The CO ladder in PDRs from HEXOS and WADI observations

V. Ossenkopf, C. Joblin, M. Röllig

Exciting CO, Leiden,
February 29, 2012

Questions

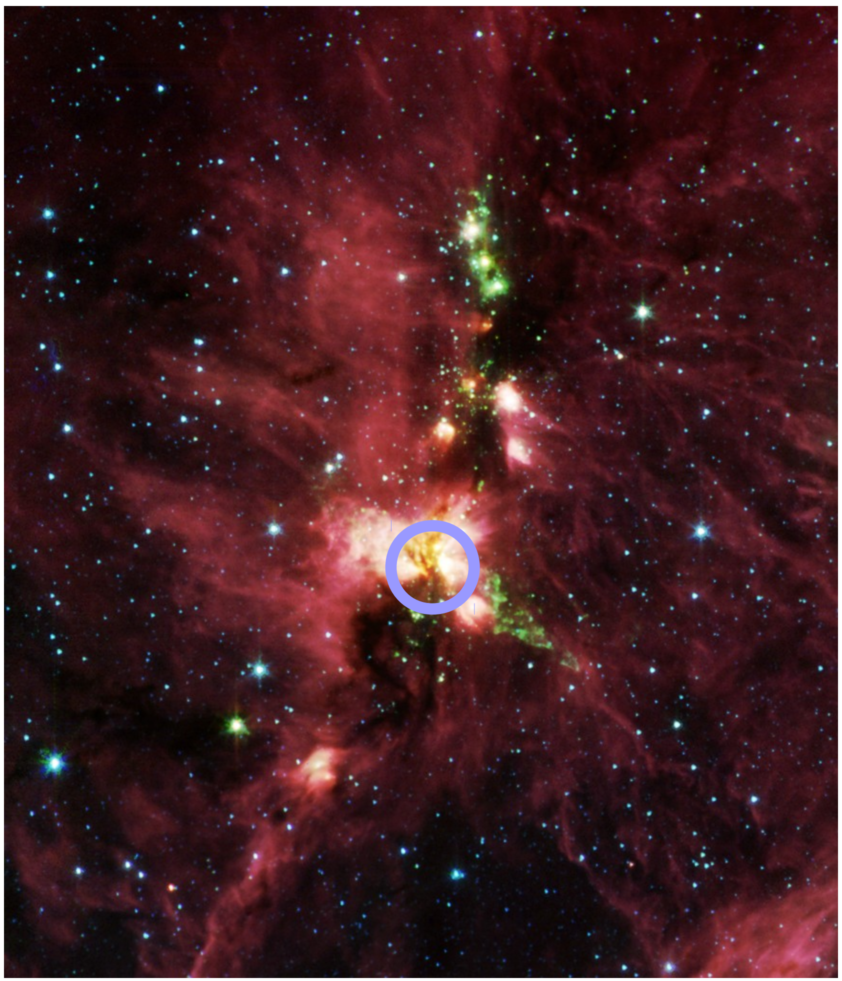
Relevant for CO-ladder workshop

Energy balance in PDRs:

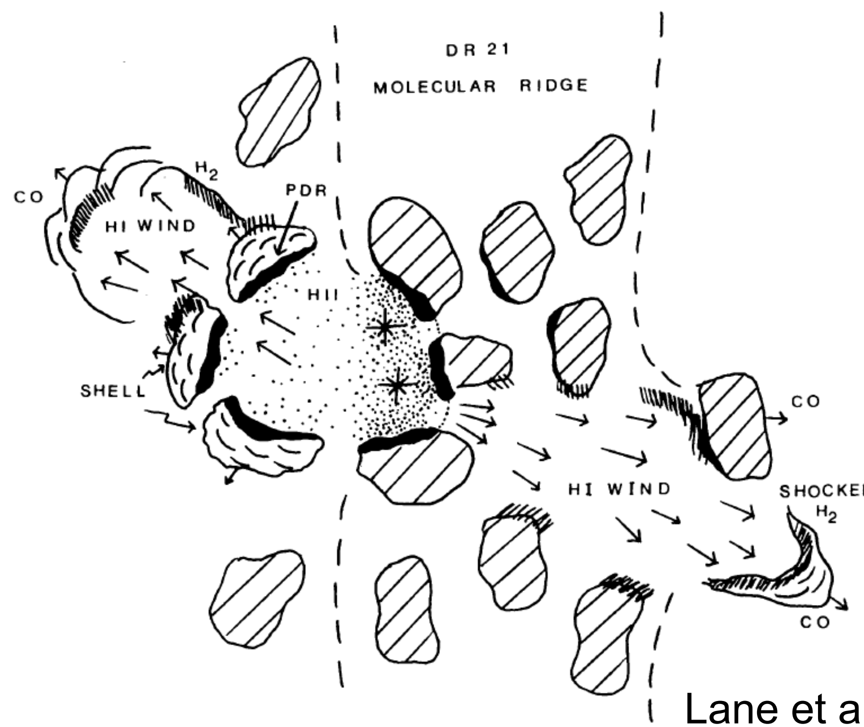
- distinguish role of UV radiation from shock heating
- gas heating efficiency
- role of different coolants and dust heating and cooling

Example 1: DR21C

- Central HII region
- Collimated outflow to SW, blister to NE
- Ridge in the front
- PDR around HII region and outflow cavities



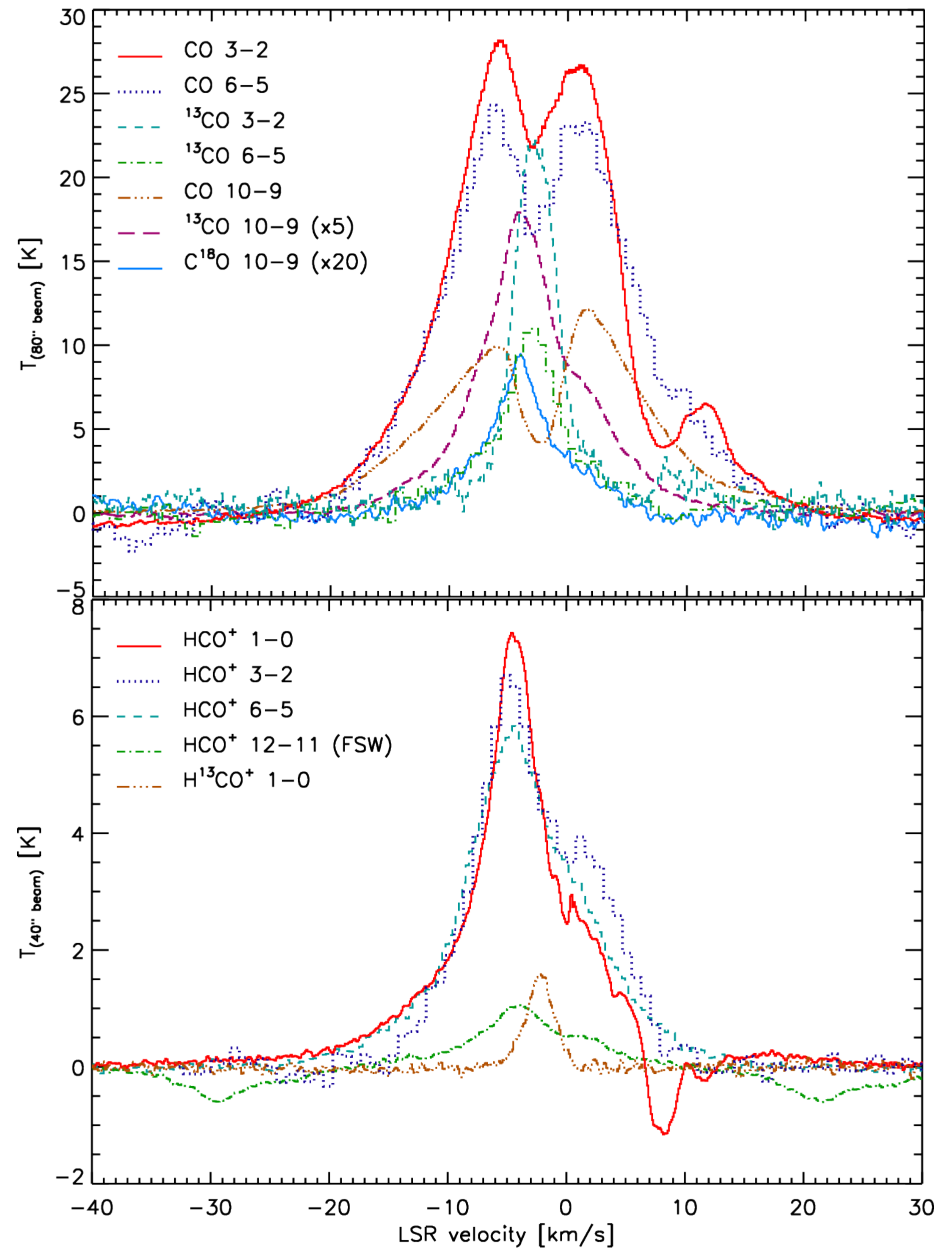
Marston et al. (2007, Spitzer)



Lane et al. (1990)

DR21C

- Line profiles allow to:
  - Distinguish line intensities from different velocity components
  - Optical depth correction of line intensities
  - Exclude outflow wings and foreground components in PDR model fit
    - ambiguous!

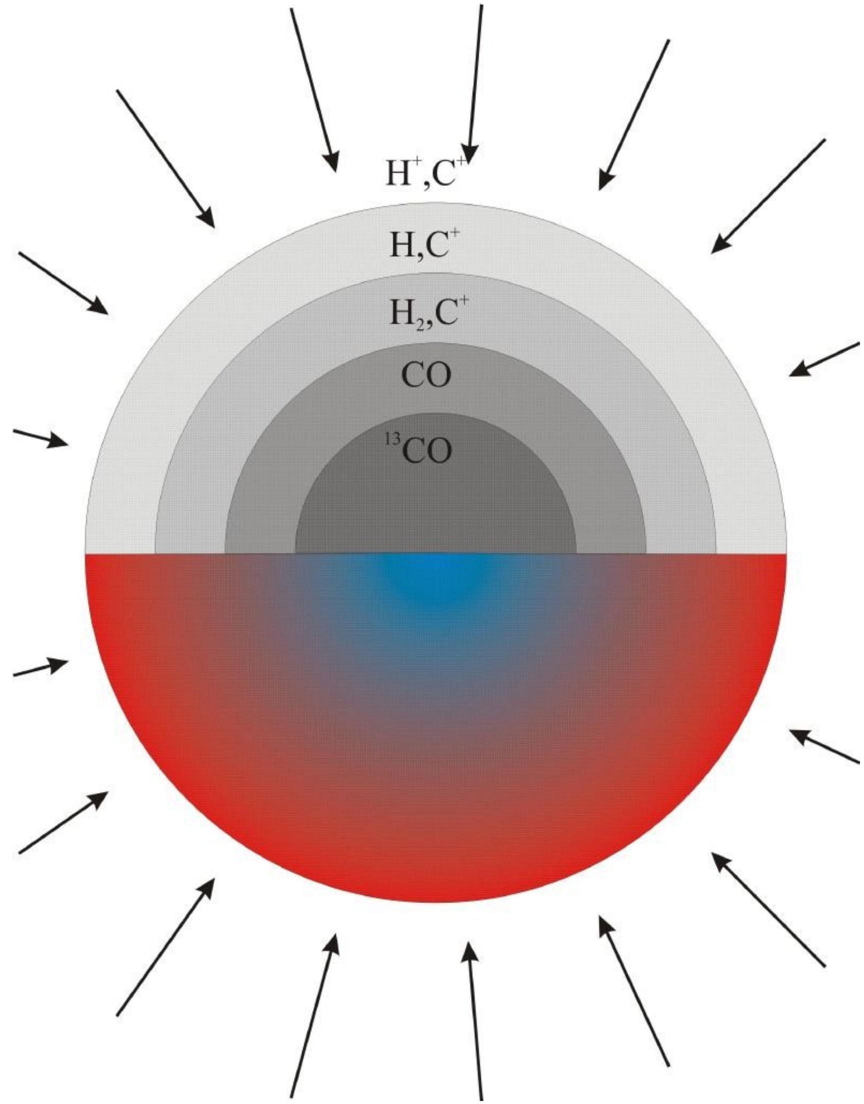


HIFI observations of high-J lines of CO and HCO^{+} isotopologues

- comparison with ground-based low-J lines

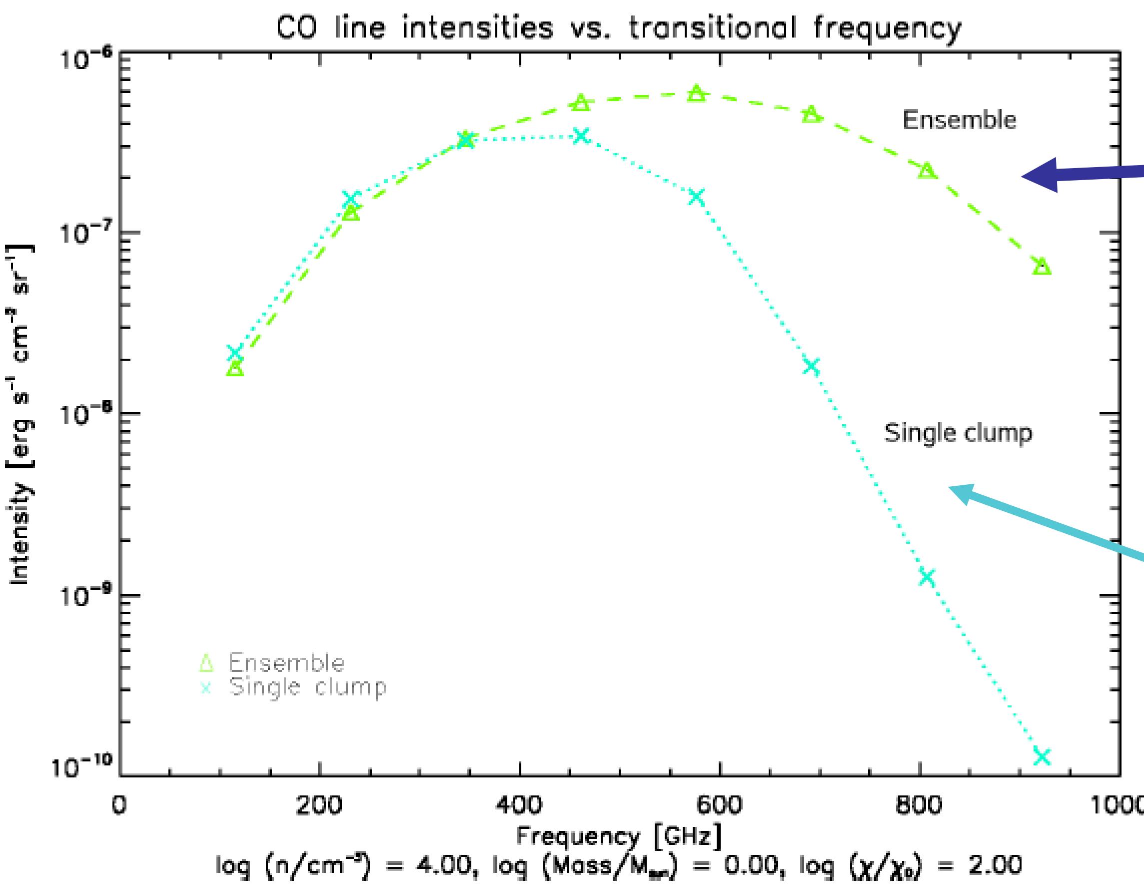
Modeling: KOSMA-τ PDR Code

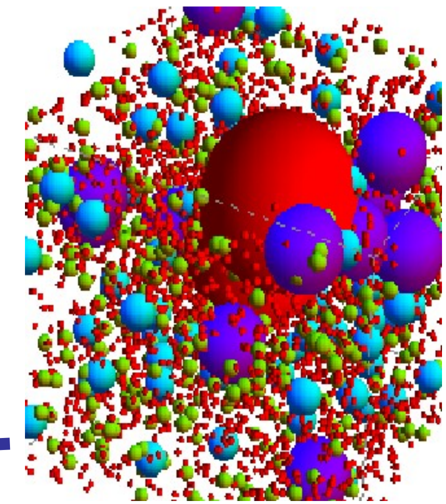
- Spherical clumps
  → Layering of species and temperature structure as function of UV field
- Recent improvements:
  - Eley-Rideal H_2 formation
  - Arbitrary dust properties
  - Full isotopologue network



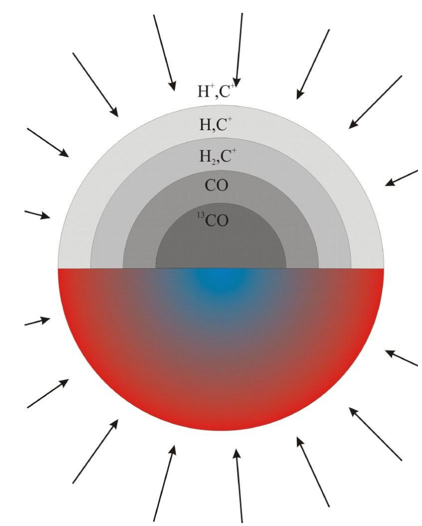
Modeling: KOSMA-τ PDR Code

- Ensemble of clumps
  - Broadening of excitation ladder





$\Sigma M_i = 1 M_\odot$



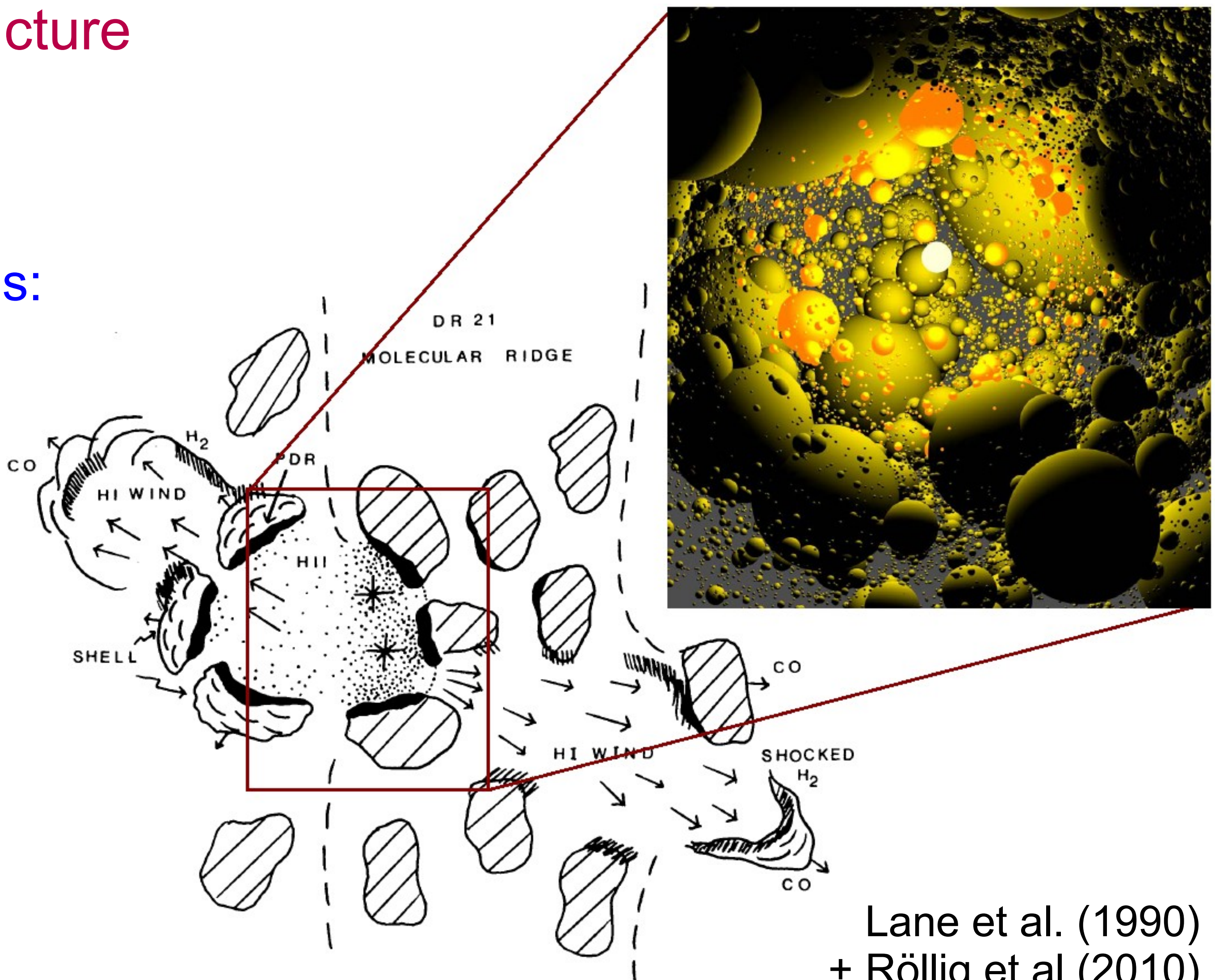
DR21C

Model for clumpy structure of PDR required

PDR model fit to all lines:

- New HIFI data show two distinct UV fields: $10^5\ \chi_D$ and $300\ \chi_D$

→ Dense clumps facing the blister outflow
+ clumpy large scale distribution



Lane et al. (1990)
+ Röllig et al (2010)

DR21C

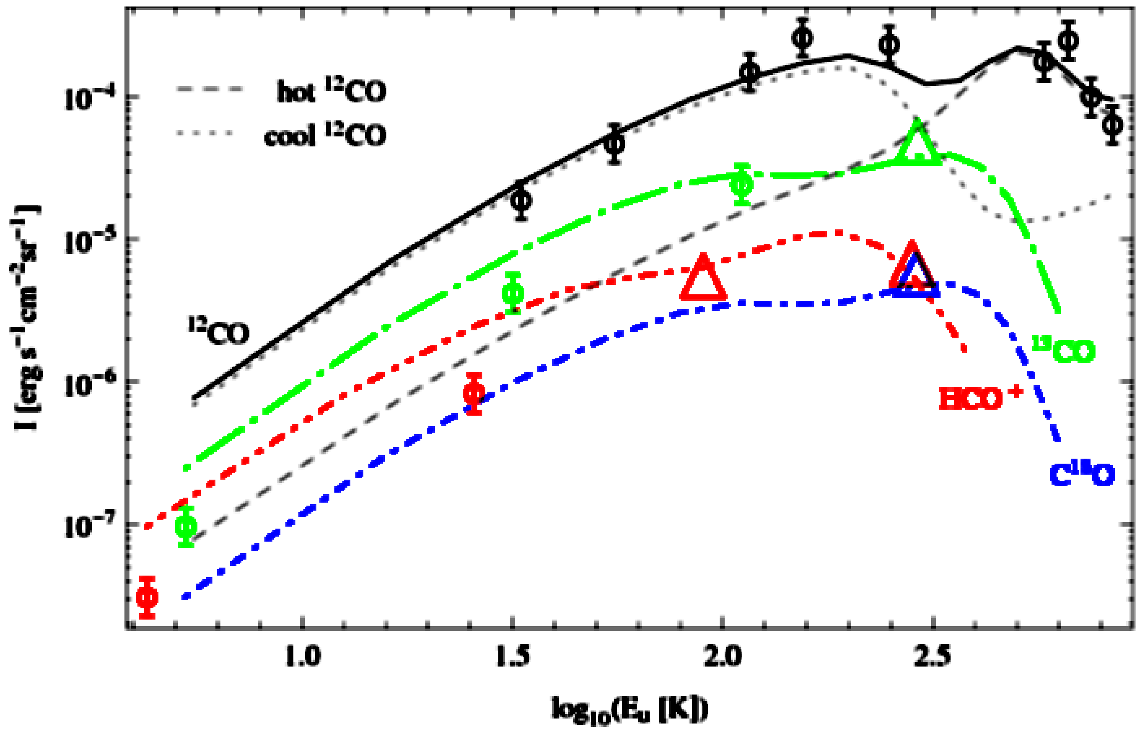
Model for clumpy structure of PDR required

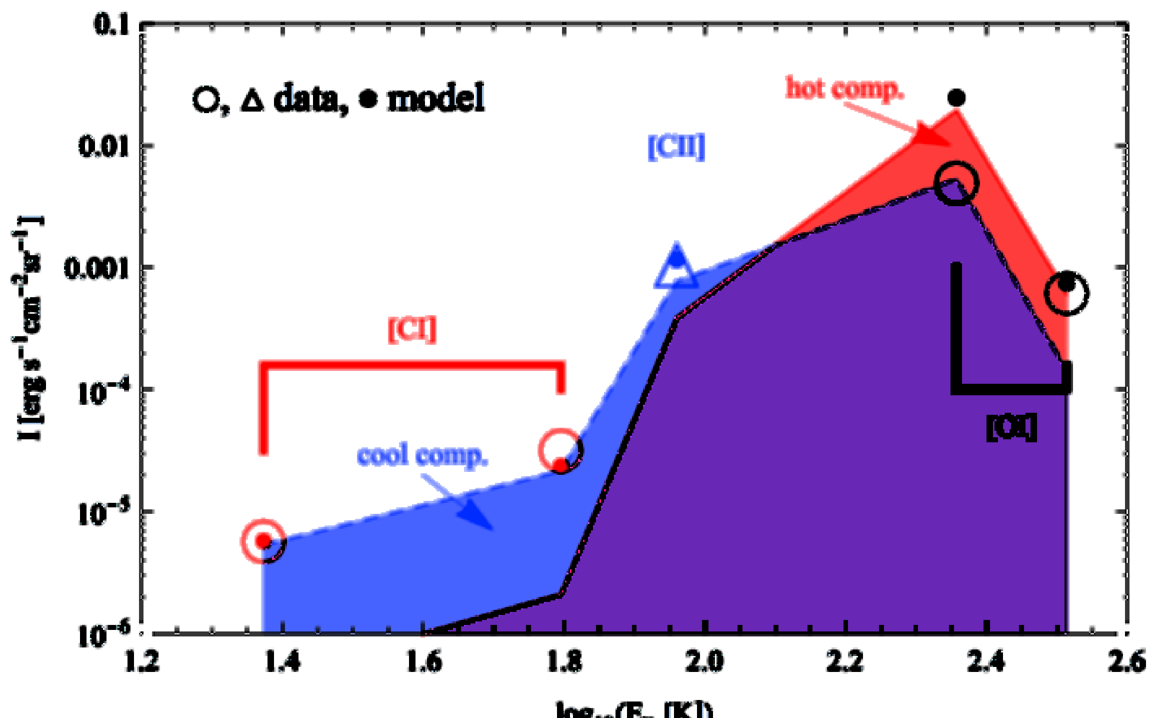
PDR model fit to all lines:

- New HIFI data show two distinct UV fields: $10^5\ \chi_D$ and $300\ \chi_D$

➔ Dense clumps facing the blister outflow
+ clumpy large scale distribution

No shock component needed !

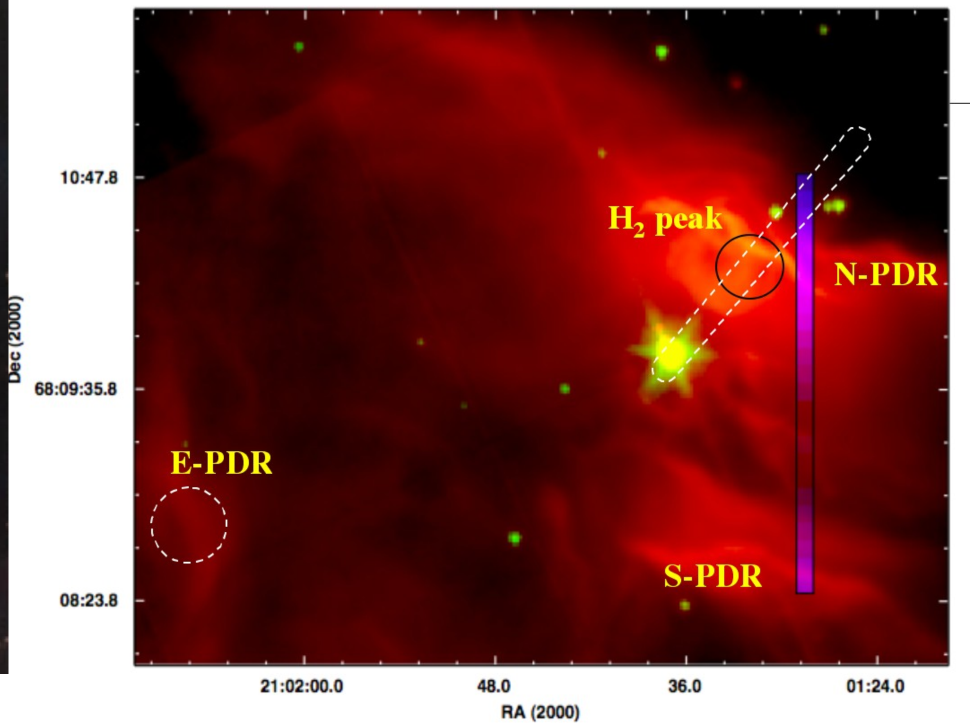




Example 2: NGC 7023

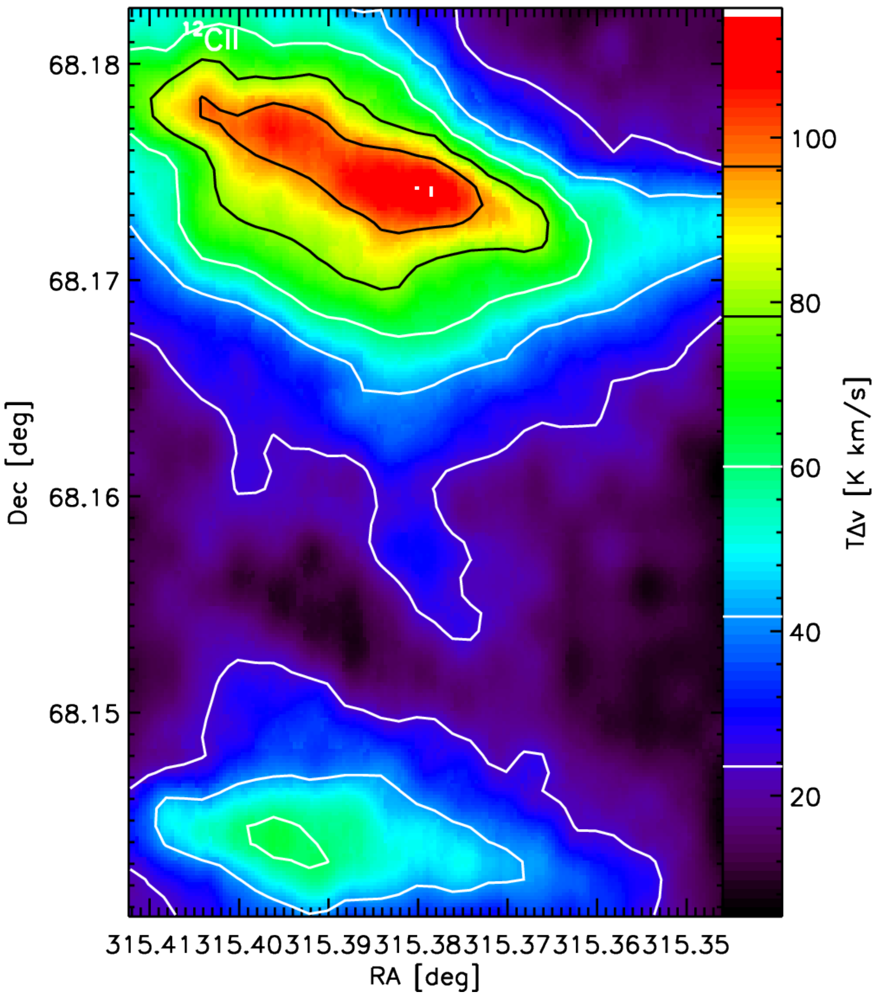
Misty (2004)

- Iris nebula
- Focus here on Northern PDR (H_2-peak)



Spitzer IRAC (Joblin et al. 2008)

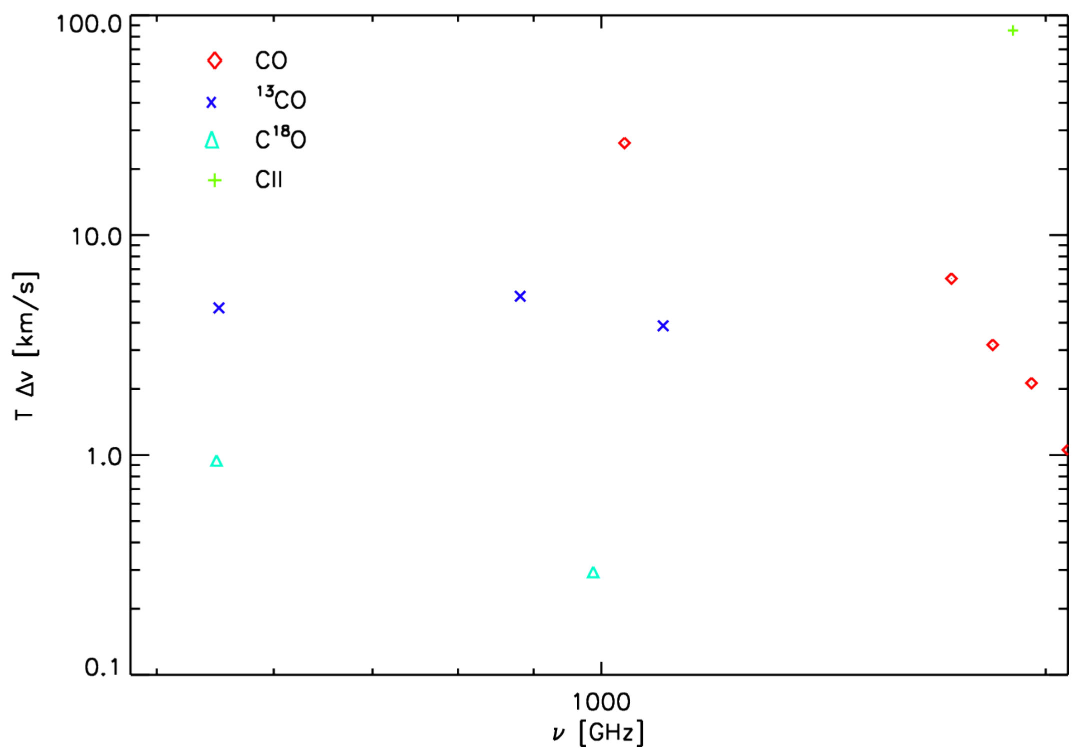
NGC 7023



CII distribution

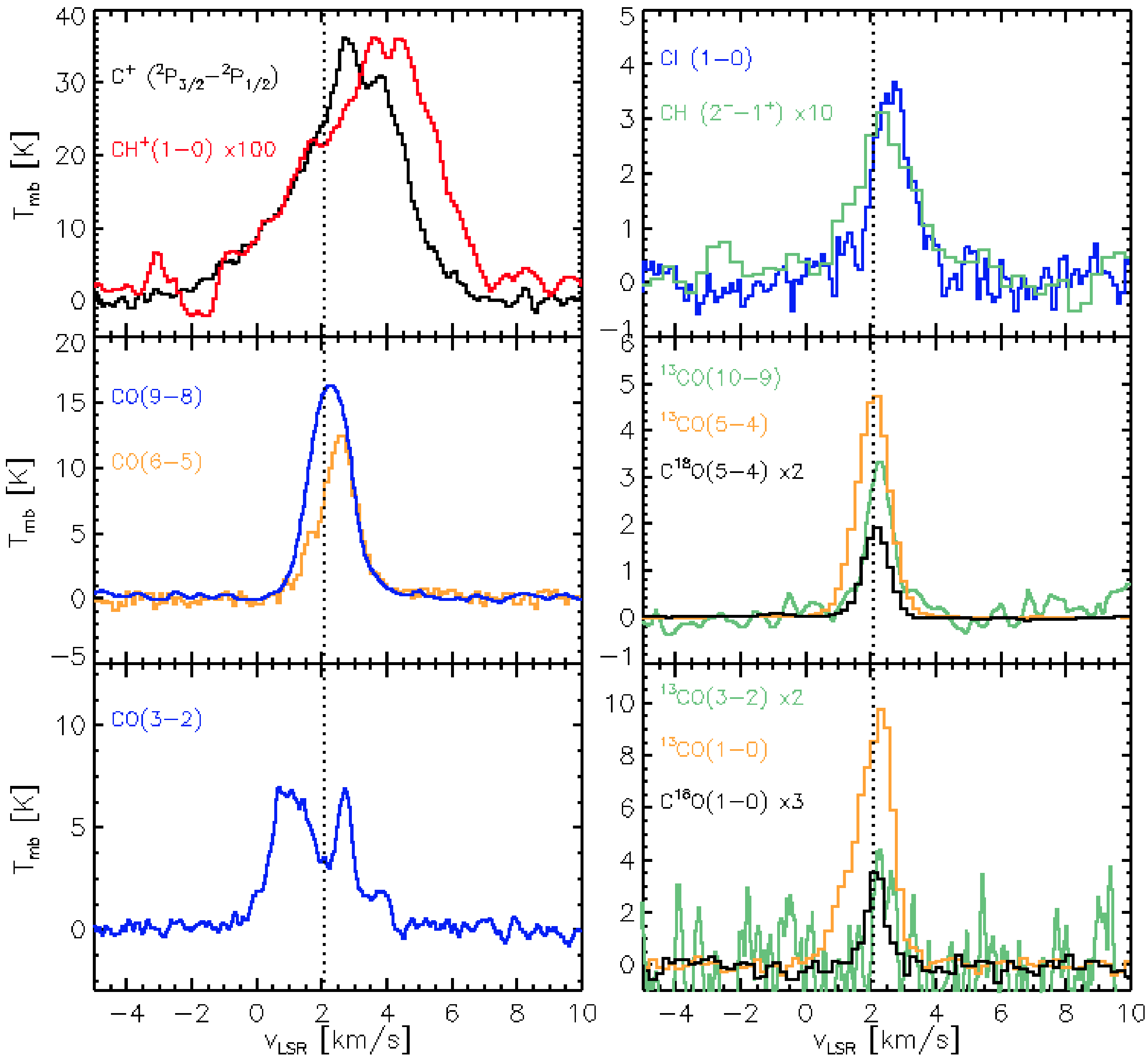
HIFI observations:

- CO ladder sparsely sampled



- Drop of CO intensities above J=10
- Not sampled in ^{13}CO and $C^{18}O$

Line profiles



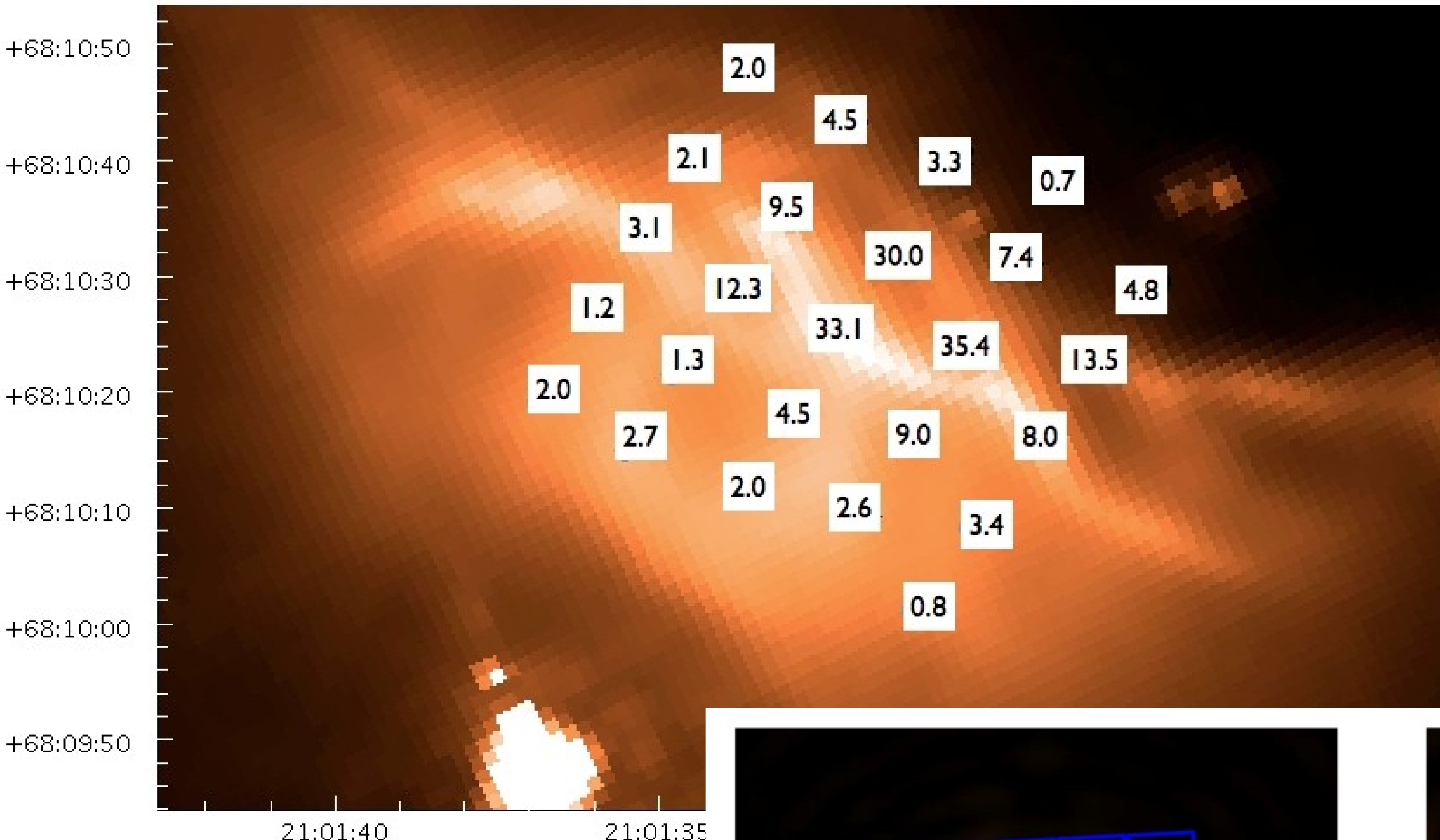
Compare 3 data sets:

- HIFI
- CO
    - *Gerin et al. (1998)*
- ^{13}CO(1-0) and $C^{18}O$(1-0) from PdBI
    - *Pety et al. (2010)*

Geometry:

shell-like structure with reabsorption by colder gas

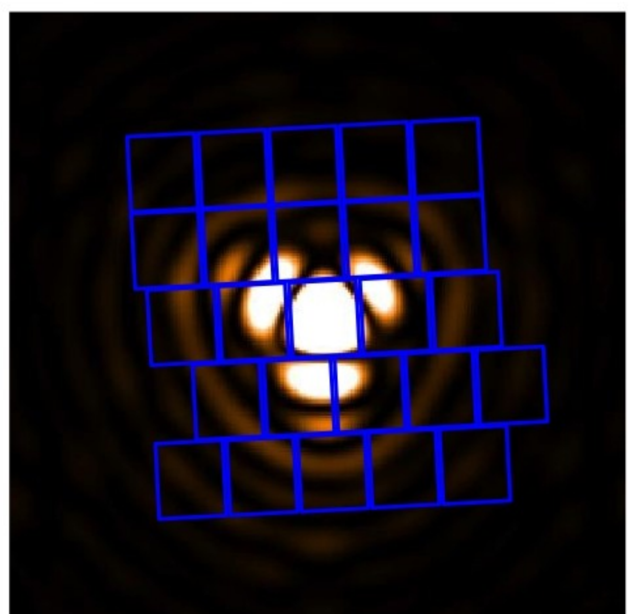
PACS spectroscopy

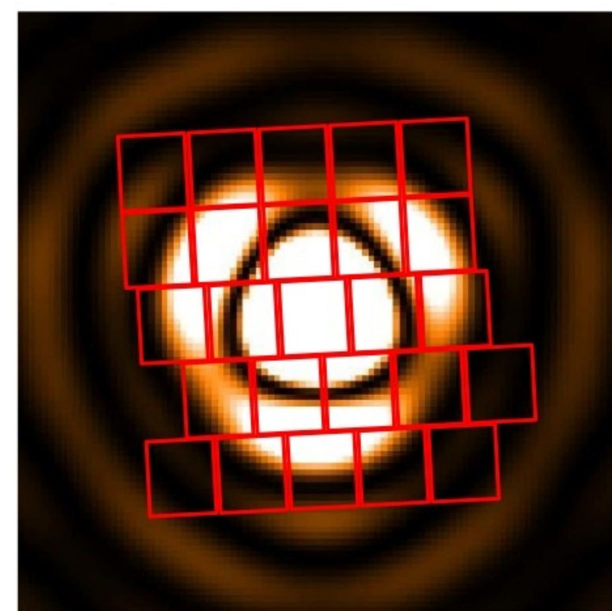


Cross-calibration extremely tricky
- Ongoing

Example: CII
- HIFI: 6.0×10^{-3} erg/(cm^2 s sr)
- PACS: 8.6×10^{-3} erg/(cm^2 s sr)

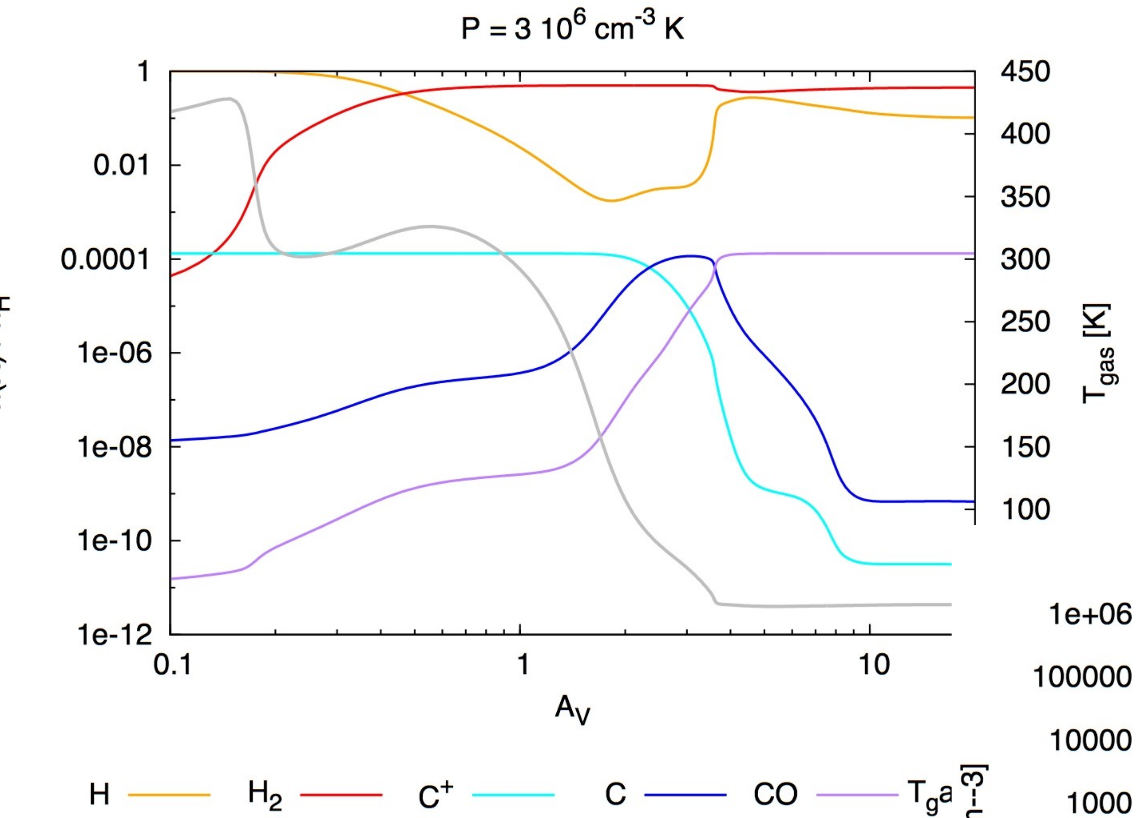
CO (15-14) line intensity on the Spitzer 8µm map





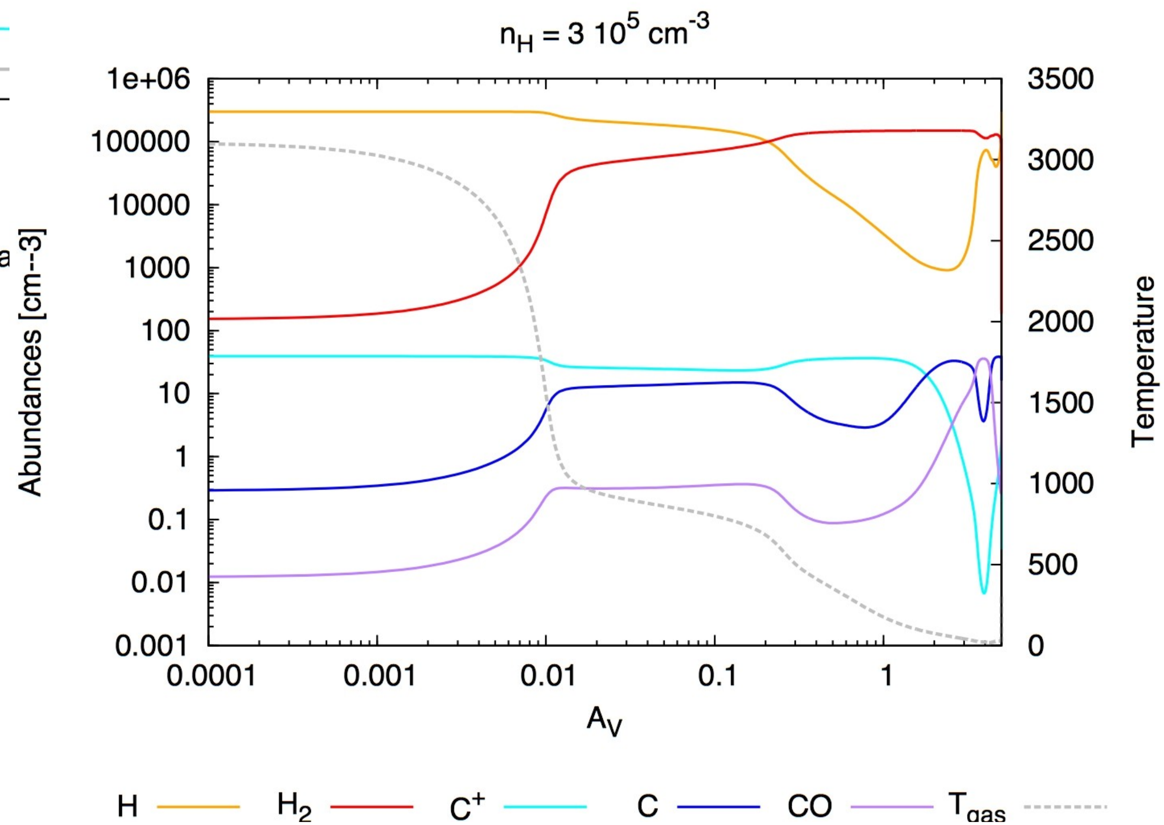
PACS matrix overlaid on the telescope PSF 75 µm (blue) and 150 µm (red)

Modelling: Meudon PDR code



Version 1.4.3
- Le Bourlot et al. (2012)
- With Eley-Rideal for H_2 formation

- Isobaric: P=3 10^6 K cm^{-3} fits [CII]
- But: second component needed for molecules/radicals



Diffuse gas:
"atomic" in warm gas (PAH, C+, O)

Dense gas (filaments):
warm molecular gas H_2, CO,...

NGC7023: PDR code results

	Instrument	Flux [W m-2 sr-1]	Flux with correction	PDR P=3E6	PDR n=3E5	PDR n=7E5	P=3E6+n=3E5	P=3E6+n=7E5	Observation	
CII	PACS	8.60E-07		5.90E-07	4.70E-07	3.00E-07	1.1E-06	8.9E-07	8.60E-07	Extended
CII	HIFI	6.00E-07								Extended
OI-145 (PACS)	PACS	4.90E-07		2.10E-07	6.40E-07	6.50E-07	8.5E-07	8.6E-07	4.90E-07	Extended
13CO (5-4)	HIFI	8.00E-10	4.00E-09	4.70E-09	1.50E-09	2.40E-09	6.2E-09	7.1E-09	4.00E-09	Filament
13CO (8-7)	HIFI	3.70E-09	1.20E-08	1.50E-10	1.90E-10	7.40E-10	3.4E-10	8.9E-10	1.20E-08	Filament
13CO (10-9)	HIFI	5.30E-09	1.40E-08	3.00E-12	7.40E-11	4.30E-10	7.7E-11	4.3E-10	1.40E-08	Filament
C18O (5-4)	HIFI	1.60E-10	8.00E-10	1.00E-09	1.00E-10	1.60E-10	1.1E-09	1.2E-09	8.00E-10	Filament
C18O (9-8)	HIFI	2.90E-10	8.30E-10	3.20E-12	7.30E-12	3.00E-11	1.1E-11	3.3E-11	8.30E-10	Filament
HCO+ (6-5)	HIFI	6.30E-11	3.30E-10	2.30E-11	3.00E-10	3.00E-09	3.2E-10	3.0E-09	3.30E-10	Filament
CH*	HIFI	1.40E-10	7.40E-10						7.40E-10	Filament
CH+ (1-0)	HIFI	6.40E-11	2.10E-10	2.50E-11	9.10E-09	1.60E-08	9.1E-09	1.6E-08	2.10E-10	**REABSORPTION**
CH+ (2-1)	PACS	7.20E-09	8.40E-09	3.40E-11	1.60E-08	3.20E-08	1.6E-08	3.2E-08	8.40E-09	Extended/filament?
CH+ (3-2)	PACS	1.00E-08		3.30E-11	1.70E-08	3.30E-08	1.7E-08	3.3E-08	1.00E-08	Extended/filament?
CO (9-8)	HIFI	3.00E-08	8.10E-08	2.70E-09	9.50E-09	5.40E-08	1.2E-08	5.7E-08	8.10E-08	Filament
CO (15-14)	PACS	3.35E-08	3.89E-08	1.40E-13	3.10E-09	6.00E-08	3.1E-09	6.0E-08	3.89E-08	Filament
CO (16-15)	PACS	2.03E-08	2.33E-08	6.90E-14	2.50E-09	5.60E-08	2.5E-09	5.6E-08	2.33E-08	Filament
CO (17-16)	PACS	1.63E-08	1.90E-08	4.00E-14	1.90E-09	5.00E-08	1.9E-09	5.0E-08	1.90E-08	Filament
CO (18-17)	PACS	9.60E-09	1.02E-08	2.80E-14	1.50E-09	4.30E-08	1.5E-09	4.3E-08	1.02E-08	Filament
CO (19-18)	PACS	3.60E-09	3.70E-09	2.30E-14	1.10E-09	3.50E-08	1.1E-09	3.5E-08	3.70E-09	Filament
H2 (v1J3-v0J1)		2.10E-07	2.60E-07	2.30E-08	2.60E-07	6.60E-07	2.8E-07	6.8E-07	2.60E-07	Filament
S(1)		1.10E-07	1.10E-07	2.20E-07	3.80E-07	4.30E-07	6.0E-07	6.5E-07	1.10E-07	Filament
S(2)		6.90E-07	7.30E-07	1.70E-07	4.70E-07	5.70E-07	6.4E-07	7.4E-07	7.30E-07	Filament
S(3)		9.30E-07	1.00E-06	3.00E-08	1.60E-06	2.50E-06	1.6E-06	2.5E-06	1.00E-06	Filament
S(4)		1.70E-07	2.20E-07	5.40E-09	4.90E-07	8.60E-07	5.0E-07	8.7E-07	2.20E-07	Filament
HD (1-0)		1.70E-08								
eVSGs		9.60E-06								Extended/filament?
PAH0		9.80E-05								Extended/filament?
PAH+		4.20E-05								Extended/filament?
PAHx		1.30E-05								Extended/filament?

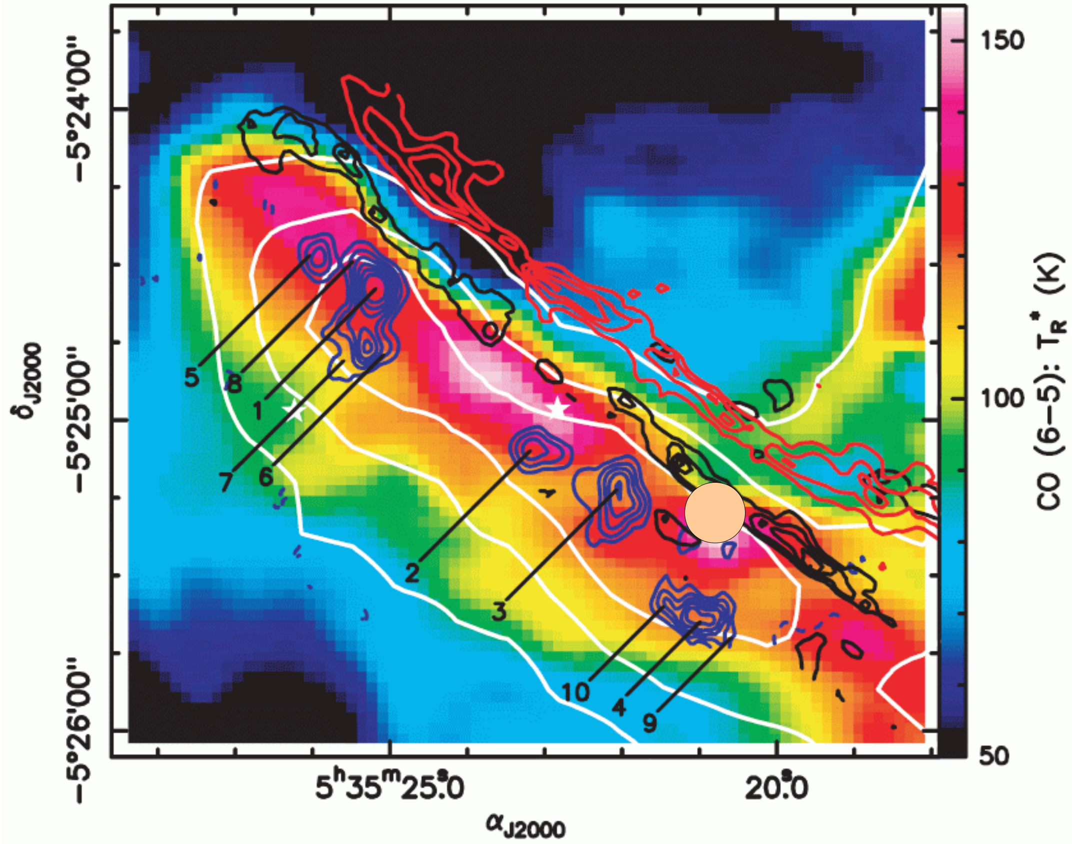
- Reasonable fit by two-component model
- But: high-J CO isotopologues still much stronger than predicted
- Problem of plane-parallel setup: stratification not resolvable (A_V=1 → 3" for 10^5 cm^{-3})

Example 3: The Orion Bar

To be clumpy or not to be clumpy?

FORECAST: 19.7 and 37µm
(Shuping et al. 2012)

CO 6-5 (color), ^{13}CO 3-2 (white contours), OI 1.32µm (red), H_2 v=1-0 S(1) (black), H^{13}CN 1-0 (blue) (Lis & Schilke 2003)

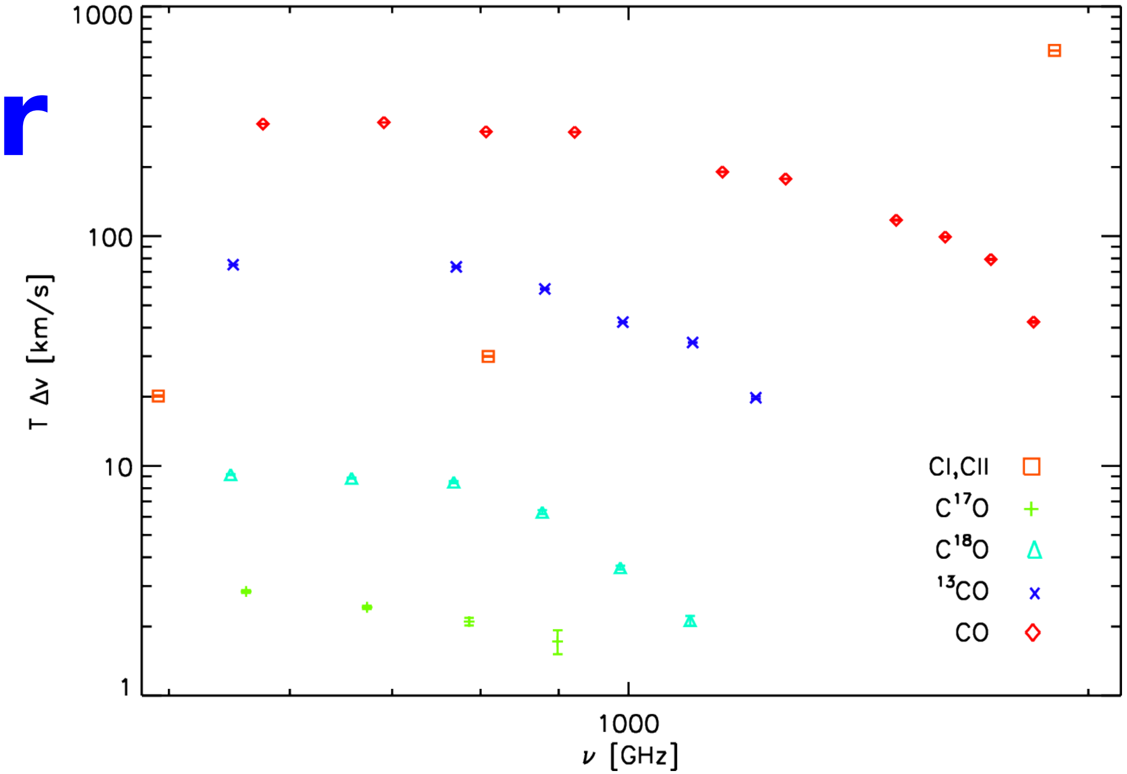


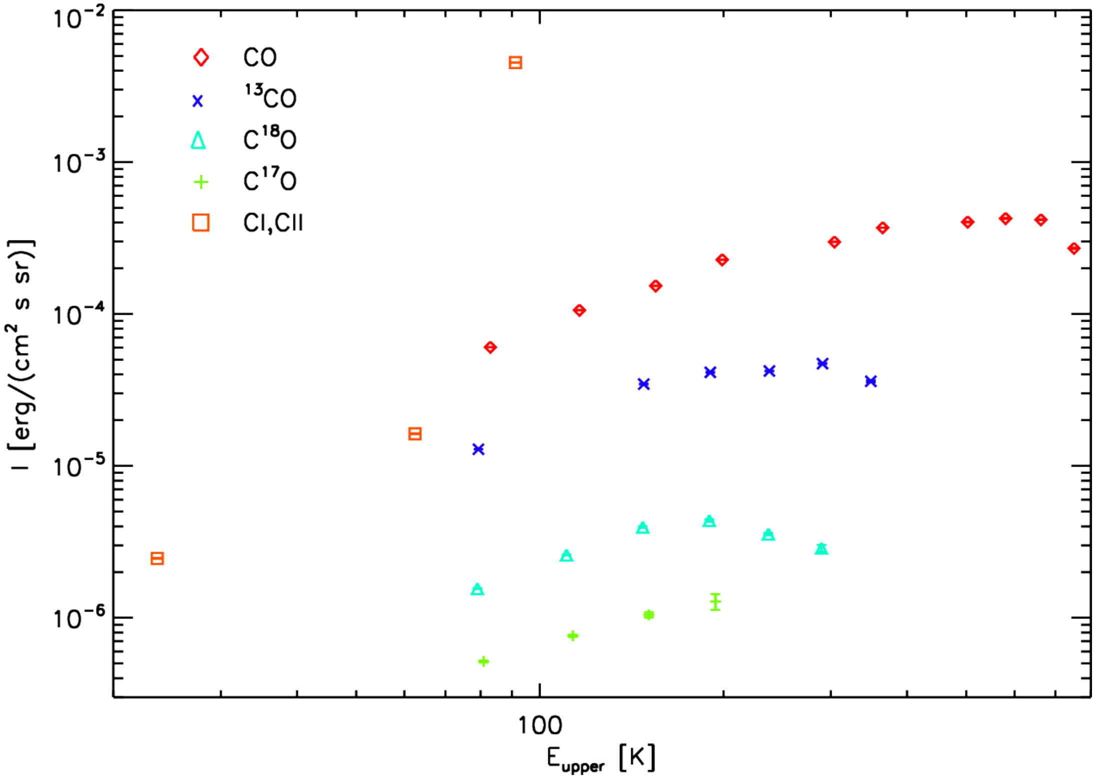
HIFI central position: 5h35m20.81s -5d25m17.1s

Orion Bar

Full HIFI spectral scan:

- CO excitation flat up to J=15
  - Excitation increasing in energy
  - Turn over around 700K
  - PACS detection up to J=22





Integrated HIFI line intensities for CO isotopologues and CI,CII:

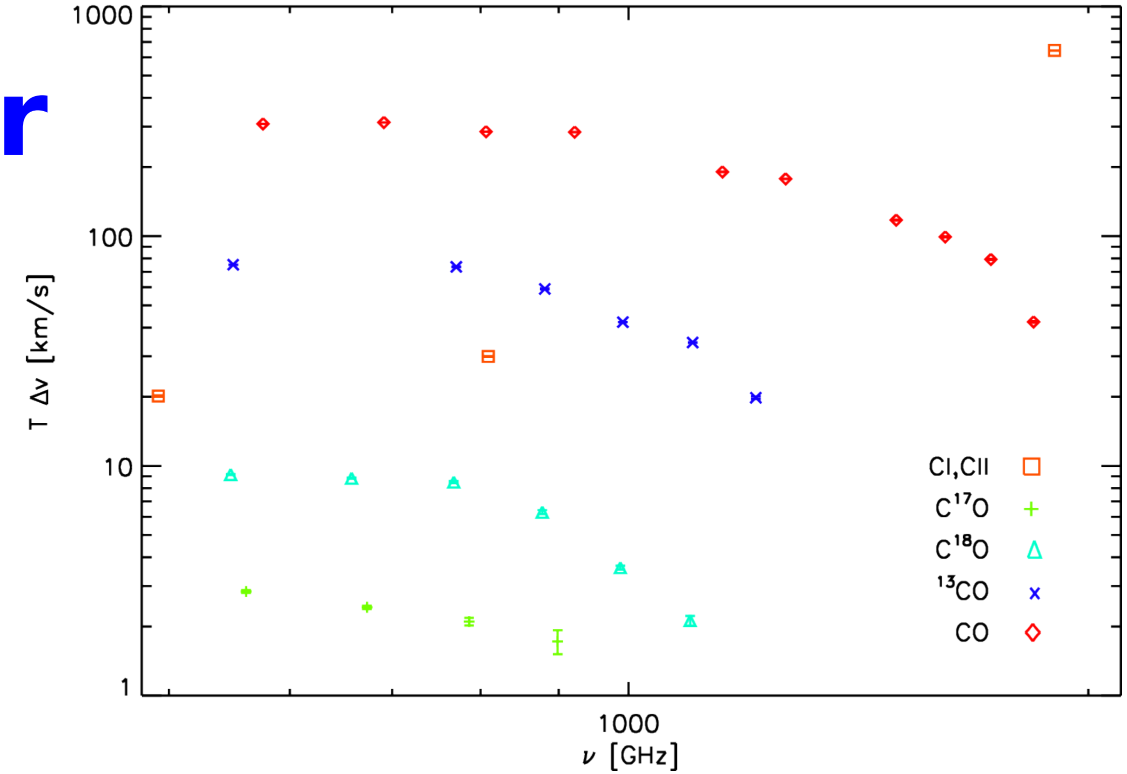
Top: in integrated intensities vs. frequency

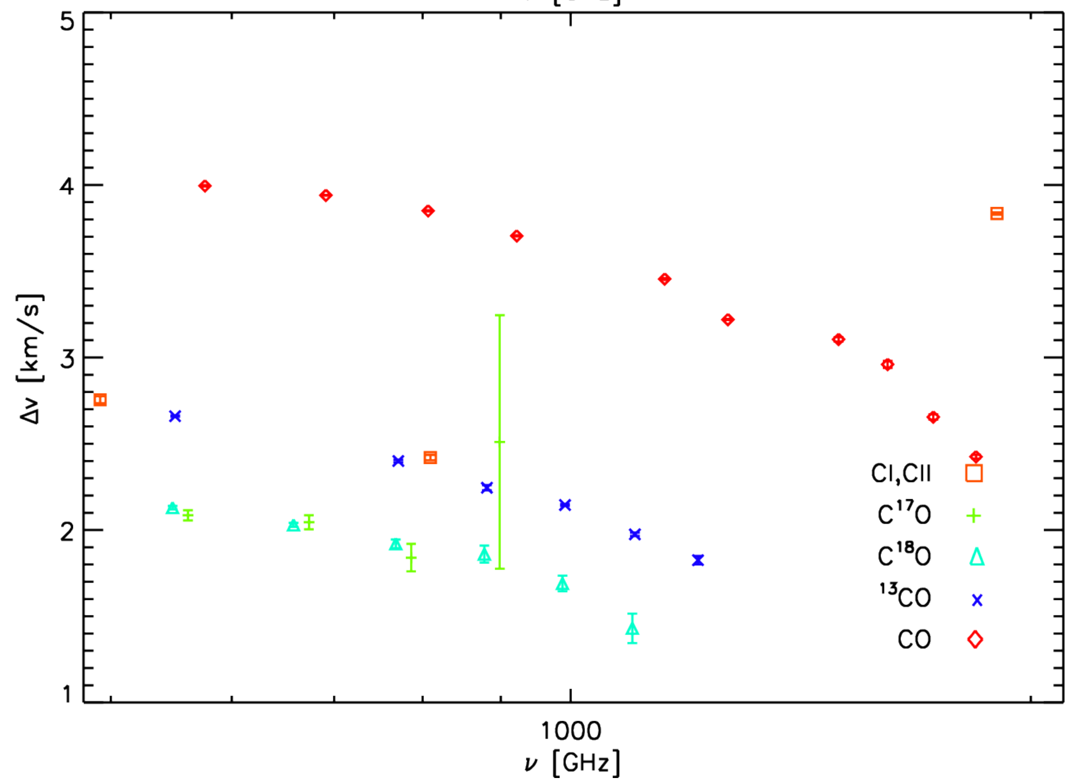
Bottom: radiated energy vs. excitation energy

Orion Bar

Full HIFI spectral scan:

- Lines Gaussian, but:
  - Line width strong function of J
    - also for optically thin species
    - Larson-like dependence (?)
    - **Contradiction to normal modelling approach**

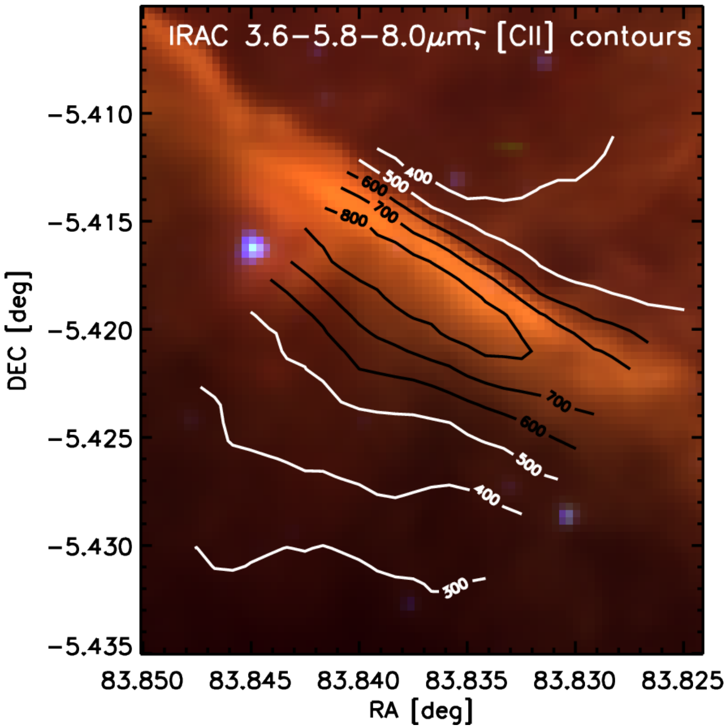




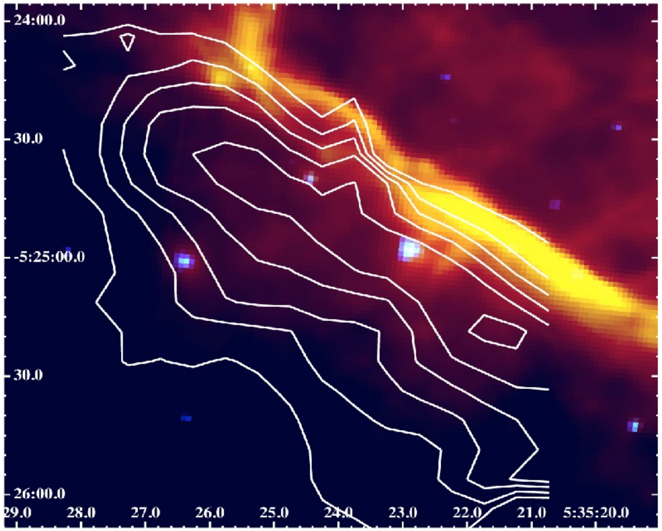
Top: integrated HIFI line intensities for CO isotopologues and CI,CII

Bottom: Corresponding measured line width

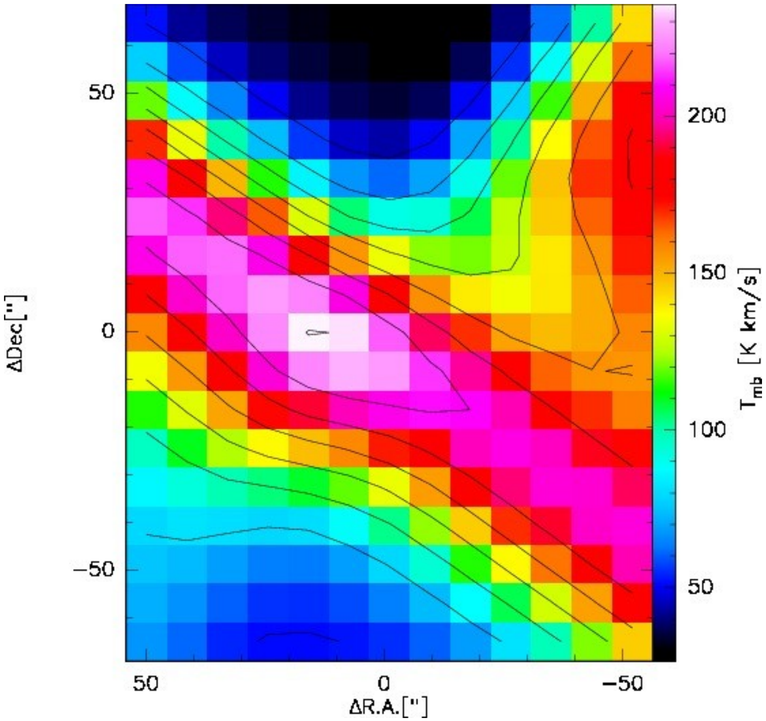
Spatial structure



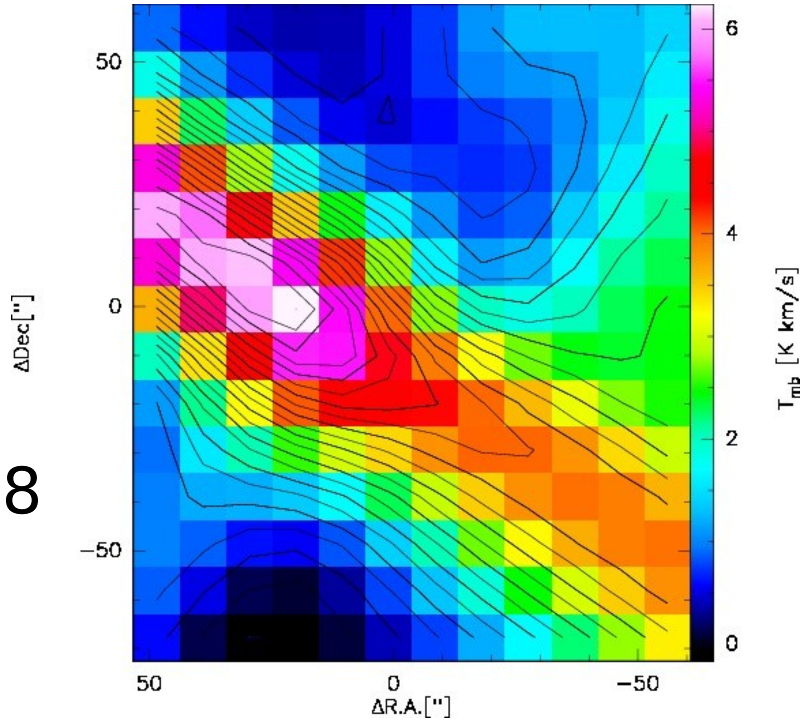
[CII]



^{13}CO 3-2



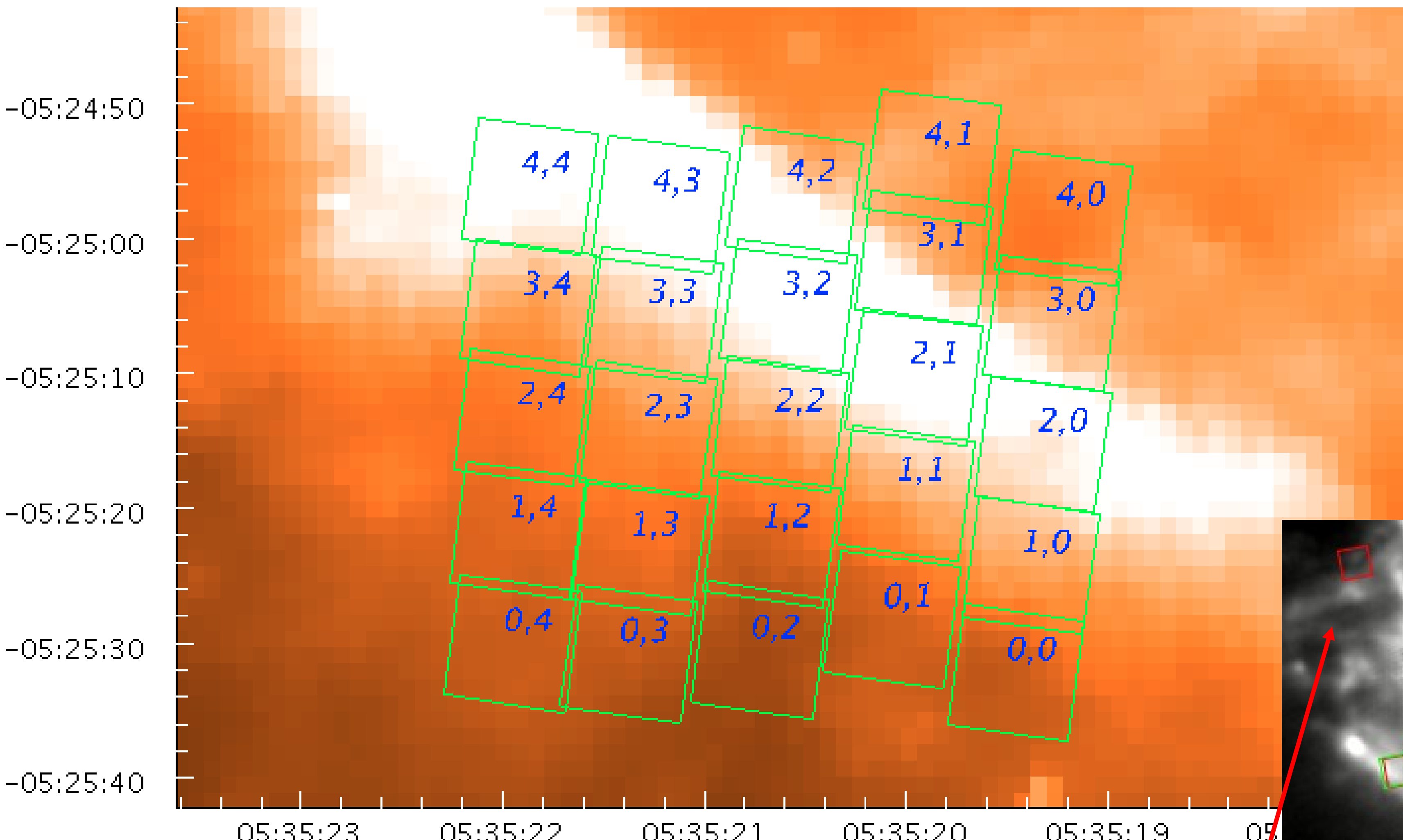
CO 10-9

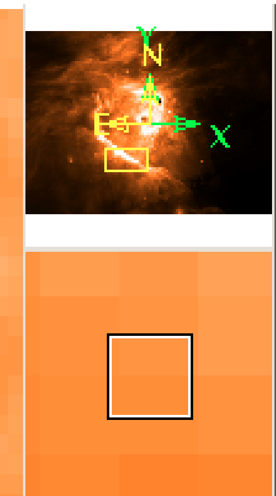


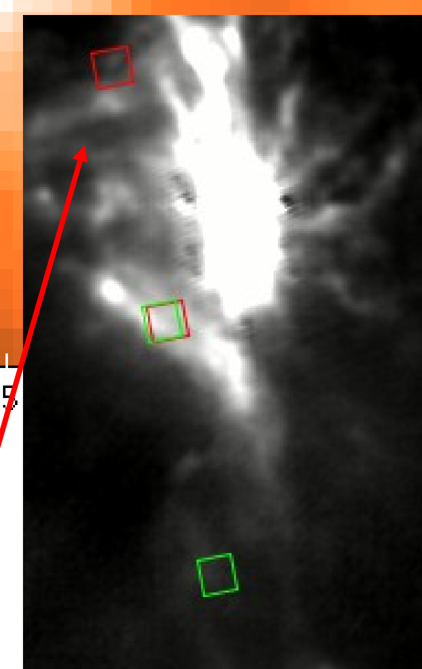
$C^{18}O$ 9-8

- Very smooth distribution

PACS SED Scan





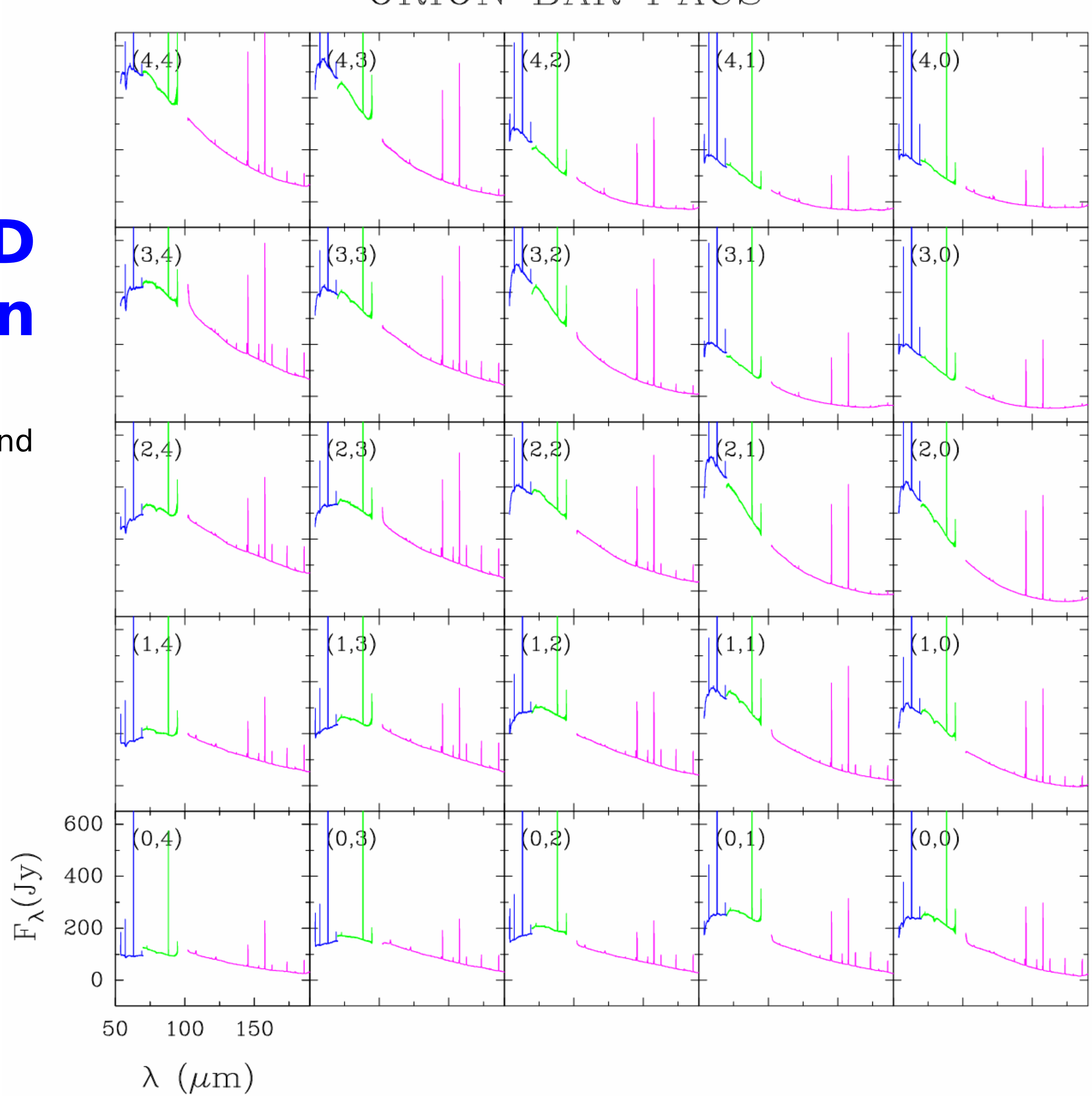


Problem:

- negative continuum flux in some spaxels at long wavelengths
- likely due to emission in 1 of the 2 reference positions.

PACS SED Scan

Dominated by [CII] and [OI]

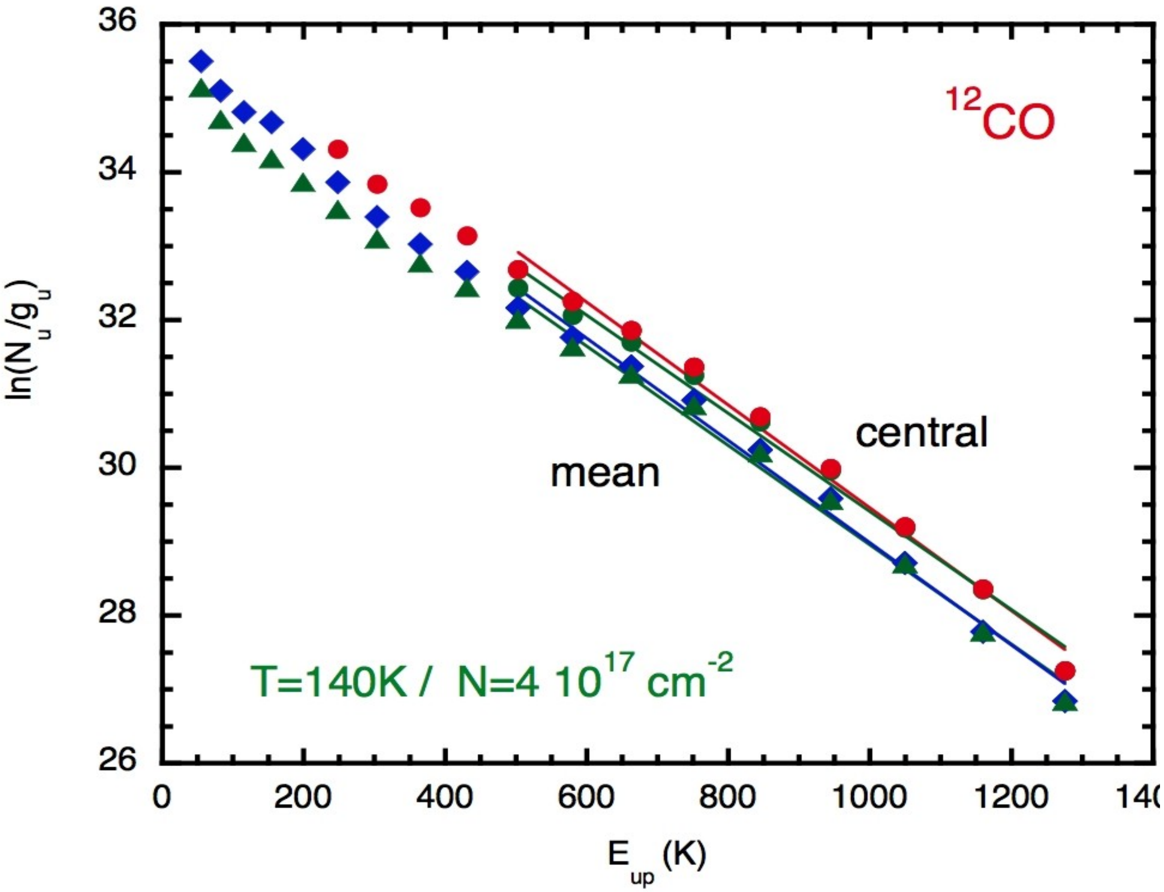


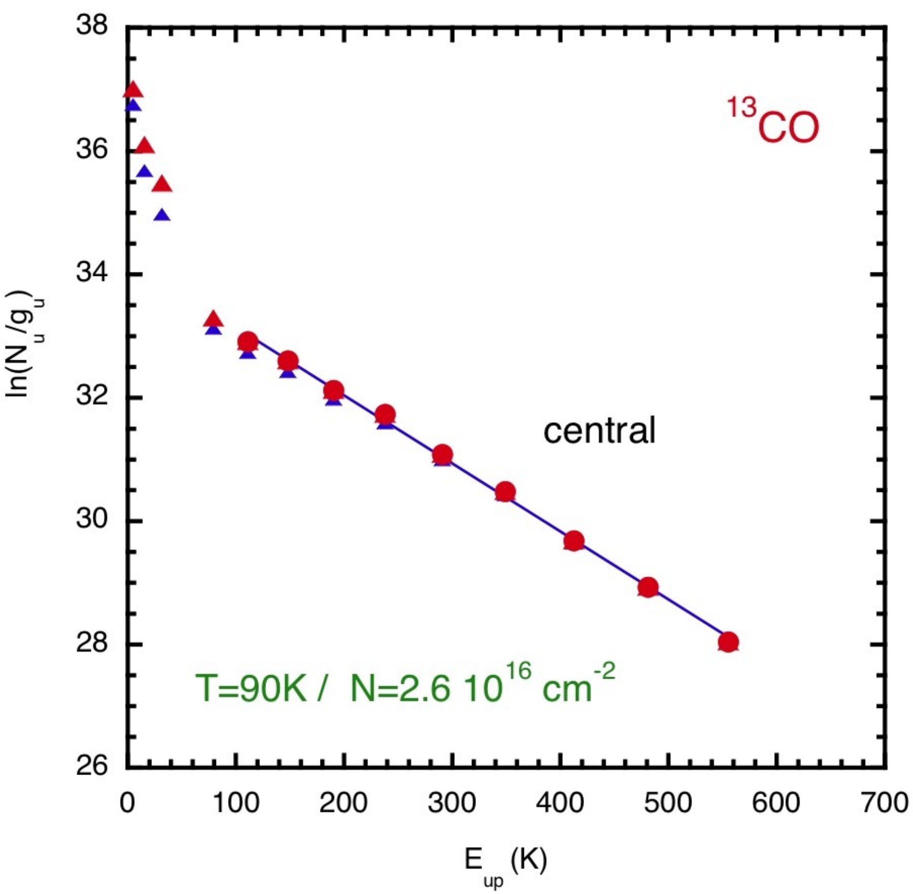
CO excitation

PACS (central + mean; HEXOS) + SPIRE (21" + convolved 42", SAG 4):

^{12}CO: Green: Measured
Blue and red: With opacity correction

^{13}CO: Blue: Measured
Red: With opacity correction

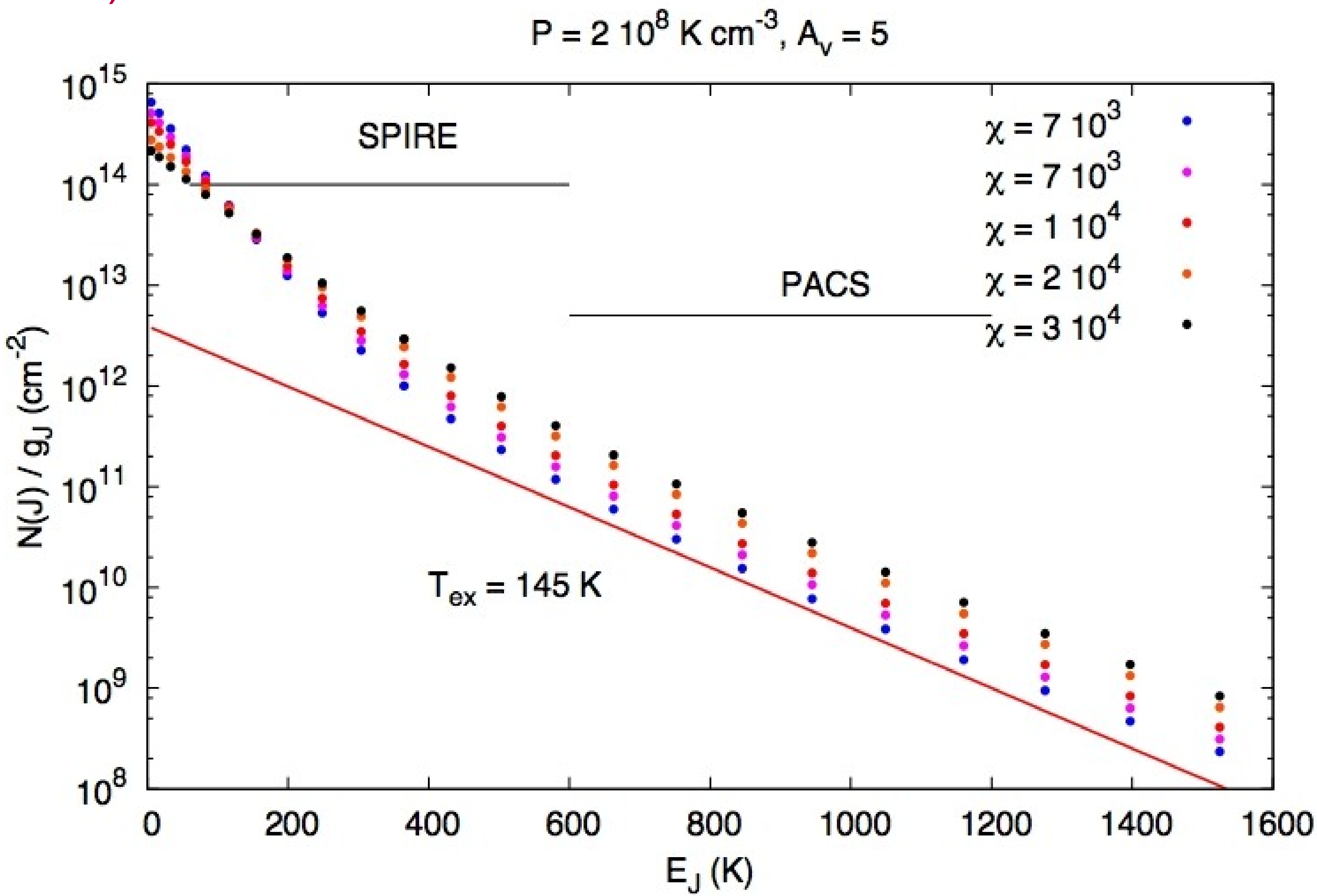




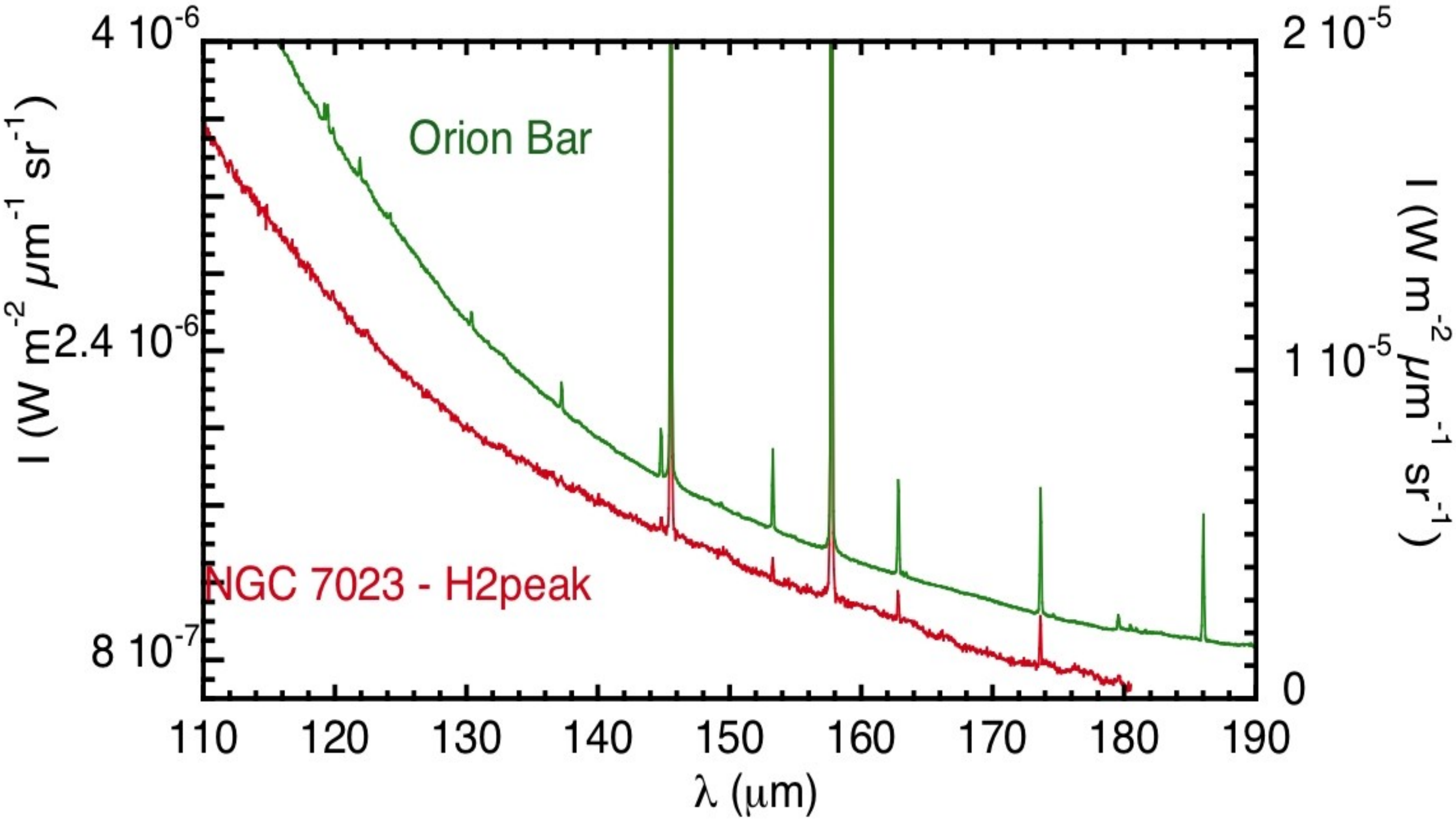
Modelling: Meudon PDR code

Fit of CO excitation temperature by isobaric model:

- For E_{up} > 500K : T_{ex}(CO) is independent of the radiation field
- Abundance and column density depend on the radiation field
- Low-J CO (E_{up} < 300K) overpredicted



Comparison to NGC7023



Orion Bar:

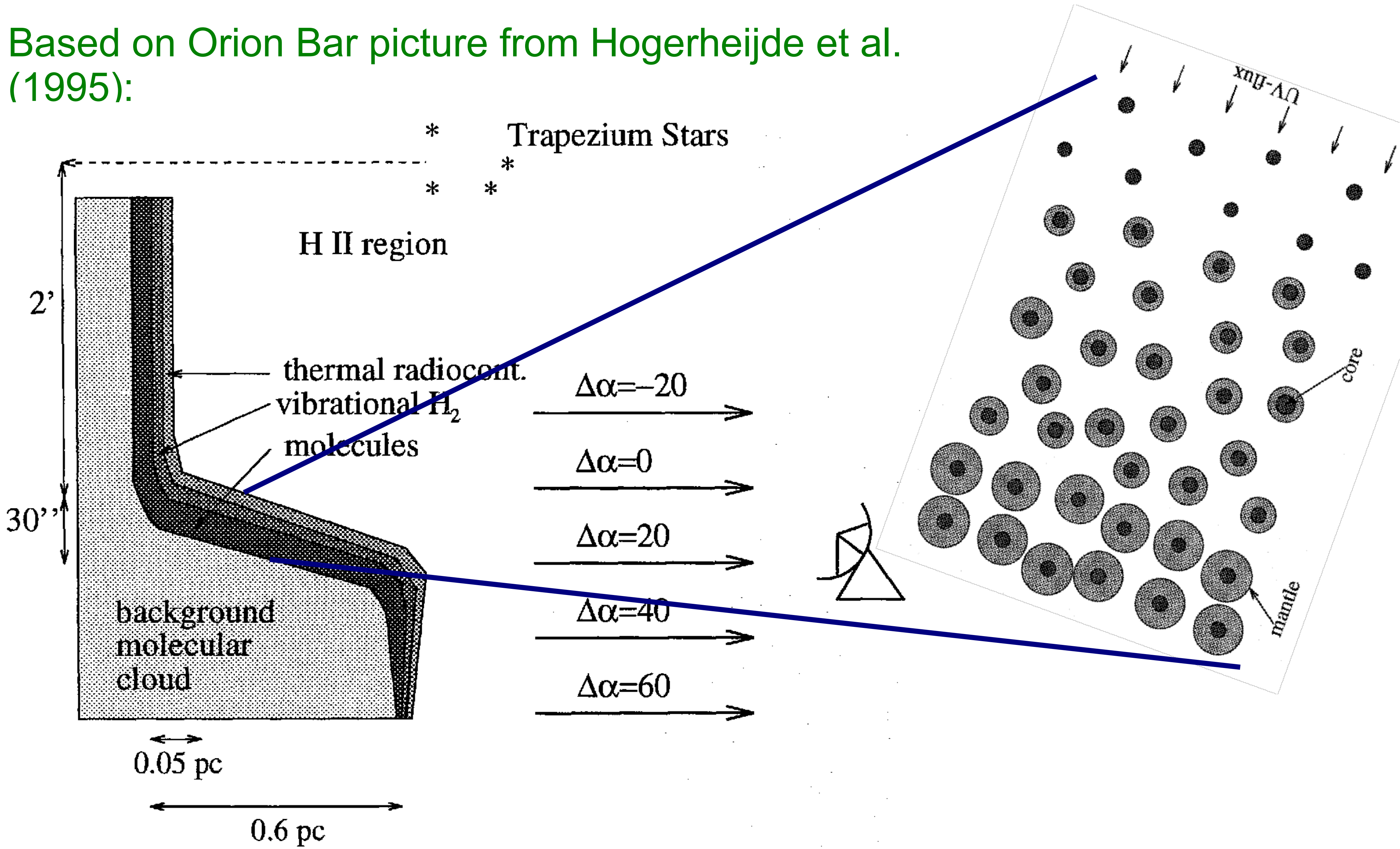
- Spitzer (Pilleri et al. 2011) :
  - N_H = 1.1 10^{22} cm^{-2} ← A_V=6.1 mag
- Herschel:
  - [CII]: 8.5 10^{-6} W m^{-2} sr^{-1} ,
  - high-J CO : T_{ex} = 140 K, N= 4 10^{17} cm^{-2}

NGC 7023:

- Spitzer:
  - N_H = 2.0 10^{22} cm^{-2} ← A_V=11.3 mag
- Herschel :
  - [CII]: 8.6 10^{-7} W m^{-2} sr^{-1},
  - high-J CO: T_{ex} ~ 110 K, N = 6 10^{16} cm^{-2}

Modeling: KOSMA-τ PDR Code

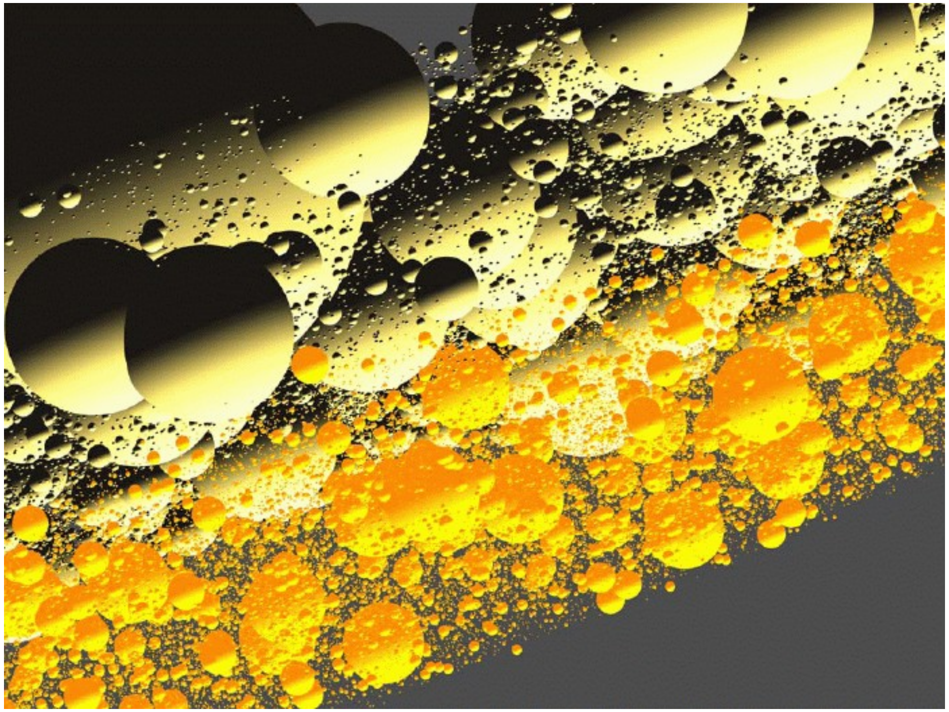
Based on Orion Bar picture from Hogerheijde et al. (1995):



Modeling: KOSMA-τ PDR Code

2-Component clumpy model

- assume stratification of 2 clumpy layers
- deeper layer sees weaker FUV field due to attenuation
- neglect mutual shielding and shadowing

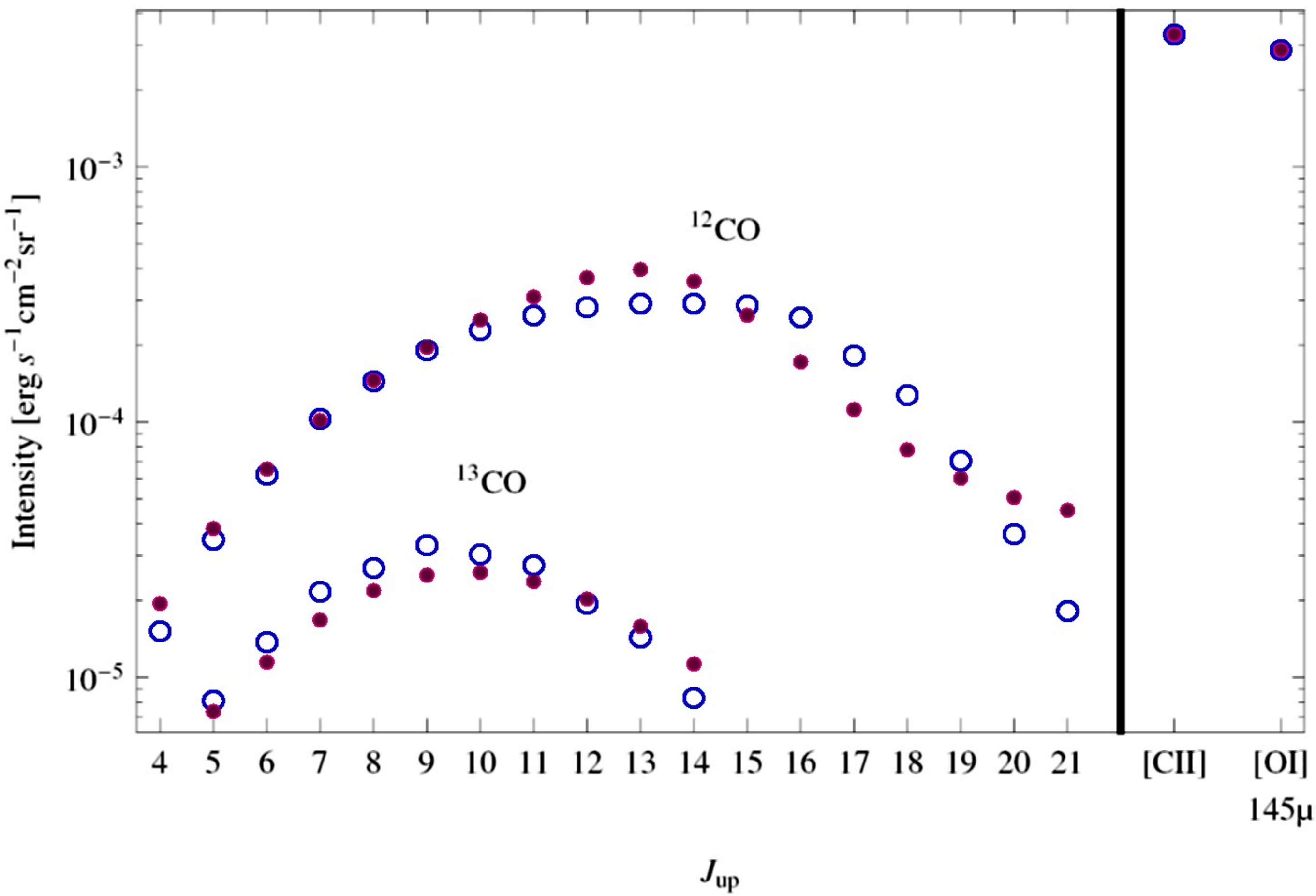


yellow: closer to the FUV source

beige: further away from the FUV source

Modeling: KOSMA-τ PDR Code

2-Component clumpy model:



- Diffuse:
  - $n = 2.7\ 10^{4}\ cm^{-3}$
  - $\chi = 3\ 10^{4}$
- Dense:
  - $n = 7\ 10^{6}\ cm^{-3}$
  - $\chi = 2000$
- model mass: $0.26\ M_{\odot}$

→ matches observed col. density of $6.5\ 10^{22}\ cm^{-2}$ on (9.6“)² pixel

Result:

- ^{12}CO lines fitted up to J=15-14 , J>20 overpredicted, ^{13}CO well reproduced
- fine structure lines reproduced ([OI] 63μm overestimated due to opt. thick.)

Summary

- High-J CO excited in all three PDRs in spite of moderate average gas temperatures.
  - Explained by enhanced H_2 formation rates at high temperatures through Eley-Rideal mechanism
- Still no comprehensive fit to full CO ladder and spatial stratification structure
- Combination of multiple density components needed
  - Nature of dense component ?
    - Filaments vs clumps ?
    - Small dense components must be transient
      - Evaporating ?
    - How many of these structures are needed?

Summary

- PDR model fits
  - Major progress made thanks to NGC7023 and Orion Bar
  - Need for a two component model:
    - diffuse gas traced by PAH and C+
    - dense component for warm molecular emission (CO, OH, H_2,...)
  - need to form H_2 in the warm layers (Eley-Rideal mechanism)
  - still challenging to get a good fit for CO (T_{ex} and N)
  - difficulties on the description of geometry and local physical conditions.
    - predicted transitions on too small scales

      → no stratification would not be observable
    - dense components: → better use KOSMA-τ approach

Summary

But:

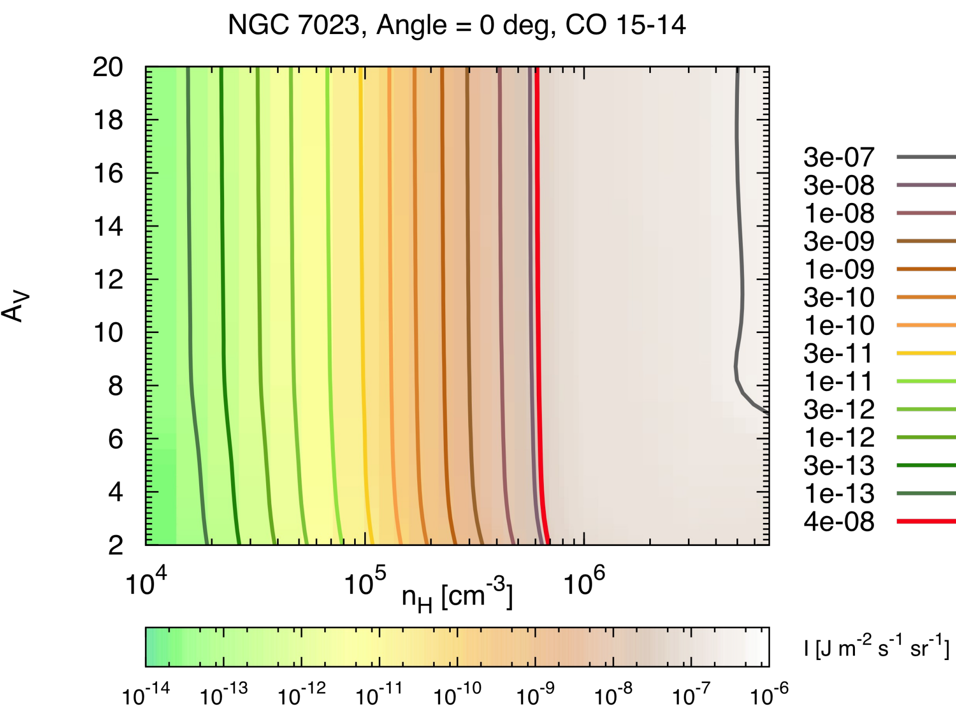
- Fits to integrated line intensities miss all the information contained in the line profiles!
  - Assumption of equal line profiles for optically thin tracers is wrong!
  - Self-absorption, outflow wings, turbulence, advection flows, pressure gradients

- More sophisticated models needed
- Modelling/interpretation has only started

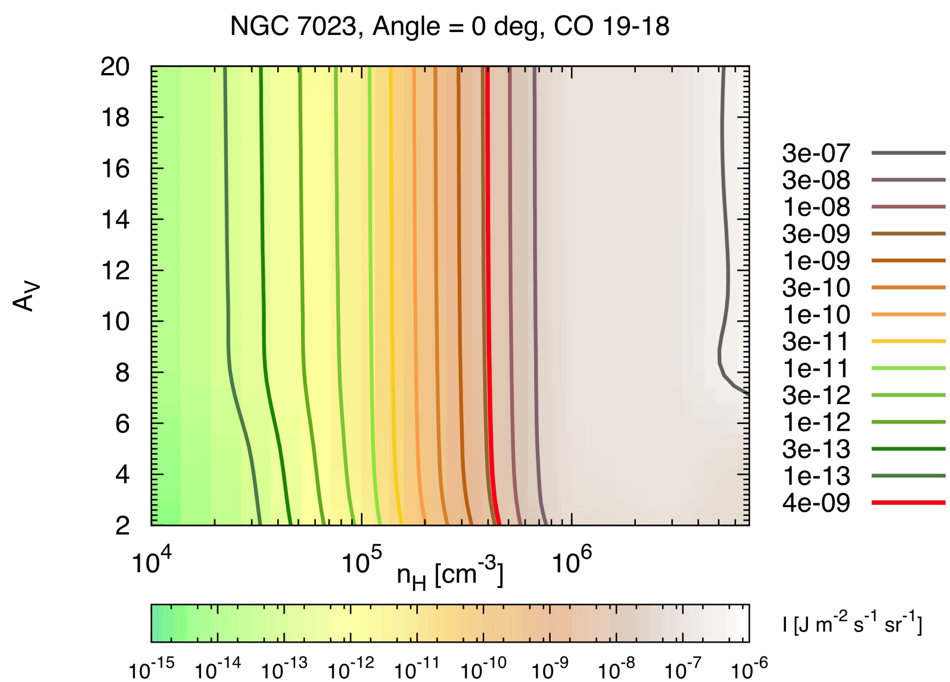
PDR code results

Star: Kurucz's spectrum at 15000 K; d=0.143pc → G_0=2600 (*Joblin et al. 2010*)

CO 15-14



CO 19-18

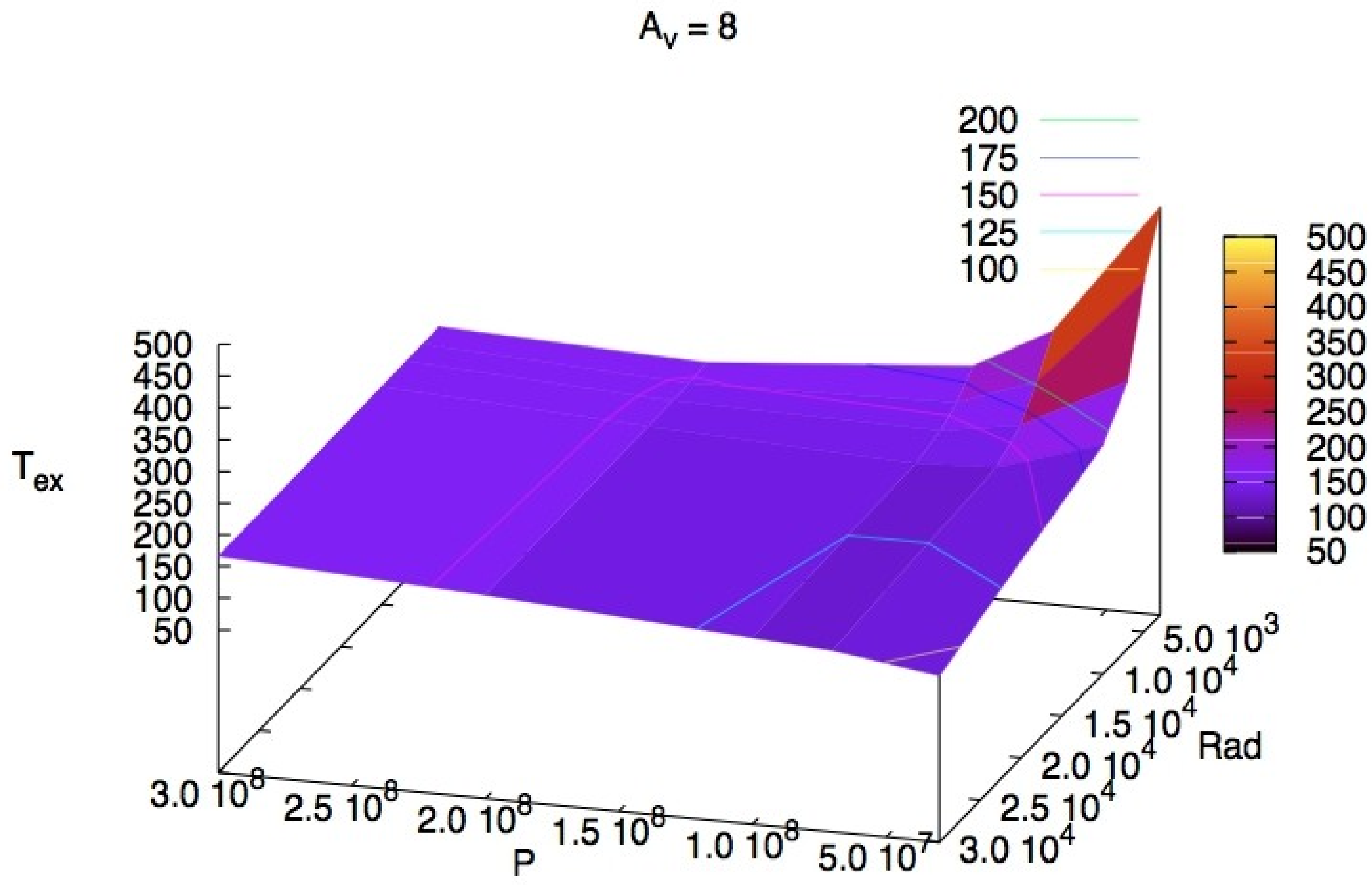


- Observed CO intensities → n_H between 4 10^5 and 6 10^5 cm^{-3}.
- The size on the cloud has no effect on the excited lines that arise from the surface.

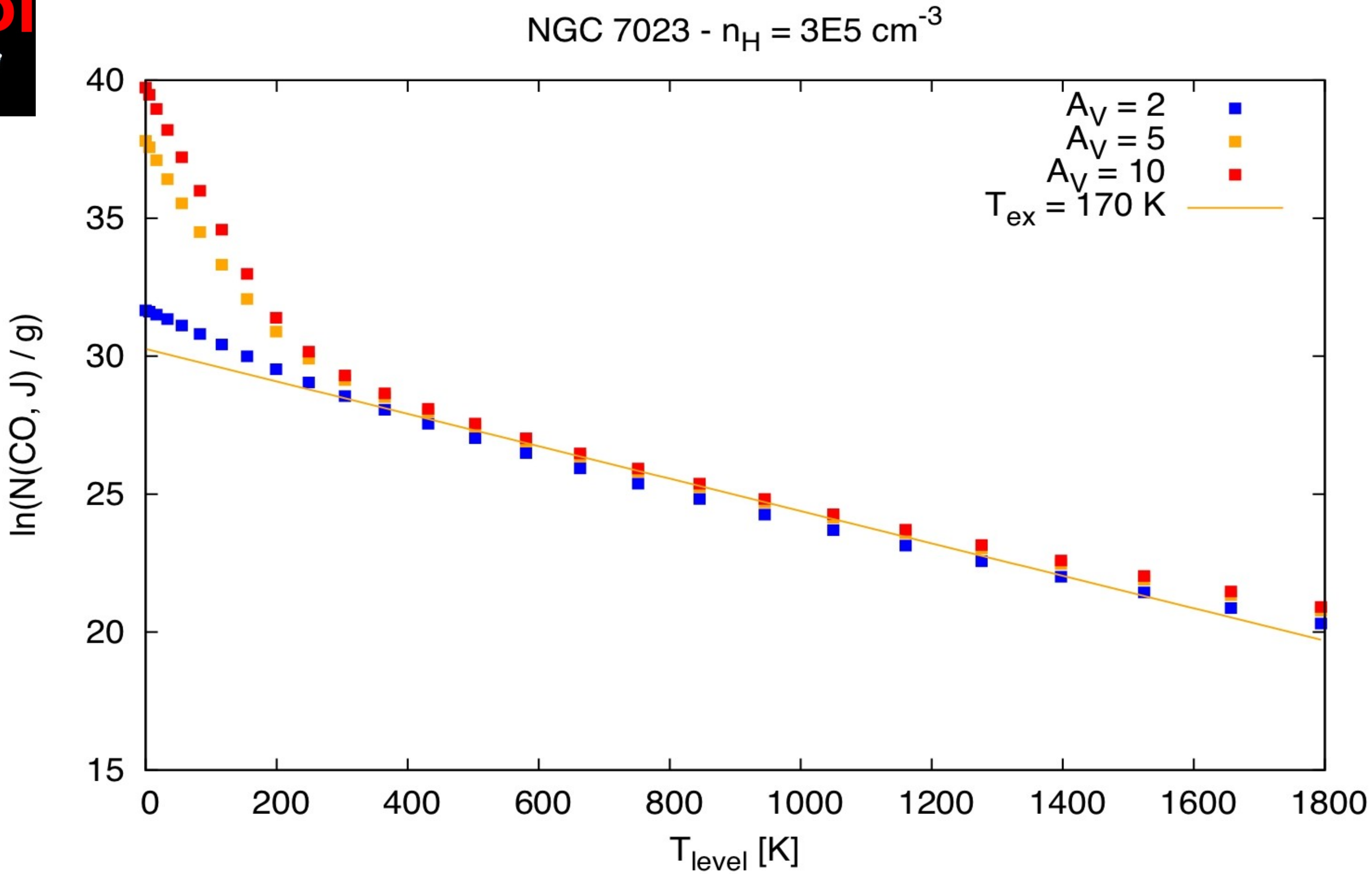
Modelling: Meudon PDR code

Fit of CO excitation temperature by isobaric model:

- Range of P and Rad. field values that match $T_{ex}(CO)$



PDR code results



PDR code/ n_H=3 10^5 cm^{-3} → Tex(CO) = 170 K (J = 14-19), N=9 10^{14} cm^{-2}
Observations: Tex(CO) ~110 K (J = 15-19), N=6 10^{16} cm^{-2}

→Further work needed on this phase, lower radiation field? Geomety? Multiple filament structure?