INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

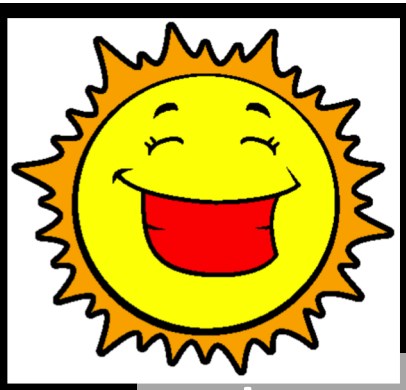
# AstroChemical Origins (ACO)
# H2020 EU Innovative Training Network


Claudio Codella
INAF – Osservatorio Astrofisico di Arcetri



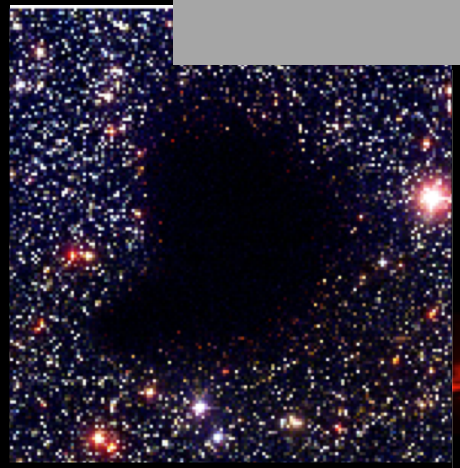


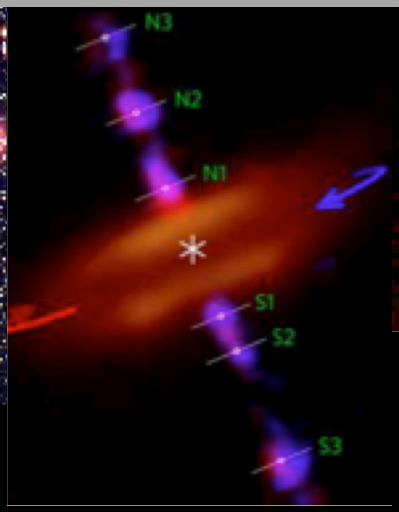
THE ROOTS OF ACO

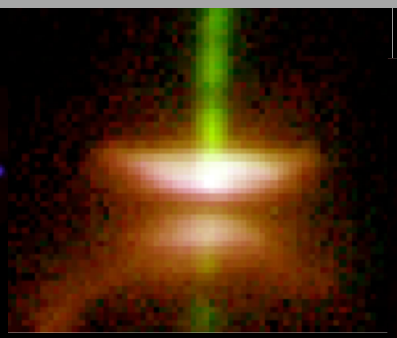


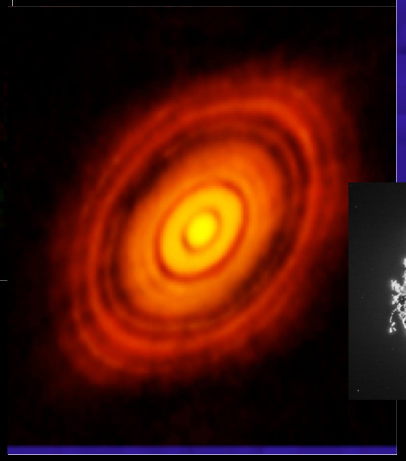
# *The formation of a Sun-like star, and its Solar System. The emergency of life*

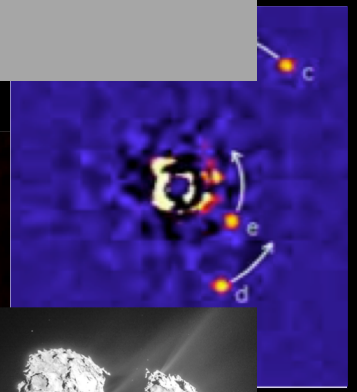
## Planetary composition: disk chemical **reset** or **inheritance** ?

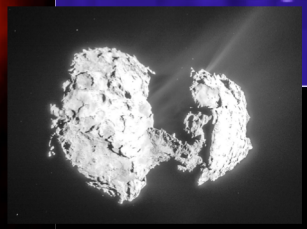




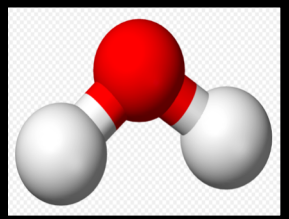



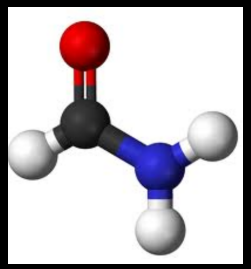


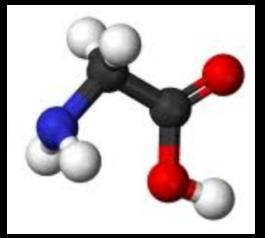


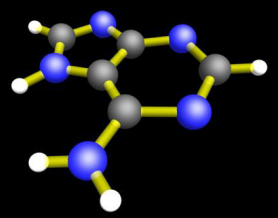



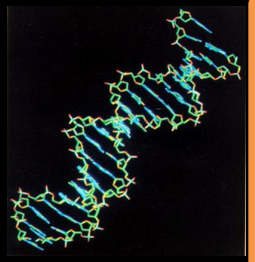
Time

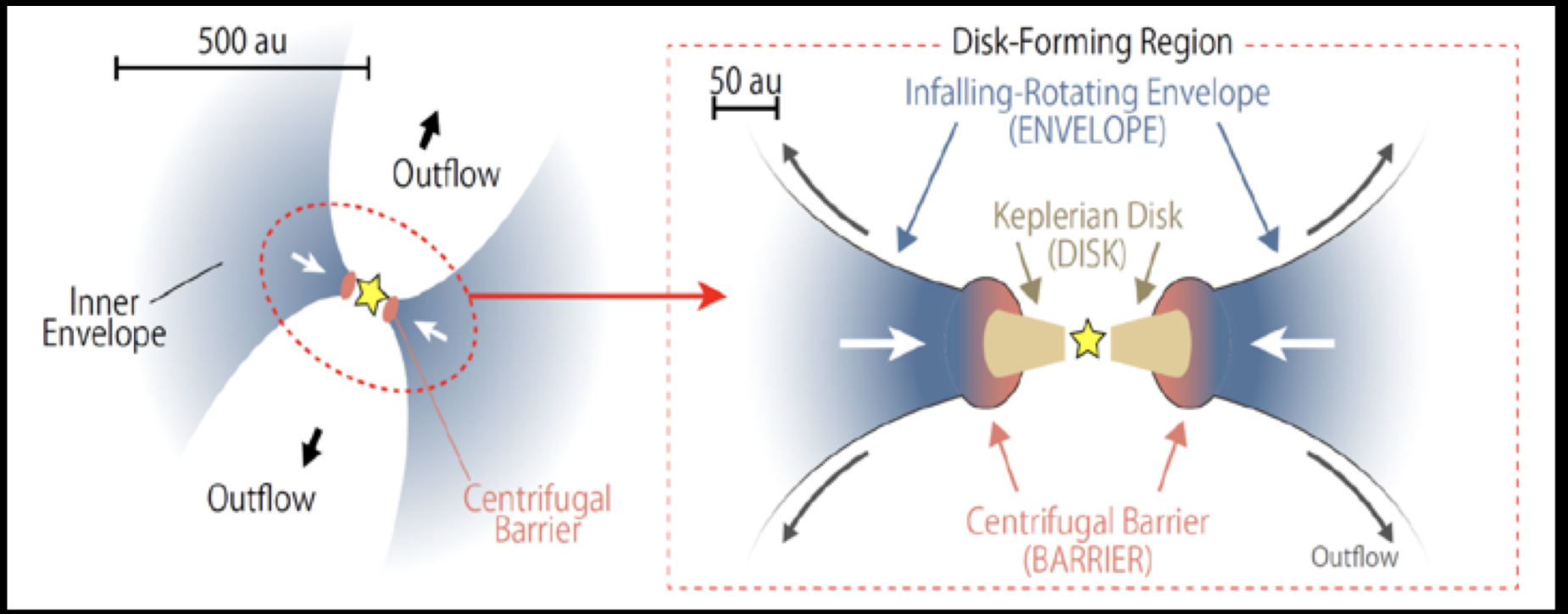


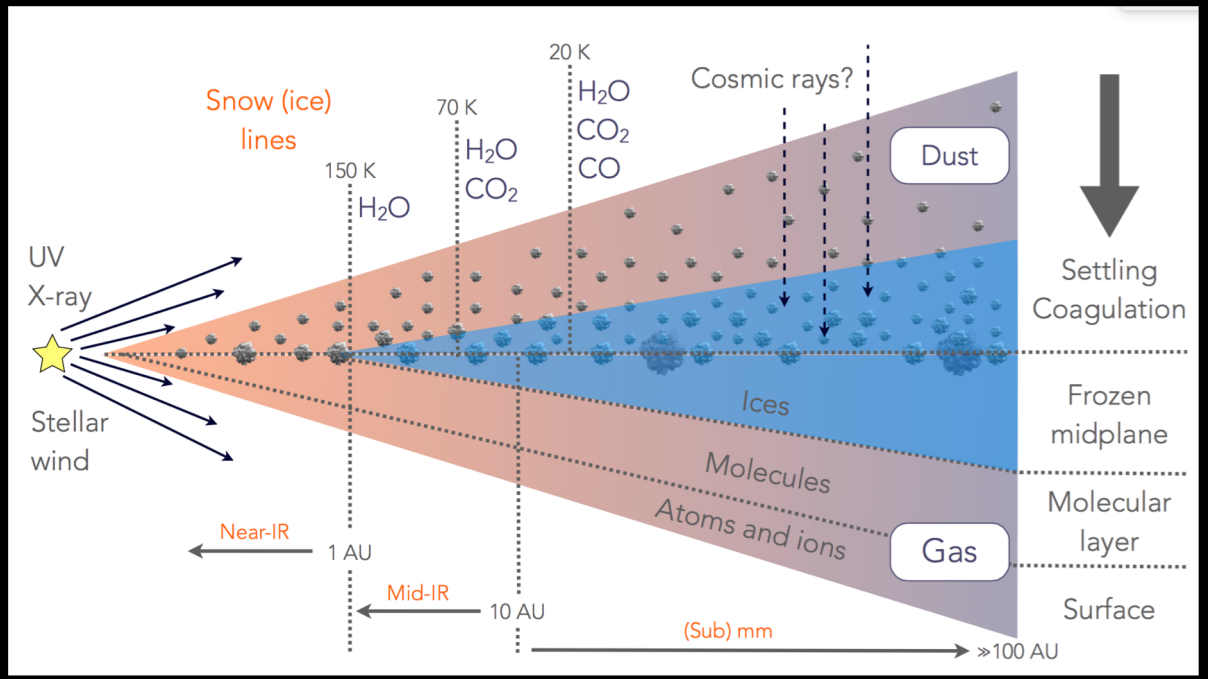




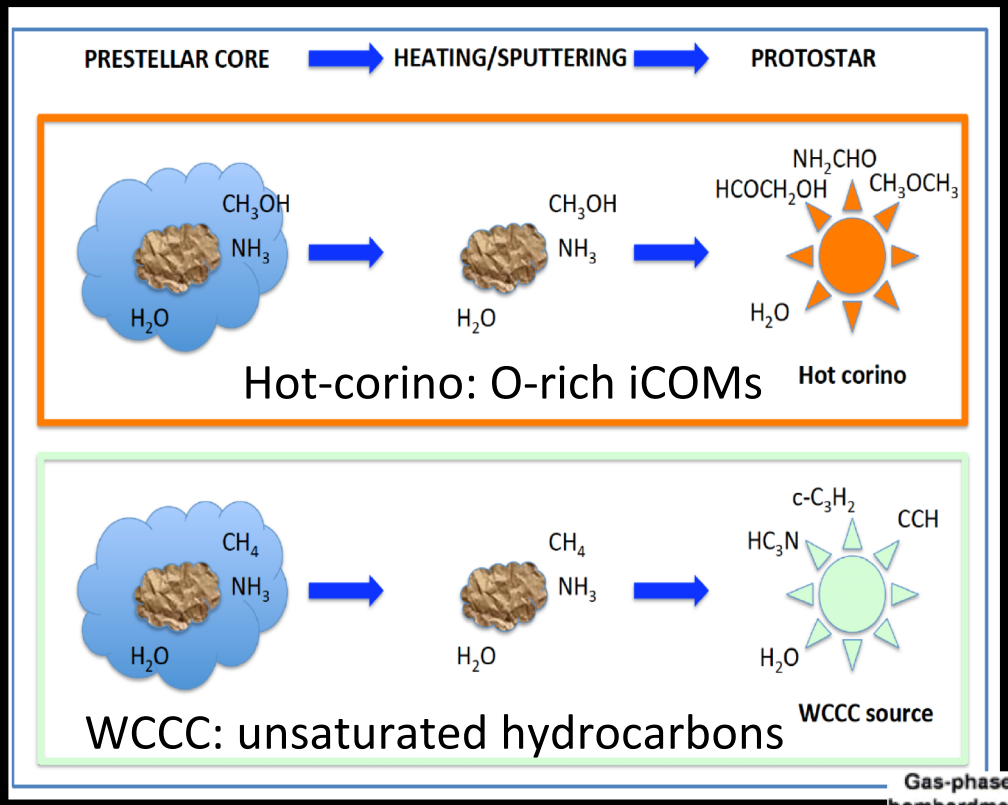


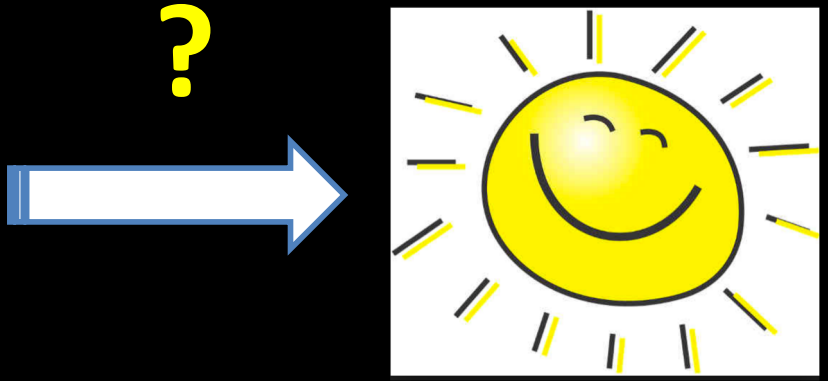


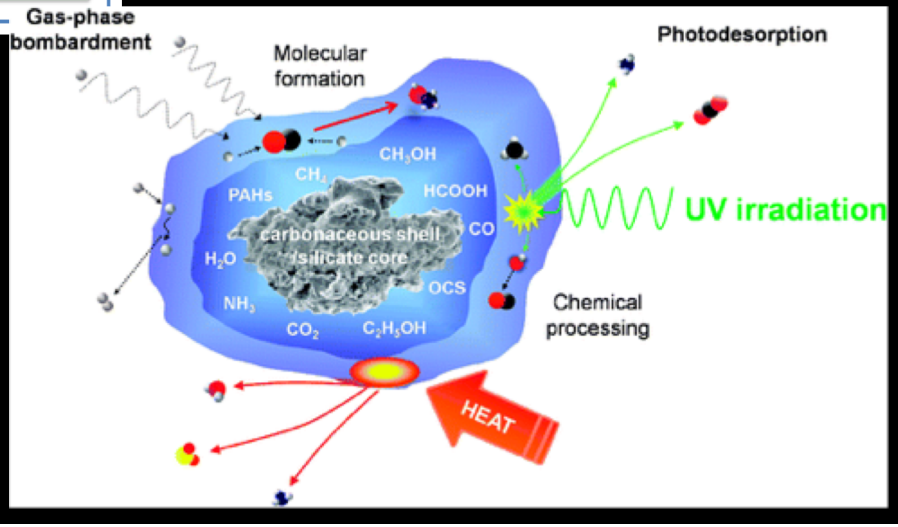

500 au
Outflow
Inner Envelope
Outflow
Centrifugal Barrier
Disk-Forming Region
50 au
Infalling-Rotating Envelope (ENVELOPE)
Keplerian Disk (DISK)
Centrifugal Barrier (BARRIER)
Outflow


Snow (ice) lines
20 K
$H_2O$
$CO_2$
CO
70 K
$H_2O$
$CO_2$
150 K
$H_2O$
Cosmic rays?
Dust
UV
X-ray
Stellar wind
Settling
Coagulation
Ices
Frozen midplane
Molecules
Atoms and ions
Gas
Molecular layer
Surface
Near-IR
1 AU
Mid-IR
10 AU
(Sub) mm
»100 AU

# Tracing ice mantle history in Solar-type protostars



# Tracing our chemical origins: Astrochemistry of forming Sun-like star

Genesis - SKA

2009

WISH

CHESS

Herschel

ASAI

IRAM 30-m

IRAM PdBI

CALYPSO

Time

1 Premiale INAF
6 Large Programs
2 Astrofit
1 SIR project
1 PRIN-MIUR
1 PRIN-INAF
1 H2020 EU-ITN

iALMA

ALMA DOT

ALMA

FAUST

EU H2020 Innovative Training Network

Astro-Chemical Origins

x12 NOEMA
NOrthern Extended Millimeter Array

SOLIS
Seeds Of Life In Space

IRAM NOEMA

ALMA

Today

# Tracing our chemical origins: Astrochemistry of forming Sun-like star

Genesis - SKA

iALMA

Herschel

CHESS

WISH

2009

IRAM PdBI

**2 Researchers TI @INAF**
**L. Podio, D. Fedele**

**6 PhDs @INAF**
**E. Bianchi, M. De Simone,**
**M. Corazzi, R.G. Urso,**
**S. Mercimek, L. Evans**

**1 Premiale INAF**
**6 Large Programs**
**2 Astrofit**
**1 SIR project**
**1 PRIN-MIUR**
**1 PRIN-INAF**
**1 H2020 EU-ITN**

ALMA DOT

ALMA

FAUST

EU H2020 Innovative Training Network

Astro-Chemical Origins

x12 NOEMA
NOrthern Extended Millimeter Array

SOLIS
Seeds Of Life In Space

IRAM NOEMA

ALMA

Today

# GENESIS - SKA
# PI C. Codella
# FOUR PILLARS


1. PLANET FORMATION:
Models, simulations, & observations

2. VOLATILES EVOLUTION:
Complex Organics as the building blocks of life
(quantum-mechanical computations of gas reactions)

3. LABORATORY EXPERIMENTS

4. COMMUNICATION AND DISSEMINATION

**www.genesis.inaf.it**
**(2018-2021: 98 papers…)**

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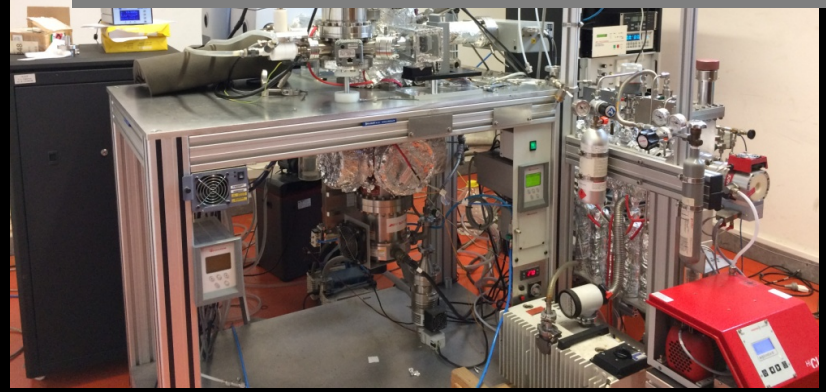
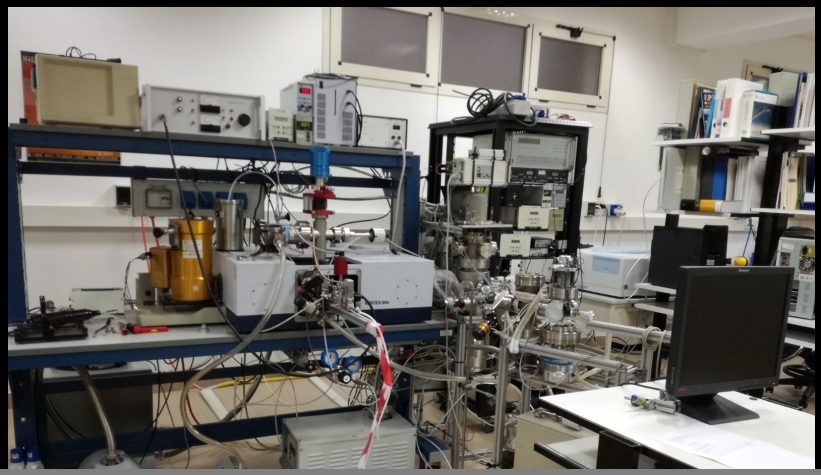
**Four laboratories involved in the study of the formation and survival of complex molecules in space**

**Laboratorio di Astrofisica Sperimentale di Catania**
**M.E. Palumbo**

**Laboratorio di Astrobiologia Arcetri**
**J.R. Brucato**

**LIFE Light Irradiation Facility for Exochemistry, Palermo**
**A. Ciaravella**





**Laboratorio di Fisica Cosmica Capodimonte**
**V. Mennella**


EU H2020 Innovative Training Network
Astro-Chemical Origins
ACO

# ACO team
# Total: 4MEuro
# INAF: 400 kEuro


| BENEFICIARIES | COORDINATOR | |
|---|---|---|
| Un. Grenoble Alpes | PI: Ceccarelli | |
| Un. Sabatier Toulouse | Vastel | |
| Un. Aix-Marseille | Theulé | |
| Istituto Nazionale Astrofisica | Codella | |
| Un. Torino | Ugliengo | |
| Un. Perugia | Balucani | |
| Un. Trento | Ascenzi | |
| Un. College London | Viti | |
| Un. Manchester | Piccirillo | |
| Un. Auton. Barcelona | Rimola | |
| *IRAM* | *Neri* | |
| *POAM Electronics* | *Amiri* | Electronics/Receivers |
| *MASTER-UP* | *Faginas-Lago* | Computations/Chemistry |

| PARTNER ORGANIZATION | |
|---|---|
| *Vastalla Srl* | Software |
| MPE Garching | |
| *Mellanox Tech.* | High Performance Computing |
| *Springer Nature* | Publishing Company |
| *PathControl* | Oil drilling: Matlab software |
| *RobertHunter* | Website Designers |
| *Oritur* | Risk Management Consultant |
| *Aethia Srl* | High Performance Computing |

Academic
*Non-academic*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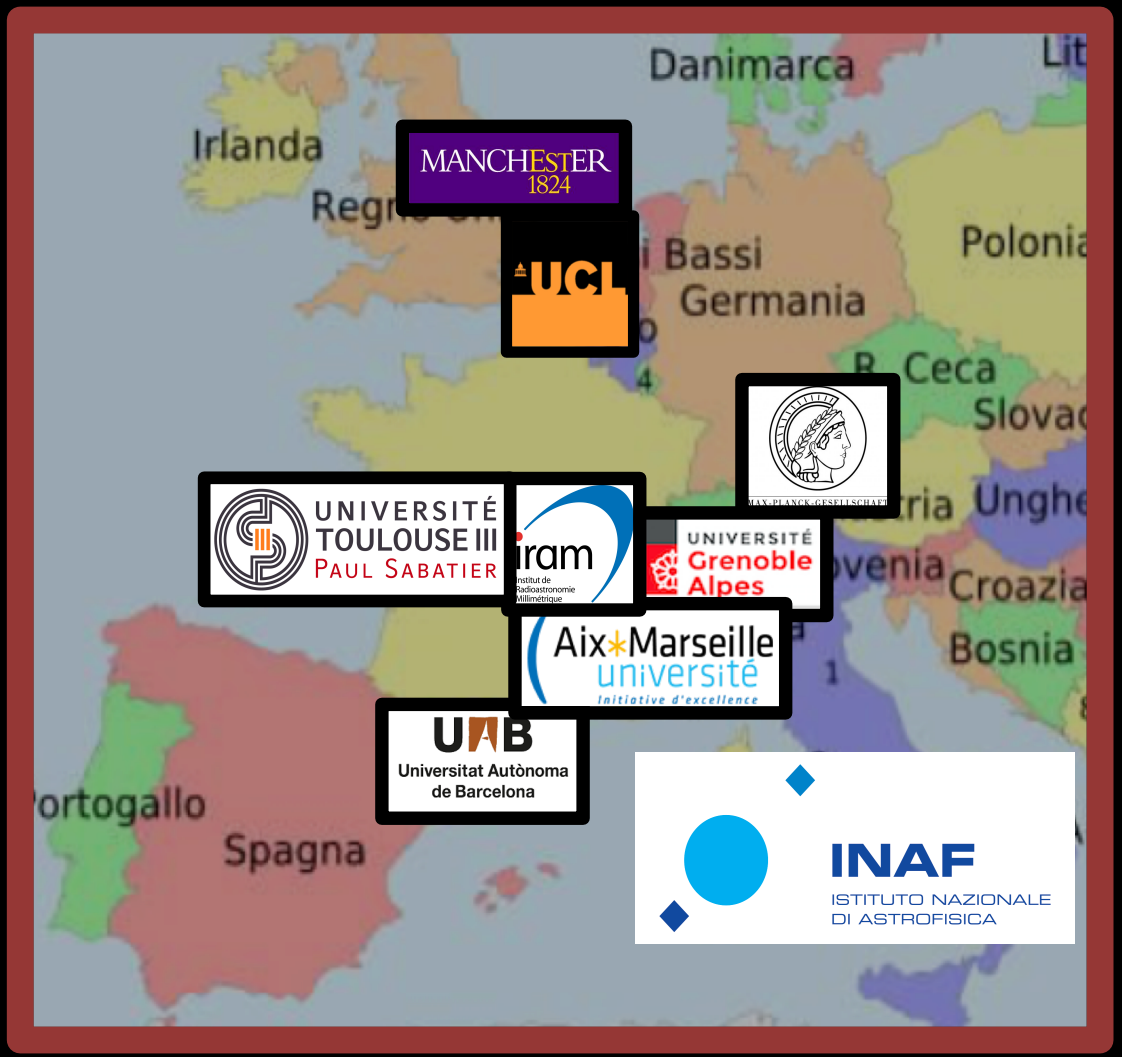
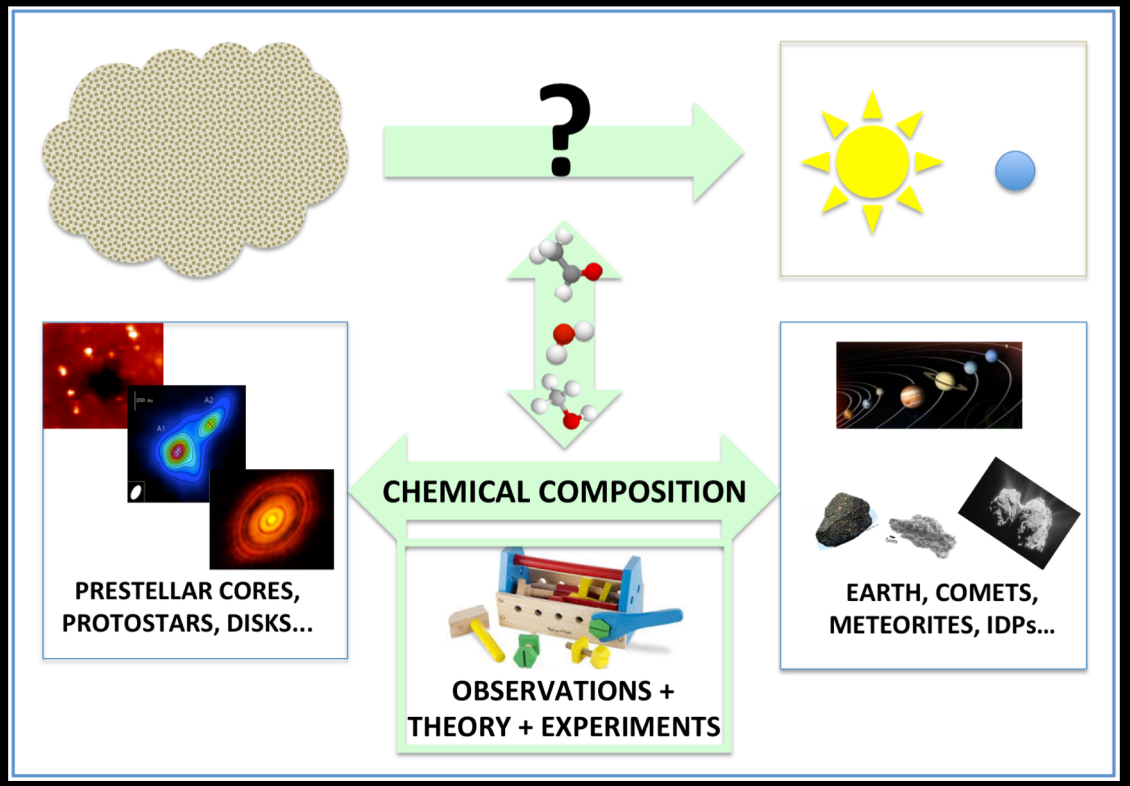
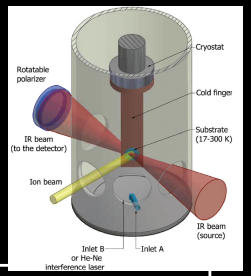


# Scientific goals

## USE THE CHEMICAL COMPOSITION AS A TOOL TO RECONSTRUCT THE EARLY PHASES OF THE SOLAR SYSTEM FORMATION

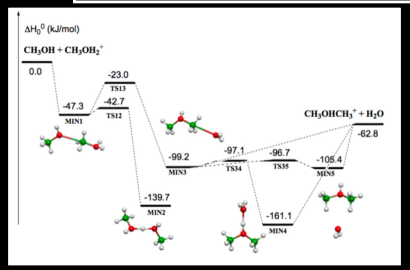


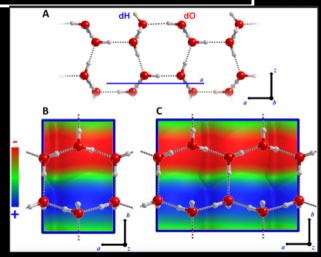




(i) laboratory outputs,

(ii) surface simulations,

(iii) quantum-mechanical computations



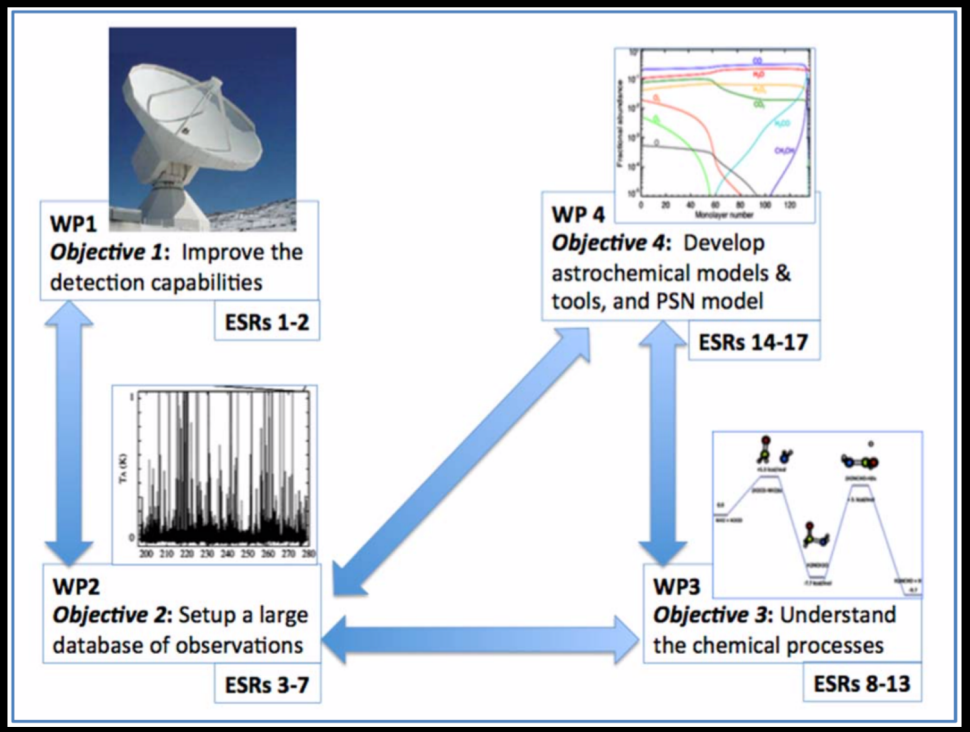




## → OBSERVE THE CHEMICAL PROXIES LINKED TO THE SOLAR SYSTEM PRIMITIVE OBJECTS TOWARDS PRESTELLAR CORES, PROTOSTARS AND PROTOPLANETARY DISKS

## → AND INTERPRET THEM VIA ASTROCHEMICAL MODELS

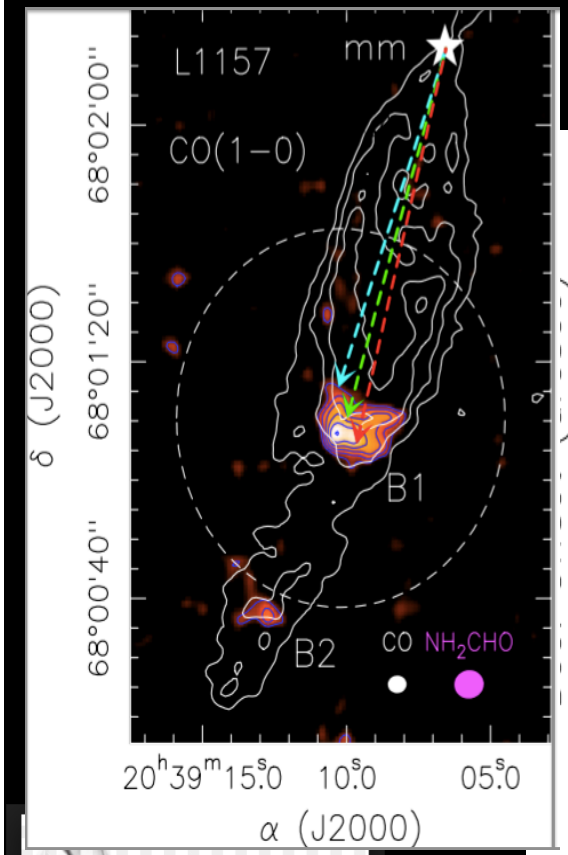
# ACO FOUR SPECIFIC OBJECTIVES

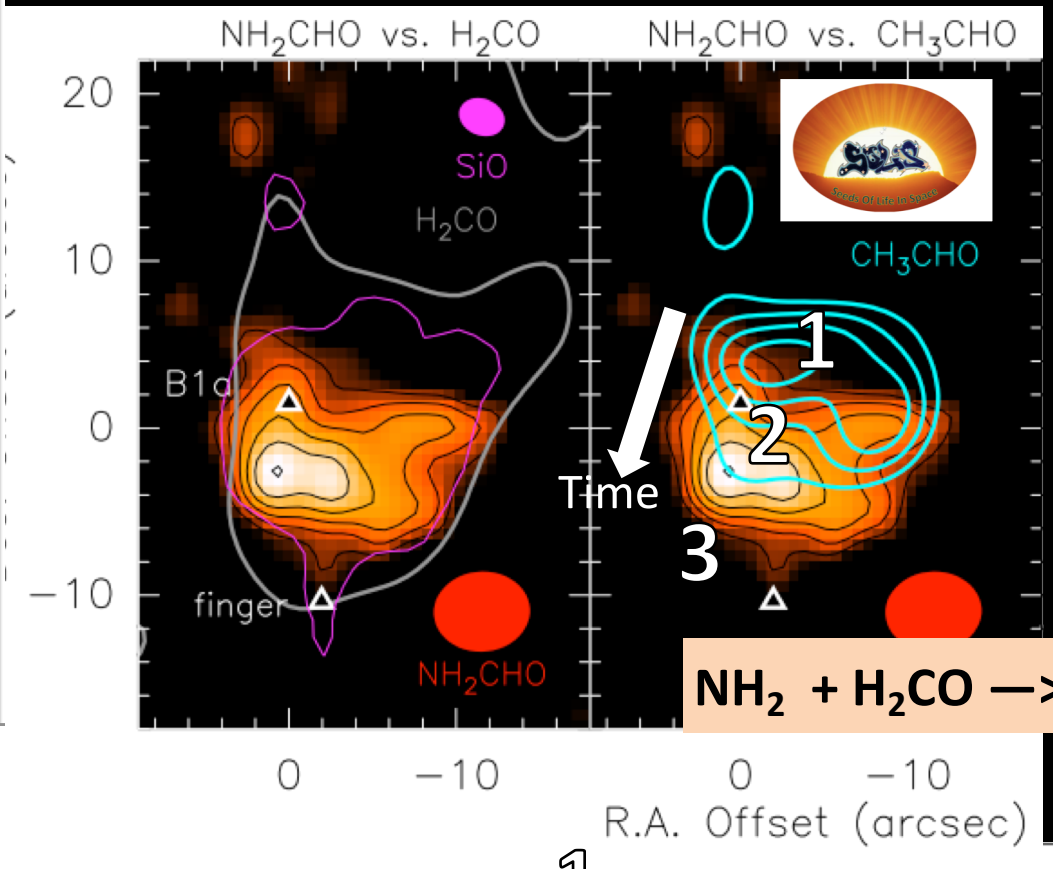
## THE ACO SCIENTIFIC PROJECT WILL BE CARRIED OUT BY 17 EARLY STAGE RESEARCHERS (ESRs)




- 3 NETWORK SCHOOLS
- IMMERSIVE VIRTUAL REALITY SCHOOL
- 2 CONFERENCES
- standard courses at host universities

# Astro + Chemictry = Astrochemistry !



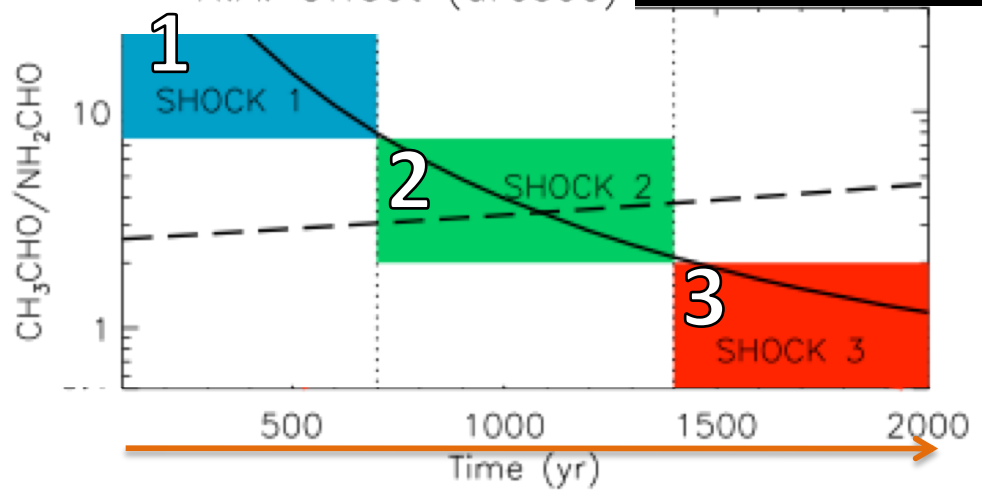




**$NH_2$ + $H_2CO$ —> $NH_2CHO$ + H**

Codella et al. (2017)

**The smoking gun of gas-phase at work (at least in L1157-B1)**

Barone et al. (2015)
Vazart et al. (2016)
Skouteris et al. (2017)



# The first ALMA LP on Astrochemistry

## The FAUST
## (Fifty AU Study of Protosun Analogues)
## ALMA Large Program


C. Ceccarelli (IPAG, Grenoble)
C. Codella (INAF-Arcetri)

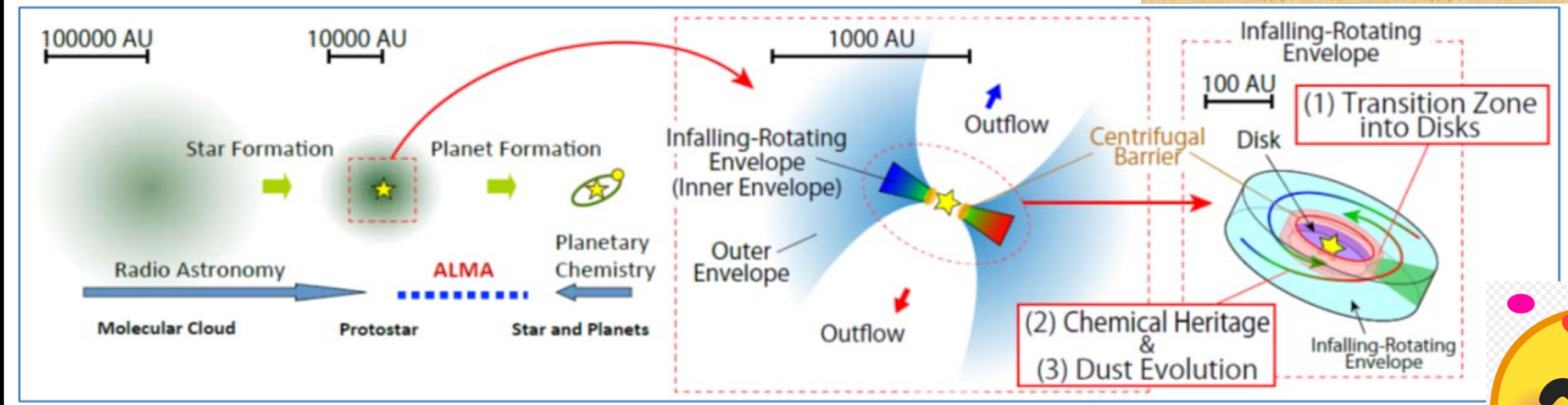
S. Yamamoto (Tokyo University)
N. Sakai (RIKEN)

C. Chandler (NRAO)


**Is the chemical diversity at a 1000 au scale also present in the inner envelope/disk system (50 au) ?**

***What molecules are passed from the envelope to the disk in which planets, asteroids, and comets form***

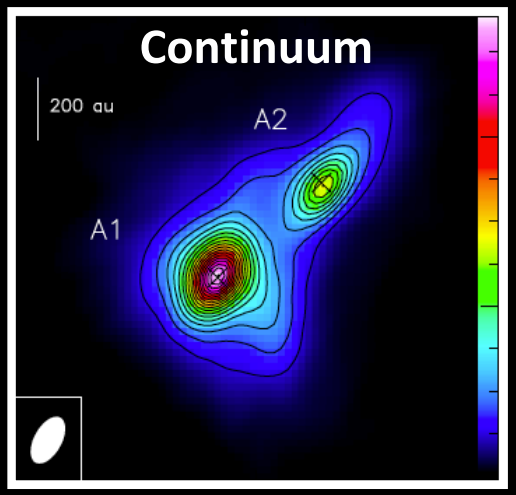
**STAY TUNED !**
**first papers**
**Bianchi+ 2020**
**De Simone+ 2020**
**Okoda+ 2021**

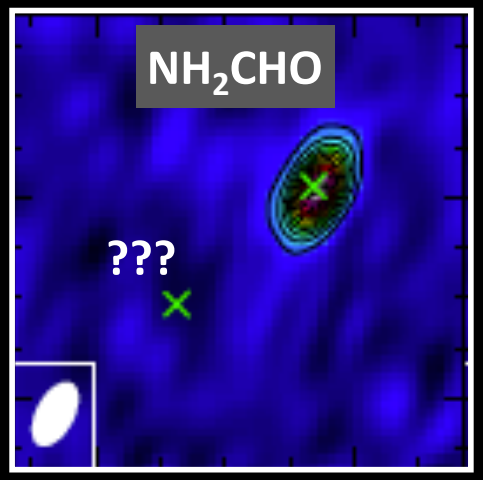



**PPVII chapter**

# ACO: ALMA and beyond: Hot-corinos at cm-wavelengths

NGC1333-IRAS4A



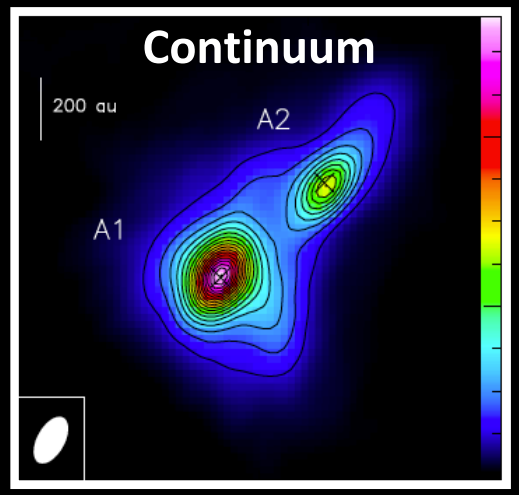

López-Sepulcre+ 2017;

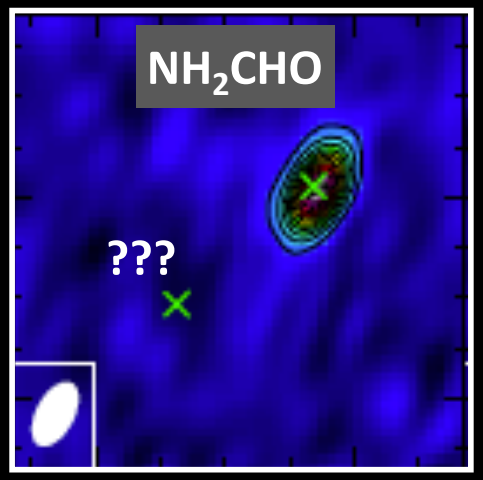
With ALMA:
Hot corino in one of the two components

iCOMs abundances at mm-wavelengths can be underestimated

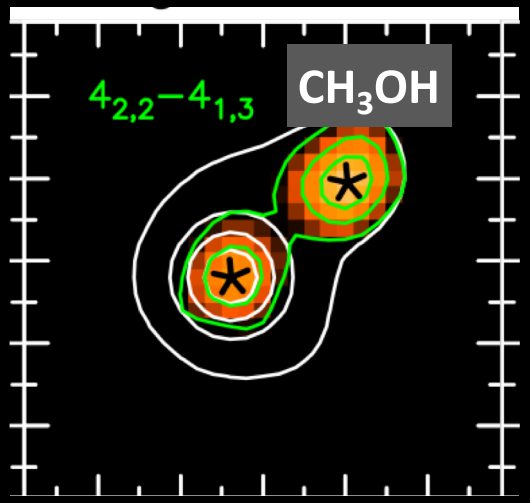
# ACO: ALMA and beyond: Hot-corinos at cm-wavelengths

NGC1333-IRAS4A




López-Sepulcre+ 2017;




De Simone+ 2020

With ALMA:
Hot corino in one of the two components

With VLA:
Both IRAS4A1 and IRAS 4A2 have a hot corino !

iCOMs abundances at mm-wavelengths can be underestimated

Food for SKA

SKA
SQUARE KILOMETRE ARRAY

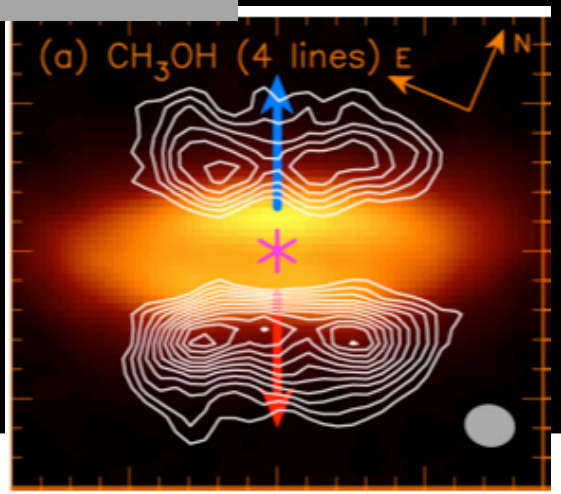
# ACO: ALMA and beyond: Hot-corinos at cm-wavelengths

The disk midplane is optically thick in continuum and show No iCOMs emission: lower abundance or opacity effect ?

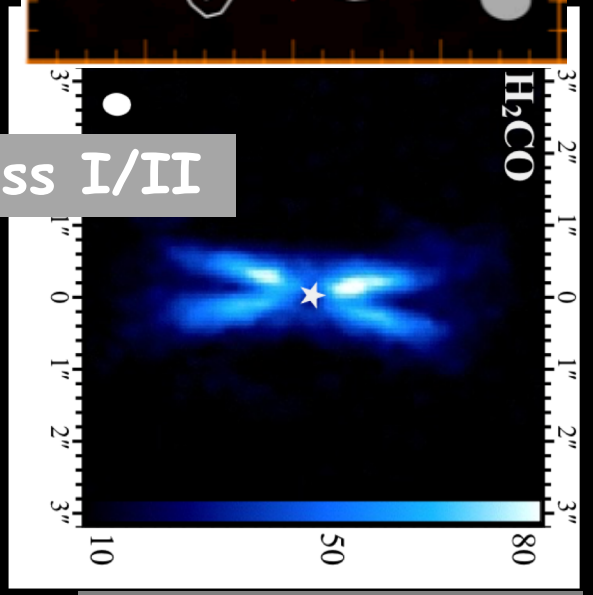
Food for SKA
(WG Cradle of Life)

Class 0

Lee+ 2019
Codella+ 2019




Class I/II




Podio+ 2020

# ACO for Ariel

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Astro-Chemical Origins

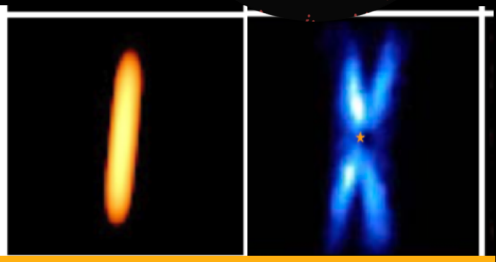
ALMA DOT

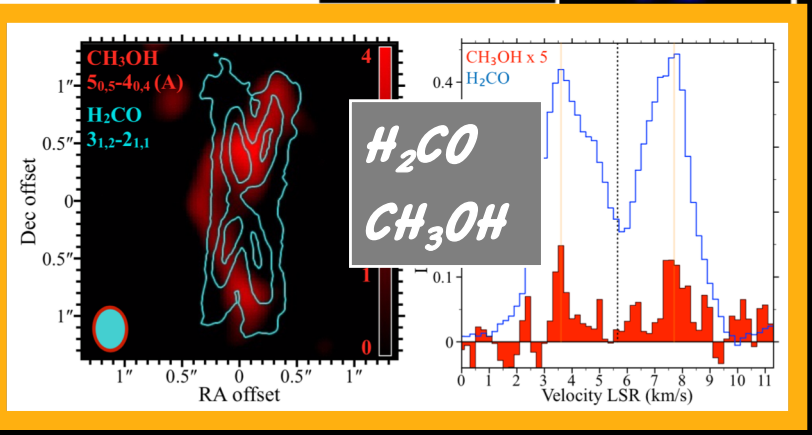
ARIEL

**WP Planet Formation**
**(Turrini+ 2021b - Ariel)**

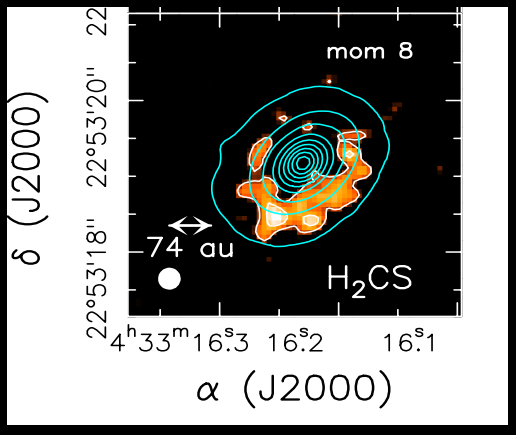
**iCOMs in protoplanetary disks:**
**- To estimate their snowlines;**
**- To estimate the fraction of C, O, and N trapped in organic molecules**
**- S/H ratio:**
**Class I SVS13A: $10^{-2}$-$10^{-1}$**
**(x $10^{-5}$)**

IRAS
04302+2247






$H_2CO$
$CH_3OH$




*Podio+ 2020ab*
*Garufi+ 2020ab,*
*Codella+ 2020*

*Turrini+ 2021b*

| Object | S/H ($\times 10^{-5}$) |
|---|---|
| Sun | 1.32 |
| DM Tau | $< 10^{-2}$ |
| GM Aur | |
| GO Tau | $< 10^{-2}$ |
| HD 100546 | $*10^{-4}$ |
| | $*10^{-3}$ |
| IM Lup | |
| LkCa 15 | $< 10^{-2}$ |
| TW Hya | $*10^{-4}$ |

# Dissemination & Outreach

ACO
EU H2020 Innovative Training Network
Astro-Chemical Origins

**www.aco-itn.org**


1° step - Visual Identity

2° step - http://www.aco-itn.org/ – here all the scientific hub.
(outreach in English, French, Italian, Spanish, Catalan, Chinese… next step: Portuguese, German, and Arabic)

3° step – courses about commuication for ESRs (INAF + APRE)

4° step – social FB and the Chinese Weibo

5° step – Torino ACO DOC conference

6° step – Virtual Reality school and Project Next July in Padova

Full PhDs engagement


THE SEEDS OF ACO
60 x 660

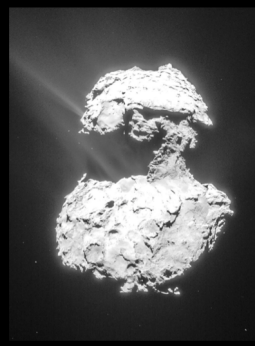
# I Congresso Nazionale di Astrochimica e Astrobiologia (proto-)planetaria
# 21-23 October 2019 Duino (TS)

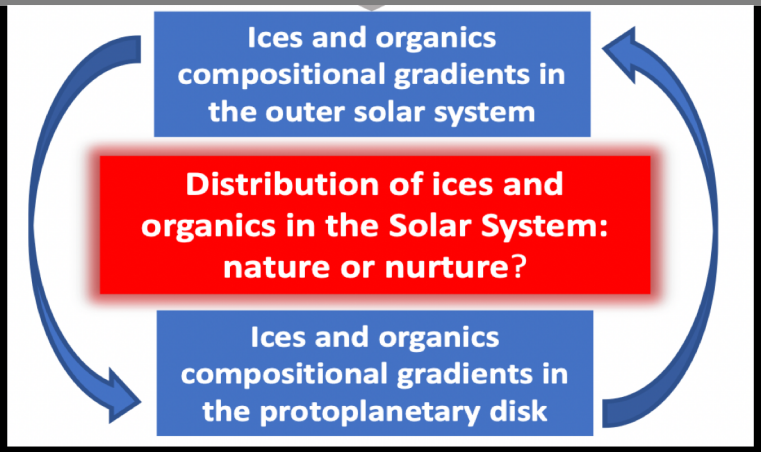
# ACO is just the start !
# Plans for next 10 years and beyond

## Outer Solar System Objects (OSSOs)

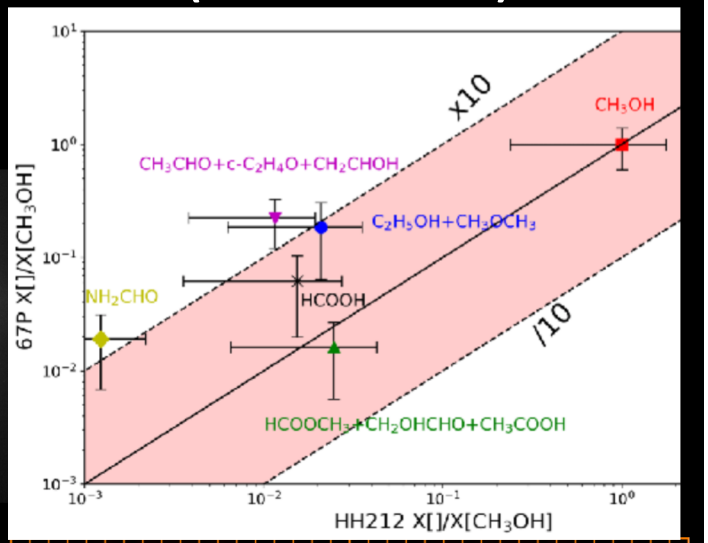
OSSOs: the most pristine material in the Solar System

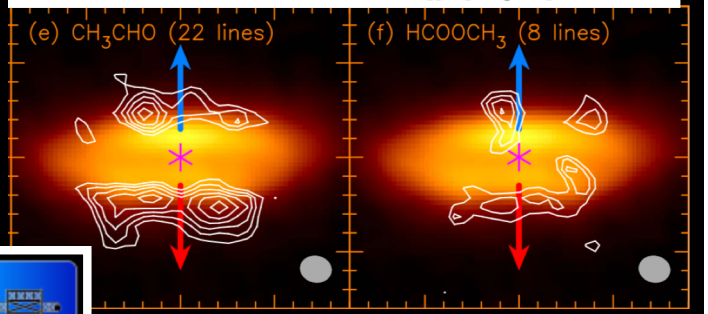
Rosetta: The Italian community (INAF-IAPS in particular), provided a leading effort in VIS-IR reflectance spectroscopy experiments (VIRTIS-Rosetta, PI: F. Capaccioni)






**Planetary composition: inheritance ? (Bianchi+ 2020)**



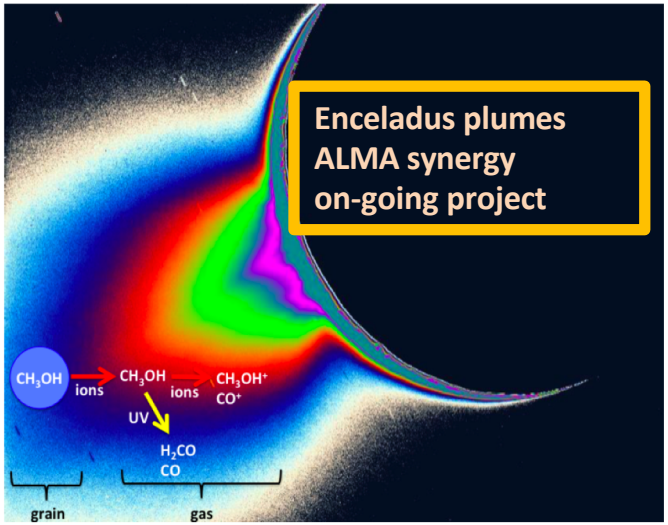

Protostellar disk

# ACO is just the start !
# Plans for the next 10 years and beyond

## AMBITION

**ESA Voyage 2050 long-term (2035-2050) plan**

**Bockelée-Morvan et al. (2019 WB, 2021)**




**Cassini** at the **Saturn system**,
**Dawn** at **Vesta and Ceres**
**New Horizon** at **the Plutonian system** and **Kuiper Belt**)
**Juno (Jupiter and its moons)**
**Leading effort in VIS-IR reflectance spectroscopy experiments onboard spacecrafts** (VIMS-Cassini, VIR-Dawn, PI: M.C. De Sanctis, JIRAM-Juno, PI: A. Mura)

This allows us to characterize the **compositional gradients in the outer Solar System;**
**Comparison with protosolar nebula by** exploiting the unique database of **ALMA data probing the disk chemical composition (FAUST, ALMA-DOT, VIPS)**

# ACO is just the start !
# Plans for the next 10 years and beyond

**Bridging exoplanet compositions and chemistry of protoplanetary disks**

**Exoplanet atmosphere**

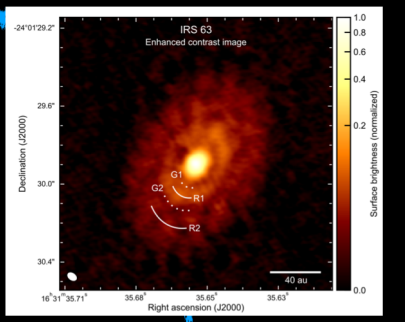
Refractory elements
and molecules (Fe, TiO)

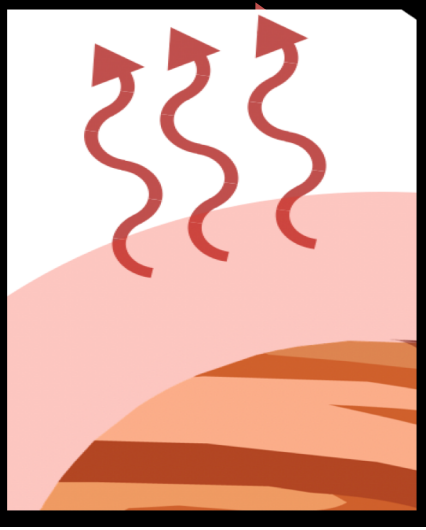
Volatile elements
and molecules ($H_2O$, CO)

**Protoplanetary disk**

Rocky component
of protoplanetary disk

Icy and gaseous component
of protoplanetary disk

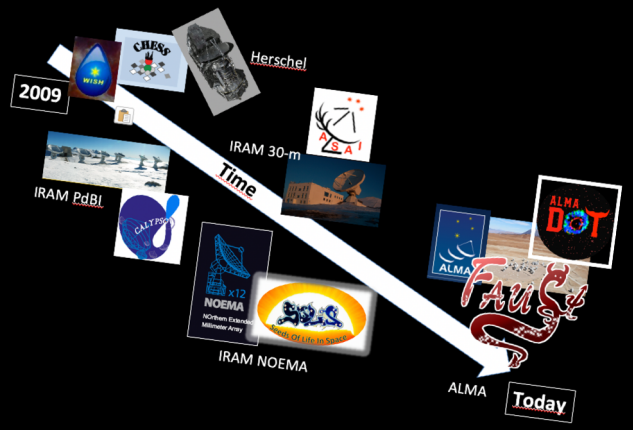


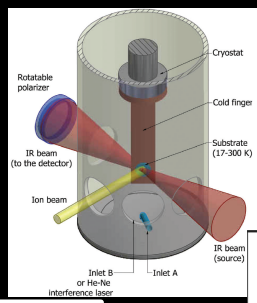
We will perform the first homogeneous characterization of refractory element abundances in exoplanet atmospheres, (Pino et al. 2020).

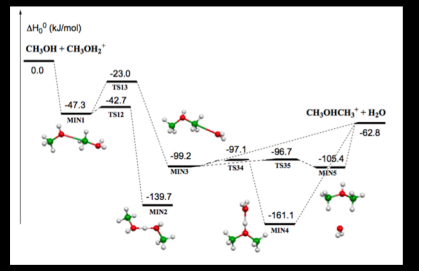
ongoing and future surveys of volatile elements (e.g. ARIEL, GAPS2).
HARPS-N@TNG
ESPRESSO@VLT
MAROON-X@Gemini-N
CARMENES@CAHA

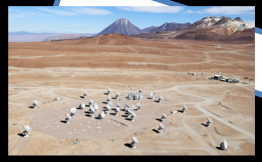
# ACO is just the start !
# Plans for the next 10 years and beyond

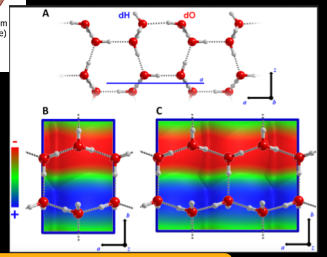



(i) laboratory outputs, (ii) surface simulations,
(iii) quantum-mechanical computations



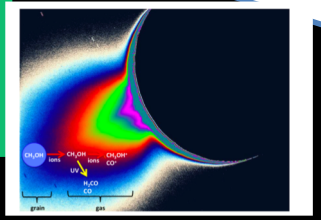






VIPS ALMA large program on disks

GBT to characterise the C-chains in the protostellar envelope



Chemical census of protoplanetary disks with VLA

ALMA characterisations of Enceladus and Europa plumes

...2030

Ariel, SKA, AMBITION

**INAF has a world-wide recognised leading role in astrochemistry.**
**A tight competiton with several outstanding groups:**

**CfA-Harvard-USA, CSIC-Madrid, NRAO-USA, University of Copenhagen**

**With the INAF's support, e.g.:**

- **performing computers for data calibration,**
- **mantaining high-level laboratories,**
- **laboratory-observation shared PhDs,**
- **hiring young experts in astrochemistry,**

**we can keep pushing!**