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Outflows from high-mass protostars: far-IR constraints on gas physical conditions and energetics

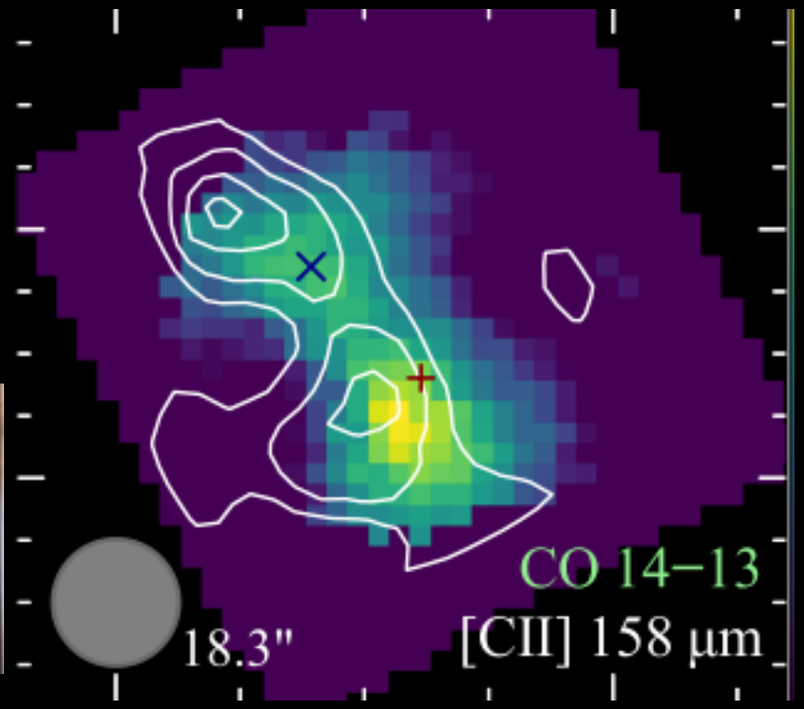
Agata Karska

Thanh Dat Hoang, Ngan Le, Miguel Figueira, Agnieszka Mirocha, Friedrich Wyrowski, Iason Skretas, Andre Beck, Christian Fischer, Randolf Klein, Maja Kaźmierczak-Barthel, Helmut Wiesemeyer, Sarwar Khan, Yao-Lun Yang, Karl Menten, Alfred Krabbe, Leslie Looney, Christof Iserlohe, Serina Latzko

SOFIA's view on high-mass outflows

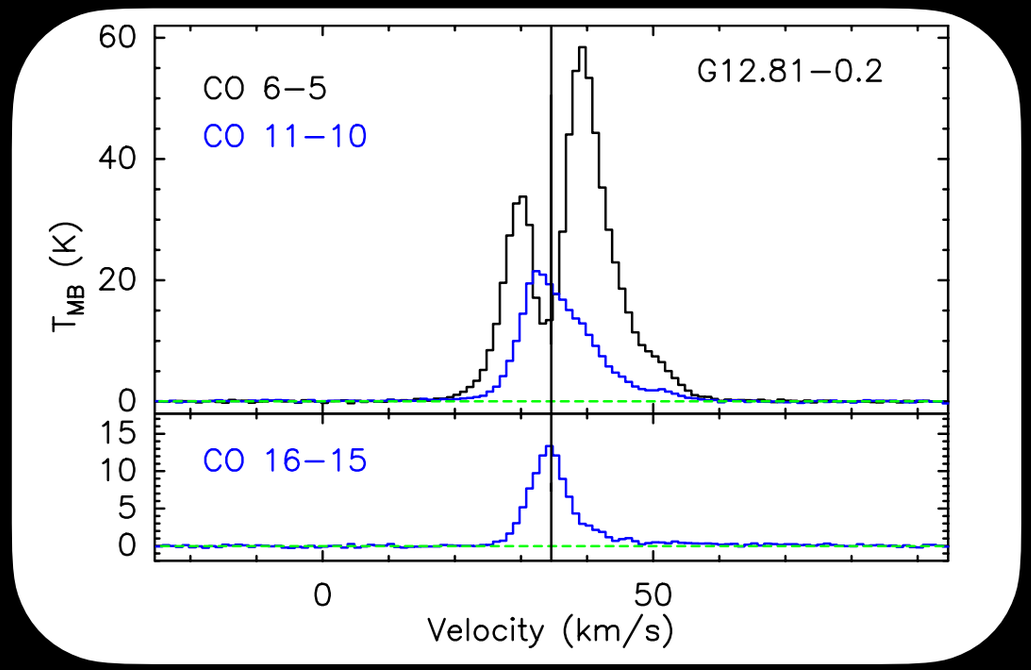
FIFI-LS

Ngan Lê
(NCU in Toruń)

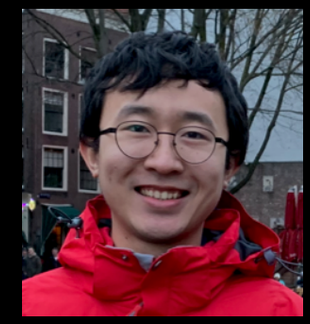


Lê, Karska+2023

GREAT



Hoang, Karska+2023

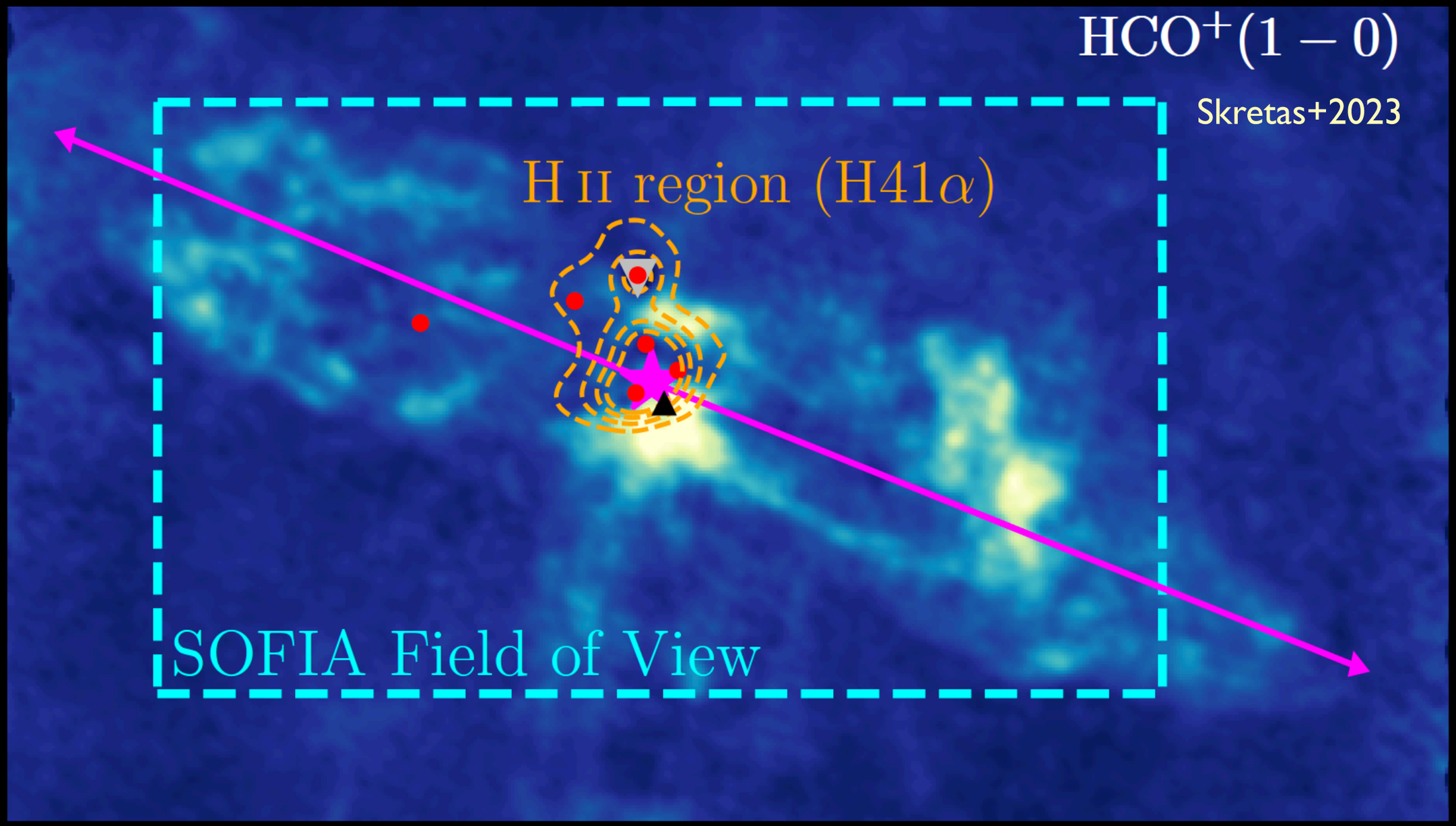


Thanh Dat Hoang
(MPIfR, Bonn)

- *FIFI-LS:* spatial distribution of far-IR emission in key gas coolants of outflows and photodissociation regions
- *GREAT*: gas kinematics associated with various physical components of typically very complex, high-mass star-forming regions

Spatially-resolved outflow of DR21 Main

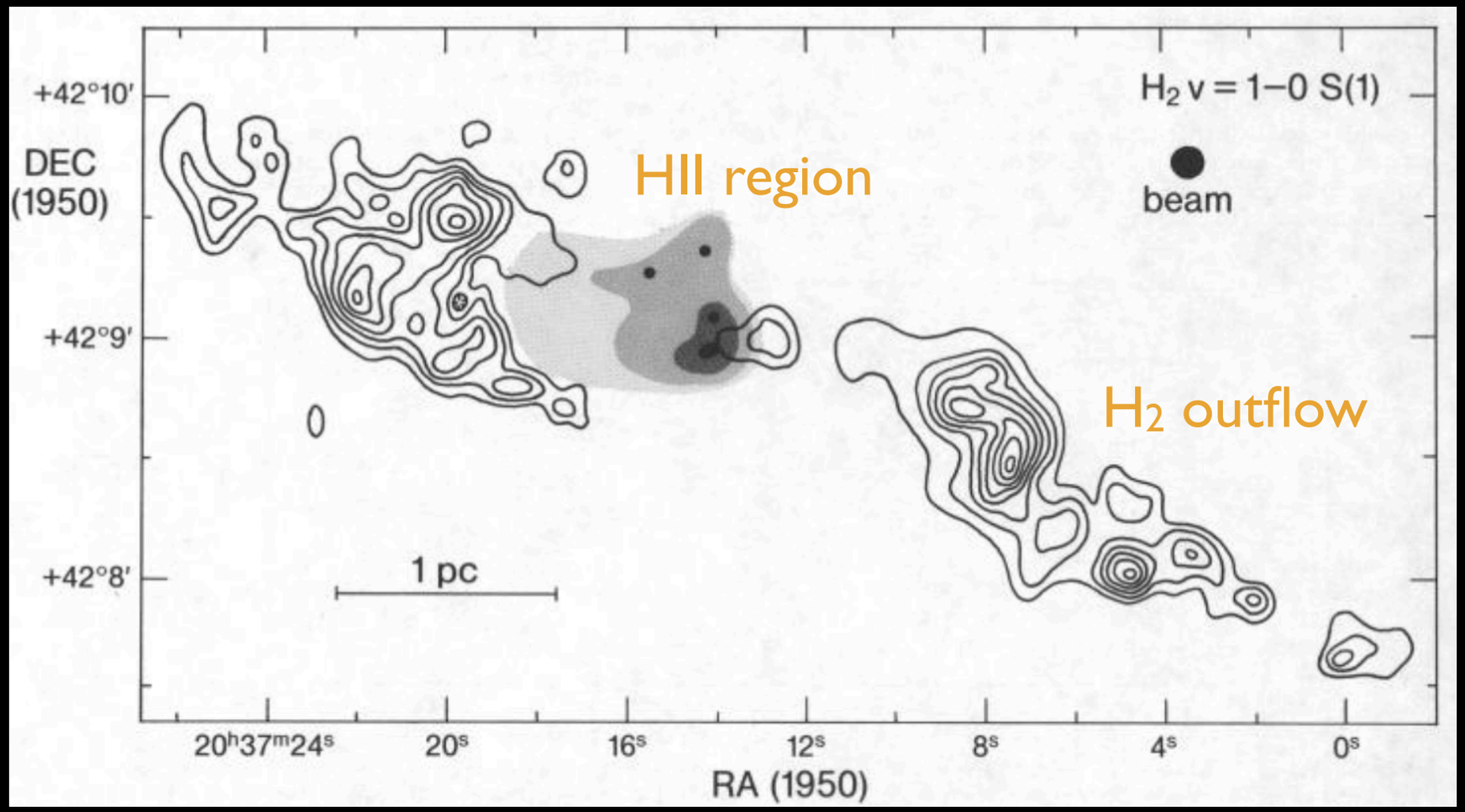
Aga Mirocha
(UJ, Kraków)



A. Karska+ in prep.

- Spatial distribution of far-IR tracers reveal complex physical structure
- FIFI-LS mosaic of 2.00’×3.75’ in CO 14-13, 16-15, OH at 163 μm, [O I] 63 and 145 μm, [C II] 157 μm, [OIII] at 52 and 88 μm

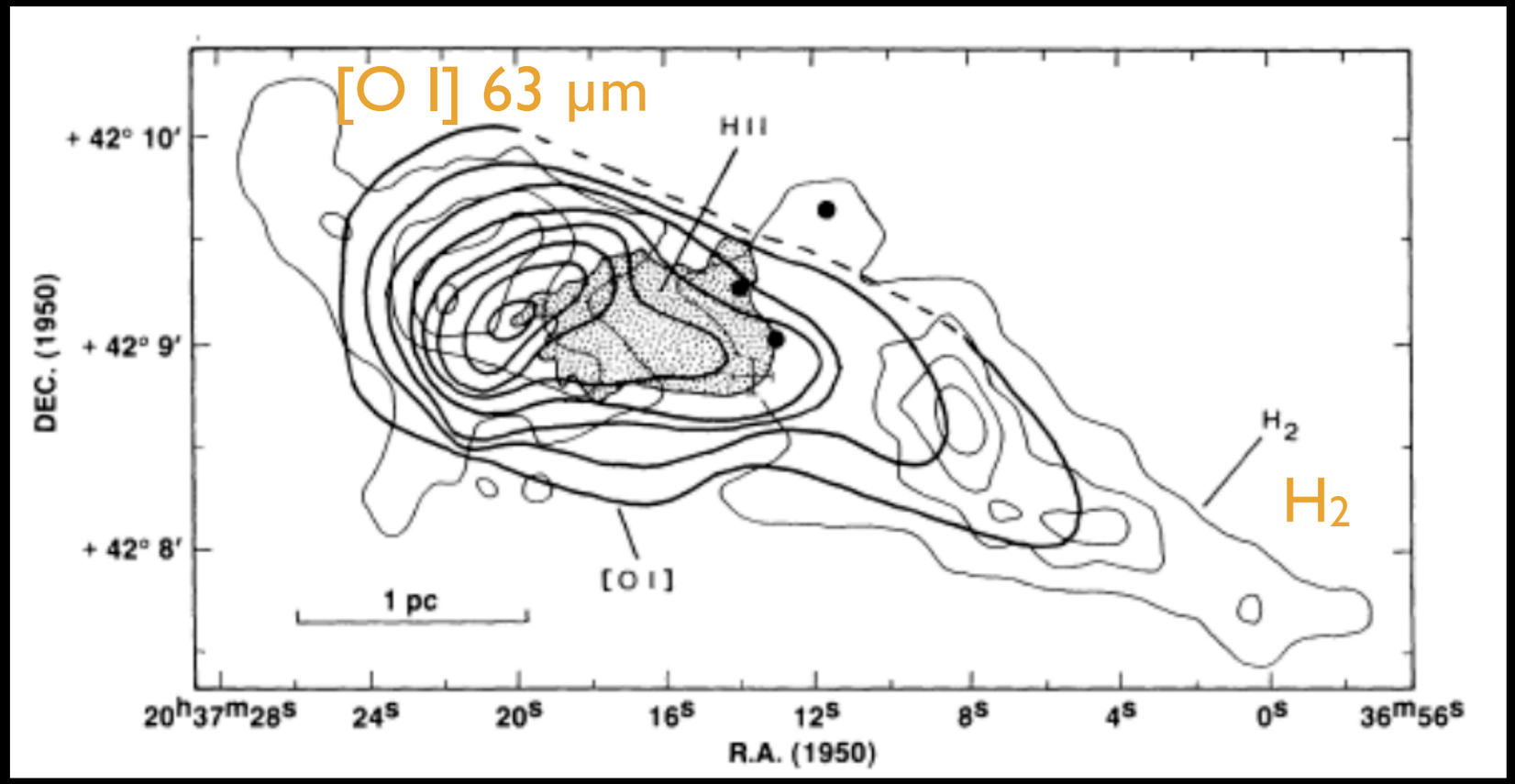
Extreme H_2 outflow in Cygnus X



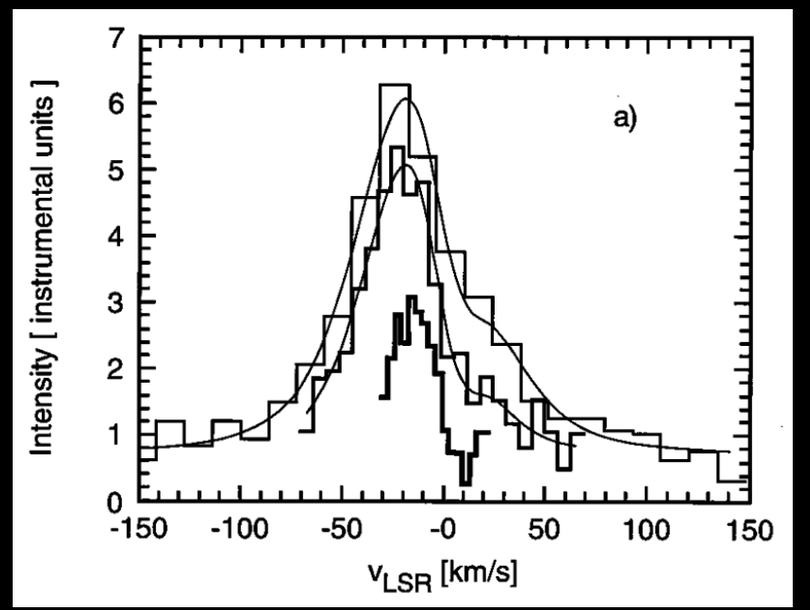
Garden+1991

- highly-collimated molecular outflow with H_2 luminosity of ~1800 $L_\odot$ (Garden+1986,1991, Davis+2007); high-velocity wings up to 100 km/s and line ratios consistent with shocks propagating in a high-density environment
- central HII region revealed by radio continuum and hydrogen recombination lines (Roelfsema+1989, Cyganowski+2003)

Far-IR emission in [O I] 63 μm line



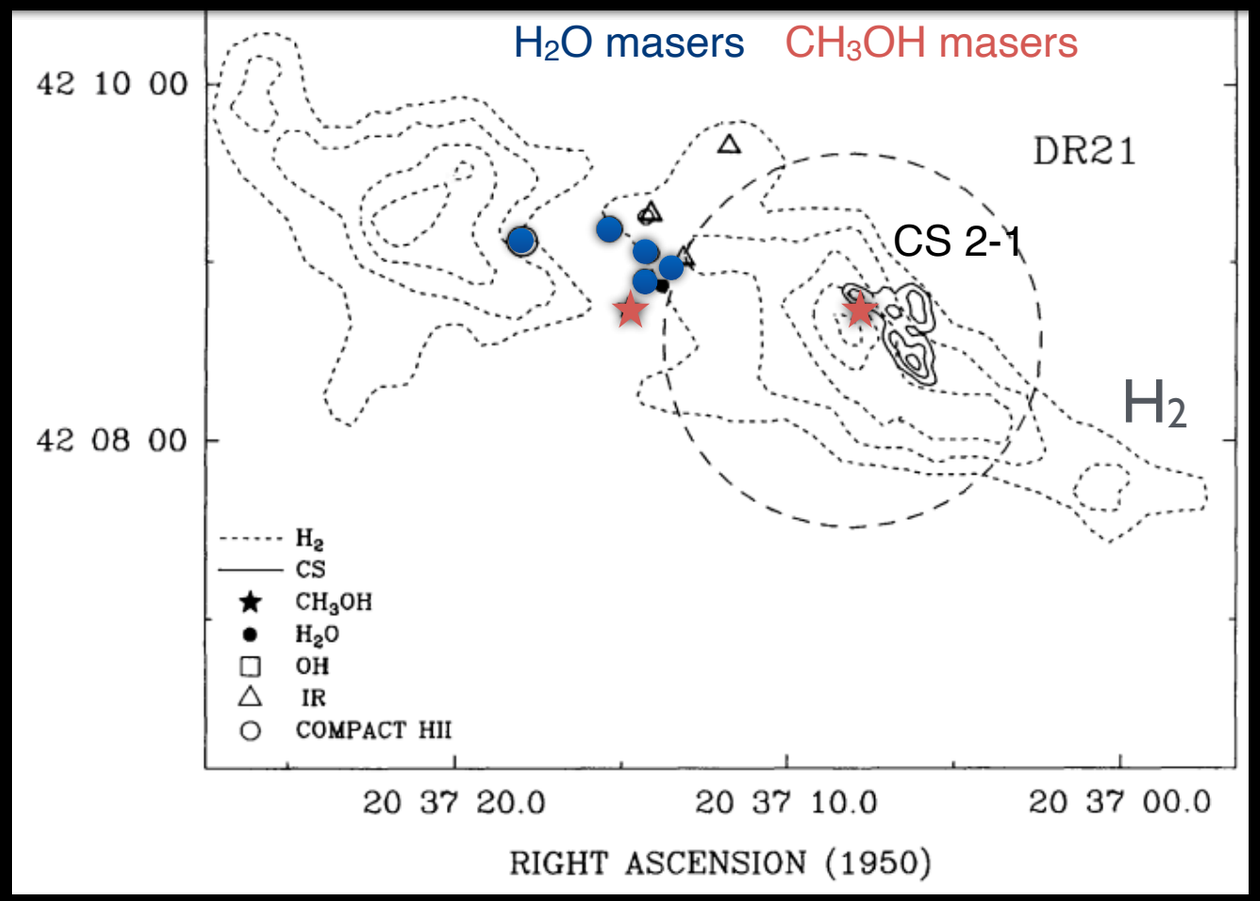
Lane+1990 (KAO/CGS)



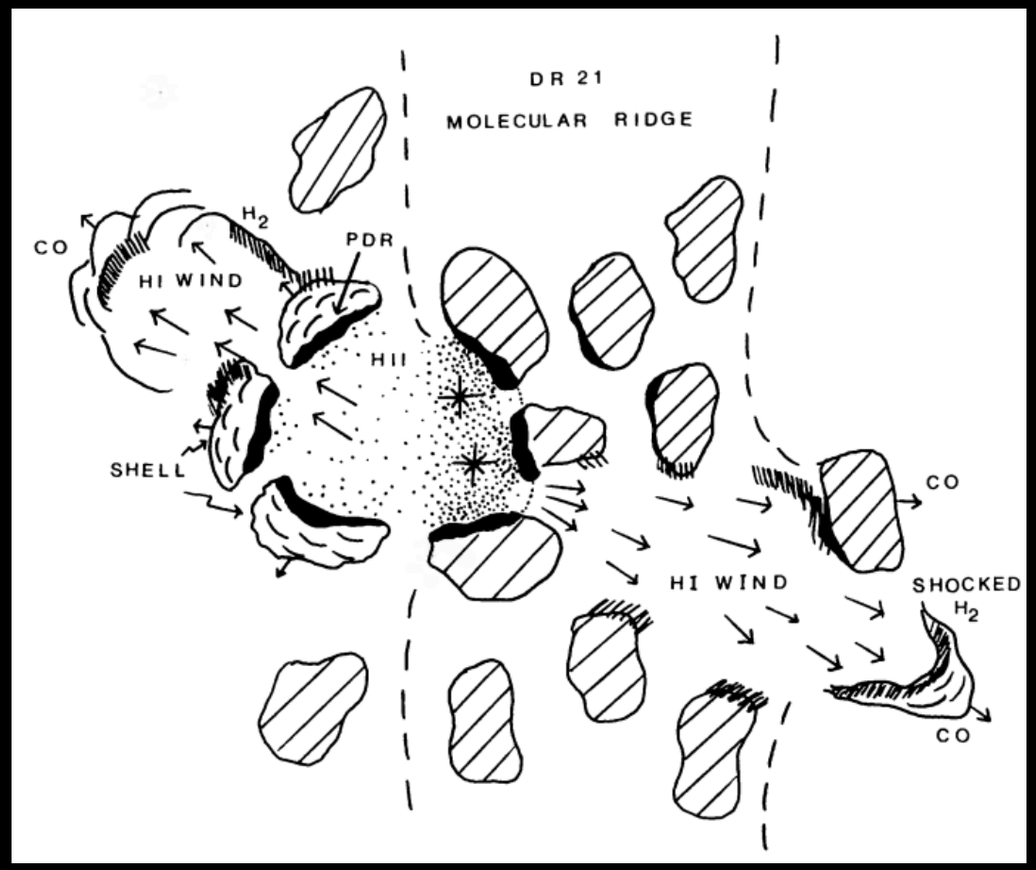
Poglitsch+1996 (KAO/Fabry Perot Interferometer): resolution down to 7 km/s

- [O I] emission peak in the eastern outflow lobe, shifted from H_2 peak and just outside of HII region (Lane+1990)
- strong absorption at source velocity in high-resolution spectra (Poglitsch+1996)
- [O I] and [C II] emission proposed to arise in photodissociation regions with $G_0 > 10^4$; none of the shock models could reproduce the far-IR emission in contrast to shock-excited H_2 (Lane+1990)

Water and methanol masers toward DR21 Main



Plambeck & Menten 1990



Lane+1990

- methanol masers in between CS 2-1 and H_2 peaks tracing the interaction of the outflow and dense clump (Plambeck & Menten 1990)
- significant differences in gas physical conditions between two outflow lobes (Lane+1990, Russel+1992)

CASCADE survey (Beuther+2022)

Skretas, Karska+2023

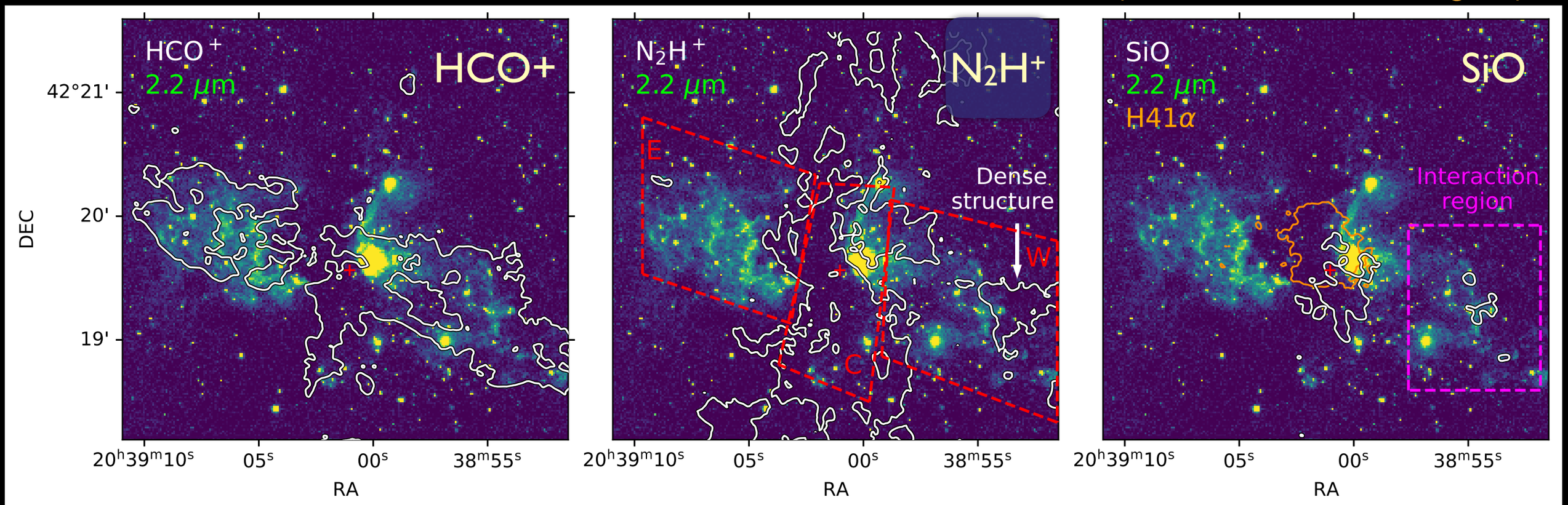
Iason Skretas
(MPIfR)

Multi-line mapping of DR21 Main in 3 mm

outflow (E-W)

DR21 ridge (N-S)

compact emission
(center, interaction region)



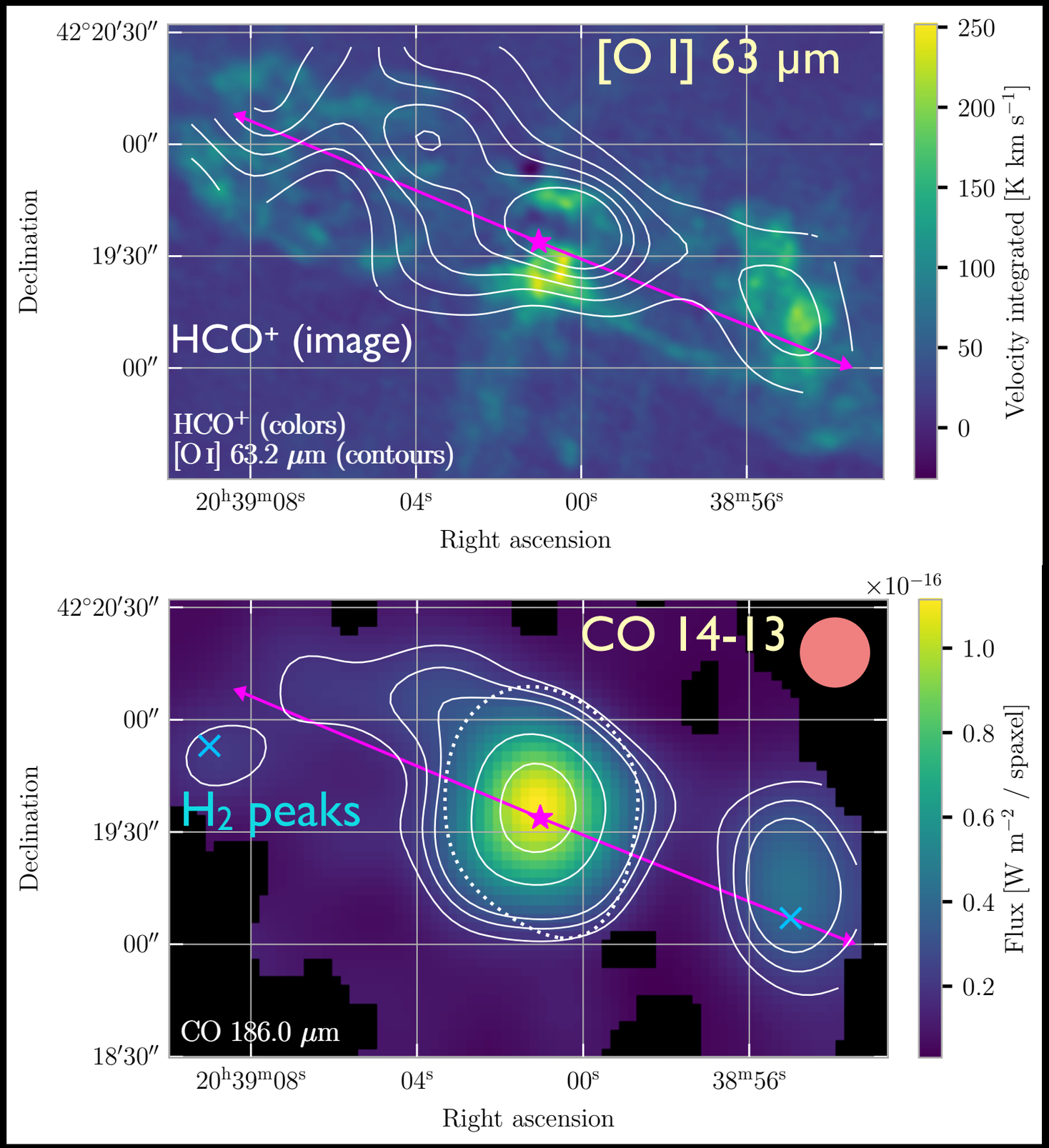
Other species: HCN

$H^{13}CO^+$,$H^{13}CN$, $HN^{13}C$, HNC,H_2CO, CCH, HCCCN

SiO, H41α, CH_3OH, DCN, DCO^+, DNC, NH_2D

- clear view of the different gas components in the DR21 Main area
- HCO^+ to calculate outflow properties: DR21 Main is one of the most powerful outflows in our Galaxy (Skretas+2023)

FIFI's [O I] and CO vs. HCO^+ and H_2

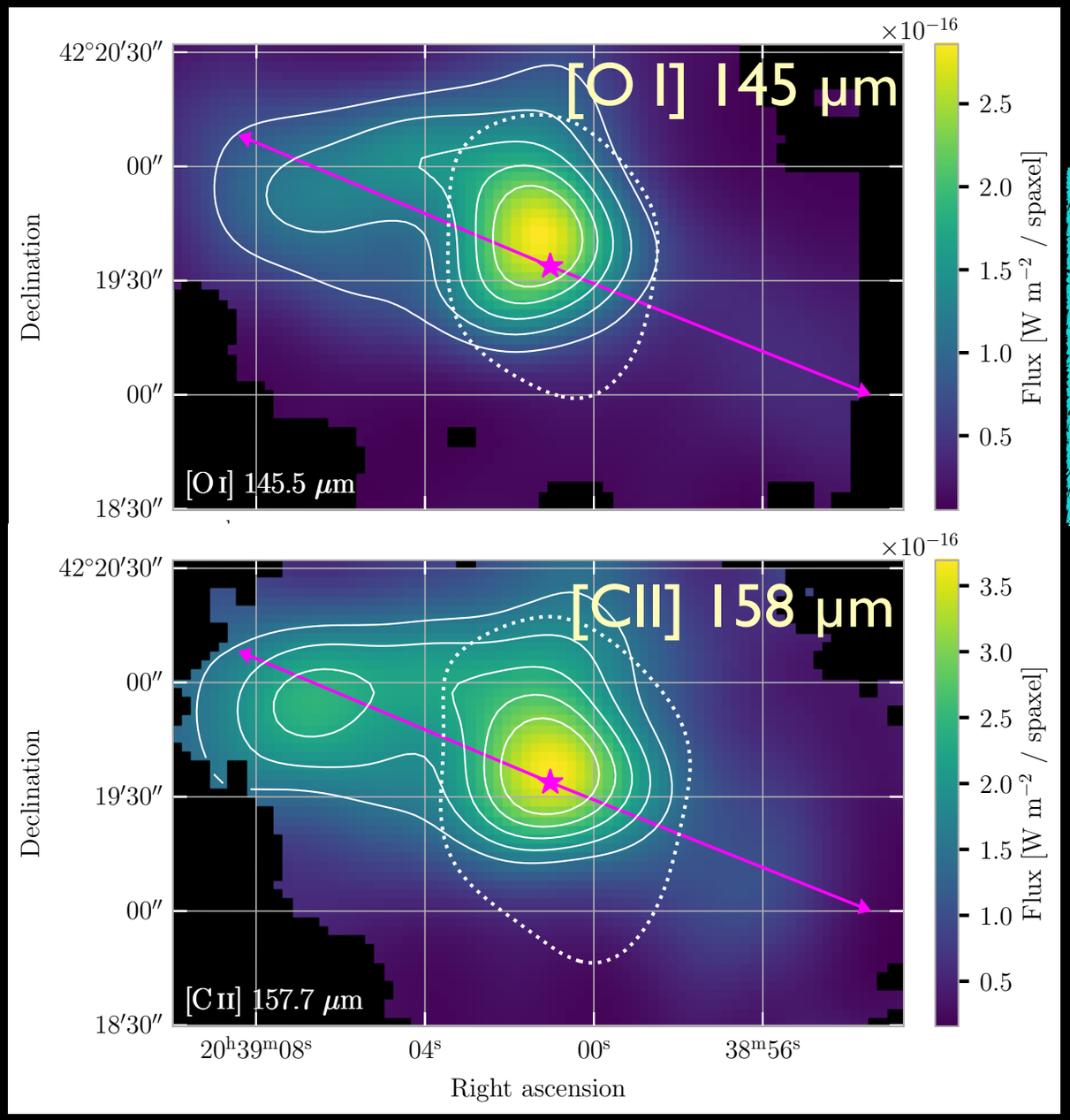


- [O I] 63 μm emission traces outflow cavity walls in the East and the interaction region in the West

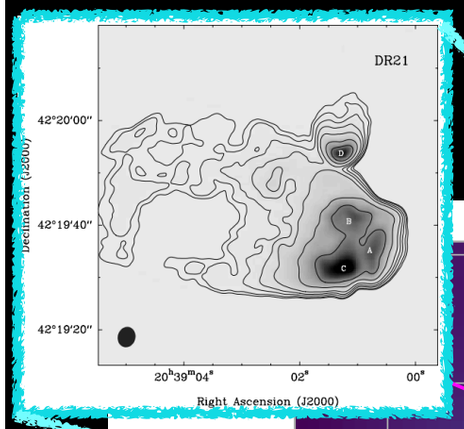
- High-J CO peaks co-spatial with peaks in H_2 and OH tracing dense gas associated with shocks

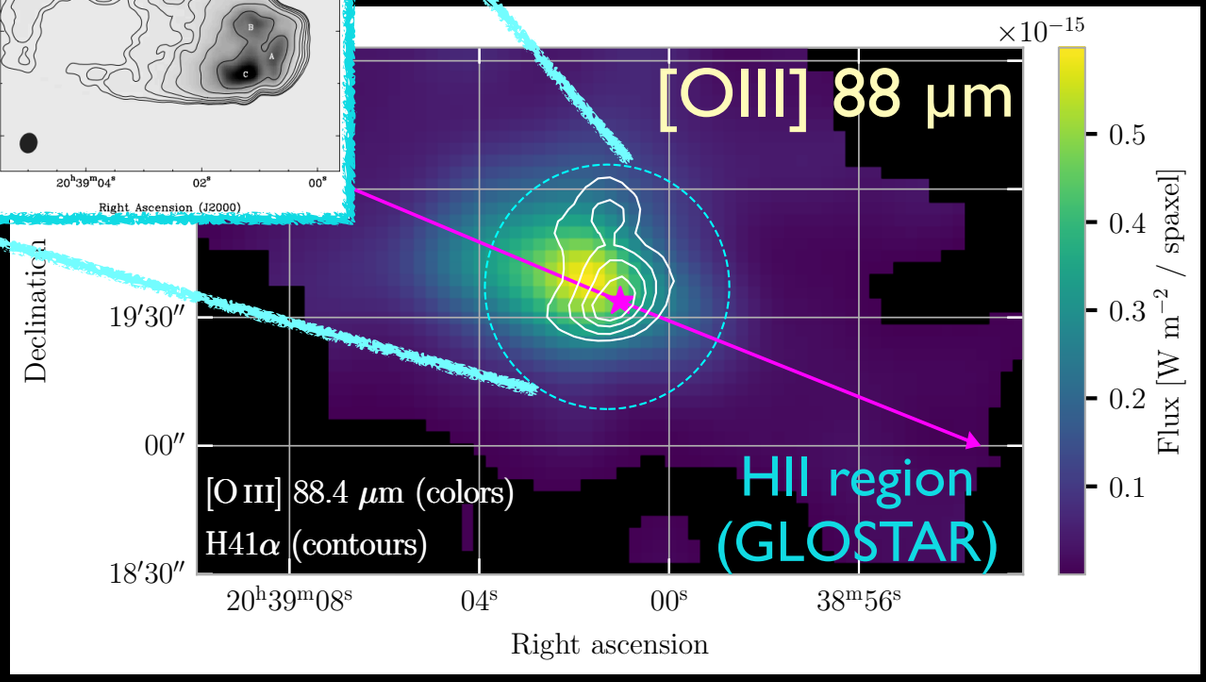
Atomic and ionised gas in DR21 Main

Sarwar Khan (MPIfR)



Cyganowski+2003



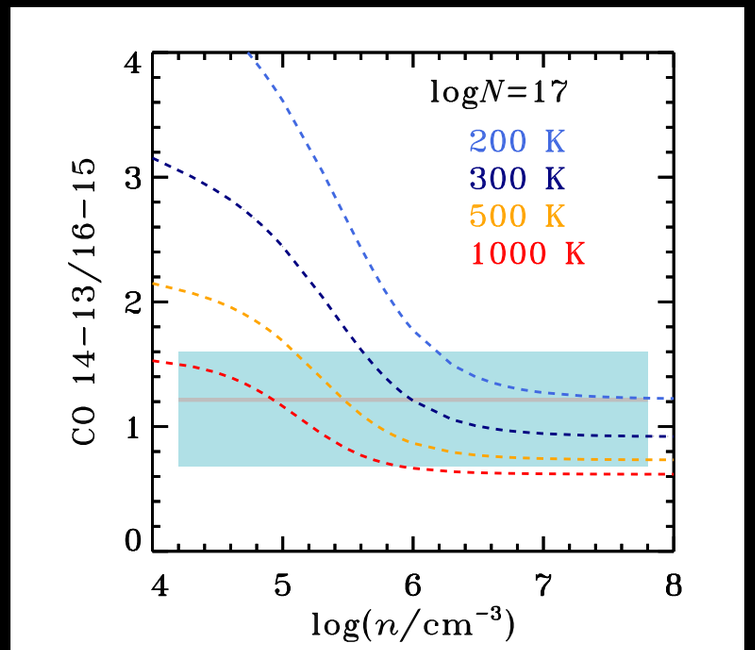


Sarwar Khan+ subm.

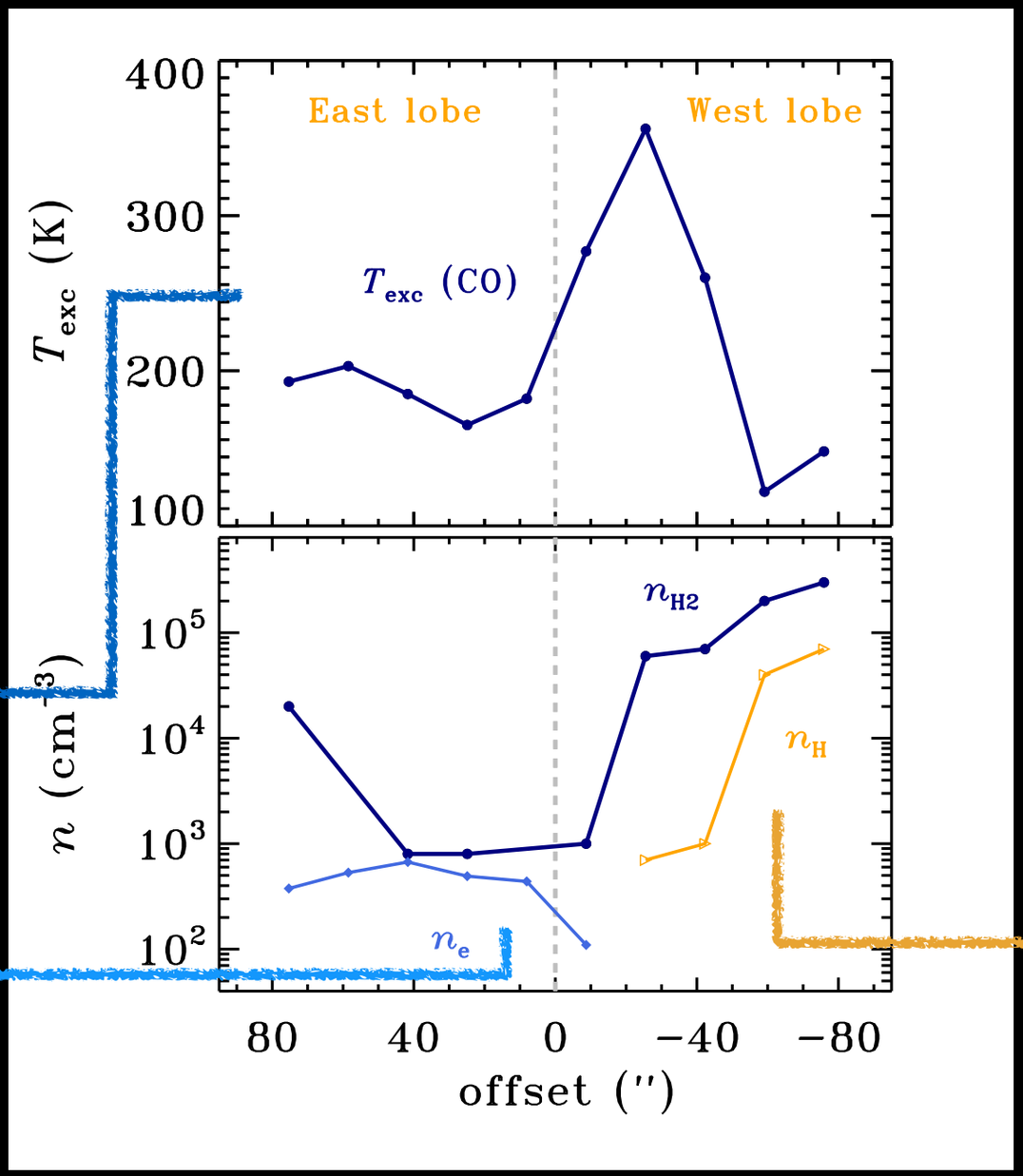
- [O I] 145 μm and [C II] detected mostly in the eastern outflow lobe
- [O III] emission traces the HII region revealed by high-resolution radio studies (Roelfsema+1989, Cyganowski+2003) and H41α from CASCADE

Physical conditions along the outflow

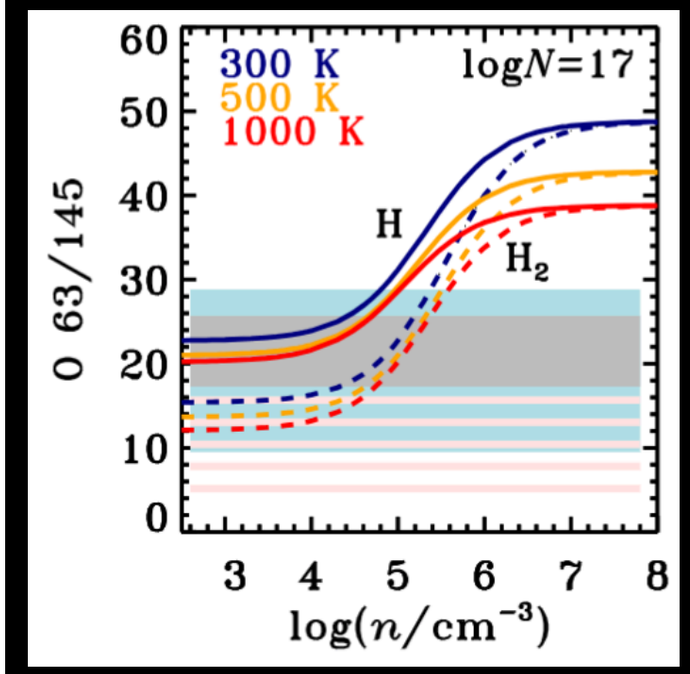
CO: T_{kin} & H_2 densities



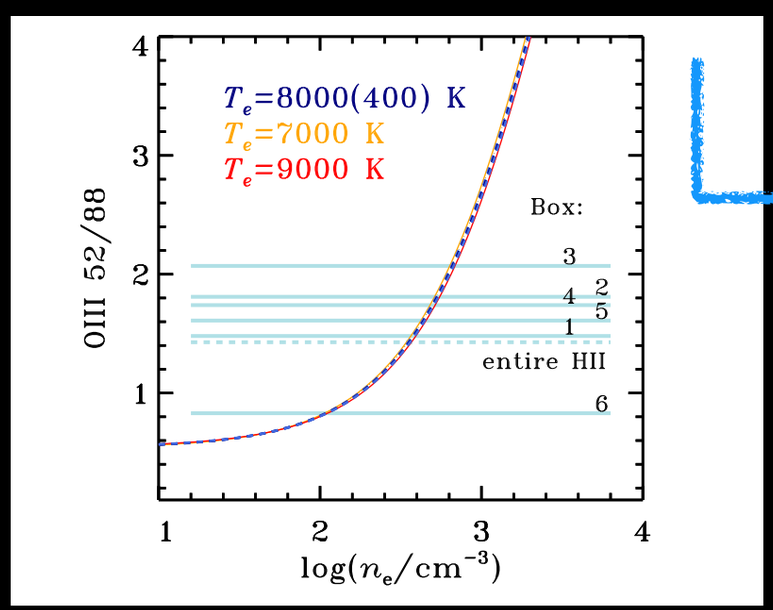
East lobe | West lobe



[O I]: H & H_2 densities

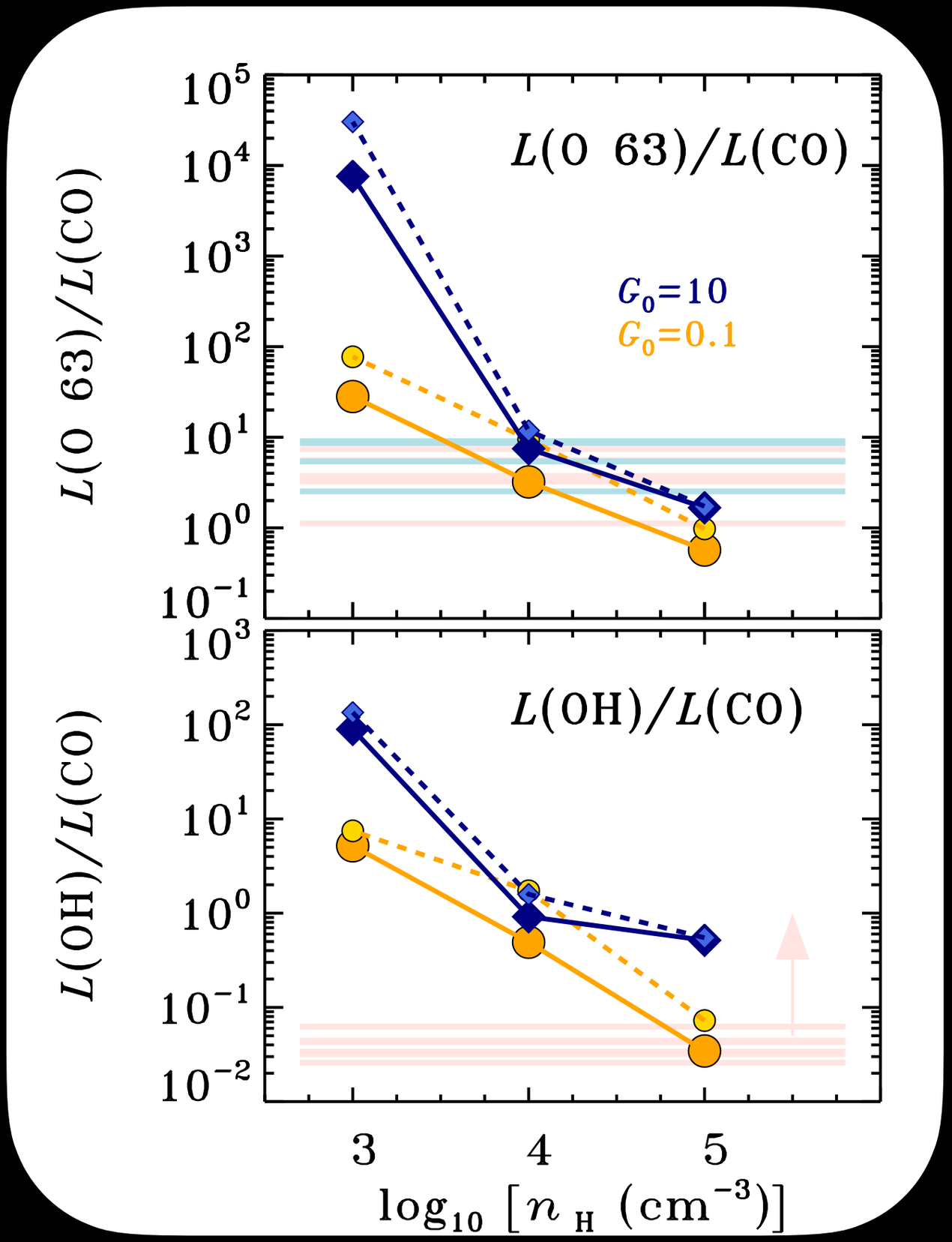


[OIII]: electron densities



- Densities above ~10^5 cm^{-3} (coll. with H_2) and ~10^4 cm^{-3} (coll. with H); electron densities of 300-420 cm^{-3}

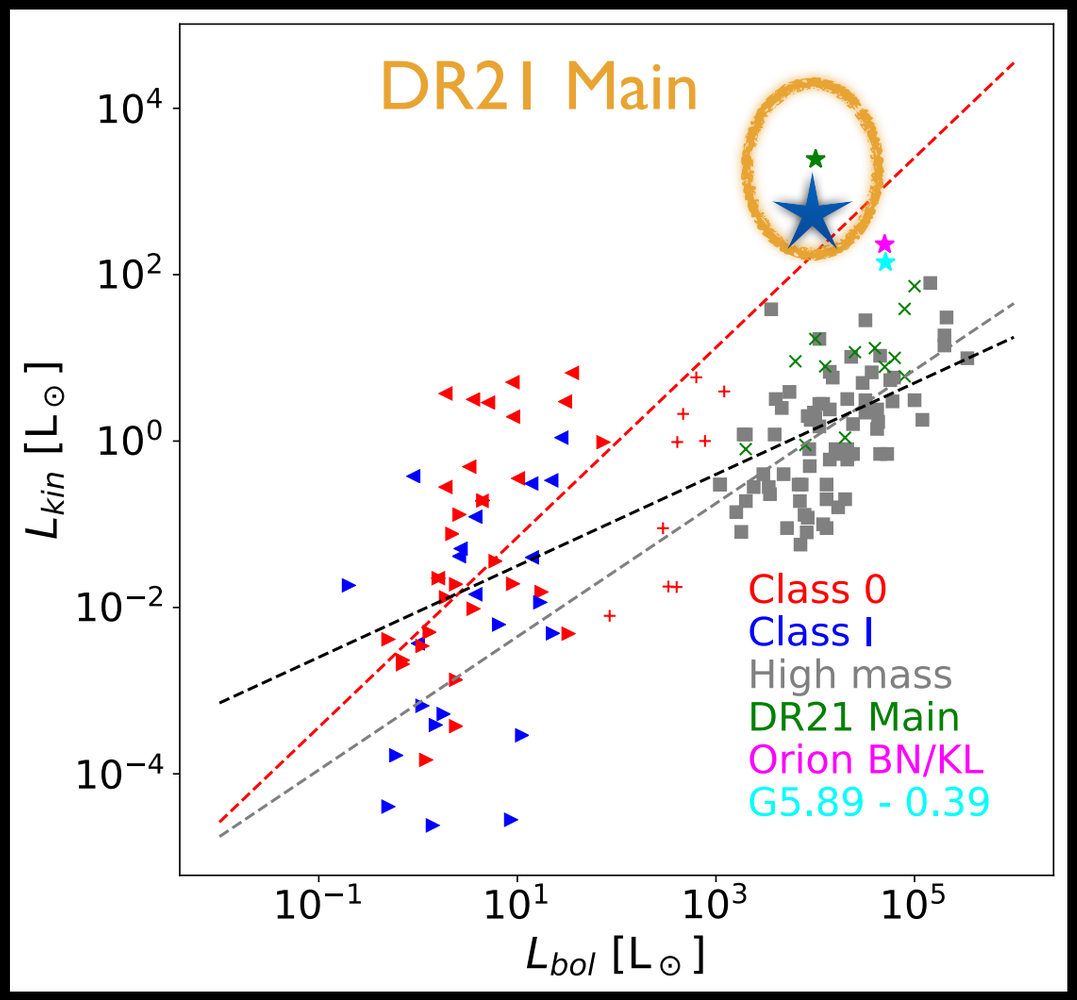
Line ratios of [O I]/CO consistent with shocks



- The ratio of (corrected) [O I] 63 μm and CO agrees with non-dissociative shock models (Melnick & Kaufman 2015, Karska, Kaufman+2018) irradiated by UV fields with G_0 of 0.1-10 and pre-shock densities of 10^4-10^5 cm^{-3}

- Higher densities expected for lower L(O) / L(CO) ratios are found in the western outflow lobe of DR21 Main, consistent with physical conditions derived from radiative-transfer models

Outflow energetics from far-IR lines



Skretas+2023:

L_{kin} = 2.4×10³ $L_\odot$

dM/dt = 3.6×10^{-2} $M_\odot$/yr

- total energy loss is a direct measure of mechanical luminosity = outflow power, L_{kin}:

1/2 dM/dt v^2 = (1-f_m) 1/f_x L_{FIRL} Maret, Bergin+09

, f_m - fraction of shock mechanical energy translated into excitation

, f_x - fraction of cooling from FIFI-LS (no H_2 and H_2O)

, L_{FIRL}=L(CO) + L(OH) + L[OI] + L[CII]

- L_{H_2} of 450 $L_\odot$ (Garden+1991) and L_{H_2O} of 7 10^{-2} $L_\odot$ (SPIRE;White+2010), L_{FIRL} of 226 $L_\odot$ (FIFI-LS)

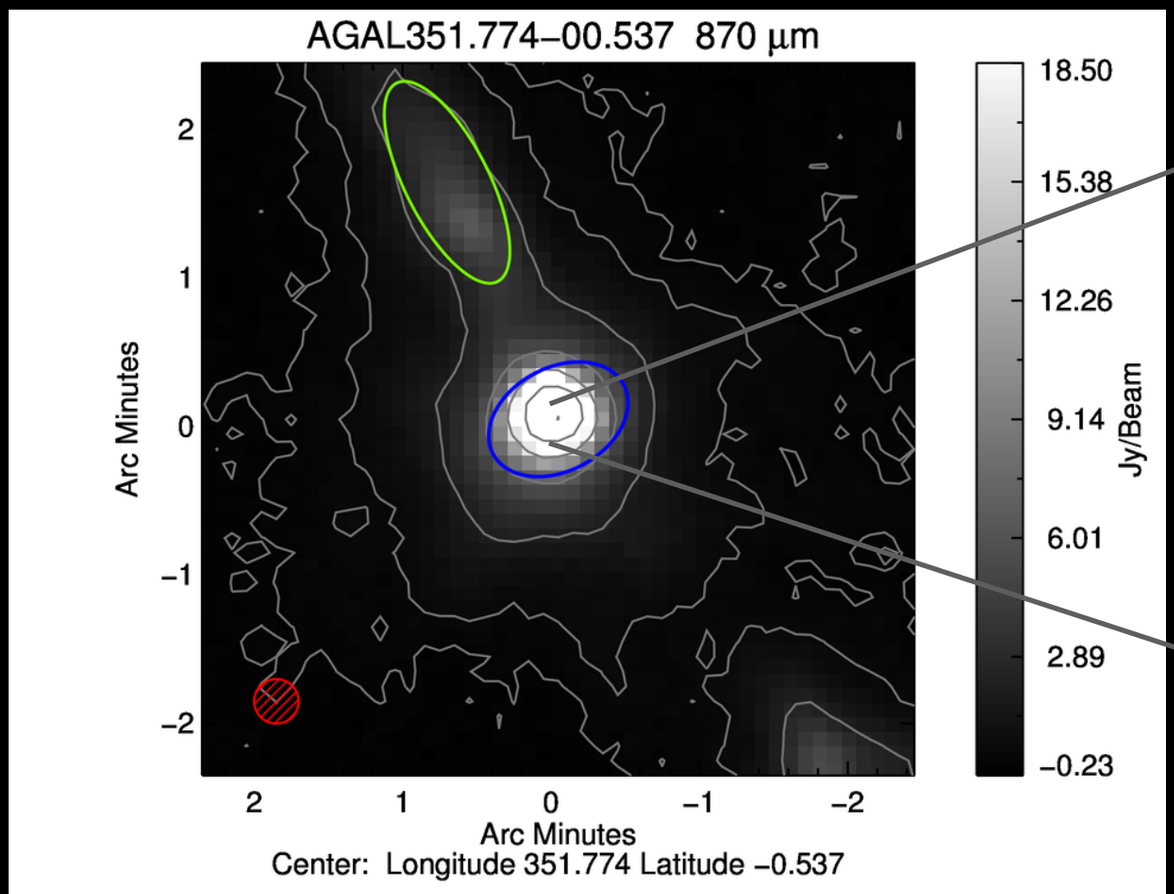
Outflow power: 4.4-5.1×10² $L_\odot$

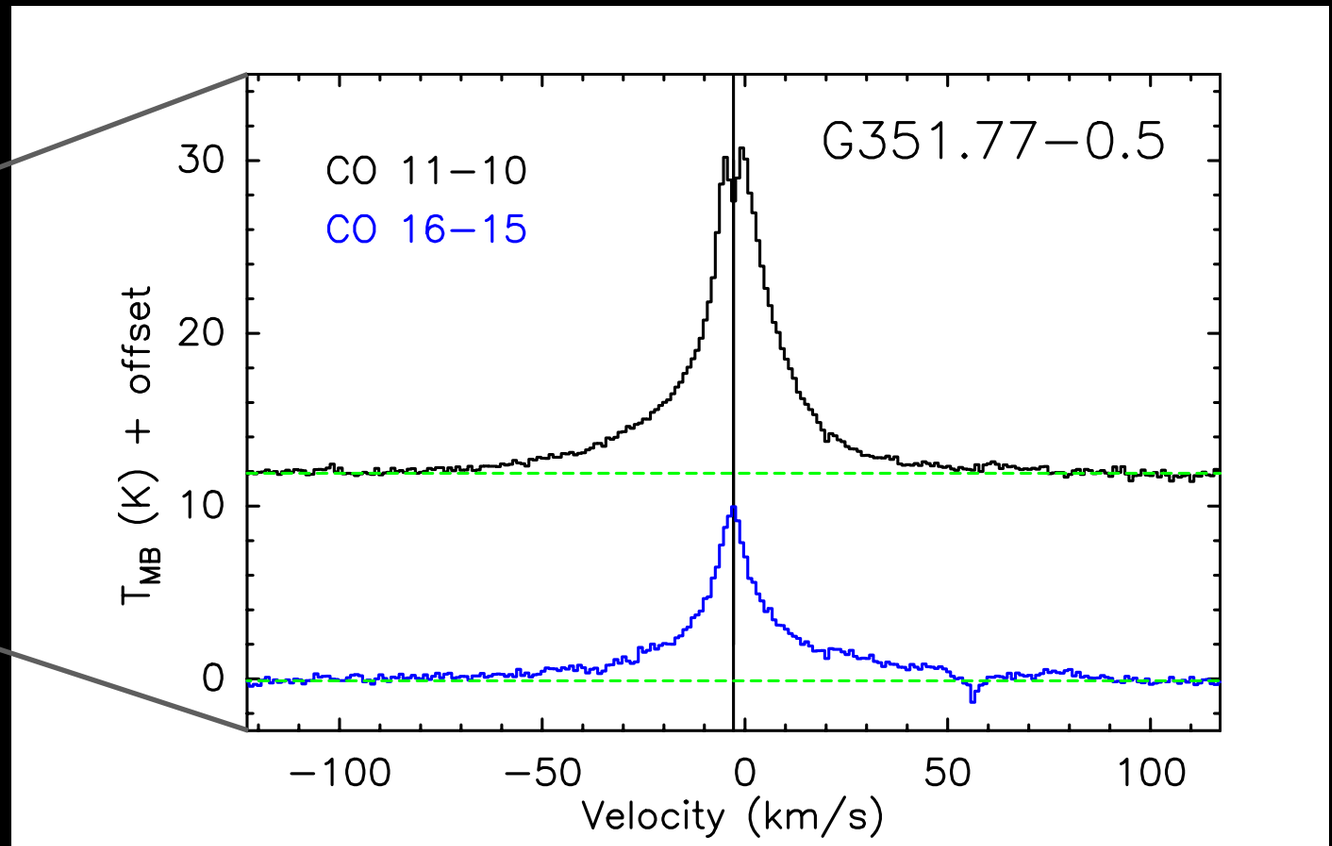
Mass loss: dM/dt ~ 3.4-3.9×10^{-3} $M_\odot$/yr

FIFI-LS measurements confirm the high mass-outflow rate and outflow power of DR21 Main and are consistent with measurements using HCO^+ (Skretas+2023)

Survey of high-mass clumps with GREAT

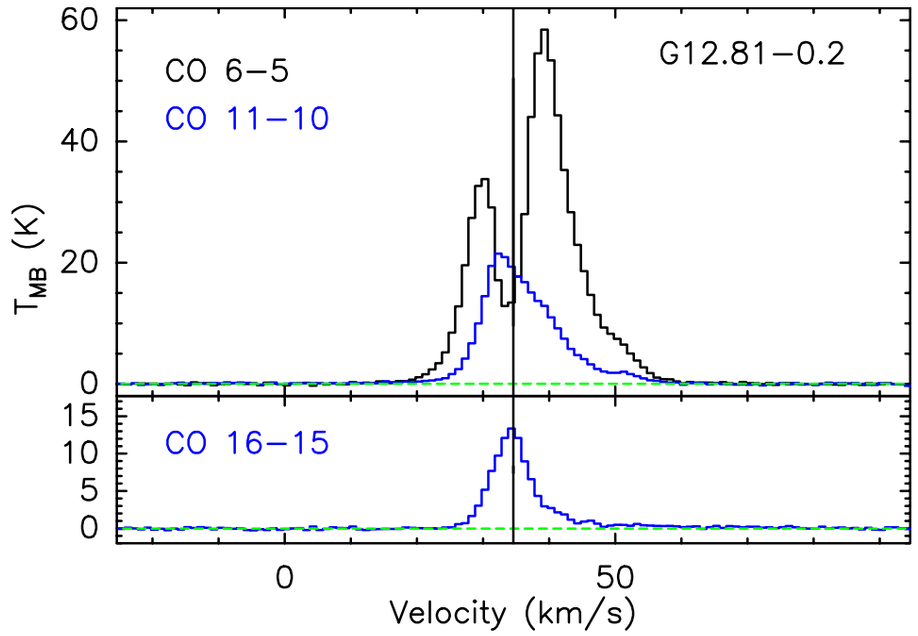
Hoang, Karska+2023

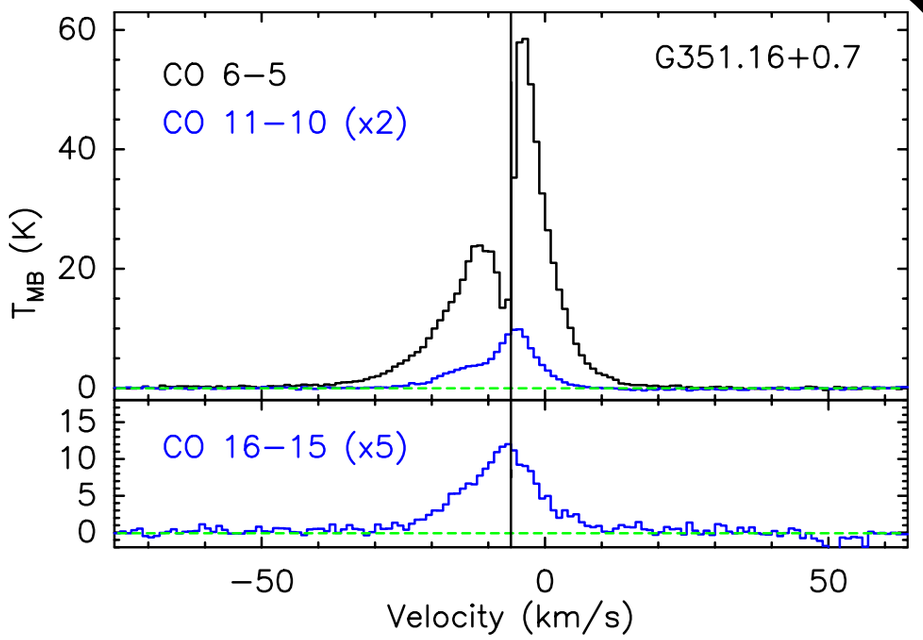


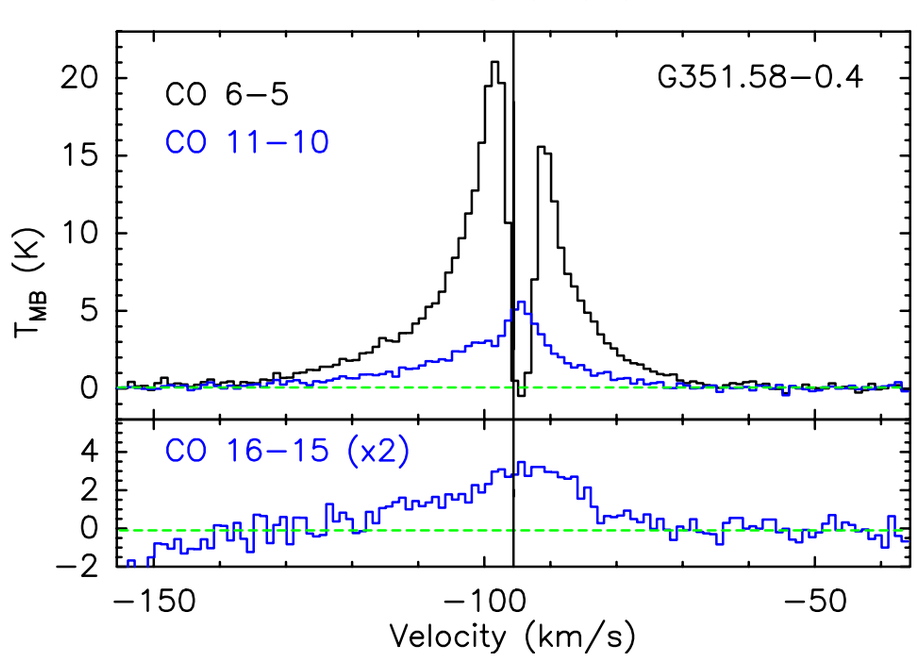


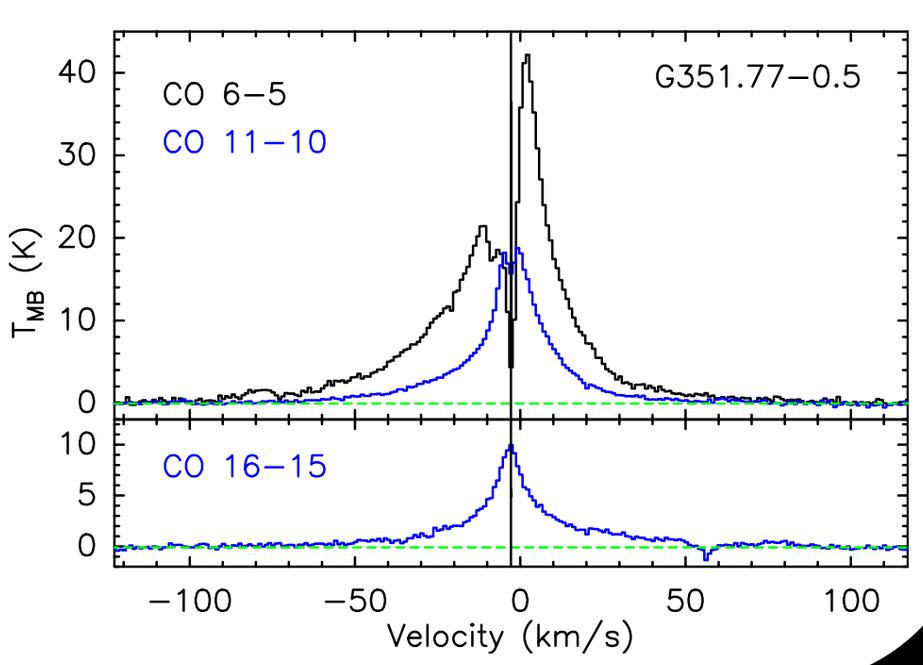
- 13 clumps spanning a range of evolutionary stages: 24d (3), IRb (7), HII regions (3) from the ATLASGAL survey (Schuller+2009)
- SOFIA/GREAT detection of CO lines: 11-10, 13-12, and 16-15 with Δv ~1 km/s and beam sizes of 14”—20”; physical scales of 0.1–0.8 pc

Line profiles of CO 6-5, 11-10, and 16-15





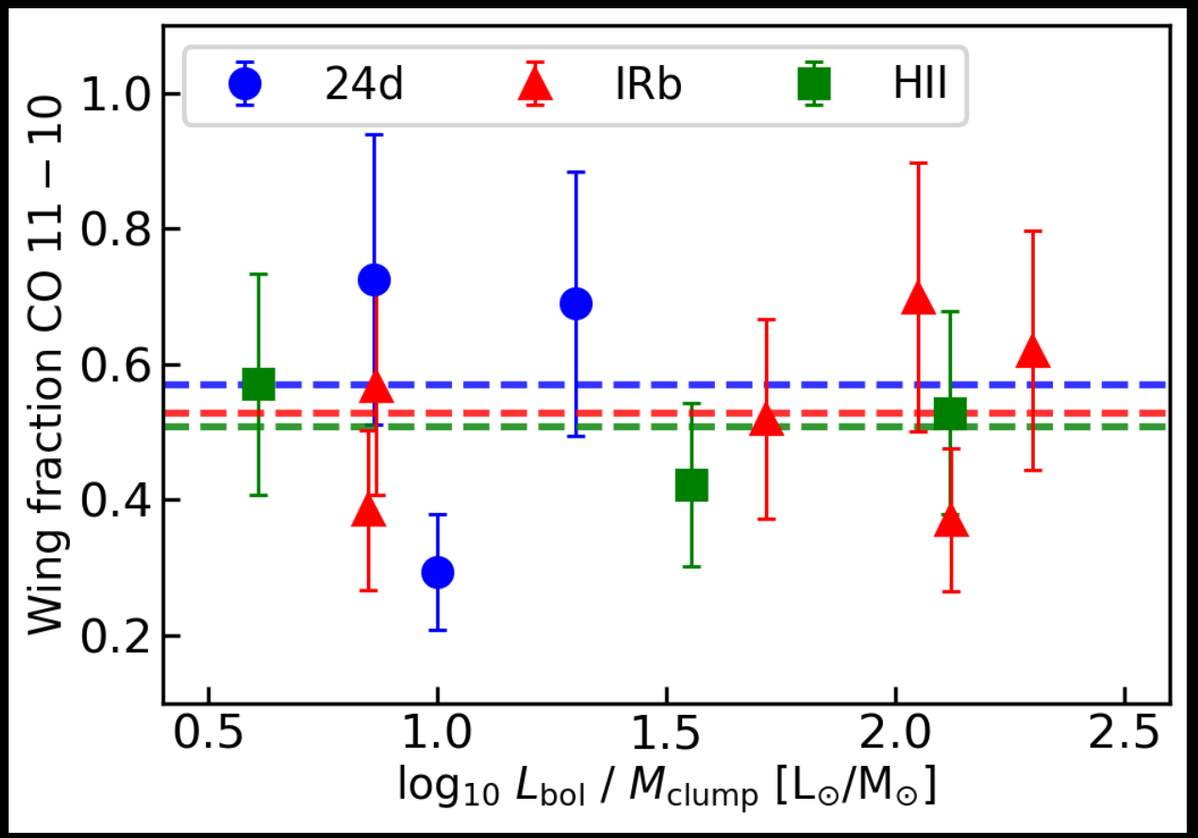




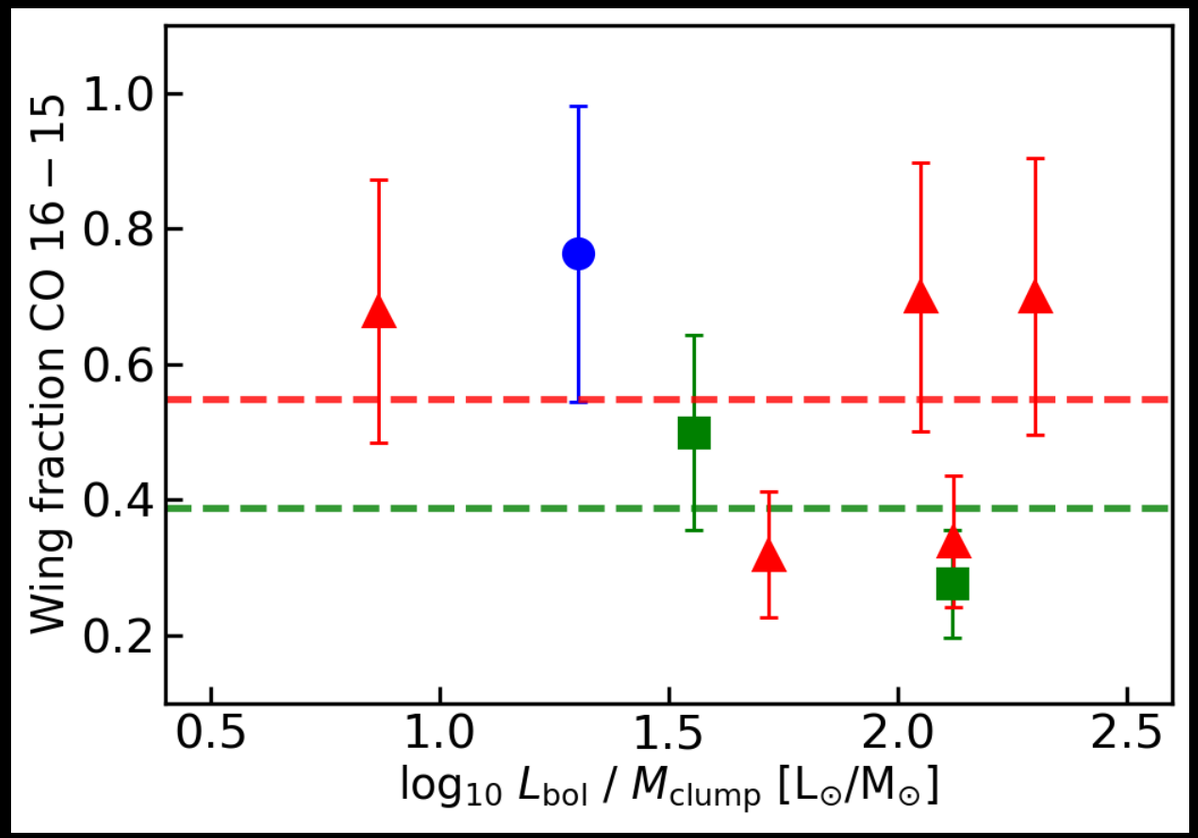
- Broad line wing emission in both high-*J* CO lines resembling CO 6-5 profiles
- High-*J* CO lines are not strongly affected by self-absorption, and no signs of extremely high velocity gas

Fraction of emission in the line wings of high-*J* CO

CO 11-10

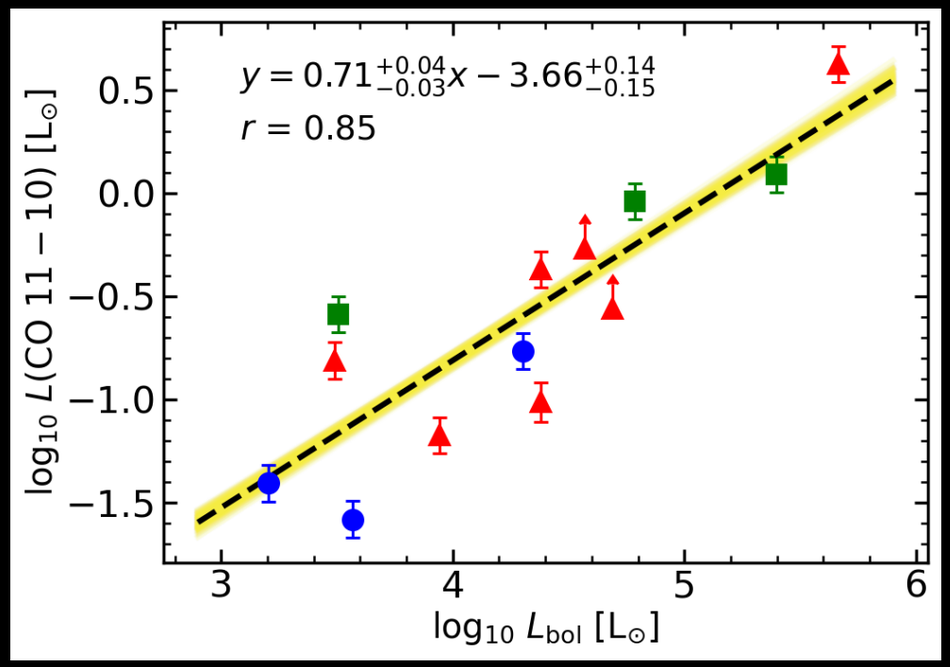


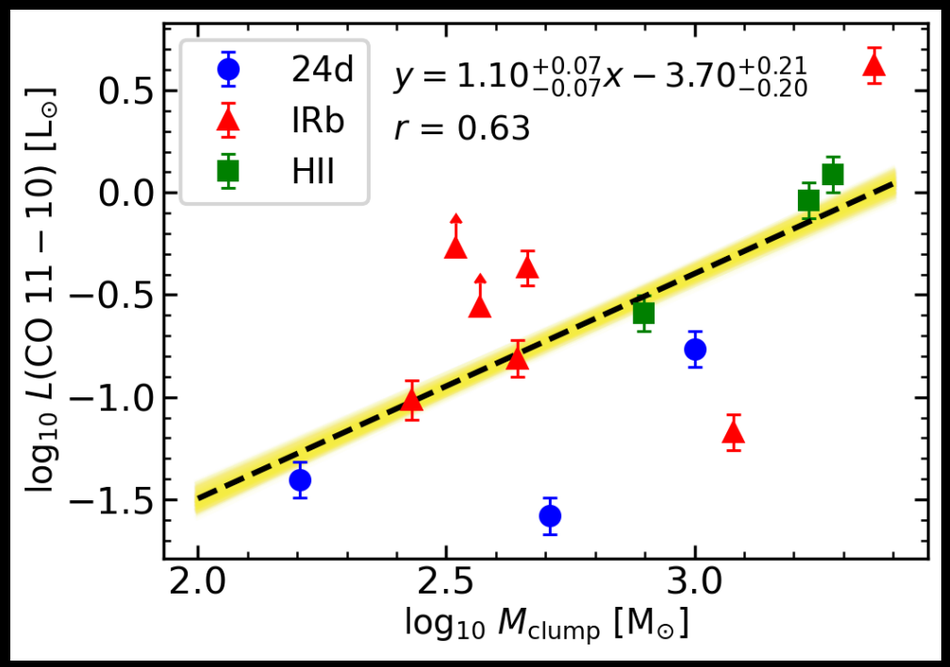
CO 16-15

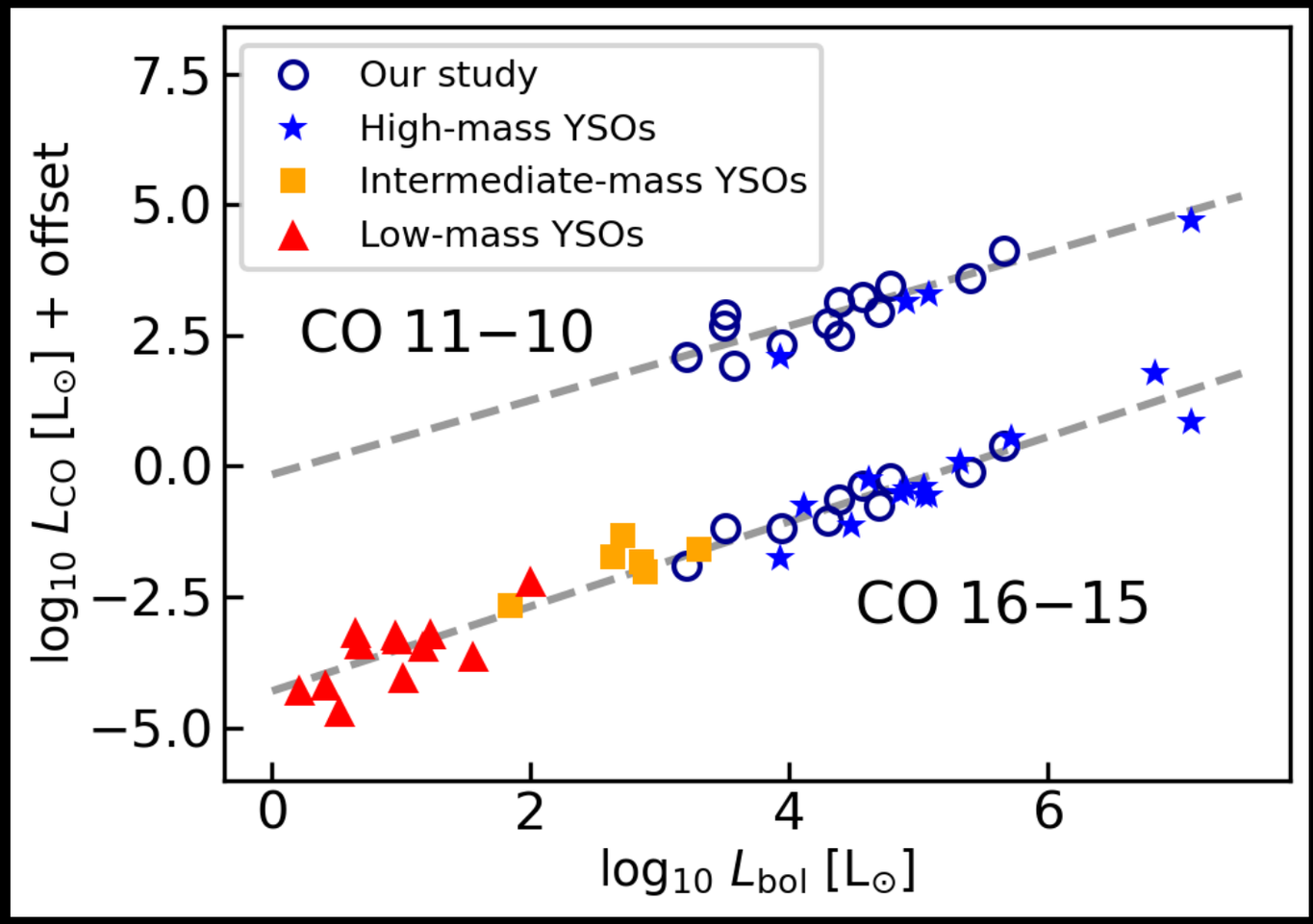


- Significant fraction of emission in the line wings: from ~ 30% to 80%; higher contributions of wing emission in CO 16-15 than 11-10 in 4 sources
- No clear correlation of emission in wings with evolutionary stages (!)

Correlations with clumps masses and luminosities



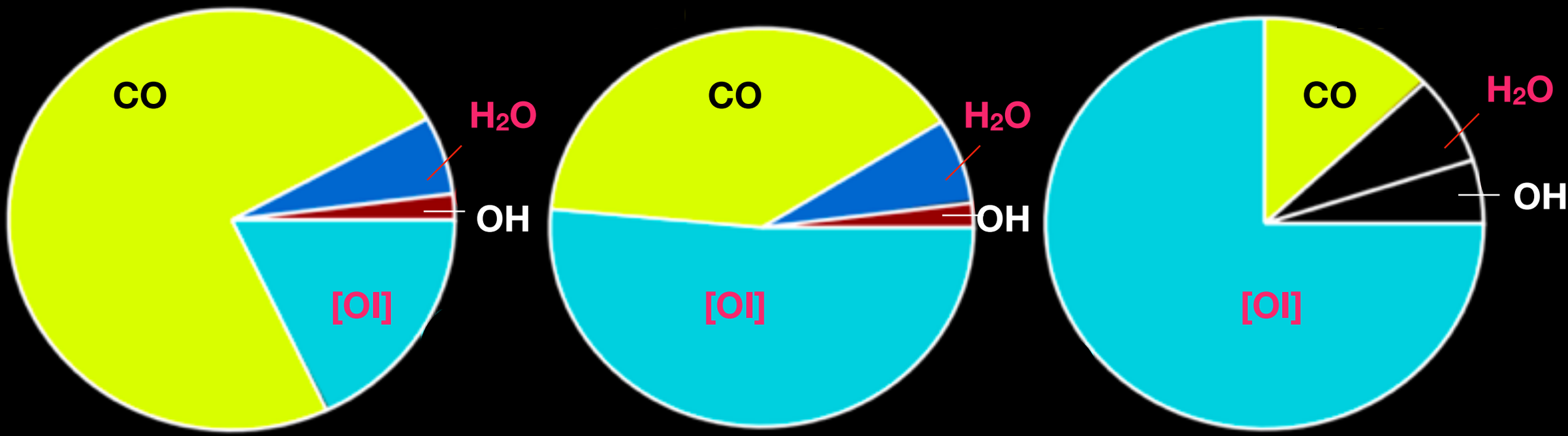




Kaźmierczak-Barthel+2014, Karska+2014, Indriolo+2017, Matuszak+2015, Kristensen+2017

- Similar physical processes responsible for emission from all high-mass clumps
- L_{CO} correlated with L_{bol} from low- to high-mass protostars

Far-IR gas cooling: impact of metallicity



YSOs in Milky Way
(Karska+2014)

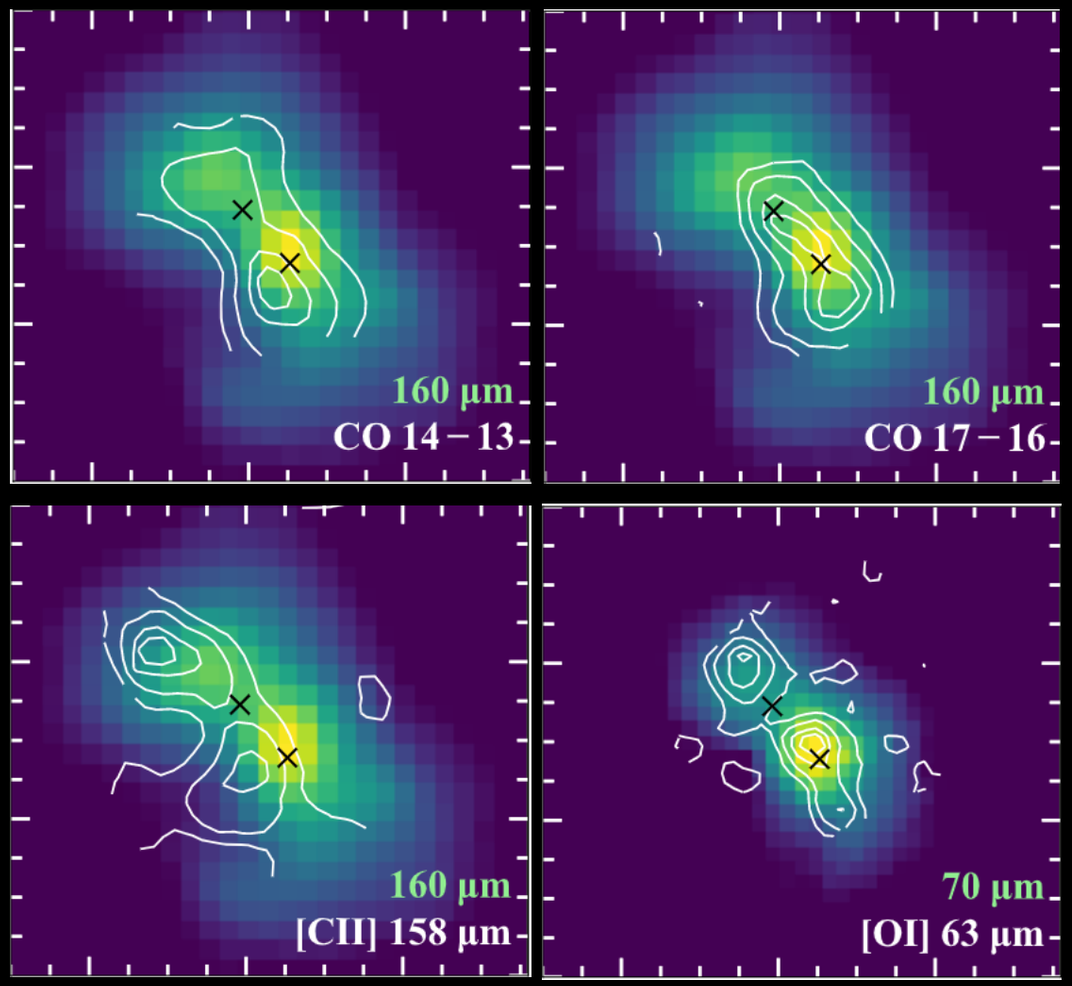
YSOs in LMC
(Oliveira+2019)
Z~0.3–0.5 $Z_\odot$

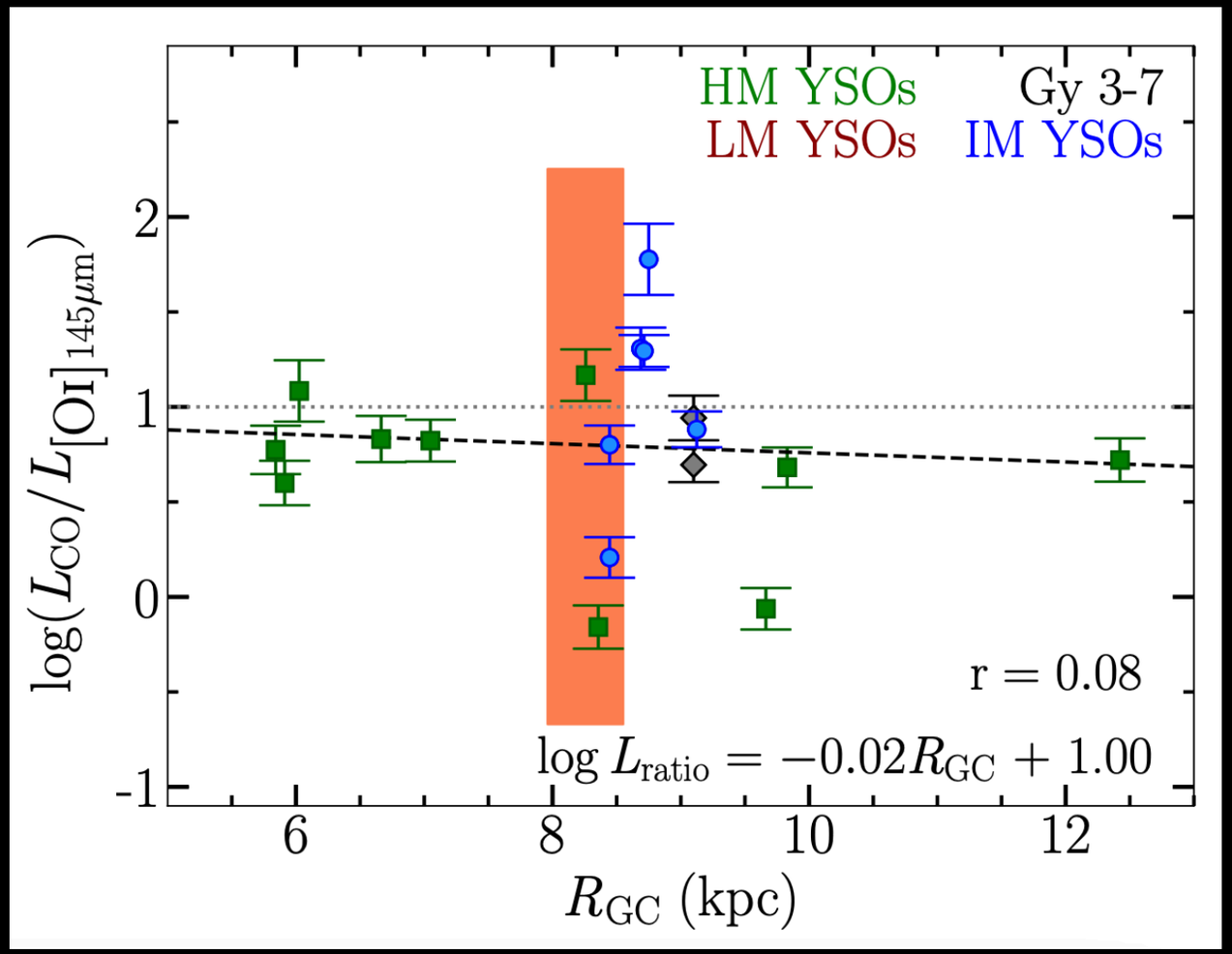
YSOs in SMC
(Oliveira+2019)
Z~0.2 $Z_\odot$

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

Embedded cluster in the outer Galaxy

Le, Karska+2023





- only a tentative trends of decreasing ratio of CO / [O I] with R_{GC}
- CO / [O I] sensitive to L_{bol}, with increasing importance of atomic cooling in higher-mass YSOs (Karska+2014, Oliveira+18, van Dishoeck+2021)

Conclusions

- FIFI-LS large-scale maps of high-mass protostars allowed us to study physical conditions and far-IR line cooling along the outflows with unprecedented sensitivity and angular resolution

- Far-IR line cooling provides an alternative measure of the power of the outflow, confirming the extreme nature of DR21 Main, consistent with results from CASCADE using HCO^+

- High-spectral resolution spectra from GREAT are critical to studying wing emission and correcting for absorptions unresolved with FIFI-LS, and understanding the evolutionary trends

- Possible impact of metallicity on far-IR cooling of YSO envelopes would require follow-up studies of clumps in the extreme outer Galaxy