Astrochemistry at work during the Class I phase

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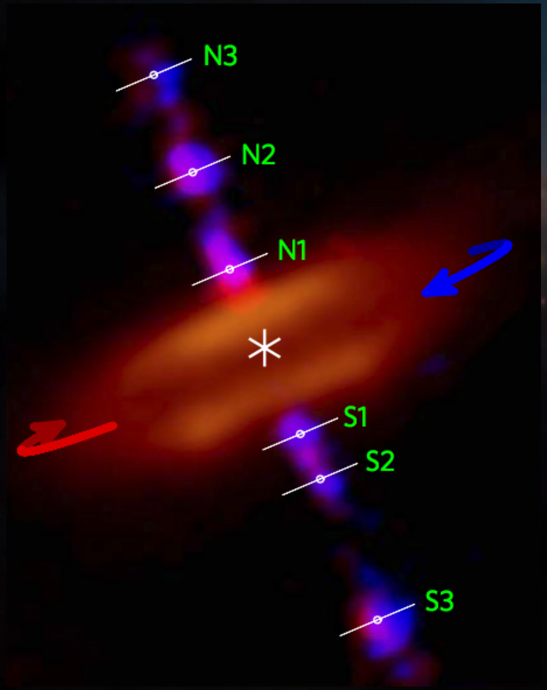
The formation of a Sun-like star

Prestellar core

Barnard 68

t=0
gravitational collapse

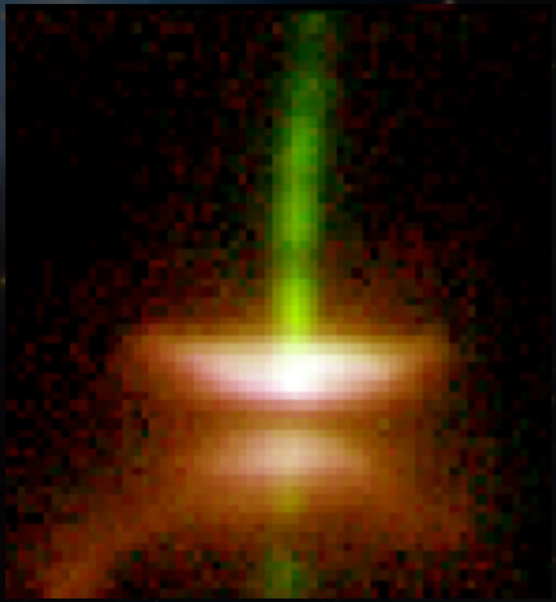
Class 0 protostar



HH212-mm

10^4 yrs
envelope,disk, jets/outflows

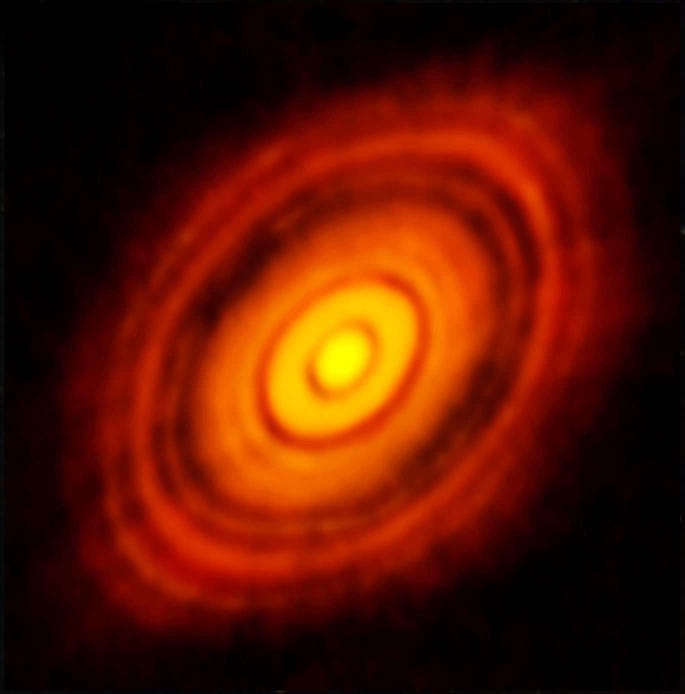
Class I protostar



HH-30

10^5 yrs
disk, jets/outflows

Protoplanetary disk

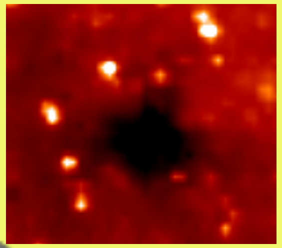


HL Tauri

10^6—10^7 yrs
dust growth & settling
planetes formation

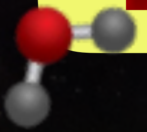
Credits: ESO, Lee et al. 2017a, Chris Burrows (STScI), ALMA, ESO/ NAOJ/ NRAO, Marois et al. 2010

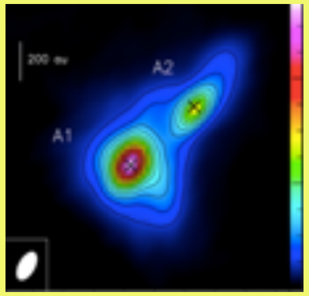
The formation of a Sun-like star



1) PRE-STELLAR PHASE: cold and dense gas

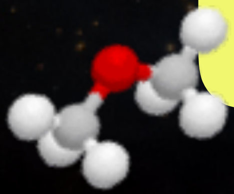
FORMATION OF SIMPLE/COMPLEX AND DEUTERATED MOLECULES

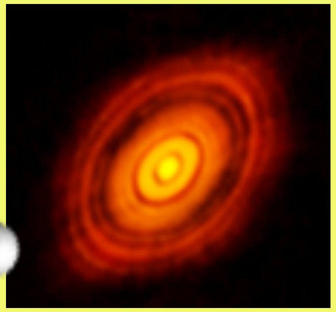




2) PROTOSTELLAR PHASE: collapsing, warm dense gas

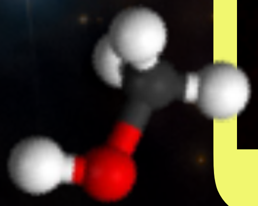
SUBLIMATION/FORMATION OF COMPLEX MOLECULES



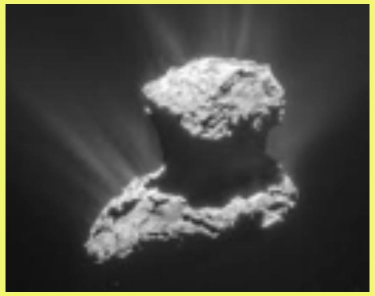


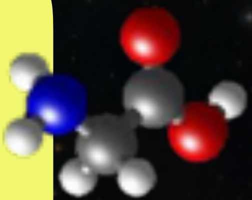
3) PROTOPLANETARY DISK PHASE: cold and warm dense gas

SIMPLE AND COMPLEX MOLECULES



Adapted from
Caselli & Ceccarelli 2012





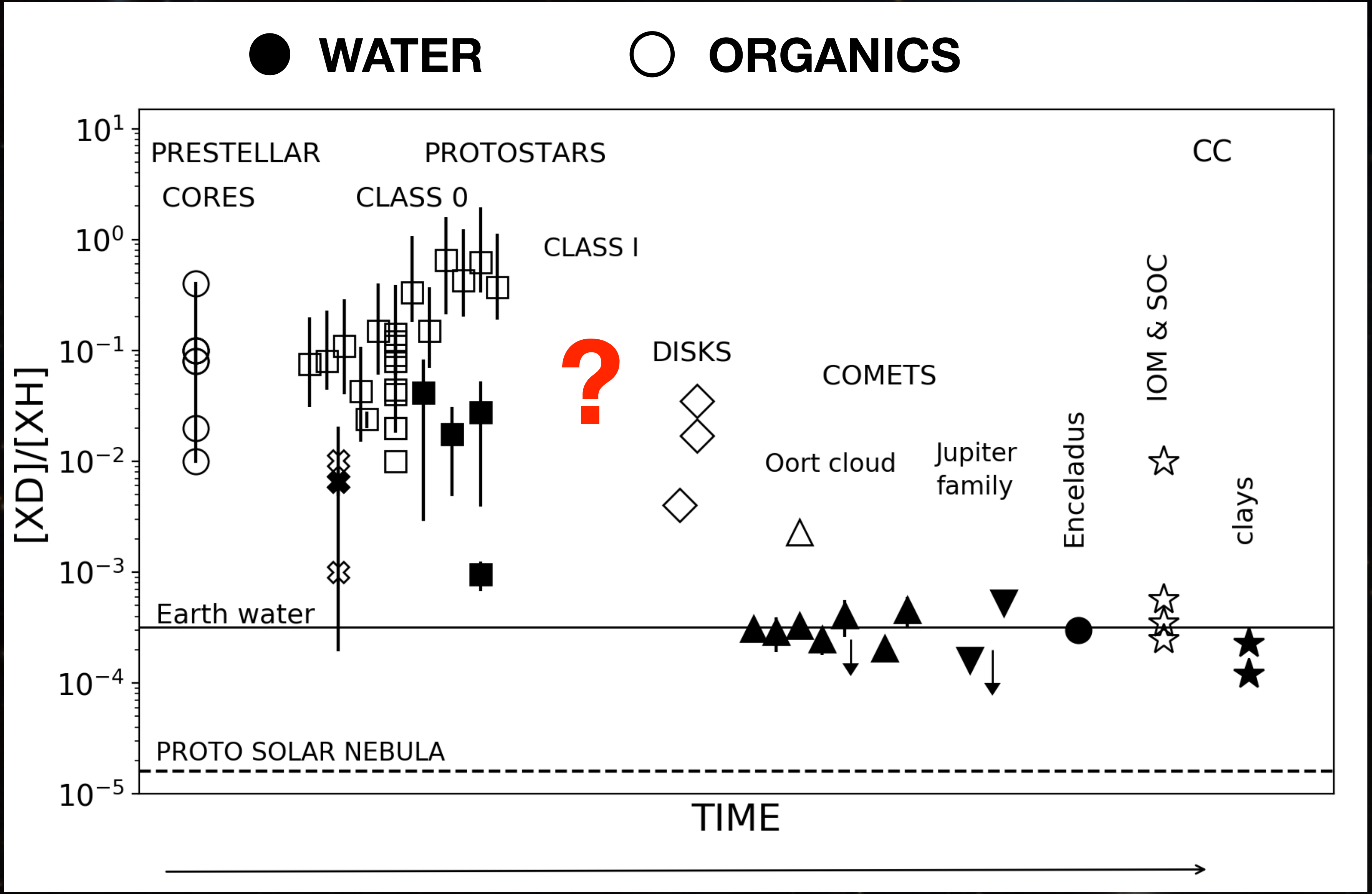
4) PLANETESIMAL FORMATION: grains agglomeration

STORAGE/REPROCESSING OF GRAIN MANTLE ICES

5) PLANET FORMATION: planet migration, small bodies scattering, Earth oceans formation?

CONSERVATION/DELIVERY OF OLD MOLECULES + LIFE?

Deuteration: the Ariane's thread



Adapted from Ceccarelli et al. 2014

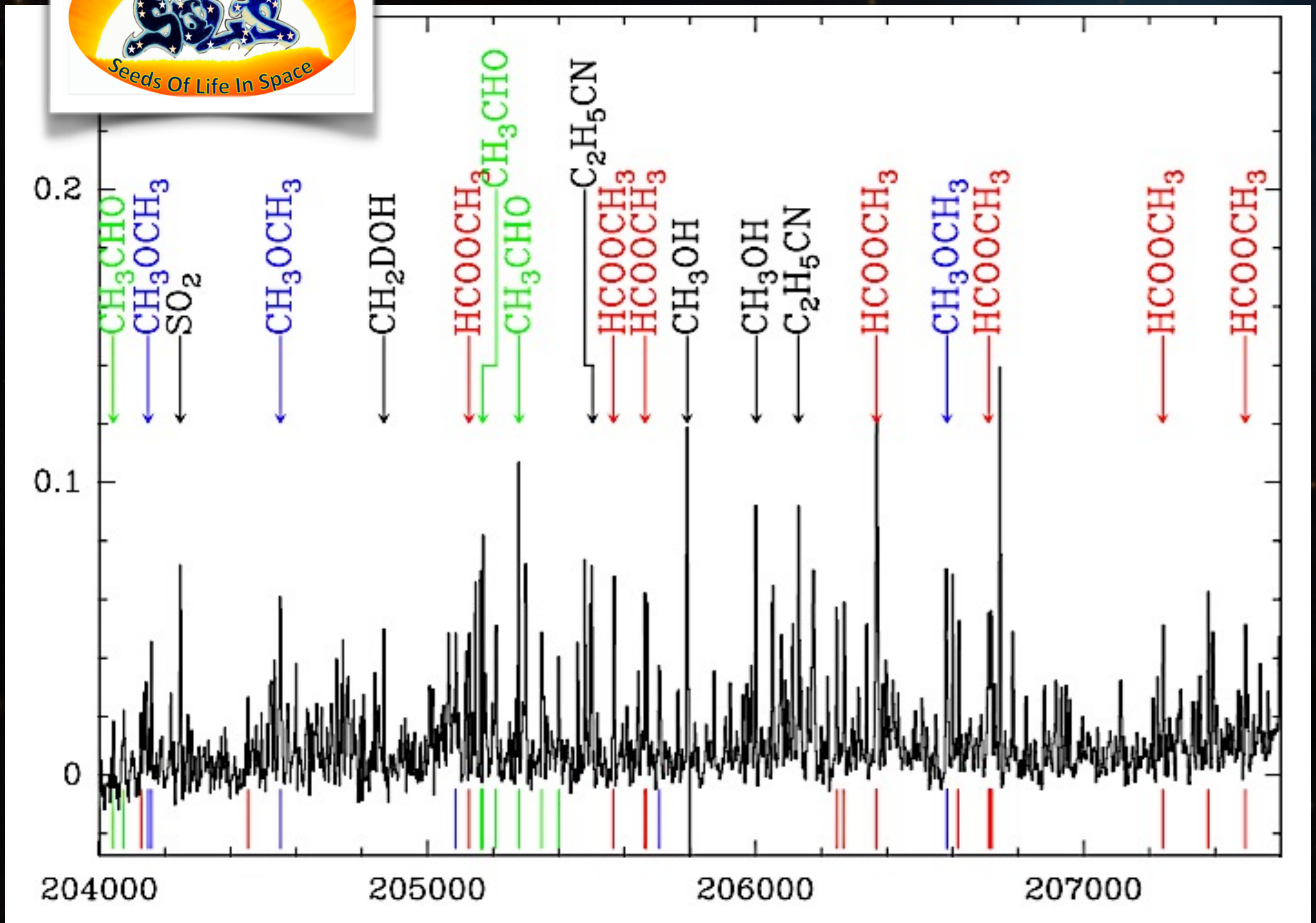
Water first
LOWER D/H

Organics later
HIGHER D/H

What about Class I protostars?

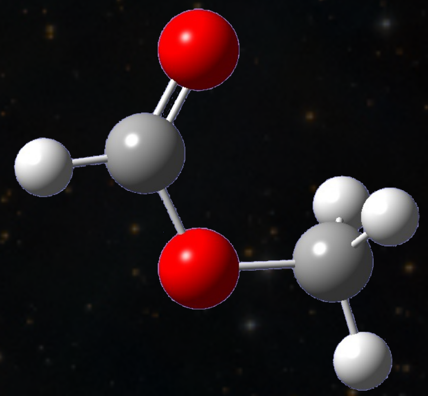
Evolution?

Interstellar Complex Organic Molecules (iCOMS)



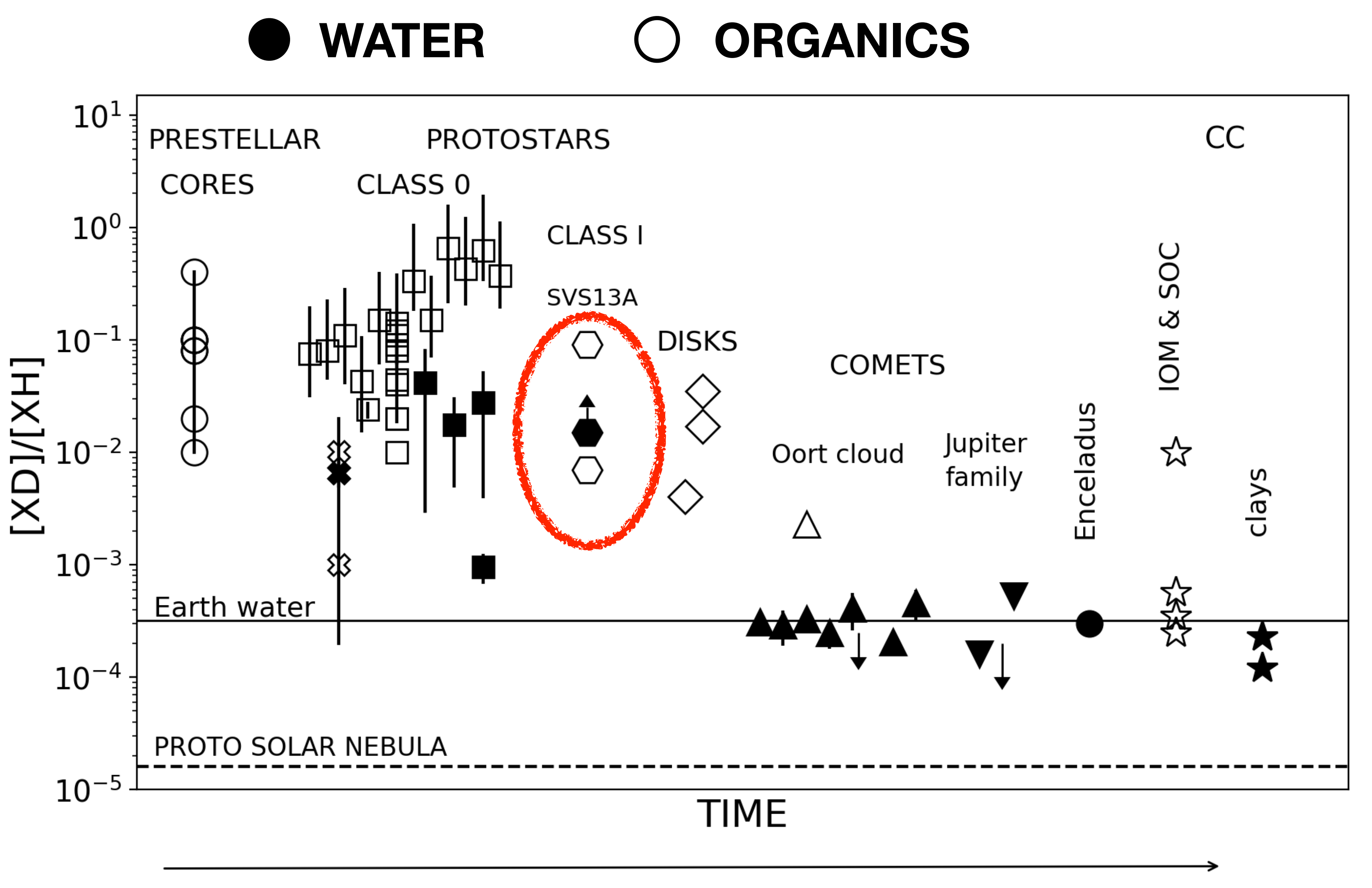
Ceccarelli et al. 2017

Molecules with 6 or more atoms and based on carbon



O-bearing
N-bearing
S-bearing

Deuteration: the Ariane's thread



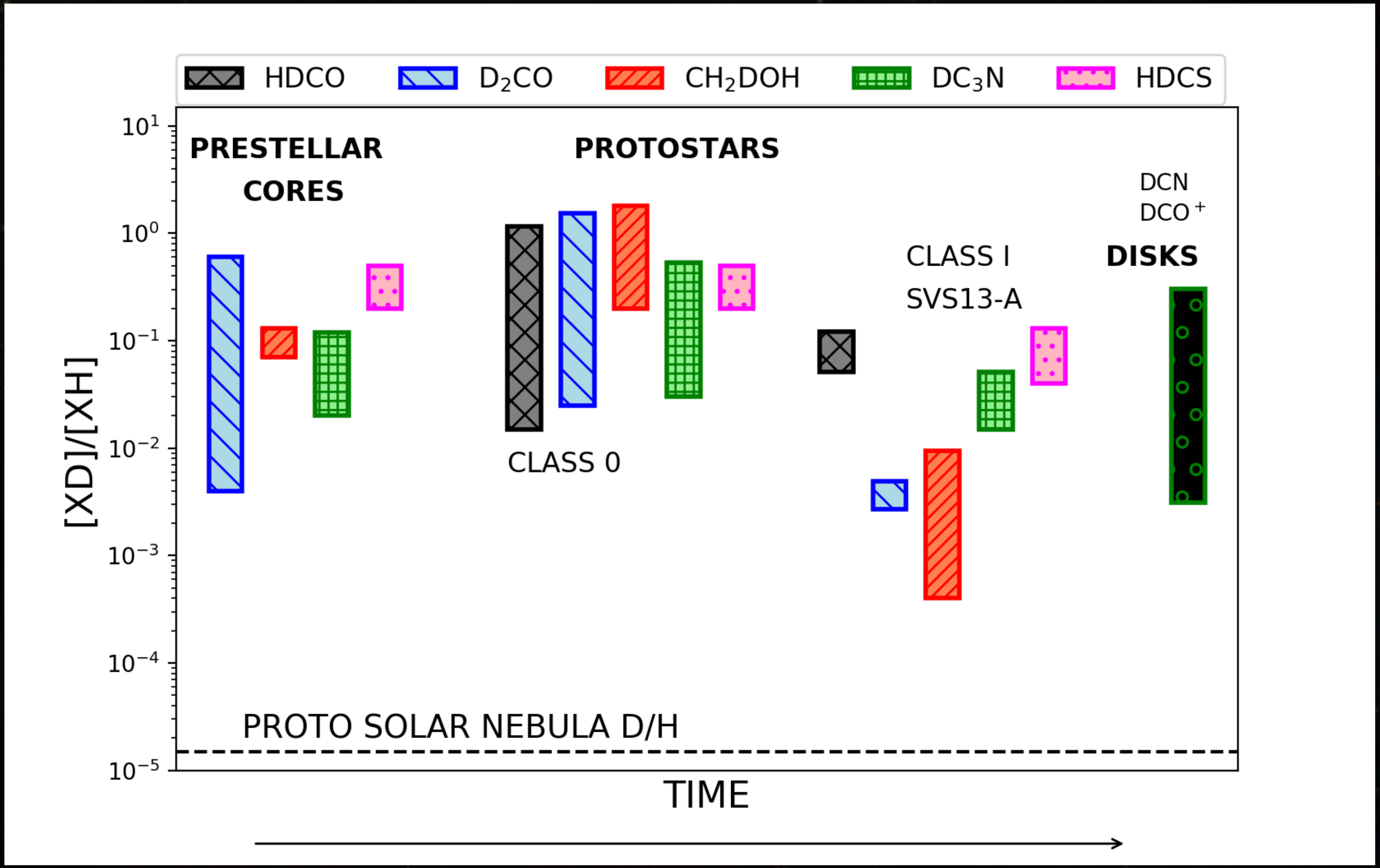
CH_3OH deuteration decreases by 2 orders of magnitude..

Evolution?

More observations needed!

Adapted from Ceccarelli et al. 2014

H_2CS and HC_3N deuteration



$[HDCS]/[H_2CS]$ ~ 0.2 (0.1)

Also measured in 2 prestellar cores and 1 Class 0

$[DC_3N]/[HC_3N]$ ~ 0.03 (0.04)

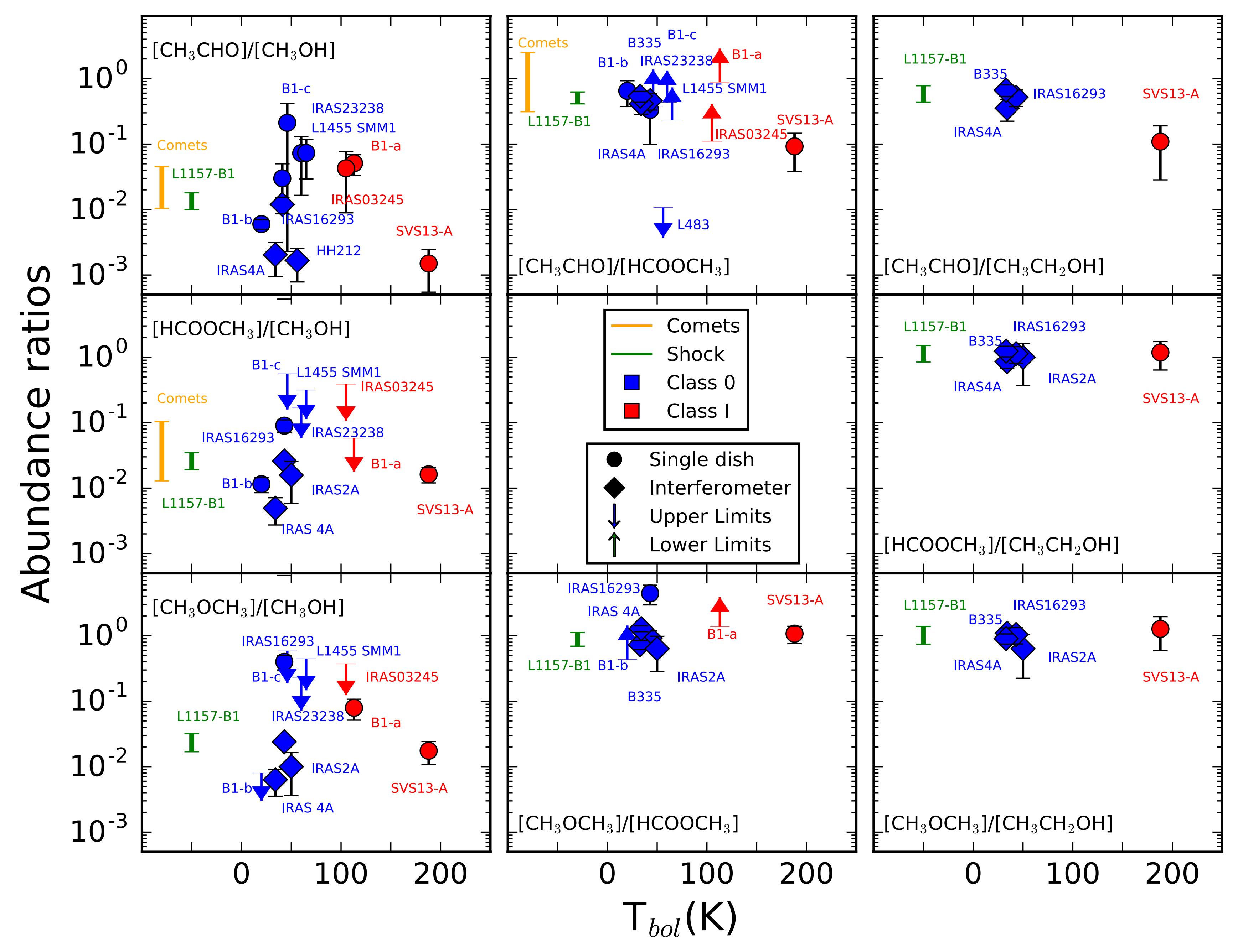
IRAS 16293

IRAS 16293-2422 50% in the cold envelope to 5% in the hot corino region (Jaber et al. 2017)

Bianchi et al. submitted

Class I hot corino

[X]/[CH_3OH] **[X]/[$HCOOCH_3$]** **[X]/[CH_3CH_2OH]**



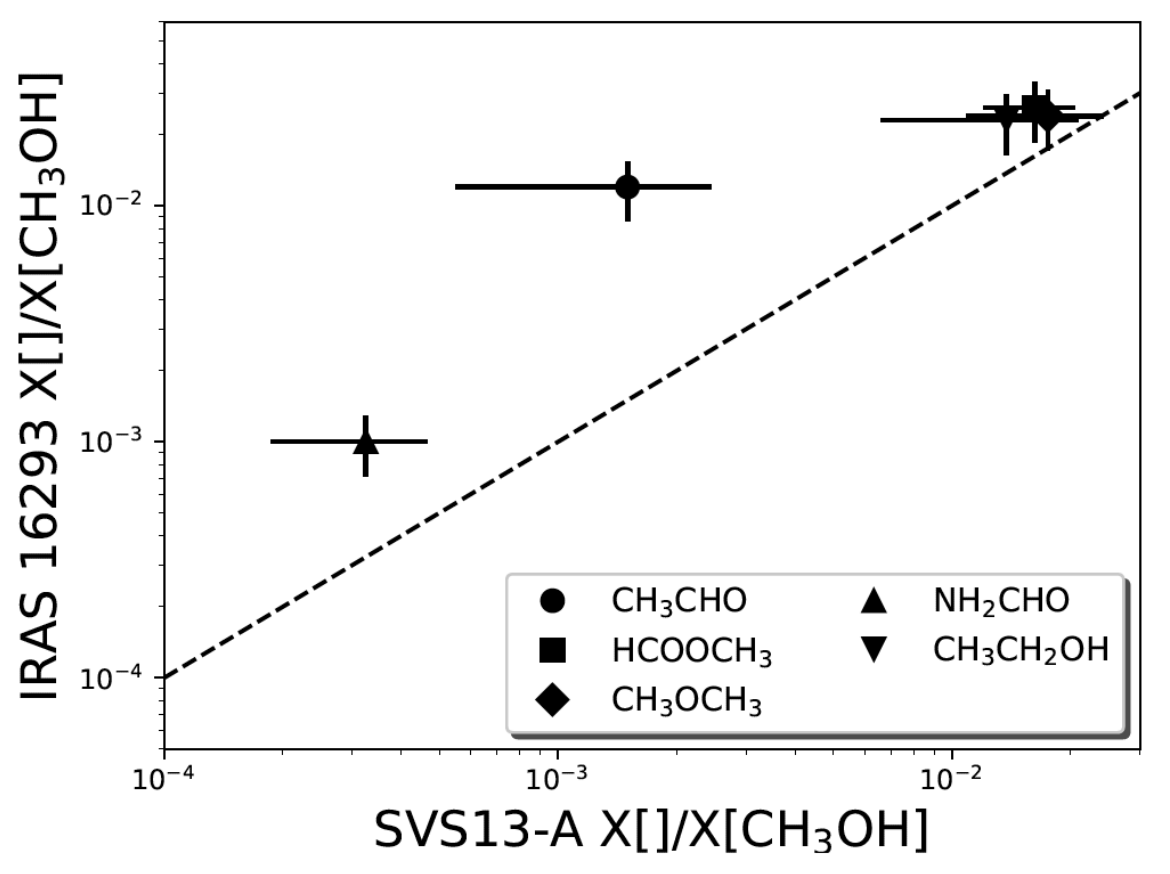
iCOMs ratios

Bianchi et al. 2019

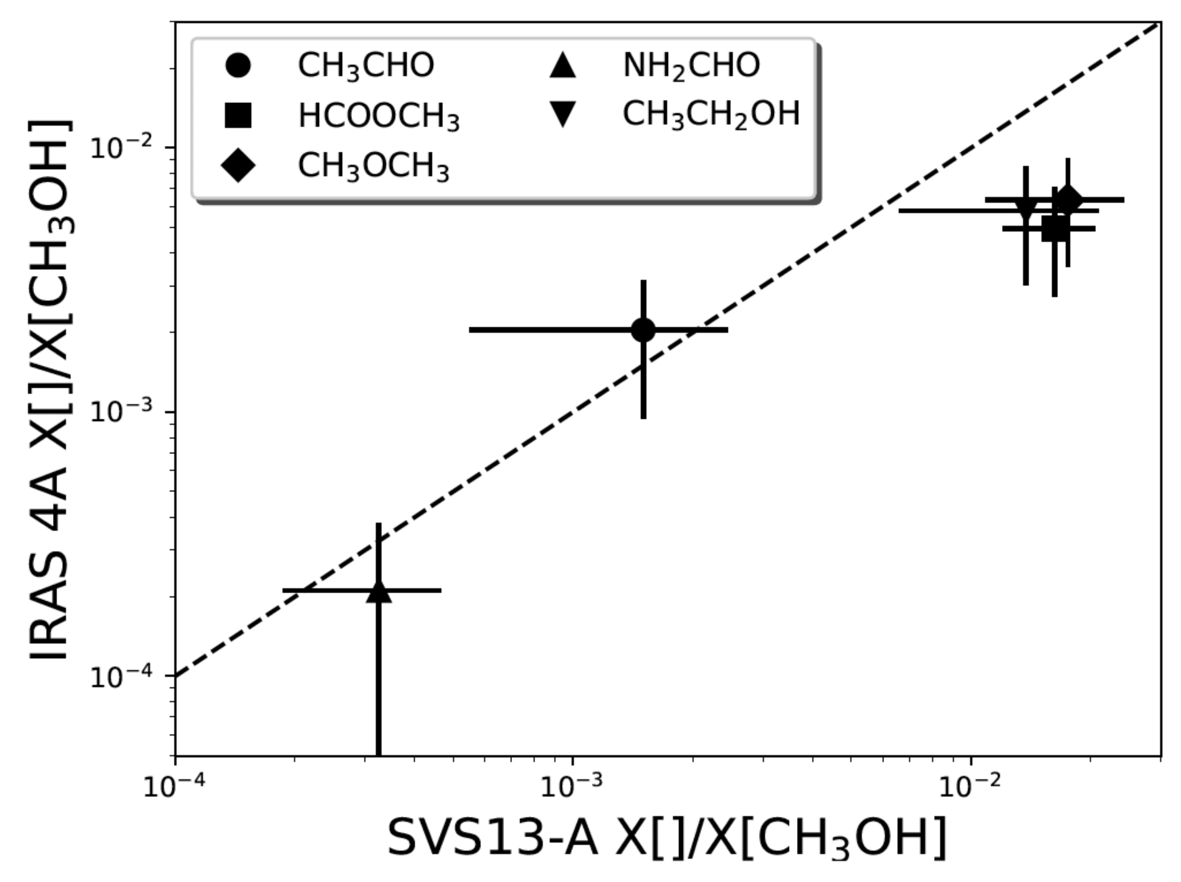
Do Class I hot corinos look like Class 0 ones ?

Class 0 vs Class I possible evolution

Do Class I hot corinos look like Class 0 ones ? **YES!** Bianchi et al. 2019



(Jørgensen et al. 2018, Coutens et al. 2016)



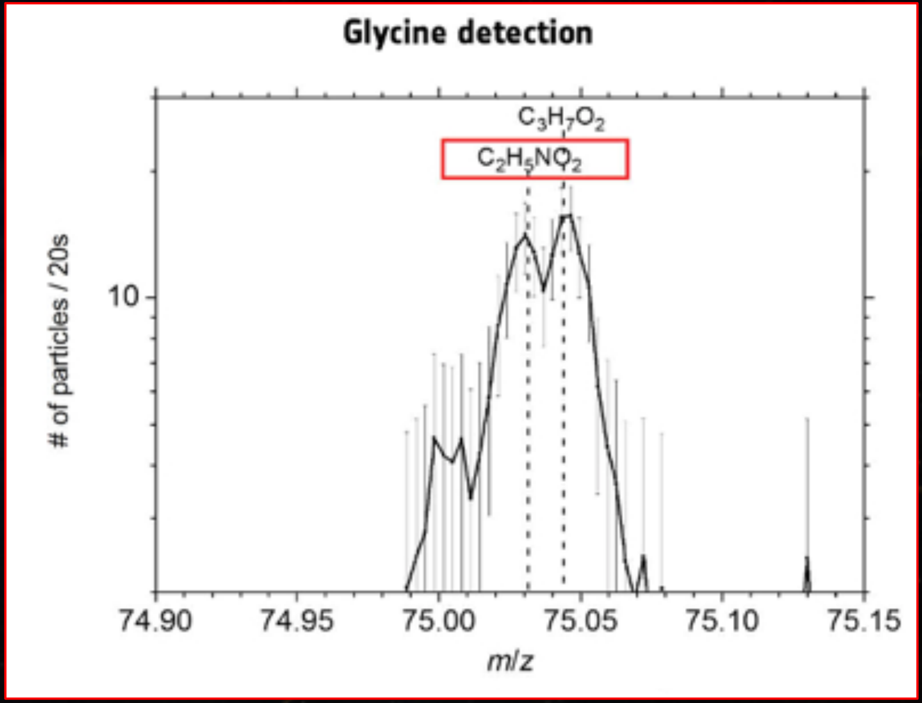
(López-Sepulcre et al. 2017, Taquet et al. 2015)

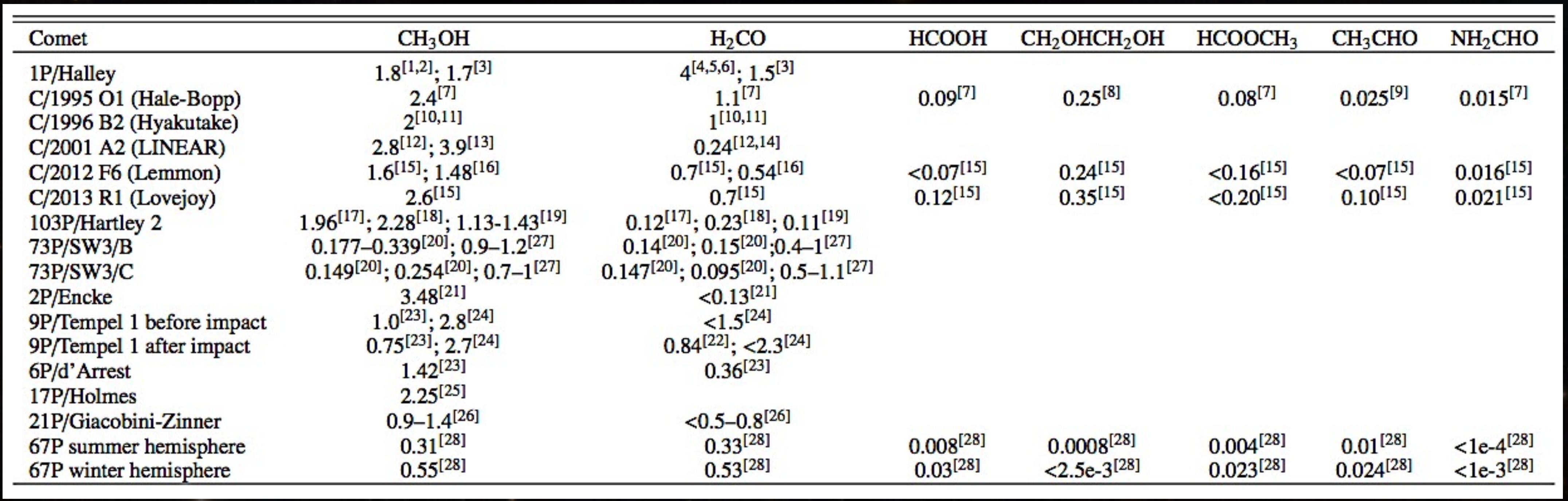
iCOMs abundances ratios do not significantly vary during the protostellar phase (but they might vary/decrease? Same chemistry when the same reactants are available..)

Interstellar complex organic molecules in comets

Not all is lost..

How much reprocessing ?



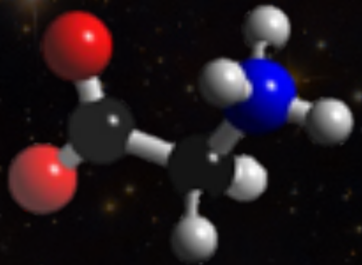


Comet	CH_3OH	H_2CO	$HCOOH$	CH_2OHCH_2OH	$HCOOCH_3$	CH_3CHO	NH_2CHO
1P/Halley	1.8[1,2]; 1.7[3]	4[4,5,6]; 1.5[3]					
C/1995 O1 (Hale-Bopp)	2.4[7]	1.1[7]	0.09[7]	0.25[8]	0.08[7]	0.025[9]	0.015[7]
C/1996 B2 (Hyakutake)	2[10,11]	1[10,11]					
C/2001 A2 (LINEAR)	2.8[12]; 3.9[13]	0.24[12,14]					
C/2012 F6 (Lemmon)	1.6[15]; 1.48[16]	0.7[15]; 0.54[16]	<0.07[15]	0.24[15]	<0.16[15]	<0.07[15]	0.016[15]
C/2013 R1 (Lovejoy)	2.6[15]	0.7[15]	0.12[15]	0.35[15]	<0.20[15]	0.10[15]	0.021[15]
103P/Hartley 2	1.96[17]; 2.28[18]; 1.13-1.43[19]	0.12[17]; 0.23[18]; 0.11[19]					
73P/SW3/B	0.177–0.339[20]; 0.9–1.2[27]	0.14[20]; 0.15[20];0.4–1[27]					
73P/SW3/C	0.149[20]; 0.254[20]; 0.7–1[27]	0.147[20]; 0.095[20]; 0.5–1.1[27]					
2P/Encke	3.48[21]	<0.13[21]					
9P/Tempel 1 before impact	1.0[23]; 2.8[24]	<1.5[24]					
9P/Tempel 1 after impact	0.75[23]; 2.7[24]	0.84[22]; <2.3[24]					
6P/d'Arrest	1.42[23]	0.36[23]					
17P/Holmes	2.25[25]						
21P/Giacobini-Zinner	0.9–1.4[26]	<0.5–0.8[26]					
67P summer hemisphere	0.31[28]	0.33[28]	0.008[28]	0.0008[28]	0.004[28]	0.01[28]	<1e-4[28]
67P winter hemisphere	0.55[28]	0.53[28]	0.03[28]	<2.5e-3[28]	0.023[28]	0.024[28]	<1e-3[28]

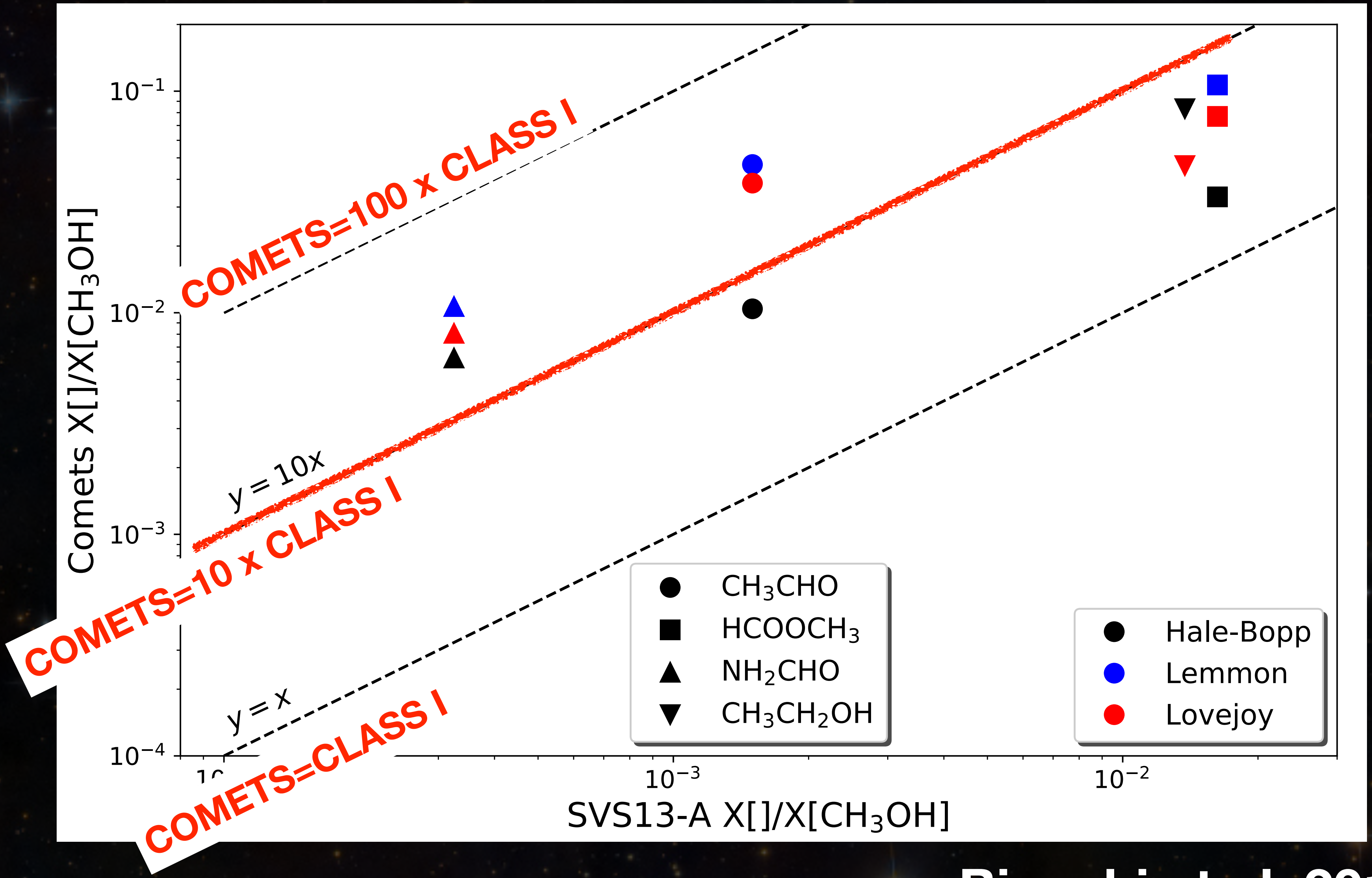
Le Roy et al. 2015

Altwegg et al. 2016

Rubin et al. 2019



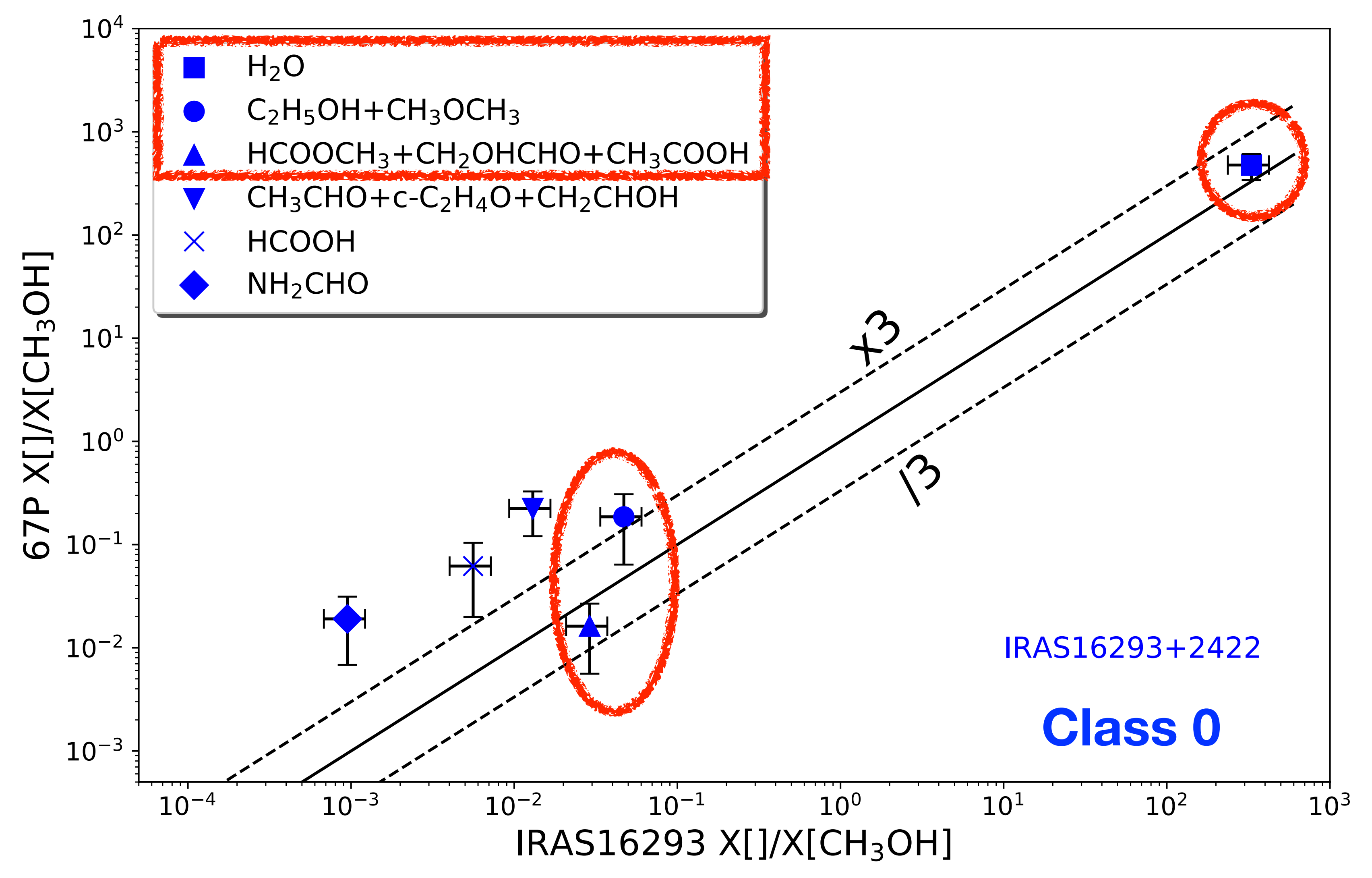
iCOMs in Class I and comets pre-Rosetta



Bianchi et al. 2019

Ethanol and Methyl formate within a factor 10, not so different..

Rosetta: the comparison with the Class 0 IRAS16293

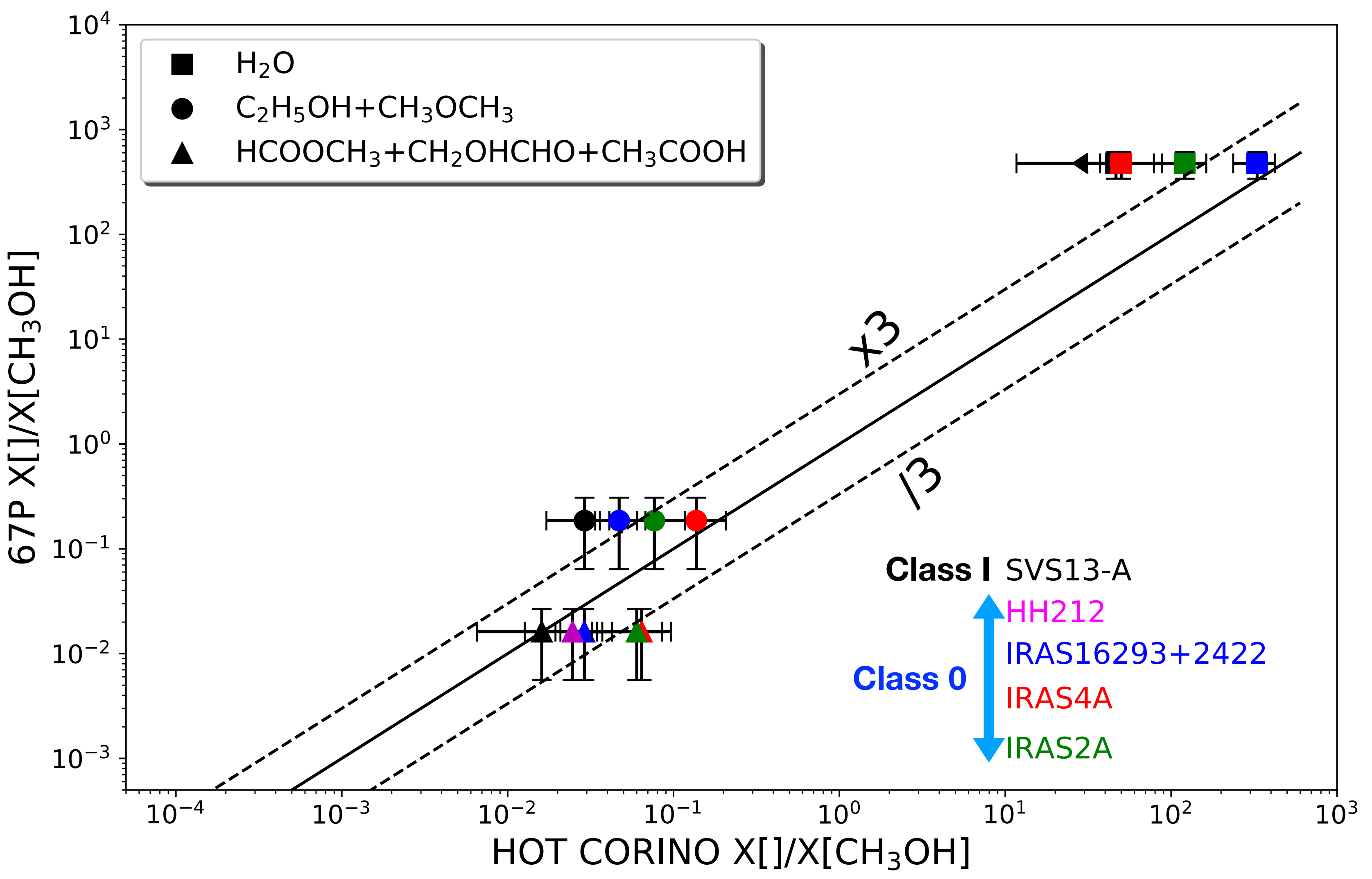


Drvdoskaya et al. 2019

Ethanol*, Methyl formate* and Water within a factor 3

Rosetta: what happens adding more (Class 0 and Class I) sources?

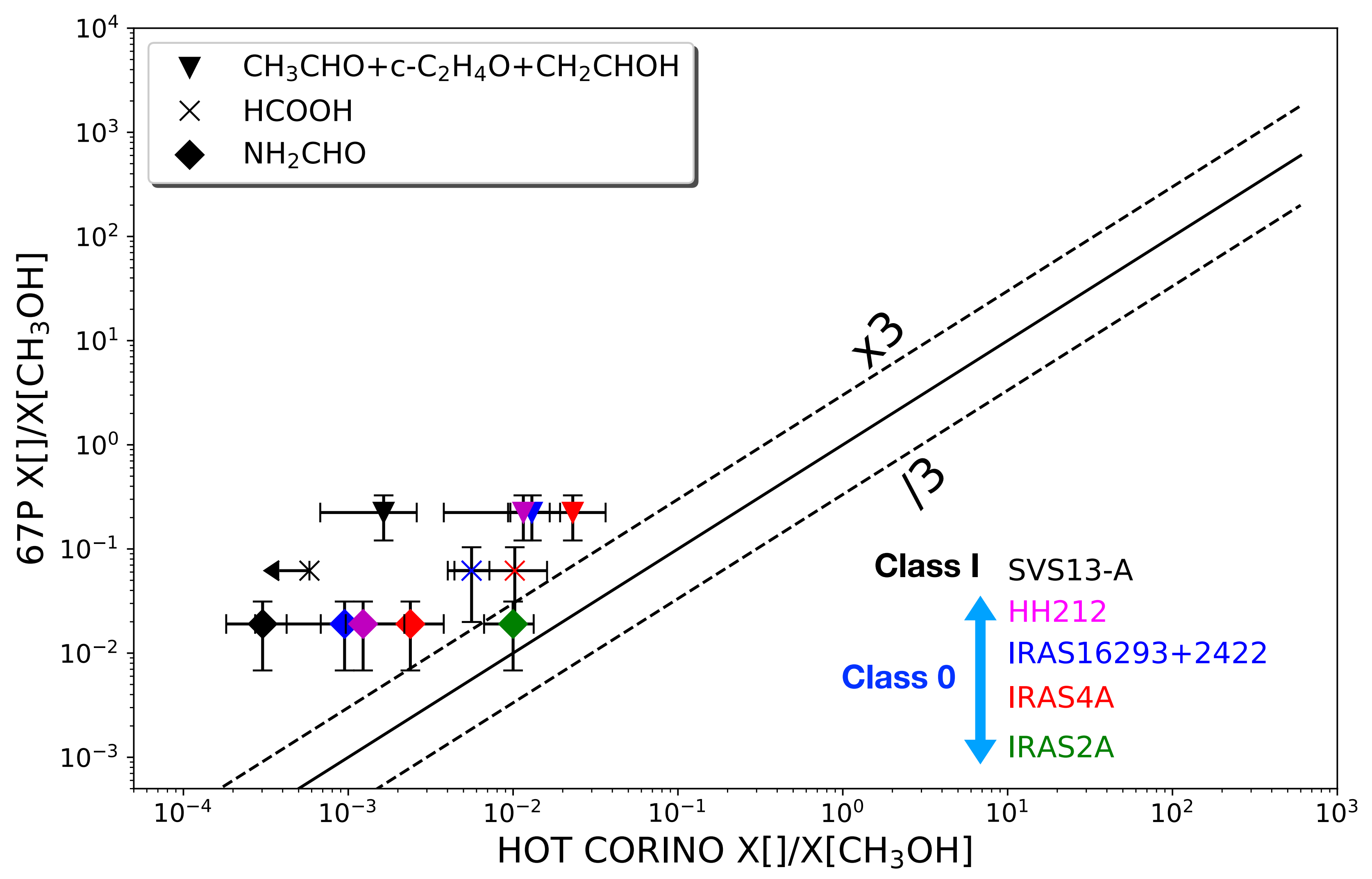
Bianchi et al. 2019 in prep.



Ethanol*, Methyl formate* still consistent even adding Class I

Rosetta: what happens adding more (Class 0 and Class I) sources?

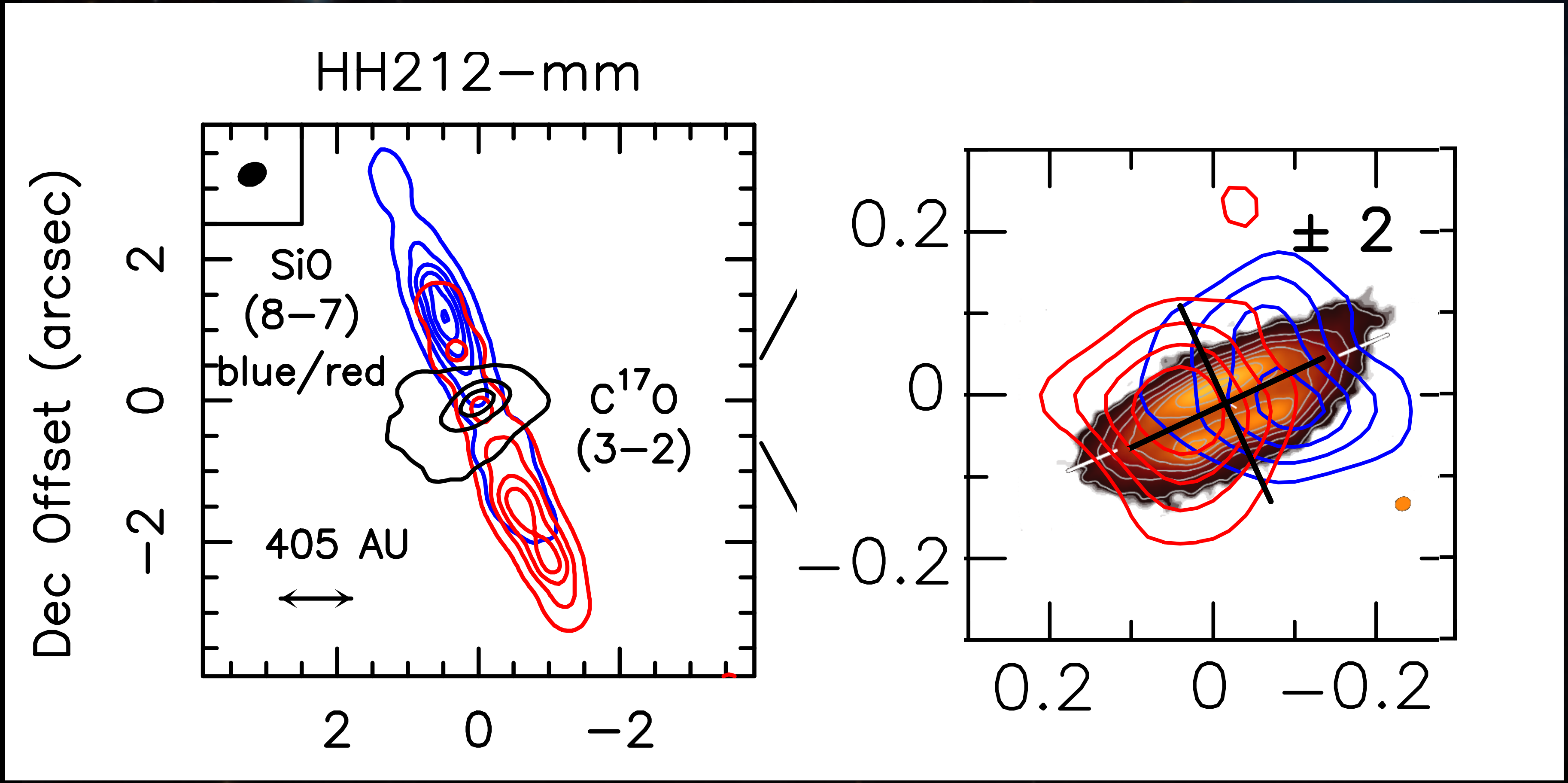
Bianchi et al. 2019 in prep.



Acetaldehyde*, Formic acid and Formamide suggest a different behaviour: why?

iCOMs abundances: the importance of sampling the protostellar disk

CH_3CHO + dust continuum

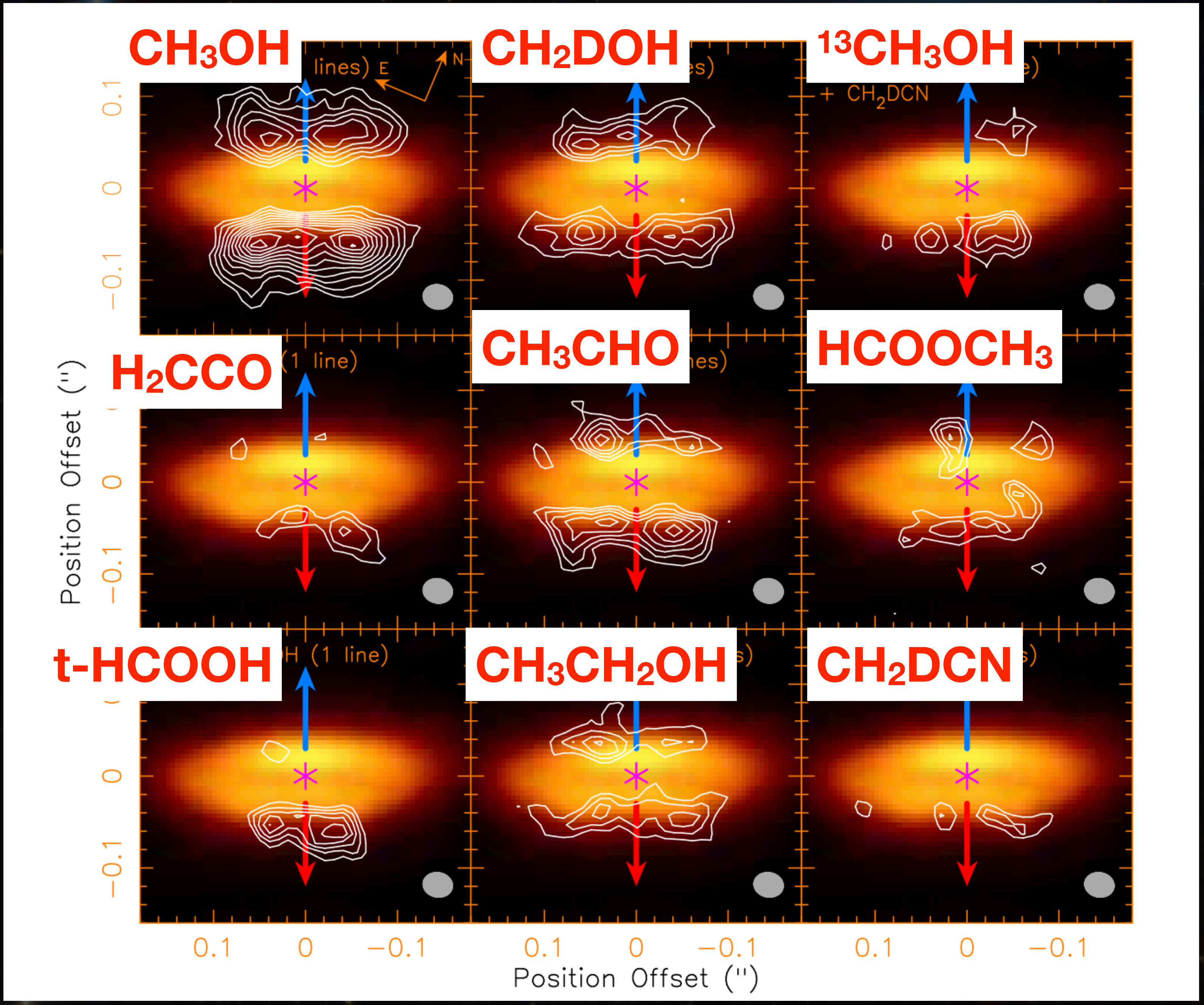


iCOMs imaged for the first time in a Class 0 protostellar disk

Lee et al. 2017, 2019
Codella et al. 2019

iCOMs abundances: the importance of sampling the protostellar disk

Class 0



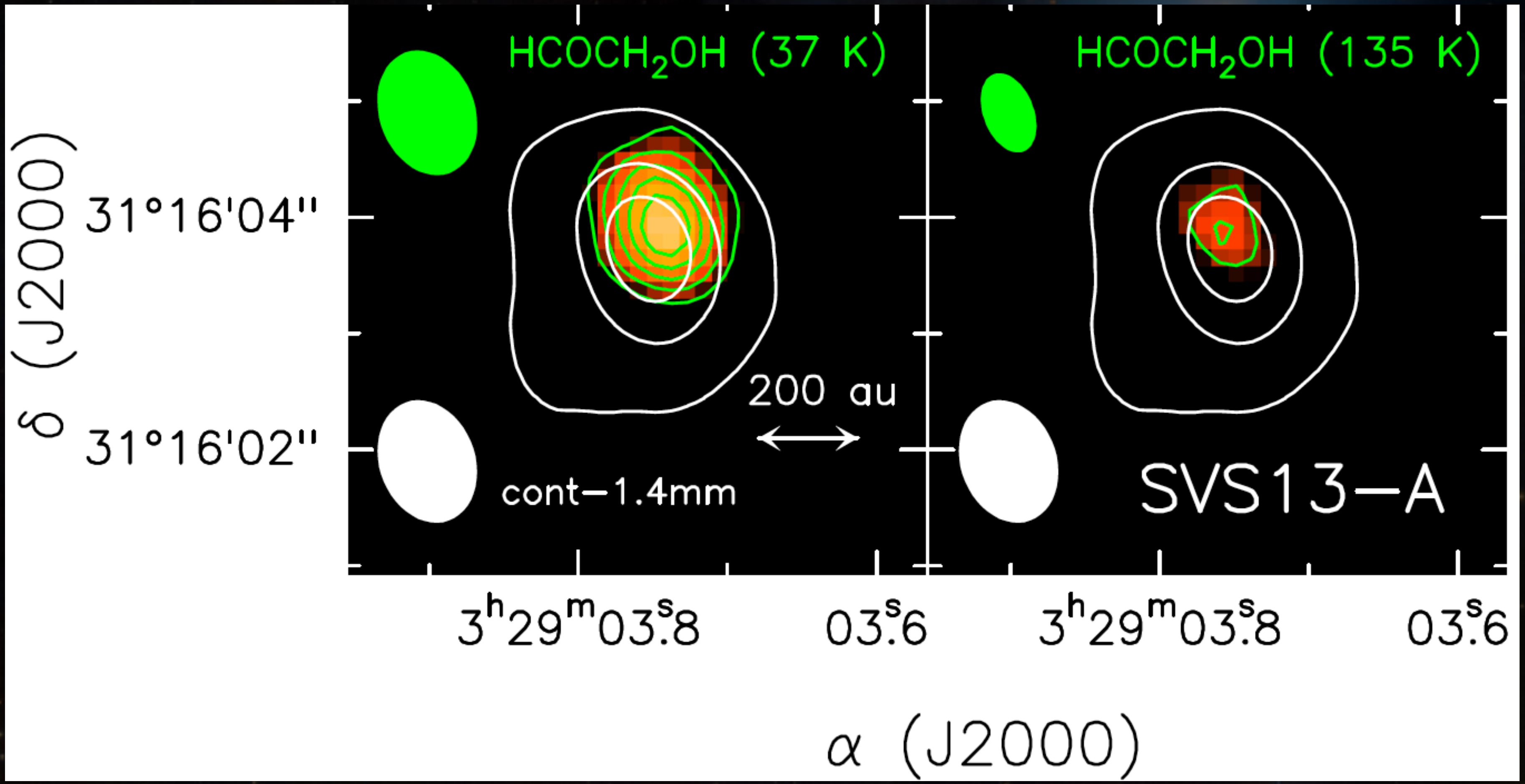
Note the absence of iCOMs in the midplane:
is it real or due to opacity problems?

Work in progress..

Stay tuned!

iCOMs abundances: the importance of sampling the protostellar disk
Class I

Caselli & Ceccarelli 2012
Ceccarelli et al. 2014



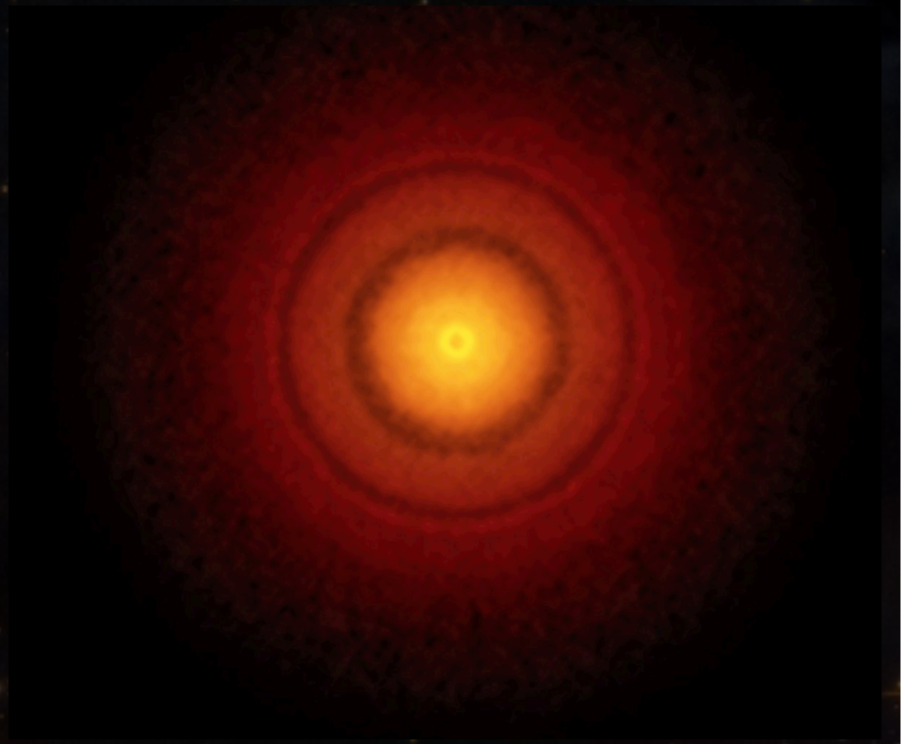
Need to spatially resolve the emission
Is the disk as in the HH212 case?

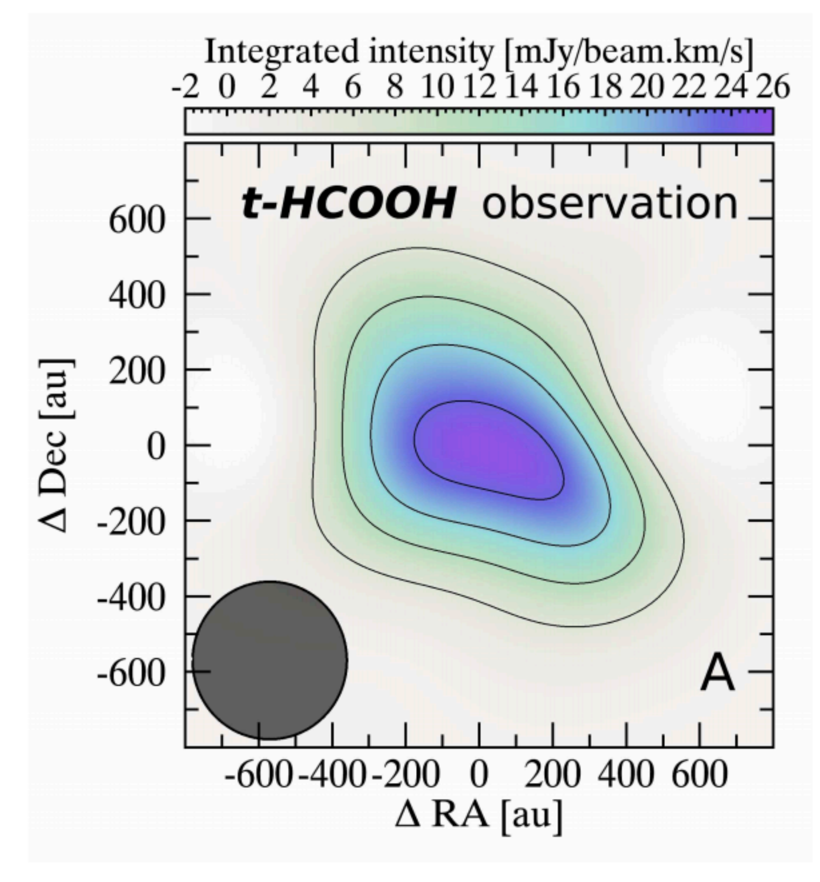
Recover the physical conditions at the time formation epoch

De Simone et al. 2017

iCOMs abundances: the importance of sampling the protostellar disk
Class II

Ceccarelli et al. 2014





Formic Acid first detected in a protoplanetary disk (Class II)

Need to spatially resolve the emission

Favre et al. 2018

TW Hydrae

TAKE HOME MESSAGES

- Class I protostars are the ideal laboratories where to investigate if the chemical richness is inherited by the protoplanetary regions
- Deuteration and iCOMs give us a lot of information on the past and present the gas conditions
- Possible evolution in deuterium fractionation content in Class I
- Class I hot corinos look like Class 0 ones in iCOMs content
- Class I hot corinos share similarities with comets in iCOMs abundance ratios

MORE OBSERVATIONS NEEDED!!

FUTURE

Seeds Of Life In Space

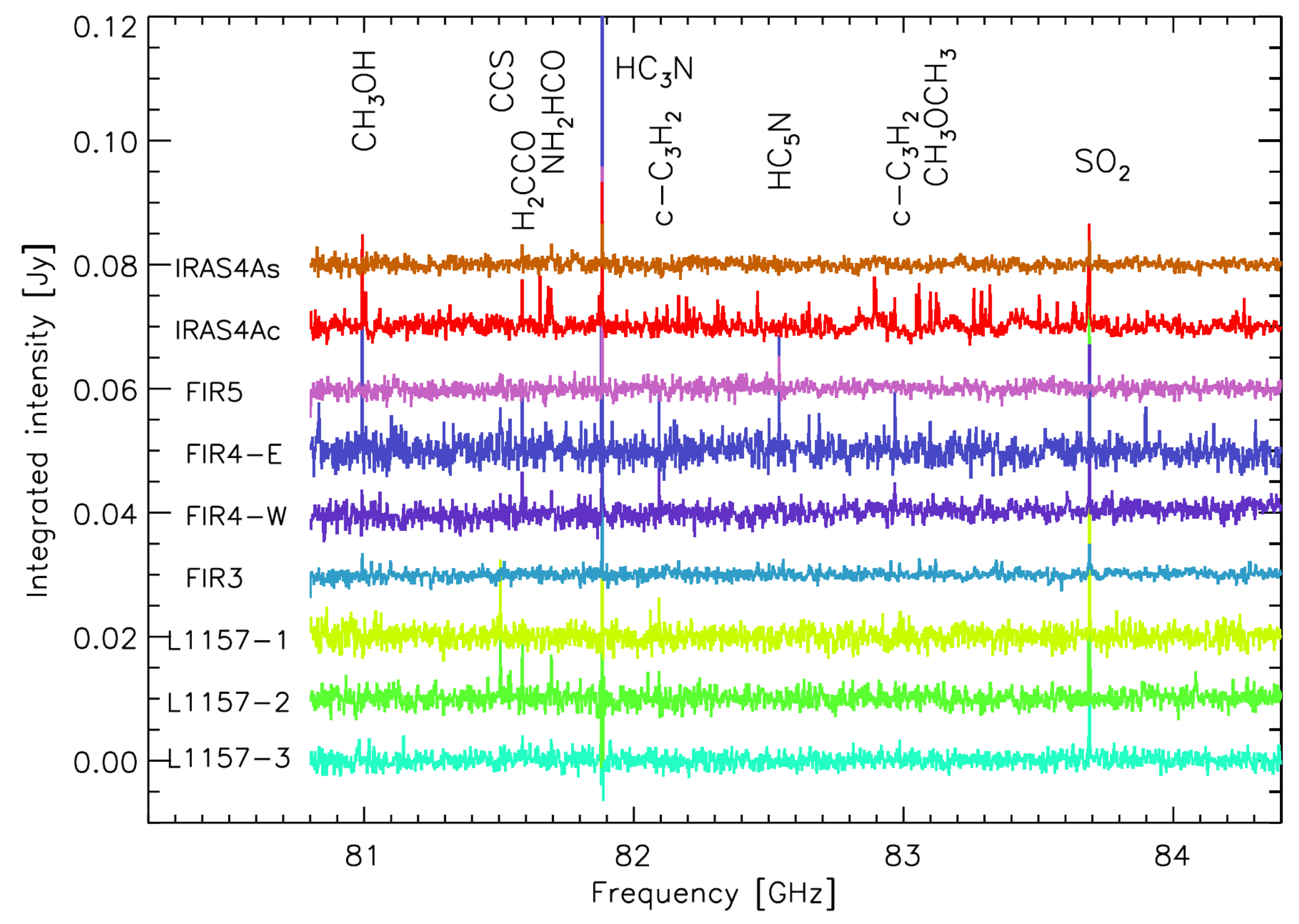
PIs: C. Ceccarelli, P. Caselli

380 hr @IRAM-NOEMA

Systematic observations of 5 key iCOMs (CH_3OH, CH_3O, CH_3OCH_3, $HCOOCH_3$, NH_2CHO) in different sources representatives of Sun-like star formation

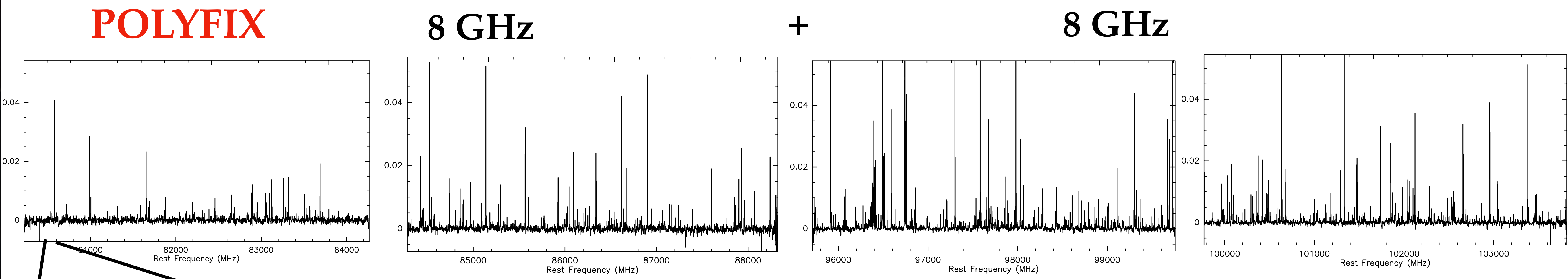
80-371 GHz
baselines up to 760 m
up to θ = 0.1”

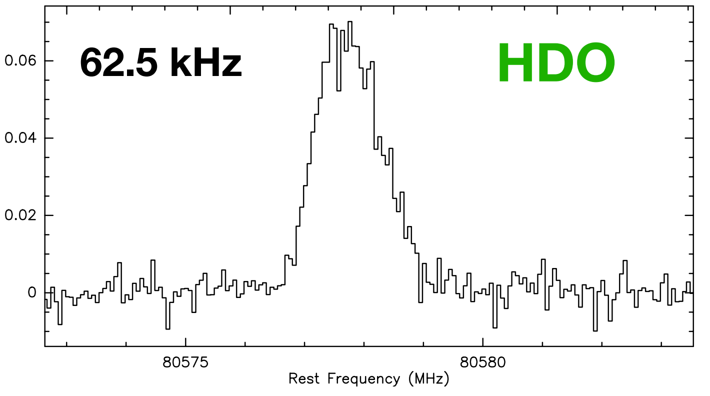
Ceccarelli et al. 2017



SVS13-A: a chemically rich hot corino

NOEMA Large Program (PI C. Ceccarelli & P. Caselli: *Ceccarelli et al. 2017*)





128 high-resolution narrow bands

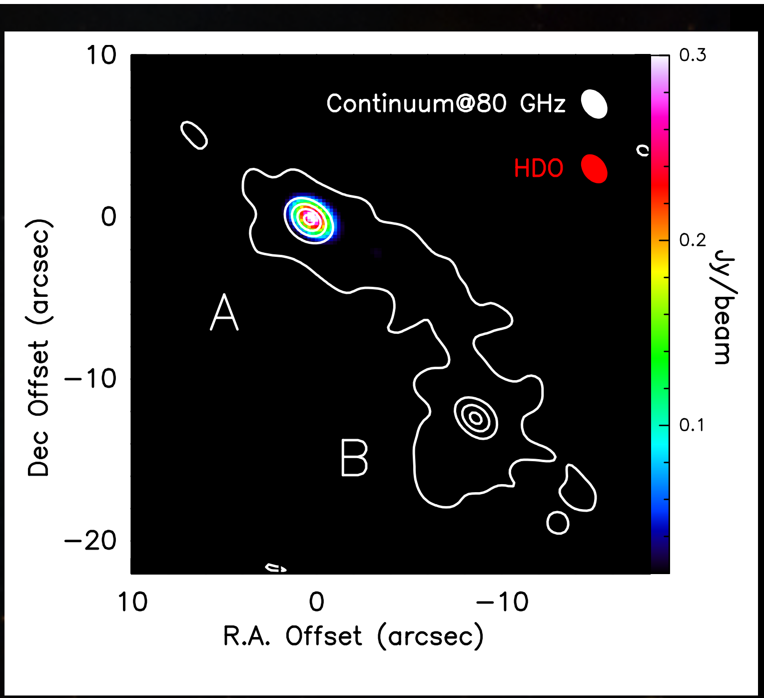
More than 100 lines detected

iCOMs: CH_3OCH_3, $HCOOCH_3$, CH_3CHO, H_2CO, H_2CCO, C_2H_5OH, CH_3OH, CH_3COCH_3, $HCOCH_2OH$,..

N-bearing: NH_2CHO, H_2NCH_2CN,..

D-bearing: CH_2DOH, HDO, HDCO, D_2CO,..

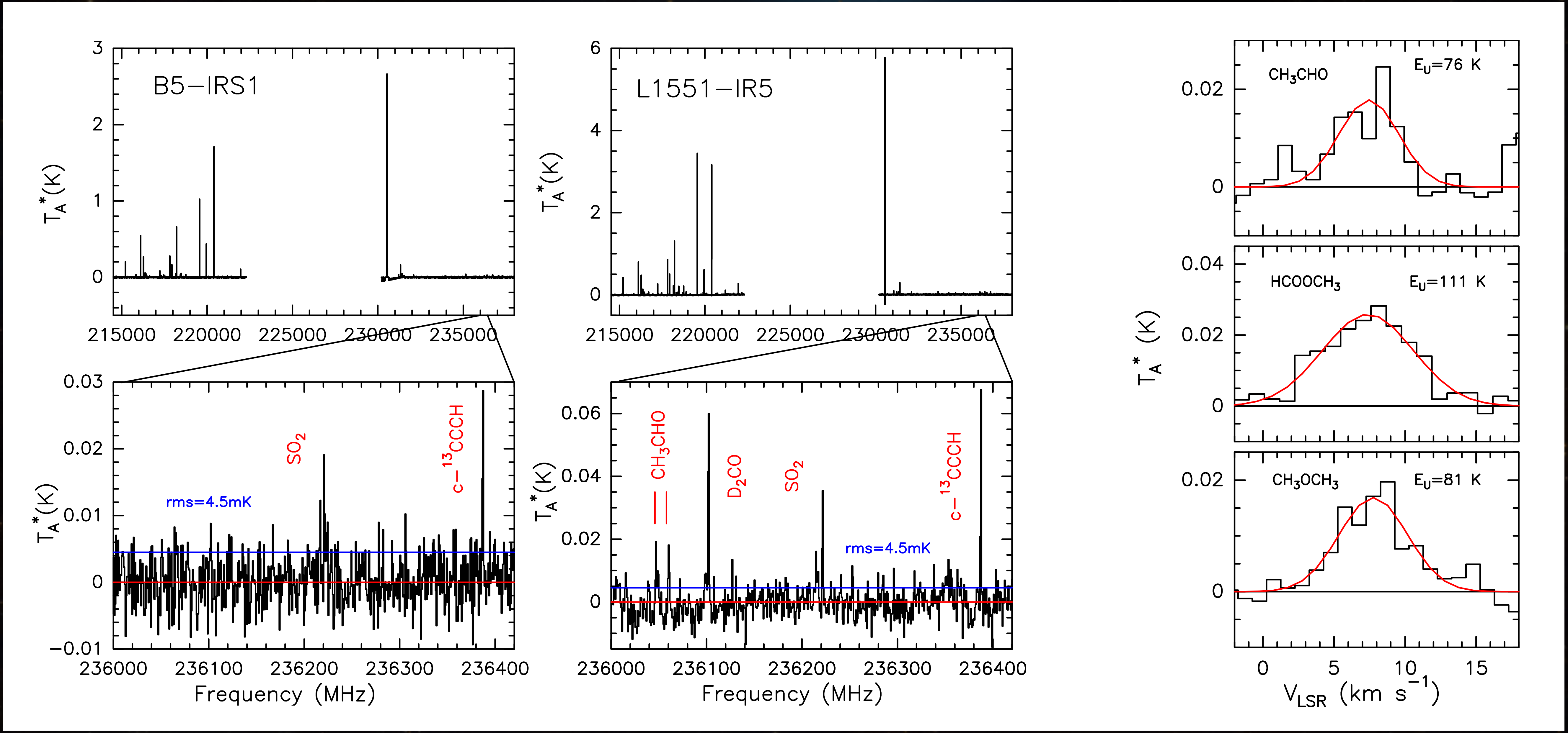
S-bearing: SO, SO_2, H_2CS..



Bianchi et al. in prep.

FUTURE: increasing the sample

Class I protostars observed with IRAM-30m (Bianchi et al. in prep.)



FUTURE

ALMA LP: Fifty AU Study of protosun analogs

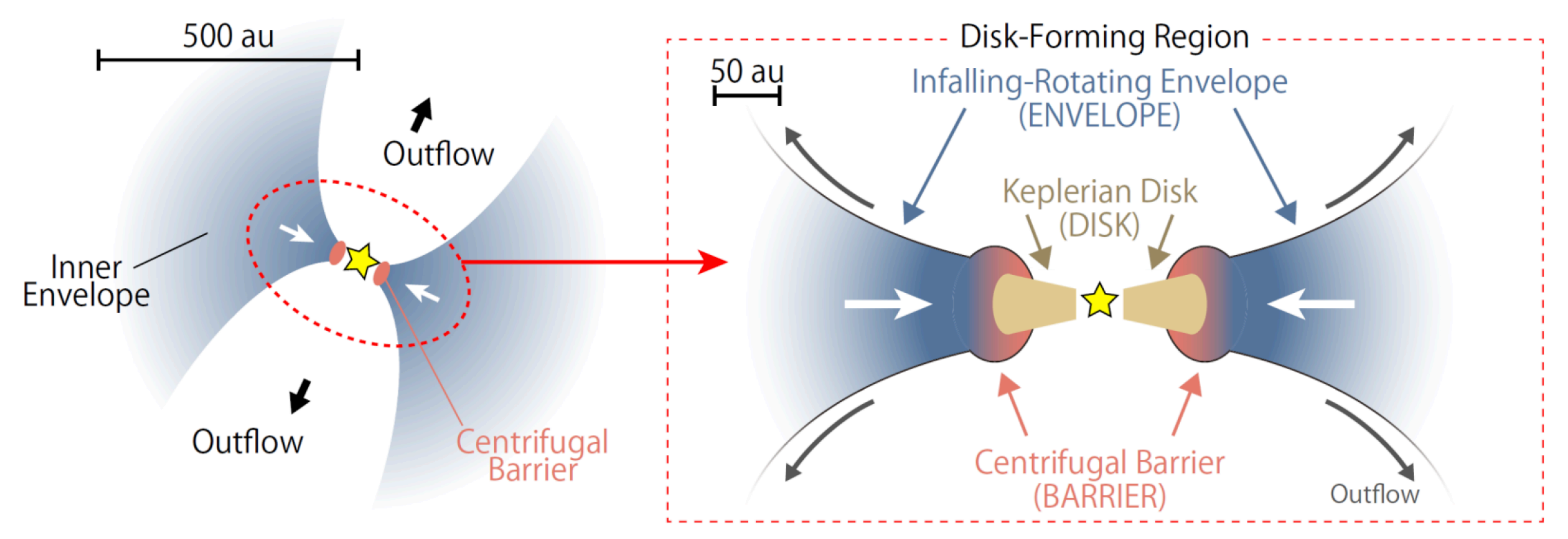
PIs: S. Yamamoto, N. Sakai, C. Codella, C. Ceccarelli, C. Chandler

- ***Envelope*** CS, c-C_3H_2
- ***Centrifugal barrier*** SO, SiO, CH_3OH
- ***Disk*** H_2CO, $C^{18}O$, HC_3N
- ***Ionization*** $H^{13}CO+$, DCO+, N_2H+
- ***Complex*** CH_3OH, NH_2CHO, CH_3CHO, CH_3OCH_3, $HCOOCH_3$
- ***Deuteration*** c-C_3HD, N_2D+, HDCO, D_2CO, CH_2DOH

assess the chemical complexity of protostars

origin of complex (pre-biotic) molecules:

reset or inheritance ?

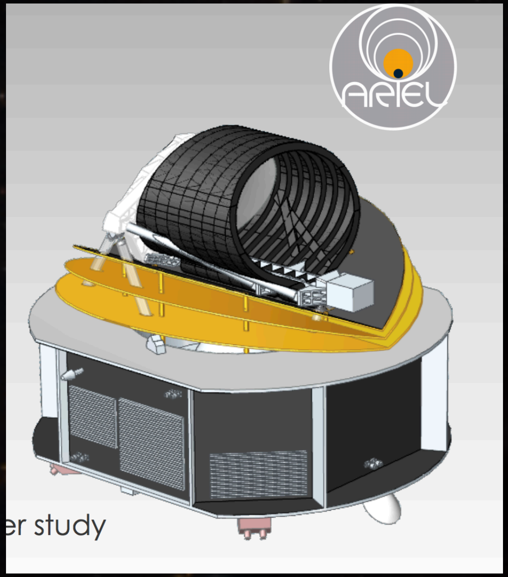


13 sources observed with uniform linear resolution and sensitivity

FUTURE

ARIEL

Turrini et al. 2018



ESA MISSION

Atmospheric
Remote-sensing
Infrared Exoplanet
Large-survey

Among the goals:

First chemical survey of exoplanets

Explore the exoplanets chemical diversity

AMBITION

Bockelée-Morvan et al. 2019

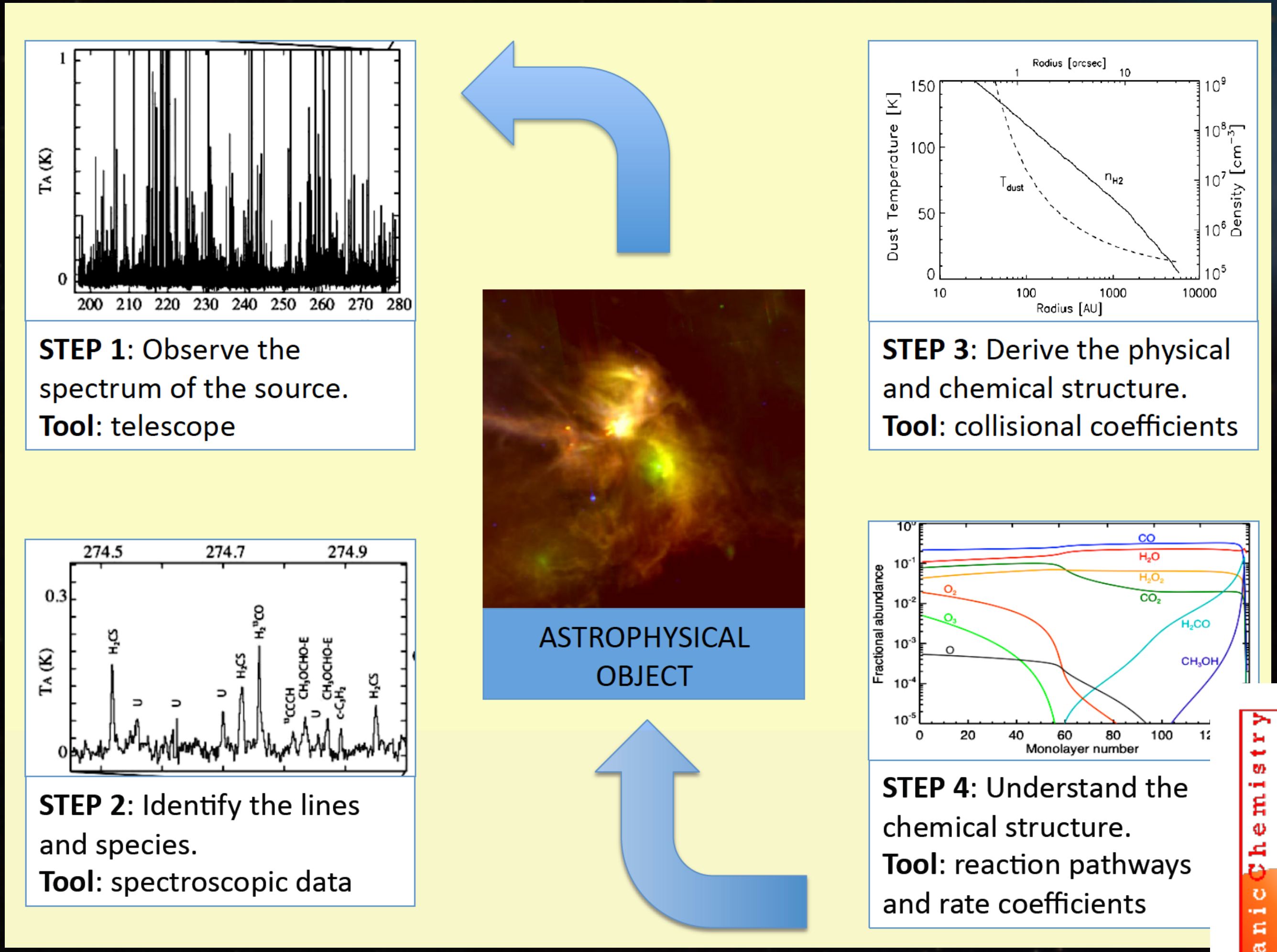
White paper for
ESA Voyage 2050
long-term
(2035-2050) plan

Among the goals:

How and where did cometary materials get assembled?

Which post-planetesimal evolution paths need to be considered?

FUTURE SYNERGIES!!



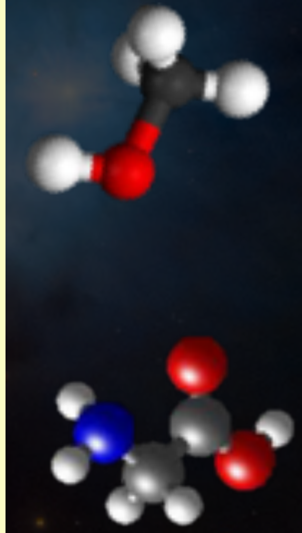
STEP 1: Observe the spectrum of the source.
Tool: telescope

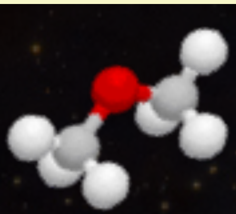
STEP 2: Identify the lines and species.
Tool: spectroscopic data

ASTROPHYSICAL OBJECT

STEP 3: Derive the physical and chemical structure.
Tool: collisional coefficients

STEP 4: Understand the chemical structure.
Tool: reaction pathways and rate coefficients





Dawn of Organic Chemistry

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ACO
EU H2020 Innovative Training Network
Astro-Chemical Origins