Pre- and Protostellar Roots of Cometary Volatiles

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Prebiotic Molecules in Space and Origins of Life on Earth
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PlanetS

b UNIVERSITÄT BERN
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The assembly line

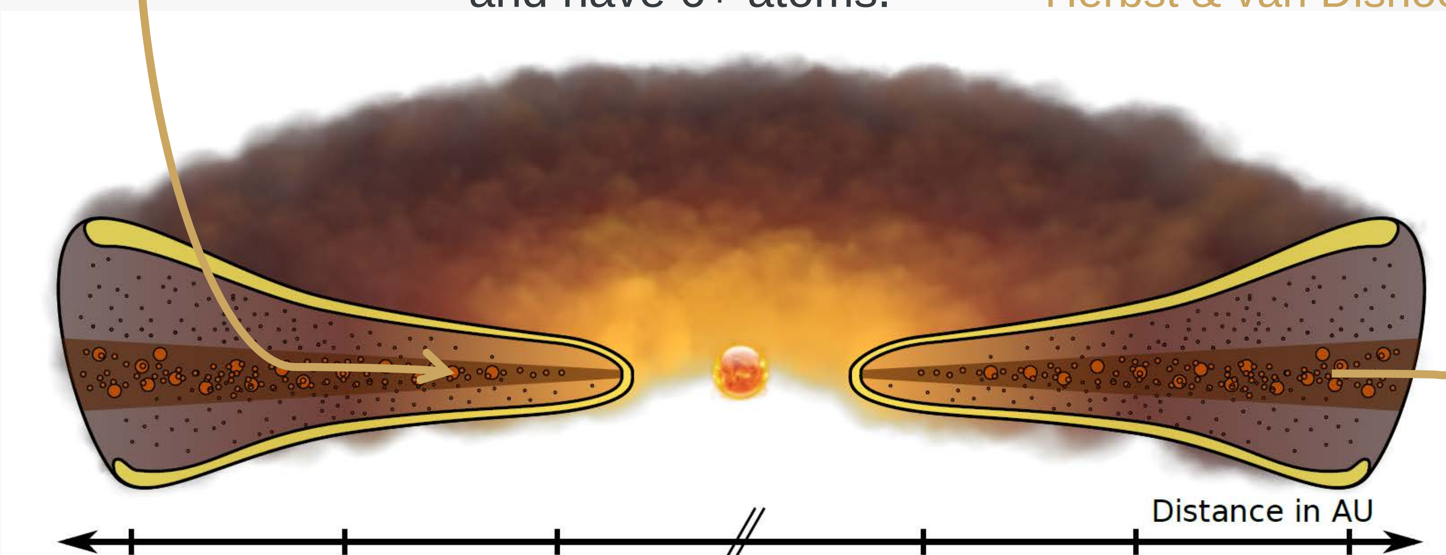
The Pillars of Creation
MUSE-VLT/ESO

Protoplanetary disk midplanes:

- Formed from the prestellar materials
- Sites of protoplanetary and cometary building block formation

When and where are the seeds to life planted?

Complex organic molecules to an astrochemist are C-containing and have 6+ atoms. Herbst & van Dishoeck 2009



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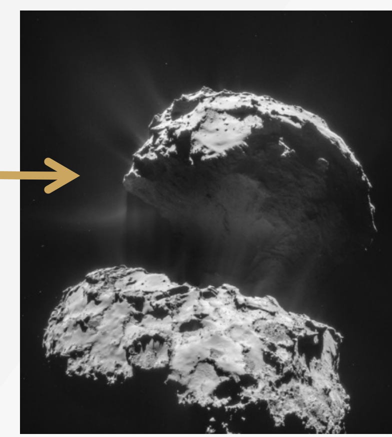


03/02/2015;
ESA/*Rosetta*/NAVCAM, CC BY-SA IGO 3.0

Simple & Complex Molecules at all Stages

The Pillars of Creation
MUSE-VLT/ESO

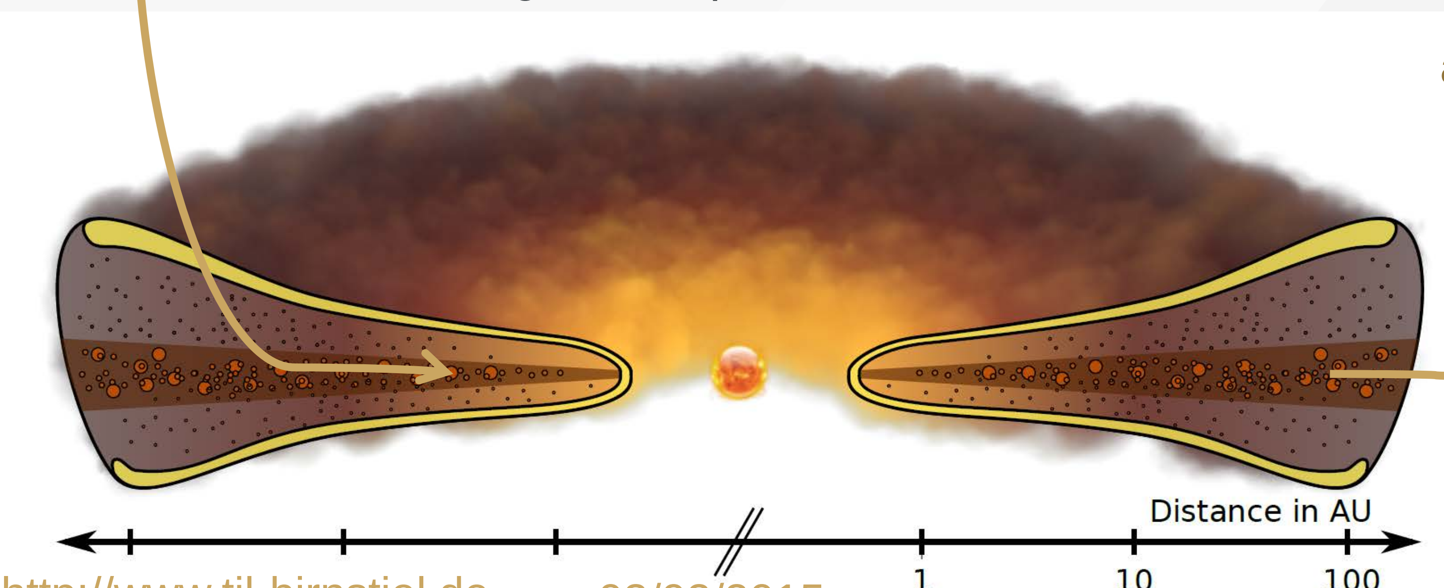
Complex Organics in the prestellar phase

L1544 & L1498 - talk of Izaskun Jiménez-Serra

and in the protostellar phase

Low-mass protostars - talk of Arnaud Belloche

High-mass protostars - talks of Maite Beltrán & Francesco Fontani



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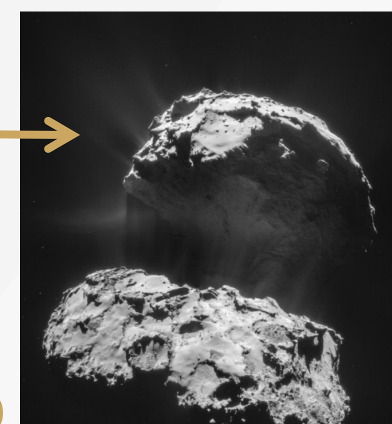
and in comets

Rosetta mission to 67P/C-G



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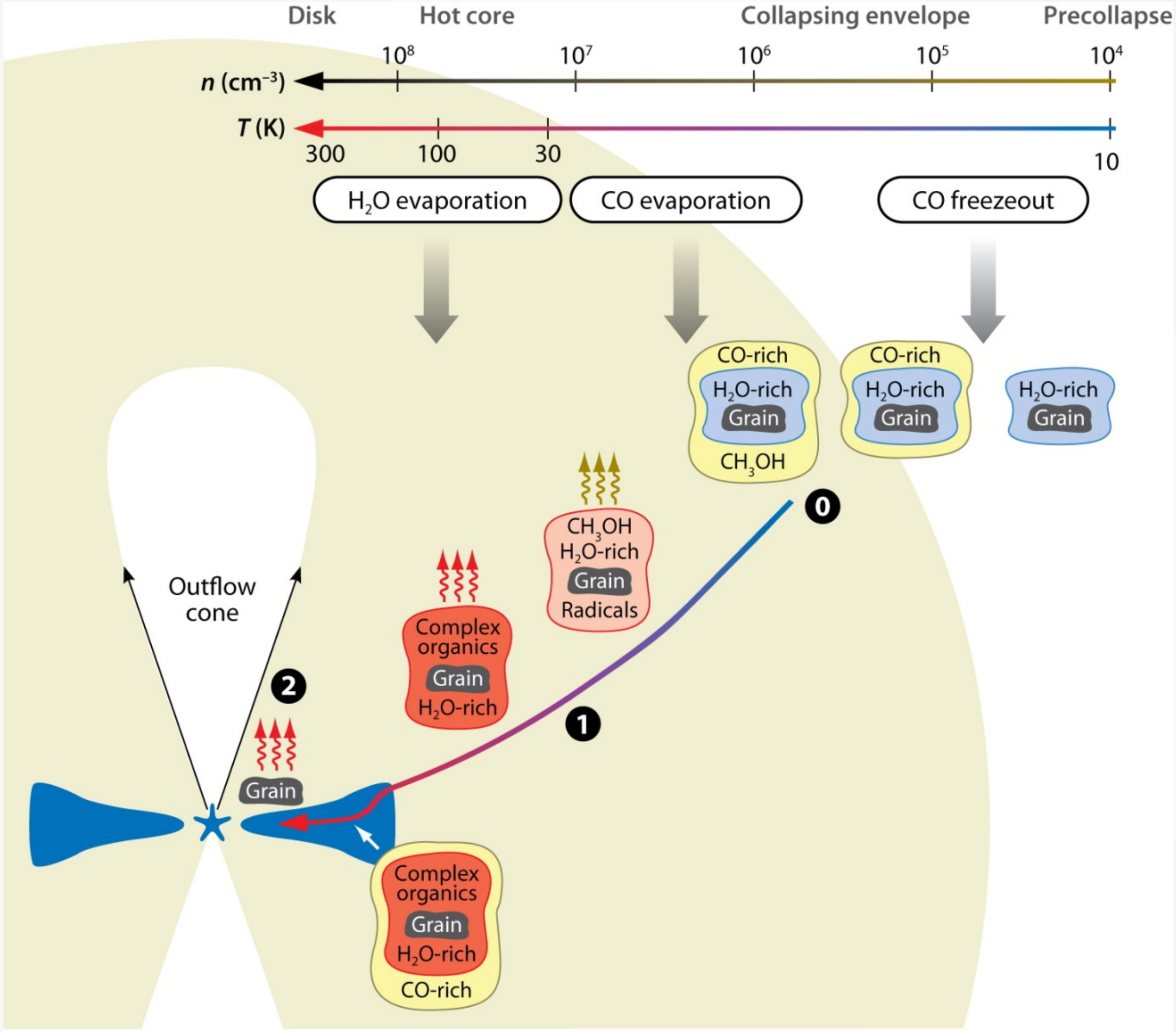


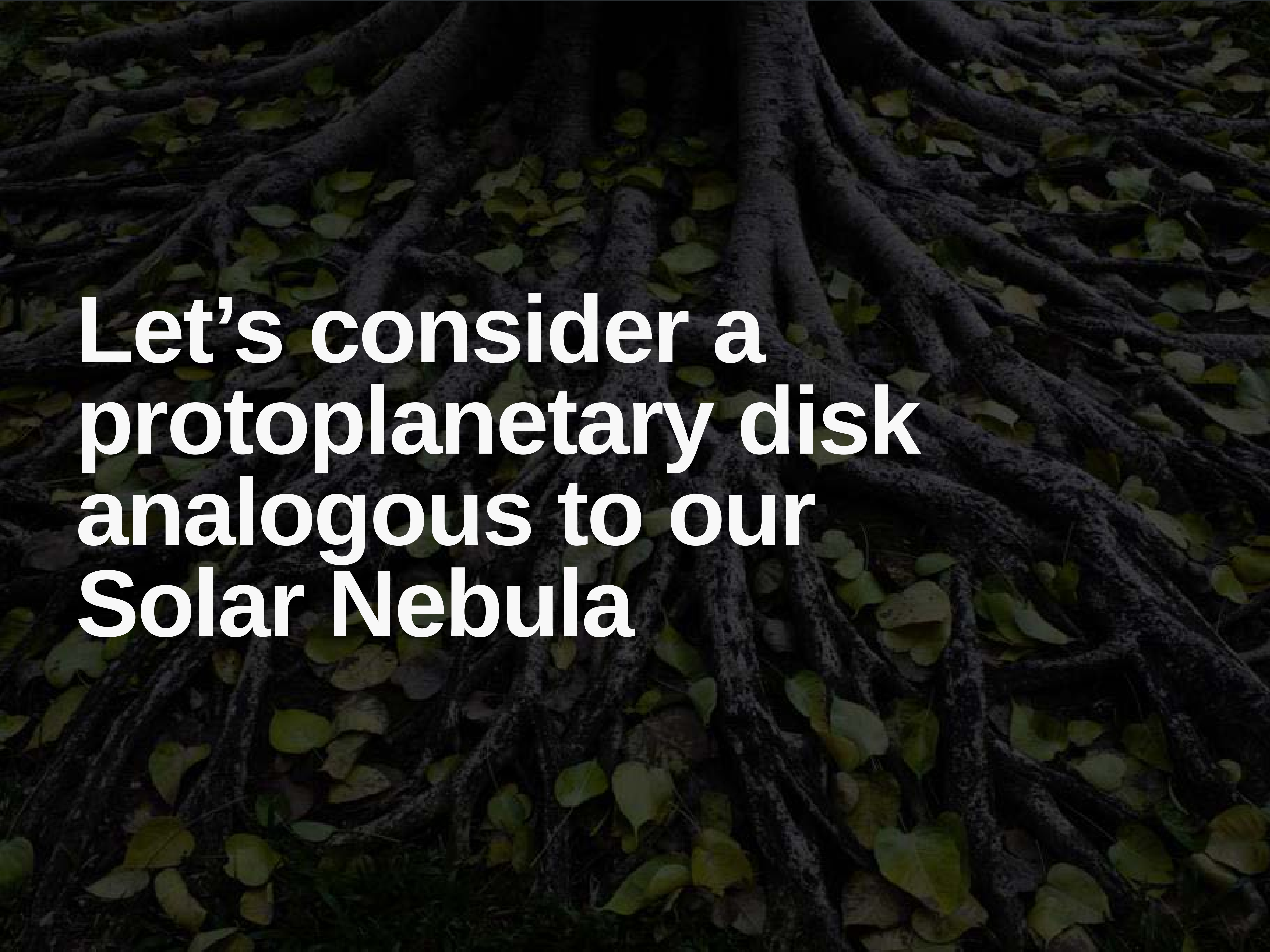
Herbst E, van Dishoeck EF. 2009.
Annu. Rev. Astron. Astrophys. 47:427–80

Chemistry during collapse

Chemistry occurs in parallel with the large-scale physical evolution of the system and with grain growth.

What survives into the disk?

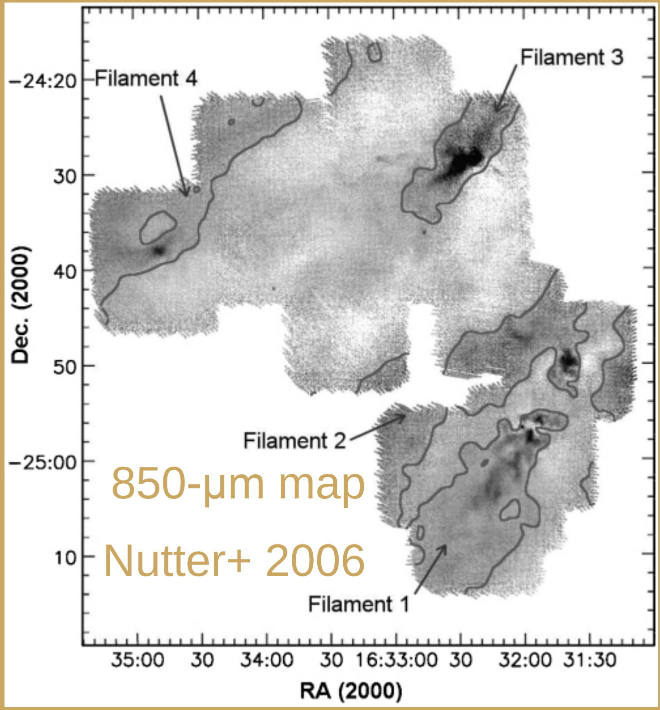
What is incorporated into comets?



Let’s consider a protoplanetary disk analogous to our Solar Nebula

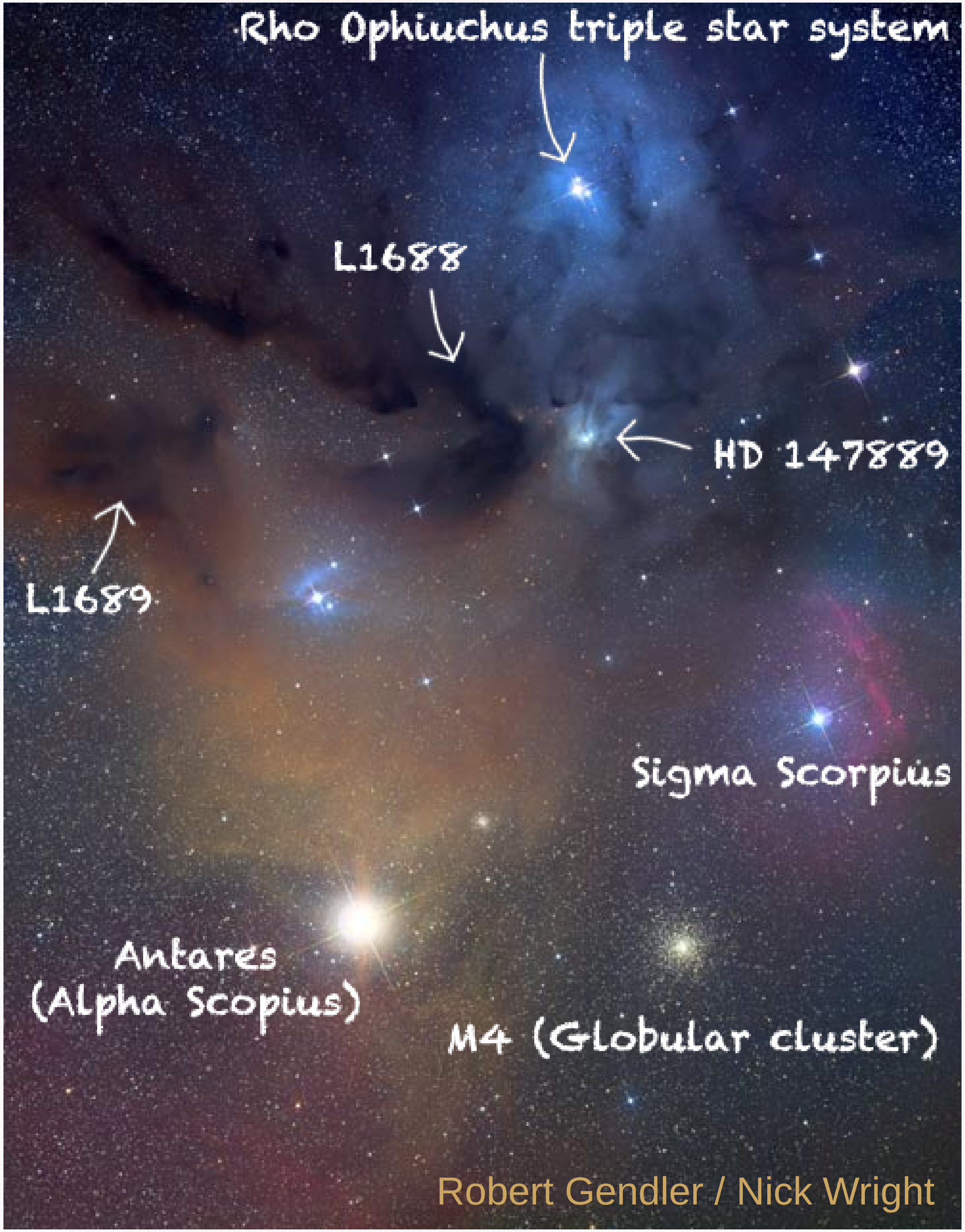
Case study: IRAS 16293-2422

- in L1689 region in ρ Oph; $d \sim 120$ pc
- low-mass; $L \sim 21\ L_\odot$
- binary with a separation of ~ 600 AU



850-μm map

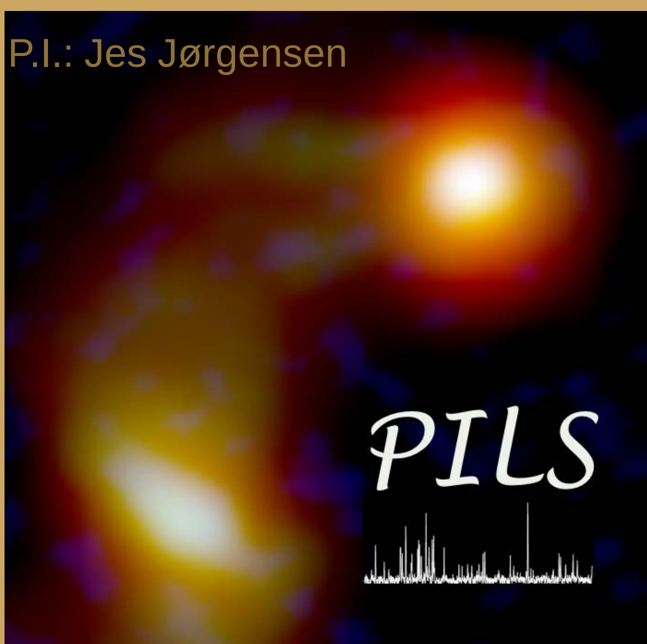
Nutter+ 2006

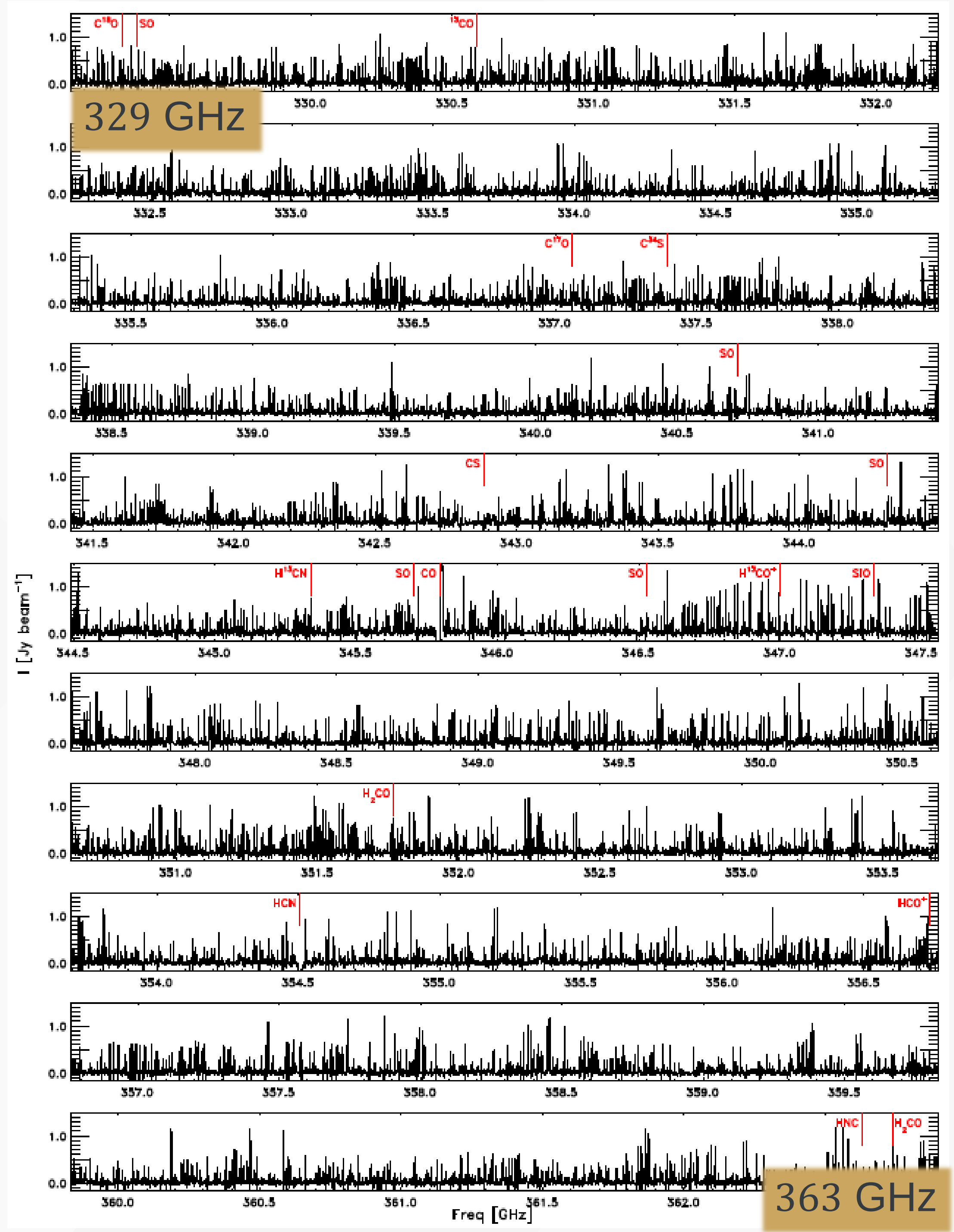


Robert Gendler / Nick Wright

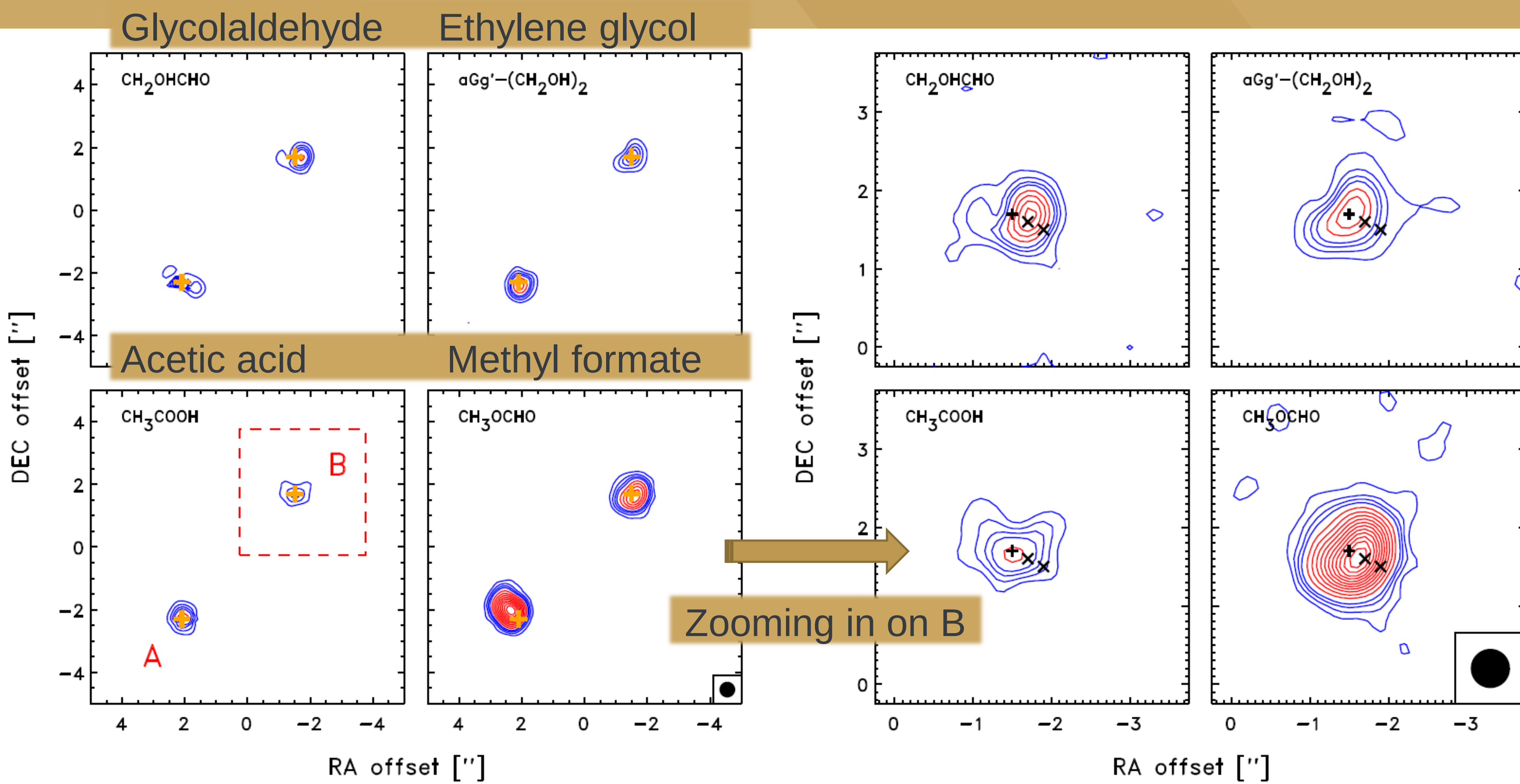
Case study: IRAS 16293-2422

- ALMA Protostellar Interferometric Line Survey
- angular res. ~60 AU
- spectral res. 0.2 km s^{-1}
- sensitivity 5 mJy $beam^{-1}$ km s^{-1}
- ∽ 10 000 lines in 33.7 GHz





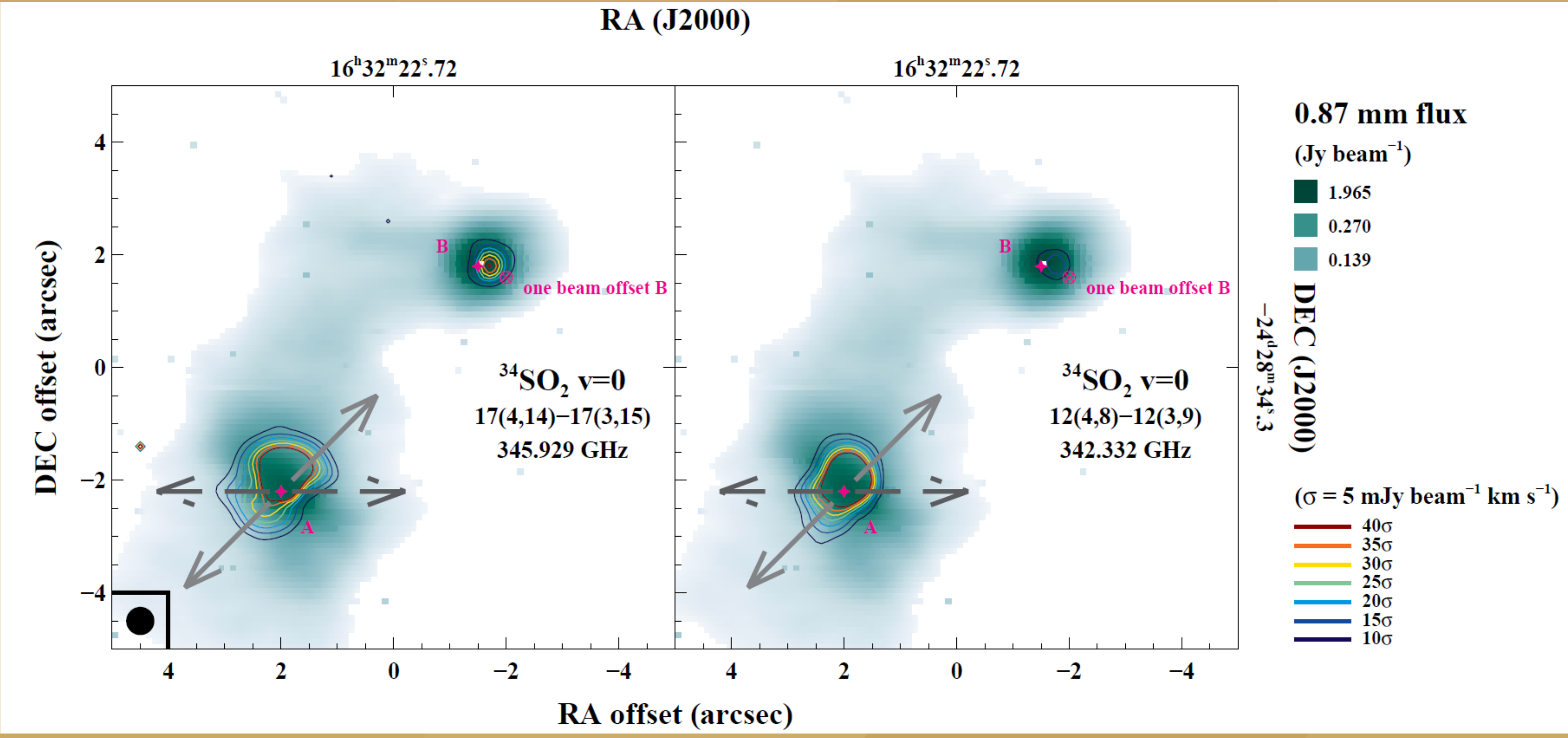
<u>Some detections:</u> glycolaldehyde (HOCH2CHO), methyl formate (HCOOCH3), acetic acid (CH3COOH), ethylene glycol (aGg'- & gGg'-(CH2OH)2), ethylene oxide (c-C2H4O), acetaldehyde (CH3CHO), acetone (CH3COCH3), propanal (C2H5CHO), formamide (NH2CHO), methyl isocyanate (CH3NCO), methyl cyanide (CH3CN), ethyl cyanide (C2H5CN), vinyl cyanide (C2H3CN), cyanamide (NH2CN), methyl mercaptan (CH3SH), ...



Face-on disk around B: chemistry isn't hidden from our view! COM emission dominated by compact homogeneous material

Jørgensen+ 2016, 2018 resubm.

Detected: SO_2, SO, OCS, CS, H_2CS, H_2S and CH_3SH, incl. $OC^{33}S$ [1st time this source] & tentatively $C^{36}S$ [1st time low-mass protostar]



diverse inventory of S-bearing volatiles and isotopologues; including complex (CH_3SH)

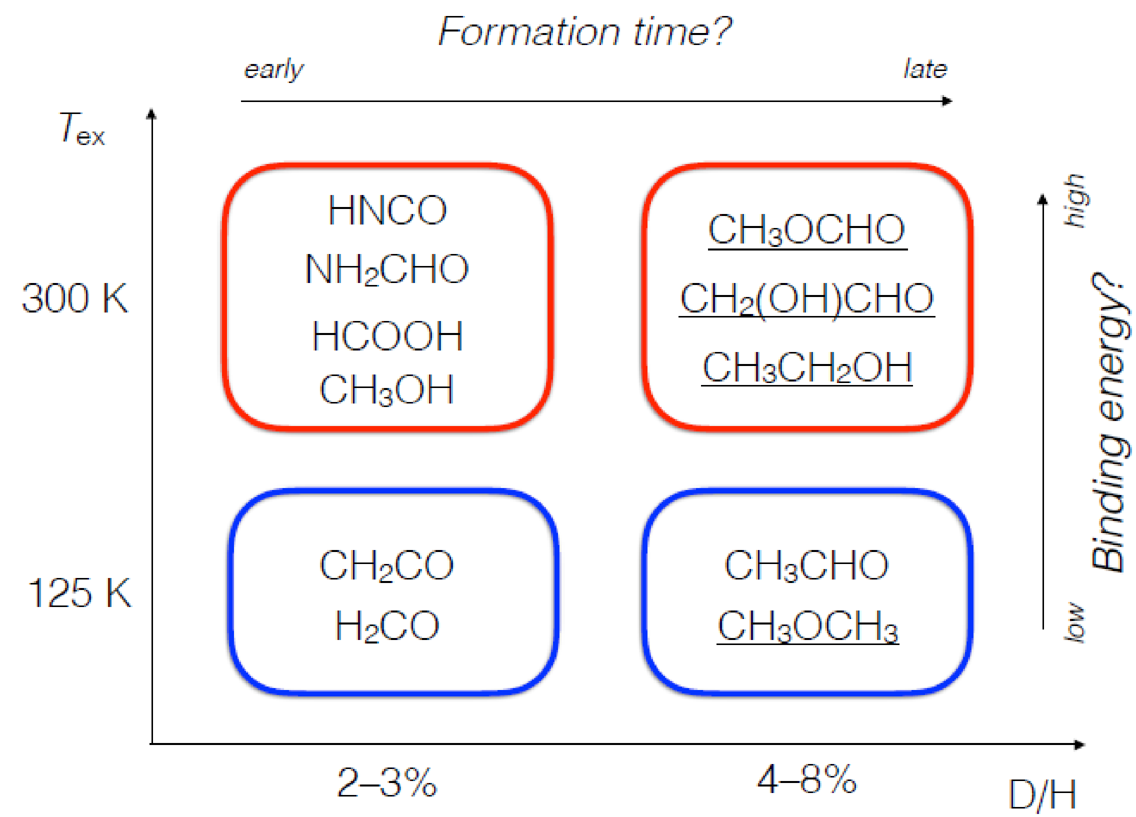
Drozdovskaya+ 2018

Distribution of S-volatiles near IRAS 16293-2422 B

Is thioformaldehyde less processed than formaldehyde?
Did it form under more D-rich conditions?

Deuteration of complex organics

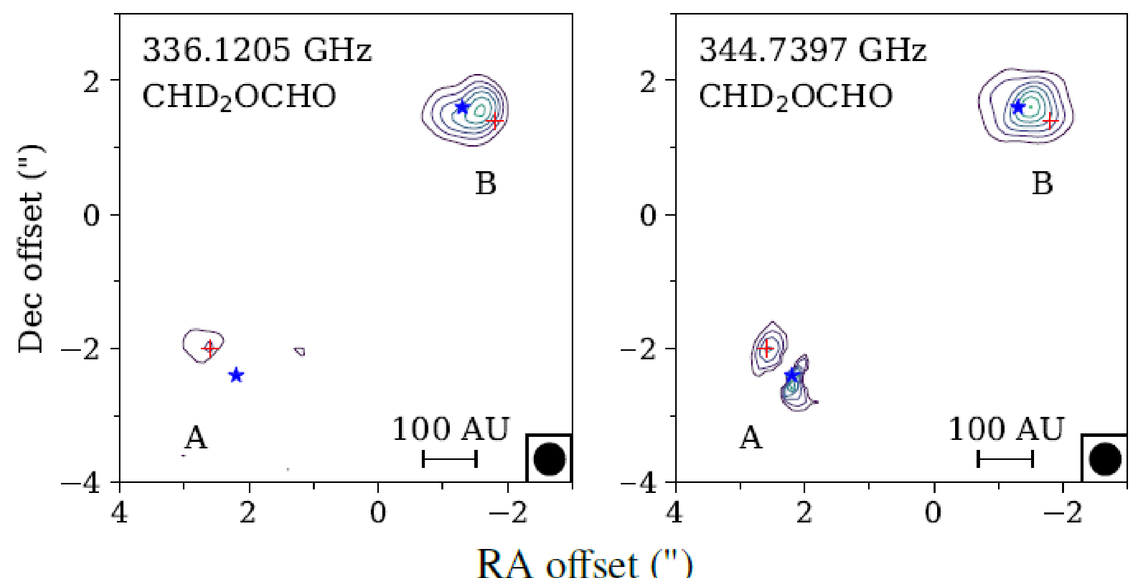
Jørgensen+ 2018 resubm.; Manigand+ 2018 subm.



More complex species show higher deuteration – formed later, before/during collapse?

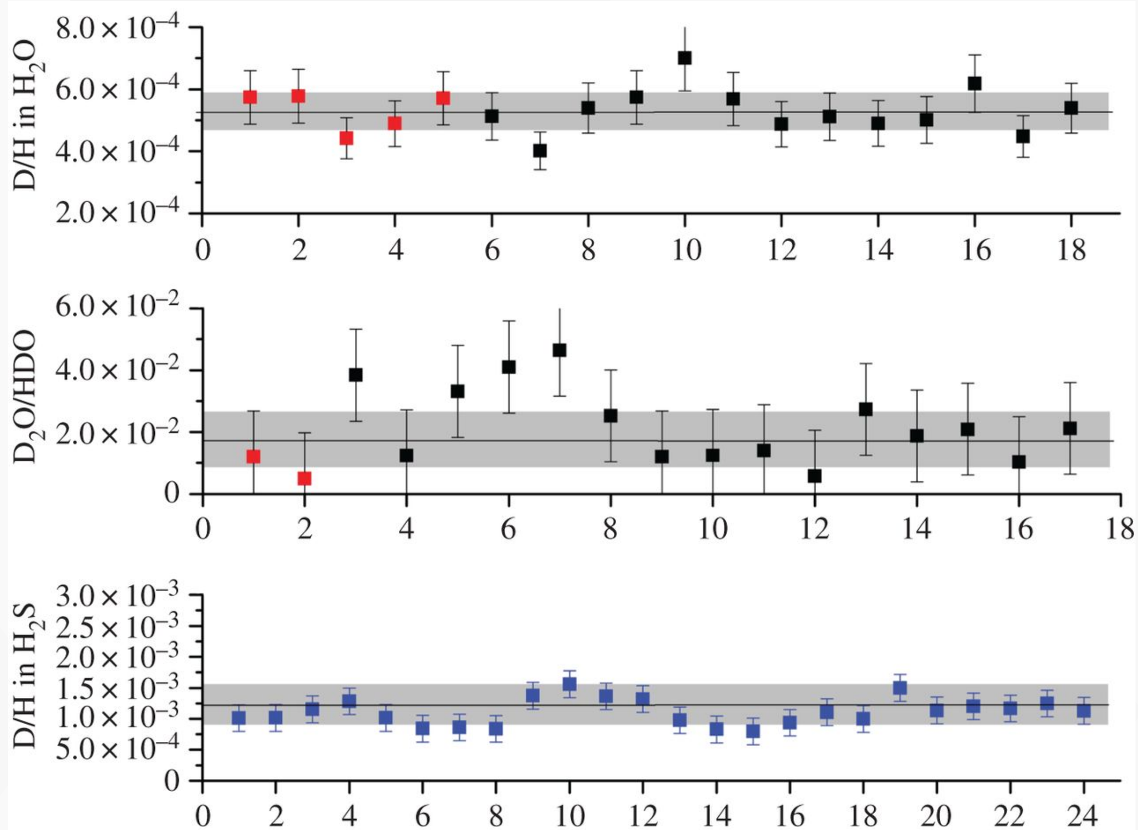
No difference seen for deuteration of various functional groups – short infall timescales limiting time for exchange reactions?

First ISM detection of doubly deuterated methyl formate with a 2-3x higher D/H than that of the singly deuterated isotopologue



Let’s suppose 67P/C-G is a probe of our innate Solar Nebula

67P/C-G is a tracer of the cold past



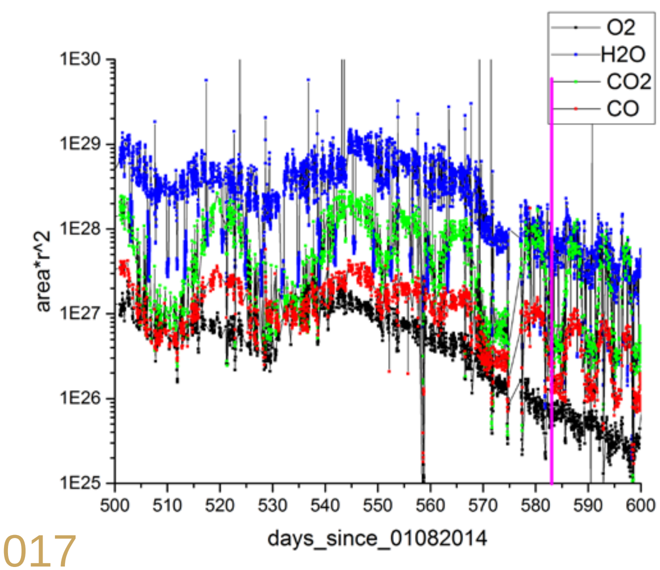
The cometary ice contains highly volatile species
~3% O2
~1% CO
~0.15% CH4
~0.1% N2
~10-4 % Ar

Statistically: [D2O/HDO] / [HDO/H2O] = 1/4

In 67P: [D2O/HDO] / [HDO/H2O] = 17

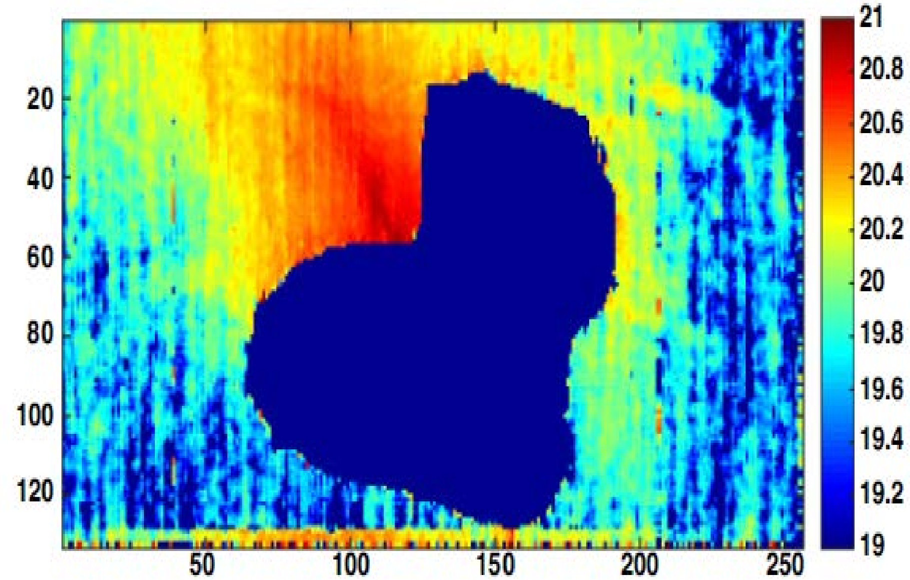
This means: at least some water was preserved as ice from earlier phases

O2 is as abundant in 67P as CO and well-mixed with H2O

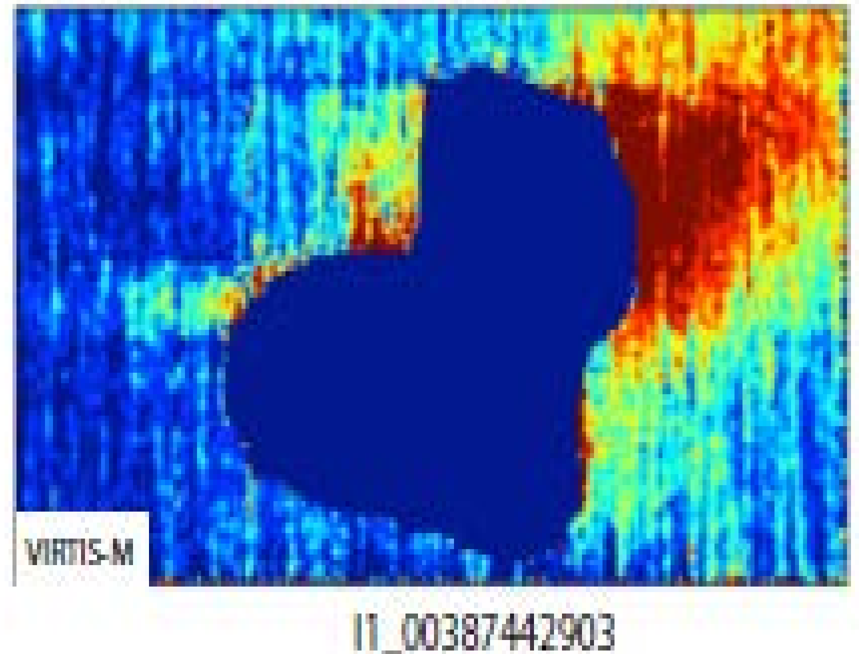


Altwegg+ 2016, 2017; Le Roy+ 2015; Calmonte+ 2016, 2017

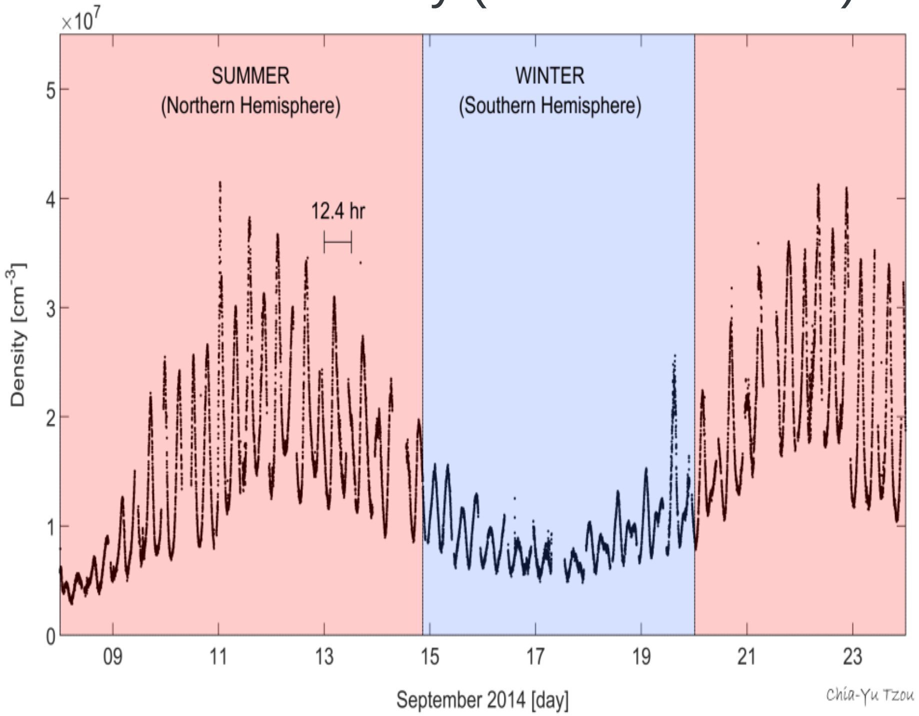
Coma is heterogenous: getting the bulk is non-trivial



Neutral water (top) and CO2 outgassing measured by VIRTIS (Fougère et al., 2016, data from Migliorini et al., 2016)



Total density (ROSINA-COPS)



Credits: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA

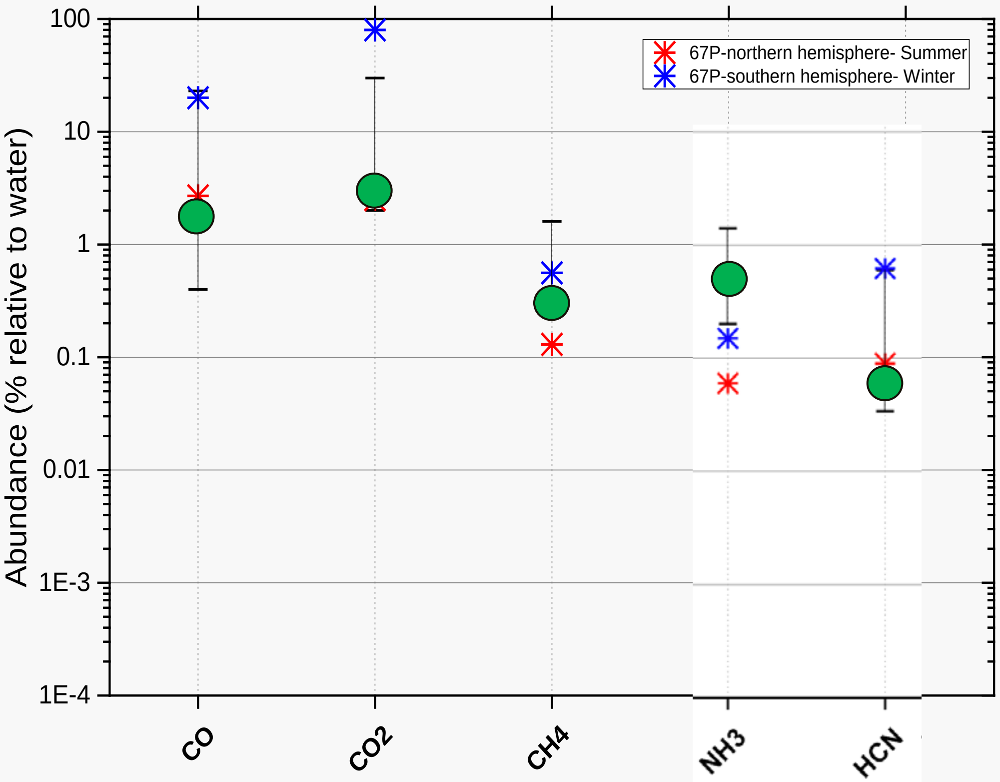
During the last orbit of 67P, the Northern hemisphere was processed:

it was the summer hemisphere during 5.5 years

=> The surface layer may have lost most of its volatiles?

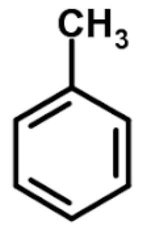
Measurements during perihelion are closer to Northern hemisphere values!

Rubin+ 2018 in prep.



ROSETTA Zoo
Macr
es
Methane
Ethane
Propane
Butane
Pentane
Hexane
Heptane
Glycine
(Aminoacid
S2
S3
S4
Methanethiole
(CH3SH)
Ethanethiol (C2H5SH)
Thioformaldehyde
(CH2S)
Ammonia
Methylamine
Ethylamine
Cyanogen
(C2N2)
Formic acid
Acetic acid
Acetaldehyde
Ethylenglycol
Propylenglycol
Butanamide
Argon
Krypton
Xenon
HF
HCl
HBr
P
Acetylene
HCN
Acetonitr
Formaldehyde
Benzene
Toluene
Xylene
Benzoic acid
Naphthalene
Methanol
Ethanol
Propanol
Butanol
Pentanol
Nitrogen
Oxygen
N≡N
Hydrogenperoxy
d
Carbon
monoxide
Carbon dioxide
Hydrogensulfide
Carbonylsulfide
Sulfur monoxide
Sulfur dioxide
Carbon disulfide
Na, Si, K

ROSINA-DFMS, COSAC & Ptolemy

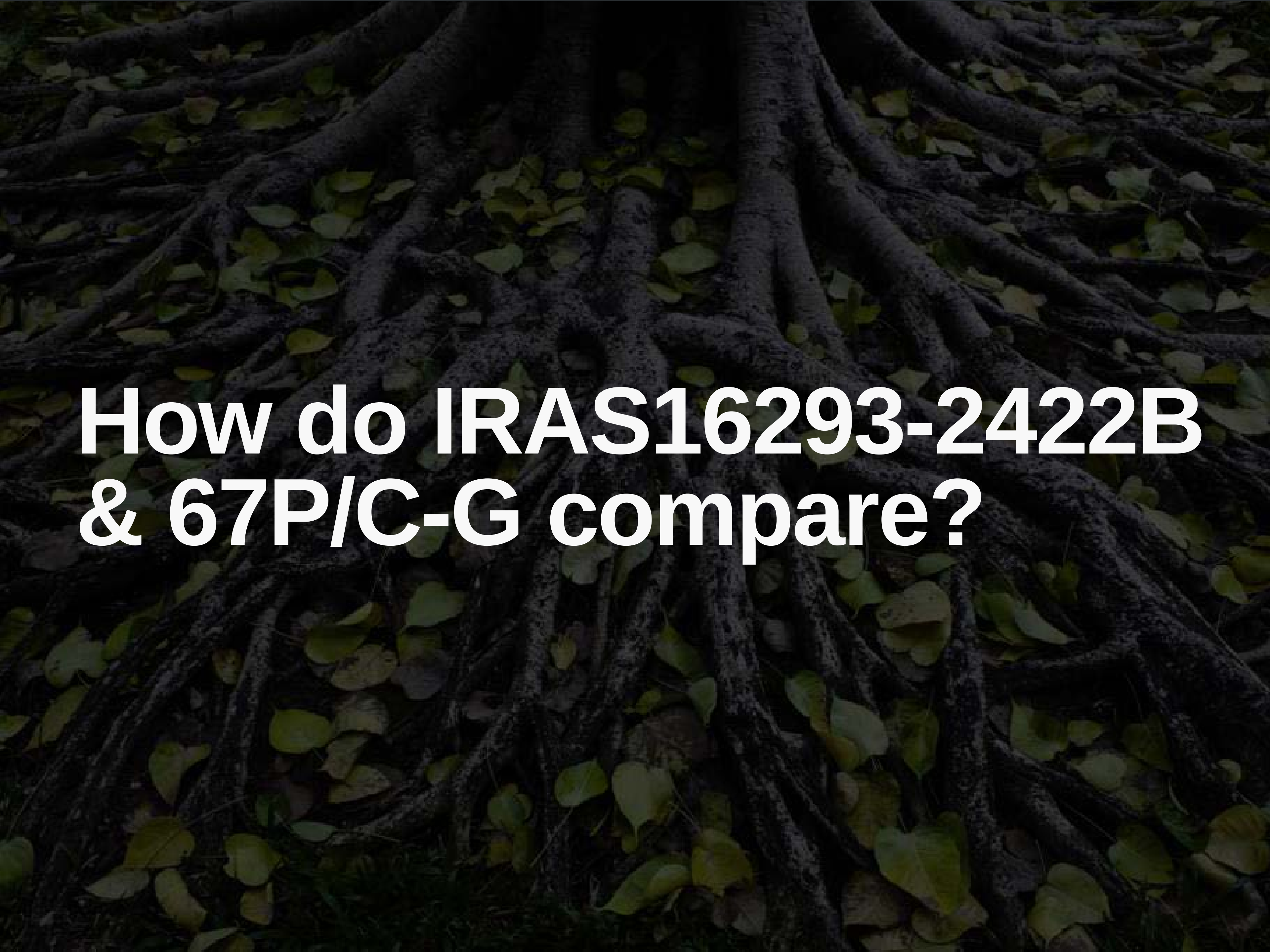


Methyl isocyanate, propanal and glycolaldehyde could not be confirmed in the original COSAC identifications.

Presence of polyoxymethylene in Ptolemy spectrum is unlikely; toluene is measured instead.

Altwegg+ 2017b

Molecule		Mass (Da)	Rel. abundance (per cent)	Identified in DFMS spectra
CH_4	Methane	16	0.7	Y
H_2O	Water	18	80.9	Y
CHN	Hydrogencyanide	27	1.1	Y
CO	Carbon monoxide	28	1.1	Y
CH_5N	Methylamine	31	1.2	Y
CH_3CN	Acetonitrile	41	0.5	minor
CHNO	Isocyanic acid	43	0.5	Y
C_2H_4O	Acetaldehyde	44	1.0	Y
CH_3NO	Formamide	45	3.7	Y
$C_2H_5NH_2$	Ethylamine	45	0.7	Y
CH_3NCO	**Methyl isocyanate**	57	3.1	
C_3H_6O	**Acetone**	58	1.0	Y
C_2H_5CHO	**Propanal**	58	0.4	?
CH_3CONH_2	**Acetamide**	59	2.2	minor
CH_2OHCHO	Glycol aldehyde	60	1.0	
$CH_2(OH)CH_2(OH)$	Ethylene glycol	62	0.8	Y

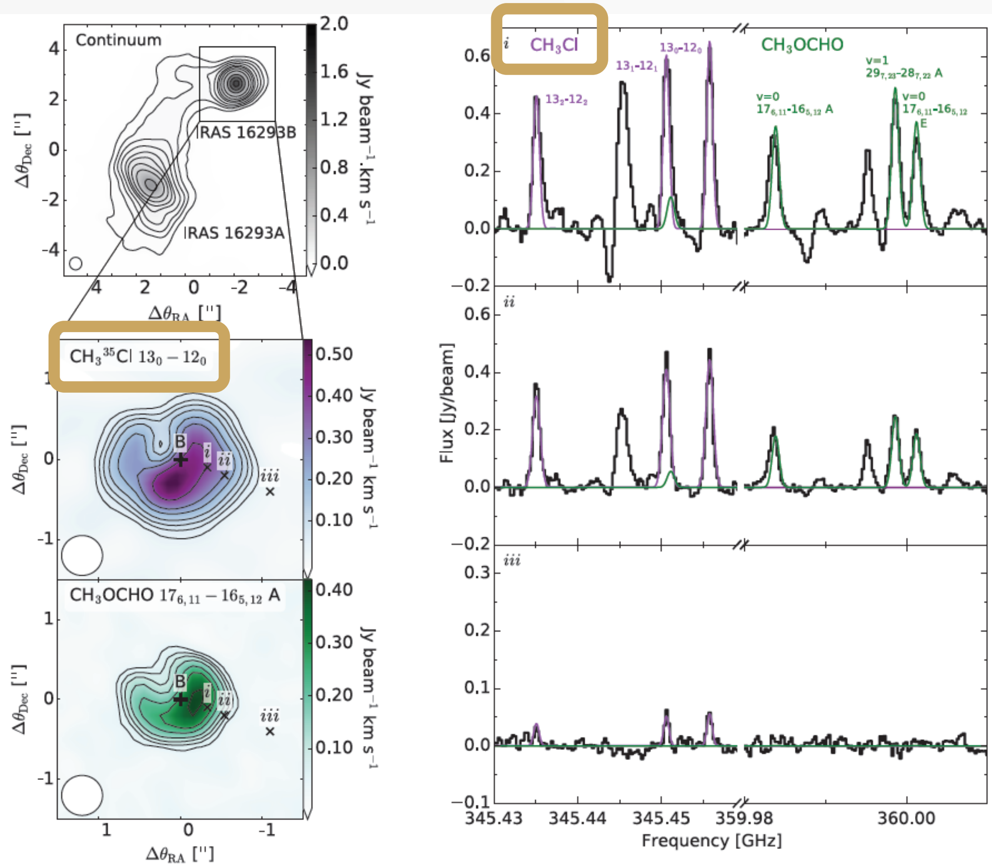


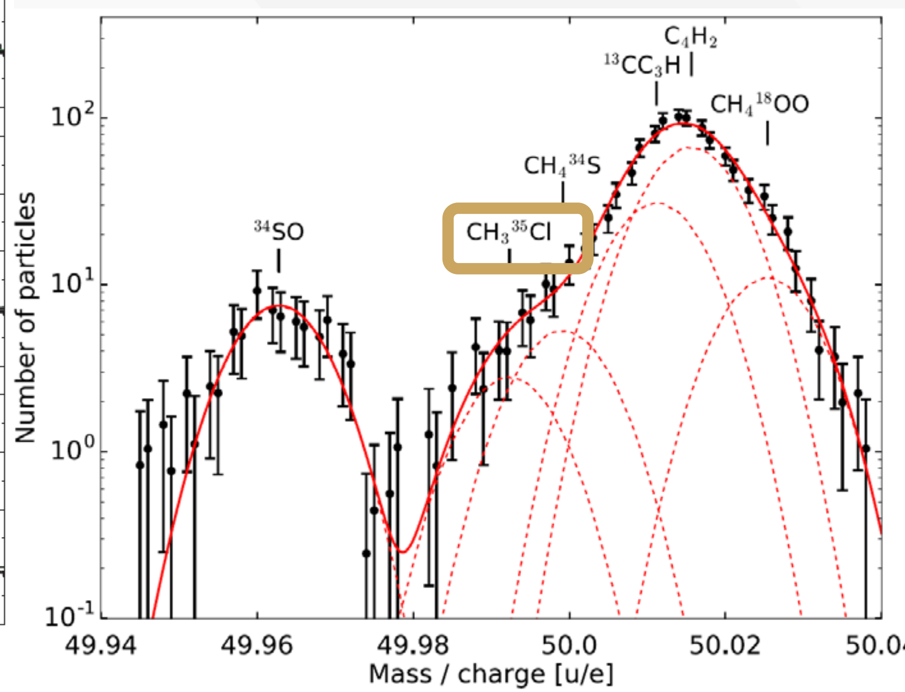
How do IRAS16293-2422B & 67P/C-G compare?

Chloromethane: CH_3Cl

No longer a biomarker….

Fayolle+ 2017, Science Astronomy





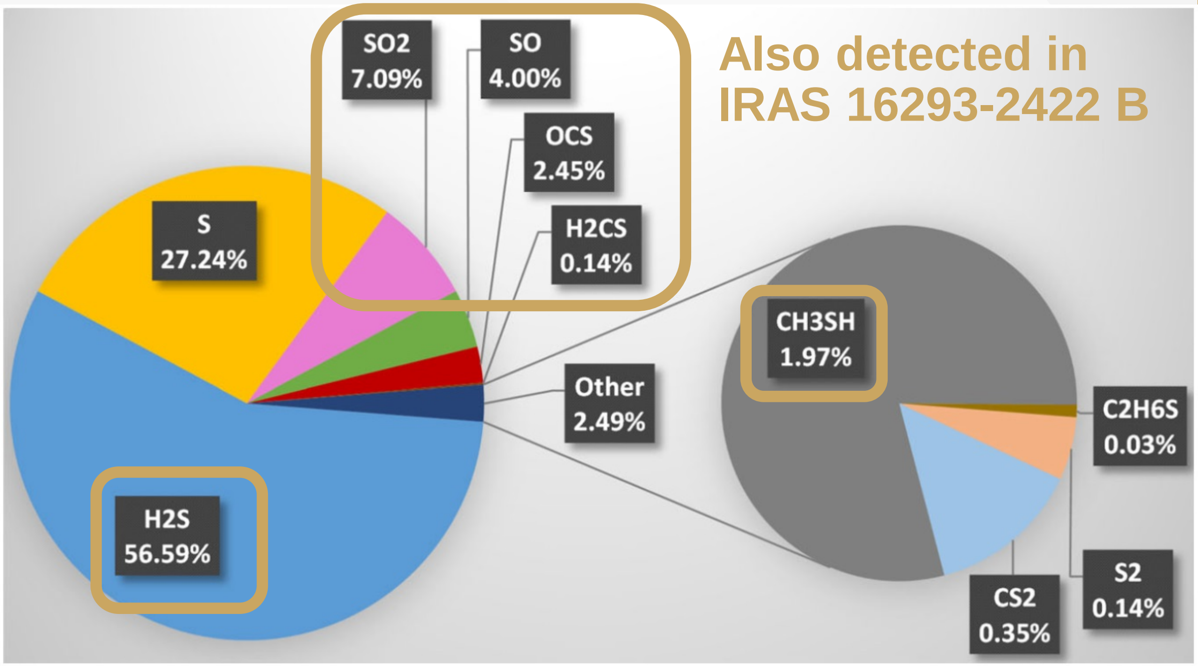
Relative to CH_3OH: IRAS 16293-2422 B: $\sim(0.9 - 1.1) \times 10^{-4}$

67P/C-G: $\sim(0.007 - 6) \times 10^{-4}$

On 67P/C-G:

only ~20% of S is in volatiles!

~80% is in refractories



Also detected in IRAS 16293-2422 B

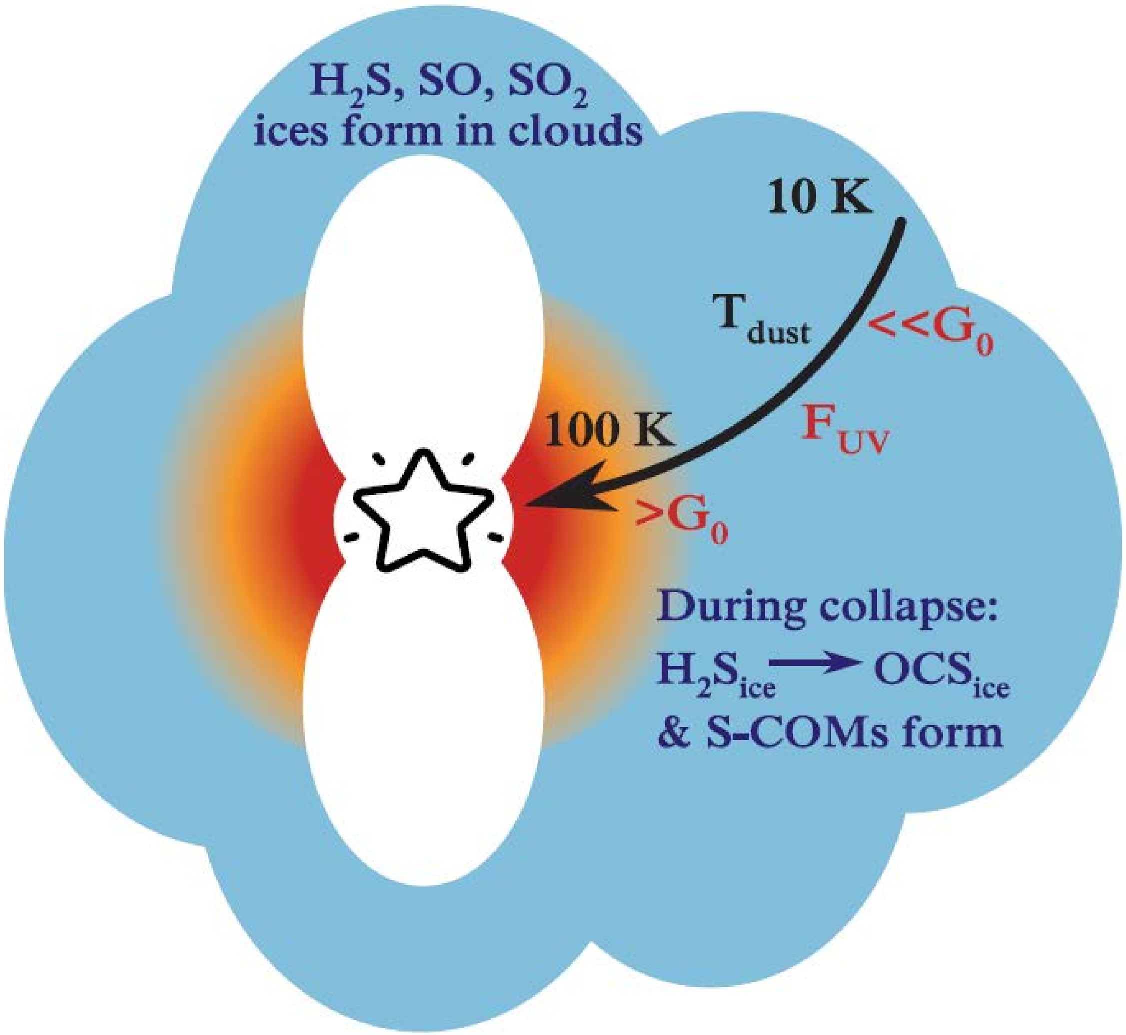
S-volatiles

- much more OCS than H_2S for IRAS 16292-2422 B than on 67P/C–G
- SO/SO_2 ratios agree
- CH_3SH/H_2CS ratios are comparable; differences of $\times\ (0.7 - 5.3)$

Main S-volatile reservoirs have been observed in IRAS 16293-2422 B.

Ratio	ALMA B	67P/C–G
SO/SO_2	0.33	0.4 – 0.7 (section 4.4 of Calmonte et al. 2016)
CH_3SH/H_2CS	3.7	0.69 – 5.2 (based on values in Table 4)
C_2H_5SH/CH_3SH	$\leqslant 0.33^p$	0.0010 – 0.021 (based on values in Table 4)

Calmonte+ 2016, 2017
Drozdovskaya+ 2018



- Stronger UV irradiation for IRAS 16293-2422 B (correlates with it being a binary)

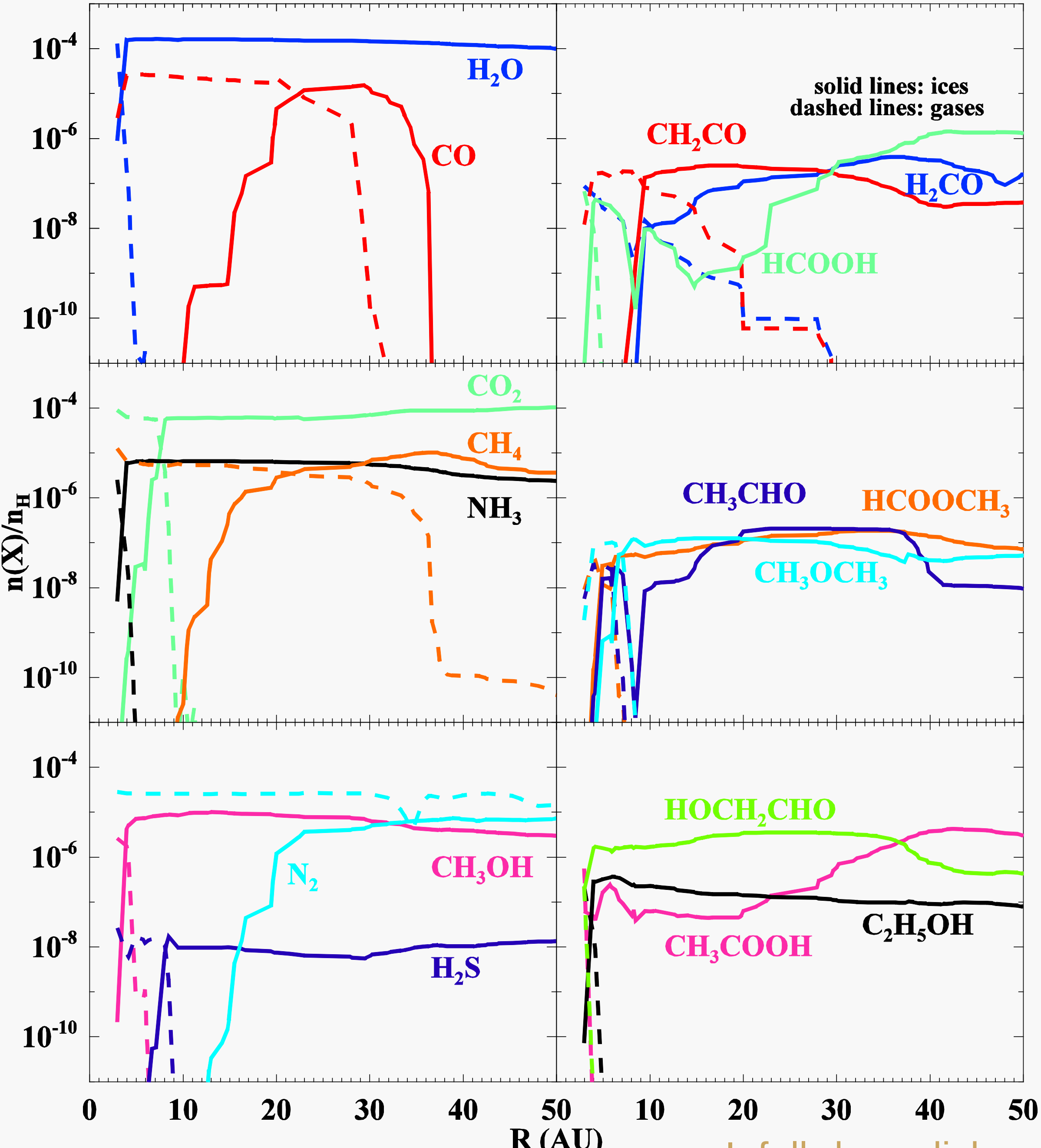
- Warmer birth cloud of the Solar System
(also supported by models of O_2 chemistry; Taquet+2016b)

Drozdovskaya+ 2018

The physics of formation set the chemical provenance!

Interpretation of O- and N-bearing species ongoing…

P-bearing: talk of Víctor Rivilla



Infall-dom. disk; Drozdovskaya+ 2016

Models back this up!

- complex organic ices are on the order of methanol ice (~1% of water ice)
- Comparable to 67P!

(Le Roy+ 2015; Goesmann+ 2015; Altwegg+ 2017b)

- total COMs ~10% of icy mantle
- transport enhances the abundance of complex organic molecules in protoplanetary disks

Key messages

- At least partial prestellar origins for the content of our protosolar nebula.
- Other low-mass systems may be analogous.
- Dynamic infall and chemistry en route are non-negligible for the composition of the protoplanetary disk and the planetesimals therein.

The seeds to life are available on comets, but the roots are already implanted in the pre- and protostellar phases.

Merci vilmal!