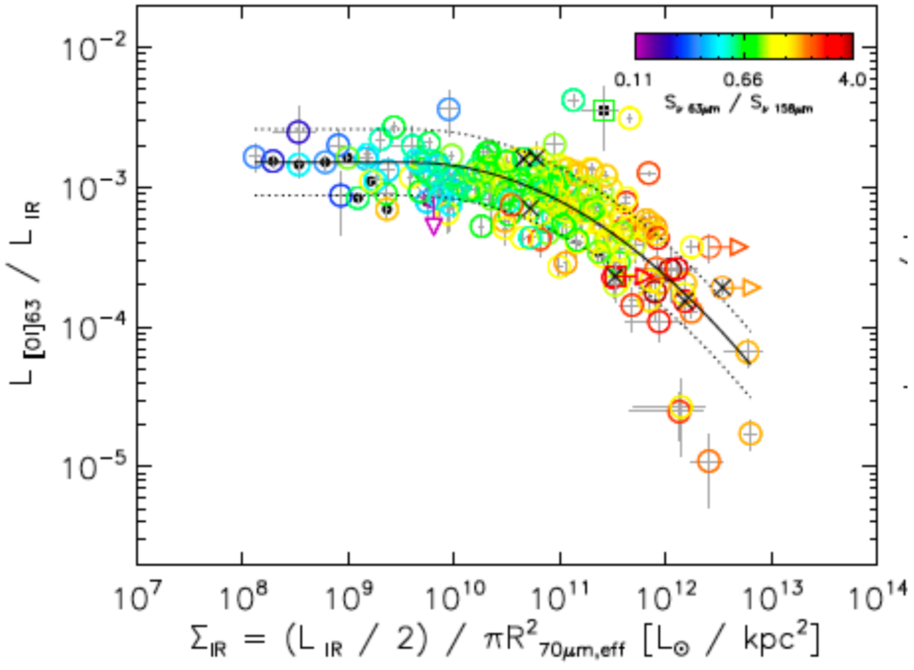
- {O}/{H} = $5\text{x}10^{-4}$
- High IP 13.62 eV
- Traces neutral ISM
- No FS lines from O^+ ; O^{++} requires 35.1 eV – [OIII] 88 μm important tracer of gas ionized by very hot stars
- Two O^0 fine structure transitions:

  [OI] 63 μm and [OI] 146 μm
- [OI] 63 μm widely used as tracer of star formation by ISO & Herschel
- Both lines are observable only from above Earth's atmosphere

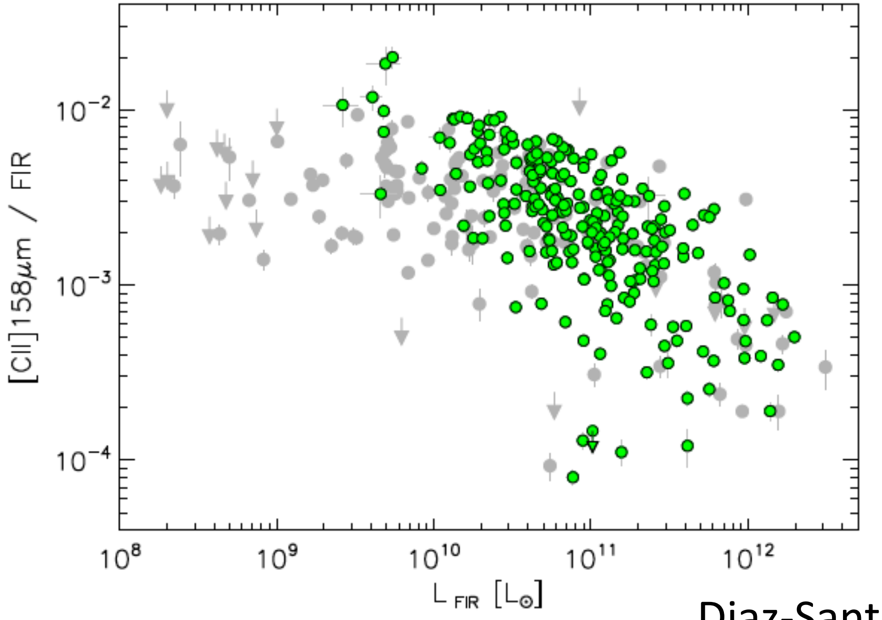


[OI] 63 µm as Tracer of Star Formation Rate

- Generally does a reasonably good job for “normal” galaxies but **as for [CII]** a “deficit” appears for more luminous galaxies with warmer dust
- Higher T_{dust} if reflected in higher T_{gas} would enhance [OI] 63 µm
- Oxygen can remain largely atomic to substantial A_v when irradiated by large flux from HII region/hot PDR
- Is the greater density of star-forming clouds for ULIRGS responsible?
- Is it related to the infamous “[CII] deficit”?



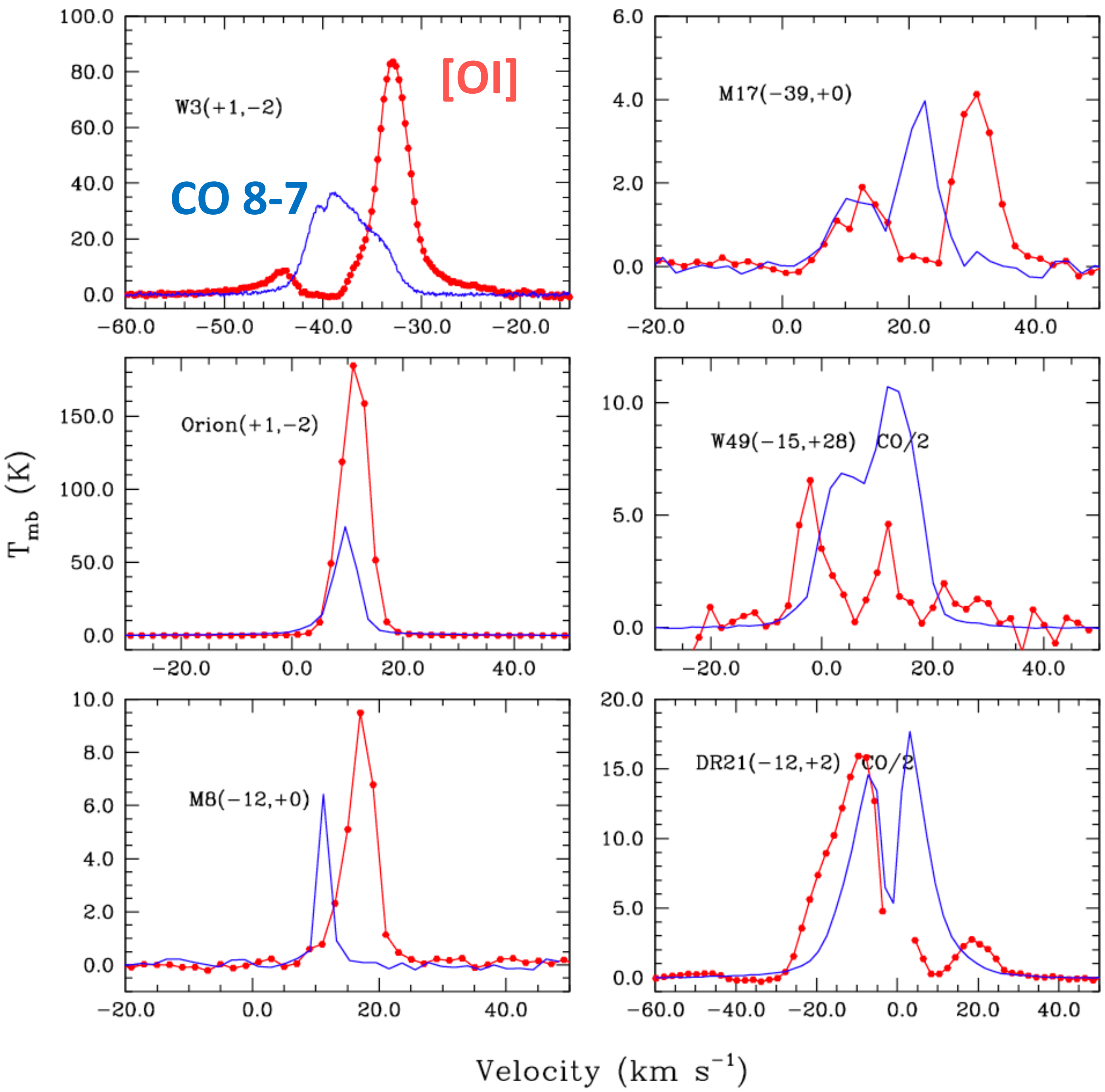
Diaz-Santos+ (2017)



Diaz-Santos+ (2013)

Survey of Massive Star-Forming Regions with SOFIA/upGREAT

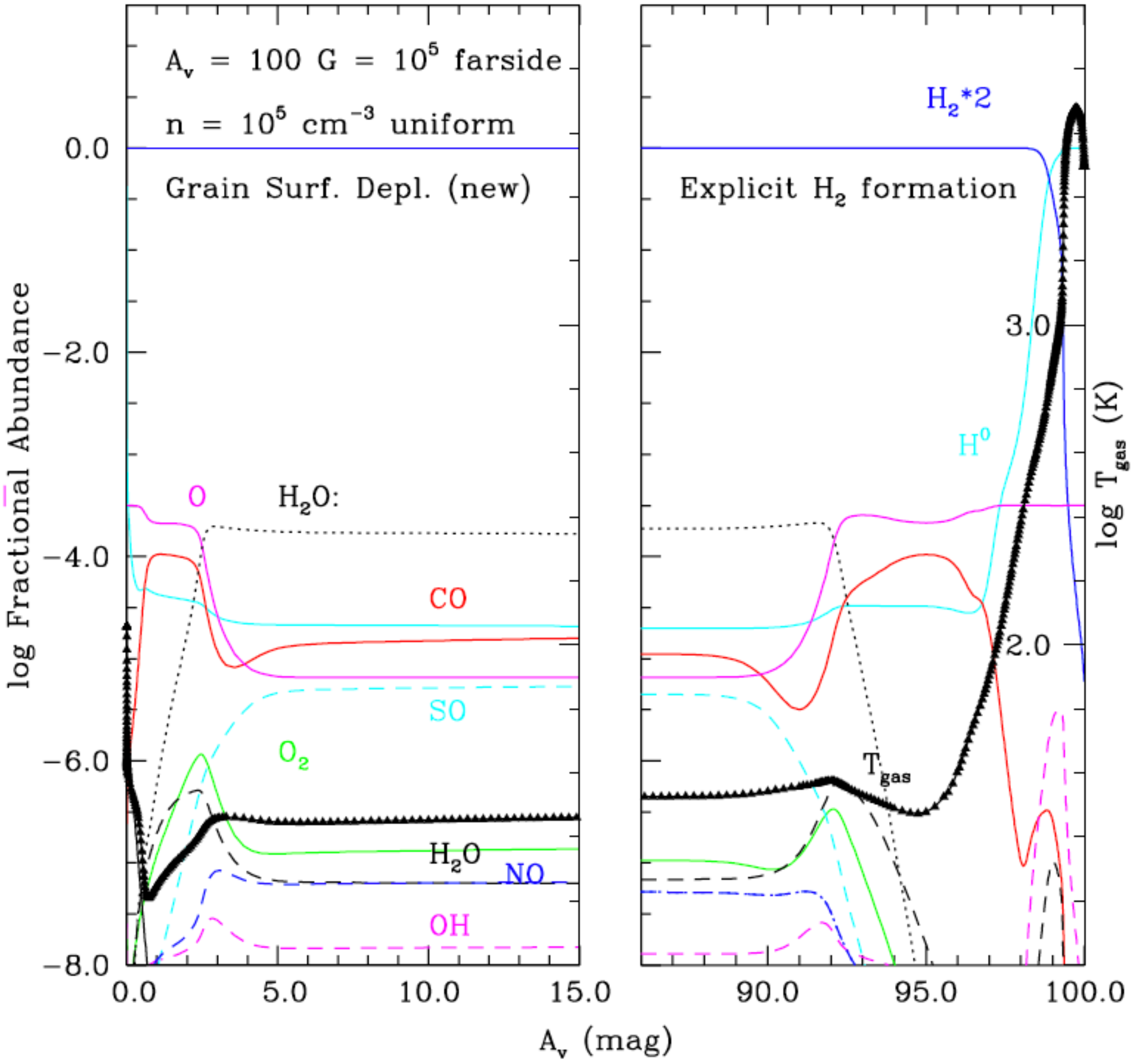
- [OI] 63µm observed in 12 regions
- Good detections – highly variable line strengths
- CO J=5-4, J=8-7, and also [NII] 205µm observed simultaneously
- CO 8-7 traces warm molecular gas heated by UV from young star(s) and HII region
- [OI] shows **clear self-absorption** in half of sources observed
- Also see possible **velocity shifts** of [OI] relative to molecular gas



Structure of Photon Dominated Region

Moving away from enhanced UV source:

- Temperature drops rapidly H converts to H_2
- Oxygen remains atomic to Av = 8 mag but too cold to emit for $A_v > 2.5$ mag
- A few % of oxygen is O^0 throughout entire region
- Total N(cold O^0) ~ 10^{18} cm^{-2}
- ⇒ 63 µm ***optically thick***



SOFIA Observations of [OI] 63 µm in W3

W3 is region of massive star formation at D = 2 kpc

Radio continuum; FIR; CO

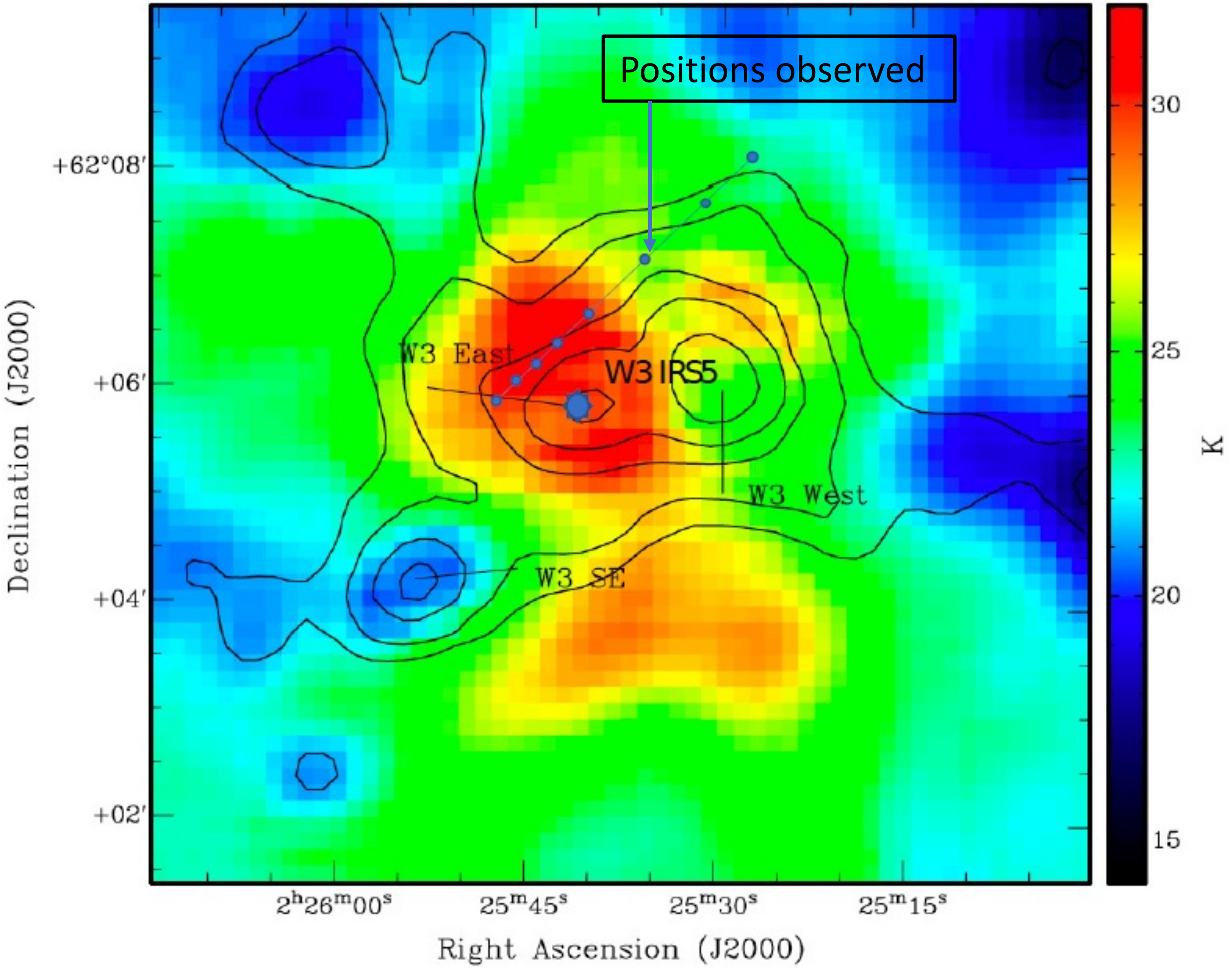
$M = 4\text{x}10^5\ M_{sun}$

$L = 5\text{x}10^5\ L_{sun}$

Dust temperature (color) and H_2 column density (contours)

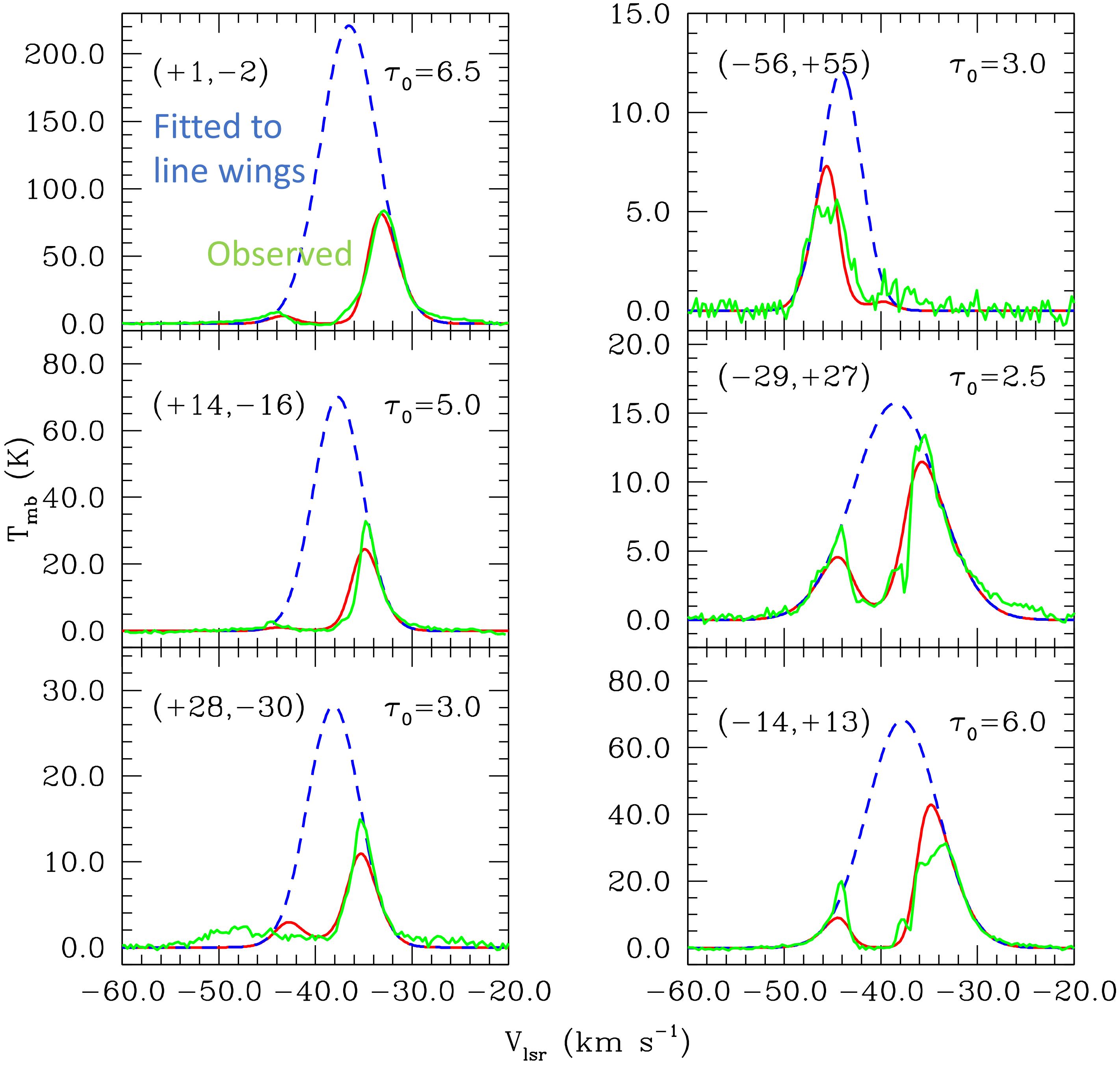
W3 IRS5 is center of stellar activity

Goldsmith+ (2021)



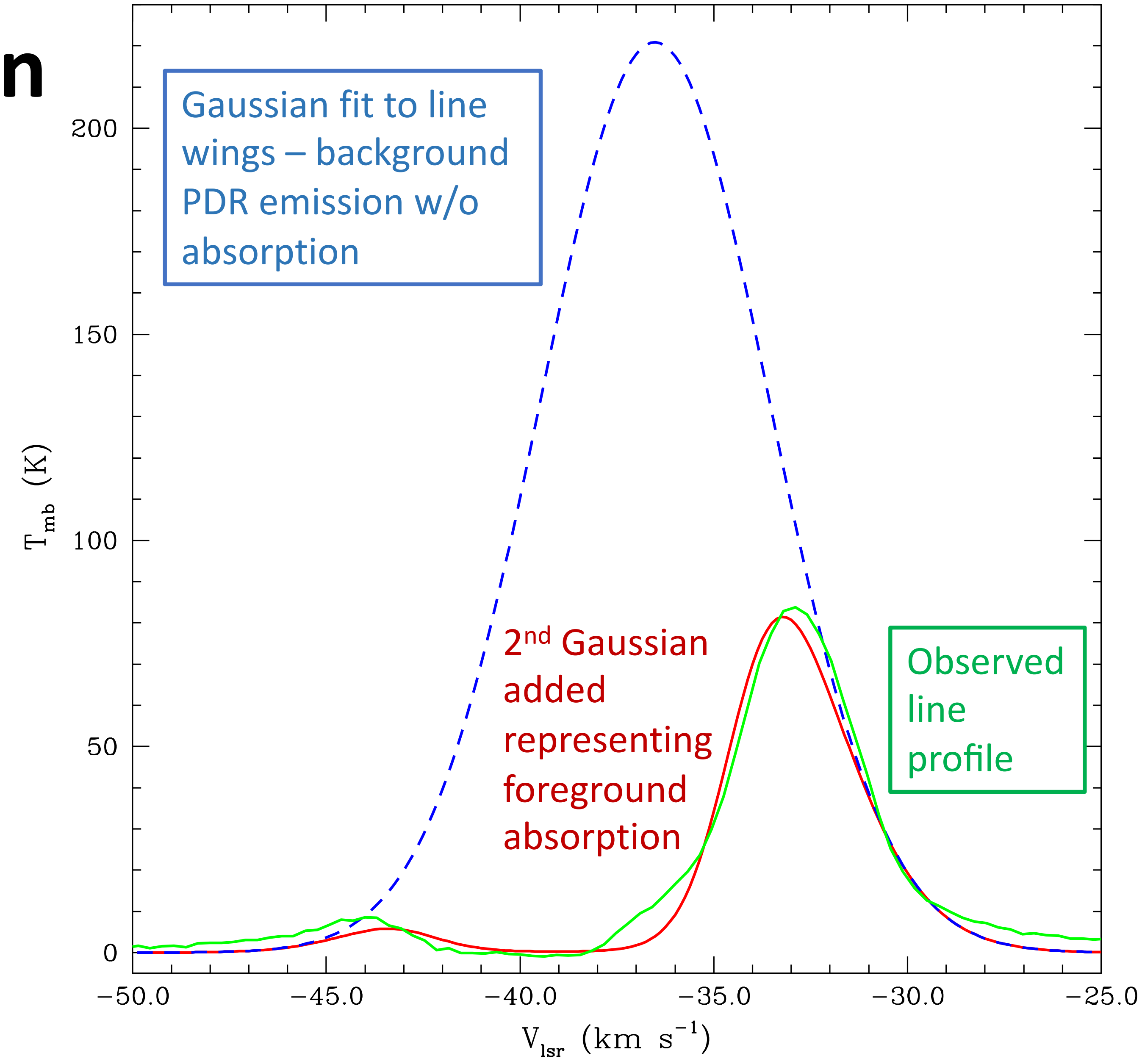
[OI] - Near W3 E

- Line wings are well-fit by Gaussians
- This should represent “PDR Emission” that **would** be observed if there were no foreground low-excitation gas
- T_{mb} ~ 220 K at central position! As strong as Orion (geometry)
- τ_0 in figure is the peak optical depth of foreground absorption



Modeling Absorption

- PDR models suggest gas at ≤ 20K which has effectively no emission
- A second Gaussian representing pure absorption fits observed line profile well
- Peak absorption optical depth = 6.5
- Velocity shift = -2 km/s
- N(low-excitation O^0) ≈ $6x10^{18}$ cm^{-2}



Gaussian fit to line wings – background PDR emission w/o absorption

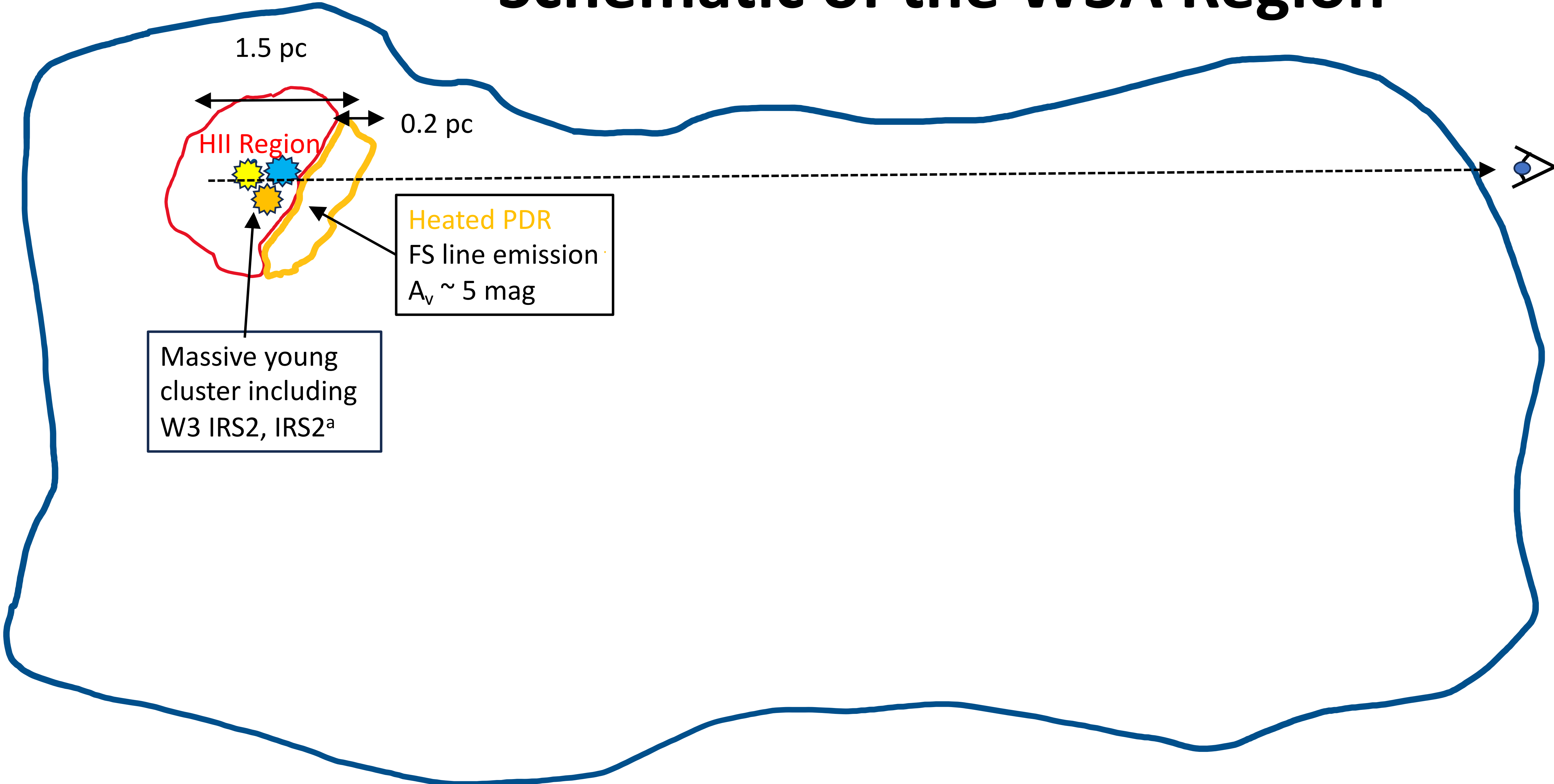
2nd Gaussian added representing foreground absorption

Observed line profile

Foreground [OI] Absorption in W3

- Peak optical depths $2 < \tau < 5$ derived for entire central region with relatively strong observed emission
- Total emission at different positions **reduced by factors 2 – 5** compared to values expected from fitted background Gaussians
- Implication is that **we may be underestimating the [OI] luminosity by a significant factor. This clearly affects estimates of thermal balance, stellar heating, and star formation rate**
- Observational occurrence depends on geometry – not seen when PDR on Earth-facing side of cloud (Orion) ⇒ should appear in ~50% of randomly selected sources as observed
- Effect will be greatest in regions with most massive (large A_V) clouds
- Will impact [OI] 63 μm line in starburst galaxies with massive GMCs and high star formation rates – "OI deficit"
- Low density required from modeling mid-J emission; $n < 200\ \mathrm{cm}^{-3}$

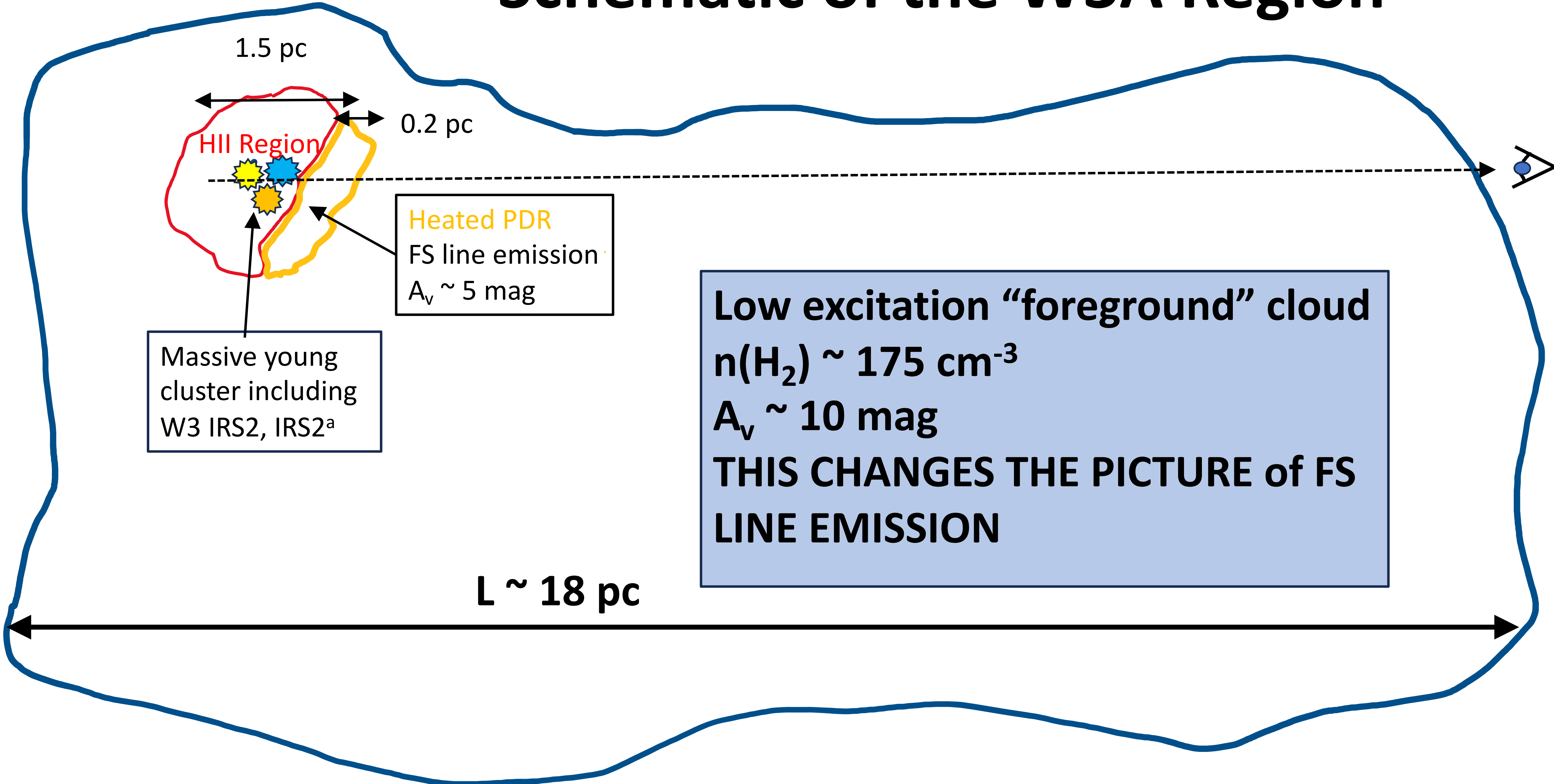
Schematic of the W3A Region



Heated PDR
FS line emission
A_v ~ 5 mag

Massive young cluster including W3 IRS2, IRS2[a]

Schematic of the W3A Region



Heated PDR
FS line emission
A_v ~ 5 mag

Massive young cluster including W3 IRS2, IRS2[a]

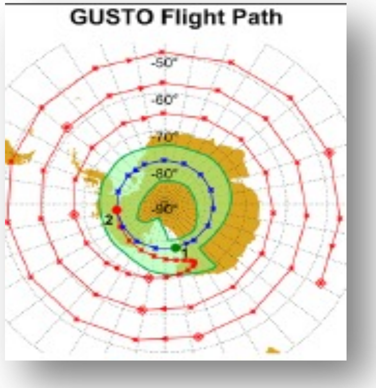
Low excitation “foreground” cloud
$n(H_2)$ ~ 175 cm^{-3}
A_v ~ 10 mag
THIS CHANGES THE PICTURE of FS LINE EMISSION

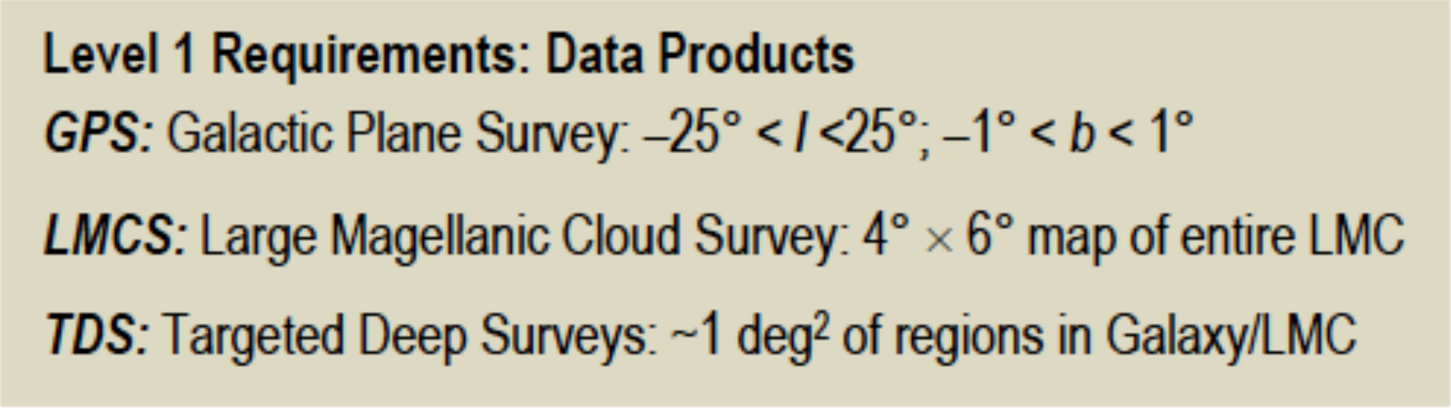
New Observational Capabilities

- upGREAT instrument on SOFIA had good capability for [NII] 205 µm, [CII] 158 µm, and [OI] 63 µm. No capability for [NII] 122 µm and limited capability for [NII] 205 µm and [OI] 146 µm ☹
- PROBE FIR missions currently being developed will cover all important fine structure lines from space with ~2m class telescopes. Some concepts have heterodyne (high spectral resolution, R ~10^6) receiver, but others have low-resolution direct detector system with R~4000.
- Origins FLAGSHIP mission will certainly have enormous sensitivity, but high velocity resolution only if HERO instrument upscope is included
- Two balloon missions, **GUSTO** and **ASTHROS** focusing on fine structure line emissions are currently nearing operation

Galactic/Extragalactic Ultra/LDB Spectroscopic/Stratospheric Terahertz Observatory **GUSTO** (C. Walker, Univ. of Arizona, PI)

- 90 cm dia. Telescope (~40” resolution)
- 8 pixel HEB arrays for [NII] 205 µm (B1), [CII] 158 µm (B2), and [OI 63 µm (B3)
- **Long Duration Balloon** offers ~ **70** day lifetime, but payload recovery is not certain





Level 1 Requirements: Data Products

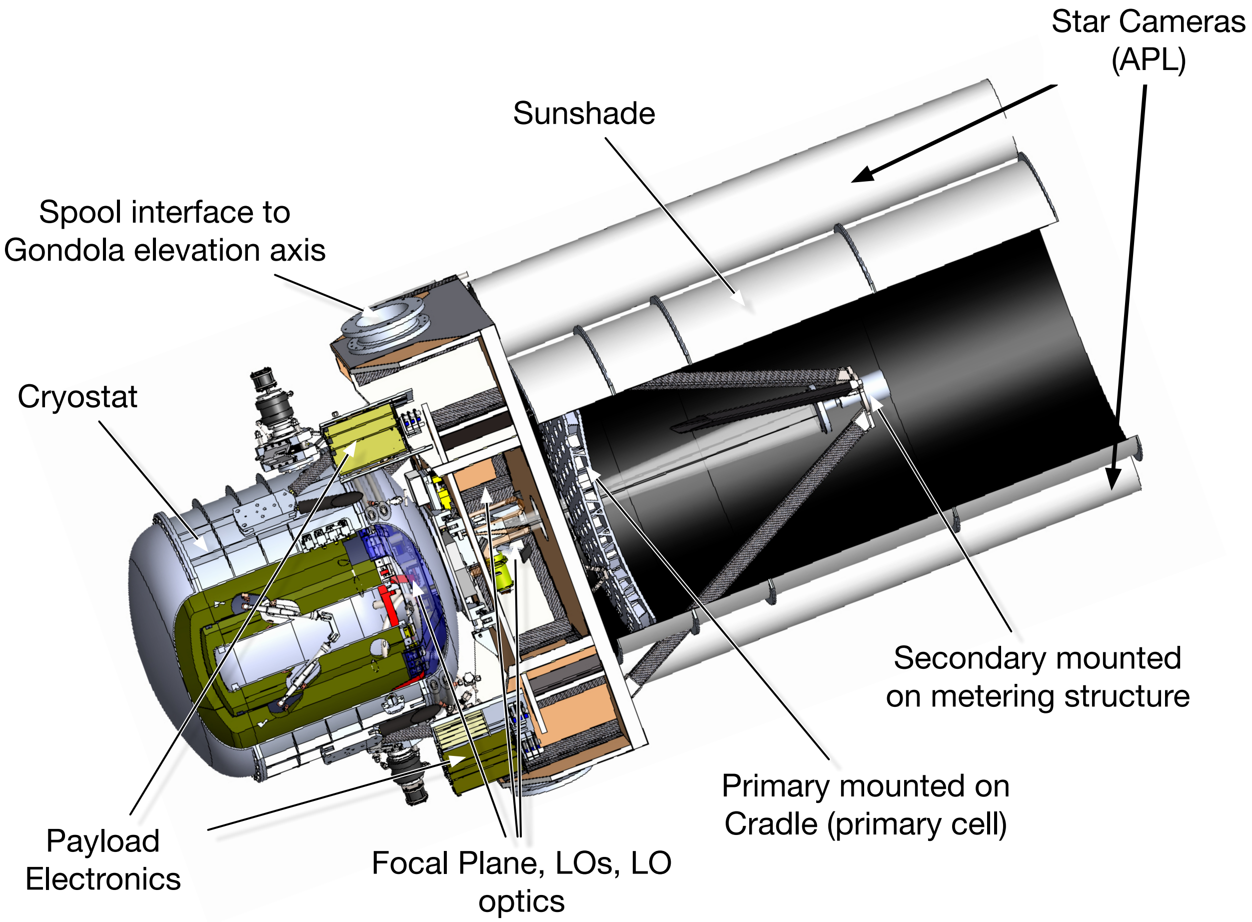
GPS: Galactic Plane Survey: $-25^\circ < l < 25^\circ$; $-1^\circ < b < 1^\circ$

LMCS: Large Magellanic Cloud Survey: 4° × 6° map of entire LMC

TDS: Targeted Deep Surveys: ~1 deg^2 of regions in Galaxy/LMC

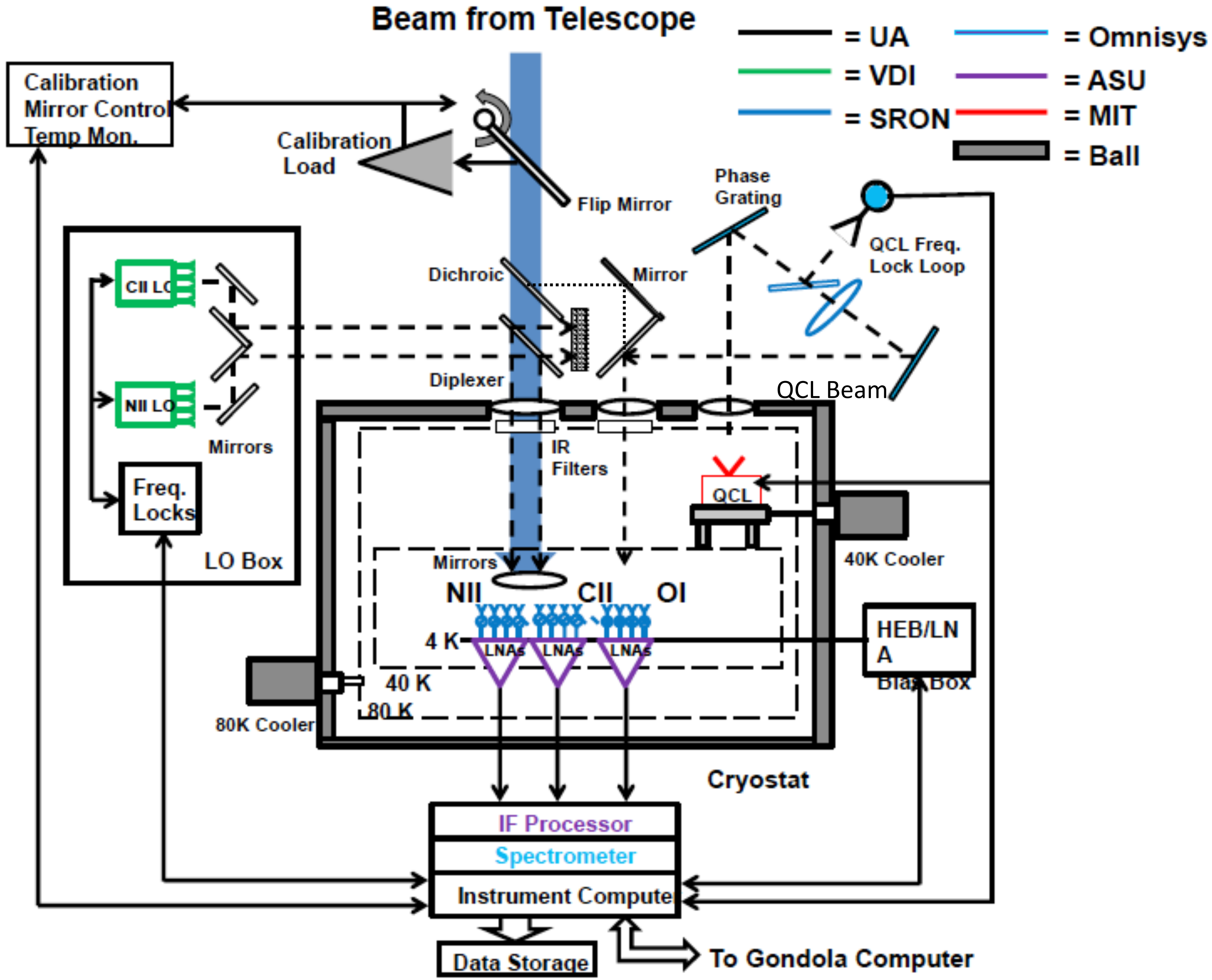
NASA Explorer Mission of Opportunity (MoO) balloon mission – Launched Dec. 312023

GUSTO Payload Overview



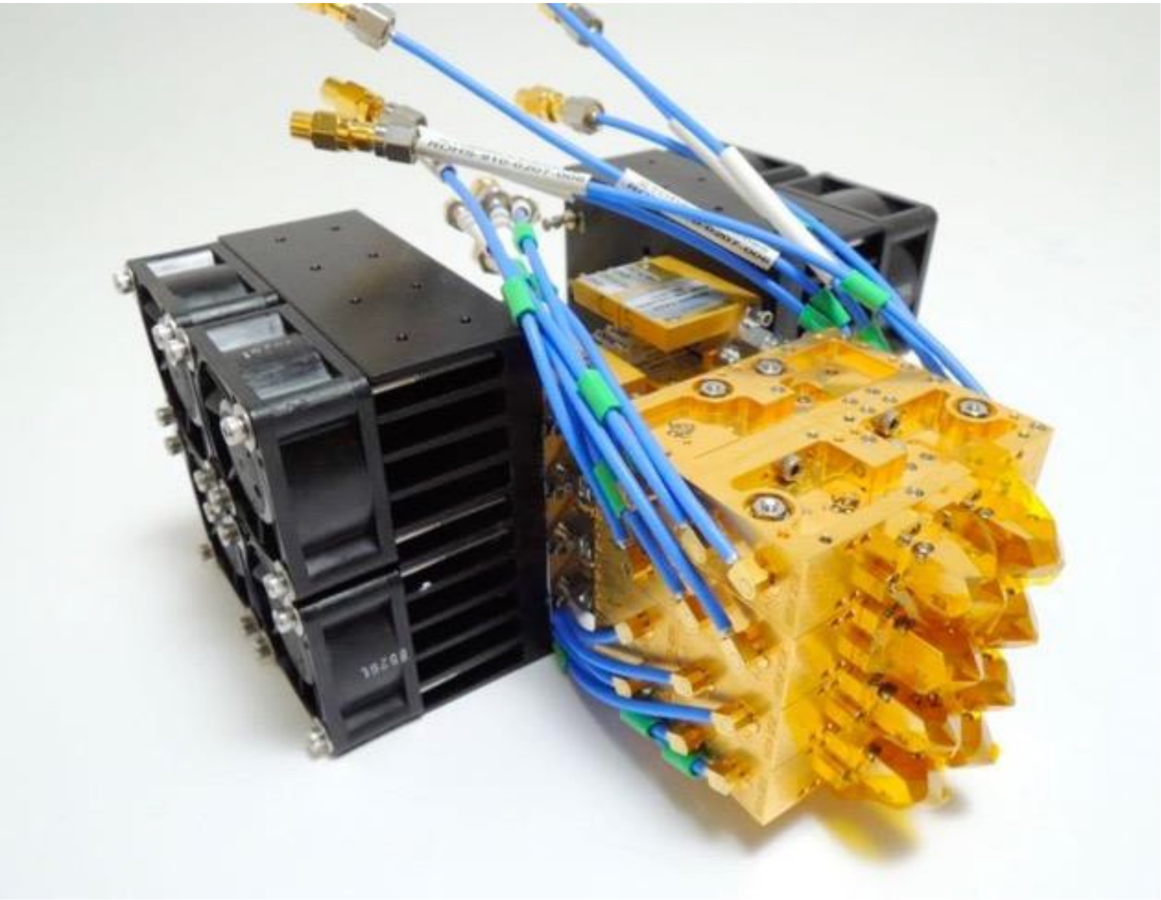
Hardware	Partner
Telescope cradle	Allred & UA
Primary mirror	Hextek, UA OSC
2ndary mirror	UA OSC
B1/B2 FMC LOs	Virginia Diodes
B3 QCL LOs	MIT
B1-B3 mixers	SRON
B3 phase grating	SRON & ASU
B3 voice coil & SLED	SRON
Cryogenic LNA	ASU
RF flex circuit	ASU
Warm IF boards	ASU
Spectrometer	Omnisys
Cryostat	Ball Aerospace
Cryocoolers	Sunpower
Optics, Mech. Electronics, SW	UA

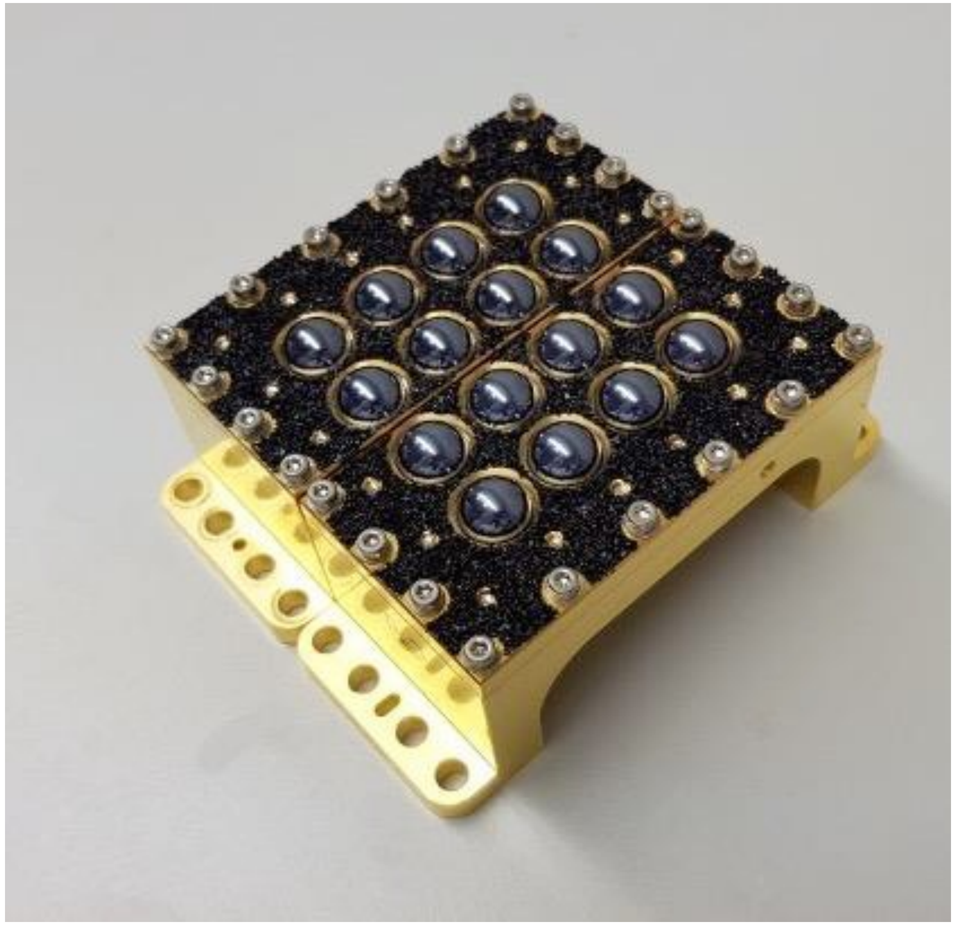
The payload represents a diverse set of hardware from a dozen major subcontracts that must be made to work together seamlessly



GUSTO

Receiver optics and spectrometer





Band 2

8-pixel frequency-multiplied LO subsystem

Separate LO for each pixel (VDI)

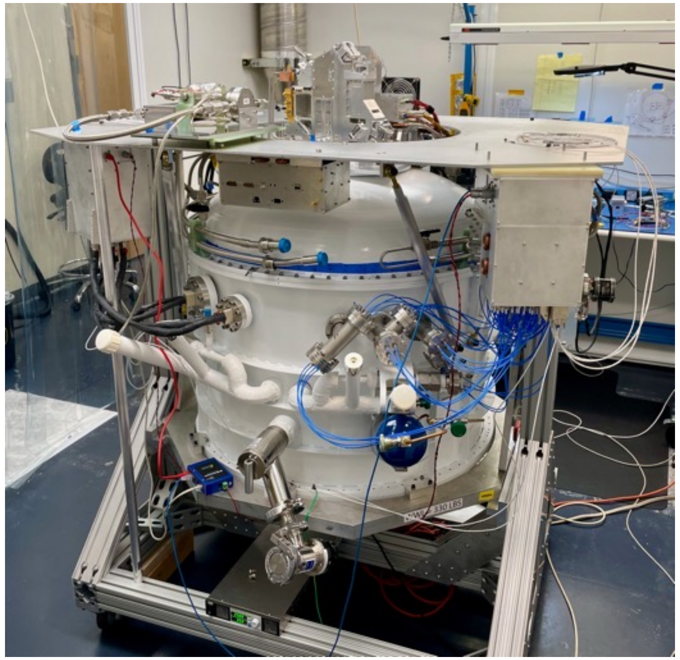
Bands 1 &2

1.4 THz and 1.9 THz

8-pixel HEB mixer array for each (SRON)

Lens-coupled spiral antennas

Implementation: the GUSTO Observatory



Cryogenic (4K) array receiver with 75-day hold time

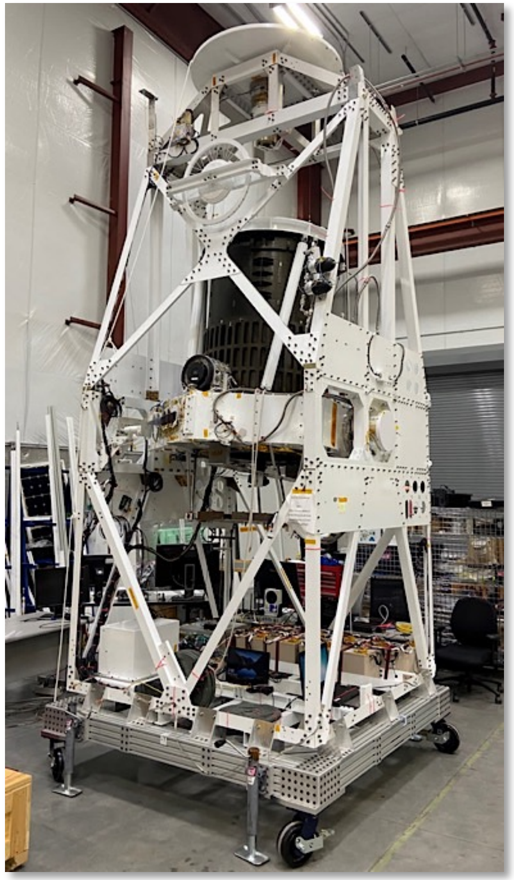
24 heterodyne receivers using hot electron bolometers as mixers from 63-205 microns

GUSTO observes [NII], [CII], and [OI] simultaneously!

0.9 m f/10 Cassegrain telescope, under-illuminated at high frequencies

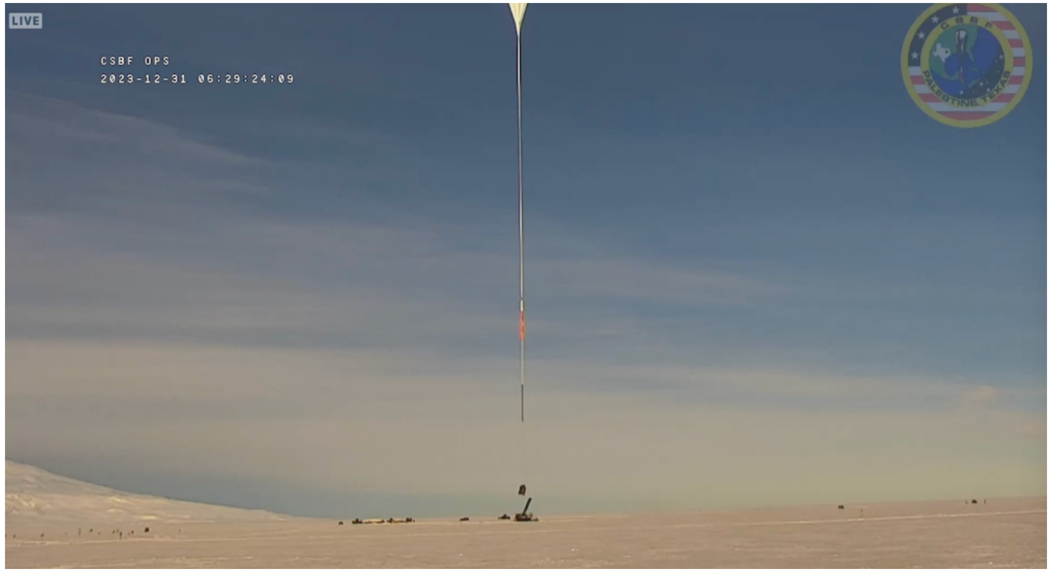
54” beam at [NII], 1461 GHz (Band 1)
44” beam at [CII], 1900 GHz (Band 2)
37” beam at [OI], 4745 GHz (Band 3)

“the Payload”

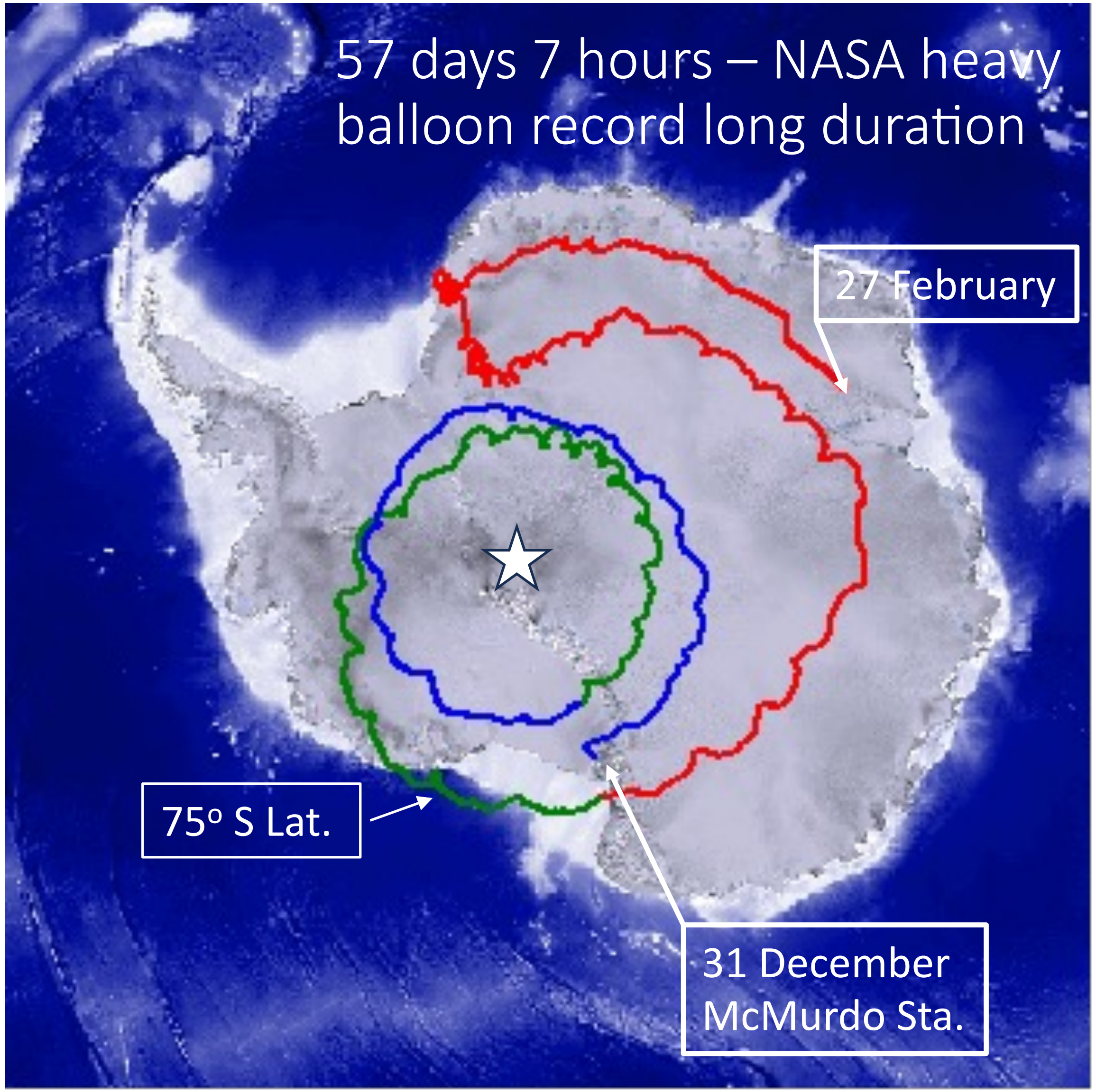


Gondola provides:
- Observatory power
- Science data telecom
- Pointing control
- Thermal control

GUSTO Launch: 31 December 2024



57 days 7 hours – NASA heavy balloon record long duration



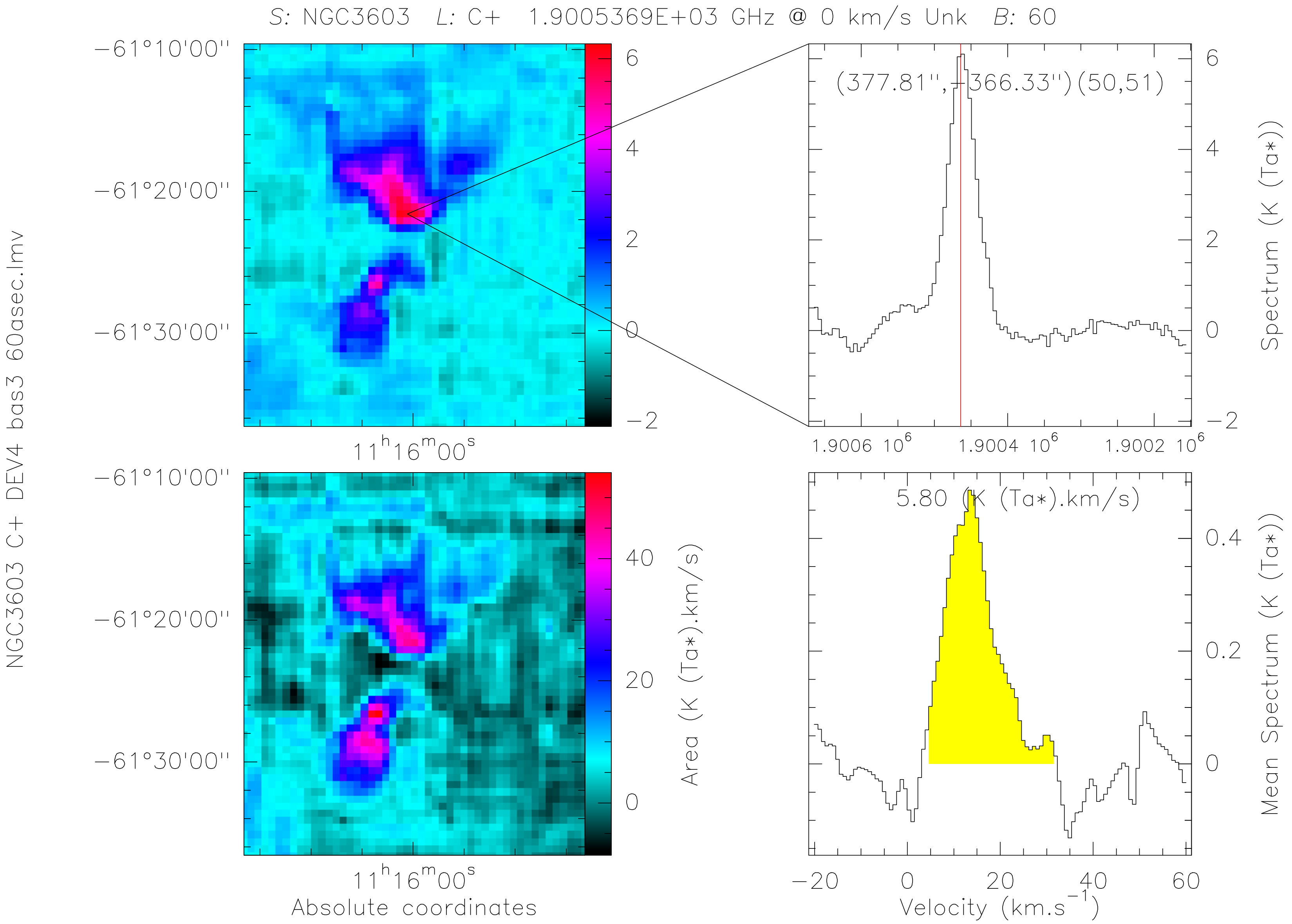
Level 0 GUSTO Data

NGC 3603

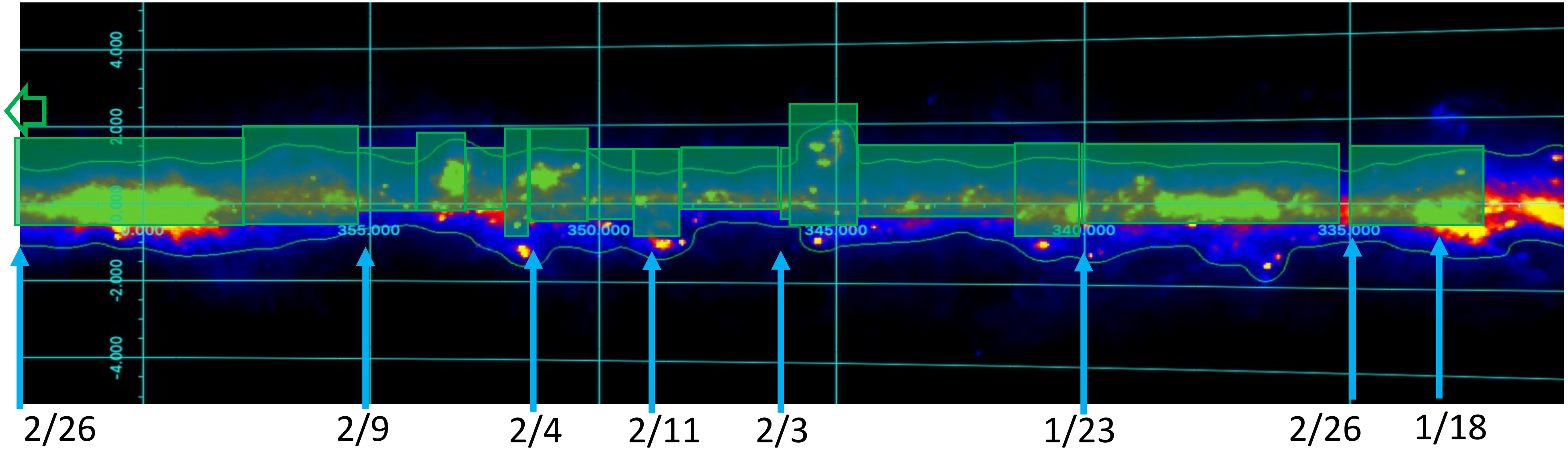
[CII] map with
0.9’ spacing (~FWHM)

Intensity calibration still being worked out

Pixel offsets measured by moon scans, but not yet incorporated here



GUSTO Galactic Plane Survey & LMC Survey



- 62 square degrees of Galactic Plane mapped in Bands 1 and 2
  - Easily exceeds mission success criteria, and 100% of Threshold mission!
- LMC Survey
  - 1.1 deg^2 map of 30 Dor region (100% complete)
  - 0.6^{o}x0.5^o map around N11 (100% complete)

ASTHROS **A**strophysics **S**tratospheric **T**elescope for **H**igh-**R**esolution **O**bservations at **S**ubmillimeter-waves

- Antarctic NASA APRA balloon mission
- Jorge Pineda (PI), Paul Goldsmith, Jon Kawamura, Youngmin Seo, Chris Groppi (ASU) + science team
- **205 μm and 122 μm[NII] fine structure lines (HD J = 1-0)**
- 4-pixel heterodyne receiver for each line; ASIC digital spectrometer with very high spectral resolution
- Baseline Mission: High angular resolution (20” and 12”) observations of ionized gas regions in the Milky Way and M83
- 21-day flight Dec. 2024

ASTHROS Telescope

2.5m dia. Al honeycomb/CFRP antenna (Media Lario, Italy)

Low blockage symmetric Cassegrain

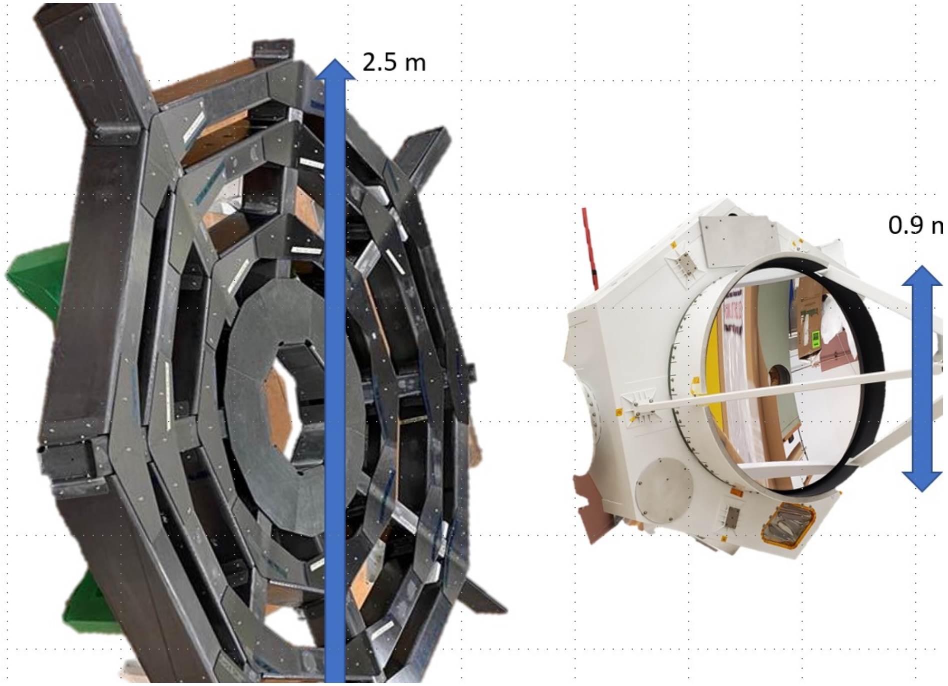
<8 μm rms aggregate surface accuracy

2: 4-pixel HEB science receiver arrays

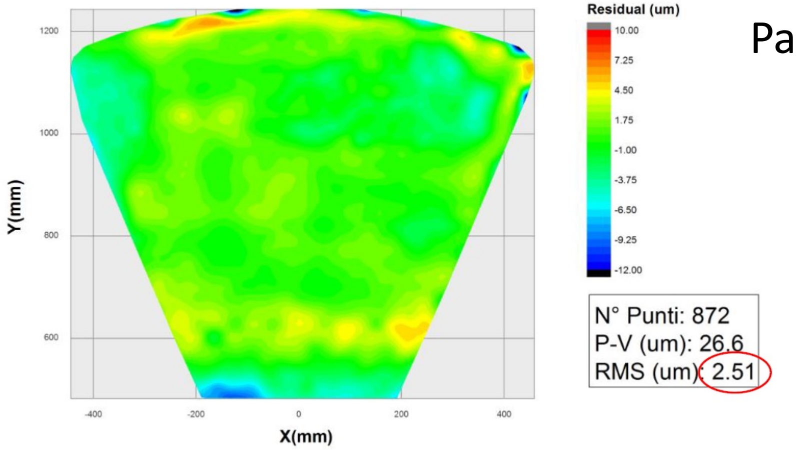
80-100 GHz receiver for system tests and pointing observations

8 ASIC digital spectrometers

4 K *closed cycle* Lockheed Martin pulse tube cryocooler

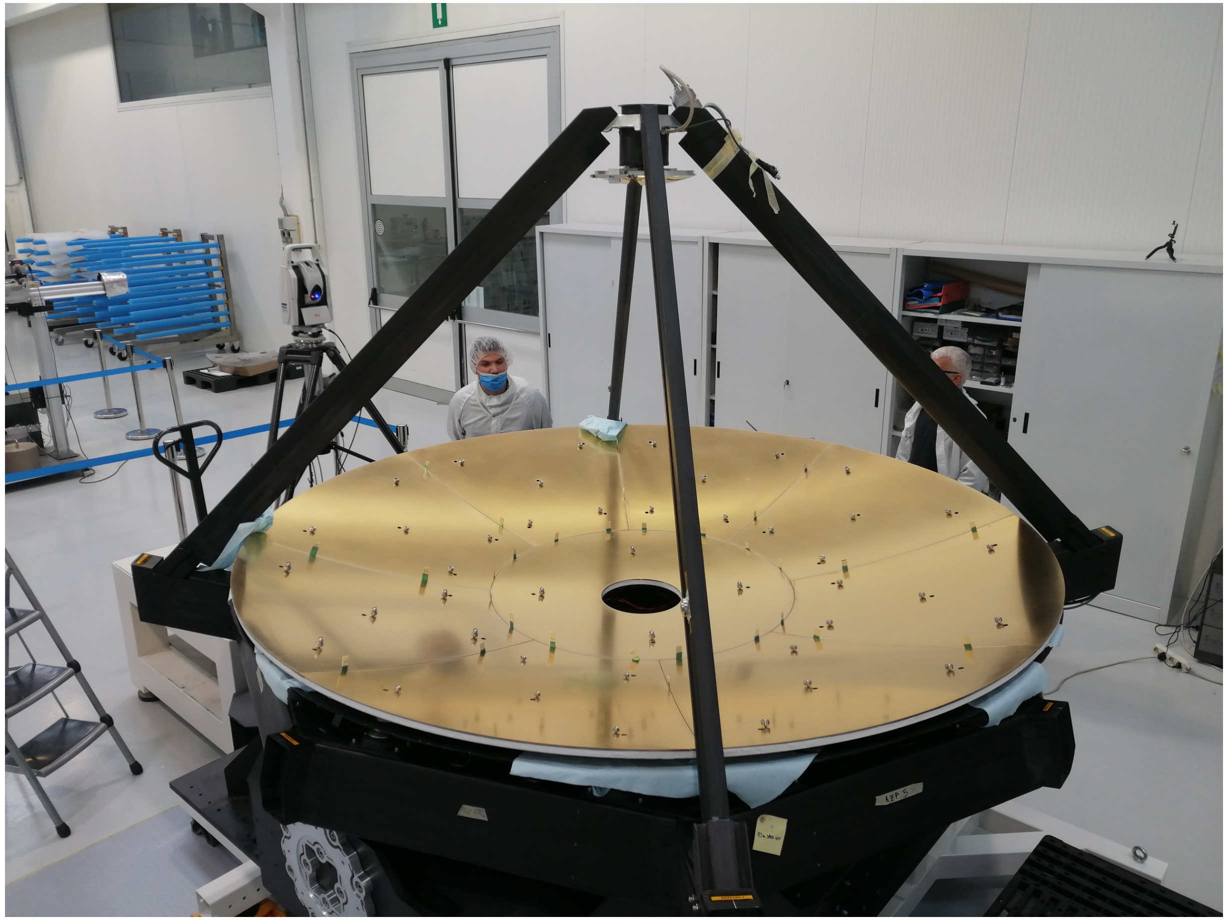


ASTHROS Telescope is a BIG Step Compared to GUSTO



Panel Mold

ASTHROS Telescope

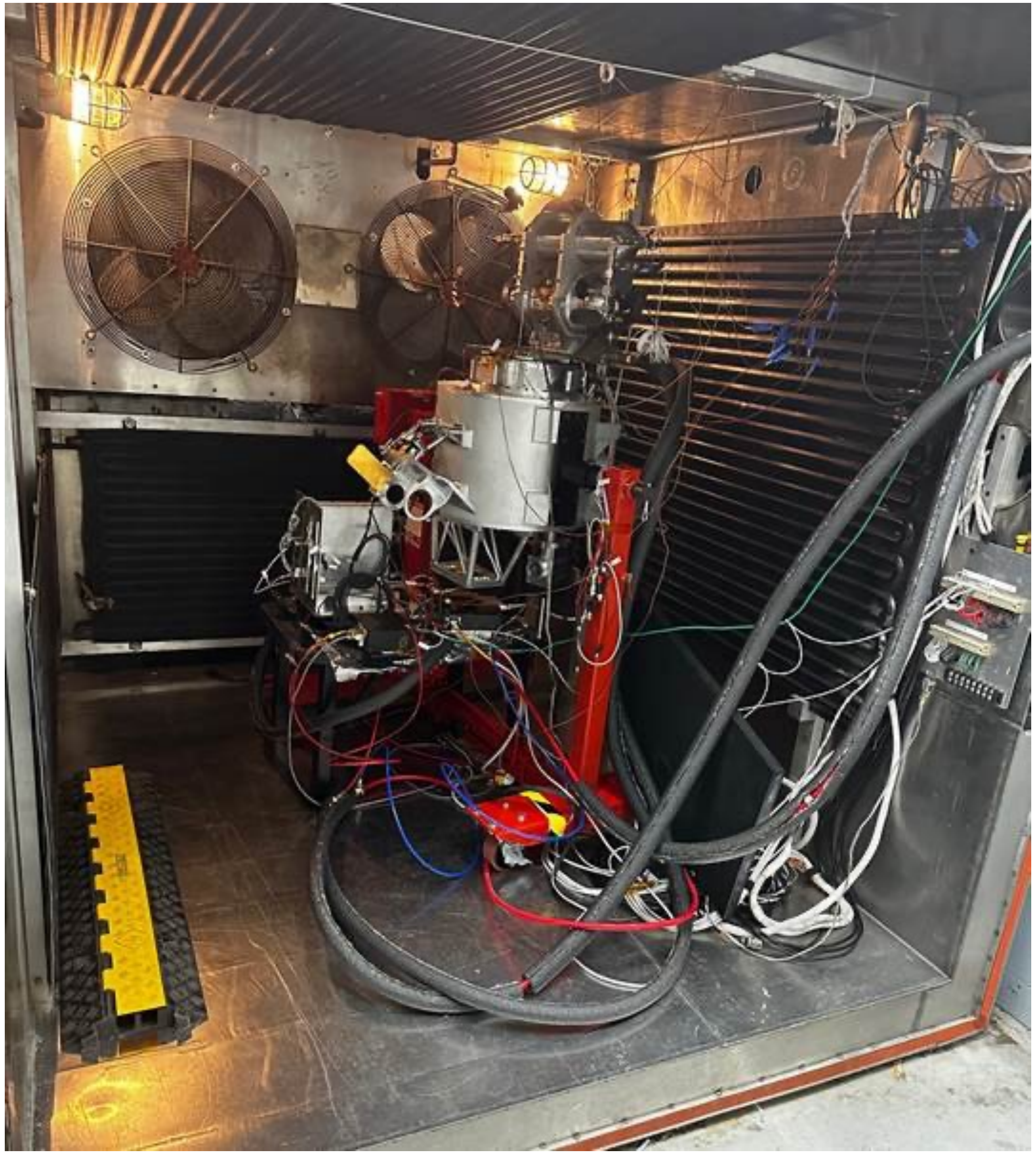


ASTHROS Receiver

- HEB mixers cooled to ~ 6K by closed-cycle refrigerator

  NO CONSUMABLES!

- 4 pixels for ~1500 GHz and 4 pixels for ~2500 GHz
- Digital ASIC spectrometer for each, covering ~4 GHz bandwidth
- Dewar has passed Thermal-Vacuum tests; currently mixers and IF amplifiers being installed



ASTHROS dewar in TVAC test in Palestine, Texas

Conclusions

- Fine structure lines are powerful tracers of the ISM, especially regions mechanically and radiatively affected by massive star formation. This "FEEDBACK" is one major controller of massive star formation
- [CII] and [OI] generally trace star formation both in Galactic sources and external galaxies but important caveats are emerging from detailed studies of velocity-resolved spectra
  - In [CII], absorption by diffuse ISM can corrupt results for emission regions when observed with inadequate velocity resolution; self-absorption difficult to explain
  - In [OI], there is evidence for extensive regions of low-excitation atomic oxygen that absorb the emission from hot gas adjacent to HII region. This results in major reduction in [OI] luminosity and affects calculations of thermal balance and use of [OI] as tracer of star formation .
- Understanding these issues will require velocity-resolved fine structure line images. These will be produced upcoming balloon & space missions!

THANK YOU FOR YOUR ATTENTION