The PILS program: a large spectral survey of the solar-type protostar IRAS 16293-2422 with ALMA

Audrey Coutens (IRAP)

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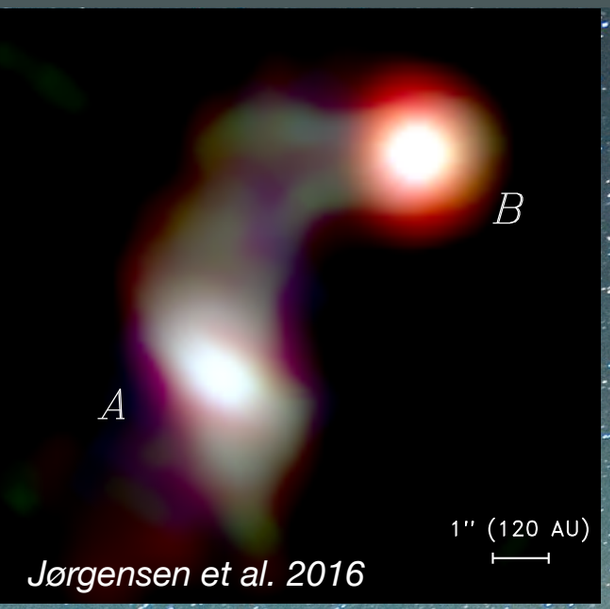

Jørgensen et al. 2016

Credit: ESO/C. Malin

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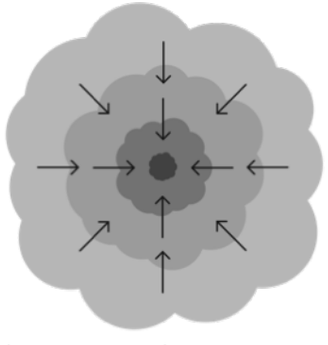
irap astrophysique & planétologie

erc European Research Council Established by the European Commission

Star and planet formation

Star formation process

Prestellar core



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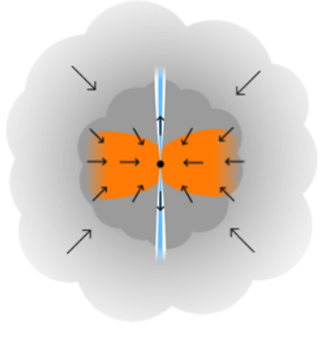

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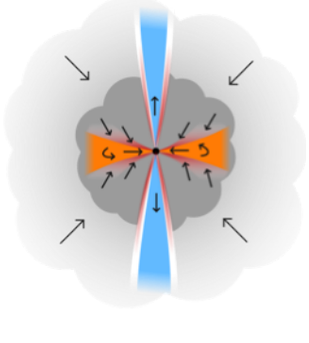

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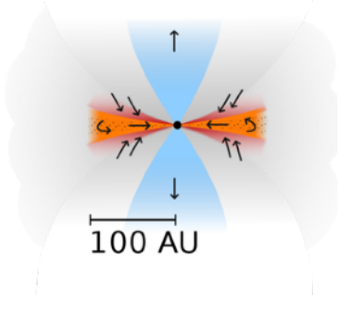

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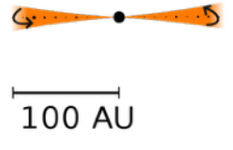
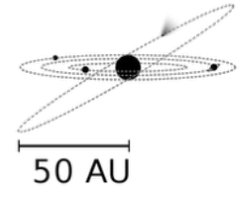


Planetary system



Credit: Adapted from M. Persson

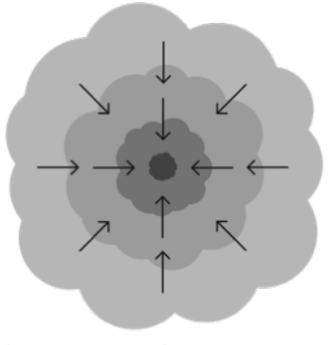
Gravitational collapse

Envelope dissipation

Star and planet formation

Star formation process

Prestellar core



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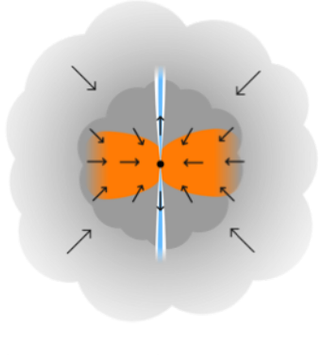

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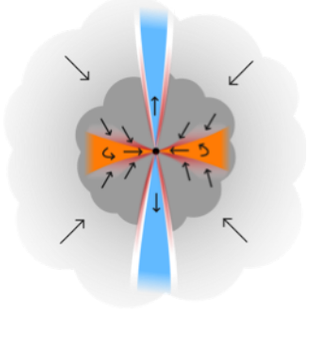

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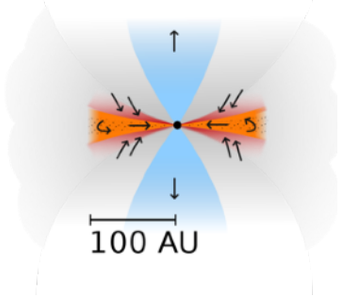

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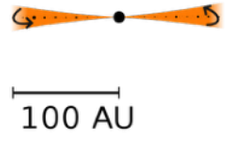

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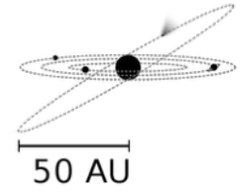


Credit: Adapted from M. Persson

Gravitational collapse → *Envelope dissipation* →

Comets & asteroids (meteorites) rich in amino acids and sugars

Churyumov-Gerasimenko

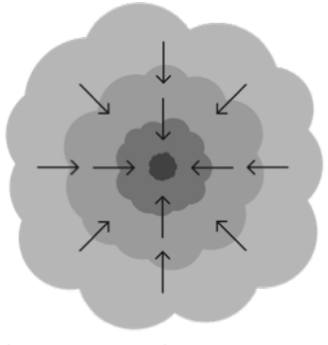
Murchison Meteorite

DNA

Star and planet formation

Star formation process

Prestellar core



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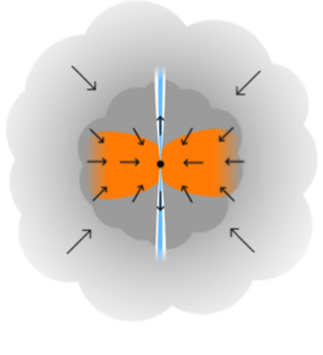

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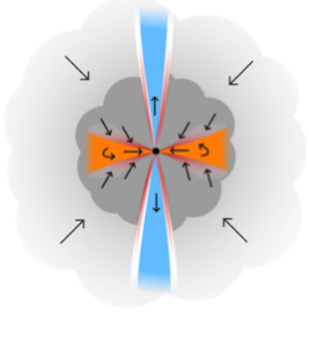

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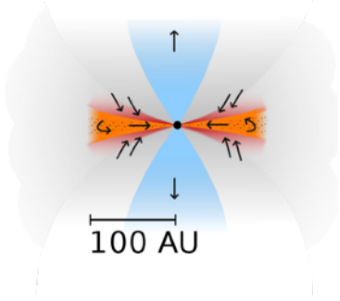

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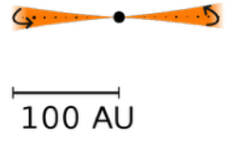

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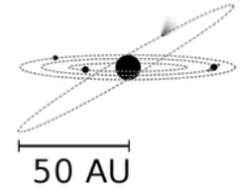


Credit: Adapted from M. Persson

Gravitational collapse ——— *Envelope dissipation* ———►

- Origin of the molecular complexity ?
- What is the level of molecular complexity in star-forming regions ?

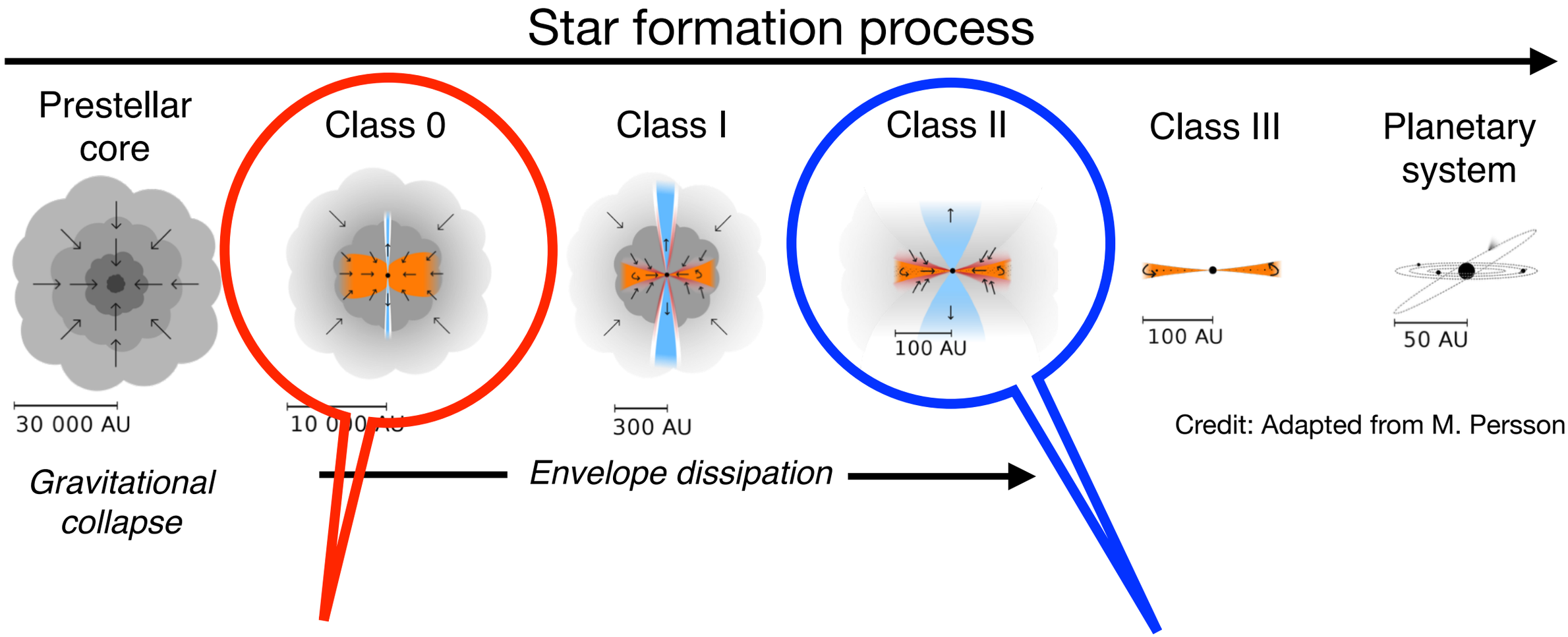
Comets & asteroids (meteorites) rich in amino acids and sugars

Churyumov-Gerasimenko

Murchison Meteorite

DNA

Star and planet formation



HOT CORINOS

Warm inner regions of protostellar envelopes (T > 100 K, ~ 100 au) in which COMs are detected

COLD DISK

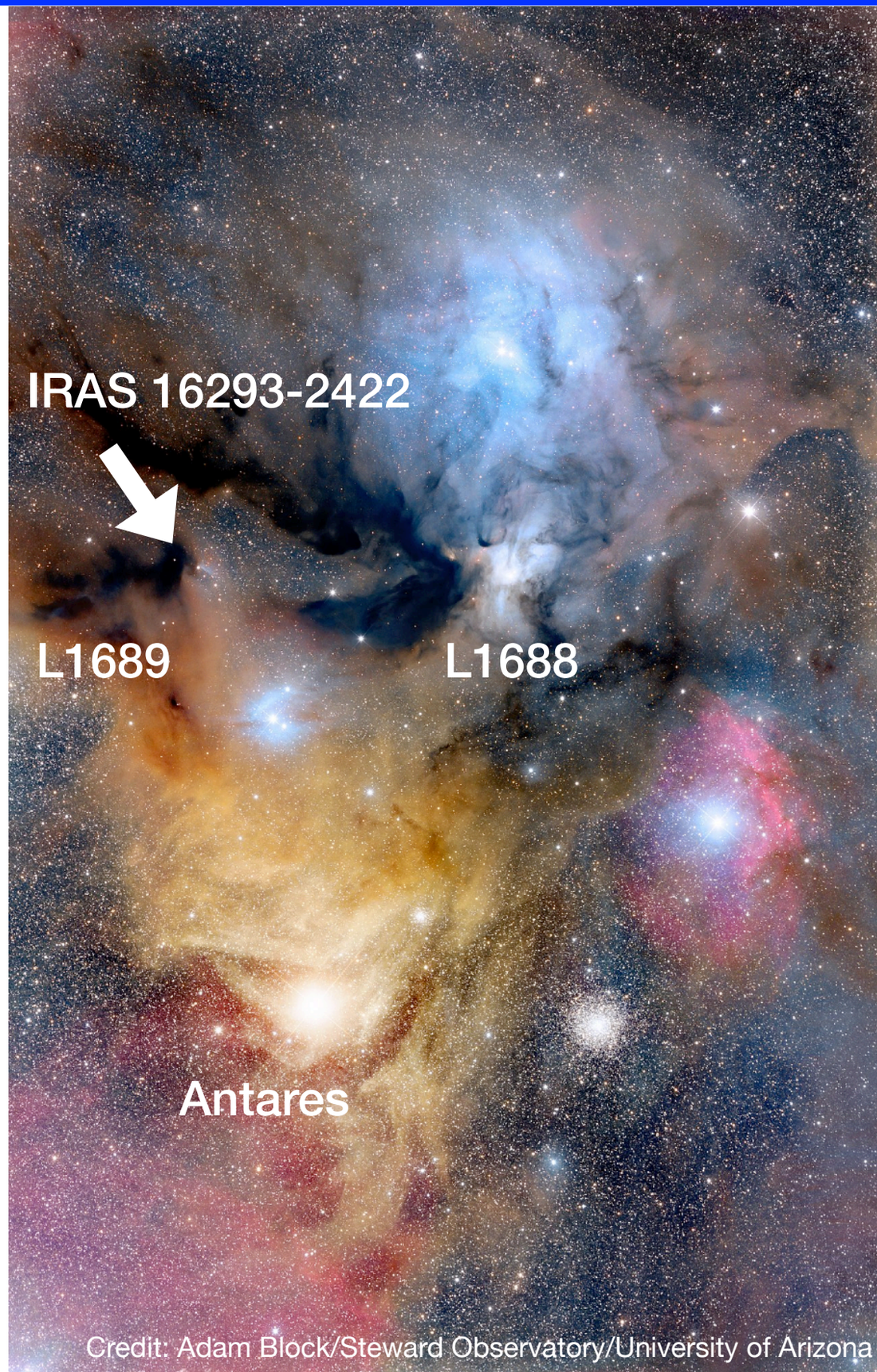
Most molecules in solid phase

The solar-type protostar IRAS 16293-2422

- Class 0 protostellar system
- Ophiuchus molecular cloud, d ~ 160 pc
- First solar-type protostar with COMs detection (*Cazaux et al. 2003*)
- High deuteration

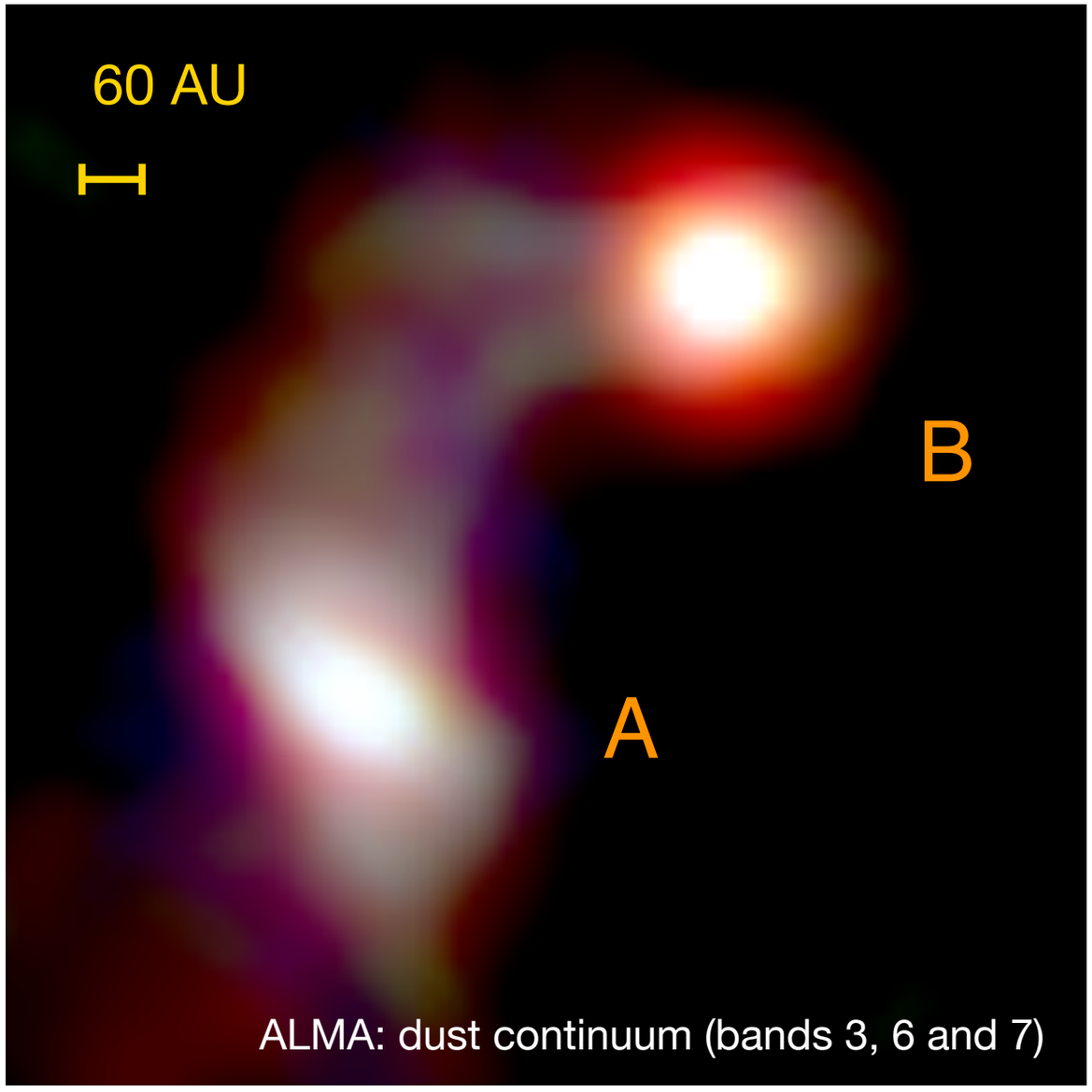
Spectral surveys :

- CSO + JCMT (239-250 GHz and 338-347 GHz) *van Dishoeck et al. 1995*
- TIMASSS : IRAM-30m + JCMT (0.9-3 mm) *Caux et al. 2011*
- SMA (~0.9 and ~1 mm) *Jørgensen et al. 2011*



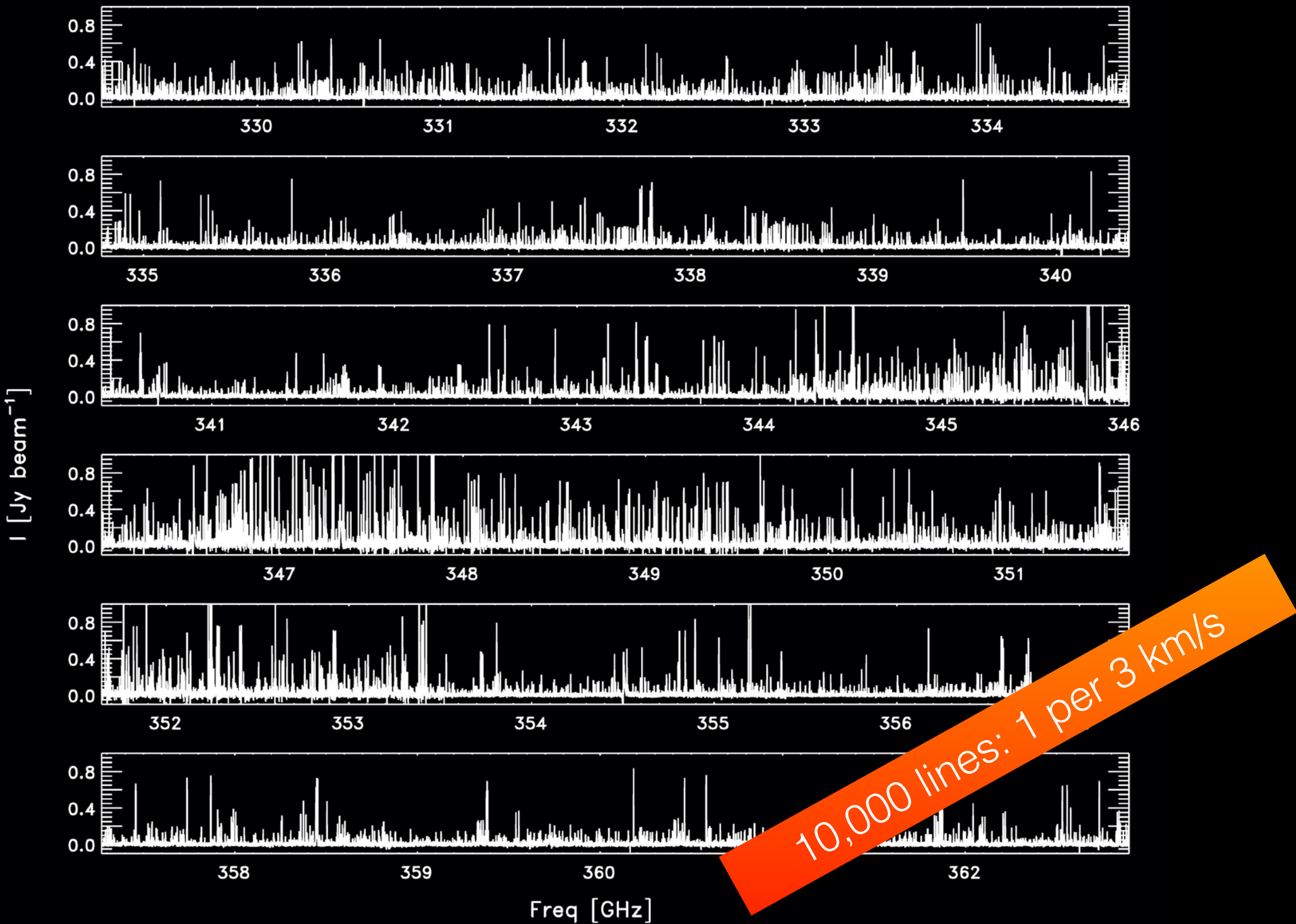
The ALMA-PILS survey

- PILS = *Protostellar Interferometric Line Survey*
- ALMA band 7 (329-363 GHz)
- Complementary observations in bands 3 and 6
- ALMA 12m array (13 h) + ACA (53 h)
- Spectral resolution ~ 0.2 km/s
- Angular resolution ~ 0.5” (60 AU)
- rms ~ 5 mJy (1 km/s)



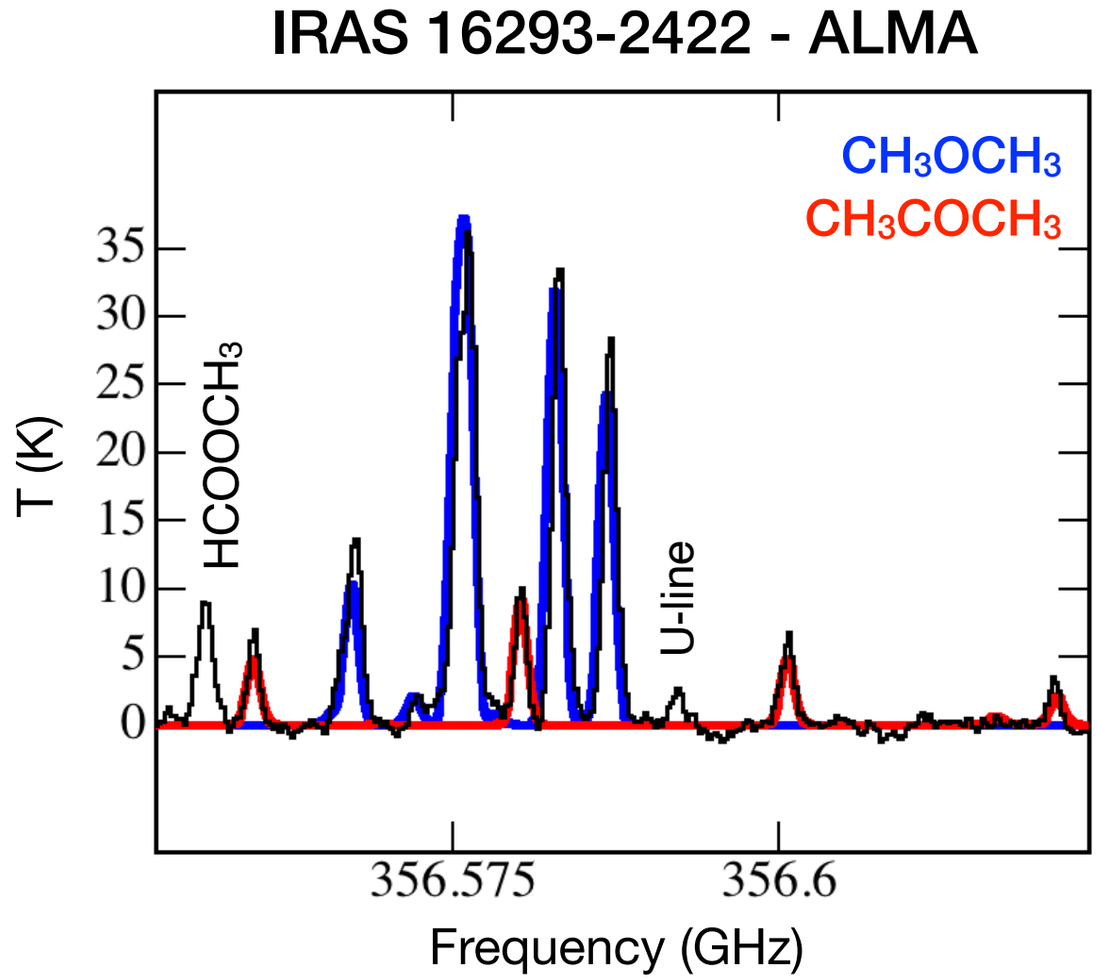
Jørgensen et al. 2016

The ALMA-PILS survey



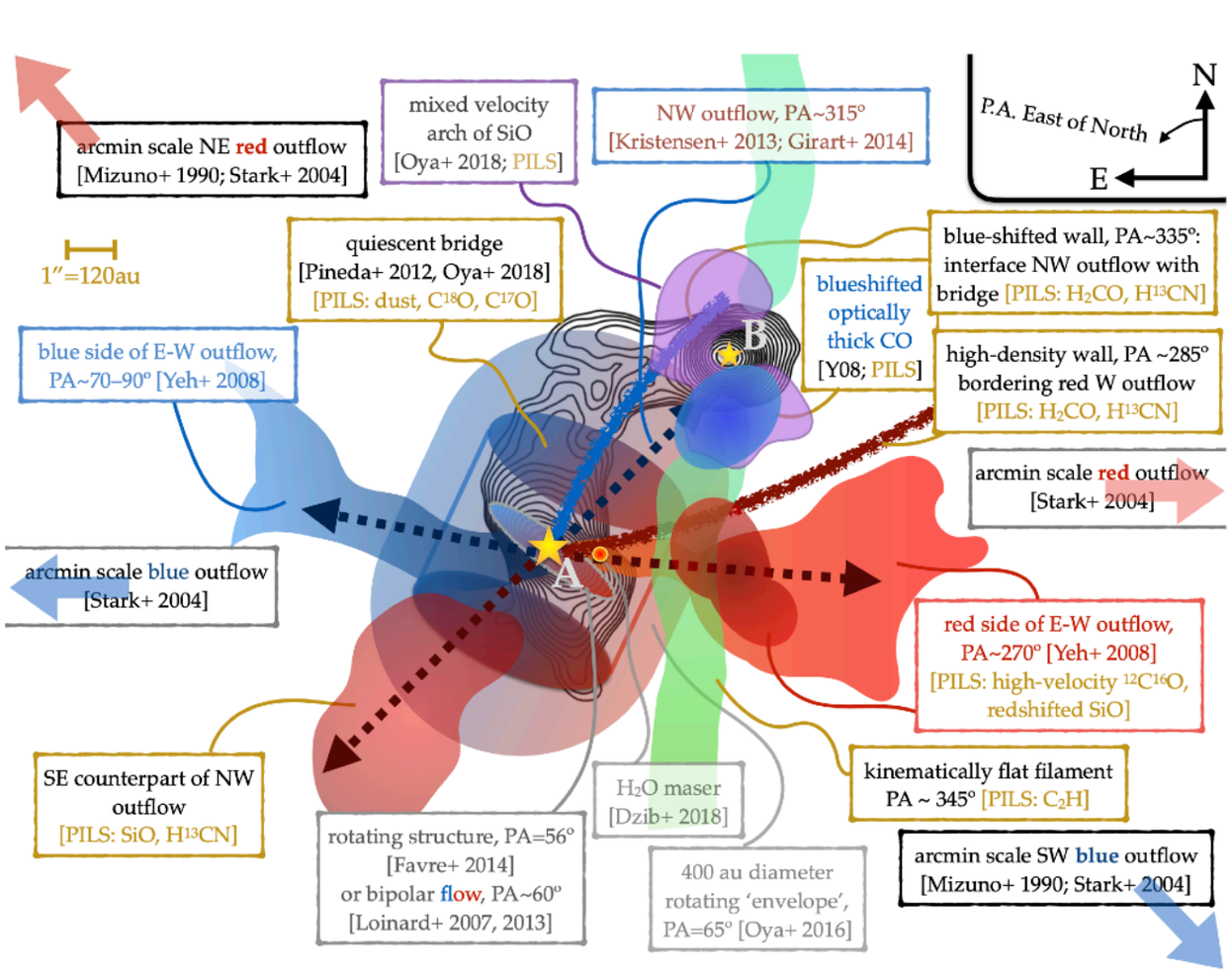
Characterizing the molecular content in protostars

- Spectroscopy (CDMS, JPL, …)
  - Frequencies
  - Relative intensities
- Radiative transfer modeling
  - Line identification
  - Abundance, temperature, …
  - Kinematics (infall, rotation, …)

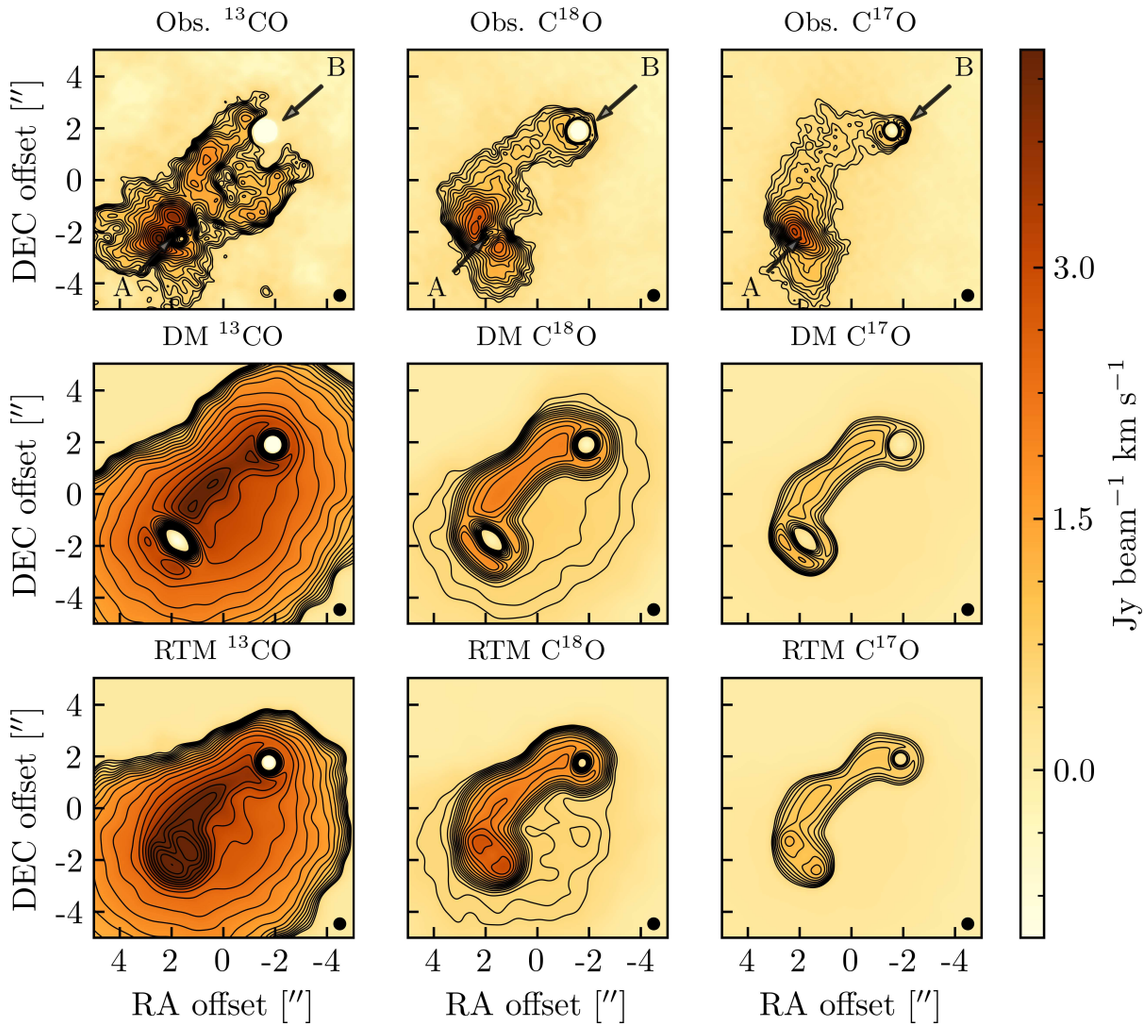


Kinematic and modeling study of IRAS 16293-2422

- The bridge arc could be a remnant of filamentary substructure in the protostellar envelope material from which protostellar sources A and B have formed
- Infalling rotating collapse or protoplanetary disk
- Source A at least 3 times (18 L_{sol}) more luminous than B (3 L_{sol})



van der Wiel et al. 2019



Jacobsen et al. 2018

Publications

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- Koucky, J, et al., "Millimetre-wave spectroscopy of 2-hydroxyprop-2-enal and an astronomical search with ALMA", 2022, A&A in press
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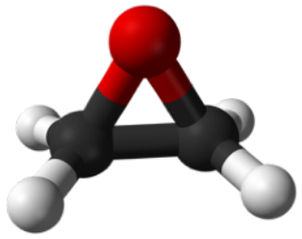
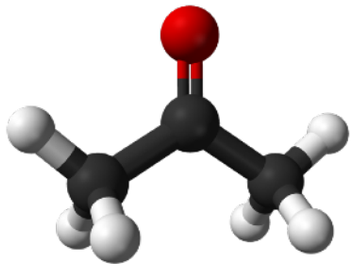
Why do all these detections matter ?

- Knowledge of the chemistry at an early stage of the star formation process
- Comparison with comets (e.g., 67P - Rosetta)
- Tests of chemical networks through the comparison between the observed and predicted abundances
- Updates of chemical networks for the species which were not previously included
- Comparisons between star forming regions : chemical differentiation ? Evolution or environment?

First detections in solar-type protostars



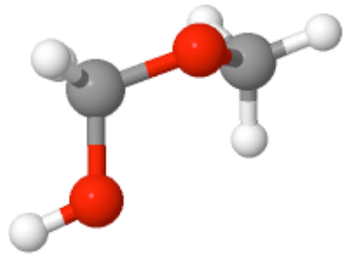
Ethylene oxide (c-C_2H_4O)

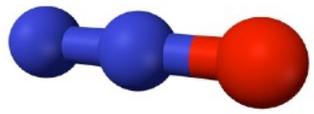


Acetone (CH_3COCH_3)

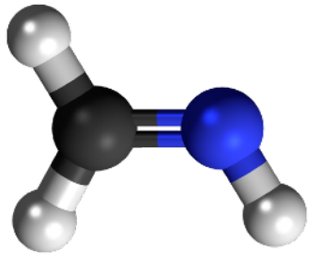
Ligterink et al. 2017
Martin-Domenech et al. 2017

Methyl isocyanate (CH_3NCO)



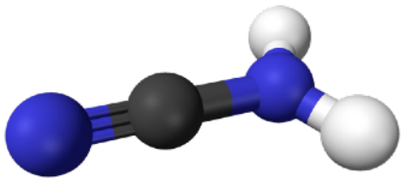


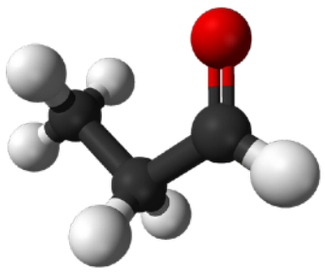
Nitrous oxide (N_2O)



Methanimine (CH_2NH)

Ligterink et al. 2018

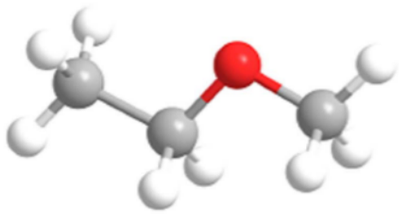




Propanal (CH_3CH_2CHO)

Lykke et al. (2017)

Methoxymethanol (CH_3OCH_2OH)

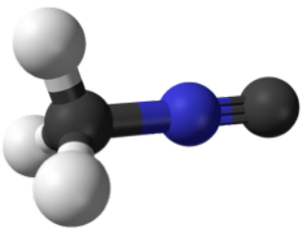


Trans-ethyl methyl ether (t-$C_2H_5OCH_3$)

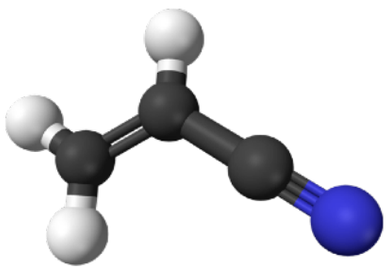
Manigand et al. 2020

Cyanamide (NH_2CN)

Coutens et al. 2018



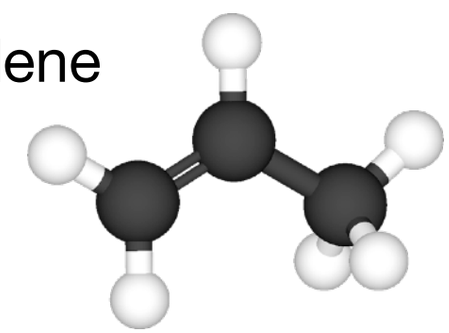
Methyl isocyanide (CH_3NC)

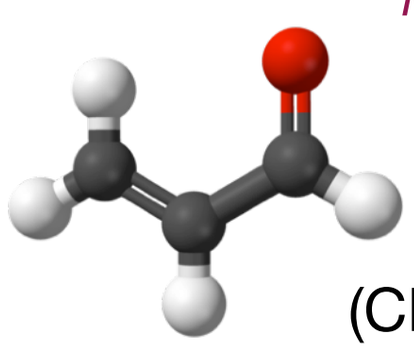


Vinyl cyanide (CH_2CHCN)

Calcutt et al. 2018

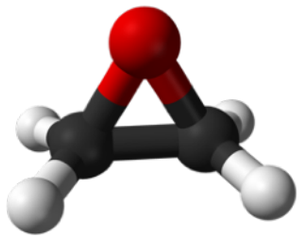
Propylene (C_3H_6)





Propenal (CH_2CHCHO) *Manigand et al. 2021*

First detections in solar-type protostars



Ethylene oxide (c-C_2H_4O)

Ligterink et al. 2017
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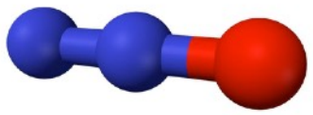
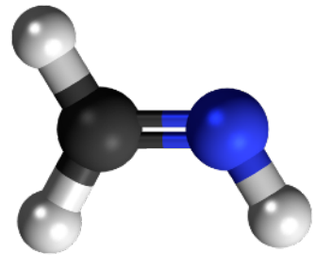
Methyl isocyanate (CH_3NCO)

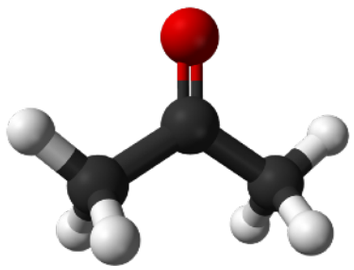


Nitrous oxide (N_2O)

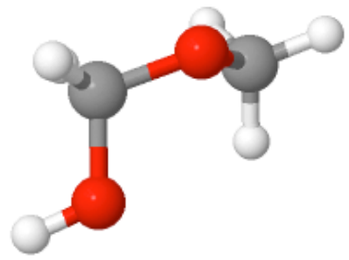


Methanimine (CH_2NH)

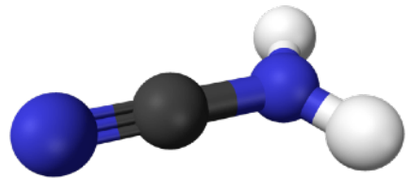
Ligterink et al. 2018



Acetone (CH_3COCH_3)

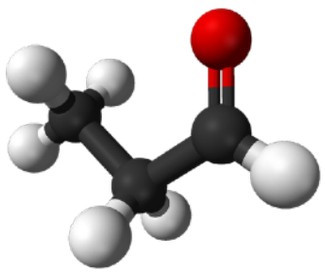


Methoxymethanol (CH_3OCH_2OH)



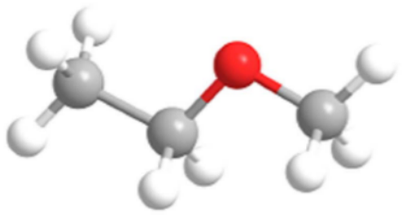
Cyanamide (NH_2CN)

Coutens et al. 2018



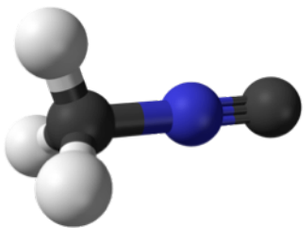
Propanal (CH_3CH_2CHO)

Lykke et al. (2017)



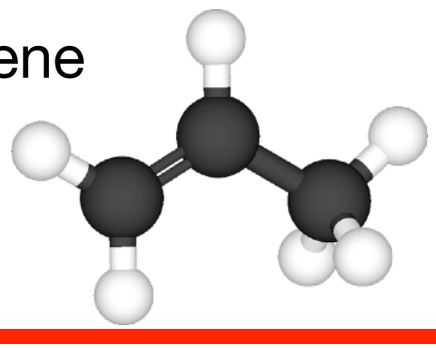
Trans-ethyl methyl ether (t-$C_2H_5OCH_3$)

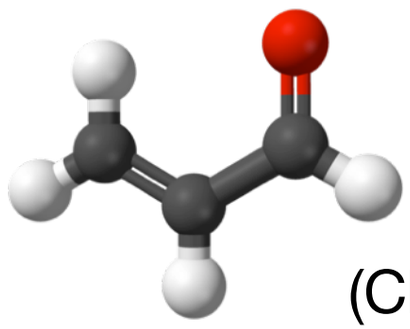
Manigand et al. 2020



Methyl isocyanide (CH_3NC)

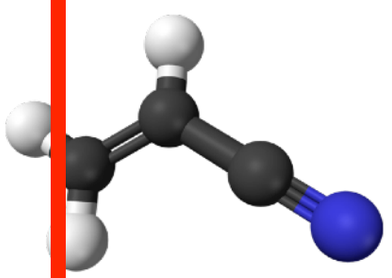
Propylene (C_3H_6)





Propenal (CH_2CHCHO)

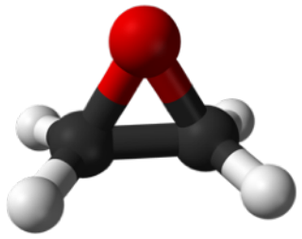
Manigand et al. 2021



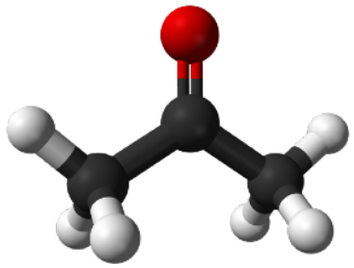
Vinyl cyanide (CH_2CHCN)

Calcutt et al. 2018

First detections in solar-type protostars



Ethylene oxide (c-C_2H_4O)



Acetone (CH_3COCH_3)

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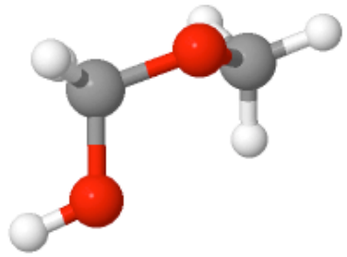
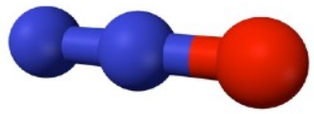
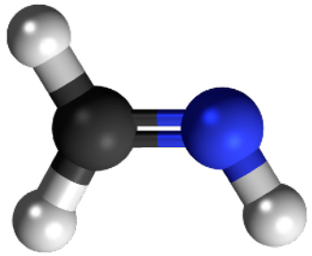


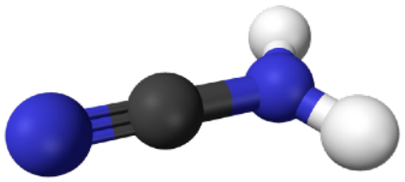


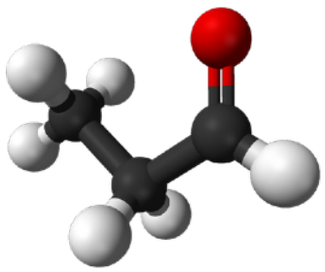
Nitrous oxide (N_2O)



Methanimine (CH_2NH)

Ligterink et al. 2018

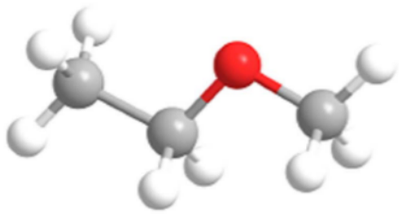




Propanal (CH_3CH_2CHO)

Lykke et al. (2017)

Methoxymethanol (CH_3OCH_2OH)



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Manigand et al. 2020

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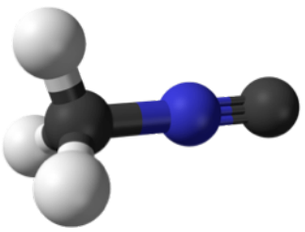
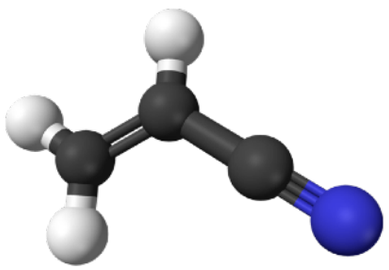
Coutens et al. 2018



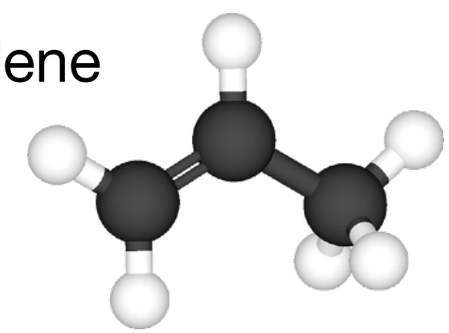
Methyl isocyanide (CH_3NC)

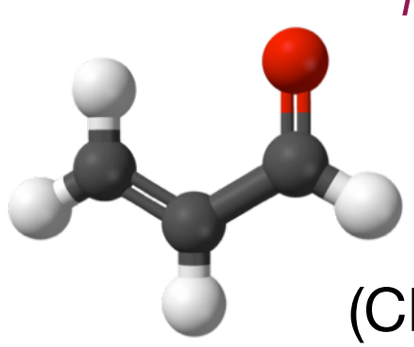


Vinyl cyanide (CH_2CHCN)

Calcutt et al. 2018

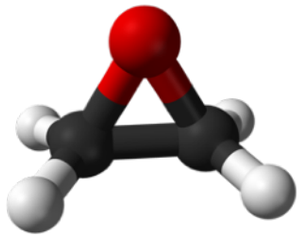
Propylene (C_3H_6)



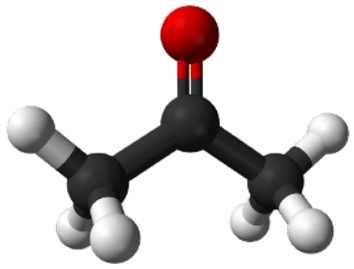


Propenal (CH_2CHCHO) *Manigand et al. 2021*

First detections in solar-type protostars



Ethylene oxide (c-C_2H_4O)



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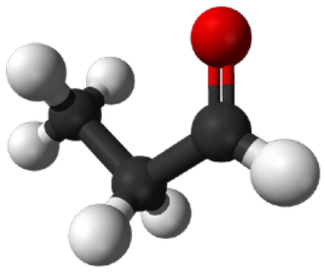
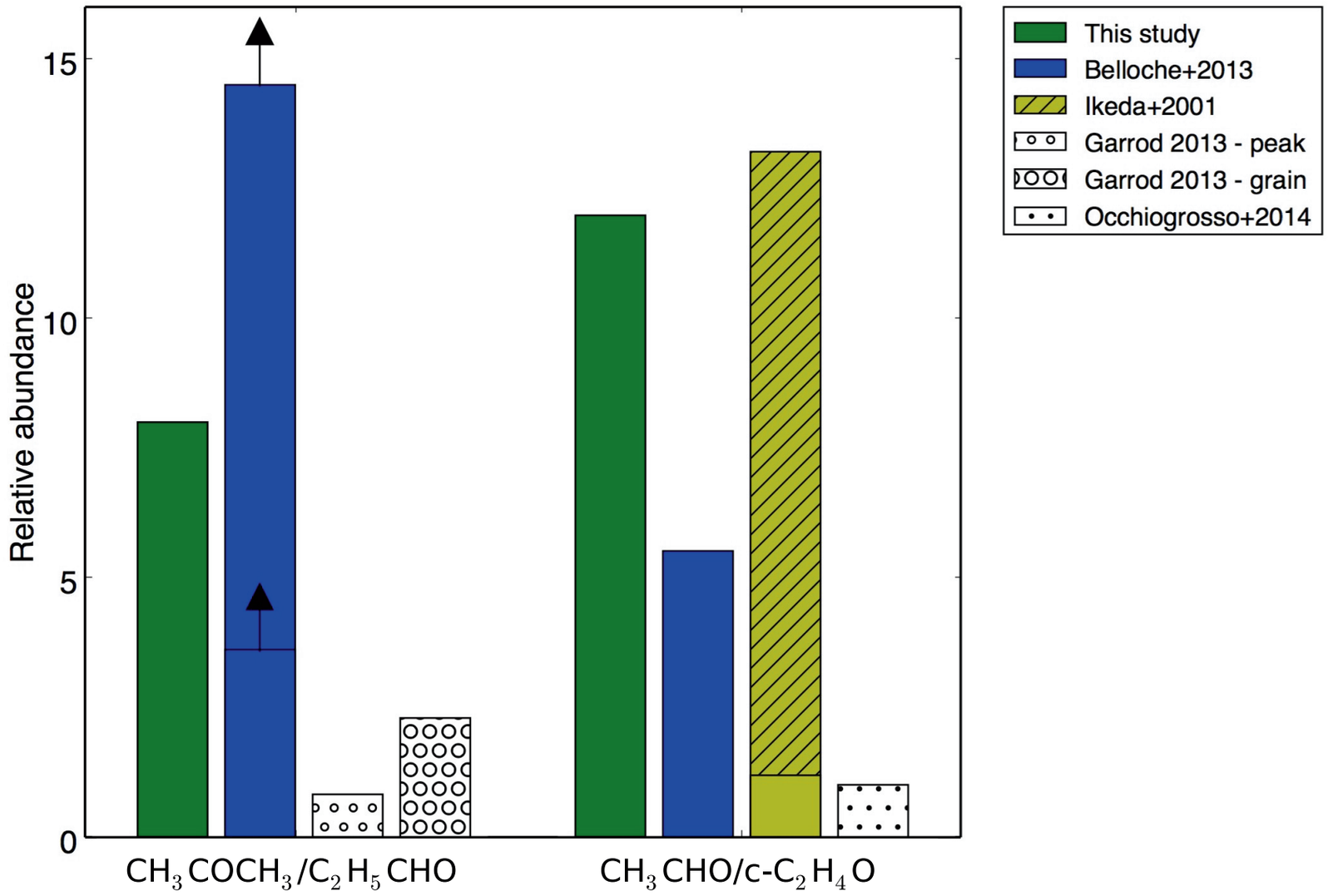


Propanal (CH_3CH_2CHO)

Lykke et al. (2017)



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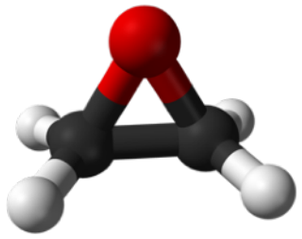

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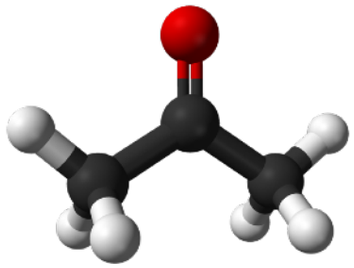

Acetone (CH_3COCH_3)

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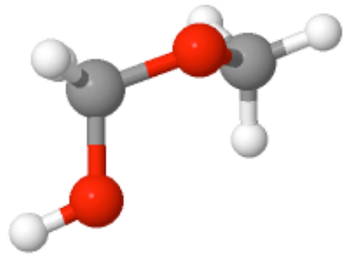
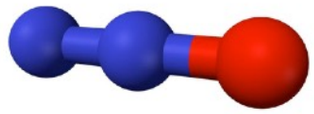
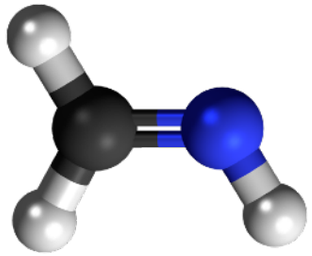


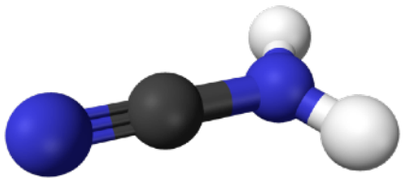


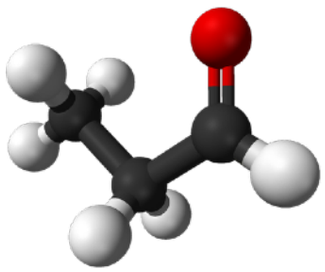
Nitrous oxide (N_2O)



Methanimine (CH_2NH)

Ligterink et al. 2018

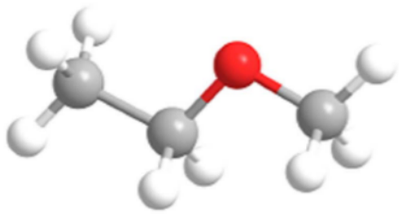




Propanal (CH_3CH_2CHO)

Lykke et al. (2017)

Methoxymethanol (CH_3OCH_2OH)

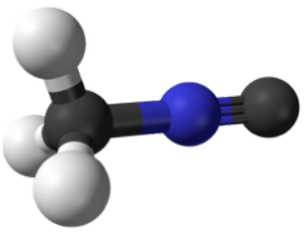


Trans-ethyl methyl ether (t-$C_2H_5OCH_3$)

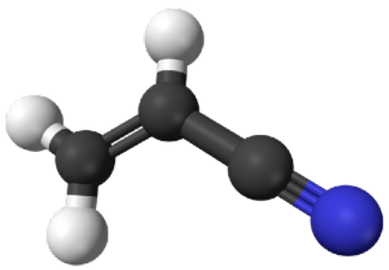
Manigand et al. 2020

Cyanamide (NH_2CN)

Coutens et al. 2018



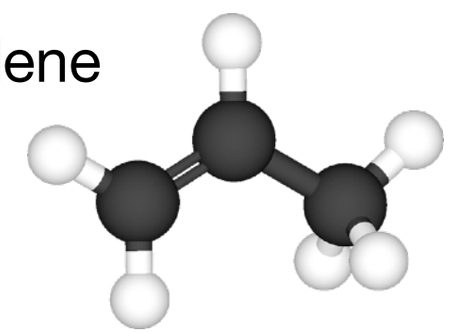
Methyl isocyanide (CH_3NC)

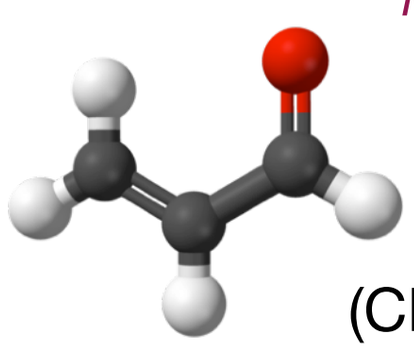


Vinyl cyanide (CH_2CHCN)

Calcutt et al. 2018

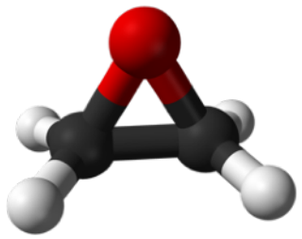
Propylene (C_3H_6)



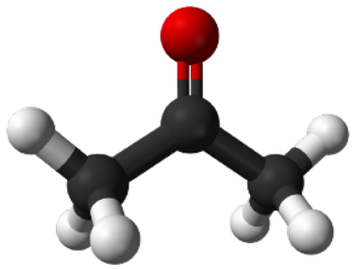


Propenal (CH_2CHCHO) *Manigand et al. 2021*

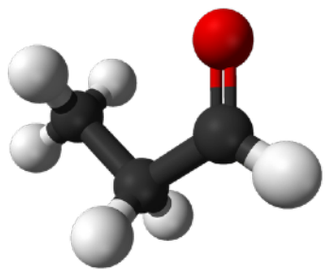
First detections in solar-type protostars



Ethylene oxide (c-C_2H_4O)



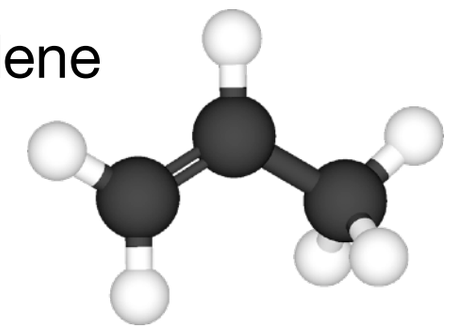
Acetone (CH_3COCH_3)

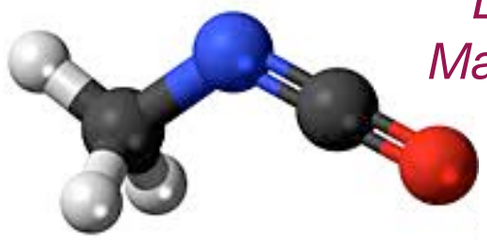


Propanal (CH_3CH_2CHO)

Lykke et al. (2017)

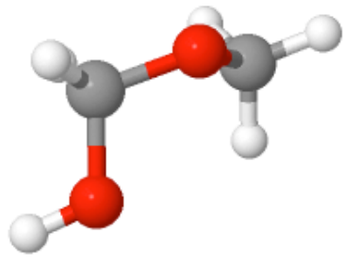
Propylene (C_3H_6)



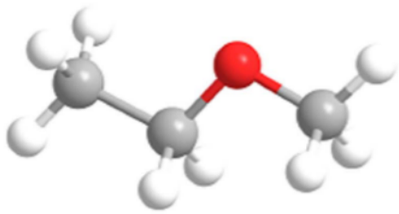


Ligterink et al. 2017
Martin-Domenech et al. 2017

Methyl isocyanate (CH_3NCO)

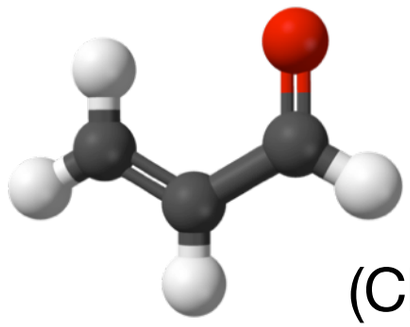


Methoxymethanol (CH_3OCH_2OH)

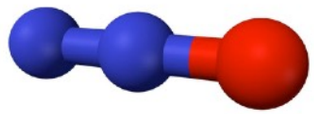


Trans-ethyl methyl ether (t-$C_2H_5OCH_3$)

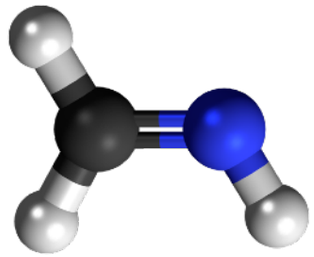
Manigand et al. 2020



Propenal (CH_2CHCHO) *Manigand et al. 2021*

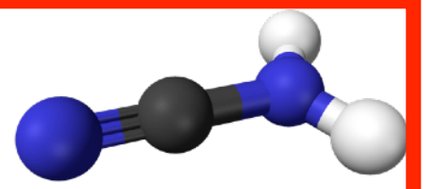


Nitrous oxide (N_2O)



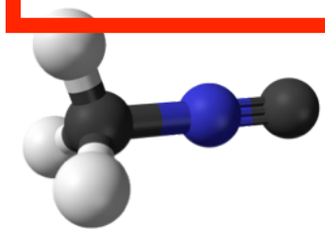
Methanimine (CH_2NH)

Ligterink et al. 2018

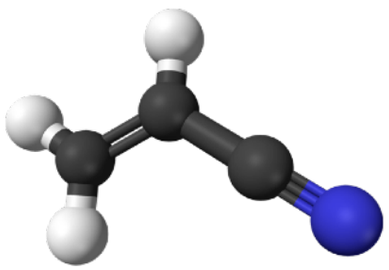


Cyanamide (NH_2CN)

Coutens et al. 2018



Methyl isocyanide (CH_3NC)

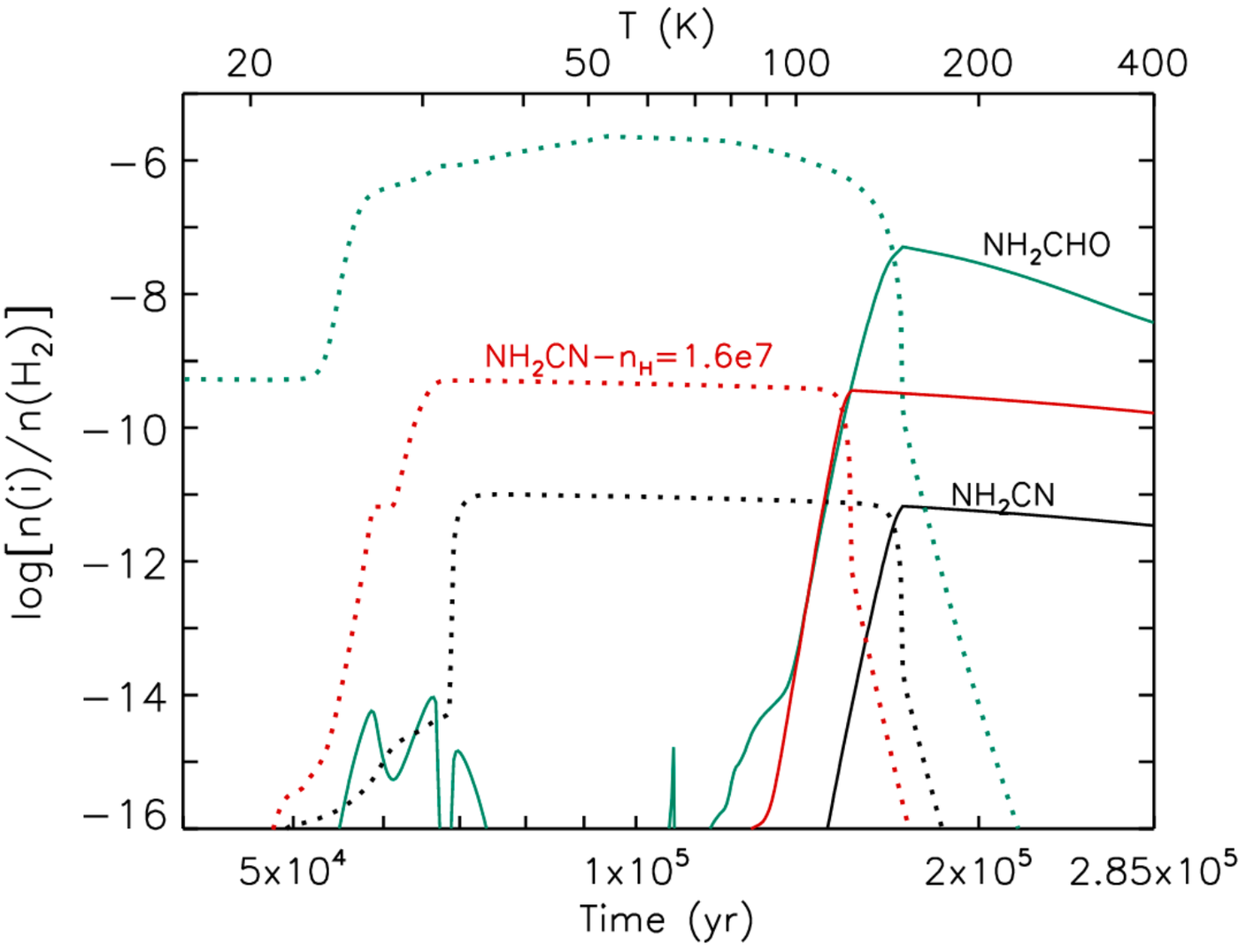


Vinyl cyanide (CH_2CHCN)

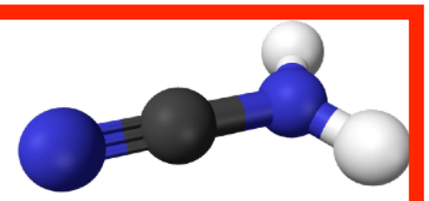
Calcutt et al. 2018

First detections in solar-type protostars

- Gas-grain chemistry model
- Possible formation of NH_2CN through the NH_2 + CN reaction on grains



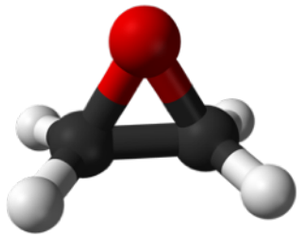
Coutens et al. 2018



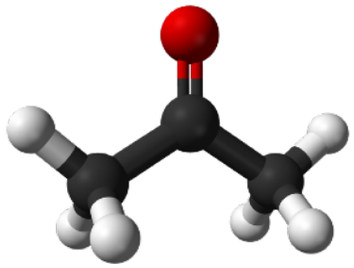
Cyanamide (NH_2CN)

Coutens et al. 2018

First detections in solar-type protostars



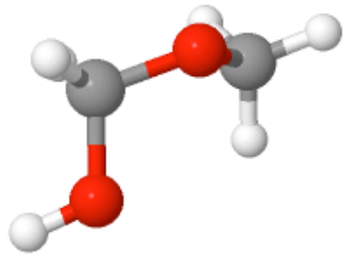
Ethylene oxide (c-C_2H_4O)

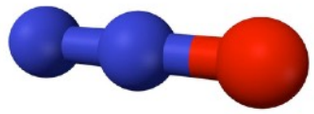


Acetone (CH_3COCH_3)

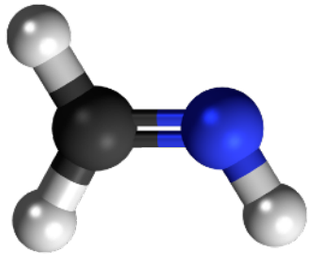
Ligterink et al. 2017
Martin-Domenech et al. 2017

Methyl isocyanate (CH_3NCO)



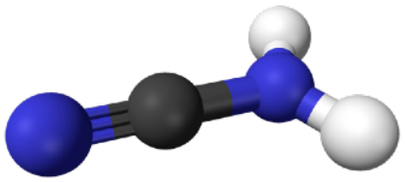


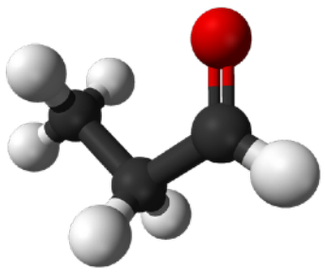
Nitrous oxide (N_2O)



Methanimine (CH_2NH)

Ligterink et al. 2018

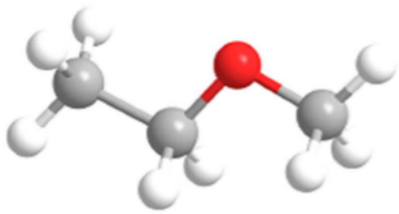




Propanal (CH_3CH_2CHO)

Lykke et al. (2017)

Methoxymethanol (CH_3OCH_2OH)

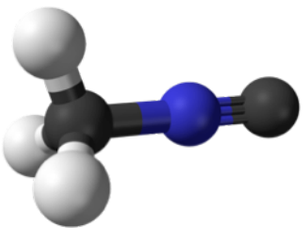


Trans-ethyl methyl ether (t-$C_2H_5OCH_3$)

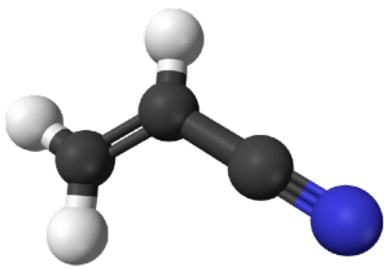
Manigand et al. 2020

Cyanamide (NH_2CN)

Coutens et al. 2018



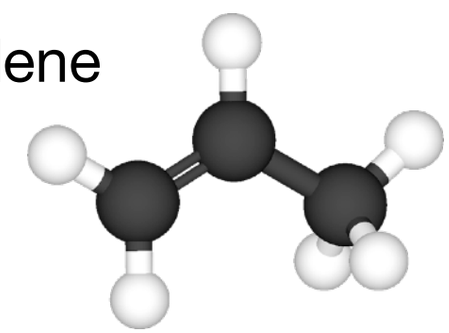
Methyl isocyanide (CH_3NC)

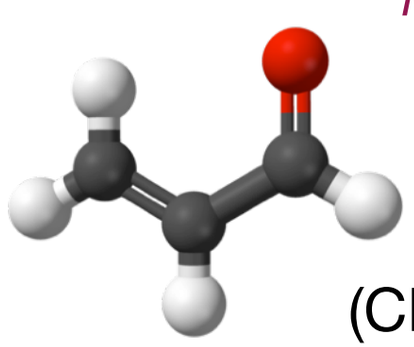


Vinyl cyanide (CH_2CHCN)

Calcutt et al. 2018

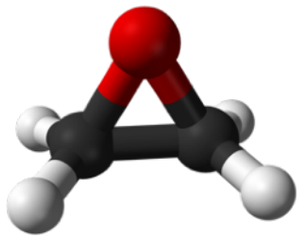
Propylene (C_3H_6)



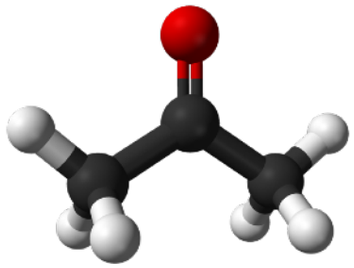


Propenal (CH_2CHCHO) *Manigand et al. 2021*

First detections in solar-type protostars



Ethylene oxide (c-C_2H_4O)



Acetone (CH_3COCH_3)

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Martin-Domenech et al. 2017

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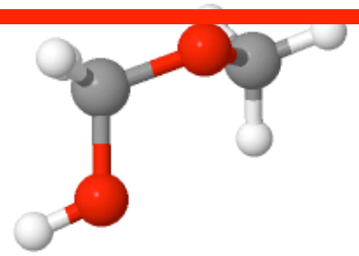
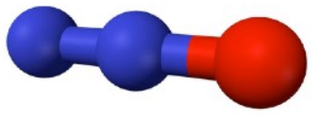
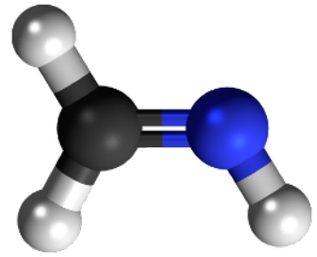


Methoxymethanol (CH_3OCH_2OH)

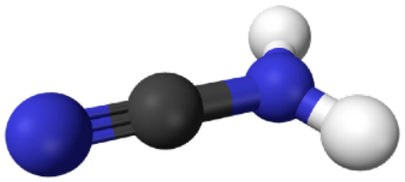


Nitrous oxide (N_2O)



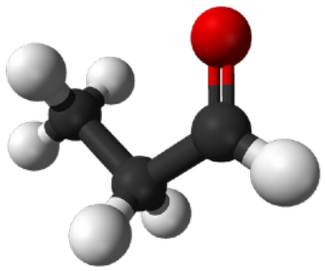
Methanimine (CH_2NH)

Ligterink et al. 2018



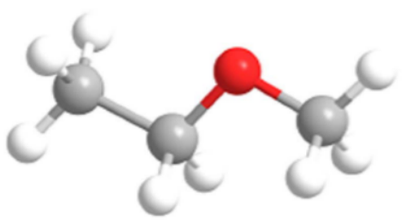
Cyanamide (NH_2CN)

Coutens et al. 2018



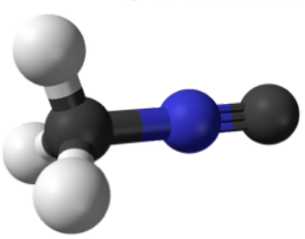
Propanal (CH_3CH_2CHO)

Lykke et al. (2017)



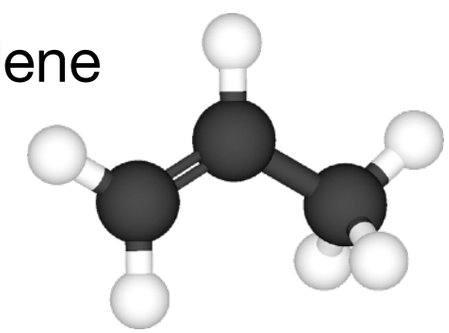
Trans-ethyl methyl ether (t-$C_2H_5OCH_3$)

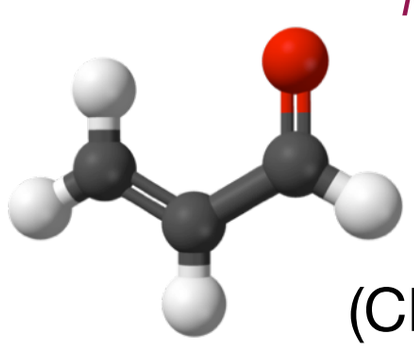
Manigand et al. 2020



Methyl isocyanide (CH_3NC)

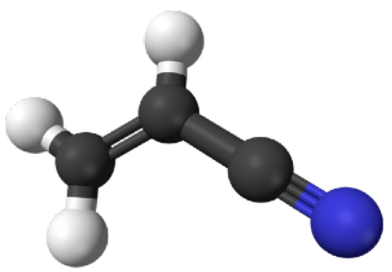
Propylene (C_3H_6)





Propenal (CH_2CHCHO)

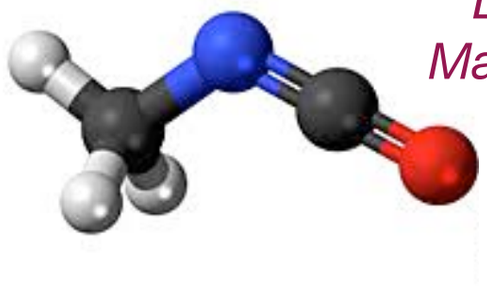
Manigand et al. 2021



Vinyl cyanide (CH_2CHCN)

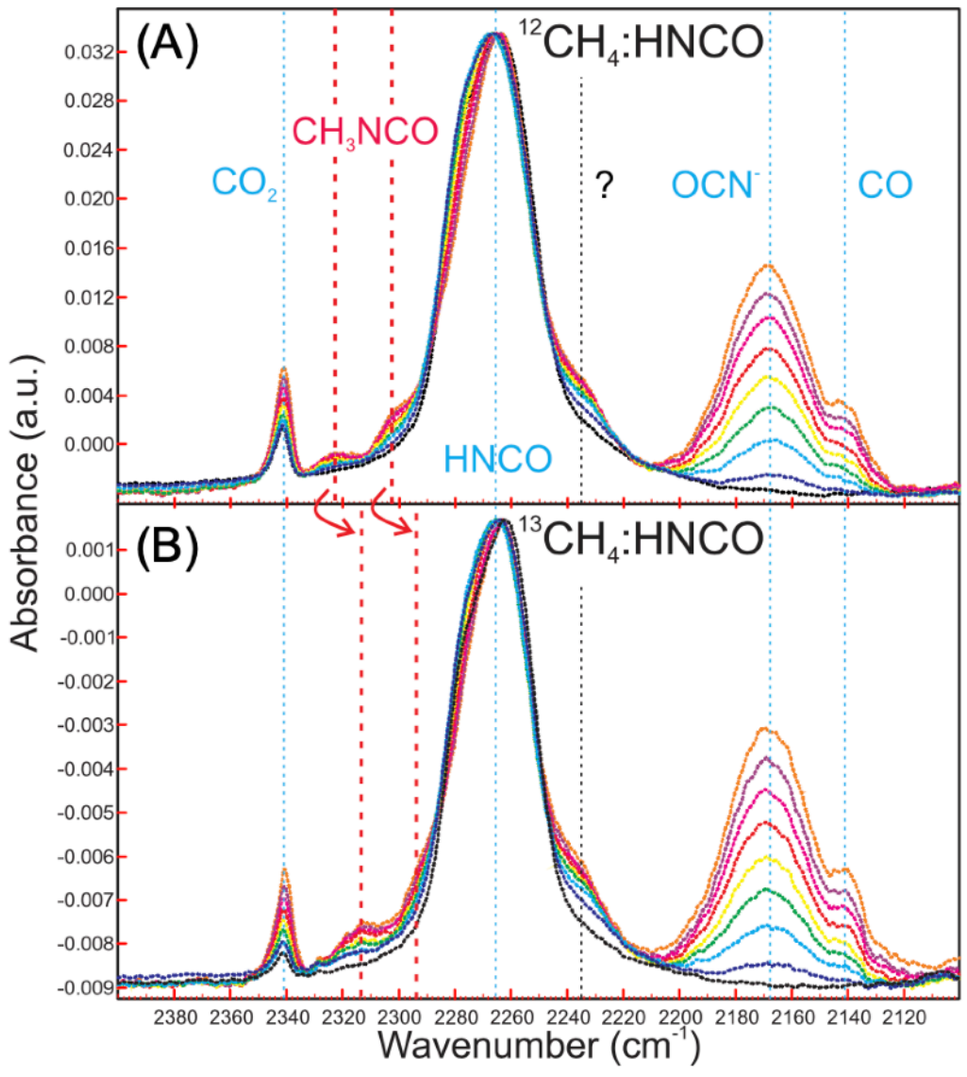
Calcutt et al. 2018

First detections in solar-type protostars



Ligterink et al. 2017
Martin-Domenech et al. 2017

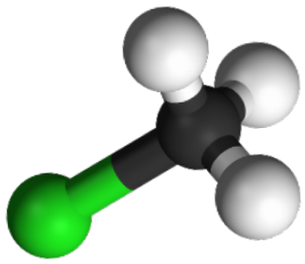
Methyl isocyanate (CH_3NCO)



- Laboratory experiments
- VUV irradiation of CH_4:HNCO mixtures at 20 K
- Formation on grains through CH_3 and (H)NCO recombinations

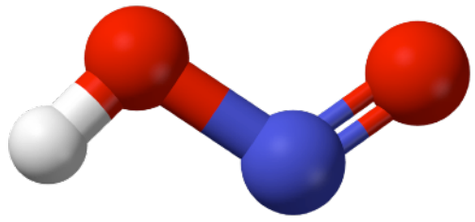
Ligterink et al. 2017

First detections in the ISM



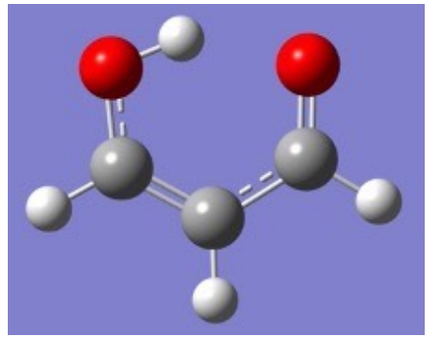
Methyl chloride (CH_3Cl)

Fayolle et al. 2017



Nitrous acid (HONO)

Coutens et al. 2019

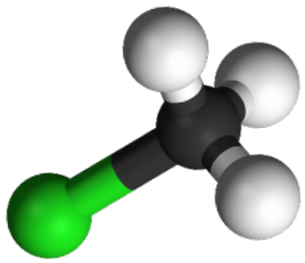


3-hydroxypropenal (HOCHCHCHO)

Coutens et al. 2022

+ a lot of isotopologues !

First detections in the ISM



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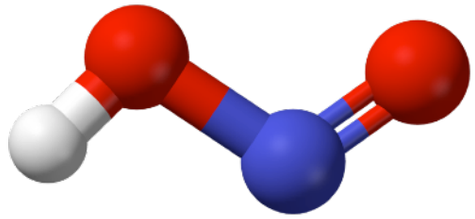

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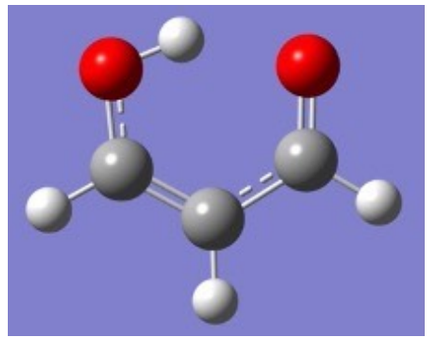
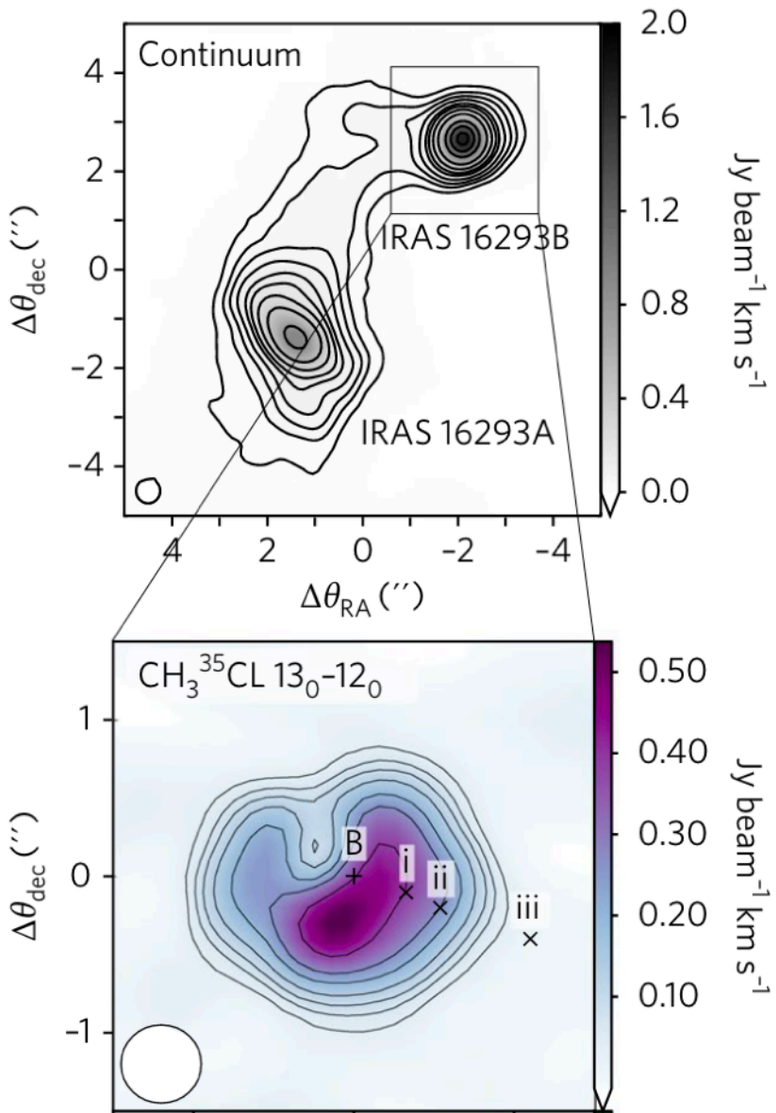


3-hydroxypropenal (HOCHCHCHO)

Coutens et al. 2022



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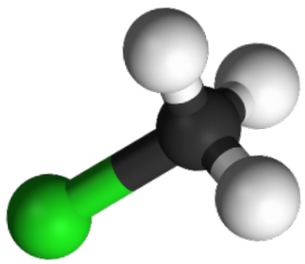

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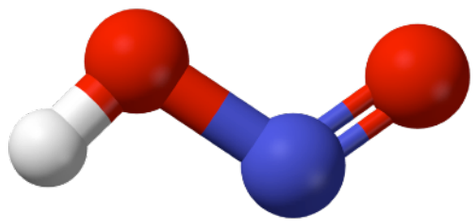

Nitrous acid (HONO)

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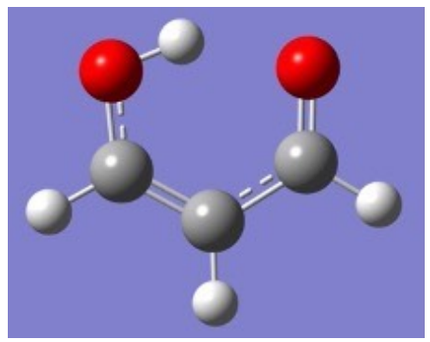


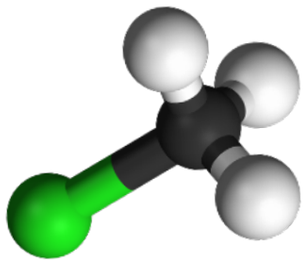
3-hydroxypropenal (HOCHCHCHO)

Coutens et al. 2022

Molecule	Formula	$N_{tot}^{\dagger}$ (cm^{-2})	T_{ex} (K)
Nitrous acid	HONO	$(9 \pm 5) \times 10^{14}$	100
Nitric oxide‡	NO	$(2.0 \pm 0.5) \times 10^{16}$	40–150
Nitrous oxide‡	N_2O	$\geq 4.0 \times 10^{16}$	25–350
Hydroxylamine‡	NH_2OH	$\leq 4 \times 10^{14}$	[100]
Nitrosyl hydride	HNO	$\leq 3 \times 10^{14}$	[100]
Nitrogen dioxide	NO_2	$\leq 2 \times 10^{16}$	[100]
Nitrosyl cation	NO^+	$\leq 2 \times 10^{14}$	[100]
Nitric acid	HNO_3	$\leq 5 \times 10^{14}$	[100]

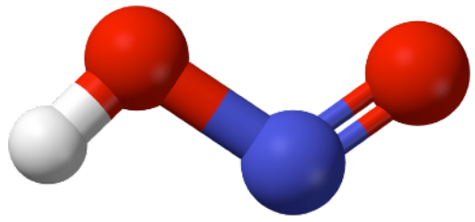
- Production on grains through s-O + s-HNO, s-H + s-NO_2, and s-OH + s-NO surface reactions

First detections in the ISM



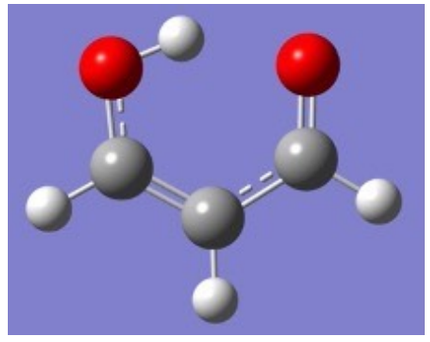
Methyl chloride (CH_3Cl)

Fayolle et al. 2017



Nitrous acid (HONO)

Coutens et al. 2019



3-hydroxypropenal (HOCHCHCHO)

Coutens et al. 2022

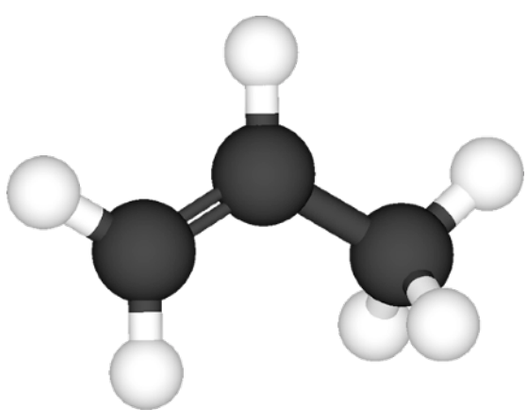
The chemistry of 3-carbon species

Major update of the chemical network to include 3-carbon species (J.-C. Loison, ISM)

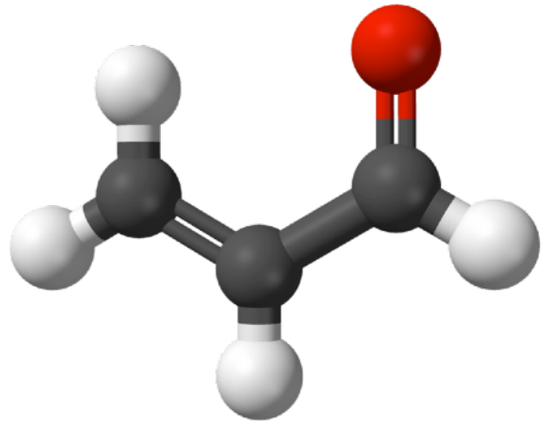
Manigand et al. 2021, Lykke et al. 2017

Species	T_{ex} (K)	N_{tot} (cm^{-2})
C_2H_3CHO	125 ± 25	$3.4 \pm 0.7 \times 10^{14}$
C_3H_6	75 ± 15	$4.2 \pm 0.8 \times 10^{16}$
HCCCHO	$100^{(a)}$	$<5.0 \times 10^{14}$
n-C_3H_7OH	$100^{(a)}$	$<3.0 \times 10^{15}$
i-C_3H_7OH	$100^{(a)}$	$<3.0 \times 10^{15}$
C_3O	$100^{(a)}$	$<2.0 \times 10^{13}$
cis-HC(O)CHO	$100^{(a)}$	$<5.0 \times 10^{13}$
C_3H_8	$100^{(a)}$	$<8.0 \times 10^{16}$
CH_3CCH	100 ± 20	$1.1 \pm 0.2 \times 10^{16}$
C_2H_5CHO	125 ± 25	$2.2 \pm 1.1 \times 10^{15}$ (†)
CH_3CHO	125 ± 25	$7.0 \pm 3.5 \times 10^{16}$ (†)
CH_3COCH_3	125 ± 25	$1.7 \pm 0.8 \times 10^{16}$ (†)
$C_2H_5OCH_3$	100 ± 20	$1.8 \pm 0.2 \times 10^{16}$ (†)

Unsaturated 3-carbon molecules

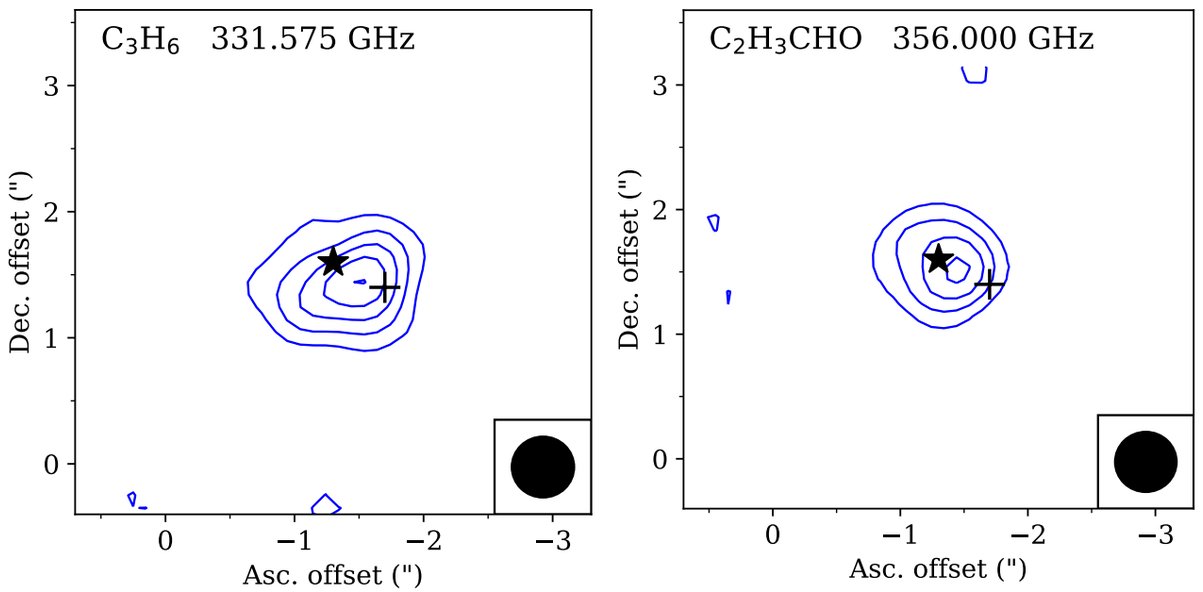


Propylene
(C_3H_6)



Propenal = Acrolein
(CH_2CHCHO)

Detection towards IRAS 16293 B



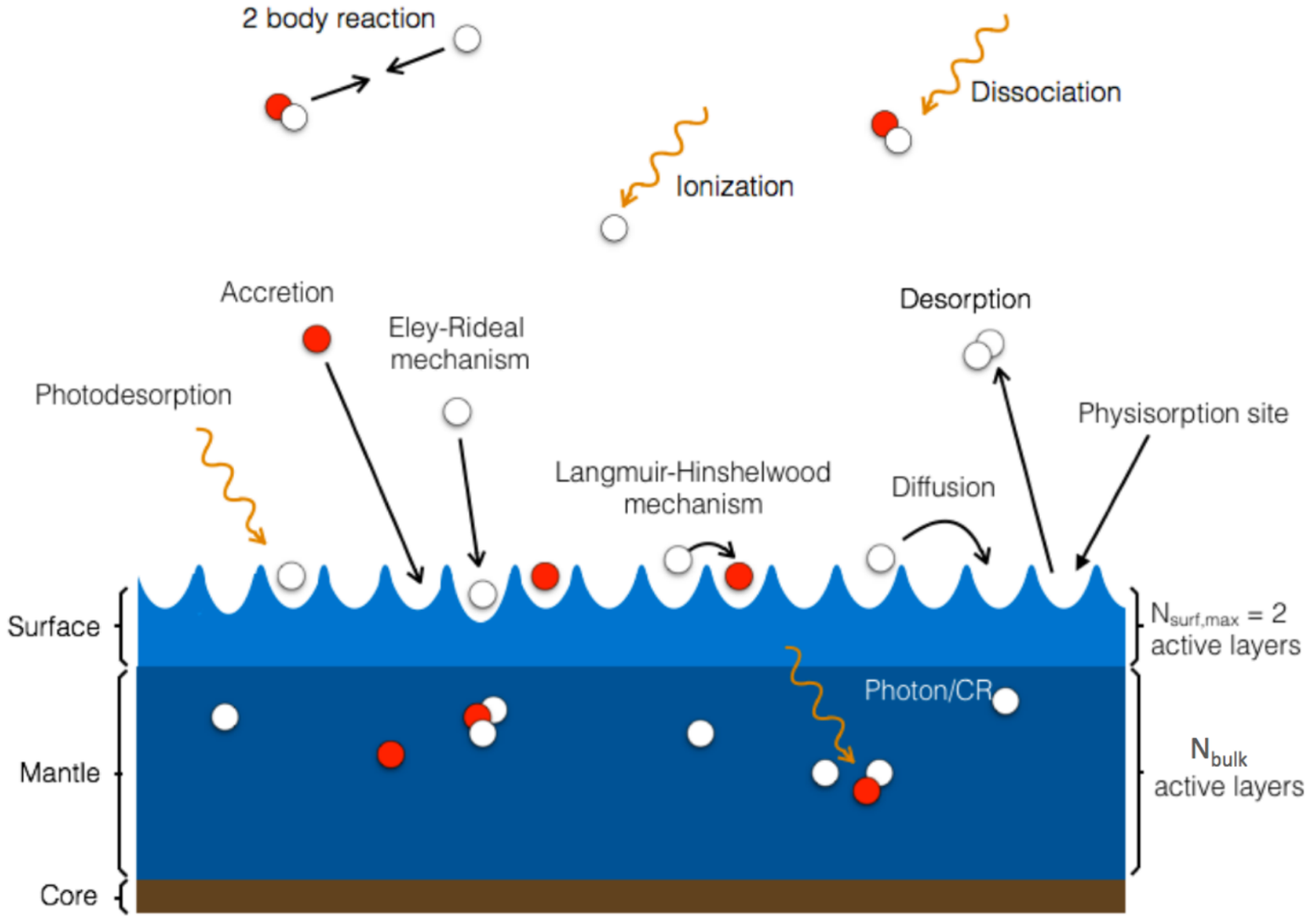
Manigand et al. 2021

The chemistry of 3-carbon species

- Three-phase chemistry code Nautilus (PI: V. Wakelam)

- Prestellar phase followed by a 1D hydrodynamical collapse (*Masunaga & Inutsuka 2000*)

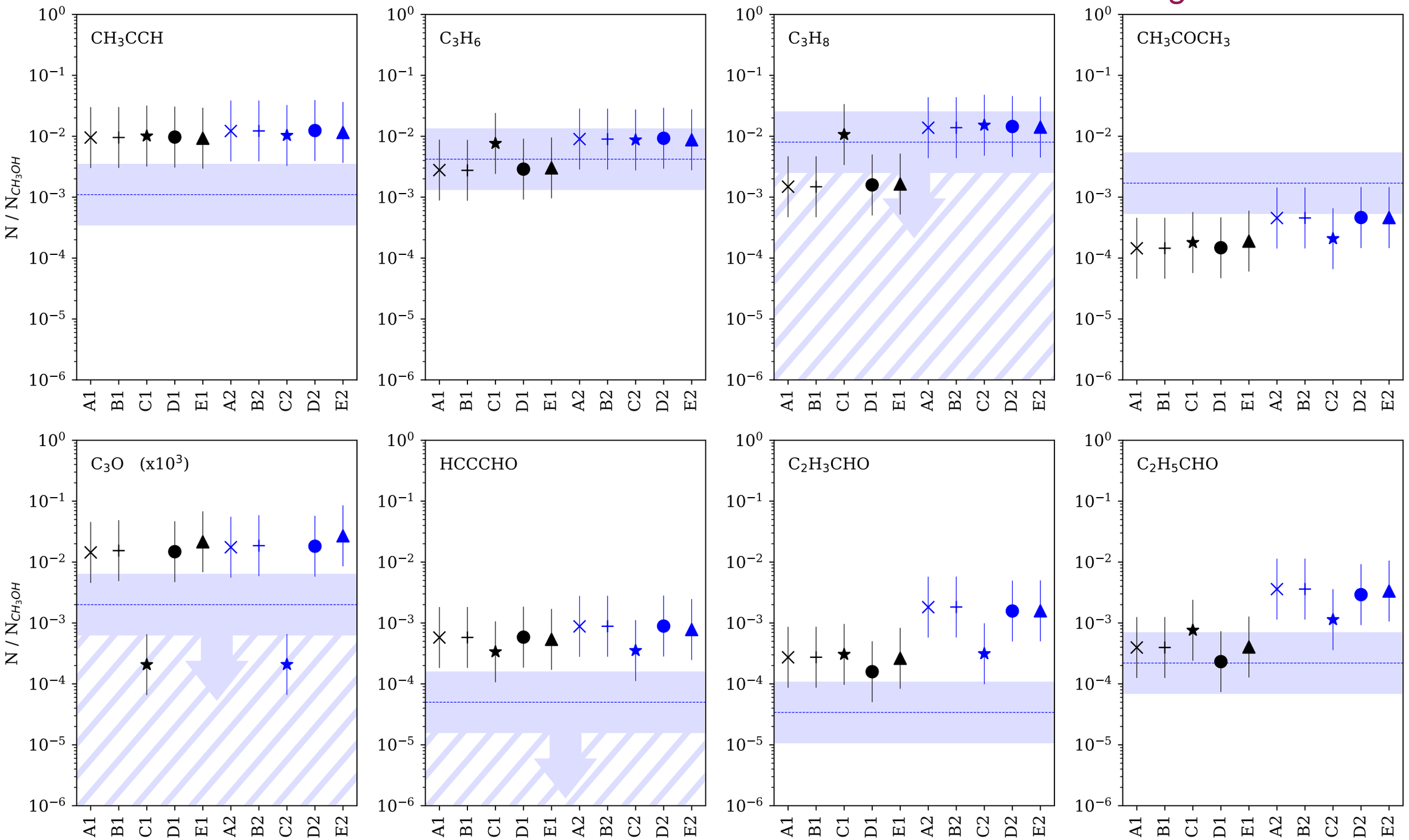
- Tests of different formation pathways (successive hydrogenation of C_3 and C_3O and radical-radical additions on grain surfaces) to assess which are the dominant formation mechanisms



Ruaud et al. 2016

The chemistry of 3-carbon species

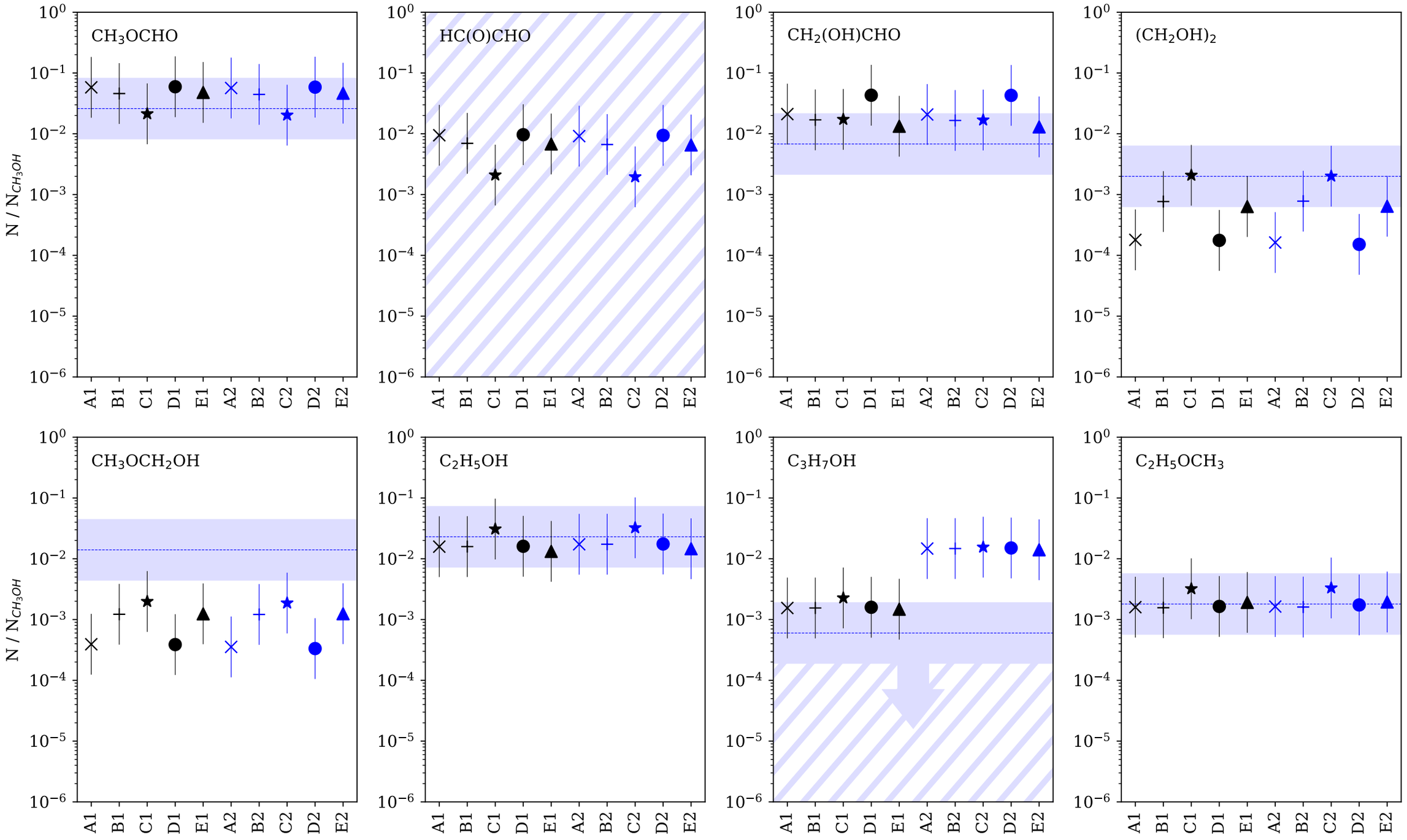
Manigand et al. 2021



The chemistry of 3-carbon species

+ comparison with 2C-species

Manigand et al. 2021

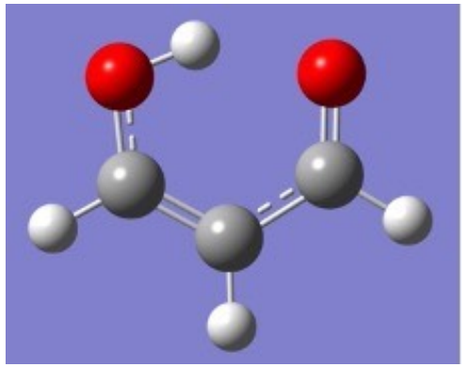


The chemistry of 3-carbon species

Main conclusions of Manigand et al. 2021

- Impact of the duration of the prestellar phase on the abundances of the saturated vs unsaturated COMs
- Formation of C_2H_3CHO and C_2H_5CHO through both :
  - successive hydrogenation reactions on ice surfaces of C_3O, with a formation of C_3O in the gas phase ($C_3 + OH \rightarrow C_3O + H$)
  - radical-radical additions of HCO and C_2H_3 or C_2H_5 on ice surfaces
- Rate of 10^{-12} cm^3 s^{-1} for the gas phase reaction $C_3 + O \rightarrow C_2 + CO$ necessary to fit the observed abundances
- Other missing consumption pathways of C_3 (PAHs) ?

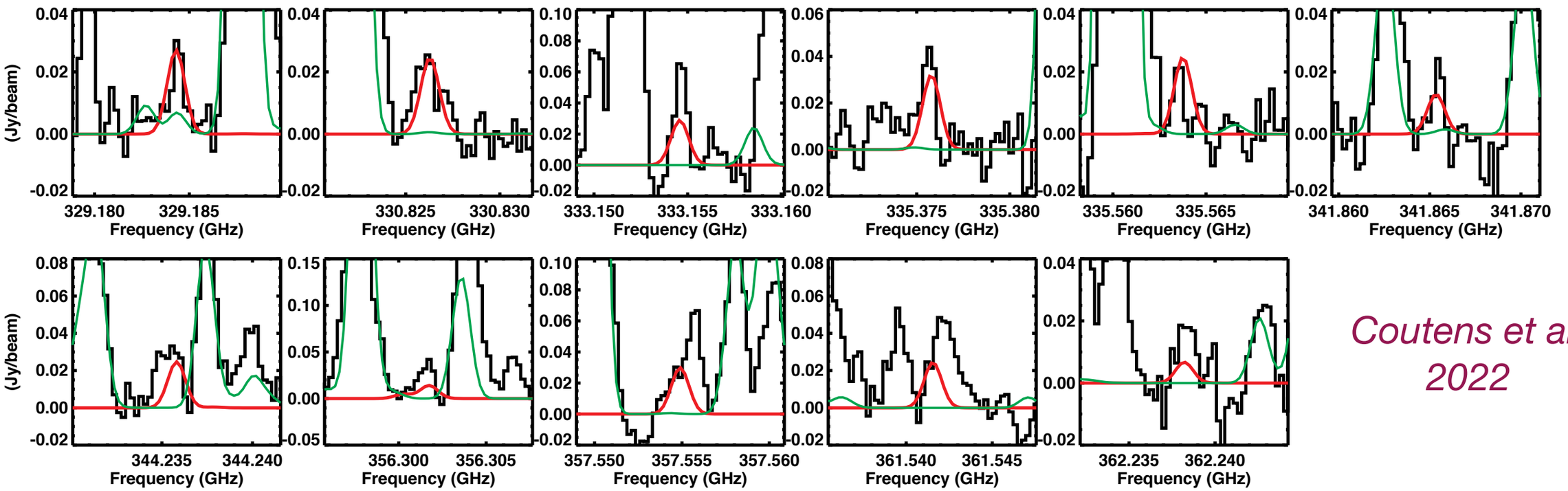
Tentative detection of 3-hydroxypropenal



3-hydroxypropenal : biomarker to measure the level of oxidative stress in living organisms

Antoine Boulanger's internship
Predicted towards source B with a Convolutional Neural Network on a large set of multi-species synthetic spectra assuming LTE (*Boulanger et al. 2022*)

Confirmation with the classical method

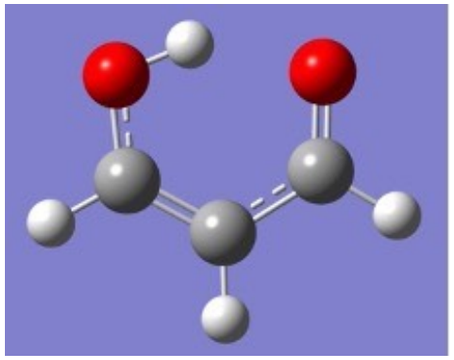


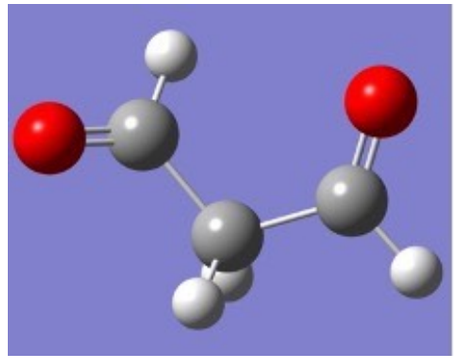
Coutens et al. 2022

3-hydroxypropenal and isomers

Tautomers

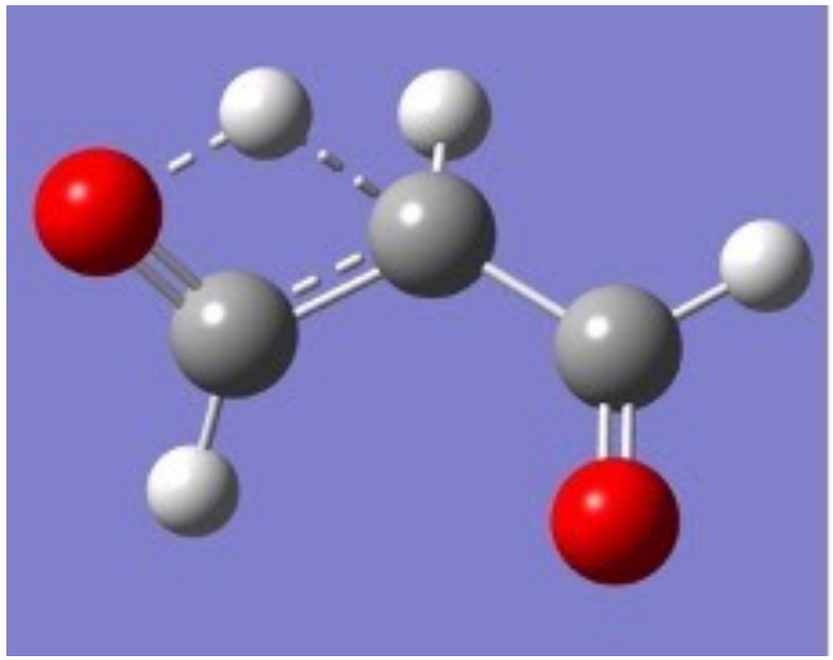
3-hydroxypropenal
enol





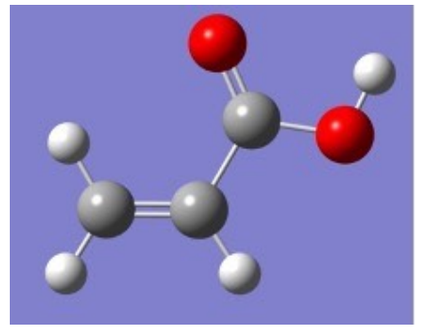
propanedial
dialdehyde

Tautomerization

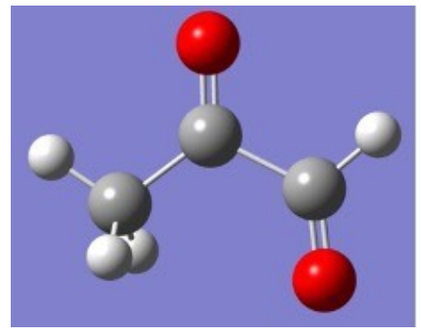


Isomers

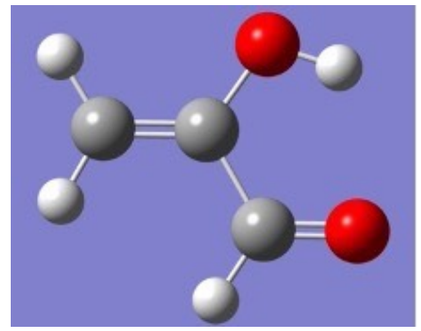
2-propenoic acid
(C_2H_3COOH)



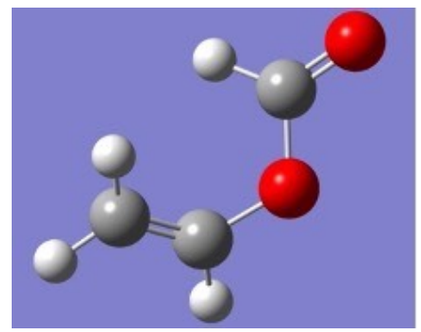
Methyl glyoxal
(CH_3COCHO)



2-hydroxypropenal
($CH_2COHCHO$)



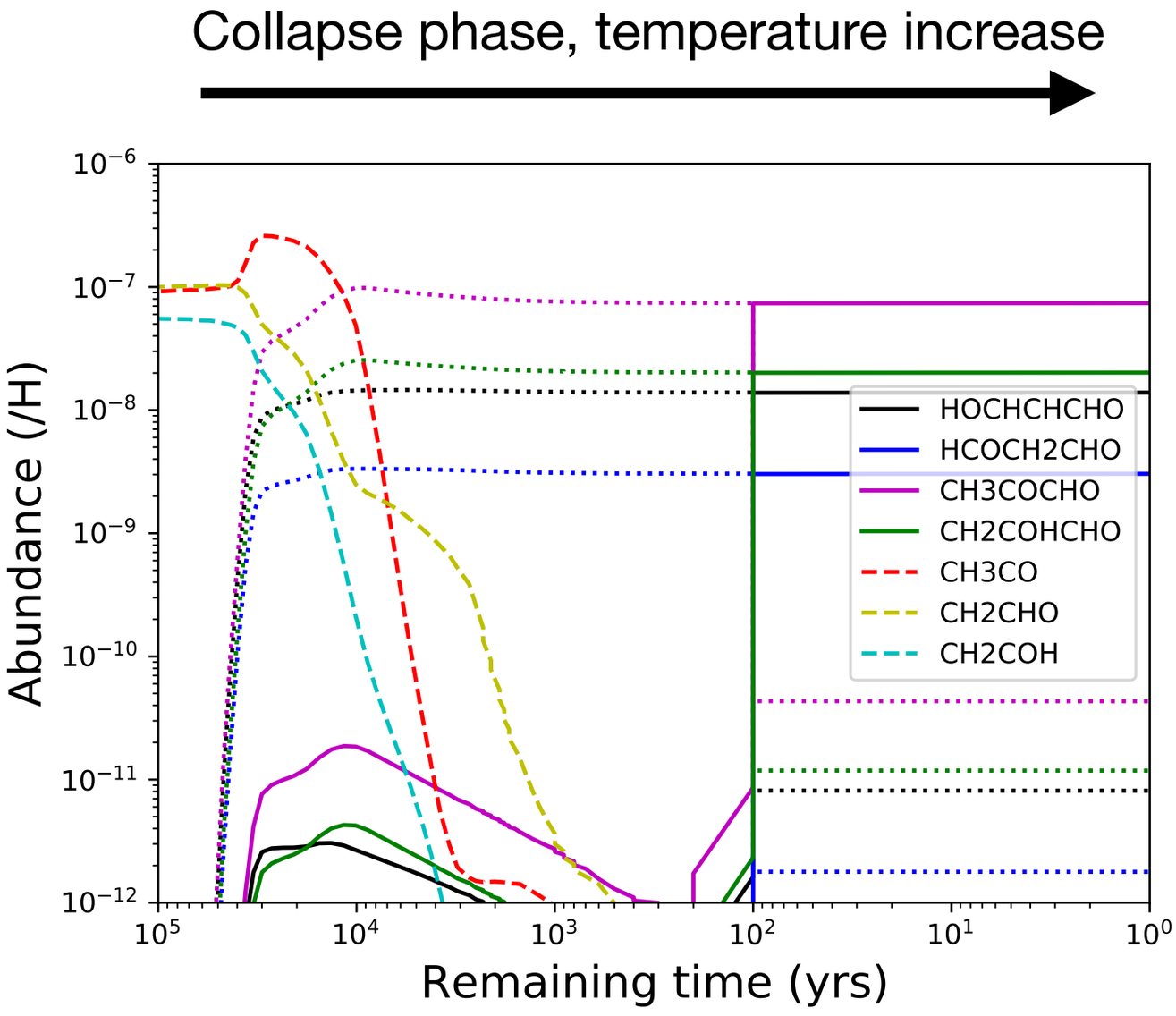
Vinyl formate
(C_2H_3OCHO)



Tautomers

Chemical modeling of the $C_3H_4O_2$ isomers

- Same physical model as in Manigand et al. 2021
- Update of the chemical network by including the reactions producing and consuming the $C_3H_4O_2$ isomers and some radical species linked to $C_3H_4O_2$
- Our model reproduces the abundance of HOCHCHCHO with respect to CH_3OH within the uncertainties (~10)
- $CH_2CHO + HCO \rightarrow HCOCH_2CHO$
  $HCOCH_2CHO \rightarrow HOCHCHCHO$



Coutens et al. 2022

Importance of spectroscopic studies

Isomer	Formula	Predicted abundance (/H)	Predicted abundance ($/CH_3OH$)	Observed abundance ($/CH_3OH$)
3-Hydroxypropenal	HOCHCHCHO	1.4×10^{-8}	4.6×10^{-4}	1.0×10^{-4}
Propanedial	$HCOCH_2CHO$	3.0×10^{-9}	9.9×10^{-5}	
Methyl glyoxal	CH_3COCHO	7.4×10^{-8}	2.4×10^{-3}	
2-Hydroxypropenal	$CH_2COHCHO$	2.0×10^{-8}	6.6×10^{-4}	
Vinyl formate	C_2H_3OCHO	8.4×10^{-10}	2.8×10^{-5}	$\leq 4 \times 10^{-4}$
2-Propenoic acid	C_2H_3COOH	2.2×10^{-13}	7.3×10^{-9}	$\leq 5 \times 10^{-4}$

- Upper limits in agreement for vinyl formate and 2-propenoic acid

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Spectroscopic studies are needed:

- **to search for propanedial, methyl glyoxal and 2-hydroxyprop-2-enal in IRAS16293 and other sources**
- **to test the chemical network**

2-hydroxyprop-2-enal

Isomer	Formula	Predicted abundance (/H)	Predicted abundance ($/CH_3OH$)	Observed abundance ($/CH_3OH$)
3-Hydroxypropenal	HOCHCHCHO	1.4×10^{-8}	4.6×10^{-4}	1.0×10^{-4}
Propanedial	$HCOCH_2CHO$	3.0×10^{-9}	9.9×10^{-5}	
Methyl glyoxal	CH_3COCHO	7.4×10^{-8}	2.4×10^{-3}	*Koucky, Kolesnikova et al. 2022*
2-Hydroxypropenal	$CH_2COHCHO$	2.0×10^{-8}	6.6×10^{-4}	**< 2.4 x 10^{-4}**
Vinyl formate	C_2H_3OCHO	8.4×10^{-10}	2.8×10^{-5}	$\leq 4 \times 10^{-4}$
2-Propenoic acid	C_2H_3COOH	2.2×10^{-13}	7.3×10^{-9}	$\leq 5 \times 10^{-4}$

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First detections of isotopologues in the ISM

Formamide
NH_2CDO
cis-NHDCHO
trans-NHDCHO

Isocyanic acid
DNCO

Cyanamide
NHDCN
$NH_2{}^{13}CN$

Glycolaldehyde
CHDOHCHO
CH_2ODCHO
CH_2OHCDO
$^{13}CH_2OHCHO$
$CH_2OH{}^{13}CHO$

Ethanol
a-a-CH_2DCH_2OH
a-s-CH_2DCH_2OH
CH_3CHDOH

Acetaldehyde
CH_3CDO
$^{13}CH_3CHO$
$CH_3{}^{13}CHO$

Oxyrane
c-C_2H_3DO

Formic acid
$H^{13}COOH$
t-DCOOH
t-HCOOD

Ketene
$^{13}CH_2CO$
$CH_2{}^{13}CO$
CHDCO

Formaldehyde
$H_2C^{17}O$
$D_2{}^{13}CO$

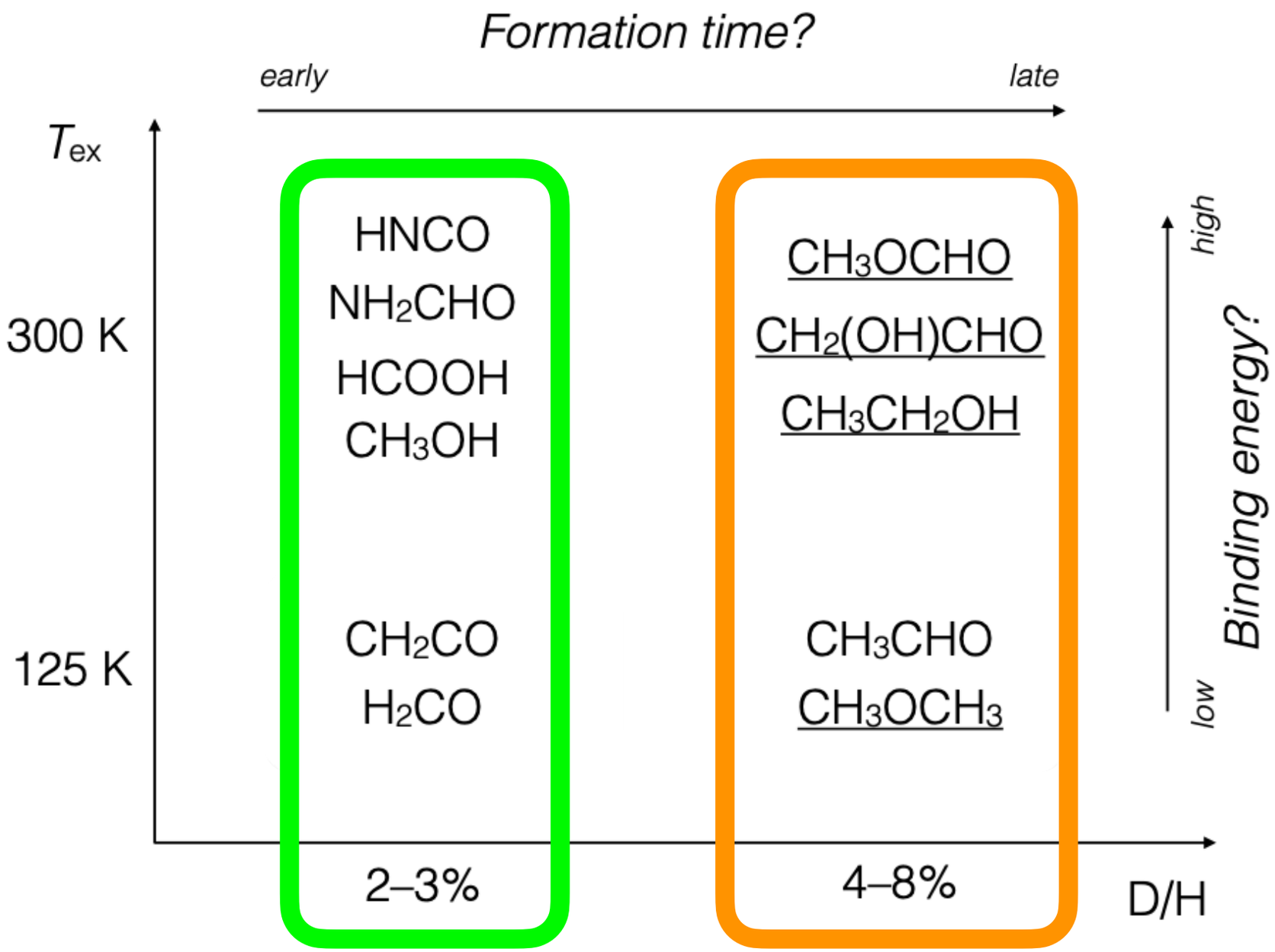
Methyl cyanide
CHD_2CN

Methyl formate
$HCOOCHD_2$

Dimethyl ether
CH_3OCHD_2

Coutens et al. 2016, 2018, Jørgensen et al. 2016, 2018, Persson et al. 2018, Calcutt et al. 2018, Manigand et al. 2019, Richard et al. 2021, Müller et al. 2022

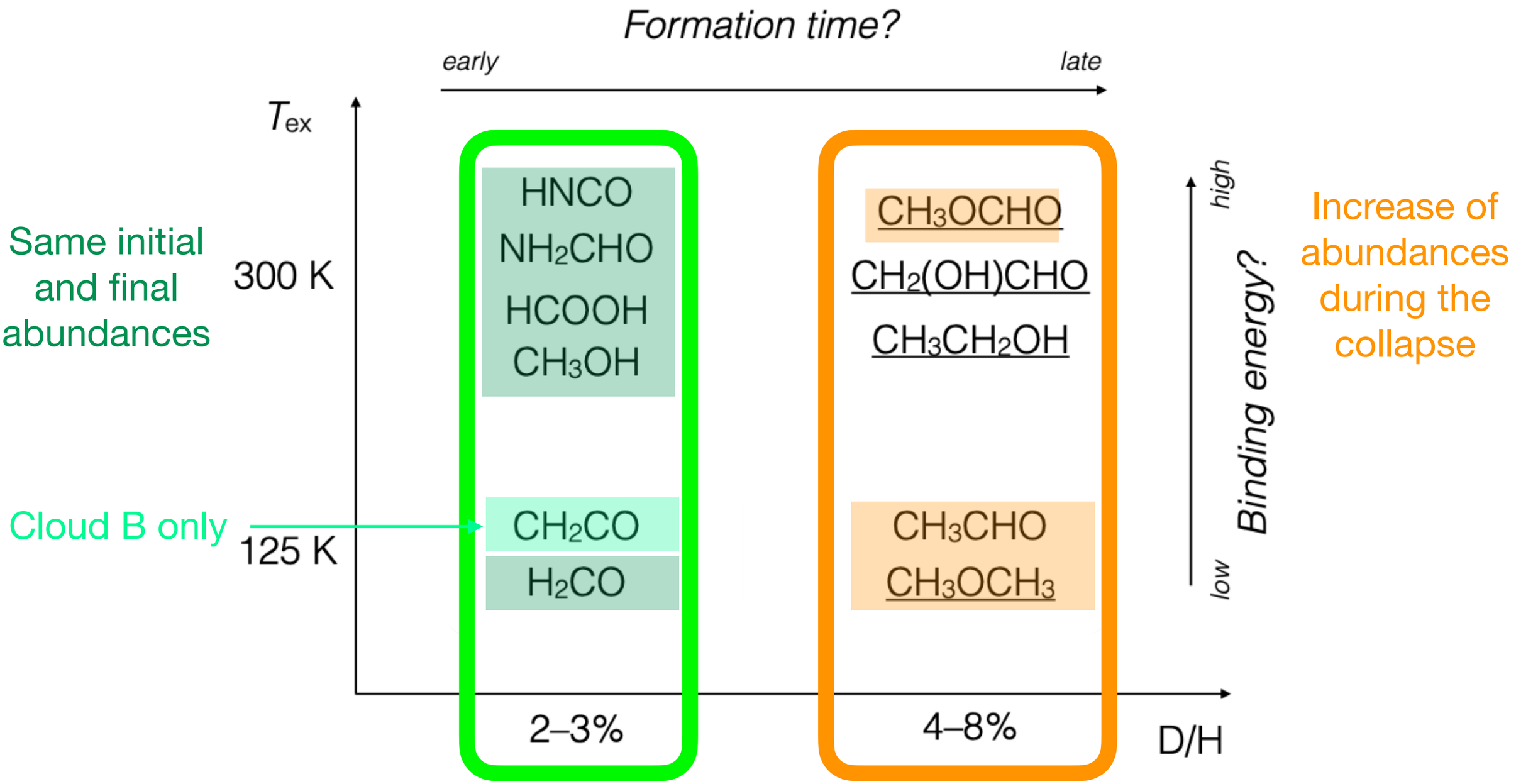
Deuteration of molecules



Jørgensen et al. 2018

Deuteration of molecules

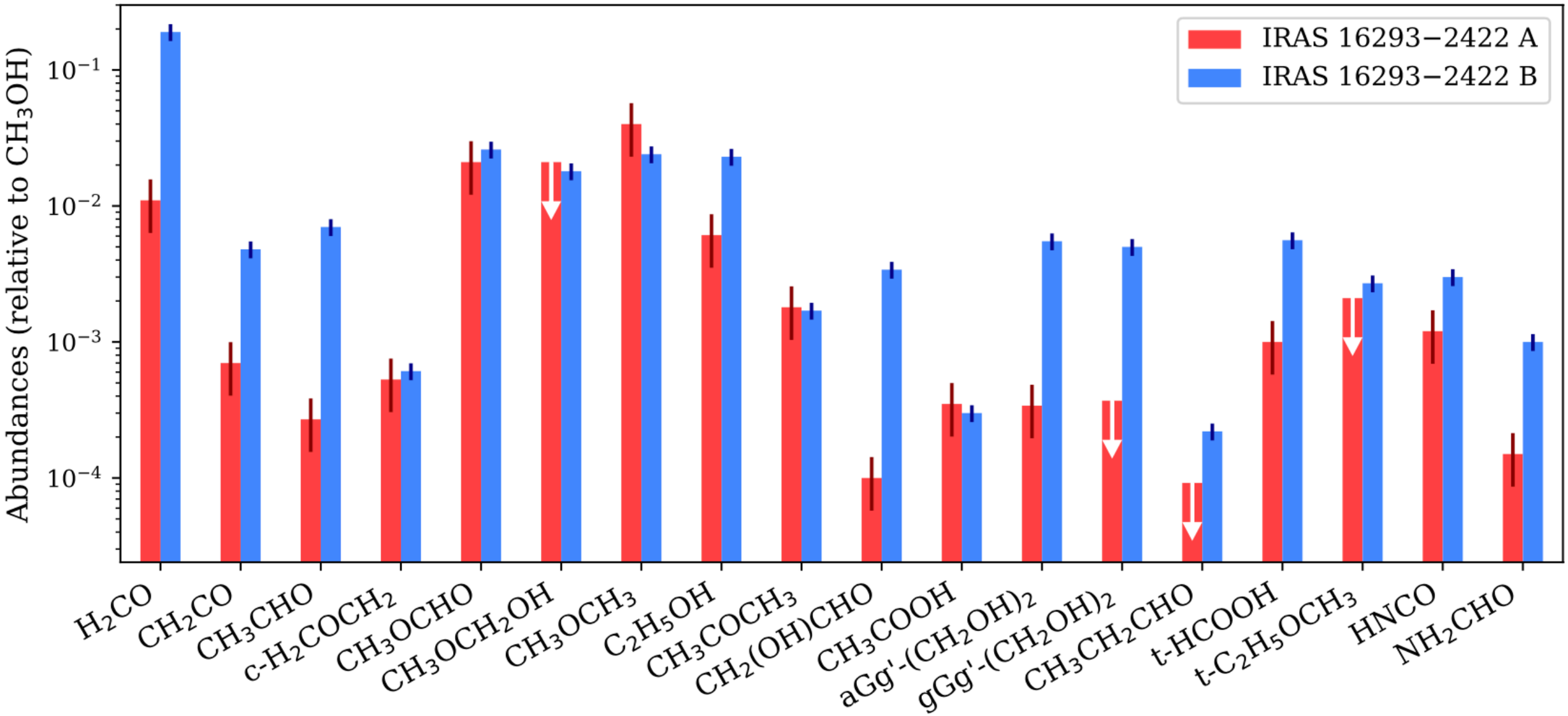
Comparison with 3D chemical modeling (*Coutens et al. 2020*)



Jørgensen et al. 2018

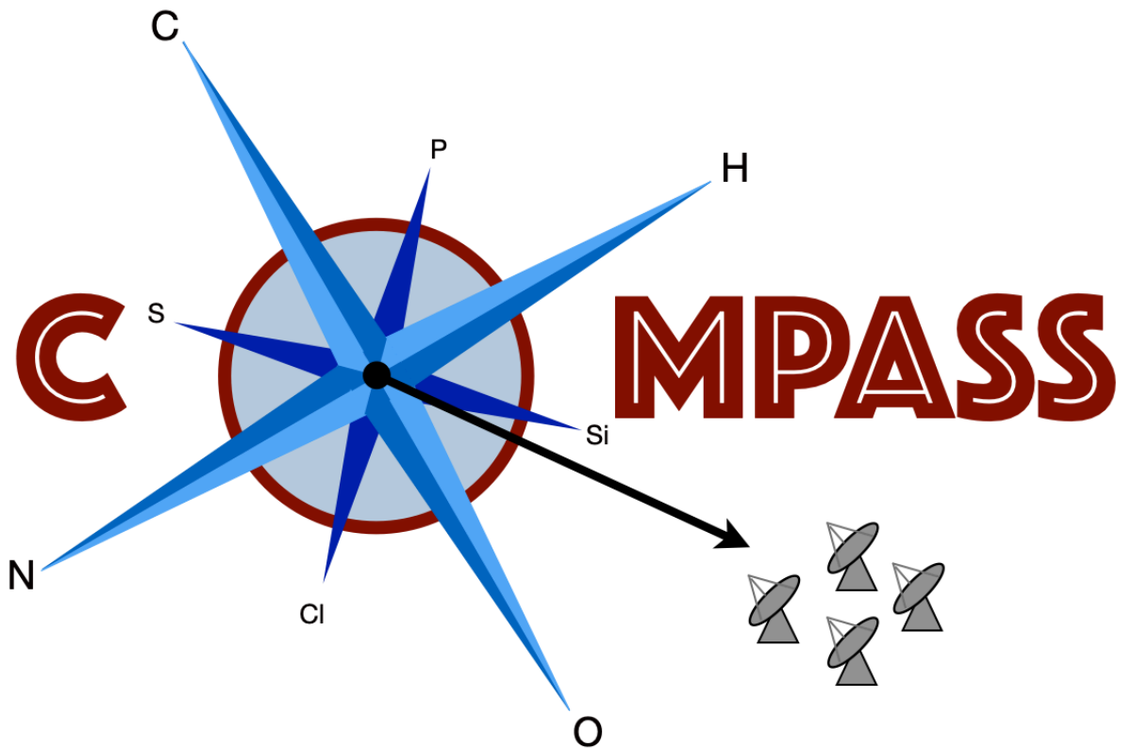
Comparison between IRAS16293 A and B

Manigand et al. 2020



- Analysis of a single position (0.6" north-east of IRAS 16293 A, narrow lines)
- Different spatial distribution of the molecules towards A would explain the differences
- The less abundant species towards A appear to be more compact

Comparison with other protostars: COMPASS



Complex Organic Molecules in Protostars with ALMA Spectral Surveys

- ALMA large program (125 h)
- Unbiased line surveys of 11 low-mass protostars (diverse evolutionary stages and different environments)

- *What are the physical, environmental, and evolutionary regulators of the formation of complex organics?*
- *Is there a universal outcome of interstellar chemistry (COMs) ?*
- *How much diversity in organic inventories do we expect for planetary systems?*

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Adele Plunkett

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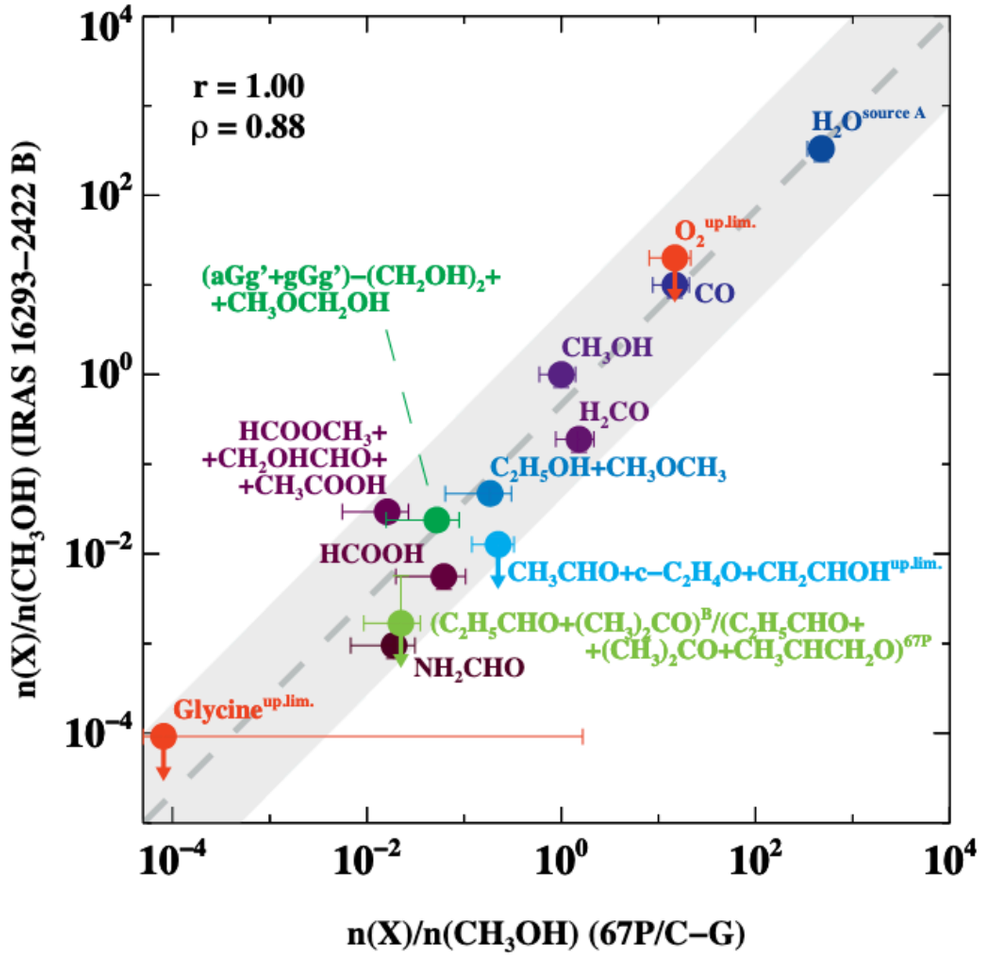
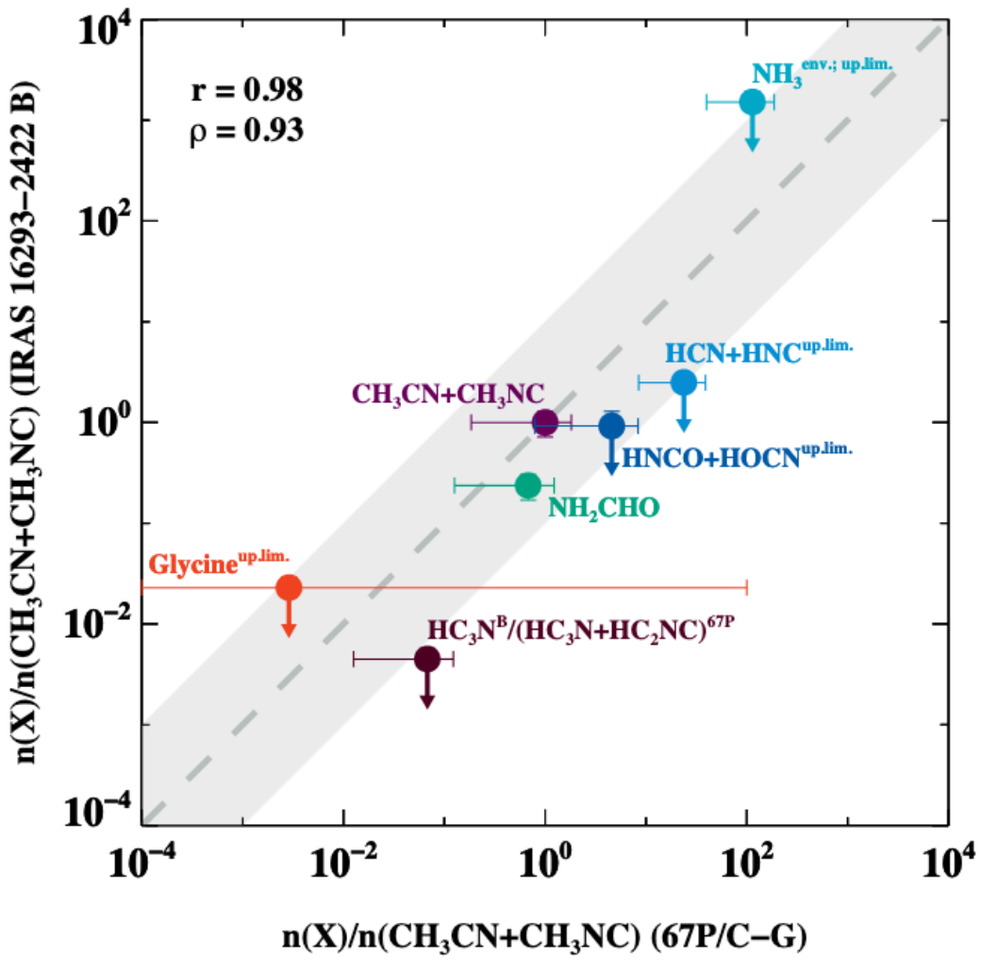
Sébastien Maret
Brett McGuire
Silvia Spezzano
Merel van't Hoff
Yao-Lun Yang

Comparison with comets





Drozdovskaya et al. 2019

Tools for astrochemical observations

- Characterizing the chemistry of more protostars with ALMA and NOEMA

  ➡ Chemical differentiation
  ➡ Chemical evolution

- Development of tools for an efficient analysis of a large amount of interferometric data

Chemtrip

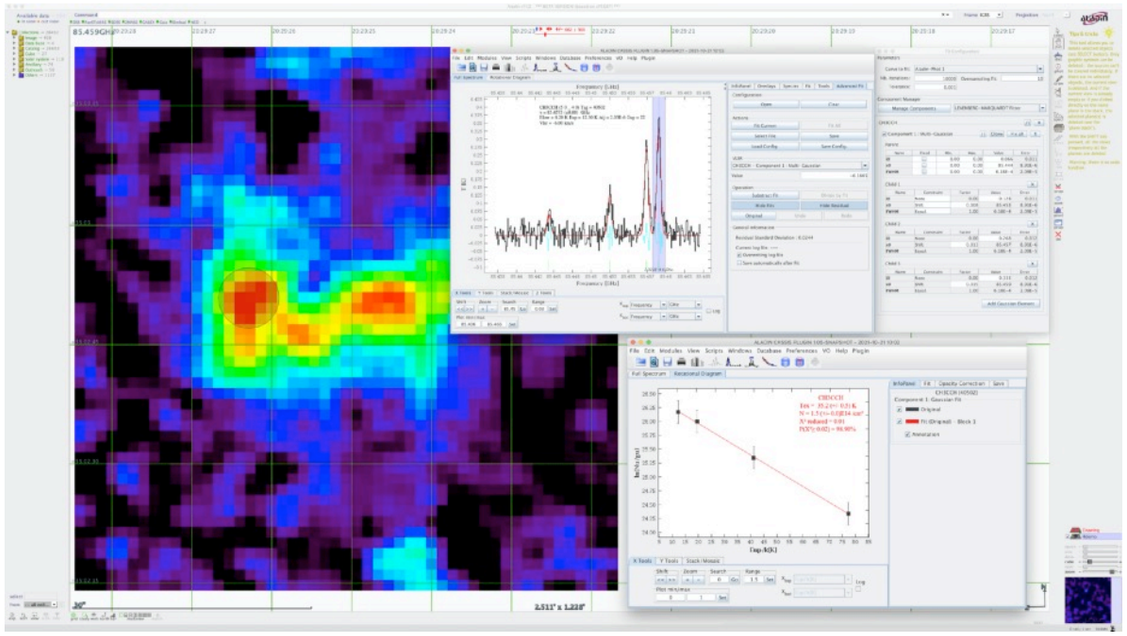
The CHEMical TRail In Protostars: From the deeply embedded phase to the planet-forming disk

✦ Interface between the CASSIS software (IRAP) and the Aladin software (CDS)

✦ ATOMIS: web interface to search for specific species in the ALMA archive (S. Ben Hmida, J.-M. Glorian)

See poster ATOMIS !

https://aladin.u-strasbg.fr/



Summary

- Very rich chemistry in solar-type protostars
- PILS: Large and unbiased spectral survey of IRAS 16293-2422 with ALMA
- A lot of first detections both in solar-type protostars and in the ISM
- Spectroscopic studies are necessary to identify all the lines in the survey
- Chemical models can be improved and tested thanks to the high number of detected species
- Chemical network with molecules with up to 3C atoms (J.-C. Loison)
- Chemical models can also help us determine the most promising species to search for
- More ALMA data coming soon (COMPASS) to investigate the chemical differentiation

Thanks for
your attention !

UNIVERSITÉ TOULOUSE III PAUL SABATIER
Université de Toulouse

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