# PDR diagnostics as observed by PACS and SPIRE

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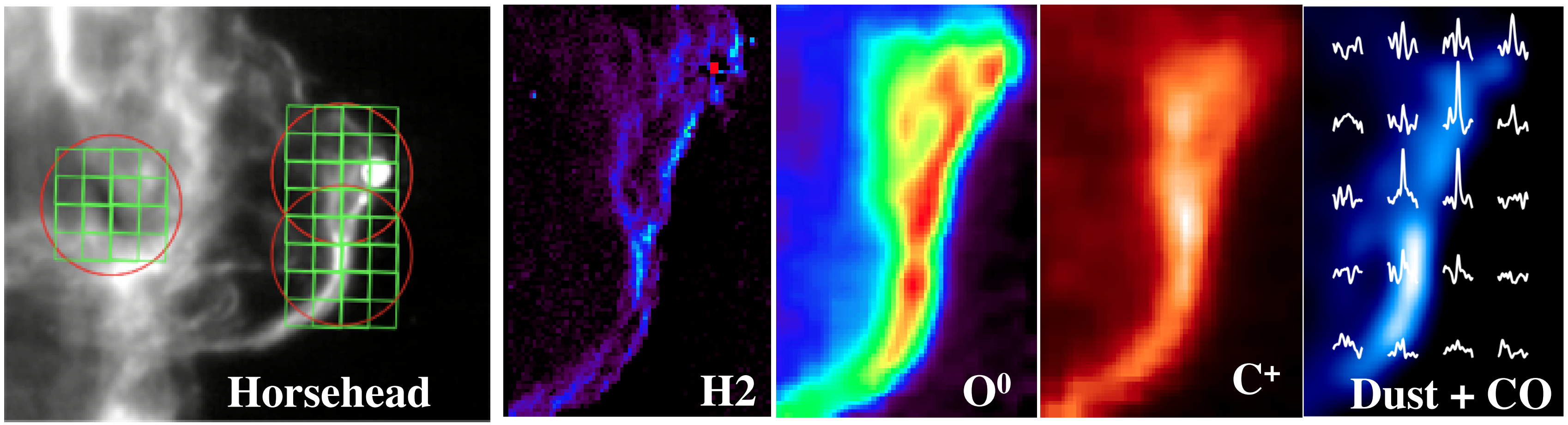
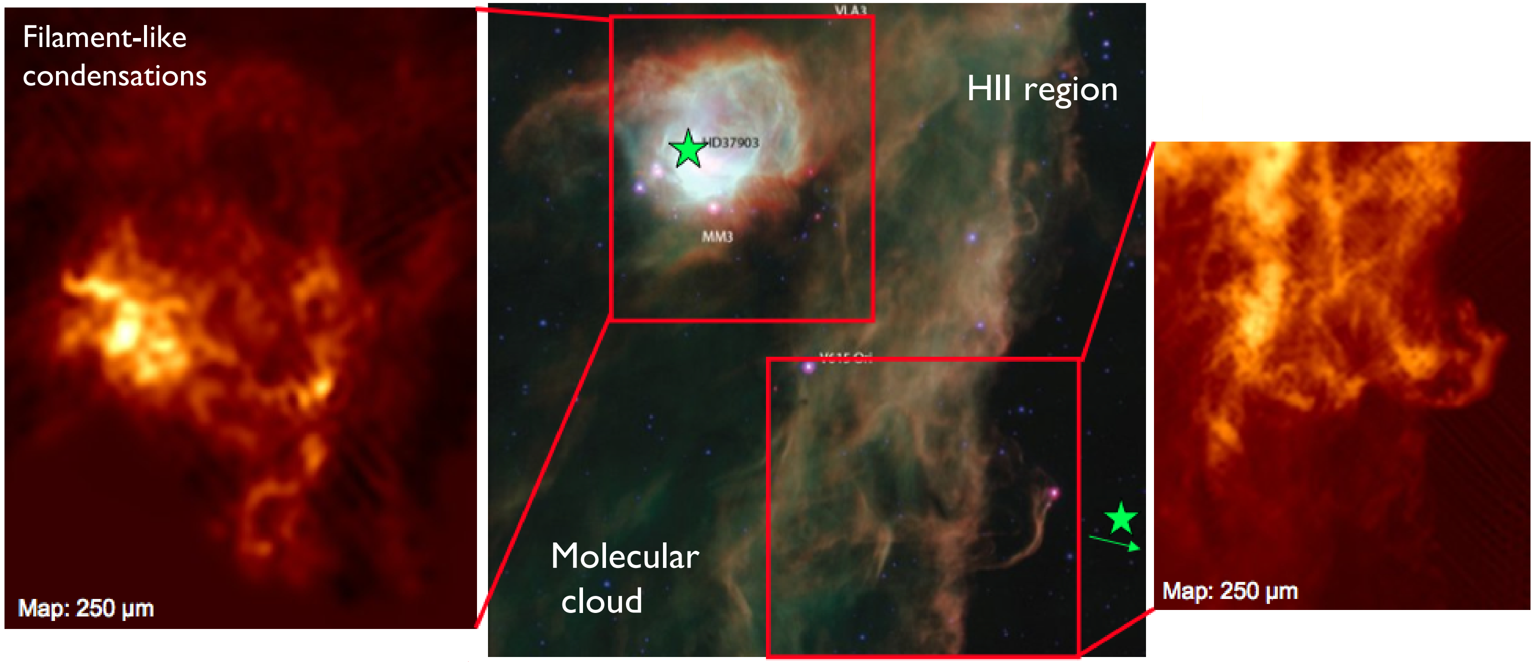
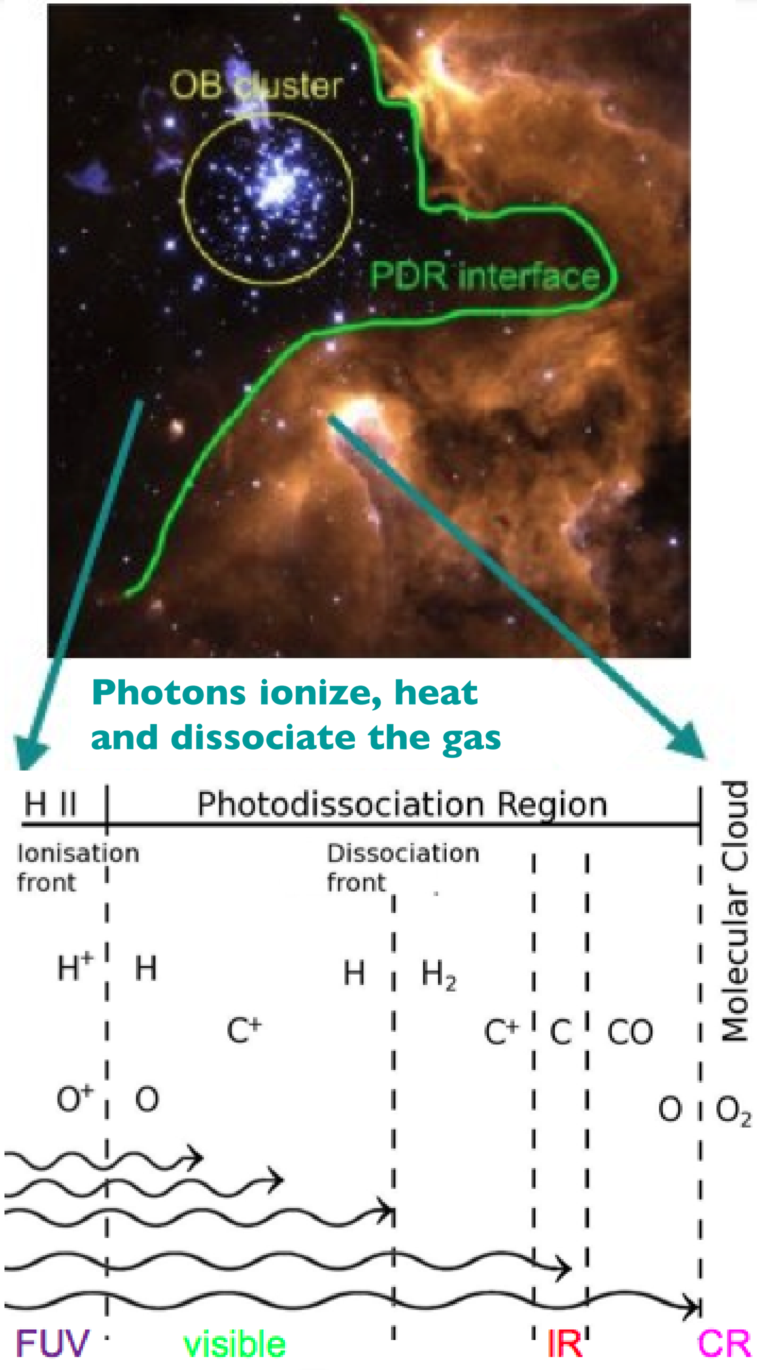
and SAG4 (ISM group of the SPIRE consortium)



# How radiation of young stars affects interstellar matter ?




- ❑ Structure
- ❑ Dynamics
- ❑ Chemistry
- ❑ Thermal balance
- ❑ Star formation




# Photon-Dominated Regions (PDRs)

- ❑ Reprocess much of the radiation energy emitted by young massive stars

- ❑ Origin of most of the non-stellar IR and sub-mm emission from galaxies

- ❑ Key regions in the chemical and physical evolution of objects from the large scales of the galaxies to the small scale of protoplanetary disks

- ❑ Spitzer and Herschel provide a wealth of spatial and spectral information of gas and dust emission in the heart of PDR

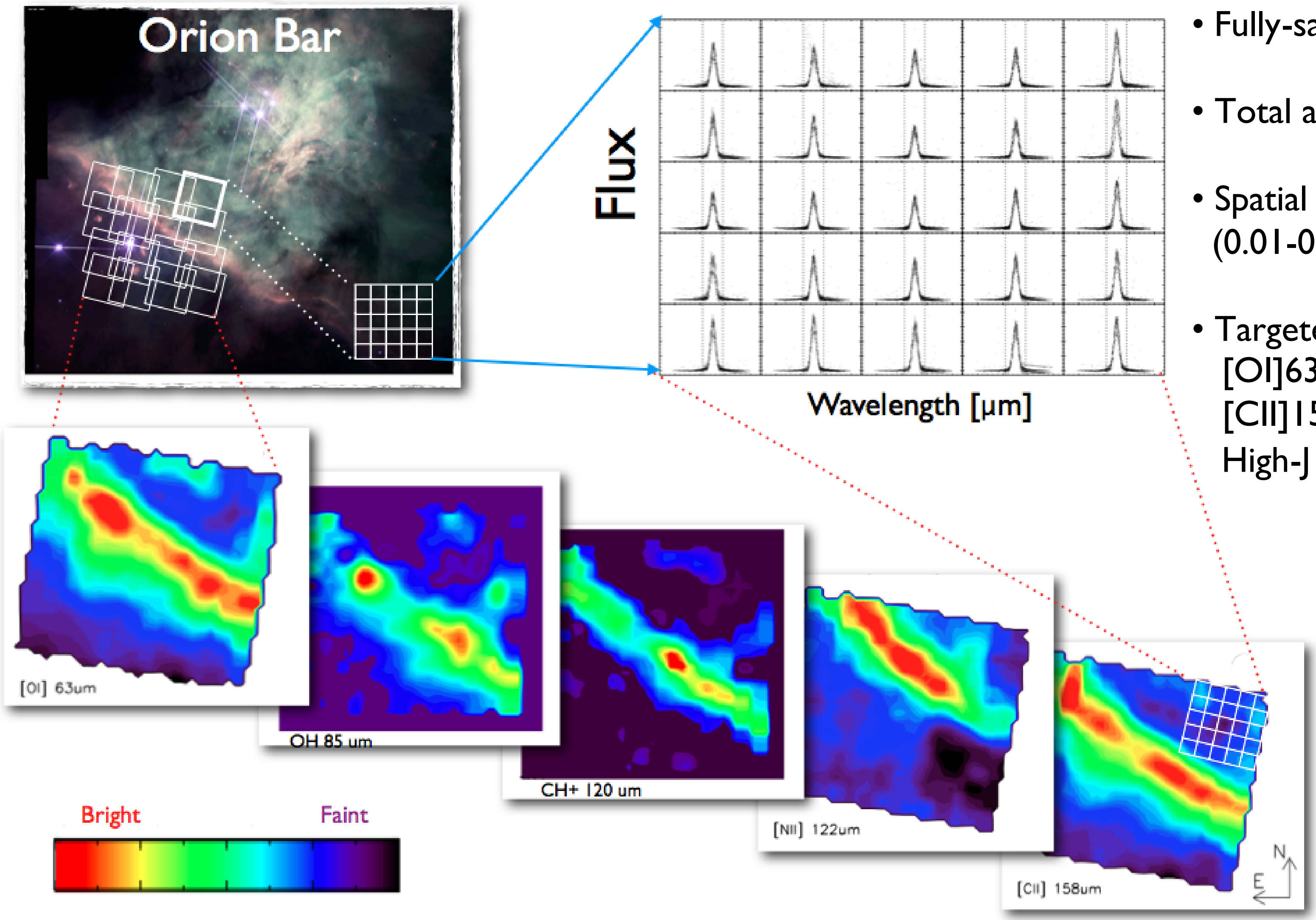
# Sample of nearby galactic PDRs

- ❑ Programs: SAG 4, WADI, HEXOS, OT..
- ❑ PDRs spanning a wide range of excitation conditions and phases of the ISM:

| Object | IRAS100 | $T_{eff}$(K), Star | $G_0$ | $n_H$ ($cm^{-3}$) |
|---|---|---|---|---|
| Orion Bar | 20,000 | 40,000, O6 | 20,000 | $10^5$-$10^7$ |
| NGC2023 | 2,000 | 23,000, B1.5V | 1,000 | $10^4$-$10^6$ |
| NGC7023 | 1,000 | 17,000, B3Ve | 2,600 | $10^4$-$10^6$ |
| Horsehead | 500 | 33,000, O9.4V | 100 | $10^4$-$10^5$ |
| p Oph filament | 500 | 22,000, B2V | 400 | $10^4$-$10^5$ |
| NGC7023 E | 200 | 17,000, B3Ve | 200 | $10^4$-$10^5$ |
| Ced201 | 100 | 10,500, B9.5V | 200 | ~$10^4$ |
| IC63 | 100 | 30,000, B0.5IV | 650 | $10^4$-$10^5$ |
| IC59 | 100 | 30,000, B0.5IV | 480 | $10^3$-$10^4$ |
| L1721 | 100 | 22,000,B2IV | 10 | $10^3$-$10^4$ |
| California | 100 | 37,000,O7 | 30 | $10^3$-$10^4$ |

$G_0$ : incident FUV radiation field (Habing)

# PACS spectral mapping



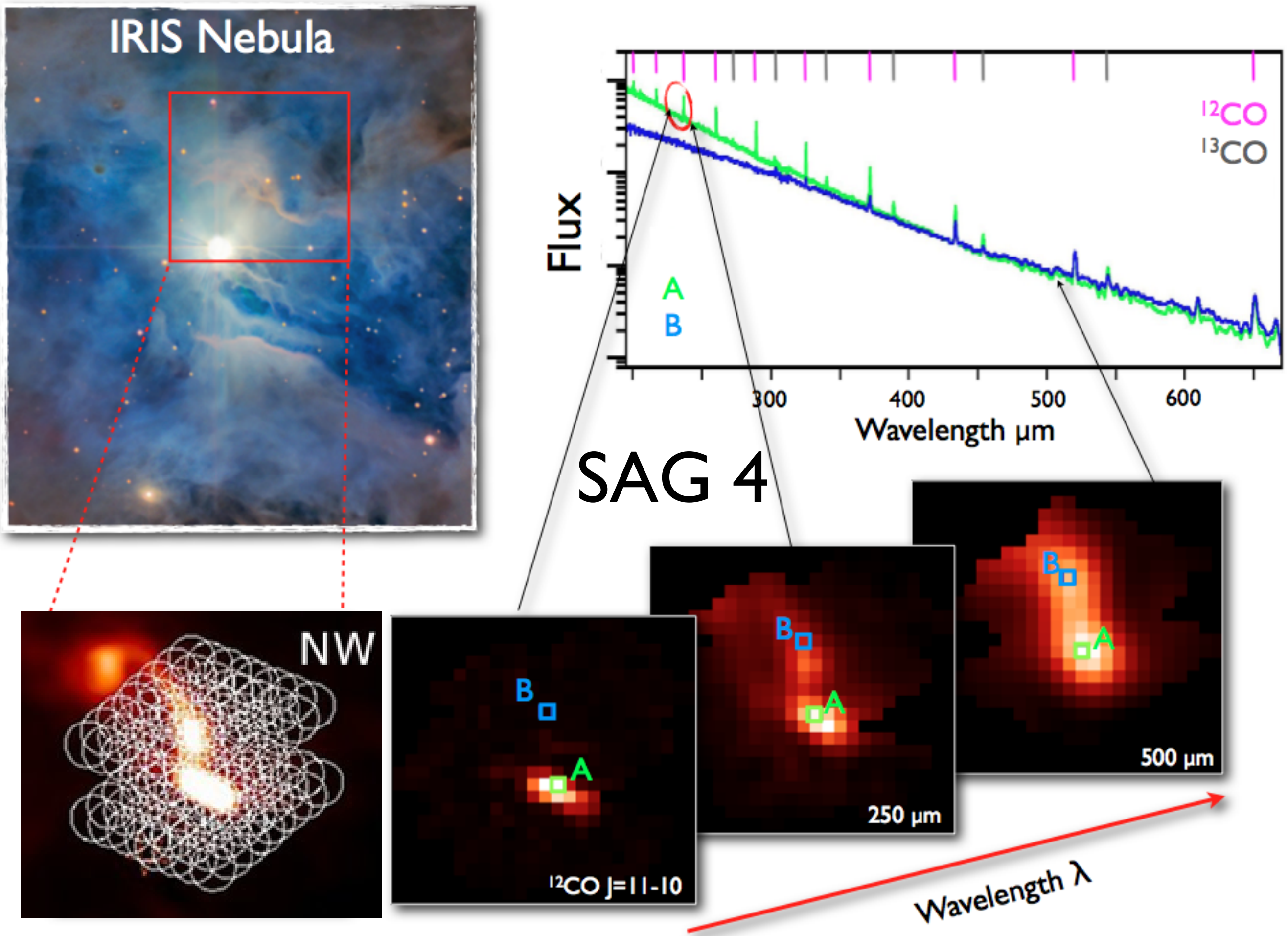

- Fully-sampled maps
- Total area : 100”x 100”
- Spatial resolution : 6” -10” (0.01-0.02 pc @ 400 pc)
- Targeted lines : [OI]63µm, [OI]145µm [CII]158 µm, [NII]122 µm High-J CO, $CH^+$, OH

Bernard et al. (2012)
Parikka et al. in prep.

Resolve the gas cooling lines; each species shows a specific morphology

Inhomogenous medium with dense structures: filaments or clumps ?

# SPIRE-FTS spectral mapping




- Spectral cube computed with the gridding and super-resolution method **SUPREME** from fully-sampled observations **(=> Poster Ayasso)**
- Spatial resolution : 17" - 42" (0.03-0.08 pc @ 400 pc)
- Maps of equal areas with SPIRE and PACS
- Dust continuum and gas lines:
  $^{12}$CO J=4-3 to J=13-12
  $^{13}$CO J=5-4 to J=13-12
  [CI]370 & 609μm, [NII]205μm
  $CH^+$ J=1-0, $H_2O$...
- Köhler et al. submitted

Study together the bulk of dust and warm molecular gas. Excited CO localised at the edge.

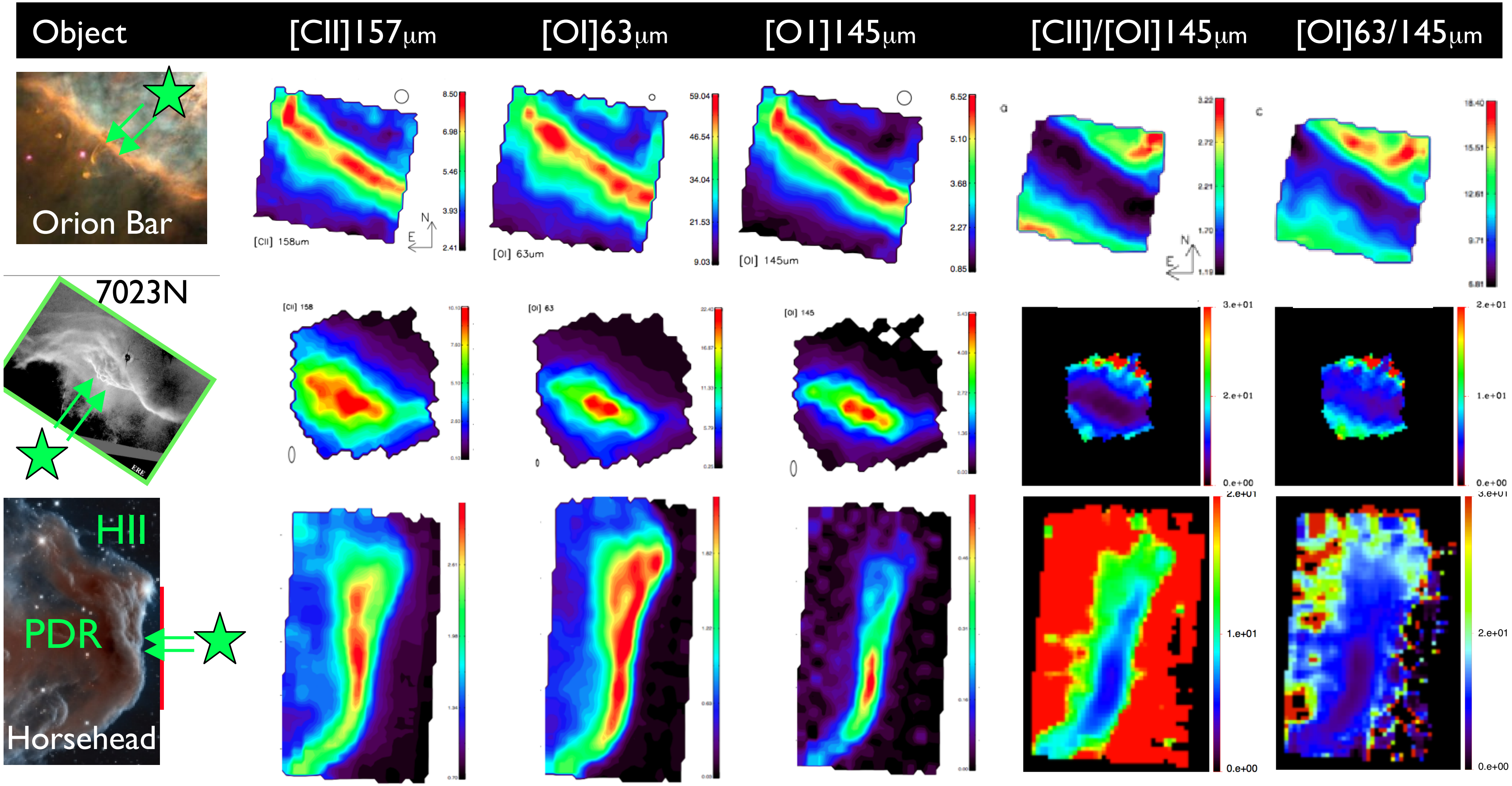
What are the key processes which regulate the emission of the different components ?

Which components originate in the same medium ?

# Results

1. Role of the different gas coolants
2. Gas thermal pressures
3. Dust properties and density structure
4. Excitation and formation processes of key molecules

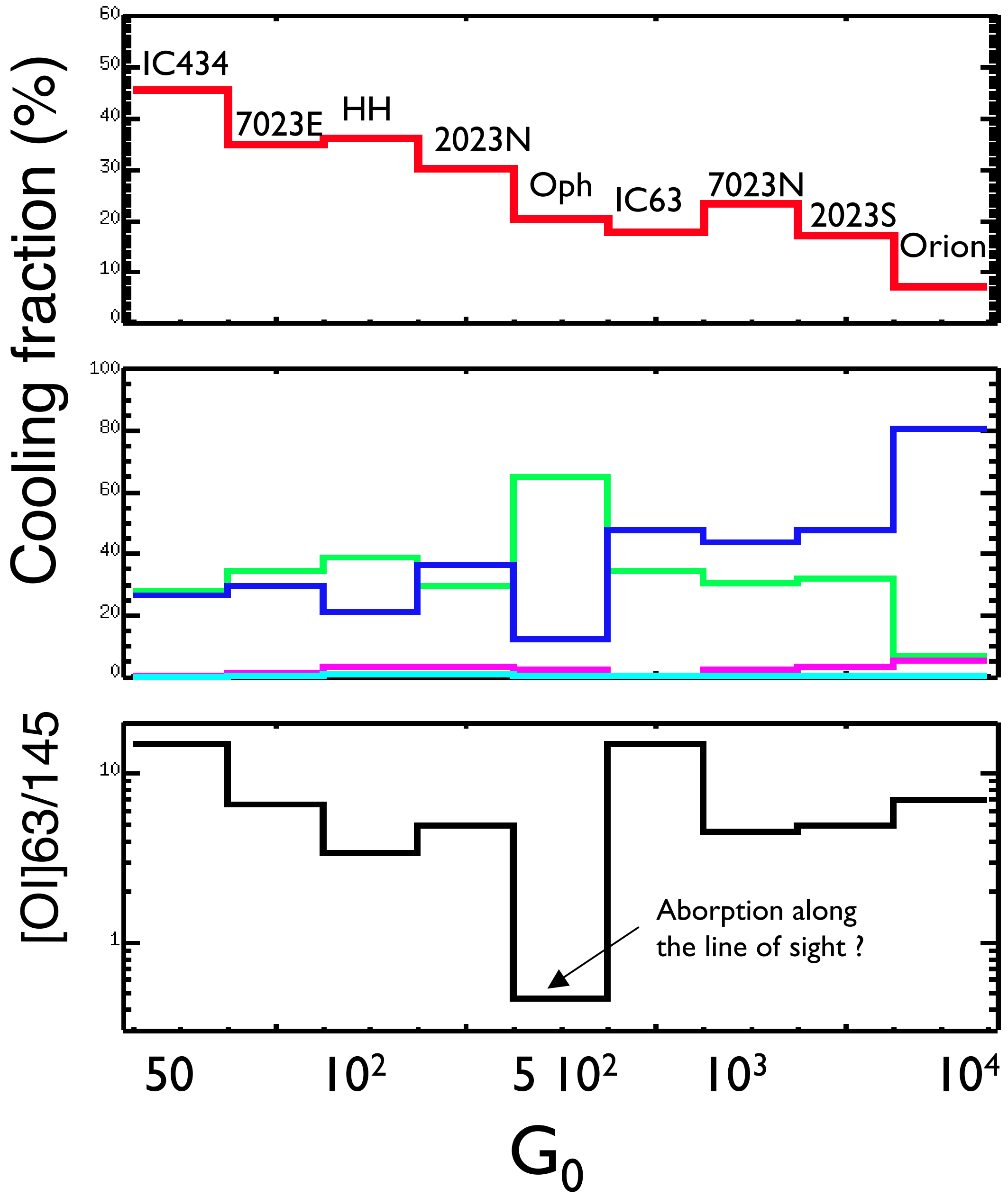
# 1. Gas cooling: spatial distribution




Bernard et al. (2012)
Bernard et al. in prep

- ❑ Trace gas cooling and efficiency of star formation up to high redshift
- ❑ Strongest emission at the cloud surface where the gas is warm
- ❑ [CII] follows [OI] => [CII] originates mostly from neutral zone; HII contribution < 25%
- ❑ [OI]145μm traces the dense PDR zone where the [CII]/[OI]145μm and [OI]63/145μm decrease
- ❑ Self-absorption of the [OI]63μm in PDR

# 1. Gas cooling: budget




[CII] contributes up to 50% for $G_0 \leq 100$

[OI] contributes up to 50% for $G_0 > 1000$
(lower limit since optically thick)

$H_2$ contributes between ~20 and 40%

[CI], CO lower than 5%

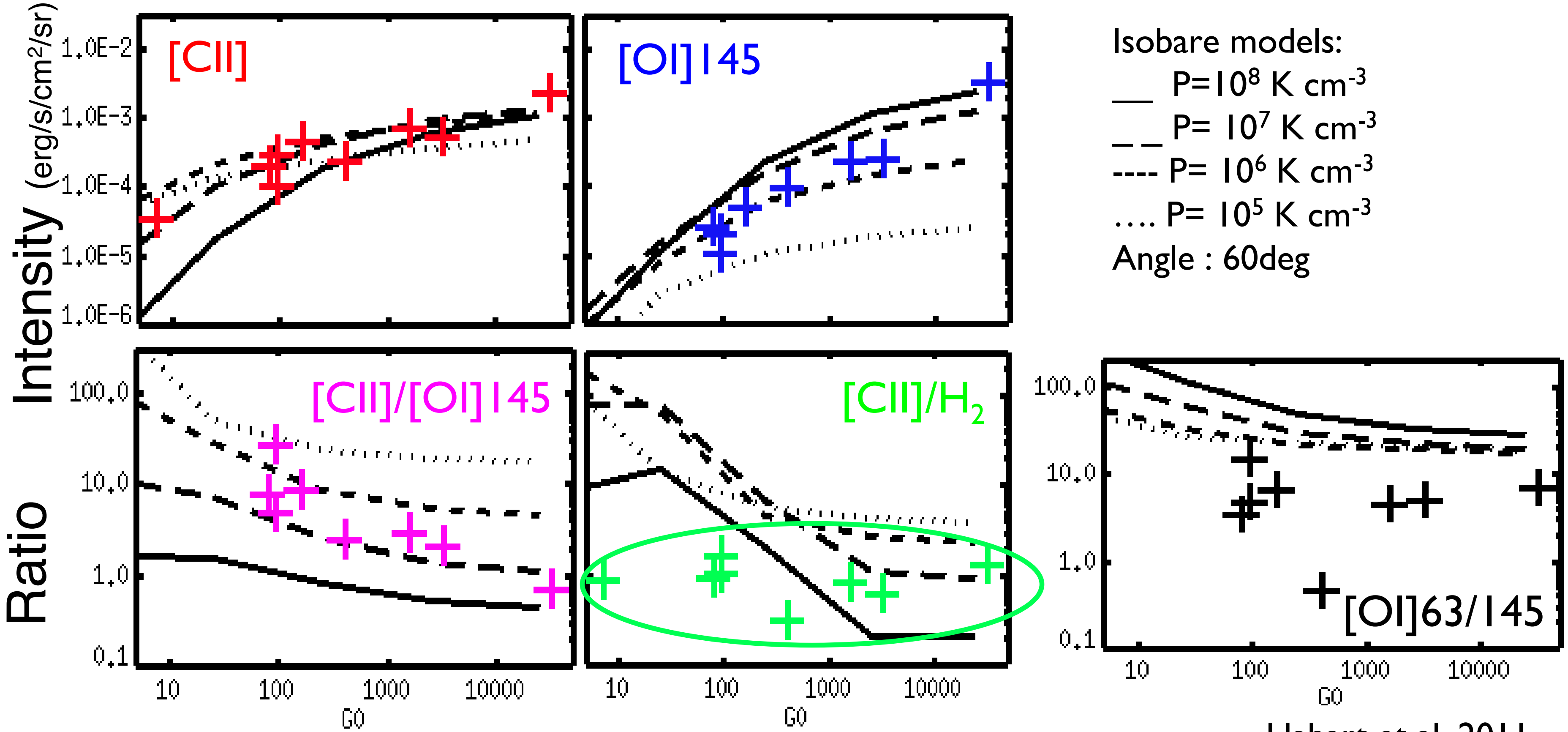
Others ($H_2O$, $CH^+$) <1%

Methods :
(I) maps convolved in the same beam
(II) background emission substracted

Habart et al. in prep.

# 1. Gas cooling: PDR code

• Meudon code (1.5.2) solves simultaneously the chemical and excitation equilibrium, the radiative transfer and the thermal balance




Habart et al. 2011
Habart et al. in prep.

❑ Large variation of [CII] and [OI]145 well reproduced

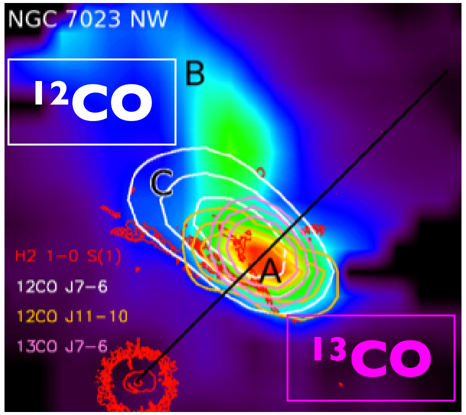
❑ [OI]63/145 in data < model: opacity inside the PDR not taken into account properly

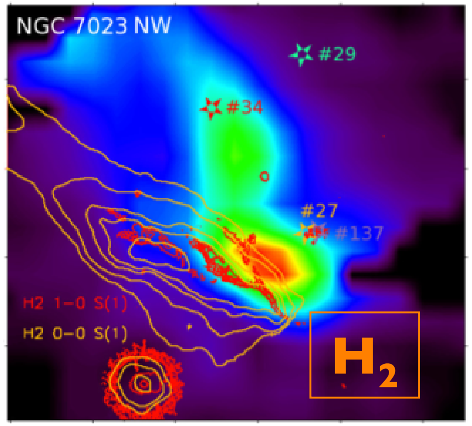
❑ [CII]/[OI]145 decreases with increasing $G_0$ as expected while [CII]/$H_2$ ~ constant

⇒Amount of warm diffuse gas underestimated by models for $G_0$<1000

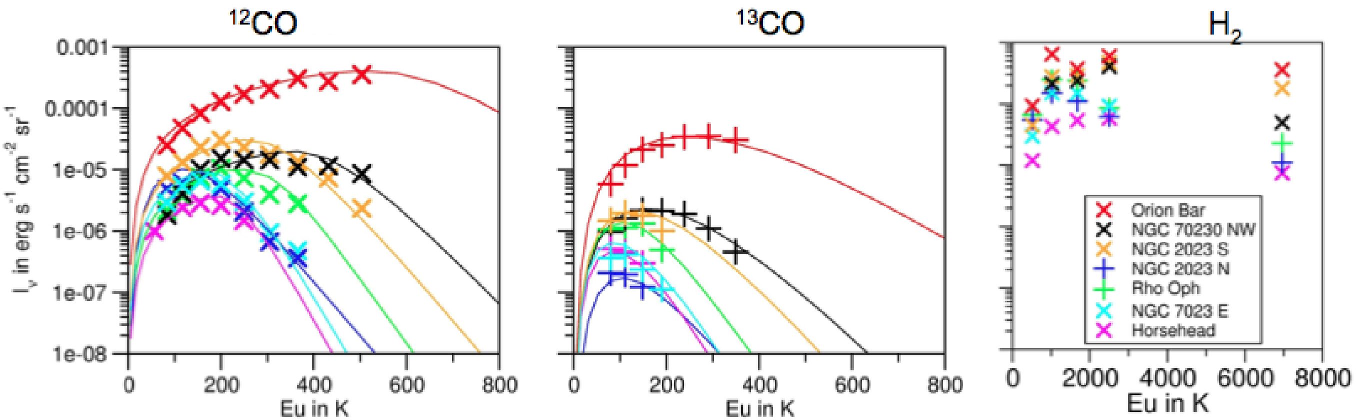
❑ Diffuse gas irradiated and slowly shocked could produce strong $H_2$ but not [OI] (Lessafre et al. 2013)

# 2. Gas temperature and pressure




Excited CO localised at the dust emission peak (RADEX analysis)



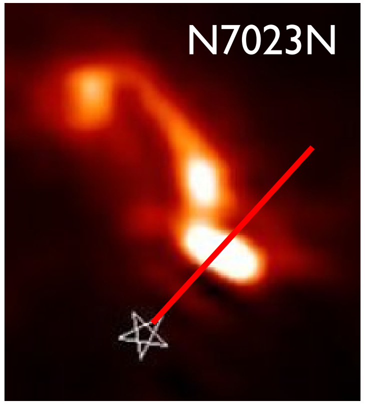

| Object | $G_0$ (Habing) | $T(H_2)$ K | T(CO) K | n $cm^{-3}$ | l pc | $NH_2(H_2)$ $cm^{-2}$ | $NH_2(CO)$ $cm^{-2}$ | T(dust) K |
|---|---|---|---|---|---|---|---|---|
| Orion bar | 20000 | 256 - 360 | 150–170 | $10^6$ | 0.01 | $1\times10^{21}$ | $1-2\times10^{22}$ | 50 |
| NGC 7023 NW | 1000 | 400 | 60–100 | $10^5-10^6$ | 0.01–0.2 | $2\times10^{20}$ | $2-2.5\times10^{22}$ | 30-35 |
| NGC 2023 S | 1000 - 10000 | 310 - 346 | 50–180 | $10^5-10^6$ | 0.003–0.3 | $7\times10^{20}-2\times10^{21}$ | $5\times10^{21}-1\times10^{22}$ | |
| NGC 2023 N | 100 - 1000 | 220 - 300 | 45–120 | $10^4-10^5$ | 0.001–0.02 | $3.5\times10^{20}-3.5\times10^{21}$ | $2-5\times10^{20}$ | |
| $\rho$ Oph | 250 | 252 - 290 | 40 | $10^4-10^5$ | 0.065 | $6.4\times10^{20}-3.6\times10^{21}$ | $2\times10^{22}$ | |
| NGC 7023 E | 50 | 269 - 327 | 40–60 | $10^4-10^5$ | 0.06–1.3 | $2.9\times10^{20}-1.5\times10^{21}$ | $1-2\times10^{22}$ | 22 |
| Horsehead | 50 | 264 - 398 | 40–70 | $10^4-10^5$ | 0.03–1.3 | $5.7\times10^{19}-6.1\times10^{20}$ | $1-4\times10^{22}$ | 20 |

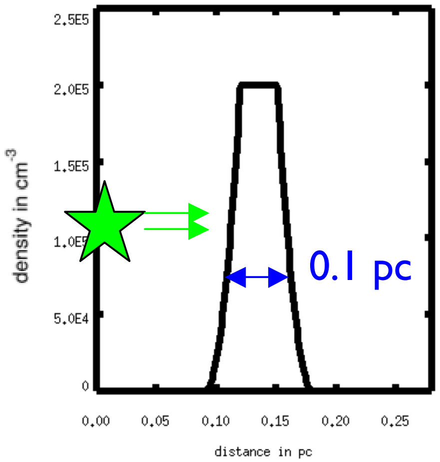
- ❑ CO and dust temperatures are directly dependent on $G_0$
- ❑ Excited CO reveals high column densities of warm and dense gas
- ❑ $H_2$ rotational temperatures higher while column densities lower than CO
- ❑ $H_2$ shifted towards the cloud edge

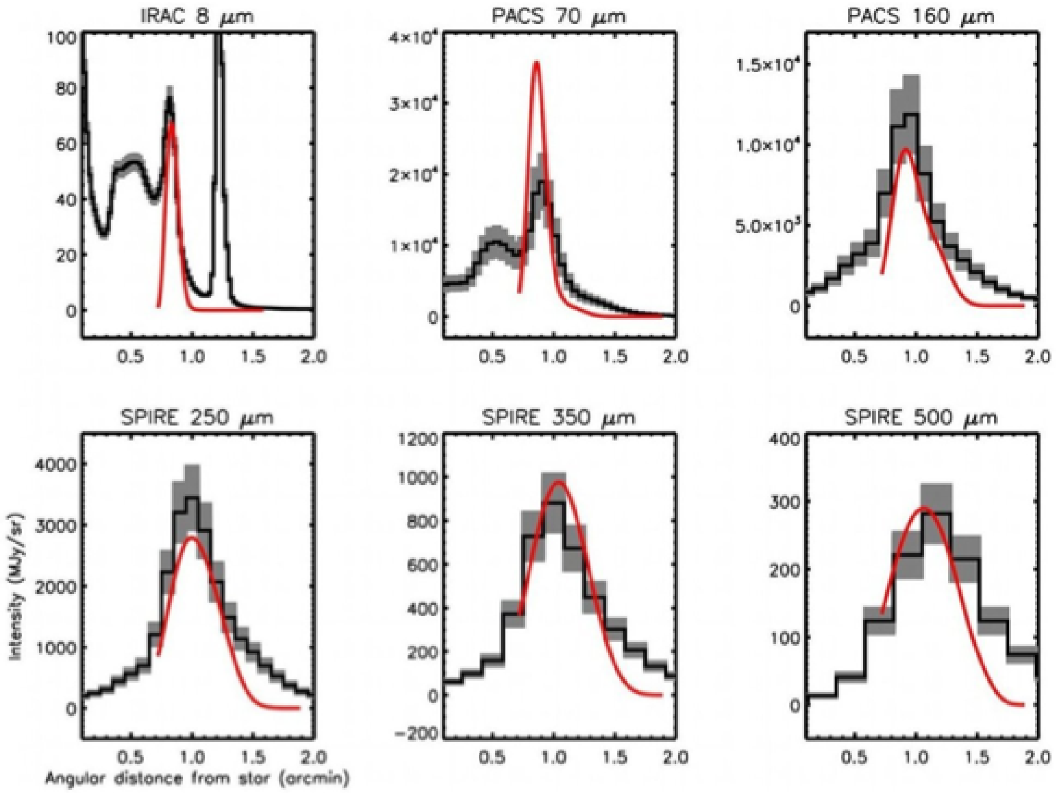
$\Rightarrow$ Excited CO traces a denser & cooler gas than $H_2$

- ❑ High gas thermal pressure up to ~$10^7$-$10^8$ K $cm^{-3}$ in regions of warm CO and dust emission

# 3. Dust properties and density structure



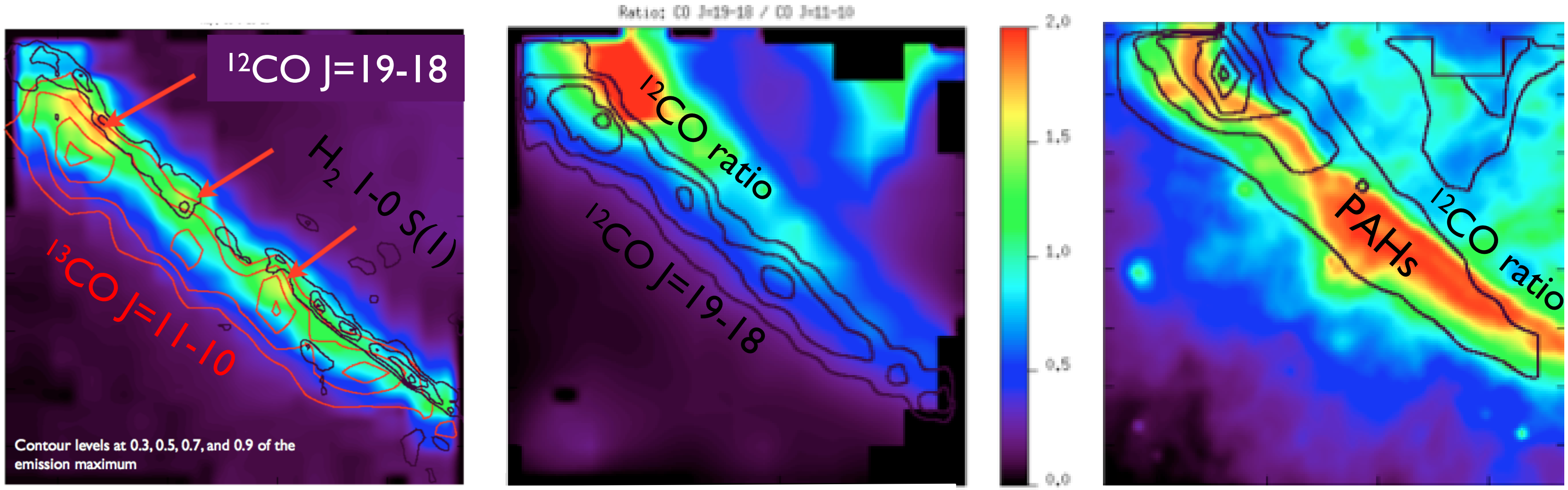




Köhler et al. submitted

- ❑ DustEM (Compiègne et al. 2011) + radiative transfer model
- ❑ Dense filaments with $n_0 > 10^5$ cm$^{-3}$
- ❑ Density profile selfconsistently reproduces atomic, molecular (CO) and dust emission
- ❑ CO emission comes from Av~1
- ❑ Dust evolution in the denser part **(=> 3 Posters : Arab, Köhler, Ysard)**

# 4. Excitation process : CO




- ❑ First maps of high-excited CO (J=18-17, 19-18, 22-21) in PDRs (Orion Bar)
- ❑ Excitation (UV, IR pumping, cosmic rays, chemical reaction, shock) depends on the environment
- ❑ Spectacular agreement between morphologies of high-J CO, intermediate-J $^{13}$CO and $H_2$ tracing irradiated dense structures
- ❑ CO excitation temperature high at PAH emission peak

⇒ **Very strong constrain on the origin of the CO excitation : UV heating**

- ❑ RADEX & PDR analysis: P~3x$10^8$ K $cm^{-3}$ (size ~0.006 pc) **(=> 2 Posters: Parikka, Joblin)**
- ❑ Pressure gradient => photoevaporation supported by gas dynamics in 7023N **(=> Poster Berné)**

# 4. Formation process: $CH^+$ and OH

❑ CH+ J=3-2 and OH 85$\mu$m lines have similar $n_{crit}$ and $E_u$: ideal for comparison

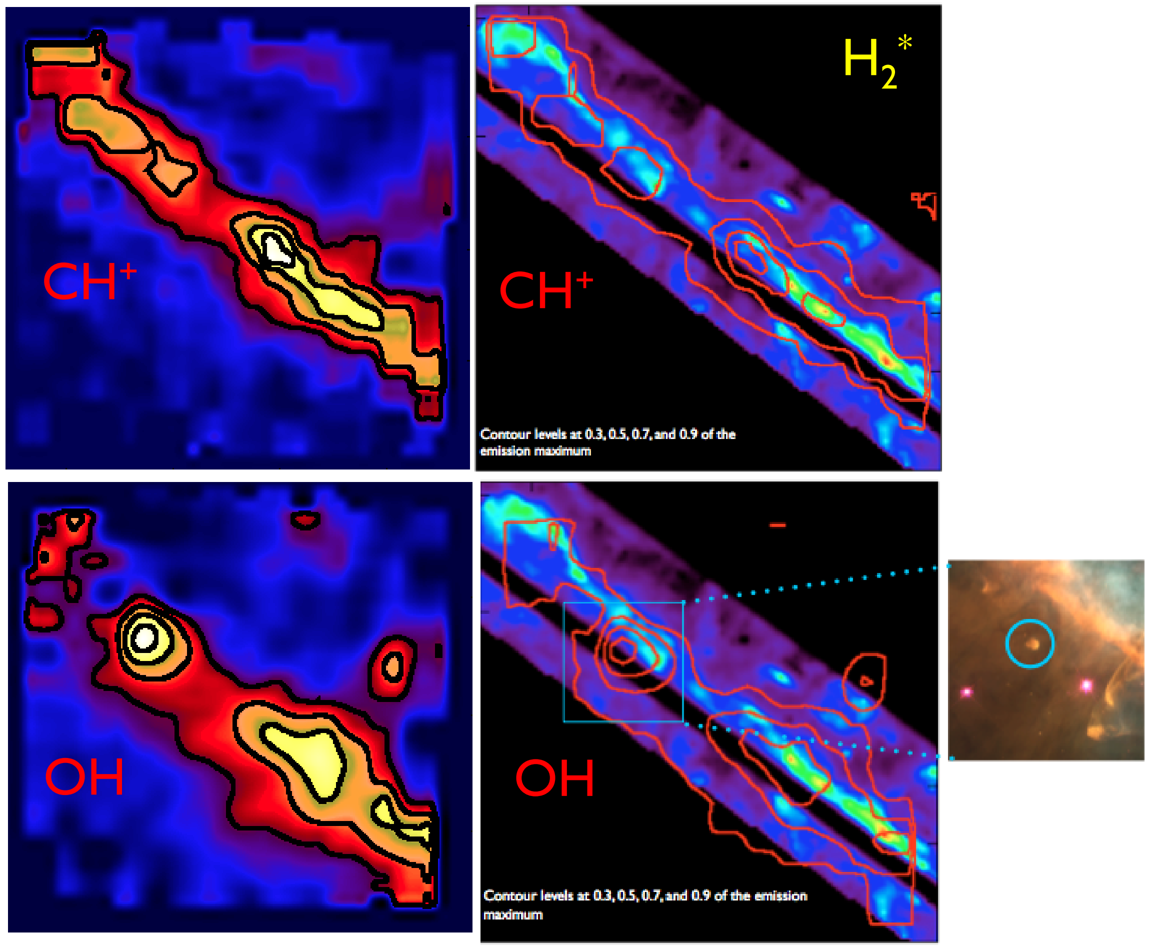
❑ $CH^+$ formation: $H_2 + C^+ \Rightarrow H + CH^+$ (endothermicity: 4300 K)

❑ $CH^+$ correlation with $H_2^*$
=> formation depends on $H_2^*$ (Naylor et al. 2010, Nagy et al. 2013)

❑ OH formation: $H_2 + O \Rightarrow H + OH$

❑ Non-correlation between OH and $H_2^*$
=> formation does not depend on $H_2^*$ (in agreement with Agundez et. al 2010).

❑ OH emission traces irradiated structures (Goicoechea et al. 2011) but also correlates with a proplyds




**(=> Poster Parikka)**

# Conclusions and Future Prospects

❑ PACS and SPIRE spectral mapping excellent to study together the bulk of dust and gas morphology and energetics

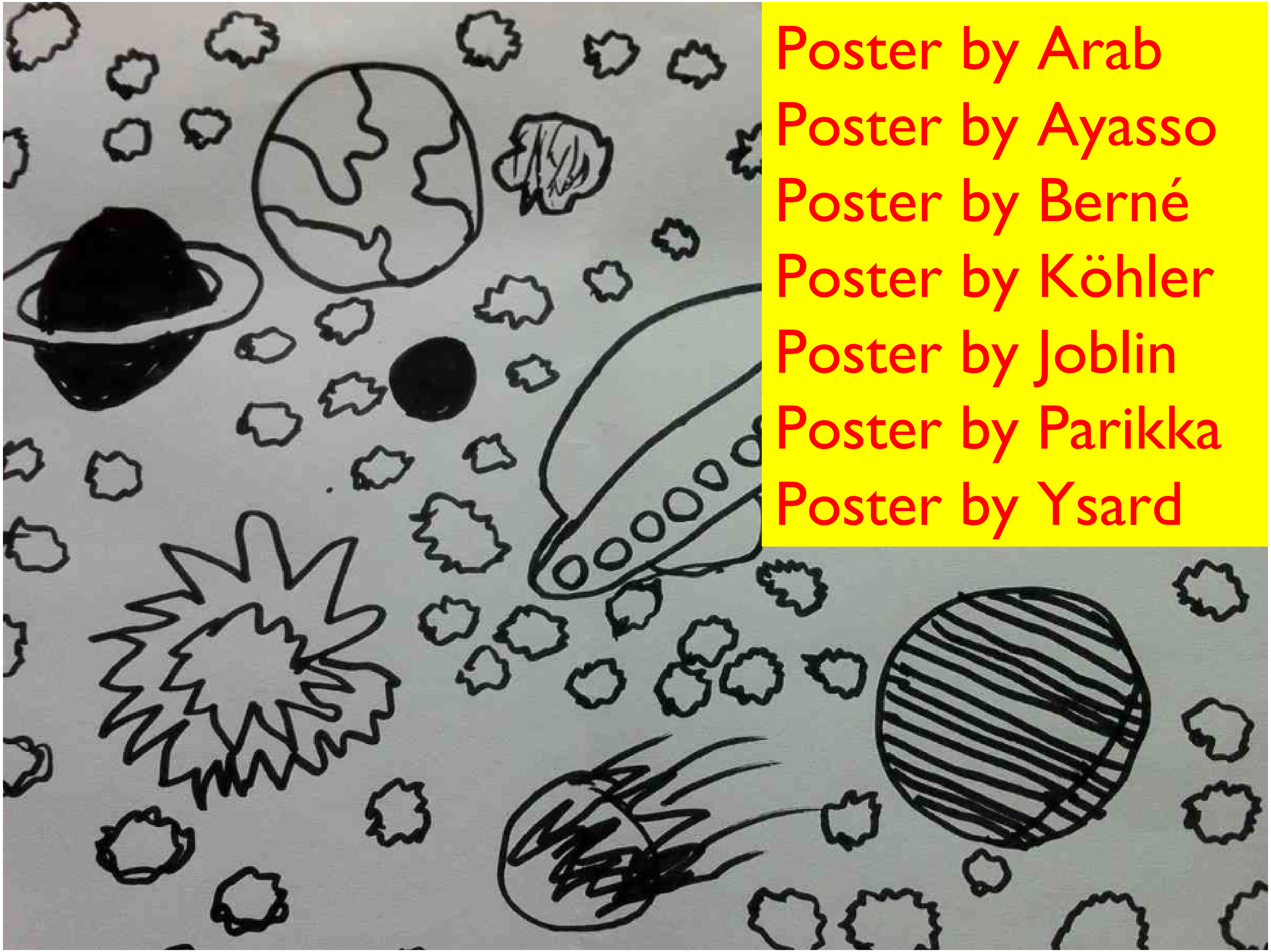
❑ Inhomogeneous medium containing small dense structures at high thermal pressures as a consequence of being directly irradiated. How long they stay ? Role in star formation ? Dust evolution in densest regions: coagulation ? Accretion ?

❑ Role of each gas coolants for ≠ radiation and phases: template for distant systems

- [CII] originates mostly from neutral zone, [CII] contribution >50% to the total cooling for G0<100 while [OI] contribution >50 % for G0>1000
- CO and dust temperatures correlate with G0
- $H_2$ traces a large amount of warm diffuse under-estimated by PDR code when G0<1000

❑ High-J CO, CH+ and OH connected to the dense irradiated structures: constrain for the modeling of the warm ISM closely related disks or active galaxies

- CO excitation due to UV heating
- $CH^+$ formation depends on excited $H_2$, but not that of OH
- Excitation and dynamic (evaporation, turbulence) have to be studied together



Poster by Arab

Poster by Ayasso

Poster by Berné

Poster by Köhler

Poster by Joblin

Poster by Parikka

Poster by Ysard