Solid-state formation of complex molecules under dense cloud conditions

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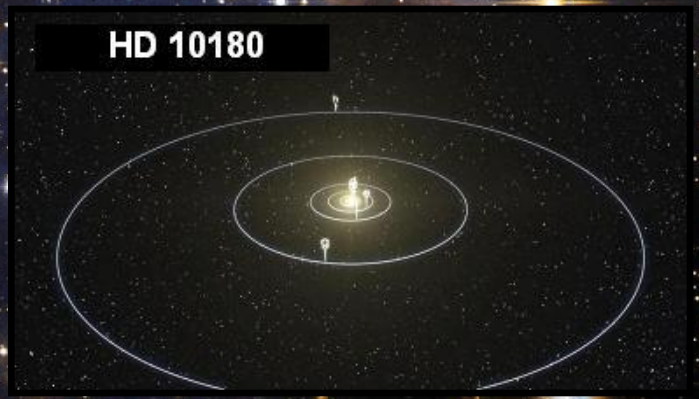
Different Stages of Star Formation

10^5-10^6 Years

~10^7 Years

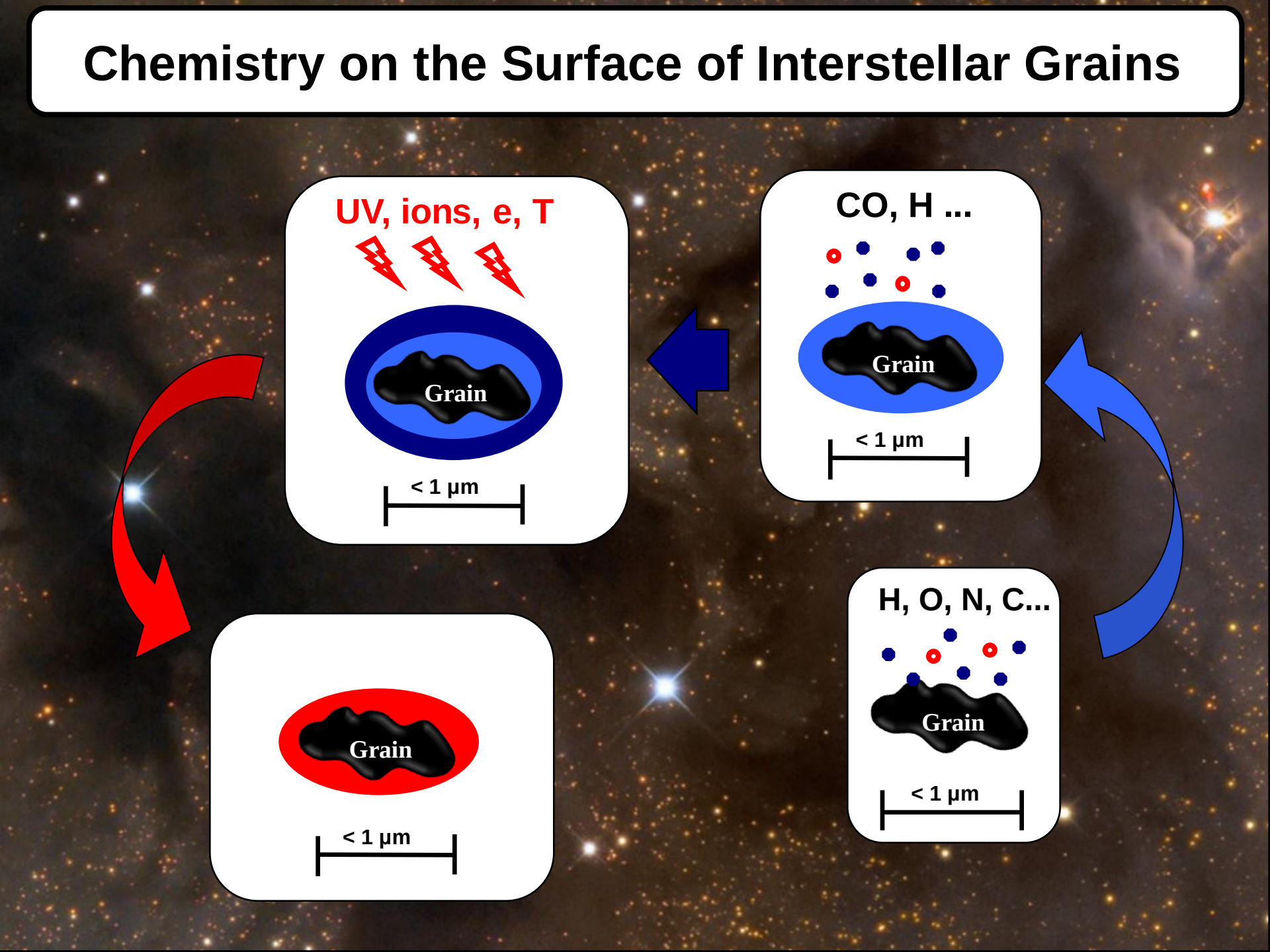
~10^9 Years



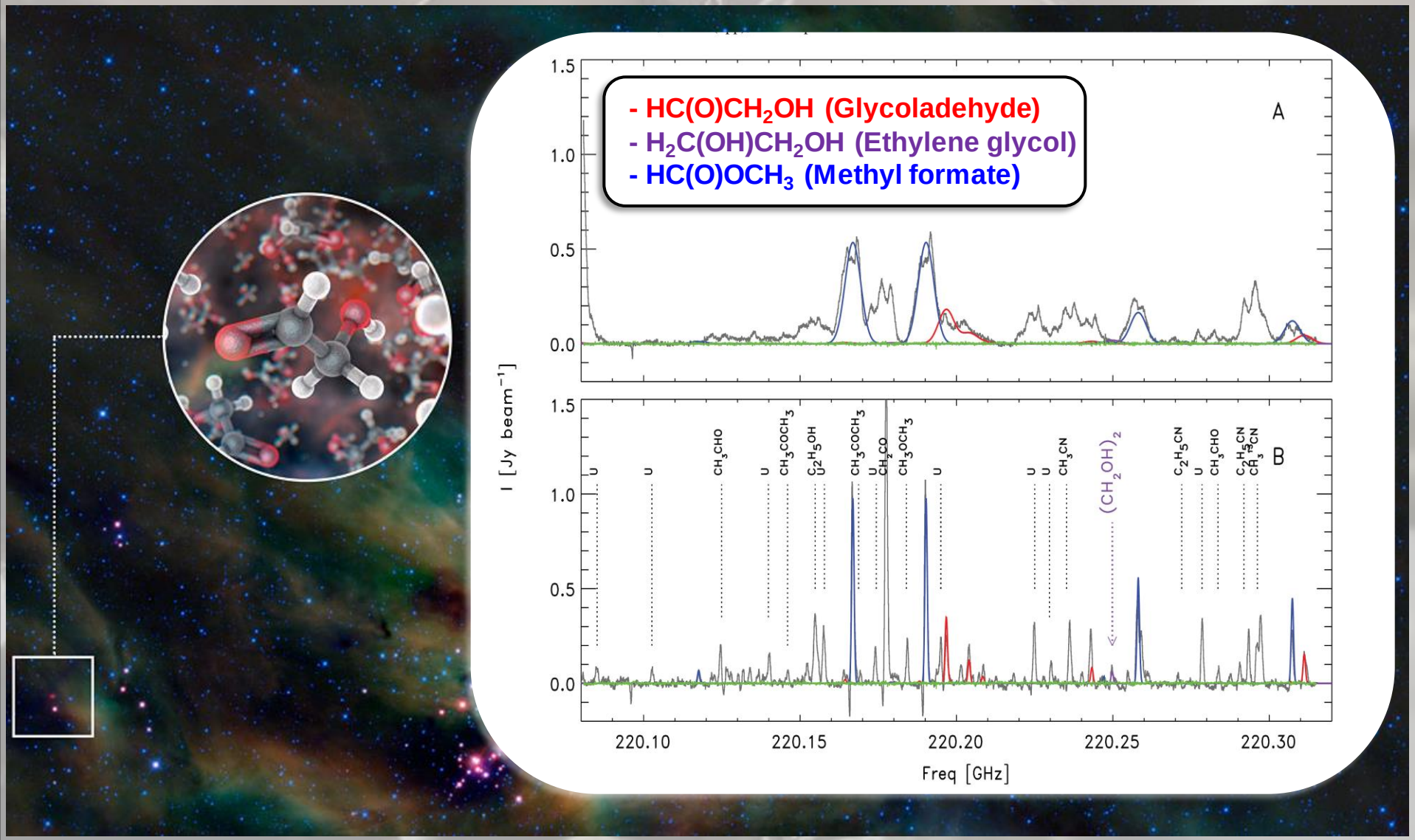
~10^{10} Years

>10^{10} Years

Chemistry on the Surface of Interstellar Grains



“Sweet Result from ALMA”

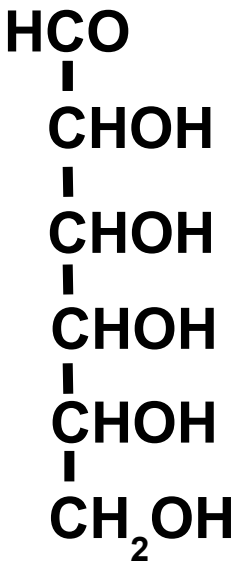


Jørgensen et al. 2012, 2016, Beltran et al. 2009
Coutens et al. 2015, Taquet et al. 2015, 2017, Rivilla et al. 2016

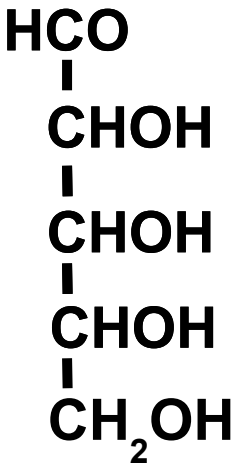
ALMA (ESO/NAOJ/NRAO)/L.Calçada (ESO) & NASA/JPL-Caltech/WISE Team

Why Glycolaldehyde and Ethylene Glycol?

SUGARS

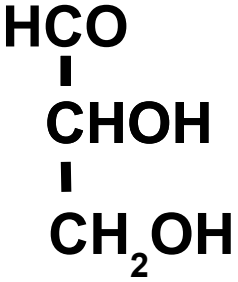


Glucose

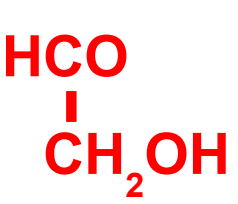


Ribose

Erythrose



Glyceraldehyde

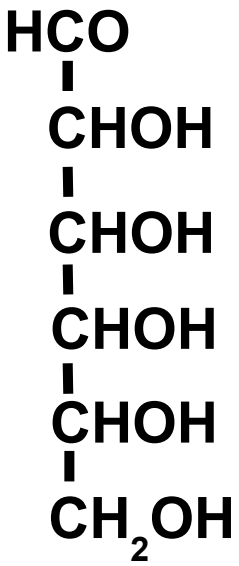


Glycolaldehyde

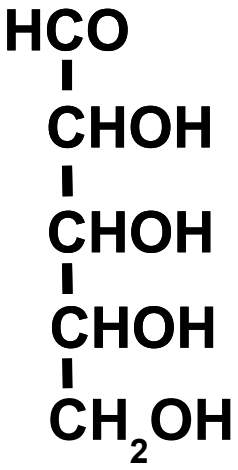
H_2CO

Why Glycolaldehyde and Ethylene Glycol?

SUGARS



Glucose



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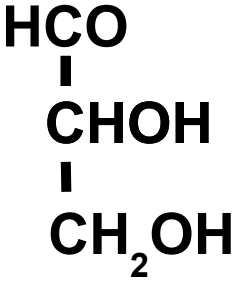
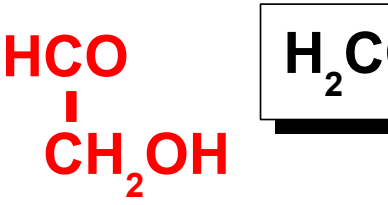
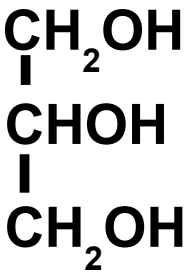


Glyceraldehyde

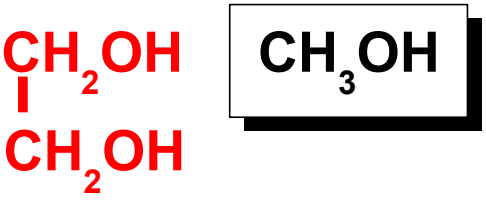


Glycolaldehyde

SUGAR ALCOHOLS:

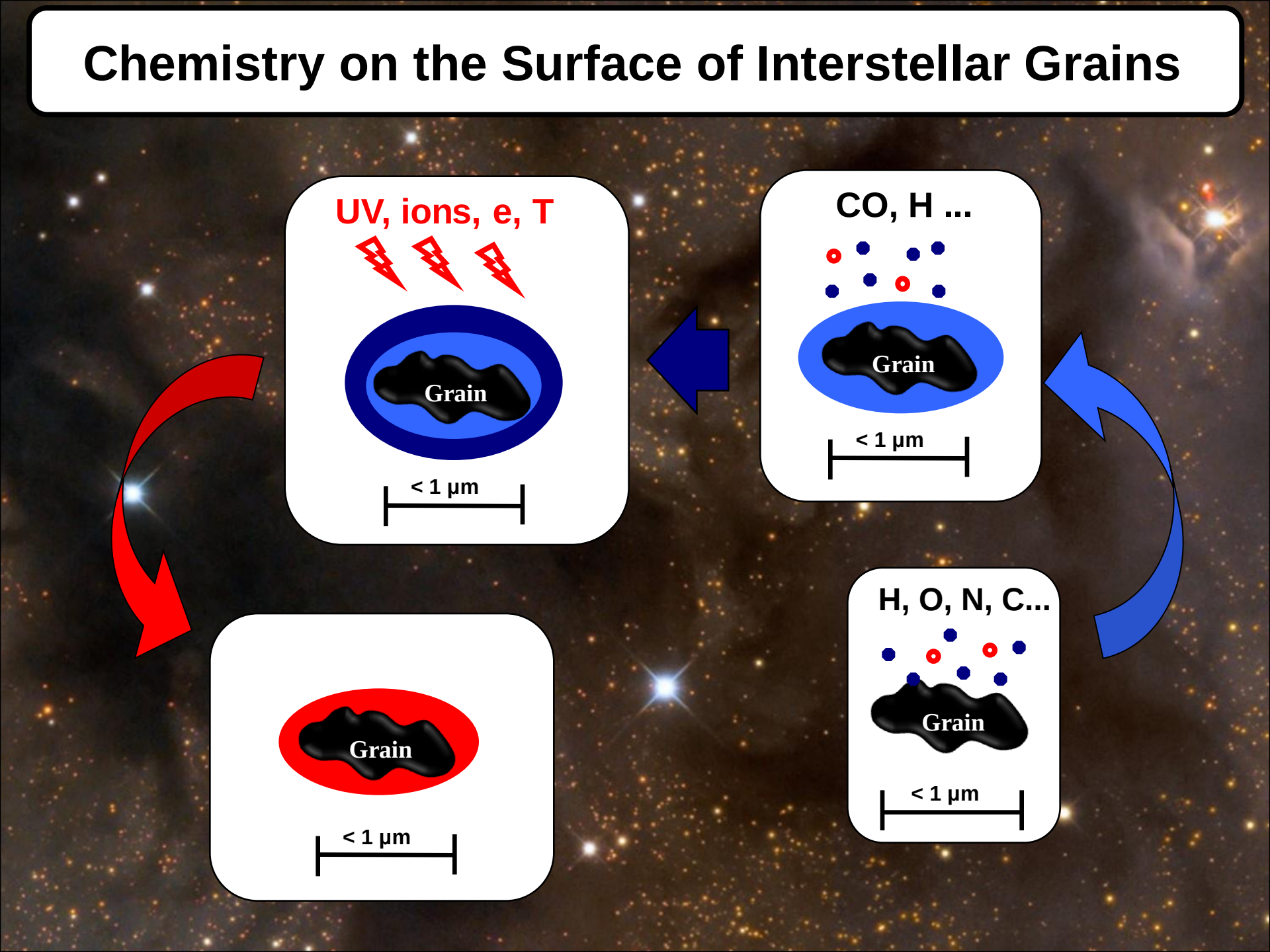


Glycerol



Ethylene Glycol

Chemistry on the Surface of Interstellar Grains



Chemistry on the Surface of Interstellar Grains

H_2O,

! CO, CO_2,

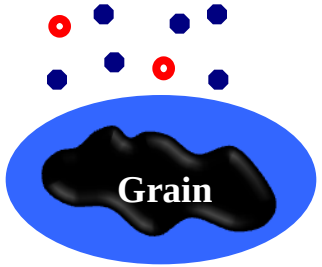
! CH_3OH, NH_3, CH_4,

XCN

$CO \rightarrow HCO \rightarrow H_2CO \rightarrow CH_3O \rightarrow CH_3OH$

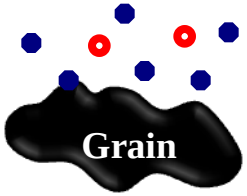
Hiraoka et al. 1994, Zhitnikov et al. 2002,
Watanabe et al 2002, Fuchs et al 2009

CO, H ...



< 1 μm

H, O, N, C...



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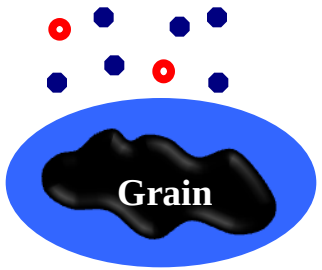

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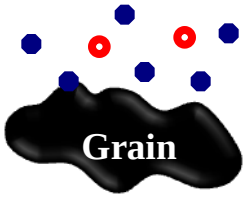
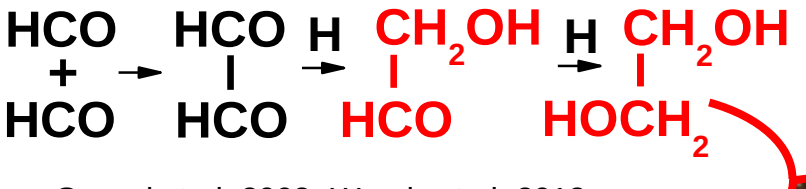
H, O, N, C...



< 1 μm

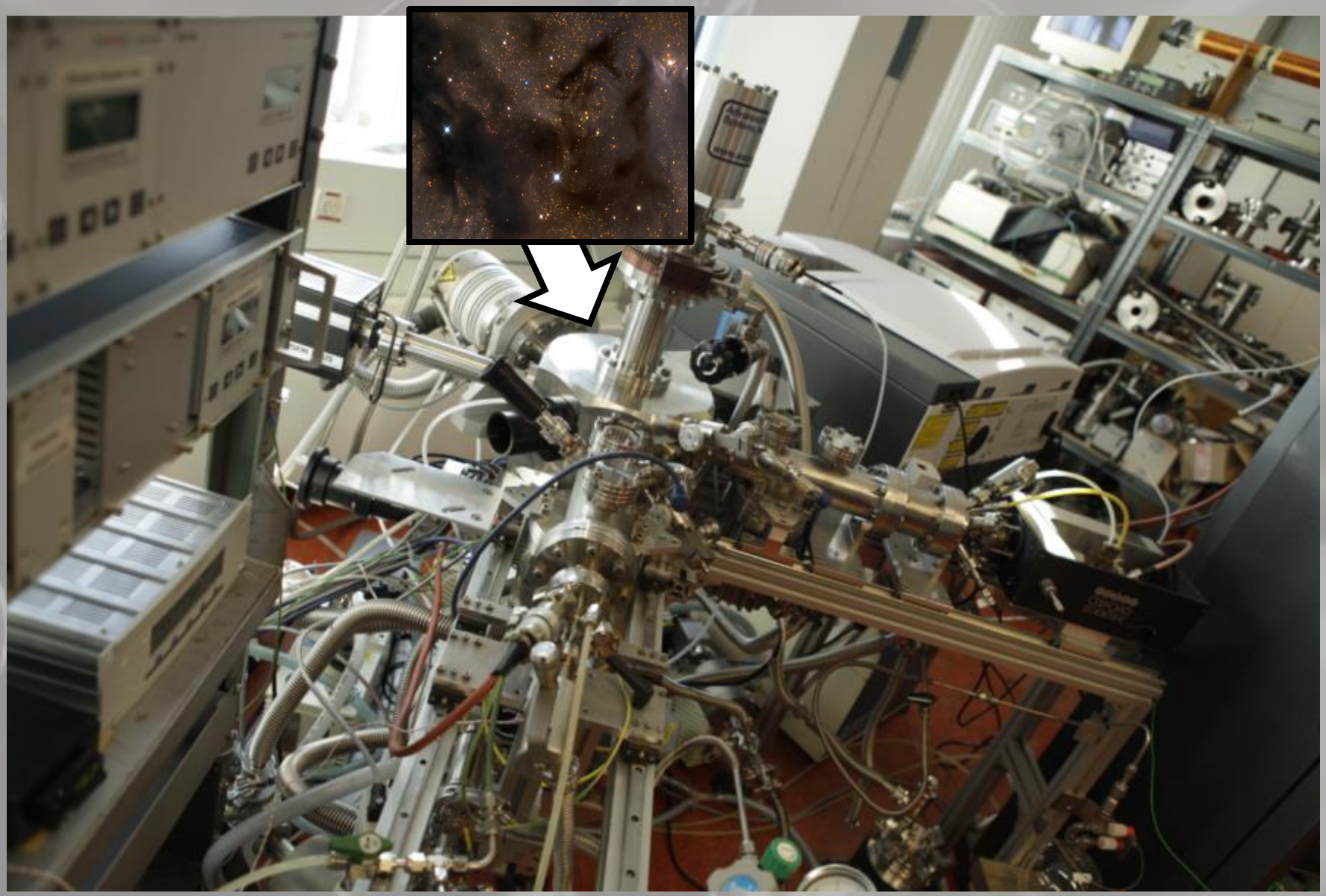


Garrod et al. 2008, Woods et al. 2013

Can We Address These Questions to the Lab?

Montage: Karoliina Isokoski (Sackler Laboratory)

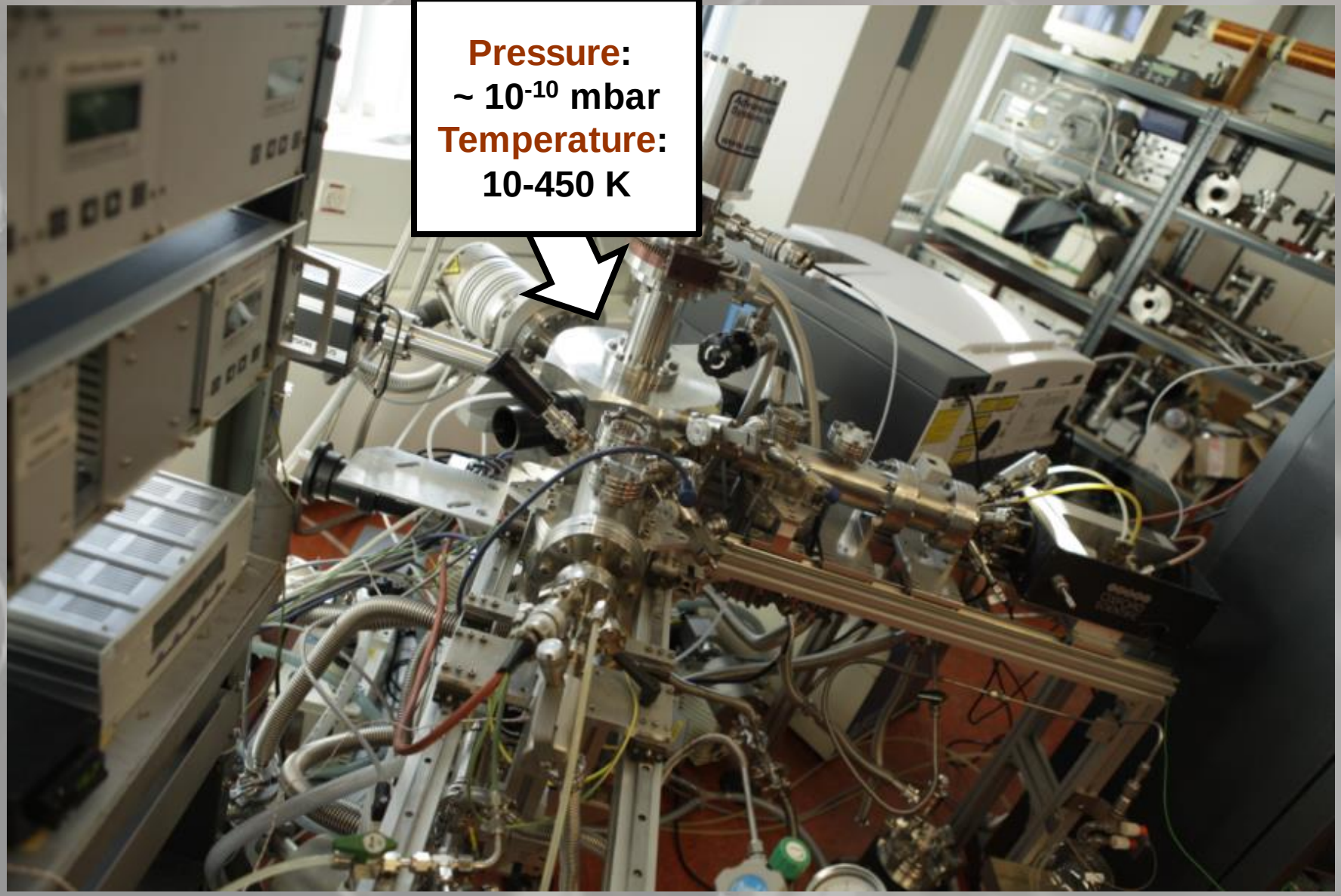
Analysis and Method



Ioppolo et al. 2013, Fedoseev et al. 2016

Sackler Laboratory for Astrochemistry

Analysis and Method



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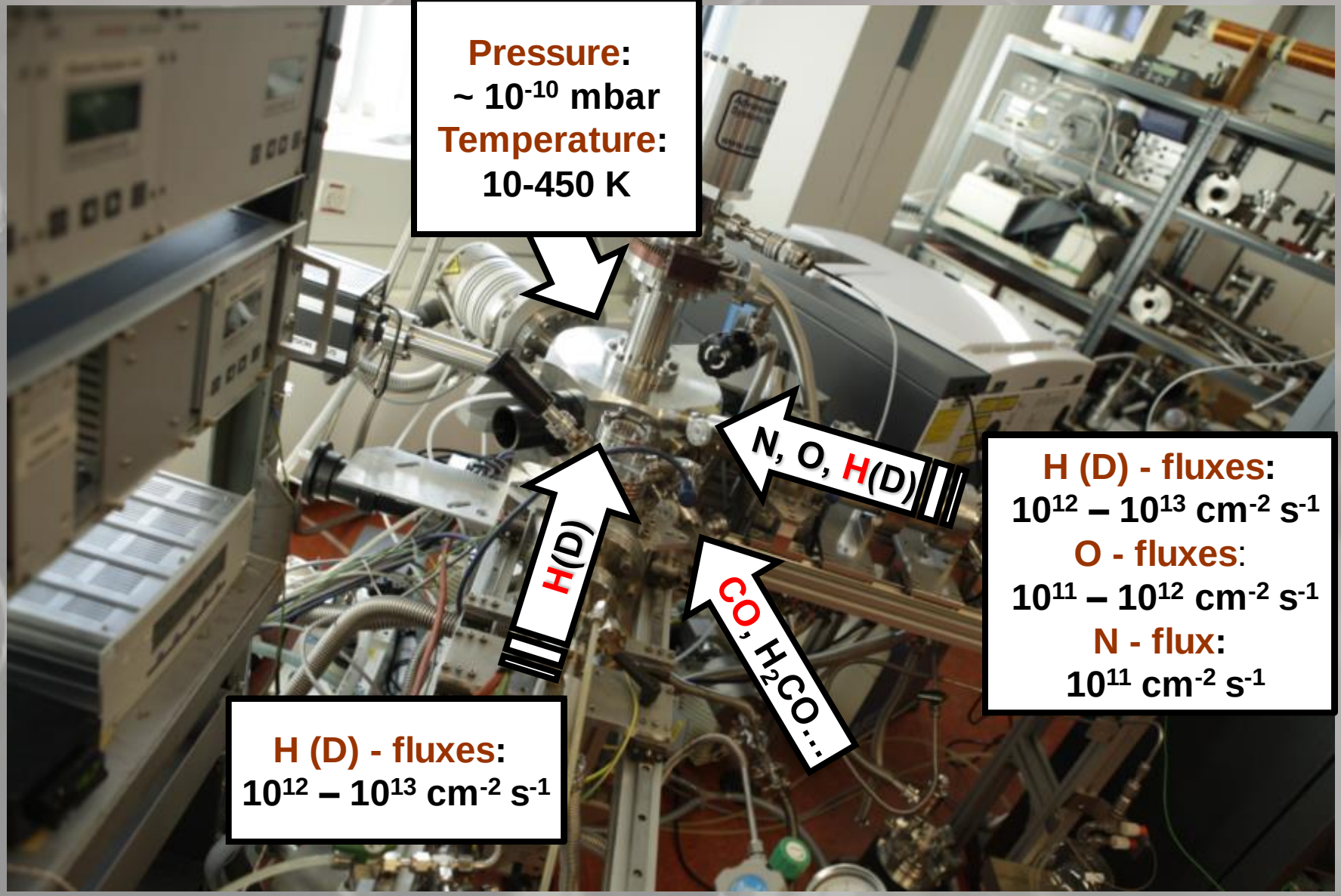
Sackler Laboratory for Astrochemistry

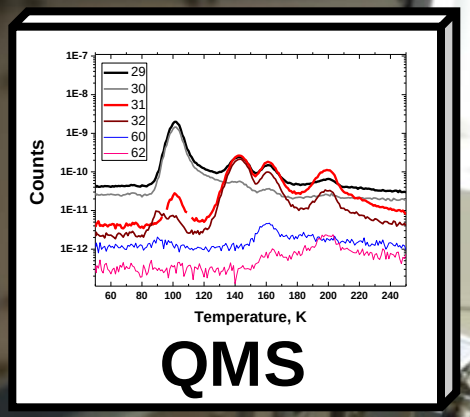
Analysis and Method



Ioppolo et al. 2013, Fedoseev et al. 2016

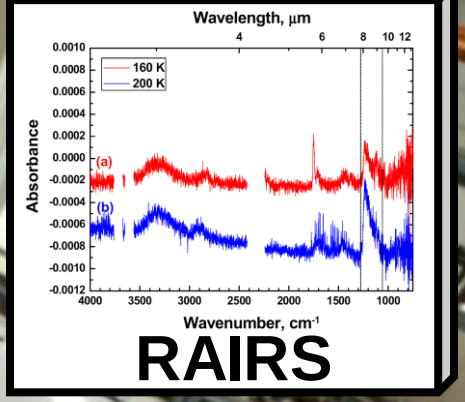
Sackler Laboratory for Astrochemistry

Analysis and Method



QMS

Pressure:
~ 10^{-10} mbar
Temperature:
10-450 K



RAIRS

N, O, H(D)

H(D)

CO, H_2CO...

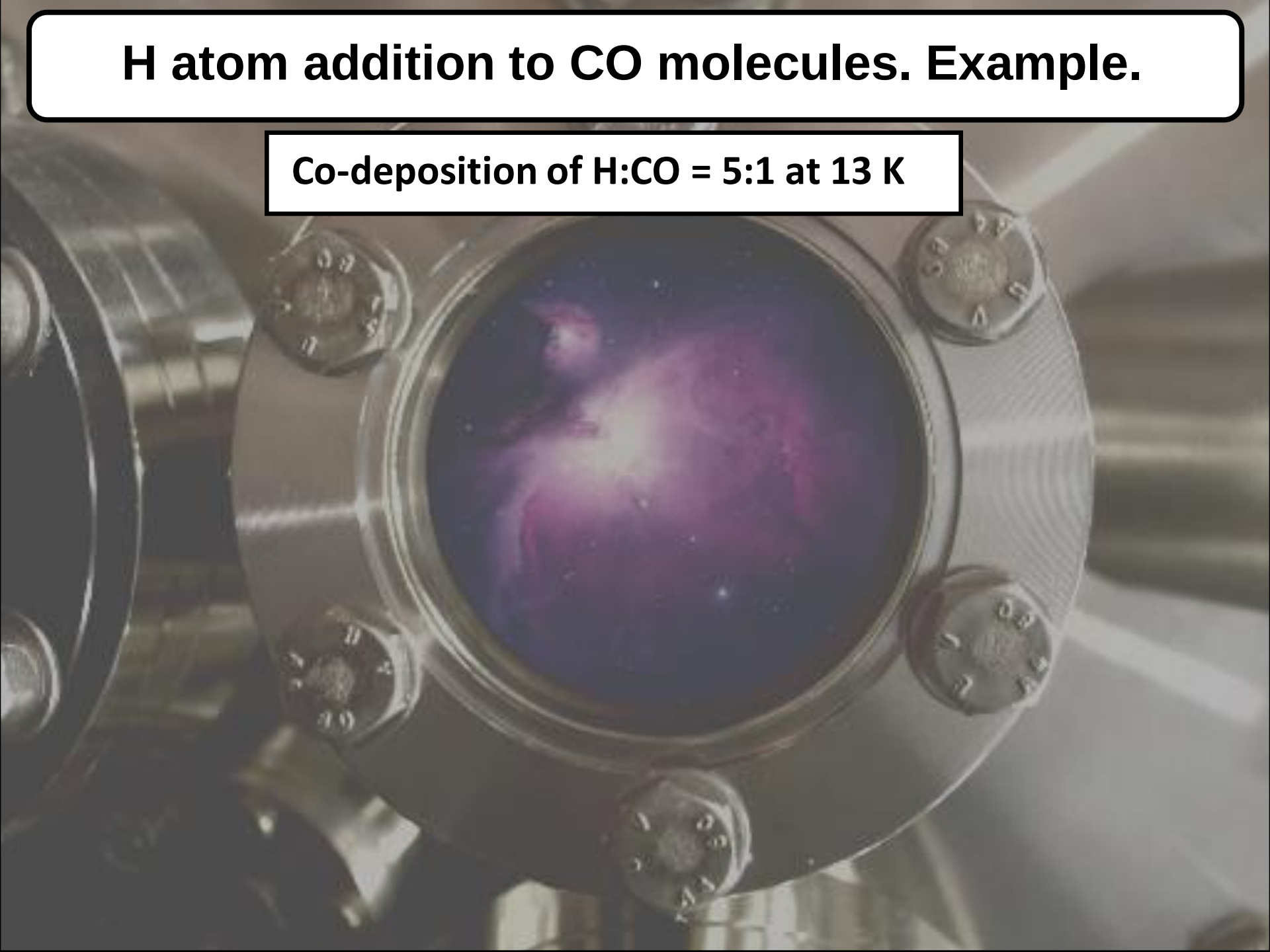
H (D) - fluxes:
10^{12} – 10^{13} cm^{-2} s^{-1}
O - fluxes:
10^{11} – 10^{12} cm^{-2} s^{-1}
N - flux:
10^{11} cm^{-2} s^{-1}

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

Ioppolo et al. 2013, Fedoseev et al. 2016

Sackler Laboratory for Astrochemistry

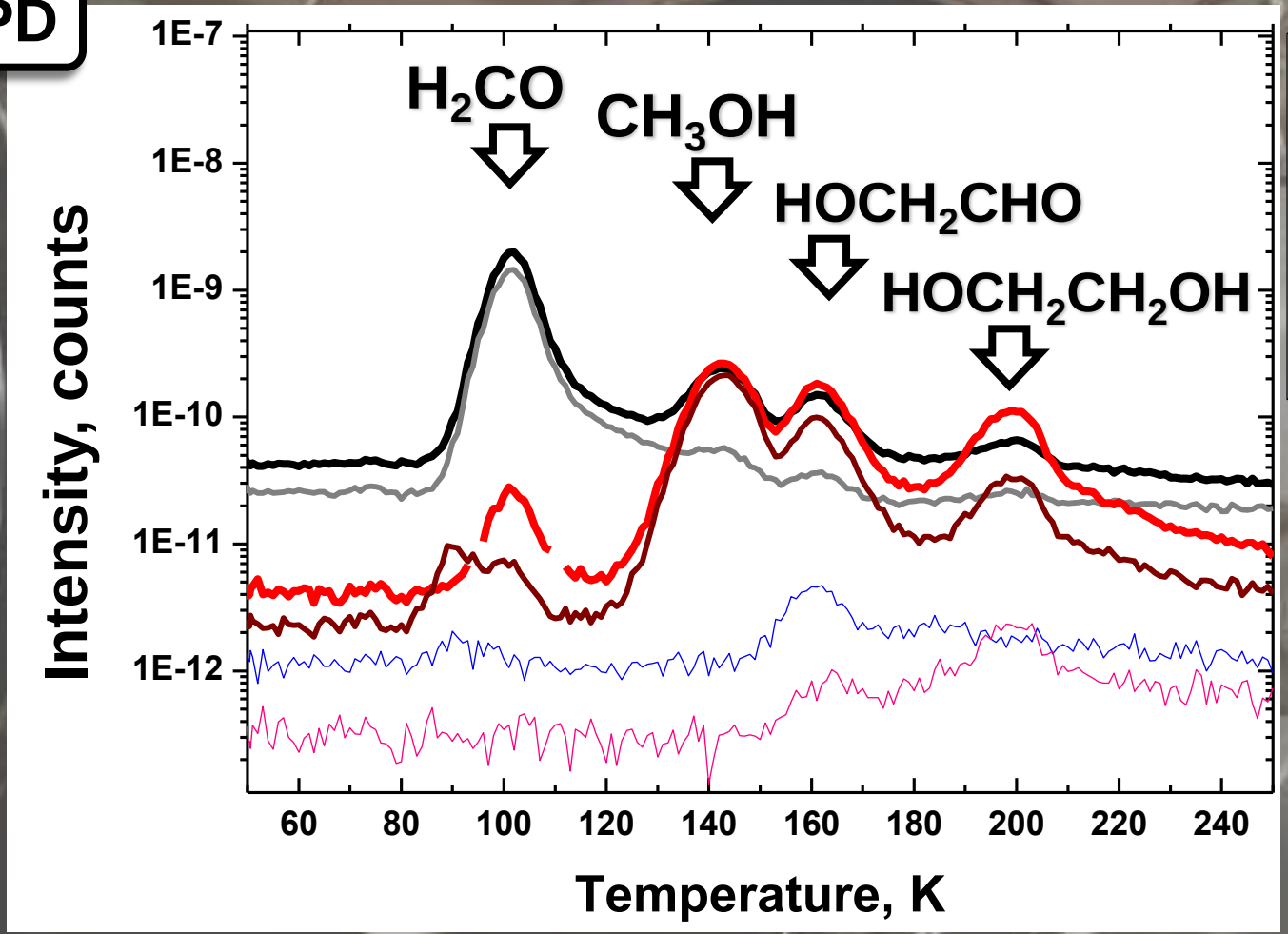
H atom addition to CO molecules. Example.



H atom addition to CO molecules. Example.

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

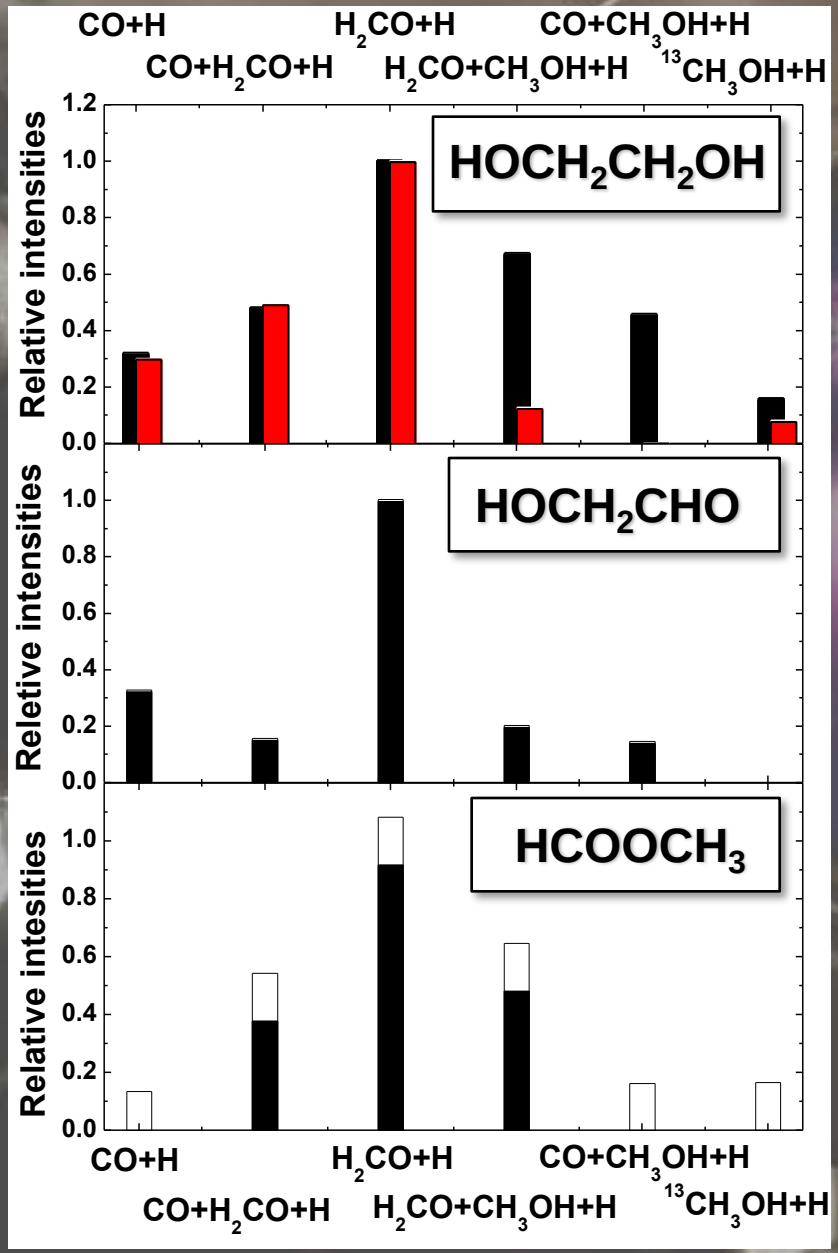
TPD

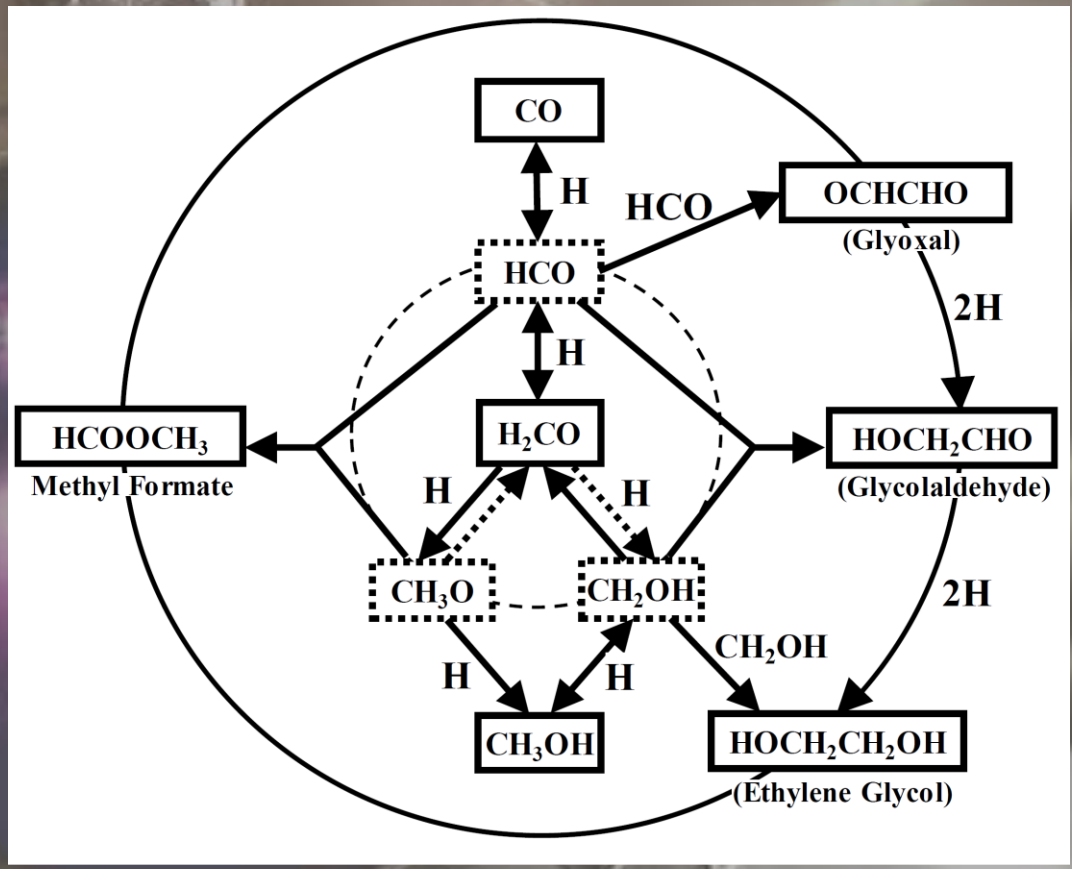


H-atom total fluence: 1.8E+17 atoms cm^{-2}

Fedoseev et al. 2015c

Constructing the Full Reaction Network

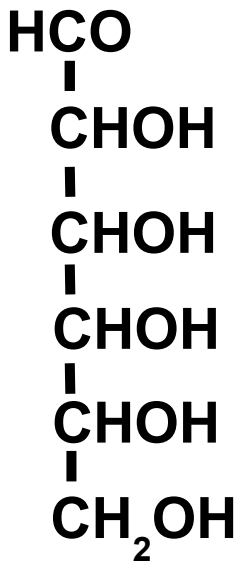




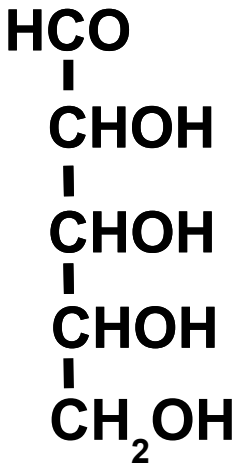
Fedoseev et al. 2015c, Chuang et al. 2016
Hidaka et al. 2009,
Butscher et al. 2015, Minissale et al. 2016

Can we form three-carbon bearing analogues?

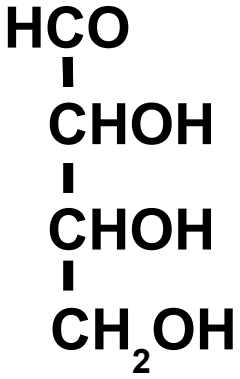
SUGARS



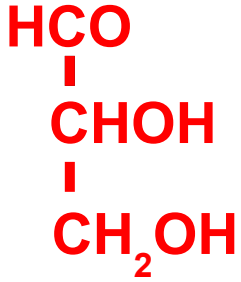
Glucose



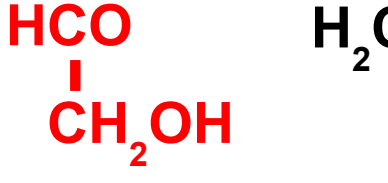
Ribose



Erythrose

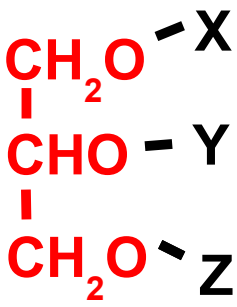


Glyceraldehyde

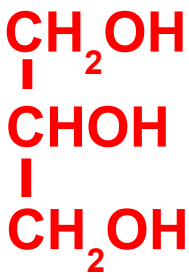


Glycolaldehyde

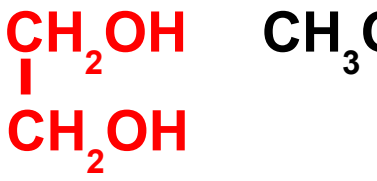
FATS:



Trygliceride

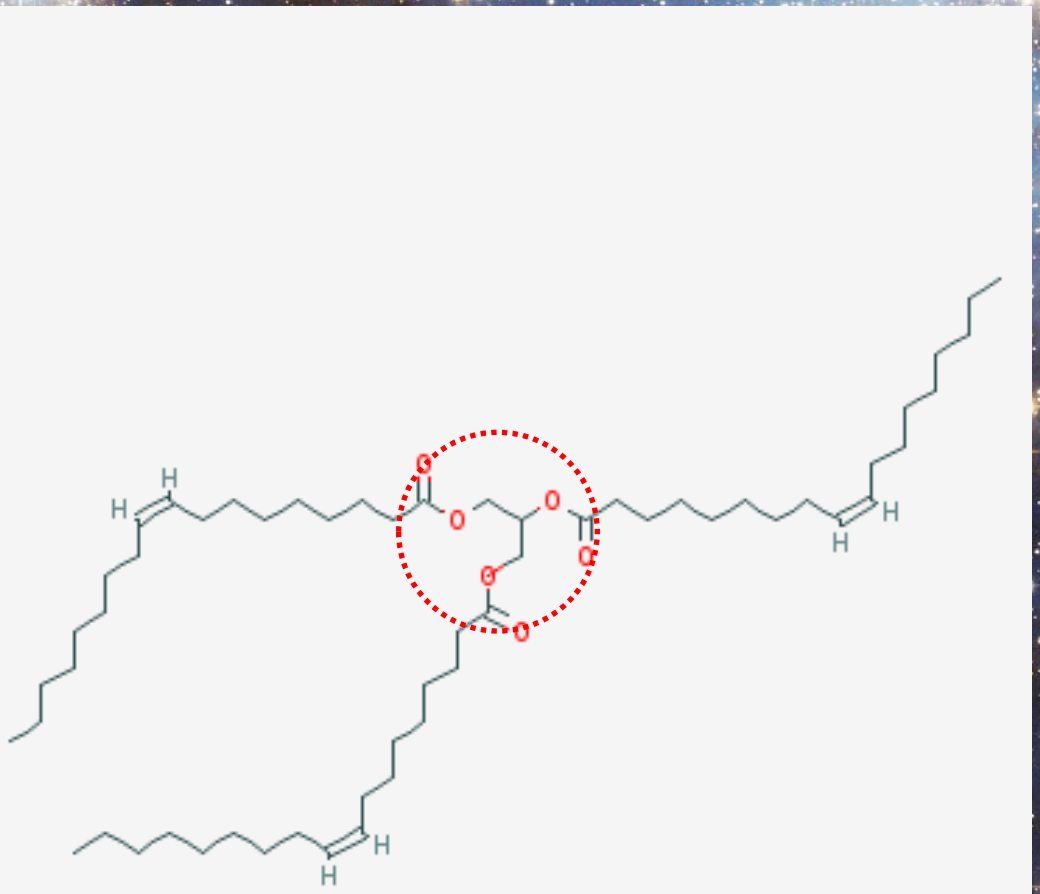


Glycerol



Ethylene Glycol

Glycerol is a backbone of all lipids

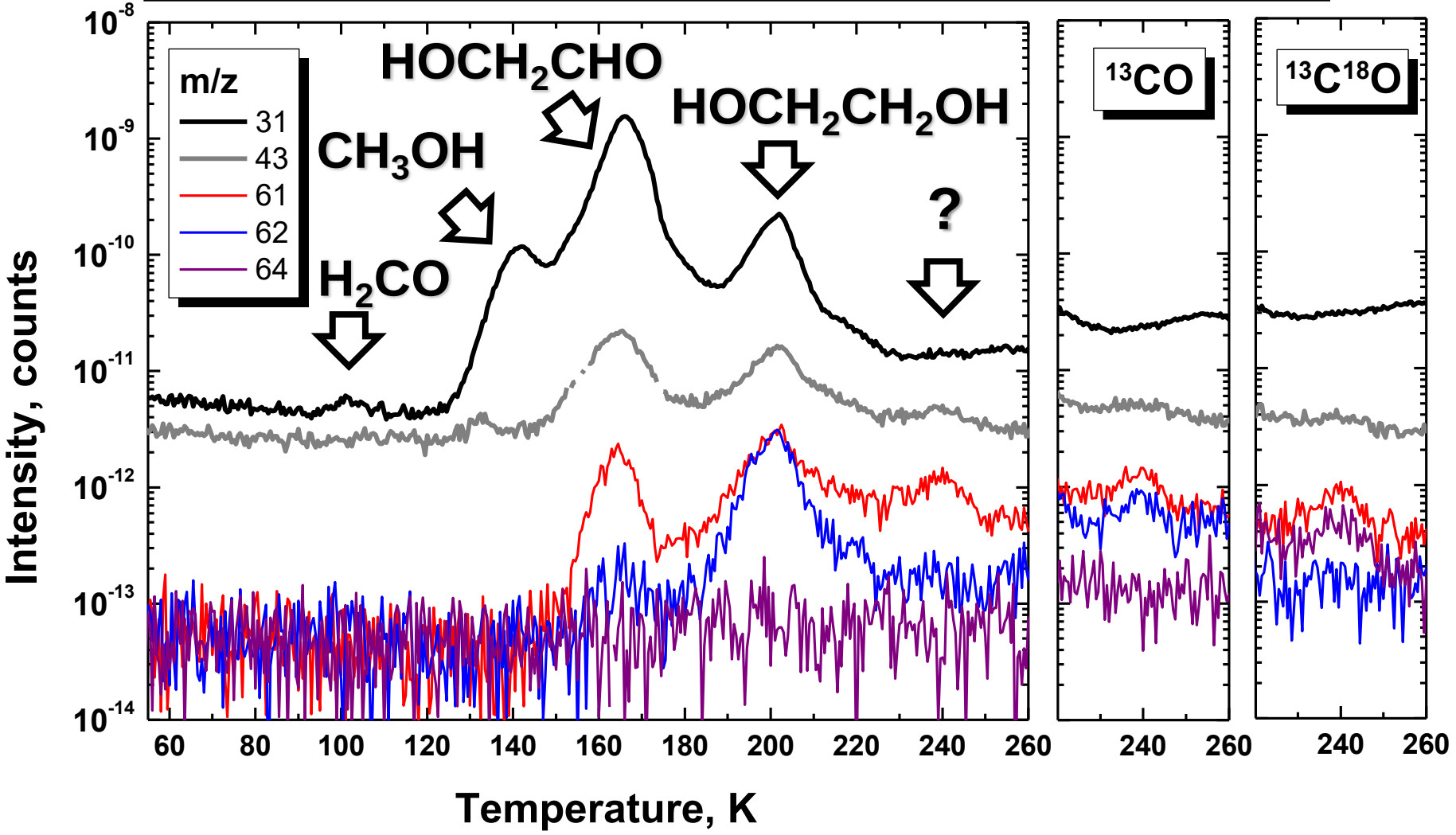


Glycerides comprise ~98% of olive oil, *e.g.*, Glyceryl trioleate (~ 50 %)

Gunstone 2011

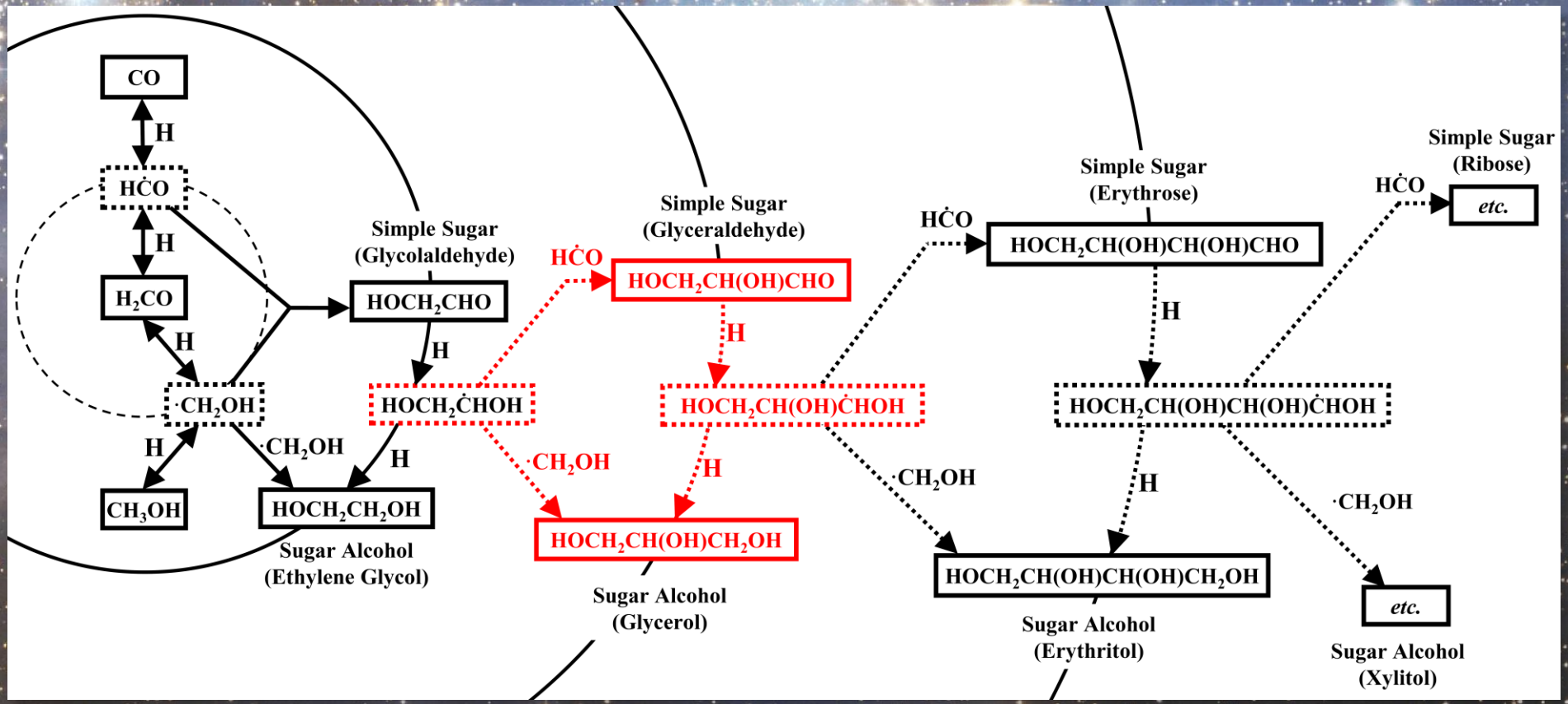
Hydrogenation of CO with Glycolaldehyde (1:1)

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



Fedoseev et al. 2017

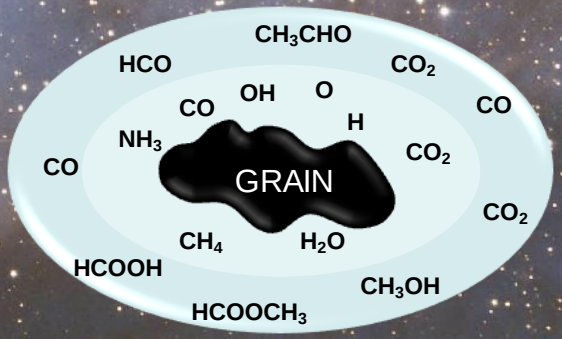
Chemistry on the Surface of Interstellar Grains

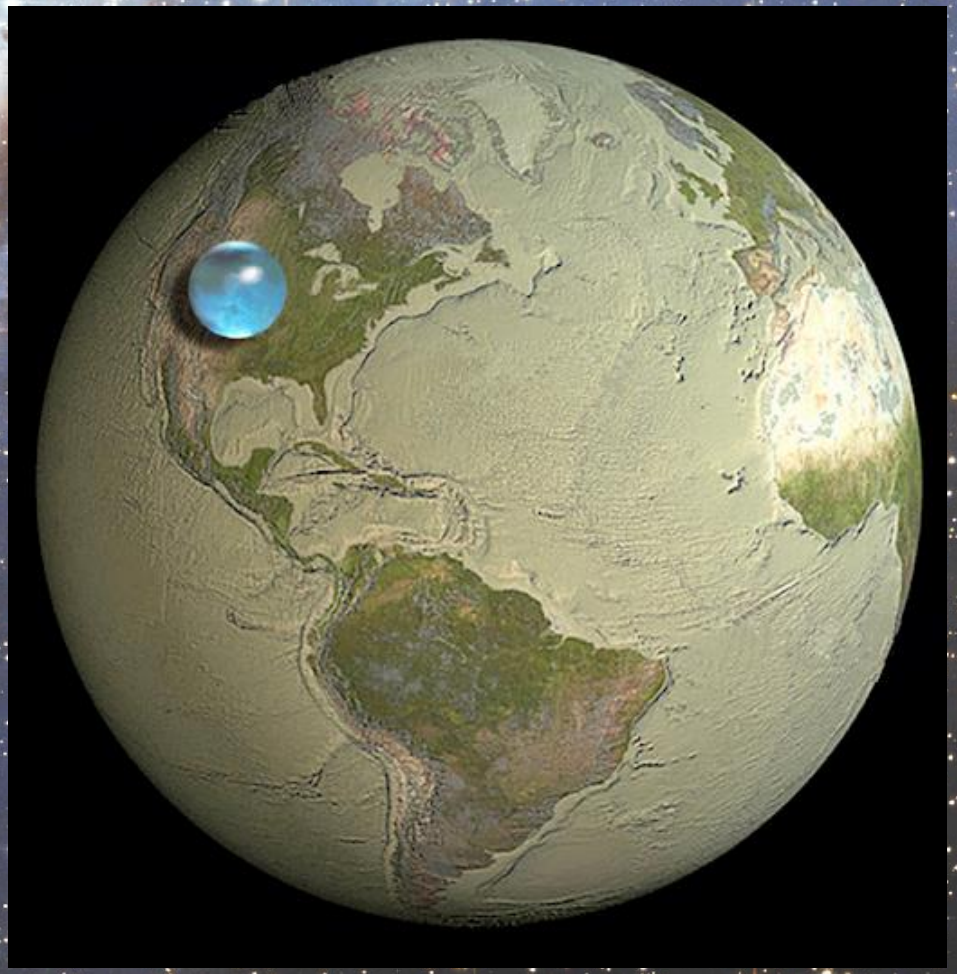


Fedoseev et al. 2017

Why is It Interesting for Us?

Icy Grain





Hartog et al. 2011

Kevin Hand (JPL/Caltech)

Why is It Interesting for Us?

H_2O in L1544:

5×10^{27} kg

CH_3OH 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

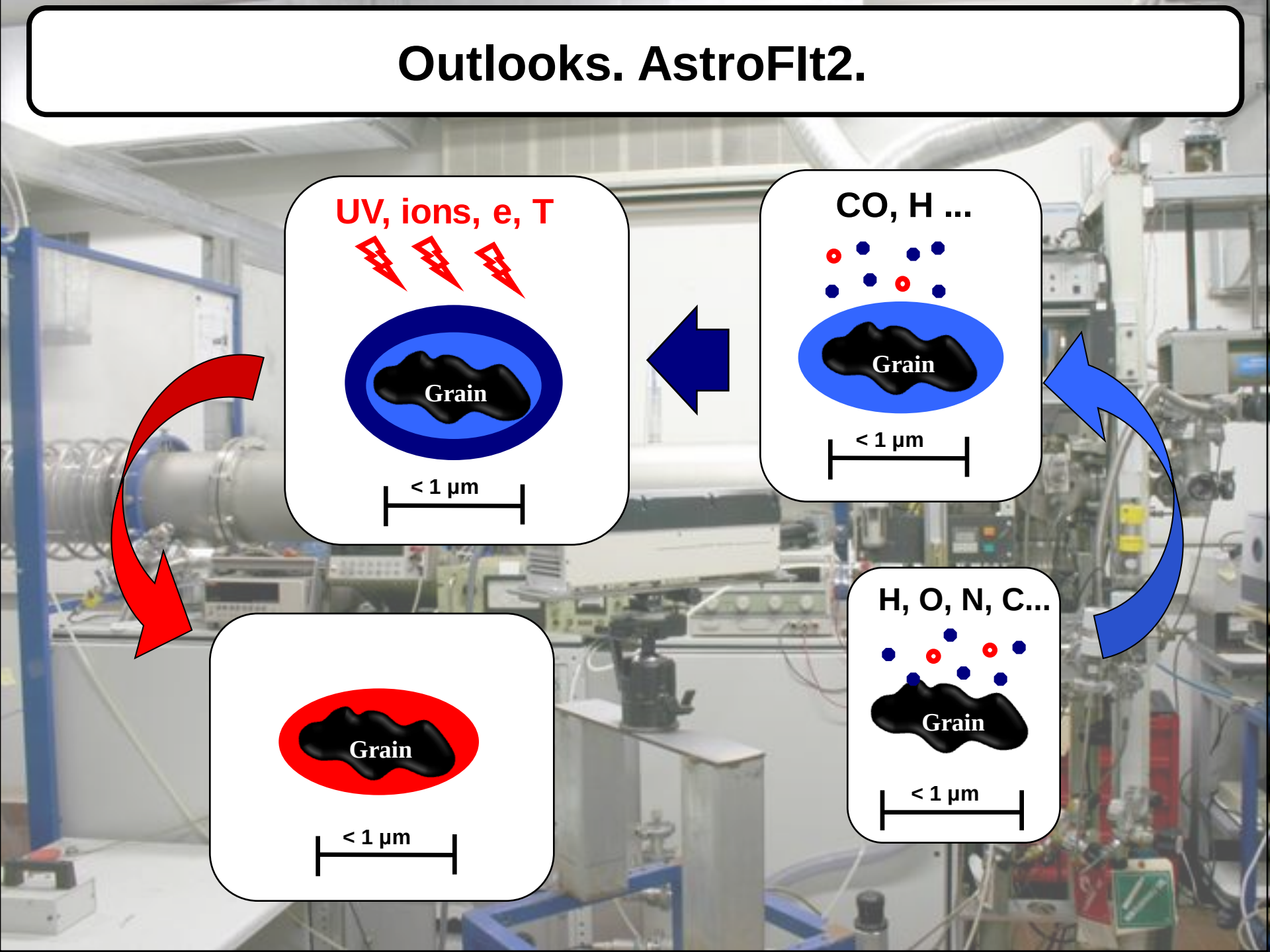
3.2×10^{12} kg

Glycerol in this life forms

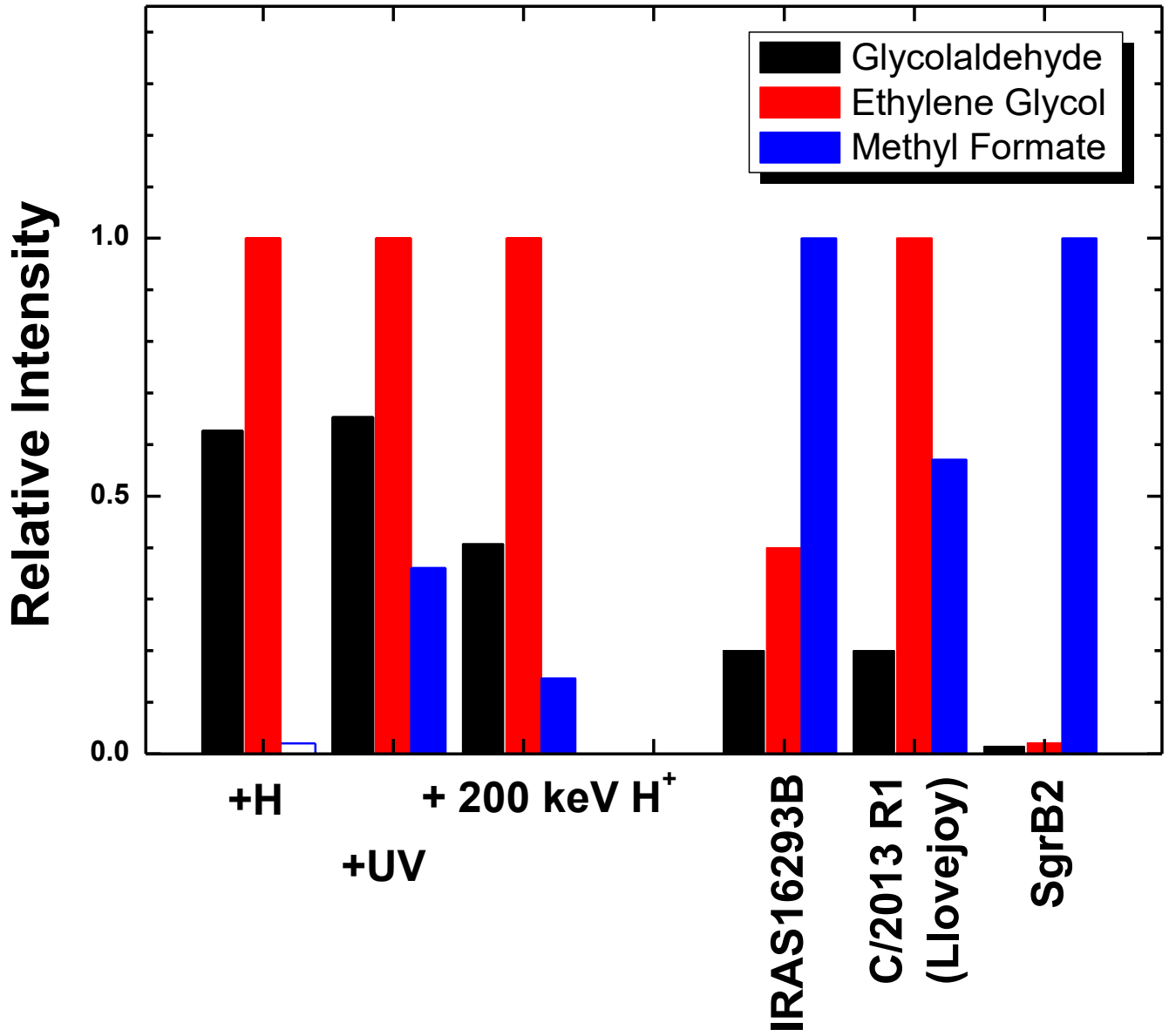
$\sim 1 \times 10^{10}$ kg

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

Outlooks. AstroFIt2.



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

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