Atomic shocks in L1551 IRS 5:
SOFIA-upGREAT [OI] observations

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Star and Planet Formation Lab, RIKEN & University of Virginia
SOFIA tele-talk
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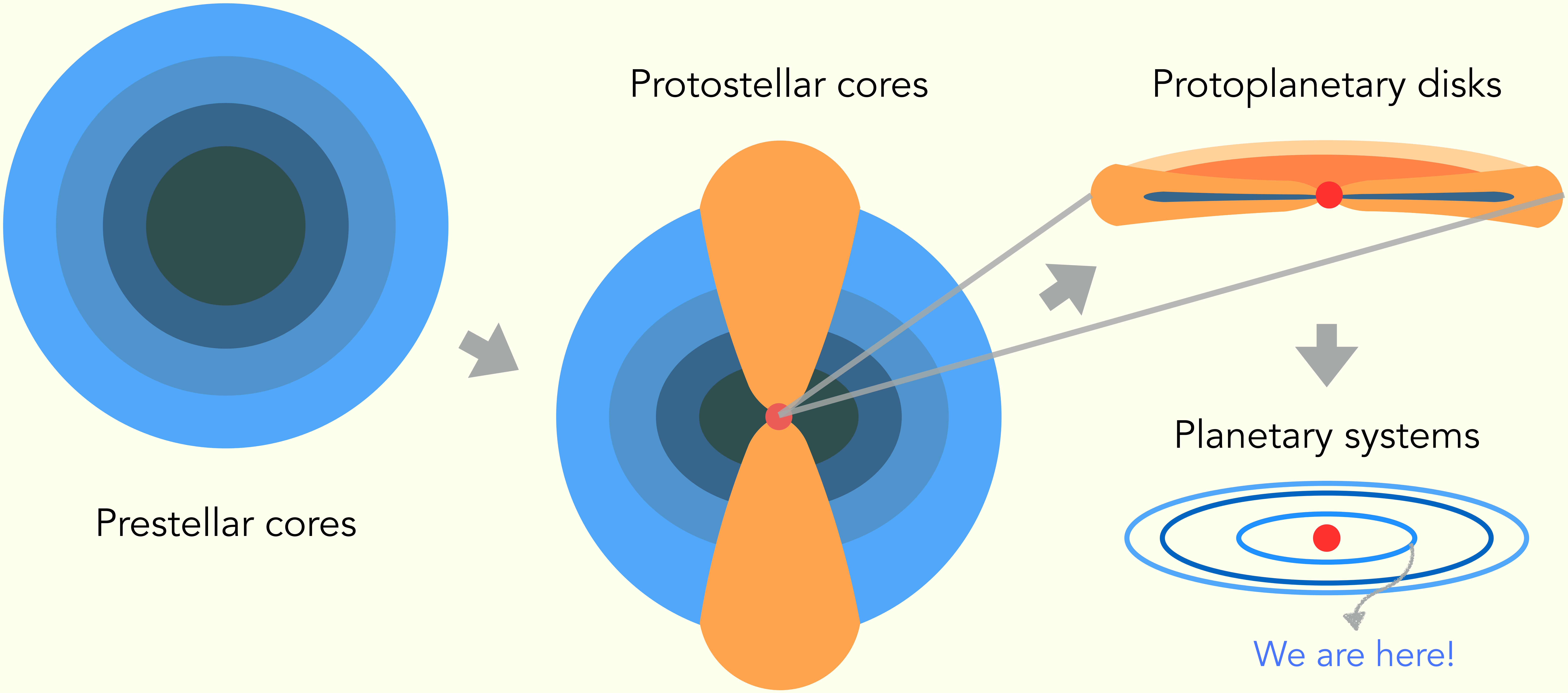
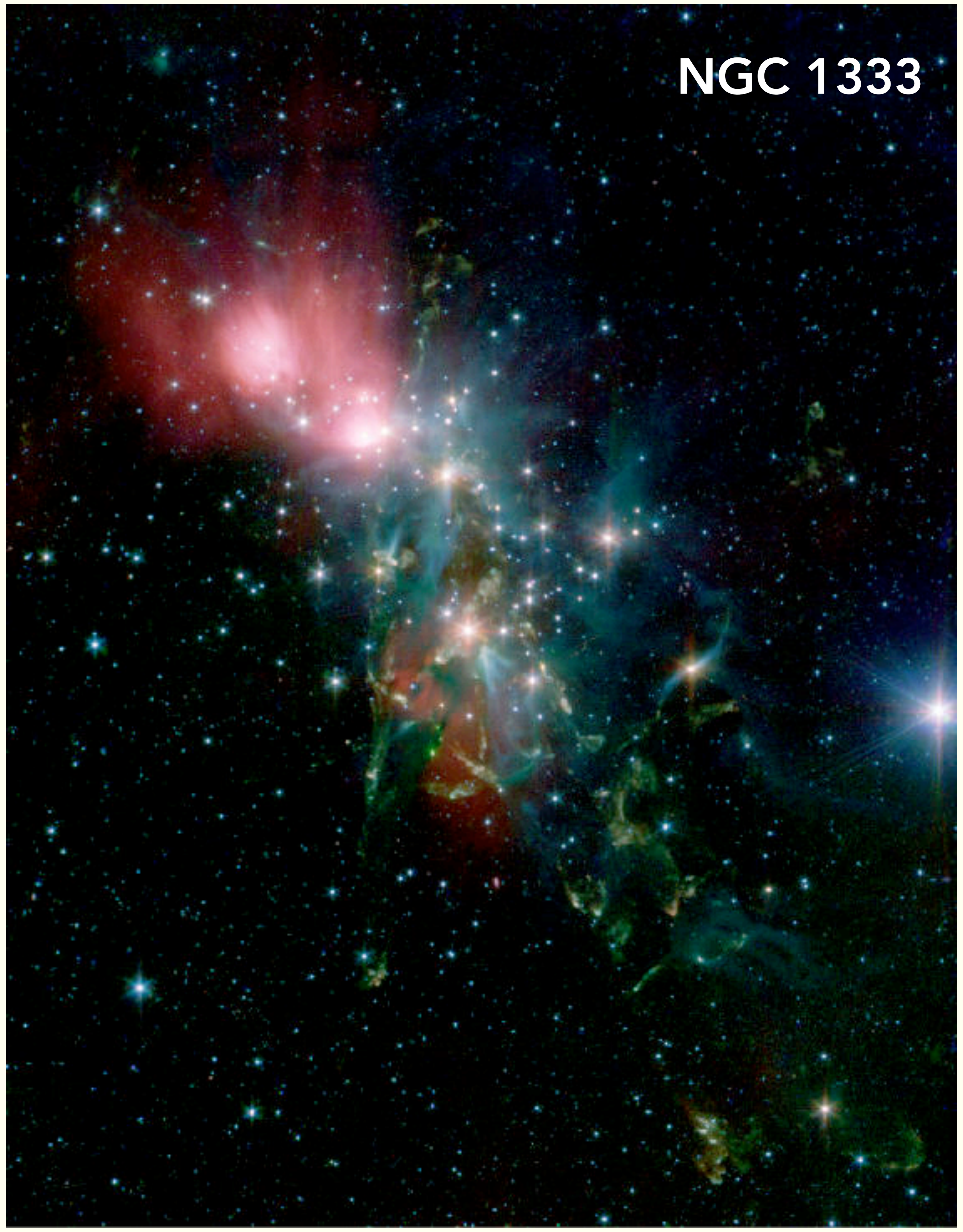
Jon Ramsey
Joel Green
Jeong-Eun Lee

Image compiled by Robert Gendler with the data taken by Bo Reipurth with Subaru

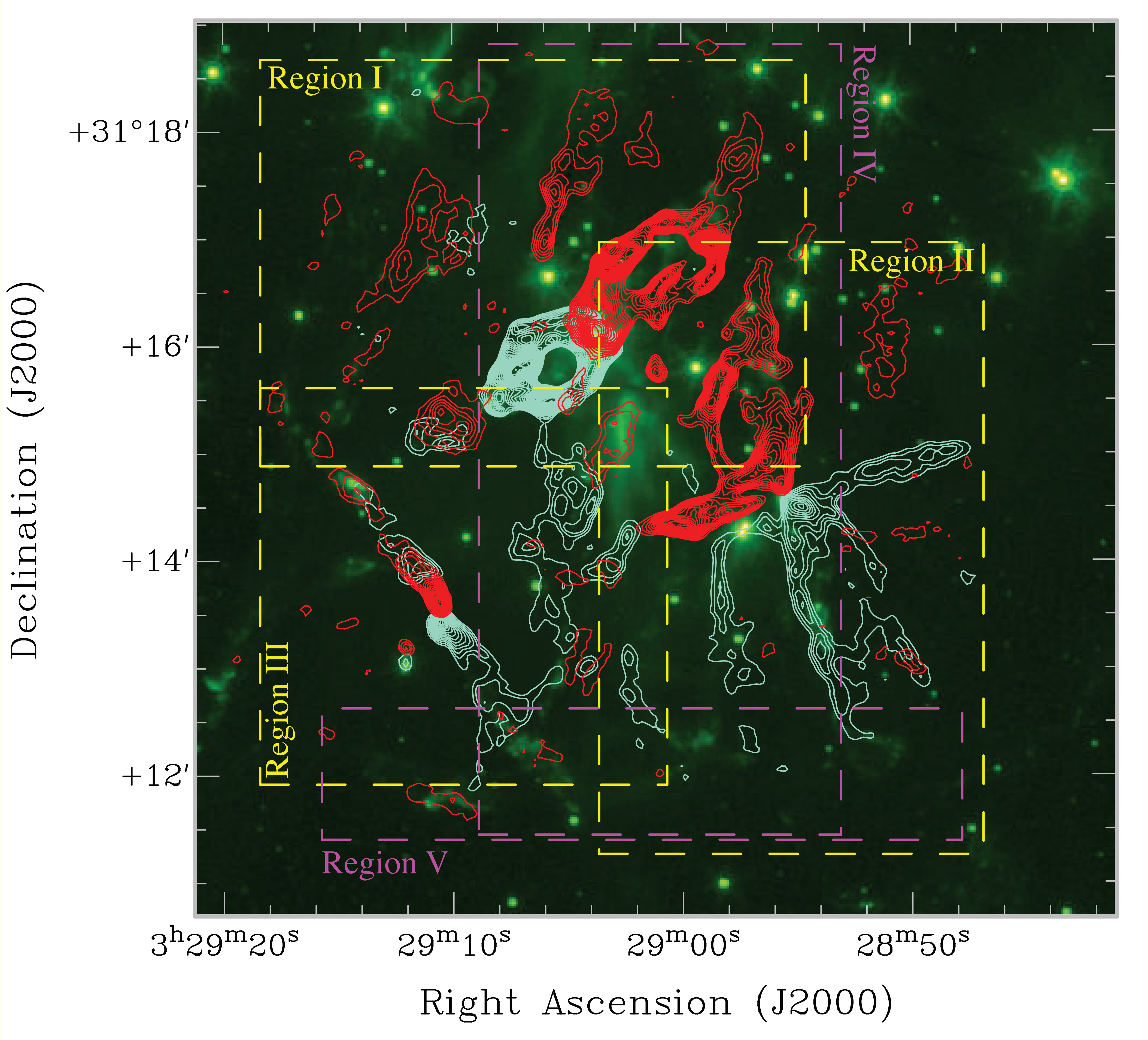
Outflows as a tracer of star formation



Outflow signatures are nearly ubiquitously associated with protostars

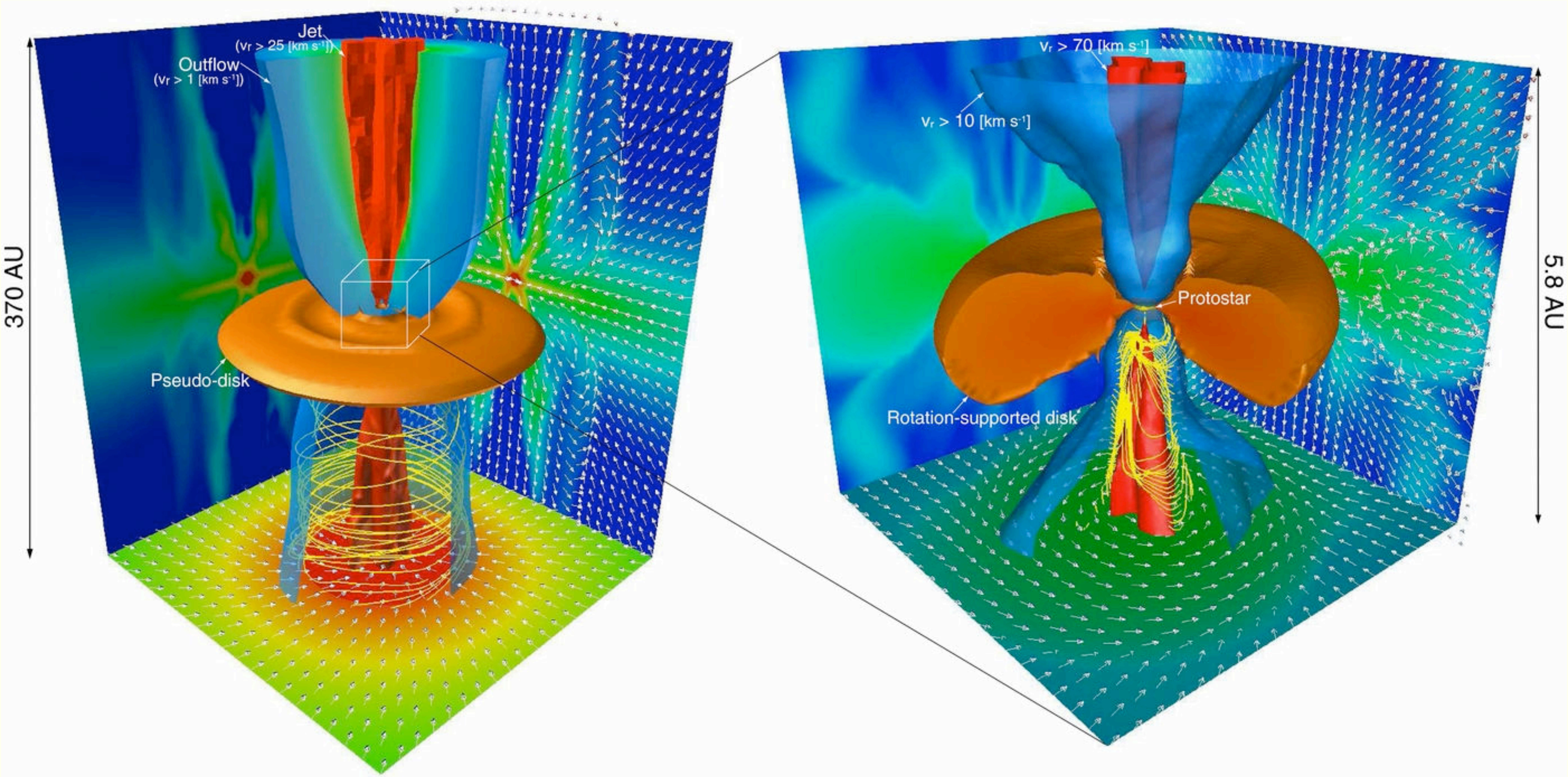


Credit: NASA/JPL-Caltech/R. A. Gutermuth (Harvard-Smithsonian CfA)



Plunkett+2013

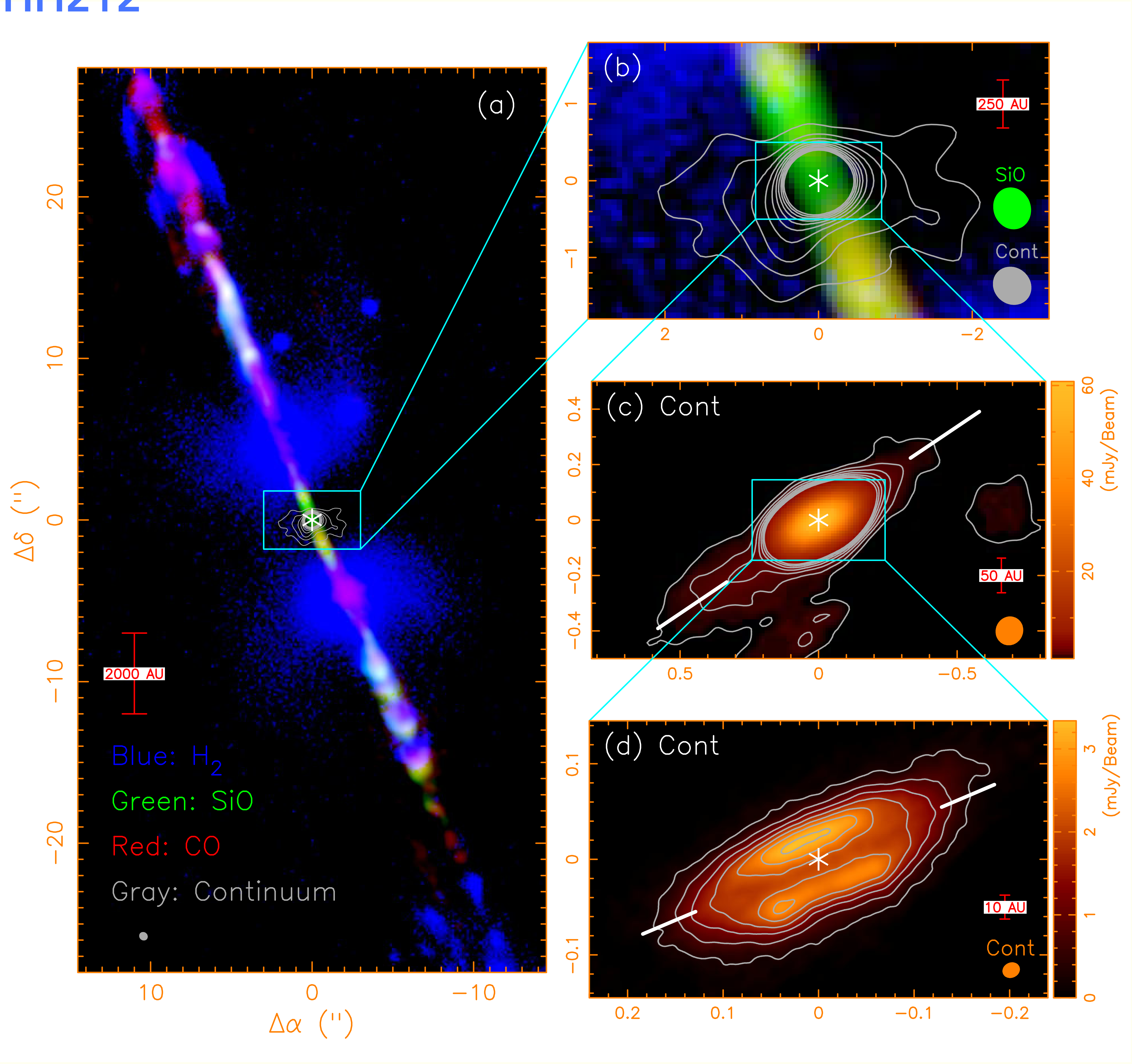
Outflow embedded jet



Machida+2015

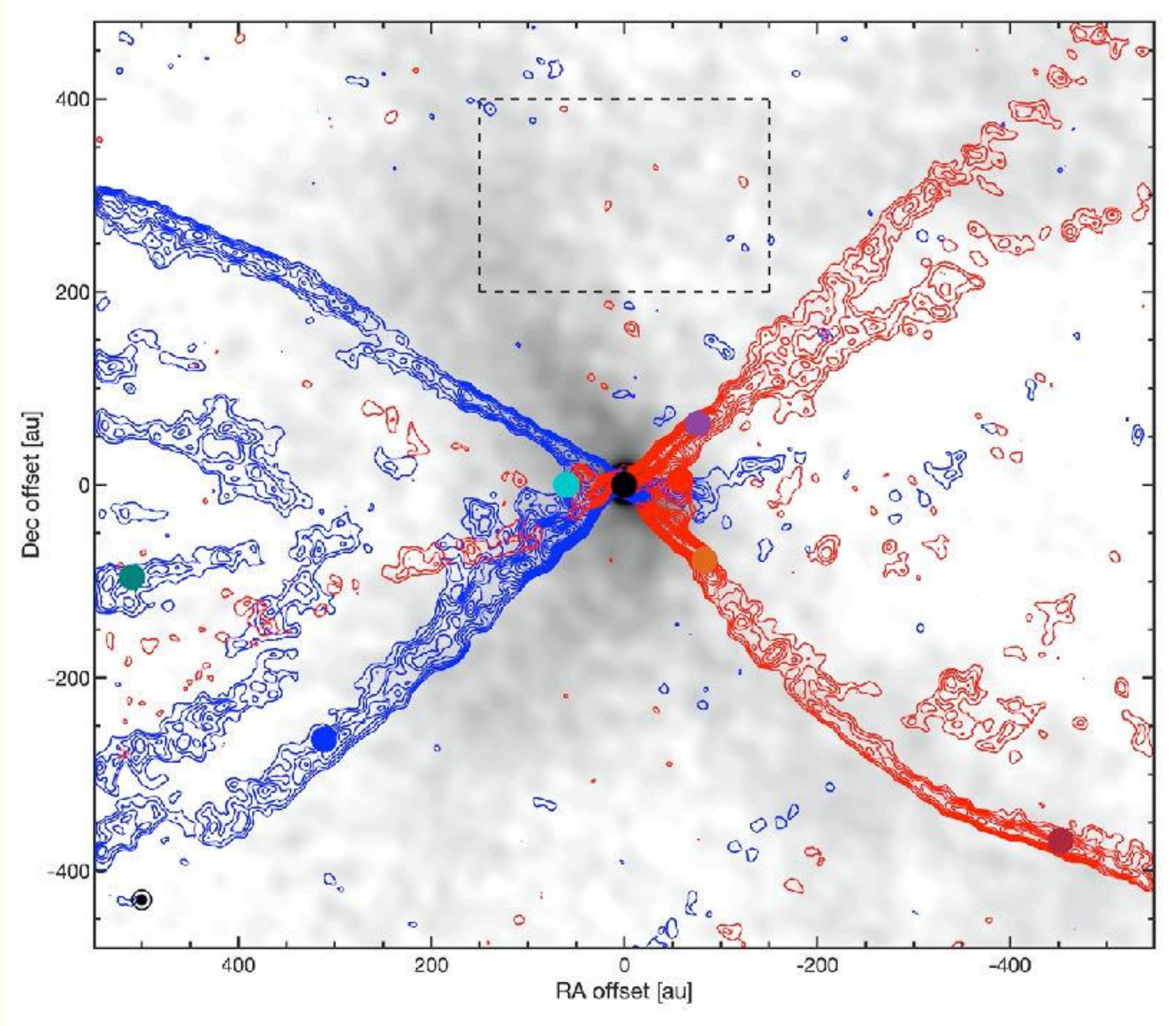
Emission of molecular outflows

HH212



Lee+2017a

B335

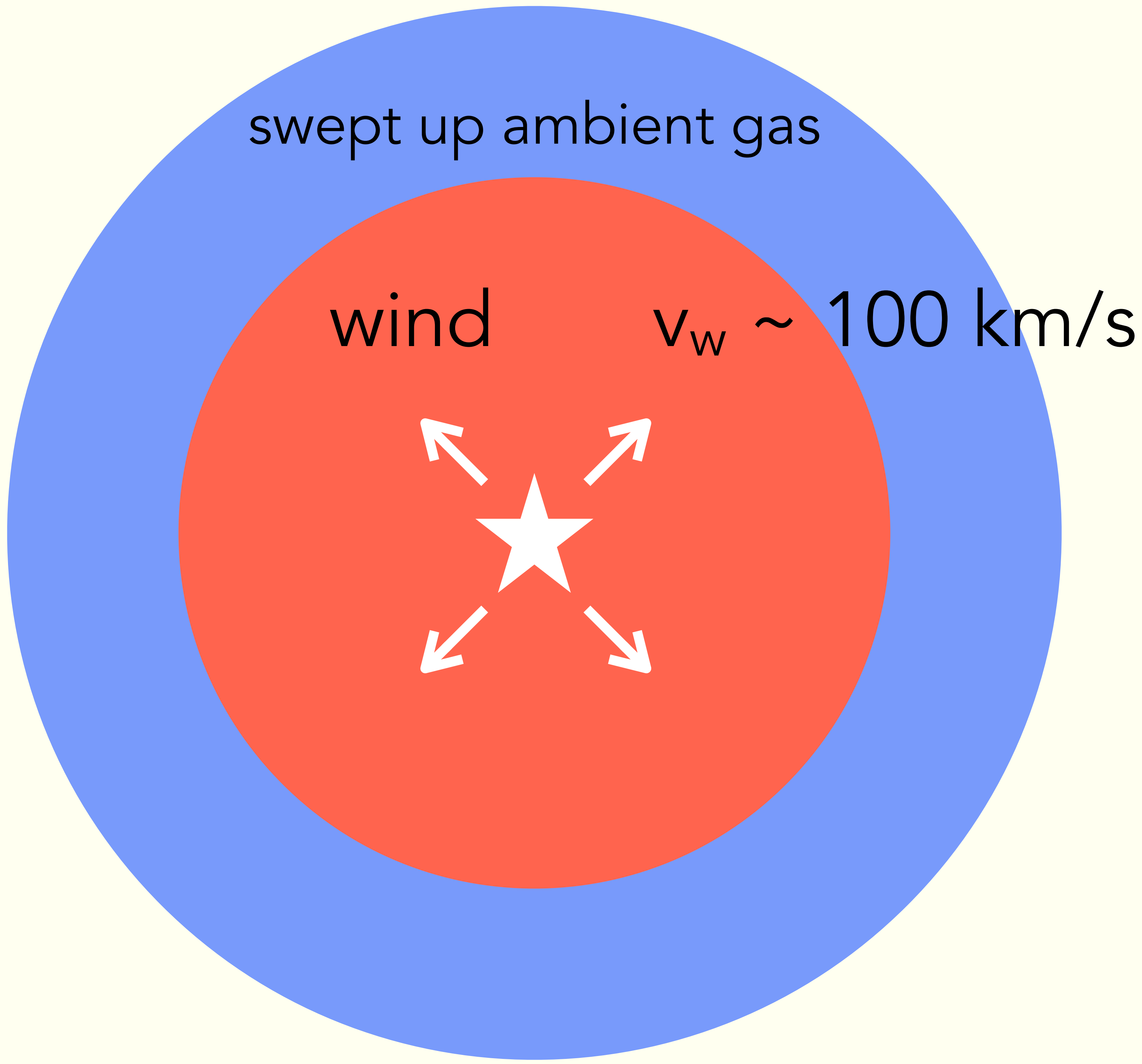


Bjerkeli+2019

Shocks provide another view of outflows

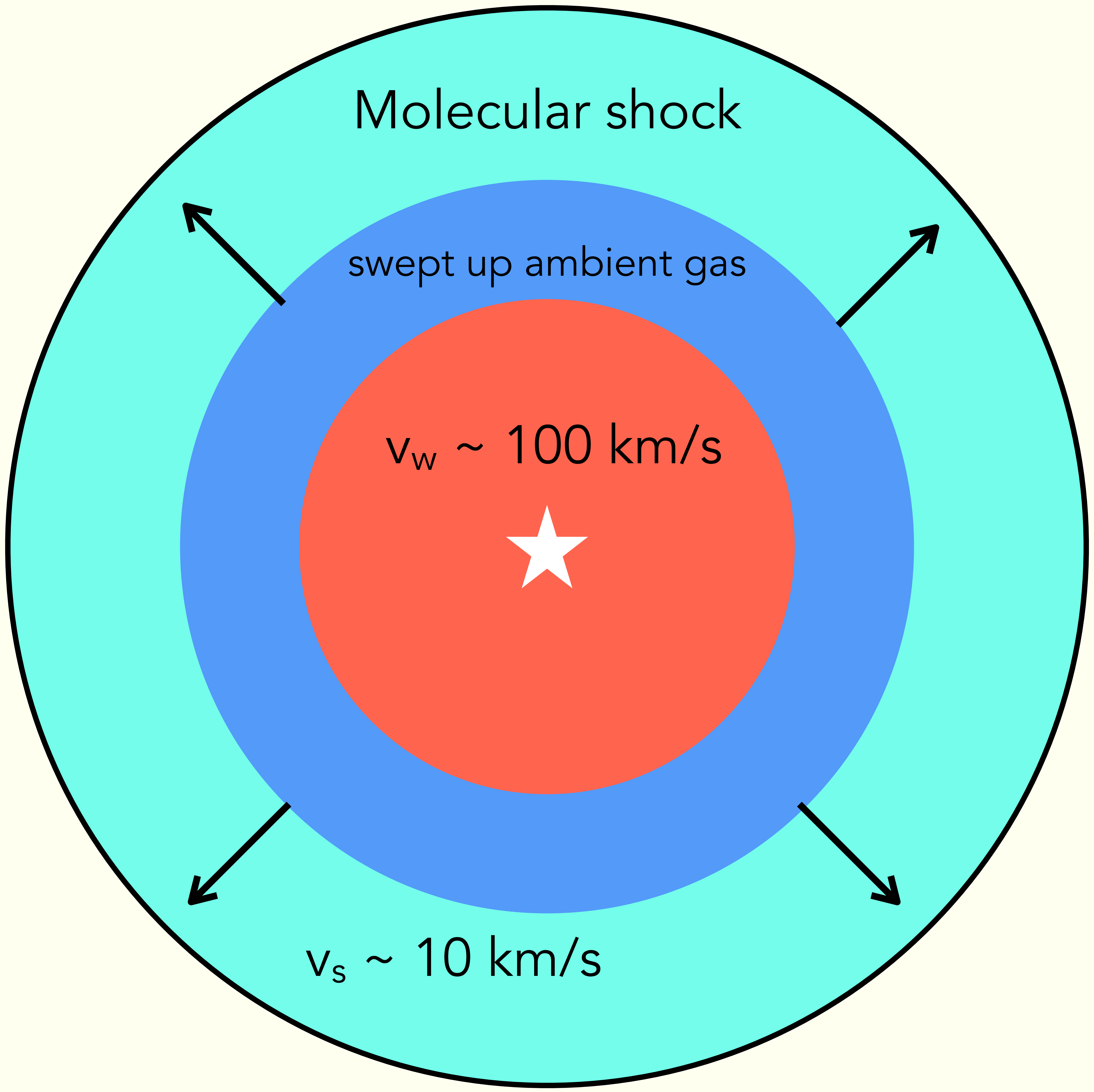
Adapted from Hollenbach 1985

Shocks provide another view of outflows



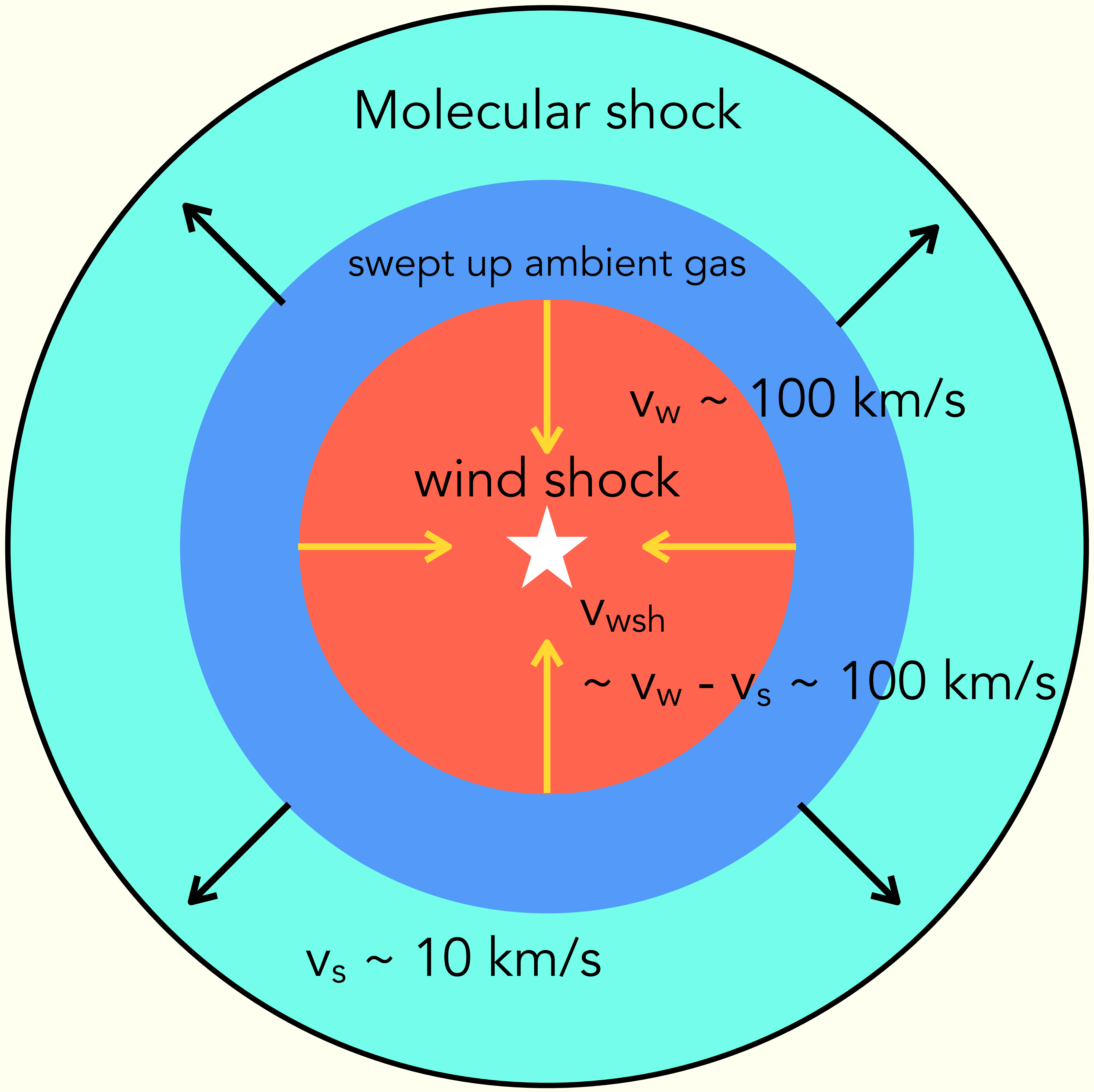
Adapted from Hollenbach 1985

Shocks provide another view of outflows



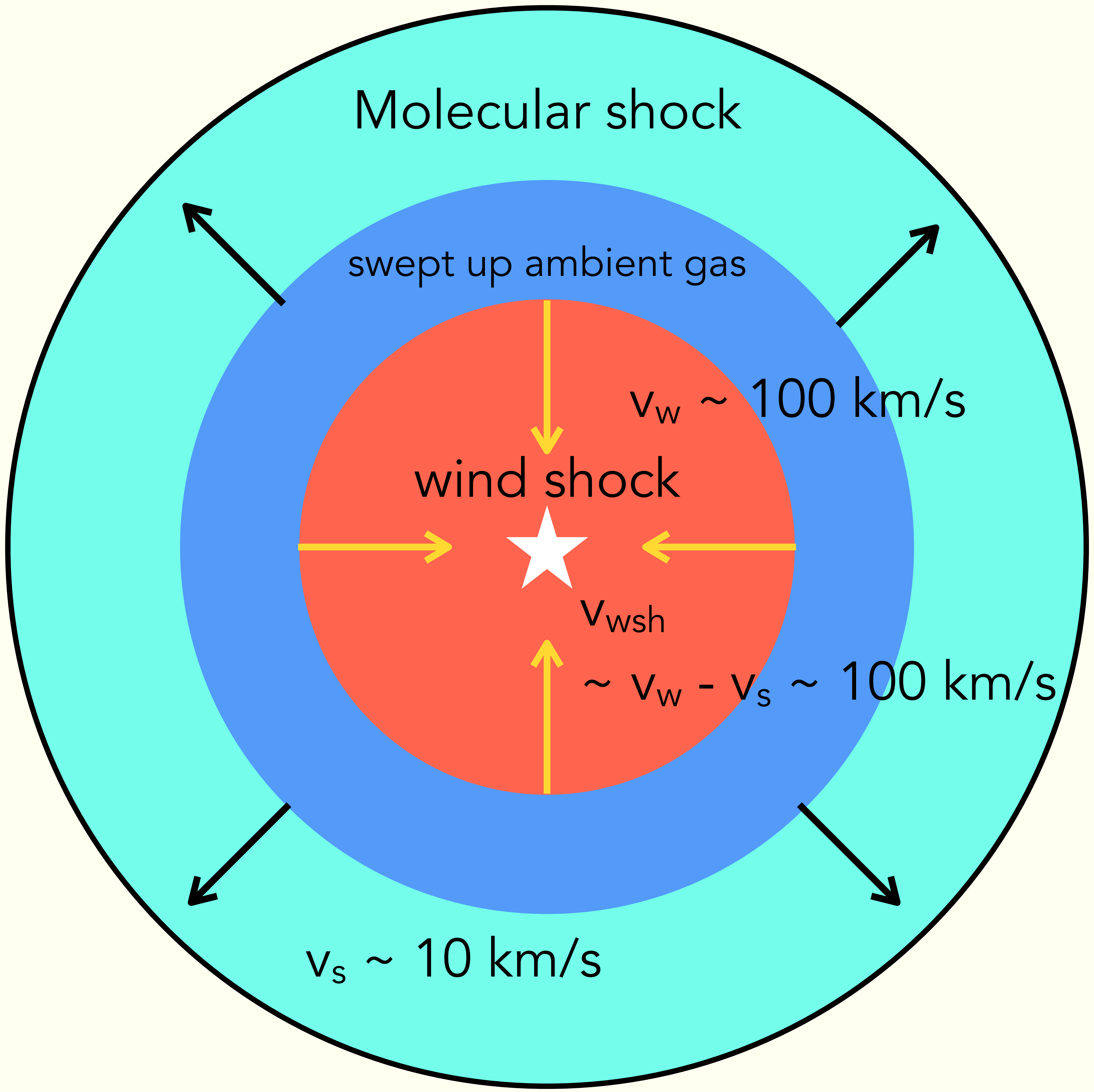
Adapted from Hollenbach 1985

Shocks provide another view of outflows

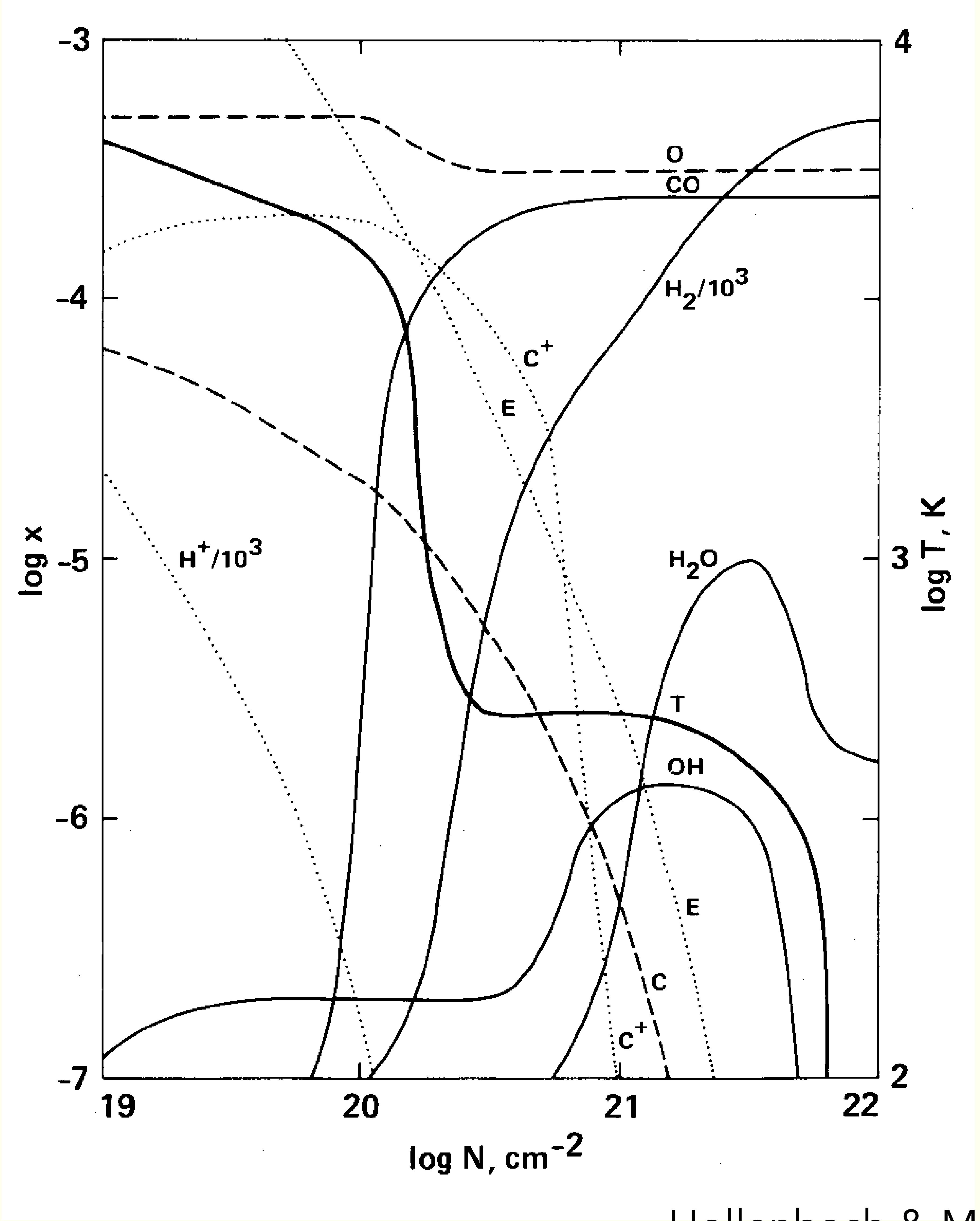


Adapted from Hollenbach 1985

Shocks provide another view of outflows

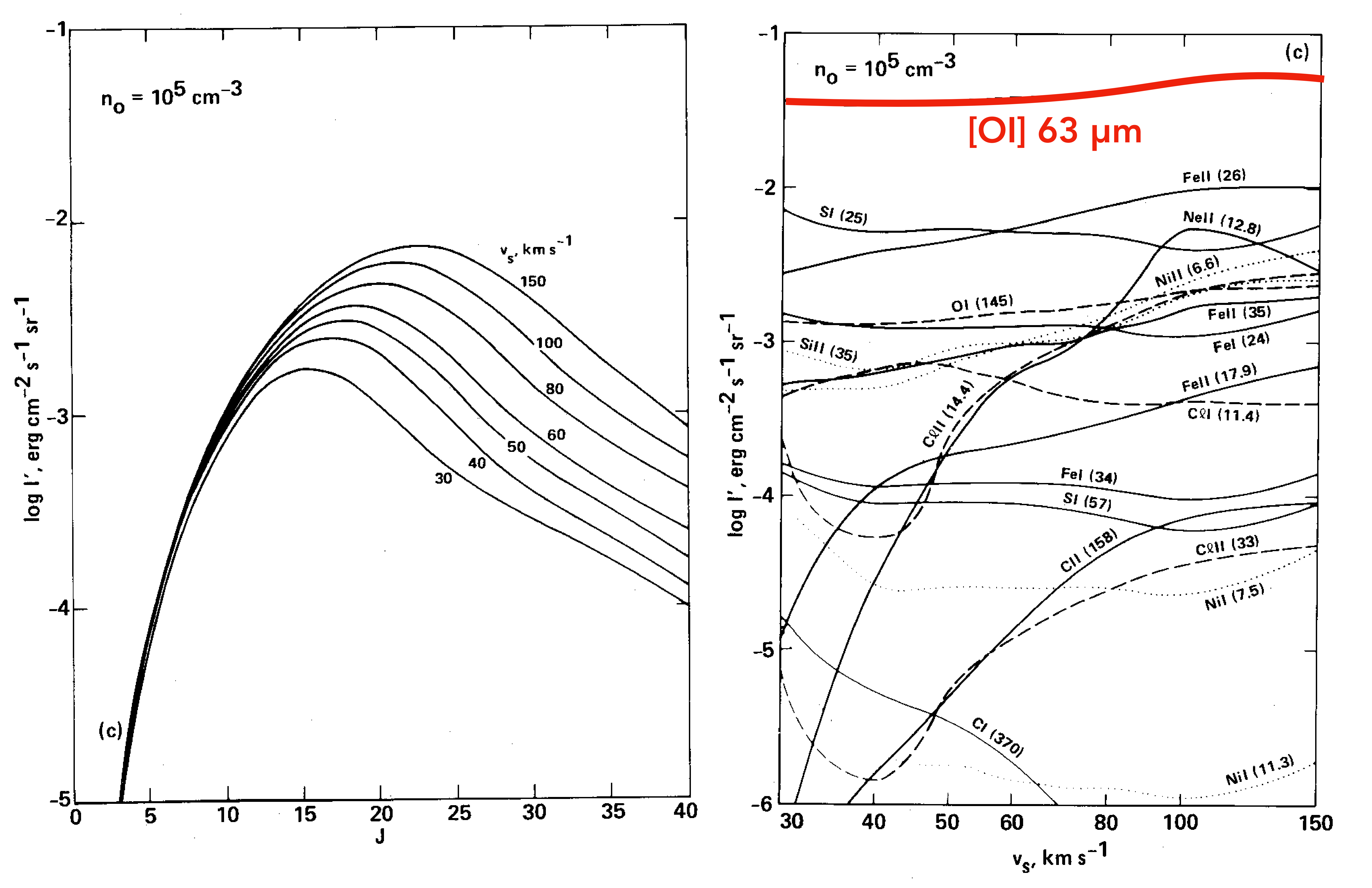


Adapted from Hollenbach 1985

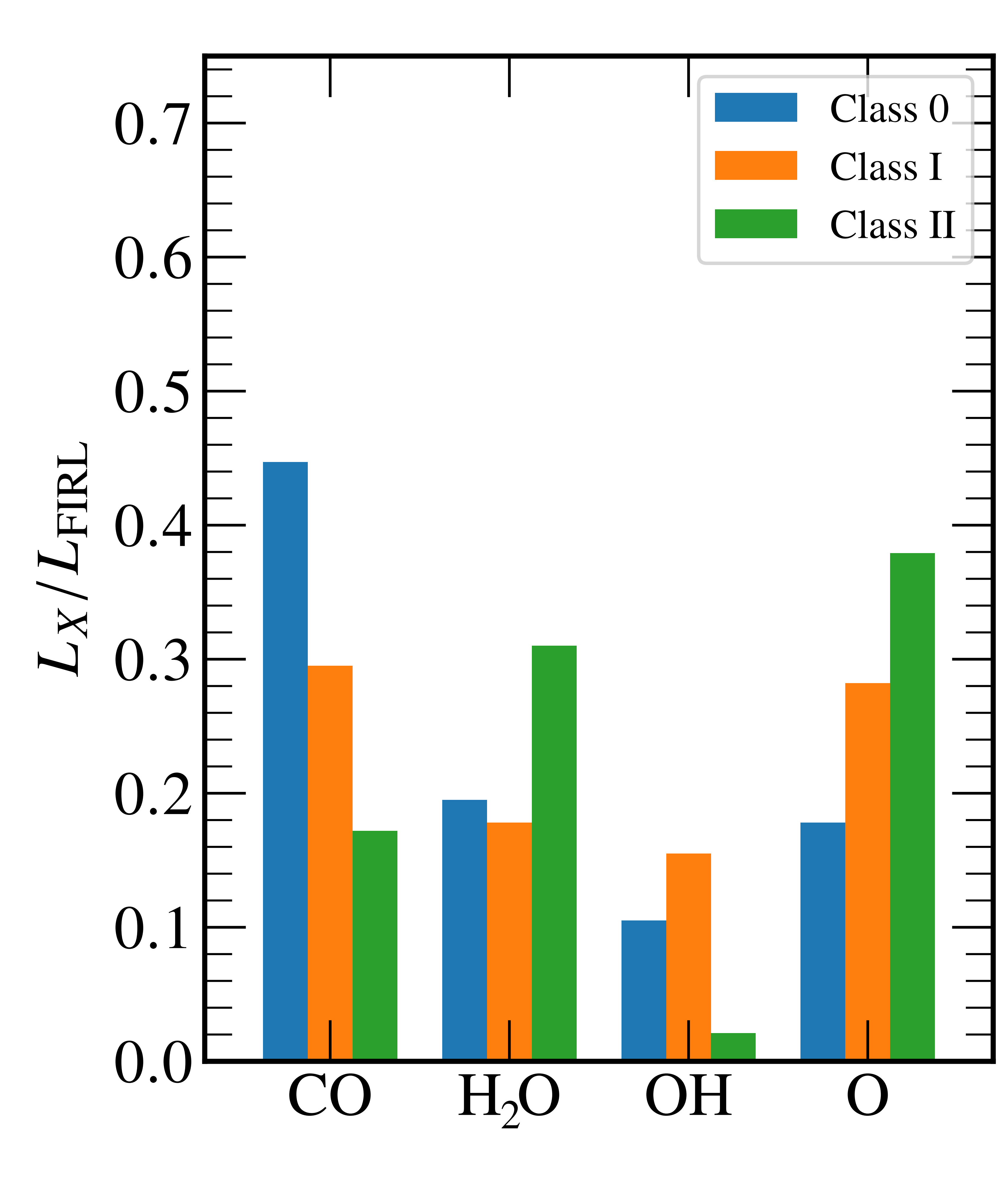


Hollenbach & McKee 1989

[OI] and CO are the dominant coolants in shocks

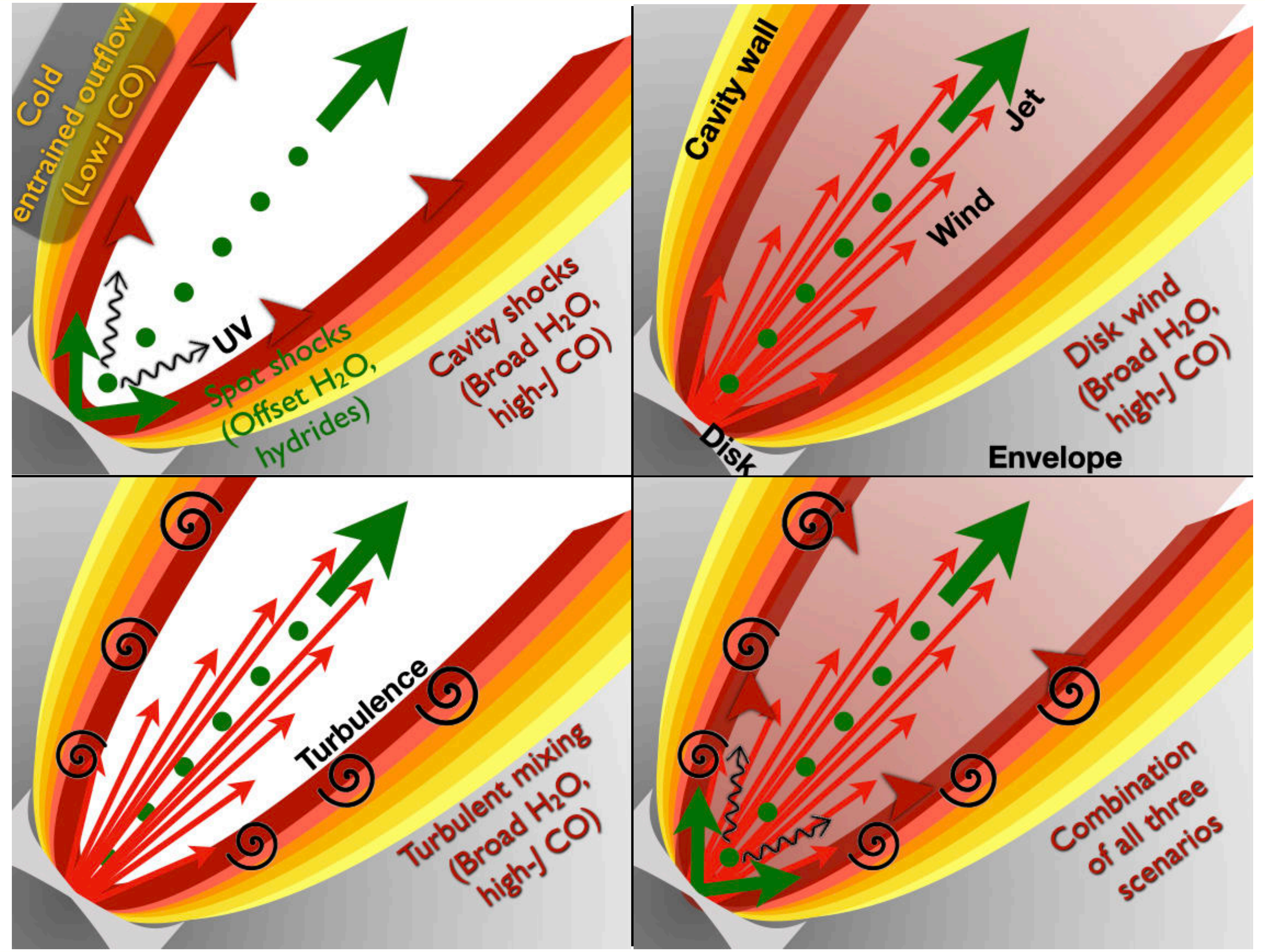


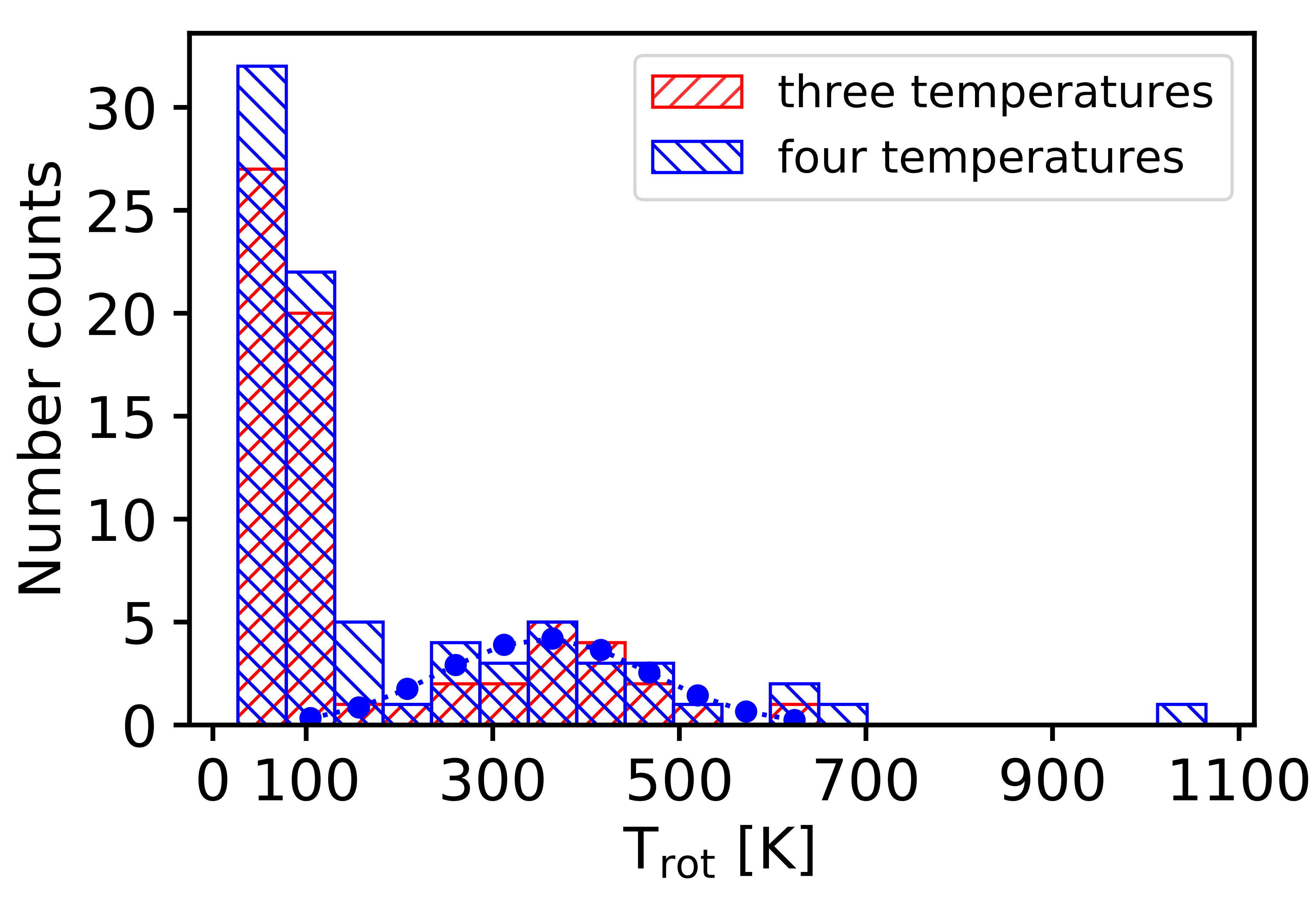
Hollenbach & McKee 1989



van Dishoeck+2021 (see also Karska+2018)

Outflow-envelope interaction probed by CO and H_2O



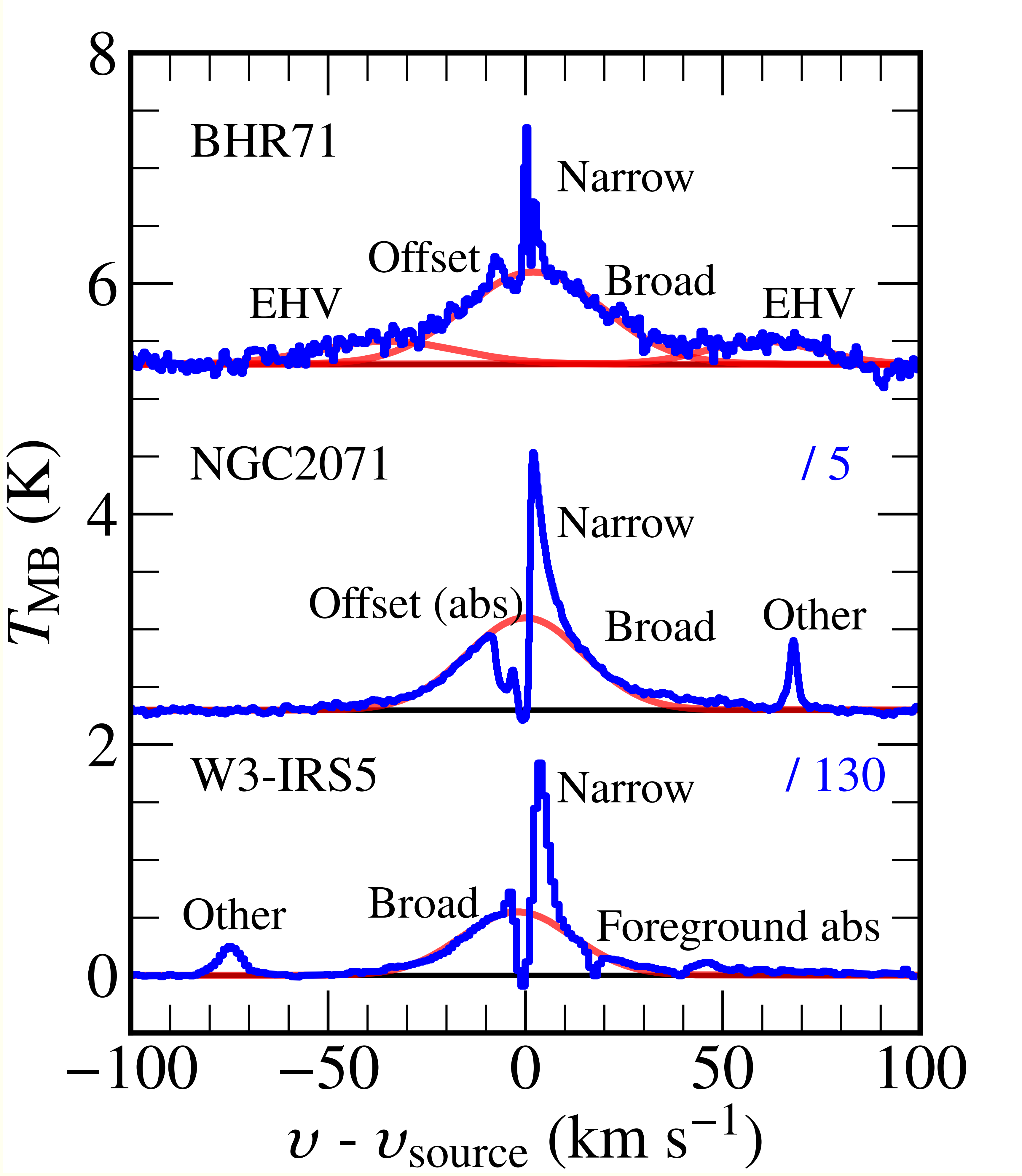


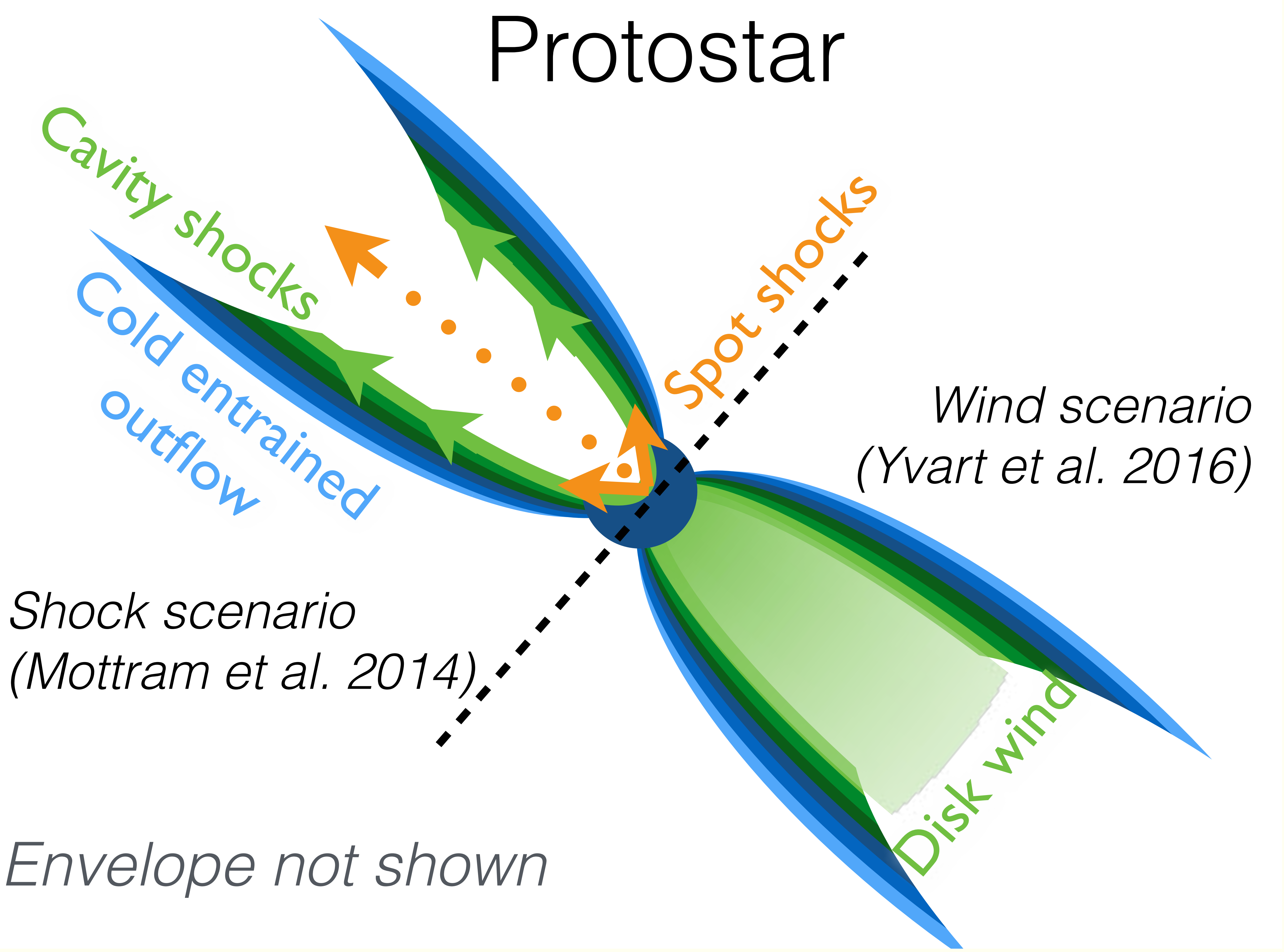
Yang+2018

Herschel WISH program; van Dishoeck+2021

Cavity shocks, spot shocks, & bullets

$H_2O\ 1_{10}\text{-}1_{01}$

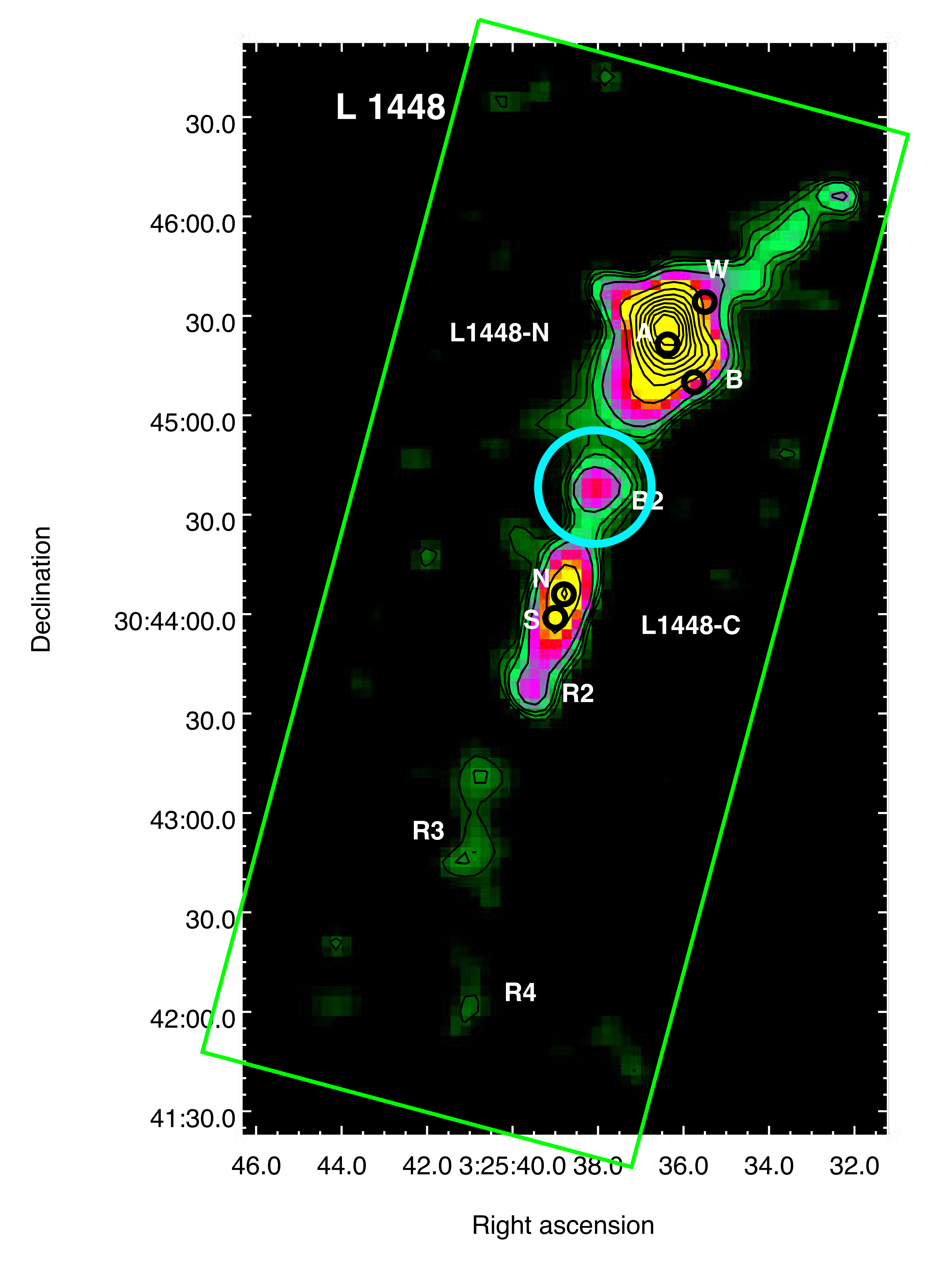


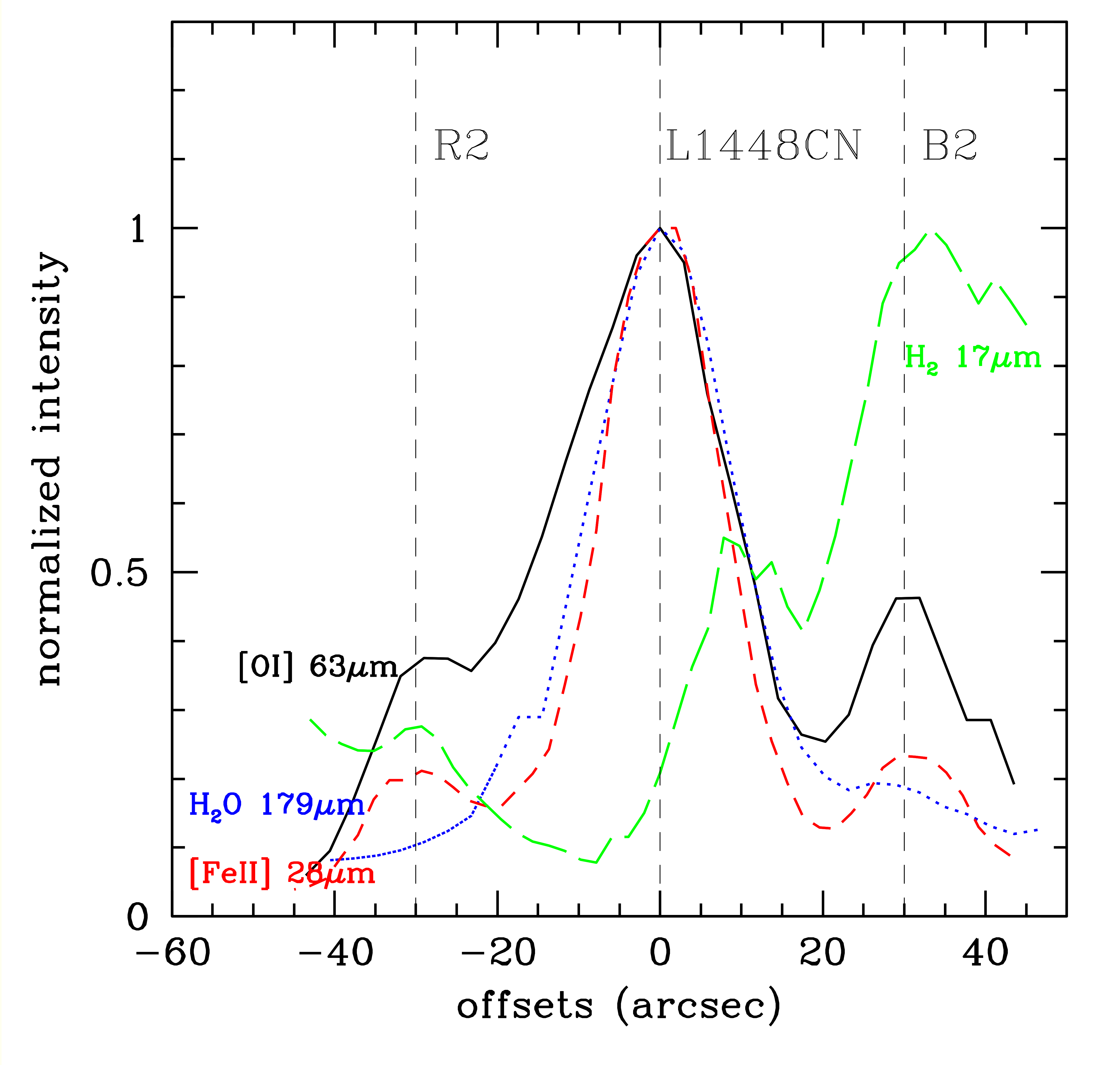


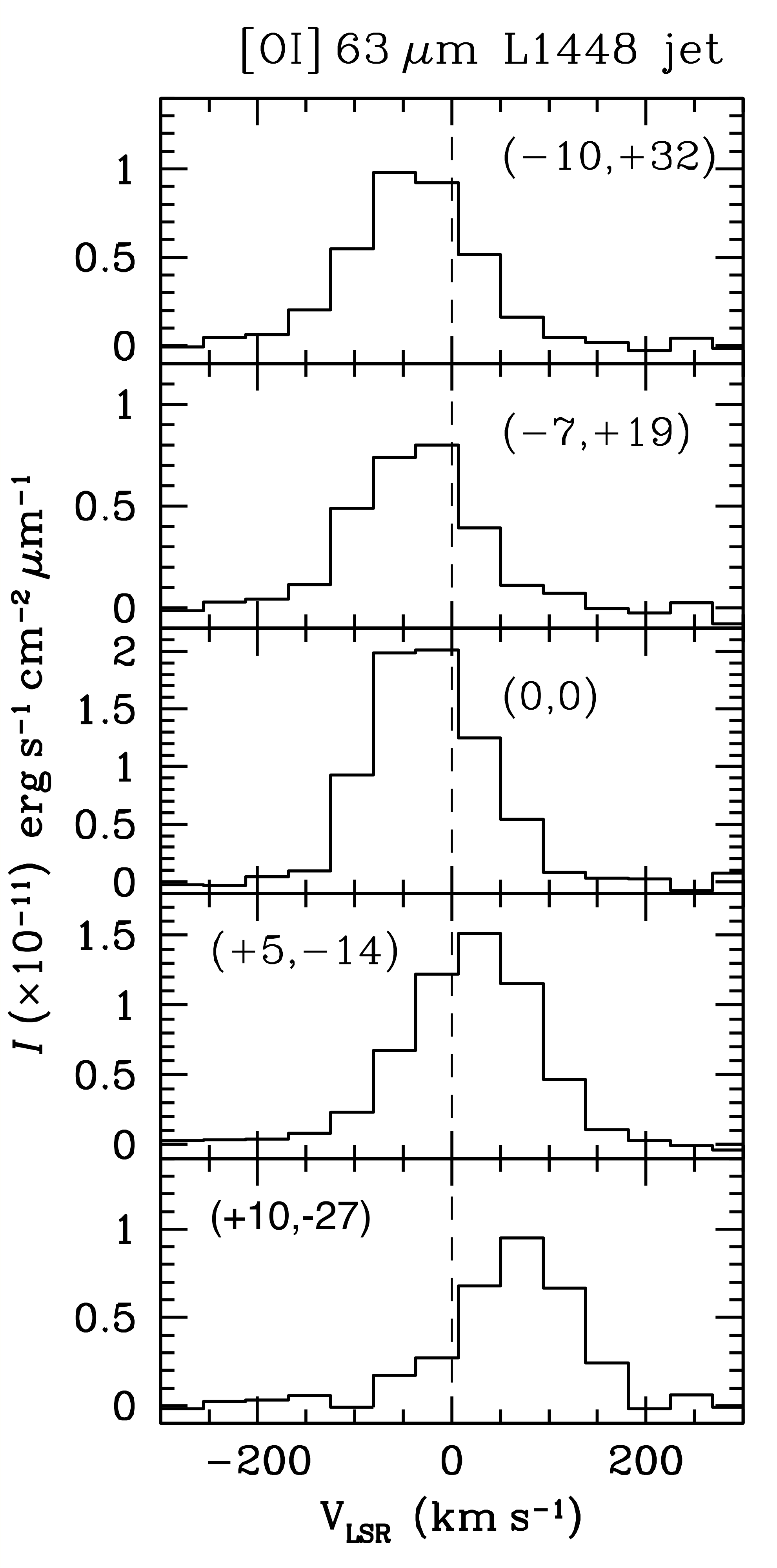
van Dishoeck+2021

Kristensen+2017b

[OI] emission dominates the shock knots

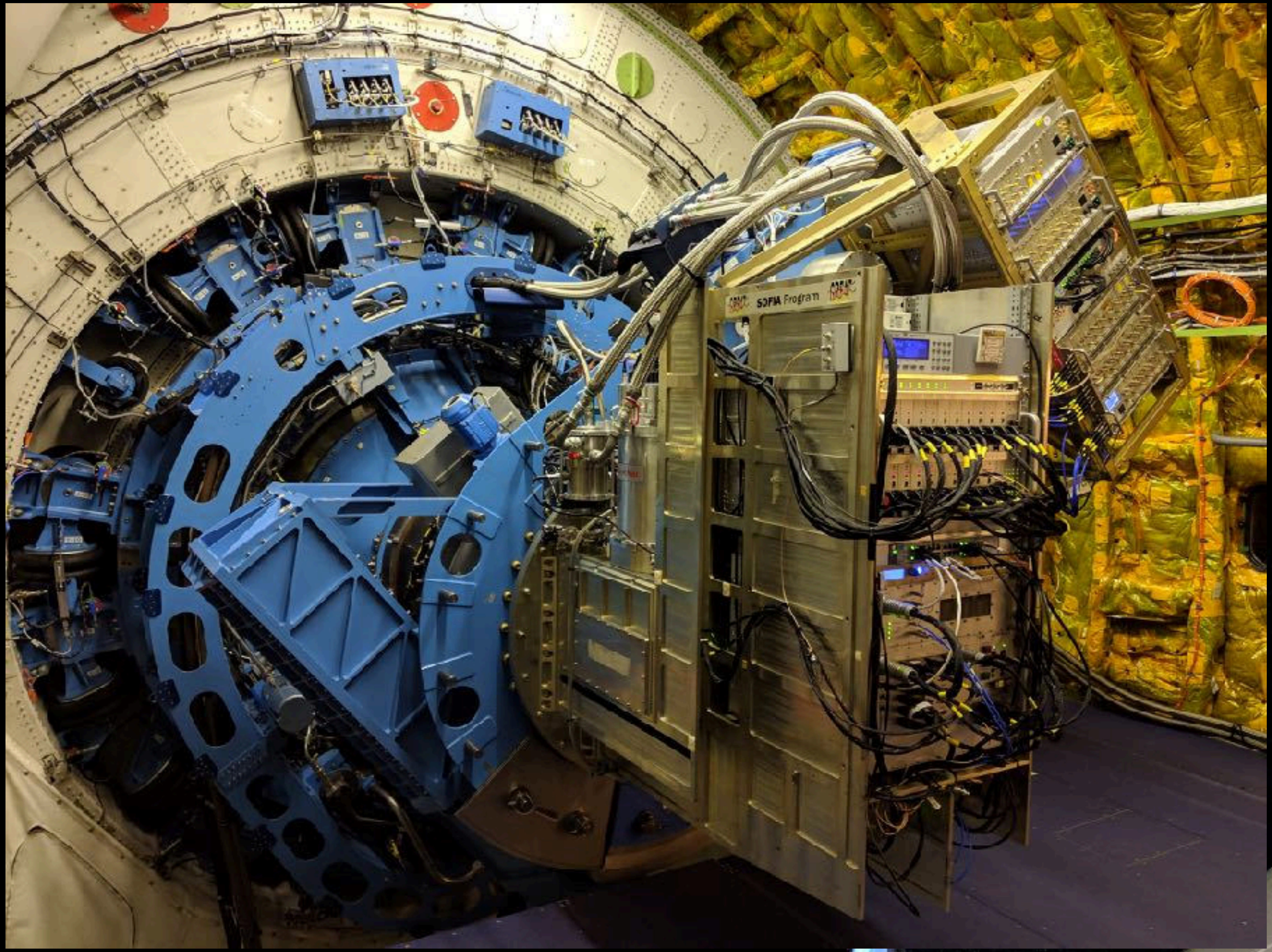






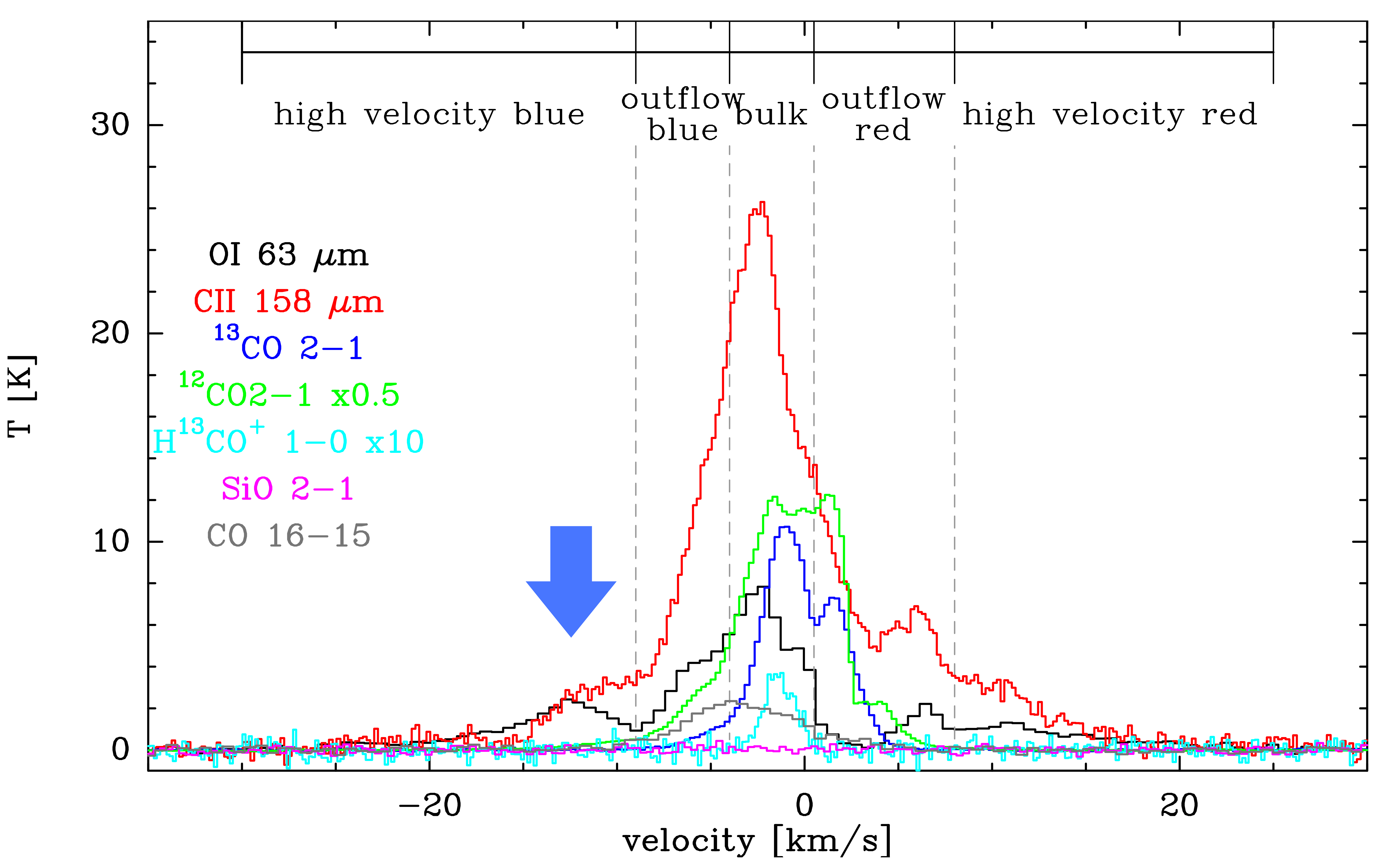
Nisini+2015

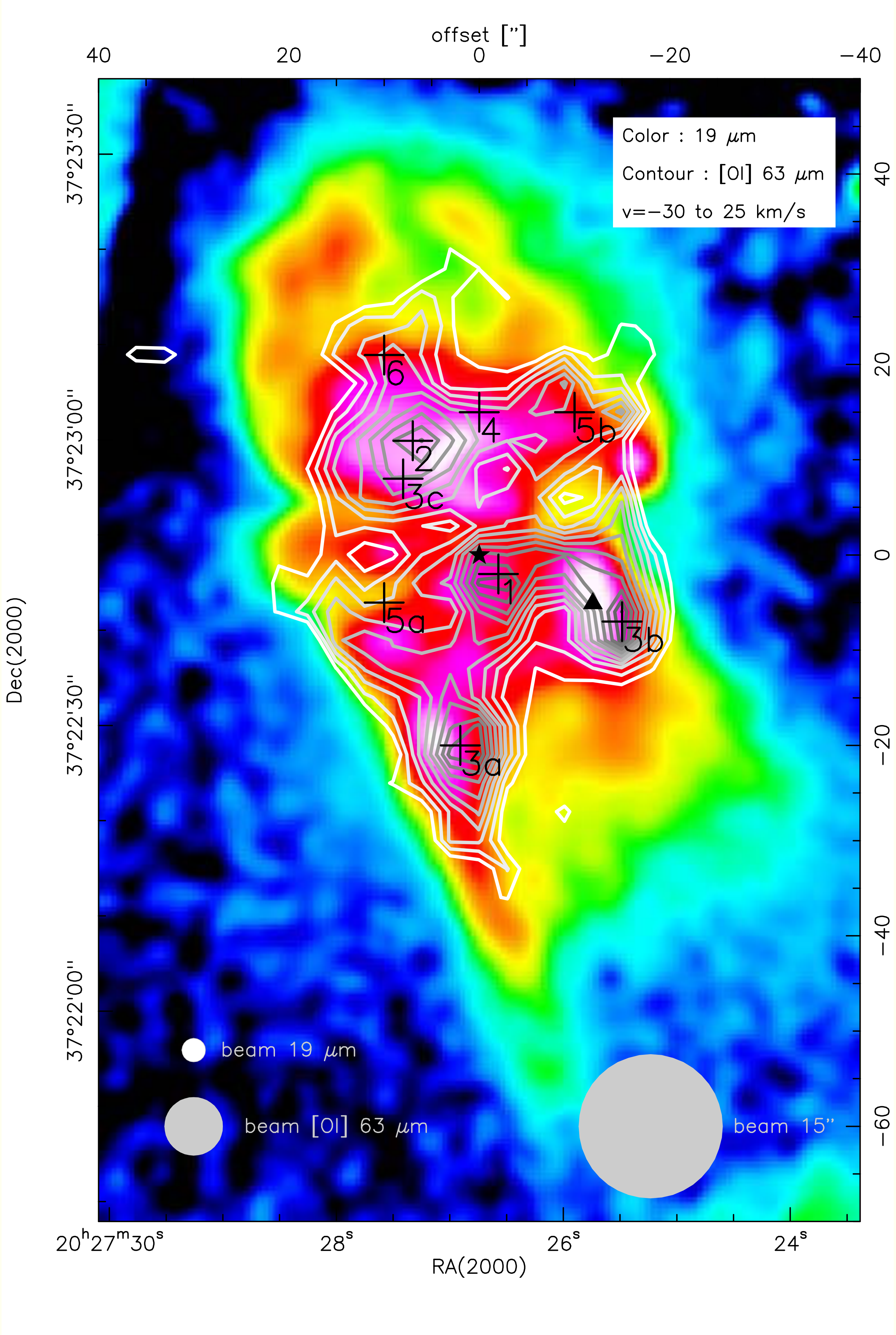
SOFIA/GREAT provides unique capability to resolve the [OI] line



[OI] emission shows a high-velocity component

HII region S106 in Cygnus X

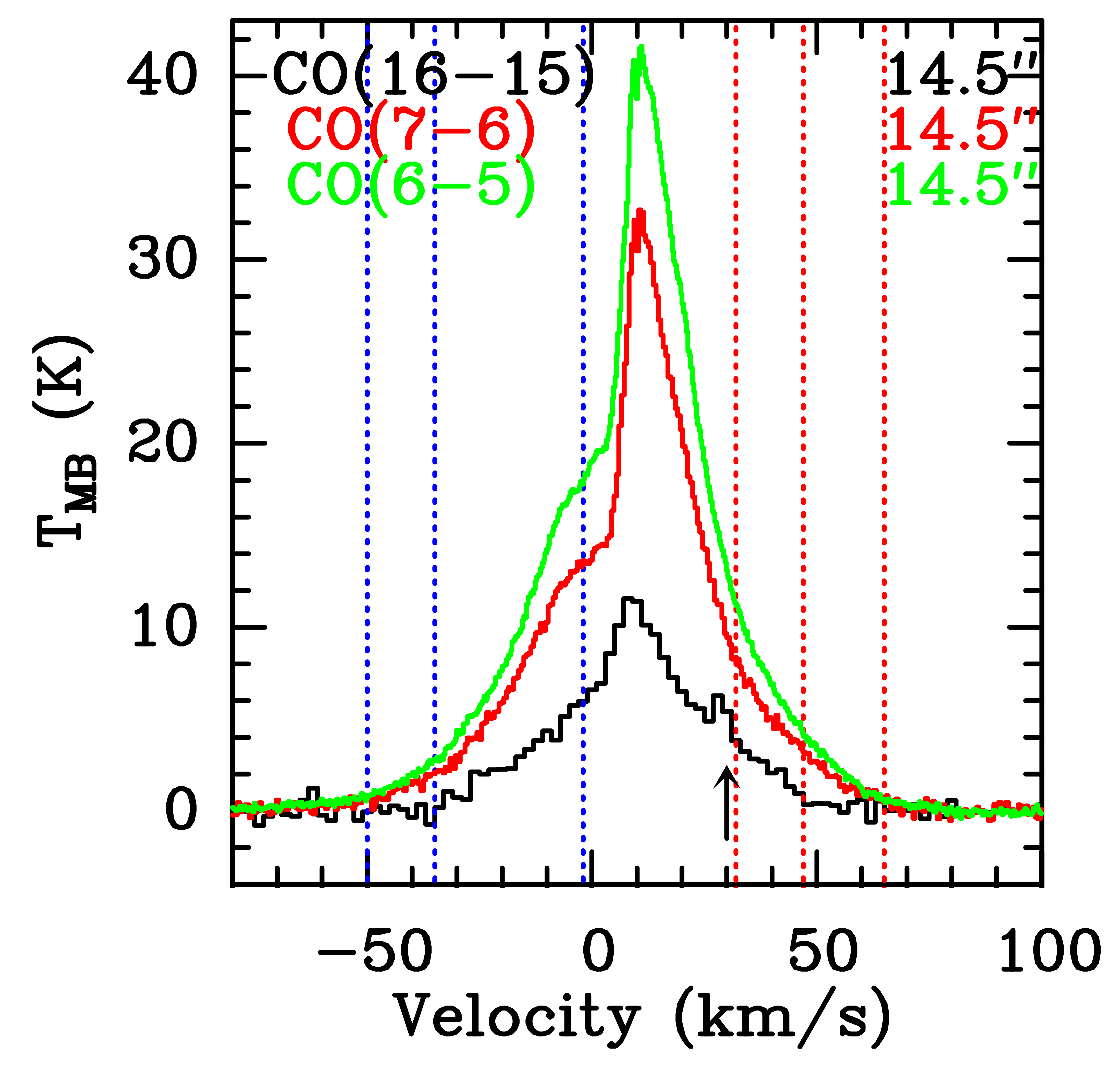




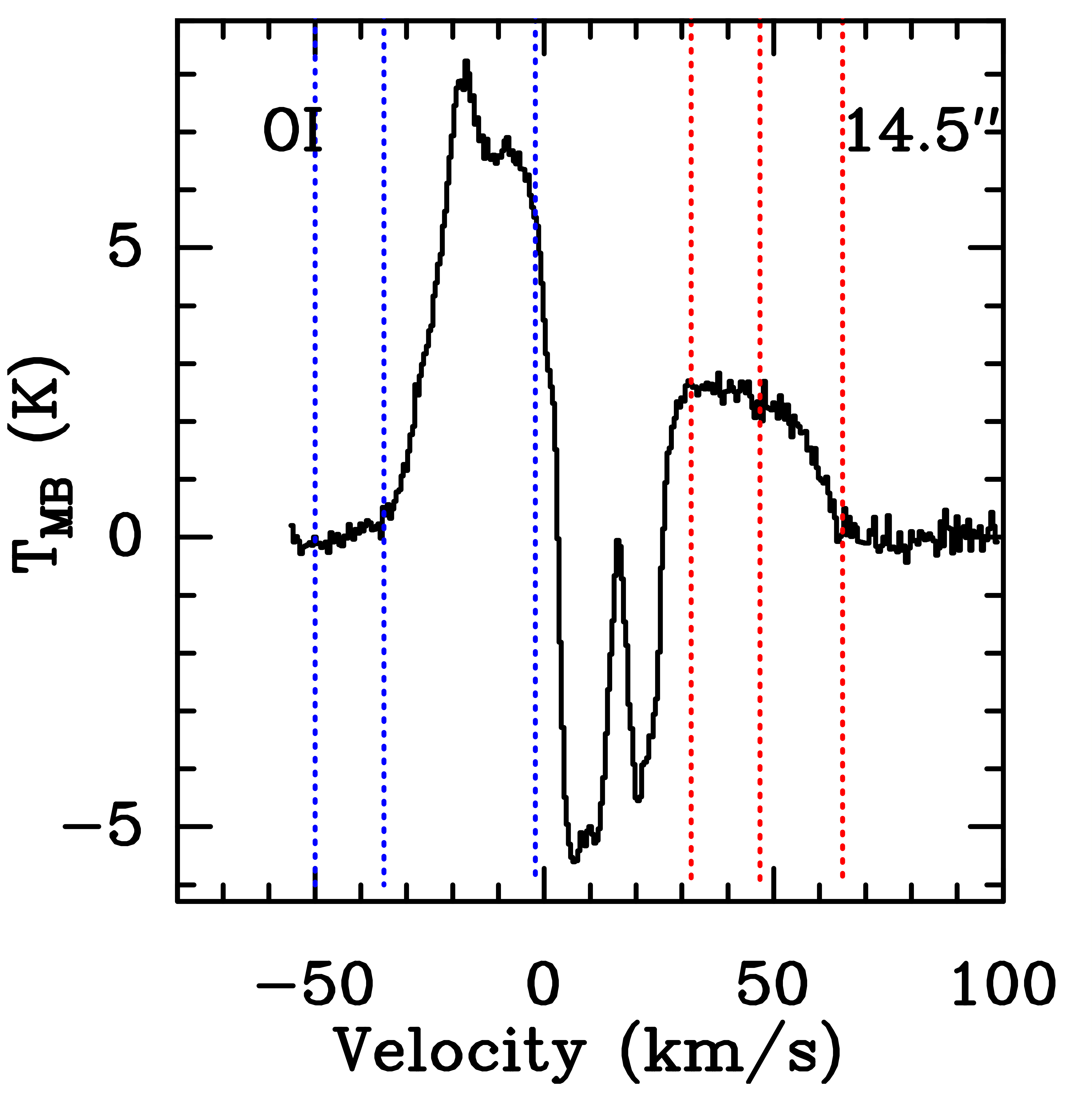
Schneider+2018

Velocity-resolved [OI] emission suggests jet-powered outflows

G5.89–0.39



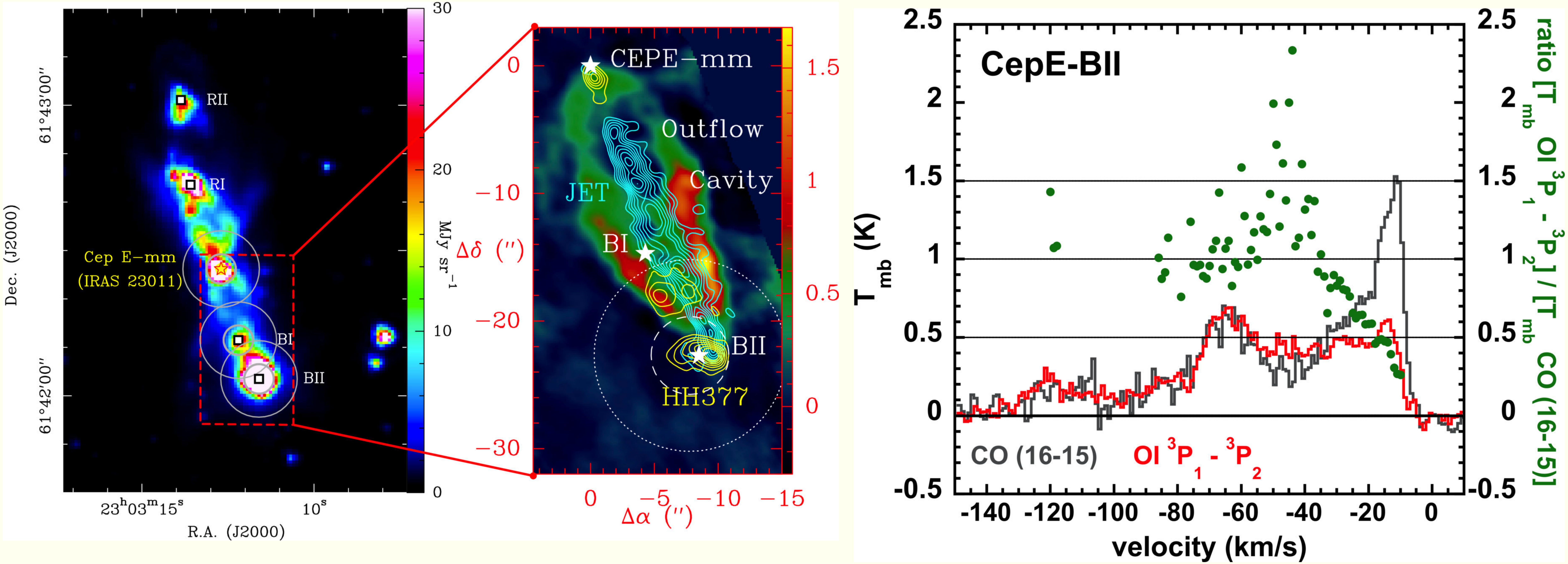
High-velocity [OI] emission> CO 16-15



Leurini+2015

[OI] 63 µm line comparable with CO 16-15 in intermediate-mass source

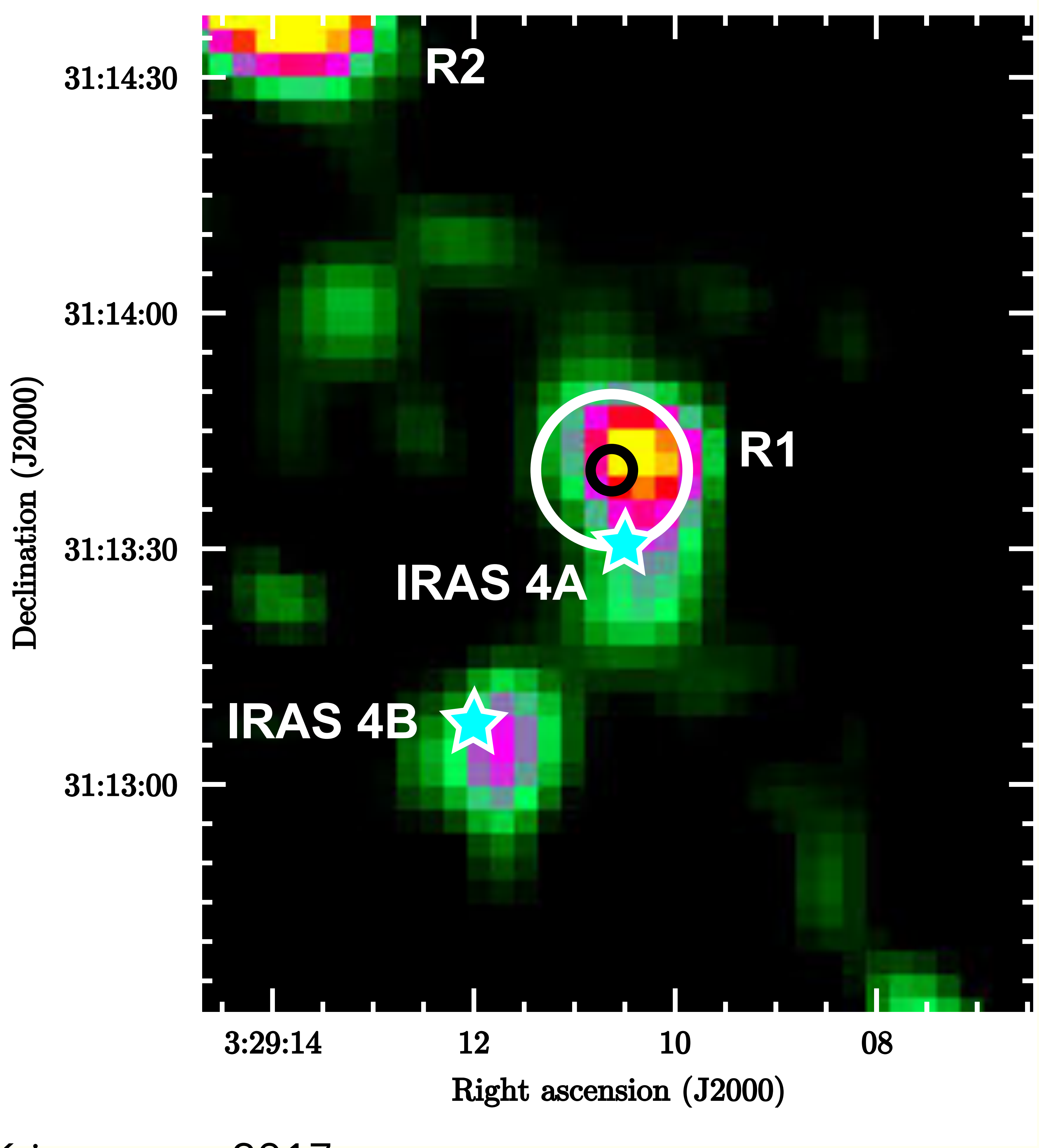
Cep E-mm



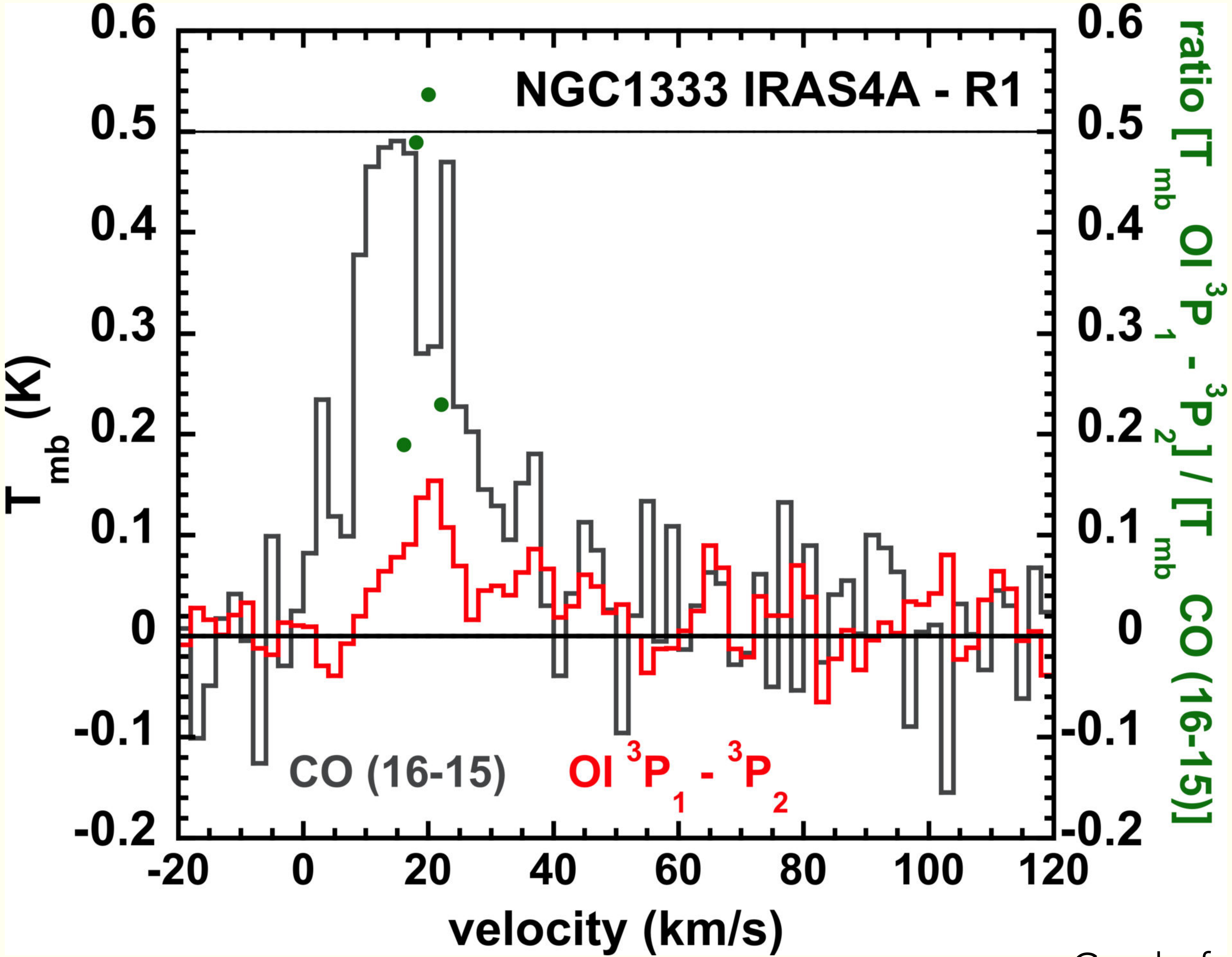
Gusdorf+2017

Weak but consistent [OI] line profile with high-*J* CO in low-mass source

NGC 1333 IRAS 4A



Kristensen+2017a



Gusdorf+2017

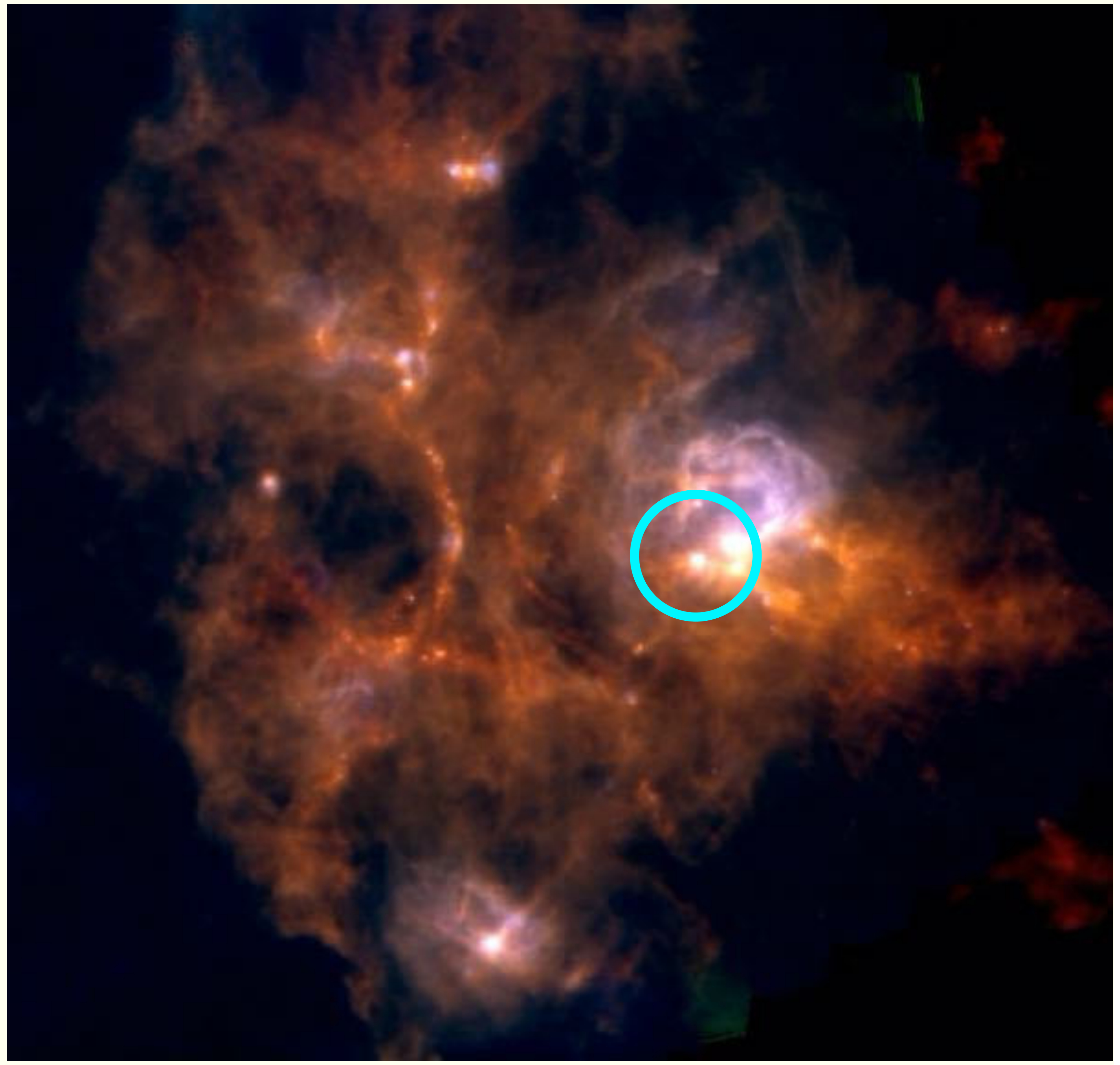
FIFI-LS observations show outflow-tracing [OI] emission

Sperling+2021

FIFI-LS survey probe the outflow feedback in massive protostars

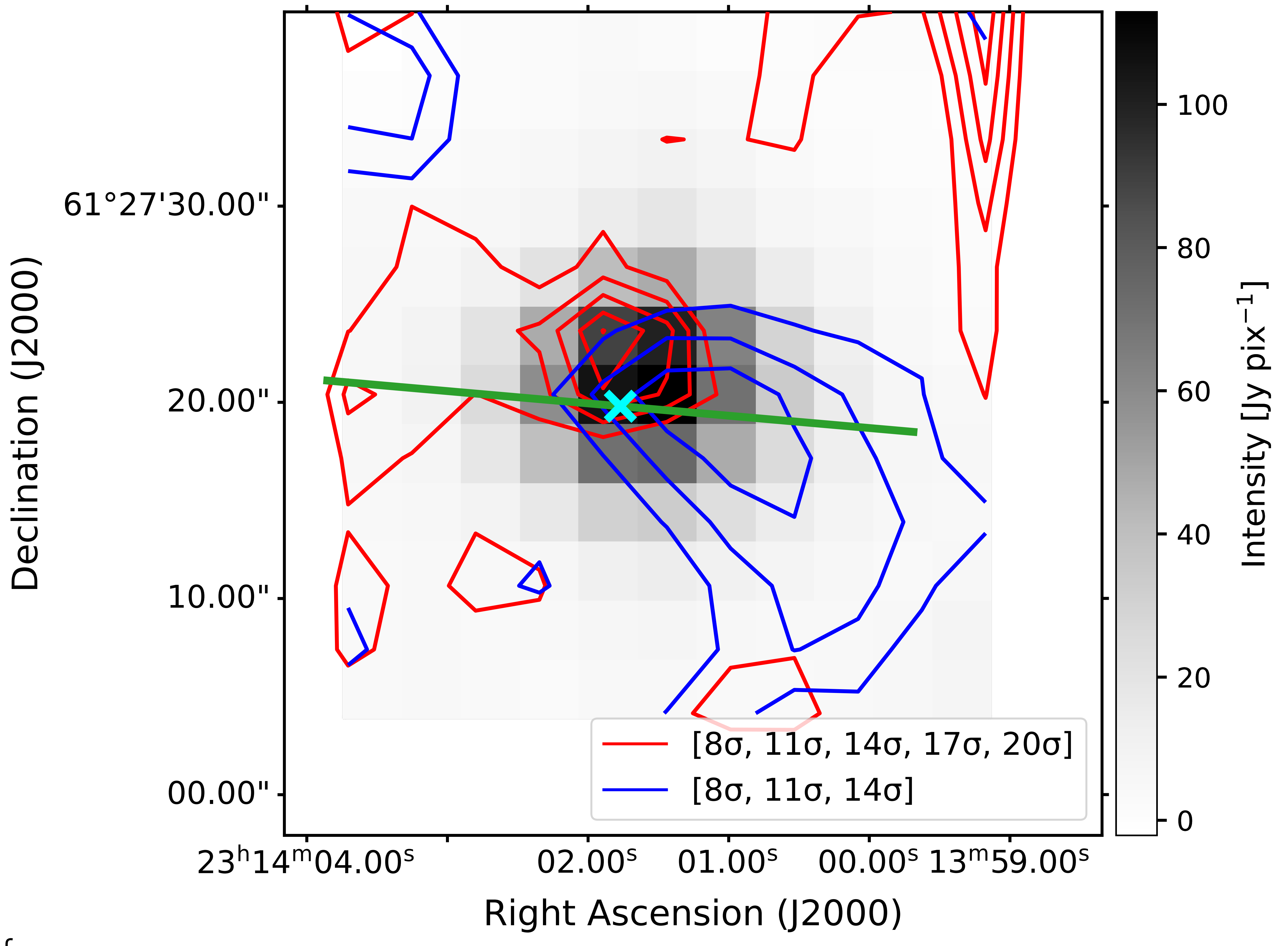
Led by Lianis V Reyes Rosa (UVA)

Program 09_0169, PI: Y.-L. Yang



ESA/Herschel/PACS/SPIRE. Acknowledgements: Cassie Fallscheer (University of Victoria), Mike Reid (University of Toronto) and the Herschel HOBYS team

NGC 7538 IRS 9



[OI] 63 μm & 145 μm

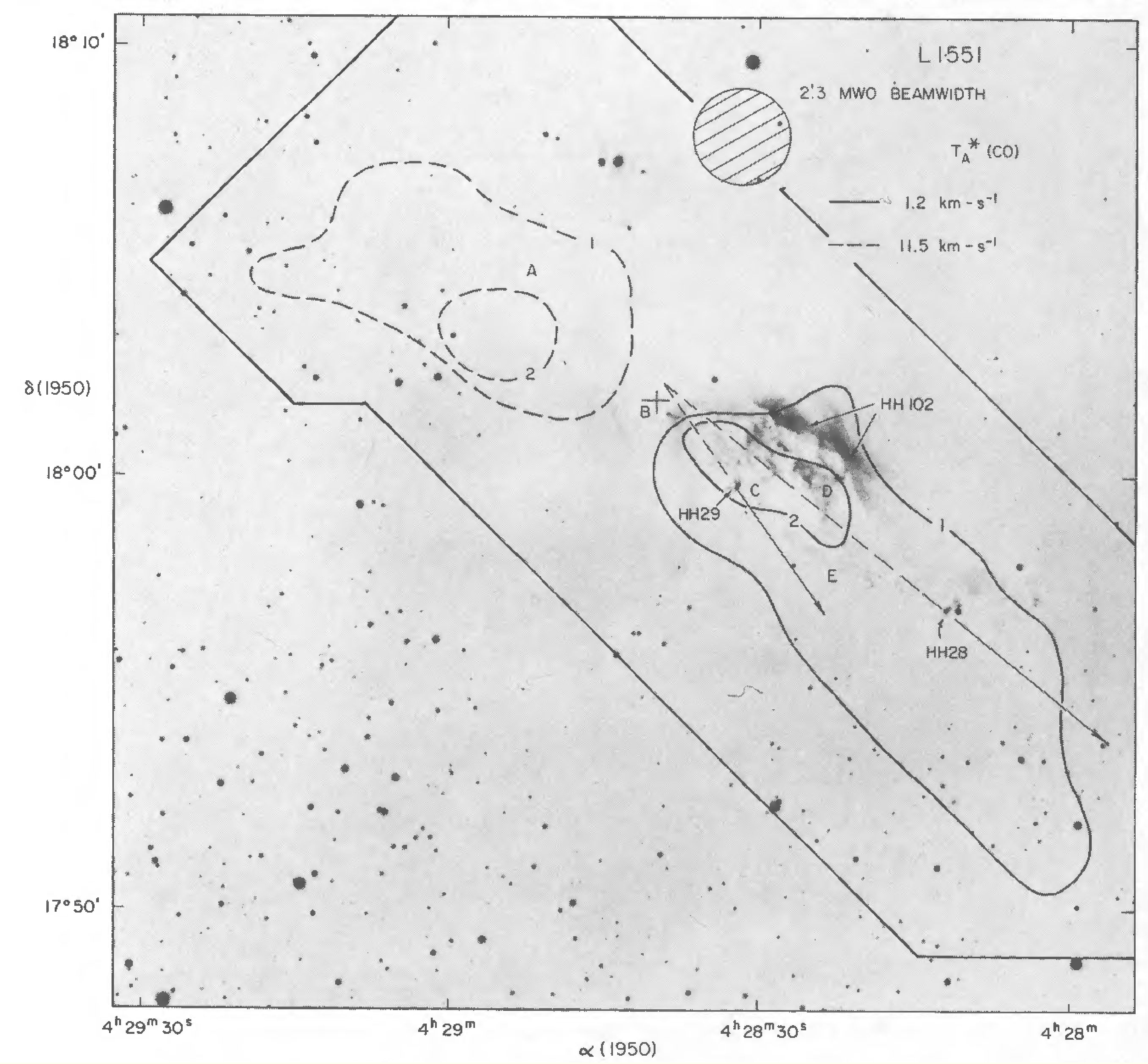
[OIII] 52 μm

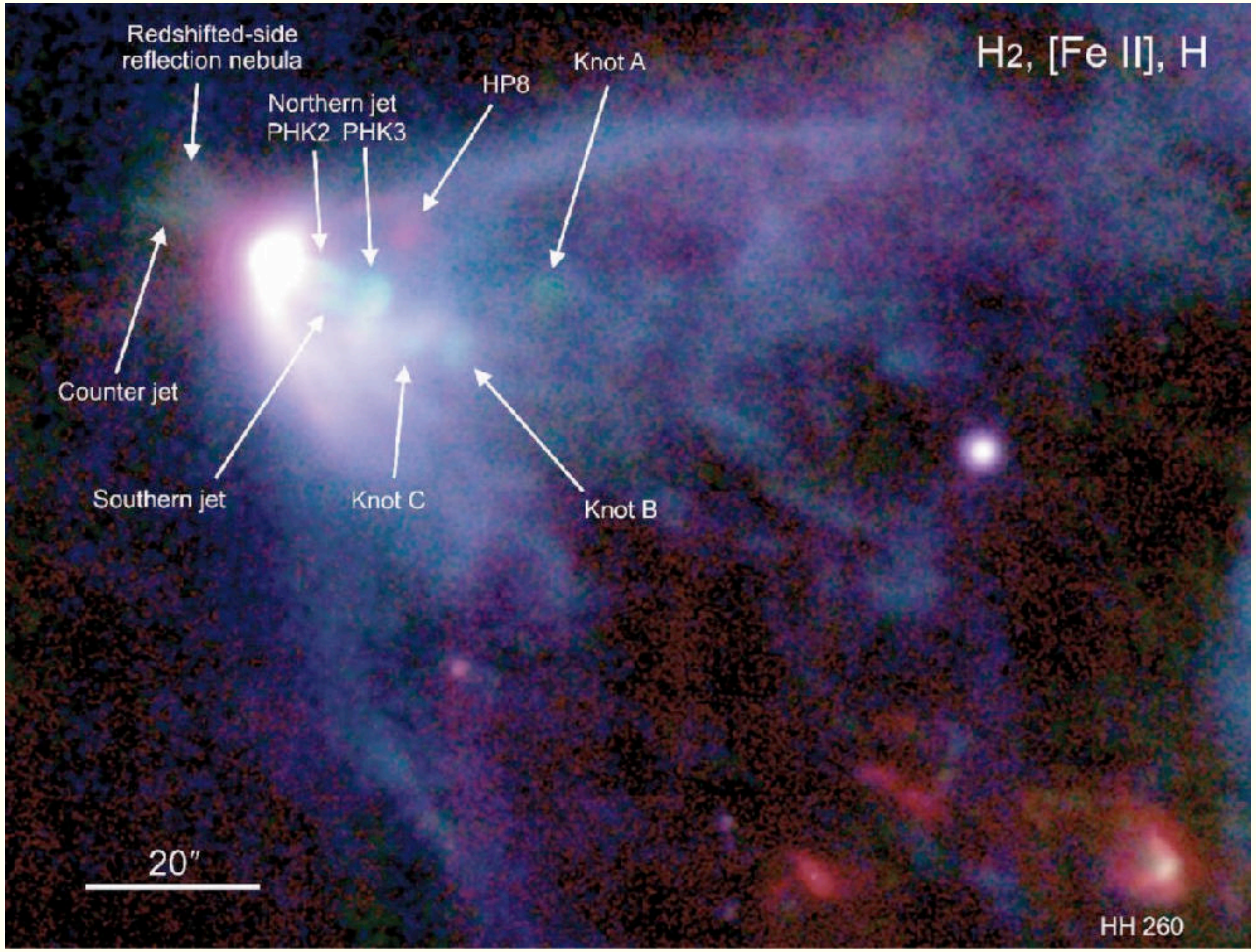
CO 14-13

Reyes Rosa, **Yang**+ in prep.

Outflows in Class I protostar: a case study of an iconic system

L1551 IRS 5

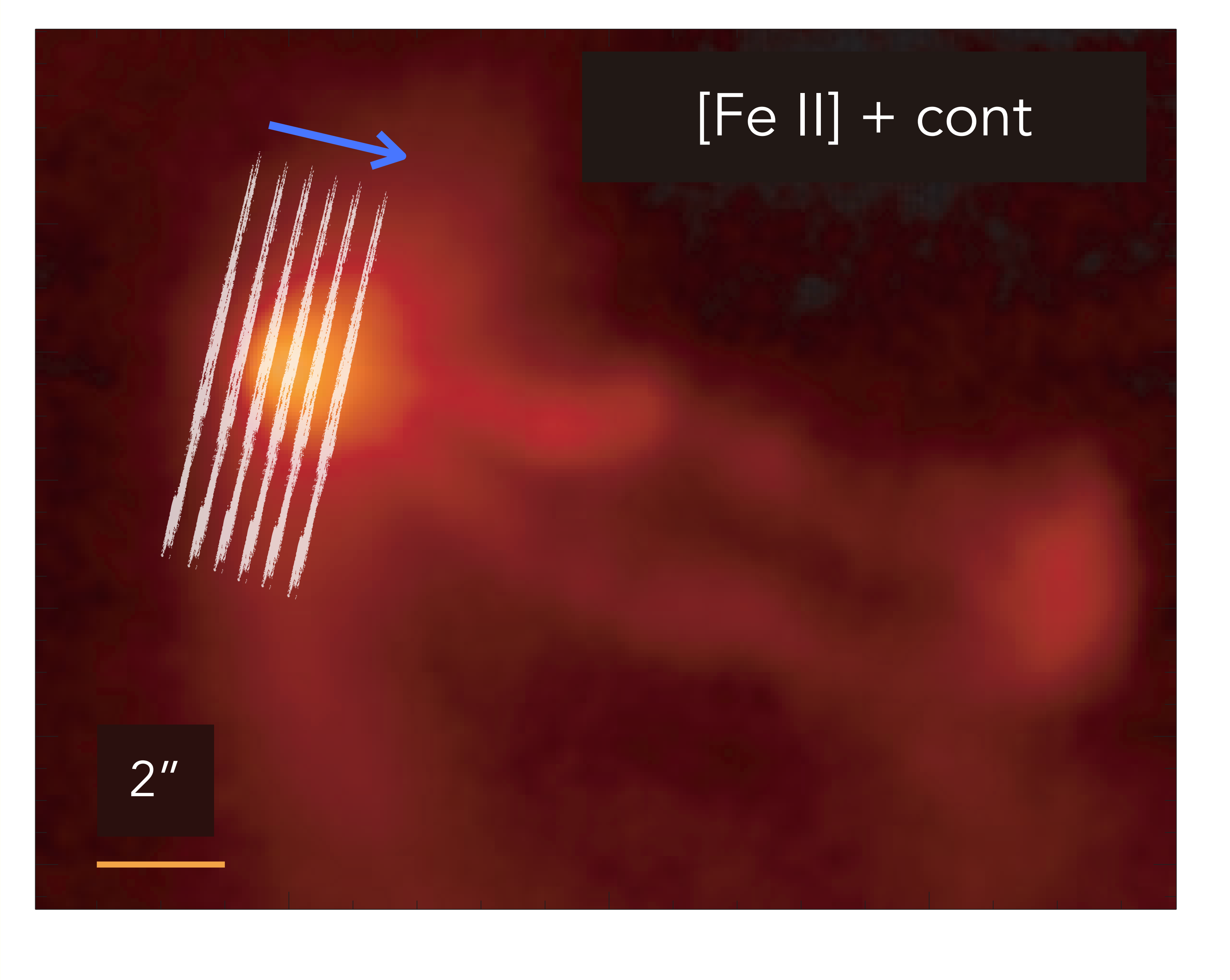


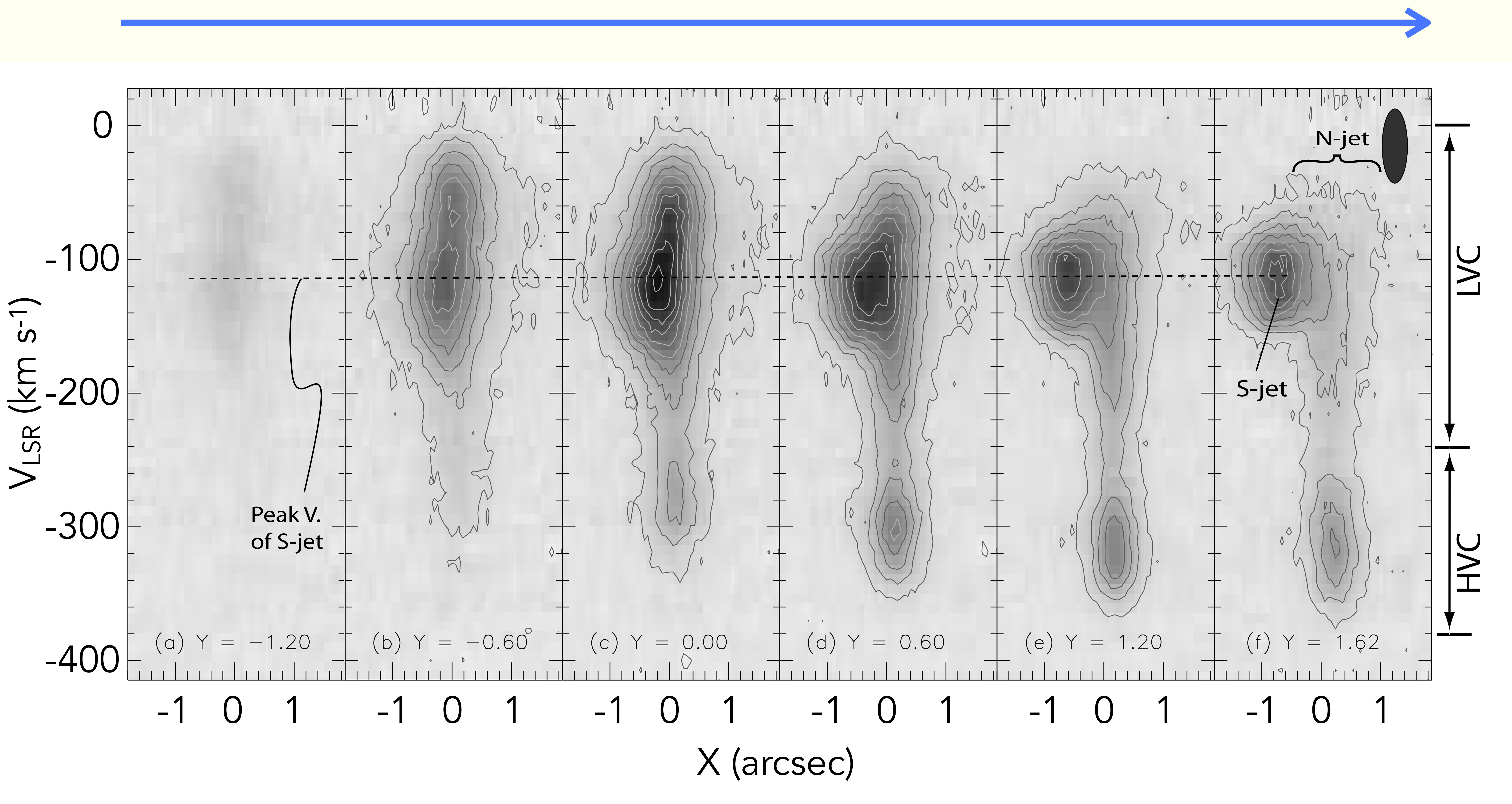


Snell, Loren, and Plambeck 1980

Hayashi+2009

Twin high-velocity jets of L1551 IRS 5

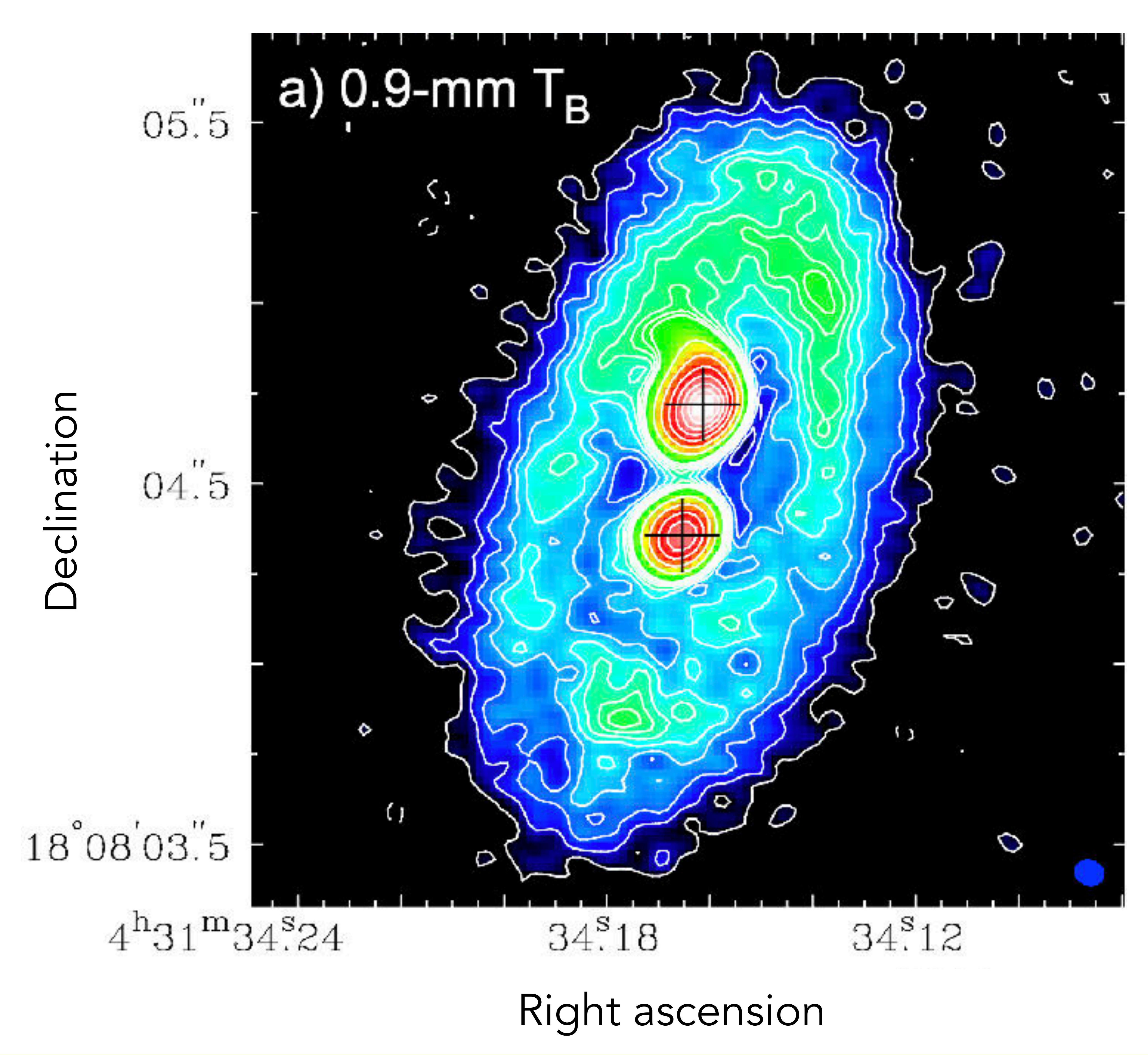


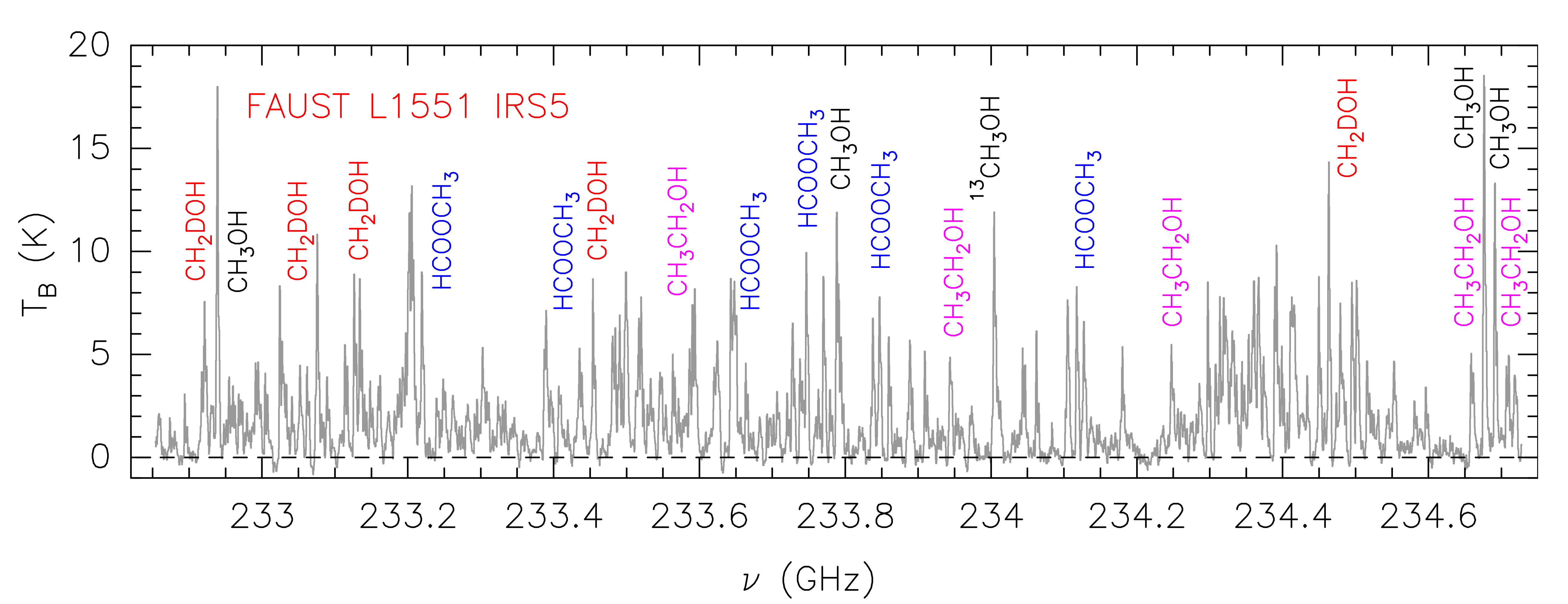


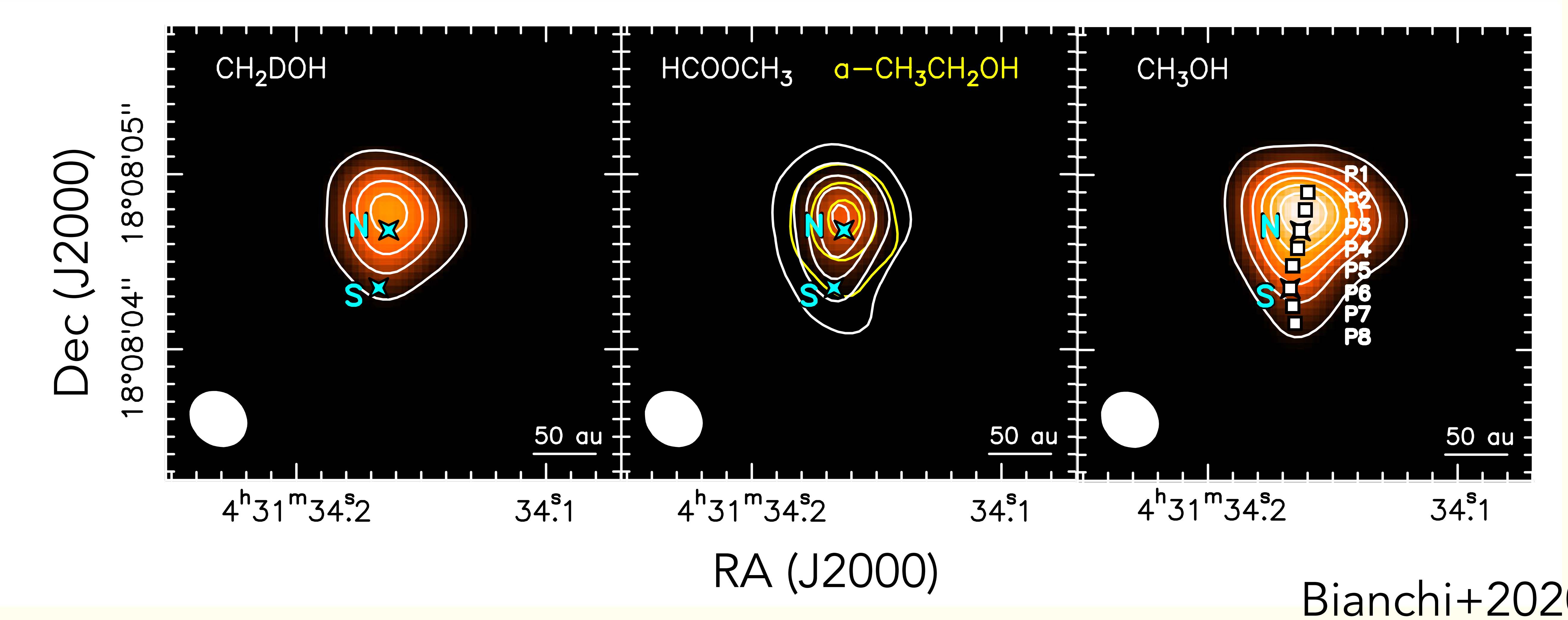
Pyo+2009

Chemically rich binary protostars with a circumbinary disk

Binary Class I protostar



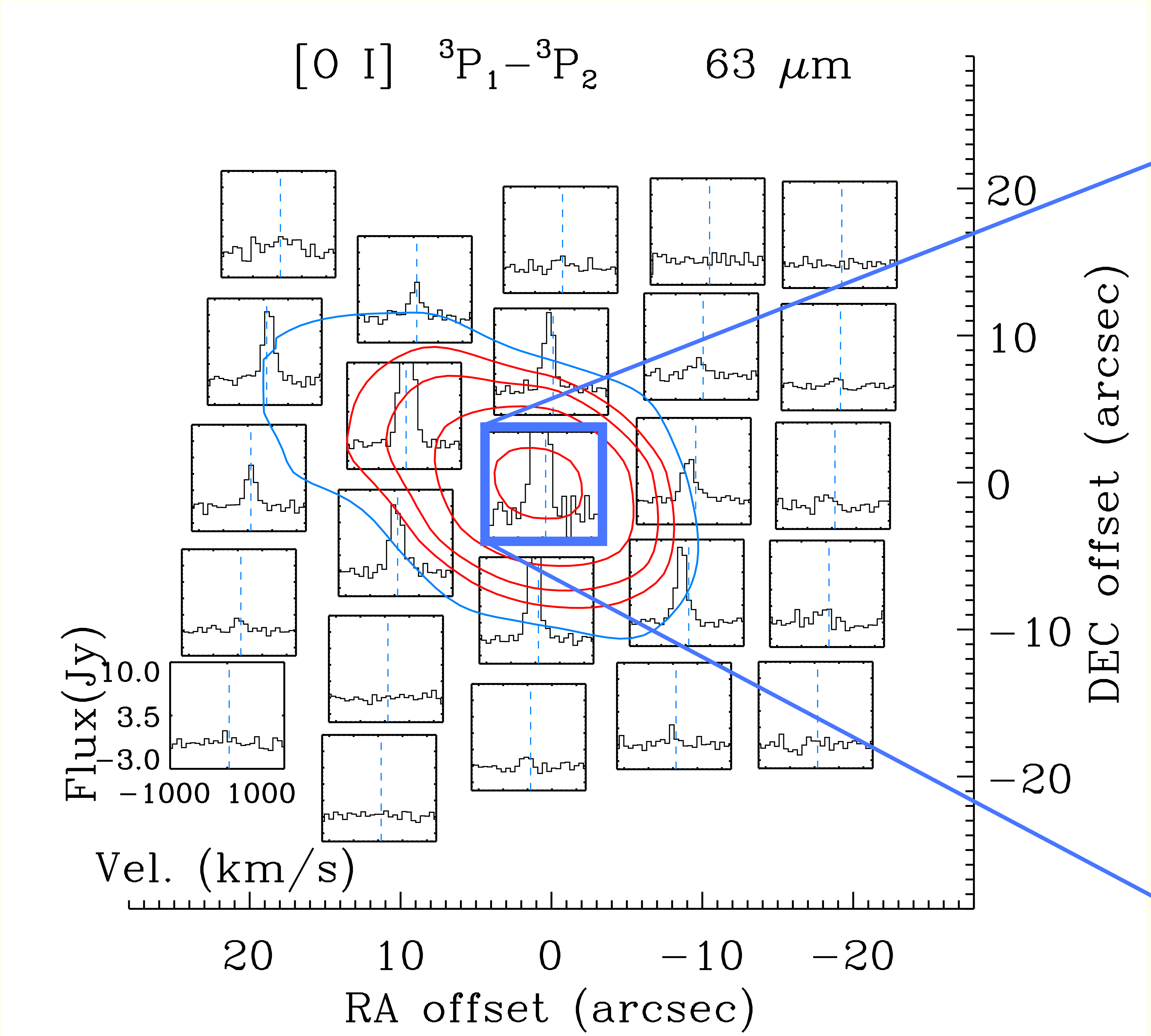




Takakuwa+2020 (see also Cruz-Sáenz de Miera+2019)

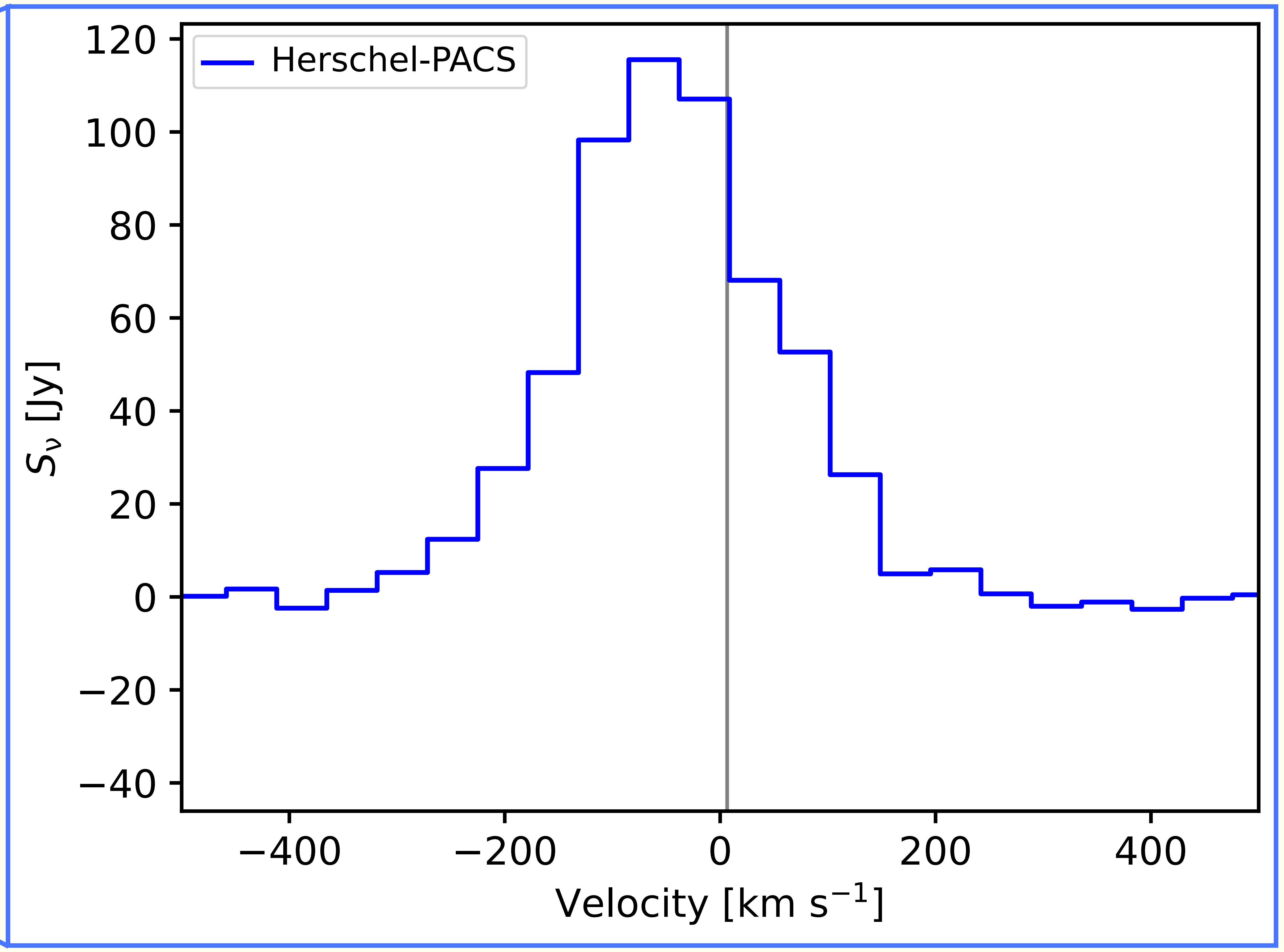
Bianchi+2020

Herschel observations show hints of outflow-tracing [OI] emission



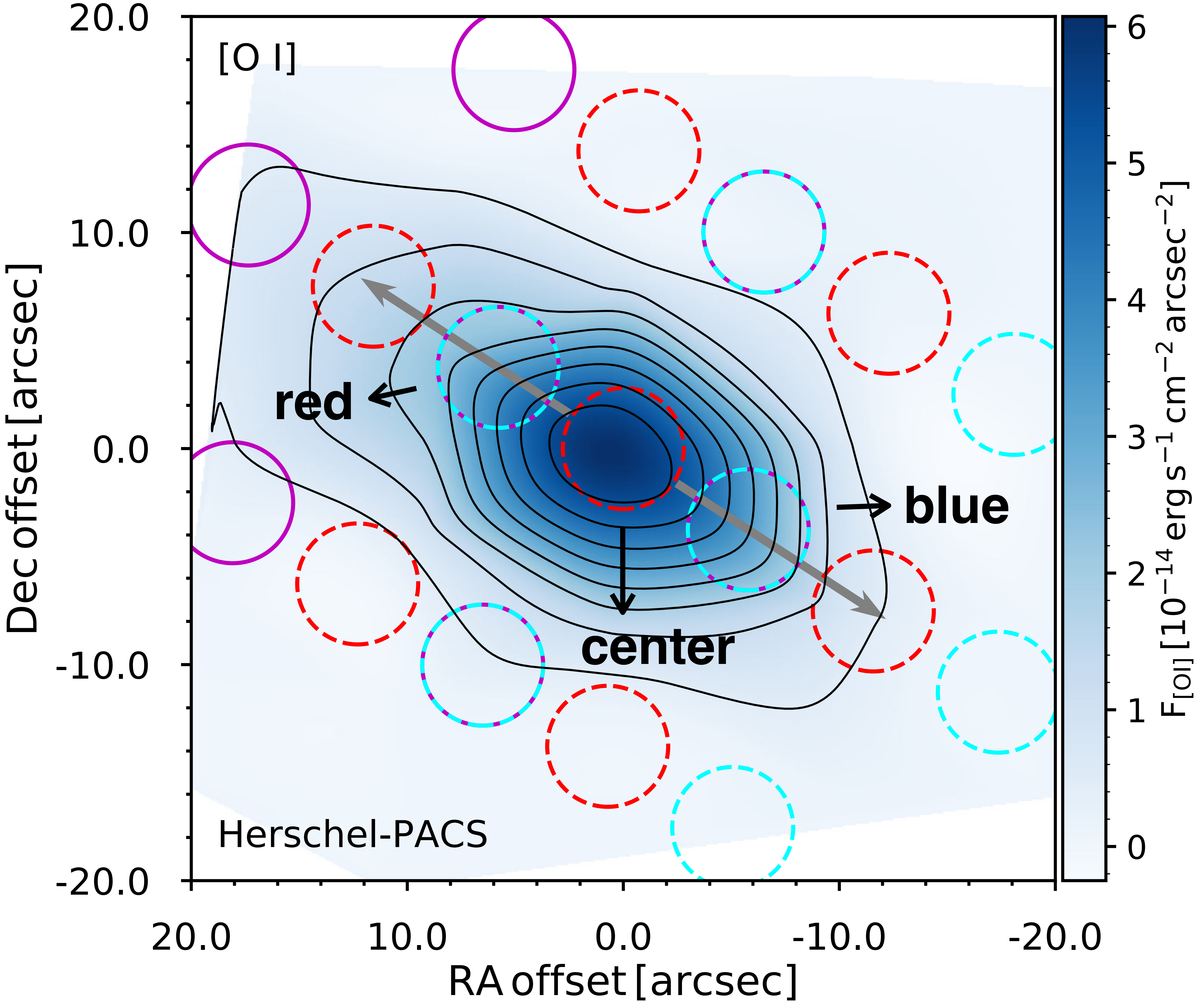
Lee+2014

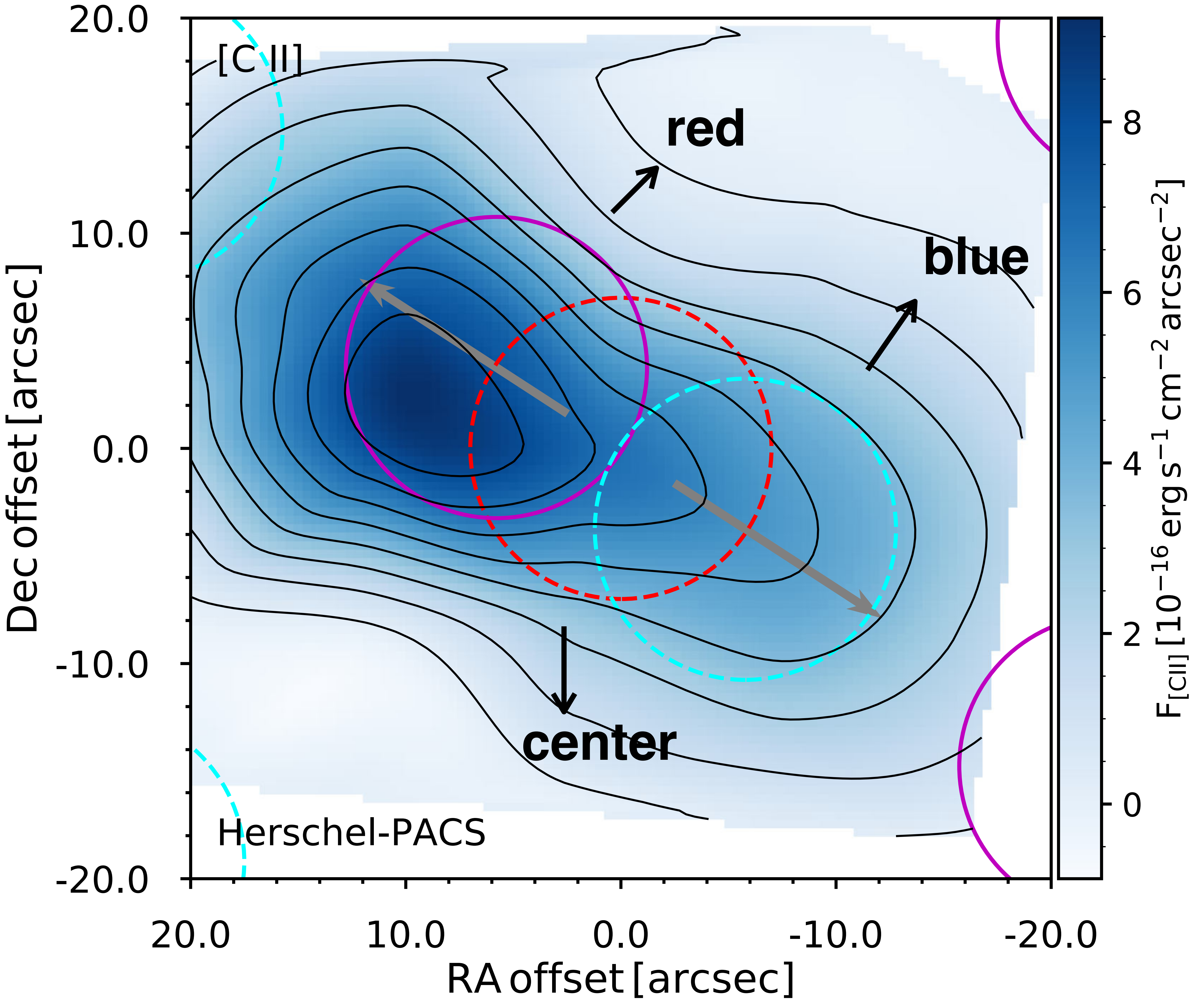
Velocity resolution ~ 190 km/s



Green, **Yang**+2016

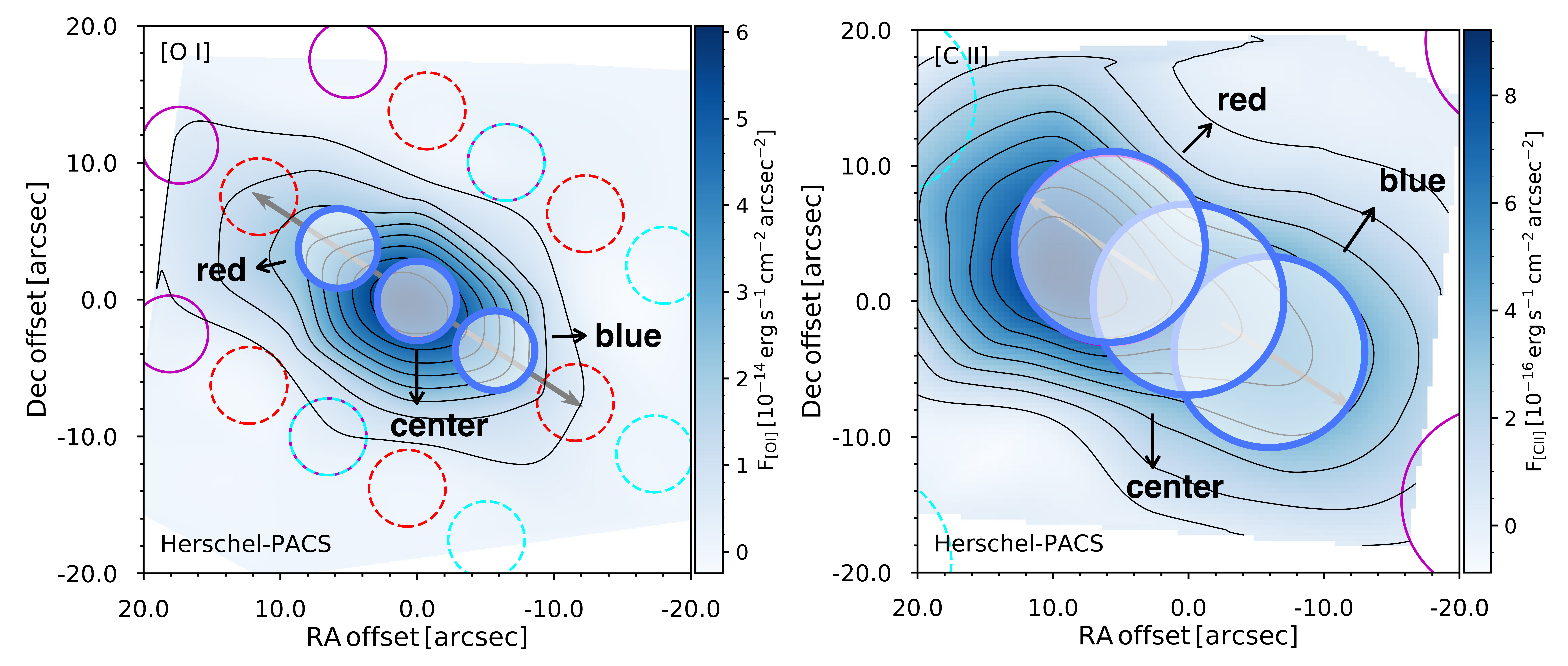
Velocity-resolved observations of [OI] and [CII]: from Herschel to SOFIA





Yang+2022

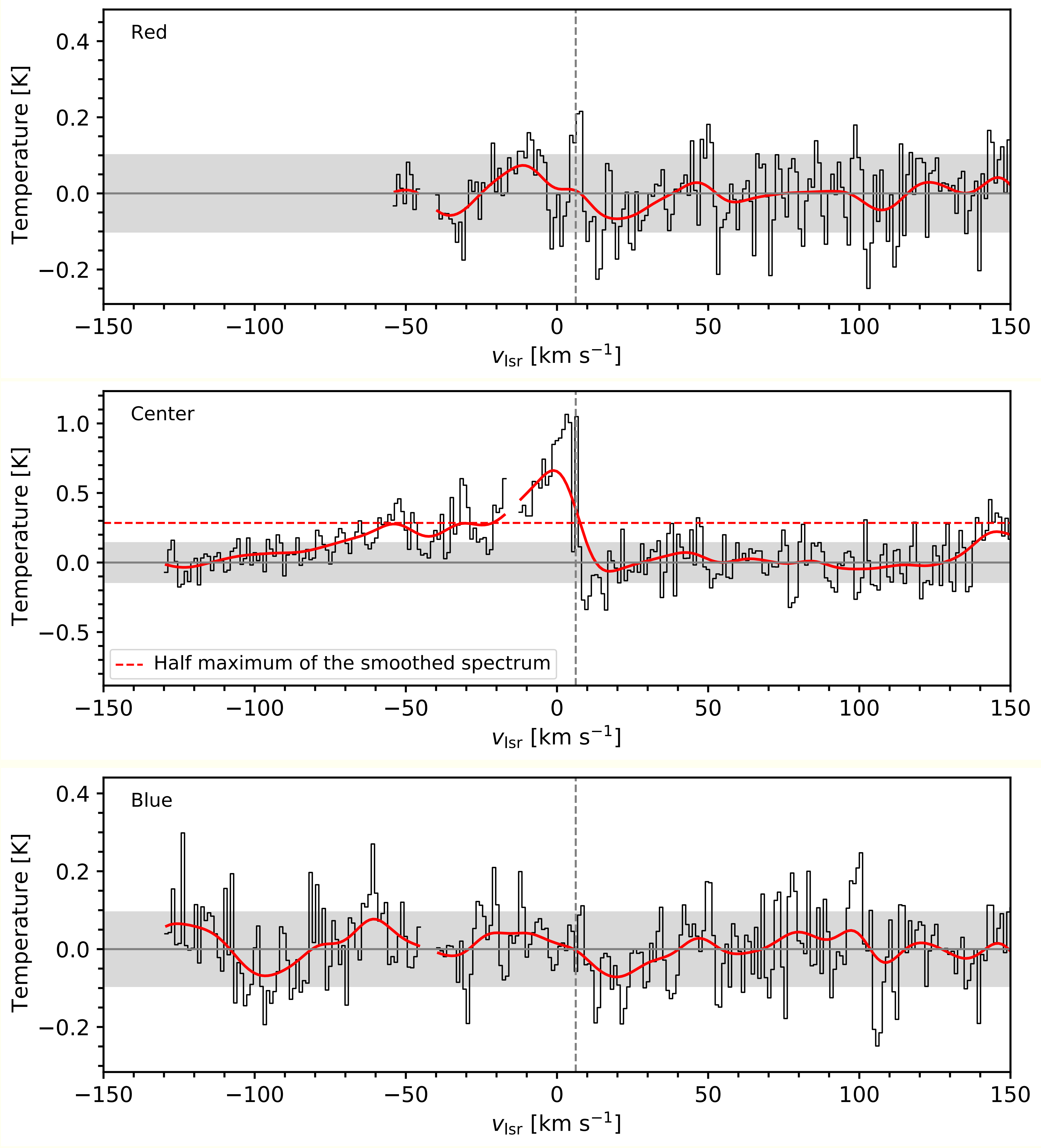
Velocity-resolved observations of [OI] and [CII]: from Herschel to SOFIA



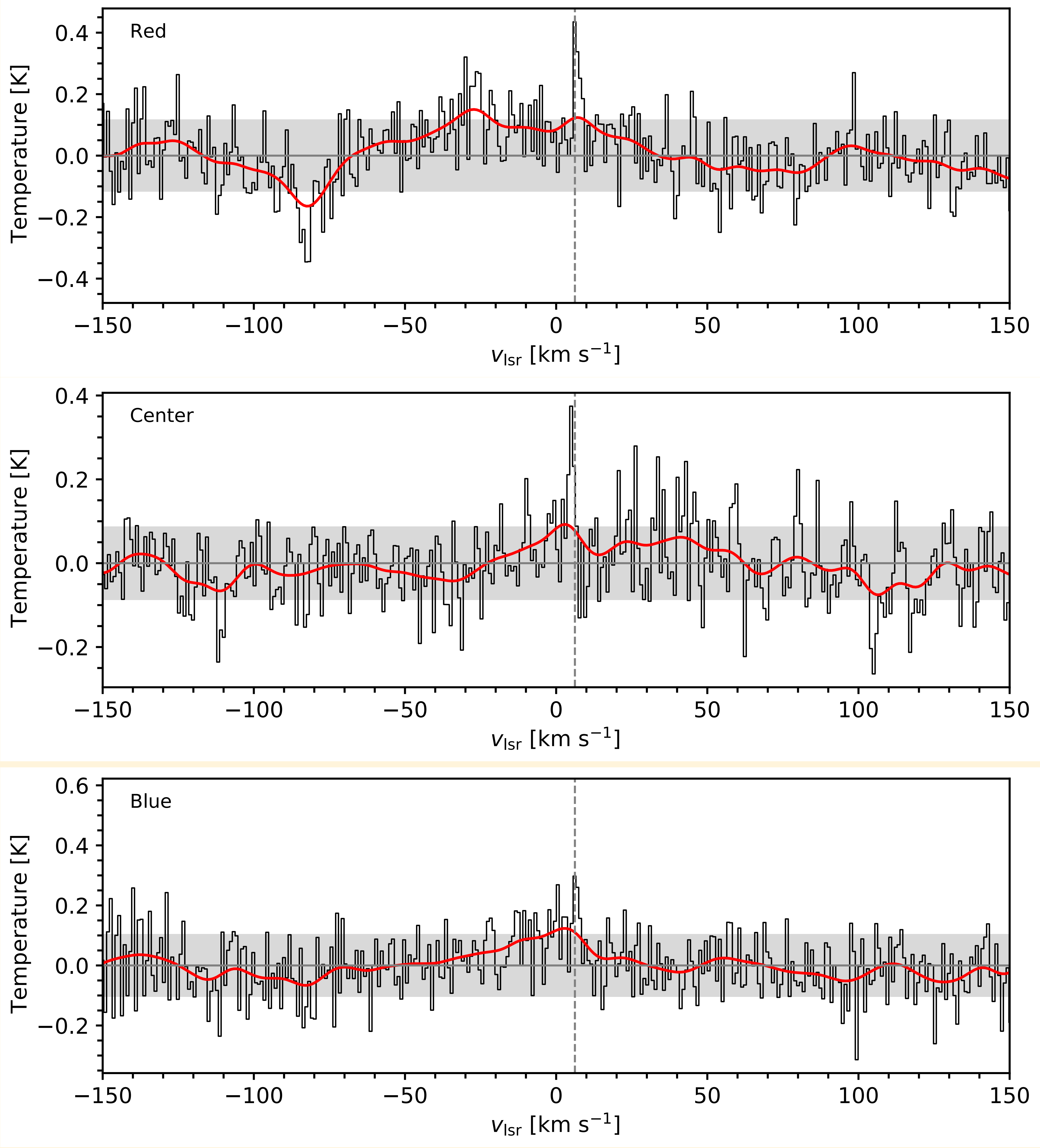
Yang+2022

SOFIA-upGREAT observations

[OI]



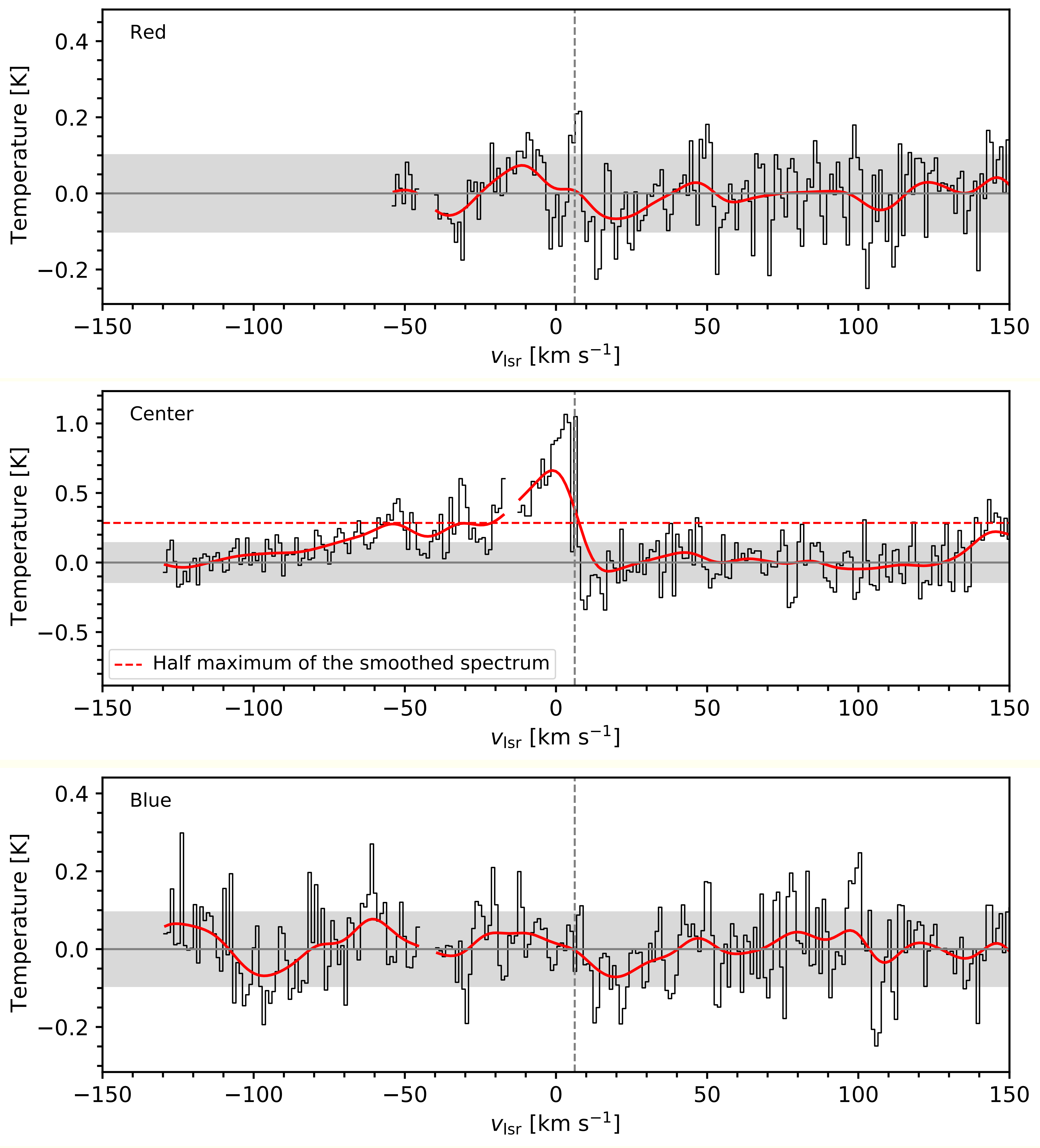
[CII]



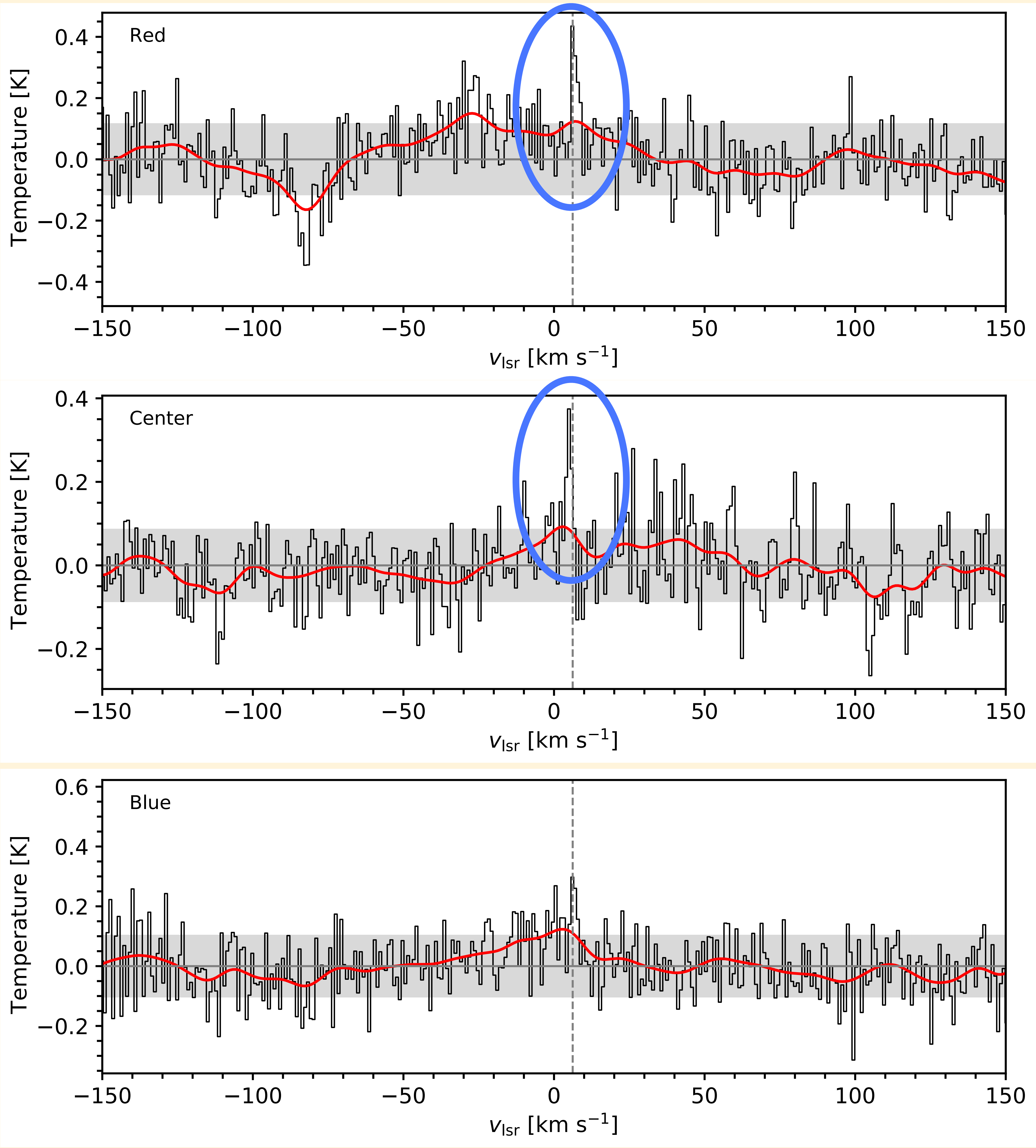
Yang+2022

SOFIA-upGREAT observations

[OI]



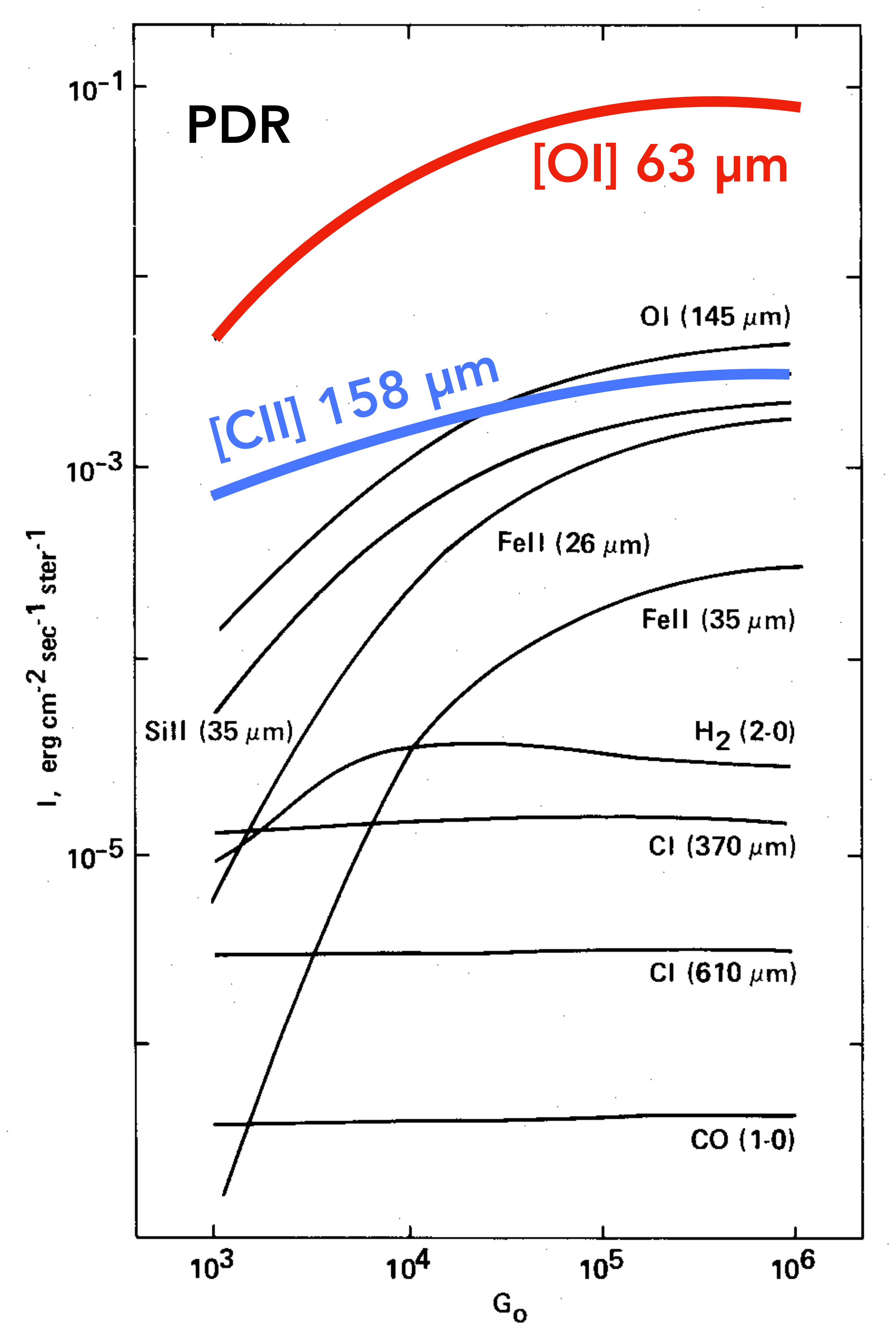
[CII]



Yang+2022

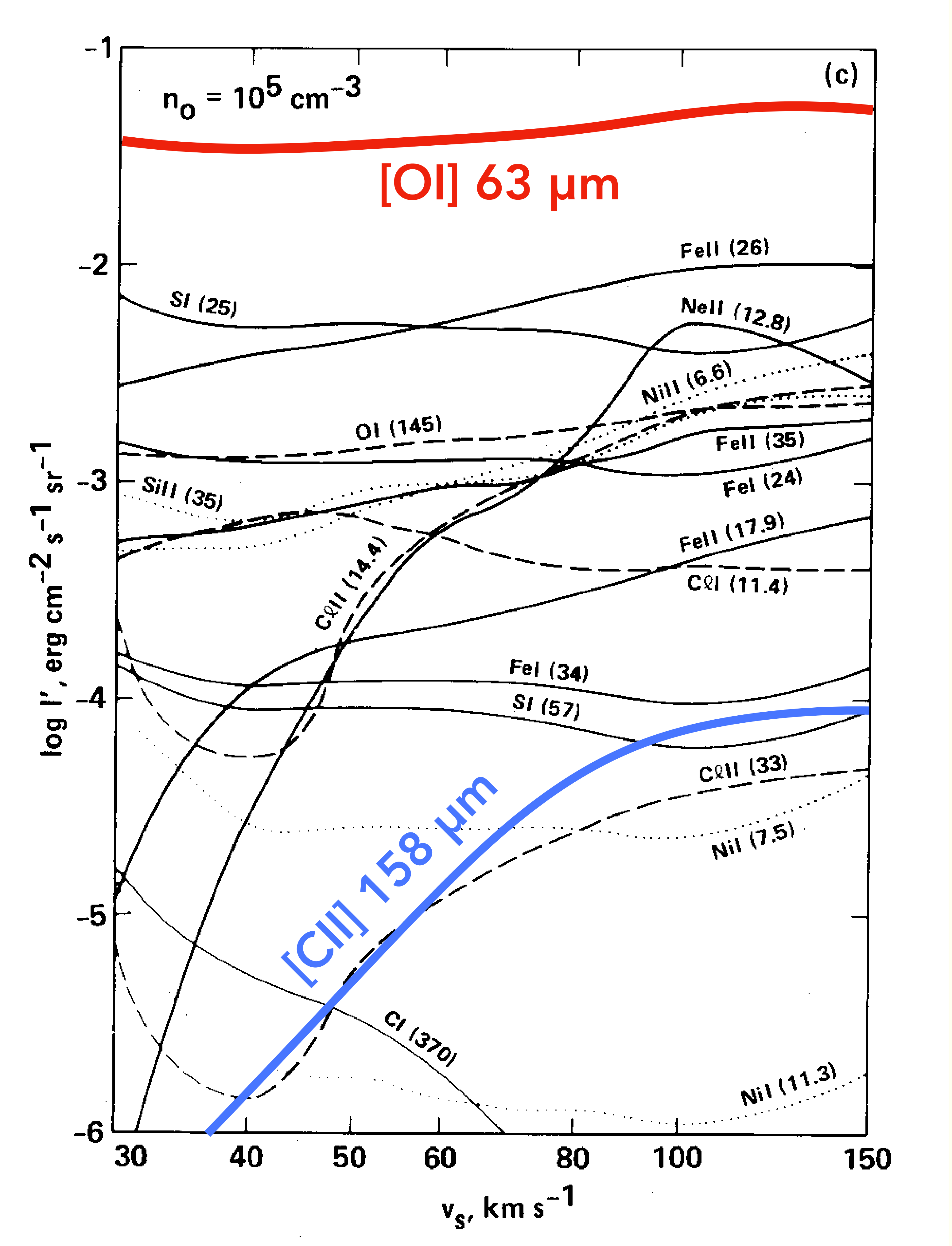
PDR contributes only 3% of [OI] flux

[CII] emission as an indicator of PDR contribution

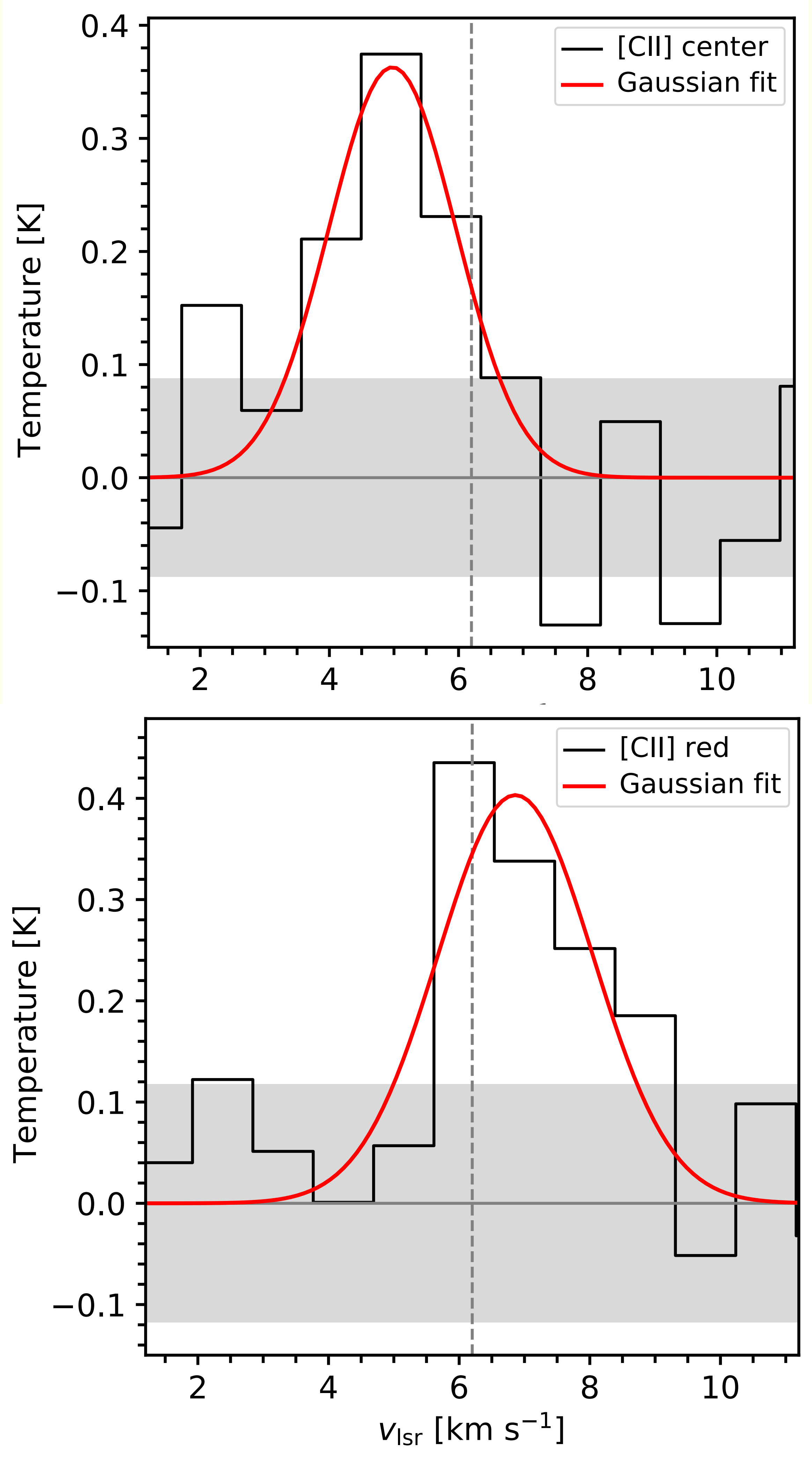


Tielens & Hollenbach 1985

Shocks

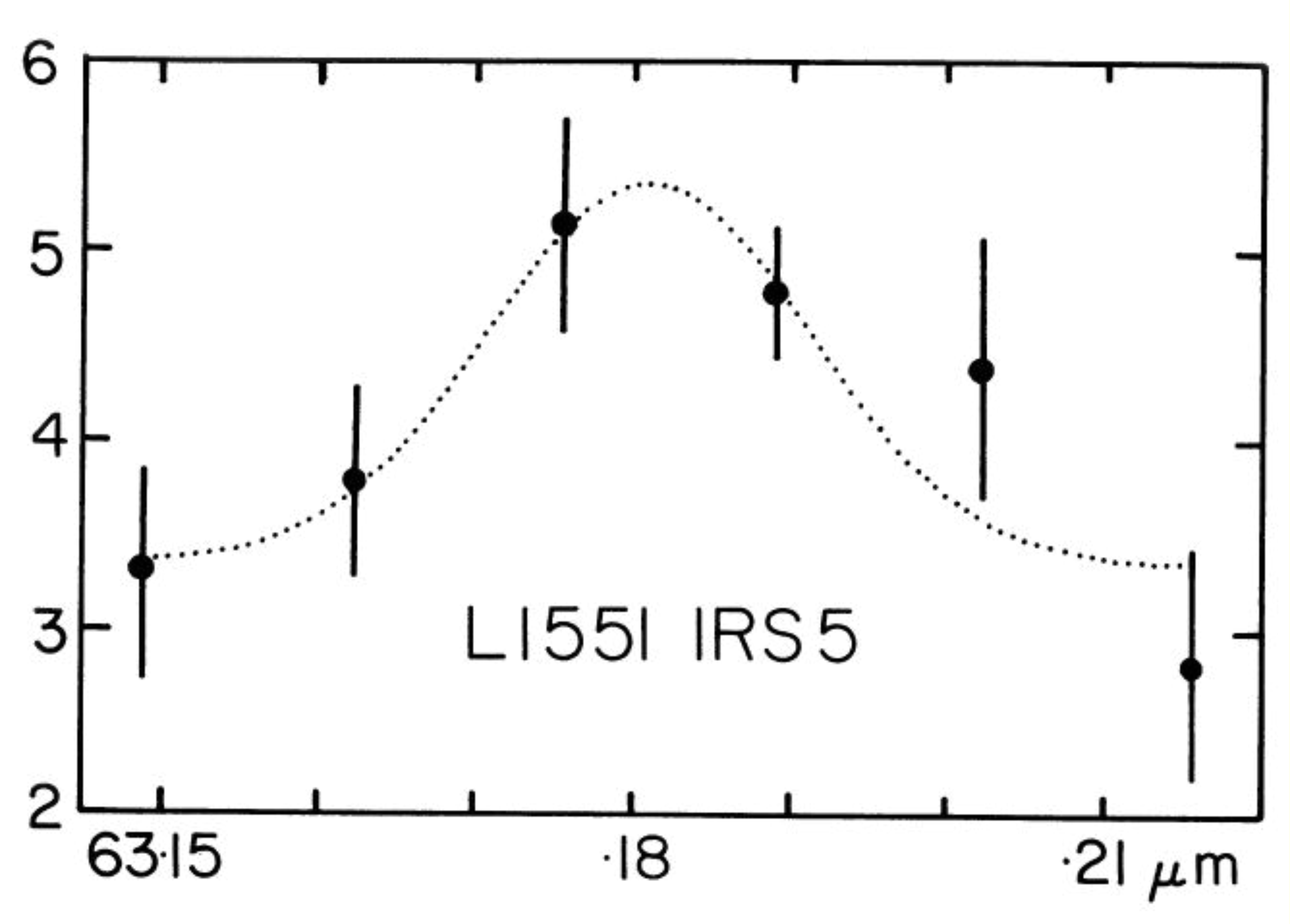


Hollenbach & McKee 1989



Yang+2022

Consistent with KAO observations

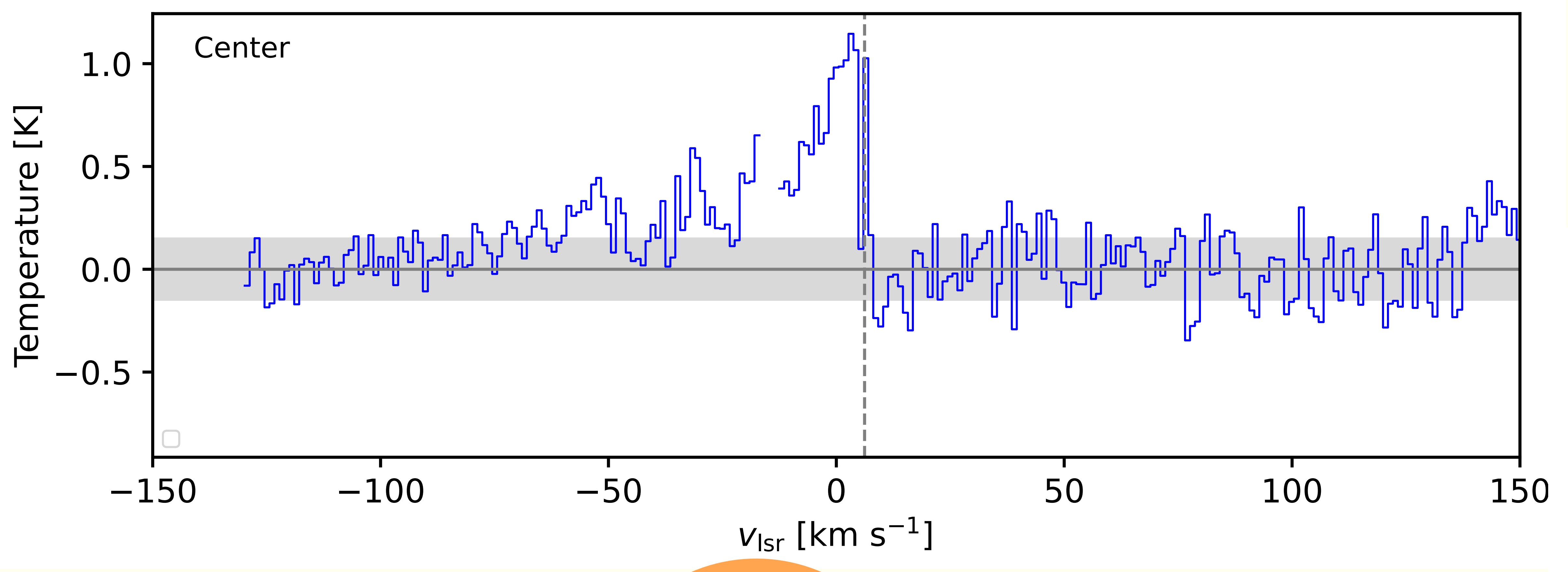


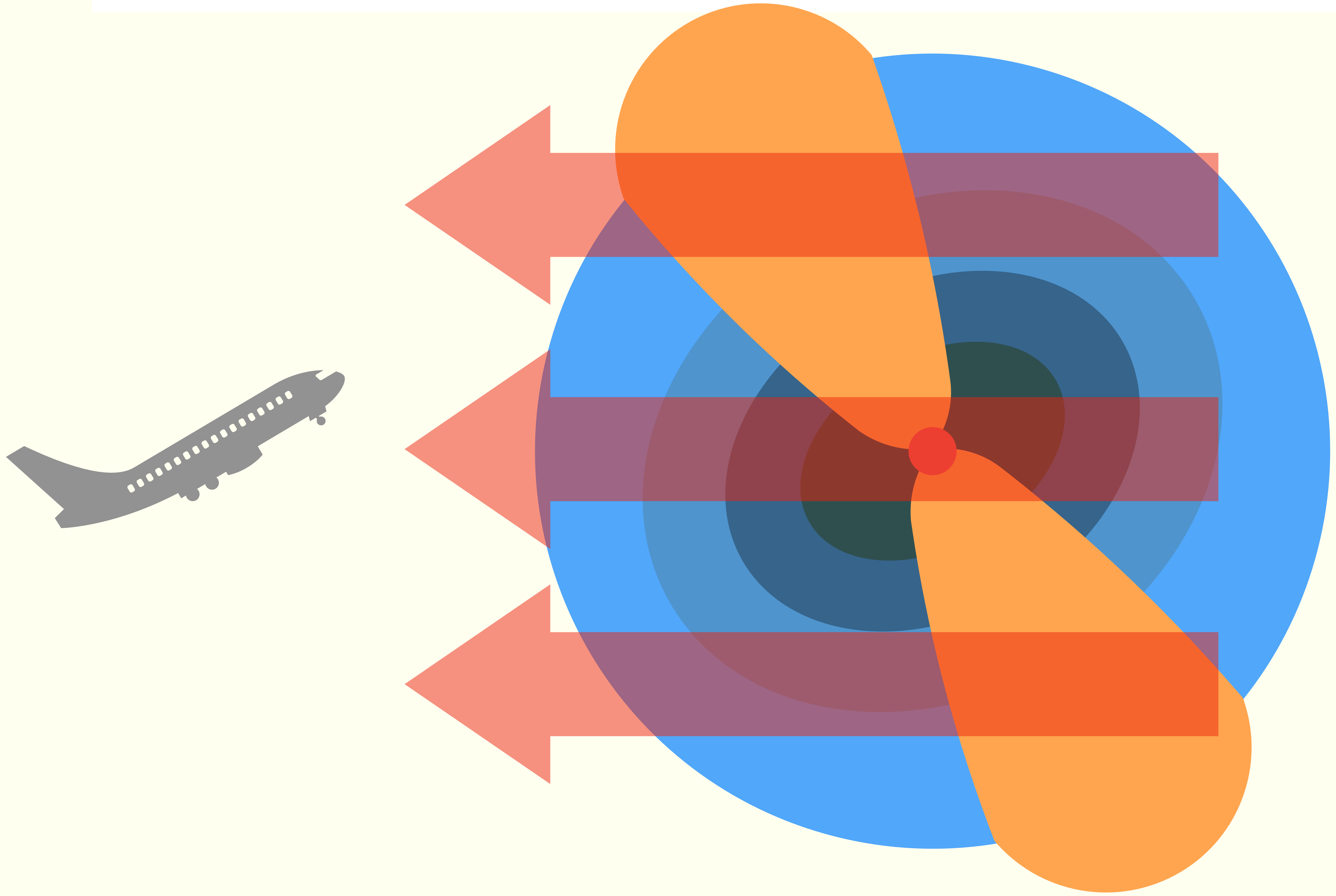
Line centroid at -43±22 km/s

The absence of a corresponding redshifted [O I] emission feature is rather puzzling since IRS 5 certainly drives a bipolar flow. Either there are no HH objects associated with the redshifted flow or these exist but are invisible in the 63 μm line.

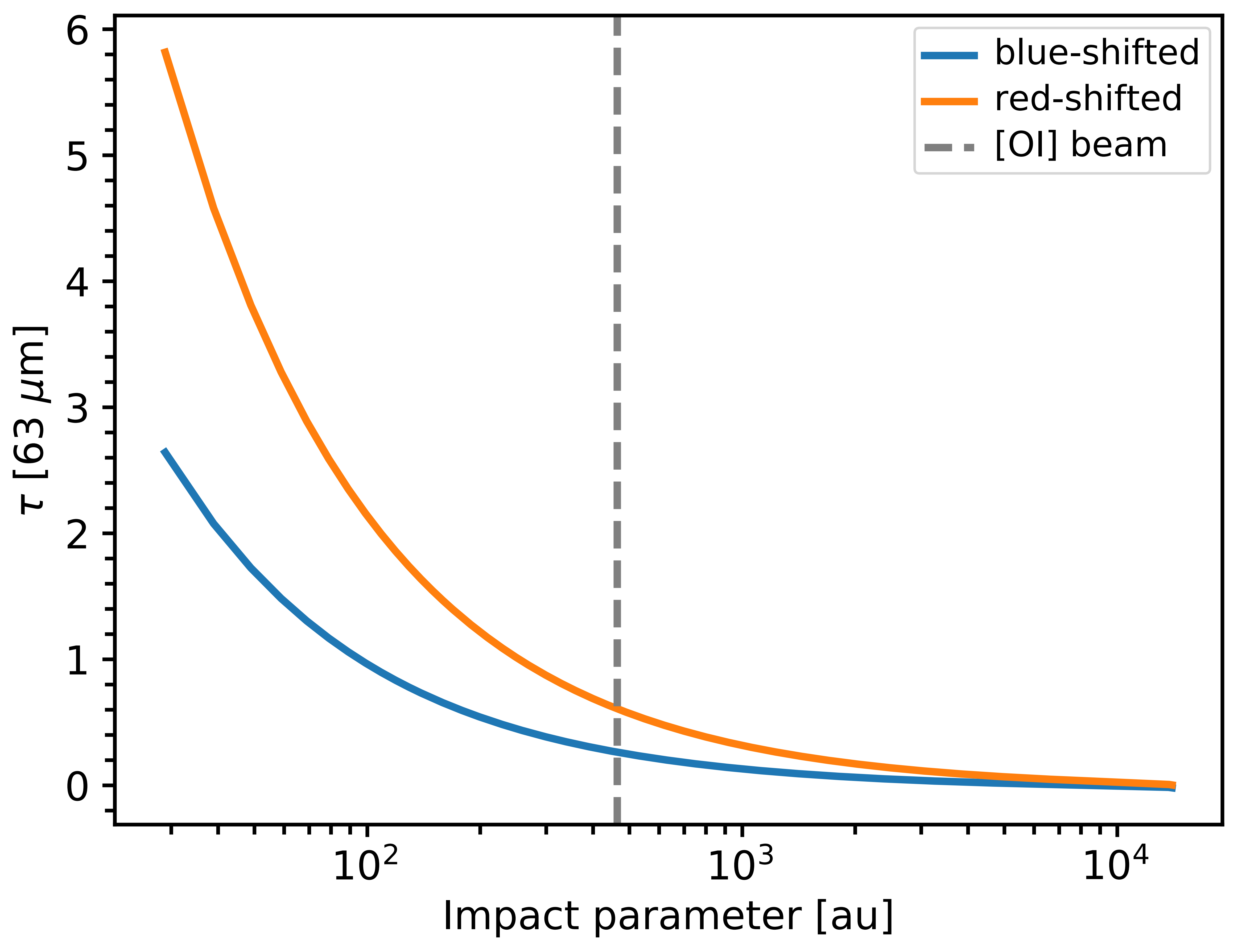
Cohen+1985

Dust in envelope blocks the red-shifted emission



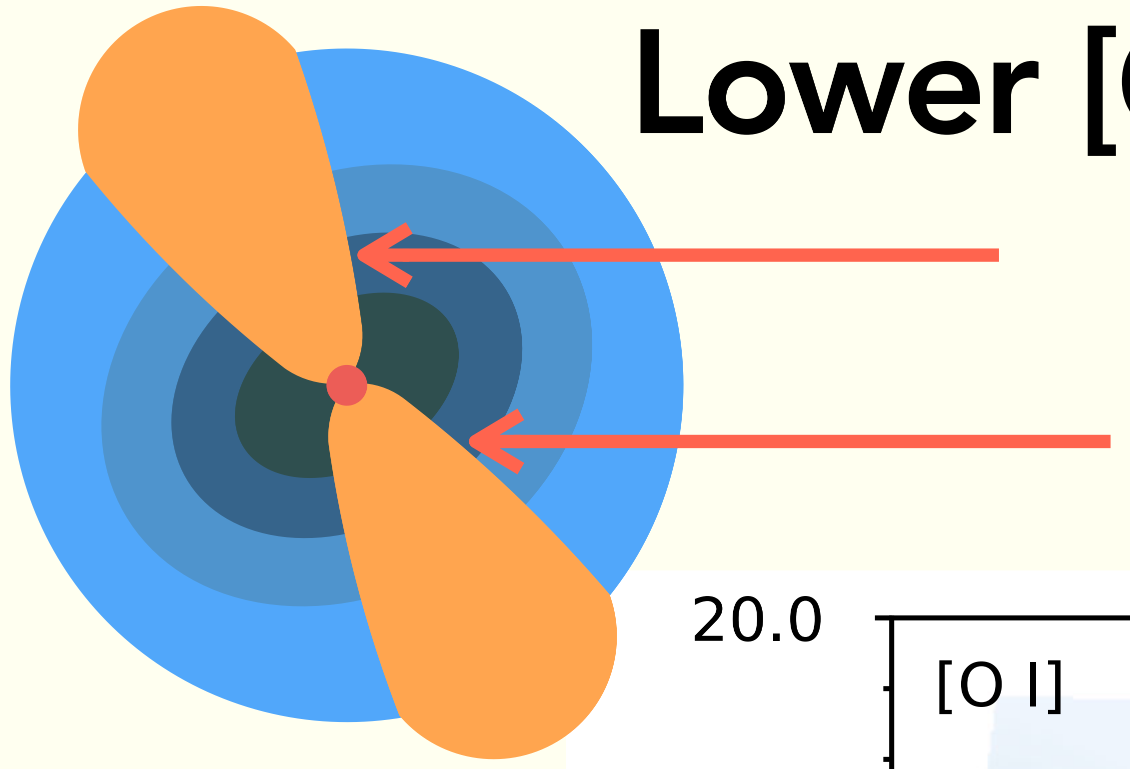


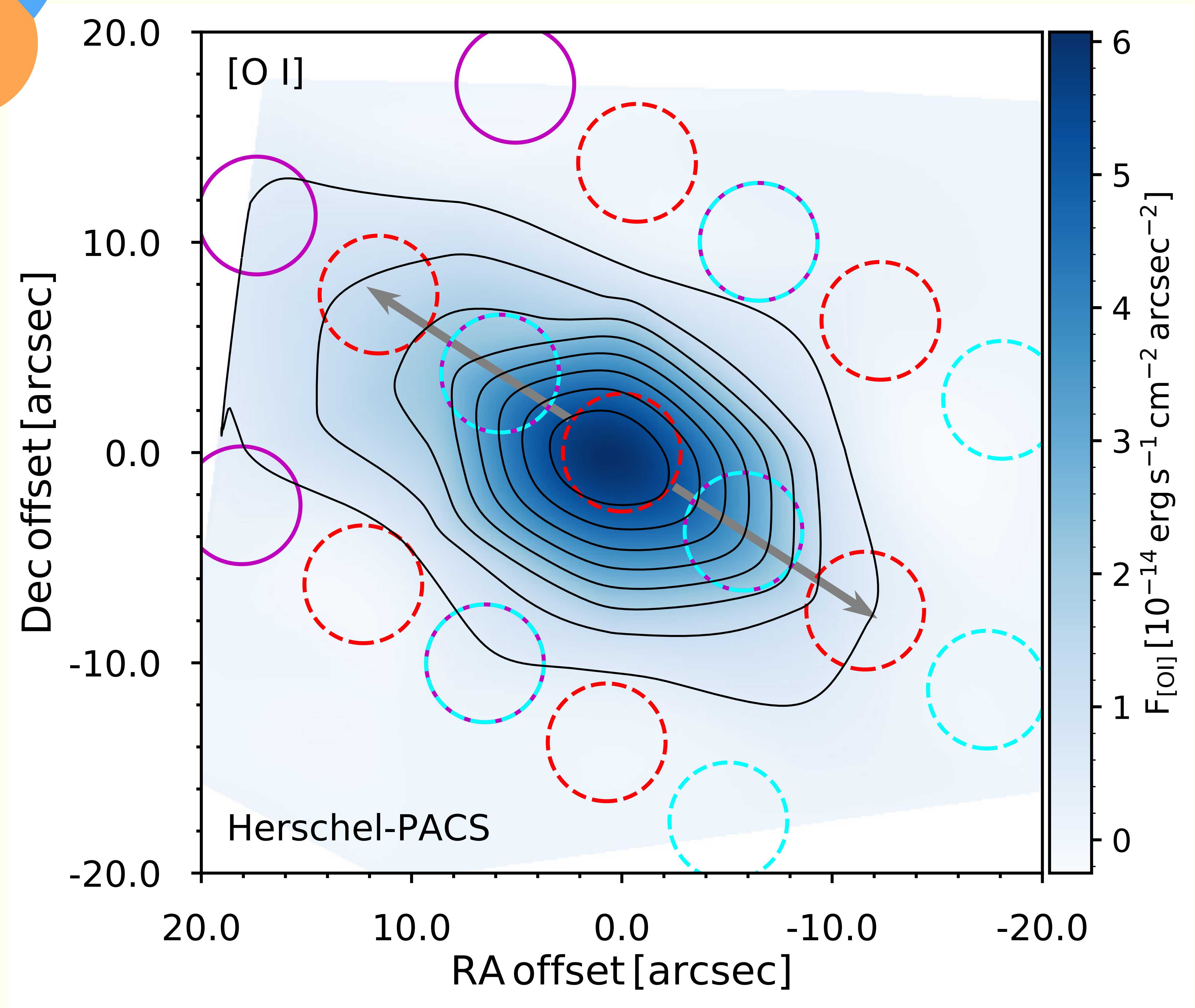
Envelope model based on Kristensen+2012

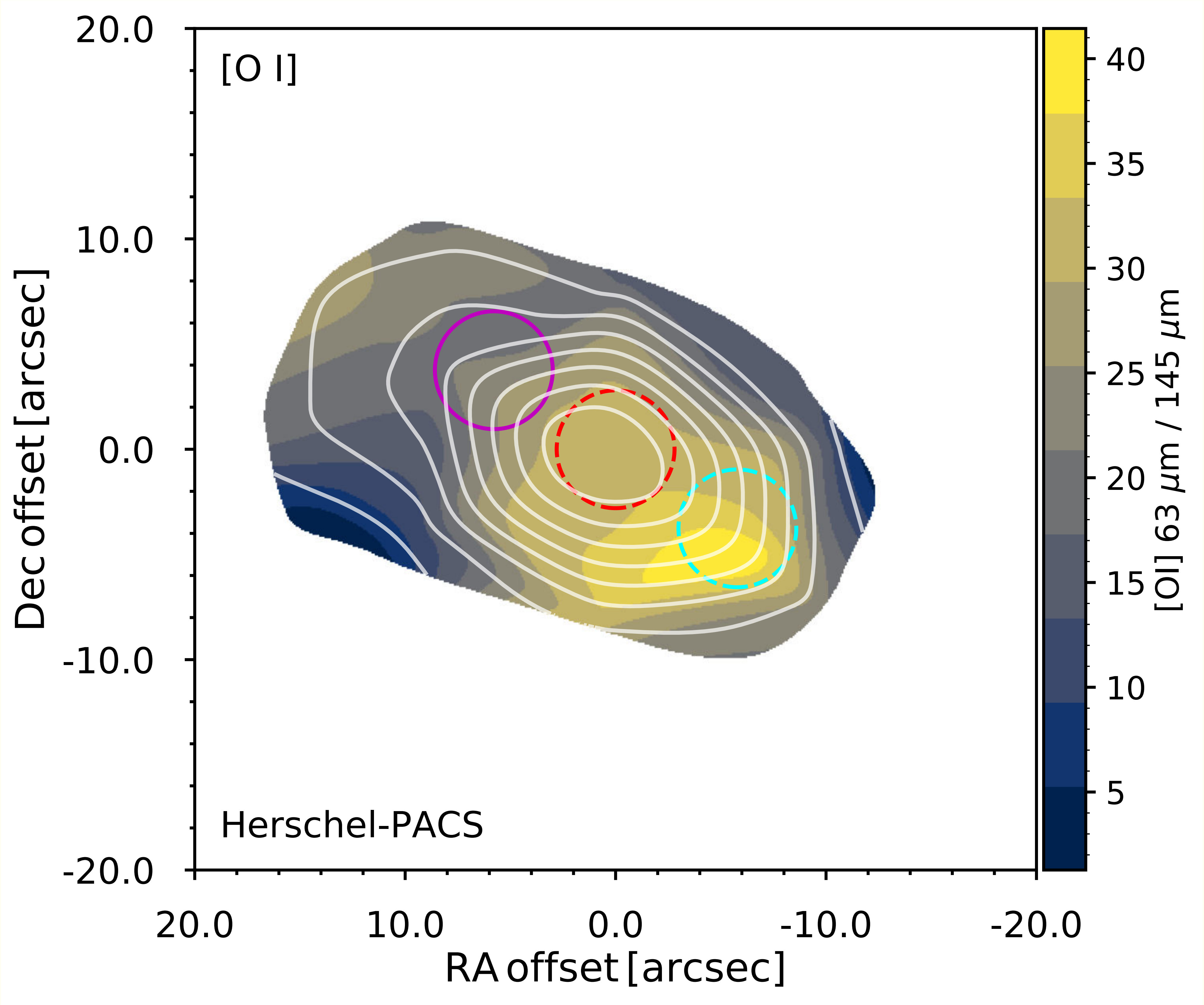


Yang+2022

Lower [OI] 63 μm/145 μm indicates high dust extinction



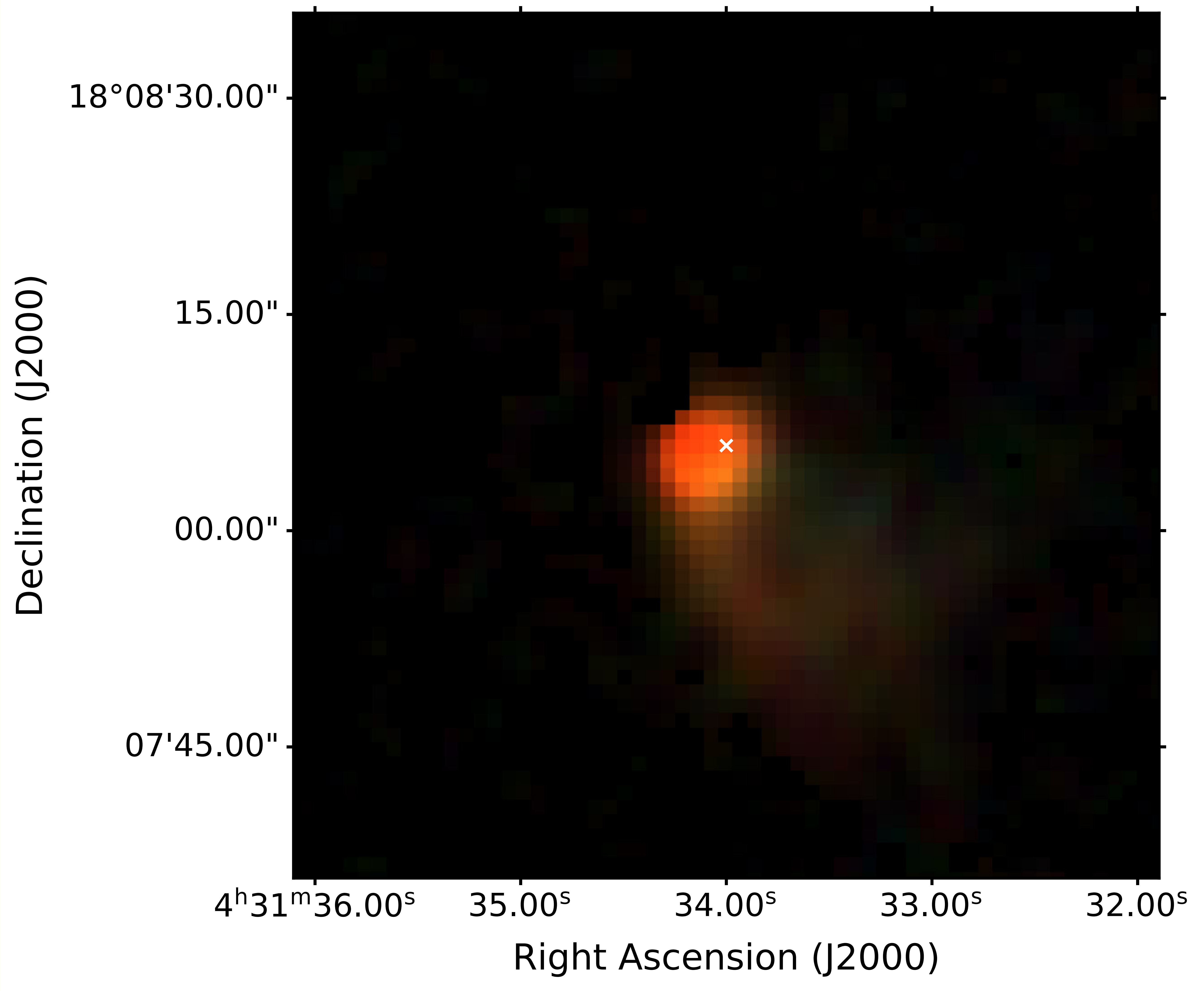


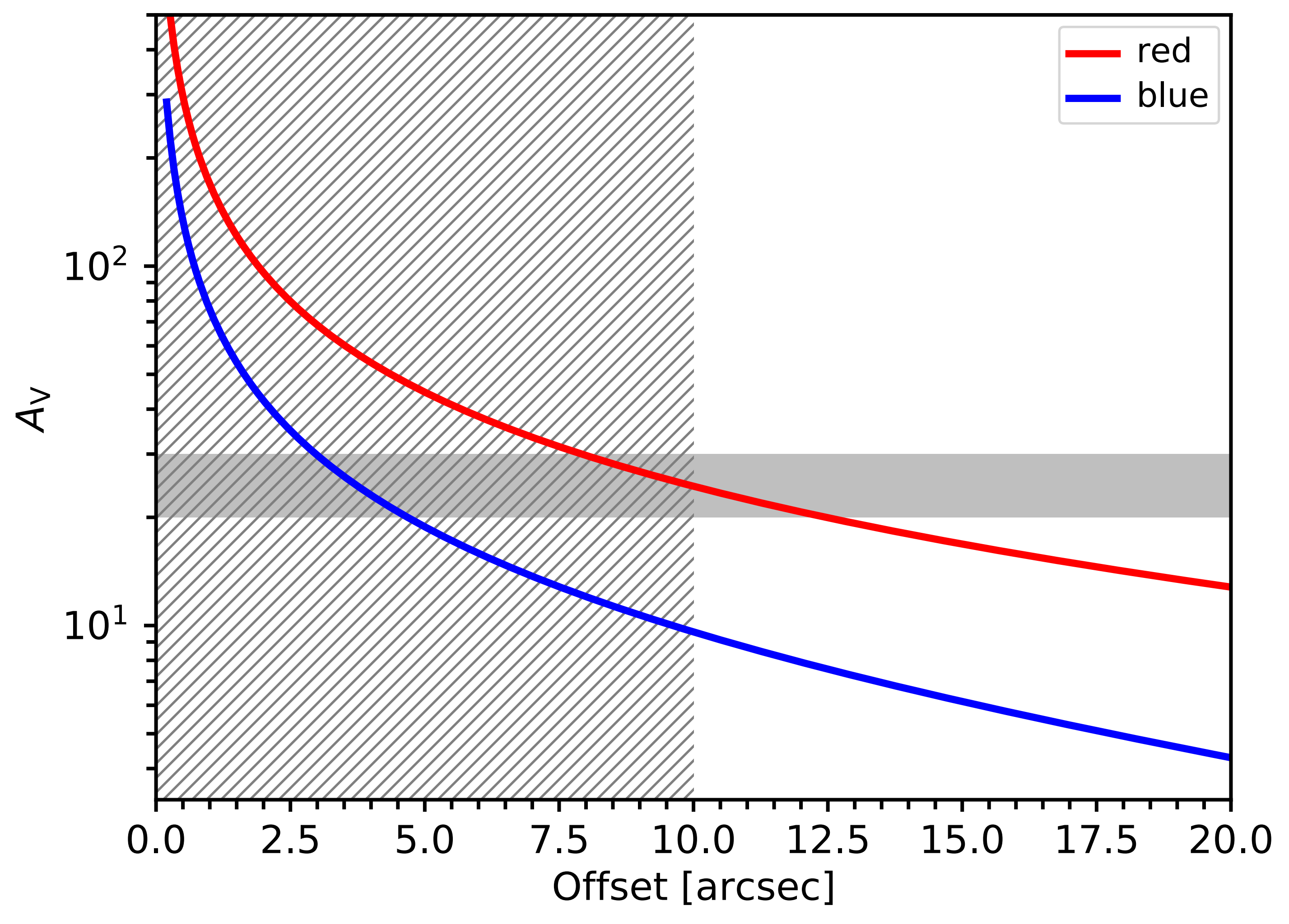


Yang+2022

Envelope appears opaque in NIR toward the red-shifted outflow

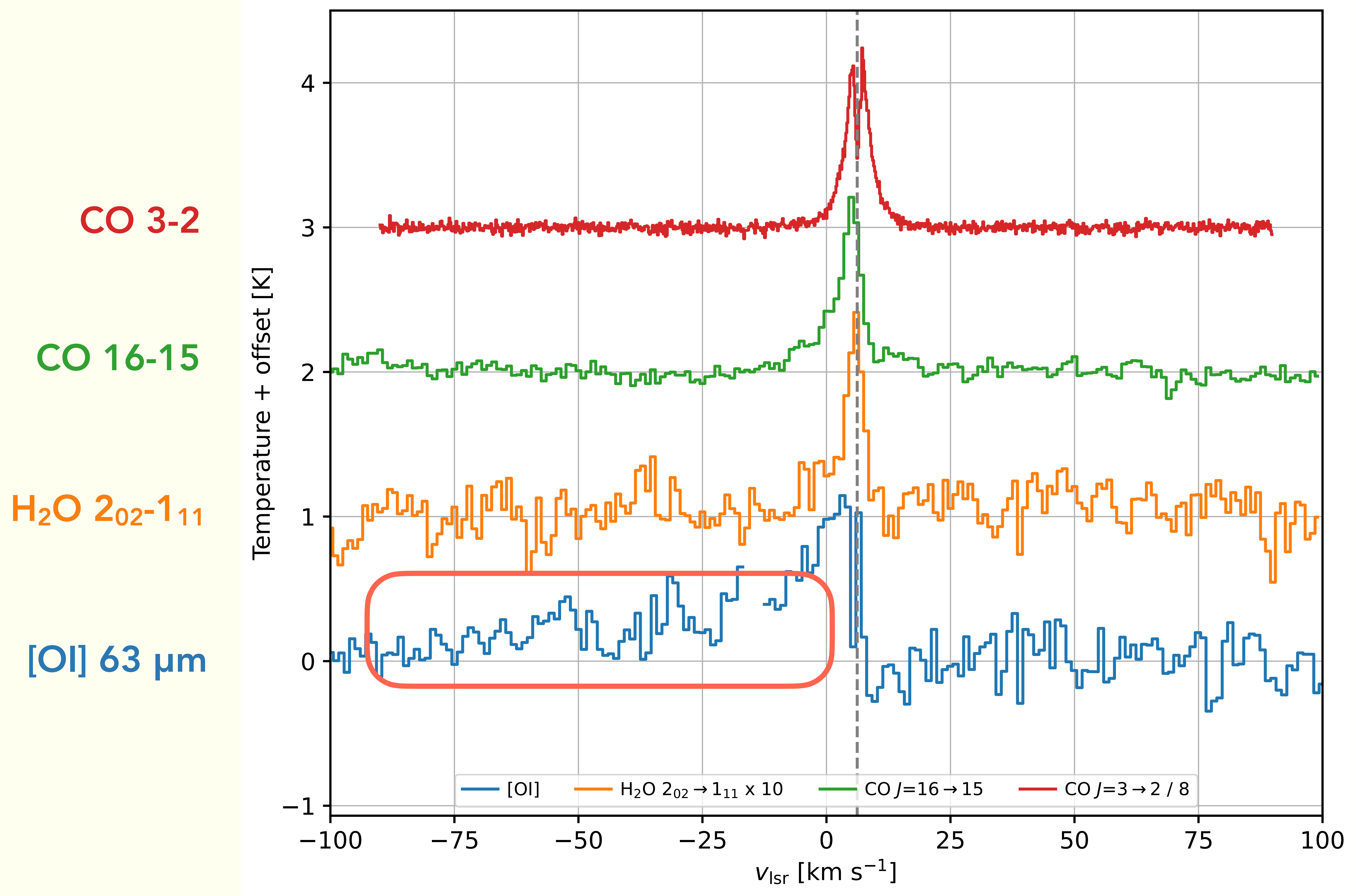
2MASS JHK image





Yang+2022

The origin of [OI] emission



Narrow line -> Envelope

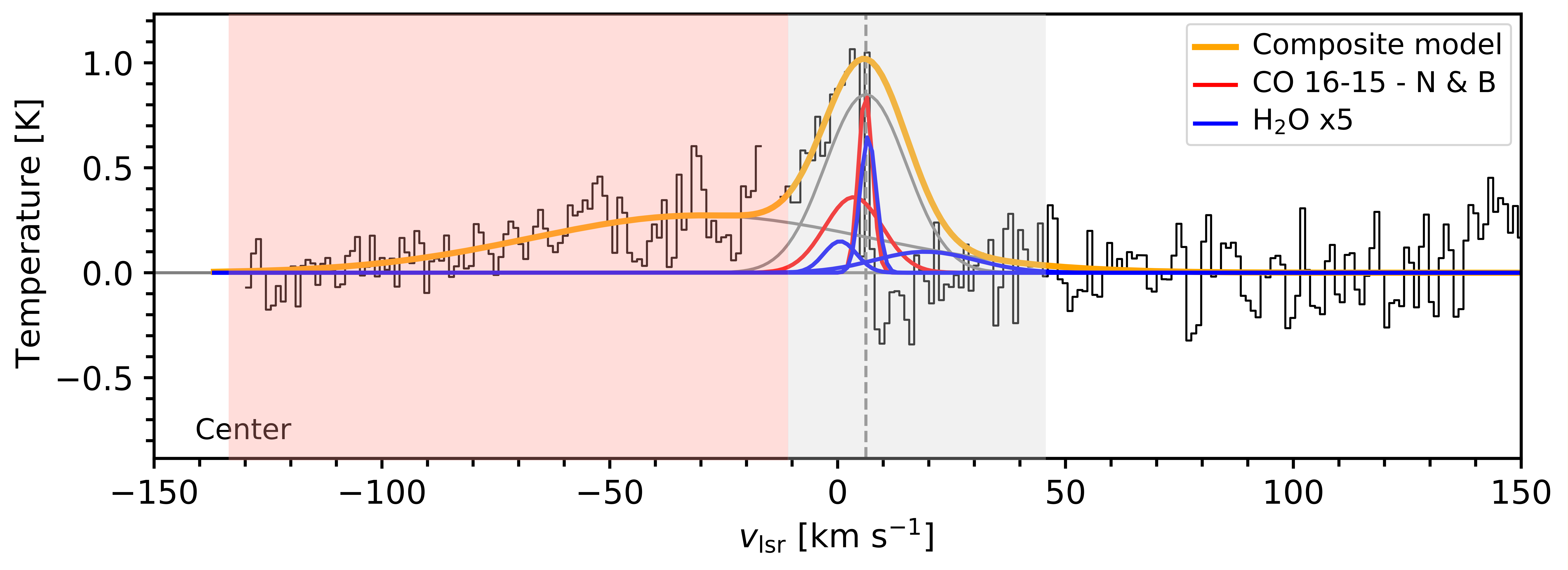
Broad line (>20 km/s) at systemic velocity

- Cavity shocks (Mottram+2014)
- Disk wind (Yvart+2016)
- Turbulent mixing (Liang+2020)

Extremely high-velocity emission at > 50 km/s

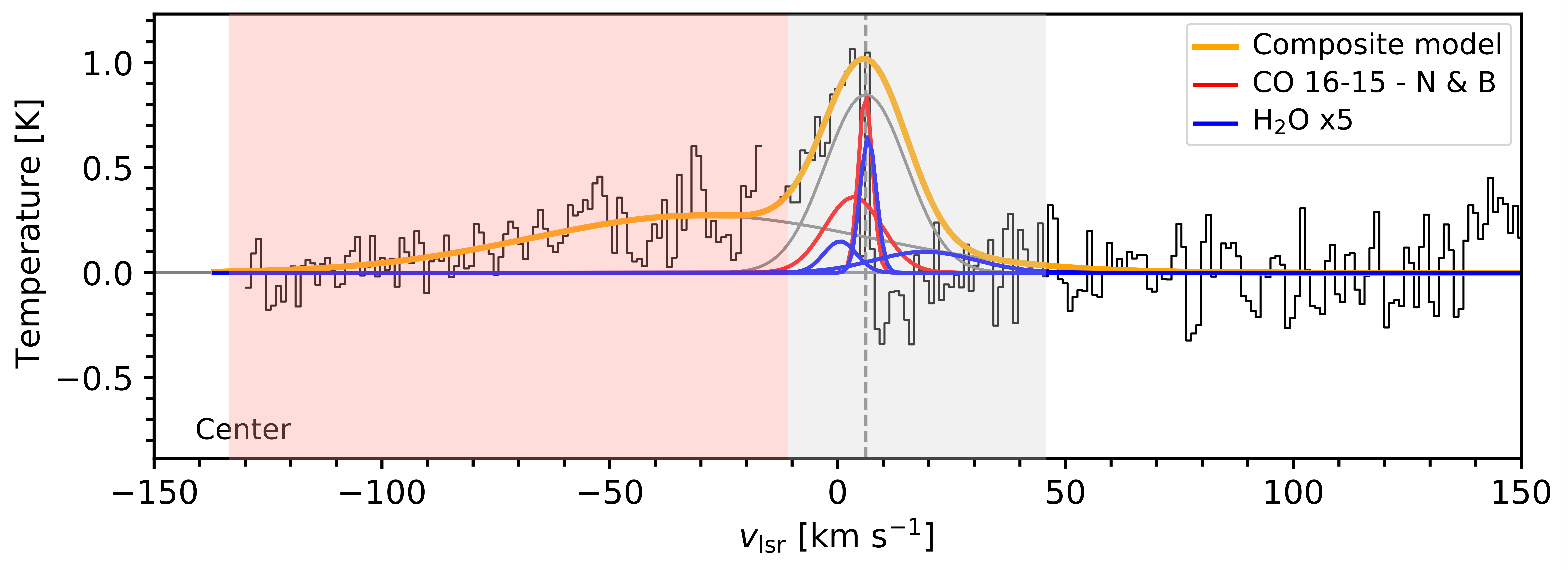
Yang+2022

Origins of the [OI], high-*J* CO, and H_2O emission



Yang+2022

Origins of the [OI], high-J CO, and H_2O emission

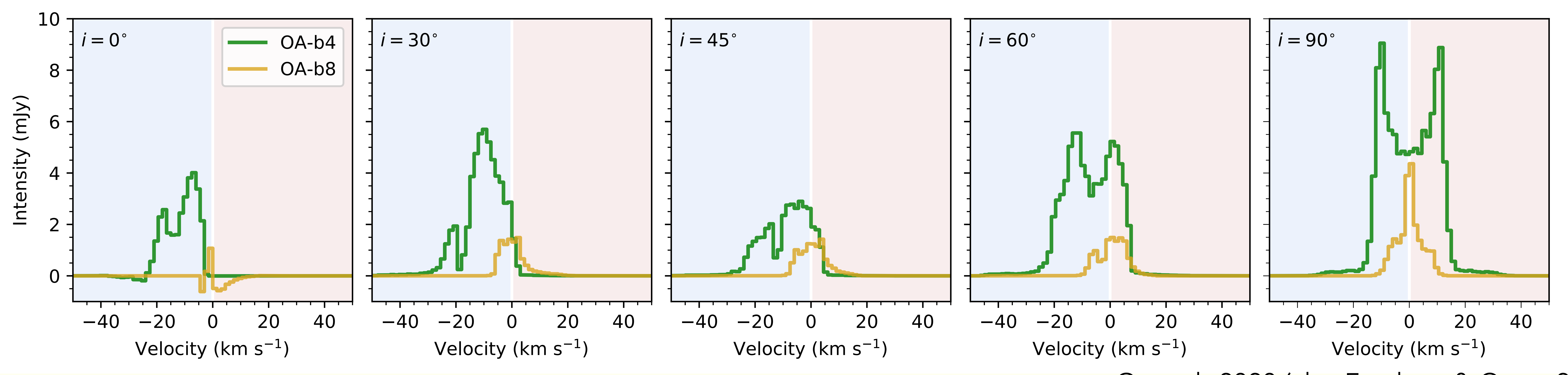


FWHM = 87.5±32.3 km/s
v = -30.0±19.6 km/s

FWHM = 21.0±4.9 km/s
(fixed at systemic velocity)

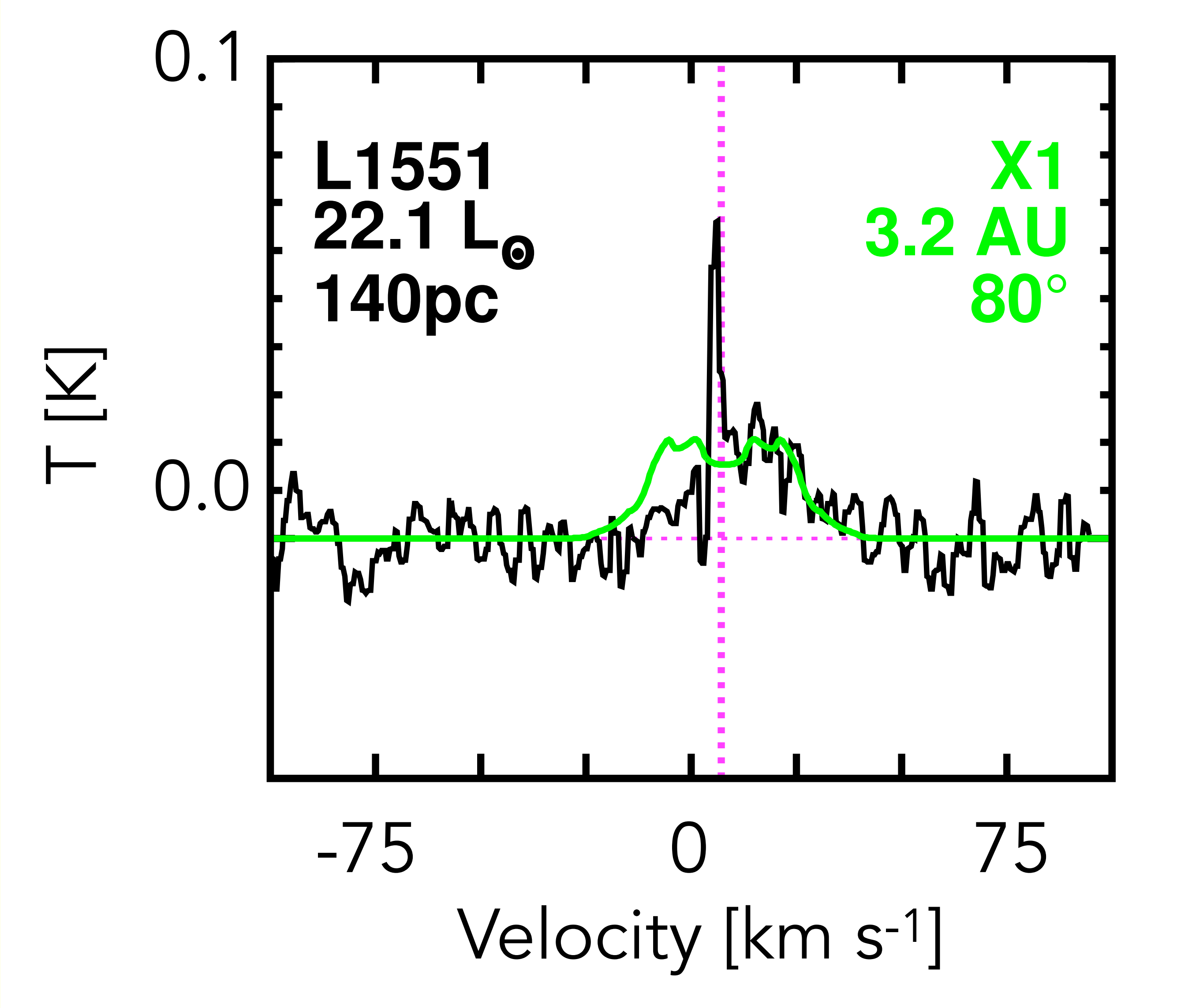
Yang+2022

The ~20 km s^{-1} component: disk wind or turbulent mixing

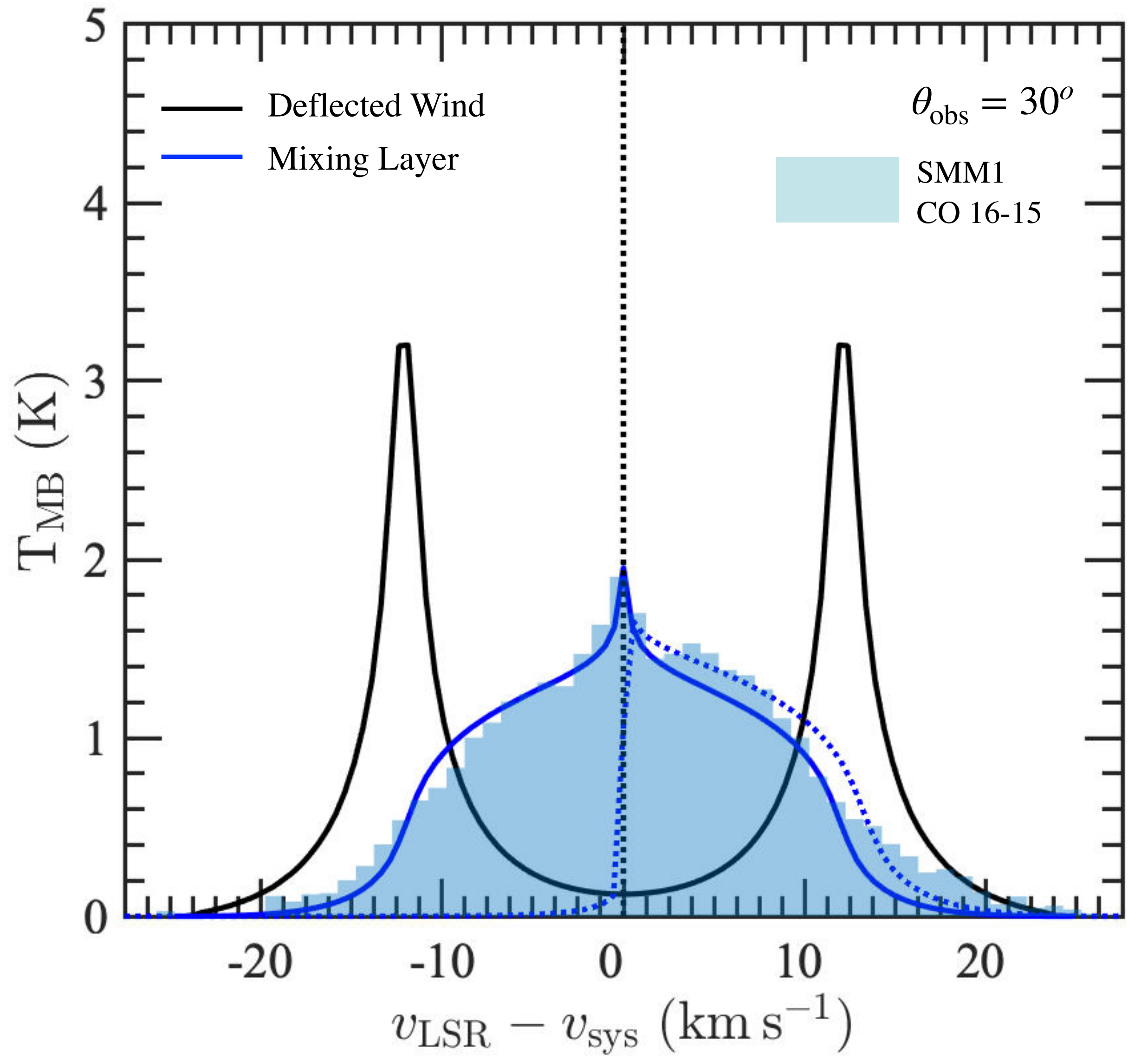


Gressel+2020 (also Ercolano & Owen 2016)

Disk wind



Yvart+2016

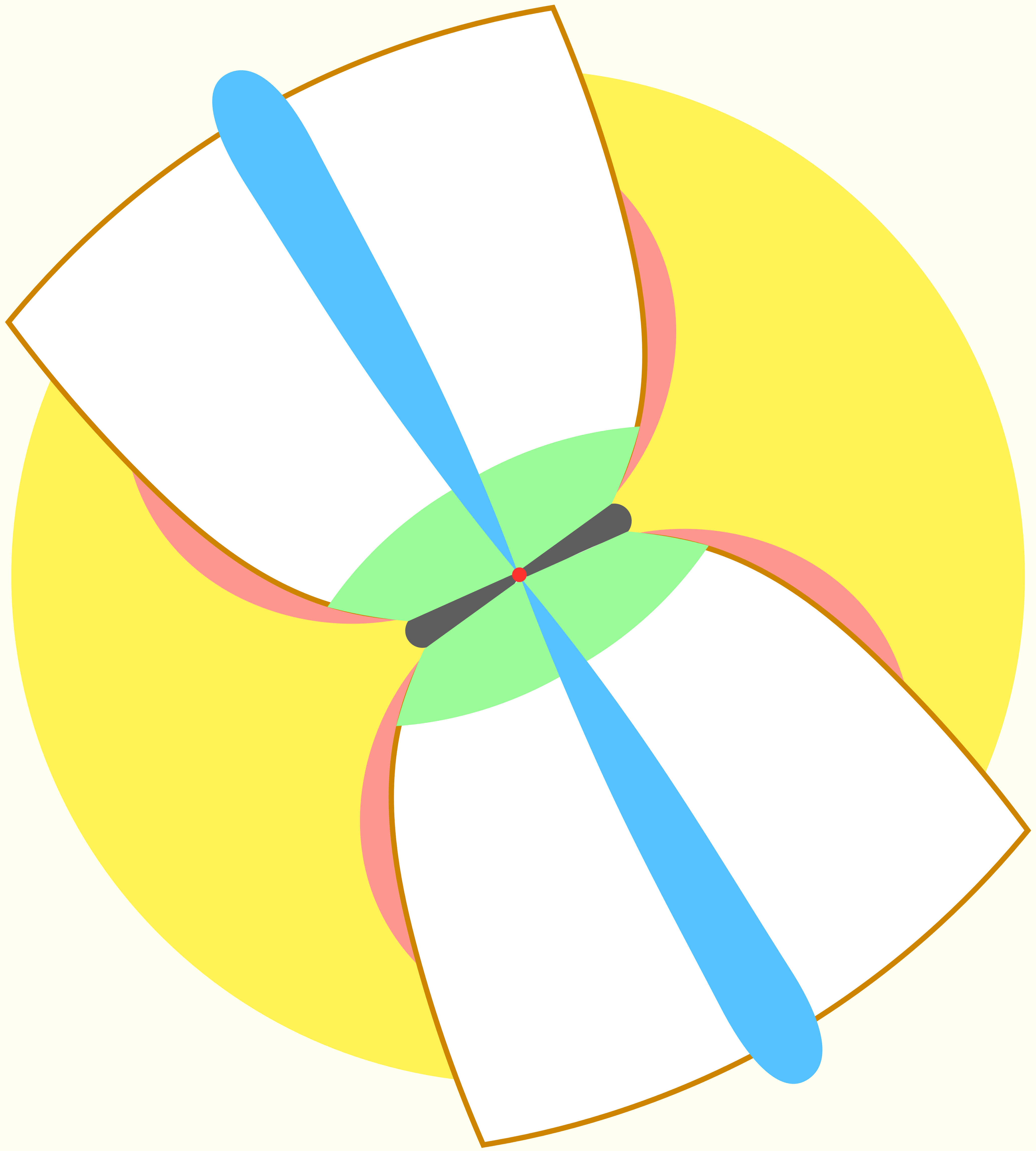


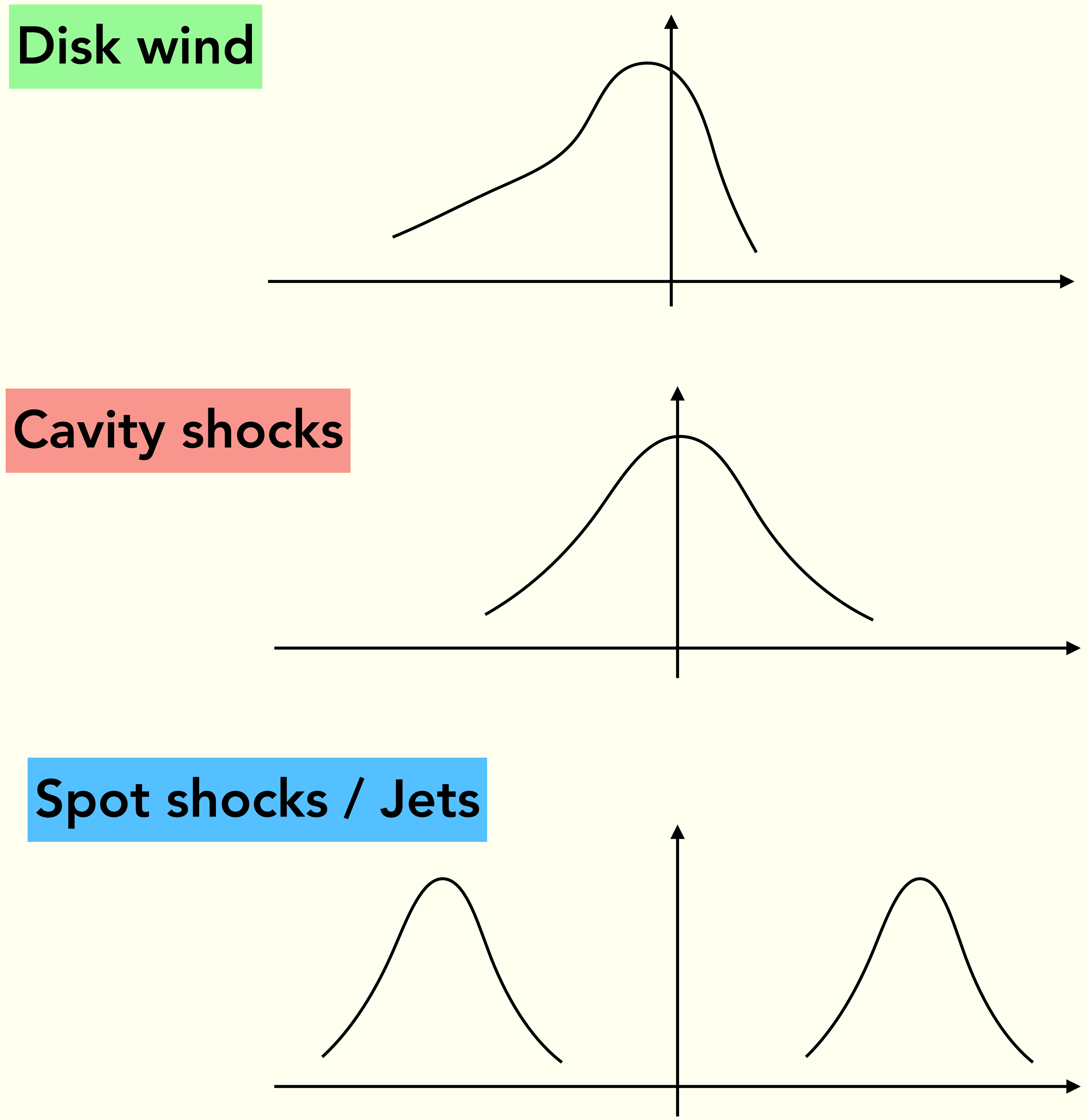
Turbulent mixing layer

None of them explain the extremely broad component

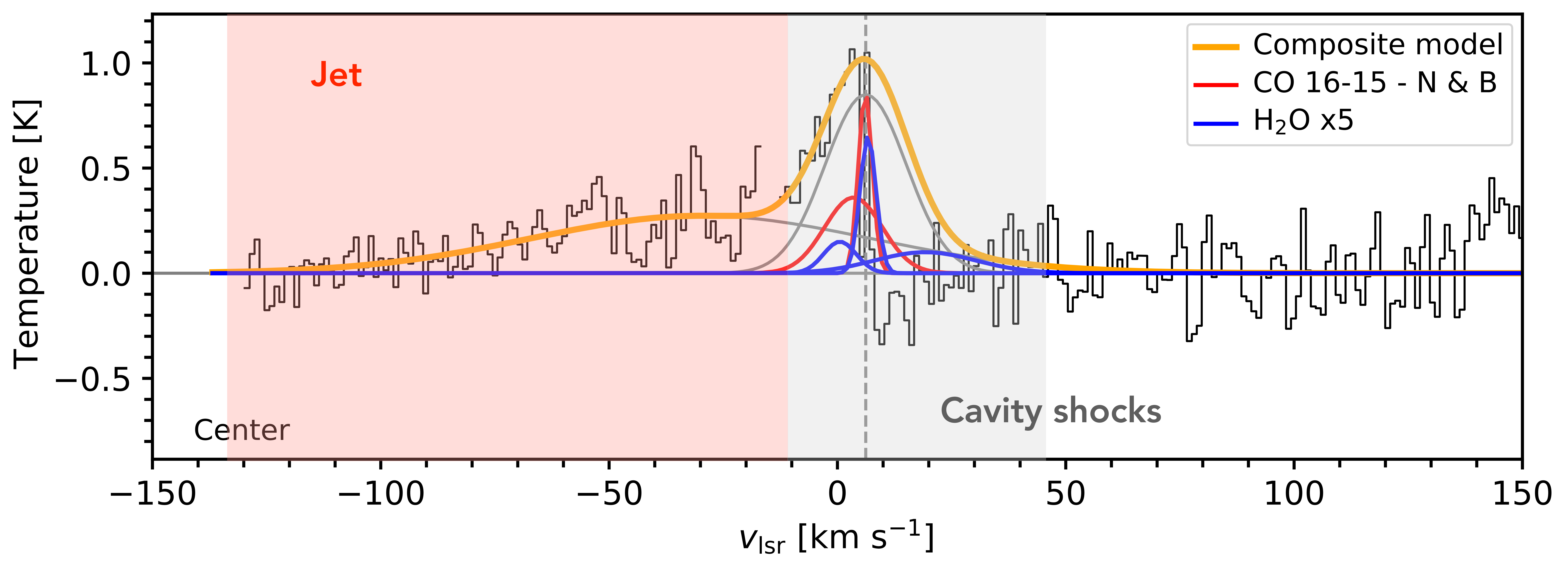
Liang+2020

Only spot shocks or jet can produce the extremely broad component





The jet is uniquely traced by the [OI] 63 μm line

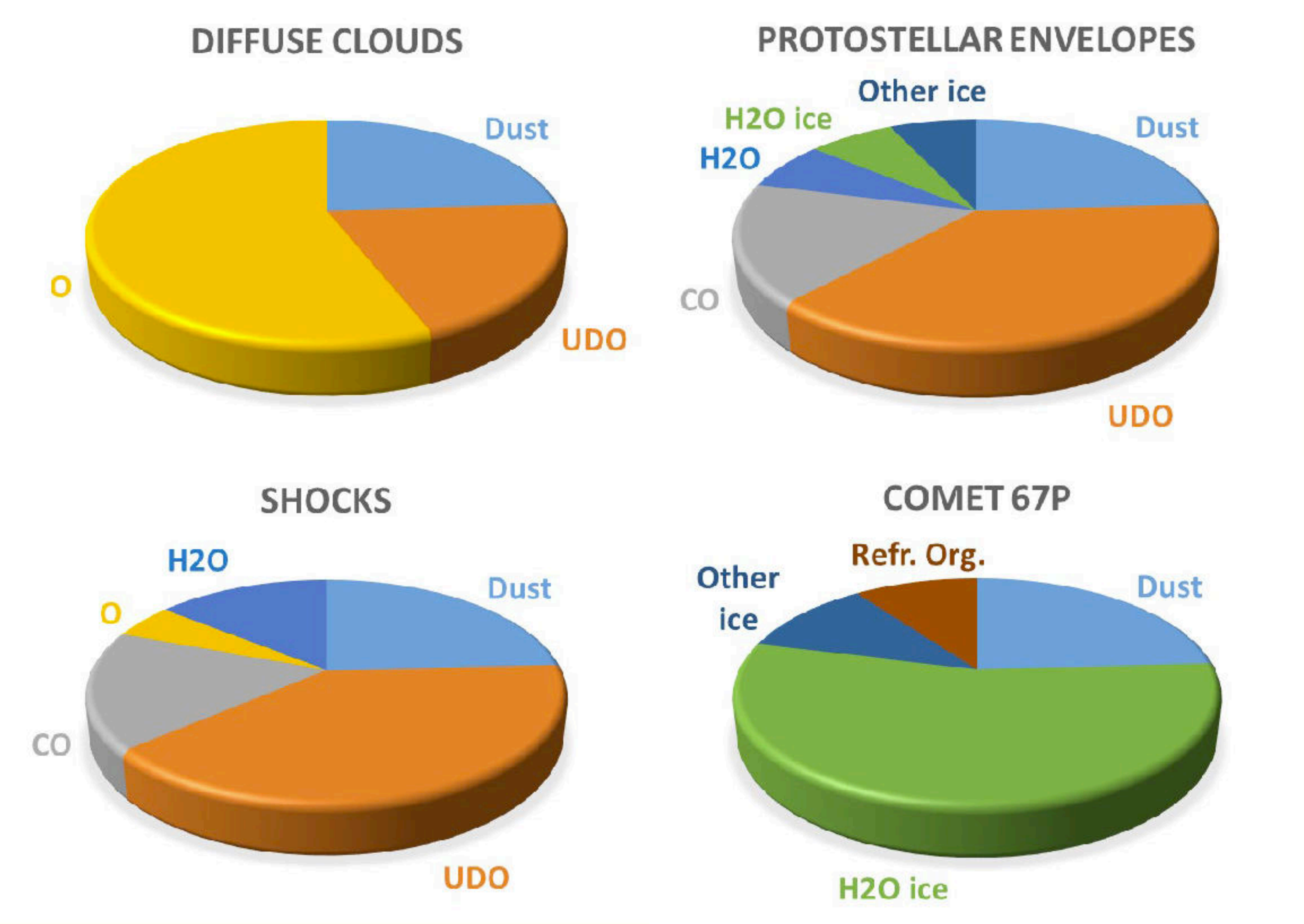


FWHM = 87.5±32.3 km/s
v = -30.0±19.6 km/s

FWHM = 21.0±4.9 km/s
(fixed at systemic velocity)

Yang+2022

Oxygen abundance in star formation

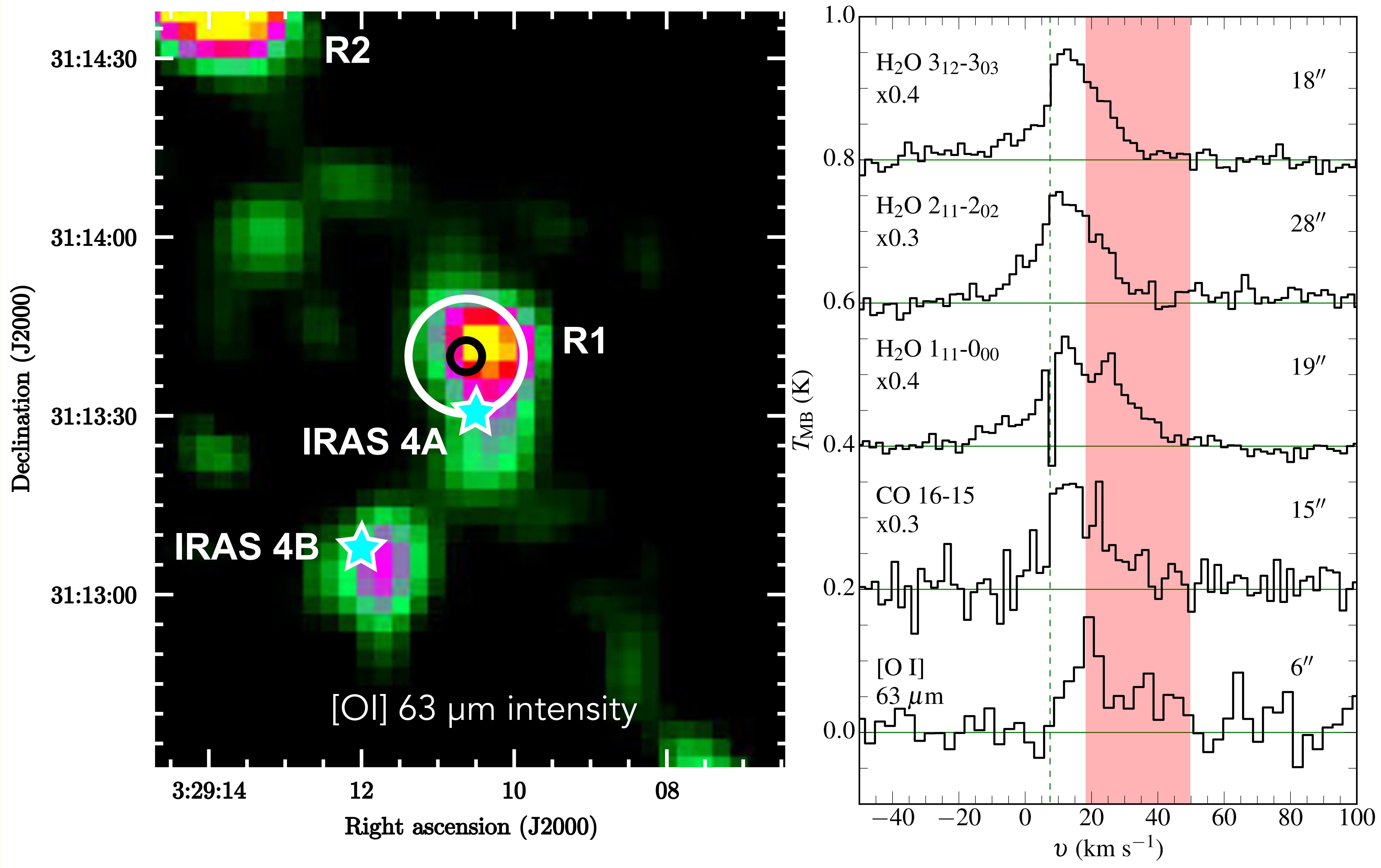


van Dishoeck+2021

Oxygen abundance in a shock knot of NGC 1333 IRAS 4A

Atomic oxygen accounts for ~15% of total oxygen

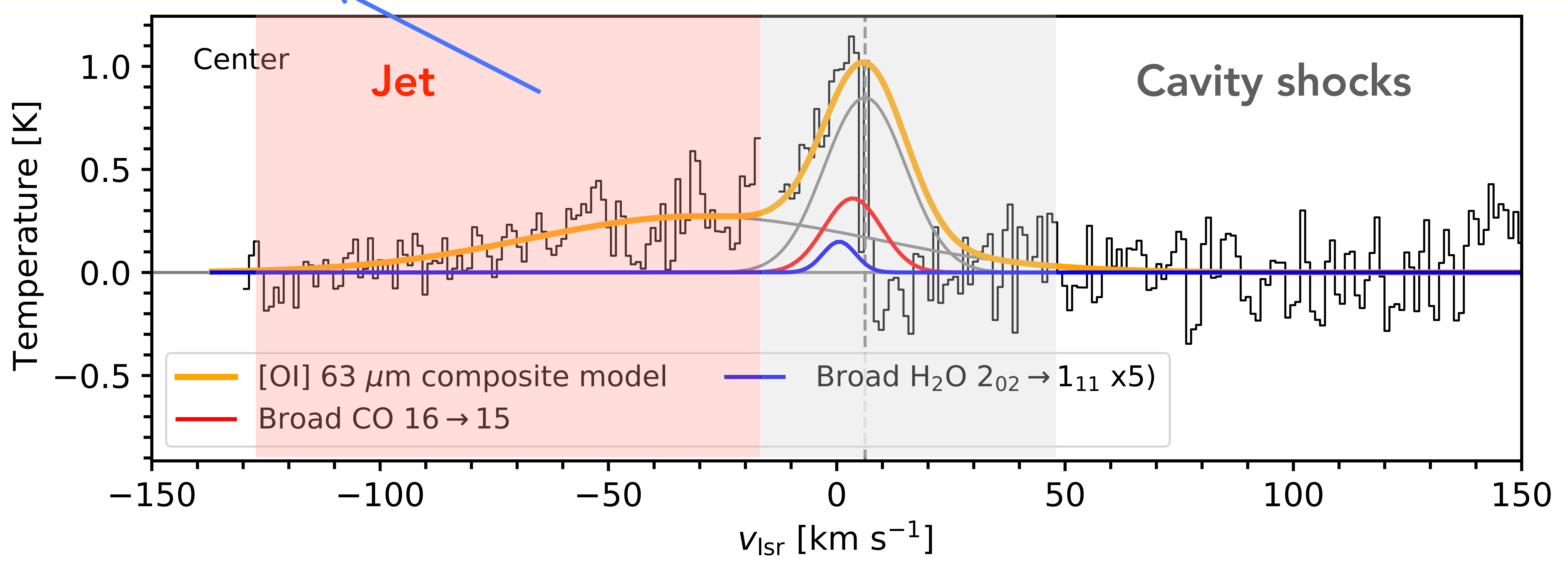
High-*J* CO, H_2O, and [OI] have a similar shape

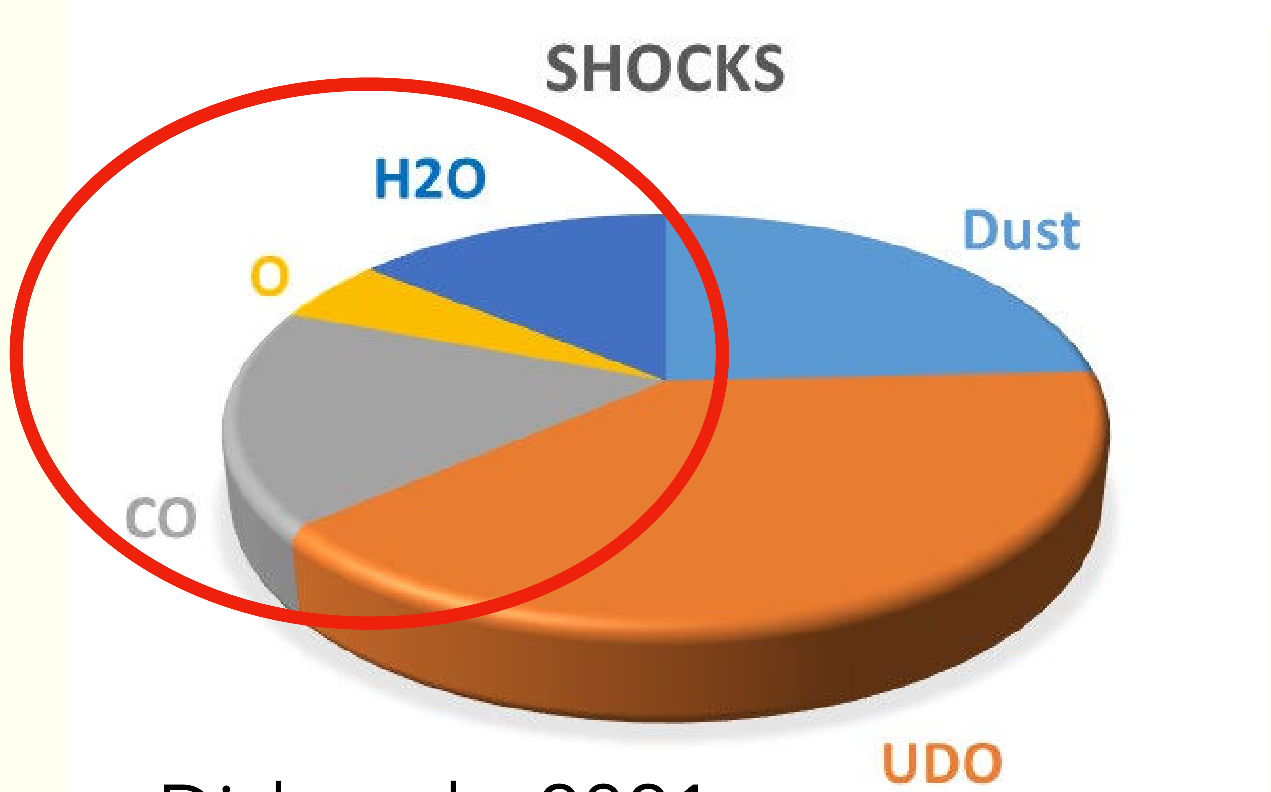


Kristensen+2017a

Atomic O dominates the shocks and the jet

Only seen [OI] -> fully atomic





van Dishoeck+2021

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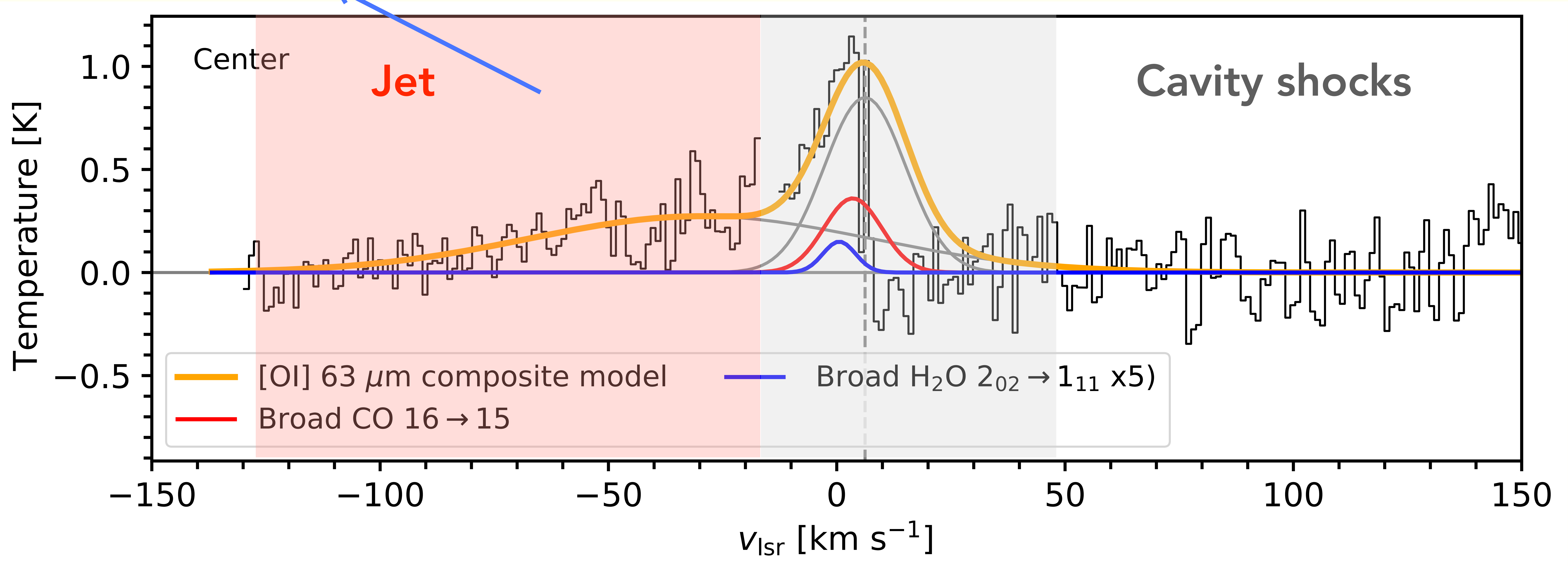
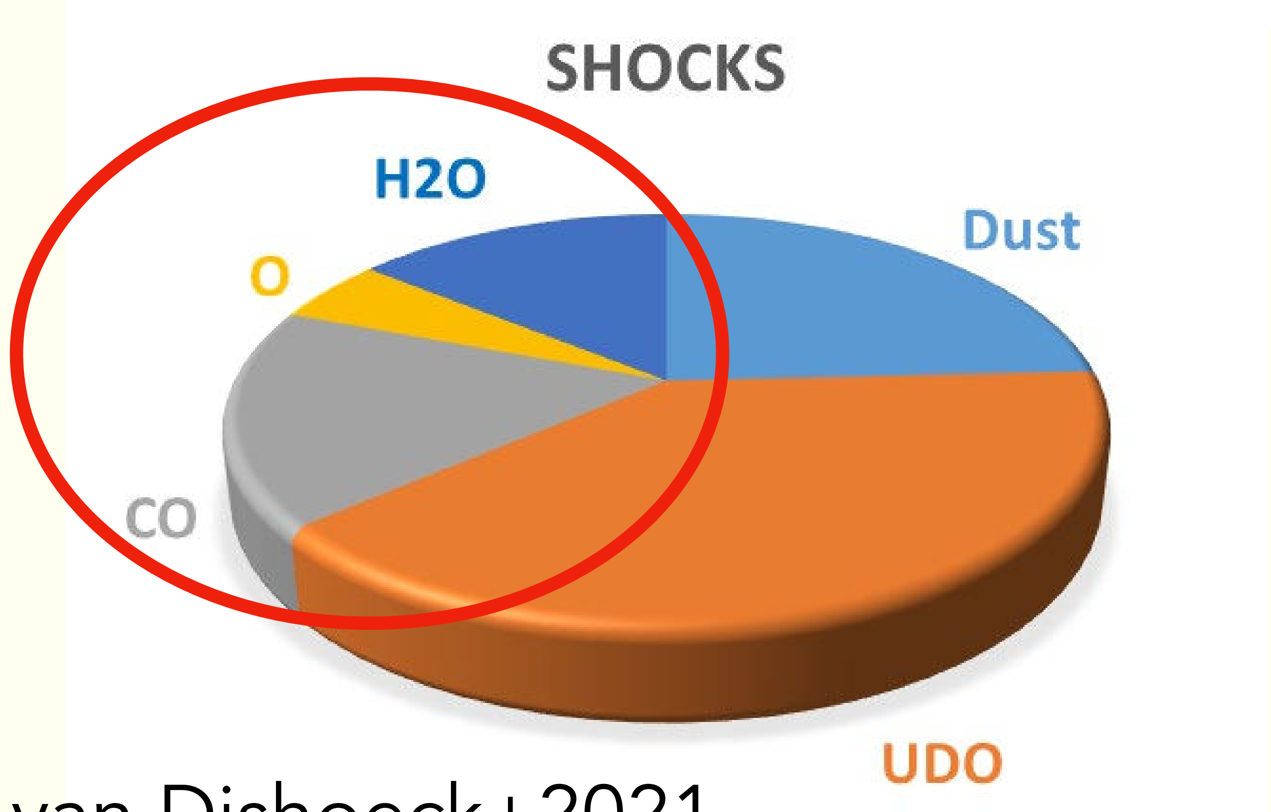




van Dishoeck+2021

X(O) / X(O_{total}) = 69±24%

X(CO) / X(O_{total}) = 31±3%

X(H_2O) / X(O_{total}) = 0.21±0.10%

If we take an elemental O abundance of 575 ppm, O(dust) =140 ppm, and UDO = 200 ppm,

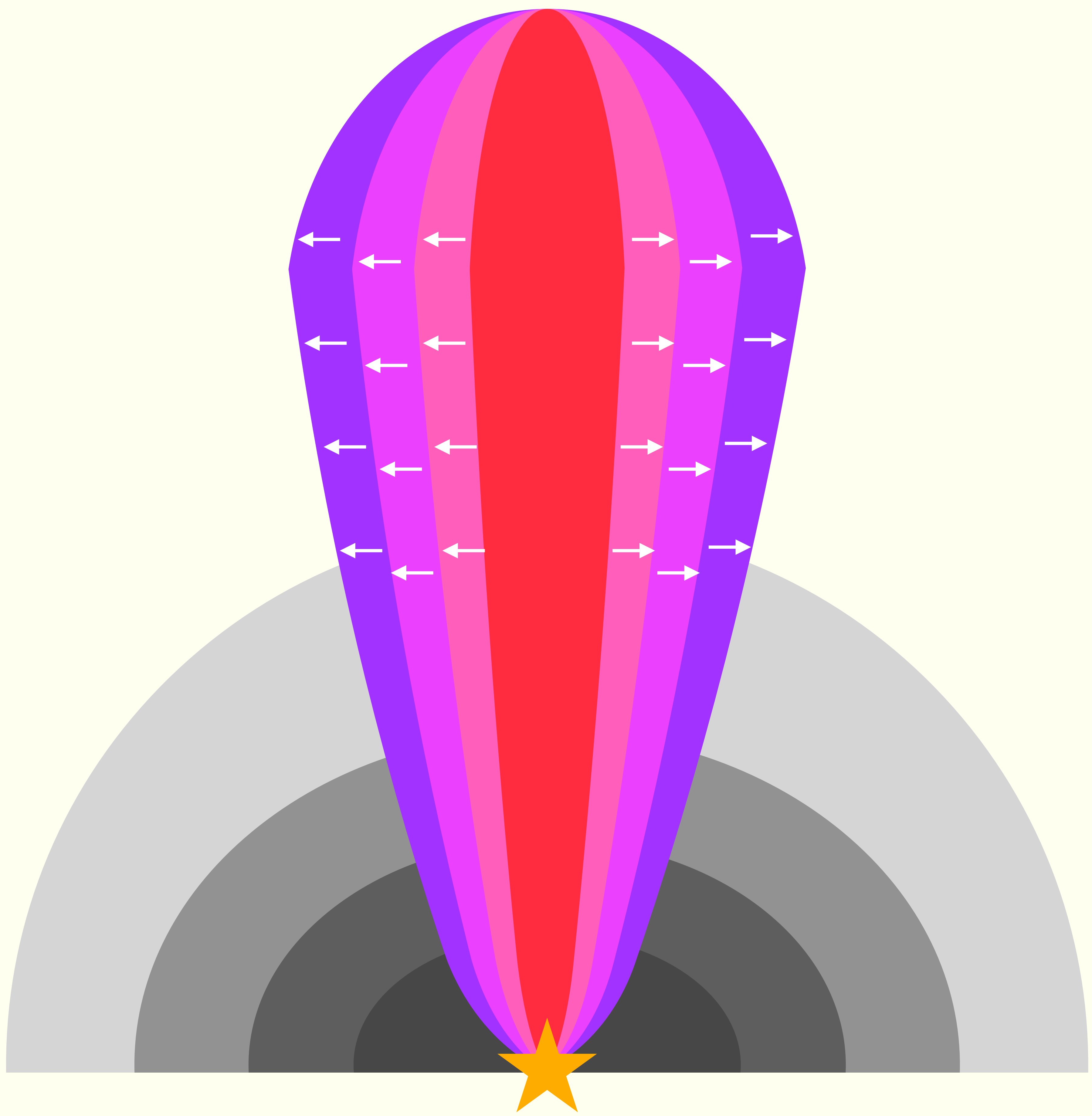
X(O) = 140±50 ppm

X(CO) = 62±6 ppm

X(H_2O) = 0.42±0.20 ppm

Momentum conservation tested by multiple outflow tracers

Momentum of the outflowing gas, **P**, would be conserved in various tracers



$\mathbf{P}_{wind} = \mathbf{P}_{[OI]} = \mathbf{P}_{CO}$ $\mathbf{P} = Mv = M_{CO}\, v_{CO}$

assume 300 km/s from [Fe II] (Pyo+2009)

$\dot{M}_w = \mathbf{P}_{CO}/(t_{CO}\, v_w) = F_{CO}/v_w$

correct for inclination of 30° (Chou+2014)

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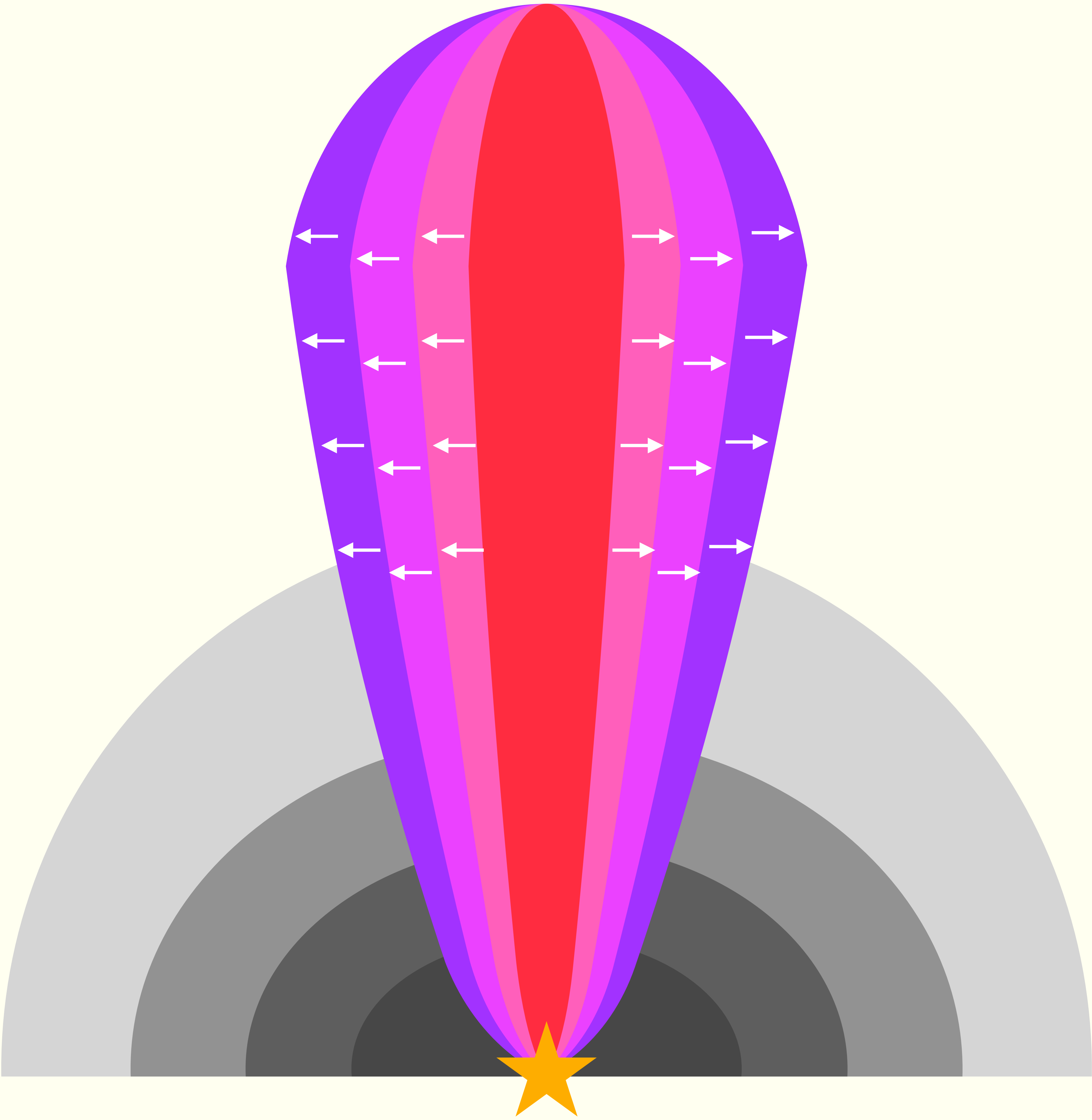

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How does the intrinsic mass loss rate vary over time?

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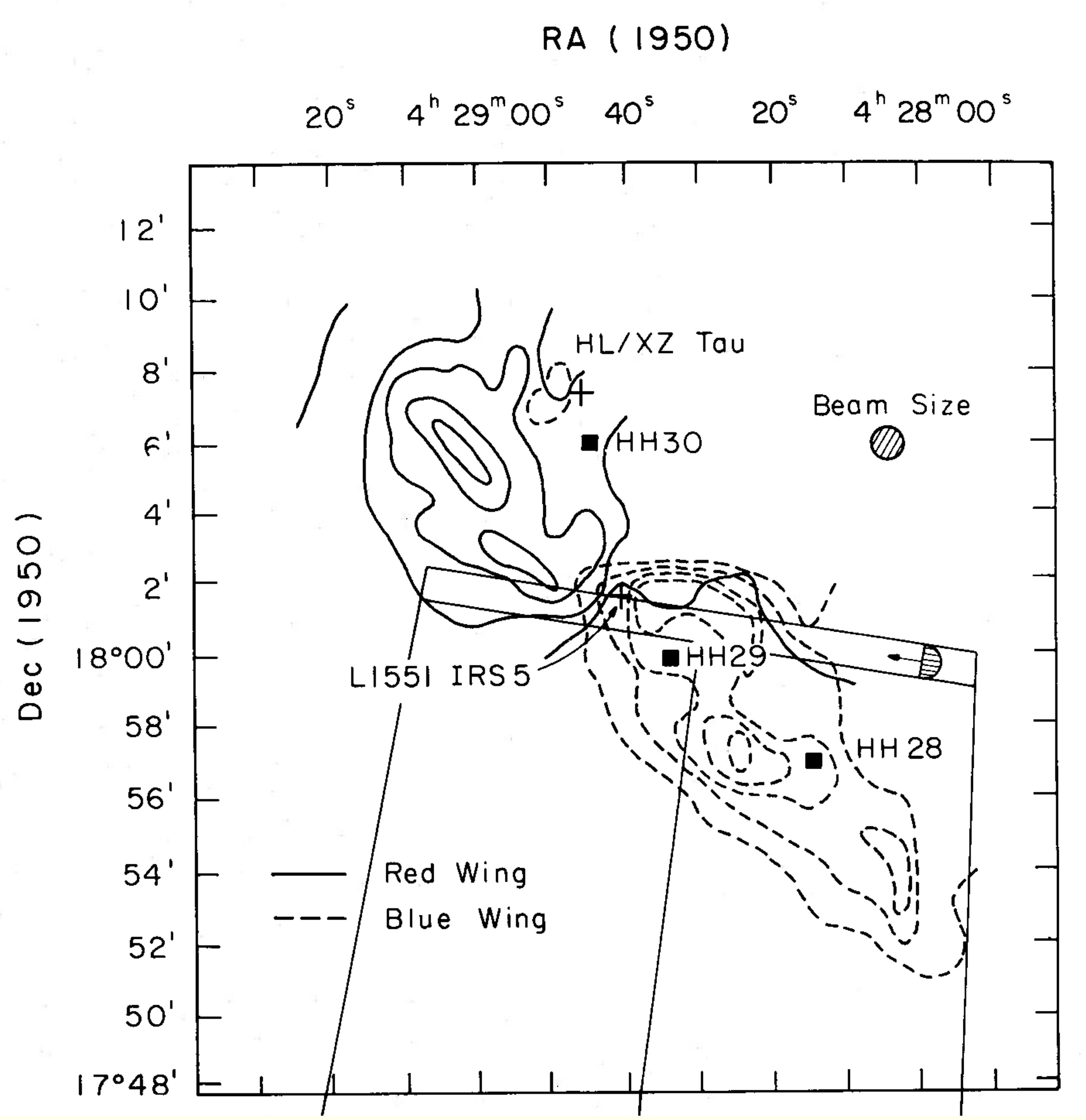
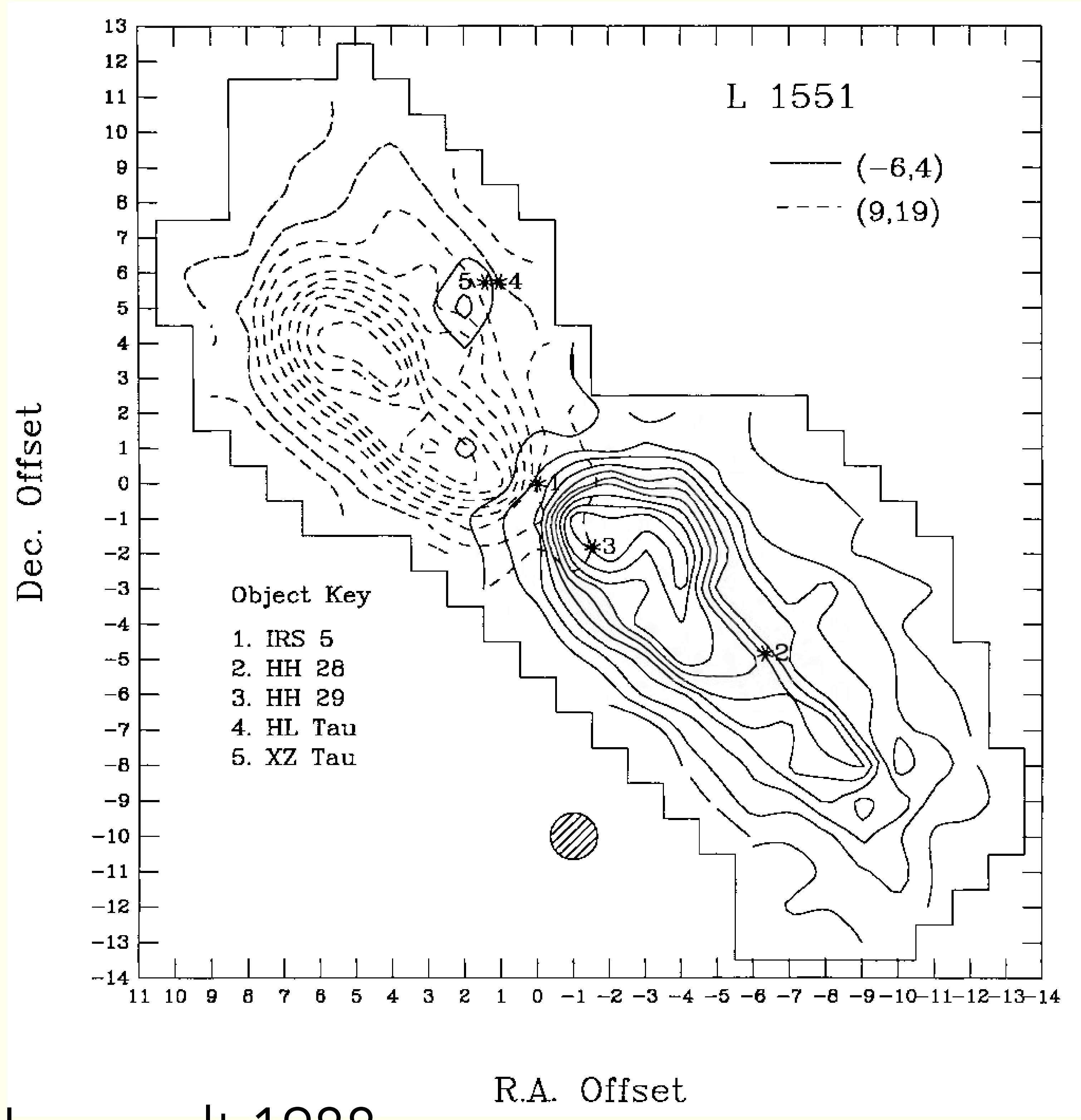
CO 1-0



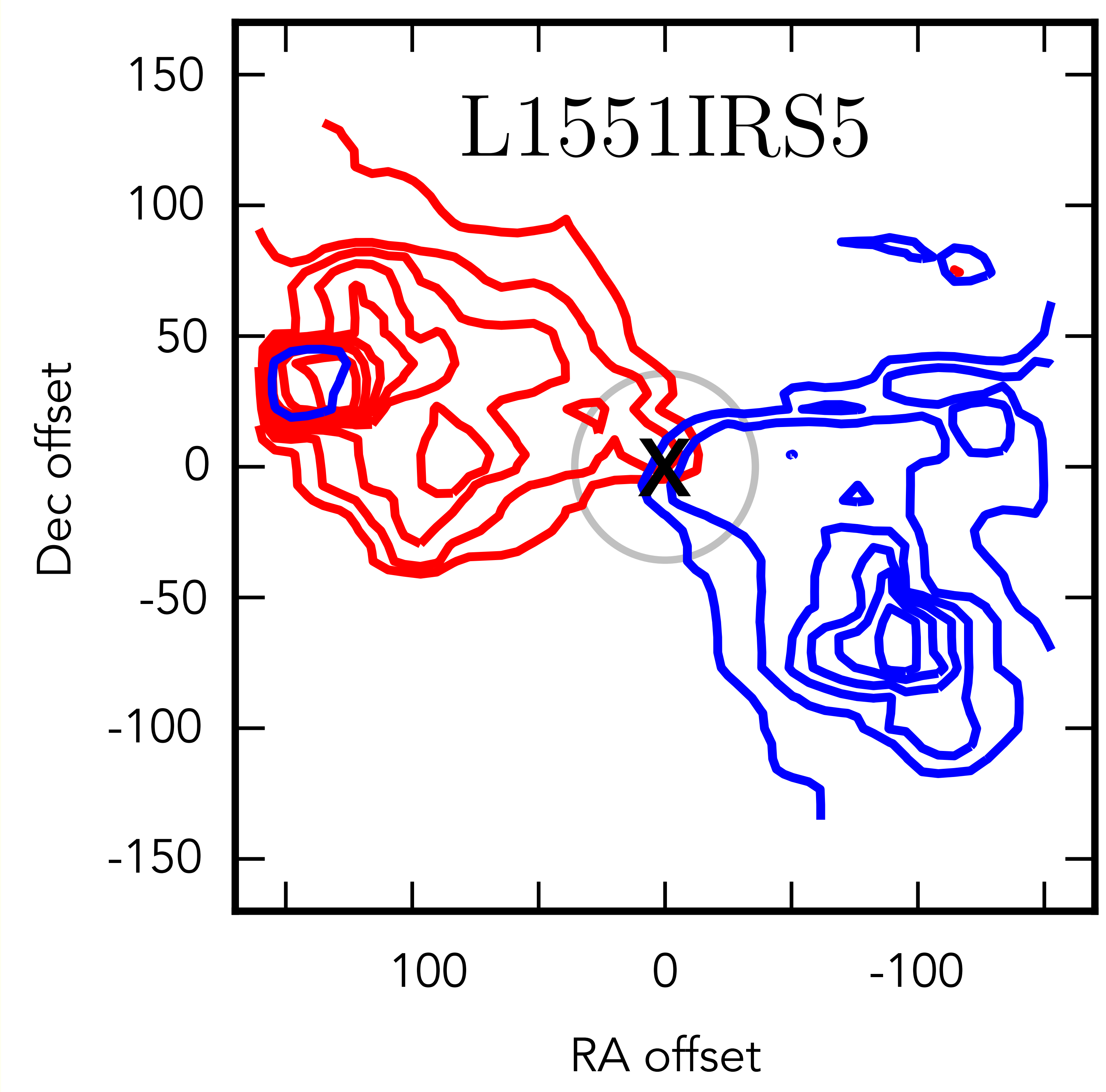
Snell & Schloerb 1985

CO 2-1



Levreault 1988

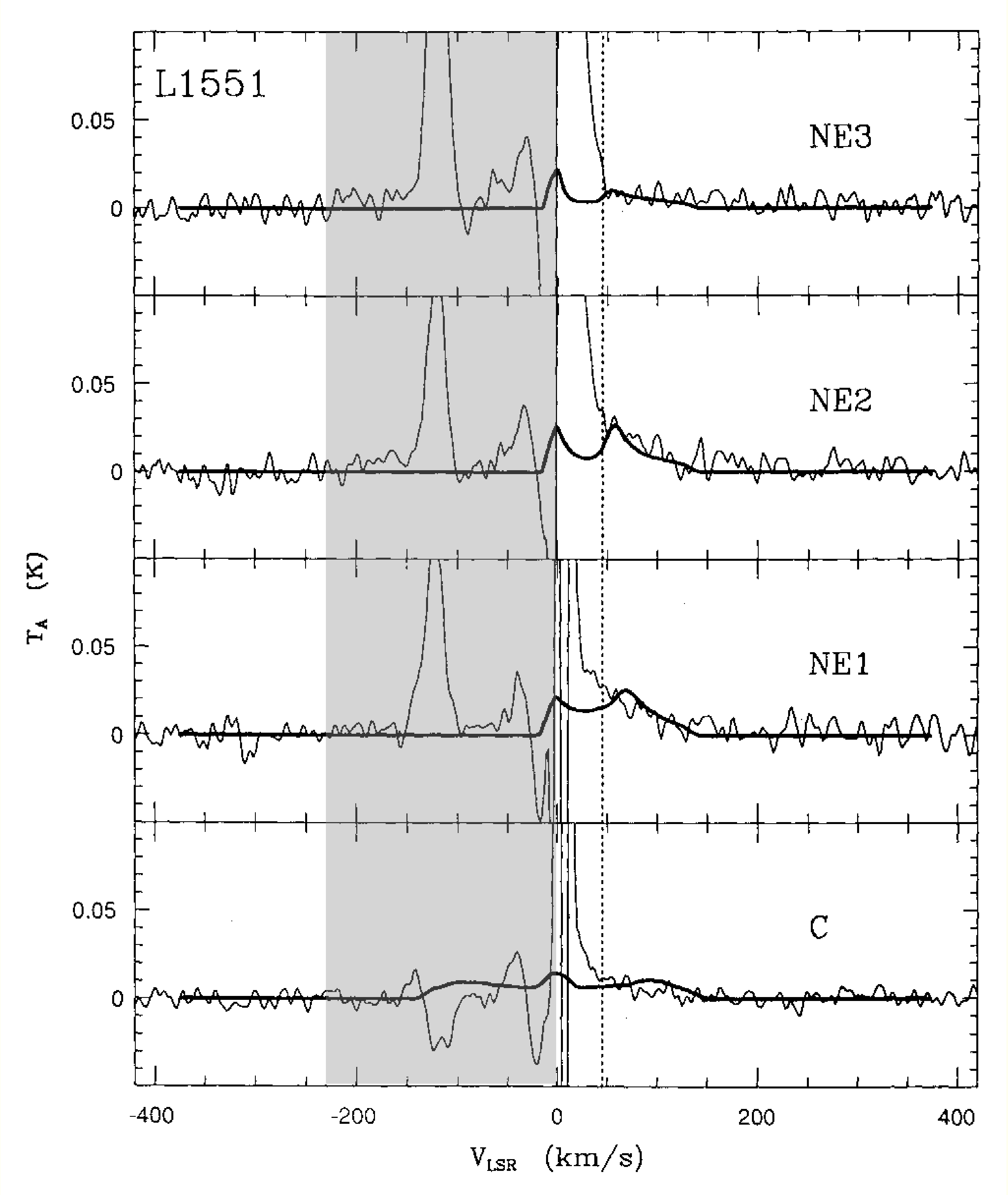
CO 3-2

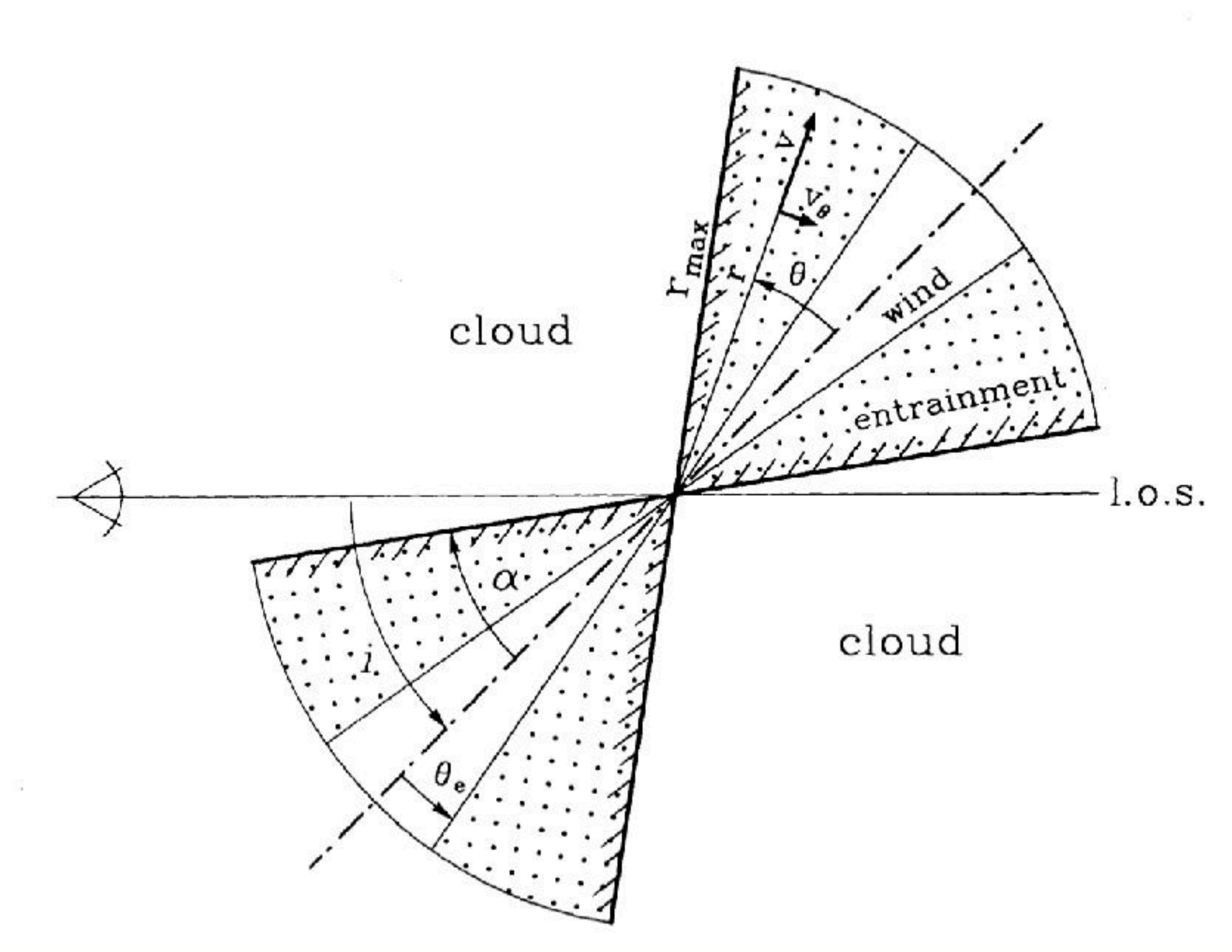


Yildiz+2015

How does the intrinsic mass loss rate vary over time?

HI wind (Arceibo)





Giovanardi+1992

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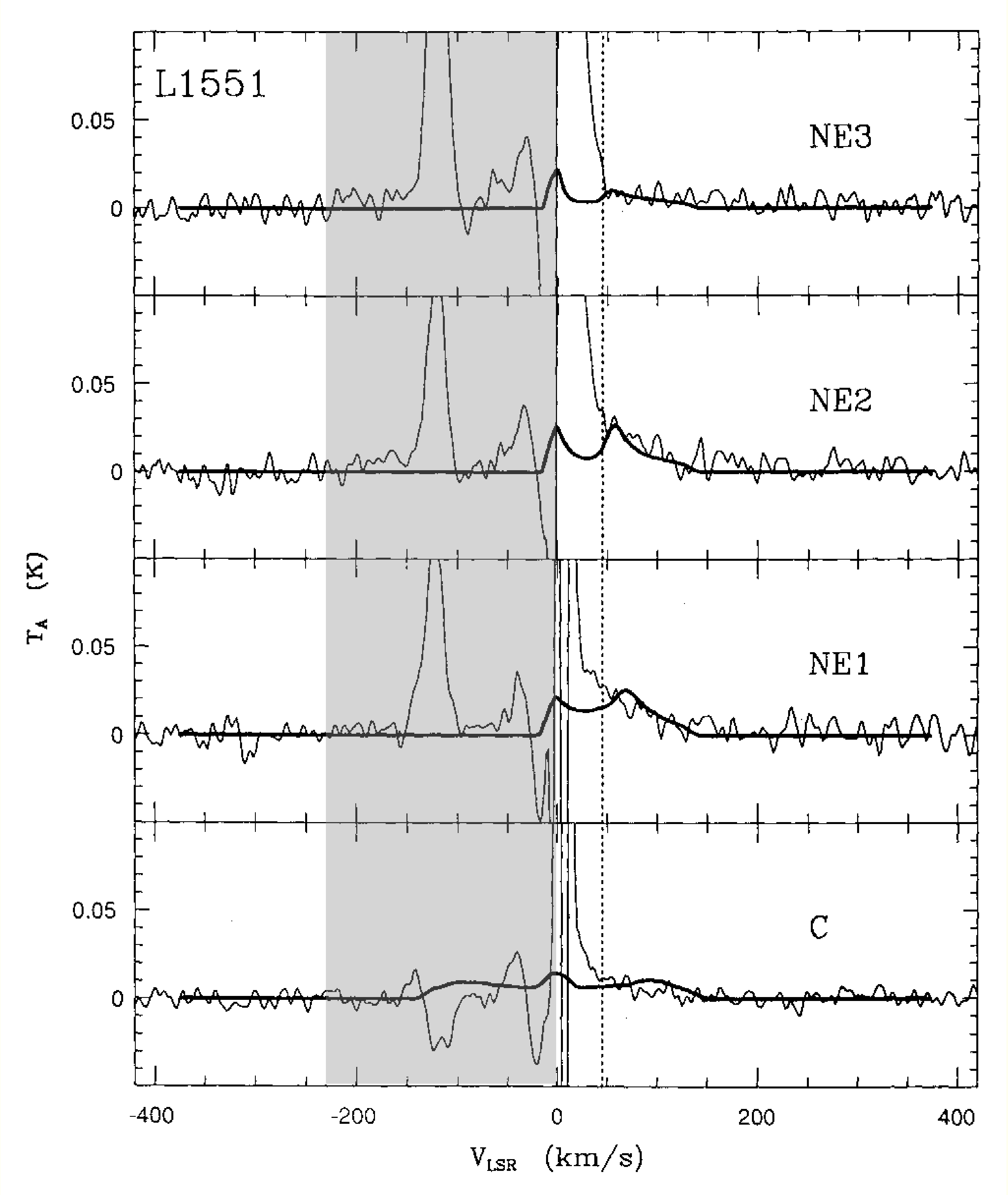
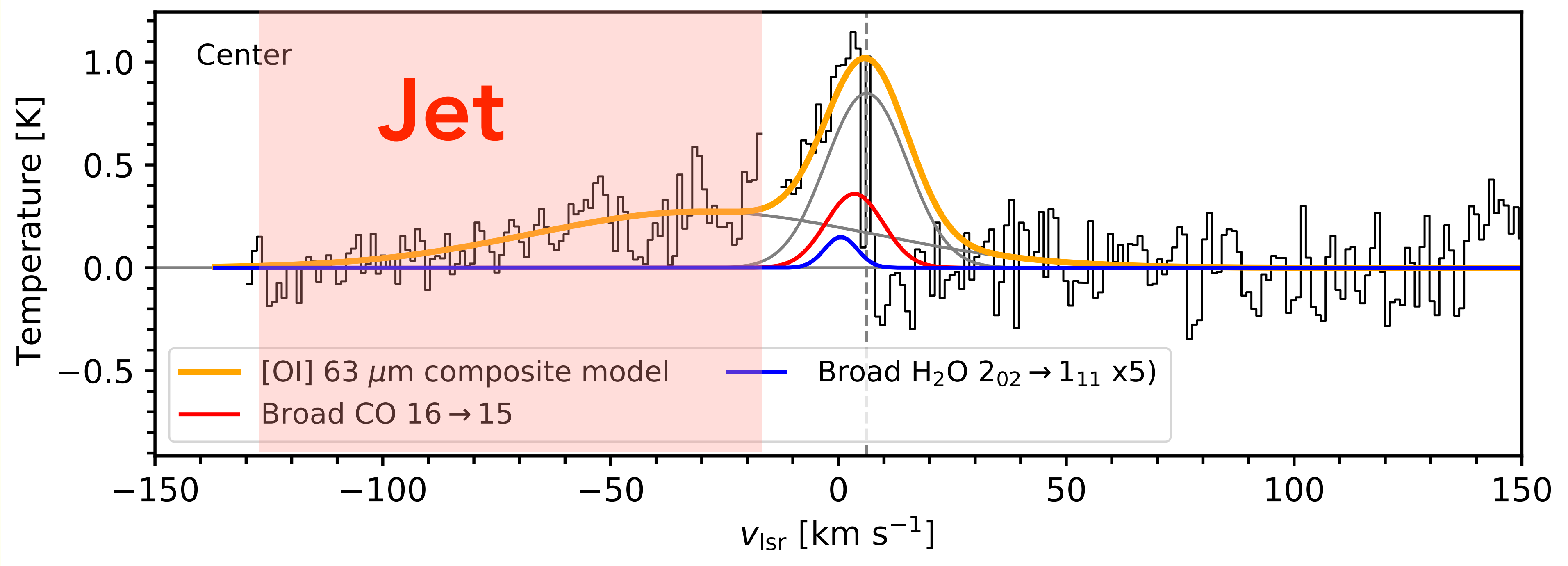


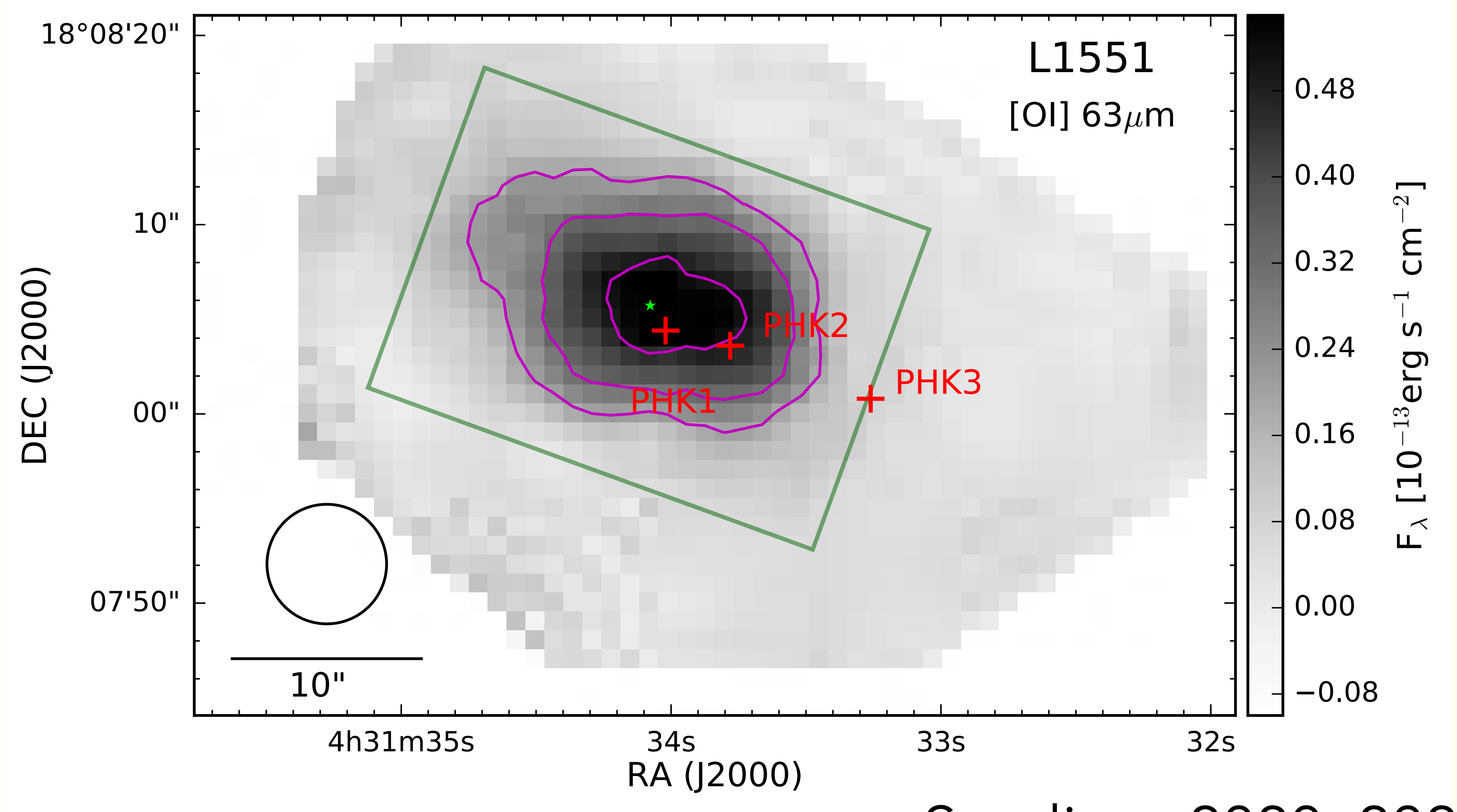
Giovanardi+1992

[OI] wind - GREAT



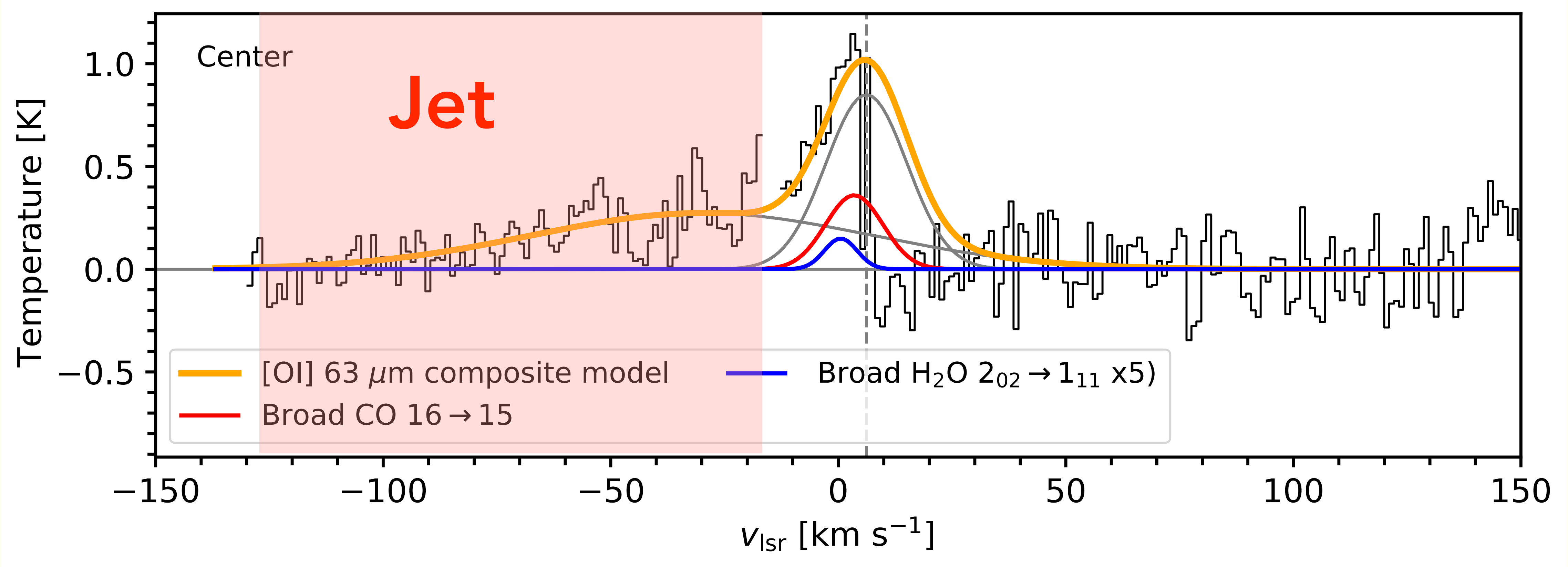
Yang+2022

[OI] wind - FIFI-LS



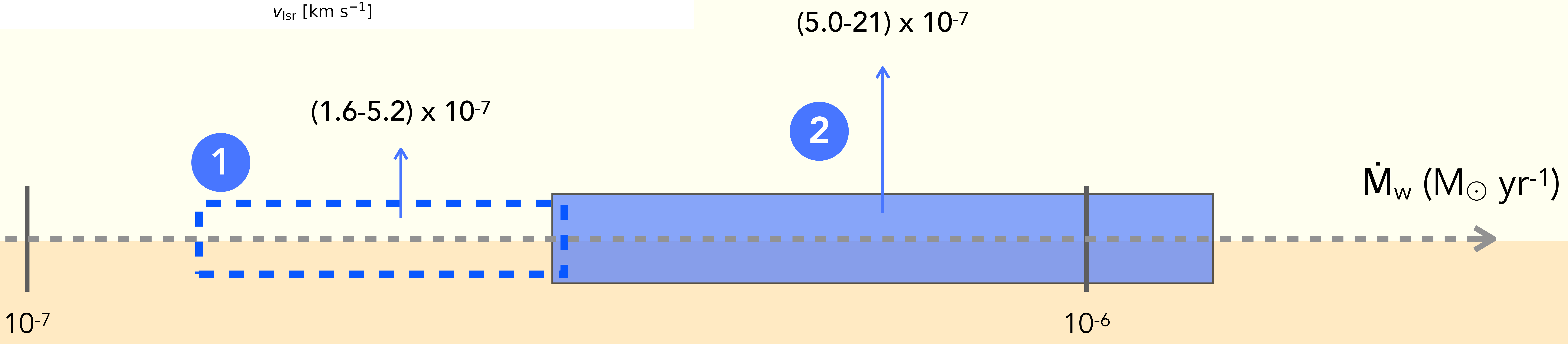
Sperling+2020, 2021

How does the intrinsic mass loss rate vary over time?



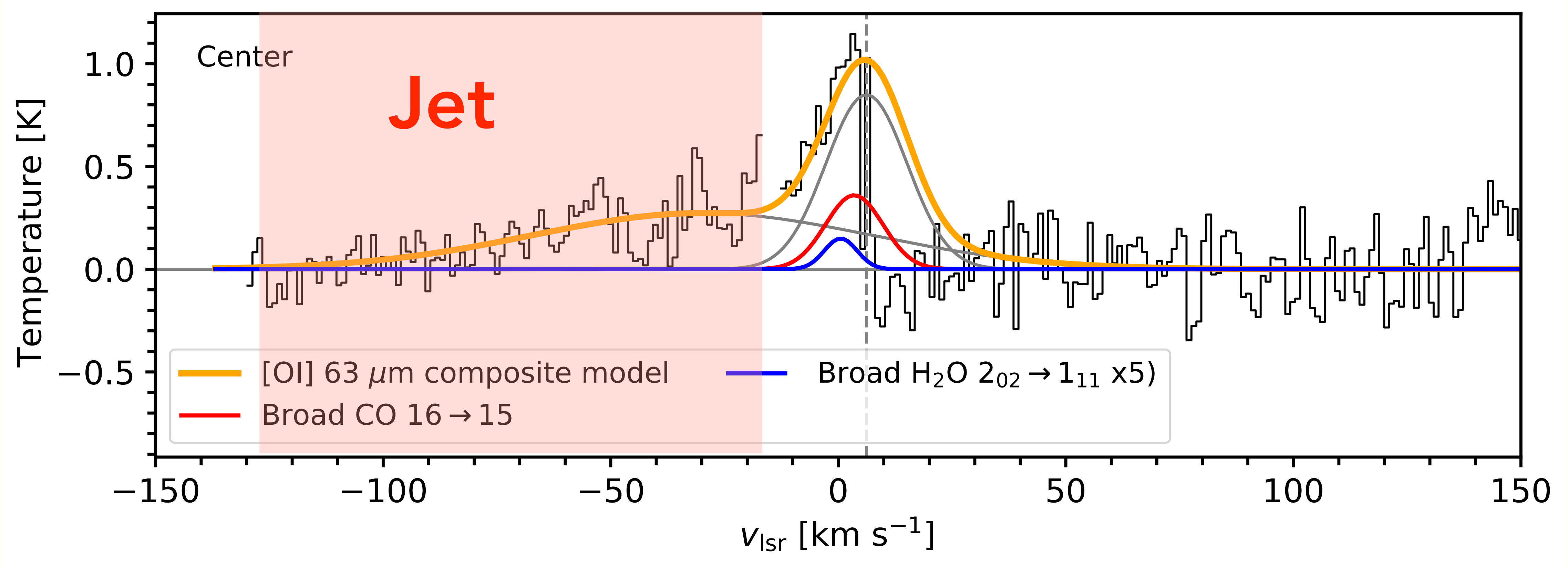
1. [OI] luminosity (Hollenbach 1985) -> $\dot{M}_w$
2. $\dot{M}_w = M_{[OI]} / t_{[OI]}$

[OI]



Other tracers

How does the intrinsic mass loss rate vary over time?



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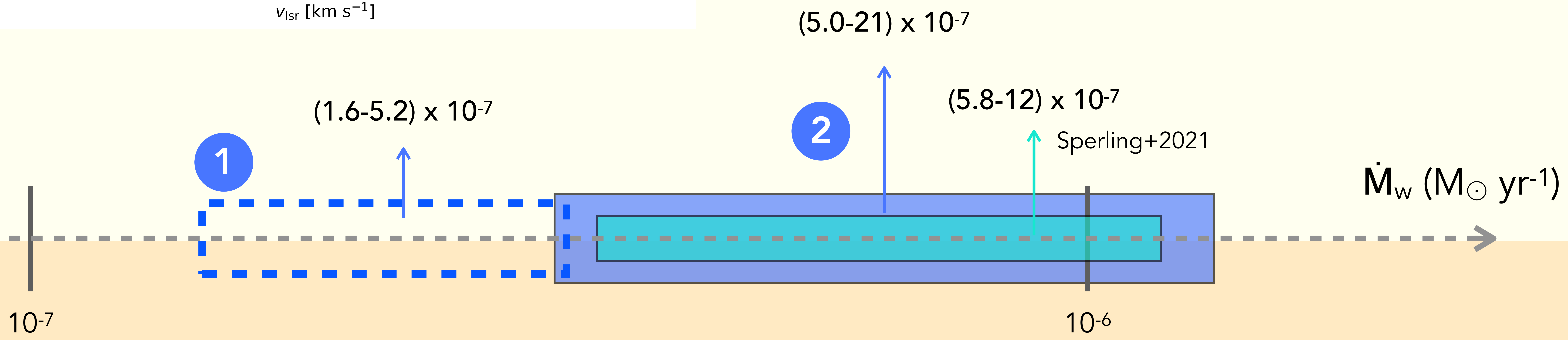
[OI]



Other tracers

Yao-Lun Yang UVa

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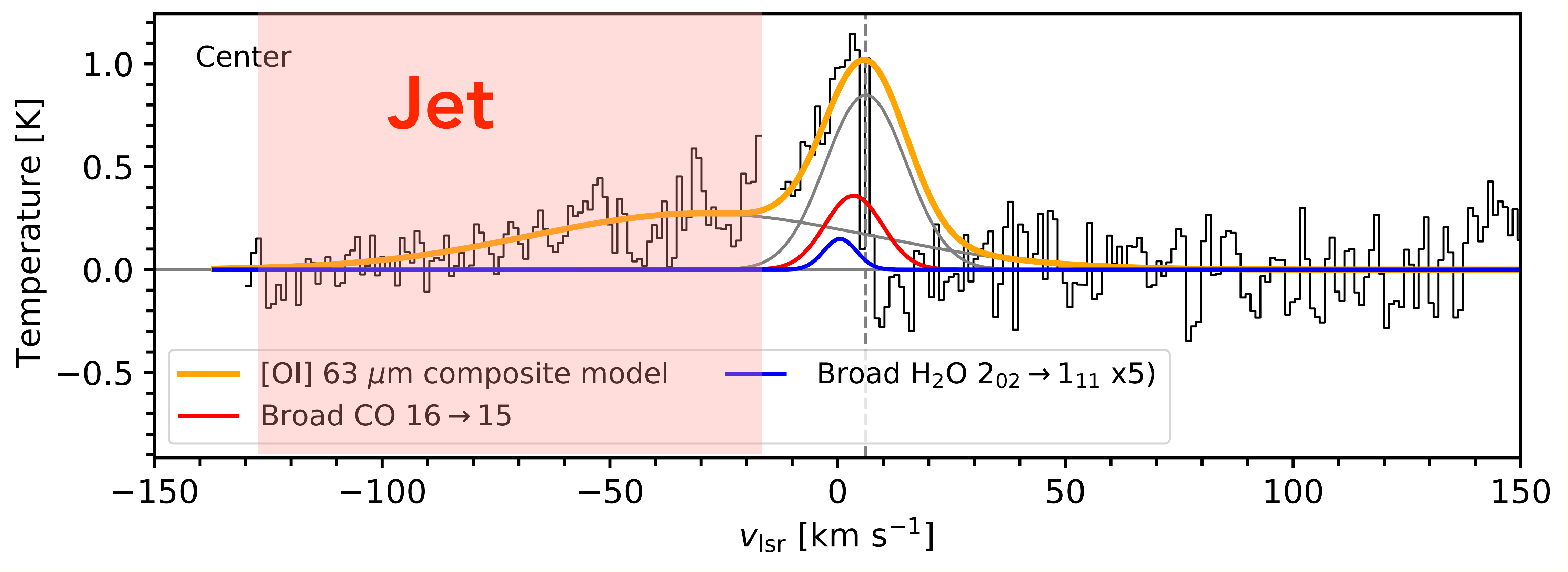

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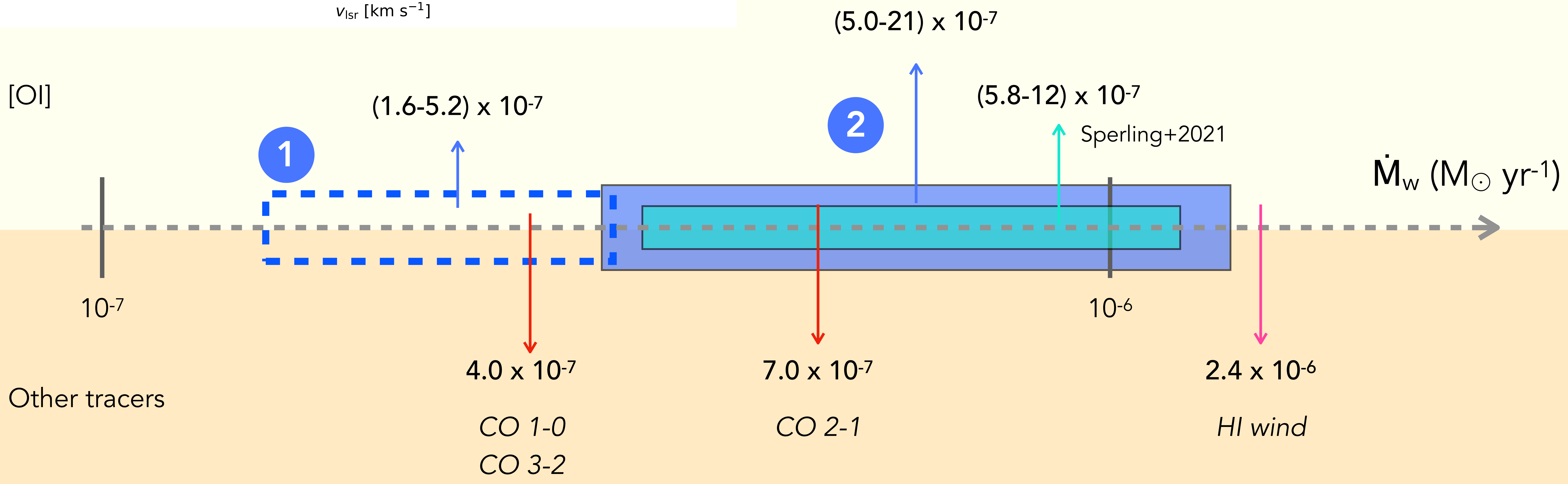


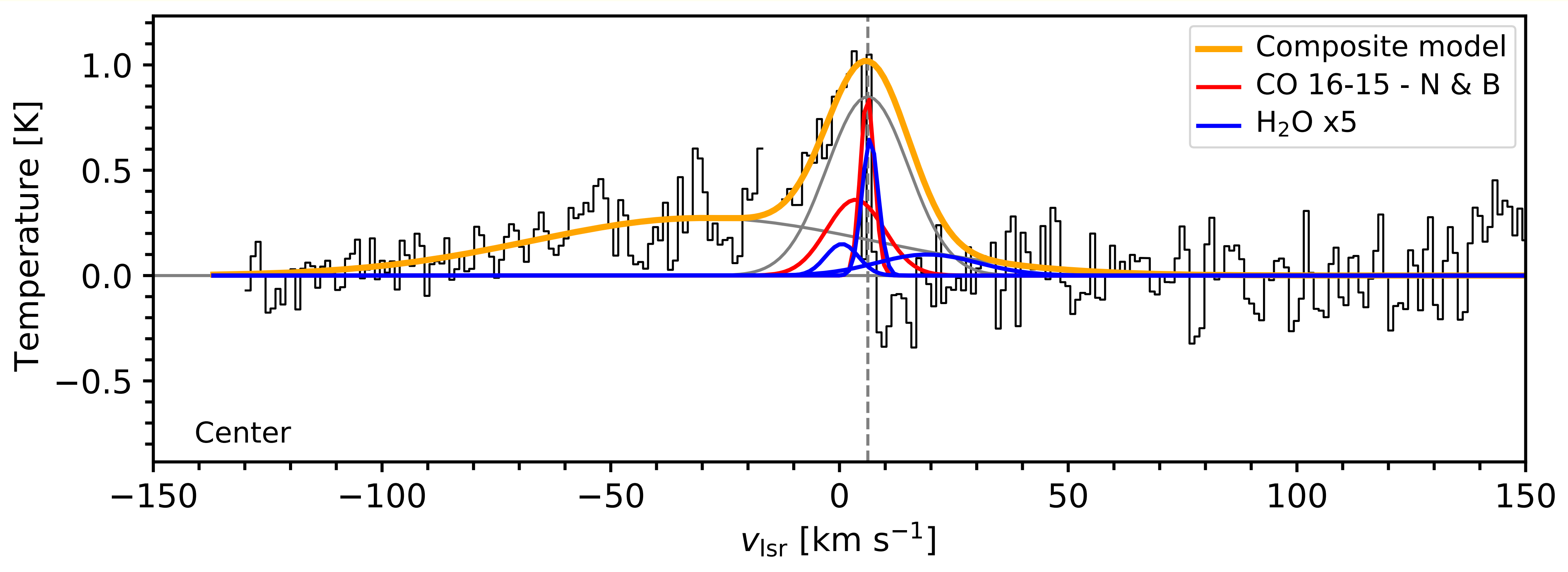
Summary

- Shocks dominate the [OI] emission in L1551 IRS 5. The extremely broad component of [OI] is detected for the first time.

- Atomic oxygen is the major oxygen carrier in the shocks, accounting for ~70% of volatile oxygen.

- The outflow of L1551 IRS 5 agrees with a momentum-conserved outflow, showing the intrinsic mass loss rate varying up to a factor of 3 over 30-50 kyr.

- Follow-up velocity-resolved [OI] observations in the outflows would confirm the jet nature of the extremely broad component.



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