

# ASTROCHEMICAL ORIGINS : THE (POTENTIAL) HERITAGE FROM PROTOSTELLAR AND PLANETARY EONS

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and the (great) DOC TEAM:

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The Solar System and the Earth are the products of a long and complex process.

We were a cloud of the Milky Way.

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The Solar System and the Earth are the products of a long and complex process.

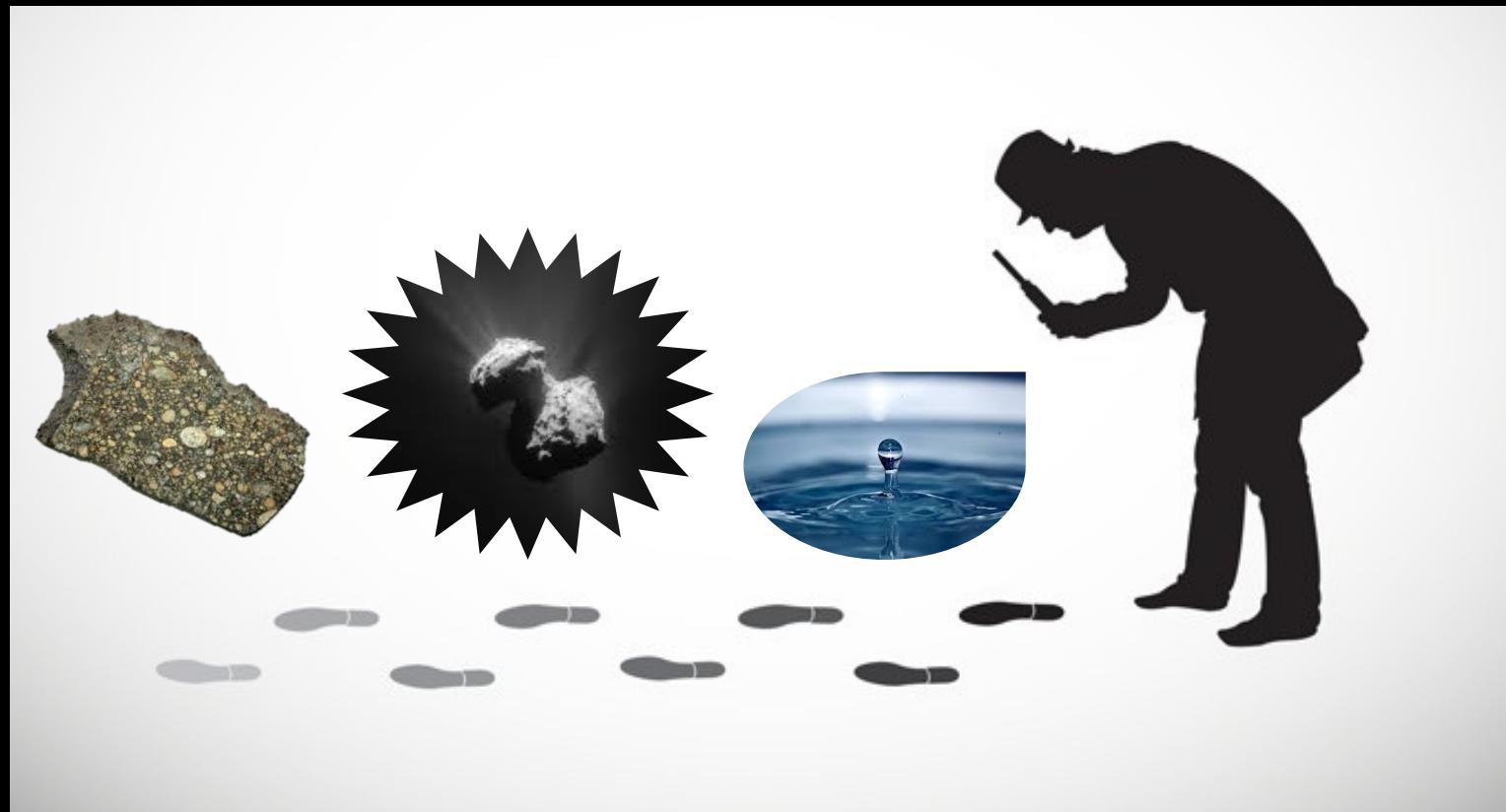


We were a cloud of the Milky Way.  
We became a system of planets.  
Life emerged on Earth.

# Is life a unique phenomenon? What happened?



Is life a unique phenomenon?  
What happened?  
We follow the traces left...



# Is life a unique phenomenon?

- 1) What ingredients does terrestrial life need?
- 2) From where and how did it get those ingredients?  
**What happened?**

# What does terrestrial life need?

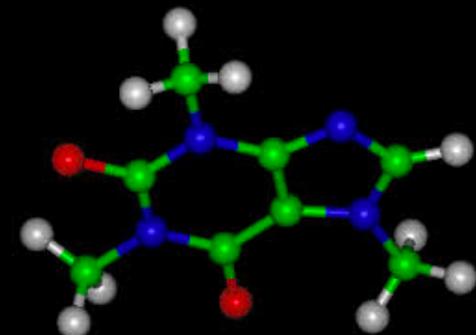


# What does terrestrial life need?

Coffee?



Caffeine!

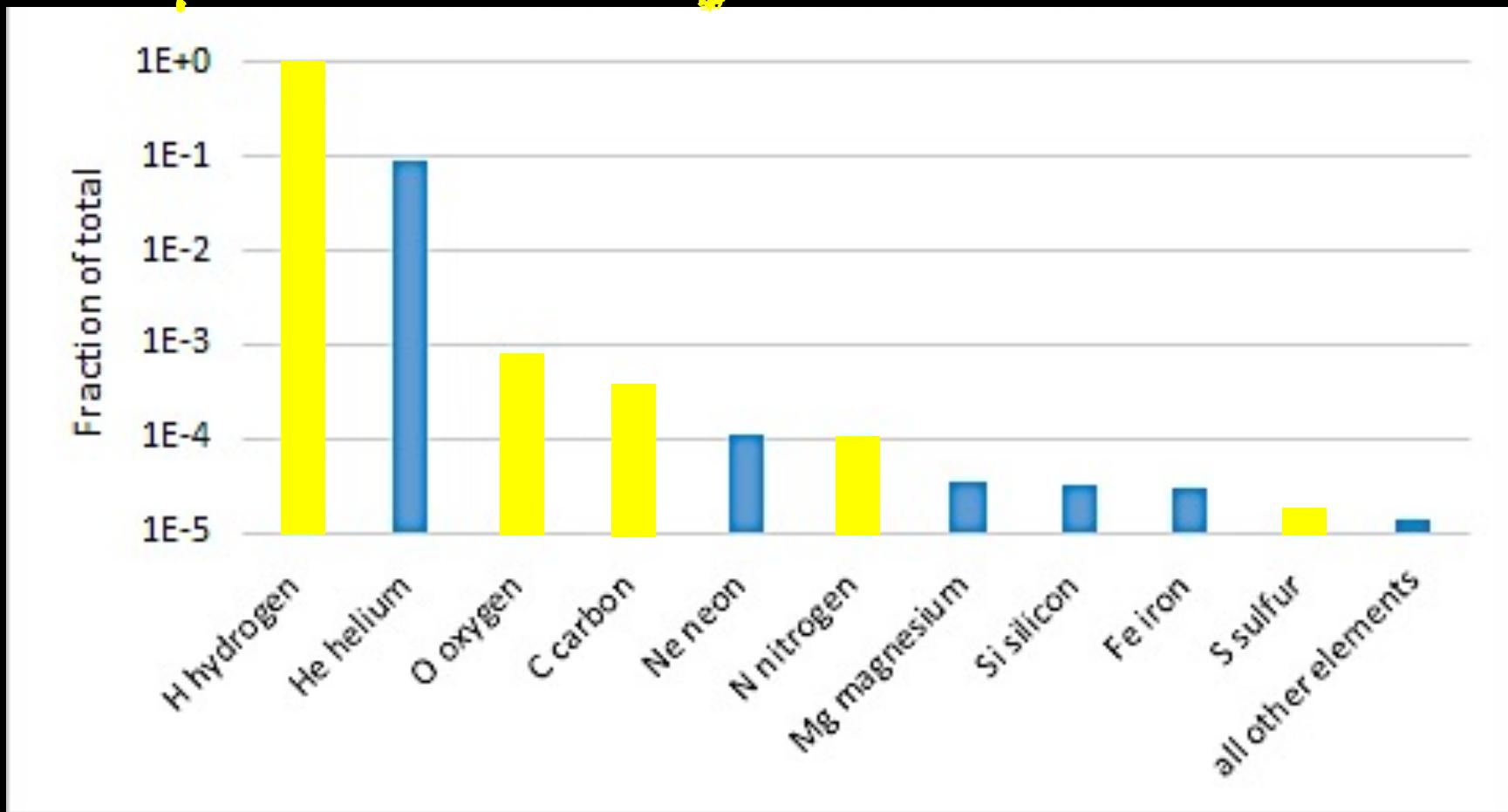


→ Carbon

+ a little of Nitrogen, Sulphur, Phosphorous...



In the Local ISM, the most abundant elements not locked in minerals are Hydrogen, Oxygen, Carbon, Nitrogen, Sulphur...exactly what life needs!



# Is Life a unique phenomenon? probably NO

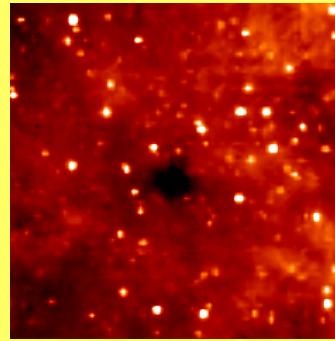


What happened?

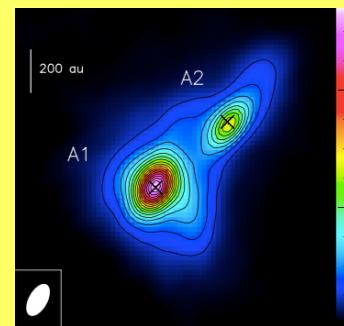
Probably nothing of  
special... what still  
happens today to newly  
forming planetary systems

# FROM A DIFFUSE CLOUD TO A PLANETARY SYSTEM FROM ATOMS & SIMPLE MOLECULES TO LIFE

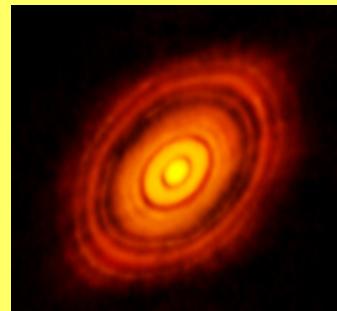
(adapted from Caselli & Ceccarelli 2012, A&ARev)



1- PRE-STELLAR PHASE: cold and dense gas  
FORMATION OF SIMPLE/COMPLEX MOLECULES



2- PROTOSTELLAR PHASE: collapsing, warm dense gas  
SUBLIMATION/FORMATION OF COMPLEX MOLECULES



3- PROTOPLANETARY DISK PHASE:  
cold and warm dense gas  
SIMPLE & COMPLEX MOLECULES

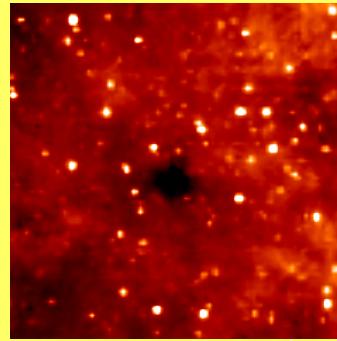


4- PLANETESIMAL FORMATION : grains agglomeration  
STORAGE/REPROCESSING OF GRAIN MANTLE ICES

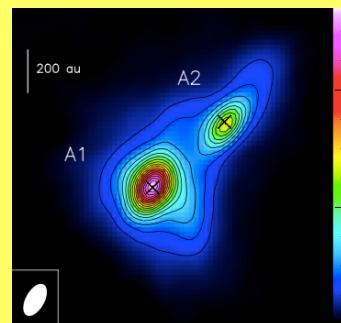
5- PLANET FORMATION AND THE “COMET/ASTEROID RAIN”:  
planet migration, small bodies scattering; Earth oceans formation  
CONSERVATION/DELIVERY OF OLD MOLECULES + LIFE?

# FROM A DIFFUSE CLOUD TO A PLANETARY SYSTEM FROM ATOMS & SIMPLE MOLECULES TO LIFE

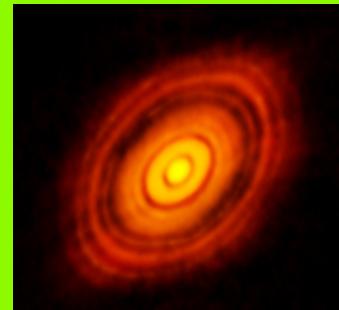
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Davide's & Linda's TALKS

Stavro's, Luis Diego & Diego's TALKS



4- PLANETESIMAL FORMATION : grains agglomeration  
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5- PLANET FORMATION AND THE “COMET/ASTEROID RAIN”:  
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Antonella's TALK

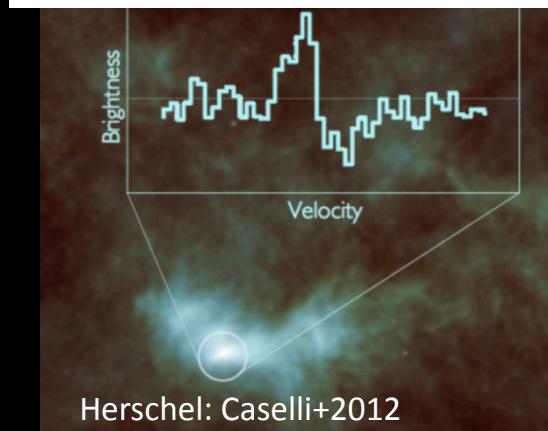
# WATER



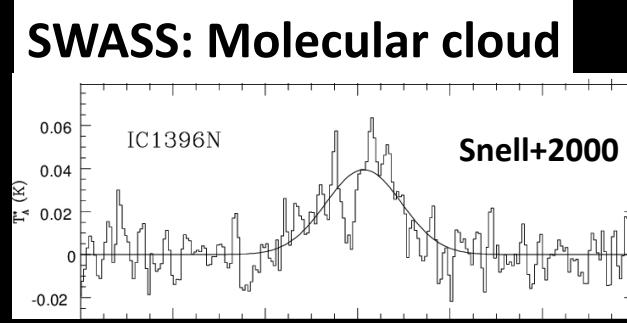
## Where, when and how

# LOADS OF WATER EVERYWHERE

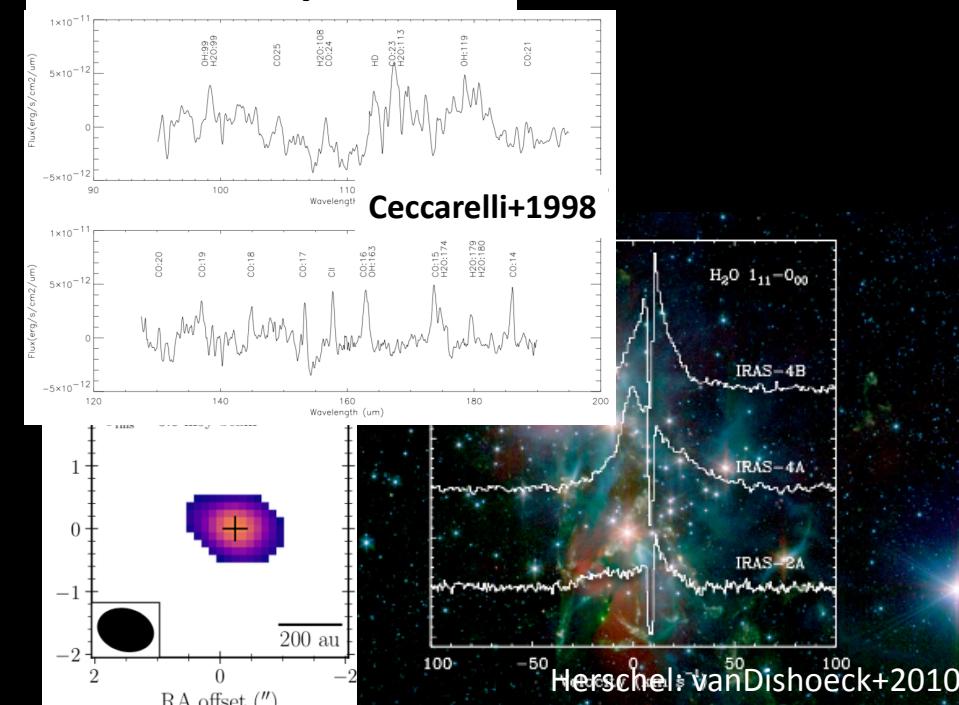
Herschel: Prestellar cores



SWASS: Molecular cloud

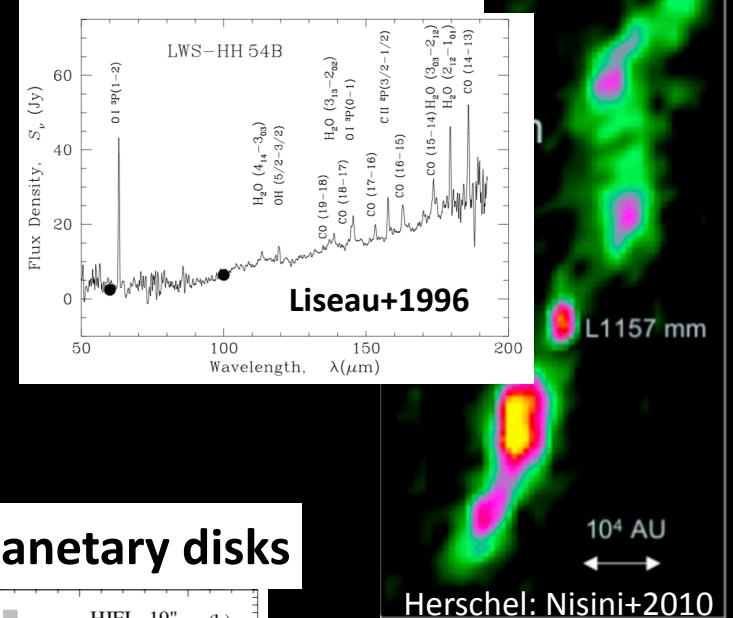


ISO: Class 0 protostar

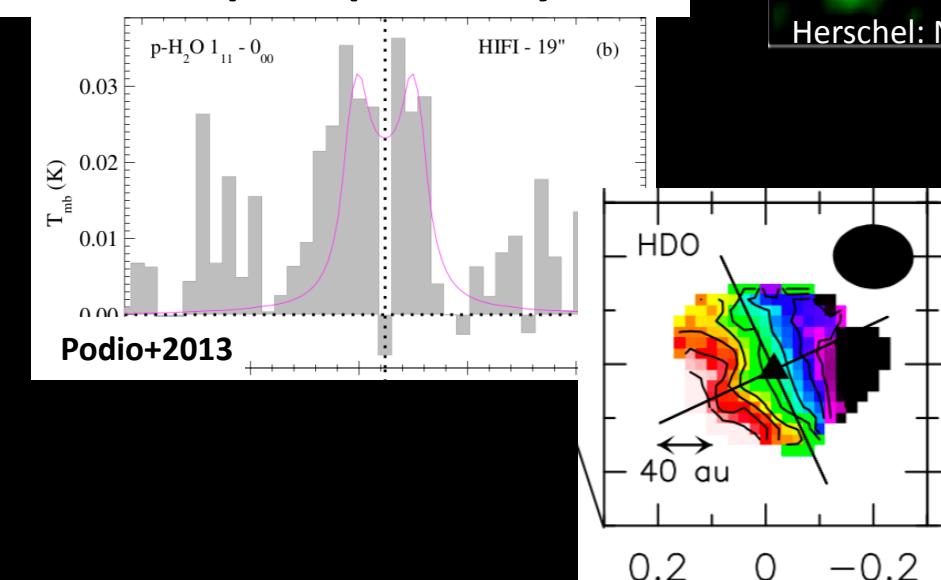


ALMA: Jensen+2019

ISO: Outflow shocks



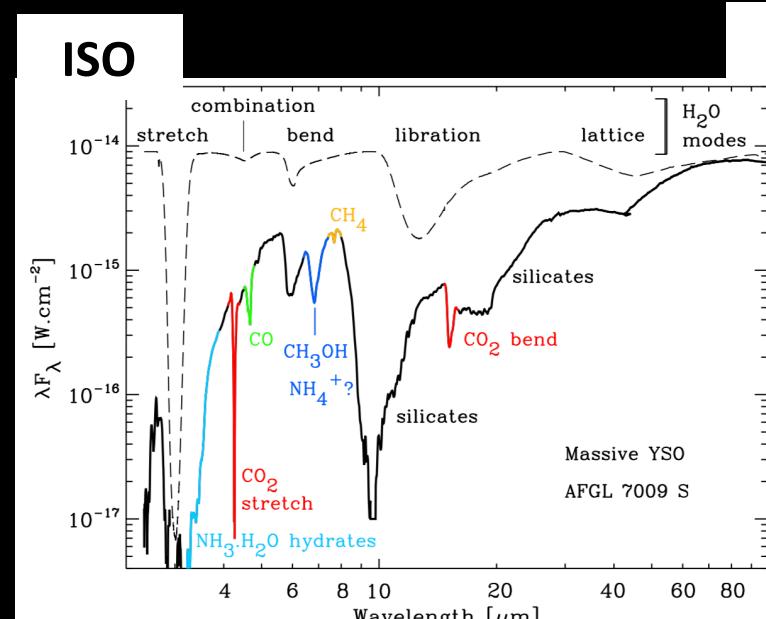
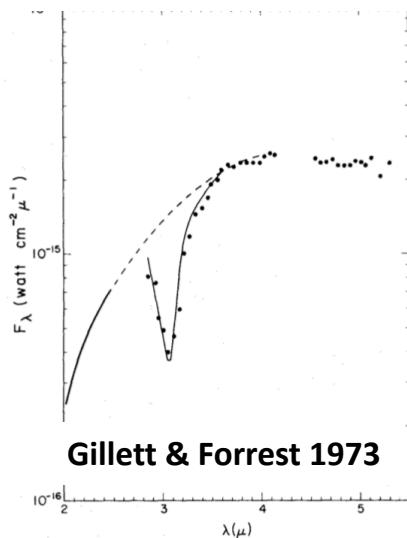
Herschel: protoplanetary disks



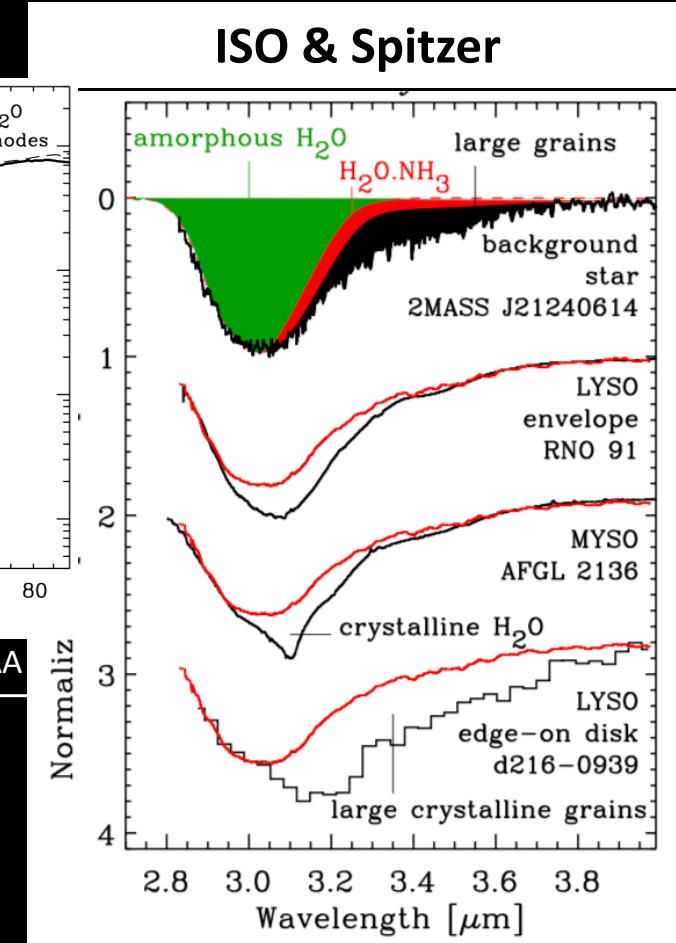
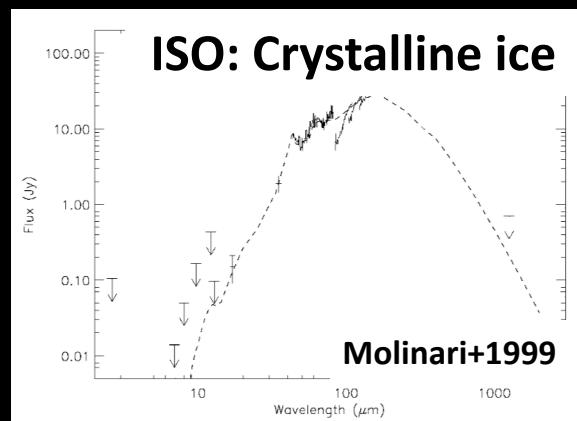
ALMA: Codella+2018

# LOADS OF WATER EVERYWHERE FROZEN

Mount Lemmon  
telescope: Orion BN/KL



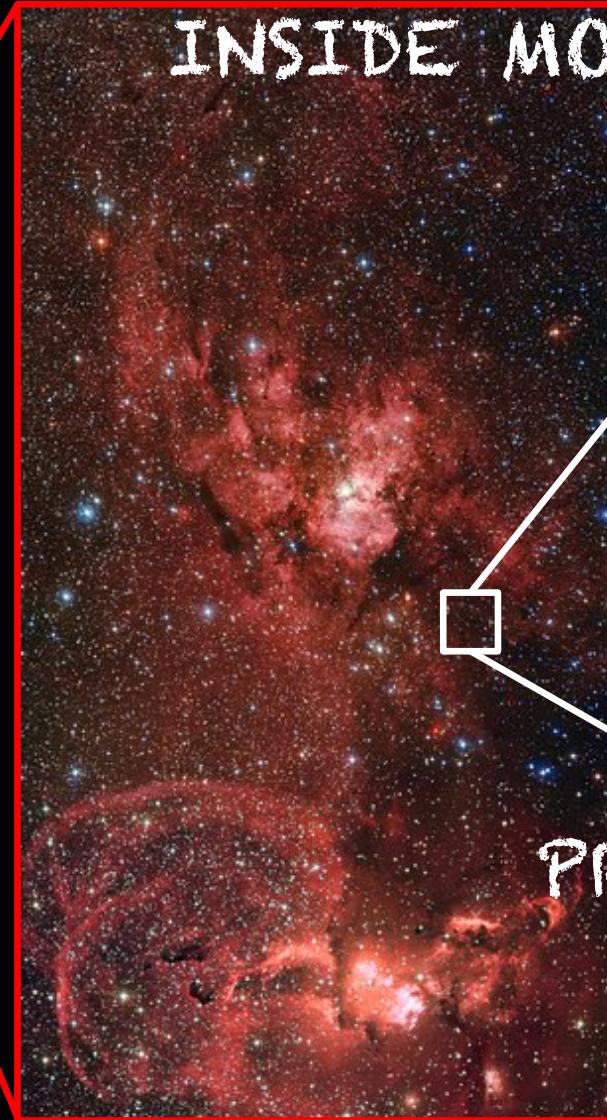
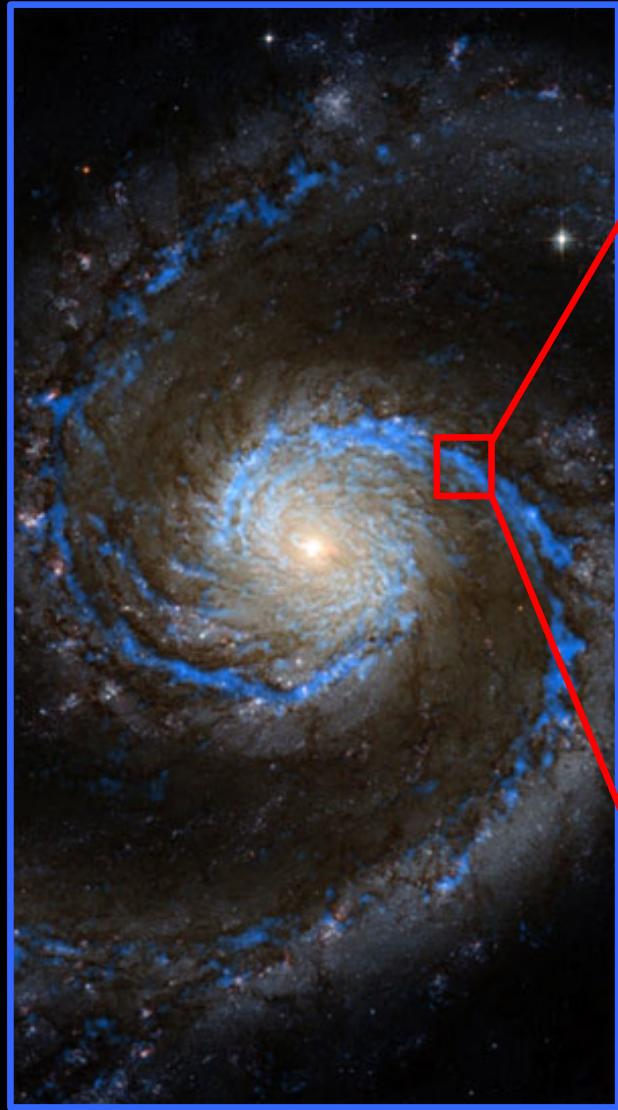
Boogert, Gerakines & Whittet 2015, ARAA



# Where & how water is formed?

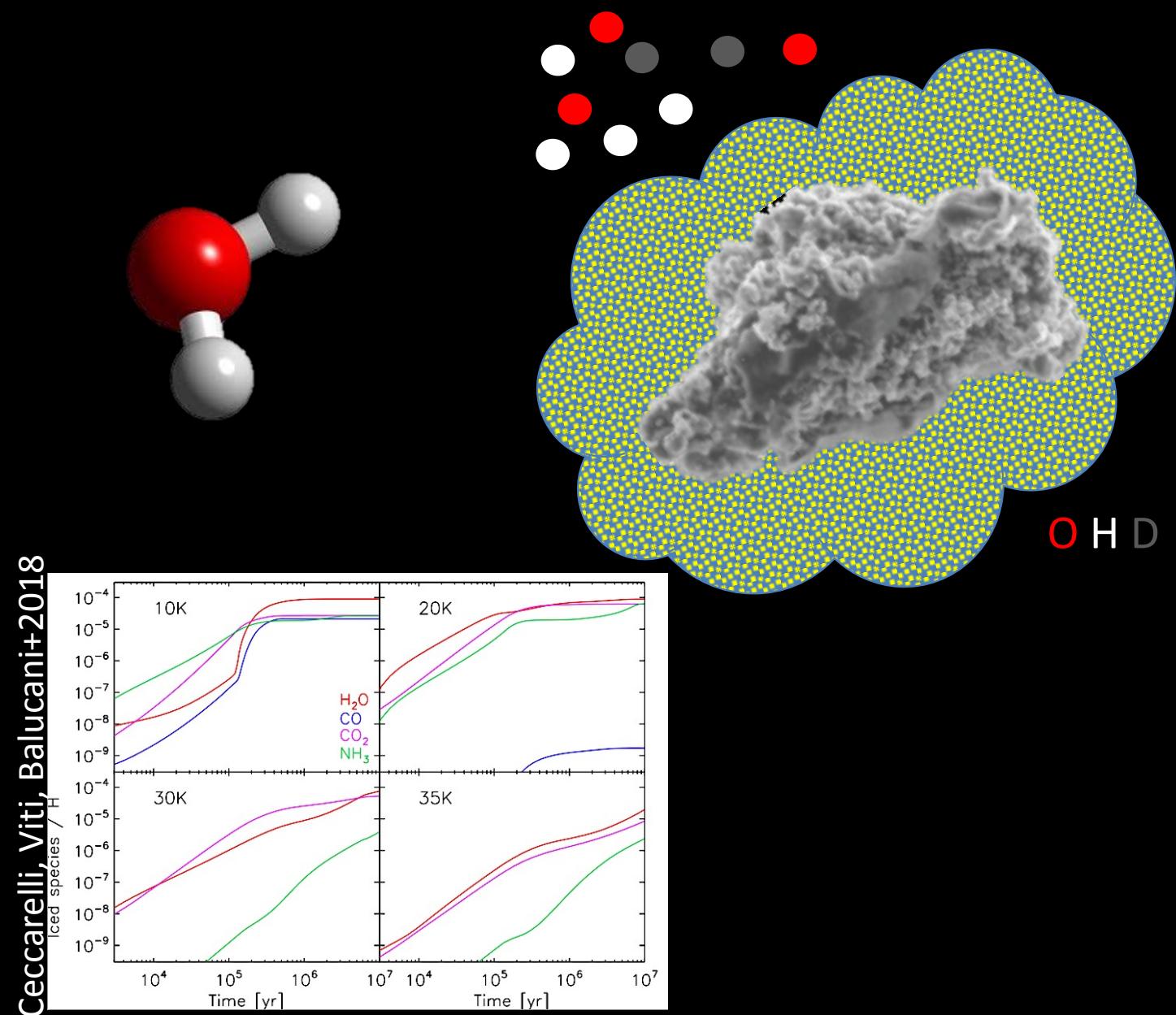
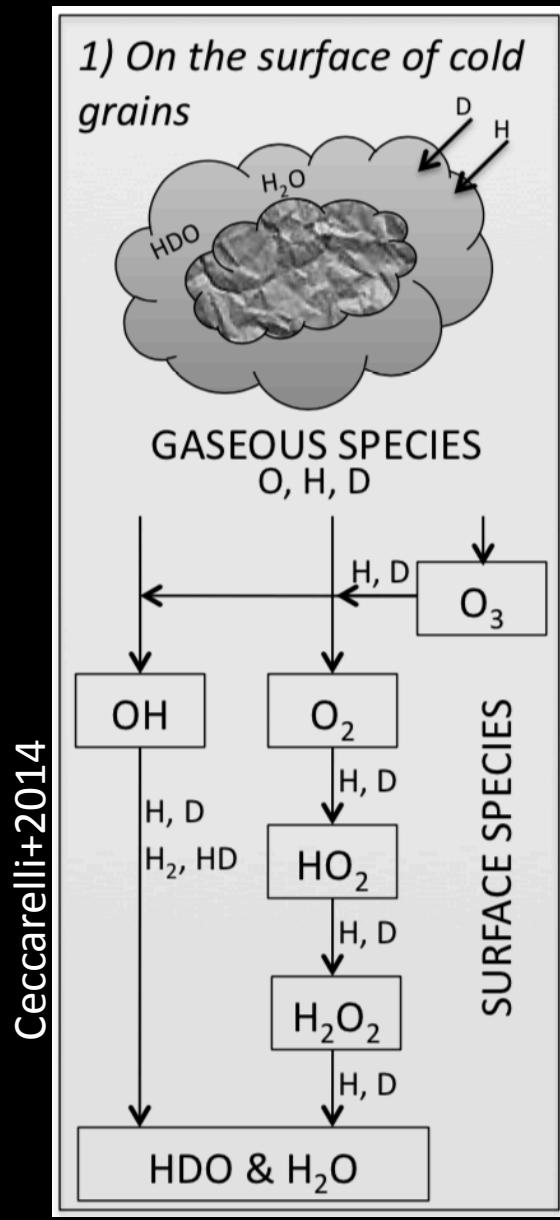
STARS ARE BORN FROM DENSE AND COLD CLUMPS

INSIDE MOLECULAR CLOUDS  
WATER TOO



PRESTELLAR CORES  
 $T \leq 10K$   
 $n_H \geq 10^6 \text{ cm}^{-3}$

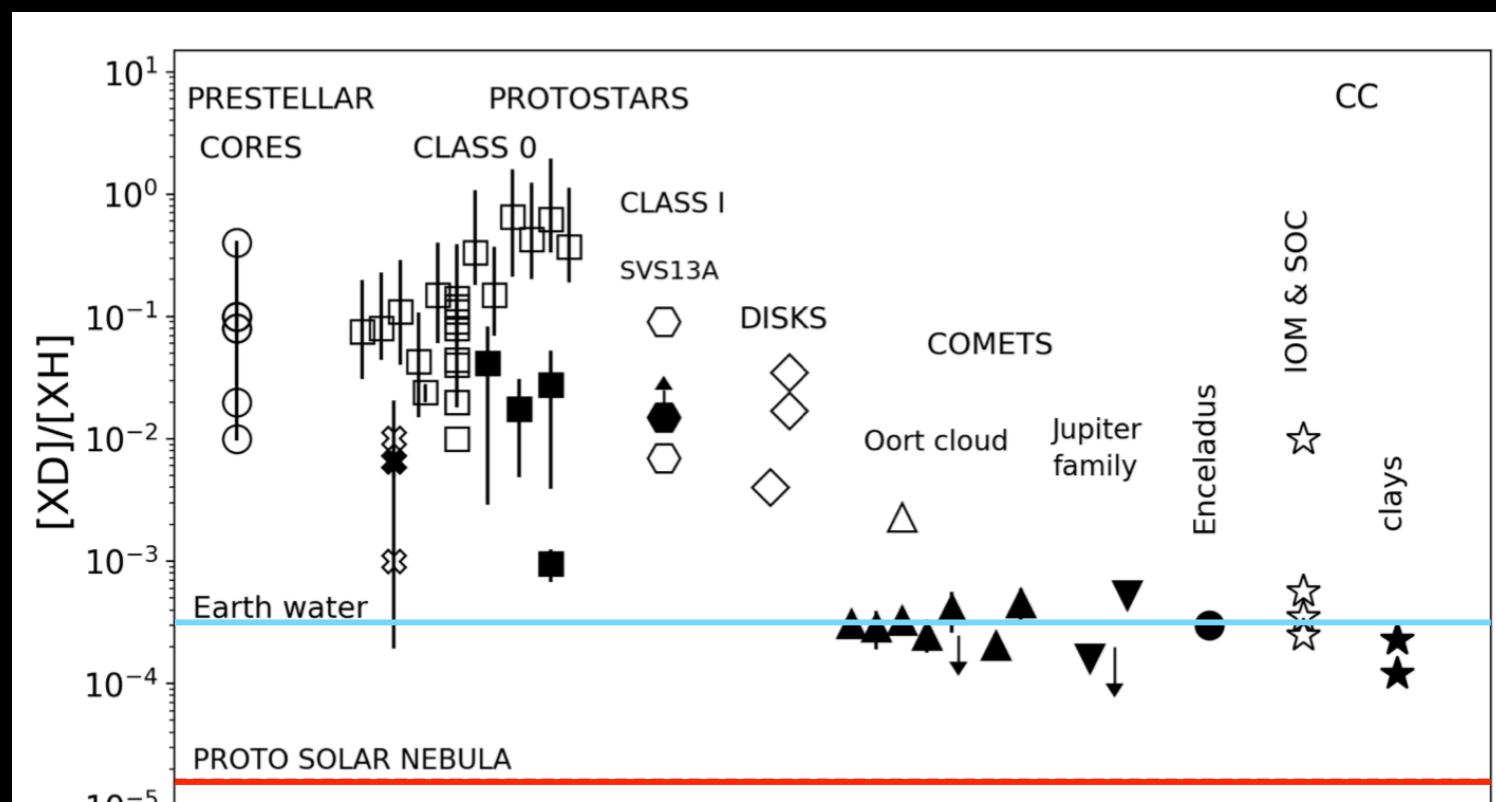
# WATER IS FORMED ON THE GRAIN SURFACES



# ...BUT DID interstellar WATER REACH EARTH?

## The answer is blown in the molecular deuteration

Bianchi+ 2020



WATER DEUTERATION TELLS US THAT  
(a good fraction of) TERRESTRIAL  
WATER WAS FORMED 4.5 BY AGO  
WHEN THE SOLAR SYSTEM WAS A  
PRESTELLAR CORE

# INTERSTELLAR COMPLEX ORGANIC MOLECULES (iCOMs)

Where, when and how

What about organic molecules?  
Are they also everywhere?  
How are they formed?

What about organic molecules?  
Are they also everywhere? yes?  
How are they formed? open q.

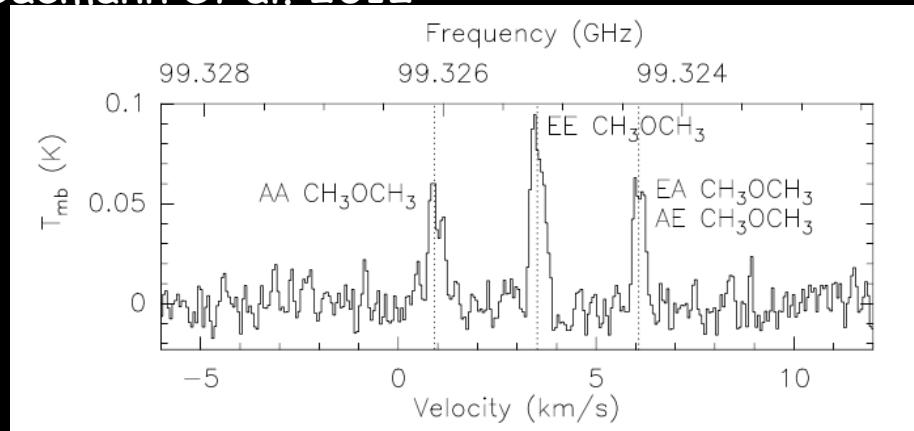
## THE SAGA OF THE iCOMs

(here you will ear almost only one bell...)

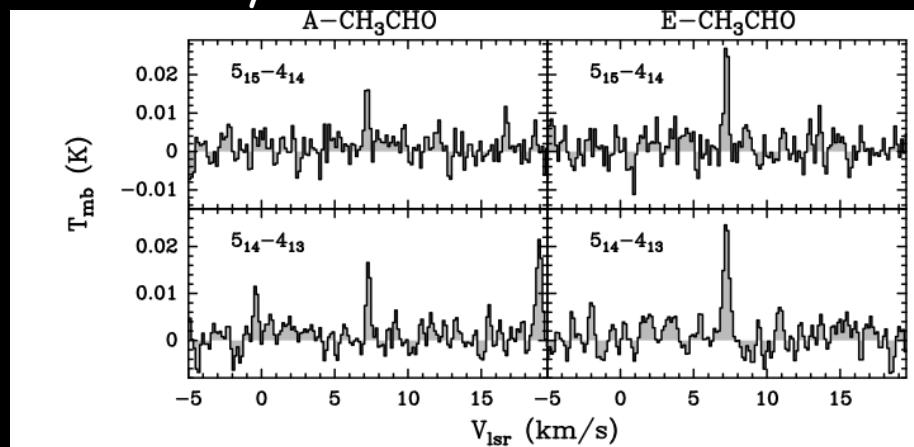
# WHERE? iCOMs in PSCs

Dimethyl ether & methyl formate in L1689B;

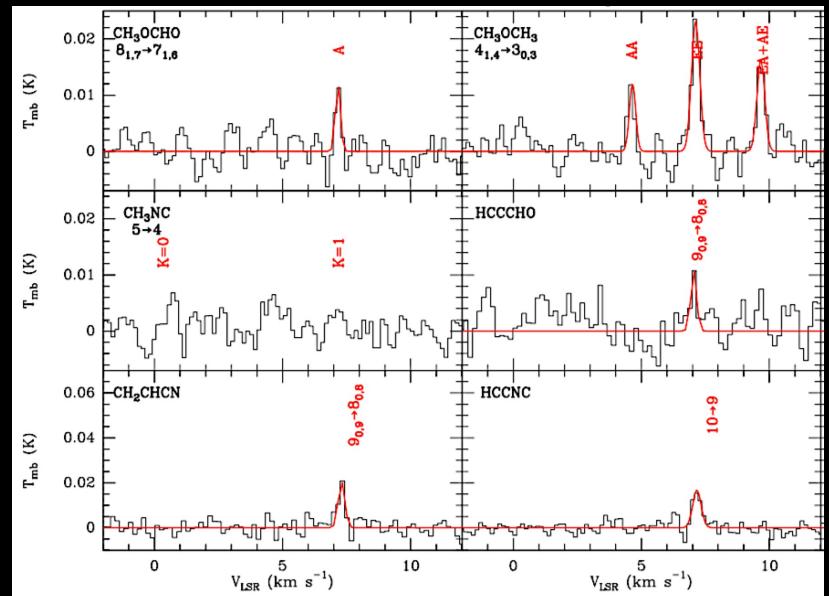
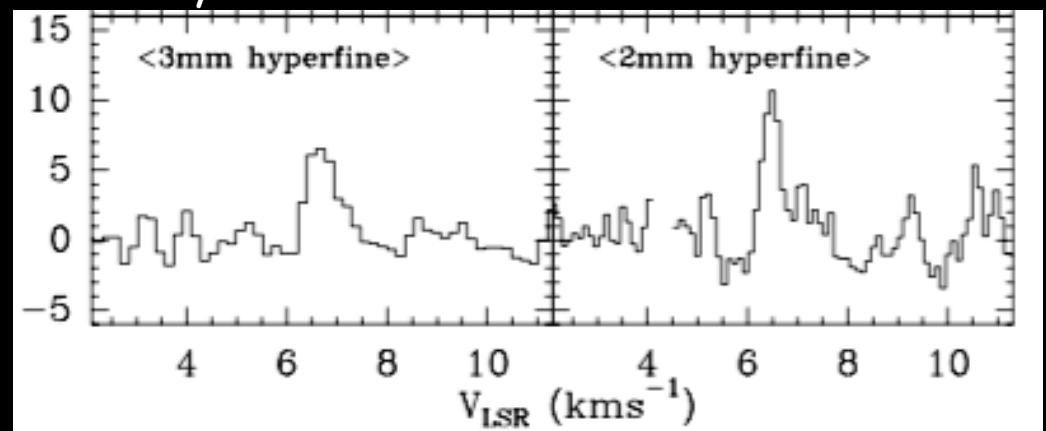
Bacmann et al. 2012



Acetaldehyde in L1544; Vastel et al. 2014



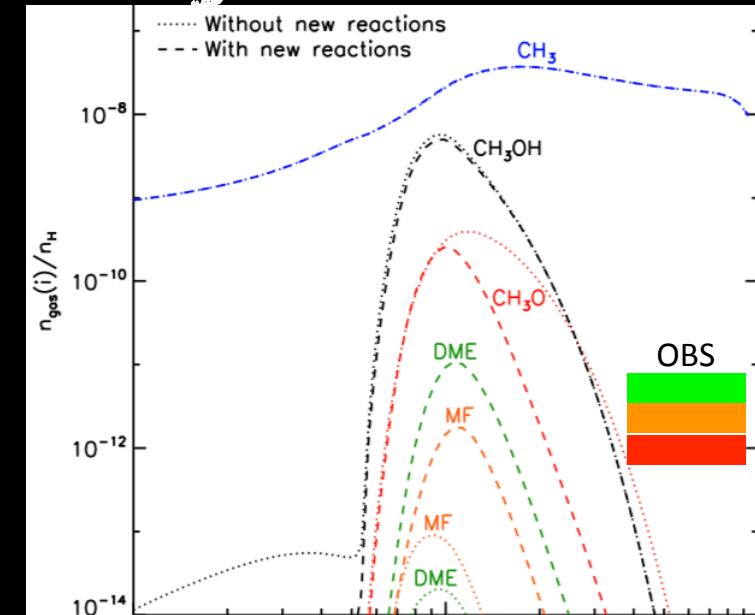
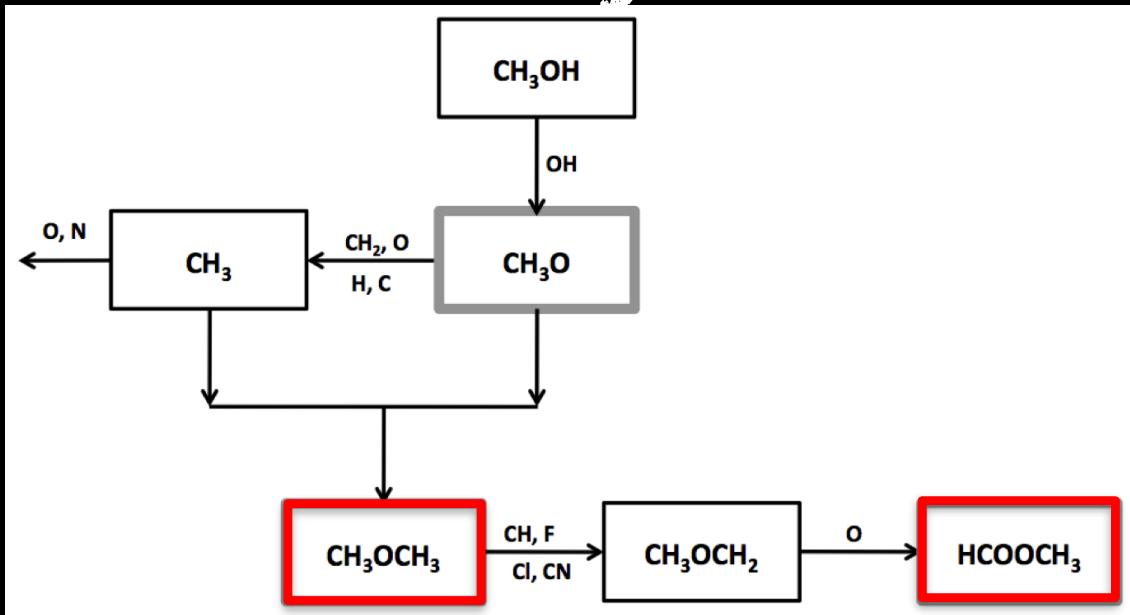
Methoxy in B1-b; Cernicharo et al. 2012



iCOMs in L1544: Jiménez-Serra et al. 2016

# HOW? iCOMs in PSCs

## Ex: Dimethyl ether & methyl formate



Balucani, Ceccarelli & Taquet 2015

**ANSWER: GAS-PHASE REACTIONS STARTED BY METHANOL INJECTED FROM THE GRAIN SURFACES INTO THE GAS**

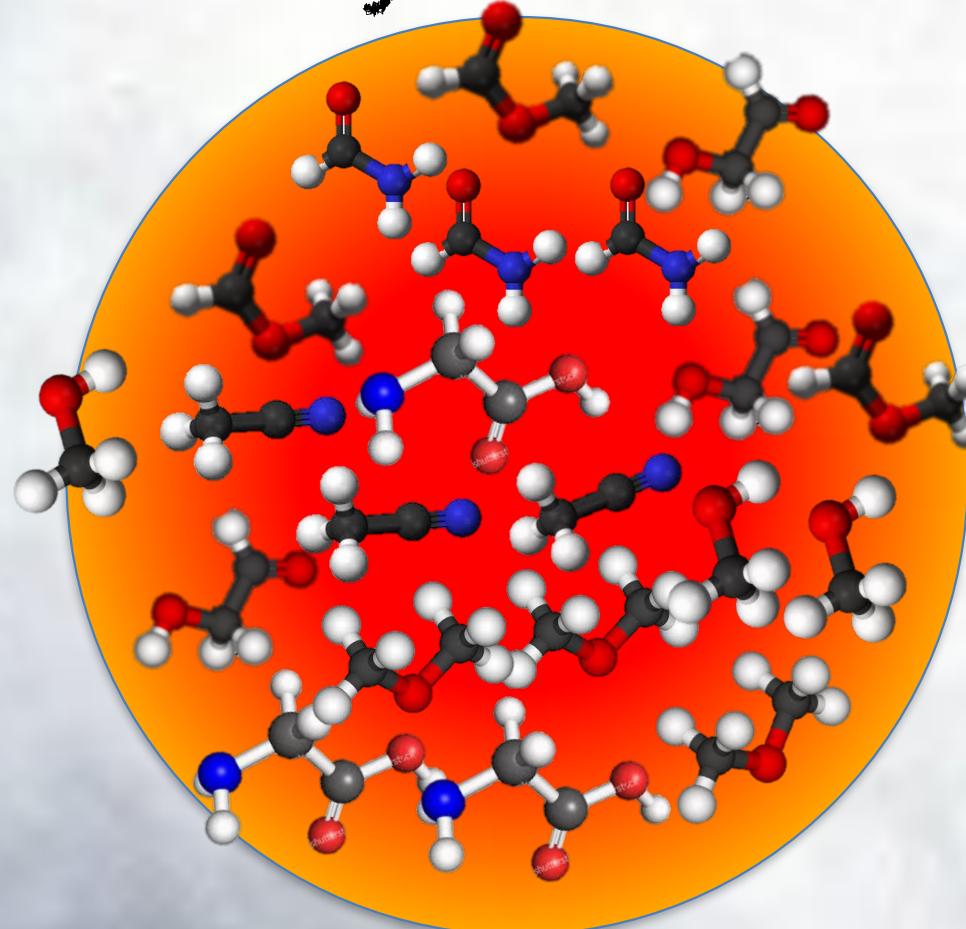
**QUESTION: WHY IS METHANOL IN THE GAS?**

# WHERE? iCOMs in HOT CORINOS

HOT CORINOS: retail shops of iCOMs

iCOMs = interstellar Complex Organic Molecules

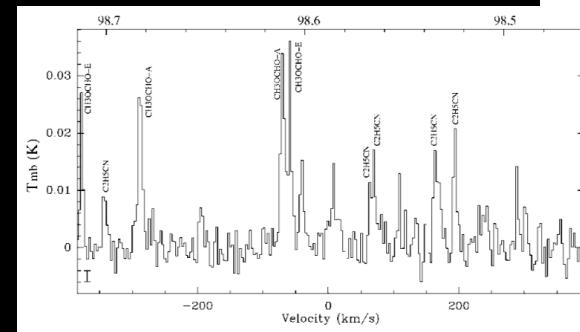
Like methanol, methyl formate, formic acid, ethanol...



see Chiara's talk  
for high-mass objects

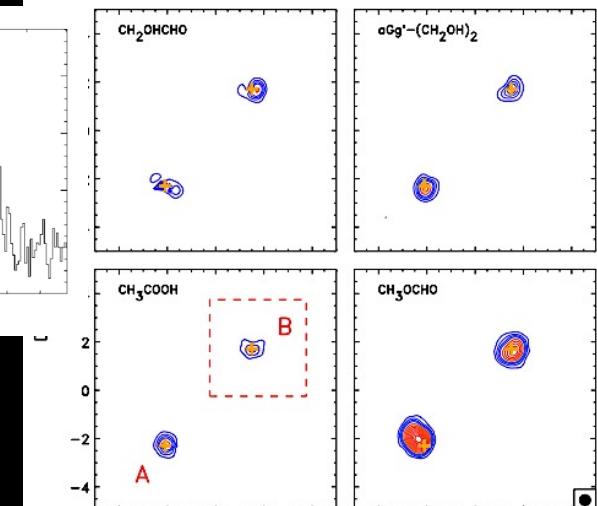
# WHERE? ICOMs in HOT CORINOS

IRAS16293-2422



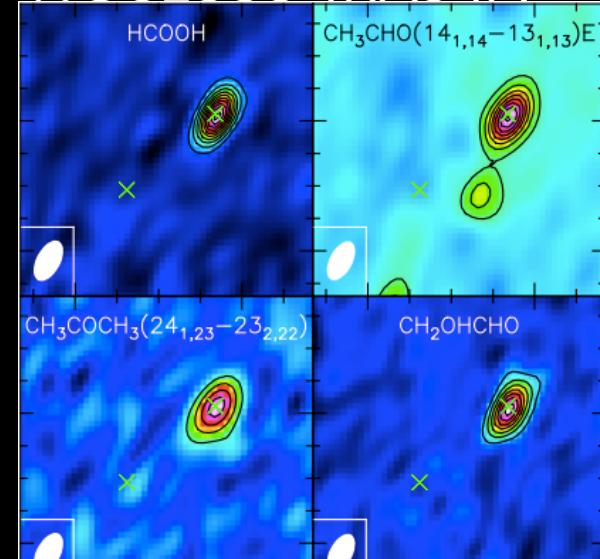
Class 0

IRAM: Cazaux+2003



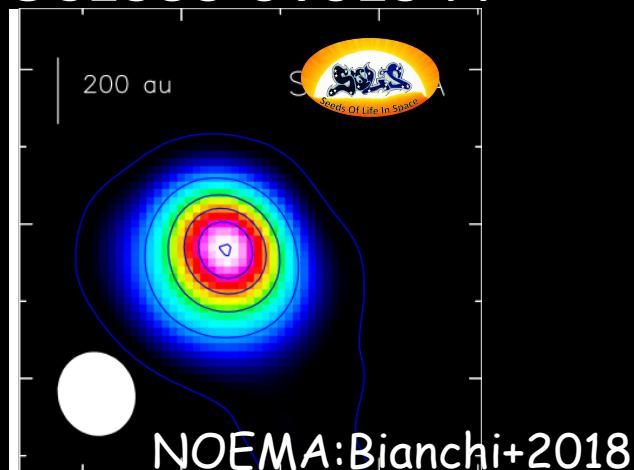
ALMA: Jorgensen+2016

NGC1333-IRAS4A



ALMA+PDBI: López-Sepulcre+2017

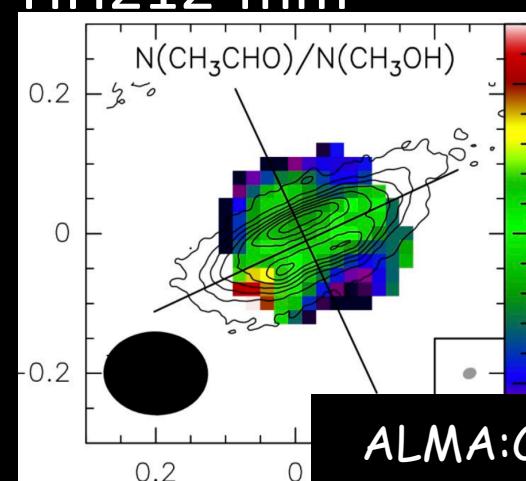
NGC1333-SVS13-A



Class I

NOEMA:Bianchi+2018

HH212-mm



ALMA:Codella+2019

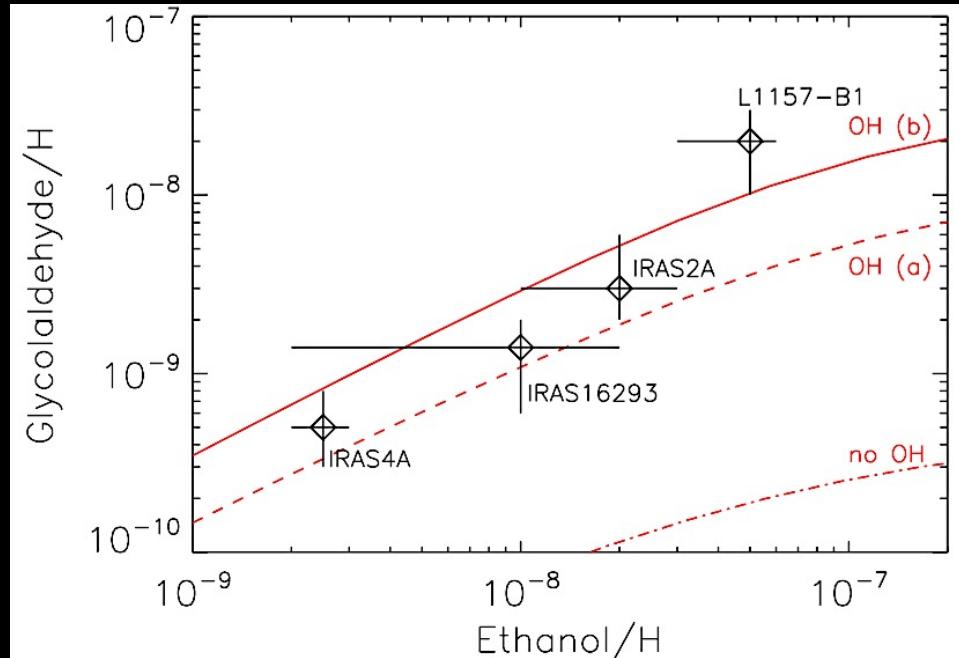
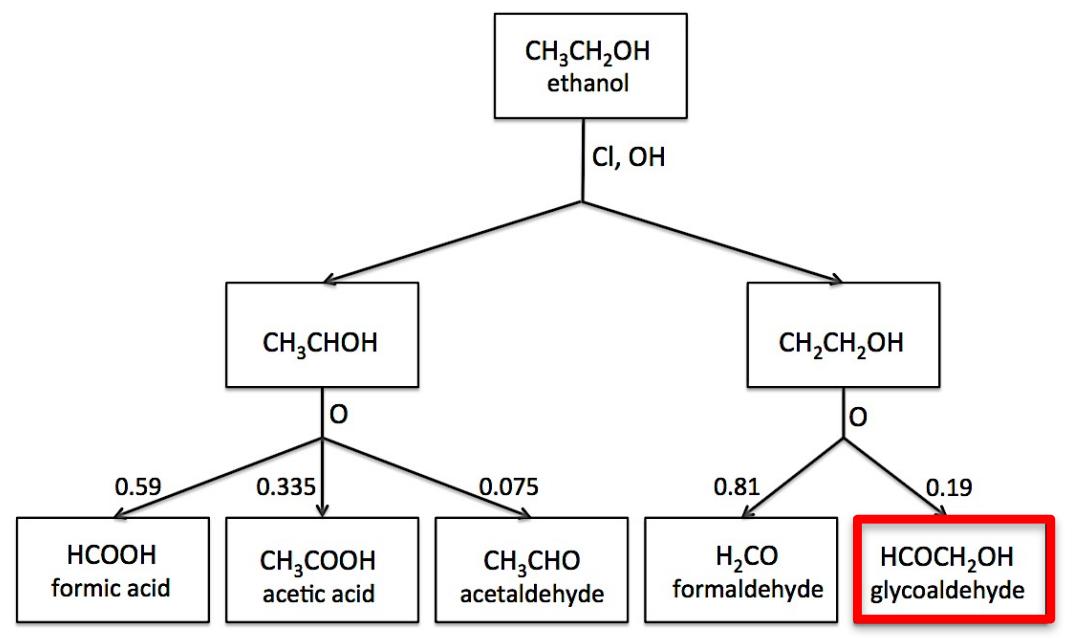
TIME



# HOW? ICOMs in HOT CORINOS

## Ex: Glycolaldehyde

Skouteris, Balucani, Ceccarelli et al. 2018

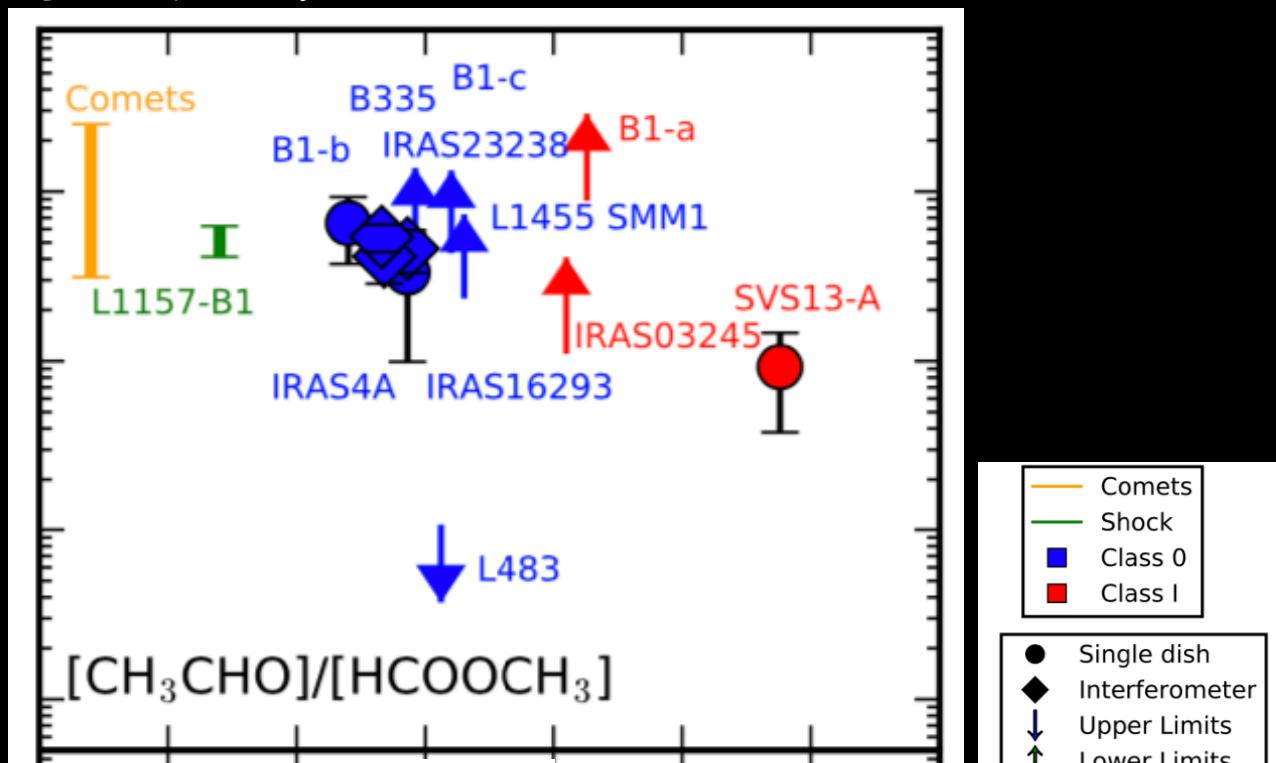


Lefloch, Ceccarelli, Codella et al. 2017

**ANSWER: GAS-PHASE REACTIONS STARTED BY ETHANOL**  
**QUESTION: HOW IS ETHANOL FORMED?**

# iCOMs in HOT CORINOS

Bianchi+2019



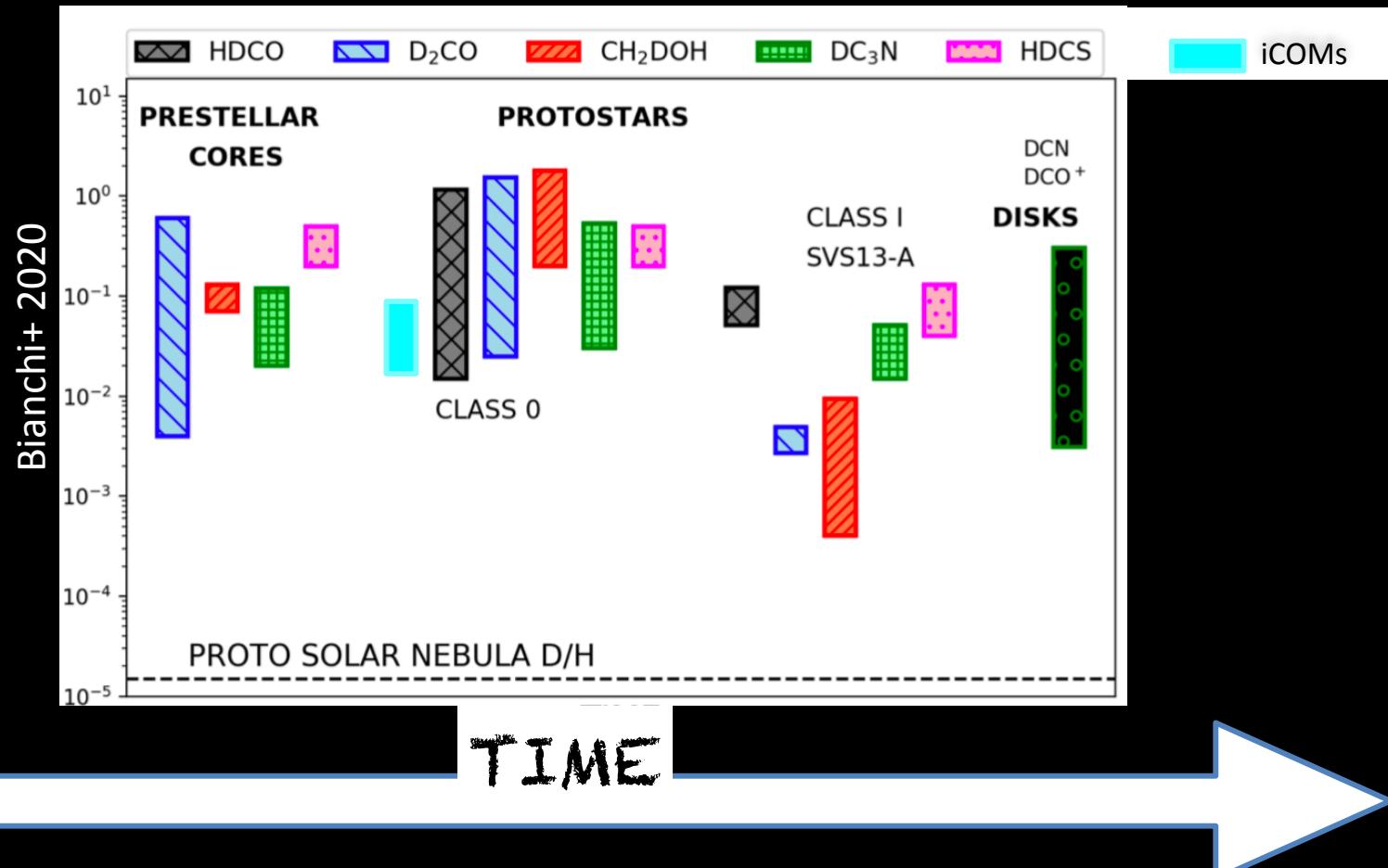
$T_{\text{bol}}$

Class 0      Class I

iCOMs EVOLUTION?

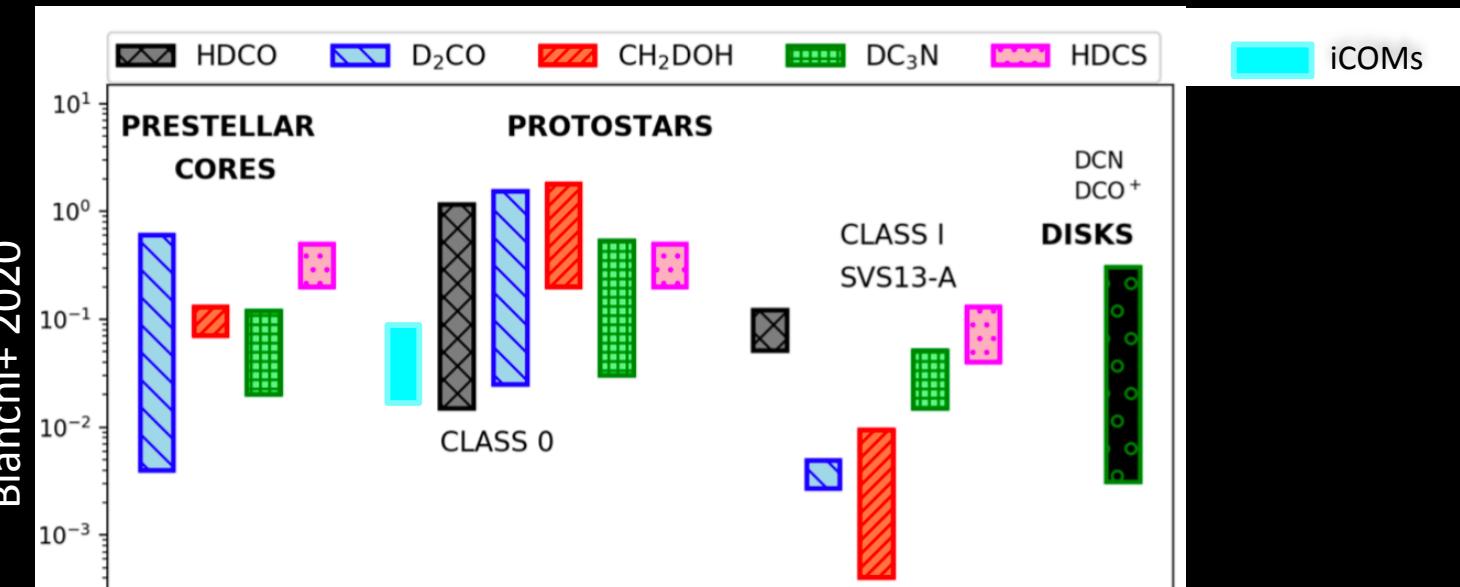
# ...BUT DID iCOMs REACH EARTH?

The answer is blown in the  
molecular deuteration



# ...BUT DID iCOMs REACH EARTH?

The answer is blown in the  
molecular deuteriation



...if we can fully understand it!  
→ Nadia's talk

# The iCOMs saga formation

## (at present) TWO PARADIGMS

### STEP 1: GRAIN MANTLE FORMATION: SPECIES HYDROGENATION

#### GAS PHASE

- 2- Grain mantle sublimation ( $\geq 100K$ )
- 3- Gas-phase reactions ( $\geq 100K$ )

Charnley, Tielens & Millar  
1992

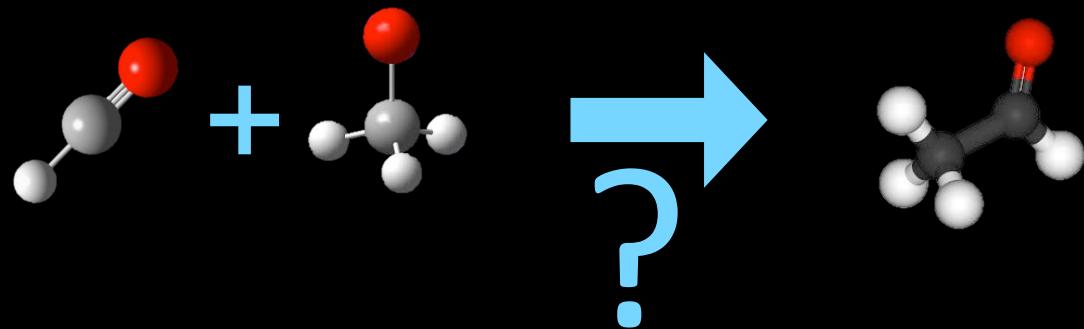
#### GRAIN SURFACES

- 2- UV and CR irradiation
  - 3- Grain mantle sublimation ( $\geq 100K$ )
- Allamandola, Bernstein,  
Sandford, Walker 1999

- 2- UV and CR irradiation
  - 3- Radical diffusion ( $\geq 30K$ )
  - 4- Radical-radical reactions
  - 5- Grain mantle sublimation ( $\geq 100K$ )
- Garrod & Herbst 2006

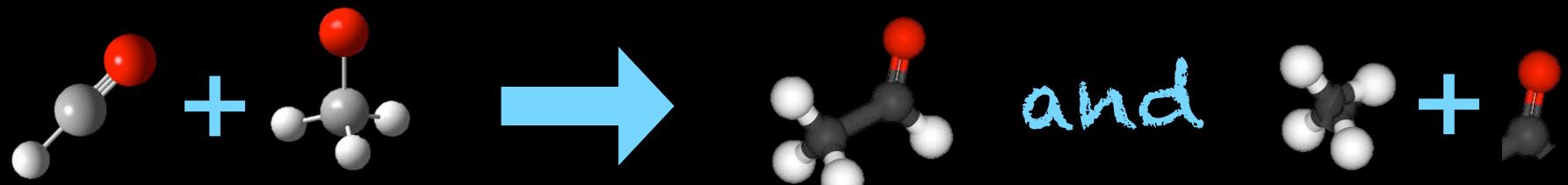
# iCOMs grain surfaces formation? RADICALS COMBINATION = iCOMs ?

EX: ACETALDEHYDE

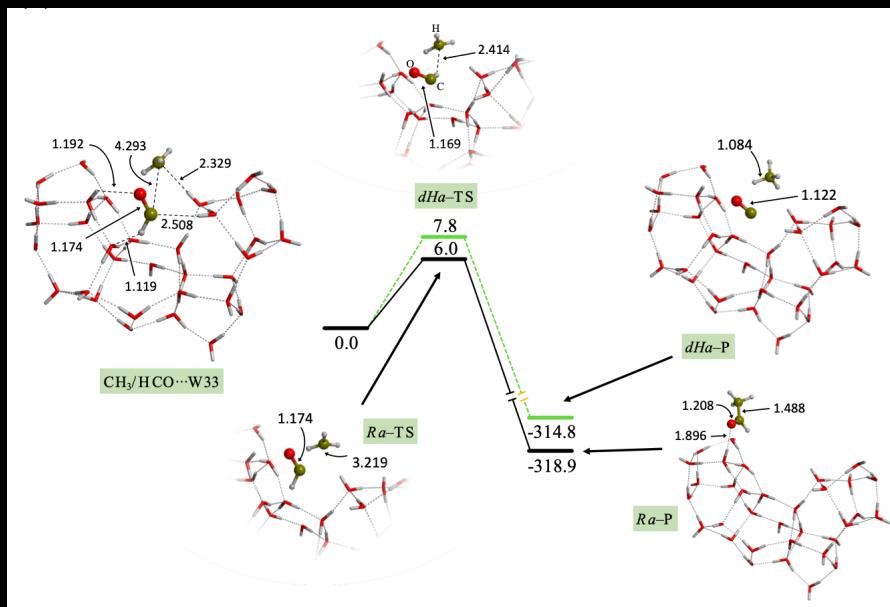


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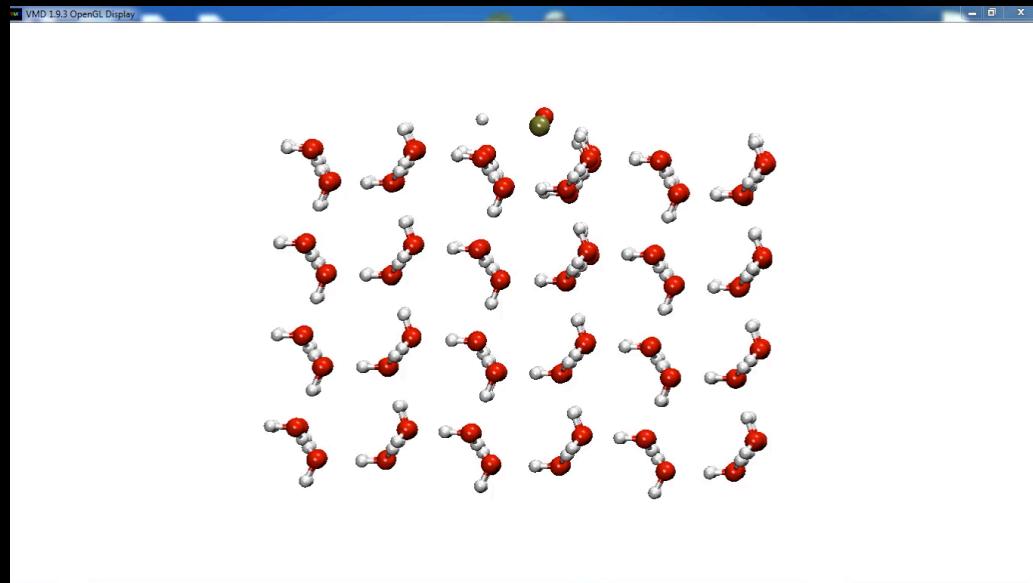
EX: ACETALDEHYDE



Enrique-Romero, Rimola, Ceccarelli et al. 2019



# iCOMs chemical desorption? DOES THE CHEMICAL ENERGY RELEASED IN THE REACTION LIBERATE iCOMs IN THE GAS ?

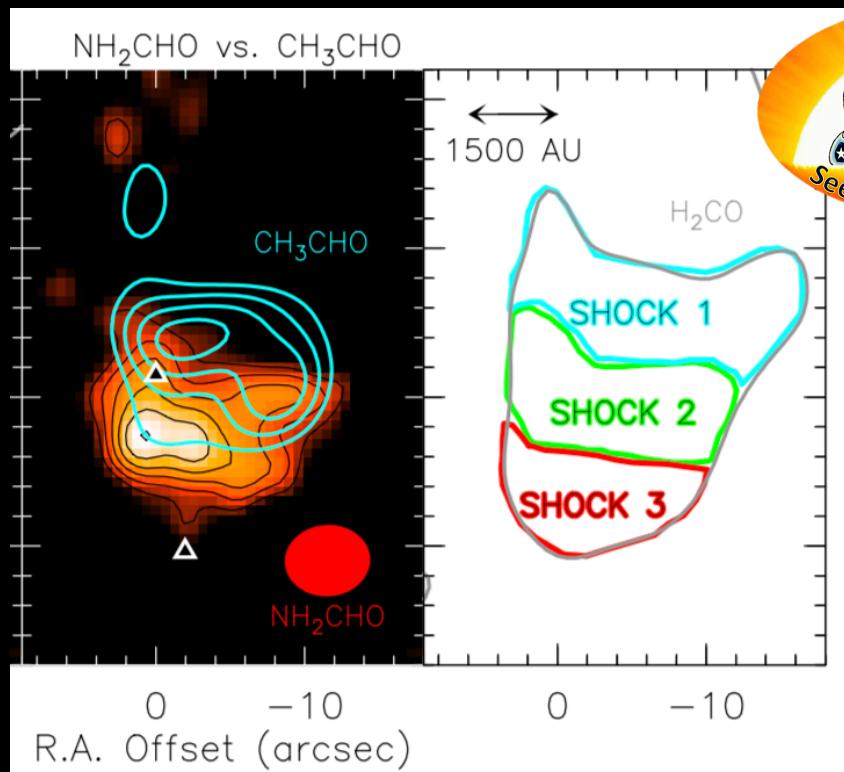


ab initio molecular  
dynamics computations  
Pantaleone+2020

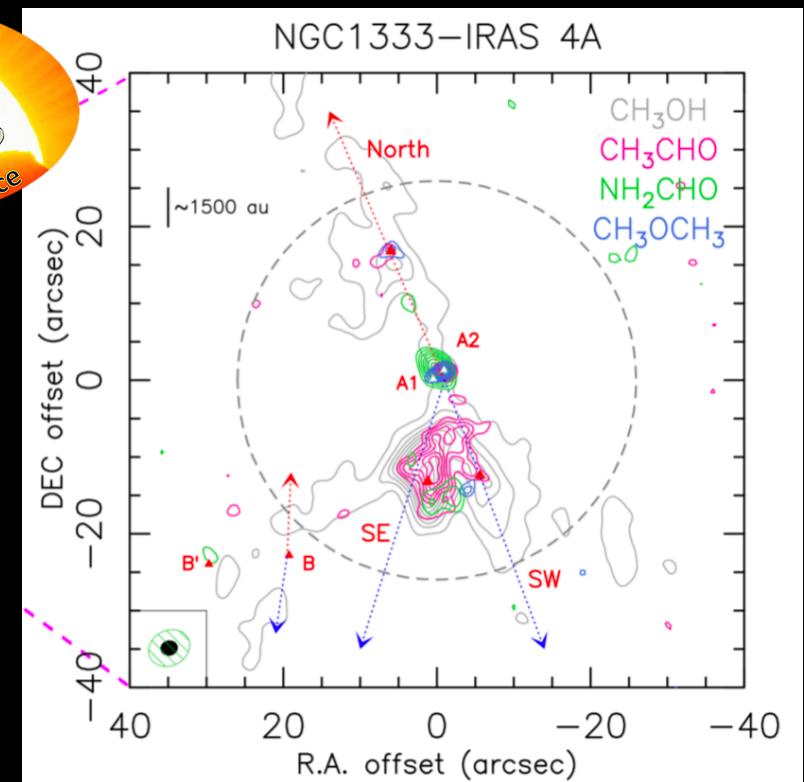
Answer: about 90% of  
the reaction energy is  
transmitted to the ice

→ the remaining 10% is not enough to  
liberate HCO from the ice to the gas

# iCOMs in MOLECULAR SHOCKS THE BEST LABORATORIES TO UNDERSTAND THE iCOMs FORMATION



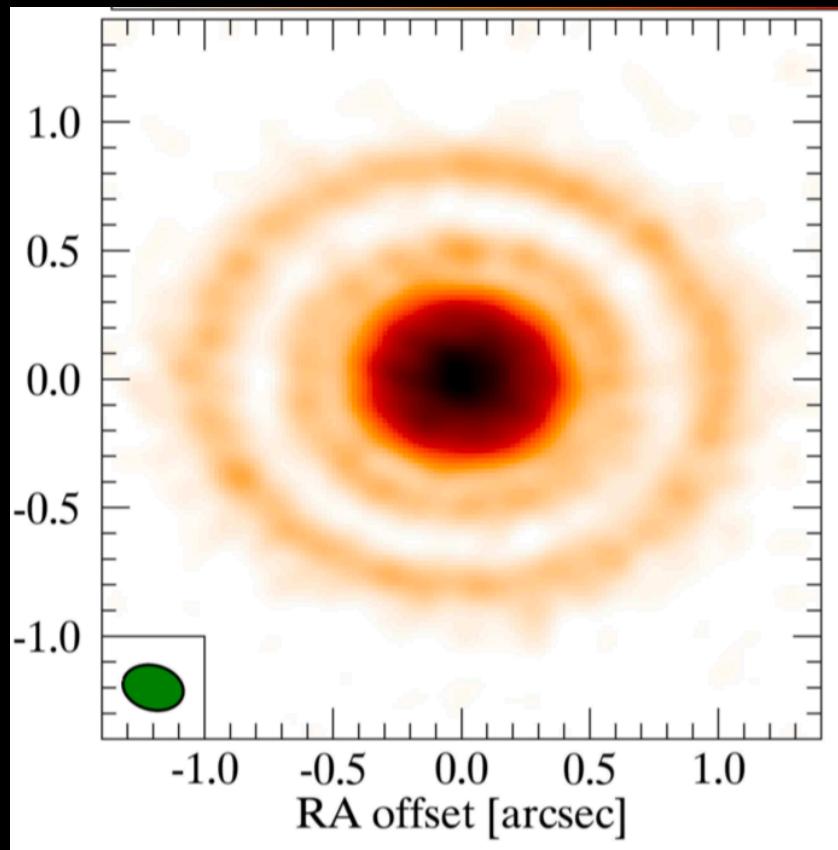
Codella+2017



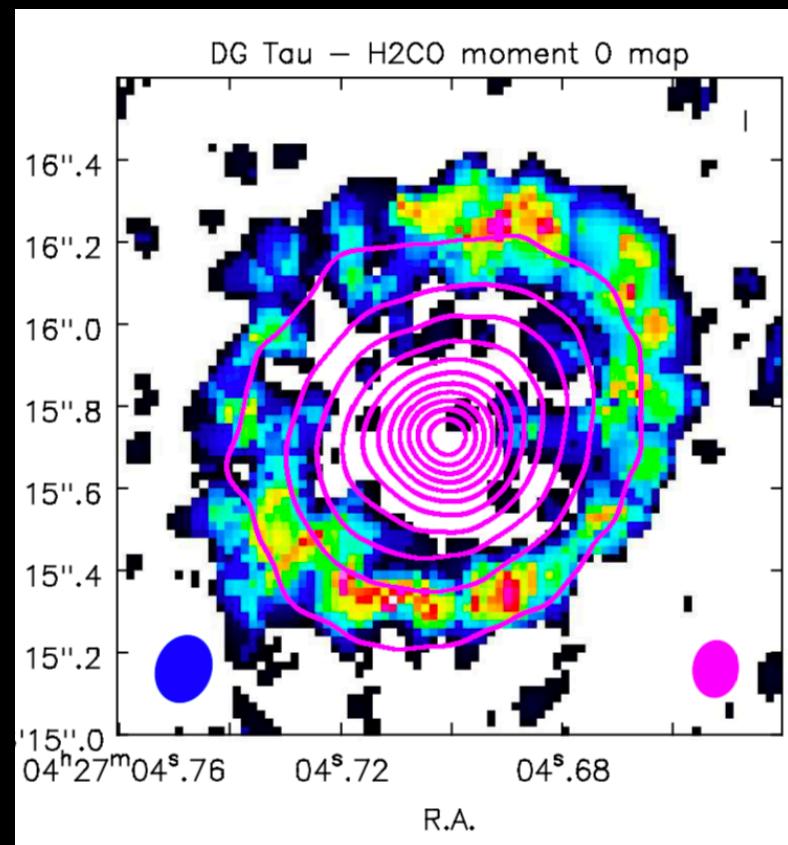
DeSimone+2020

→ Claudio's talk

# iCOMs in PROTOPLANETARY DISKS



Fedele+2018

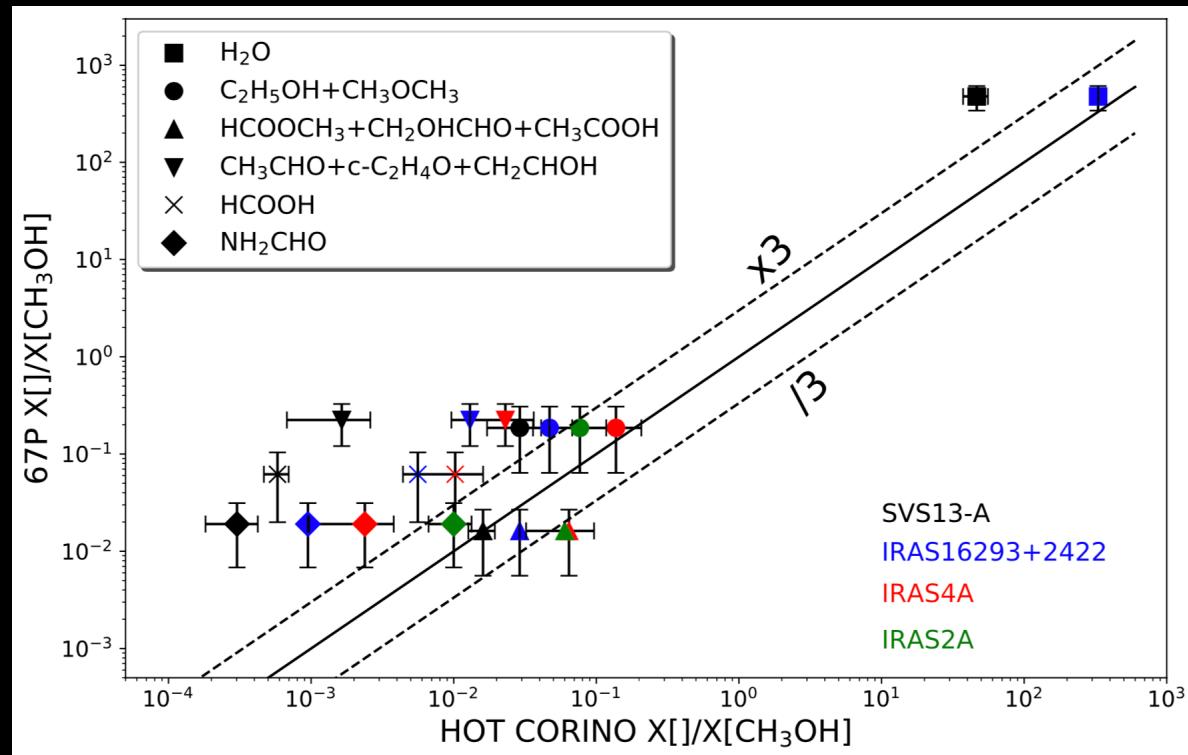


Podio+2019

→ Davide & Linda's talks

# ...BUT DID iCOMs REACH EARTH?

DID THE 67P COMET (visited by ROSETTA)  
FORMED IN A HOT CORINO-LIKE REGION?



→ Eleonora's talk

# CONCLUSIONS/WRAP-UP

Two inter-related questions:

1. Is life a unique phenomenon?

Very likely no, the major ingredients are available in (almost) all planetary systems: water and organic molecules.

2. What happened?

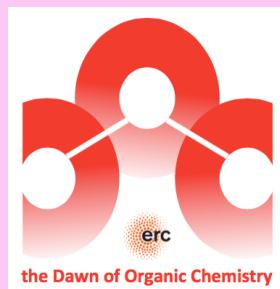
We do not know all steps yet, especially on the formation and fate of the organic molecules → a lot of information still to discover and understand.

# LA VIE EN ROSE

IRAM NOEMA + ALMA Large Programs



ERC DOC + ITN ACO

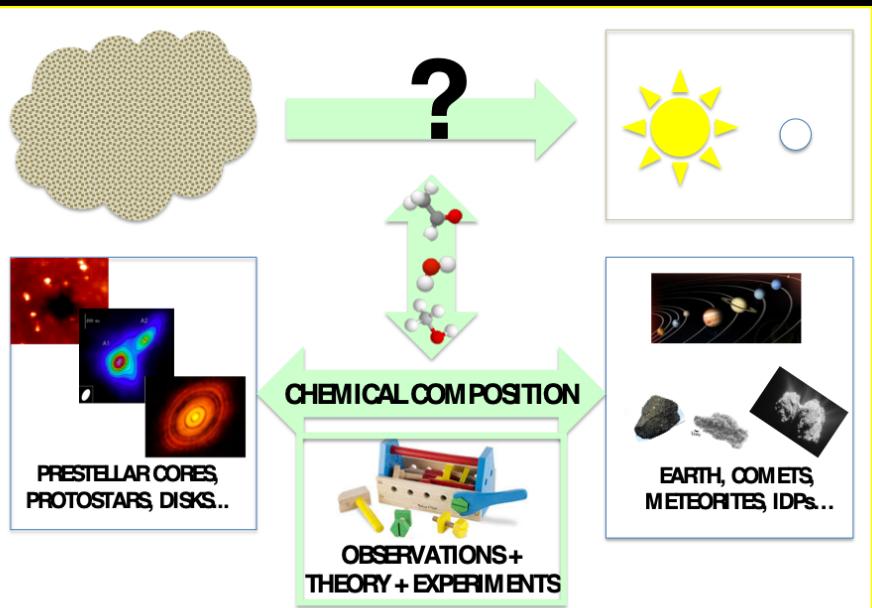


# TN Astro-Chemical Origin (ACO)

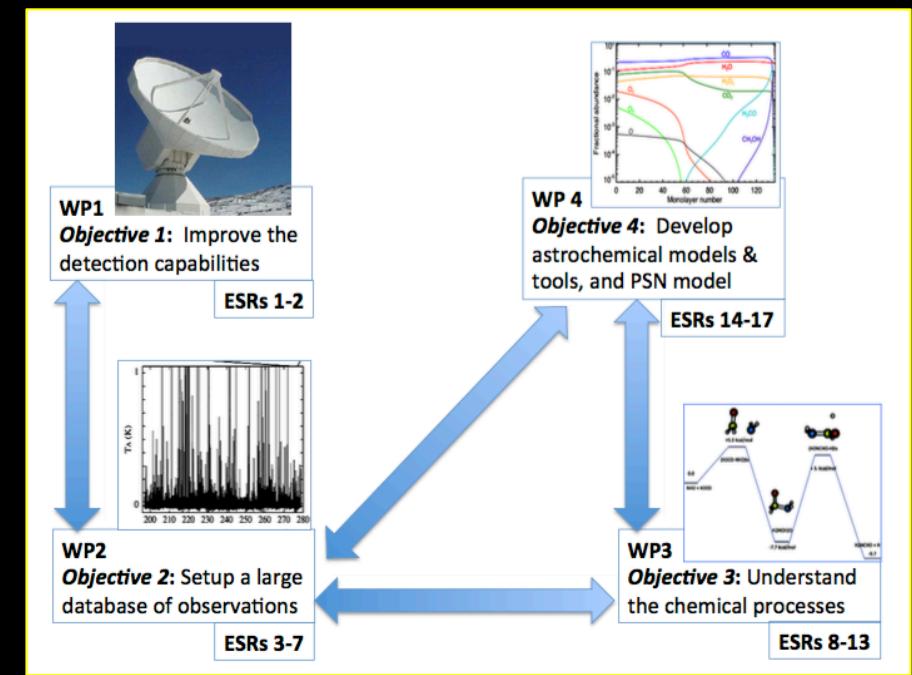
PI: C.Ceccarelli (UGA/IPAG) + 12 Nodes



Codella (INAF-Arcetri), Vastel (U. Toulouse), Theulé (U. Marseille), Ugliengo (U.Torino), Balucani (U. Perugia), Ascenzi (U. Trento), Viti (UCL), Piccirillo (U. Manchester), Rimola (U. Barcellona), Neri (IRAM), Amiri (POAM), Faginas (Masterup)



**SCIENTIFIC GOAL:** Use the chemical composition of present solar-like planetary-forming systems to unveil the early history of the Solar System



**TRAINING GOAL:** 17 students enrolled to carry out PhD thesis in a wide range of interdisciplinary topics



THANKS FOR THE ATTENTION