

# From cores to disks: *astrochemistry and initial conditions for planetary formation*

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ESO - Arc Astronomer

*Astrophysics school "Francesco Lucchin" - Bertinoro - 20 October 2026*



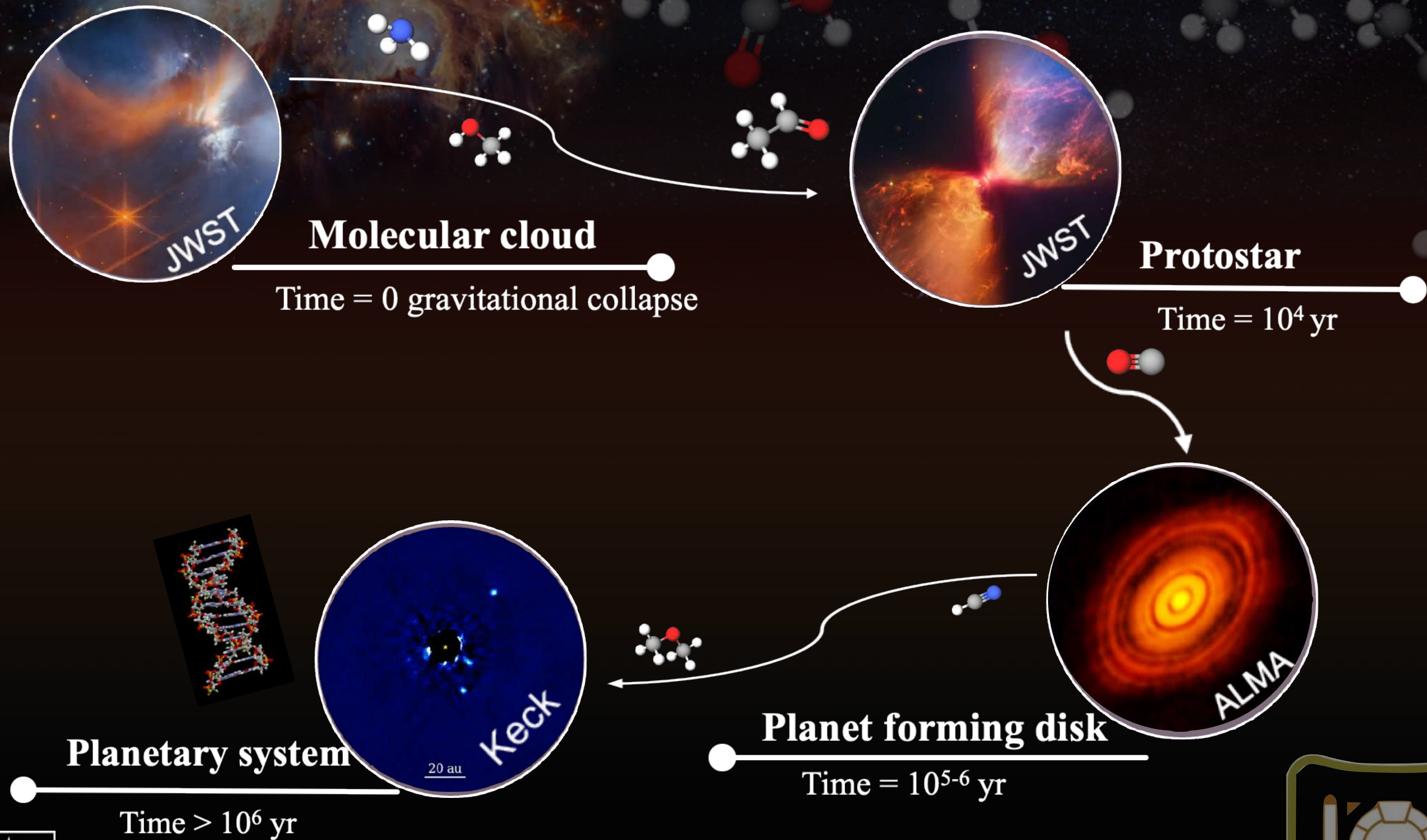
# Large variety of planetary systems all different from each other and from our Solar System



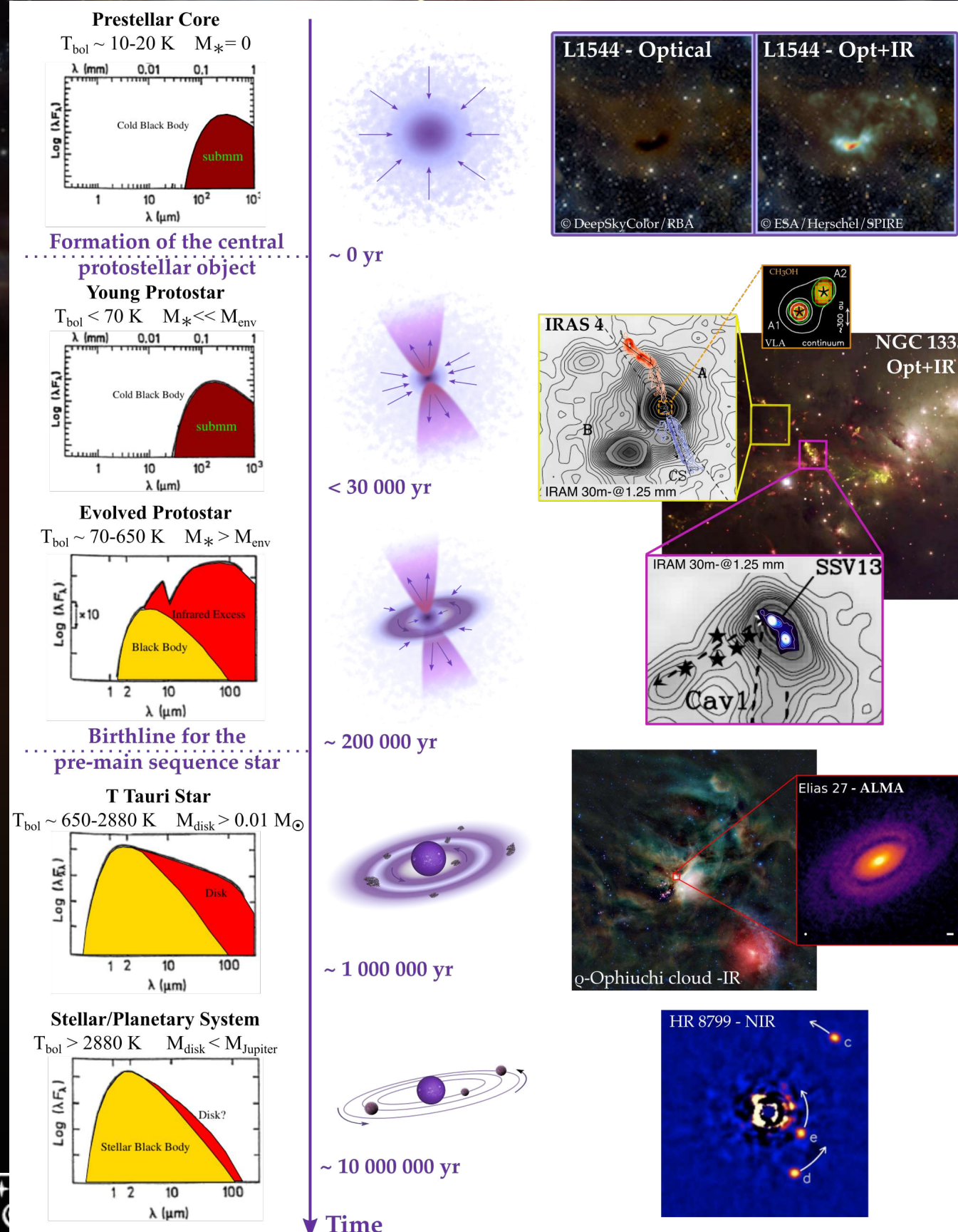
The Earth is so far  
the only planet  
hosting life



# Low mass star formation process



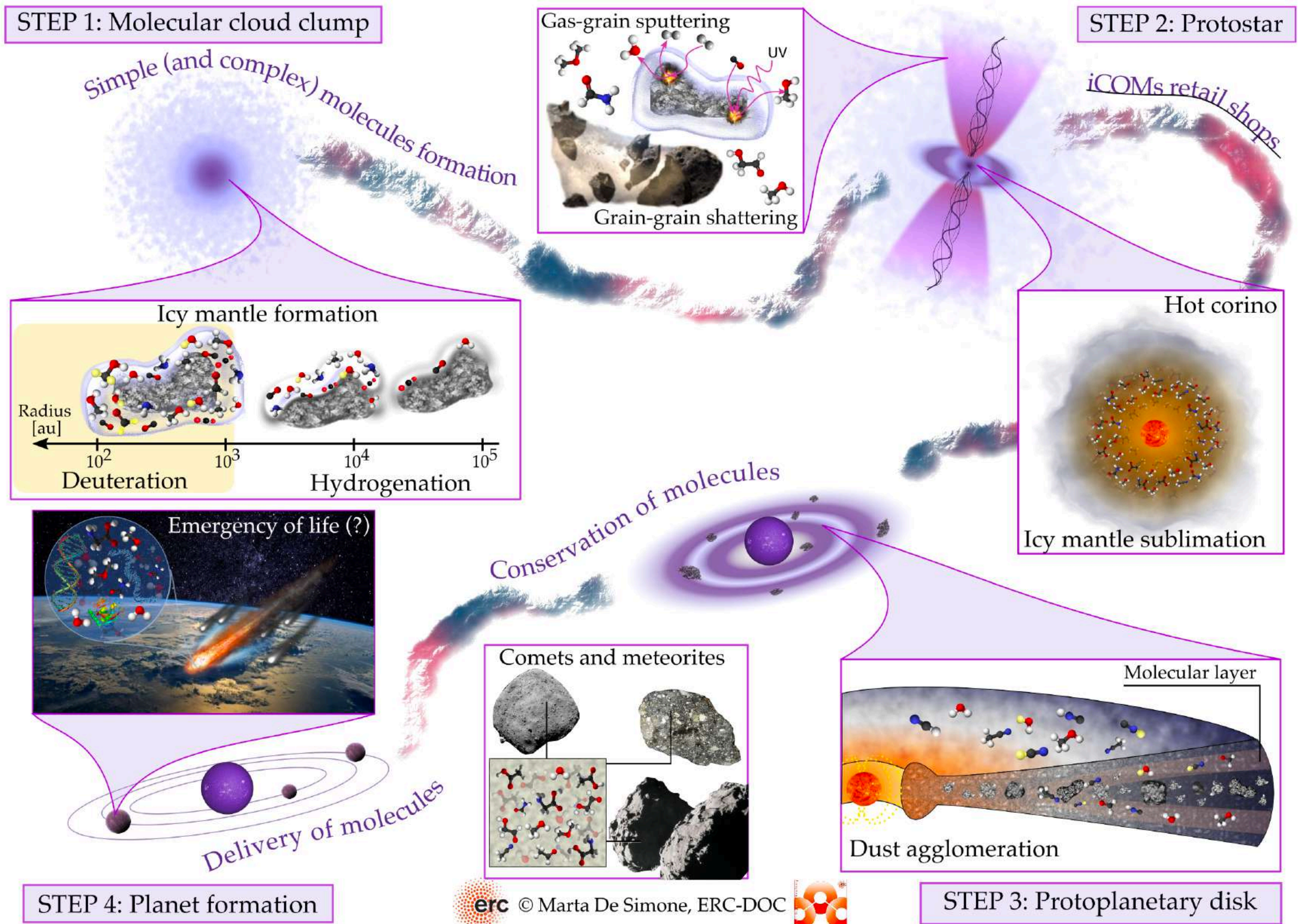
# Evolutionary Classification of Young Stellar Objects



Spectral energy distributions (SEDs) of the different formation stages of a Sun-like star (Adapted from Persson 2014).

- 1) Cold Black Body (sub-)mm  
The envelope is the main component
- 2) Black Body + IR excess (disk)  
Emission from envelope + disk
- 3) Black body  
Envelope dissipates and we see the black body from the star

# Chemical Evolution in Young Stellar Objects

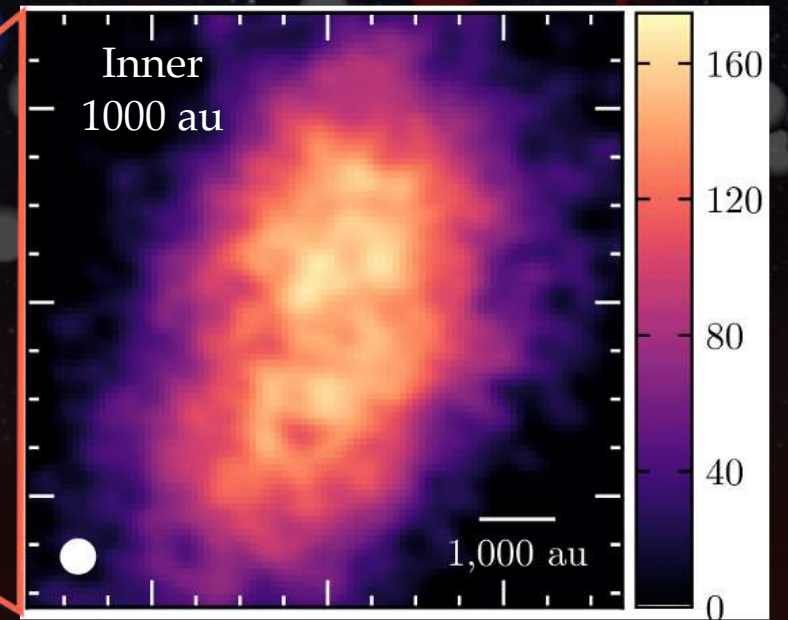


# Starless and Prestellar Cores: Cold but complex!

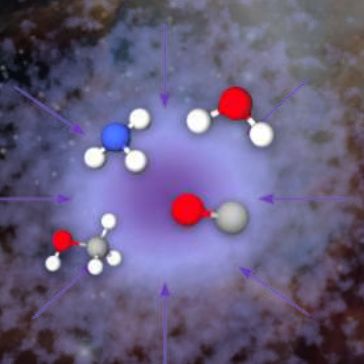
$T_{\text{kin}} \sim 10\text{-}30\text{ K}$   
(down to 6 K in the central core)  
 $n \sim 10^4\text{-}6\text{ cm}^{-3}$

L1544 - Opt+IR

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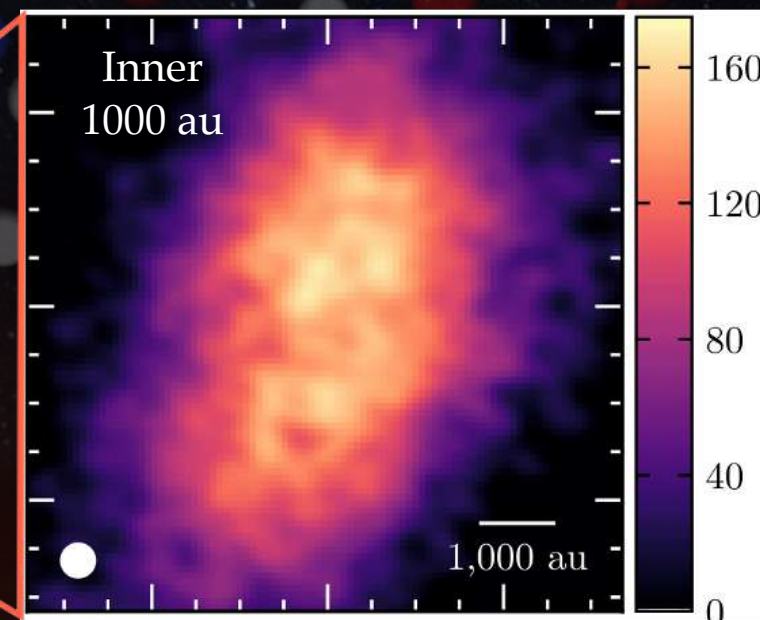
# Starless and Prestellar Cores: Cold but complex!



In the central 2000 au, 99.99% of all species heavier than He are frozen onto dust grains

L1544 - Opt+IR

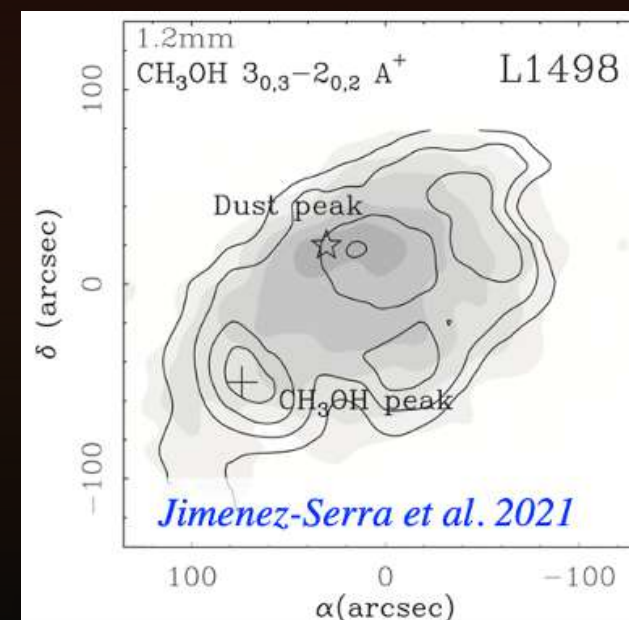
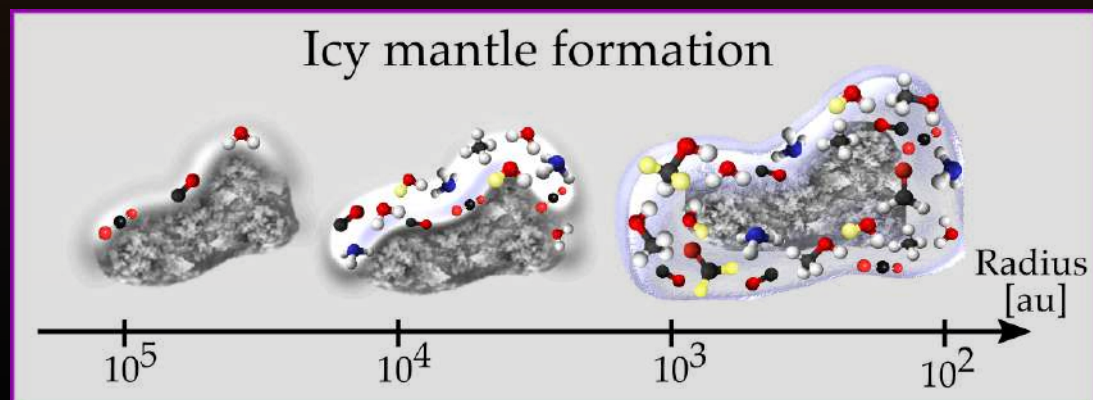
© ESA / Herschel / SPIRE



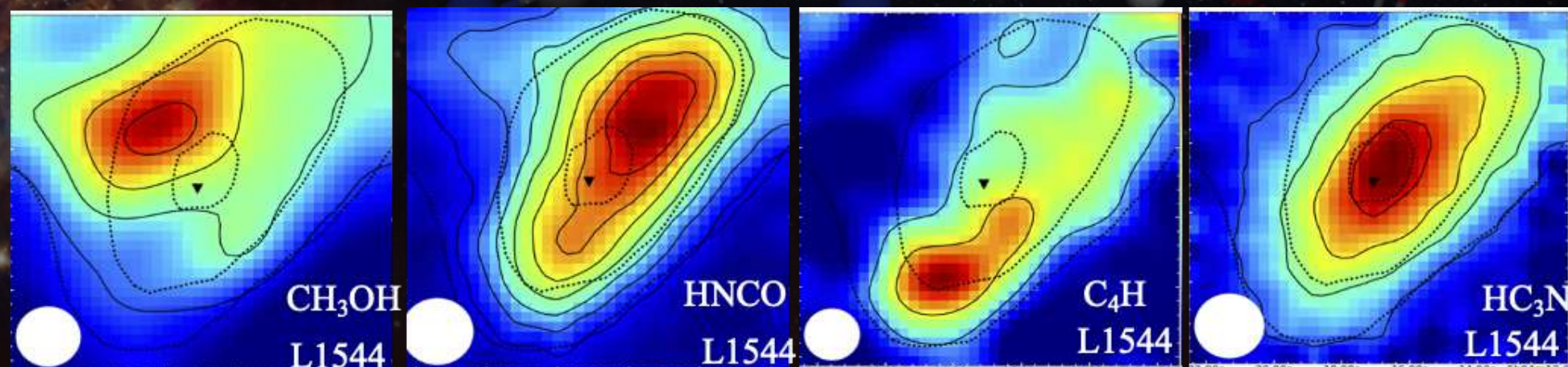
*Caselli et al. 2022*

|                                 |                                   |
|---------------------------------|-----------------------------------|
| c-C <sub>3</sub> H <sub>2</sub> | CH <sub>3</sub> O                 |
| C <sub>4</sub> H                | c-C <sub>3</sub> H <sub>2</sub> O |
| HNCO                            | HCOOH                             |
| H <sub>2</sub> CCC              | CH <sub>3</sub> OH                |
| H <sub>2</sub> CCO              | CH <sub>3</sub> CN                |

Hydrogenated species

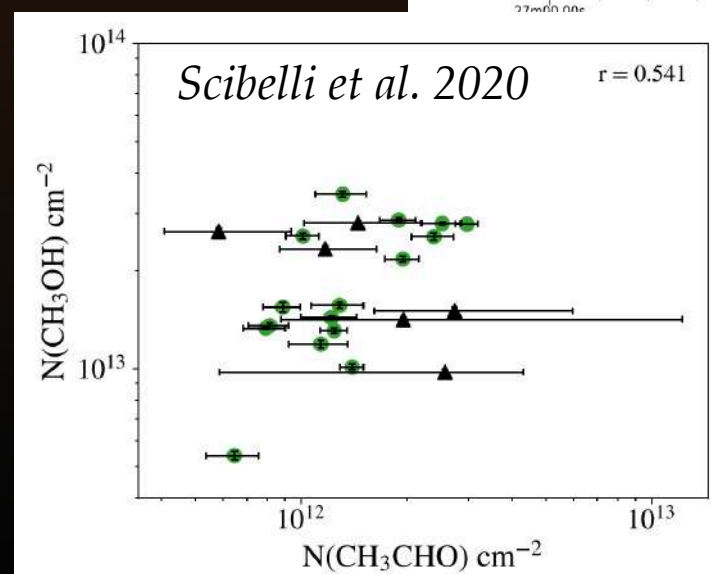
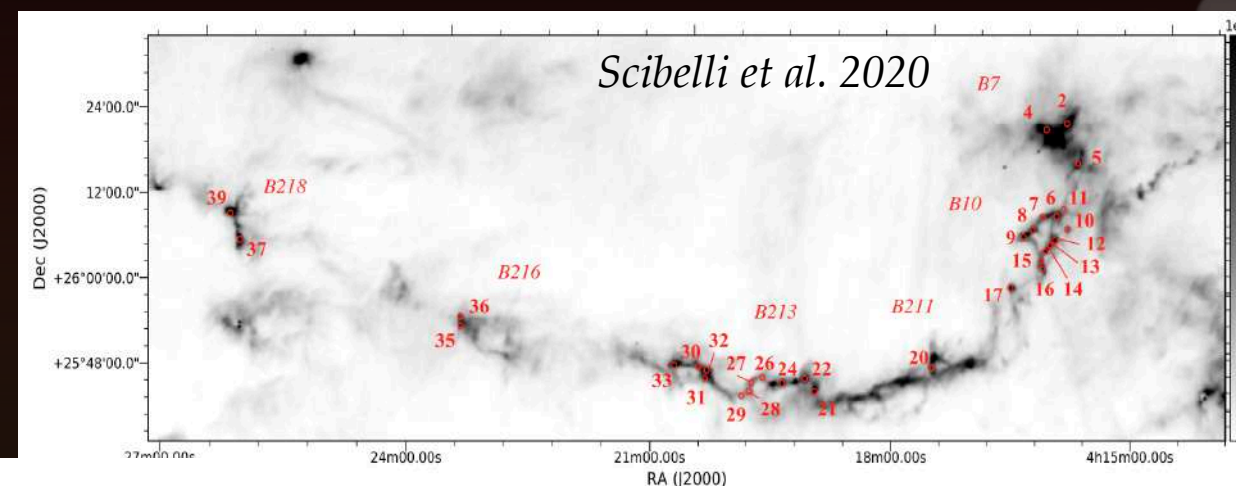


# Starless and Prestellar Cores: Cold but complex!



|                                  |                                   |
|----------------------------------|-----------------------------------|
| c-C <sub>3</sub> H <sub>2</sub>  | CH <sub>3</sub> O                 |
| C <sub>4</sub> H                 | c-C <sub>3</sub> H <sub>2</sub> O |
| HNCO                             | HCOOH                             |
| H <sub>2</sub> CCC               | CH <sub>3</sub> OH                |
| H <sub>2</sub> CCO               | CH <sub>3</sub> CN                |
| HC <sub>5</sub> N                | CH <sub>2</sub> CHCN              |
| HC <sub>7</sub> N                | CH <sub>3</sub> CCH               |
| HC <sub>9</sub> N                | CH <sub>3</sub> CHO               |
| C <sub>2</sub> H <sub>3</sub> CN | HCOOCH <sub>3</sub>               |
|                                  | CH <sub>3</sub> OCH <sub>3</sub>  |

Rather complex,  
structurally ...



31 cores in Taurus  
CH<sub>3</sub>OH ~100%  
CH<sub>3</sub>CHO ~70%

Vastel et al. 2014, 2016, 2018, 2019, Jiménez-Serra et al. 2016, 2021, Punanova et al. 2018, McGuire et al. 2018, Fuente et al. 2019, Caselli et al. 2019, Cernicharo et al. 2021, 2023 Burkhardt et al. 2021, Scibelli et al. 2020, 2023, Bianchi et al. 2023

# Starless and Prestellar Cores: Cold but complex!

McGuire et al. 2020

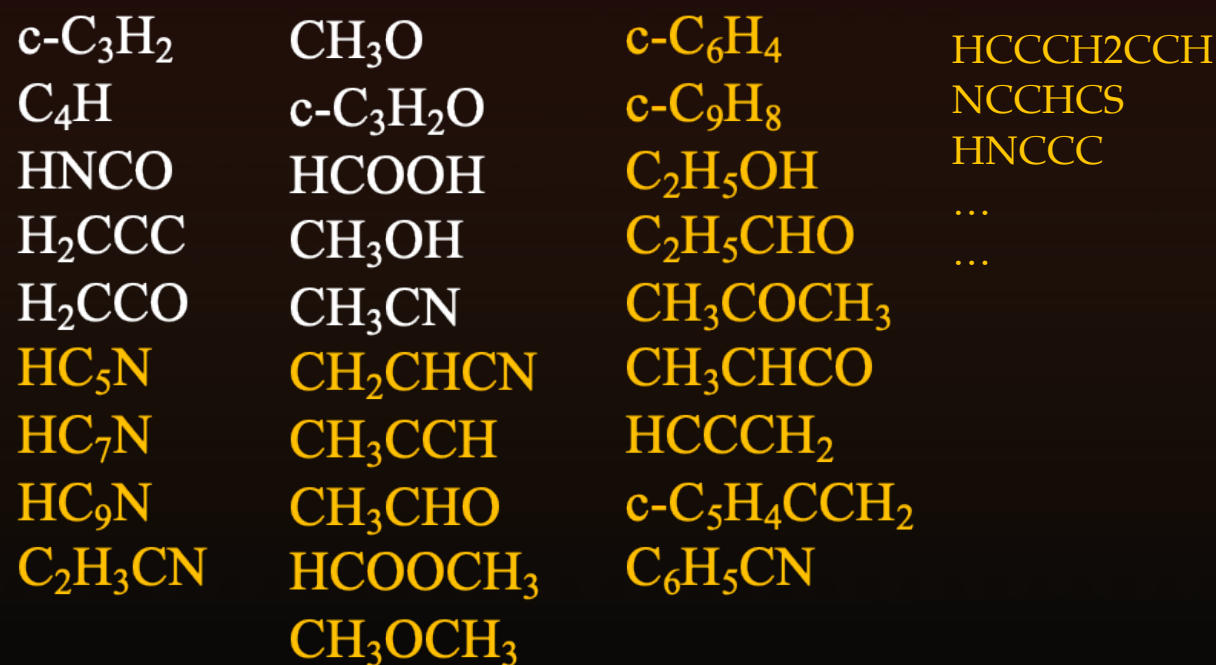
The cm saga!



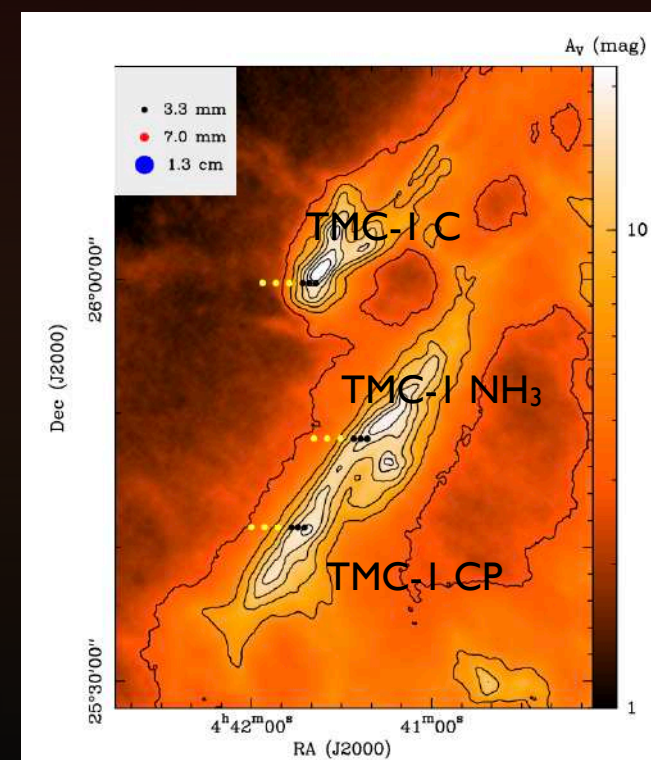
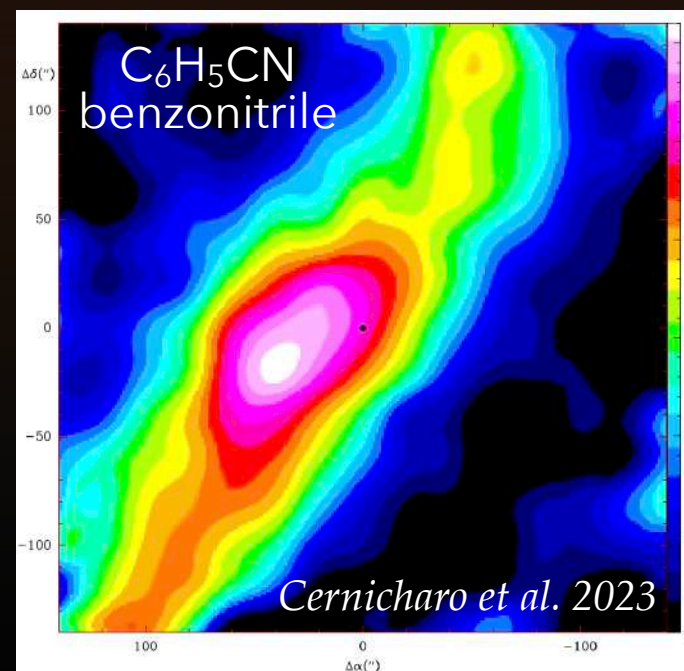
GBT: GOTHAM, ARKHAM

YEBES: QUIJOTE. SANCHO

...and chemically

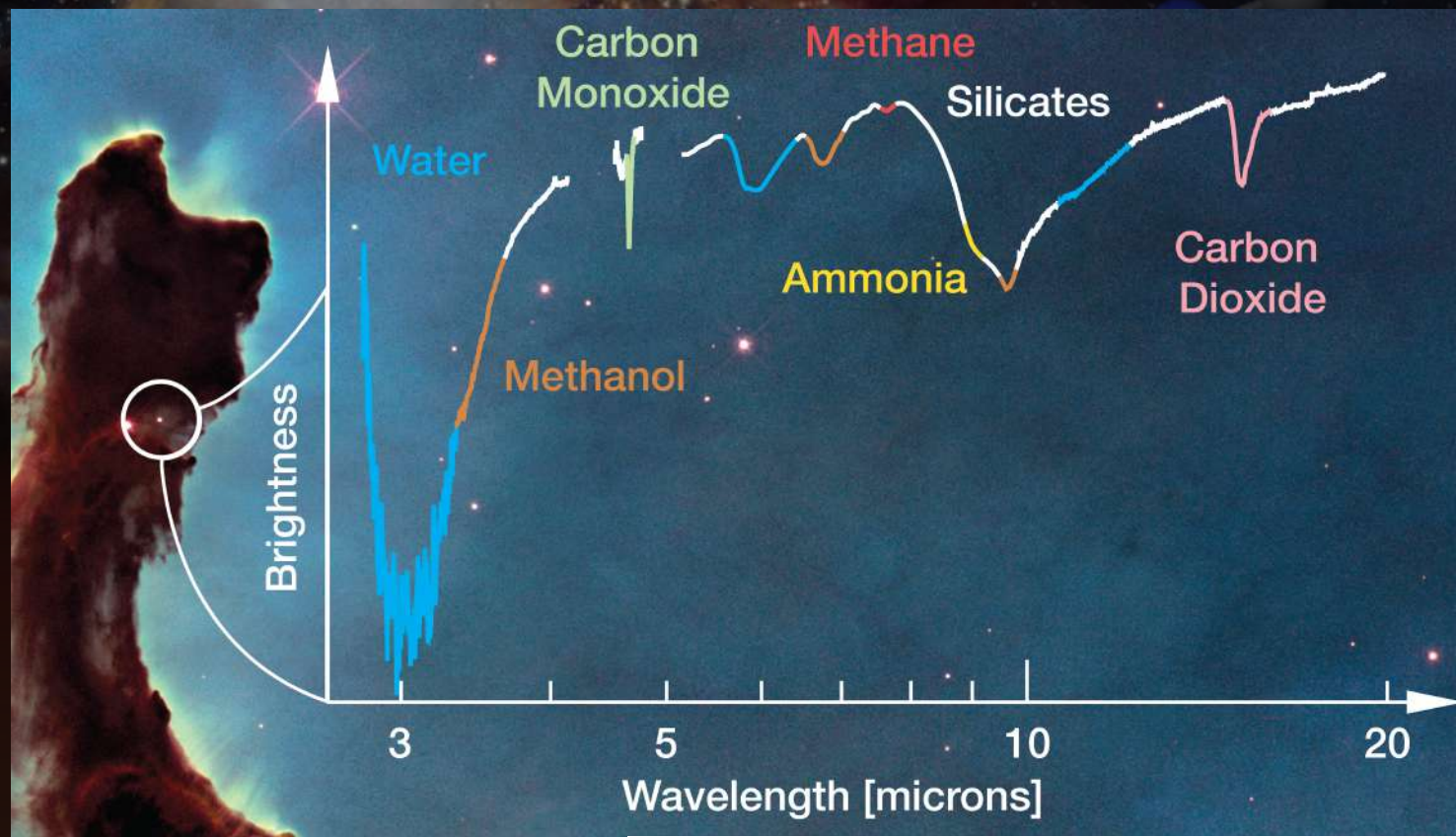


Widespread presence of complex organic molecules, carbon chains and benzonitriles



McGuire et al. 2018, Burkhardt et al. 2021, Agúndez et al. 2023, 2024, Fuentetaja et al. 2023, 2024a,b, Cernicharo et al. 2021a,b, 2022a..d, 2023a,..e, 2024a..f, Cabezas et al. 2024

# Ice Observations of Prestellar Cores

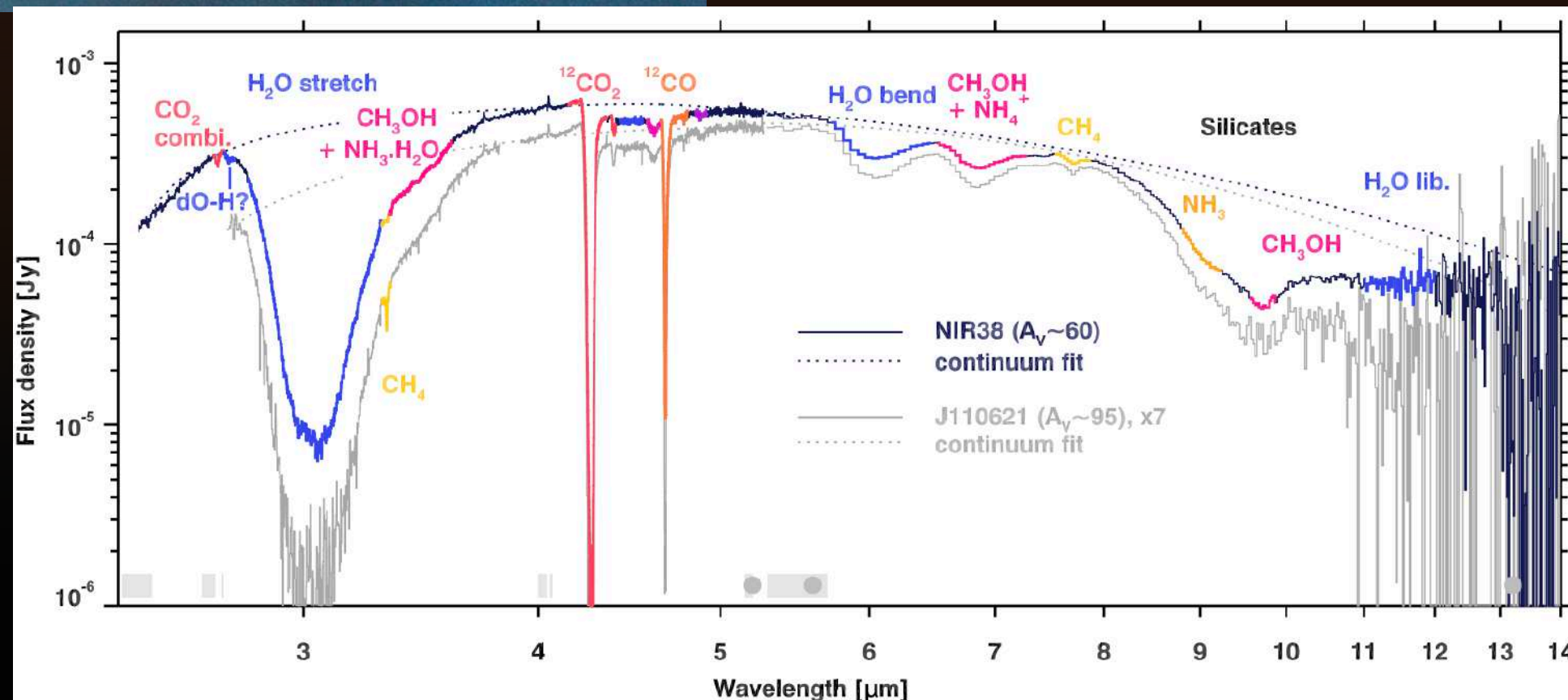


ICE AGE

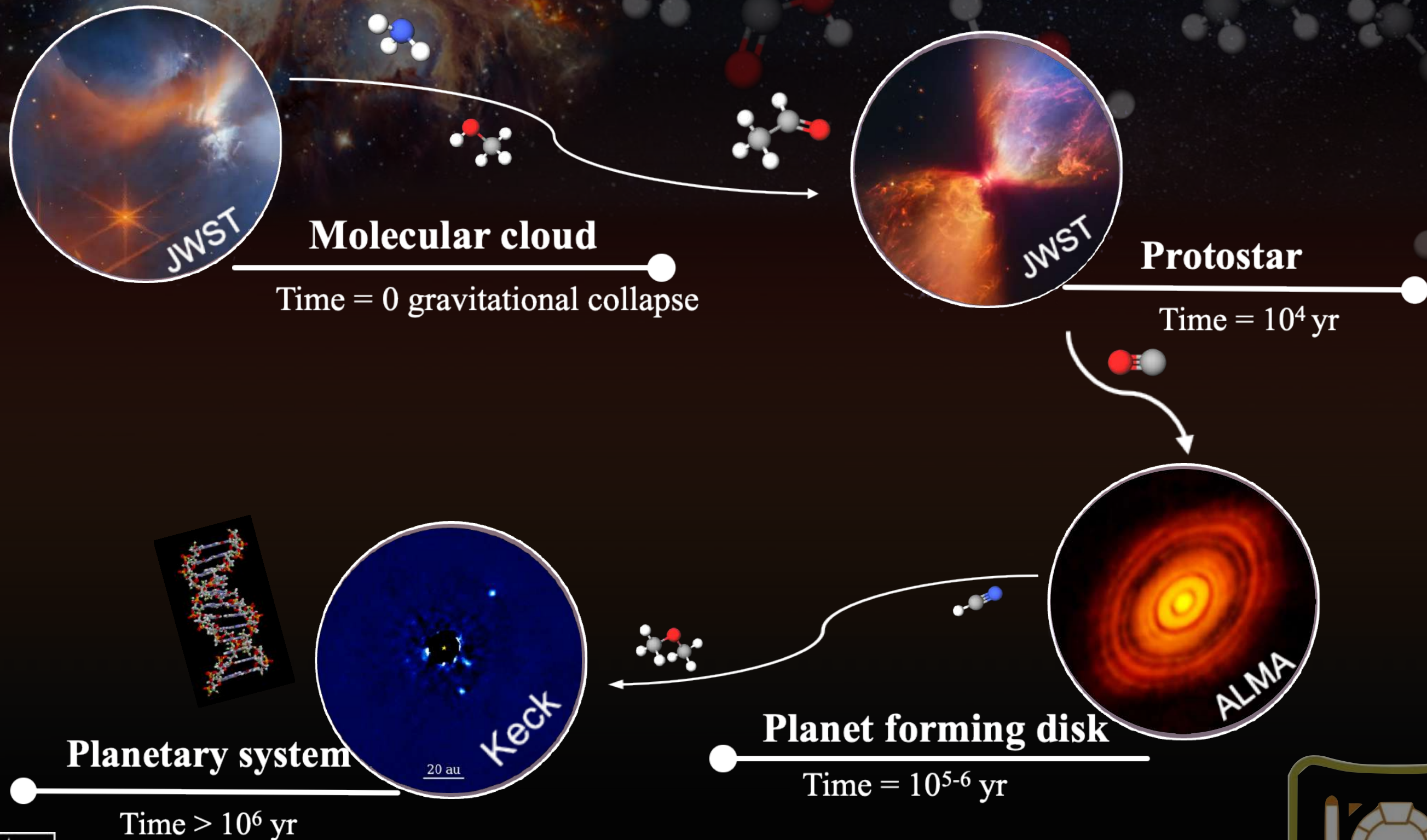
*McClure et al. 2023, Rocha et al. 2024*

## Major ice components:

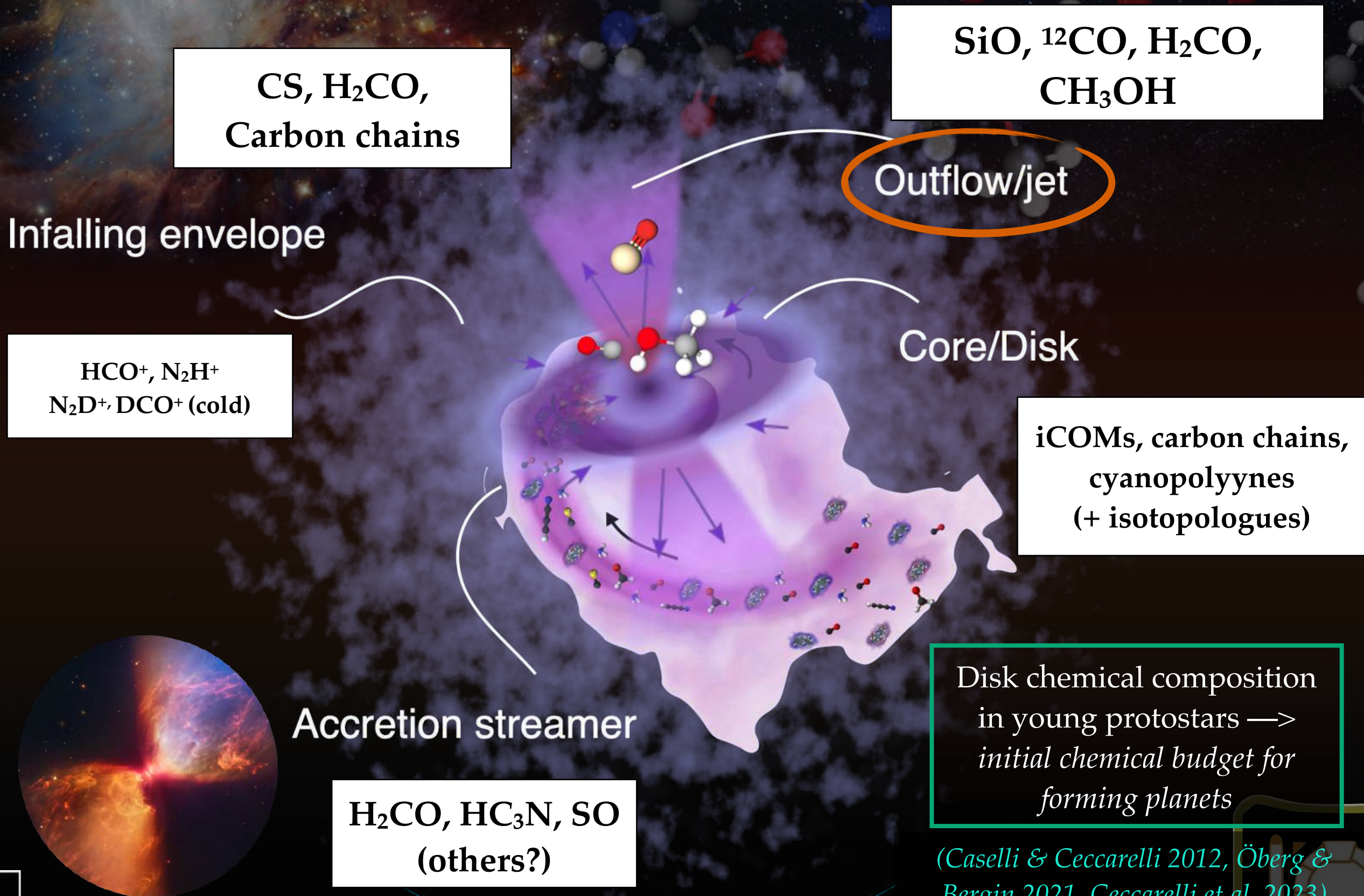
- Water
- CO
- CO<sub>2</sub>
- NH<sub>4</sub>
- Methanol



# Low mass star formation process



# Protostars: astrochemical laboratories and molecular factories

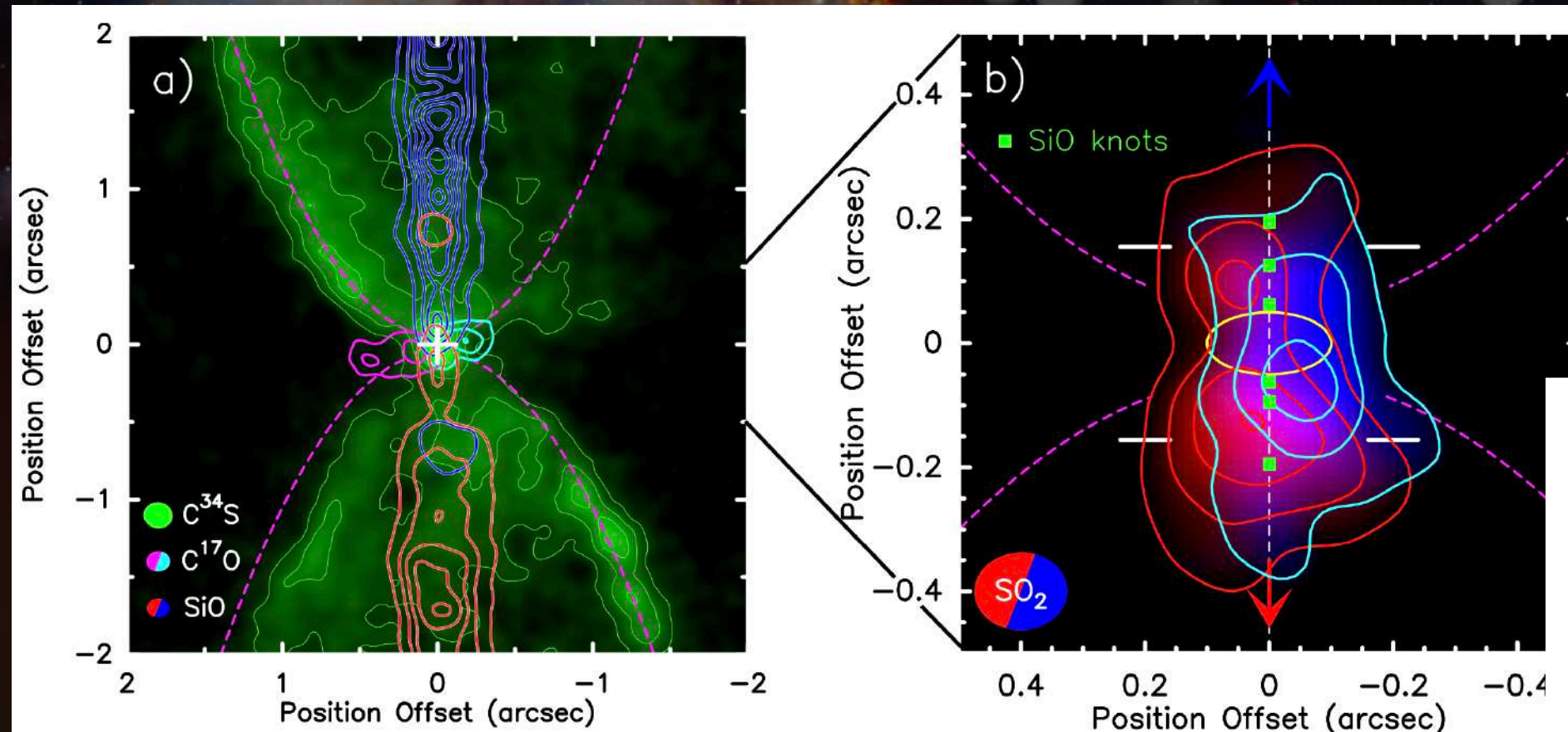


(Caselli & Ceccarelli 2012, Öberg & Bergin 2021, Ceccarelli et al. 2023)



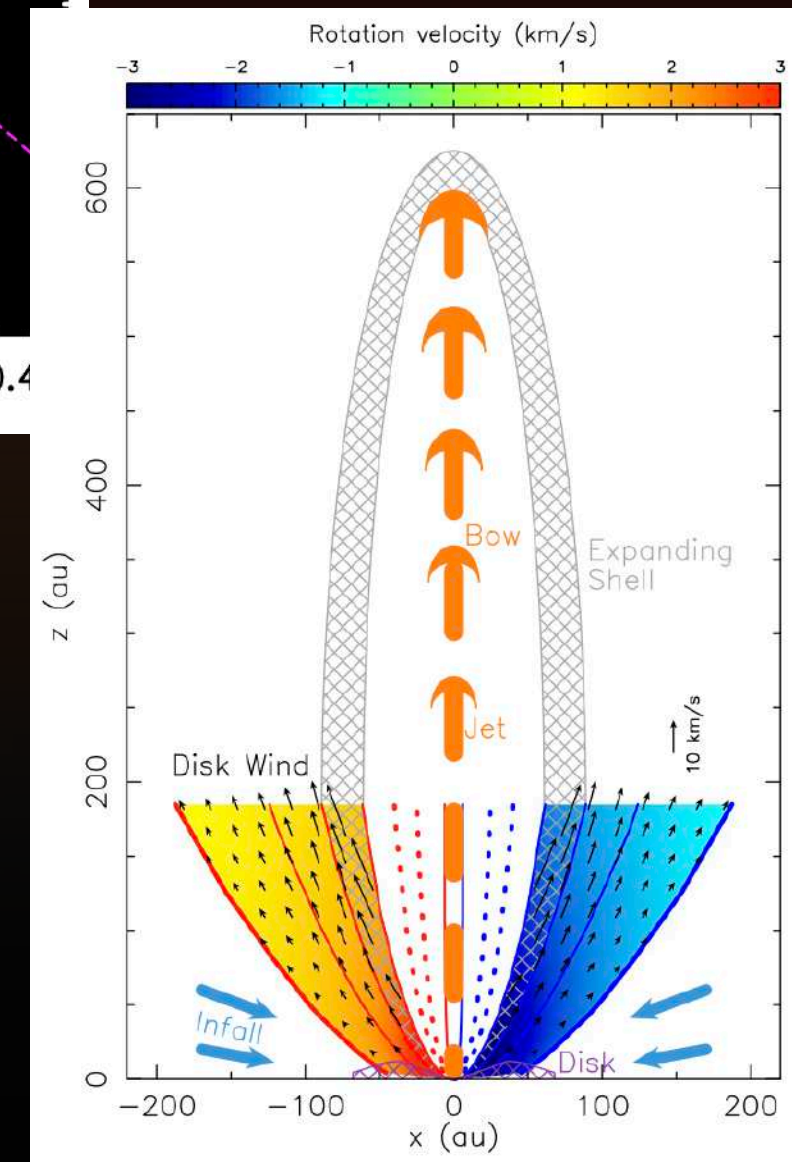
# The energetic phenomena around protostars

## Oufflows, cavities and winds



*Tabone et al. 2017, Lee et al. 2021*

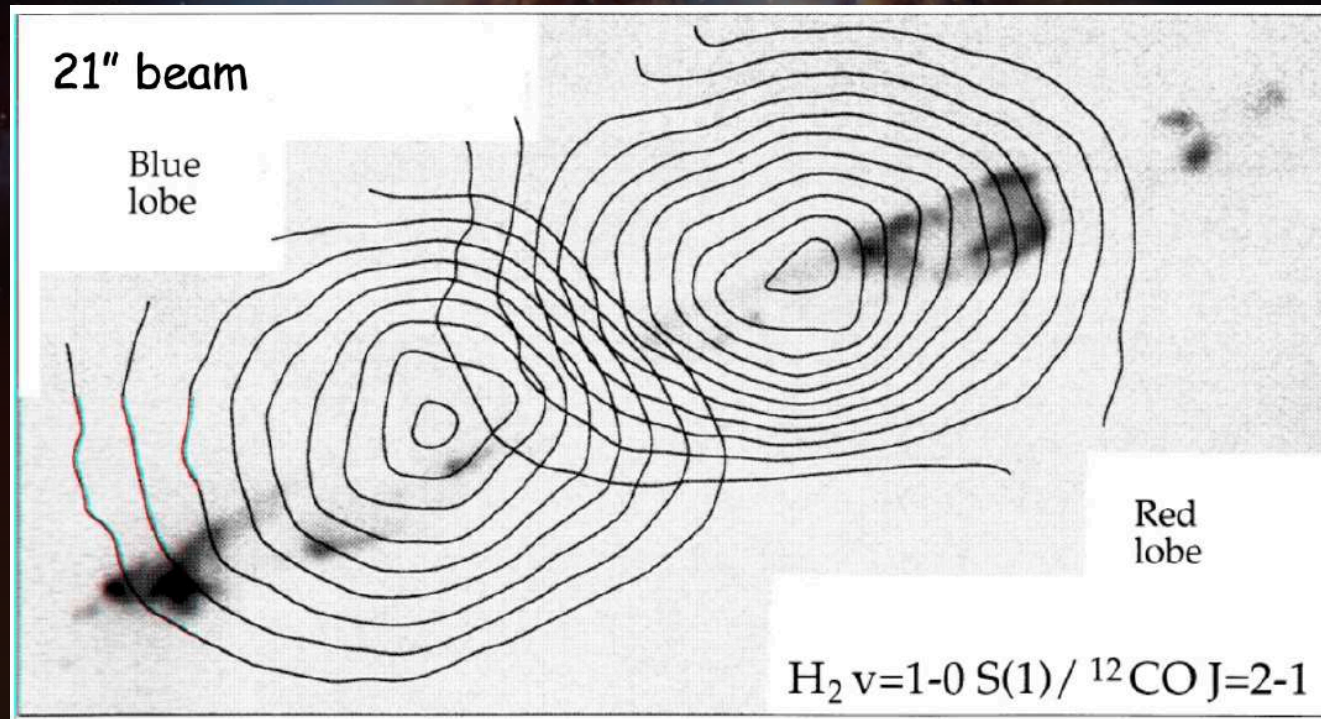
- ✦ Low density molecular gas seen at high velocities 10-50 km/s
- ✦ Red and blue wings spatially separated  $\rightarrow$  bipolar flow
- ✦ Usually poorly collimated  $\rightarrow$  length/width  $\sim 2$
- ✦ Extent  $\sim$  arcmins ( $\sim 0.1$ -3 pc); Mass  $\sim 0.1$ -100  $M_{\text{sun}}$
- ✦ Wind launching radius  $\sim 4$  to 40 au



# The energetic phenomena around protostars

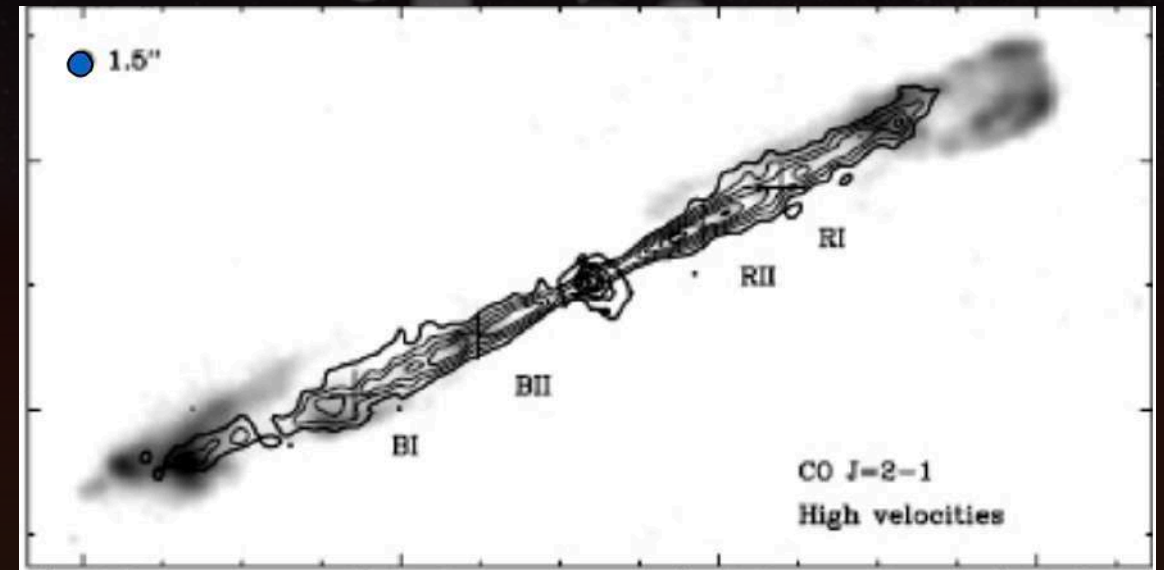
## Jets

### Resolution does matter!



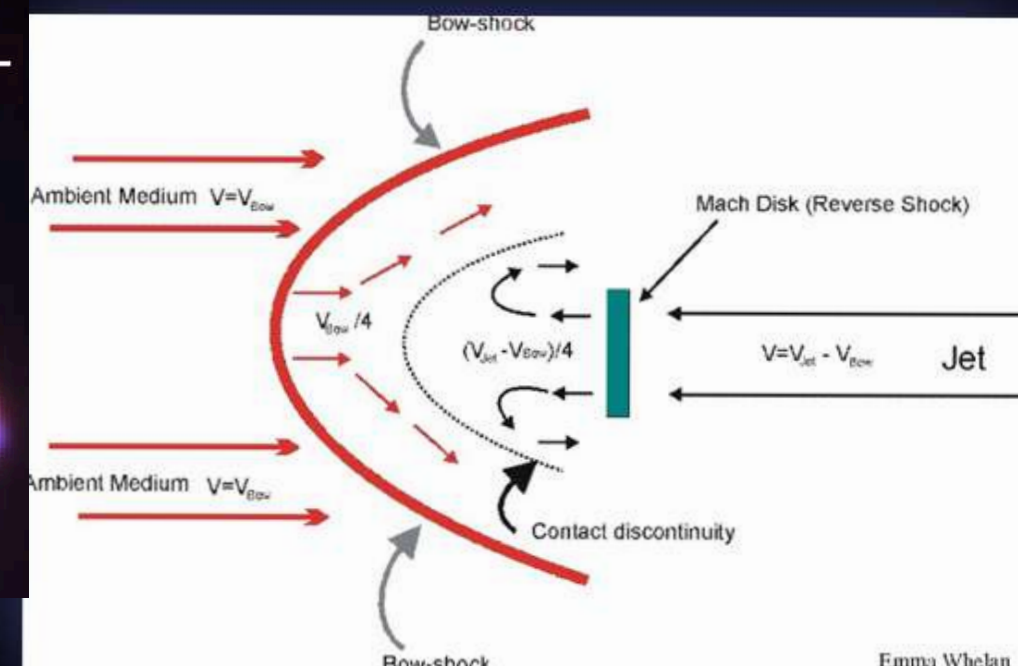
HH211 Outflow

Greyscale: NIR image  
Contours: CO (2-1)



### Collimated flow

- ✦ Rapid heating (from  $\sim 10$  K to a few 1000 K) and compression of the gas (Shock chemistry)
- ✦ Jet launching radius  $\sim 0.05\text{--}0.20$  au.
- ✦ High-T chemistry: endothermic reactions
- ✦ Ice sublimation & grain disruption
- ✦ The gas acquires a chemical composition distinct from that of the unperturbed medium



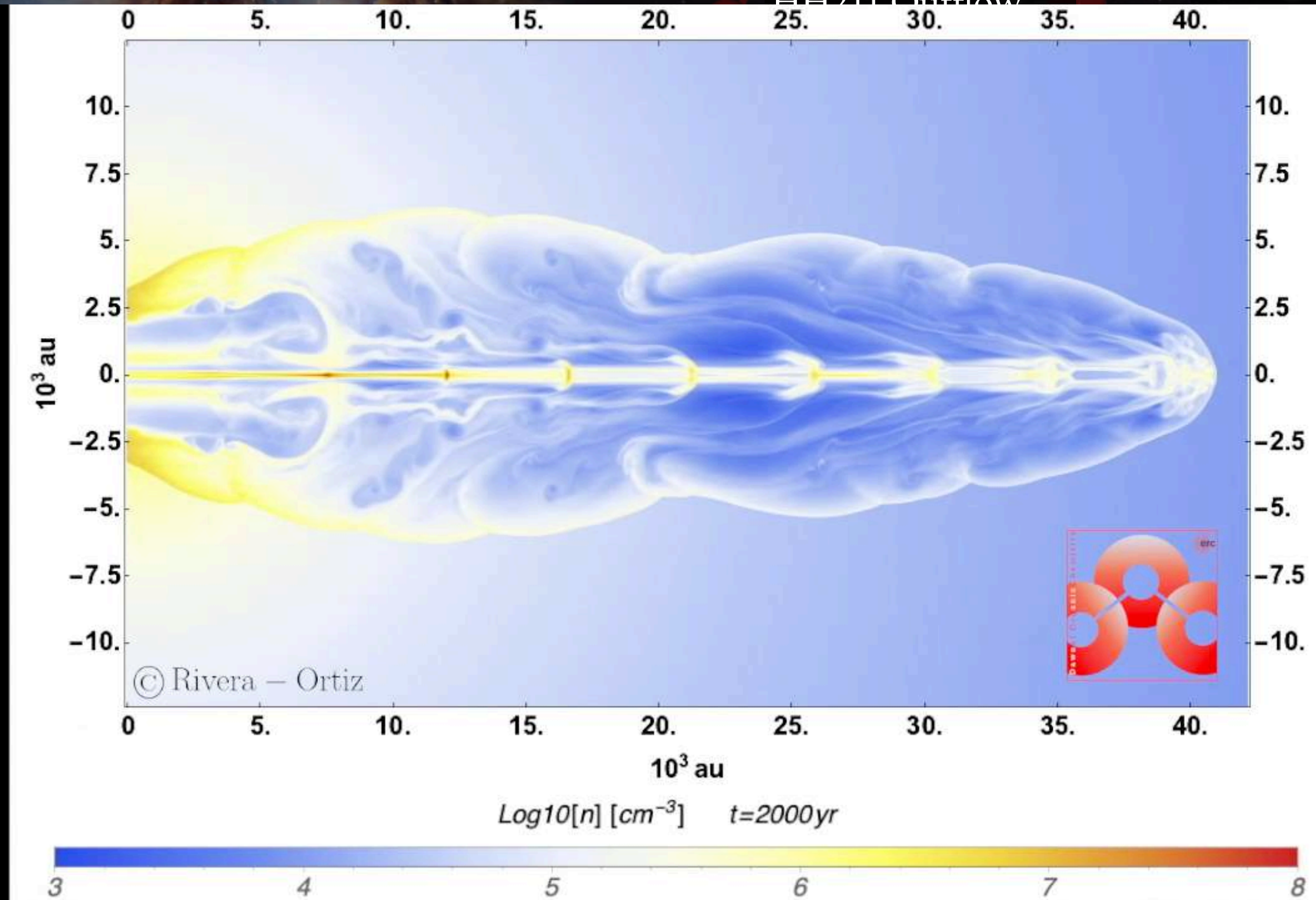
# The energetic phenomena around protostars

Jets

Resolution does matter!

HH211 Outflow

Greyscale: NIR image



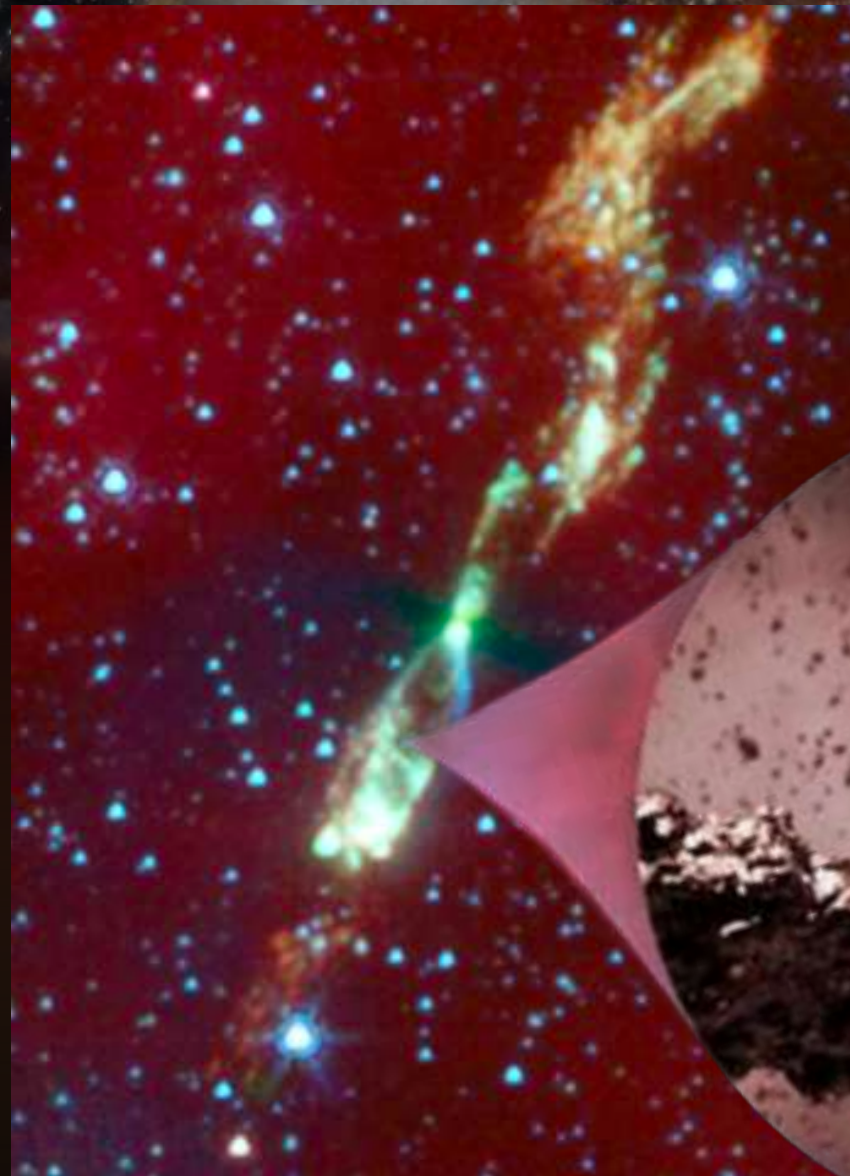
5 arcse

Bow-shock

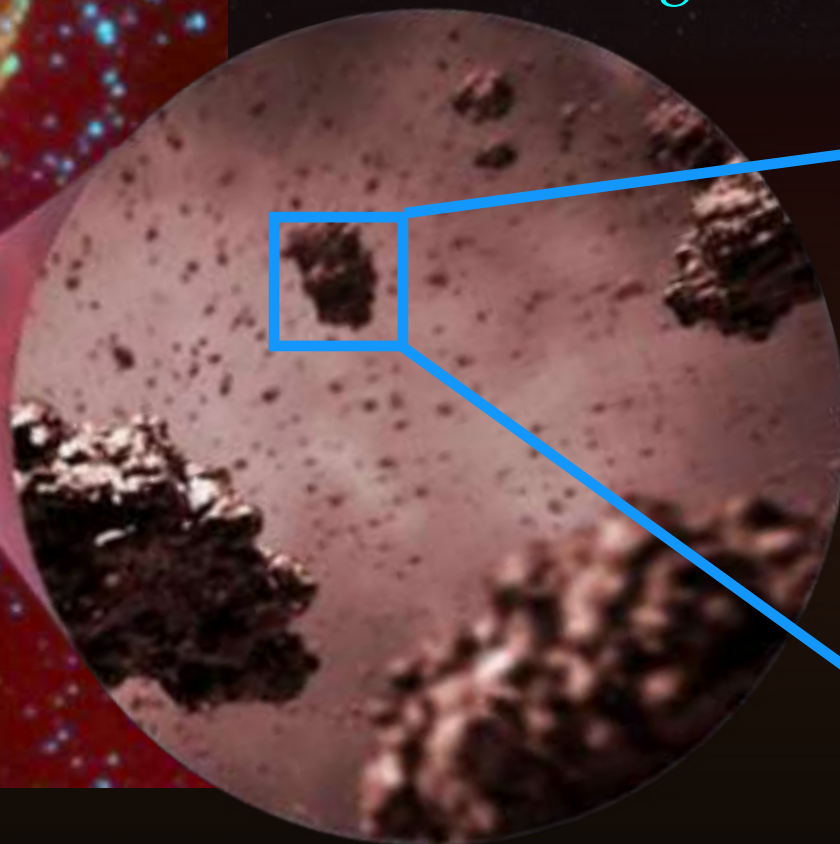
Emma Whelan



# The energetic phenomena around protostars

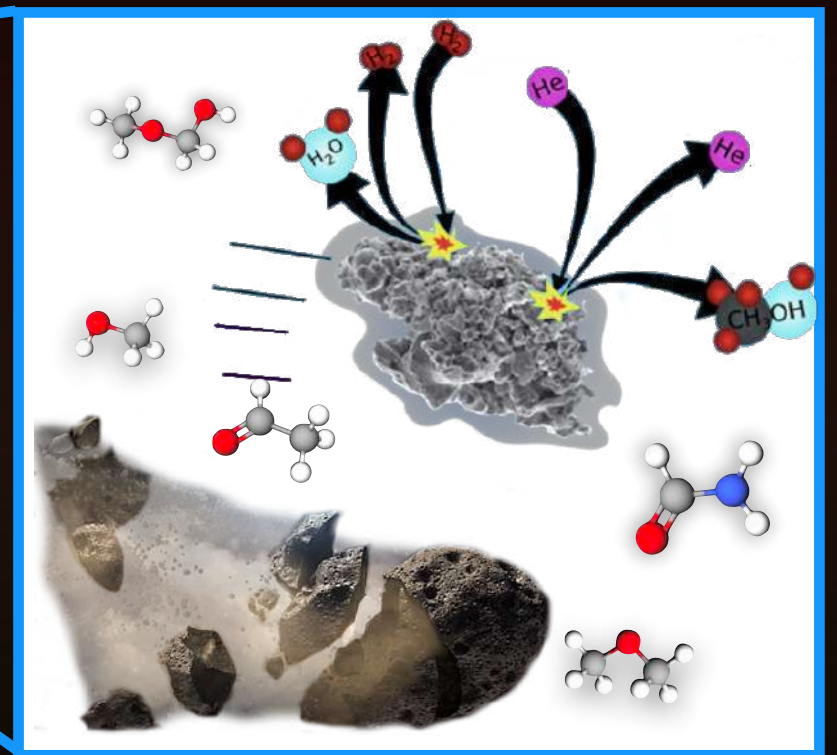


Shocks sputter/shutter  
dust grains

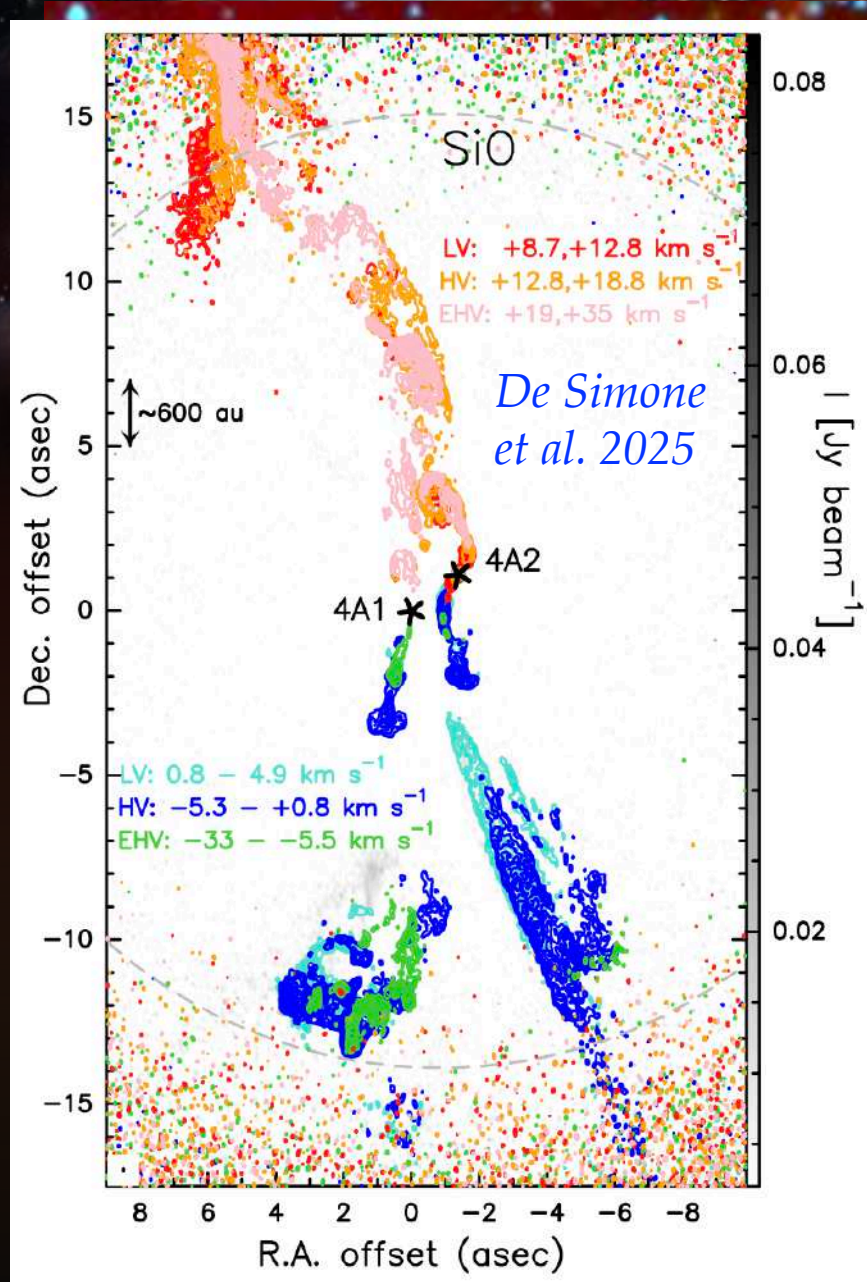


## Shocked Regions

Unique environments to study  
possible time-dependent effects



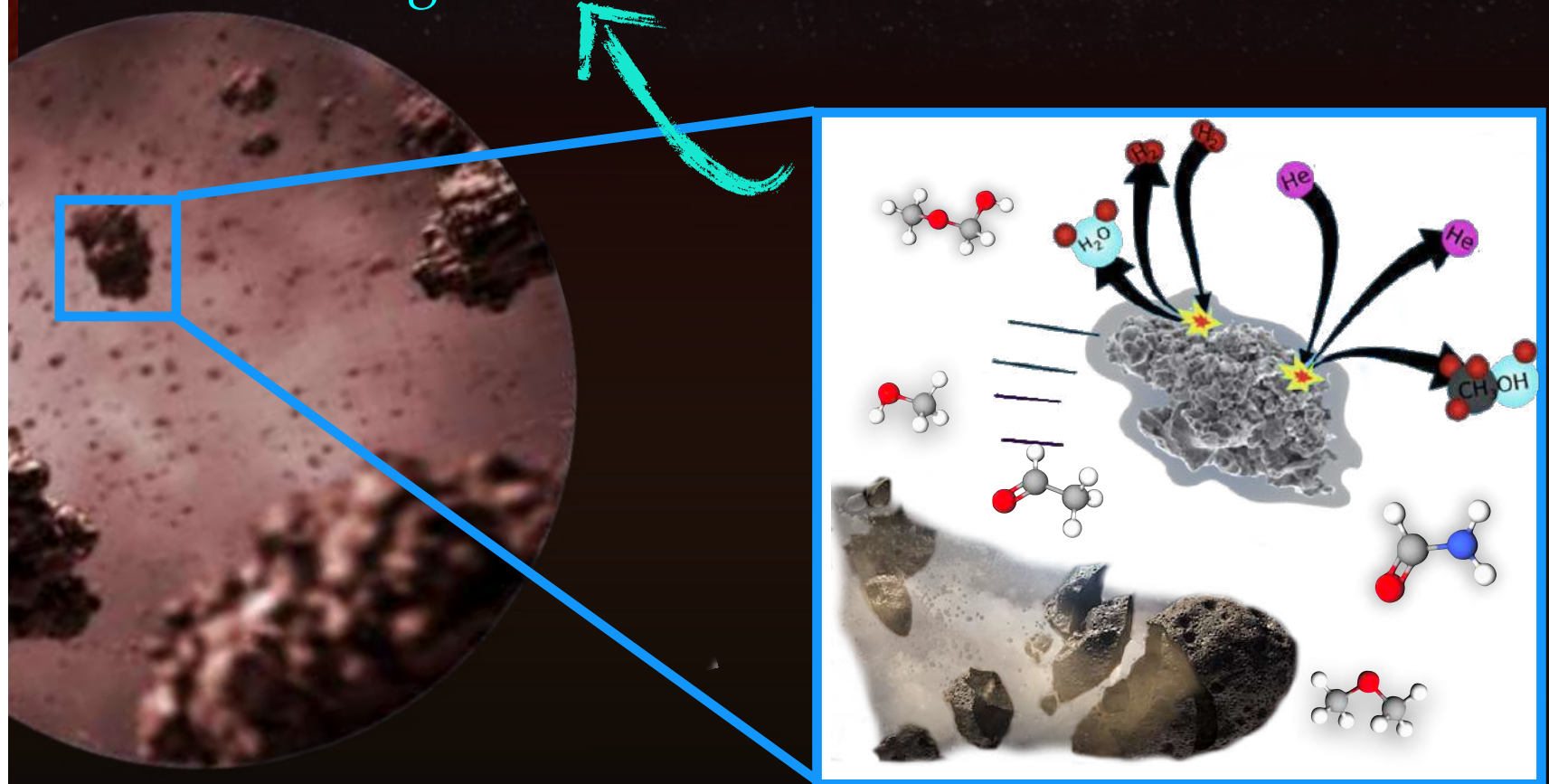
# The energetic phenomena around protostars



Shocks sputter/shutter dust grains

## Shocked Regions

Unique environments to study possible time-dependent effects

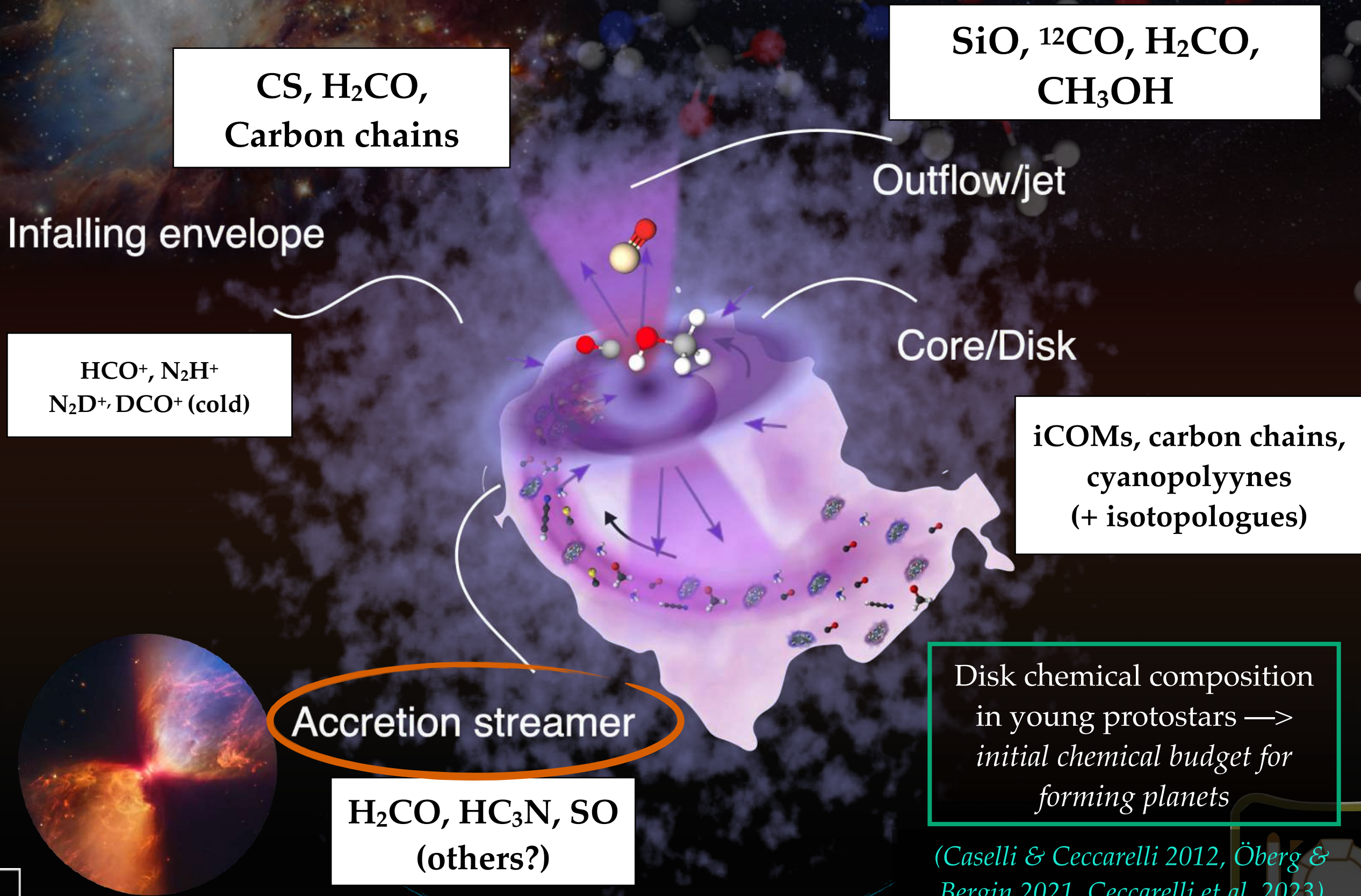


Tracers:

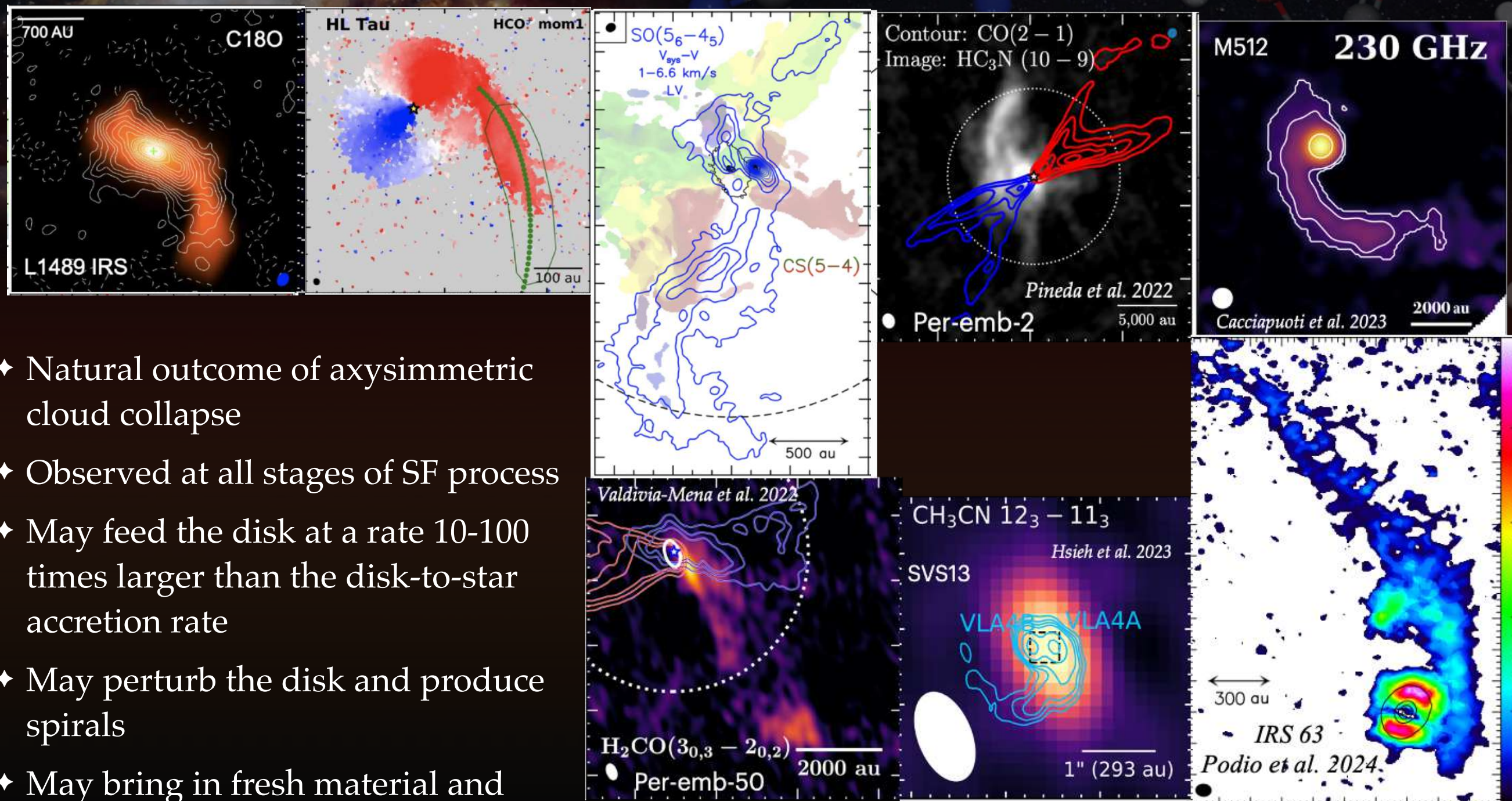
**SiO** —> Si, released from the refractory core to the gas phase, fast oxides  
(e.g. Caselli et al. 1997; Schilke et al. 1997; Gusdorf et al. 2008a,b; Guillet, Pineau Des Forêts & Jones 2011)

**CH<sub>3</sub>OH** —> formed efficiently on the grain mantles and released into the gas phase  
(e.g. Watanabe & Kouchi 2002; Rimola et al. 2014; Flower, Pineau des Forêts & Rabli 2010)

# Protostars: astrochemical laboratories and molecular factories

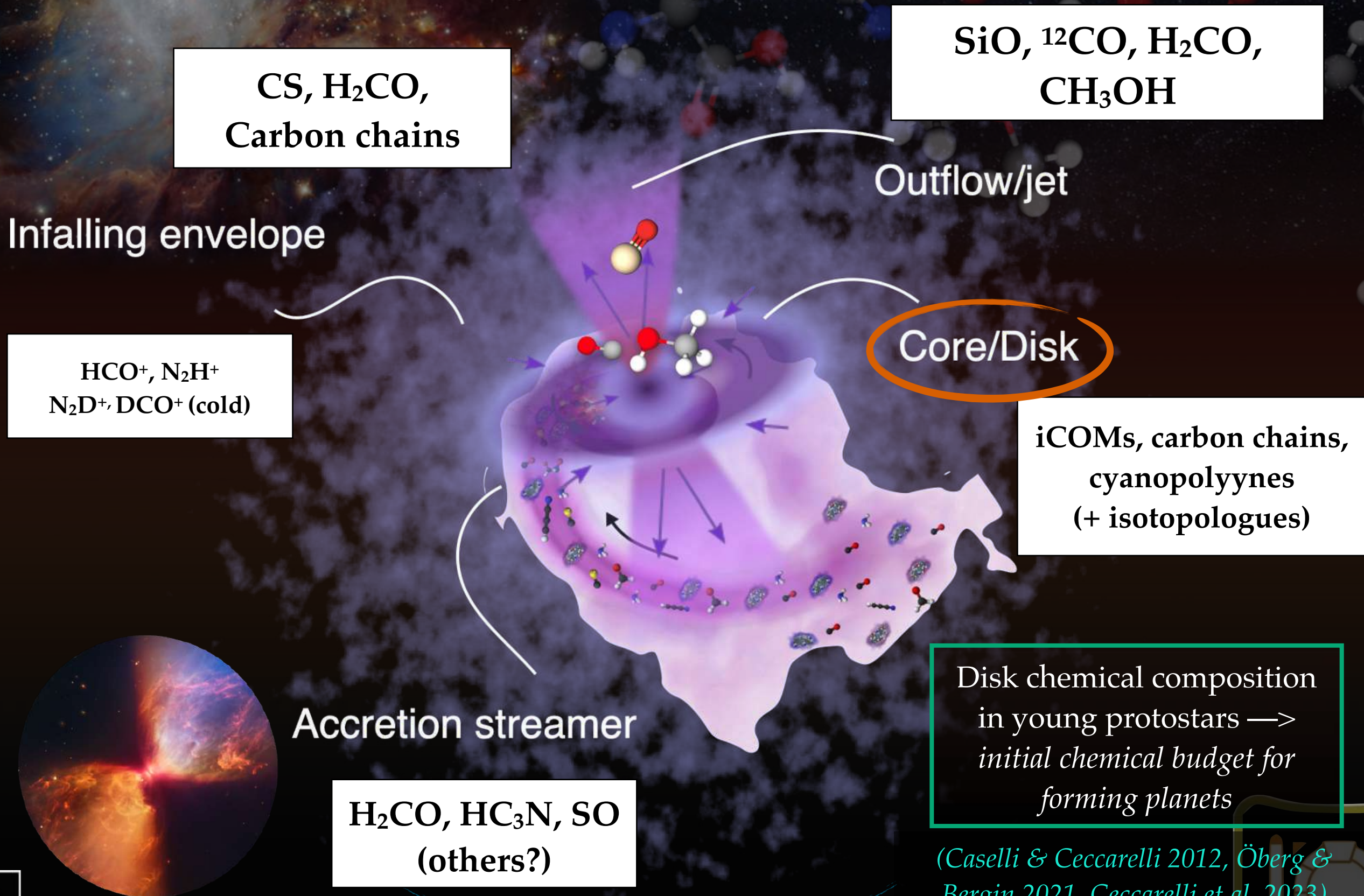


# The accretion streamers



- ✦ Natural outcome of axysimmetric cloud collapse
- ✦ Observed at all stages of SF process
- ✦ May feed the disk at a rate 10-100 times larger than the disk-to-star accretion rate
- ✦ May perturb the disk and produce spirals
- ✦ May bring in fresh material and alter the chemistry at the accretion shock front

# Protostars: astrochemical laboratories and molecular factories



(Caselli & Ceccarelli 2012, Öberg &  
Bergin 2021, Ceccarelli et al. 2023)

20 October 2026

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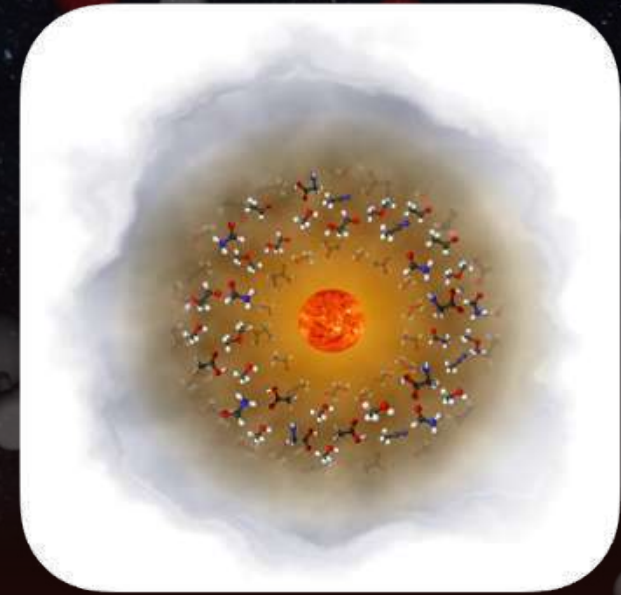


# In the earth of protostars

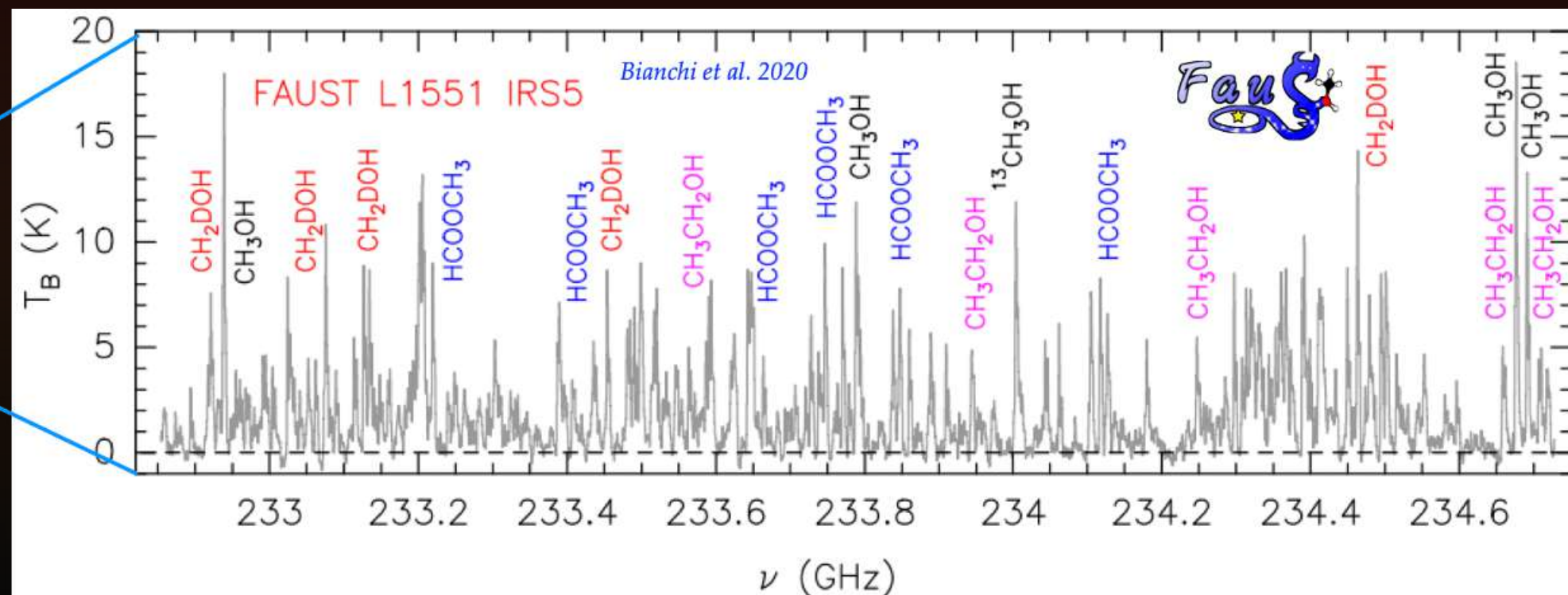
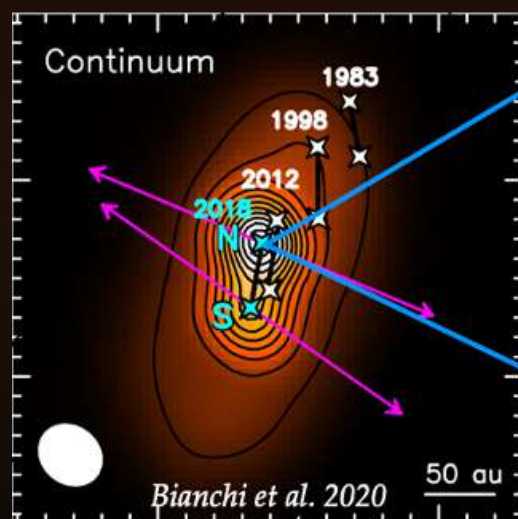
## Hot Corinos:

Compact ( $<100$  au), hot ( $>100$  K),  
dense ( $>10^7$  cm $^{-3}$ ) region enriched in iCOMs\*  
chemistry dominated by ice mantle sublimation

*Ceccarelli 2004 Ceccarelli et al. 2007*



## FOREST of lines



\*iCOMs (interstellar Complex Organic Molecules):

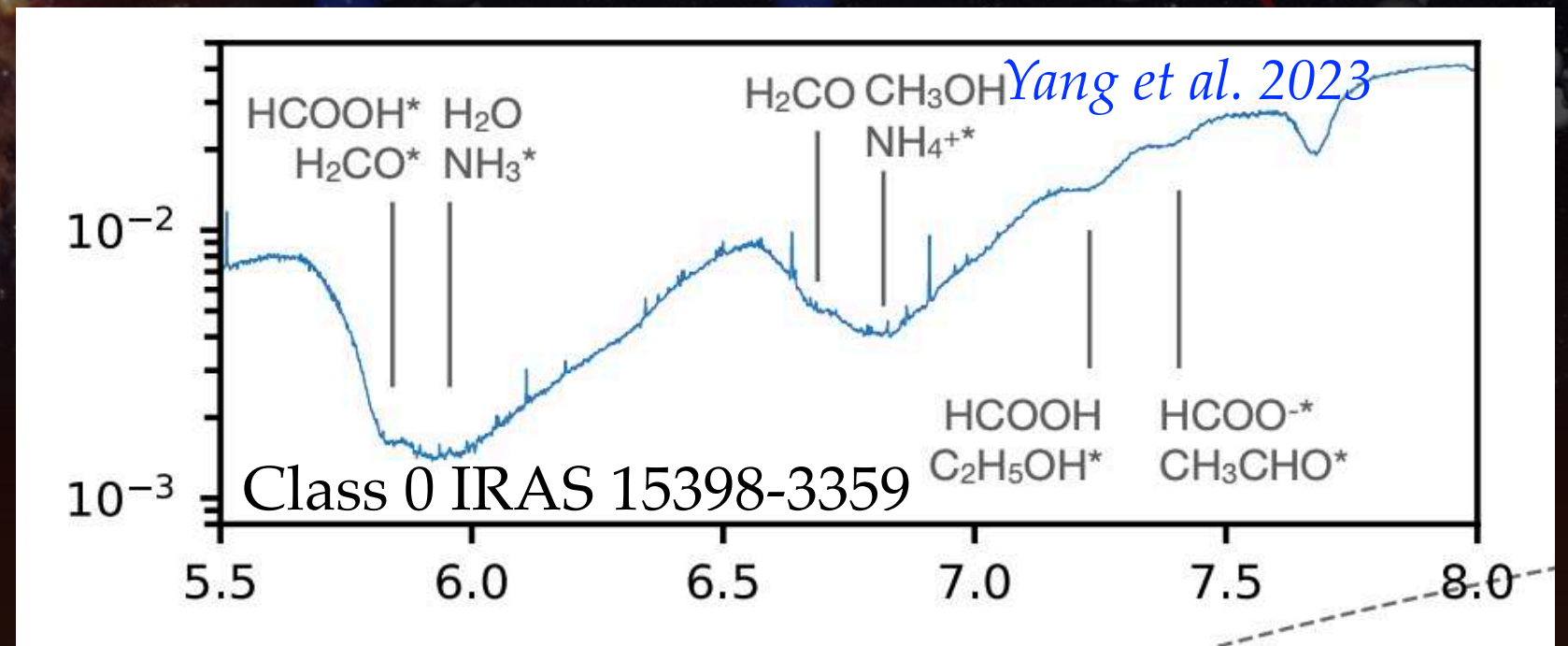
C-bearing molecules with more than six atoms and containing heteroatoms (like N, O, ...)

*(Herbst & Van Dishoeck 2009, Sakai & Yamamoto 2013, Ceccarelli et al. 2023)*

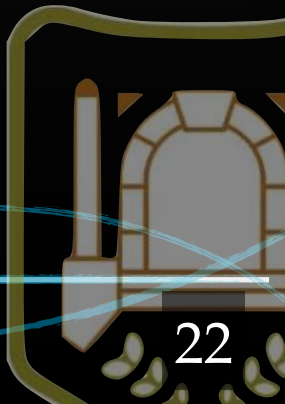
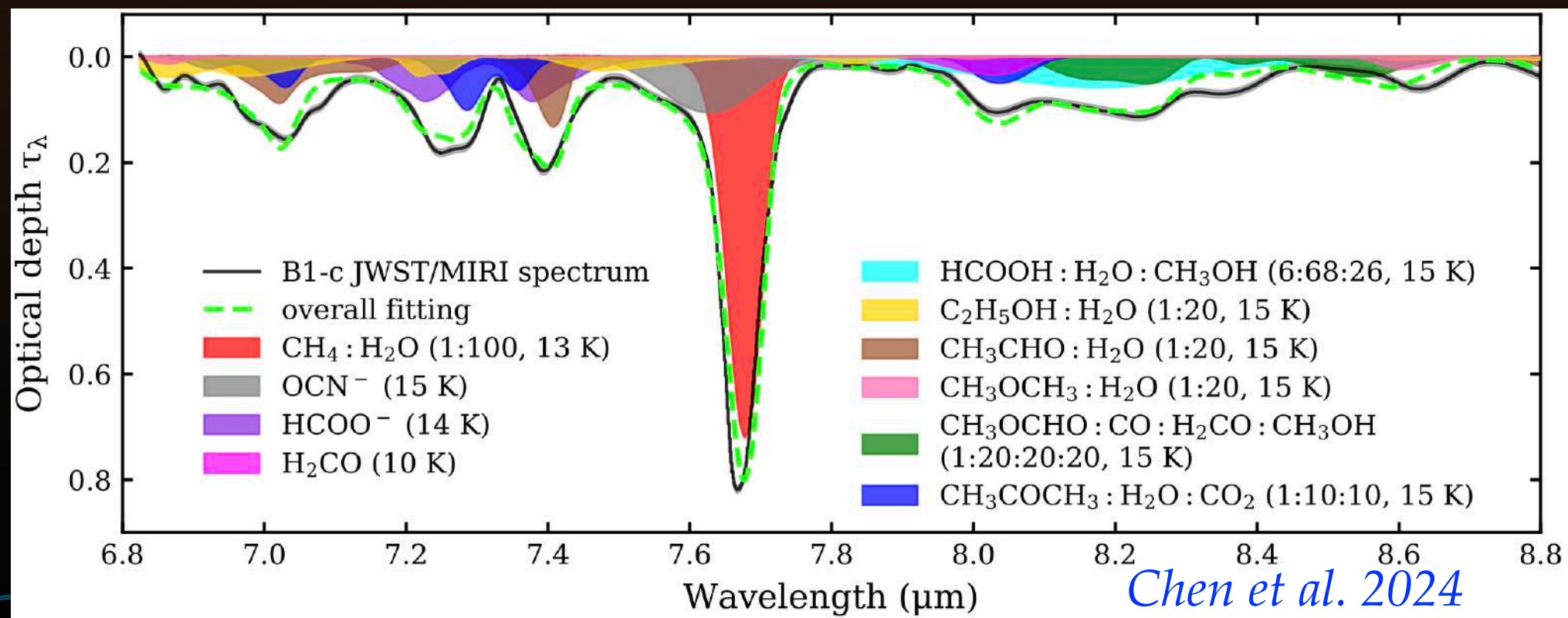
# Ice observations of protostellar environments



Detection of COMs in the ices around young protostars and in the really hot gas

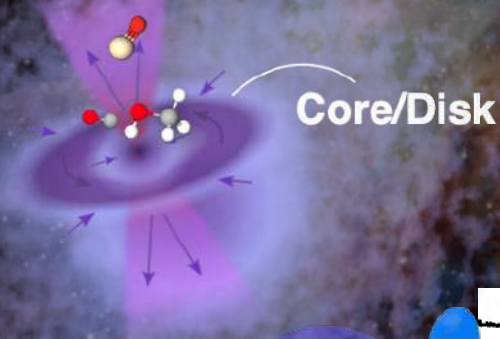


See also Rocha et al. 2024, Van Gelder et al. 2024a, b,



# In the earth of protostars

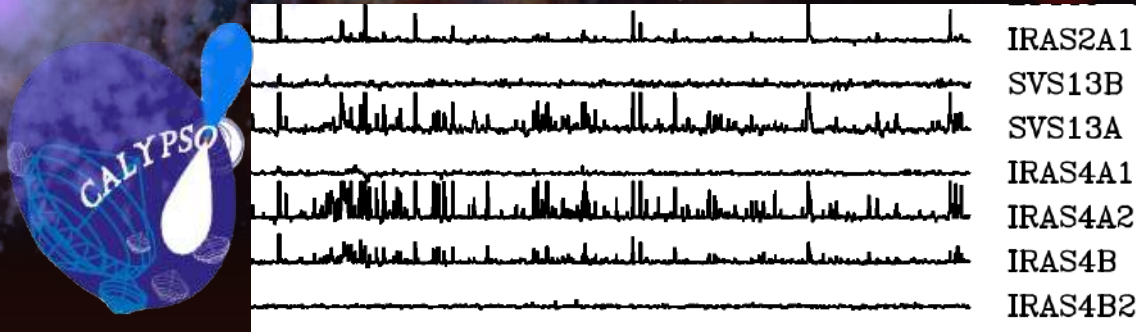
Hot corinos mainly studied at mm wavelengths



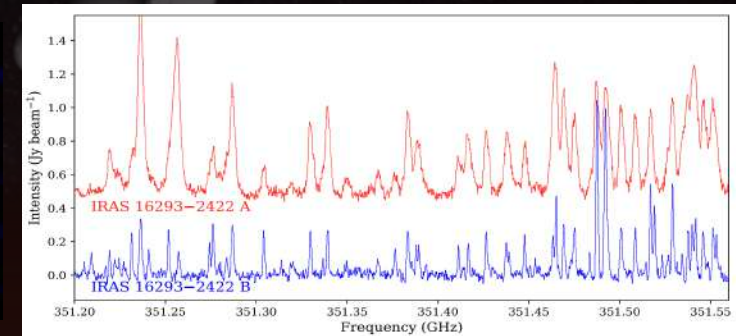
PdBI/NOEMA

ALMA

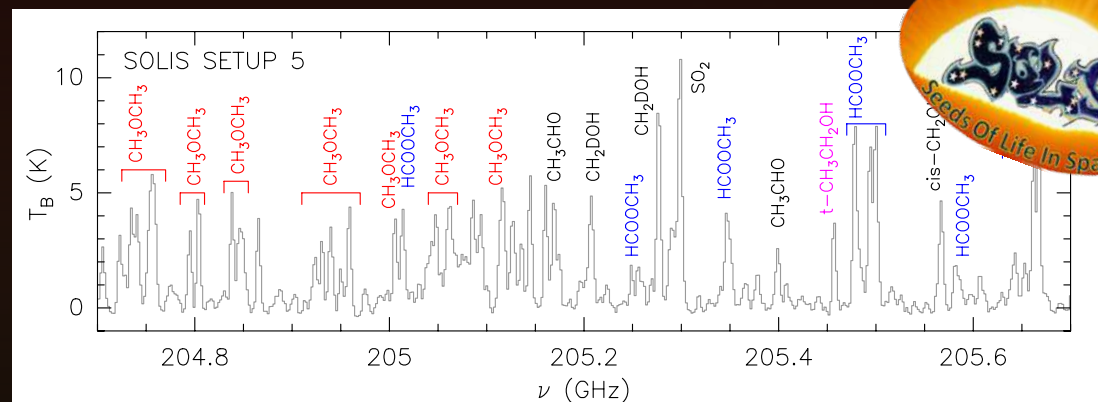
*Joergensen et al. 2016, Manigand et al. 2020*



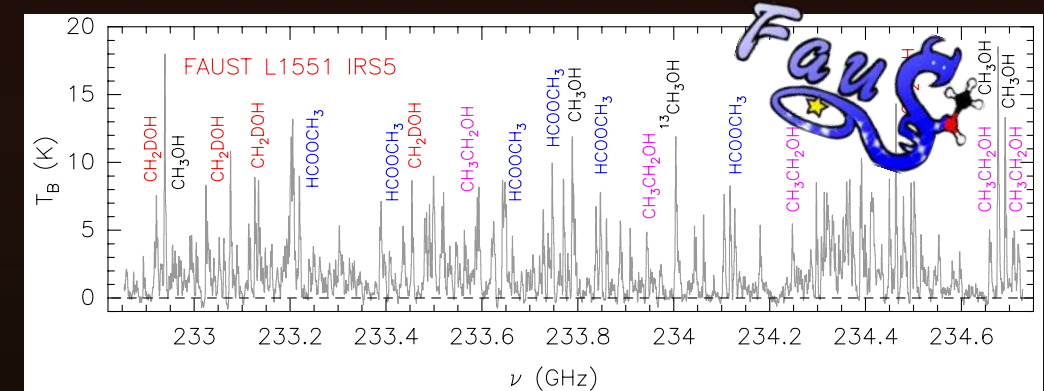
*Belloche et al. 2020*



*Codella et al. 2021, Bianchi et al. 2020*



*Ceccarelli et al. 2017*



+ PEACHES & ORANGES  
*Yang et al. 2021, Bouvier et al. 2022*

Other Large Programs:

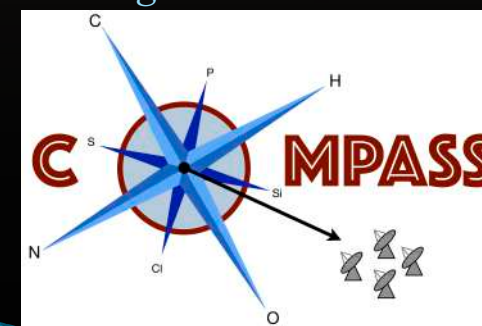
*Joergensen et al. 2026*



IRAM 30m



*Lefloch et al. 2017*



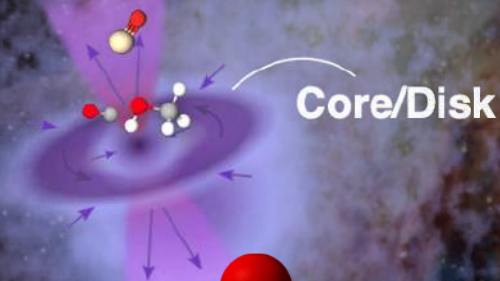
Marta De Simone

Astrophysics School  
"Francesco Lucchin"

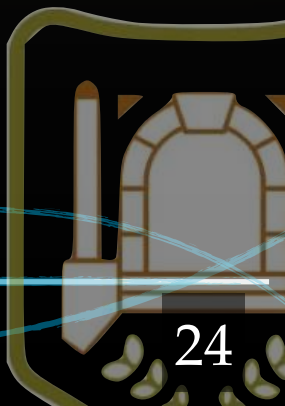
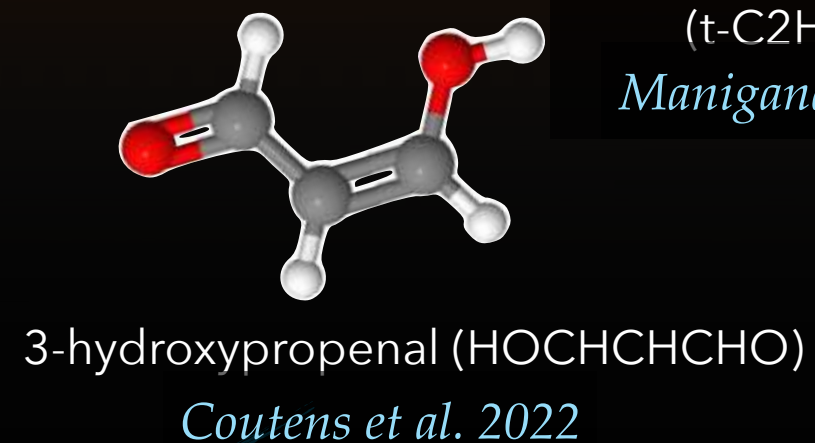
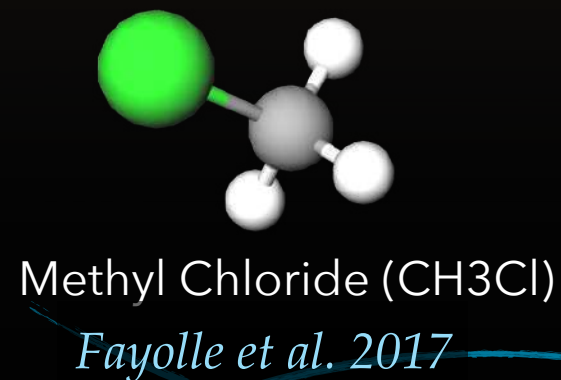
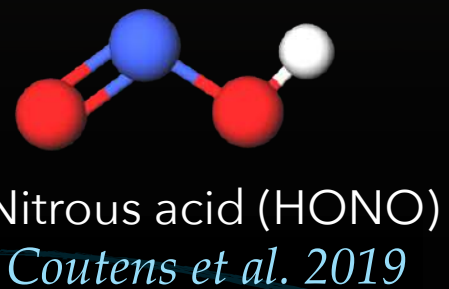
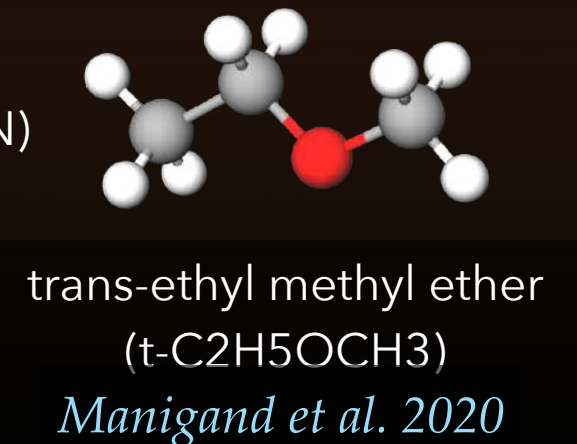
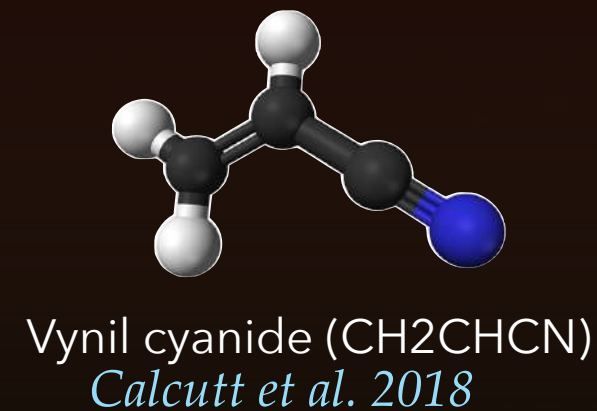
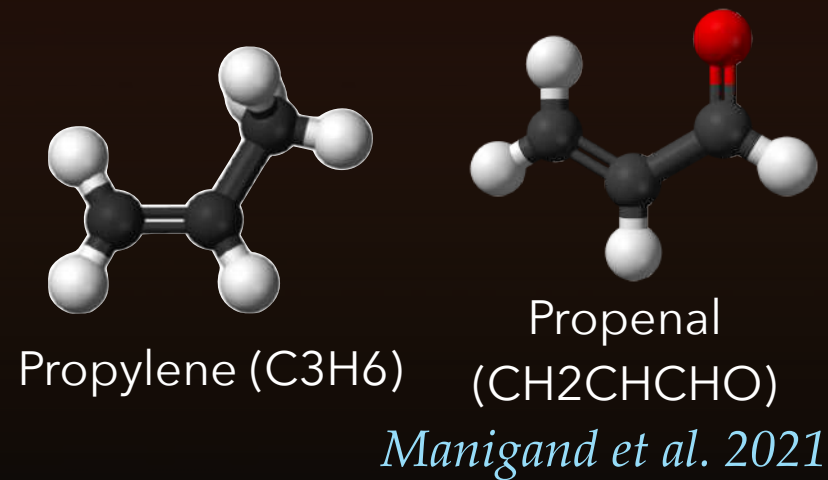
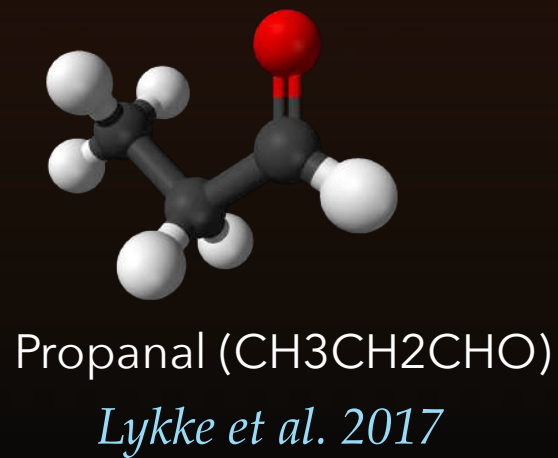
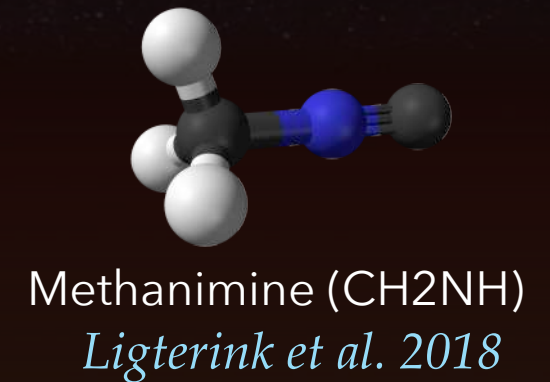
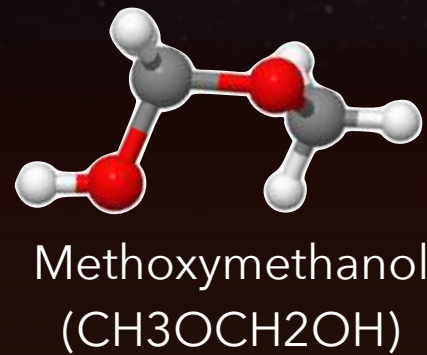
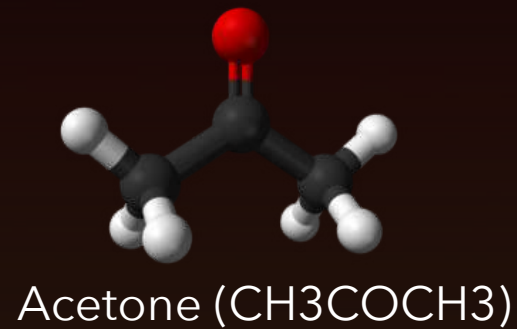
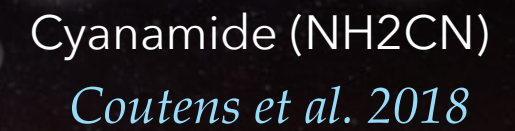
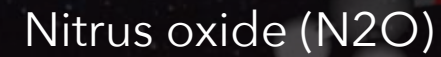
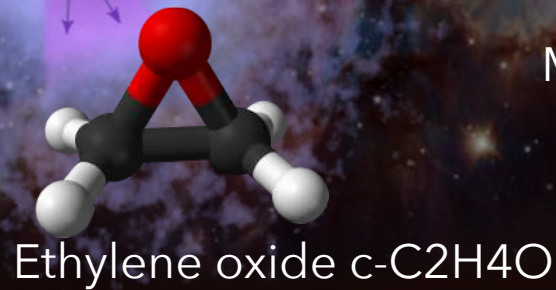
20 October 2026

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# In the earth of protostars



Core/Disk



# In the earth of protostars

Does every protostar possess a hot corino? **NO!**

Protostars are far to be fully chemically characterised

- \* Not every protostar possesses a hot corino region
- \* Protostellar systems show different mm molecular spectra
- \* Very few hot corinos are resolved

**< 5 WCCC**

Rich in carbon chains

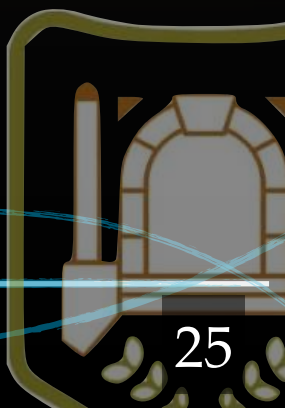
(e.g., C<sub>3</sub>H<sub>2</sub>,  
C<sub>x</sub>H<sub>x</sub>, HC<sub>x</sub>N, etc.)

**< 3 Hybrids**

(WCCC+ hot corino)

**< 30 iCOMs-rich Hot  
Corinos**

Rich in organics  
(e.g., CH<sub>3</sub>OH, CH<sub>3</sub>OCH<sub>3</sub>,  
NH<sub>2</sub>CH...)



# In the earth of protostars

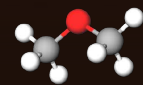
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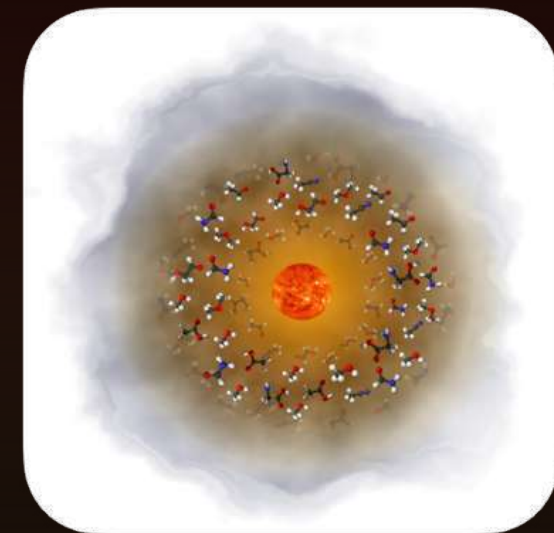
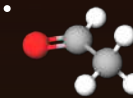
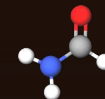
- \* Not every protostar possesses a hot corino region
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## Hot corino

interstellar complex organic molecules (iCOMs)  
e.g.  $\text{HCOOCH}_3$ ,  $\text{CH}_3\text{OCH}_3$ ,  $\text{CH}_3\text{CH}_2\text{OH}$ ,  $\text{NH}_2\text{CHO}$ ...



Abundances  $\sim 100\times$  WCCCs

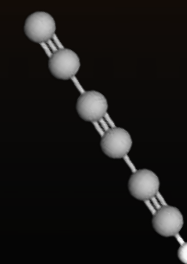
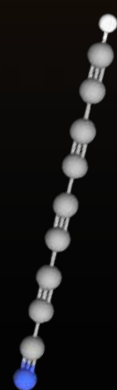


Examples: IRAS4A, IRAS16293...

size  $< 100$  au

## Warm Carbon Chains Chemistry (WCCC)

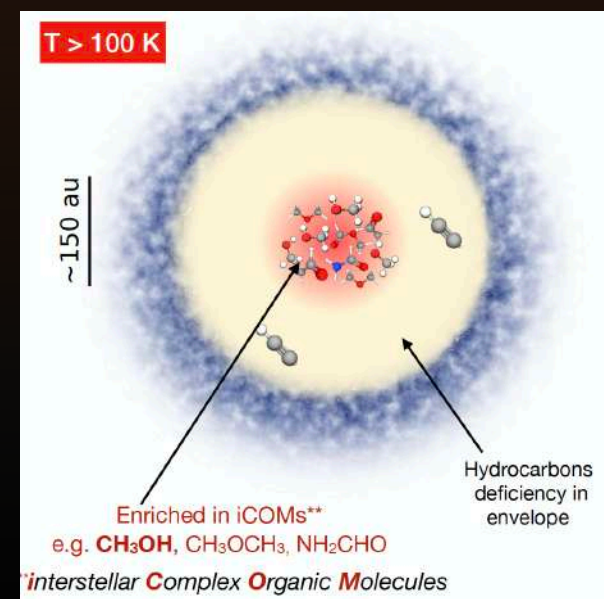
Unsaturated (long) carbon chains  
e.g.  $\text{C}_4\text{H}_2$ ,  $\text{C}_4\text{H}$ ,  $\text{C}_6\text{H}$ ,  $\text{HC}_7\text{N}$ ,  $\text{HC}_9\text{N}$ ...



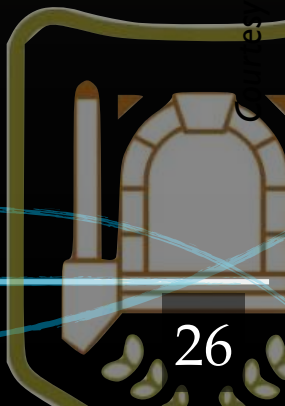
Abundances  $\sim 10\times$  those in hot corinos

Examples: L1527

size  $\sim 2000$  au



Courtesy by M. Bouvier



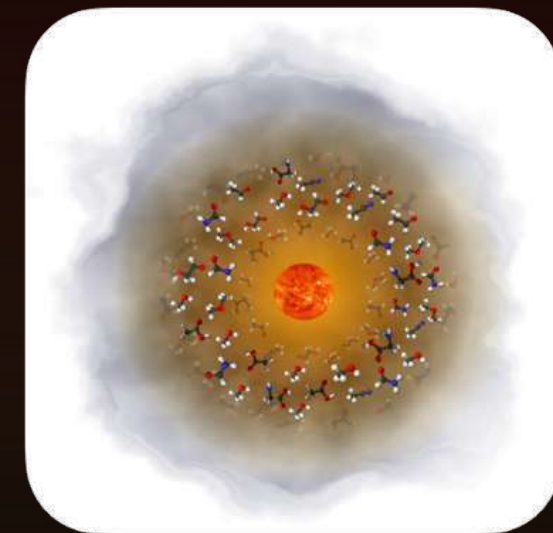
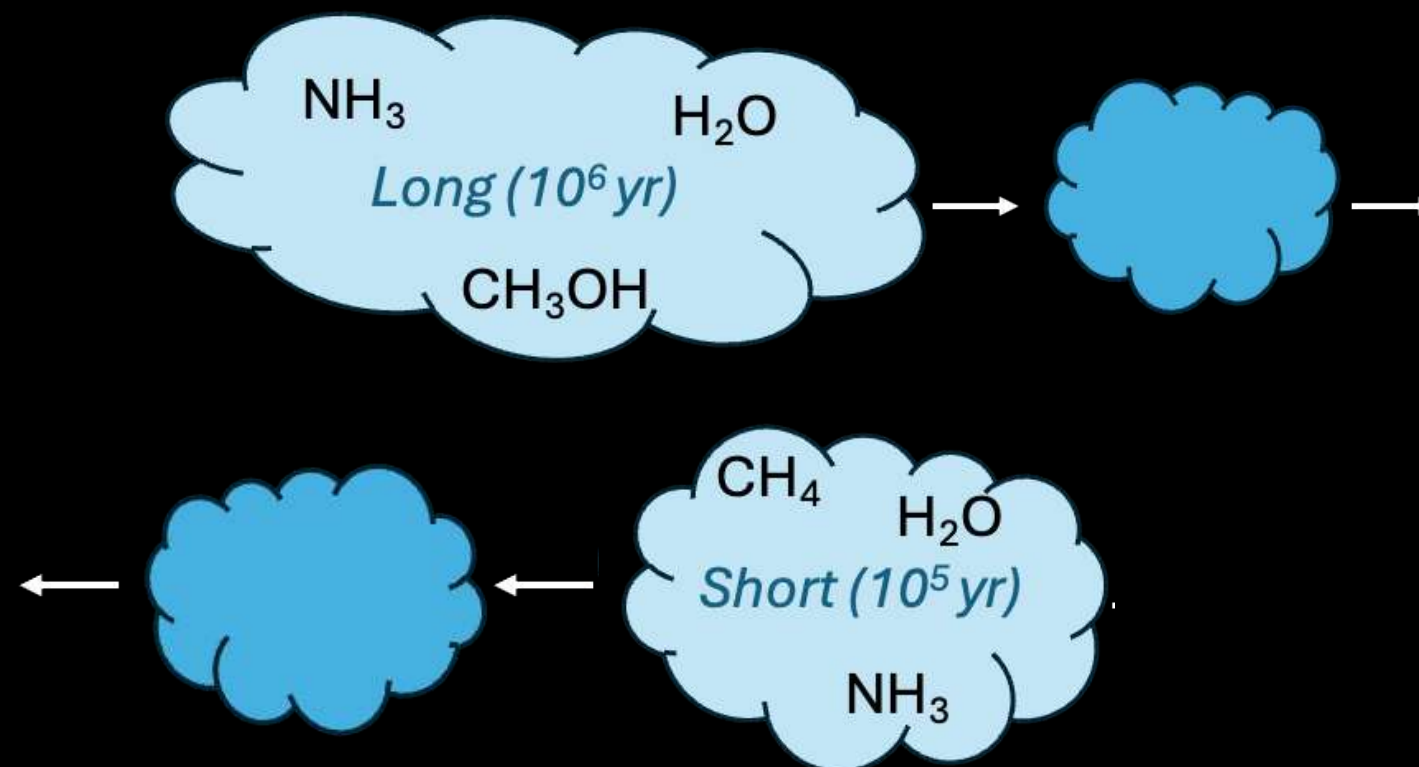
# In the earth of protostars

Does every protostar possess a hot corino? **NO!**

Protostars are far to be fully chemically characterised

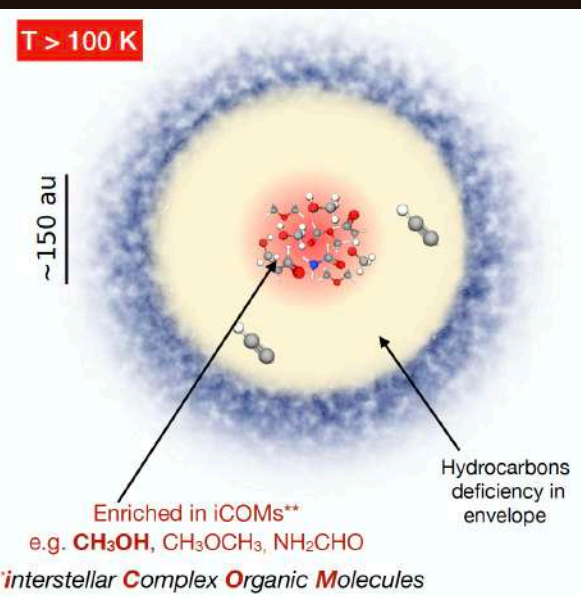
- \* Not every protostar possesses a hot corino region
- \* Protostellar systems show different mm molecular spectra
- \* Very few hot corinos are resolved

Different timescale of the ice mantle formation



Courtesy by M. Bouvier

Different UV illumination



Courtesy by M. Bouvier



# In the earth of protostars

## *WCCC vs Hot Corinos*

ORion Alma New GEneration Survey (ORANGES)

Perseus ALMA Chemistry Survey (PEACHES)

ORANGES are different from PEACHES

Unbiased survey ALMA Band 6, same sensitivity and angular resolution

—> *how many hot corinos and WCCCs?*

In Orion 30 % hot corinos

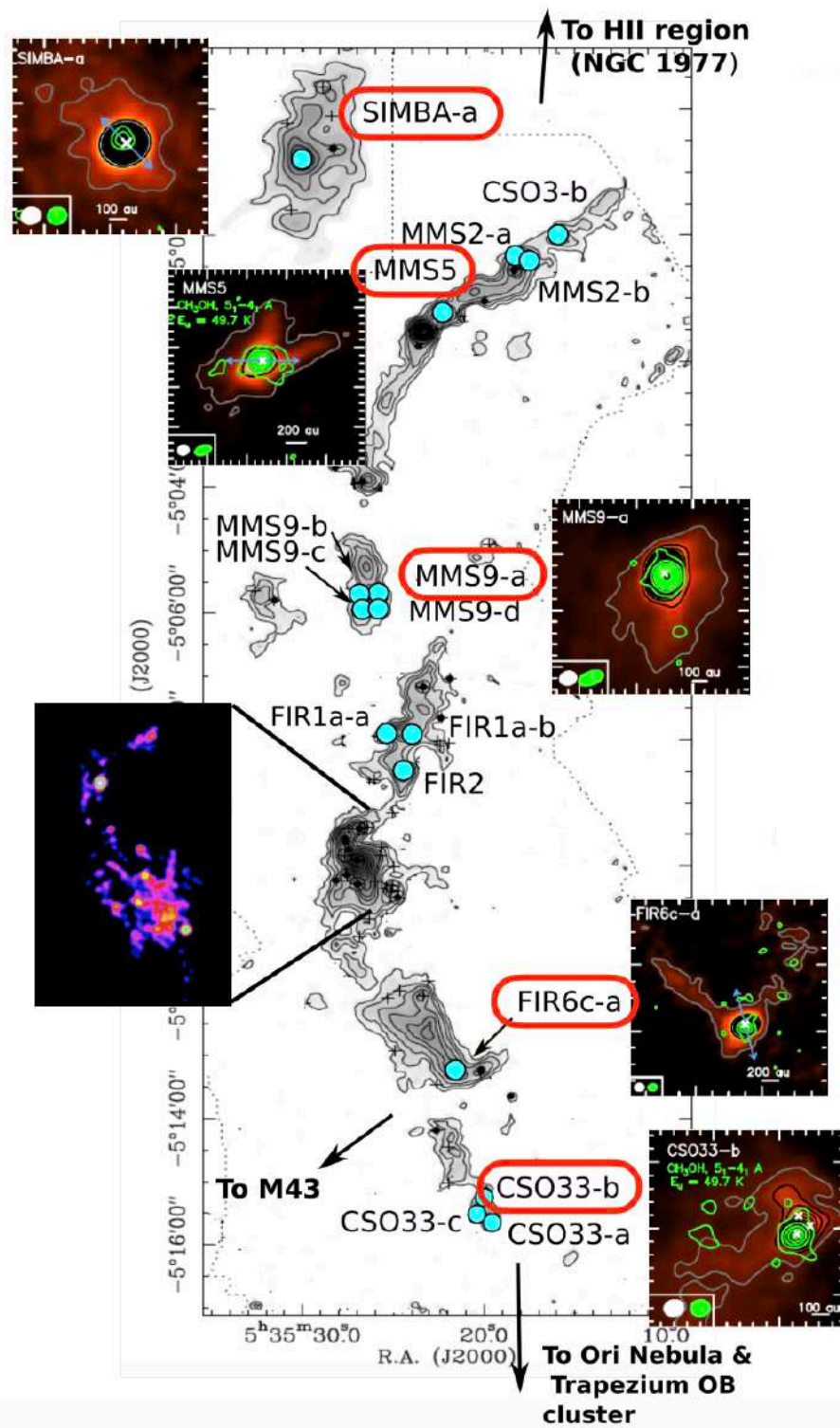
In Perseus >50% hot corino

CCH and c-C<sub>3</sub>H<sub>2</sub> not good tracers for WCCC, need for longer chains and rings

*Bouvier et al. 2020, 2021, 2022*

*Fontani et al. 2017, Lattanzi et al. 2023, Chahine et al. 2022, Favre et al. 2018, Ceccarelli et al. 2014*

Bouvier et al. 2022



Courtesy by E. Bianchi

Marta De Simone

Astrophysics School  
"Francesco Lucchin"

20 October 2026

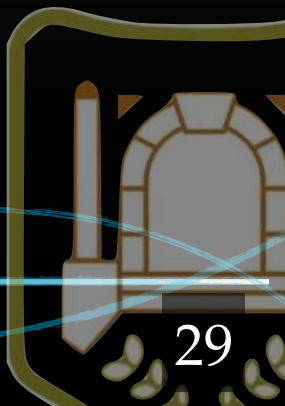
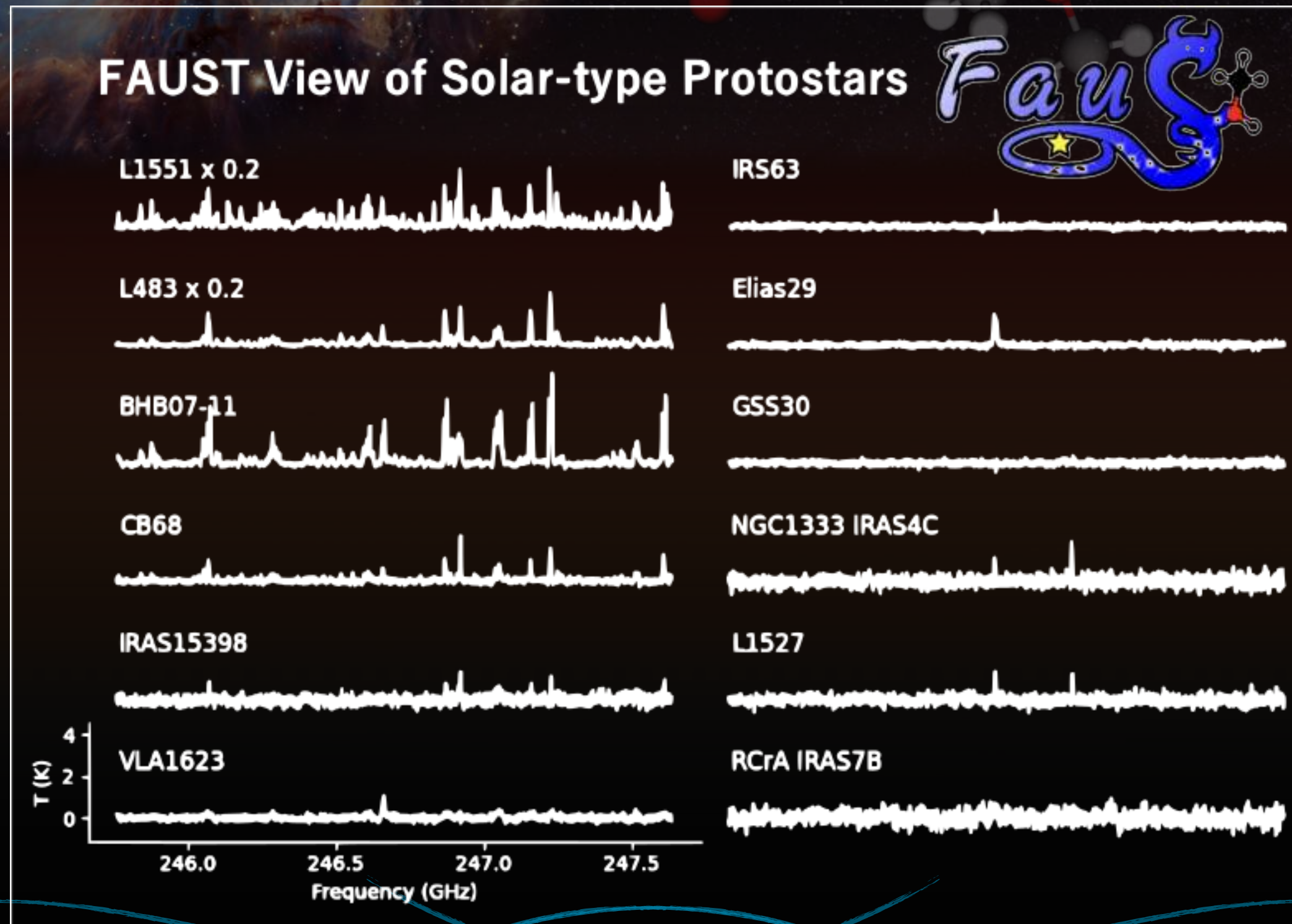
28



# In the earth of protostars

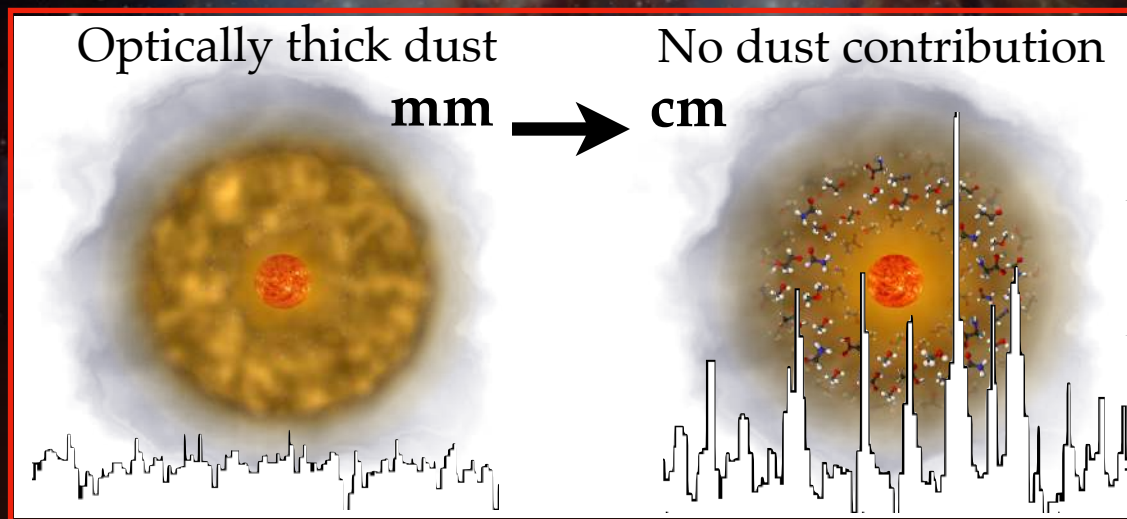
## *WCCC vs Hot Corinos*

FAUST: Fifty AU STudy of the chemistry in disk/envelope systems of Solar-like protostars

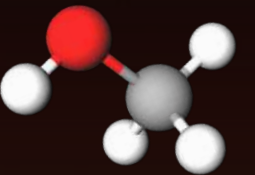


# In the earth of protostars

## *Hidden Hot Corinos*

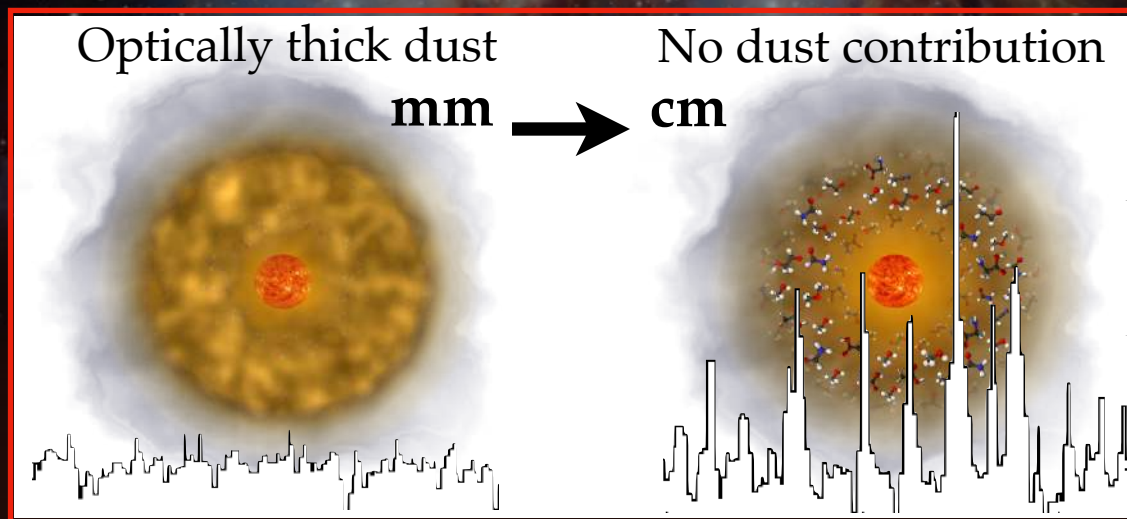


→ dust opacity effects on iCOMs emission through mm + cm observations of  $\text{CH}_3\text{OH}$

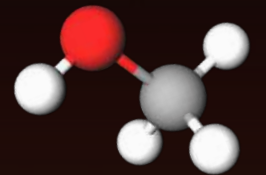


# In the earth of protostars

## *Hidden Hot Corinos*



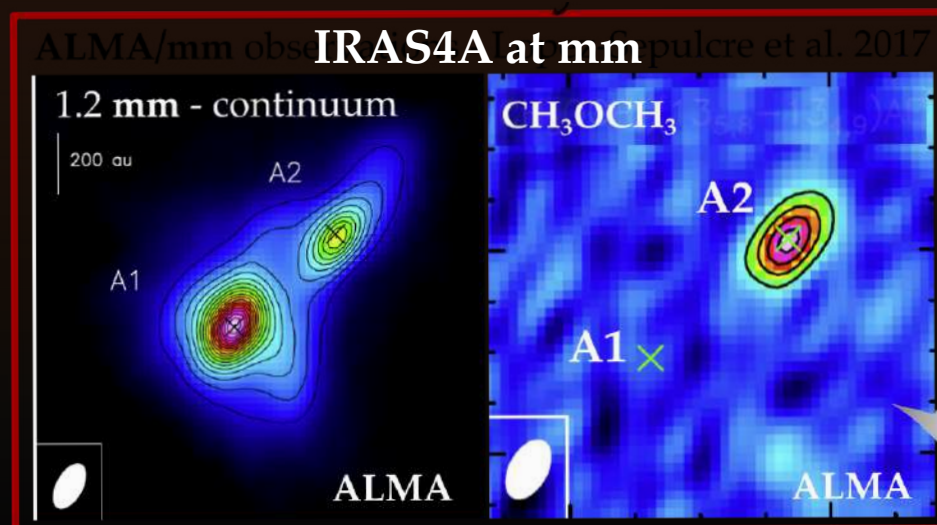
→ dust opacity effects on iCOMs emission through mm + cm observations of  $\text{CH}_3\text{OH}$



Moving from millimetre to centimetre wavelengths

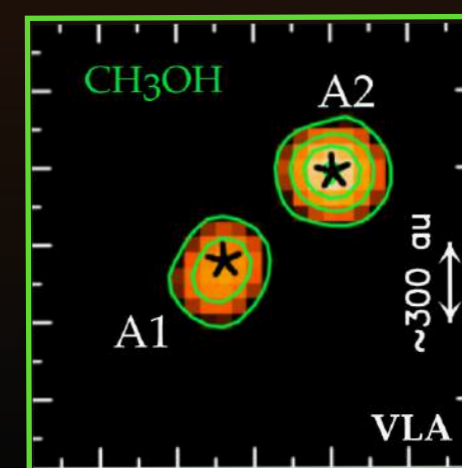


IRAS4A at mm  
Hot Corino in one of  
the two companion



*Lopez-Sepulcre et al. 2017*

IRAS4A at cm



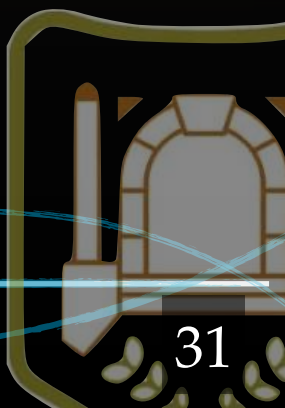
*De Simone et al. 2020a*



The mm dust is  
hiding the IRAS  
4A1 hot corino



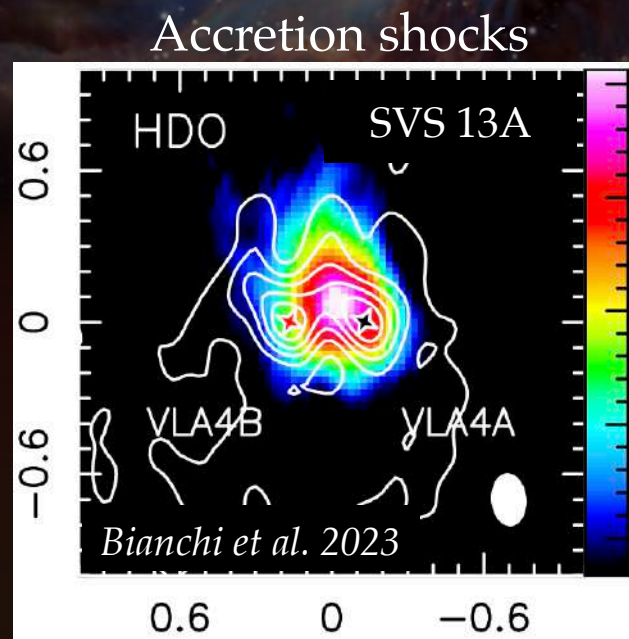
- hot corinos may be hidden behind the dust
- mm molecular abundances are underestimated!



# In the earth of protostars

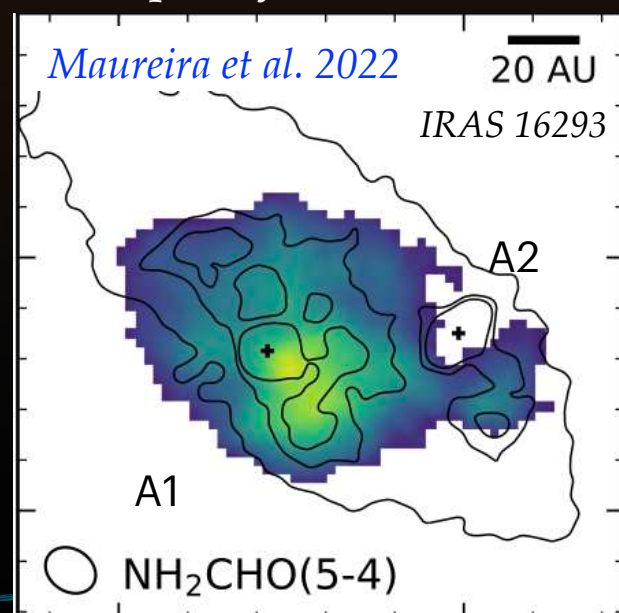
## Resolving Hot Corinos

Hot corinos structure is not so clear! Very few have been resolved so far : need  $< 50\text{-}100$  au resolution



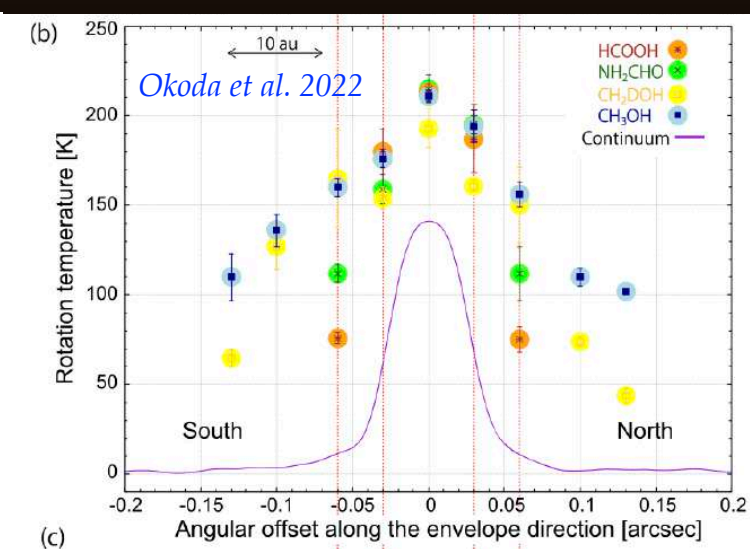
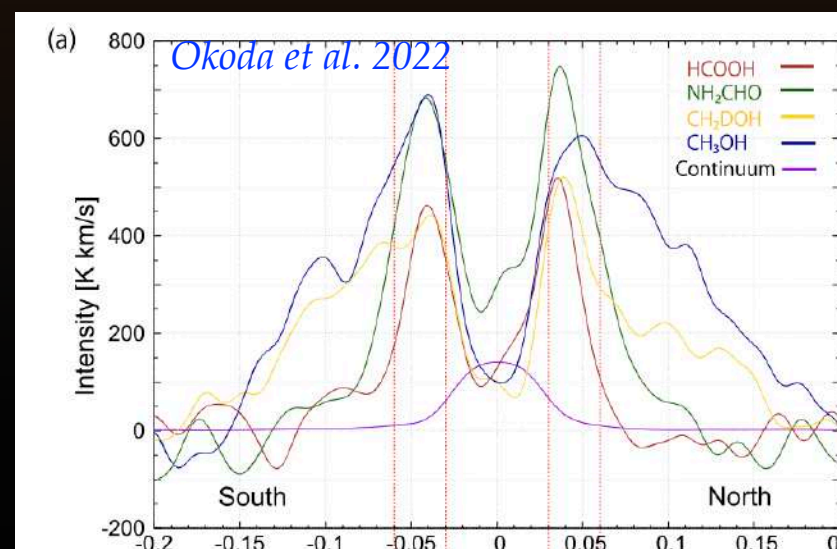
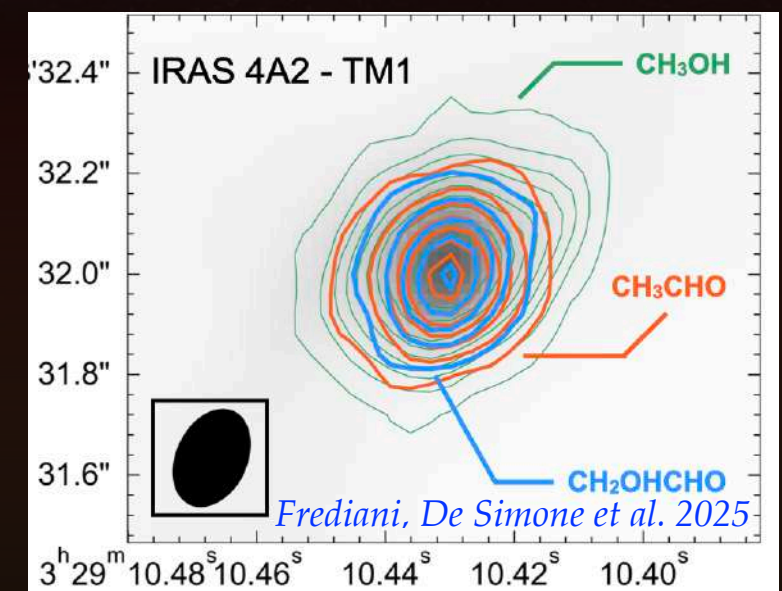
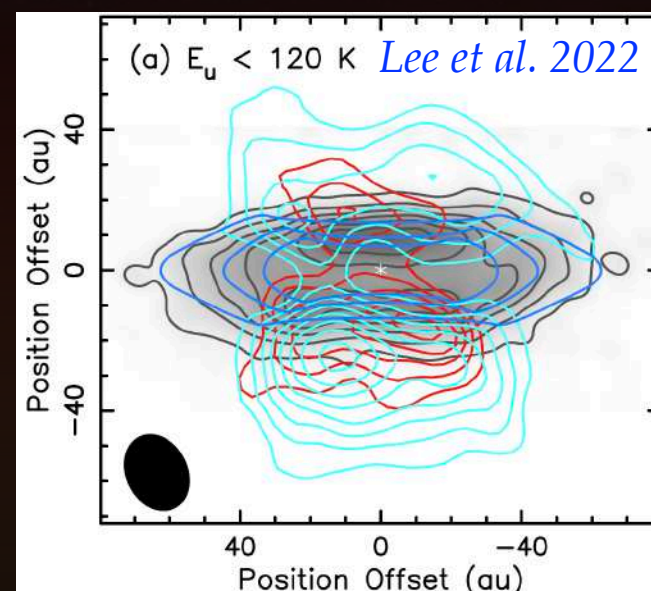
also Garufi et al. 2022

High multiplicity & iCOMs in hot spots



HH212, B335, IRAS4A:

Disk Atmosphere & stratification (chemical differentiation)



(c)

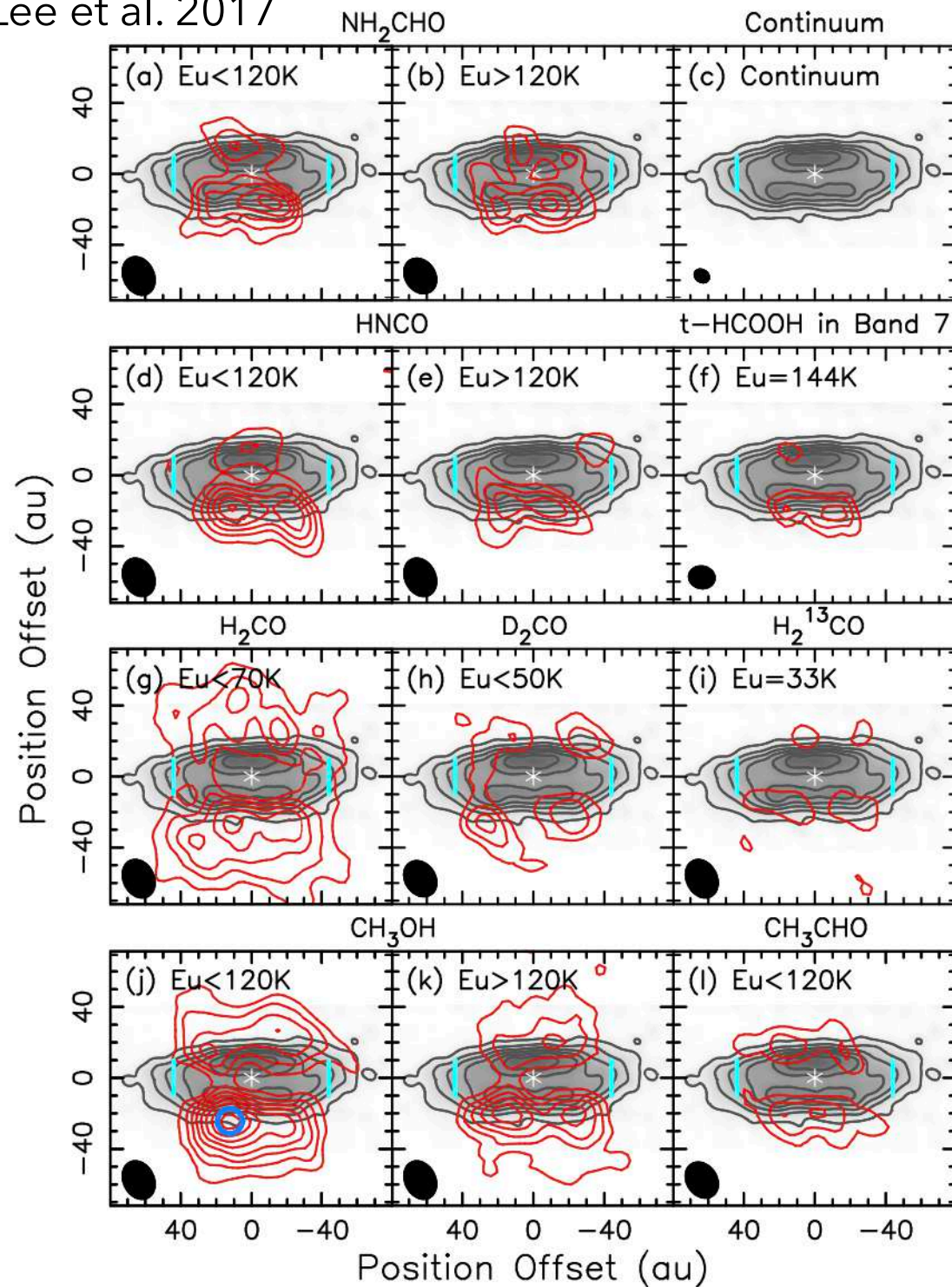
# In the earth of protostars

## Resolving Hot Corinos

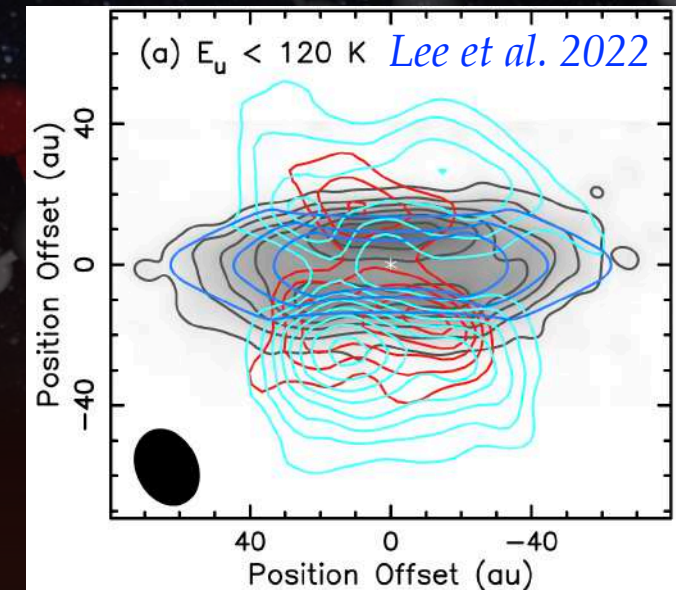
Angular resolution 10 au!

Disk stratification

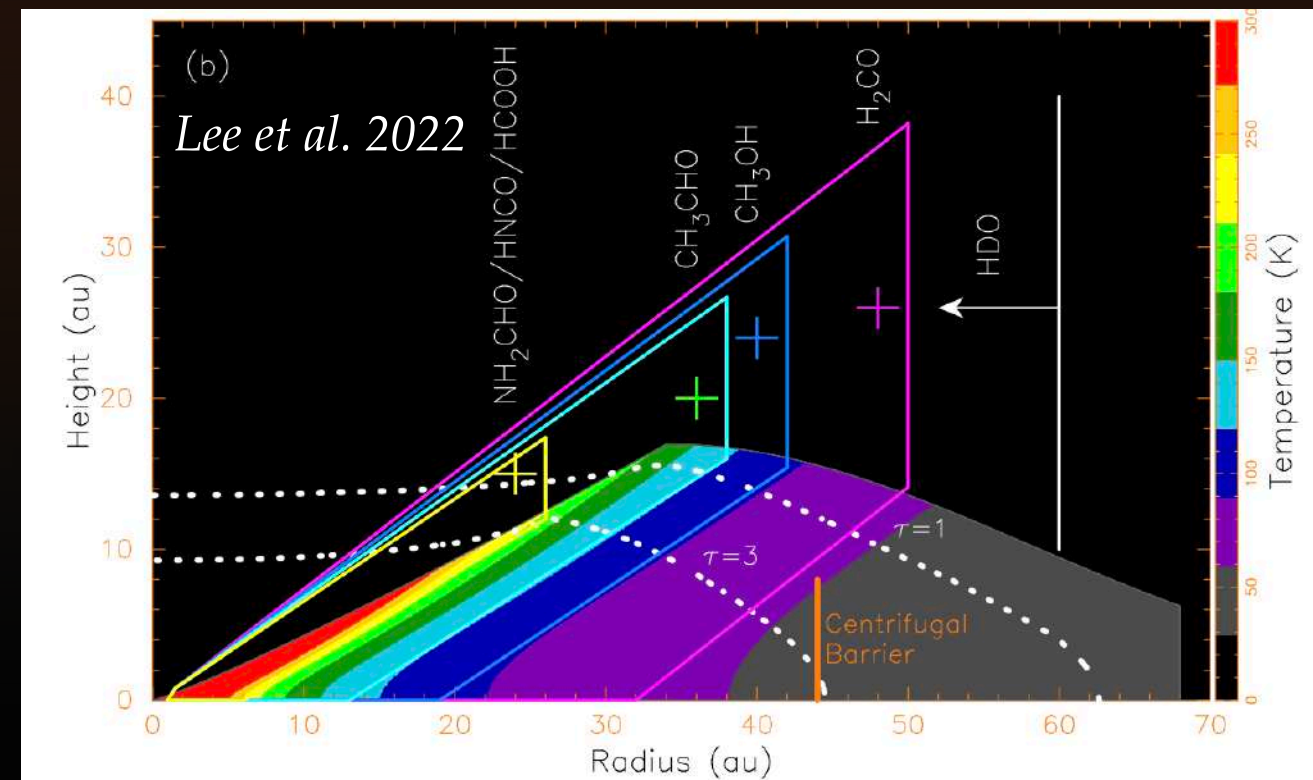
Lee et al. 2017



The dusty disk in the middle is **obscuring** molecular lines.



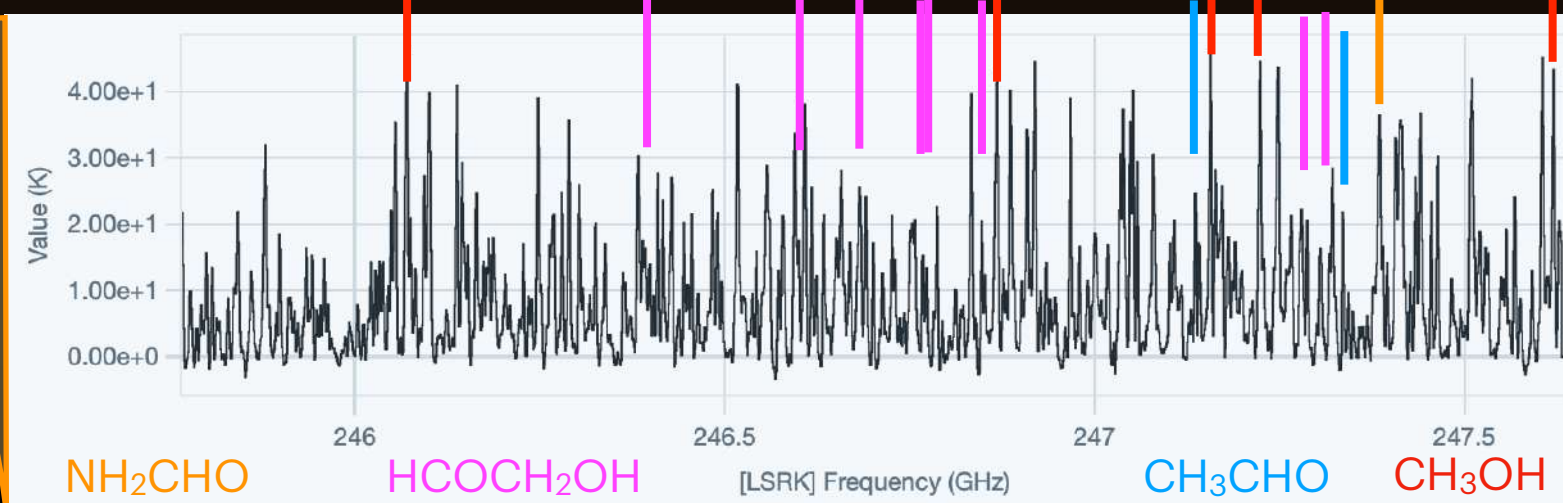
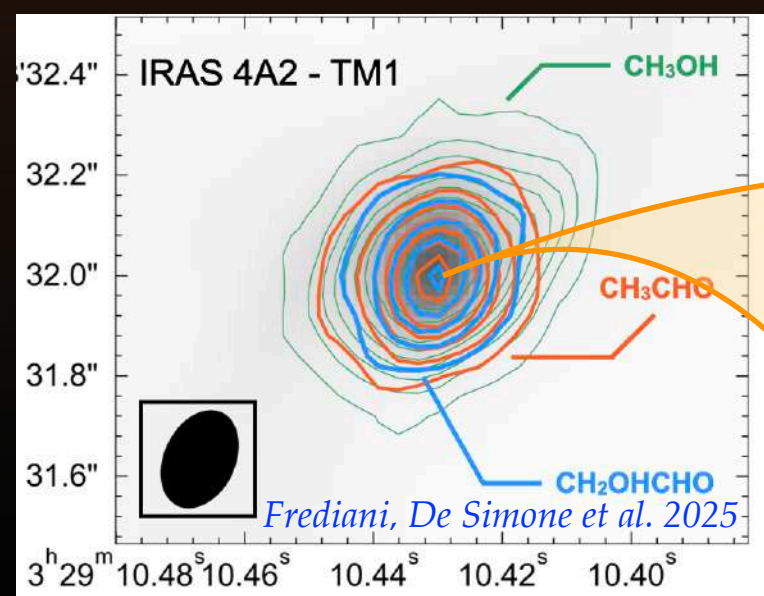
Different species traces different scales due to different **binding energies**



Chemistry gives information on the physical disk structure

# In the earth of protostars *Resolving Hot Corinos*

Disk stratification



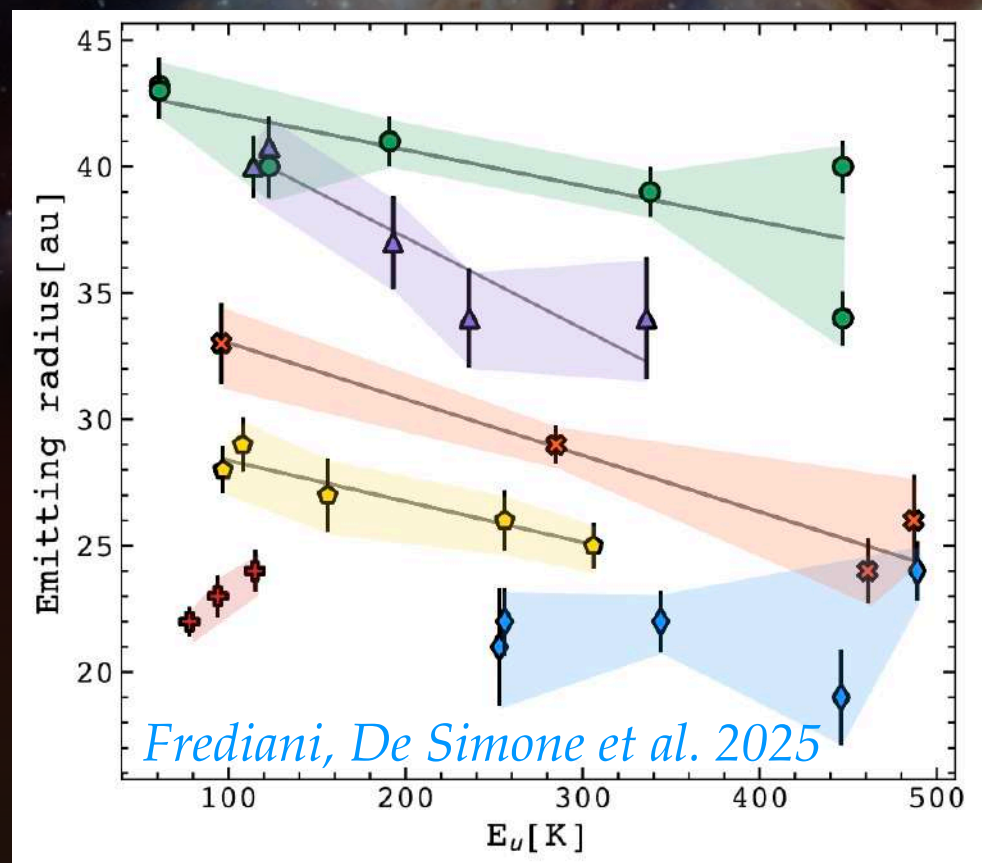
*Chemistry gives information on the physical disk structure*

# In the earth of protostars

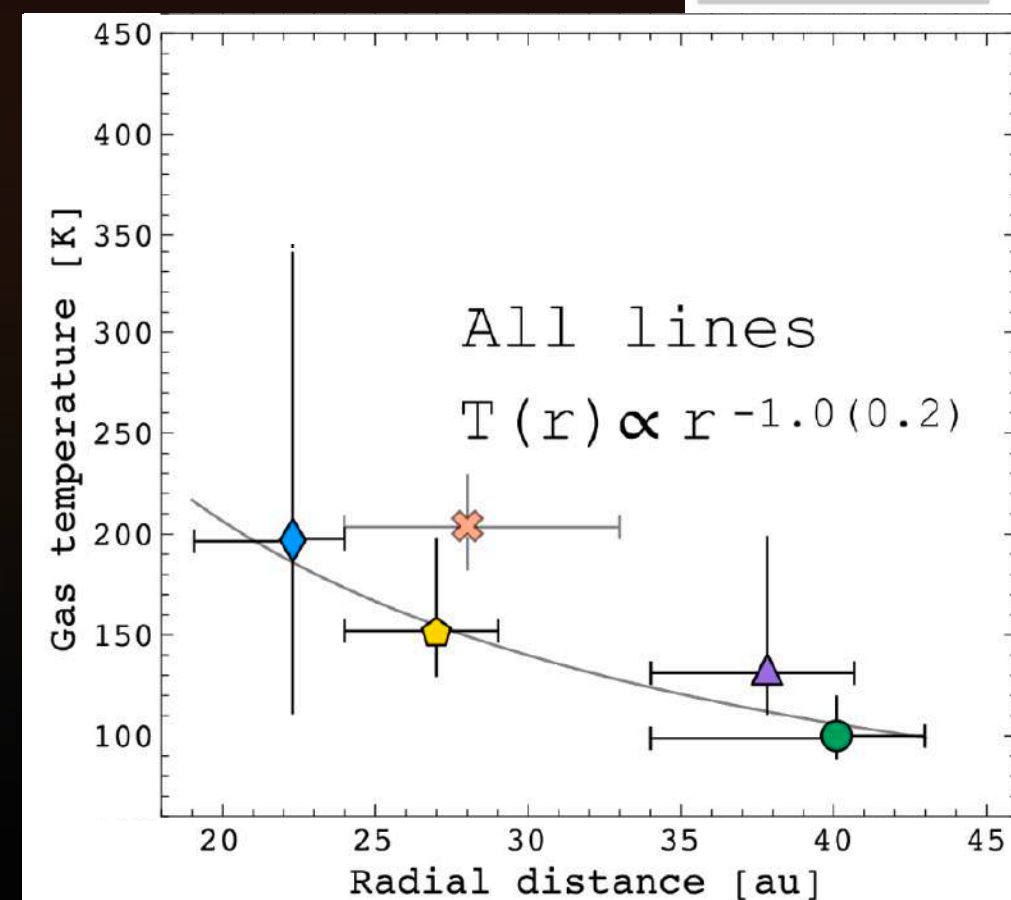
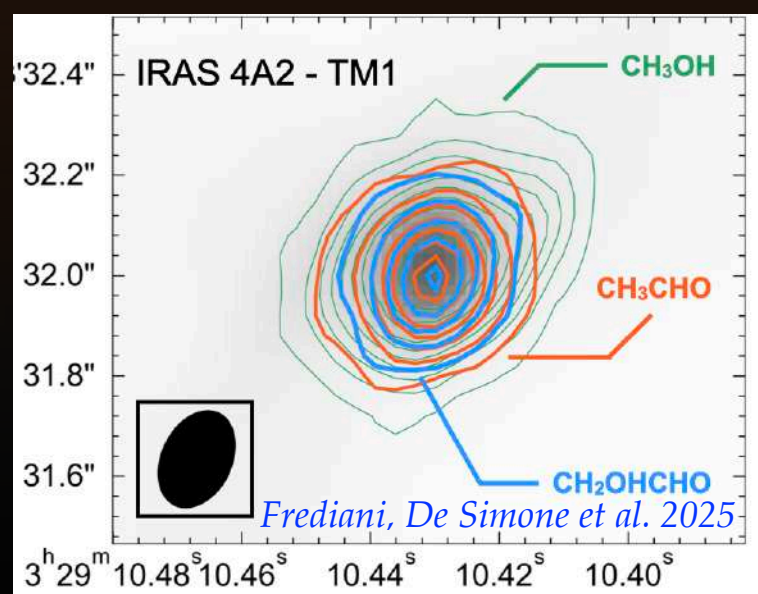
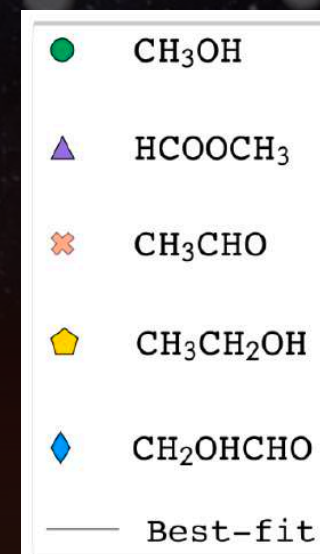
## Resolving Hot Corinos

Disk stratification

Angular resolution 50 au!



- **Methanol** trace the most extended emission, followed by:
- **Methyl formate**,
- **Acetaldehyde**,
- **Ethanol**,
- **Glycolaldehyde** & **Formamide** the most compact (unresolved) emission



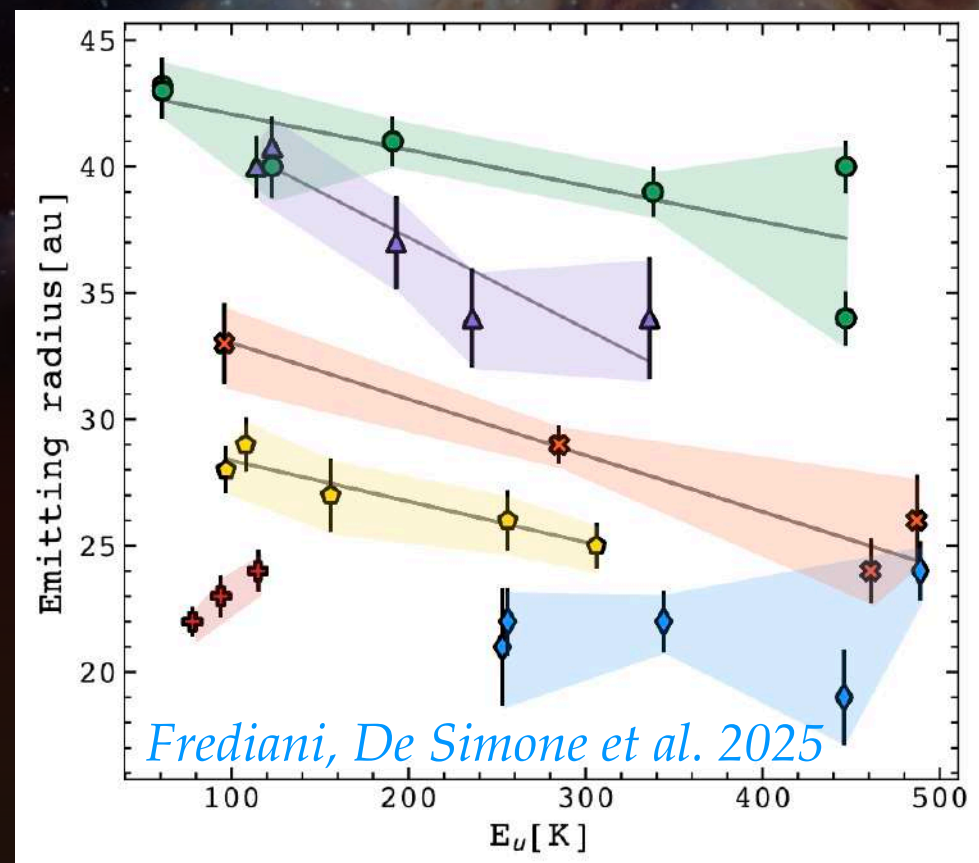
Chemistry gives information on the physical disk structure

# In the earth of protostars

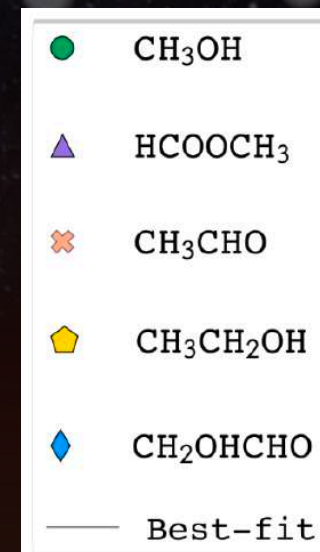
## Resolving Hot Corinos

Disk stratification

Angular resolution 50 au!

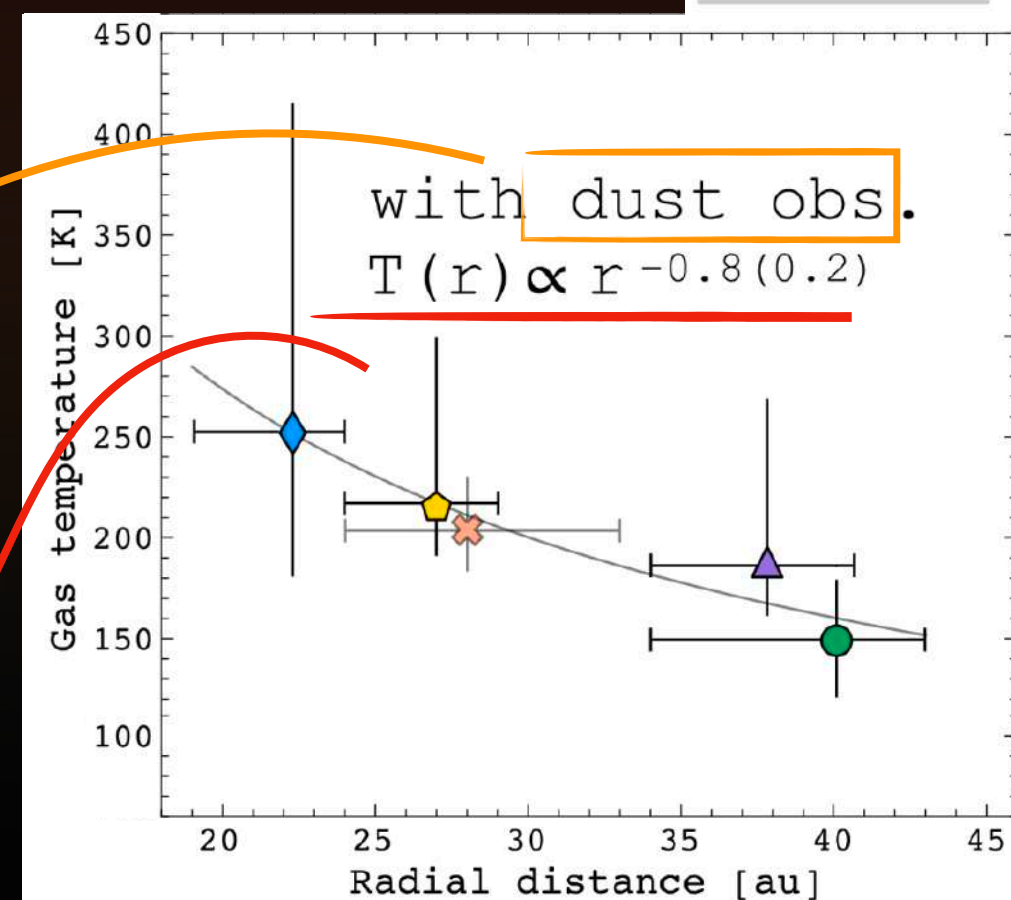


- **Methanol** trace the most extended emission, followed by:
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- **Acetaldehyde**,
- **Ethanol**,
- **Glycolaldehyde** & **Formamide** the most compact (unresolved) emission



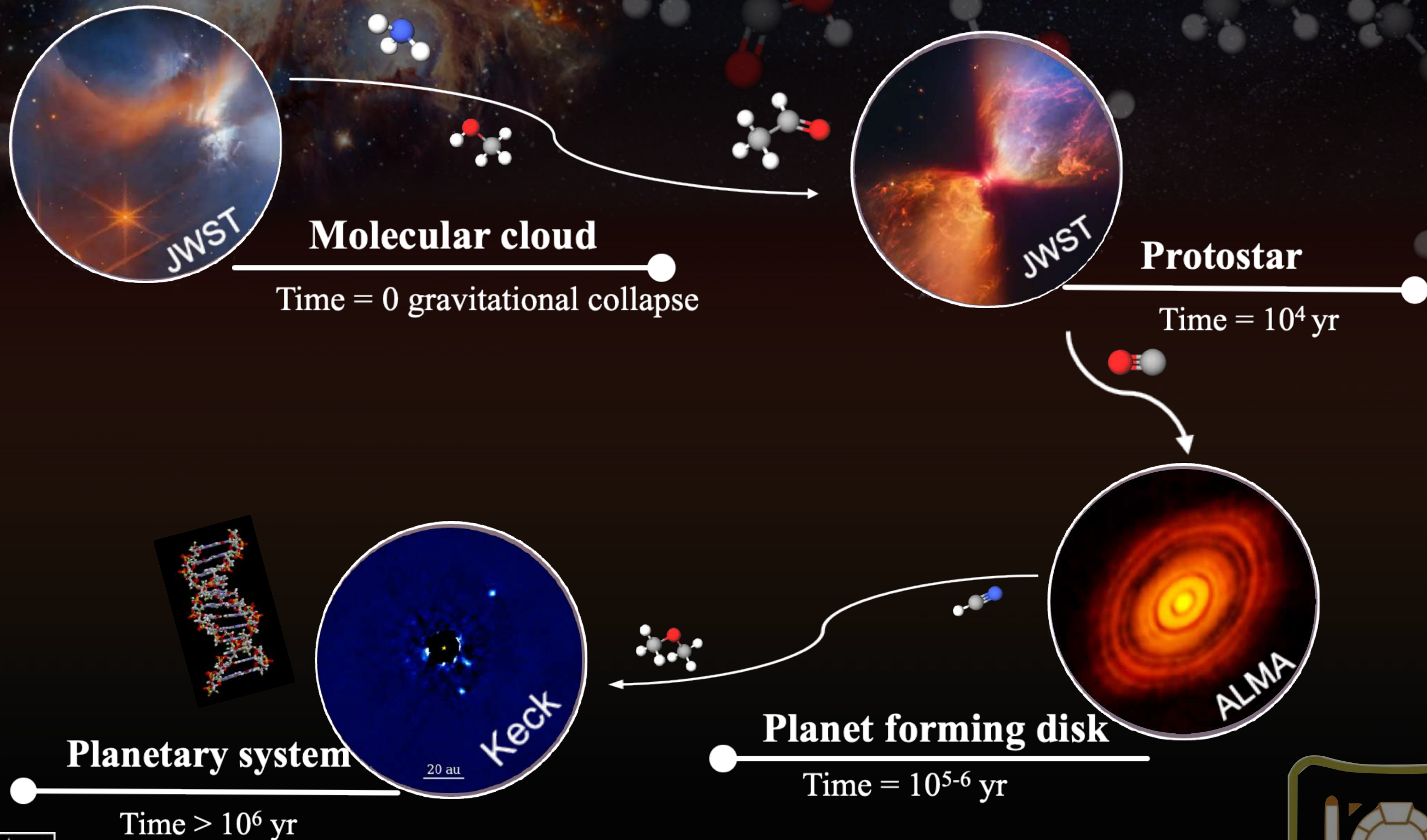
The dust absorption affects both **column density** and **temperature** estimation (*with optically thick lines*)

**Temperature profile** traced observationally using different species down to 50 au!



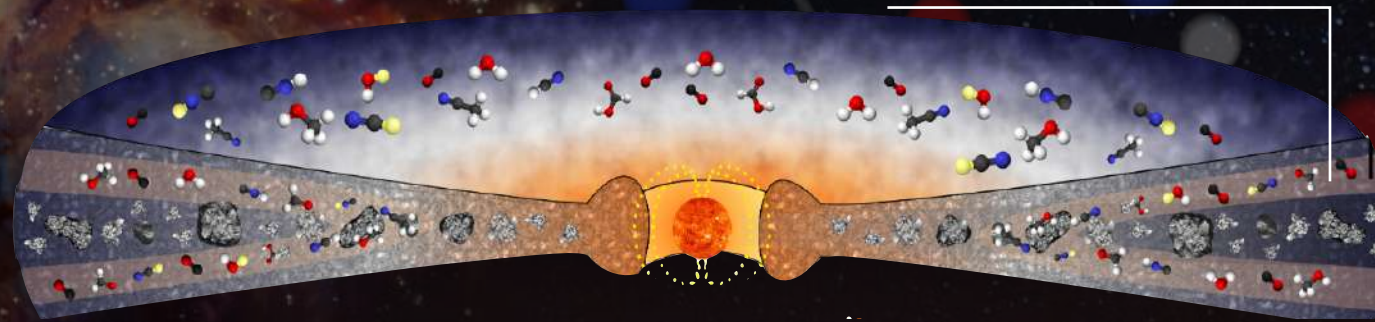
Chemistry gives information on the physical disk structure

# Low mass star formation process

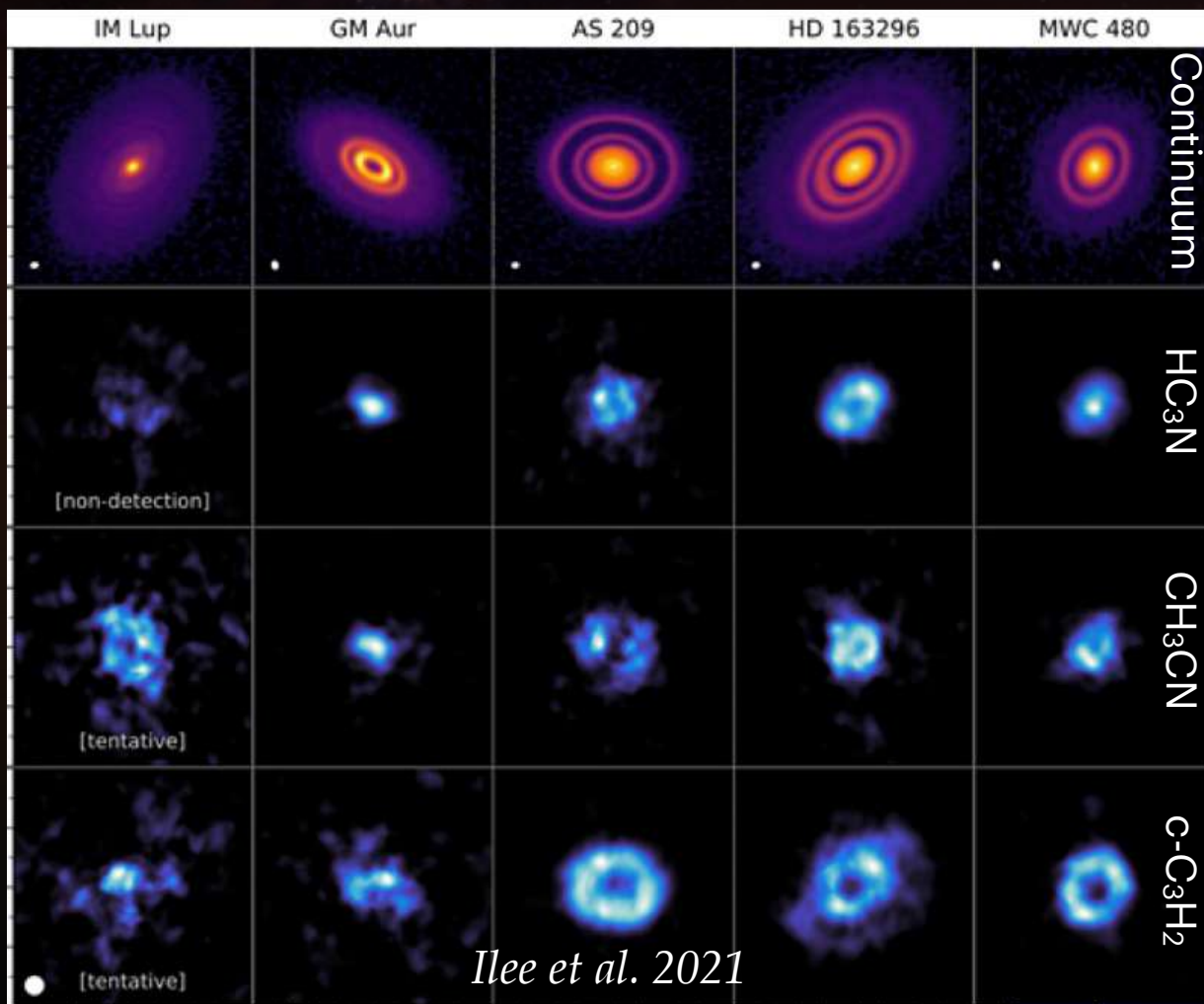


# Planet forming disks

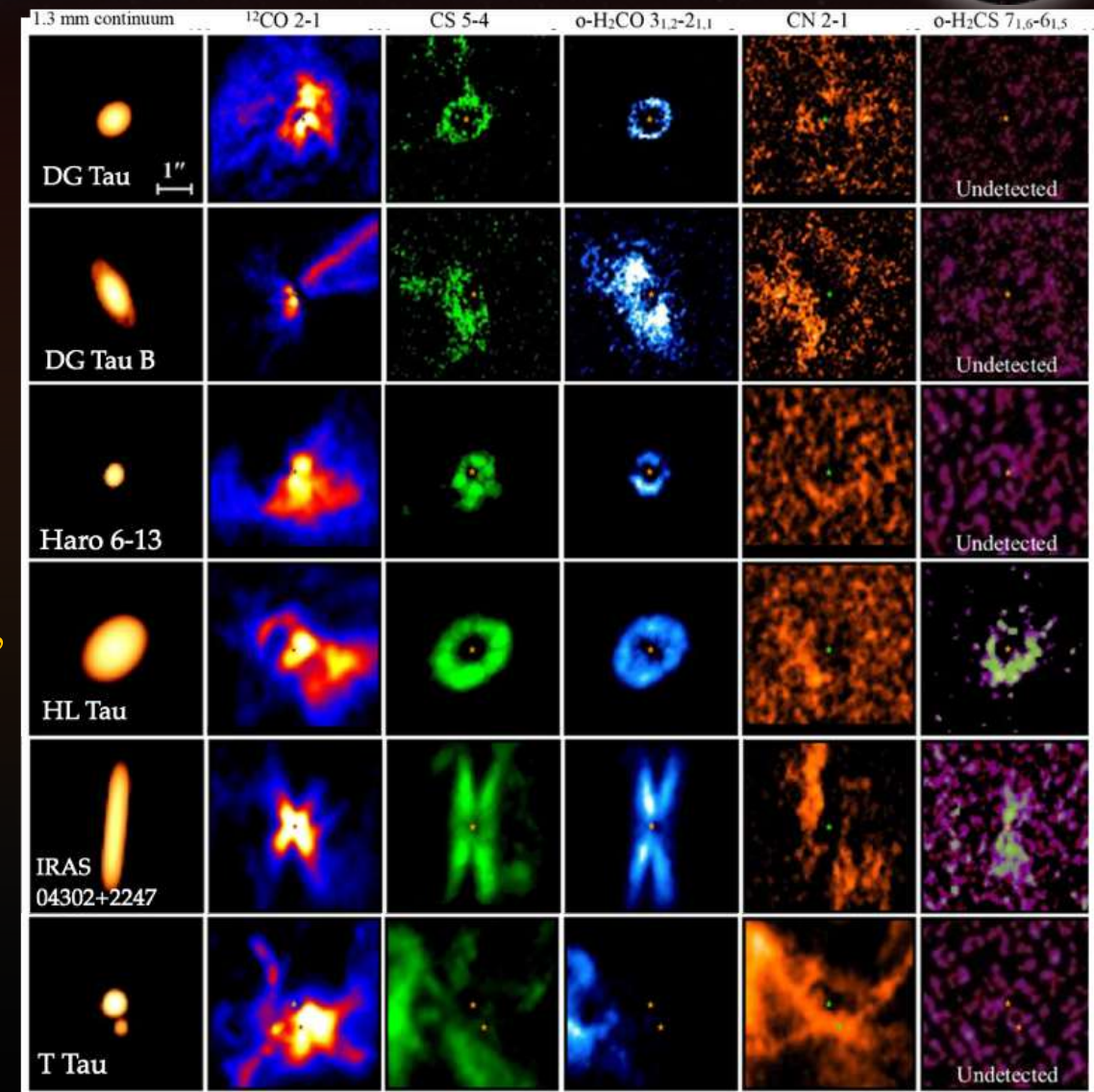
Warm molecular layer



Garufi et al. 2021



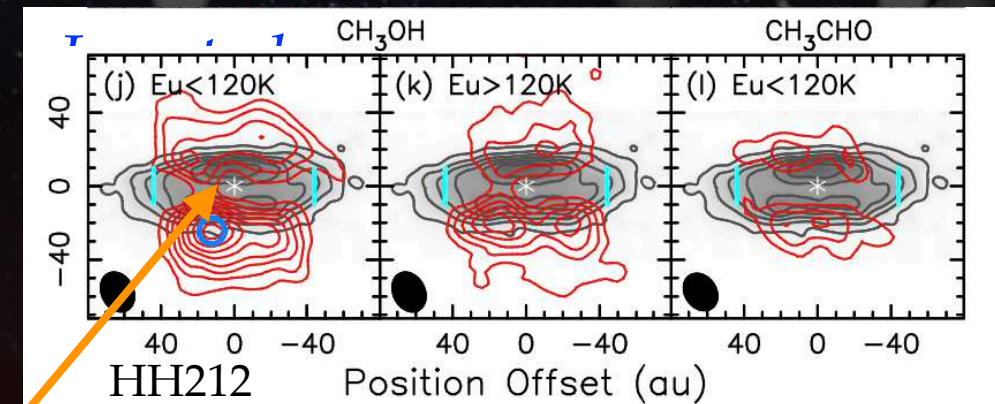
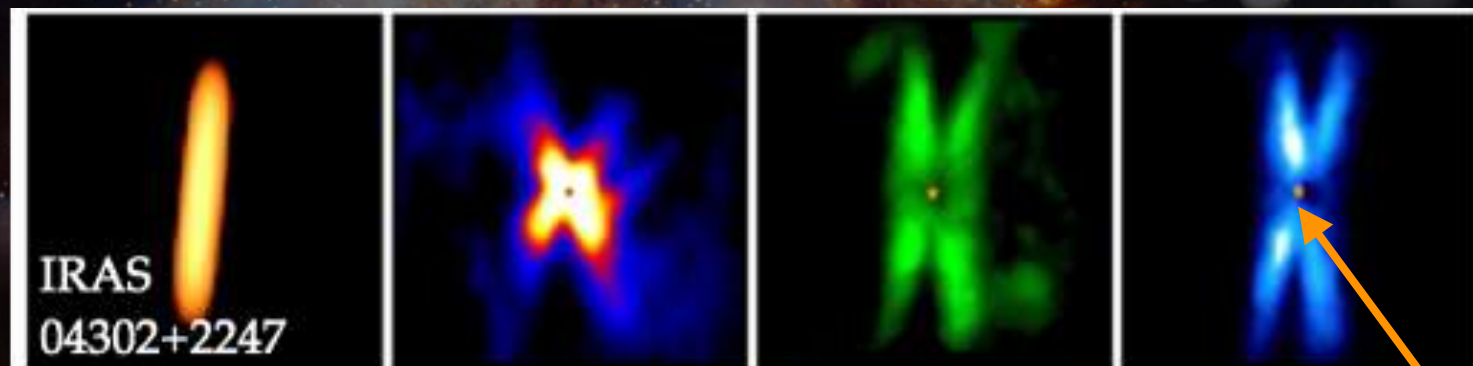
CO, CS,  
H<sub>2</sub>CO, CN,  
H<sub>2</sub>CS,  
HC<sub>3</sub>N,  
CH<sub>3</sub>OH,  
CH<sub>3</sub>CN,  
HCOOH,  
**CH<sub>3</sub>OCHO,**  
**CH<sub>3</sub>OCH<sub>3</sub>**



- Gaps and rings in both gas and dust
- Different molecular distribution



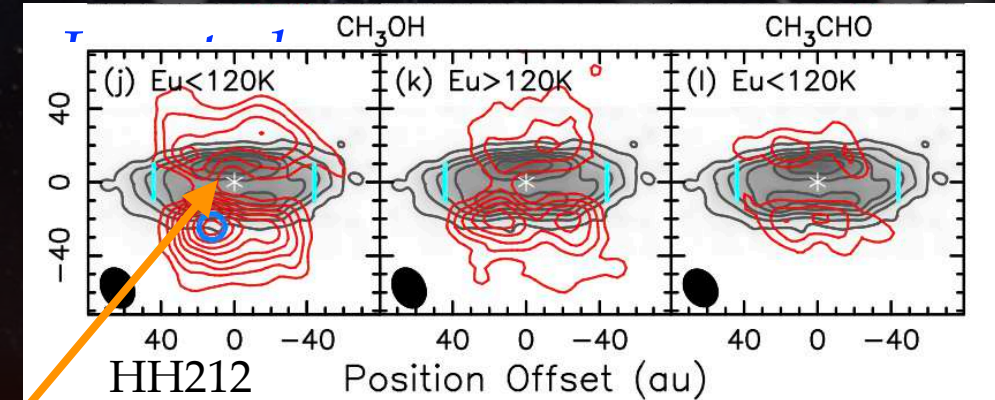
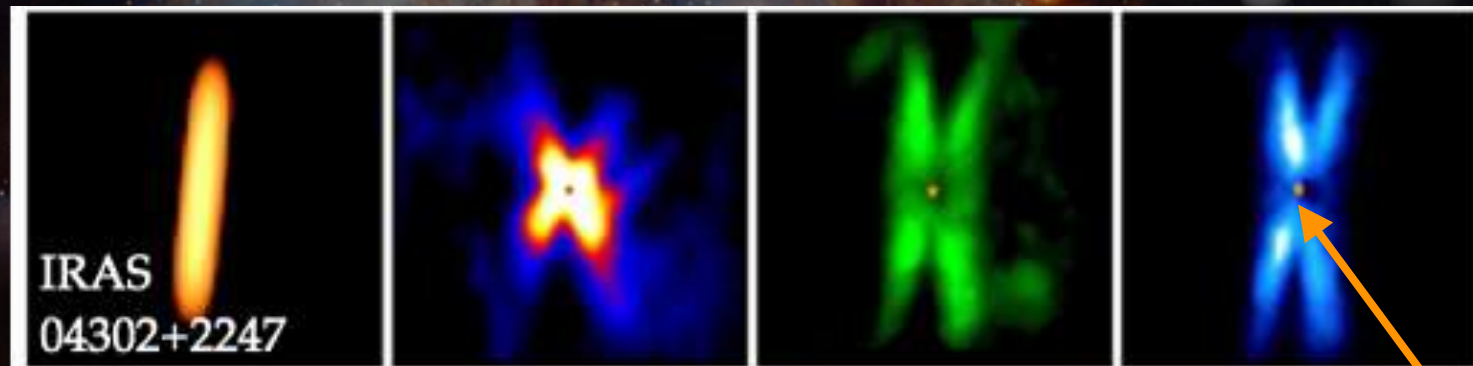
# Planet forming disks



Emission lines absorbed in the midplane  
—> need for **cm** wavelength observations

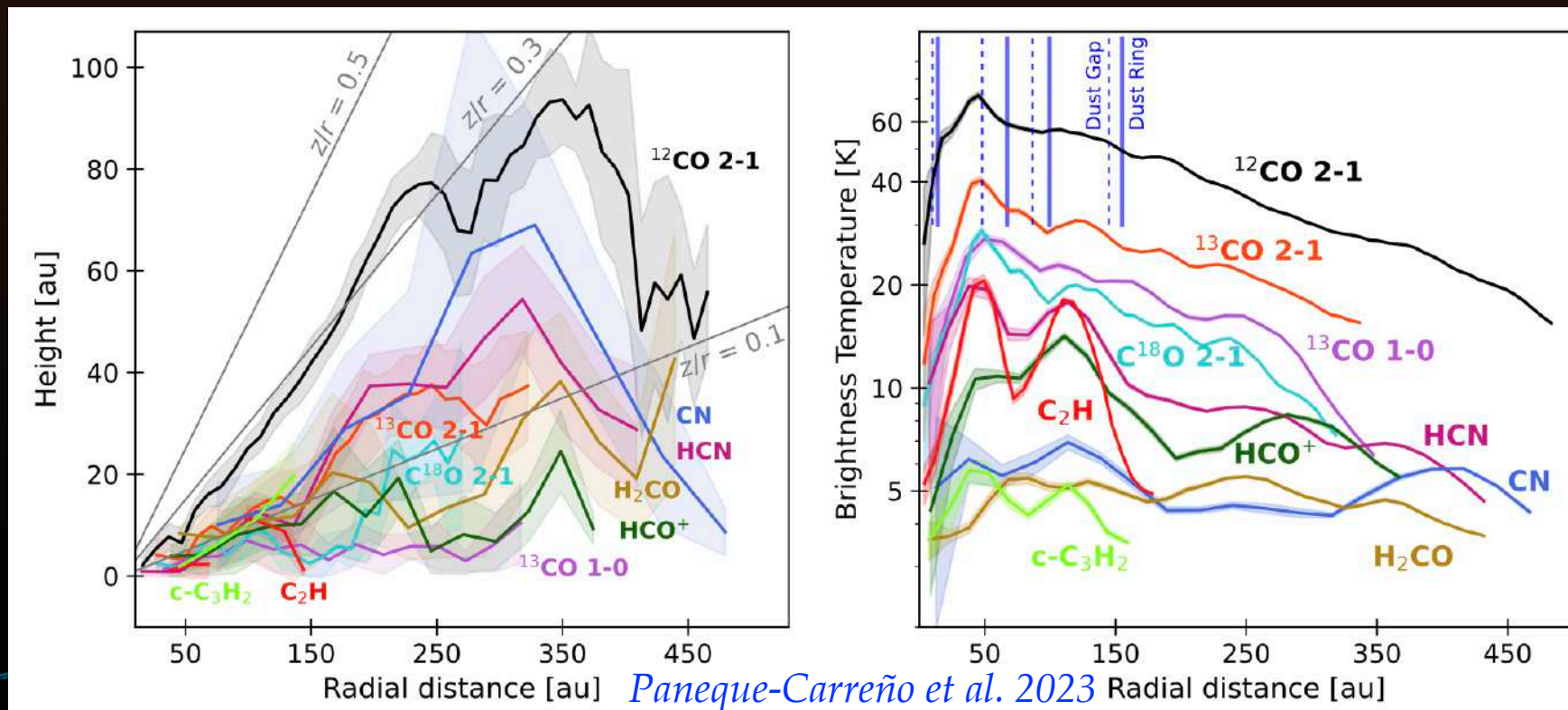
*However, need for  $\sim 10\text{au}$   
resolution at high sensitivity*

# Planet forming disks



Emission lines absorbed in the midplane  
—> need for **cm** wavelength observations

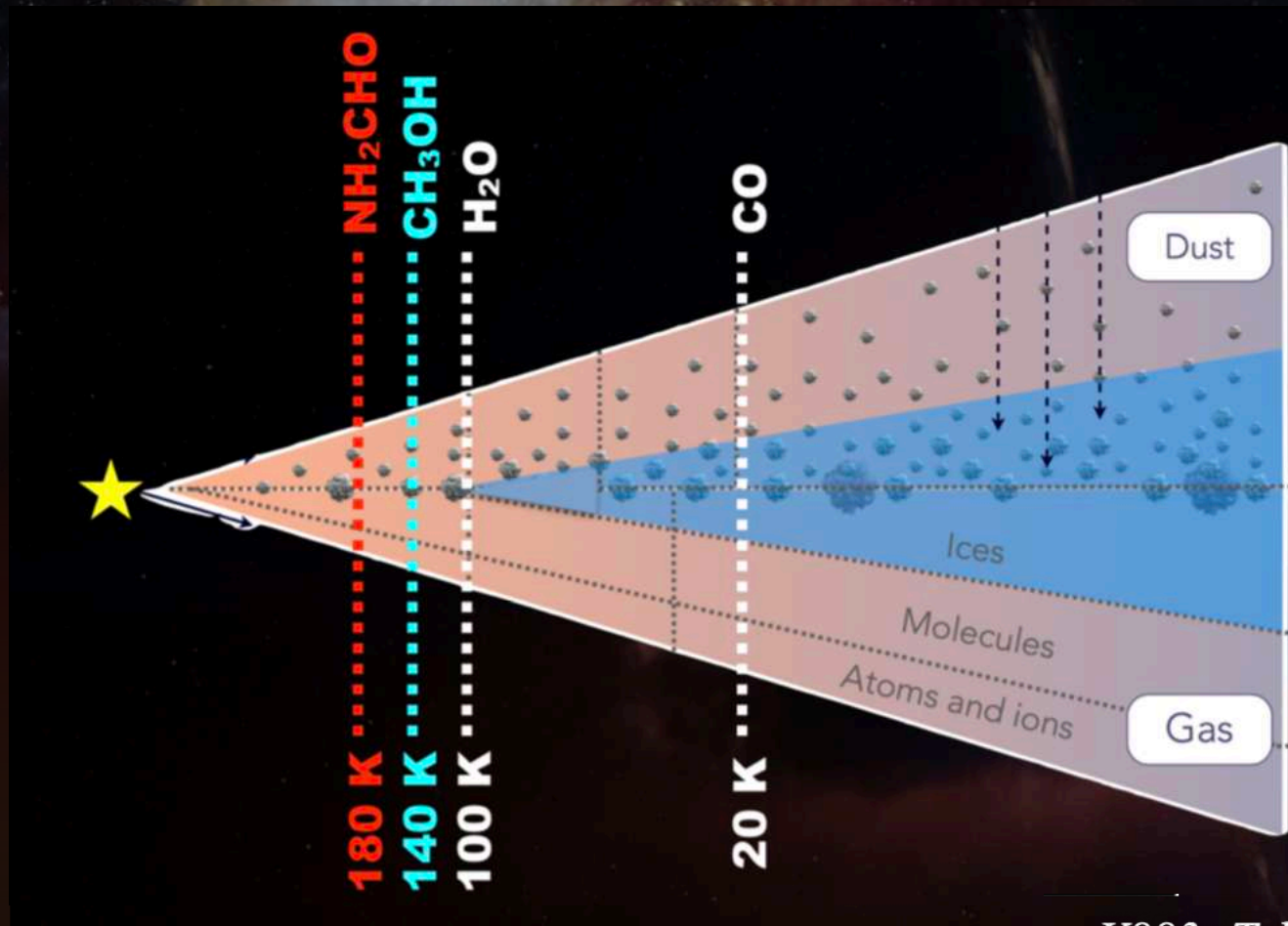
However, need for  $\sim 10\text{au}$  resolution at high sensitivity



## Vertical stratification

Paneque-Carreño et al. 2022, 2023, 2024, Law et al. 2021a, 2021b, Dutrey et al. 2025, Temminik et al. 2025

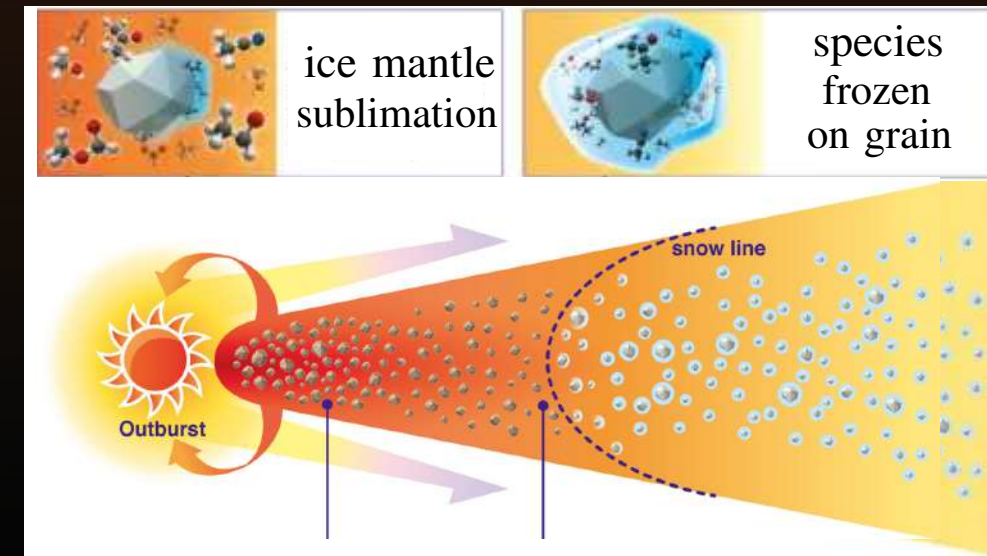
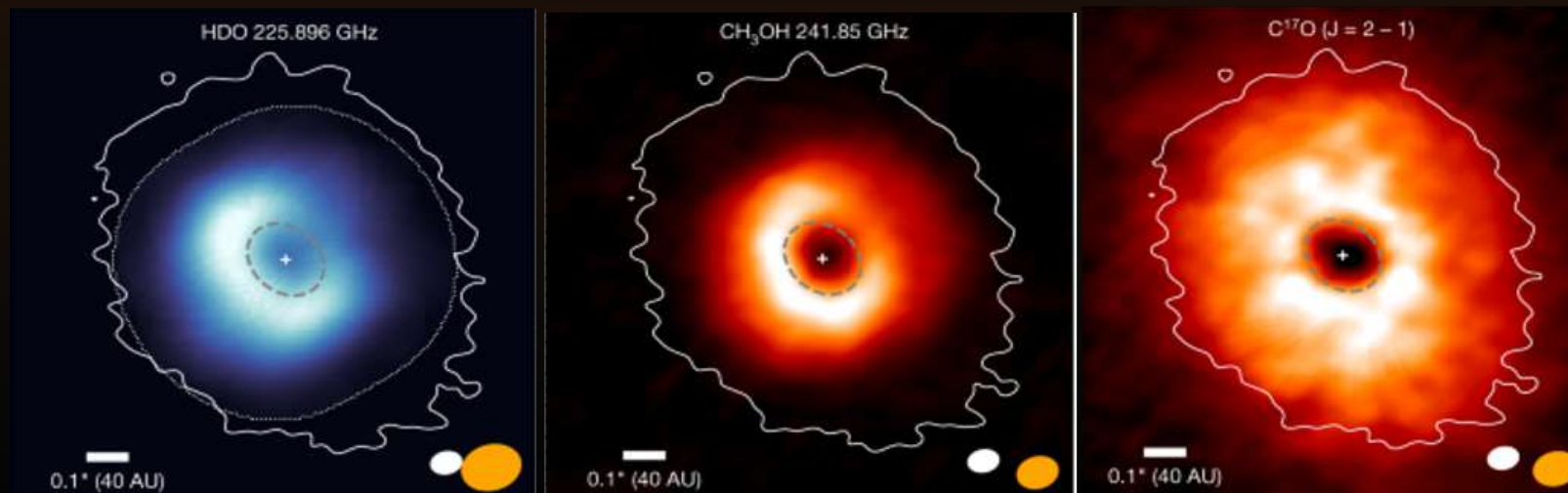
# Planet forming disks



Molecules more complex than CO, CN,  $\text{HCO}^+$ , HCN are more difficult to observe...

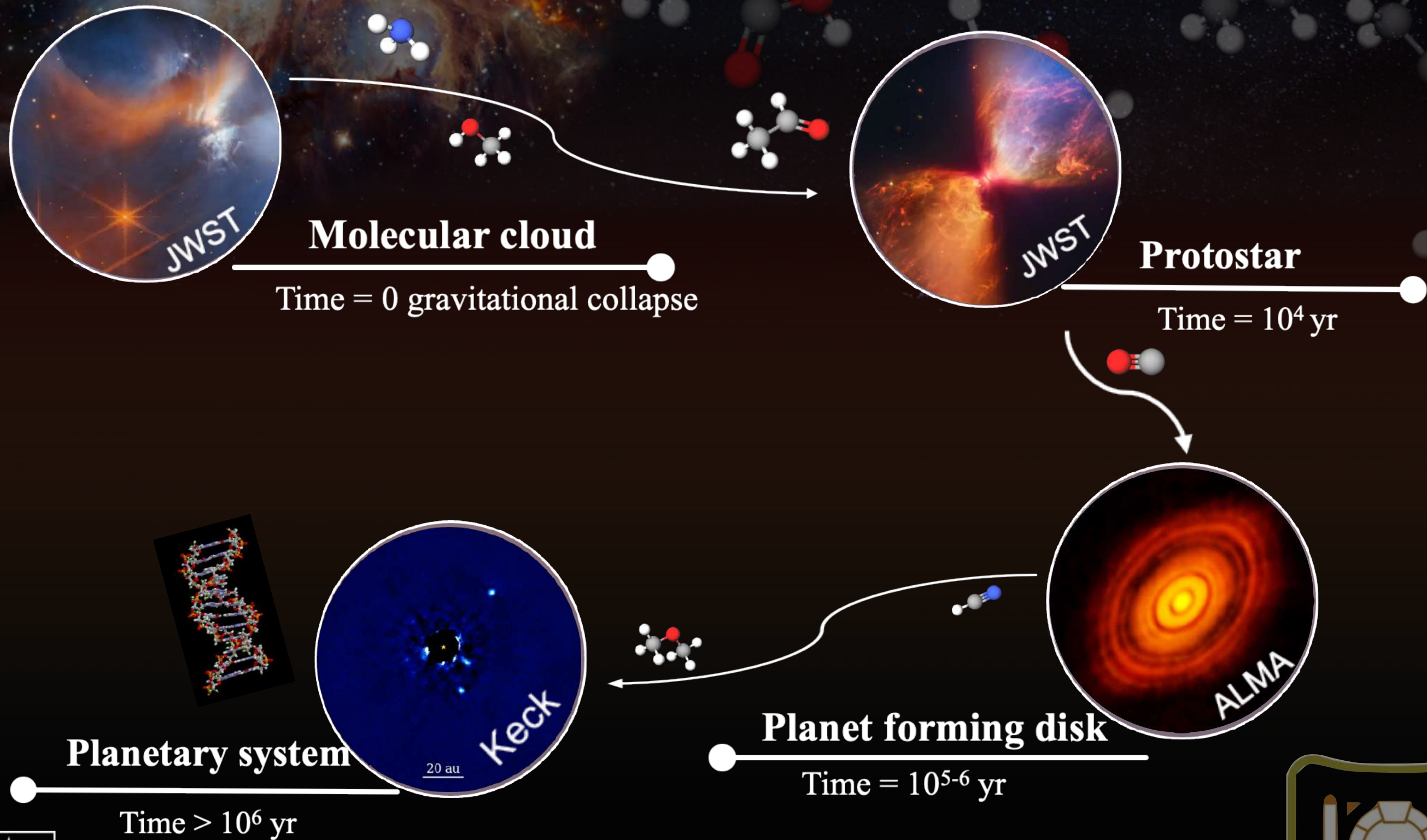
*Need for  $< 5\text{ au}$  resolution at high sensitivity*

*V883; Tobin et al. 2024*



Outburst move snowlike outwards

# Low mass star formation process



# Solar System objects and planets

*Follow the heritage...*

*Lippi et al. 2024*

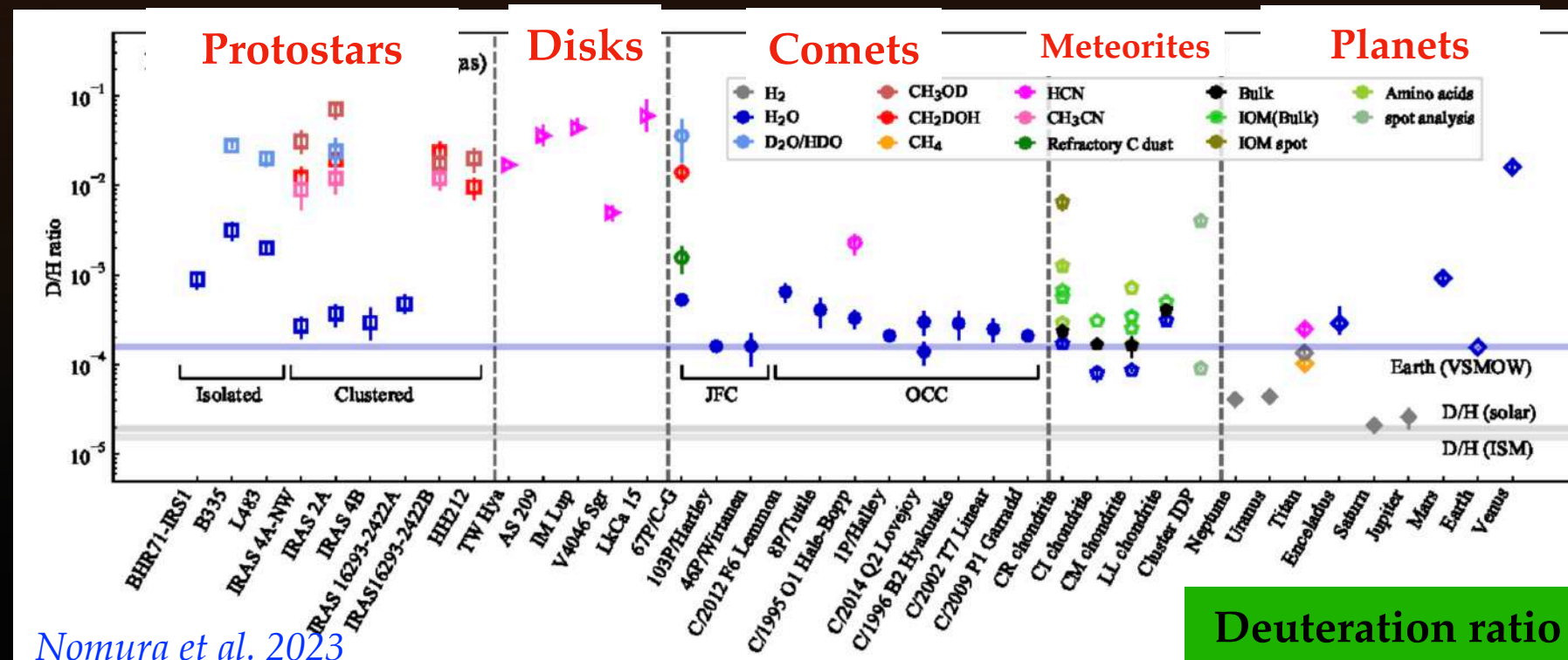
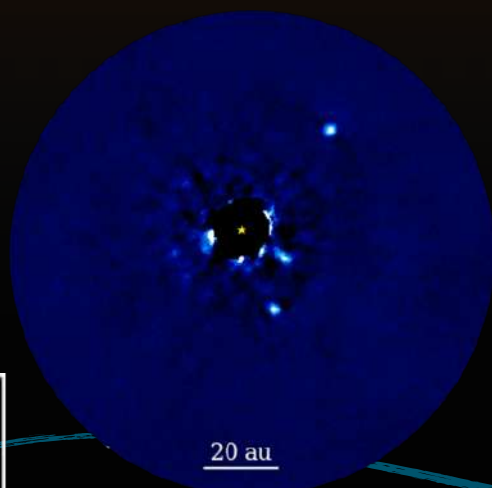
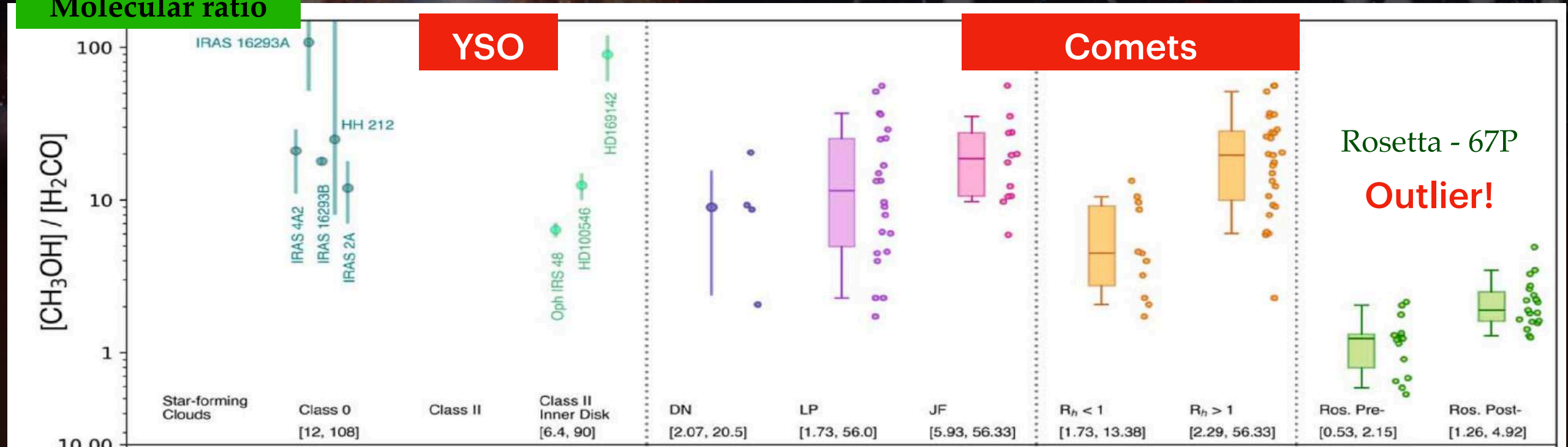
**Molecular ratio**

**YSO**

**Comets**

Rosetta - 67P

**Outlier!**



*Nomura et al. 2023*

**Deuteration ratio**



Marta De Simone

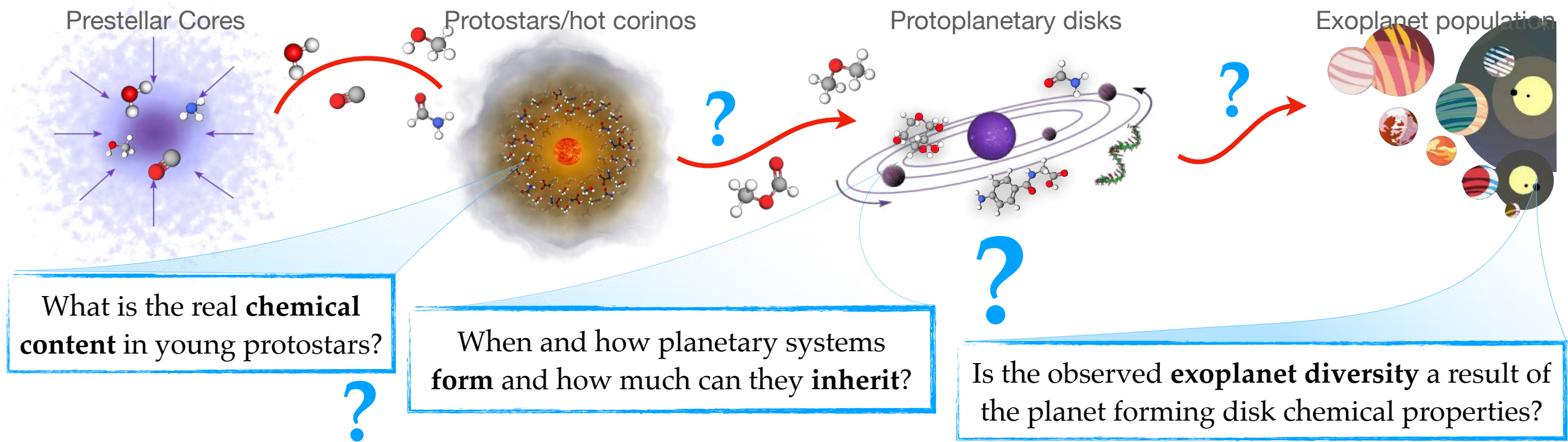
Astrophysics School  
"Francesco Lucchin"

20 October 2026

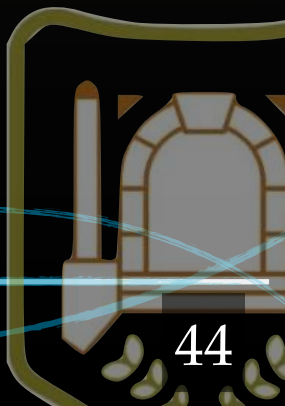
43

# Future steps...exoplanets?

*Follow the heritage...*

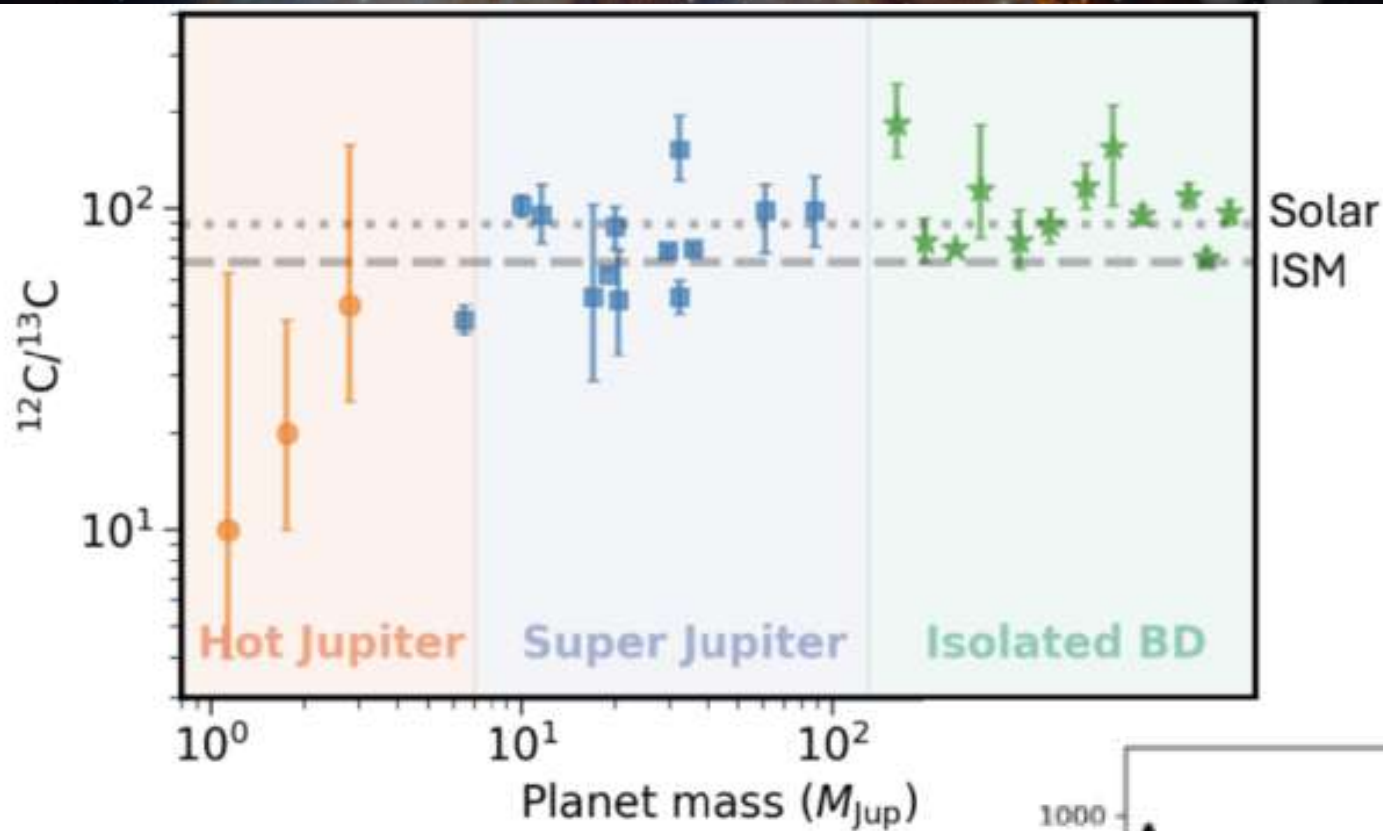


Search for **good proxies** to follow the evolution:  
Isotopologues, deuteration, molecular / elemental ratio ?



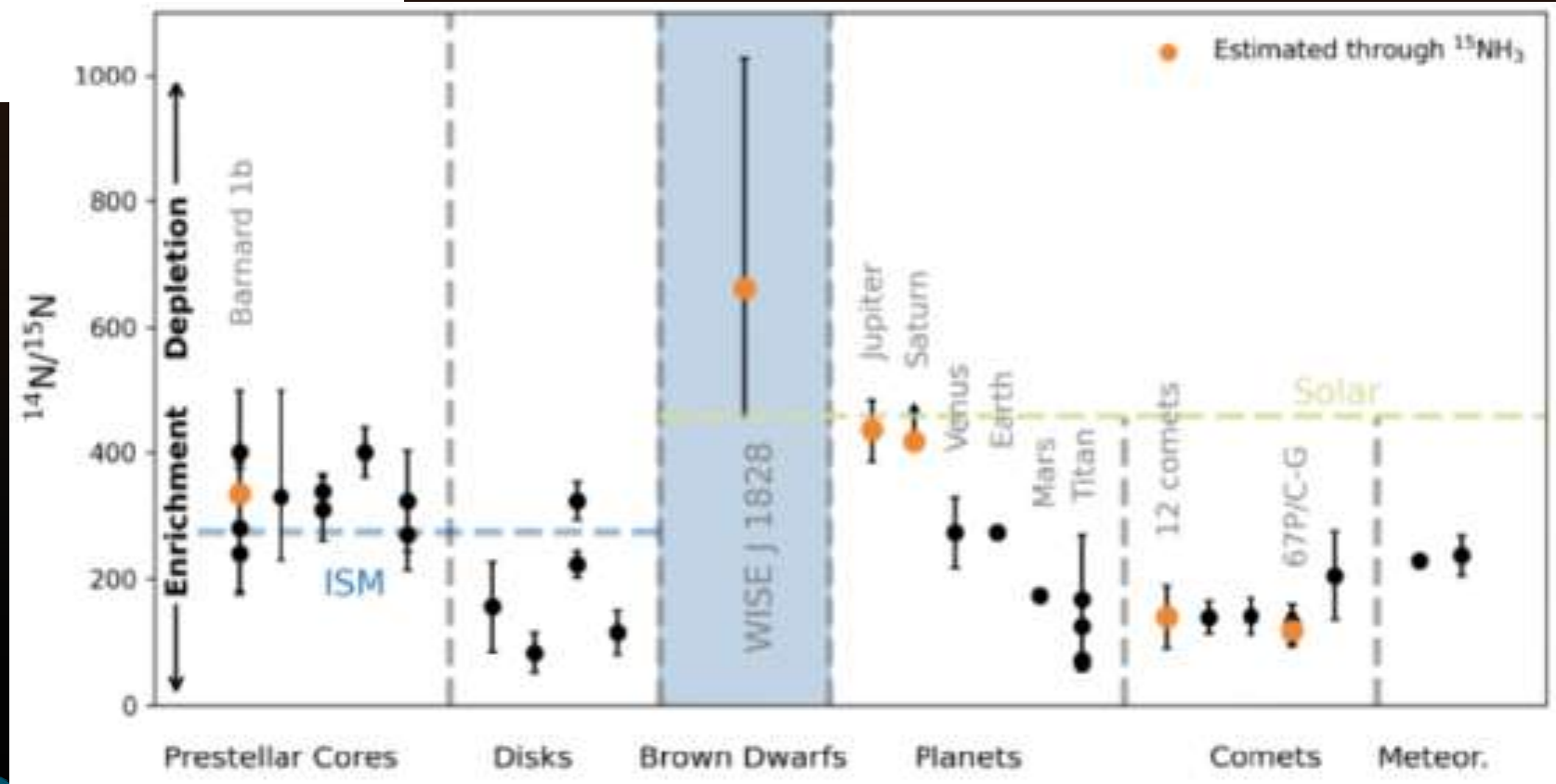
# Future steps...exoplanets?

## Isotopic ratios for super Jupiters

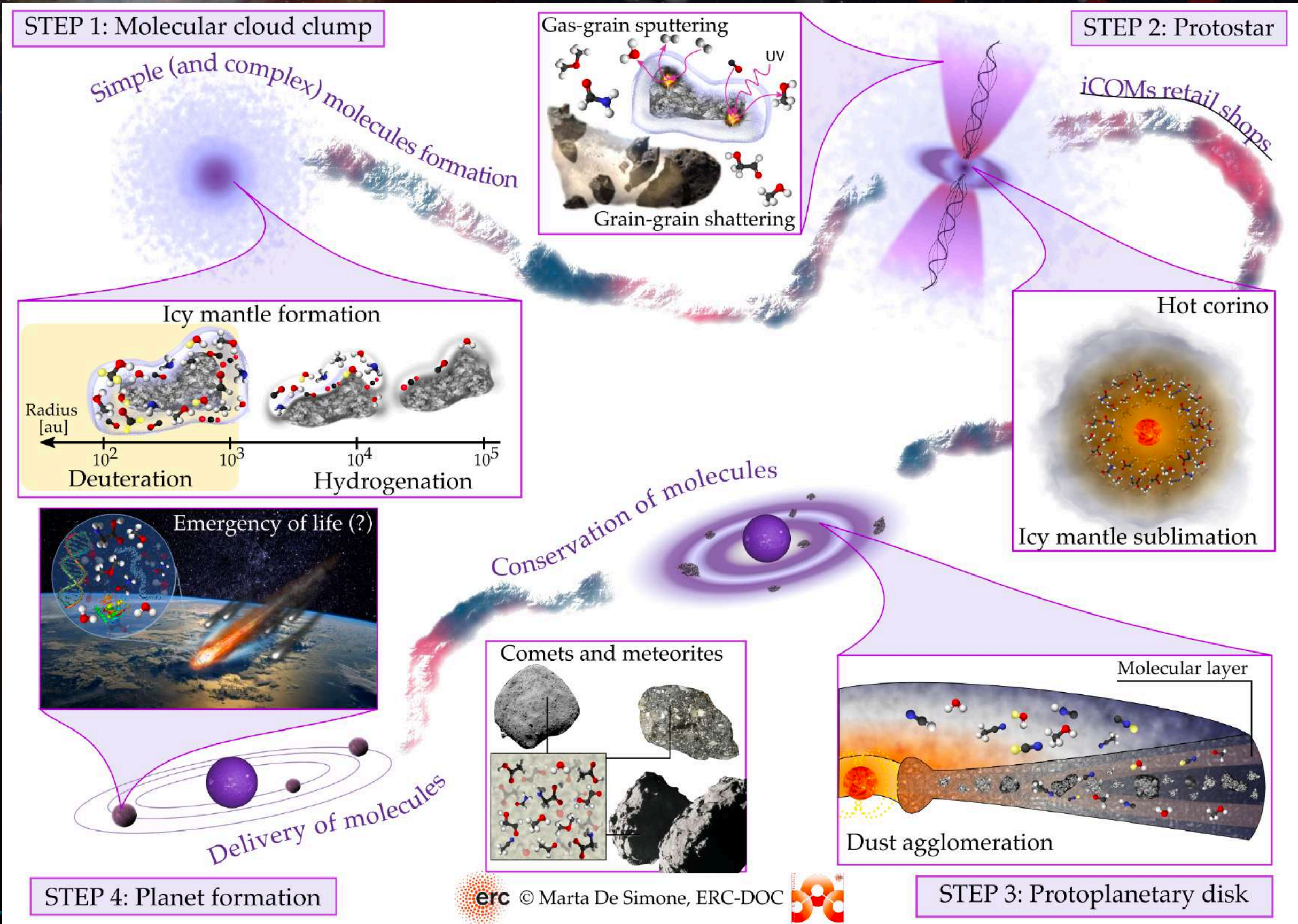


Zhang+2021ab, 2022, 2024; Line+2021; Finnerty+2023, 2024; Gandhi+2023, 2025; Costes+2024; Xuan+2024ab; de Regt+2024, 2025; González Picos+2024, 2025; Hood+2024; Mulder+2025; Grasser+2025; Mollière+2025; Wang+2026; Liu+2026

- $^{12}\text{C}/^{13}\text{C}$  ongoing work
- $^{14}\text{N}/^{15}\text{N}$  to understand in YSO
- Waiting D/H in exoplanets

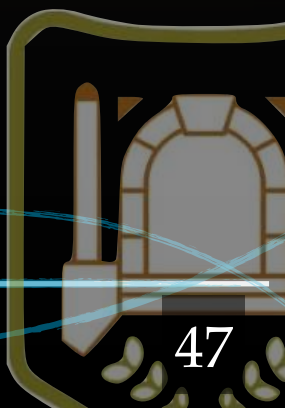


# In Summary....

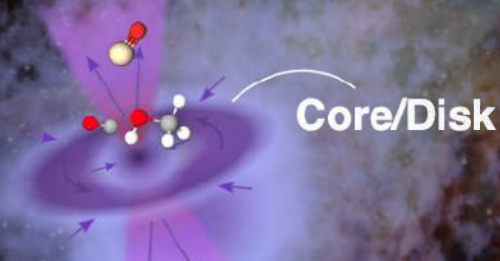


The background of the slide features a vibrant, colorful nebula on the left side, transitioning into a dark space filled with numerous small, distant stars. On the right side, there are several 3D ball-and-stick molecular models, likely representing complex organic molecules found in interstellar space, such as water, methanol, and formaldehyde. The text "Let's take a step back..." is centered in a large, elegant, yellow serif font.

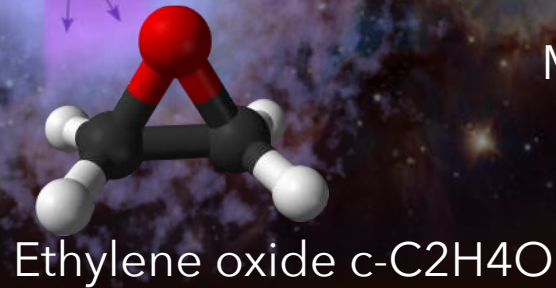
*Let's take a step back...*



# Chemical complexity of the ISM

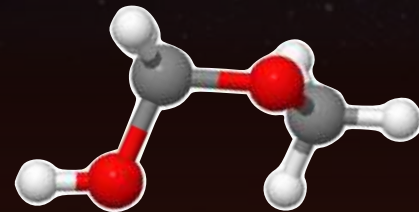


Core/Disk



Methyl isocyanate (CH3NCO)

*Ligterink et al. 2017*



Methoxymethanol

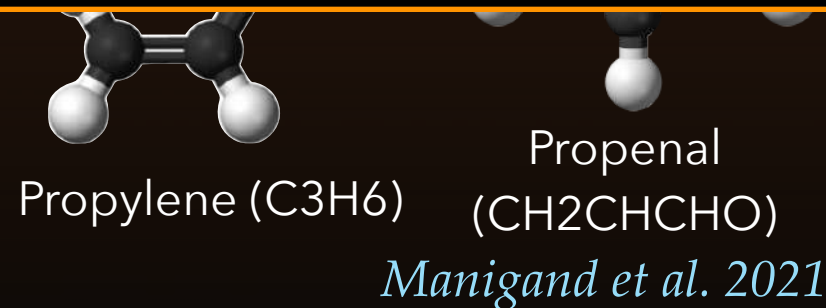
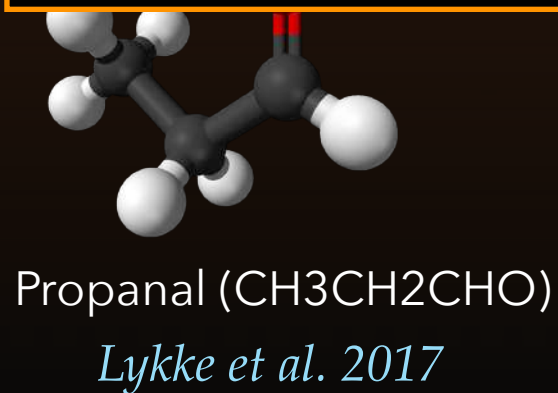
Nitrus oxide (N2O)

Methyl isocyanide (CH3NC)

Cyanamide (NH2CN)

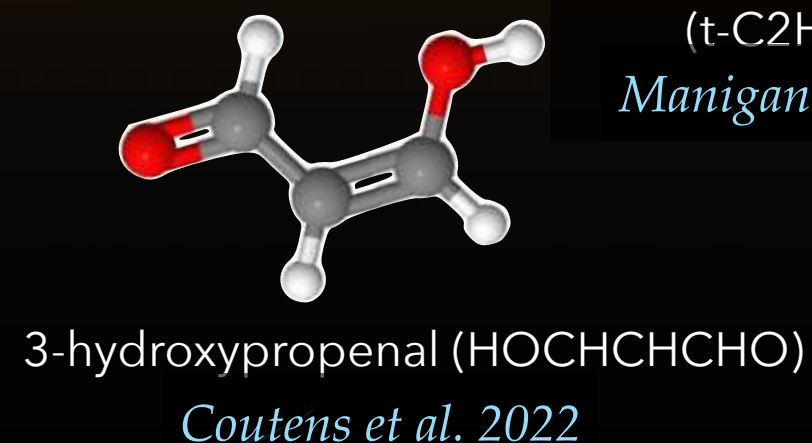
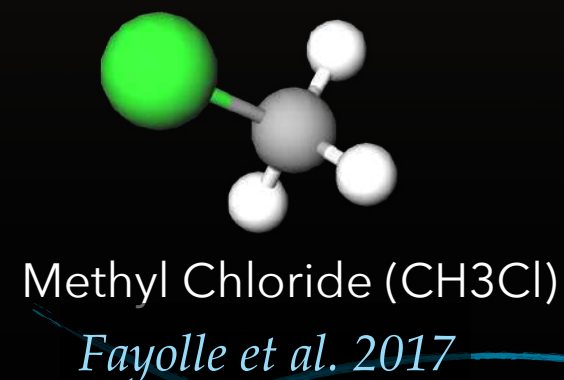
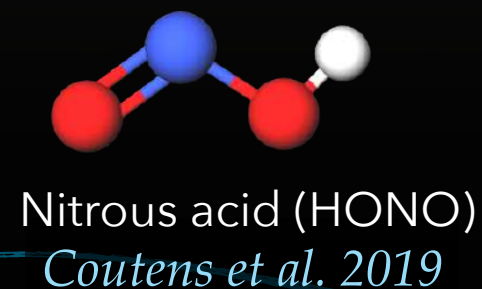
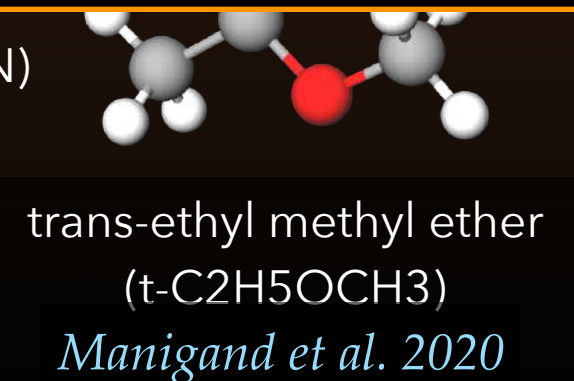
*Coutens et al. 2018*

*Why do we have so many molecules in space?*



Vynil cyanide (CH2CHCN)

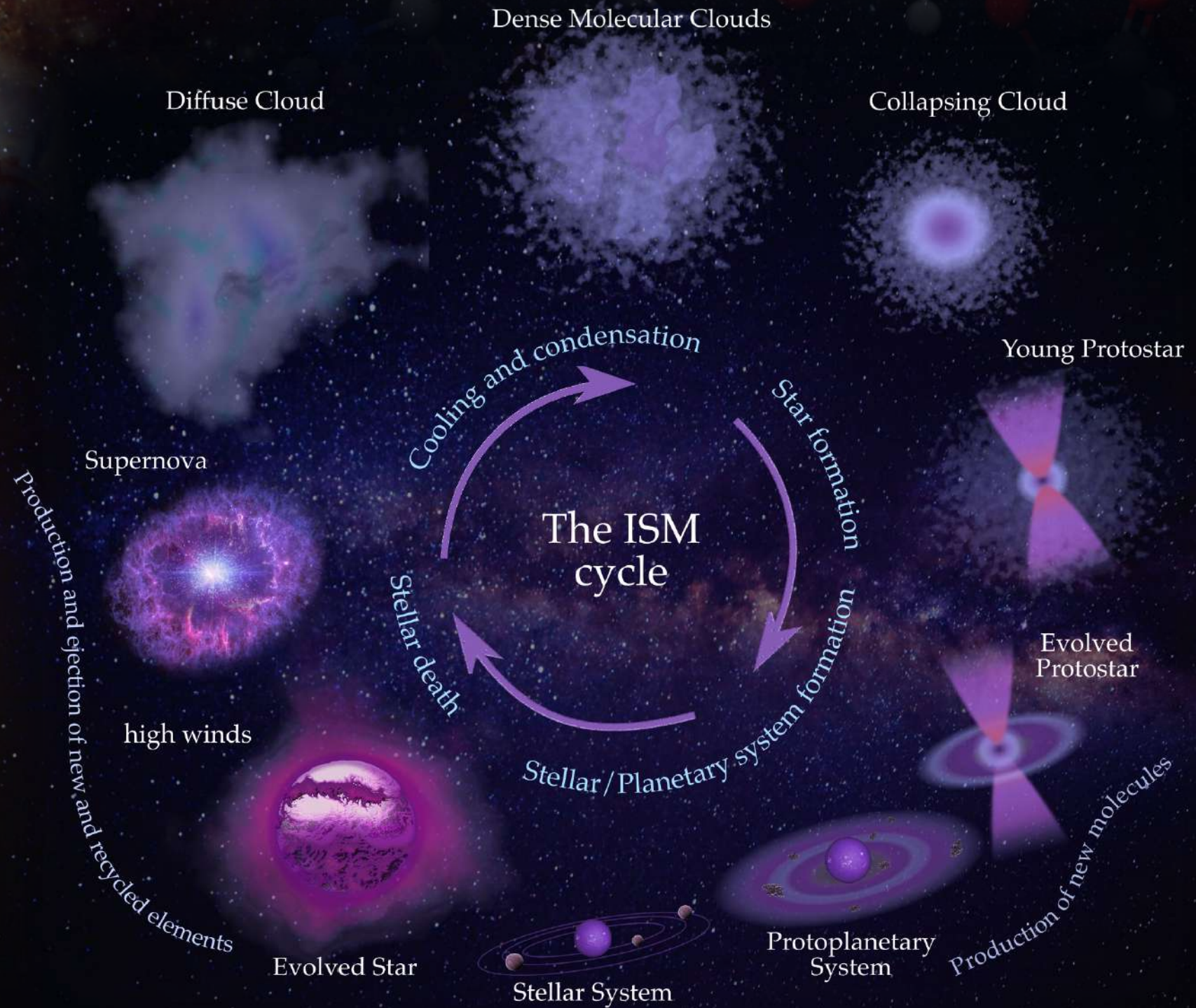
*Calcutt et al. 2018*



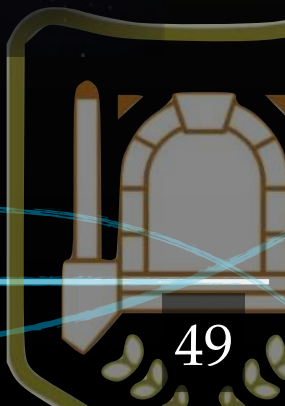
# The life cycle of the interstellar medium



Super  
important!



© Marta De Simone, ERC-DOC



# The life cycle of the interstellar medium

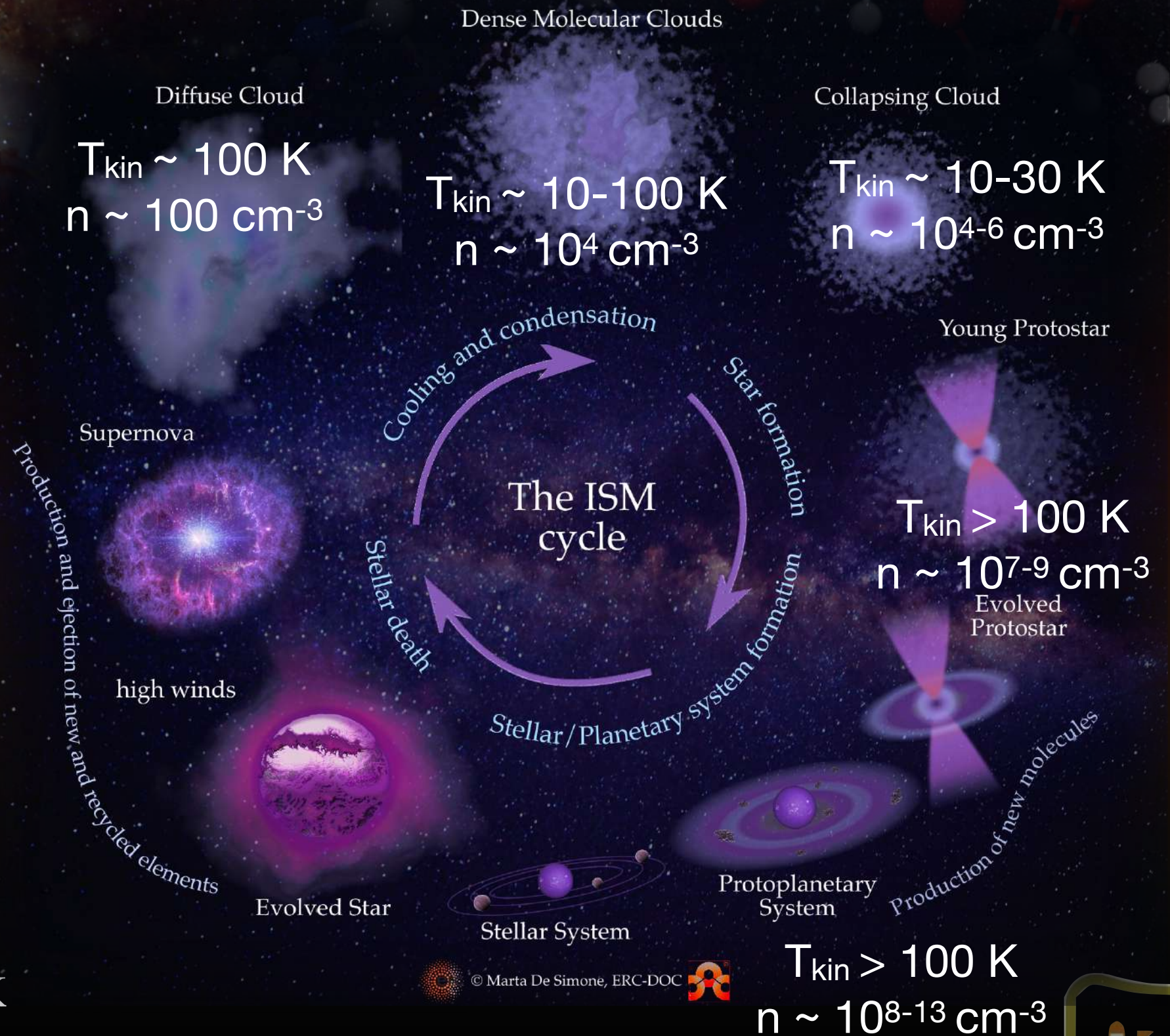


Super  
important!

Physical conditions  
in the ISM are **very  
different** from  
those on Earth:



$n_{\text{Earth atm}} \sim 10^{19} \text{ cm}^{-3}$   
at sea level at 273 K



*Is there ANY chemistry at play under these harsh conditions?*

# Where everything start... The Origins of the Elements

1  
IA  
1A

2  
IIA  
2A

3  
IIIB  
3B

4  
IVB  
4B

5  
VB  
5B

6  
VIB  
6B

7  
VIIB  
7B

8  
VIII  
8

9  
VIII  
8

10  
VIII  
8

11  
IB  
1B

12  
IIB  
2B

13  
IIIA  
3A

14  
IVA  
4A

15  
VA  
5A

16  
VIA  
6A

17  
VIIA  
7A

18  
VIIIA  
8A

1  
H  
Hydrogen  
1.008

2  
He  
Helium  
4.003

3  
Li  
Lithium  
6.941

4  
Be  
Beryllium  
9.012

11  
Na  
Sodium  
22.990

12  
Mg  
Magnesium  
24.305

19  
K  
Potassium  
39.098

20  
Ca  
Calcium  
40.078

21  
Sc  
Scandium  
44.956

22  
Ti  
Titanium  
47.88

23  
V  
Vanadium  
50.942

24  
Cr  
Chromium  
51.996

25  
Mn  
Manganese  
54.938

26  
Fe  
Iron  
55.845

27  
Co  
Cobalt  
58.933

28  
Ni  
Nickel  
58.693

29  
Cu  
Copper  
63.546

30  
Zn  
Zinc  
65.38

31  
Ga  
Gallium  
69.723

32  
Ge  
Germanium  
72.631

33  
As  
Arsenic  
74.922

34  
Se  
Selenium  
78.971

35  
Br  
Bromine  
79.904

36  
Kr  
Krypton  
84.798

37  
Rb  
Rubidium  
85.468

38  
Sr  
Strontium  
87.62

39  
Y  
Yttrium  
88.906

40  
Zr  
Zirconium  
91.224

41  
Nb  
Niobium  
92.906

42  
Mo  
Molybdenum  
95.95

43  
Tc  
Technetium  
98.907

44  
Ru  
Ruthenium  
101.07

45  
Rh  
Rhodium  
102.906

46  
Pd  
Palladium  
106.42

47  
Ag  
Silver  
107.868

48  
Cd  
Cadmium  
112.414

49  
In  
Indium  
114.818

50  
Sn  
Tin  
118.711

51  
Sb  
Antimony  
121.760

52  
Te  
Tellurium  
127.6

53  
I  
Iodine  
126.904

54  
Xe  
Xenon  
131.294

55  
Cs  
Cesium  
132.905

56  
Ba  
Barium  
137.328

57-71

72  
Hf  
Hafnium  
178.49

73  
Ta  
Tantalum  
180.948

74  
W  
Tungsten  
183.85

75  
Re  
Rhenium  
186.207

76  
Os  
Osmium  
190.23

77  
Ir  
Iridium  
192.22

78  
Pt  
Platinum  
195.08

79  
Au  
Gold  
196.967

80  
Hg  
Mercury  
200.59

81  
Tl  
Thallium  
204.383

82  
Pb  
Lead  
207.2

83  
Bi  
Bismuth  
208.980

84  
Po  
Polonium  
[208.982]

85  
At  
Astatine  
209.987

86  
Rn  
Radon  
222.018

87  
Fr  
Francium  
223.020

88  
Ra  
Radium  
226.025

89-103

104  
Rf  
Rutherfordium  
[261]

105  
Db  
Dubnium  
[262]

106  
Sg  
Seaborgium  
[266]

107  
Bh  
Bohrium  
[264]

108  
Hs  
Hassium  
[269]

109  
Mt  
Meitnerium  
[268]

110  
Ds  
Darmstadtium  
[278]

111  
Rg  
Roentgenium  
[280]

112  
Cn  
Copernicium  
[285]

113  
Nh  
Nihonium  
[286]

114  
Fl  
Flerovium  
[289]

115  
Mc  
Moscovium  
[289]

116  
Lv  
Livermorium  
[293]

117  
Ts  
Tennessine  
[294]

118  
Og  
Oganesson  
[294]

Atomic Number

Symbol

Name

Atomic Mass

Lanthanide Series

57  
La  
Lanthanum  
138.905

58  
Ce  
Cerium  
140.116

59  
Pr  
Praseodymium  
140.908

60  
Nd  
Neodymium  
144.243

61  
Pm  
Promethium  
144.913

62  
Sm  
Samarium  
150.36

63  
Eu  
Europium  
151.964

64  
Gd  
Gadolinium  
157.25

65  
Tb  
Terbium  
158.925

66  
Dy  
Dysprosium  
162.500

67  
Ho  
Holmium  
164.930

68  
Er  
Erbium  
167.259

69  
Tm  
Thulium  
168.934

70  
Yb  
Ytterbium  
173.055

71  
Lu  
Lutetium  
174.967

Actinide Series

89  
Ac  
Actinium  
227.028

90  
Th  
Thorium  
232.038

91  
Pa  
Protactinium  
231.036

92  
U  
Uranium  
238.029

93  
Np  
Neptunium  
237.048

94  
Pu  
Plutonium  
244.064

95  
Am  
Americium  
243.061

96  
Cm  
Curium  
247.070

97  
Bk  
Berkelium  
247.070

98  
Cf  
Californium  
251.080

99  
Es  
Einsteinium  
[254]

100  
Fm  
Fermium  
257.095

101  
Md  
Mendelevium  
258.1

102  
No  
Nobelium  
259.101

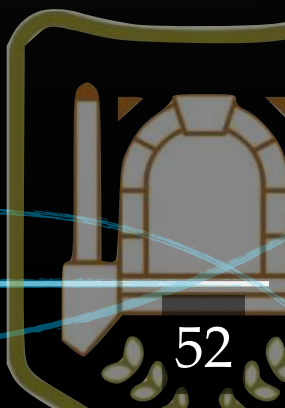
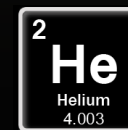
103  
Lr  
Lawrencium  
[262]

# Where everything start... The Origins of the Elements

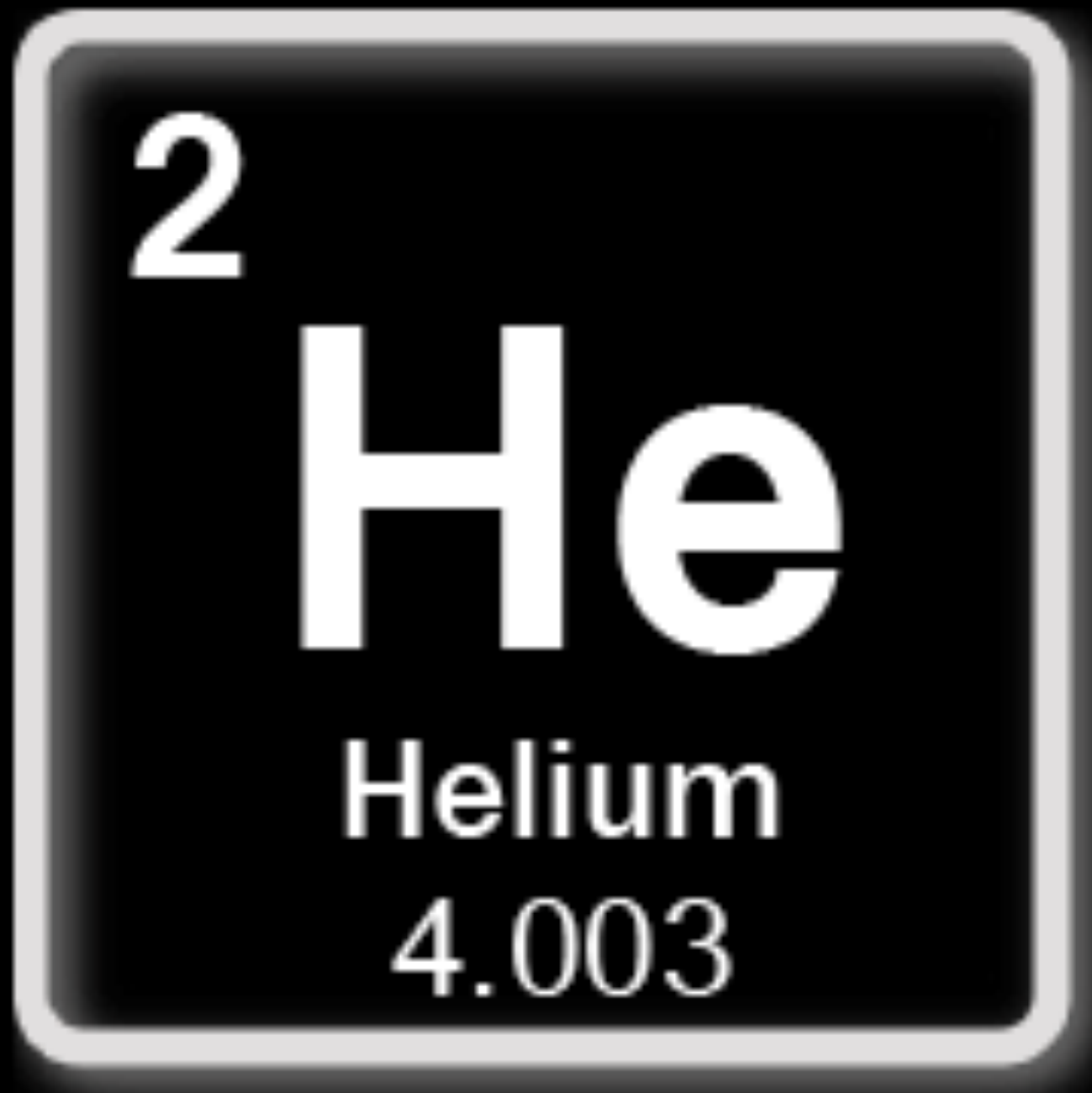


| Element | Abundance            | Element | Abundance            |
|---------|----------------------|---------|----------------------|
| H       | 1.00                 | Mg      | $4.2 \times 10^{-5}$ |
| He      | 0.075                | Al      | $3.1 \times 10^{-6}$ |
| C       | $3.5 \times 10^{-4}$ | Si      | $4.3 \times 10^{-5}$ |
| N       | $8.5 \times 10^{-5}$ | S       | $1.7 \times 10^{-5}$ |
| O       | $5.5 \times 10^{-4}$ | Ca      | $2.2 \times 10^{-6}$ |
| Na      | $2.1 \times 10^{-6}$ | Fe      | $4.3 \times 10^{-5}$ |

Cosmic (solar) abundances elements

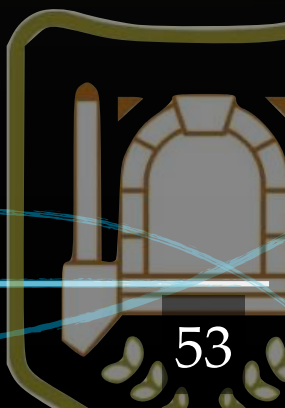


# Where everything start... The Origins of the Elements



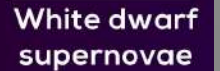
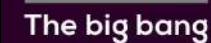
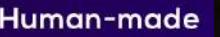
| Element | Abundance            | Element | Abundance            |
|---------|----------------------|---------|----------------------|
| H       | 1.00                 | Mg      | $4.2 \times 10^{-5}$ |
| He      | 0.075                | Al      | $3.1 \times 10^{-6}$ |
| C       | $3.5 \times 10^{-4}$ | Si      | $4.3 \times 10^{-5}$ |
| N       | $8.5 \times 10^{-5}$ | S       | $1.7 \times 10^{-5}$ |
| O       | $5.5 \times 10^{-4}$ | Ca      | $2.2 \times 10^{-6}$ |
| Na      | $2.1 \times 10^{-6}$ | Fe      | $4.3 \times 10^{-5}$ |

Cosmic (solar) abundances elements

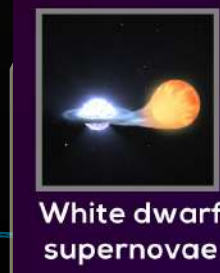
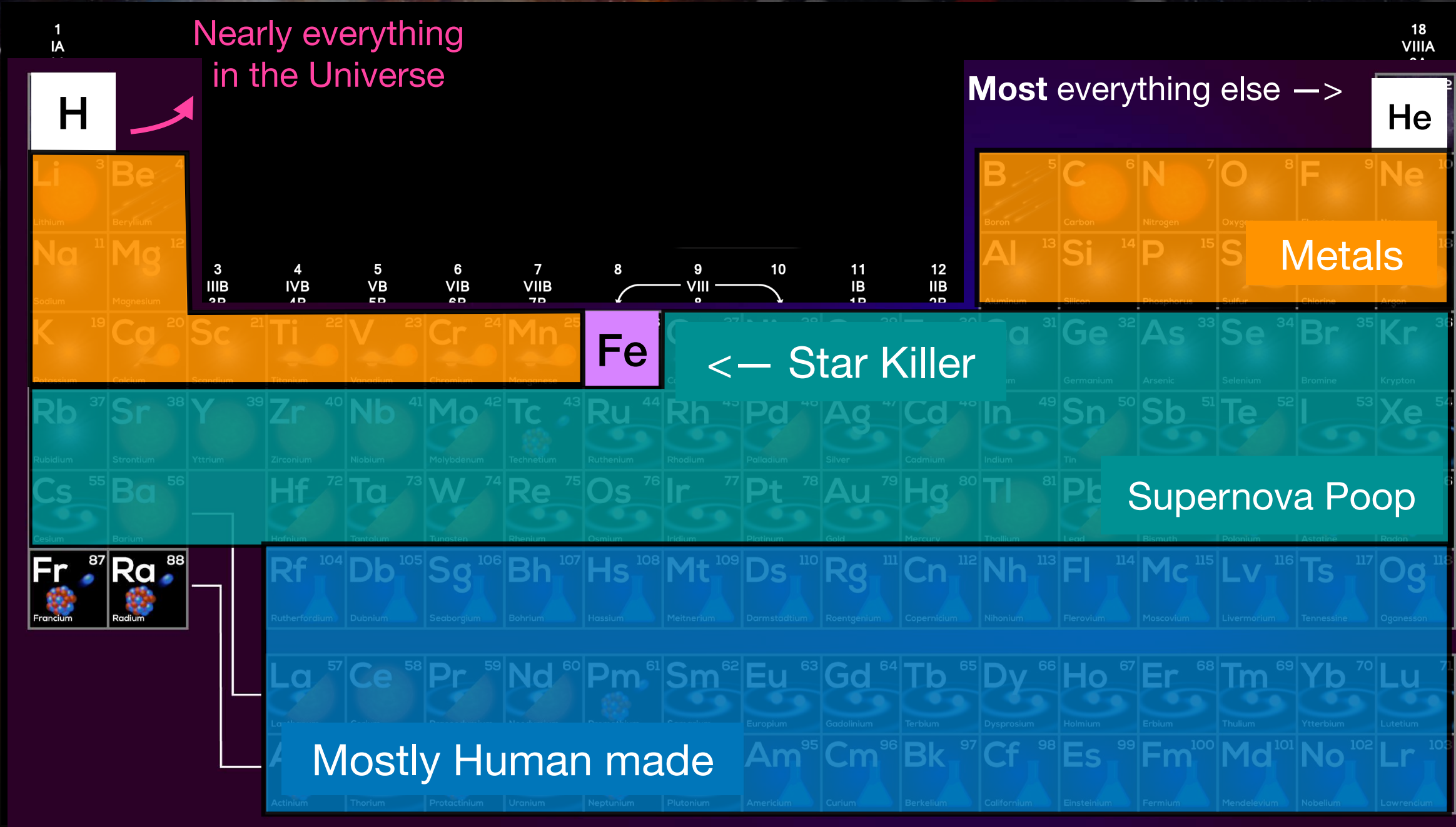


# The Origins of the Elements

|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|----------------|--|-----------------|--|----------------|--|-----------------|--|---------------|--|------------------|--|------------------|--|-----------------|--|---------------|--|---------------------|--|----------------|--|------------------|--|---------------|--|-----------------|--|------------------|--|--------------------|--|-------------------|--|-------------------|--|----------------|--|-----------------|--|-----------------|--|-------------------|--|------------------|--|-----------------|--|--|--|--|--|--|--|
| 1<br>IA        |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  | 18<br>VIIIA    |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
| H<br>Hydrogen  |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  | He<br>Helium   |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
| Li<br>Lithium  |  | Be<br>Beryllium |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  | B<br>Boron          |  | C<br>Carbon    |  | N<br>Nitrogen    |  | O<br>Oxygen   |  | F<br>Fluorine   |  | Ne<br>Neon       |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
| Na<br>Sodium   |  | Mg<br>Magnesium |  | 3<br>IIIB      |  | 4<br>IVB        |  | 5<br>VB       |  | 6<br>VIB         |  | 7<br>VIIB        |  | 8<br>VIII       |  | 9<br>VIII     |  | 10<br>VIII          |  | 11<br>IB       |  | 12<br>IIB        |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
| K<br>Potassium |  | Ca<br>Calcium   |  | Sc<br>Scandium |  | Ti<br>Titanium  |  | V<br>Vanadium |  | Cr<br>Chromium   |  | Mn<br>Manganese  |  | Fe<br>Iron      |  | Co<br>Cobalt  |  | Ni<br>Nickel        |  | Cu<br>Copper   |  | Zn<br>Zinc       |  | Ga<br>Gallium |  | Ge<br>Germanium |  | As<br>Arsenic    |  | Se<br>Selenium     |  | Br<br>Bromine     |  | Kr<br>Krypton     |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
| Rb<br>Rubidium |  | Sr<br>Strontium |  | Y<br>Yttrium   |  | Zr<br>Zirconium |  | Nb<br>Niobium |  | Mo<br>Molybdenum |  | Tc<br>Technetium |  | Ru<br>Ruthenium |  | Rh<br>Rhodium |  | Pd<br>Palladium     |  | Ag<br>Silver   |  | Cd<br>Cadmium    |  | In<br>Indium  |  | Sn<br>Tin       |  | Sb<br>Antimony   |  | Te<br>Tellurium    |  | I<br>Iodine       |  | Xe<br>Xenon       |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
| Cs<br>Cesium   |  | Ba<br>Barium    |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  | Hf<br>Hafnium       |  | Ta<br>Tantalum |  | W<br>Tungsten    |  | Re<br>Rhenium |  | Os<br>Osmium    |  | Ir<br>Iridium    |  | Pt<br>Platinum     |  | Au<br>Gold        |  | Hg<br>Mercury     |  | Tl<br>Thallium |  | Pb<br>Lead      |  | Bi<br>Bismuth   |  | Po<br>Polonium    |  | At<br>Astatine   |  | Rn<br>Radon     |  |  |  |  |  |  |  |
| Fr<br>Francium |  | Ra<br>Radium    |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  | Rf<br>Rutherfordium |  | Db<br>Dubnium  |  | Sg<br>Seaborgium |  | Bh<br>Bohrium |  | Hs<br>Hassium   |  | Mt<br>Meitnerium |  | Ds<br>Darmstadtium |  | Rg<br>Roentgenium |  | Cn<br>Copernicium |  | Nh<br>Nihonium |  | Fl<br>Flerovium |  | Mc<br>Moscovium |  | Lv<br>Livermorium |  | Ts<br>Tennessine |  | Og<br>Oganesson |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
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|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
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|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
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|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
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|                |  |                 |  |                |  |                 |  |               |  |                  |  |                  |  |                 |  |               |  |                     |  |                |  |                  |  |               |  |                 |  |                  |  |                    |  |                   |  |                   |  |                |  |                 |  |                 |  |                   |  |                  |  |                 |  |  |  |  |  |  |  |
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# The Origins of the Elements

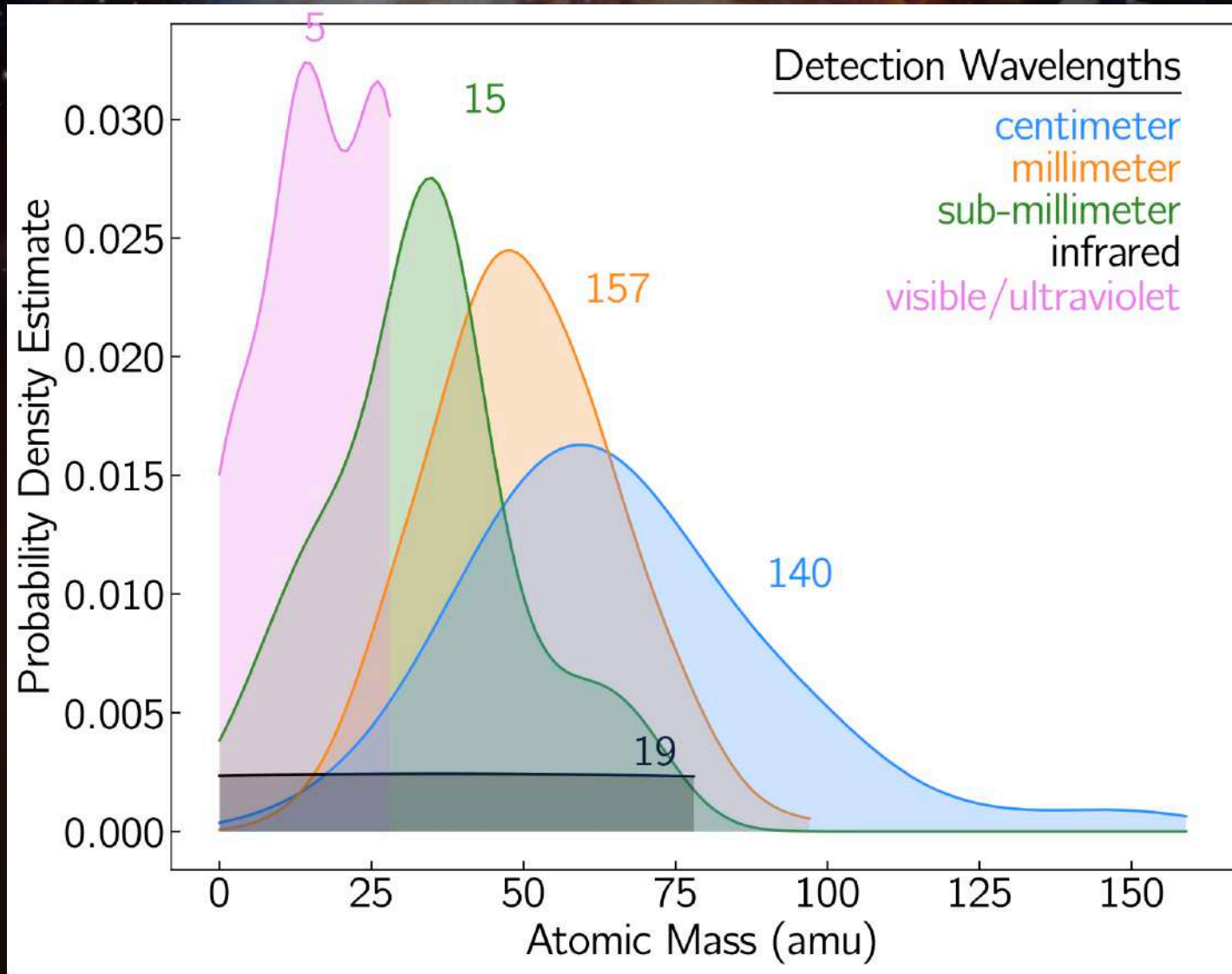


# The chemical complexity in the ISM

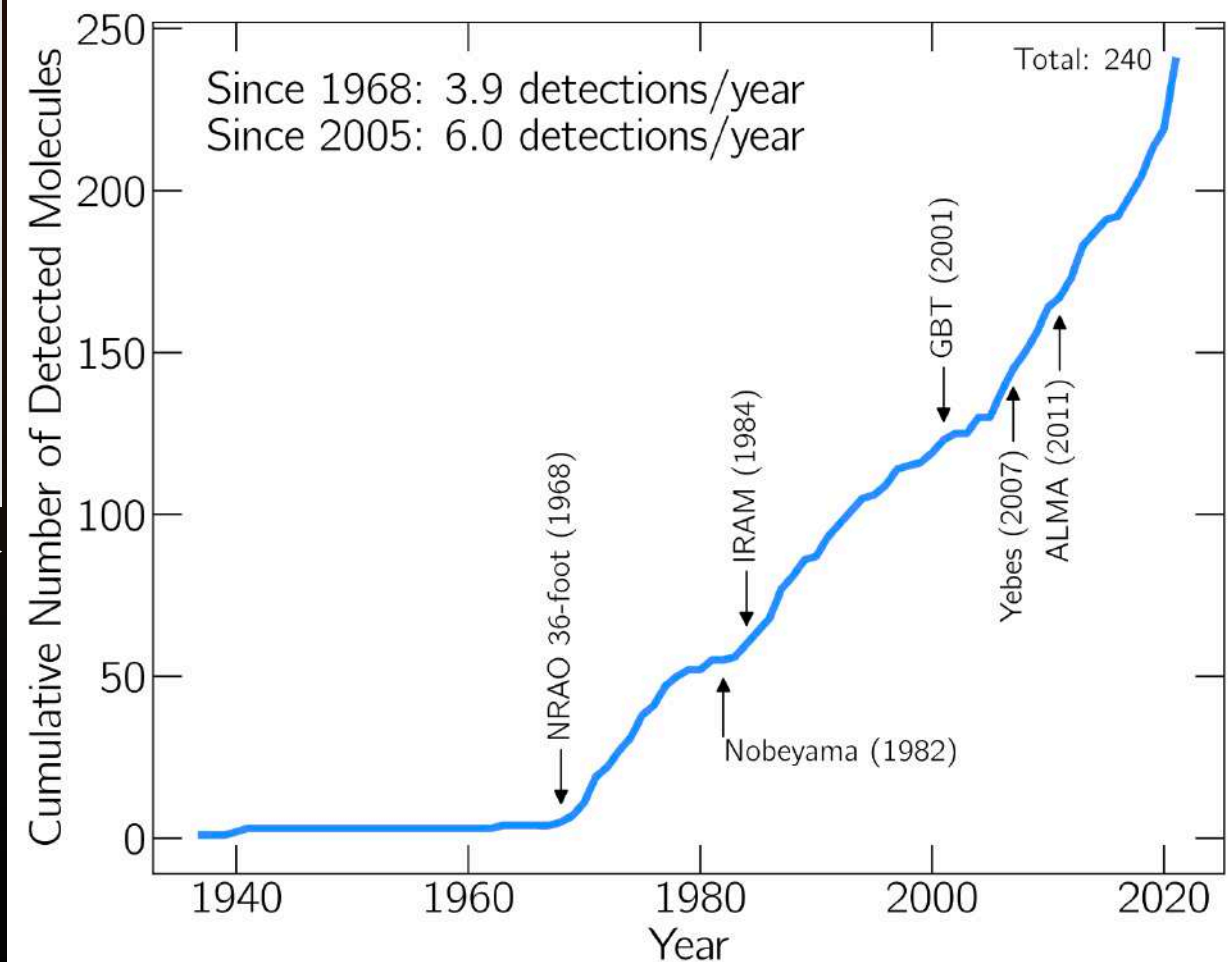
In the cm  
YEBES & GBT



At mm with ALMA



“As of **October 2026**, about **350** molecules have been detected in the interstellar medium or circumstellar shells” [CDMS]

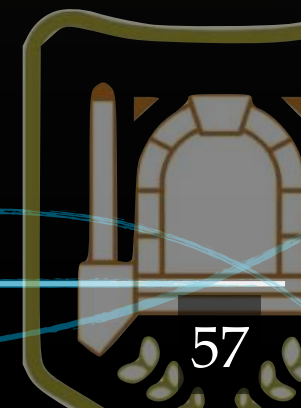


# Detected Interstellar Molecules

*Not complete list!*

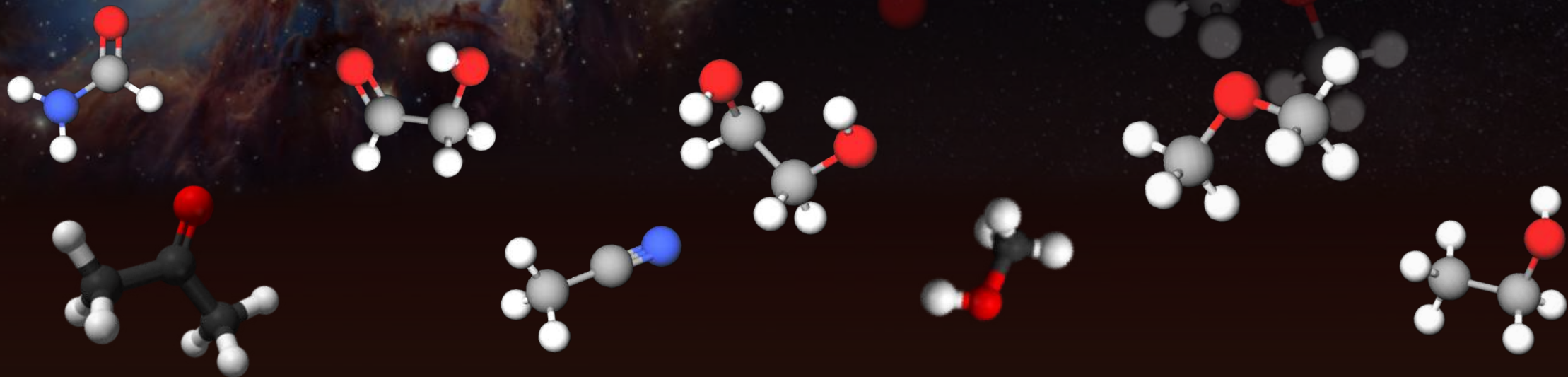
| 2 atoms           | 3 atoms          | 4 atoms                         | 5 atoms                         | 6 atoms                         | 7 atoms                           | 8 atoms                             | 9 atoms                             | 10 atoms                                          | 11 atoms                                          | 12 atoms                                       | >12 atoms                                                  |
|-------------------|------------------|---------------------------------|---------------------------------|---------------------------------|-----------------------------------|-------------------------------------|-------------------------------------|---------------------------------------------------|---------------------------------------------------|------------------------------------------------|------------------------------------------------------------|
| H <sub>2</sub>    | C <sub>3</sub> * | c-C <sub>3</sub> H              | C <sub>5</sub> *                | C <sub>5</sub> H                | C <sub>6</sub> H                  | CH <sub>3</sub> C <sub>3</sub> N    | CH <sub>3</sub> C <sub>4</sub> H    | CH <sub>3</sub> C <sub>5</sub> N                  | HC <sub>9</sub> N                                 | c-C <sub>6</sub> H <sub>6</sub> *              | C <sub>60</sub> *                                          |
| AlF               | C <sub>2</sub> H | I-C <sub>3</sub> H              | C <sub>4</sub> H                | I-H <sub>2</sub> C <sub>4</sub> | CH <sub>2</sub> CHCN              | HC(O)OCH <sub>3</sub>               | CH <sub>3</sub> CH <sub>2</sub> CN  | (CH <sub>3</sub> ) <sub>2</sub> CO                | CH <sub>3</sub> C <sub>6</sub> H                  | n-C <sub>3</sub> H <sub>7</sub> CN             | C <sub>70</sub> *                                          |
| AlCl              | C <sub>2</sub> O | C <sub>3</sub> N                | C <sub>4</sub> Si               | C <sub>2</sub> H <sub>4</sub> * | CH <sub>3</sub> C <sub>2</sub> H  | CH <sub>3</sub> COOH                | (CH <sub>3</sub> ) <sub>2</sub> O   | (CH <sub>2</sub> OH) <sub>2</sub>                 | C <sub>2</sub> H <sub>5</sub> OCHO                | i-C <sub>3</sub> H <sub>7</sub> CN             | C <sub>60</sub> <sup>++</sup>                              |
| C <sub>2</sub> ** | C <sub>2</sub> S | C <sub>3</sub> O                | I-C <sub>3</sub> H <sub>2</sub> | CH <sub>3</sub> CN              | HC <sub>5</sub> N                 | C <sub>7</sub> H                    | CH <sub>3</sub> CH <sub>2</sub> OH  | CH <sub>3</sub> CH <sub>2</sub> CHO               | CH <sub>3</sub> OC(O)CH <sub>3</sub>              | C <sub>2</sub> H <sub>5</sub> OCH <sub>3</sub> | c-C <sub>6</sub> H <sub>5</sub> CN                         |
| CH                | CH <sub>2</sub>  | C <sub>3</sub> S                | c-C <sub>3</sub> H <sub>2</sub> | CH <sub>3</sub> NC              | CH <sub>3</sub> CHO               | C <sub>6</sub> H <sub>2</sub>       | HC <sub>7</sub> N                   | CH <sub>3</sub> CHCH <sub>2</sub> O               | CH <sub>3</sub> C(O)CH <sub>2</sub> OH            | 1-c-C <sub>5</sub> H <sub>5</sub> CN           | HC <sub>11</sub> N                                         |
| CH <sup>+</sup>   | HCN              | C <sub>2</sub> H <sub>2</sub> * | H <sub>2</sub> CCN              | CH <sub>3</sub> OH              | CH <sub>3</sub> NH <sub>2</sub>   | CH <sub>2</sub> OHCHO               | C <sub>8</sub> H                    | CH <sub>3</sub> OCH <sub>2</sub> OH               | c-C <sub>5</sub> H <sub>6</sub>                   | 2-c-C <sub>5</sub> H <sub>5</sub> CN           | 1-C <sub>10</sub> H <sub>7</sub> CN                        |
| CN                | HCO              | NH <sub>3</sub>                 | CH <sub>4</sub> *               | CH <sub>3</sub> SH              | c-C <sub>2</sub> H <sub>4</sub> O | I-HC <sub>6</sub> H*                | CH <sub>3</sub> C(O)NH <sub>2</sub> | c-C <sub>6</sub> H <sub>4</sub>                   | HOCH <sub>2</sub> CH <sub>2</sub> NH <sub>2</sub> | CH <sub>3</sub> C <sub>7</sub> N (?)<br>(2022) | 2-C <sub>10</sub> H <sub>7</sub> CN                        |
| CO                | HCO <sup>+</sup> | HCCN                            | HC <sub>3</sub> N               | HC <sub>3</sub> NH <sup>+</sup> | H <sub>2</sub> CCHOH              | CH <sub>2</sub> CHCHO               | C <sub>8</sub> H <sup>-</sup>       | H <sub>2</sub> CCCHC <sub>3</sub> N               | H <sub>2</sub> CCCHC <sub>4</sub> H<br>(2022)     | n-C <sub>3</sub> H <sub>7</sub> OH<br>(2022)   | c-C <sub>9</sub> H <sub>8</sub>                            |
| CO <sup>+</sup>   | HCS <sup>+</sup> | HCNH <sup>+</sup>               | HCCNC                           | HCCCHO                          | C <sub>6</sub> H <sup>-</sup>     | CH <sub>2</sub> CCHCN               | C <sub>3</sub> H <sub>6</sub>       | C <sub>2</sub> H <sub>5</sub> NCO                 | C <sub>10</sub> H <sup>-</sup> (2023)             | i-C <sub>3</sub> H <sub>7</sub> OH<br>(2022)   | 1-c-C <sub>5</sub> H <sub>5</sub> CCH                      |
| CP                | HOC <sup>+</sup> | HNCO                            | HCOOH                           | NH <sub>2</sub> CHO             | CH <sub>3</sub> NCO               | H <sub>2</sub> NCH <sub>2</sub> CN  | CH <sub>3</sub> CH <sub>2</sub> SH  | C <sub>2</sub> H <sub>5</sub> NH <sub>2</sub> (?) |                                                   |                                                | 2-c-C <sub>5</sub> H <sub>5</sub> CCH                      |
| SiC               | H <sub>2</sub> O | HNCS                            | H <sub>2</sub> CNH              | C <sub>5</sub> N                | HC <sub>5</sub> O                 | CH <sub>3</sub> CHNH                | CH <sub>3</sub> NHCHO               | HC <sub>7</sub> NH <sup>+</sup> (2022)            |                                                   |                                                | c-C <sub>5</sub> H <sub>4</sub> CCH <sub>2</sub><br>(2022) |
| HCl               | H <sub>2</sub> S | HOCO <sup>+</sup>               | H <sub>2</sub> C <sub>2</sub> O | I-HC <sub>4</sub> H*            | HOCH <sub>2</sub> CN              | CH <sub>3</sub> SiH <sub>3</sub>    | HC <sub>7</sub> O                   | CH <sub>3</sub> CHCHCN<br>(2022)                  |                                                   |                                                | 2-C <sub>9</sub> H <sub>7</sub> CN<br>(2022)               |
| KCl               | HNC              | H <sub>2</sub> CO               | H <sub>2</sub> NCN              | I-HC <sub>4</sub> N             | HCCCHNH                           | H <sub>2</sub> NC(O)NH <sub>2</sub> | HCCCHCHCN                           | CH <sub>3</sub> C(CN)CH <sub>2</sub><br>(2022)    |                                                   |                                                |                                                            |

*Some are common on Earth, some others are radical, ions, transient species that do not survive on Earth and, among them....*

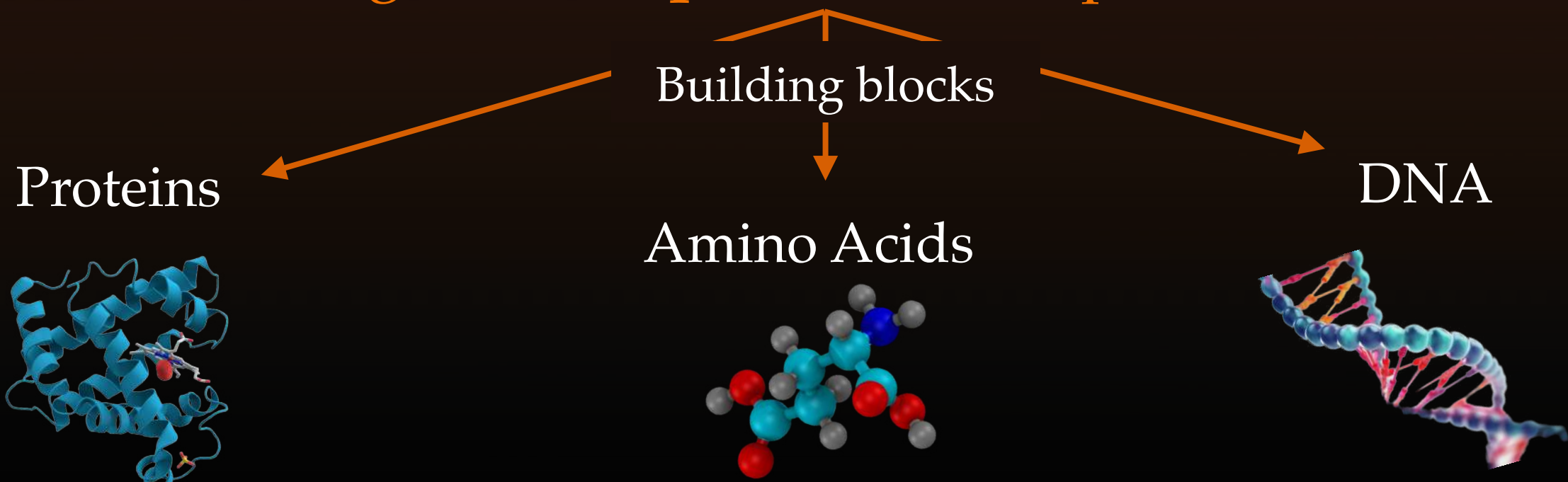


# Detected Interstellar Molecules

## Interstellar Complex Organic Molecules (iCOMs\*)



Organic and **prebiotic** compounds!

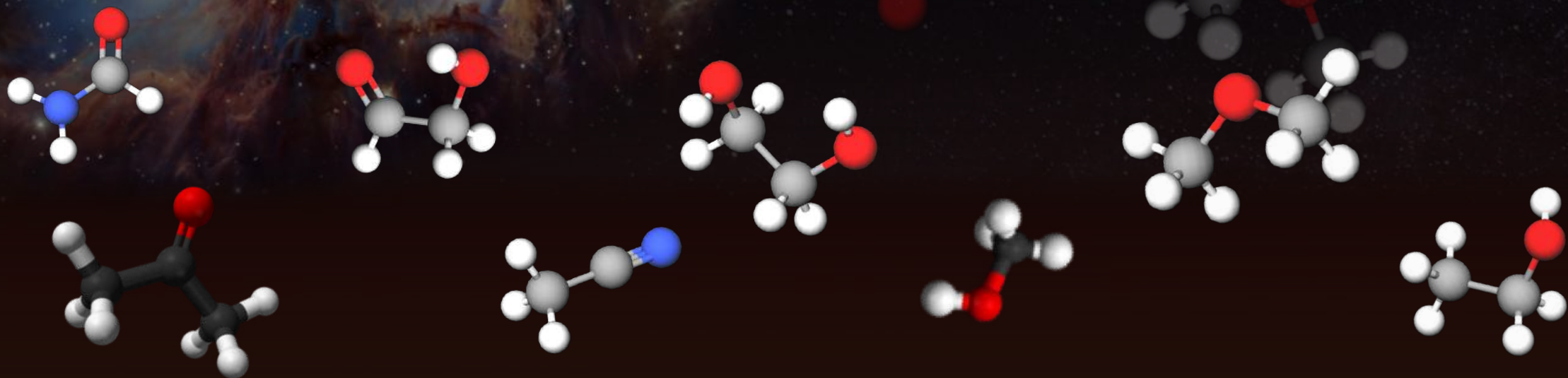


\*iCOMs: Saturated C-bearing molecules with more than six atoms and containing heteroatoms

(Herbst & Van Dishoeck 2009, , Yamamoto 2017, Ceccarelli et al. 2023)

# Detected Interstellar Molecules

## Interstellar Complex Organic Molecules (iCOMs\*)



Organic and **prebiotic** compounds!

How can you form these species in the harsh ISM environment?

How and where do we observe these molecules?

How can we use these species?

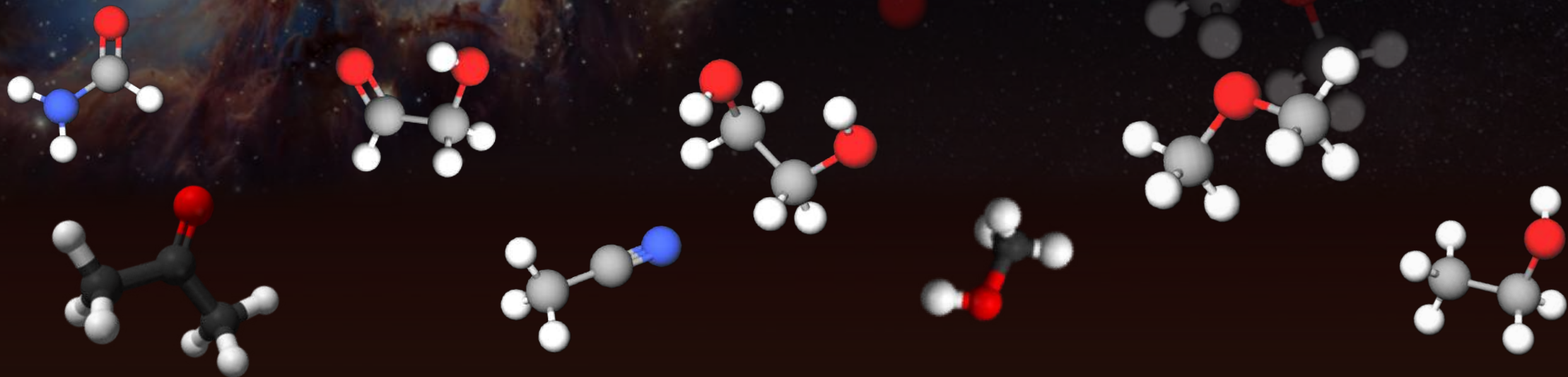
\*iCOMs: Saturated C-bearing molecules with more than six atoms and containing heteroatoms

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# Detected Interstellar Molecules

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\*iCOMs: Saturated C-bearing molecules with more than six atoms and containing heteroatoms

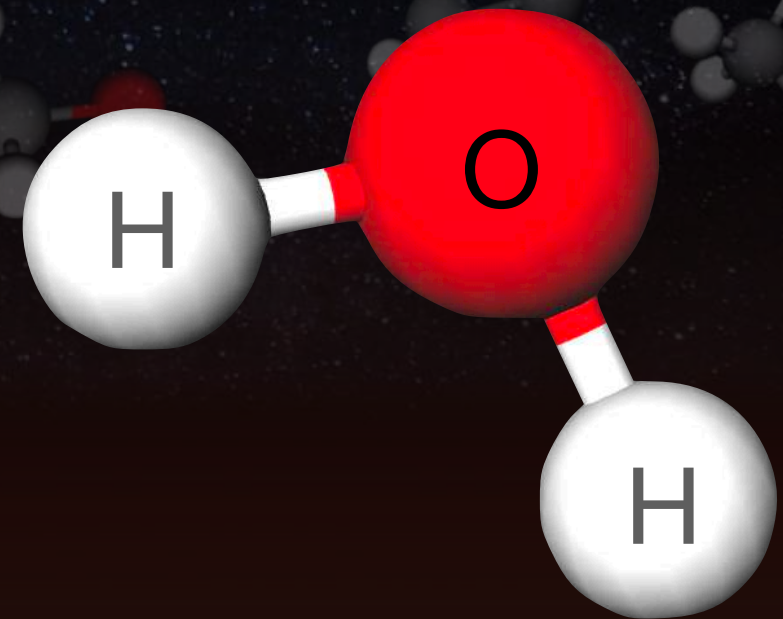
(Herbst & Van Dishoeck 2009, Yamamoto 2017, Ceccarelli et al. 2023)



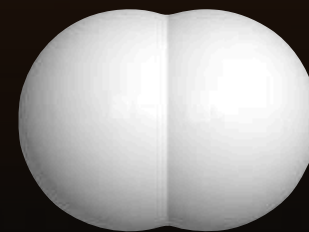
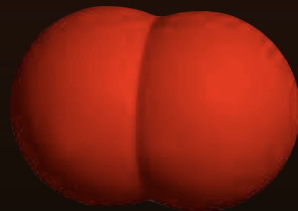
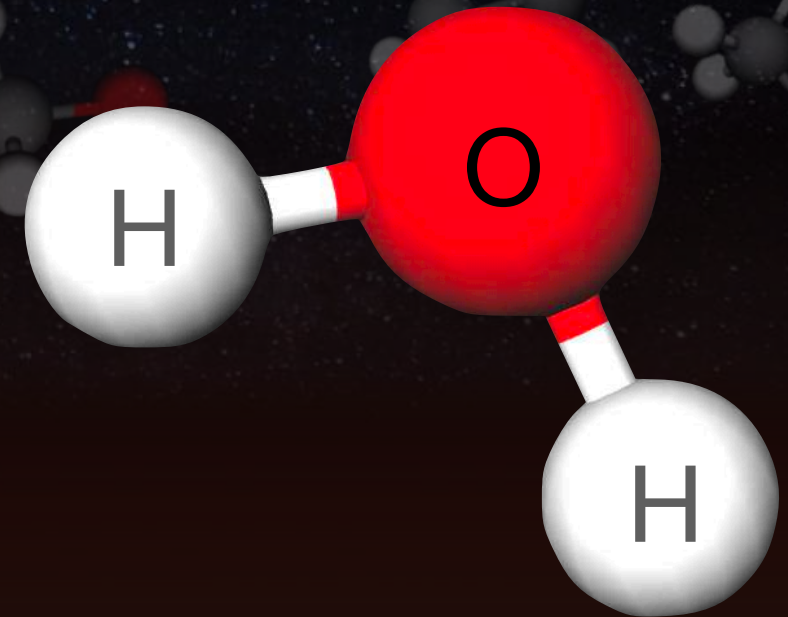
# Do you know how water ( $\text{H}_2\text{O}$ ) is formed?



We have three atoms,  
how do we combine them?

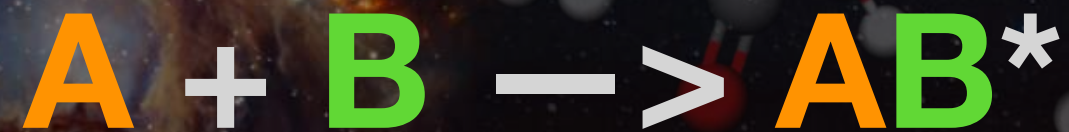


# Do you know how water (H<sub>2</sub>O) is formed?



This is efficient on Earth, but not in space...why?

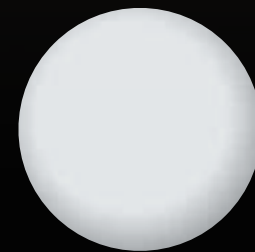
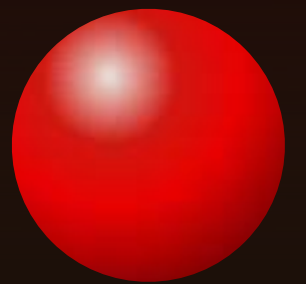
# How do molecules form in the ISM?



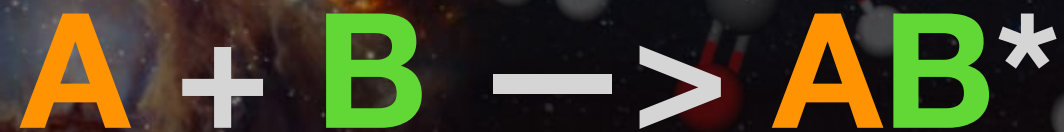
$AB^*$  must lose the internal energy  
on Earth atmosphere  $n \sim 10^{19} \text{ cm}^{-3} \rightarrow$  three-body reactions



$\rightarrow$  not efficient in the ISM gas conditions!



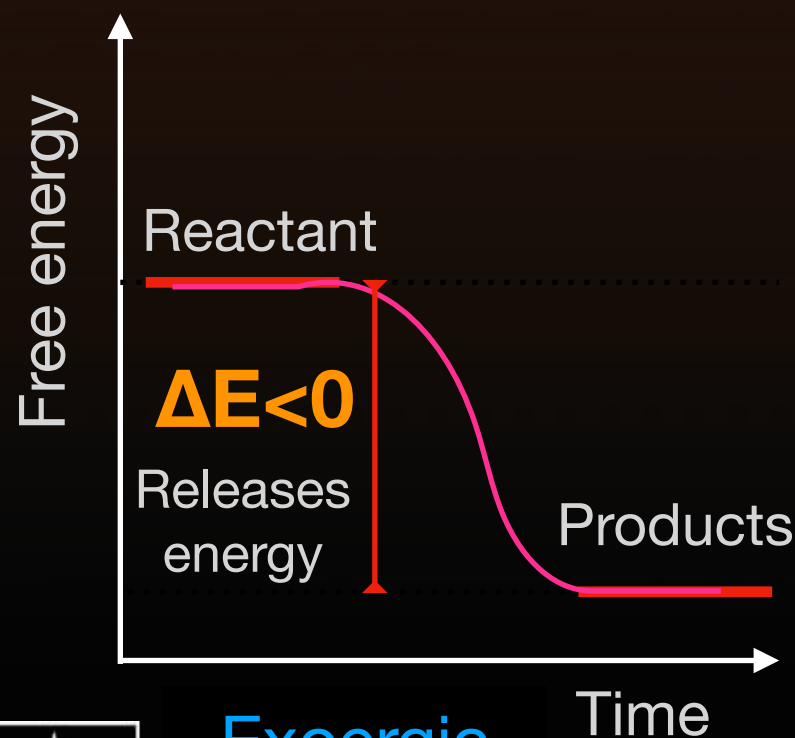
# How do molecules form in the ISM?



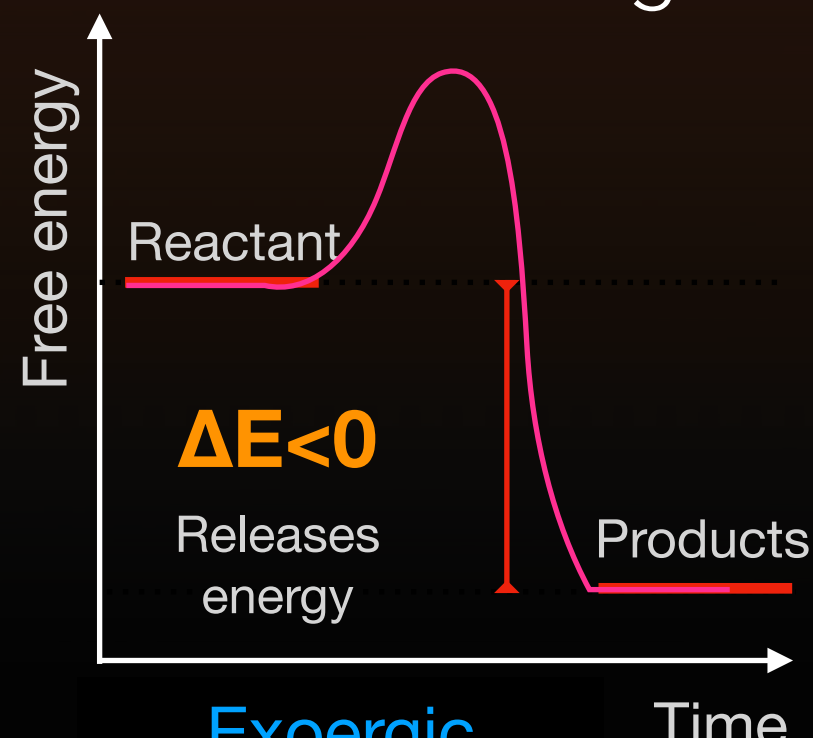
$AB^*$  must lose the internal energy  
on Earth atmosphere  $n \sim 10^{19} \text{ cm}^{-3}$   $\rightarrow$  three-body reactions



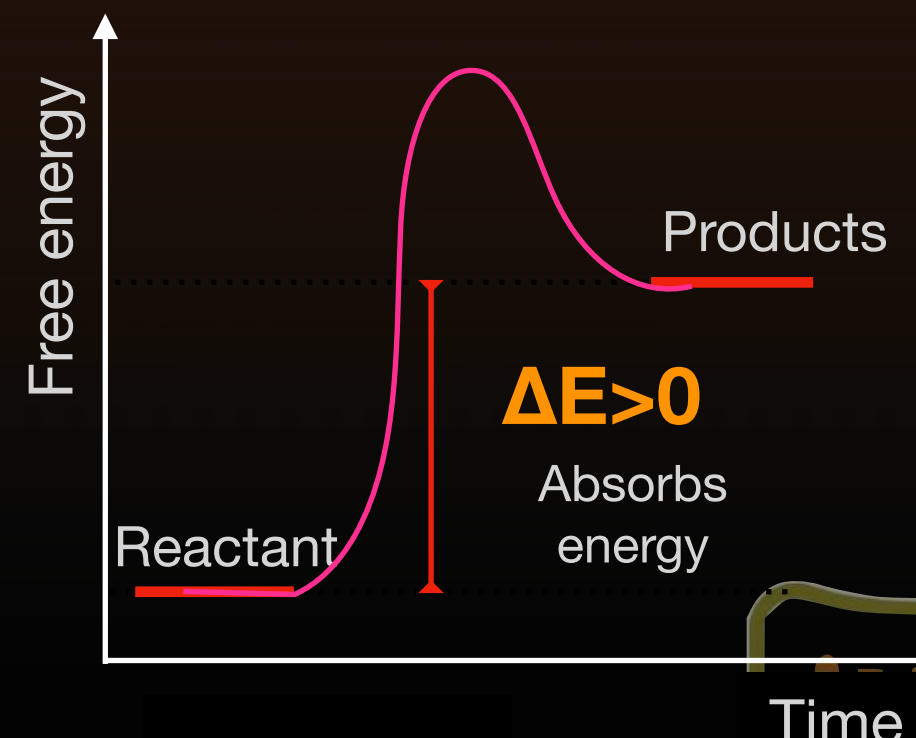
$\rightarrow$  not efficient in the ISM gas conditions!



Exoergic  
barrierless

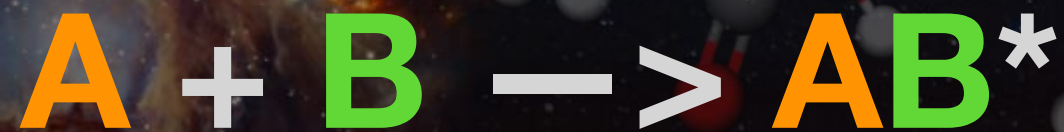


Exoergic  
with barrier



Endoergic

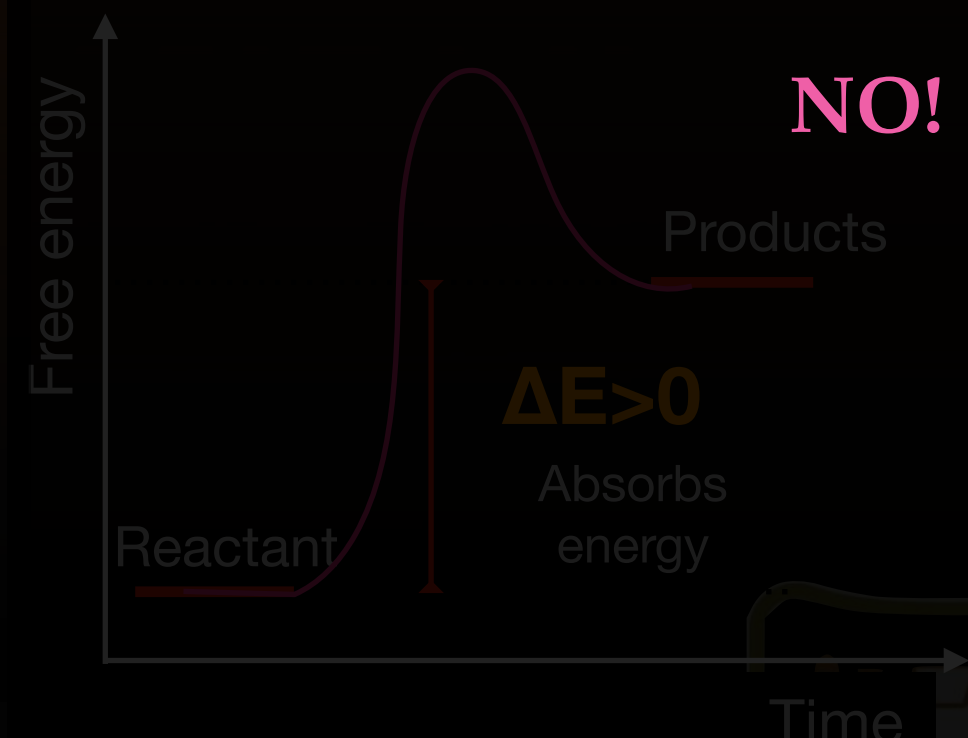
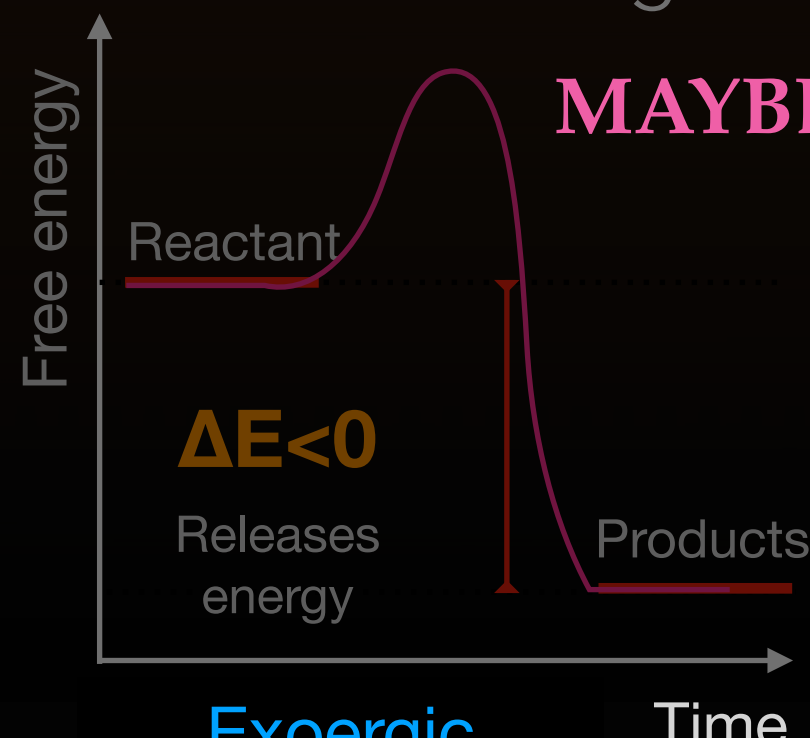
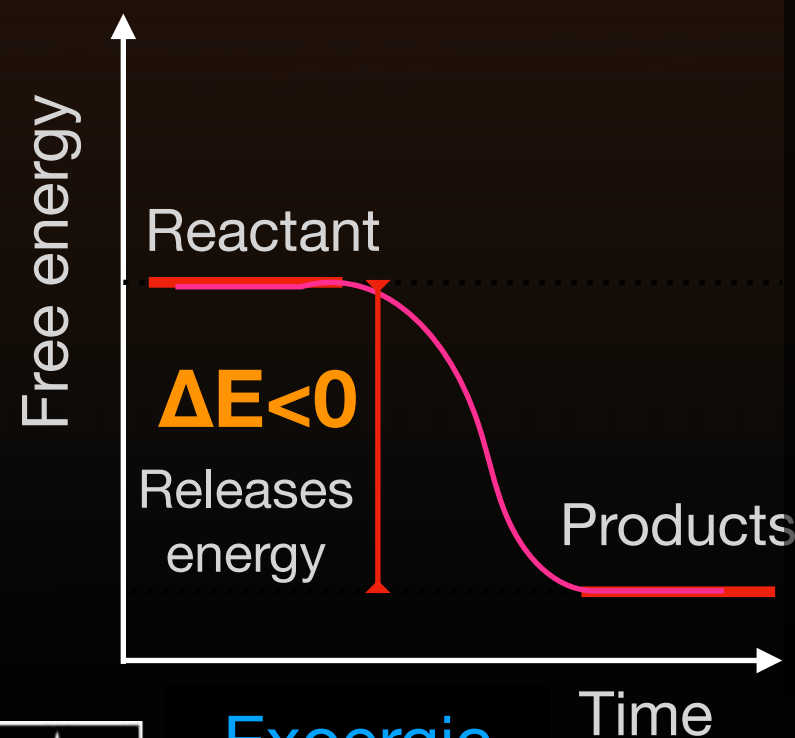
# How do molecules form in the ISM?



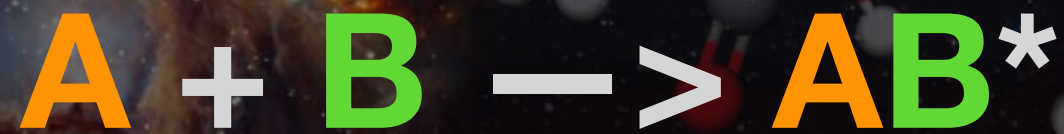
$AB^*$  must lose the internal energy  
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$\rightarrow$  not efficient in the ISM gas conditions!



# How do molecules form in the ISM?

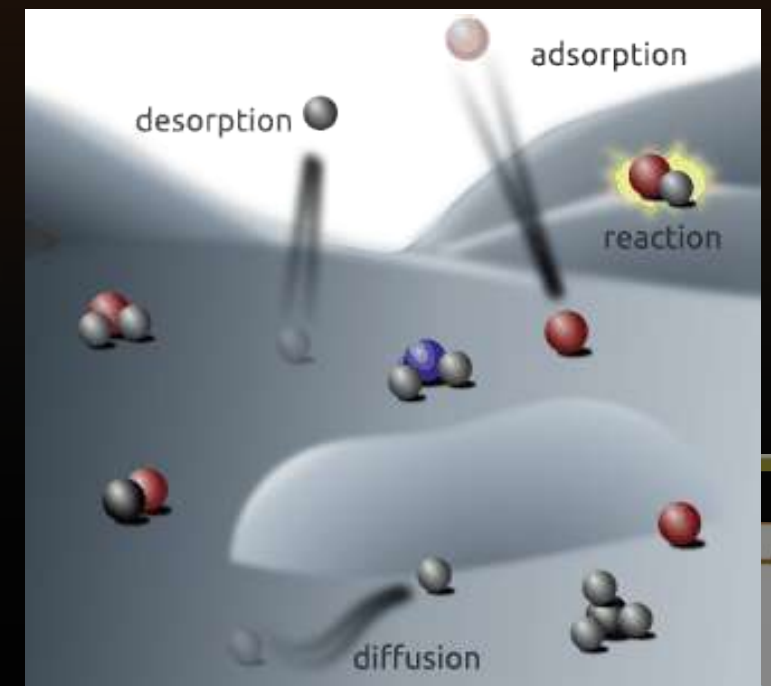
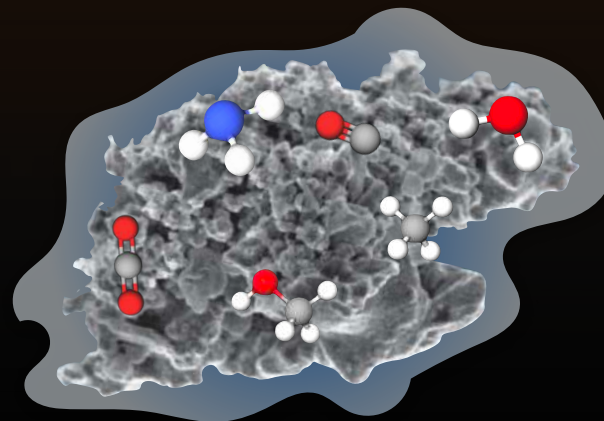
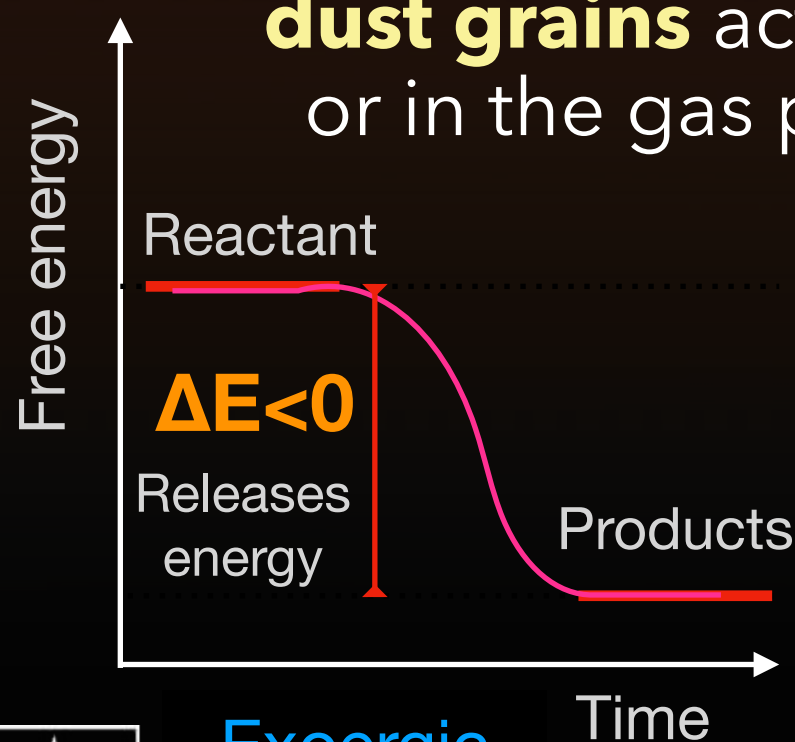


$AB^*$  must lose the internal energy  
on Earth atmosphere  $n \sim 10^{19} \text{ cm}^{-3} \rightarrow$  three-body reactions



In the ISM:

**dust grains** act as third body for molecular reactions,  
or in the gas phase **barrierless** reactions can occur



Exoergic  
barrierless

Marta De Simone

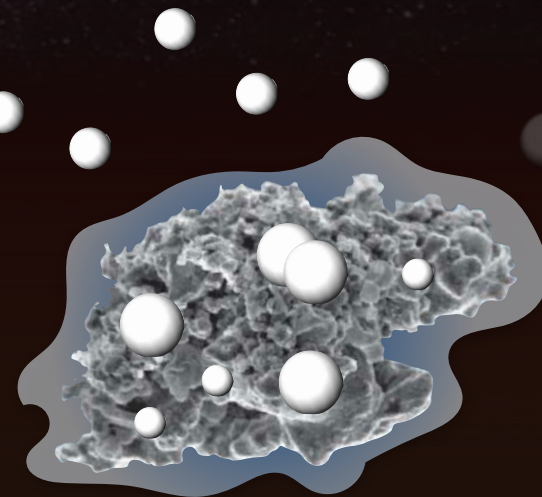
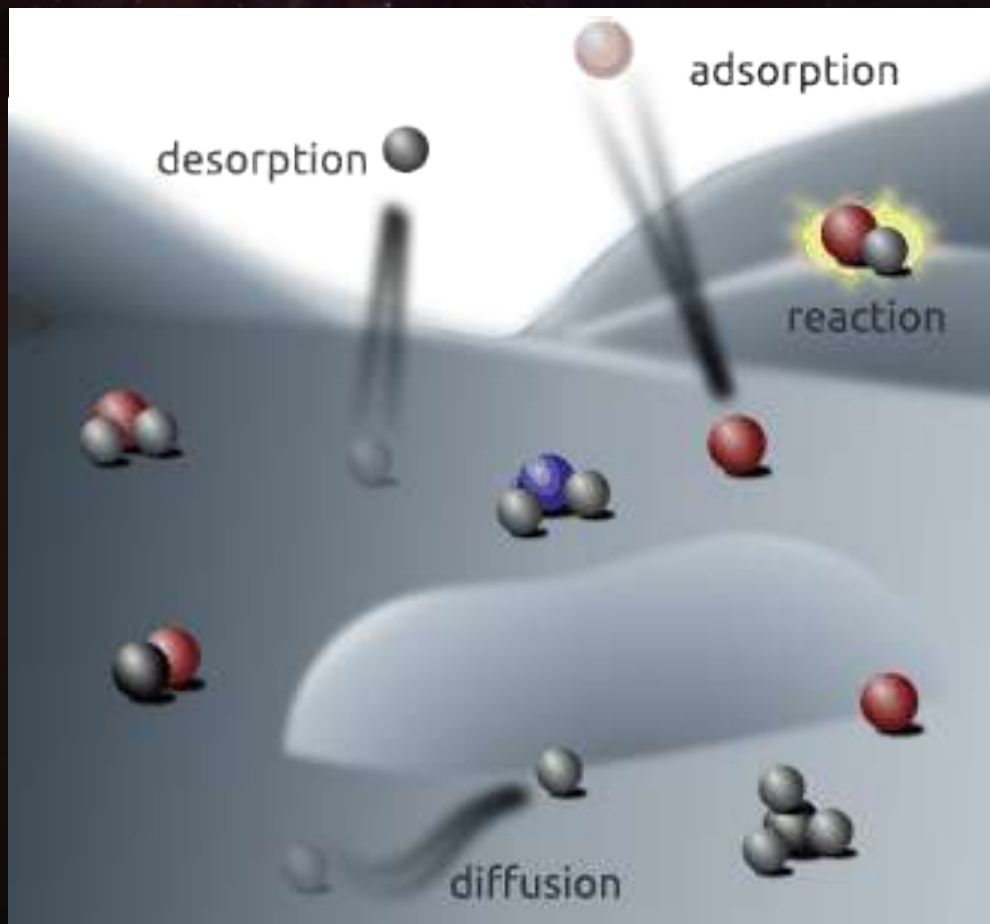
Astrophysics School  
"Francesco Lucchin"

20 October 2026

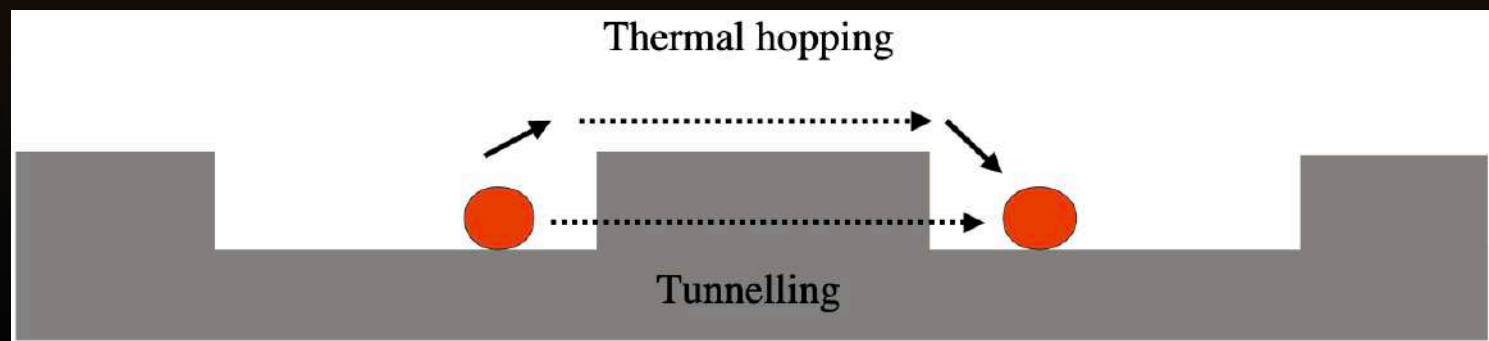
66

# Where everything starts: H<sub>2</sub>

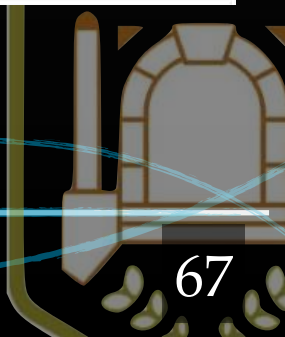
The reaction that starts the chemistry in the ISM is the one between two hydrogen atoms (H) to form molecular hydrogen (H<sub>2</sub>).  
**This reaction happens on the surface of dust grains.**



*Tielens & Hagen (1982); Tielens & Allamandola (1987); Hasegawa et al. (1992); Tielens 1993; Cazaux & Tielens (2002); Cuppen & Herbst (2005); Cazaux et al. (2008); Garrod (2008); Garrod+(2022)*



*Once H<sub>2</sub> is formed, the fun starts...*



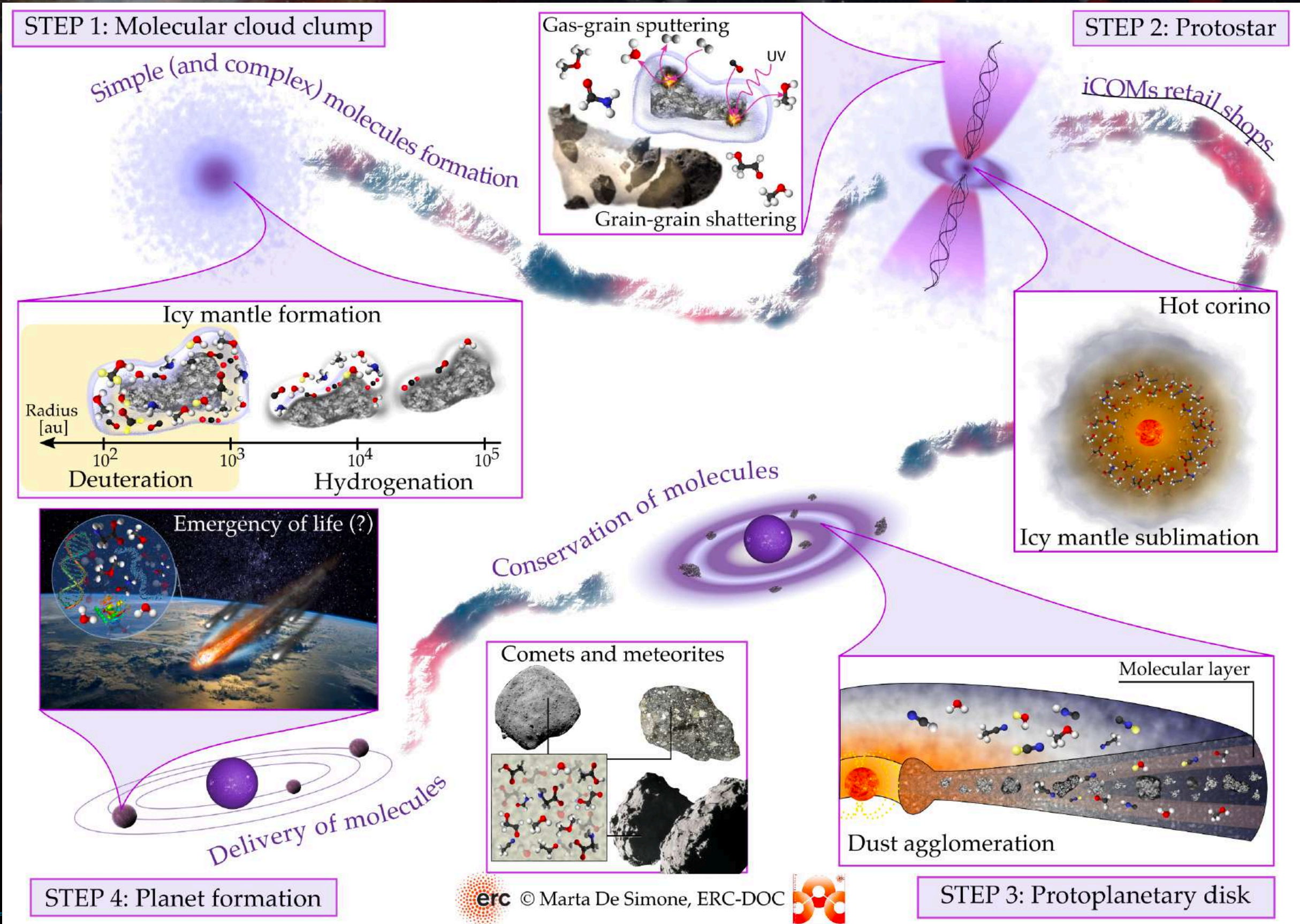
# The formation of water on interstellar dust particles

Line F. van Dishoeck, PhD, A.L.M. “Thanja” Lamberts, MSc

 **Universiteit  
Leiden**  
The Netherlands

Discover the world at Leiden

# In Summary....

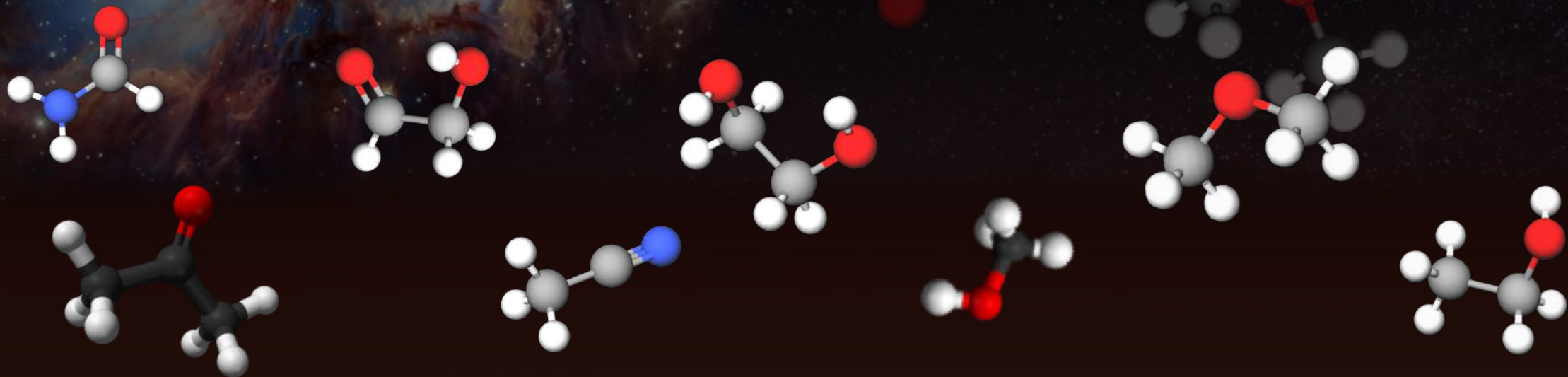


erc © Marta De Simone, ERC-D0C



# Detected Interstellar Molecules

## Interstellar Complex Organic Molecules (iCOMs\*)



Organic and **prebiotic** compounds!

How can you form these species in the harsh ISM environment?

How and where do we observe these molecules?

How can we use these species?

\*iCOMs: Saturated C-bearing molecules with more than six atoms and containing heteroatoms

(Herbst & Van Dishoeck 2009, Yamamoto 2017, Ceccarelli et al. 2023)

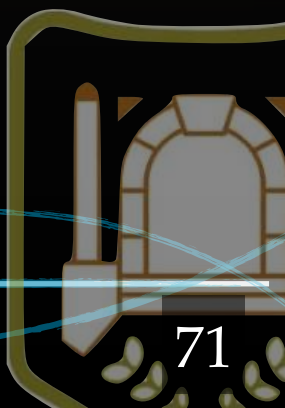


# Where everything starts: H<sub>2</sub>

H<sub>2</sub> is the key to the whole interstellar chemistry. Some important species (C, O, N,...) can react with H<sub>2</sub> but how to decide which ones?



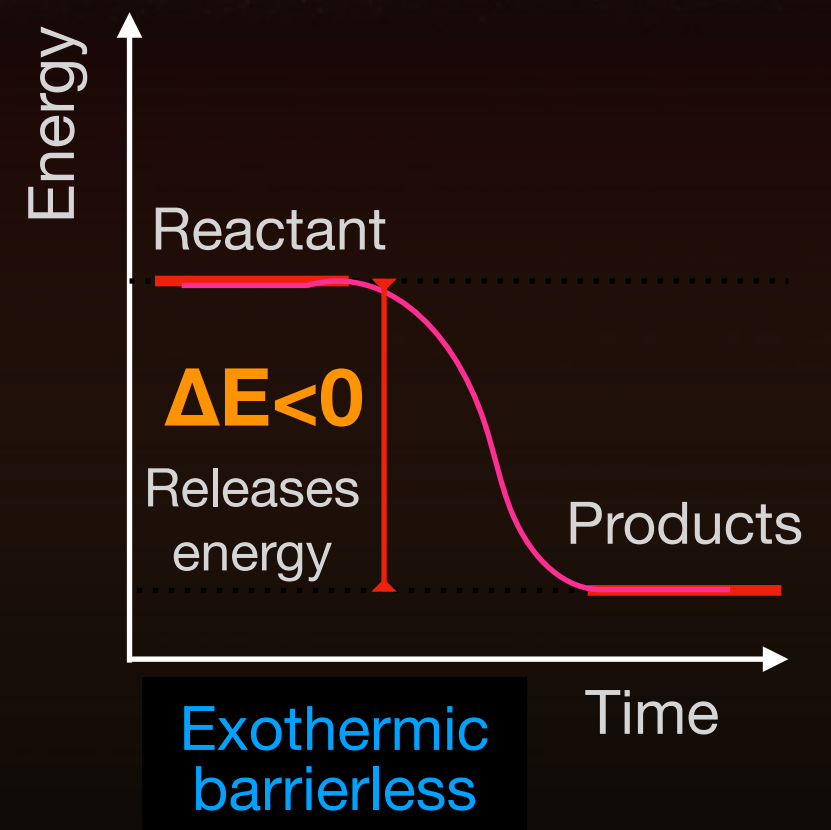
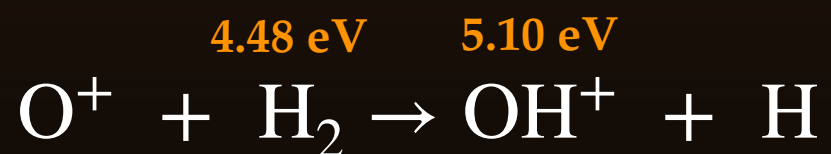
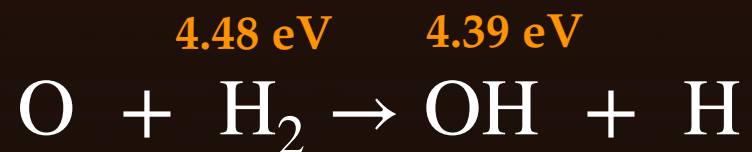
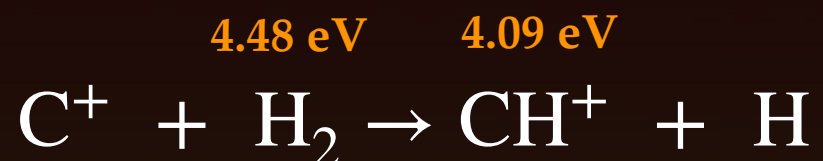
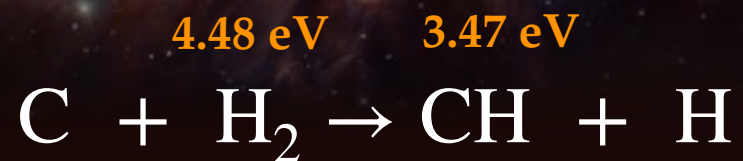
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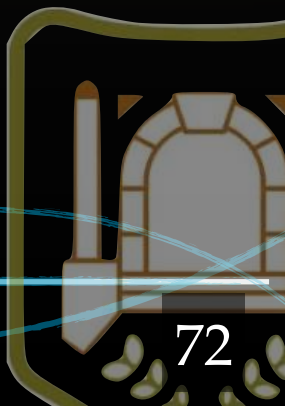
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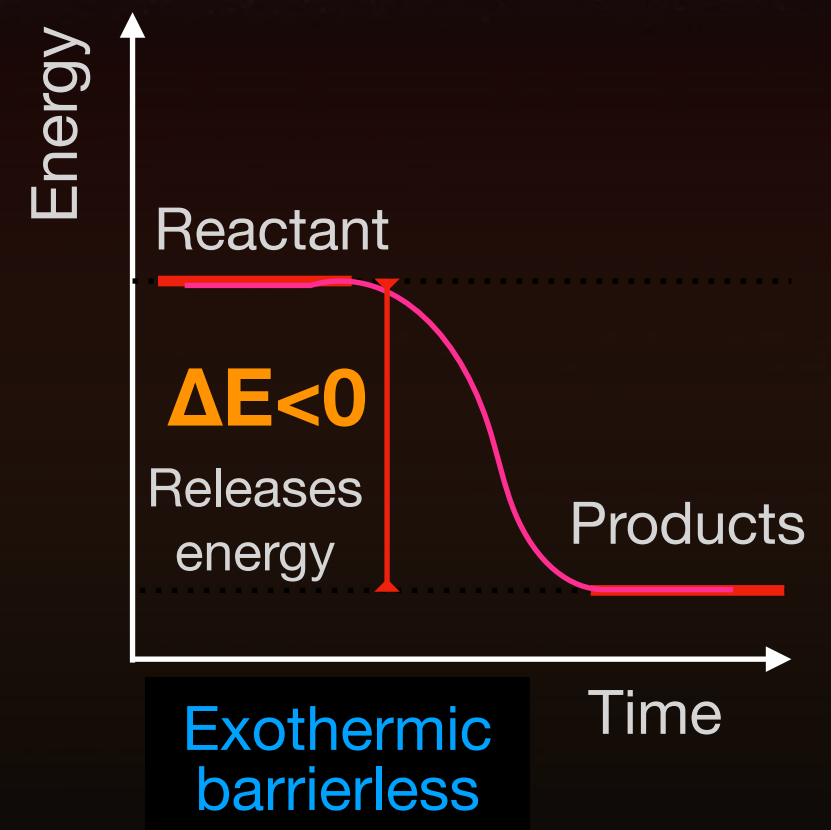
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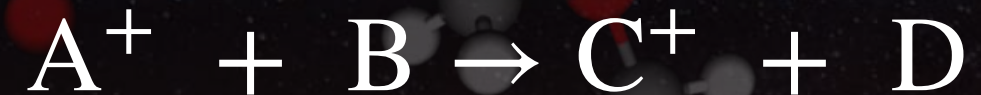


*Once H<sub>2</sub> is formed, the fun starts...*

# What kind of gas-phase reactions?

- **Ion-Neutral reactions**

*Fast, with no activation barrier, and dominant at 10 K  
Herbst & Klemperer 1973; Anicich & Huntress 1986*



- **Neutral-Neutral reactions**

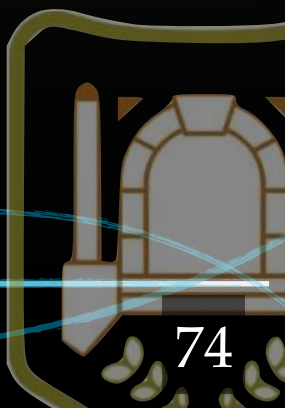
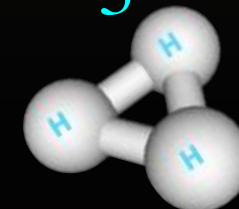
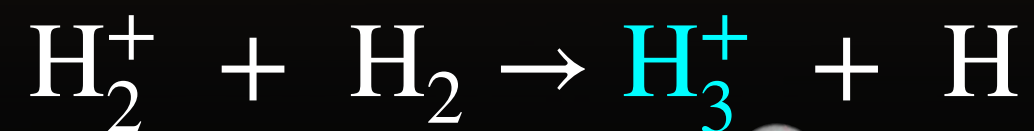
*Often requires activation energy; slow at low temperatures (~10 K), important in warm gas, shock chemistry Duley & Williams 1984,*



*Shannon et al. 2013*

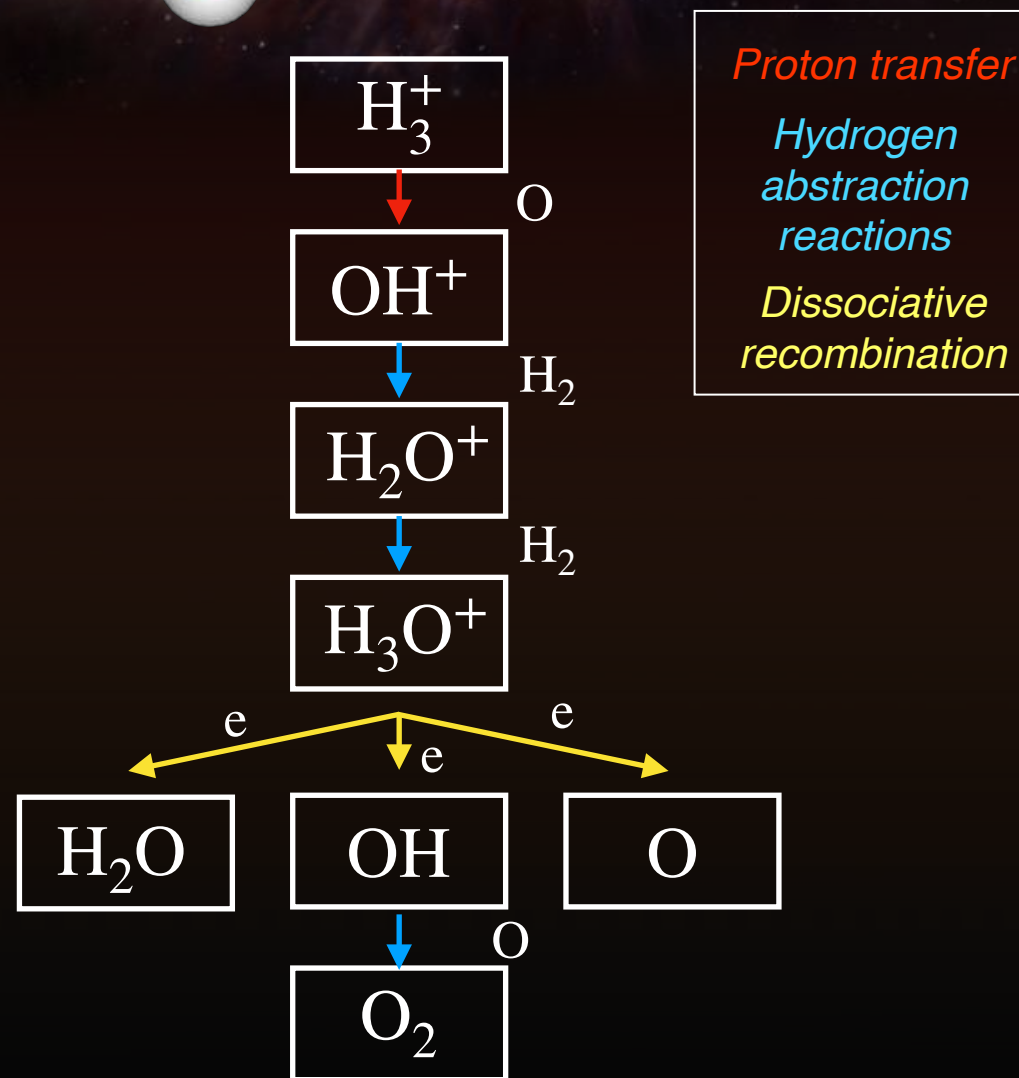
- **Cosmic rays**

*Create ions and initiate chemistry*

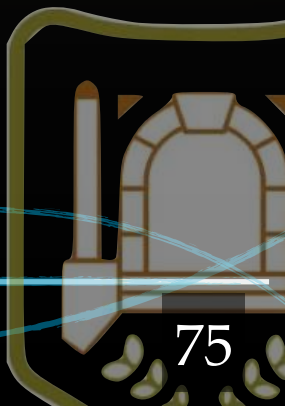


# Oxygen, Carbon gas phase chemistry

Once  $\text{H}_3^+$  is formed, a cascade of ion-molecule reactions enhances the chemical complexity of the ISM ( $\text{H}_3^+$  easily donates a proton)

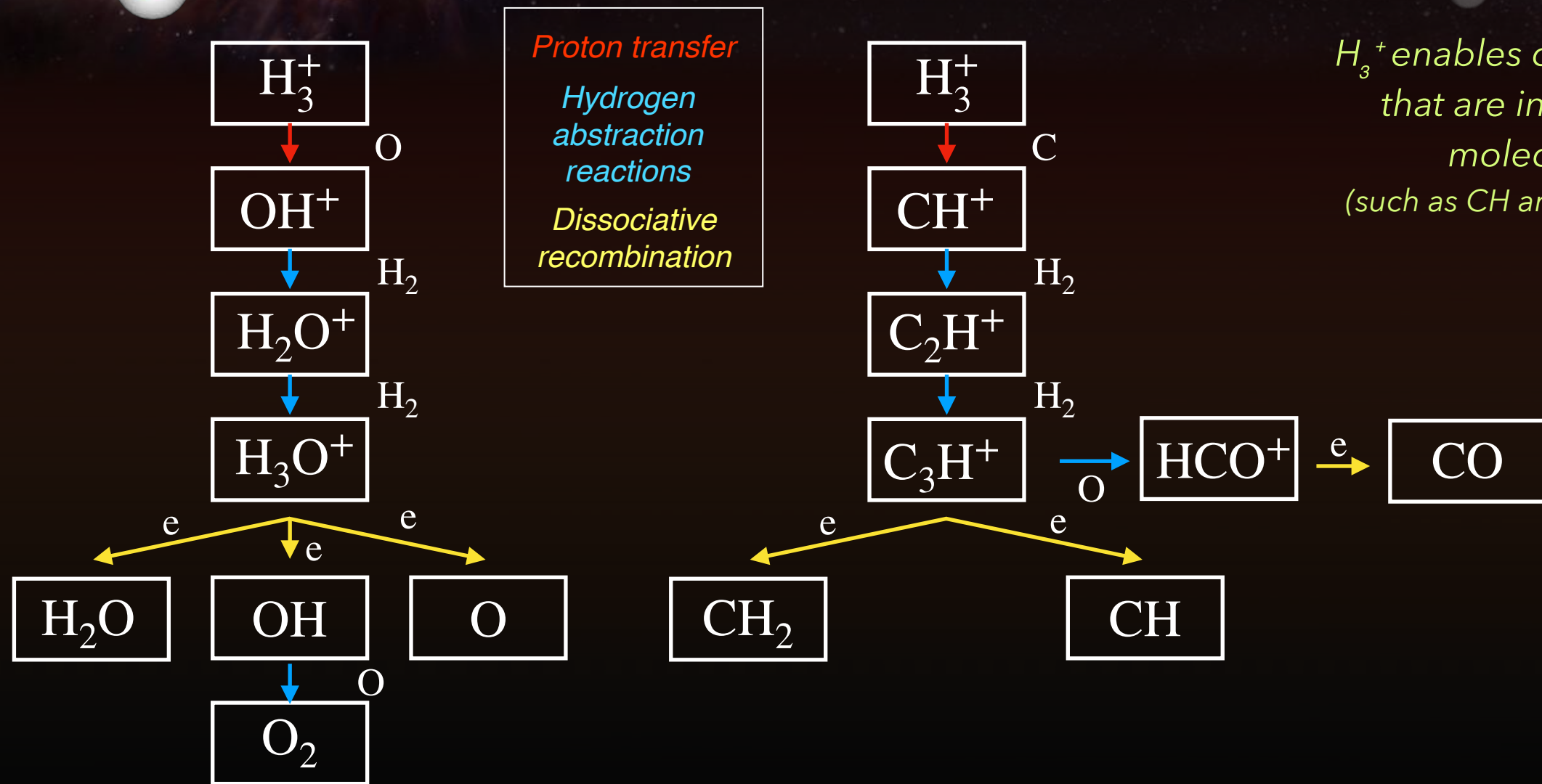


Oxygen Chemistry



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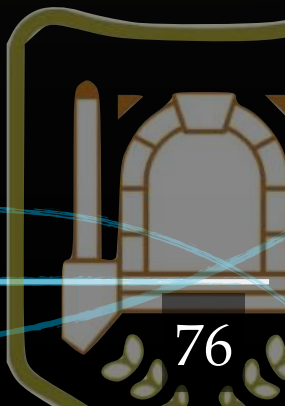


*Proton transfer*  
*Hydrogen abstraction reactions*  
*Dissociative recombination*

$\text{H}_3^+$  enables chemical pathways that are inefficient in cold molecular clouds (such as CH and OH from C and O)

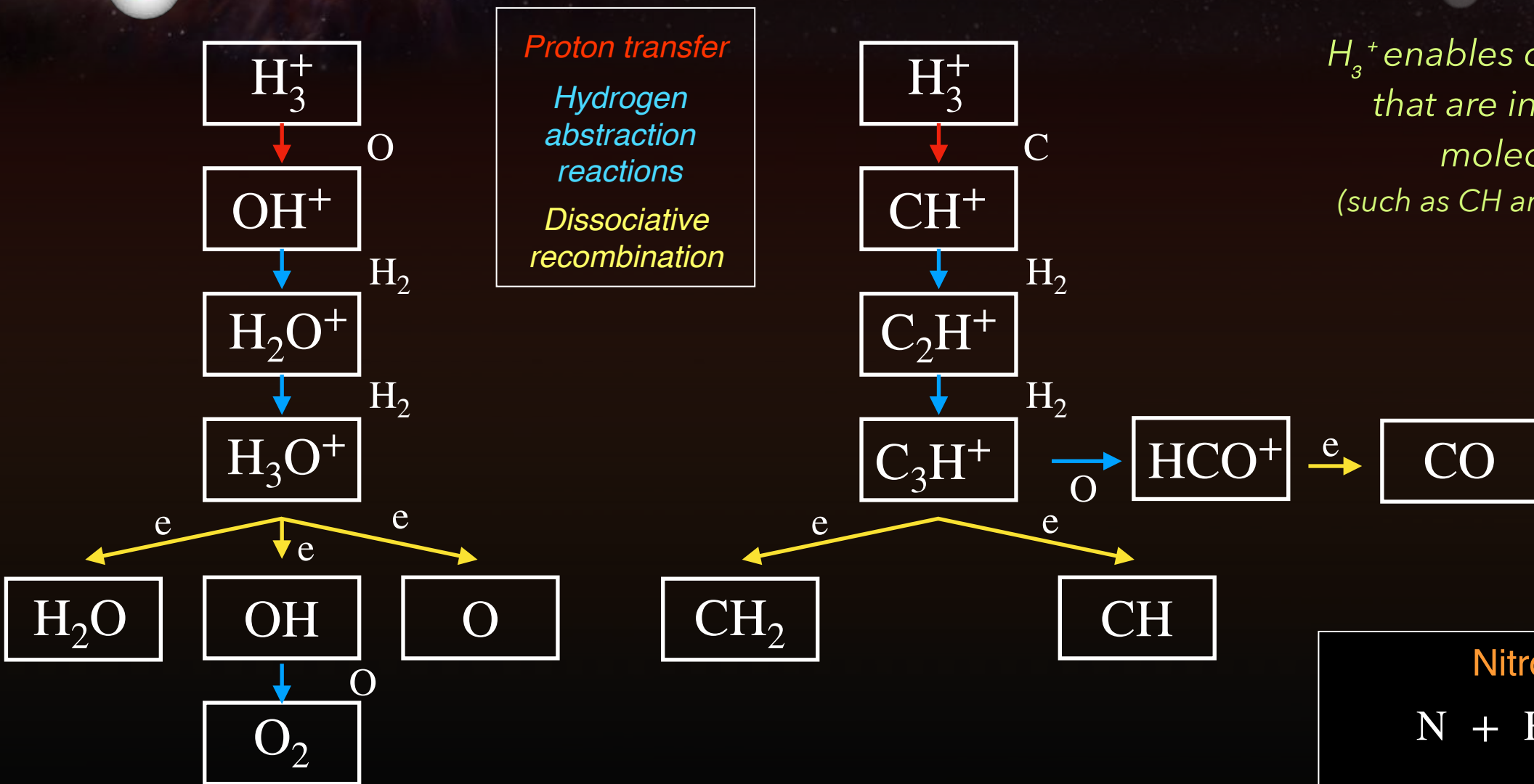
Oxygen Chemistry

Carbon Chemistry



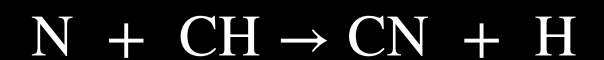
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## Nitrogen Chemistry



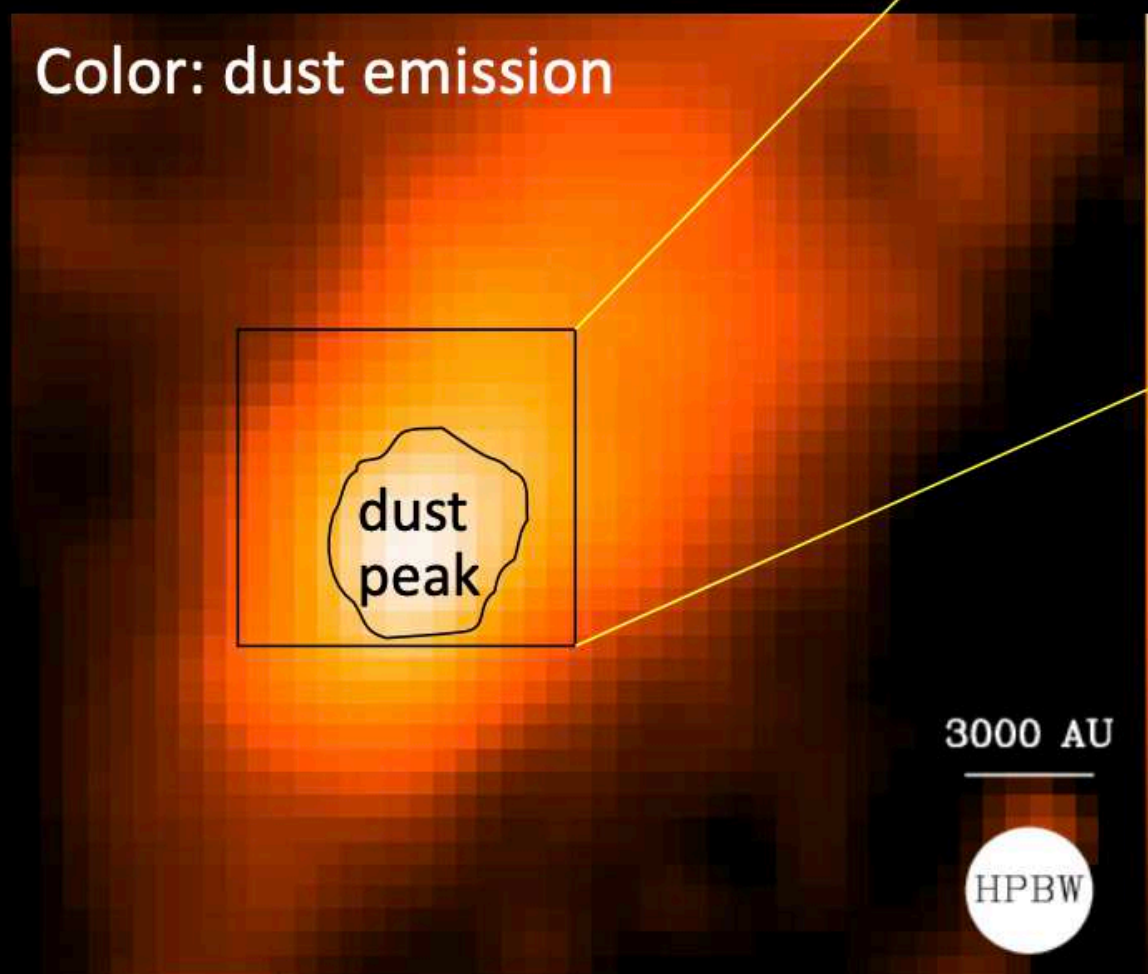
*Flower et al. 2006; Hily-Blant et al. 2010*



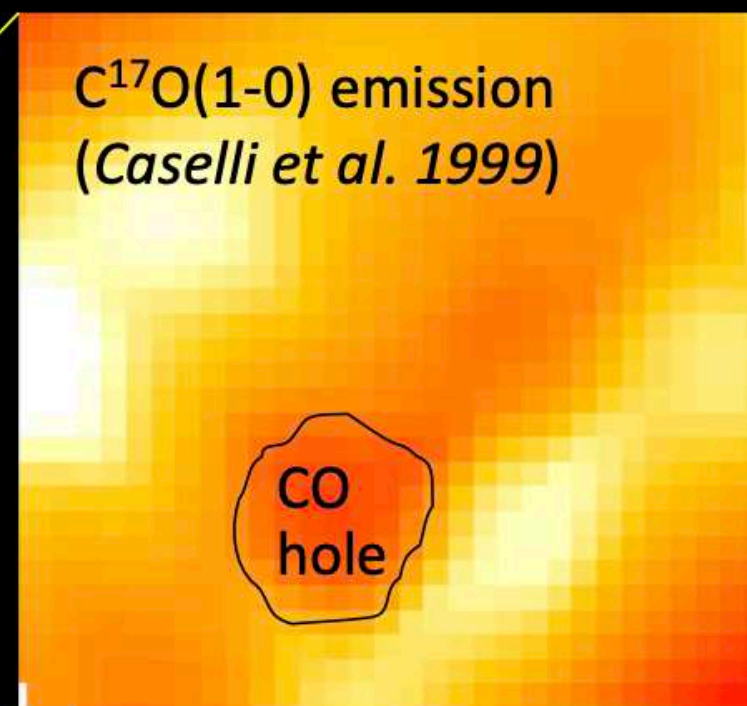
# How deuteration works?

“Catastrophic” CO  
freeze-out within the central  
7000 au

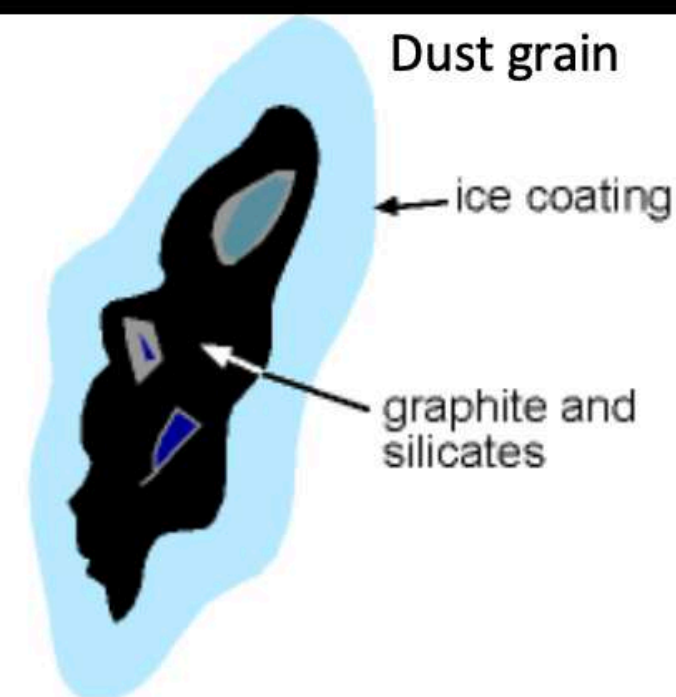
Color: dust emission



$\text{C}^{17}\text{O}(1-0)$  emission  
(Caselli et al. 1999)



Molecules  
freeze out  
onto dust  
grains in the  
center of pre-  
stellar cores

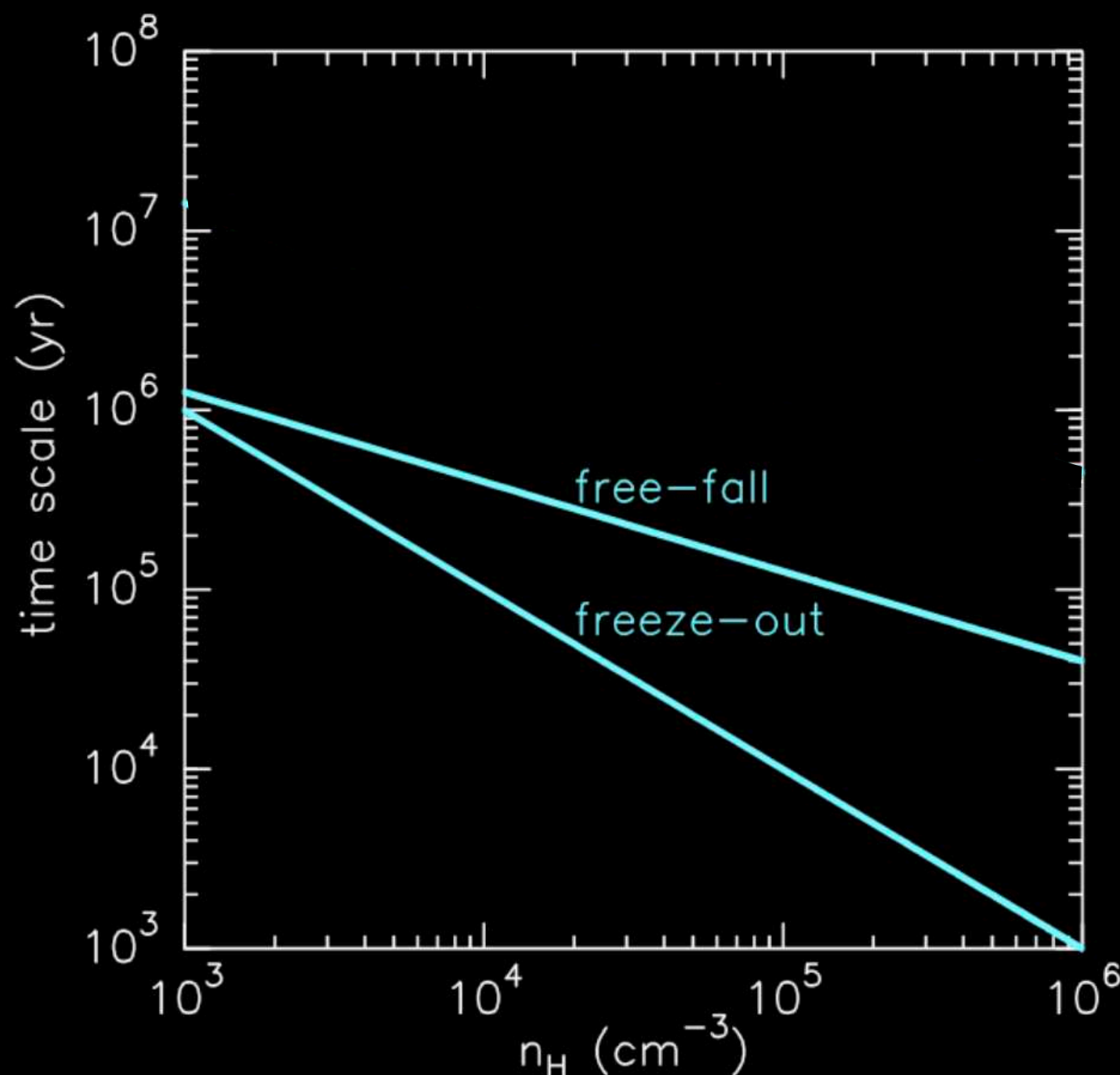


>90% of CO molecules are frozen onto  
dust grains



# How deuteration works?

## Dynamical and freeze-out timescales



The freeze-out timescale decreases very rapidly with density, faster than the gravitational collapse timescale.

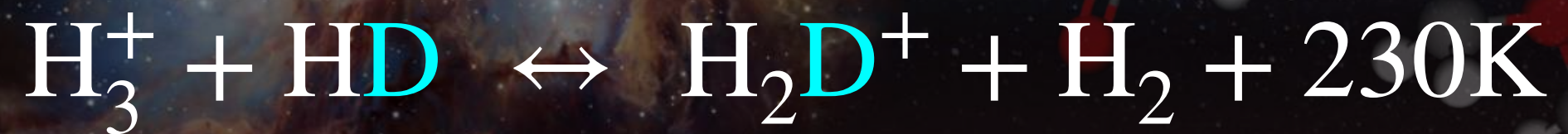
$$t_{\text{free-fall}} = \sqrt{\frac{3\pi}{32G\rho}}$$
$$\approx 4 \times 10^7 / \sqrt{n_H} \text{ yr}$$

$$t_{\text{freeze-out}} = \frac{1}{\alpha n_d \pi a_d^2 v_t}$$
$$\approx 10^9 / n_H \text{ yr}$$

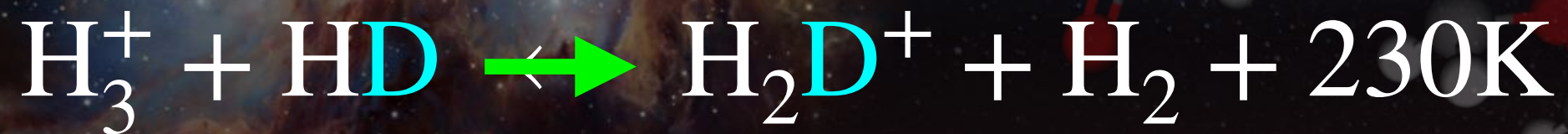
CO is removed from the gas phase, the chemistry changes, and deuterated species are enhanced

Shu, Adams & Lizano 1987; Walmsley 1991; Bergin & Tafalla (2007)

# How deuteration works?

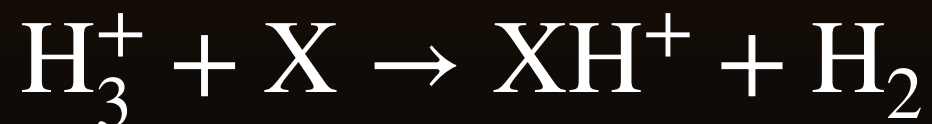


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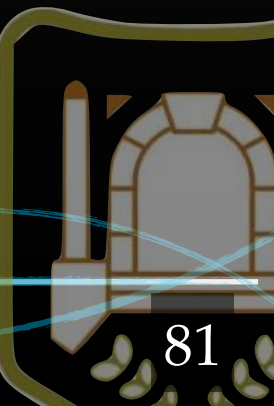
1. If  $T < 20\text{ K}$

2. If CO depletes

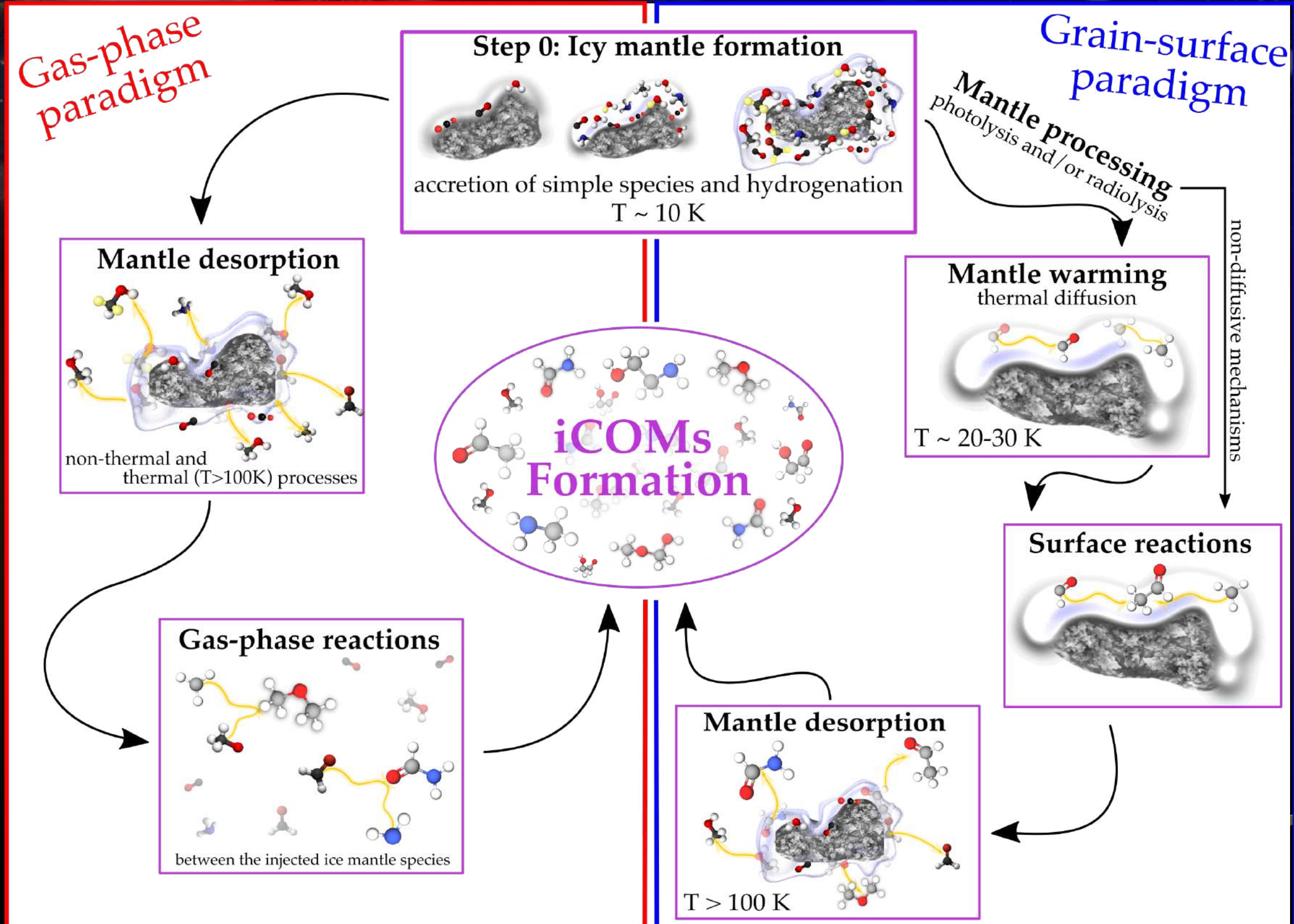


*These conditions are typical in dense and cold cores.*

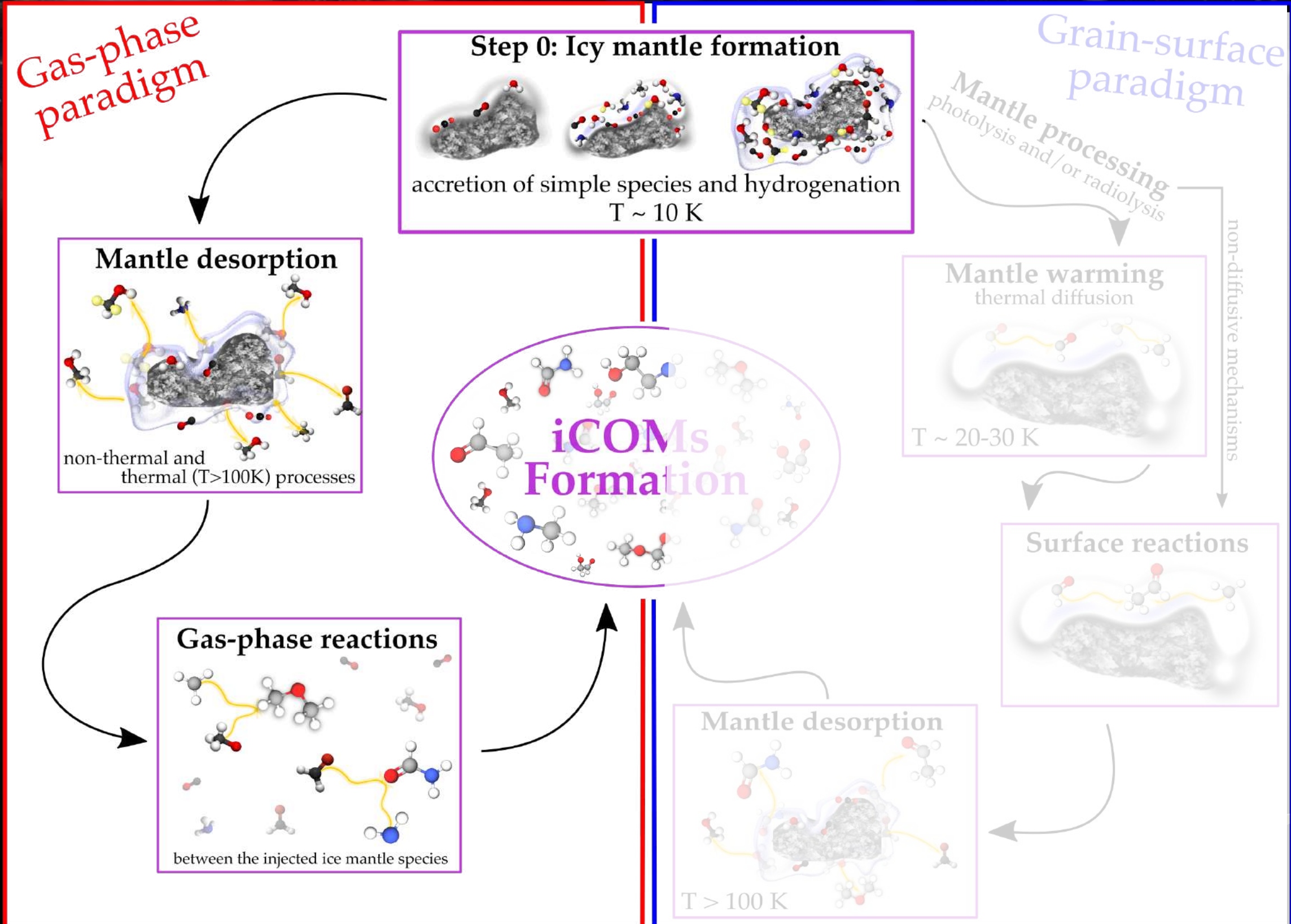
*$\text{XD}^+/\text{XH}^+$  are order of magnitude larger than the elemental interstellar  $\text{D}/\text{H}$*



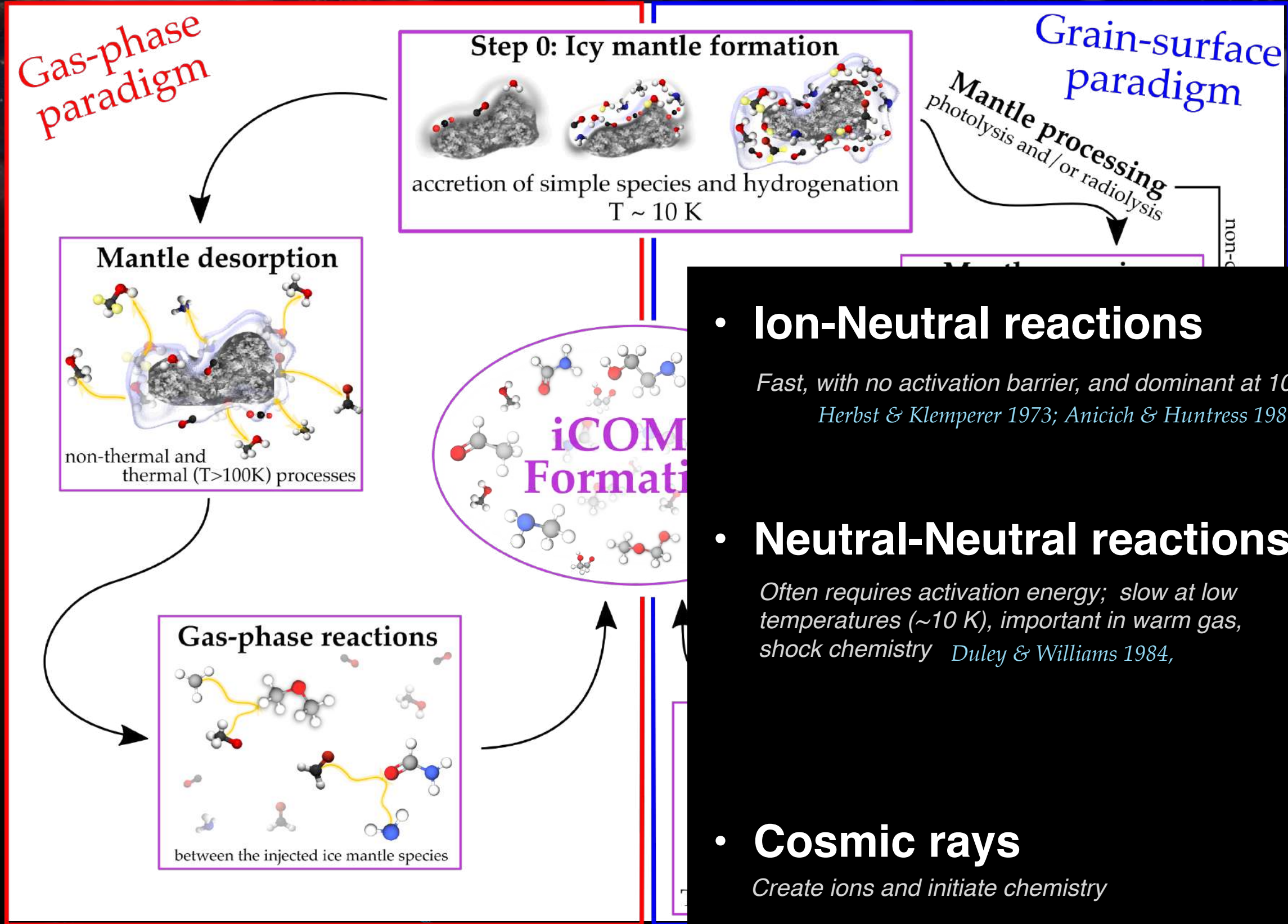
# How can we form iCOMs in the ISM?



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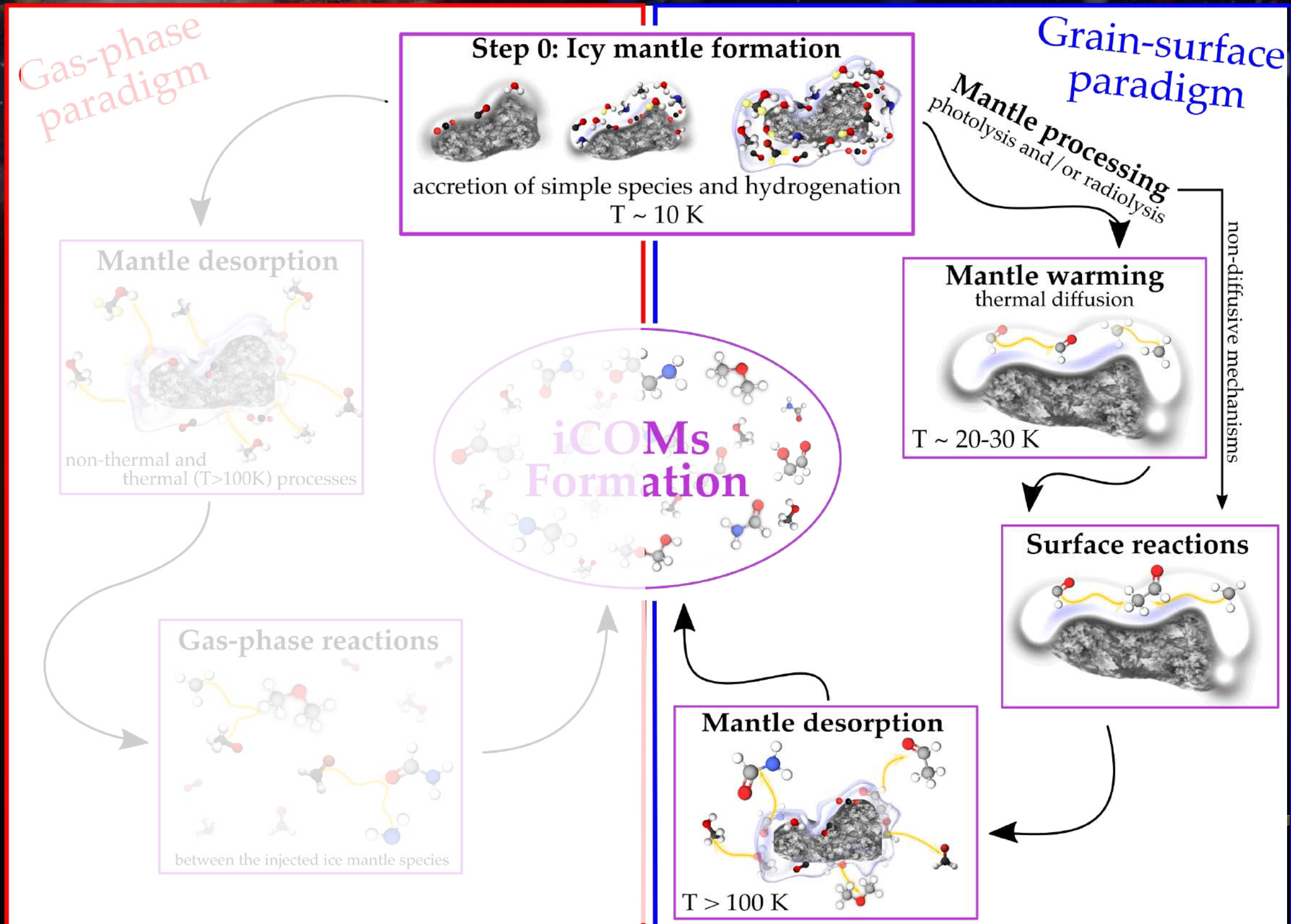
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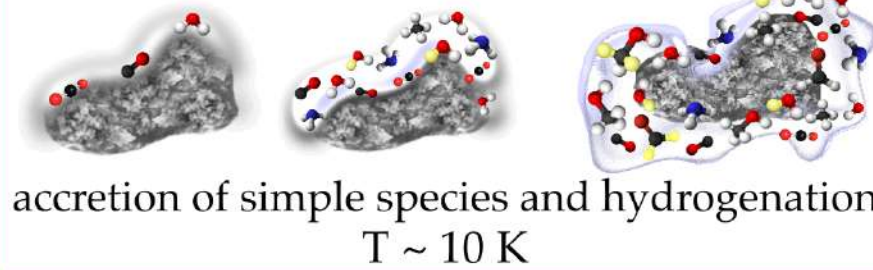
# How can we form iCOMs in the ISM?



# How can we form molecules in the ISM?

Gas-phase  
paradigm

Step 0: Icy mantle formation



Grain-surface  
paradigm

Mantle processing  
photolysis and/or radiolysis

Mantle warming  
thermal diffusion

$T \sim 20\text{-}30 \text{ K}$

non-diffusive mechanisms

Surface reactions

Mantle desorption

$T > 100 \text{ K}$

Langmuir-Hinshelwood

Hot-Atom

Eley-Rideal

Adsorption from  
gas phase

Diffusion via  
thermal  
hopping  
( $E_{\text{dif}}$ )

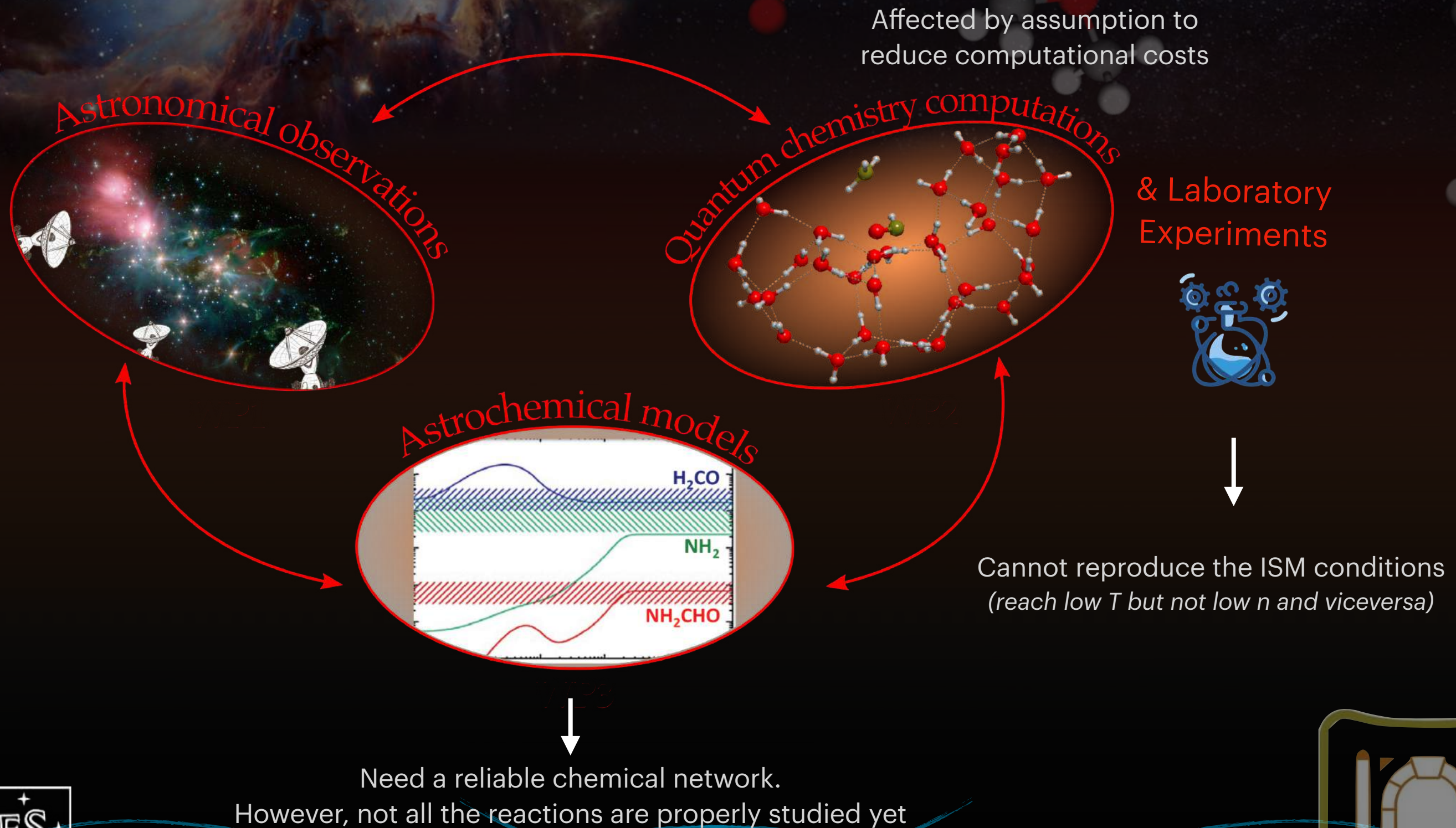
Reaction

Thermal  
desorption  
( $E_{\text{des}}$ )

Ice surface

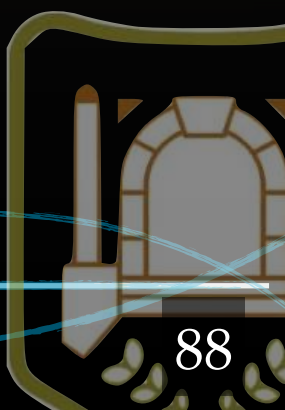
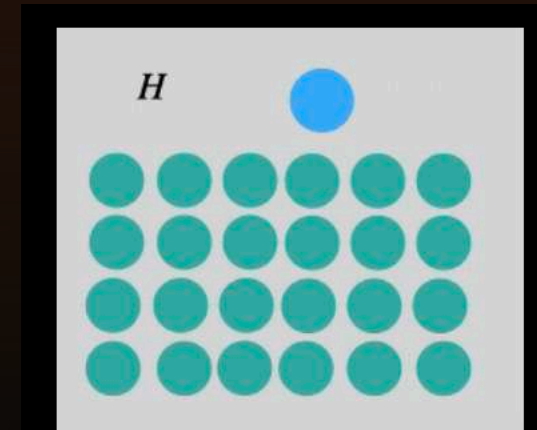
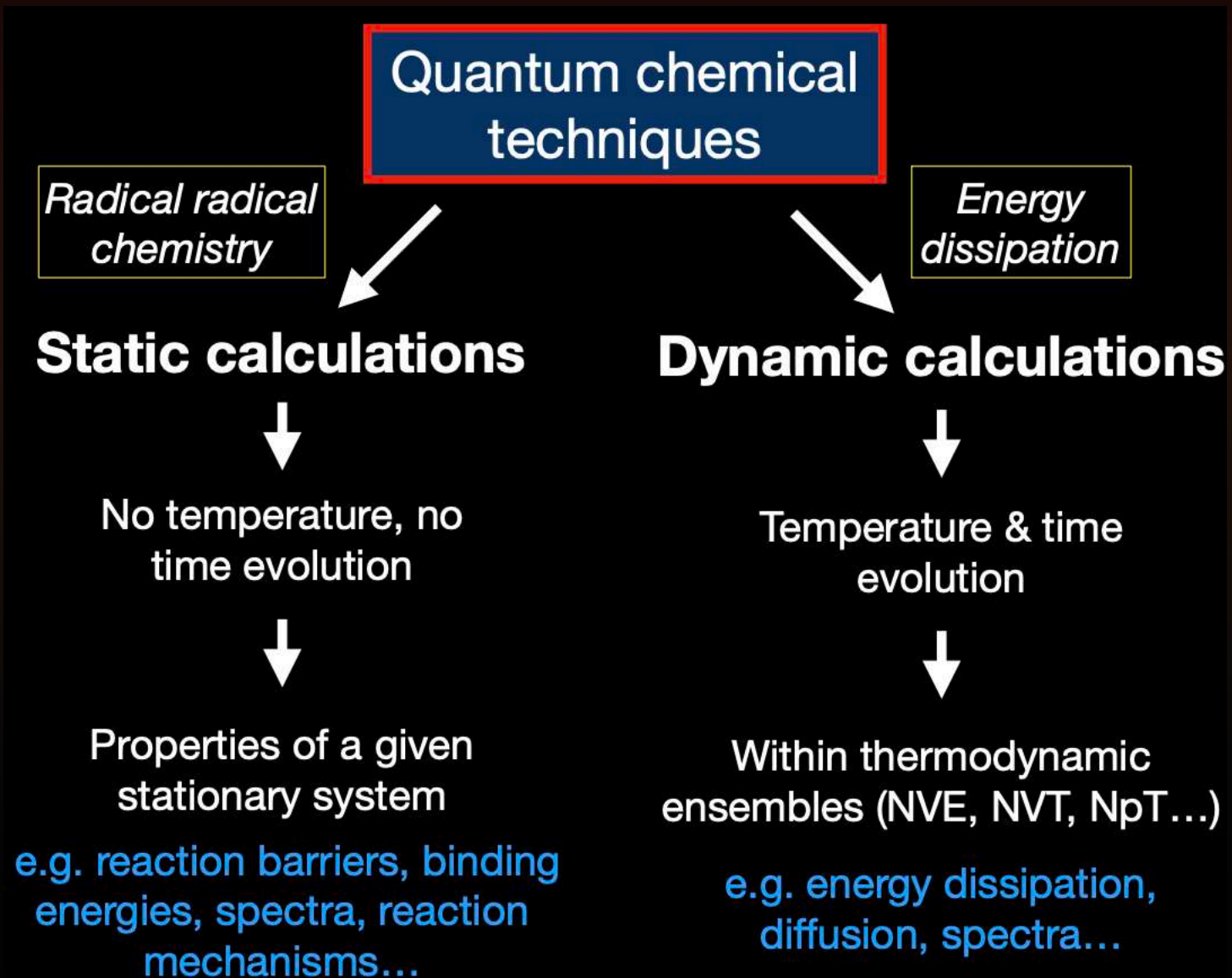
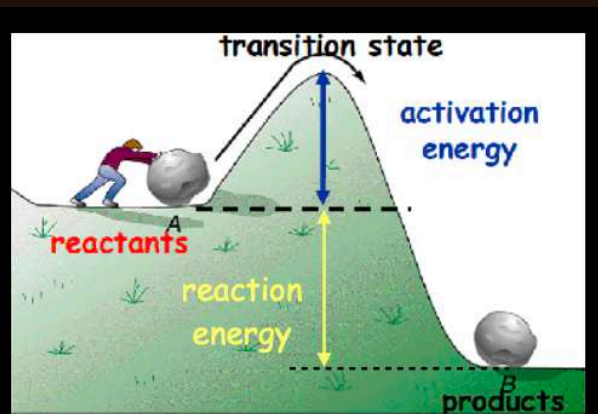


# How to constrain iCOMs formation routes?



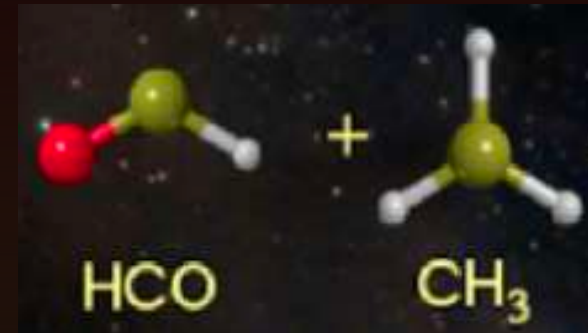
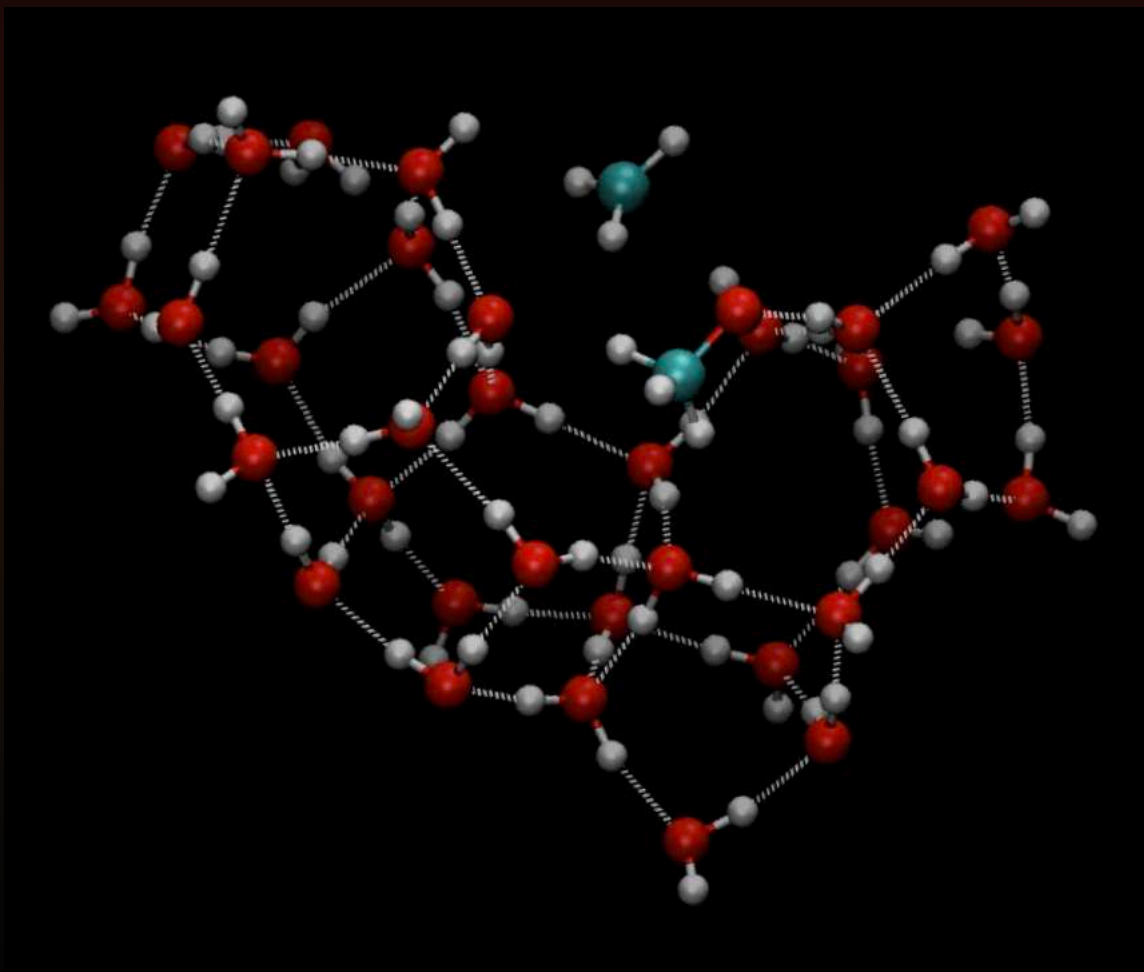
# The role of computational chemistry and laboratory

- Study reaction network/pathways and rate coefficients
- Retrieve binding energy values/distribution
- Study Chemical/reactive desorption



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- Study reaction network/pathways and rate coefficients
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Form acetaldehyde - formamide?  
(CH<sub>3</sub>CHO - NH<sub>2</sub>CHO)  
Not necessarily....

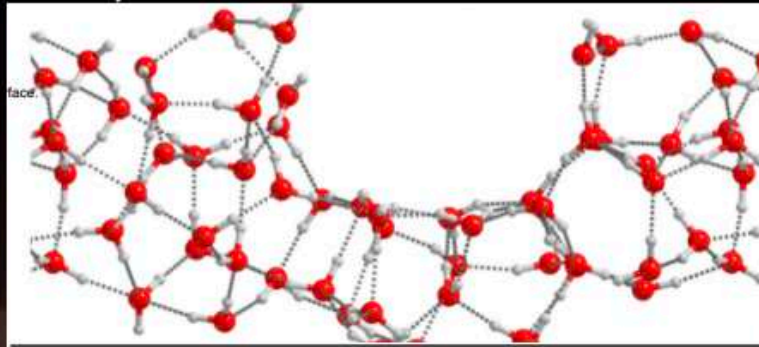
*Some radical-radical reactions have  
competitive channels*

*e.g., Enrique-Romero et al. 2019, 2021, 2022*

# The role of computational chemistry and laboratory

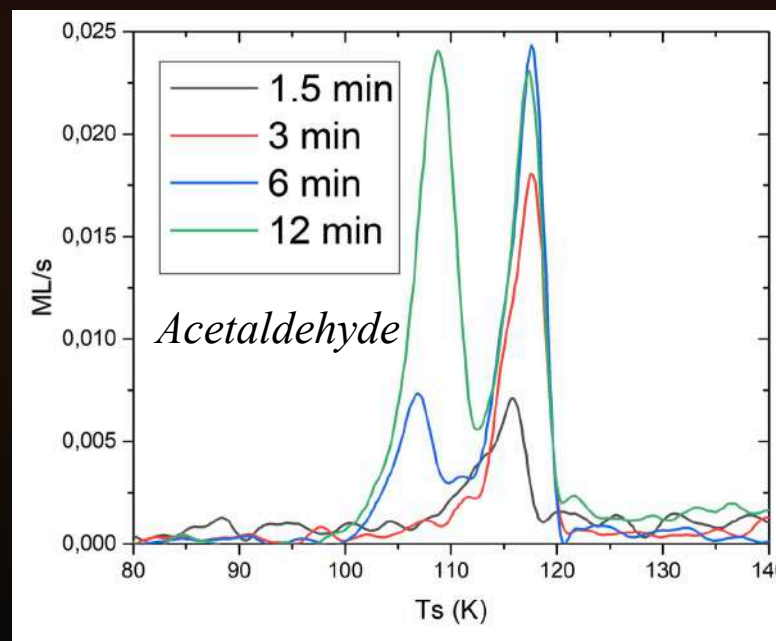
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molecular BE computed  
with periodic surface models of water

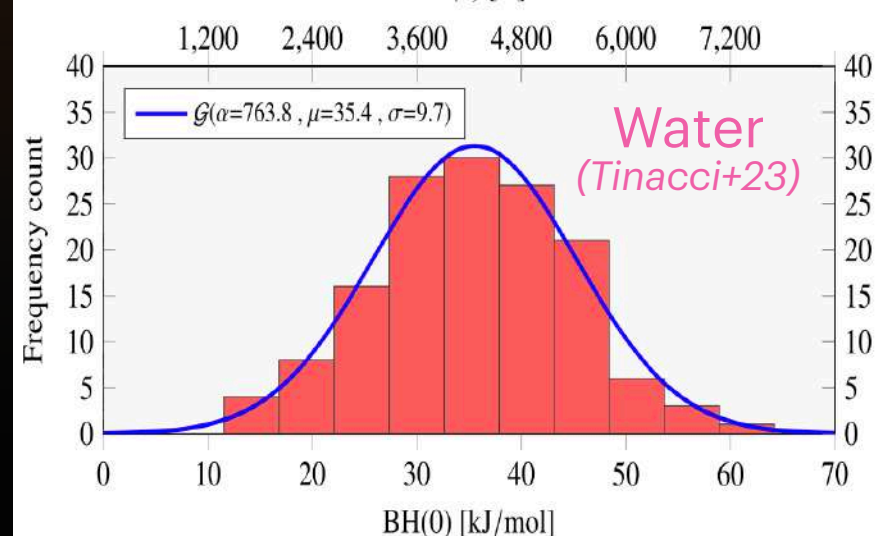
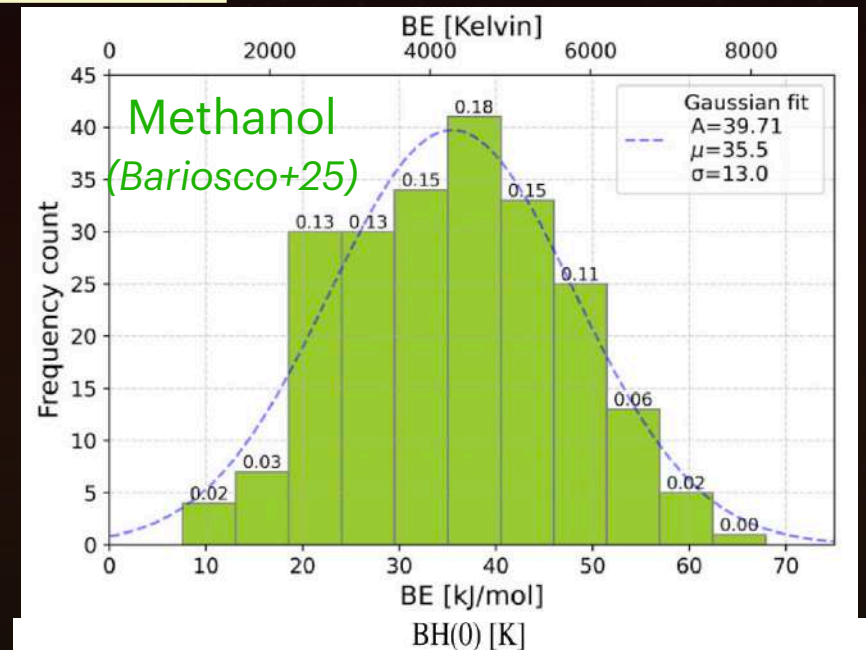


| Species             | Binding Energy (K) | $T_{\text{sub}}$ (K) |
|---------------------|--------------------|----------------------|
| CH <sub>3</sub> CHO | 2809-6038(4423)    | 48-102(75)           |
| H <sub>2</sub> CO   | 3071-6194(4632)    | 52-104(78)           |
| HNCO                | 2400-8400(4800)    | 41-140(81)           |
| CH <sub>3</sub> OH  | 3770-8618(6194)    | 64-144(104)          |
| HCOOH               | 5382-10559(7970)   | 91-176(133)          |
| NH <sub>2</sub> CHO | 5793-10960(8376)   | 97-183(140)          |
| NH <sub>3</sub>     | 4314-7549(5931)    | 73-126(100)          |
| H <sub>2</sub> O    | 3605-6111(4858)    | 61-103(82)           |

molecule BE depends on its structure  
and on the binding site on the ices



Temperature Programmed Desorption  
*Ferrero et al. 2022*

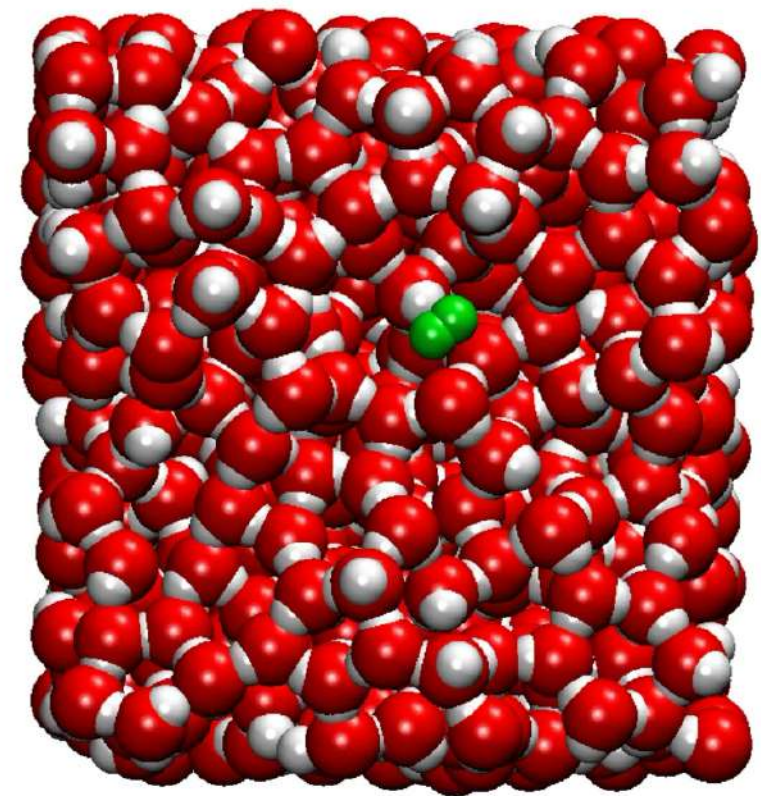
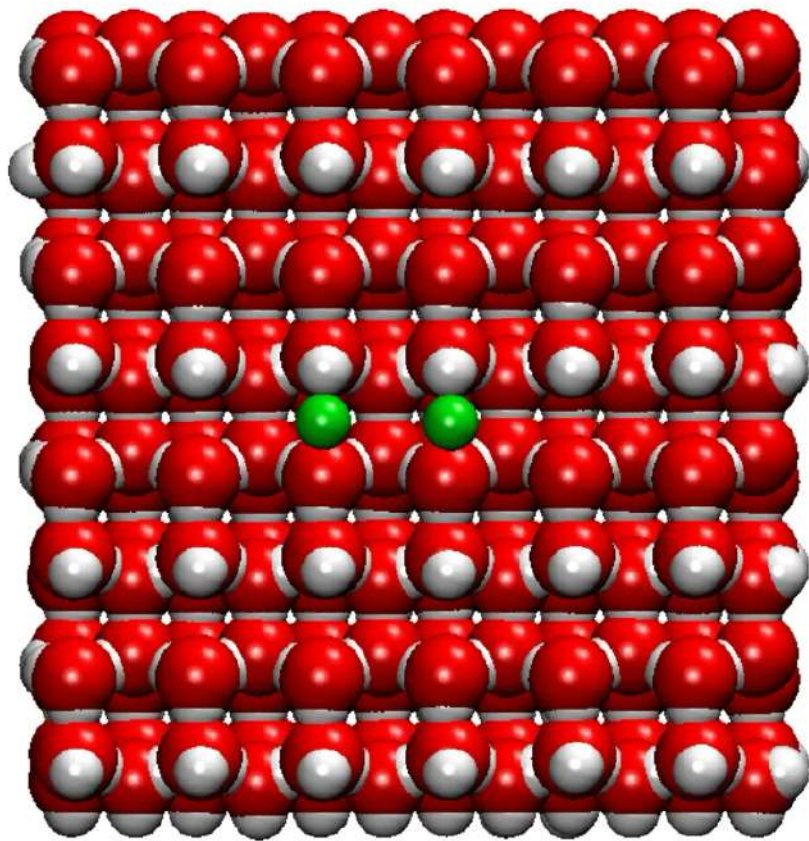


See also Perrero et al. 2022, Molpeceres et al. 2022, Tinacci et al. 2023, Bariosco et al. 2024, Kakkan et al. 2025

# The role of computational chemistry and laboratory

- Study reaction network/pathways and rate coefficients
- Retrieve binding energy values/distribution
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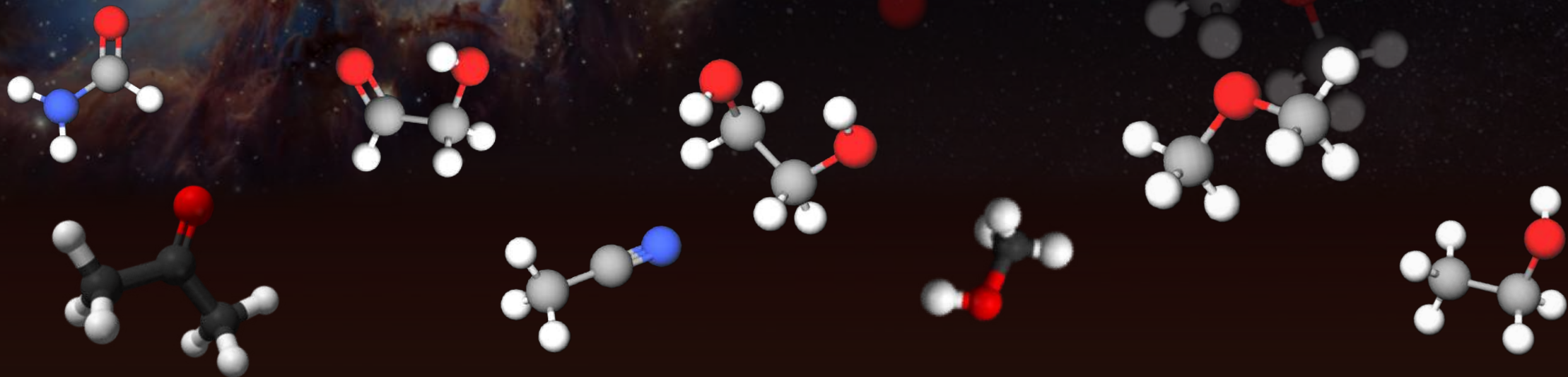
*Pantaleone et al. 2020*



*See also Martin-Doménech et al. 2016; Minissale et al. 2016; Chuang et al. 2018; Enrique-Romero et al. 2020*

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How and where do we observe these molecules?

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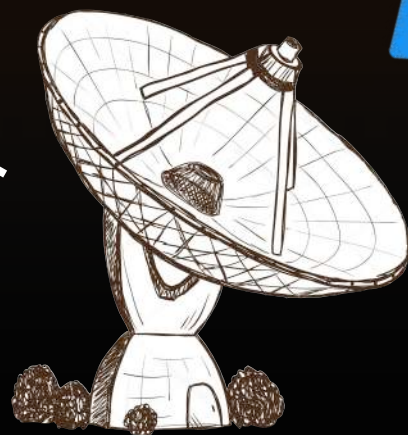
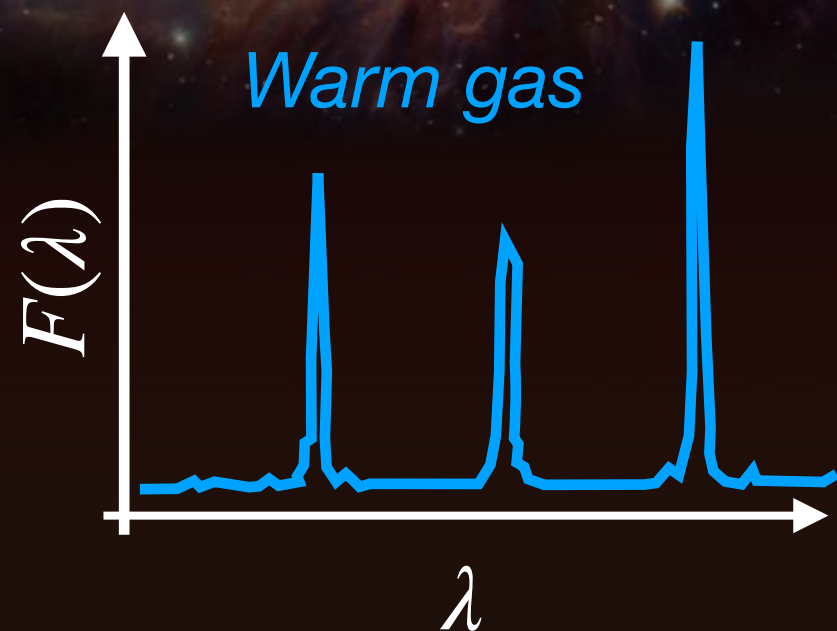
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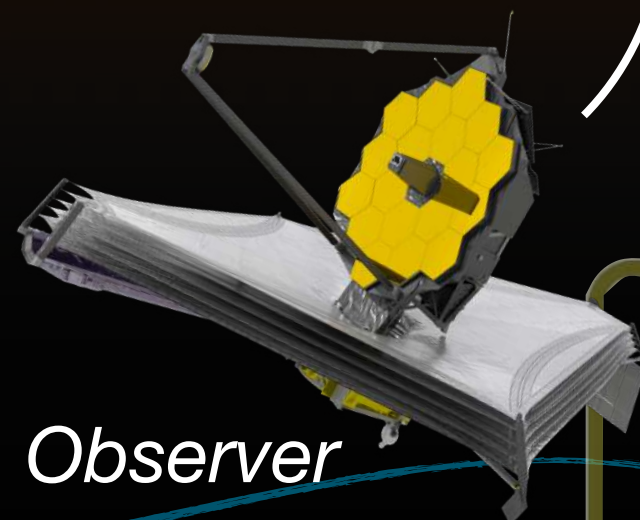
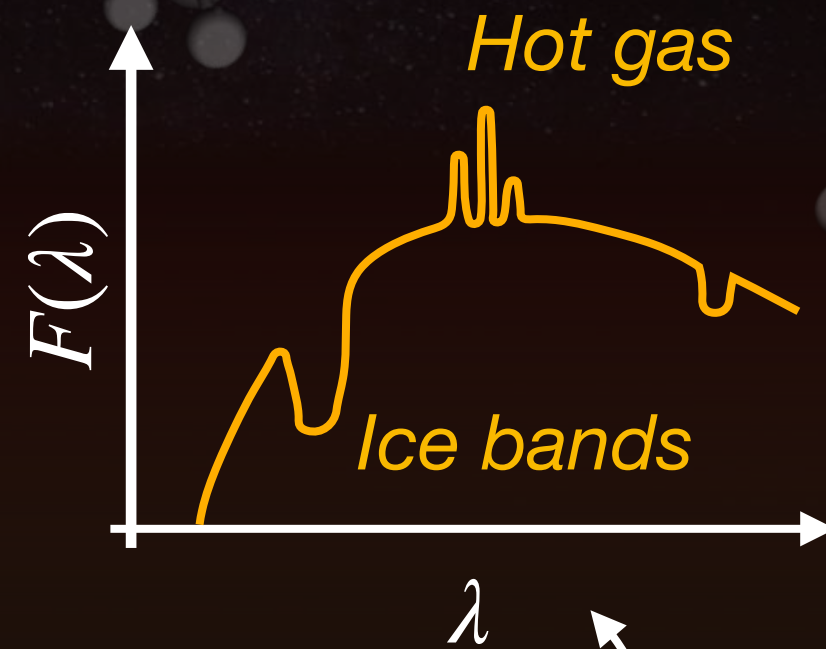
# How can we observe molecules?

Gas phase molecules are studied in emission



Observer

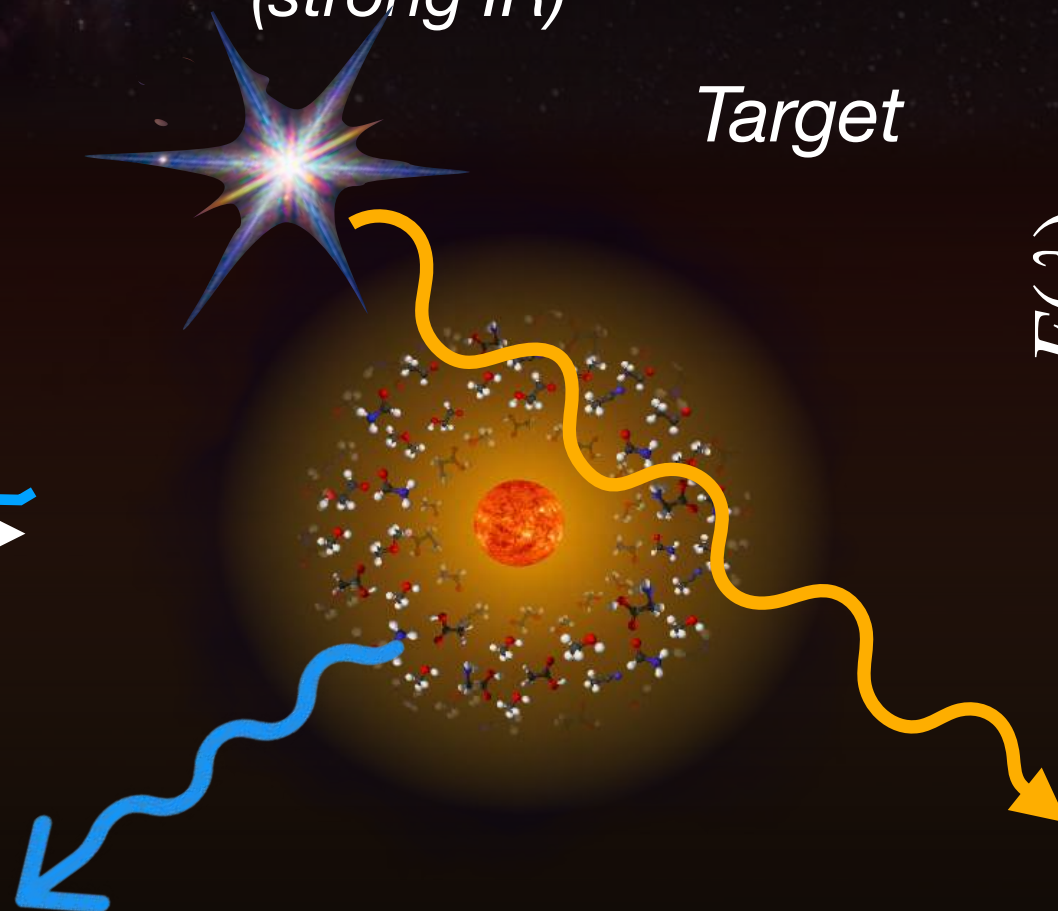
Solid state (ice) molecules are studied in absorption



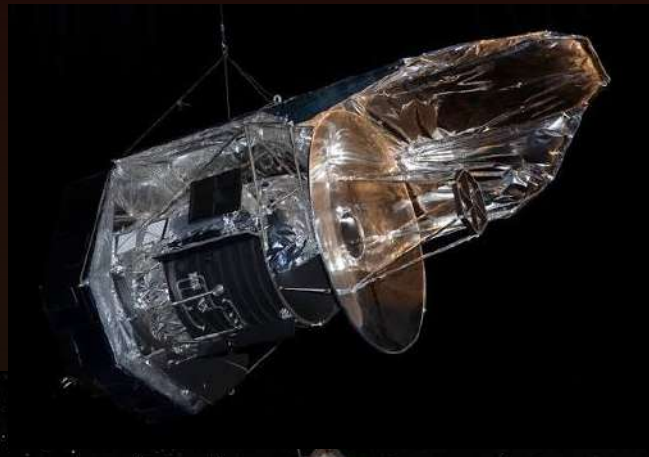
Observer

Background star  
(strong IR)

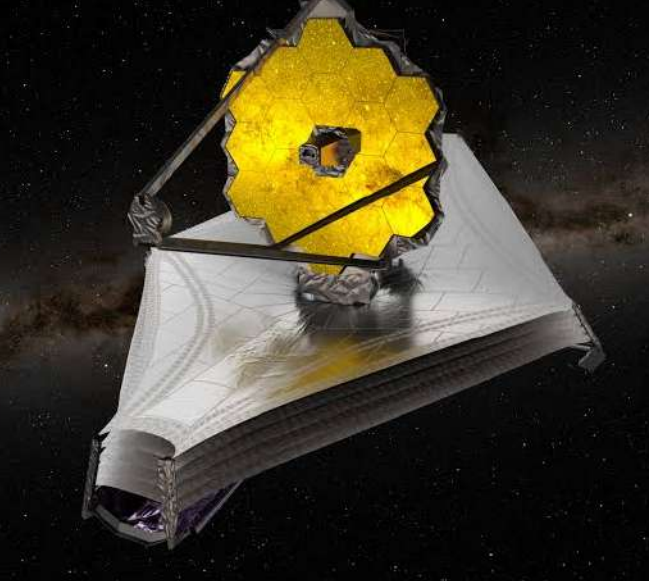
Target



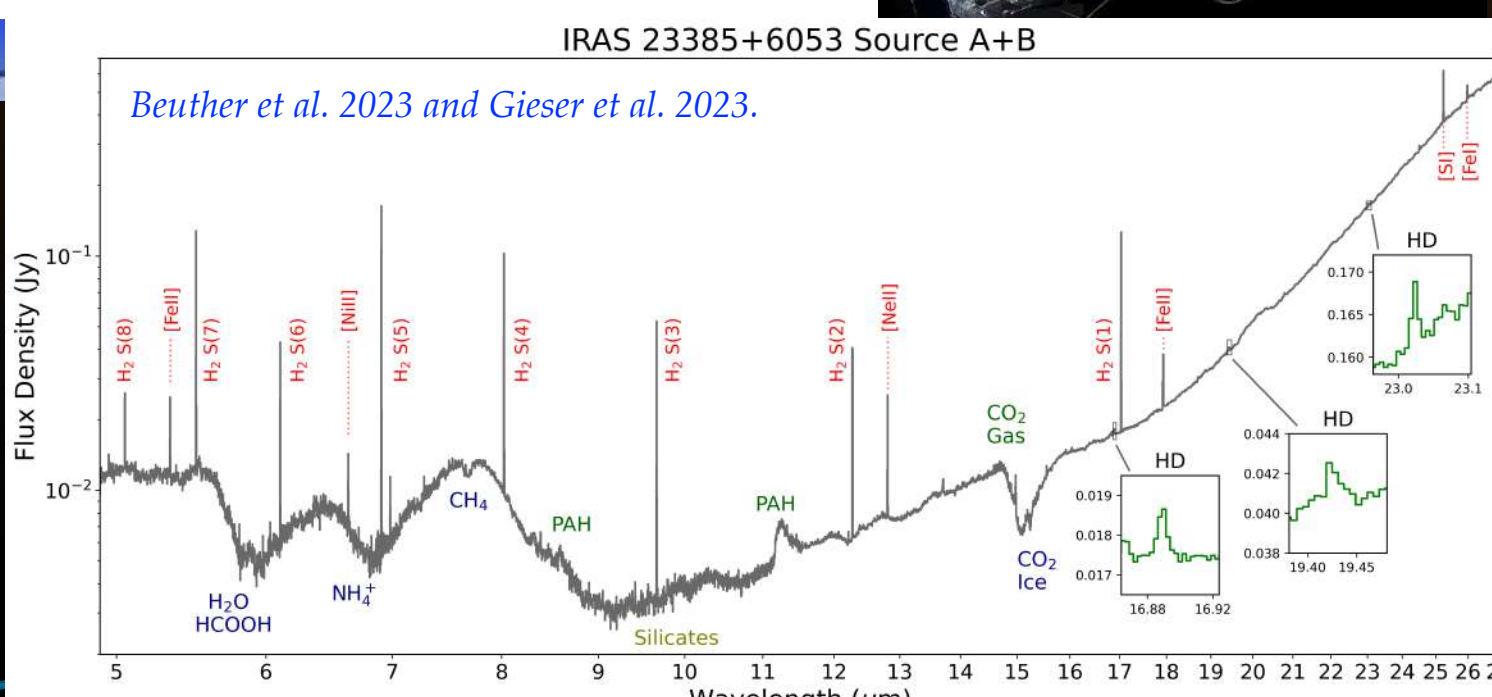
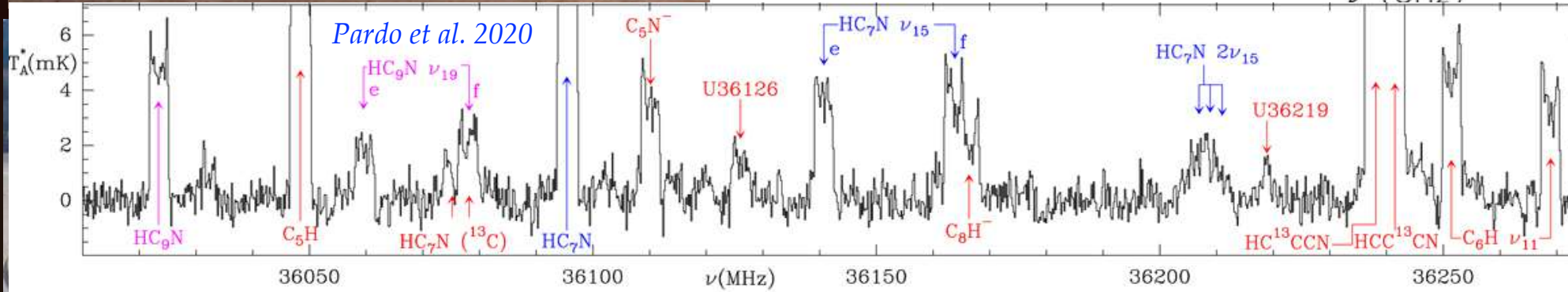
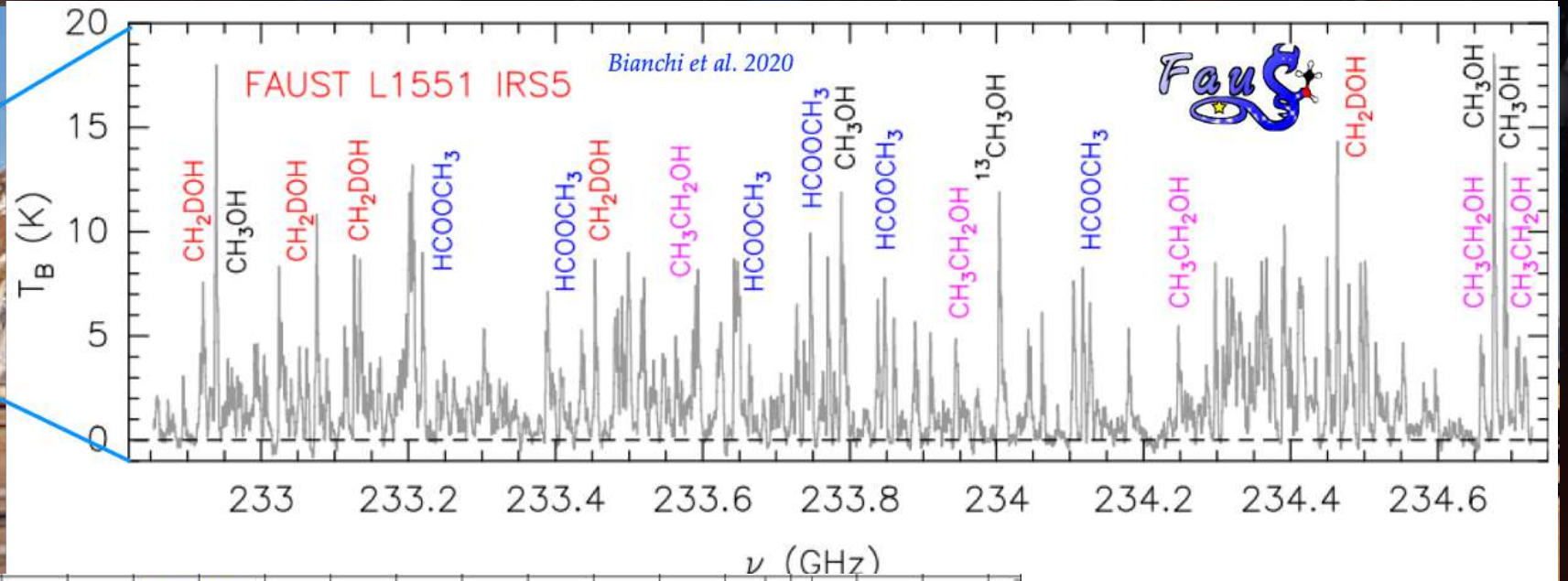
# How can we observe molecules?



*IR - mm - cm  
facilities*

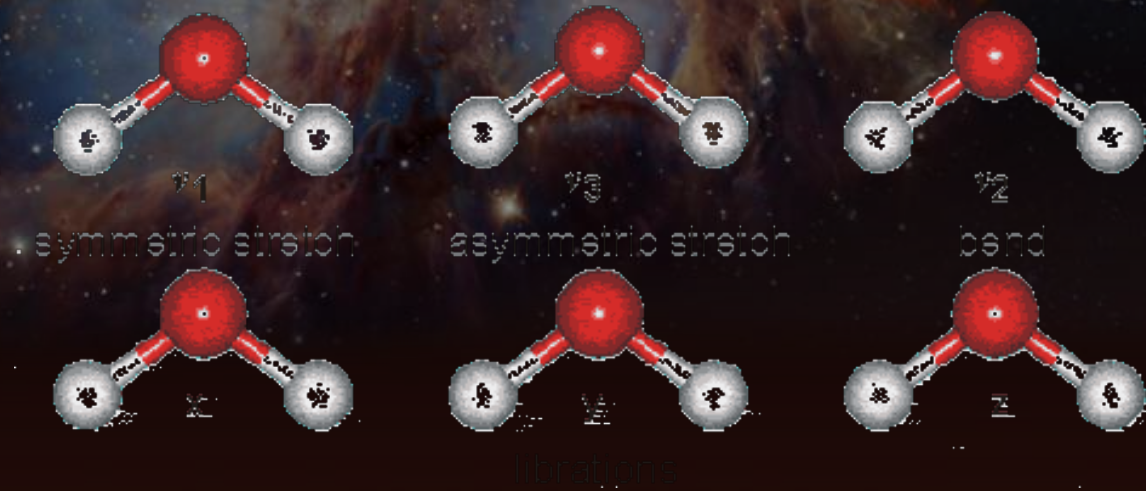


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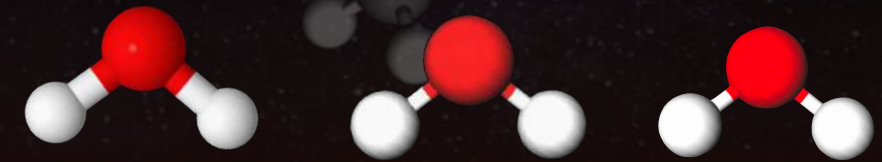


# How can we observe (gas phase) molecules?

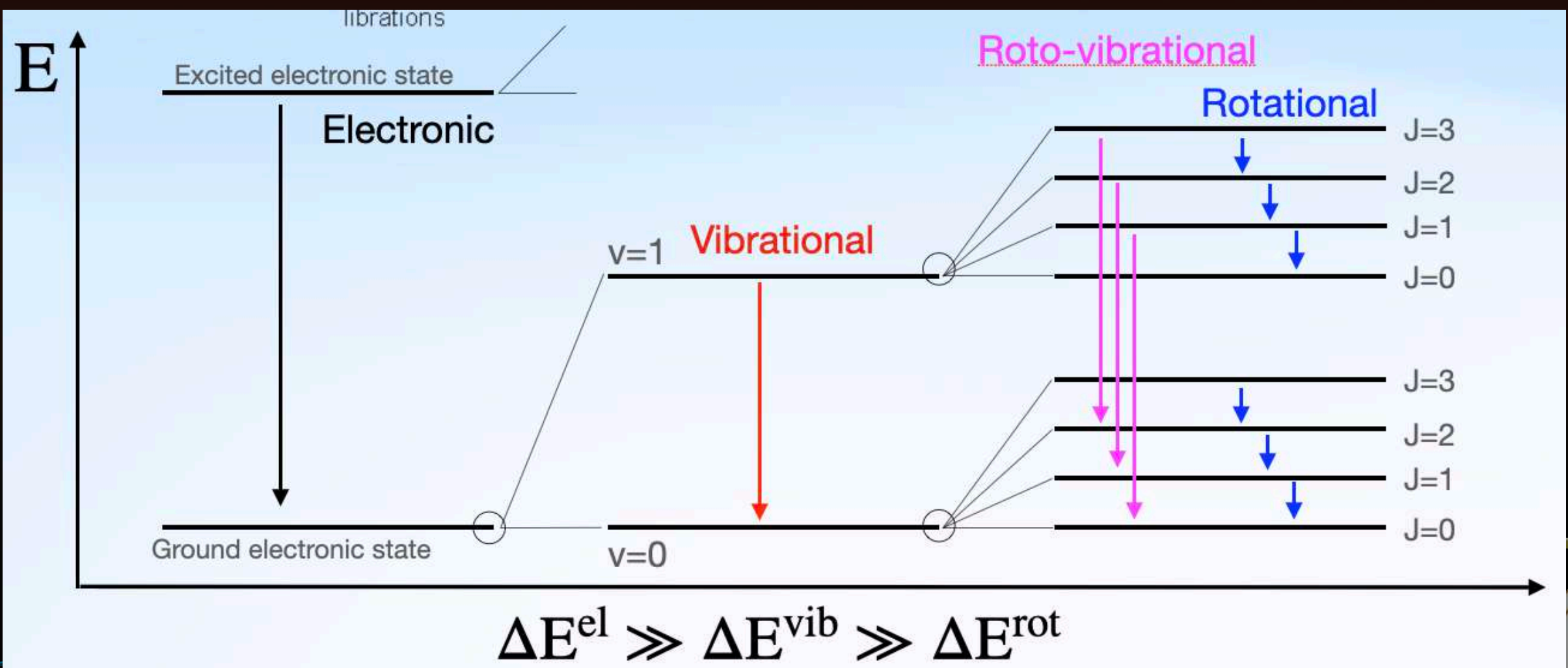
Vibrational modes



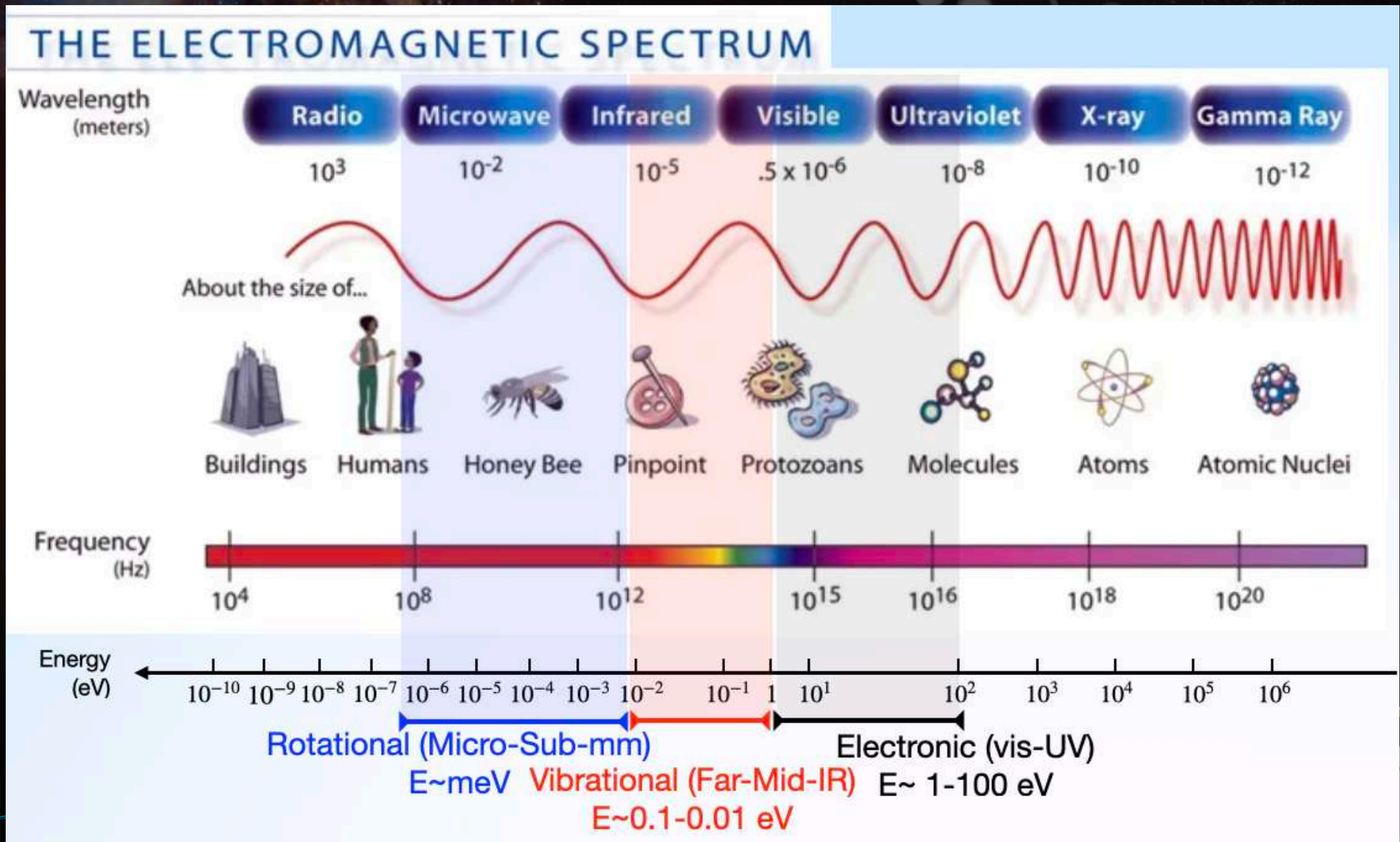
$$E = E^{\text{el}} + E^{\text{vib}} + E^{\text{rot}}$$



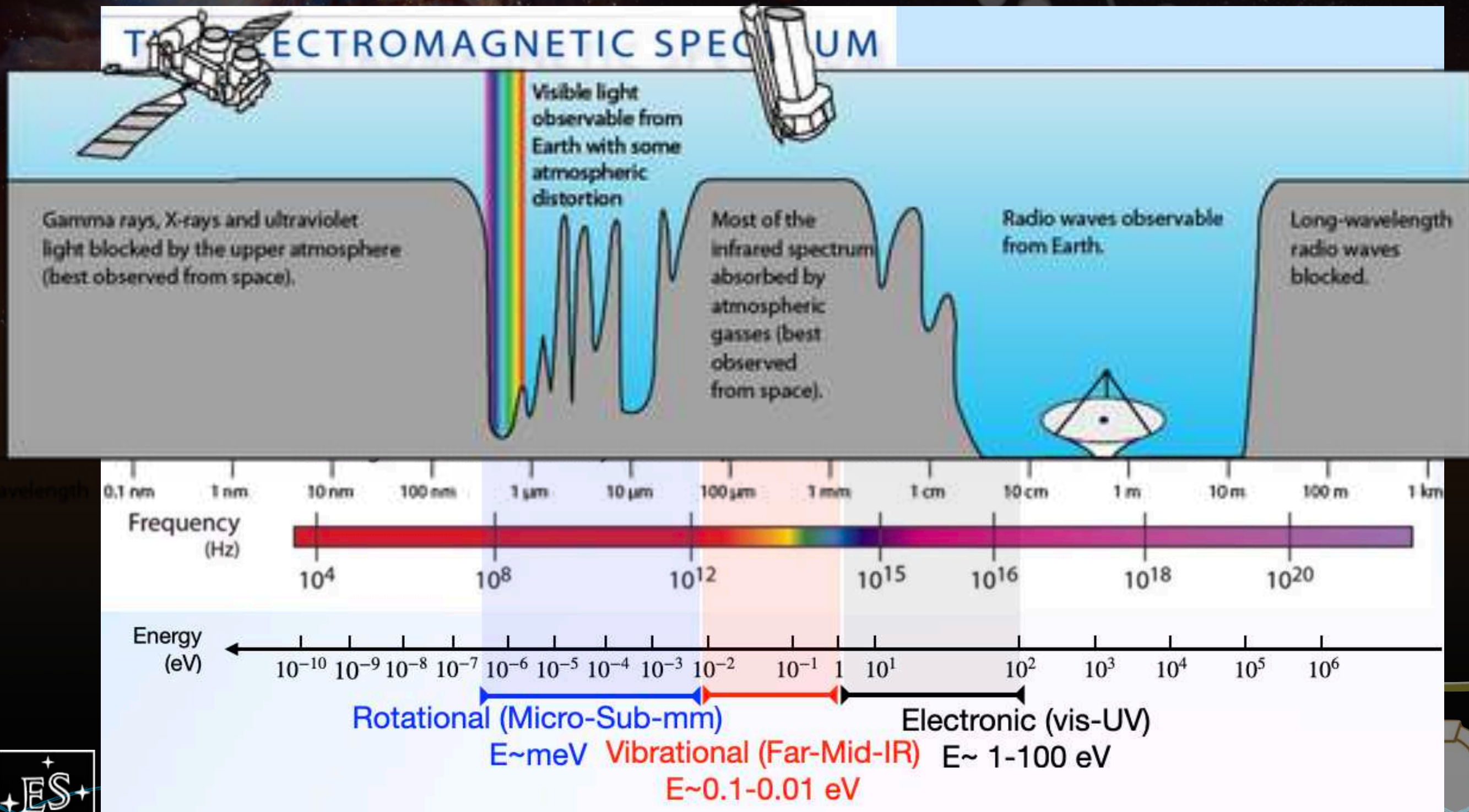
Rotational modes



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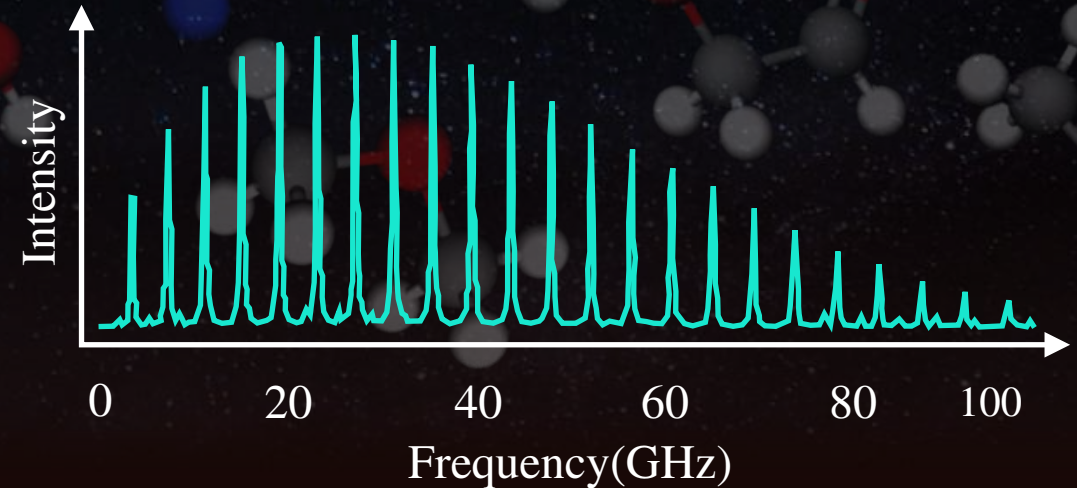


Permitted transitions following the quantum mechanic rules

$$H\Psi = E\Psi$$

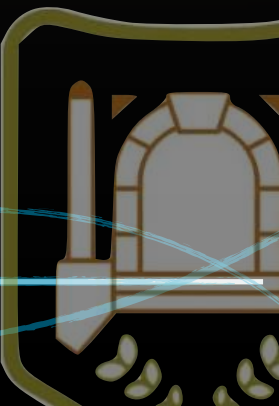
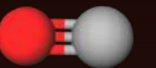
In the case of Rotational transitions →

$$\Delta E(J+1 \leftarrow J) = 2B(J+1)$$

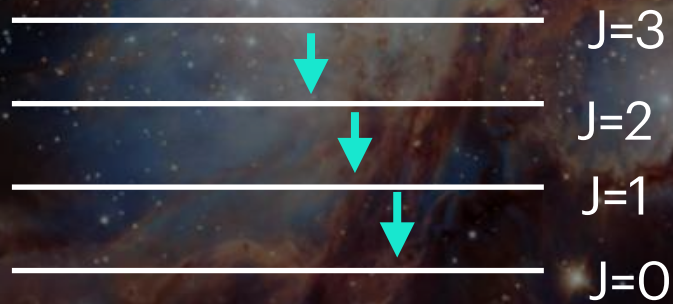


In the case of diatomic linear molecule →

$$\Delta J = \pm 1$$

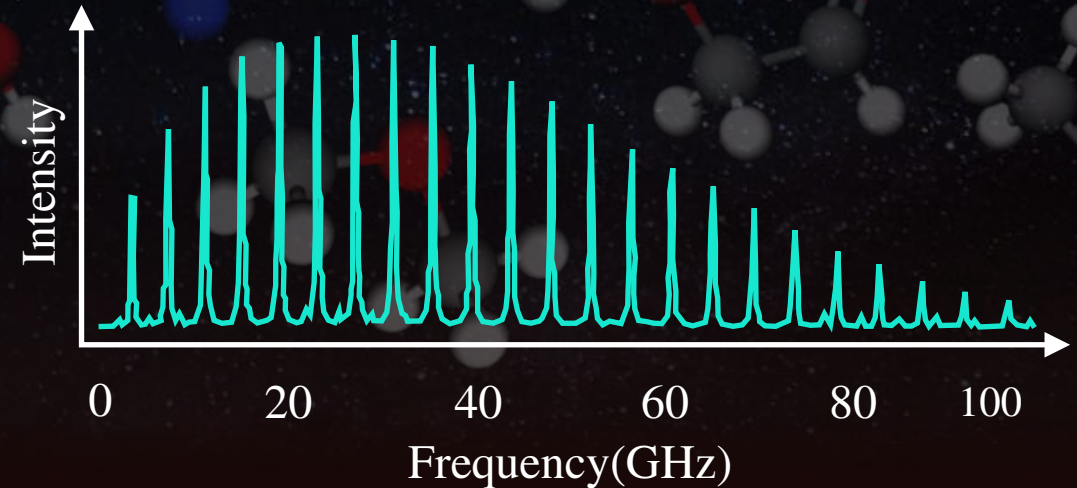


# How can we observe (gas phase) molecules?



Permitted transitions following the quantum mechanic rules

$$H\Psi = E\Psi$$



In the case of Rotational transitions →

$$\Delta E(J+1 \leftarrow J) = 2B(J+1)$$

In the case of diatomic linear molecule →

$$\Delta J = \pm 1$$

$$B = \frac{h}{8\pi^2 c I}$$

Rotational constant

$$I = \mu r^2$$

Separation

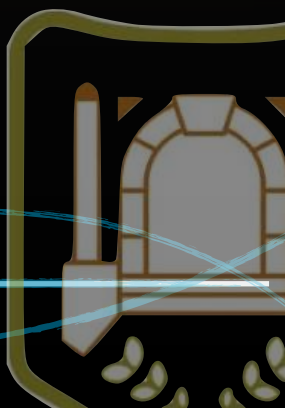
$$\mu = \frac{m_1 m_2}{m_1 + m_2}$$

Atomic Masses

$$I \propto |\langle \mu \rangle|^2$$

Dipole moment

The rotational frequency of a molecule are “just” determined by the **masses** and how they are **arranged** in the 3D space

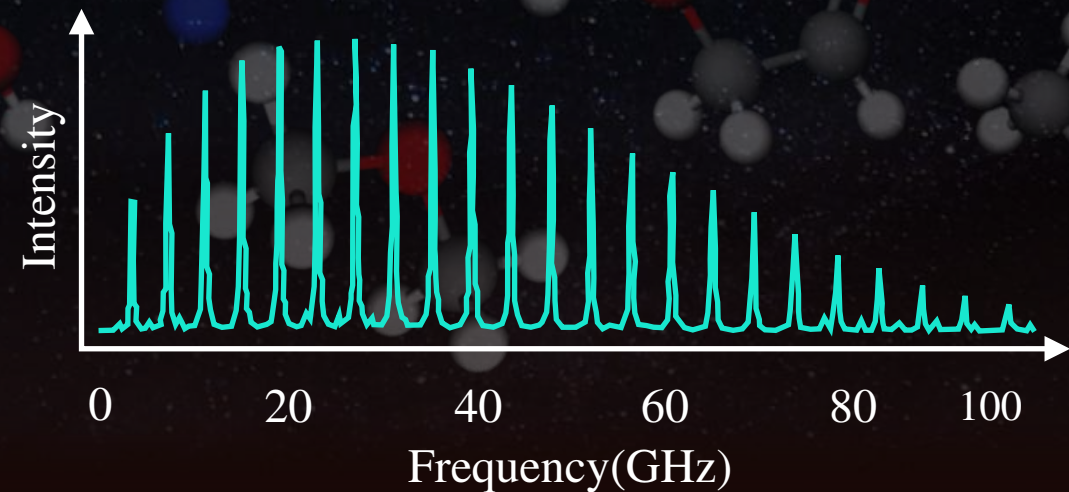


# How can we observe (gas phase) molecules?



Permitted transitions following the quantum mechanic rules

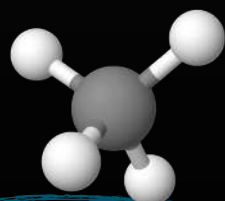
$$H\Psi = E\Psi$$



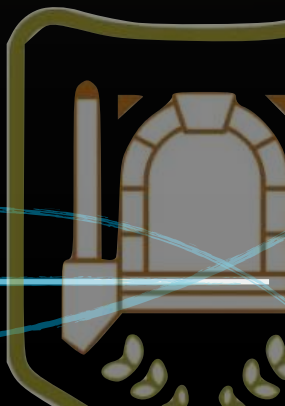
**Each molecule has its own spectrum —> Fingerprint!**  
*More complex is the molecule, more transitions are there and more complex is the spectrum*



*Symmetric (e.g.  $H_2$ ) and Spherical Molecules (e.g.  $CH_4$ ), have **zero** dipole moment —> do not have Rotational transitions!*



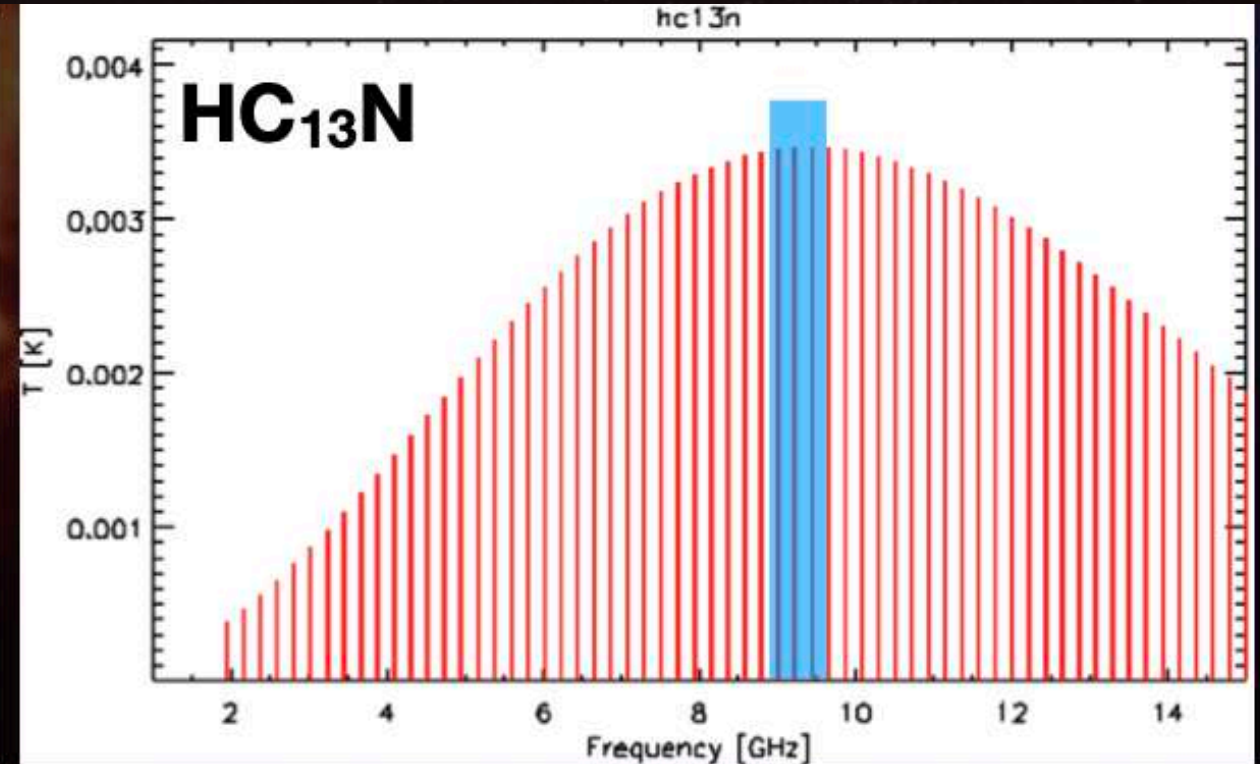
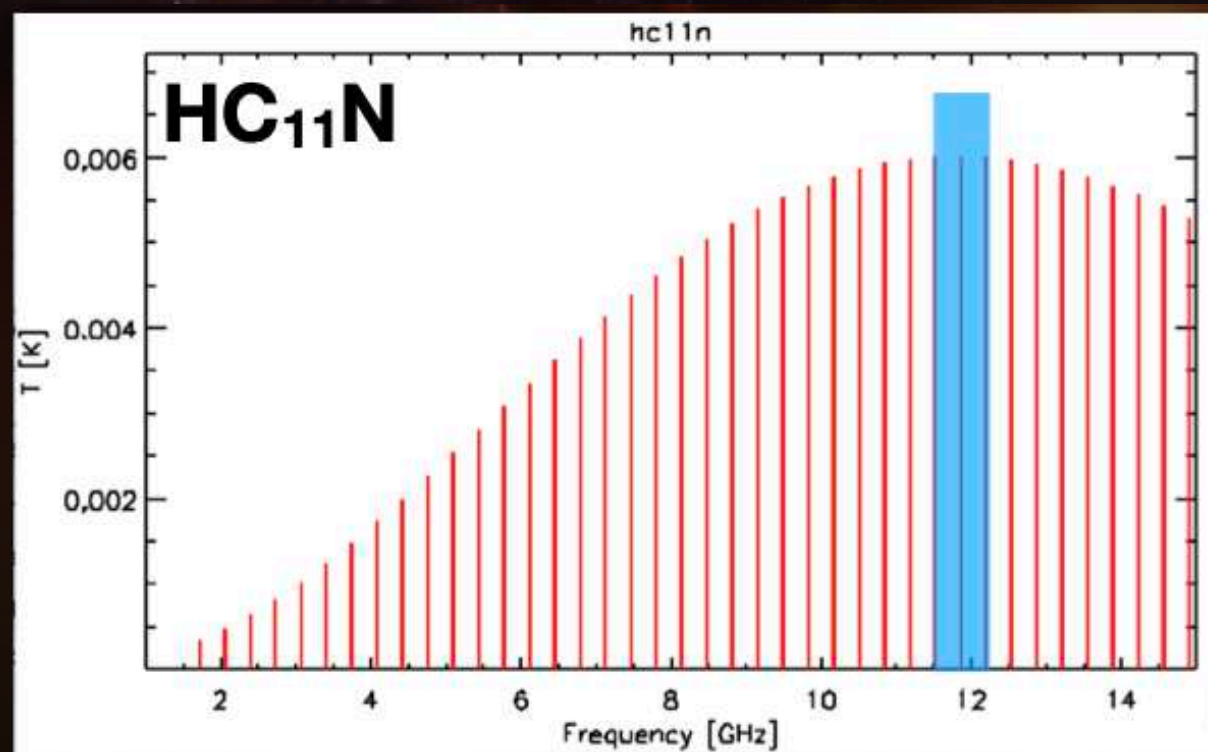
*More complex is the species, more transitions are present*



# How can we observe (gas phase) molecules?

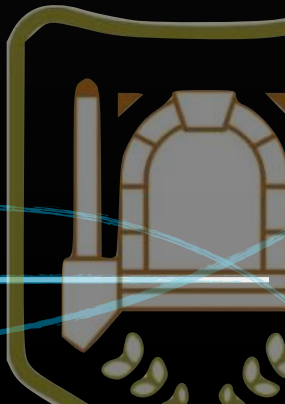
Large molecules peak at lower Frequencies

Predicted LTE spectrum



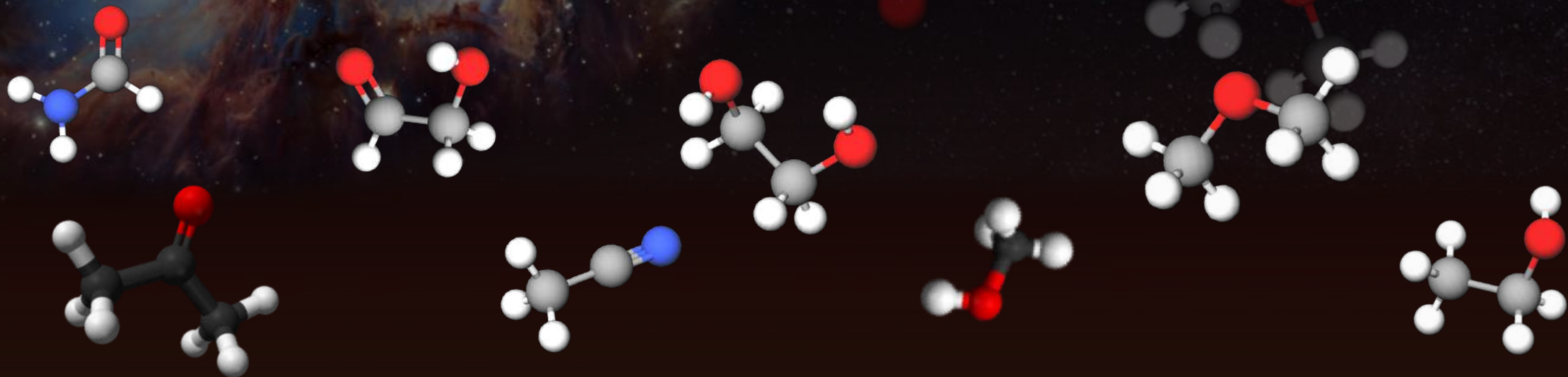
Increasing complexity

*Simple prediction for a pre stellar core with  $T=10$  K,  $N=10^{11} \text{ cm}^{-2}$ ,  $\text{FWHM}=0.2 \text{ km/s}$ , and extended emitting size*



# Detected Interstellar Molecules

## Interstellar Complex Organic Molecules (iCOMs\*)



Organic and **prebiotic** compounds!

How can you form these species in the harsh ISM environment?

How and where do we observe these molecules?

How can we use these species?

\*iCOMs: Saturated C-bearing molecules with more than six atoms and containing heteroatoms

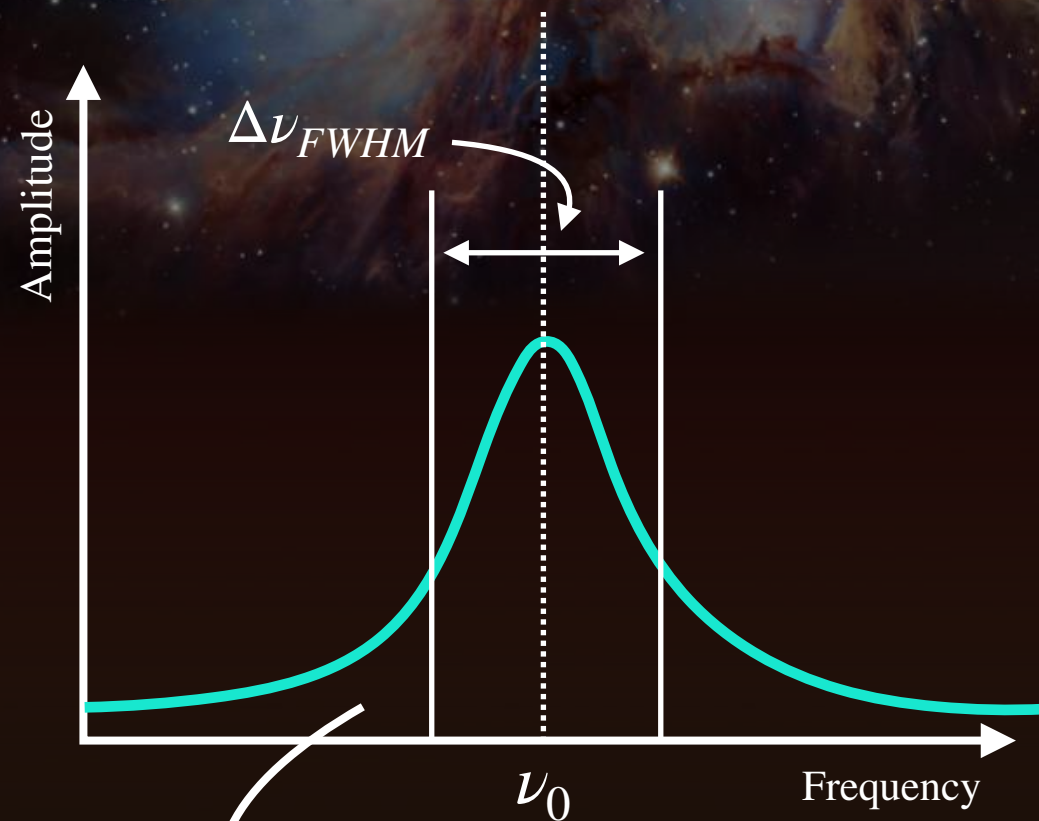
(Herbst & Van Dishoeck 2009, Yamamoto 2017, Ceccarelli et al. 2023)



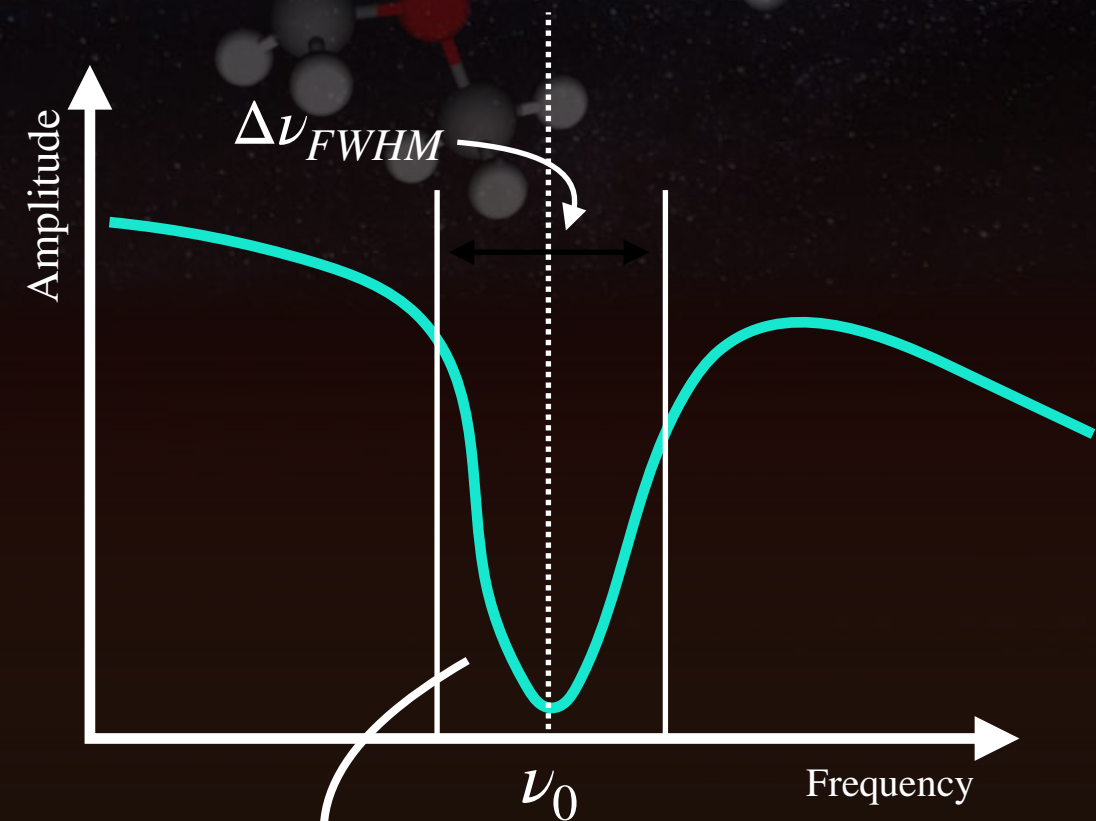
# What the molecular emission tells us?

## Line Profile

From the lines we can get important physical informations.



Line profile gives information on kinematics



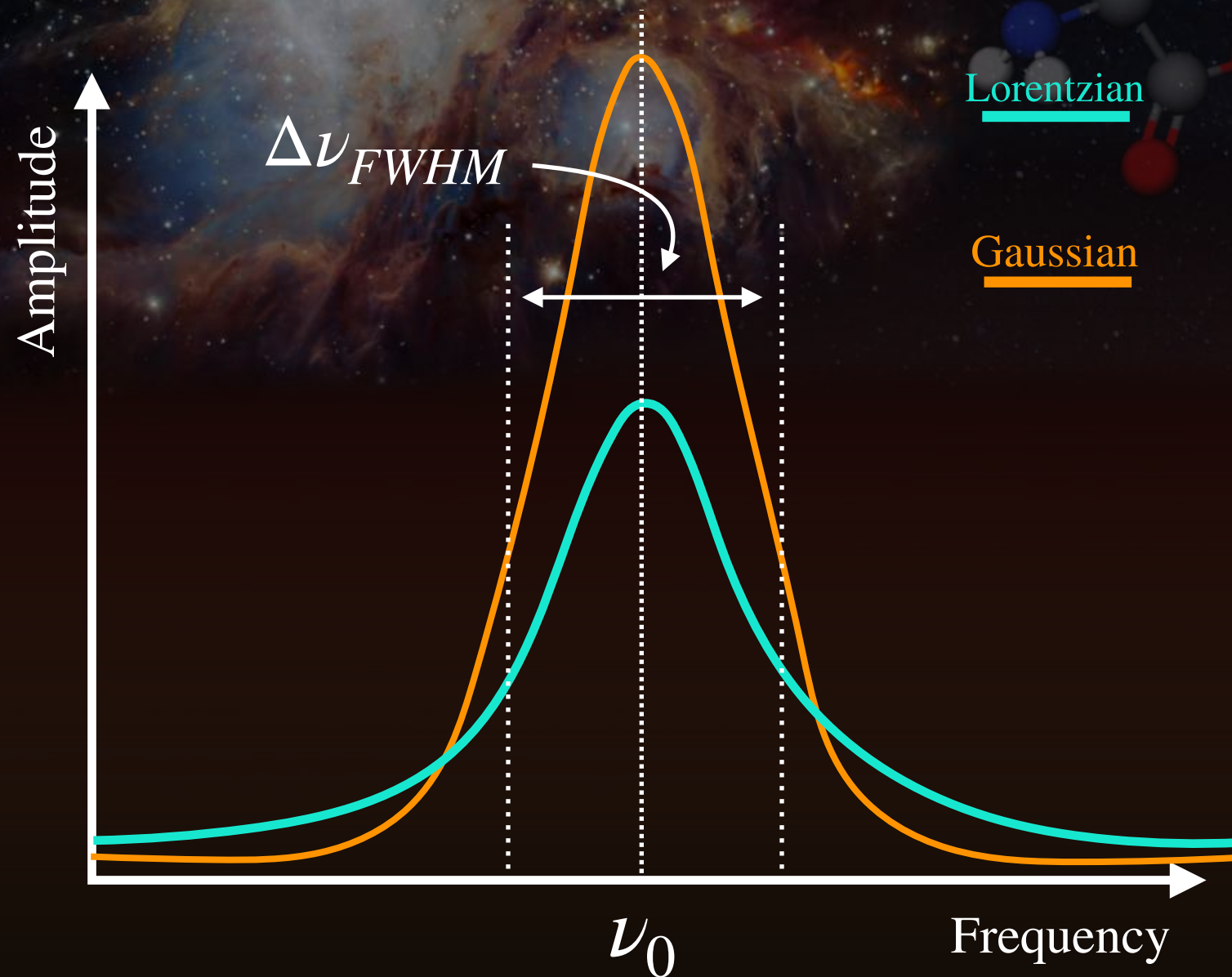
The line width and velocity peak depends on the ice composition.

*The line intensity and profile depends on physical properties (temperature, abundances)*



# What the molecular emission tells us?

## Line Profile



### Natural Broadening

$$\Phi(\nu) = \frac{2}{\pi\Delta\nu_{\text{int}}} \frac{1}{1 + 4(\nu - \nu_0)^2/\Delta\nu_{\text{int}}^2}$$

### Thermal (or Doppler) Broadening

$$\Phi(\nu) = \frac{1}{\Delta\nu_D\sqrt{\pi}} e^{-\frac{(\nu - \nu_0)^2}{\Delta\nu_D^2}}$$

$$\Delta\nu_D = \frac{\nu_0}{c} \sqrt{\frac{2k_B T}{m_X}}$$

Heavily dependent on the frequency and the Temperature of the gas

$$\Delta\nu_{FWHM}^{\text{natural}} \ll \Delta\nu_{FWHM}^{\text{thermal}} < \Delta\nu_{FWHM}^{\text{observed}}$$

In most cases

\*e.g. CH<sub>3</sub>OH at 96.8 GHz at 100K has a thermal line width of 0.4 km/s

### Non-thermal Broadening

Turbulence or systematic motions, velocity fields

$$\Delta\nu_{\text{obs}}^2 = \Delta\nu_D^2 + \Delta\nu_{\text{syst}}^2 + \Delta\nu_{\text{turb}}^2$$

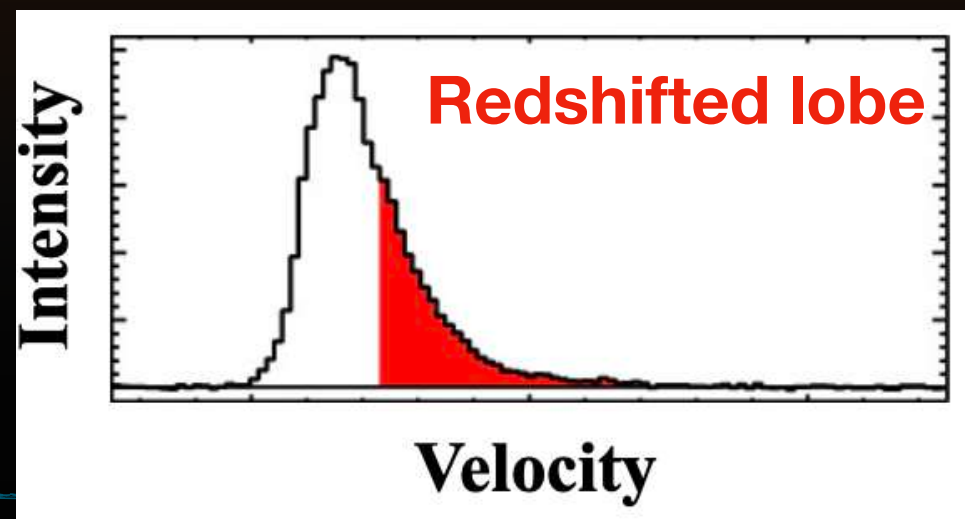
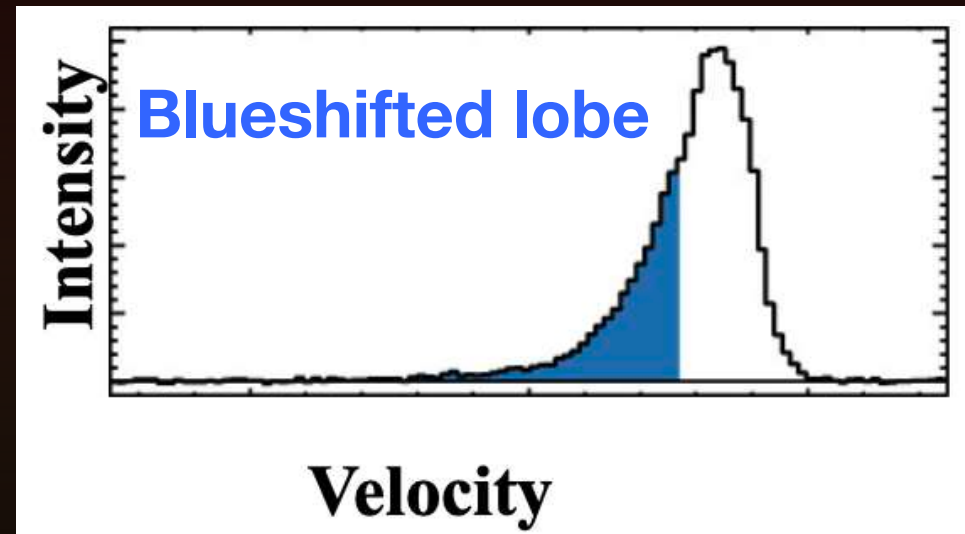


# What the molecular emission tells us?

## Line Profile

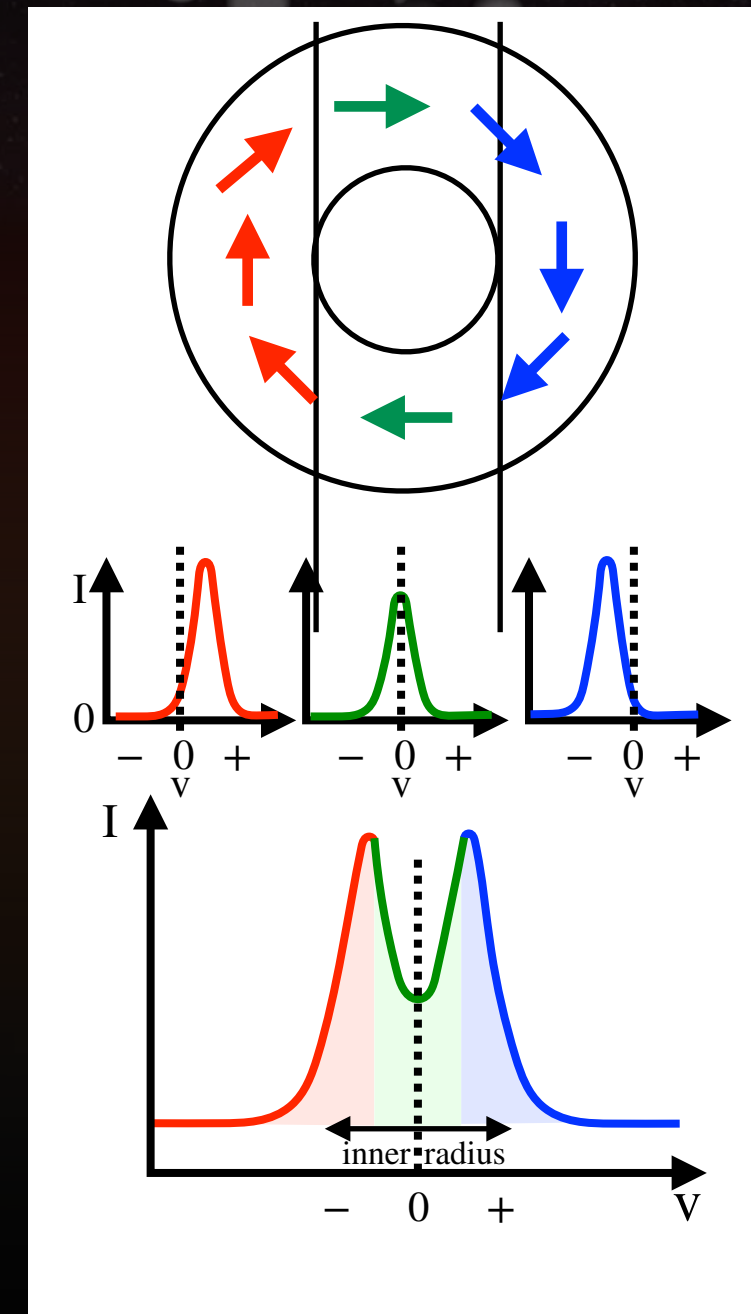
- Red/blue shifted shoulders

Ejecting jet/outflow

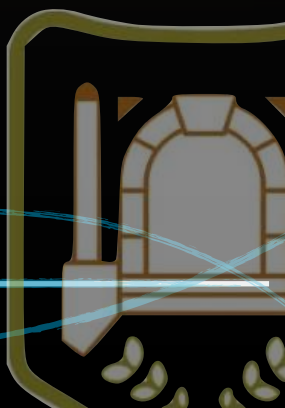


- Double-peak profile

Rotating Disk



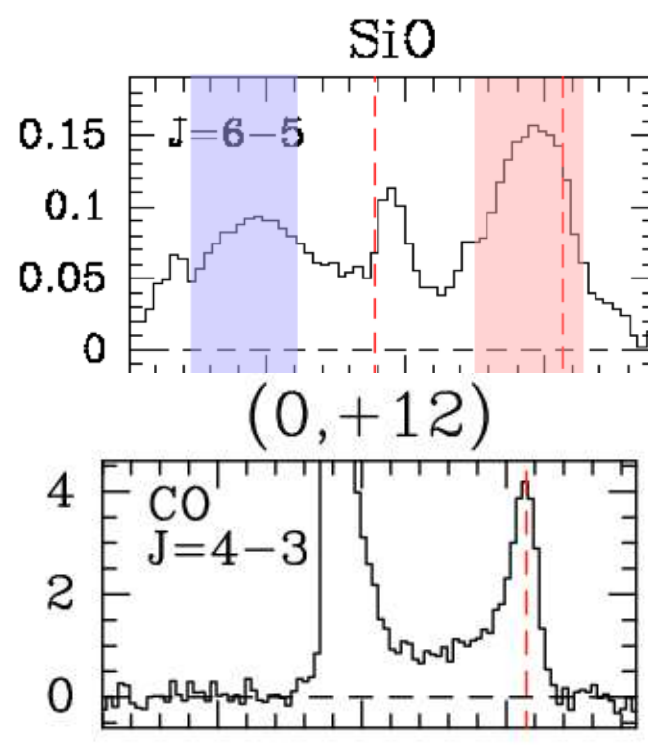
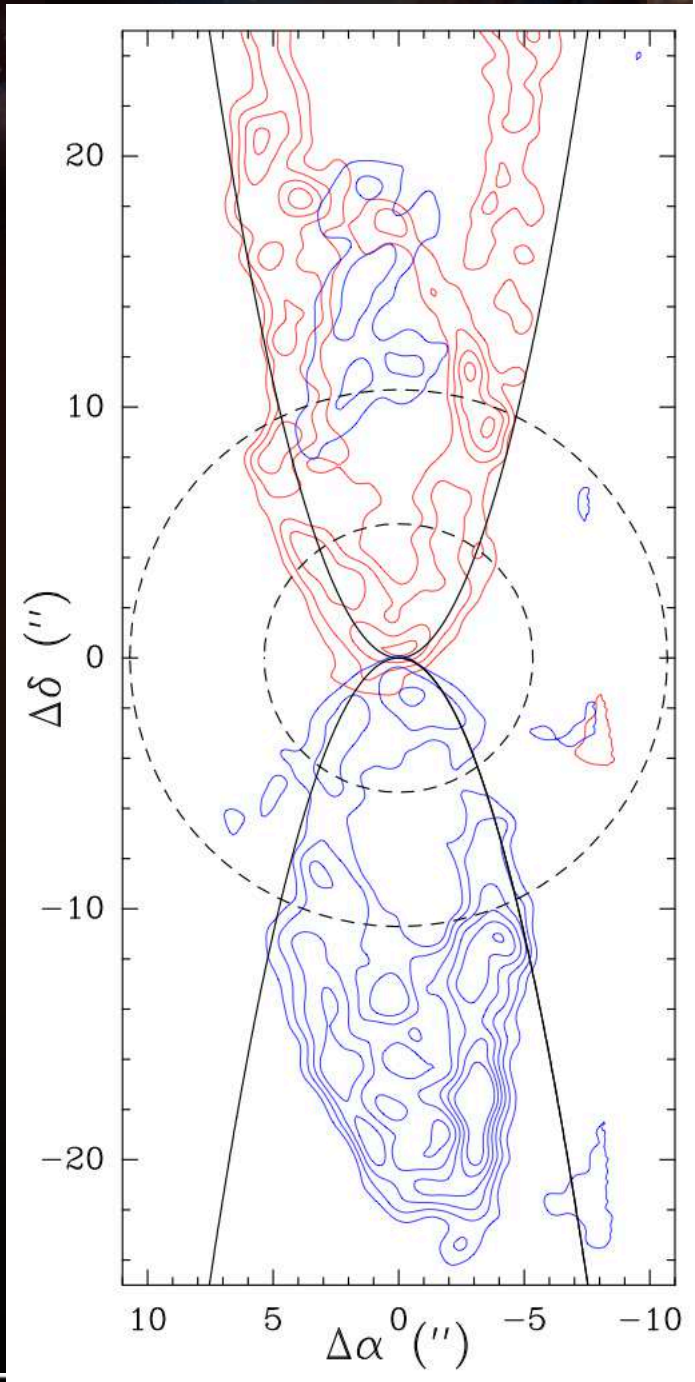
Observer



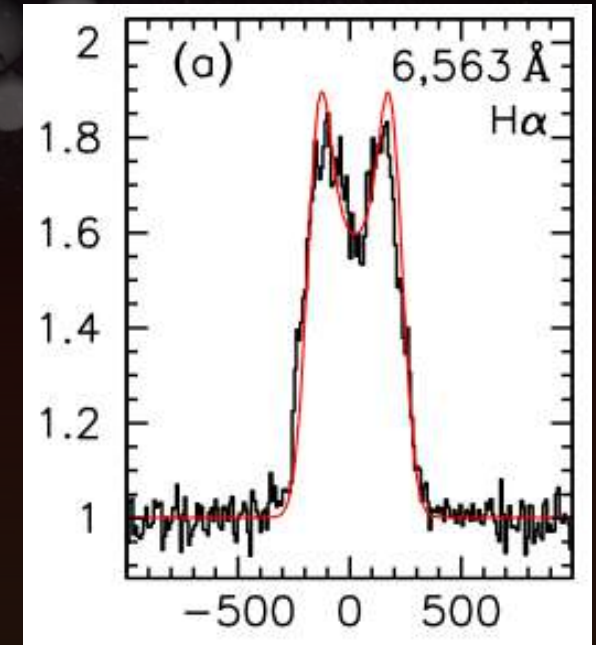
# What the molecular emission tells us?

## Line Profile

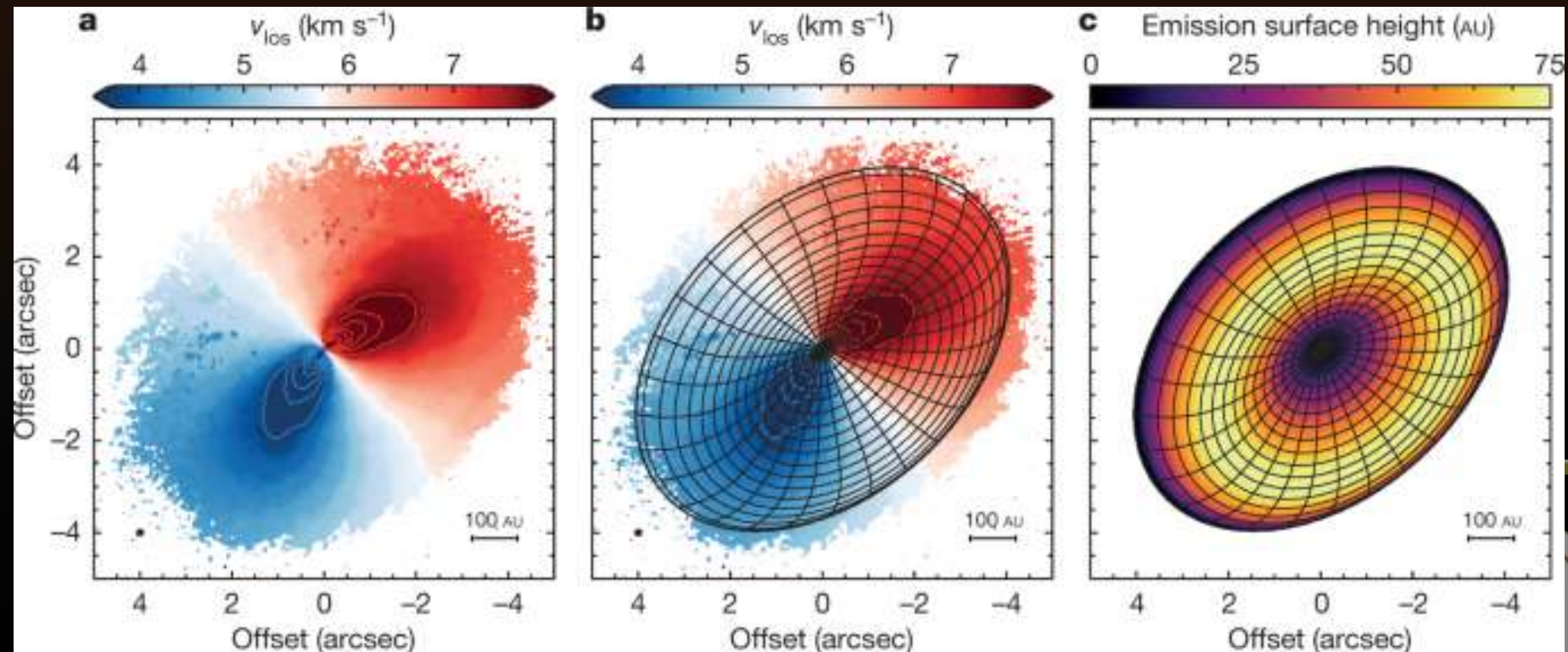
*Ospina-Zamudio et al. 2019*



*Gänsicke et al. (2019)*



*Tegue et al. 2019*



# What the molecular emission tells us? Integrated emission

Derive physical properties of the emitting gas  $\rightarrow$  column density and temperature

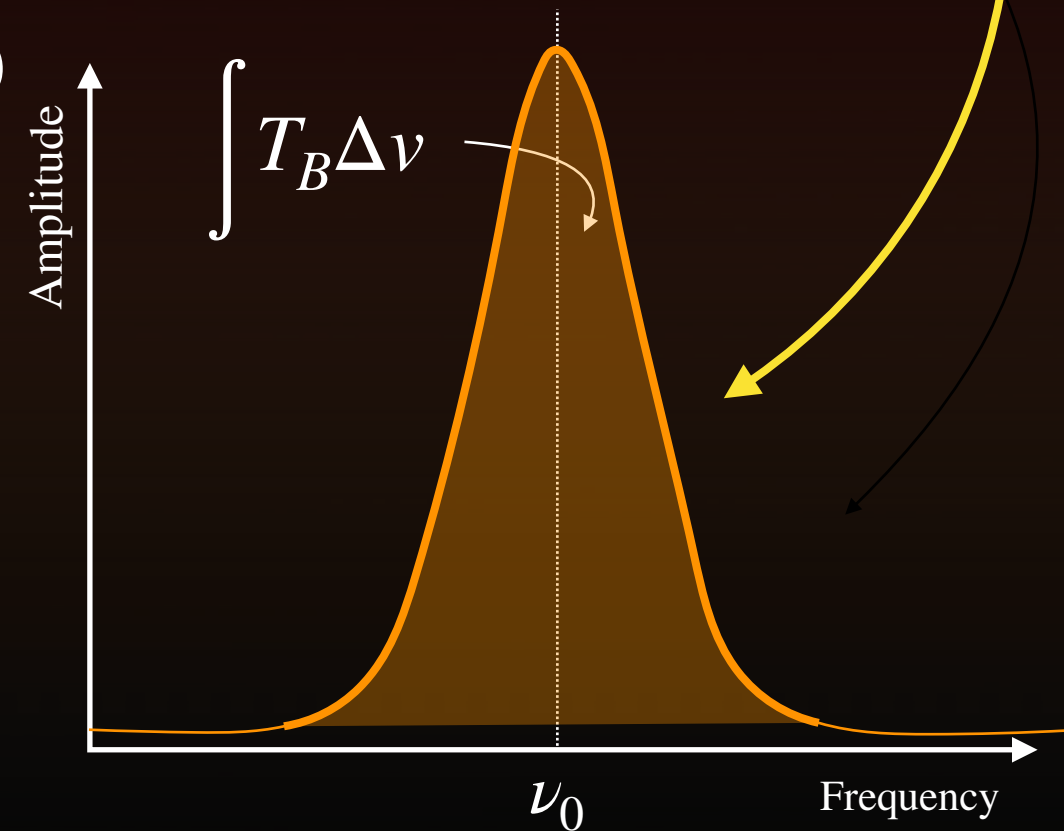
The **integrated line profile** gives us access to:

- Temperature (via level population)
- Column density / abundance (via line strength)
- Density (affects excitation, LTE vs sub-thermal)

These depend on:

- Spectral properties of the molecules
- Environmental conditions

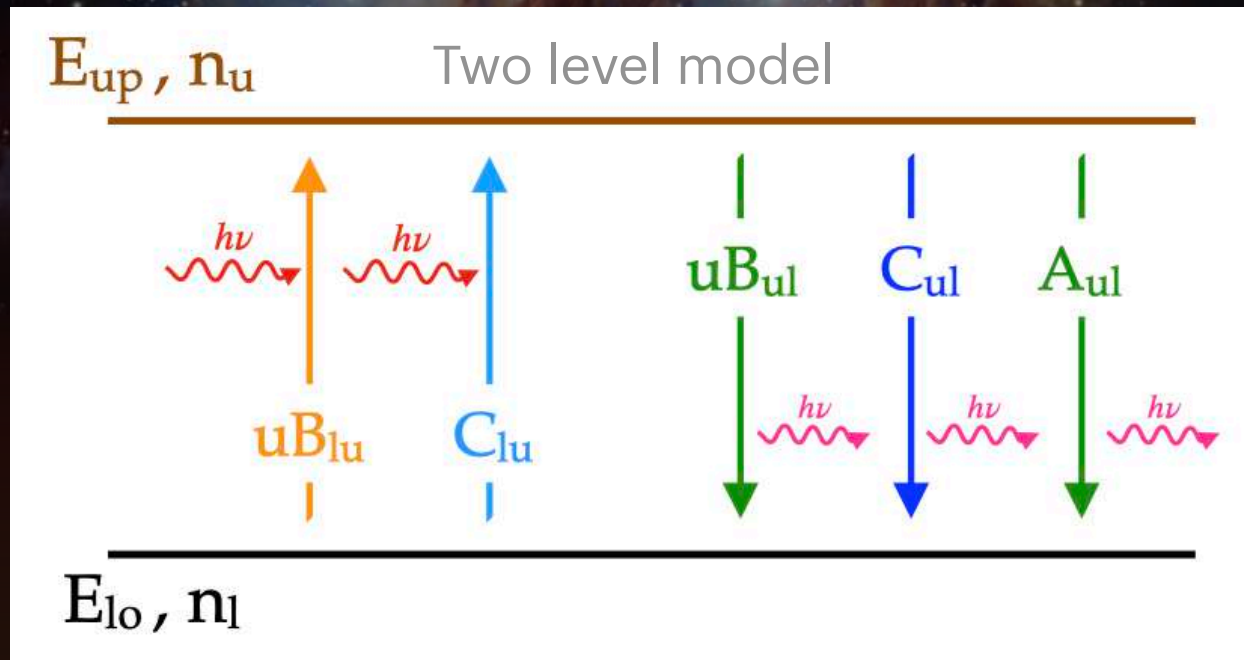
**But...How?**



# What the molecular emission tells us?

## Integrated emission

Derive physical properties of the emitting gas  $\rightarrow$  column density and temperature



Einstein coefficients:

$A_{ul} \rightarrow$  spontaneous emission

$B_{ul} \rightarrow$  stimulated emission

$B_{lu} \rightarrow$  absorption

$C_{ul}$  and  $C_{lu} \rightarrow$  collision coefficient

Excitation of lower energy level

$$\left. \frac{dn_u}{dt} \right|_{\text{abs.}} = n_l B_{lu} J_\nu$$

$$\left. \frac{dn_u}{dt} \right|_{\text{coll.}} = n_l C_{lu}$$

De-excitation of upper energy level

$$\left. \frac{dn_l}{dt} \right|_{\text{spont.em}} = n_u A_{ul}$$

$$\left. \frac{dn_l}{dt} \right|_{\text{stim.em.}} = n_u B_{ul} J_\nu$$

Statistical equilibrium

$$\left. \frac{dn_l}{dt} \right|_{\text{coll.}} = n_u C_{ul}$$

Critical Density

$$n_{\text{crit}} = \frac{A_{ul}}{C_{ul}}$$

Collisions negligible

$$g_l B_{lu} = g_u B_{ul}$$

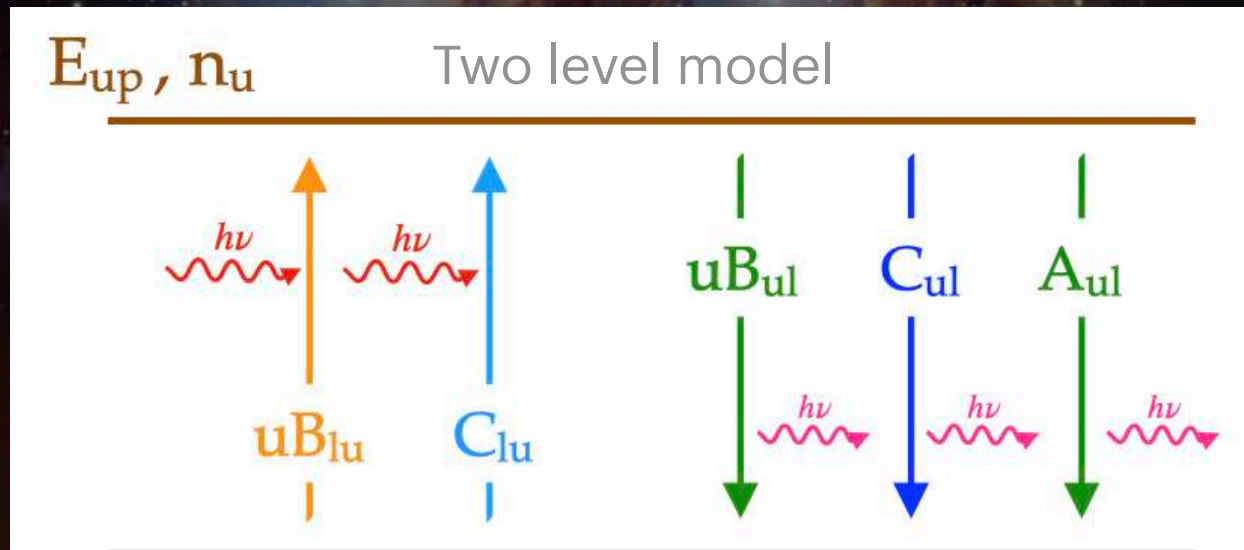
$$B_{ul} = \frac{c^2}{2h\nu_{ul}^3} A_{ul}$$

Independent on Temperature!

# What the molecular emission tells us?

## Integrated emission

Derive physical properties of the emitting gas  $\rightarrow$  column density and temperature



Einstein coefficients:

$A_{ul} \rightarrow$  spontaneous emission

$B_{ul} \rightarrow$  stimulated emission

$B_{lu} \rightarrow$  absorption

$C_{ul}$  and  $C_{lu} \rightarrow$  collision coefficient

*How much of the emitted radiation reaches us?*  
*How does it reflect the physical properties of the gas?*

$$\begin{aligned} \left. \frac{dn_u}{dt} \right|_{\text{abs.}} &= n_l B_{lu} J_\nu \\ \left. \frac{dn_u}{dt} \right|_{\text{coll.}} &= n_l C_{lu} \\ \left. \frac{dn_l}{dt} \right|_{\text{spont.em}} &= -n_u A_{ul} \\ \left. \frac{dn_l}{dt} \right|_{\text{stim.em.}} &= -n_u B_{ul} J_\nu \\ \left. \frac{dn_l}{dt} \right|_{\text{coll.}} &= -n_u C_{ul} \end{aligned}$$

Statistical equilibrium

Collisions negligible

Critical Density  $n_{\text{crit}} = \frac{A_{ul}}{C_{ul}}$

$g_l B_{lu} = g_u B_{ul}$

$B_{ul} = \frac{c^2}{2h\nu_{ul}^3} A_{ul}$  Independent on Temperature!

# Integrated emission

Derive physical properties of the emitting gas —> column density and temperature

The radiation emitted by the molecules that we observe depends on :

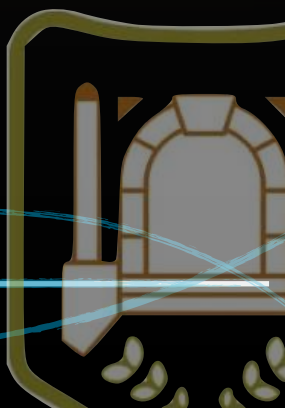
- How much radiation reach us (**emitted vs absorbed**)
- The temperature of the gas (which affects level populations)
- The column density of the molecule (how many emitters there are)

# Radiative transfer equation

$$\frac{dI_\nu}{ds} = j_\nu - k_\nu I_\nu$$

↓
↘

Emission:  
related to  $A_{ul}$ 
Absorption:  
related to  $B_{ul}, B_{lu}$



# What the molecular emission tells us? Integrated emission

Derive physical properties of the emitting gas → column density and temperature

The radiation emitted by the molecules that we observe depends on :

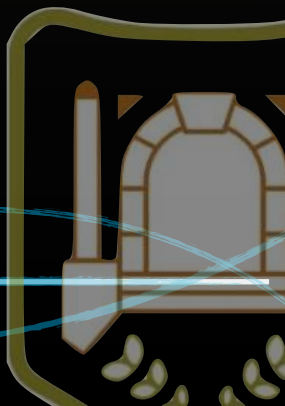
- How much radiation reach us (**emitted vs absorbed**)
- The temperature of the gas (which affects level populations)
- The column density of the molecule (how many emitters there are)

$$\frac{dI_\nu}{ds} = j_\nu - \cancel{k_\nu I_\nu} \xrightarrow{\text{Optically thin LTE}} I_\nu \sim \int j_\nu ds$$

$$j_\nu = n_u A_{ul} \frac{h\nu}{4\pi} \psi(\nu)$$

$I_\nu = B_\nu(T_B)$   
R-J approx  
( $h\nu \ll kT_B$ )

$$I_\nu \propto \frac{2k\nu^2}{c^2} T_B$$



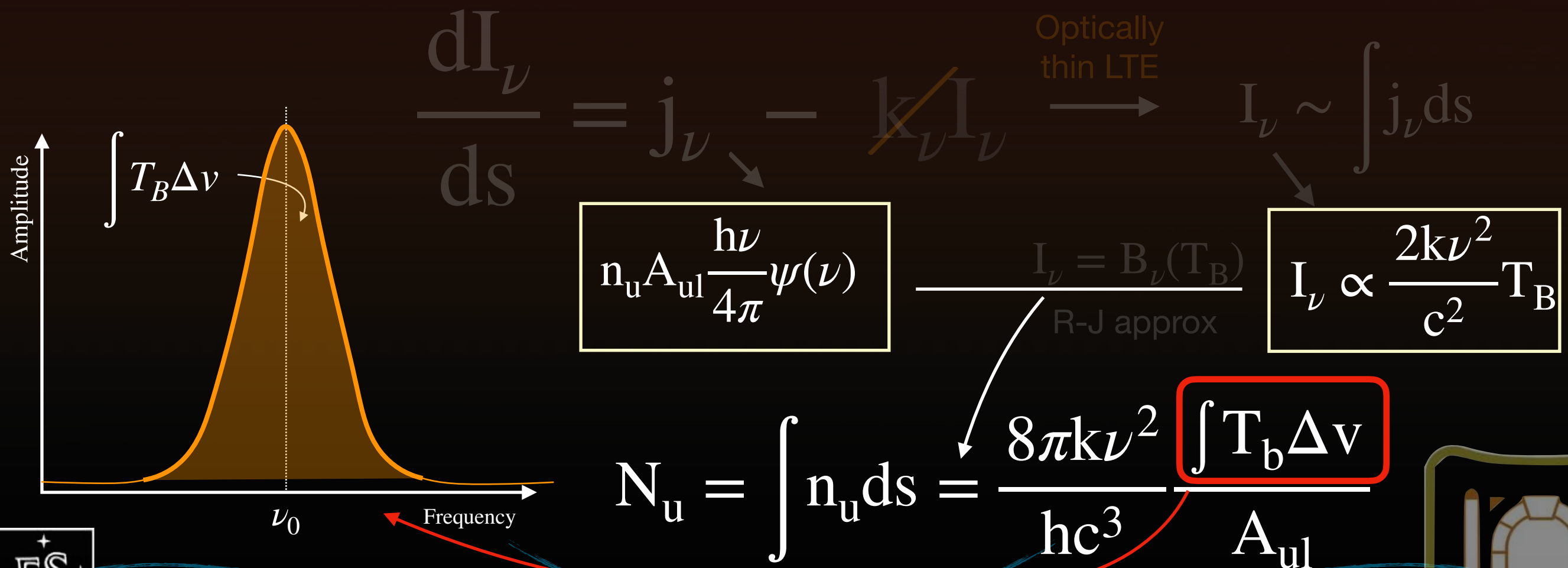
# What the molecular emission tells us?

## Integrated emission

Derive physical properties of the emitting gas → column density and temperature

The radiation emitted by the molecules that we observe depends on :

- How much radiation reach us (**emitted vs absorbed**)
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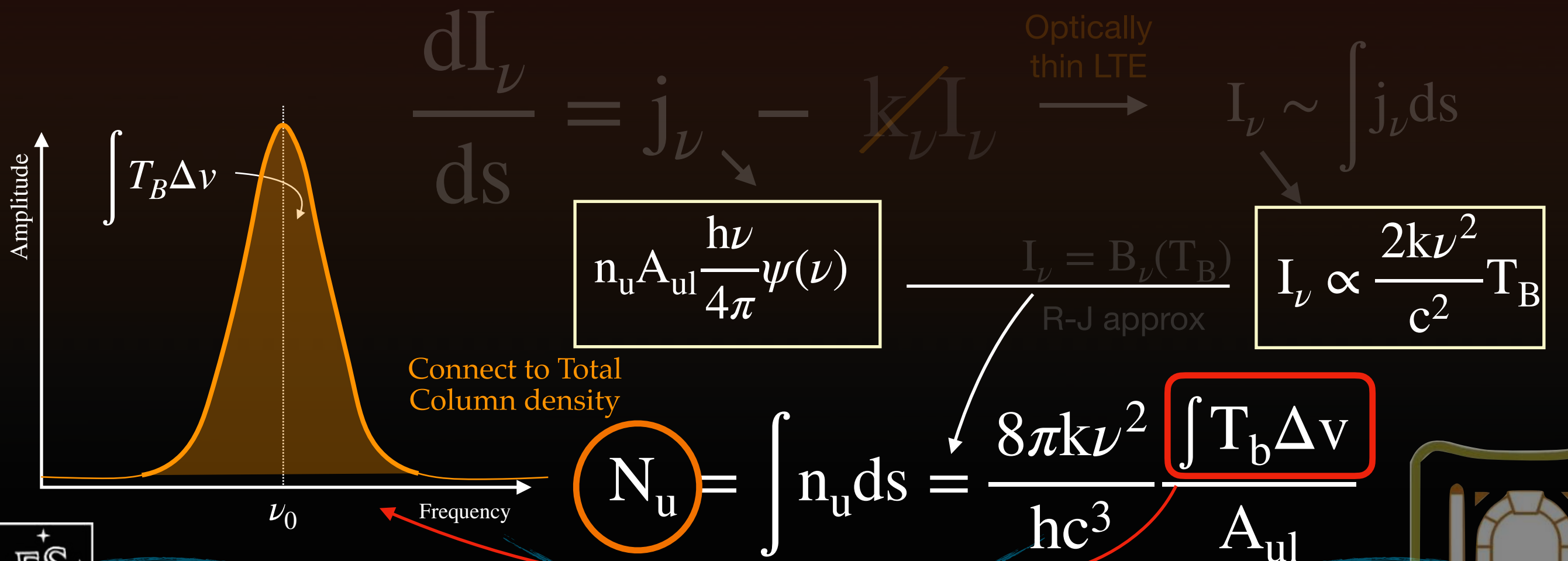


# What the molecular emission tells us? Integrated emission

Derive physical properties of the emitting gas → column density and temperature

The radiation emitted by the molecules that we observe depends on :

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# What the molecular emission tells us? Integrated emission

Derive physical properties of the emitting gas → column density and temperature

The radiation emitted by the molecules that we observe depends on :

- How much radiation reach us (**emitted vs absorbed**)
- The **temperature** of the gas (which affects level populations)
- The **column density** of the molecule (how many emitters there are)

## LTE (Local Thermodynamic Equilibrium) Conditions

Collisions dominate and matter follows **Boltzmann distribution**:

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} e^{-\frac{h\nu}{kT}}$$

*probability of a molecule occupying a particular energy state*

if we consider all the energy levels, that  $h\nu = (E_u - E_l)$  and integrating along the line of sight:  $N_{\text{tot}} = \sum_1 n_l$

$$\frac{N_u}{g_u} = \frac{N_{\text{tot}}}{Q(T)} e^{-\frac{E_u}{kT}}$$

$$Q(T) = \sum g_l e^{-E_l/KT}$$

→ *Partition function*

Column density and Temperature of emitting gas

# What the molecular emission tells us?

Integrated emission

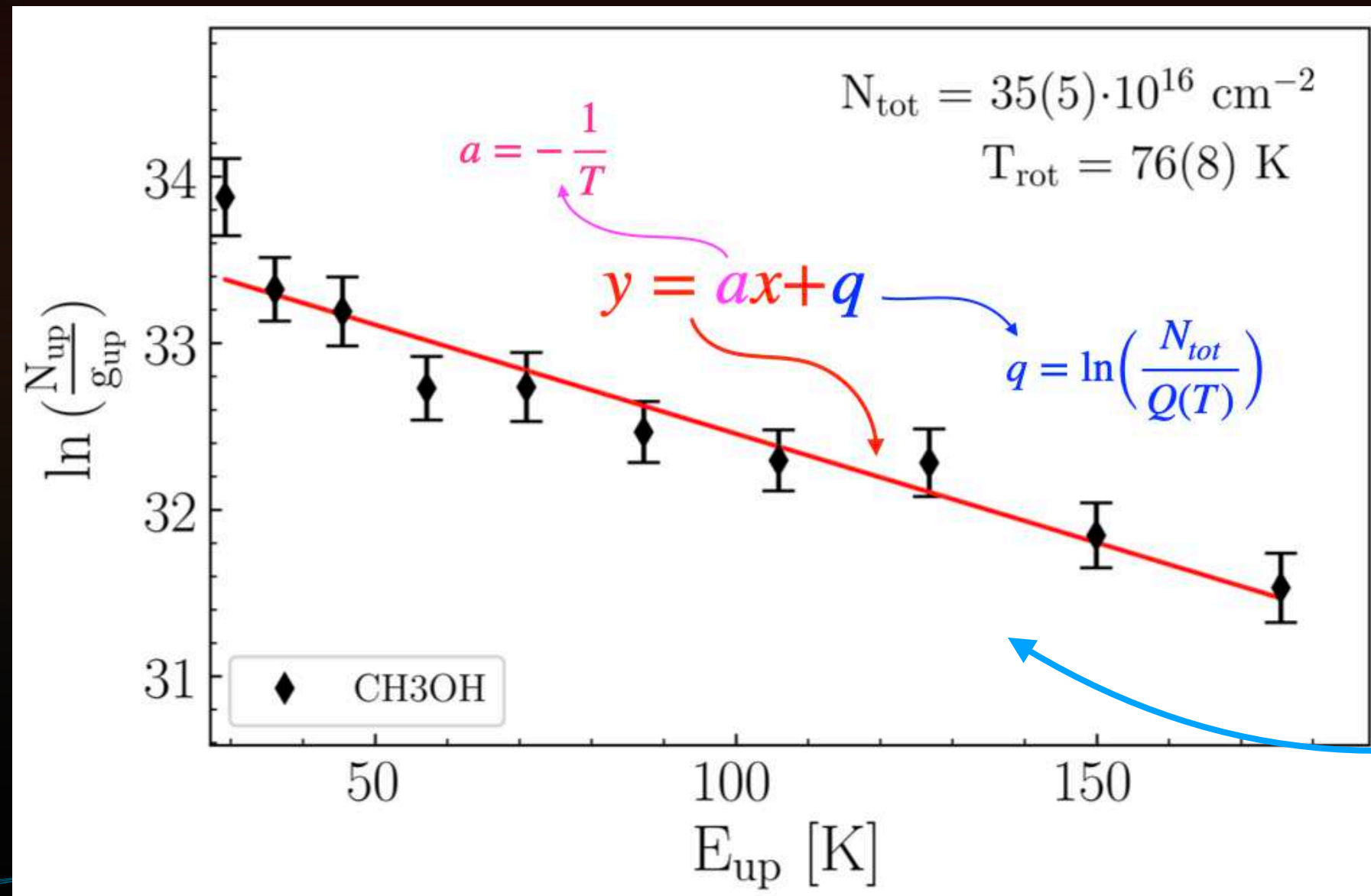
Derive physical properties of the emitting gas → column density and temperature

Linked to

$$\int T_B \Delta\nu \leftarrow \ln\left(\frac{N_u}{g_u}\right) = \ln\left(\frac{N_{\text{tot}}}{Q(T)}\right) - \frac{E_u}{kT}$$

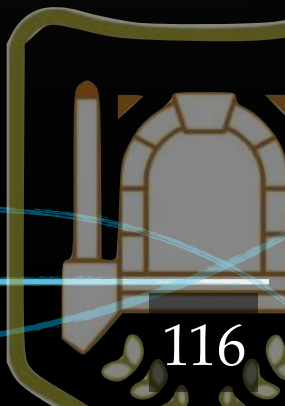
**Assumptions:**

LTE and optically thin lines



**Multi-line analysis!**

Different transitions of the same species with different spectral parameters (e.g., excitation of the upper state  $E_u$ )

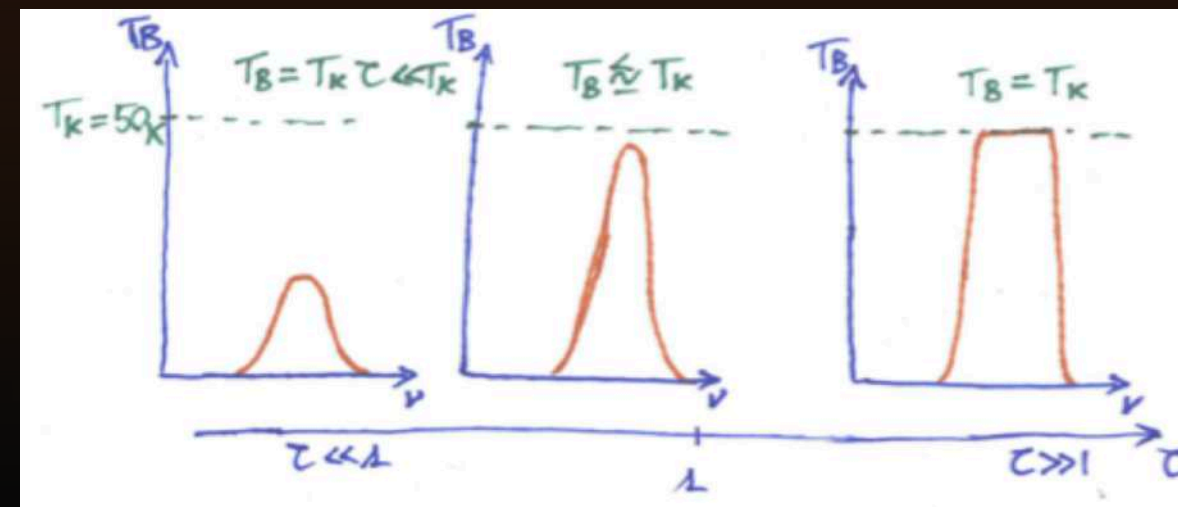
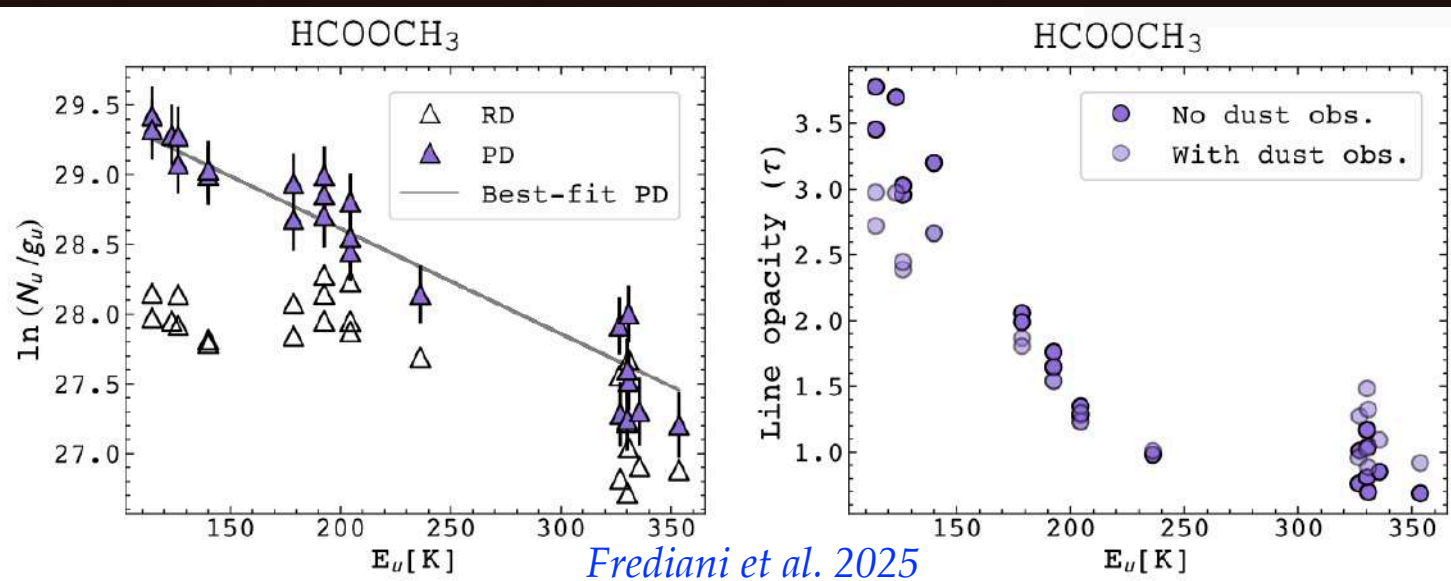


# What the molecular emission tells us?

## How do I know if emission is optically thin?

- Observe less abundant isotopologues (e.g.,  $^{13}\text{CO}$ ,  $^{13}\text{CH}_3\text{OH}$ ...) and compare the ratio with elemental isotopic ratio from the Sun, local ISM, ...
- Observe possible signature in the emission spectra
- Check for signs of it in the Rotational Diagram

More abundant isotopologues are more likely to have optically thick emission

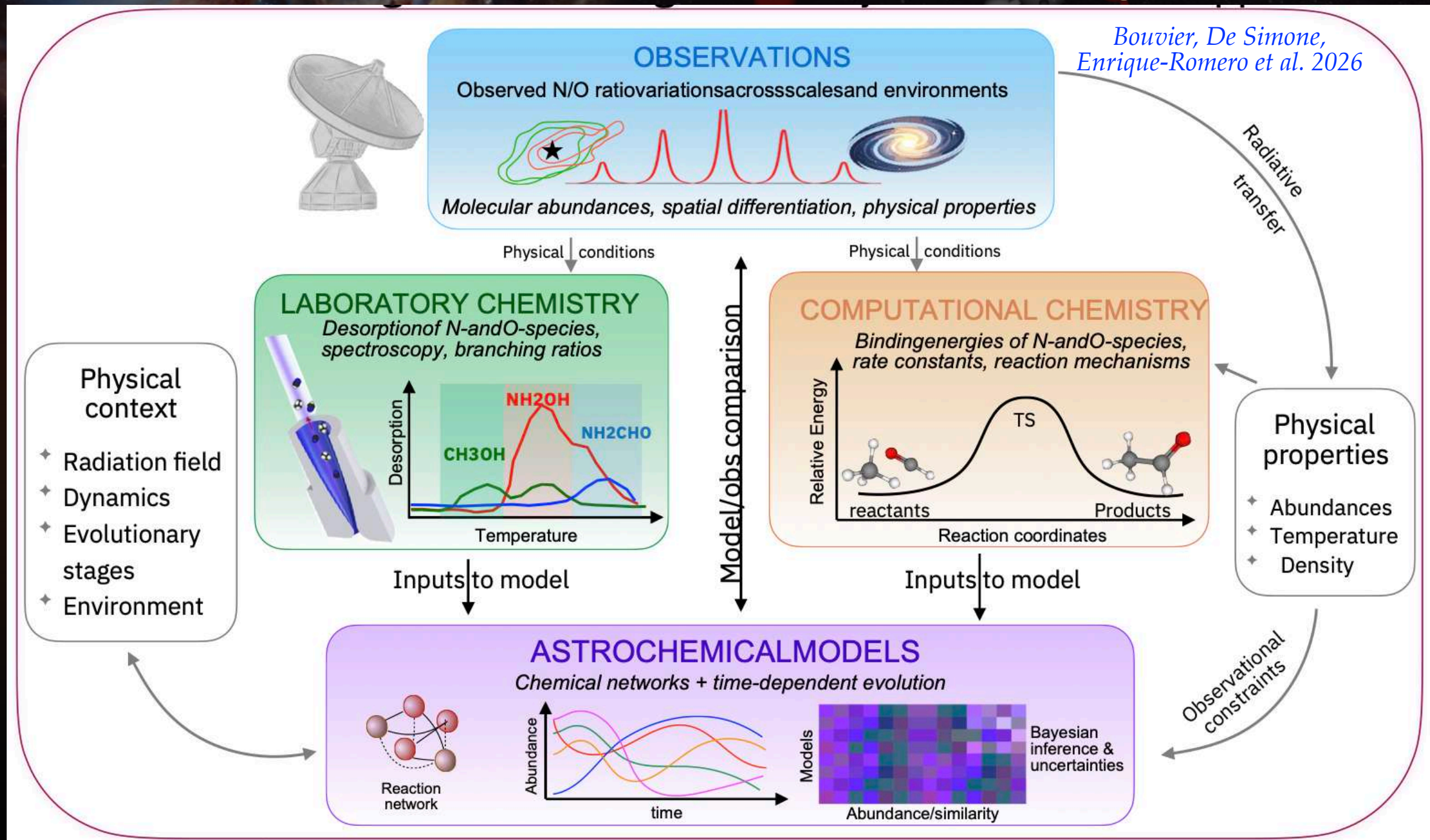


—> Population Diagram

$$N_u \cdot \frac{1 - e^{-\tau}}{\tau}$$

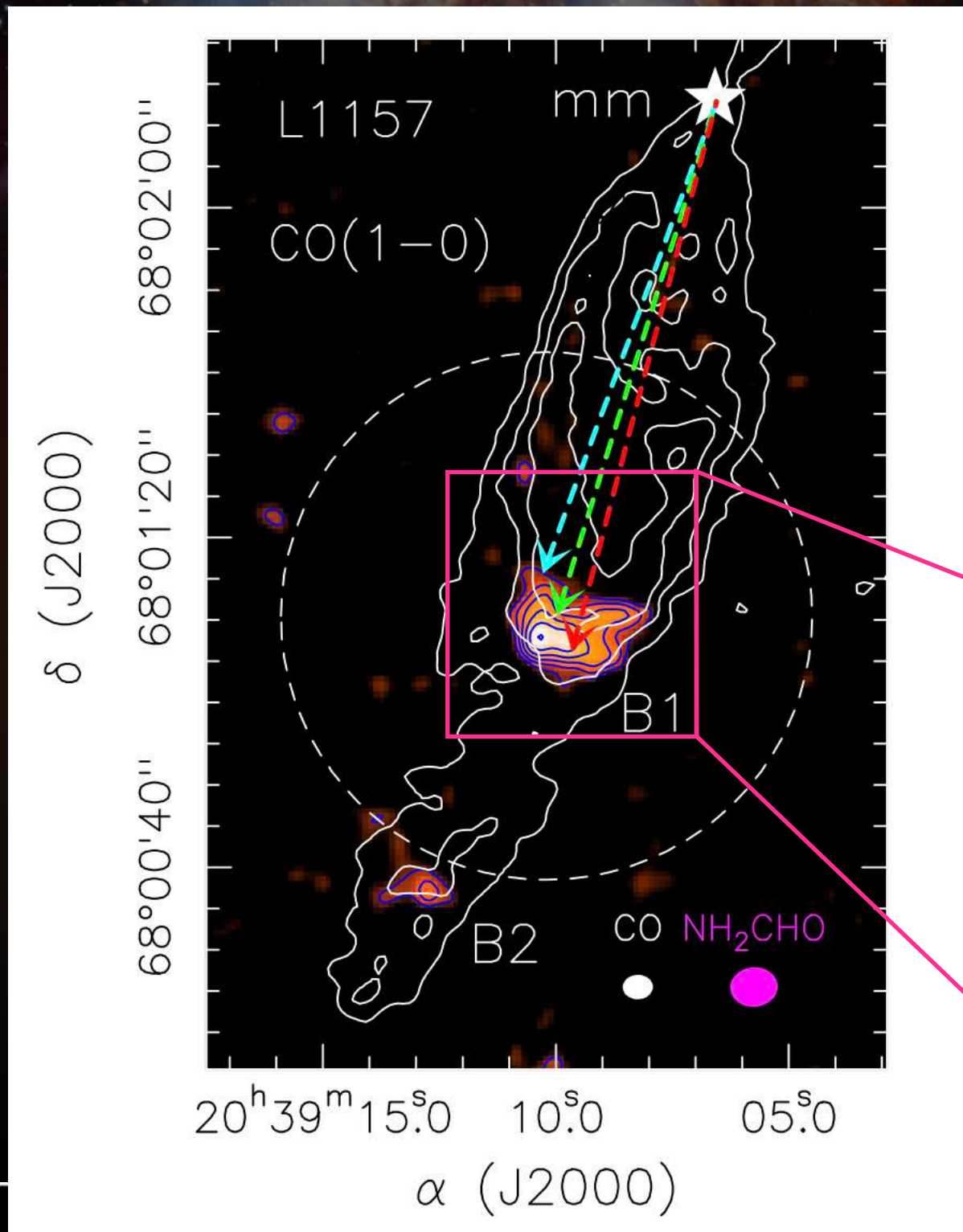
# How to constrain iCOMs formation routes?

...Looking at shocked regions  
...Looking at correlations

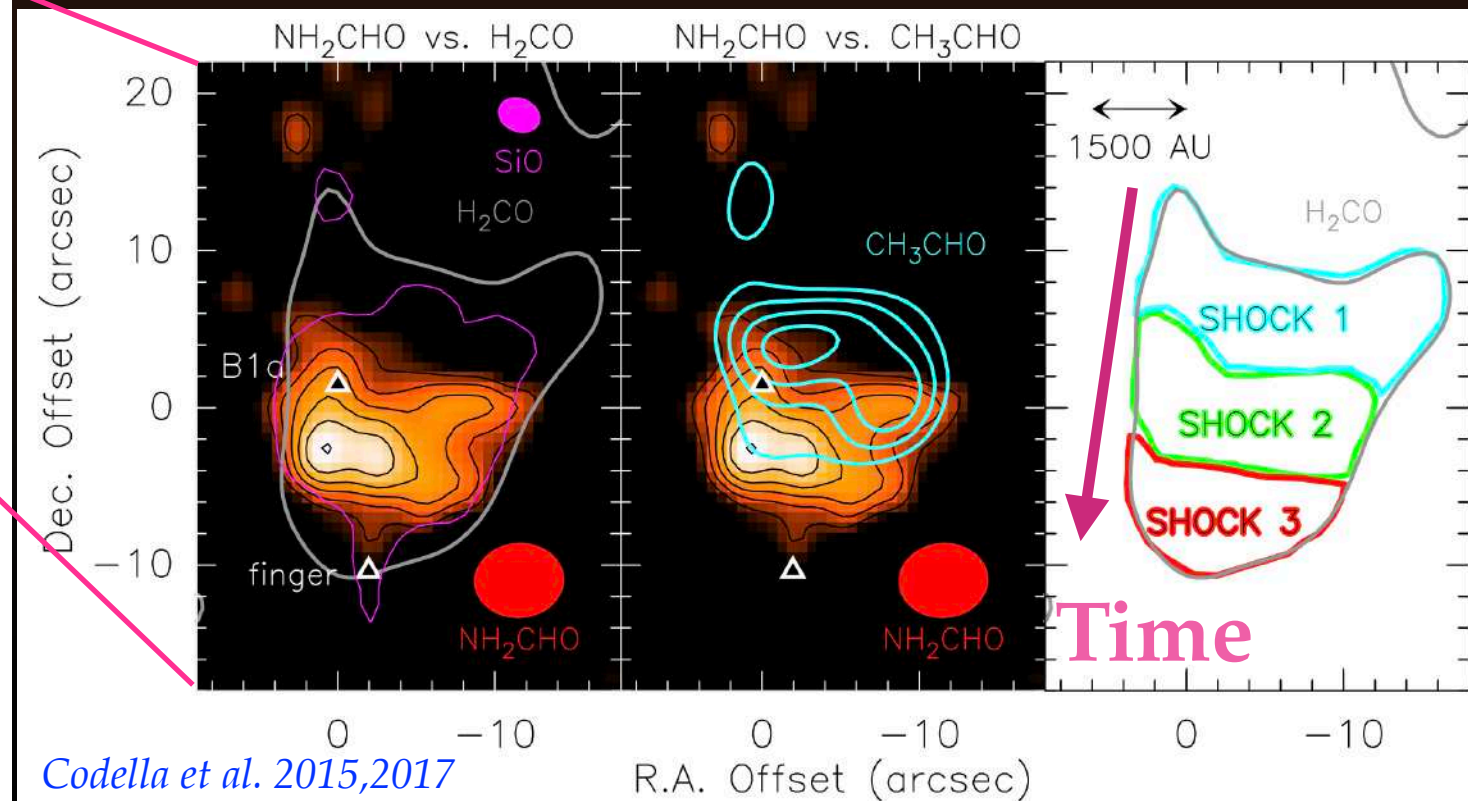


# How to constrain iCOMs formation routes?

...Looking at shocked regions



- Detection of formamide ( $\text{NH}_2\text{CHO}$ ) and acetaldehyde ( $\text{CH}_3\text{CHO}$ ) segregated
- In the shock we have temporal evolution, B1 is younger than B2



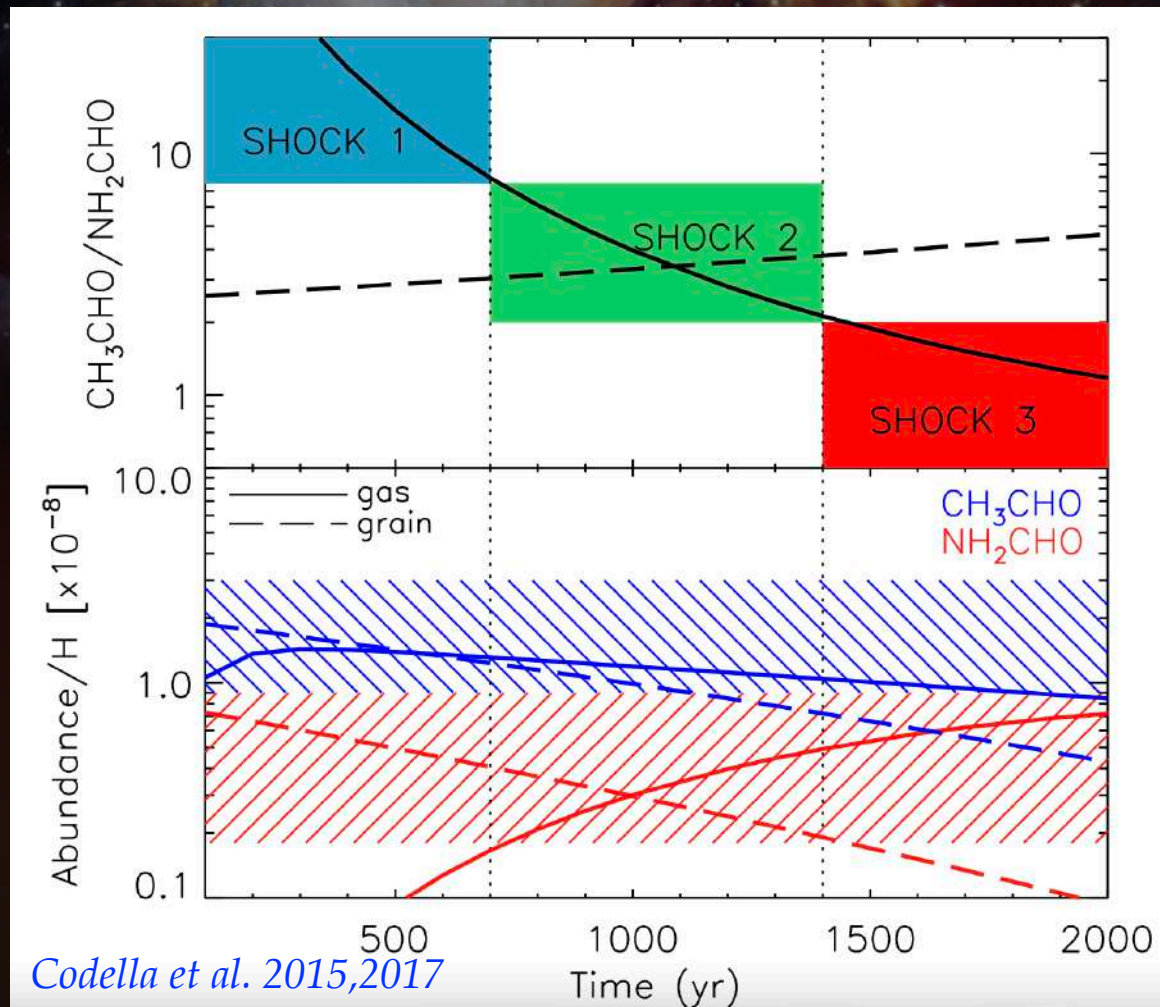
Codella et al. 2015, 2017

# How to constrain iCOMs formation routes?

...Looking at shocked regions

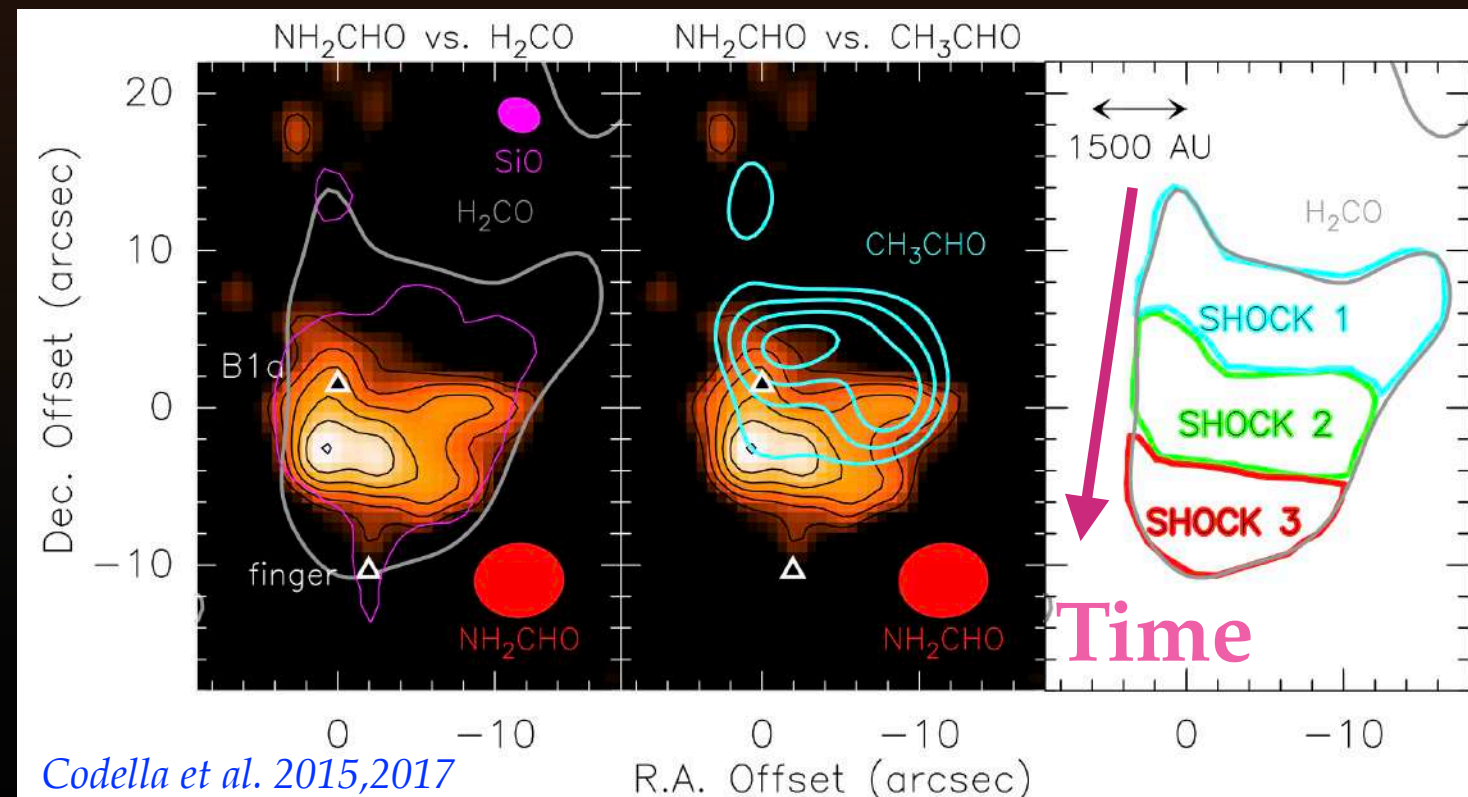
See also De Simone et al. 2020b, Giani et al. 2026

- Detection of formamide ( $\text{NH}_2\text{CHO}$ ) and acetaldehyde ( $\text{CH}_3\text{CHO}$ ) segregated
- In the shock we have temporal evolution, B1 is younger than B2



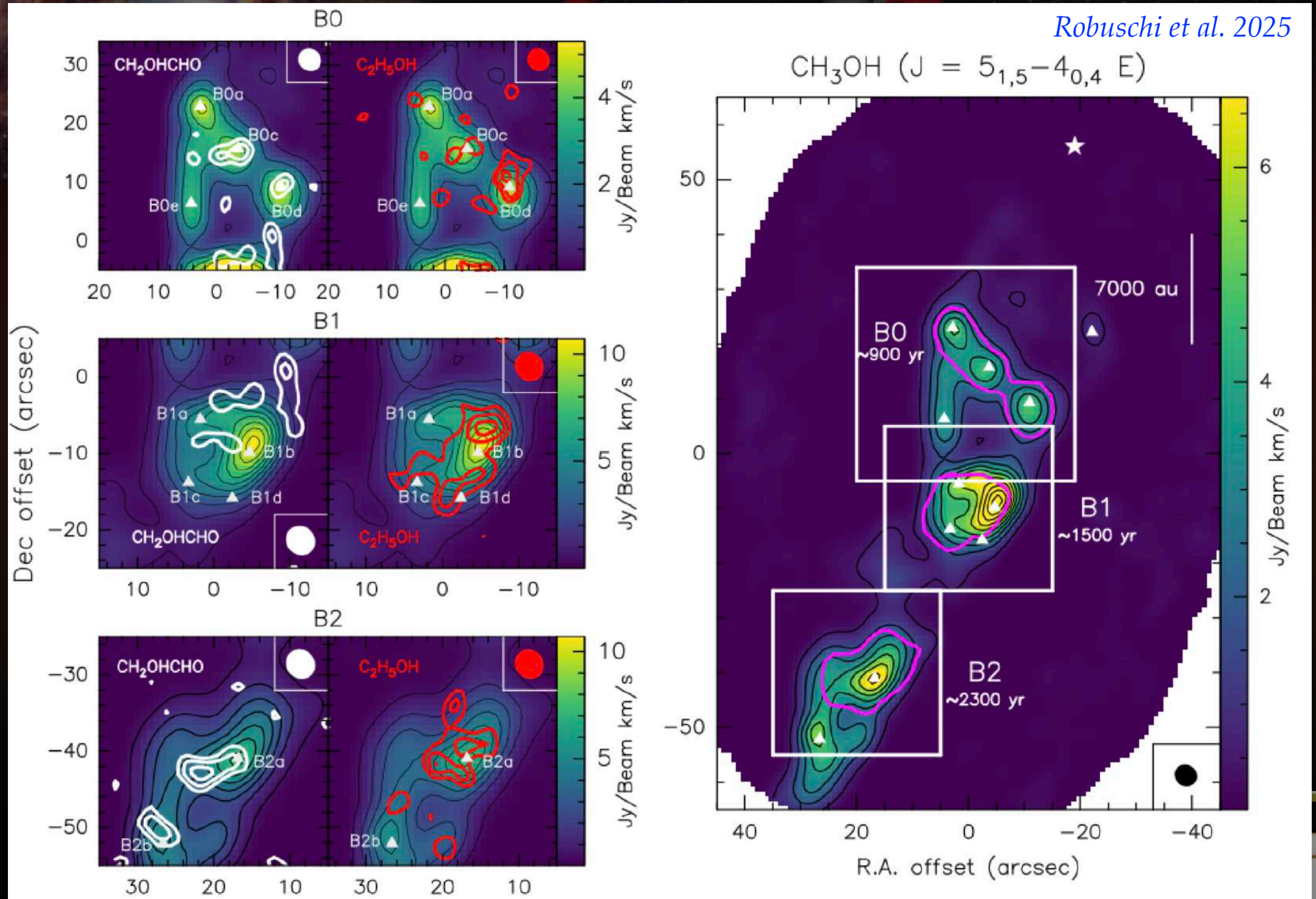
*Formamide formed  
in gas phase*

Codella et al. 2017, Barone et al. 2015,  
Vazart et al. 2016, Skouters et al. 2017  
Lopez-Sepulcre et al. 2024



# How to constrain iCOMs formation routes?

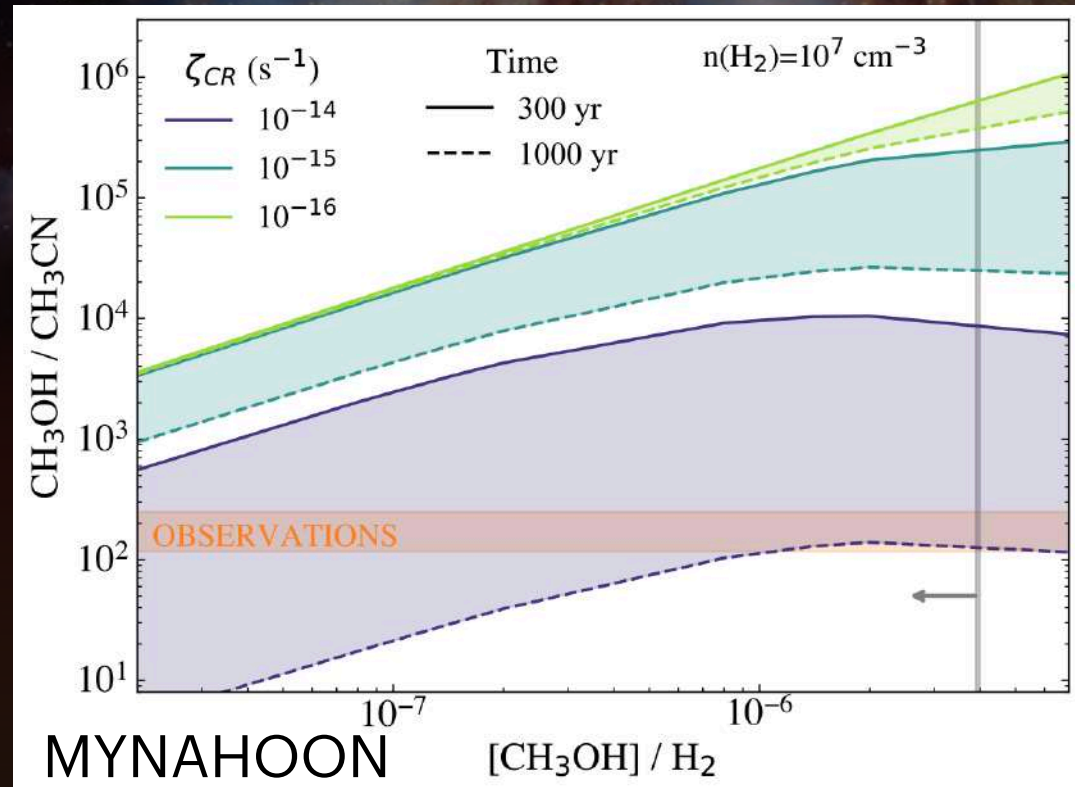
...Looking at shocked regions



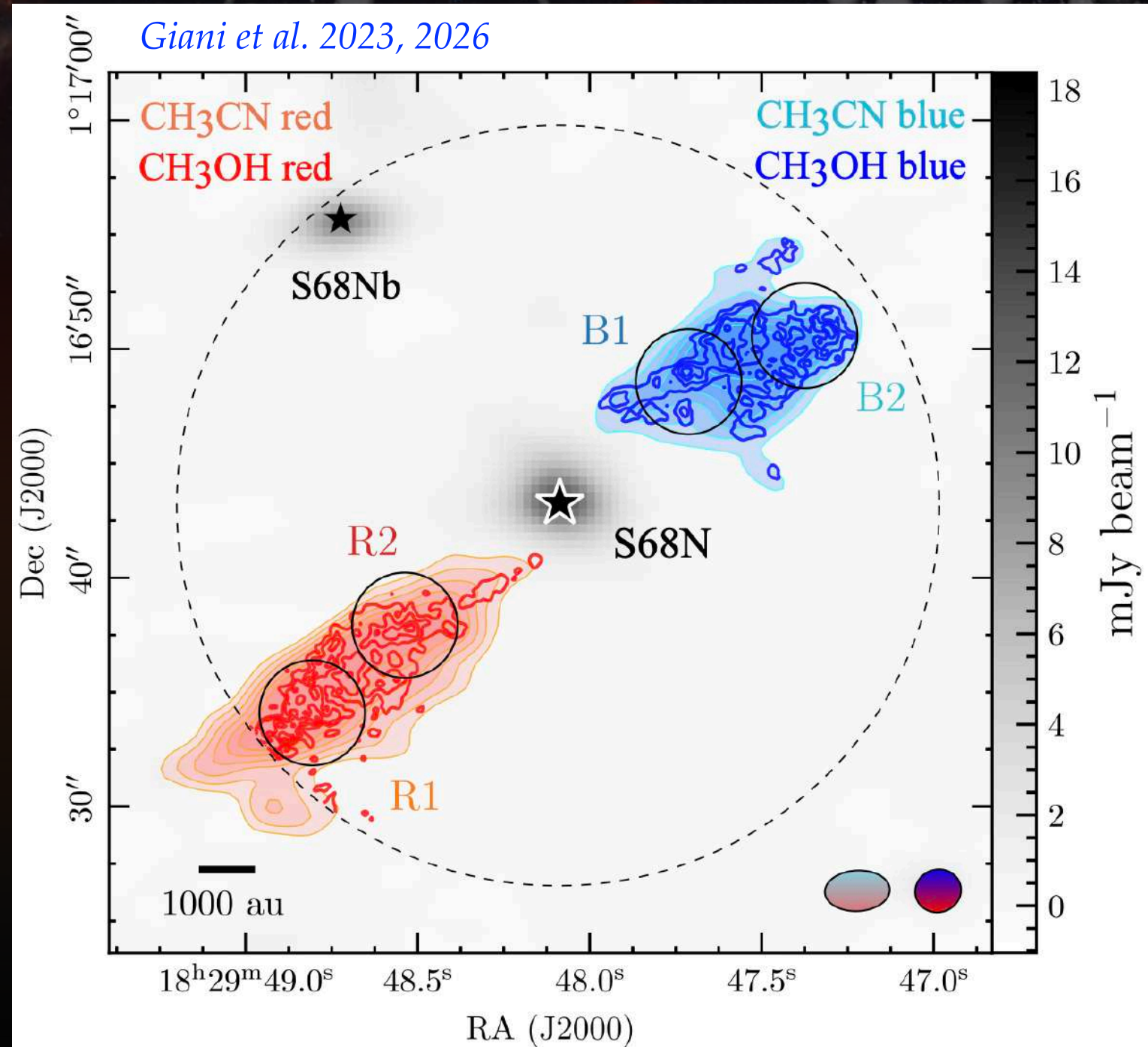
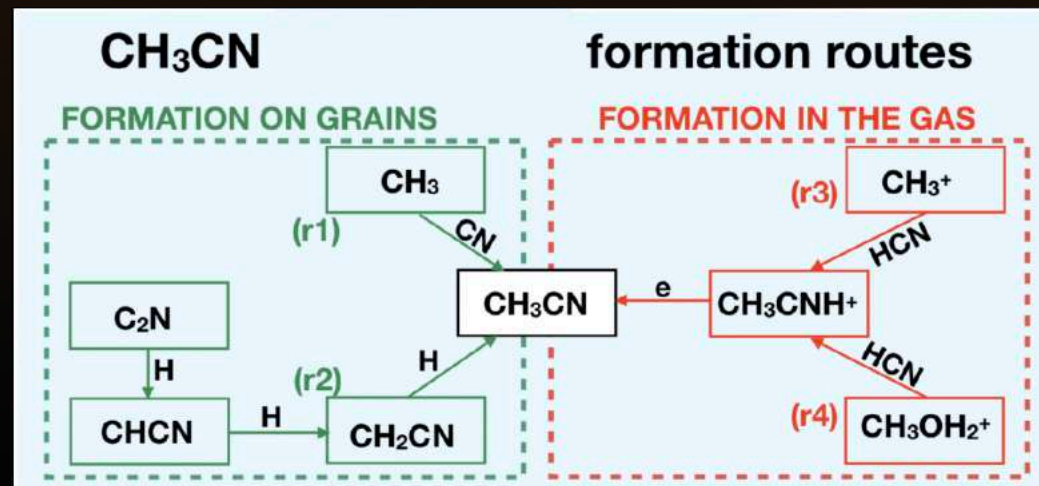
*Suggesting a  
gas phase  
formation of  
glycolaldehyde  
in B1 and B2  
(not in B0)  
From ethanol*

# How to constrain iCOMs formation routes?

...Looking at shocked regions



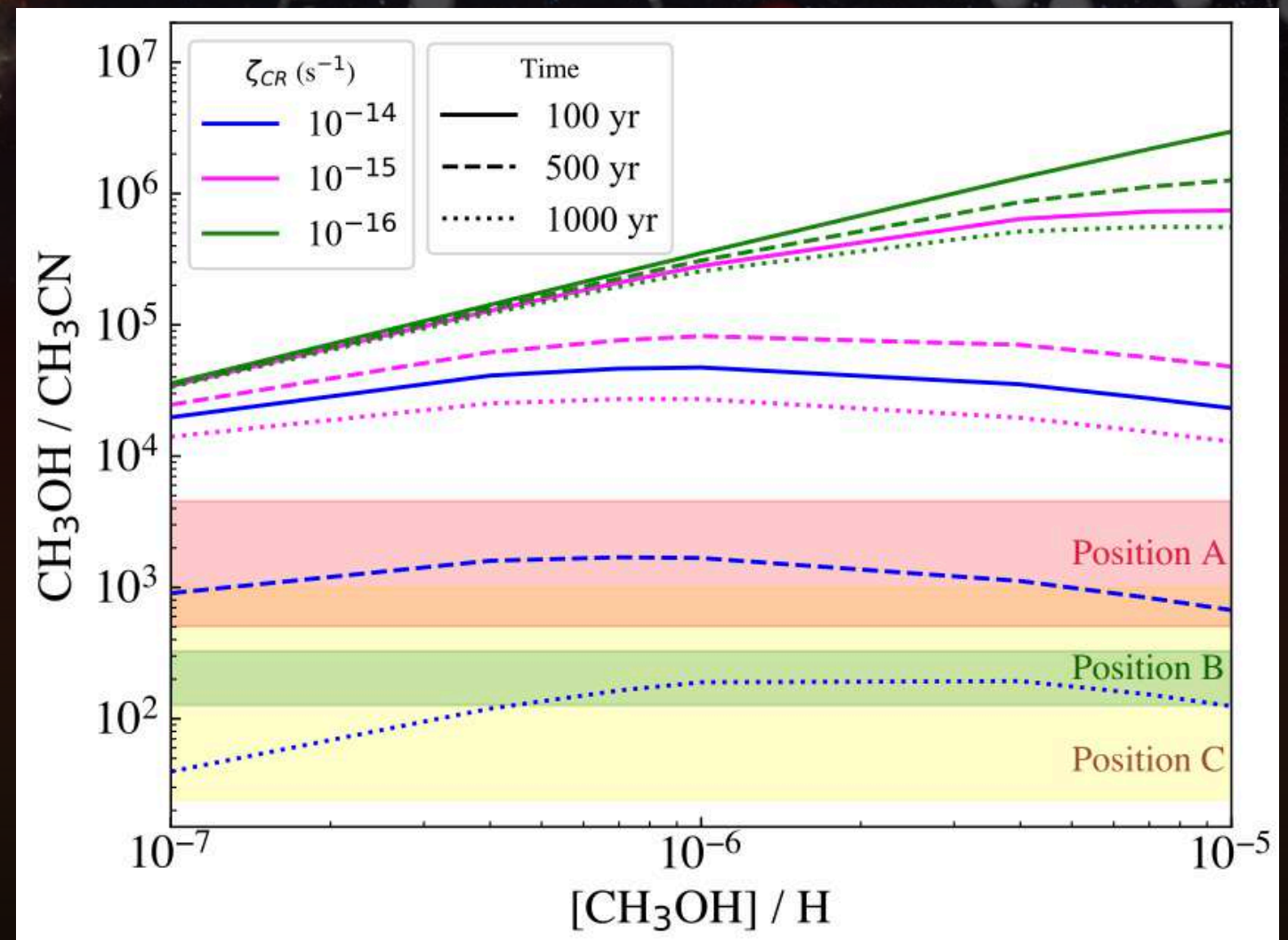
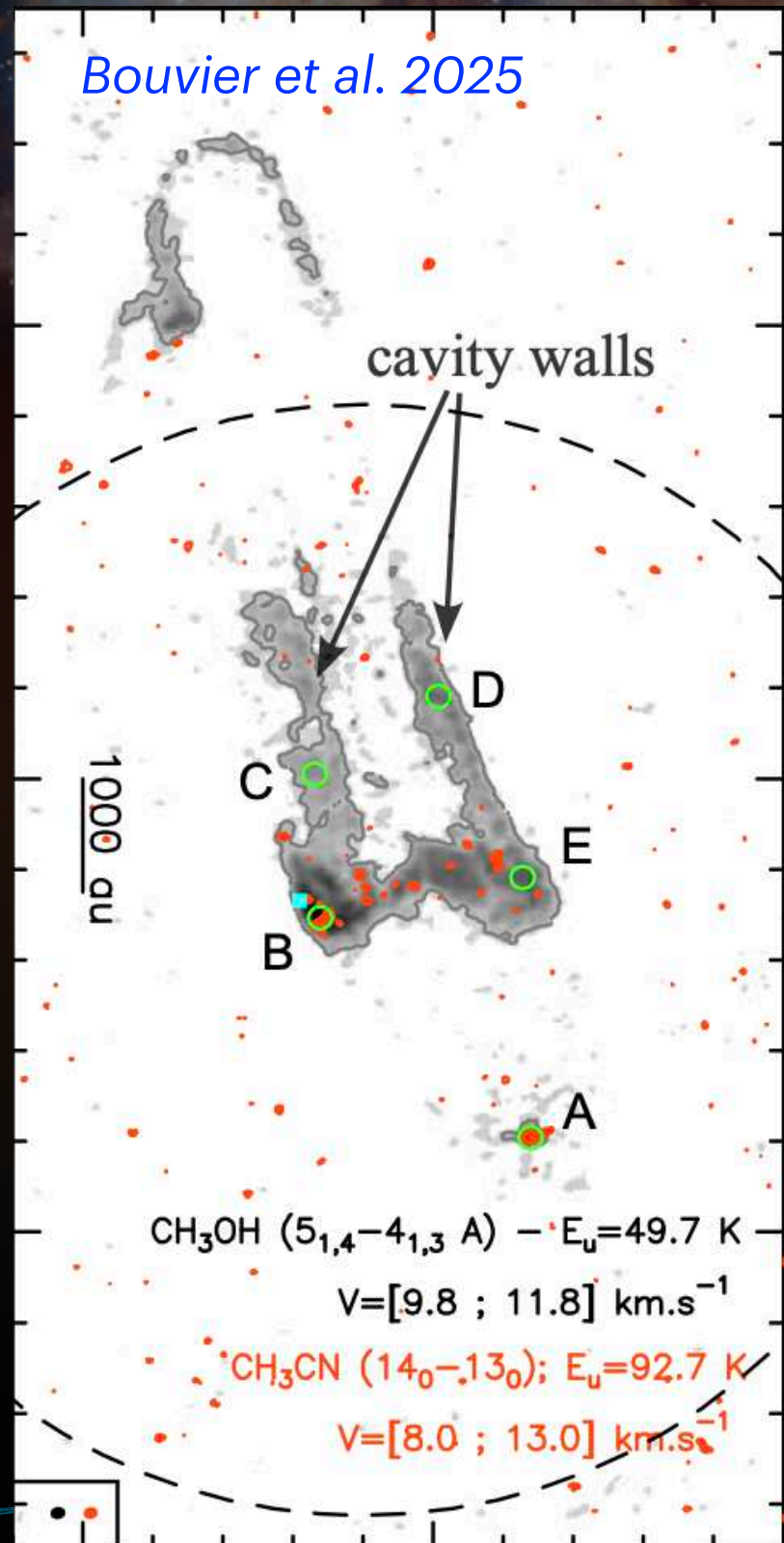
$\text{CH}_3\text{OH}$  and  $\text{CH}_3\text{CN}$  chemically linked



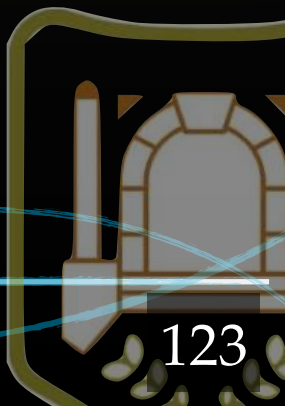
Species correlations does not imply same origin but can be a chemical link

# How to constrain iCOMs formation routes?

...Looking at correlations

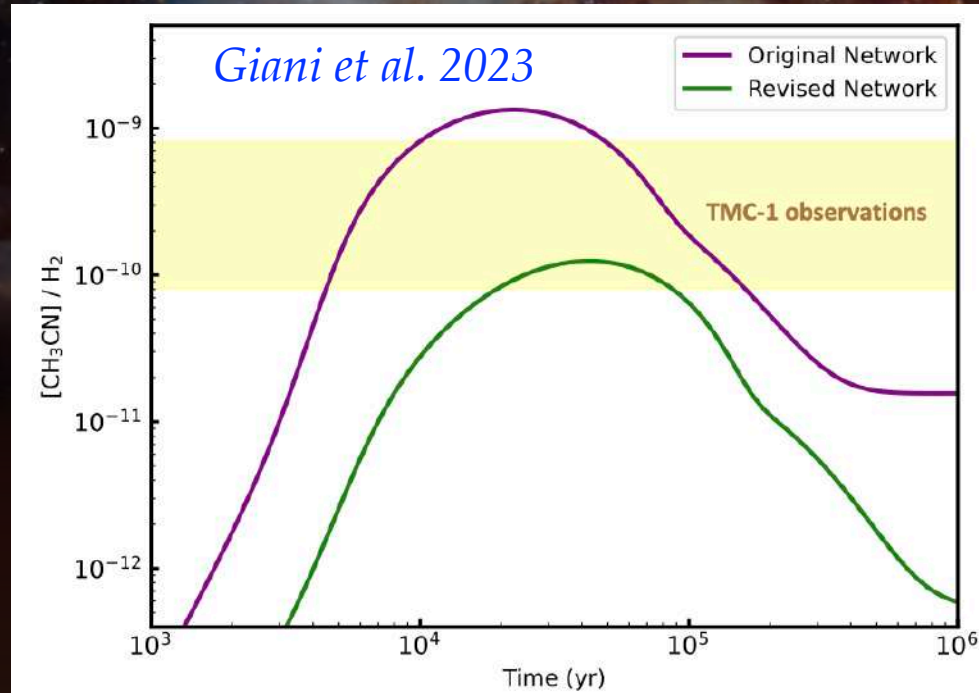


With a robust chemical network, the physical properties can be derived

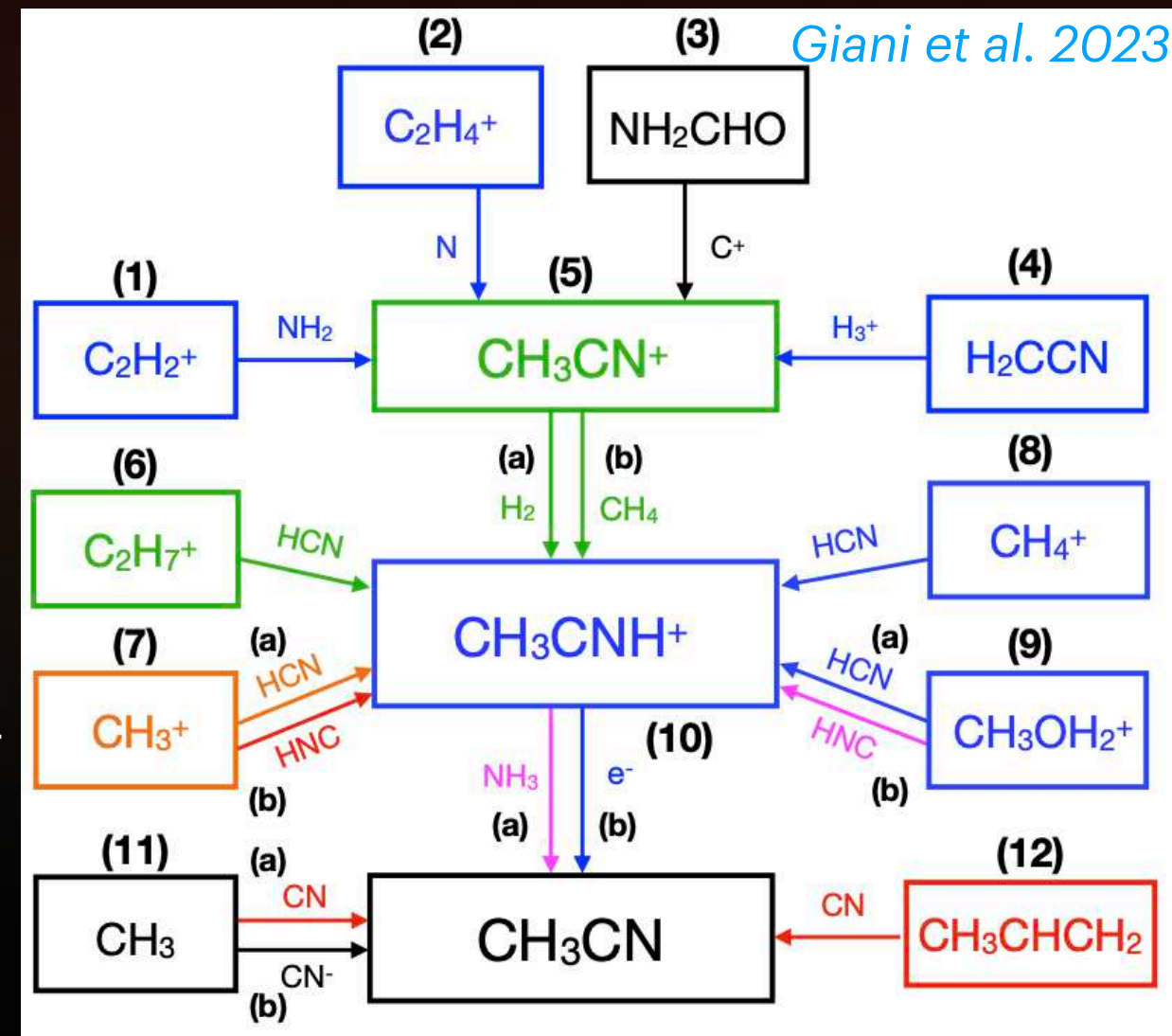
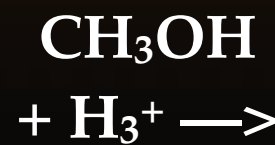
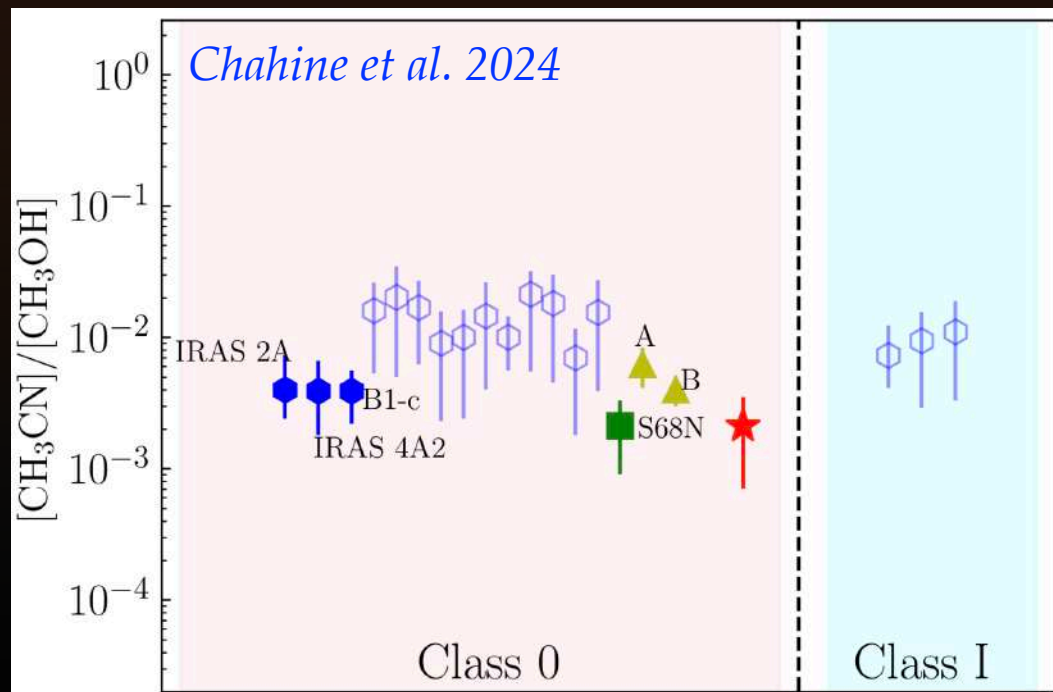


# How to constrain iCOMs formation routes?

...Looking at correlations



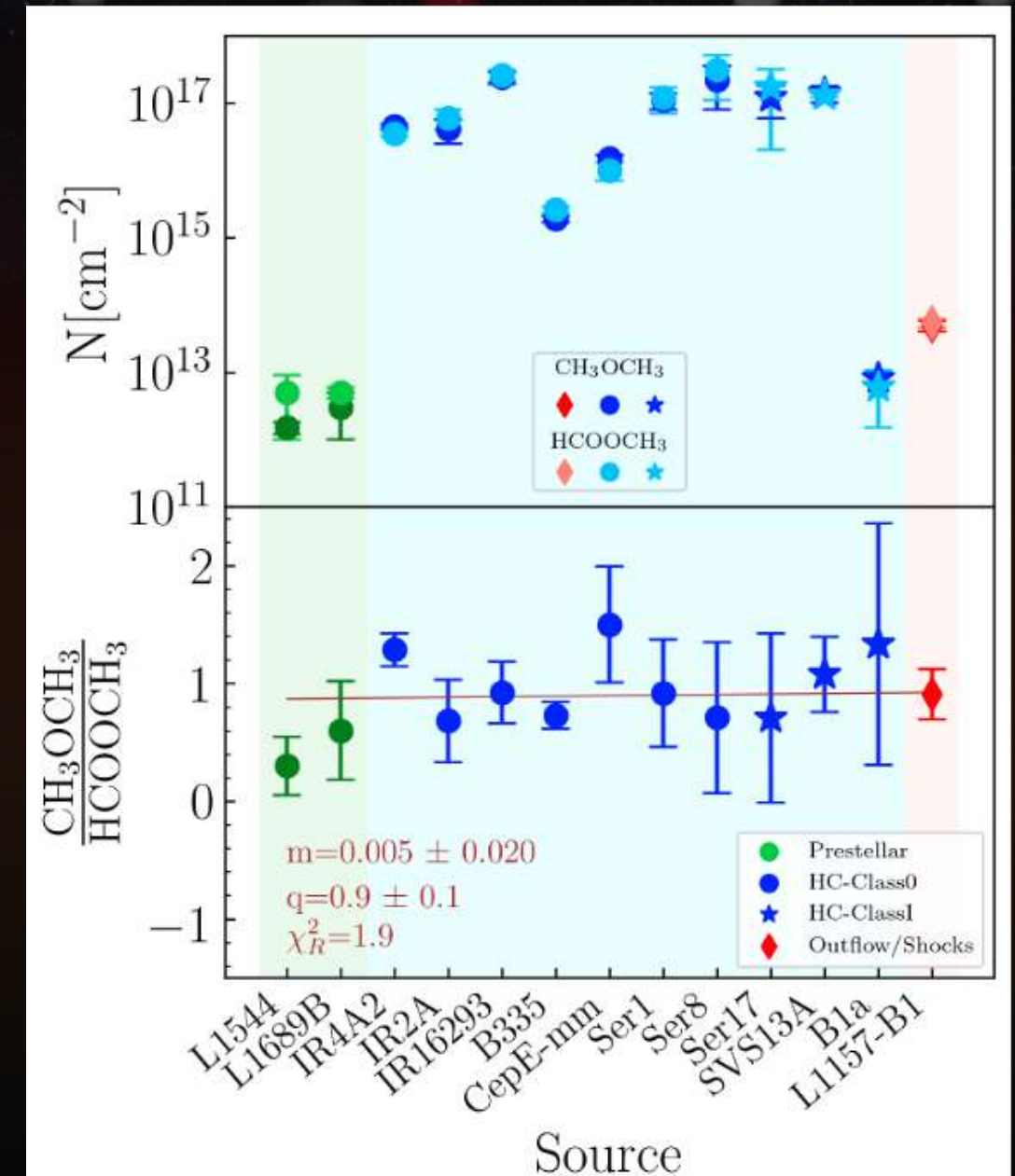
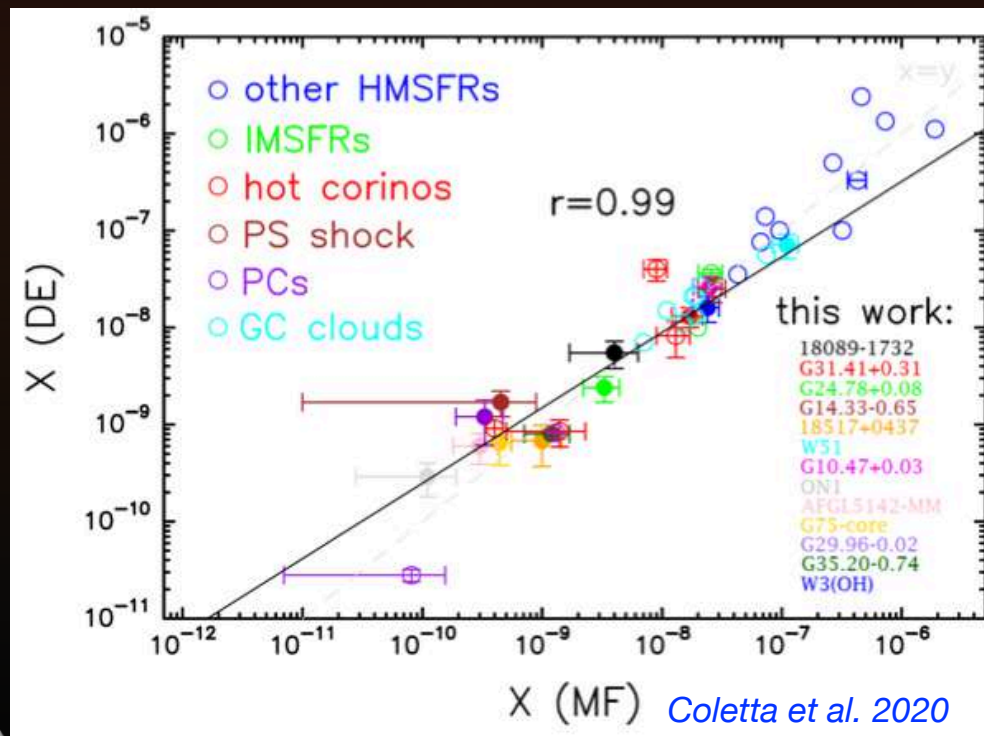
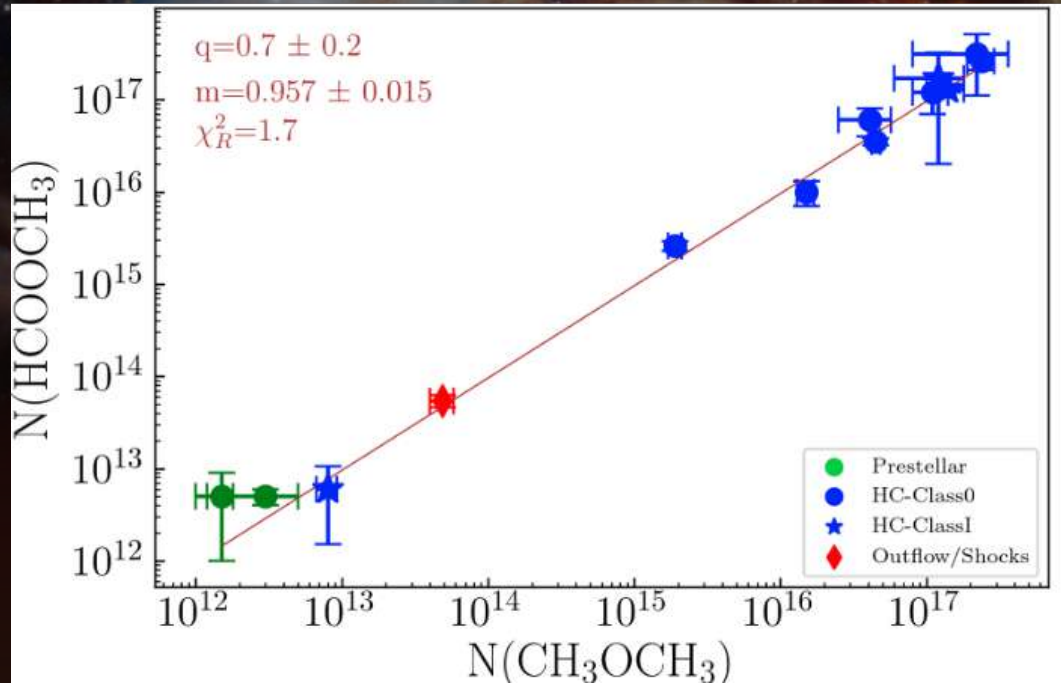
A correlation can be a **hint** of chemical link,  
Not necessarily of a shared formation route



See also Belloche et al. 2020, Yang et al. 2021

# How to constrain iCOMs formation routes?

...Looking at correlations



Jaber et al. 2014, Coletta et al. 2020, Nazari et al. 2022

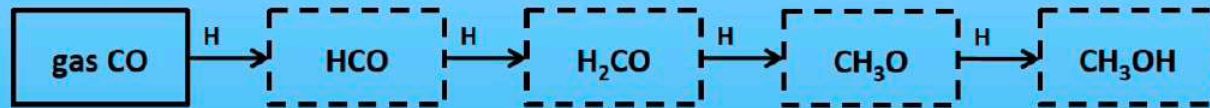
Strong correlation between  
Dimethyl Ether and Methyl Formate

# How to constrain iCOMs formation routes?

...Looking at correlations

On the grain surface:

Phase I: hydrogenation



Phase II: (CR-induced) hydrolysis



Phase III: warm-up

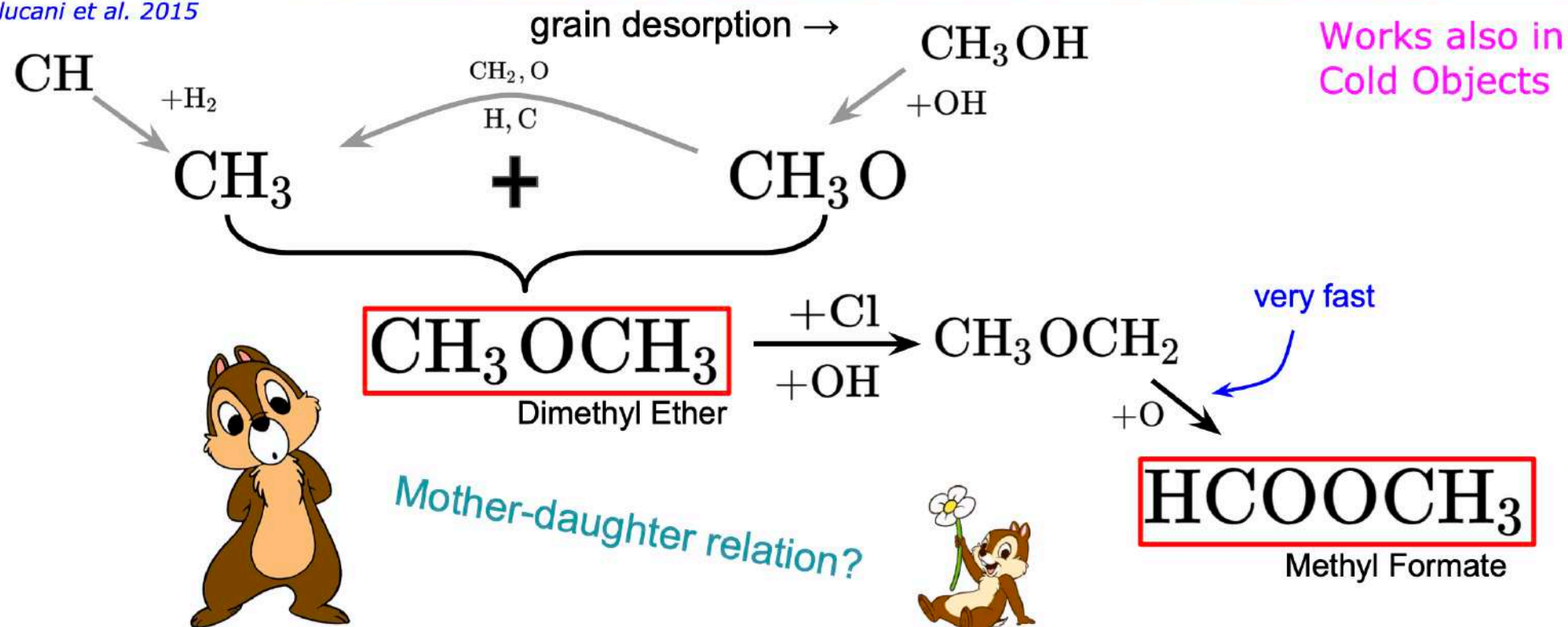


Garrod & Herbst 2006; Garrod et al. 2008; Oberg et al. 2009; Kalvans 2015

Not clear the efficiency, and how to release the iCOMs in cold objects?

In the gas phase

Balucani et al. 2015

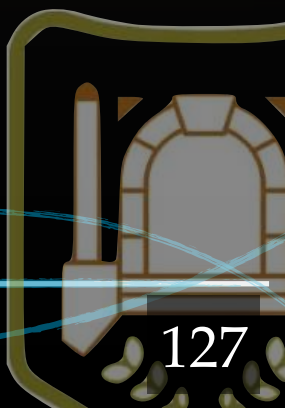


The gas phase route can reproduce the observations, especially in COLD objects ...

# In Summary....

- ✦ **Chemistry starts early:** complex molecules are already present in cold prestellar cores
  - ✦ **Chemistry evolves with star formation:** collapse, shocks, irradiation and disks continuously reshape the molecular inventory
  - ✦ Tracing chemical **inheritance** is the natural next step, but requires careful treatment of observational and methodological biases
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- ✦ **Molecules are powerful diagnostics:** they trace temperature, density, kinematics and physical structure.
  - ✦ **A interdisciplinary approach is crucial:** Observations + computation/ experiments + modelling

*Chemistry is one of the most powerful tools we have to understand how planetary systems emerge*



# The origin of chemical complexity from clouds to disks

*Questions, curiosities?*

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