PHYSICS AND CHEMISTRY OF UV ILLUMINATED GAS: THE HORSEHEAD CASE

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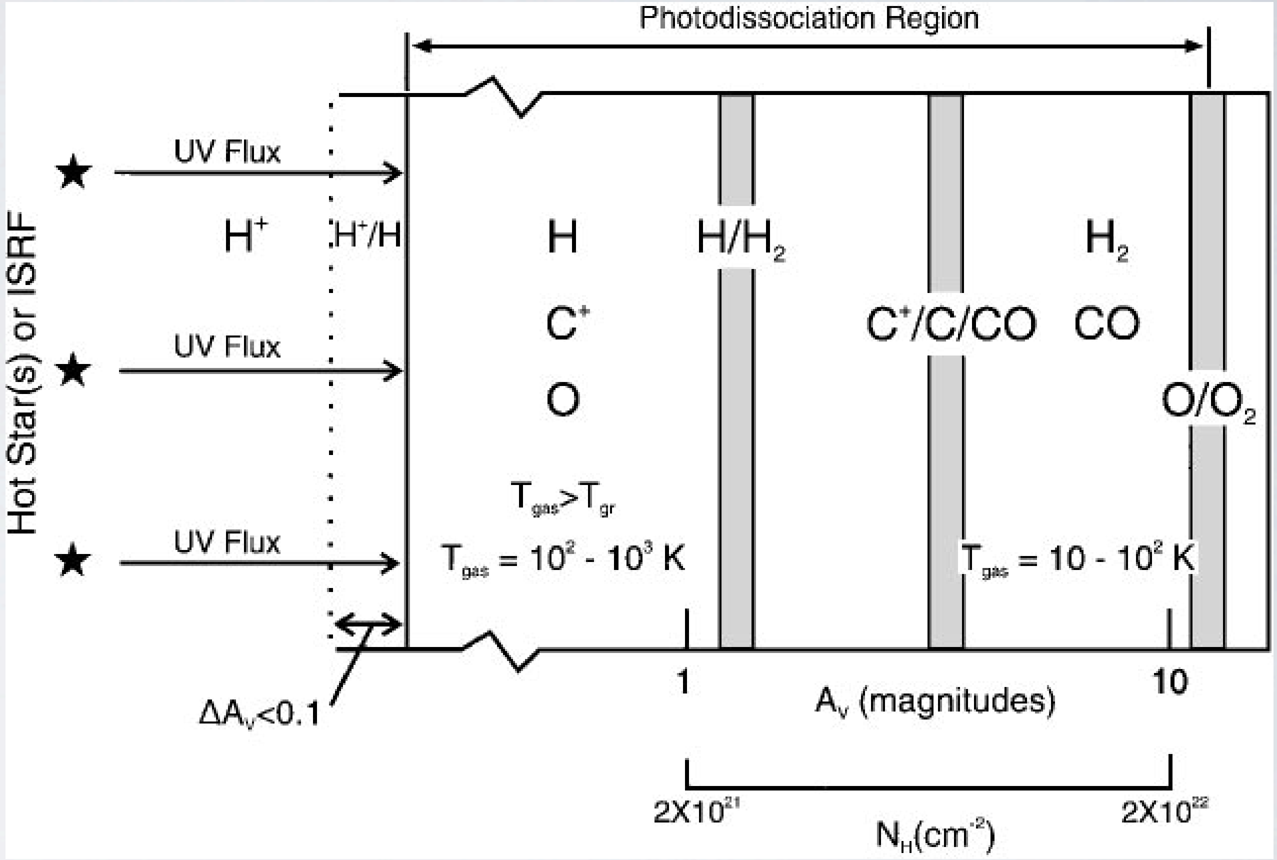
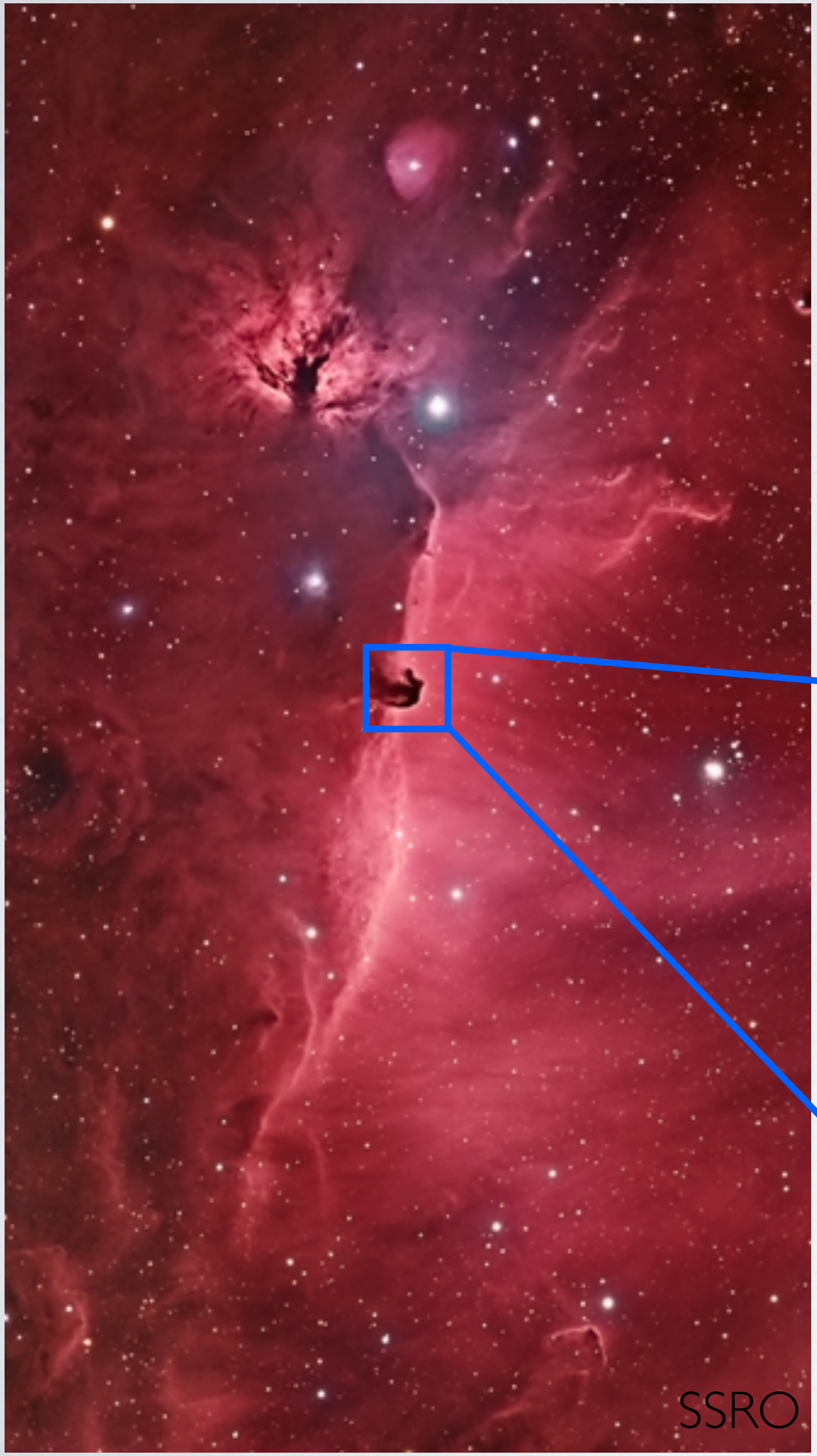
PDR: Photo Dissociation Regions

- UV photons determine the physical (temperature, density) and chemical properties.
- Examples: diffuse clouds, starburst galaxies, surface of protoplanetary disks, ...
- PDR models : Understand physics and chemistry of UV-illuminated matter.
- Model used: Meudon PDR code http://pdr.obspm.fr/



- Complex PDR models and chemical networks need well-defined observations to serve as benchmarks.
  - Several species and many lines with high spectral resolution $\Longrightarrow$ Radiative transfer models $\Longrightarrow$ Column densities and abundances
  - Spatial resolution $\Longrightarrow$ resolve gradients predicted by models $\Longrightarrow$ Interferometers (ALMA, NOEMA)

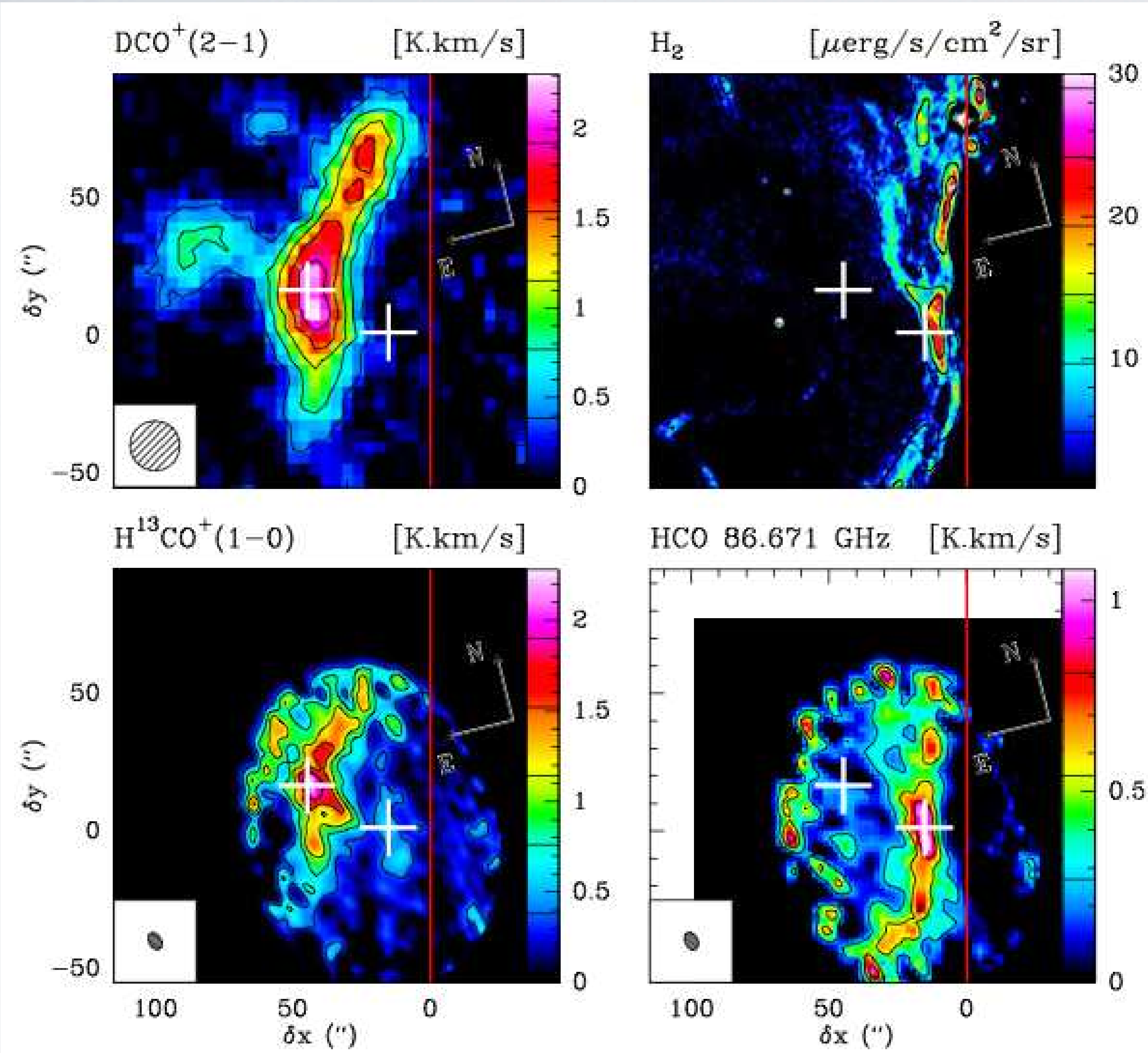
PDR BENCHMARK: THE HORSEHEAD NEBULA



- Viewed nearly edge-on (Abergel et al. 2003)
- Nearby (~400 pc, 10'' ↔ 0.02 pc).
- Illuminated by the O9.5 star σ Ori ~ 3.5pc away (Moderate radiation field: 60 in Draine units).
- Gas density is well constrained (Habart et al. 2005).

Reference for PDR models.

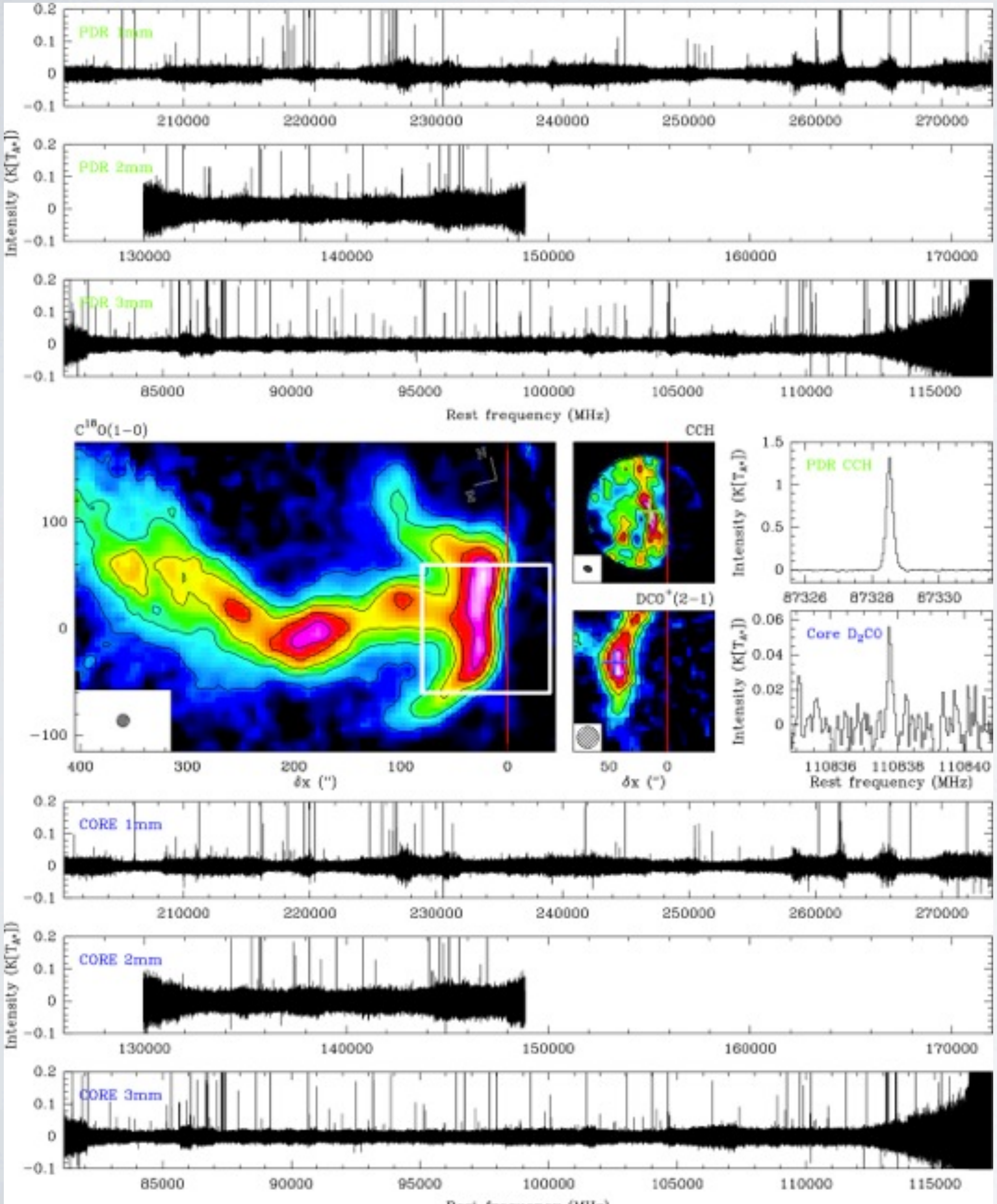
TWO DIFFERENT ENVIRONMENTS LESS THAN 40'' AWAY



- A far-UV illuminated PDR HCO (Gerin et al. 2009)
  - Av ~1.5
  - Warm T_{kin} ~60K
  - Relatively dense n_H ~ 6×10^4 cm^{-3}
- A shielded, dense core DCO^+ (Pety et al. 2005)
  - Av ~ 20
  - Cold T_{kin} ~20K
  - Dense n_H ~ 2 × 10^5 cm^{-3}
  - High fractionation $[DCO^+]/[HCO^+]$ = 2%

HORSEHEAD WHISPER: 3, 2 AND 1MM

Wideband High-resolution Iram-30m Surveys at two Positions with Emir Receivers



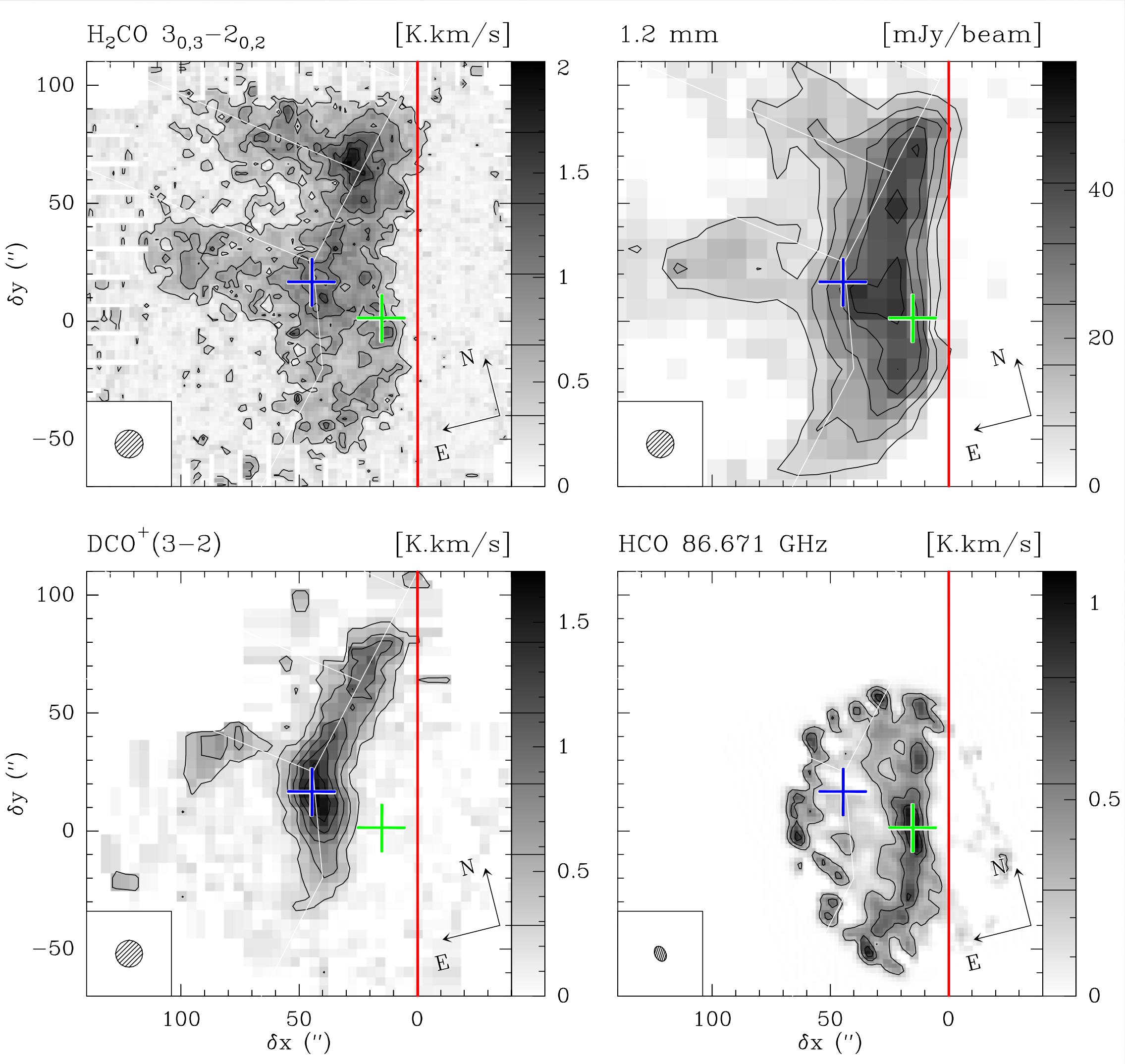
	3mm	2mm	1mm
Bandwidth	36 GHz	25 GHz	76 GHz
Resolution	49 kHz	49 kHz	195 kHz
Number of channels	738900	387468	391425
Median noise	8.1	18.5	8.4

~120 lines

~ 30 species + isotopologues

see poster n° 30 by Viviana Guzmán

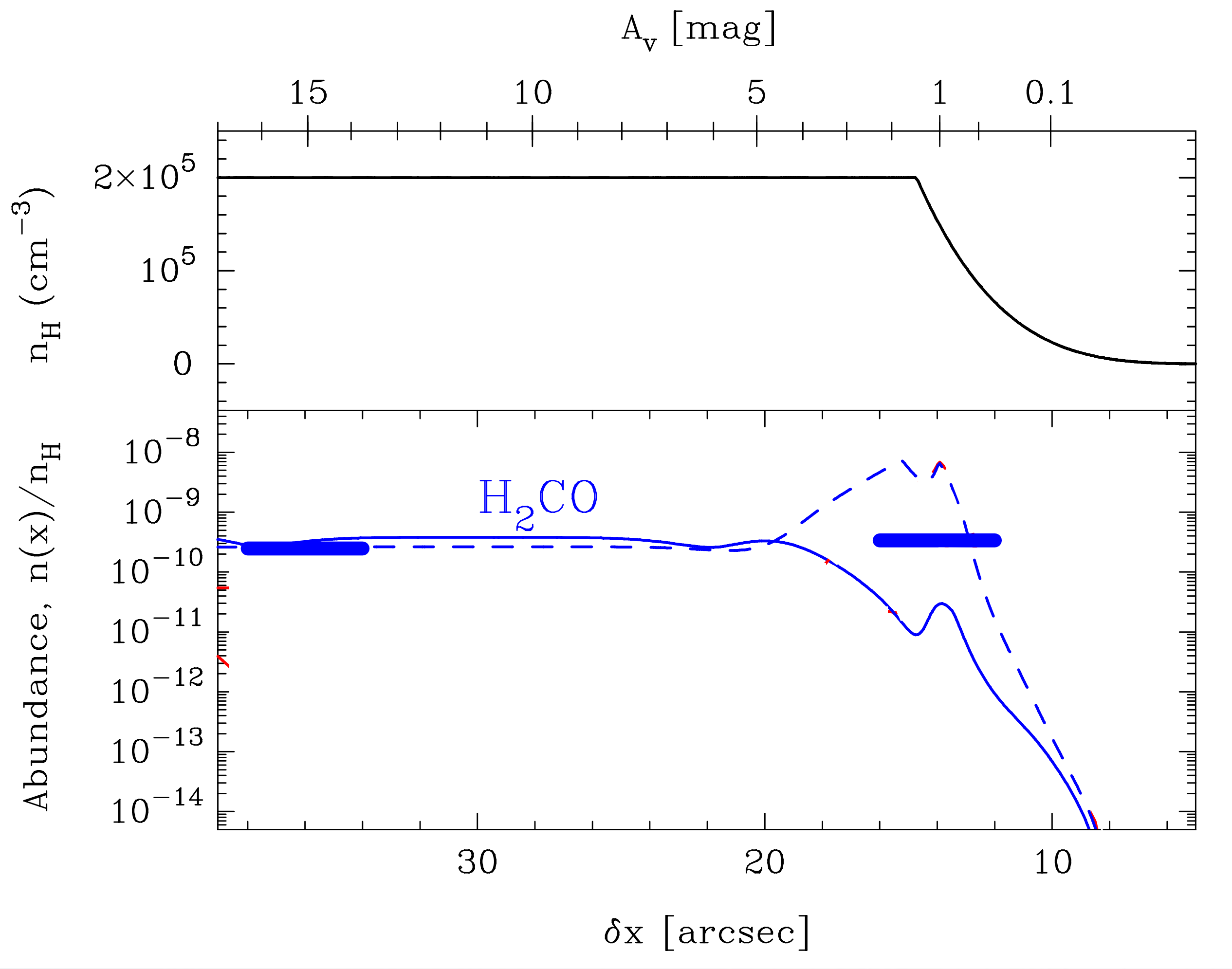
H_2CO: Photo-desorption from dust grain ice mantles (Guzmán et al. 2011)



- Abundance:
  - PDR : $[H_2CO] = 2.8 \times 10^{-10}$
  - Core : $[H_2CO] = 2.0 \times 10^{-10}$
  - Similar in PDR and dense core
- Dust temperature:
  - PDR : $T_{dust} \simeq 30K$
  - Core : $T_{dust} \simeq 20$ K
- Thermal desorption of H_2CO needs $T_{dust} > 50K$

Clean environment to isolate the role of photodesorption.

H_2CO: PHOTO-DESORPTION FROM DUST GRAIN ICE MANTLES (GUZMÁN ET AL. 2011)



- Pure gas-phase chemistry
  - Core: OK
  - PDR: abundance underestimated
- Gas-phase + Grain surface chemistry: Successive hydrogenation of CO

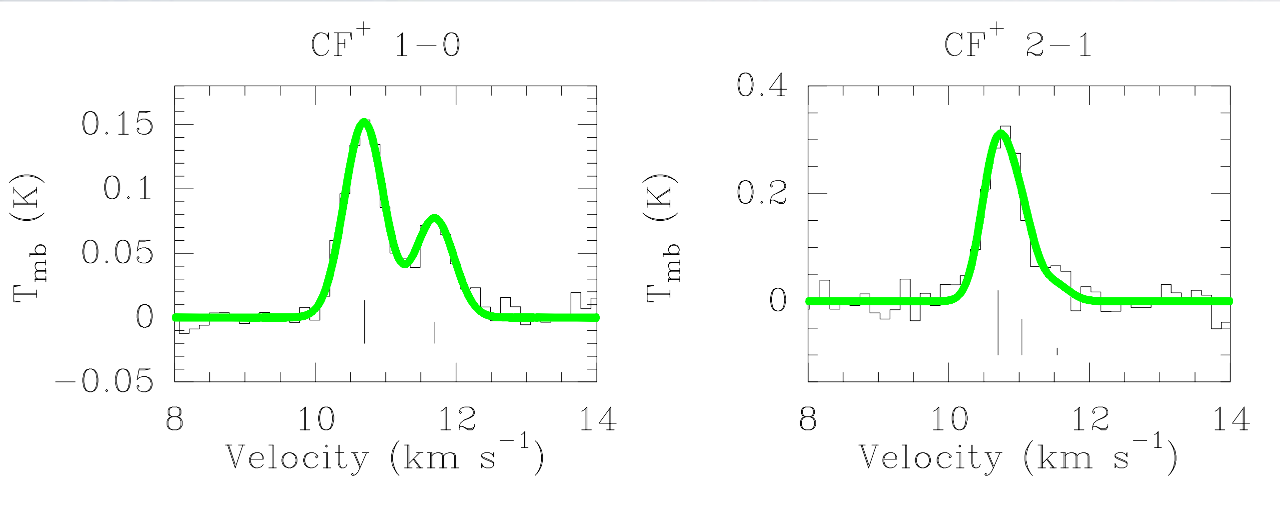
  $CO \rightarrow HCO \rightarrow H_2CO \rightarrow CH_3O \rightarrow CH_3OH$

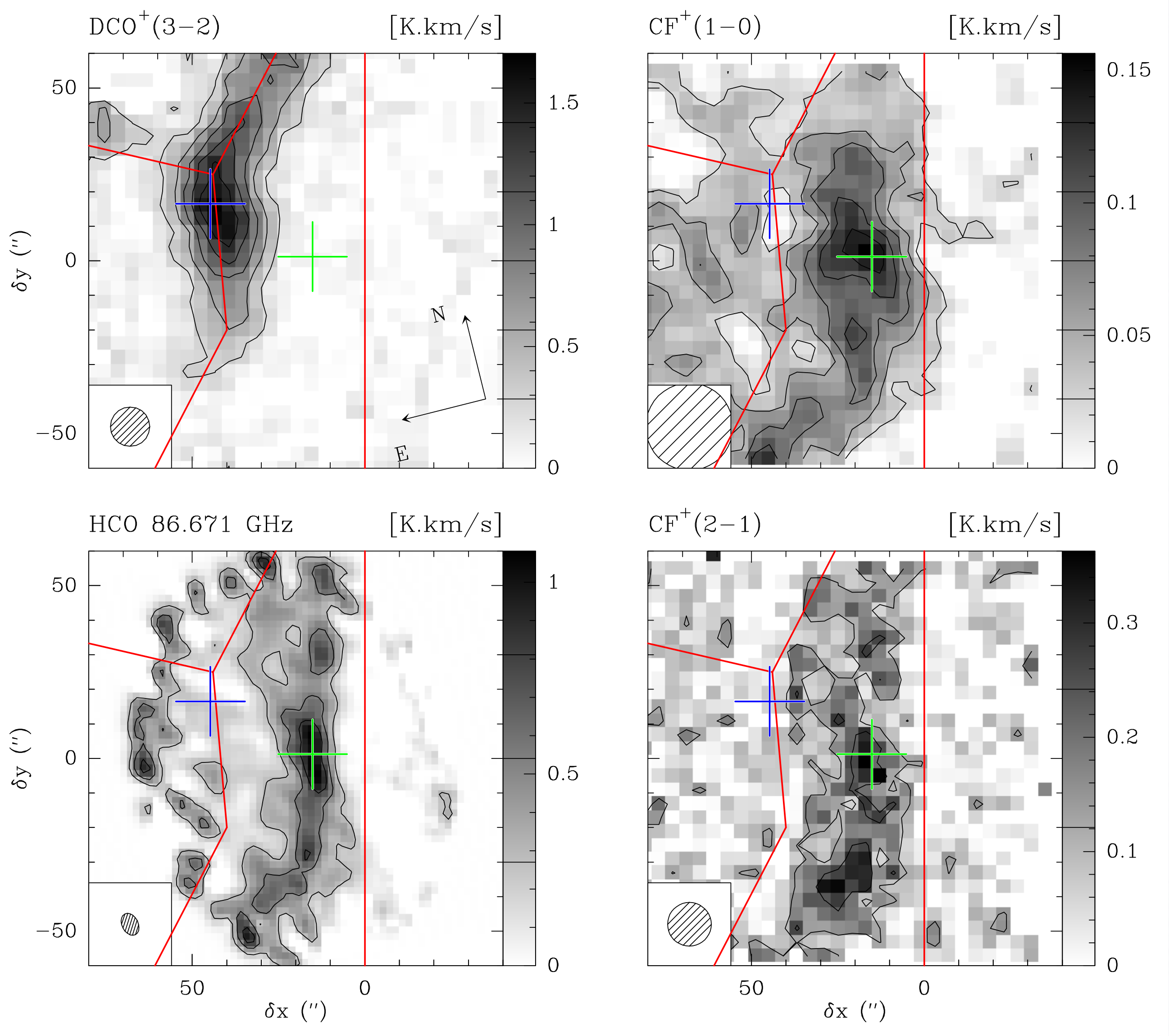
  - PDR : OK

Photo-desorption is needed to explain the observed H_2CO abundance in the PDR

Ongoing interferometric observation to study small scale variations in the PDR

CF^+: AS A PROXY OF C^+ (GUZMÁN ET AL. 2012ab)





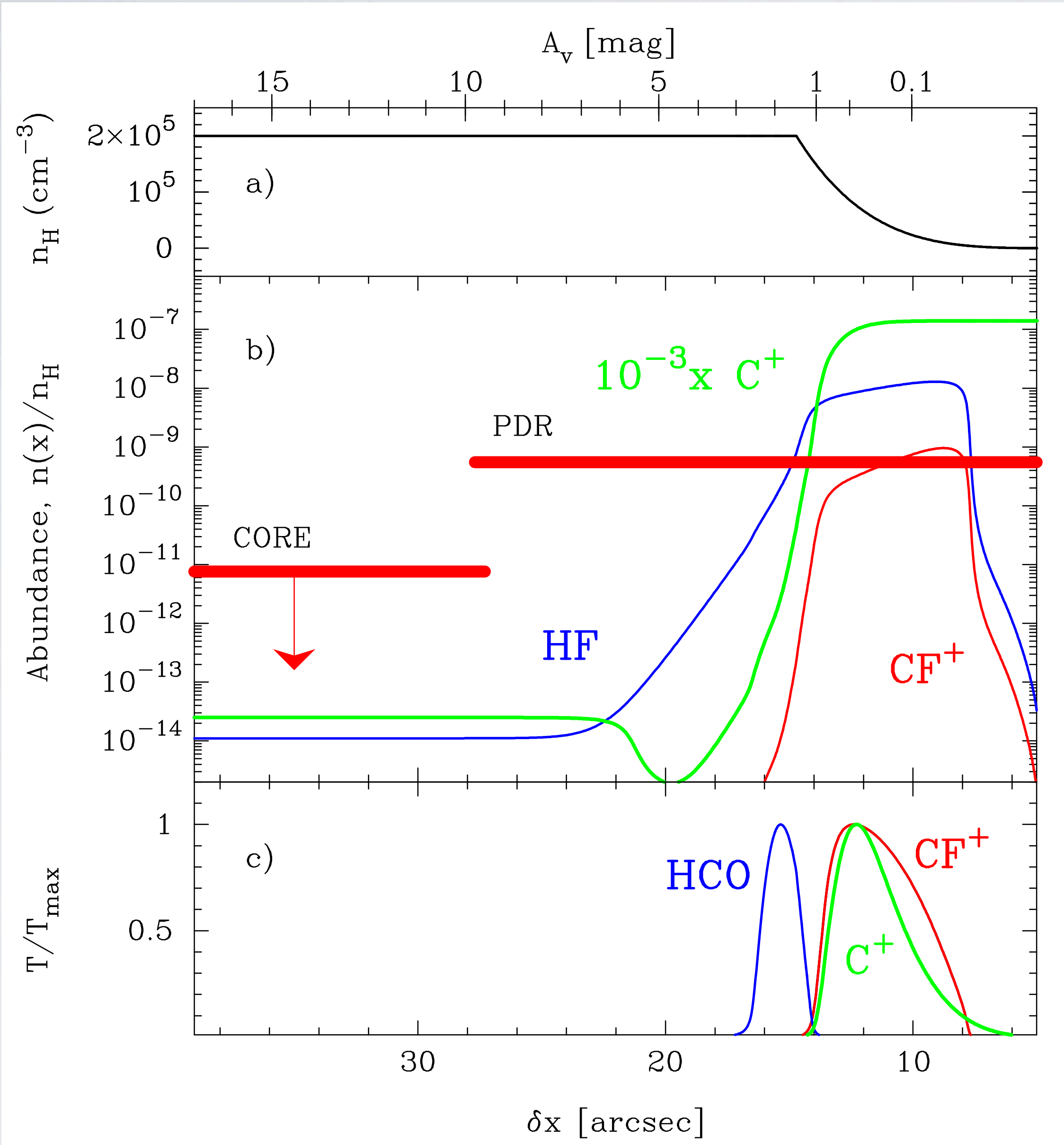
- First detection and spectroscopic characterization of the CF^+ hyperfine splitting due to the F nuclear spin

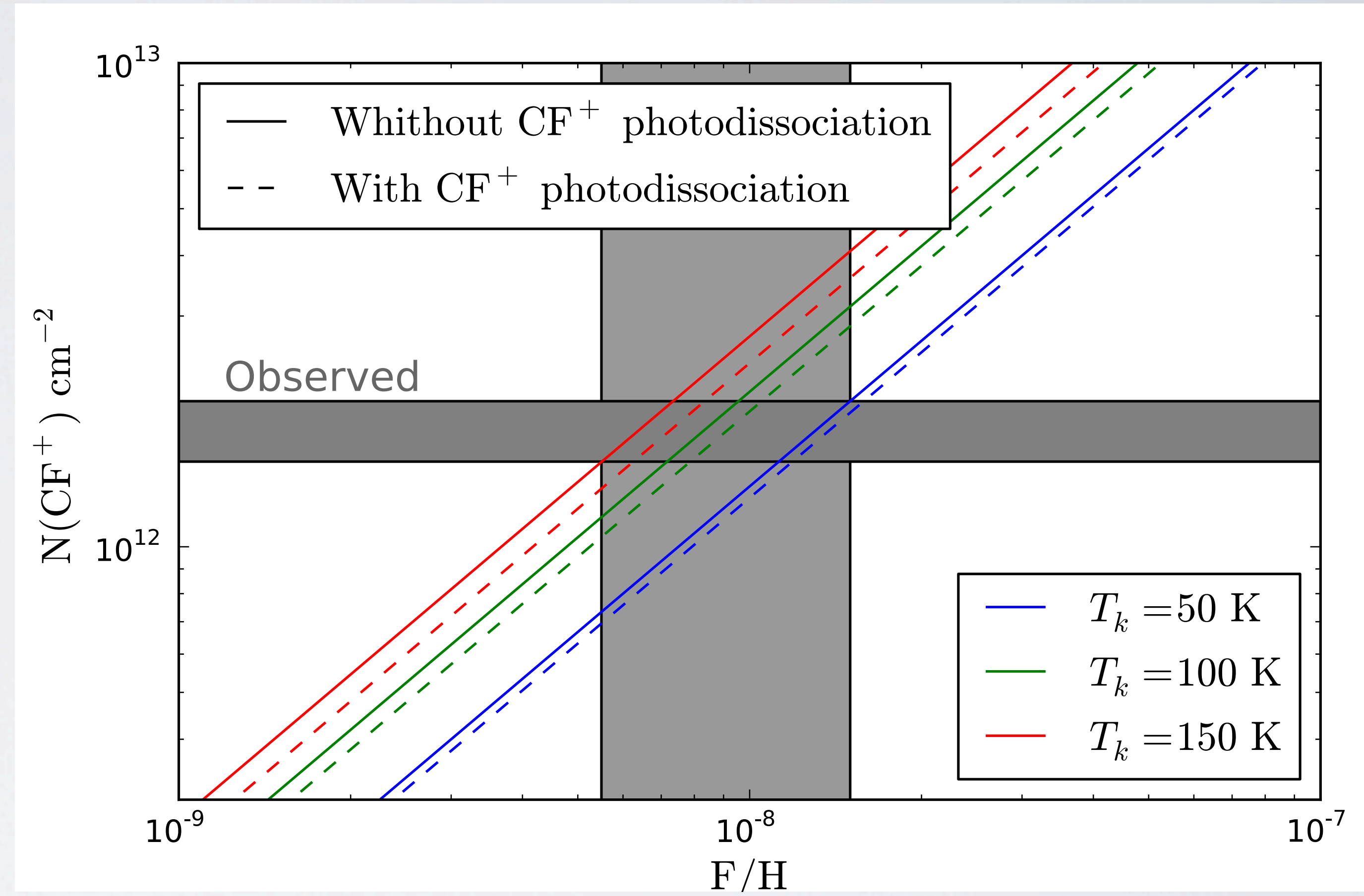
- Emission from the PDR not from the dense core

- Abundance:

  PDR $[CF^+]$: 4.9 – 6.5 × 10^{-10}

CF^+: AS A PROXY OF C^+ (GUZMÁN ET AL. 2012ab)





- Simple chemistry:
  - Formation: $F + H_2 \rightarrow HF + H$

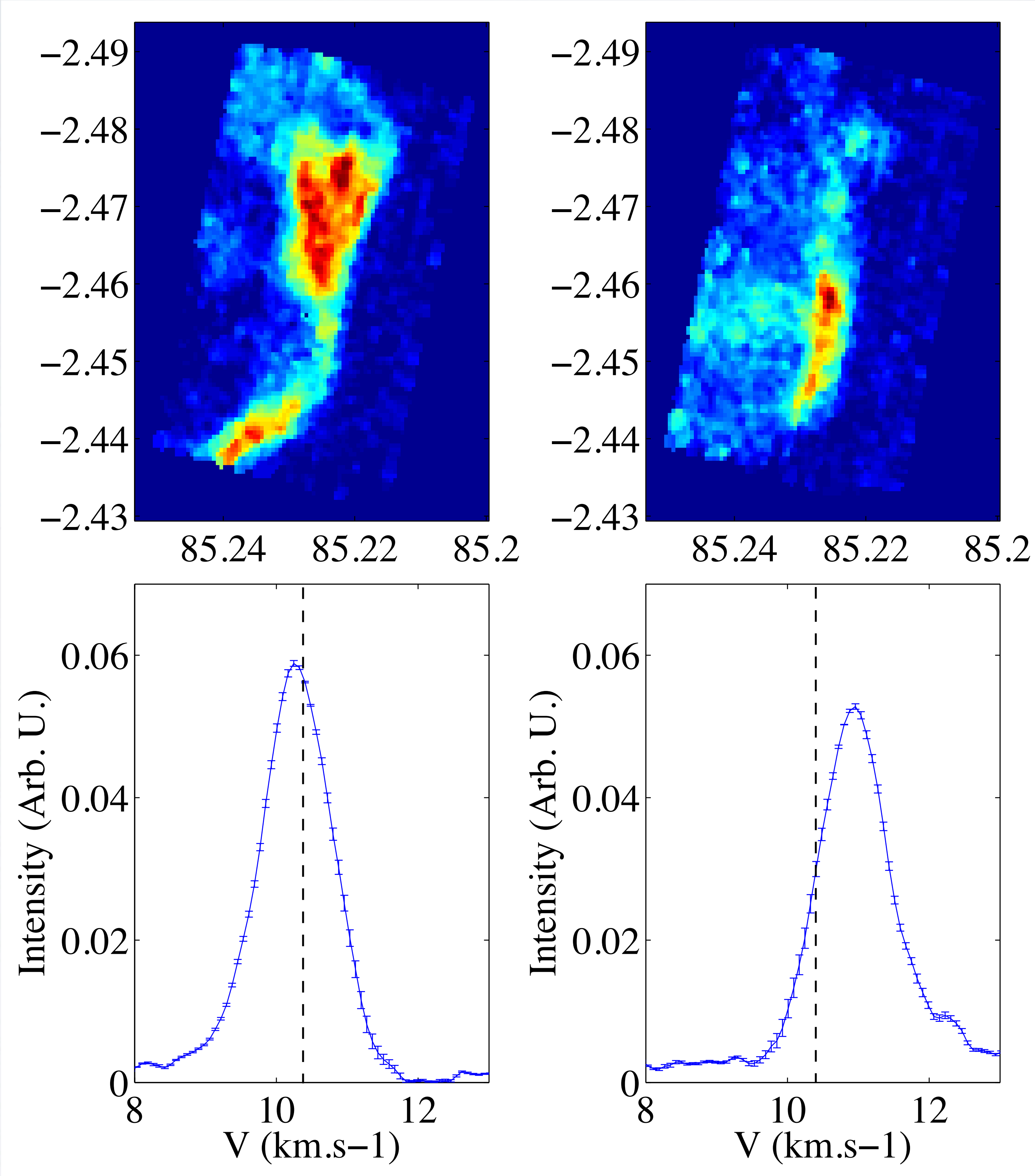
    $HF + C^+ \xrightarrow{k_1} CF^+ + H$
  - Destruction: $CF^+ + e^- \xrightarrow{k_2} C + F$

    $CF^+ + h\nu \xrightarrow{k_{pd}} C^+ + F$

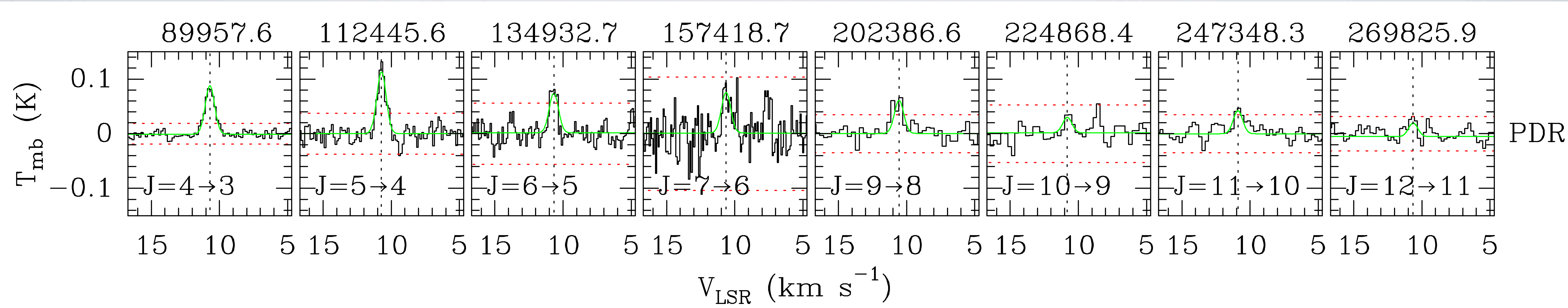
- Significant overlap between CF^+ and C^+
- $N(CF^+) \simeq \frac{k_1}{k_2}[F]\, n_H\, l \quad [\,cm^{-2}]$
- **F/H = (0.6–1.5) × 10^{-8}**

COMPLEX VELOCITY STRUCTURE C^+

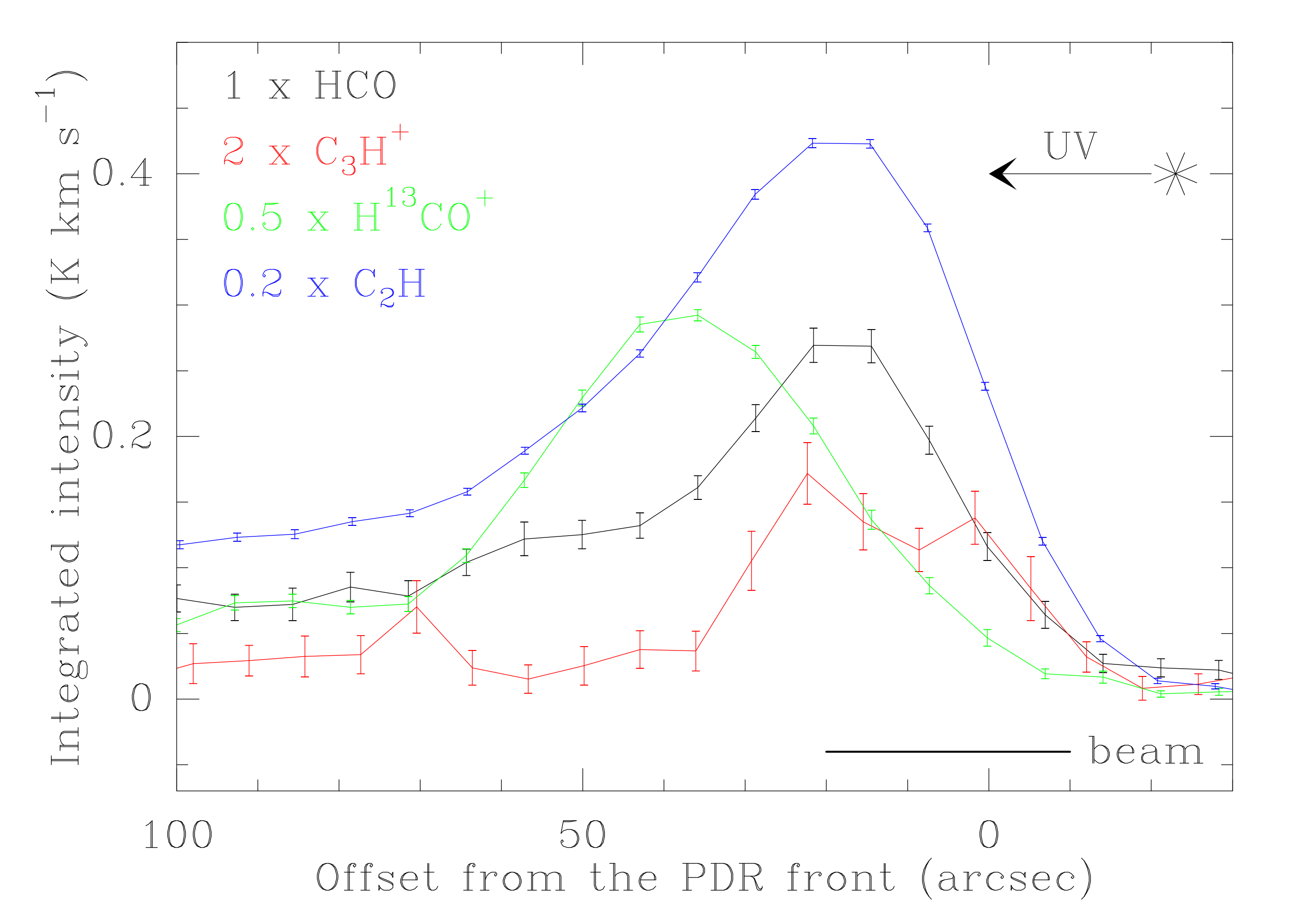
- C^+ traces the outer skin of the PDR
- Herschel HIFI observations
- Non Negative Matrix Factorization
- see poster n° 3 by Olivier Berné
- Complex velocity structure



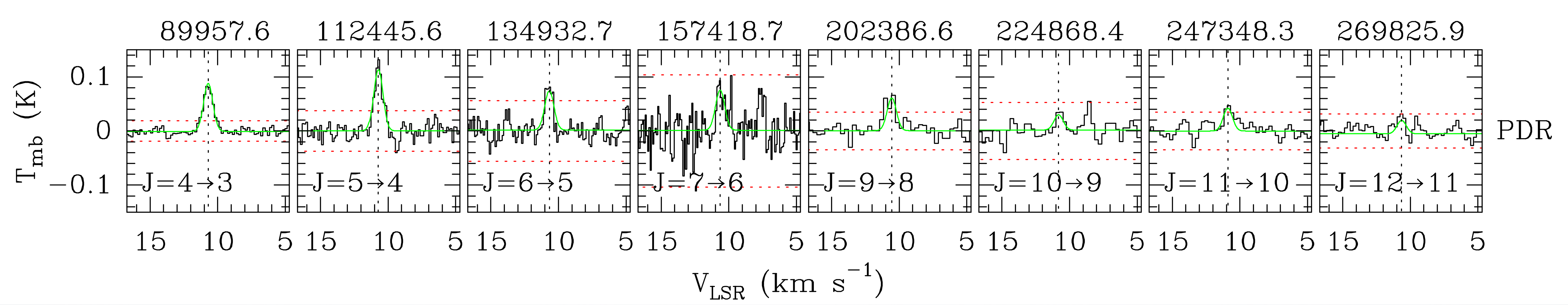
FIRST DETECTION OF C_3H^+ IN THE ISM (PETY ET AL. 2012)



- Consistent set of 8 unidentified lines towards the PDR position.
- Linear rotor, with a $1\Sigma^+$ electronic ground state.
- The deduced rotational constant is close to l-C_3H.
- Reactive molecule with a spatial distribution similar to small hydrocarbon chains.



First detection of C_3H^+ in the ISM (Pety et al. 2012)



- Consistent set of 8 unidentified lines towards the PDR position.
- Linear rotor, with a 1Σ electronic ground state.
- The deduced rotational constant is close to l-C_3H.
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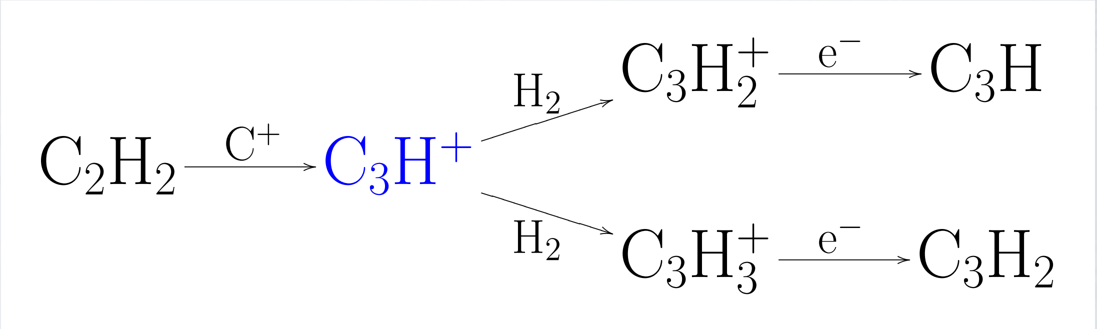
Most probable candidate: C_3H^+

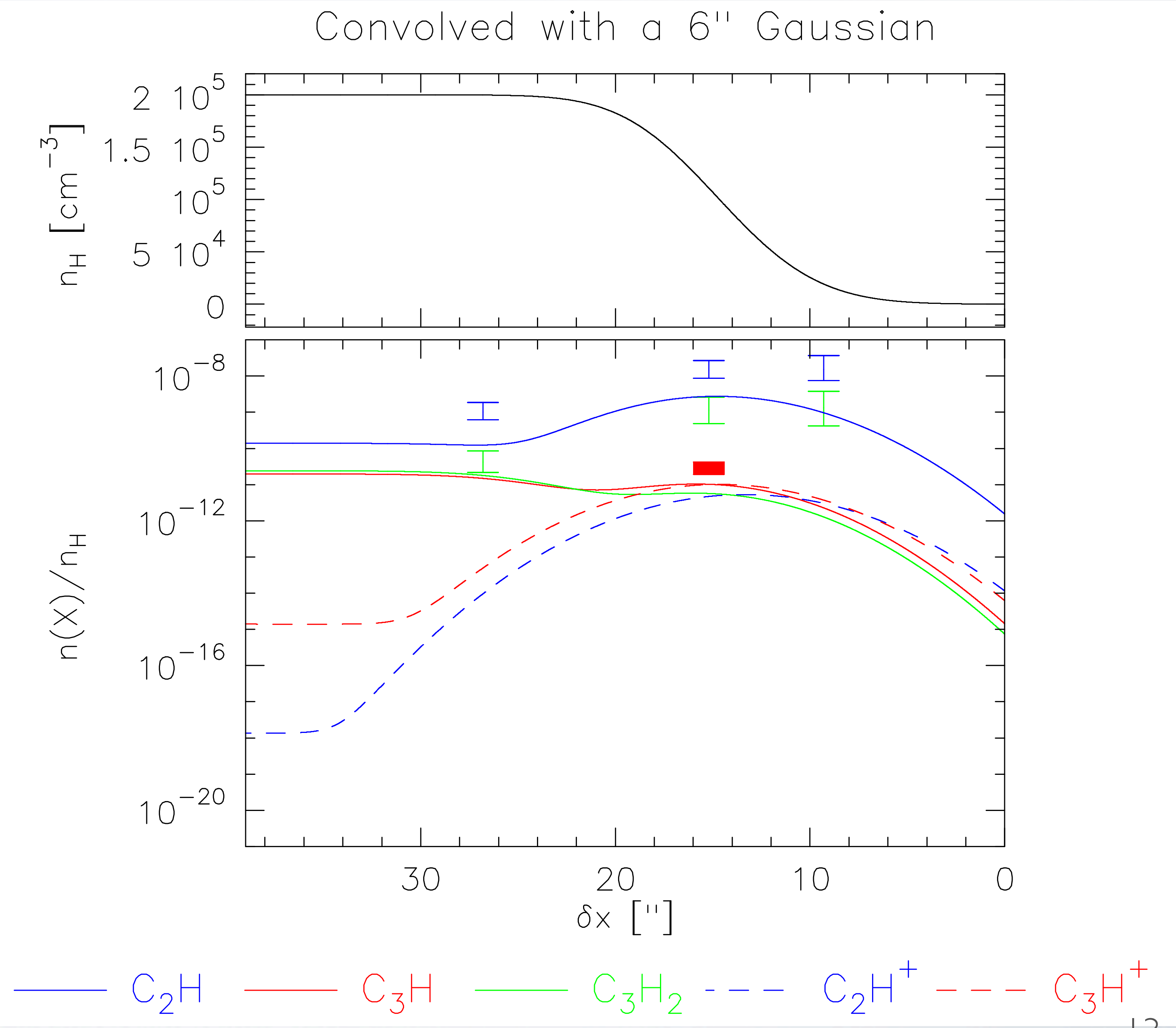
- Correct electronic state.
- Computed rotational constant (Cooper & Murphy 1988) close to deduced value.
- Dipole moment: 3 Debye
- On-going experimental spectroscopic confirmation PhLAM (Bailleux & Margulès, priv. comm.)

FIRST DETECTION OF C_3H^+ IN THE ISM (PETY ET AL. 2012)

- Abundance:
  $[C_3H^+] = 1.9 \pm 4.2 \times 10^{-11}$
- H_2 reactions with C_3H^+ → important pathways to form hydrocarbons chains. (Wakelam et al. 2010)

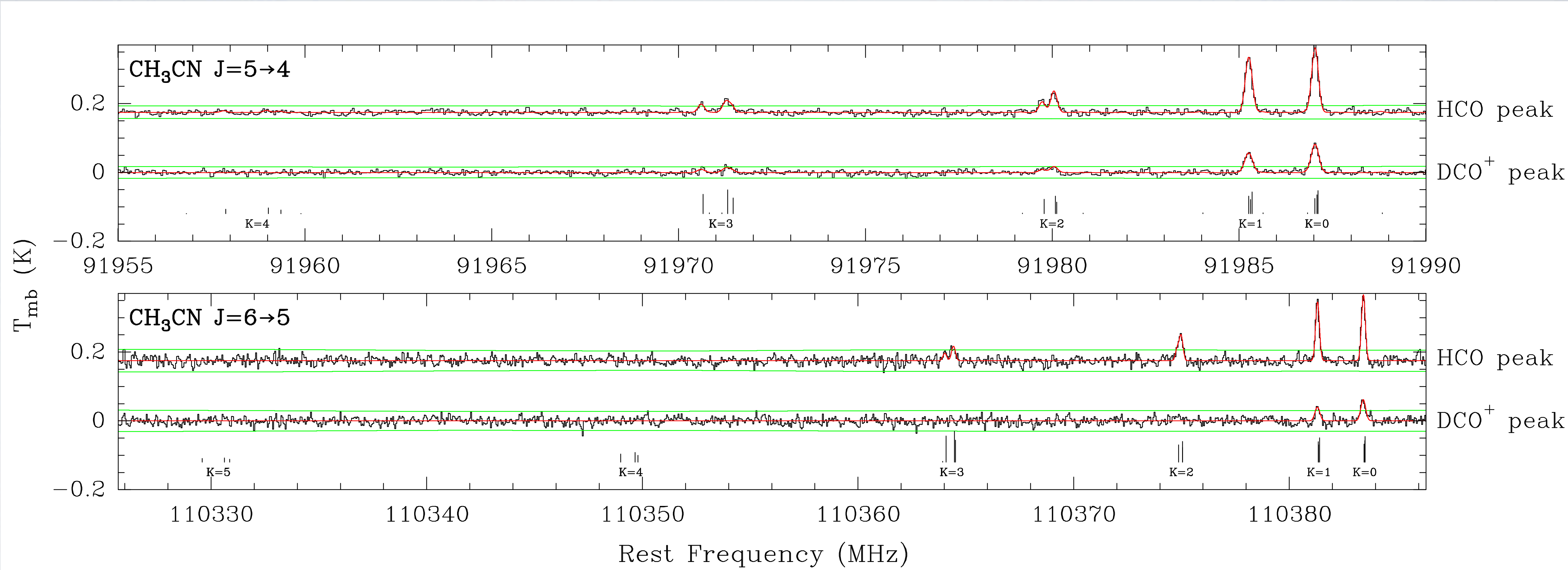


- Model:
  - Abundances vary ~ 7 orders of magnitude in ~ 20″



- Interferometric observations:
  - C_2H and C_3H_2 : High-resolution observations (Pety et al. 2005)
  - Accepted proposal to map C_3H^+ at PdBI

High (iso)nitrile abundance in the PDR (Gratier et al.)

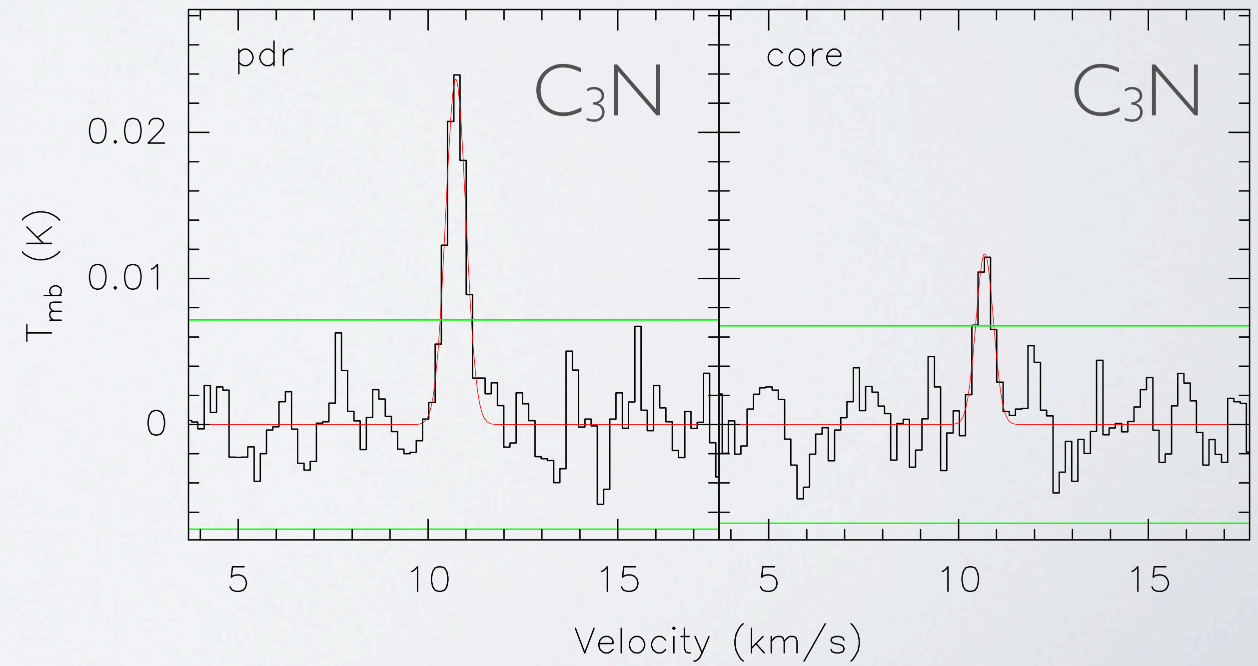


- CH_3CN methylcyanide
    - Good thermometer for large densities (n >10^5 cm^{-3})
    - Resolved hyperfine structure of CH_3CN
    - Stronger in PDR than in the dense core
- Detection of CH_3NC : [CH_3NC]/[CH_3CN] = 0.15 (cf DeFrees et al. 1985 0.1–0.4)

High (iso)nitrile abundance in the PDR (Gratier et al.)

- Abundance determination: RADEX modeling
  - Non negligible electron excitation for CH_3CN
  - CH_3CN 30 x more abundant in the PDR than in the dense core
  - CH_3CN overabundant in UCHII regions (Purcell et al. 2006)
- Several possibilities:
  - Higher abundance of precursors (CH_3^+, HCN in the PDR)
  - UV photoprocessing if N bearing ices followed by photodesorption (Danger et al. 2011)

- Other nitriles:
  - HC_3N as abundant in the PDR than in the dense core
  - HC_3N 30 times less abundant as CH_3CN in the PDR
  - C_3N brighter in the PDR than in the dense core (after stacking)



Conclusion

- Horsehead nebula is a benchmark for PDR modeling and interstellar chemistry
- Horsehead WHISPER full 1, 2 and 3mm high resolution sensitive line survey at 2 positions : PDR and dense core
  - Importance of grain surface reaction and photodesorption for H_2CO, CH_3OH
  - Hyperfine structure of CF^+, F abundance and C^+ proxy
  - First detection of C_3H^+, key ion for carbon chain chemistry
  - High abundance of CH_3CN in the PDR position
- Further work with the WHISPER survey:
  - Description of the new data reduction methods for spectral surveys
- Ongoing followups with PdBI interferometer (H_2CO, CH_3OH, C_3H^+)