Deuteration around the ultracompact HII region Mon R2

Sandra Patricia Treviño-Morales

P. Pilleri, A. Fuente, Á. Sánchez-Monge, C. Kramer, E. Roueff, M. González-García, J. Cernicharo, M. Gerin, J. R. Goicoechea, J. Pety, O. Berné, V. Ossenkopf, D. Ginard, S. García-Burillo, J. R. Rizzo, and S. Viti.

Outline

Introduction
- HII regions and PDRs
- Monoceros R2

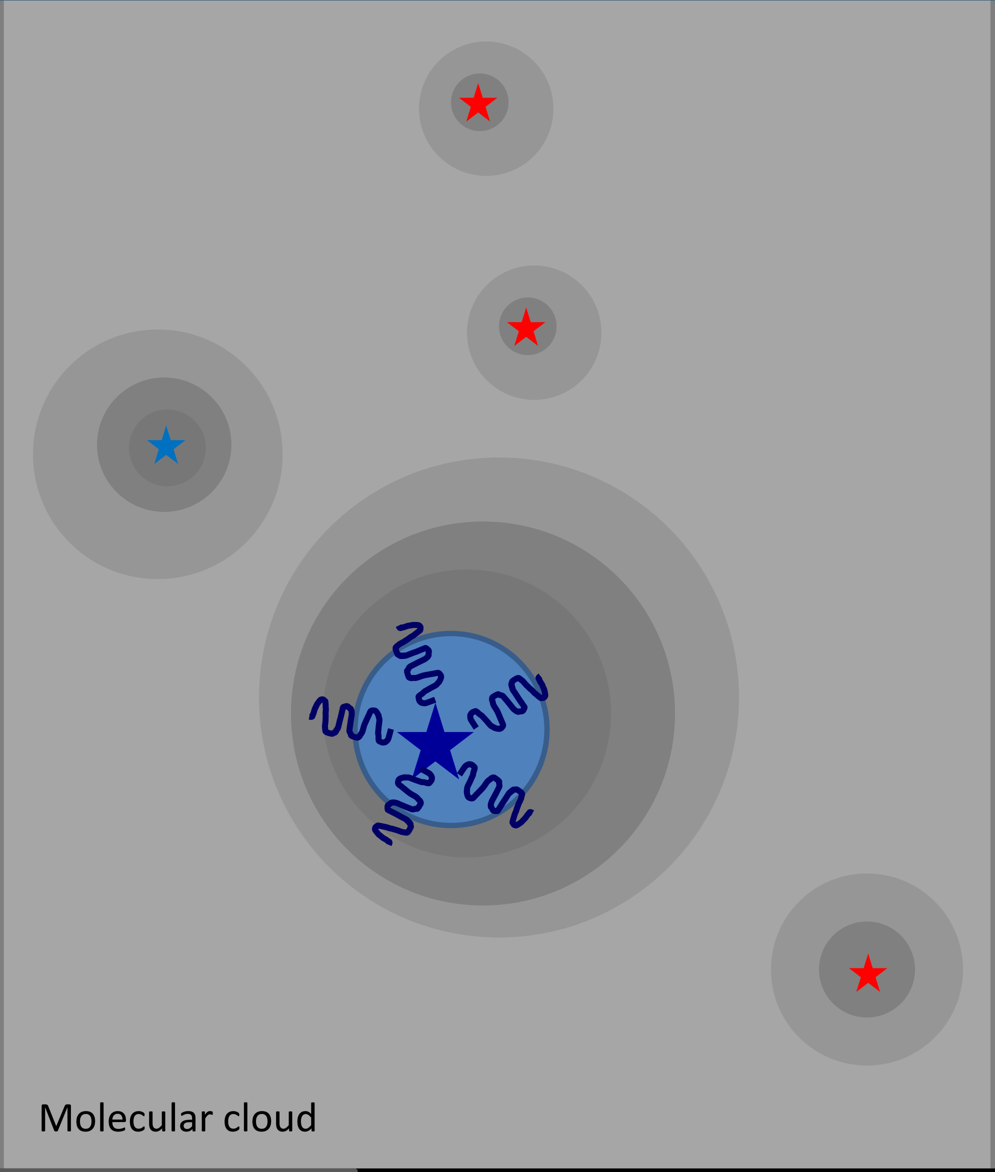
Deuterated molecules
- Observations
- General results
- Deuterated molecules

Summary

HII region and Photon-Dominated Region (PDR) system

A massive star (O & B type) radiates enough **UV photons** with **energies E > 13.6 eV** that ionize the surrounding gas and generate an **HII region**

… radiates **photons** with energies **6 < E < 13.6 eV** that **dissociate H_2** and **CO** molecules and generate a **PDR (phodon-dominated region)**.



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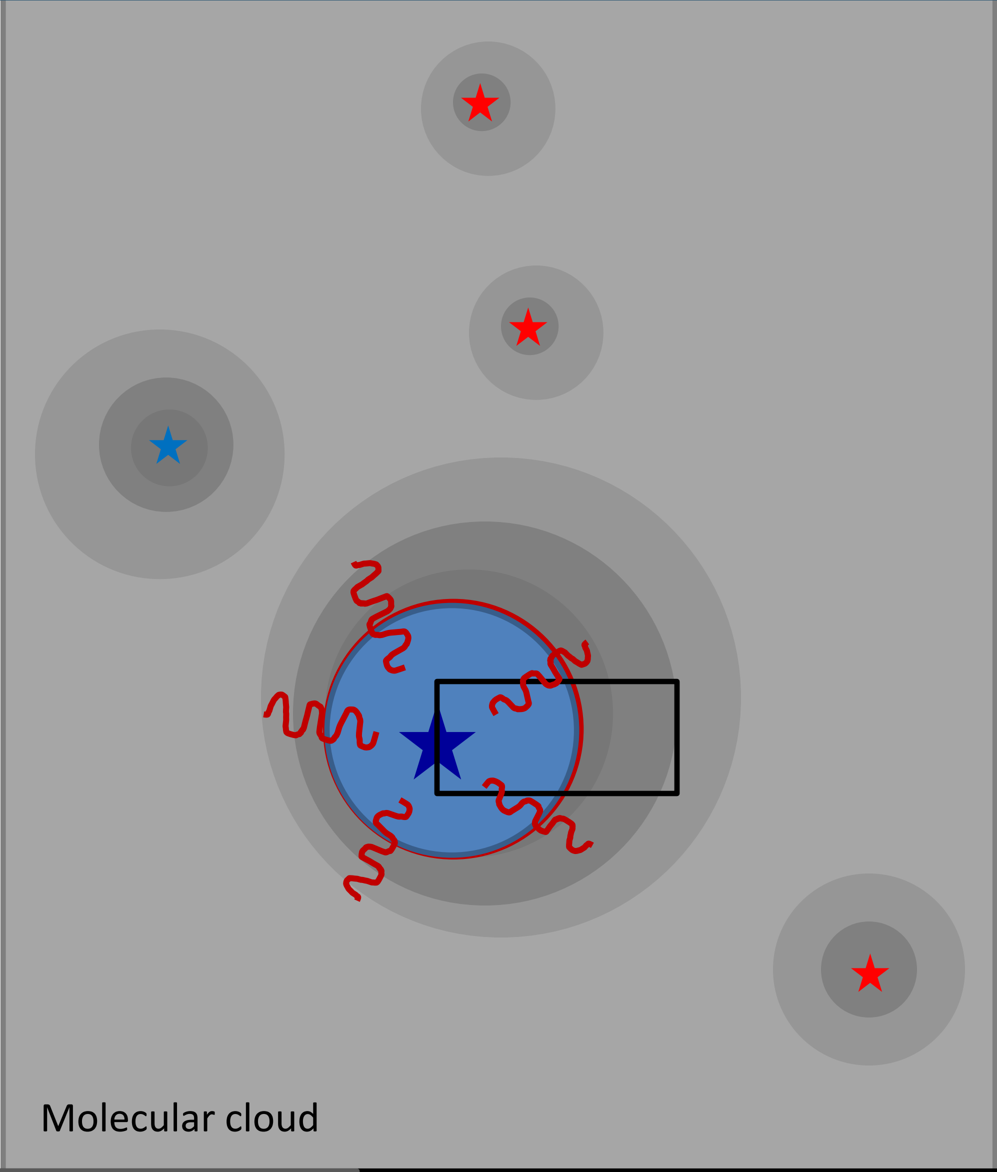
- ***Link*** between HII region and molecular cloud
- Chemistry dominated by ***FUV photons***
- Structure (chemistry/physics) determined by
  - n, ***gas density***
  - G_0, ***incident flux***

G_0, incident flux: from 1.7 (interstellar radiation field) to 10^6 (close to high-mass stars)

with $G_0 \approx 1.6 \cdot 10^{-3}$ erg cm^{-2} s^{-1} (Habing 1968)

Hollenbach & Tielens (1997)



HII region and Photon-Dominated Region (PDR) system

Adapted from Hollenbach & Tielens (1997)

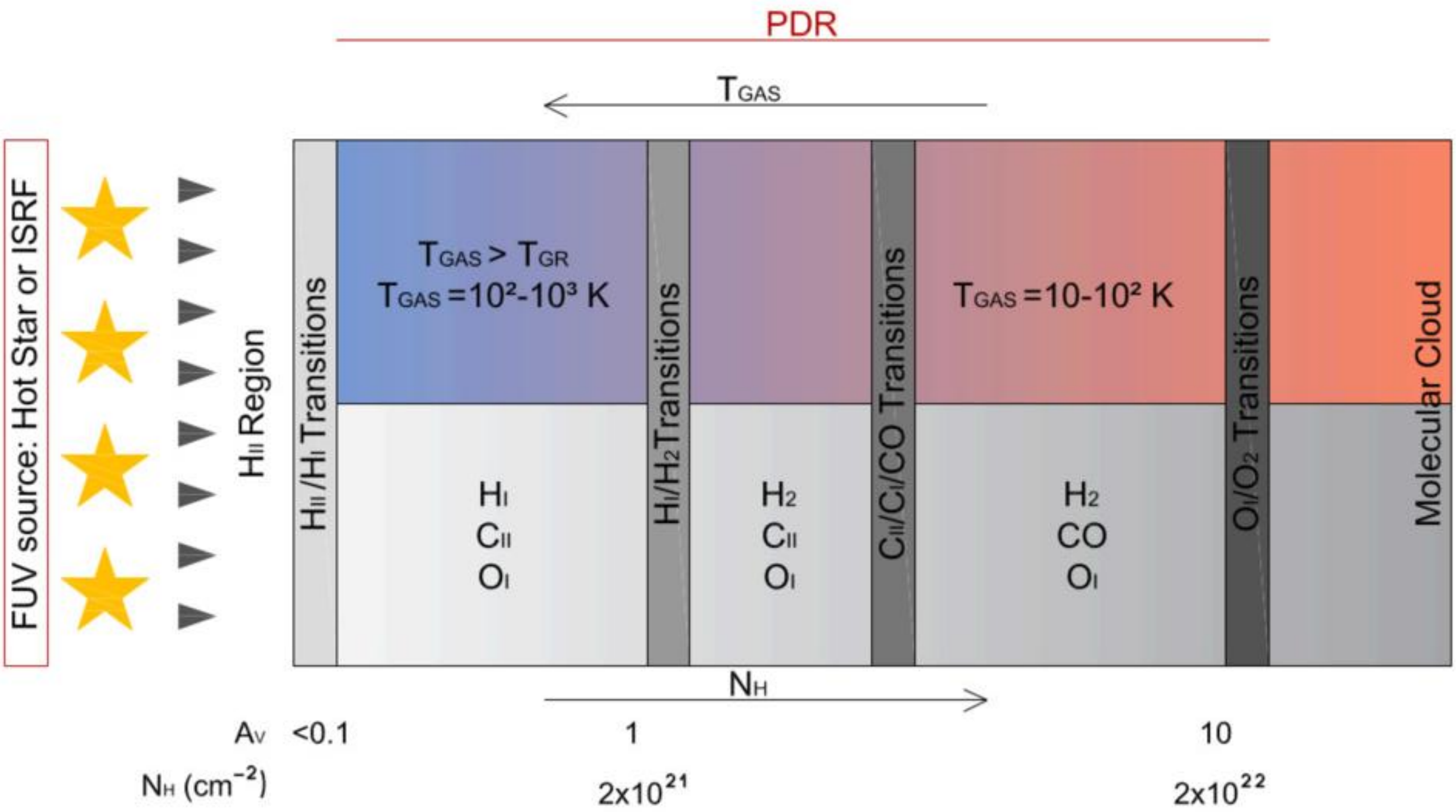
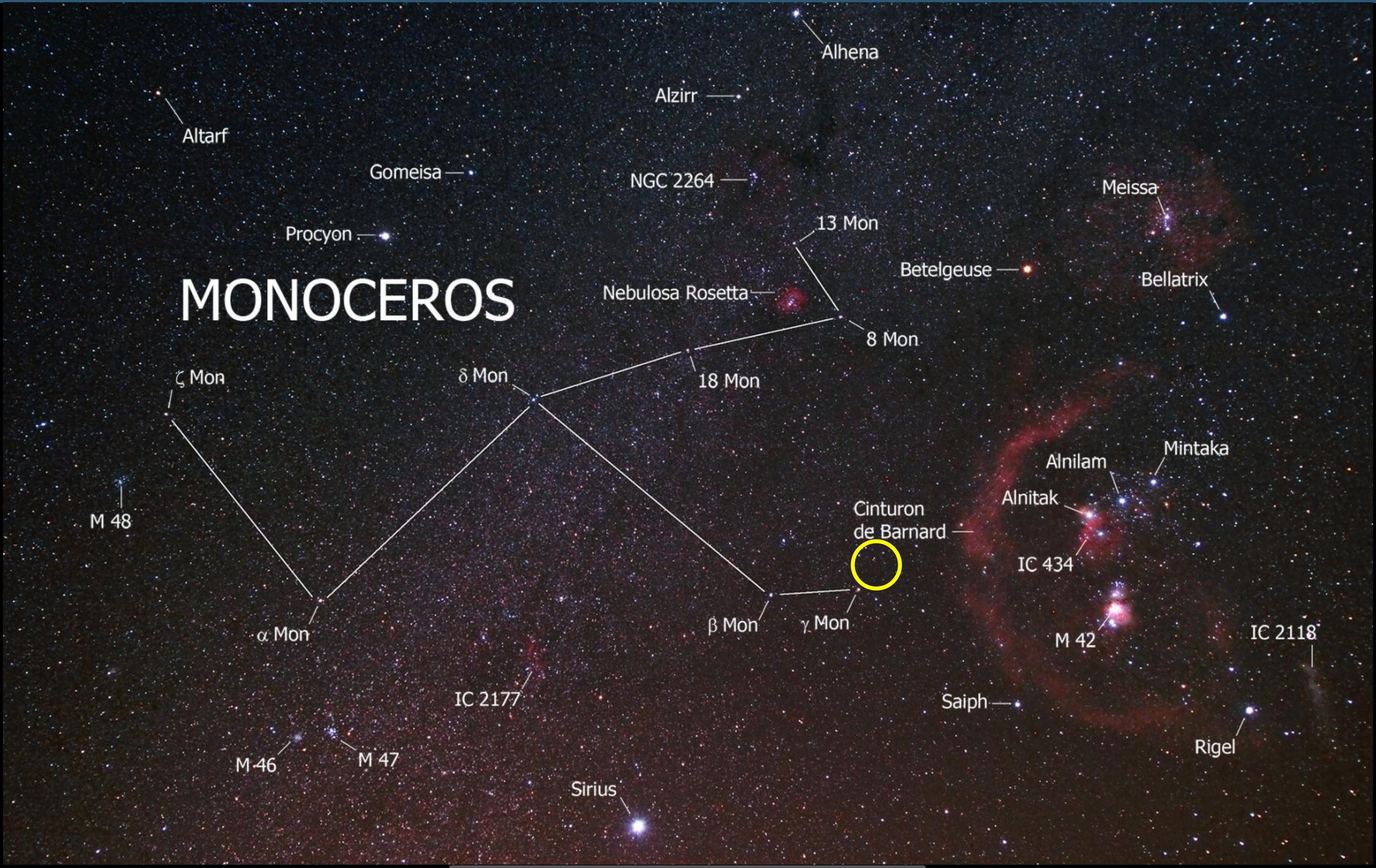


Image courtesy of B. Sánchez-Monge and R. Delgado


… where to study a HII region and PDR system?

Monoceros R2



Monoceros R2

Carpenter (2000); Carpenter & Hodapp (2008)

- The **Monoceros molecular cloud** (at **830 pc**) contains several sites of active star formation
- ***Monoceros R2*** is the most massive and prominent cluster:
  - … rich cluster with 371 objects, including massive (***B-type***) stars
  - … large mass reservoir, with a total mass of 10^4-10^5 $M_\odot$
  - … ***ultracompact HII region***, with a cometary shape
  - … ***series of PDRs*** with different densities and incident radiation fields

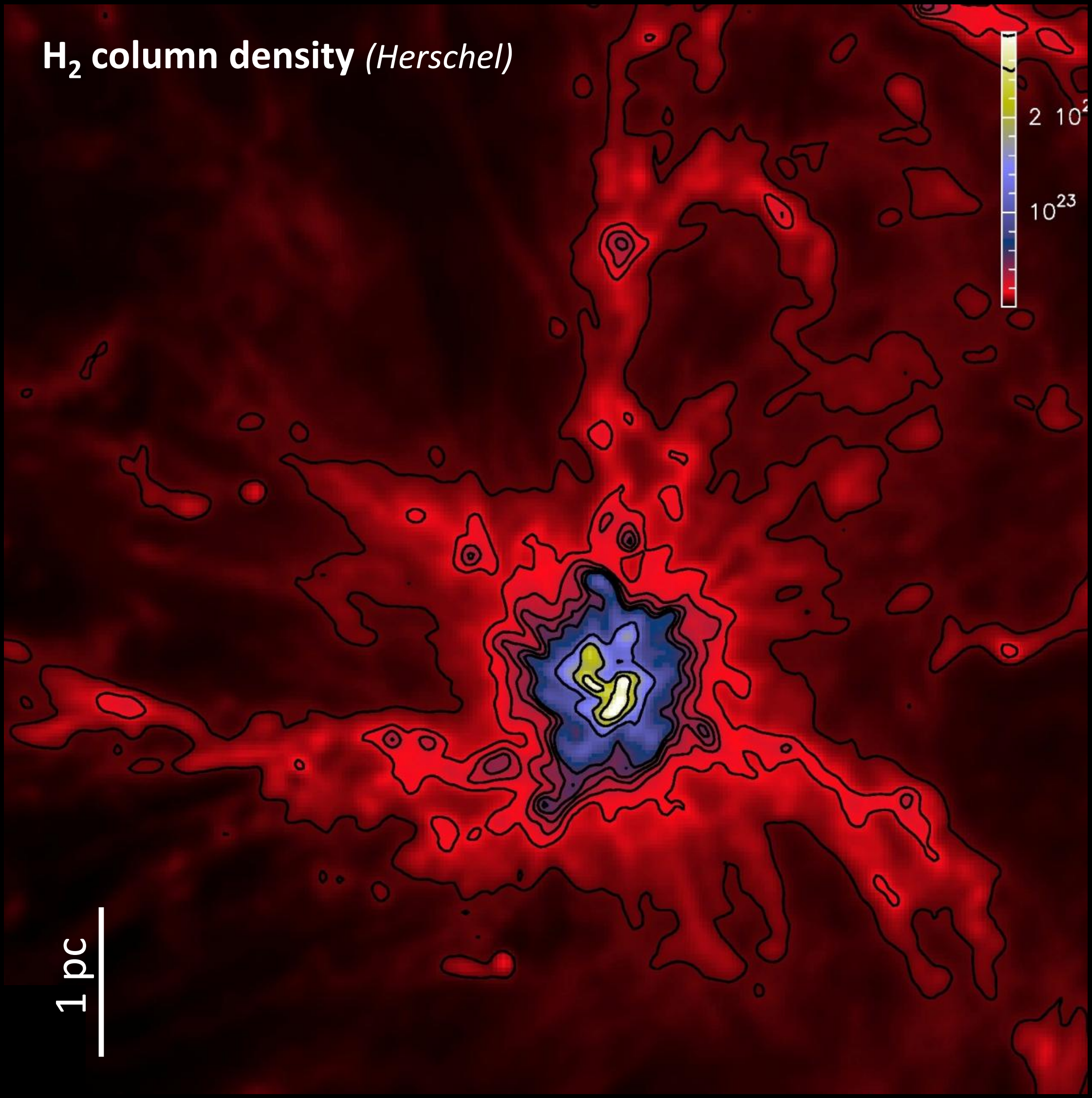
Monoceros R2

National Optical Astronomy Observatory

Monoceros R2 cloud contains:

… ***hot*** (ionized gas) ***bubbles***

Monoceros R2



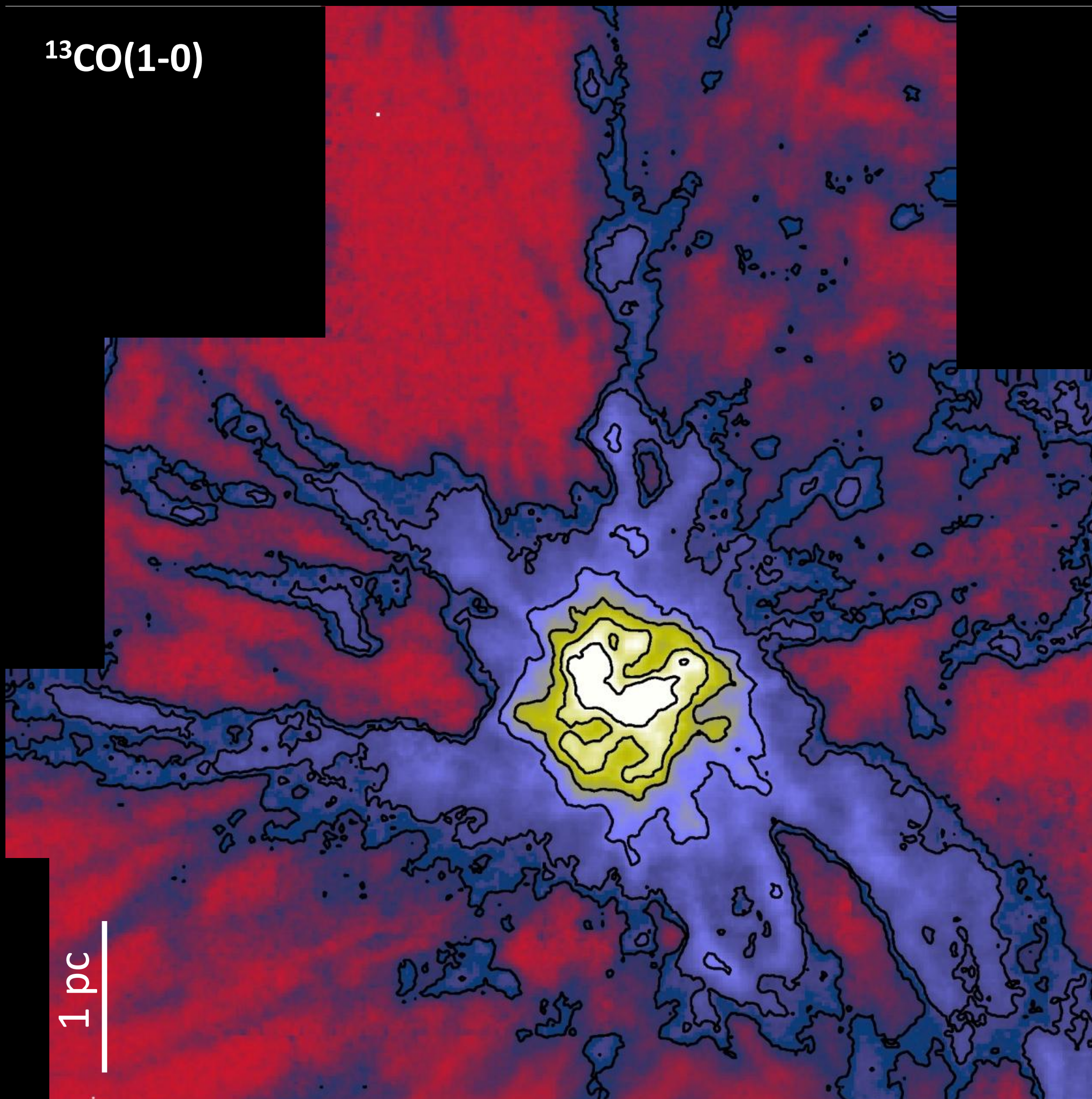
Didelon et al (2015) ; Rayner et al (2016, in prep)

Monoceros R2 cloud contains:

... ***hot*** (ionized gas) ***bubbles***

... large-scale ***filamentary structure*** converging in a central ***hub***

Monoceros R2



Treviño-Morales et al (2016, in prep)

Monoceros R2 cloud contains:

… ***hot*** (ionized gas) ***bubbles***

… large-scale ***filamentary structure*** converging in a central ***hub***

New **IRAM** 30m **data** (projects: 027-14, 035-15 and D03-16; PI: Treviño-Morales) allowed us to perform a **dynamical** and **stability study** of the filamentary structure

Monoceros R2

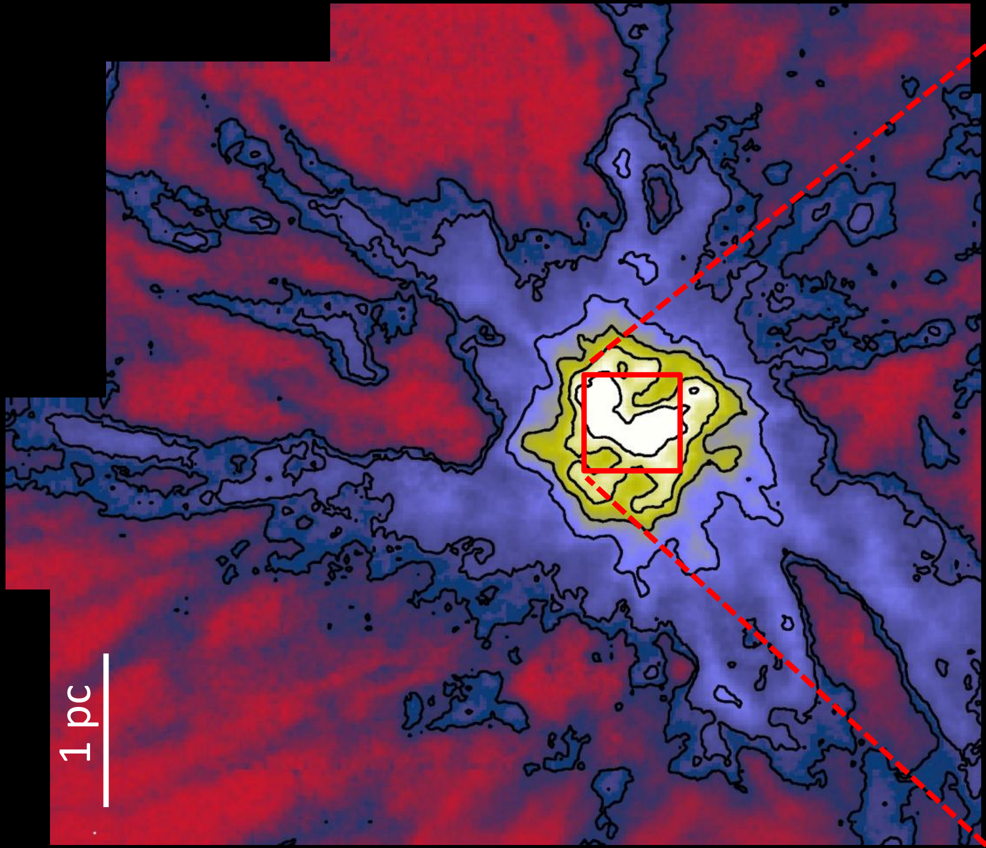
Monoceros R2 core contains:

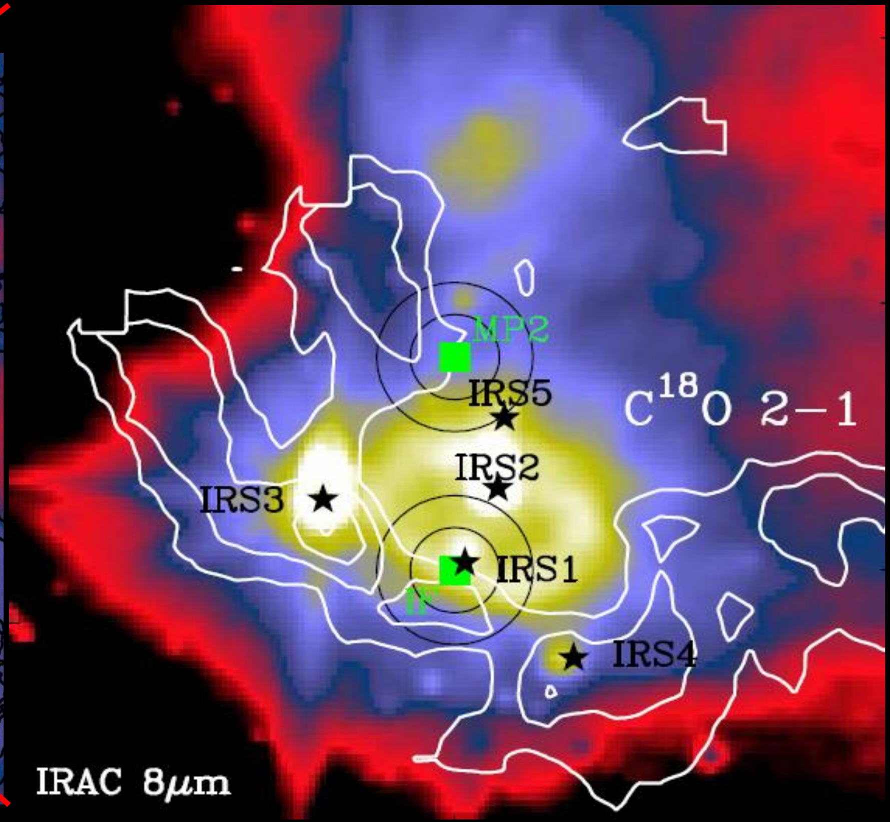
… cluster of ***IR young stars***

… cometary ***ultracompact HII region***

… ***PDRs*** irradiated by different UV fields: ***IF*** with $G_0 \approx 10^5$ and ***MP2*** with $G_0 \approx 10^2$

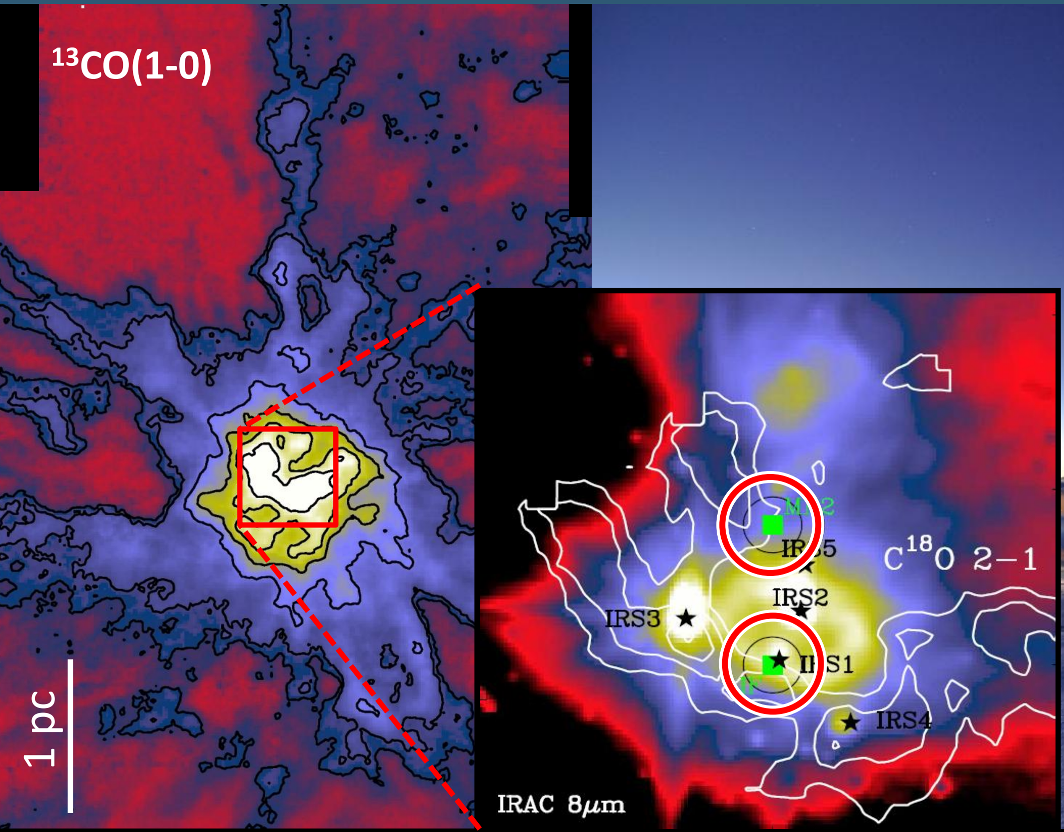
… extreme physical conditions (density and temperature)





Treviño-Morales et al (2014)

Observations



Spectral survey observations

- From 2011 to 2014
- Single pointing and On-The-Fly maps (2'x2')
- Frequency bands: ***3, 2, 1 and 0.8 mm***
- Spectral resolution: 200 kHz (***0.2 – 0.7 km/s***)
- EMIR + FTS (dual polarization)

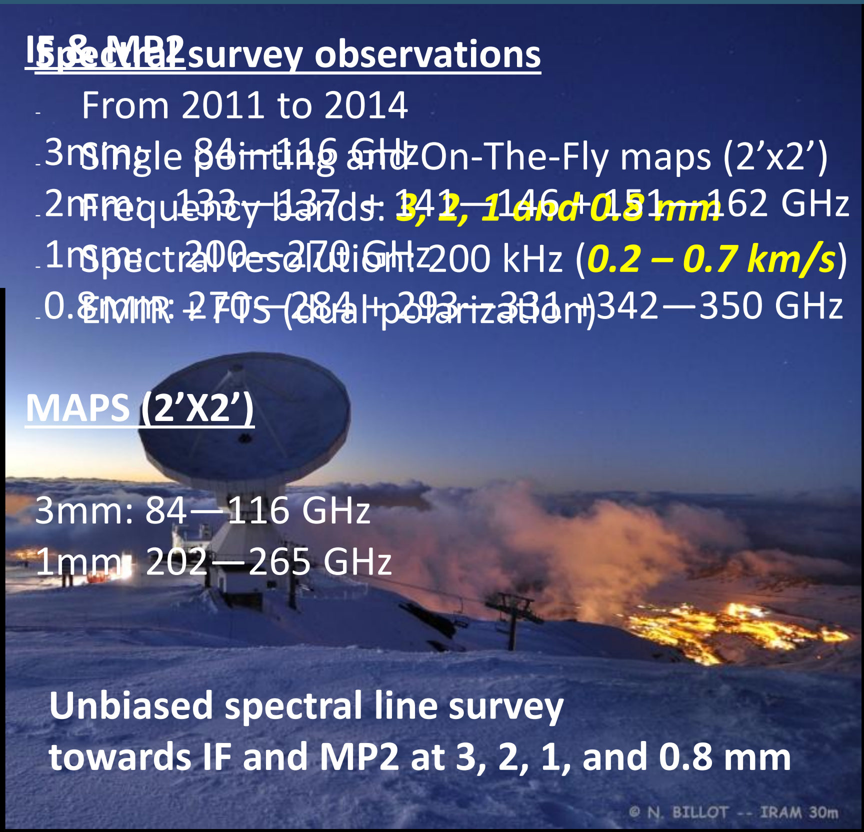
IF & MP2

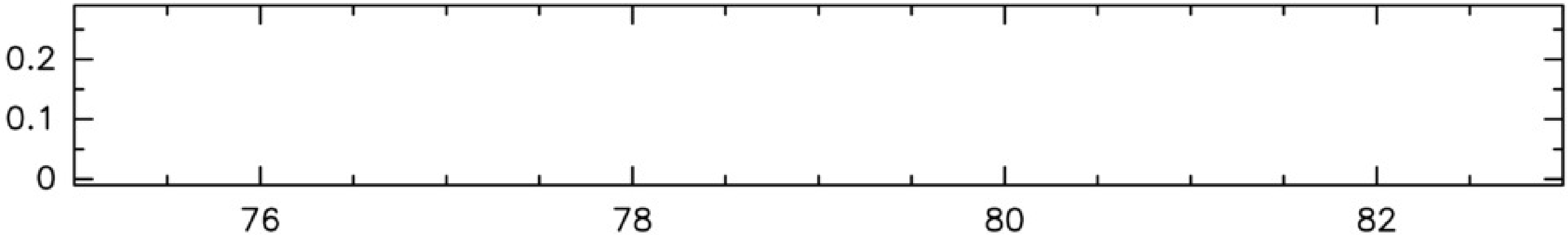
- 3mm: 84—116 GHz
- 2mm: 133—137 + 141—146 + 151—162 GHz
- 1mm: 200—270 GHz
- 0.8mm: 270—284 + 293—331 +342—350 GHz

MAPS (2'X2')

3mm: 84—116 GHz
1mm: 202—265 GHz

Unbiased spectral line survey towards IF and MP2 at 3, 2, 1, and 0.8 mm





Molecular families

- Radio Recombination Lines
- Ionic species
- Sulphurated molecules
- Complex molecules
- Hydrocarbons
- Nitrogenated species
- Deuterated molecules

≈ 60 different species grouped in ***families***

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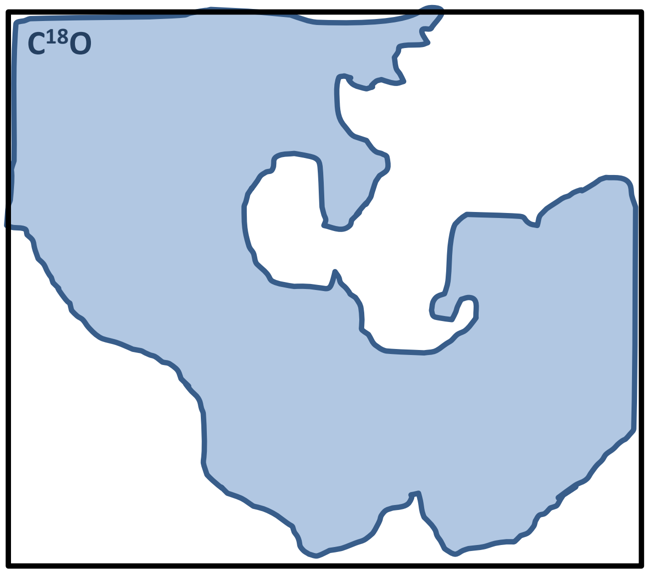

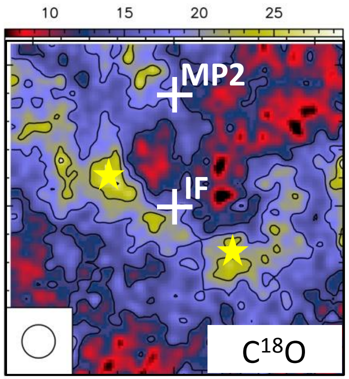

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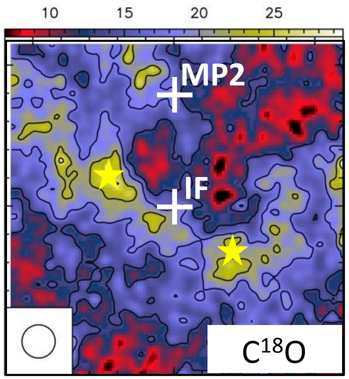

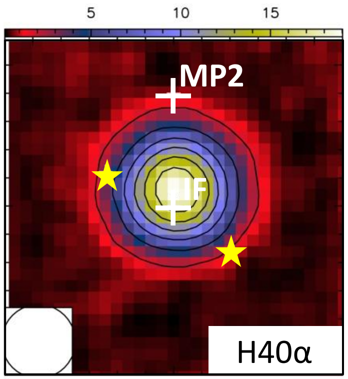

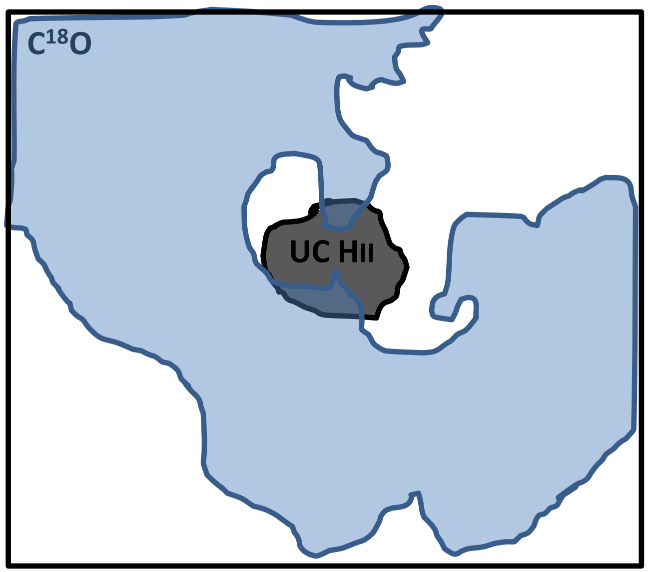

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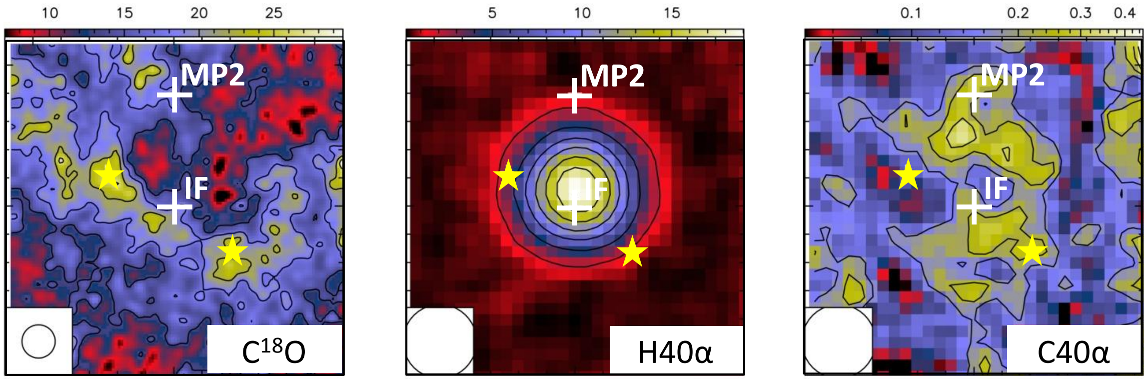

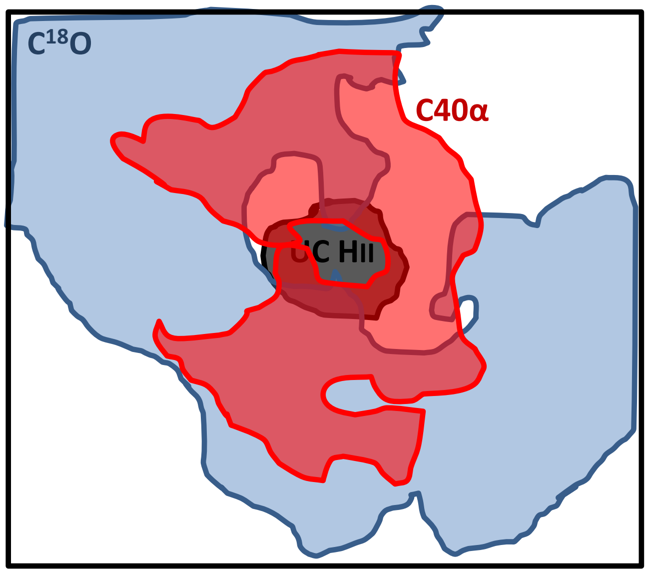

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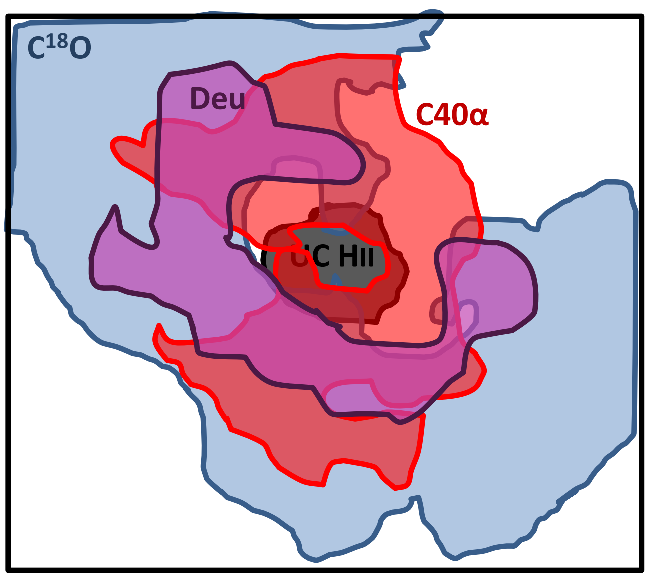

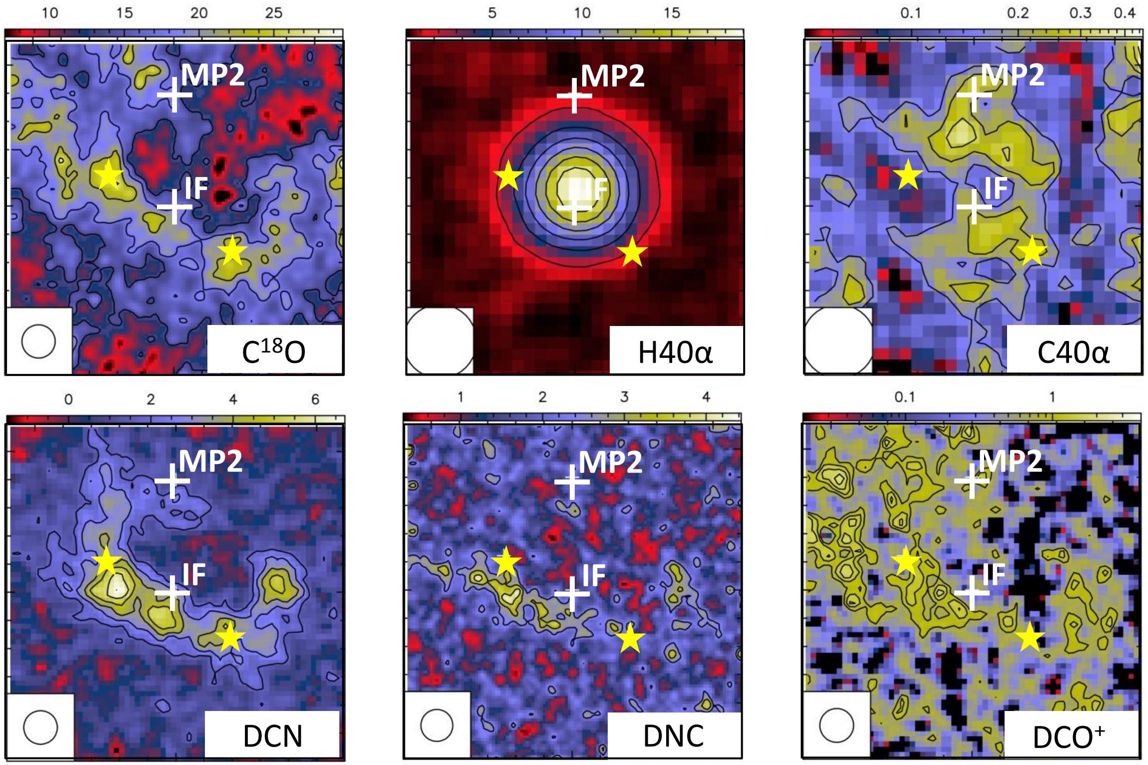

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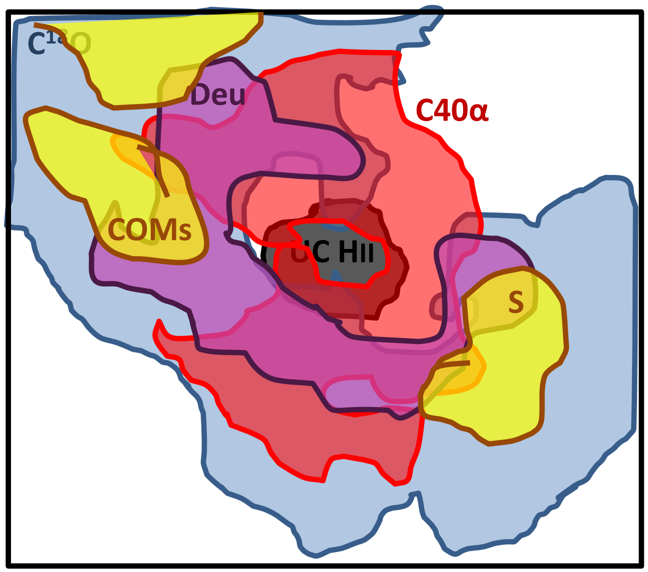

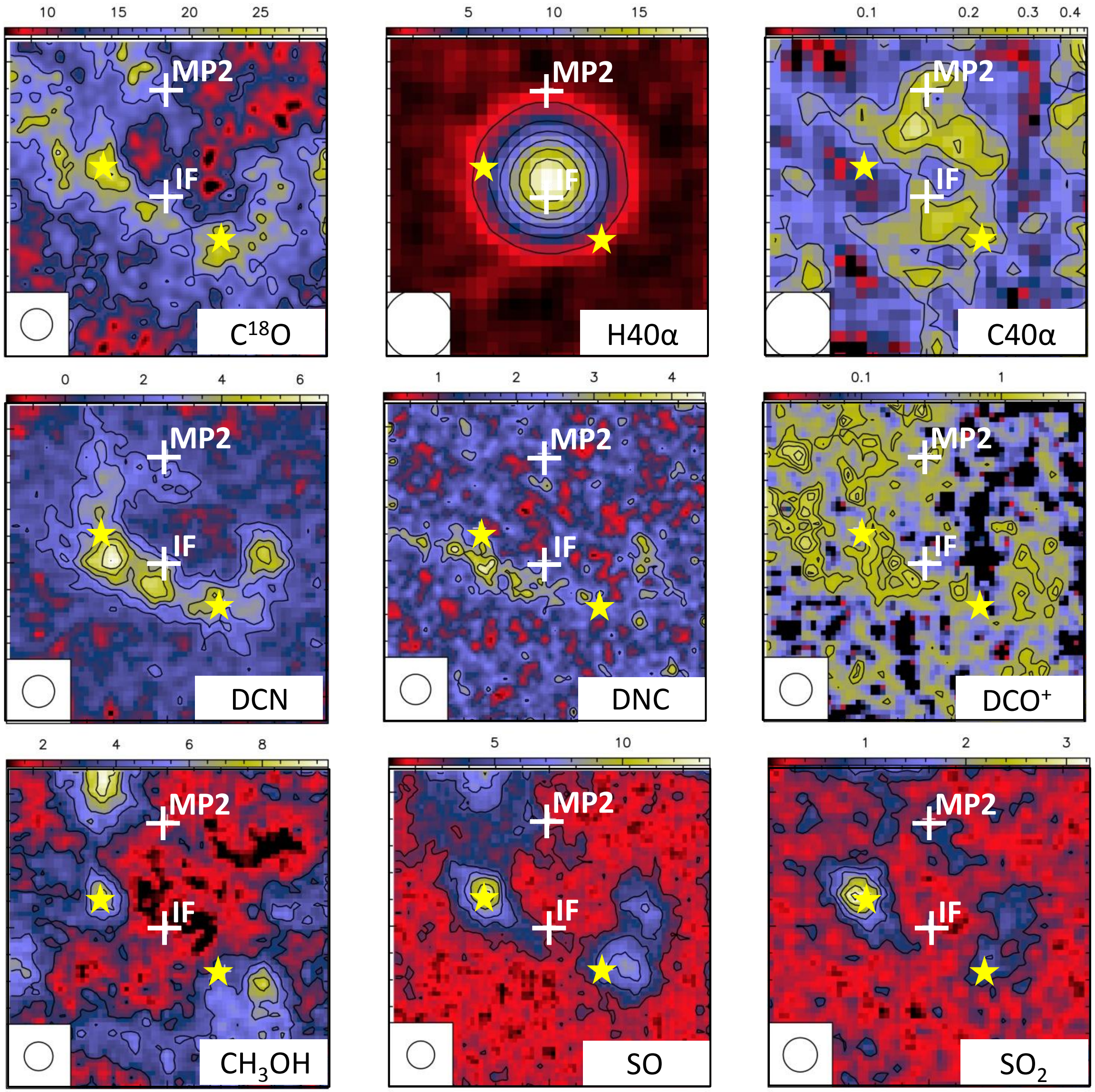

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… chemical segregation
… tracers of PDRs with different physical properties
… kinematical properties for each molecular family
… if you want to know more about this, ***please, talk to me!***

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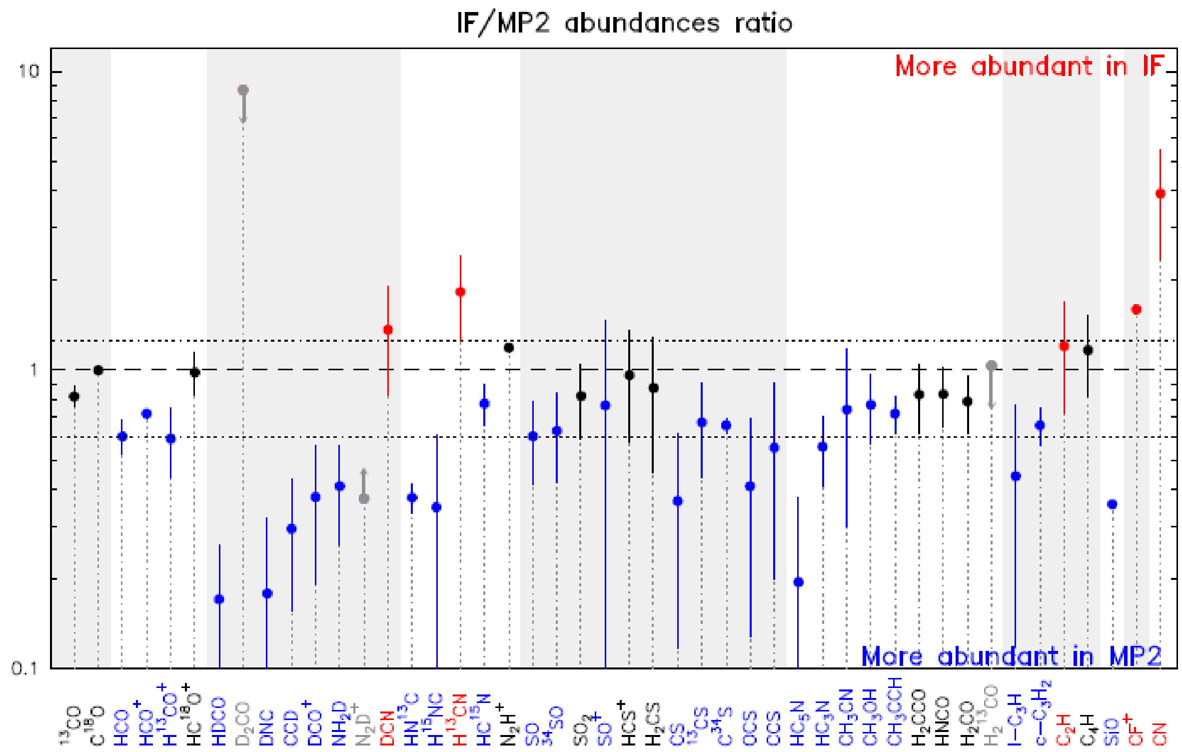
… **chemical abundances towards the two PDRs**



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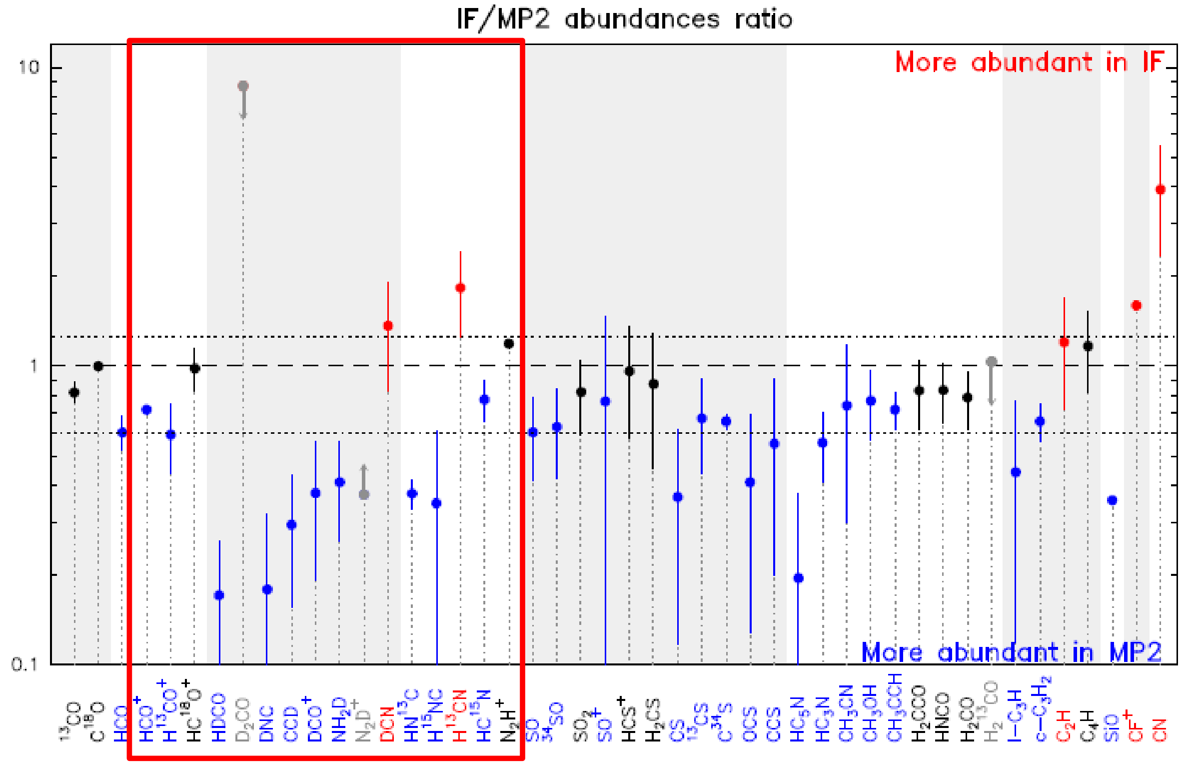
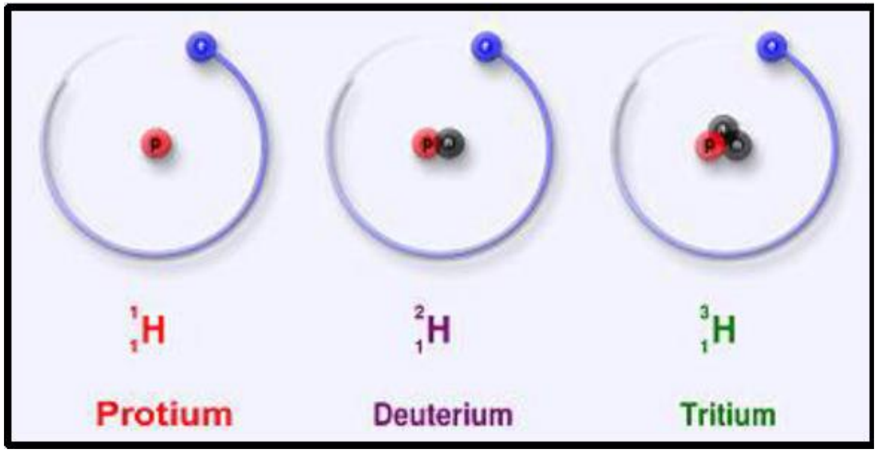


Why are important the deuterated molecules?



It is thought that all the deuterium found in nature was produced during the Big Bang (elemental abundance of $\boldsymbol{10^{-5}}$)

… but D_{frac} in star forming regions has been mesured to be ≈ 0.1 (Busquet et al 2010; Fontani et al 2011)

Deuteration in ***cold clouds*** ($T_K < 20$ K) occurs via $\mathbf{H_3^+ + HD \rightarrow H_2D^+ + H_2}$ (e.g. in pre-stellar cores)
For $T_K > 30$ K, this reaction is very inefficient

Deuteration in ***warm regions*** ($30 < T_K < 100$ K) has been proposed to proceed via the ion reactions

$$CH_3^+ + HD \rightarrow \mathbf{CH_2D^+} + H_2$$
$$C_2H_2^+ + HD \rightarrow \mathbf{C_2HD^+} + H_2$$

Roueff et al (2007)

Deuteration in ***hot cores*** ($T_k > 100$ K) is originated by the ***evaporation of ice dust mantles***
The deuteration is a fossil of the pre-stellar phase (Parise et al 2004)

Deuterated molecules

Parise et al (2007) detected DCN, DCO^+ and HDCO in the ***Orion Bar***.

D_{frac}(HCN) → 0.01

D_{frac}(HCO^+) → 0.0006

D_{frac}(H_2CO) → 0.006

Deuteration in ***warm regions*** (30 < T_K < 100 K) has been proposed to proceed via the ion reactions:

CH_3^+ + HD → $\mathbf{CH_2D^+}$ + H_2

$C_2H_2^+$ + HD → $\mathbf{C_2HD^+}$ + H_2

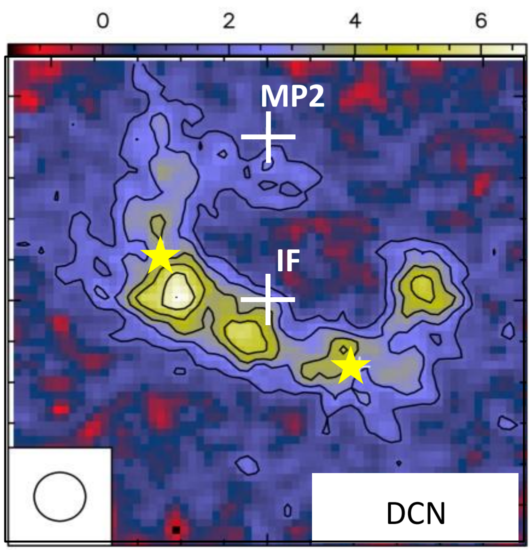
Roueff et al (2007)

They interpreted these values as the consequence of ***gas-phase chemistry*** driven by ion-molecule reactions with CH_2D^+ and C_2HD^+… But, they did not detect species such as C_2D and DNC, which are not expected to form on grain surfaces, and an extensive ***comparison with gas-phase models was not possible***

Deuterated molecules

DCN, DNC, DCO⁺, D_2CO, CCD, HDCO, NH_2D and ***N_2D^+***
have been detected in ***MonR2***

	IF		***MP2***	
Species	***T_{rot} (K)***	***N (10^{12} cm^{-2})***	***T_{rot} (K)***	***N (10^{12} cm^{-2})***
C_2D	19	3.1	20	9.6
DCN	44	2.1	12	1.4
DNC	45	0.1	12	0.5
DCO^+	19	0.1	31	0.3
D_2CO	38	<23.7	38	2.5
HDCO	38	0.4	49	2.3
NH_2D	19	0.4	19	0.9
N_2D^+	…	…	19	<0.2



Treviño-Morales et al (2014)

Deuteration is high in both PDRs suggesting
… deuteration comes from dense warm clumps instead of the most exposed PDR layers.

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NH_2D	19	0.4	19	0.9
N_2D^+	…	…	19	<0.2

Deuterium fractionation (D_{frac})

Ratio	***IF***	***MP2***
HCN/HNC	11.36	2.33
DCN/HCN	0.02	0.03
DNC/HNC	0.01	0.02
C_2D/C_2H	0.02	0.08
$HDCO/H_2CO$	0.01	0.01
DCO^+/HCO^+	0.002	0.005
D_2CO/H_2CO	0.02	0.05
N_2D^+/N_2H_+	…	<0.05
NH_2D/NH_3	0.04	0.06

Treviño-Morales et al (2014)

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… deuteration comes from dense warm clumps instead of the most exposed PDR layers.

Deuterated molecules

	Warm regions			Cold regions		Hot regions	
	Mon R2[a]		Ori Bar[b]	TMC1[c]	Barnard 1[d]	IRAS 16293[e]	Ori KL[f]
	IF	MP2	(Clump 3)				
$H^{13}CN/HN^{13}C$	10	2.33	2.5	0.9–1.5	1.04	...	...
DCN/HCN	0.02	0.03	0.01	0.008	0.025	0.01	...
DNC/HNC	0.01	0.02	< 0.01	0.01	0.11	...	...
DCO^+/HCO^+	0.2×10^{-2}	0.5×10^{-2}	0.6×10^{-3}	0.01	...	0.7×10^{-2}	0.14
C_2D/C_2H	0.02	0.08	< 0.11	0.03–0.06	...	...	...
$HDCO/H_2CO$	0.01	0.01	0.6×10^{-2}	0.05	0.14	0.15	0.14
$D_2CO/HDCO$	< 38.47	1.00	...	...	0.40	0.3	0.021
N_2D^+/N_2H^+	0.015*	$< 5.0 \times 10^{-2}$	...	0.08	0.35	...	< 0.30
NH_2D/NH_3	0.39×10^{-2}	0.6×10^{-2}	...	0.02	0.63	...	0.062

(a) Treviño-Morales et al (2014). (b) Parise et al. (2009). (c) Turner (2001). (d) Daniel et al. (2013); Gerin et al. (2001), Marcelino et al. 2005. (e) Lis et al. (2001); Loinard et al. (2000, 2001); Tiné et al. (2000). (f) Turner 1990.

D_{frac} in MonR2 similar to the Orion Bar

In MonR2 ***deuteration*** seems more ***efficient for HCN, HNC*** and ***C2H***

Different [HDCO]/[H_2CO] and [DCO^+]/[HCO^+] values suggest … ***different deuteration processes at low and high temperatures***

[HDCO]/[H_2CO] suggest… ***ice-mantle-evaporation*** chemistry is ***not dominant*** in MonR2

Treviño-Morales et al (2014)

Pseudo-time-dependent gas-phase chemical model

Parameter		Model A
T_k	Temperature	50 K
n_H	H density	2×10^6 cm^{-3}
He/H	Helium abundance	0.1
O/H	Oxygen abundance	1.8×10^{-4}
C/H	Carbon abundance	7.3×10^{-5}
N/H	Nitrogen abundance	2.1×10^{-5}
S/H	Sulfur abundance	8×10^{-8}
Fe/H	Iron abundance	2×10^{-8}
D/H	Deuterium fraction	1.5×10^{-5}
ortho/para ratio	OPR	1×10^{-2}
ζ	Cosmic ray ionization rate	5×10^{-17} s^{-1}

Chemical model by Roueff et al (2007)

Meudon gas-phase network (Gerlich et al 2002, Roueff et al 2005)

- *214 species* (including deuterated compounds)
- more than *3300 chemical reactions*

For **MonR2** we build a grid of models with

- temperature of **50 K**
- two densities: n_H = **3 x 10^5 cm^{-3}** and **2 x 10^6 cm^{-3}**
- ortho/para = 0.3 (equilibrium value at 50 K), 0.01, 0.001

no big differences for t < 1 Myr

Treviño-Morales et al (2014)

Pseudo-time-dependent gas-phase chemical model

Parameter		Model A	Model B	Model C	Model D
T_k	Temperature	50 K	50 K	50 K	50 K
n_H	H density	2×10^6 cm^{-3}	3×10^5 cm^{-3}	2×10^6 cm^{-3}	3×10^5 cm^{-3}
He/H	Helium abundance	0.1	0.1	0.1	0.1
O/H	Oxygen abundance	1.8×10^{-4}	1.8×10^{-4}	3.3×10^{-4}	3.3×10^{-4}
C/H	Carbon abundance	7.3×10^{-5}	7.3×10^{-5}	1.3×10^{-4}	1.3×10^{-4}
N/H	Nitrogen abundance	2.1×10^{-5}	2.1×10^{-5}	7.5×10^{-5}	7.5×10^{-5}
S/H	Sulfur abundance	8×10^{-8}	8×10^{-8}	1.8×10^{-5}	1.8×10^{-5}
Fe/H	Iron abundance	2×10^{-8}	2×10^{-8}	2×10^{-8}	2×10^{-8}
D/H	Deuterium fraction	1.5×10^{-5}	1.5×10^{-5}	1.5×10^{-5}	1.5×10^{-5}
ortho/para ratio	OPR	1×10^{-2}	1×10^{-2}	1×10^{-2}	1×10^{-2}
ζ	Cosmic ray ionization rate	5×10^{-17} s^{-1}	5×10^{-17} s^{-1}	5×10^{-17} s^{-1}	5×10^{-17} s^{-1}

Parameter		Model E		Model F	
		Phase 1	Phase 2[a]	Phase 1	Phase 2[b]
T_k	Temperature	15 K	50 K	15 K	50 K
n_H	H density	2×10^6 cm^{-3}	2×10^6 cm^{-3}	2×10^6 cm^{-3}	2×10^6 cm^{-3}
He/H	Helium abundance	0.1	...	0.1	...
O/H	Oxygen abundance	1.8×10^{-4}	...	1.8×10^{-4}	...
C/H	Carbon abundance	7.3×10^{-5}	...	7.3×10^{-5}	...
N/H	Nitrogen abundance	7.5×10^{-5}	...	7.5×10^{-5}	...
S/H	Sulfur abundance	2.1×10^{-5}	...	2.1×10^{-5}	...
Fe/H	Iron abundance	8×10^{-8}	...	8×10^{-8}	...
D/H	Deuterium fraction	2×10^{-8}	...	2×10^{-8}	...
ortho/para ratio	OPR	1×10^{-4}	1×10^{-2}	1×10^{-4}	1×10^{-2}
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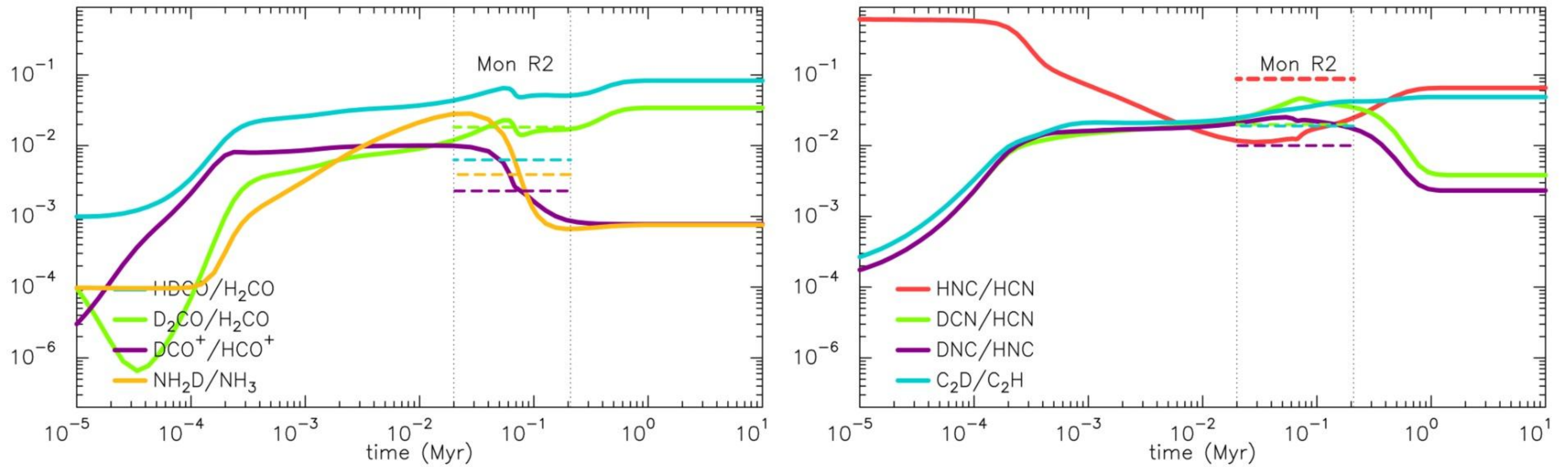
For **MonR2** we build a grid of models with
- temperature of **50 K**
- densities n_H = **2×10^6 cm^{-3}**
- ortho/para = 0.01



Treviño-Morales et al (2014)

Pseudo-time-dependent gas-phase chemical model

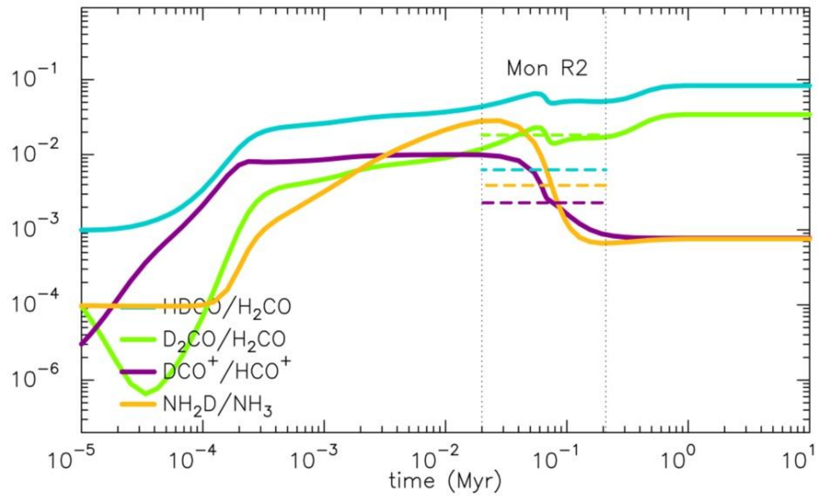
$D_{frac} \approx 0.01$ for HNC, HCN, C_2H, H_2CO
$D_{frac} < 0.001$ for HCO^+, N_2H^+

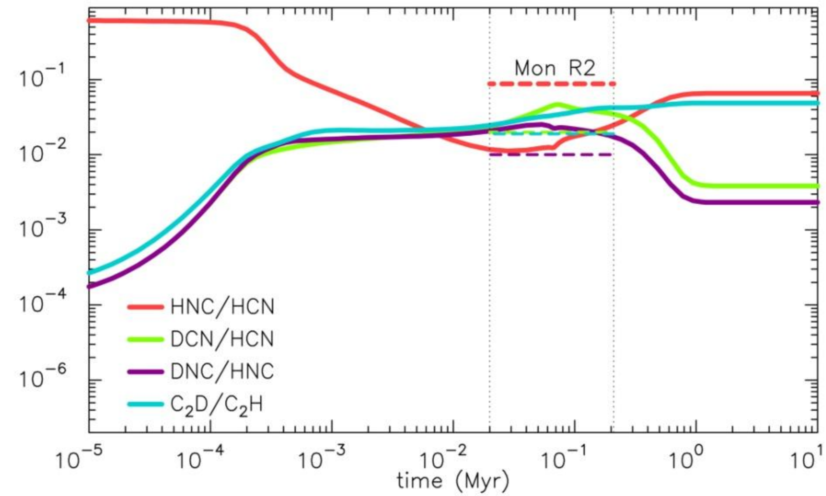
... values consistent with gas-phase model predictions for a time of ≈ 0.1 Myr (i.e. age of UC HII regions)

Deuteration in warm regions seems to proceed via the ***gas-phase reactions***

$$CH_3^+ + HD \rightarrow CH_2D^+ + H_2$$
$$C_2H_2^+ + HD \rightarrow C_2HD^+ + H_2$$

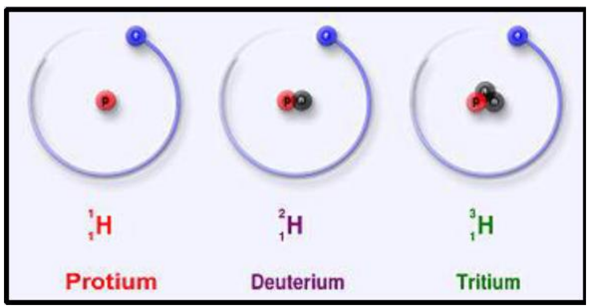
Deuterium chemistry is a good chemical clock. D_{frac} values of different molecules (eg HCN, HNC and C_2H), with long chemical scale-times, are necessary to obtain accurate age estimates



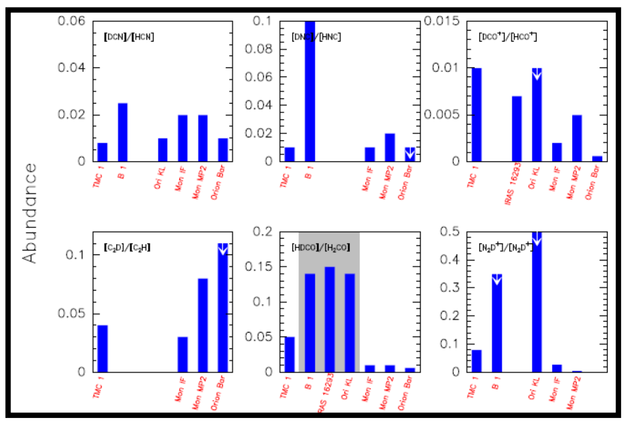


Treviño-Morales et al (2014)

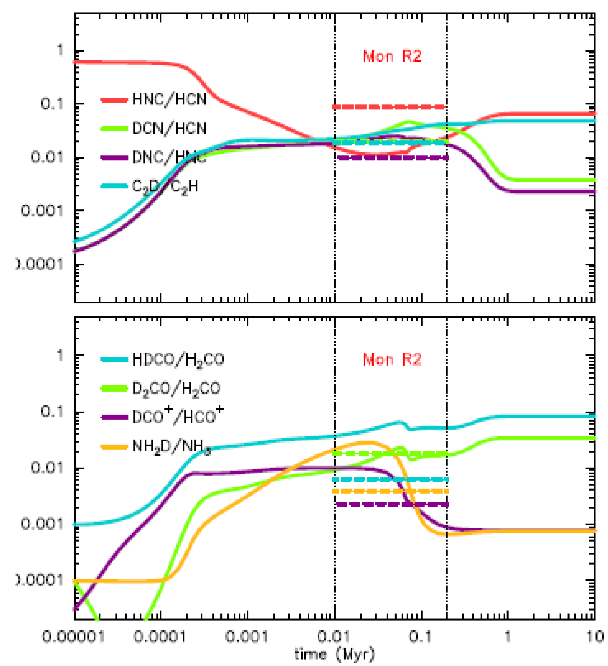
Take-home messages



High deuteration levels in warm regions



Ice-mantle-evaporation chemistry is not dominant in MonR2

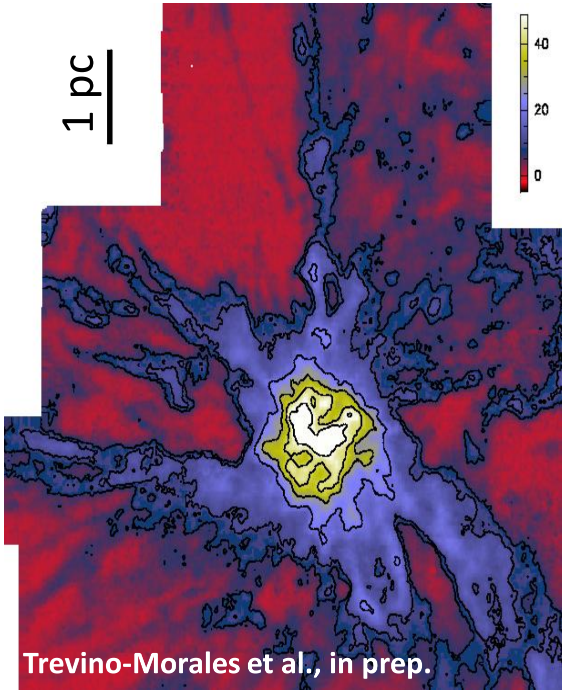


Deuteration consistent with gas-phase chemistry

D_{frac} is good chemical clock

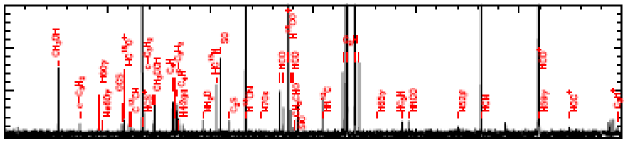
Thanks for your attention

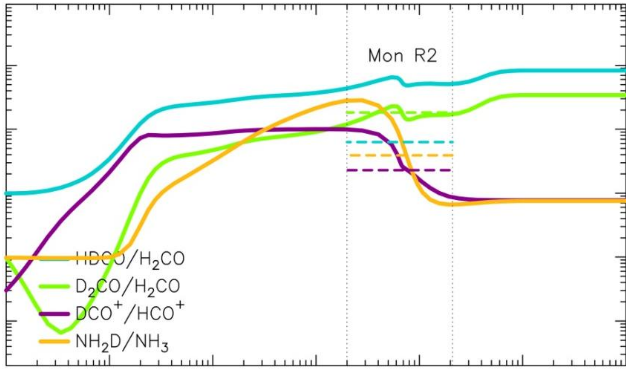
Future work



Characterization of filaments:

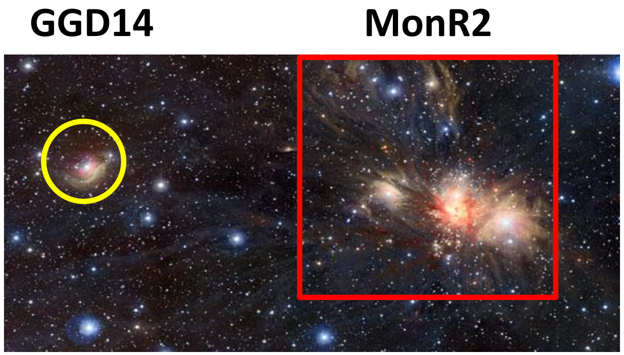
- Dynamical study
- Comparison with simulations





Chemical models:

- Detailed study of all the molecular families
- PDR time-dependent chemical model applied to all the species



Other PDRs?

- Expand the study to other regions
- Next target: GGD14
- Observations already on-going:
  spectral survey
  small maps