The chemical and physical structure of pre-stellar cores

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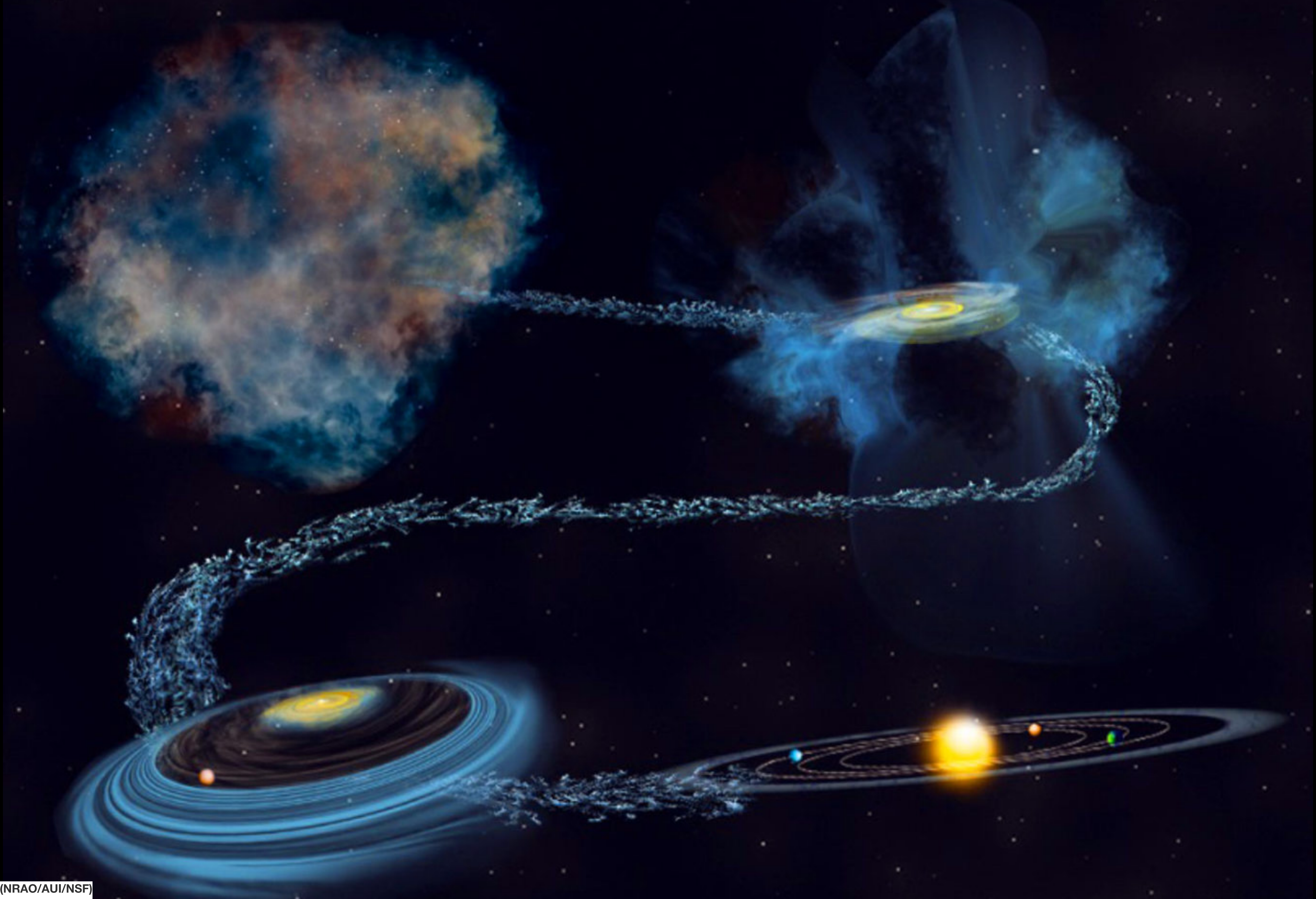
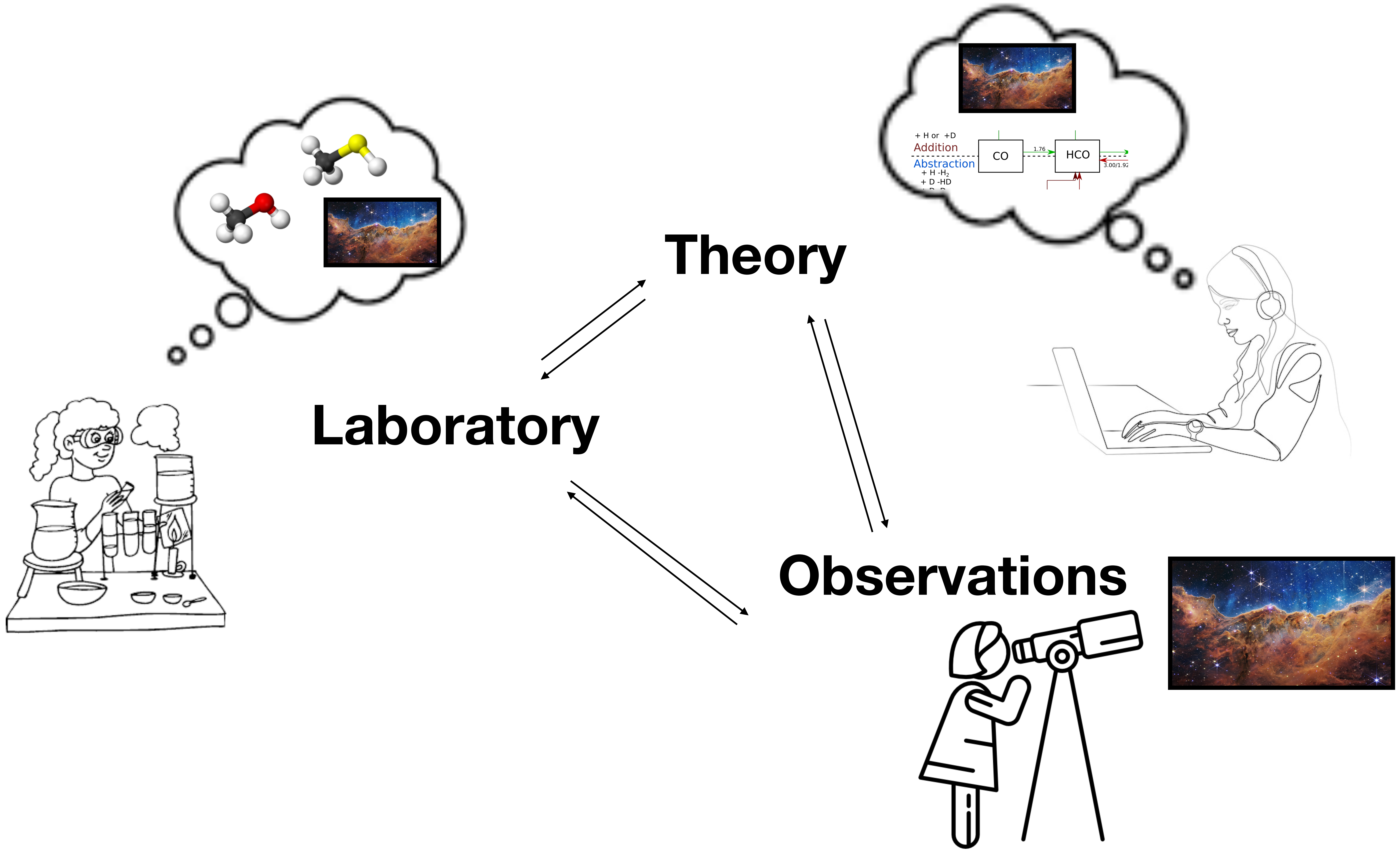


Image credit: Bill Saxton (NRAO/AUI/NSF)

What information can we infer from the observation of molecules?

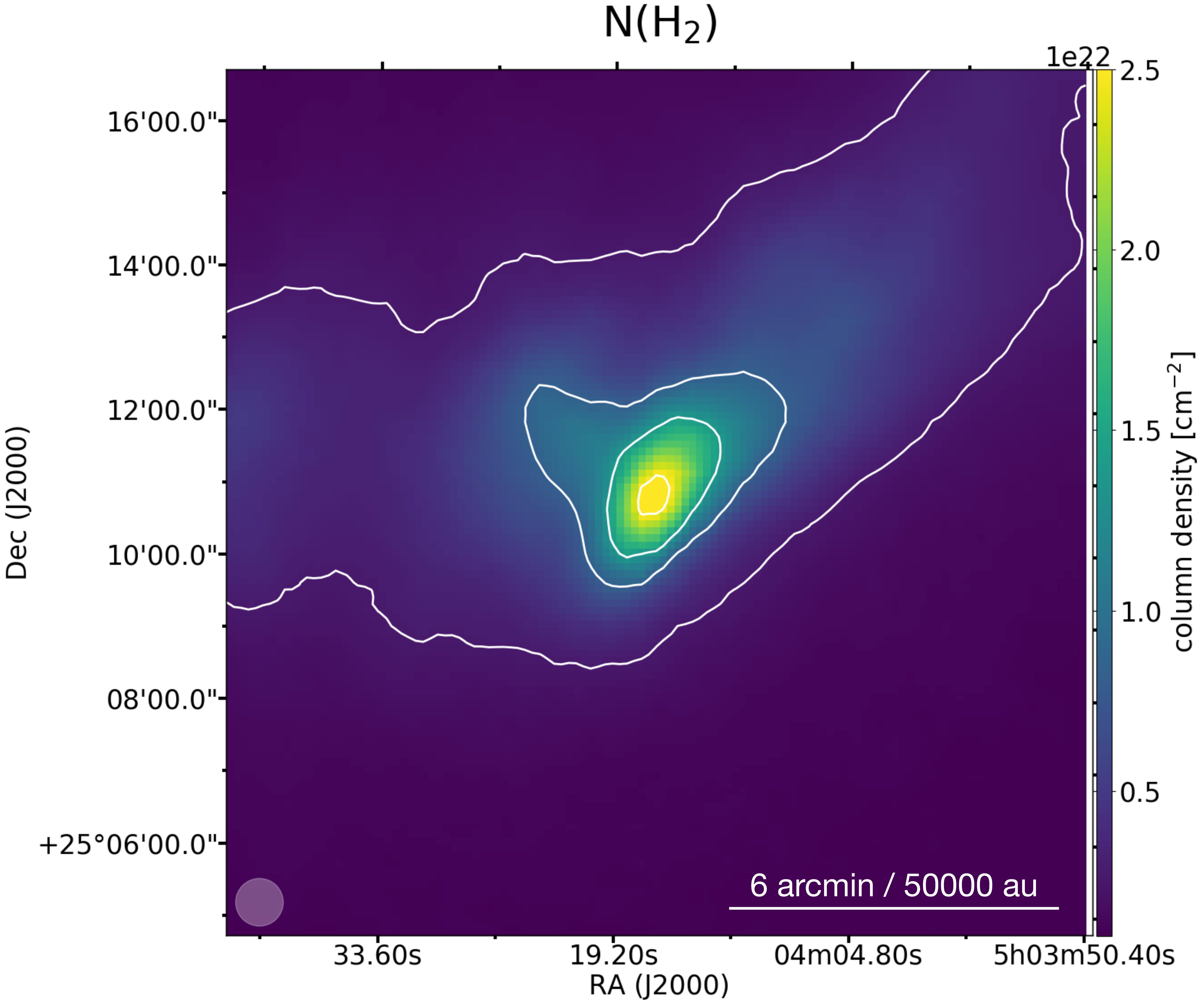
- Chemical inventory
- Isotopic fractionation
- Temperature
- Density
- Kinematics

Image credit: NASA, ESA, CSA, and STScI



Theory
+ H or +D
Addition
Abstraction
+ H -H2
+ D -HD
CO
1.76
HCO
Laboratory
Observations

The prototypical pre-stellar core L1544



[Spezzano et al. 2016]

H_2 column density map computed from *Herschel*/SPIRE data at 250, 350 and 500 micron

- centrally concentrated (Ward-Thompson et al. 1999)
- shows signs of contraction motion (Caselli et al. 2012, Redaelli et al. 2022)
- central density is ~10^6 cm^{-3} and the central temperature is ~ 6 K (Crapsi et al. 2007)
- high degree of CO freeze-out and high level of deuteration towards its center (Crapsi et al. 2005)
- chemically rich, showing spatial inhomogeneities in the distribution of molecular emission (Spezzano et al. 2017)

***Herschel* Space Observatory**

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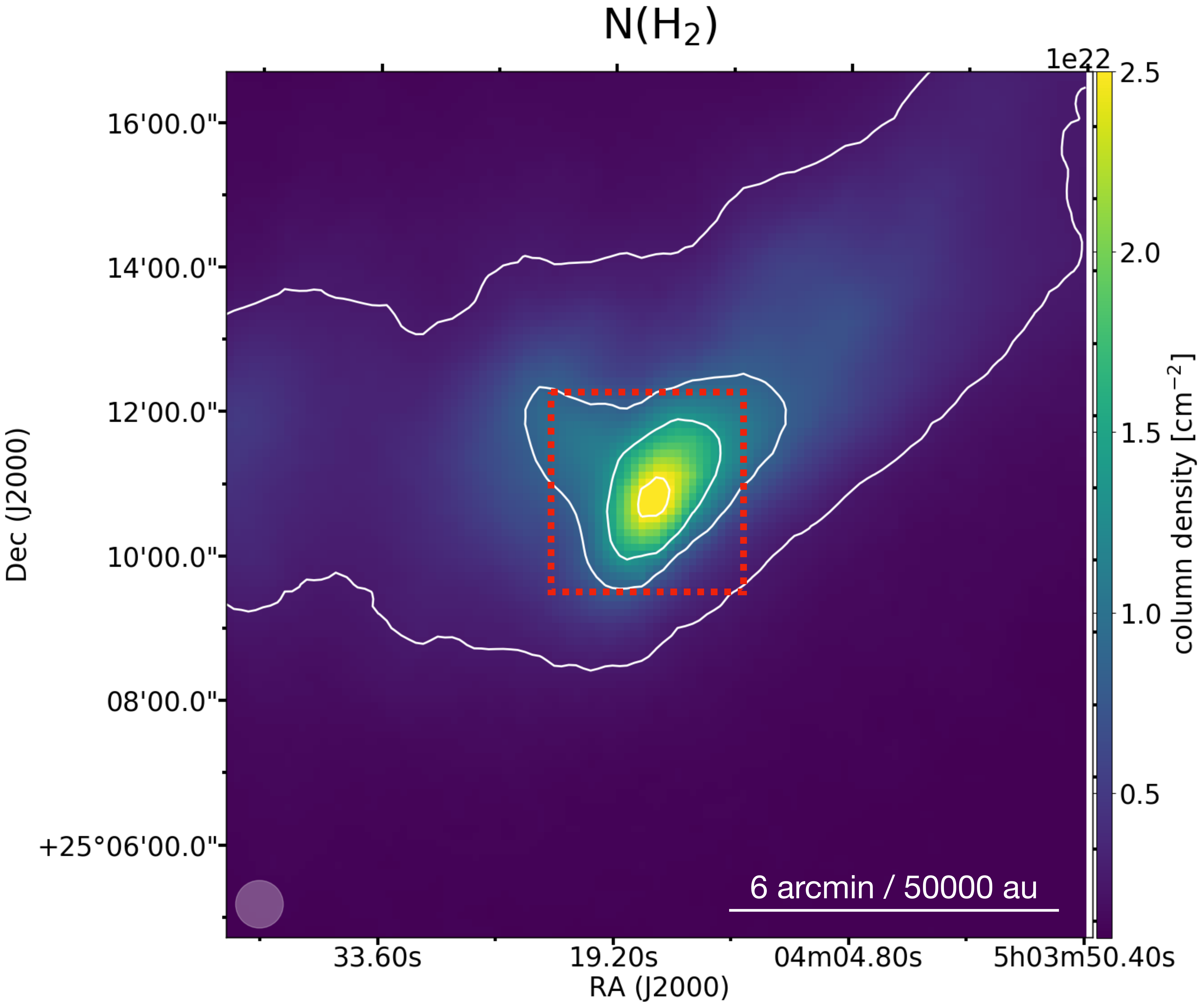

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The chemical structure of pre-stellar cores

Image credit: Olivia Harper Wilkins

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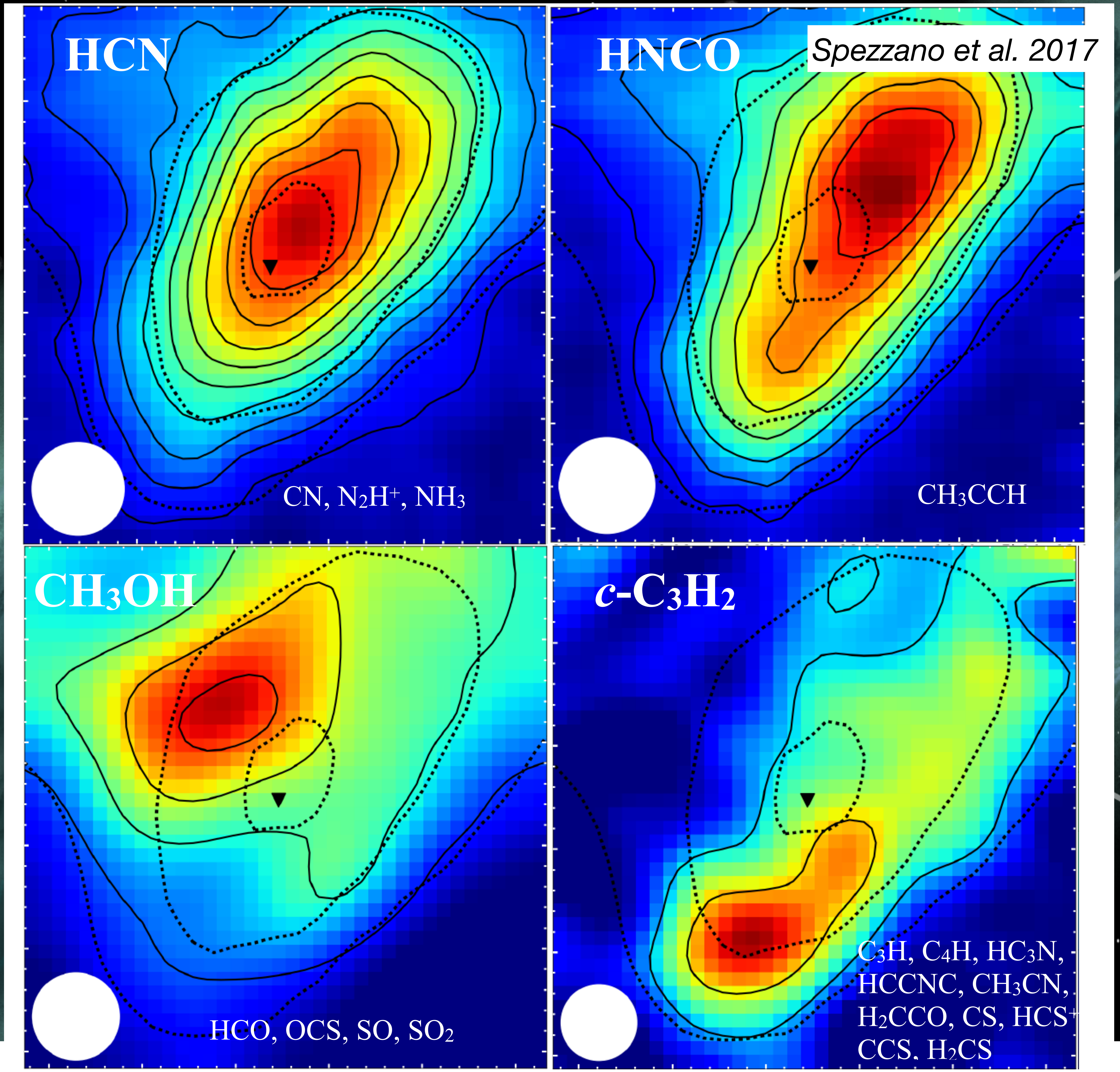
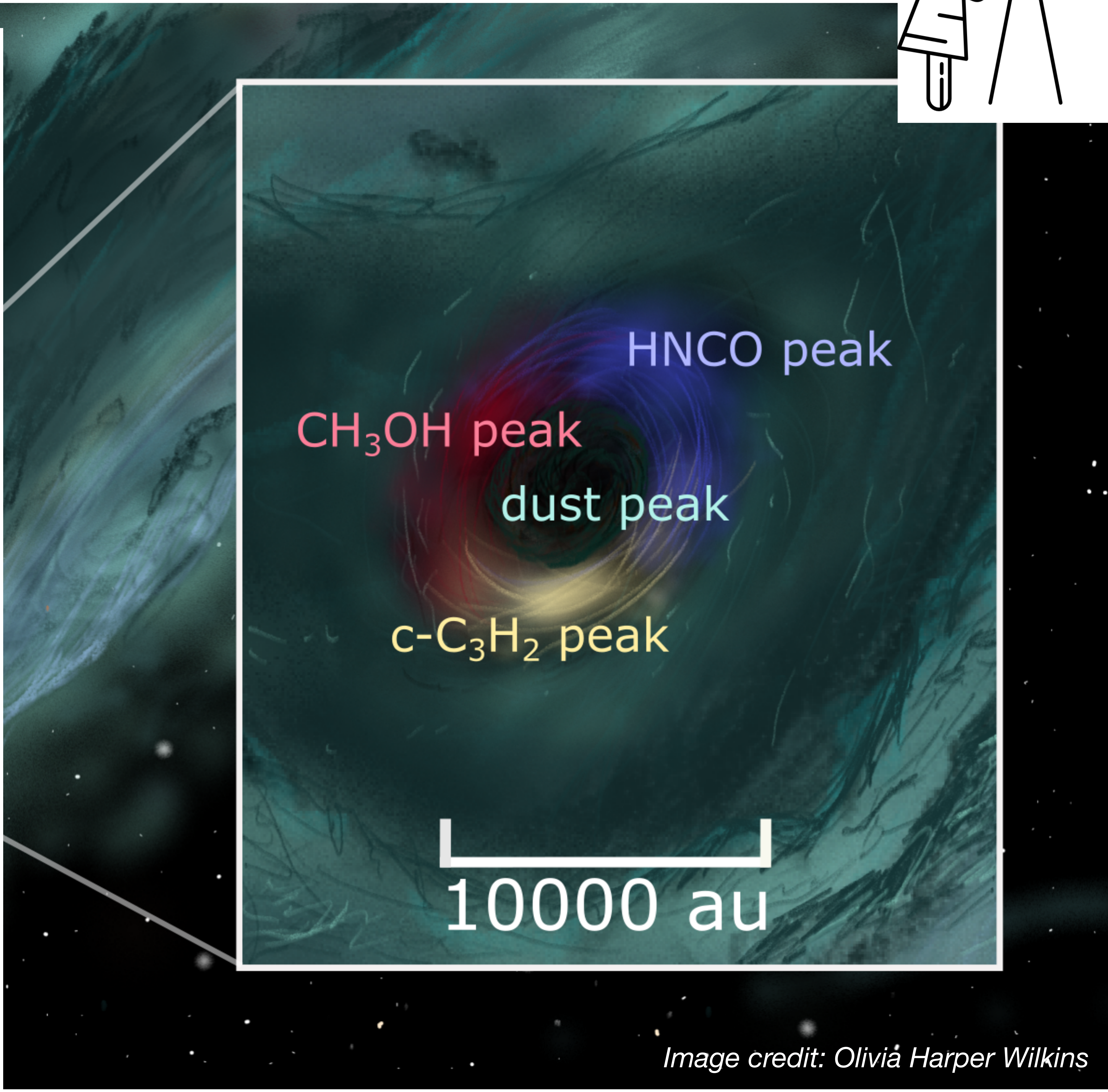
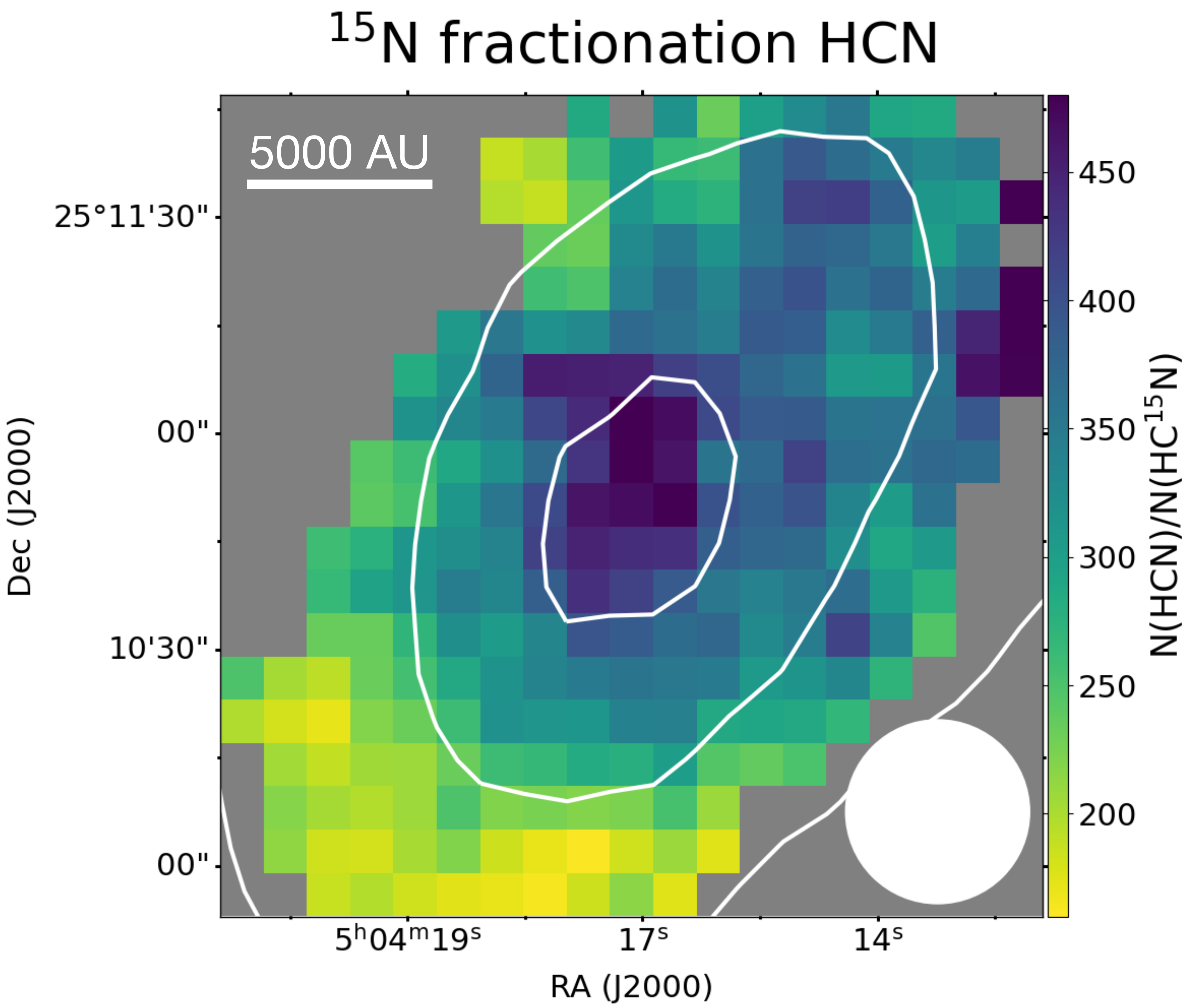




Nitrogen fractionation and non-uniform illumination

IRAM 30m telescope

Pre-stellar core



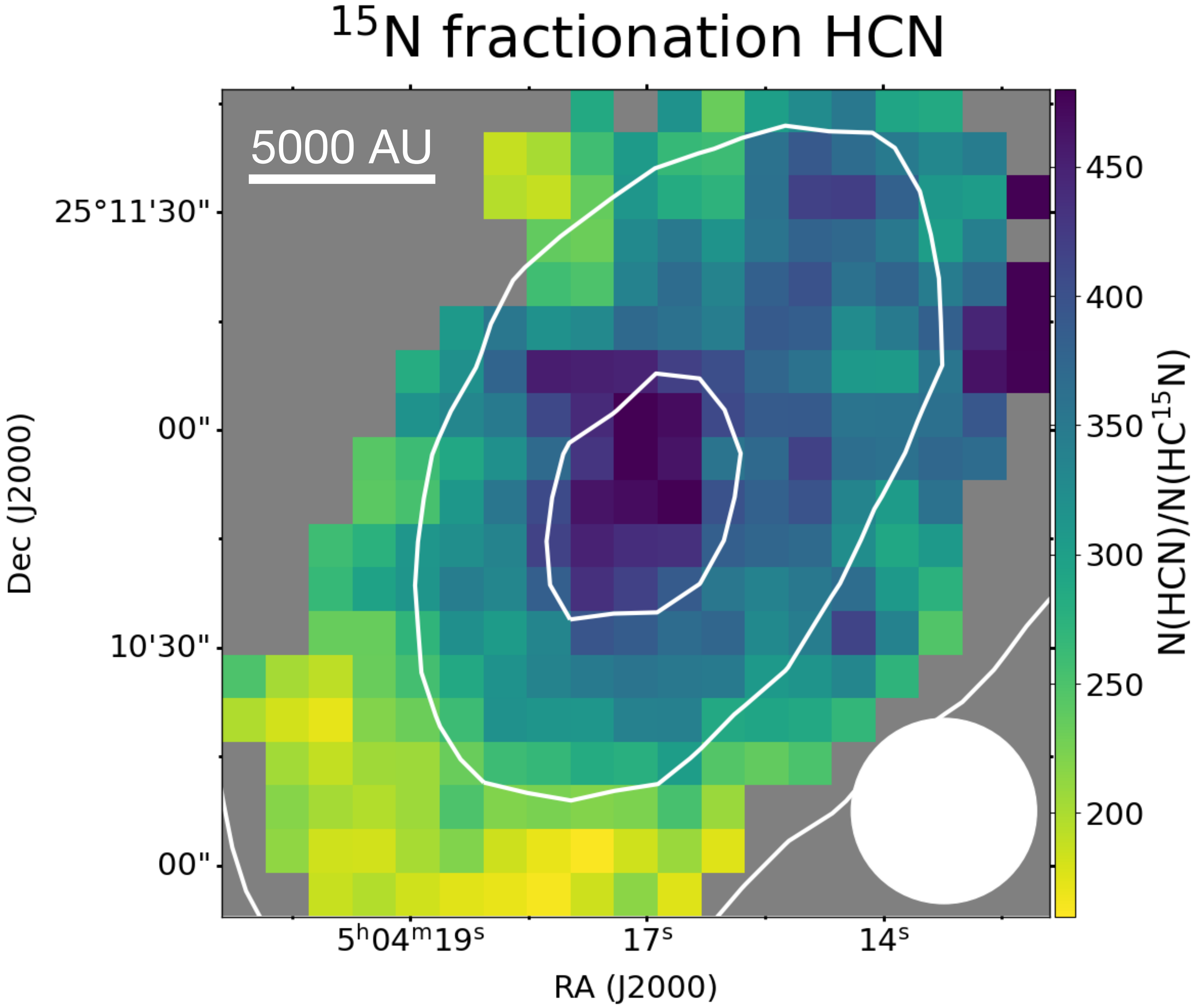
Spezzano et al. in 2022

Nitrogen fractionation and non-uniform illumination

IRAM 30m telescope

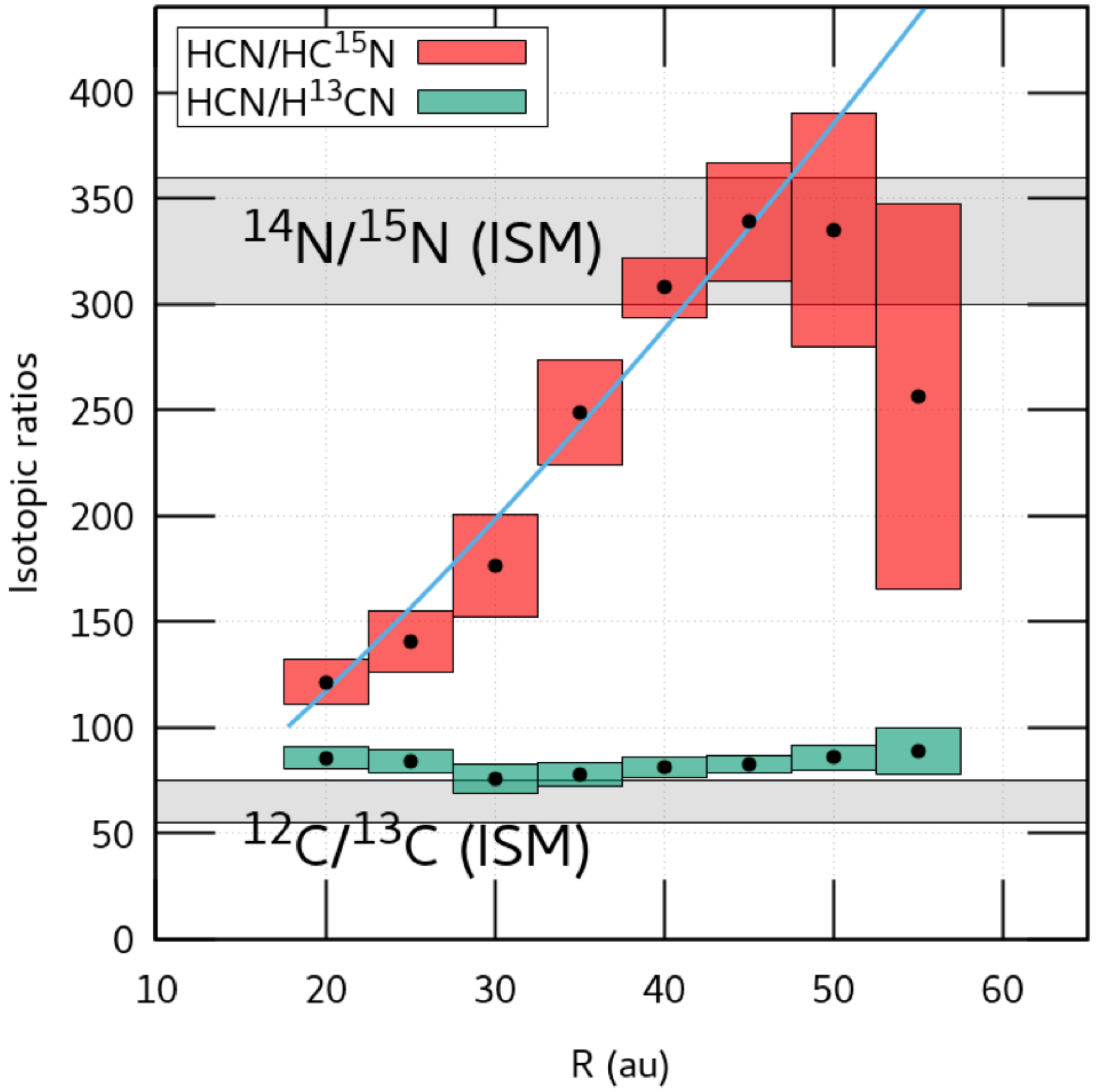
ALMA

Pre-stellar core



Spezzano et al. in 2022

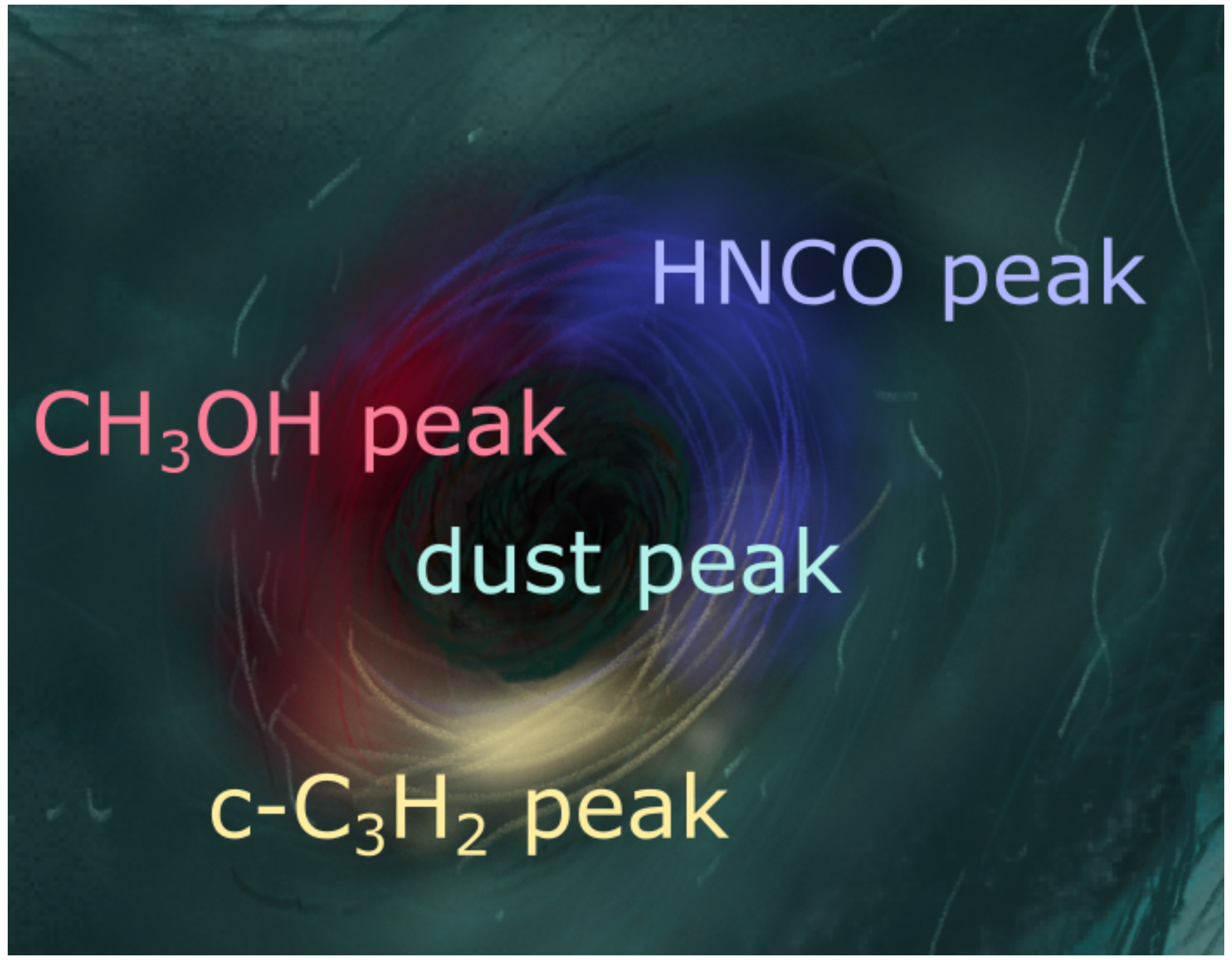
Protoplanetary disk



Hily-Blant et al. 2019

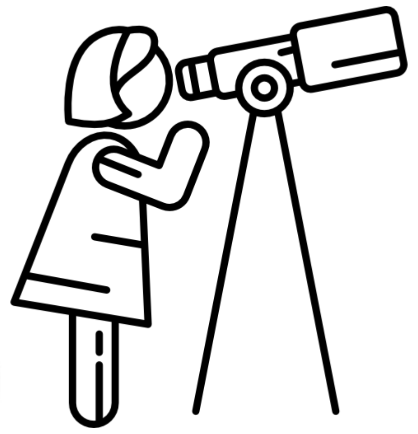
The physical structure of pre-stellar cores

Lin, Spezzano et al. 2022



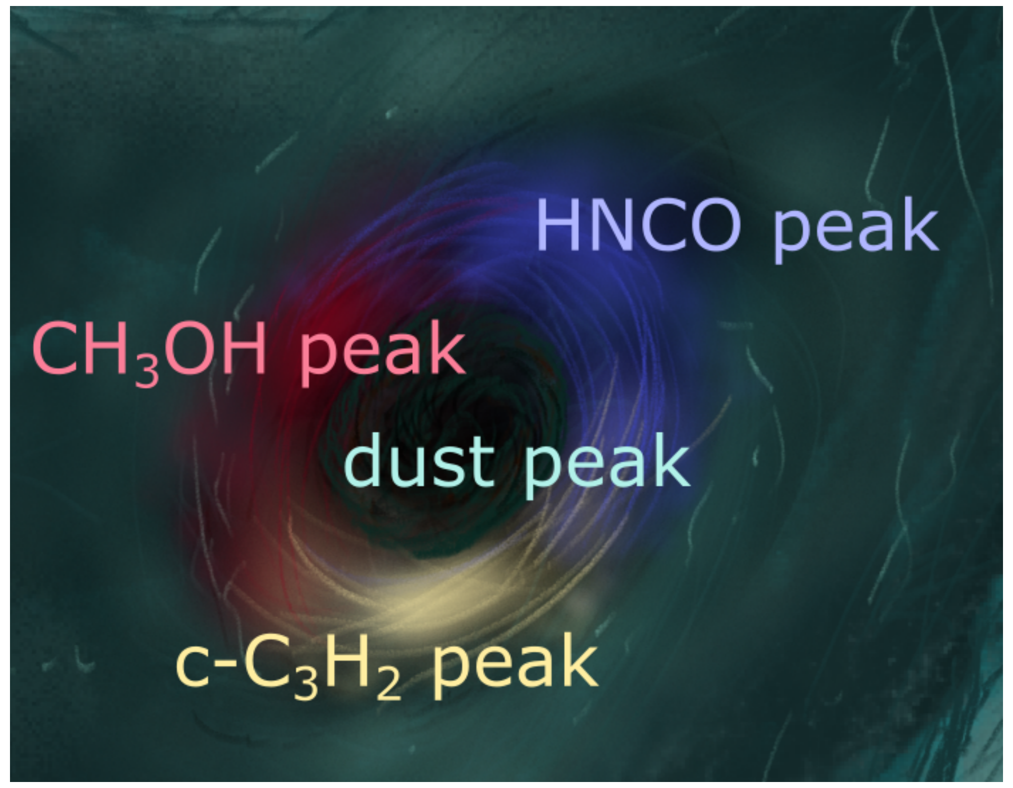
Molecule	Transitions	Frequency (GHz)	E_{up} (K)	Critical density [a] ($\times10^4$ cm^{-3})
CH_3OH-*E*	$2_{-1,2}$-$1_{-1,1}$	96.7394	12.5	1.3
	$2_{0,2}$-$1_{0,1}$	96.7445	20.1	15.4
	$2_{1,2}$-$1_{1,1}$	96.7555	28.0	31.5
	$3_{0,3}$-$2_{0,2}$	145.0938	27.1	26.2
	$3_{-1,3}$-$2_{-1,2}$	145.0974	19.5	4.4
	$3_{1,3}$-$2_{1,2}$	145.1319	35.0	46.1
	$4_{0,4}$-$4_{-1,4}$	157.2461	36.3	44.2
	$1_{0,1}$-$1_{-1,1}$	157.2708	15.4	9.3
	$3_{0,3}$-$3_{-1,3}$	157.2723	27.1	26.2
	$2_{0,2}$-$2_{-1,2}$	157.2760	20.1	15.3
c-C_3H_2	$3_{1,2}$-$2_{2,1}$	145.0896	16.1	10.4
	$3_{3,0}$-$2_{2,1}$	216.2788	19.5	33.7
	$6_{1,6}$-$5_{0,5}$	217.8221	38.6	70.8
	$4_{3,2}$-$3_{2,1}$	227.1691	29.1	52.0
HNCO[b]	$5_{0,5}$-$4_{0,4}$	109.9058	15.8	5.1
	$6_{0,6}$-$5_{0,5}$	131.8857	22.1	8.8
	$7_{0,7}$-$6_{0,6}$	153.8651	29.5	13.9
	$8_{0,8}$-$7_{0,7}$	175.8437	38.0	21.5

What are the physical conditions at the different molecular peaks?

The physical structure of pre-stellar cores

Lin, Spezzano et al. 2022



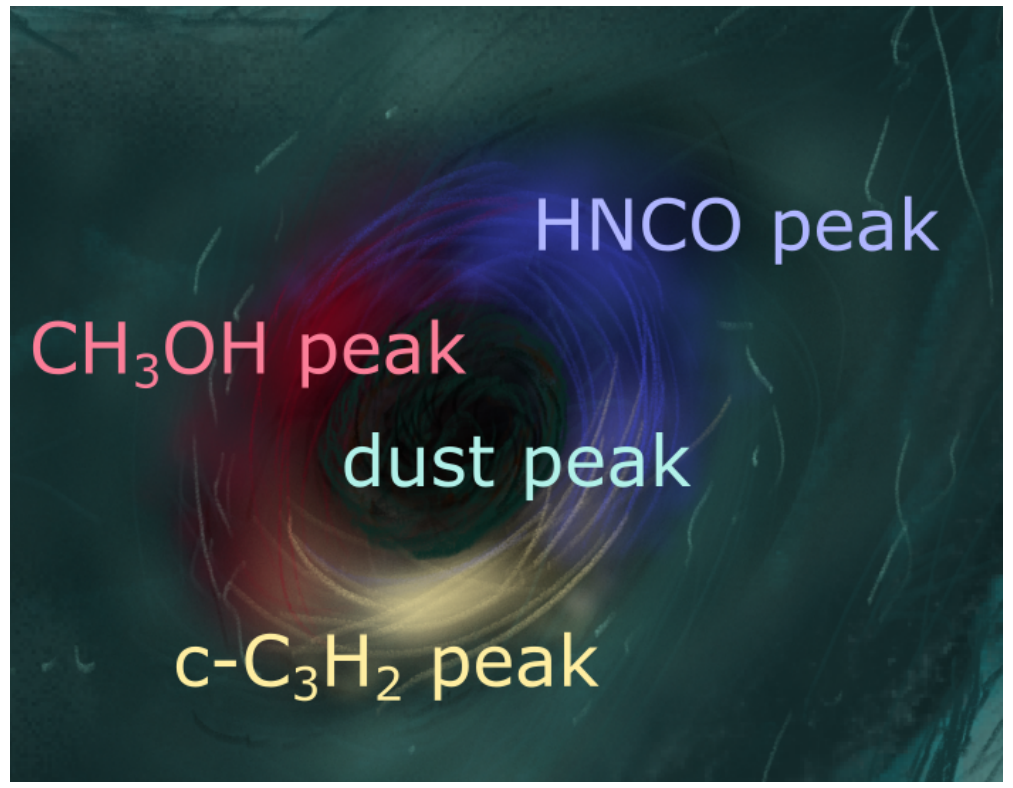
Results from RADEX models

Position	CH_3OH $n(H_2)$ cm^{-3}	CH_3OH T_{kin} K	CH_3OH N_{mol} cm^{-2}	c-C_3H_2 $n(H_2)$ cm^{-3}	c-C_3H_2 T_{kin} K	c-C_3H_2 N^a_{mol} cm^{-2}	HNCO $n(H_2)$ cm^{-3}	HNCO T_{kin} K	HNCO N_{mol} cm^{-2}
Dust peak	4.7×10^5(0.05)	7.4(0.2)	1.3×10^{13}(0.05)	5.9×10^4(0.3)	13.2(1.2)	1.4×10^{13}(0.2)	6.9×10^4(0.4)	11.8(1.0)^b	4.3×10^{12}(0.1)
CH_3OH peak	3.4×10^5(0.05)	16.5(0.2)	1.6×10^{13}(0.03)						
c-C_3H_2 peak	6.7×10^5(0.2)	8.4(0.7)	0.9×10^{13}(0.07)	7.0×10^3(0.3)	15.2(0.7)^b	1.5×10^{14}(0.3)			
HNCO peak	6.3×10^5(0.1)	15.0(1.5)	1.2×10^{13}(0.03)				4.4×10^4(1.1)	11.6(3.0)^b	8.2×10^{12}(0.1)

The emission of the three molecules traces different gas layers!

The physical structure of pre-stellar cores

Lin, Spezzano et al. 2022

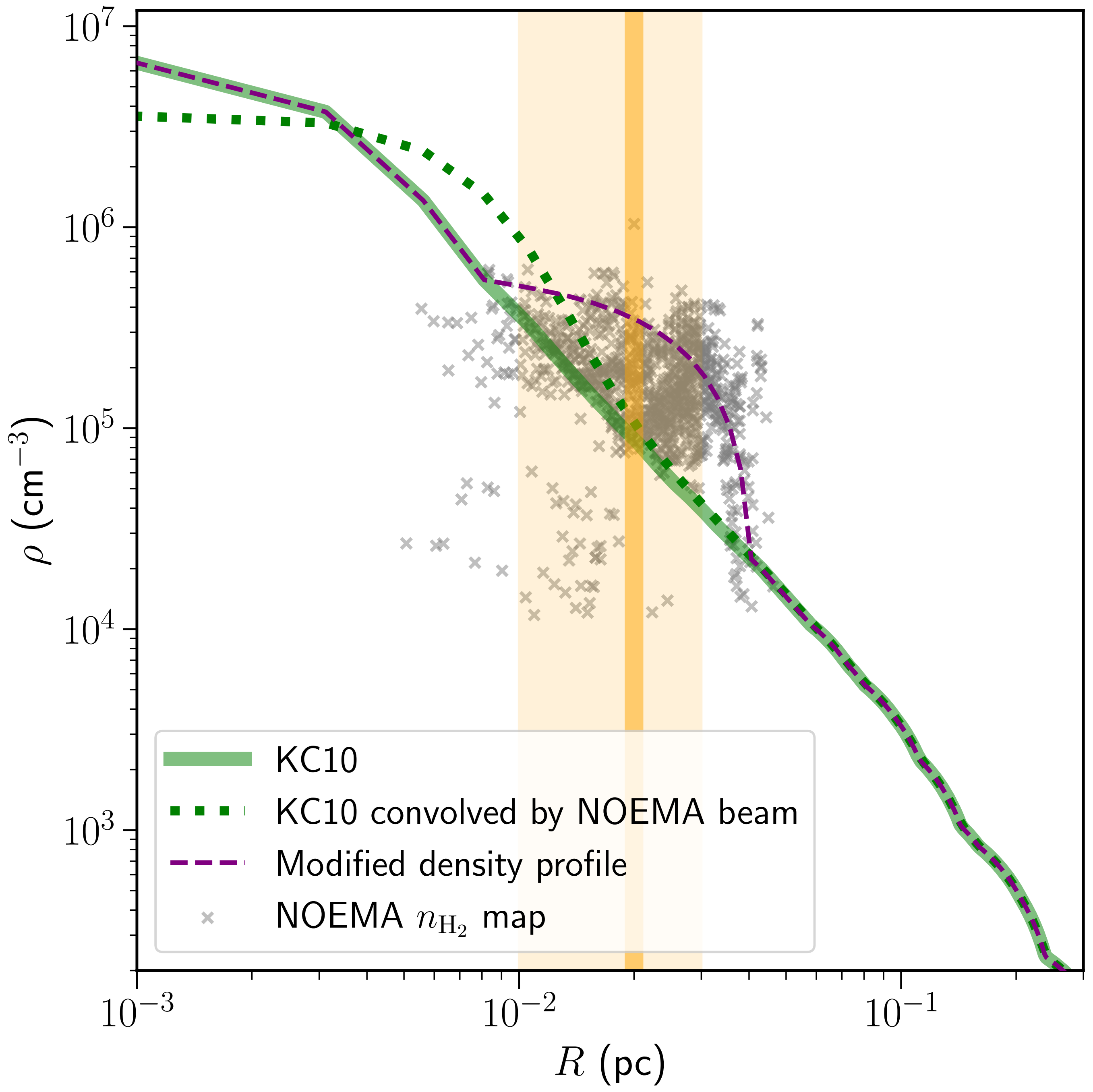


Full RT models with LOC (**L**ine transfer with **O**pen**C**L, Juvela 2020)

Abundance profiles from chemical models of Sipilä et al. (2015) and Vasyunin et al. (2017).

$n(r), T(r), V_r(r)$ from Keto & Caselli (2010).

- c-C_3H_2 and HNCO lines can be well reproduced with a factor of 3-5 increment of the abundance profiles
- CH_3OH lines can only be well reproduced if we include a bump in the density profile



location of the molecular peaks

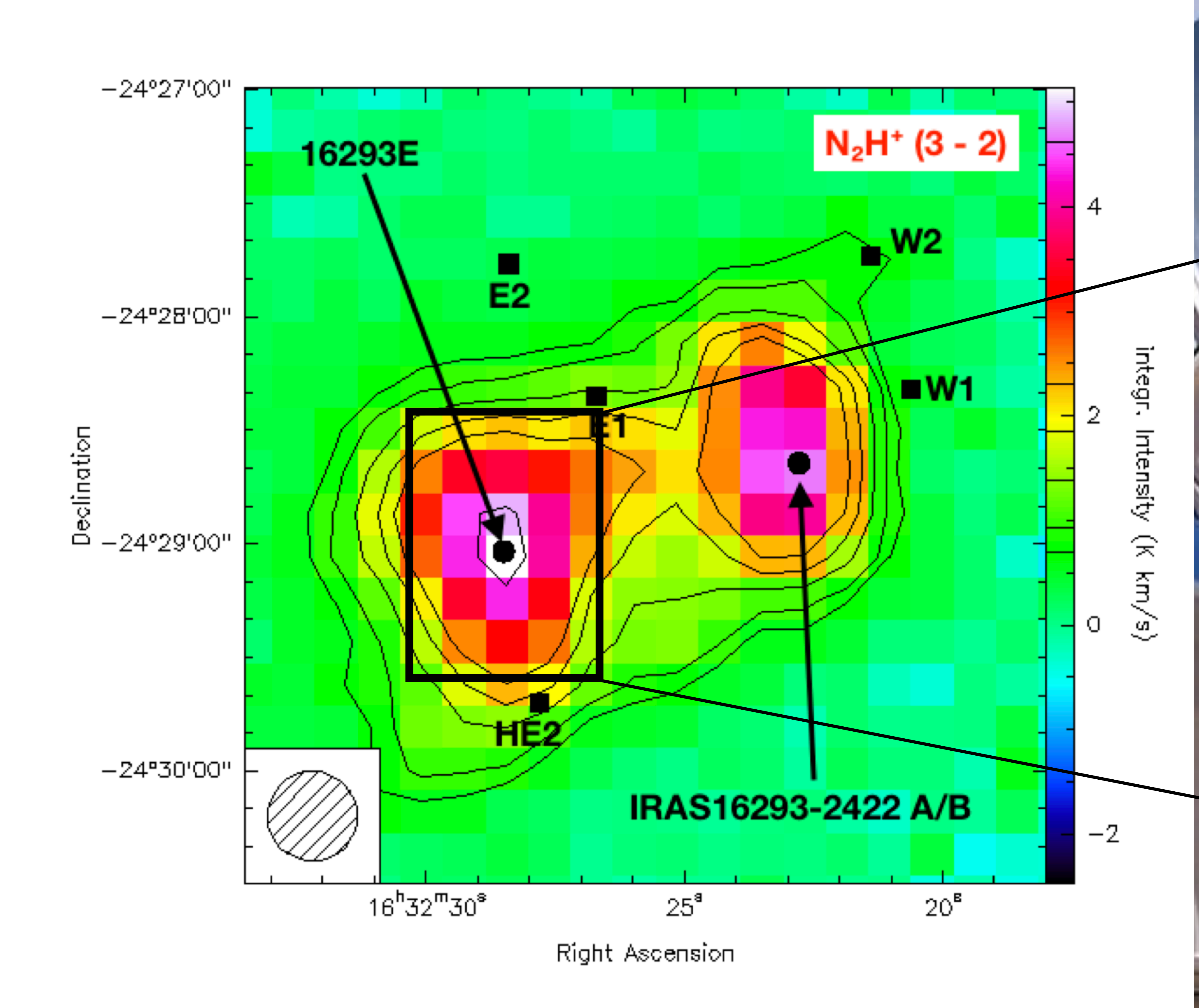
Shocks induced by asymmetric and dynamic accretion flows?

More observations needed!

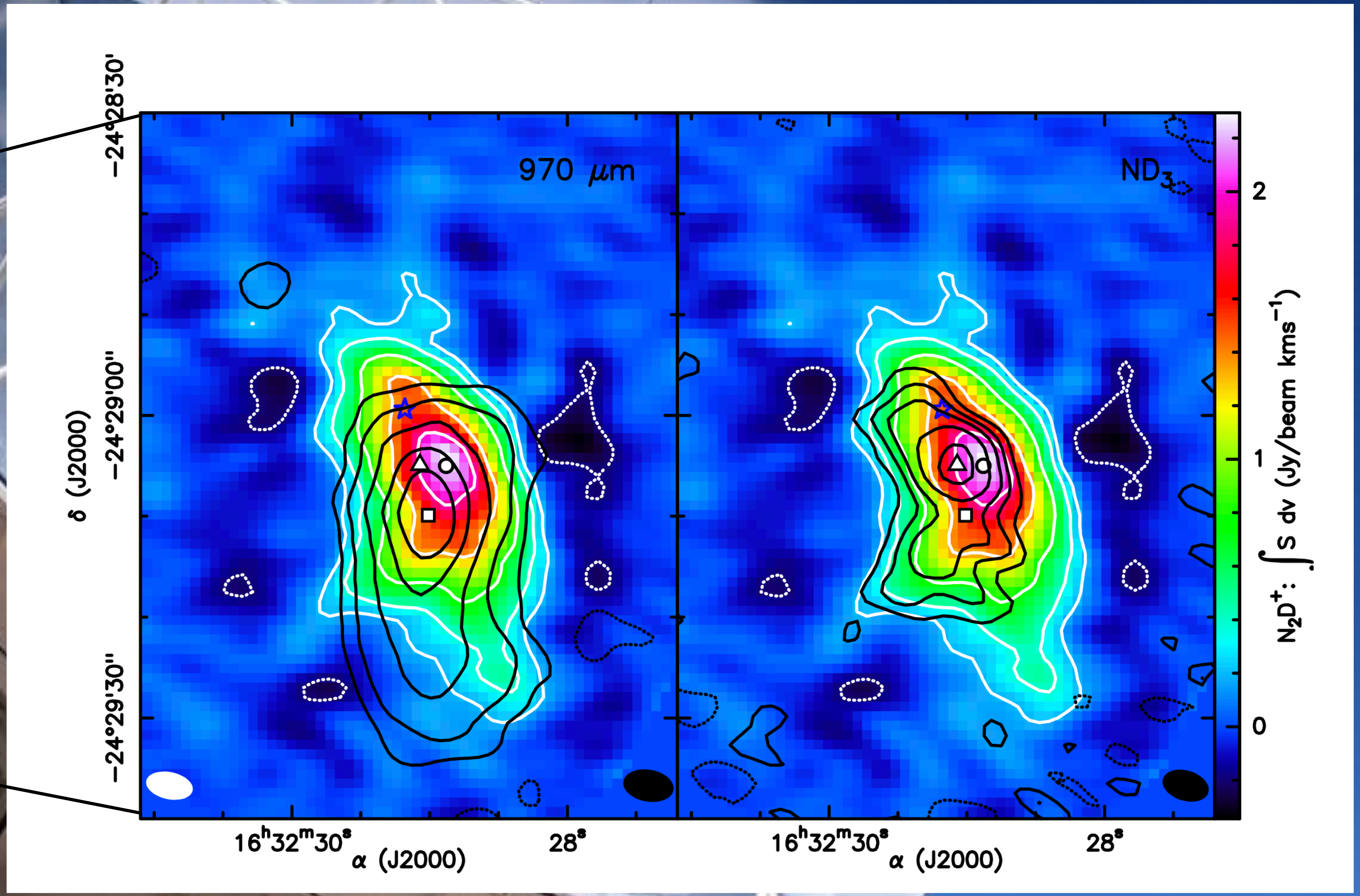
Hunting for pre-stellar cores with APEX

- N_2D^+/N_2H^+ survey of the densest starless cores within 200 pc from Sun (PI: Caselli)
- Selection *Herschel* Gould Belt Survey Archive (HGBSA; André et al. 2010)
- From a total sample of 1746 starless cores we selected those with the average $n(H_2) > 3\times10^5$ cm^{-3} within the central 20 arcsec (~ *Herschel* beam at 250 μm).

IRAS16293E/Oph464

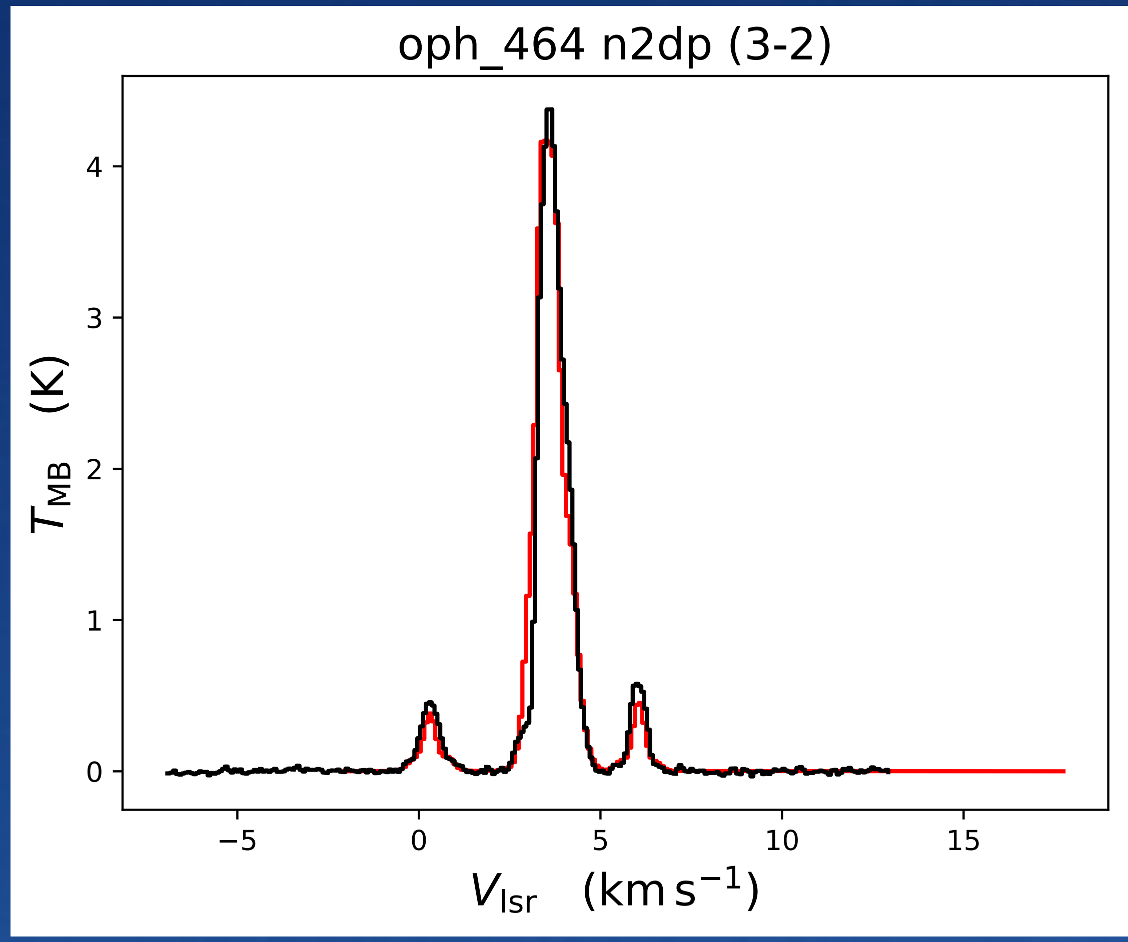


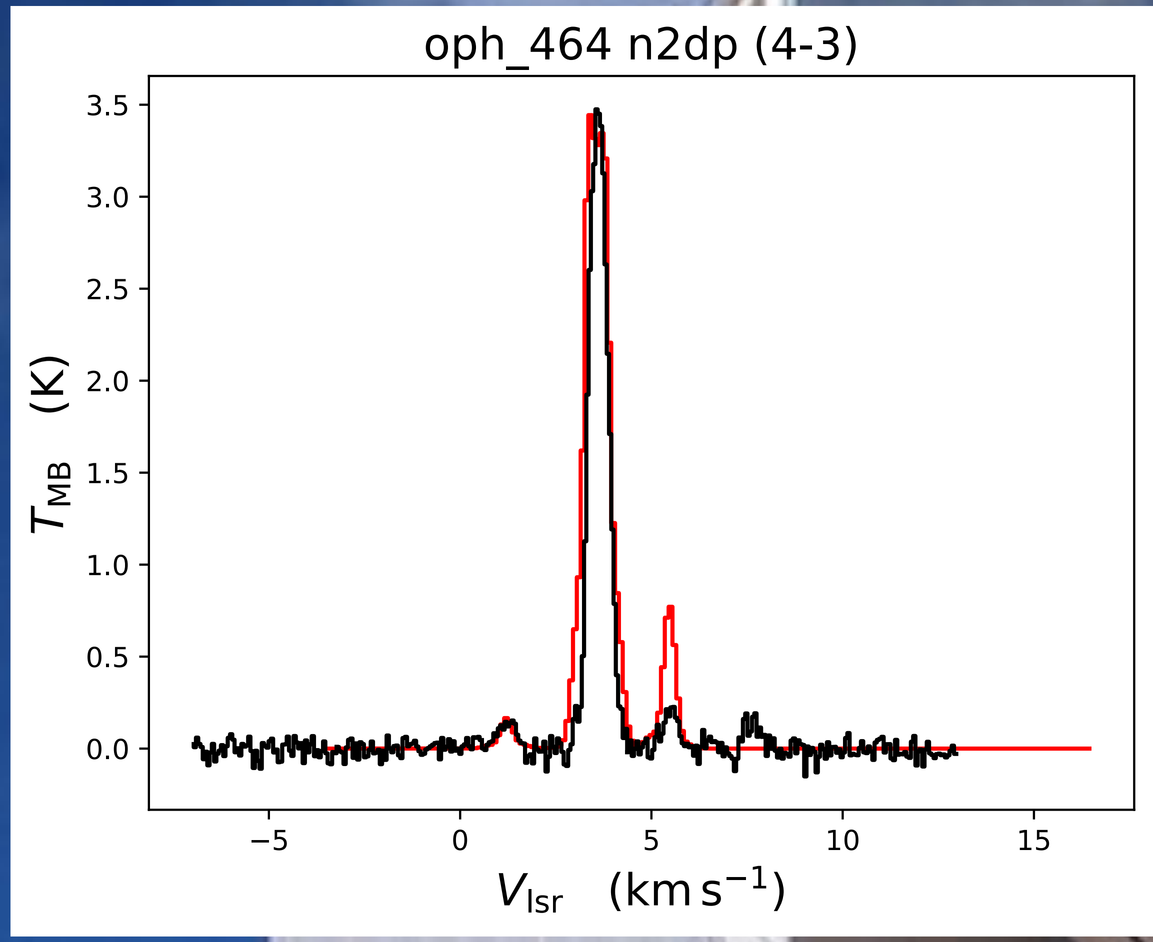
Khale et al. 2023

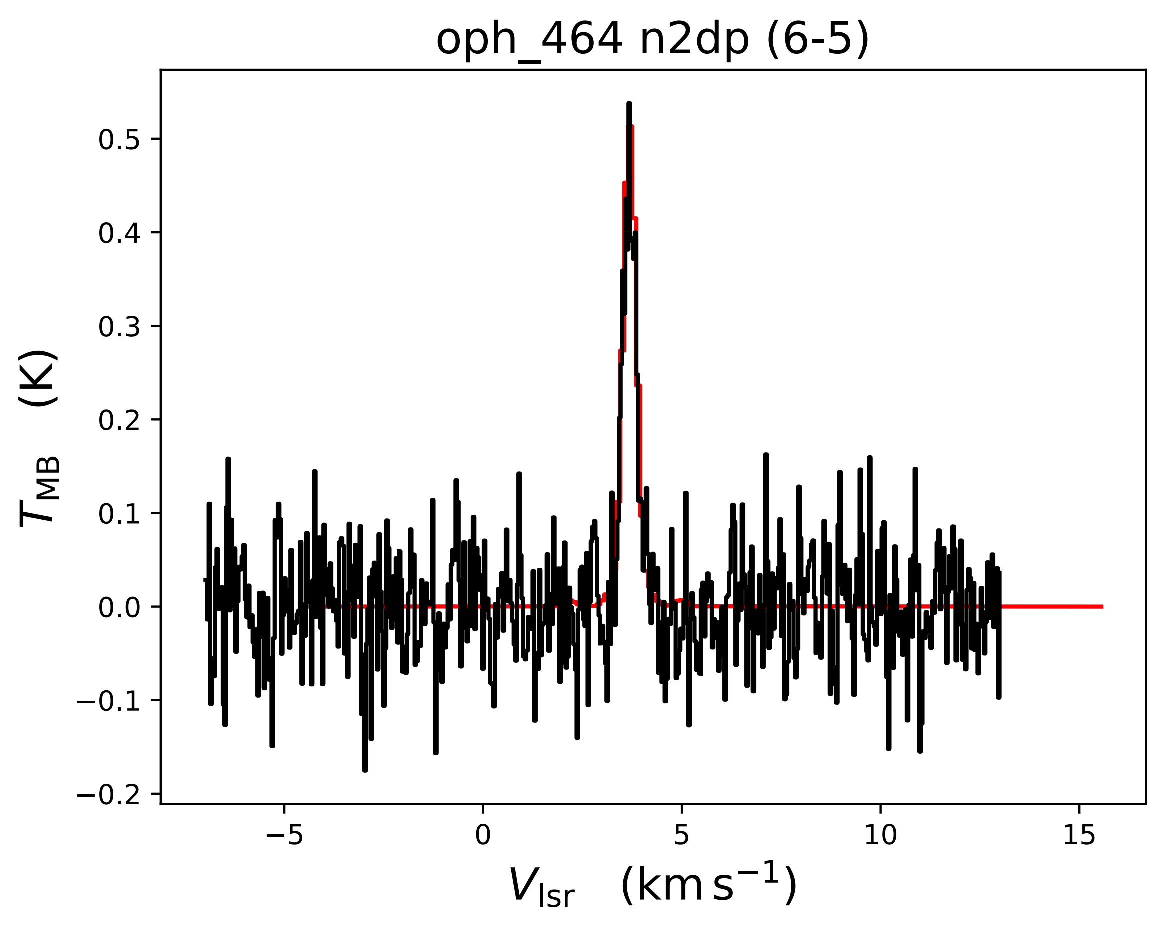


Lis et al. 2016

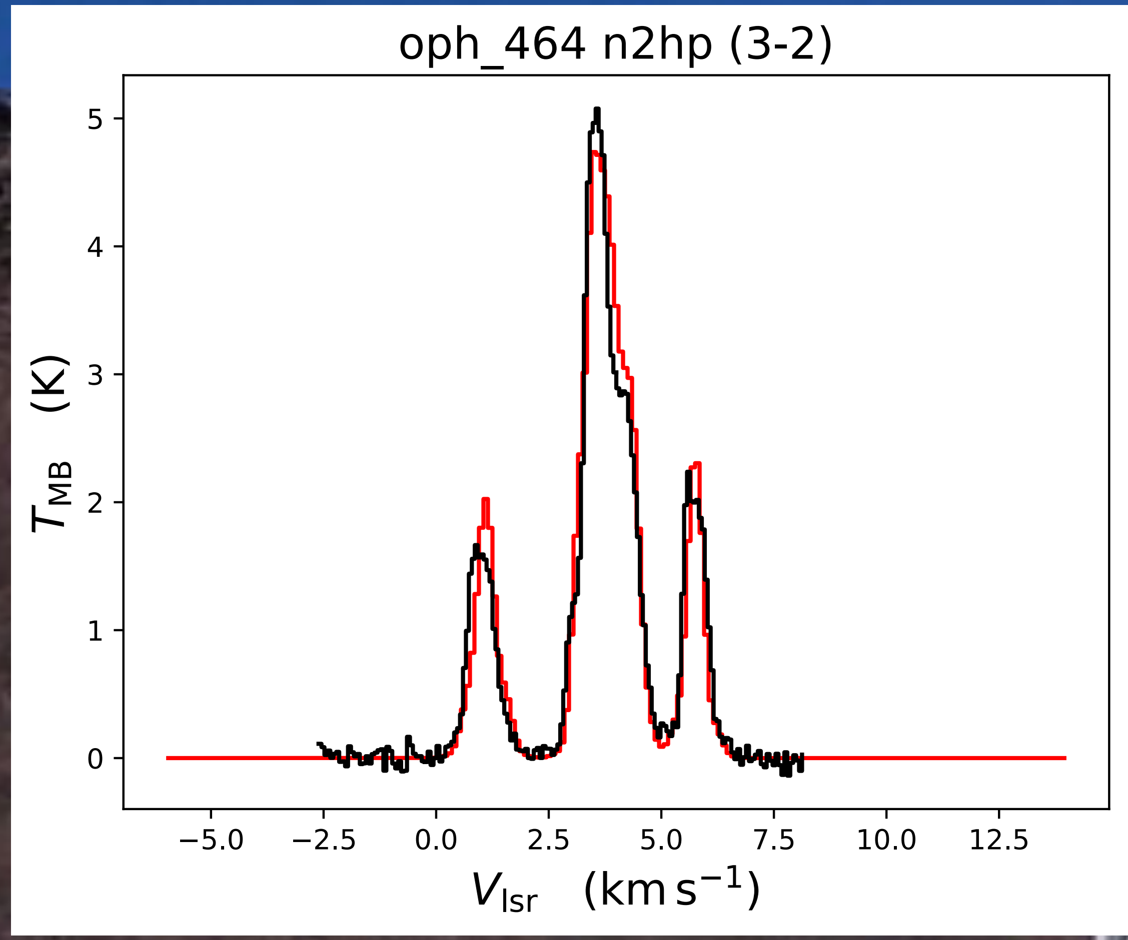
IRAS16293E/Oph464

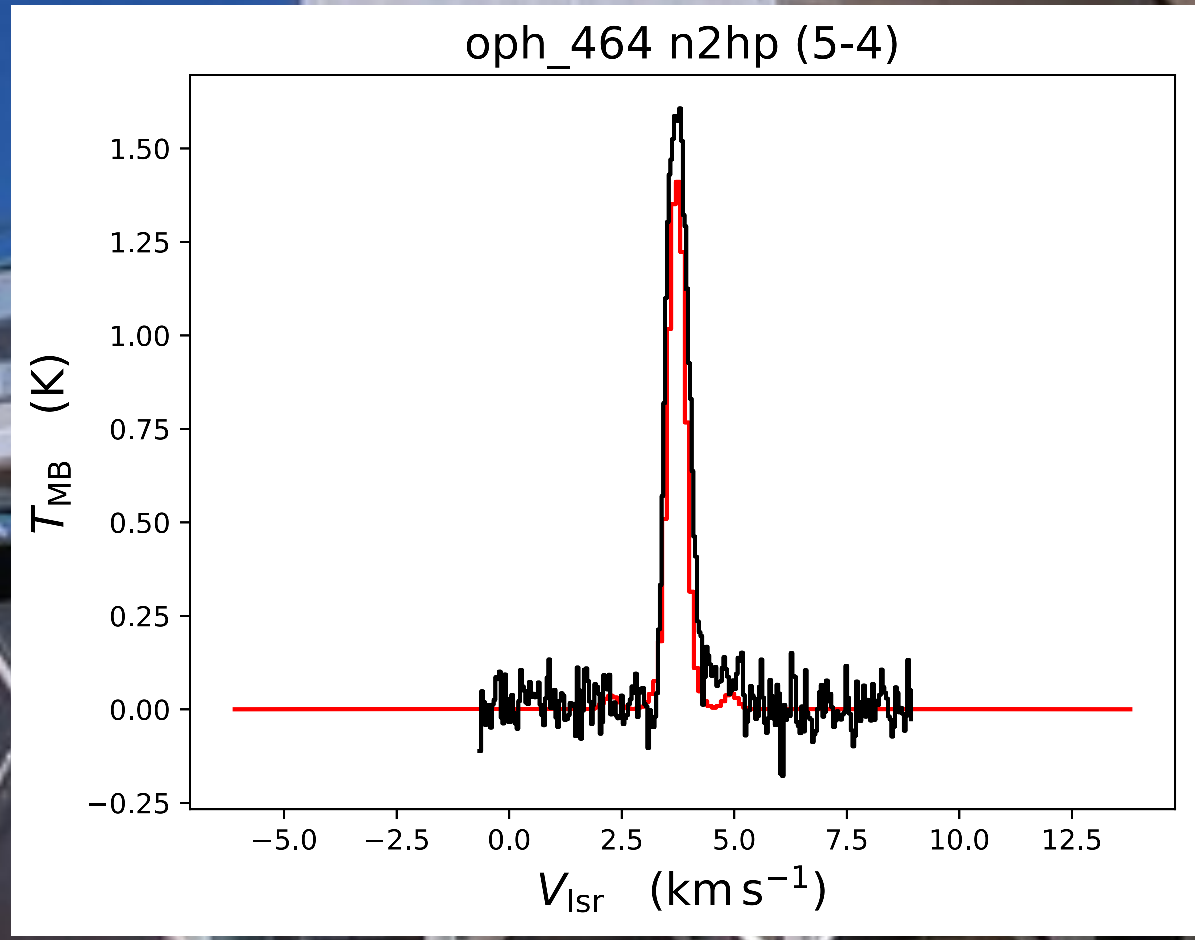


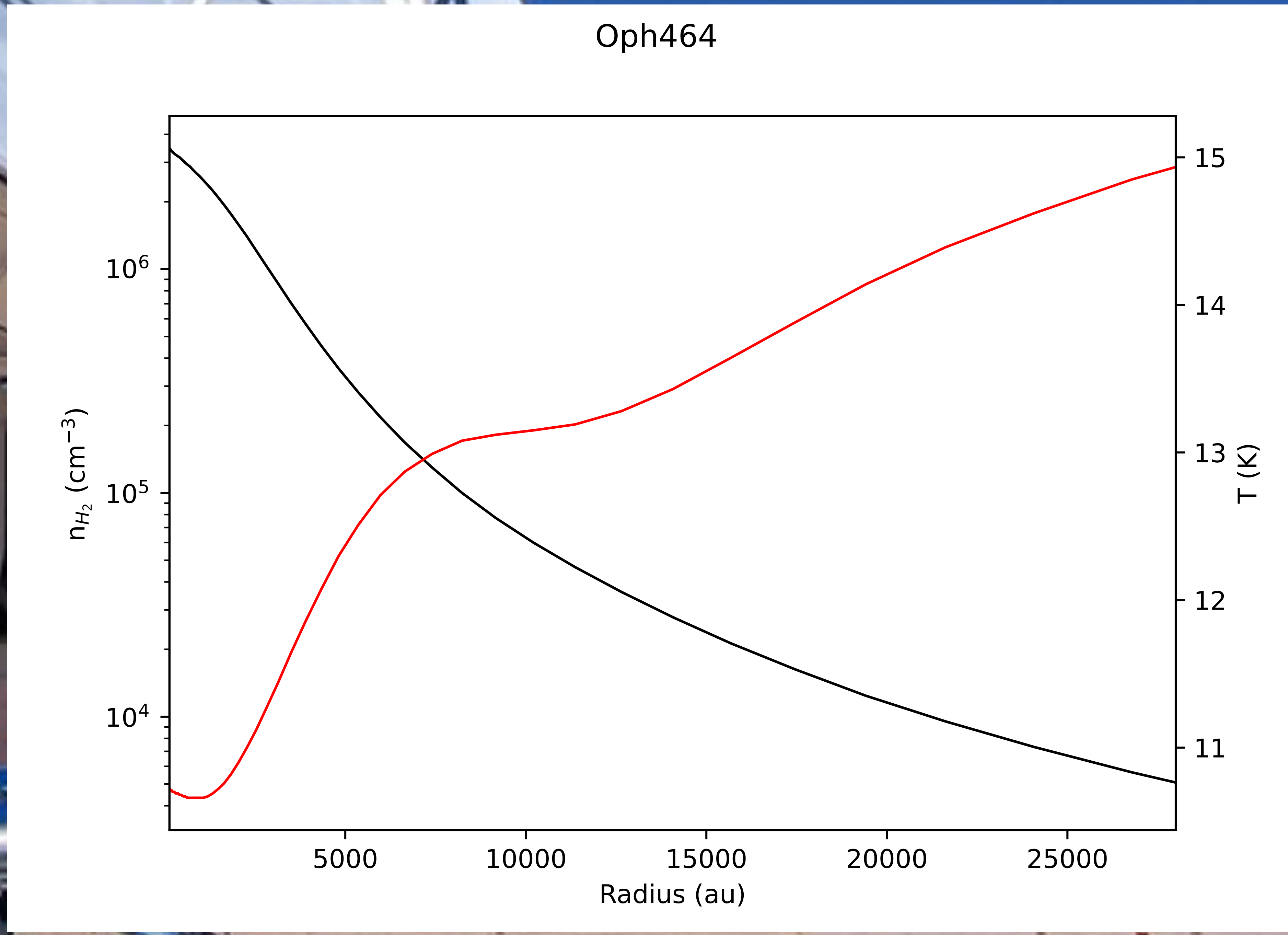




v=0 in the inner 3000 au
v=-0.5 km/s at r>3000 au
Constant abundance
Turbulent velocity = 0.2 km/s
N_2D^+/N_2H^+ abundance ratio of ~65%







Spezzano et al. in prep.

Conclusions and Outlook

- Physics and chemistry in pre-stellar cores are deeply interconnected
- Molecules are very powerful astrophysical tools (use them wisely!)
- The environment where pre-stellar cores are embedded plays a key role in the chemical distribution across the core
- Variation of the $^{14}N/^{15}N$ ratio across a pre-stellar core have been observed for the first time
- A tomographic view of pre-stellar cores is possible with multiline observations (and shows density enhancements with respect to the Bonnor-Ebert sphere)

The future will bring:
more (cores) and better (spatial and spectral resolution)

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