FIR-line spectroscopy of S106 with GREAT/SOFIA as a versatile diagnostic tool for the evolution of massive stars

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***Objectives**:*

→ Nature of the bipolar nebula and star-forming region **S106**
(enigmatic region studied since long, e.g. *Bally et al 1982, 1998; Hopdapp & Rayner 1991; Schneider et al. 2002, 2003, 2007; van den Ancker et al. 2000; Stock et al. 2015*)

→ Understanding the origin of far-infrared cooling lines, i.e. C^+ and OI emission: **photodissociation regions**, **shocks**,…

↓

Evolutionary phases of massive star formation

- **[CII] 158 µm** upGREAT/SOFIA data from may 2015 GT time (PI *R. Simon*)
- **[OI] 63 µm** upGREAT/SOFIA data from december 2015 OT time (PI *N. Schneider*)
- **[OI] 145 µm upGREAT/SOFIA data in november 2016**

Complementary data from FORECAST/SOFIA + molecular line data from IRAM 30m, *Herschel*, VLA, optical, Spitzer…

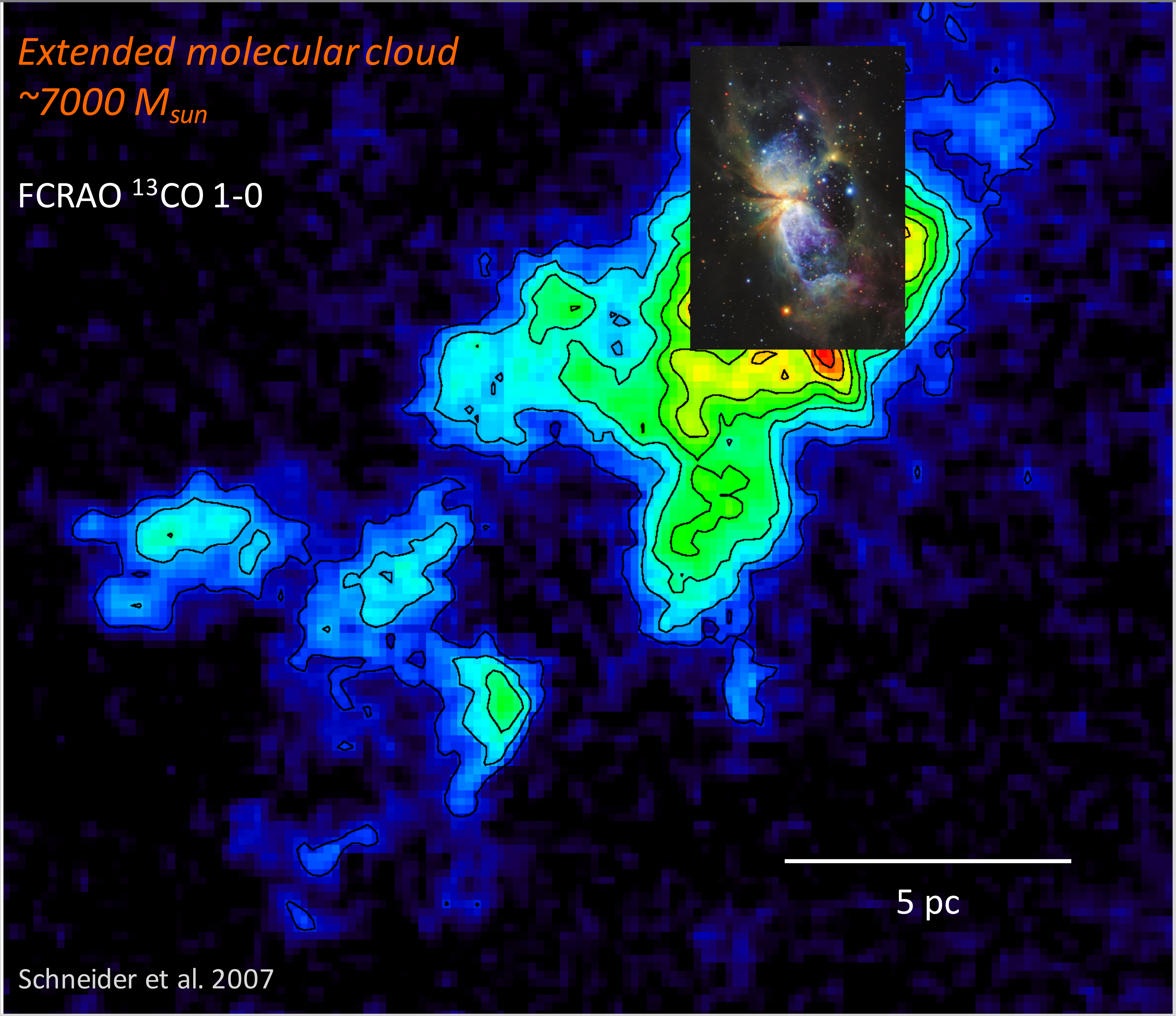
Anatomy of a massive star-forming region: S106

- A **bipolar nebula** with two lobes filled with ionized gas

- distance **1.3 kpc** (parallax measurement, Xu et al. 2013)

- embedded in a large molecular cloud

Anatomy of a massive star-forming region: S106



Anatomy of a massive star-forming region: S106

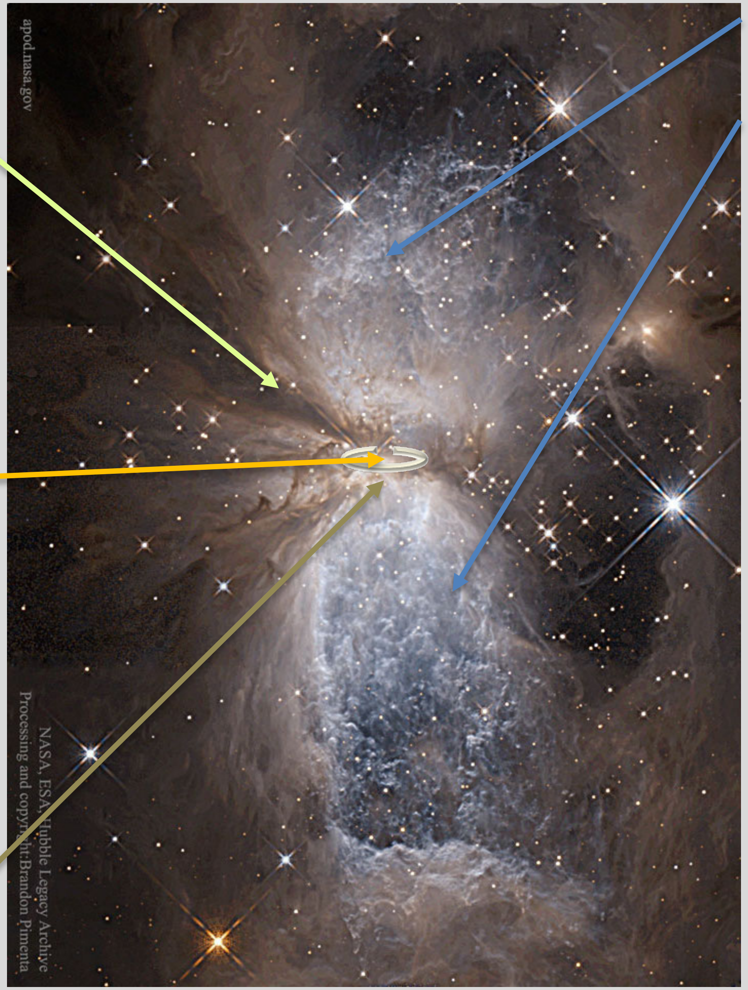
- 'dark lane'

- **S106 IR** is the exciting source, its evolutionary status not clear
  -> Main sequence *late O* or *early B-type star* ?

- UV radiation up to 10^{4-5} G_o at 0.1 pc

- stellar wind ~100-200 km/s

- small circumstellar disk



- A **bipolar nebula** with two lobes filled with ionized gas

- distance **1.3 kpc**

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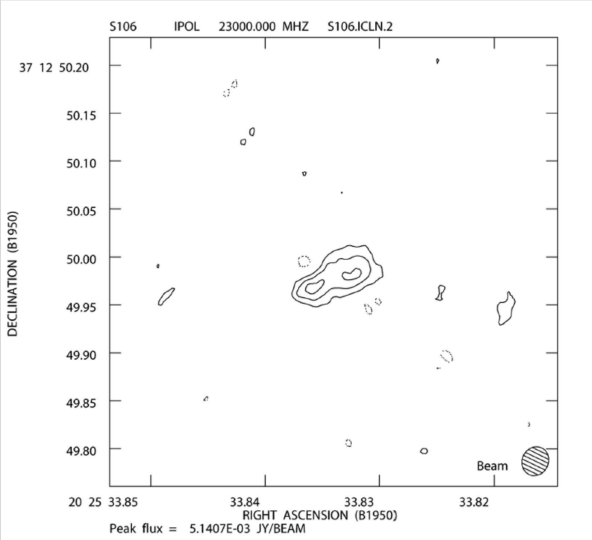
associated low-mass star cluster (>100 stars, Hodapp & Rayner 1991)

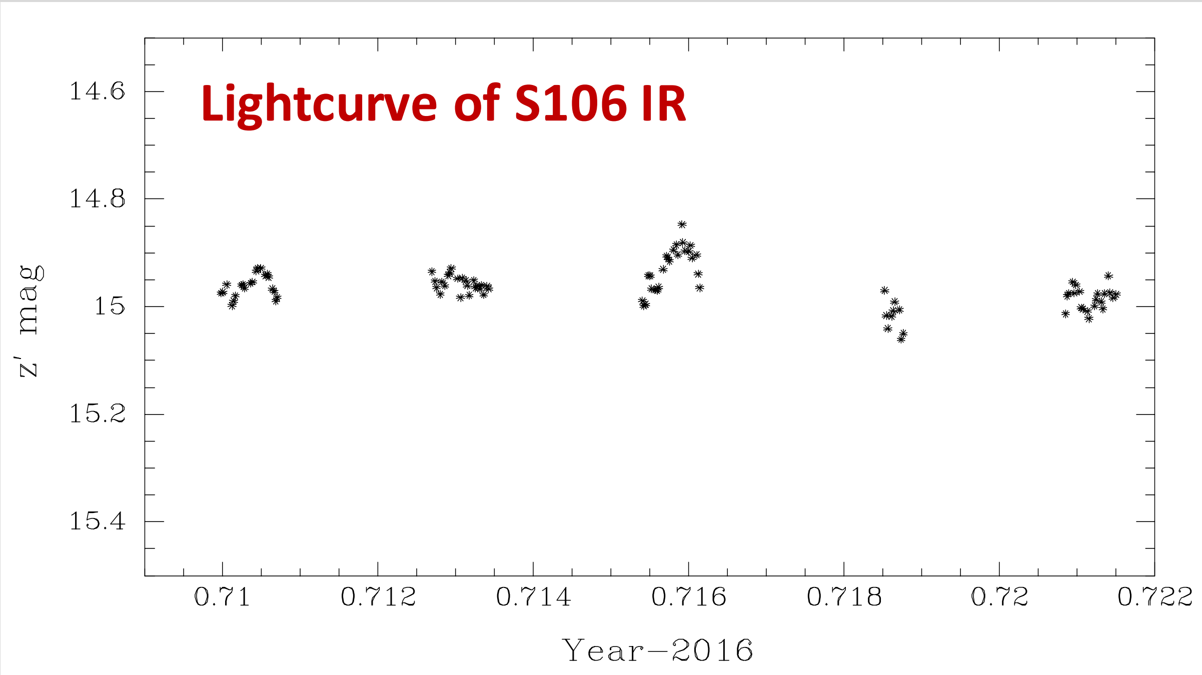
Is there a circumstellar disk around S106 IR ?



Hoare & Muxlow 1996

- Merlin 1.3 cm emission resolves a **disk-like feature**.

- Very short brightening episode due to **accretion on the surface** of the star, thus indirect ***disk evidence.***

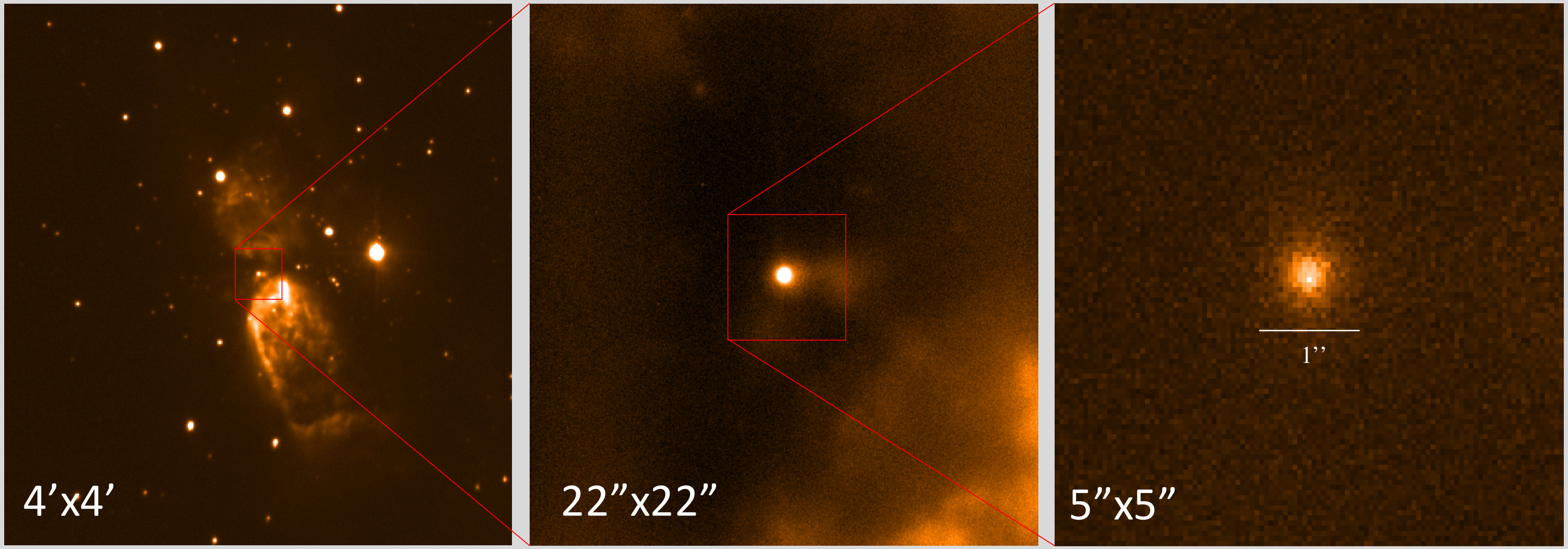


Comeron et al., in prep (Tenerife observations)

Is S106 IR a binary ?

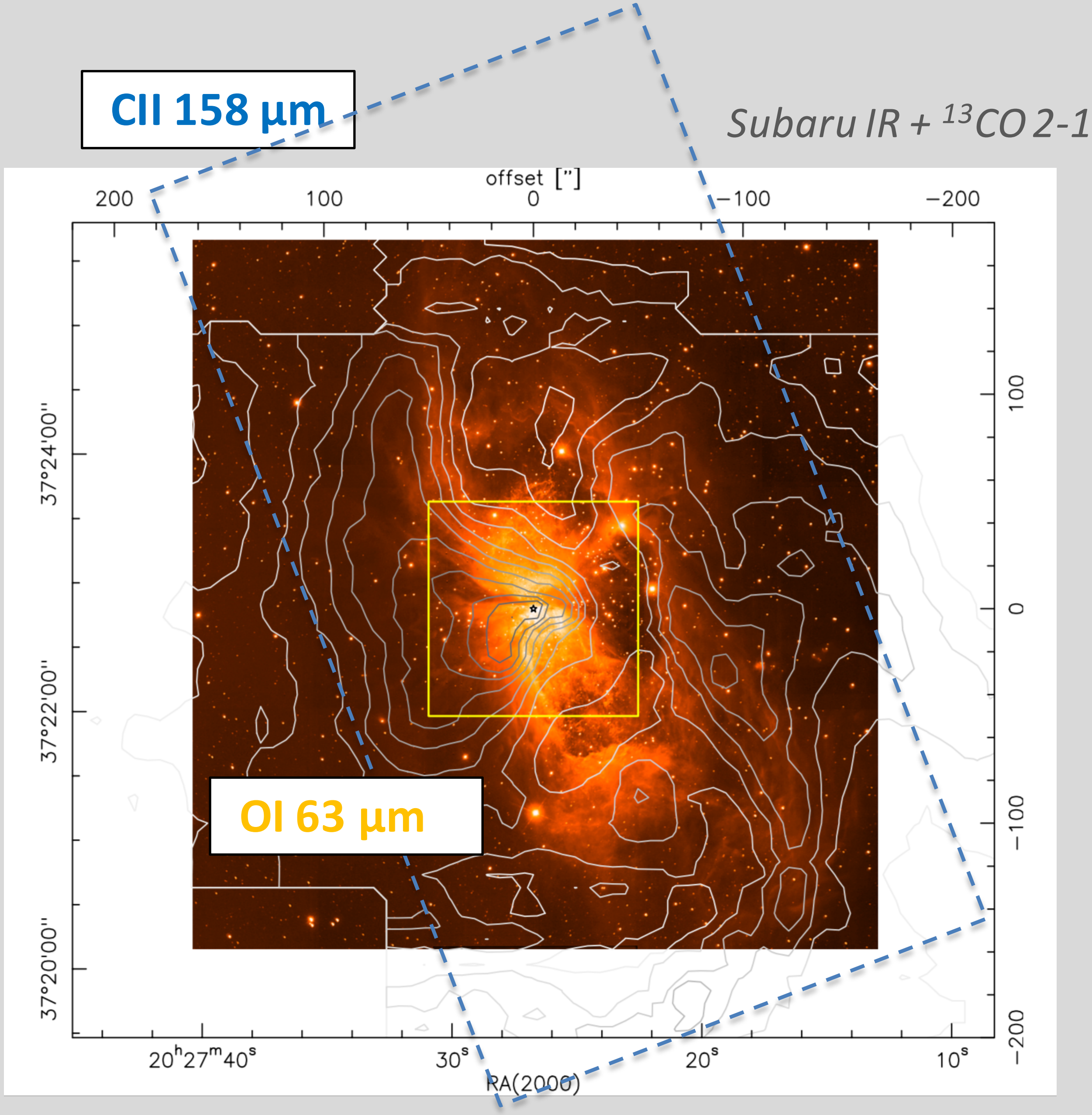
- Sharpest IR imaging so far still shows **no companion ~200 AU**.

Tenerife: z'-band (0.9 µm) Calar Alto Astralux observations



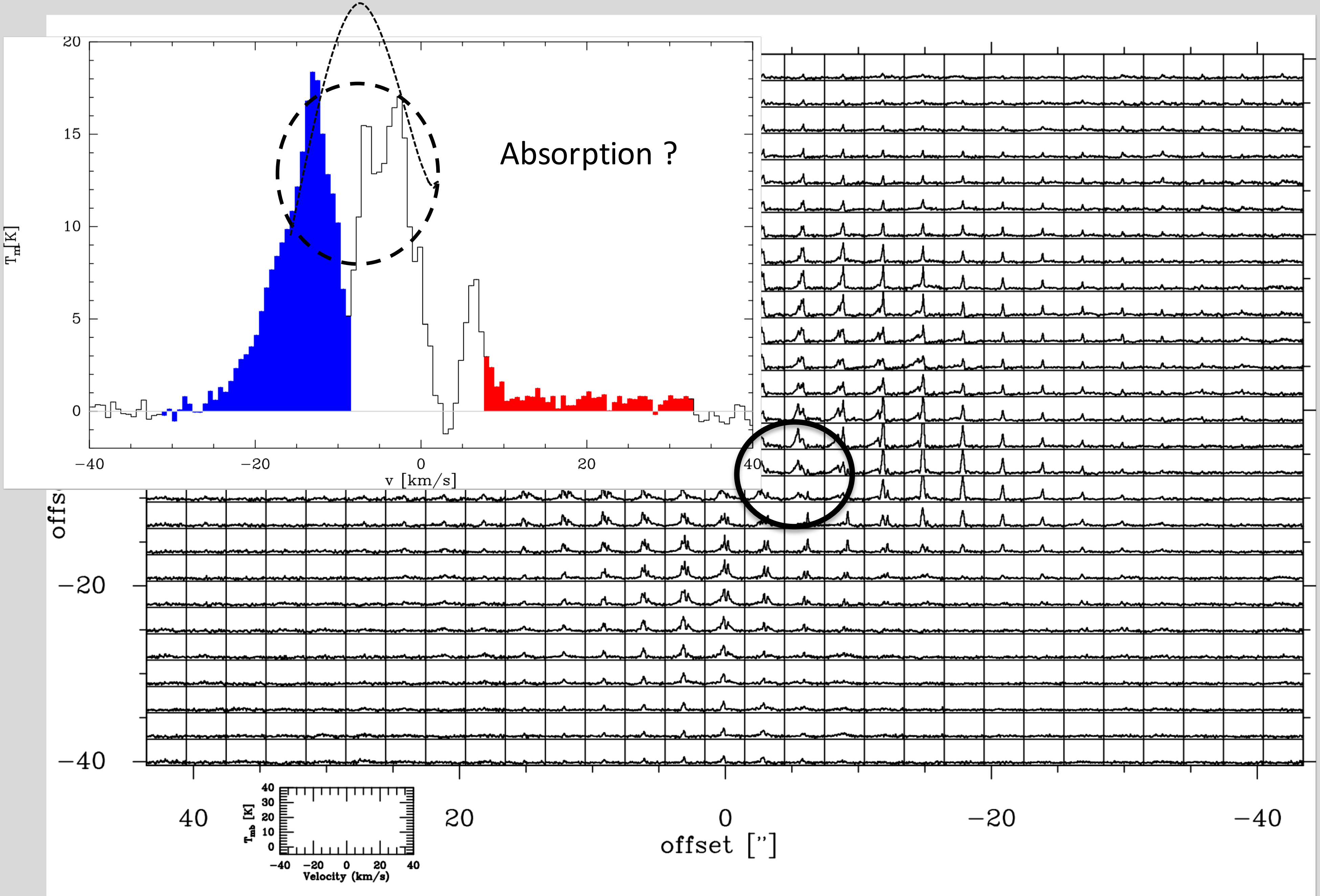
Cameron et al., in prep.

upGREAT/SOFIA CII and OI observations



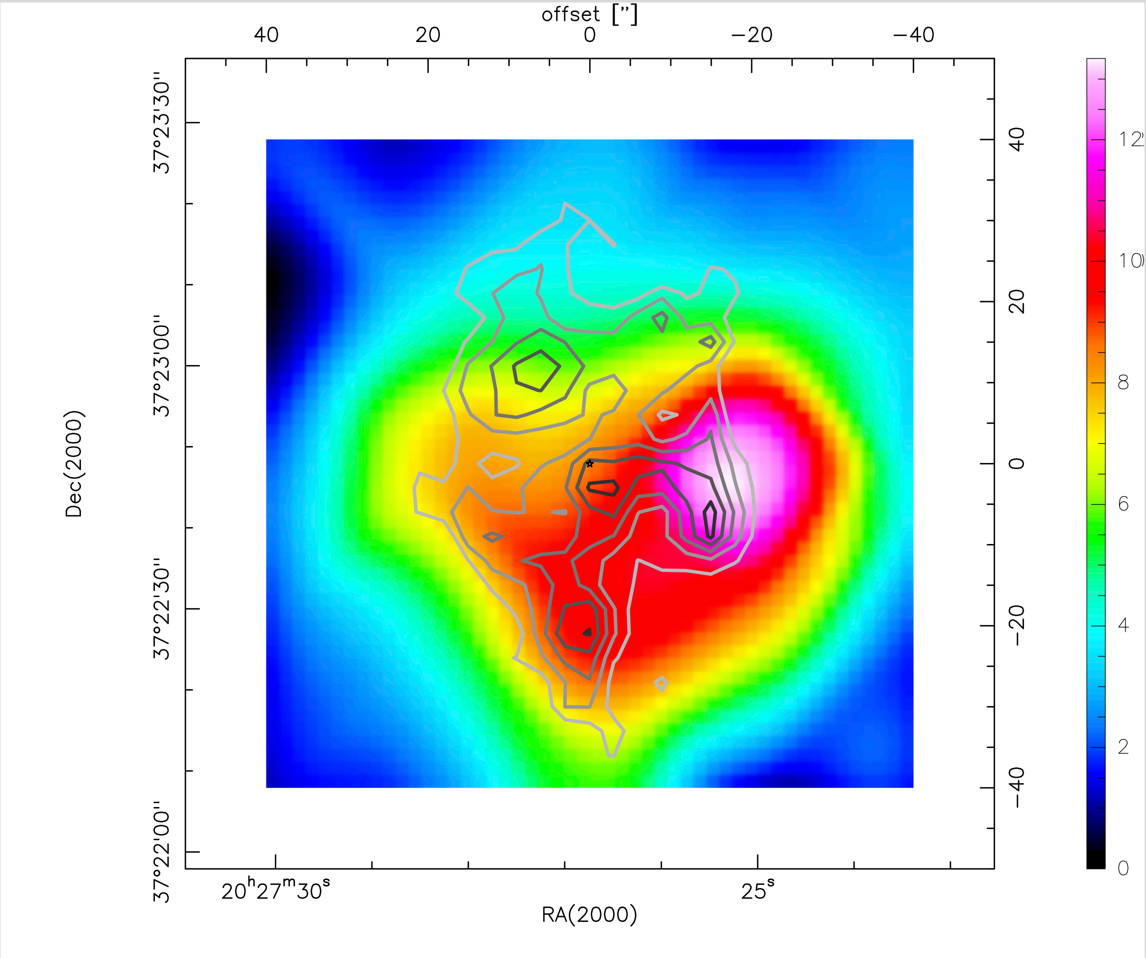
Schneider et al. 2016, in prep., Simon et al. 2016, in prep.

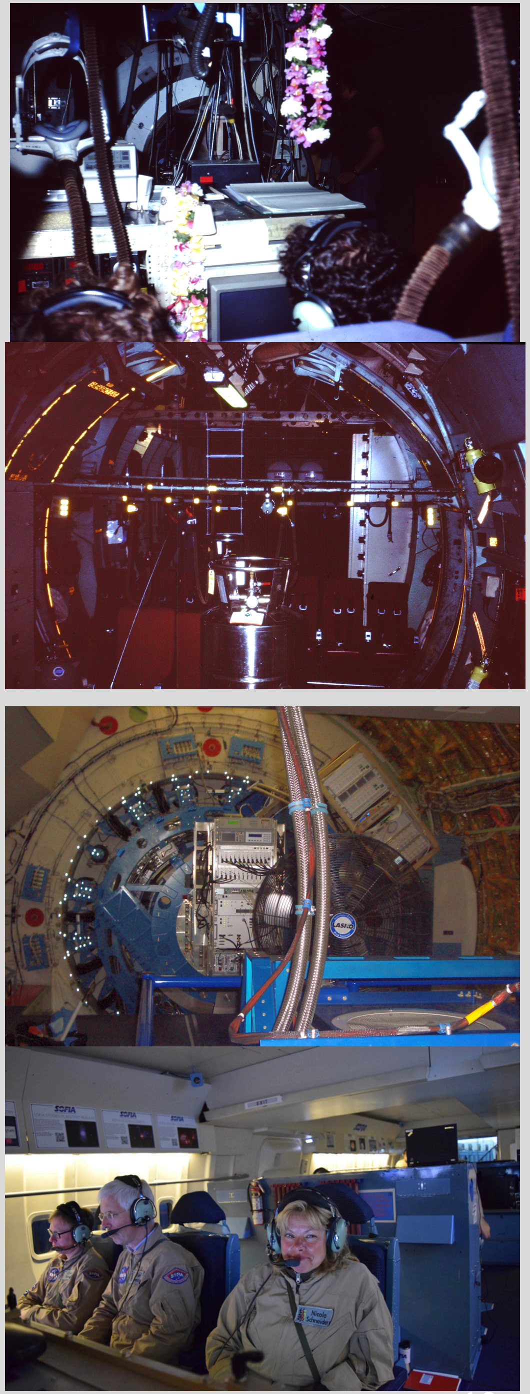
upGREAT/SOFIA OI 63 µm map at 6" angular resolution



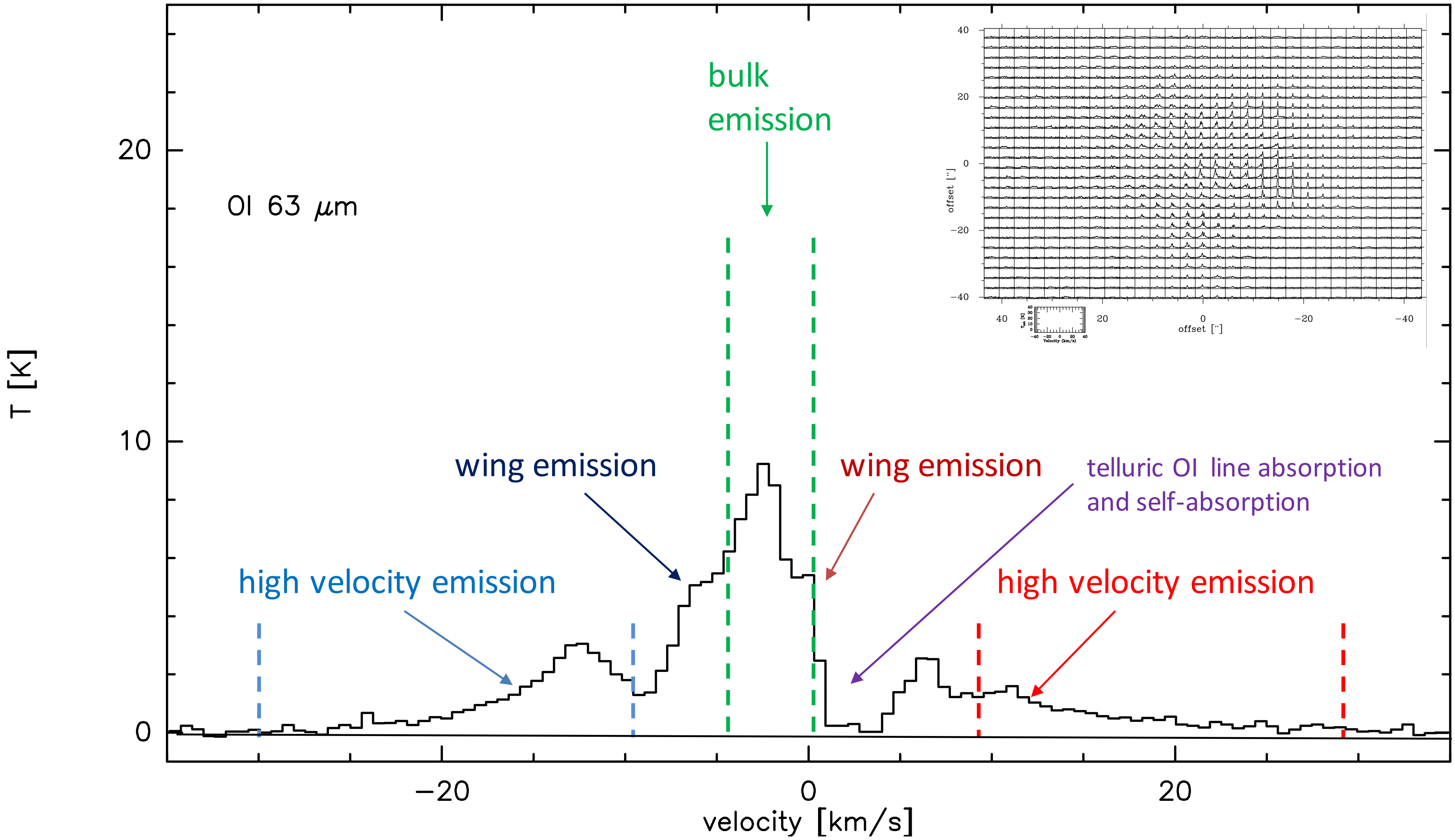
FIR observations .... now and then

KAO (FIFI) 1994 **SOFIA 2015**

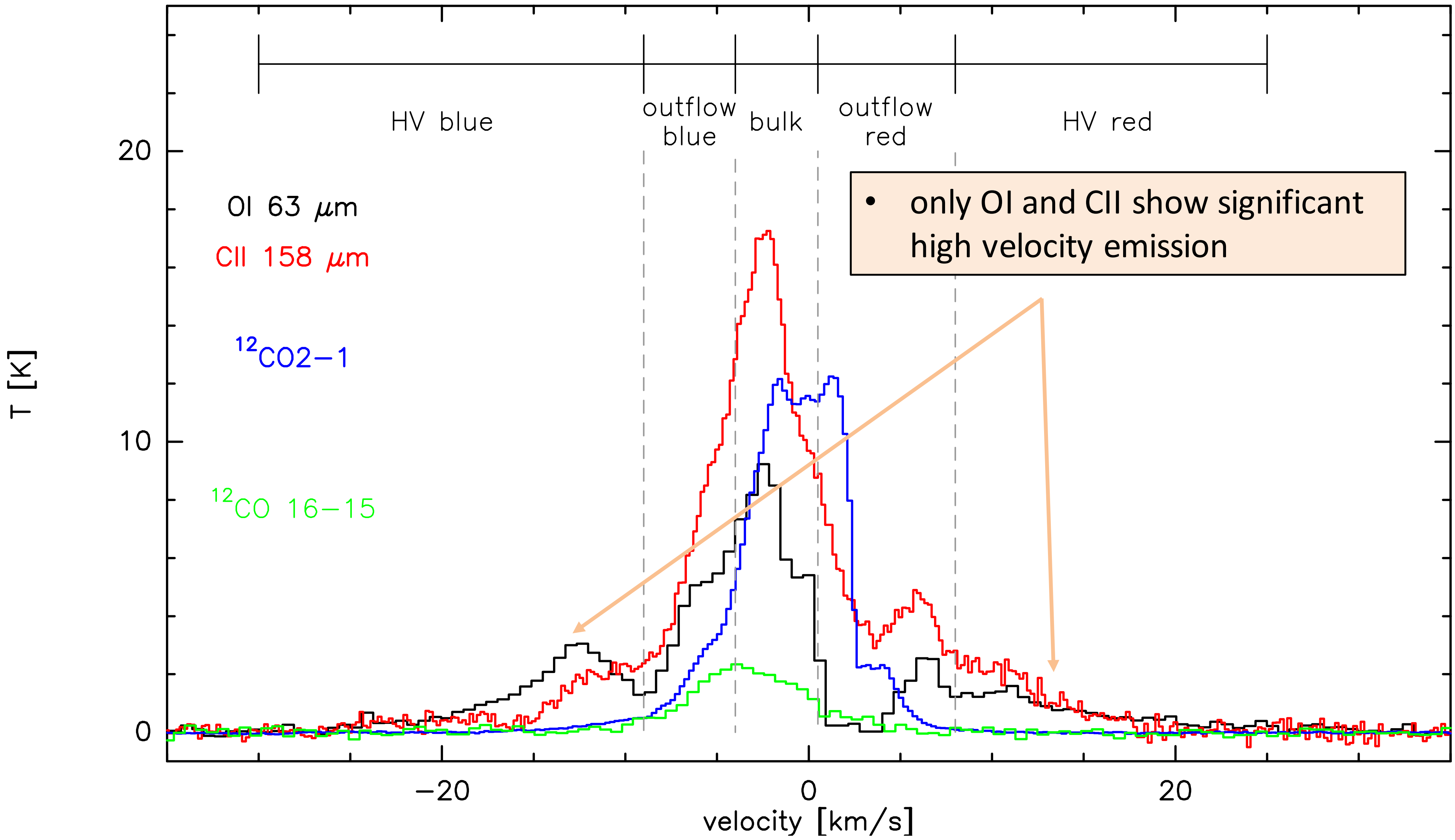




Average spectrum across OI mapping area

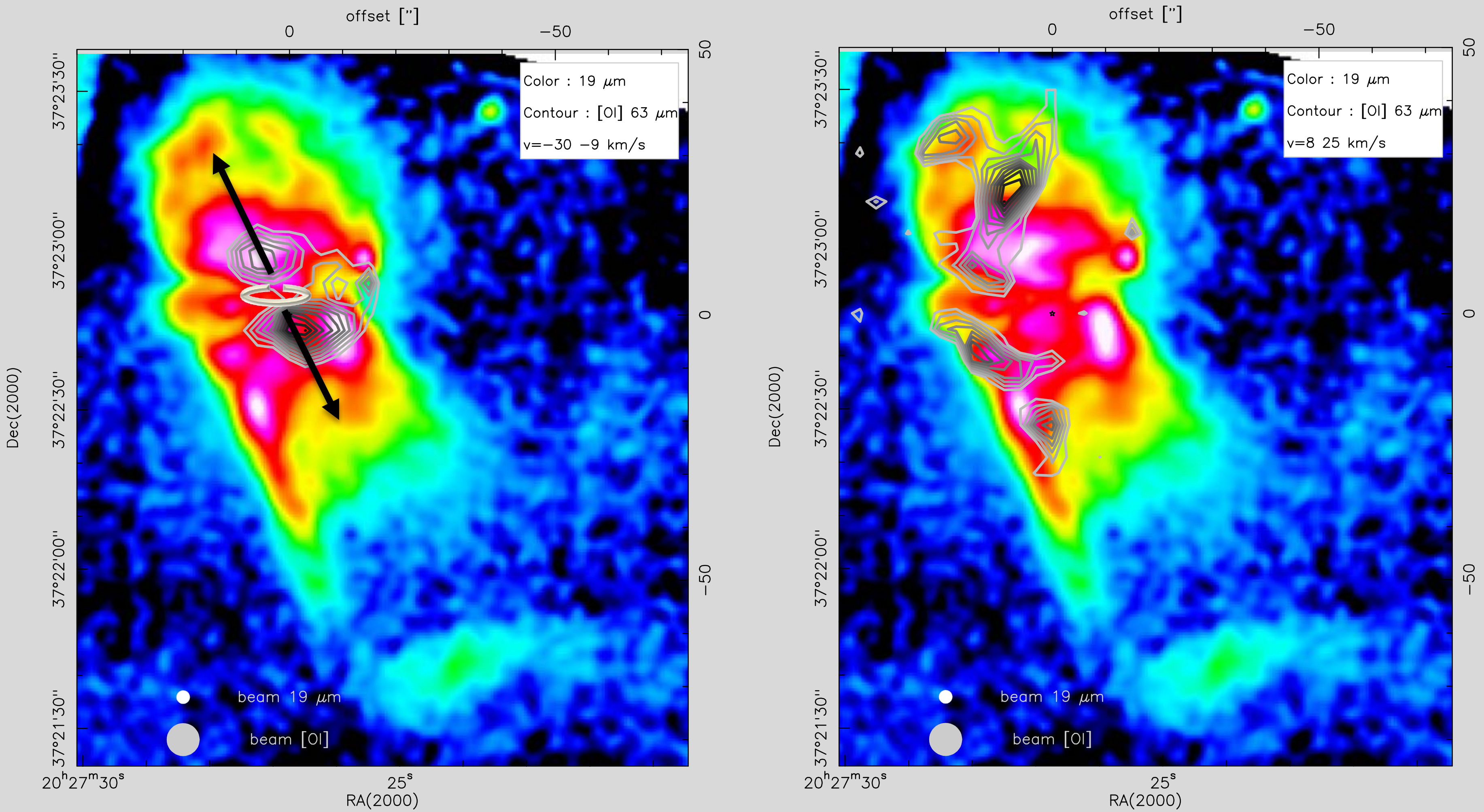


upGREAT/SOFIA OI 63 μm average spectrum and other tracers



OI 63 µm on 19 µm FORCAST/SOFIA mid-IR emission (warm dust)

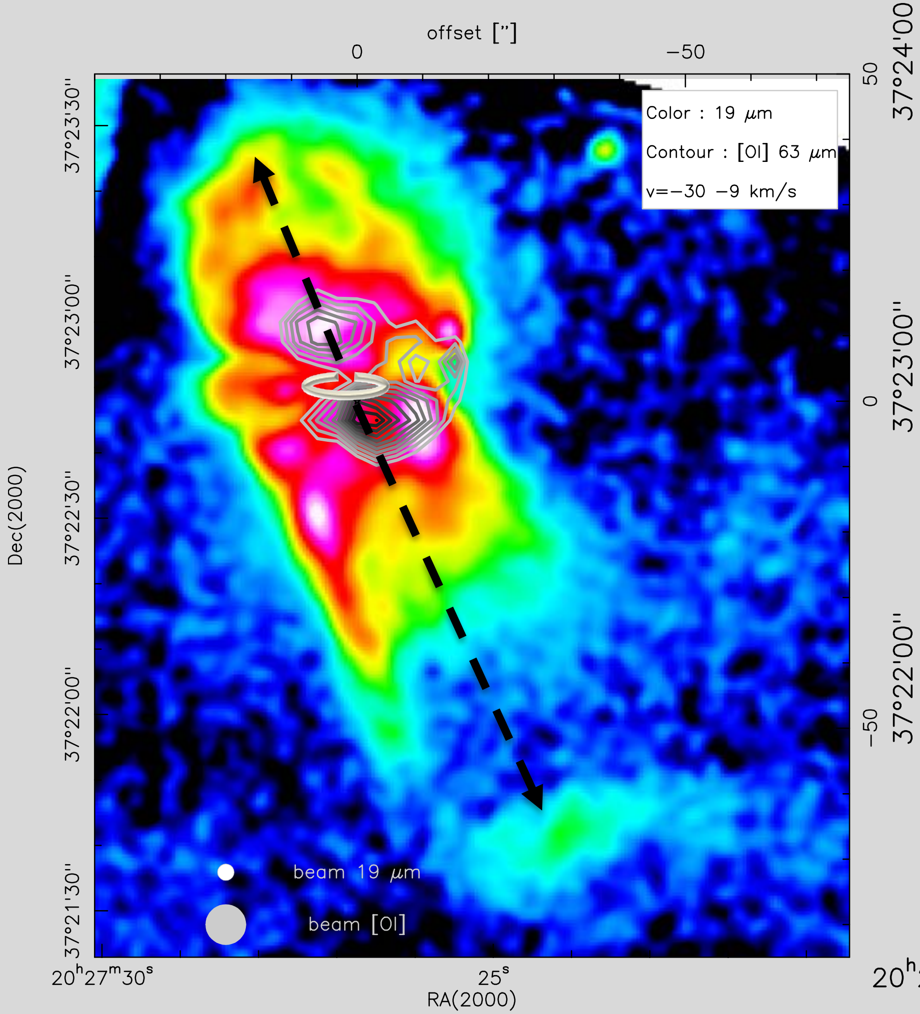
An atomic OI jet ? No... emission is not in the plane of the sky.



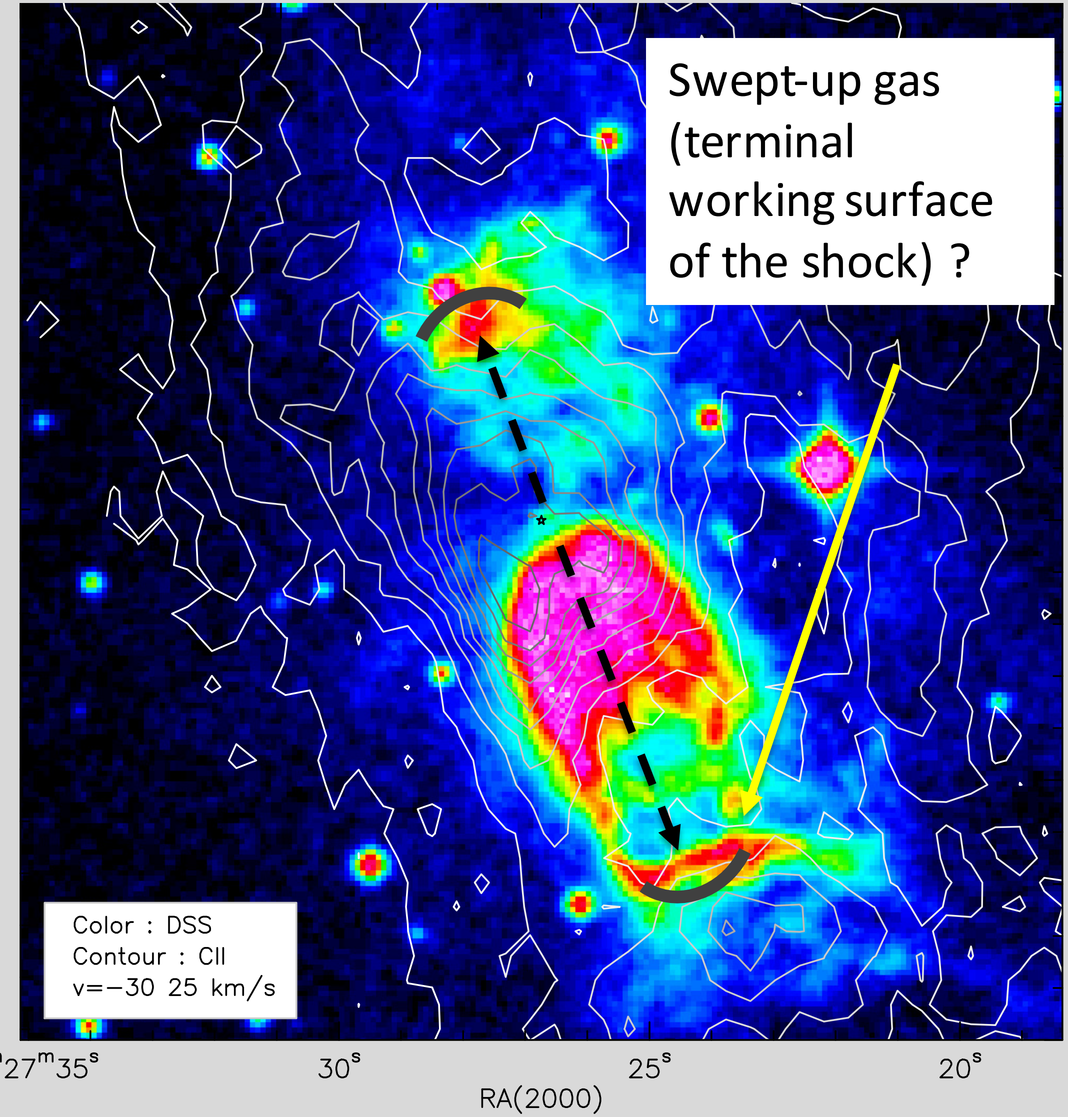
FORCAST observations : Adams et al. 2015

Understanding the origin of OI 63 μm emission: high velocity emission

But there was probably once an atomic OI jet, driven by disk – envelope interaction.

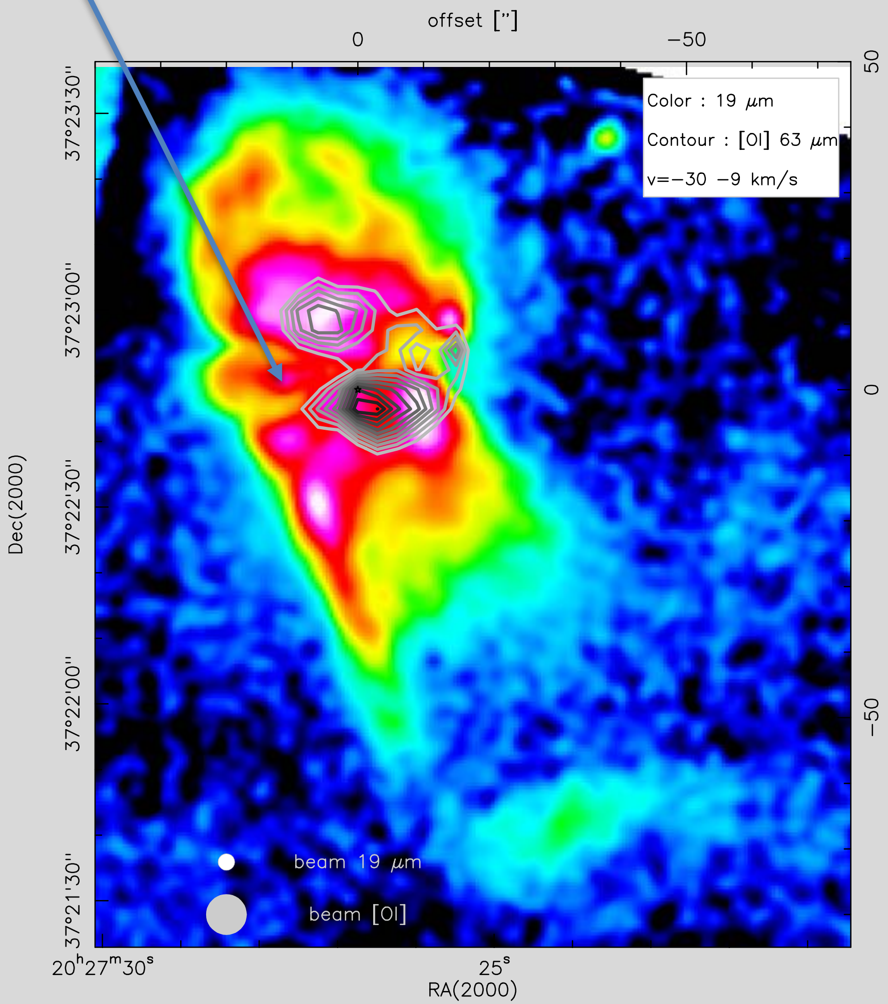


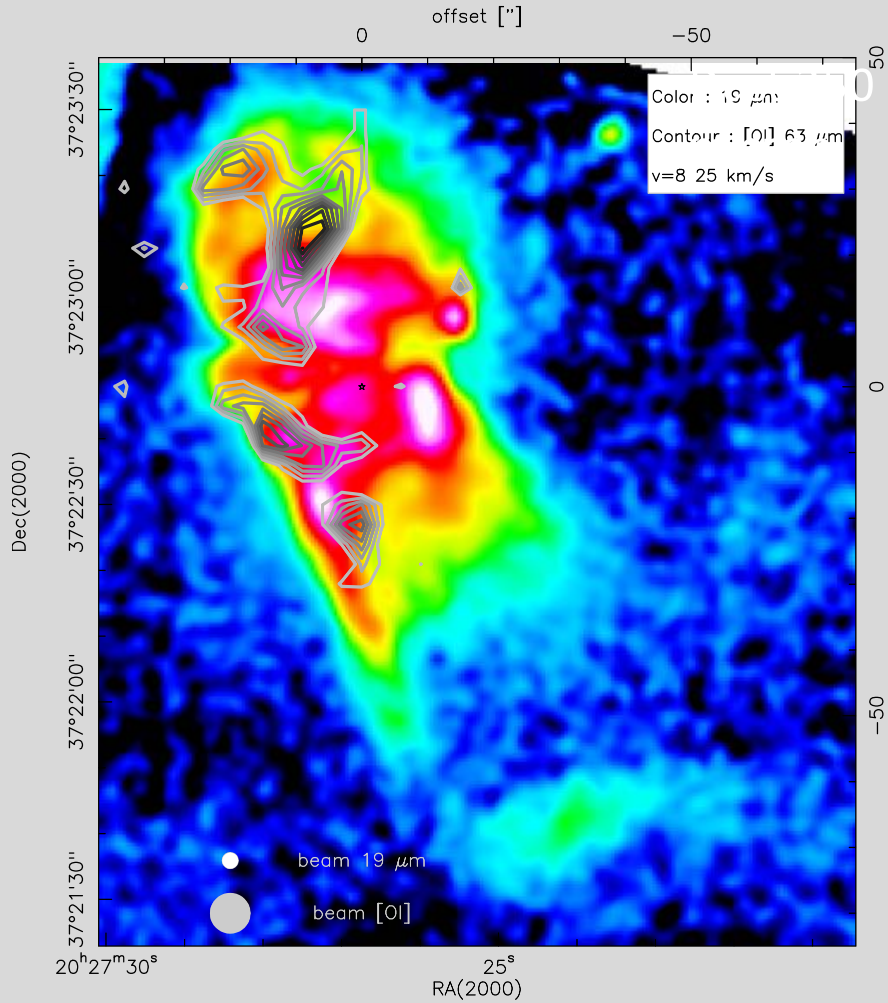
FORCAST observations : Adams et al. 2015



OI 63 μm on 19 μm FORCAST/SOFIA mid-IR emission (warm dust)

- Emission looks 'squeezed' by the **dark lane**.
- What if the lane is not only a foreground feature but has a **physical link** to S106 IR ?

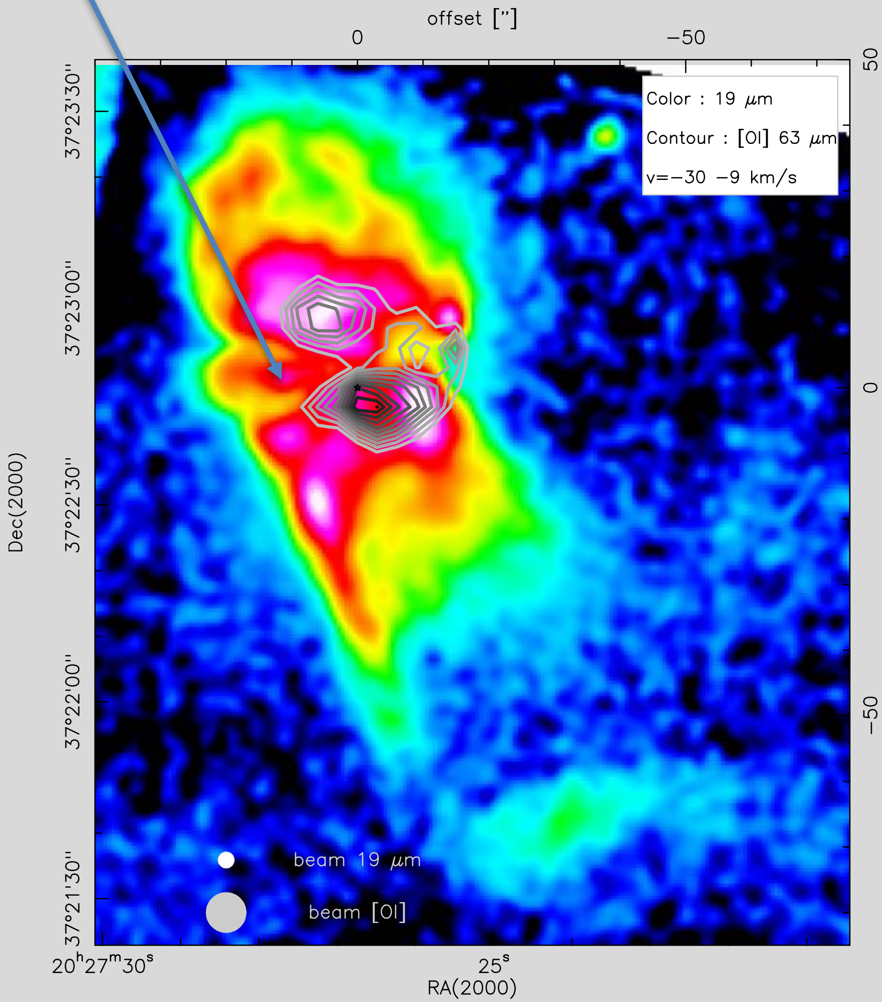


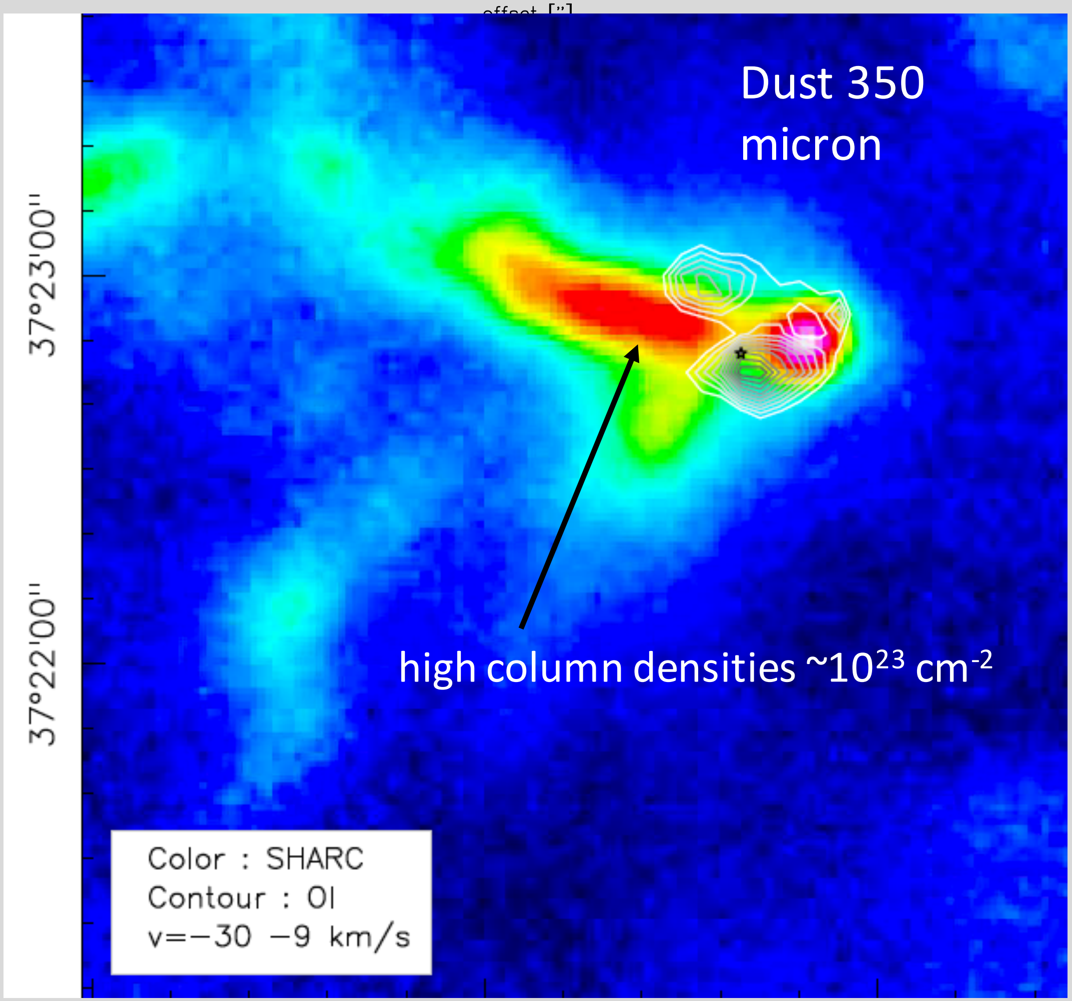


FORCAST observations : Adams et al. 2015

OI 63 µm on 19 µm FORCAST/SOFIA mid-IR emission (warm dust)

Is the 'dark lane' an accretion flow, ionized on its backside ?





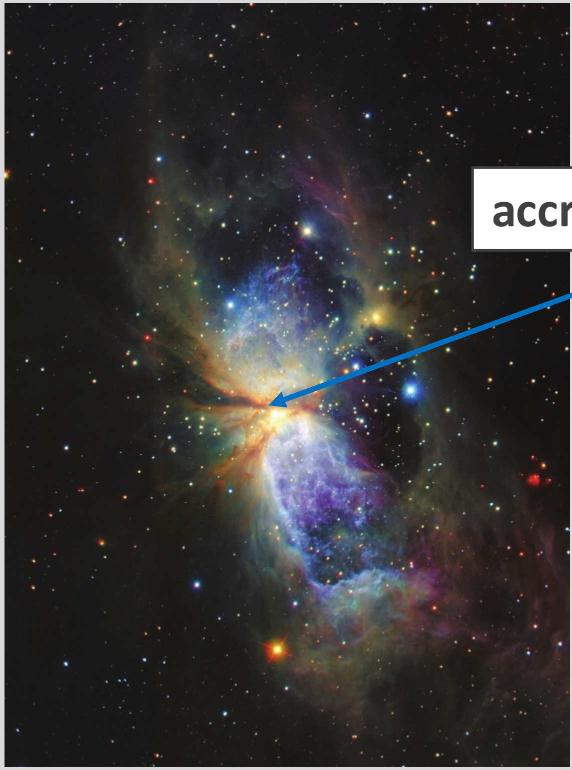
FORCAST observations : Adams et al. 2015

Understanding the origin of OI 63 μm emission: high velocity emission

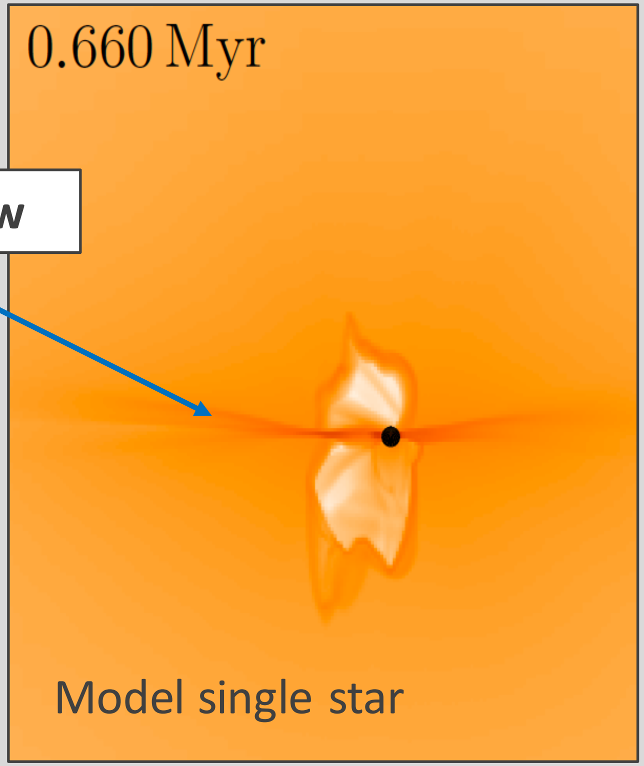
Model *(Peters, Banerjee, Klessen et al. 2010):*
FLASH code compressible gas dynamic, self-gravity, radiation feedback

- ***non-uniform*** expansion of HII region
- strong ***accretion flow*** absorbs the ionizing radiation
- (ionized) gas gas expands downward perpendicularly to the accretion flow, down the ***steepest density gradient***

accretion flow



Subaru IR



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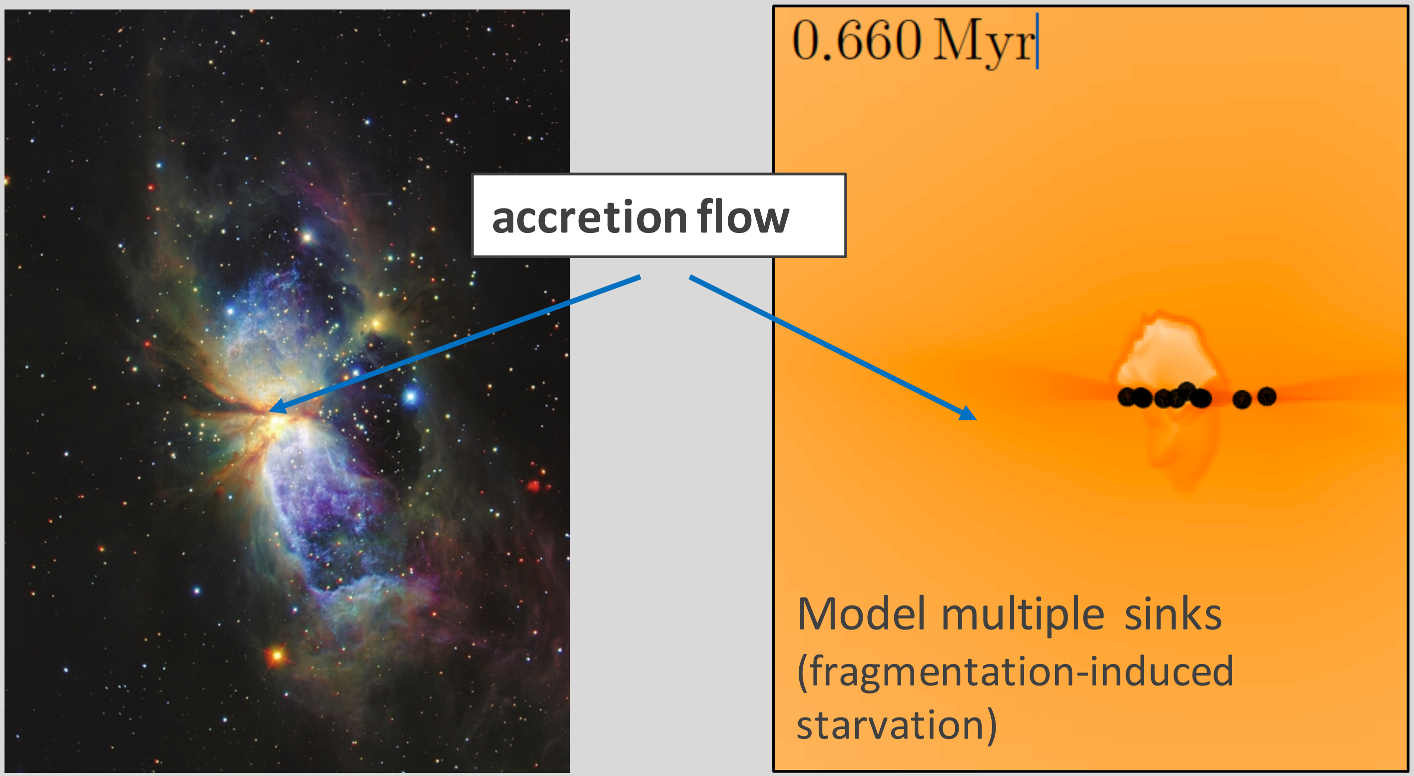
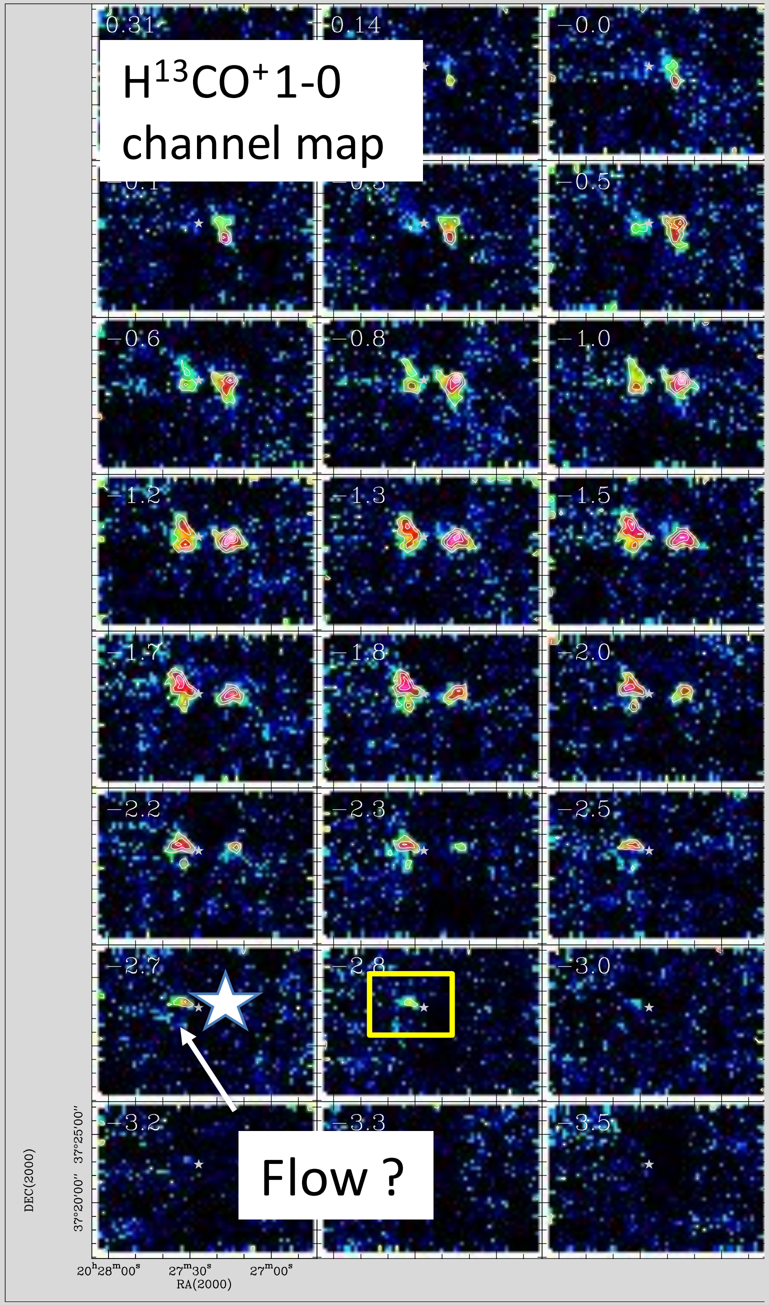
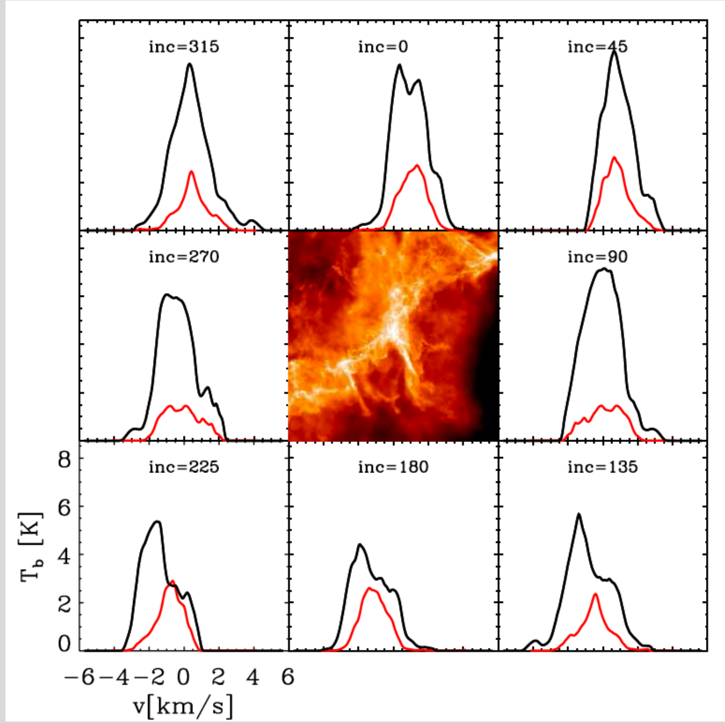


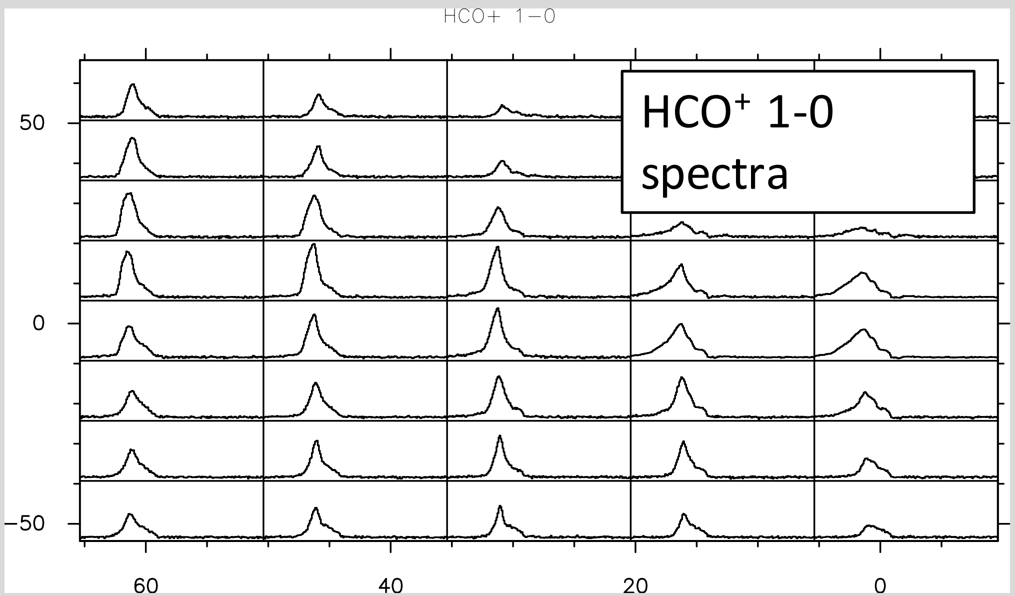
Subaru IR

Dynamics of the molecular gas HCO^+ and $H^{13}CO^+$ 1-0



Simulations
HCO^+ 1-0
(Smith et al. 2013)

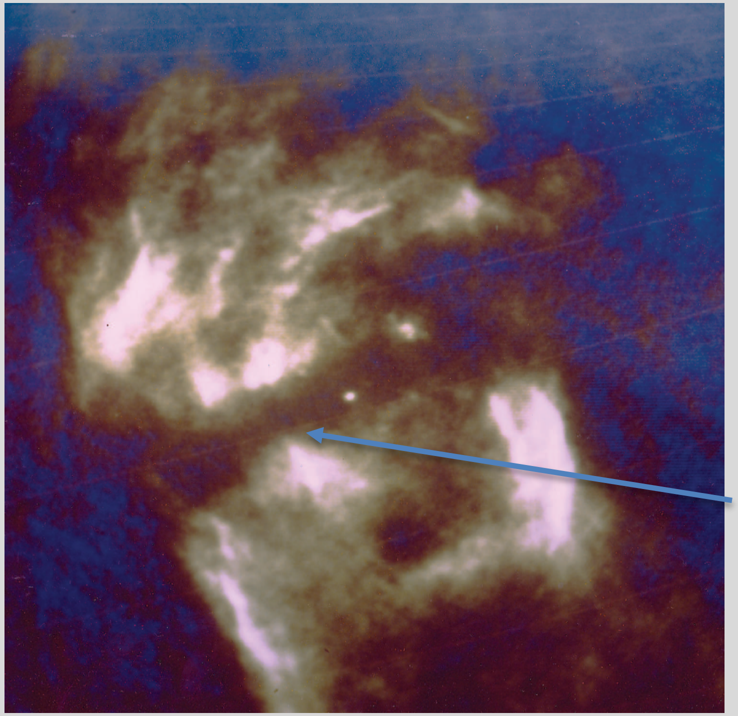




Bally et al. 1983:

- Dark lane could be an **extention of the small-scale disk** around S106 IR.
- Its density is so large that it **absorbs all ionizing radiation**.

Yes… an **accretion flow** onto S106 IR with a **photodissociation region** on its backside -> ***OI, CII, high-J CO emission….***



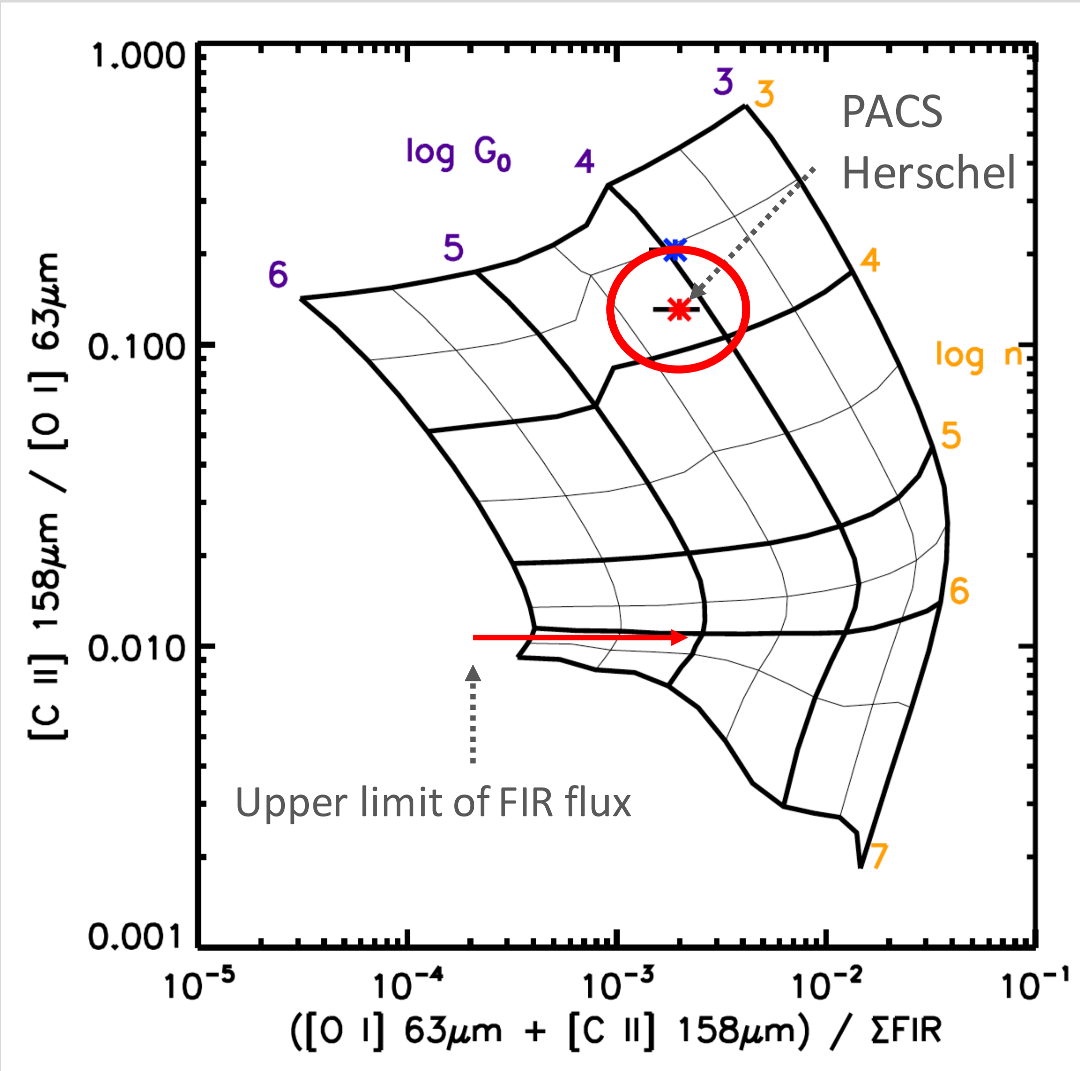
Region devoid of cm emission.

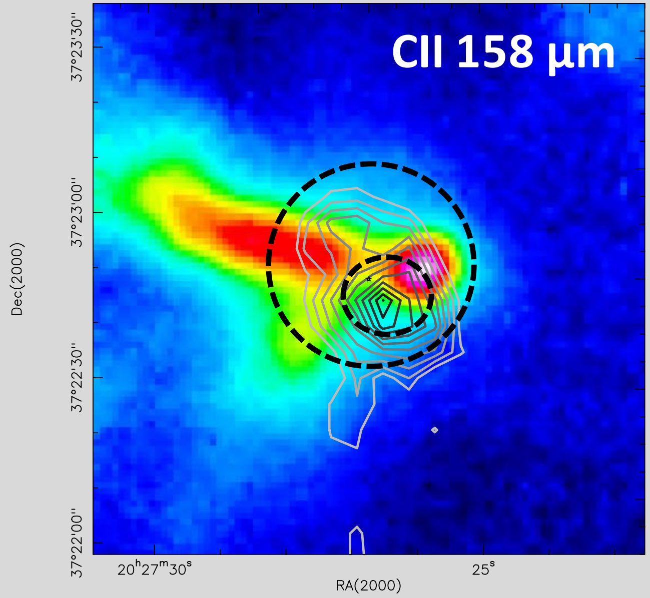
VLA 5 GHz Bally et al. 1983

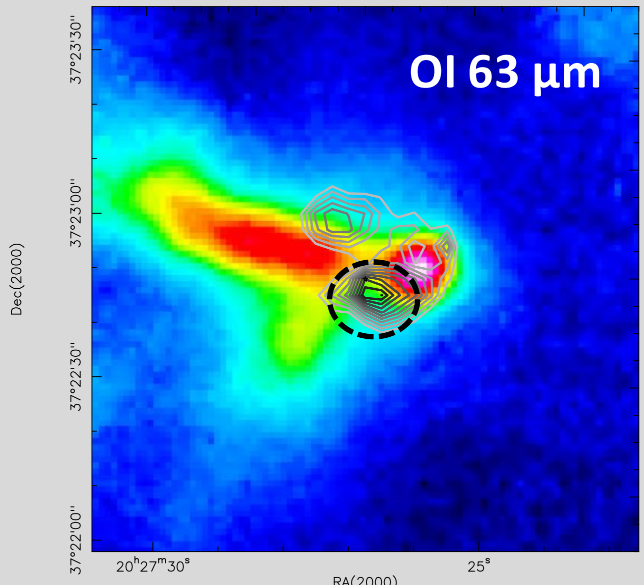
PDR model of ***Wolfire et al. 2010, Hollenbach et al. 2012*** shown in ***Stock et al. 2015***

(*Herschel* PACS/SPIRE study of central position around S106 IR.)

CII and OI high velocity blue component: **radiation field 10^5-10^6 G_o, density 10^6 cm^{-3}**







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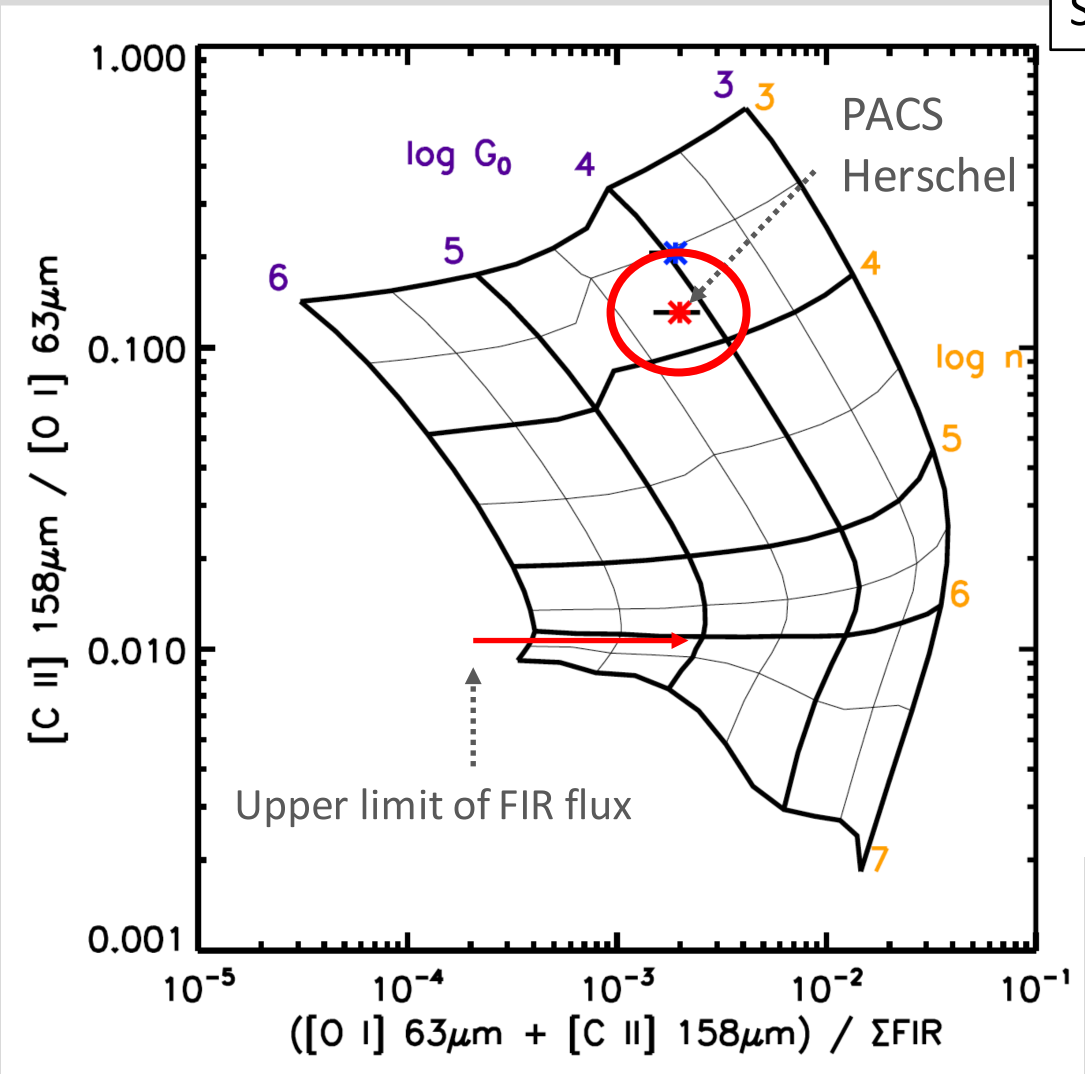
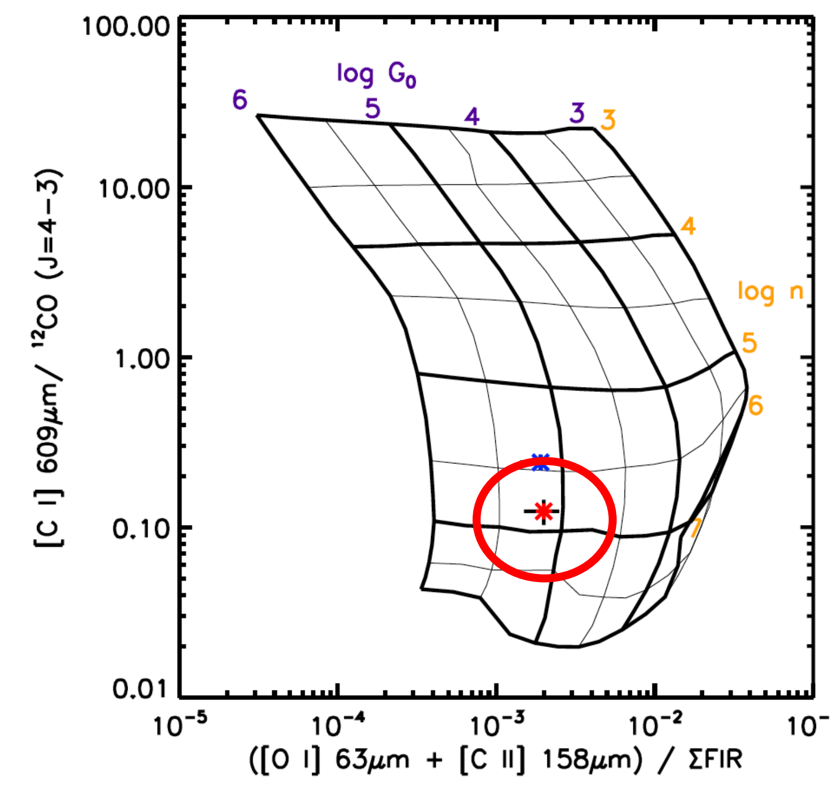
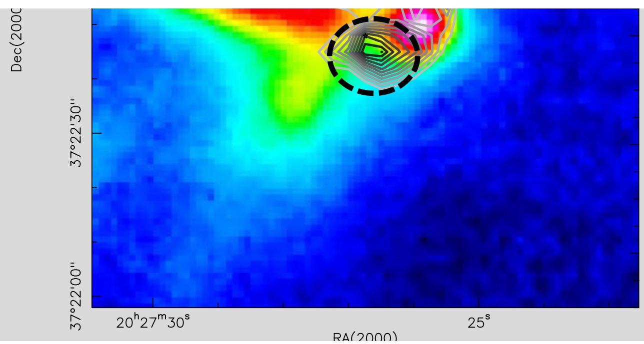


Same model with CI/CO ratio.





KOSMA-tau clumpy PDR model (e.g. Roellig et al. 2006) and line intensitities of

- low-J CO lines ^{12}CO 2-1, ^{13}CO 2-1
- high-J CO lines ^{12}CO 7-6, ^{12}CO 11-10, ^{12}CO 16-15
- OI 63 µm
- CII 158 µm

Many runs… 1-phase, 2-phase, filling factors… ->

Best reproduction of all line intensities **except OI** is for a 2-phase model with

Phase 1 **$n \sim 10^5$ cm^{-3}, $G_o \sim 10^6$**

Phase 2 $n \sim 10^{3-4}$ cm^{-3}, $G_o \sim 10^{3-4}$ (depending on filling factors)

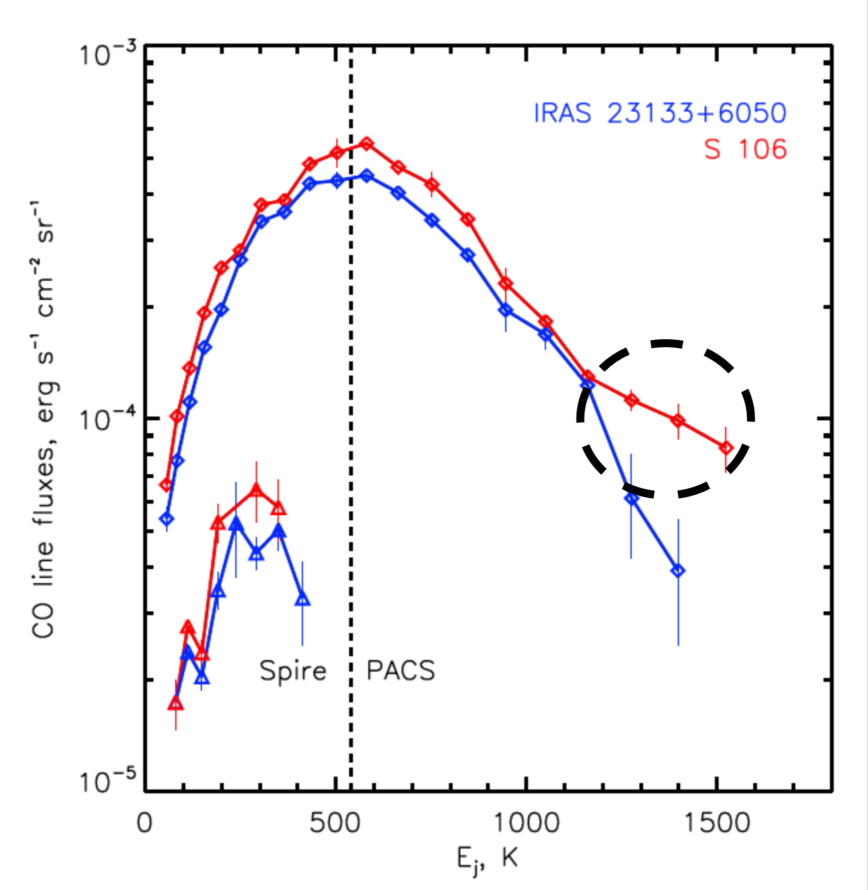
What about shocks ?

Recent results (e.g. Karska et al. 2014):

- FUV radiation affects the ***pre-shock abundances*** of some species and controls the length scale of C-shocks.

- High-J CO lines from PACS/SPIRE show ***excess.***

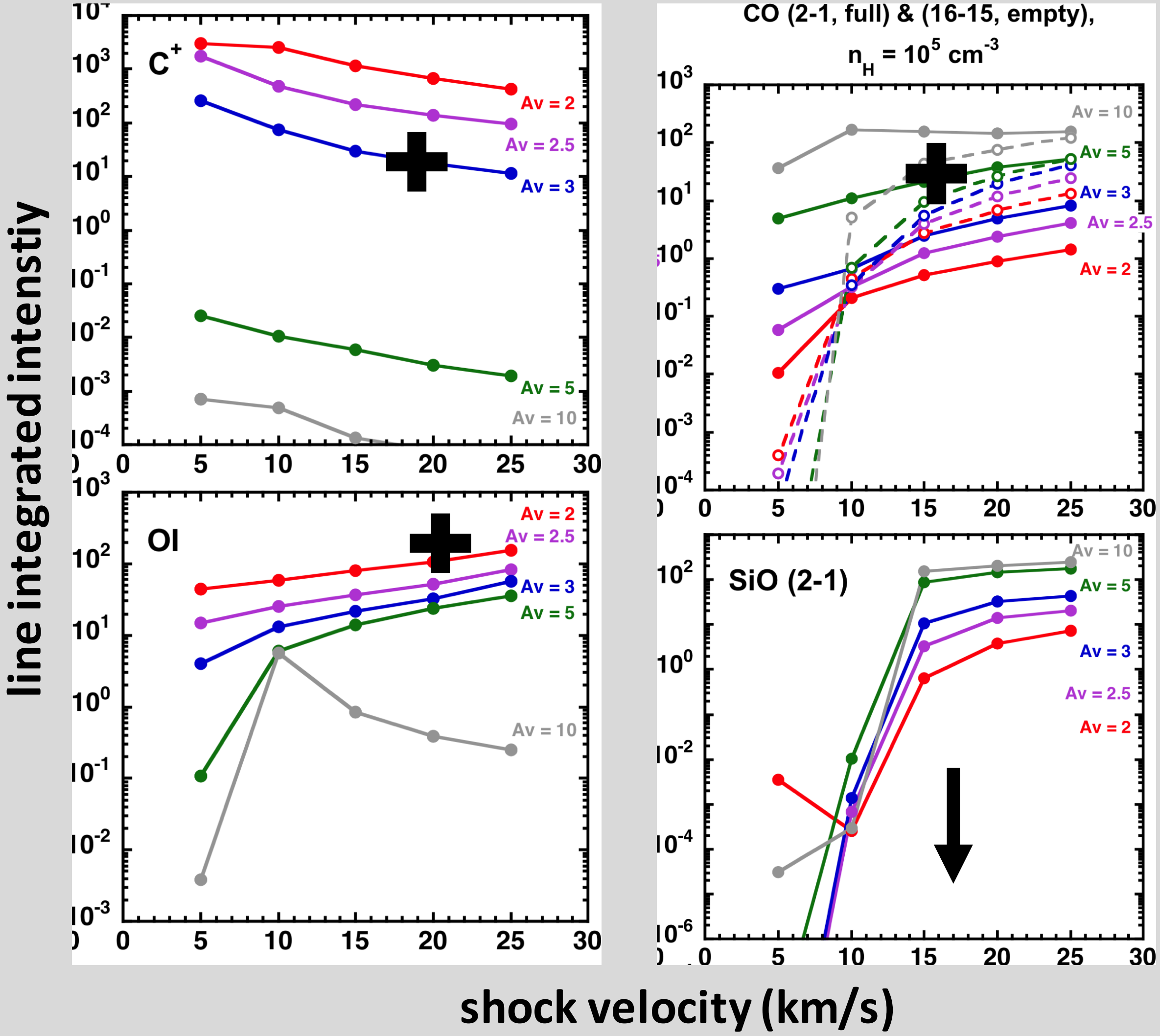
Stock et al. 2015



Important to model irradiated shocks !

Irradiated shock models of *A. Gusdorf, P. Lesaffre, S. Anderl*

- pre-shock density $n_H = 10^5$ cm^{-3}, $G_0 = 3\ 10^4$
- shock velocities v_s = 5 - 25 km/s
- A_v = 2 - 10 (A_v of the 'protective layer' inside of which the shock propagates),



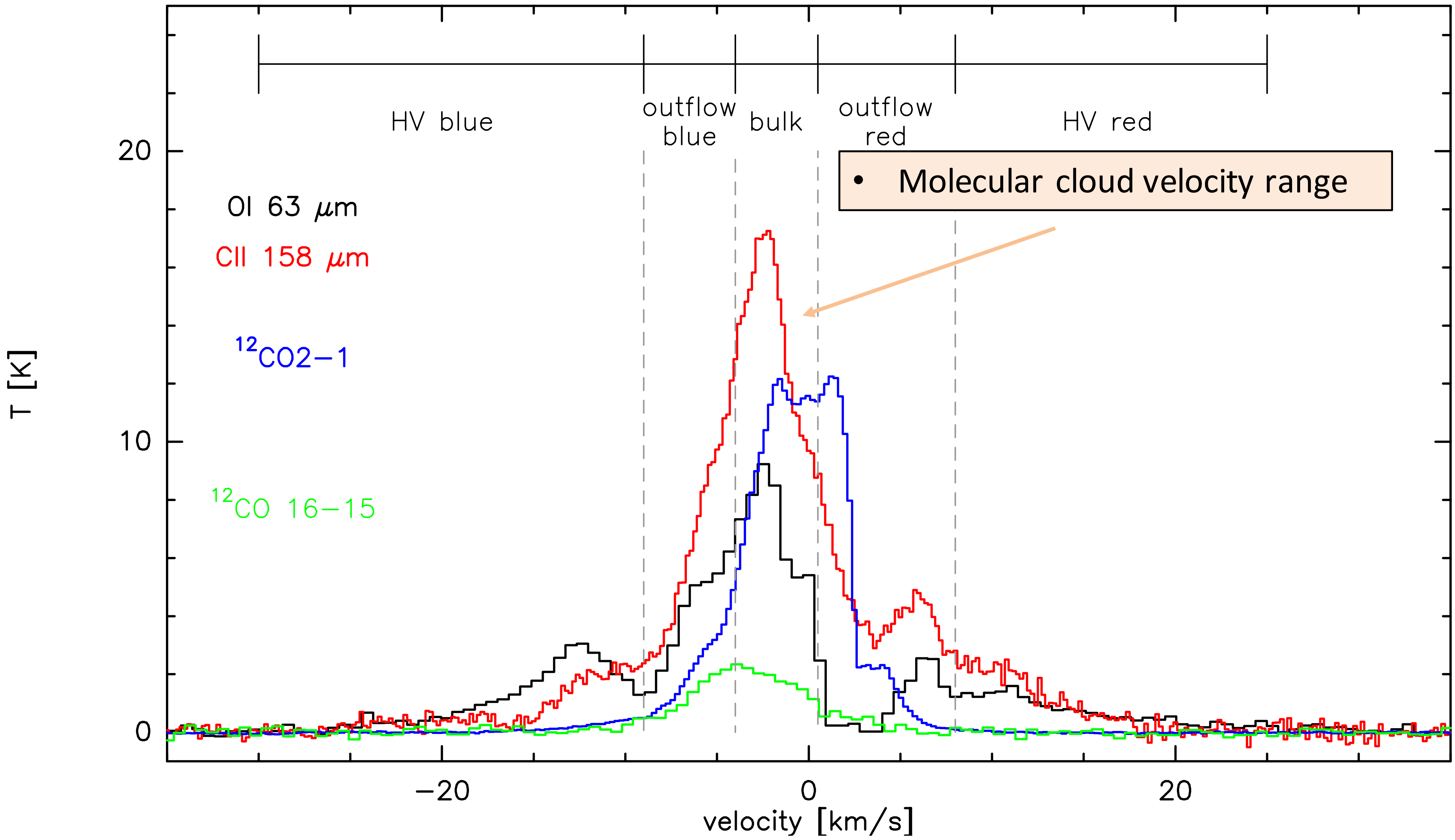
- A_v too small ?

Neither ***PDRs only***
nor ***shocks only***
can explain observations.

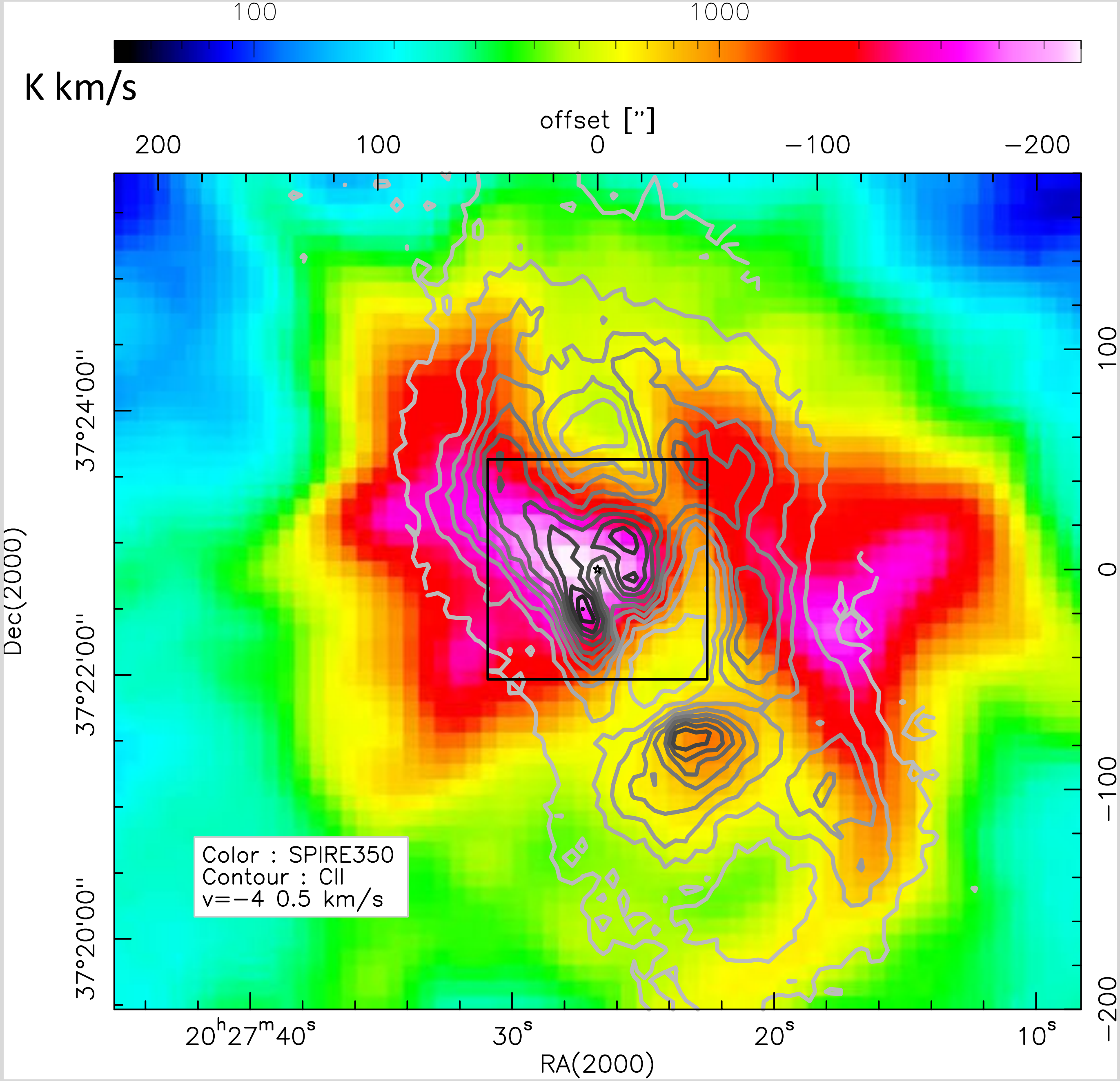
⬇

a mixture of both ?

upGREAT/SOFIA OI 63 µm average spectrum and other tracers

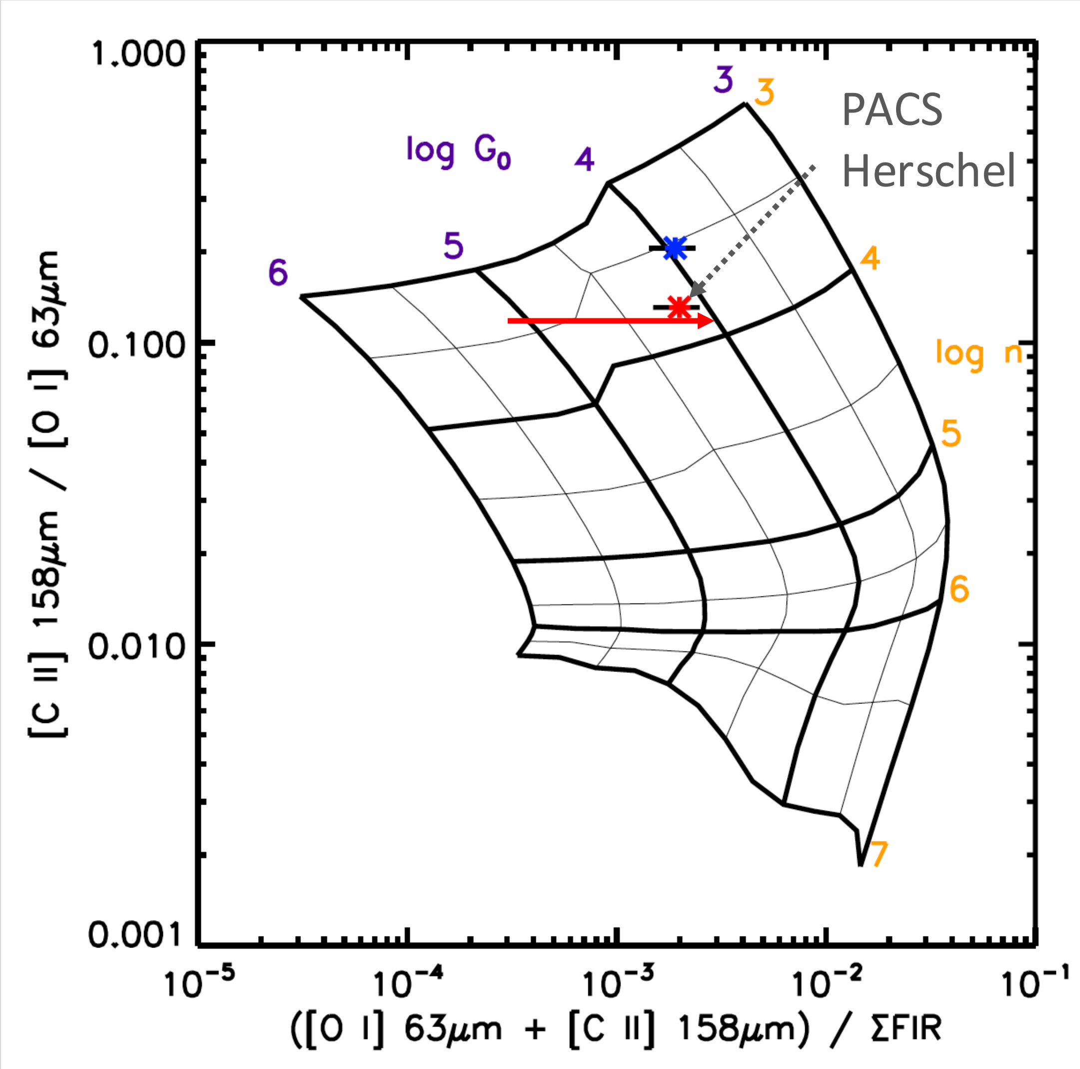


PDR modelling : bulk emission of the cloud



PDR model of *Wolfire et al. 2010, Hollenbach et al. 2012* shown in *Stock et al. 2015*

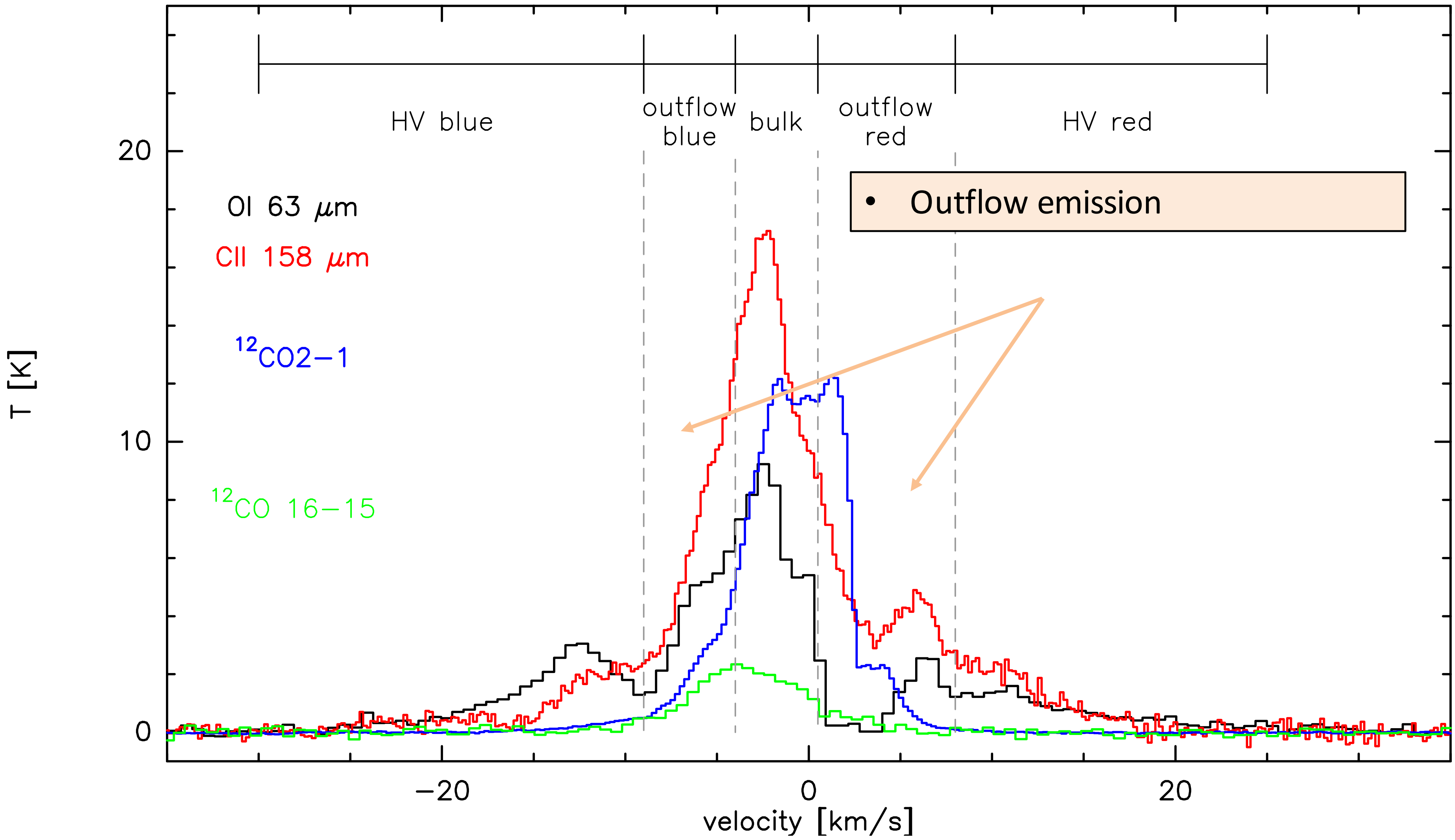
CII and OI bulk emission ('classical PDR'): **radiation field 10^4-10^5 G_o, density $10^{3.5-4}$ cm^{-3}**



Results consistent with

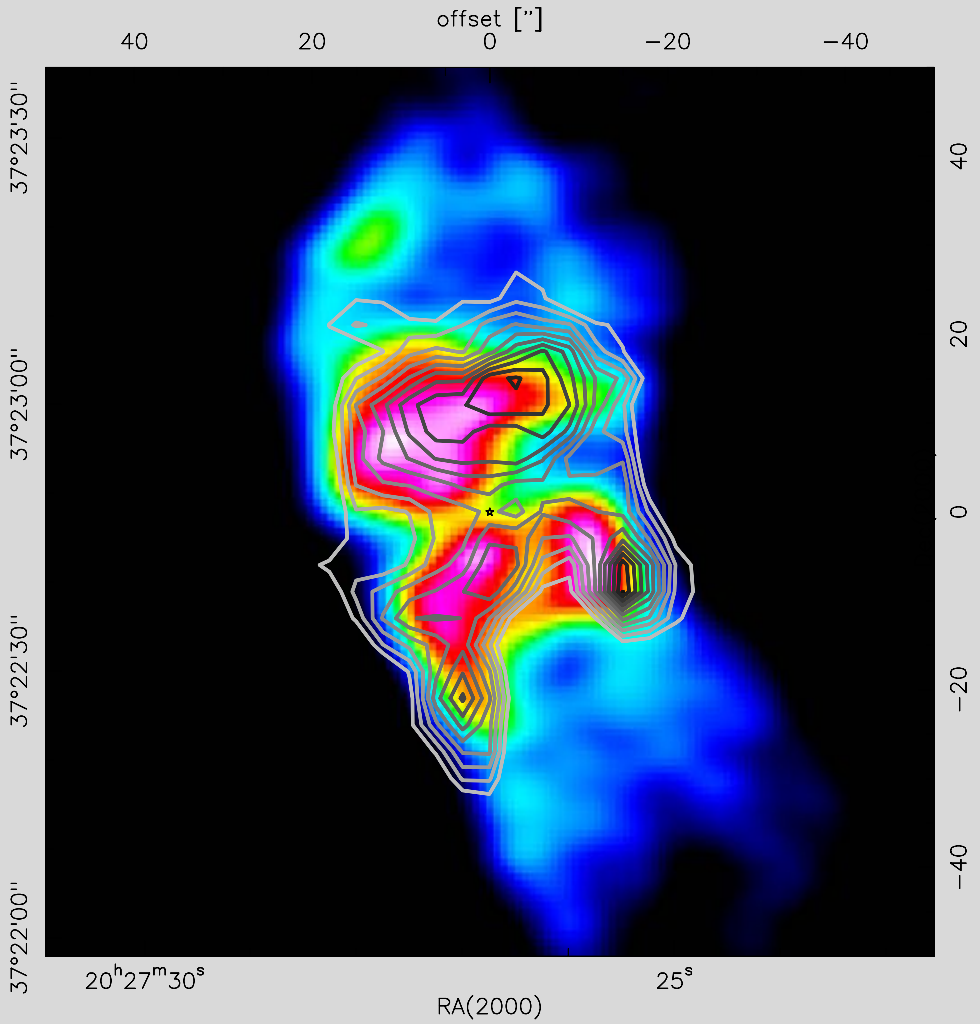
van den Ancker et al. 2000,
Schneider et al. 2003,
Stock et al. 2015.

upGREAT/SOFIA OI 63 μm average spectrum and other tracers

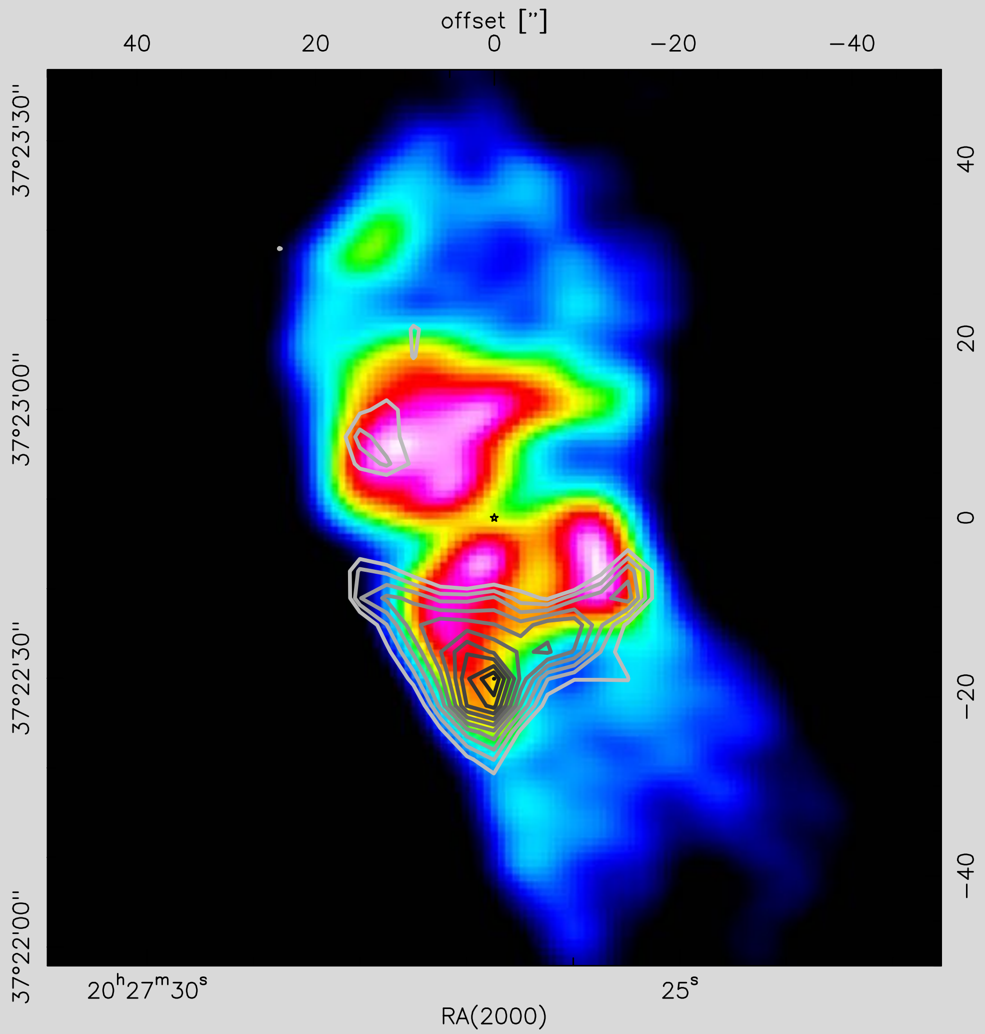


OI 63 micron on VLA (tracing the HII region)

Outflow emission from cavity **blue**

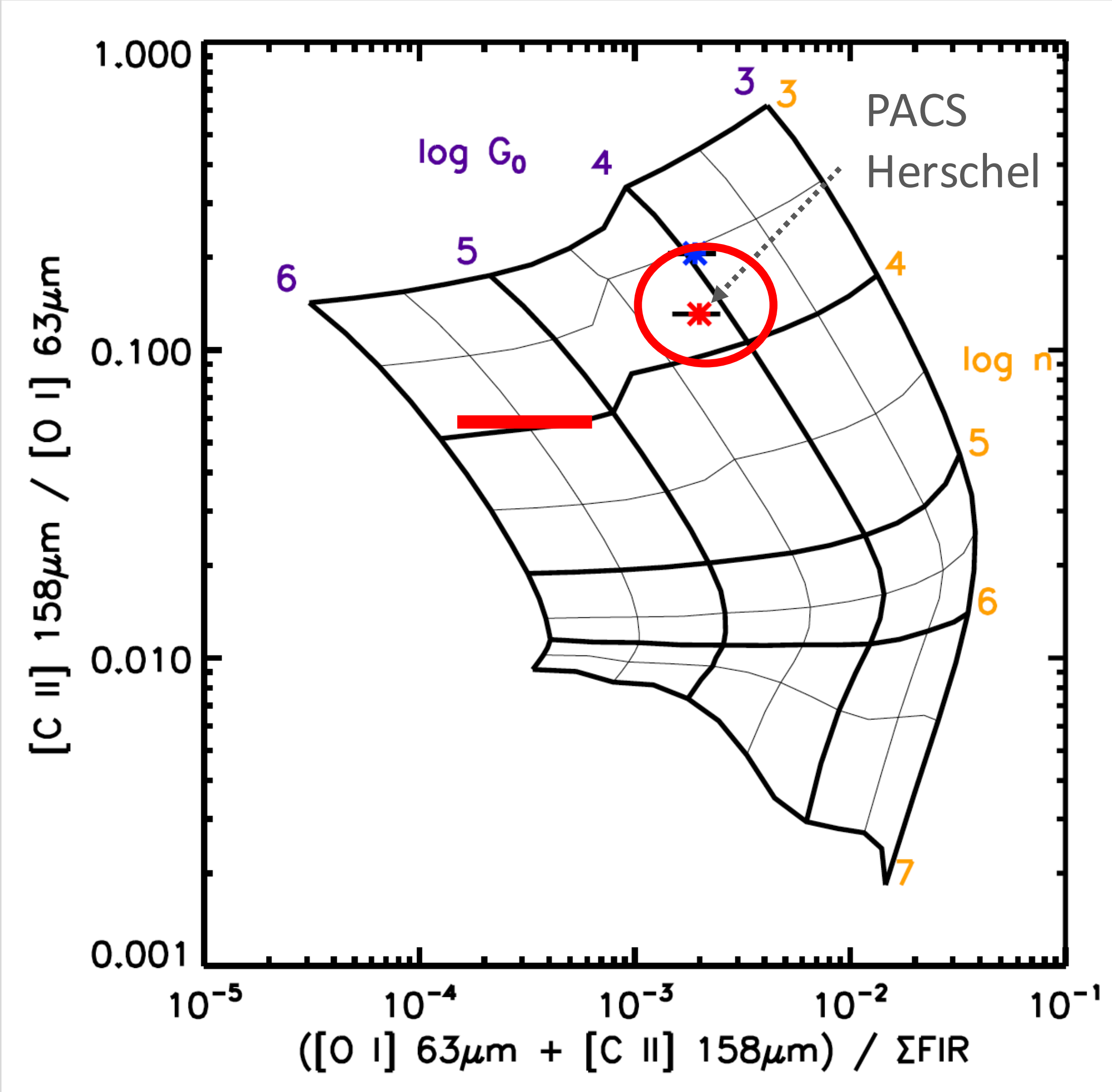


Outflow emission from cavity **red**



PDR model of *Wolfire et al. 2010, Hollenbach et al. 2012* **shown in** *Stock et al. 2015*

Outflow (PDRs on cavity walls): **radiation field 10^5-10^6 G_o, density 10^4 cm^{-3}**



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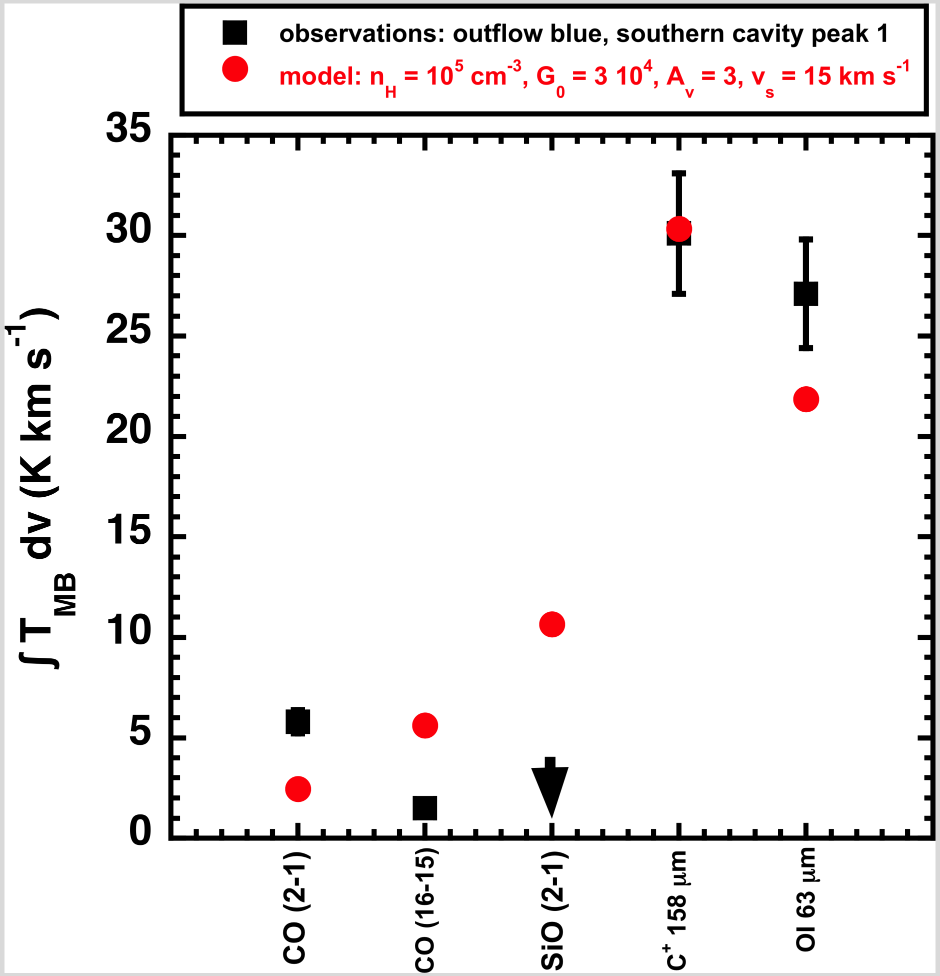

- OI too low (self -absorption?)
- No SiO

But in general works quite well…

Conclusions

- ***velocity resolved*** observations of cooling lines indispensible for complex sources.

  -> otherwise difficult to interprete line intensities and ratios
  -> to which extend can we trust extragalactic observations ?

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- OI, CII, high-J CO line observations very useful to better understand **processes of massive star formation**.

  -> massive stars form by rapid, unorganized accretion within a dense, ionized flow
  -> more observations with SOFIA required