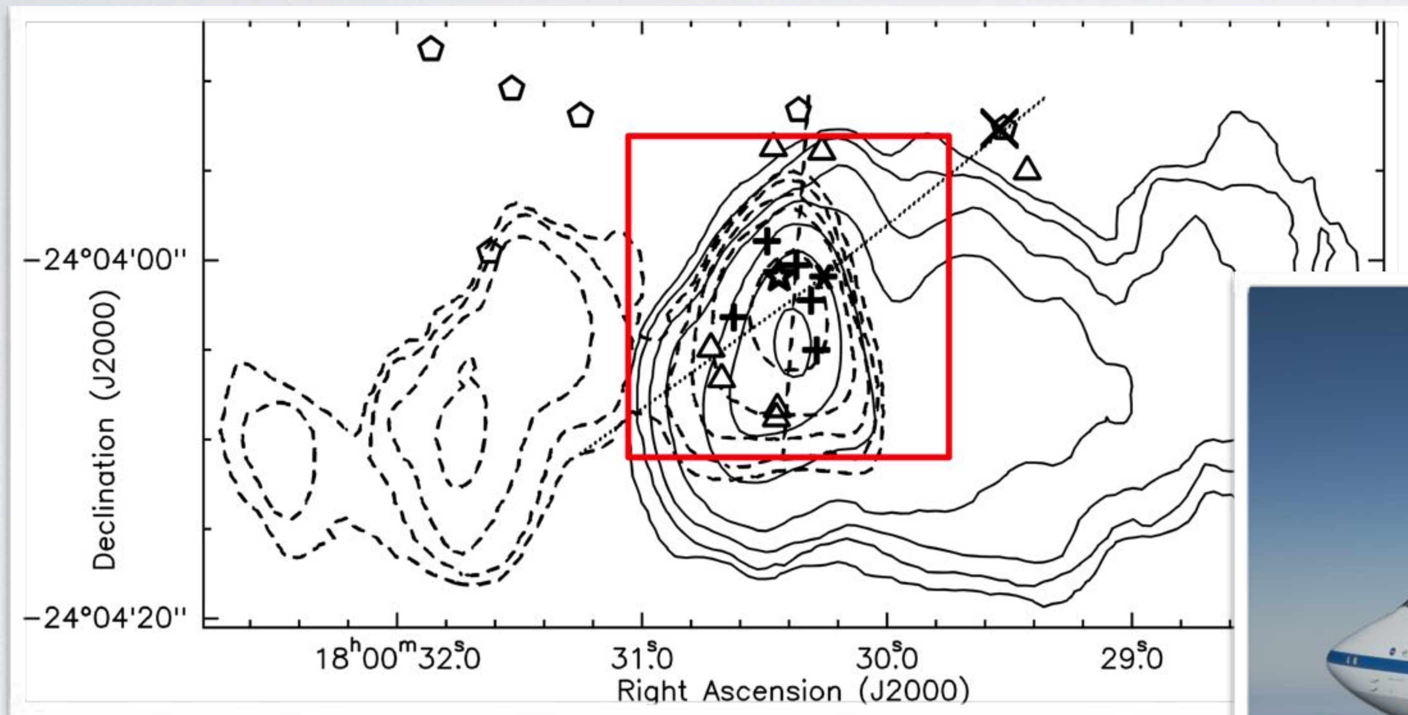
Far-IR cooling in massive star-forming regions: a case study of G5.89-0.39



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Outline

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- Far-IR cooling in star-forming regions
- Herschel view and open questions
- Far-IR cooling with SOFIA/GREAT: *a case study of G5.89-0.39*
- Far-IR cooling in ATLASGAL selected sources: *a teaser!*

Far-IR cooling in star-forming regions

Cooling processes can be:

1. dust cooling ⇒ efficient only ay high densities when the dust and the gas are thermally coupled

2. atomic and molecular lines (depending on the chemical composition of the gas)

Far-IR cooling in star-forming regions

Cooling processes can be:

1. dust cooling ⇒ efficient only ay high densities when the dust and the gas are thermally coupled

2. **atomic and molecular lines (depending on the chemical composition of the gas)**

The inner regions around YSOs are peculiar:

i. FUV from the (proto)star

ii. shocks (winds, jets)

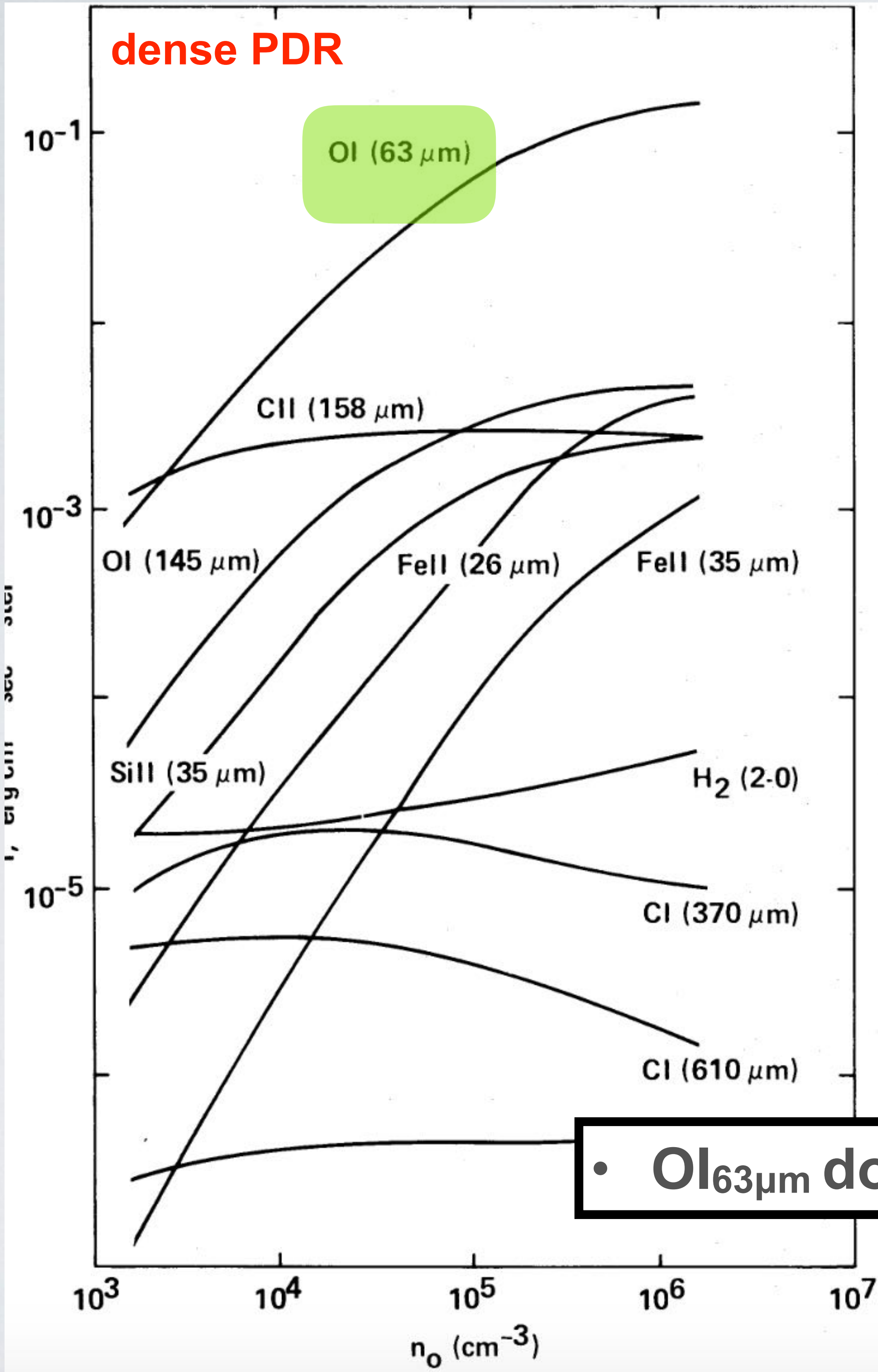
iii. but still surrounded by the dense molecular gas

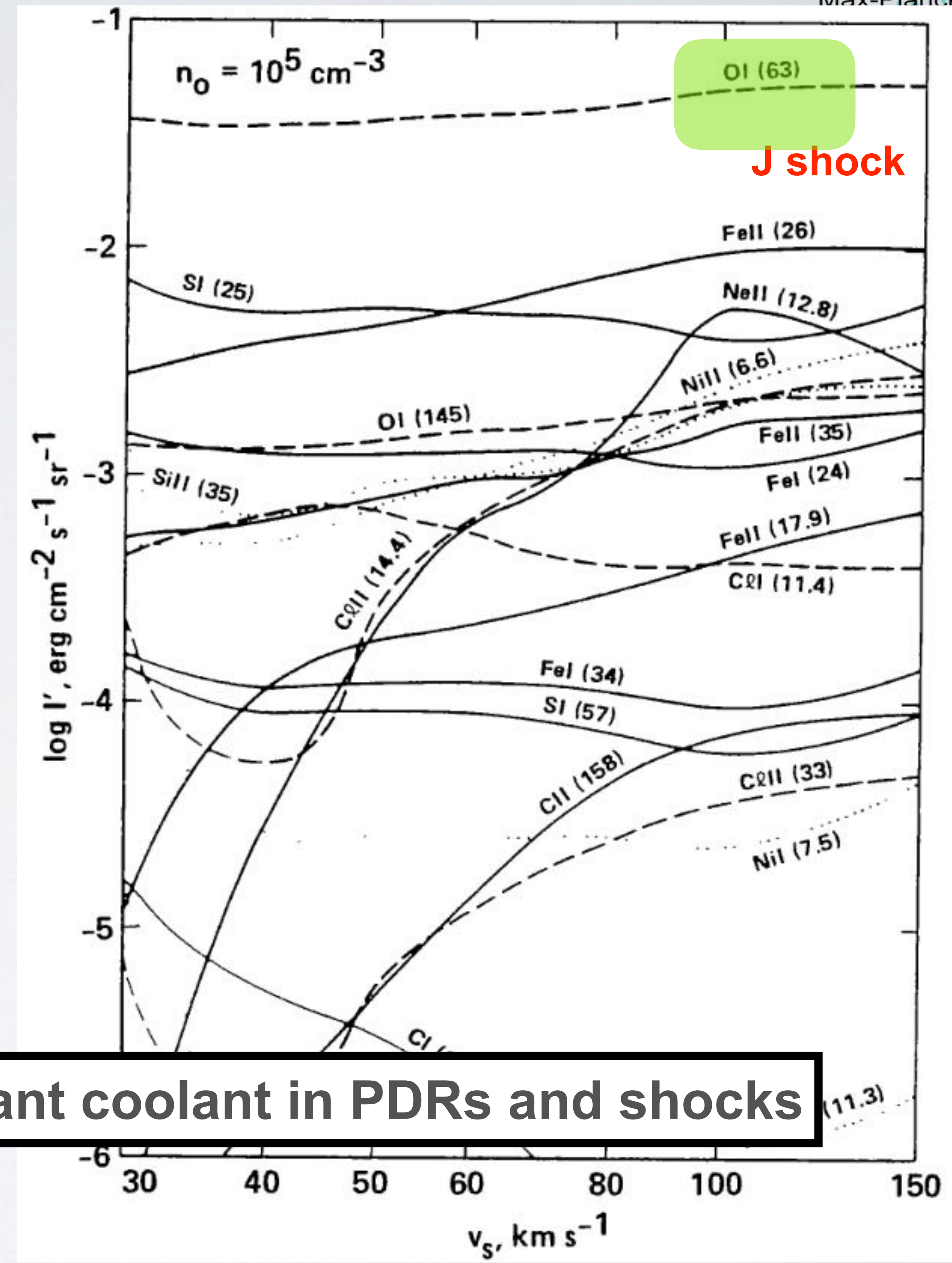
Far-IR cooling in star-forming regions

The line cooling should be dominated by:

1. fine structure lines of atomic species (CII, OI, CI etc) from the PDR around the protostar and from J-shocks

Hollenbach+1985,1989





- $OI_{63\mu m}$ dominant coolant in PDRs and shocks

Far-IR cooling in star-forming regions

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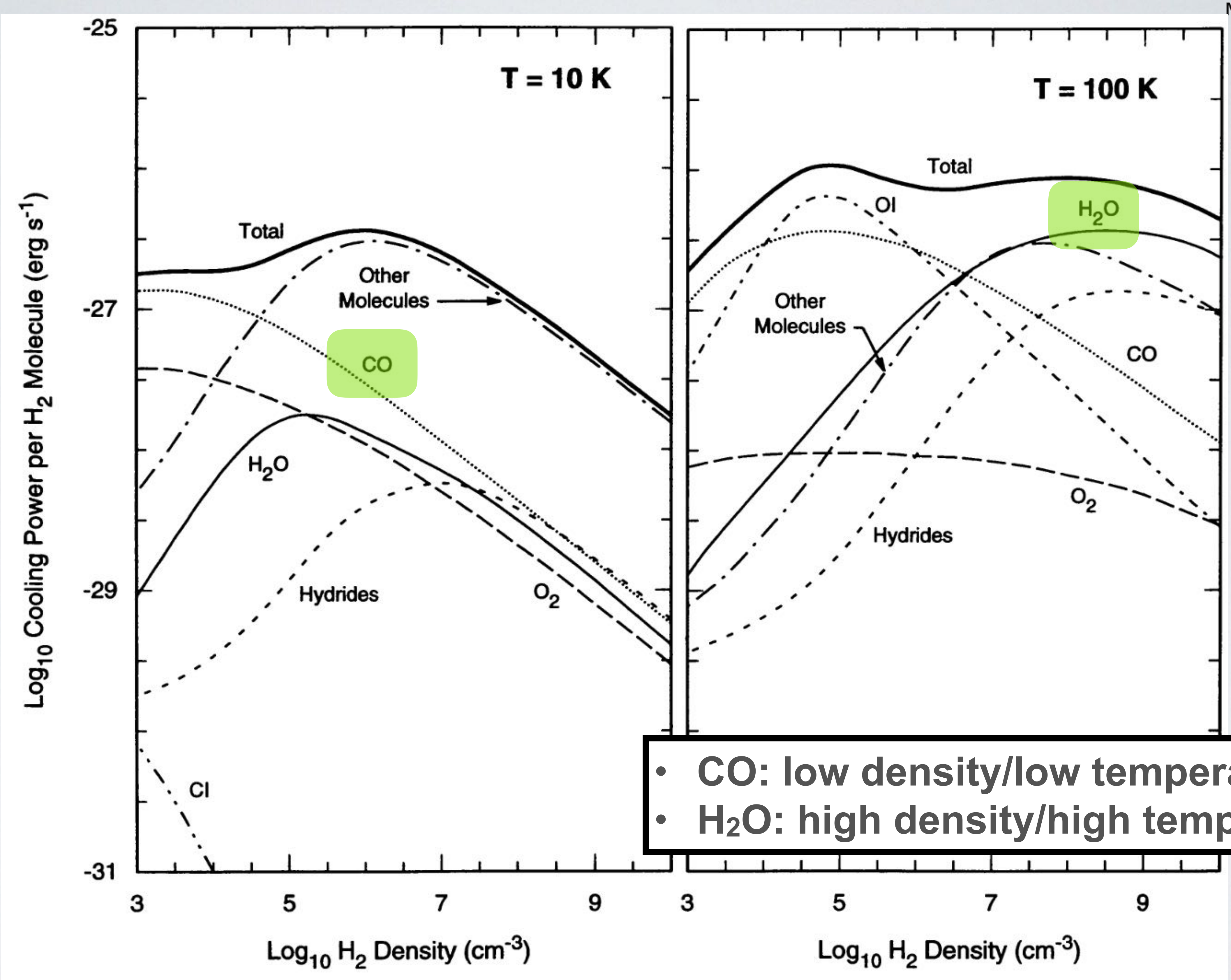
The line cooling should be dominated by:

1. fine structure lines of atomic species (CII, OI, CI etc) from the PDR around the protostar and from J-shocks
2. rotational lines of CO, H_2O etc (depending on T and n)

Neufled+1995



- CO: low density/low temperature
- H_2O: high density/high temperature

Far-IR cooling in star-forming regions

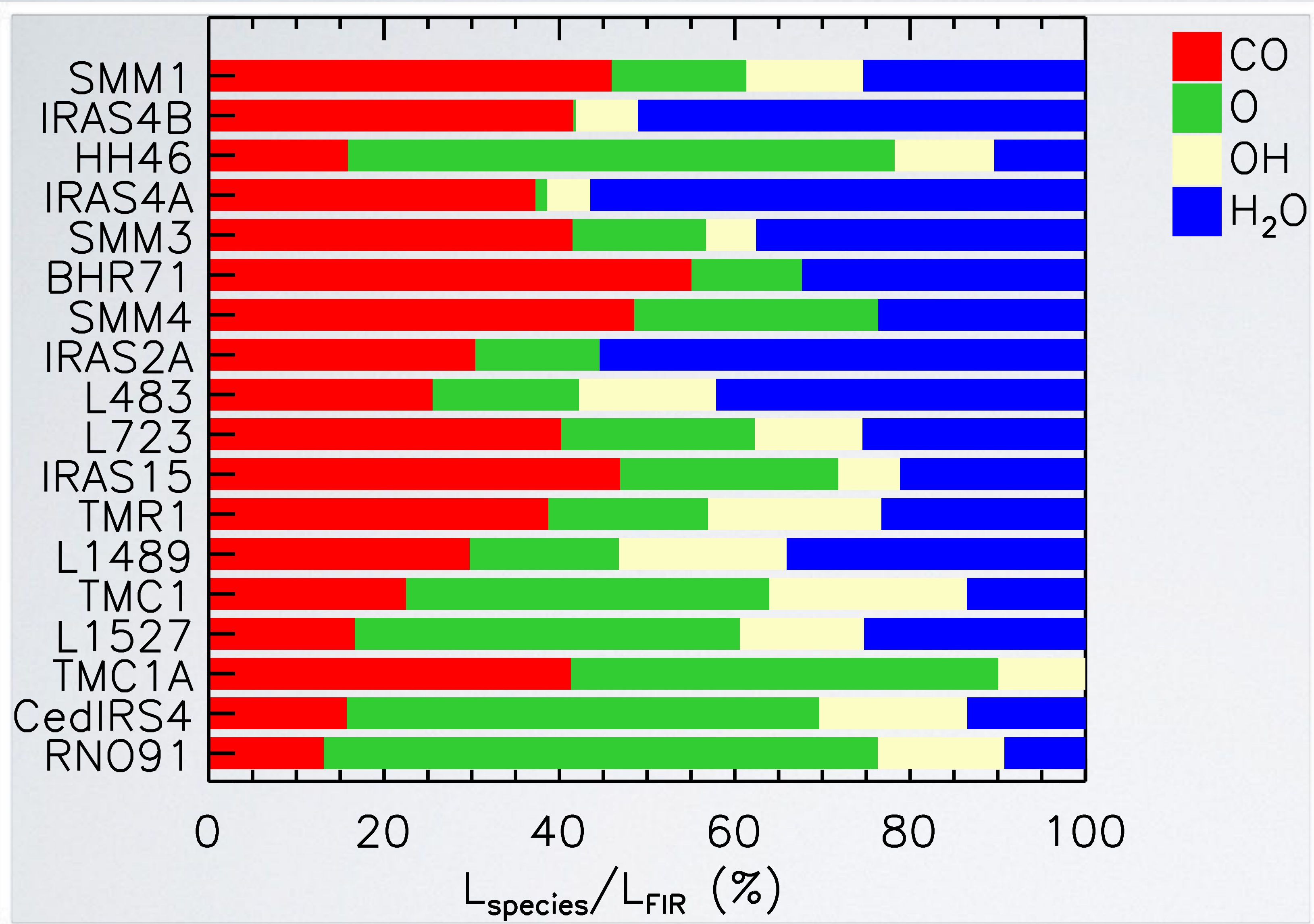
The line cooling should be dominated by:

1. fine structure lines of atomic species (CII, OI, CI etc) from the PDR around the protostar and from J-shocks
2. rotational lines of CO, H_2O etc (depending on T and n)

- **OI, CO and H_2O are fundamental species to investigate the physics of the gas in star-forming regions**
- **If $[OI]_{63\mu m}$ is confirmed to be the dominant coolant in dense PDRs and in jets from YSOs ⇒possible star-formation rate tracer unaffected by extinction; tracer of mass-loss rate in YSOs (Hollenbach+1985)**

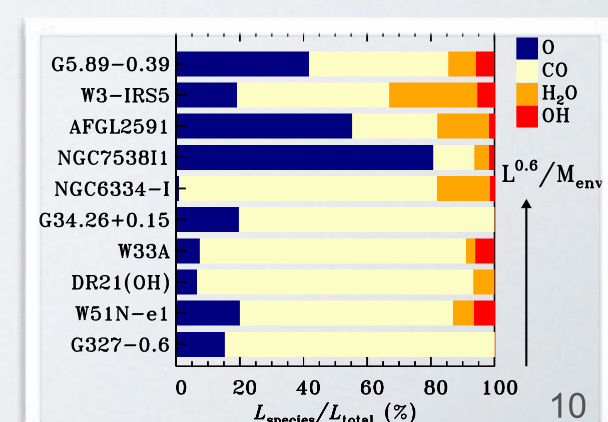
Herschel view…

SOFIA Stratospheric Observatory for Infrared Astronomy
GREAT
Max-Planck-Institut für Radioastronomie



Karska+2013, 2014

high-mass YSOs

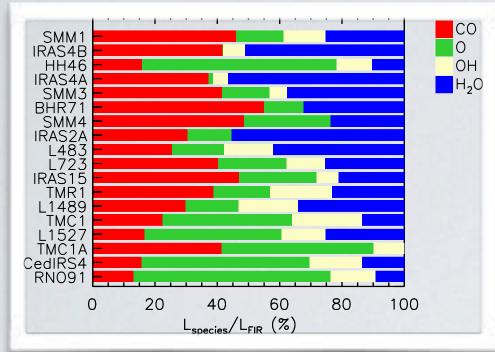


low-mass YSOs

- ➡ total far-IR line cooling dominated by H_2O (25%-50%) and CO (5%-50%)
- ➡ OI (5%-30%) and it increases with time

Herschel view…

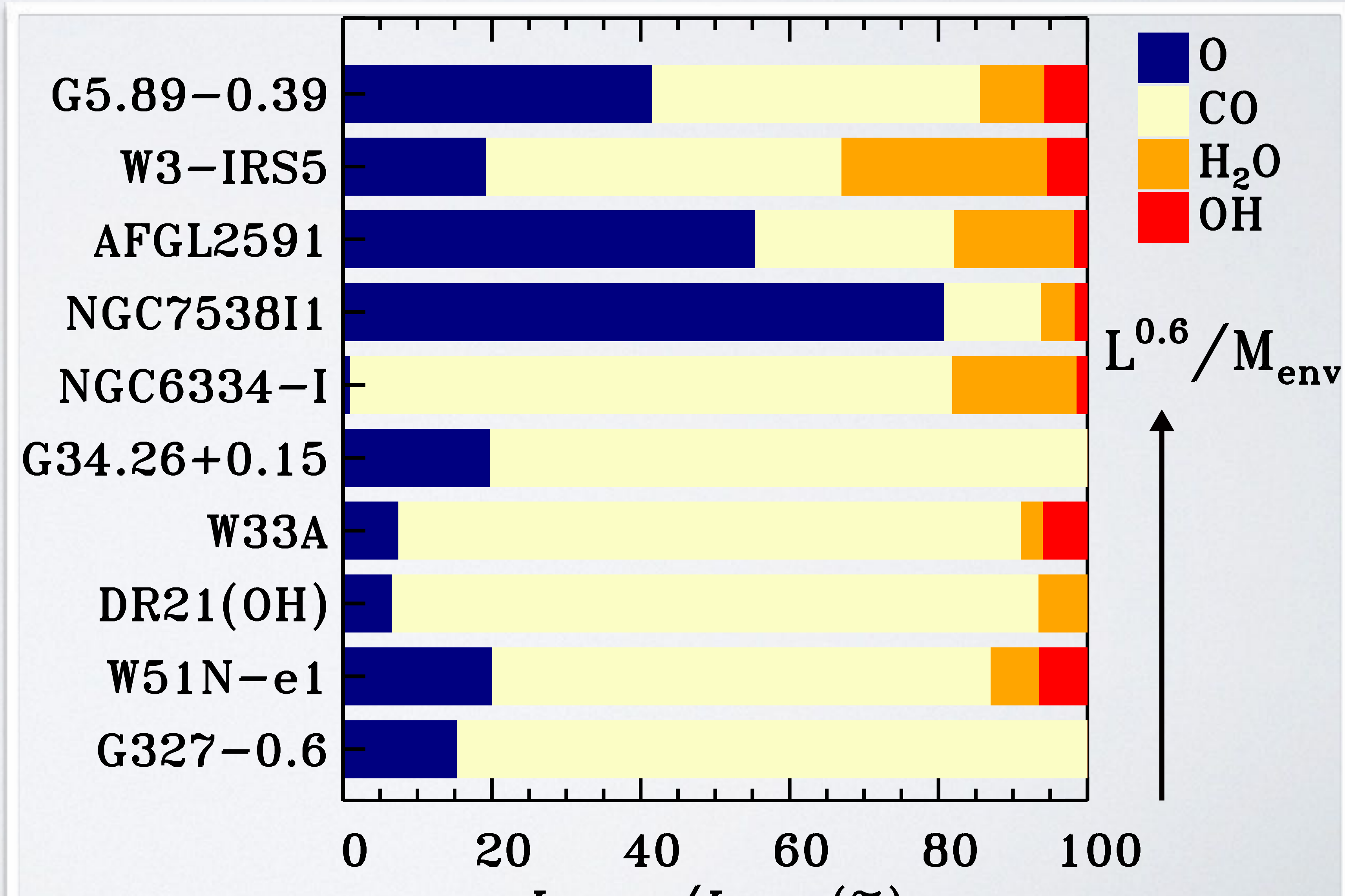
low-mass YSOs



high-mass YSOs

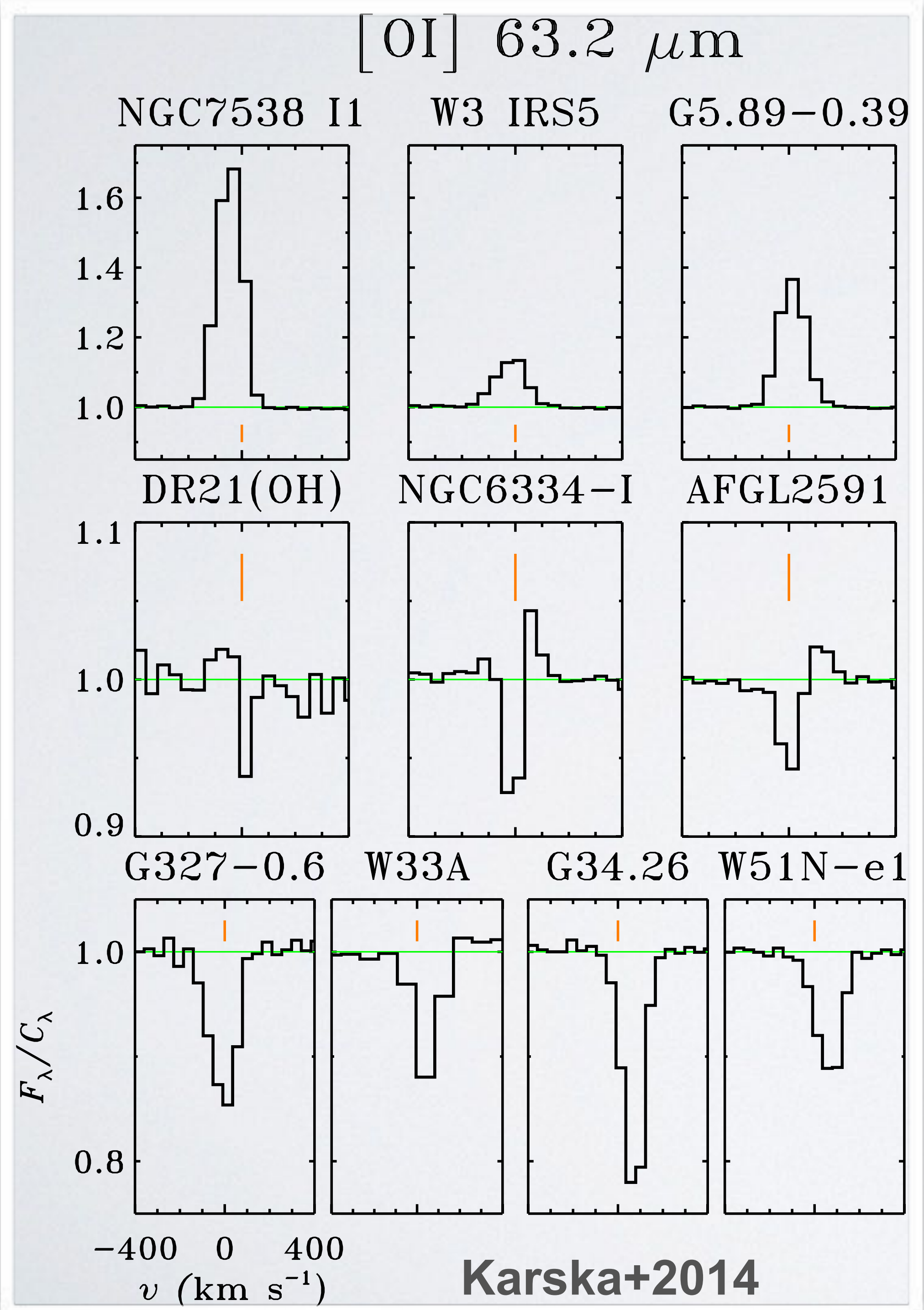
- ➡ total far-IR line cooling dominated by CO (~74%) followed by OI (~20%)
- ➡ H_2O contribution is negligible (~1%)
- ➡ importance of OI increases with time

Karska+2013, 2014



…and open questions

Emission/absorption in [OI]$_{63\mu m}$



Karska+2014

- PACS data with ~90 km s^{-1} resolution;
- variety of profiles:
  1. pure emission
  2. pure absorption
  3. P-Cygni profiles
  4. inverse P-Cygni

…and open questions

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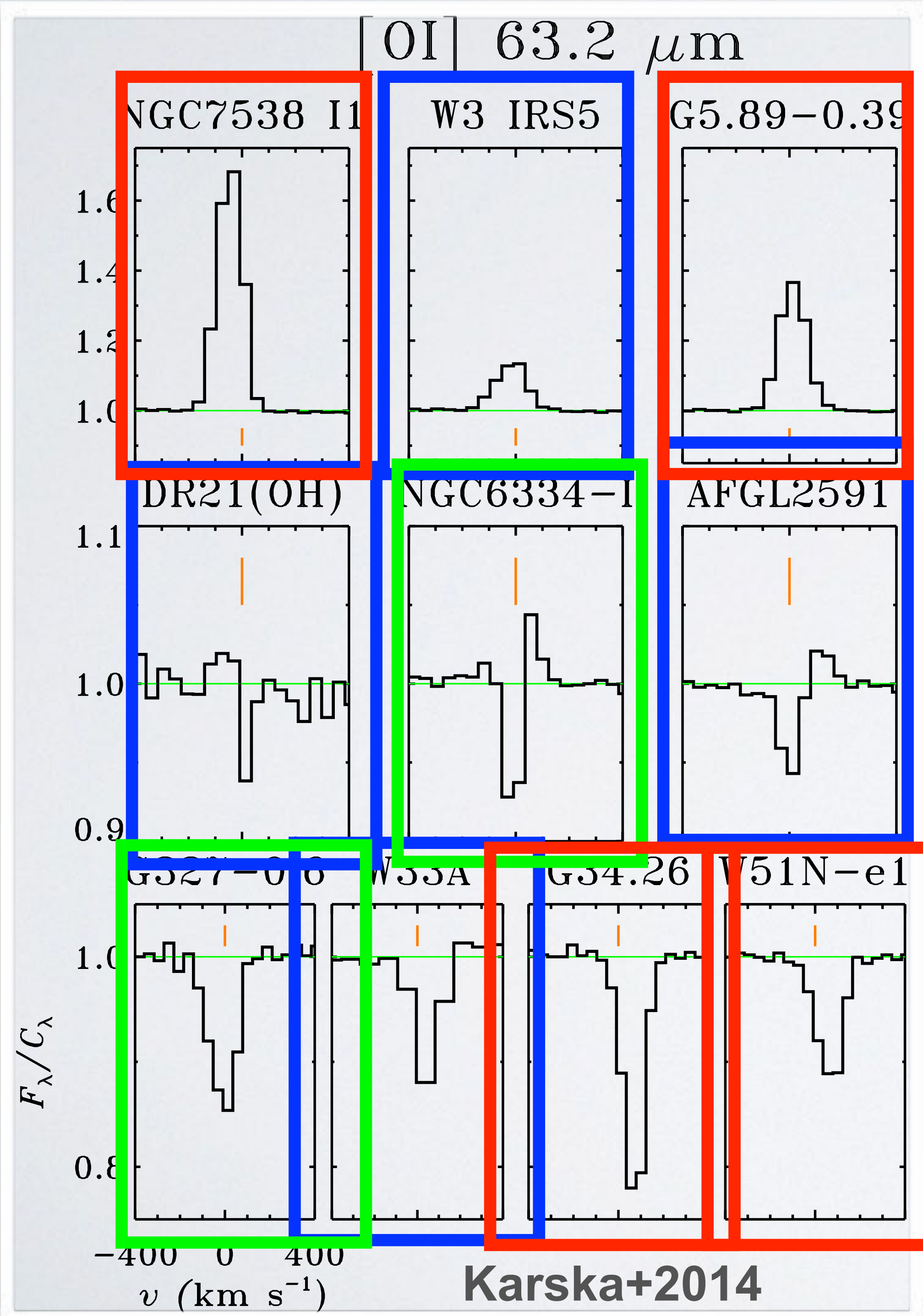

Karska+2014

- PACS data with ~90 km s^{-1} resolution;
- variety of profiles:
    1. pure emission
    2. pure absorption
    3. P-Cygni profiles
    4. inverse P-Cygni
- no trend with evolution (HMPO, HMC, UCHII)

...and open questions

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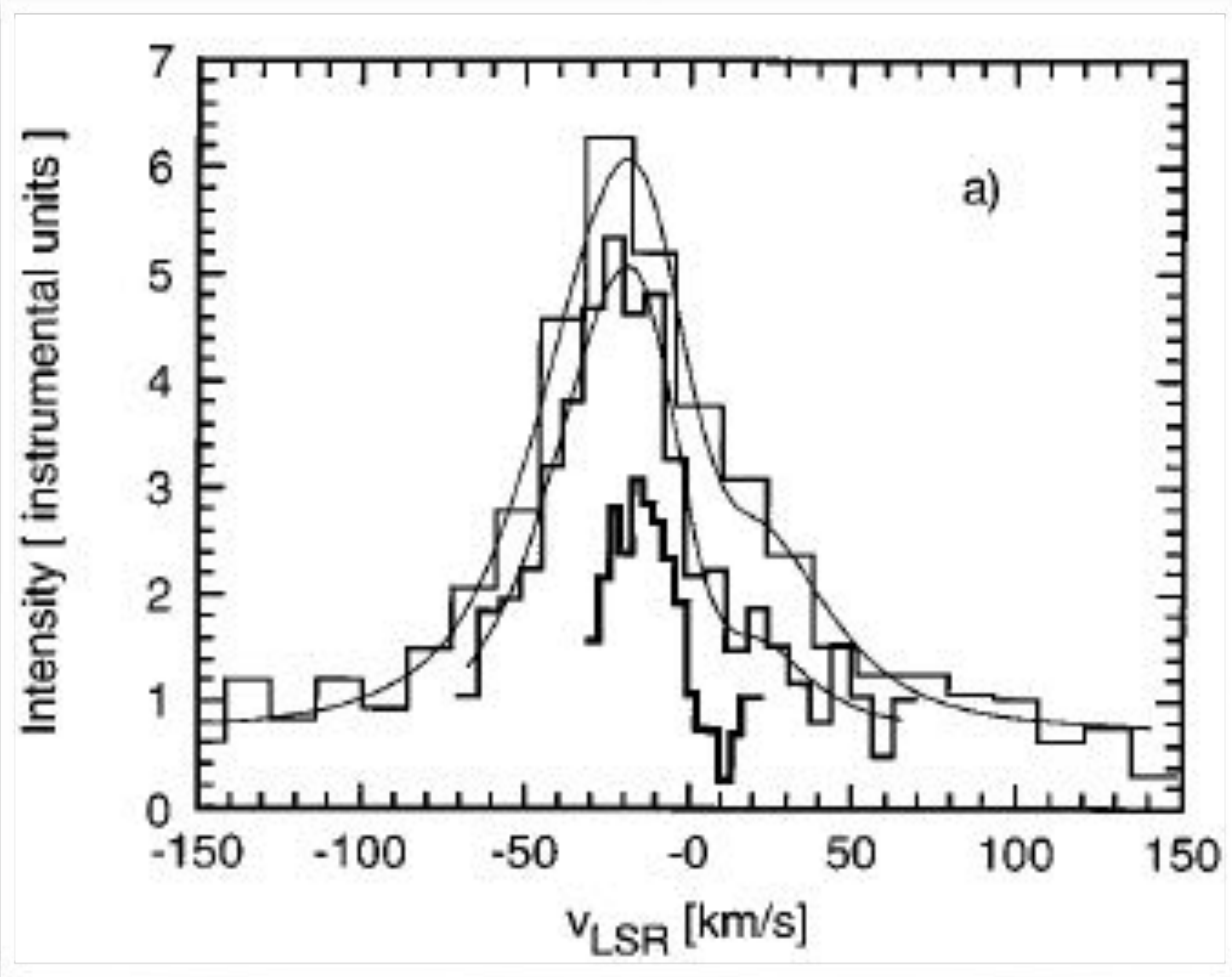
Emission/absorption in $[OI]_{63\mu m}$

DR21OH KAO $[OI]_{63\mu m}$ spectrum
Poglitsch et al. 1996)



KAO and ISO pioneering study:

foreground clouds and self-absorption can contaminate the profile

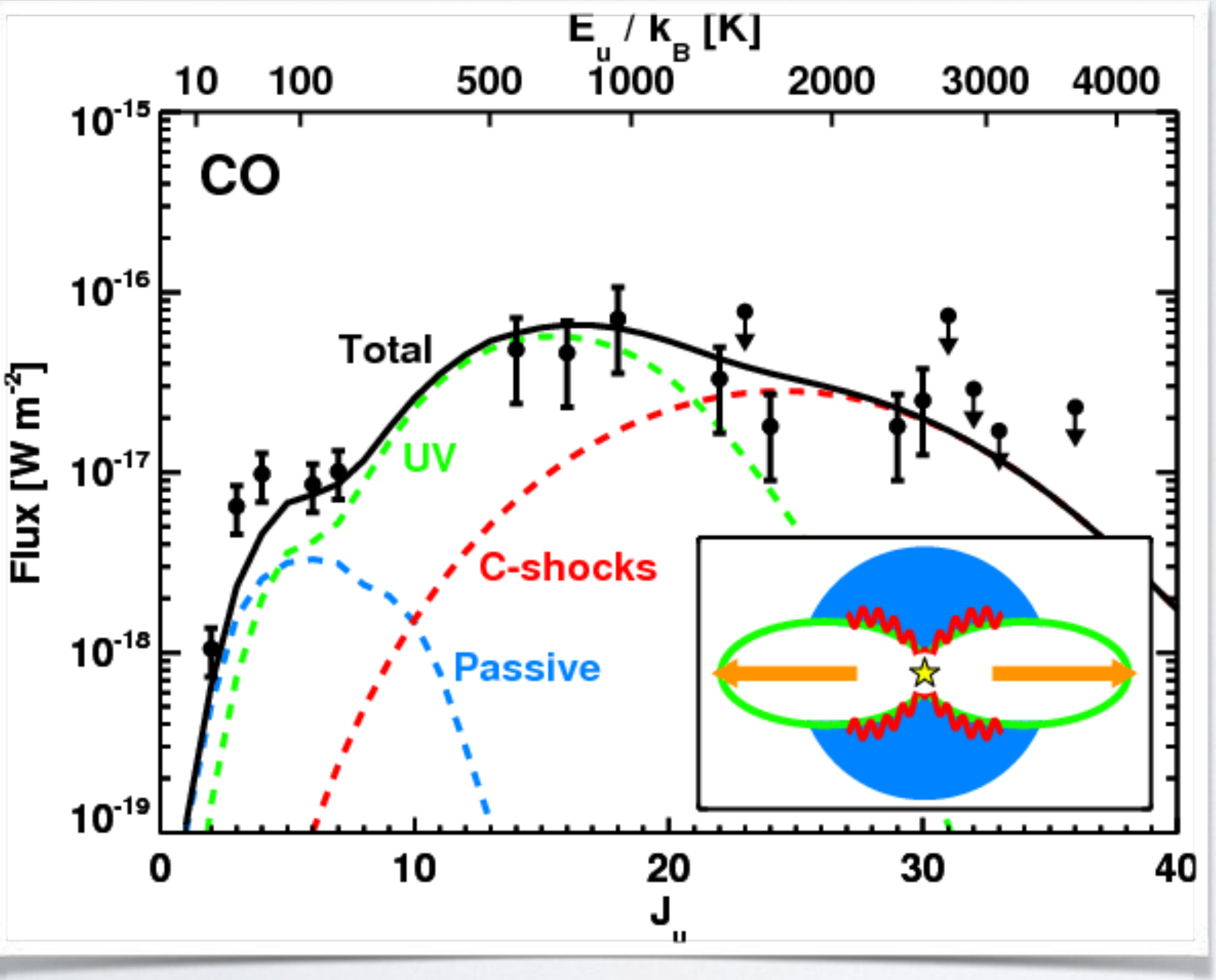
(Poglitsch+1996, Liseau+2006)

⇒ spectroscopically resolved observations of the $[OI]_{63\mu m}$ line are fundamental to exploit its full potential

…and open questions

The origin of hot CO emission

van Kempen+2010



Different origin for CO emission:

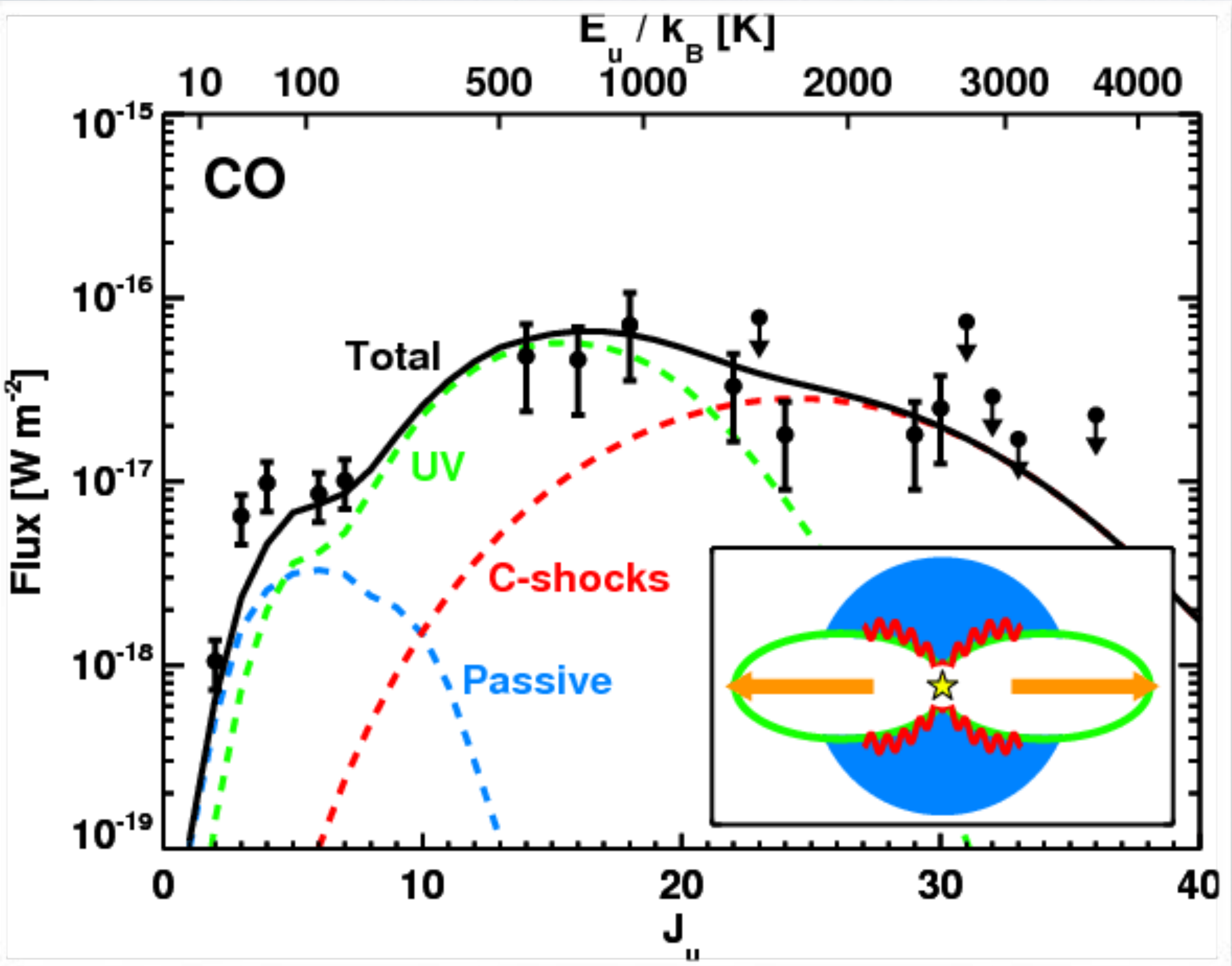
i. low-/mid-*J*: passively heated envelope

ii. high-J: UV heating of cavity walls and/or C-shocks

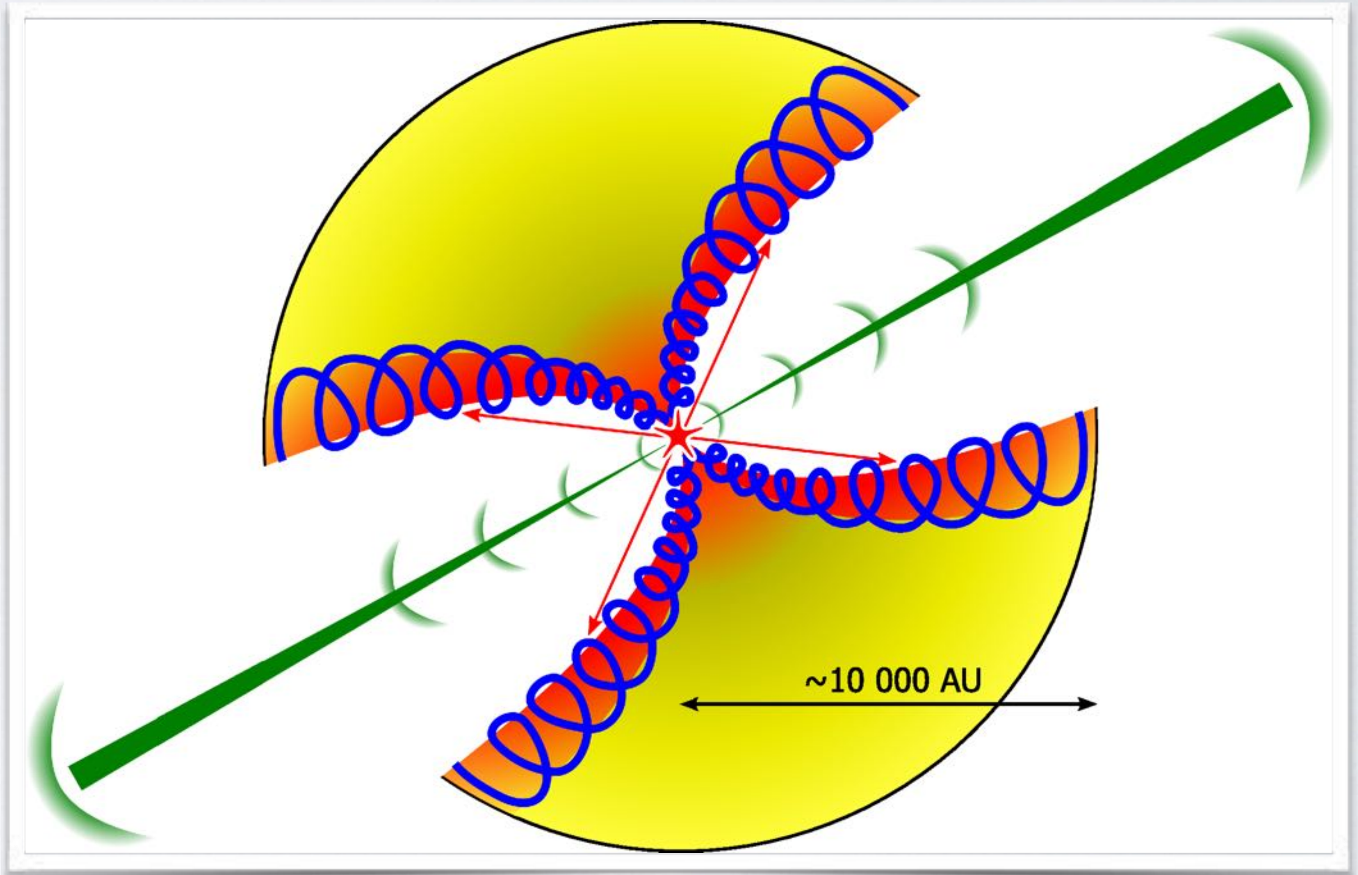
…and open questions

The origin of hot CO emission

van Kempen+2010



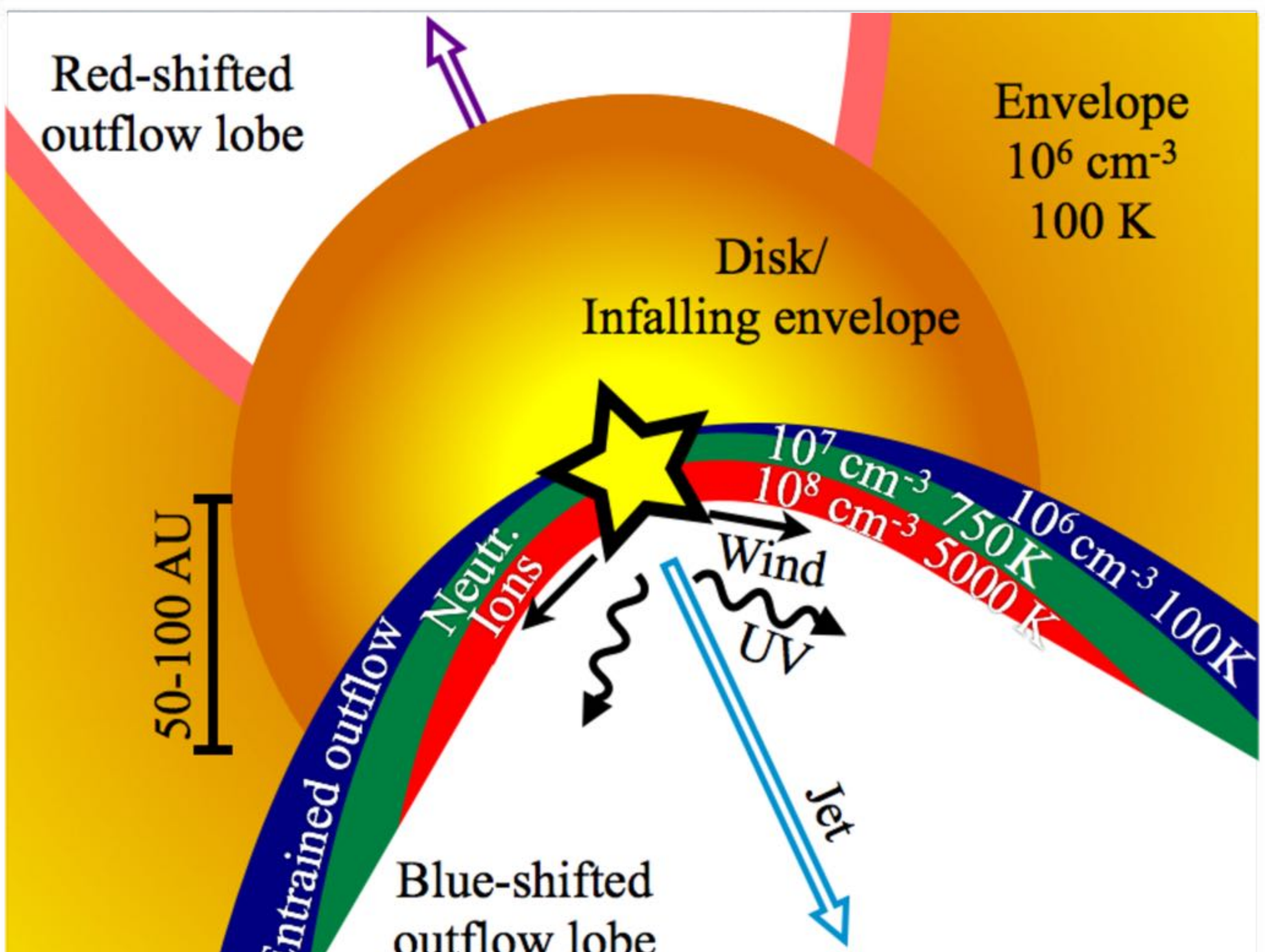
Visser+2012



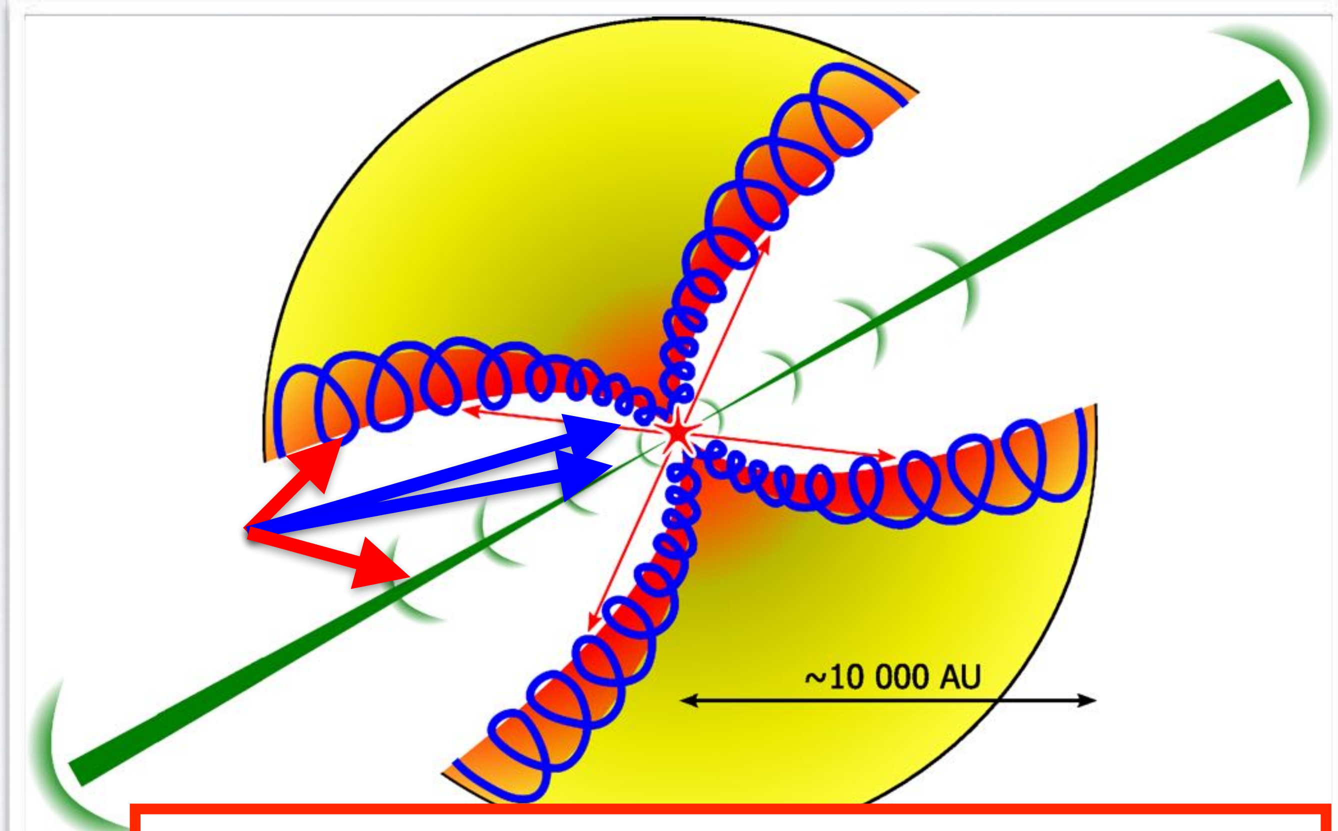
…and open questions

The origin of hot CO emission

Kristensen+2013



Neufeld+2012; Manoj+2013



CO in LTE: dense gas ~100 AU of the central star

sub-thermal CO: shocks along outflow/cavity walls at several 100 to 1000 AU

Far-IR cooling in massive YSOs

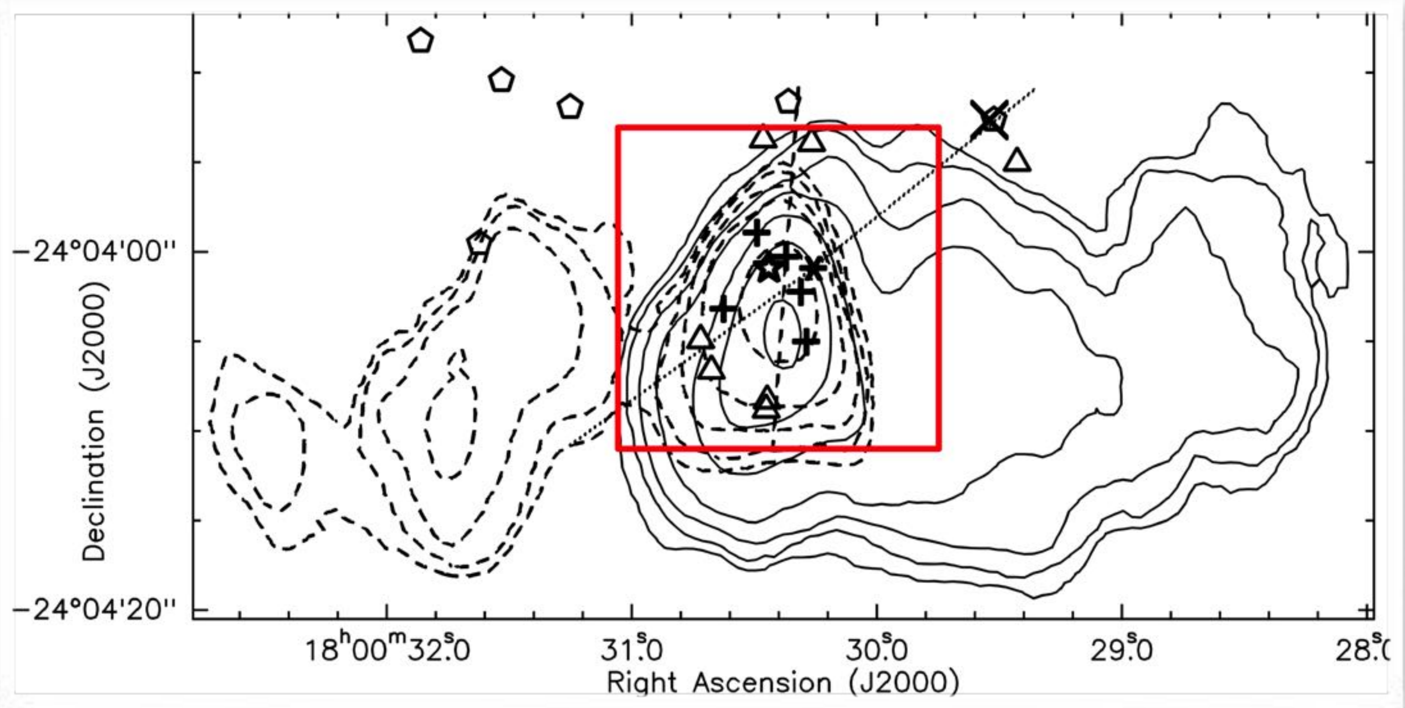
SOFIA Stratospheric Observatory for Infrared Astronomy
GREAT
Max-Planck-Institut für Radioastronomie

1. Is the $[OI]_{63\mu m}$ profile contaminated by absorption and how much?
2. In high-mass star-forming regions, does $[OI]_{63\mu m}$ trace the low-velocity PDR component or a high-velocity jet?
3. Is $[OI]_{63\mu m}$ the main coolant at high-velocity? How does the contribution of the main species (OI, CII, CO, H_2O) change in different velocity ranges?
4. Is H_2O a minor contributor to the total far-IR cooling also in molecular outflows?
5. How do these results change with the evolution of the source?

Feasibility study on G5.89-0.39 followed by a survey of high-mass YSOs in the main cooling lines with SOFIA/Heschel

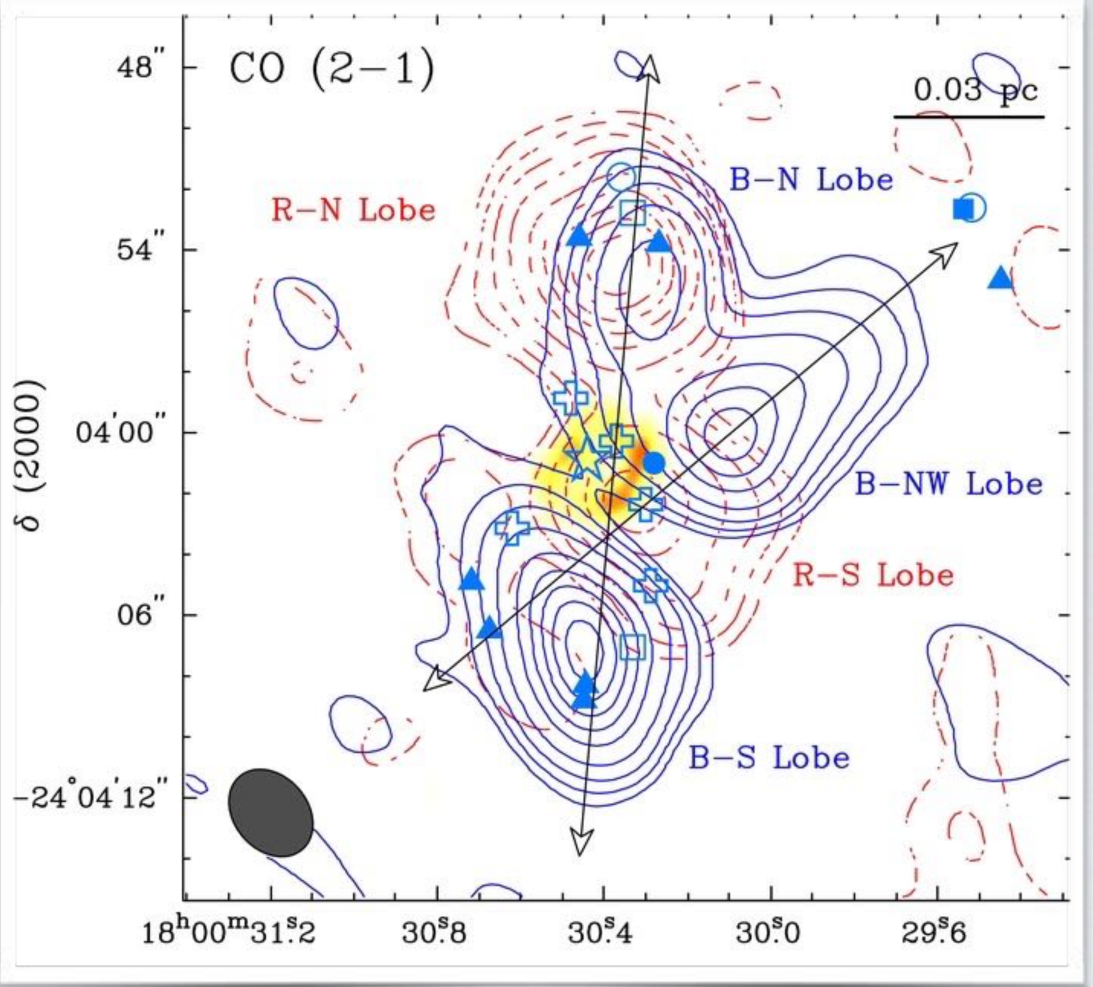
G5.89-0.39

Hunter+2008



d=1.28 kpc (Motogi+2011)

Su+2012



G5.89-0.39 hosts

- a UCHII from a O8 star (Feldt+2003)
- one of the most extreme massive outflows (Harvey & Forveille 1988)
- compact EHV N-S and NW-SE outflows associated with HV H_2 emission (Puga+2006)

SOFIA/HERSCHEL/APEX synergies

SOFIA observations

- $[OI]_{63\mu m}$ 18”×18” **map**
- CO(16-15) 18”×18” **map**
- OH triplets **single pointings** at 2514 GHz, 1838 GHz and 1834 GHz

HIFI observations (Gusdorf+2016, van der Tak+2013)

- *Herschel* HIFI H_2O (752 GHz, 987 GHz, 1113 GHz, 1661 GHz, 1669 GHz)

APEX data (Gusdorf+2016)

- CO(6-5)/(7-6) maps

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SOFIA/HERSCHEL/APEX synergies

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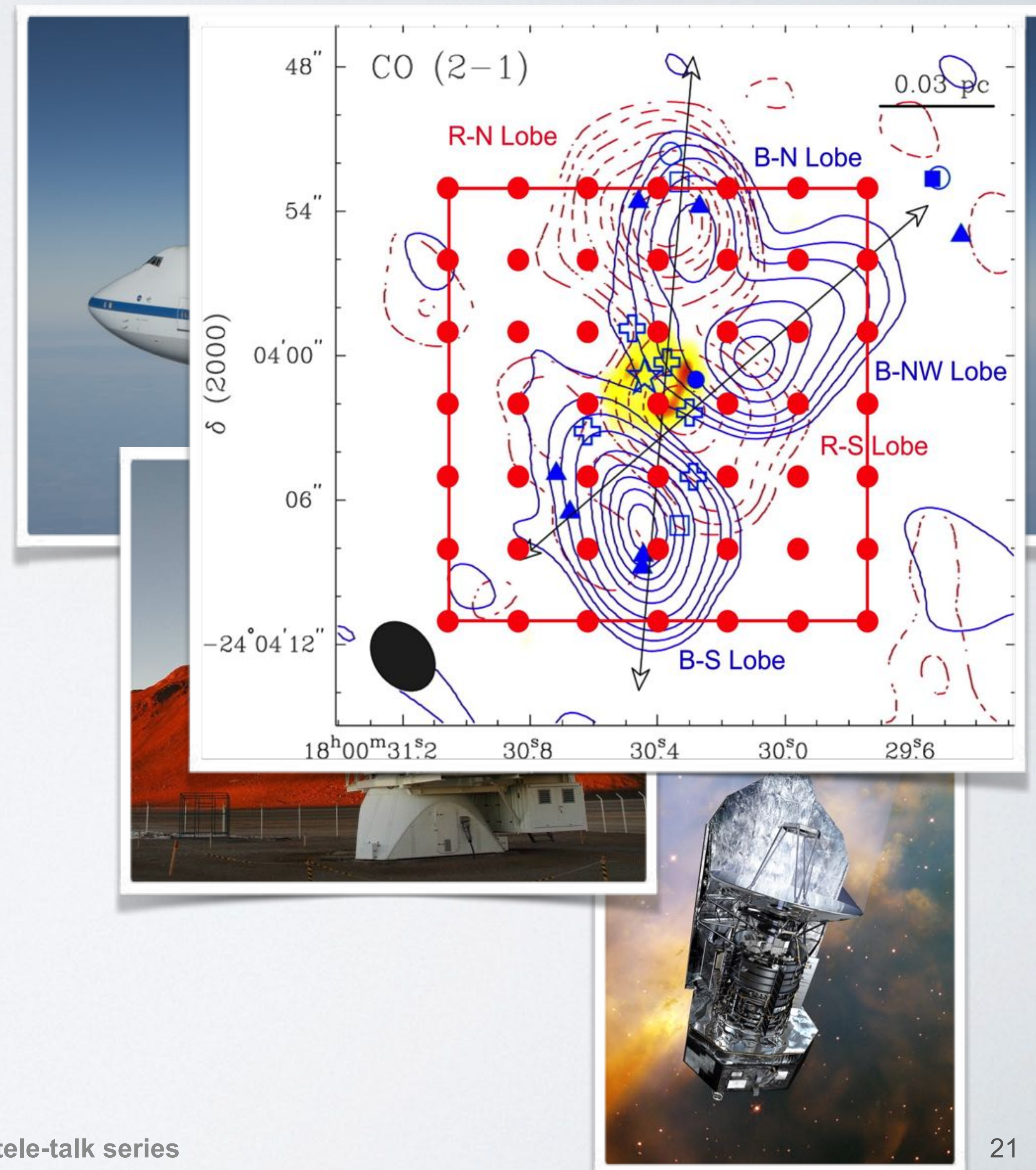
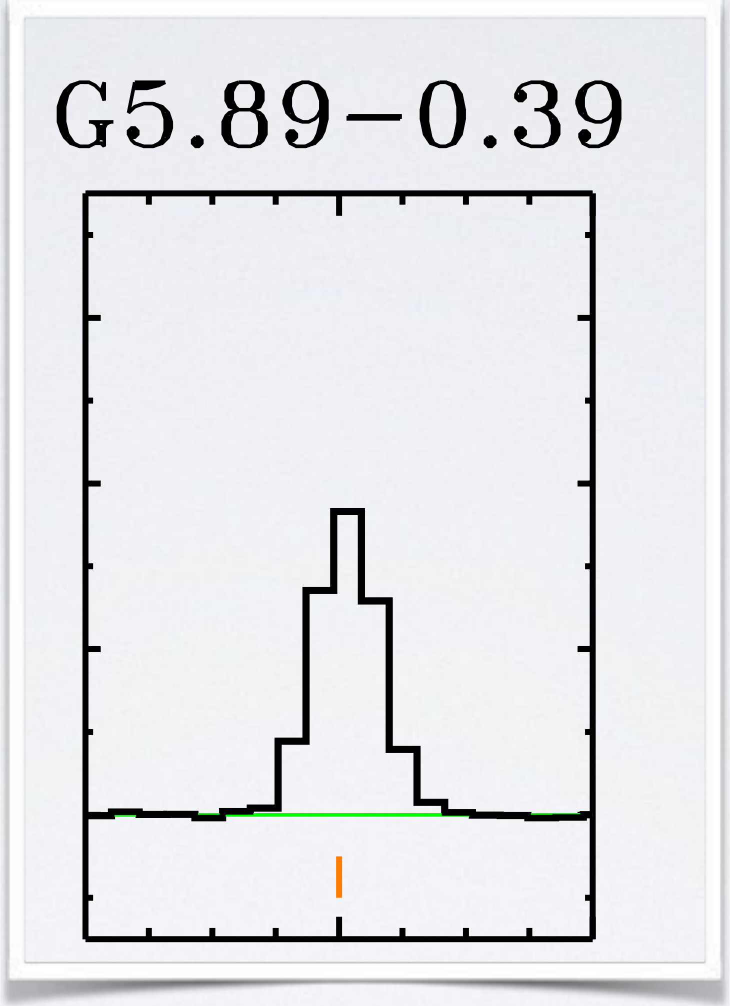


[OI] in G5.89-0.39

before SOFIA…

Karska+2014



- Δv~90 km/s
- beam ~9.4”

✦ pure Gaussian profile no sign of absorption

[OI] in G5.89-0.39

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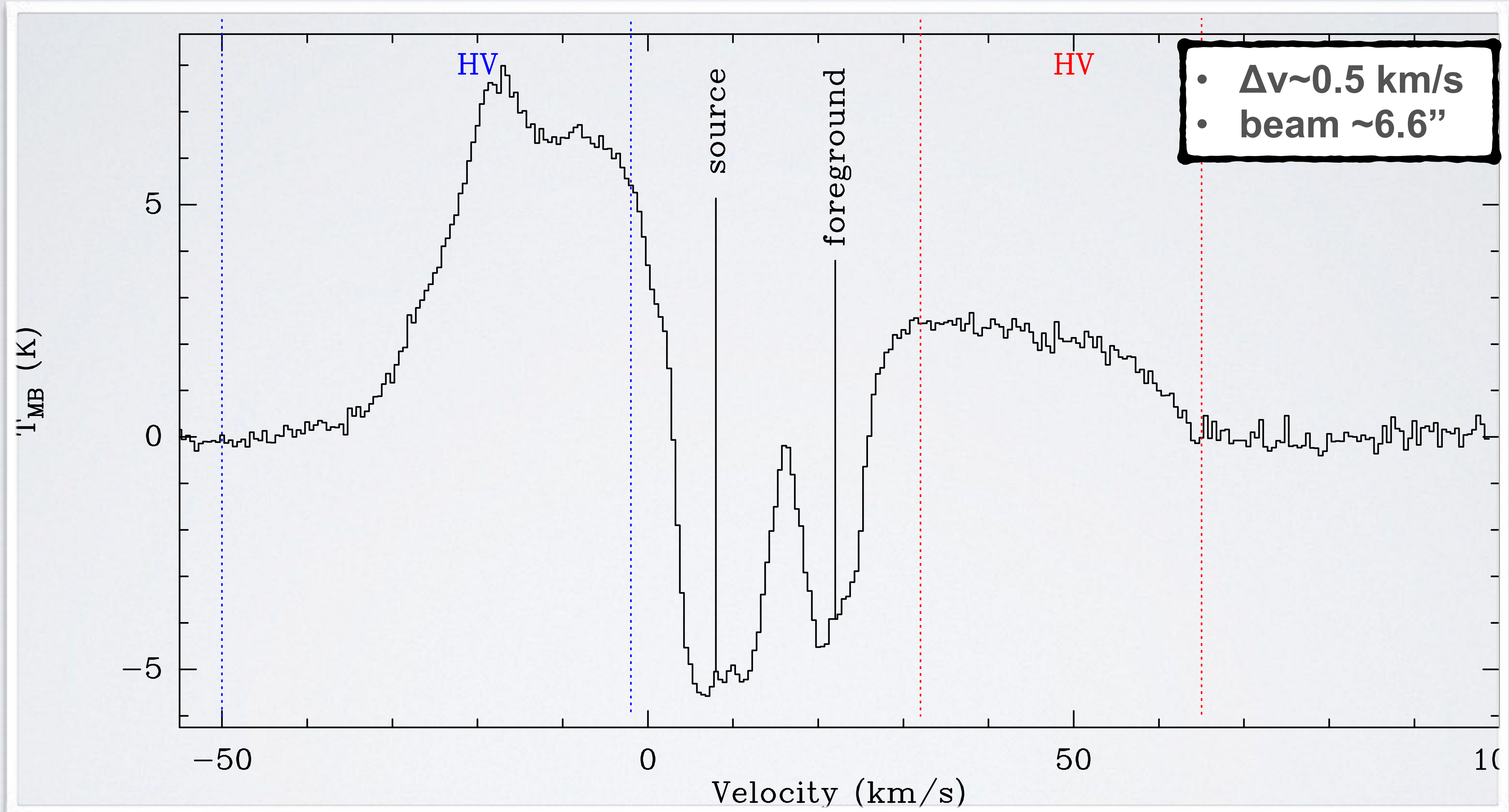
…and with SOFIA

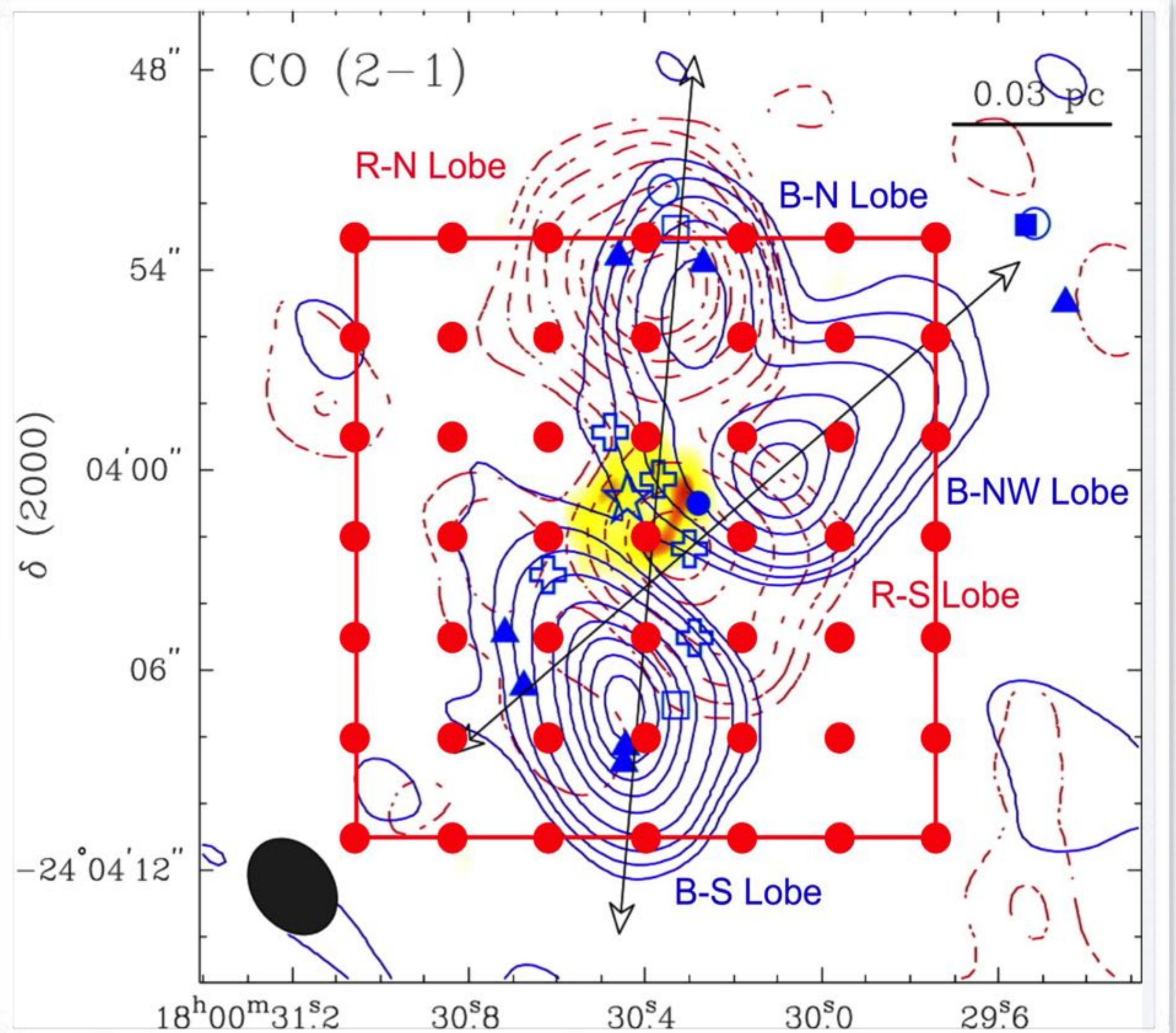
Leurini+2015

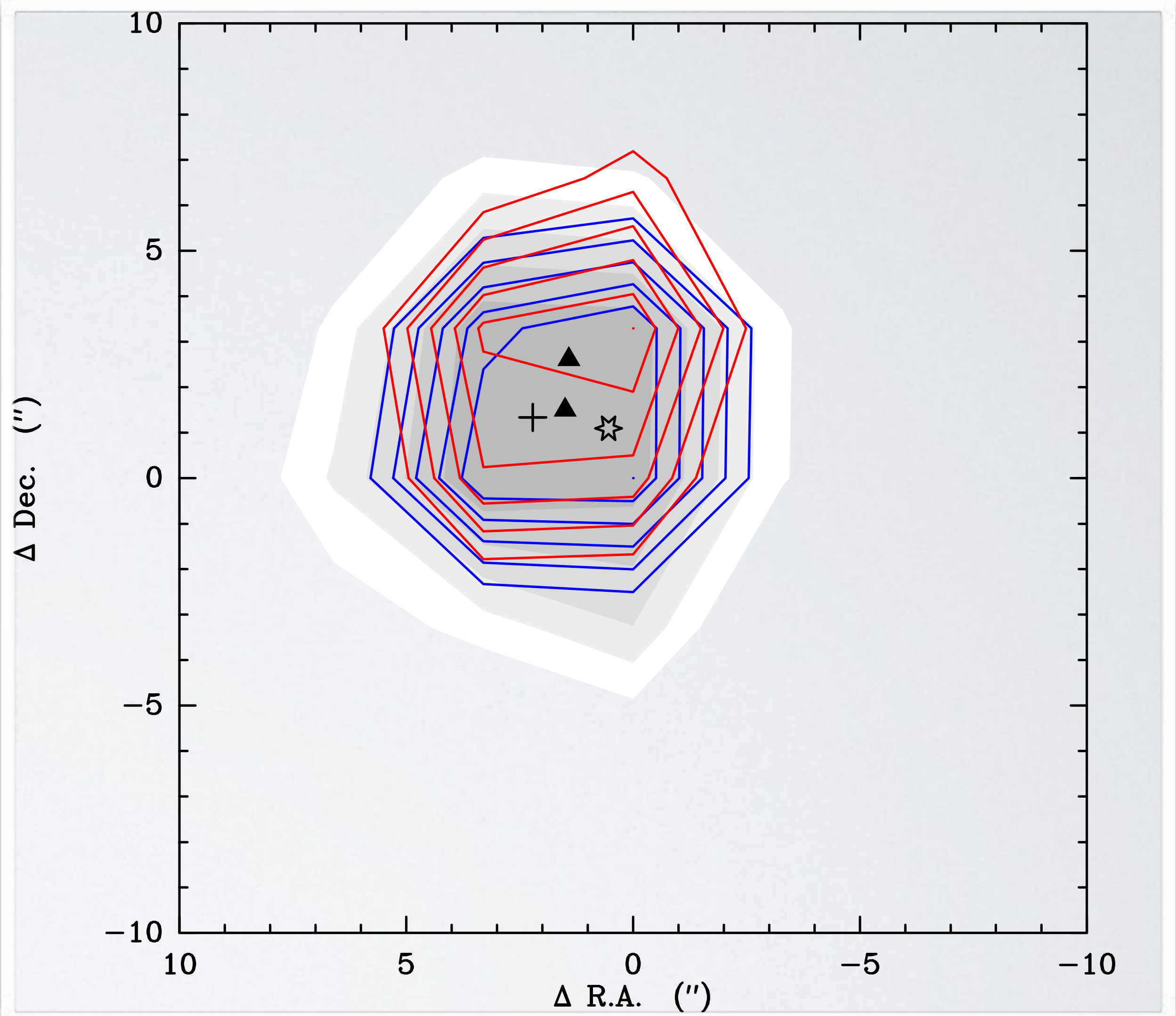


➡ *deep absorptions from the source and from different line of sight clouds;*
➡ *emission completely dominated by the HV wings ($|v_{max}-v_{lsr}| \simeq 70$ km s^{-1})*

[OI] distribution in G5.89-0.39

Leurini+2015

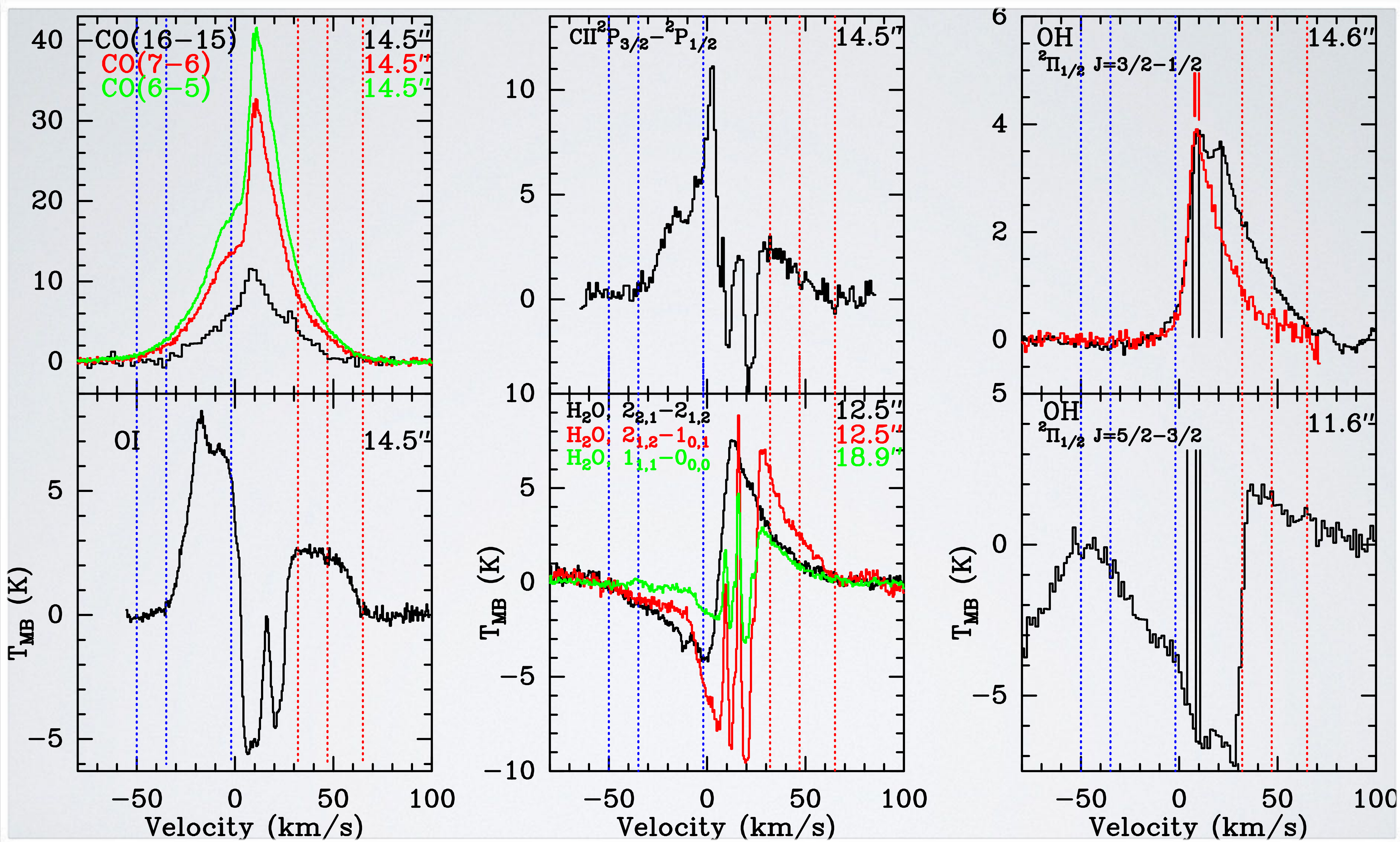




- ➡ *HV emission along the north-south as CO(6-5)*
- ➡ *HV emission from the inner region of EHV outflows*
- ➡ *HV emission more compact (<6".6 beam) than EHV CO outflow (~12")*

The major coolants

Leurini+2015



➡ *[OI]$_{63\mu m}$ is characterised by* ***emission at HV in the same velocity range as mid- and high-J CO, H_2O, OH;***

Far-IR LINE cooling

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PACS

Karska+2014

Values from Karska et al. (2014) (9″.4 beam)						
Velocity range	L_{CO}[e]	L_{OH}[f]	L_{H_2O}[f]	$L_{OI\,63\mu m}$[g]		
total profile	3.9	0.5	0.8	3.7	–	8.8

- Far-IR gas cooling of **high-mass YSOs is dominated by CO** (44%), and to a smaller extent by **[OI]** (42%). H_2O and OH are less than 1%.
- In contrast, for **low-mass YSOs, the H2O, CO, and [O i] contributions are comparable.**

Far-IR LINE cooling

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GREAT/HIFI

Leurini+2015

This work (14″.5 beam)						
Velocity range	$L_{CO(16-15)}$ ($L_\odot$)	L_{OH}[a] ($L_\odot$)	L_{H_2O}[b] ($L_\odot$)	$L_{OI\,63\mu m}$ ($L_\odot$)	L_{CII} ($L_\odot$)	L_{FIRL} ($L_\odot$)
total profile ([−50, +65] km s^{-1})	0.65	0.44	–	5.7	0.42	7.21
HV-red ([+47, +65] km s^{-1})	–	0.08	0.03	0.9	0.02	1.03
LV-red ([+32, +47] km s^{-1})	0.06	0.13	0.09	1.2	0.06	1.48
ambient[c] ([−2, +26] km s^{-1})	0.42	0.12	0.08[d]	–	0.1	0.72
HV-blue ([−35, −50] km s^{-1})	–	–	–	0.02	–	0.02
LV-blue ([−35, −2] km s^{-1})	0.17	–	–	5.3	0.2	5.67

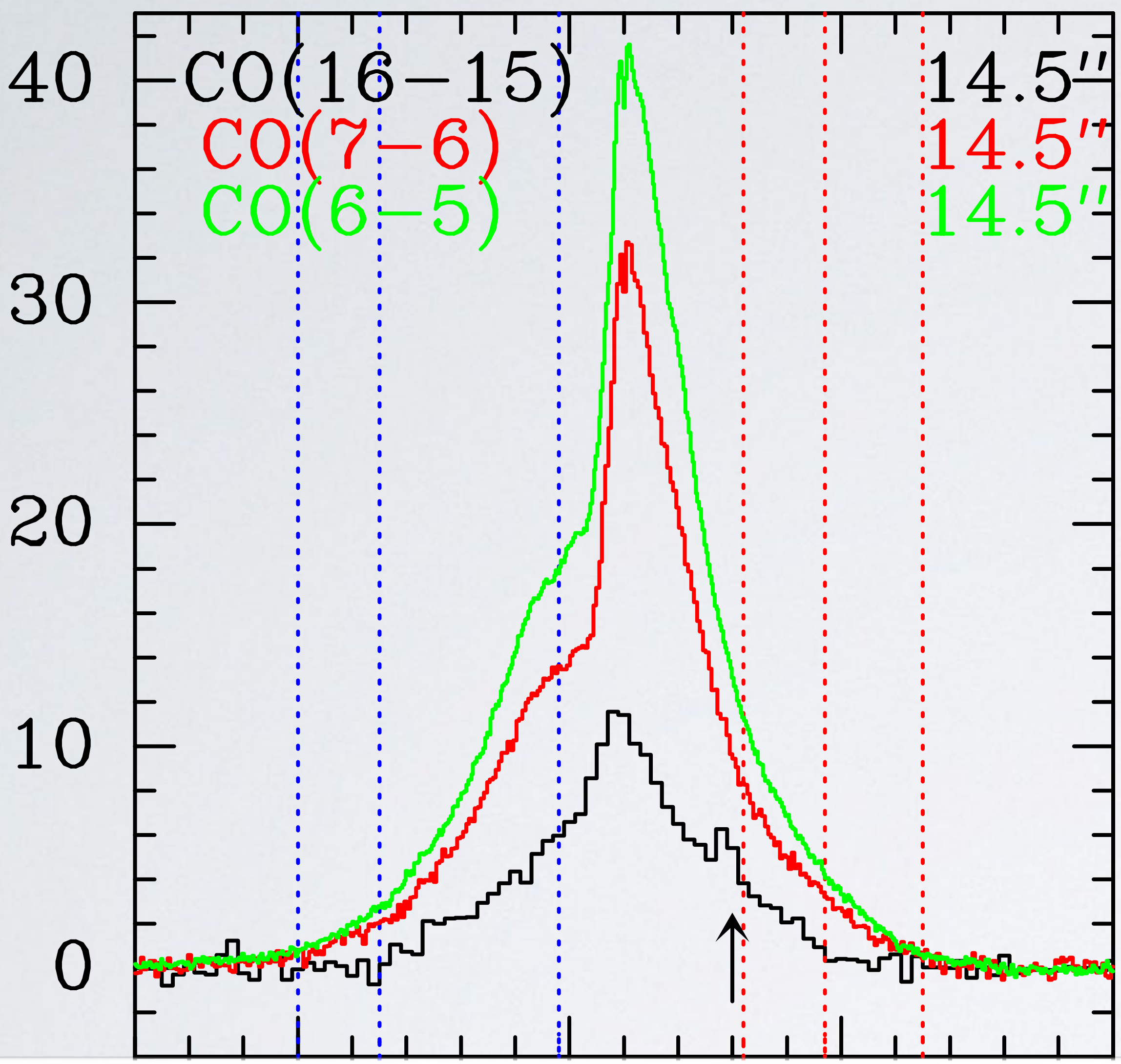
I. In the **LV wings**, [OI] is the main contributor (5.3/1.2 $L_\odot$) to the line L_{FIR} followed by CO

II. H_2O is **not** a significant contributor even at HV

➡ *The line **luminosity of the [OI] line at high velocities can be used as tracer of the mass-loss rate** of the jet since [OI] is the main coolant of the gas in this velocity regime*

Hot CO emission

Max-Planck-Institut für Radioastronomie



- ➡ ~2/3 of the CO(16-15) emission is due to outflows
- ➡ 1/3 hot quiescent gas

Gusdorf+2016

line	W_{tot} (K km s^{-1})	W_{blue} (K km s^{-1})	W_{blue}/W_{tot} (%)	W_{amb} (K km s^{-1})	W_{amb}/W_{tot} (%)	W_{red} (K km s^{-1})	W_{red}/W_{tot} (%)
CO (3–2)	1334	630	47.2	387	29.0	317	23.8
CO (4–3)	1512	643	42.5	469	31.0	401	26.5
CO (6–5)	1969	647	32.9	674	34.2	648	32.9
CO (7–6)	2003	650	32.5	692	34.3	661	33.0
CO (16–15)	396	119	30.1	127	32.1	150	37.9

Line cooling in ATLASGAL selected sources

How typical is G5.89-0.39? how does the line cooling change with evolution in the process of massive SF?

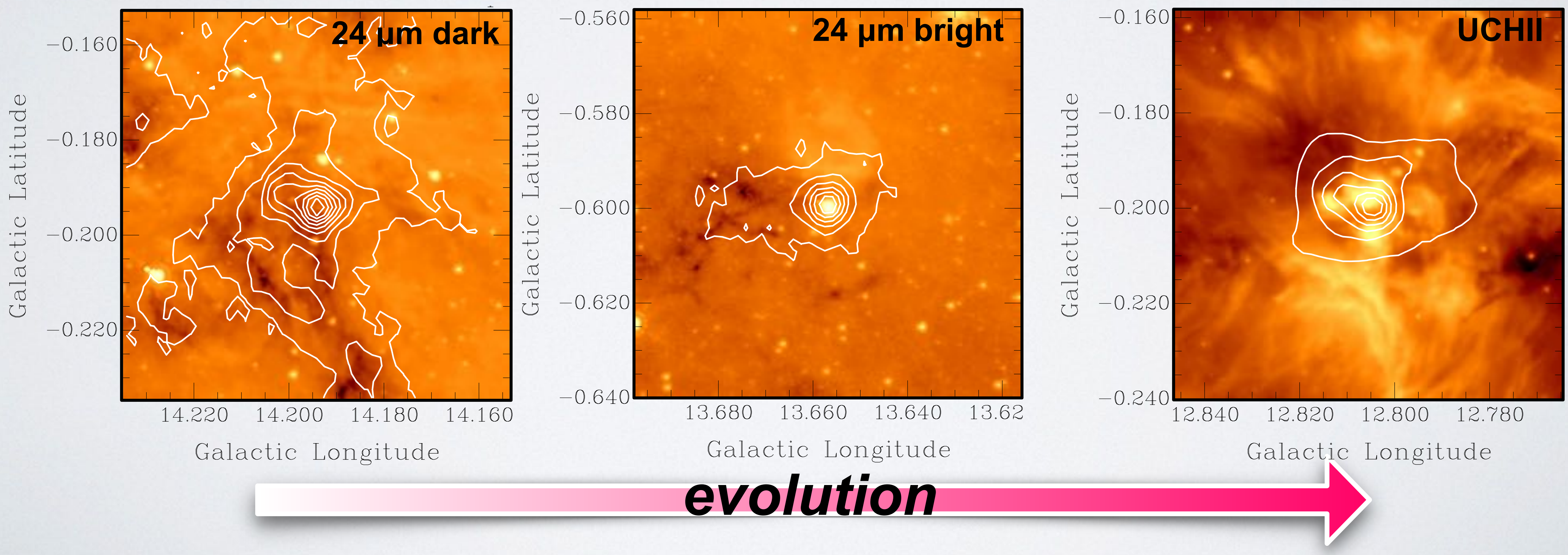
1. OI:
   i. how severe is absorptions in other sources?
   ii. does the atomic jet become important with time and is the jet purely mostly molecular in early evolutionary phases? (Nisini +2015)
2. CO:
   i. what is the origin of hot CO?
3. H_2O:
   i. is H_2O an important coolant at least in the high-velocity outflow gas?

Line cooling in ATLASGAL selected sources

The ATLASGAL TOP100:

a flux-limited sample of 100 massive star-forming clumps with alarge range of evolutionary stages and luminosities

Giannetti+2014; König+subm.



Line cooling in ATLASGAL selected sources

Max-Planck-Institut für Radioastronomie

The ATLASGAL TOP100:

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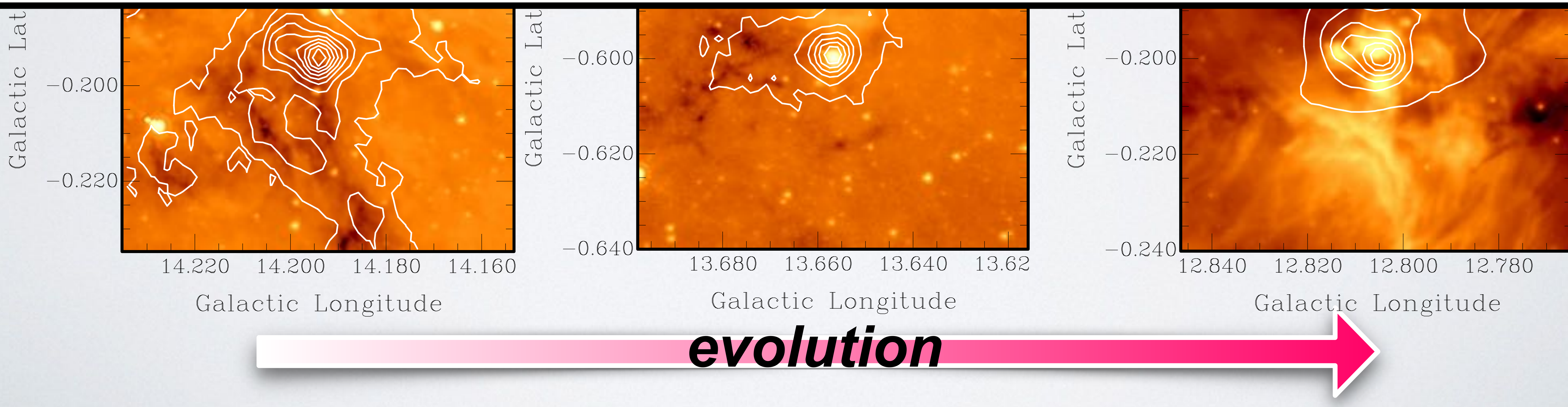
➡ *SOFIA/GREAT follow-up in high-J CO, OI, OH.*
Ongoing program ***25 sources accepted****,* ***17 done in CO, 5 in OI, 7 in OI***

➡ *Herschel/HIFI in three water line: ~100 sources*



SOFIA CO observations
(preliminary results)

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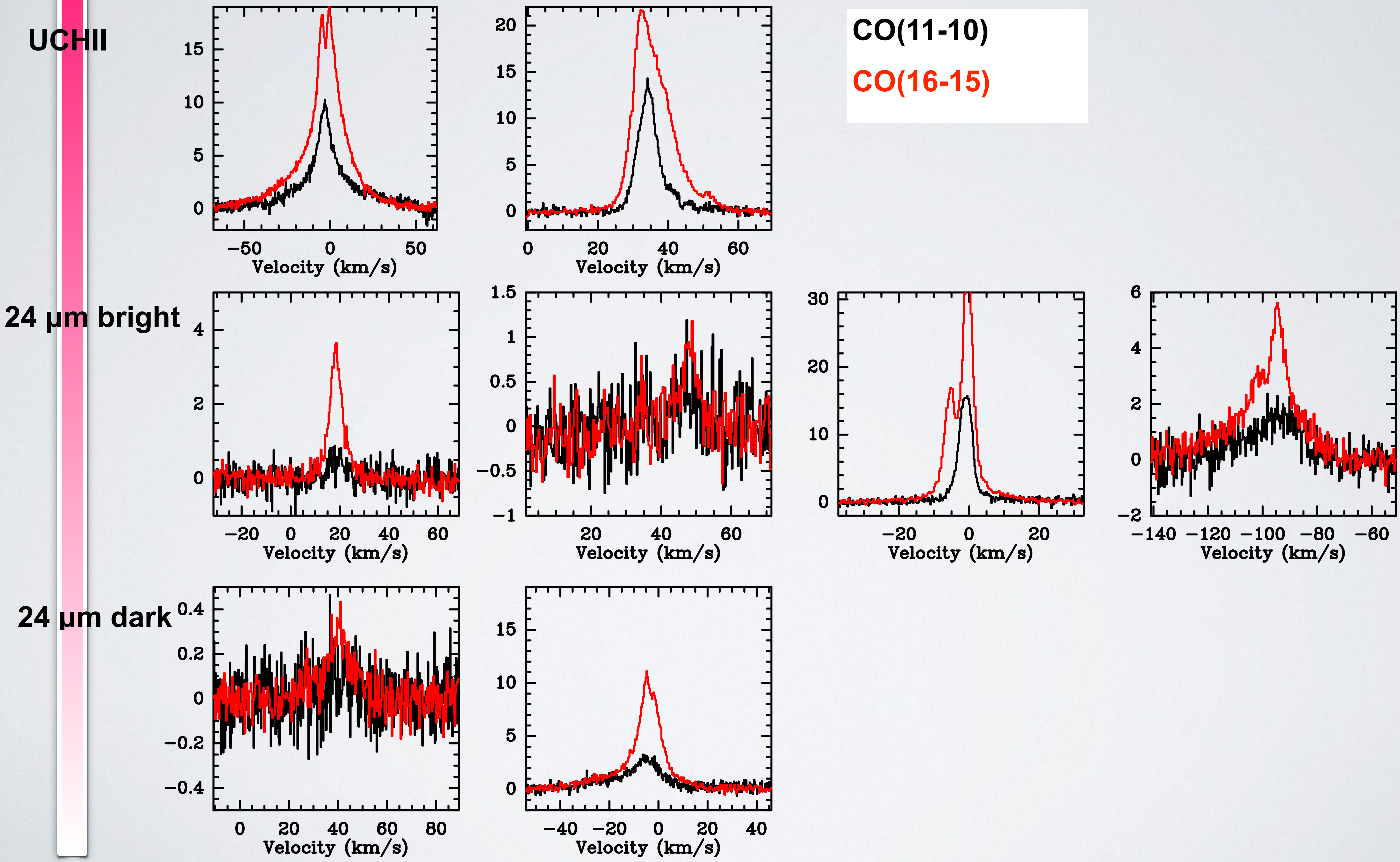
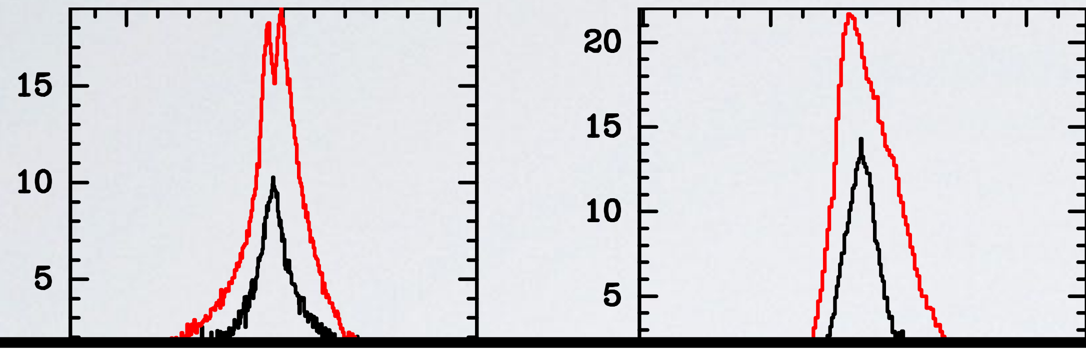


SOFIA CO observations

(preliminary results)

UCHII



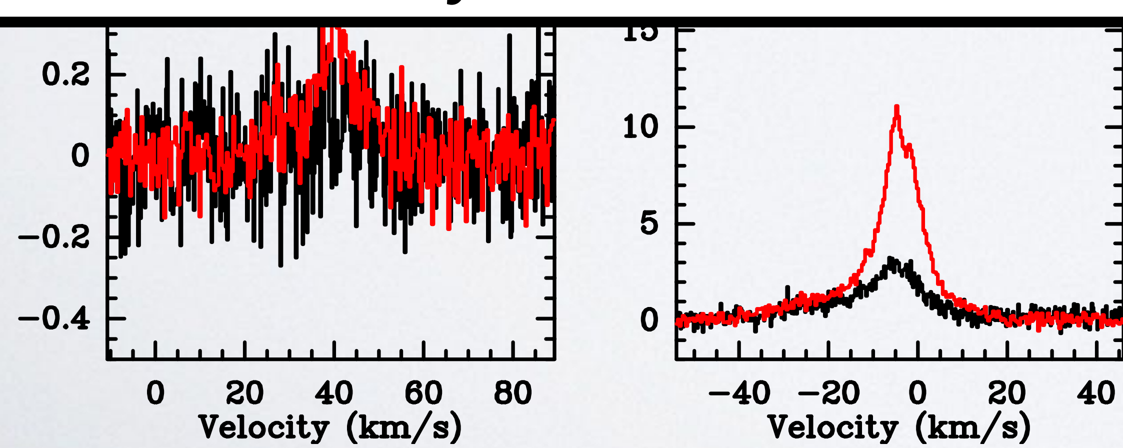
CO(11-10)

CO(16-15)

- *high-J CO is detected in all sources; however, the highest J CO line observed is not detected in the earliest phases;*
- *the luminosity of the lines increases with evolution;*
- *lines are broad (>5-7 kms^{-1})*
- *in several cases non Gaussian wings*
- *the contribution of the wings (red+blue) varies from 20% to 76% of the total intensity*

24

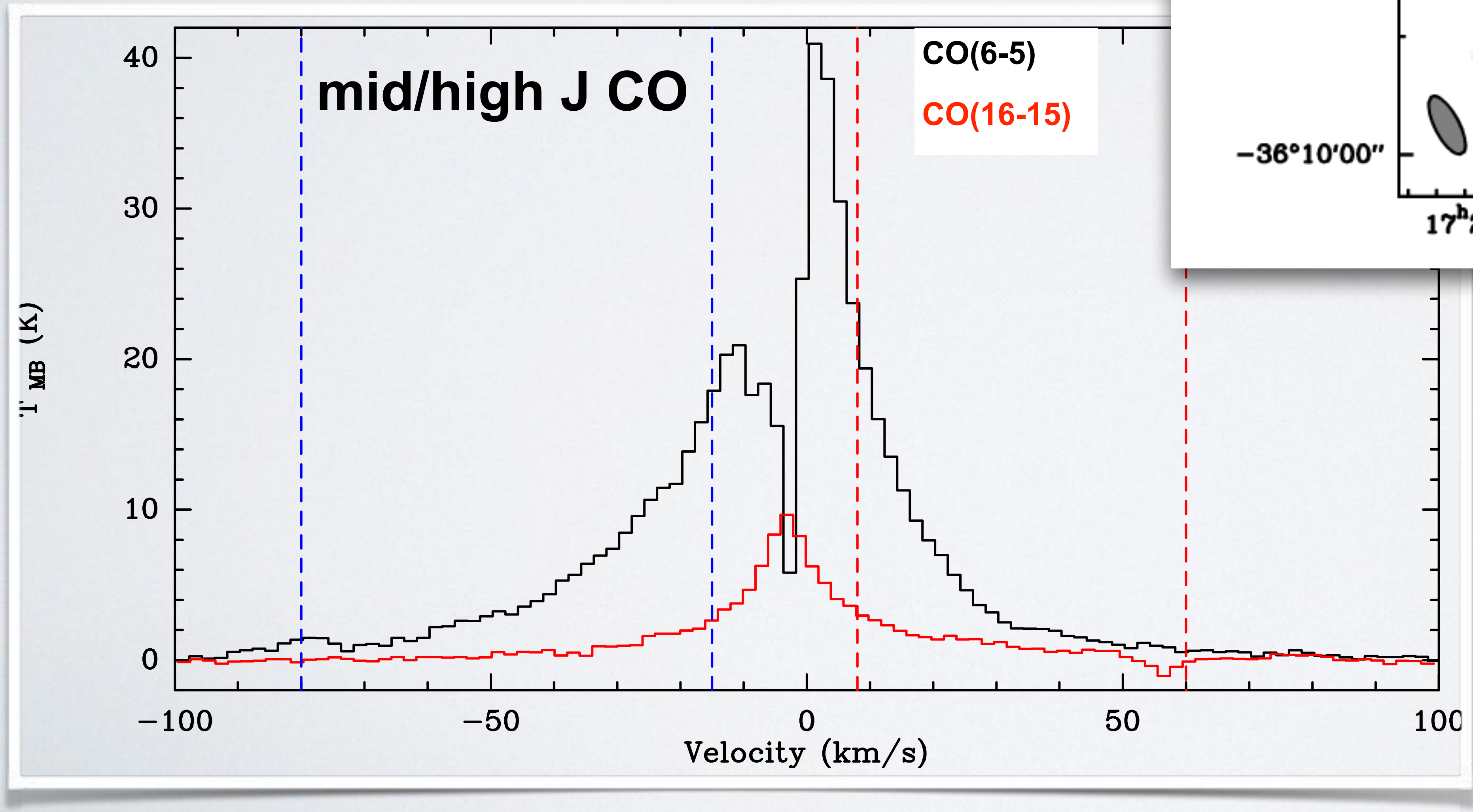
24

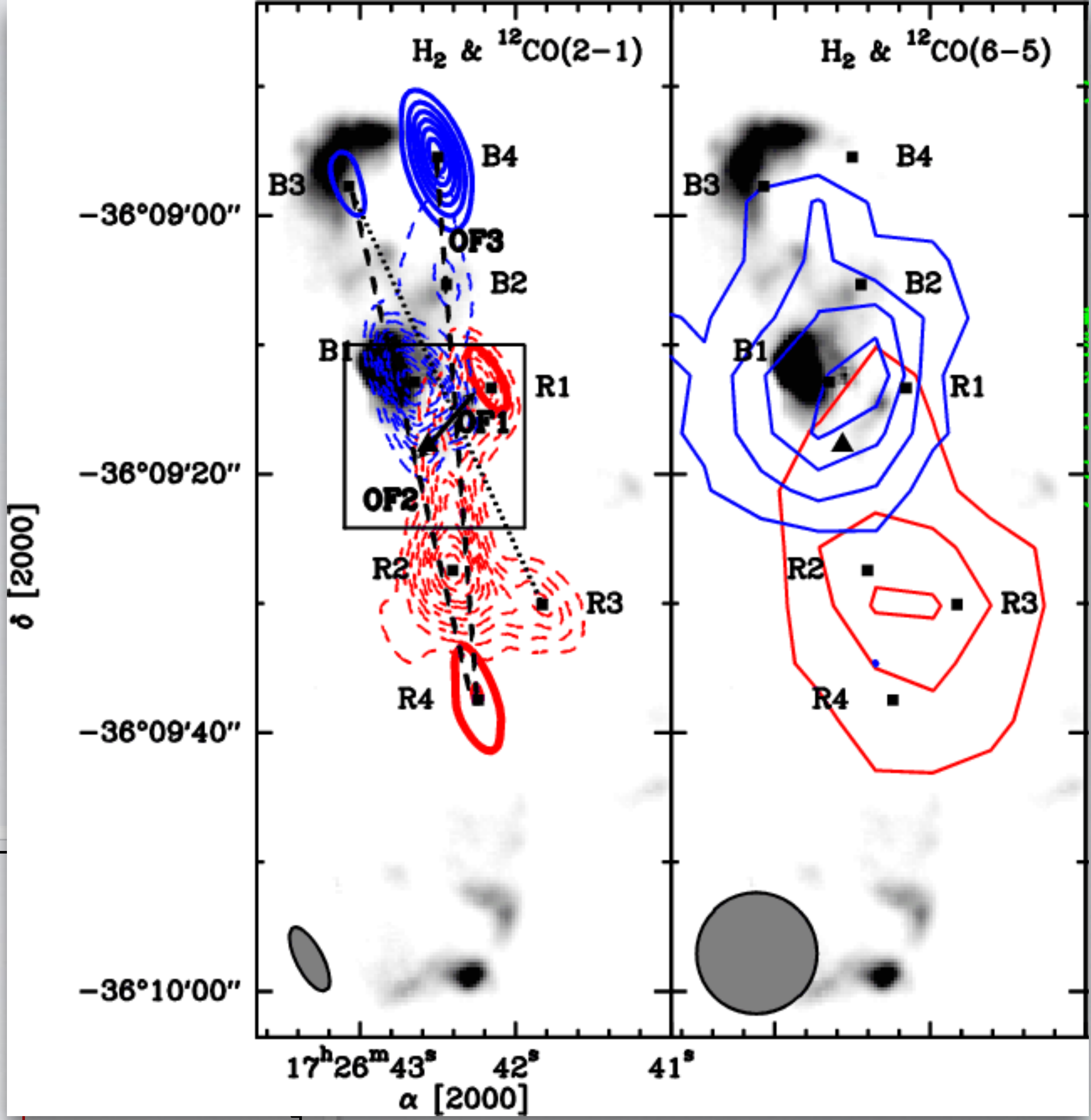


SOFIA/APEX/Herschel synergies

G351.77-0.54

Leurini+2009, +2014





SOFIA/APEX/Herschel synergies

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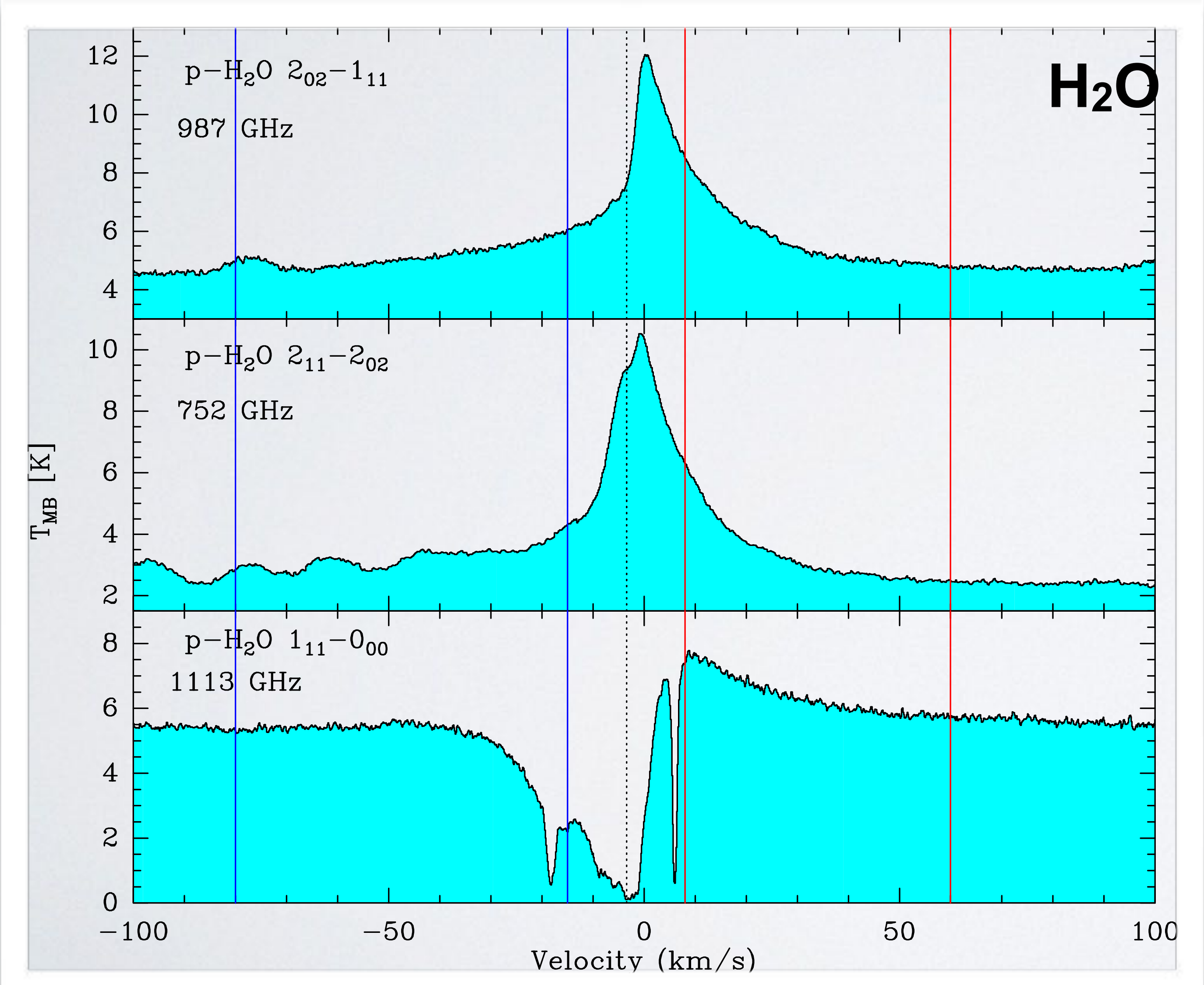
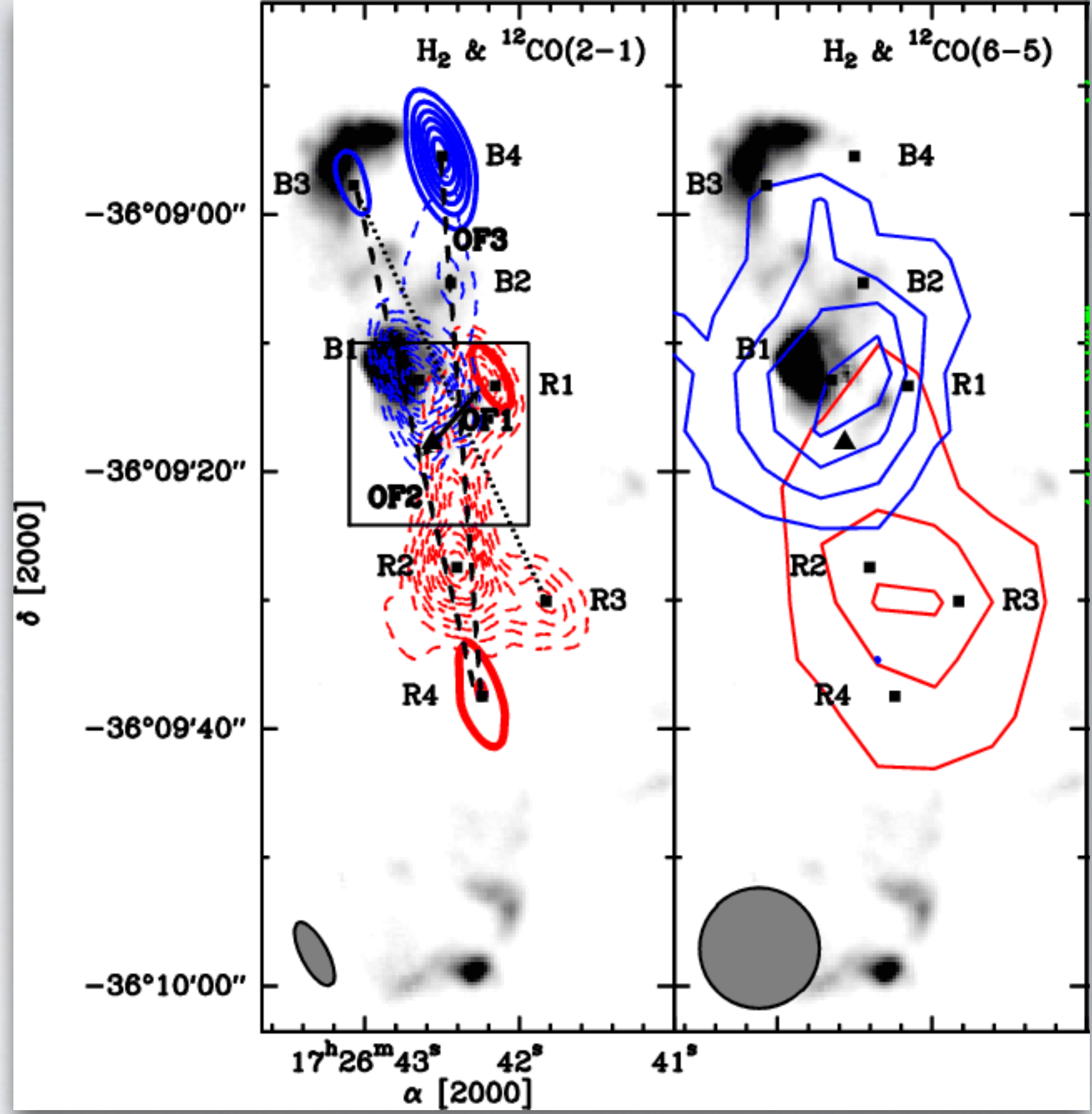
Leurini+2009, +2014





High velocity high-J CO and water emission clearly associated with molecular outflow

Modelling of the full CO ladder needed!

Conclusions

- High spectral resolution is needed to understand the emission of OI, CO, H_2O and their origin

- G5.89-0.39:

  - $[OI]_{63\mu m}$ is heavily contaminated by absorption at low velocities;

  - [OI] is the major coolant at HV ⇒ mass loss-rates!

  - CO is the major coolant at low-velocity

  - H_2O is a minor coolant in all velocity regimes

- ATLASGAL selected massive clumps: stay tuned!