Velocity-Resolved Fine Structure Line Observations and Star Formation:

Some New Results

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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

W49N

Extremely Massive & Luminous Star-Forming Region

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

Smith+ (2009)

Herschel HIFI observations

Gerin+ (2014)

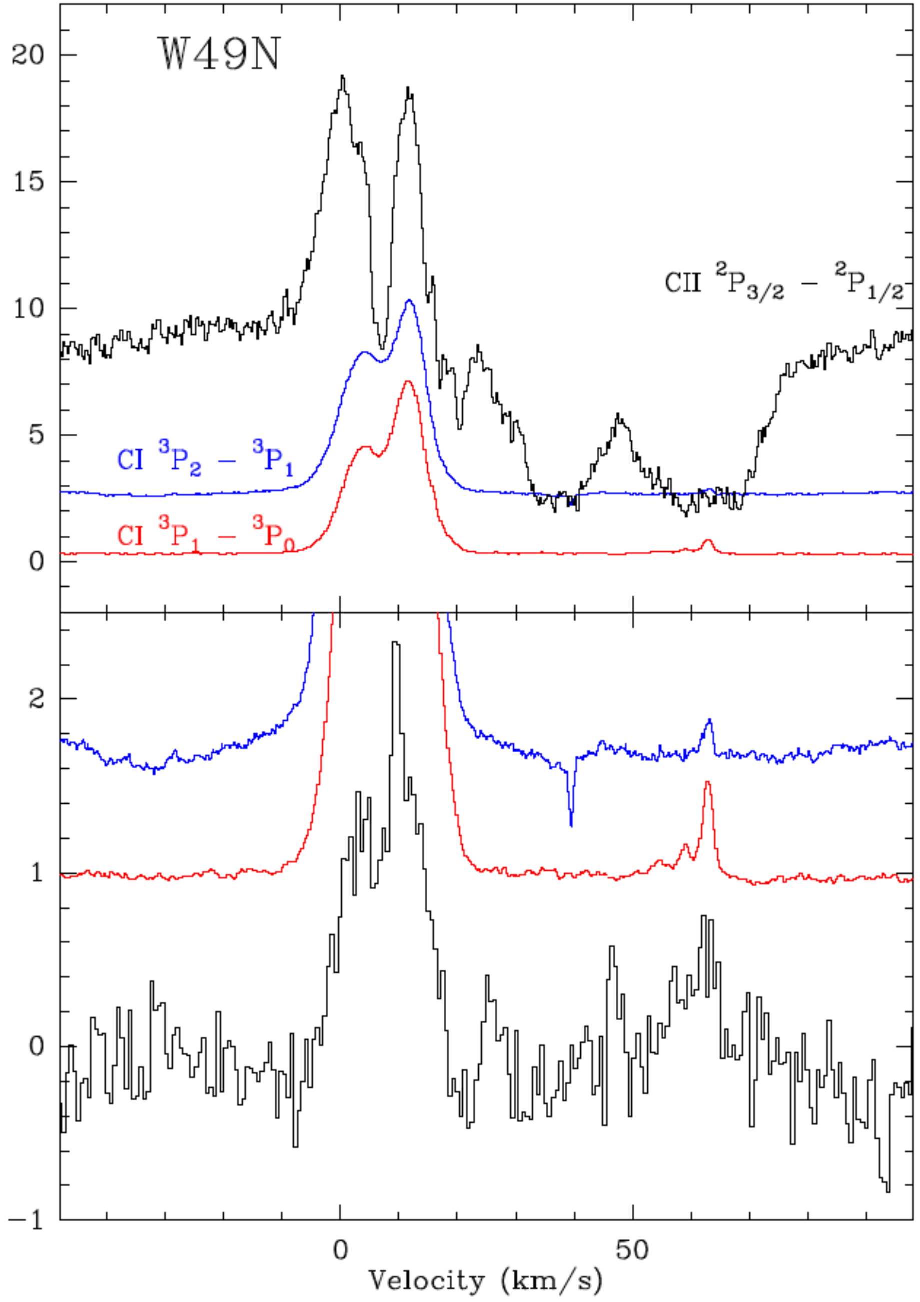
SIGNIFICANT FEATURES

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

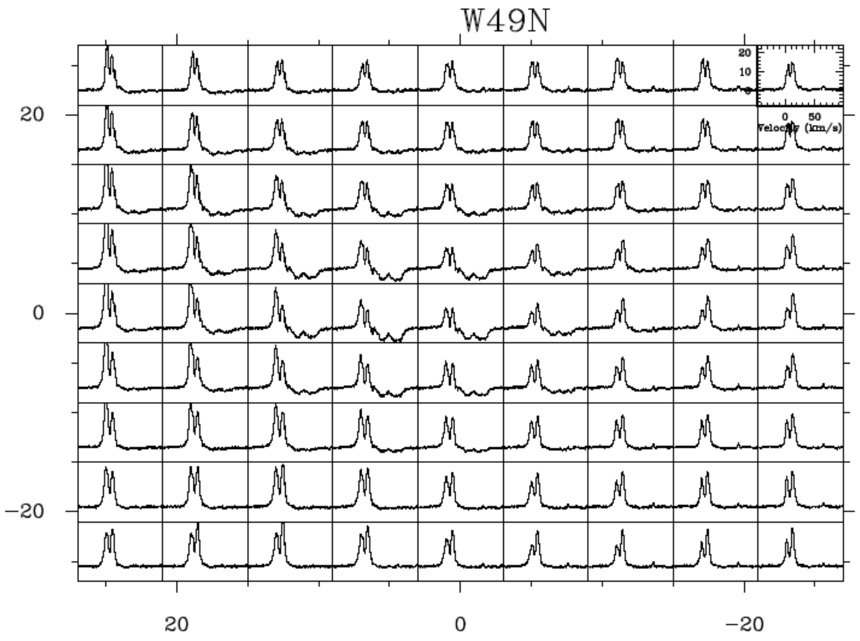
[CI] 809 GHz

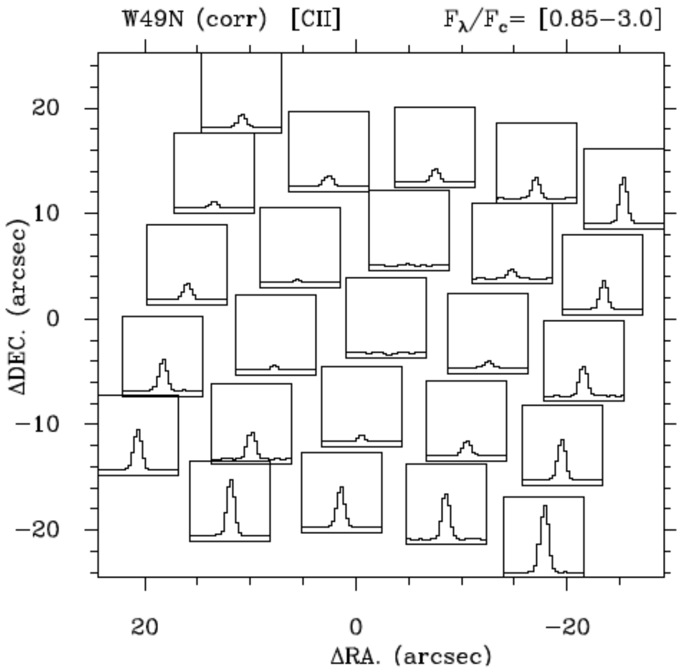
[CI] 492 GHz

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

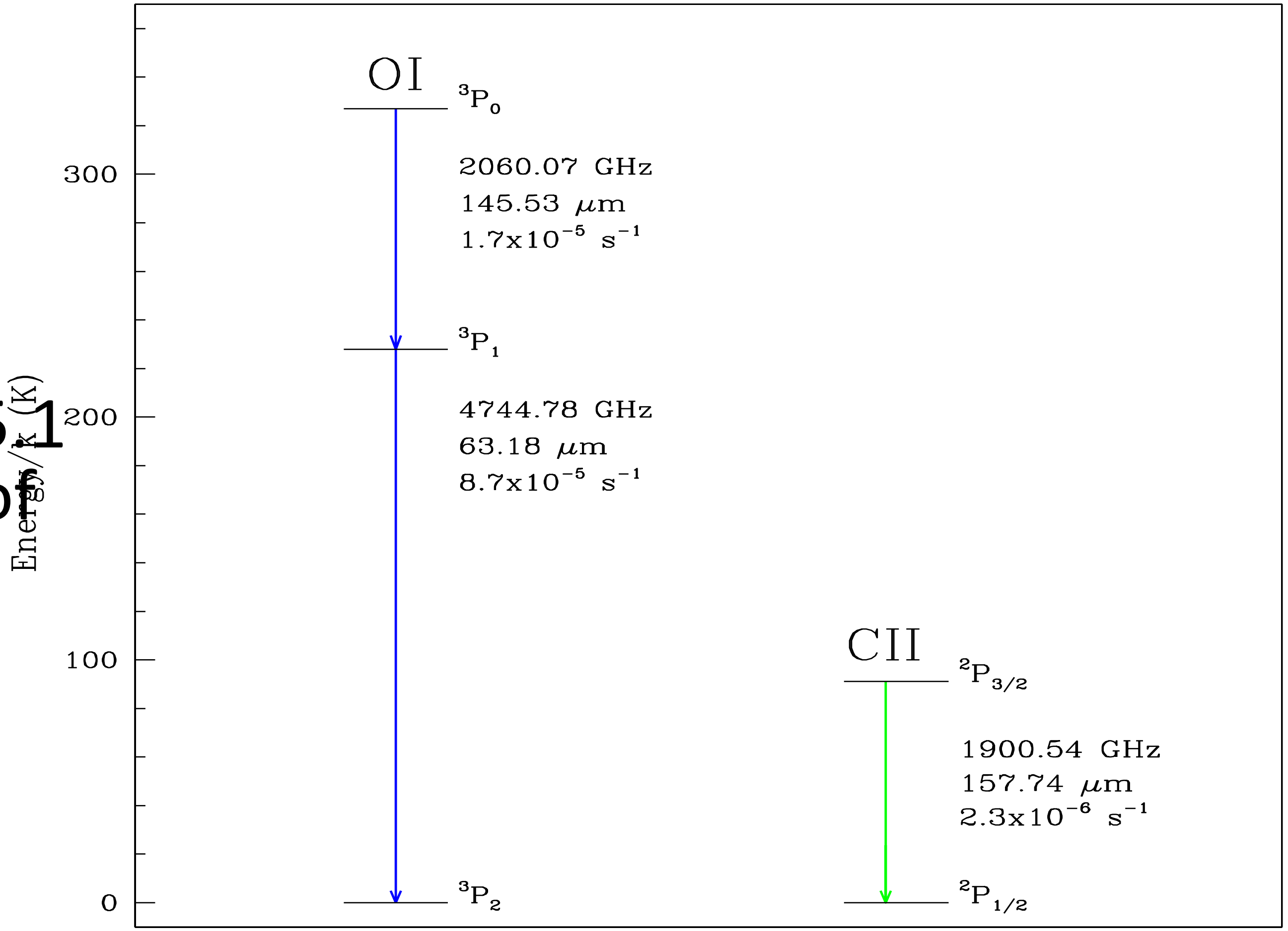
In unresolved data, line/continuum ratio drops dramatically as continuum strengthens
A consequence of equal area of diffuse cloud absorption and true W49 emission

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

Atomic Oxygen (O^0)

- $\{O\}/\{H\} = 5x10^{-4}$
- 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

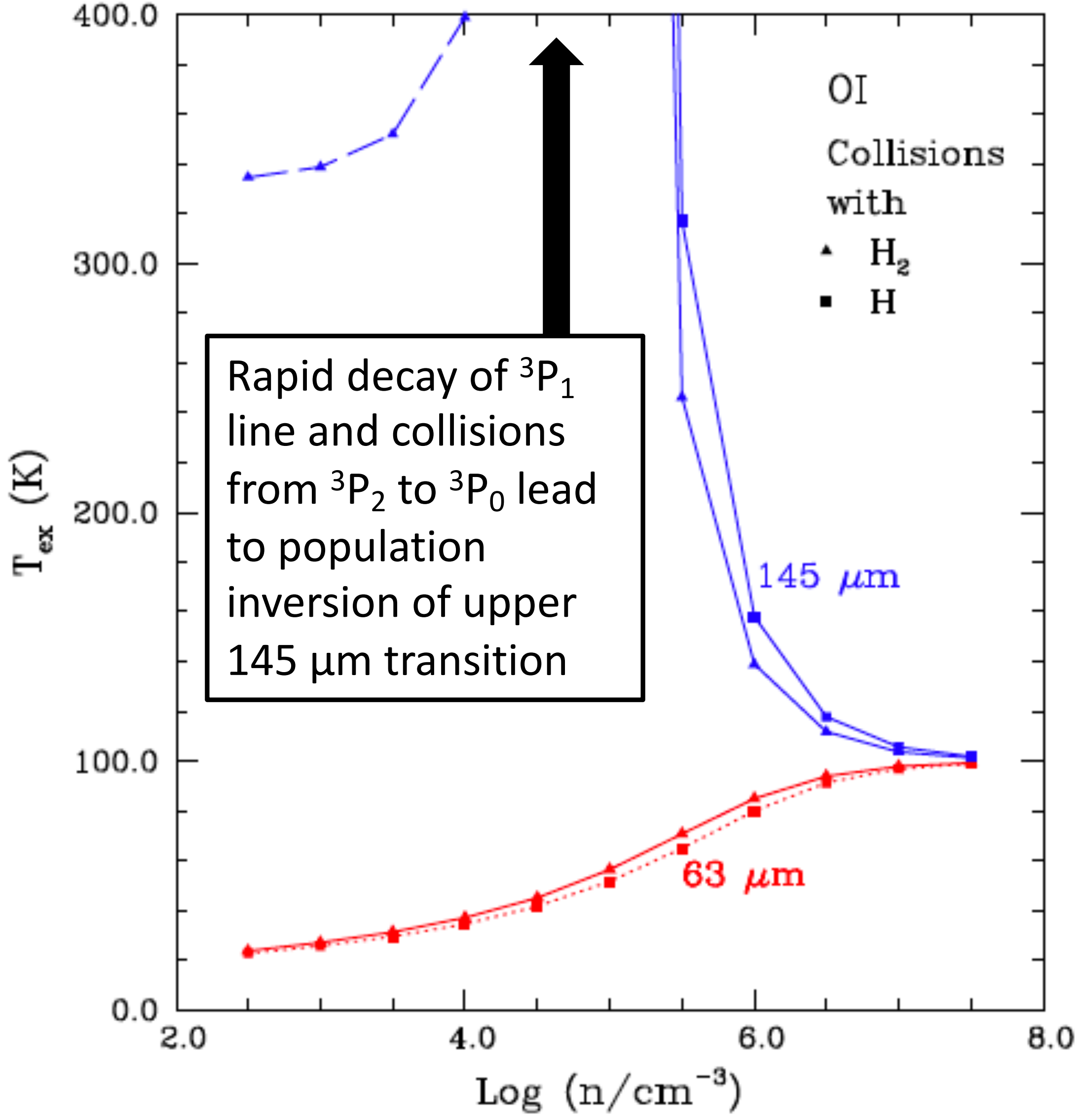


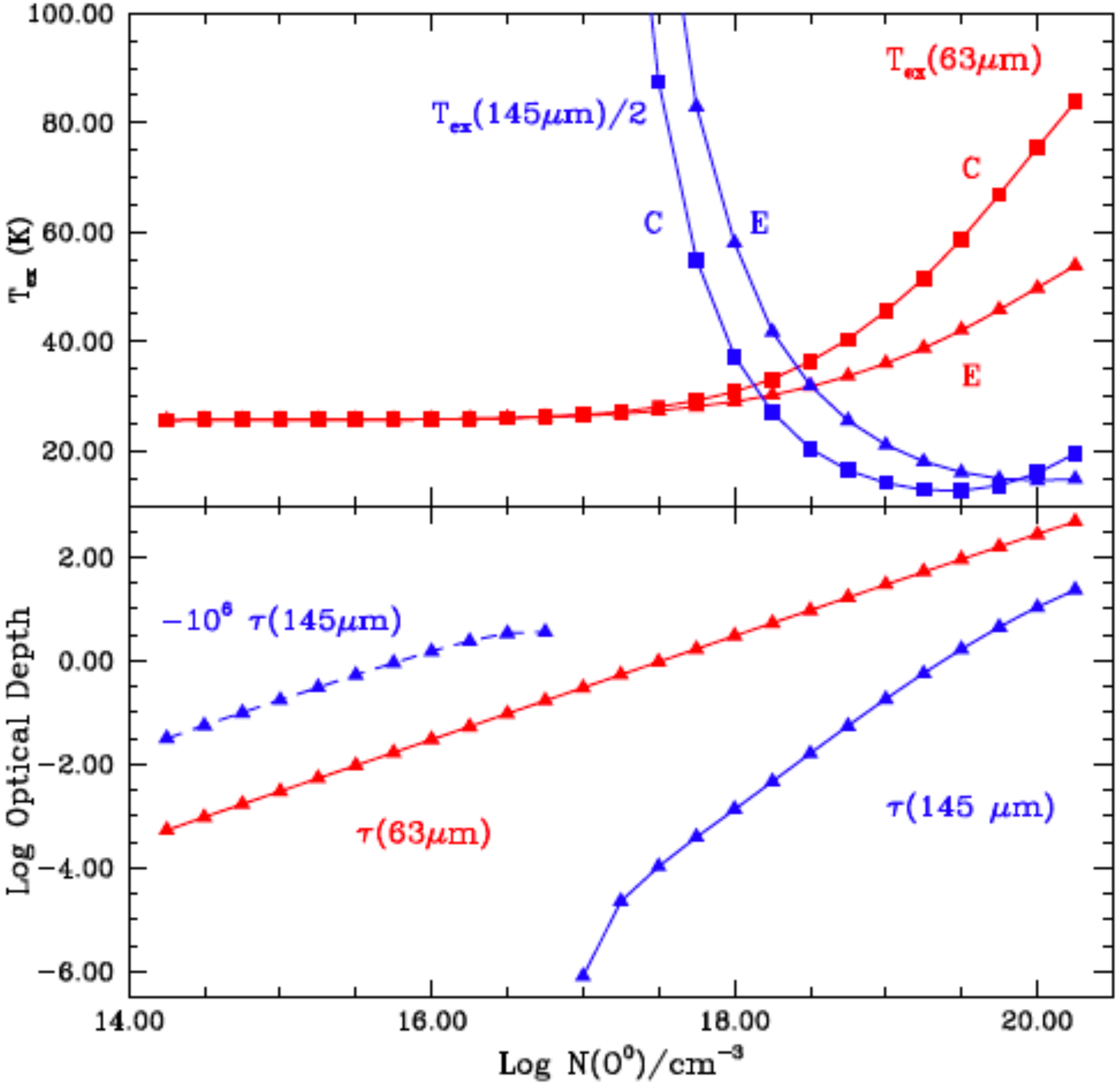
[OI] 63 μm E_u = 228 K E_l = 0 K

[OI] 146 μm E_u = 327 K E_l = 228 K

[CII] 158 μm E_u = 92 K E_l = 0 K

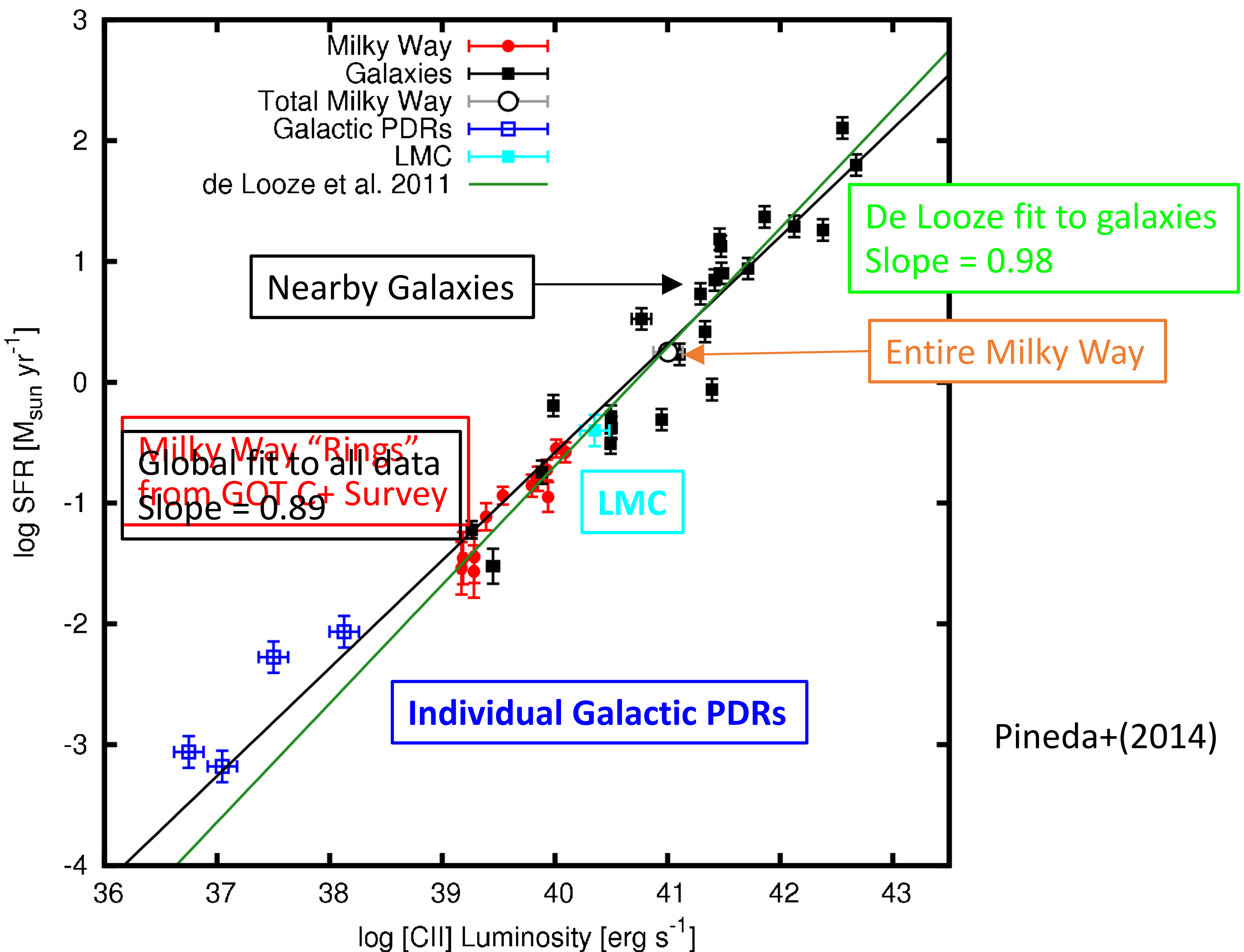
[OI] Excitation and Emission





Does [CII] Emission Trace Star Formation?

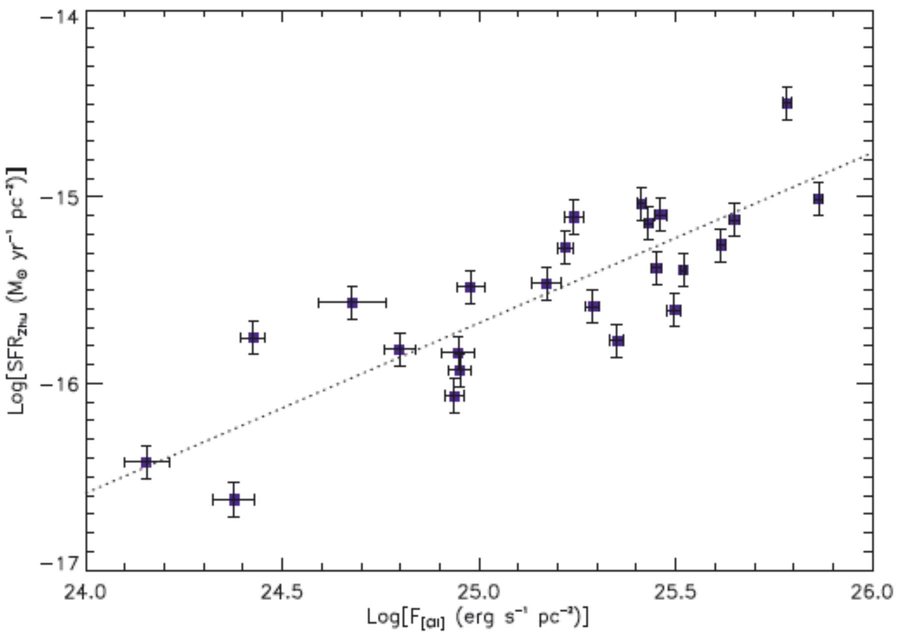
GOT C+ Survey Sampled 500 los in Milky Way using *Herschel* HIFI instrument Velocity-resolved [CII] spectra



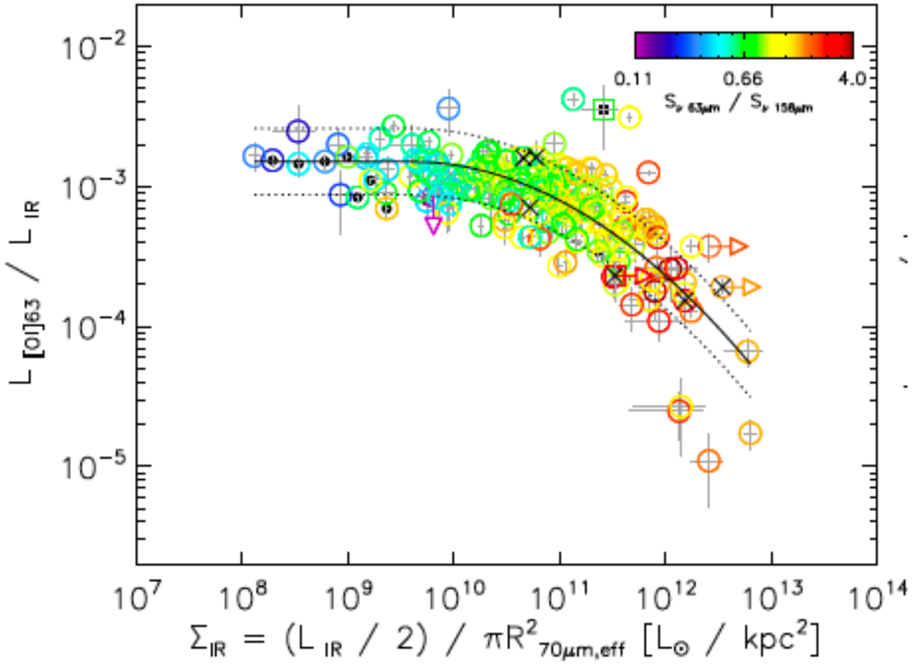
Pineda+(2014)

[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 somehow responsible?
- Is it related to the infamous "[CII] deficit"?

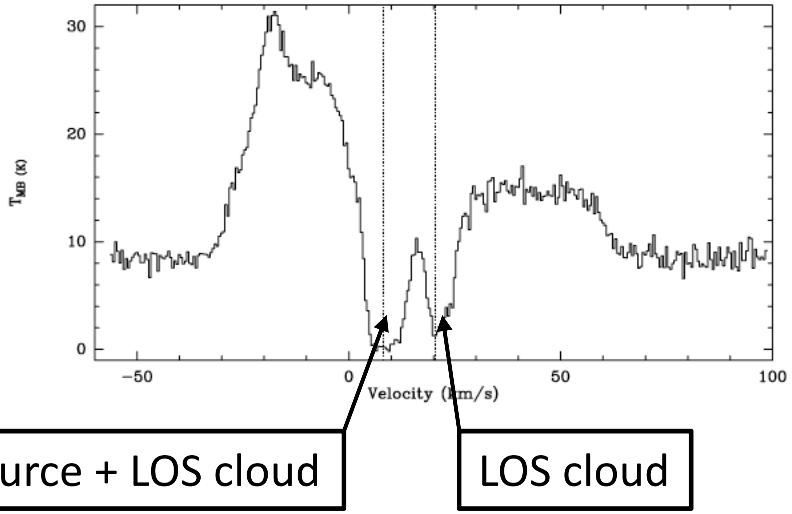


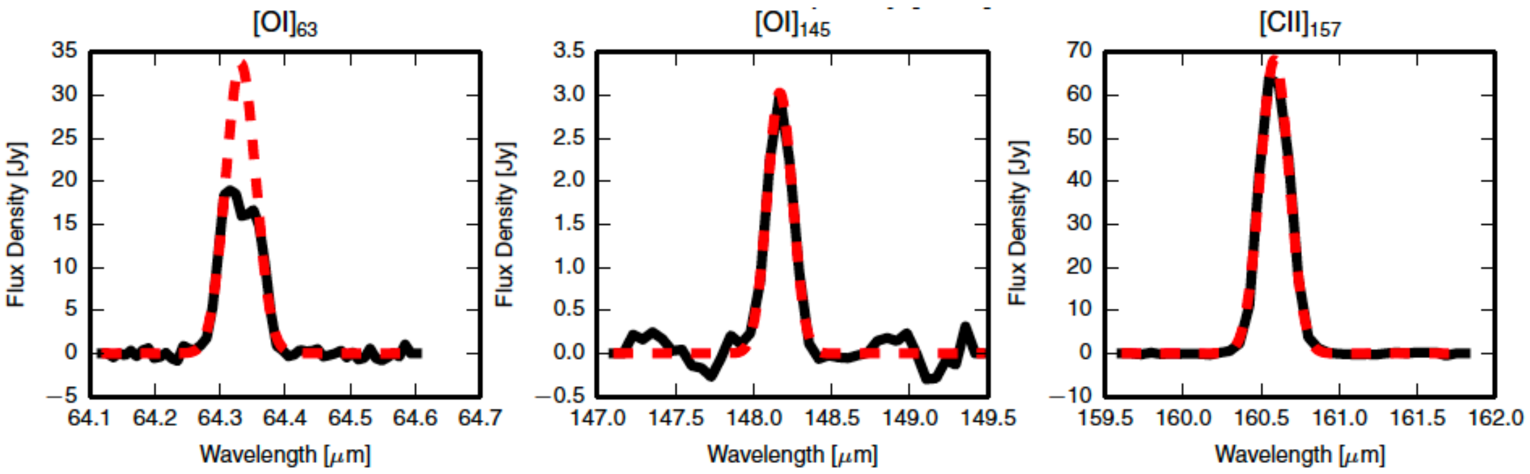
deLooze + (2017)



Diaz-Santos+ (2017)

Hints of Problem with the [OI] 63 μm Line





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!

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

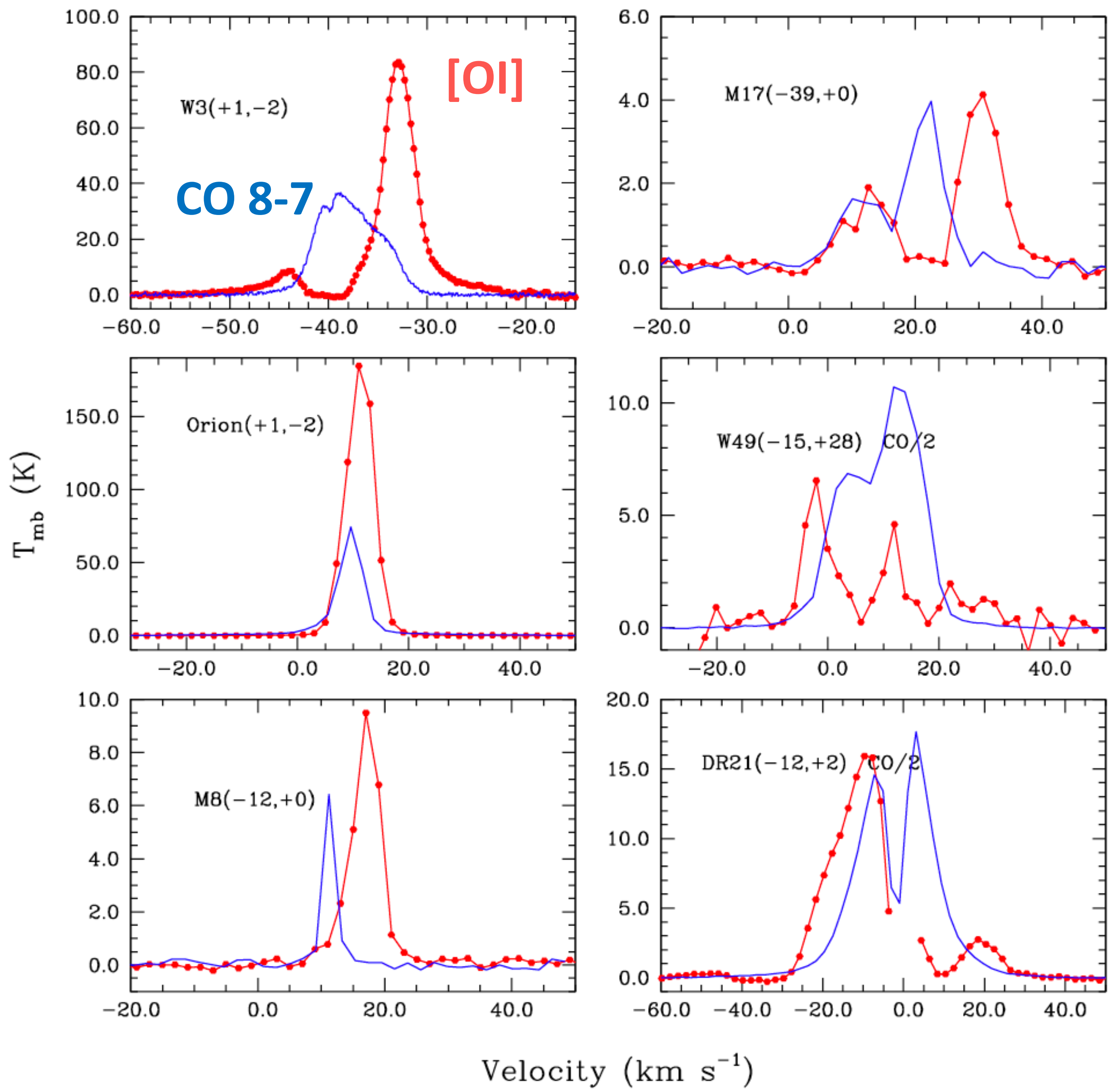
Of interest not only for understanding individual galaxies but also for modeling results of "Intensity Mapping" studies of high-redshift galaxies in which individual galaxies are NOT resolved, but collective emission is measured

But there are concerns:

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

Survey of Massive Star-Forming Regions with SOFIA/upGREAT

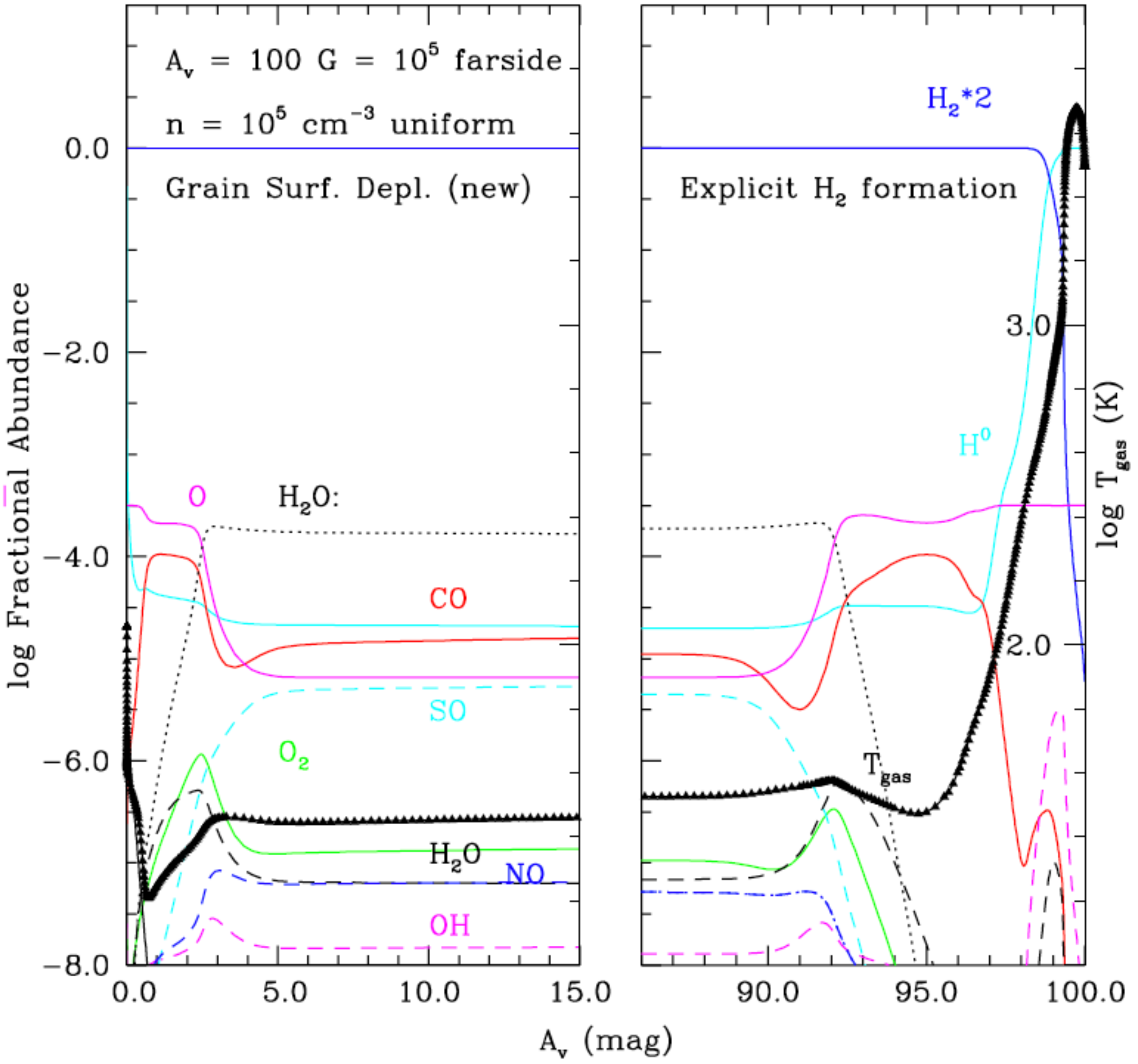
- [OI] 63µm observed in 12 regions
- Good detections – very variable line strengths
- CO J=5-4, J=8-7, and also [NII] 205µm observed simultaneously
- CO 8-7 traces warm molecular gas heated by UV from young star(s) and HII region
- [OI] shows **clear self-absorption** in half of sources observed
- Also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



SOFIA Observations of [OI] 63 μm in W3

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

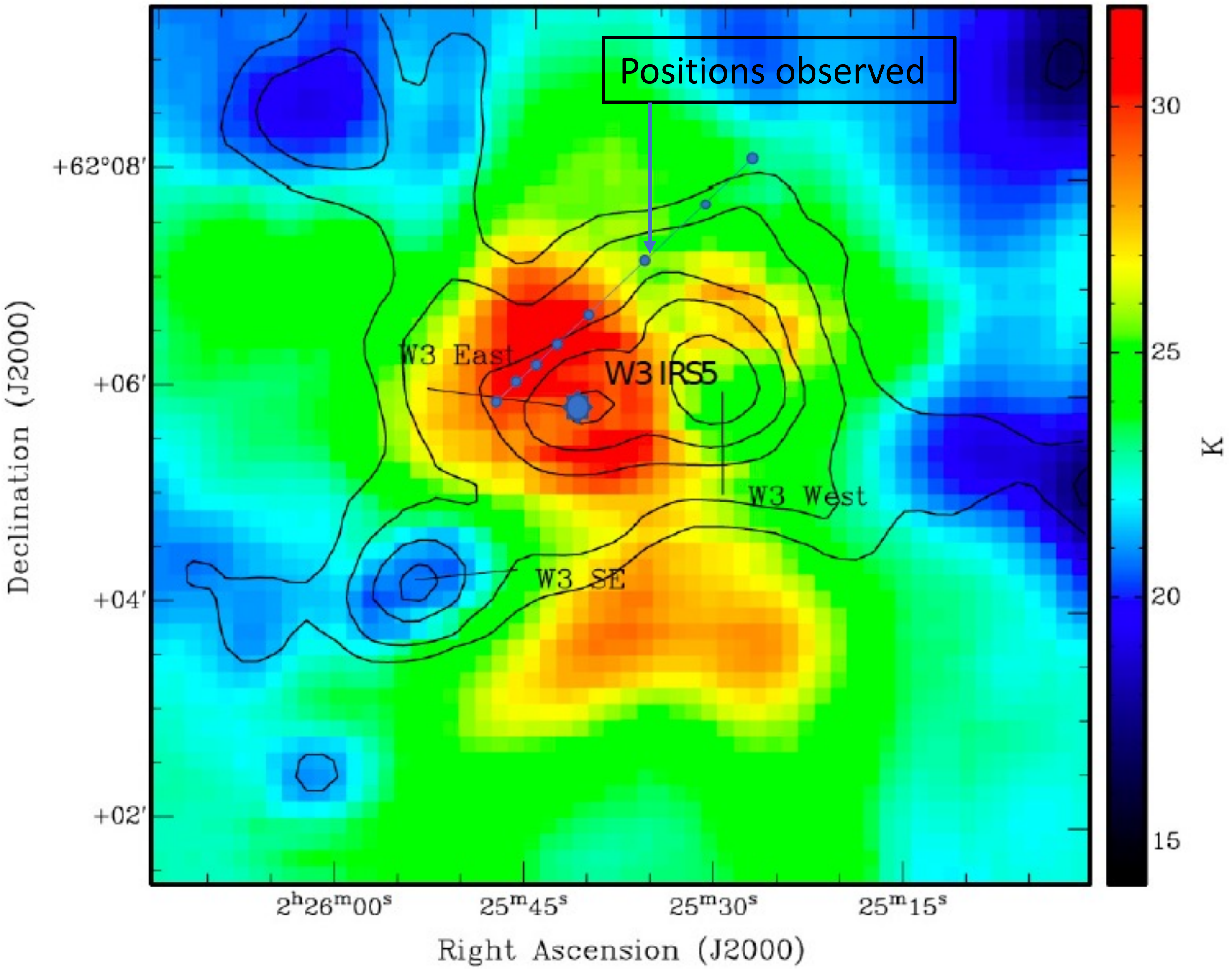
Radio continuum; FIR; CO

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

$L = 5 \times 10^5\ L_{sun}$

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

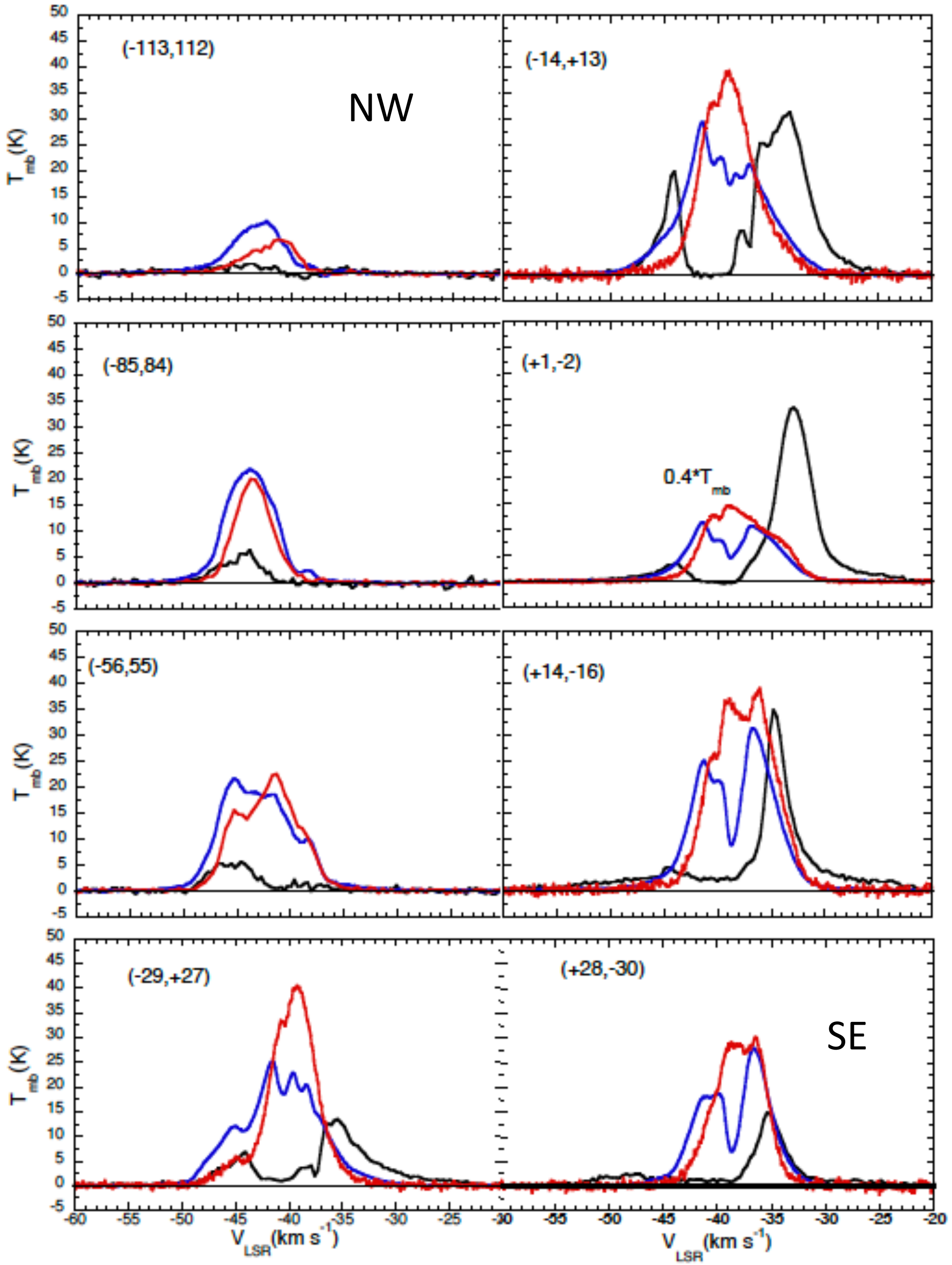
W3 IRS5 is center of stellar activity



Goldsmith+ (2021)

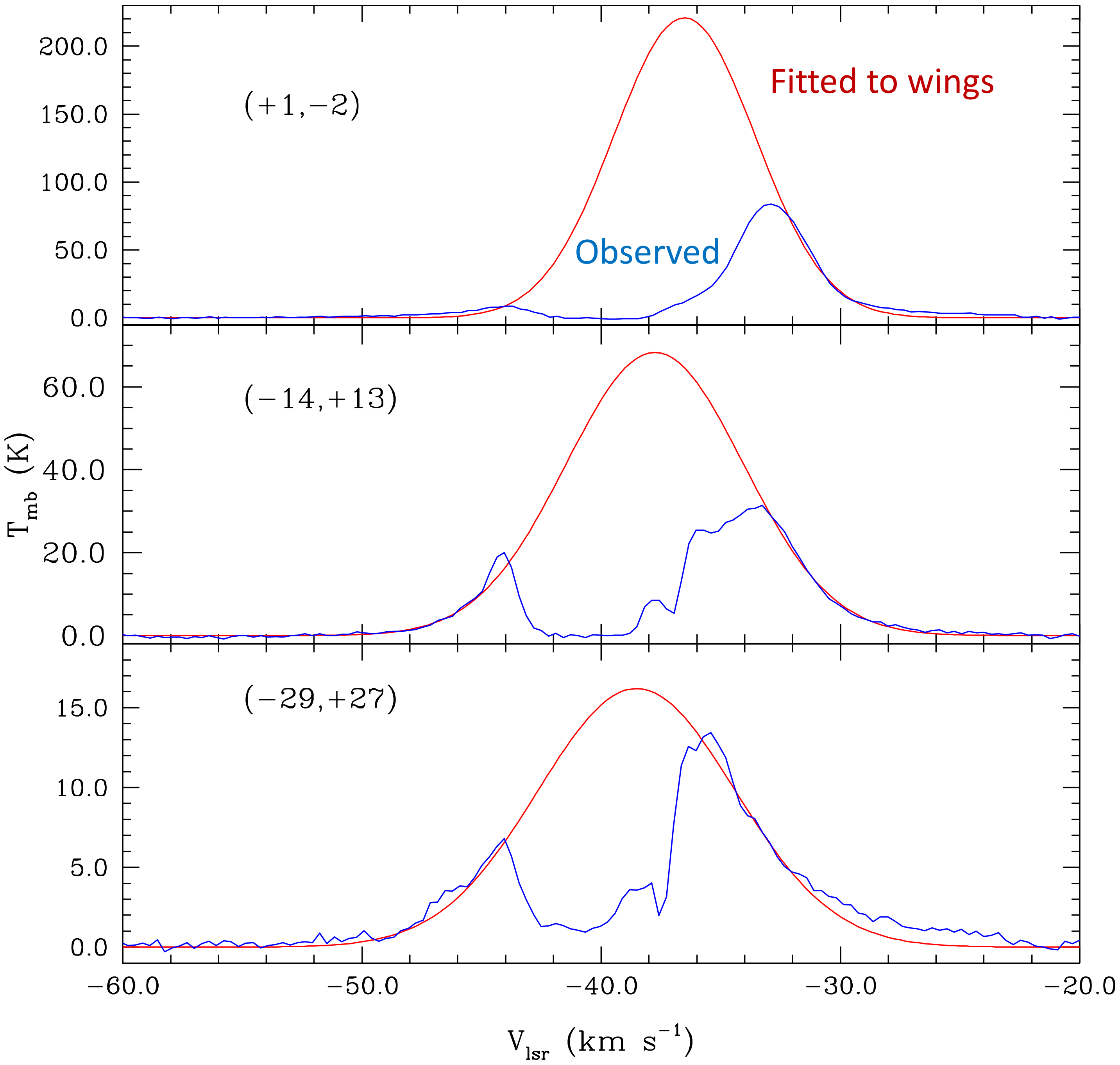
[OI] and CO in W3

- 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 the central region



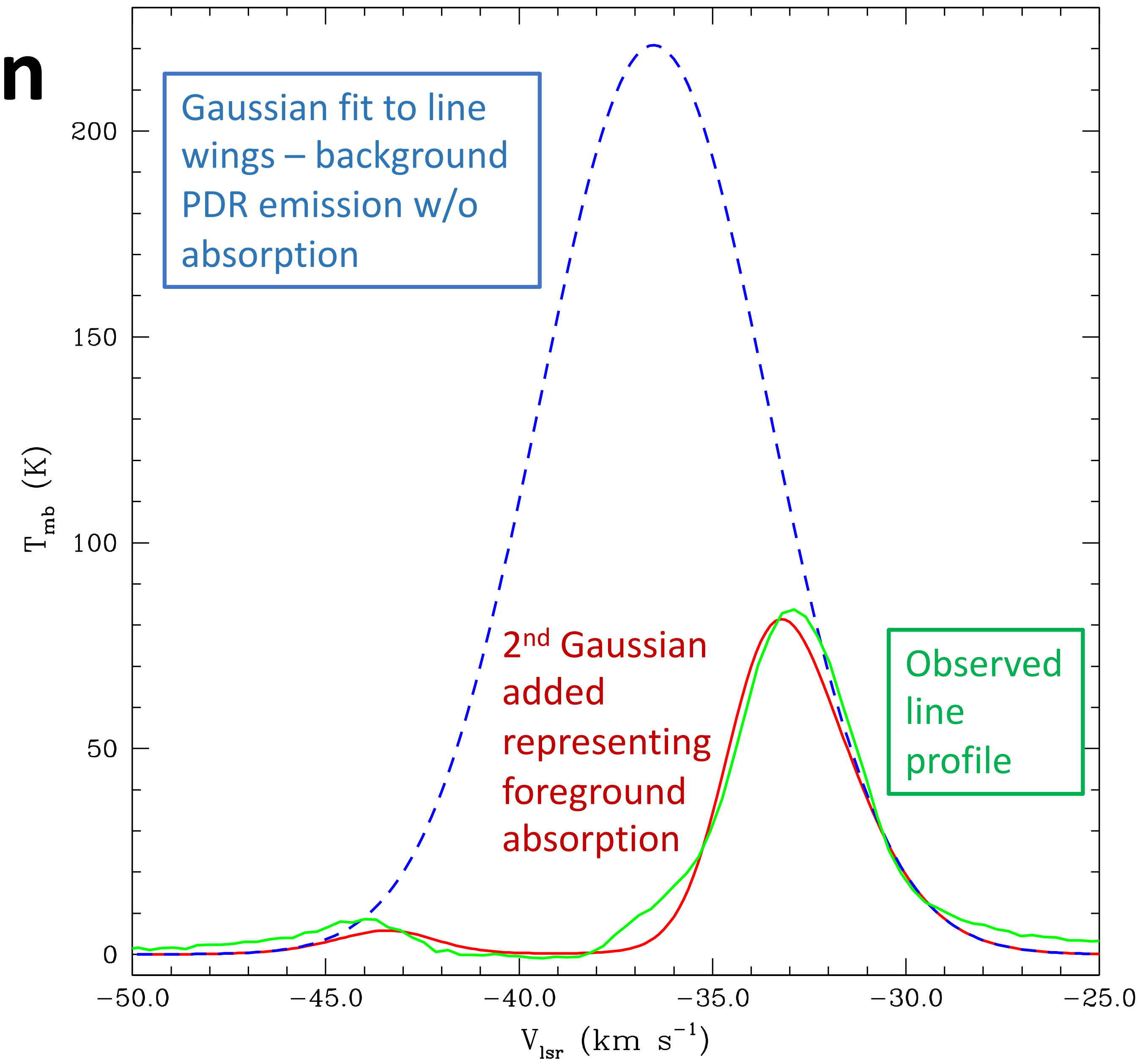
[OI] - Near W3 E

- Line wings well-fit by Gaussians
- **This should represent "PDR Emission" that would be observed if there were no foreground low-excitation gas**
- T ~ 220 K at central position! As strong as Orion (geometry)



Modeling Absorption

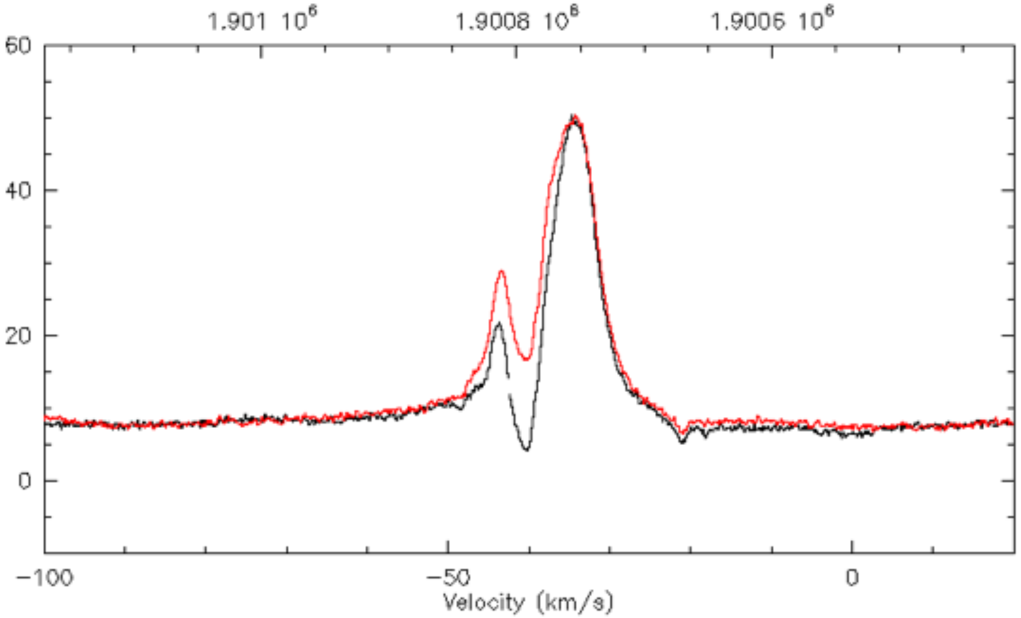
- PDR models suggest gas at ~30K which has effectively no emission
- A second Gaussian representing pure absorption fits observed line profile well
- Peak absorption optical depth = 7.8
- Velocity shift = -2 km/s
- N(low-excitation O^0) consistent with PDR models



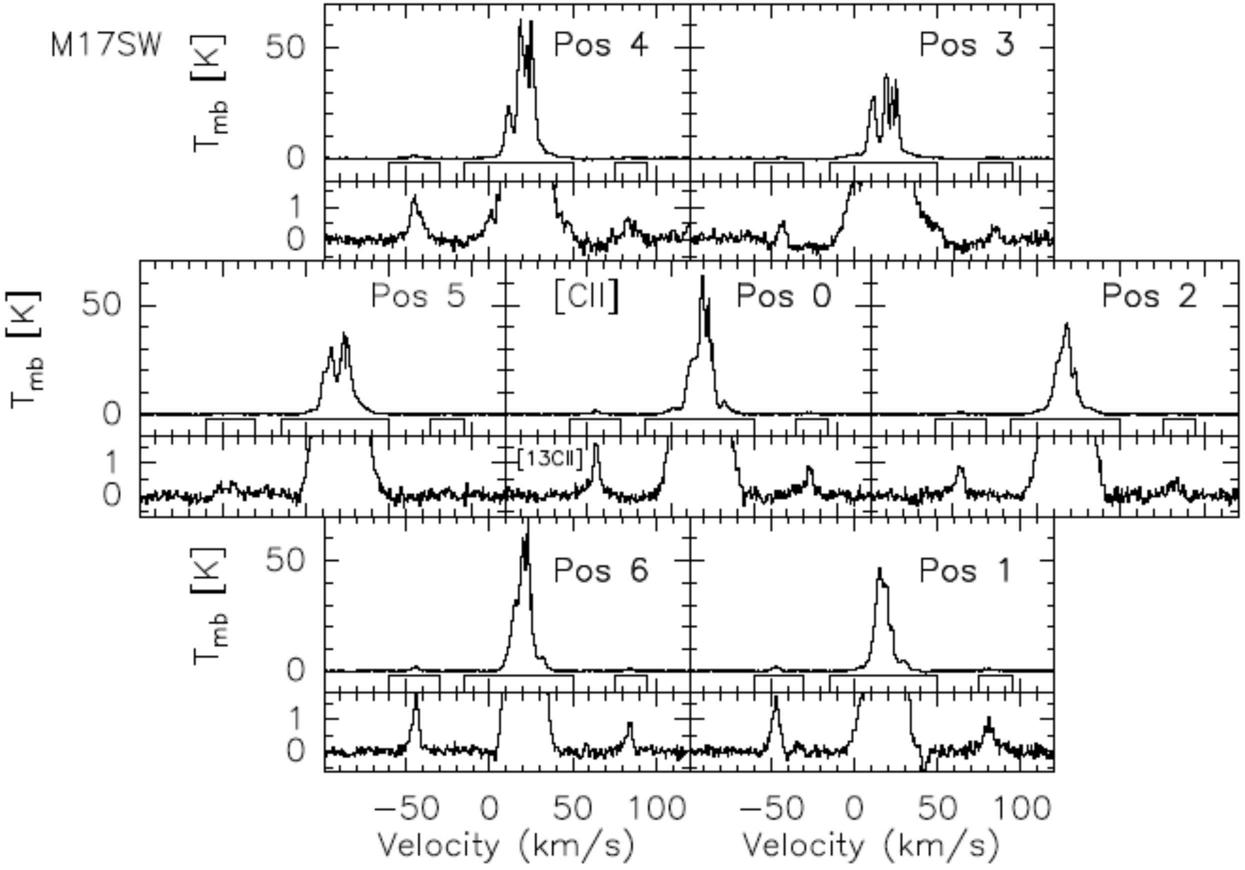
Foreground [OI] Absorption in W3

- Peak optical depths $\tau > 2$ 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
- Observational occurrence depends on geometry – not seen when PDR on Earth-facing side of cloud (Orion) $\Rightarrow$ 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"
- One way to confirm/correct is to observe the 146 μm line

[CII] Self-Absorption is More Widespread than Generally Appreciated



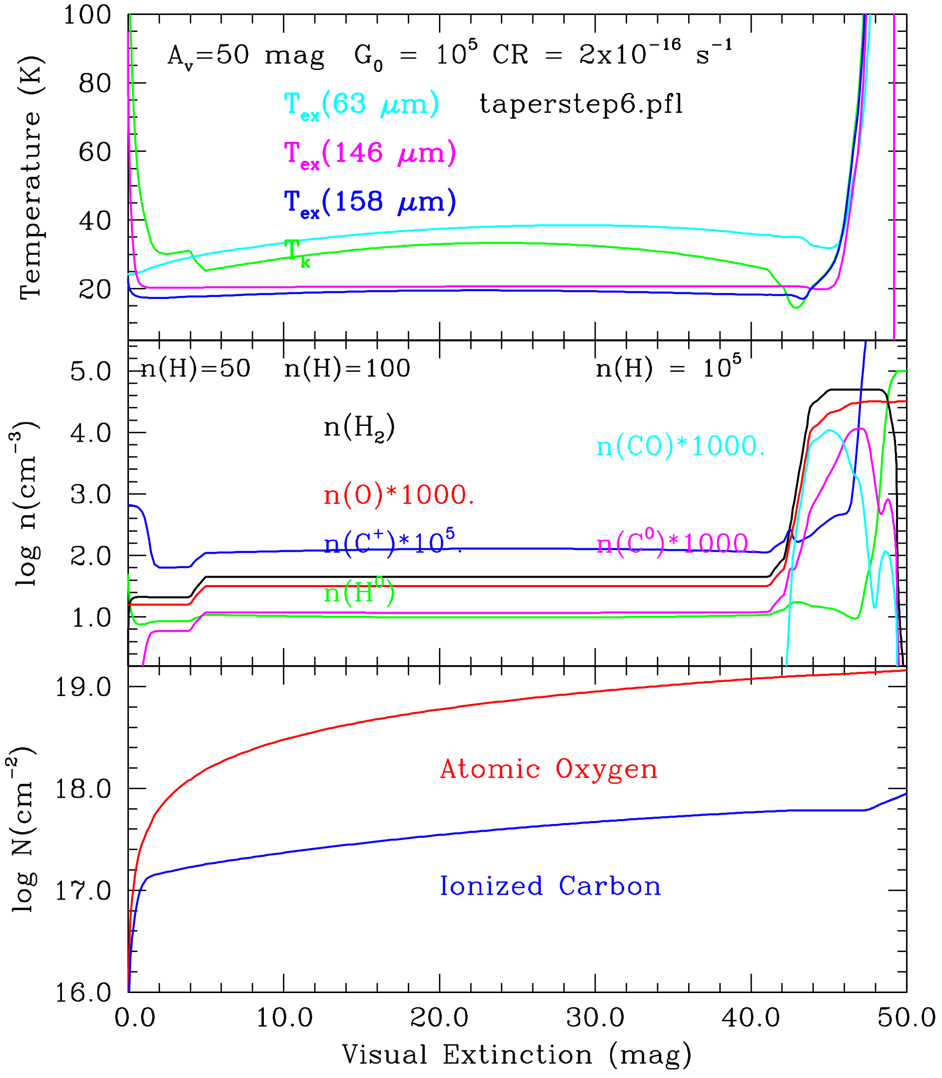
W3 IRS5
Two observing modes: OTF and DBS
Gerin+ (2015) – self-absorption present in many sources
-40 km/s velocity agrees with center of [OI] 63 μm absorption

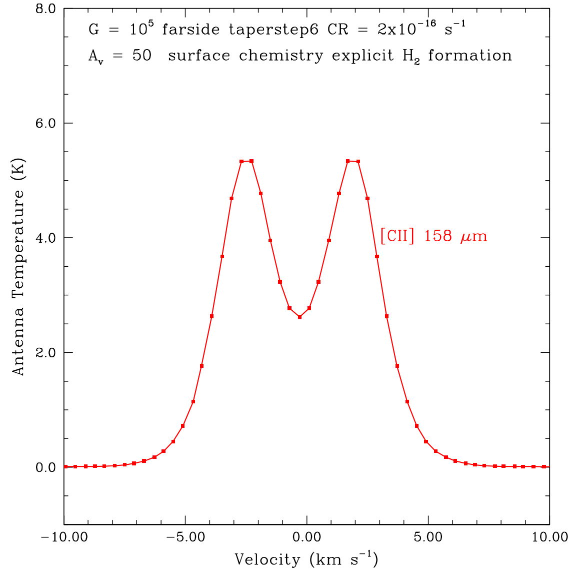


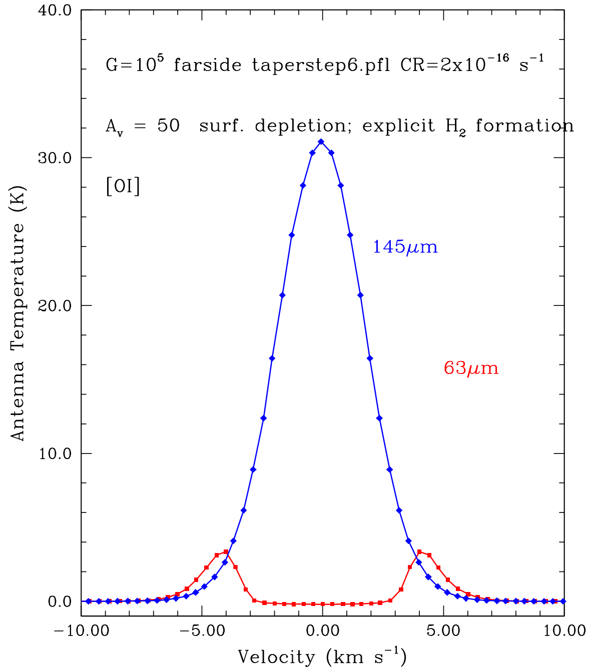
[CII] in M17SW from Guevara+ (2020)

Producing [CII] Absorption

- C^+ has significant abundance ONLY at boundaries: very hot part heated by HII region and boundary heated by ISRF
- $N(C^+)$ very low in dense PDR material in which oxygen remains atomic
- Need low density, material to produce [CII] absorption
- Enhanced CR ionization rate can moderately enhance $X(C^+)$







Conclusions

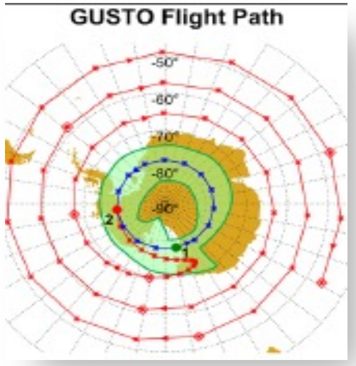
- Fine structure lines are powerful tracers of ISM, especially regions mechanically and radiatively affected by massive star formation
- [CII] and [OI] generally trace star formation both in Galactic sources and external galaxies but there are important caveats emerging from detailed studies of velocity-resolved spectra
  - In [CII], absorption by diffuse ISM can corrupt results for emission regions when observed with inadequate velocity resolution. Self-absorption is more significant than generally appreciated with modest optical depths affecting line emission
  - In [OI], there is evidence for extensive regions of low-excitation atomic oxygen, that absorbs the emission from hot gas adjacent to HII region and dramatically reduces emitted flux, significantly affecting use of [OI] as tracer of star formation
- Understanding these issues will require velocity-resolved fine structure line images, which will be produced by SOFIA and GUSTO & ASTHROS balloon missions, and hopefully by FIR Probe mission

Observational Capabilities

- Currently upGREAT instrument on SOFIA has 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
- Fine structure line capability will be enhanced if HIRMES instrument is selected to be completed for SOFIA
- A large-format (e.g. 128 pixel) Fine structure mapping line instrument has also been proposed for SOFIA ([CII] and [OI] 146 µm)
- Origins Flagship mission will certainly have enormous sensitivity, but high velocity resolution only if HERO instrument upscope is included
- Two balloon missions focusing on fine structure line emissions are currently under development

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



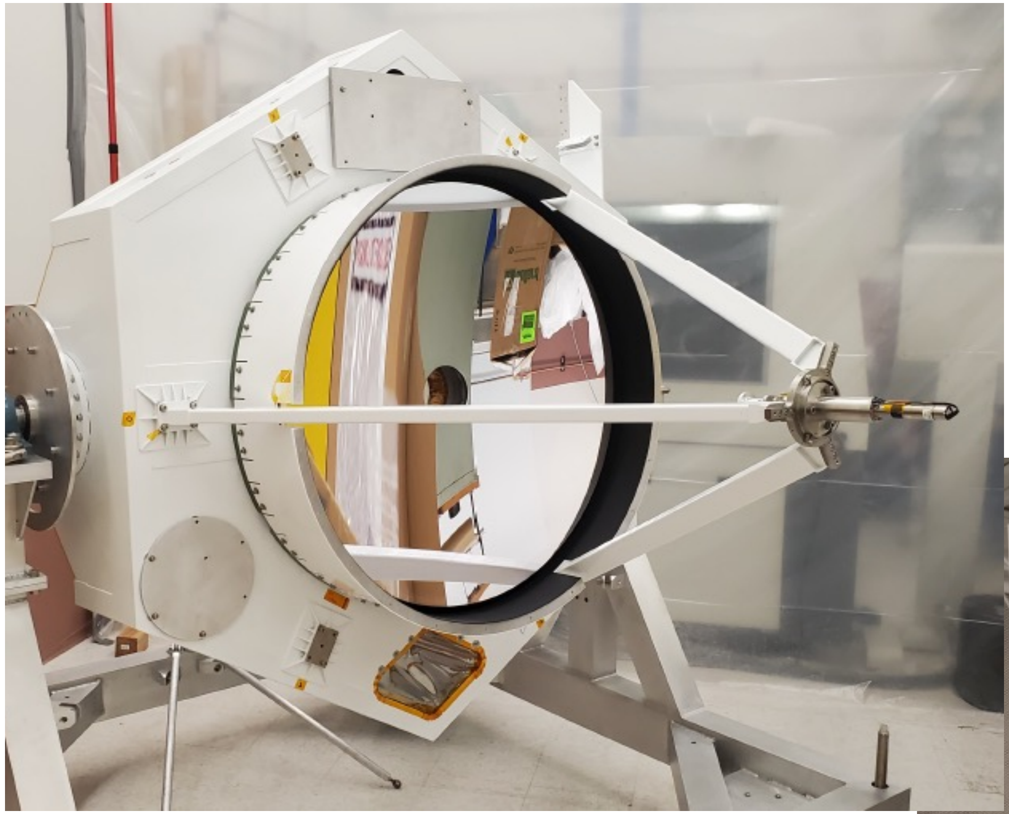
Level 1 Requirements: Data Products

GPS: Galactic Plane Survey: $-25° < l < 25°$; $-1° < b < 1°$

LMCS: Large Magellanic Cloud Survey: $4° \times 6°$ map of entire LMC

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

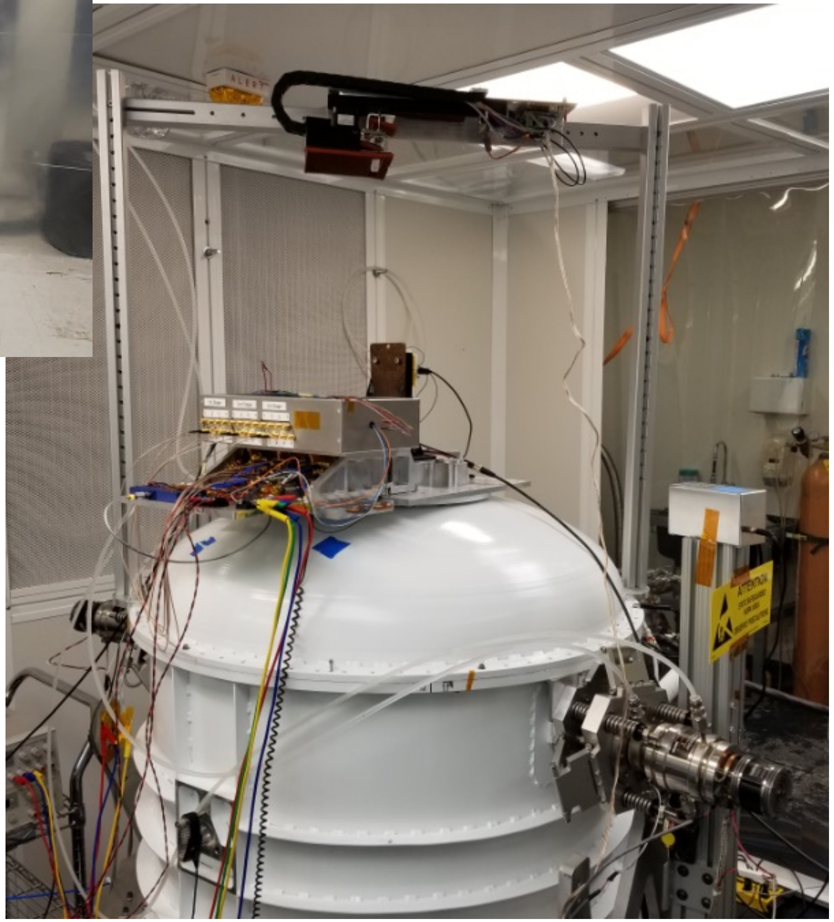
NASA Explorer Mission of Opportunity (MoO) balloon mission – Launch Dec. 2022



GUSTO Status

January 2022

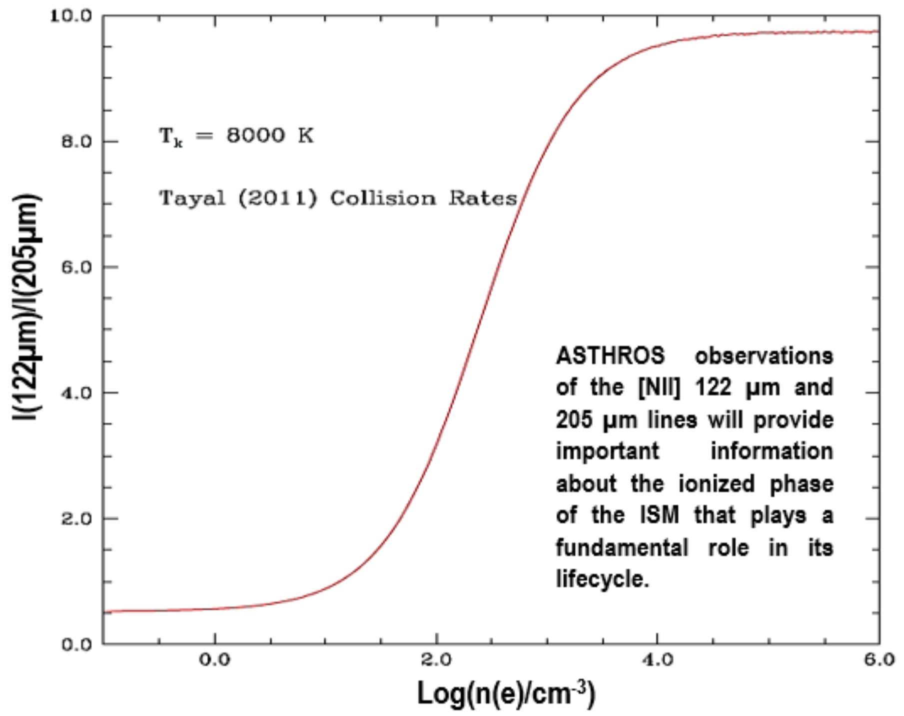
90 cm "optical" telescope



LHe dewar
Refrigerator-cooled radiation shield
~100 day hold time

ASTHROS Astrophysics Stratospheric Telescope for High-Resolution Observations at Submillimeter-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 Instrument

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

Low blockage symmetric Cassegrain

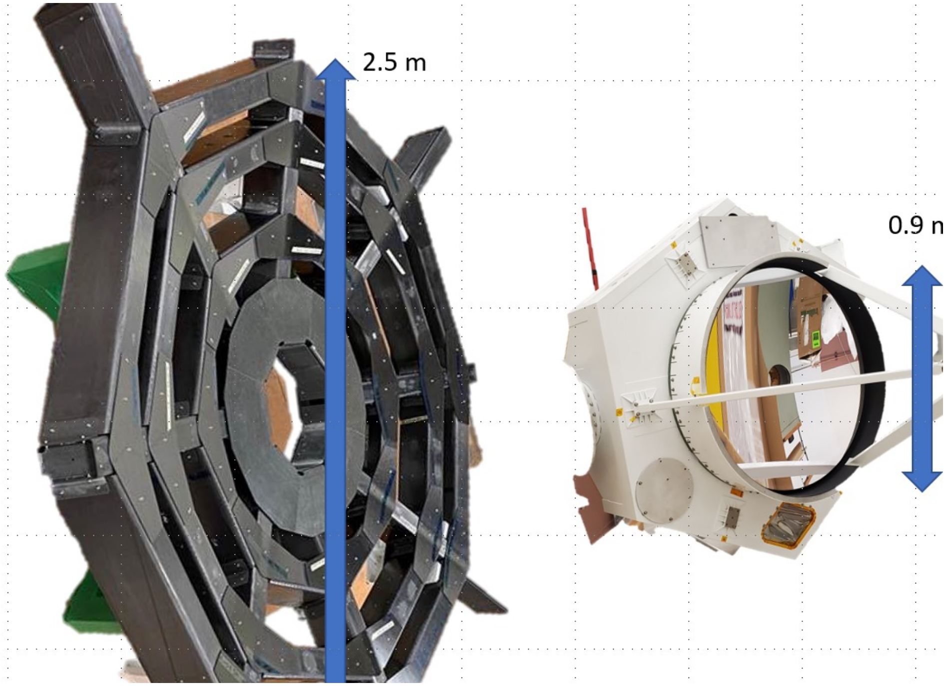
<8 μm rms aggregate surface accuracy

2 4-pixel HEB science receiver arrays

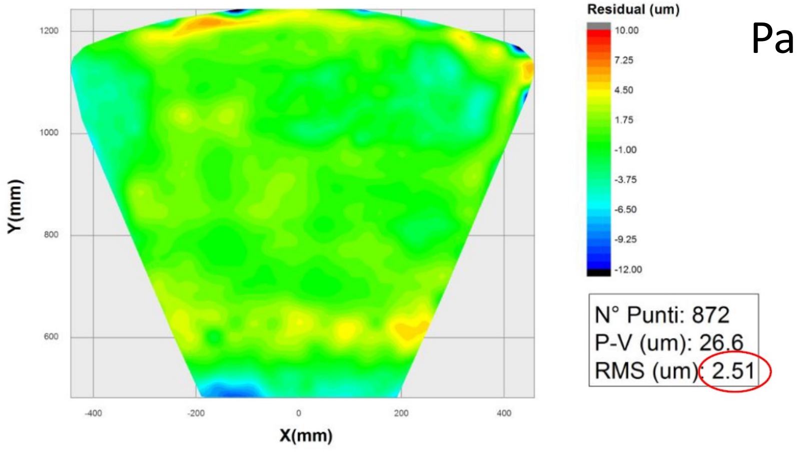
80-100 GHz receiver for system tests and pointing observations

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