Spectroscopic tracers of radiative feedback from massive stars in the ISM and protoplanetary disks


The Orion Bar as seen by JWST (ERS-PDRs4All team)

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(with special thanks to **Cornelia Pabst** and **Miram Santa-Maria** for their brilliant PhD work)

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

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CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Outline

Motivation:

- Most stars (thus planets) are formed within stellar clusters that harbor massive stars emitting strong UV radiation and powerful stellar winds.

- Star & Planet formation are not independent of **feedback** processes in GMCs.

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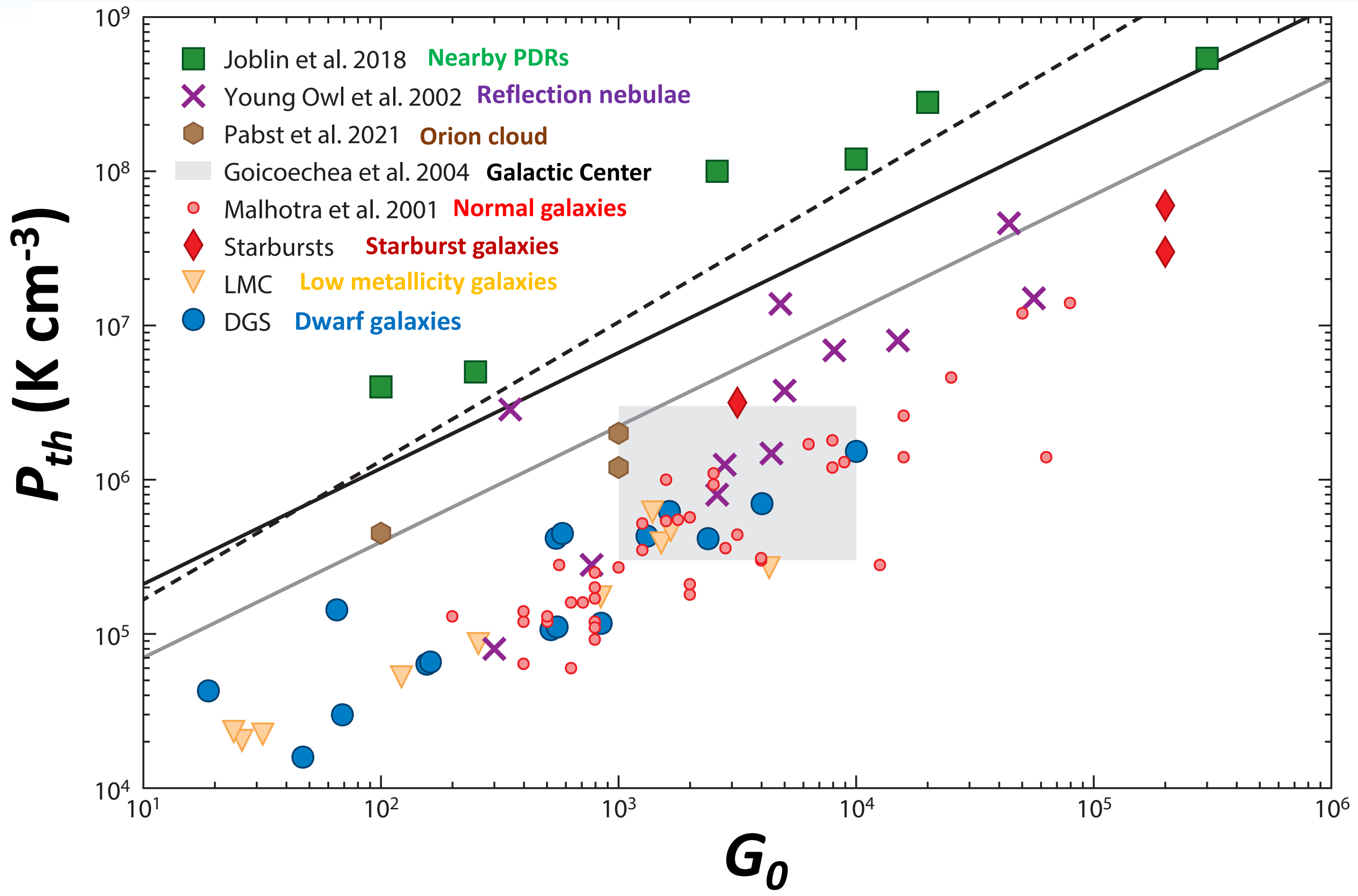
This talk:

1) Radiative feedback at large cloud scales → **line mapping of GMCs** (PDR component)

2) The role of external FUV radiation in protoplanetary disks → **sub-arcsec resolution**

Stellar FUV *vs.* Gas thermal pressure correlation

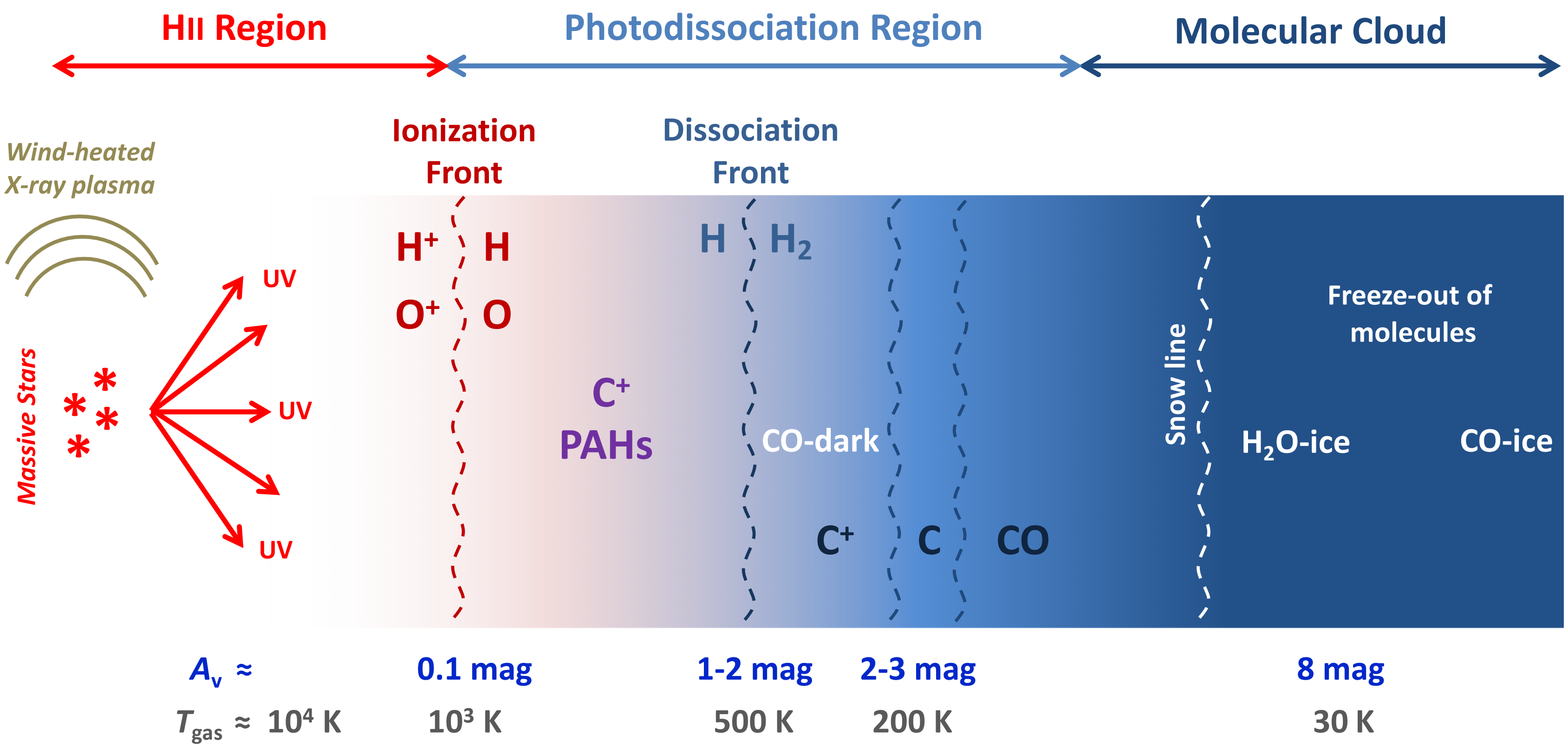


Wolfire+ ARAA, 2022

PDRs, where FUV radiation regulates:

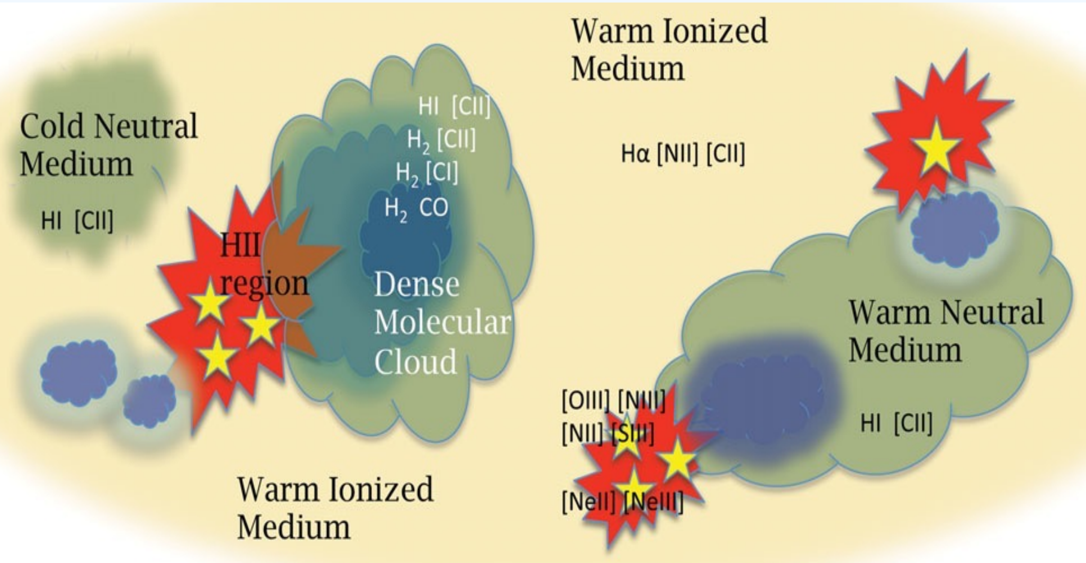
- → **Gas heating**
- → **Chemistry**
- → **Mass-loss** (photoevaporation)
- → **Star & planet formation ??**

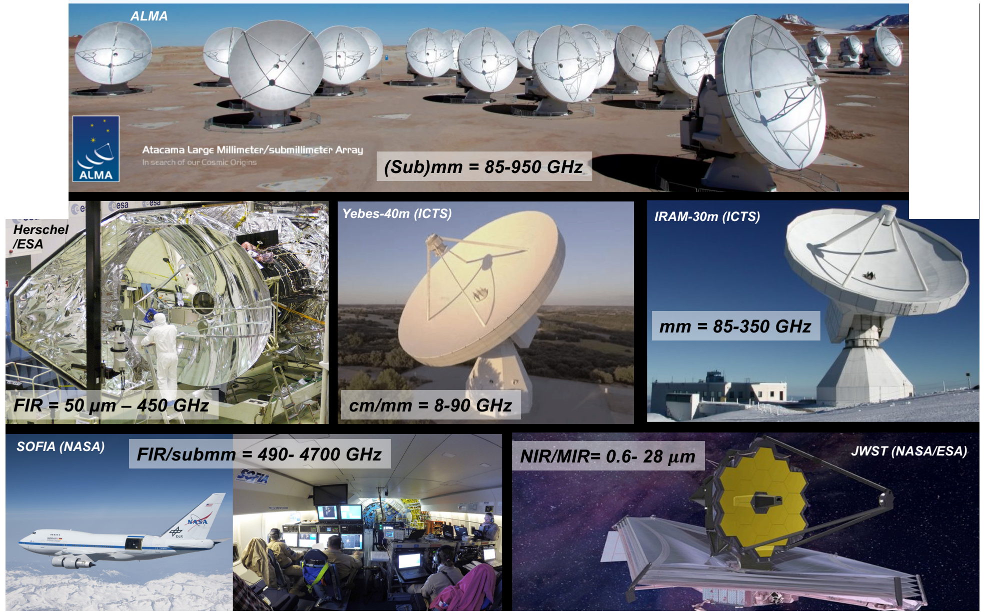
Interaction of FUV radiation & ISM



Goicoechea, Cuadrado, Le Petit 2022

Golden observational era…





Spectroscopic tracers of radiative feedback:

FIR (Herschel, SOFIA) = main coolants of neutral gas → **[CII]158μm**, [OI]63,145μm, …

Submm (SOFIA, ALMA, …) = warm molecular gas → mid-*J* CO, [CI]609,306μm, CH^+ 1-0, …

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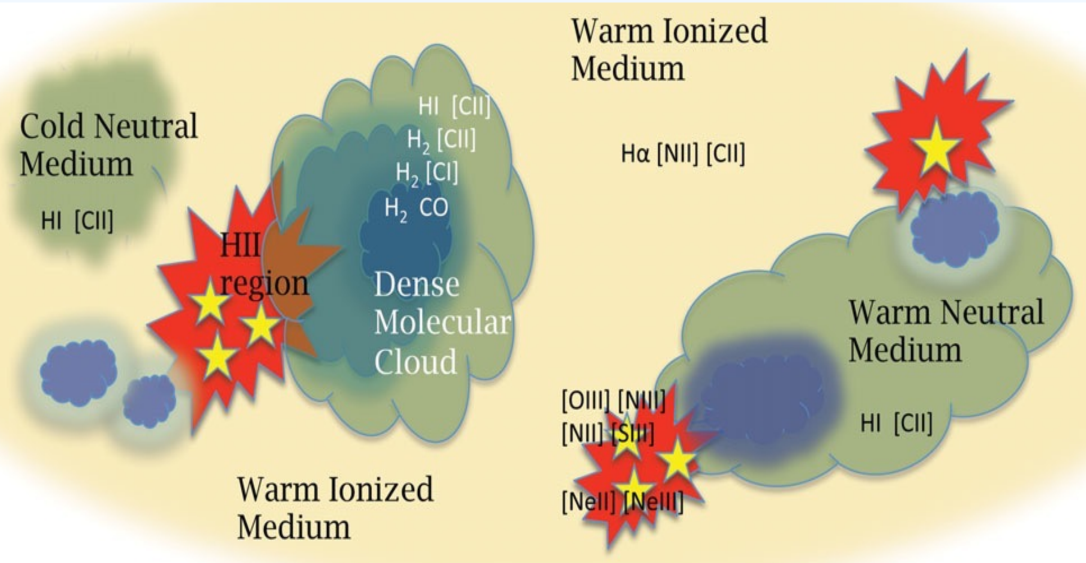

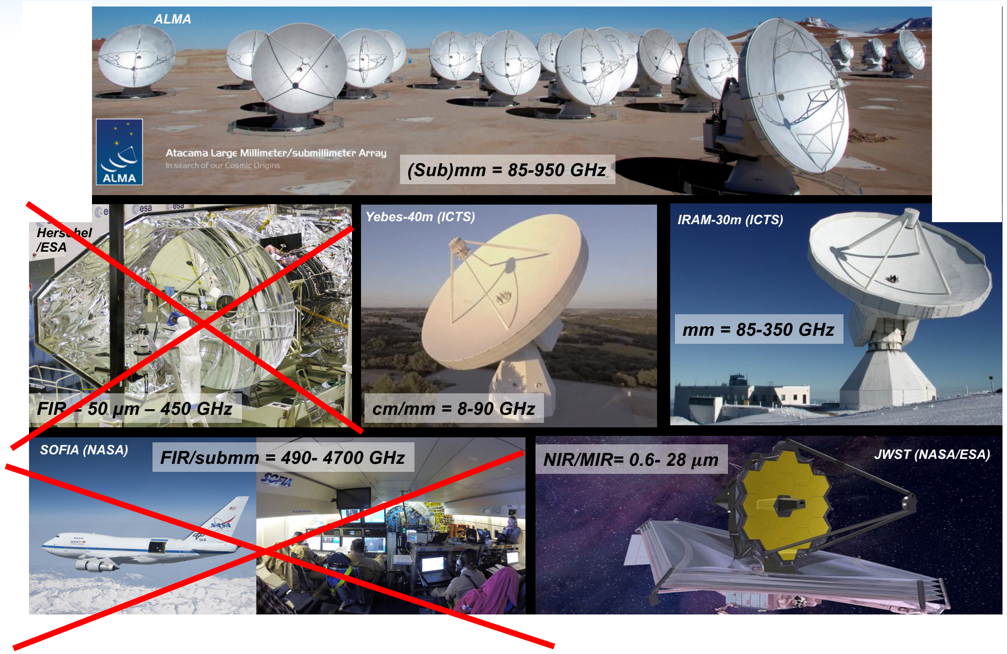

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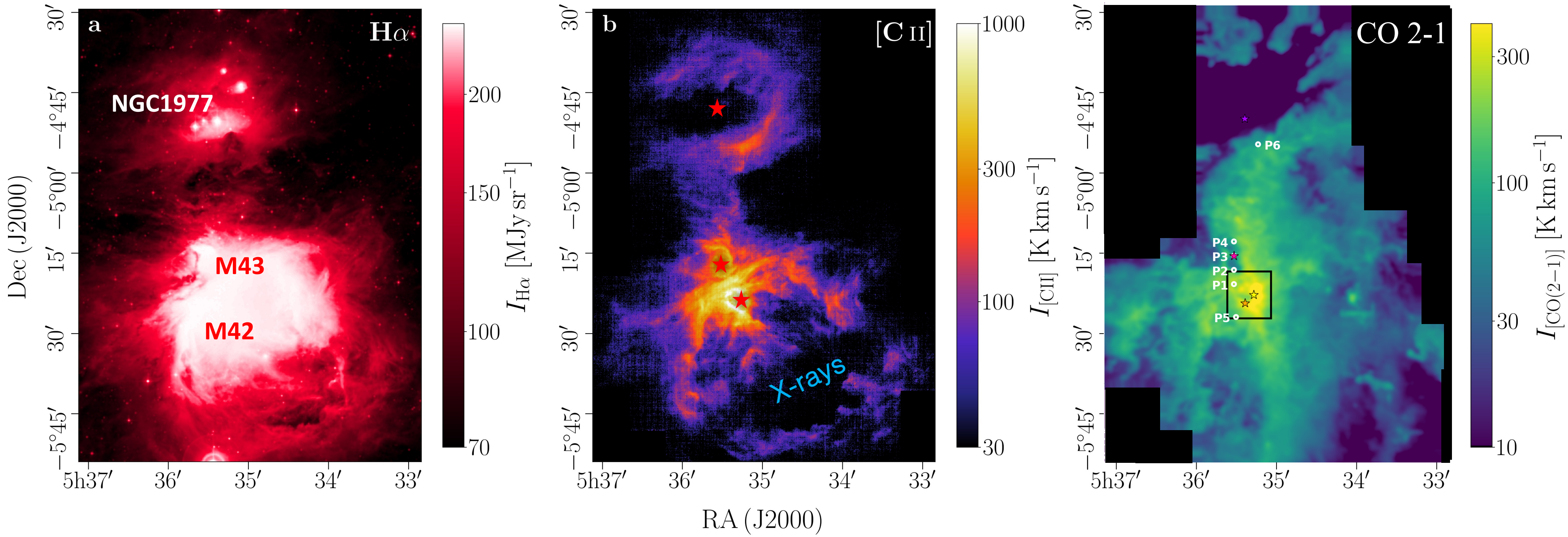
‘**New**’ **tracers** (NIR & radio) → **C^+** & **C^0** with **JWST**, **VLT** (+ **ELT**) and Yebes 40m (+ **SKA**)

[CII]158μm: direct tracer of energy input (FUV or mechanical)

1.2-deg² (~62 pc²) maps of Orion A



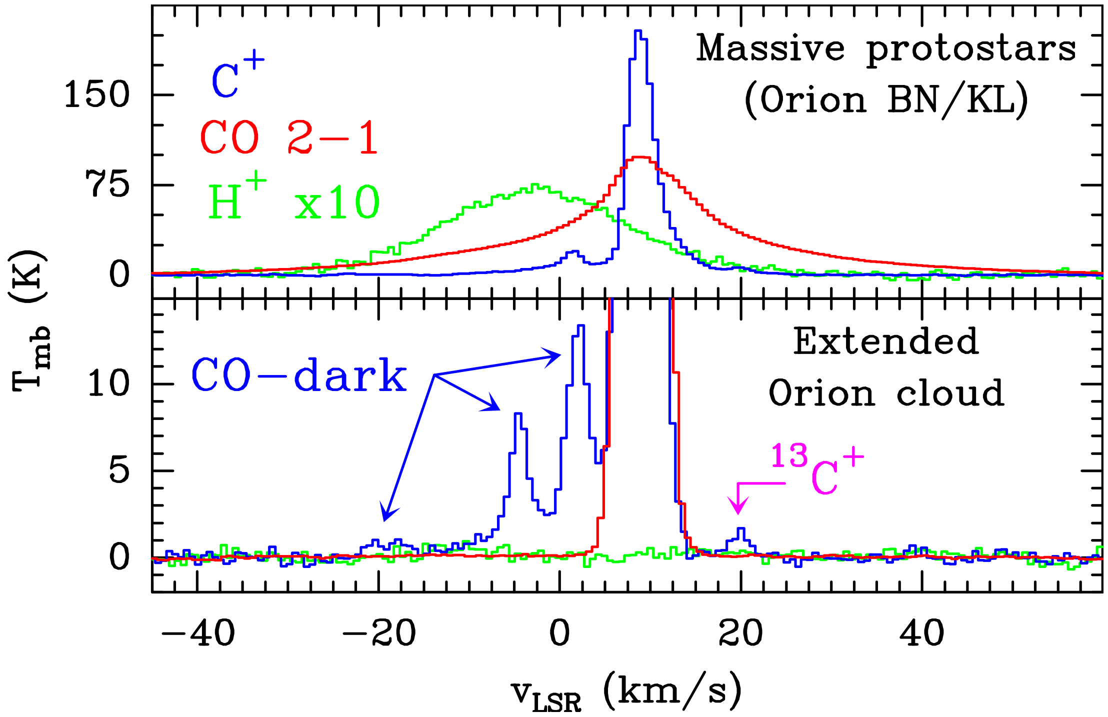
Ionized gas from HII regions
H alpha @ optical

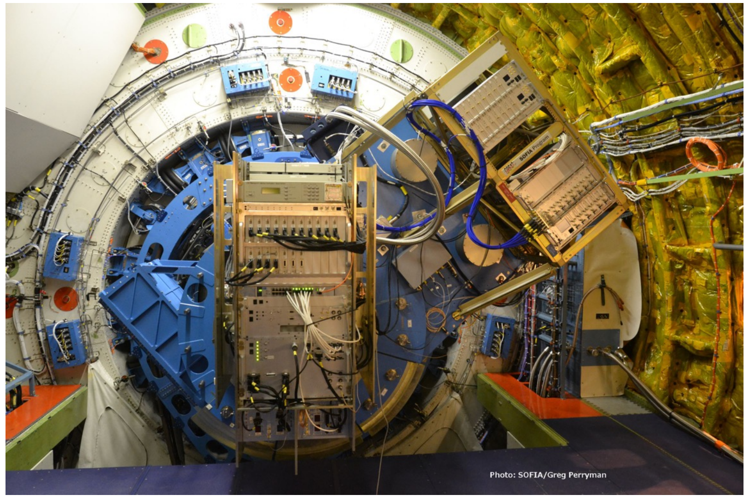
[CII]158μm from "PDR gas"
SOFIA/upGREAT @ 16'' res.
~ 2 million spectra

CO 2-1 from molecular cloud
IRAM 30m @ 11'' res.

SOFIA C+ SQUAD (Tielens et al.) and IRAM30m Large Programs (Goicoechea et al.)

Velocity-resolved [CII]158μm line maps measure the kinematics and energetics of gas disrupted by stellar feedback





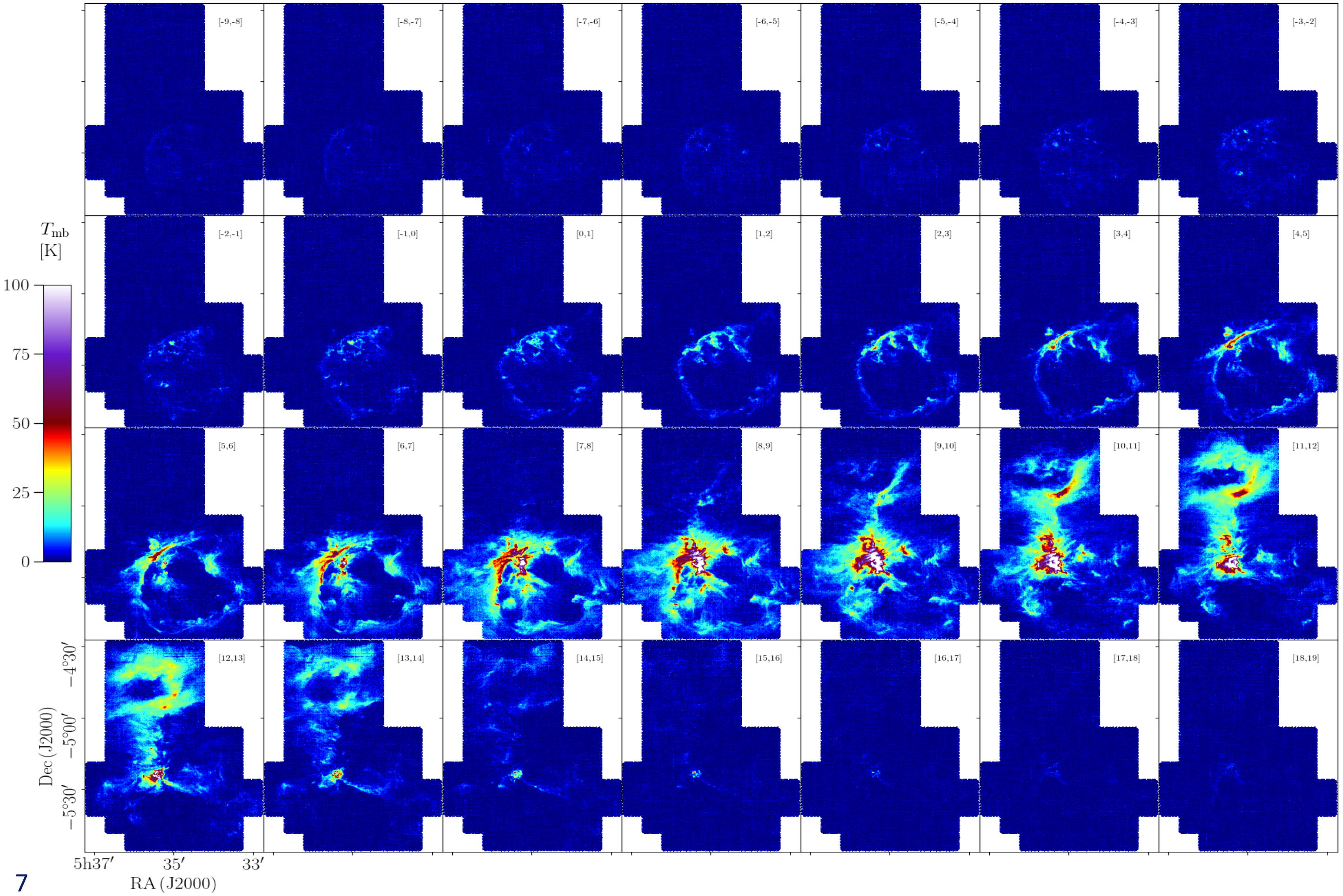
“Velocity-resolved” spectroscopy with SOFIA/UPGRATE

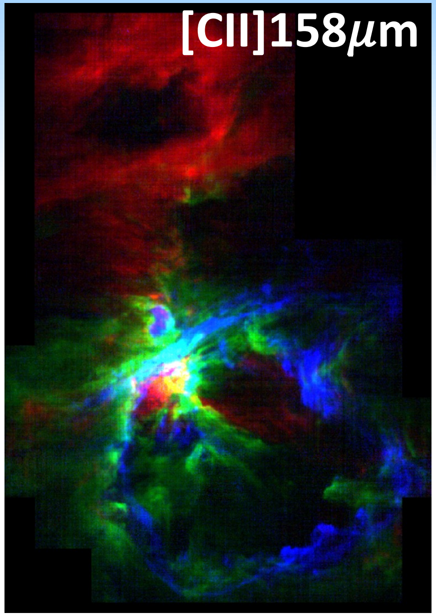
SOFIA C+ SQUAD papers:

Pabst+2019,+2020,+2021+2022
Goicoechea +2020
Higgins+2021; Kavak+2022a,b

Shells and bubbles in Orion A …

[CII]158μm





The physics is in the velocities

Pabst+ *Nature*, 2019,+2020,+2021
Higgins+2021; Kavak + 2022ab

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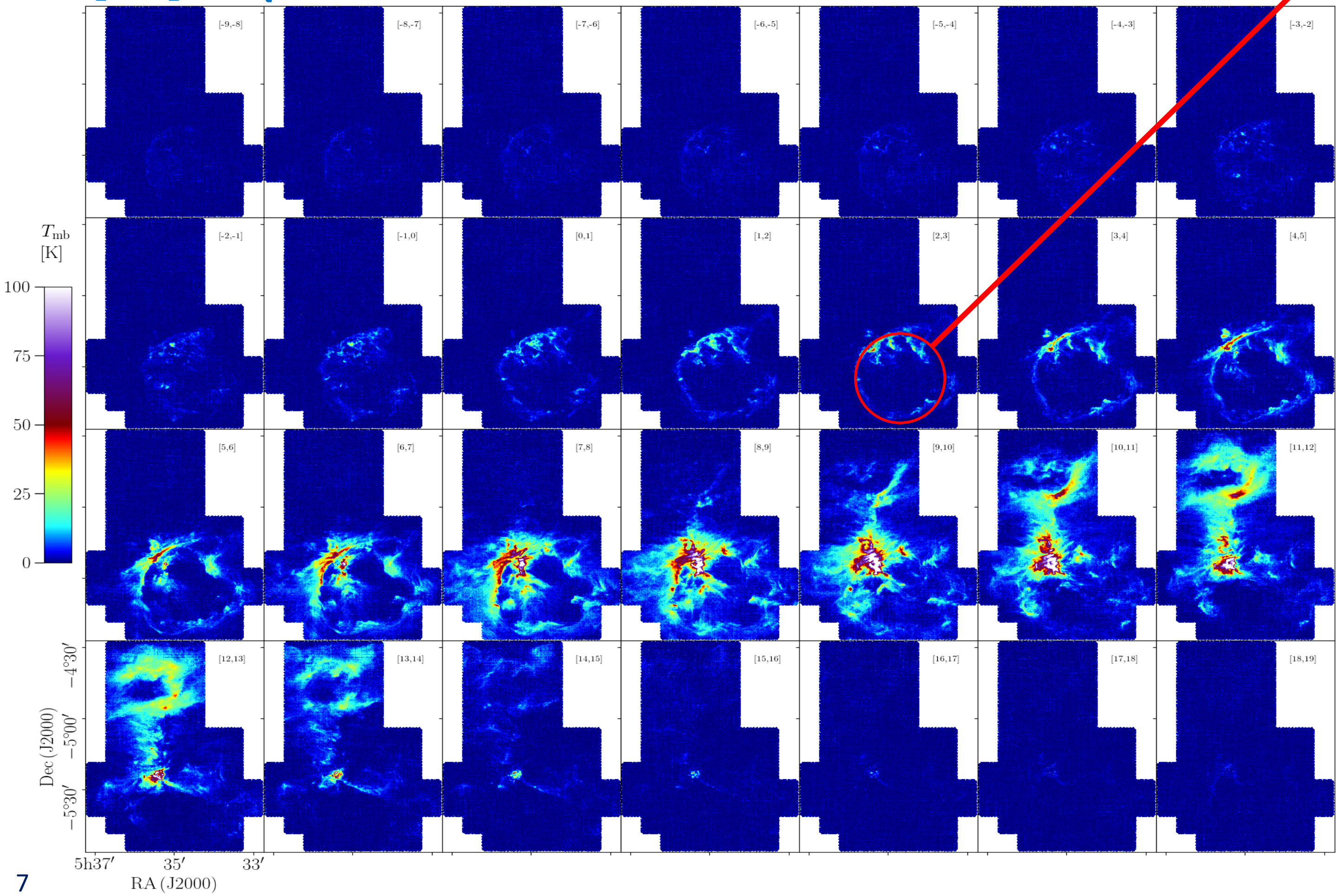


M42: “half" shell expanding @ 13 km/s, R~2.7 pc, age ~0.2 Myr
→ seen in C^+ (not in CO) **!**

radius ~2.7 pc, ~ 1500 $M_{\rm Sun}$
(swept-up gas disrupted from the molecular cloud)

The physics is in the velocities

Pabst+ *Nature*, 2019,+2020,+2021
Higgins+2021; Kavak + 2022ab

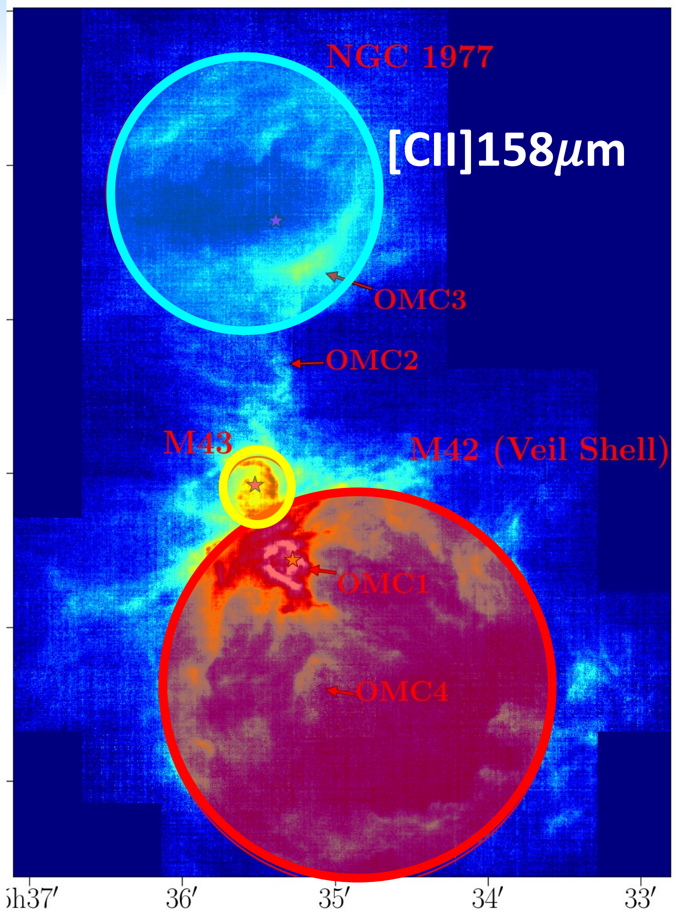
Shells and bubbles in Orion A ...

Bubble:	M 42 (Veil shell)	M 43	NGC 1977
$\mathbb{N}_{\text{Lyc}}$ [10^{47} s^{-1}]	70	1.5	1
L_{w} [$L_\odot$]	400	$\sim 1.5 \times 10^{-2}$	$\sim 1.5 \times 10^{-2}$
Mass of neutral gas [$M_\odot$]	1500	7	700
Mass of ionized gas [$M_\odot$]	24	0.3	16
E_{kin} of neutral gas [10^{46} erg]	250	0.3	2
E_{kin} of ionized gas [10^{46} erg]	6	–	–
E_{th} of ionized gas [10^{46} erg]	3	0.7	5
E_{th} of hot gas [10^{46} erg]	10	–	–
L_{FIR} [$L_\odot$]	3.2×10^4	8.5×10^3	1.5×10^4
$L_{\text{[C II]}}$ [$L_\odot$]	170	24	140

C^+ 13 km/s 6 km/s 1.5 km/s

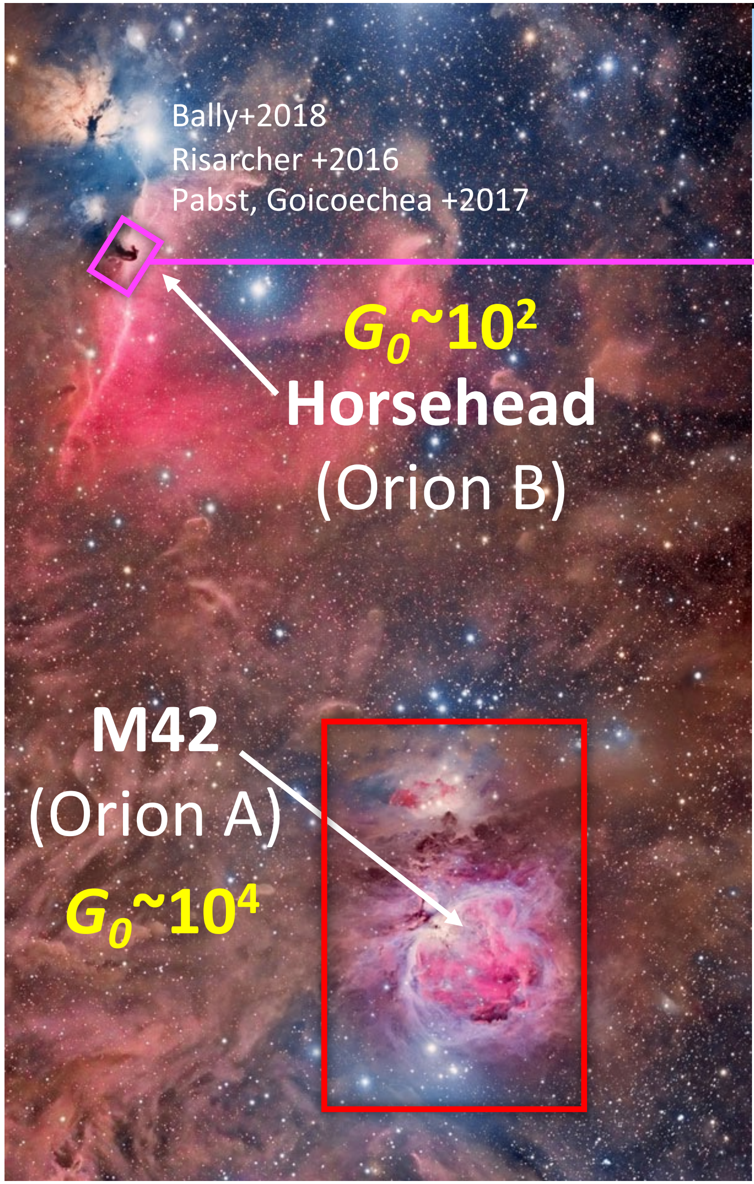
Stellar wind-driven
(**theta[1] Ori C**, O7-type star)

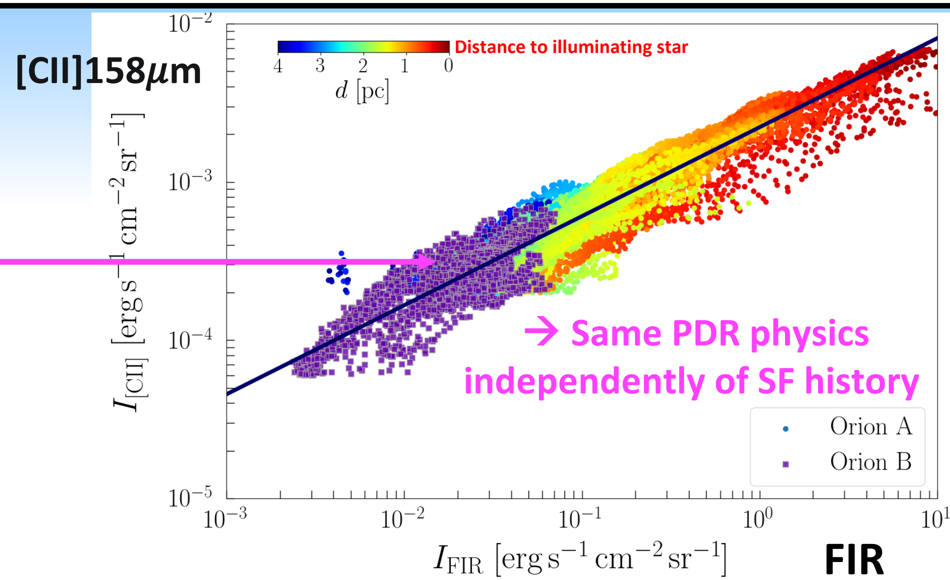
Thermal expansion
of ionized gas in HII region
(**NU Ori**, B0.5-type star, M43)
(**42 Ori** B1-type star NGC 1977)



See talks by Cornelia, Xander, etc.

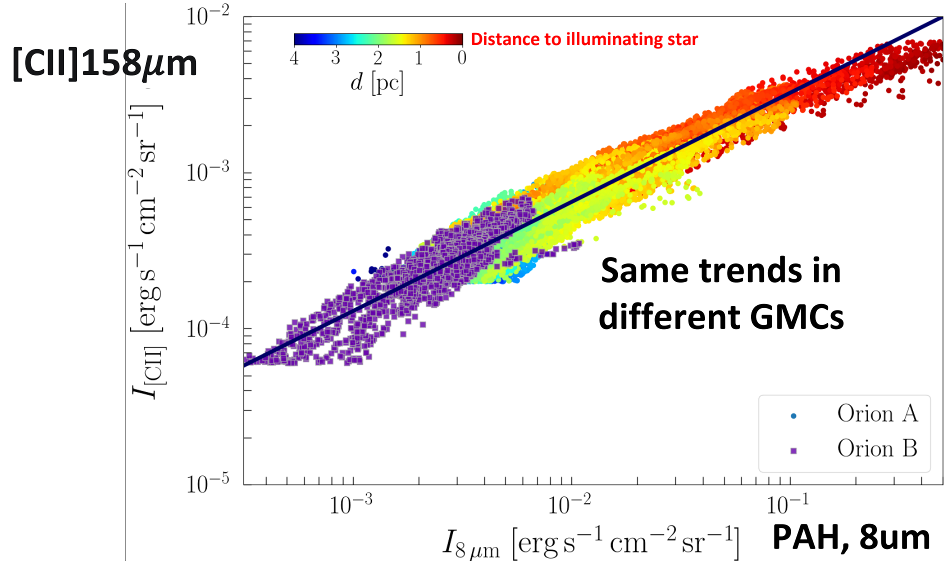
Pabst+2019,+2020,+2021,+2022





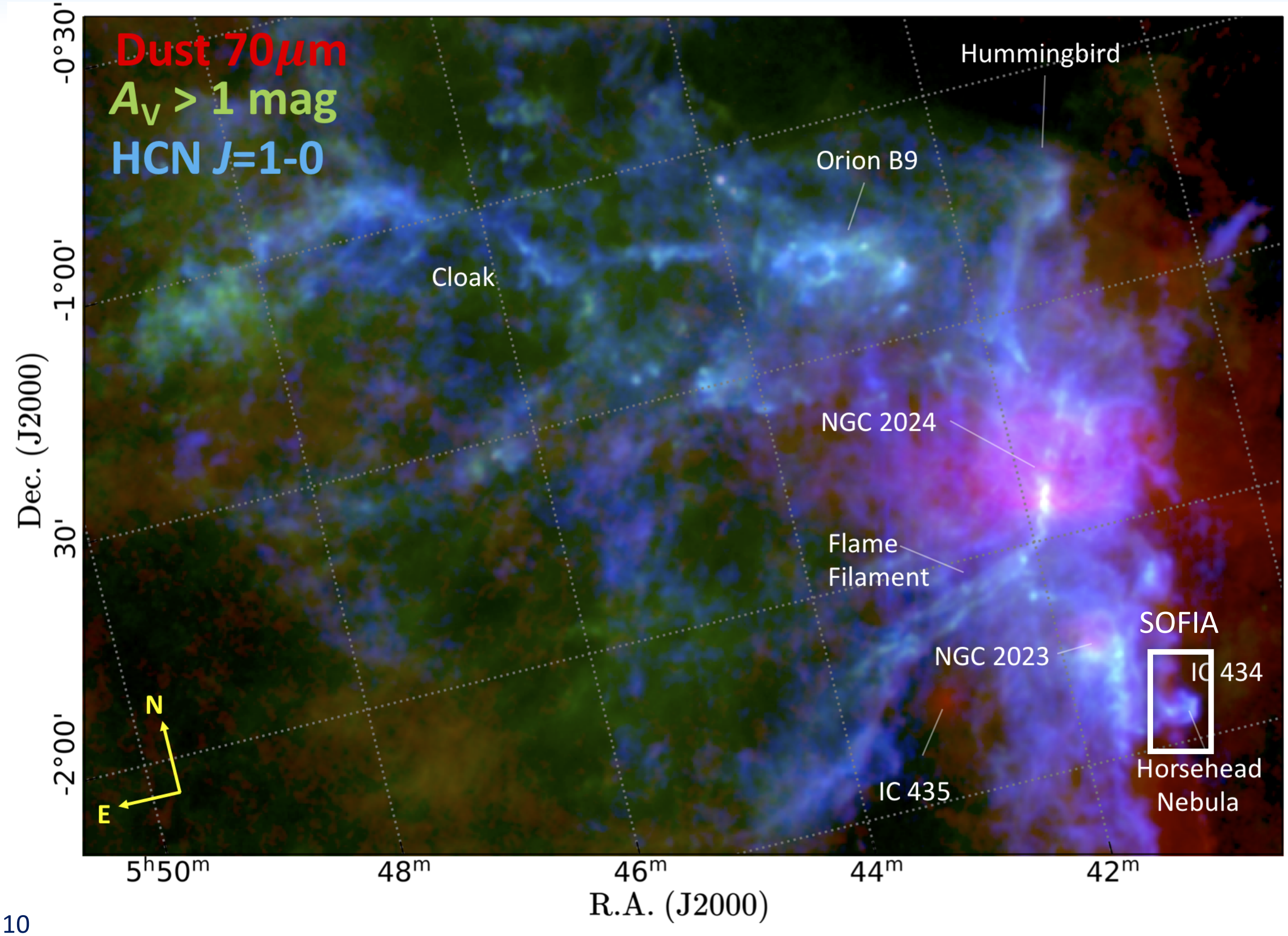
Pabst +2021

Less than linear



Less than linear

5-sq degree line maps of Orion B GMC (250 pc^2)



~ 20 molecules @ 30'' res.

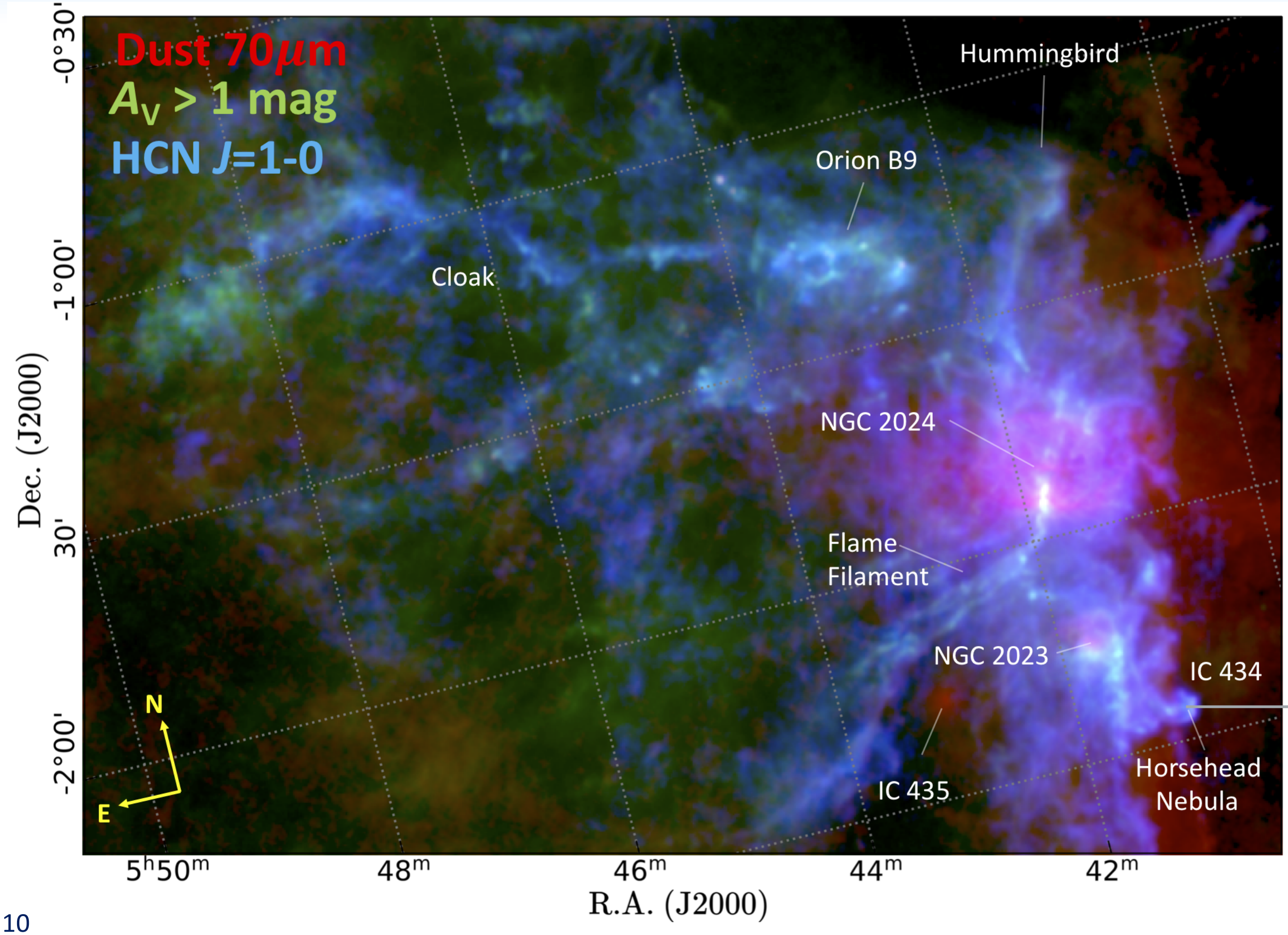
Largest velocity-resolved line maps ever taken with the IRAM 30m telescope

~ 850h (single-beam)

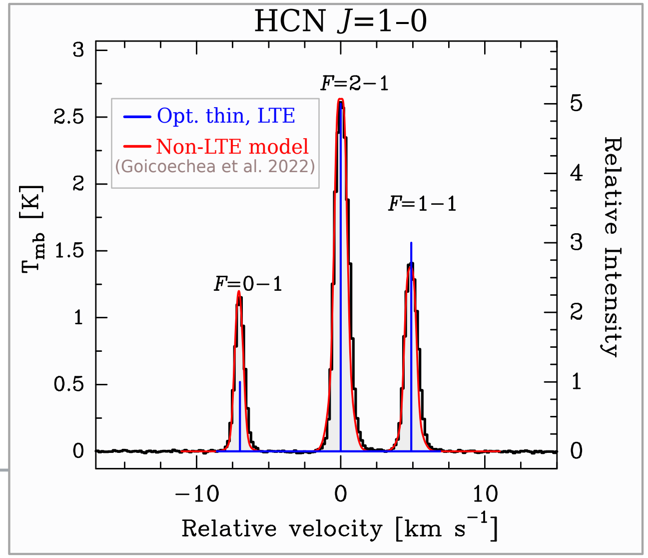
PI: Dr. Jerome Pety (IRAM, Obs. Paris)
Dr. Maryvonne Gerin (LERMA/Obs. Paris)

Santa-Maria, Goicoechea +2023

5-sq degree line maps of Orion B GMC (250 pc^2)



~30 % of *L*(HCN 1-0) from gas at A_V > 8 mag



Santa-Maria, Goicoechea +2023

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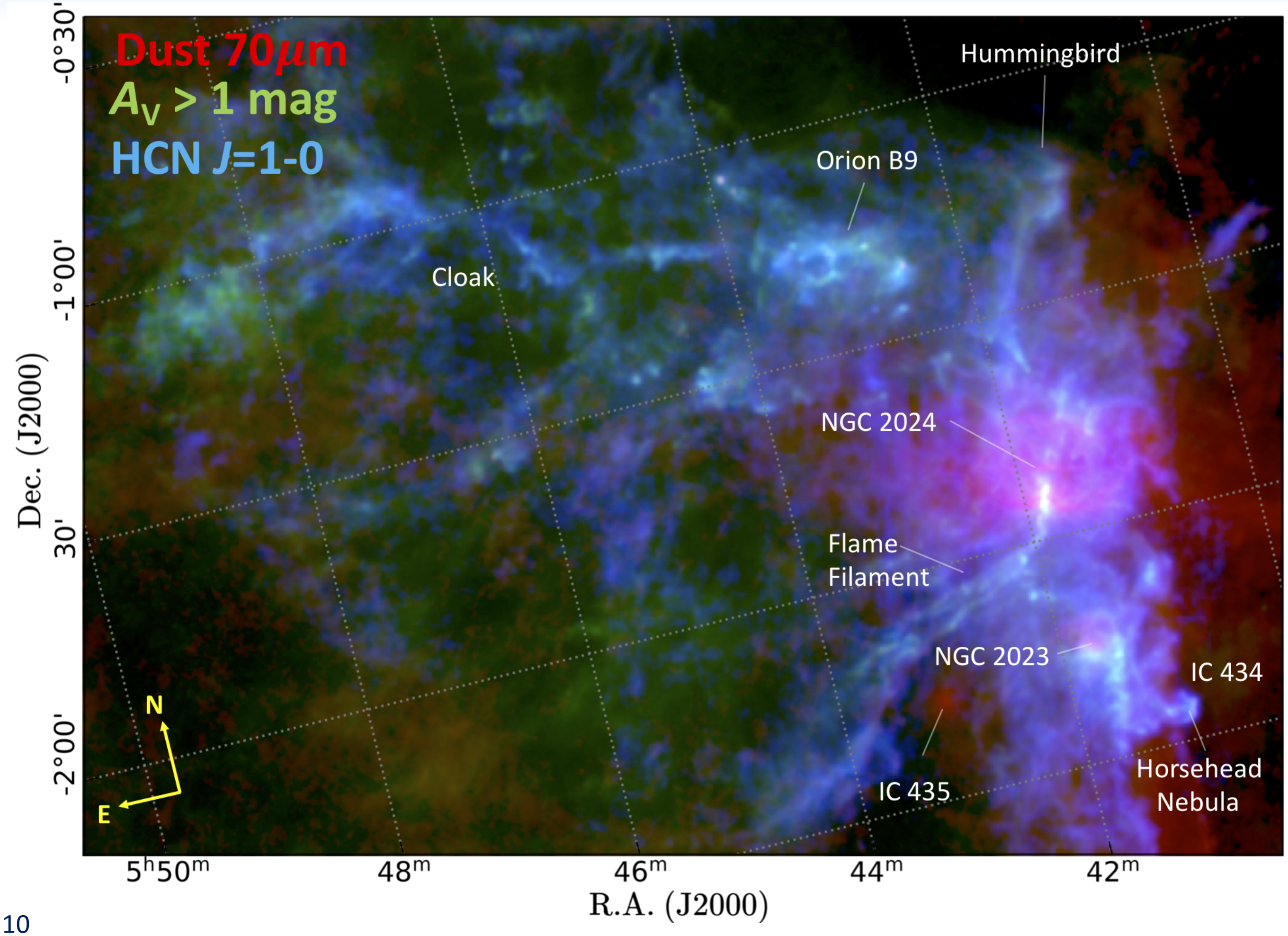


~30 % of L(HCN 1-0) from gas at A_V > 8 mag

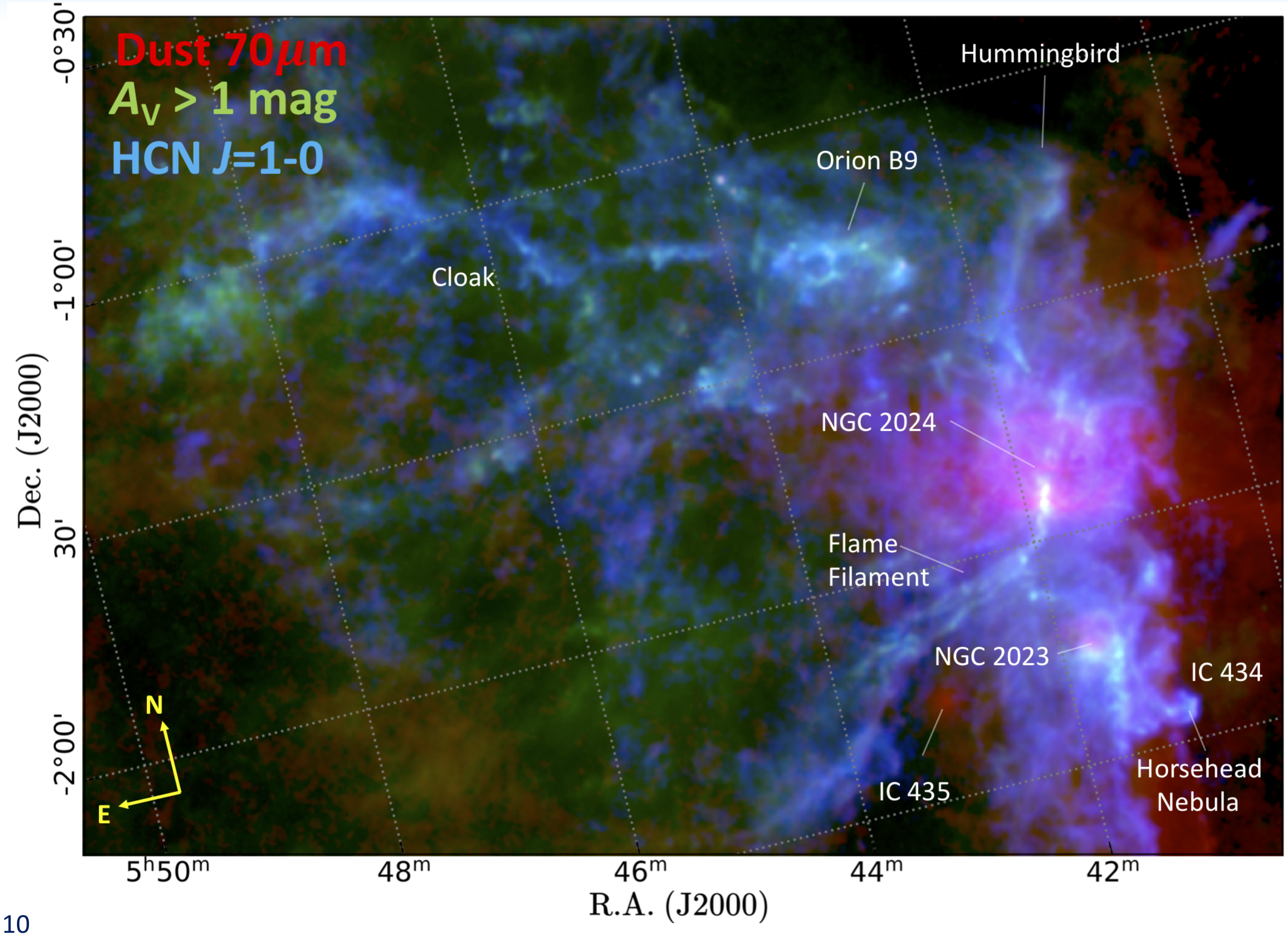
~70 % of L(HCN 1-0) from faint but very extended & FUV-illuminated translucent gas

n_{H2} ~ several 10^3 cm^{-3}

(from non-LTE models including HFS line overlaps and electron excitation; Goicoechea +2022)

Santa-Maria, Goicoechea +2023

5-sq degree line maps of Orion B GMC (250 pc^2)



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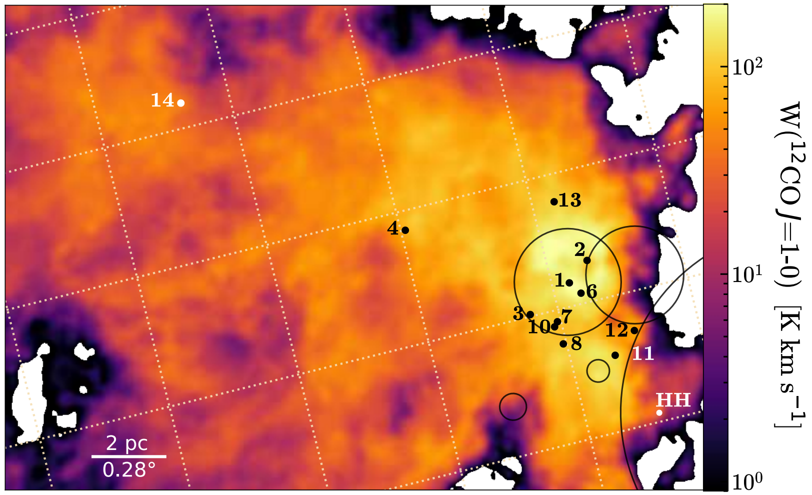
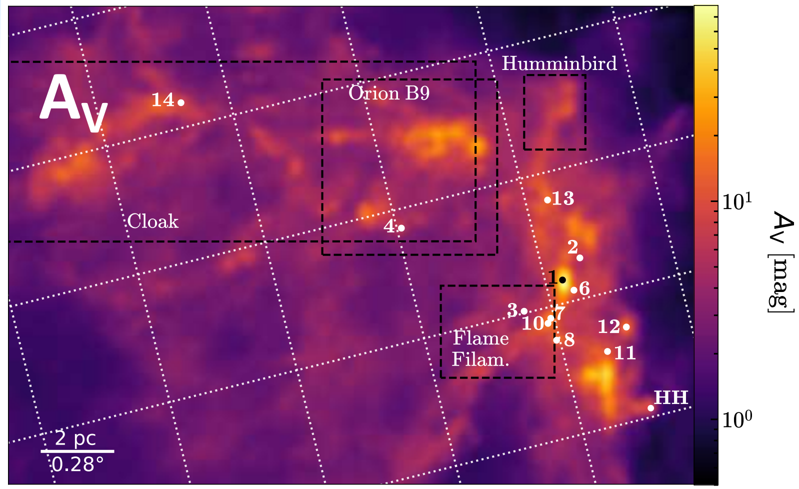
HCN *J*=1-0 does not always trace dense star-forming gas !

Santa-Maria, Goicoechea +2023

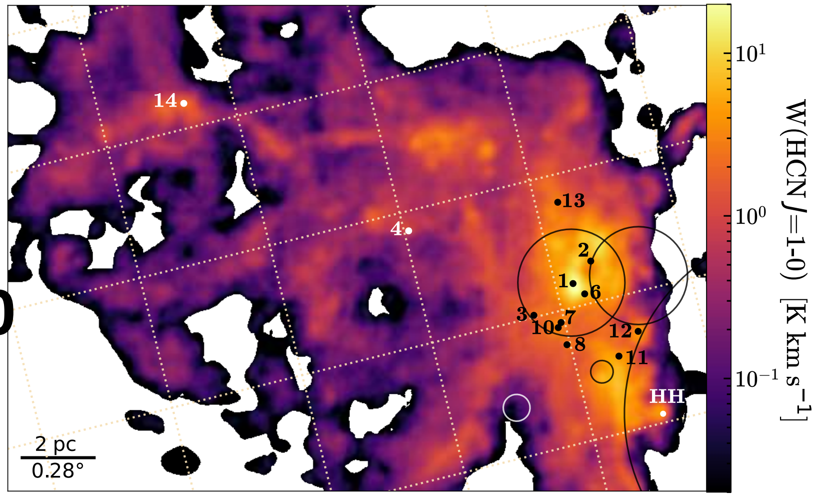
5-sq degree line maps of Orion B GMC (250 pc^2)

CO 1-0

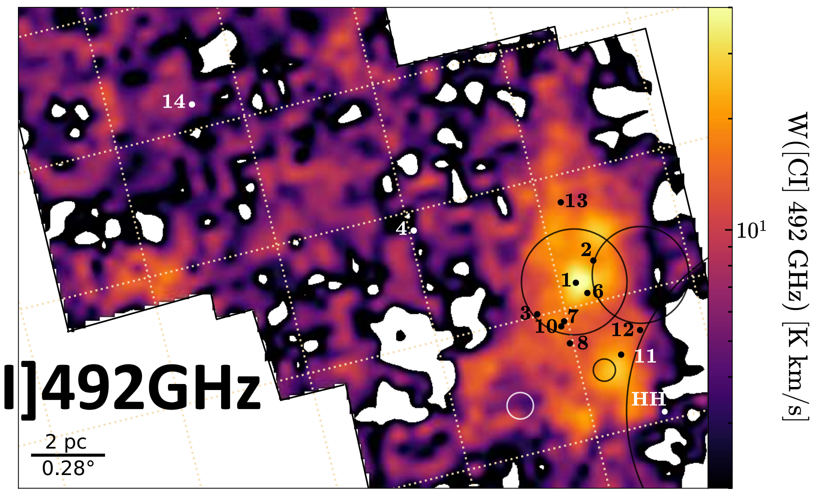




HCN 1-0

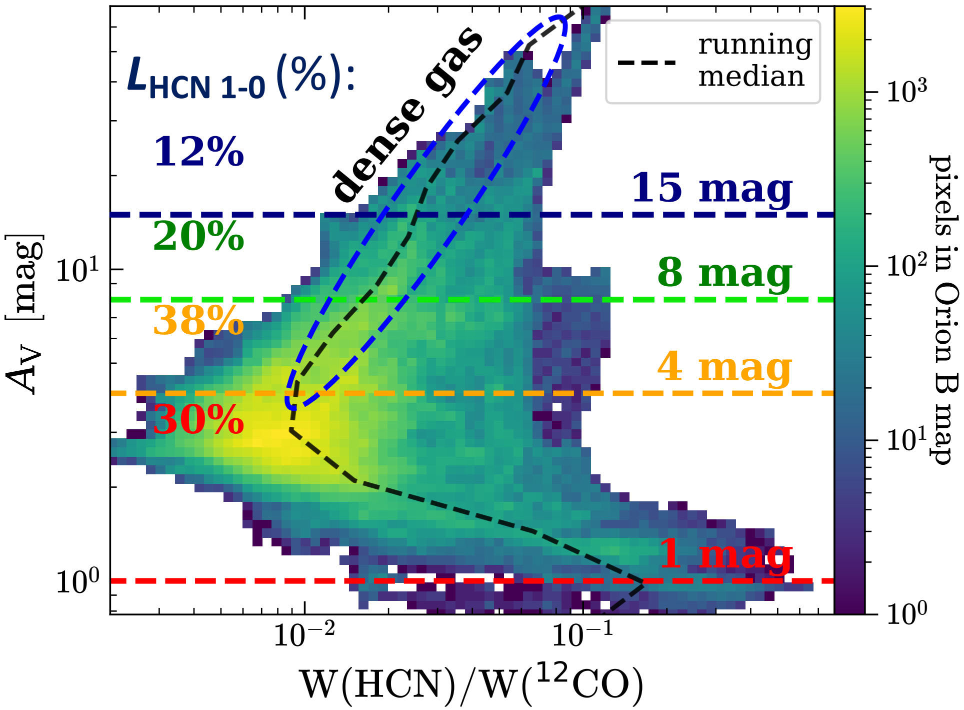


[CI]492GHz



Santa-Maria, Goicoechea +2023

High HCN/CO 1-0 intensity ratios in translucent gas and cloud edges (PDRs)



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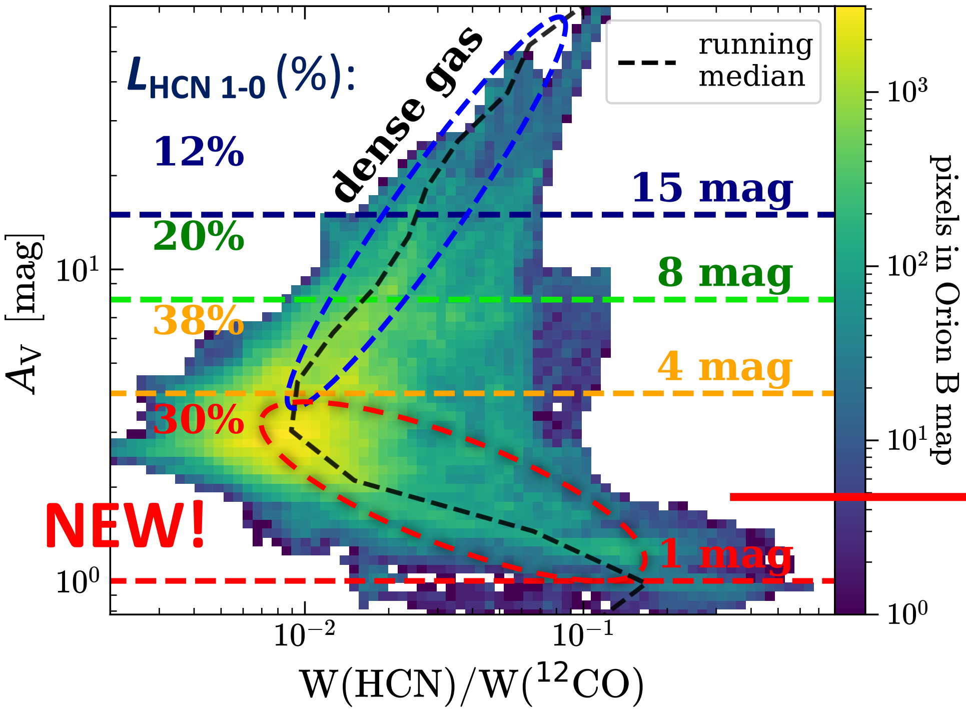
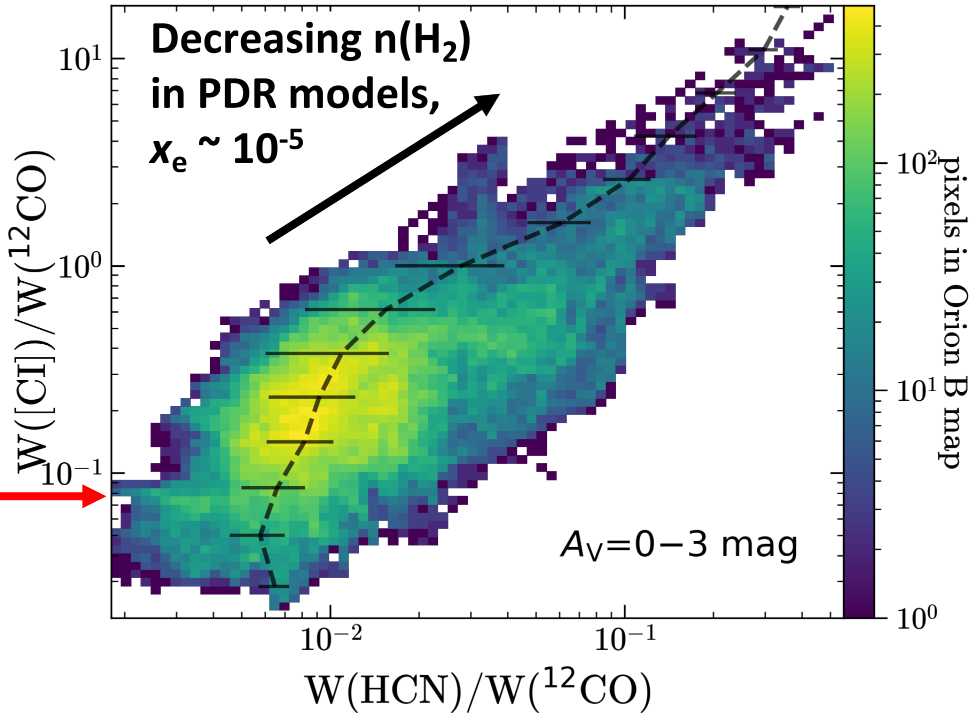




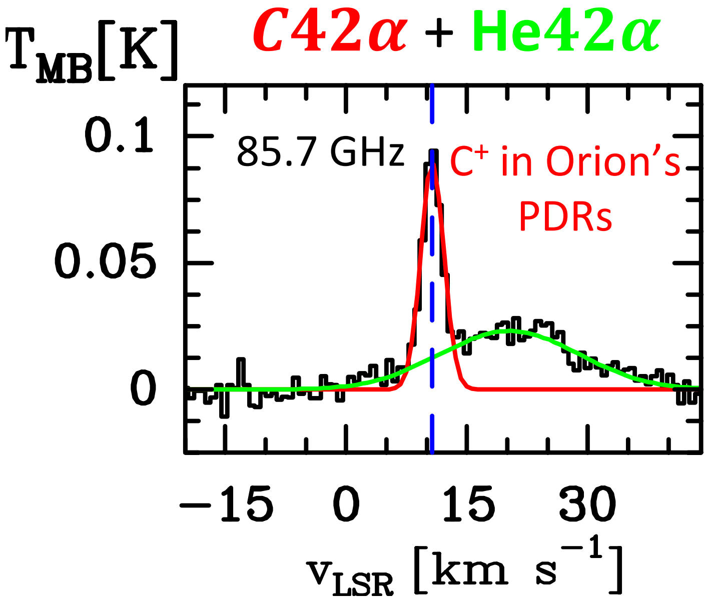
Santa-Maria, Goicoechea +2023

Widespread 1-0 emission from weakly collisionally excited gas, n(H_2) < 10^4 cm^{-3}, enhanced by e$^-$ collisions

Goldsmith & Kauffmann 2017; Goicoechea +2022 (HFS line overlap models)

Physical conditions of C^+-PDR gas from Carbon RRLs

$C^+ + e^- \rightarrow C^0$ + photon (high-*n*: radio & mm)

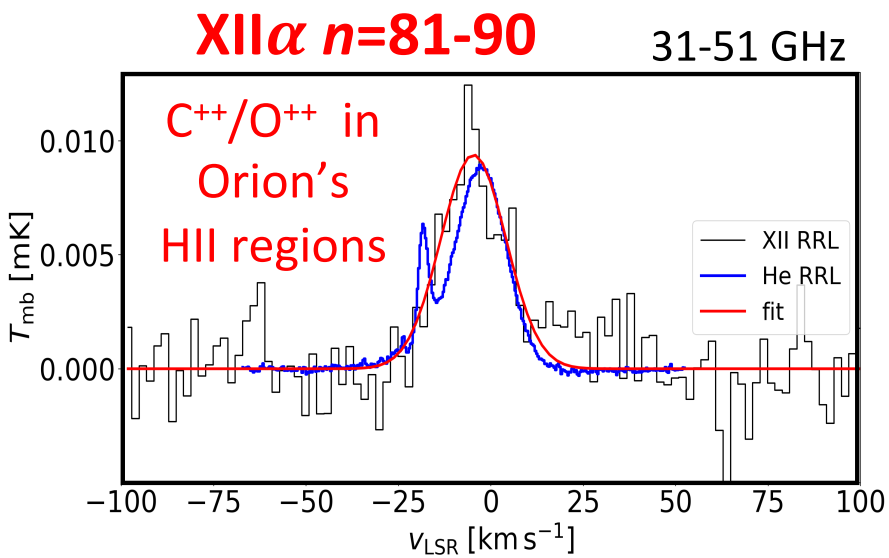


Cuadrado, Salas +2019 (**IRAM 30m**)
Pabst, Goicoechea +2024, accepted (**Yebes 40m**)

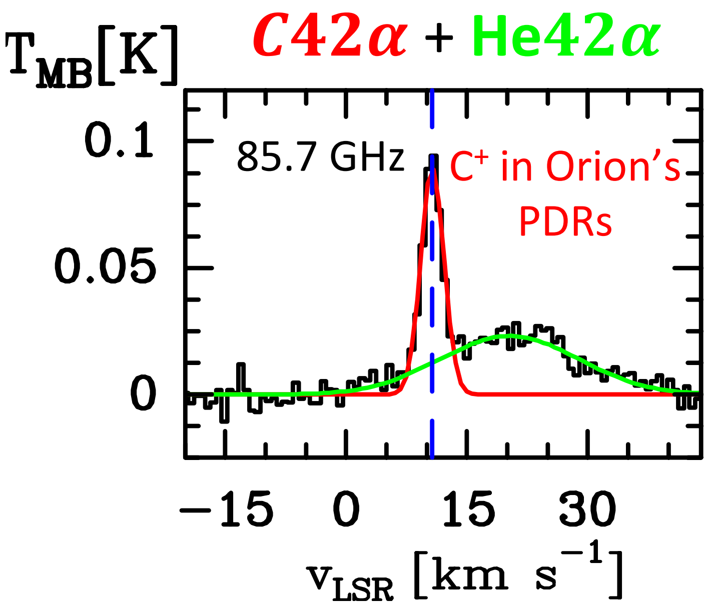
Physical conditions of C^+-PDR gas from Carbon RRLs

$C^+ + e^- \rightarrow C^0$ + photon (high-*n*: radio & mm)

$C^{++} + e^- \rightarrow C^+$ + photon



Pabst, Goicoechea +2024 (**Yebes 40m**)
See also Liu +2023 (**TianMa 65-m**)



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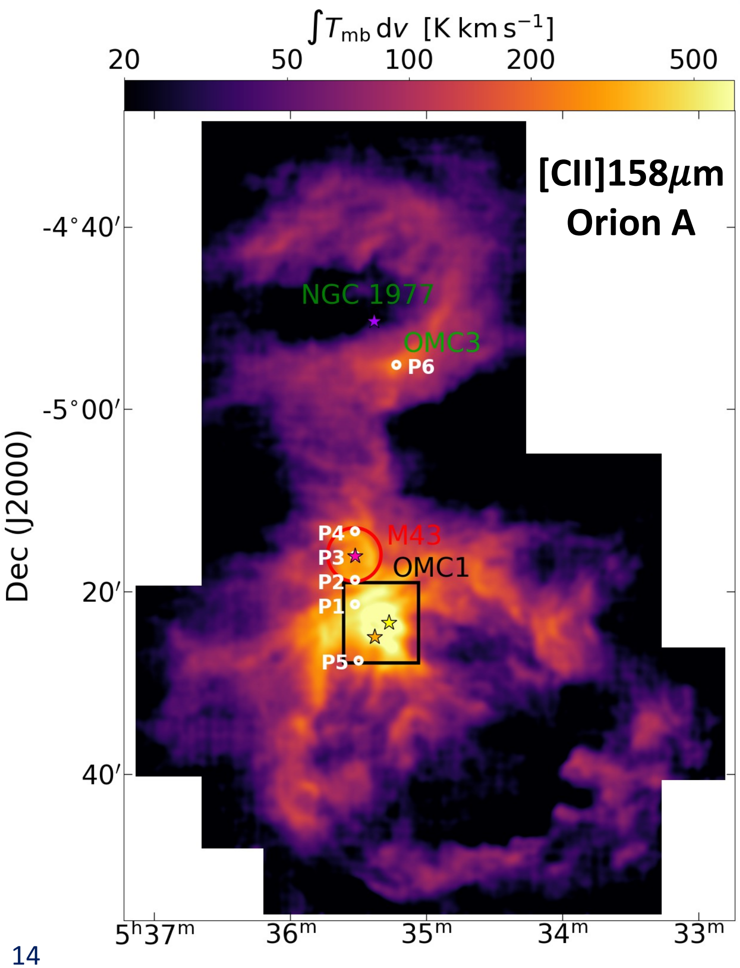
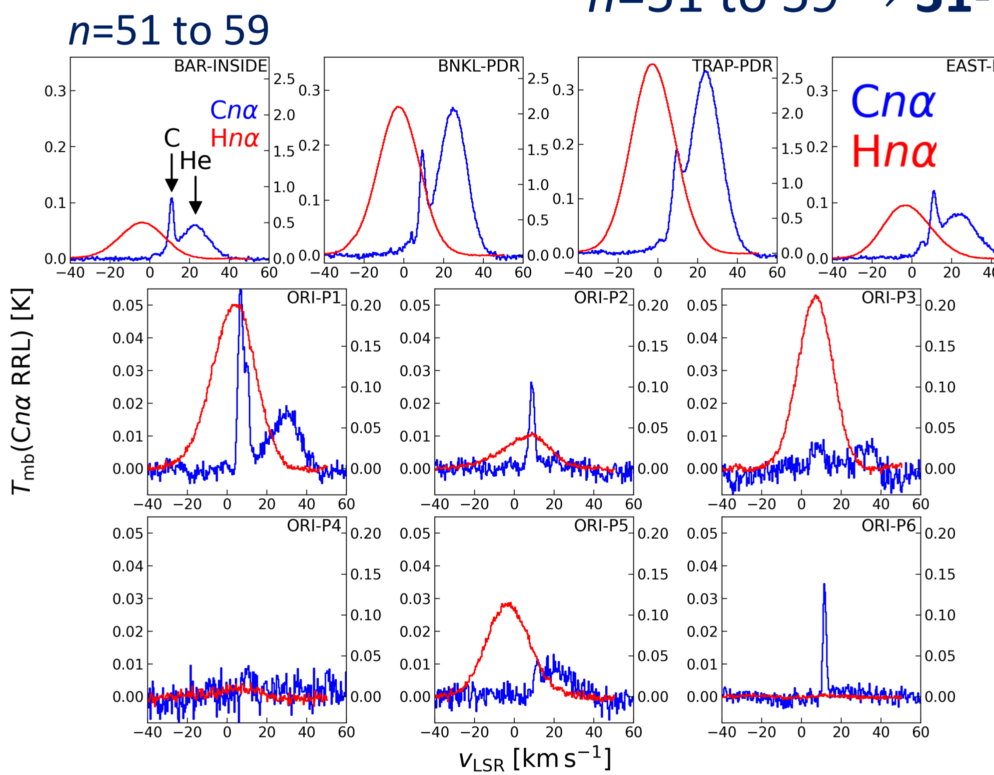
Physical conditions of C⁺-PDR gas from Carbon RRLs



Detection of C RRLs Cnα : n=42 to 38 → **85-115 GHz**

n=51 to 59 → **31-51 GHz**



Yebes 40m

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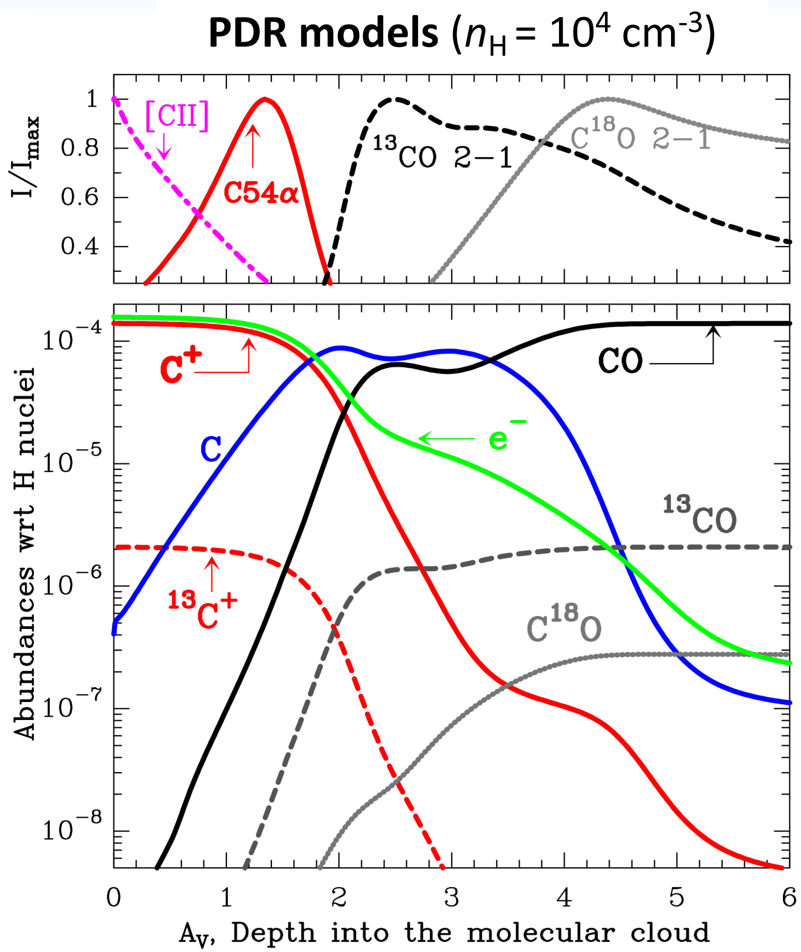
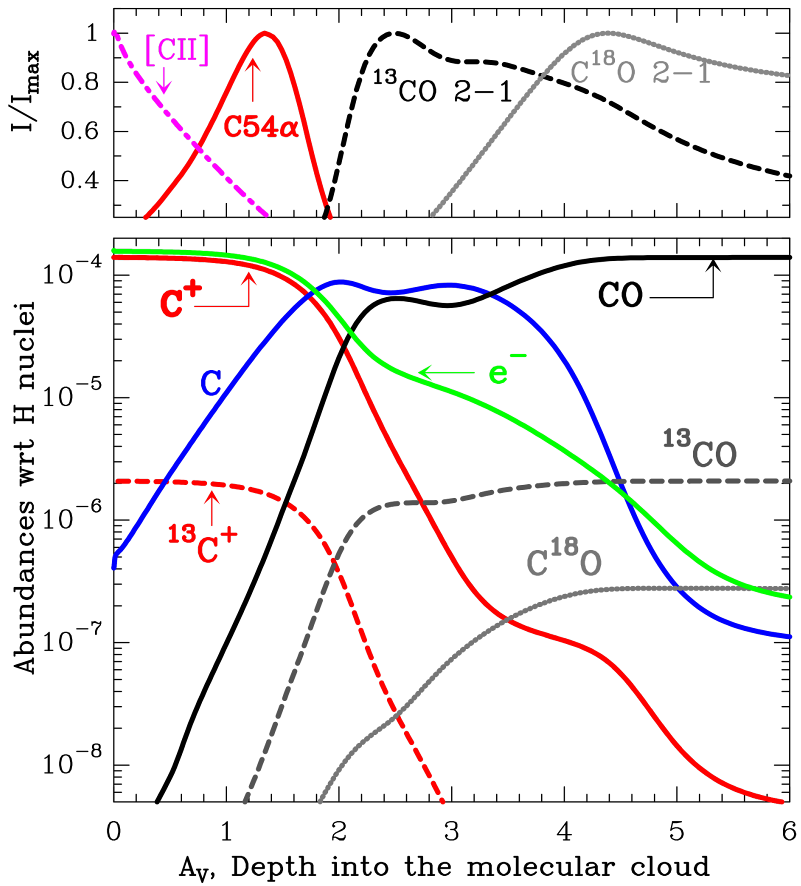
Physical conditions of C^+-PDR gas from Carbon RRLs



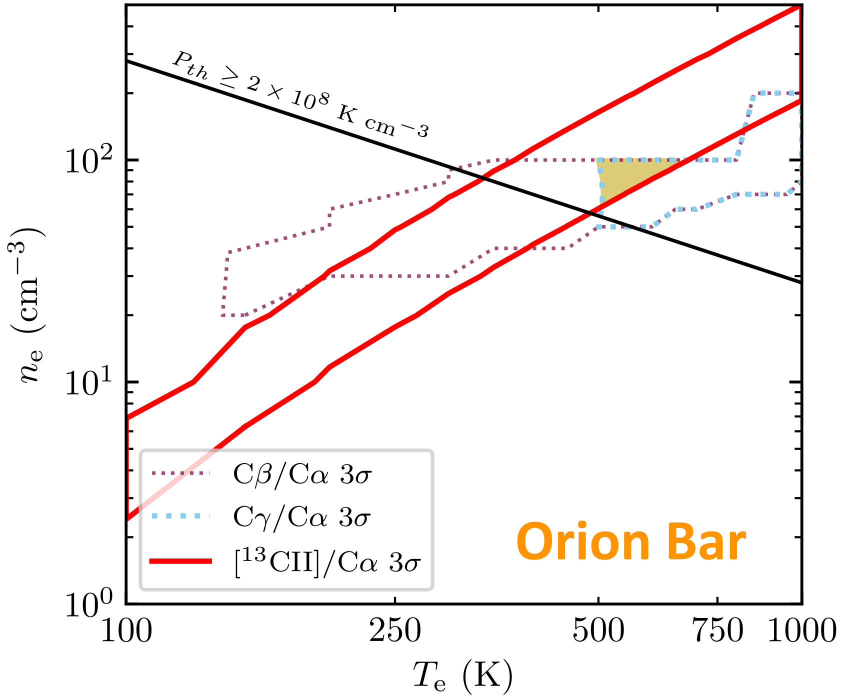
T_P (RRLs) $\propto$ n_e^2 $T_e^{-1.5}$ & optically thin

Physical conditions of C^+-PDR gas from Carbon RRLs

PDR models ($n_H = 10^4$ cm^{-3})



Non-LTE C RRL excitation models



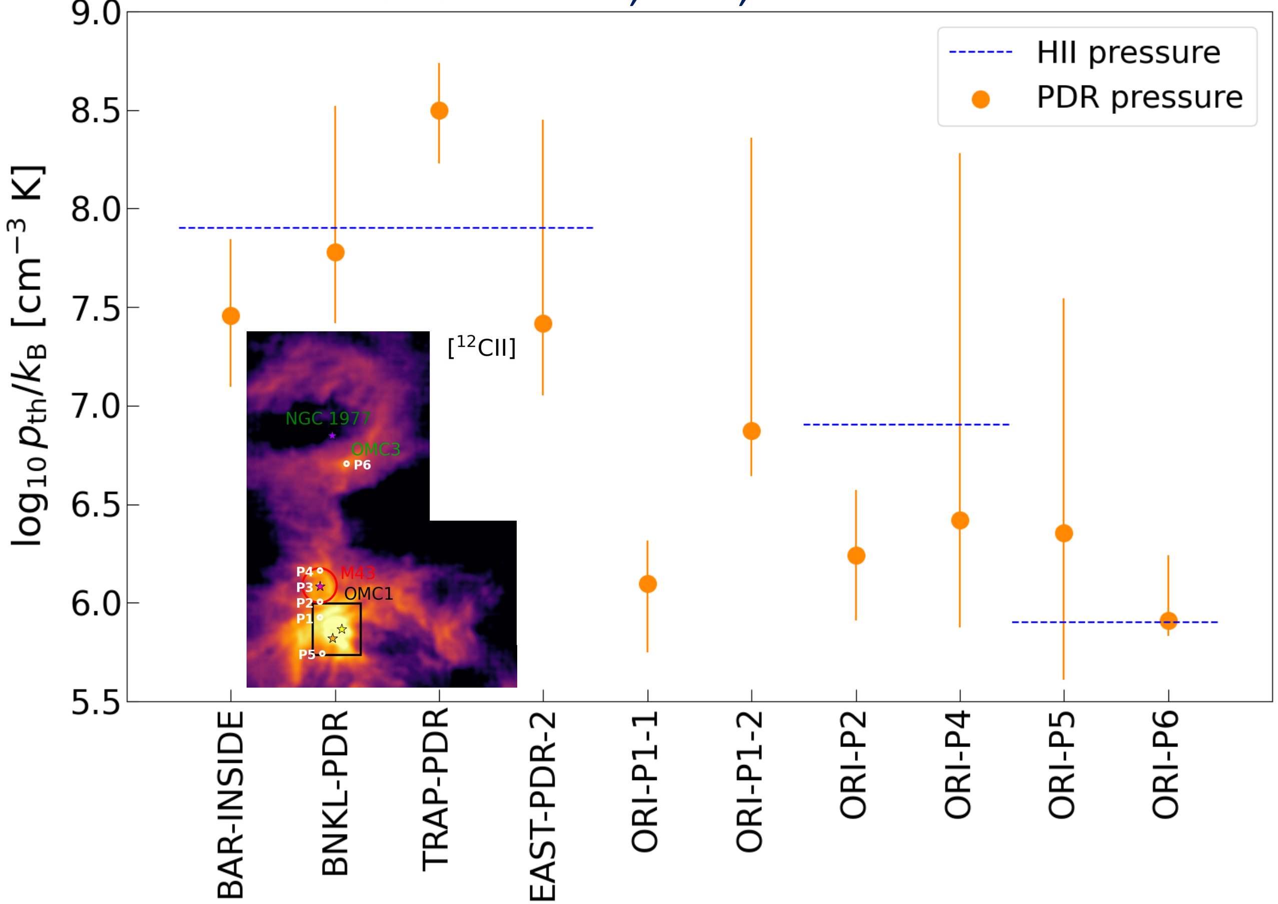
Constrains gas thermal pressure from n_e and T_e

T_P (RRLs) $\propto n_e^2\ T_e^{-1.5}$

Cuadrado, Salas +2019
Pabst, Goicoechea +2024
Models: Salgado +2017

Physical conditions of C^+-PDR gas from Carbon RRLs

Orion A: M42, M43, and NGC1977



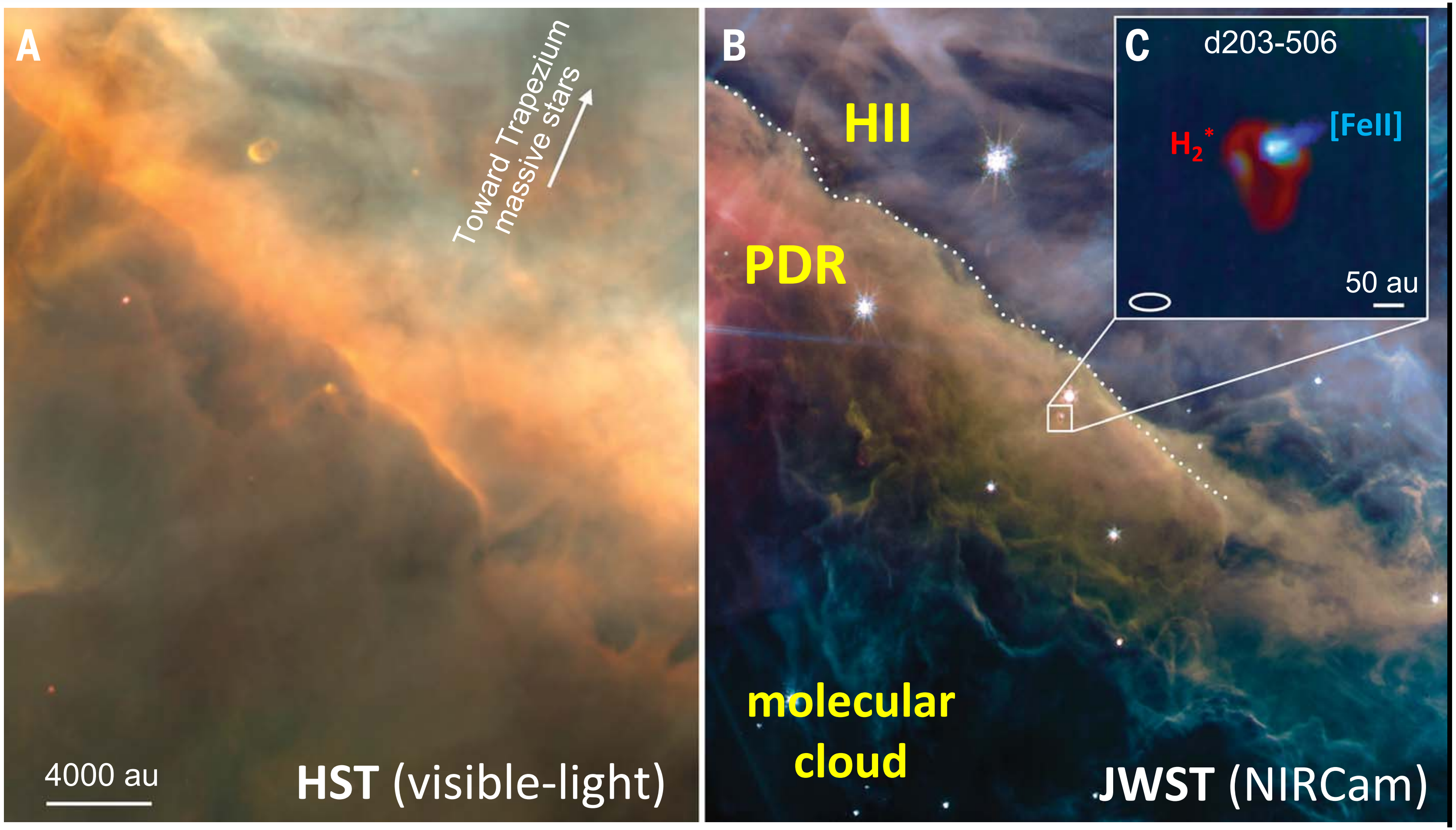
- At large scales, $\boldsymbol{P_{turb} \geq P_{th}}$
- HII regions and PDRs roughly in **pressure equilibrium**
- Beam of ~ 45'' (Yebes40m) or 0.09 pc
- Need higher angular resolution: **ALMA**, **SKA**, …

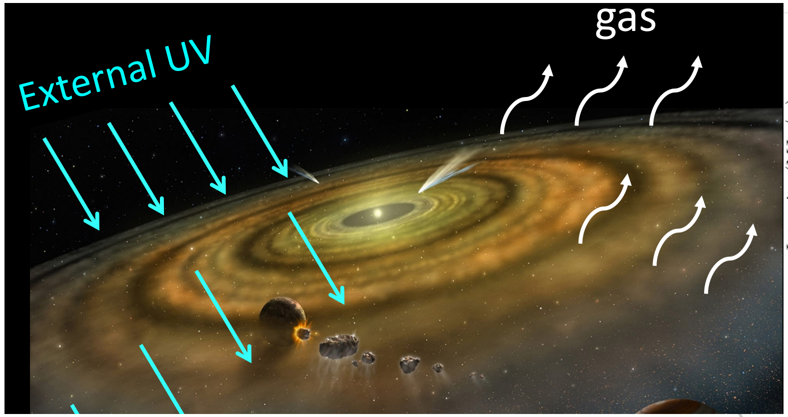
… and **JWST** !

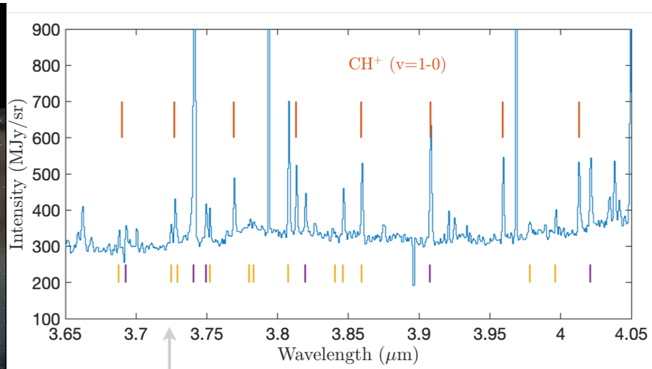
Pabst, Goicoechea, accepted +2024

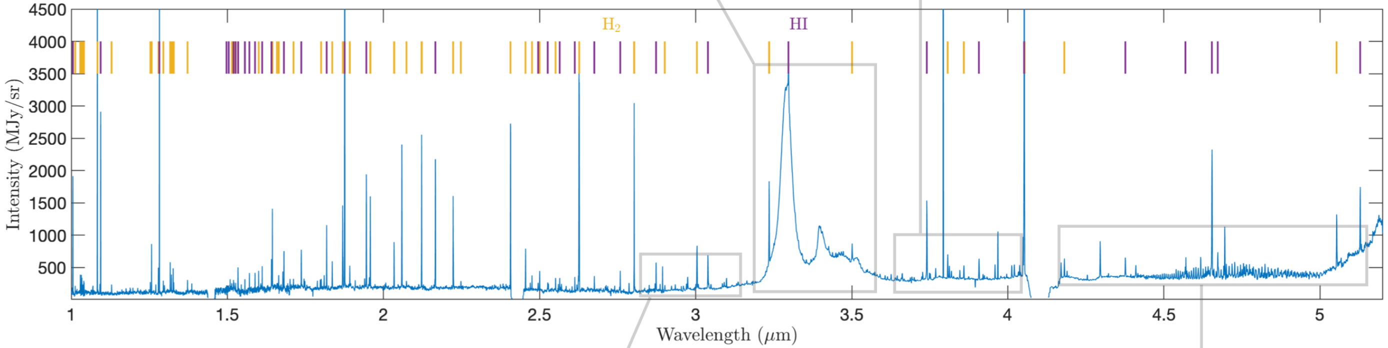
JWST images of the Orion Bar PDR at 0.1’’ res.

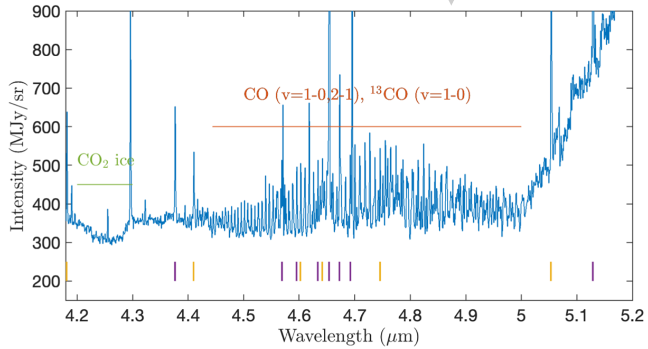
PDRs4All JWST-ERS (PIs: Berné, Habart & Peeters)

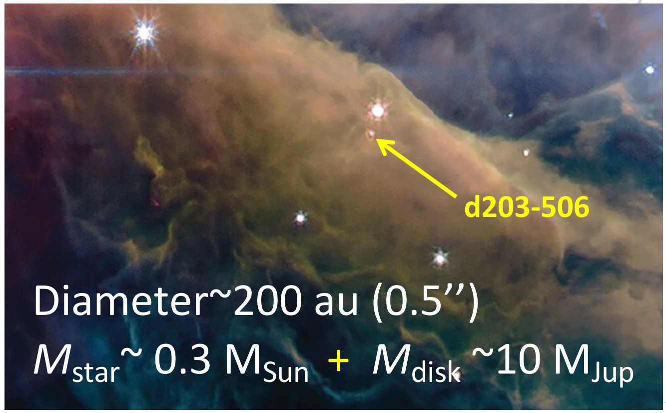












H_2 vib.

PAH

CO *v*=1-0

OH *v*=1-0

CH^+ *v*=1-0

CH_3^+ vib.

CI elect.

Berné &
PDRs4All team
2024, *Science*

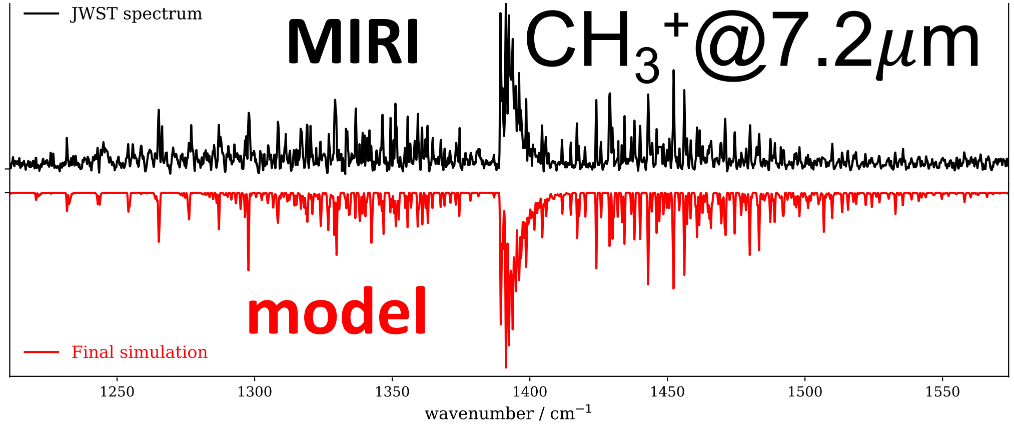
Article

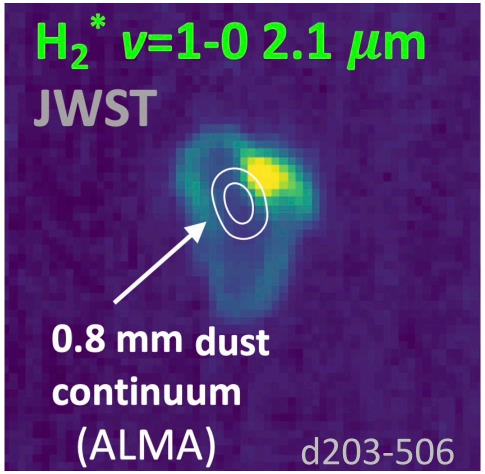
Formation of the methyl cation by photochemistry in a protoplanetary disk

Nature | www.nature.com

https://doi.org/10.1038/s41586-023-06307-x

Olivier Berné[1✉], Marie-Aline Martin-Drumel[2], Ilane Schroetter[1], Javier R. Goicoechea[3],





First detection of CH_3^+ in Space

Berné +23, Nature (detection)

Changala +23, A&A (accurate ro-vibrational spectroscopy)

Article

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Nature | www.nature.com

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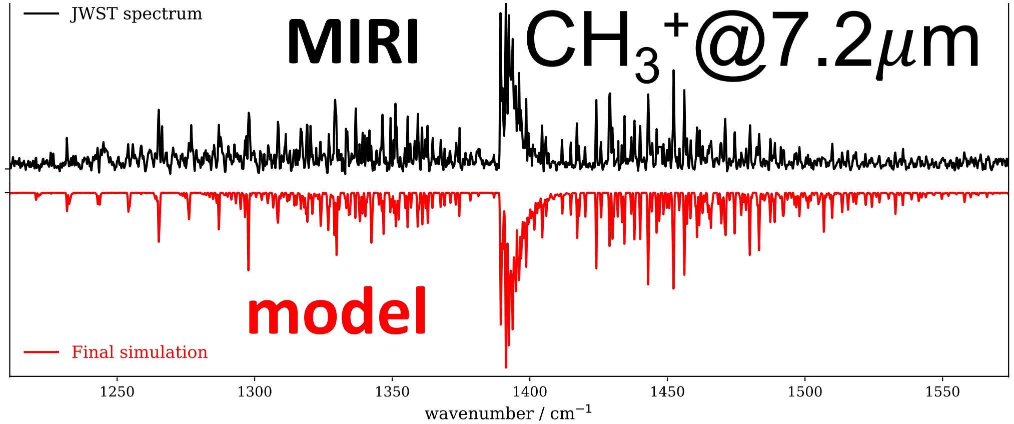

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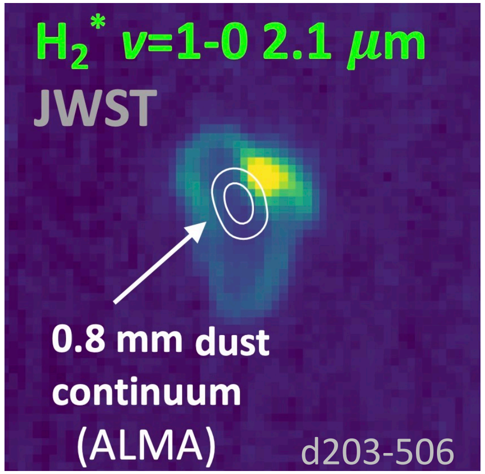
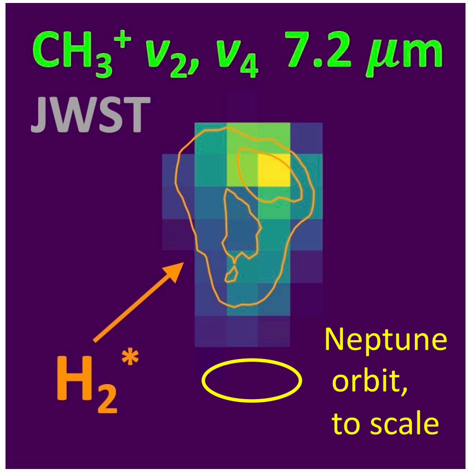
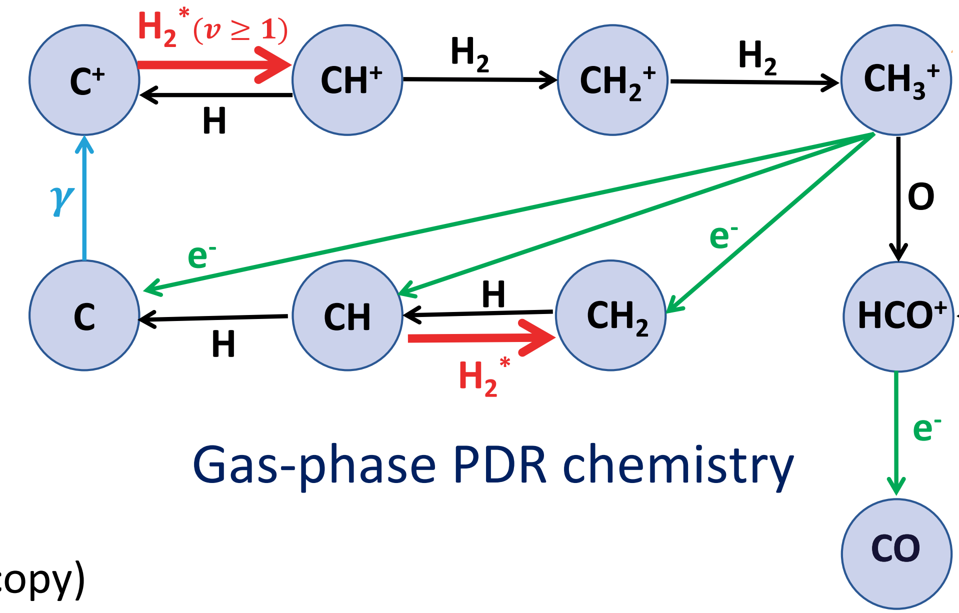


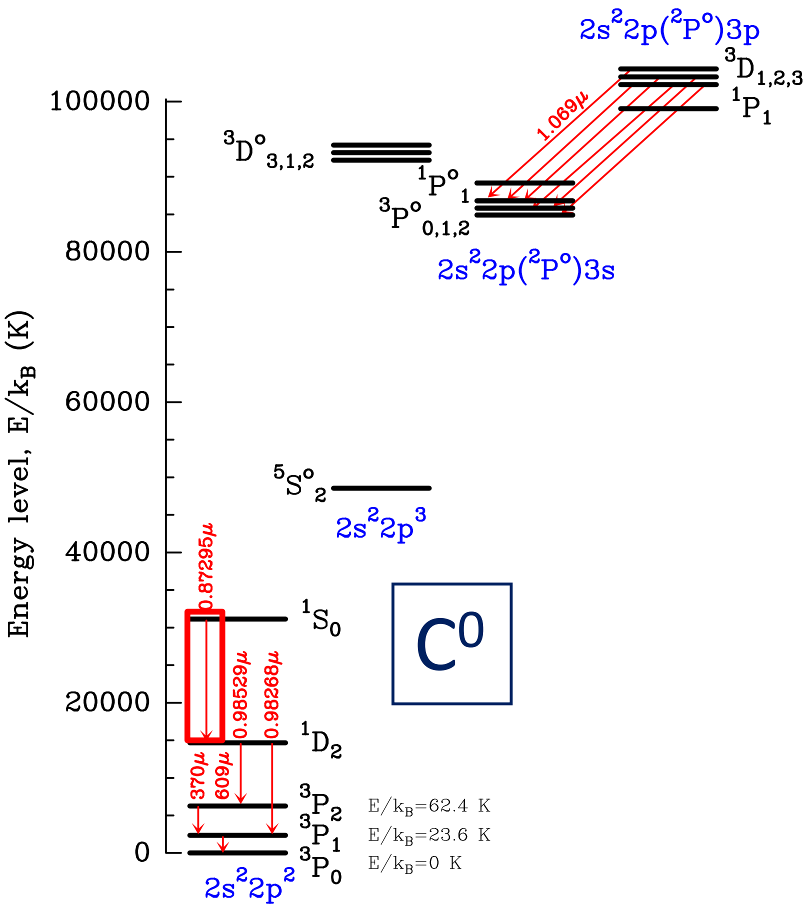


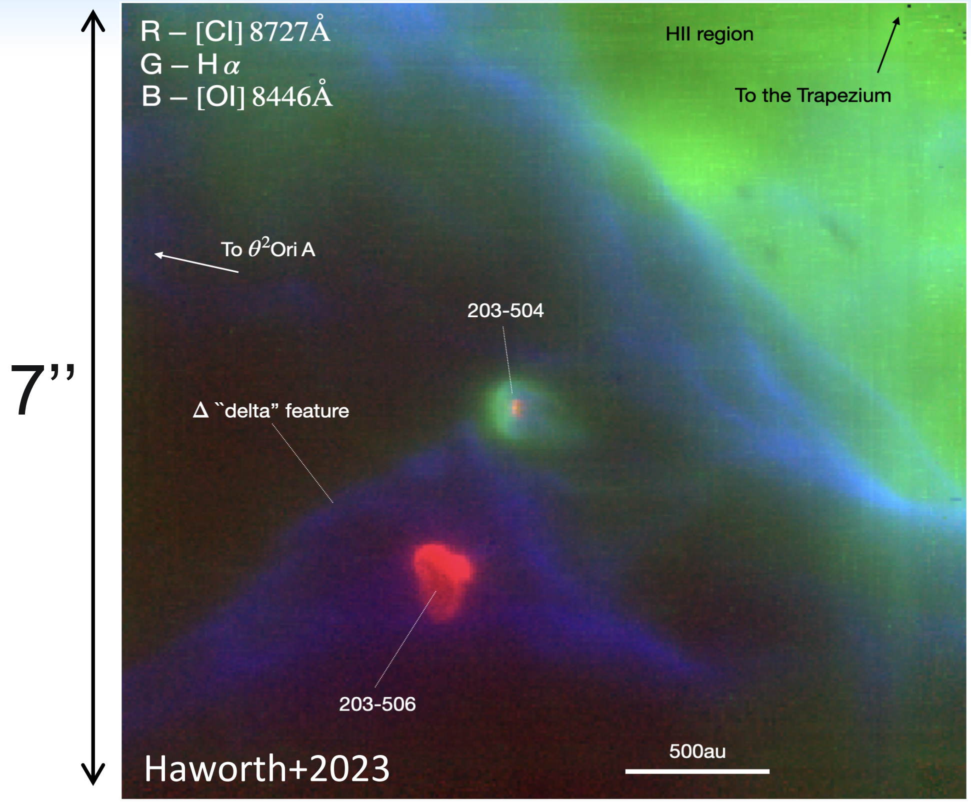


Gas-phase PDR chemistry

Berné +23, Nature (detection)
Changala +23, A&A (accurate ro-vibrational spectroscopy)

Detection of neutral atomic carbon in d203-506

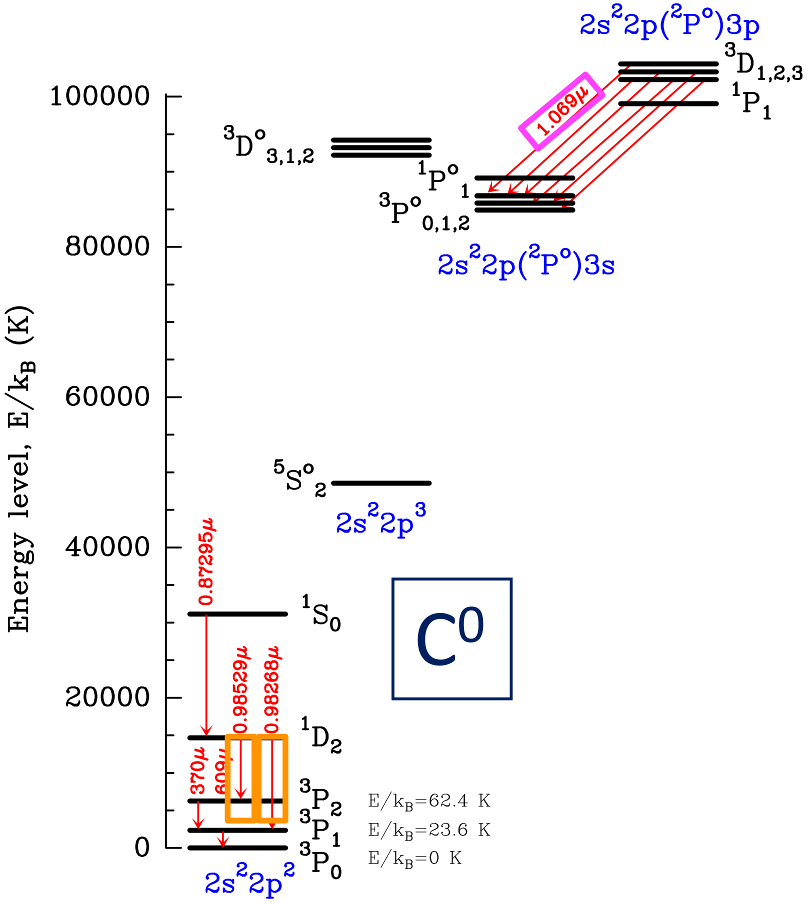


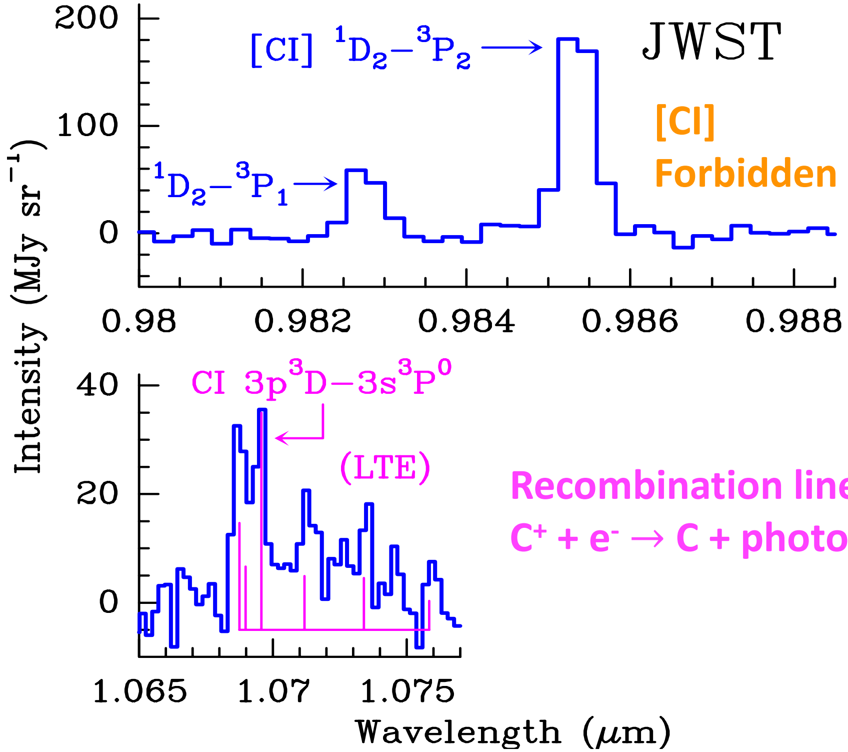


- **VLT/MUSE** images of the Orion Bar edge at **0.09''** res.
- Electronically-exicted **[CI] $^1S_0$-$^1D_2$ line** @ λ=0.873 μm

Detection of neutral atomic carbon in d203-506

Near-IR carbon lines: **electronically excited lines** detected with **JWST/NIRSpec**





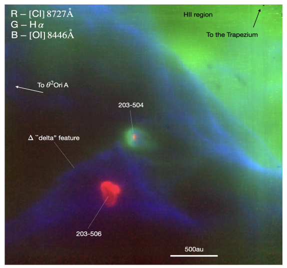
Recombination line?
$C^+ + e^- \rightarrow C$ + photon

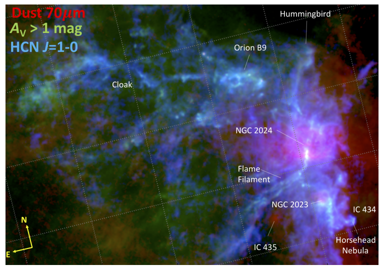
Goicoechea & PDRs4All 2024, in prep.

Take home messages

+ Star and planet formation are not independent of **feedback** processes in GMCs.

+ **Radio** to **near-IR** emission lines from C^+ and C^0 are excellent tracers of these processes:





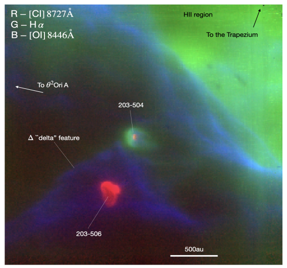
Take home messages

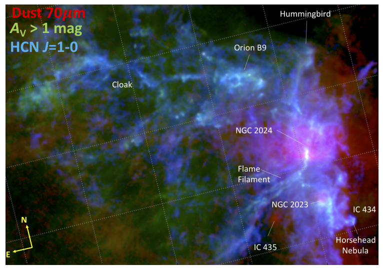
+ Star and planet formation are not independent of **feedback** processes in GMCs.

+ **Radio** to **near-IR** emission lines from C^+ and C^0 are excellent tracers of these processes:

  - **3D mapping** of GMCs in **atomic FS lines** provides unique information.
    → **velocity-resolved multi-beam mapping of the Milky Way**

  - External UV radiation affects protoplanetary disks but we still know little
    → **spectroscopy @ sub-arcsecond resolution**



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