

Solid-state formation of complex molecules under dense cloud conditions

Gleb Fedoseev^{1,2}

K.-J. Chuang^{2,3}, **S. Ioppolo**⁴, **E. F. van Dishoeck**³, **M. E. Palumbo**¹
and **H. Linnartz**²

¹*INAF – Osservatorio Astrofisico di Catania, Catania, Italy*

²*Sackler Laboratory for Astrophysics, Leiden Observatory, Leiden University,
Leiden, The Netherlands*

³*Leiden Observatory, Leiden University, Leiden, The Netherlands*

⁴*Department of Physical Sciences, The Open University, Milton Keynes, UK*

Padova, 15 September 2017

e-mail: gfedo@oact.inaf.it

Different Stages of Star Formation



$10^5 - 10^6$
Years



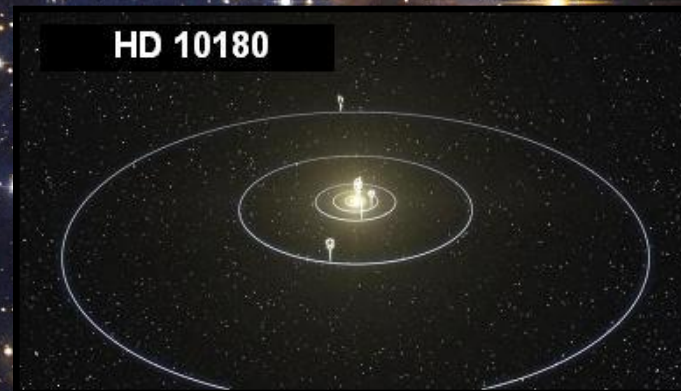
$\sim 10^7$
Years



$> 10^{10}$ Years

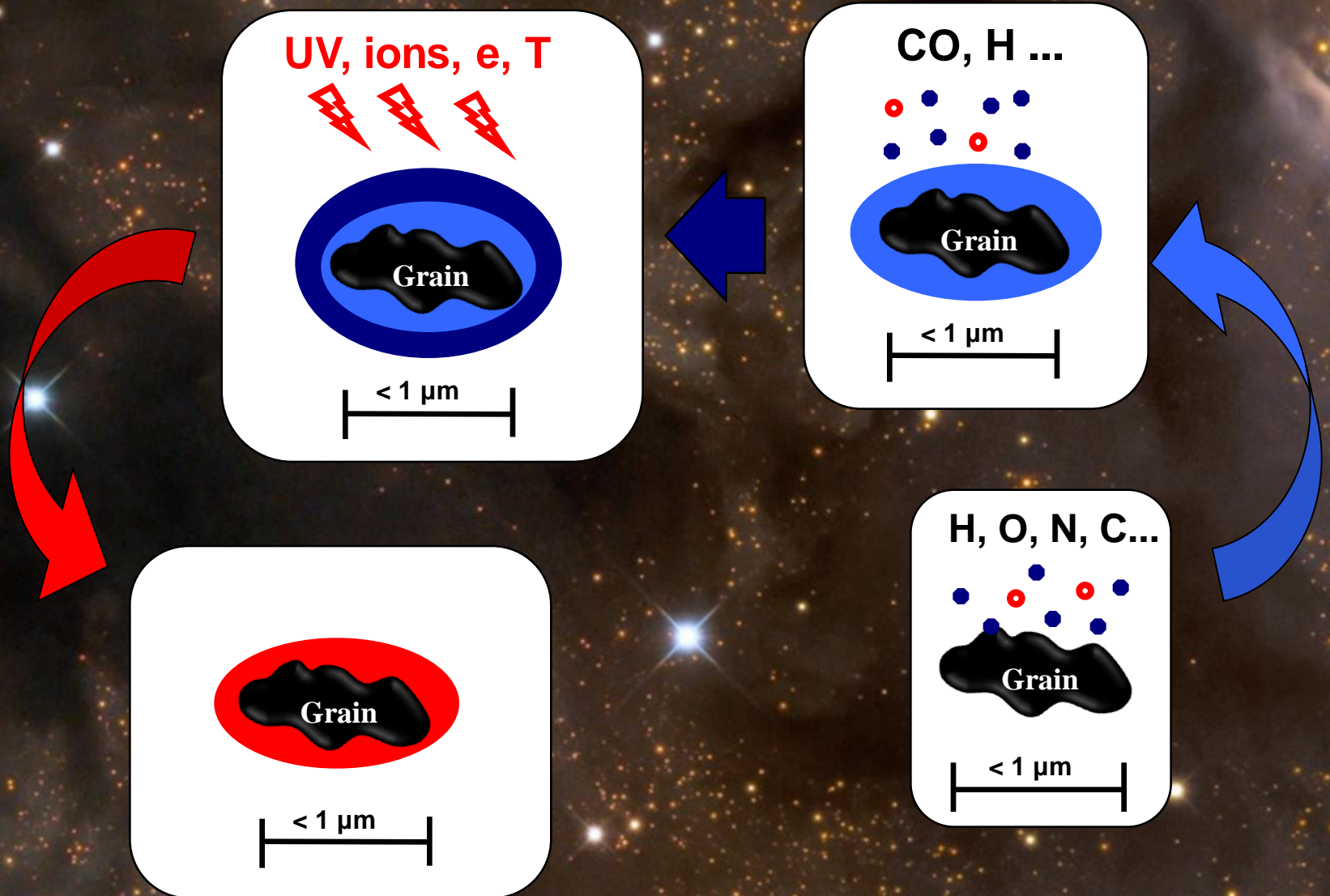


$\sim 10^{10}$
Years

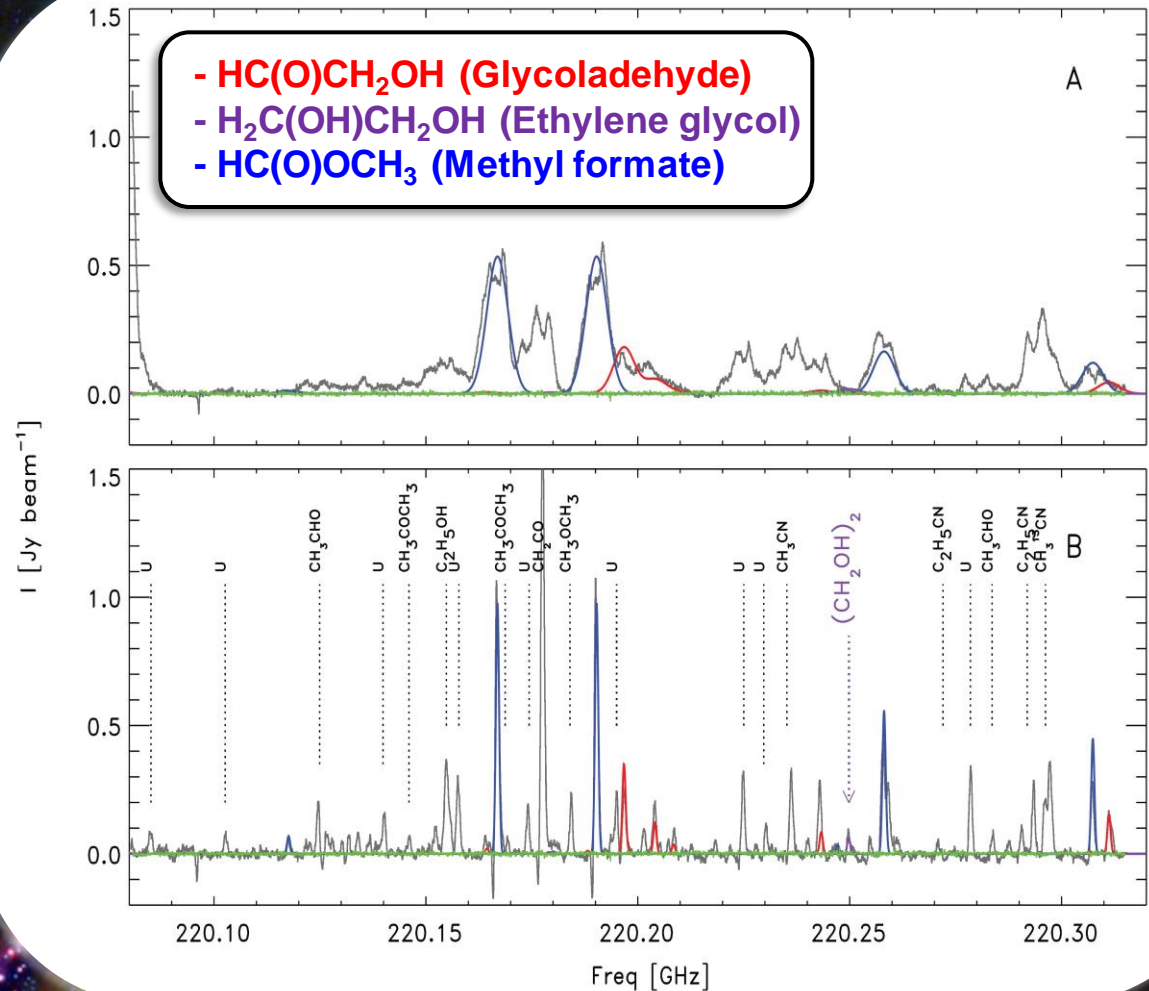
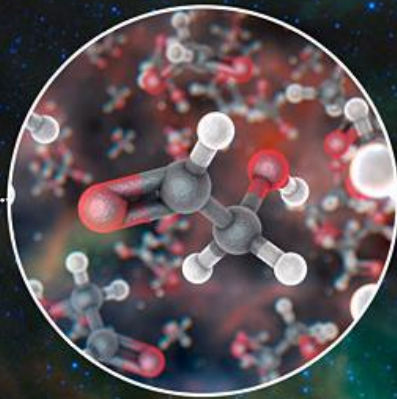


$\sim 10^9$ Years

Chemistry on the Surface of Interstellar Grains

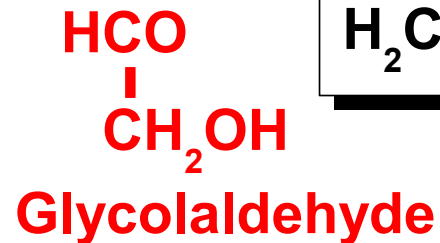
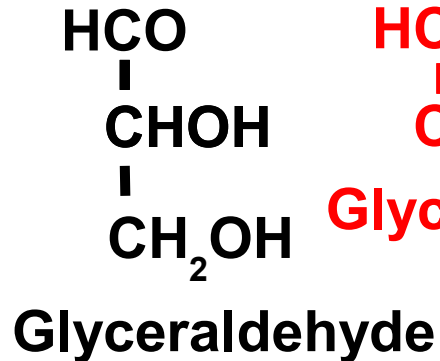
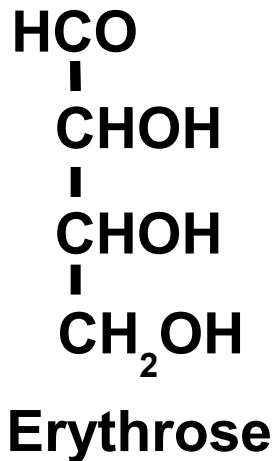
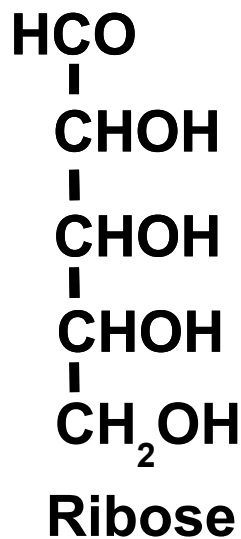
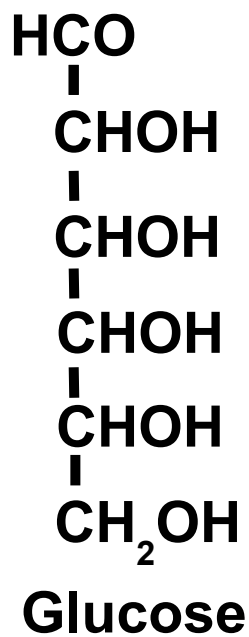


“Sweet Result from ALMA”



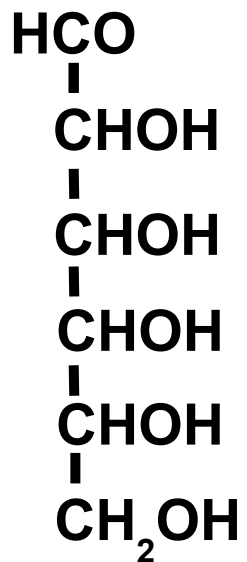
Why Glycolaldehyde and Ethylene Glycol?

SUGARS

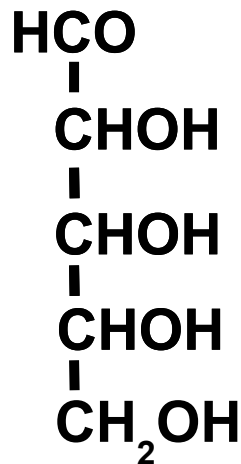


Why Glycolaldehyde and Ethylene Glycol?

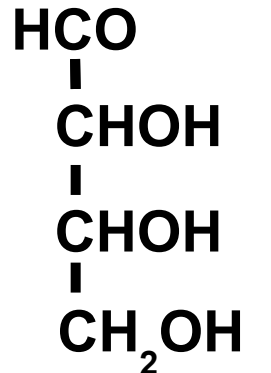
SUGARS



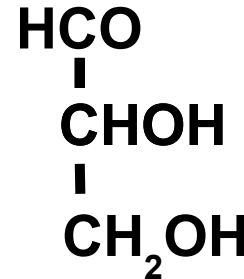
Glucose



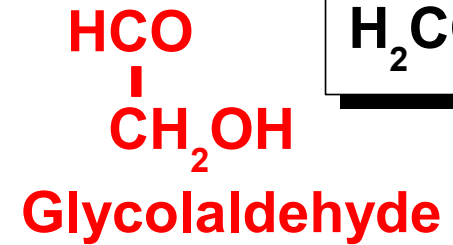
Ribose



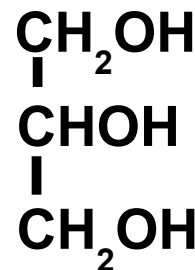
Erythrose



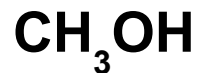
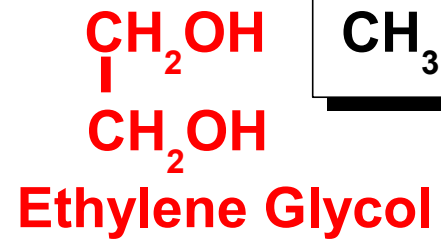
Glyceraldehyde



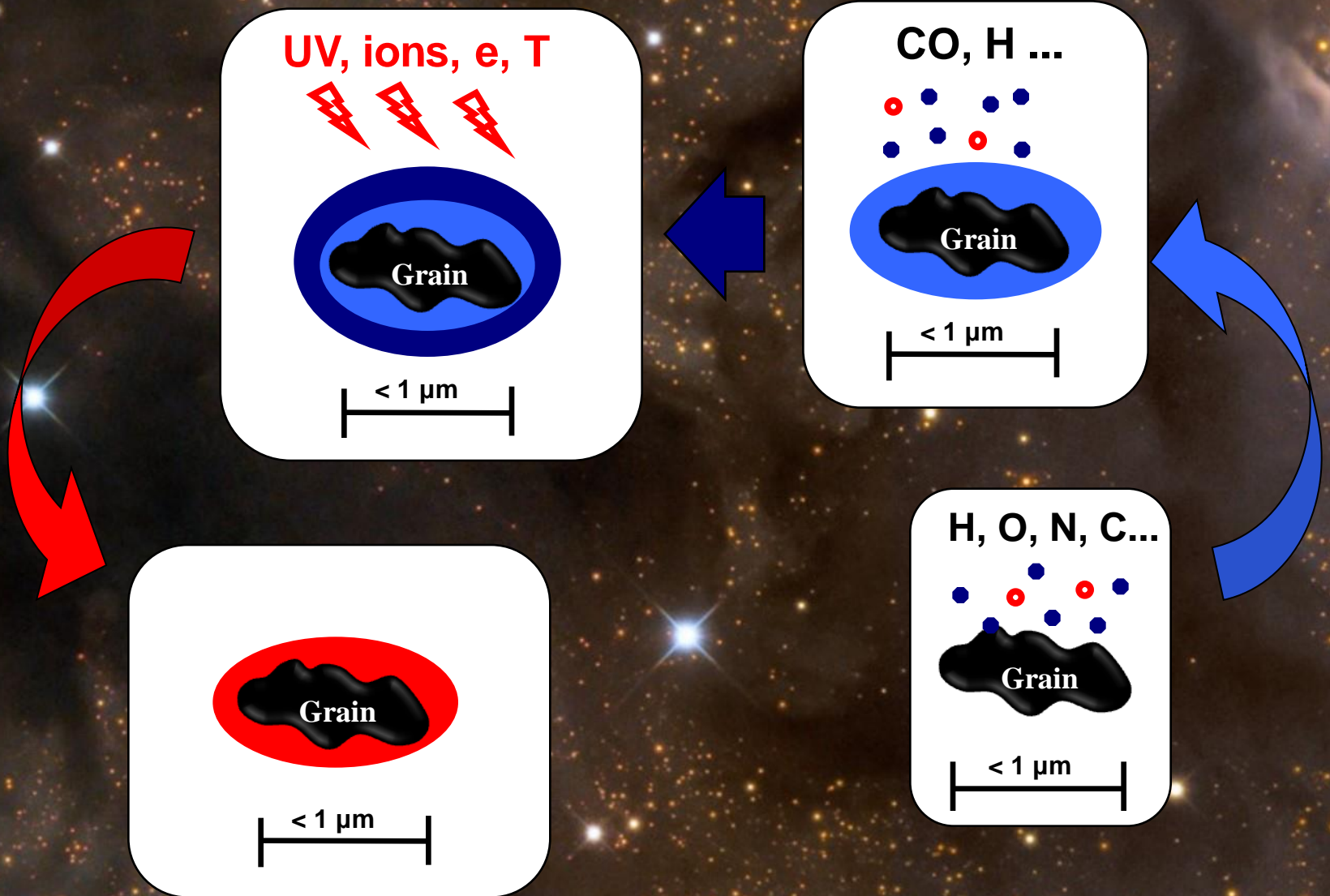
SUGAR ALCOHOLS:



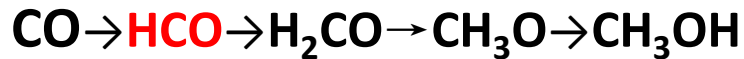
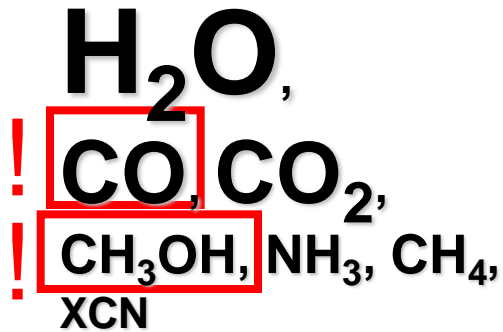
Glycerol



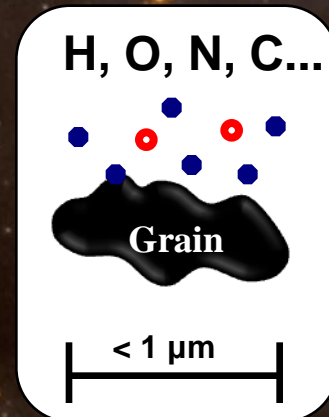
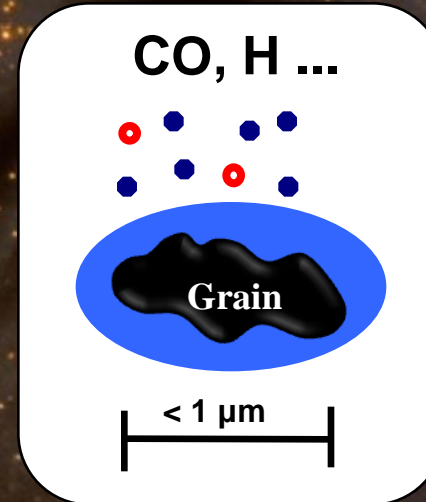
Chemistry on the Surface of Interstellar Grains



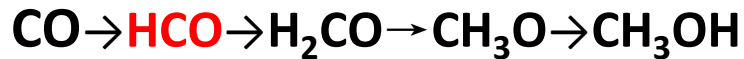
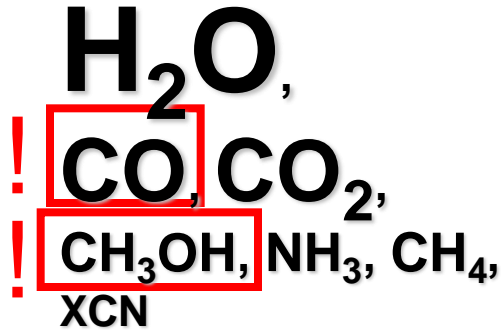
Chemistry on the Surface of Interstellar Grains



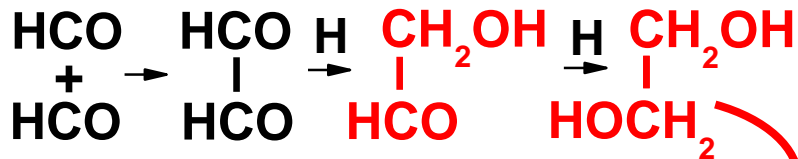
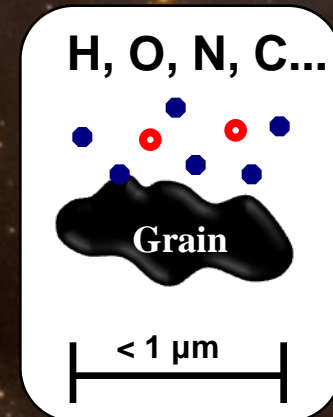
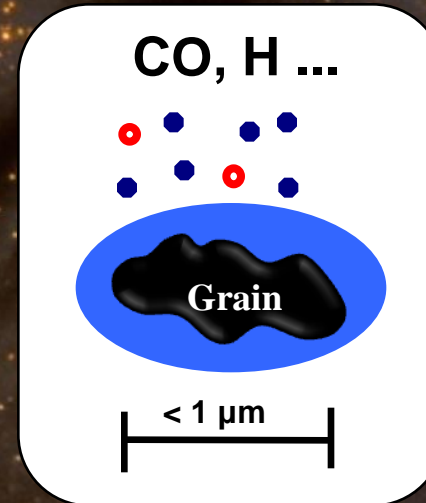
Hiraoka et al. 1994, Zhitnikov et al. 2002,
Watanabe et al 2002, Fuchs et al 2009



Chemistry on the Surface of Interstellar Grains



Hiraoka et al. 1994, Zhitnikov et al. 2002,
 Watanabe et al 2002, Fuchs et al 2009

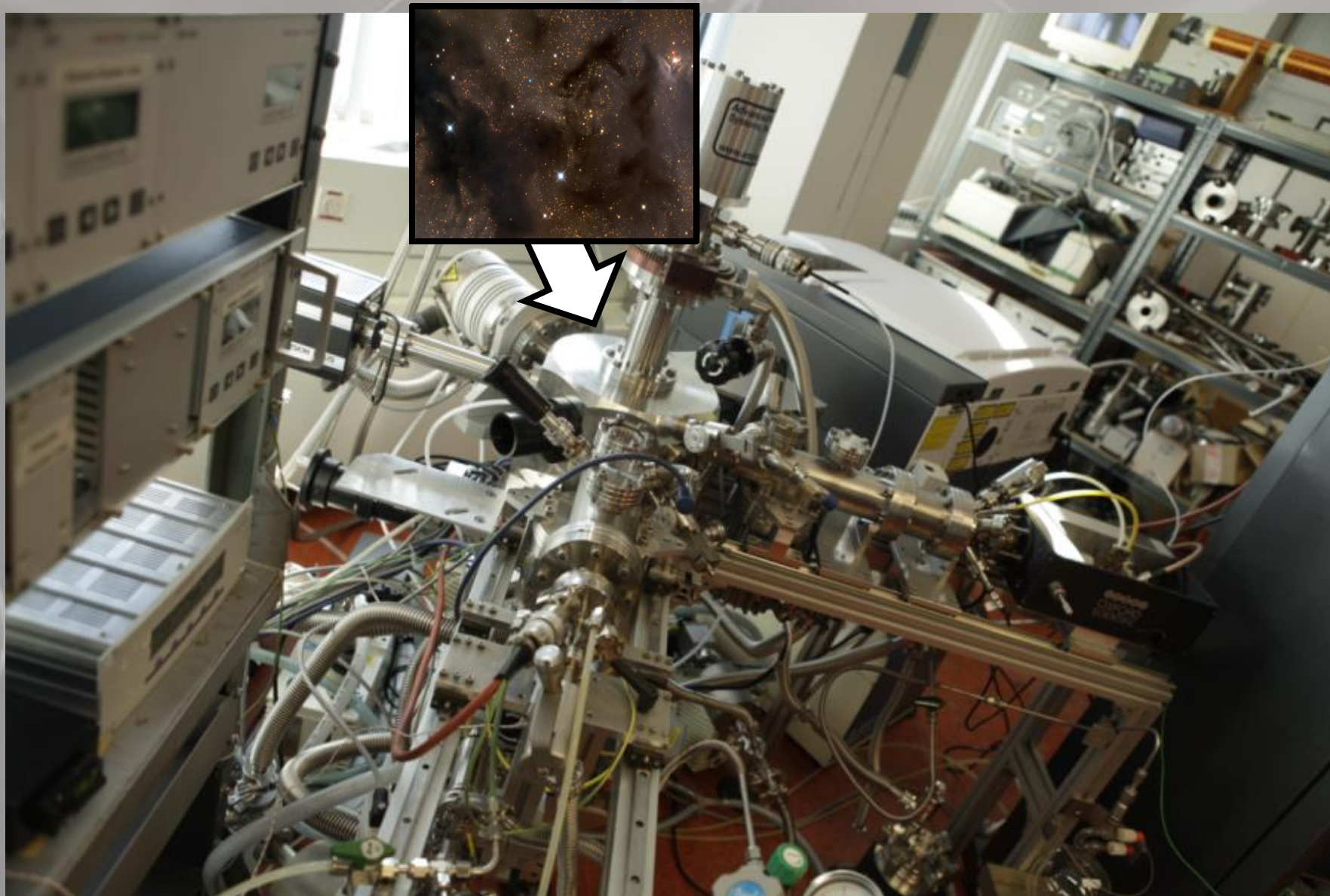


Garrod et al. 2008, Woods et al. 2013

Can We Address These Questions to the Lab?

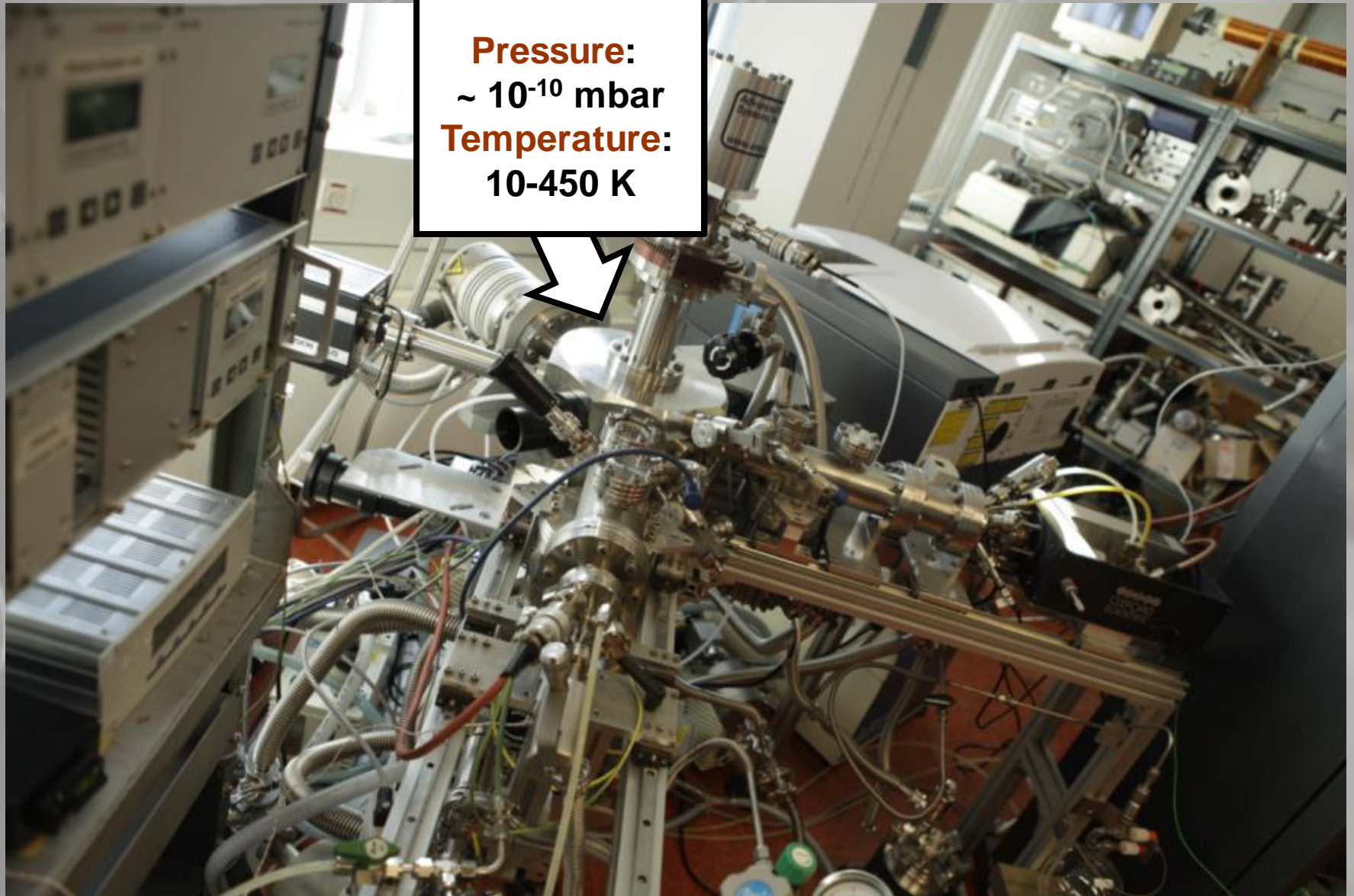


Analysis and Method



Analysis and Method

Pressure:
 $\sim 10^{-10}$ mbar
Temperature:
10-450 K



Analysis and Method

Pressure:
 $\sim 10^{-10}$ mbar
Temperature:
10-450 K

H (D) - fluxes:
 $10^{12} - 10^{13} \text{ cm}^{-2} \text{ s}^{-1}$
O - fluxes:
 $10^{11} - 10^{12} \text{ cm}^{-2} \text{ s}^{-1}$
N - flux:
 $10^{11} \text{ cm}^{-2} \text{ s}^{-1}$

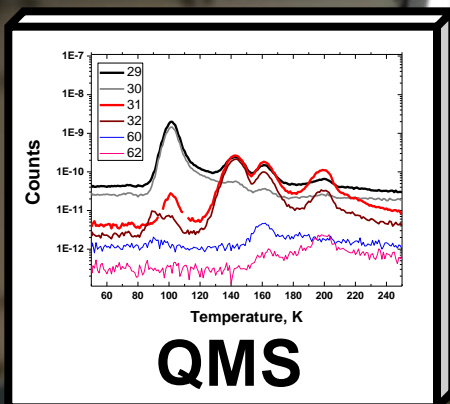
N, O, H(D)

H(D)

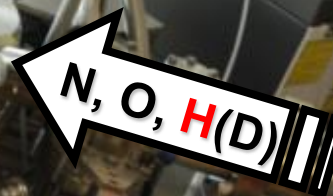
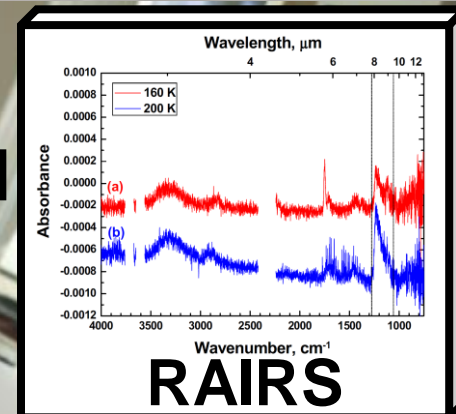
CO, H₂CO...

H (D) - fluxes:
 $10^{12} - 10^{13} \text{ cm}^{-2} \text{ s}^{-1}$

Analysis and Method



Pressure:
 $\sim 10^{-10}$ mbar
Temperature:
10-450 K

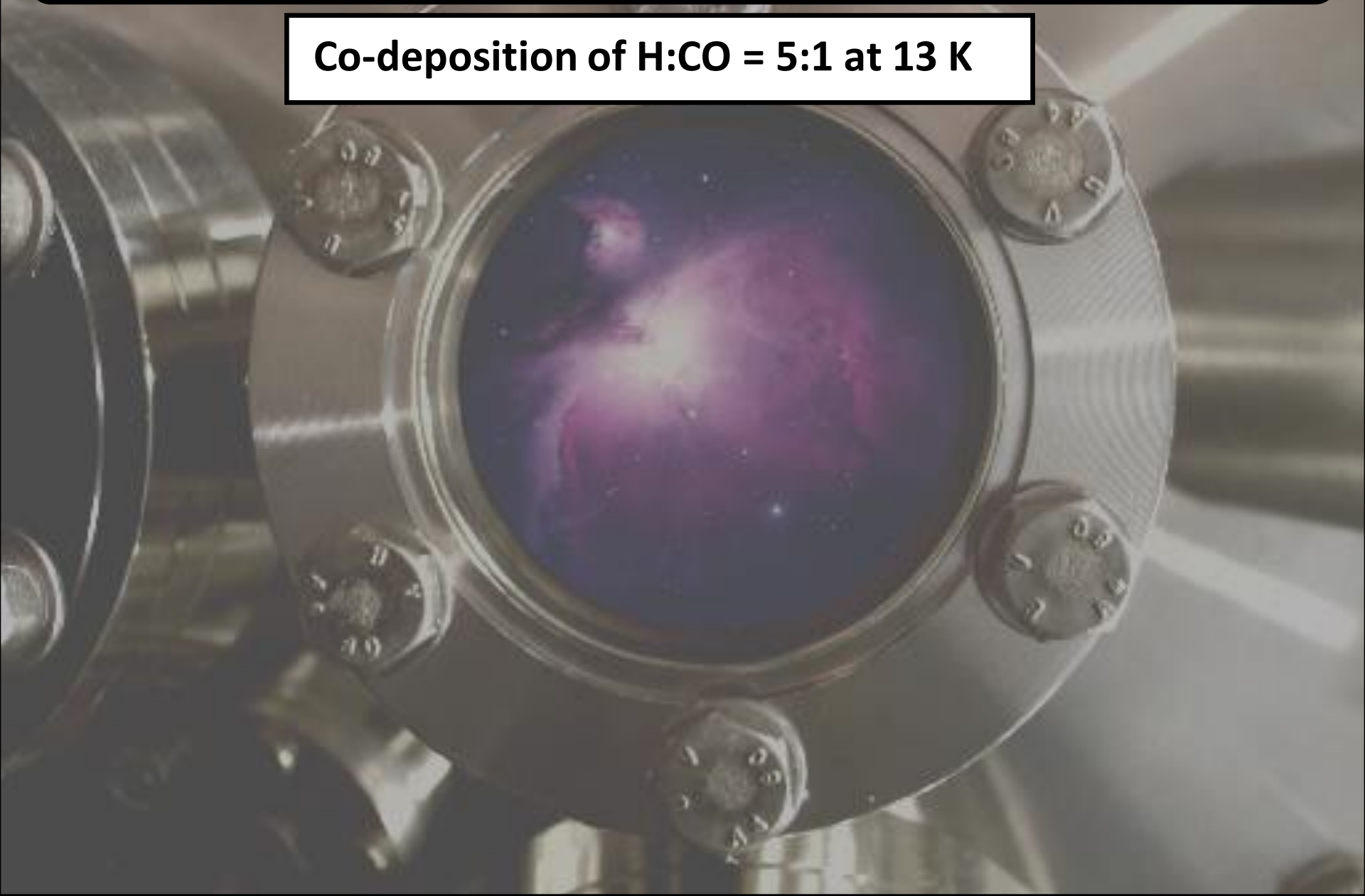


H (D) - fluxes:
 $10^{12} - 10^{13} \text{ cm}^{-2} \text{ s}^{-1}$

H (D) - fluxes:
 $10^{12} - 10^{13} \text{ cm}^{-2} \text{ s}^{-1}$
O - fluxes:
 $10^{11} - 10^{12} \text{ cm}^{-2} \text{ s}^{-1}$
N - flux:
 $10^{11} \text{ cm}^{-2} \text{ s}^{-1}$

H atom addition to CO molecules. Example.

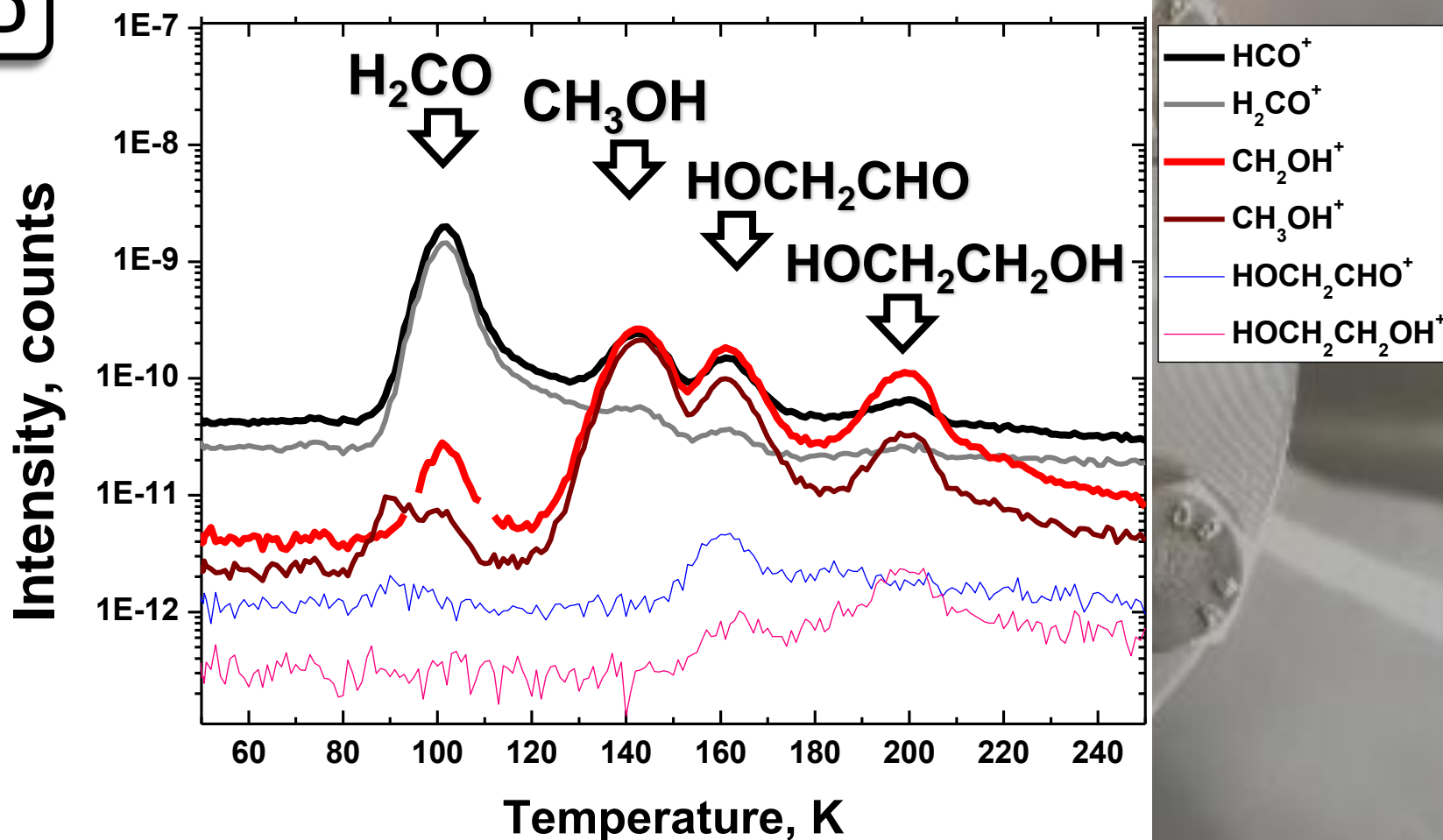
Co-deposition of H:CO = 5:1 at 13 K



H atom addition to CO molecules. Example.

Co-deposition of H:CO = 5:1 at 13 K

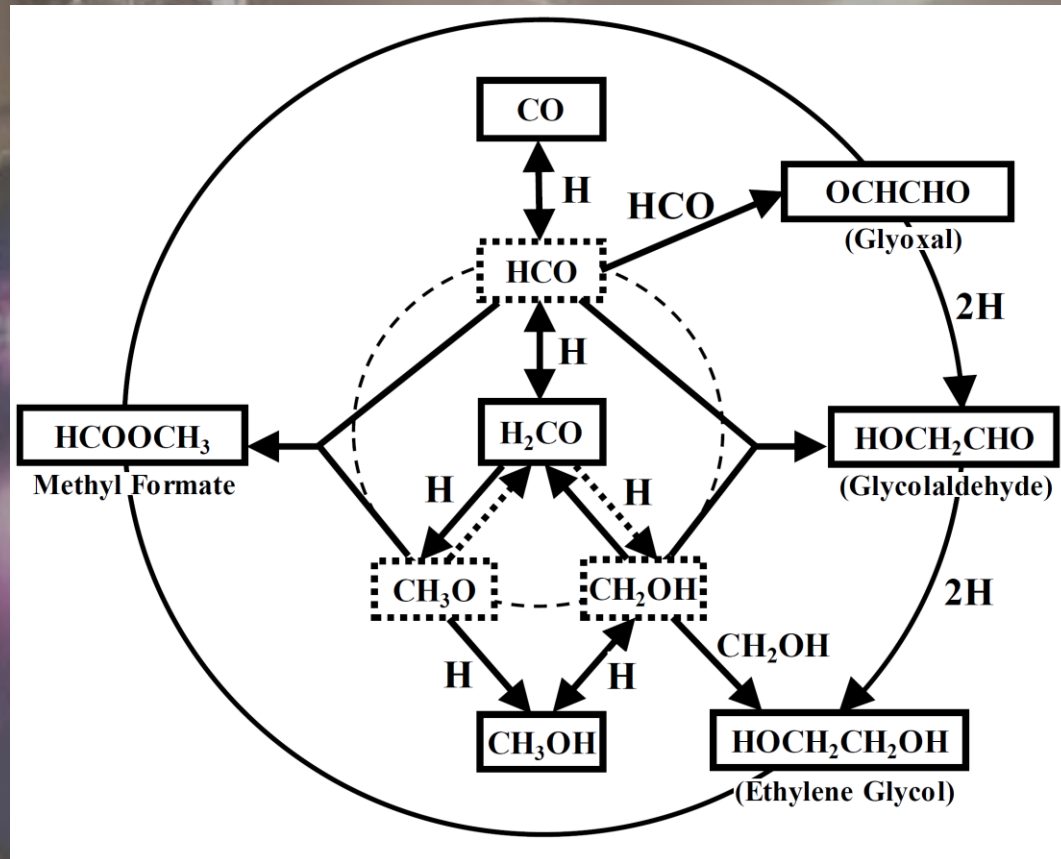
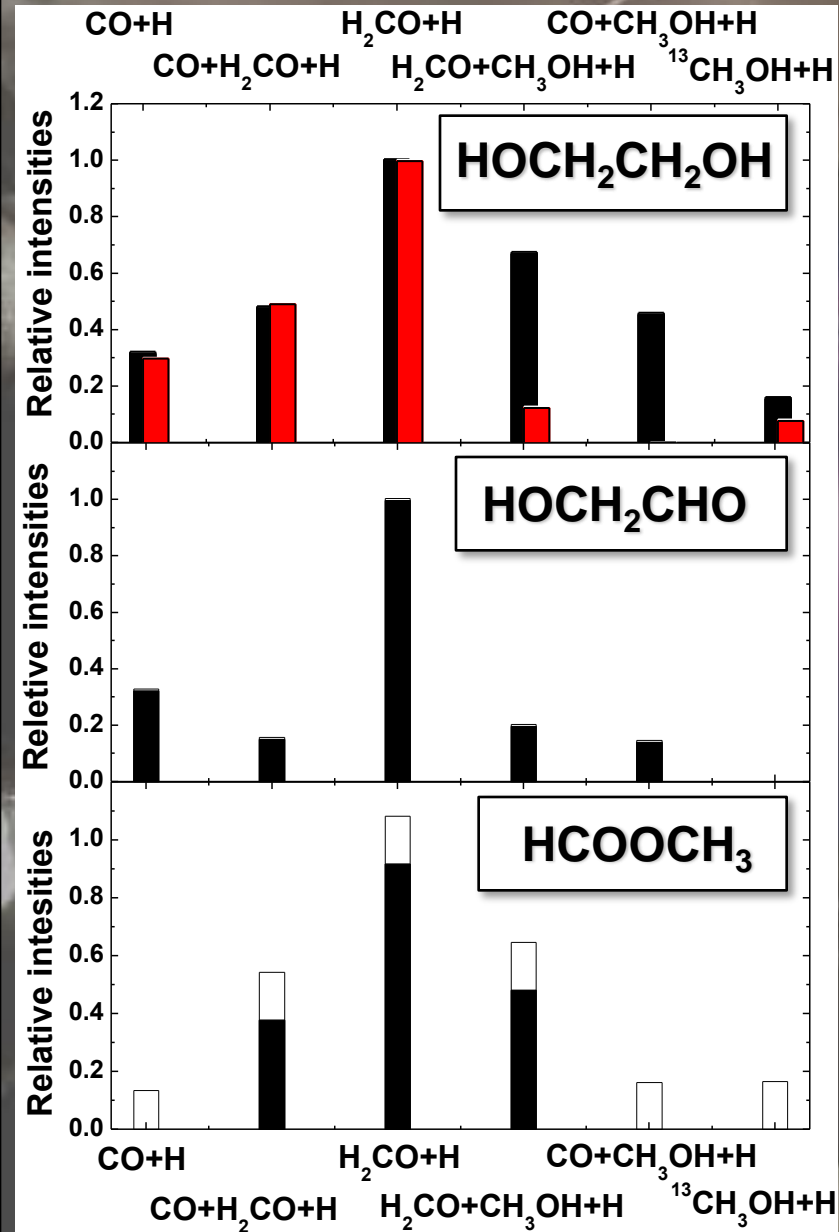
TPD



H-atom total fluence: **1.8E+17** atoms cm^{-2}

Fedoseev et al. 2015c

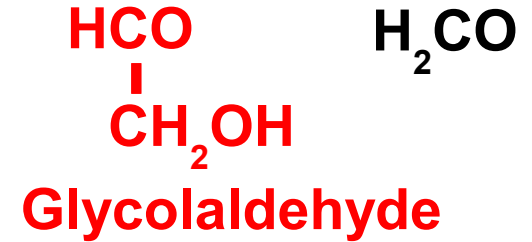
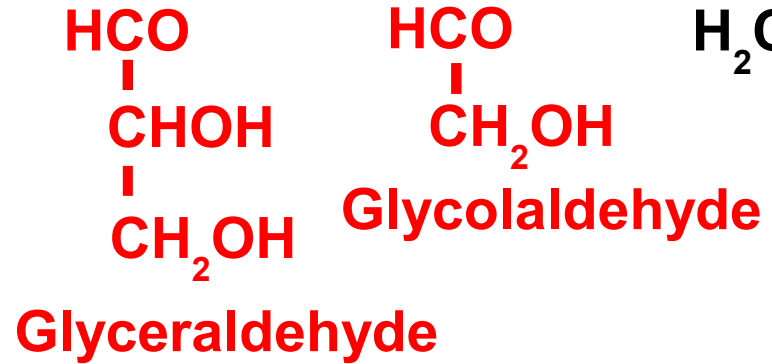
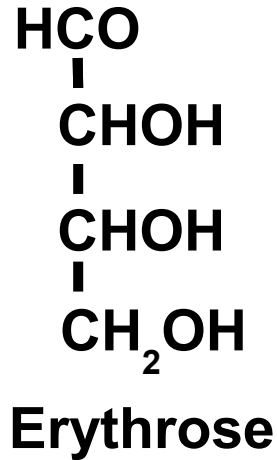
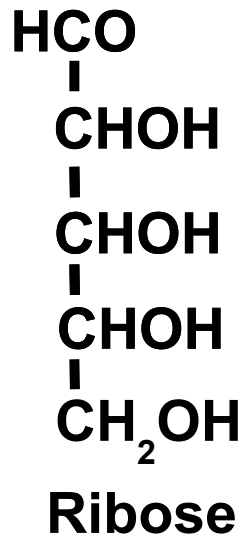
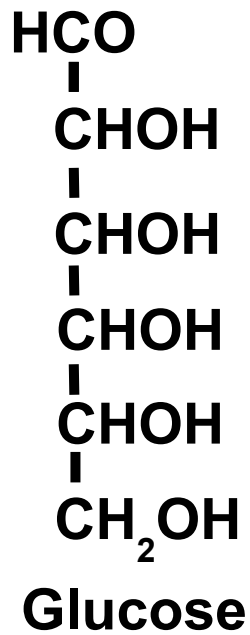
Constructing the Full Reaction Network



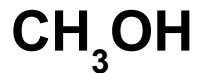
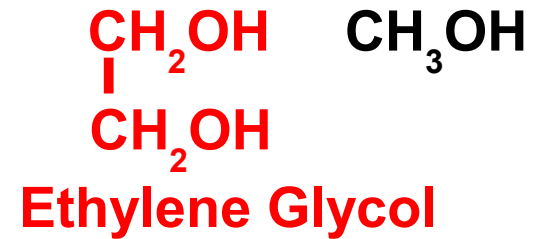
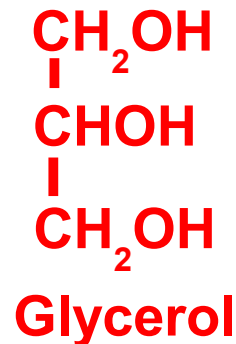
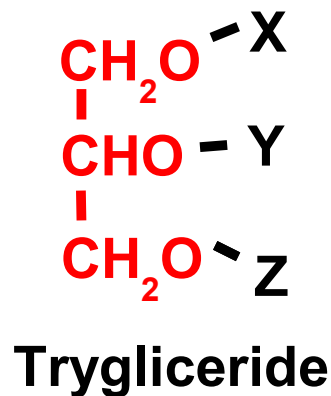
Fedoseev et al. 2015c, Chuang et al. 2016
 Hidaka et al. 2009,
 Butscher et al. 2015, Minissale et al. 2016

Can we form three-carbon bearing analogues?

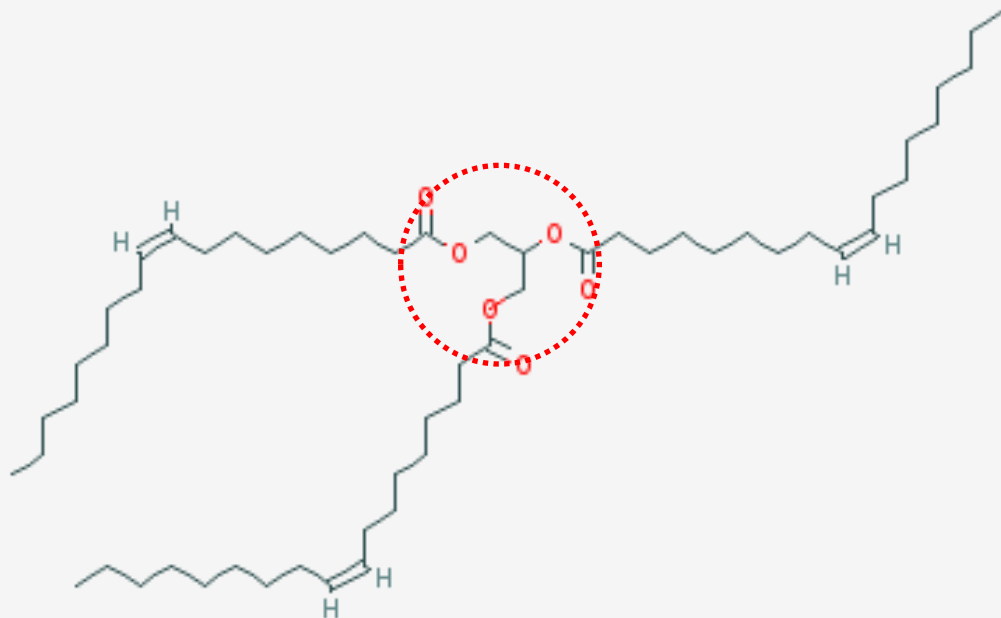
SUGARS



FATS:



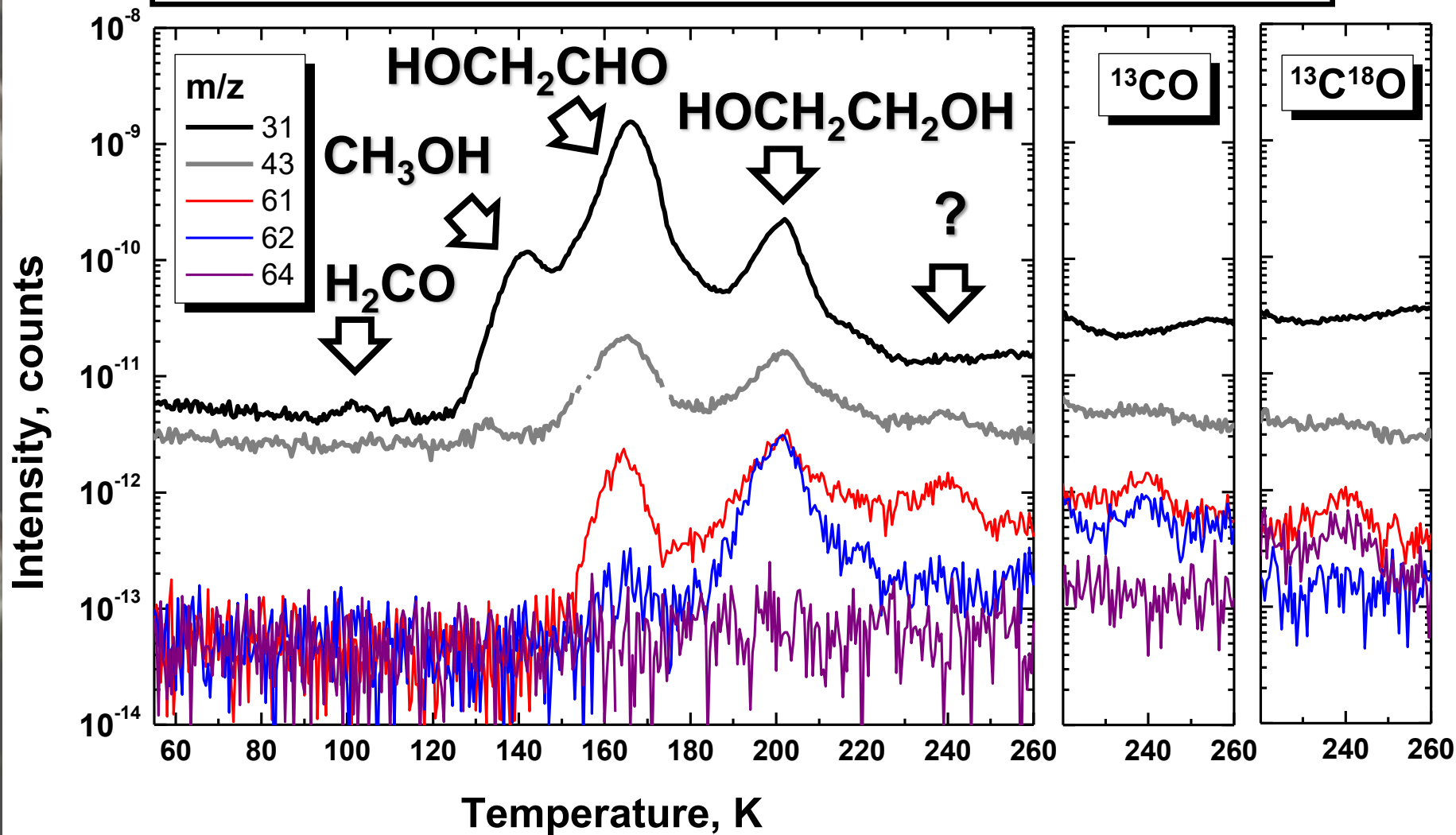
Glycerol is a backbone of all lipids



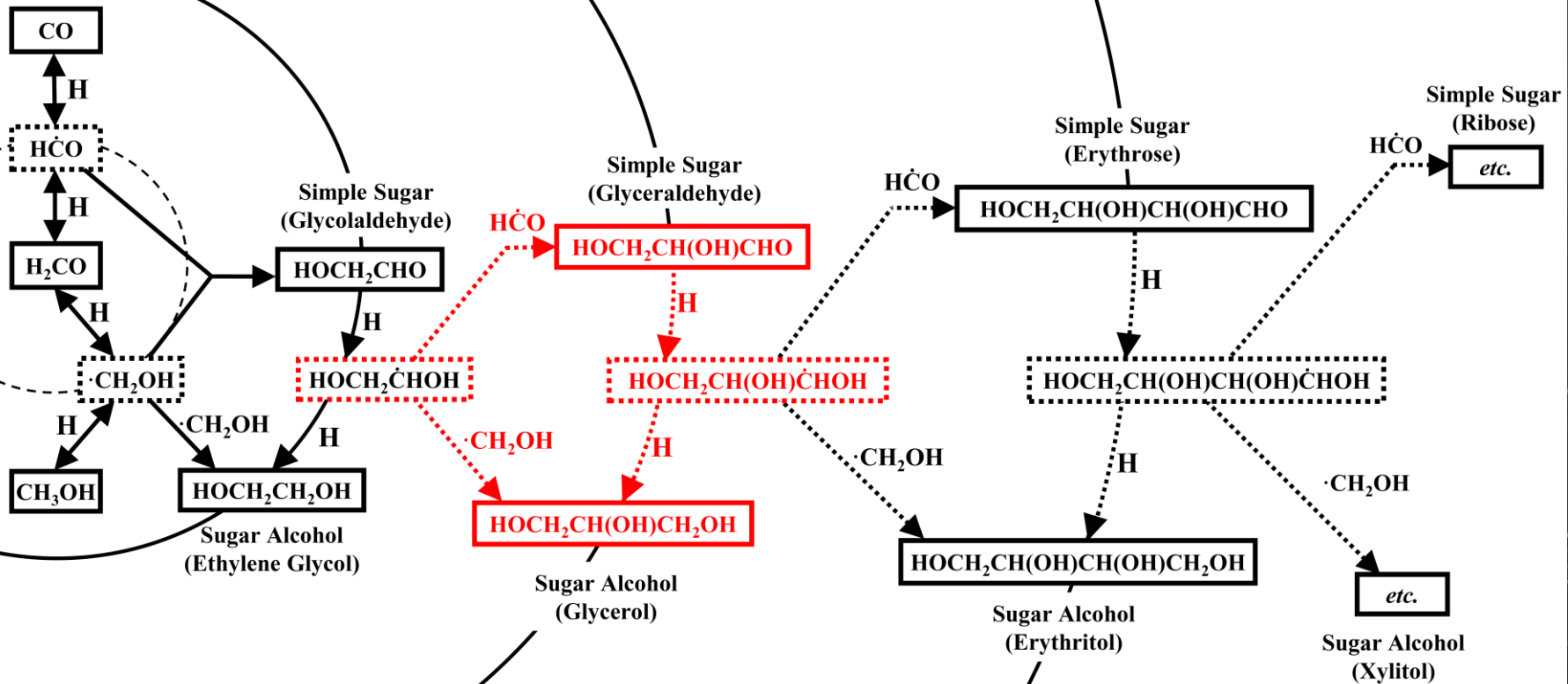
Glycerides comprise ~98% of olive oil, e.g., Glyceryl trioleate (~ 50 %)

Hydrogenation of CO with Glycolaldehyde (1:1)

Co-deposition of H-atoms with CO:GA (1:1) at 15 K

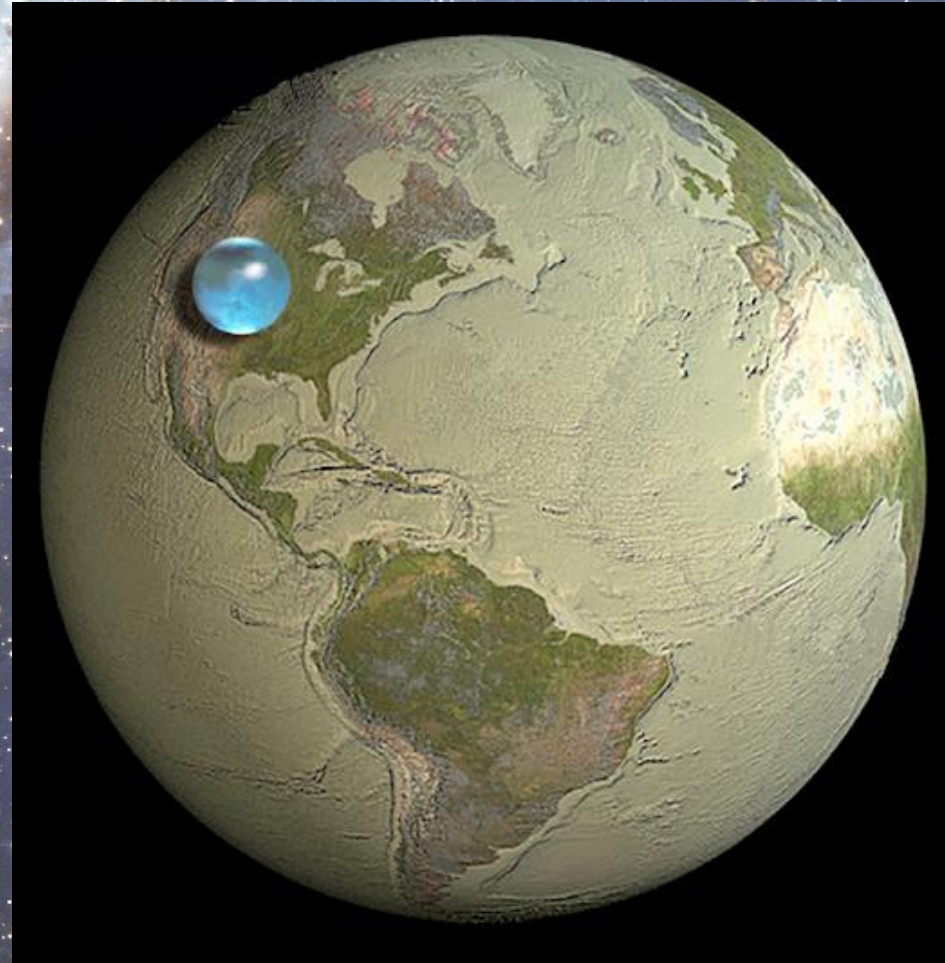
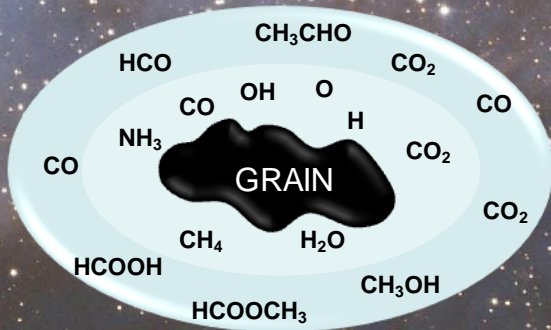


Chemistry on the Surface of Interstellar Grains



Why is It Interesting for Us?

Icy Grain



Hartog et al. 2011

Kevin Hand (JPL/Caltech)

Why is It Interesting for Us?

H₂O in L1544:

5×10^{27} kg

CH₃OH in L1544

4×10^{26} kg

Glycerol in L1544

4×10^{22} kg

**Caselli et al. 2012
Boogert et al. 2015
Evans II et al. 2001**

Oceans on the Earth:

1.4×10^{21} kg

All oceanic life forms

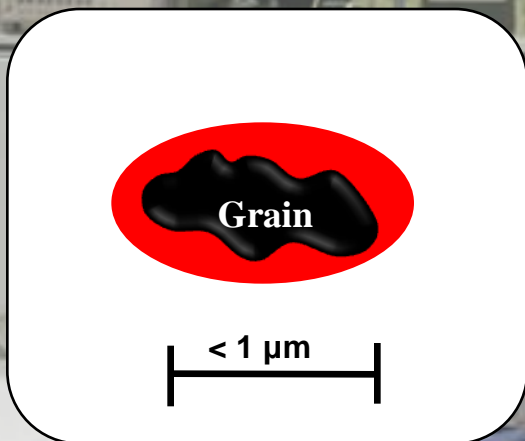
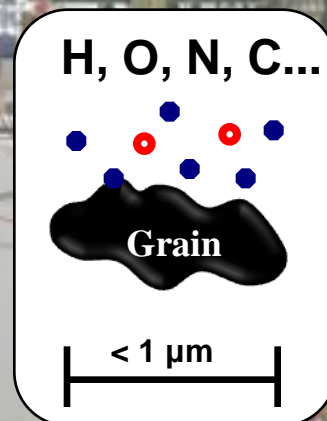
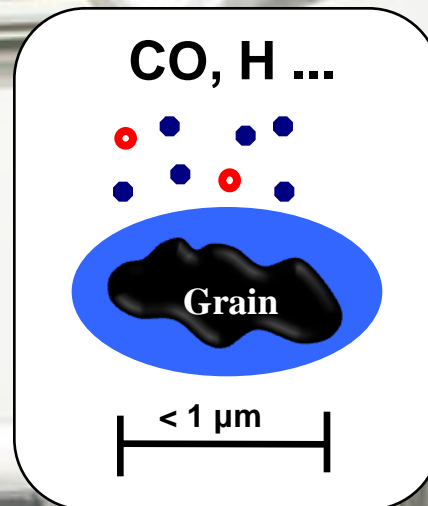
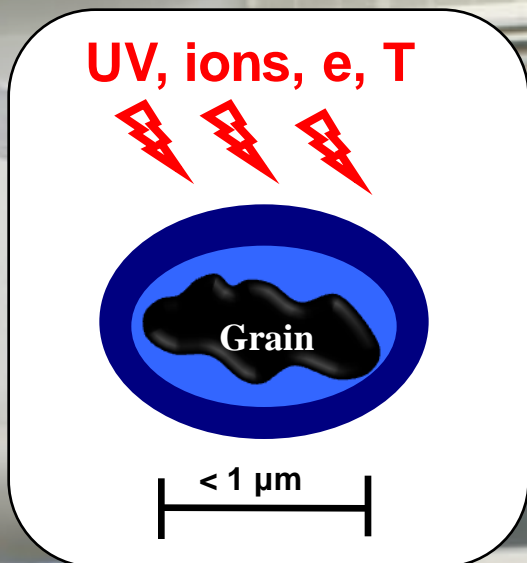
3.2×10^{12} kg

Glycerol in this life forms

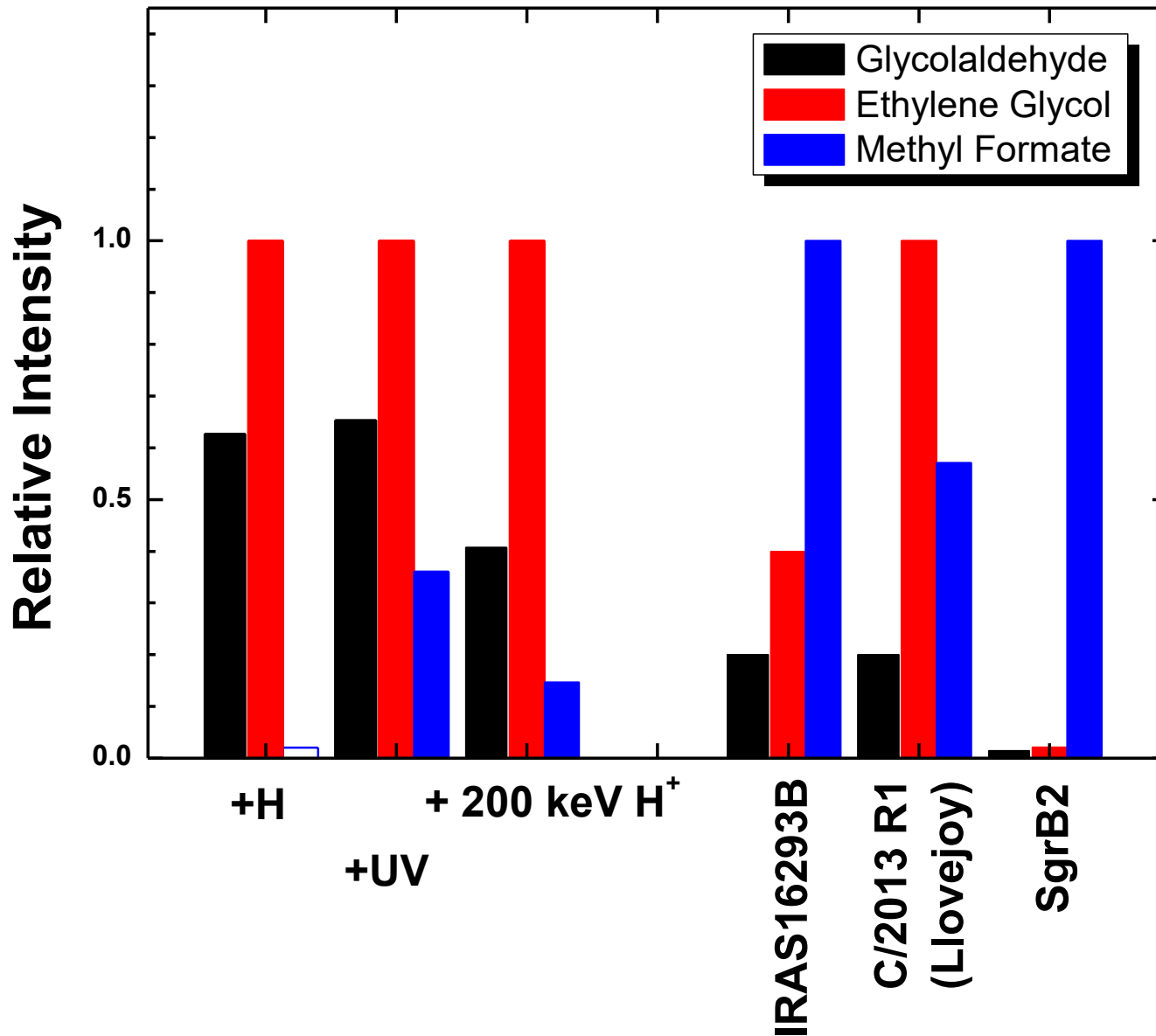
$\sim 1 \times 10^{10}$ kg

**Vernadsky 2001,
Basilevich et al. 1971
Alberts et al. 2002**

Outlooks. AstroFlt2.



Comparison between various chemical triggers



+H and +UV

QMS current
integration:

GA: ~160K

EG: ~200K

MF: ~120K

200 keV H⁺
irradiation

IR optical depth
integration:

GA: 1073 cm⁻¹

EG: 1087 cm⁻¹

MF: 1160 cm⁻¹

Chuang et al. 2016 (in prep)

Modica & Palumbo 2010

Jørgensen et al. (2016)

Biver et al. (2014)

Maity et al. 2015

Henderson & Gudipati 2015

Paardekooper et al. 2016

Abou Mrad et al. 2016

Öberg 2016

Vasyunin & Herbst 2013

Conclusions

- **The formation of Complex Organic Molecules (COMs) in the solid state proceeds already in dark molecular clouds before the formation of a protostar**
- **Various COMs are formed in interstellar ices through accretion of simplest species**
- **Among these species are prebiotic compounds, Glycerol and the simplest representatives of sugar row**

Acknowledgments

*Leiden Observatory,
Leiden University:*

**Dr. T. Lamberts
Dr. D.M. Paardekooper
Dr. J. F. Zhen**

*Radboud University,
Nijmegen*

Dr. H.M. Cuppen

*INAF – Osservatorio
Astrofisico di Catania*

**Prof. G. Strazzulla
Dr. M. Accolla
Dr. G. A. Baratta
Dr. P. Modica
Dr. C. Scirè
Msc. R. G. Urso**

Fine mechanical workshop FMD/ELD, in particular M. J. A. Witlox

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement n. 664931