Velocity-Resolved [OI] (and other) Line Observations and Star Formation:

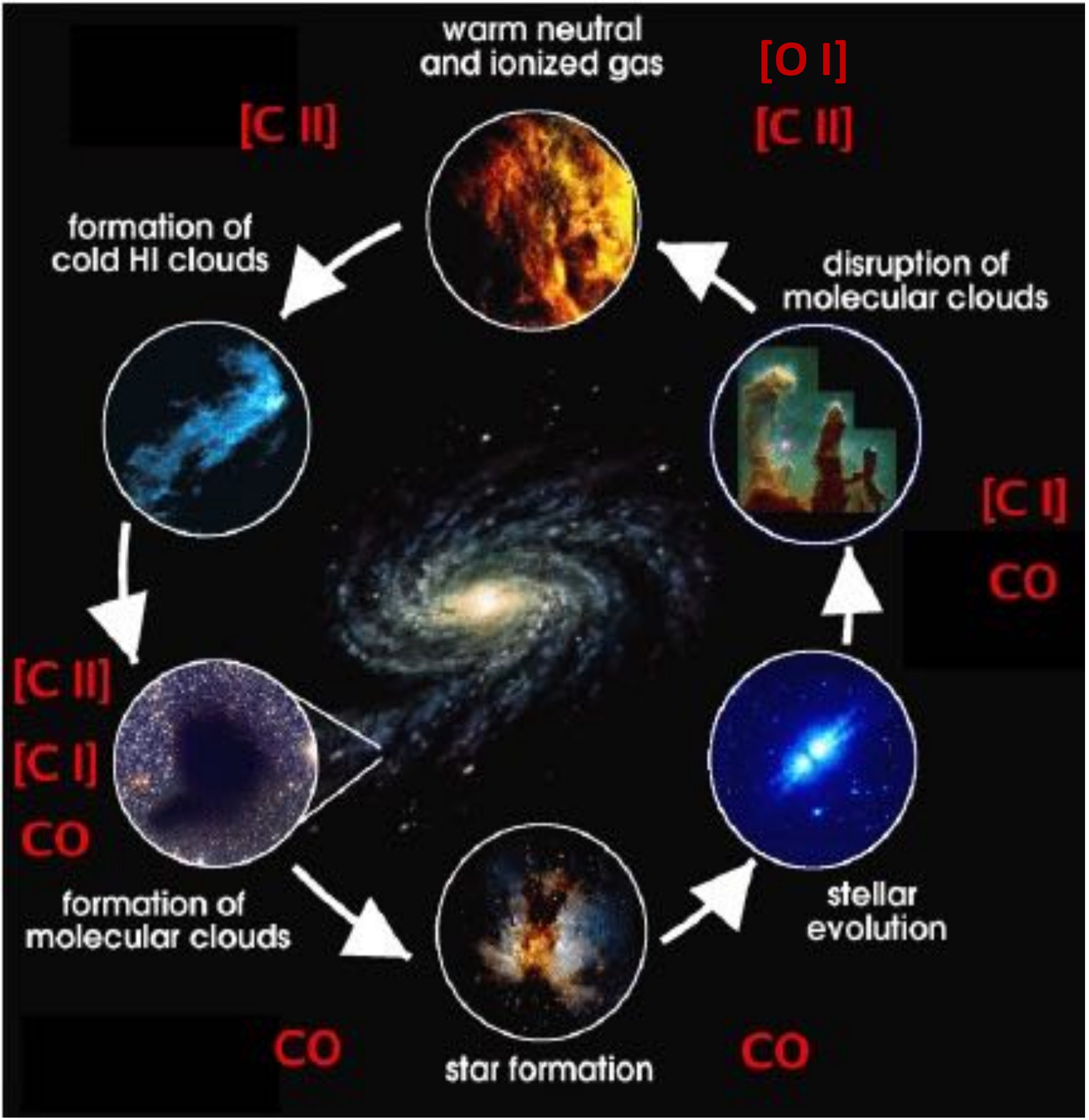
New Results and New Capabilities

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

SOFIA Tele-talk
Dec 8, 2021

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



The Baryonic Lifecycle of the Interstellar Medium

- Describes the cycling of material between different ISM phases and incorporation into new stars
- Star formation takes place in relatively quiescent, dense, cold molecular clouds
- Massive young stars disrupt star-forming regions, heating & ionizing them and increasing turbulence

Tracers of different Phases

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 **FEEDBACK** from young stars

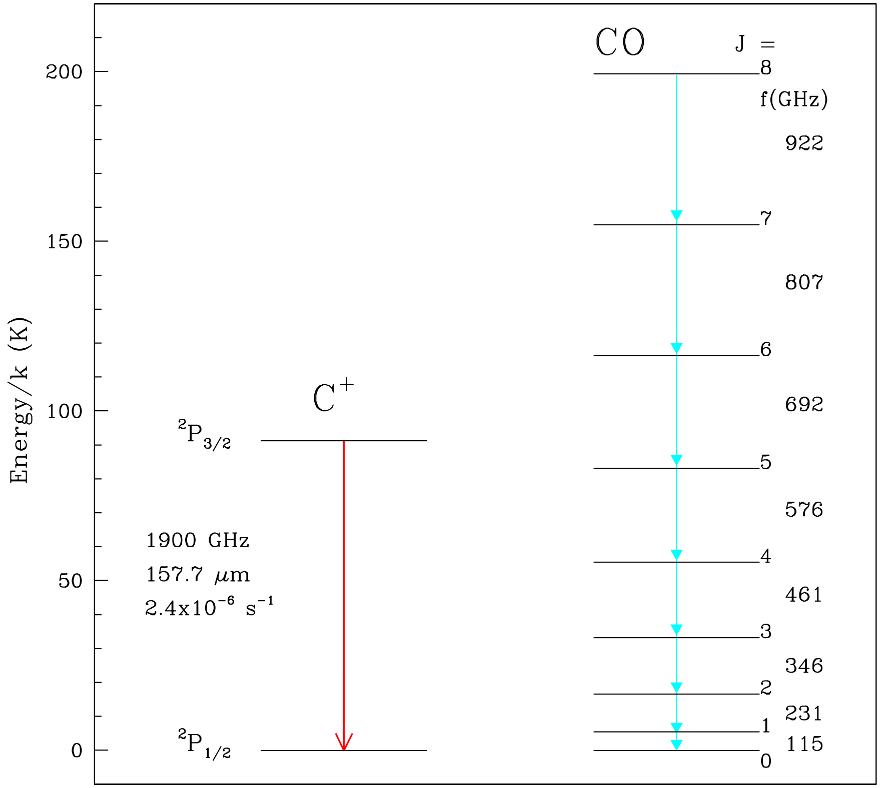
We would like to understand the relationship between ISM and young stars to quantify roles of above processes

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

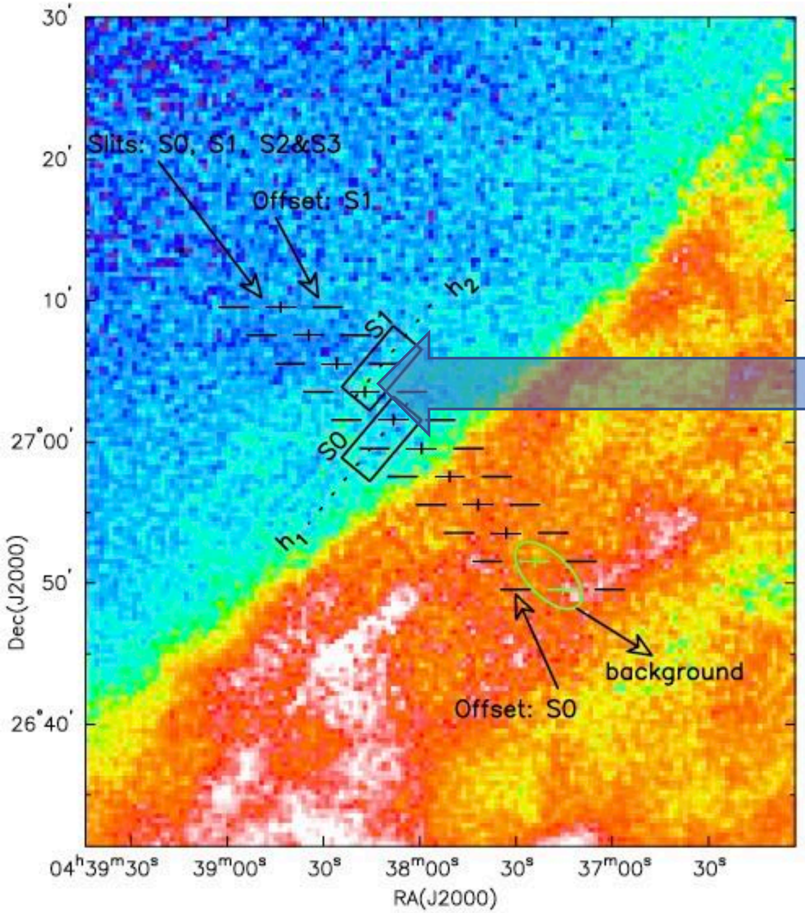
Molecular Clouds and CO-dark Gas

- The temperatures of "dark clouds" – those lacking massive star formation – are 8 K to 12 K
- Chemical models indicate that for $A_v \gtrsim 1.5$ mag., most of the carbon is in the form of CO, as is oxygen not tied up in dust grains.
- In BOUNDARY LAYER, carbon is C^+, but hydrogen is H_2 due to efficient self-shielding. This is the **CO-dark molecular gas.**
- HI and CO do **not** trace this ISM phase
- The temperature of CO-dark H_2 is ~50 K due to photoelectric heating by ISRF and ≥100 K if you are in neighborhood of young star or stars.



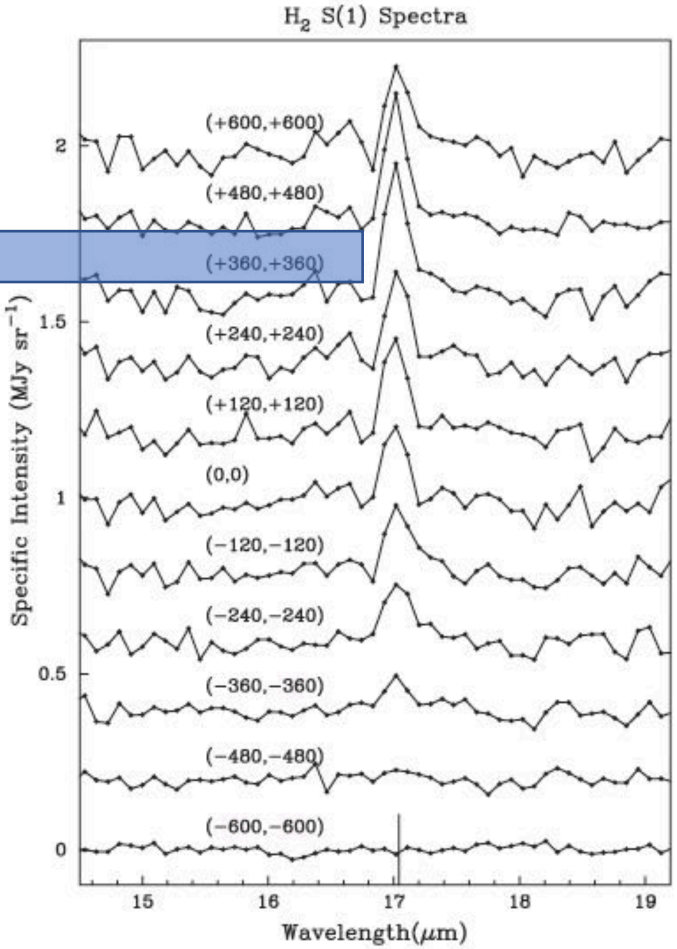
$E_u = hf/k = 92.1$ K for [CII] making it well-suited for tracing regions with T > 50 K

Complexity of Cloud Boundaries



Taurus cloud boundary: sharp in ^{13}CO
Goldsmith+ (2010)

H_2 emission (Spitzer) peaks
10' outside ^{13}CO edge



Taurus is very low ISRF region χ **~ 0.5**

Nonetheless, strong H2 S(1) emission is seen

λ = 17 μm

Eu/k = 845 K

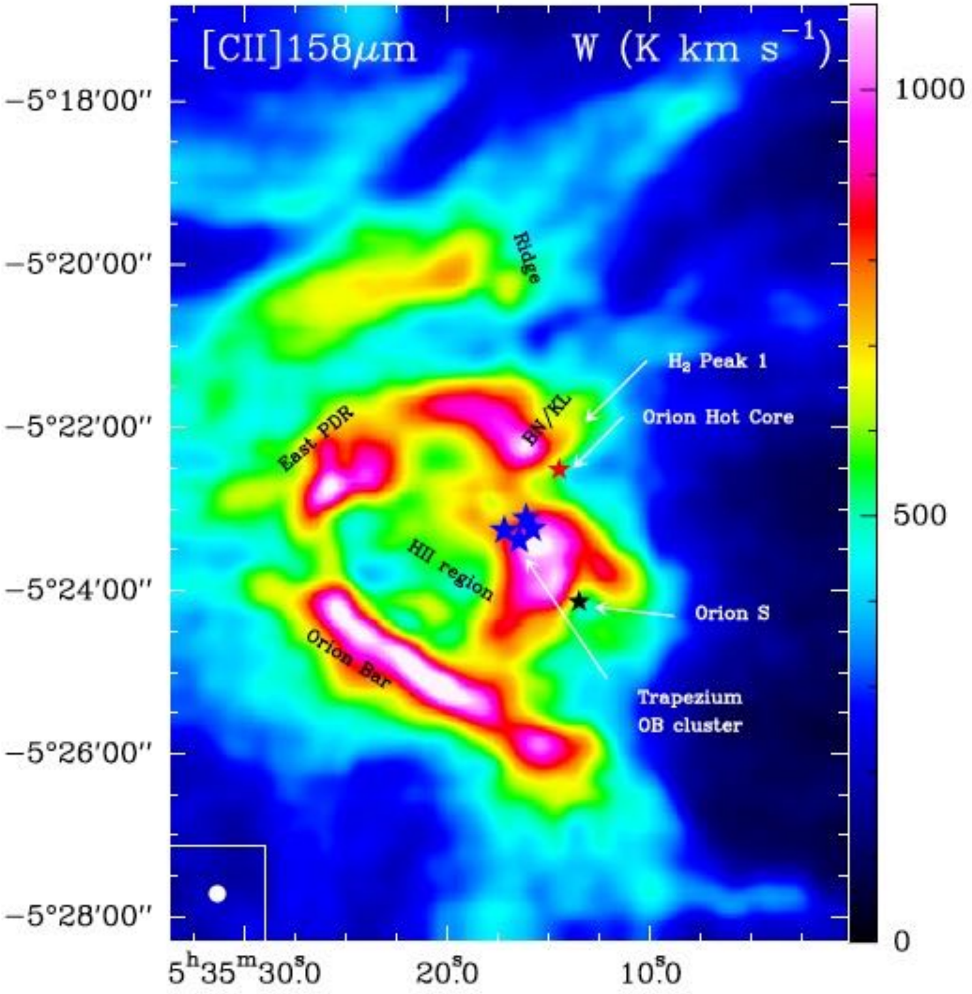
Peaks 0.5 pc *outside* ^{13}CO edge

Turbulent dissipation could be additional heating source

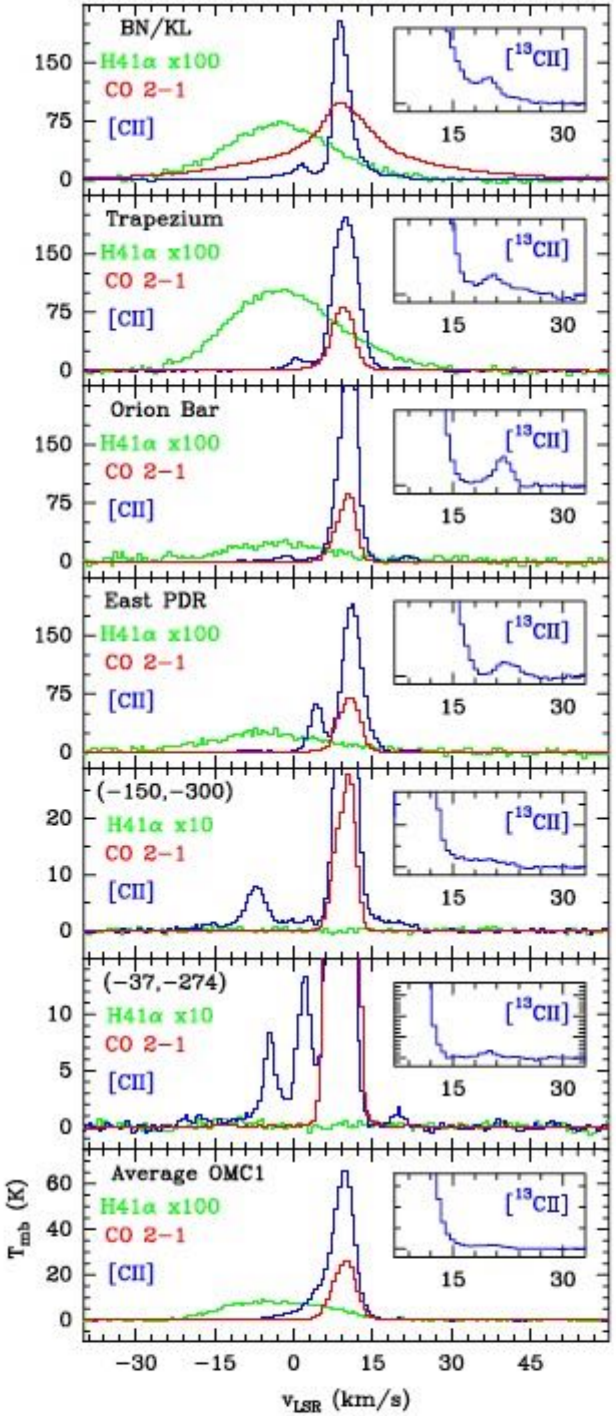
What is the source of this turbulent energy?

[CII] From Regions of Massive Star Formation

Orion: $\chi \geq 10^4$



Complex Kinematics Indicated!



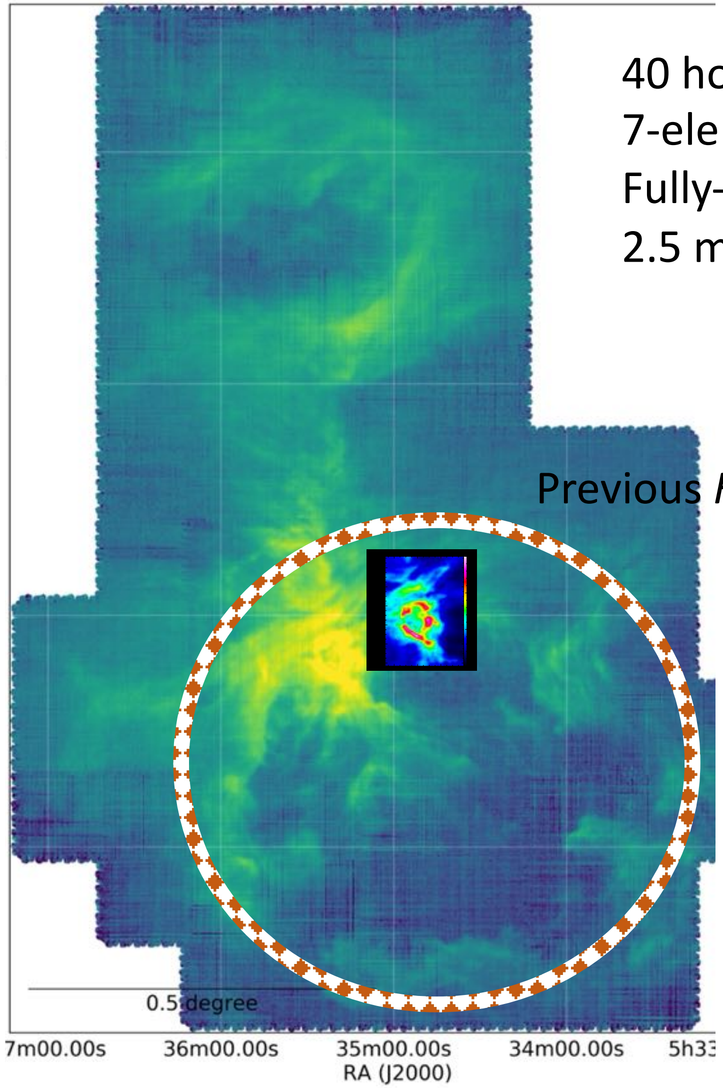
Goicoechea+ (2015)

Dust Continuum

Blue = warm dust
Red = cool dust

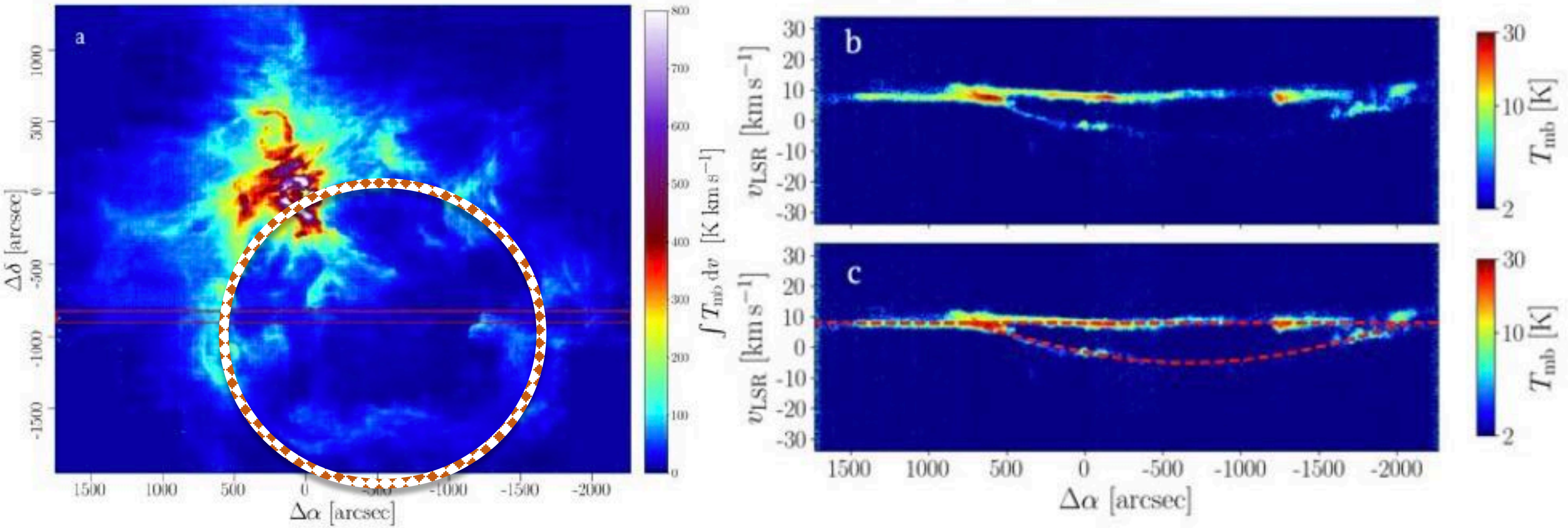
Herschel PACS
& SPIRE

[CII]



40 hours with SOFIA upGREAT
7-element receiver
Fully-sampled image
2.5 million spectra

Previous *Herschel* map of [CII]



Pabst+ (2019)

Expanding spherical half shell with constant expansion velocity v = 13 km s^{-1}

Mass of shell ~ 2600 M_{sun}

Age ~ $2x10^5$ yr

Kinetic energy in shell = $4x10^{48}$ ergs

[CII] luminosity of shell is 0.3*luminosity of θ^1C Ori

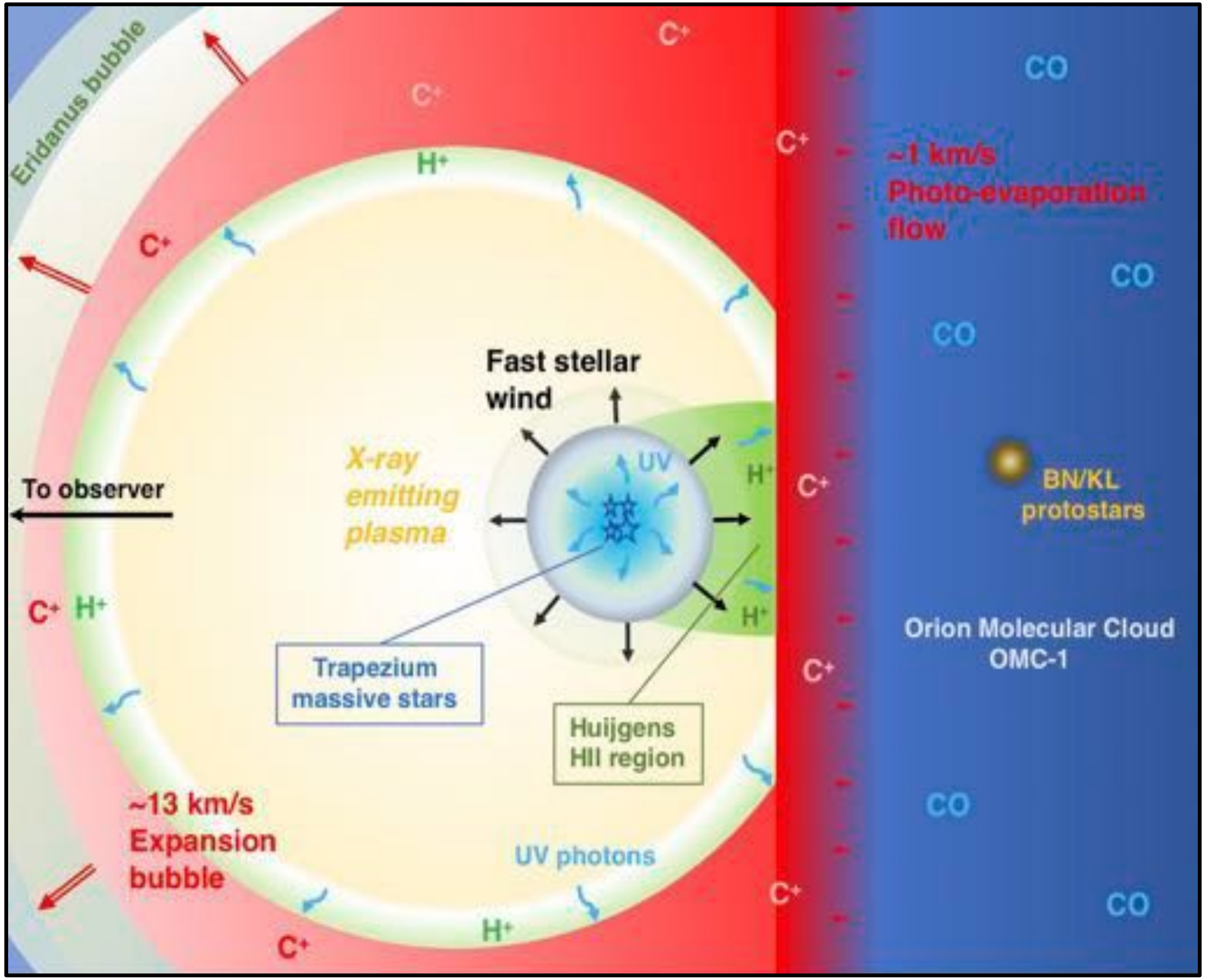
The Structure of the Expanding Orion Bubble

The Trapezium and PDR are on ”our” side of the Orion Molecular Cloud

The expansion is largely into the low density material towards the Earth

The feedback in terms of stimulated star formation is limited

The PDR has relatively little foreground material



Pabst + (2019)

The Importance of High Velocity Resolution

W49N Extremely Massive & Luminous Star-Forming Region

$M = 10^6\ M_{sun}\quad L = 10^7\ L_{sun}$

Smith+ (2009)

***Herschel* HIFI observations**

Gerin+ (2014)

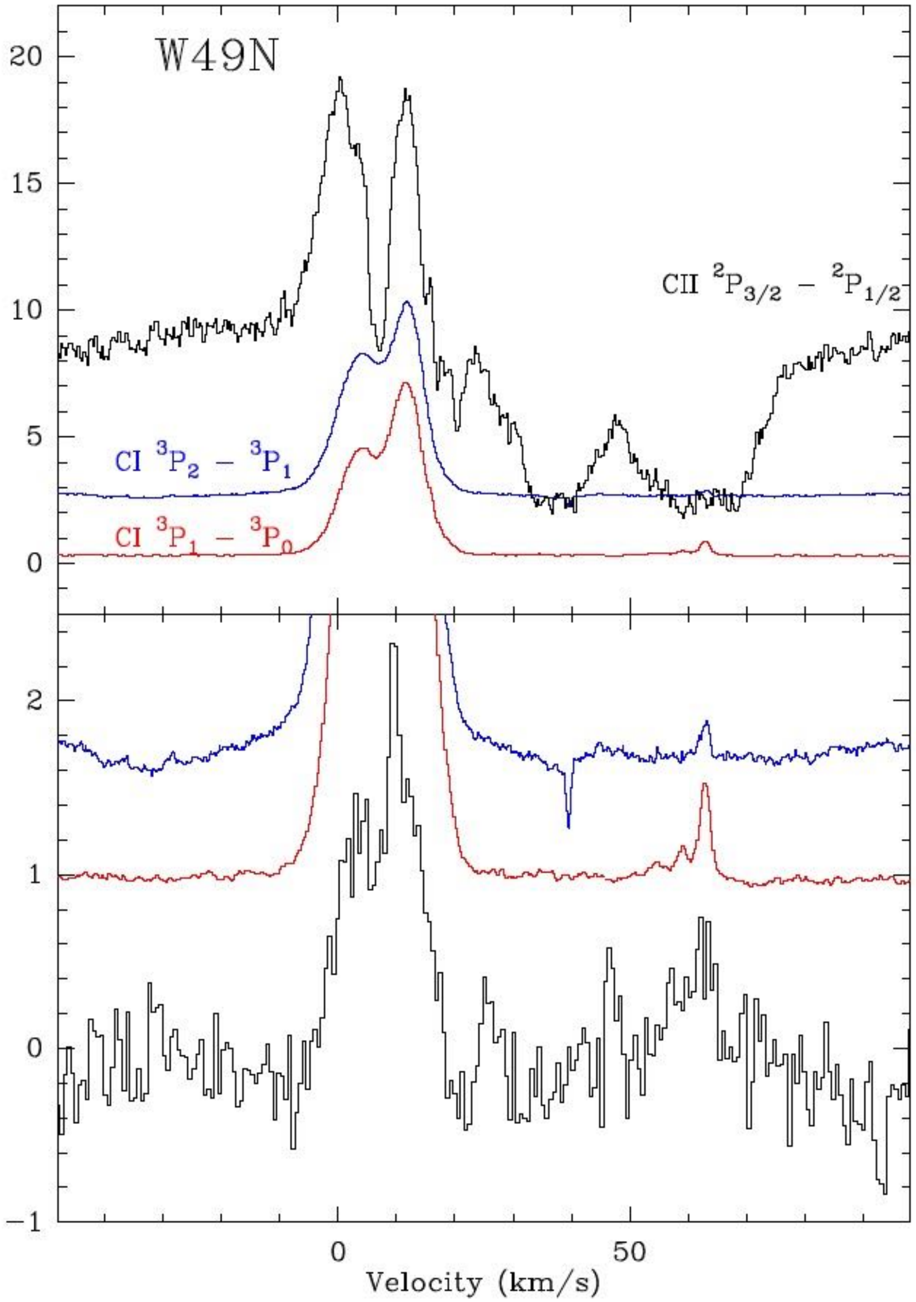
SIGNIFICANT FEATURES

Emission at ~ 5 km/s is **hugely** self-absorbed

There is strong absorption at higher velocities unrelated to the source

This is low-excitation C^+ in diffuse clouds along the line of sight

Consistent with 11.4 kpc distance to W49



[CII] 1900 GHz

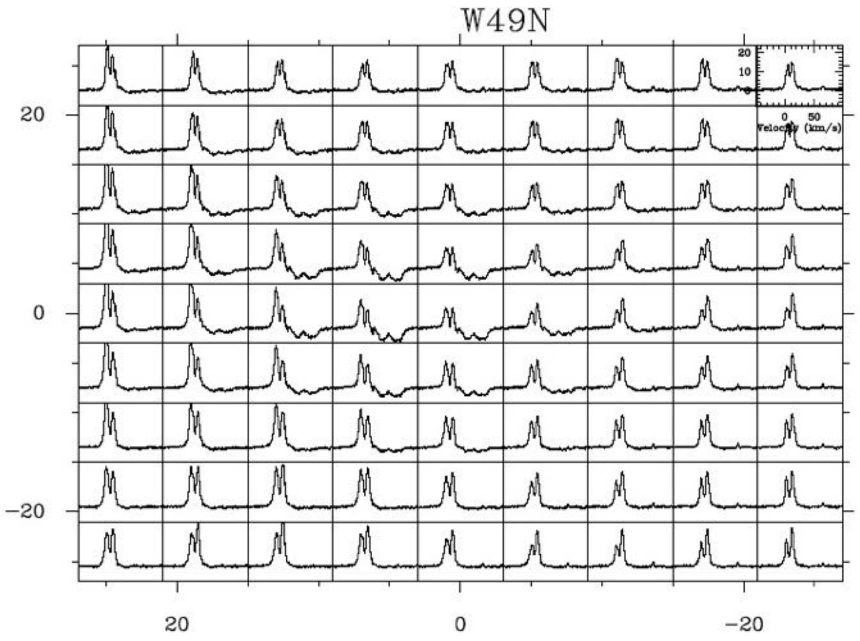
[CI] 809 GHz

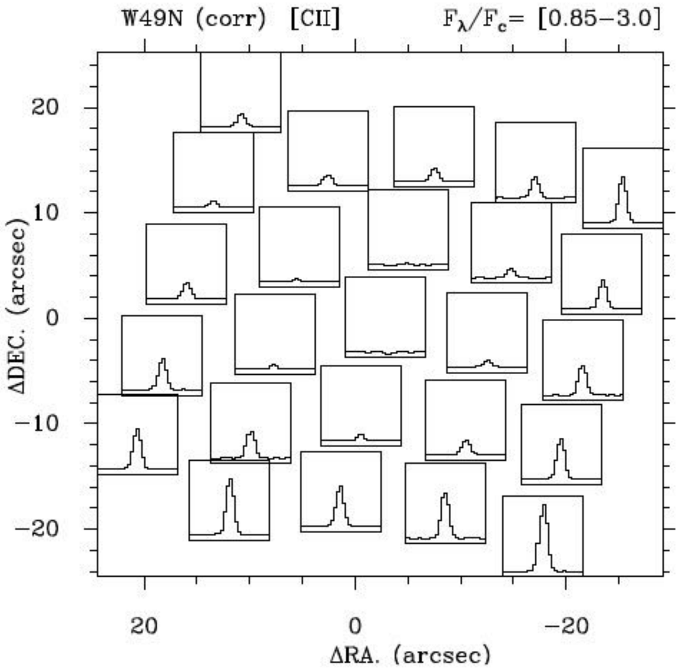
[CI] 492 GHz

Average of reference positions
(expanded scale)
(continuum shifted)

Velocity-Resolved *vs.* Unresolved Spectroscopy

HIFI





PACS

PDR emission and diffuse cloud absorption are clearly distinguished in velocity-resolved spectra

In unresolved data, line/continuum ratio drops dramatically as continuum strengthens
A consequence of equal area of diffuse cloud absorption and true W49 emission

Distant galaxies typically observed with low-resolution spectrometers
What will happen in Starburst or ULIRG with multiple regions with C^+ in beam?

Weak [CII] from Diffuse ISM (CNM) is Thin (or Effectively Thin) but this is NOT the Case for Strong Emission from PDRS

PDR emission likely to dominate emission from galaxies

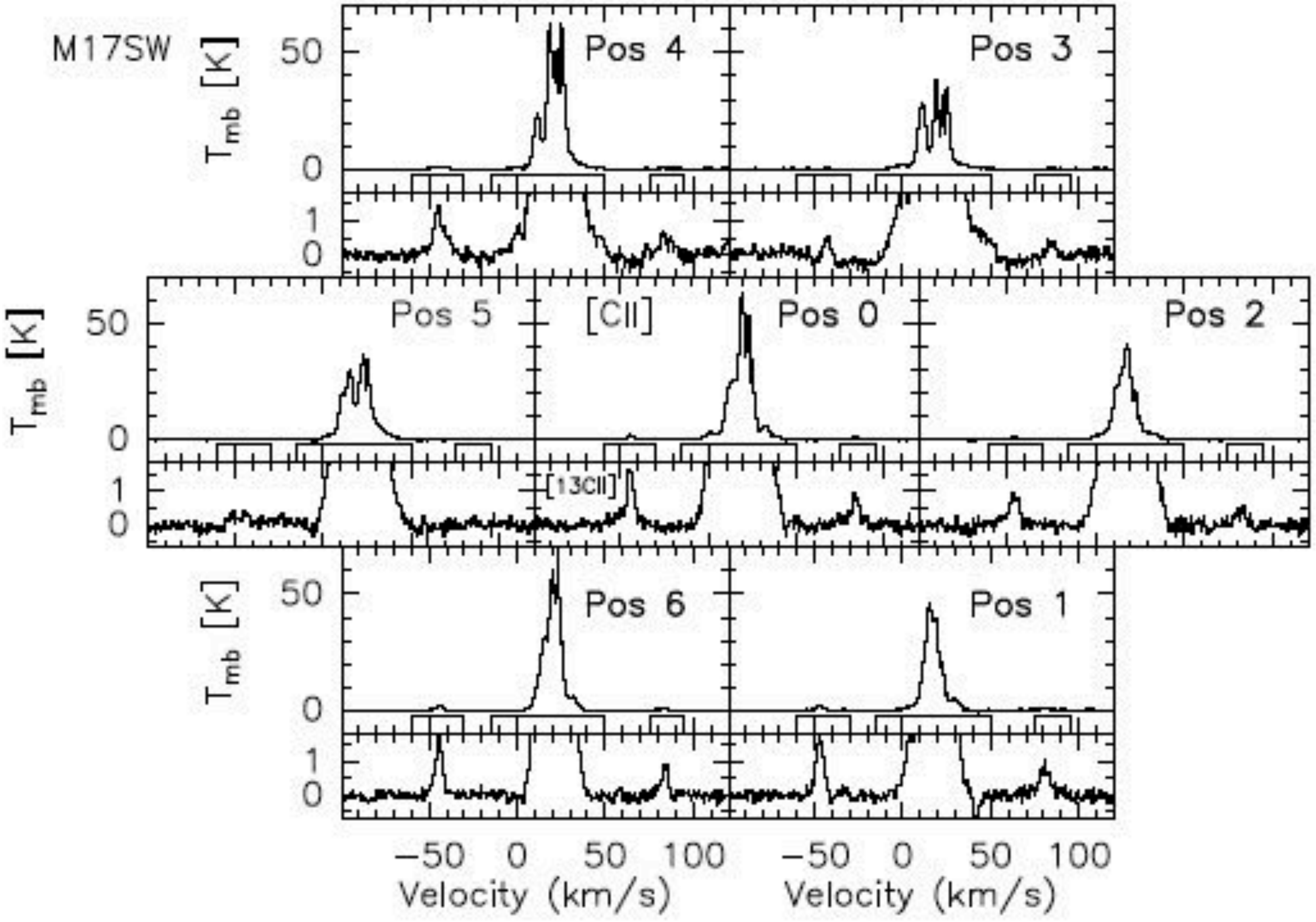
We need studies such as this that can determine the optical depth of [CII]

The self-absorption seen in M17 and Mon R2 requires

N(C^+) = 4-20x10^{17} cm^{-2}

This corresponds to ~ 10 mag of material with carbon completely ionized but so little excited that it *absorbs* background PDR emission

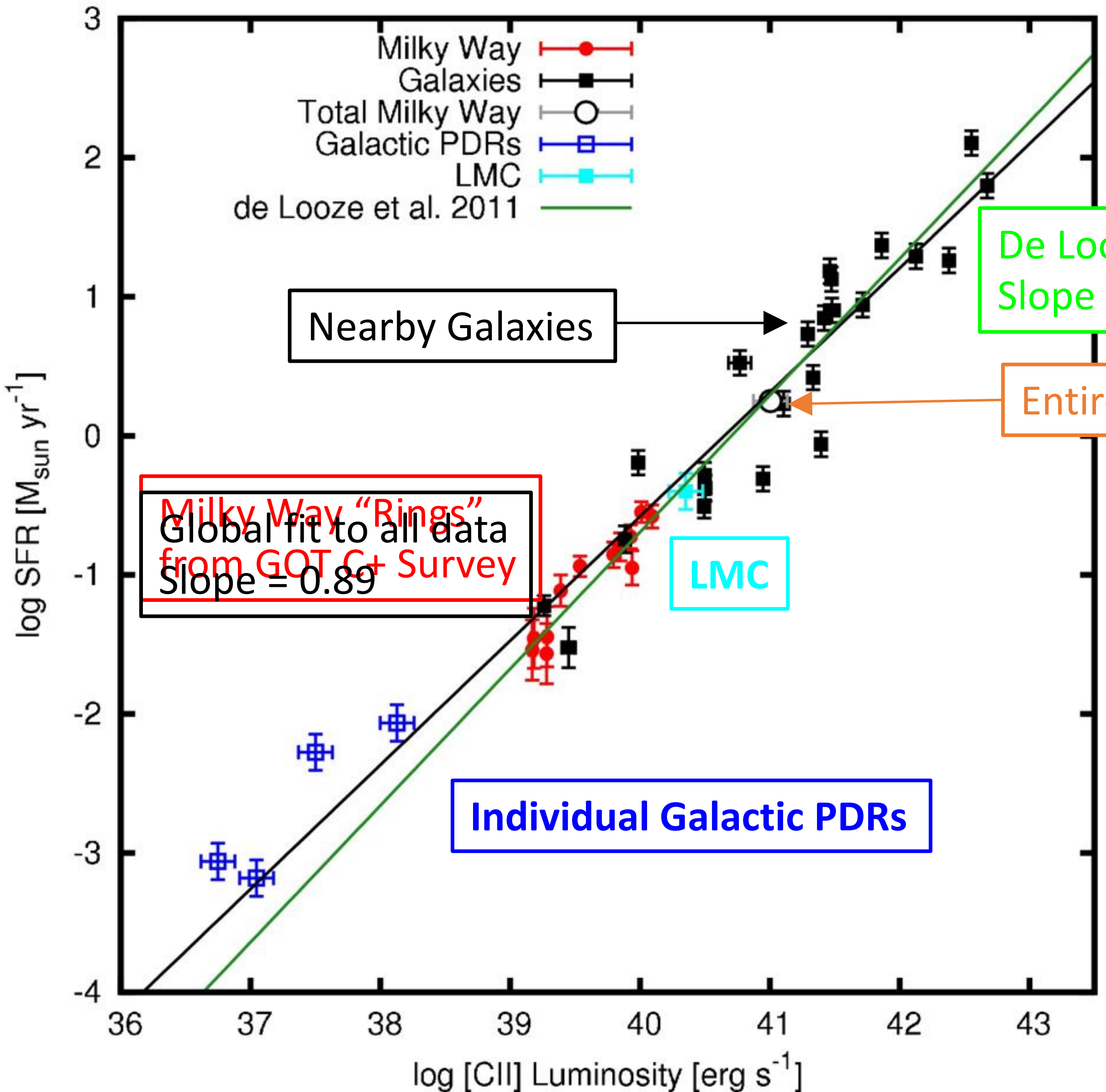
Worse when stars/PDRs are packed together



Guevara+ (2020) – 4 sources studied with SOFIA/upGREAT

Does [CII] Emission Trace Star Formation?

GOT C+ Survey Sampled 500 los in Milky Way using *Herschel* HIFI instrument Velocity-resolved [CII] spectra



Nearby Galaxies

De Looze fit to galaxies
Slope = 0.98

Entire Milky Way

Milky Way "Rings" from GOT C+ Survey

Global fit to all data
Slope = 0.89

LMC

Individual Galactic PDRs

Pineda+(2014)

Conclusions About [CII] (& Other Fine Structure Lines) as Star Formation Tracers

[CII] works well for local galaxies

Concern has been raised for ULIRGs and other "exotic" galaxies

Of interest not only for understanding individual galaxies but also for modeling results of "Intensity Mapping" studies of high-redshift galaxies in which individual galaxies are NOT resolved, but collective emission is measured

But there are concerns:

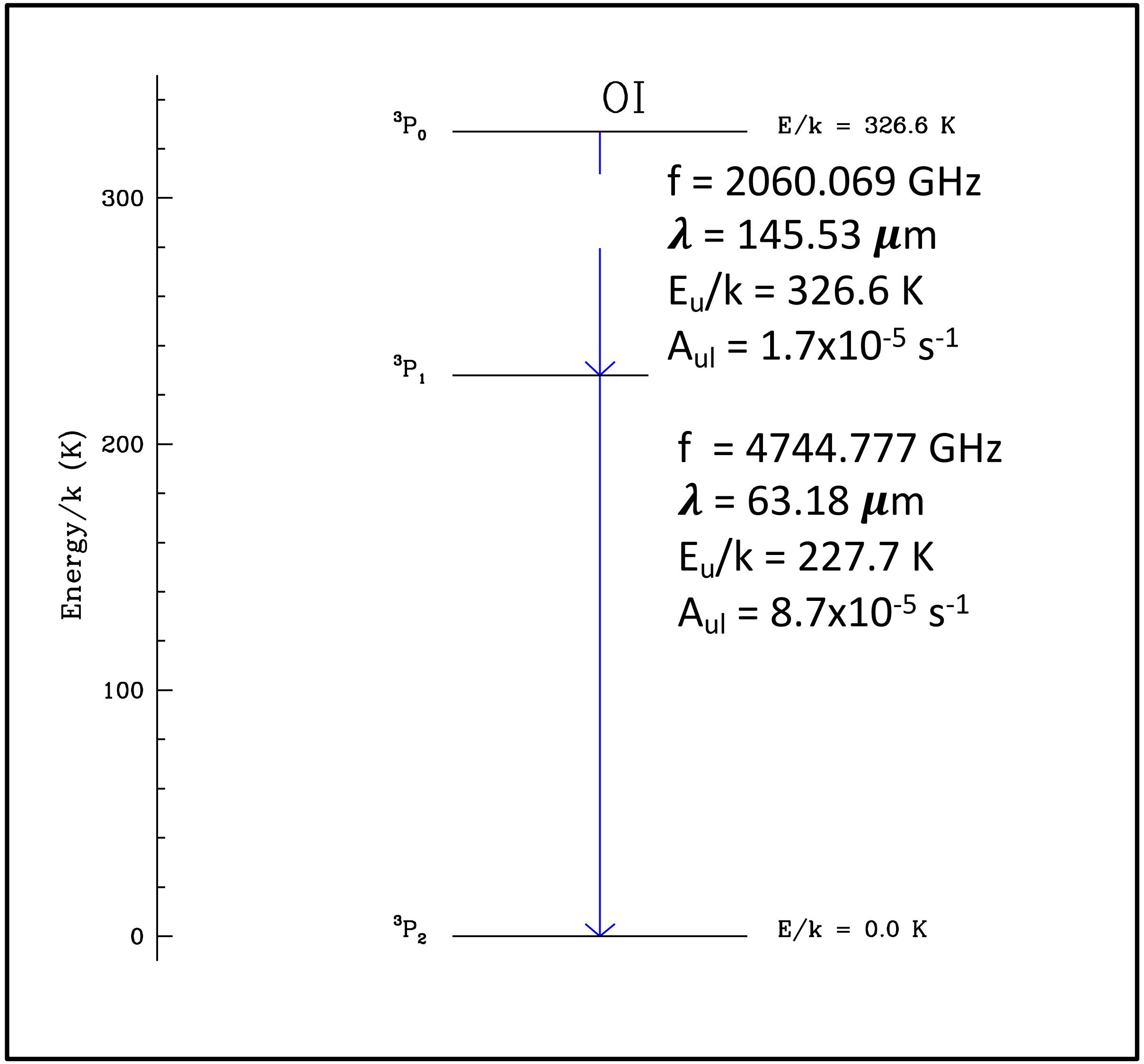
The greatest is **optical depth** and how it may effect observed intensities

Atomic Oxygen (O^0)

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

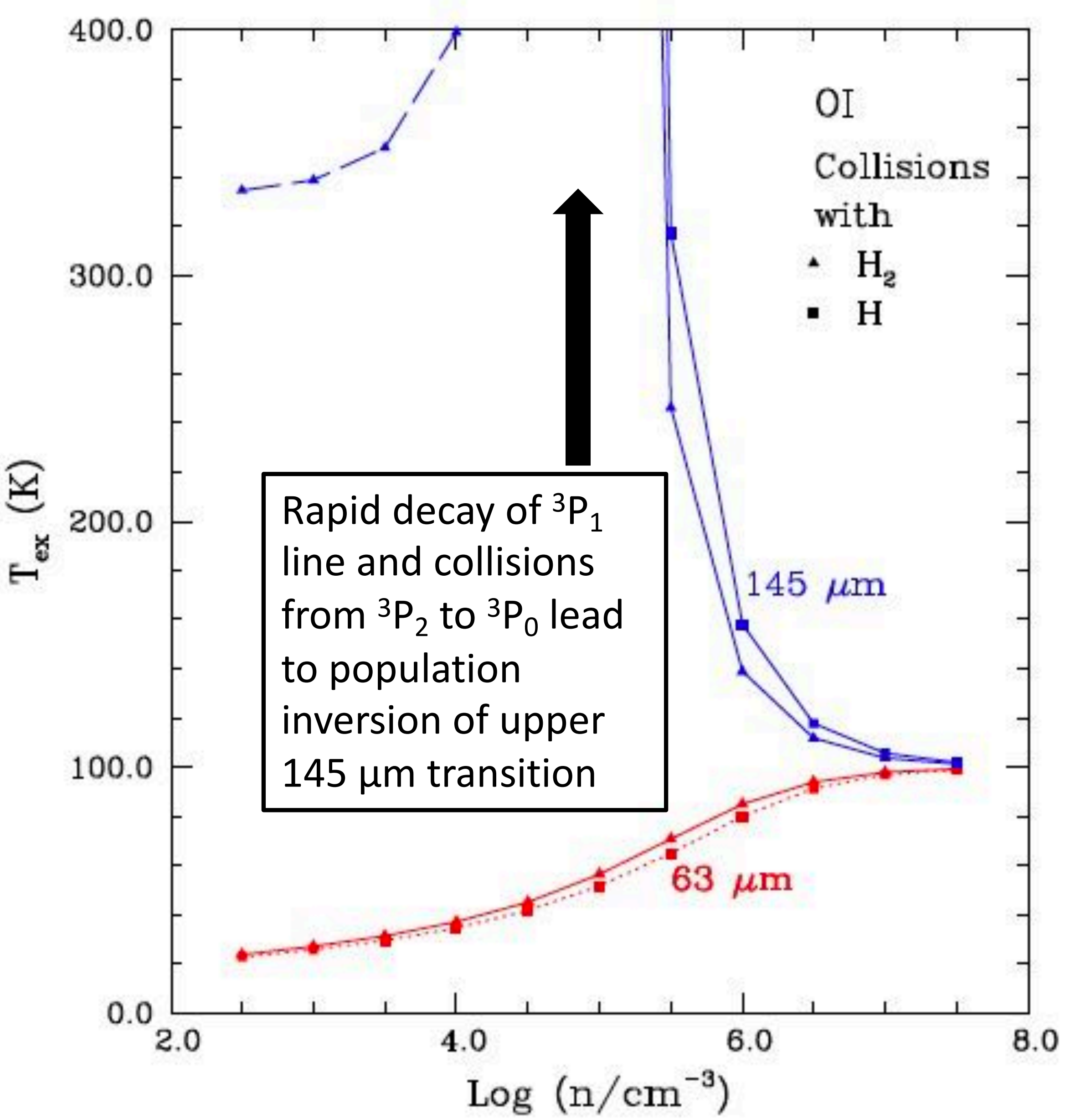
  [OI] 63 µm and [OI] 146 µm

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

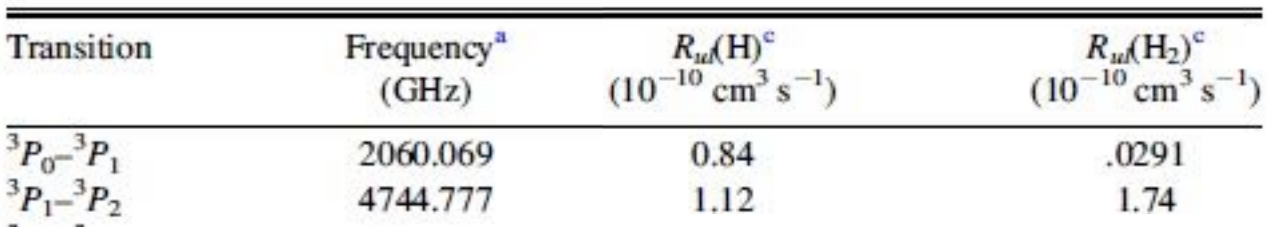


[OI] Excitation and Emission

Goldsmith 2019



Rapid decay of $^3P_1$ line and collisions from $^3P_2$ to $^3P_0$ lead to population inversion of upper 145 µm transition

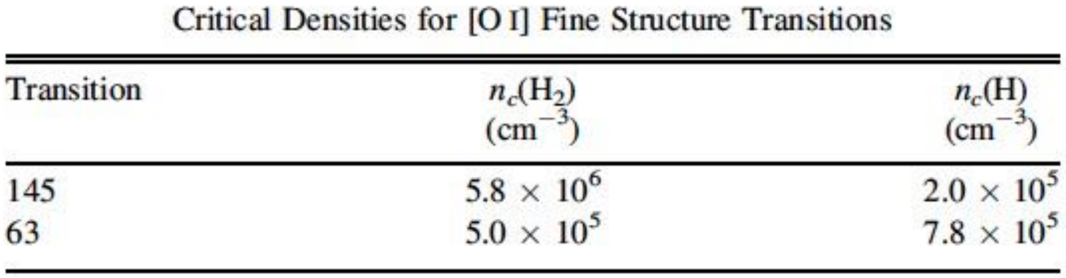


Transition	Frequency[a] (GHz)	R_{ul}(H)[c] (10^{-10} cm^3 s^{-1})	R_{ul}(H_2)[c] (10^{-10} cm^3 s^{-1})
$^3P_0$–$^3P_1$	2060.069	0.84	.0291
$^3P_1$–$^3P_2$	4744.777	1.12	1.74

The excitation of lower (63 **µ**m) transition is well-behaved; its excitation temperature increases monotonically as function of collision rate and thus density

The upper (145 **µ**m) line is more complex due to rapid decay of lower level & small R_{ul}

This does not end up having major effect on emergent intensity

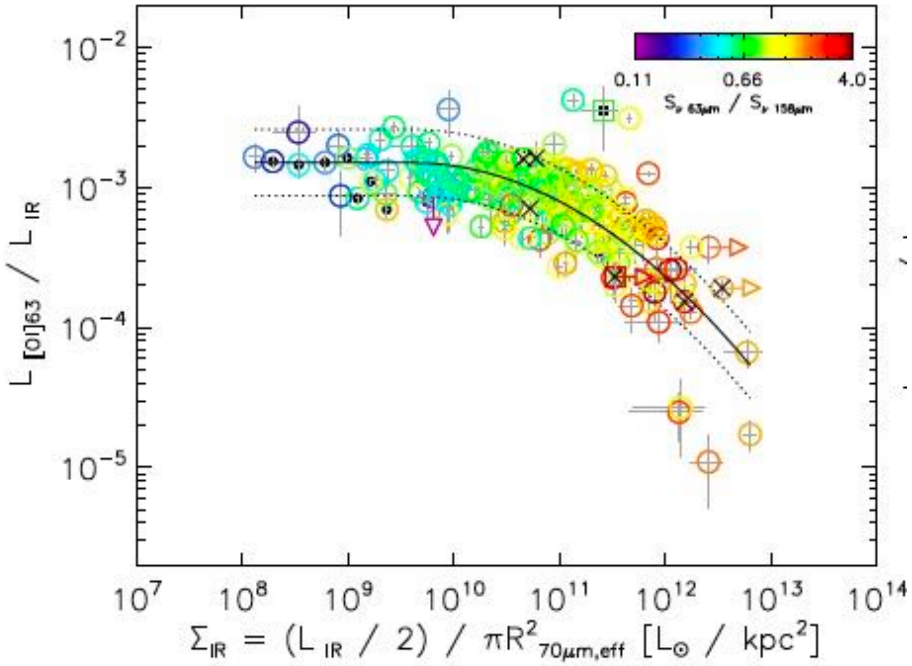


Critical Densities for [O I] Fine Structure Transitions

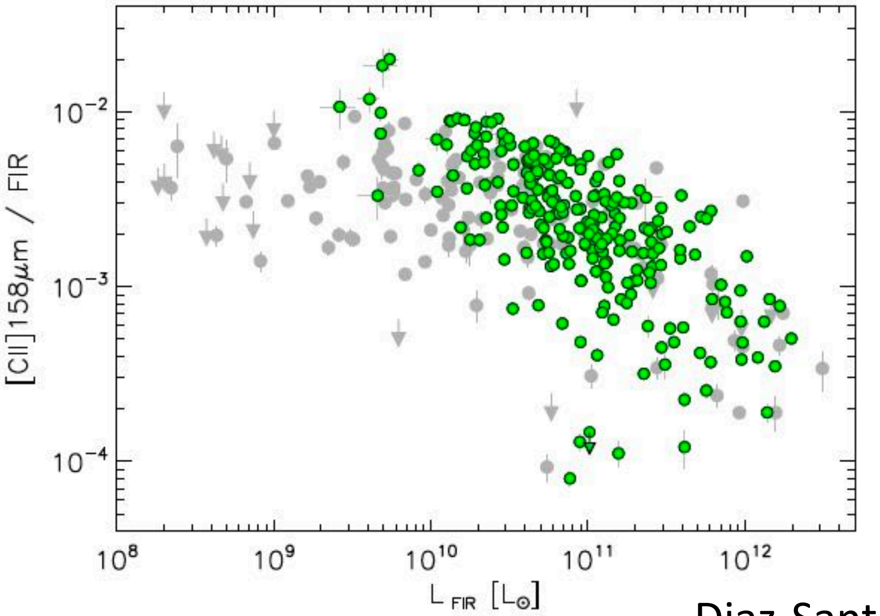
Transition	n_c(H_2) (cm^{-3})	n_c(H) (cm^{-3})
145	5.8×10^6	2.0×10^5
63	5.0×10^5	7.8×10^5

[OI] 63 µm as Tracer of Star Formation Rate

- Generally does a reasonably good job for “normal” galaxies but 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”?

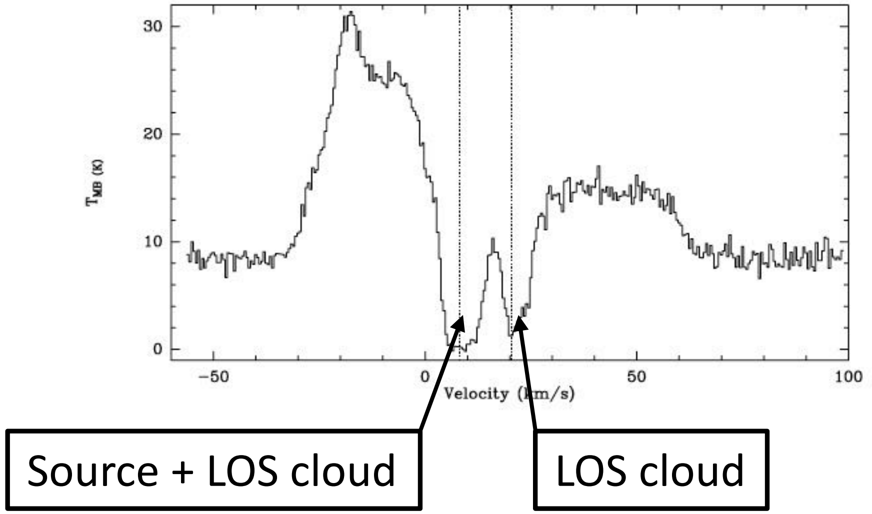


Diaz-Santos+ (2017)



Diaz-Santos+ (2013)

Hints of Problem with [OI] 63 µm Line

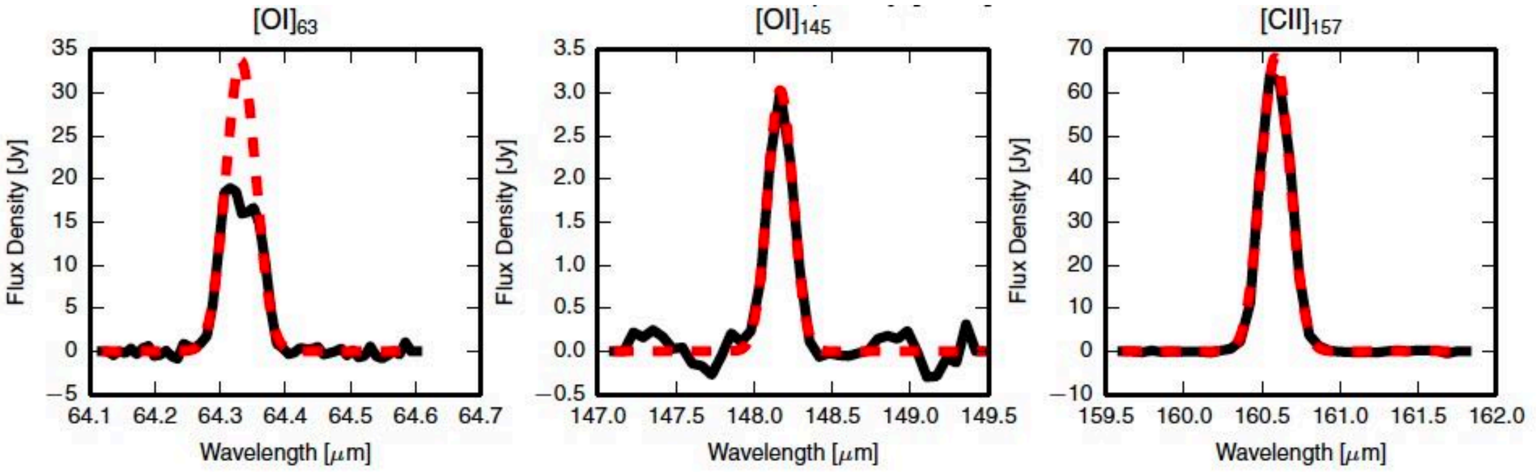


Source + LOS cloud

LOS cloud

Galactic Star-forming Region
G5.89-0.39
D = 1.28 kpc
Powered by single O-star
Massive outflows

Leurini+ (2015)



Galaxy NGC 7552 – Rosenberg+ (2015)

Strong suggestion of significant self-absorption!

Velocity-Resolved Spectroscopy of [OI] with (SOFIA/upGREAT) Confirmed Clear Evidence of Absorption by Low-Excitation O^o

Risacher 2018

Where is it located?
How common is it?
What is impact on PDR energetics?

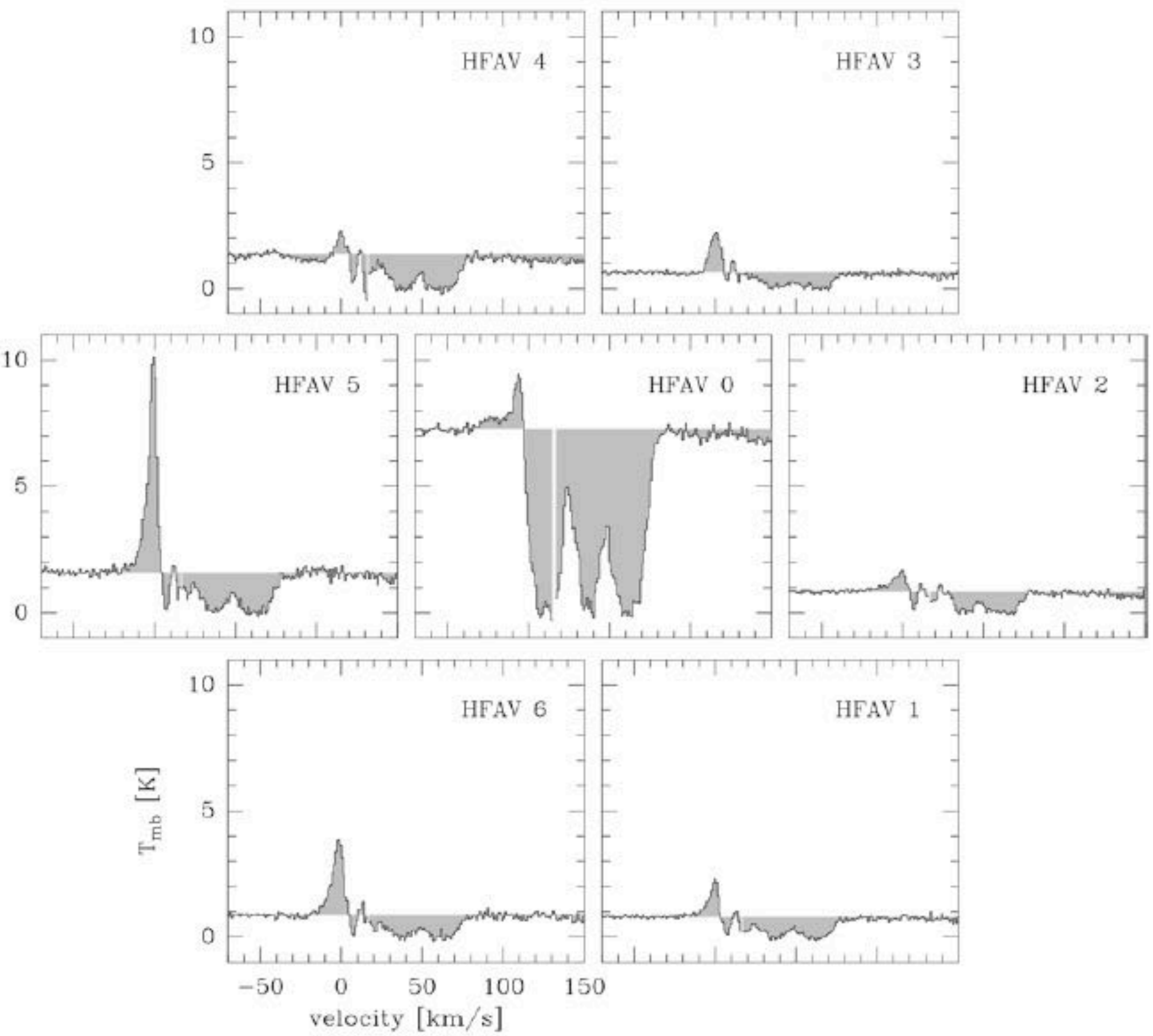
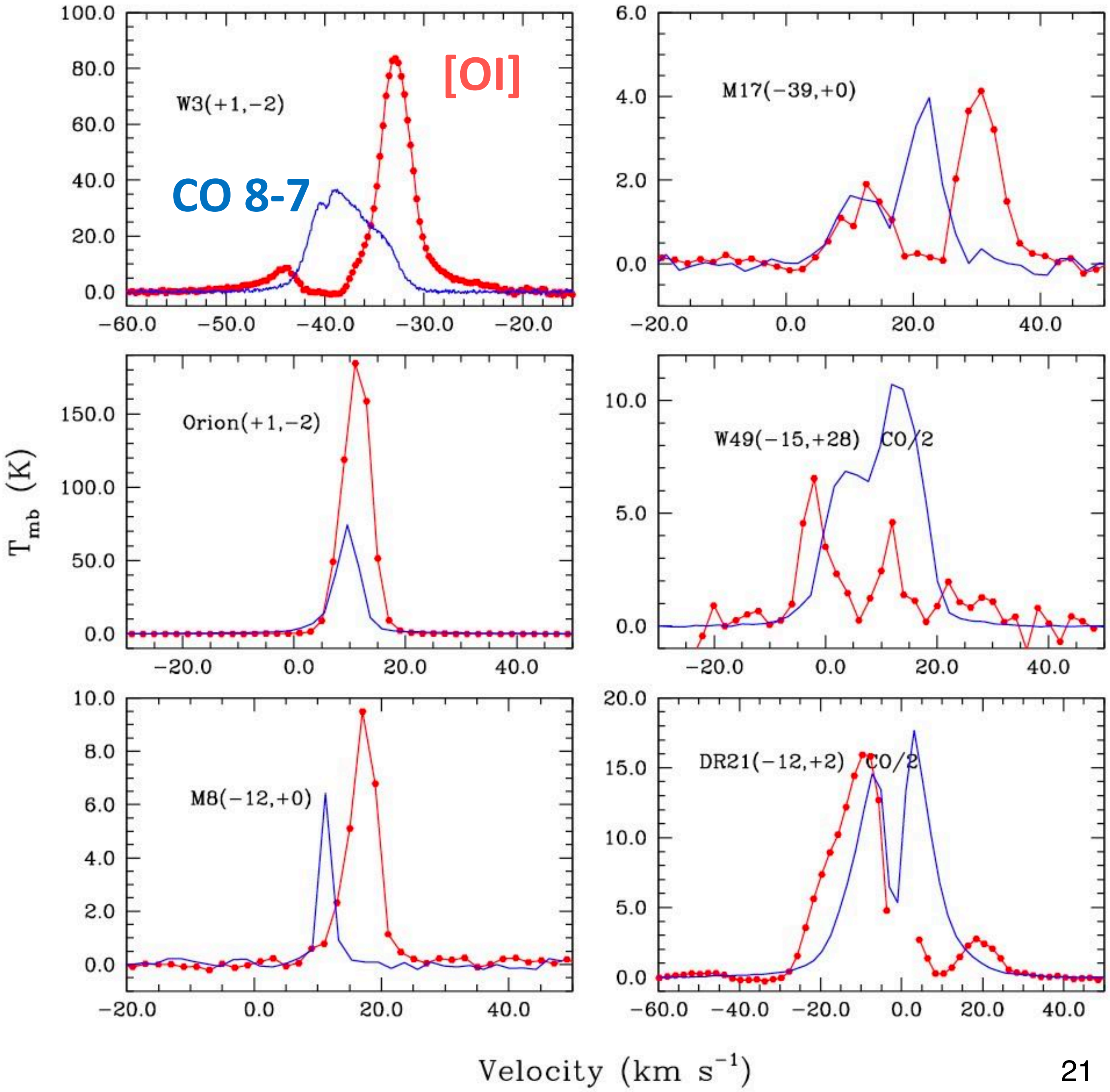


Fig. 17. OI 63 μm spectra observed with the upGREAT/HFA towards the high-mass star forming core W49N, showing emission and strong absorption along the line-of-sight towards the prominent dust continuum emission of the source. The data was acquired on SOFIA flight 420 out of Christchurch, New Zealand, on July 15, 2017, during a 1.2 h flight leg at an altitude of 43 kft. Observations were performed in double-beam chopped mode, wobbling the subreflector at 2.5 Hz with a throw of 180″. No baseline was removed, the spectra were box-smoothed to a spectral resolution of 1 km/s.

Survey of Massive Star-Forming Regions with SOFIA/upGREAT (Goldsmith+ 2021)

- [OI] 63µm observed in 12 regions
- Good detections – widely varying line intensities
- 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



Geometry, Statistics, and Impact of [OI] Absorption by Low-Excitation Foreground O^o

- Observational occurrence depends on geometry – not seen when PDR on Earth-facing side of cloud (Orion) ⇒ should appear in ~50% of randomly selected sources
- This is the fraction of the (12) sources in our initial survey found to have clear foreground absorption.
- While we may call this foreground absorption, we mean absorption by low-excitation gas associated with the source (defined by velocity, line width, etc.)
- 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”

SOFIA Observations of [OI] 63 µm in W3

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

Radio continuum; FIR; CO

M = 4×10^5 M_{sun}

L = 5×10^5 L_{sun}

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

W3 IRS5 is center of stellar activity

Goldsmith+ (2021)

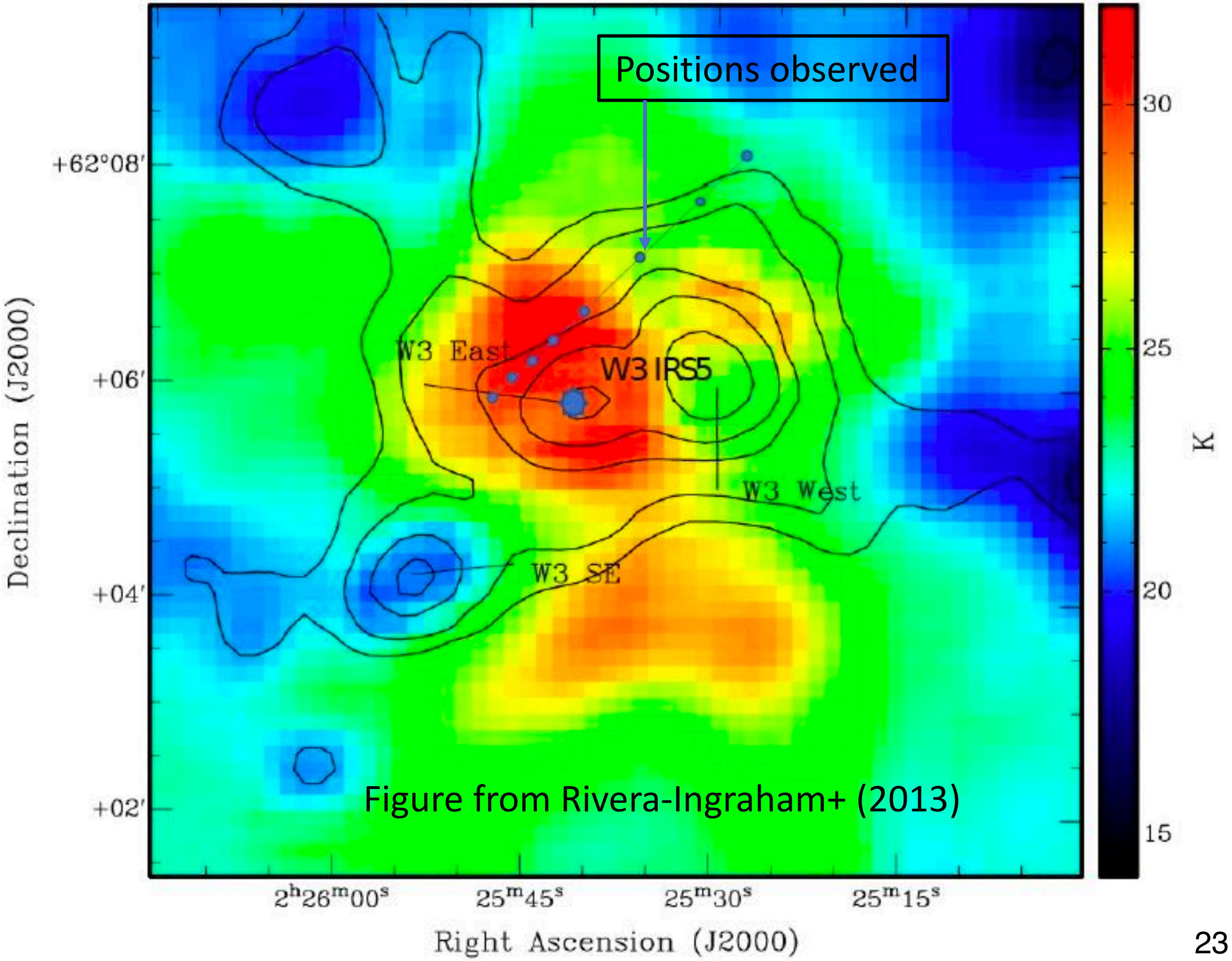
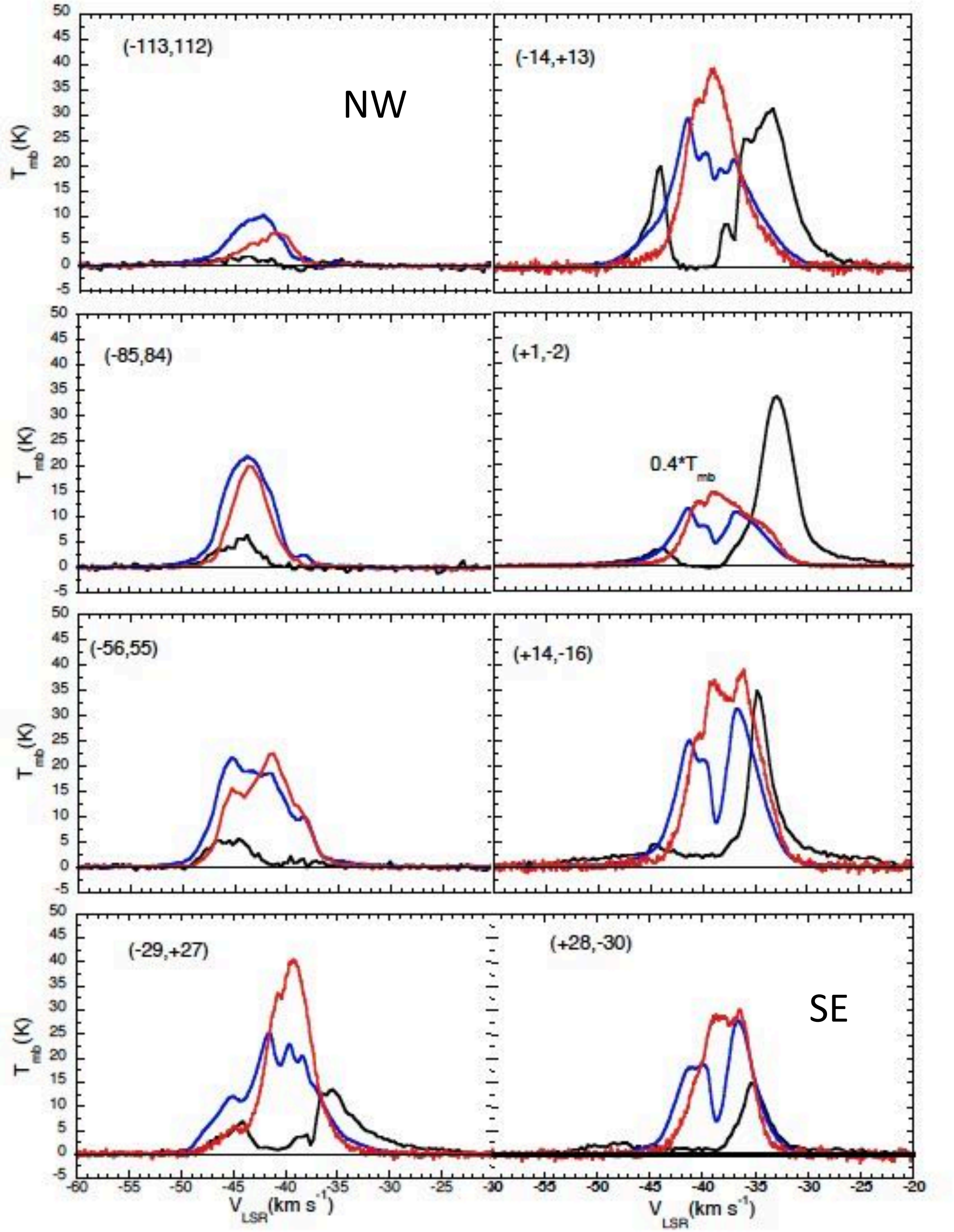


Figure from Rivera-Ingraham+ (2013)

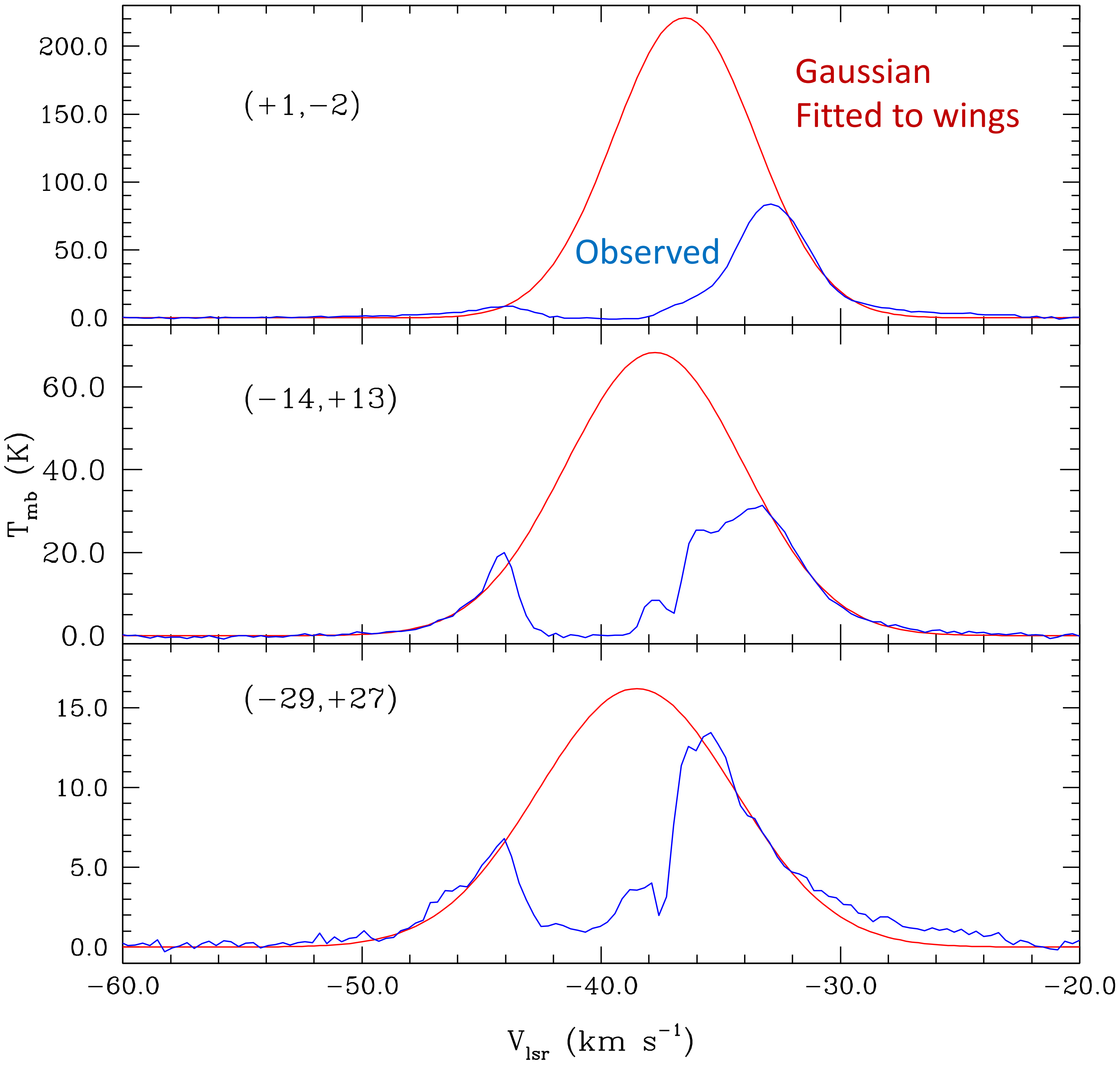
[OI] and CO in W3

- 8 positions along NW-SE cut
- **[OI]** and **CO 8-7**, **CO 5-4** shown
- In ALL but extreme NW positions, [OI] is drastically self-absorbed as indicated by line profiles and comparison with CO
- CO 5-4 also self-absorbed in central region



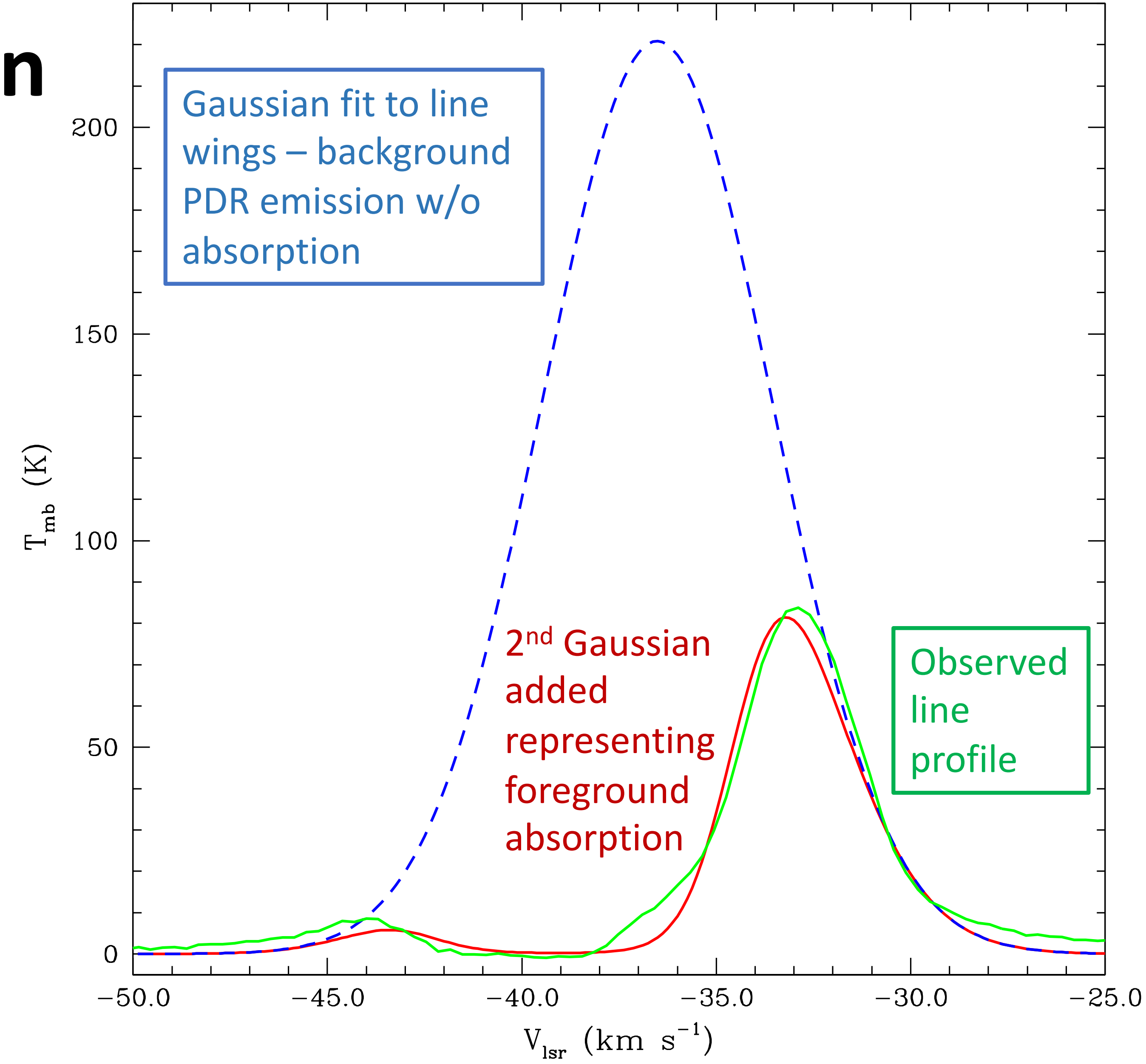
[OI] - Near W3 E

- Line wings 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
- It is all a matter of geometry!



Modeling Absorption

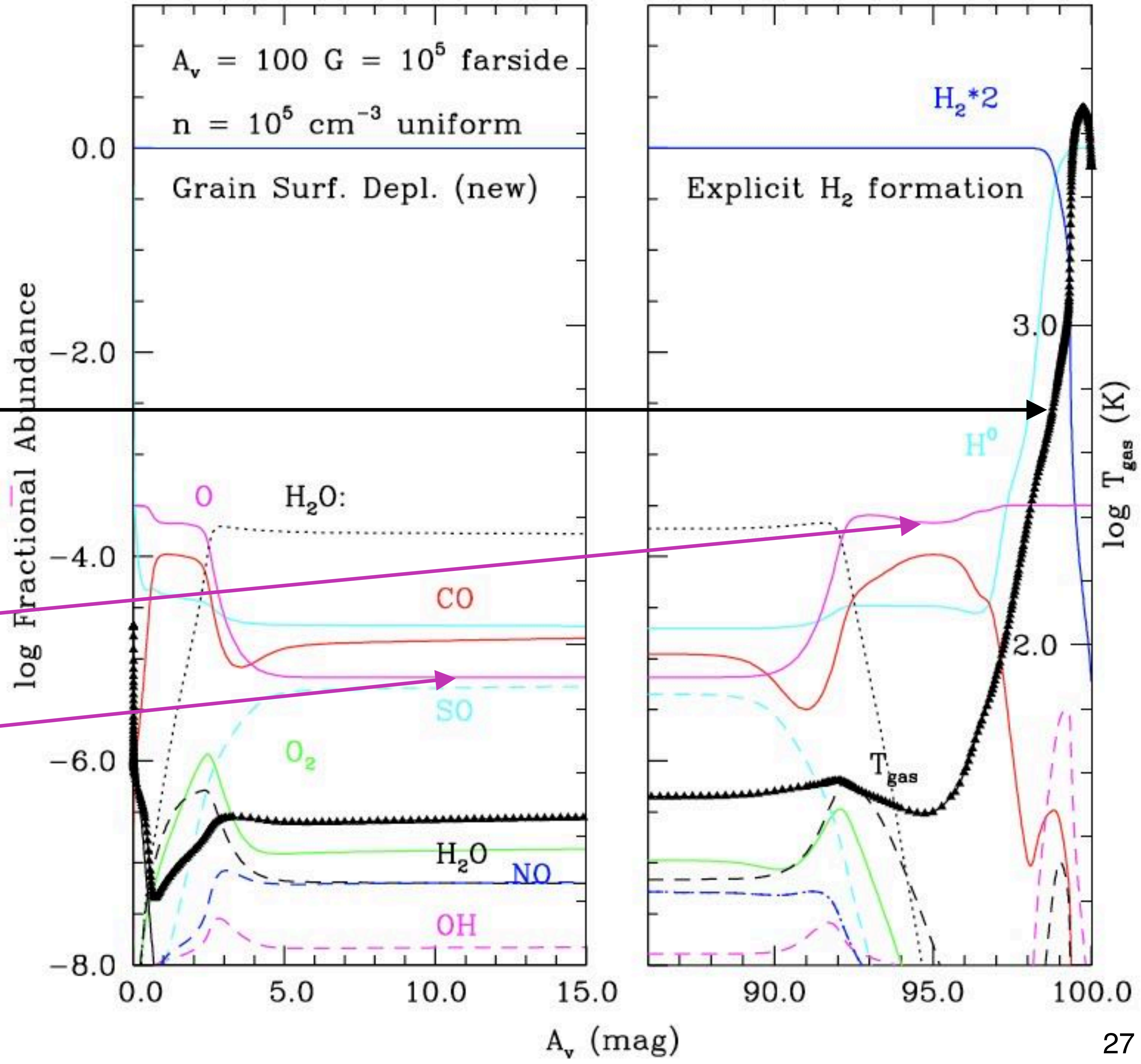
- PDR models suggest gas at ~30K which has effectively no emission
- A second Gaussian representing pure absorption fits observed line profile well
- Peak absorption optical depth $\tau_{pk} = 7.8$
- Velocity shift = -2 km/s
- N(low-excitation O^0) consistent with PDR models



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(low-excitation O^0) ~ few x 10^{18} cm^{-2}
- ⇒ 63 µm line optically thick

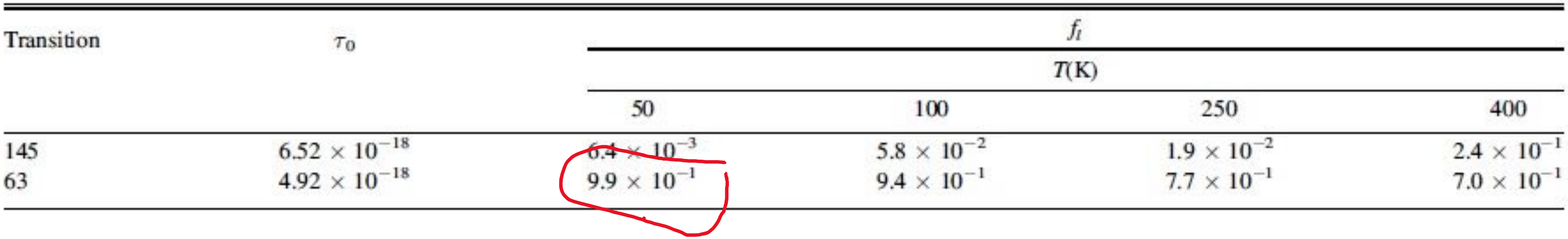


Optical Depth of [OI]

For low –excitation ($N_u << N_l$)

$$\tau = \tau_0 \frac{f_l\, N(/cm^2)}{\delta v(km/s)}$$

τ decreases only moderately even for very high Densities (e.g. LTE) if T < 100 K.



Transition	τ_0	f_l			
		T(K)			
		50	100	250	400
145	6.52×10^{-18}	6.4×10^{-3}	5.8×10^{-2}	1.9×10^{-2}	2.4×10^{-1}
63	4.92×10^{-18}	9.9×10^{-1}	9.4×10^{-1}	7.7×10^{-1}	7.0×10^{-1}

For T < 100 K, essentially ALL O^o is in the $^3P_2$ (ground) state

Since δv ~ few km s^{-1}, **$N(O^o) = 1 \times 10^{18}$ cm^{-2}** is the boundary of optically thick 63 μm [OI]

τ([OI] 145 μm) is a factor of a few to ~100 lower than τ([OI] 63 μm). Foreground absorbing gas is in physically cold regions and likely subthermal, so [OI] 145 μm is almost certainly optically thin

Foreground [OI] Absorption in W3

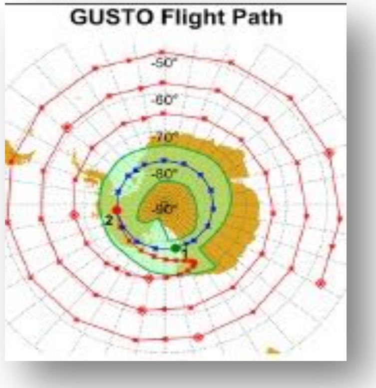
- Peak optical depths τ > 2 derived for entire central region with relatively strong observed emission
- Total emission at different positions **reduced by factors 2 – 4** compared to values expected from fitted background Gaussians
- Implication is that we may be **underestimating the [OI] luminosity** by a significant factor
- The most direct way to confirm/correct is to observe the 146 µm line
- Prediction: in sources with strong foreground absorption, the 145 μm [OI] line will be much stronger than expect from ratio derived from “PDR model” and 63 μm antenna temperature

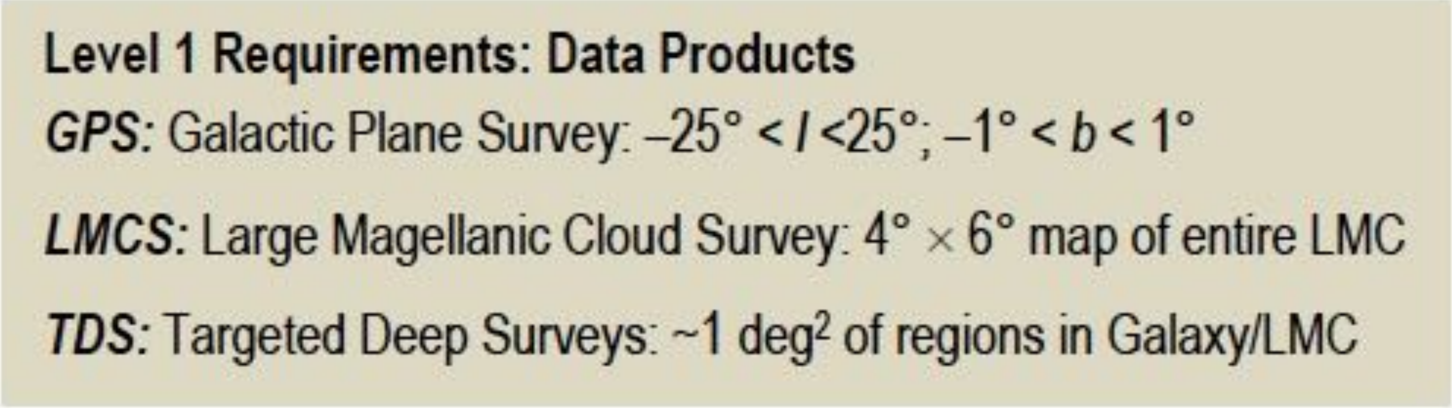
Observational Capabilities

- Currently upGREAT instrument on SOFIA has multipixel capability for [CII] 158 µm and [OI] 63 µm. No capability for [NII] 122 µm and single-pixel capability for [NII] 205 µm and [OI] 146 µm
- Fine structure line capability will be enhanced if HIRMES instrument is completed or if a large-format heterodyne FIR line mapper is flown on SOFIA
- Origins Flagship mission will certainly have enormous sensitivity, but high velocity resolution only if HERO instrument upscope is included
- A FIR Probe mission might have capability for velocity-resolved observations of both [OI] lines ONLY if the community makes this need clear
- There are two balloon missions focusing on fine structure line emissions are currently under development: GUSTO and ASTHROS

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, [CII] 158 µm, and [OI 63 µm
- **Long Duration Balloon** offers ~ **70** day lifetime, but payload recovery is not certain





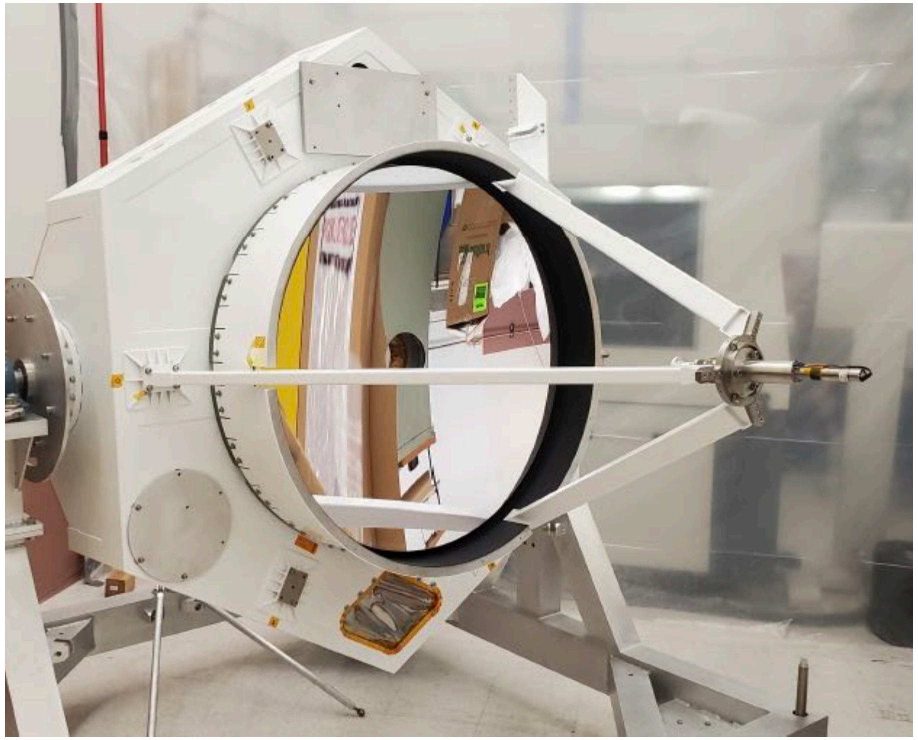
Level 1 Requirements: Data Products

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 – Launch Dec. 2022



GUSTO Telescope

90 cm symmetric Cassegrain telescope

- Glass primary reflector
- Diamond turned aluminum secondary reflector

Status:

- Assembly completed
- Surface accuracy verified
- Final alignment underway at U of A Mirror Laboratory

Shortest GUSTO wavelength is 63 μm so required accuracy is ~2 μm, far larger than measured. Will be enclosed in “trash can” style sunshield

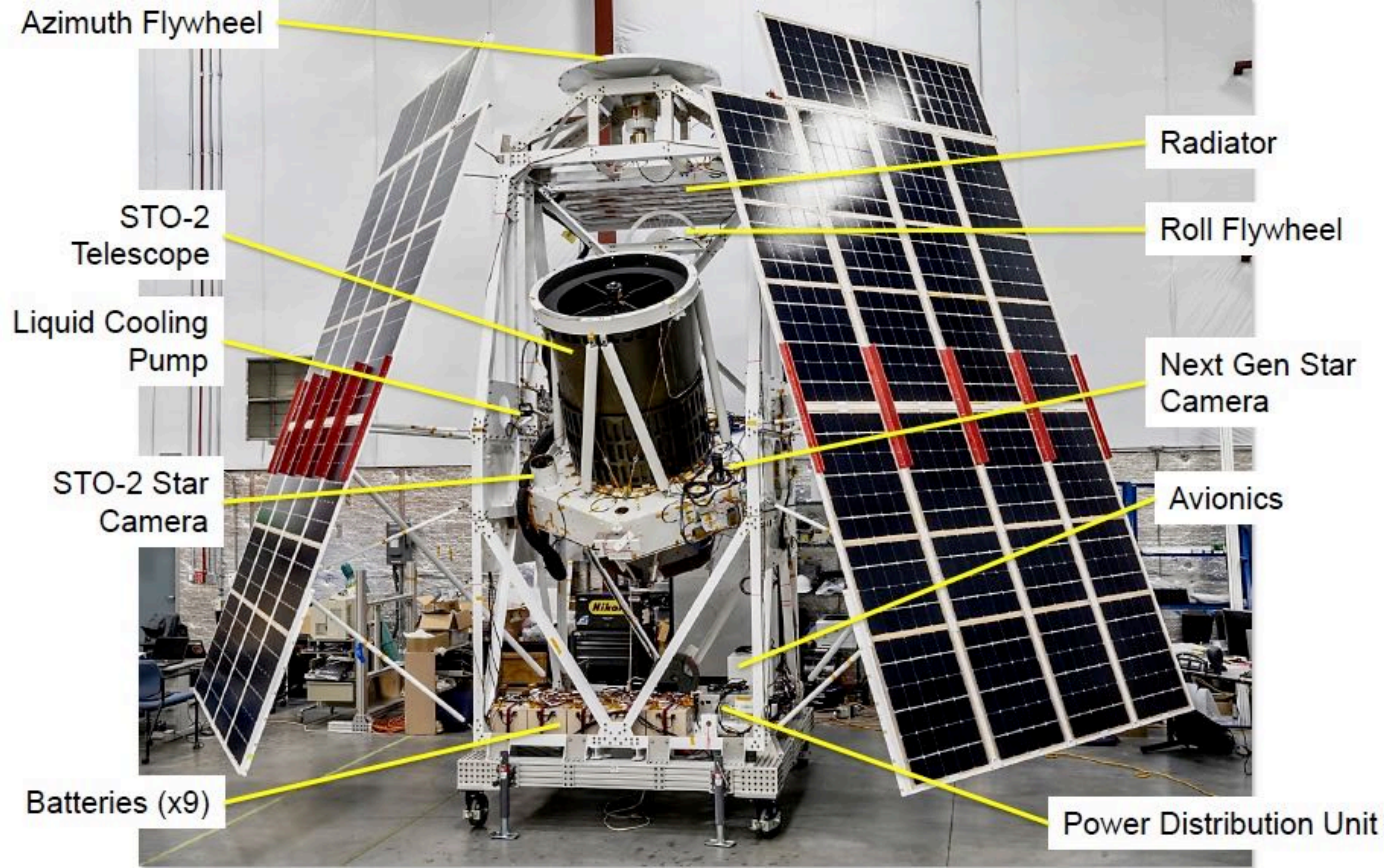
Gusto Gondola (JHU/APL)

Follows design of successful STO2 gondola, but with

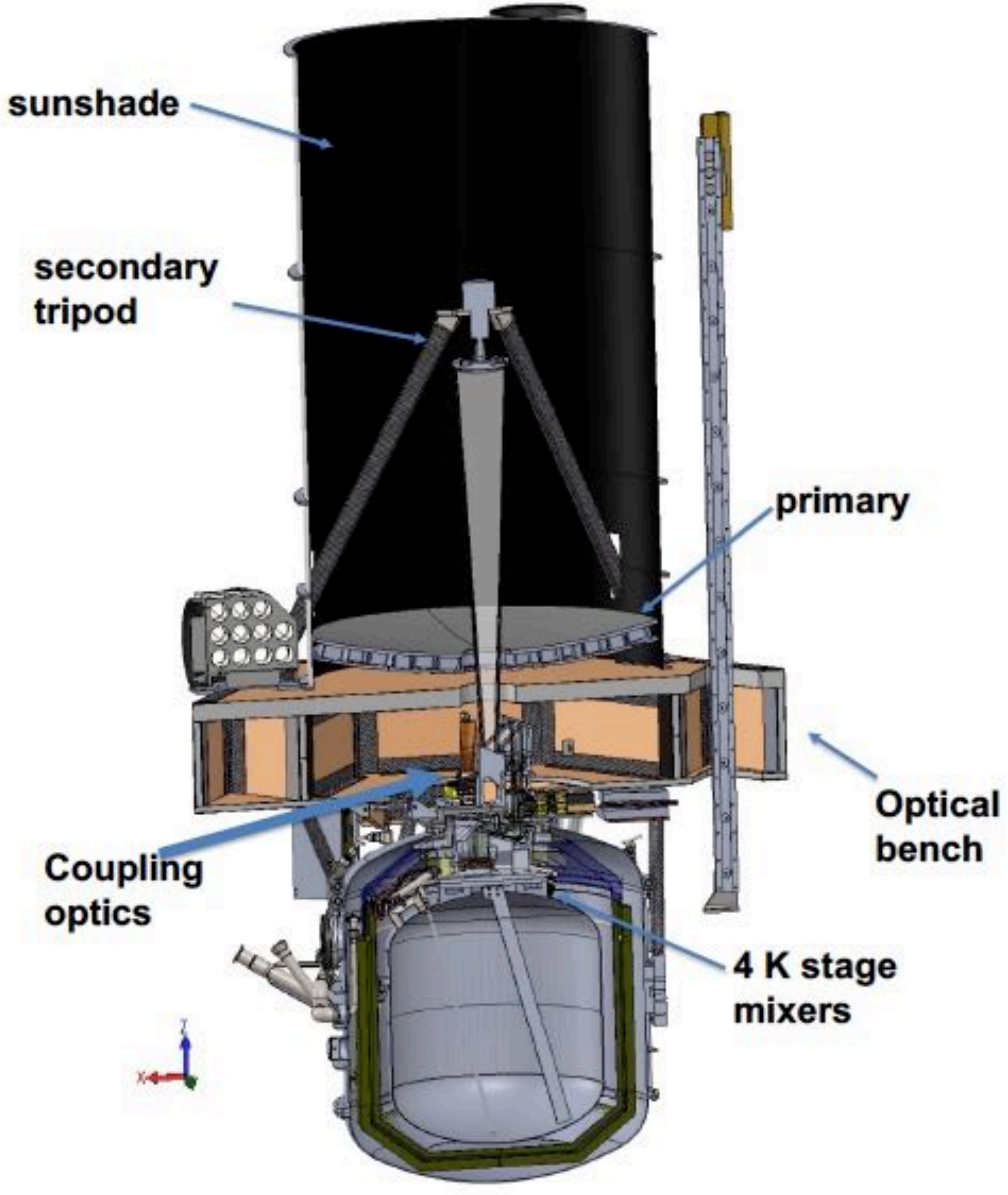
- Improved star trackers
- More capable liquid cooling loop for thermal control of high-dissipation electronics (local oscillators, digital spectrometer)

Indoor and outdoor “hang tests” completed at APL using STO2 telescope with gondola suspended from crane

- Test/Exercise both star cameras
- Verify Pointing Accuracy
- Calibrate IMU bias drift
- Verify capability to point at and track Planets
- Verify capability to point at, track, and do region pointing on Moon


Azimuth Flywheel
STO-2 Telescope
Liquid Cooling Pump
STO-2 Star Camera
Batteries (x9)
Radiator
Roll Flywheel
Next Gen Star Camera
Avionics
Power Distribution Unit

GUSTO OPTICS



Telescope Optical Design	
Focal Ratio	10.4
Focal Length	9350 mm
Primary Diameter	900 mm
Field of View	0.07° x 0.07°
Total track	2400 mm

Materials	
Primary	Lightweight Borosilicate on Titanium flexures
Secondary	Diamond turned Aluminum
Optical Bench & Tripod	CFRP
Sunshade	Aluminum white exterior Black interior
Coupling optics	Diamond milled off-axis mirrors

GUSTO Receivers

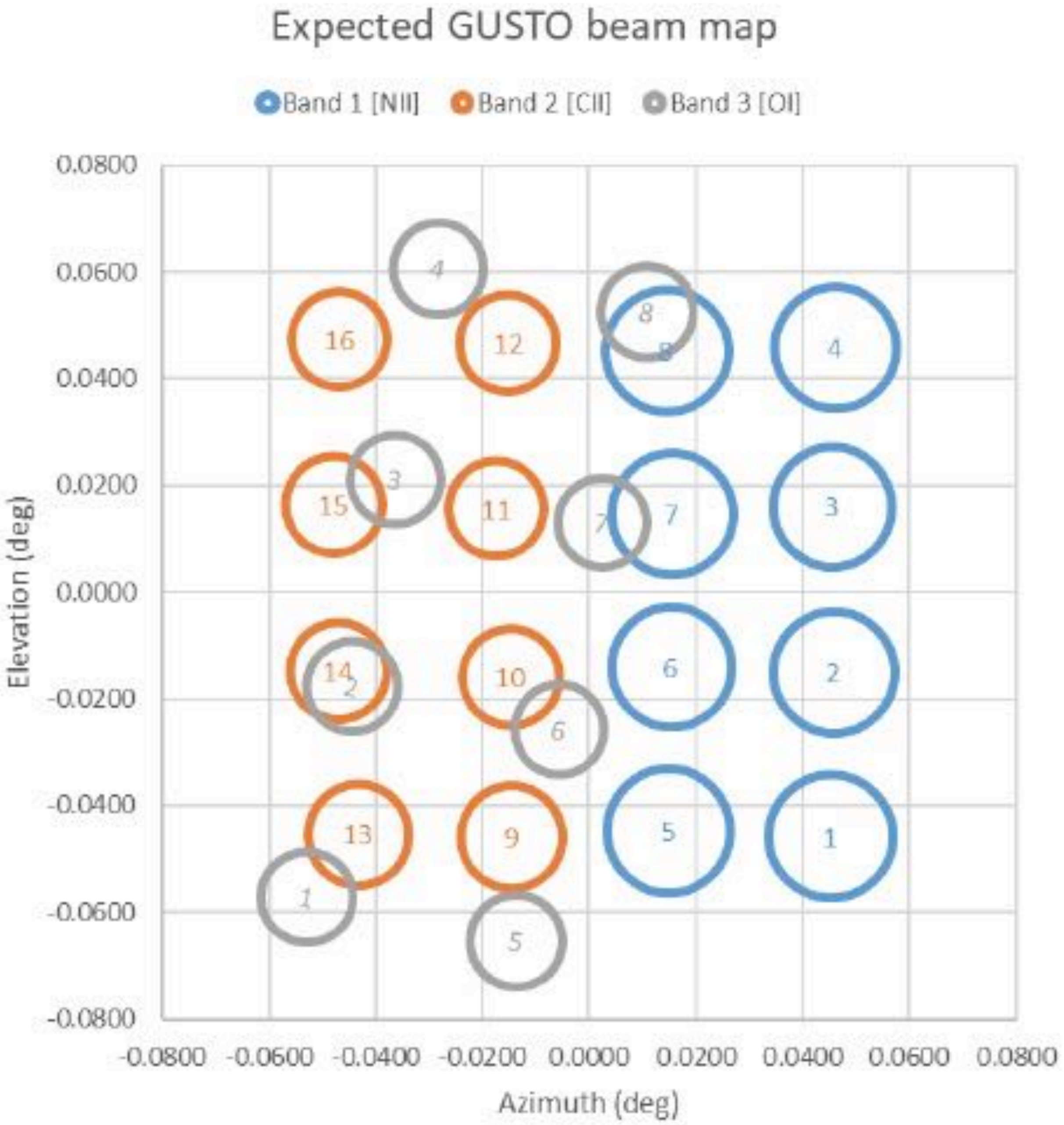
24 Heterodyne receivers in 3 bands with 8 pixels each

B1	1.4 THz	[NII] 205 μm	$\Delta\theta$ = 55”
B2	1.9 THz	[CII] 158 μm	$\Delta\theta$ = 42”
B3	2.7 THz	[OI] 63 μm	$\Delta\theta$ = 37”

All employ spiral antennas and HEB mixer elements

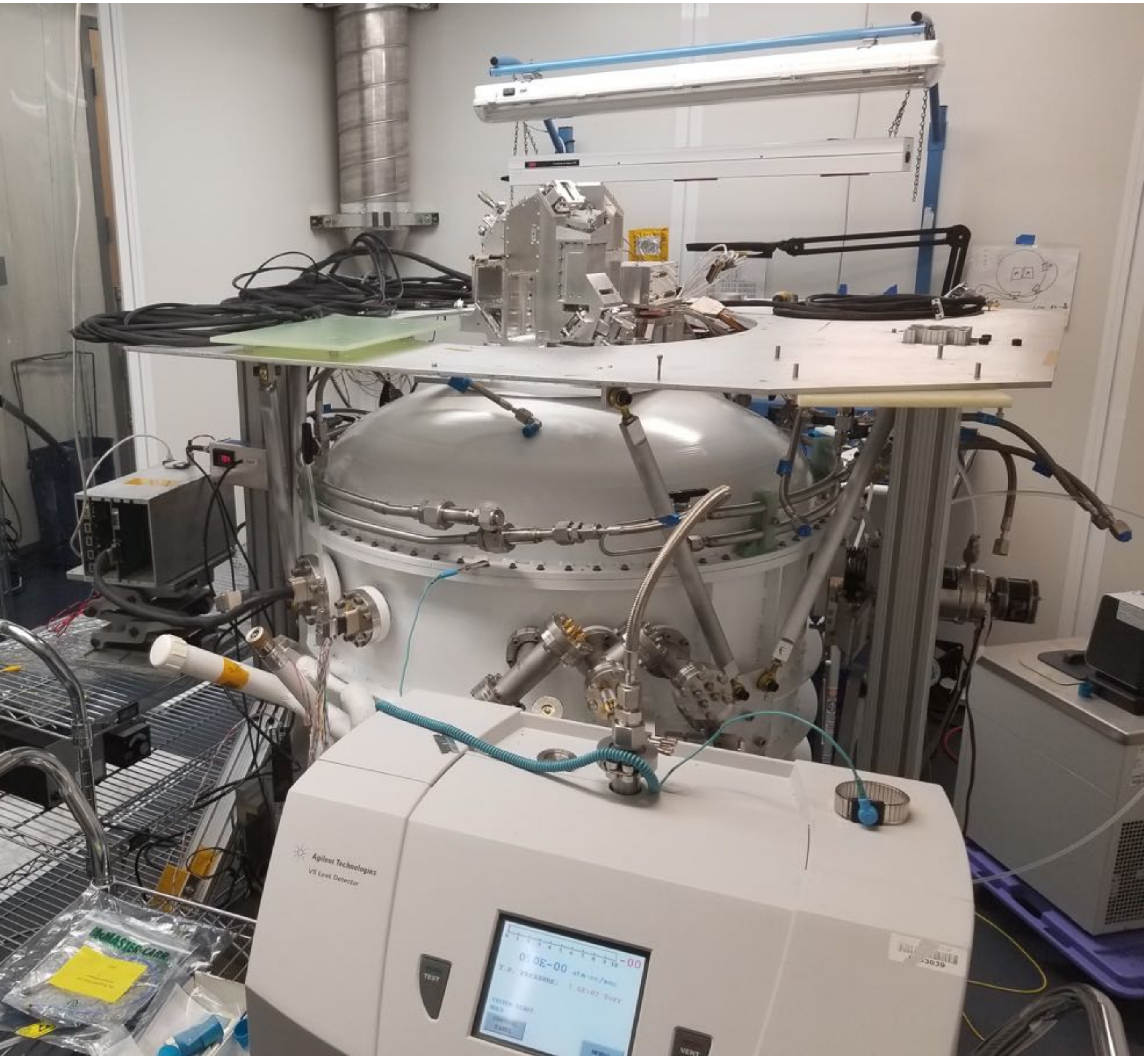
B1 and B2 local oscillators are frequency-multiplied microwave sources

B3 local oscillator is frequency-locked quantum cascade laser (QCL)



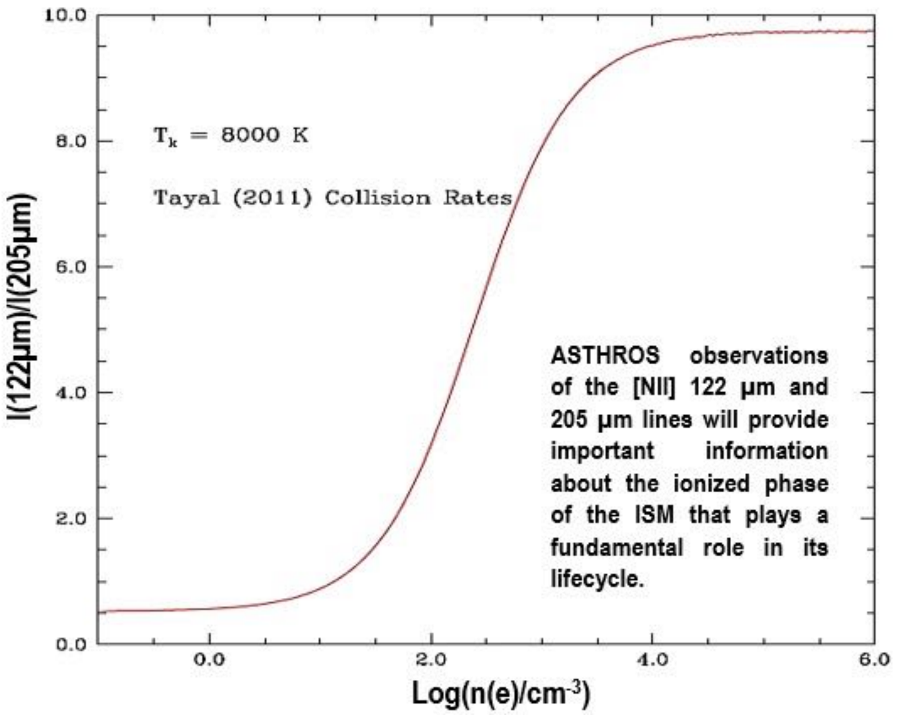
GUSTO Dewar

Cold, 24 mixers in focal plane
Waiting for addition of external LO box and optics for receiver testing to start



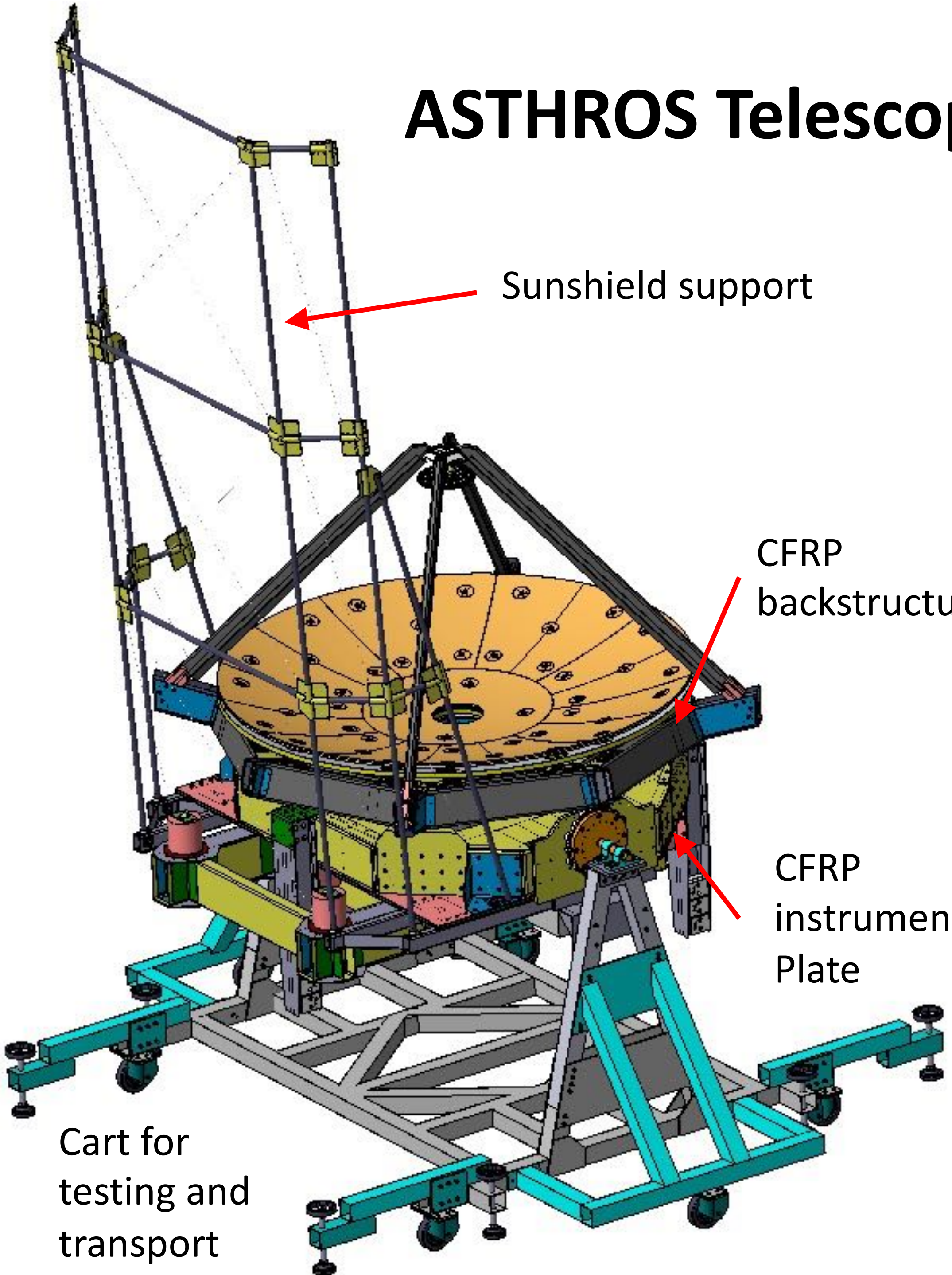
ASTHROS **A**strophysics **S**tratospheric **T**elescope for **H**igh-**R**esolution **O**bservations at **S**ubmillimeter-waves (J. Pineda, PI)

- Antarctic NASA APRA balloon mission
- 205 μm and 122 μm[NII] fine structure lines
- High angular resolution (20" and 12") of ionized gas regions in the Milky Way and M83
- Study the extended, dense WIM (D-WIM) and determine electron densities from line ratio
- Observe 112 μm HD line in a protoplanetary disk
- 21-day flight **Dec. 2023**



ASTHROS observations of the [NII] 122 μm and 205 μm lines will provide important information about the ionized phase of the ISM that plays a fundamental role in its lifecycle.

ASTHROS Telescope



Sunshield support

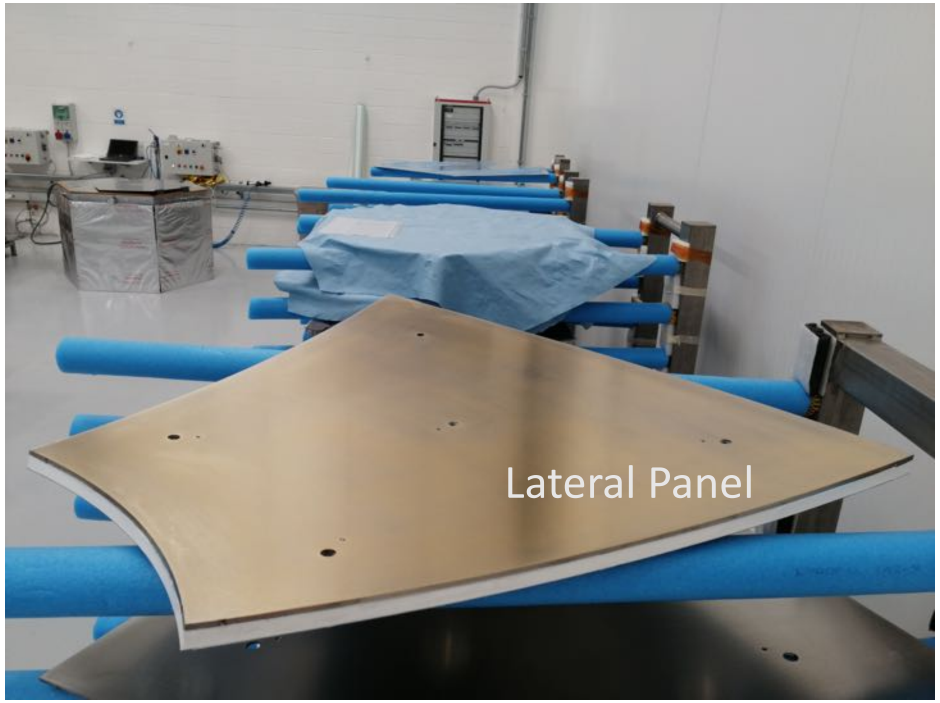
CFRP backstructure

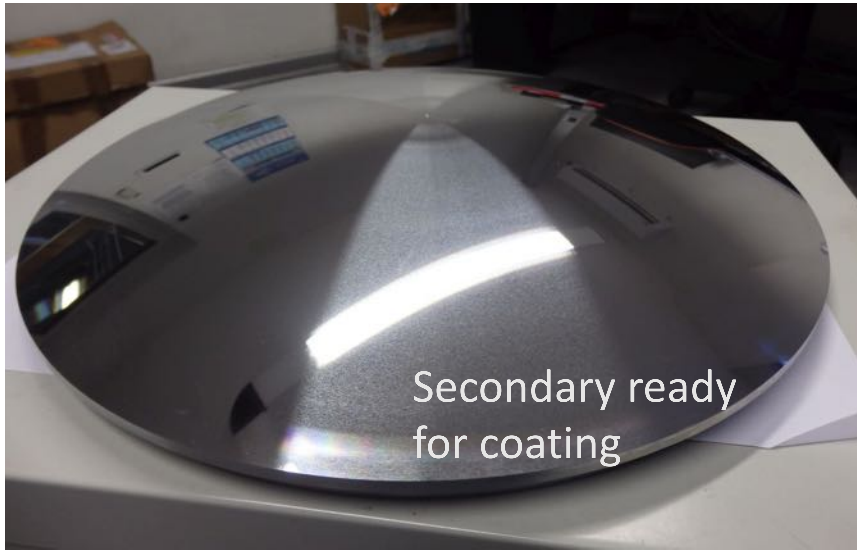
CFRP instrument Plate

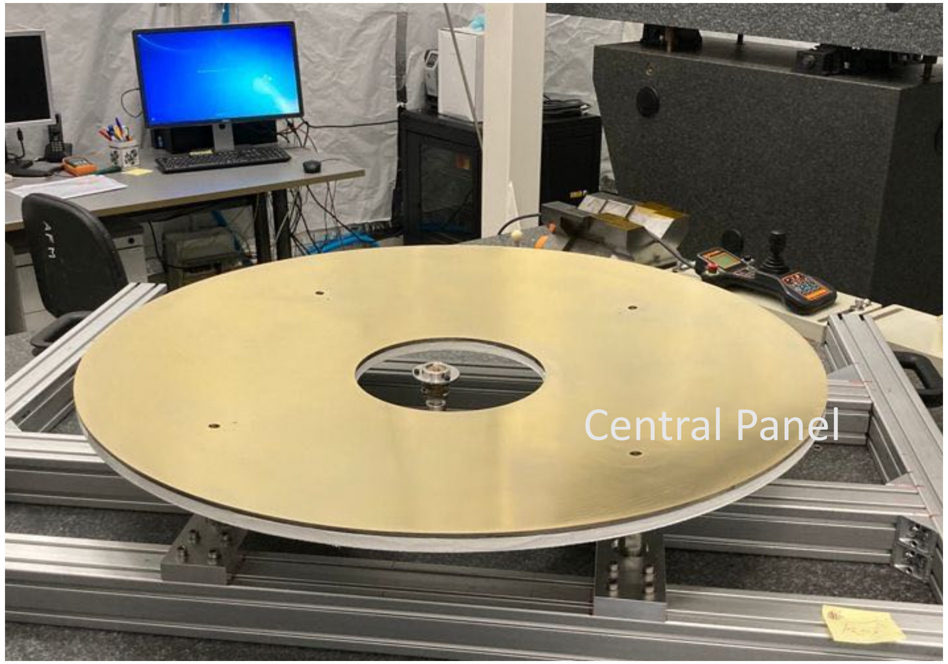
Cart for testing and transport

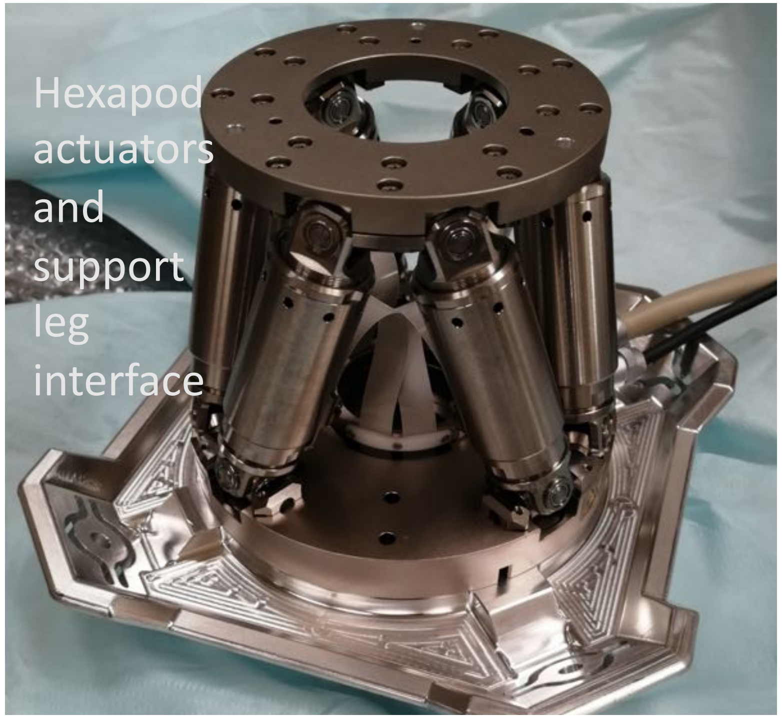
ASTHROS Telescope Elements

Media Lario (Italy)

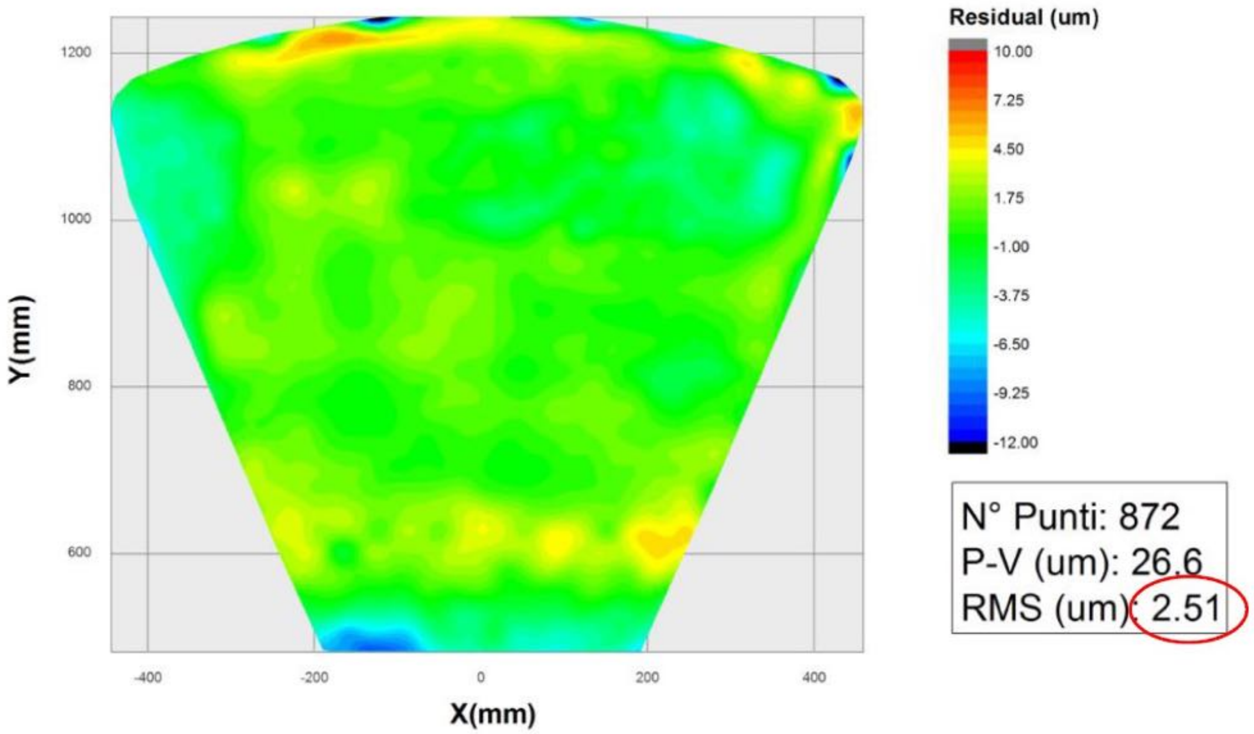




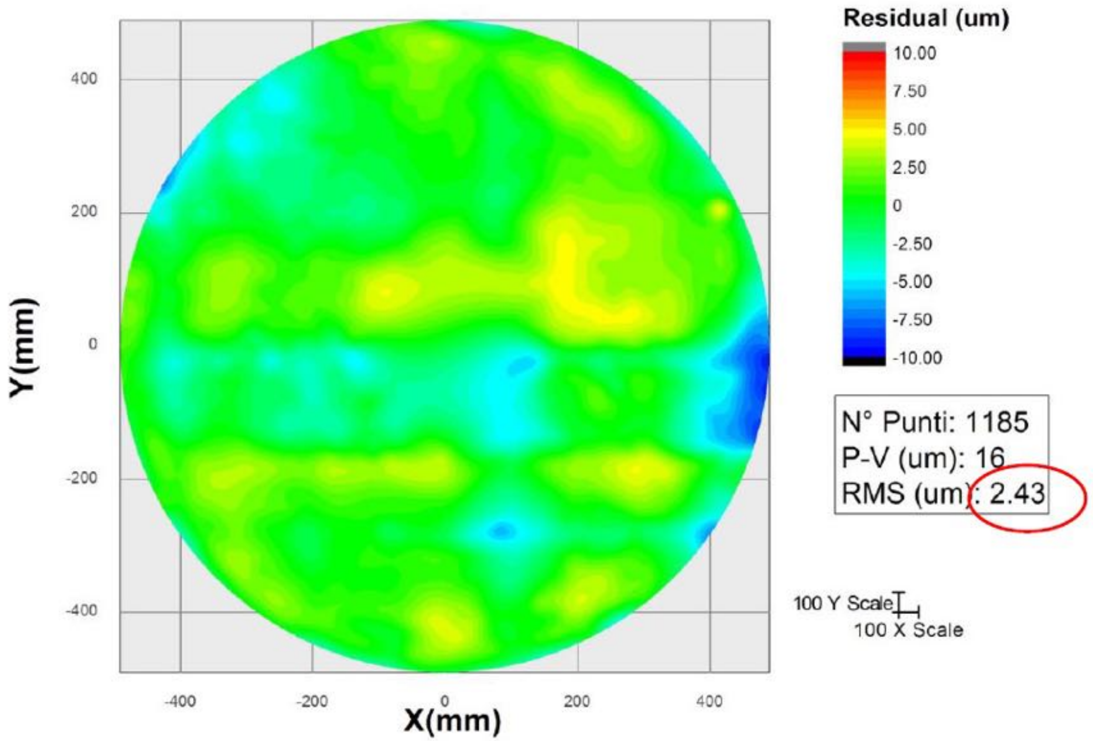




ASTHROS Surface Panel Metrology



N° Punti: 872
P-V (um): 26.6
RMS (um): 2.51



N° Punti: 1185
P-V (um): 16
RMS (um): 2.43

Design target <3micron: **achieved**

ASTHROS Status

- Telescope schedule good –Inspection/Acceptance in Spring 2022
- Dewar being fabricated
- Receivers making good progress
- Digital spectrometer has some issues related to circuit board
- Gondola being fabricated by the JHU/APL team who are doing the GUSTO gondola
- At this point, December 2023 launch appears entirely feasible

Conclusions

- Fine structure lines are powerful tracers of ISM, especially regions mechanically and radiatively affected by massive star formation
- [CII] and [OI] generally trace star formation both in Galactic sources and external galaxies but there are important caveats 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 and optical depths may be significant in large PDRs
    - In [OI], there are extensive regions of low-excitation atomic oxygen that significantly absorb the emission from hot PDR gas adjacent to HII region
- Understanding these issues will require velocity-resolved fine structure line images, which will be produced by SOFIA and upcoming balloon missions