OI 63 µm and CII 158 µm mapping of S106 with upGREAT/SOFIA as a diagnostic for the evolution of massive stars

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GENESIS

„**GEN**eration and **E**volution of **S**tructures in the **IS**m“

- German (DFG)-french(ANR) collaboration project since 5/2017 until 12/2020
- Partners **Laboratoire d‘astrophysique de Bordeaux (LAB)** and
  I. Physikalische Institut, University of Cologne (KOSMA)
- PI Bordeaux: ***Sylvain Bontemps***
- PIs Cologne: ***Nicola Schneider, Robert Simon***

https://www.astro.uni-koeln.de/GENESIS

GENESIS „**GEN**eration and **E**volution of **S**tructures in the **Is**m“

- Disentangle the relative importance of ***gravity, turbulence, (magnetic fields)***, and ***radiation*** during the cloud- and star-formation process.
- Understanding how ***dense structures*** (filaments, cores,..) are forming.
- Identifying the ***spatial scales*** on which physical processes are happening (dissipation of turbulence, heating- and cooling, transition HI/H_2...).

What makes GENESIS different from other projects ?

- Observations covering a large parameter space of density and excitation conditions.

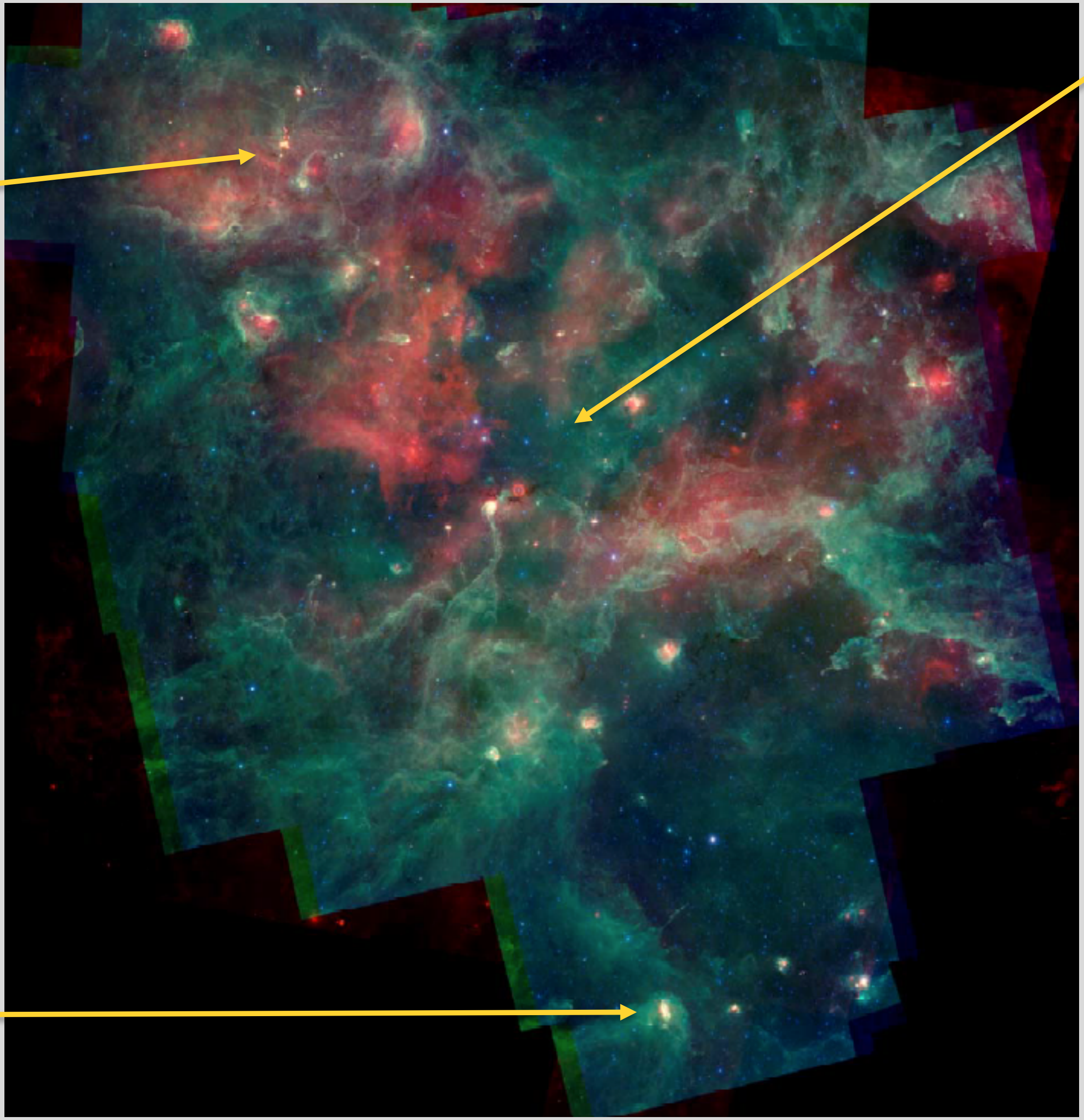
  Diffuse gas → molecular clouds → filaments → dense cores

FIR dust (*Herschel*) + **THz spectroscopy (SOFIA)** + molecular lines + HI

- Comparison with simulations, applying the same analysis tools.

- New and innovative image analysis techniques.

Workpackage: Observations of FIR cooling lines in the ISM - massive star formation



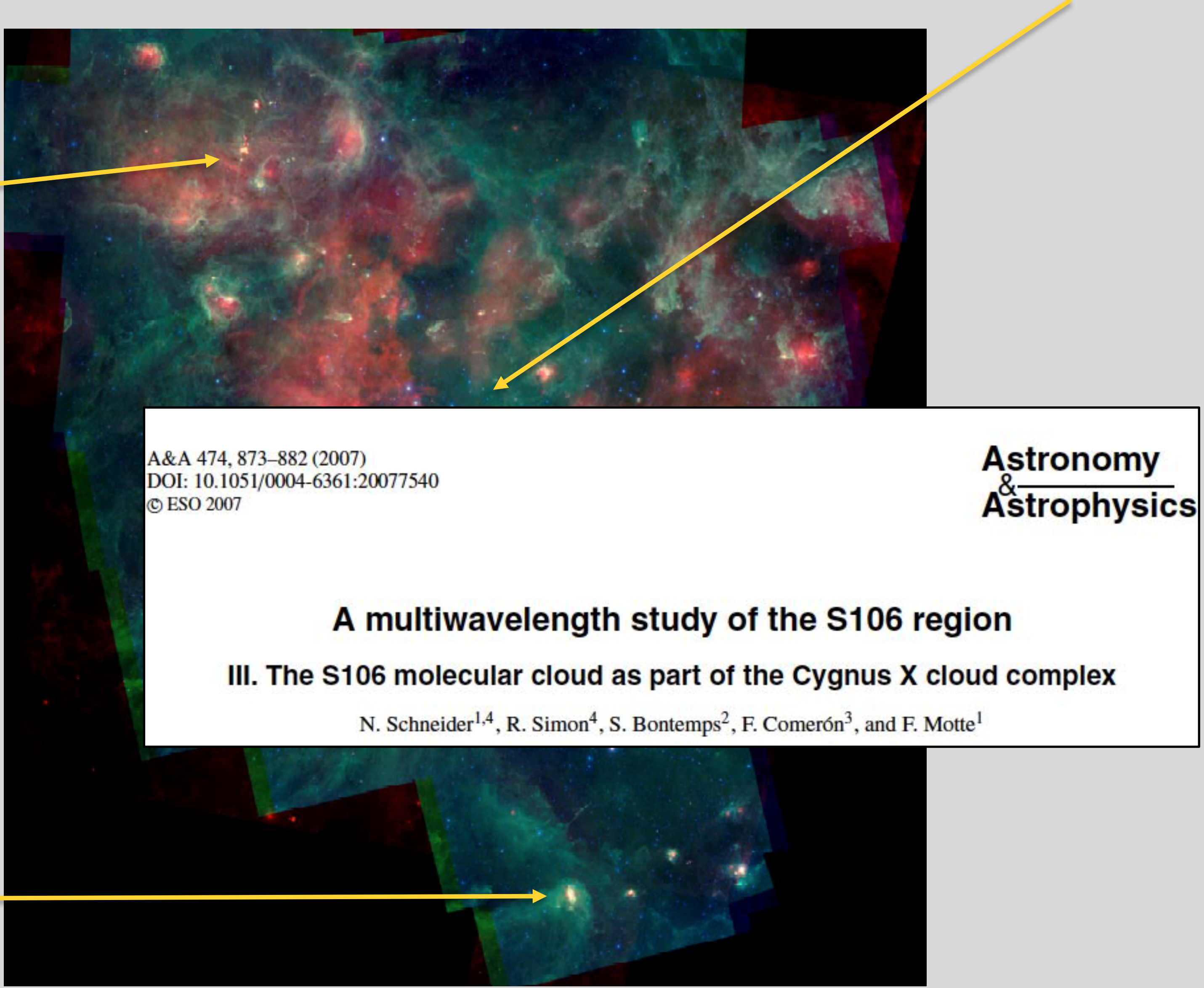
Hora et al. 2010

Workpackage: Observations of FIR cooling lines in the ISM - massive star formation

Spitzer Cygnus X Legacy

Cyg OB2

DR21/W75 N
ridge



A&A 474, 873–882 (2007)
DOI: 10.1051/0004-6361:20077540

Astronomy & Astrophysics

A multiwavelength study of the S106 region

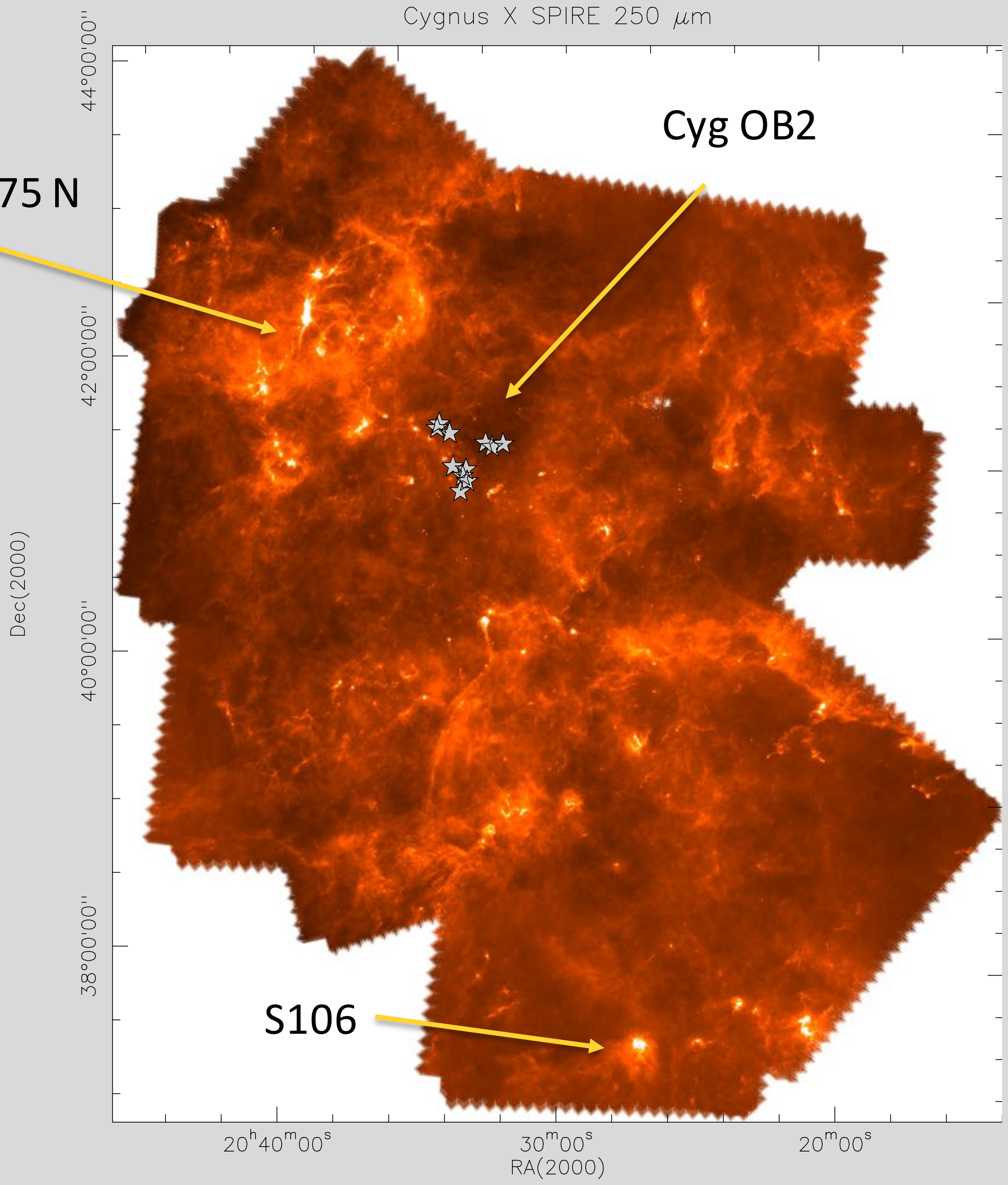
III. The S106 molecular cloud as part of the Cygnus X cloud complex

N. Schneider[1,4], R. Simon[4], S. Bontemps[2], F. Comerón[3], and F. Motte[1]

S106

Hora et al. 2010

Anatomy of a massive star-forming region: Cygnus X



DR21/W75 N ridge

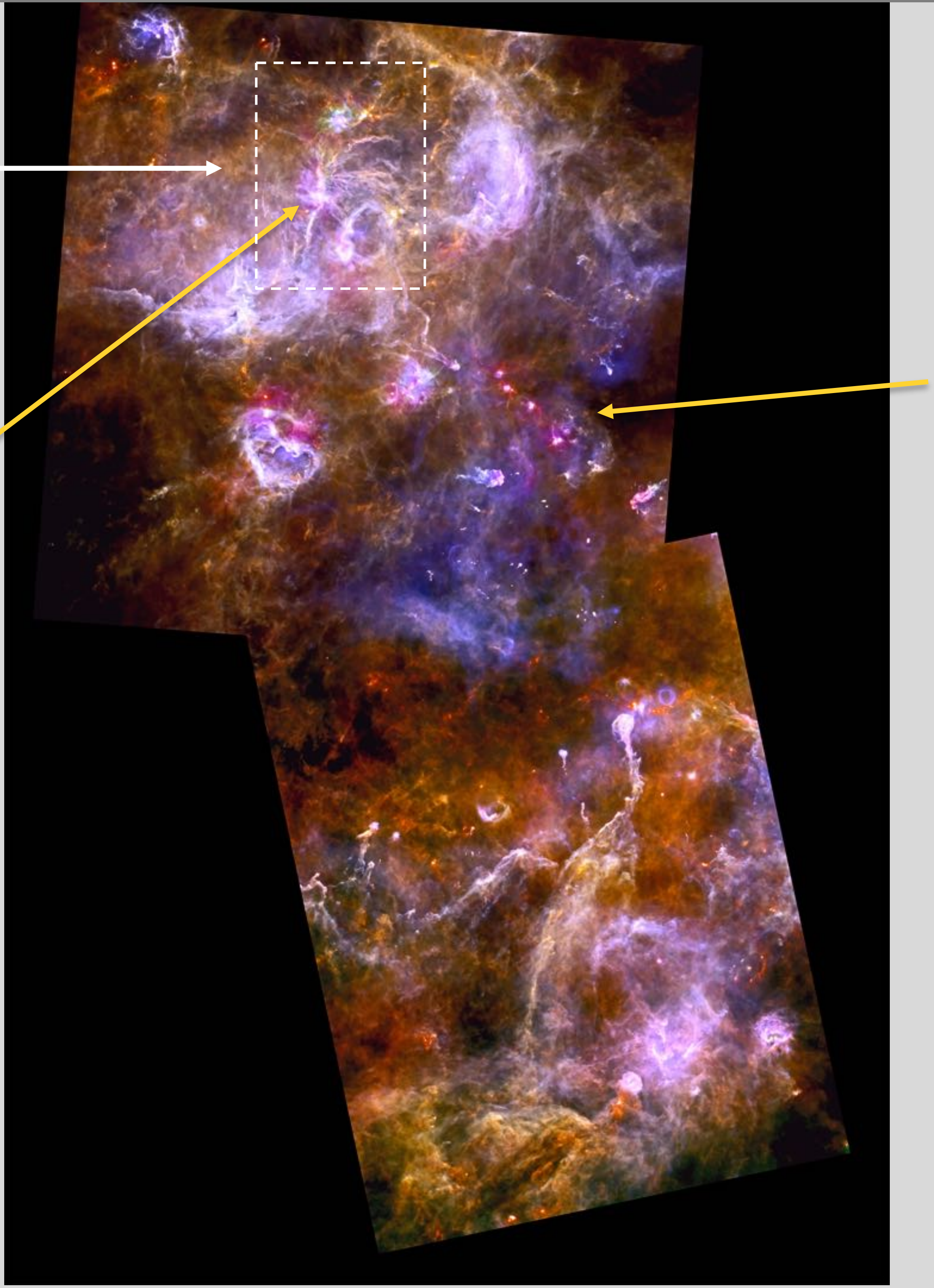
Cyg OB2

S106

Herschel

Cygnus X is star-forming engine

Herschel image (70, 160, 250 µm)



Area proposed for SOFIA legacy upGREAT CII mapping (*Tielens & Schneider*)

DR21/W75 N ridge

Cyg OB2 cluster

Schneider et al. 2016

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**,…

⬇

<u>Evolutionary phases of massive star formation</u>

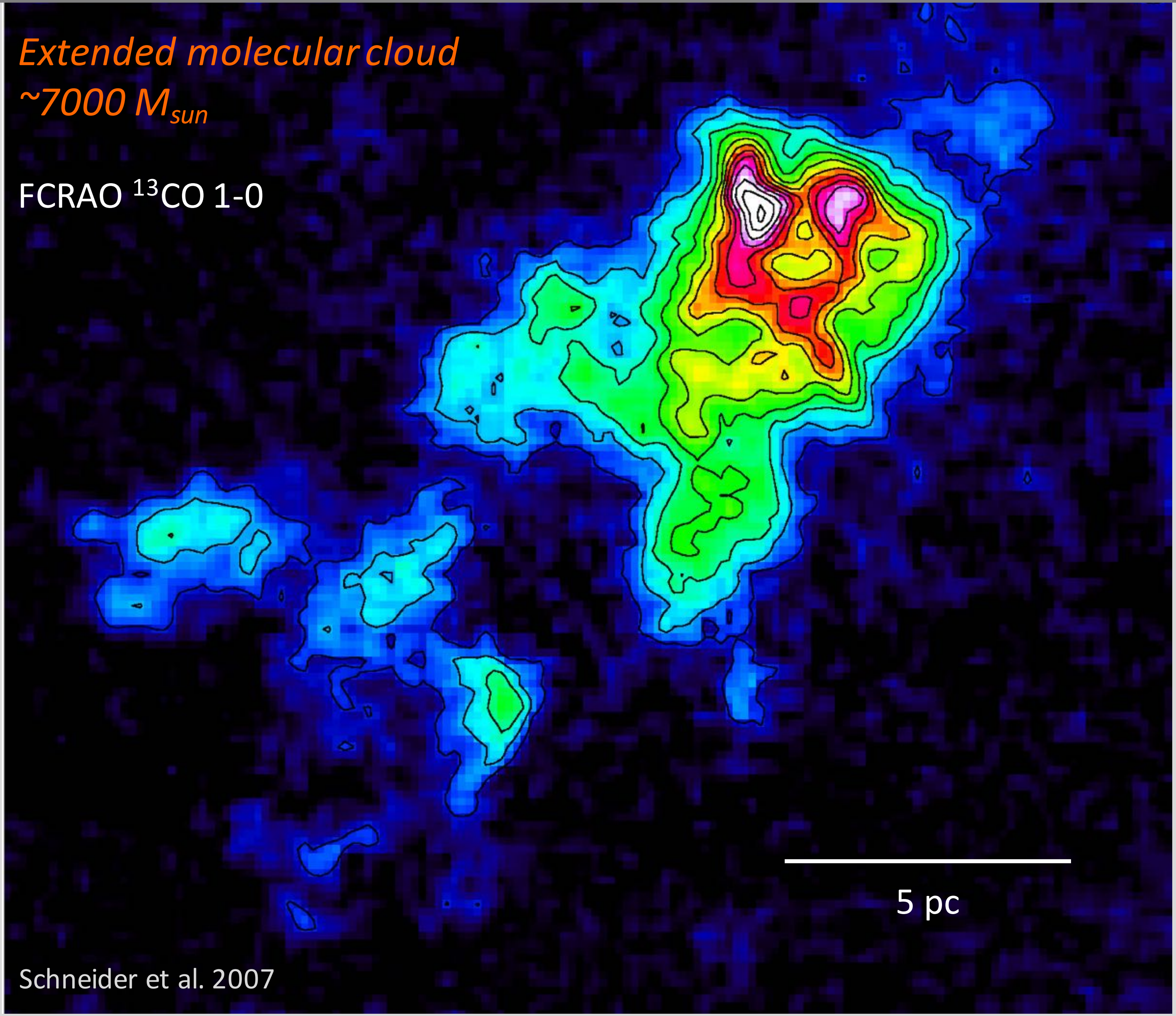
Anatomy of a massive star-forming region: S106

- **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



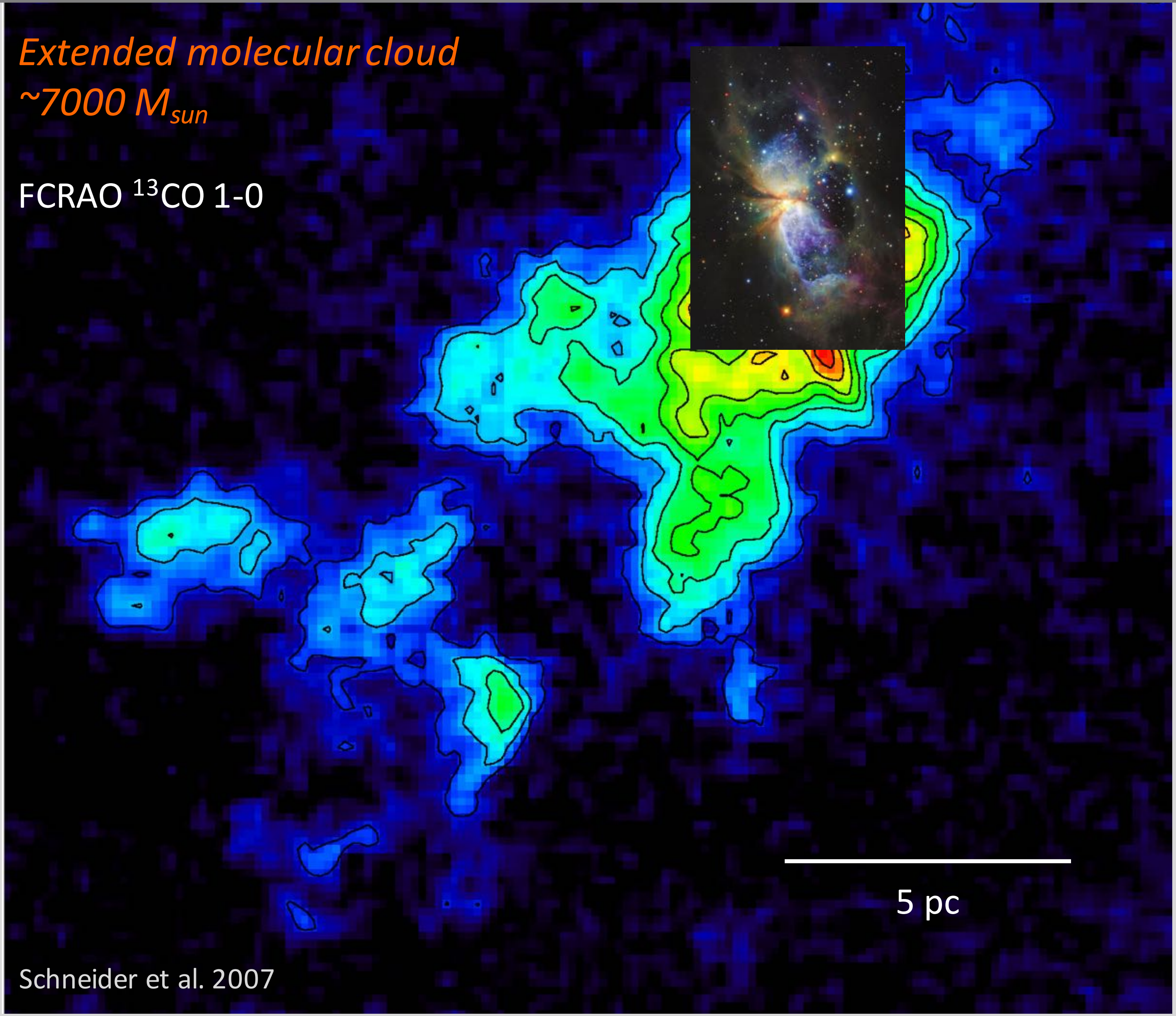
Extended molecular cloud

~7000 M_{sun}

FCRAO ^{13}CO 1-0

Schneider et al. 2007

Anatomy of a massive star-forming region: S106



Extended molecular cloud

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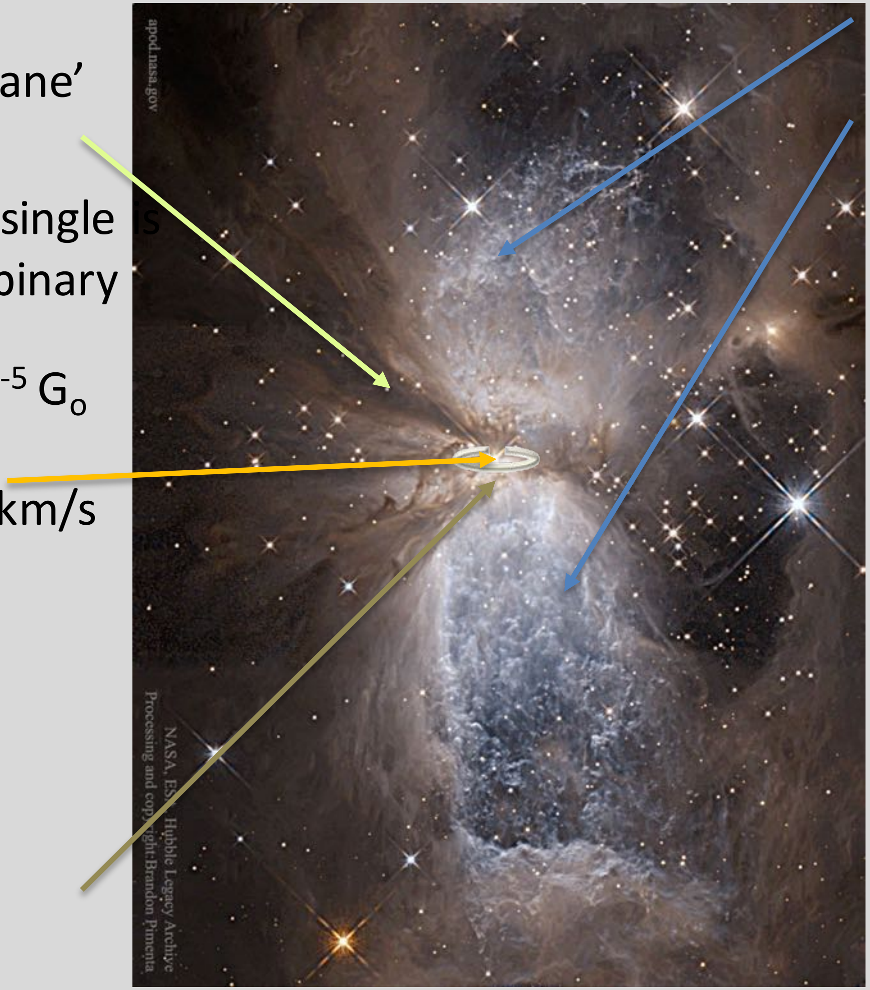
Schneider et al. 2007

Anatomy of a massive star-forming region: S106



- ‘dark lane’

- **S106 IR,** thought to be single star was found to be a binary (Comeron et al. 2018)
- UV radiation up to 10^{4-5} G_o at 0.1 pc
- stellar wind ~100-200 km/s

- small disk-like feature

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

- distance **1.3 kpc**

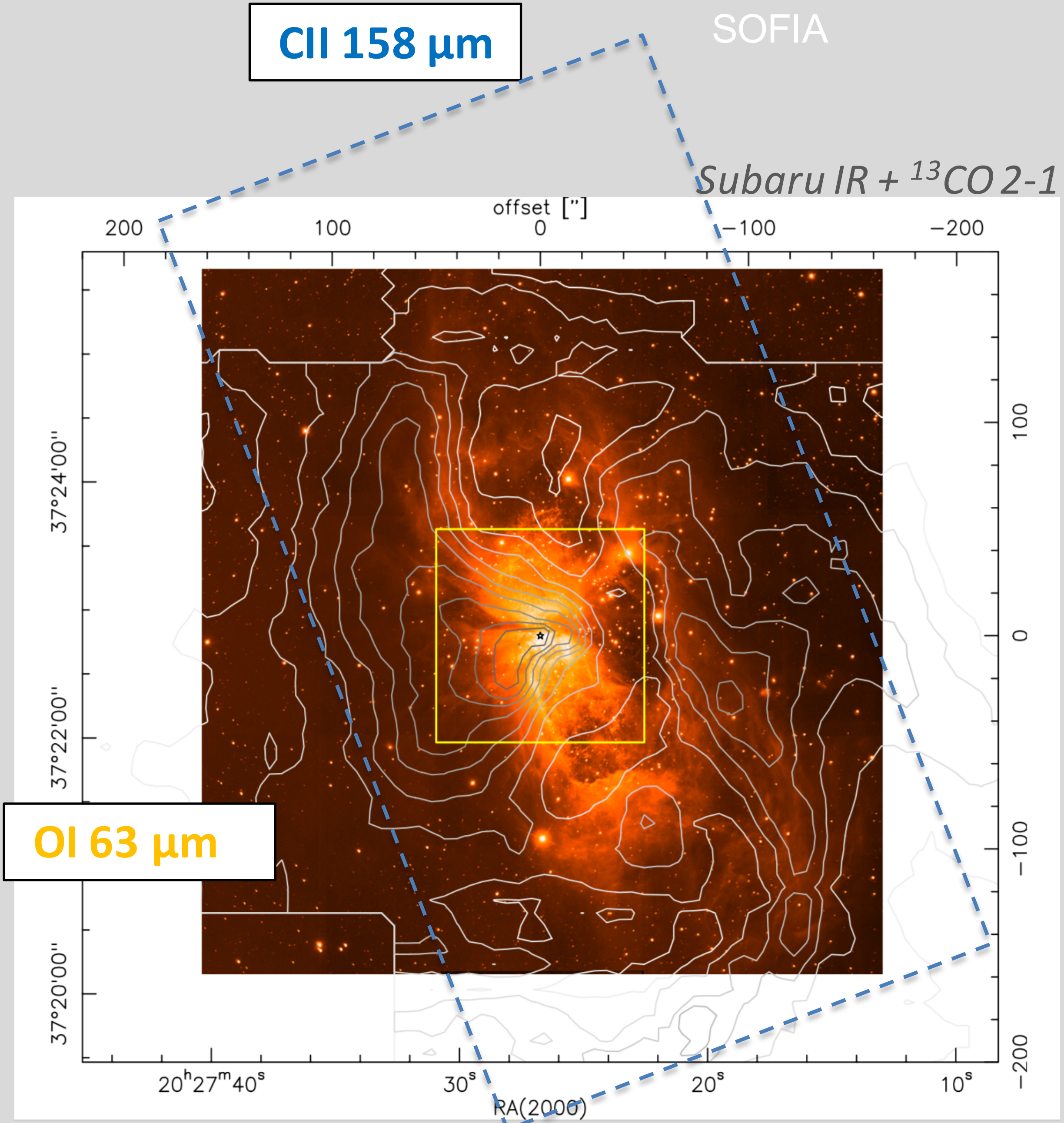
- embedded in a large molecular cloud

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

upGREAT/SOFIA CII and OI observations

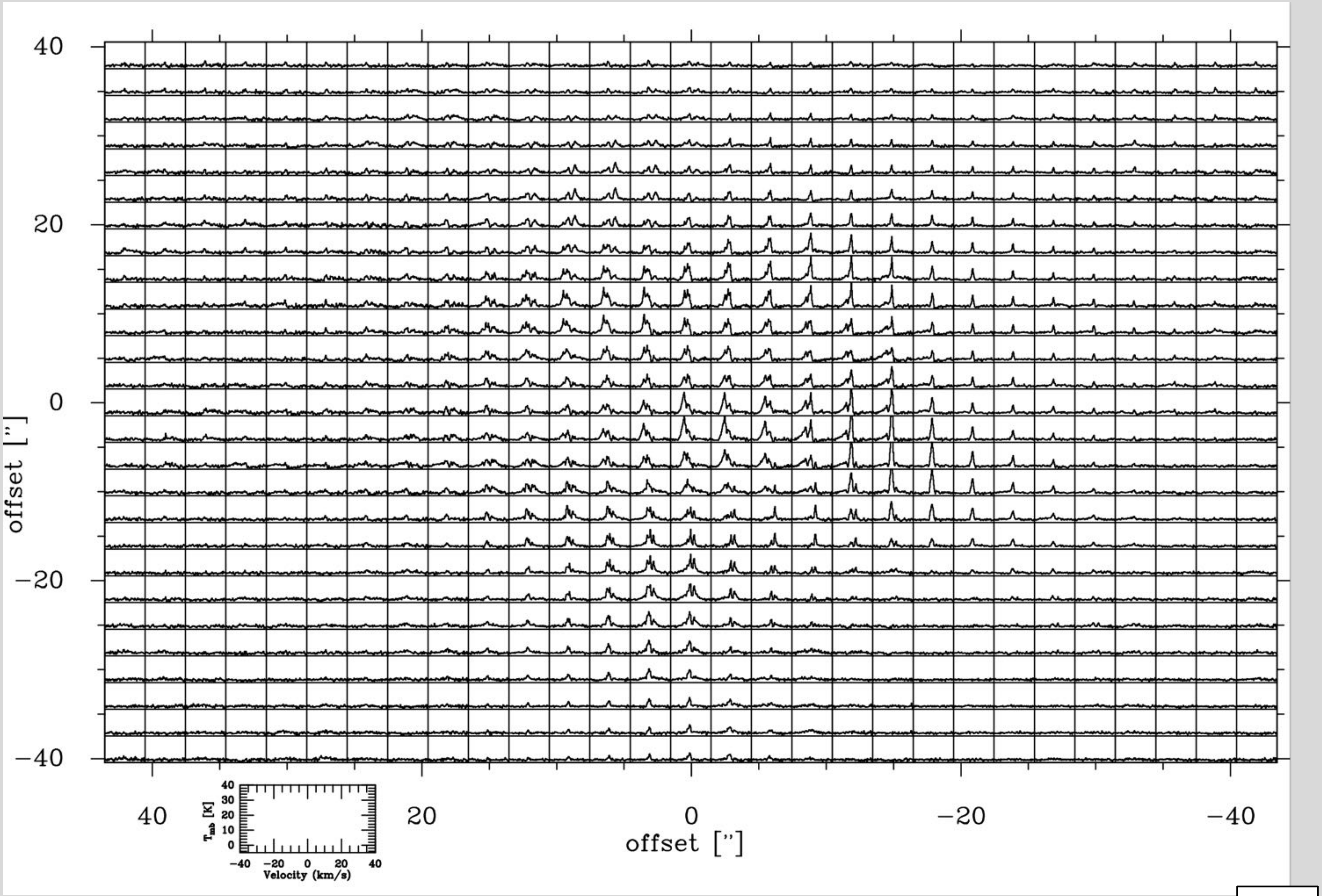
- **[CII] 158 µm** upGREAT/SOFIA data (GT time) (PI *R. Simon*)
- **[OI] 63 µm** GREAT/SOFIA data from december 2015 OT time (PI *N. Schneider*)

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

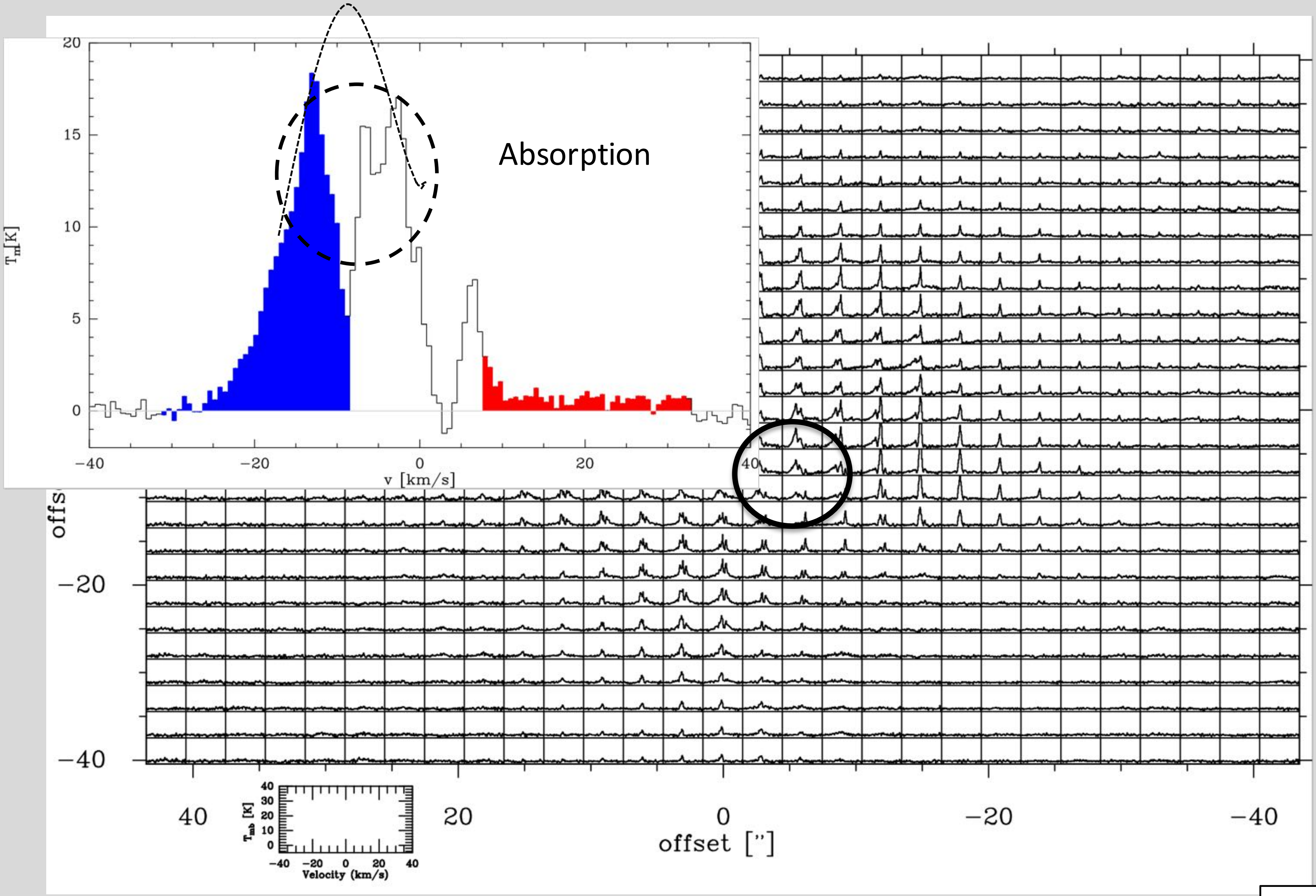


Schneider et al. 2018, A&A 617, 45; Simon et al. in prep.

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

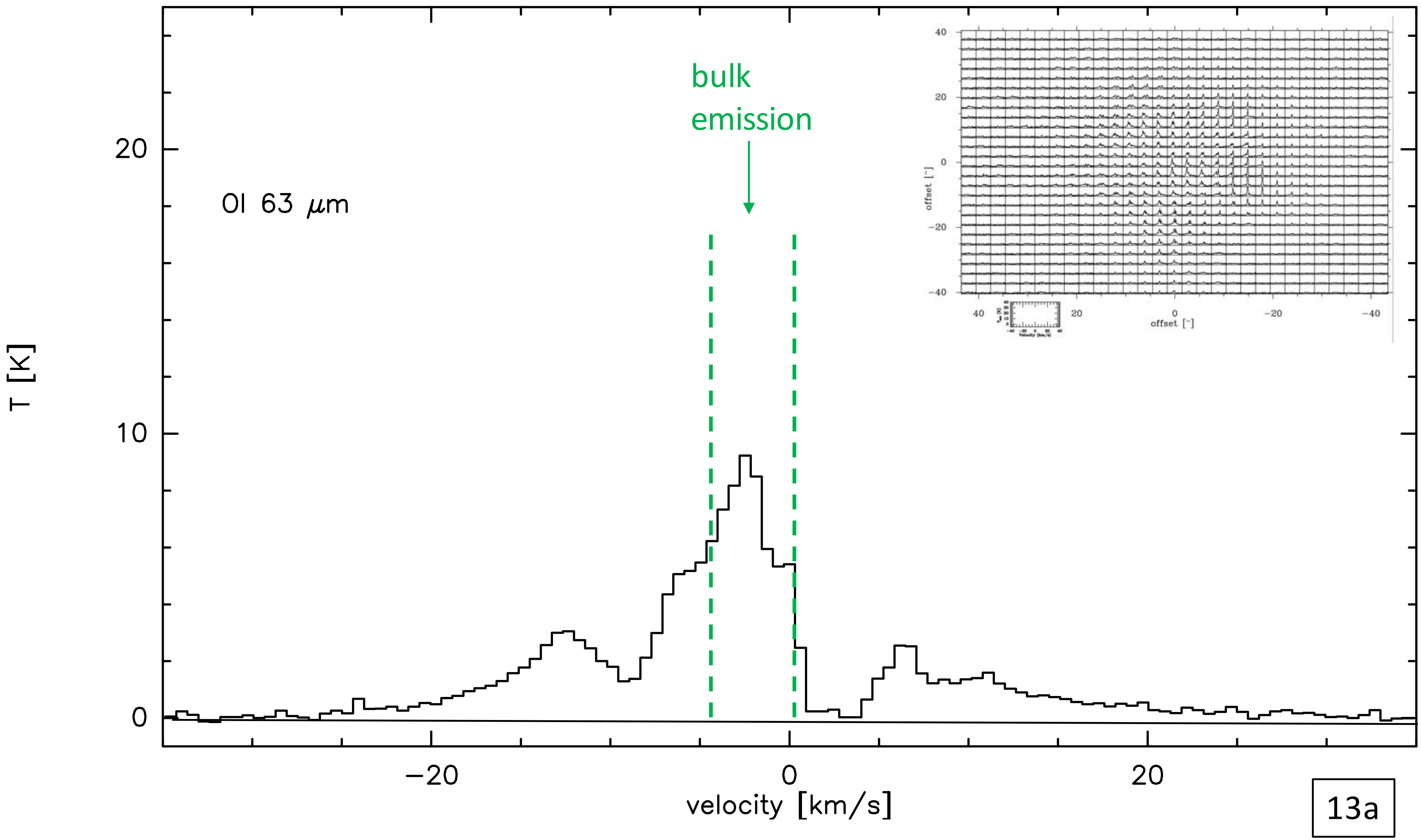


upGREAT/SOFIA OI 63 μm map at 6“ angular resolution


Absorption

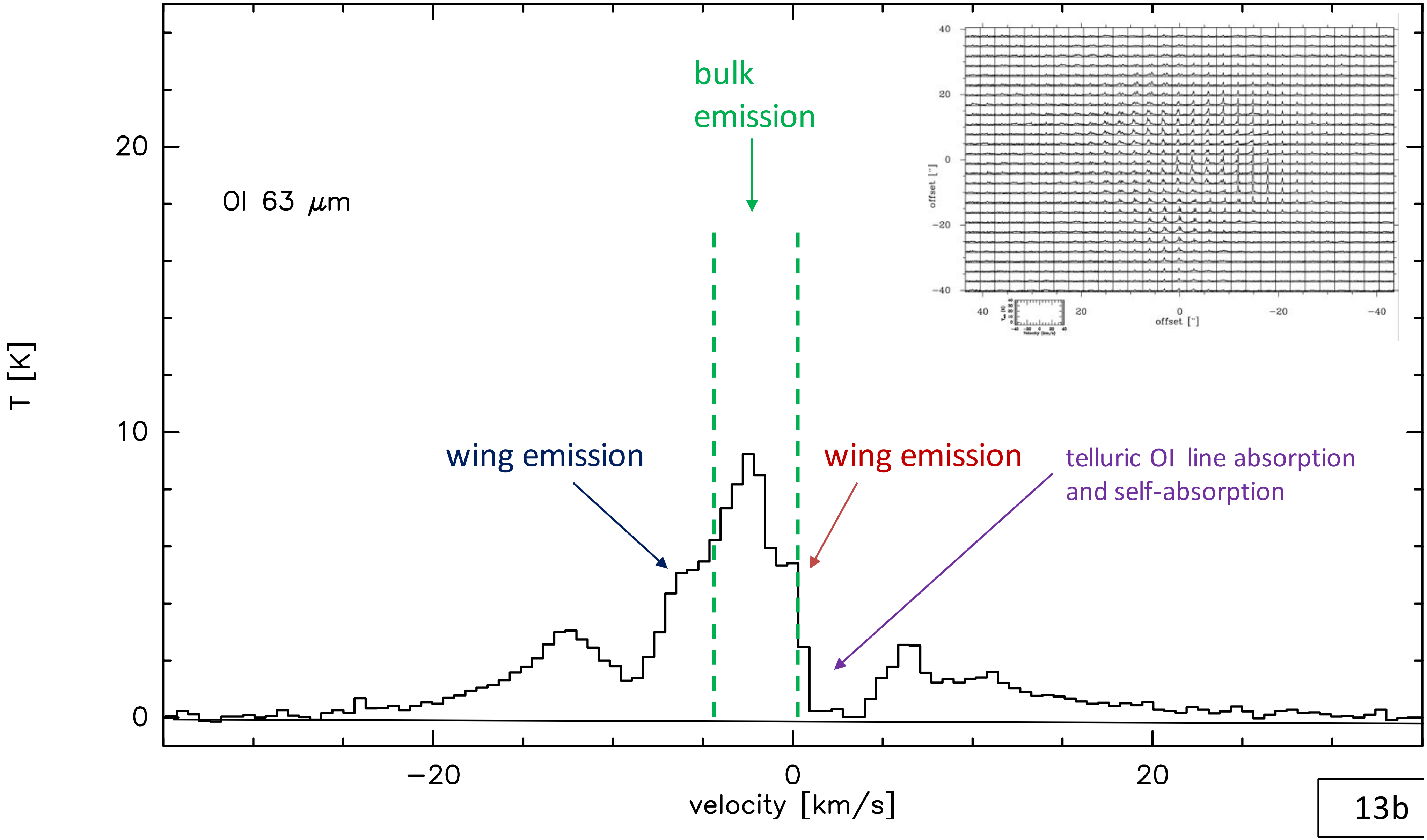
upGREAT/SOFIA OI 63 μm

Average spectrum across OI mapping area



upGREAT/SOFIA OI 63 μm

Average spectrum across OI mapping area



bulk emission

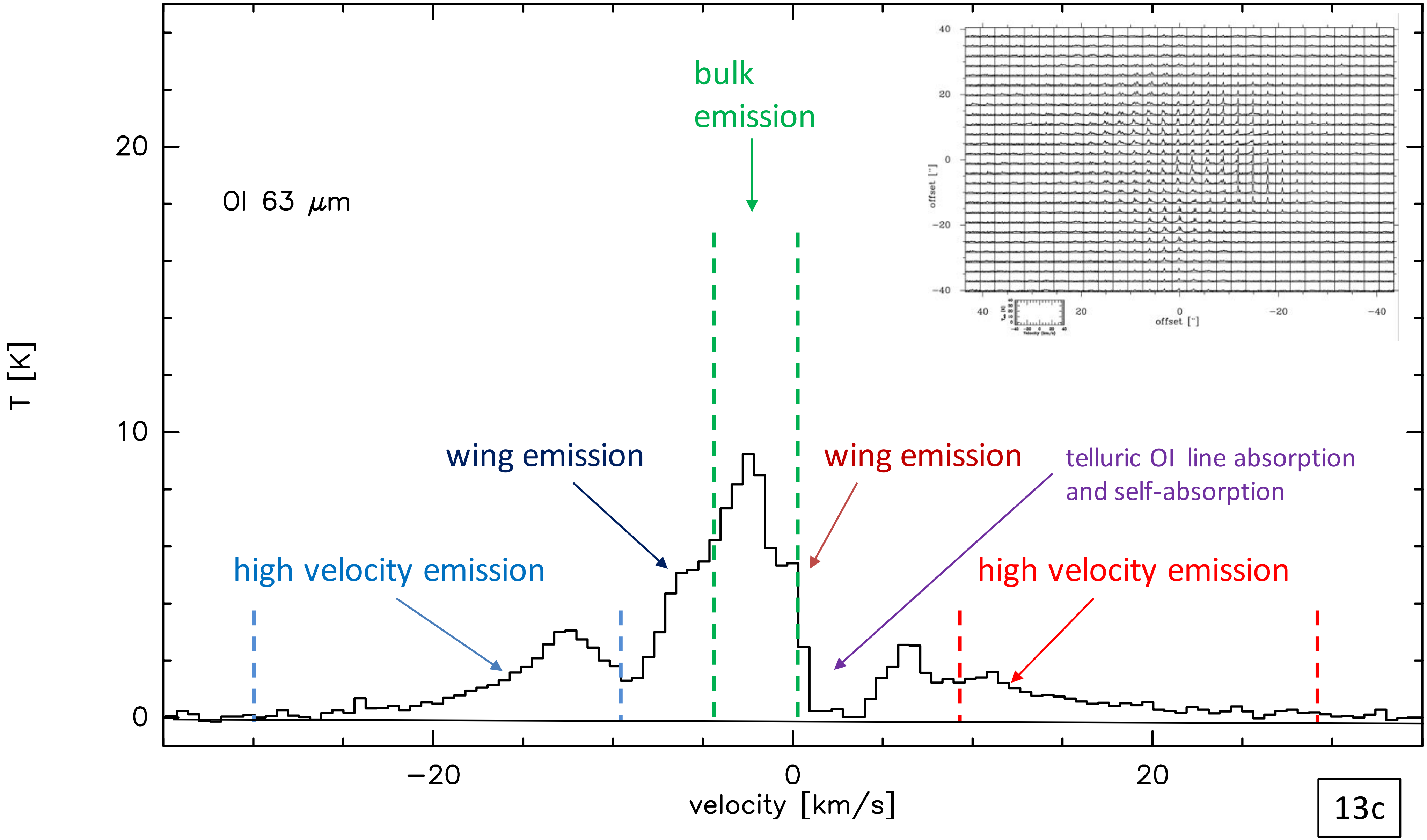
wing emission

wing emission

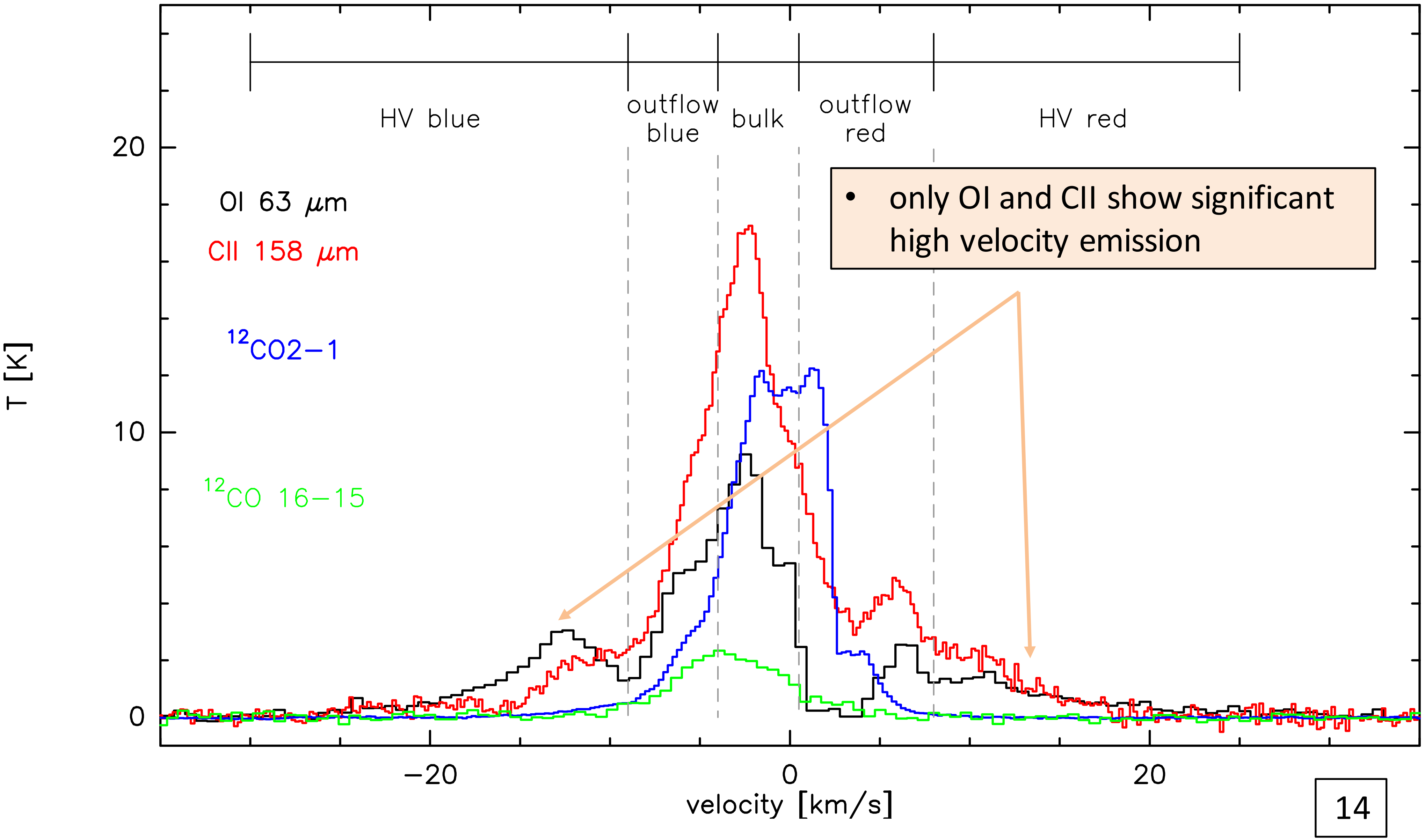
telluric OI line absorption and self-absorption

upGREAT/SOFIA OI 63 µm

Average spectrum across OI mapping area



upGREAT/SOFIA OI 63 µm average spectrum and other tracers

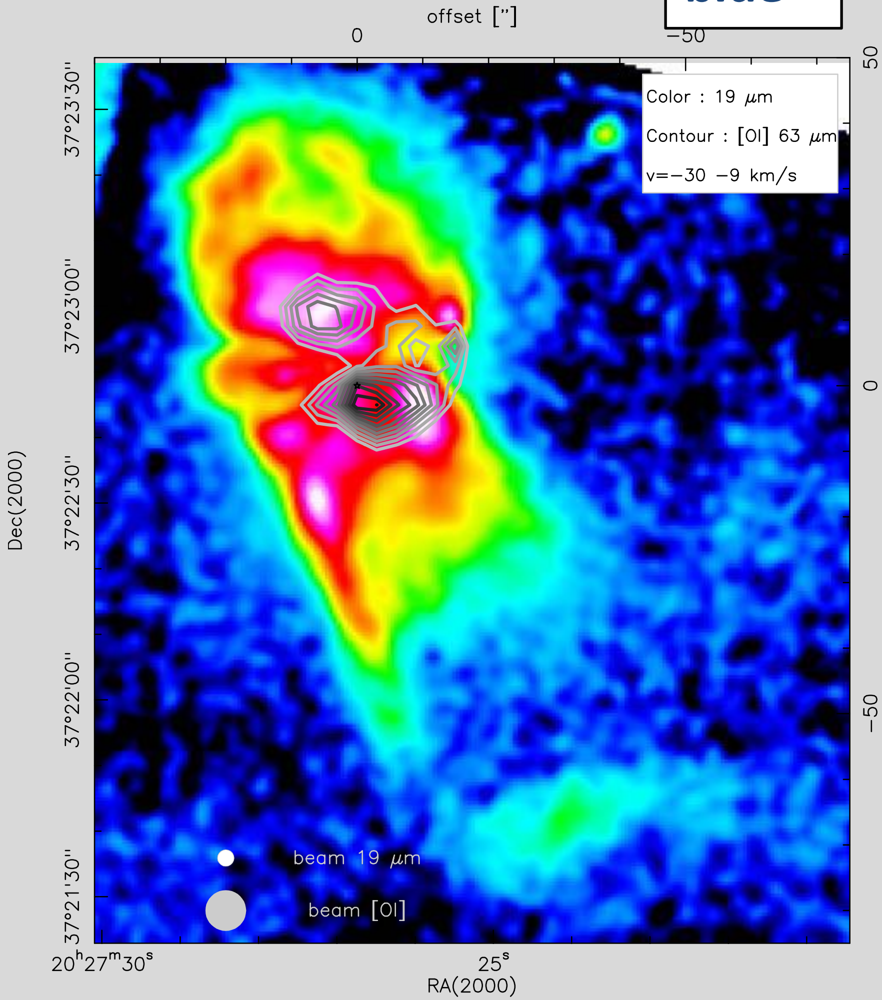


- only OI and CII show significant high velocity emission

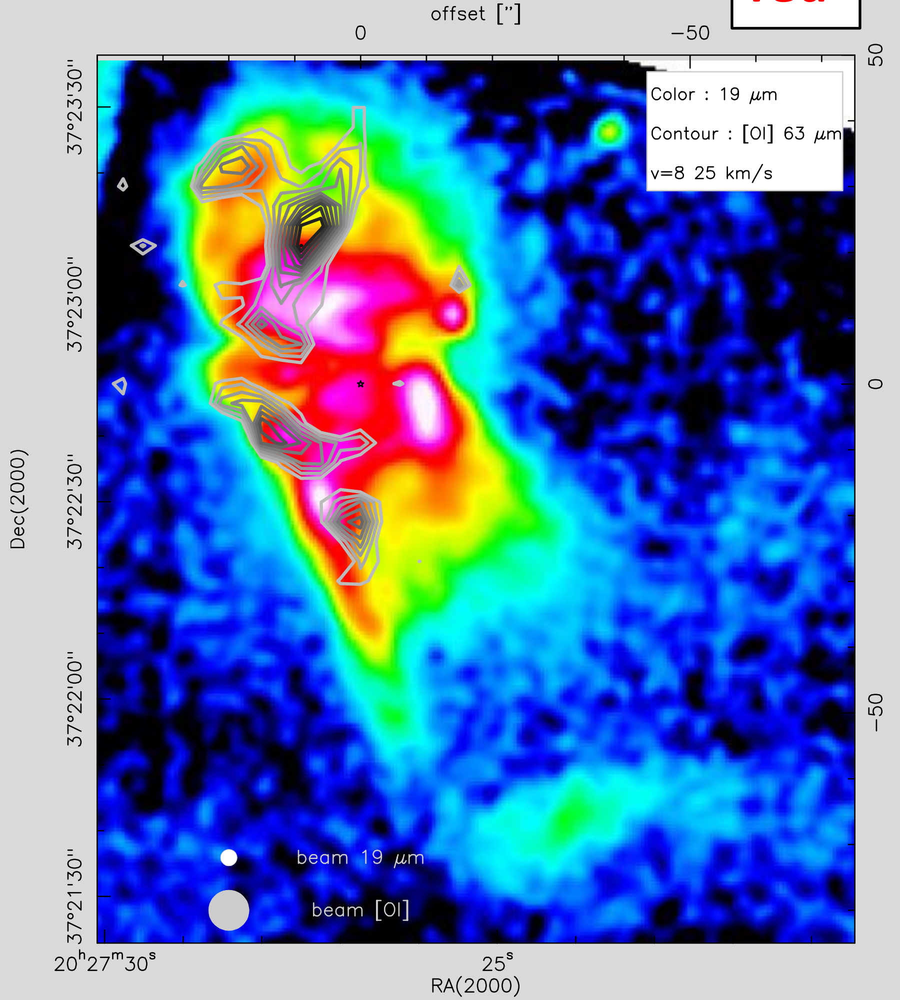
OI 63 μm on 19 μm FORCAST/SOFIA mid-IR emission (warm dust)

- 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 ?

blue



red



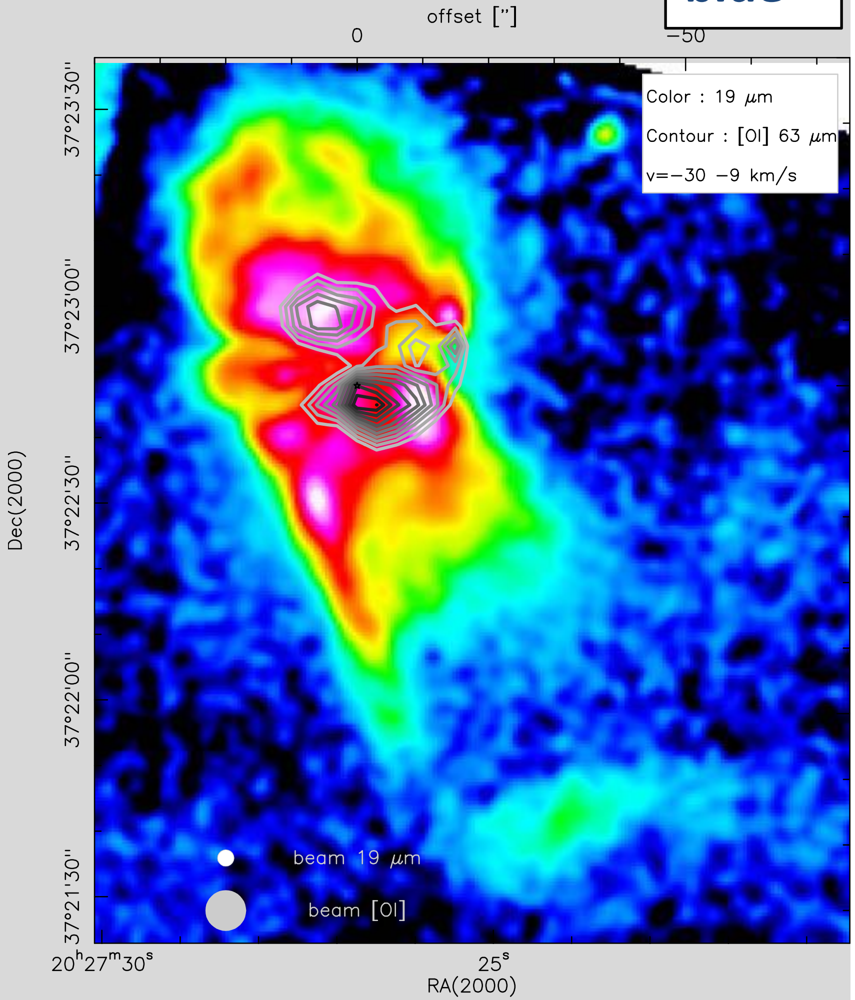
FORCAST observations : Adams et al. 2015

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

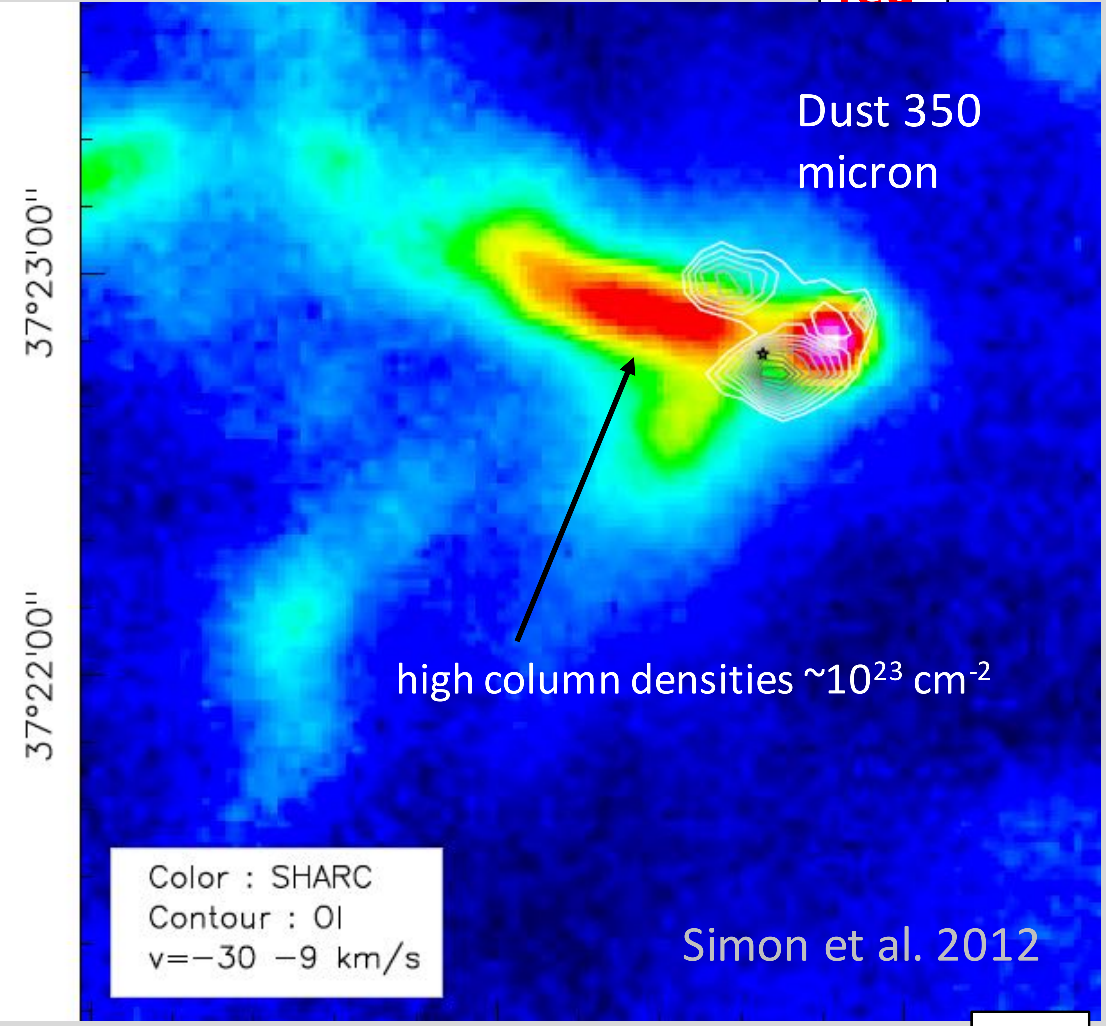
Is the ‘dark lane’ an accretion flow, ionized on its front/backside ?

blue

red



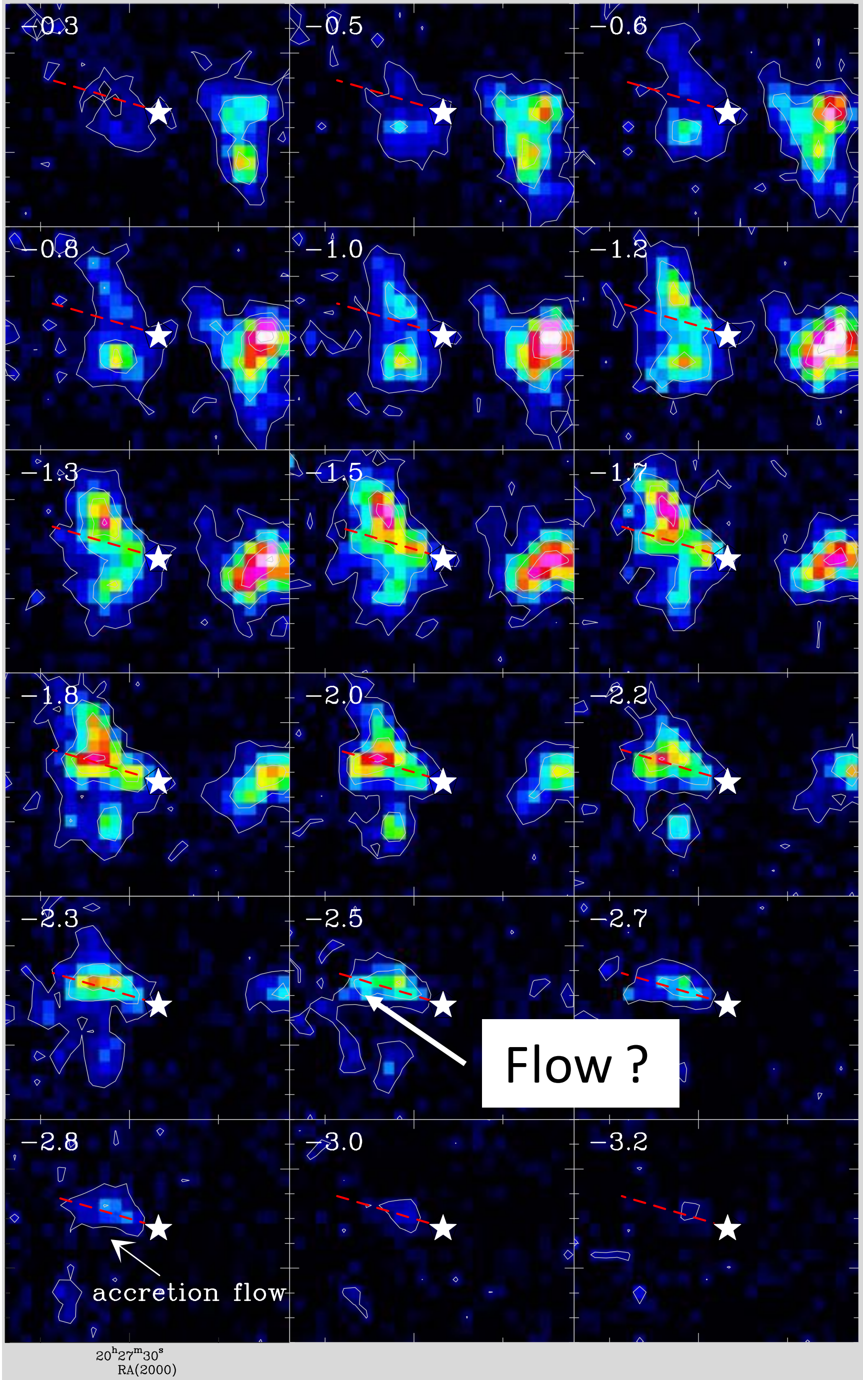
FORCAST observations : Adams et al. 2015



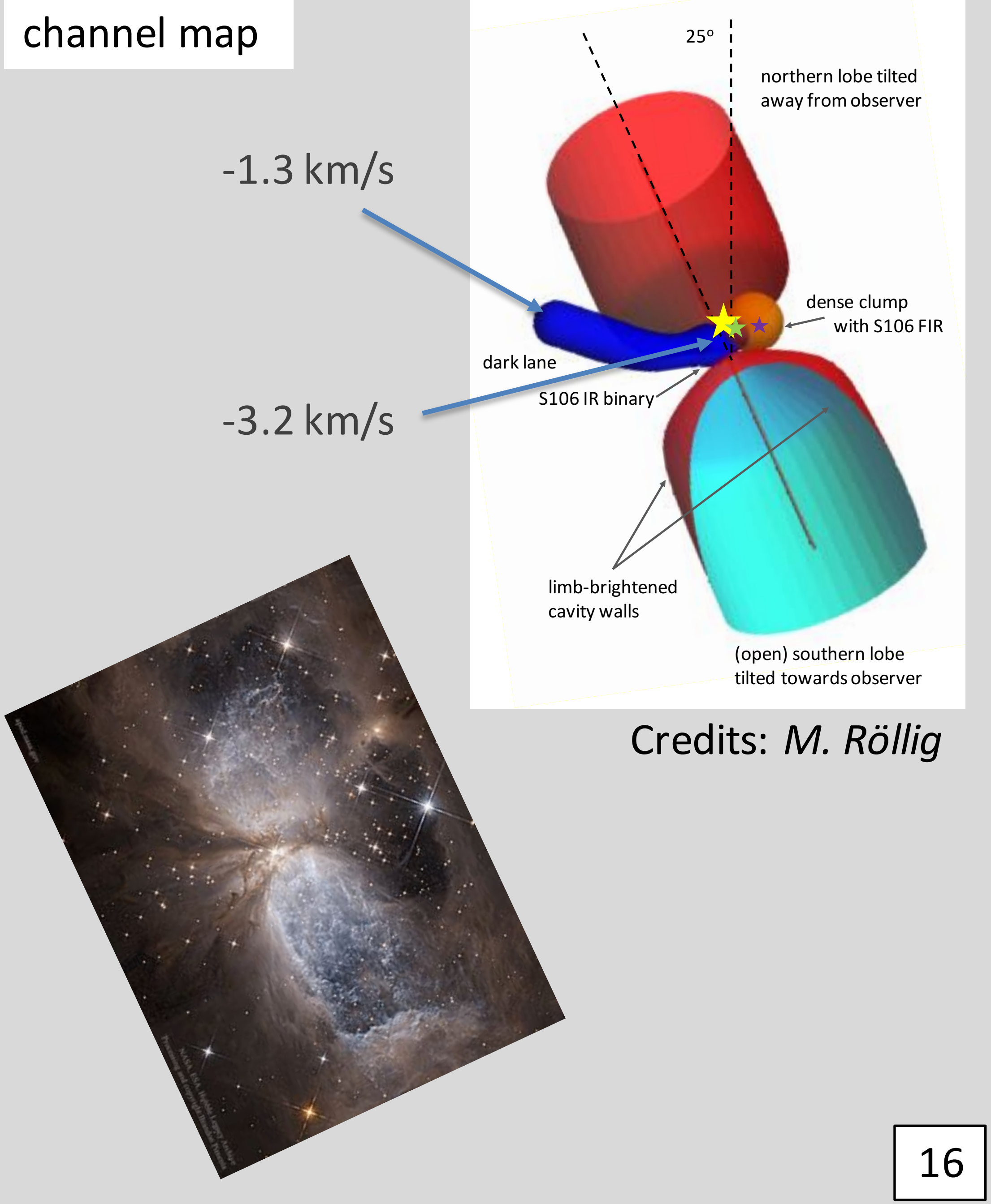
high column densities ~10^{23} cm^{-2}

Simon et al. 2012

Dynamics of the molecular gas $H^{13}CO^+$ 1-0 (density ~ 10^5 cm^{-3}, T~10-20 K)

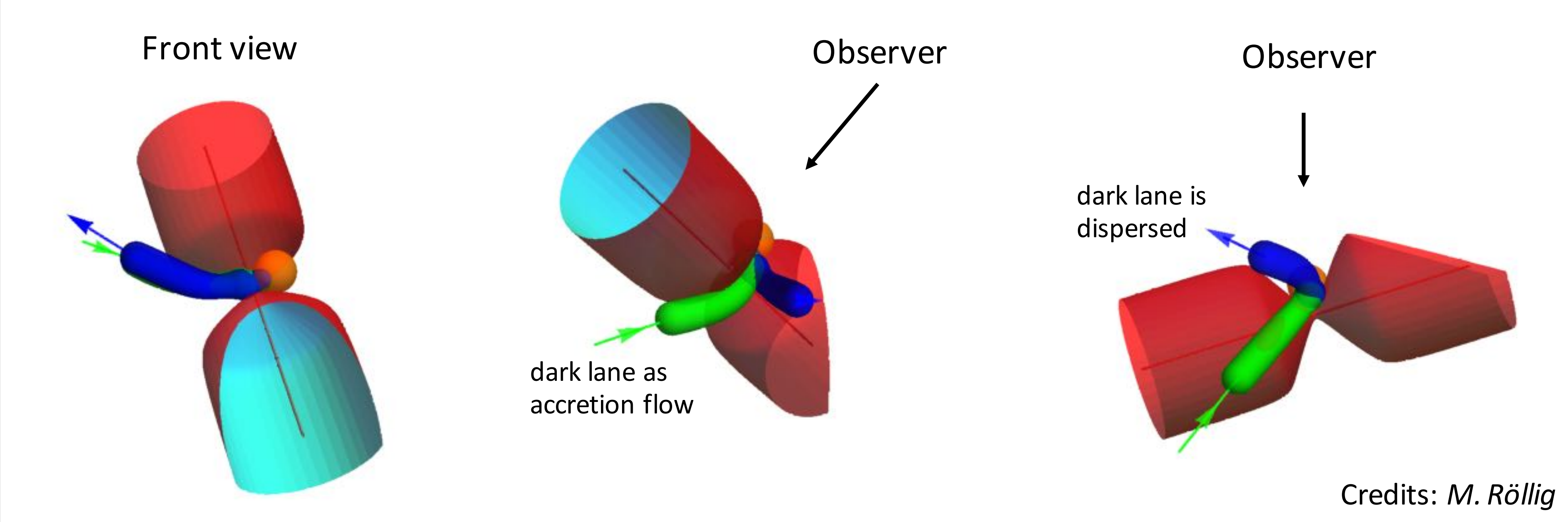


$H^{13}CO^+$ 1-0 channel map



Credits: *M. Röllig*

Is the dark lane an accretion flow or gas being dispersed ?



Credits: *M. Röllig*

Lane is tilted away from observer -> ***accretion***

Lane is tilted towards observer -> ***dispersal***

→ Total mass of dark lane ~ **275 M_{sun}** (*Herschel* dust)
Lifetime ~ 5.3 10^5 yr
Input mass rate ~ **5.2 10^{-4} M_{sun}/yr**

→ consistent with MonR2 (Rayner et al. 2017), lower than DR21 filament (Schneider et al. 2010)

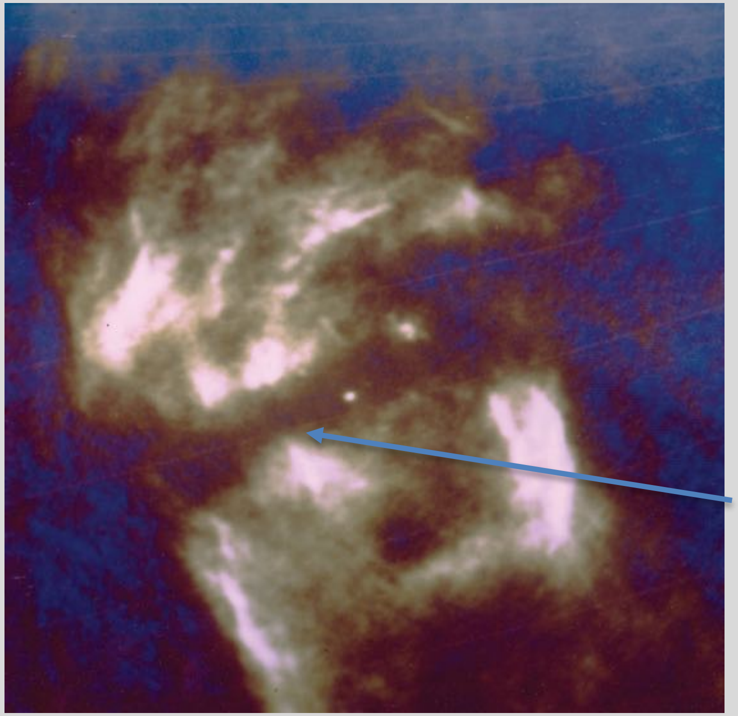
Understanding the origin of OI 63 µm emission: high velocity emission

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**.

Schneider et al. 2018:

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



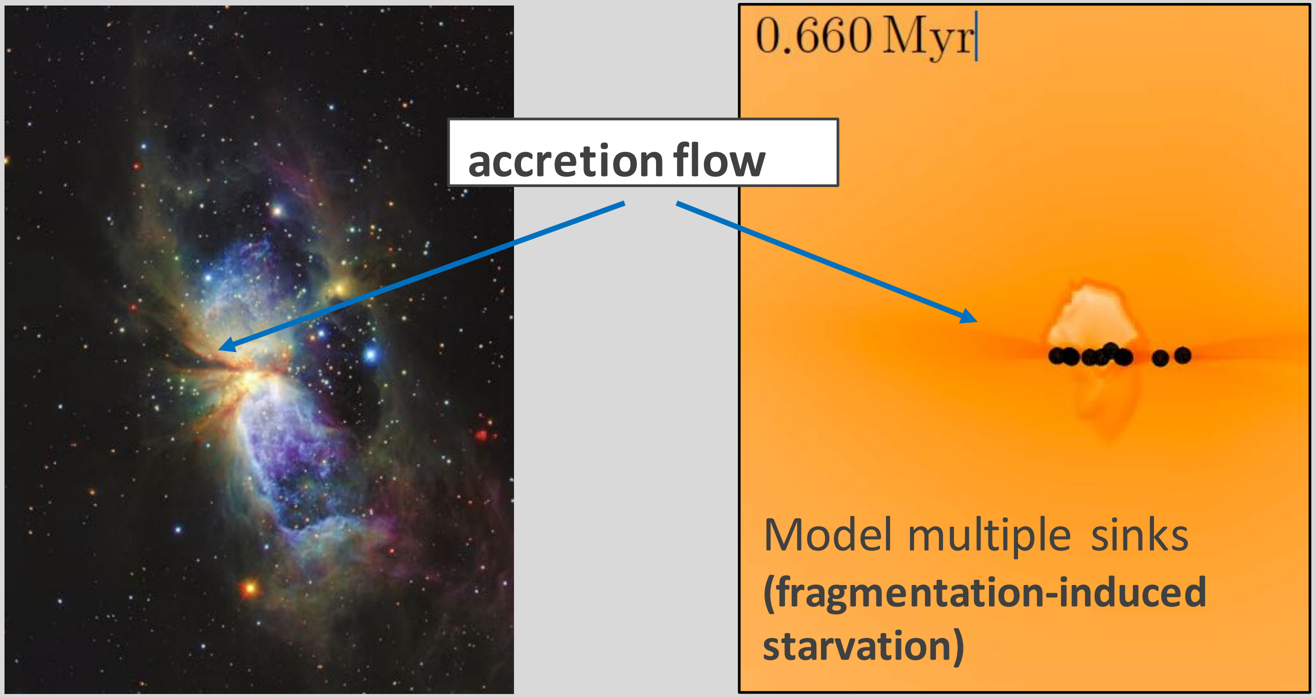
Region devoid of cm emission.

VLA 5 GHz Bally et al. 1983

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 expands downward perpendicularly to the accretion flow, down the ***steepest density gradient***
  (see also Keto et al. 2002, 2007; Kuiper & Yorke 2013; ….)



Model multiple sinks
(fragmentation-induced starvation)

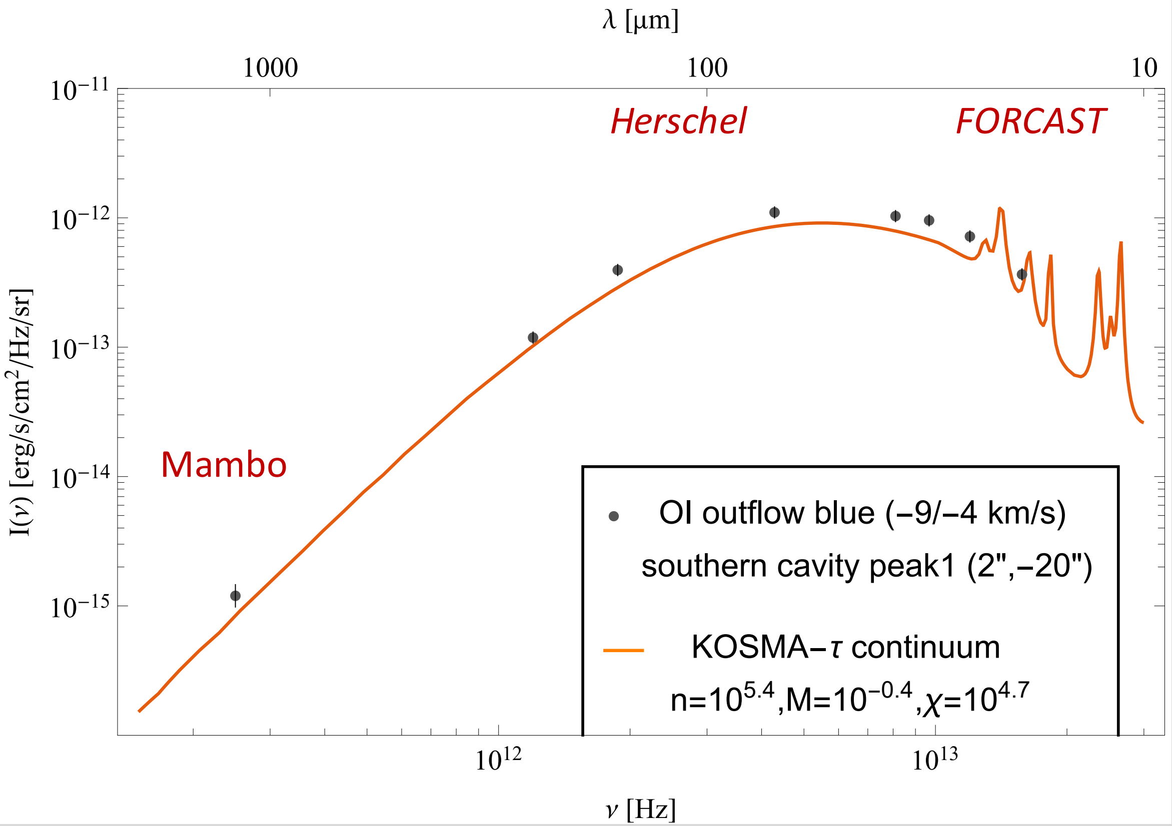
Subaru IR

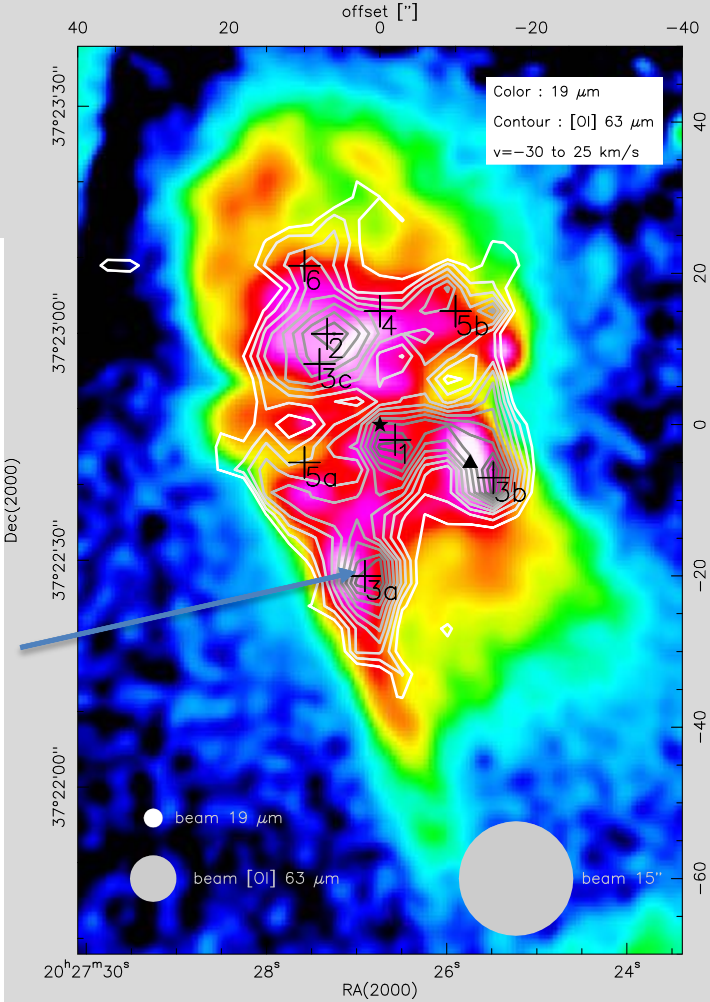
Physical properties of the OI emitting gas: PDR modelling

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

- OI 63 µm and CII 158 µm
- high-J CO lines ^{12}CO 11-10, ^{12}CO 16-15
- dust continuum

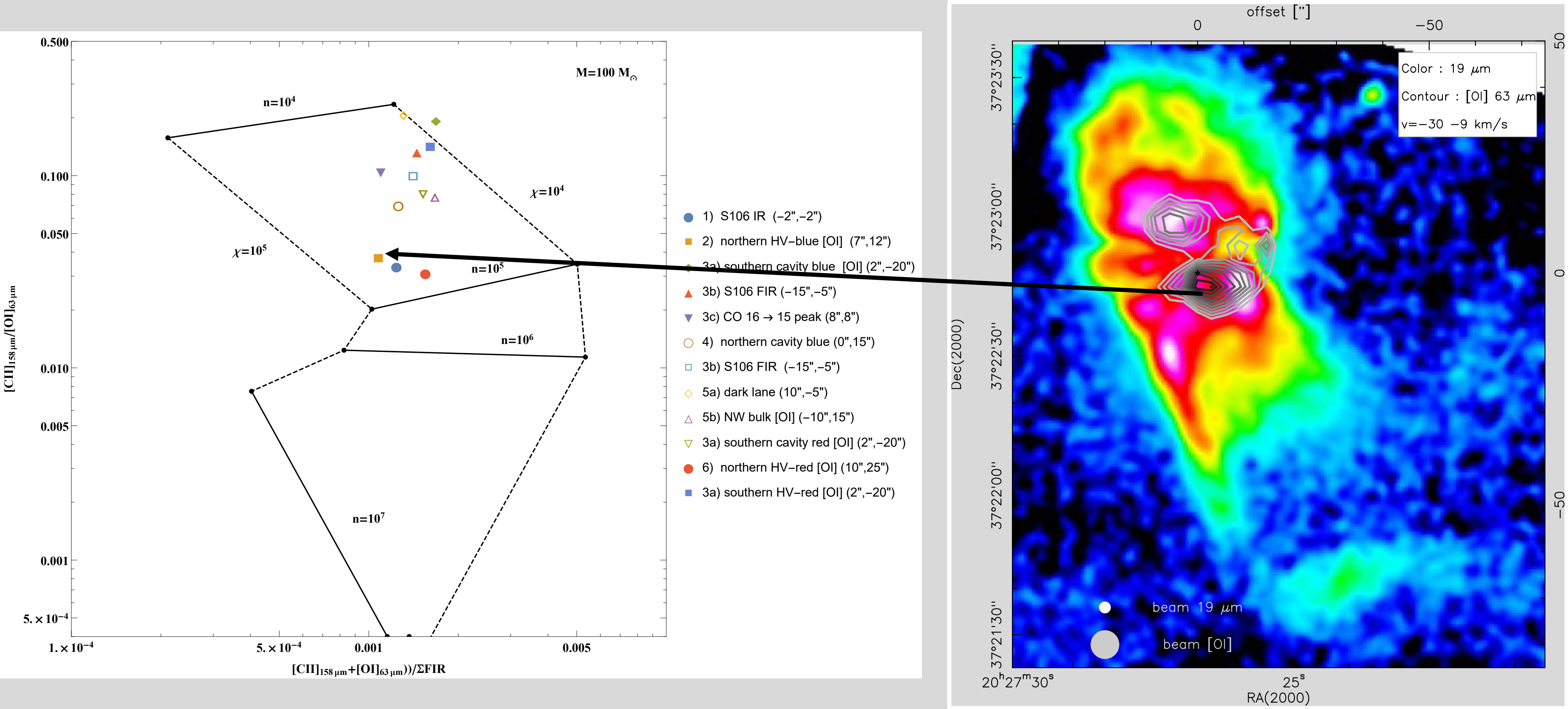
at *9 different positions* in S106





SED fit to observed continuum data (all on 15” angular resolution)

PDR modelling high-velocity blue



Parameter space UV-field and density for different positions (offsets given in panel) and velocity ranges.

$X = 7.2\ 10^{4}$, $n = 5.0\ 10^{4}\ \mathrm{cm}^{-3}$ from **CII/OI** ratio for the high-velocity blue component (-30 to 9 km/s)

What about shocks ?

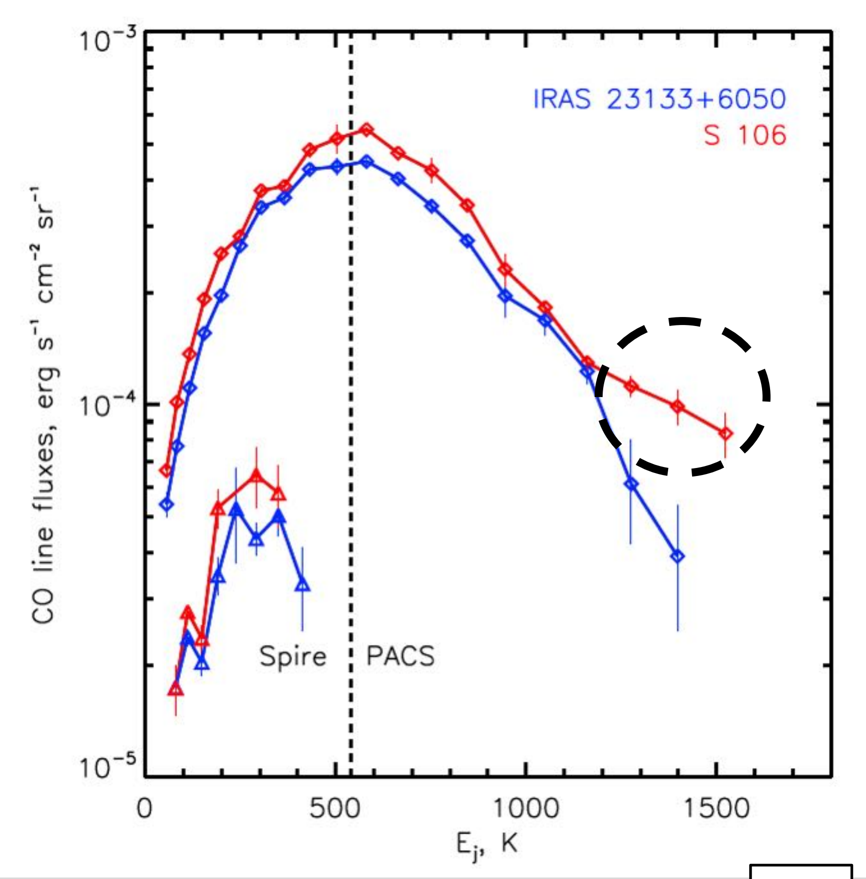
Recent results (e.g. Karska et al. 2014):

- FUV radiation affects the ***pre-shock abundances*** of some species and controls the length scale of C-shocks.
- High-J CO lines show ***excess.***

Important to model irradiated shocks !

S106 *Herschel* PACS/SPIRE data

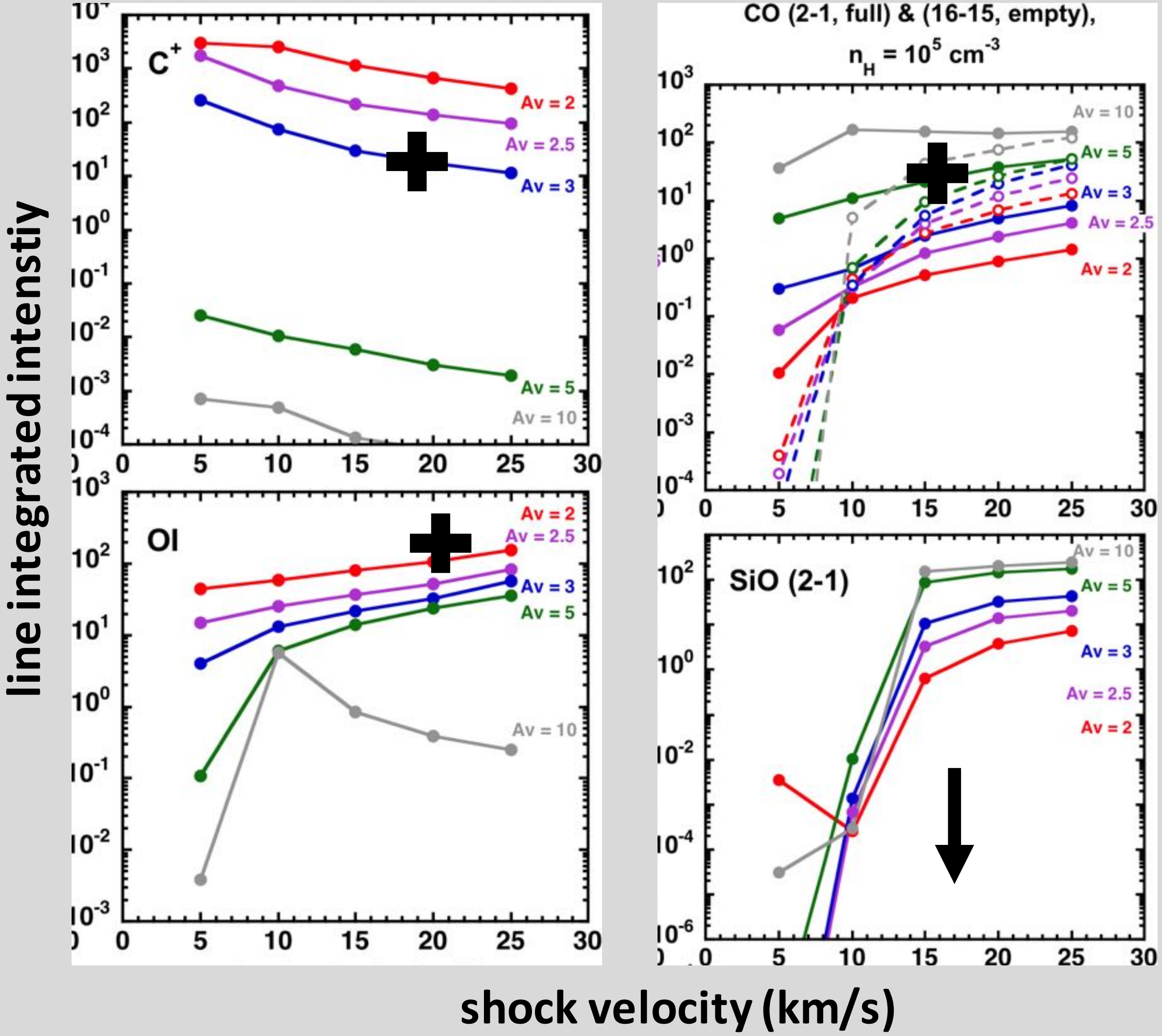
(Stock et al. 2015)



What about shocks ?

Irradiated shock models of *A. Gusdorf*

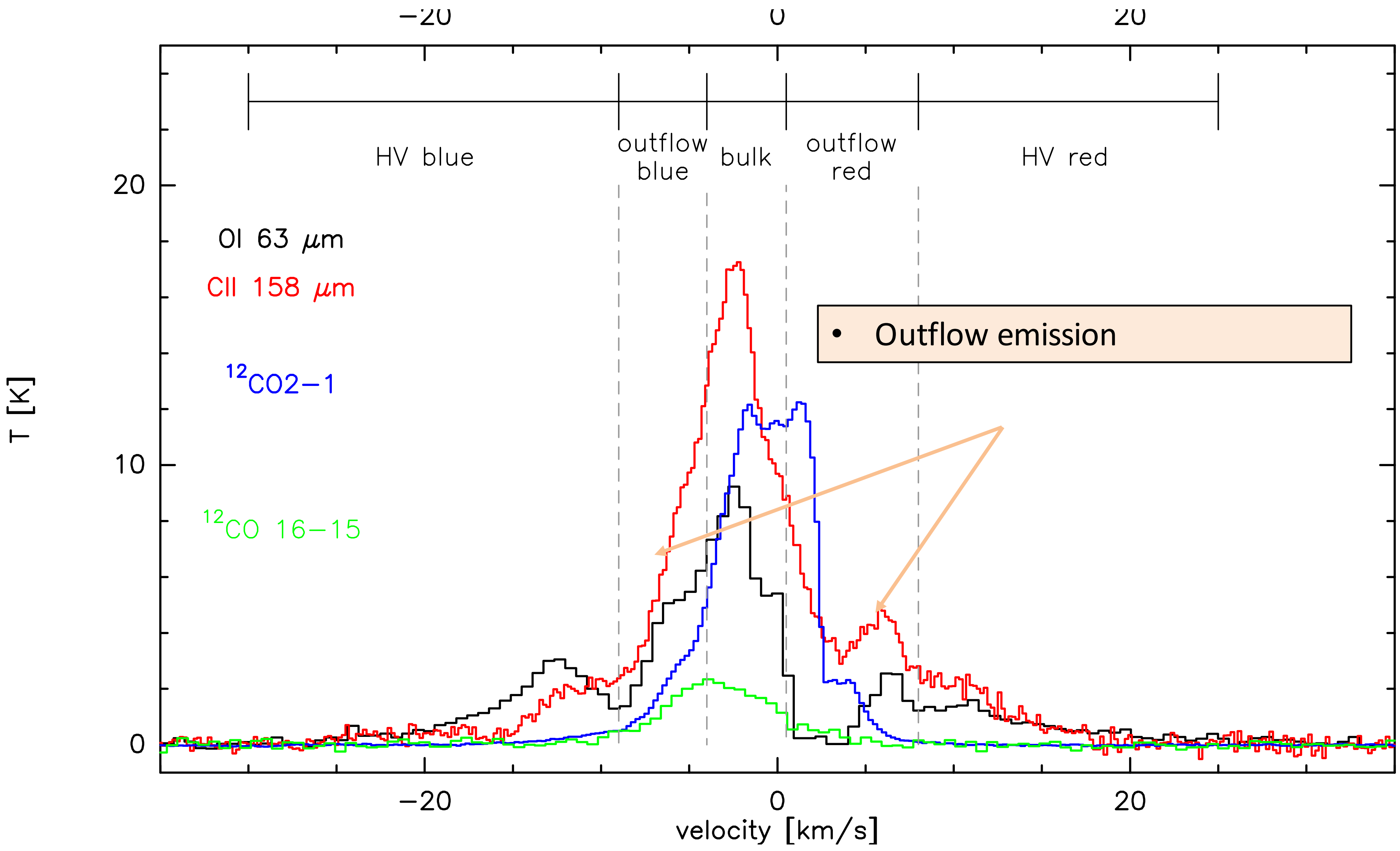
- pre-shock density $n_H = 10^5$ cm^{-3}, $G_0 = 3\ 10^4$
- shock velocities v_s = 5 - 25 km/s
- A_v = 2 - 10 (A_v of the 'protective layer' inside of which the shock propagates),



- A_v varies between 2 and 5
- no SiO observed
  (but densities and
  radiation field very high)

-> work in progress !

upGREAT/SOFIA OI 63 µm average spectrum and other tracers

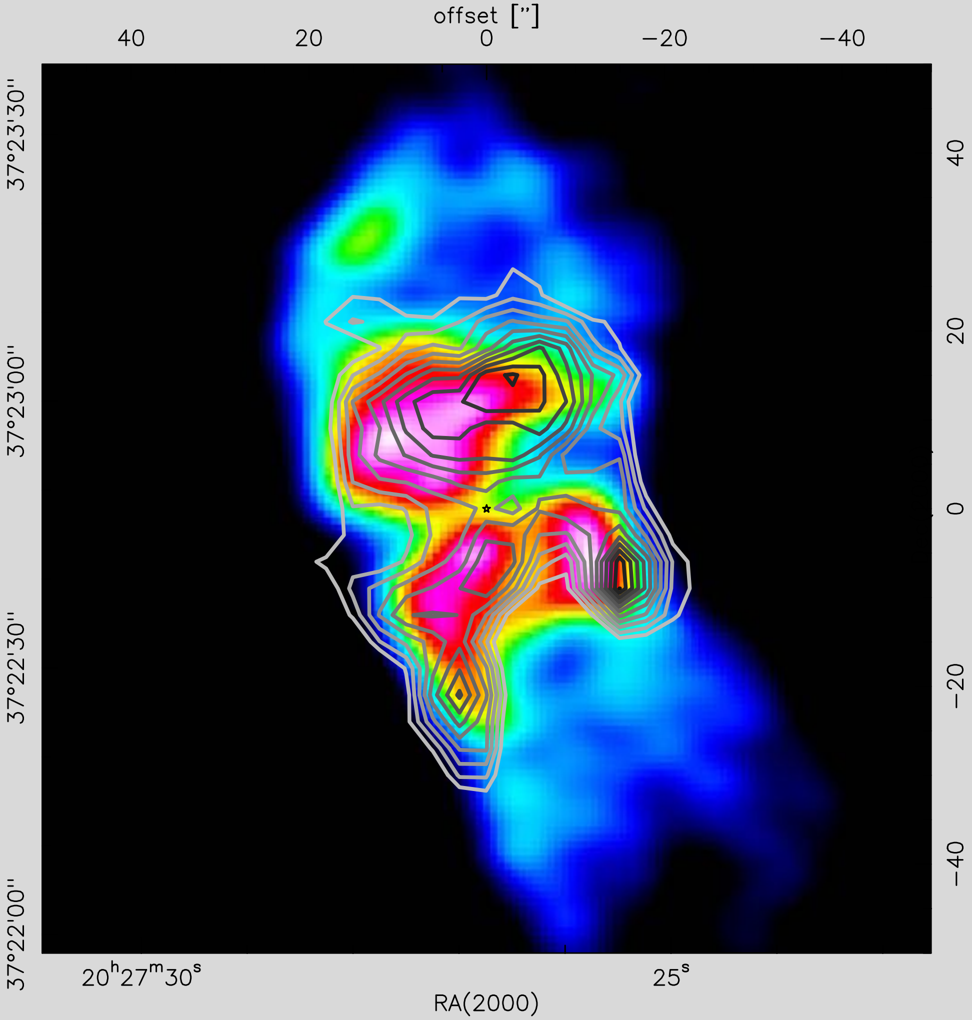


- Outflow emission

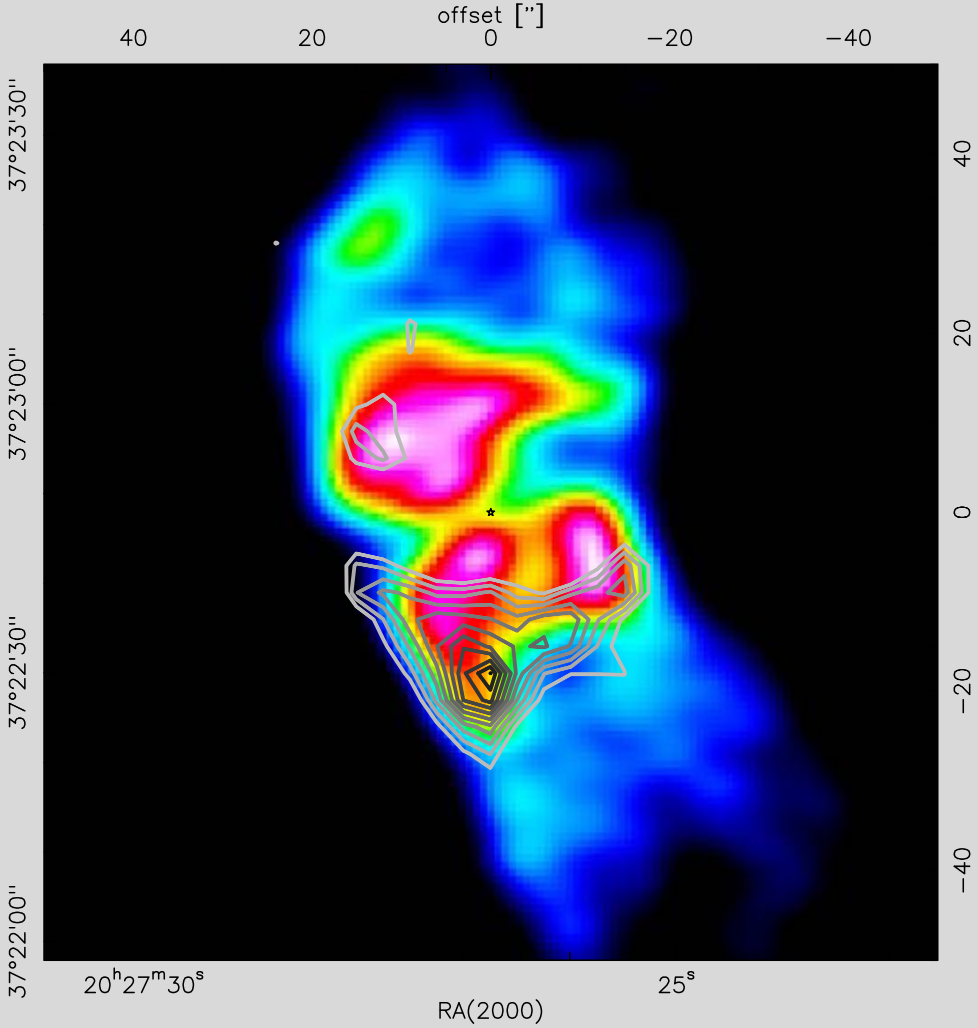
Understanding the origin of OI 63 µm emission: outflow emission

OI 63 micron on VLA (tracing the HII region)

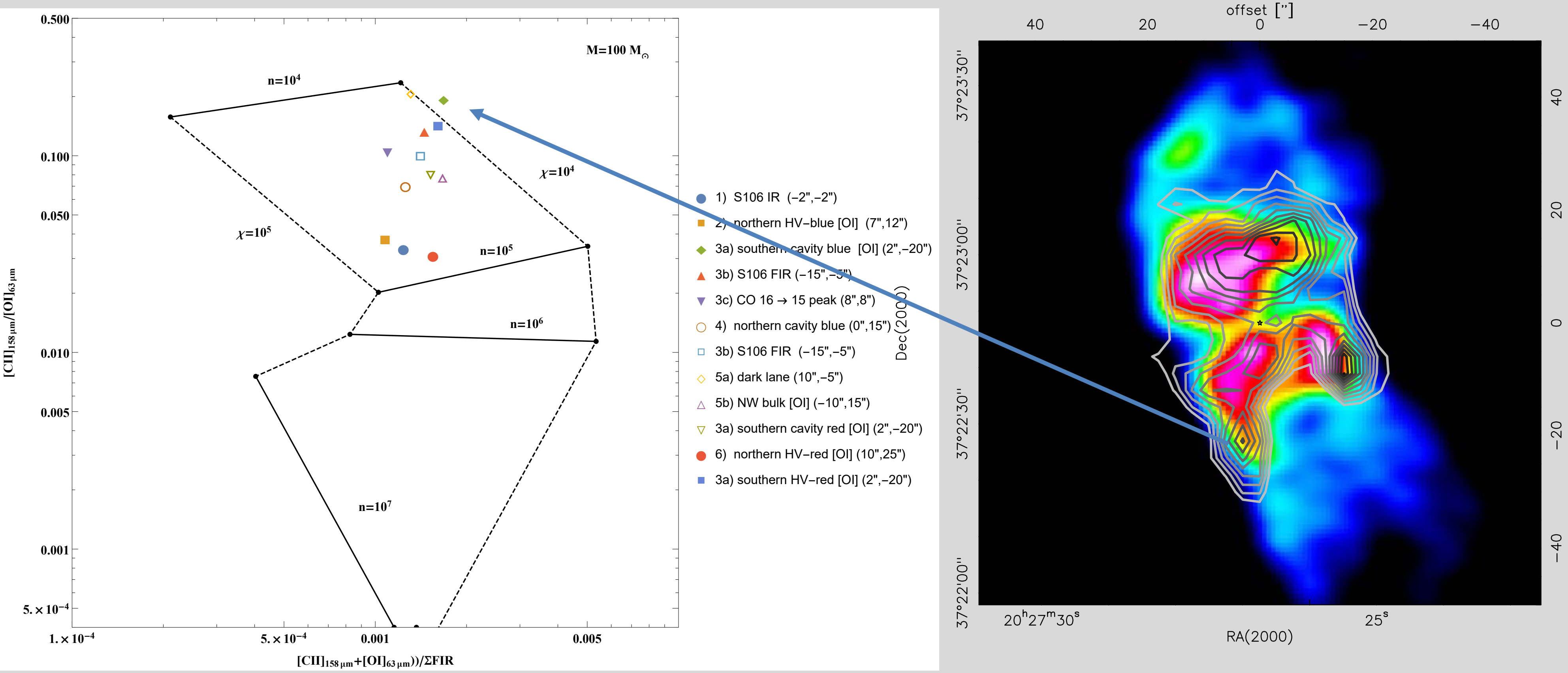
Outflow emission from cavity **blue**



Outflow emission from cavity **red**



PDR modelling outflow blue



Parameter space UV-field and density for different positions (offsets given in panel) and velocity ranges.

***X* = 9.4 10^3** , **n = 1.3 10^4 cm^{-3}** from **CII/OI** ratio for the outflow blue component (-9 to -4 km/s)

What about shocks ?

Irradiated shock models of *A. Gusdorf*

- pre-shock density $n_H = 10^5$ cm^{-3}, $G_0 = 3\ 10^4$
- shock velocities v_s = 5 - 25 km/s
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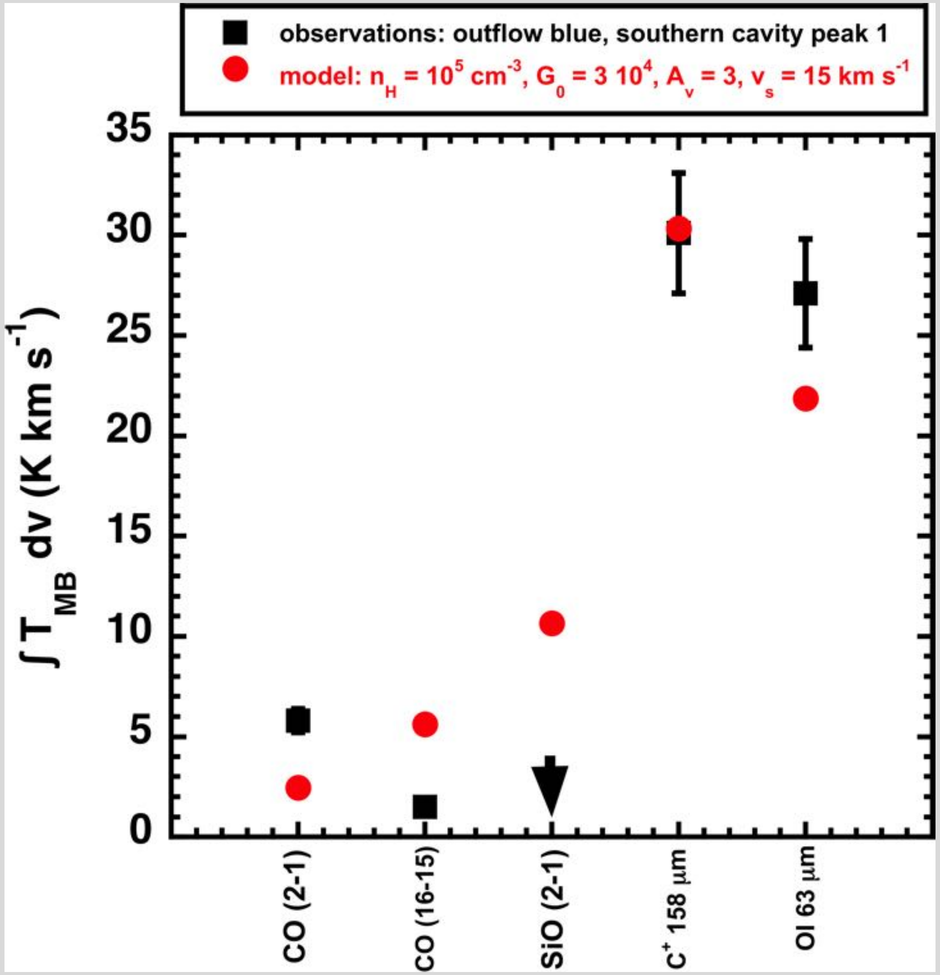


- No SiO

But first results promising !

What about self-absorption ?

OI 63 µm can be strongly **self-absorbed** (mostly for bulk emission, probably less for high-velocity emission).

Simple approach to estimate how **density** and **radiation field** vary is to increase the OI intensity by a factor of 2, 4, ...

-> factor 2 still reasonable (e.g. **χ = a few 10^4 , n = up to 10^6 cm^{-3}** for high-velocity blue emission) but higher factors give unrealistic values.

Need (hopefully) optically thin **OI 145 µm** observations (planned for November 2018).

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 ?

- Modeling of ***irradiated shocks*** with high FUV field required.

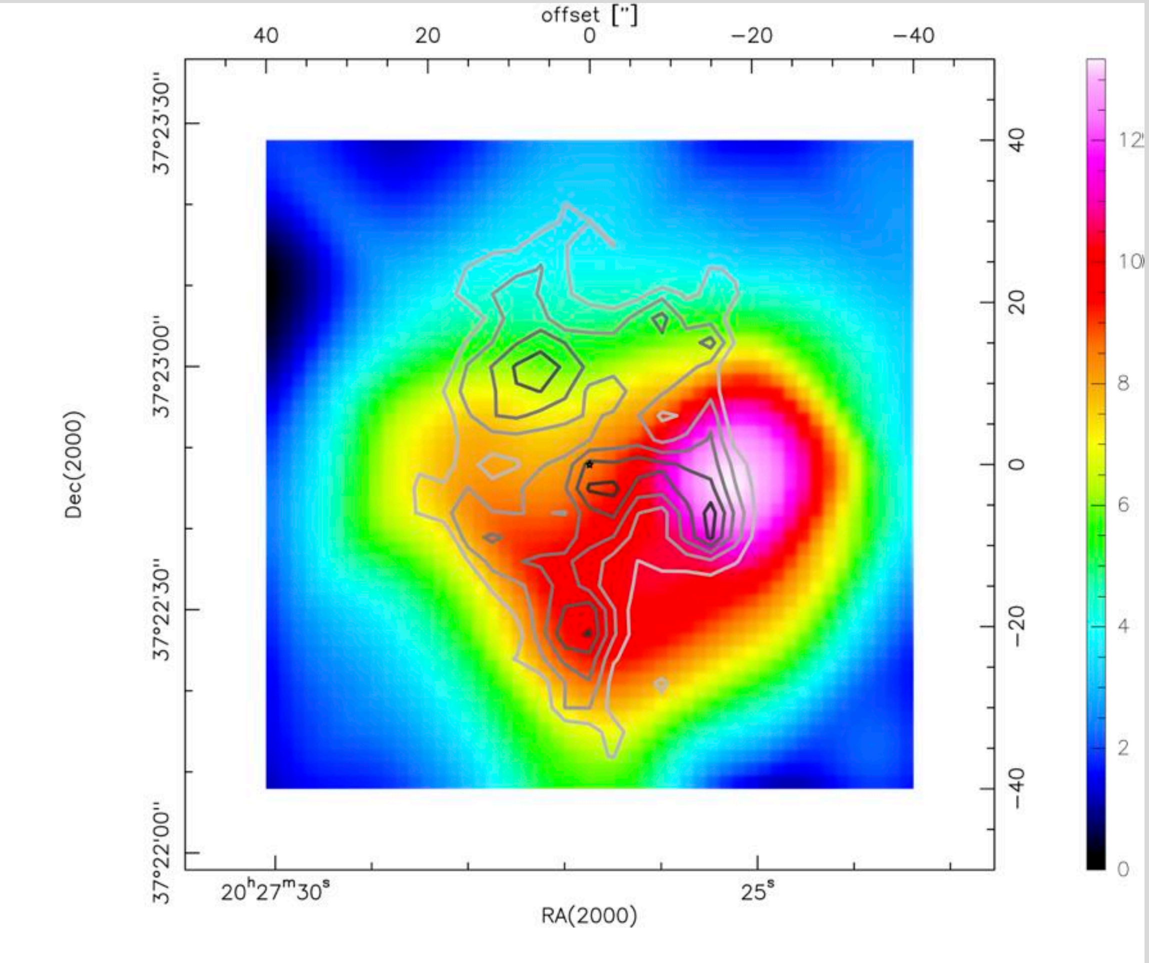
  -> PDRs vs shocks
  -> more observations with SOFIA required (OI 145 µm)

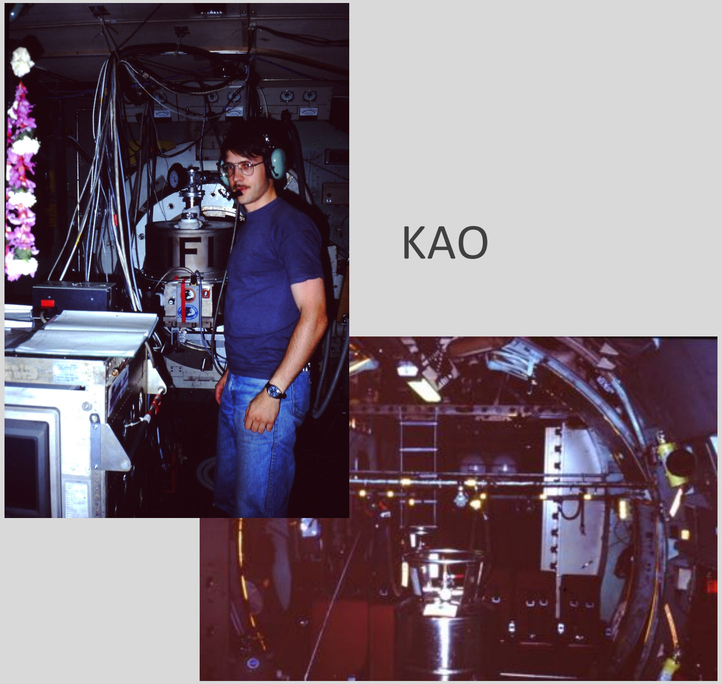
- OI, CII, high-J CO line observations very useful to better understand the ***processes of massive star formation***.

  -> massive stars form by rapid accretion from a dense, ionized flow
  (***starvation induced fragmentation***, Peters et al. 2010)
  -> longer sustained feeding of the circumstellar core by the molecular cloud
  (Kuiper & Yorke 2013)

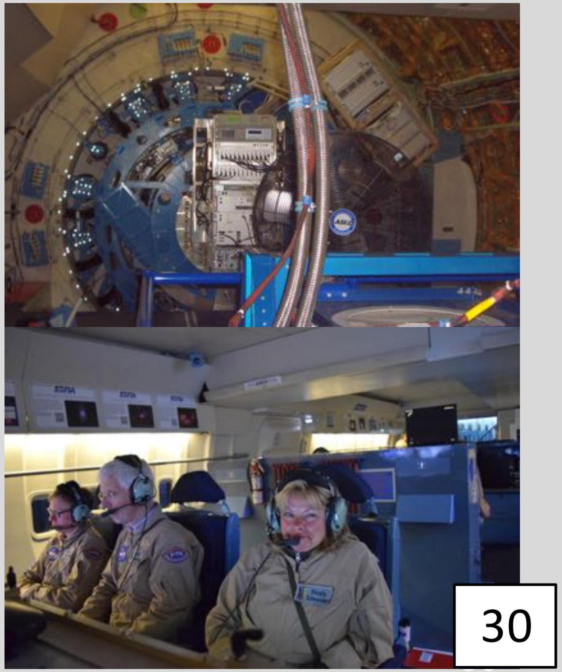
Airborne FIR observations .... now and then

KAO (FIFI) 1994 **SOFIA (GREAT) 2015**



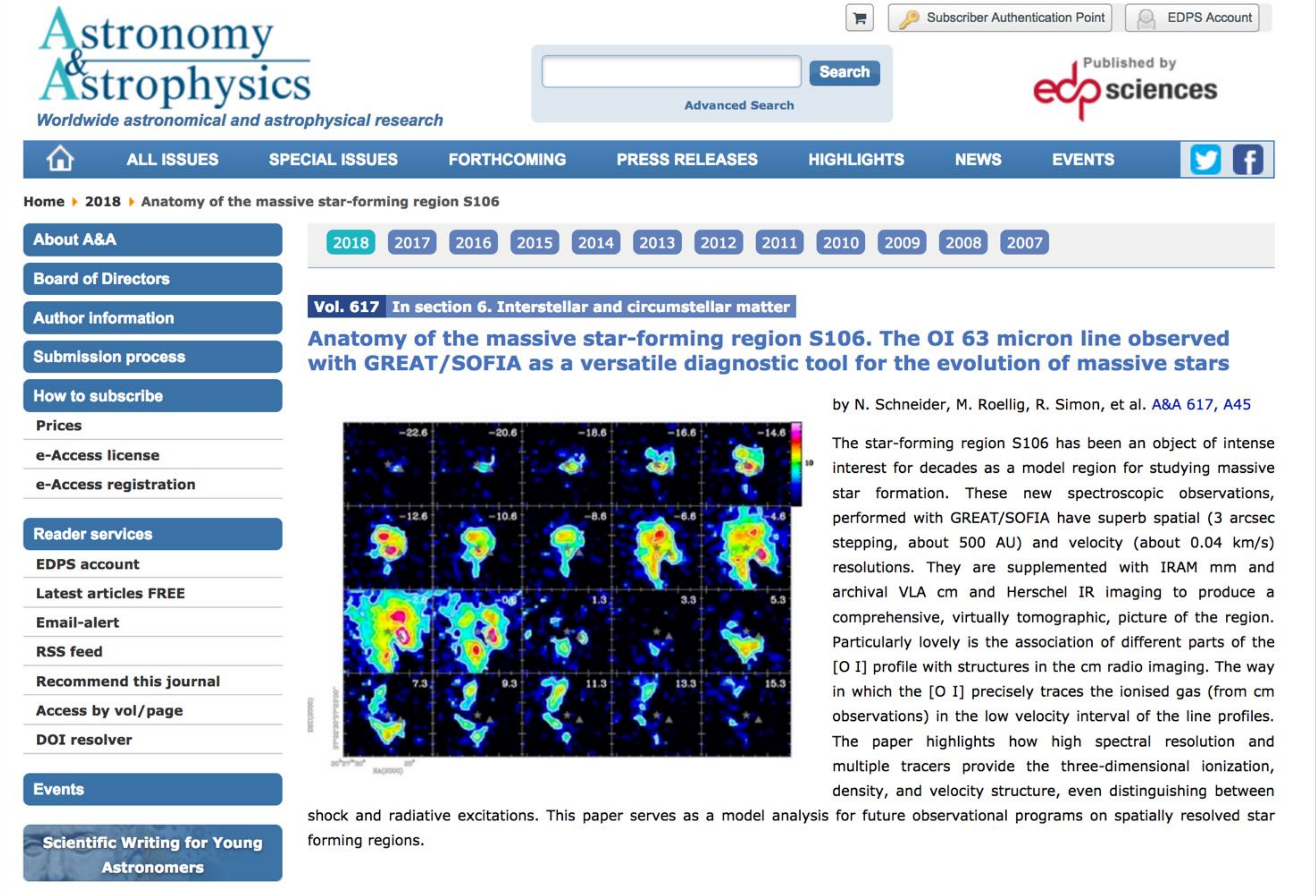


KAO



SOFIA

A&A highlight paper: A&A 617, A45 (september 2018)



Vol. 617 In section 6. Interstellar and circumstellar matter

Anatomy of the massive star-forming region S106. The OI 63 micron line observed with GREAT/SOFIA as a versatile diagnostic tool for the evolution of massive stars

by N. Schneider, M. Roellig, R. Simon, et al. A&A 617, A45

The star-forming region S106 has been an object of intense interest for decades as a model region for studying massive star formation. These new spectroscopic observations, performed with GREAT/SOFIA have superb spatial (3 arcsec stepping, about 500 AU) and velocity (about 0.04 km/s) resolutions. They are supplemented with IRAM mm and archival VLA cm and Herschel IR imaging to produce a comprehensive, virtually tomographic, picture of the region. Particularly lovely is the association of different parts of the [O I] profile with structures in the cm radio imaging. The way in which the [O I] precisely traces the ionised gas (from cm observations) in the low velocity interval of the line profiles. The paper highlights how high spectral resolution and multiple tracers provide the three-dimensional ionization, density, and velocity structure, even distinguishing between shock and radiative excitations. This paper serves as a model analysis for future observational programs on spatially resolved star forming regions.