# Unveiling the physical conditions and UV fields in embedded cluster Gy 3–7 in the outer Galaxy with FIFI-LS spectrometer onboard SOFIA

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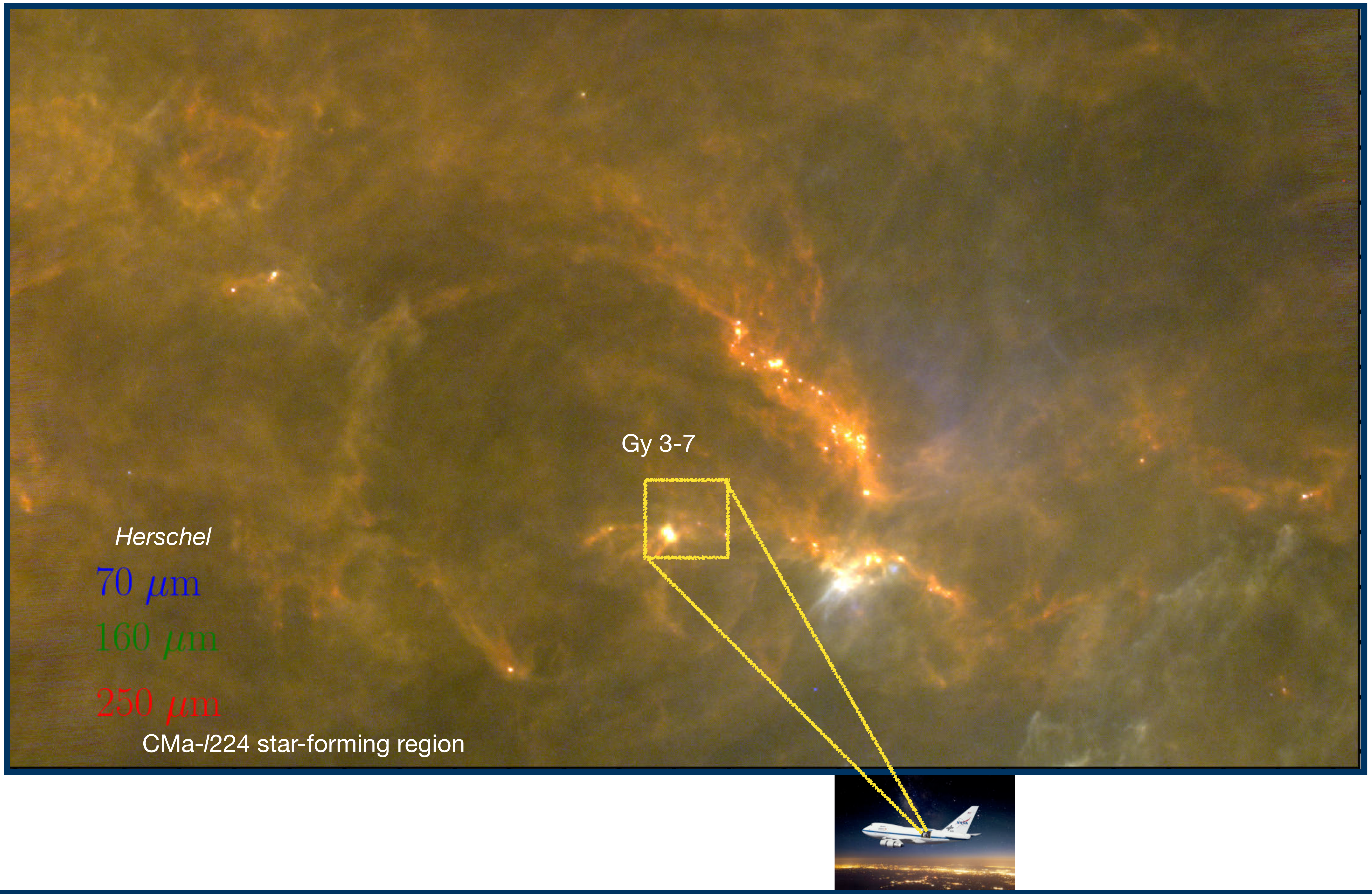
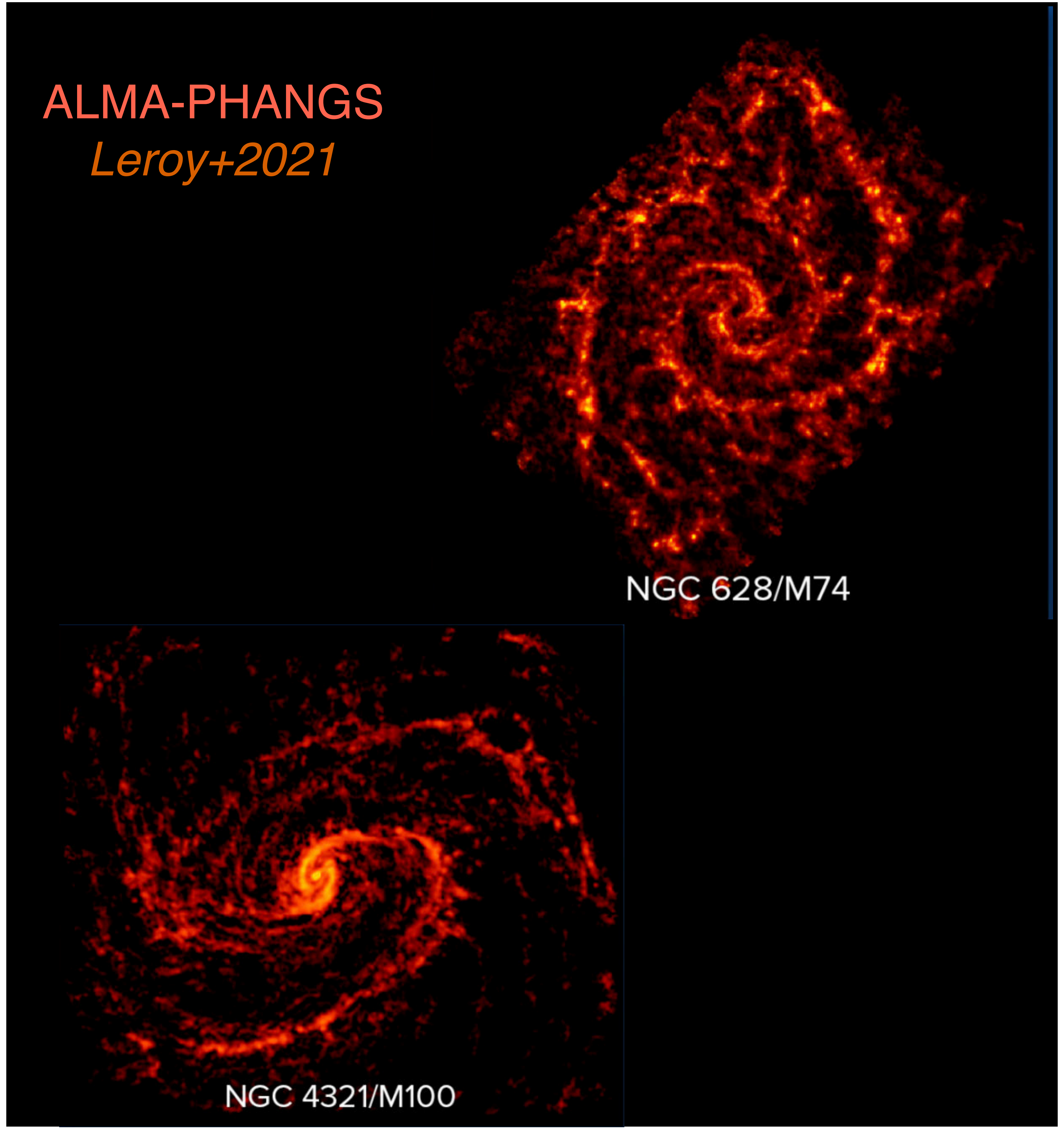
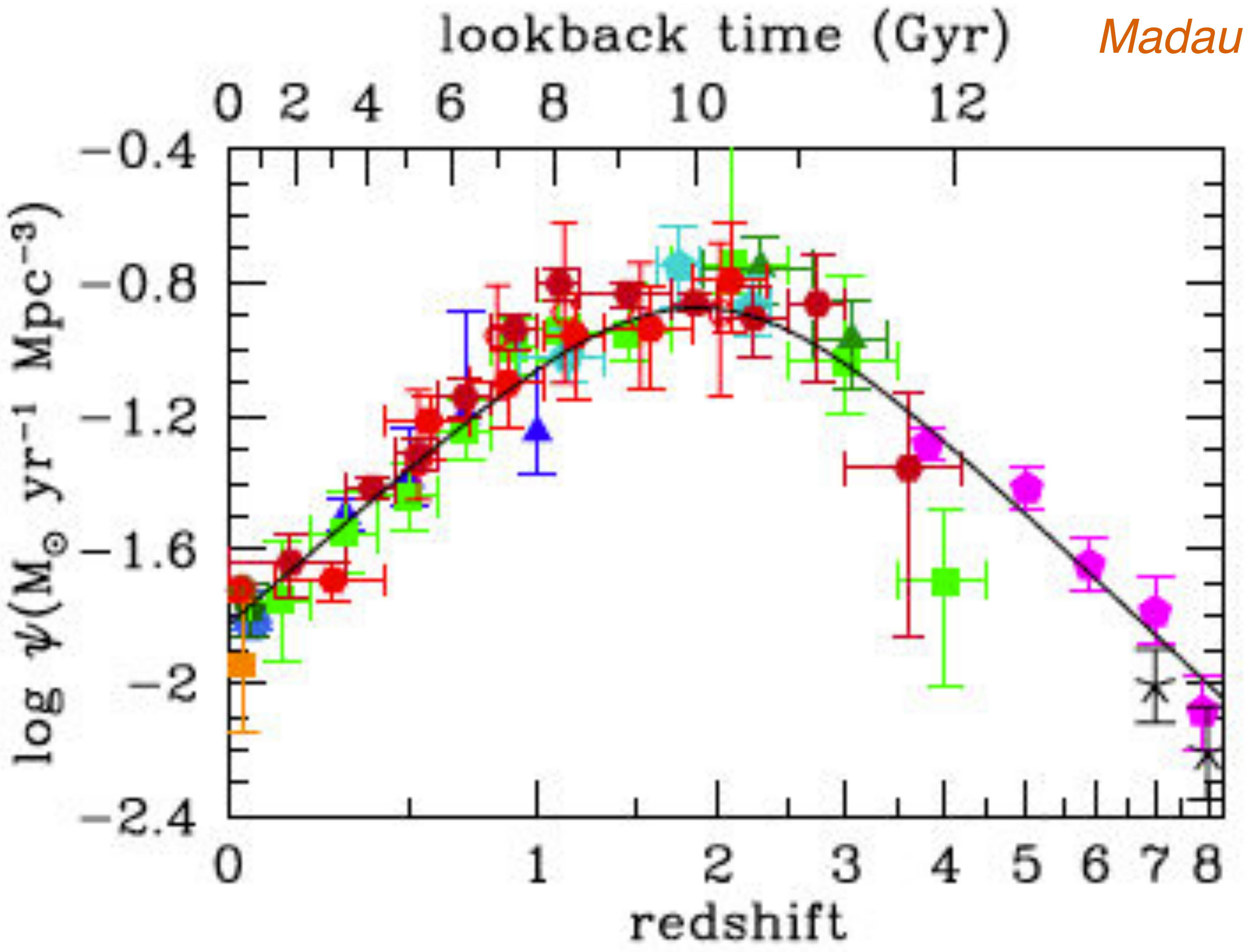


# Ubiquity of star formation

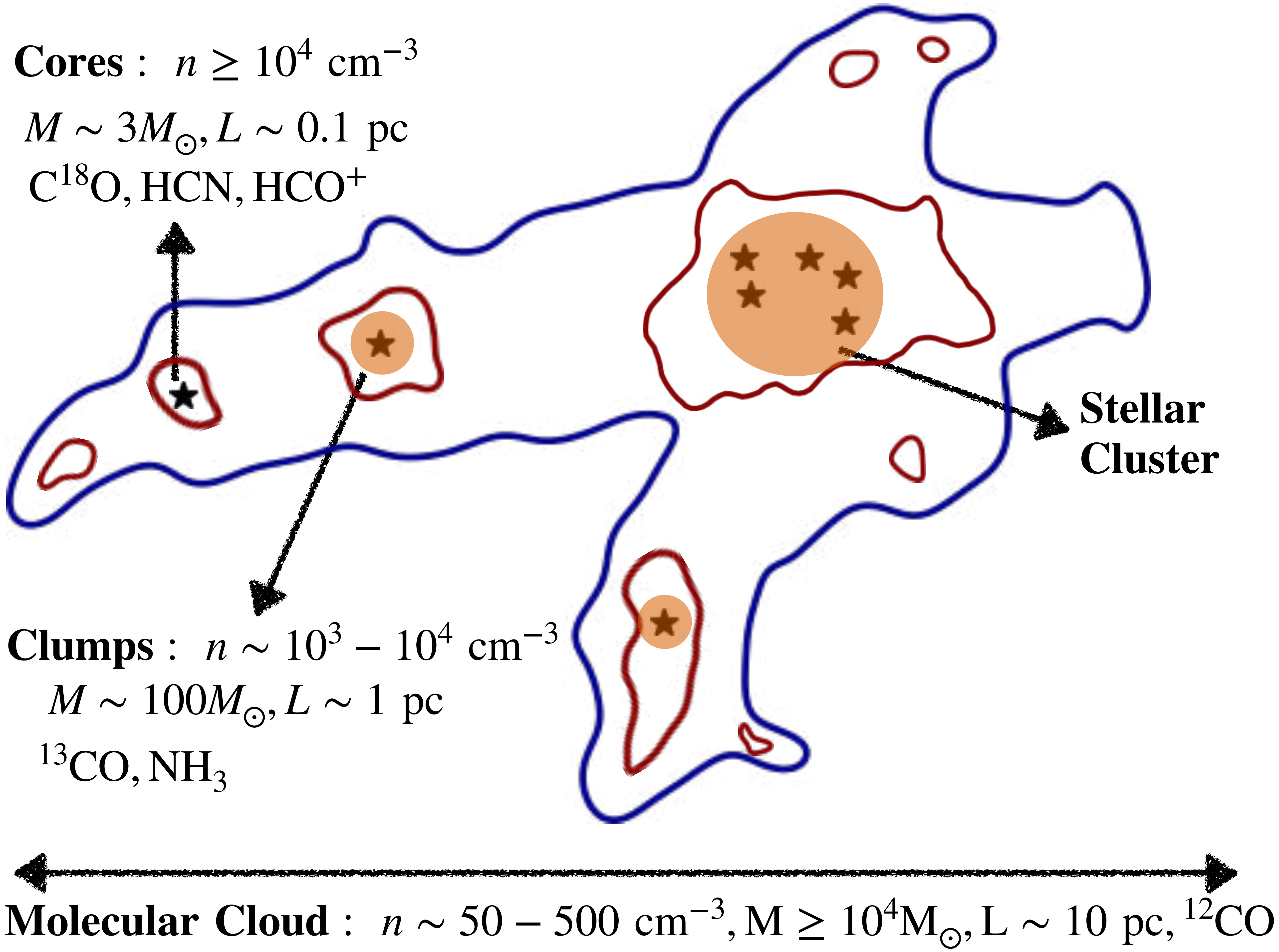




*Madau & Dickinson 2014*

- Formation of stars is ubiquitous in galaxies at near and far distances, spanning a wide range of environments, and physical and chemical conditions
- Peak of star formation occurred in low-metallicity environments with z~1.9

# Molecular clouds - The stellar nurseries



**Cores** : $n \geq 10^4\ \text{cm}^{-3}$

$M \sim 3M_\odot, L \sim 0.1\ \text{pc}$

$C^{18}O, HCN, HCO^+$

**Clumps** : $n \sim 10^3 - 10^4\ \text{cm}^{-3}$

$M \sim 100M_\odot, L \sim 1\ \text{pc}$

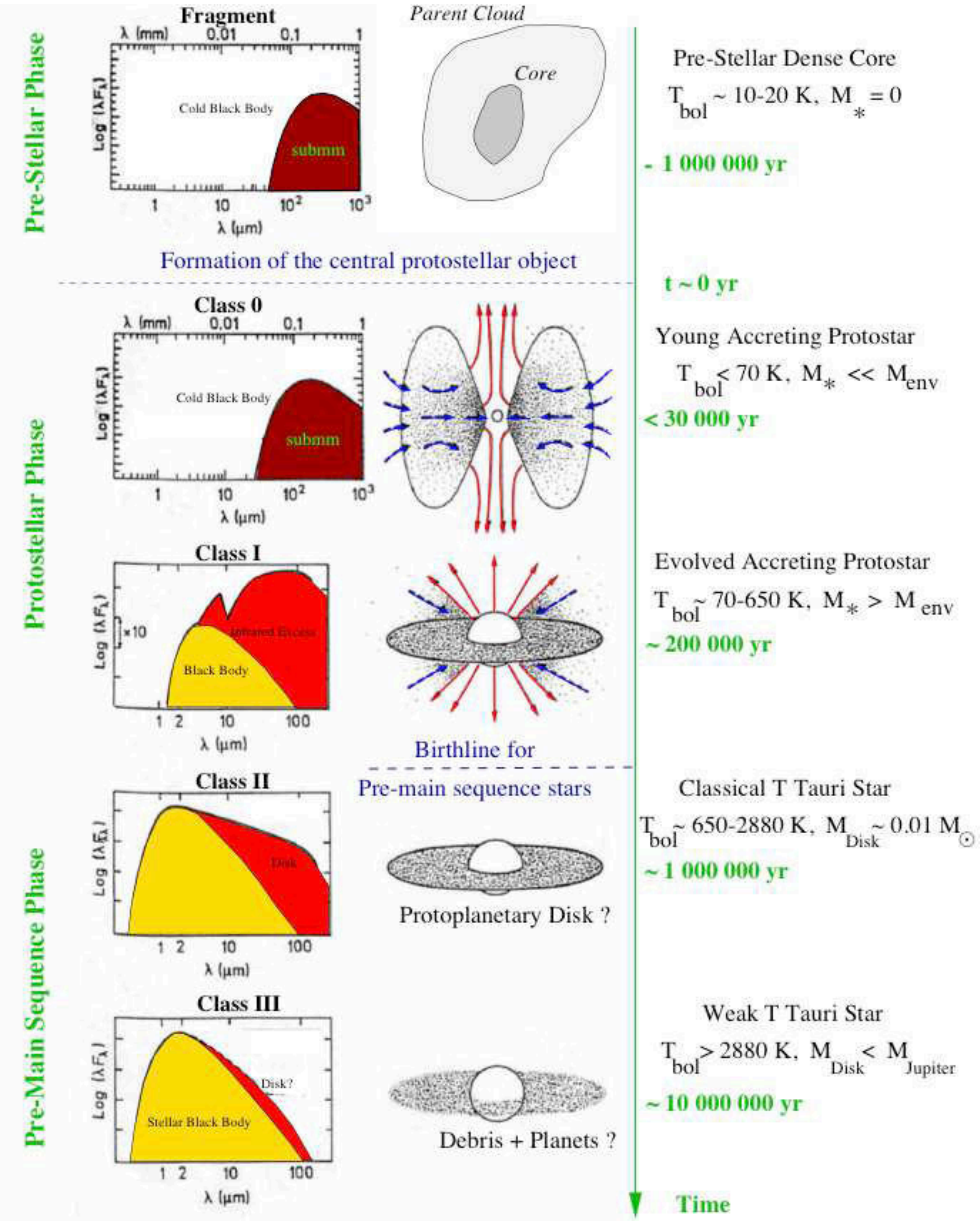
$^{13}CO, NH_3$

**Stellar Cluster**

**Molecular Cloud** : $n \sim 50 - 500\ \text{cm}^{-3}, \text{M} \geq 10^4\text{M}_\odot, \text{L} \sim 10\ \text{pc}, {}^{12}\text{CO}$

- Stars like our Sun form in the cold and dense parts of molecular clouds, which consist of filaments, clumps, and dense cores

# Evolutionary sequence of a low-mass star



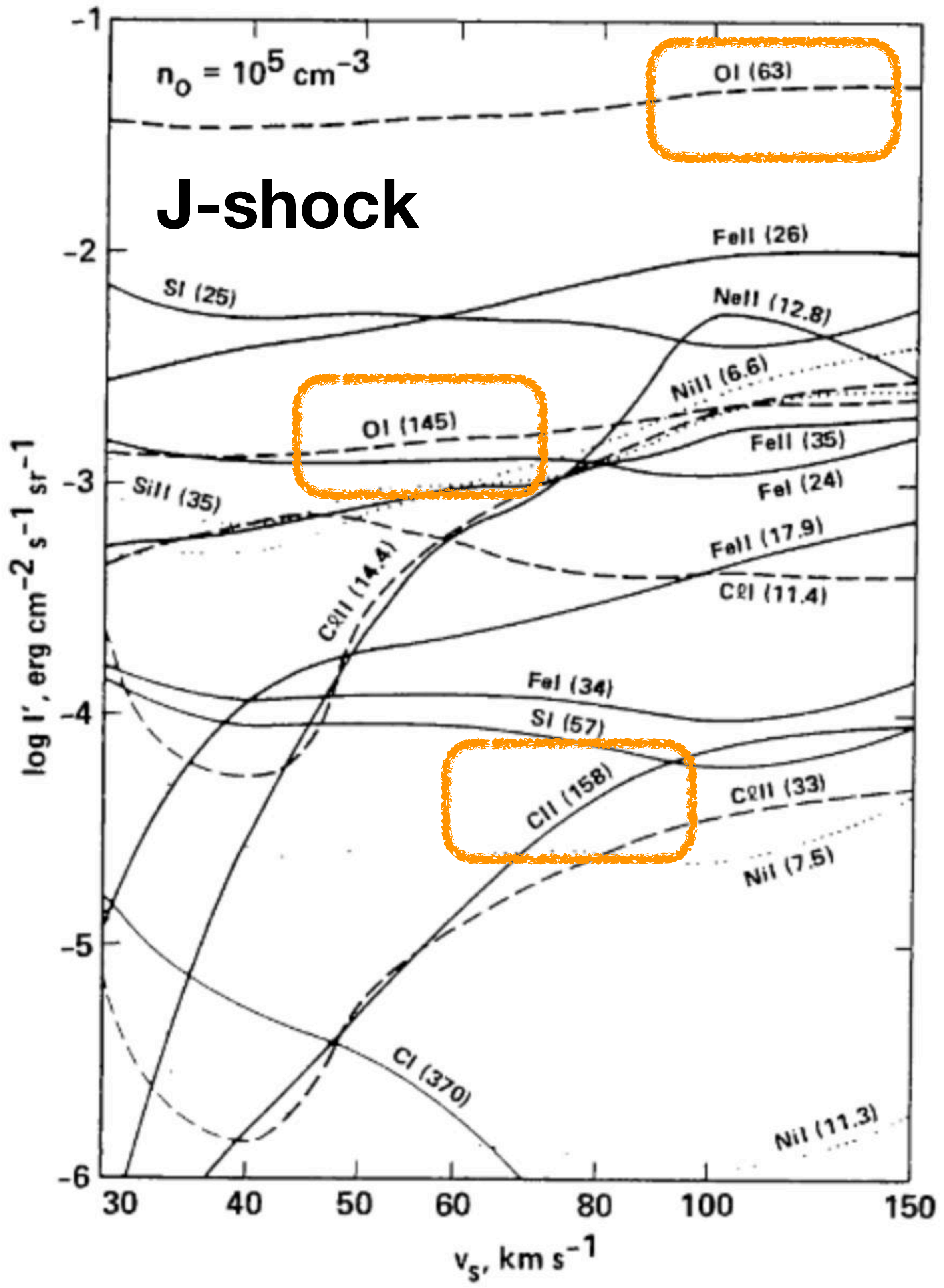
**Jets/Outflows:**

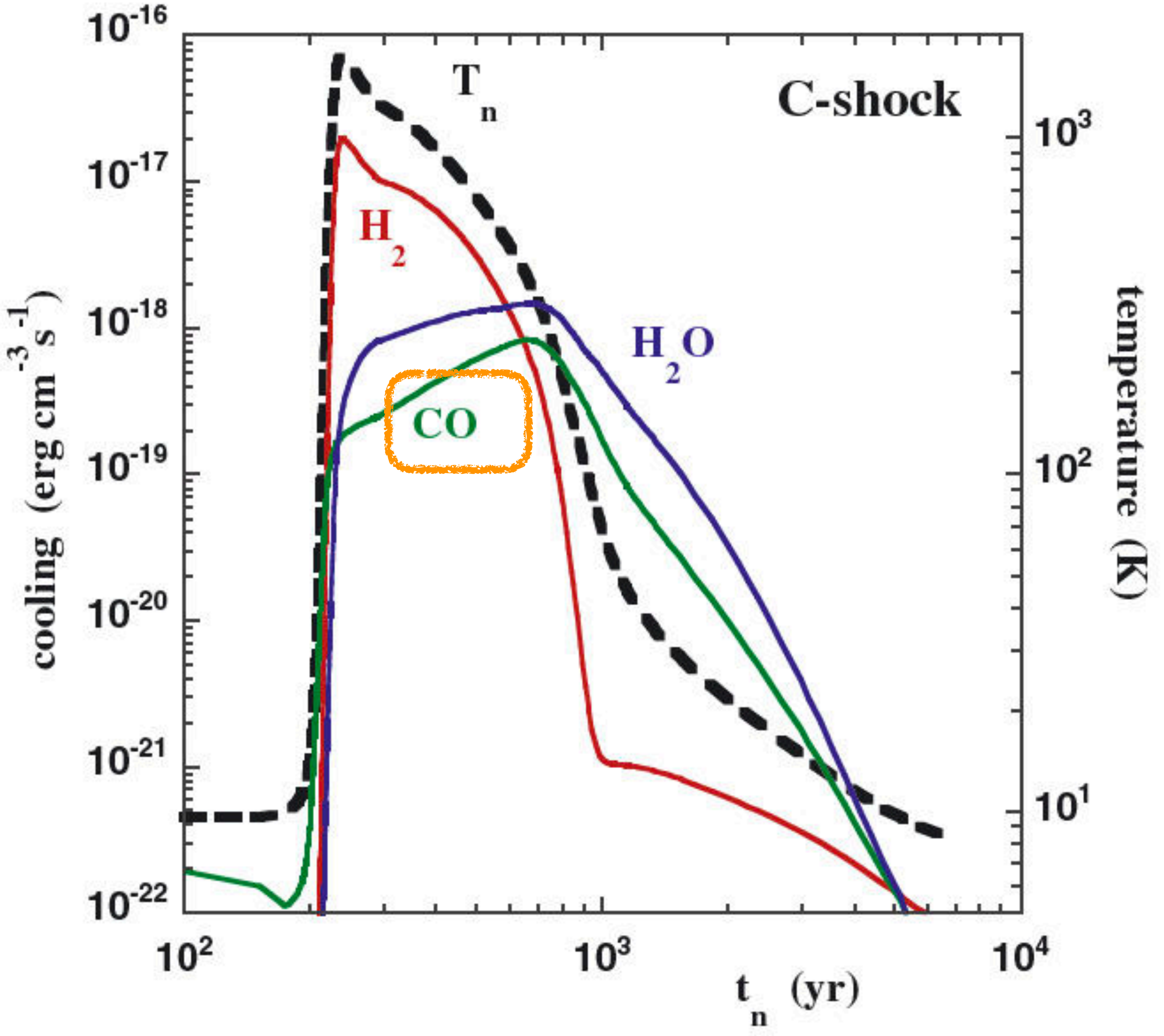
- are associated with the deeply embedded protostar --> tracers of star formation (Class 0/I phases)
- develop non-dissosiative shocks heating-up gas up to ~ 300 K seen in ionized, atomic, molecular emission.

**UV photons:**

- contribute to gas heating
- influence chemical composition in the surrounding envelope

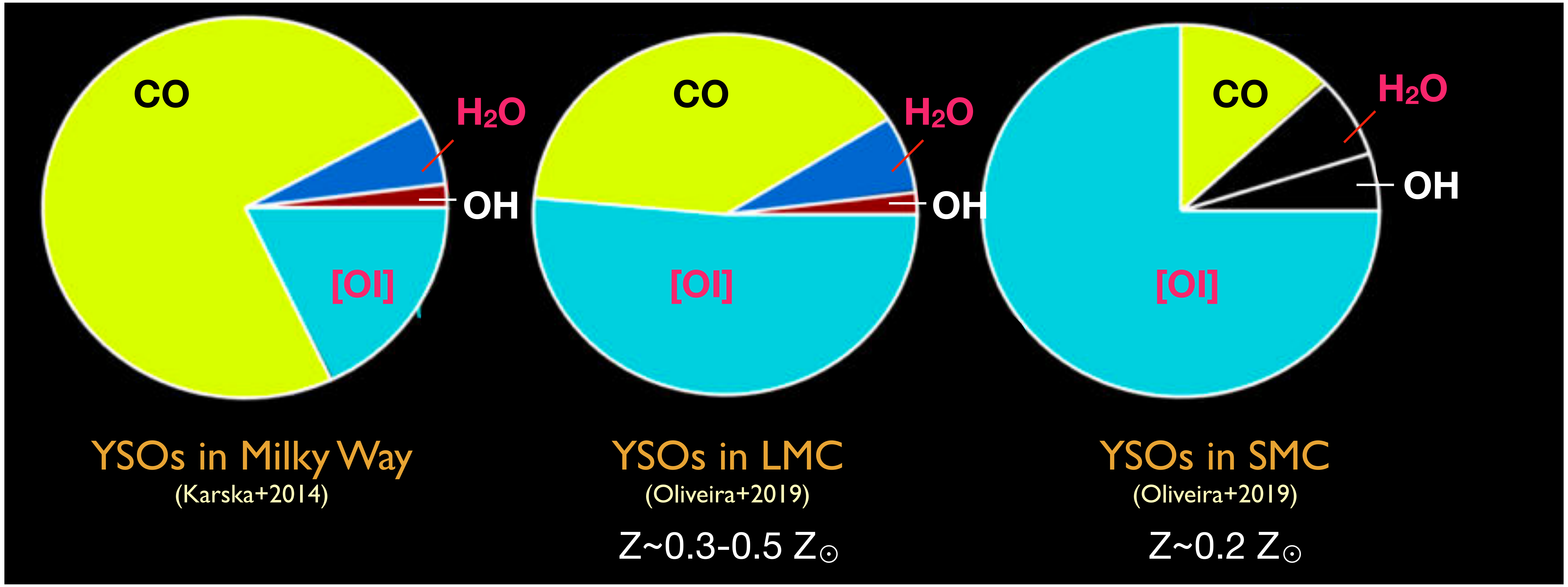
# Far-IR line emission as tracers of shocks





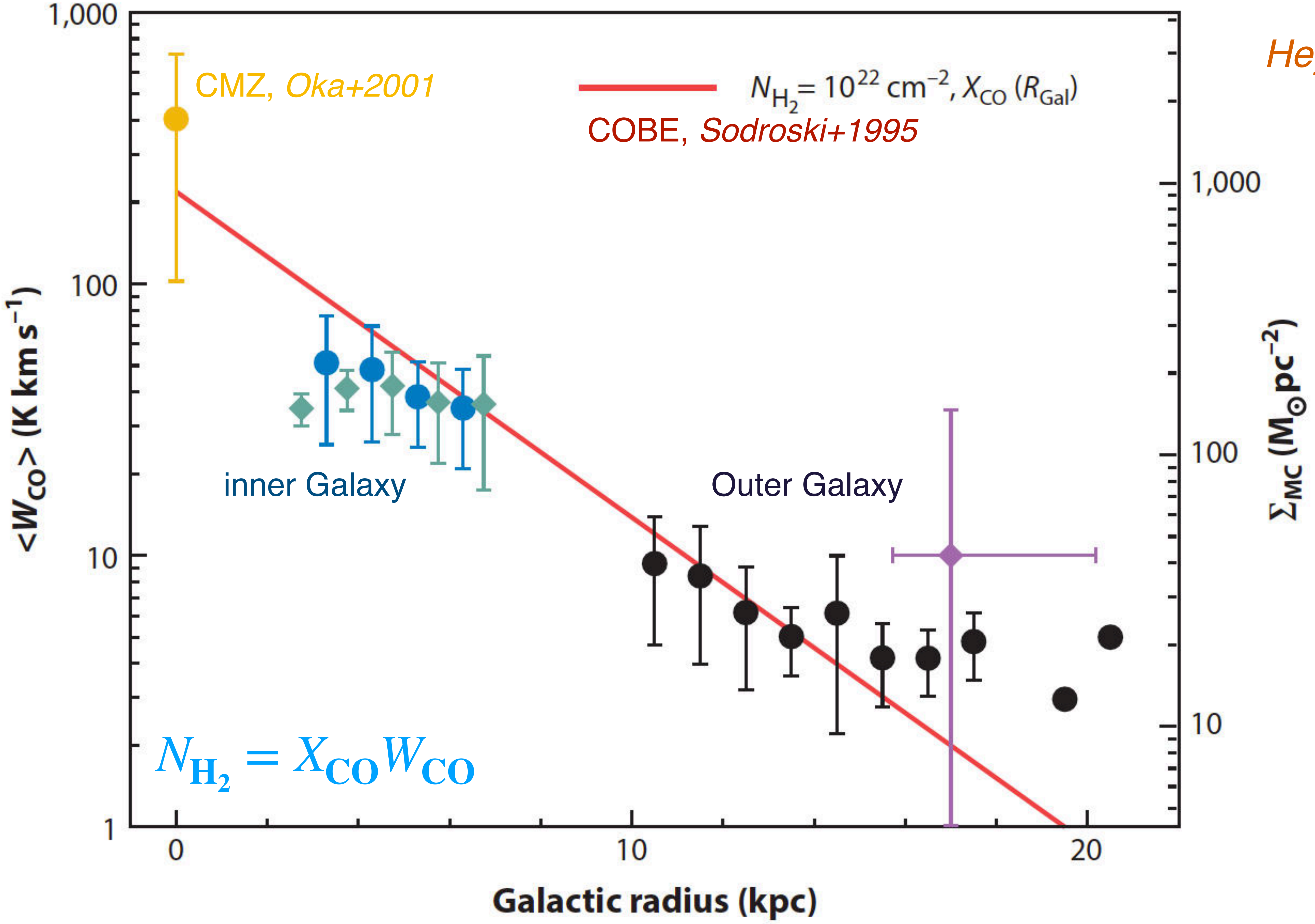
- essential tracers of heating and cooling processes
- allow to constrain physical conditions in star-forming environment (gas temperature and density, UV radiation fields, ..)

# Far-IR line cooling in different environments



Atomic gas cooling is more dominant in low-metallicity environments
(lower molecular and dust abundances, less shielding from UV)

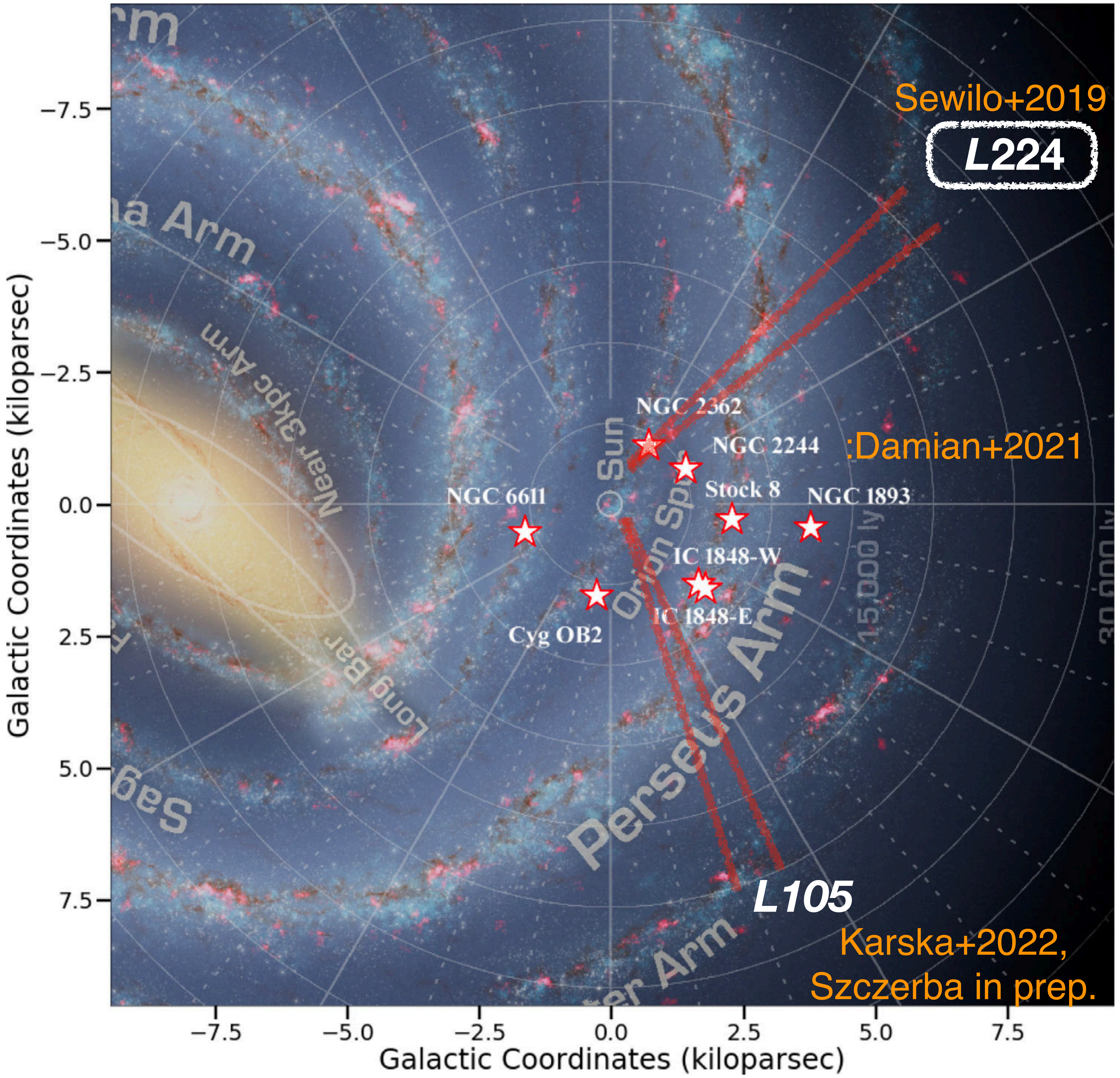
# CO vesus galactocentric distance in our Galaxy



*Heyer & Dame 2015*

- Changes of metallicity, gas-to-dust ratio, and environmental conditions (UV, CR, gas densities) might influence star formation in the outer Galaxy
- Star formation efficiency might also depend on the distance from the center of the Milky Way

# Outer Galaxy as a laboratory of star formation at low metallicities



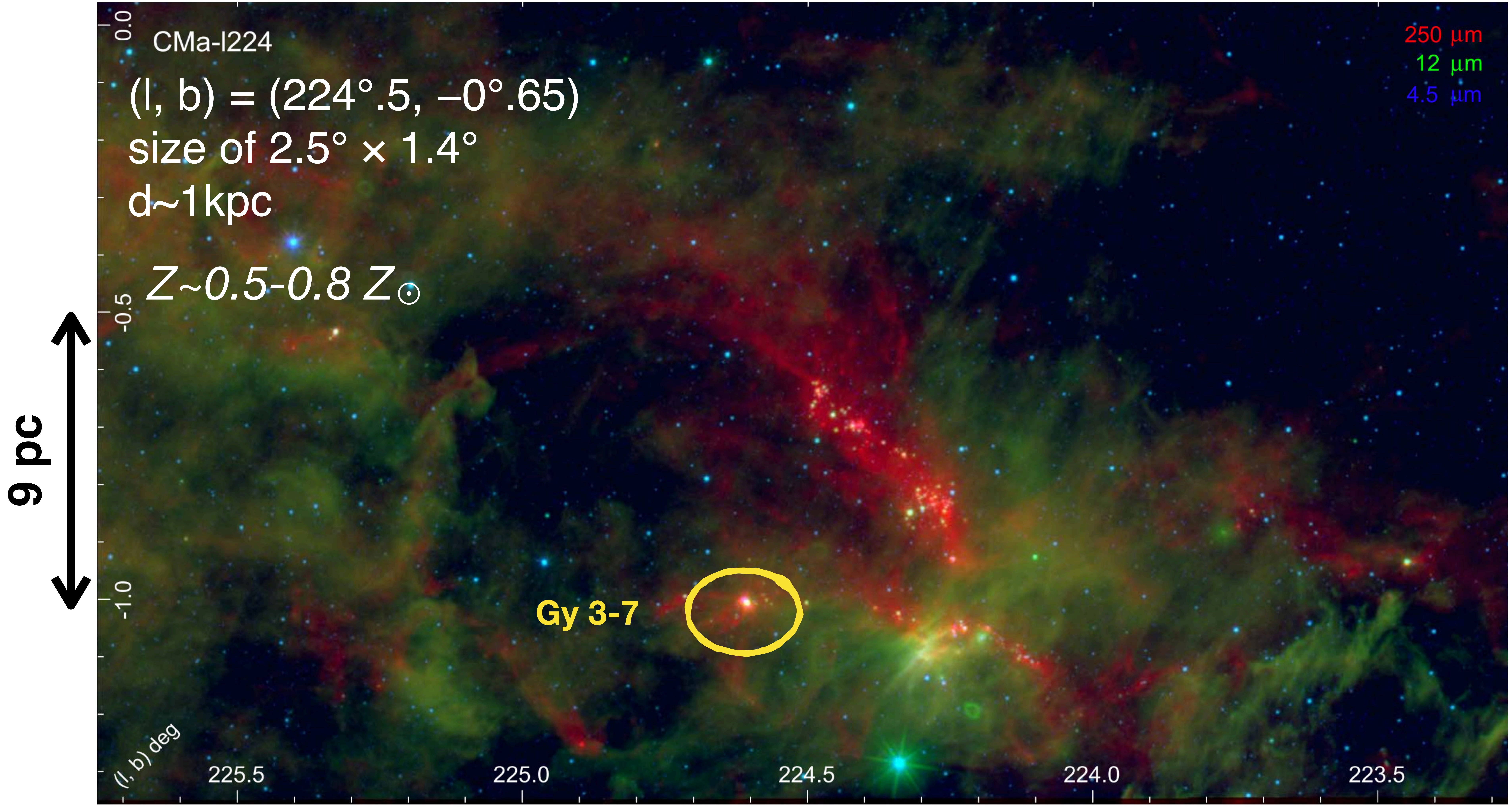
Sewilo+2019

:Damian+2021

Karska+2022, Szczerba in prep.

- potential to reveal the impact of environment (metallicity, UV radiation fields, etc., ) on star formation on YSO scales and global gradients in our Galaxy

# Canis Major star-forming region at l ~ 224°



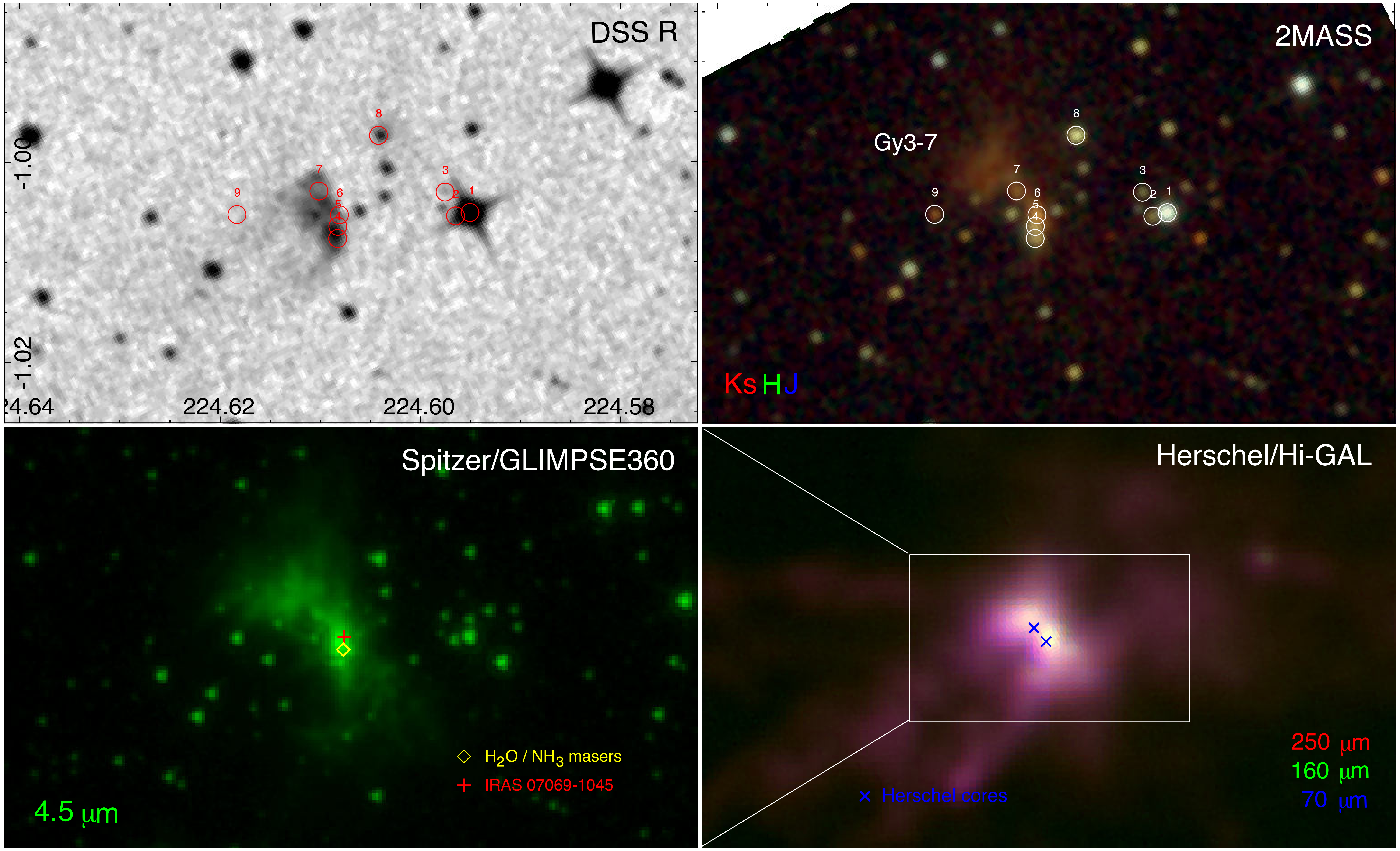
(l, b) = (224°.5, –0°.65)
size of 2.5° × 1.4°
d~1kpc

*Z~0.5-0.8 $Z_\odot$*

Sewiło+2019

- *Spitzer*/GLIMPSE360 + *Herschel*/Hi-GAL surveys
- Region with low dust temperatures and high $H_2$ column densities
- Gy 3-7 is an embedded cluster in the CMa-*l*224 region, very bright at far-IR

# Embedded Gy 3-7 cluster with extended 4.5 microns

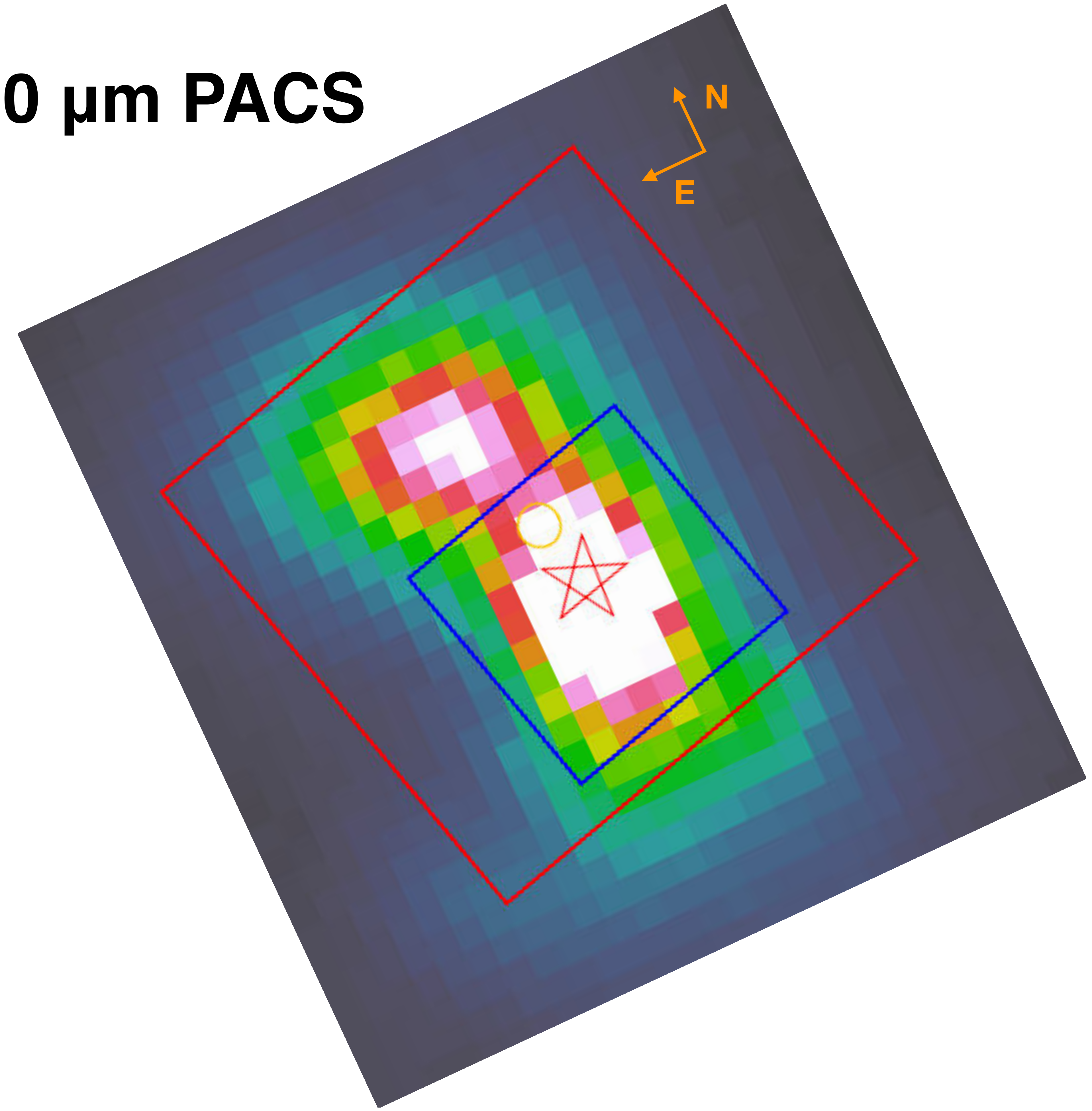


Two dense cores in the far-IR and a nebulosity in the near-IR (outflow shocks)

**What is the impact of metallicity on the far-IR line cooling?**

# What is the impact of metallicity on the far-IR line cooling?

**160 µm PACS**



**SOFIA/FIFI-LS far-IR spectroscopy of Gy 3-7 cluster**

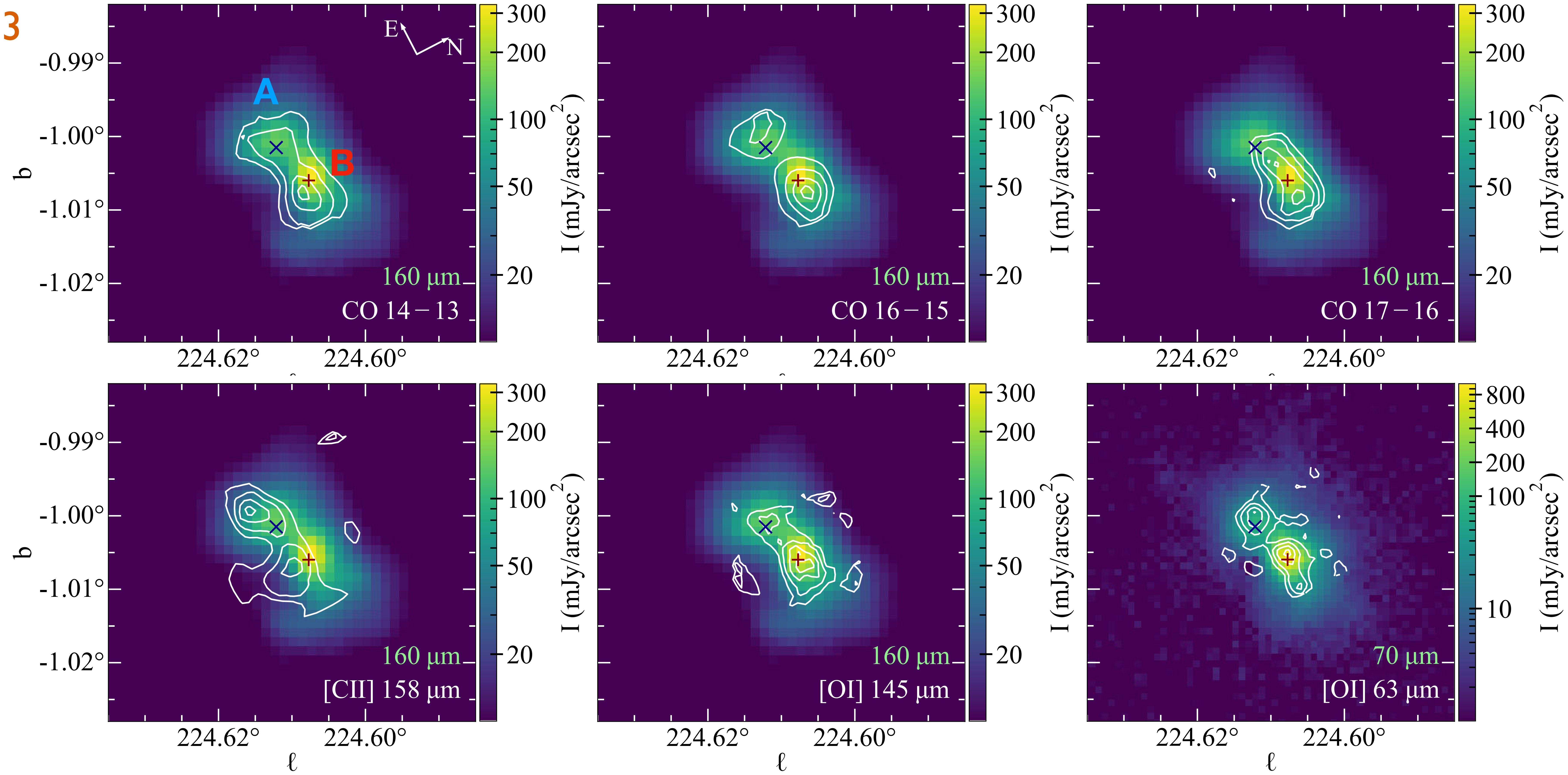
CO $J_{\mathrm{up}}$ = 14-31
[OI] at 63 and 145 µm
[CII] at 158 µm
OH at 79 µm

**FIFI-LS: Field-Imaging Far-Infrared Line Spectrometer**

- Two spectral channels: 50 – 120µm (blue) and 100 – 200 µm (red)
- Simultaneous spatial imaging with field of view ~ 30″ x 30″ and 60″x60″ (5x5 spatial size)
- Resolution R ~ 500-2000 with the spectral coverage ~ 1500 km/s

# Spatial extent of far-IR line emission

Lê +2023



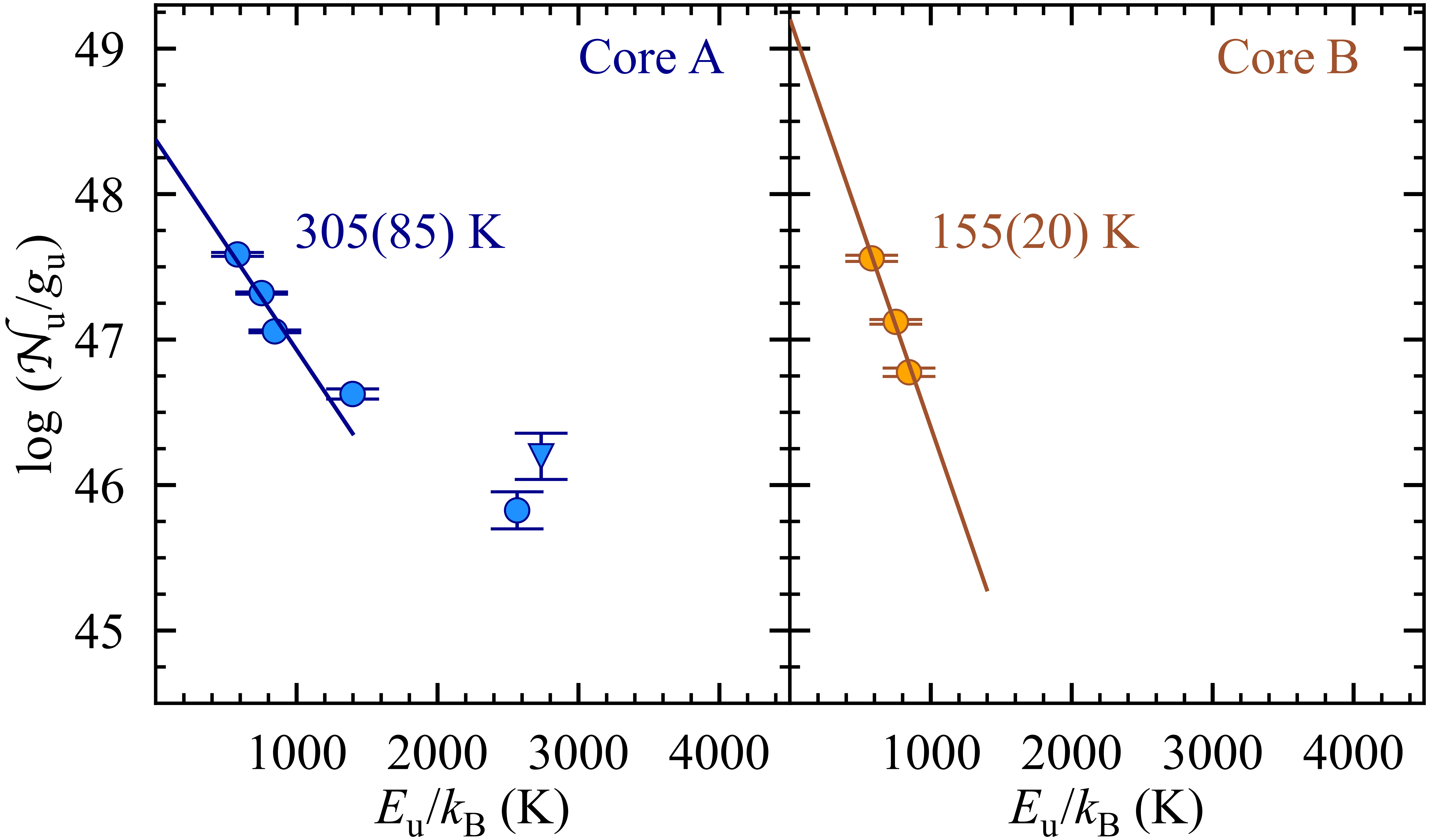
- Spatial extent of high-*J* CO($J_{up}$ ≥14) emission resembles that of elongated continuum emission at 160 µm.
- [O I] lines at 63 µm and 145 µm follow a similar pattern.
- Extended [C II] emission with peaks shifted away the far-IR continuum, tracing lower density gas.

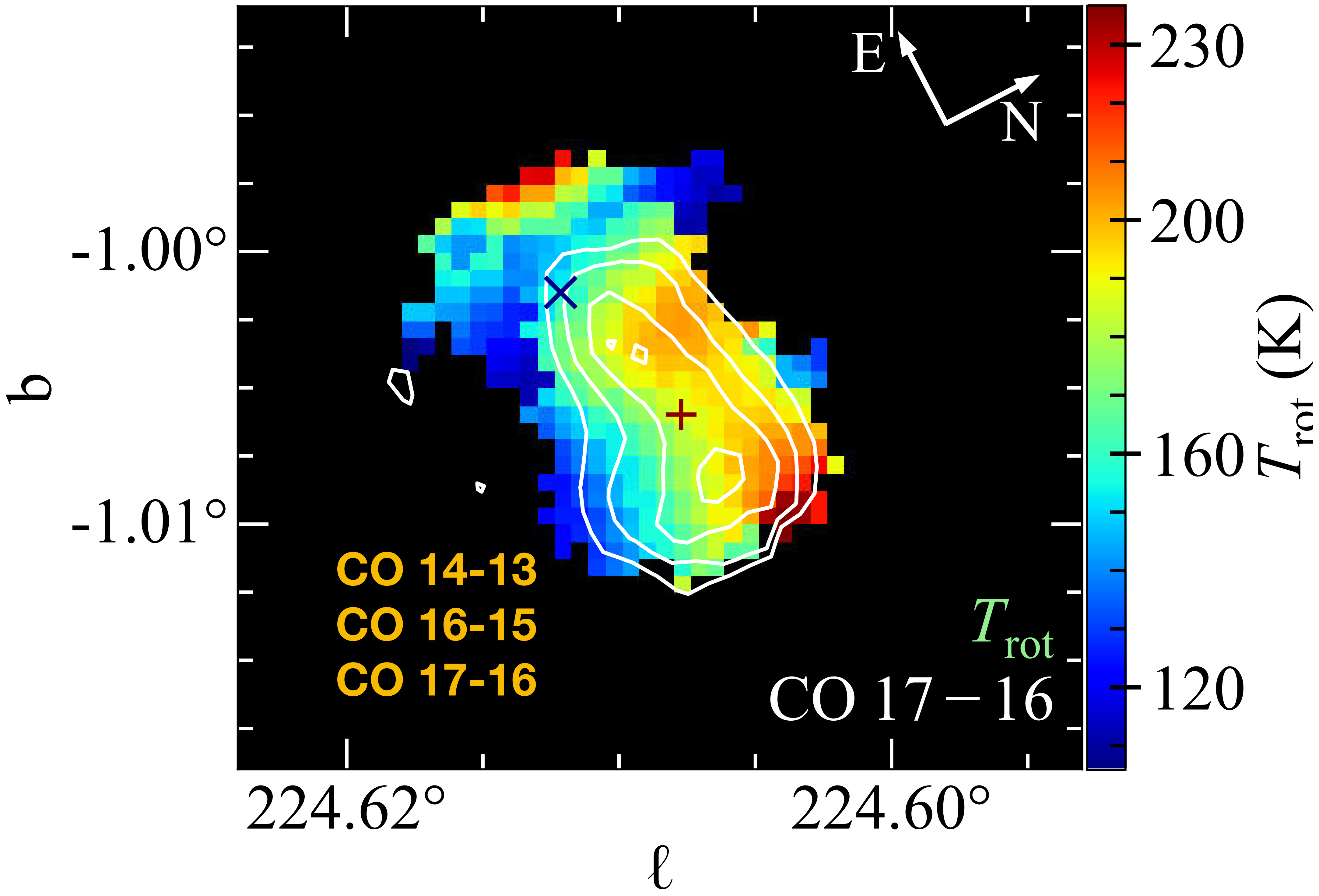
# Spectra of far-IR line emission

SOFIA FIFI-LS continuum-subtracted spectra toward 2 dense cores

(the emission is extracted within a beam size of 20″)

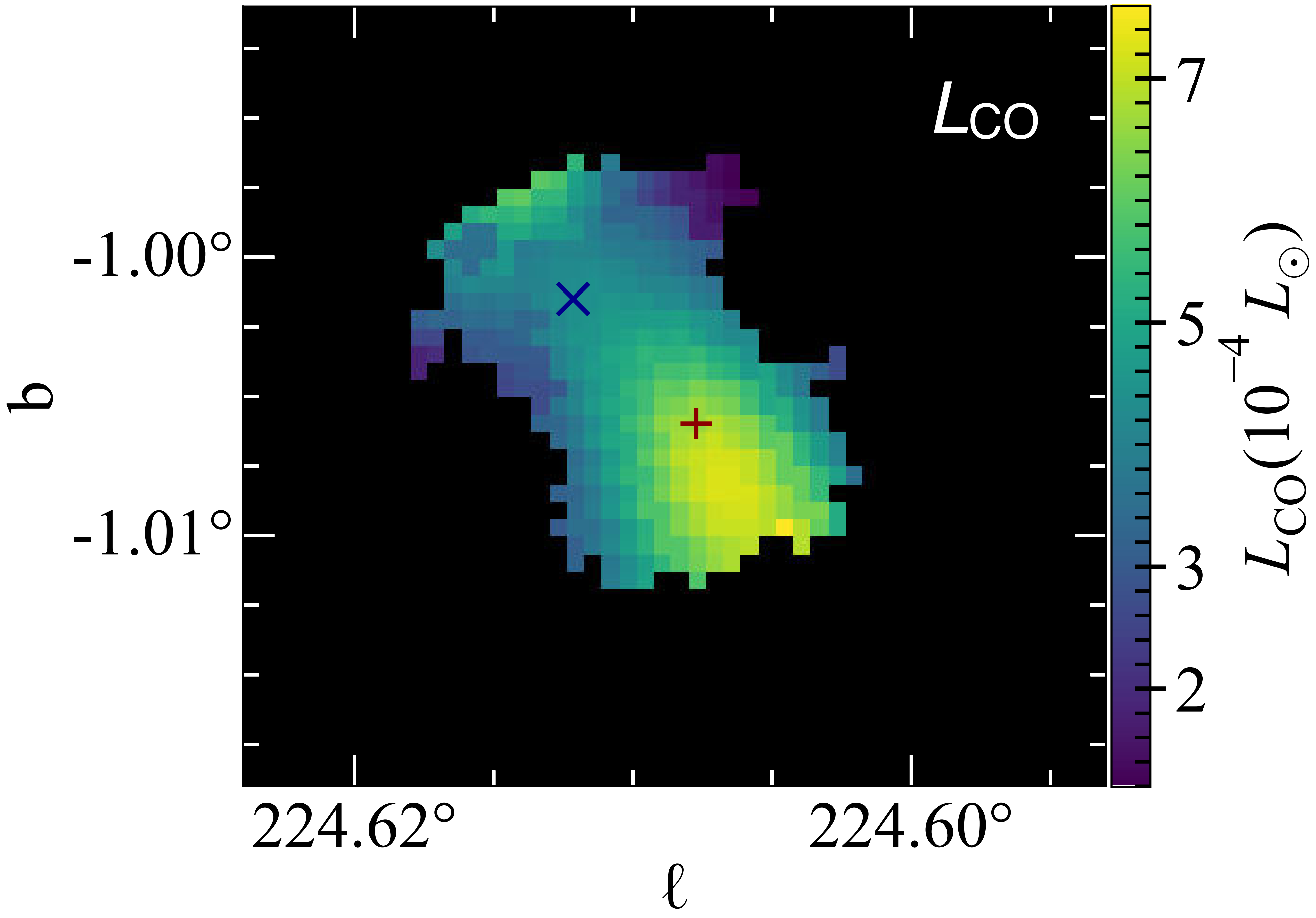
# CO rotational temperatures

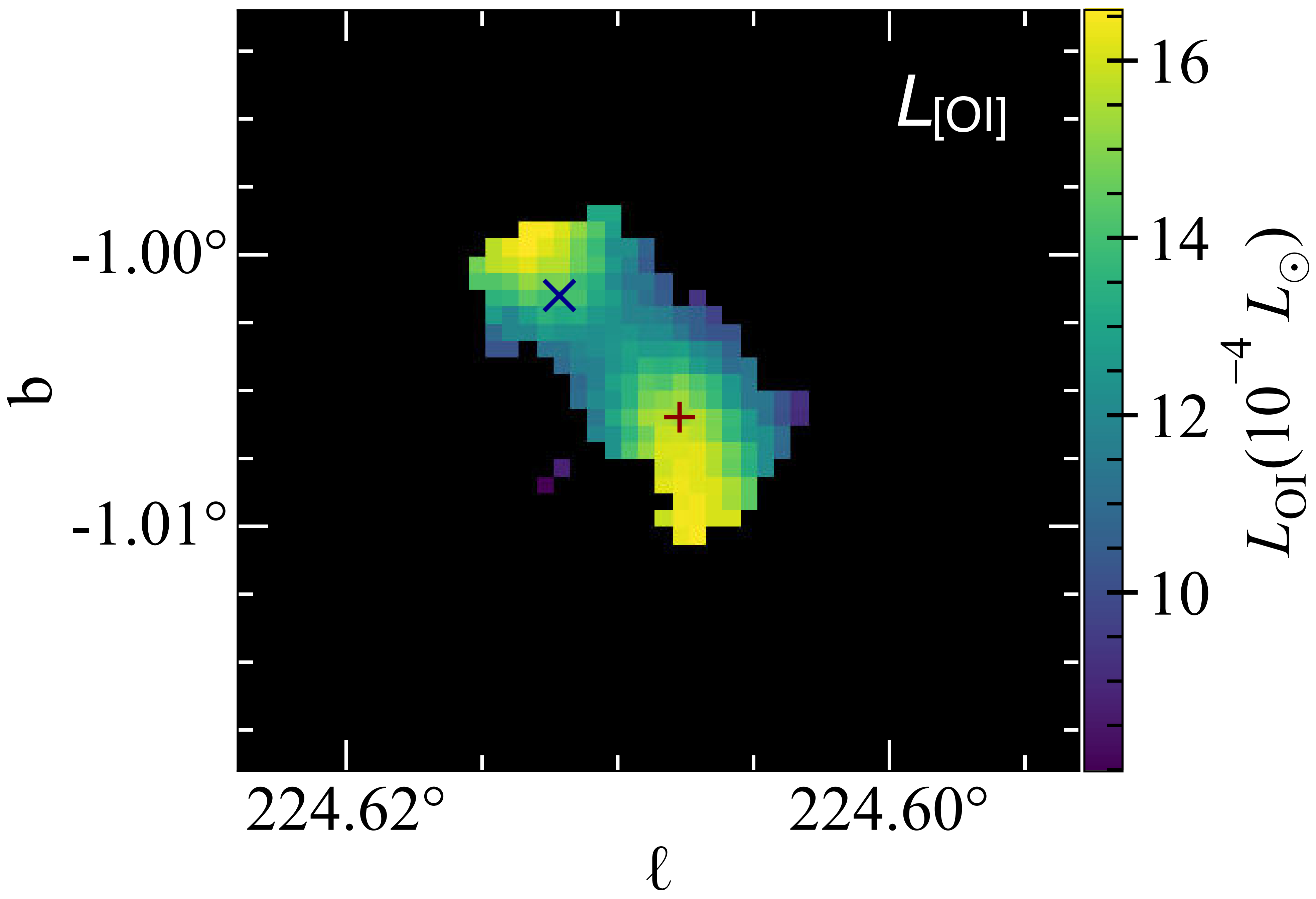




- CO rotational diagrams show the warm components toward two cores with $T_{rot}$ of 305 and 155 K
- $T_{rot}$~105 - 230 K throughout the cluster, using high–*J* CO lines with $J_{up}$ = 14, 16, 17
- The highest $T_{rot}$ in the vicinity of dense cores (slightly shifted)

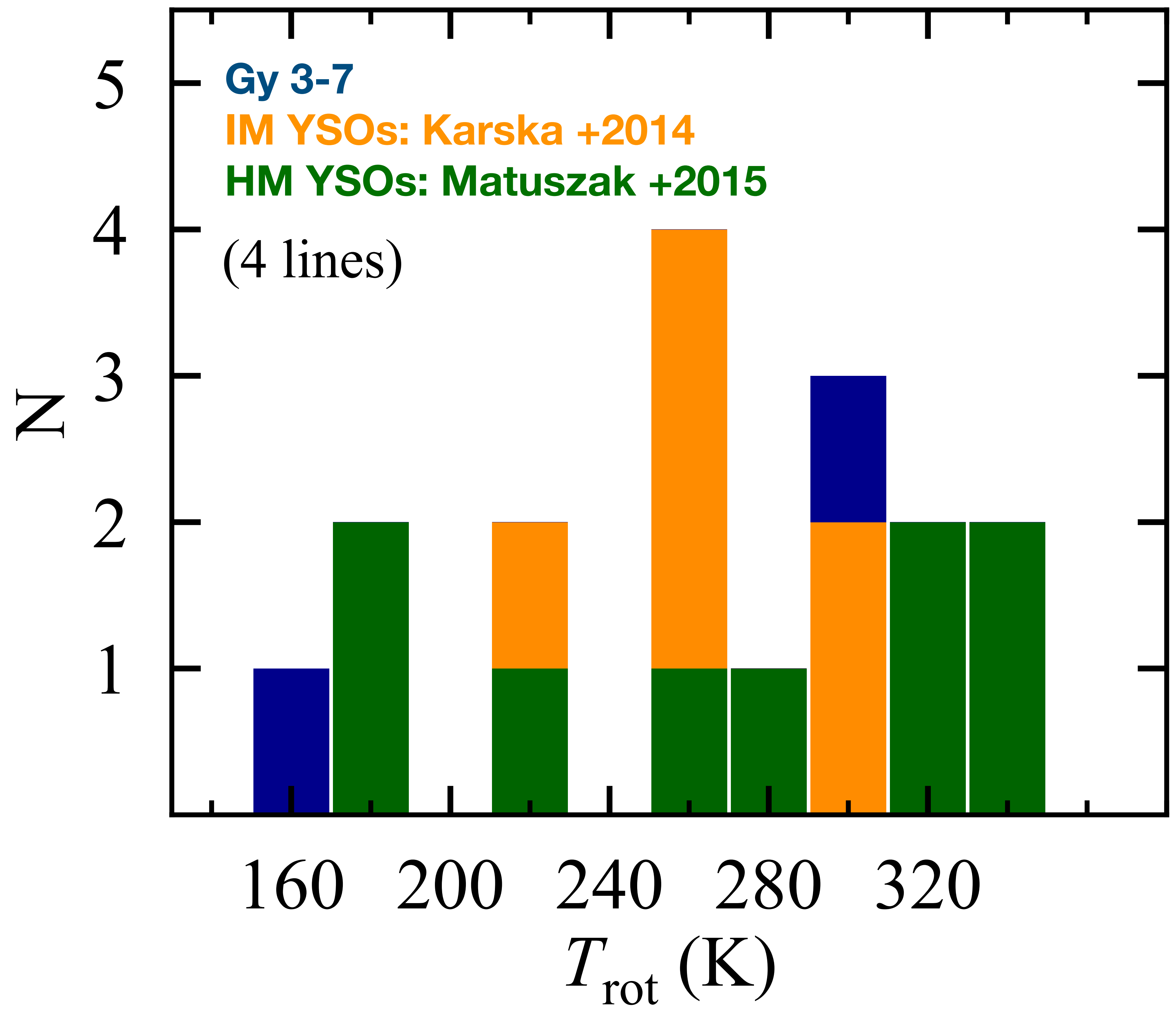
# Far-IR line cooling budget





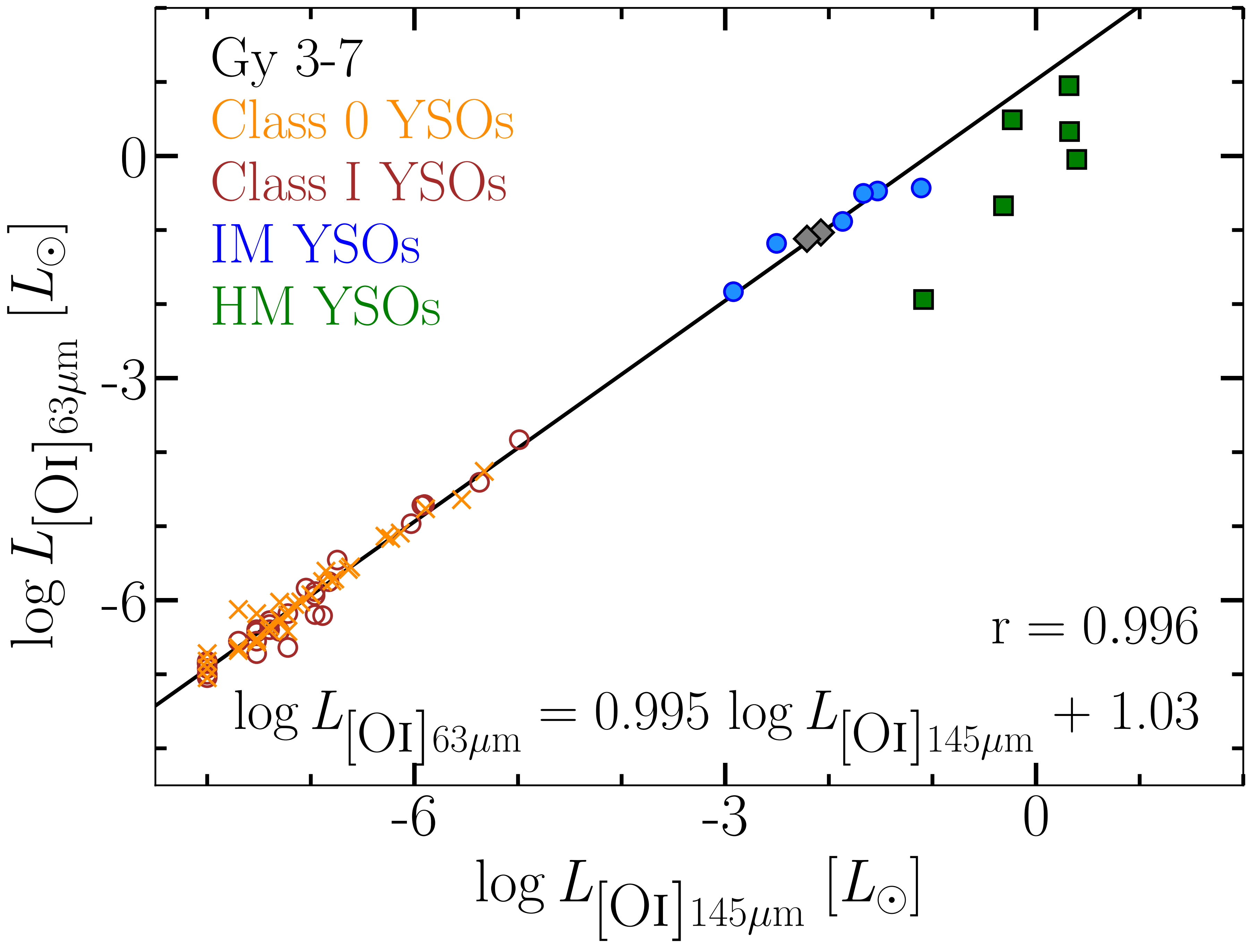
- Total luminosity of "warm" CO component and of [OI] lines are derived from CO rotational diagrams fitting

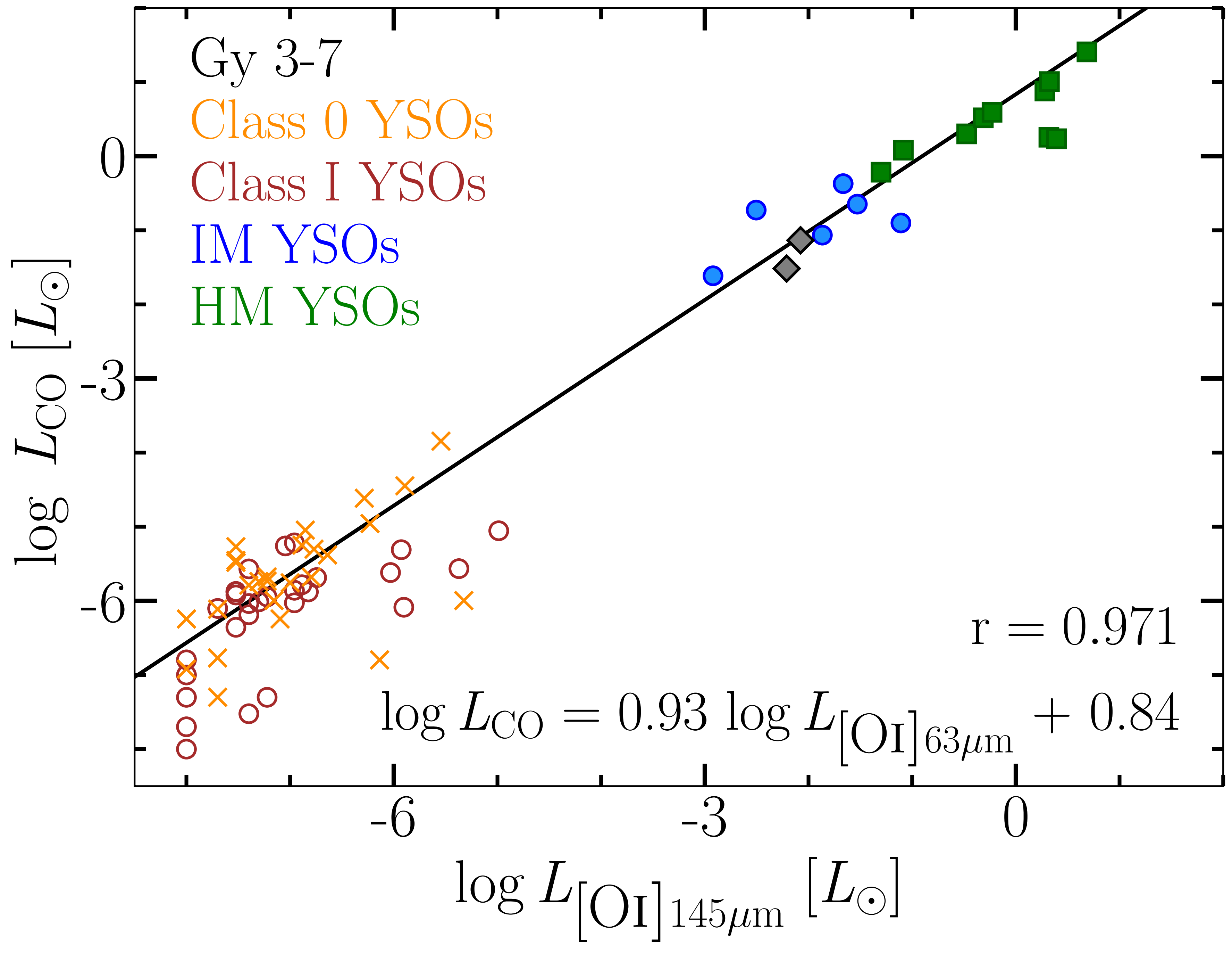
# CO rotational temperatures



- Similar $T_{rot}$ values have been detected toward IM and HM YSOs in the inner Milky Way (we calculated $T_{rot}$ using the same or similar CO transitions )

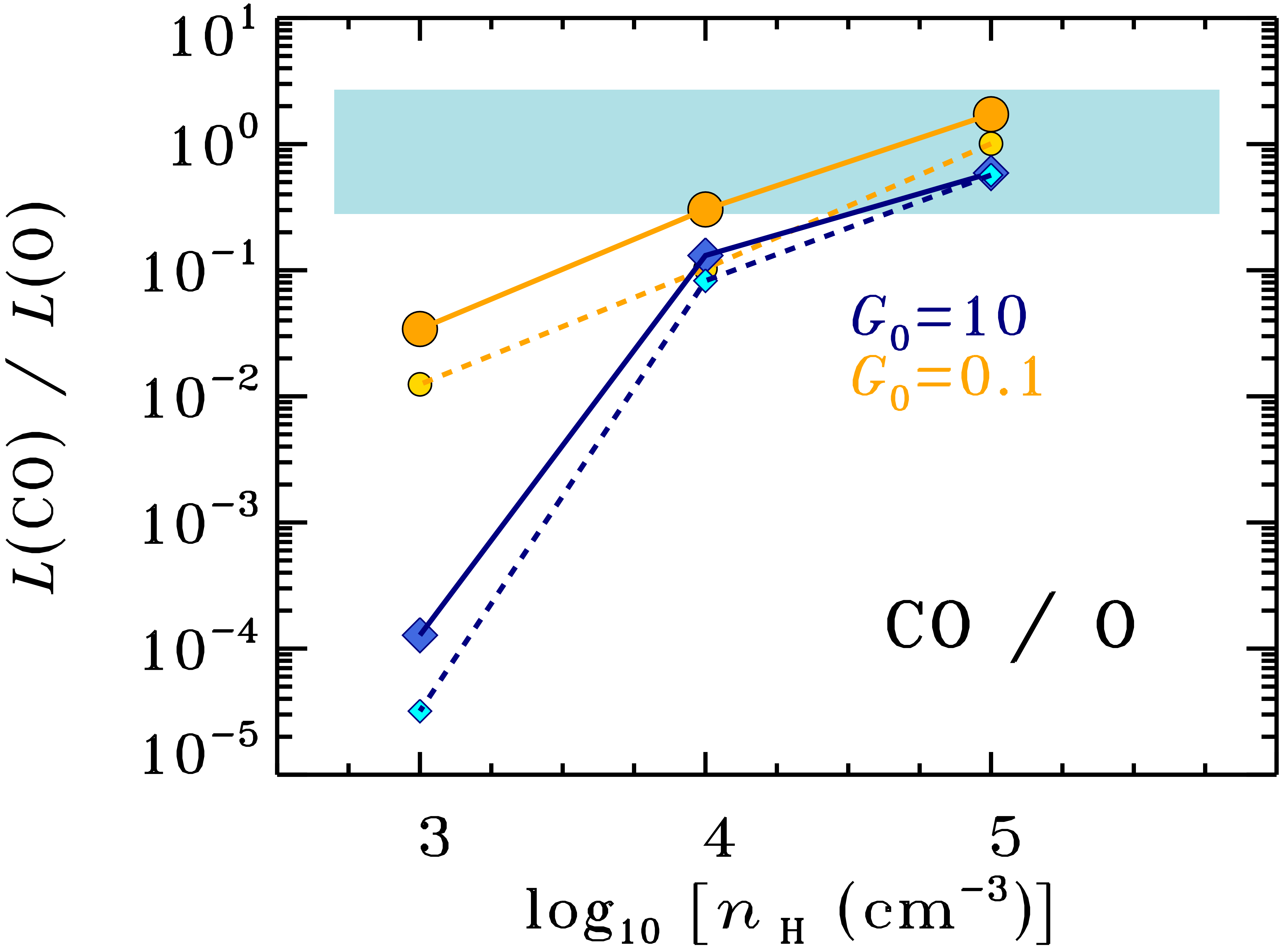
# Far-IR line cooling budget





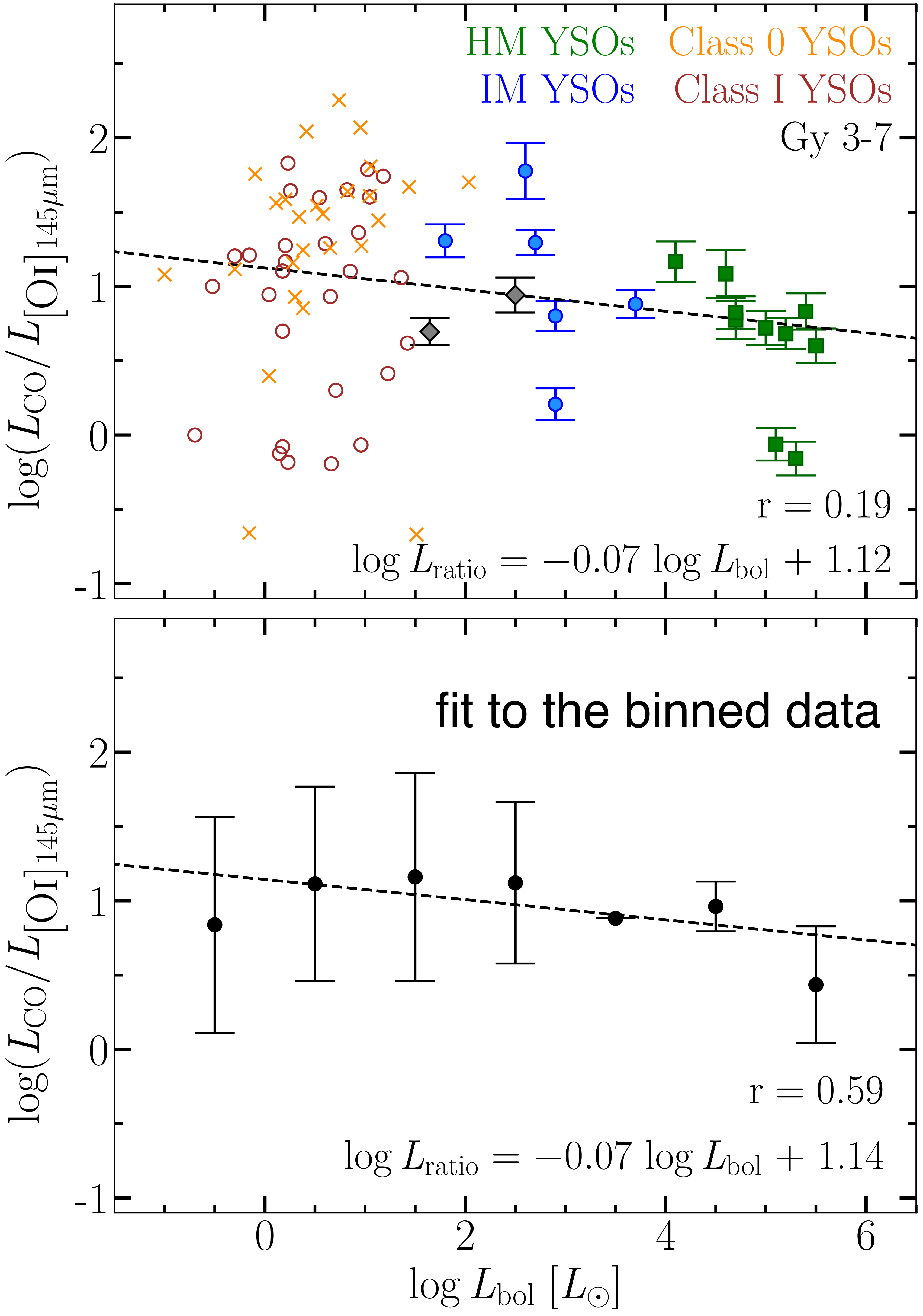
- Strong correlation between luminosities of [OI] lines, and of [OI] 145 µm and CO lines in Gy 3-7 cores
- Consistent with results found in other low- to high-mass YSOs in the Milky Way

# Gas density and UV radiation fields



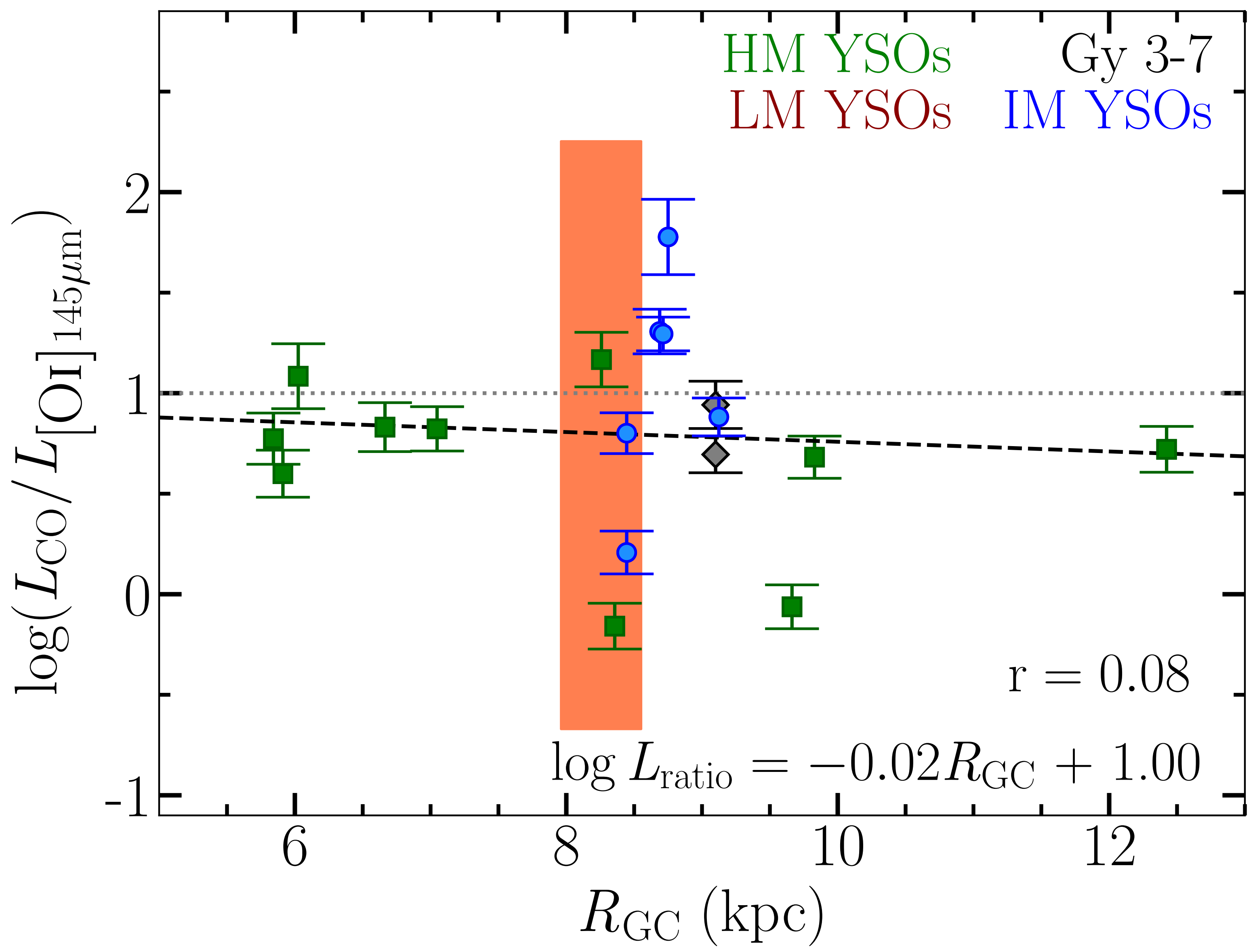
- The CO / [O I] line luminosity ratio of Gy 3–7 cores and other intermediate-mass YSOs is consistent with C-type shocks propagating at pre-shock densities of $10^4$ –$10^5$ cm$^{-3}$ and UV fields of 0.1-10 times the average interstellar radiation field (G0).

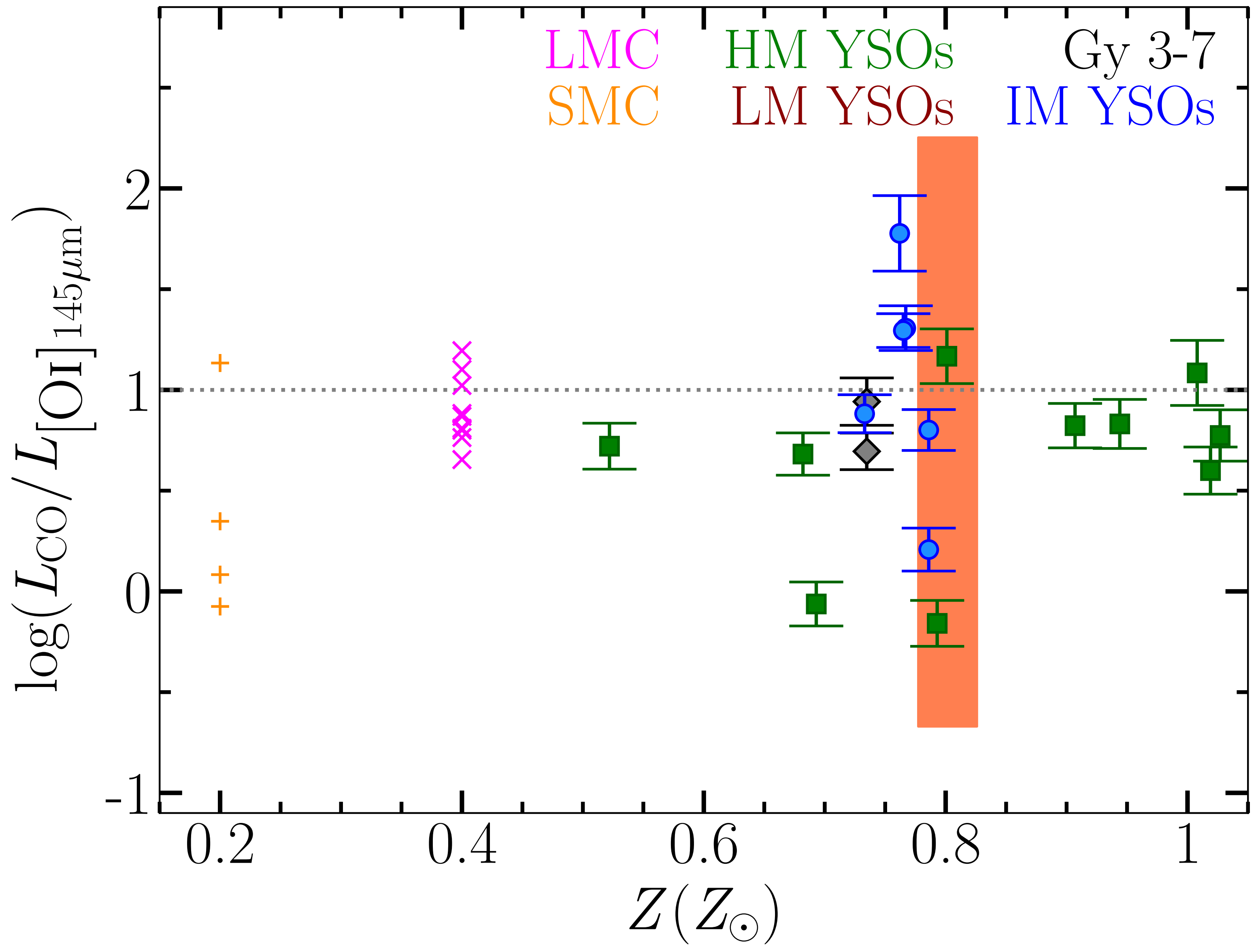
# Impact of metallicity on line cooling?



- The ratio of warm CO and [O I] at 145 µm line luminosities from protostellar envelopes reveals a weak decreasing trend with the bolometric luminosity

# Impact of metallicity on line cooling?



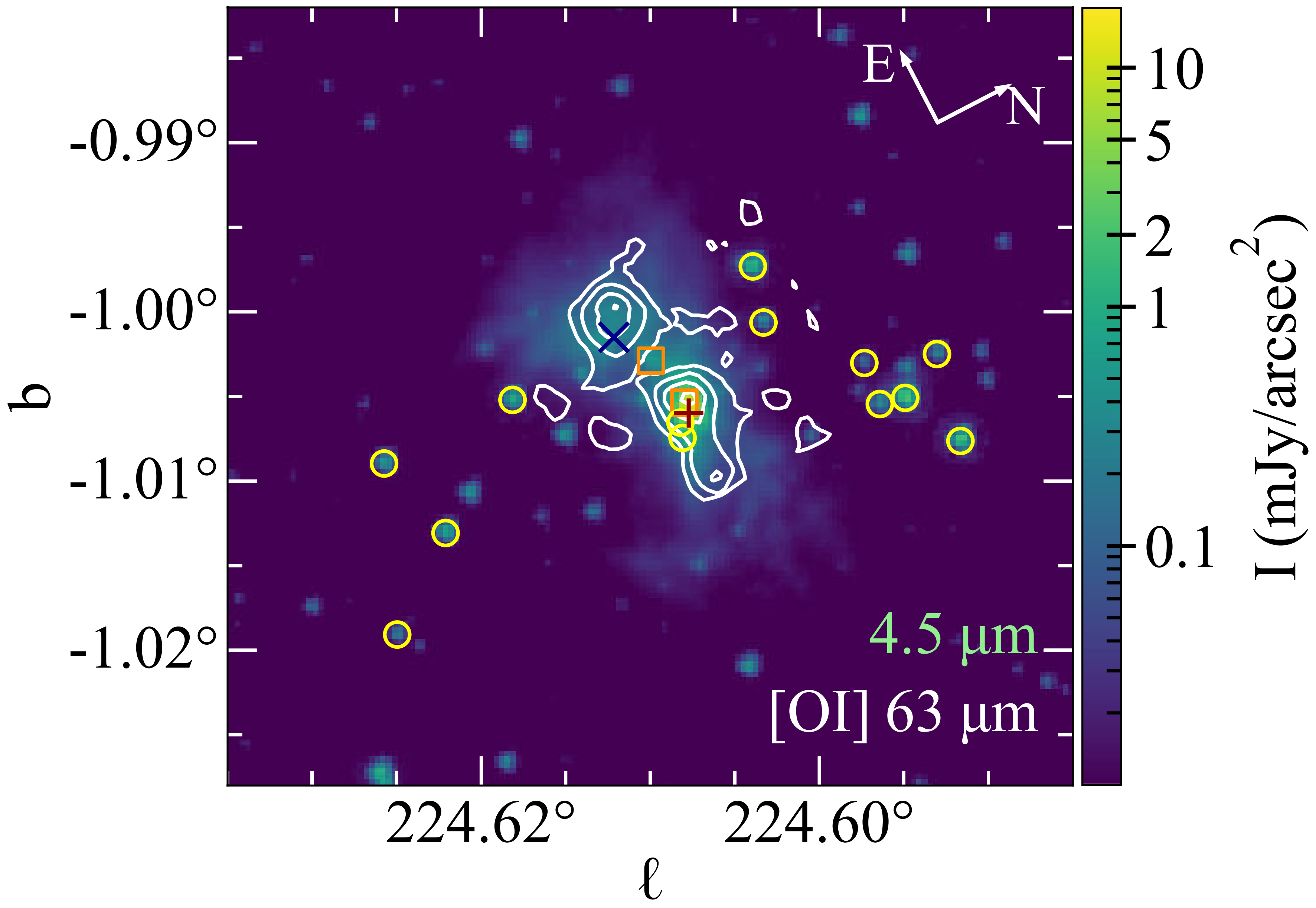


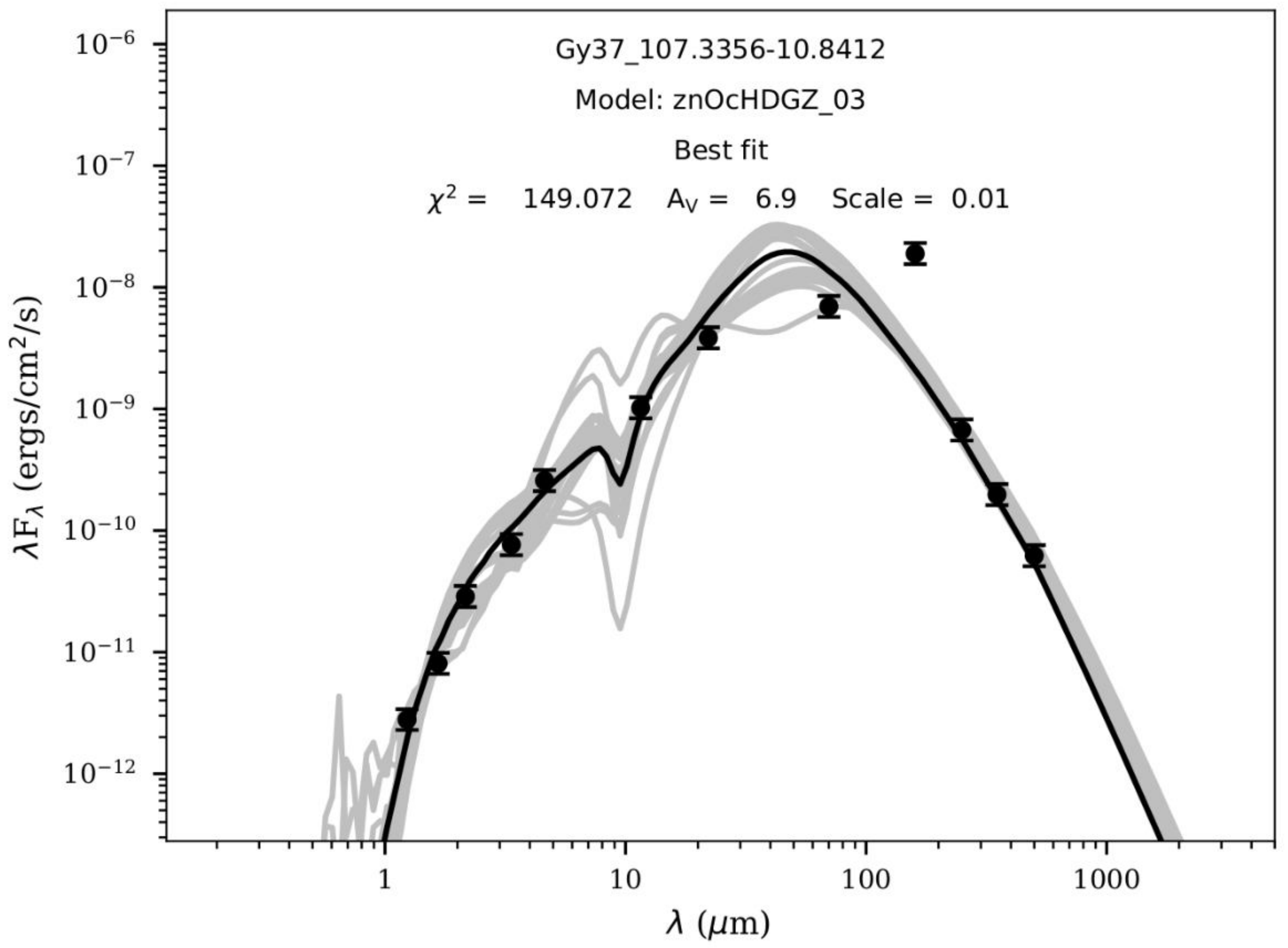
- The ratio of warm CO and [O I] at 145 µm line luminosities from protostellar envelopes reveals a weak decreasing trend with the Galactocentric radius

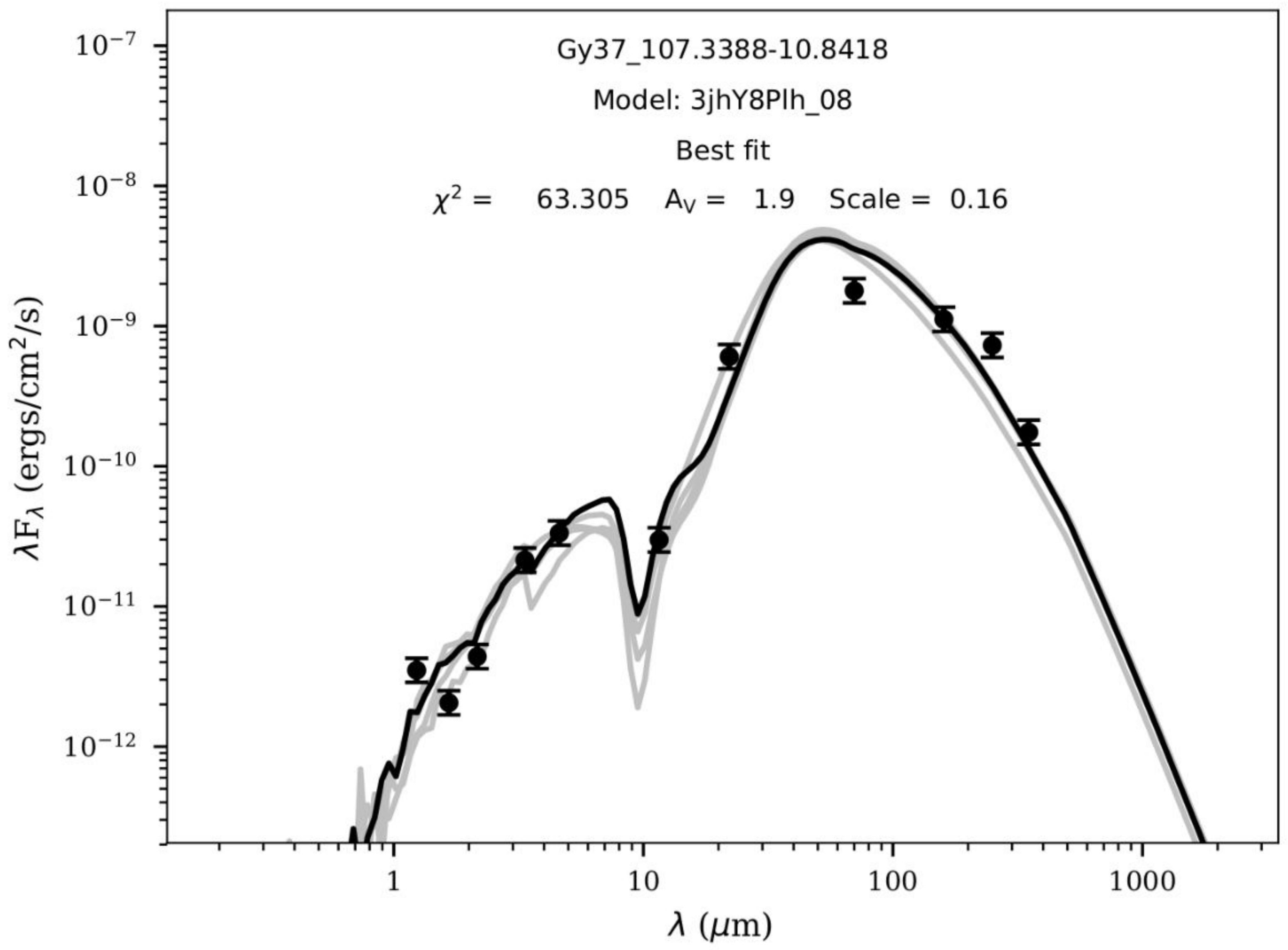
- No significant dependence of the line cooling in Gy 3–7 on metallicity is found.

# Physical properties of YSOs in Gy 3-7

candidates



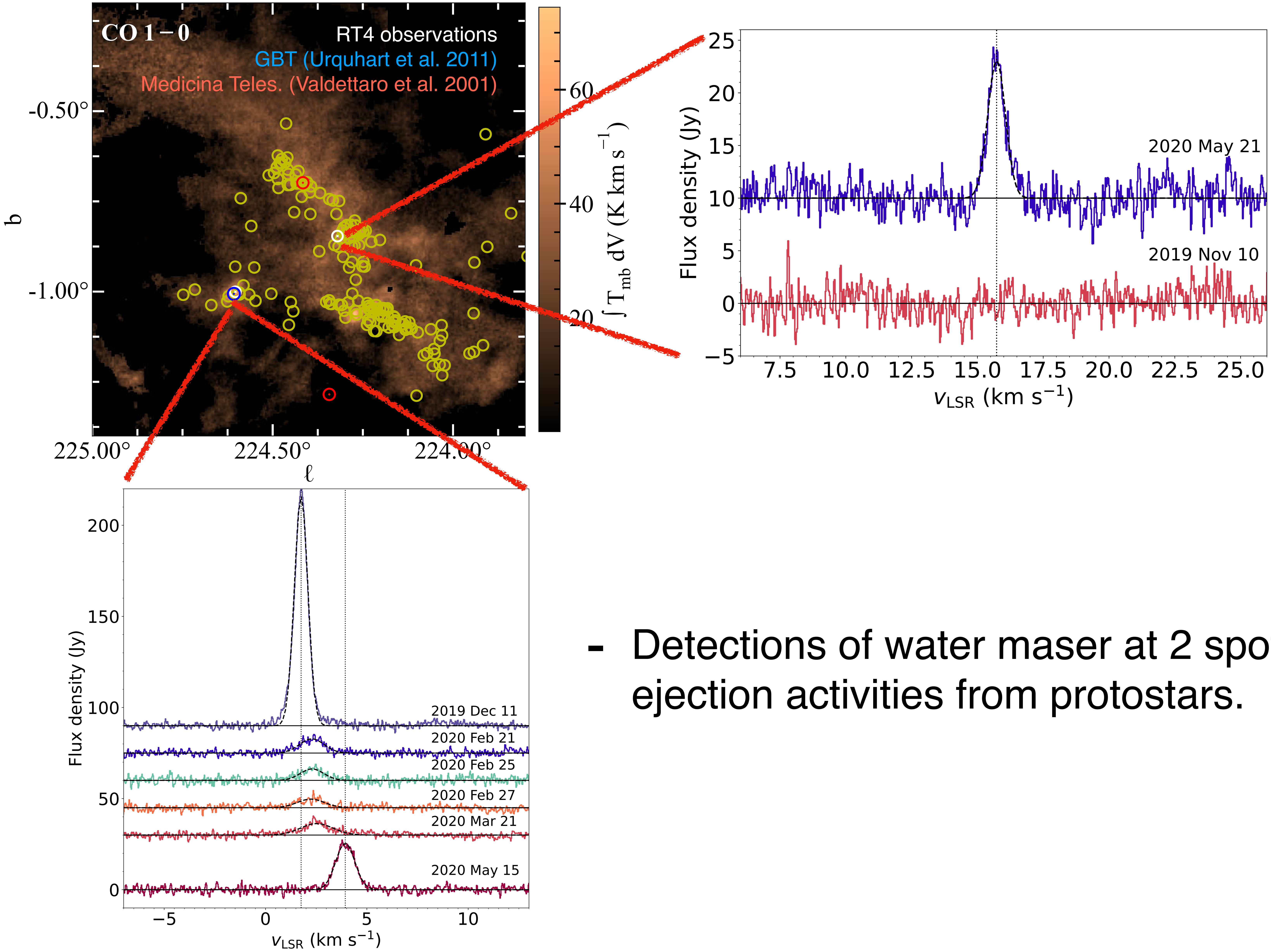




- 15 YSO candidates are collected from Tapia et al. (1997) and Sewiło et al. (2019)
- Physical parameters of 12/15 YSOs are obtained from a YSO SED model fitting (Robitaille 2017).
- 2 YSOs associated with Hi-GAL dense cores are well-fitted with YSO models including the envelope, confirming their early evolutionary stage (Class 0/I).
- The location of the Class 0 source at the center of Gy 3–7 cluster suggests that it might be the driving source of the outflow revealed by FIR emission

# 22 GHz water maser in CMa-l224

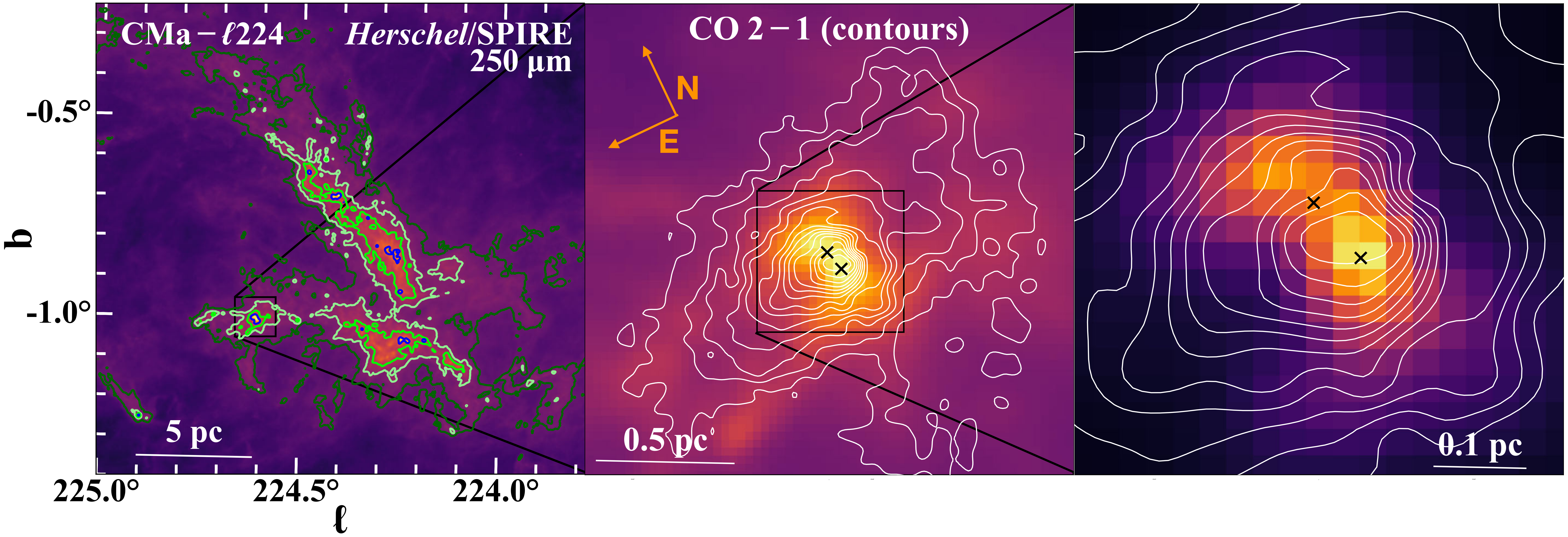
candidates



- Detections of water maser at 2 spots in CMa-*l*224 region confirm ejection activities from protostars.

# Gas kinematics: low-*J* CO lines

Lê + in prep., APEX PI 230
(OGHReS, König +2021)



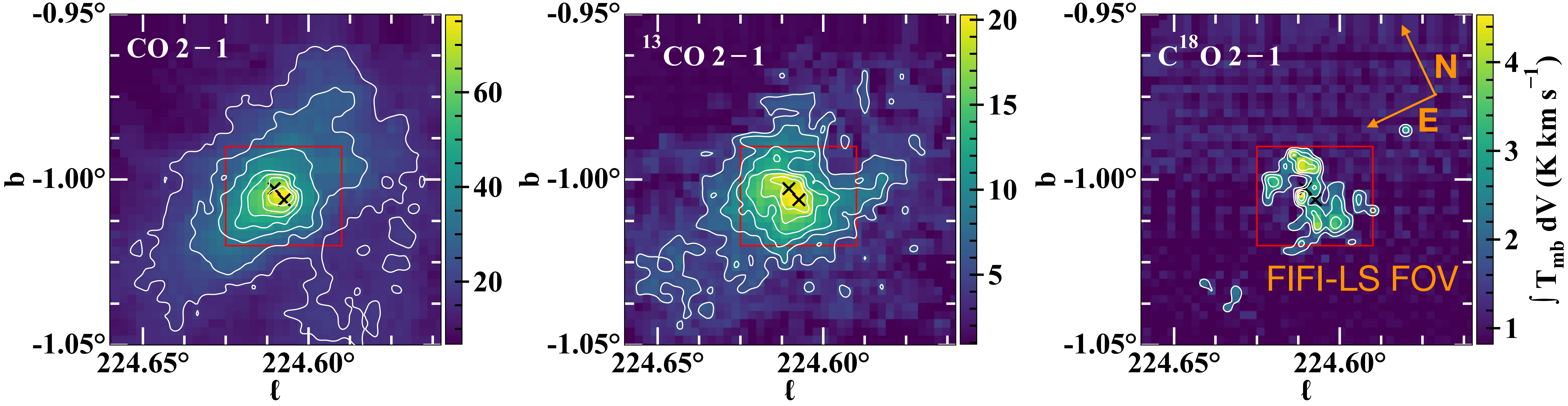
- Integrated line intensities of CO 2-1 show relatively low-density gas associated with the filament in the CMa-*l*224 region

- SPIRE 250 $\mu$m on 0.1 pc scales shows the region observed with FIFI-LS

# Maps of CO 2-1 isotopologues

Lê + in prep., APEX PI 230

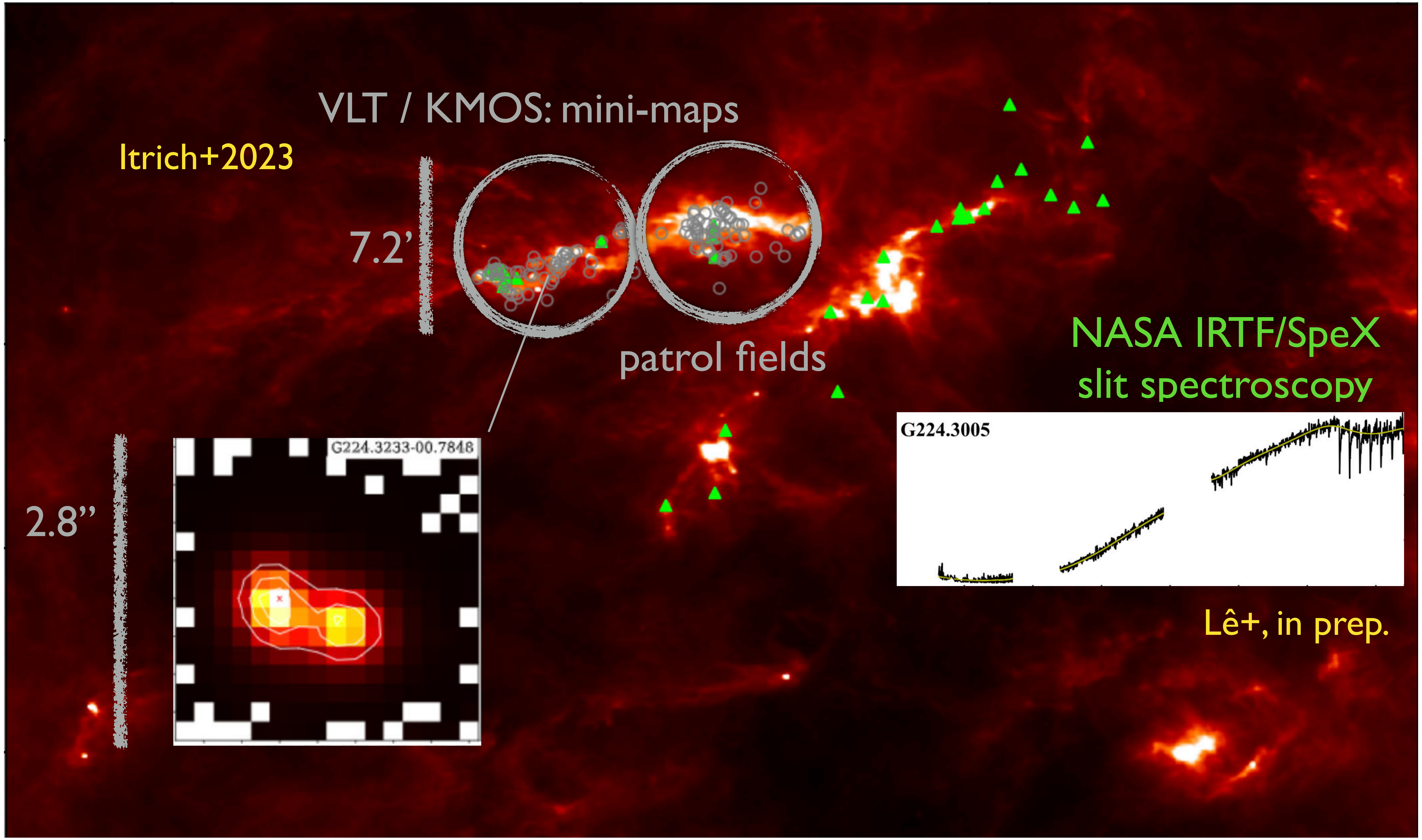
(OGHReS, König +2021)



- FIFI-LS field-of-view consists of the highest density gas traced by C$^{18}$O
- $^{12}$CO 2-1 is extended perpendicular to the far-IR and C$^{18}$O line emission; traces either the filament or some outflows

# Impact of metallicity on accretion of YSOs?

For details check:
Dominika Itrich et al.(2023) ApJS 267 46



- NASA IRTF: 33 sources, no spatial information; JHK bands
- KMOS: 2.8'' x 2.8'' maps of ~120 sources; K-band

# Conclusions and future plans

- Gy 3-7 shows a bright emission in high-*J* CO, [OI], and [CII] transitions, associated with dense cores.
- Rotational temperature ~ 305 and 155 K were obtained toward the dense cores using Boltzmann diagrams; they are consistent with results for other protostars in the inner Milky Way.
- Strong correlation between CO and [OI] luminosities their similar spatial extent suggest their common origin in outflows.
- Pre-shock gas density of $10^4$- $10^5$ cm$^{-3}$ and UV fields of 0.1-10 G0 are obtained toward Gy 3-7.
- The ratio of molecular-to-atomic far-IR line emission shows a decreasing trend with bolometric luminosities of the protostars, but does not show impact of metallicity

- Higher-resolution observations would be essential to unambiguously associate far-IR emission with candidate YSOs and their outflows.

**For details check:**

N. Lê et al. (2023), A&A, 674, 64