# Ingredients for Solar-like Systems

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PlanetS

UNIVERSITÄT BERN

CSH
CENTER FOR SPACE AND HABITABILITY

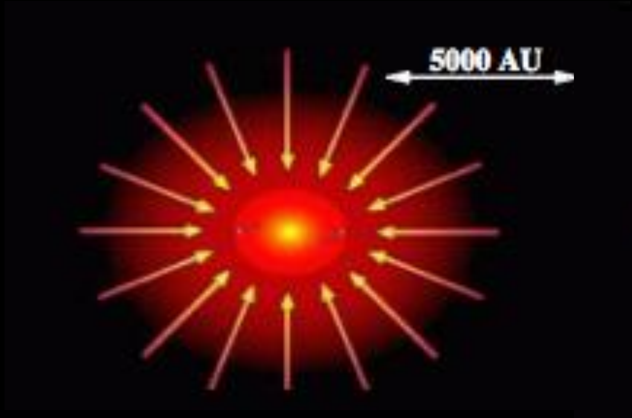
# How to make our Solar System?

**1.** Prepare all raw ingredients

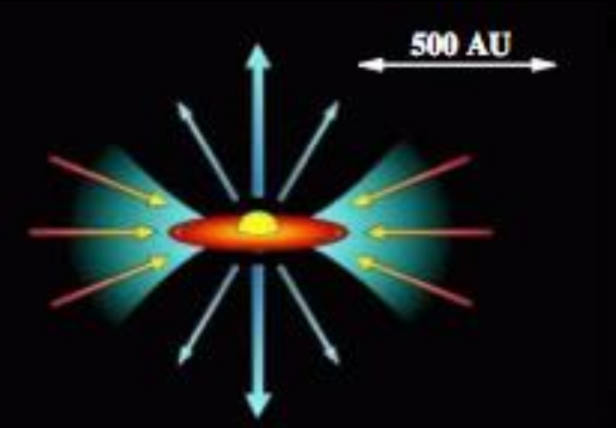
**2.** Process these ingredients

**3.** Assemble individual components

**4.** Arrange the final product




Prestellar

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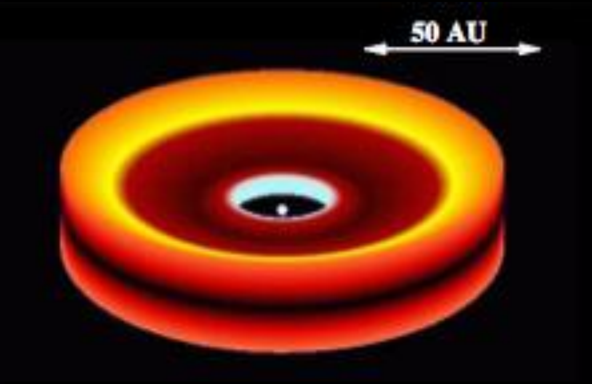
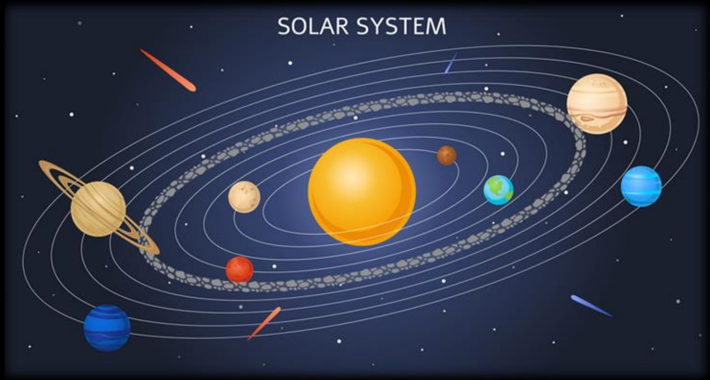



T Tauri



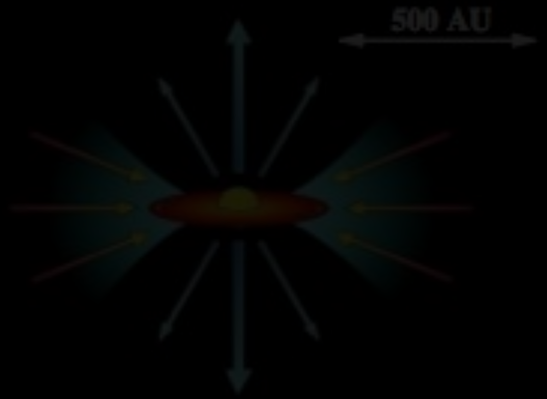

Mature

# What were the raw ingredients for our Solar System?

- ❖ Investigate the left-over mess: meteorites, asteroids, trojans, centaurs, comets
- ❖ Look at what the neighbors are doing: Solar-like systems still in their earlier phases of formation

*In this talk, I will focus on the* ***volatiles*** *(gas & ice), not refractories (dust & rock)*


Prestellar

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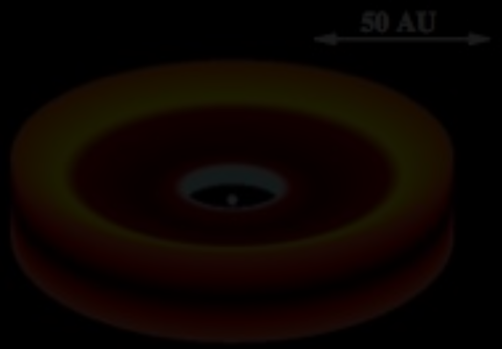
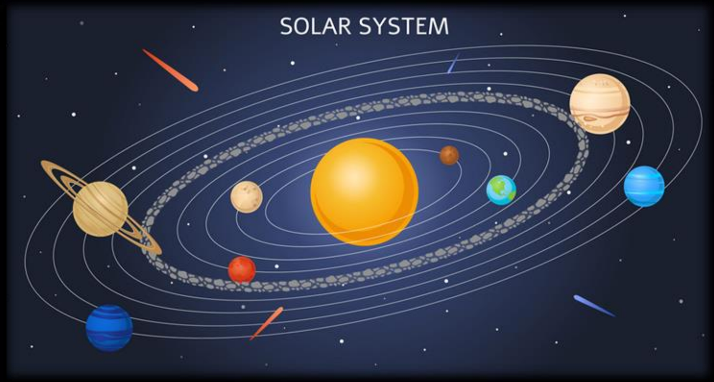



T Tauri

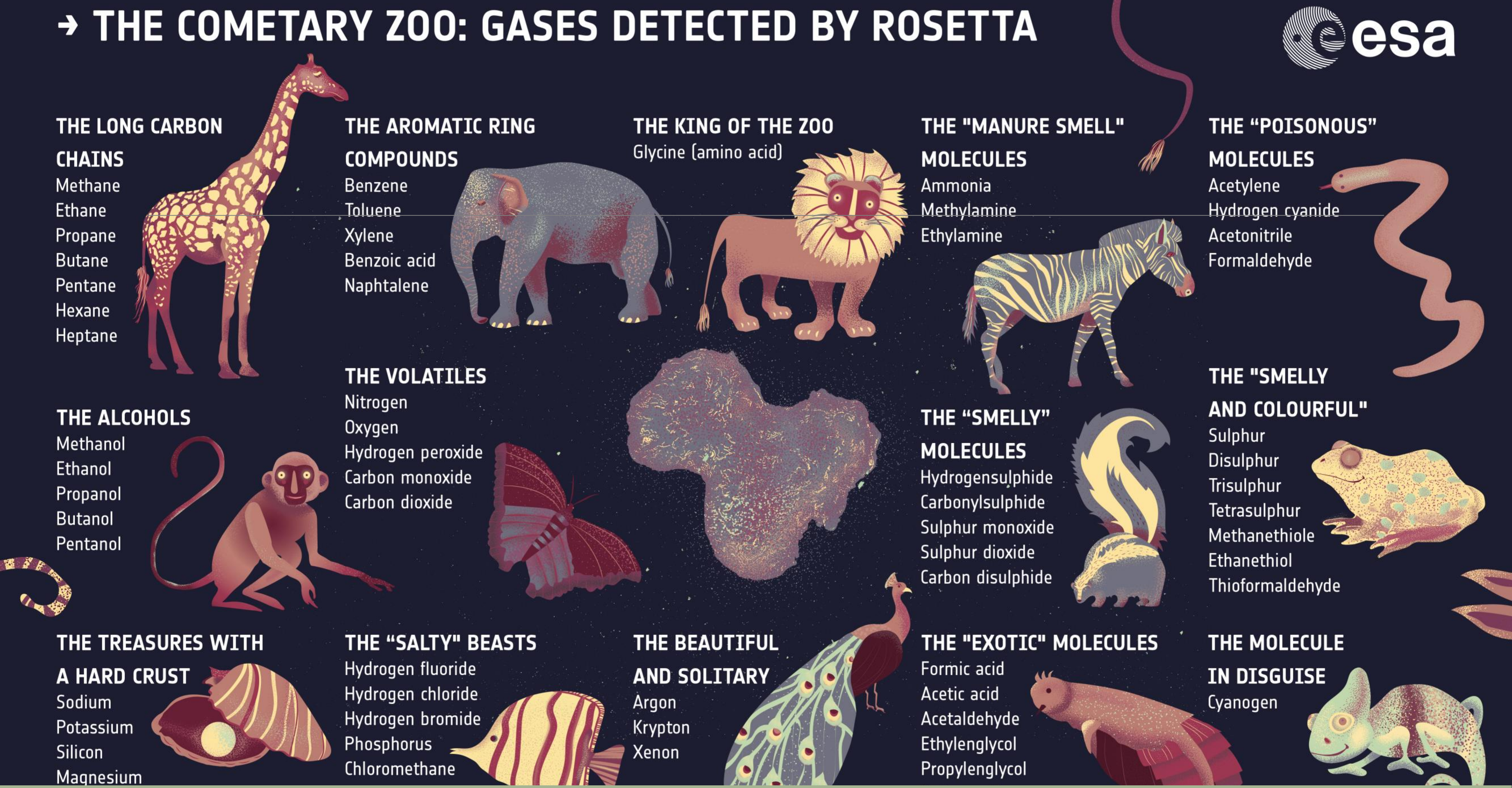


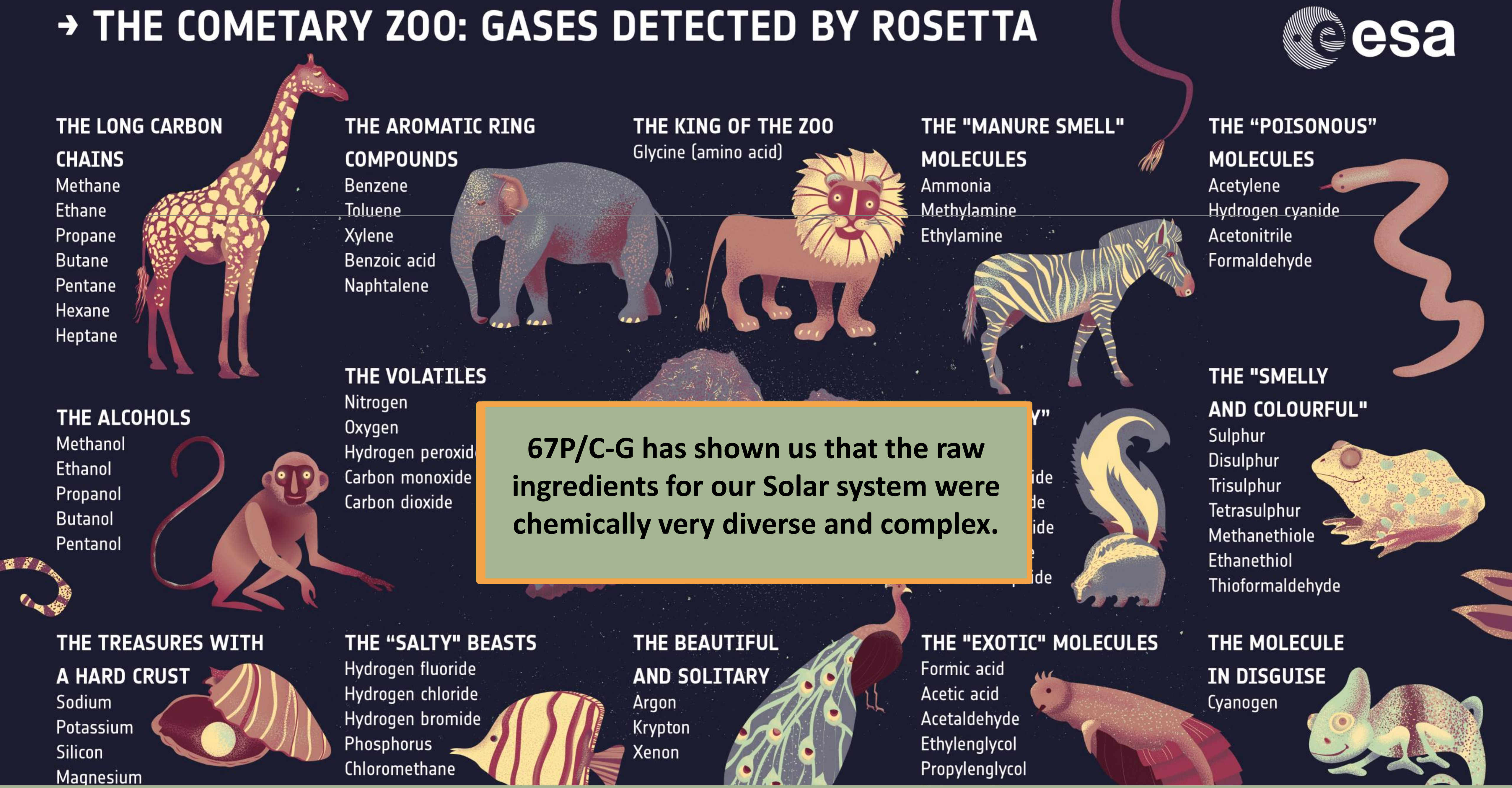

Mature

# Cometary ices

- Most pristine left-overs of the proto-Solar disk volatiles (based on disk dynamics)
- Have large reservoirs of volatiles (=> tails)
- Have long-been observed to have a large variety of volatile molecules

ESA *Rosetta* Mission to comet 67P/C-G


→ THE COMETARY ZOO: GASES DETECTED BY ROSETTA
esa
THE LONG CARBON CHAINS
Methane
Ethane
Propane
Butane
Pentane
Hexane
Heptane
THE AROMATIC RING COMPOUNDS
Benzene
Toluene
Xylene
Benzoic acid
Naphtalene
THE KING OF THE ZOO
Glycine (amino acid)
THE "MANURE SMELL" MOLECULES
Ammonia
Methylamine
Ethylamine
THE "POISONOUS" MOLECULES
Acetylene
Hydrogen cyanide
Acetonitrile
Formaldehyde
THE ALCOHOLS
Methanol
Ethanol
Propanol
Butanol
Pentanol
THE VOLATILES
Nitrogen
Oxygen
Hydrogen peroxide
Carbon monoxide
Carbon dioxide
THE "SMELLY" MOLECULES
Hydrogensulphide
Carbonylsulphide
Sulphur monoxide
Sulphur dioxide
Carbon disulphide
THE "SMELLY AND COLOURFUL"
Sulphur
Disulphur
Trisulphur
Tetrasulphur
Methanethiole
Ethanethiol
Thioformaldehyde
THE TREASURES WITH A HARD CRUST
Sodium
Potassium
Silicon
Magnesium
THE "SALTY" BEASTS
Hydrogen fluoride
Hydrogen chloride
Hydrogen bromide
Phosphorus
Chloromethane
THE BEAUTIFUL AND SOLITARY
Argon
Krypton
Xenon
THE "EXOTIC" MOLECULES
Formic acid
Acetic acid
Acetaldehyde
Ethylenglycol
Propylenglycol
THE MOLECULE IN DISGUISE
Cyanogen




**67P/C-G has shown us that the raw ingredients for our Solar system were chemically very diverse and complex.**

# Interior of 67P/C-G seems to be pristine

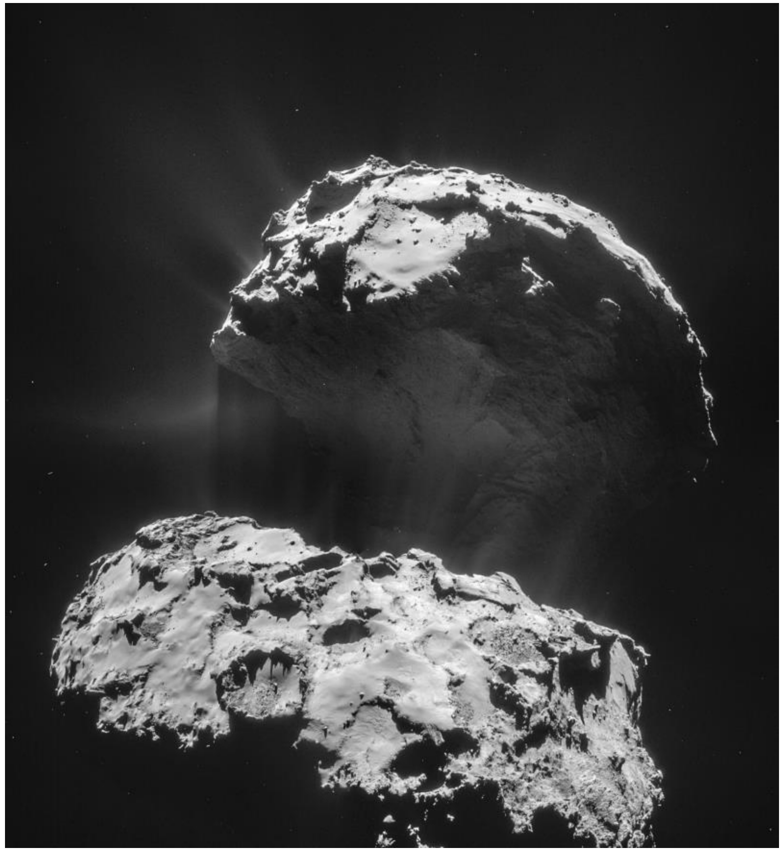


Figure: ESA/Rosetta/NAVCAM

- Homogeneous nucleus: CONSERT & RSI (Kofman et al. 2015, Pätzold et al. 2016)
- A perihelion passage at 1.2 au from the Sun only heats the most outer few tens of cm: MIRO & models (Schloerb et al. 2015; Capria et al. 2017)
- Very high ratio of 17 for $D_2O/HDO$ relative to $HDO/H_2O$ in comparison to the statistically expected value of 0.25 (Altwegg et al. 2017a)
- Highly volatile species (CO, $N_2$, noble gases) abundant (Rubin et al. 2018)
- **Bulk**: averages of DFMS measurements obtained between the 22$^{nd}$ of May and the 2$^{nd}$ of June, 2015: suff. hot (within 2 au), but before strong dust pollution (Rubin et al. 2019a)
- May 2015: summer for the Southern hemisphere, which is thought to be less covered by resettled dust (Keller et al. 2017)

# What is an us-like neighbor doing?

# IRAS 16293-2422 B is Solar-like

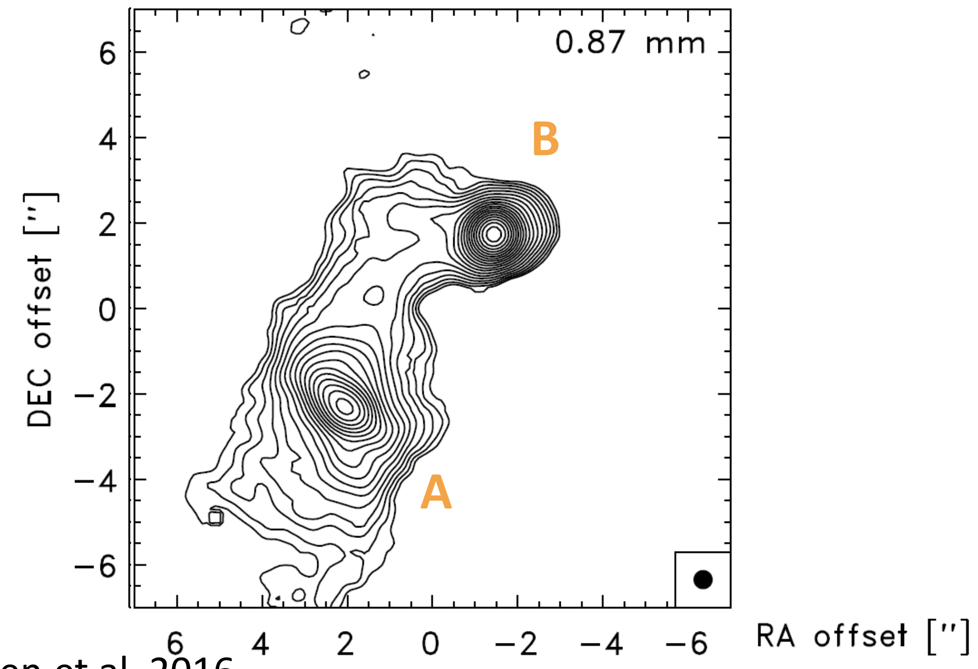



Figure: Jørgensen et al. 2016

Photo: Tomas Munita for The New York Times


- Deeply embedded binary system at 141 pc with a projected separation of 5.3″ (747 au; Dzib et al. 2018)
- A: 1.0 $M_\odot$, 18 $L_\odot$; B: 0.1 $M_\odot$, 3 $L_\odot$; envelope: 4 $M_\odot$ (Jacobsen et al. 2018b)
- Disk A is nearly edge-on, disk B is face-on (Pineda et al. 2012; Zapata et al. 2013; Liu et al. 2018; Sadavoy et al. 2018)
- Disk B: dust $R \sim 30 - 56$ au
  gas (OCS, $H_2CS$, $CH_3OH$, $HCOOCH_3$) $R \sim 30 - 50$ au
  (Rodríguez et al. 2005; Zapata et al. 2013; Oya et al. 2018)
- Velocity gradient of disk B shallower than of A (Zapata et al. 2013; Girart et al. 2014)
- Relative ages inconclusive: signatures of infall and chemical differentiation
  (Chandler et al. 2005; Zapata et al. 2013; Calcutt et al. 2018b; Rivilla et al. 2019; van der Wiel et al. 2019)

# The protostellar petting farm: gases detected with ALMA

**IRAS 16293-2422 B has shown us that Solar-like systems in the early embedded phase of formation are also chemically diverse and complex.** *(to a lesser extent than comets?)*

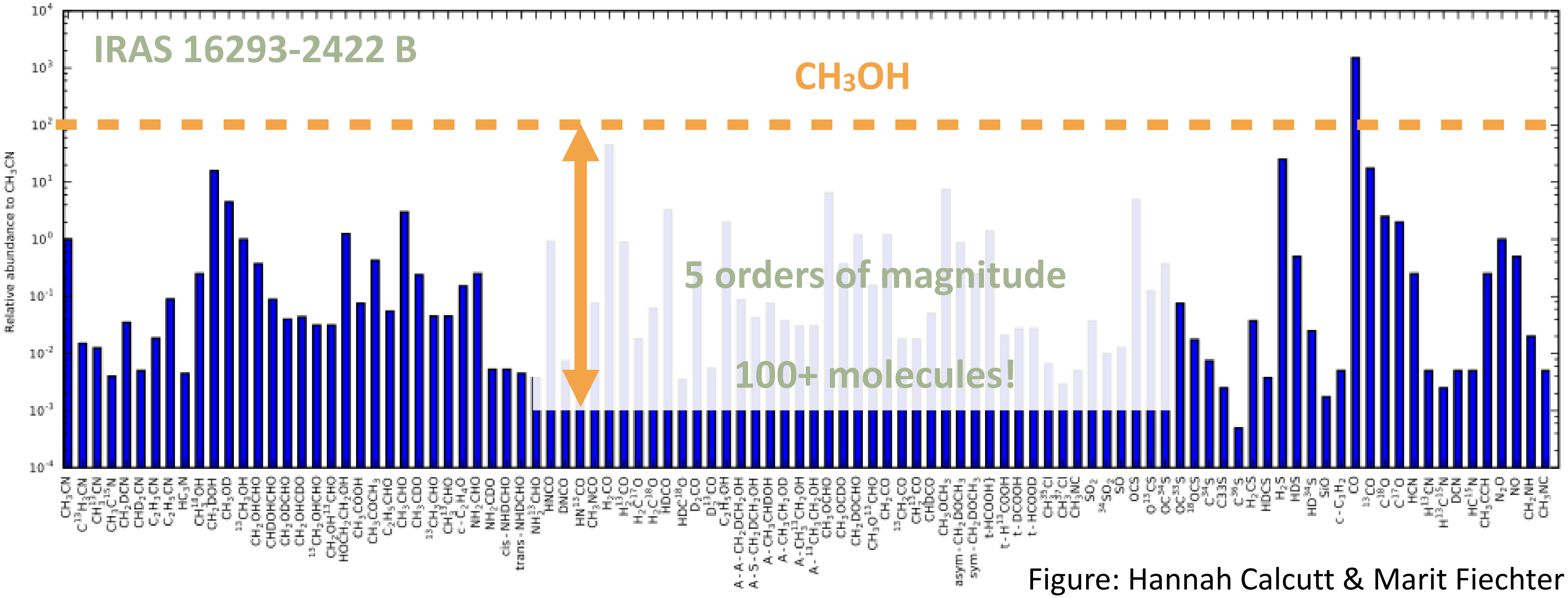
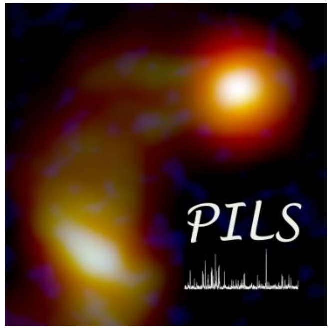



Figure: Hannah Calcutt & Marit Fiechter & Jes Jørgensen

# Powerful synergy: PILS & ROSINA

- Unbiased Protostellar Interferometric Line Survey (PI: Jes Jørgensen) ALMA: $329 - 363$ GHz (Band 7)
- Most complete spectral characterization of a low-mass protostar on (almost) identical spatial scales
- High spectral resolution: 0.2 km $s^{-1}$ (0.244 MHz)
- Restored with a uniform circular 0.5'' beam
  12-m dishes+ACA: LAS 13''
- At 0.5'' (70 au) from the source, the observations probe thermally desorbed material entering the protoplanetary disk

Jørgensen et al. 2016, 2018; Coutens et al. 2016; Lykke et al. 2017; Ligterink et al. 2017; Calcutt et al. 2018b; Drozdovskaya et al. 2018; Manigand et al. 2019 and more



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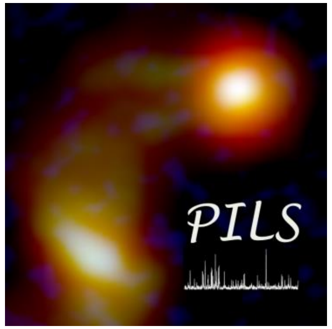
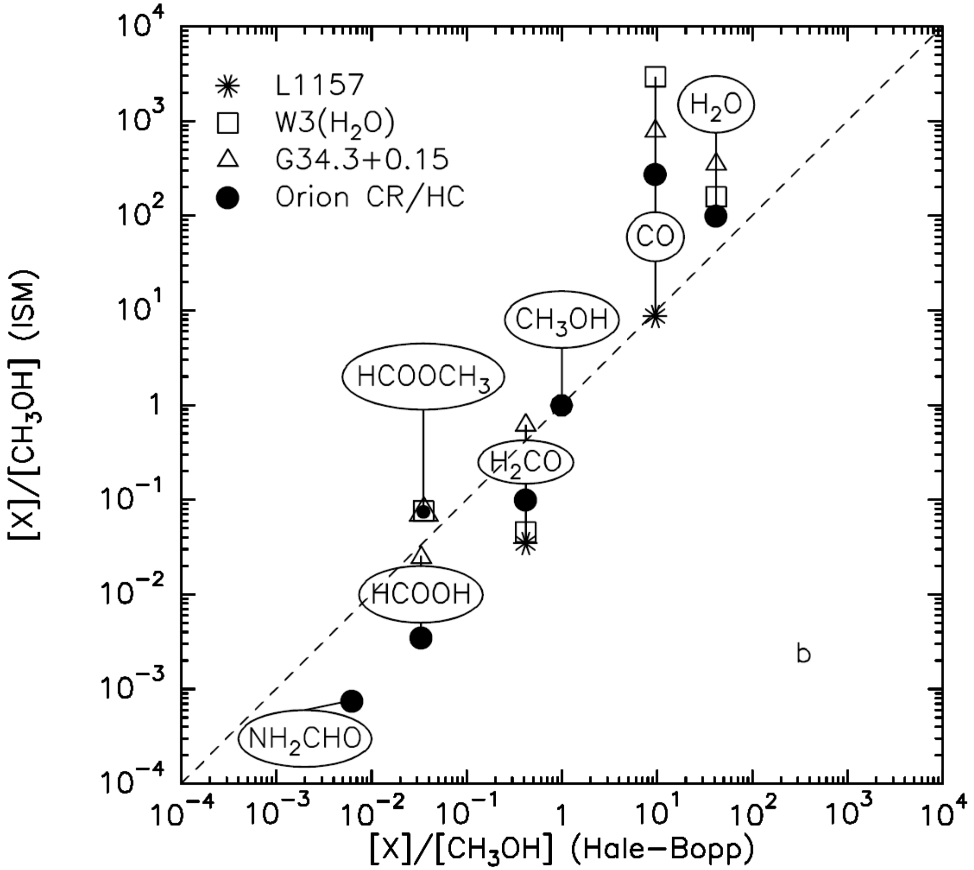
- Double Focusing Mass Spectrometer (DFMS): high mass resolution ($m/\Delta m = 3000$ on mass/charge of 28 u/e at the 1% peak height)
- Reflection-type Time-of-flight (RTOF) mass spectrometer: wide mass range ($1 - 1000$ u/e)
- Unambiguous identification of small and large molecules with in situ measurements (Balsiger et al. 2007)

Jørgensen et al. 2016, 2018; Coutens et al. 2016; Lykke et al. 2017; Ligterink et al. 2017; Calcutt et al. 2018b; Drozdovskaya et al. 2018; Manigand et al. 2019 and more




Le Roy et al. 2015; Calmonte et al. 2016; Gasc et al. 2017; Altwegg et al. 2017a, 2017b, 2019; Rubin et al. 2018, 2019; Schuhmann et al. 2019 and more

# CHO-bearing Molecules




Bockelée-Morvan et al. 2000

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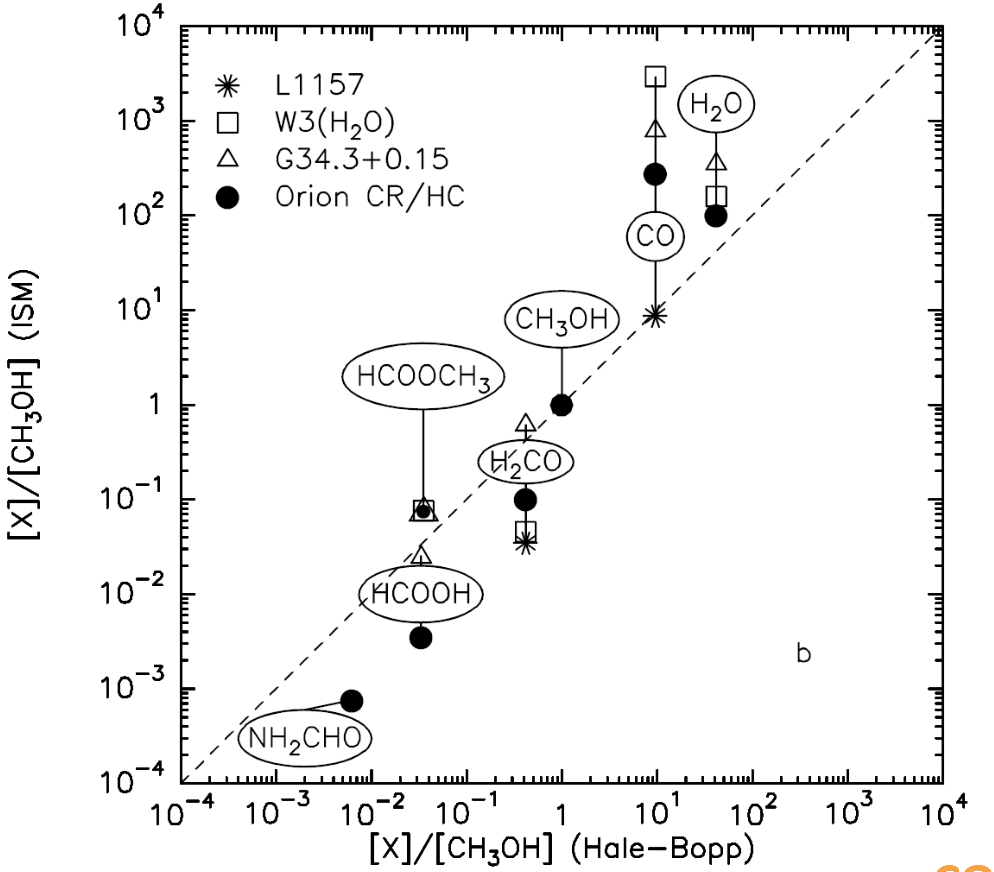
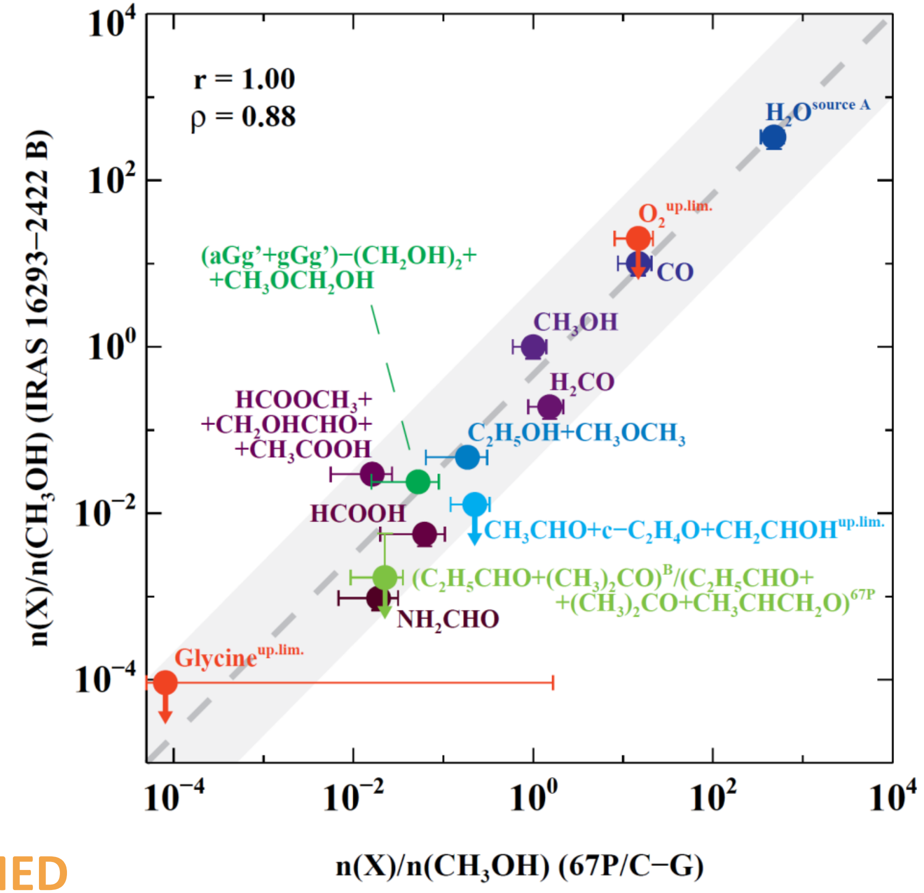


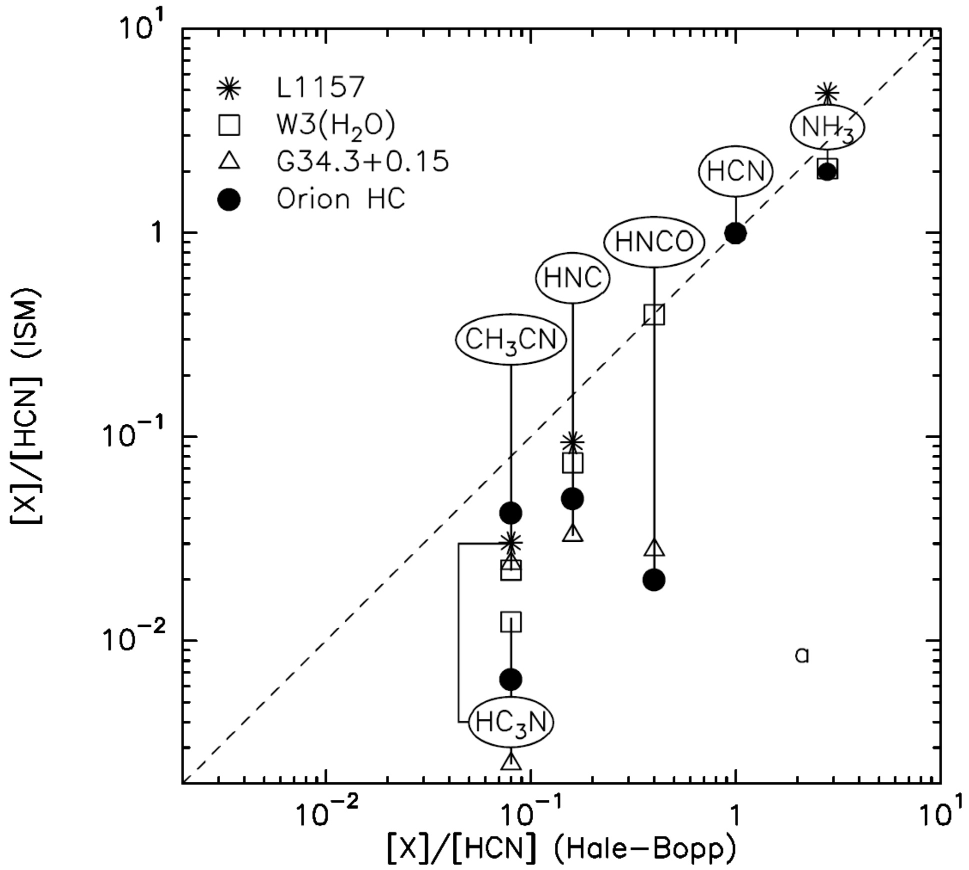

Bockelée-Morvan et al. 2000

CONFIRMED




Drozdovskaya et al. 2019

# N-bearing Molecules




Bockelée-Morvan et al. 2000

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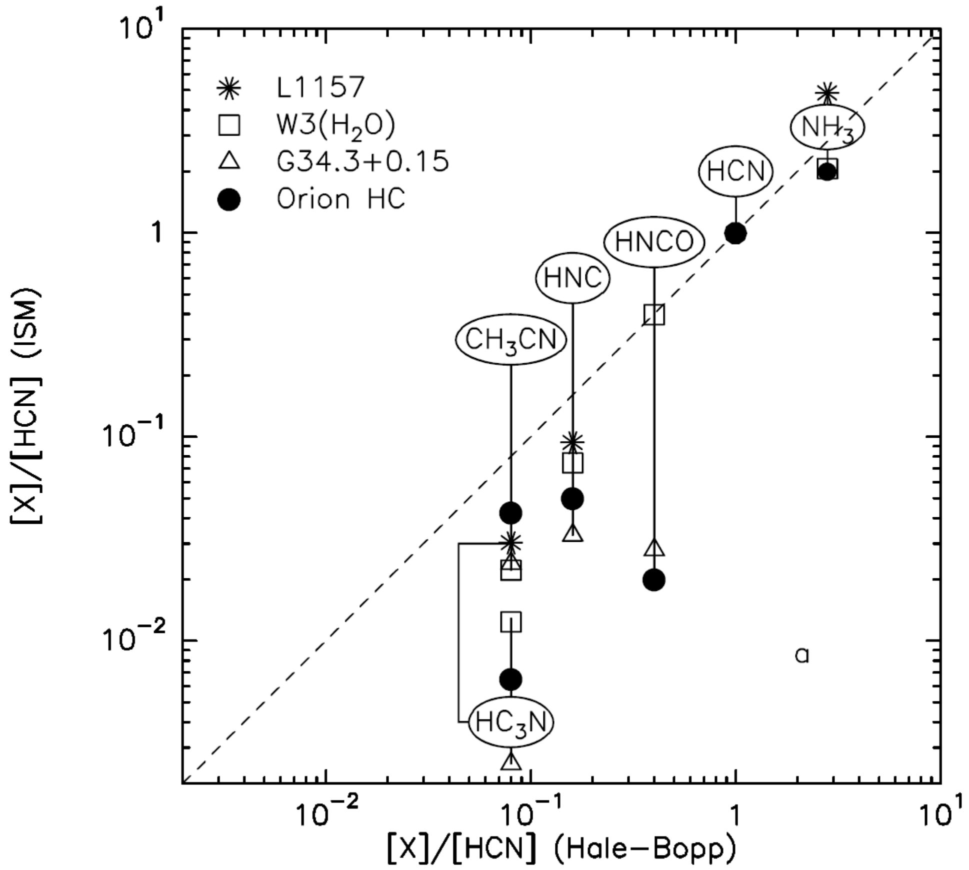
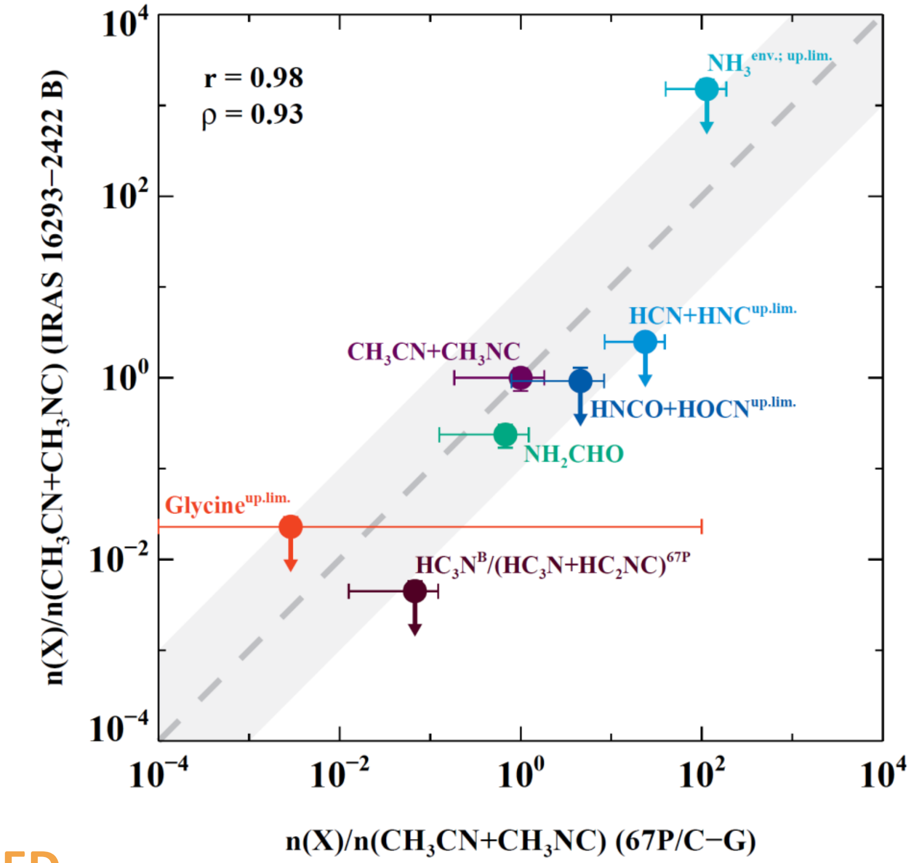


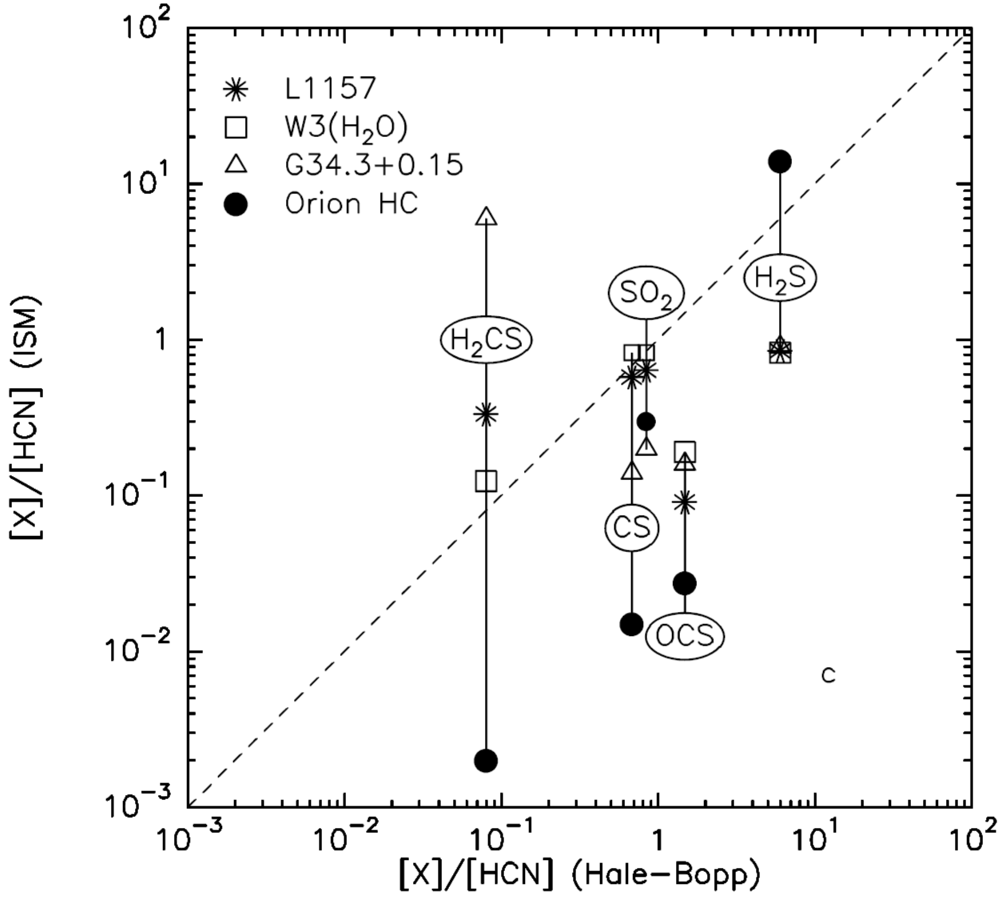




CONFIRMED

Bockelée-Morvan et al. 2000

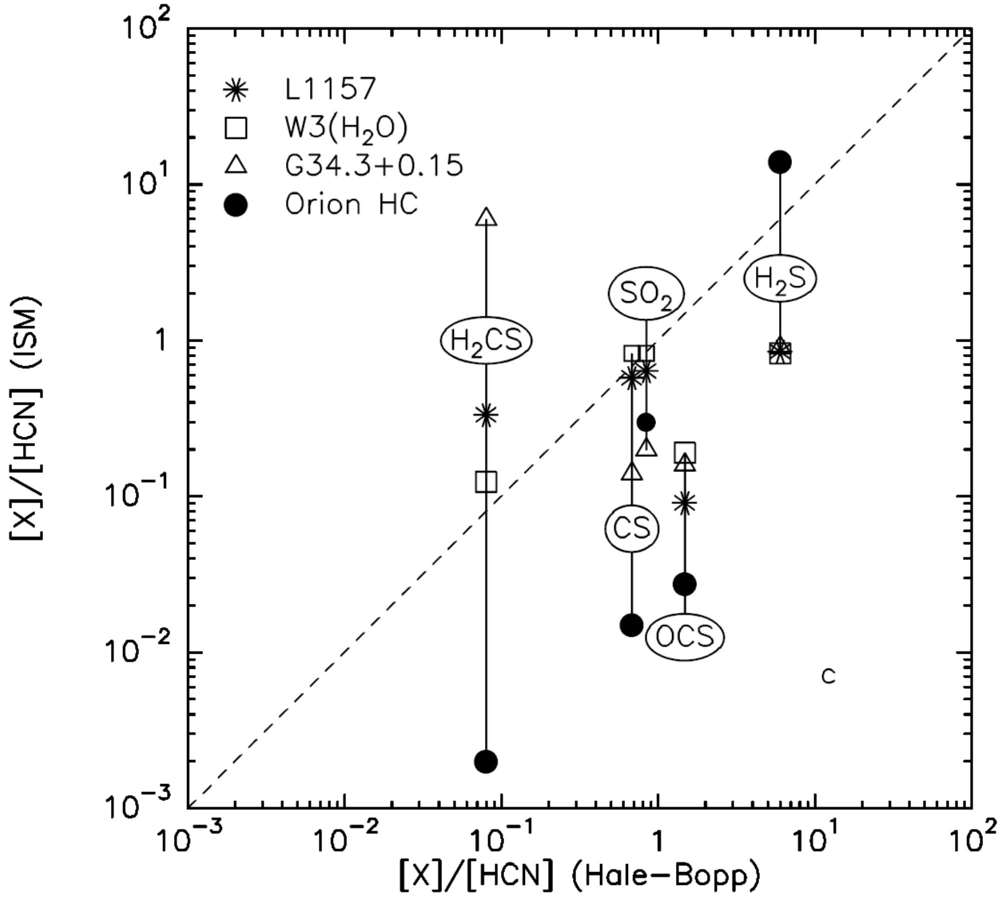
Drozdovskaya et al. 2019

# S-bearing molecules

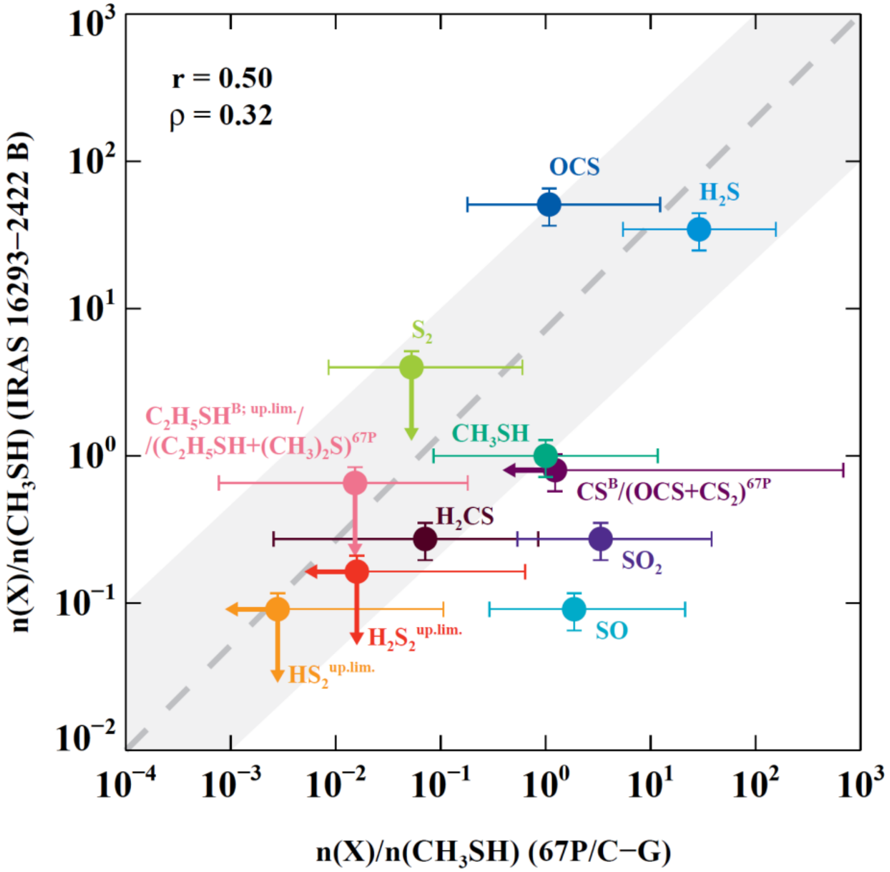



Bockelée-Morvan et al. 2000

# S-bearing molecules



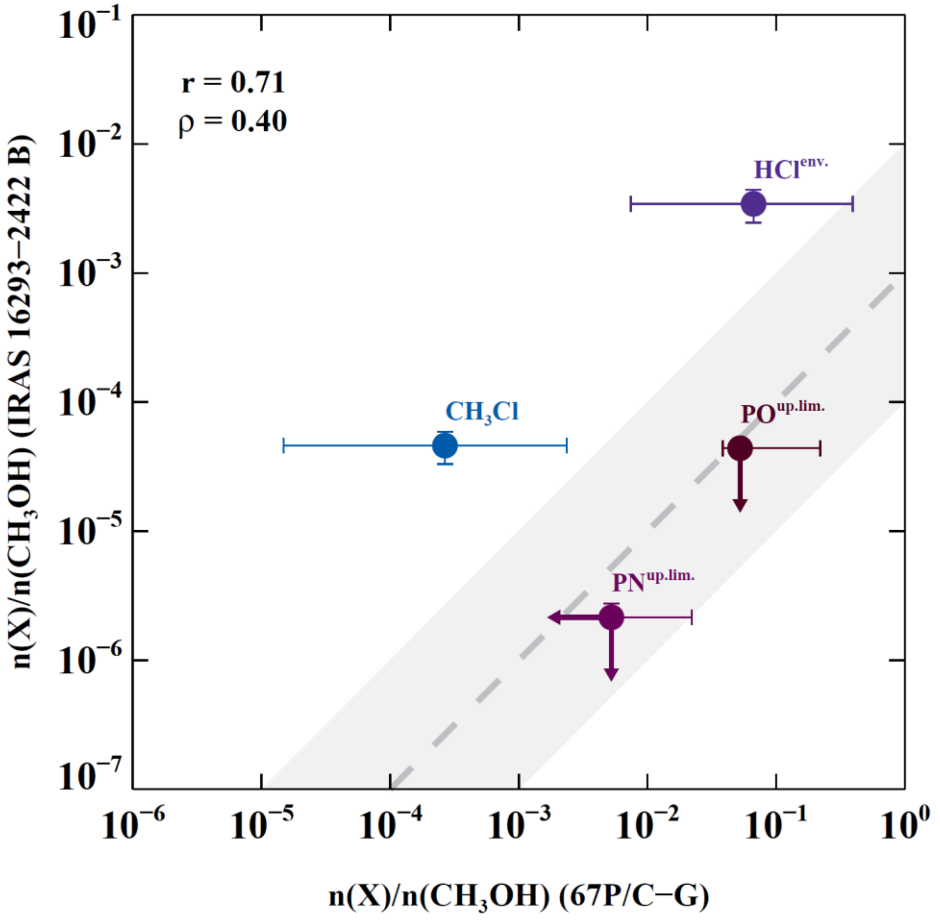

Bockelée-Morvan et al. 2000




**NEWLY ESTABLISHED**

Drozdovskaya et al. 2019

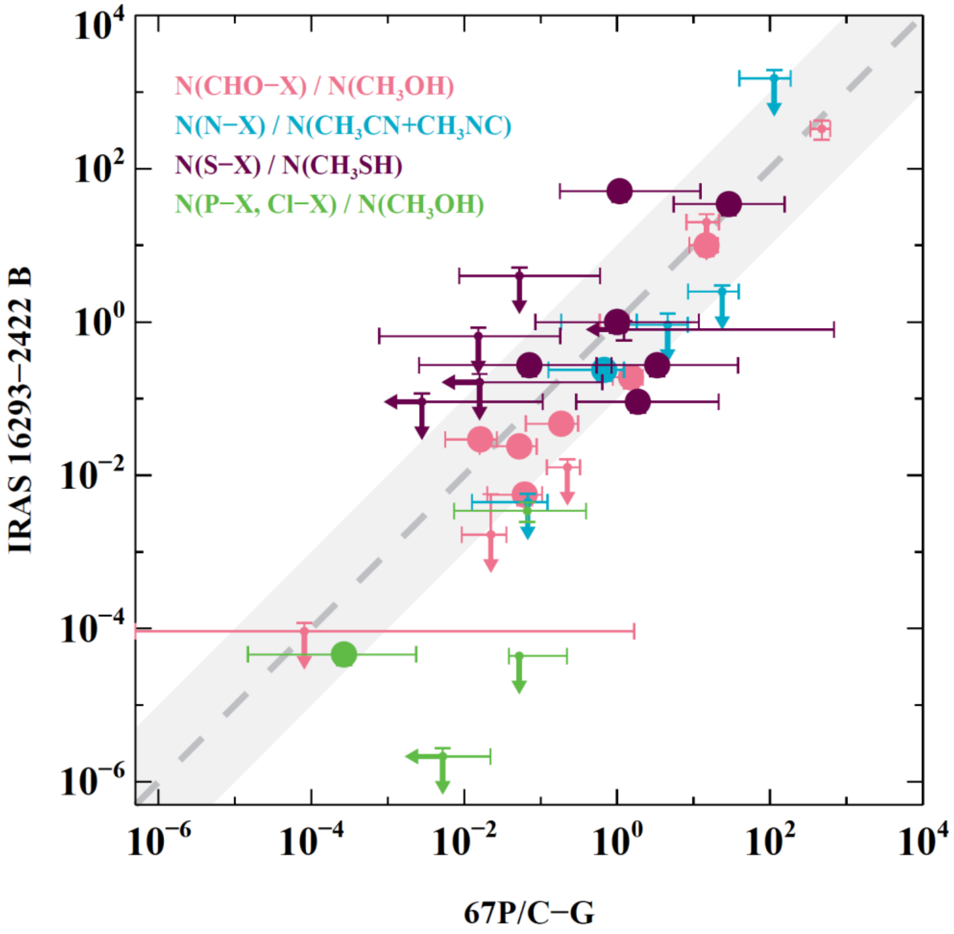
# P- and Cl-bearing Molecules




**NEVER BEFORE PROBED**

Drozdovskaya et al. 2019

# Protostellar & Cometary Correlations



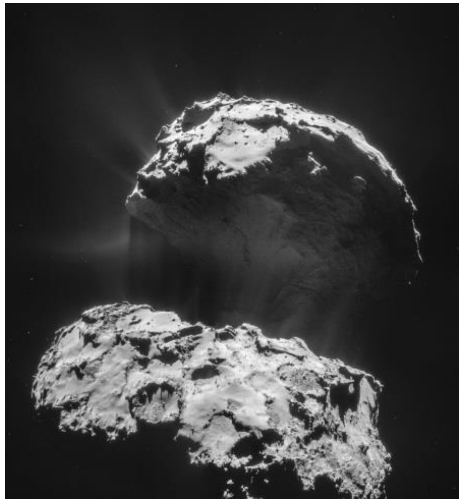

- CHO-, N-, S-, P- and Cl-bearing volatiles correlate between protostar IRAS 16293-2422 B and comet 67P/C–G, with some scatter
- Cometary relative abundances tend to be higher than protostellar for CHO- and N-bearing species:
  - Are volatile molecules destroyed near the protostar before entry into the protoplanetary disk?
  - Have more been produced by the time of incorporation into the comet?
  - Could it stem solely from variations in the reference molecules ($CH_3OH$ and $CH_3CN$)?

→ **Some chemical alteration occurs!**

Drozdovskaya et al. 2019

# As far as we know, not atypical

- Bilobate shape similar to 103P/Hartley 2 (A'Hearn 2011) and trans-Neptunian object (486958) 2014 MU69 (Stern et al. 2019)
- Topographically heterogeneous surface of 67P/C–G dominated by smooth-floored pits appears to be most similar to 81P/Wild 2 (Birch et al. 2017)
- Dominant volatile is water ice hidden in the interior and almost completely absent from the surface: typical of comets (Filacchione et al. 2016a) [at least pre-$2^{nd}$ equinox]
- Low-density and high porosity ($72 - 74\%$) of the nucleus is comparable to 9P/Tempel 1 (Pätzold et al. 2016)
- Coma tenuous in comparison to brightest comets (Hale–Bopp's production rates x100 higher; Altwegg et al. 2019)
- Chemical richness: consequence of superior measurement techniques (long-term monitoring at close distances + high sensitivity); e.g.: ethylene glycol and formamide on C/2012 F6 (Lemmon) and C/2013 R1 (Lovejoy), as well as ethanol and glycolaldehyde in the latter target (Biver et al. 2014, 2015)
- Volatile composition: no major differences from that seen in other comets (Cochran et al. 2015; Dello Russo et al. 2016)



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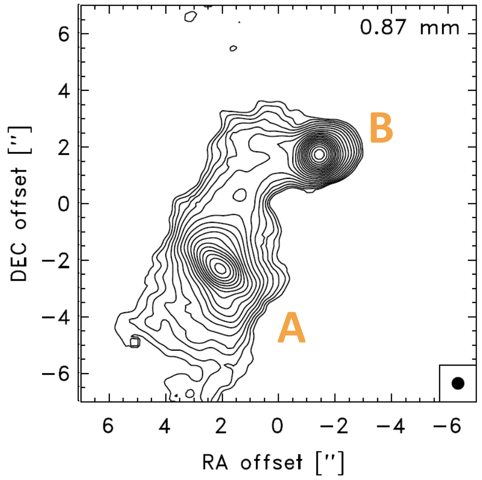
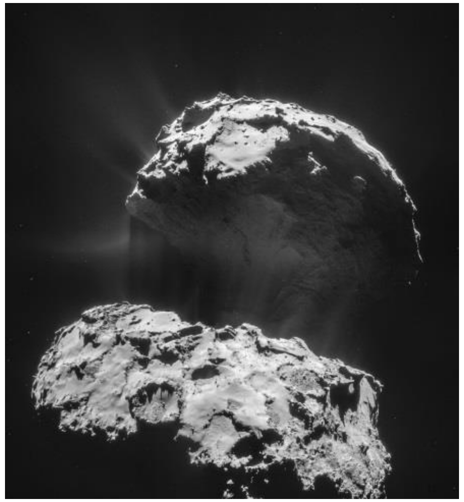
- Volatile composition: no major differences from that seen in other comets (Cochran et al. 2015; Dello Russo et al. 2016)
- No firm support for IRAS 16293-2422 being in any way a unique young stellar object in terms of the chemical abundances and diversity
(Jørgensen, Schöier & van Dishoeck 2004; Taquet et al. 2015)
- Complex organic molecule abundances of L483 as observed with ALMA compare well to those of IRAS 16293-2422 B
(Jacobsen et al. 2018a)
- Physical structure: nothing out of the ordinary within the large morphological diversity that is seen in star-forming regions
- Binarity/Multiplicity is common

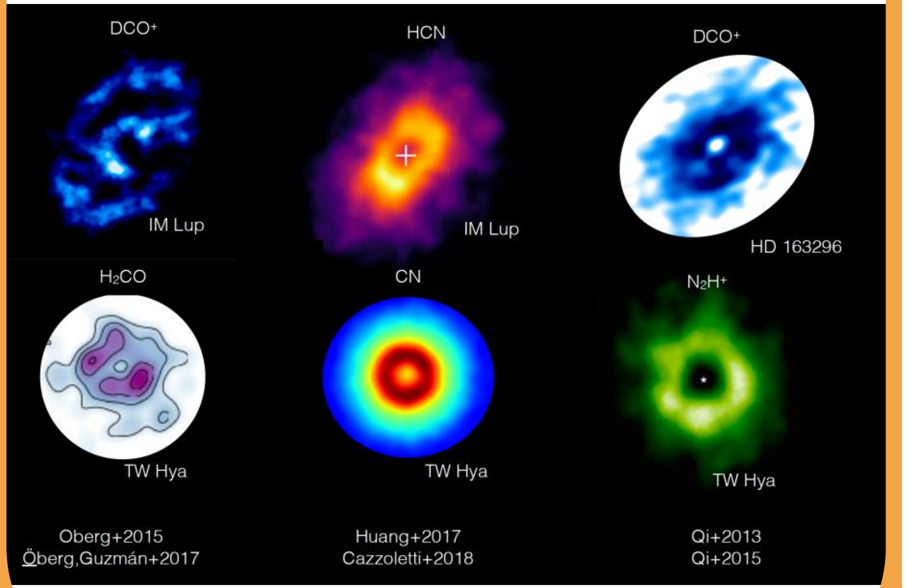


Figures: Jørgensen et al. 2016 & ESA/Rosetta/NAVCAM

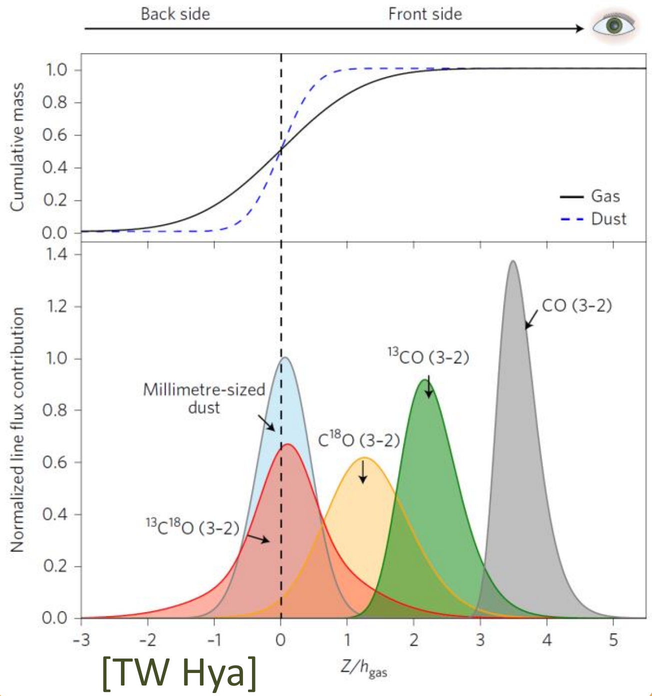
# Why not compare with protoplanetary disk gases directly?

## NON-TRIVIAL RADIAL MORPHOLOGY ON SMALL SCALES




Huang et al. 2018; van Terwisga et al. 2019a & more

## VERTICAL STRUCTURE RESOLVED ONLY WITH ISOTOPOLOGUES




[TW Hya]
Ke Zhang et al. 2017

## LOW ABUNDANCES (esp. of COMs)

**Mini-(no-)methanol survey**

| Source | Stellar mass | Spectral type | Age | Distance | Value |
|---|---|---|---|---|---|
| | [T Tauri] | | | | Det. |
| TW Hya | 0.8 $M_\odot$ | K6 | ~ 3 -10 Myr | 59 pc | 2 x $10^{12}$ cm$^{-2}$ |
| V4046 Sgr | 2 x 0.9 $M_\odot$ | K5 + K7 | ~ 12 Myr | 73 pc | 5 x $10^{12}$ cm$^{-2}$ |
| | | | | | Tent det. |
| LkCa 15 | 1 $M_\odot$ | K3-K5 | ~ 2 Myr | 140 pc | < 9 x $10^{12}$ cm$^{-2}$ |
| IM Lup | ~ 1 $M_\odot$ | M0 | ~ 1 Myr | 161 pc | < 1 x $10^{13}$ cm$^{-2}$ |
| | [Herbig Ae] | | | | |
| MWC 480 | 1.7-2.3 $M_\odot$ | A4 | ~ 7 Myr | 142 pc | < 8 x $10^{12}$ cm$^{-2}$ |
| HD 163296 | 2.3 $M_\odot$ | A1 | ~ 4 Myr | 122 pc | < 5 x $10^{11}$ cm$^{-2}$ |

Kastner et al., 2018; Carney et al., 2019; Booth et al., subm.; Ilee et al. in prep.; Loomis et al., subm.; Loomis et al. in prep.

# Chemical inventory of protoplanetary disk gases

**Protoplanetary disks (Class II) are poor in complex organic gases, but are likely rich in complex organic ices in the midplane.**

## NOT THAT MANY MOLECULES DETECTED THUS FAR

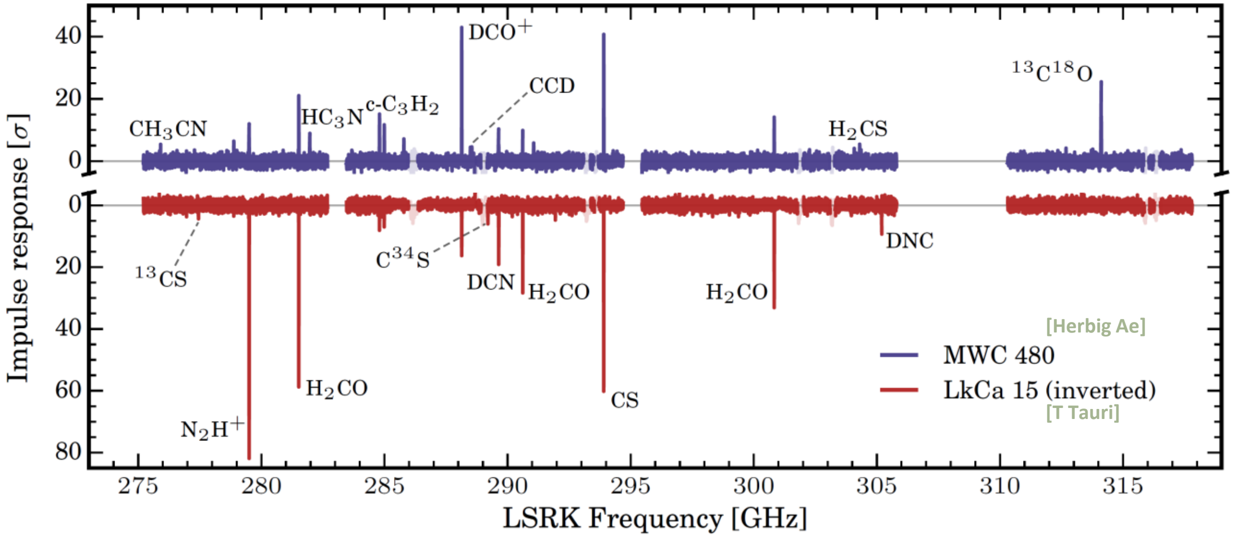
### H/C/O-BEARING
$CO$, $^{13}CO$, $C^{18}O$, $^{13}C^{18}O$
$HCO^+$, $DCO^+$, $H^{13}CO^+$
$C_2H$
$H_2O$
HD
C-$C_3H_2$
$H_2CO$

### N-BEARING
CN, $C^{15}N$
HCN, DCN, $H^{13}CN$, $HC^{15}N$
HNC
$N_2H^+$, $N_2D^+$
$NH_3$
$HC_3N$

### S-BEARING
CS, $^{13}CS$, $C^{34}S$
SO
$H_2S$
$H_2CS$

### COMPLEX ORGANICS
$CH_3CN$
$CH_3OH$
t-HCOOH

## COHERENT CHEMICAL SURVEYS JUST STARTING




Loomis et al. subm.
V4046 Sgr: Karstner et al. 2018

# Conclusions

- CHO-, N- and S-bearing volatiles correlate between disk-materials of protostar IRAS 16293-2422 B and comet 67P/C–G (relative to $CH_3OH$, $CH_3CN$, and $CH_3SH$) with some scatter
  - P- and Cl-bearing volatiles correlate tentatively (relative to $CH_3OH$)
- Cometary relative abundances tend to be higher than protostellar for CHO- and N-bearing species
- **Solar-like systems and our Solar System are formed from raw prestellar ingredients that are partially modified during protostellar collapse and (likely) within the protoplanetary disk**

**The next big thing?**

- Deeper and higher spatial resolution **ALMA** observations
- Compare directly with ices based on **JWST** data (only possible for most-abundant volatiles)
  - Mid-Infrared Instrument (MIRI) European Consortium (EC) "Protostars Survey" Guaranteed Time Observations (GTO) program, PI: Ewine van Dishoeck
  - "IceAge: Chemical Evolution of Ices during Star Formation" Director's Discretionary Early Release Science (DDERS) program, McClure et al. 2018)
- ESA **Comet Interceptor** mission