Astrochemical Recipes for Solar-like Systems

MARIA DROZDOVSKAYA
SNSF AMBIZIONE FELLOW

NCCR PlanetS GA 8; 26 April 2022

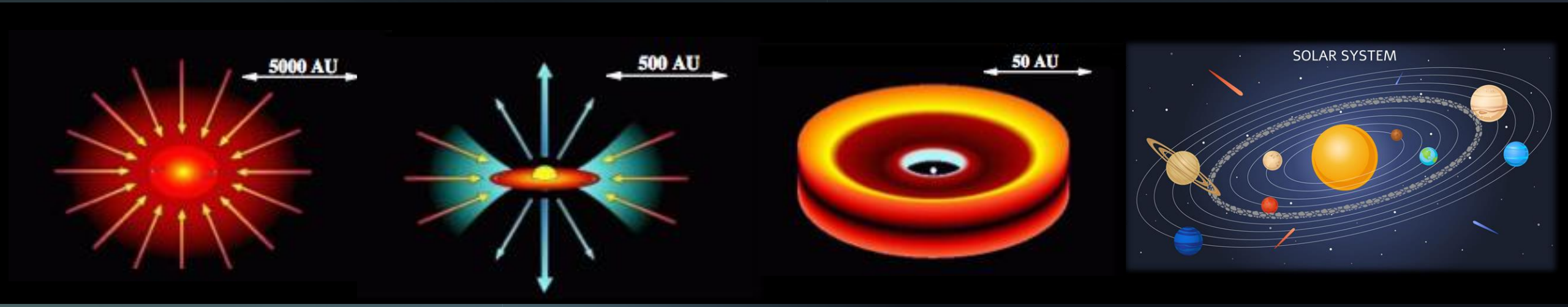
How to make our Solar System?

1. Prepare all raw ingredients

2. Process these ingredients

3. Assemble individual components

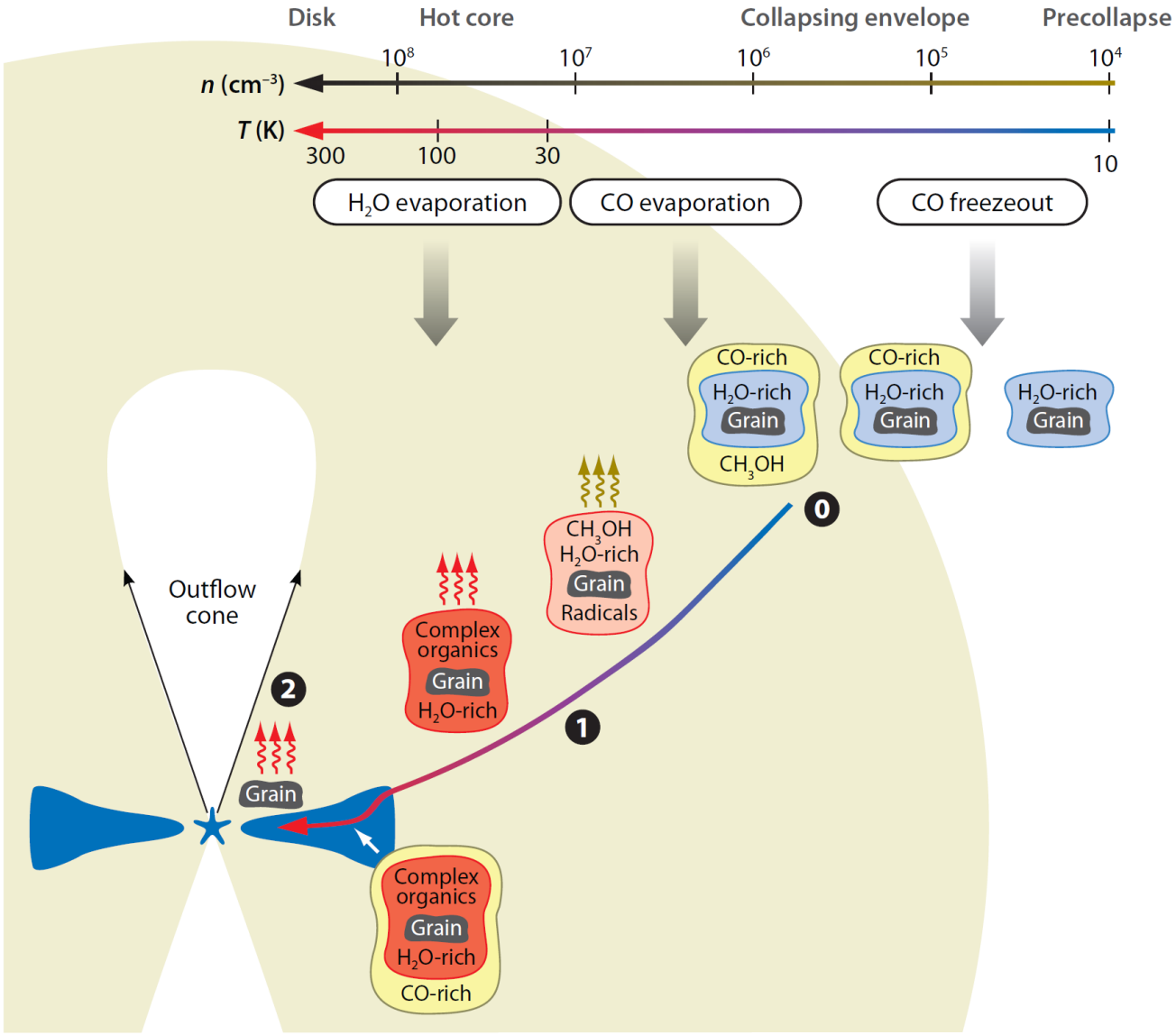
4. Arrange the final product



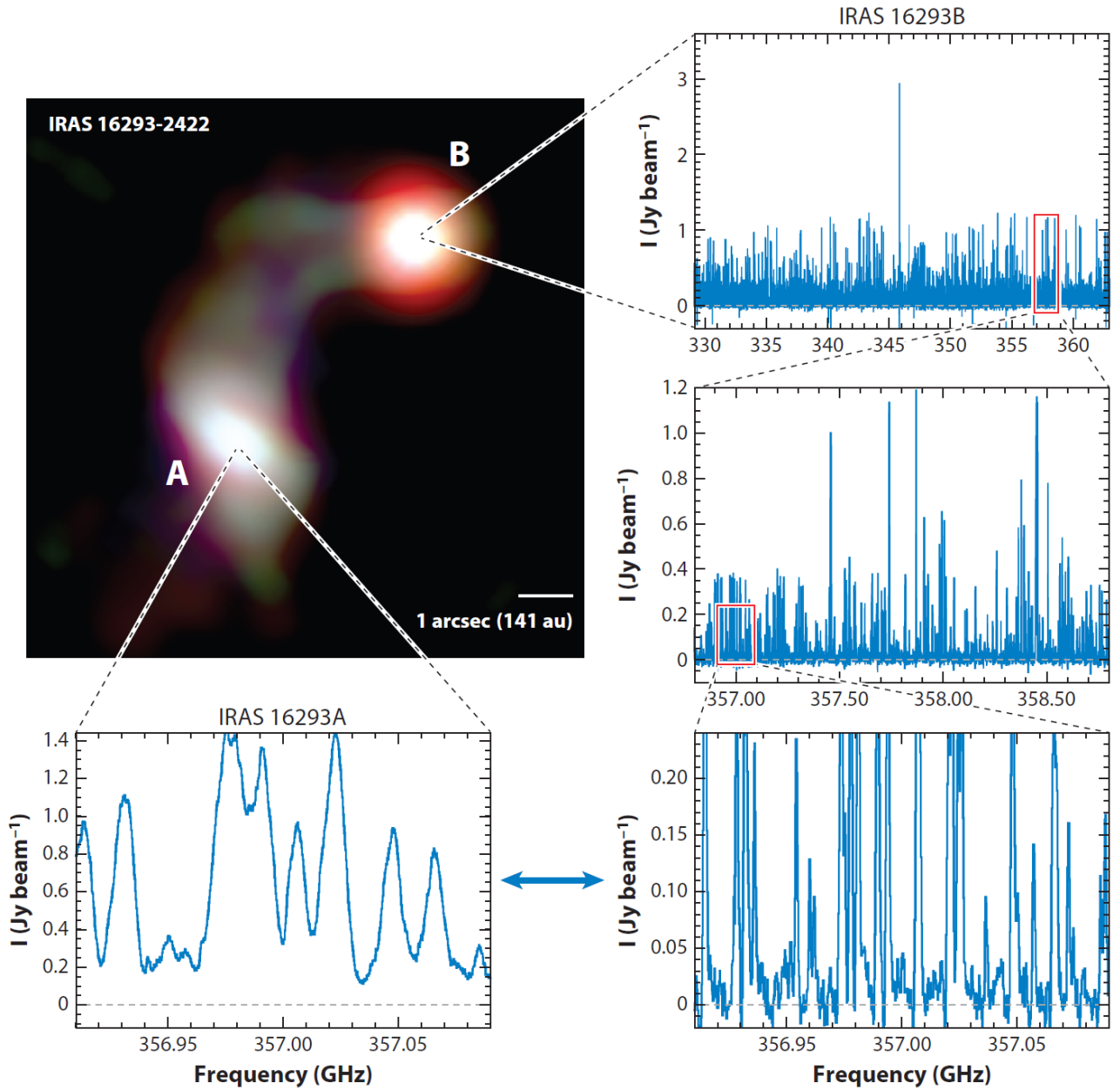
Prestellar **Embedded** **T Tauri** **Mature**

Chemistry in gas and ice from cores to disks

- First water-rich layers of icy mantles of dust grains are made in molecular clouds
- On top, more volatile species adsorb in prestellar cores
- Non-energetic & energetic processes increase chemical complexity during the prestellar & protostellar stages
- **Molecular abundances and isotopic ratios trace the physical evolution**



Herbst & van Dishoeck 2009



Jørgensen et al. 2016, 2018, **2020**; Coutens et al. 2016, 2018, 2019a; Lykke et al. 2017; Fayolle et al. 2017; Persson et al. 2018; **Drozdovskaya et al. 2018**; Calcutt et al. 2018a, b, 2019; Ligterink et al. 2017, 2018a,b; Murillo et al. 2018; Jacobsen et al. 2018; van der Wiel et al. 2019; van 't Hoff et al. 2020; Manigand et al. 2019, 2020, 2021

Molecules of IRAS 16293-2422

- Key facility for astrochemistry: Atacama Large Millimeter Array (**ALMA**)
- Unbiased Protostellar Interferometric Line Survey (**PILS**; PI: Jes K. Jørgensen) 329 – 363 GHz (Band 7)
- Most complete spectral characterization of a low-mass protostar on (almost) identical spatial scales
- **ALMA's high spatial and spectral resolutions are key!**

https://youngstars.nbi.dk/PILS/

ALMA-PILS: IRAS 16293-2422

Wide spectral coverage allows multi-line observations => well-determined parameters (N, T_{ex})!

High sensitivity allows to probe minor species and isotopologues & constrain τ .

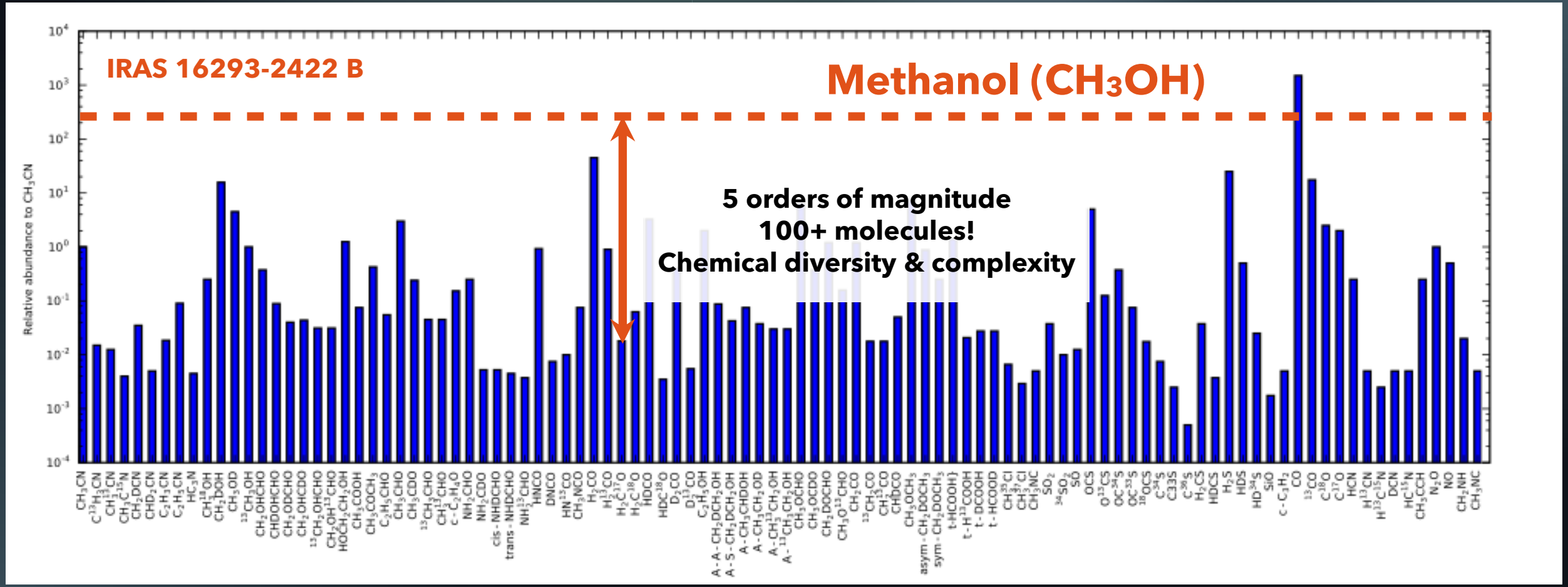
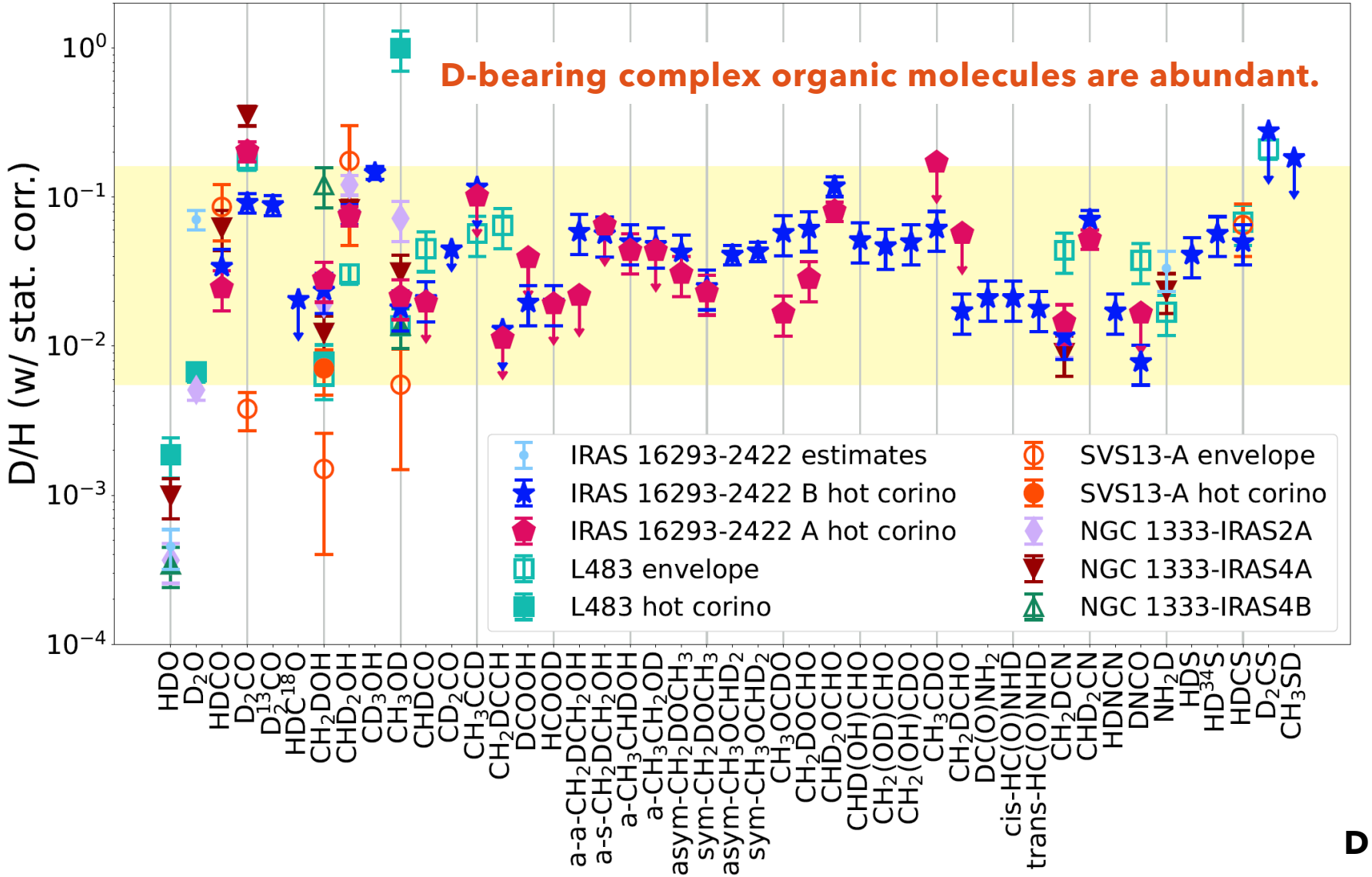
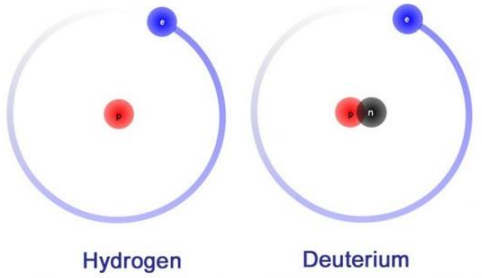


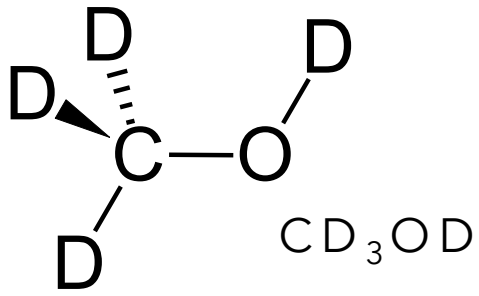
Figure: Hannah Calcutt & Marit Fiechter & Jes Jørgensen

Abundant D-molecules in IRAS 16293-2422



Deuteration is the process of introducing a D into a molecule instead of an H.





Drozdovskaya et al. 2022

Comets are relics

- Most distant residents of our Solar System
- Either steppingstones or by-products of the physical processes of planet formation
- **The presence and abundance of highly volatile molecules supports cometary nuclei suffering little processing in the Solar Nebula.**

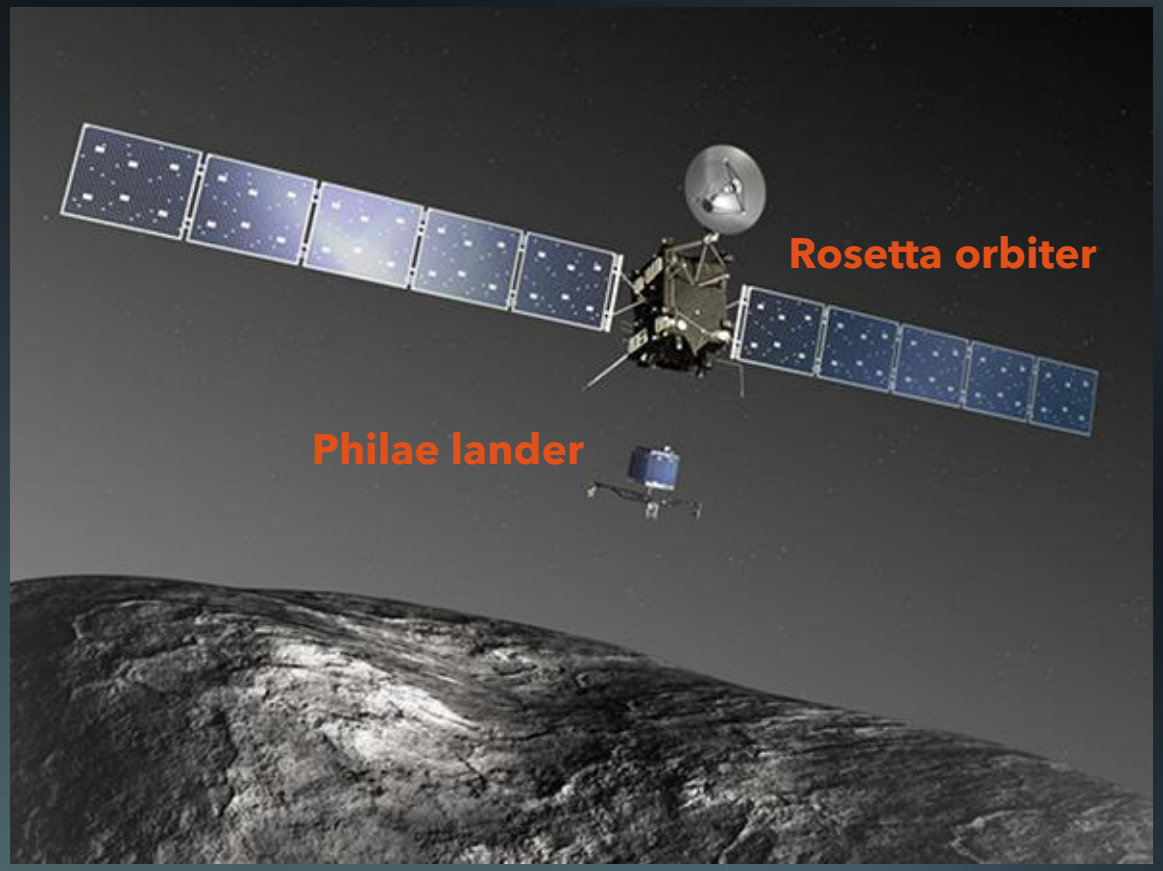
A'Hearn 2011b; Mumma & Charnley 2011; Bockelée-Morvan+ 2015a; Altwegg+ 2019; Rubin et al. 2015a; Bieler et al. 2015b; Rubin+ 2019a

67P/CHURYUMOV-GERASIMENKO

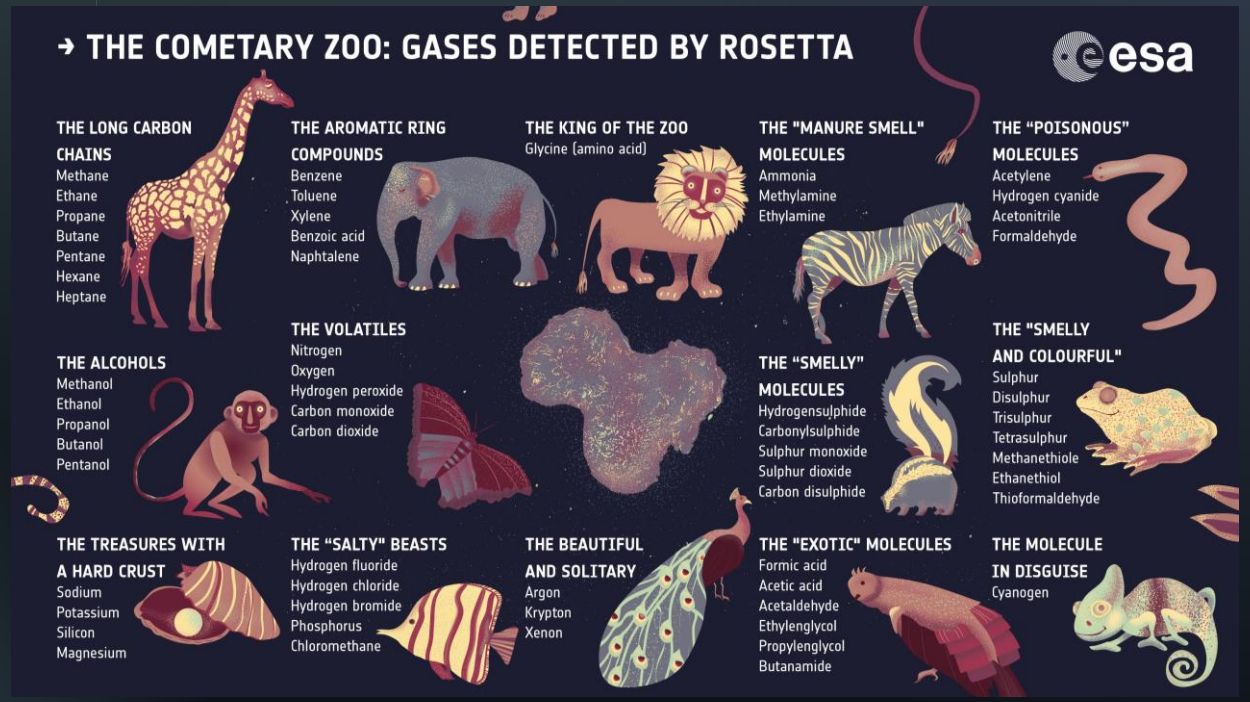
03/02/2015; ESA/Rosetta/NAVCAM, CC BY-SA IGO 3.0

ESA *Rosetta* Mission

Key instrument: *Rosetta* Orbiter Spectrometer for Ion and Neutral Analysis (**ROSINA**; Balsiger et al. 2007)



Le Roy et al. 2015; Calmonte et al. 2016; Gasc et al. 2017; Altwegg et al. 2017a, 2017b, 2019; Rubin et al. 2018, 2019a, 2019b; Schuhmann et al. 2019; **Drozdovskaya et al. 2021**



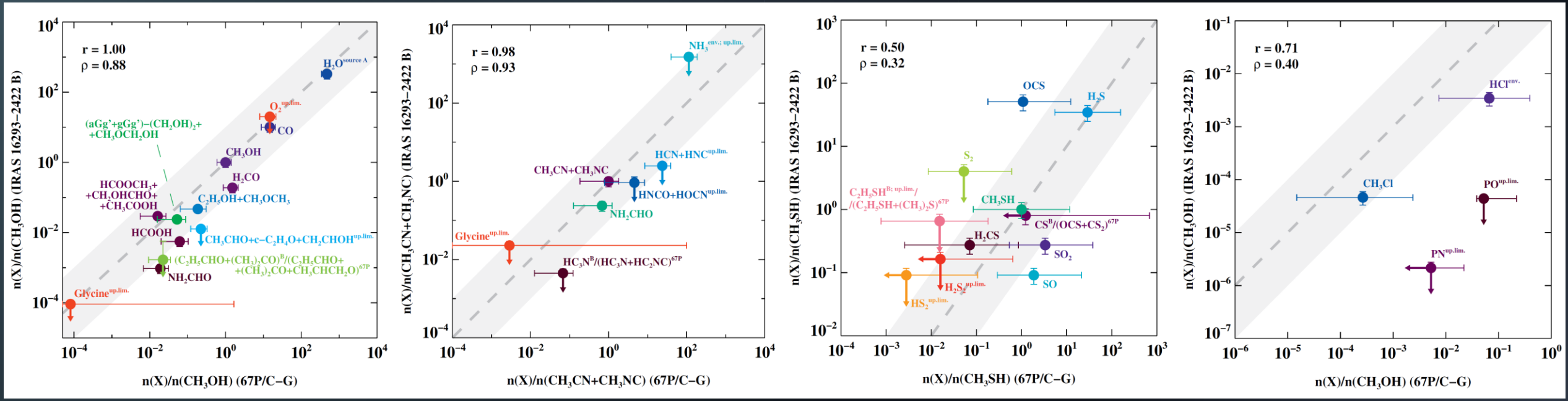
Altwegg et al. 2019

Chemical Inventories Correlate

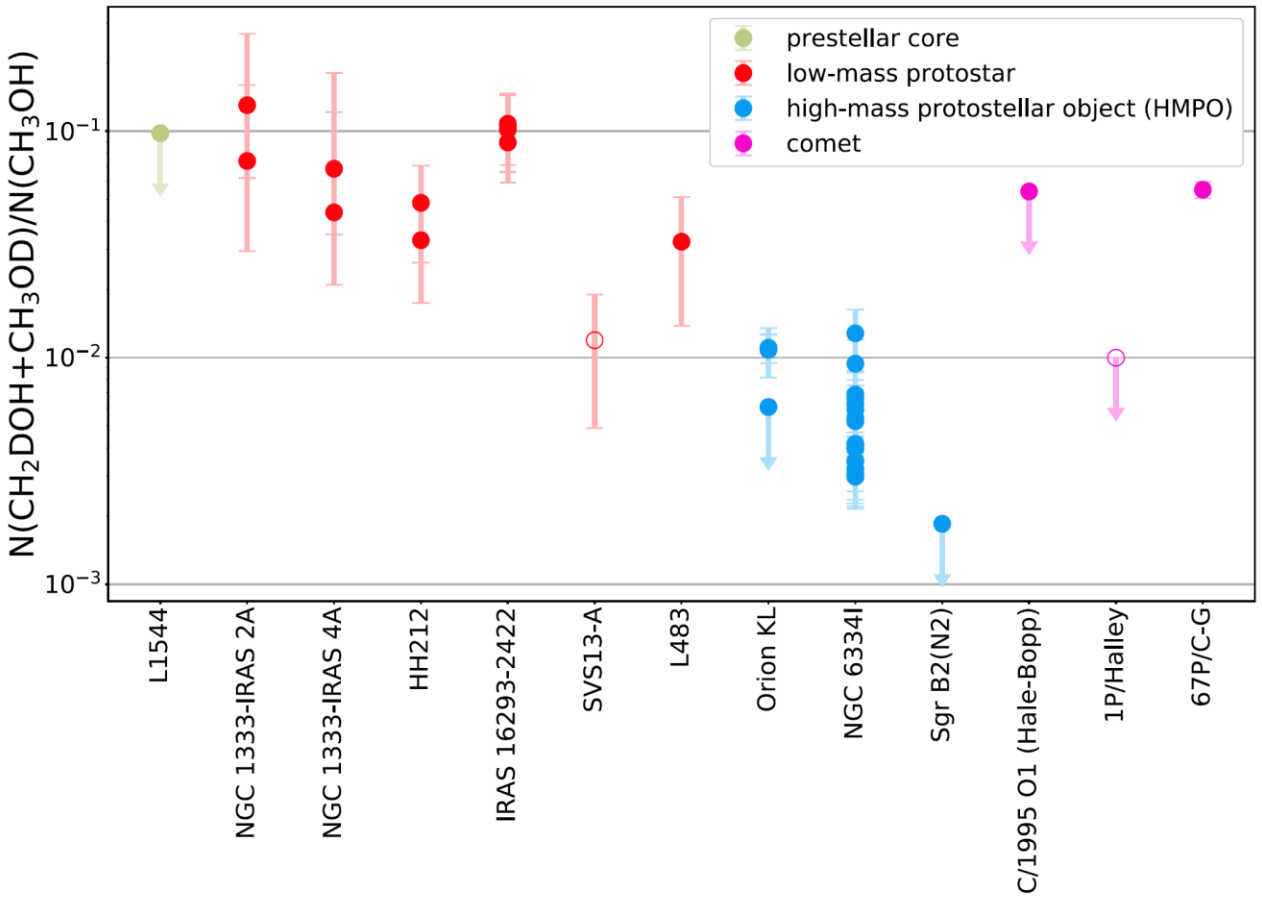
The volatile composition of cometesimals & planetesimals is partially inherited from pre- & protostellar phases of evolution

Drozdovskaya+ 2019; Bockelée-Morvan+ 2000

CHO-FAMILY N-FAMILY S-FAMILY Cl- & P-FAMILY



MONO-DEUTERATED METHANOL



Methanol & its deuterated isotopologues in 67P/C–G must have formed in the innate prestellar core that would go on to birth our Solar System at a time when it was at a temperature of 10–20 K.

Drozdovskaya+ 2021

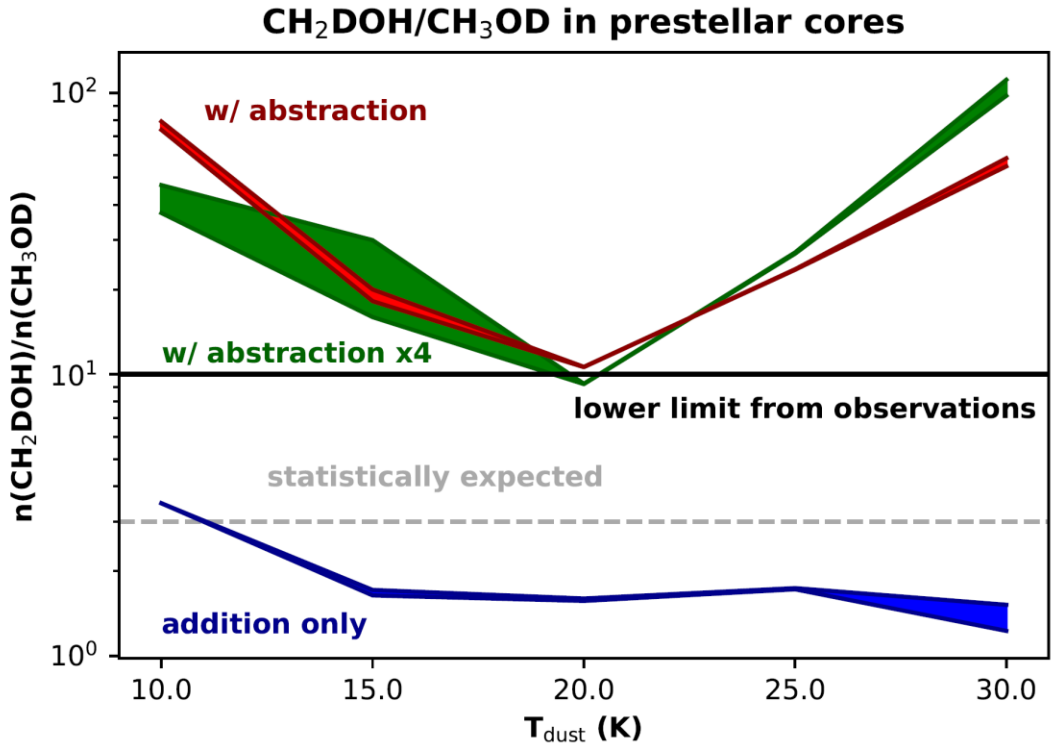
Isotopic Links in COMs

- Methanol is the simplest complex organic molecule (COM)
- Deuteration is an indicator of cold (<20 K) temperatures
  Watson 1974; Dalgarno & Lepp 1984; Caselli & Ceccarelli 2012
- Methanol & its deuteration have been thoroughly studied experimentally & theoretically
  Watanabe & Kouchi 2002; Osamura+ 2004; Kerkeni & Clary 2004; Nagaoka+ 2005; Fuchs+ 2009; Hidaka+ 2009; Goumans & Kästner 2011; Chuang+ 2016, 2017; Cooper & Kästner 2019

Understanding CH_2DOH/CH_3OD

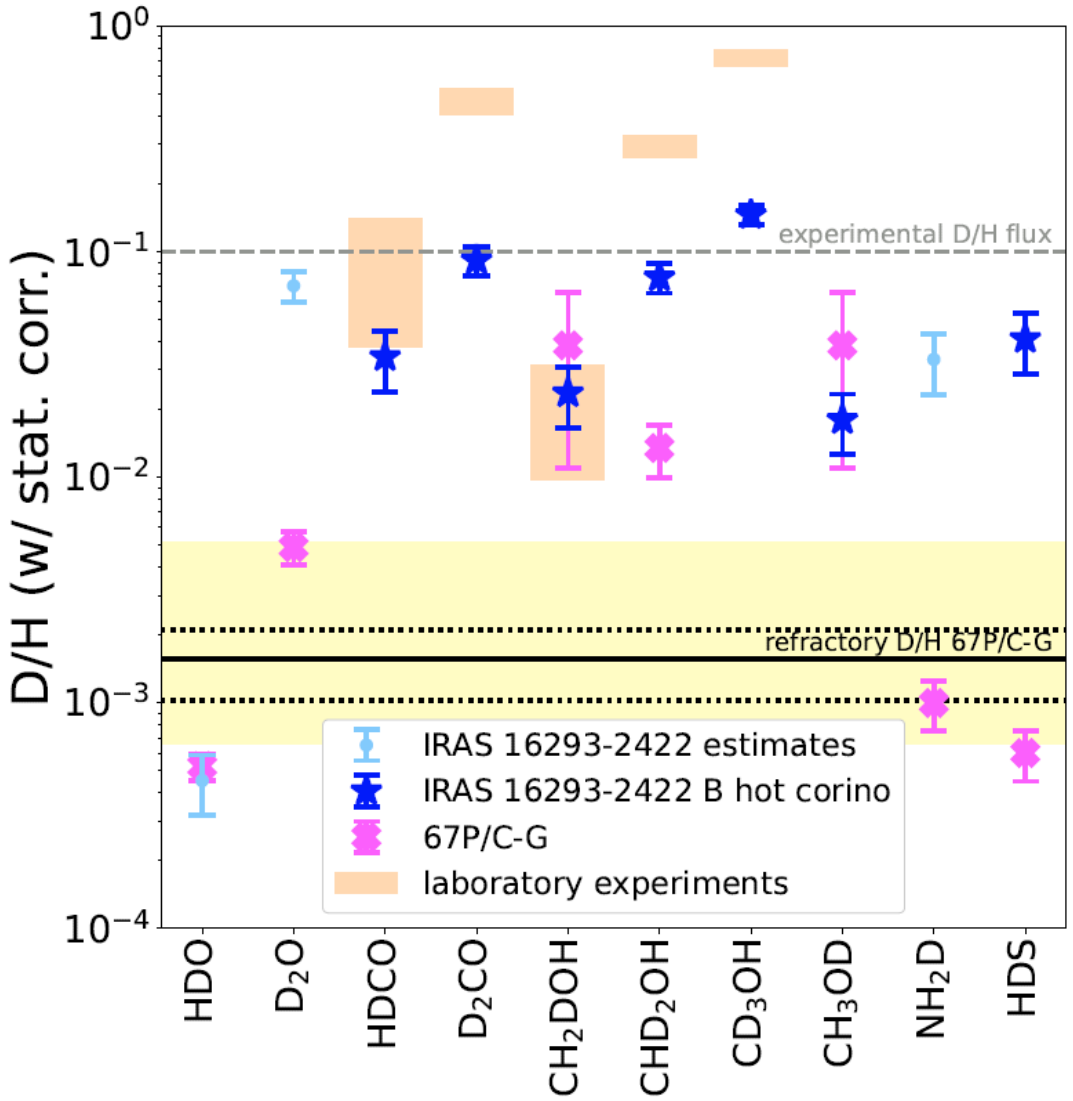
- CH_2DOH is efficiently formed through H-D substitution reactions from CH_3OH (low T<20 K)
  Nagaoka+ 2005; Hiraoka+ 2005; Hidaka+ 2009
- CH_3OD may be formed through H-D exchange reactions between CH_3OH and D_2O or HDO (warm T~70 K)
  Souda 2003, 2004; Ratajczak+ 2009; Faure+ 2015b; Kawanowa+ 2004

CH_2DOH is inherited from the prestellar stage, but CH_3OD is not. CH_2DOH/CH_3OD is a thermometer for interstellar ices.



FEVERING INTERSTELLAR ICES HAVE MORE CH_3OD

Kulterer et al. 2022
beatrice.kulterer@unibe.ch



Drozdovskaya et al. 2022

Cometary D/H ratios

67P/CHURYUMOV-GERASIMENKO

Volatiles measured with *Rosetta*-ROSINA
Altwegg+ 2015, 2017, 2019; Drozdovskaya+ 2021

- Firm & pronounced discrepancy in di-deuterated methanol and HDS (tentatively, in D_2O and NH_2D)

Carbonaceous refractory material measured with *Rosetta*-COSIMA *Paquette+ 2021*

- Refractory D/H at most 1/10th of volatiles (except HDO)

There could be differences between clouds that birthed our Solar System and IRAS 16293-2422 (e.g., atomic D availability).

Astrochemical Recipes for Solar-like Systems

- Volatiles for Solar-like systems are initially made in **prestellar cores**, even including some complex organic molecules
- Raw prestellar ingredients are then **lightly chemically altered** during protostellar collapse and (likely) within the protoplanetary disk though gas-phase and solid-state processes
- Correlations in chemical inventories between star-forming regions and comets in our Solar System suggest **partial inheritance** of materials across evolutionary phases
- Isotopic ratios further support the **importance of the earliest stages** for the final composition of planetesimals in protoplanetary disks

Are the building blocks of life widely and readily available in all star-forming regions?

Read us: Drozdovskaya et al. 2019, 2021, 2022; Kulterer et al. 2022
& Comets III book chapter under rev.

Ask us: **maria.drozdovskaya@unibe.ch, beatrice.kulterer@unibe.ch**