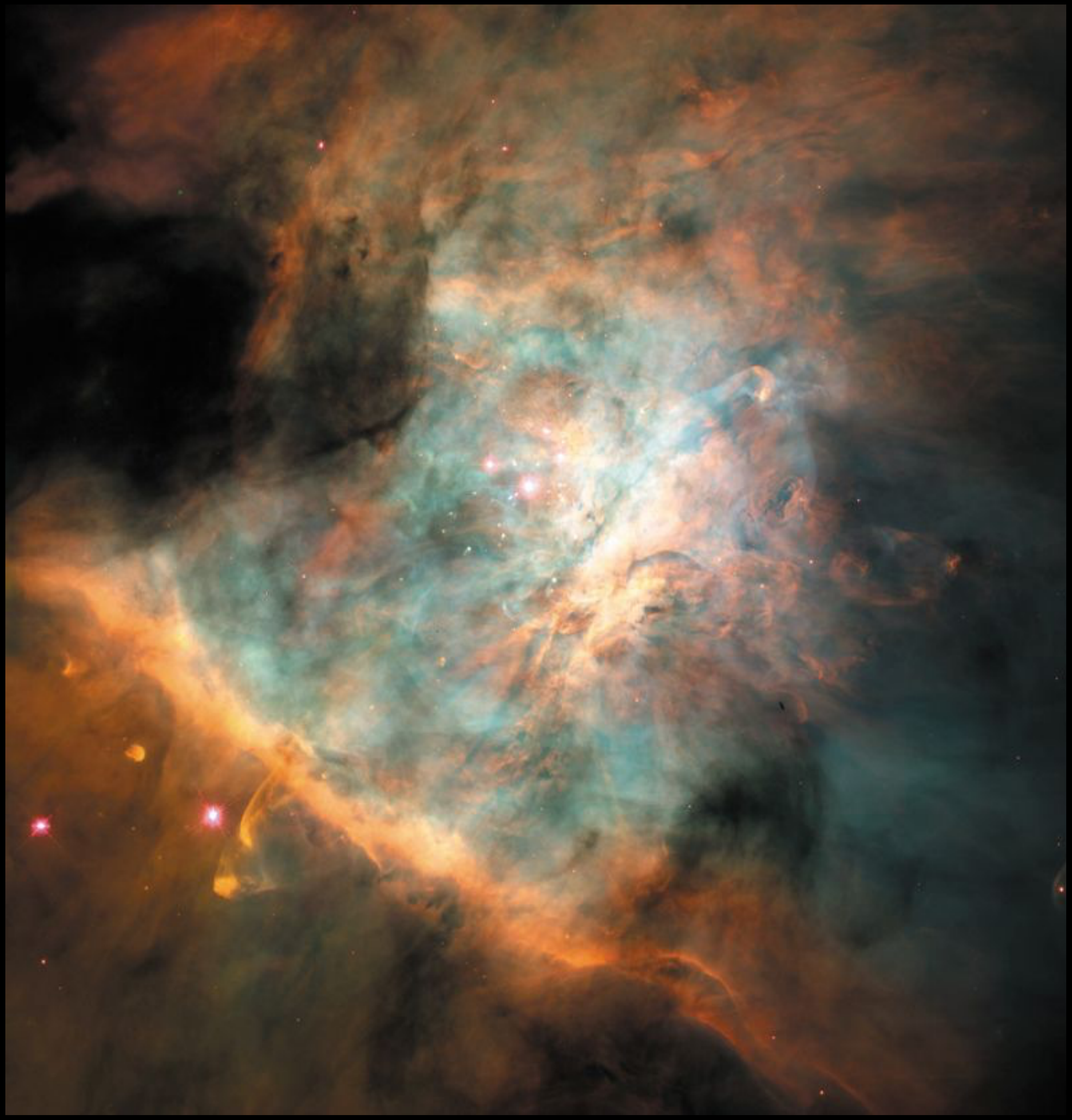
The Orion Bar: from ALMA to new PDR models



Orion/M42 HST-NASA / O'Dell & Wong

Javier R. Goicoechea
IFF-CSIC, Madrid

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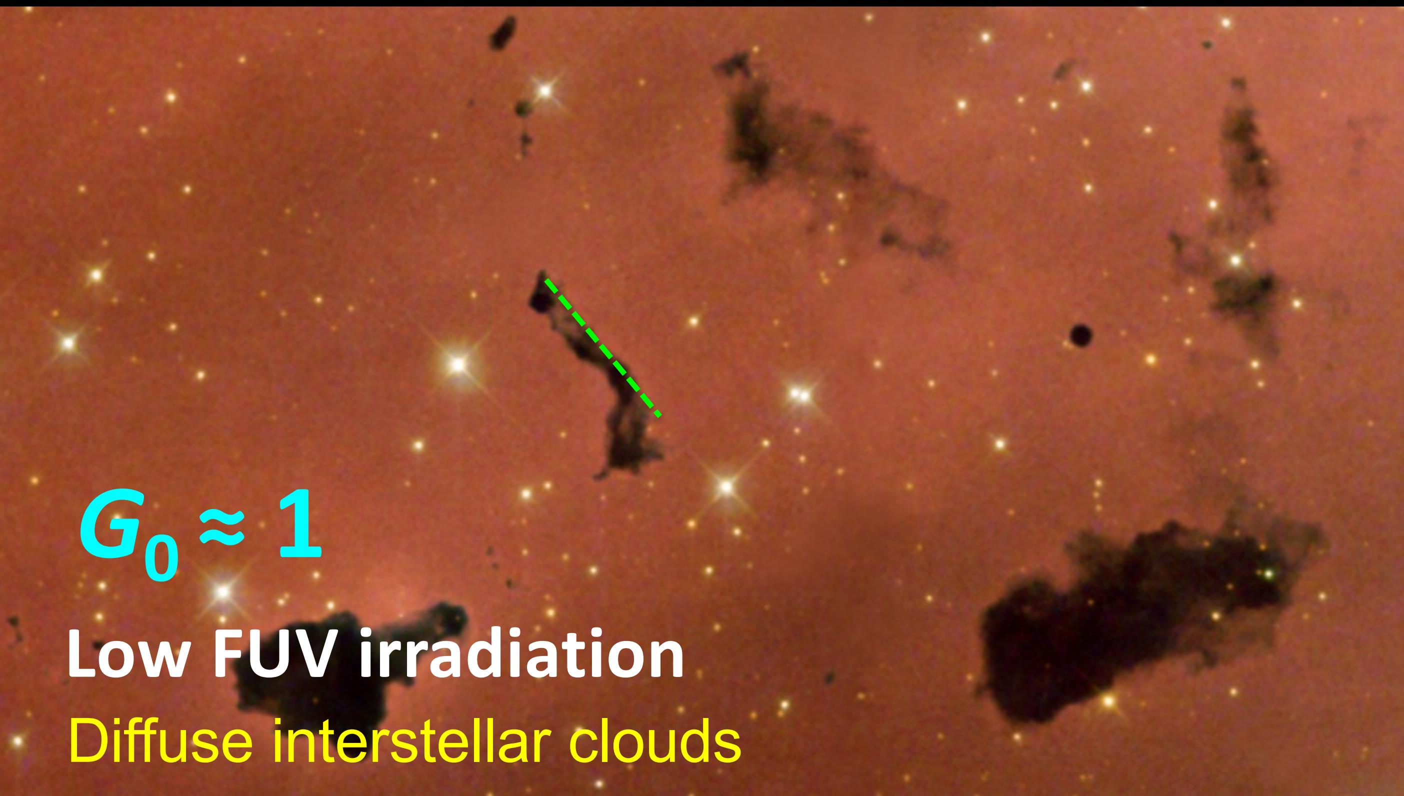
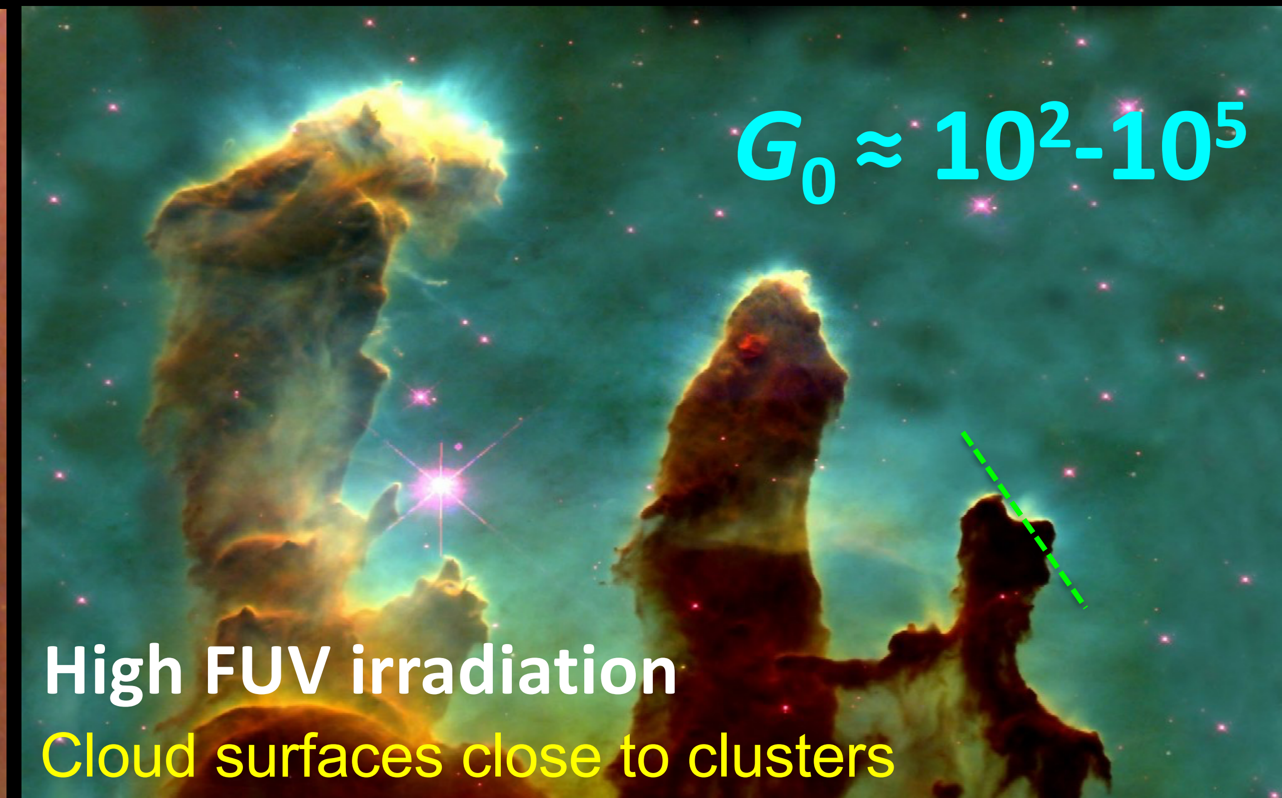
Sara Cuadrado (IFF-CSIC, Madrid)
Emeric Bron (Obs. de Paris)

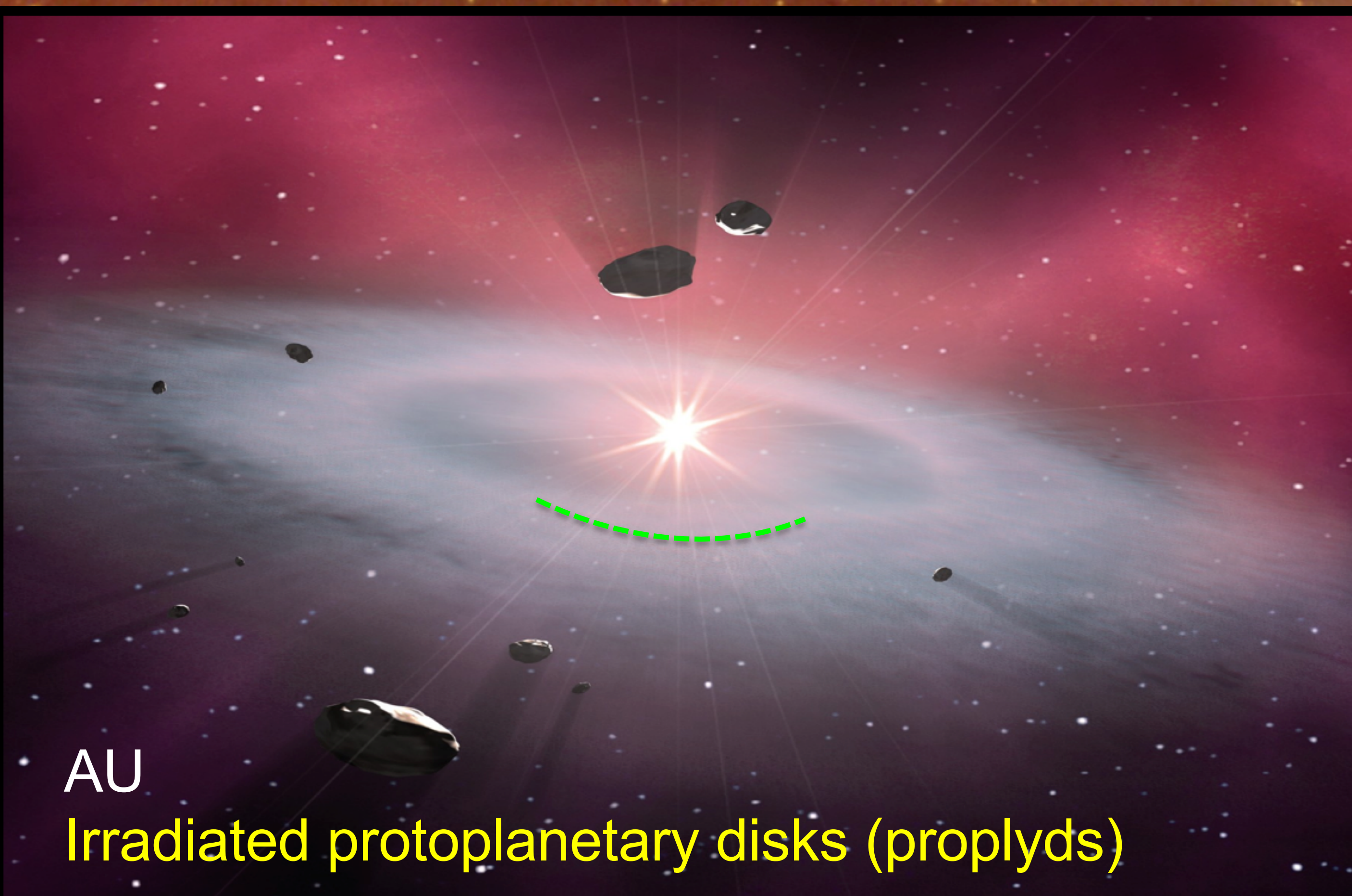
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

CSIC Consejo Superior de Investigaciones Científicas

Most neutral ISM is permeated by far-UV photons E < 13.6 eV from massive stars → PDR emission dominates







PDR models explain “most” of the neutral ISM

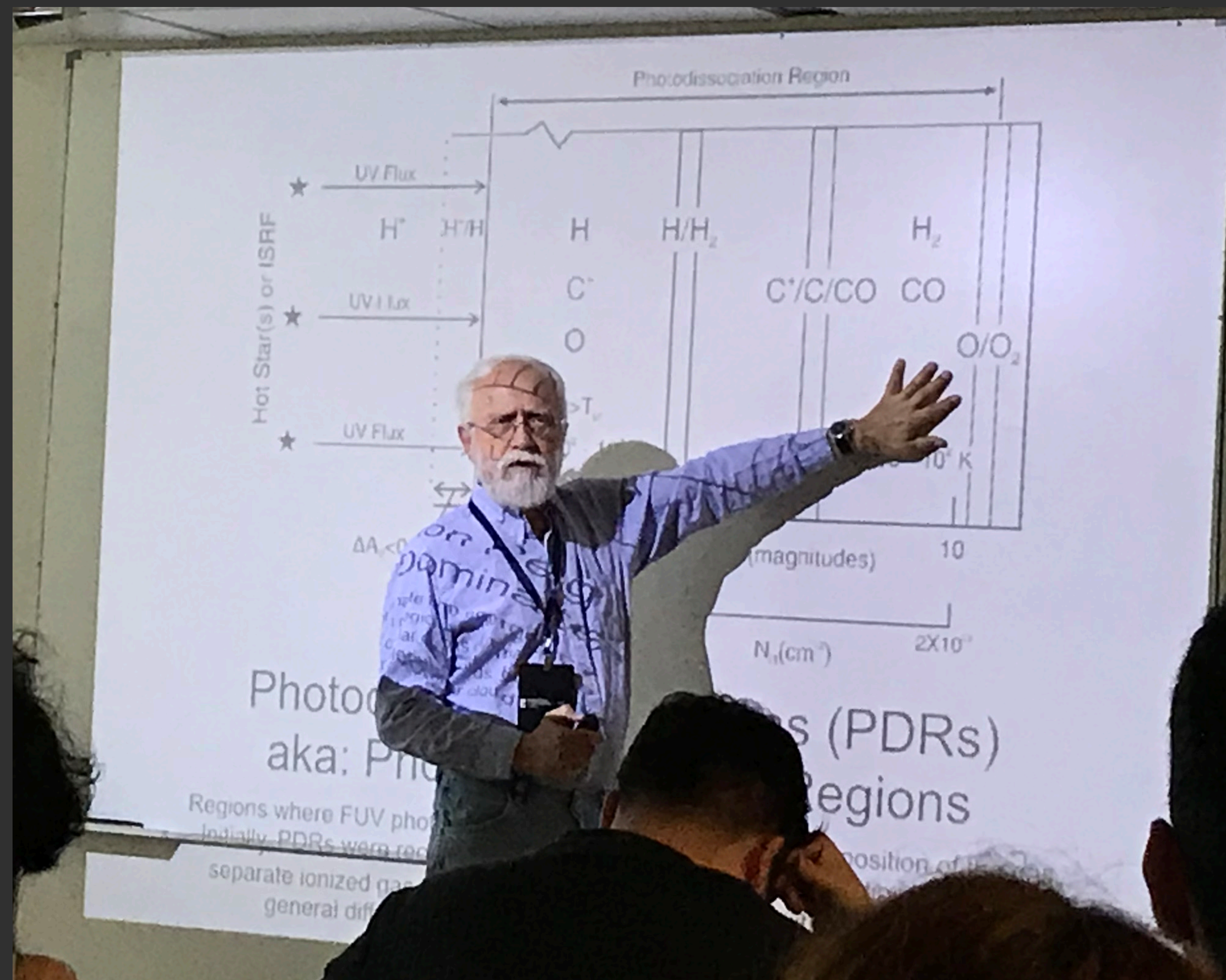
80’s

Penetration of stellar FUV photons into neutral clouds

Heating and cooling

Excitation & gas chemistry

H/H_2 $C^+/C/CO$



Grain surface chemistry

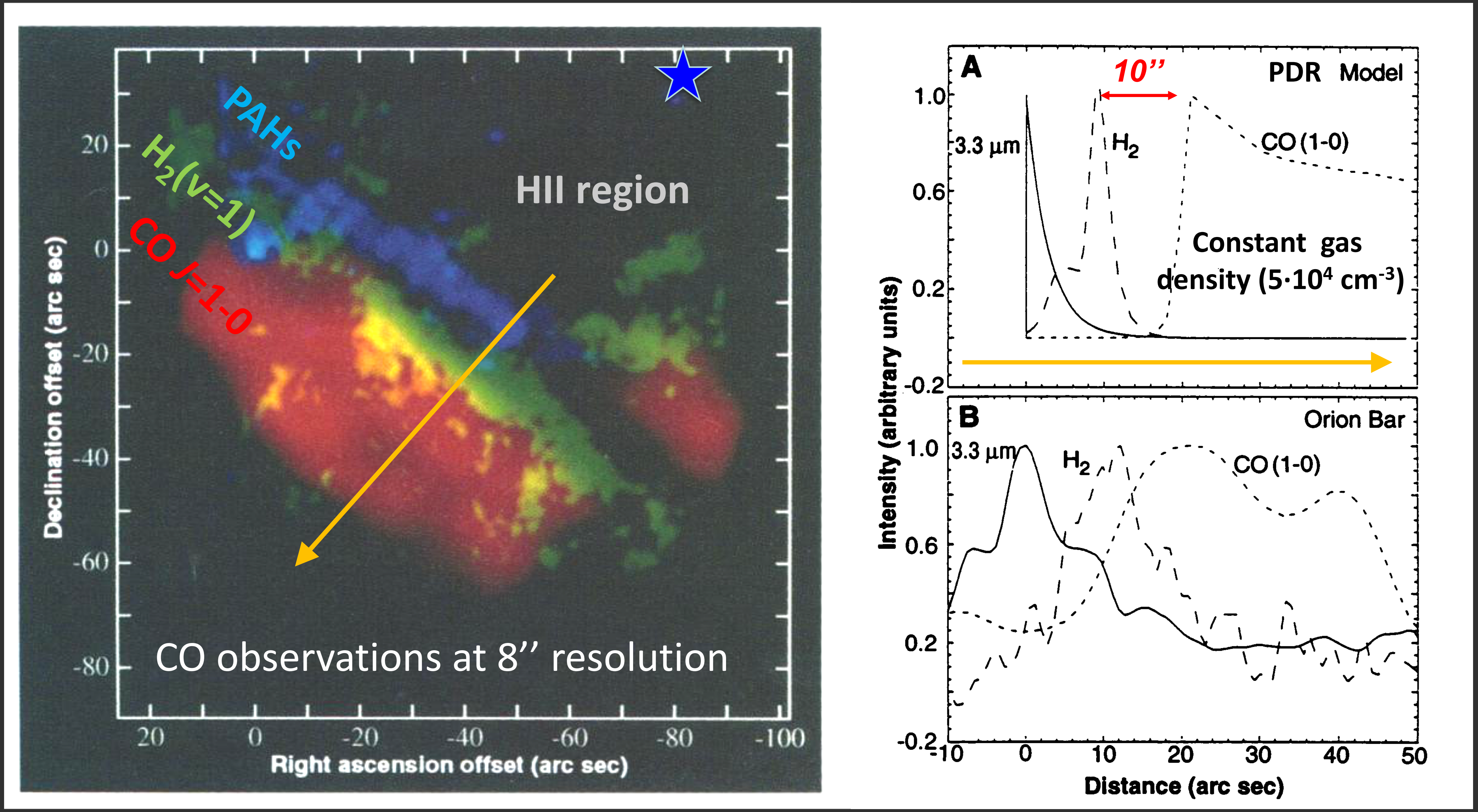
Dynamics, time-dependence

2D, 3D …

Stationary PDR codes: Tielens & Hollenbach 85; van Dishoeck & Black 86; Wolfire+90; Le Bourlot+93; Hogerheijde+95; Abel+05; Sternberg & Dalgarno 95; Le Petit+06; Bell+06; Röllig+06, Bisbas +15, Esplugues +16; Andree-Labsch +17 …

The Orion Bar PDR (in the 90s)

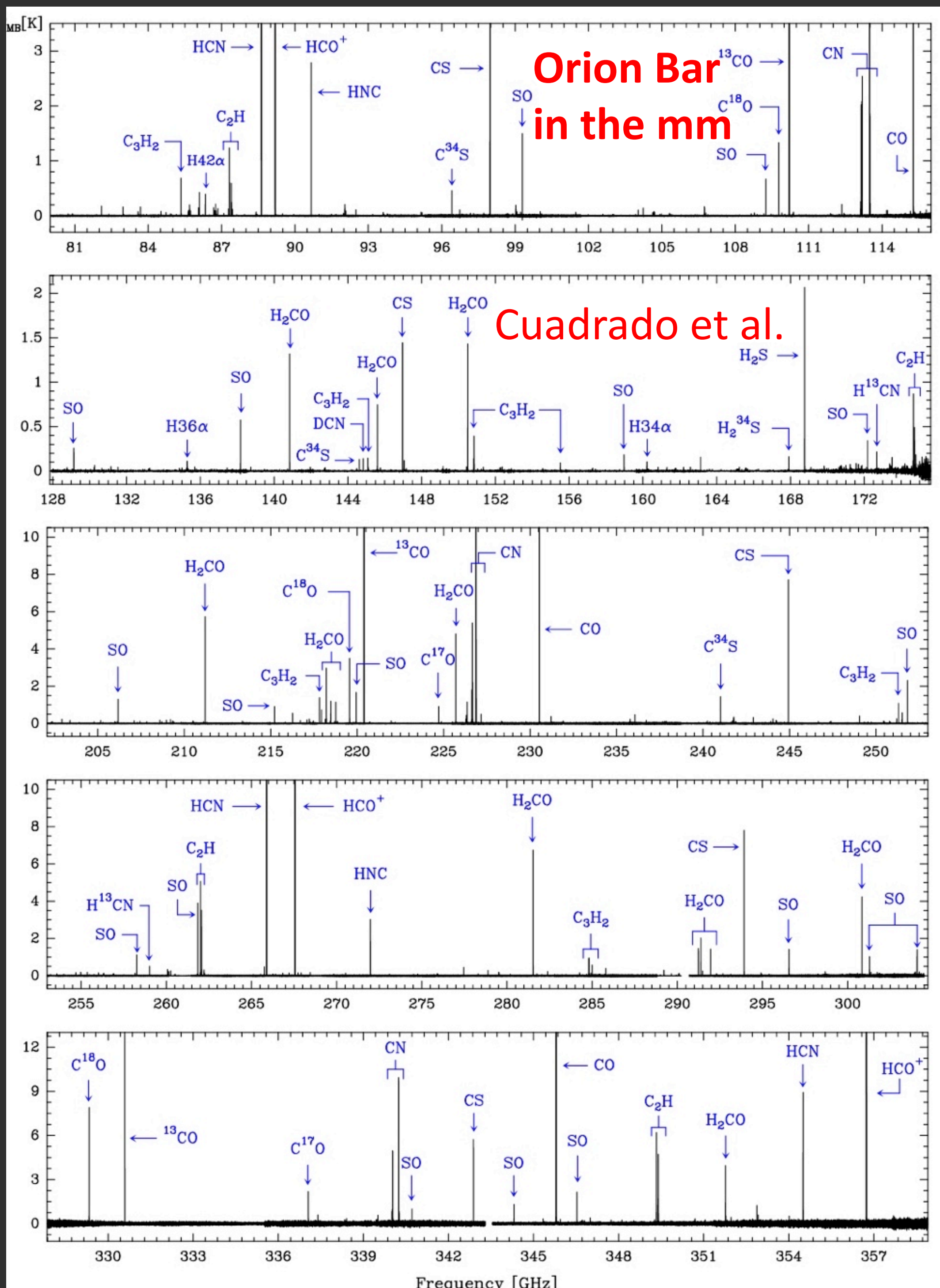
Physics & structure of a HII region/cloud interface



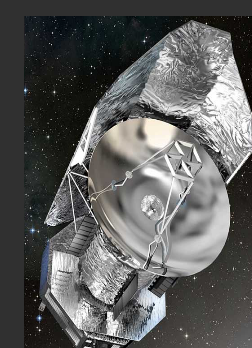
Tielens *et al.* 1993 *Science*

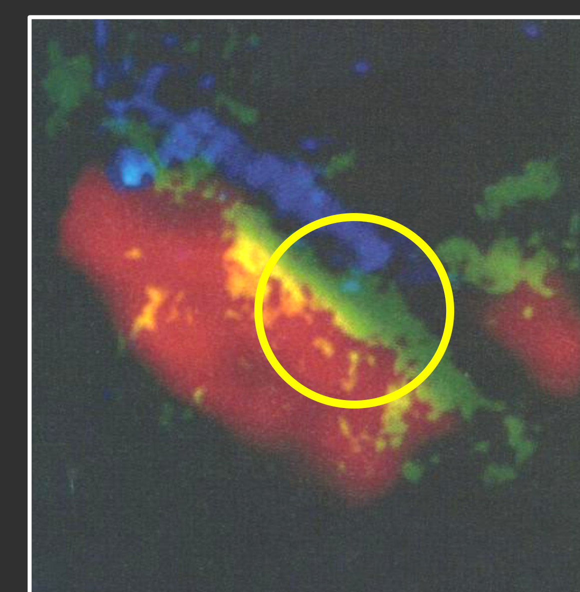
Separated **H/H_2** and **C^+/CO** fronts
(A_v ~2) (A_v~4)

Orion Bar a strongly FUV-irradiated PDR
harsh environment but peculiar chemistry



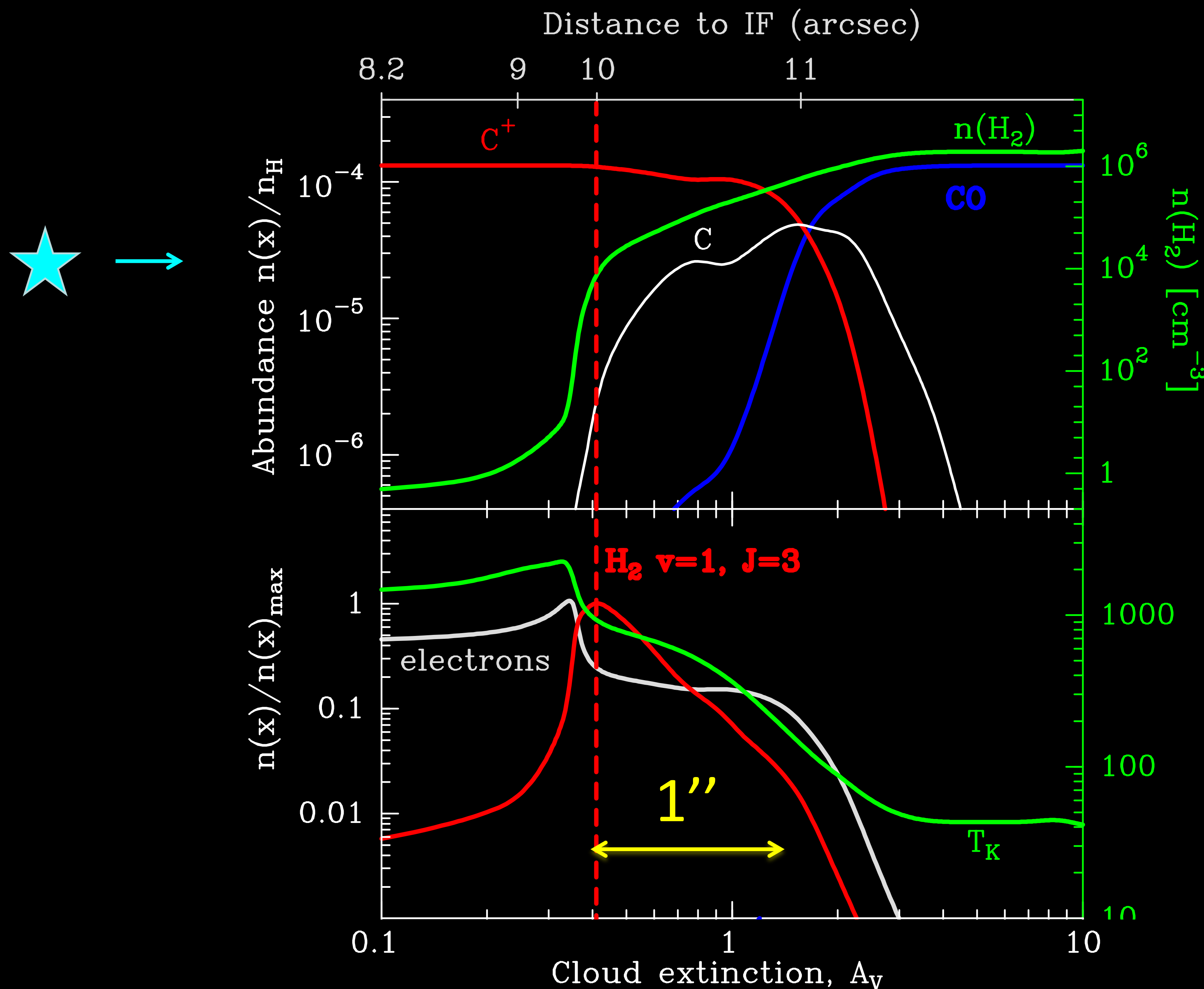
- C^+, S^+, … ions and H, O, … atoms
- *e^-* and vibrationally excited H_2^*
- Reactive ions (CH^+, SH^+, …)
- PAHs and COMs' isomers (*cis*-HCOOH, …)





Herschel,
IRAM 30m, etc
~20'' resolution

Orion Bar Chemistry: Jansen +95, Young+00; Fuente +03; Simon+97; Marconi+98; Allers+05; van der Wiel +09; Habart+10 Goicoechea +11,+17; van der Tak+12,+13; Cuadrado +15,+16, +17; Nagy+13+17, Faure+17; Putaud+19 and **many others**



1D stationary
Meudon PDR code

Isobaric
$P_{th}/k \sim 10^8$ K cm^{-3}
$G_0 \sim 3\cdot10^4$

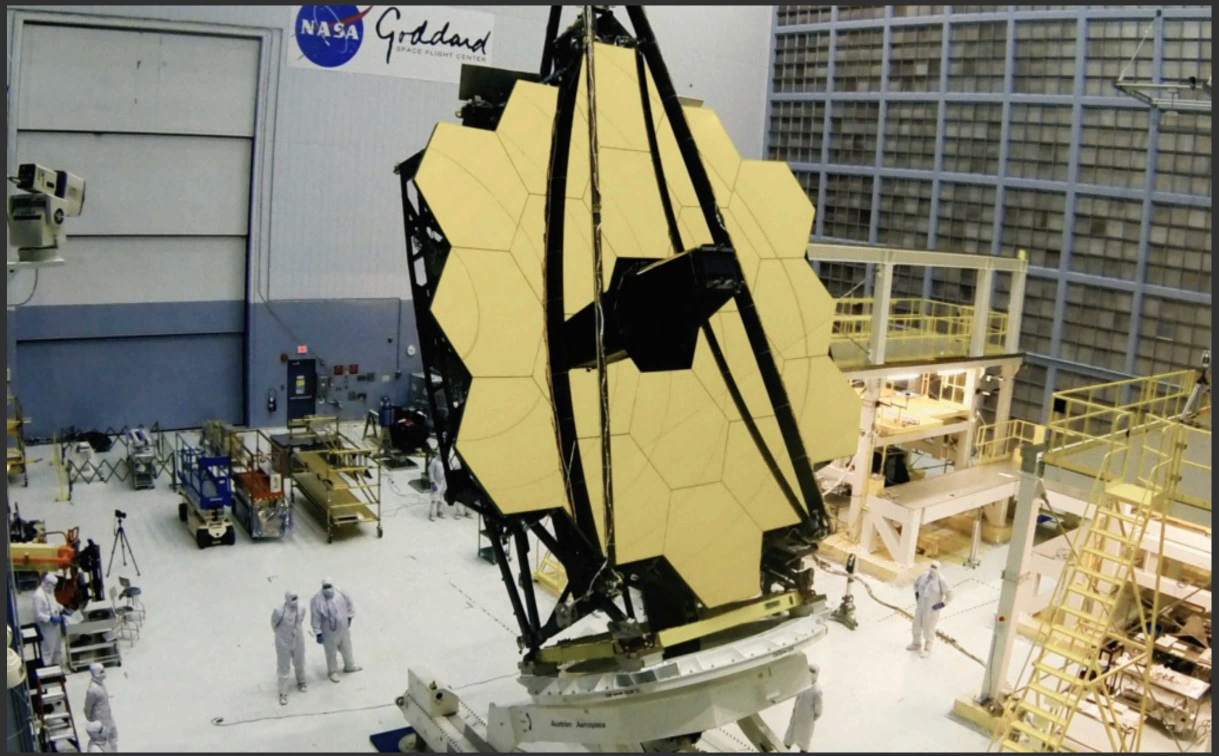
Distance to Orion

Steep gradients in physical conditions and abundance profiles

Sharp physical and chemical gradients in PDRs at **small** scales

→ 414 AU ≈ 1’’ in Orion → ΔA_V ~ 1 mag @ 10^6 cm^{-3} → **ALMA** & **JWST**

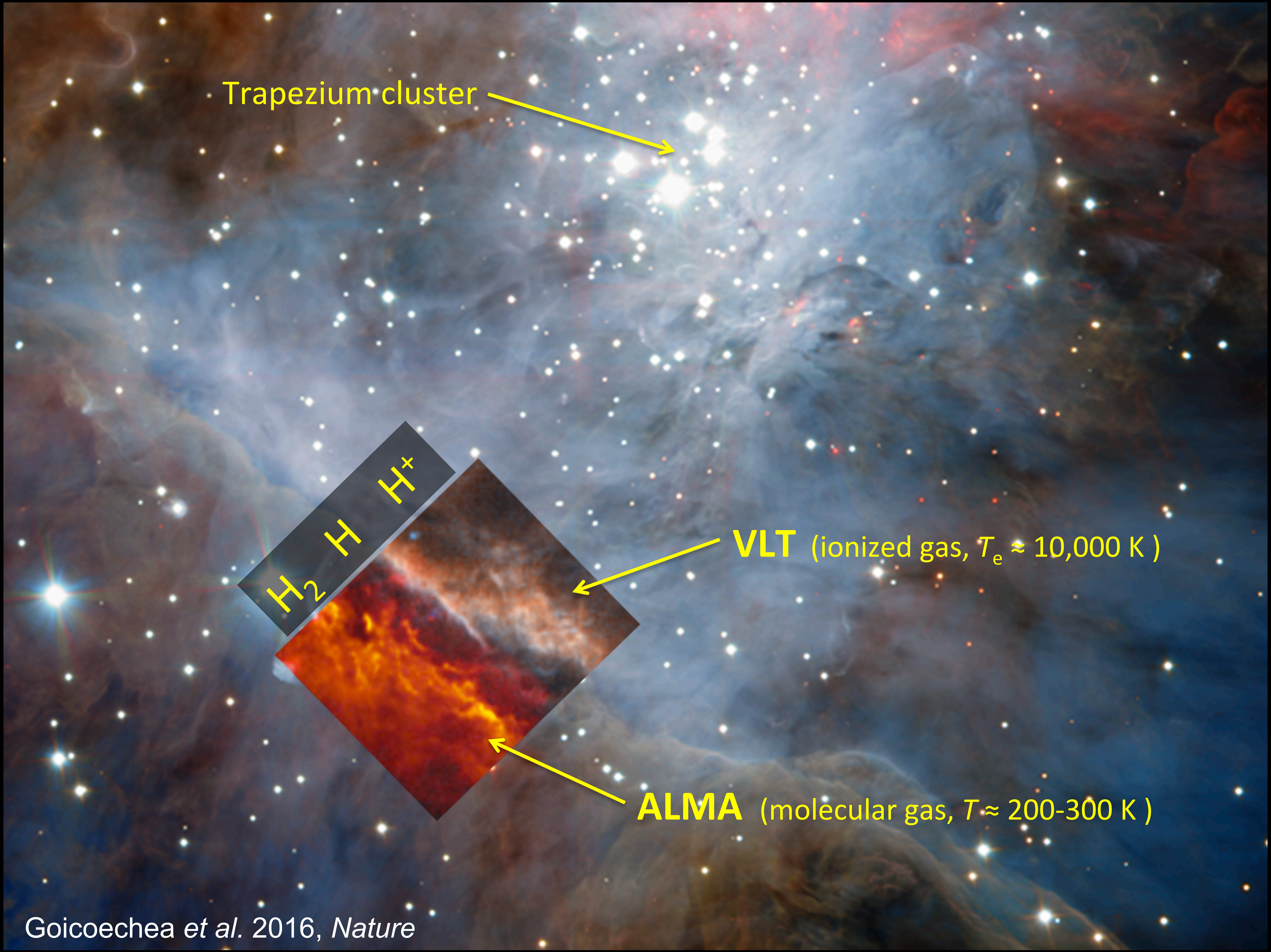
(sub)mm: polar molecules



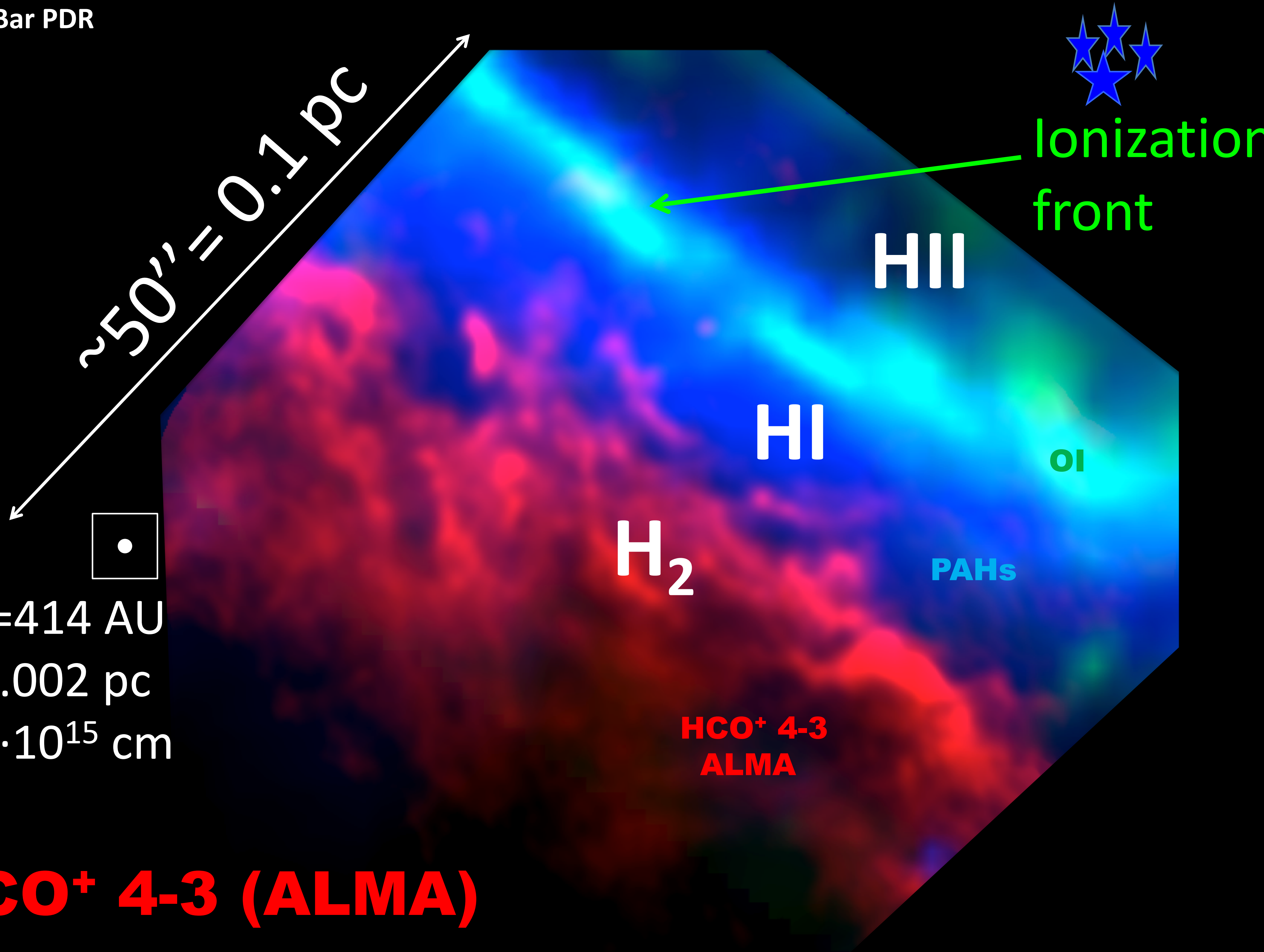
Mid-IR: H_2 & PAHs

The Orion Bar today ...

1'' resolution



Orion Bar PDR



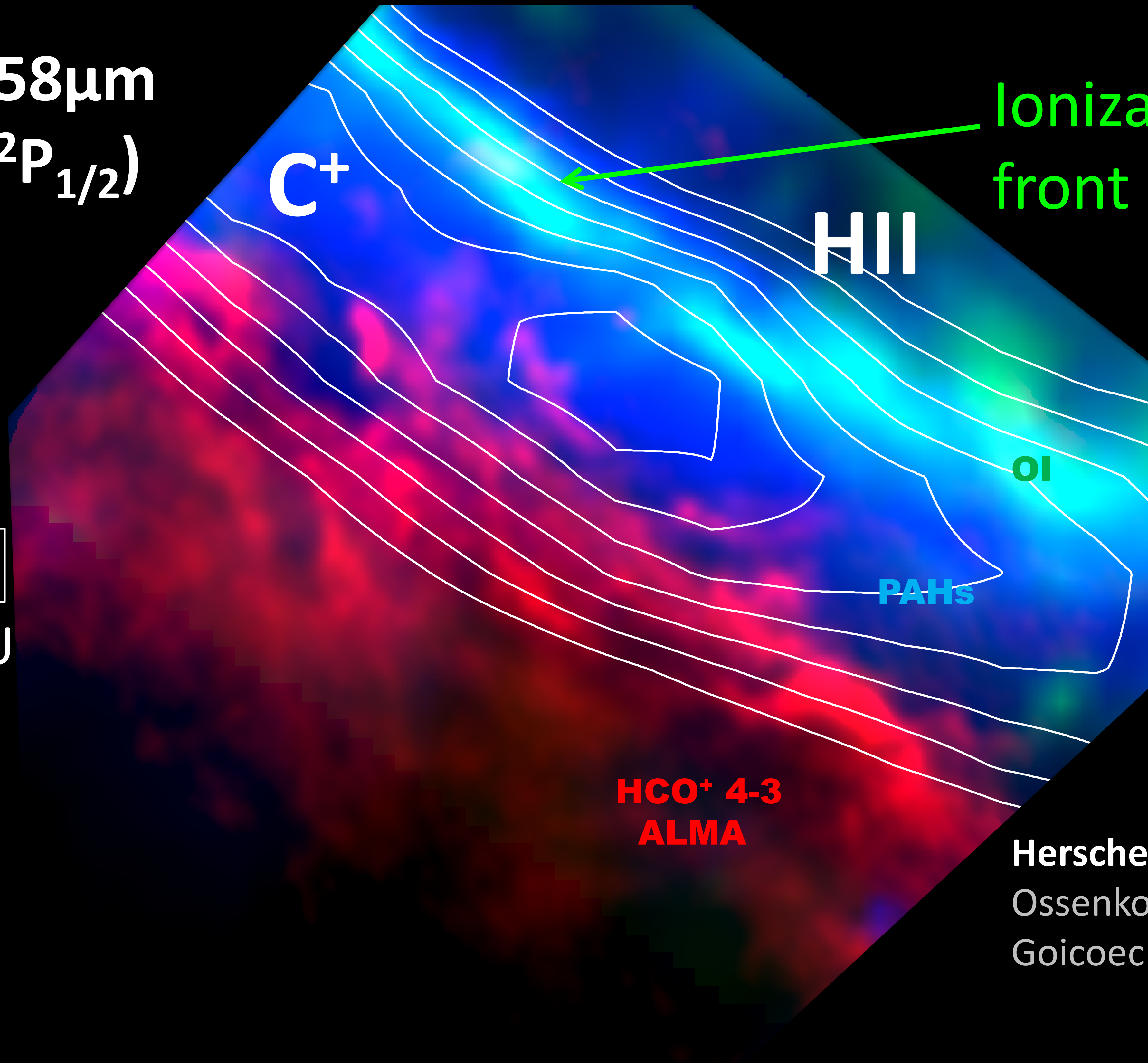
1''=414 AU
= 0.002 pc
= $6 \cdot 10^{15}$ cm

HCO^+ 4-3 (ALMA)

PAHs (8.0um, Spitzer/IRAC ~**2''**)

Ionized front (OI 1.3um, NTT ~**0.6''**; Walmsley+2000)

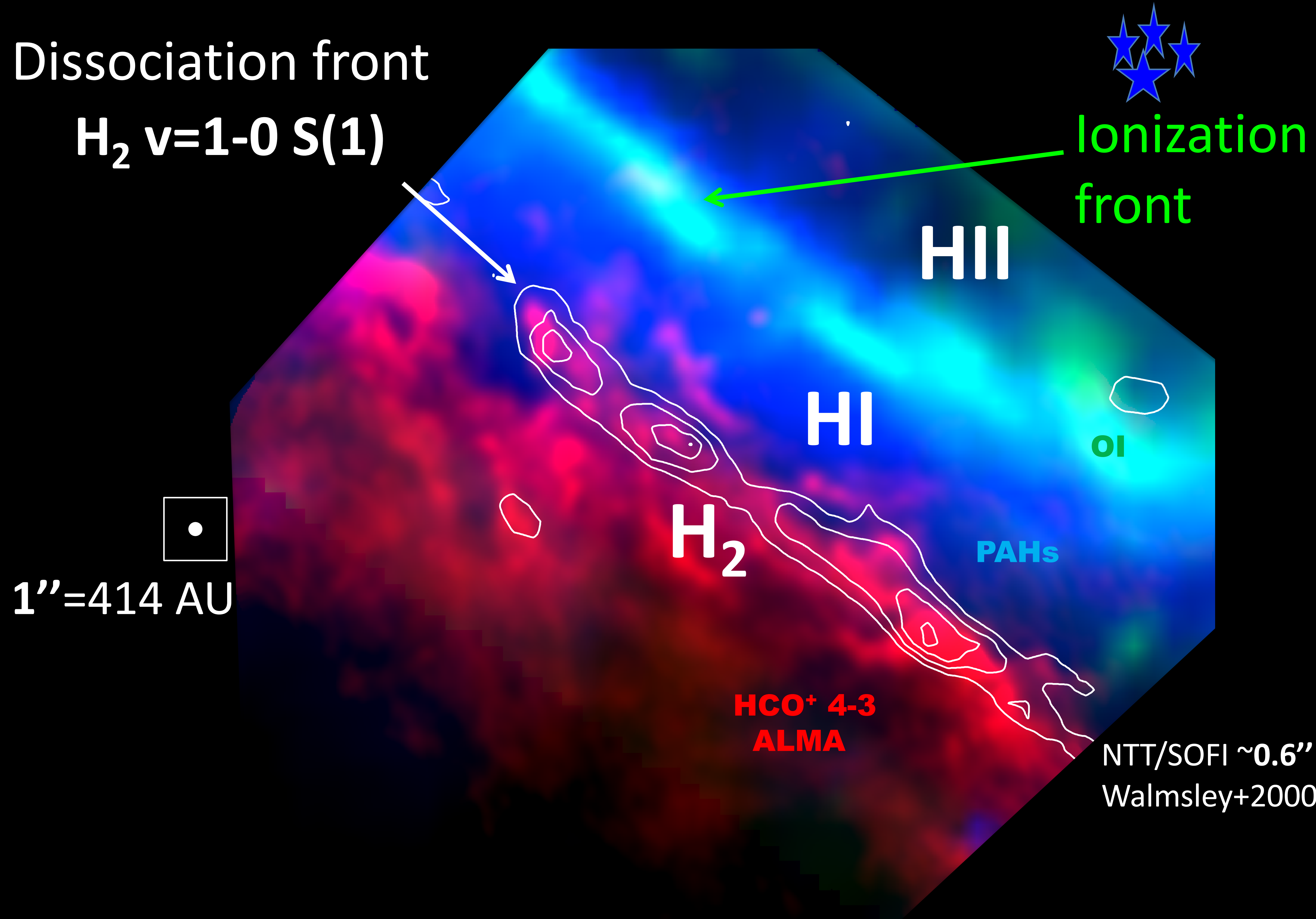
[CII] 158μm
($^2P_{3/2}$-$^2P_{1/2}$)



1''=414 AU

Herschel/HIFI **~12''**
Ossenkopf +13, A&A
Goicoechea +15, ApJ

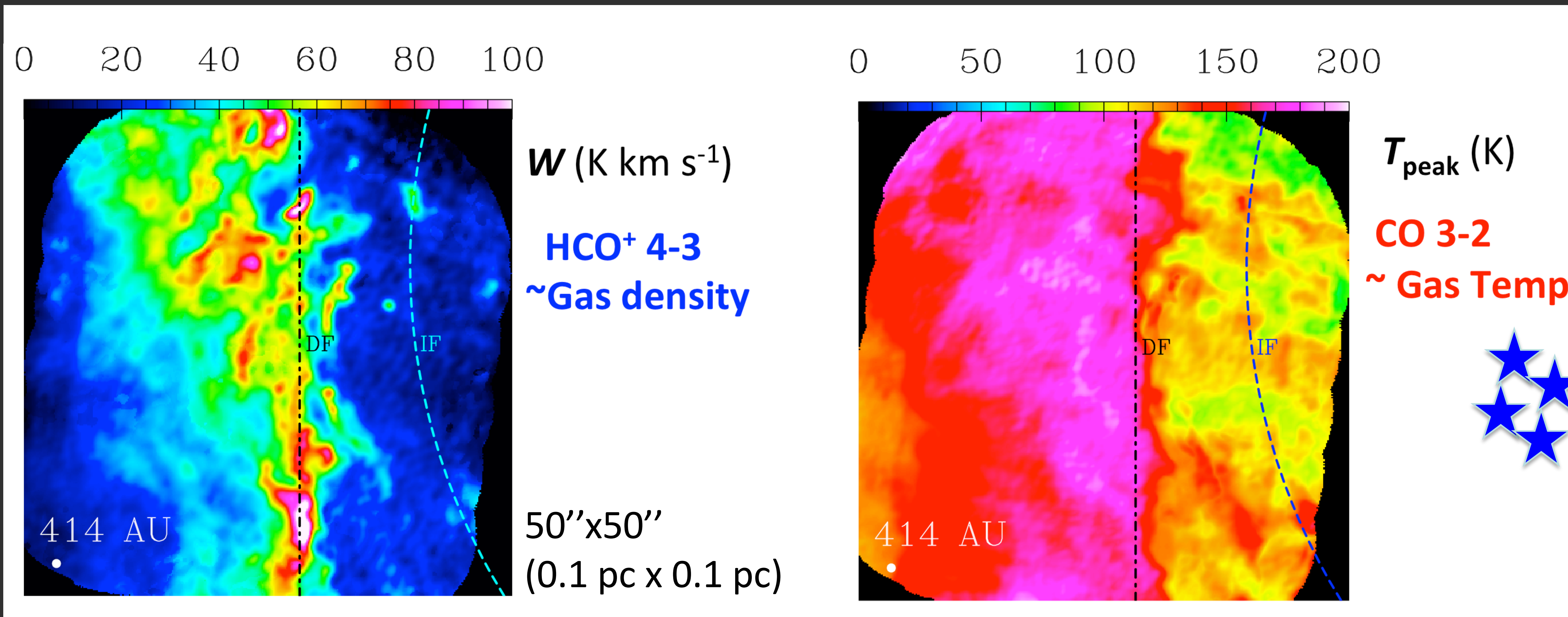
Orion Bar PDR



H/H_2 and C^+/CO transition zones seem much closer to each other than (30 years of) PDR model predictions !!

Orion Bar PDR

Small-scale density and temperature structures at the cloud edge

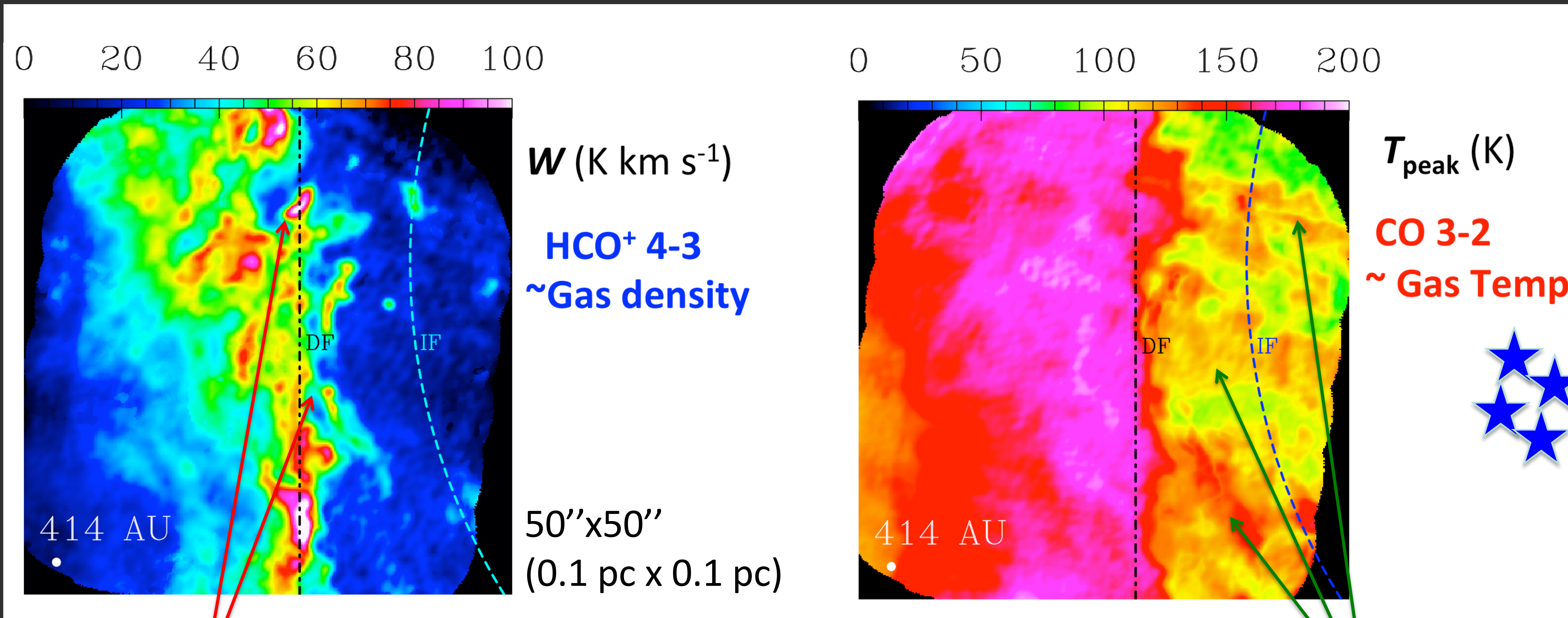


DF = H_2 *dissociation front*

IF = *Ionization front*

Orion Bar PDR

Small-scale density and temperature structures at the cloud edge



Ridge of high-pressure substructures very close to DF
$P_{th}/k \approx n_H \cdot T_k$ a few 10^8 cm^{-3} K

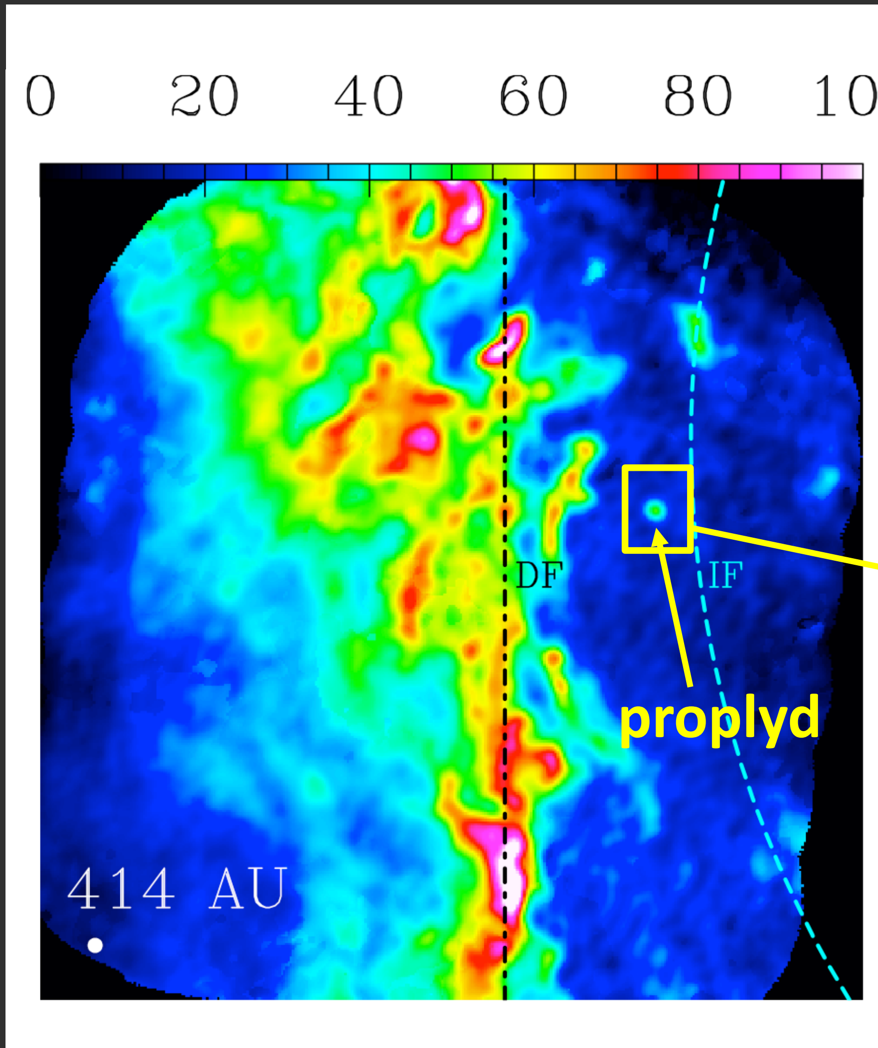
Photoevaporative gas flows ?

DF = H_2 *dissociation front*

IF = *Ionization front*

Orion Bar PDR

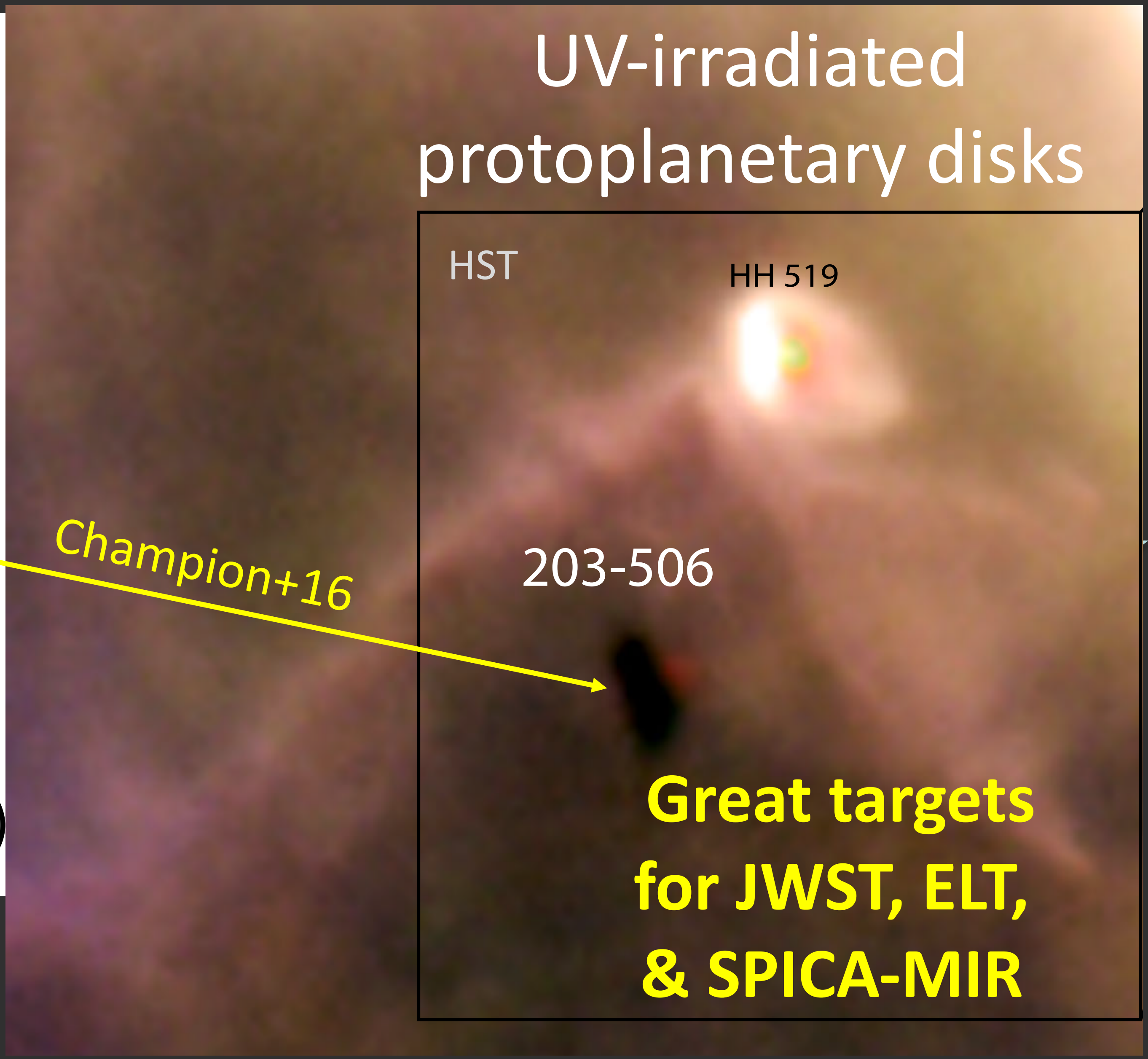
Small-scale density and temperature structures at the cloud edge



W (K km s^{-1})

HCO$^+$ 4-3
~Gas density

50''x50''
(0.1 pc x 0.1 pc)



DF = H_2 *dissociation front*
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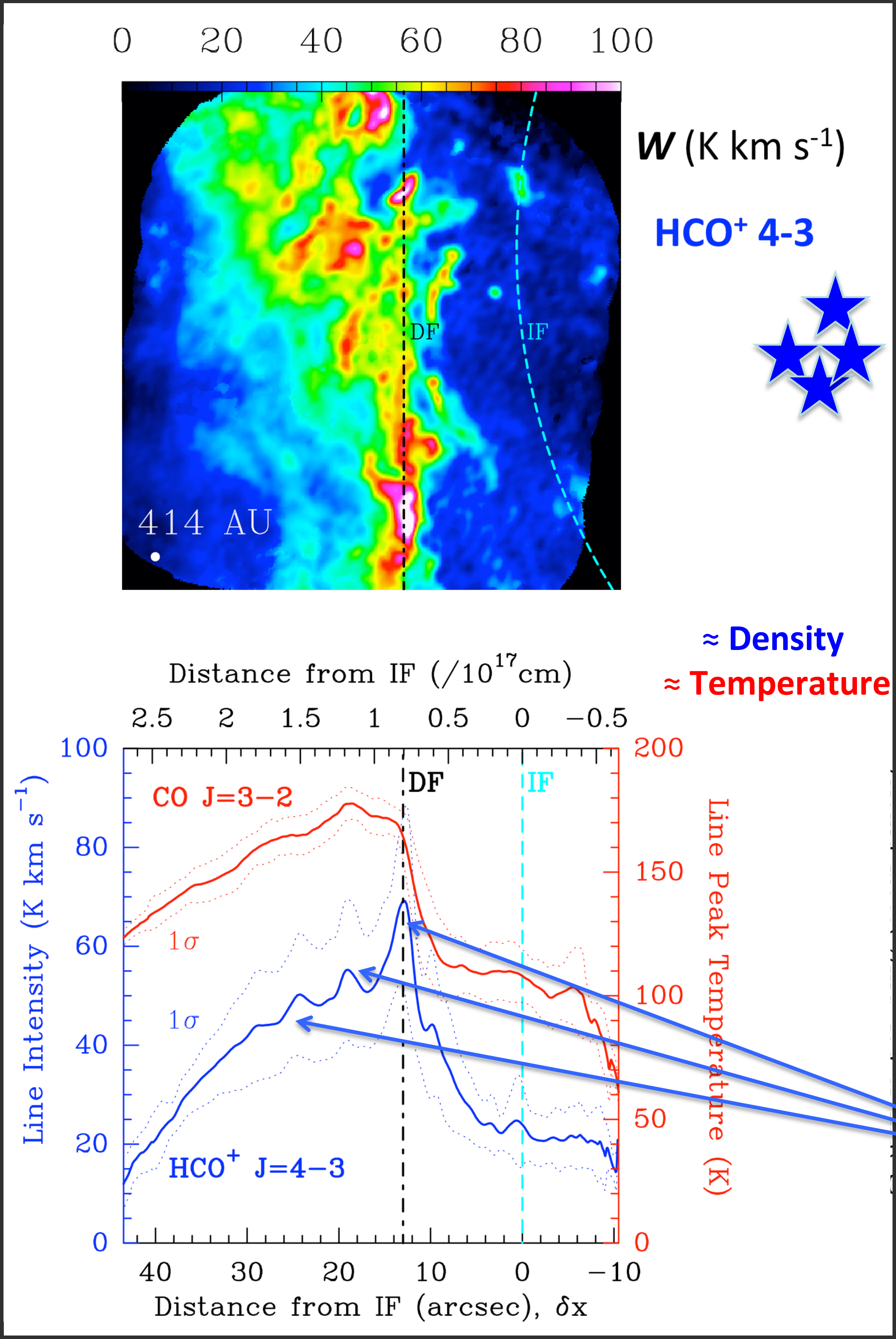
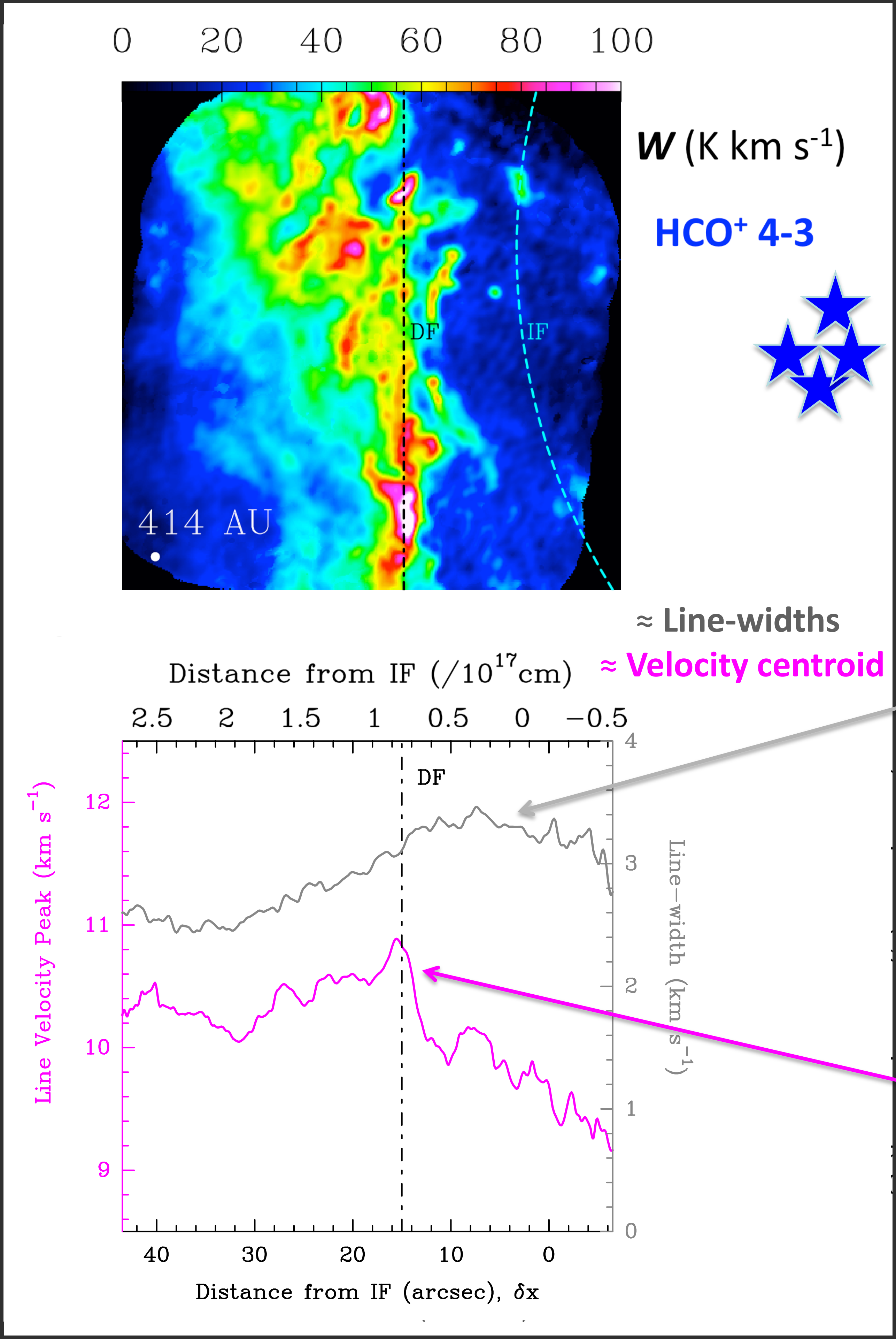
Orion Bar PDR



Vertically averaged line-intensity crosscuts perpendicular to the Bar

Periodic density peaks (every ~5'')
Cloud edge compressed (x 5-30) by a high-pressure wave moving into the molecular cloud ?
OR gas density instabilities ?

Vertically averaged velocity dispersion & centroid profiles perpendicular to the Bar



Gas velocity dispersion decreases inwards the molecular cloud

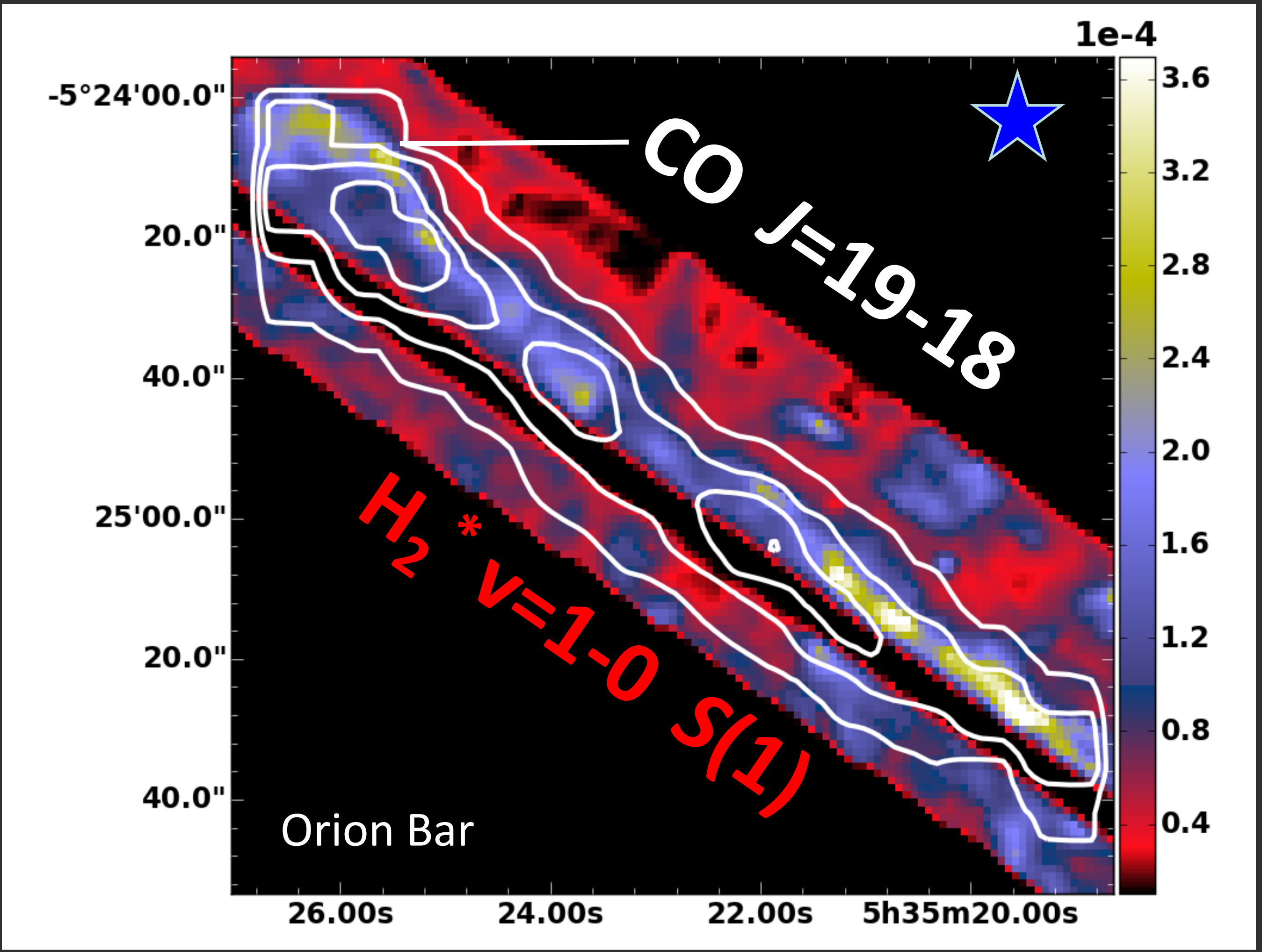
~1 km/s velocity "jump" at the dissociation front

Signature of low-velocity shock moving inwards the cloud?

e.g. Hill & Hollenbach 78

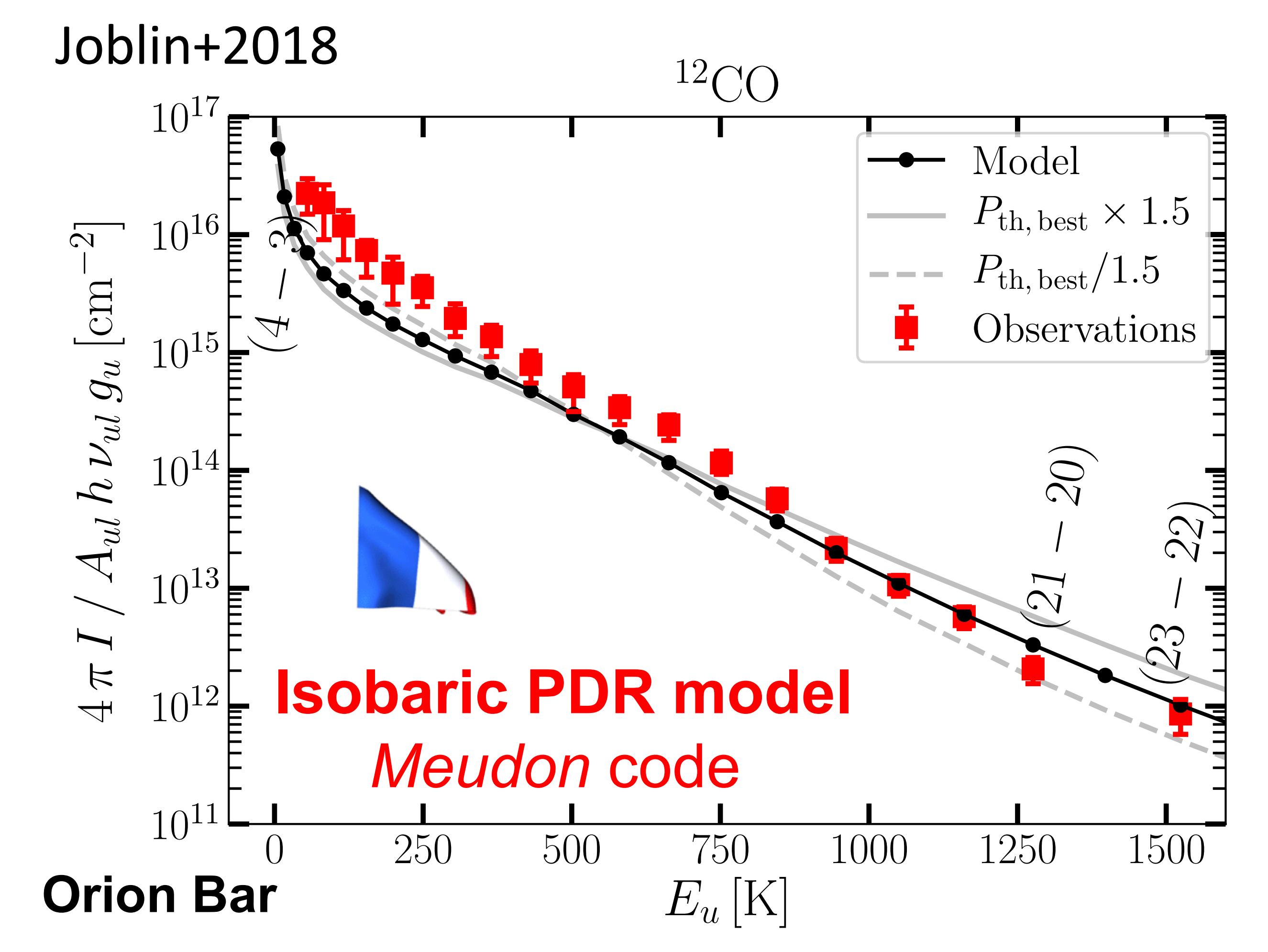
Hosokawa & Inutsuka 06

Far-IR high-J CO at >10'' resolution

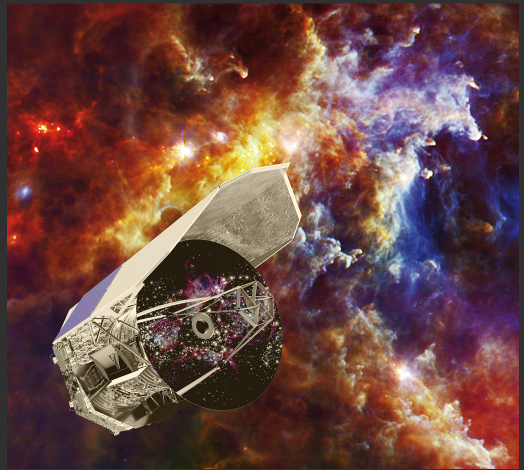


Fully sampled **high-J CO** maps
Herschel/PACS Parikka, Habart +2018

Stationary 1D PDR models:
Emission comes from a **thin layer at high thermal pressure** P_{th} ~10^8 K cm^{-3}



SOFIA



Herschel

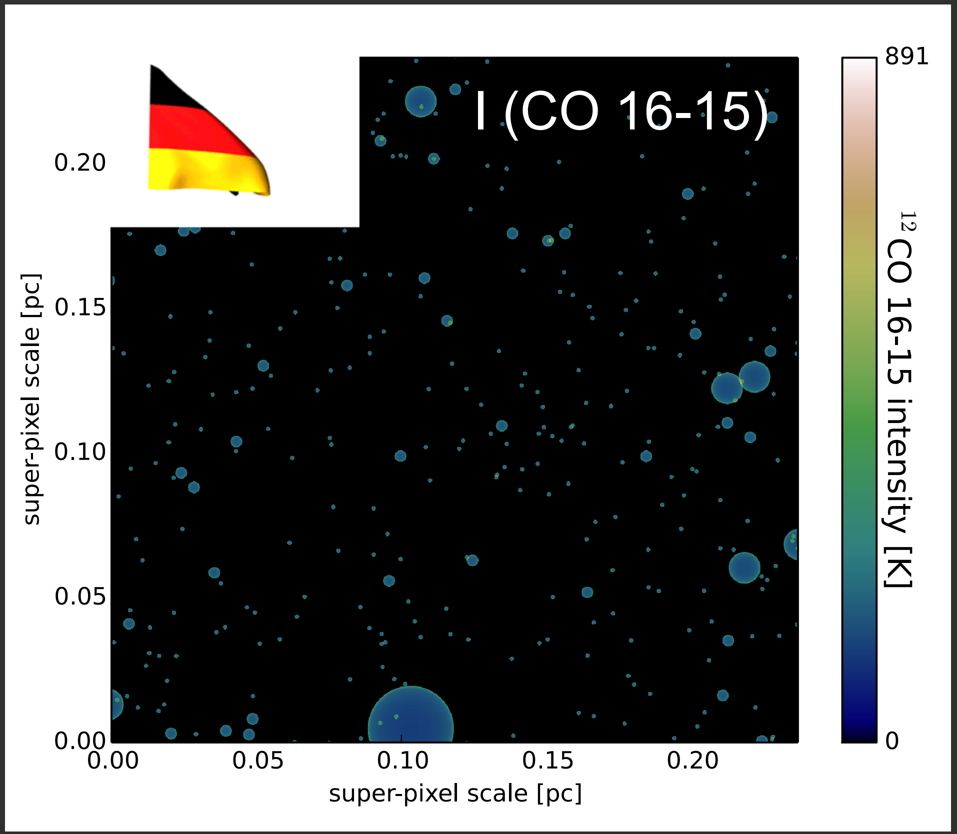
Model fits many H_2, high-J CO, CH^+, OH lines, …

"Isobaric PDR" interpretation

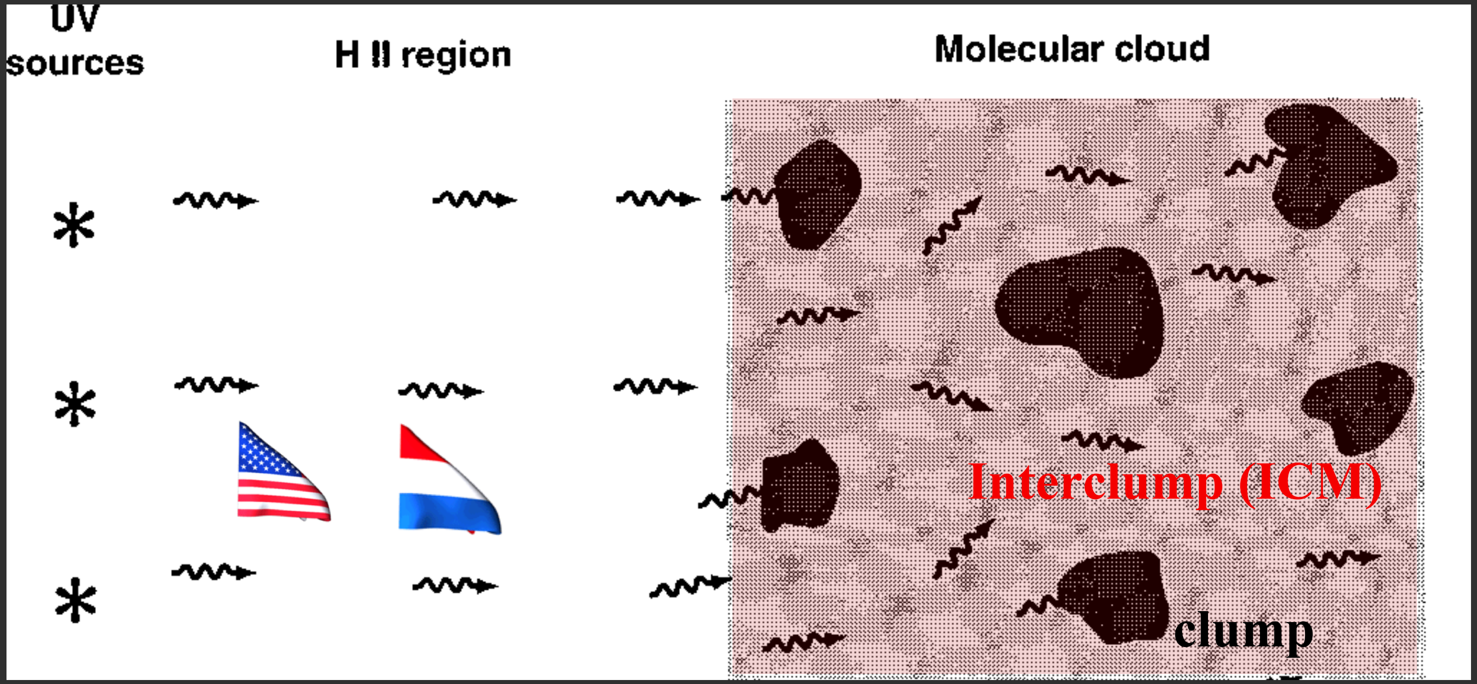
See also Allers +05 for H_2 lines at constant pressure

“Clump + interclump” interpretation

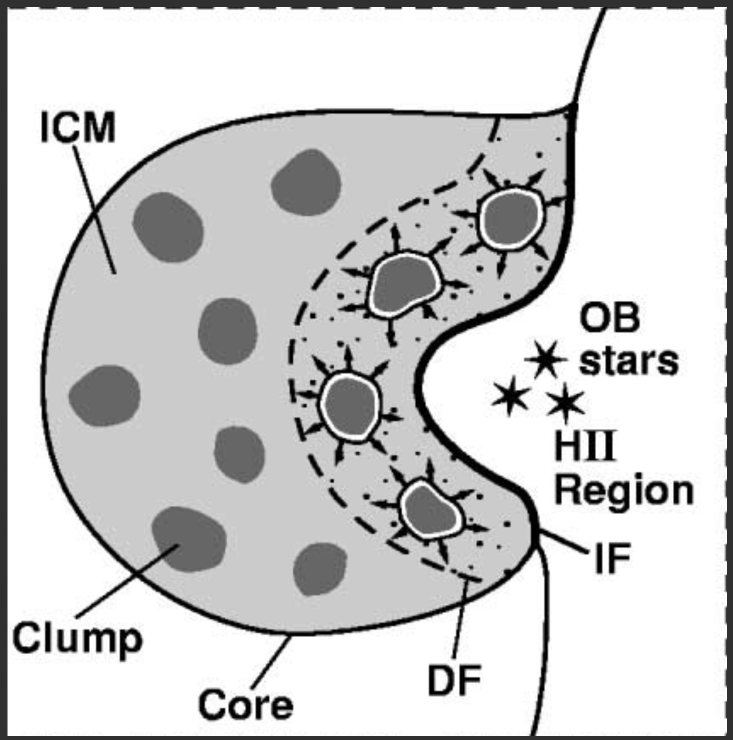
- C^+ … mostly from low density interclump
- High-J CO, … lines from small (mpc) dense clumps



Randomly distributed clumps, fractal ISM
3D stationary-PDR model (**kosma-tau**)
Stutzki+88
Andree-Labsch, Ossenkopf-Okada, Röllig+17



~10% of material is in small & very dense (~10^7 cm^{-3}) clumps
Tauber & Goldsmith 90; Burton +90; Meixner & Tielens 93;
Parmar +91; Hogerheijde+95, Störzer+95; Young-Owl+00 ;
Lis & Schilke 03 …

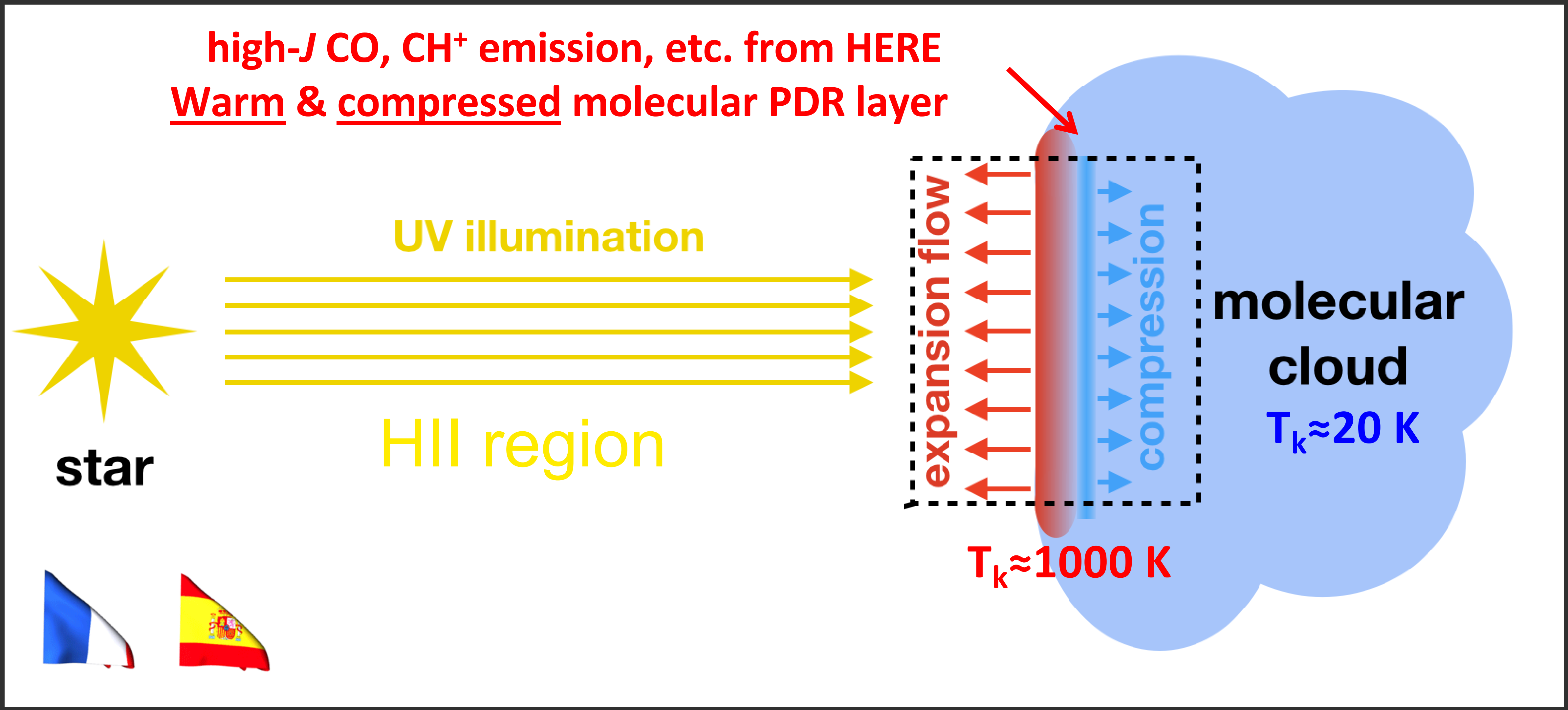


Topology of the ISM ??

Very small (~mpc) clumps can quickly photoevaporate or rocket out
Gorti & Hollenbach+02

Photoevaporating PDRs (dynamic & time-dep.)

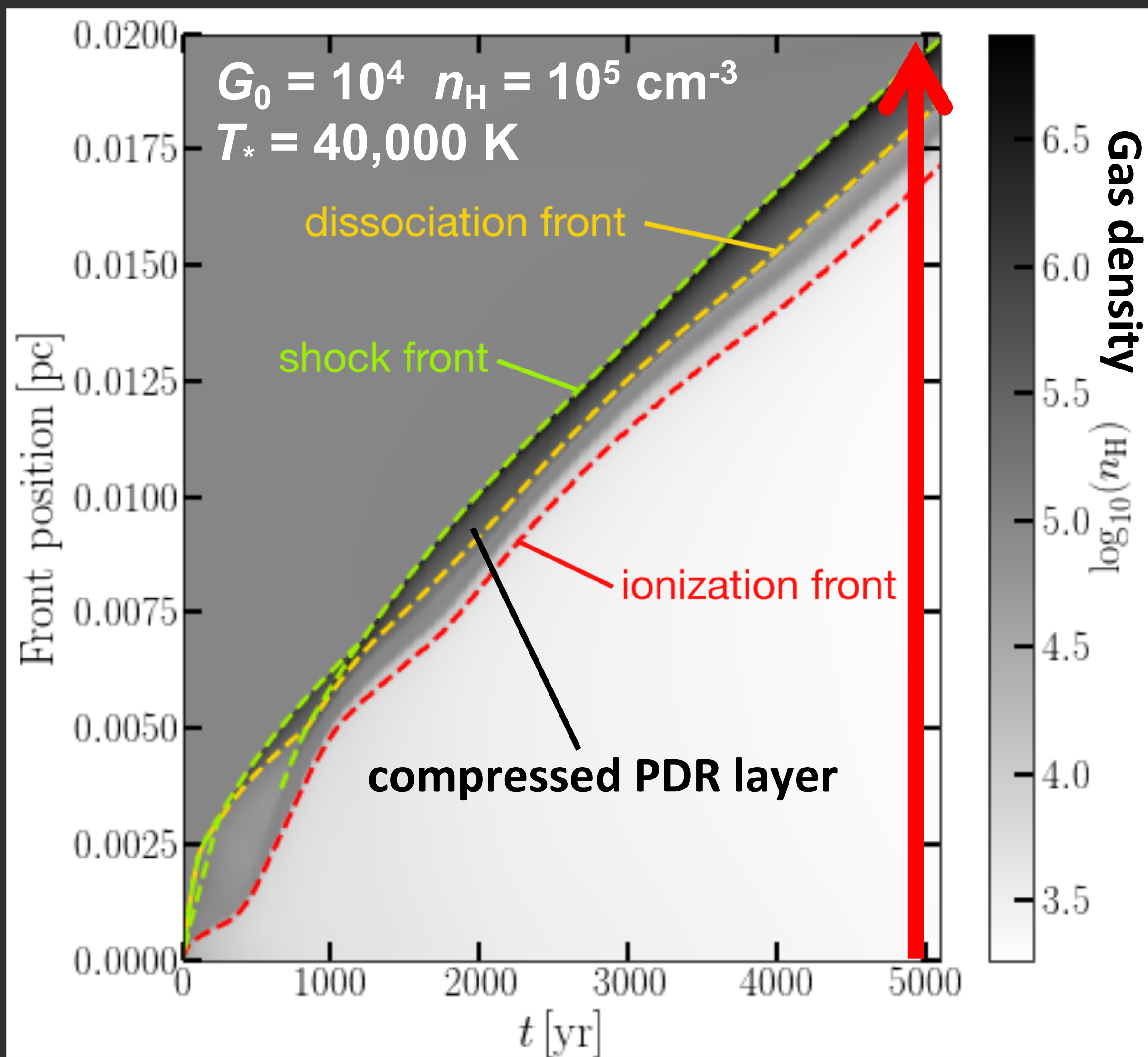
Hydro-PDR model: 1D hydrodynamics, EUV/FUV, **time-dependent** thermo and chemistry



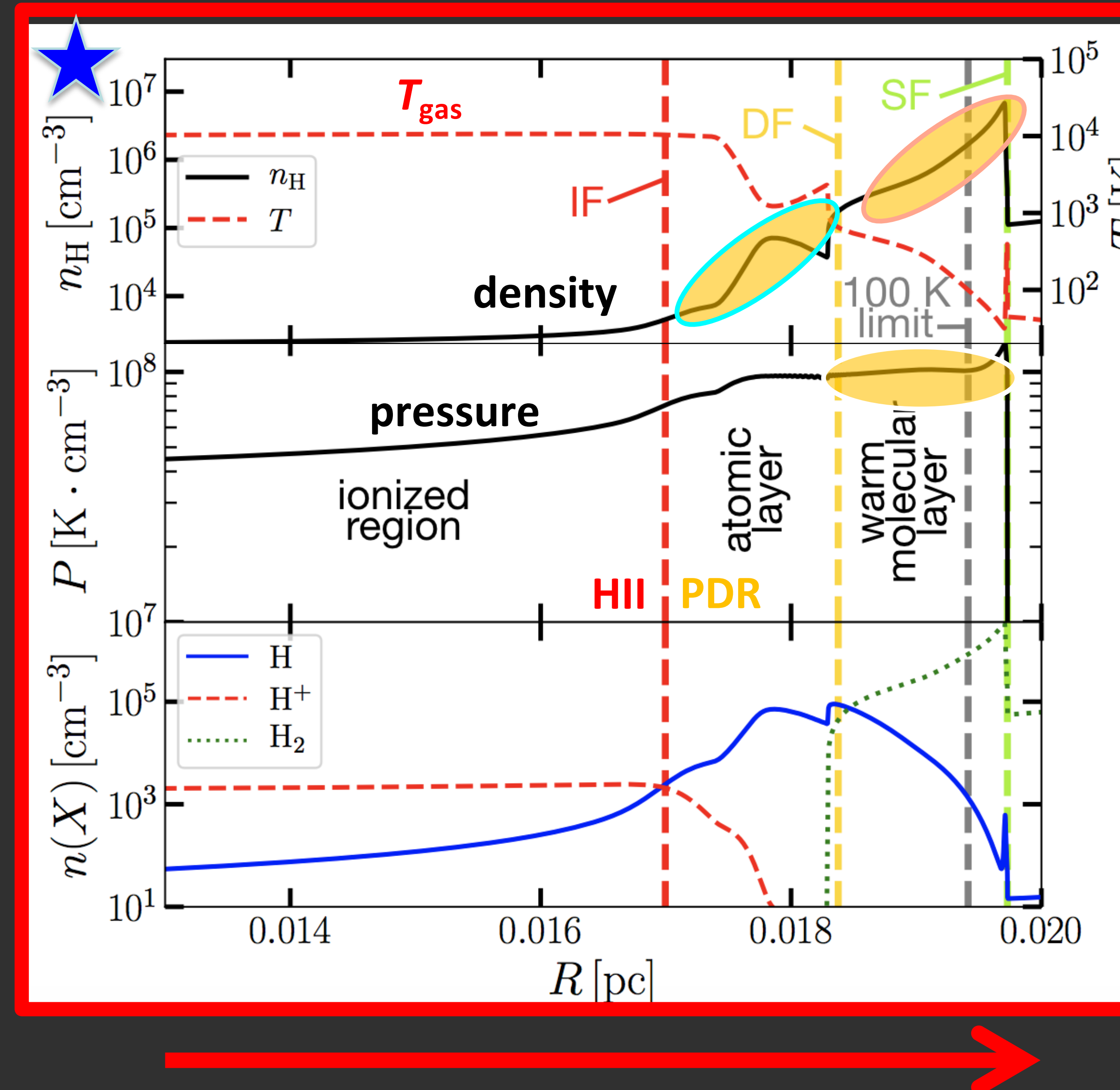
Bron *et al.*, A&A

Previous non-stationary PDR dynamical models:
Bertoldi & Draine 96; Lefloch & Lazareff 94; Storzer & Hollenbach 98; Gorti & Hollenbach 02; Hosokawa & Inutsuka 05, 06; Bisbas +15

Photoevaporating PDRs



Bron+2018



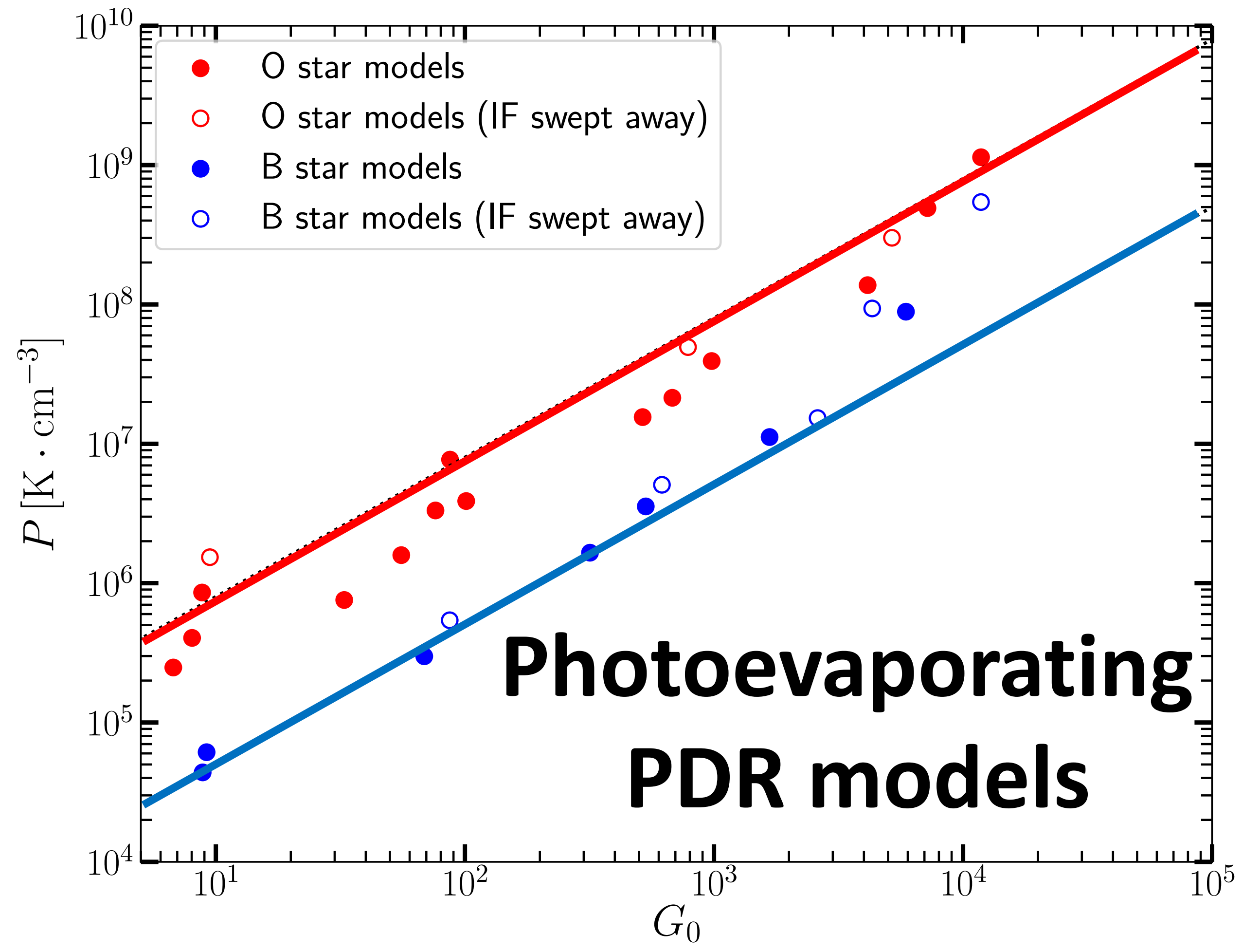
PDR compressed layers are roughly isobaric

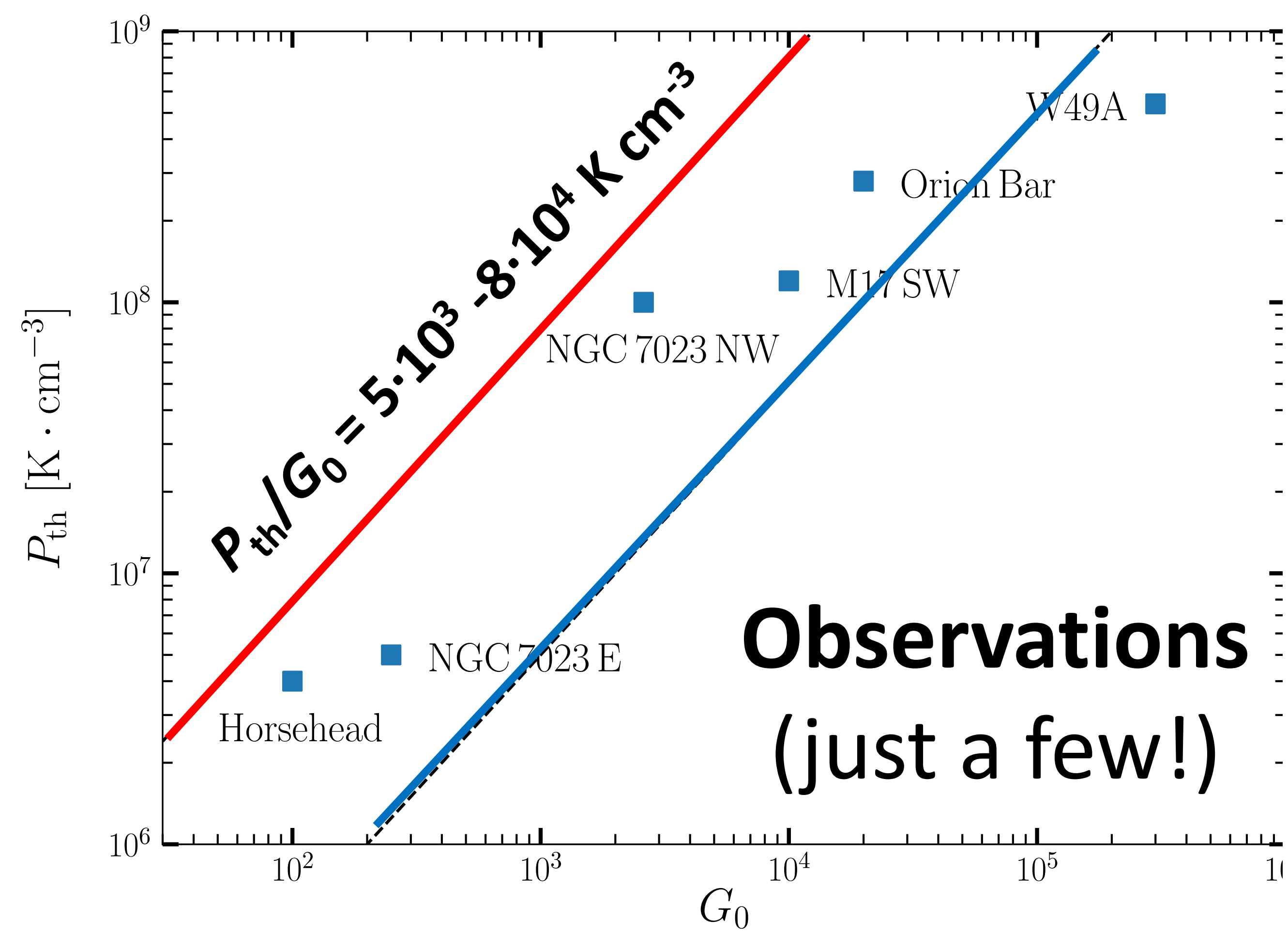
→ 1D Stationary isobaric PDR models do better than "*classical*" constant-density PDR models

Density contrast between atomic (C^+) and compressed molecular layers (high-J CO, CH^+, …) !

→ Don't need to invoke a small clump + interclump scenario of a PDR

Photoevaporating PDR models predict the observed $G_0 - P_{th}$ correlation





Bron+2018,
Predictions from hydro PDR model

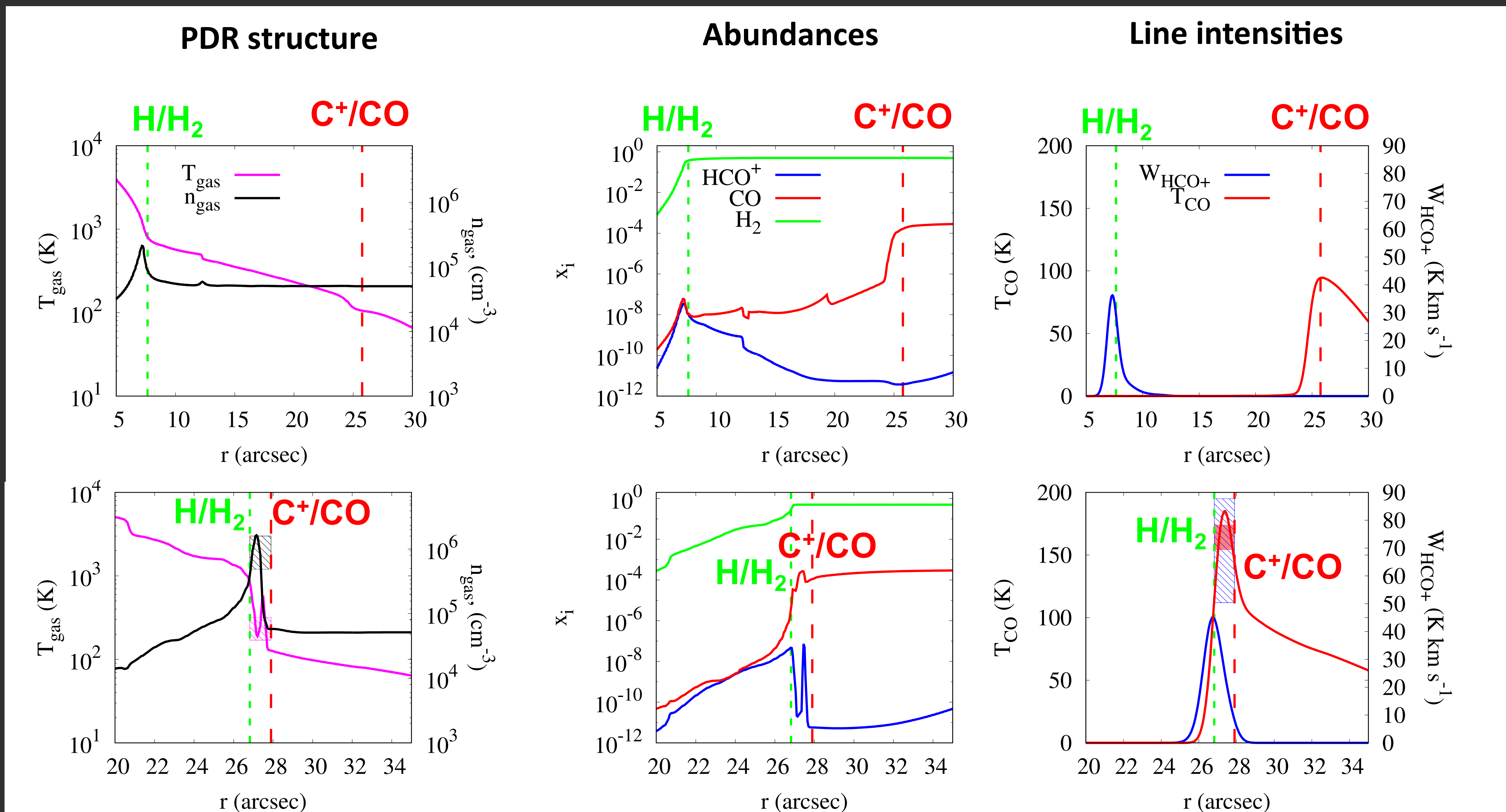
Joblin+2018, Wu+2018
Multi-molecule, multi-line observations of Galactic PDRs

Merged H/H_2 and $C^+/C/CO$ transitions in the Orion Bar

Maria S. Kirsanova[1*], Dmitri S. Wiebe[1]
[1] Institute of Astronomy, Russian Academy of Sciences, 48 Pyatnitskaya St. 119017, Moscow, Russia

MNRAS, 2019

Other recent dynamical-PDR developments…



Early times

Later times

- 1D time-dependent, dynamical, thermo-chemical code (**only FUV**, no EUV)
- FUV heat the gas → **compression and high P_{th} neutral layer**

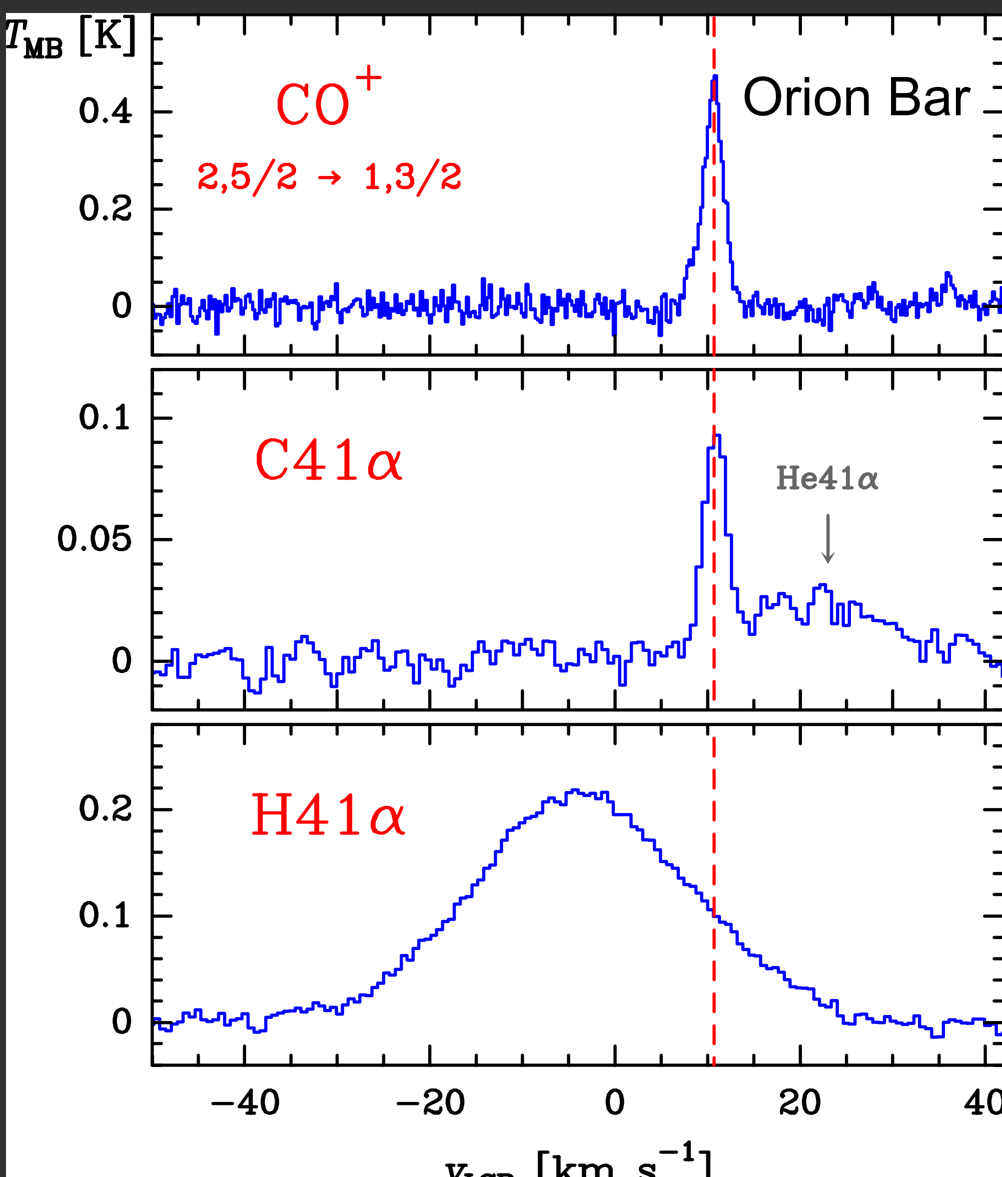
A&A 625, L3 (2019)
https://doi.org/10.1051/0004-6361/201935556

Astronomy & Astrophysics

Letter to the Editor

Direct estimation of electron density in the Orion Bar PDR from mm-wave carbon recombination lines★

S. Cuadrado[1], P. Salas[2], J. R. Goicoechea[1], J. Cernicharo[1], A. G. G. M. Tielens[2], and A. Báez-Rubio[3]



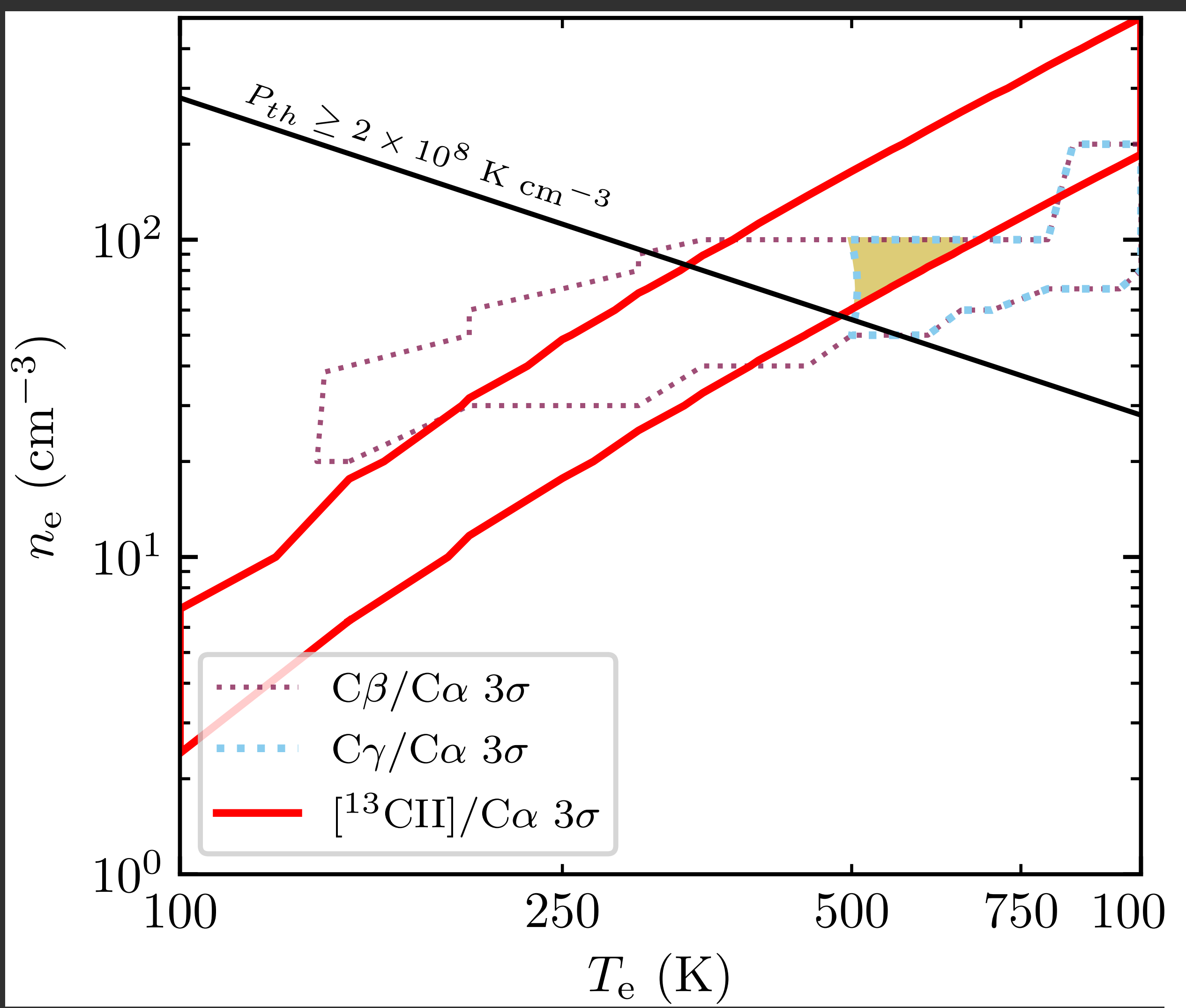
- Narrow line-profiles, as molecular lines → **They arise from the C⁺/C/CO transition and not from the HII region**

IRAM 30m telescope

See also:
Natta, Walmsley, Tielens 94,
Wyrowski +97

Role of electrons   Orion Bar PDR

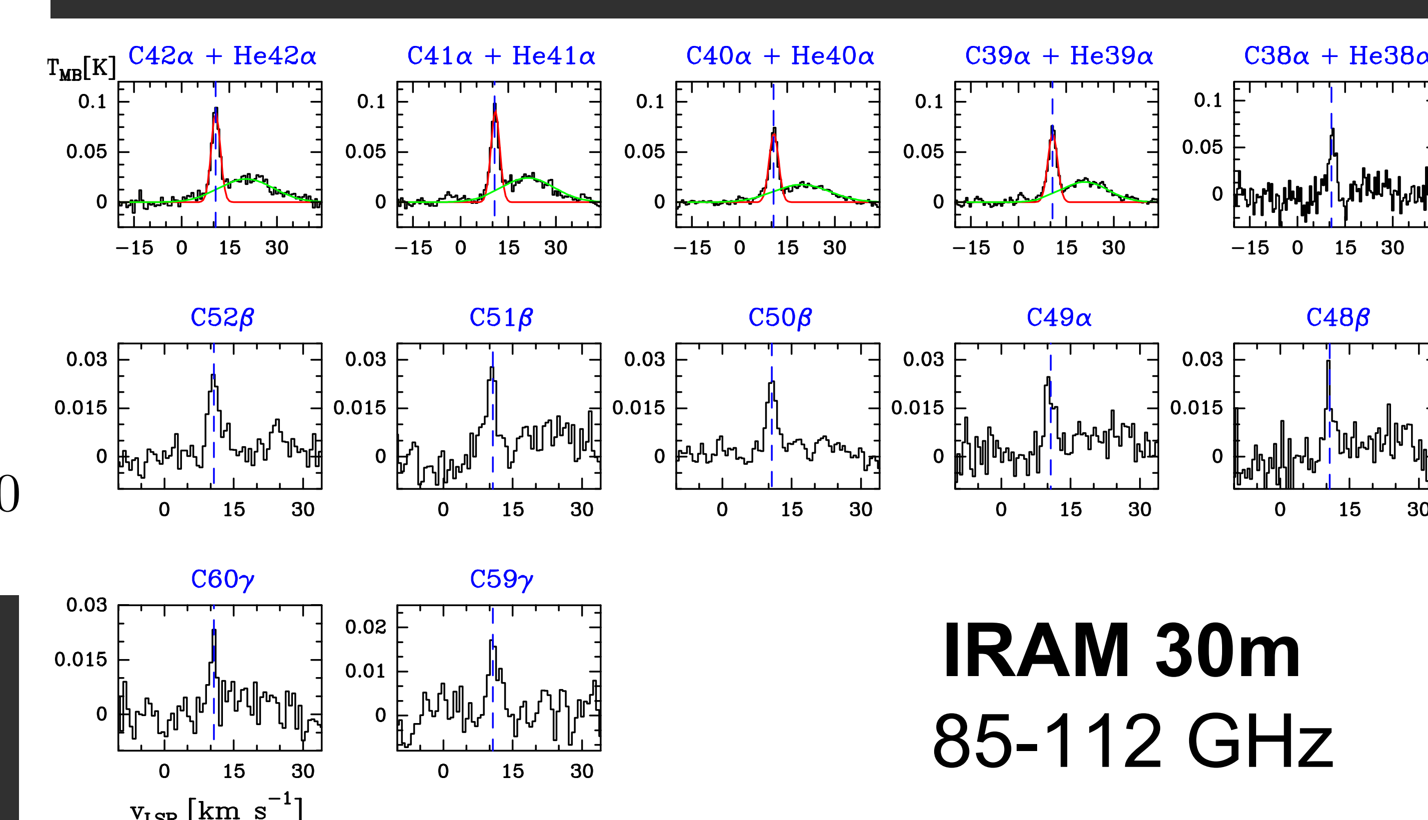
- Excitation models for [^{13}CII]158μm and CRRLs developed in **Leiden** (Salgado +17)
- **n_e = 60-100 cm^{-3}** and **T_e = 500-600 K** toward the H_2 dissociation front position.
- If $x_e \leq x(C^+)$ **= 1.4·10^{-4}** then $P_{th} \geq$ **(2-4)·10^8 cm^{-3} K** without using molecular tracers.



electron densities x10 times higher than previously thought

→ Confirms high P_{th}

→ PDR photoevaporation



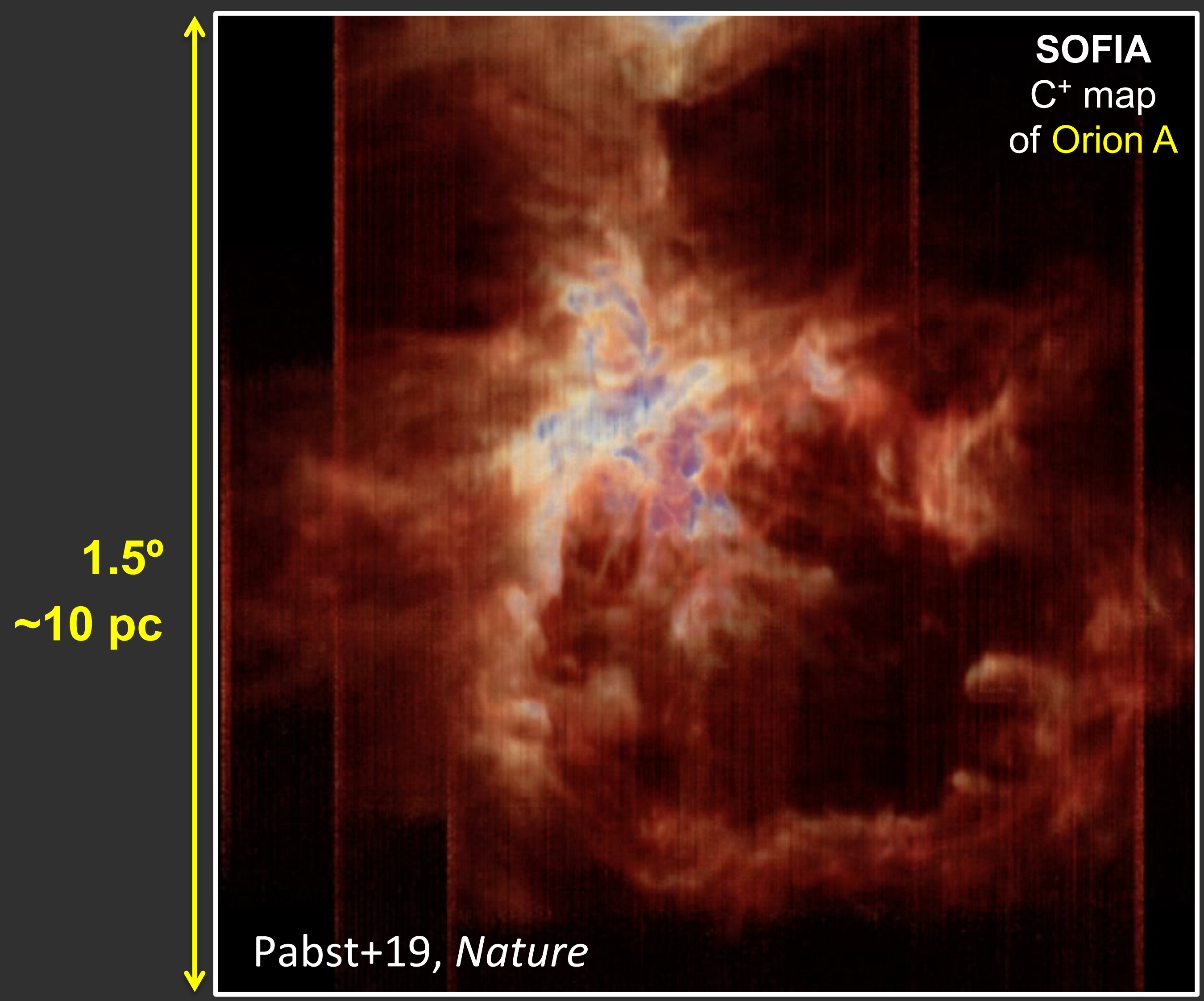
mm-wave carbon recombination lines toward the Bar including (α, β, γ transitions)   Cuadrado +19

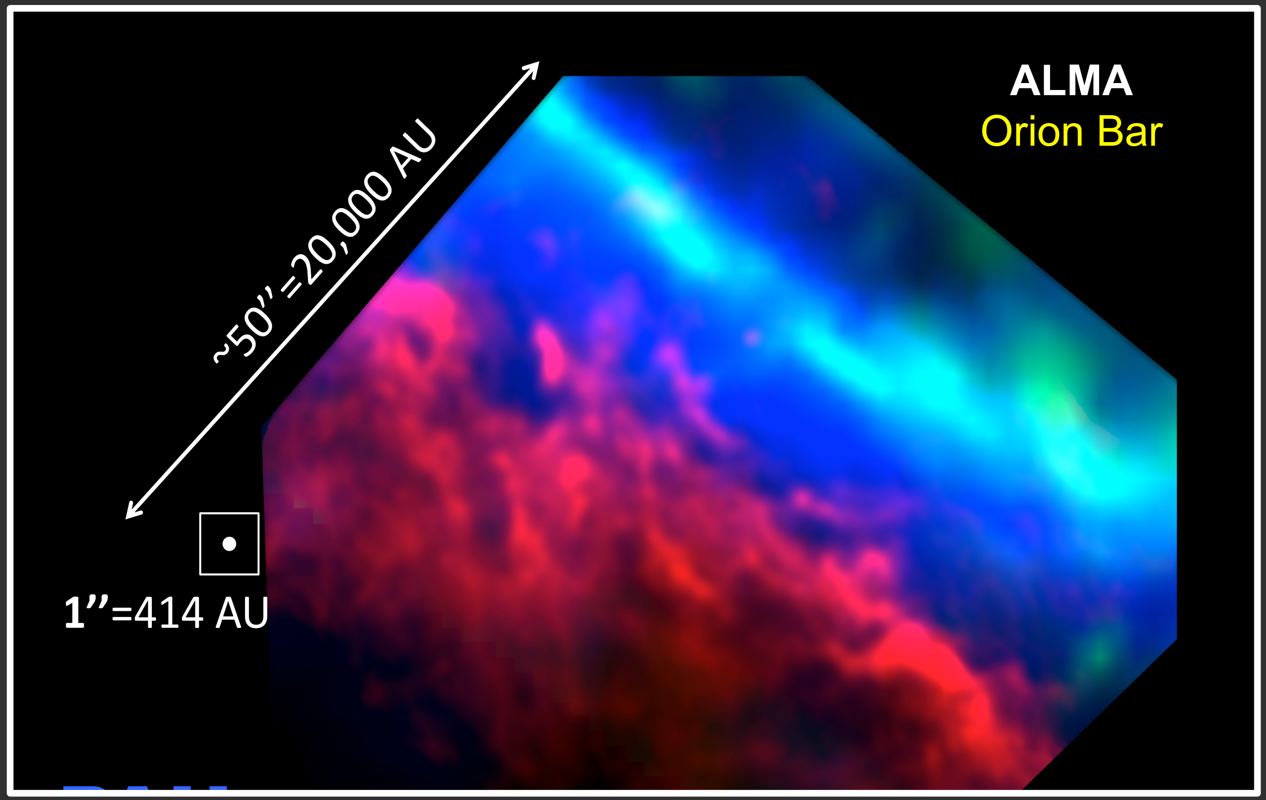
Take home message

- Massive stars drive the evolution of the ISM through **UV, winds & SNe explosions → feedback**

- Stellar FUV radiation heats the neutral gas, induces dynamical effects, and triggers a specific chemistry → **PDRs everywhere, at all spatial scales**

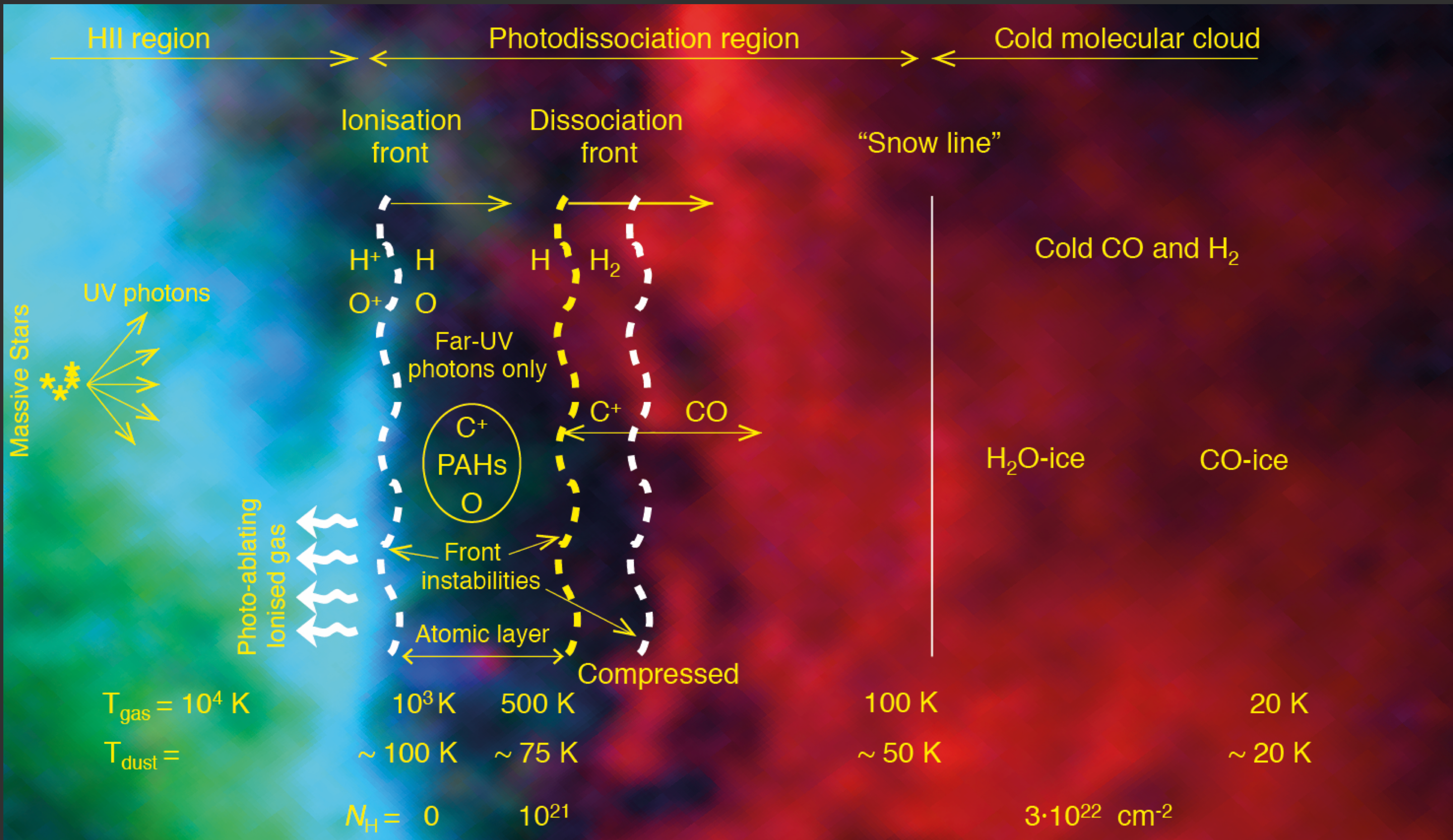
- **Exciting times..** New generation **models** and **observations** (SOFIA, ALMA, JWST, etc.) …





... projects in which Xander will be involved - I suspect.

... as future President of Chile to get ALMA time ??



Goicoechea *et al.* 2016, *Nature*