NanoSpace

DAN Dutch Astrochemistry Network III

Laboratory Surface Physics

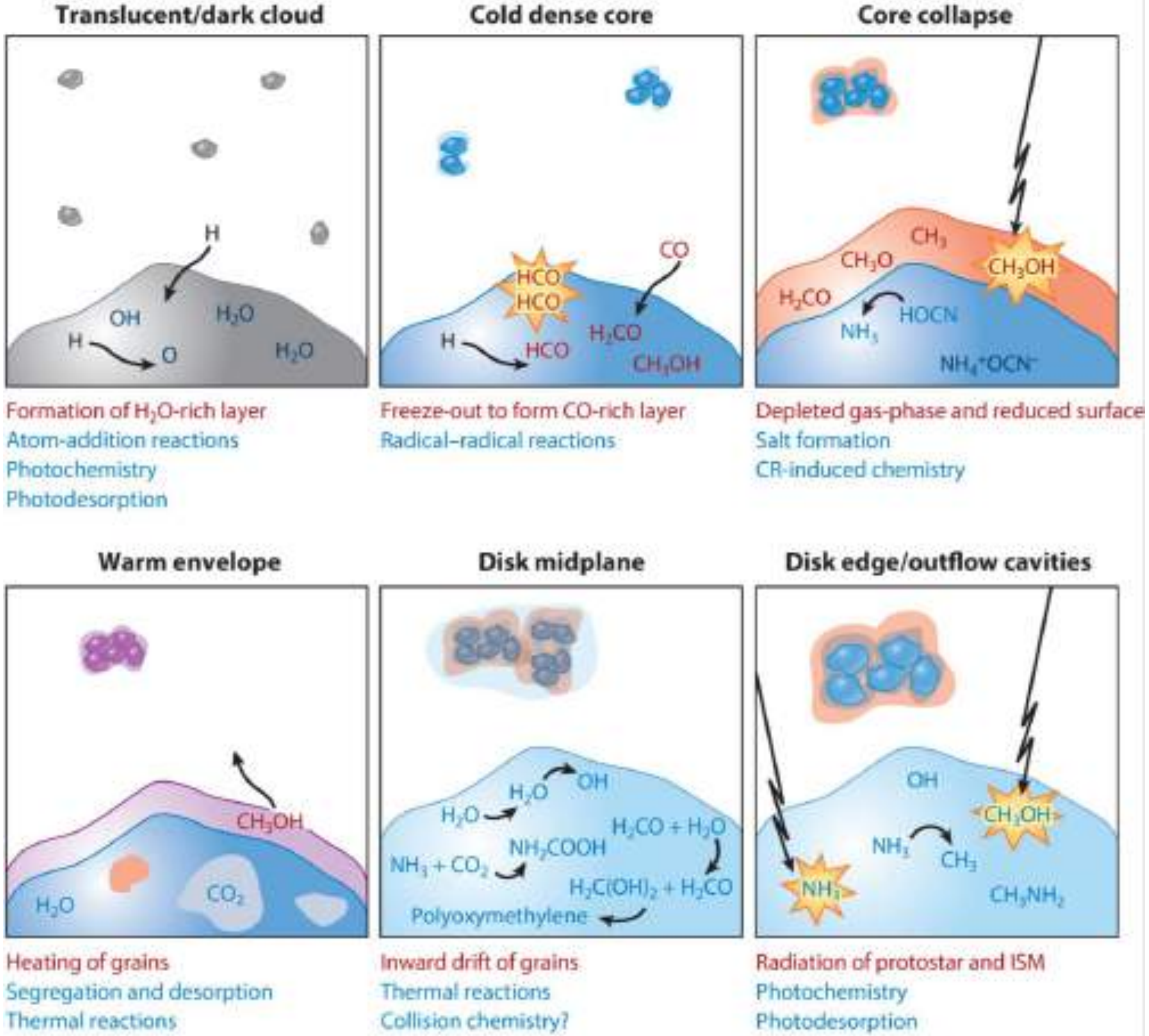
Sergio Ioppolo

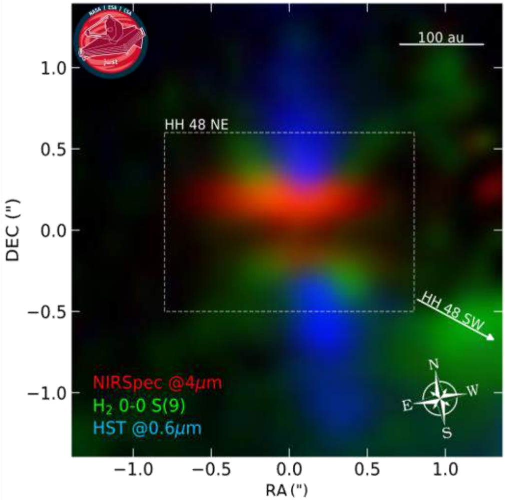
InterCat, Department of Physics and Astronomy, Aarhus University

AARHUS UNIVERSITY

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

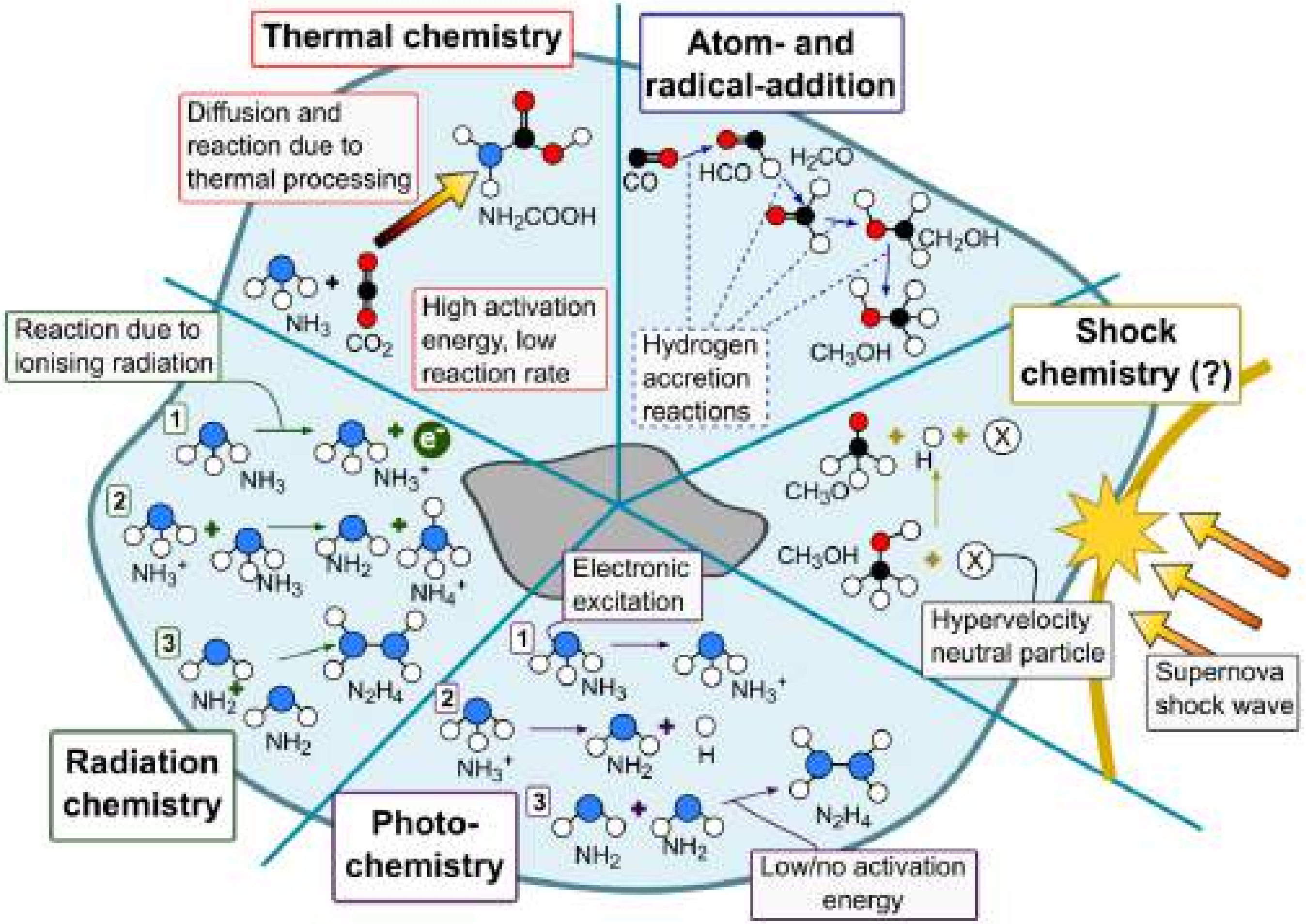
Funded by the European Union





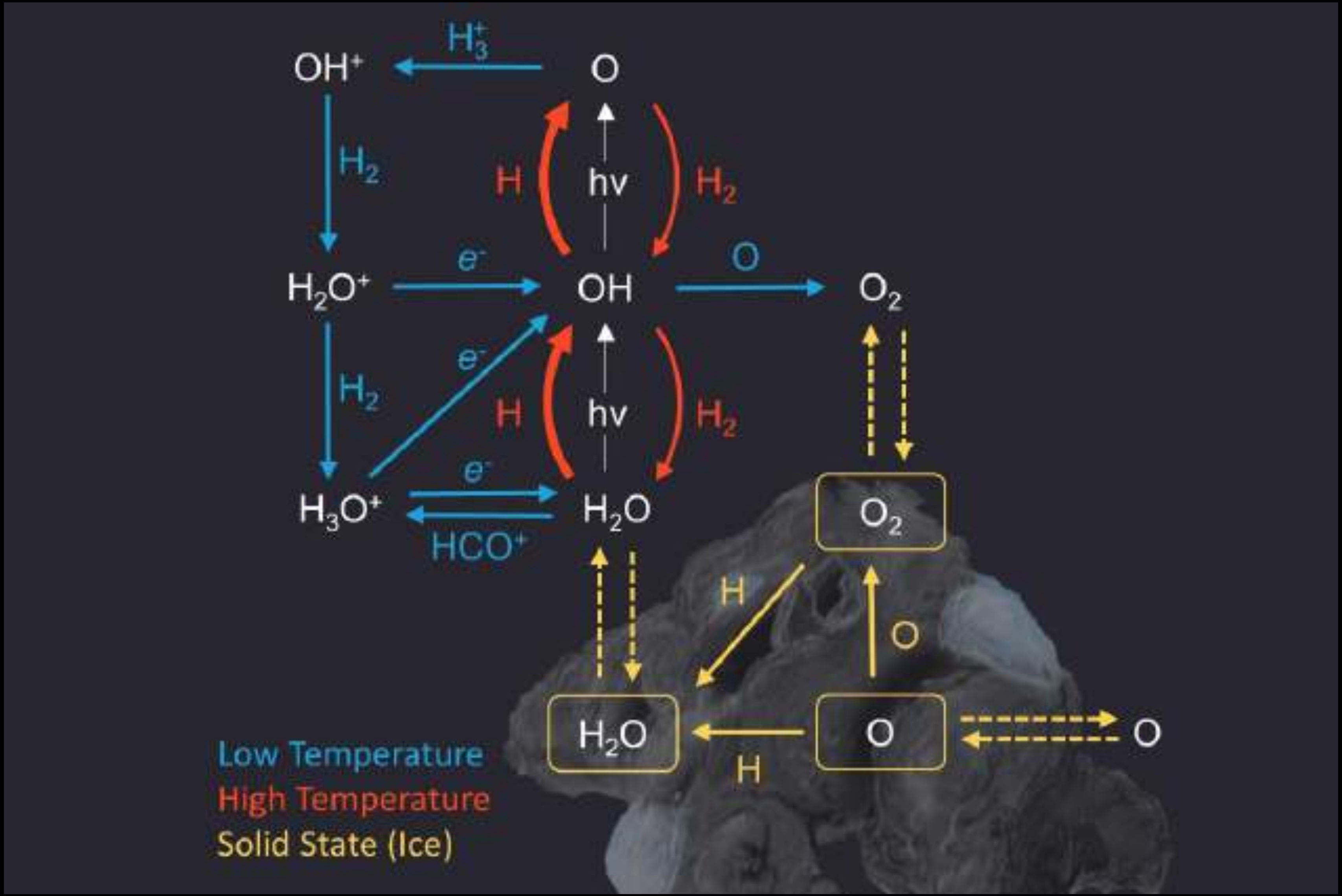
Cuppen, Linnartz & Ioppolo ARAA (2024)

Ice Grain Chemistry



Arumainayagam *et al.*, Chem. Soc. Rev. (2019)

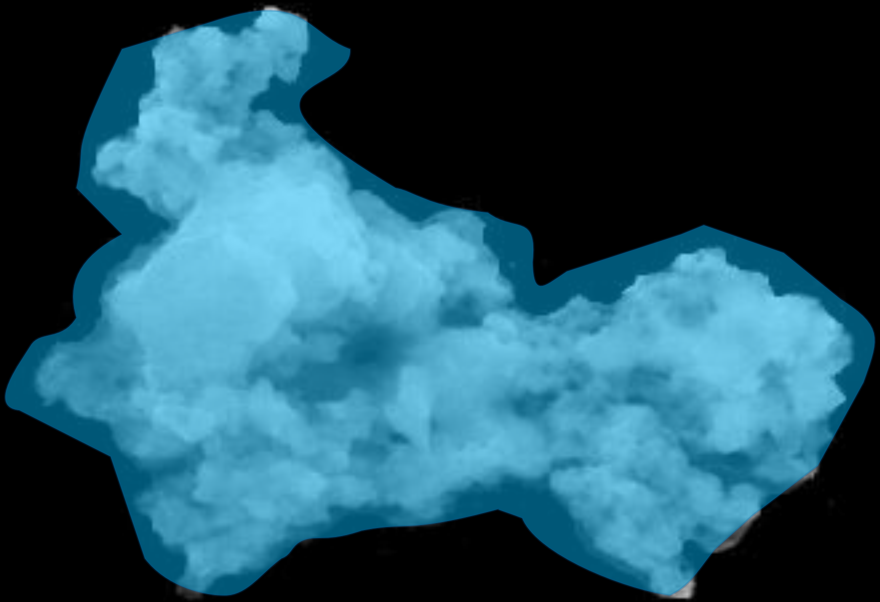
Formation Routes of Water Ice



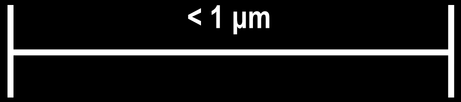
Low Temperature
High Temperature
Solid State (Ice)

Wilkins & Blake (2021)

Interstellar Water Ice



T = 10-20 K
$n > 10^2$ cm^{-3}

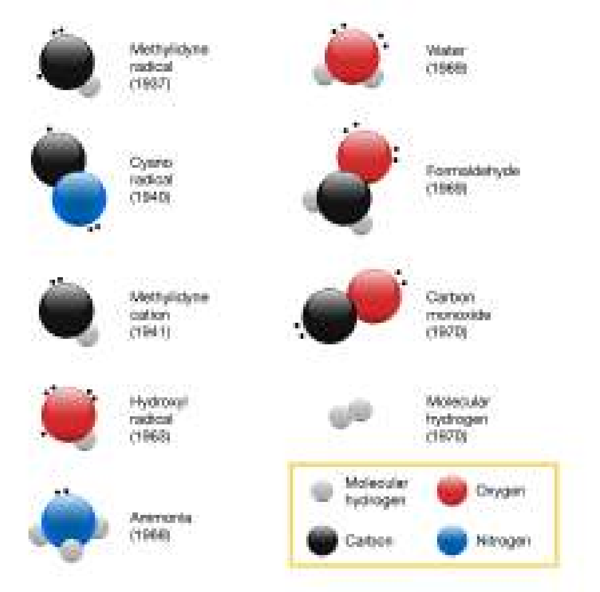


RECHERCHES ASTRONOMIQUES
DE L'OBSERVATOIRE D'UTRECHT

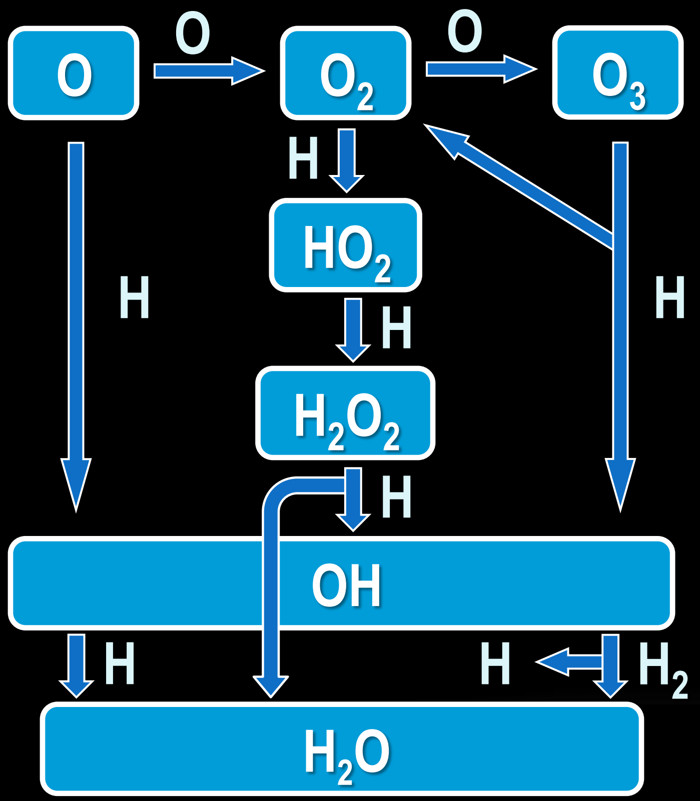
XI
PART 2

THE SOLID PARTICLES IN INTERSTELLAR SPACE
BY H. C. VAN DE HULST

van de Hulst, (1949)

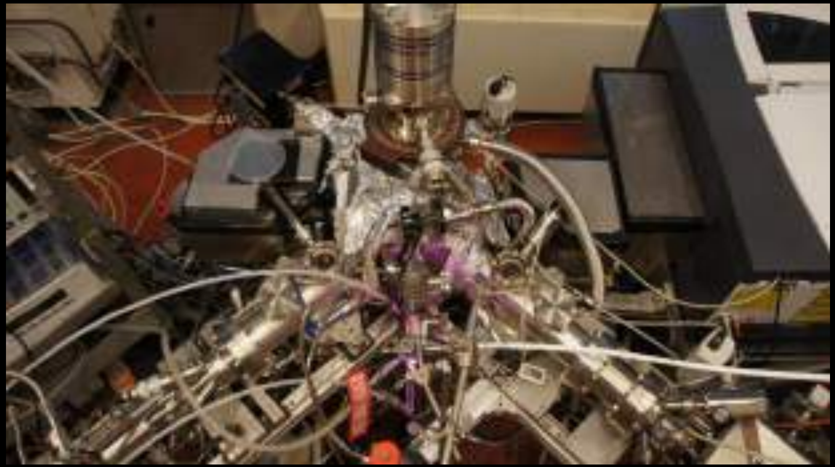


Interstellar Water Ice



Tielens & Hagen, A&A (1982)

Interstellar Water Ice

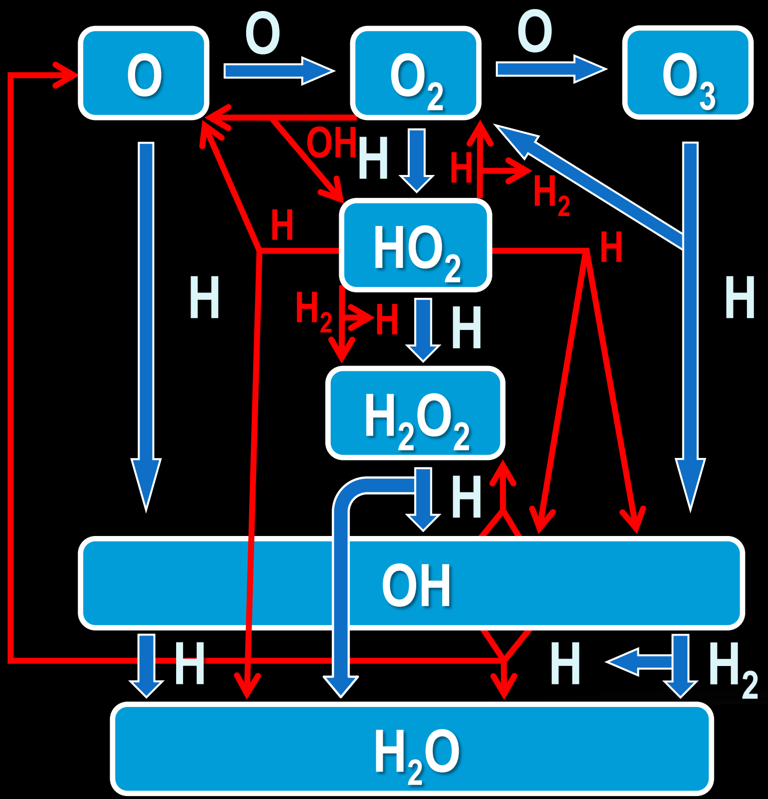


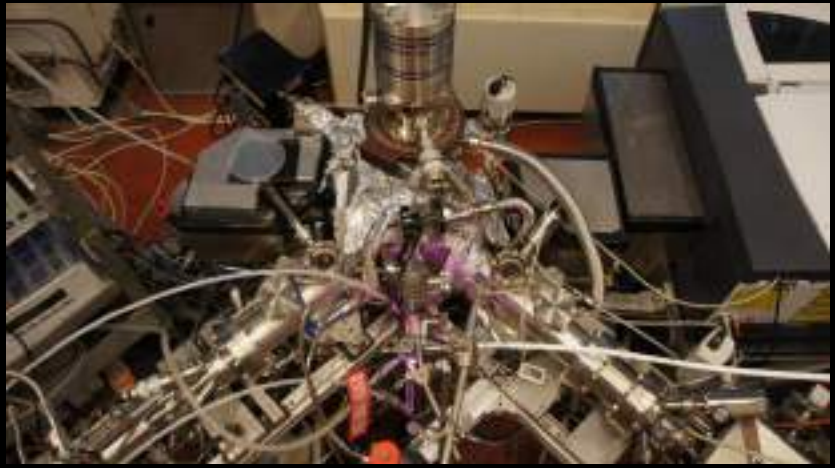
Miyauchi *et al.*, CPL (2008)

Ioppolo *et al.*, ApJ (2008)

Matar *et al.*, A&AL (2008)

Interstellar Water Ice

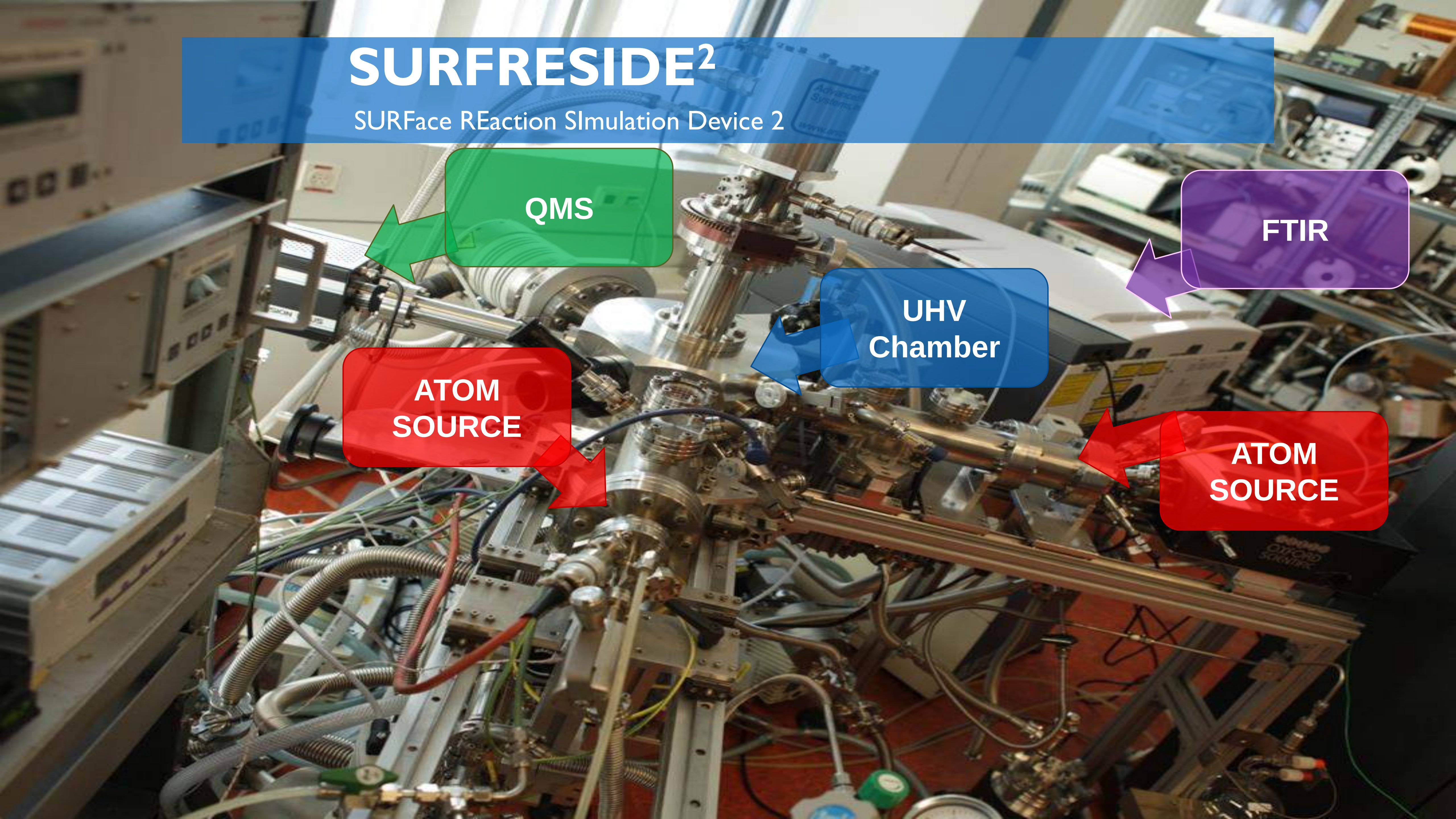




van Dishoeck *et al.*, CR (2013)
van Dishoeck *et al.*, A&A (2021)

SURFRESIDE^2

SURFace REaction SImulation Device 2



QMS

FTIR

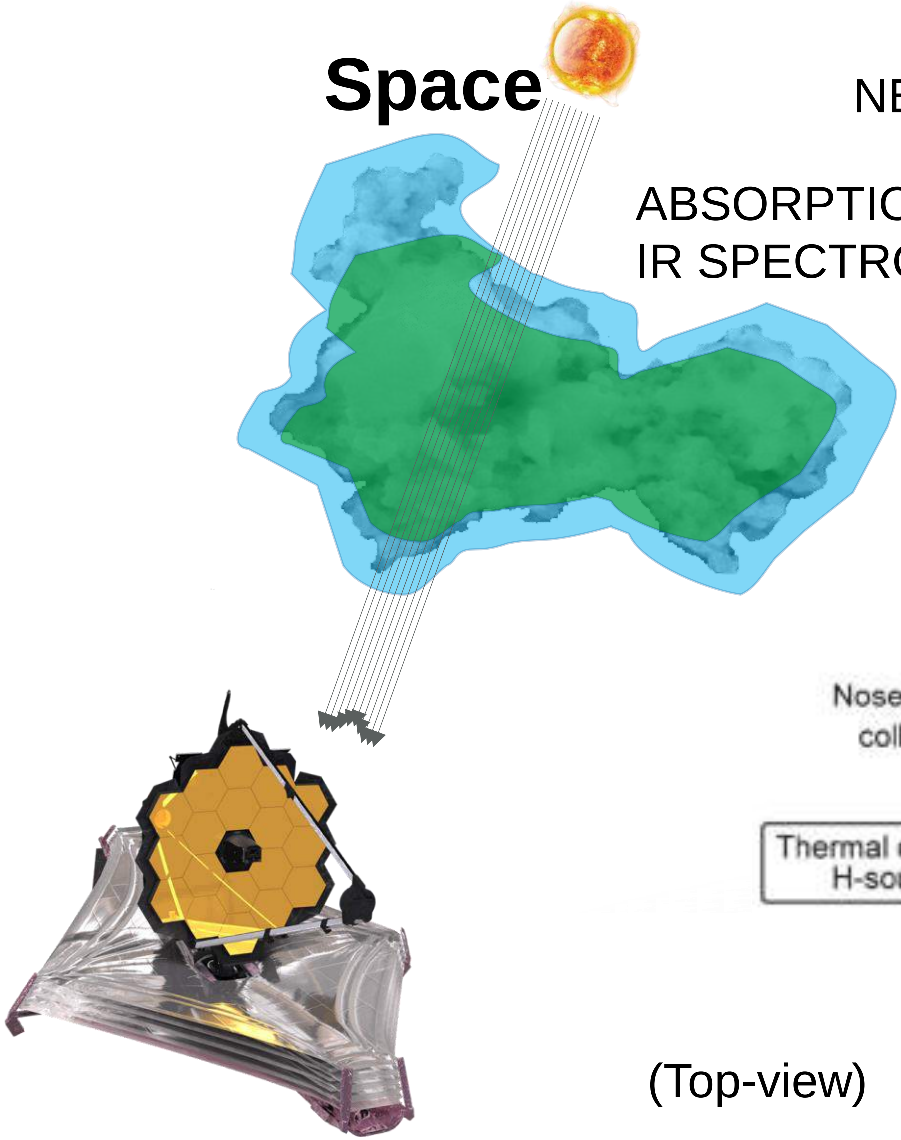
UHV Chamber

ATOM SOURCE

ATOM SOURCE

Experimental Techniques

Space

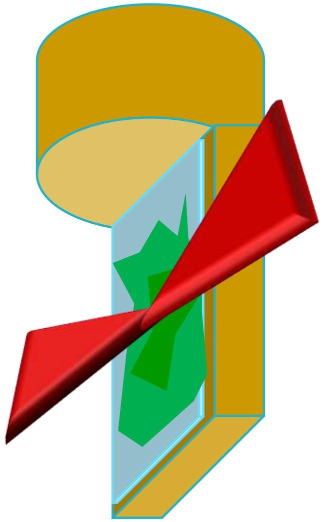


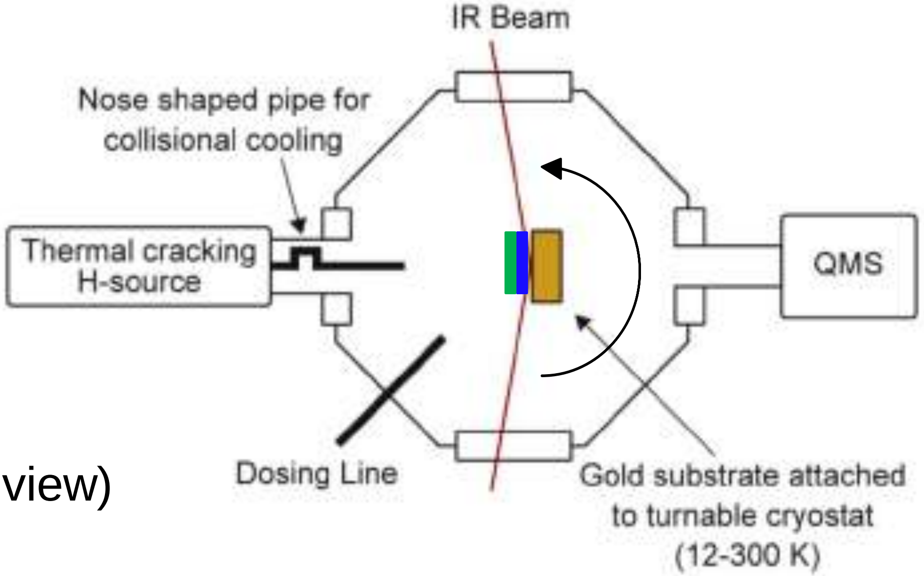
NEW SPECIES FORMED

ABSORPTION
IR SPECTROSCOPY

Lab

RAIR
REFLECTION
ABSORPTION
IR SPECTROSCOPY



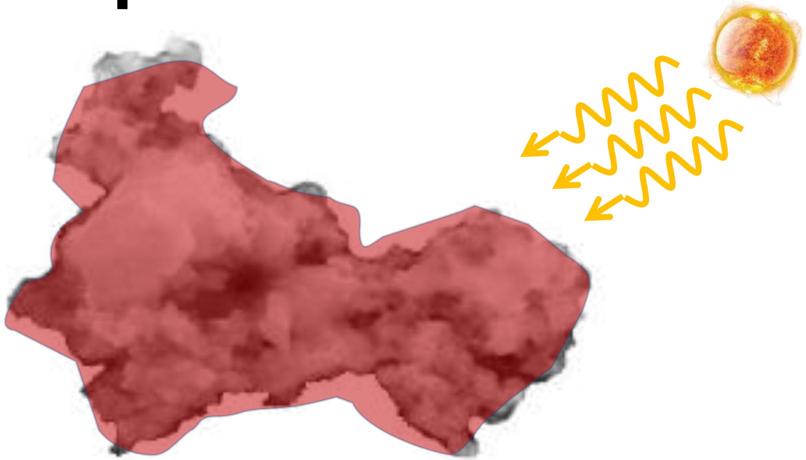


(Top-view)

Experimental Techniques

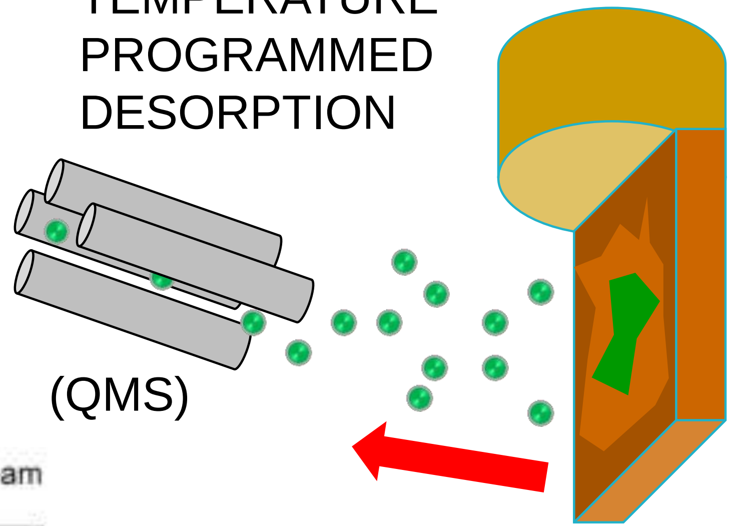
Space

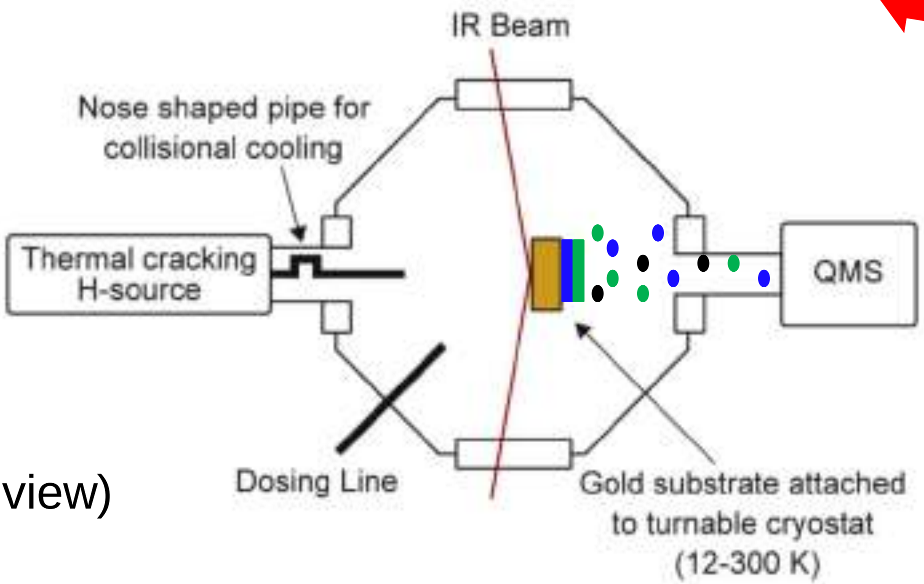
THERMAL PROCESSING



TPD
TEMPERATURE
PROGRAMMED
DESORPTION

Lab

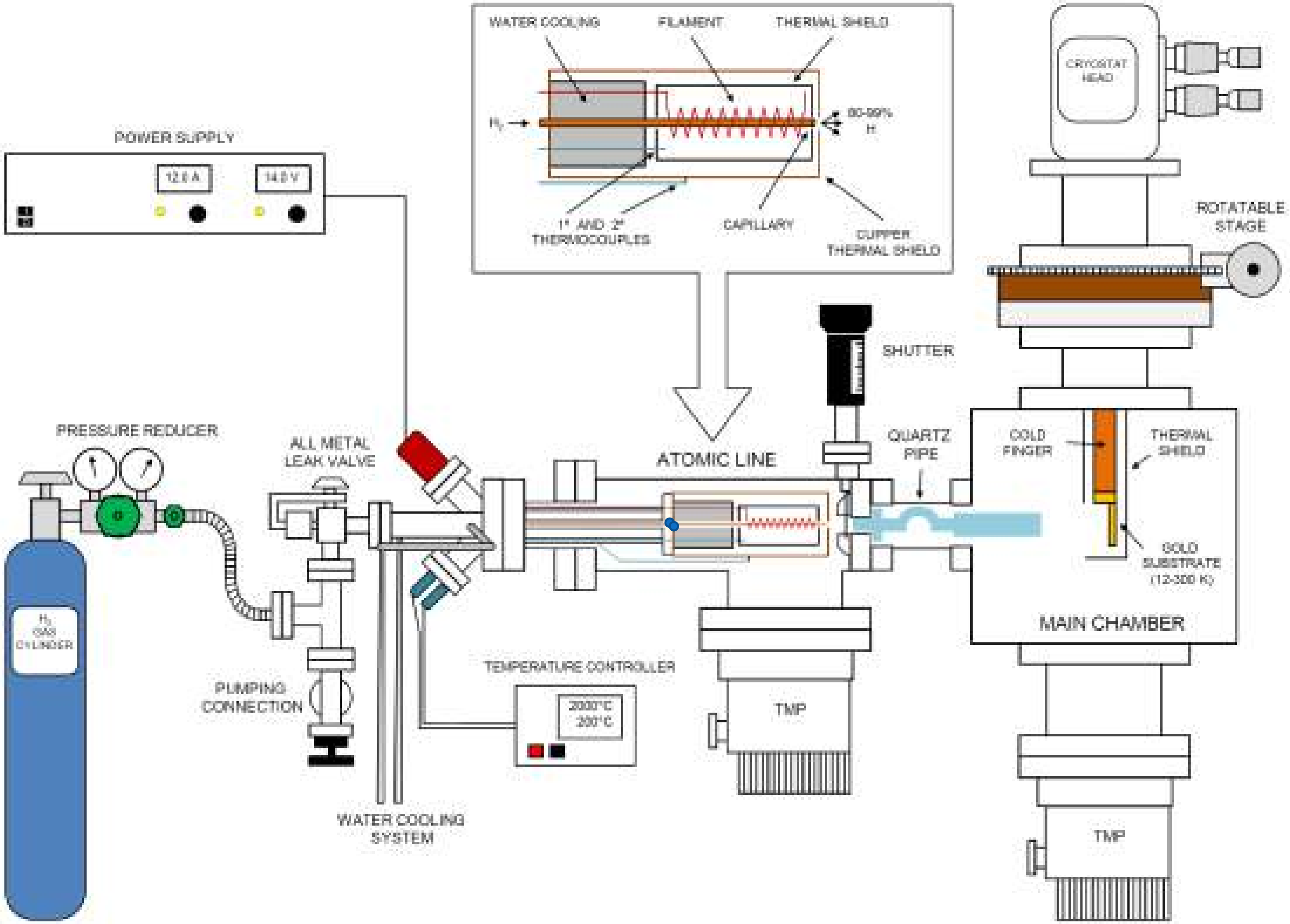




(Top-view)

SURFRESIDE^2

Hydrogen Atom Beam Source (HABS)



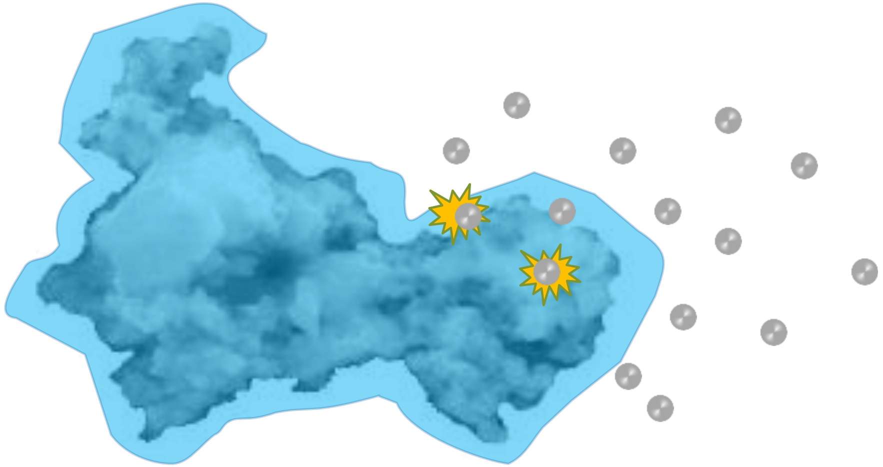
Experimental Procedure

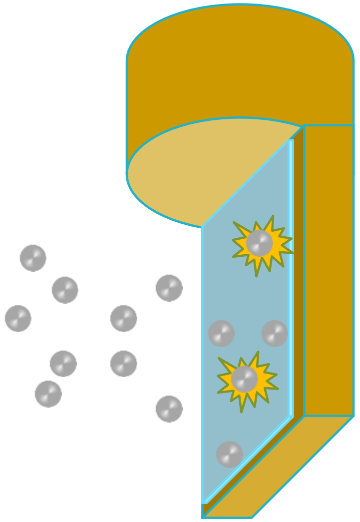
Pre-deposition Experiments

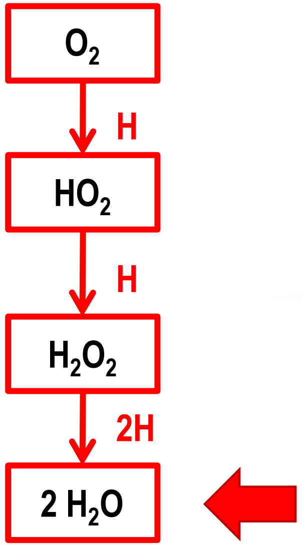
Space

ATOMIC BOMBARDMENT

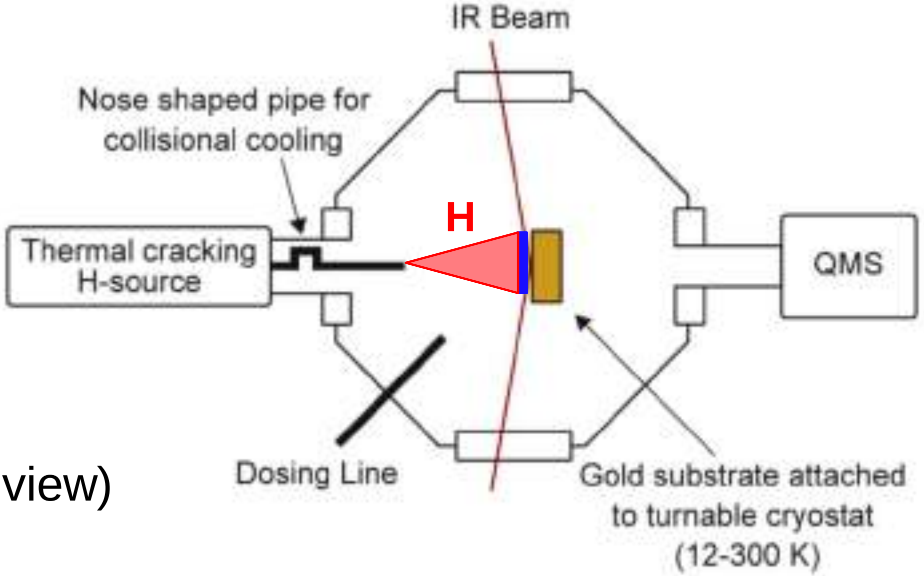
Lab







$$O_2 \xrightarrow{H} HO_2 \xrightarrow{H} H_2O_2 \xrightarrow{2H} 2\,H_2O$$



(Top-view)

Surface Hydrogenation of O_2

Pre-deposition Experiments

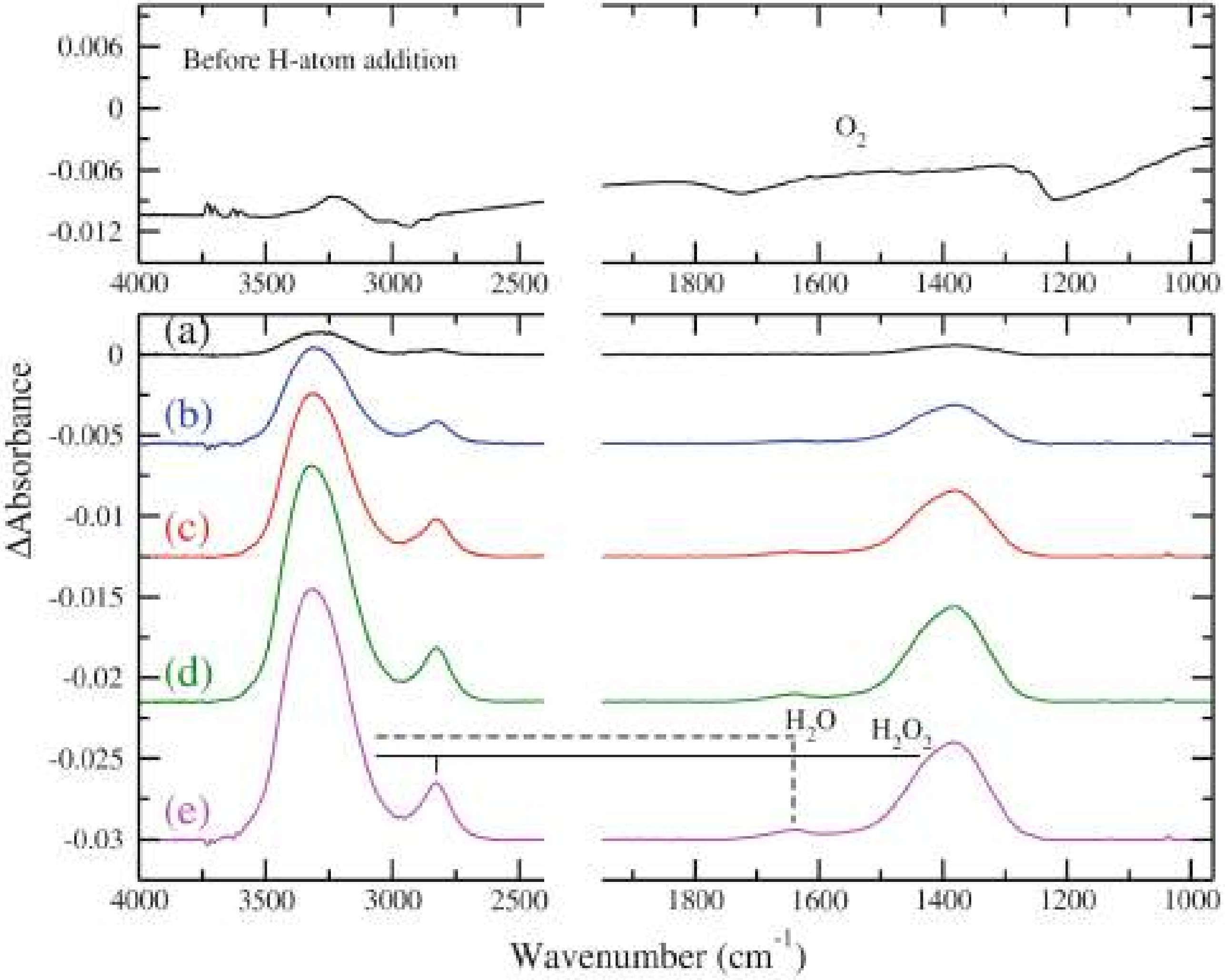
Ioppolo *et al.*, RFAL (2011)

Pre-deposition:
35 ML of O_2 ice

Temperature:
T = 25 K

H-atom flux:
2.5×10^{13} cm^{-2} s^{-1}

H-atom fluences:
(a) 4×10^{15} atoms cm^{-2}
(b) 4×10^{16} atoms cm^{-2}
(c) 7×10^{16} atoms cm^{-2}
(d) 1×10^{17} atoms cm^{-2}
(e) 2×10^{17} atoms cm^{-2}

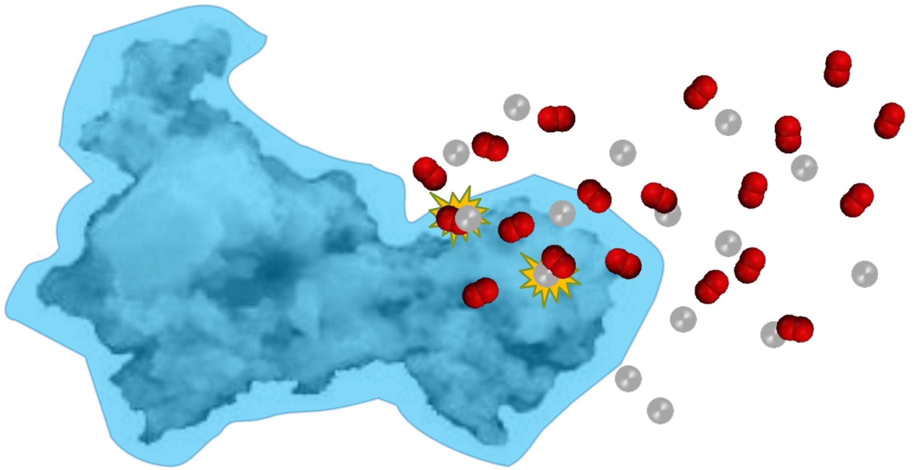


Experimental Procedure

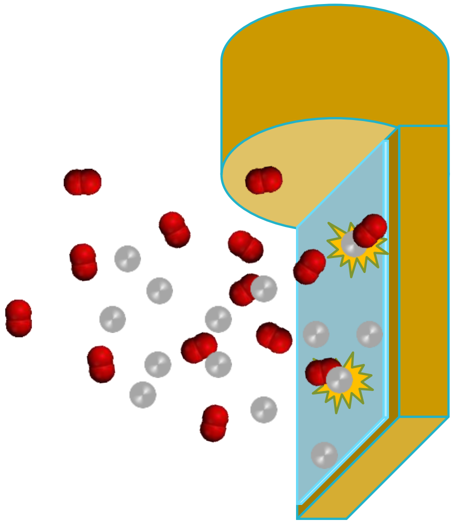
Co-deposition Experiments

Space

LAYERING



Lab



O_2

↓ H

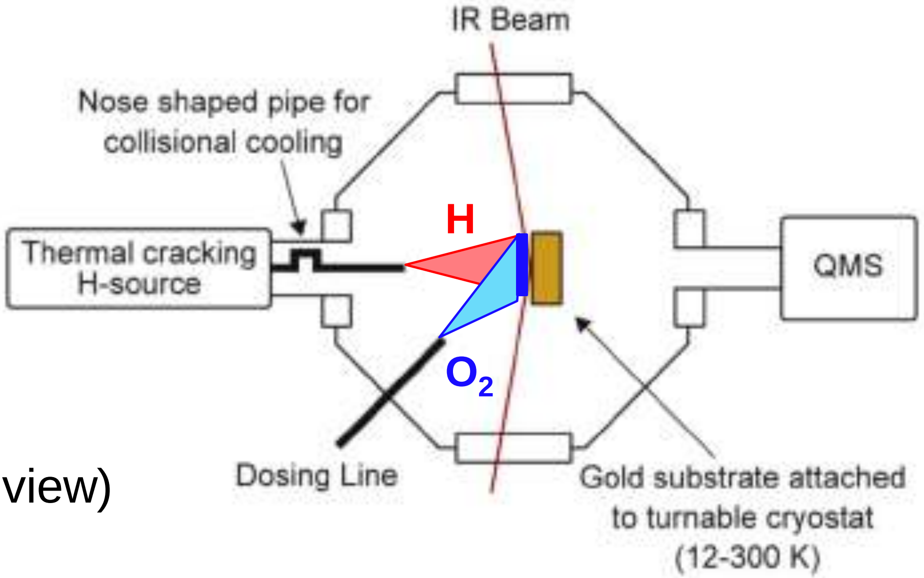
HO_2

↓ H

H_2O_2

↓ 2H

$2\ H_2O$



(Top-view)

Surface Hydrogenation of O_2

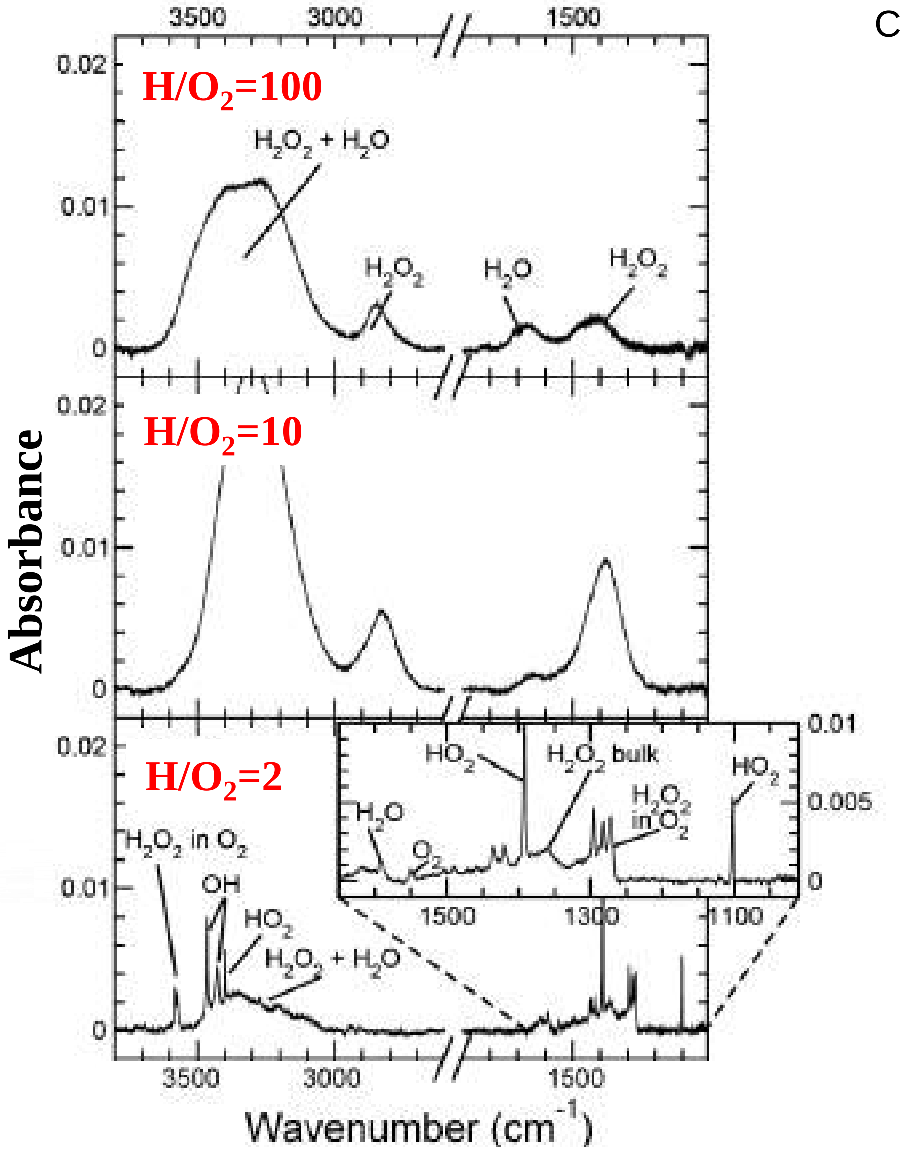
Co-deposition Experiments

Co-deposition:
O_2 + H ice

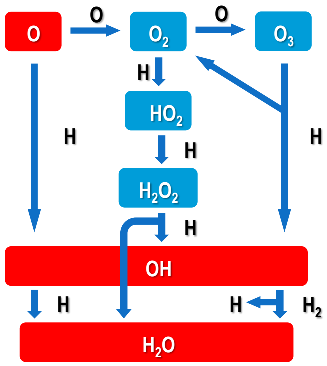
Temperature:
T = 20 K

H-atom flux:
2.5×10^{13} cm^{-2} s^{-1}

H-atom fluences:
3×10^{17} atoms cm^{-2}

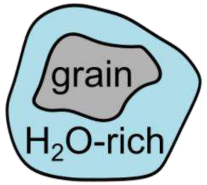


Cuppen *et al.*, PCCP (2010)

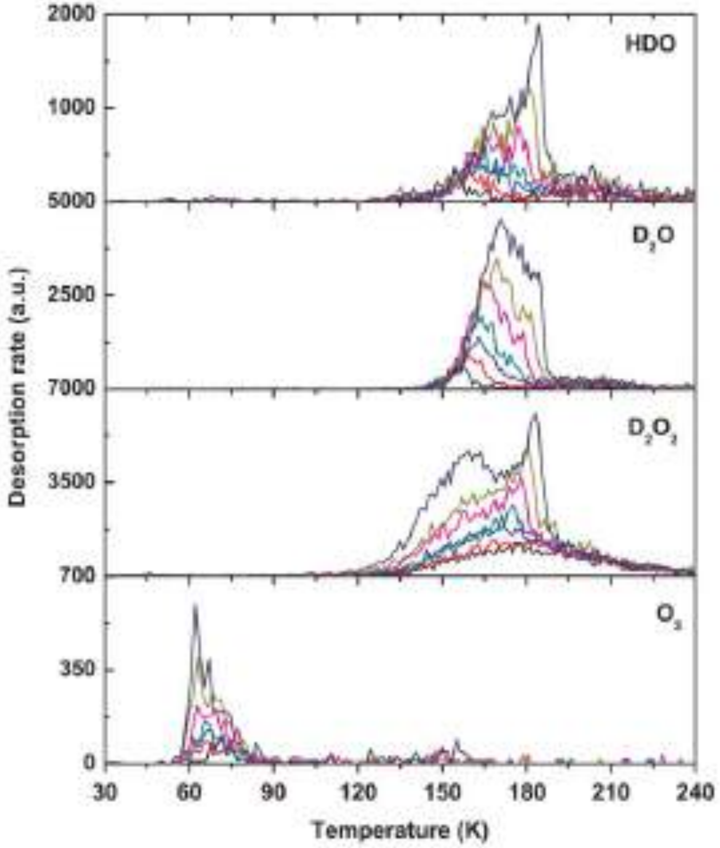


Hydrogenation of O Atoms

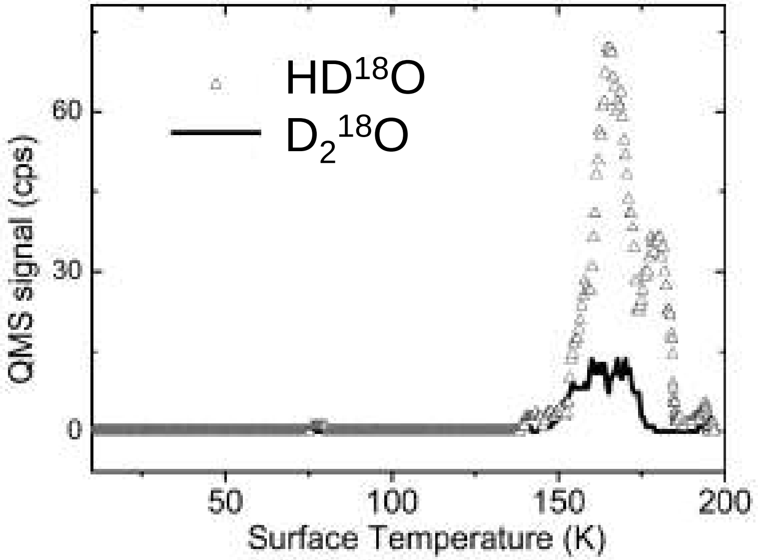
Transition from Diffuse to Dense Clouds (A_v ~ 1–5)



D + ^{16}O on bare grain analogs (15K)



D + ^{18}O on water ice (10K)

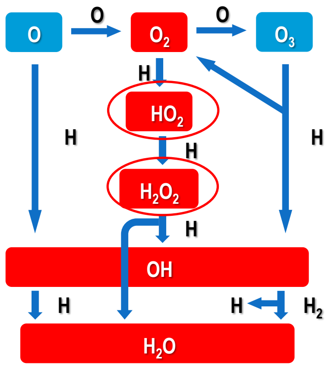


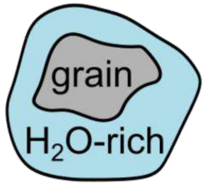
Dulieu *et al.*, A&A (2010)

Jing *et al.*, ApJL (2011)

Hydrogenation of O_2

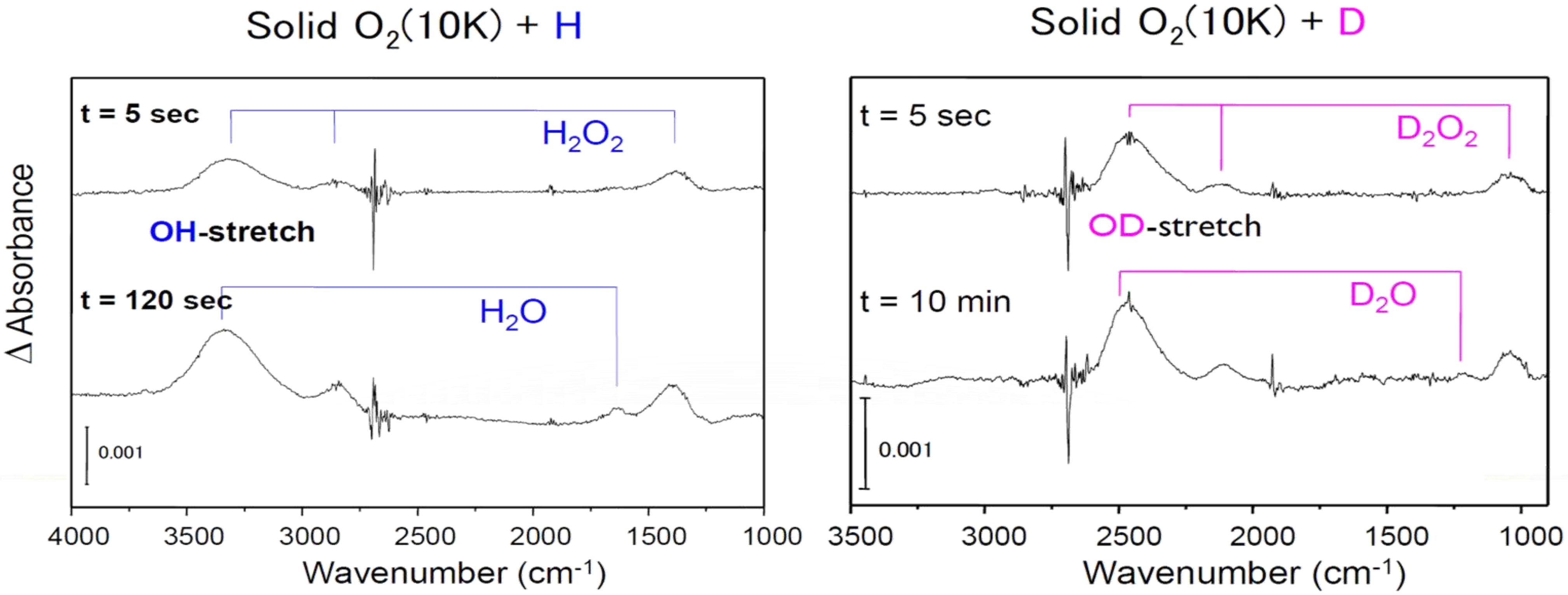
Dense Molecular Clouds (A_v > 5)

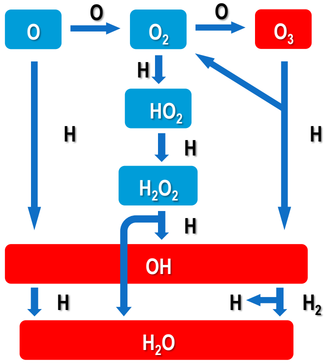




Detected in 2011 and 2012
Bergman, Parise et al.

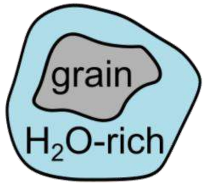
Miyauchi *et al.*, CPL (2008)

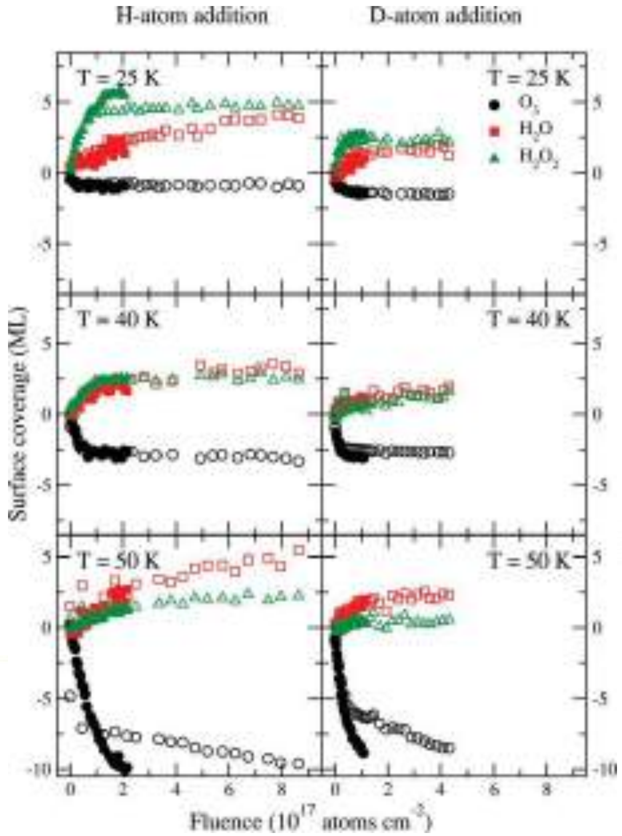


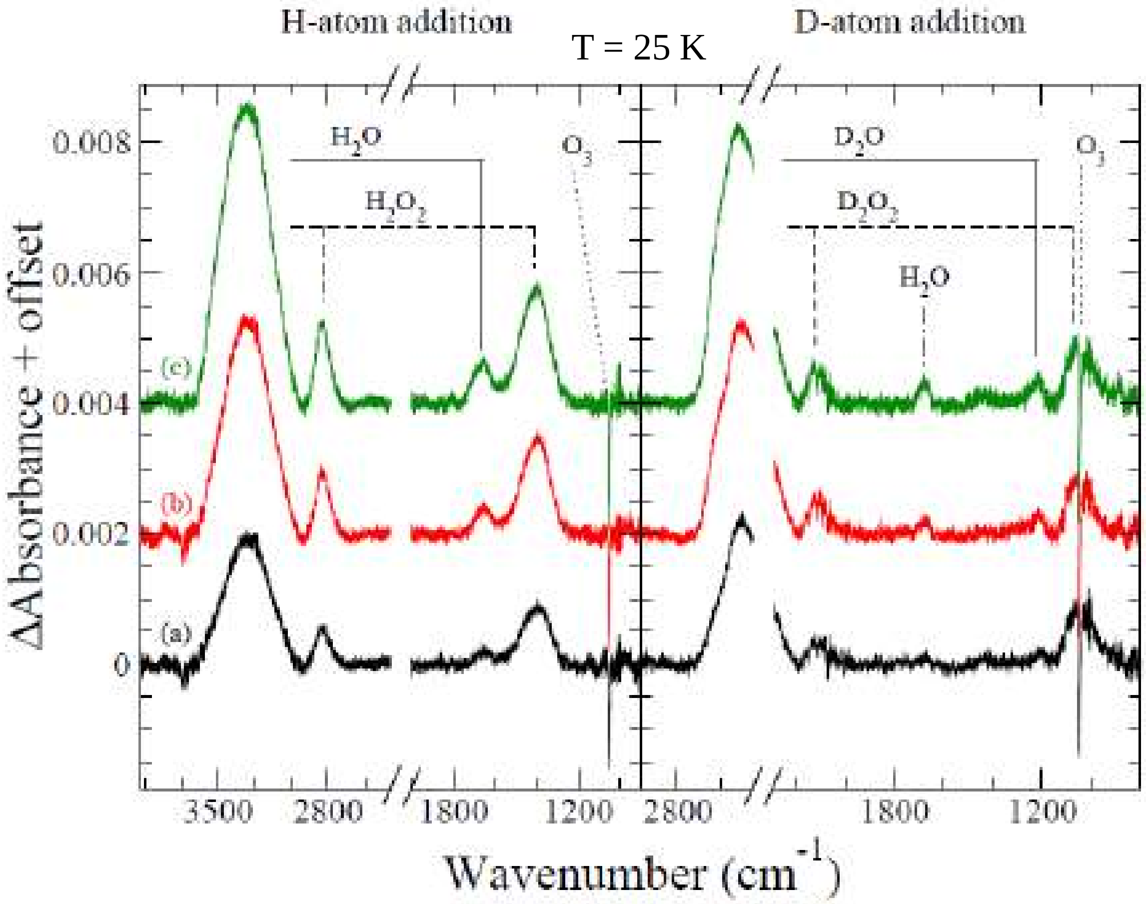


Hydrogenation of O_3

Dense Molecular Clouds (A_v > 5)



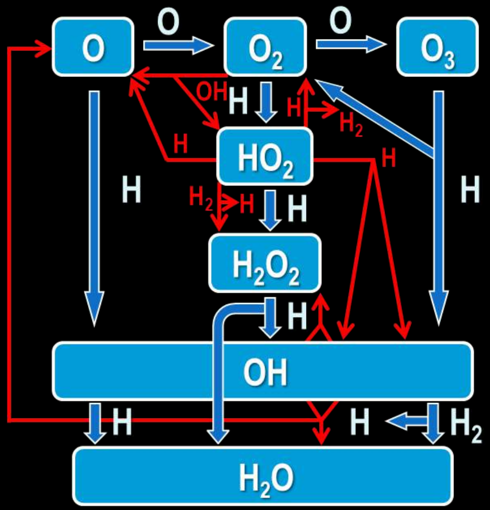


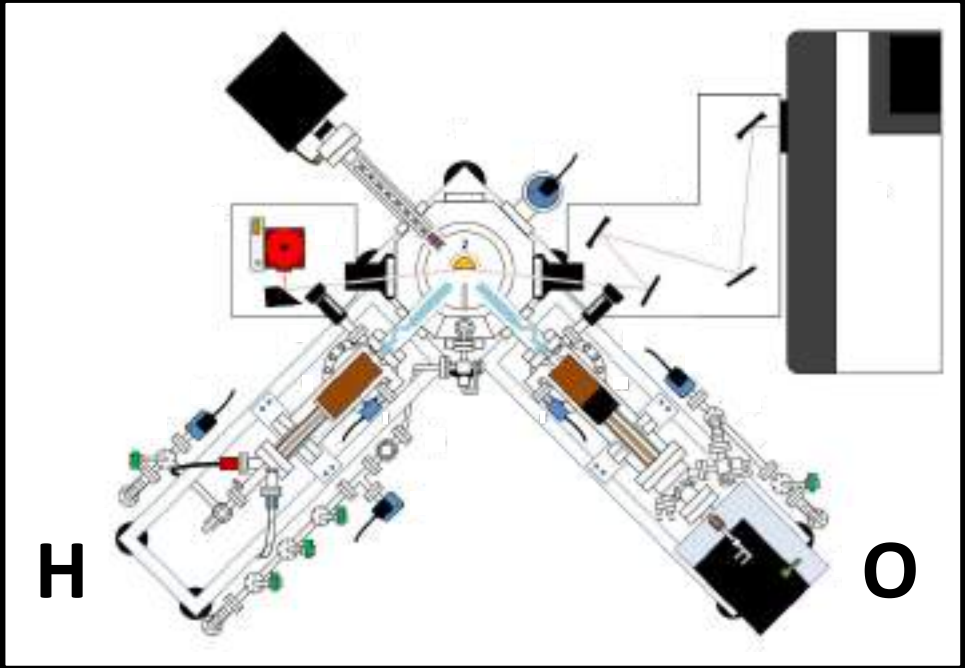


Romanzin *et al.*, JCP (2011)

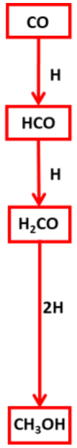
Surface Hydrogenation of O/O_2/O_3

grain
H_2O-rich



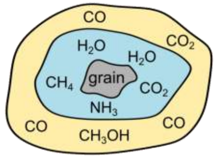


O + H	Dulieu *et al*. 2010; Jing *et al*. 2011
O_2 + H	Miyauchi *et al*. 2008; Ioppolo *et al*. 2008, 2010; Matar *et al*. 2008; Oba *et al*. 2009, 2012, 2014; Cuppen *et al*. 2010; Chaabouni *et al*. 2012; Lamberts *et al*. 2013, 2014a; 2014b; 2015; 2016
O_3 + H	Mokrane *et al*. 2009; Romanzin *et al*. 2011



Surface Hydrogenation of CO

Pre-deposition Experiments **SURFRESIDE**



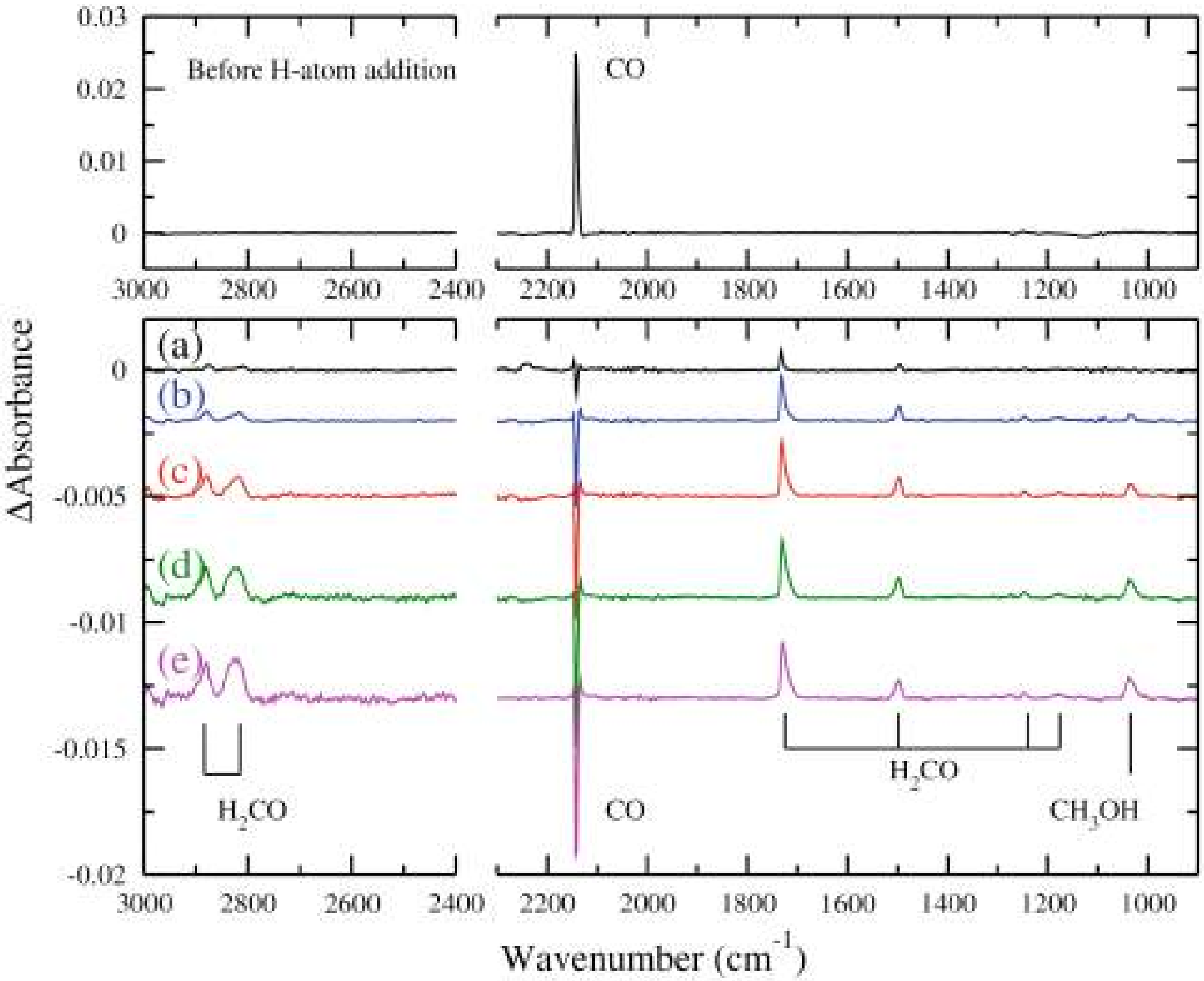
Fuchs *et al.*, A&A (2009)

Deposition:
30 ML of CO ice

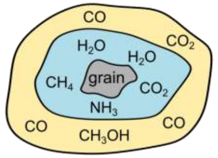
Temperature:
T = 15 K

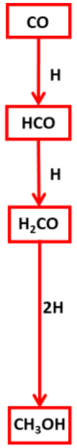
H-atom flux:
2.5×10^{13} cm^{-2} s^{-1}

H-atom fluences:
(a) 1.5×10^{16} atoms cm^{-2}
(b) 4.5×10^{16} atoms cm^{-2}
(c) 9×10^{16} atoms cm^{-2}
(d) 1.8×10^{17} atoms cm^{-2}
(e) 2.7×10^{17} atoms cm^{-2}



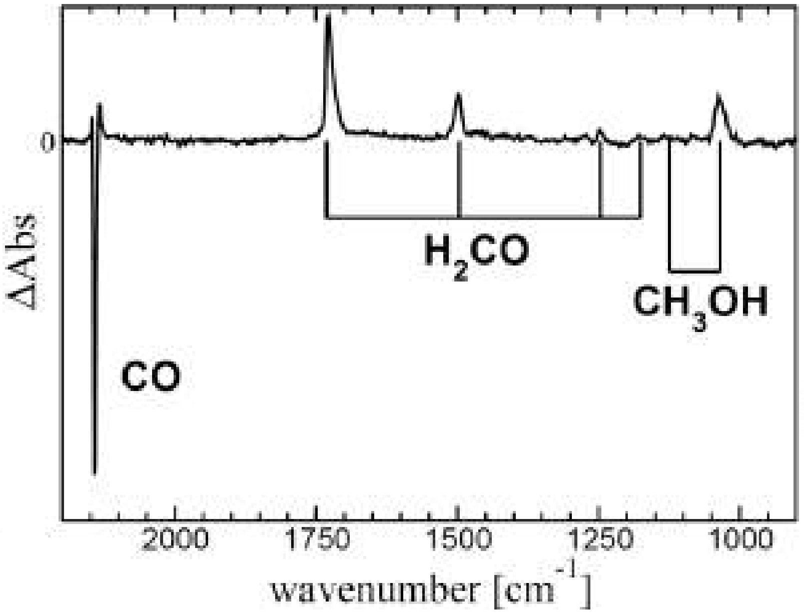
Surface Hydrogenation of CO



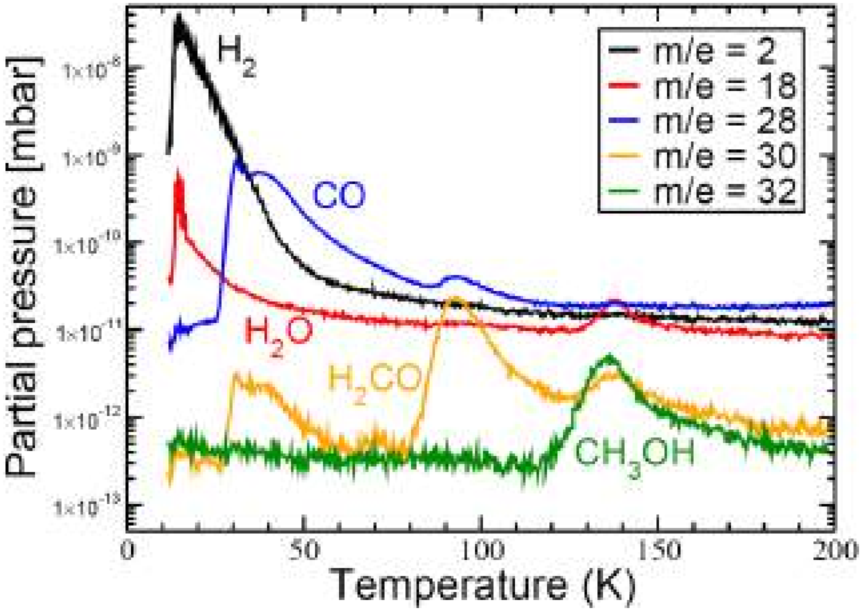


$$CO \xrightarrow{2H} H_2CO \xrightarrow{2H} CH_3OH$$

RAIR Spectrum

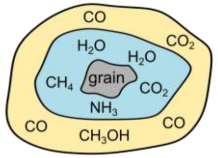


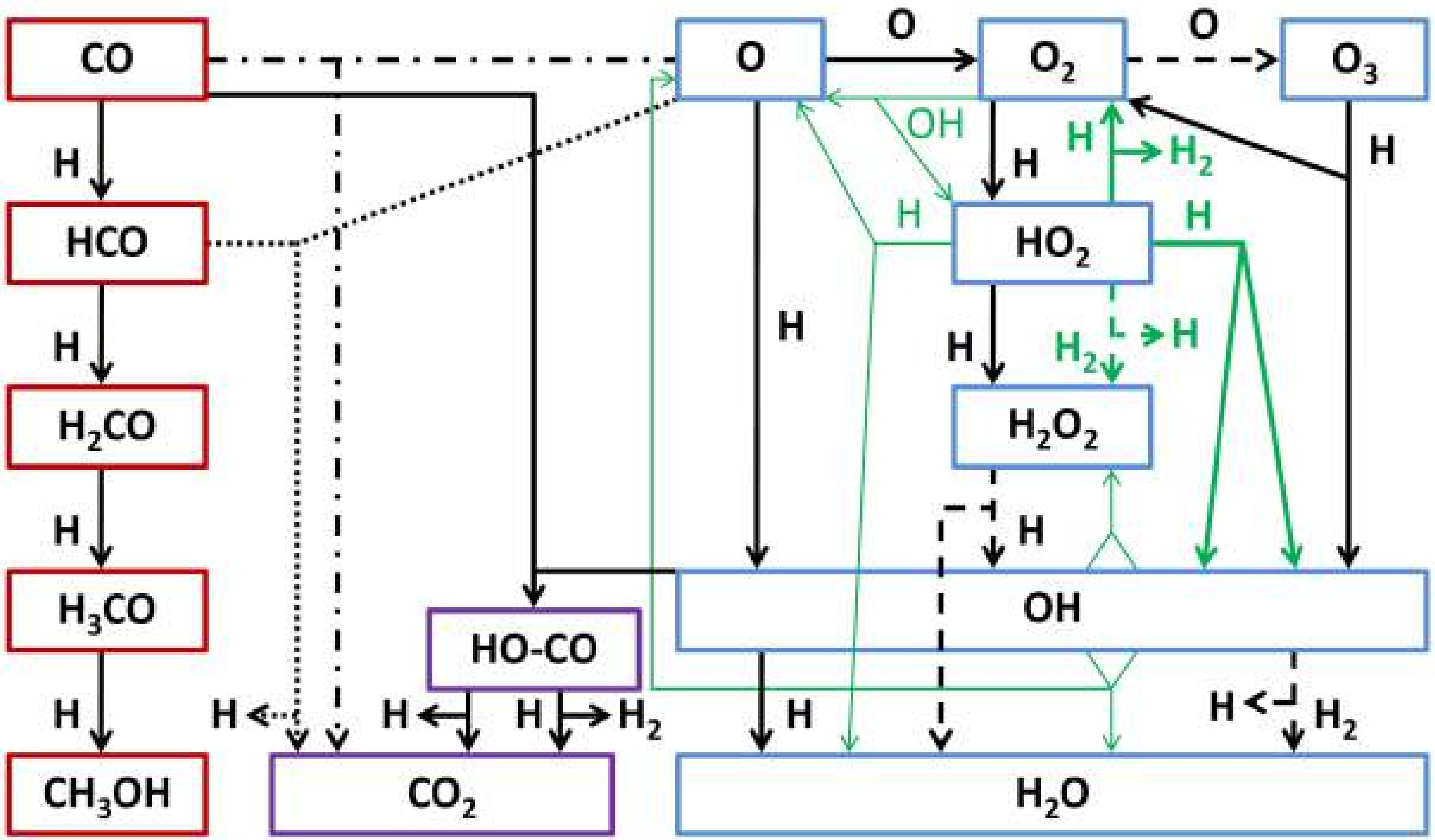
TPD Spectrum (rate = 2 K min^{-1})



Watanabe *et al.*, ApJ (2004)
Hidaka *et al.*, ApJ (2004)
Hiraoka *et al.*, ApJ (2002)
Fuchs *et al.*, A&A (2009)

Formation of H_2O, CH_3OH, …, and CO_2

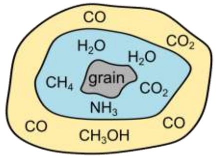


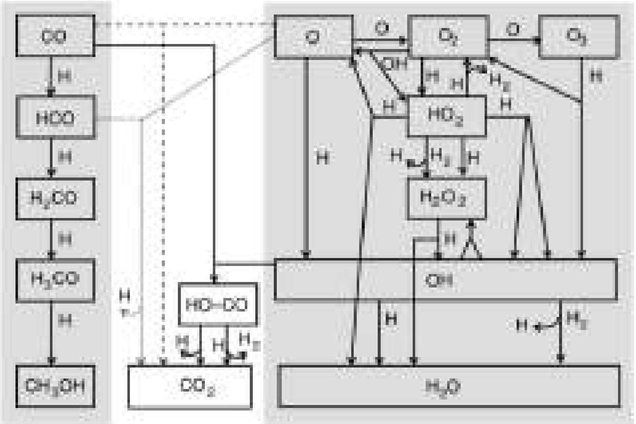


Solid: no or small barrier; thin: inefficient

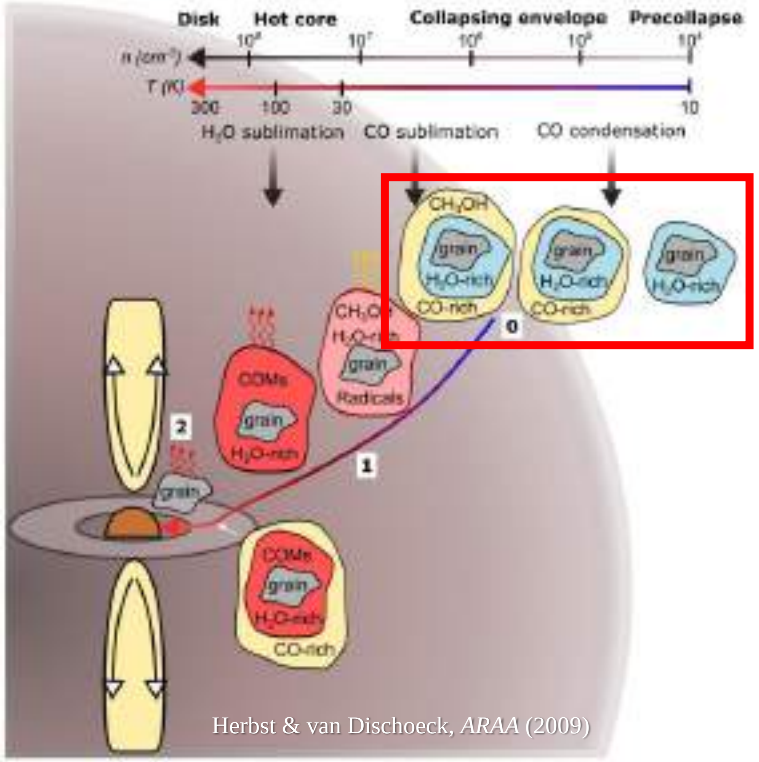
Dashed: large barrier; dotted: not measured

Formation of CO_2 in Space

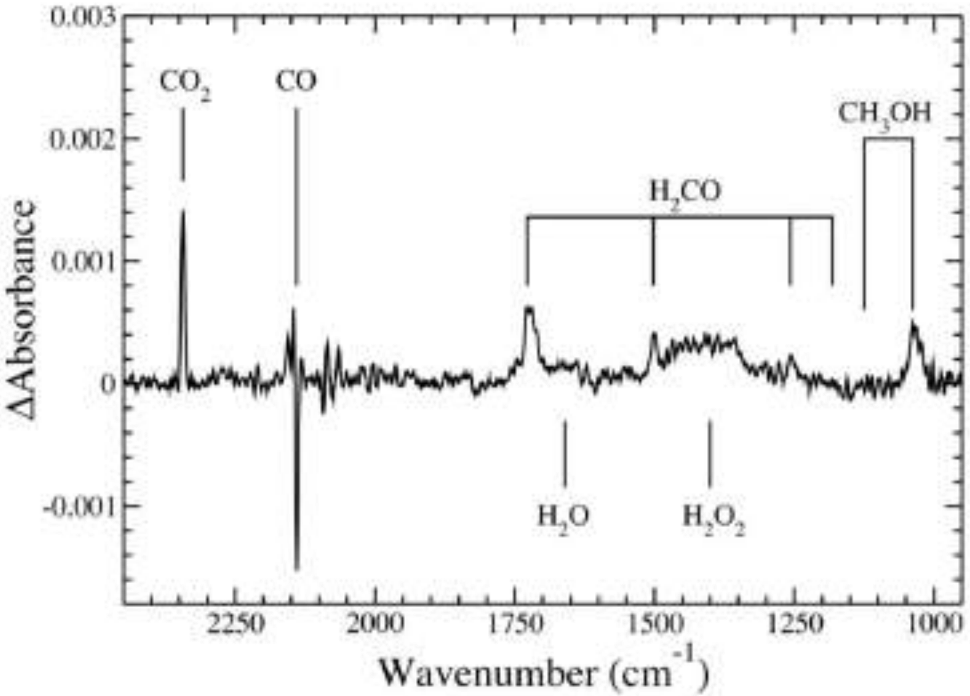




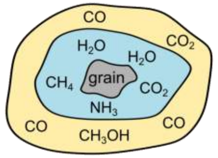
Oba *et al.*, ApJL (2010)
Ioppolo *et al.*, MNRAS (2011)
Noble *et al.*, ApJ (2011)

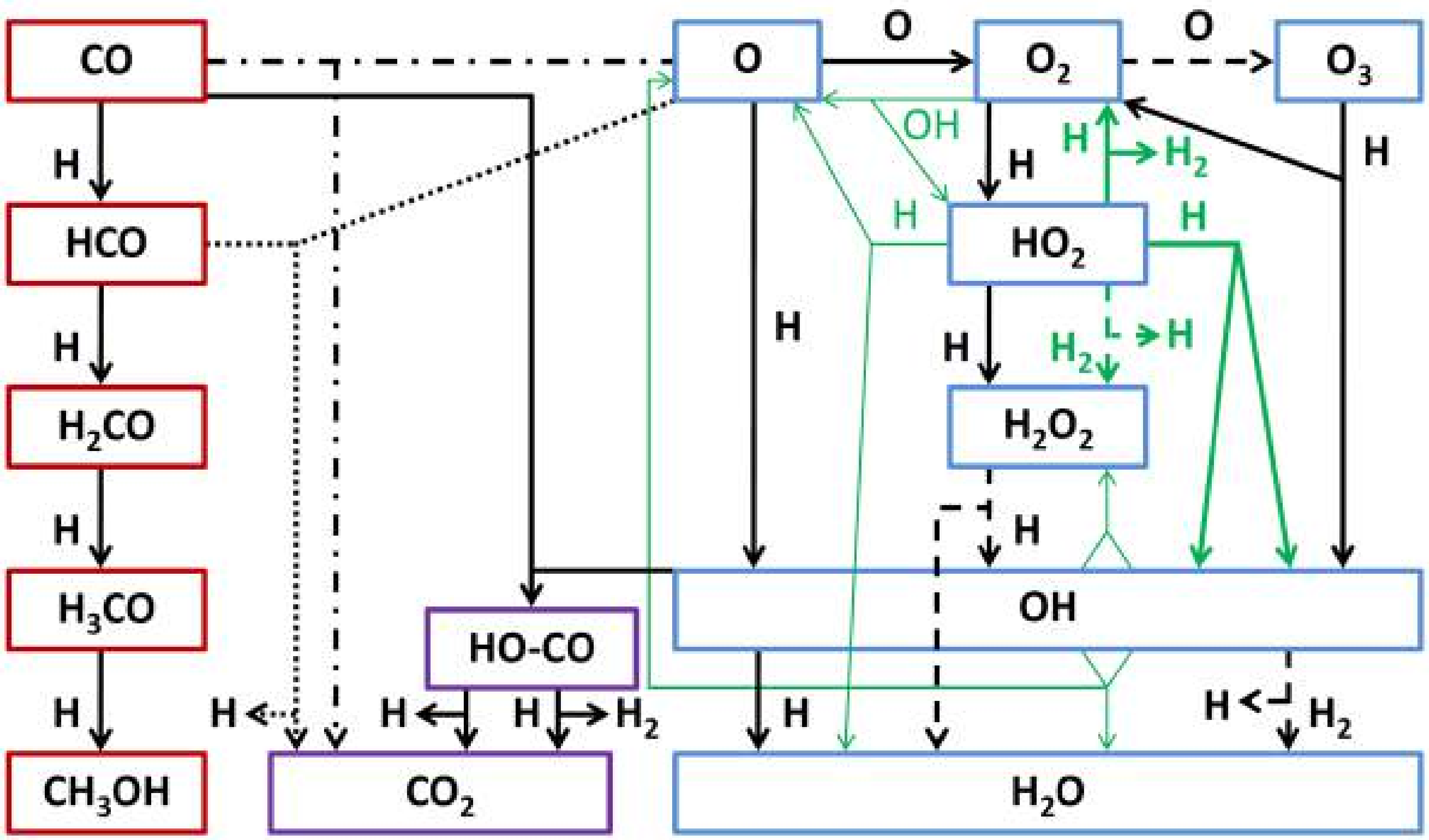


Herbst & van Dischoeck, *ARAA* (2009)



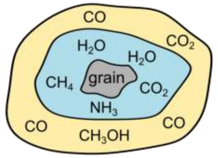
Formation of H_2O, CO_2, CH_3OH ice, …

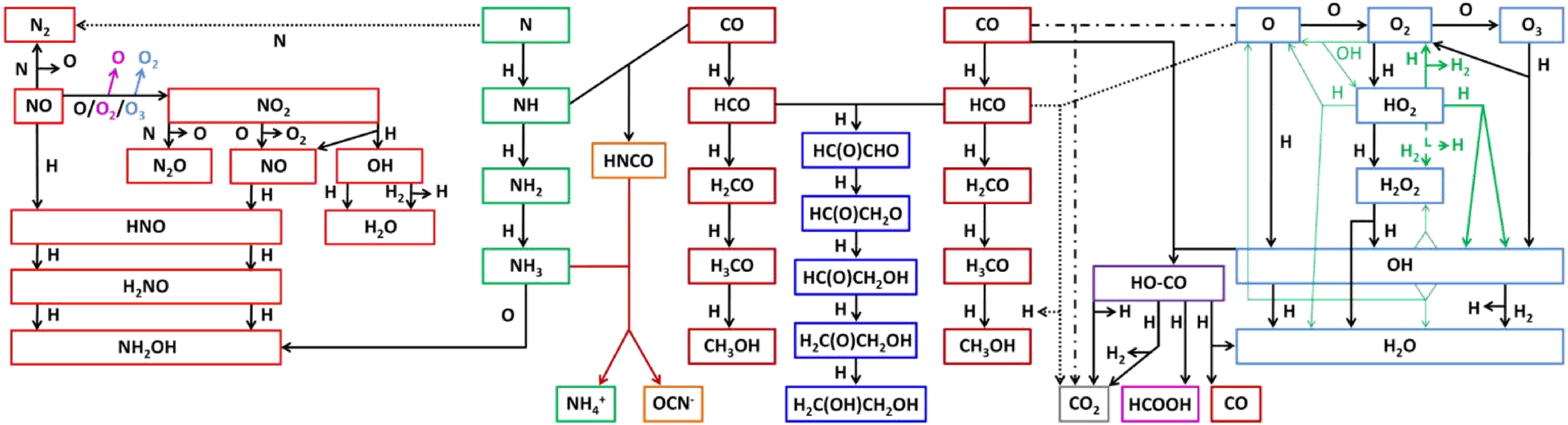




Solid: no or small barrier; thin: inefficient
Dashed: large barrier; dotted: not measured

Formation of H_2O, CO_2, CH_3OH ice, …



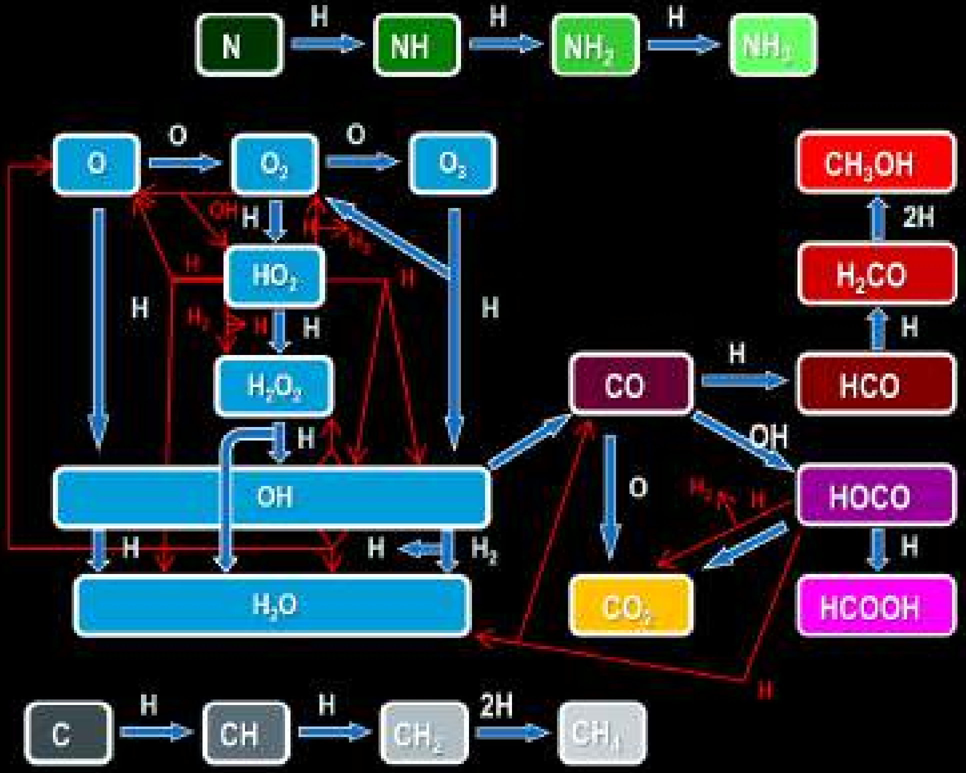


Solid: no or small barrier; thin: inefficient
Dashed: large barrier; dotted: not measured

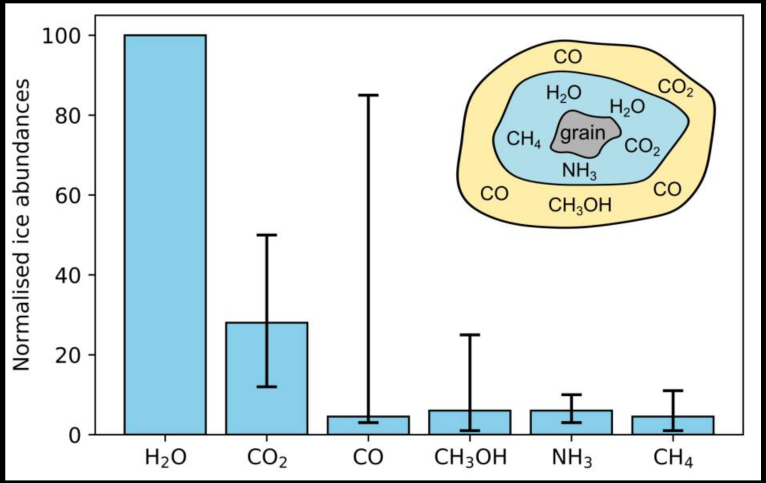
Linnartz *et al.*, Int. Rev. Phys. Chem. (2015)

Simple Molecules form via Dark Chemistry

Dark Chemistry = Atom/Radical-Addition Surface Chemistry
= No photons involved in chemistry, no light!



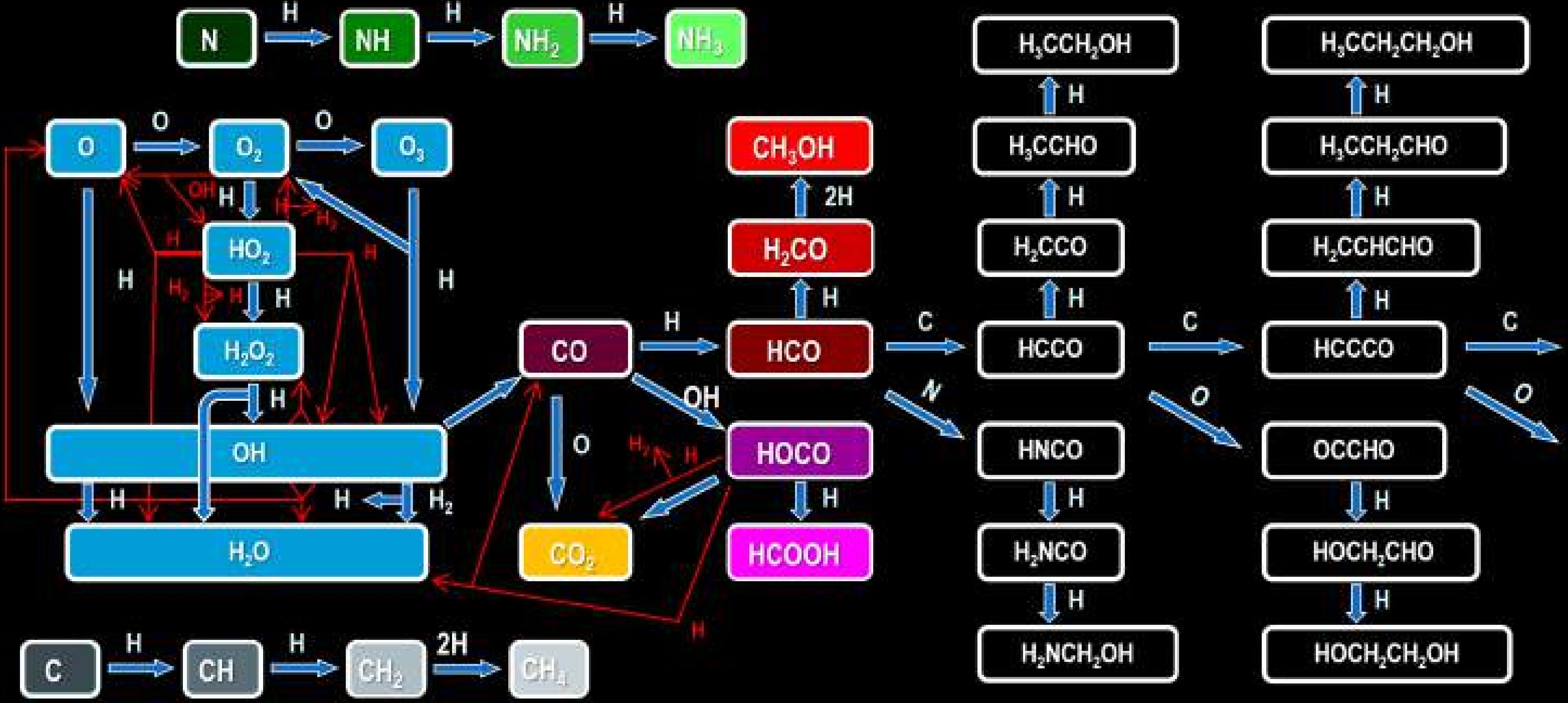
Linnartz *et al.*, Int. Rev. Phys. Chem. (2015)



Öberg, Chem. Rev. (2016)

Ioppolo *et al.*, *ApJ* (2008)	H_2O
Fuchs *et al.*, *A&A* (2009)	CH_3OH
Ioppolo *et al.*, *MNRAS* (2011a)	CO_2
Ioppolo *et al.*, *MNRAS* (2011b)	HCOOH
Fedoseev *et al.*, *MNRAS* (2015)	NH_3
Qasim *et al.*, *Nature Astron.* (2020)	CH_4

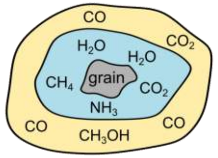
Can COMs form via Dark Chemistry?



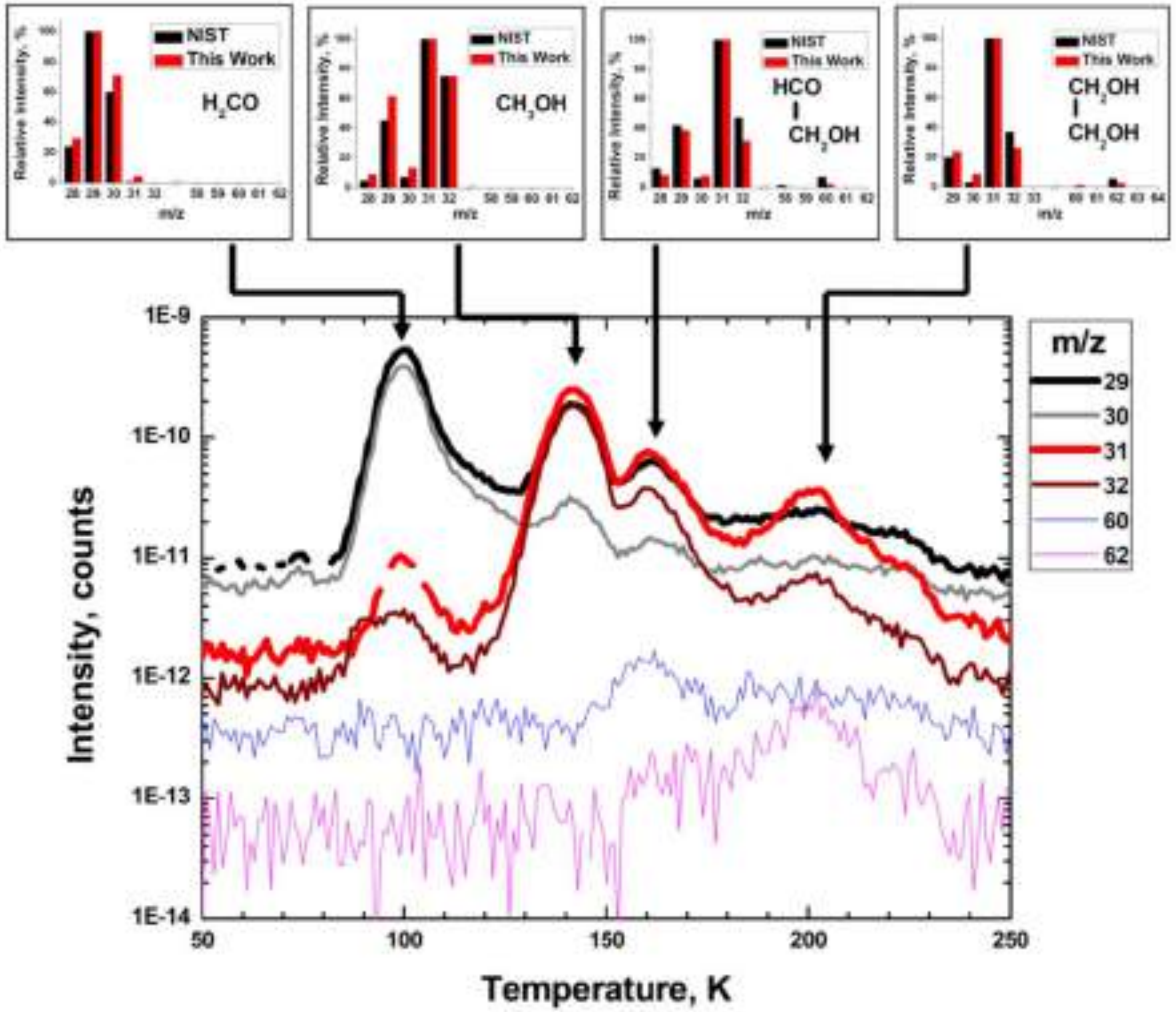
Charnley *et al.* A&A (2001)

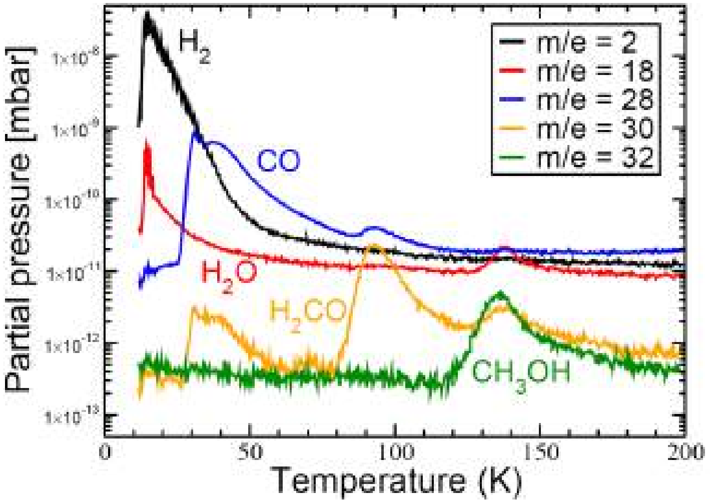
Surface Hydrogenation of CO

Co-deposition Experiments (CO+H)



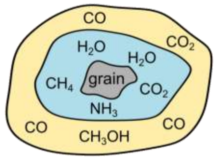
Fedoseev *et al.*, MNRAS (2015)





360 min (co)deposition at 13 K of CO:H=1:25 with H-atom flux of 5×10^{14} atoms min^{-1} cm^{-2} (~ 7 ML of ice)

COMs formed via Dark Chemistry

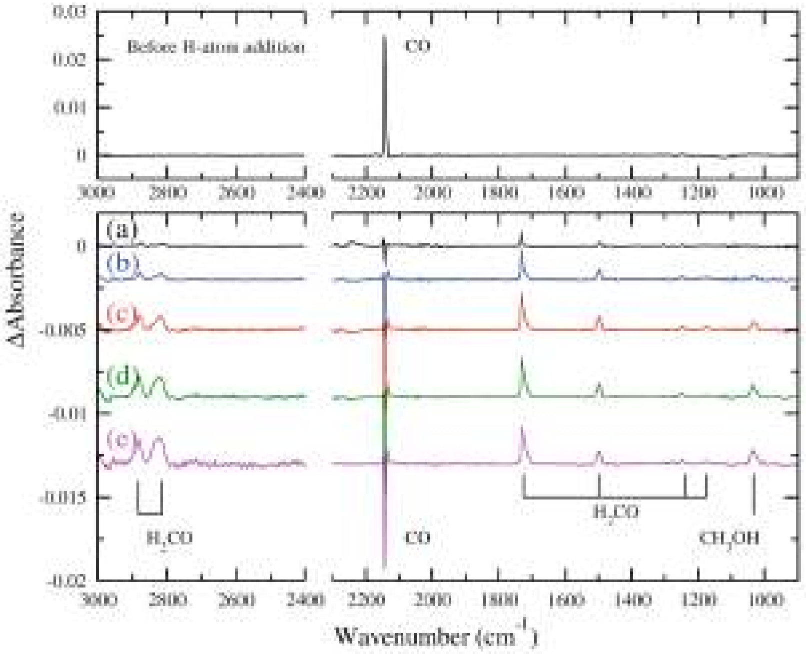


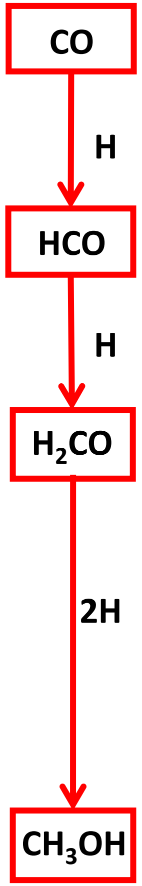
Watanabe *et al.*, ApJ (2004)

Hidaka *et al.*, ApJ (2004)

Hiraoka *et al.*, ApJ (2002)

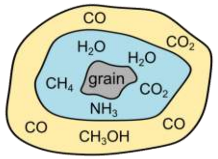
Fuchs *et al.,* A&A (2009)





$CO \xrightarrow{H} HCO \xrightarrow{H} H_2CO \xrightarrow{2H} CH_3OH$

COMs formed via Dark Chemistry



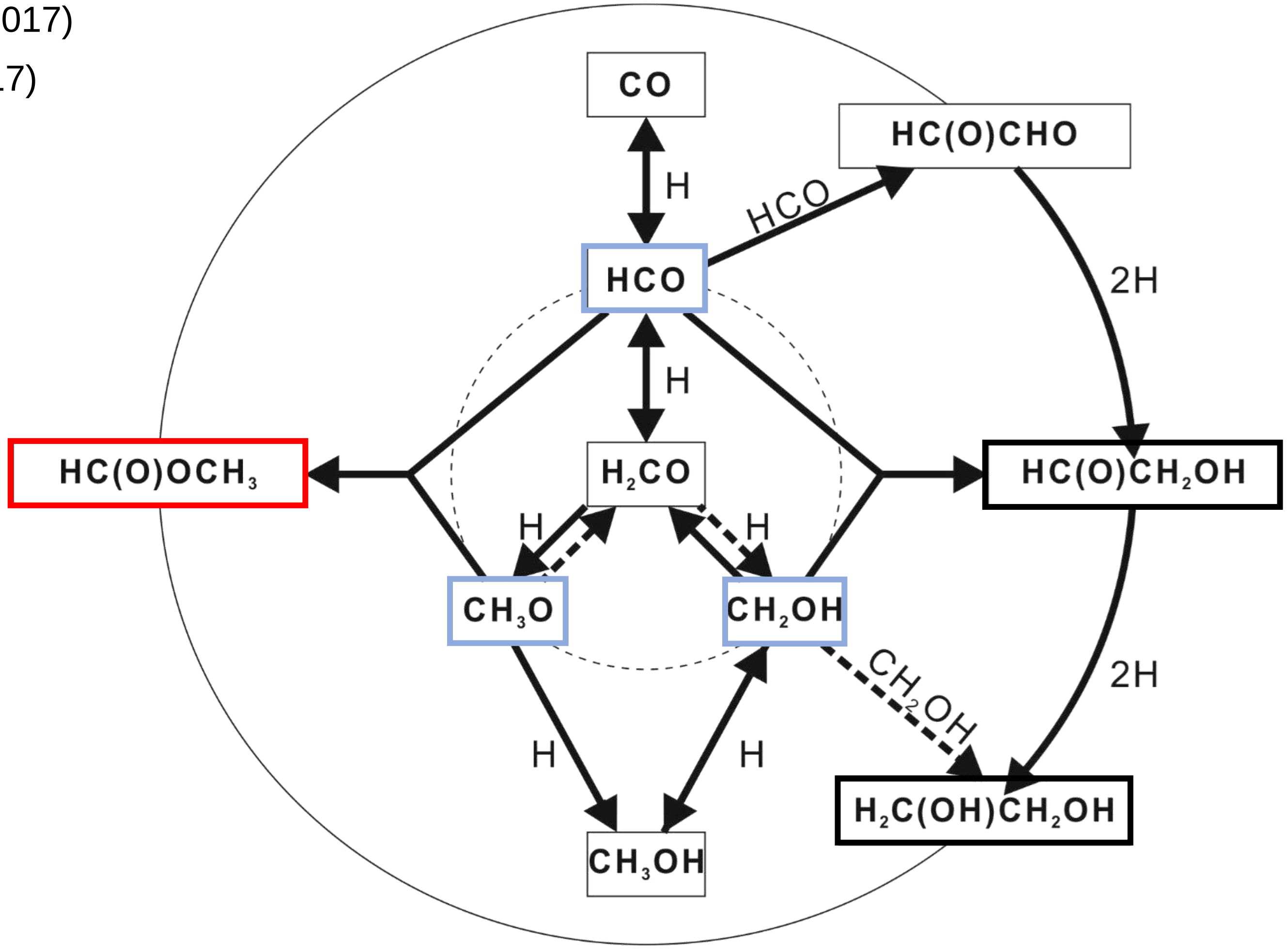
Fedoseev *et al.*, MNRAS (2015)

Chuang *et al.*, MNRAS (2016)

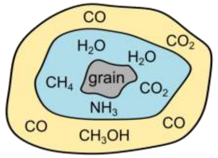
Chuang *et al.*, MNRAS (2017)

Fedoseev *et al.*, ApJ (2017)

Qasim *et al.*, A&A (2019)

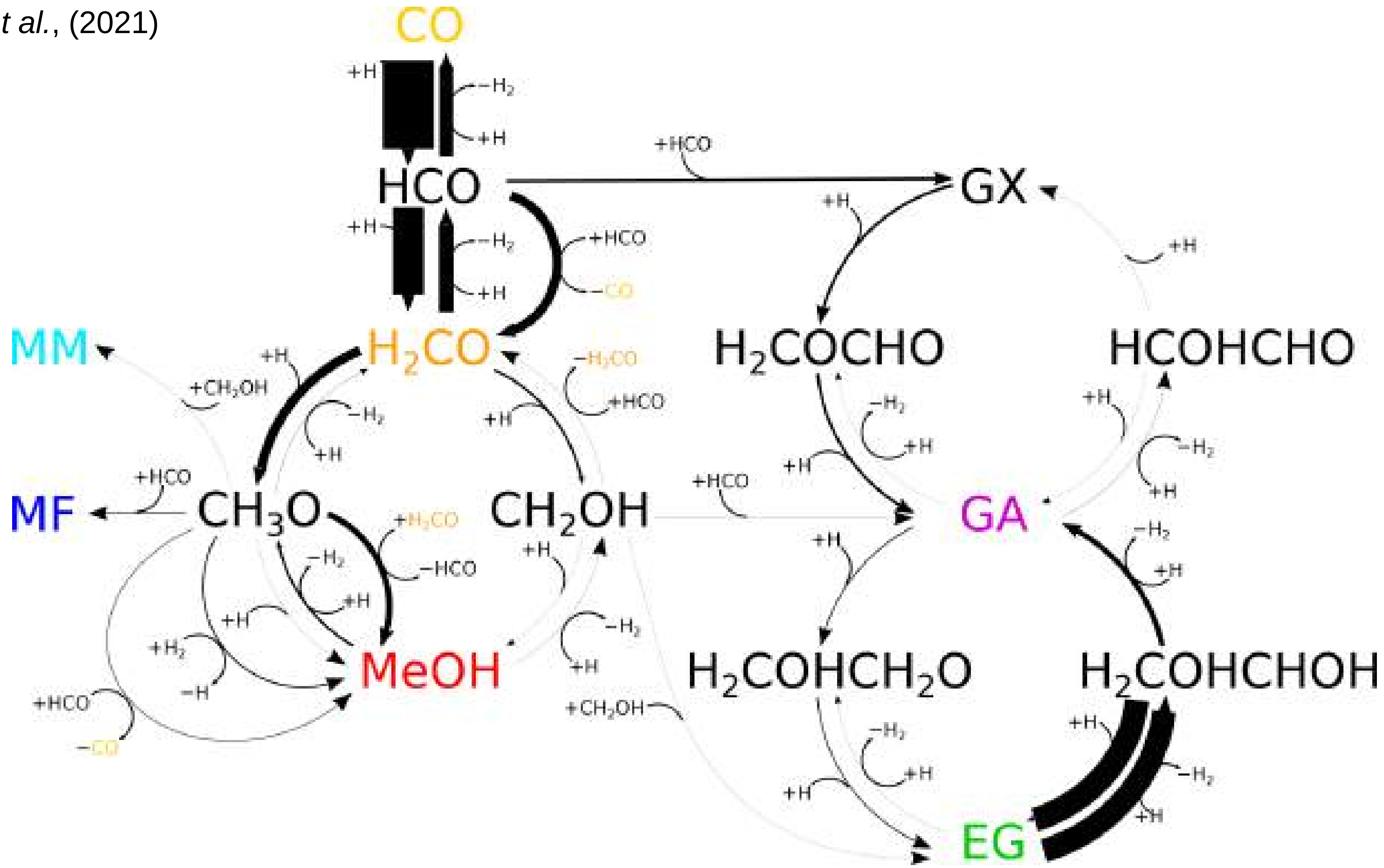


COMs formed via Dark Chemistry



Simons *et al.*, (2020)

He *et al.*, (2021)

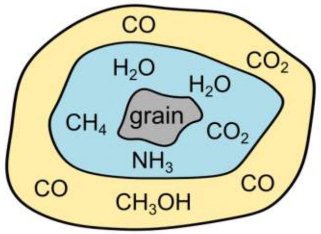


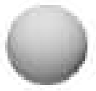
COMs formed via Dark Chemistry

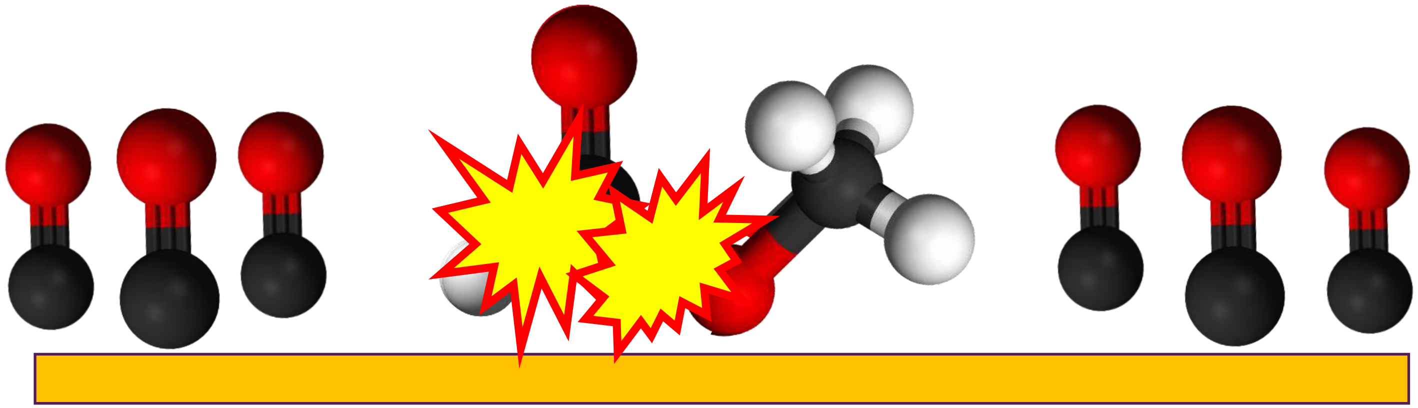
A non-diffusive reaction mechanism at 10 K

Fedoseev *et al.*, MNRAS (2015)
Chuang *et al.*, MNRAS (2016)
Chuang *et al.*, MNRAS (2017)
Fedoseev *et al.*, ApJ (2017)

Qasim *et al.*, A&A (2019)
Chuang *et al.*, A&A (2020)
Qasim *et al.*, Nat. Astro*n.* (2020)
Ioppolo *et al.*, Nat. Astron*.* (2021)







COMs formed via Dark Chemistry

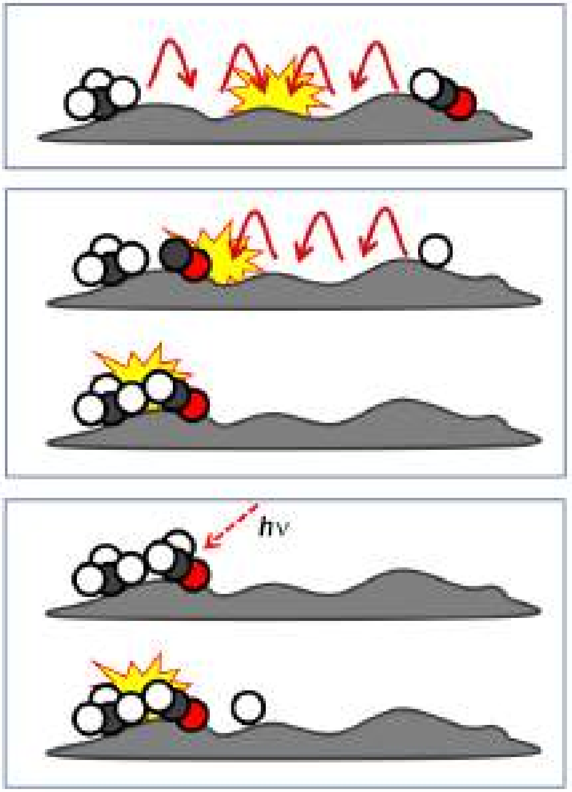
A non-diffusive reaction mechanism at 10 K

Jin and Garrod, ApJS (2020)
Garrod *et al*., ApJS (2021)

- *Diffusive:* $CH_3 + HCO \rightarrow CH_3CHO$
  (very slow at low temps)

- *Non-diffusive* (***3-body reaction, 3B***)*:*
  [initiating reaction] $H + CO \rightarrow HCO$
  [follow-on reaction] $CH_3 + HCO \rightarrow CH_3CHO$
  ⇒ *only* H needs to move!

- *Non-diffusive* (***photodissociation-induced, PDI***)*:*
  [initiating process] $H_2CO + h\nu \rightarrow HCO\ (+H)$
  [follow-on reaction] $CH_3 + HCO \rightarrow CH_3CHO$

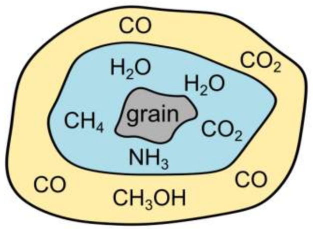


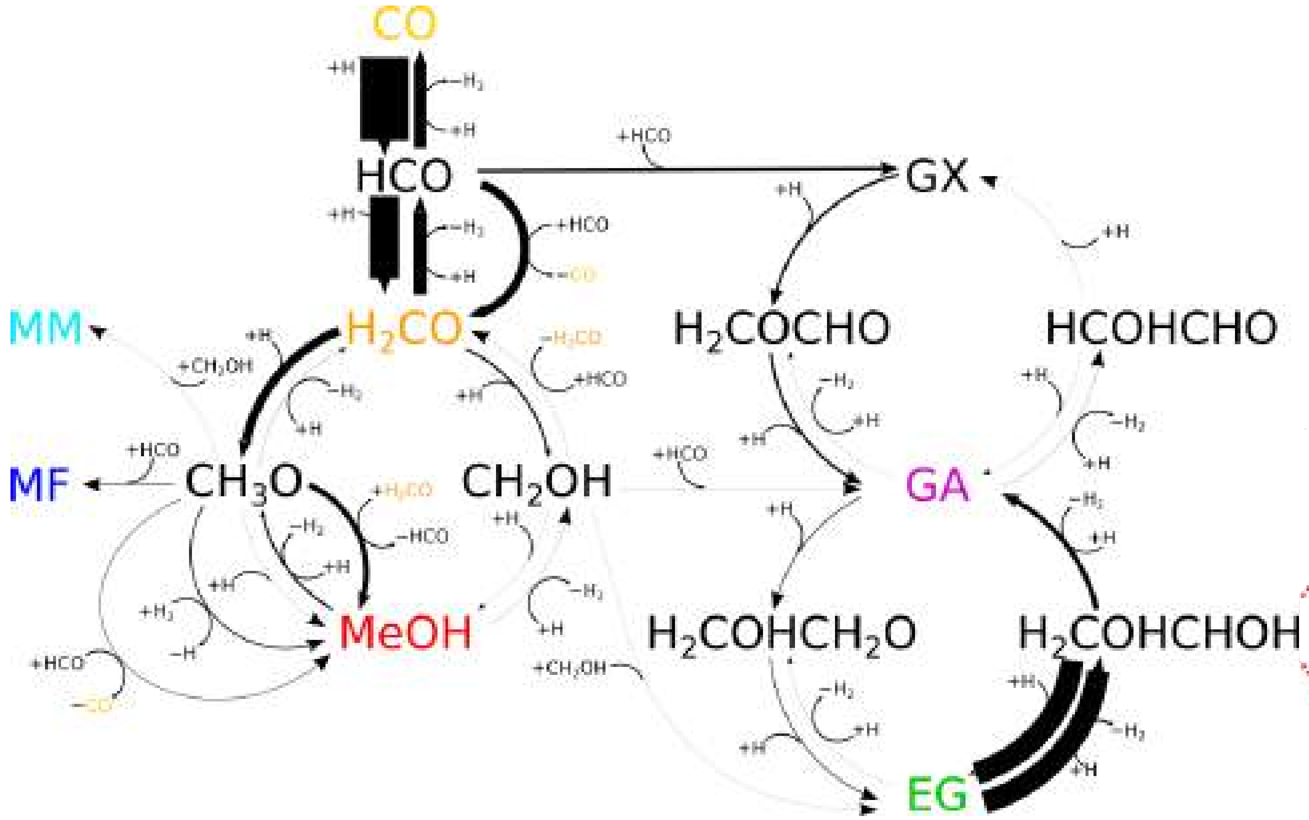
First models of hot cores to use a **diffusive + non-diffusive** treatment.

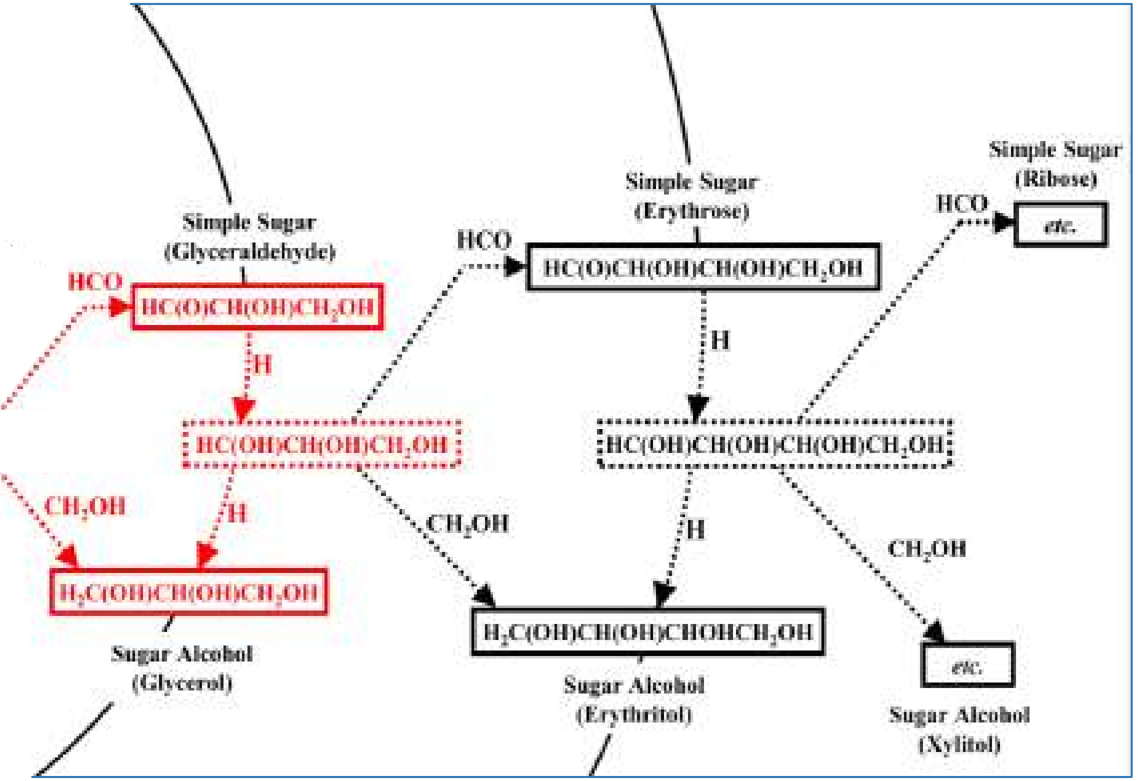
COM production shifted to much earlier times / lower temperatures.

Credit R. Garrod

Sugars form via Dark Chemistry

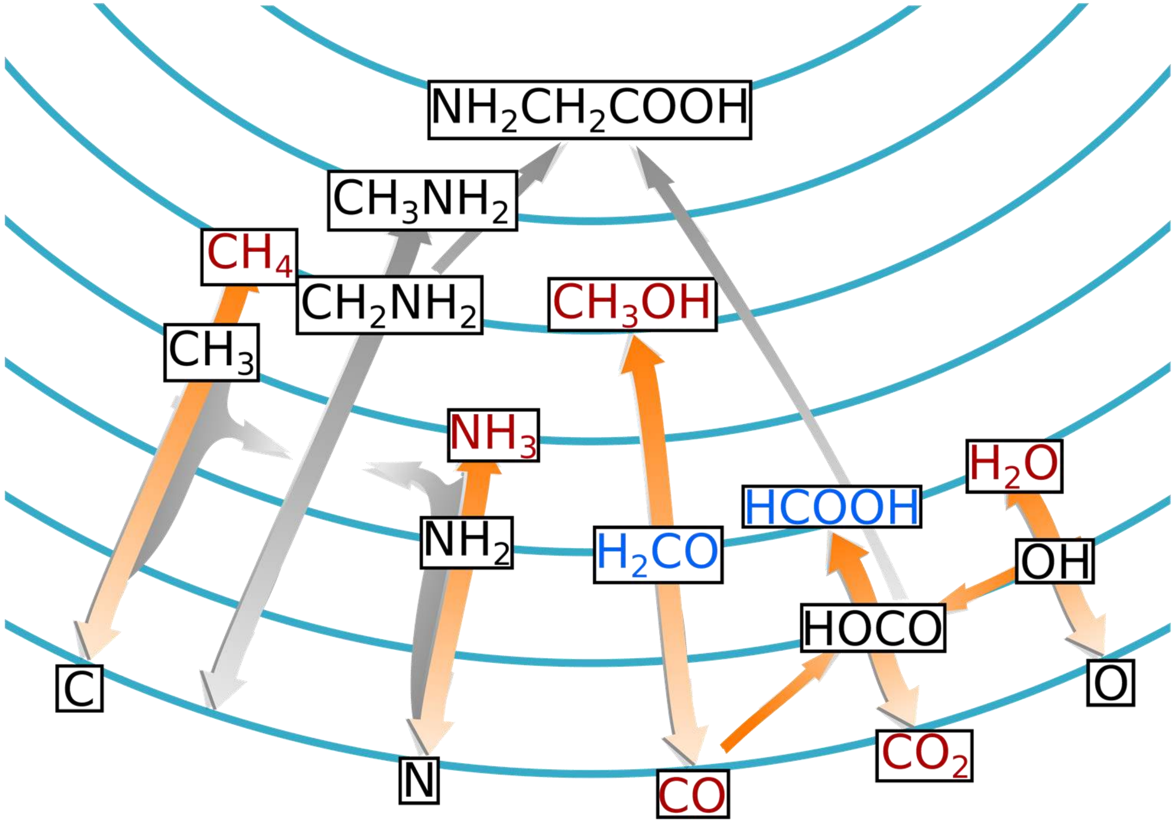






Fedoseev *et al.*, ApJ (2017)
Simons *et al.*, A&A (2020)
He *et al.*, A&A (2021)

Can Glycine form in a water-rich ice?



NH_2CH_2COOH

CH_3NH_2

CH_4

CH_2NH_2

CH_3OH

CH_3

NH_3

H_2O

$HCOOH$

NH_2

H_2CO

OH

$HOCO$

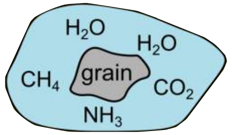
C

O

CO_2

N

CO



Qasim *et al.*, Nat. Astron. (2020)

Fedoseev *et al.*, MNRAS (2015)

Fuchs *et al.*, A&A (2009)

Ioppolo *et al.*, MNRAS (2011a)

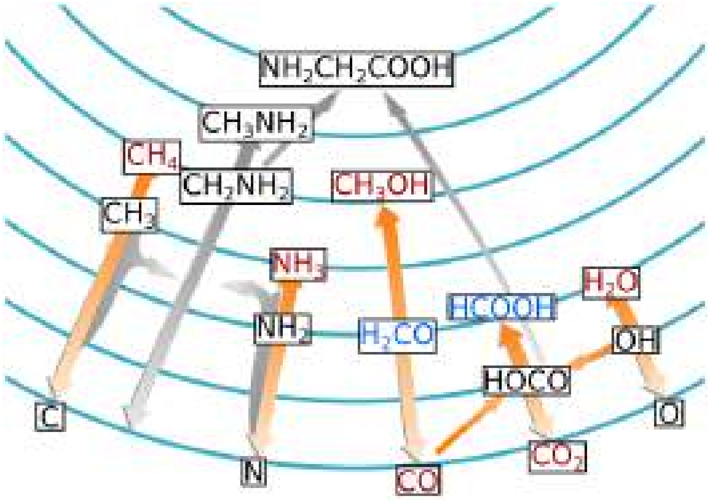
Ioppolo *et al.*, MNRAS (2011b)

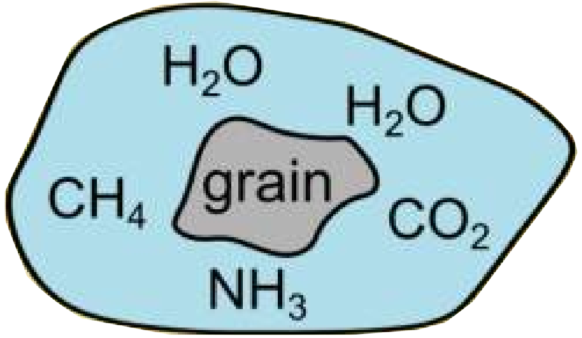
Ioppolo *et al.*, ApJ (2008)

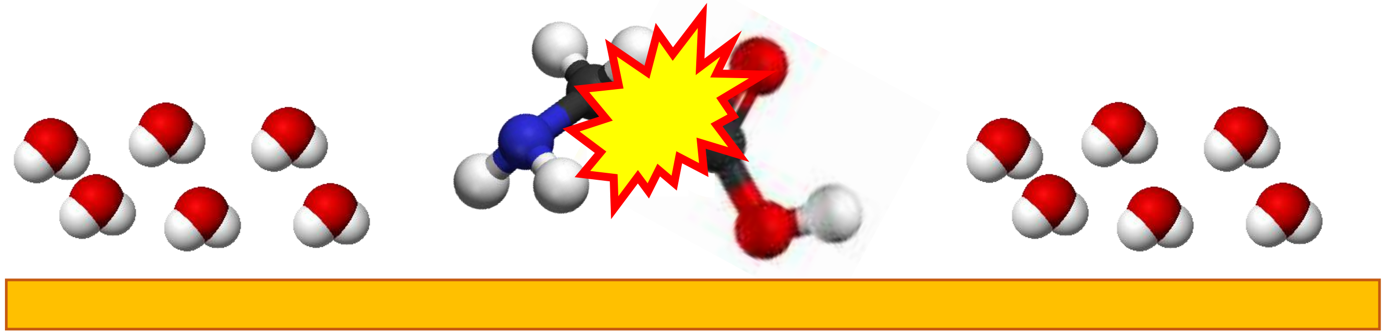
Surface Glycine Formation

Testing the reaction channel

(Ioppolo *et al.*, Nat. Astron. 2020)



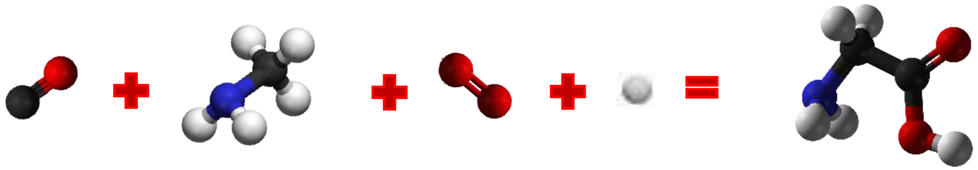




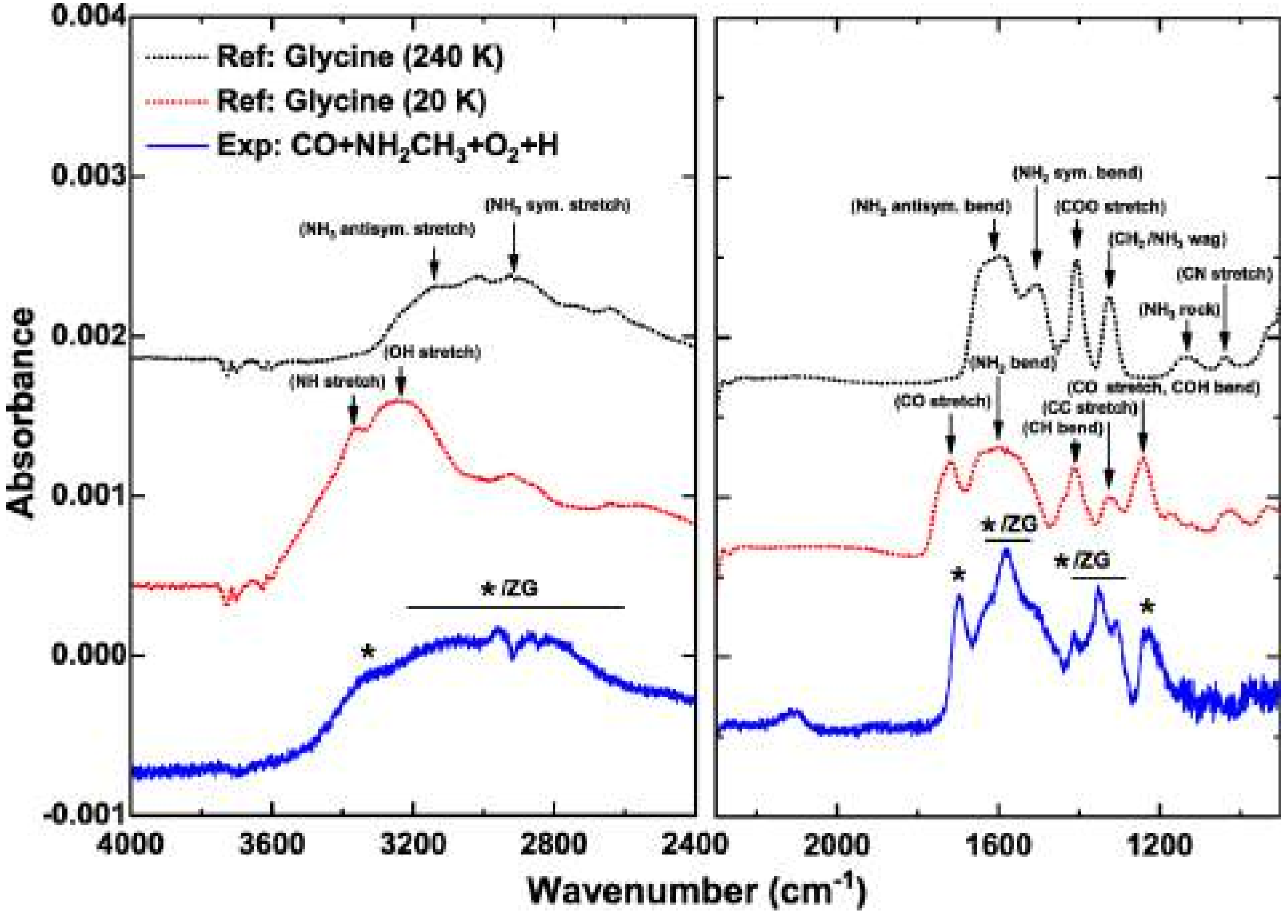
10 K

Surface Glycine Formation

Main experiments FTIR-TPD



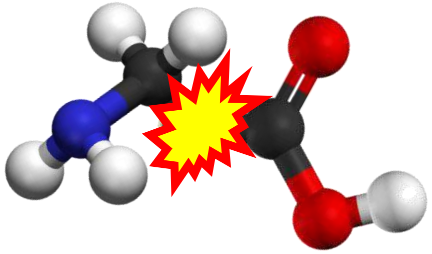
Neutral and zwitterionic Glycine at 234 - 285 K



Ioppolo *et al.*, Nat. Astron. (2020)

Beyond Experimental Limits: Model I

Microscopic kinetic Monte Carlo model (see Cuppen & Herbst, 2007)



Reaction	k (s^{-1})	Branching ratio	Reaction	k (s^{-1})	Branching ratio
$H + H \rightarrow H_2$	2×10^{11}		$NH_2CH_3 + H \rightarrow NCH_4 + H_2$	9×10^{-1}	
$H + O \rightarrow OH$	2×10^{11}		$NH_2CH_3 + OH \rightarrow NCH_4 + H_2O$	4×10^{-3}	
$H + OH \rightarrow H_2O$	2×10^{11}		$NCH_4 + HO\text{-}CO \rightarrow NH_2CH_2COOH$	2×10^{11}	
$CO + H \rightarrow HCO$	2×10^{-3}		$OH + H_2 \rightarrow H_2O + H$	2×10^{5}	
$HCO + H \rightarrow H_2CO$	2×10^{11}	0.33	$O + O \rightarrow O_2$	2×10^{11}	
$HCO + H \rightarrow H_2 + CO$		0.67	$O_2 + H \rightarrow HO_2$	1×10^{11}	
$H_2CO + H \rightarrow HCO + H_2$	2×10^{-4}	0.5	$H + HO_2 \rightarrow OH + OH$	2×10^{11}	0.94
$H_2CO + H \rightarrow H_3CO$		0.5	$H + HO_2 \rightarrow H_2 + O_2$		0.02
$H_3CO + H \rightarrow H_3COH$	2×10^{11}		$H + HO_2 \rightarrow H_2O + O$		0.05
$CO + OH \rightarrow HO\text{-}CO$	7×10^{-2}	0.5	$OH + OH \rightarrow H_2O_2$	2×10^{11}	0.87
$CO + OH \rightarrow CO_2 + H$		0.5	$OH + OH \rightarrow H_2O + O$		0.13
$HO\text{-}CO + H \rightarrow CO_2 + H_2$	2×10^{11}	0.5	$H_2O_2 + H \rightarrow H_2O + OH$	3×10^{4}	
$HO\text{-}CO + H \rightarrow HCOOH$		0.5	$N + N \rightarrow N_2$	2×10^{11}	
$N + H \rightarrow NH$	2×10^{11}		$N + O \rightarrow NO$	2×10^{11}	
$NH + H \rightarrow NH_2$	2×10^{11}		$NO + H \rightarrow HNO$	2×10^{11}	
$NH_2 + H \rightarrow NH_3$	2×10^{11}		$HNO + H \rightarrow H_2NO$	2×10^{11}	0.5
$C + H \rightarrow CH$	2×10^{11}		$HNO + H \rightarrow NO + H_2$		0.5
$CH + H \rightarrow CH_2$	2×10^{11}		$HNO + O \rightarrow NO + OH$	2×10^{11}	
$CH_2 + H \rightarrow CH_3$	2×10^{11}		$O + NH \rightarrow HNO$	2×10^{11}	
$CH_3 + H \rightarrow CH_4$	2×10^{11}		$N + NH \rightarrow N_2 + H$	2×10^{11}	
$CH_4 + OH \rightarrow CH_3 + H_2O$	5×10^{2}		$NH + NH \rightarrow N_2 + H_2$	2×10^{11}	
$NH_2 + CH_3 \rightarrow NH_2CH_3$	2×10^{11}		$C + O \rightarrow CO$	2×10^{11}	
$NH_3 + CH \rightarrow NCH_4$	2×10^{11}		$CH_3 + OH \rightarrow CH_3OH$	2×10^{11}	
$NCH_4 + H \rightarrow NH_2CH_3$	2×10^{11}				

Beyond Experimental Limits: Model 2

Full gas-grain astrochemical kinetics model

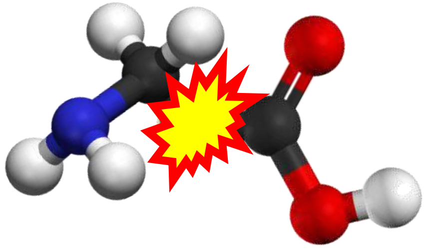
(see Garrod, 2013; Jin & Garrod, 2020)

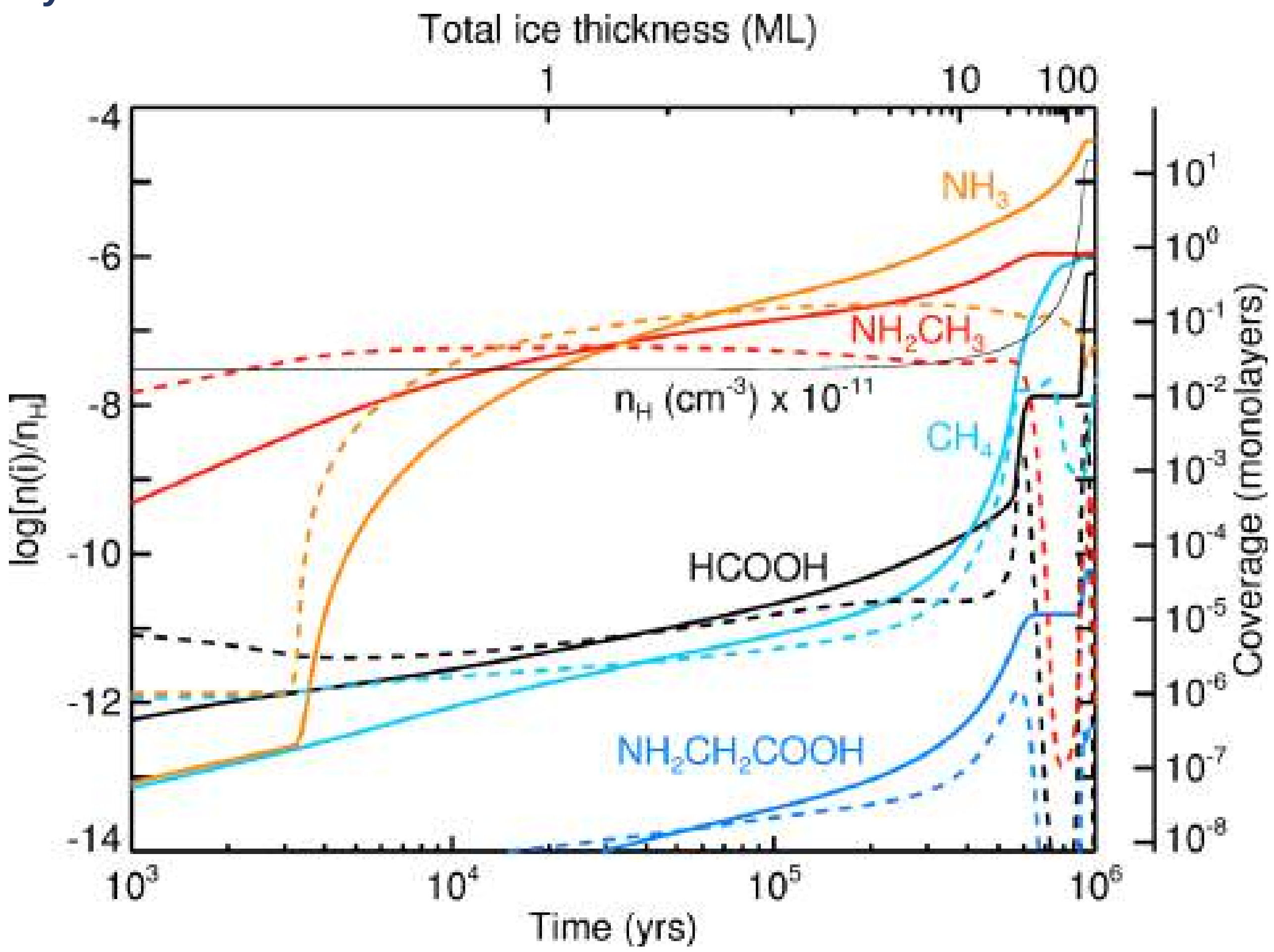
Density_{gas} = 3×10^3 to 2×10^6 cm^{-3} in 9.3×10^5 yrs

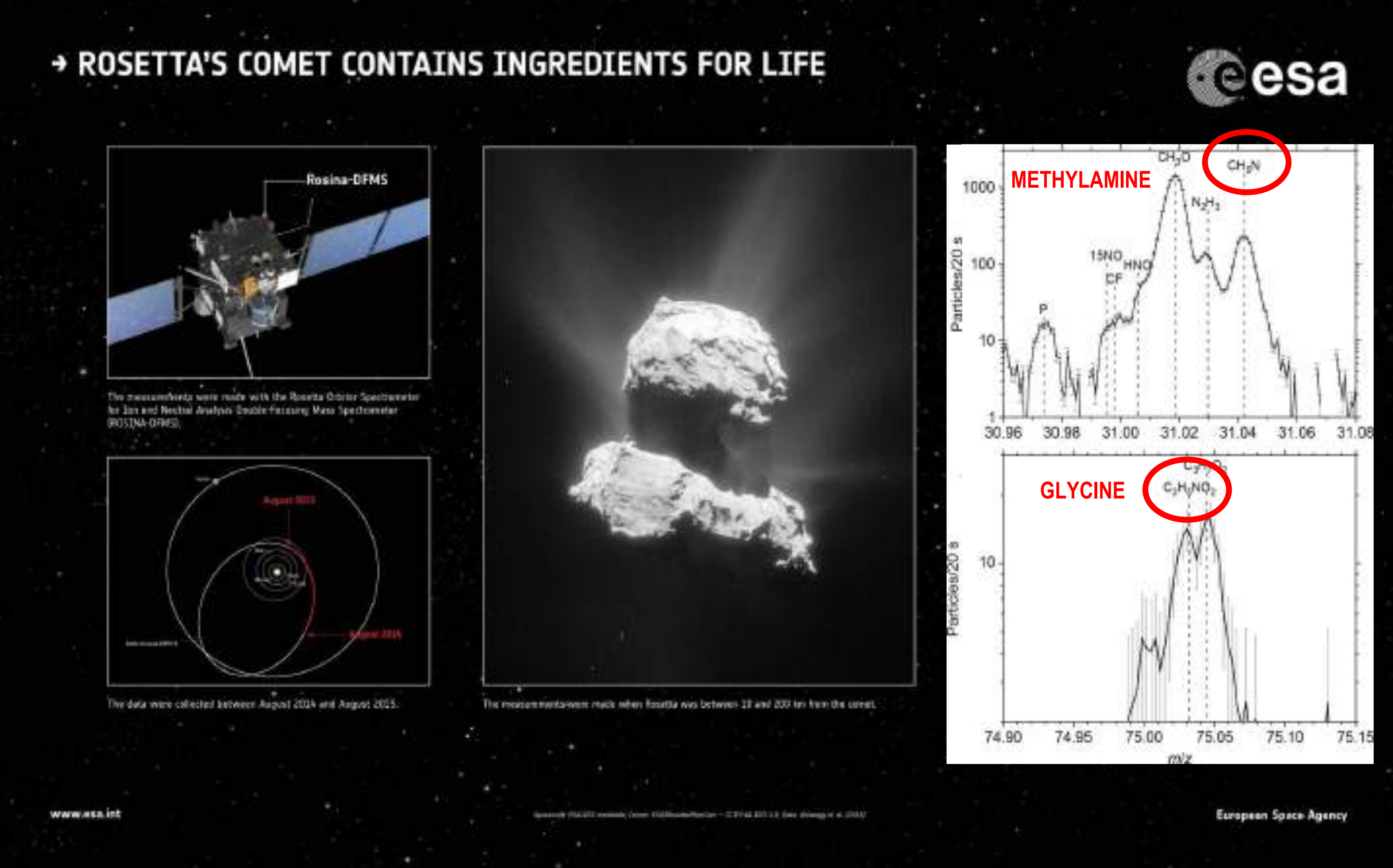
T_{dust} = 16 to 8 K

T_{gas} = 10 K

A*v* = 2 to ~150 mag







→ ROSETTA'S COMET CONTAINS INGREDIENTS FOR LIFE

The measurements were made with the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis Double Focusing Mass Spectrometer (ROSINA-DFMS).

The data were collected between August 2014 and August 2015.

The measurements were made when Rosetta was between 10 and 200 km from the comet.

www.esa.int

European Space Agency

Altwegg *et al.*, Sci. Adv. (2016)

Beyond Experimental Limits:

Model vs Obs

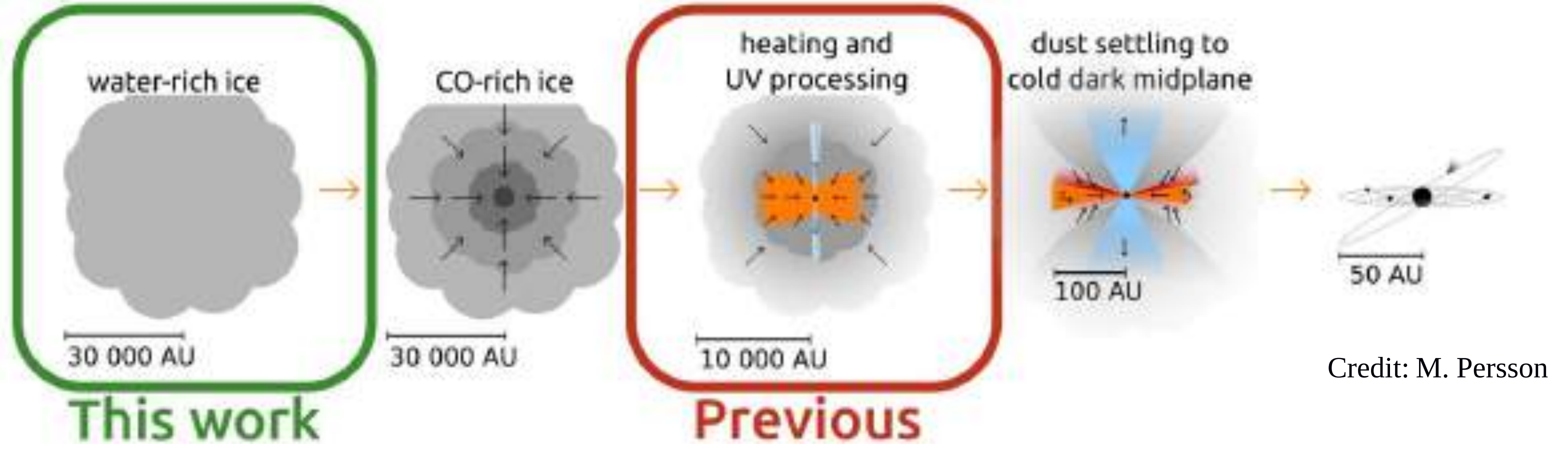
Species	**Bkg Stars**	**LYSOs**	**67P/CG**	**Model 1**	**Model 1**	**Model 2**
			Summer hem.	low n_H	high n_H	prestellar
H_2O	100	100	100	100	100	100
CO	9-67	(< 3)-85	2.7	8.0	17.3	19.7
CO_2	14-43	12-50	2.5	4.0	6.9	9.3
CH_3OH	(< 1)-12	(< 1)-25	0.31	4.0	2.4	35.9
NH_3	< 7	3-10	0.06	8.6	5.6	21.3
CH_4	< 3	1-11	0.13	3.6	3.0	0.65
HCOOH	< 2	(< 0.5)-4	0.008	0.44	0.69	0.35
NH_2CH_3			0-0.16	2.9	1.8	0.65
NH_2CH_2COOH		<0.3 [a]	0-0.16	0.04	0.07	3.5×10^{-5}

[a] Upper limit for the massive young stellar object W33 A from Gibb *et al.*, (2004)
Bkg Stars and LYSOs from Boogert *et al.*, (2015)
67P/CG from Altwegg *et al*., (2016) & Le Roy *et al.*, (2015)

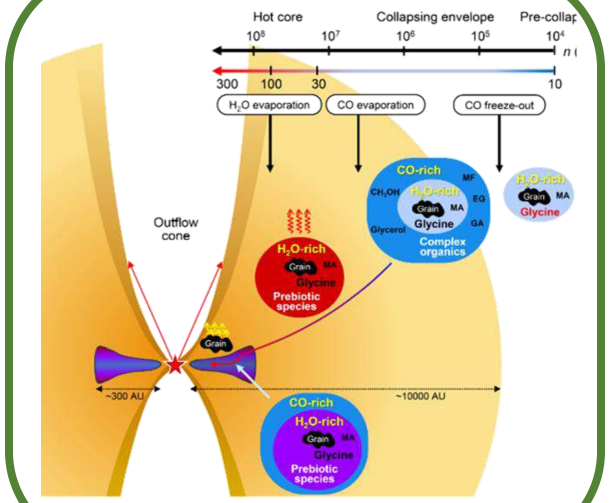
Glycine forms via Dark Chemistry

In Prestellar Cores

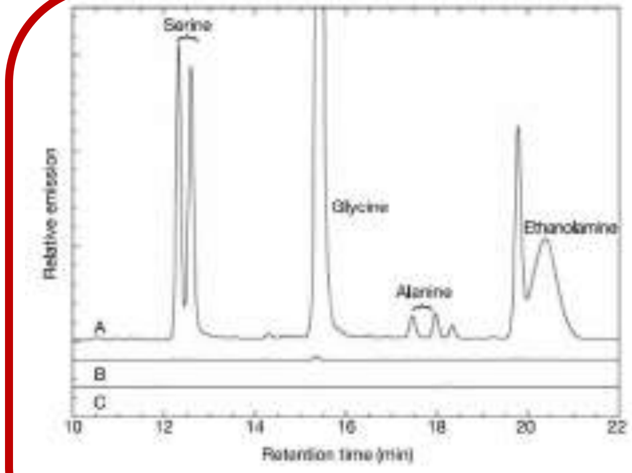
Ioppolo *et al.*, Nat. Astron. (2020)



Credit: M. Persson



Star Formation Process

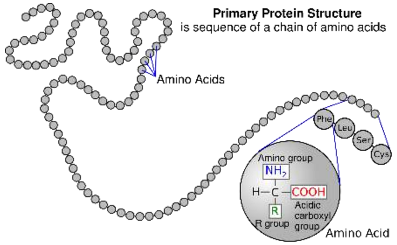


UV photolysis of interstellar ice analogues

$H_2O:CH_3OH:NH_3:HCN = 20:2:1:1$

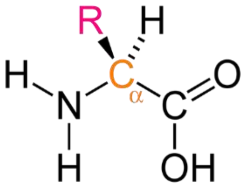
Bernstein et al., *Nature* 416, 401 (2002)

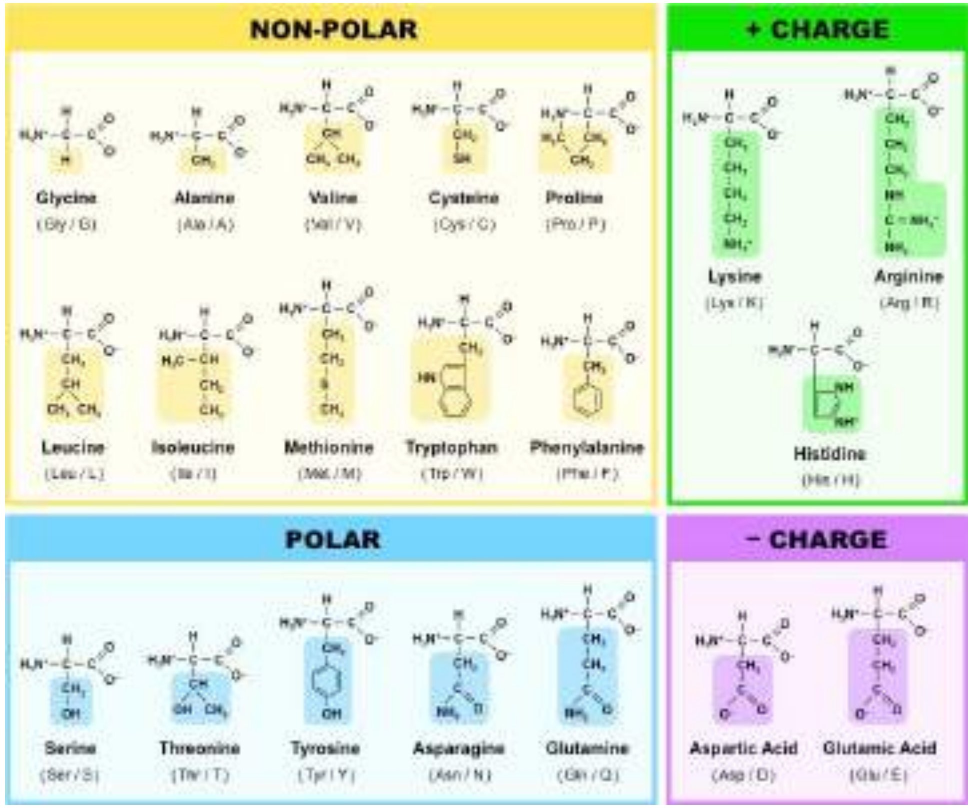
Amino acids formation via Dark Chemistry

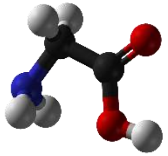


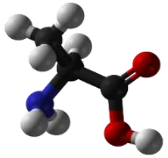
Oba *et al.*, CPL (2015) showed H-abstraction on R-group

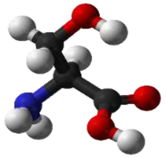
Formation of proteinogenic α-amino acids?





α-glycine  ✓

α-alanine  ?

α-serine  ?

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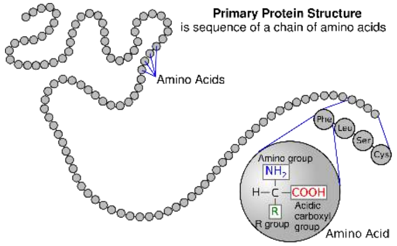
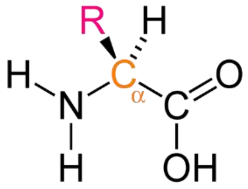
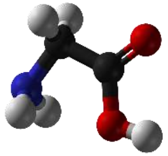
Amino acids formation via Dark Chemistry

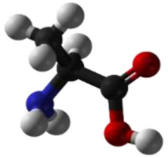


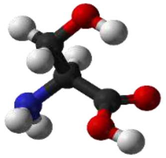
Oba *et al.*, CPL (2015) showed H-abstraction on R-group

Formation of proteinogenic α-amino acids?



α-glycine  ✓

α-alanine  ?

α-serine  ?

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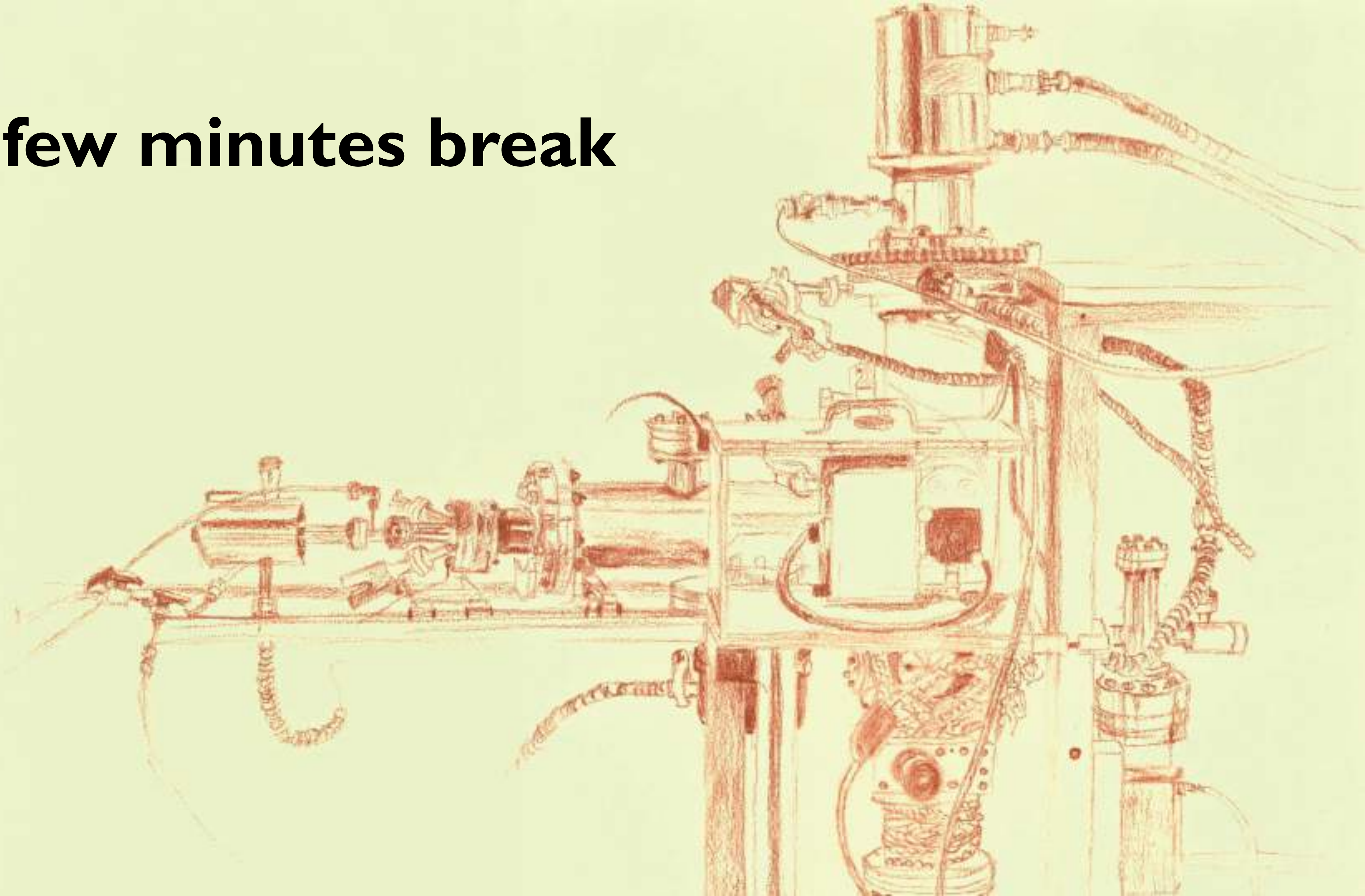
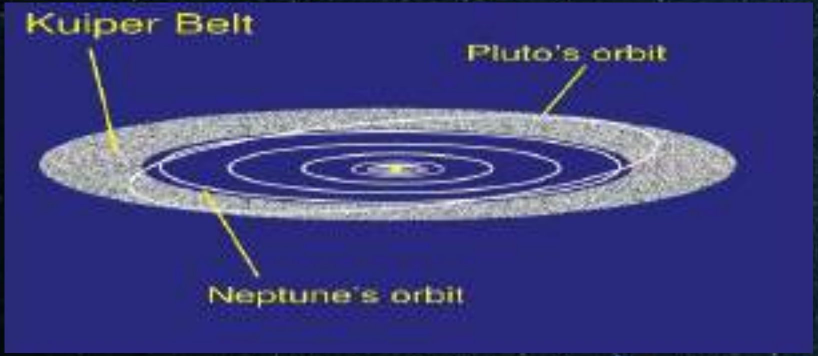
A few minutes break

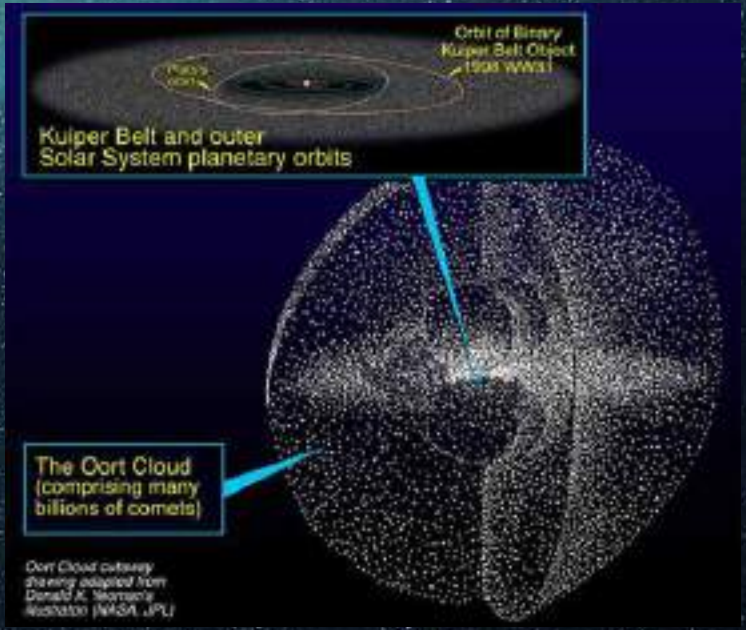


Comets



Kuiper belt
AU 30 - 100

Oort cloud
2,000 – 100,000 AU



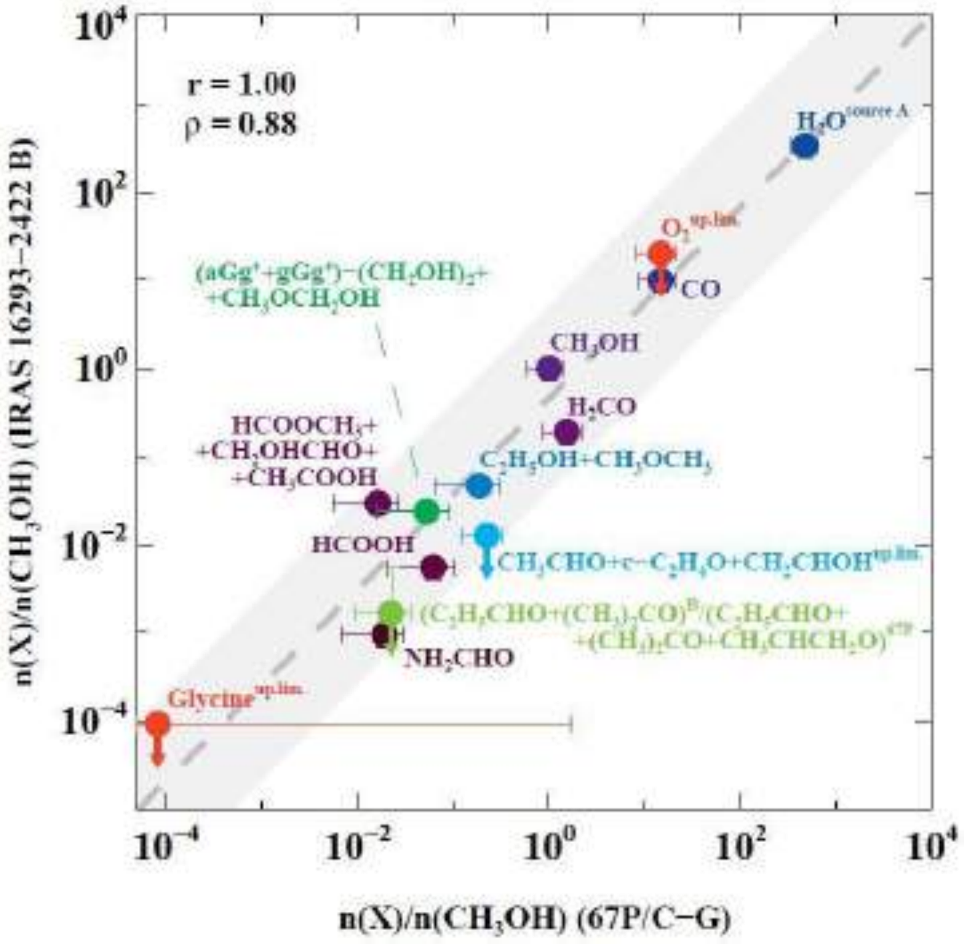
Cometary chemistry

- Comets are thought to have formed in the outer part of the disk which formed our Solar System
- **Comets contain the least-modified original interstellar material**
- Early optical observations probed mostly daughter molecules

  (CH, CN, C_2, CO^+, OH, OH^+, …).
- IR and (sub)mm observations provide direct information on parent molecules, i.e., ***original composition of ices***
- Lots of data from comets Halley, Hyakutake, and Hale-Bopp

Comparison young disk - comet

O-bearing



Comet somewhat richer in COMs than young disk

Drozdovskaya *et al.*, (2019)

Meteorites

Australia 1969, 100 kg

~92 amino acids
8 important for life

~20 different sugar groups
RNA base - Uracil

- Most of the material formed at the same time as the Solar System.
- However, there are small inclusions that have isotopic anomalies indicating a presolar and interstellar origin.
- These include SiC grains, graphite grains, diamonds, and larger organic carbon-based molecules (Kerogens – soot).

Credit: Rodney Start, Museums Victoria

Delivery of extraterrestrial material to Earth

- **Solar System: ~4.6 Gyr**

The period of heavy cratering or heavy bombardment ended ~4 Gyr ago

- **Today:**

Total influx: ~3,000 - 50,000 tonnes/year

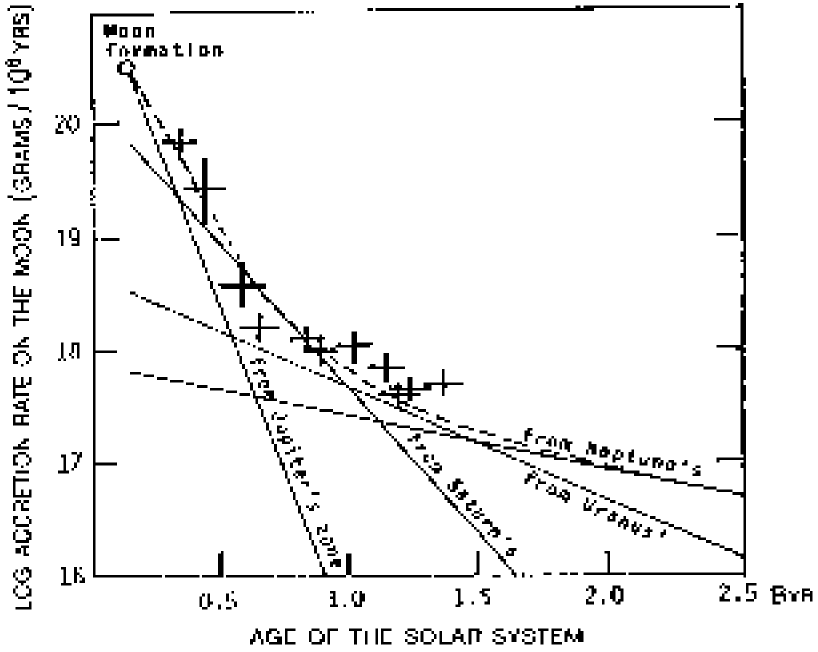
Influx of coal-based material: ~300 tonnes/year

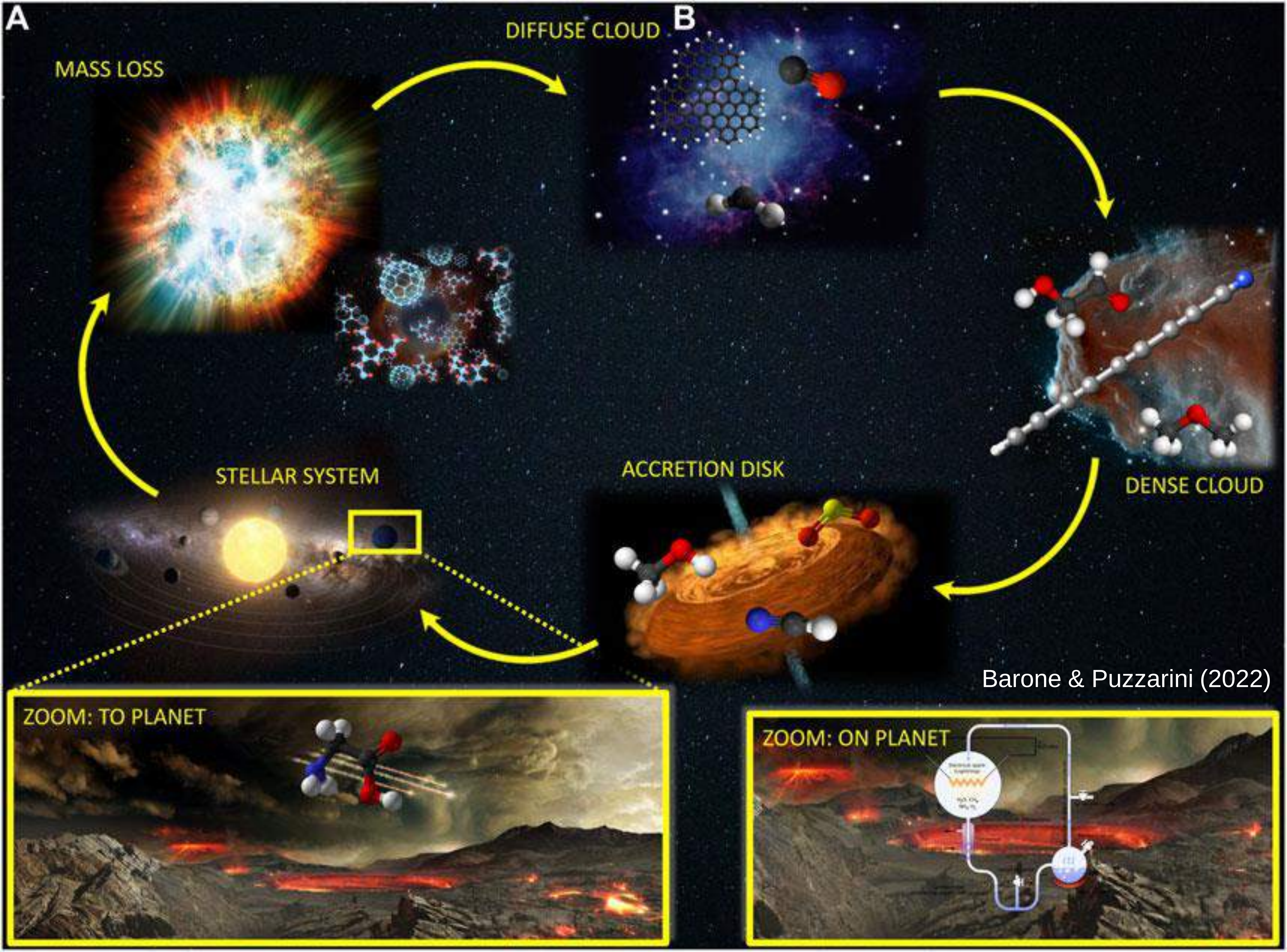
- **During the "period of heavy bombardment":**

Total influx: ~500,000 tonnes/year

Influx of coal-based material: ~50,000 tonnes/year

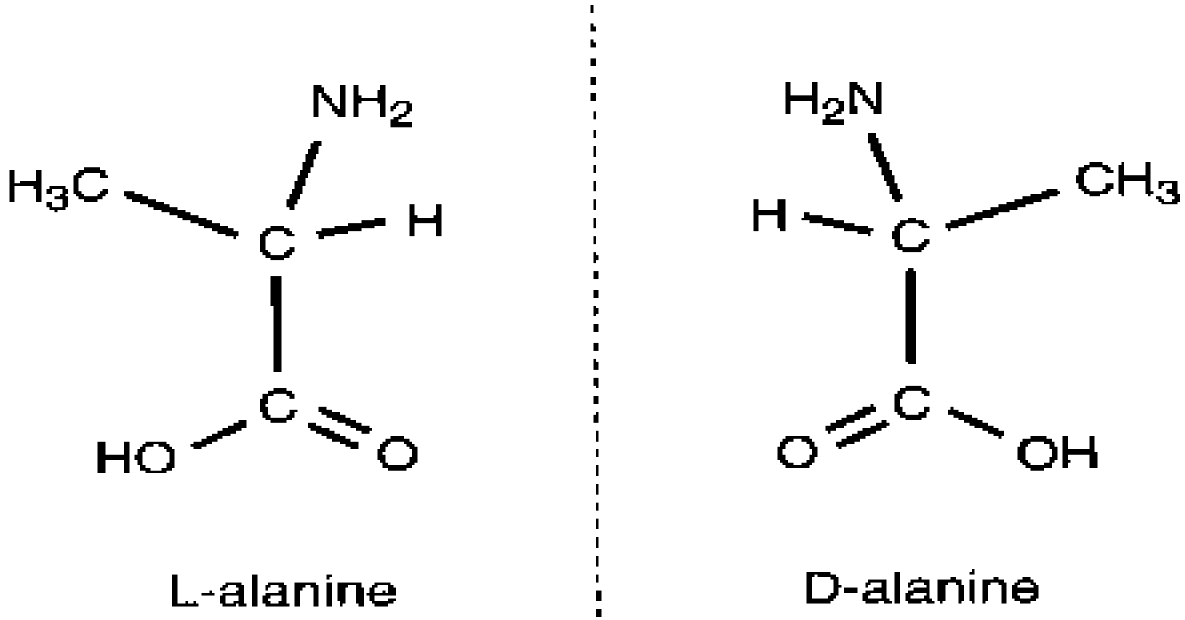
- ~50% of water on Earth may be from comets





Barone & Puzzarini (2022)

Chirality



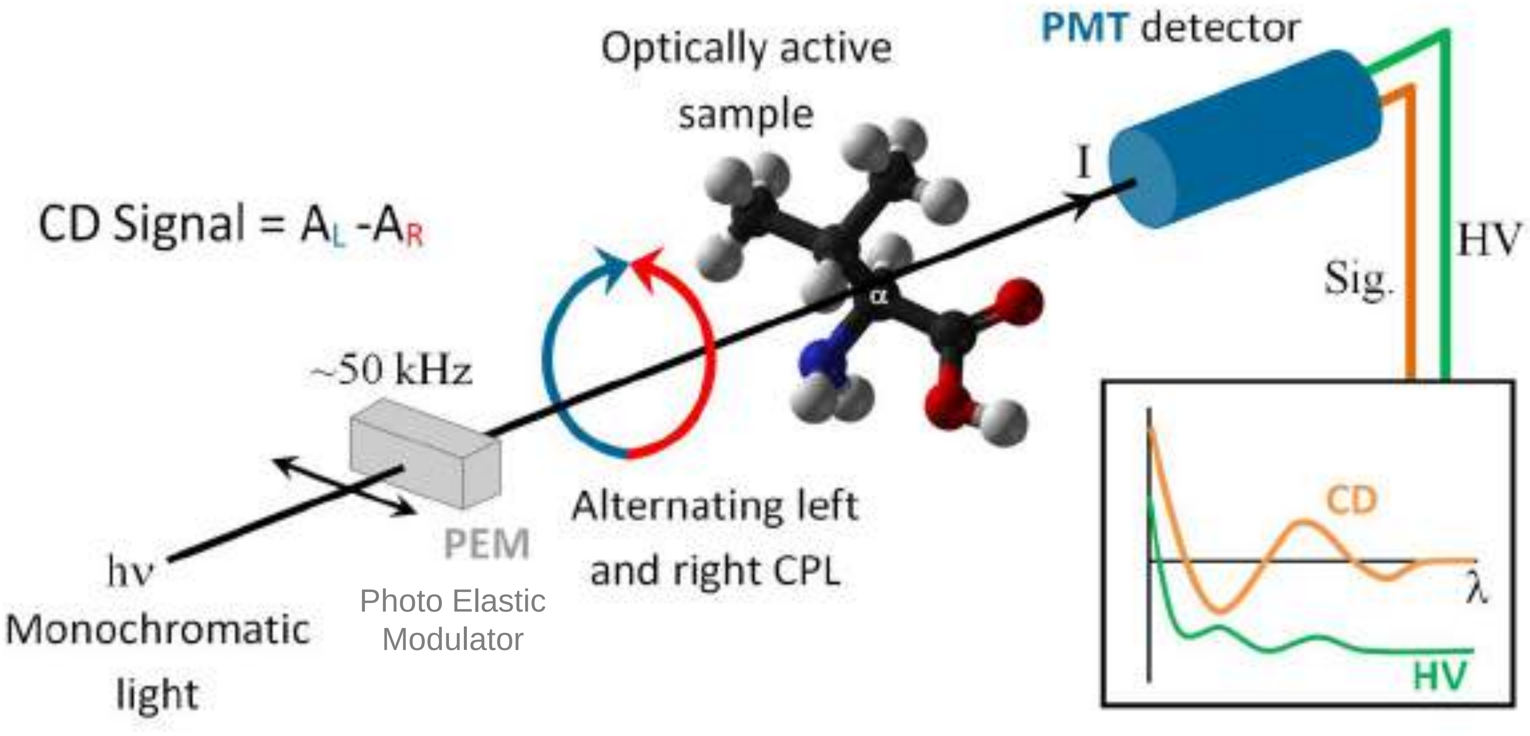
L-alanine

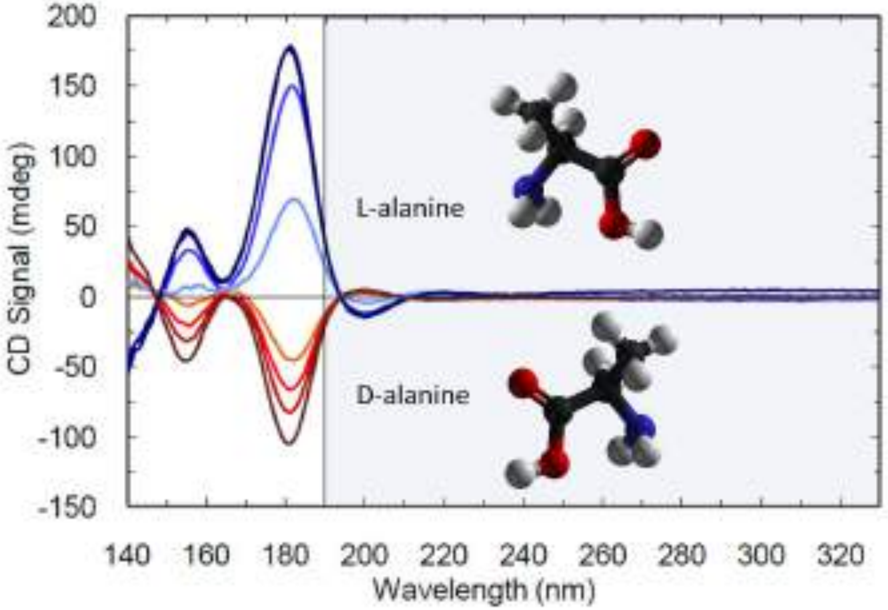
D-alanine

- Life on Earth is based on **left-handed** amino acids and **right-handed** sugar groups in RNA and DNA
- Enantiomeric specificity: a prerequisite for or a result of life?

Chirality

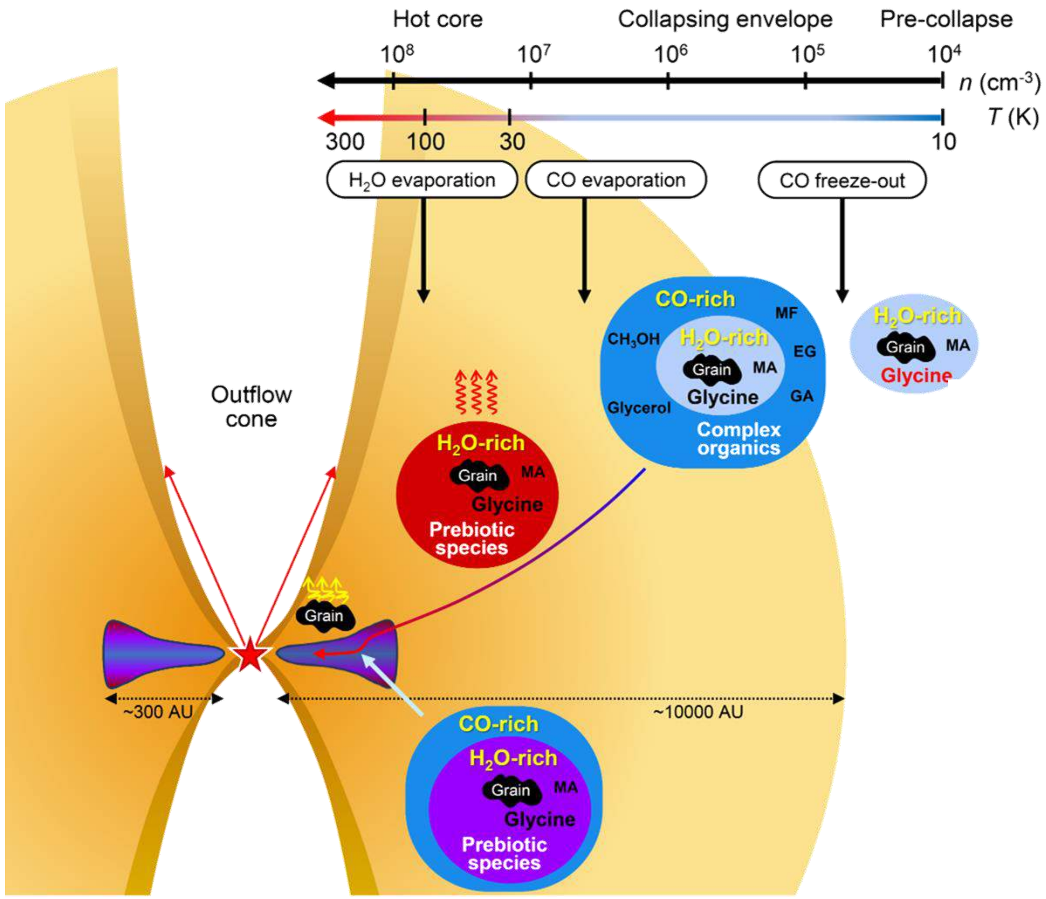
Circular Dichroism (CD) spectroscopy





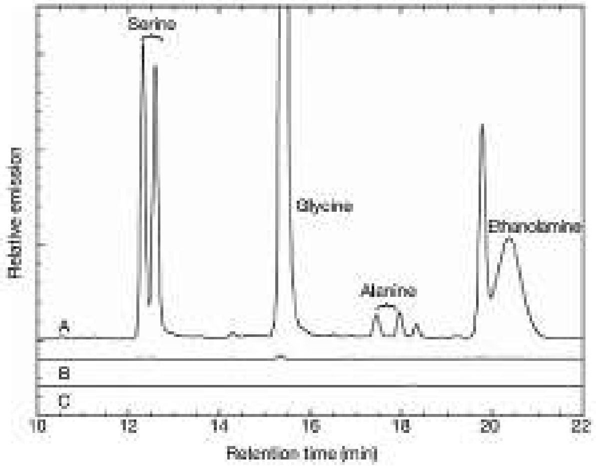
Meinert *et al.*, Met. & Plan. Sci. (2022)

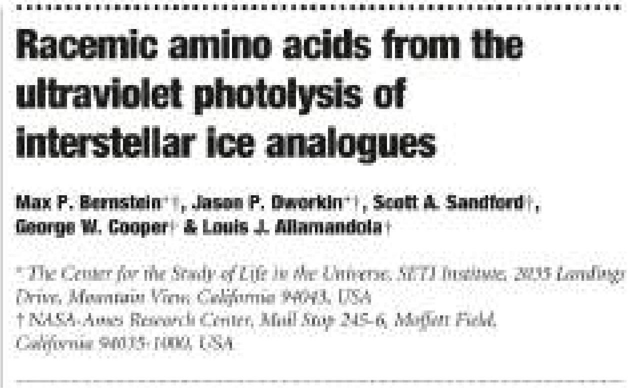
Ice Chemistry in Star Forming Regions



Star Formation Process

- Dark Chemistry can explain formation of Simple and Complex molecules in the early stages of Star Formation
- Energetic Processing still important in the ISM





Racemic amino acids from the ultraviolet photolysis of interstellar ice analogues

Max P. Bernstein*†, Jason P. Dworkin*†, Scott A. Sandford†, George W. Cooper† & Louis J. Allamandola†

** The Center for the Study of Life in the Universe, SETI Institute, 2035 Landing Drive, Mountain View, California 94043, USA*

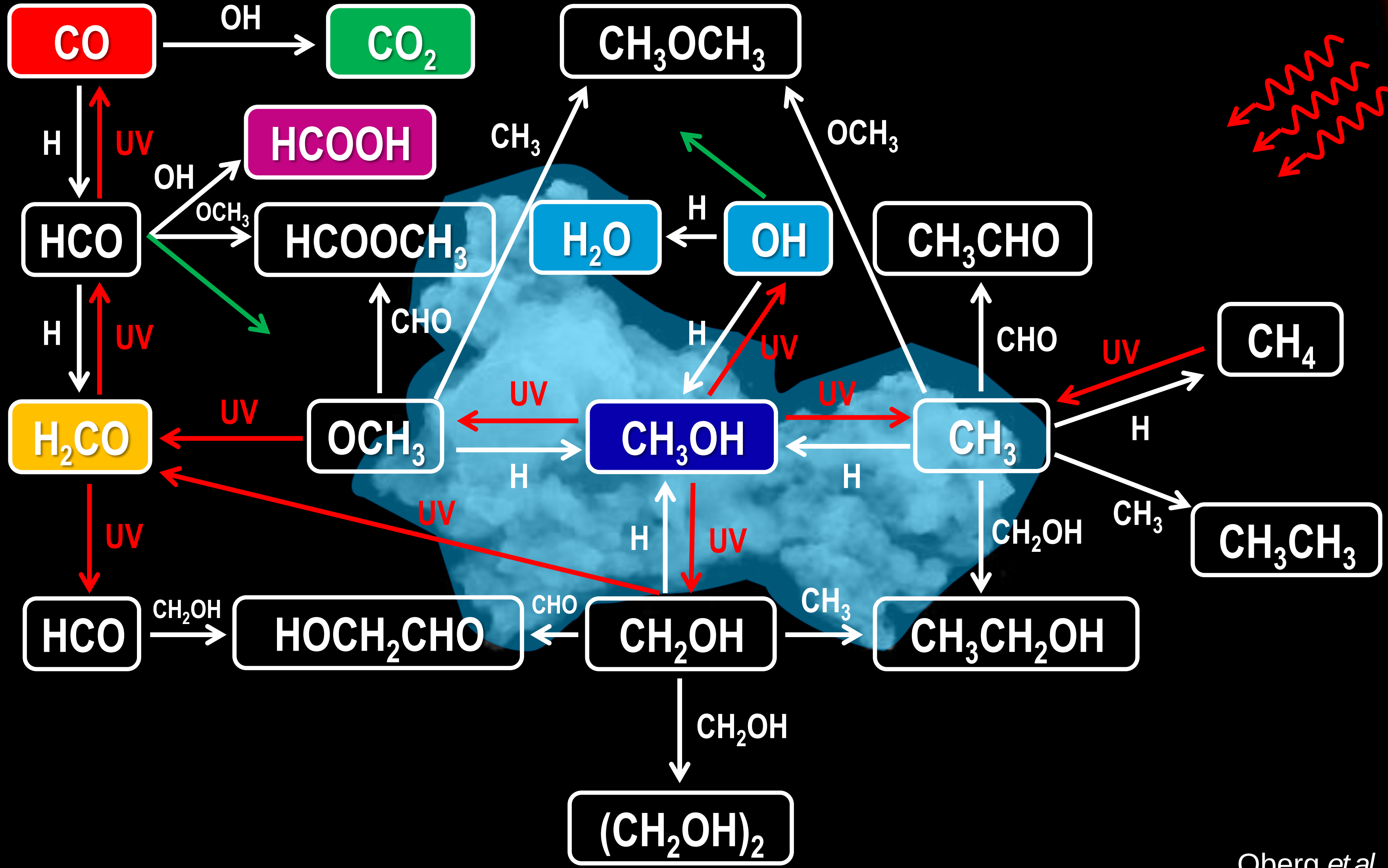
† NASA-Ames Research Center, Mail Stop 245-6, Moffett Field, California 94035-1000, USA

UV photolysis of interstellar ice analogues:

$H_2O:CH_3OH:NH_3:HCN = 20:2:1:1$

Bernstein *et al.*, Nature 416, 401 (2002)

UV Photolysis of Ice Dust Grains



CO

OH

CO_2

CH_3OCH_3

H

UV

OH

$HCOOH$

CH_3

OCH_3

HCO

OCH_3

$HCOOCH_3$

H_2O

H

OH

CH_3CHO

H

UV

CHO

H

UV

CHO

UV

CH_4

UV

UV

UV

H_2CO

OCH_3

CH_3OH

CH_3

H

H

H

UV

UV

H

UV

CH_2OH

CH_3

UV

CH_3CH_3

HCO

CH_2OH

$HOCH_2CHO$

CHO

CH_2OH

CH_3

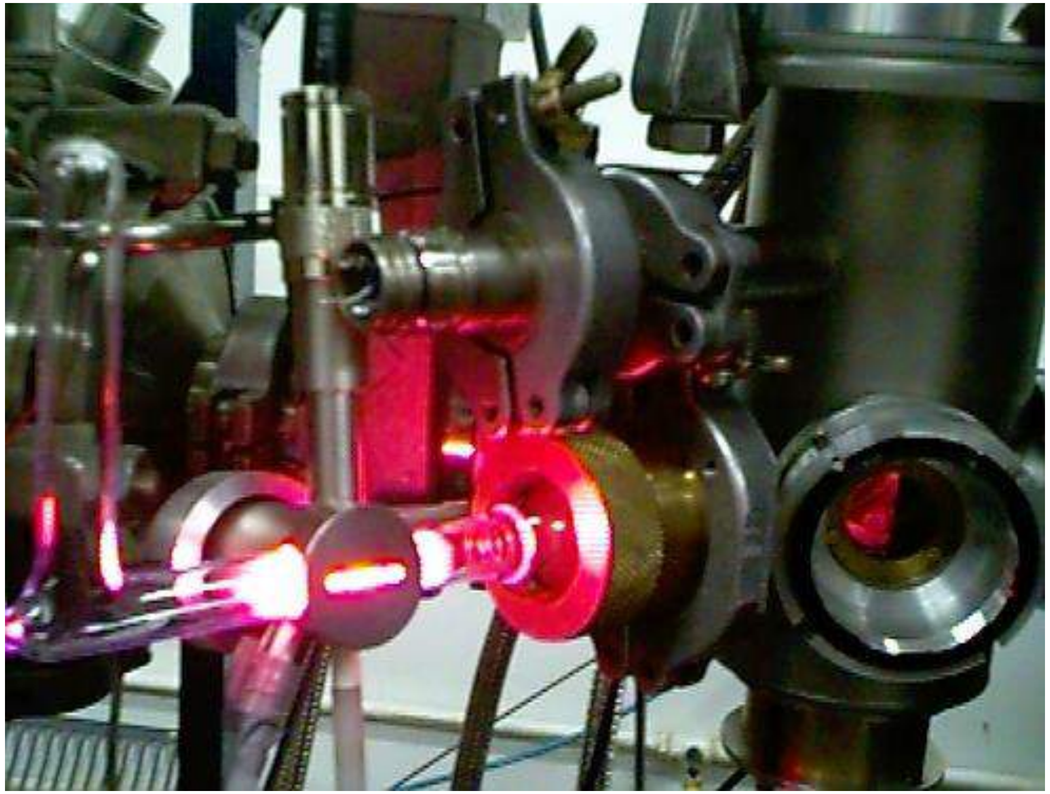
CH_3CH_2OH

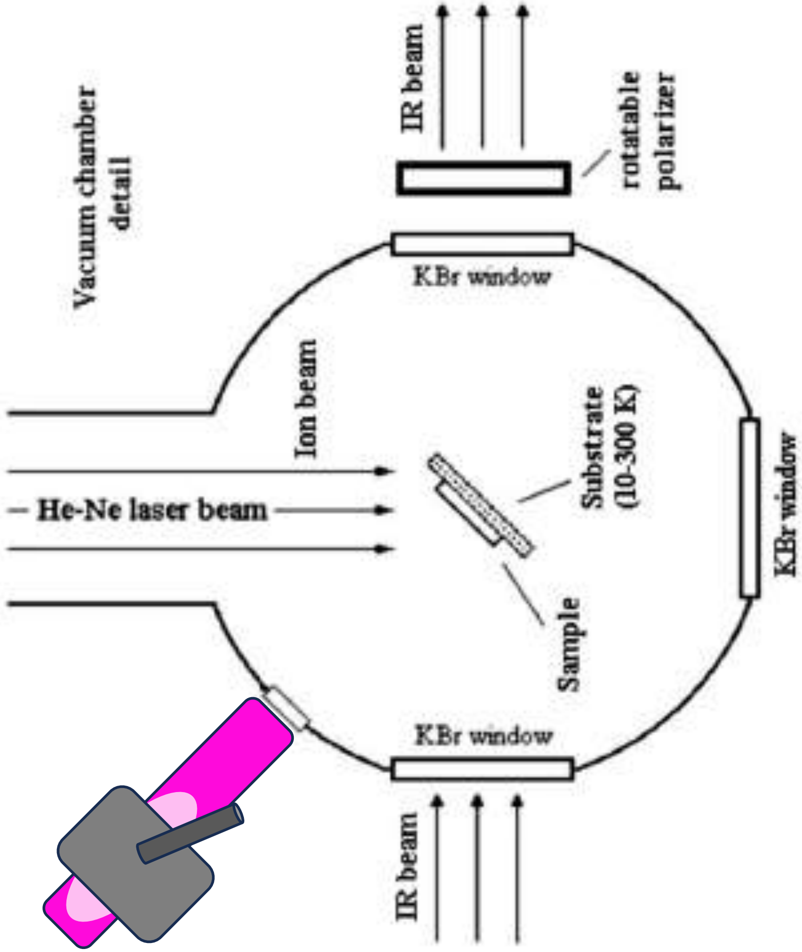
CH_2OH

$(CH_2OH)_2$

Oberg *et al.*, A&A (2009)

UV Photolysis Studies

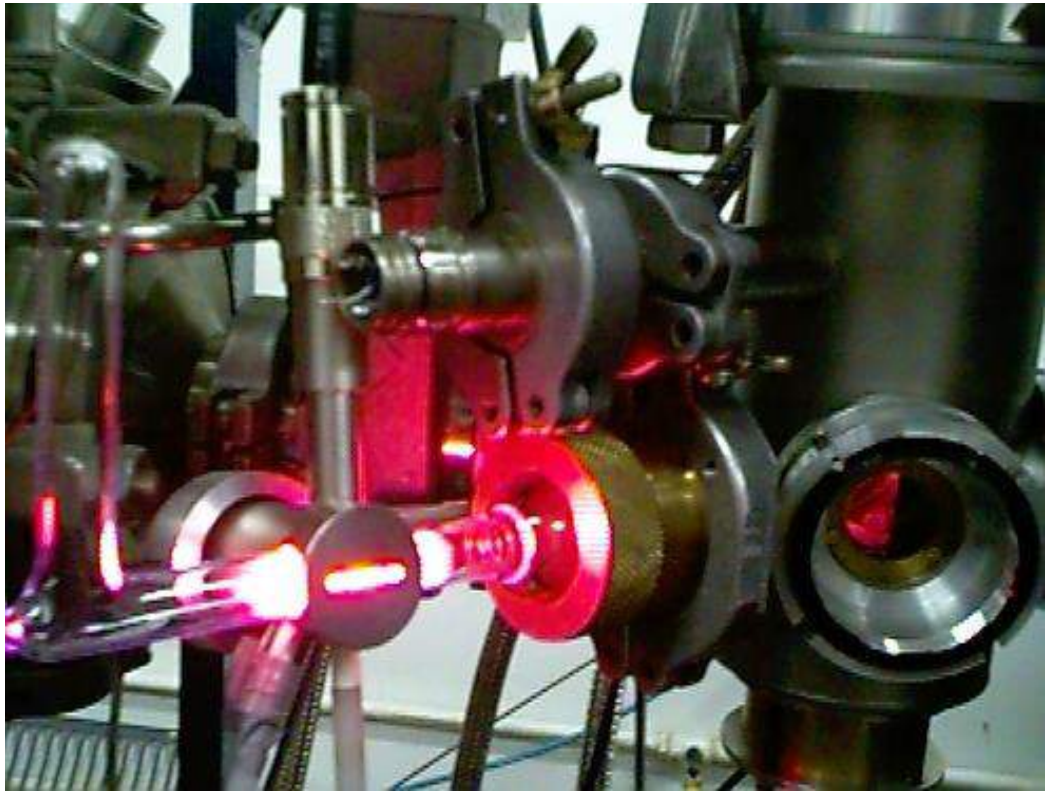


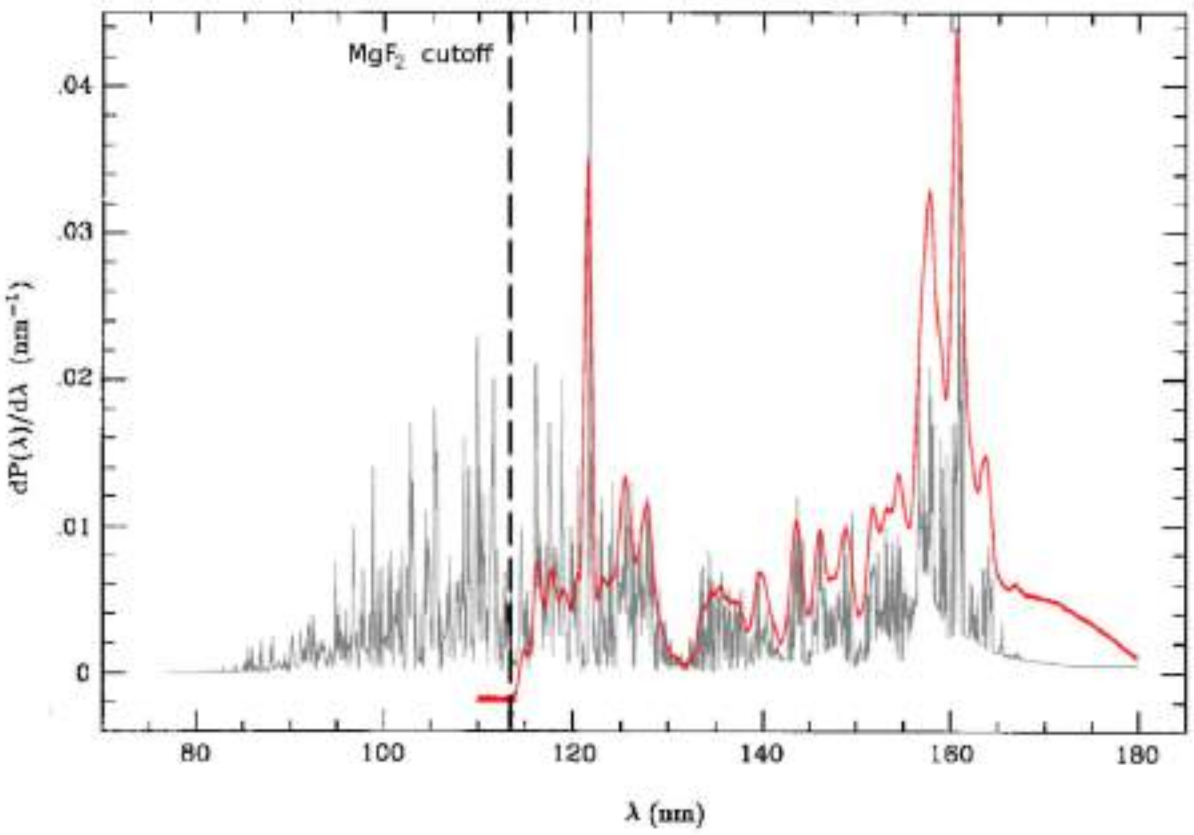


UV Lamp

Oberg, CR (2016)

UV Photolysis Studies



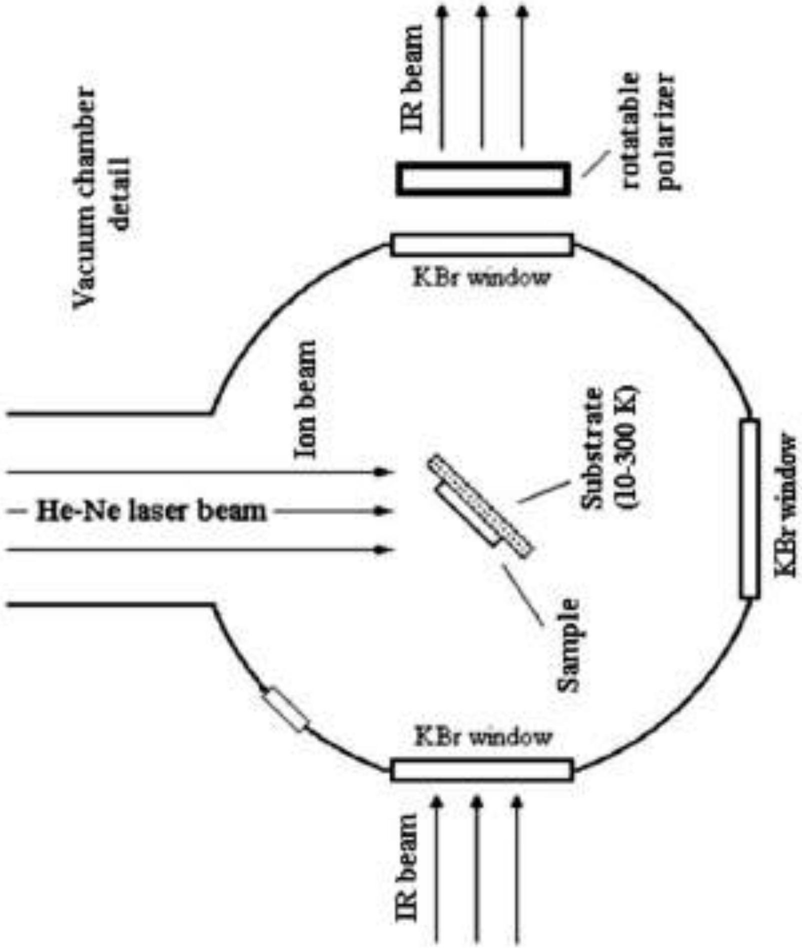


Cruz-Diaz *et al.*, A&A (2014)

Cosmic Rays Processing Studies

LASP INAF-Catania

- Ultra High Vacuum (UHV) chamber ($P<10^{-9}$ mbar)
- Cryostat (15-300 K)
- Ion implanter (Danfysik-200 kV)
- UV lamp (Lyman-alpha)
- IR, UV-Vis-NIR, and Raman spectrometers



HUN-REN ATOMKI

CRs and electron irradiation of ice material relevant to ISM & Solar System

ICA

$P < 1\times10^{-9}$ mbar

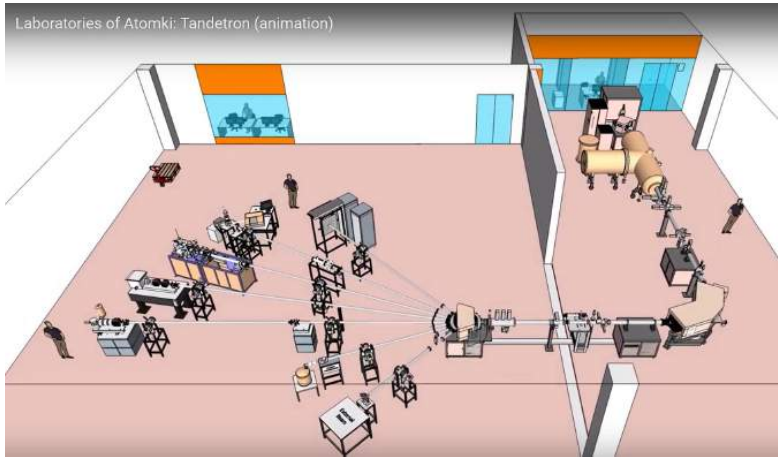
$T_{surf} = 20 - 300$ K

E_{ions} = 200 keV – 4 MeV H^+

H^+, He^+, He^{++}, C^+, C^{++}, O^+, O^{++}, S^+, S^{++}

Current = nA - µA

- **2 keV electron gun**
- **Effusive Cell**



AQUILA

$P < 1\times10^{-9}$ mbar

$T_{surf} = 20 - 300$ K

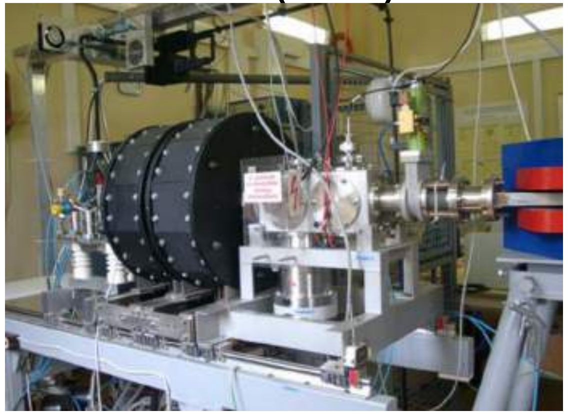
E_{ions} = 100s eV – 10s keV

Solar Wind: H, He, C, O, Si, Fe, Ni ions

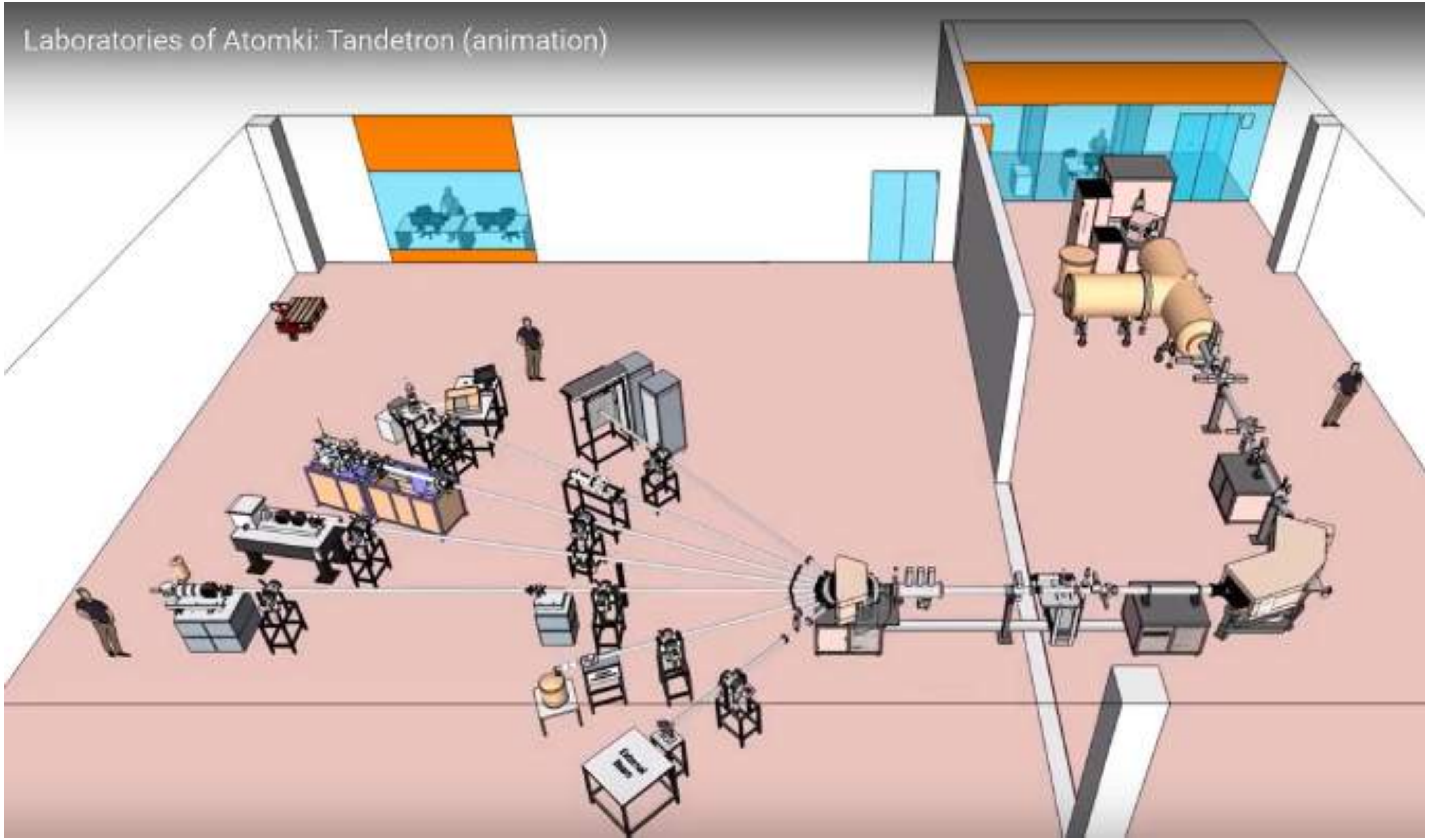
High charge state of ions

Positive/negative ions or molecular ions

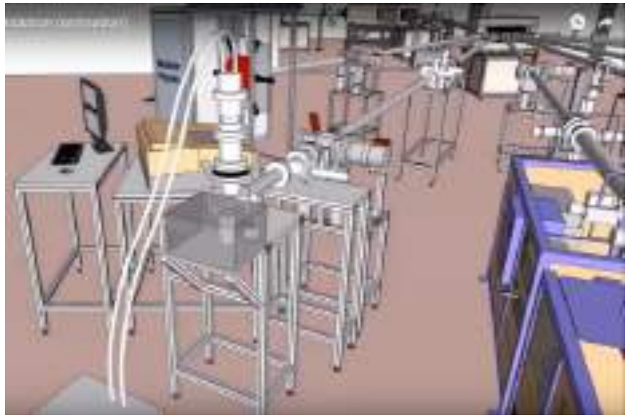
ECR Ion Source (ECRIS)



Ice Chamber for Astrophysics/Astrochemistry (ICA)

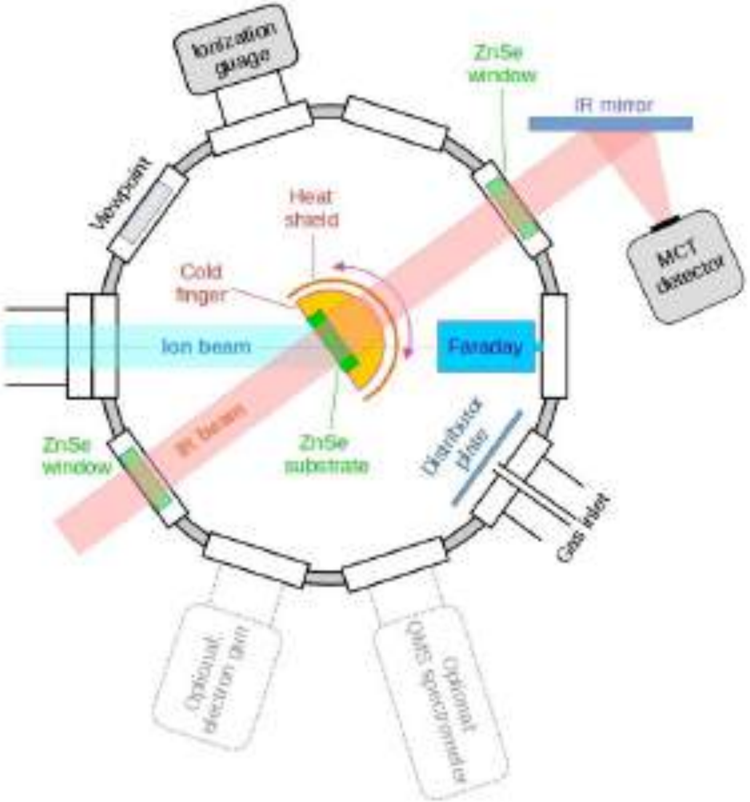


atomki
DEBRECEN



Ice Chamber for Astrophysics/Astrochemistry (ICA)

Systematic investigation of CR-induced chemistry and spattering in space relevant ices



***P* < 1x10^{-9} mbar**

***T_{surf}* = 20 - 300 K**

E_{ions} = 200 keV – 4 MeV H^+

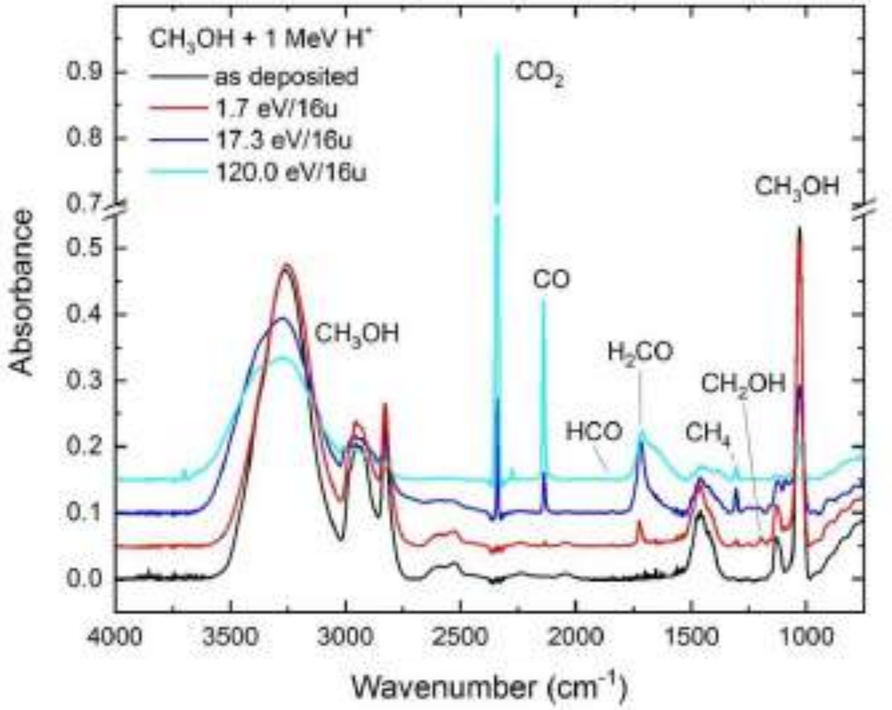
H^+, He^+, He^{++}, C^+, C^{++}, O^+, O^{++}, S^+, S^{++}

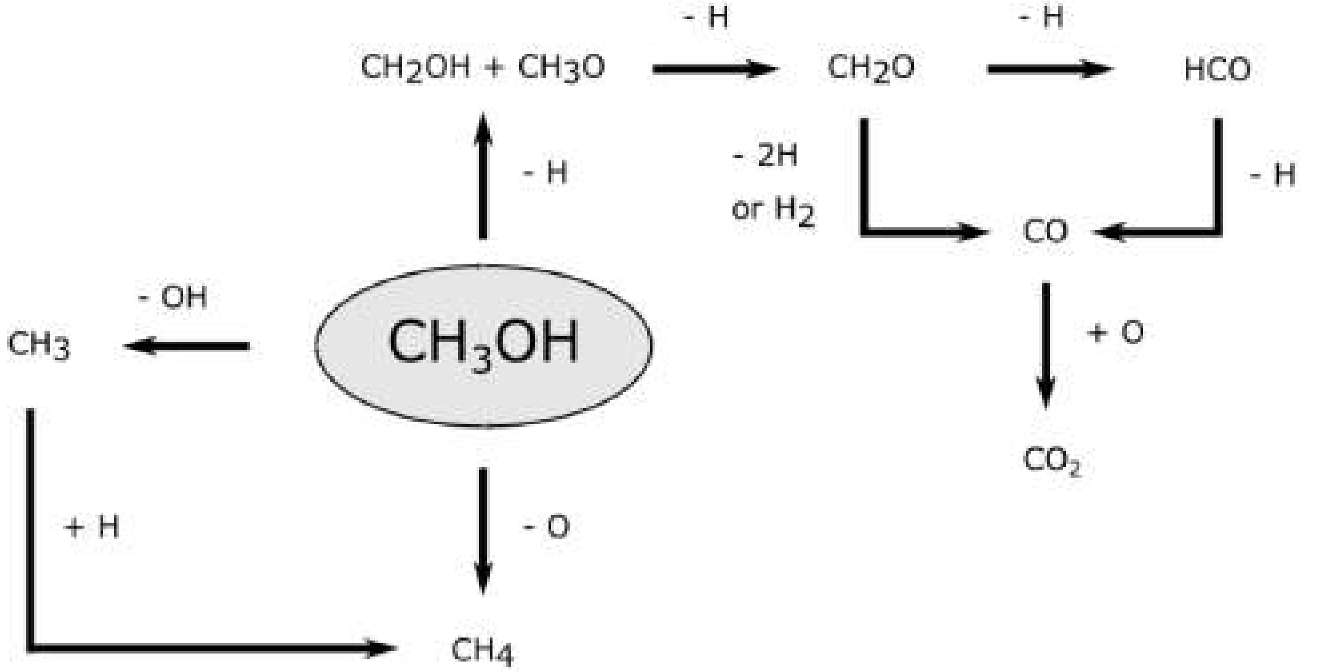
Current = nA - µA

- **2 keV electron gun**
- **Effusive Cell**

Herczku *et al.*, Rev. Sci. Inst. (2021)

Ice Chamber for Astrophysics/Astrochemistry (ICA)





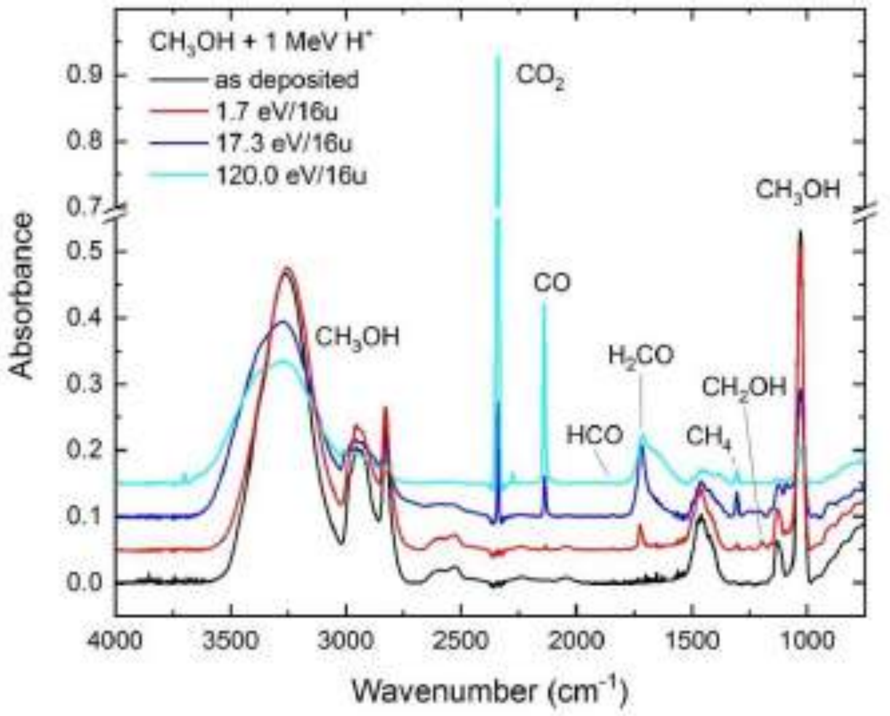
Methanol (CH_3OH) ice

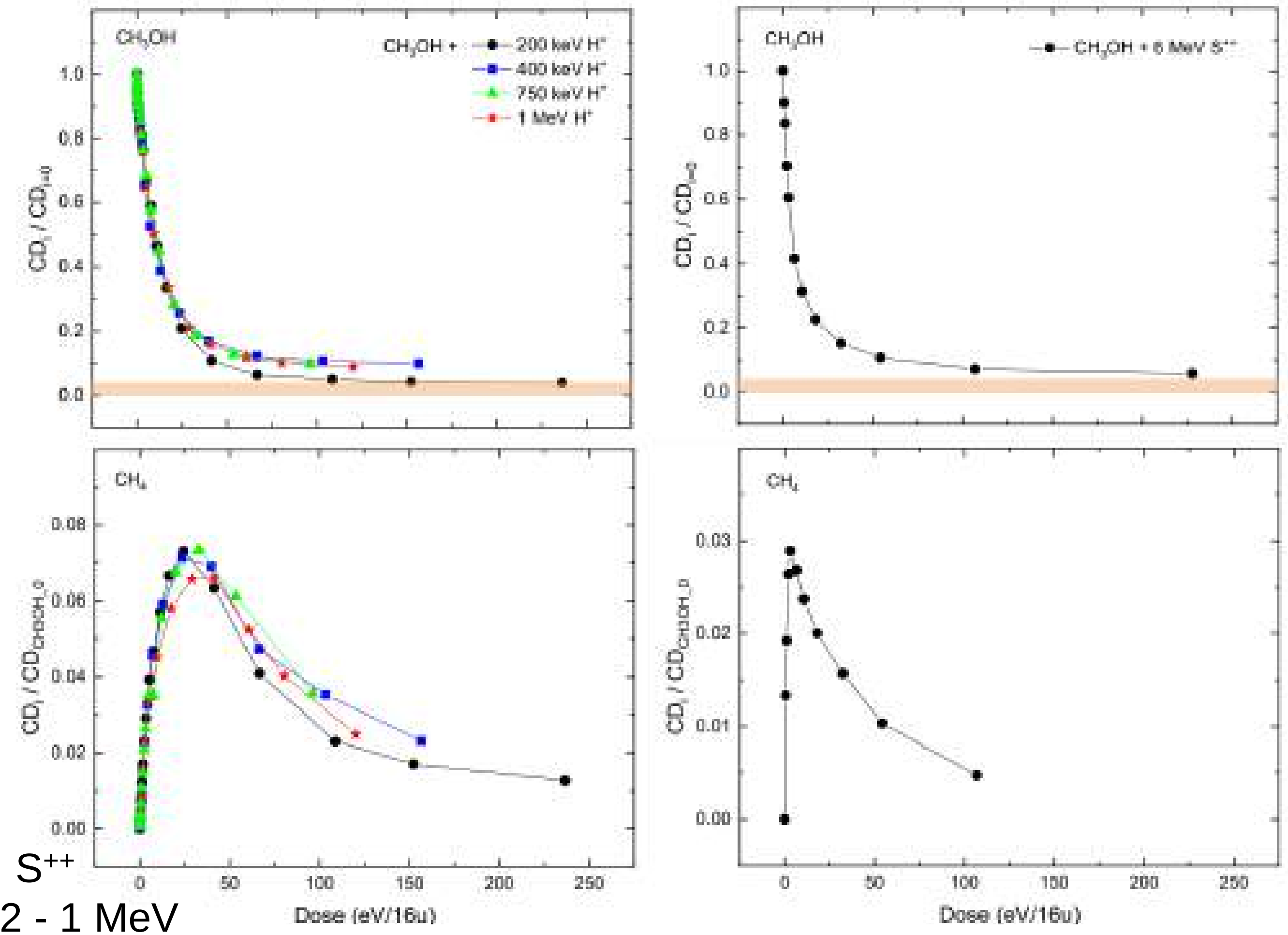
Temperature: 20 K
Deposition: Background
Ice thickness: ~ 0.5 µm

Projectile: H^+, S^{++}
H^+ Energy: 0.2 - 1 MeV
S^{++} Energy: 6 MeV

Herczku *et al.*, Rev. Sci. Inst. (2021)

Ice Chamber for Astrophysics/Astrochemistry (ICA)





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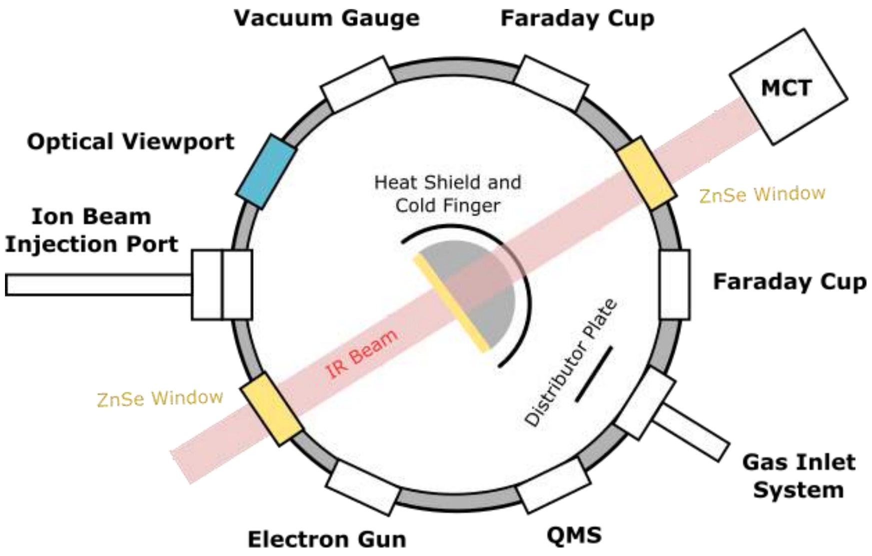
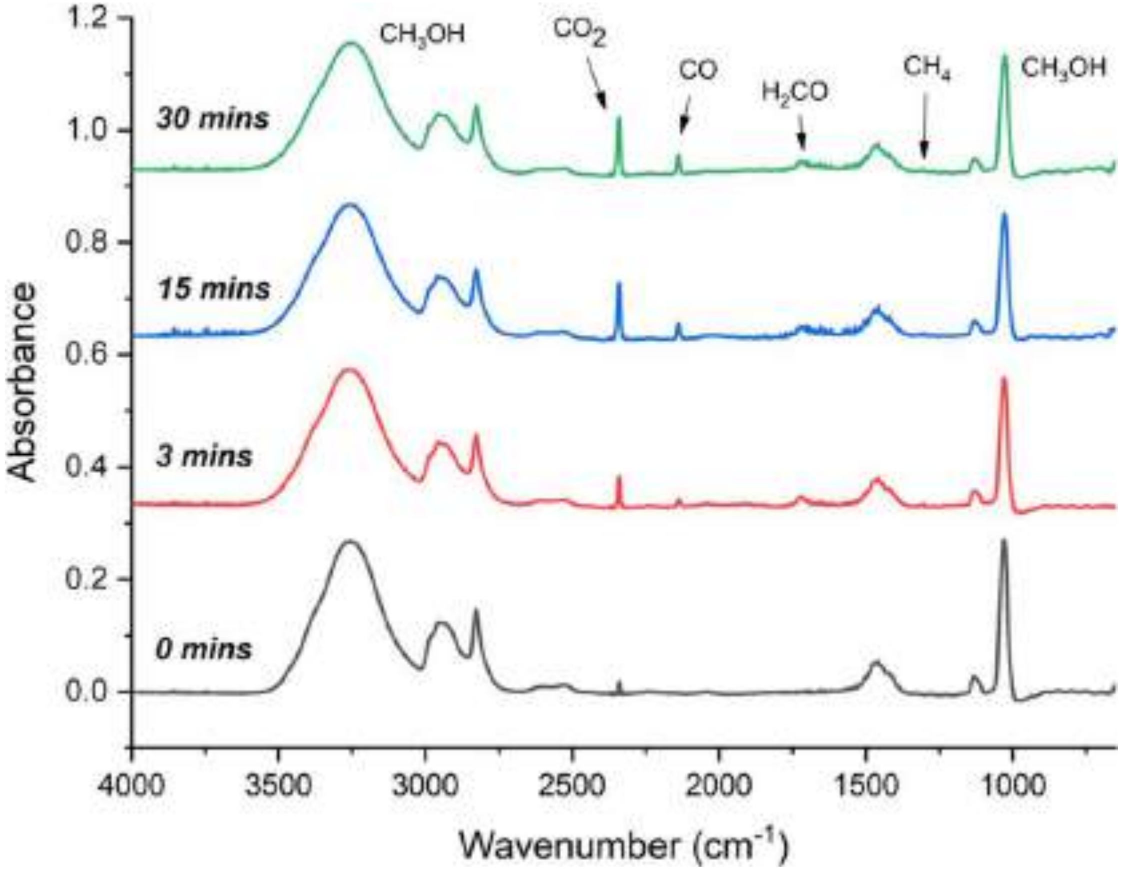




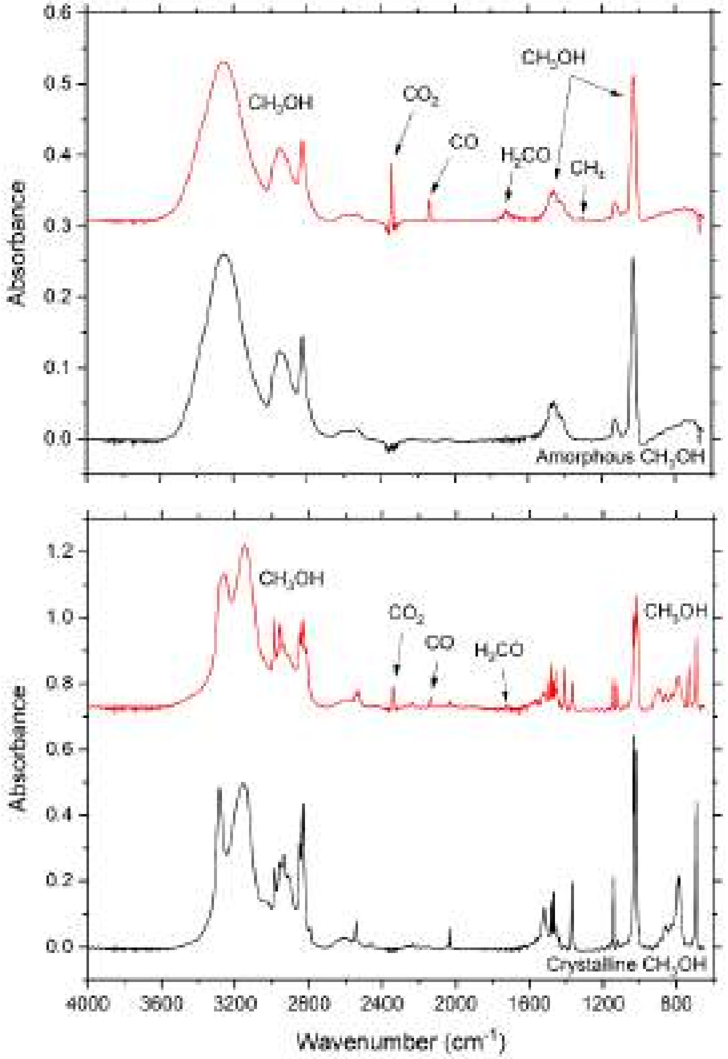
Methanol (CH_3OH) ice

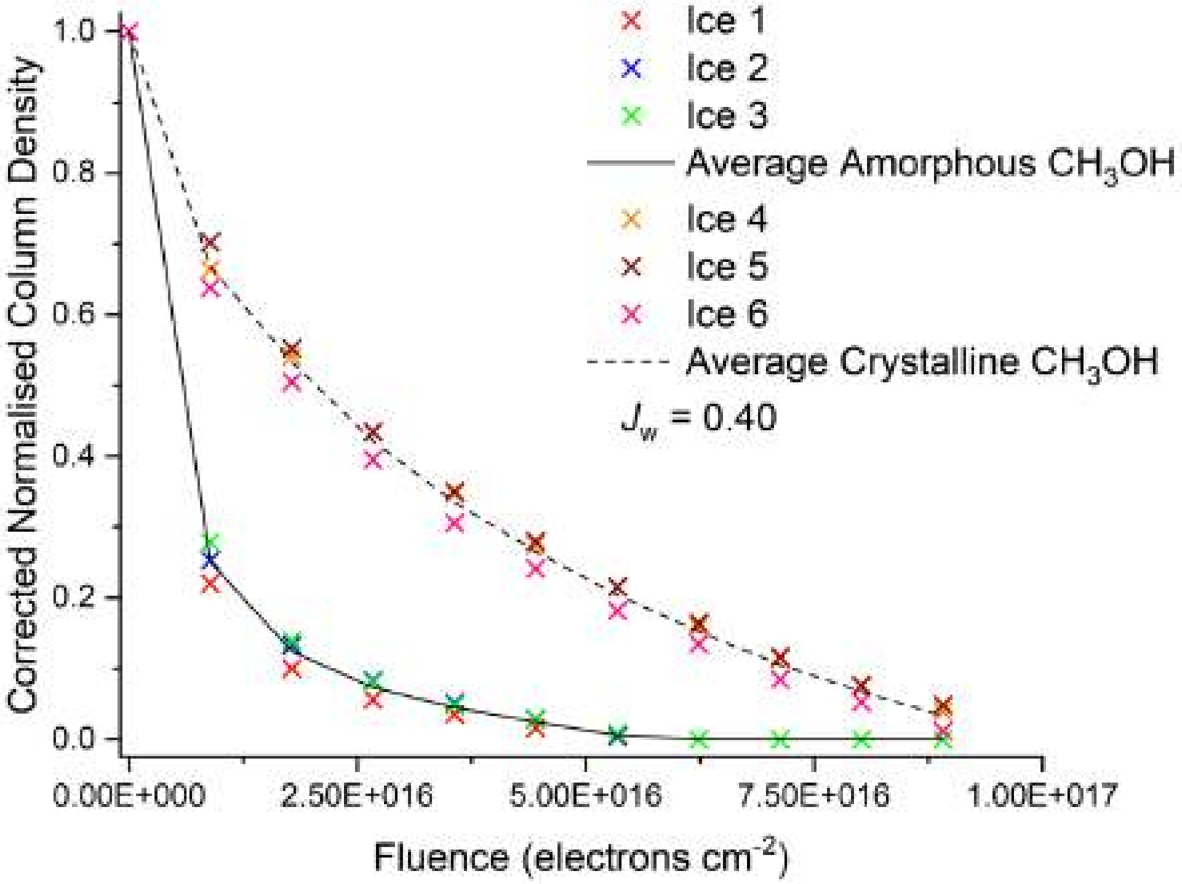
Temperature: 20 K
Deposition: Background
Ice thickness: ~ 1 µm

Projectile: e$^-$
Energy: 2 keV
$\Phi = 4.5\times10^{14}$ e$^-$ cm^{-2} s^{-1}

Mifsud *et al*., Eur. Phys. J. D (2021)

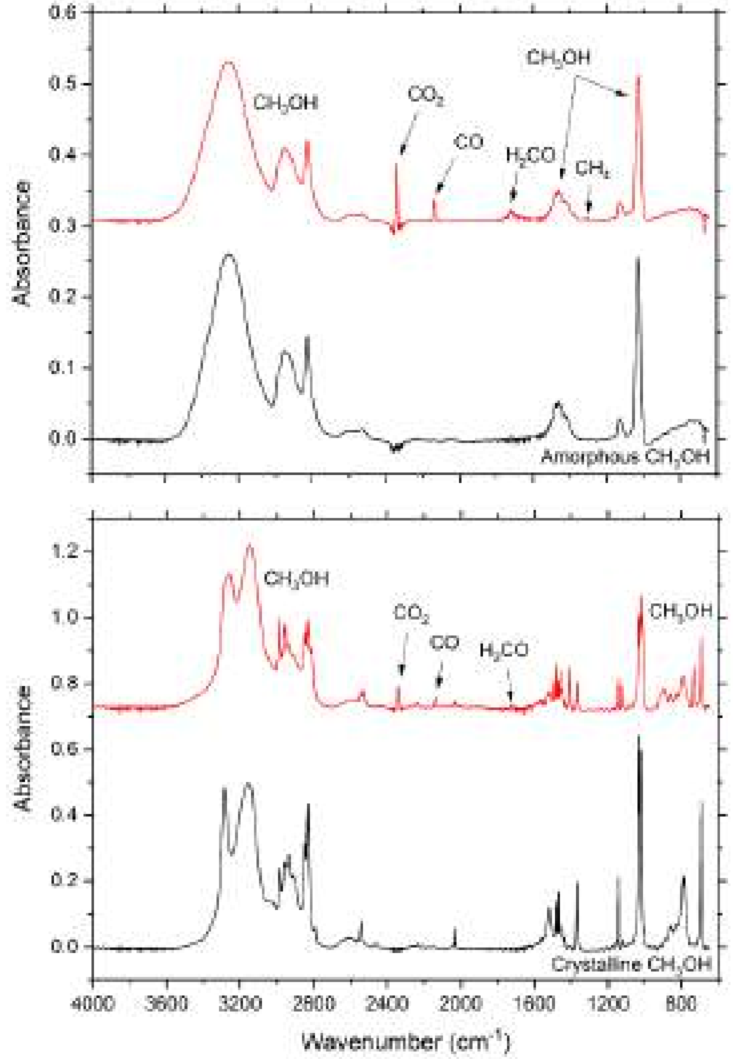
Ice Chamber for Astrophysics/Astrochemistry (ICA)

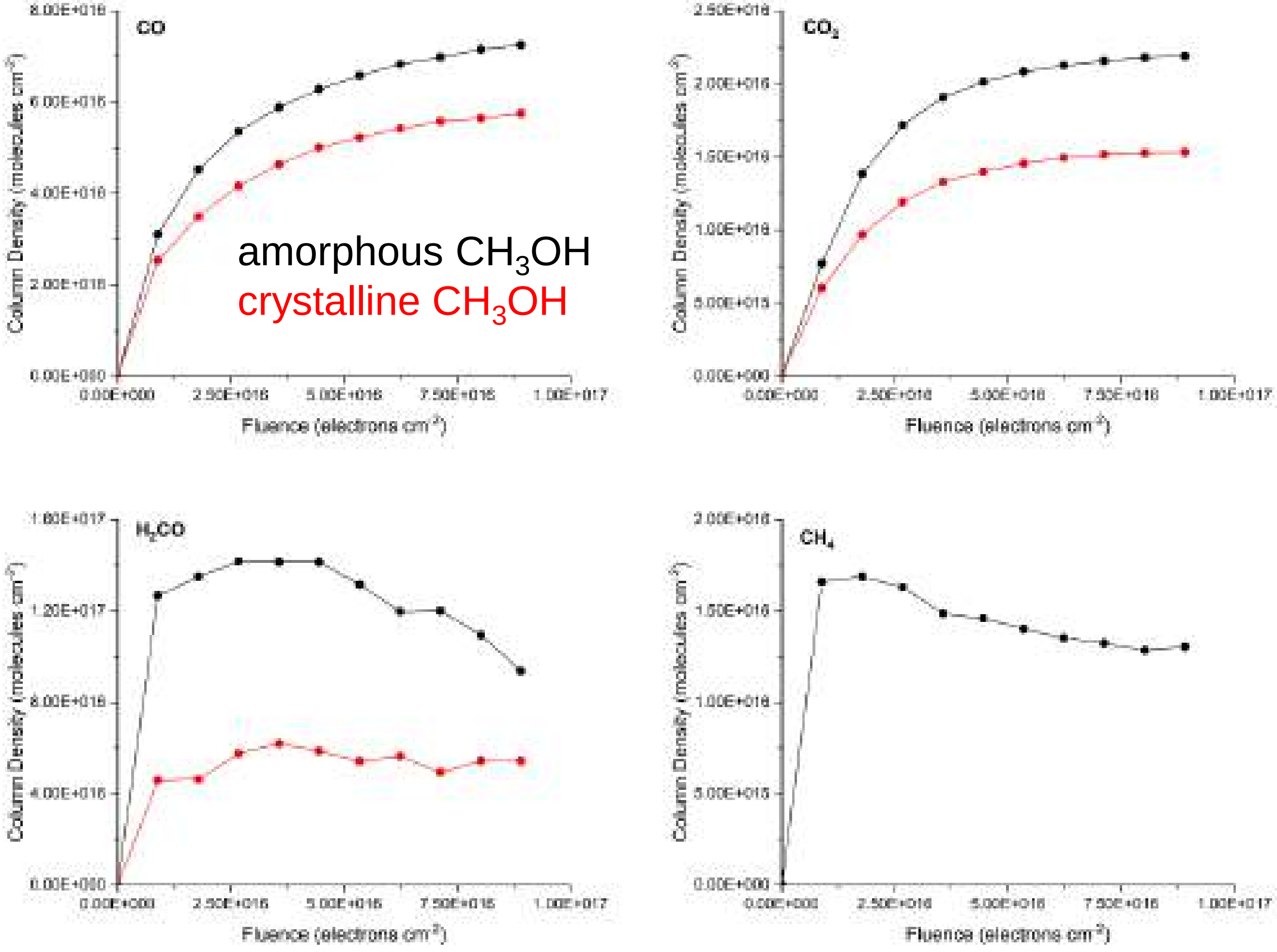




Mifsud *et al*., PCCP (2022)

Ice Chamber for Astrophysics/Astrochemistry (ICA)



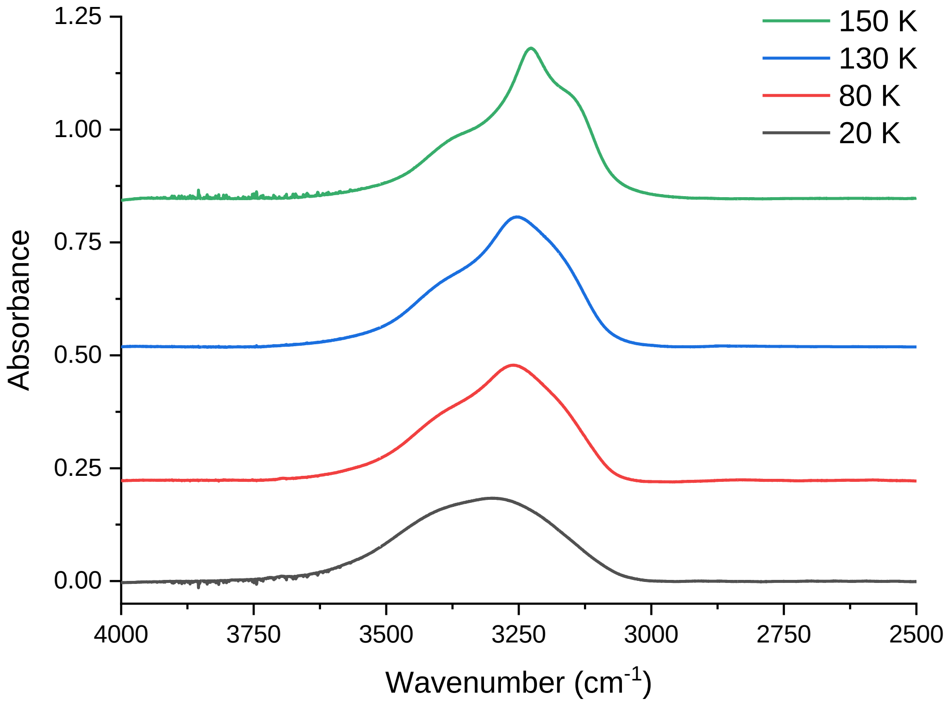


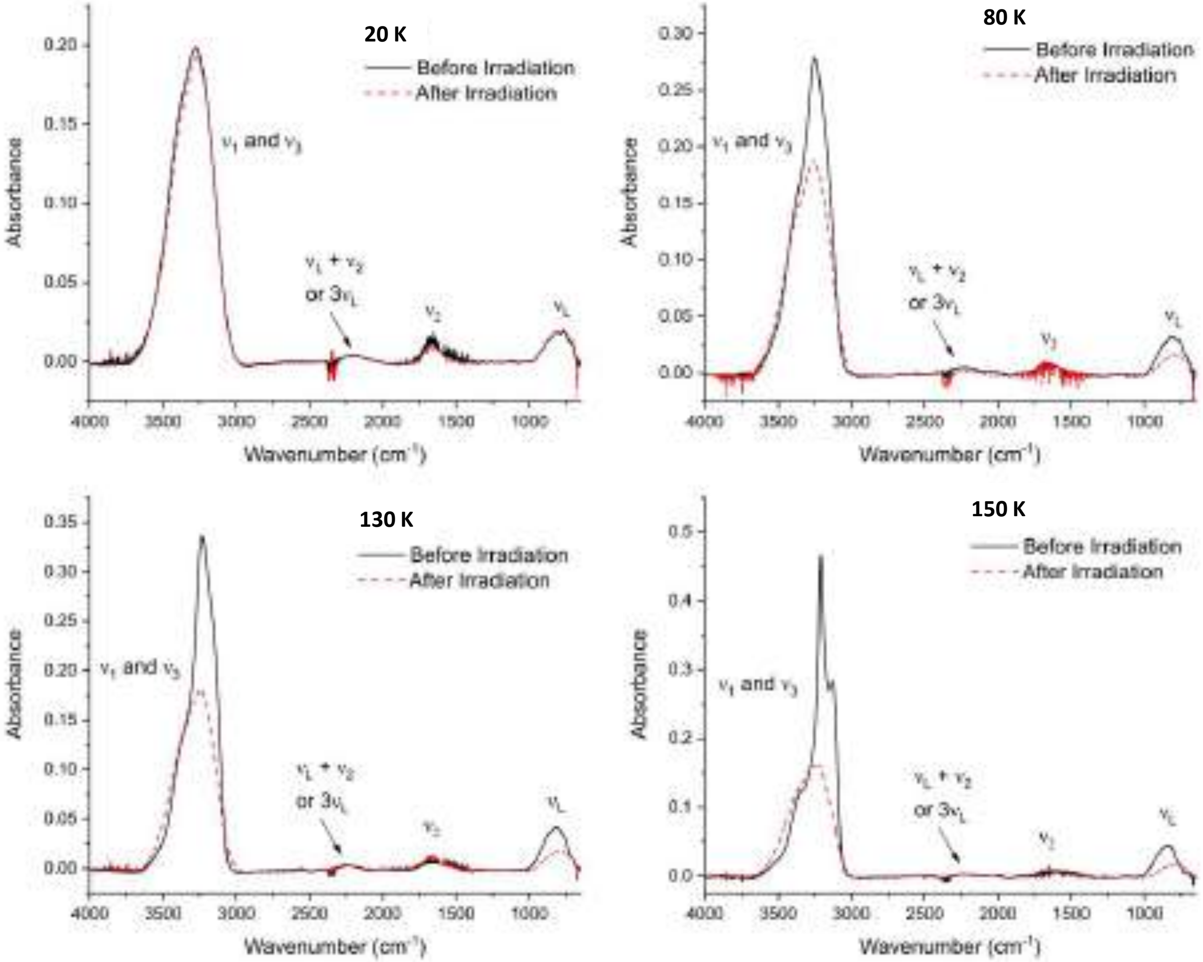
amorphous CH_3OH

crystalline CH_3OH

Mifsud *et al*., PCCP (2022)

Ice Chamber for Astrophysics/Astrochemistry (ICA)





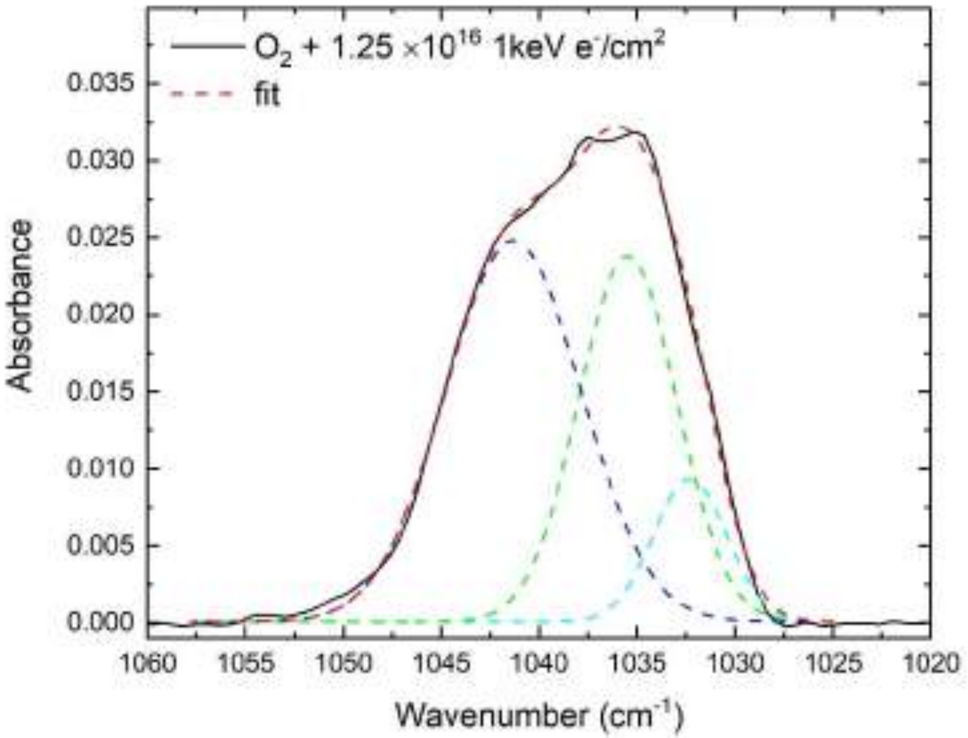
Water (H_2O) ice

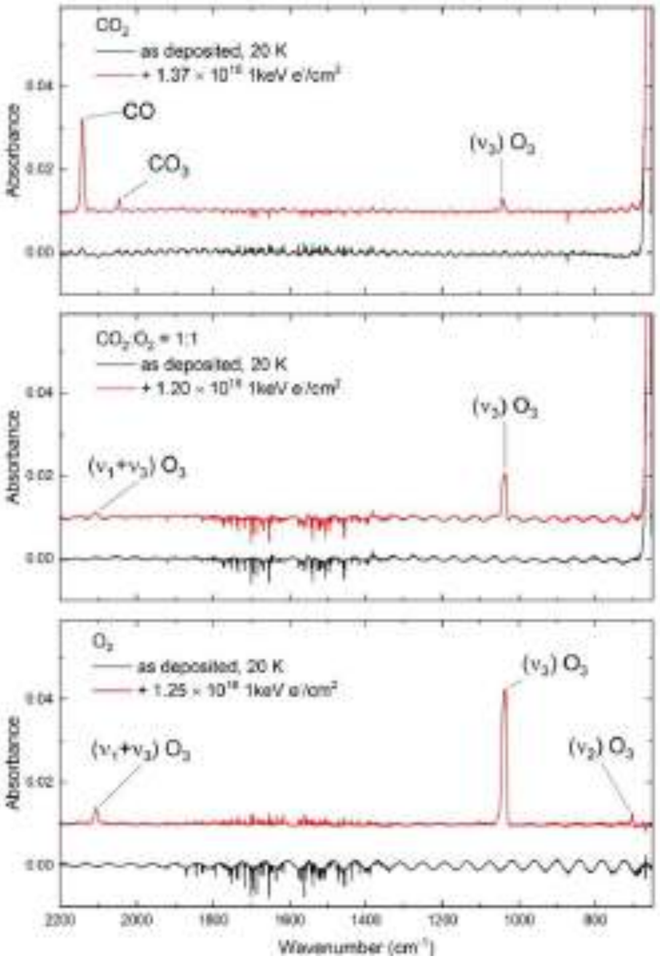
Temperature: 20 - 150 K
Deposition: Background
Ice thickness: ~ 0.2 µm

Projectile: e^-
Energy: 2 keV
$\Phi = 4.5 \times 10^{14}$ e^- cm^{-2} s^{-1}

Mifsud *et al*., Eur. Phys. J. D (2022)

Ice Chamber for Astrophysics/Astrochemistry (ICA)





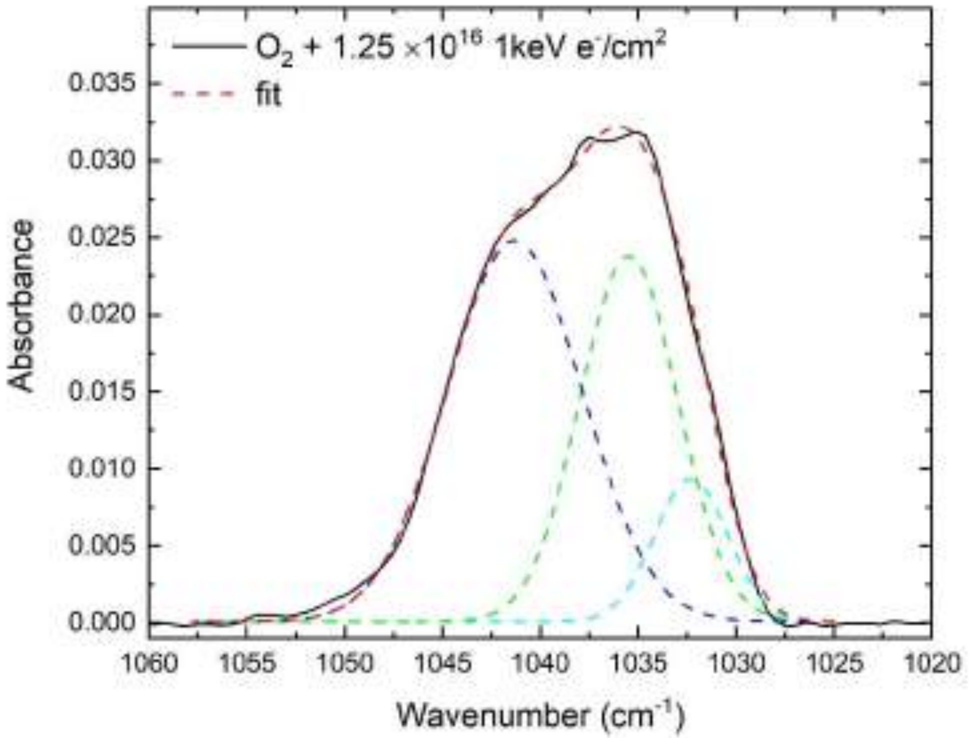
Mixtures containing CO_2:O_2 ice

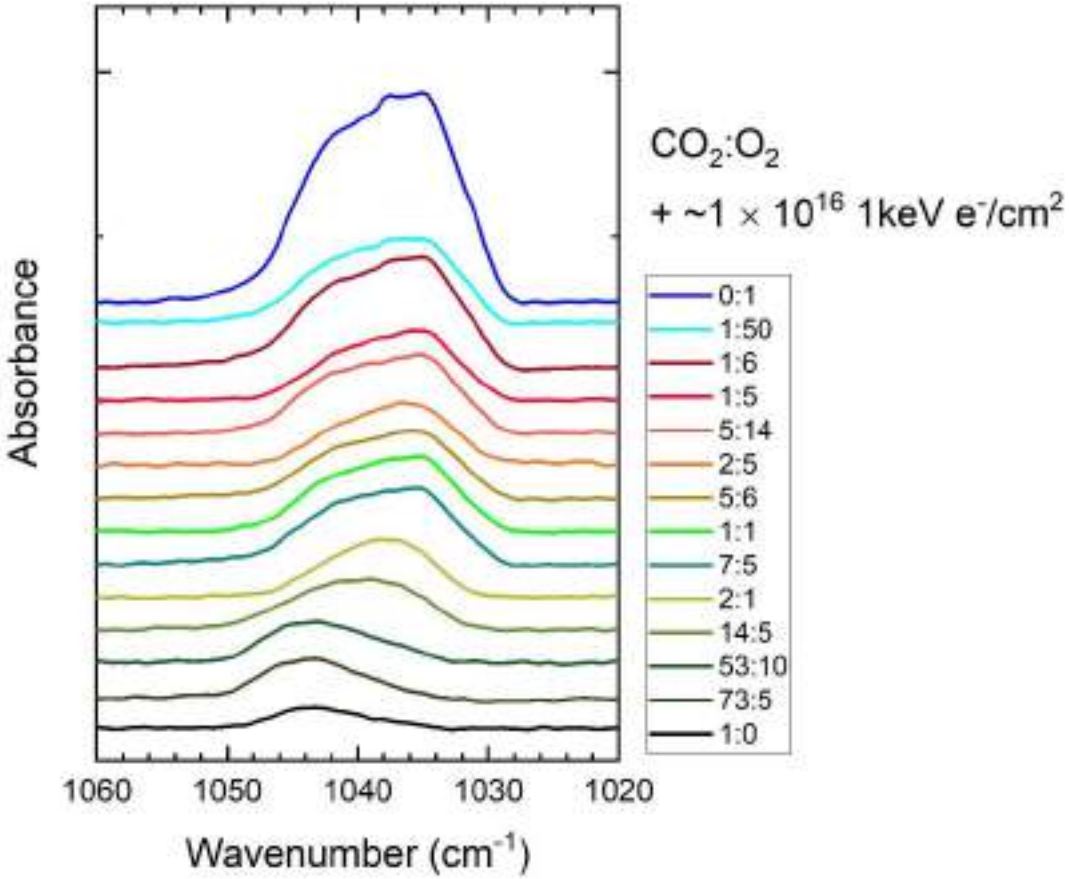
Temperature: 20 K
Deposition: Background
Ice thickness: ~ 0.5 µm

Projectile: e$^-$
Energy: 1 keV
$\Phi = 2.5\times10^{13}$ e$^-$ cm^{-2} s^{-1}

Mifsud *et al*., PCCP (2022)

Ice Chamber for Astrophysics/Astrochemistry (ICA)





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Deposition: Background
Ice thickness: ~ 0.5 µm

Projectile: e$^-$
Energy: 1 keV
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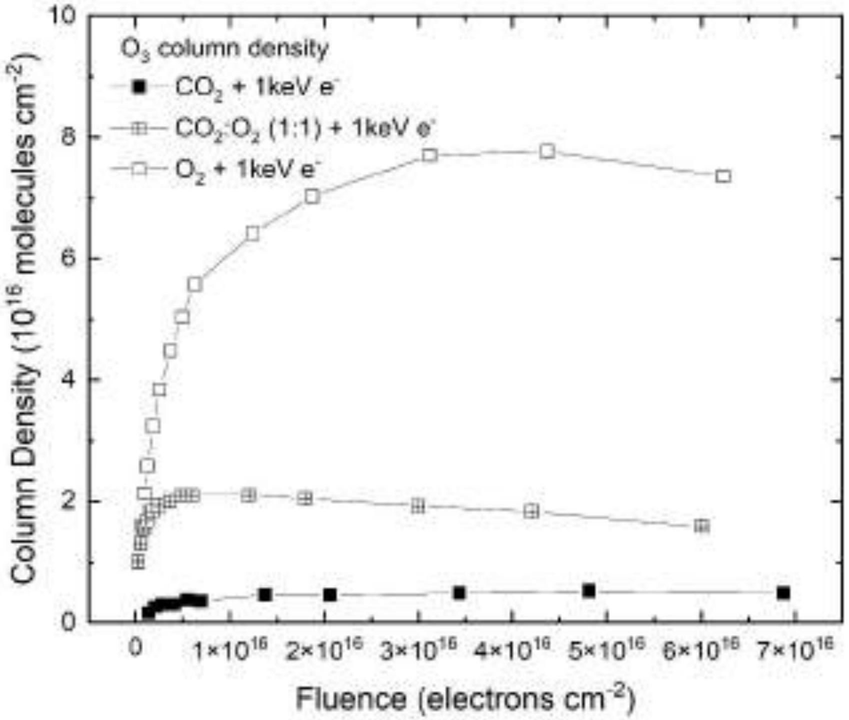
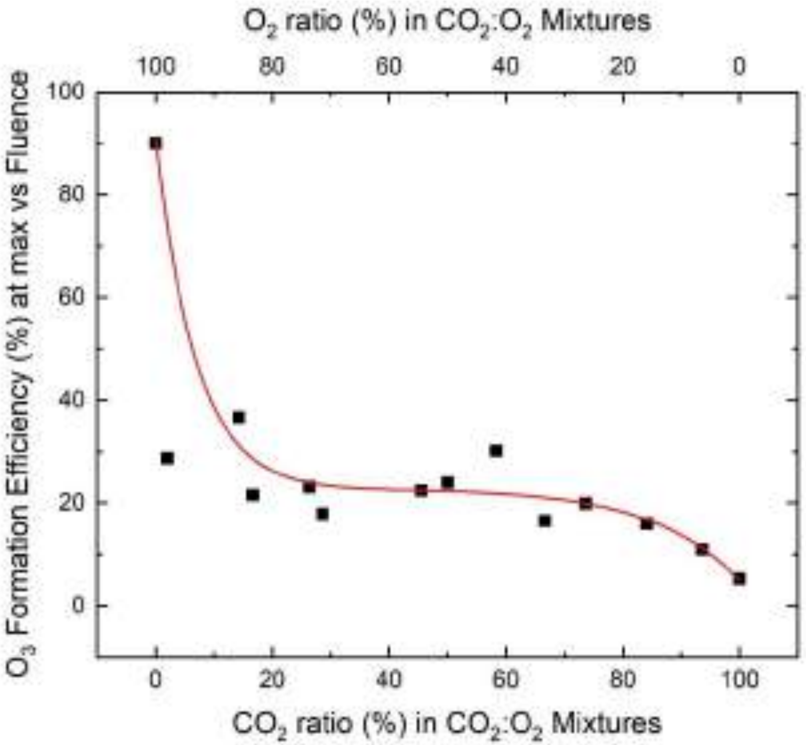
Mifsud *et al*., PCCP (2022)

Ice Chamber for Astrophysics/Astrochemistry (ICA)





Mixtures containing $CO_2:O_2$ ice

Temperature: 20 K
Deposition: Background
Ice thickness: ~ 0.5 µm

Projectile: e^-
Energy: 1 keV
$\Phi = 2.5\times10^{13}$ e^- cm^{-2} s^{-1}

Mifsud *et al*., PCCP (2022)

Atomki QUeens Ice chamber for Laboratory Astrochemisty (AQUILA)

Set-up ideal for studying solar wind radiation physics and chemistry

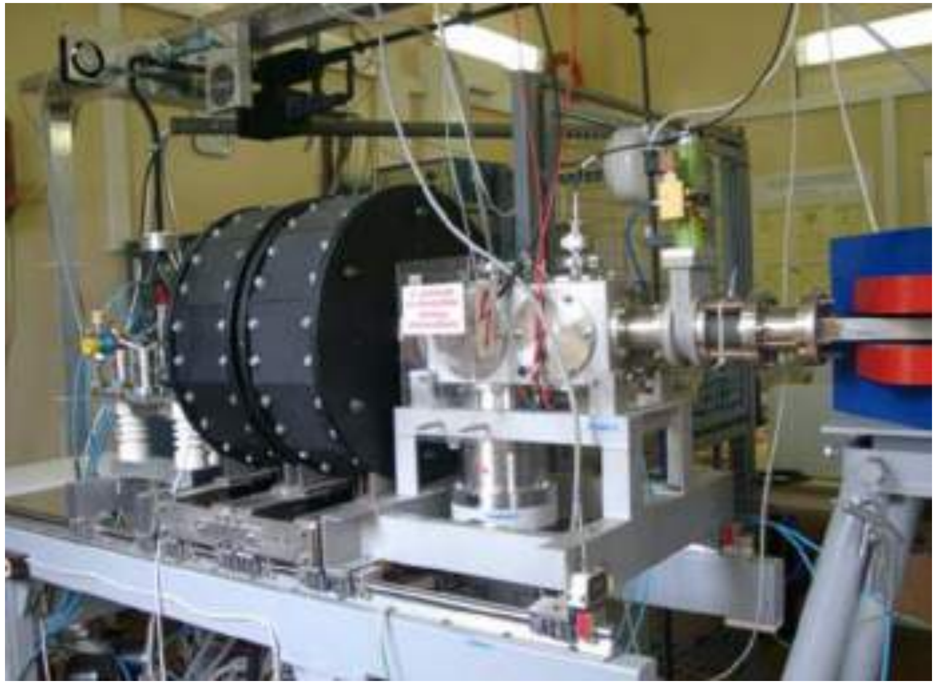
ECR Ion Source (ECRIS) Laboratory

E_{ions} = 100s eV – 10s keV

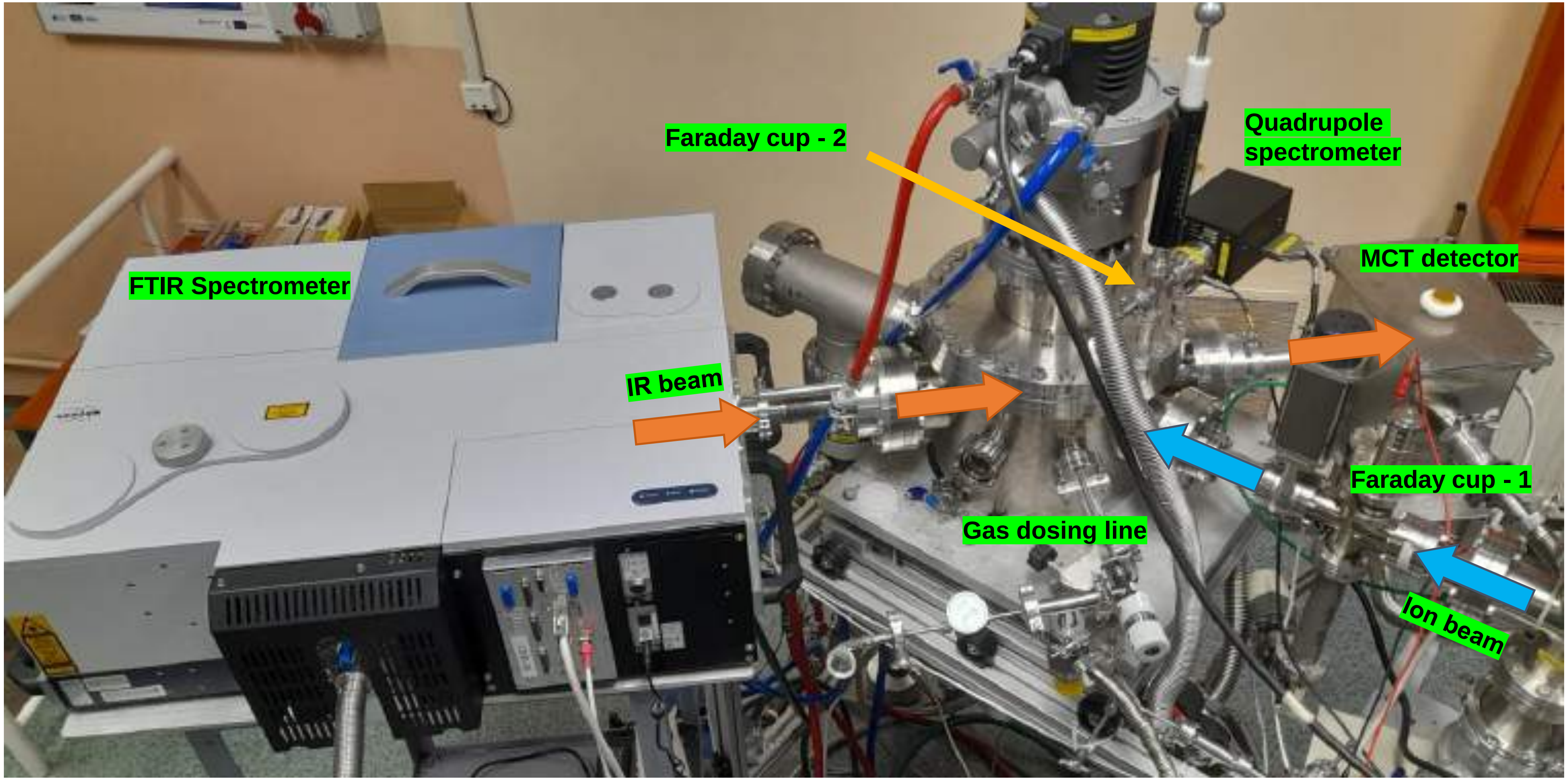
All known components of the **solar wind** can be produced by ECRIS: **H, He, C, O, Si, Fe, Ni**.

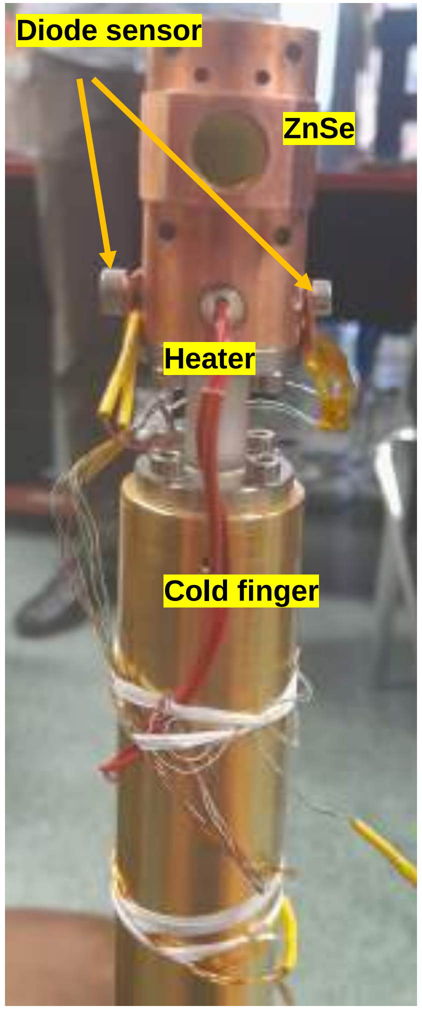
ECRIS can produce reasonably **high charge state of ions**.

ECRIS is able to produce certain **negative ions or molecular ions of H, C, O, OH, O_2**, and **single charged, positive molecular ions of H_2, H_3, OH, H_2O, H_3O, O_2**.



Atomki QUeens Ice chamber for Laboratory Astrochemisty (AQUILA)





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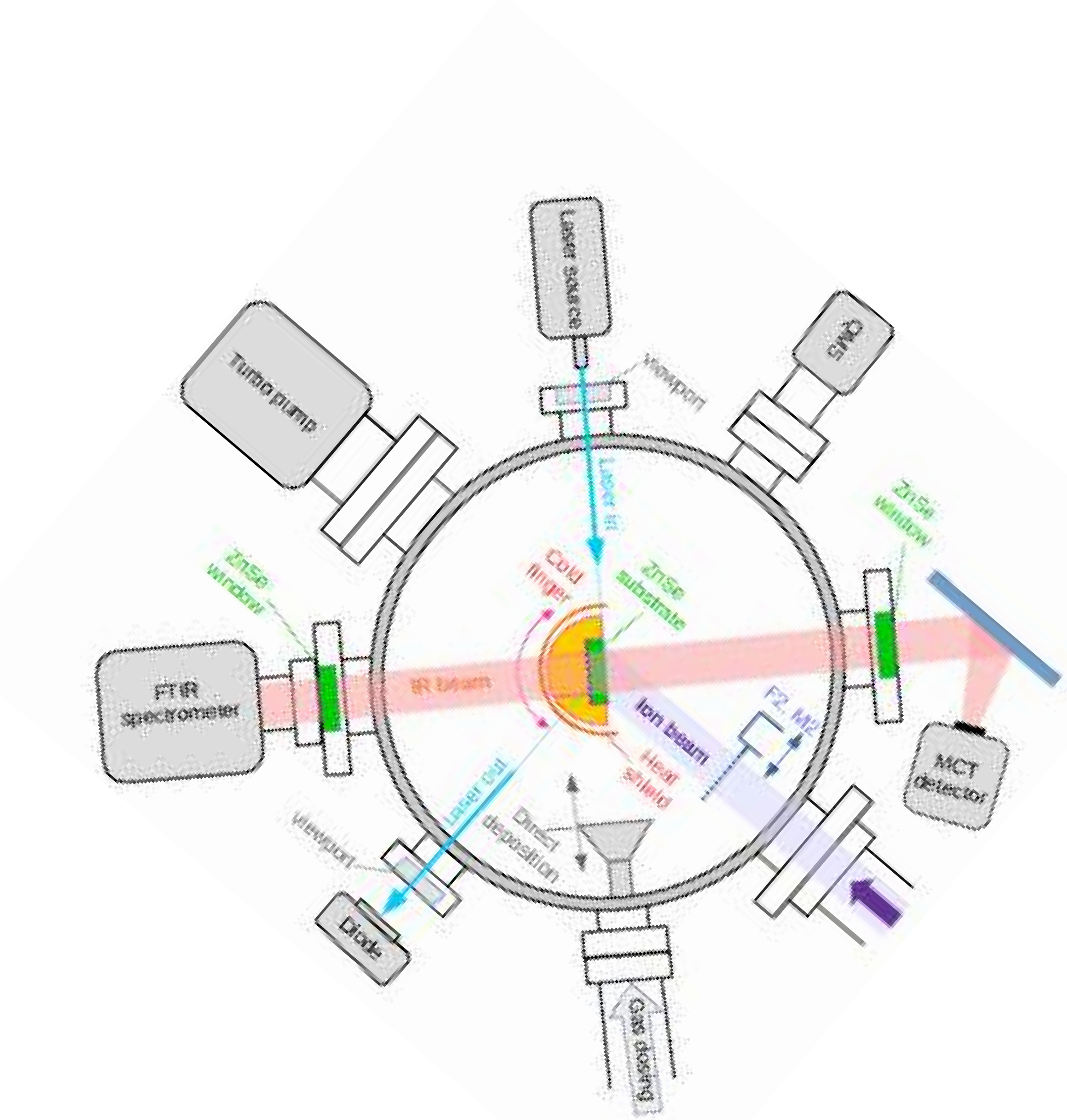
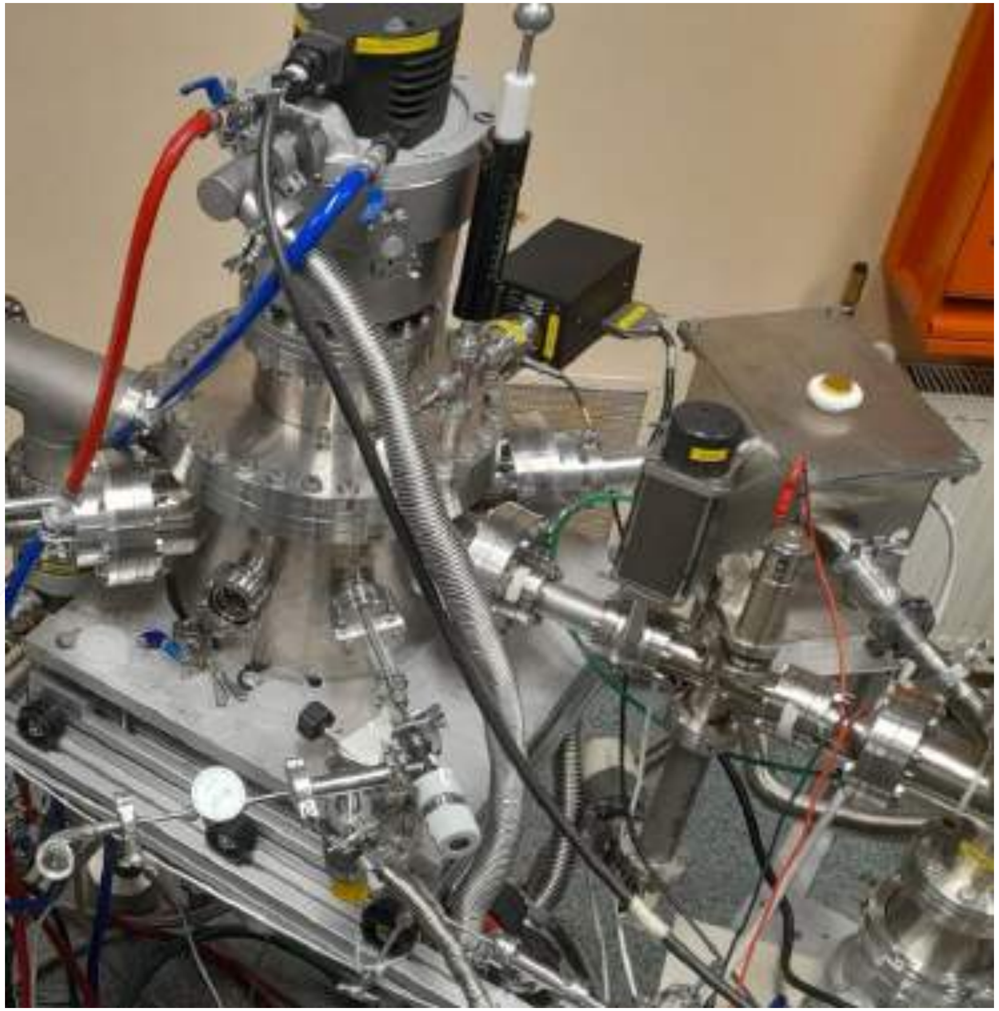
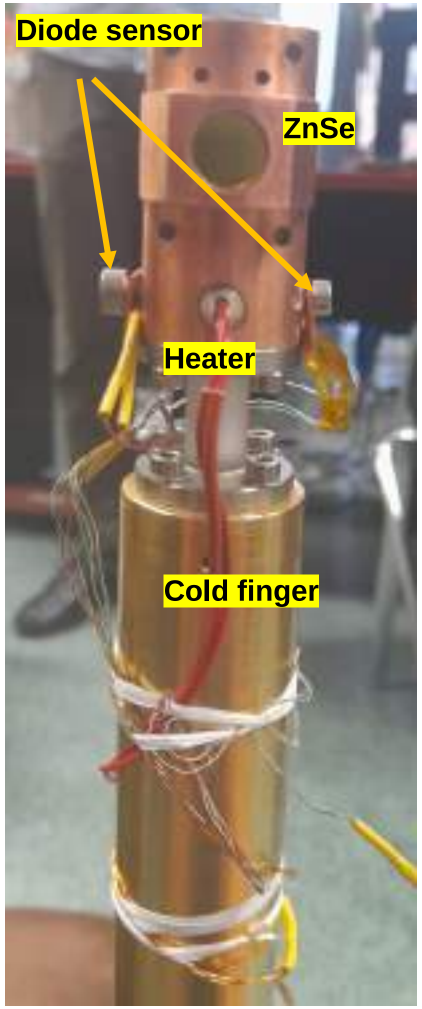
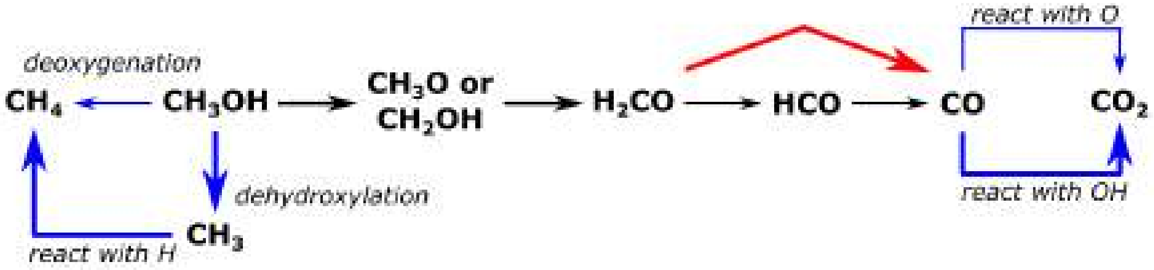
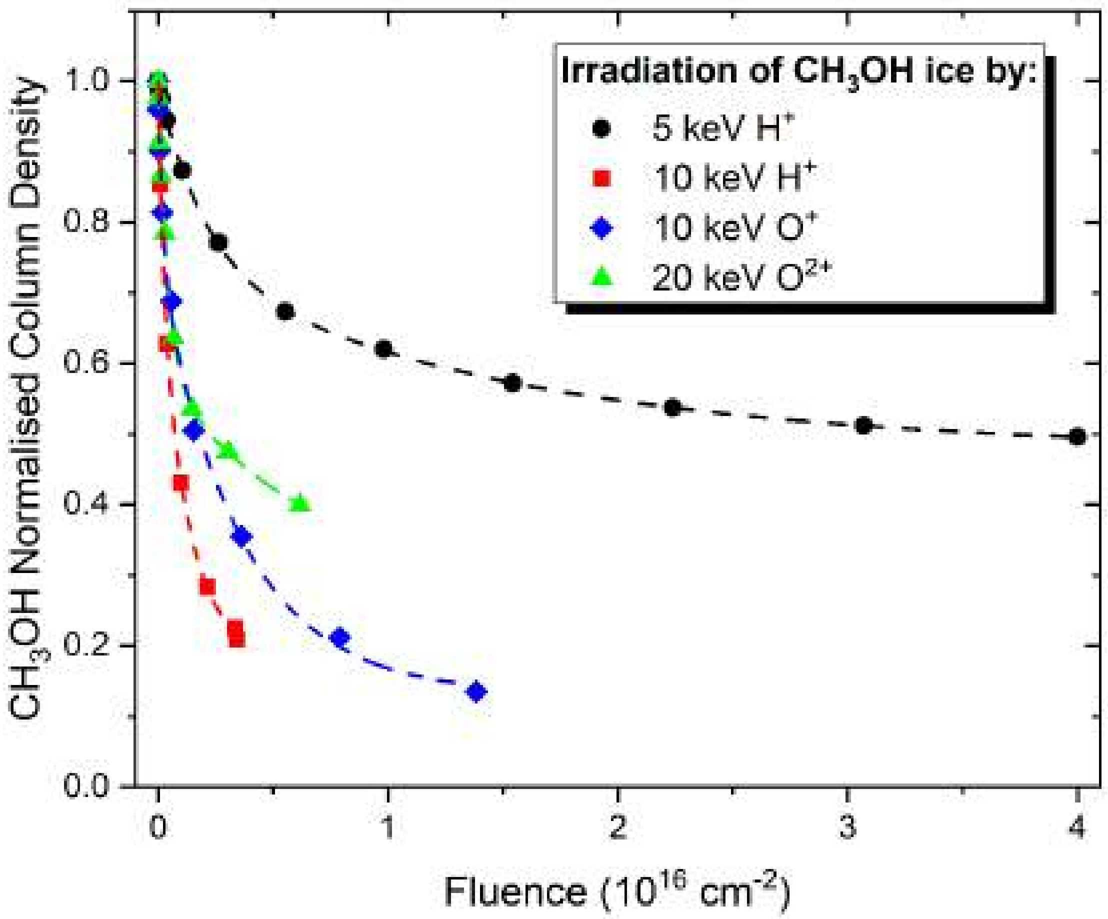






Atomki QUeens Ice chamber for Laboratory Astrochemisty (AQUILA)





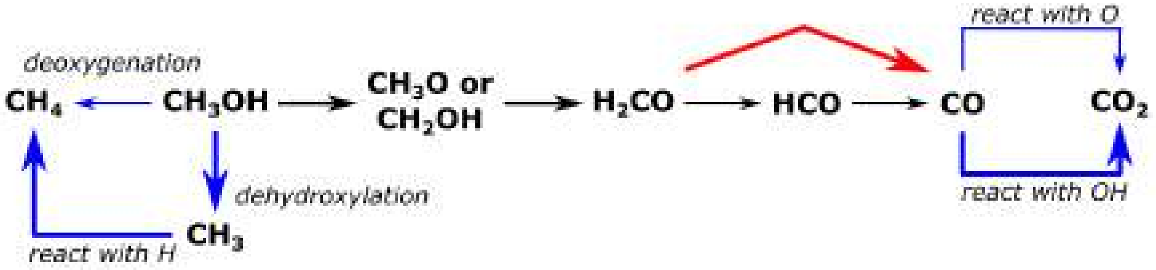
Rácz *et al*., RSI in press.

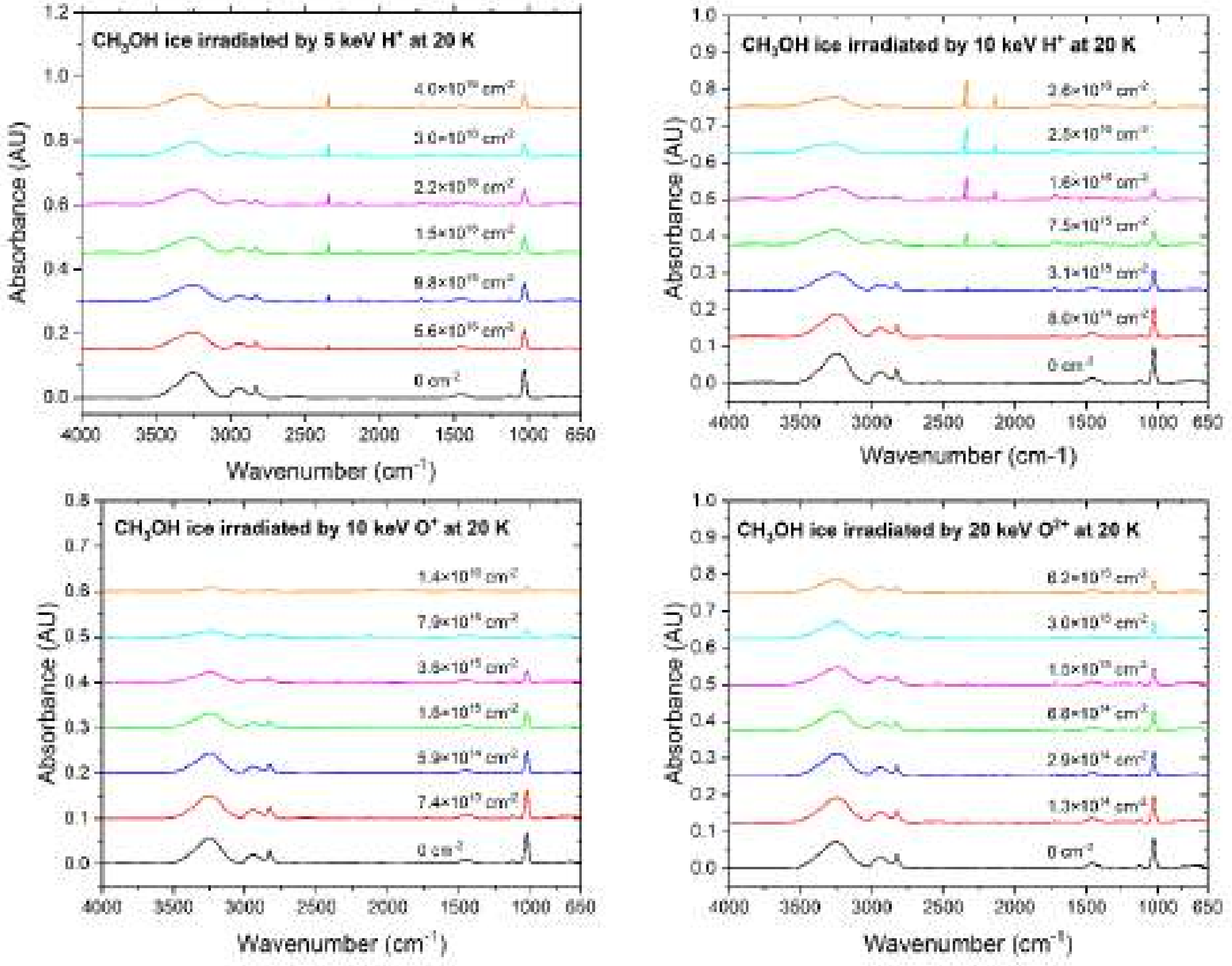
Methanol (CH_3OH) ice

Temperature: 20 K
Deposition: Background
Ice thickness: ~ 0.3 µm

Projectile: H^+, O^+, O^{2+}
Energy: 5-20 keV
Current: a few µA

Atomki QUeens Ice chamber for Laboratory Astrochemisty (AQUILA)


deoxygenation
CH_4 ← CH_3OH → CH_3O or CH_2OH → H_2CO → HCO → CO → CO_2
dehydroxylation
CH_3
react with H
react with O
react with OH



Methanol (CH_3OH) ice

Temperature: 20 K
Deposition: Background
Ice thickness: ~ 0.3 µm

Projectile: H^+, O^+, O^{2-}
Energy: 5-20 keV
Current: a few µA

Rácz *et al*., RSI in press.

COMs form in the ISM, but can they also survive?

Bill Saxton (NRAO)

Detection of prebiotic molecules in GMC

RNA-world scenario for the origin of life

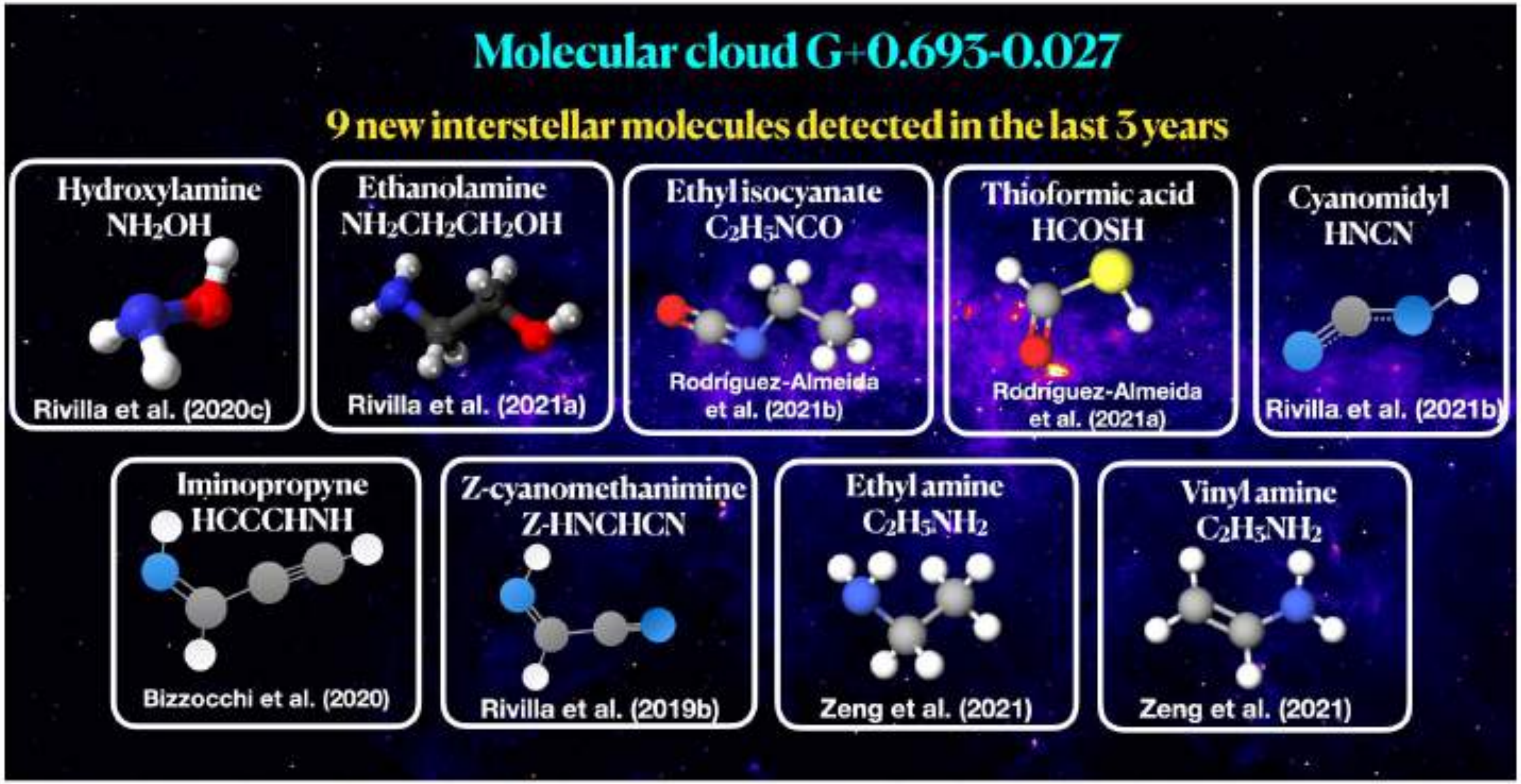


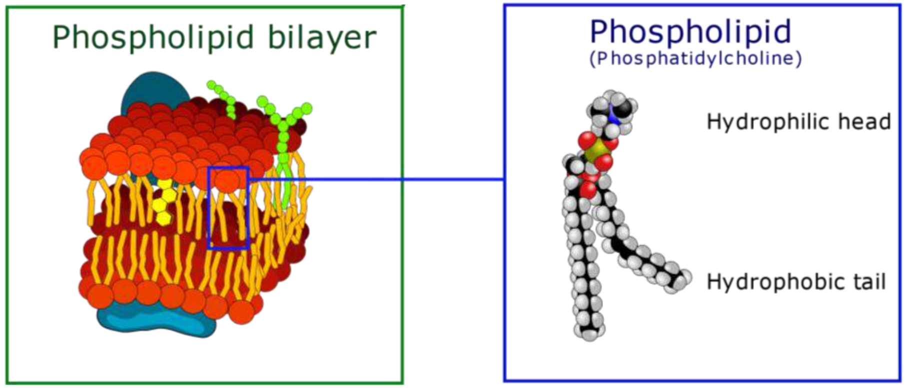
Figure 1: New interstellar molecules detected towards the molecular cloud G+0.693-0.027 using a deep unbiased spectral survey conducted with the Yebes 40m and IRAM 30m telescope.

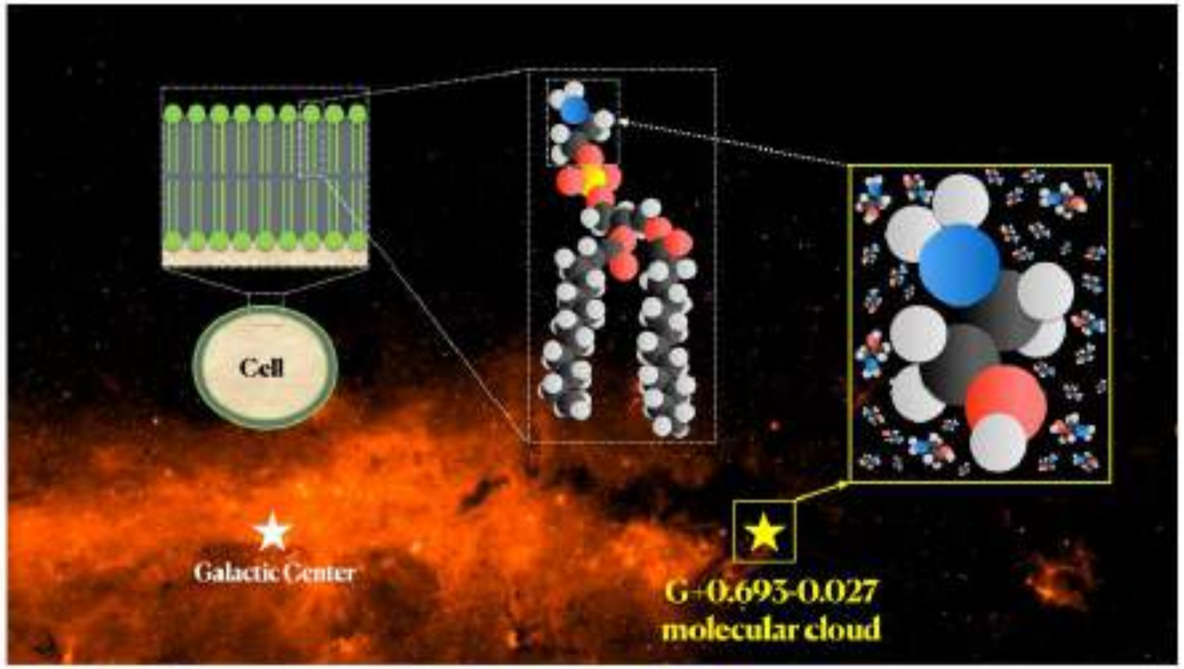
Detection of EtA in the ISM

Discovery in space of ethanolamine, the simplest phospholipid head group

Victor M. Rivilla[a,b,1], Izaskun Jiménez-Serra[a], Jesús Martín-Pintado[a], Carlos Briones[a], Lucas F. Rodríguez-Almeida[a], Fernando Rico-Villas[a], Belén Tercero[c], Shaoshan Zeng[d], Laura Colzi[a,b], Pablo de Vicente[c], Sergio Martín[e,f], and Miguel A. Requena-Torres[g,h]

[a]Centro de Astrobiología, Consejo Superior de Investigaciones Científicas-Instituto Nacional de Técnica Aeroespacial "Esteban Terradas", 28850 Madrid, Spain; [b]Osservatorio Astrofisico di Arcetri, Istituto Nazionale di Astrofisica, 50125 Florence, Italy; [c]Observatorio Astronómico Nacional, Instituto Geográfico Nacional, 28014 Madrid, Spain; [d]Star and Planet Formation Laboratory, Cluster for Pioneering Research, RIKEN, Wako 351-0198, Japan; [e]ALMA Department of Science, European Southern Observatory, Santiago 763-0355, Chile; [f]Department of Science Operations, Joint Atacama Large Millimeter/Submillimeter Array Observatory, Santiago 763-0355, Chile; [g]Department of Astronomy, University of Maryland, College Park, MD 20742; and [h]Department of Physics, Astronomy and Geosciences, Towson University, Towson, MD 21252





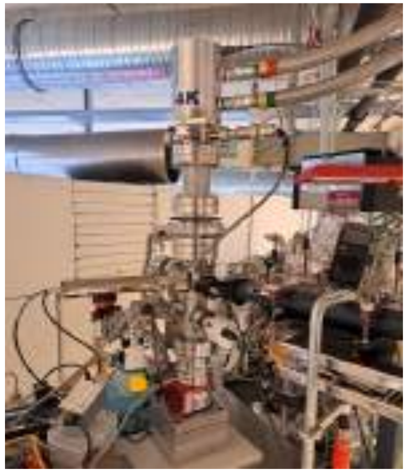
Discovery of ethanolamine, the simplest head of phospholipids (building blocks of cell membranes) towards the molecular cloud G+0.693–0.027 located in the center of our Galaxy. Credits: Victor M. Rivilla & Carlos Briones (Centro de Astrobiología, CSIC-INTA) / NASA Spitzer Space Telescope, IRAC4 camera (8 microns).

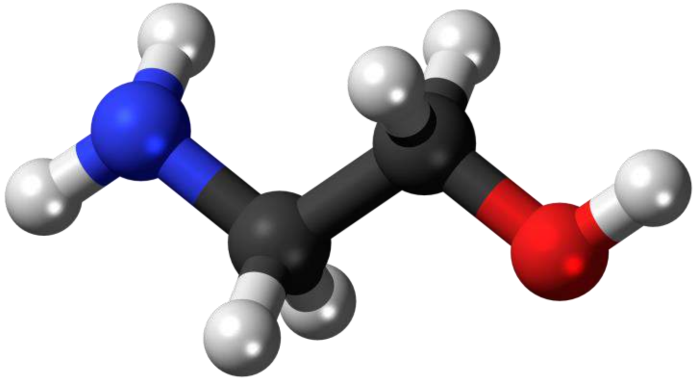
Rivilla *et al.*, (2021)

IR and VUV spectroscopic investigation

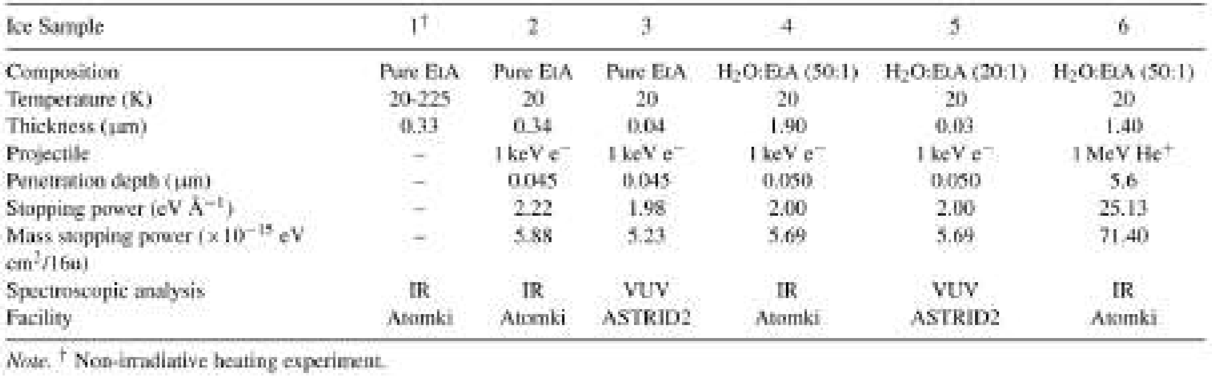
Survivability of EtA ice in space

UV-IC





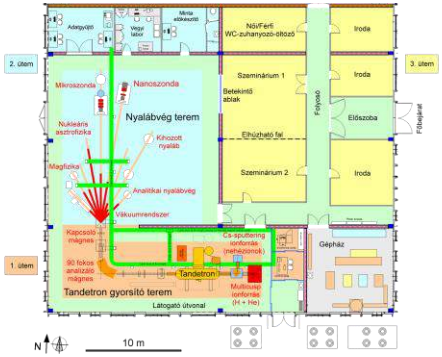
ICA



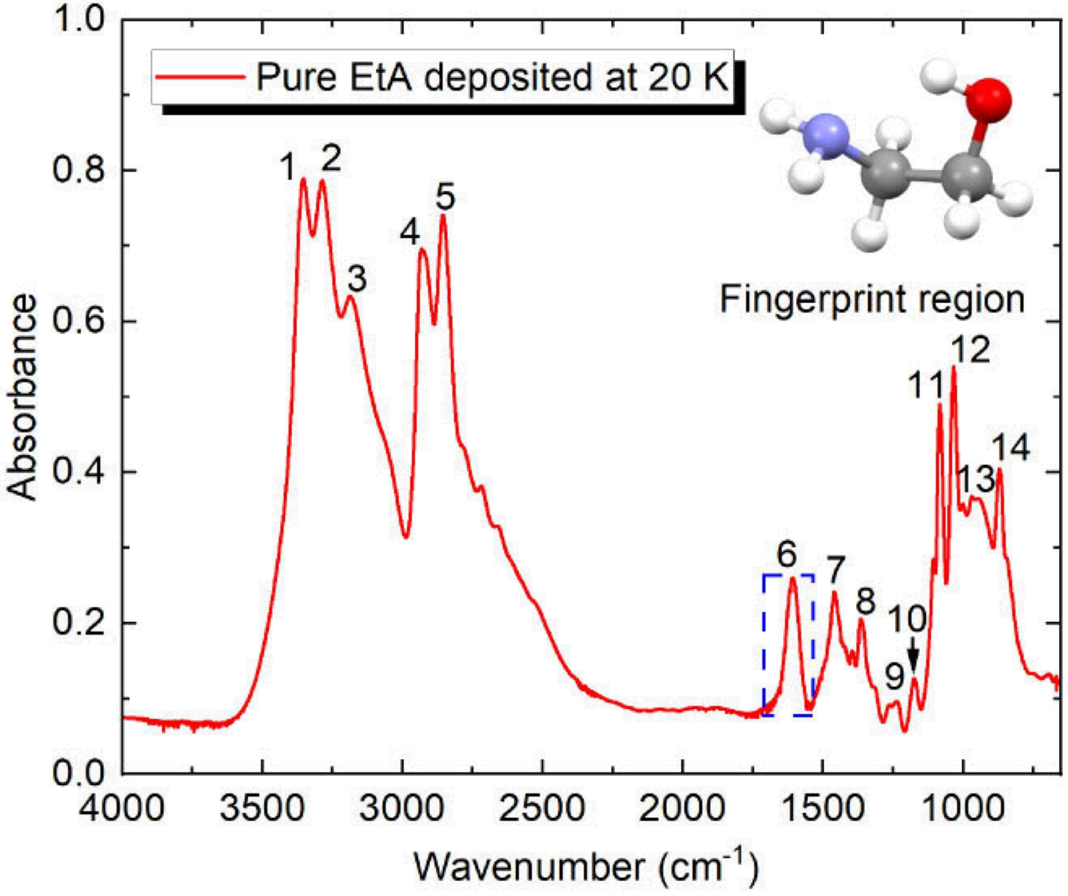
Ice Sample	1†	2	3	4	5	6
Composition	Pure EtA	Pure EtA	Pure EtA	H_2O:EtA (50:1)	H_2O:EtA (20:1)	H_2O:EtA (50:1)
Temperature (K)	20-225	20	20	20	20	20
Thickness (μm)	0.33	0.34	0.04	1.90	0.03	1.40
Projectile	–	1 keV e^-	1 keV e^-	1 keV e^-	1 keV e^-	1 MeV He^+
Penetration depth (μm)	–	0.045	0.045	0.050	0.050	5.6
Stopping power (eV $Å^{-1}$)	–	2.22	1.98	2.00	2.00	25.13
Mass stopping power ($\times 10^{-15}$ eV cm^2/16u)	–	5.88	5.23	5.69	5.69	71.40
Spectroscopic analysis	IR	IR	VUV	IR	VUV	IR
Facility	Atomki	Atomki	ASTRID2	Atomki	ASTRID2	Atomki

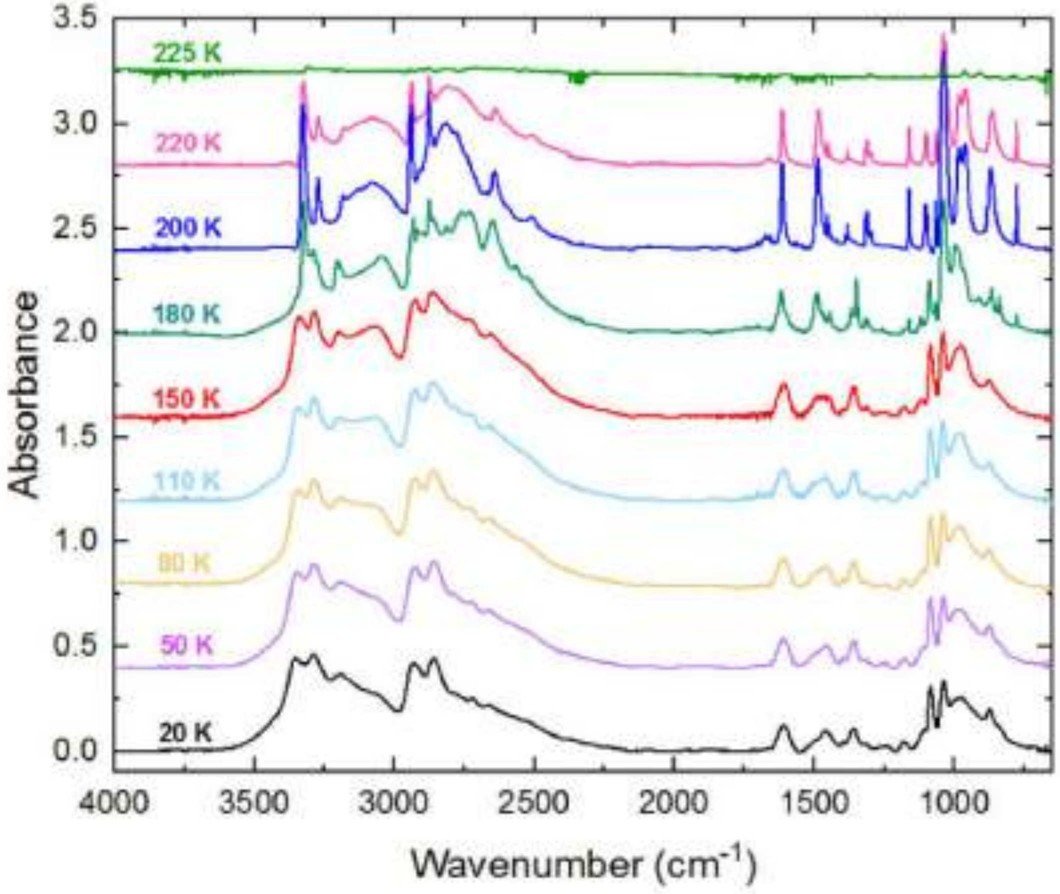
Note. † Non-irradiative heating experiment.

Zhang *et al.*, (2024)



IR and VUV spectroscopic investigation of ion, electron, and thermally processed EtA ice





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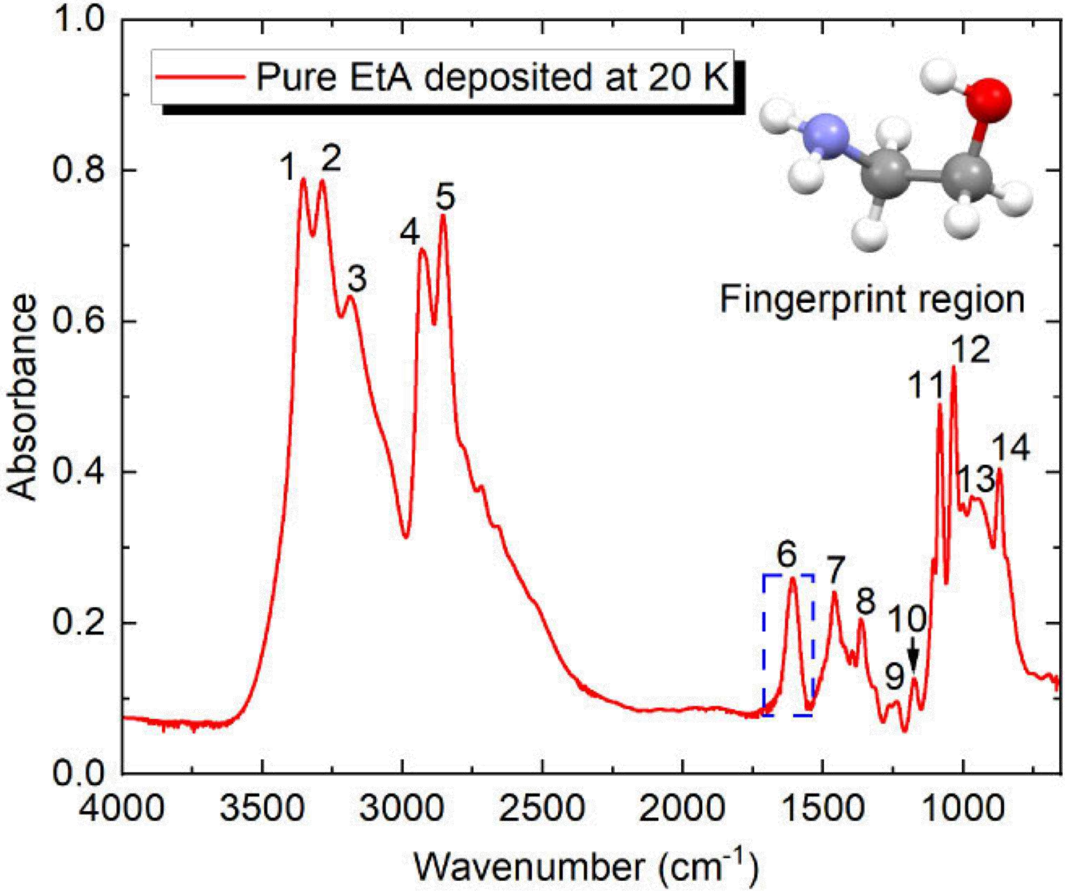

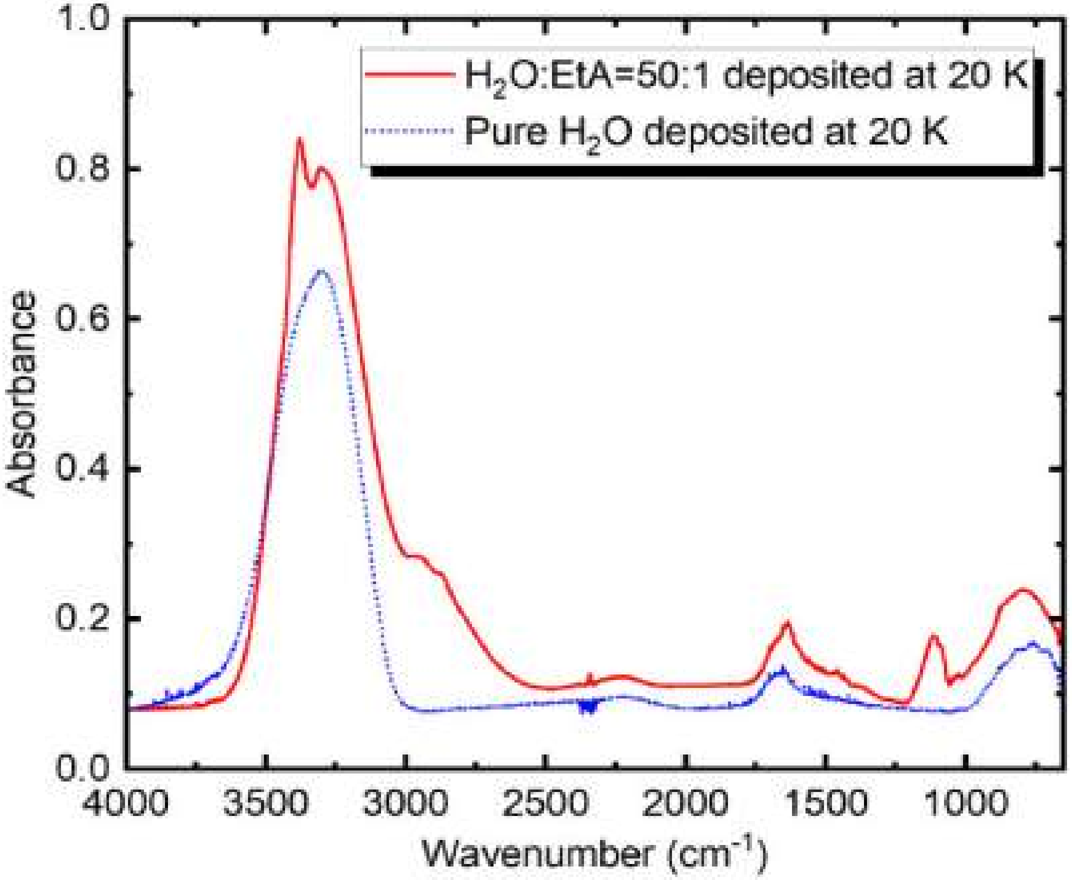

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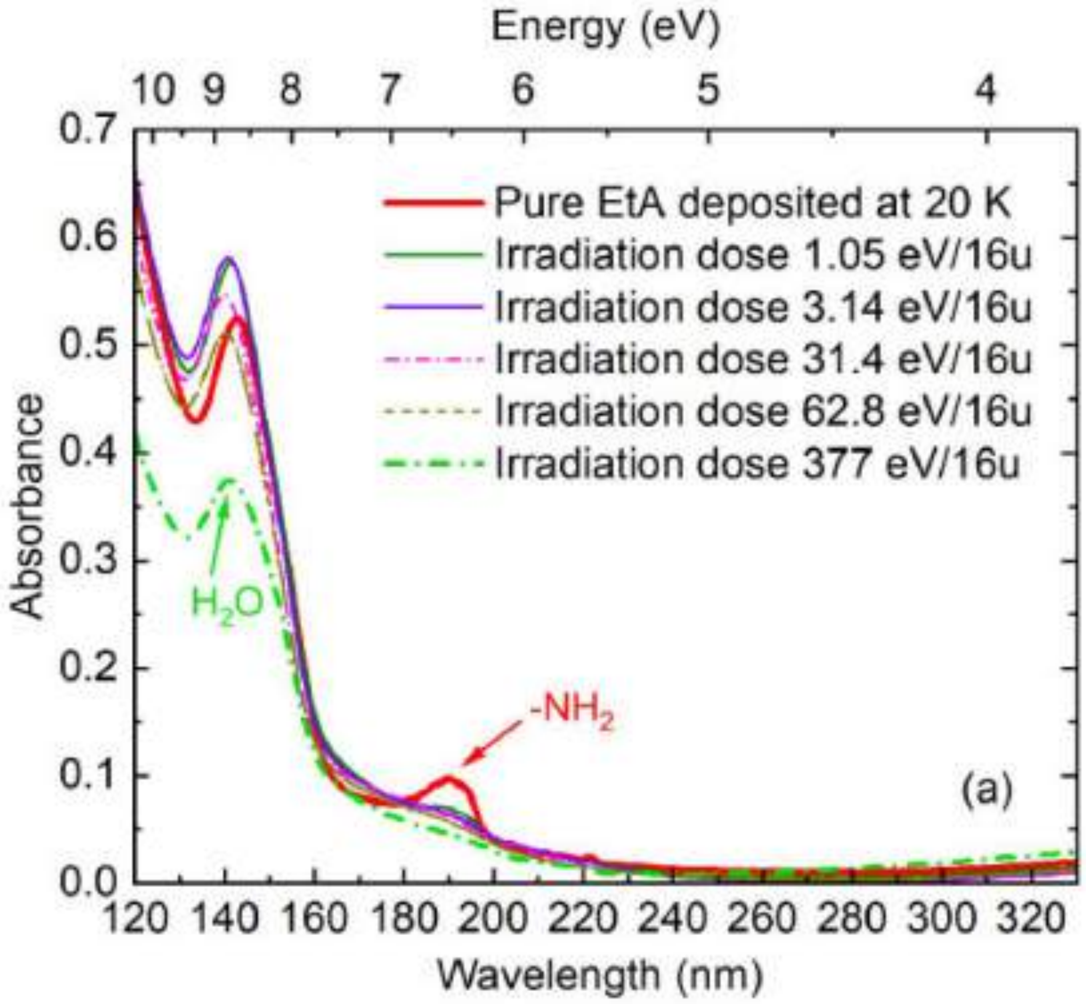
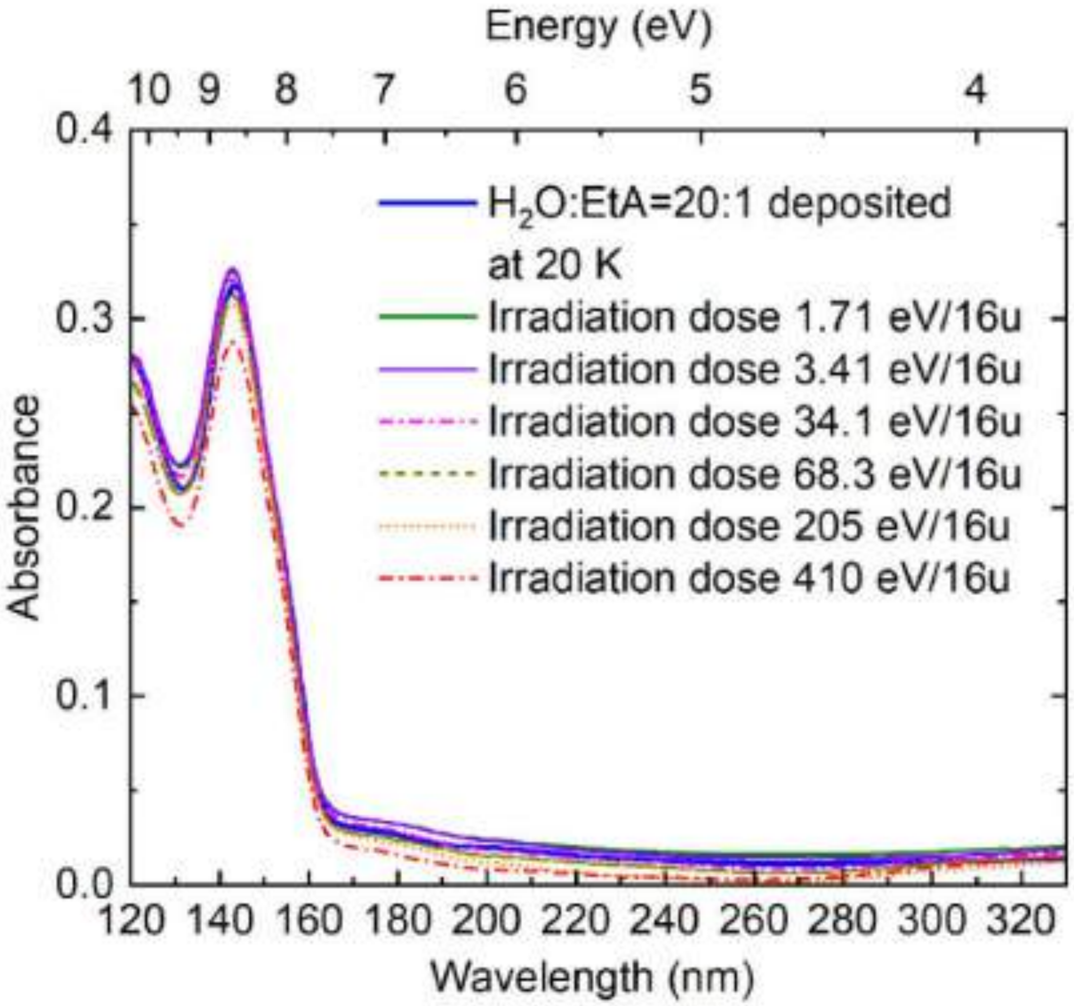
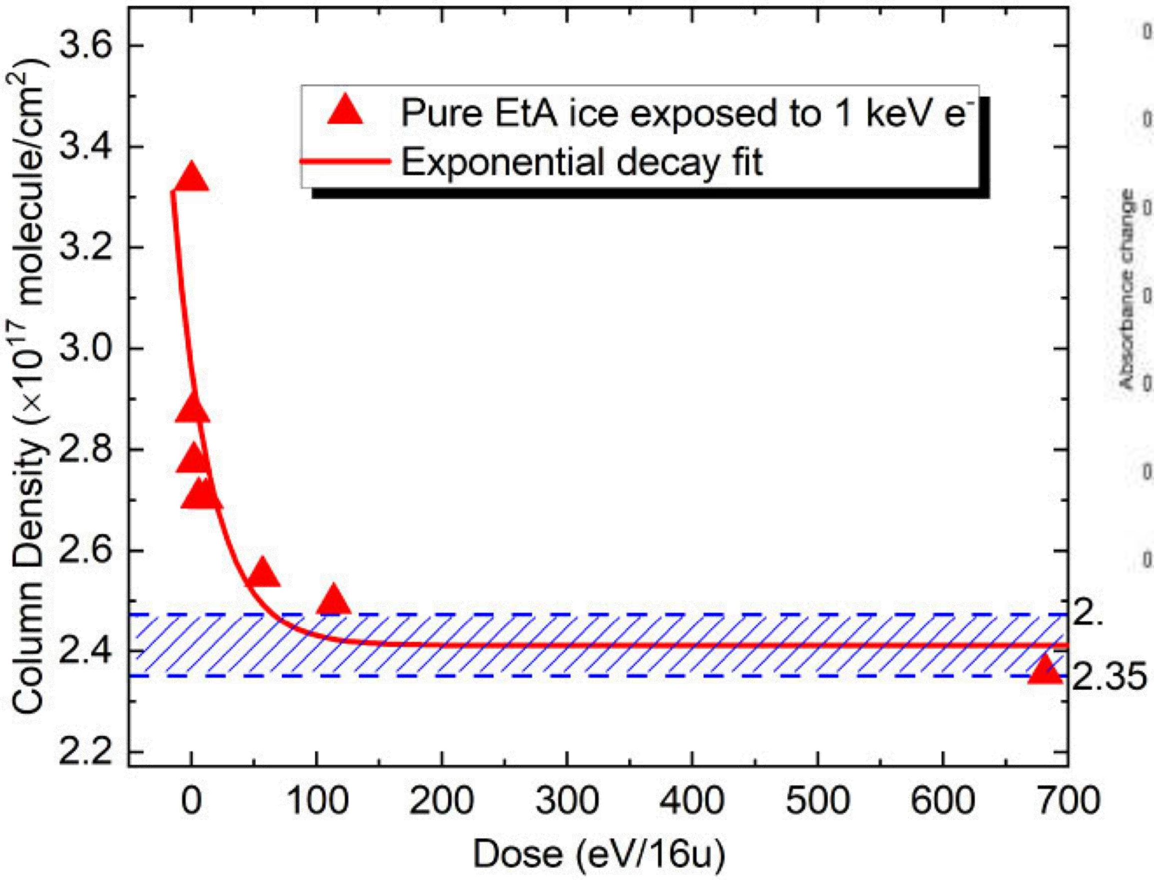
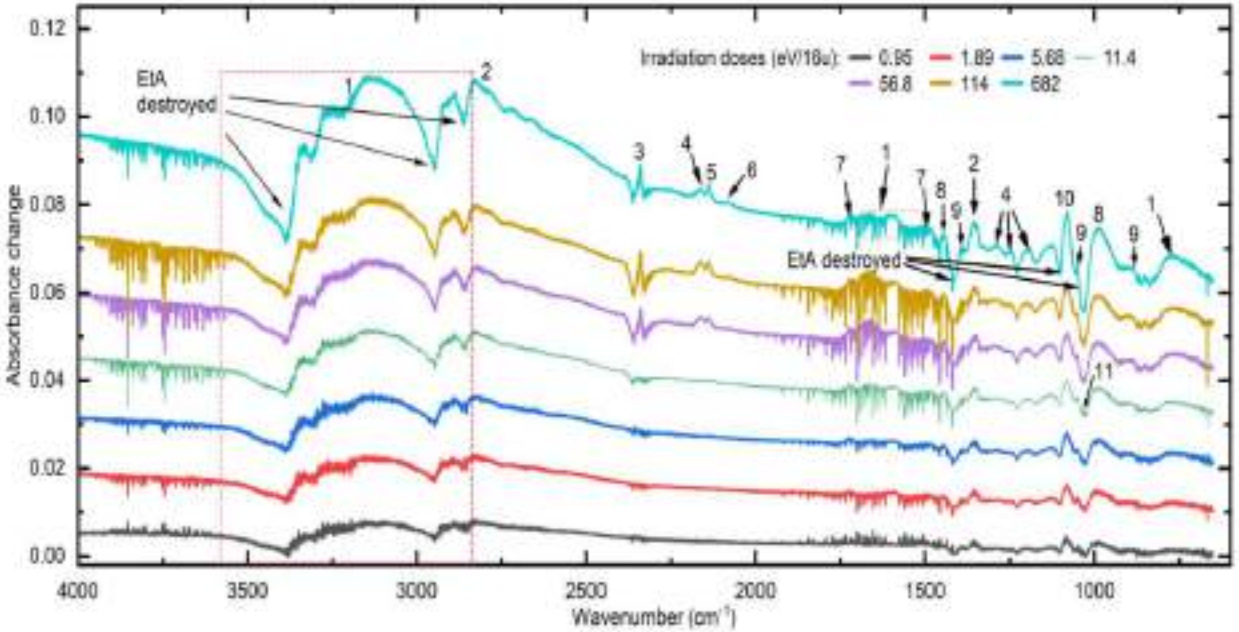




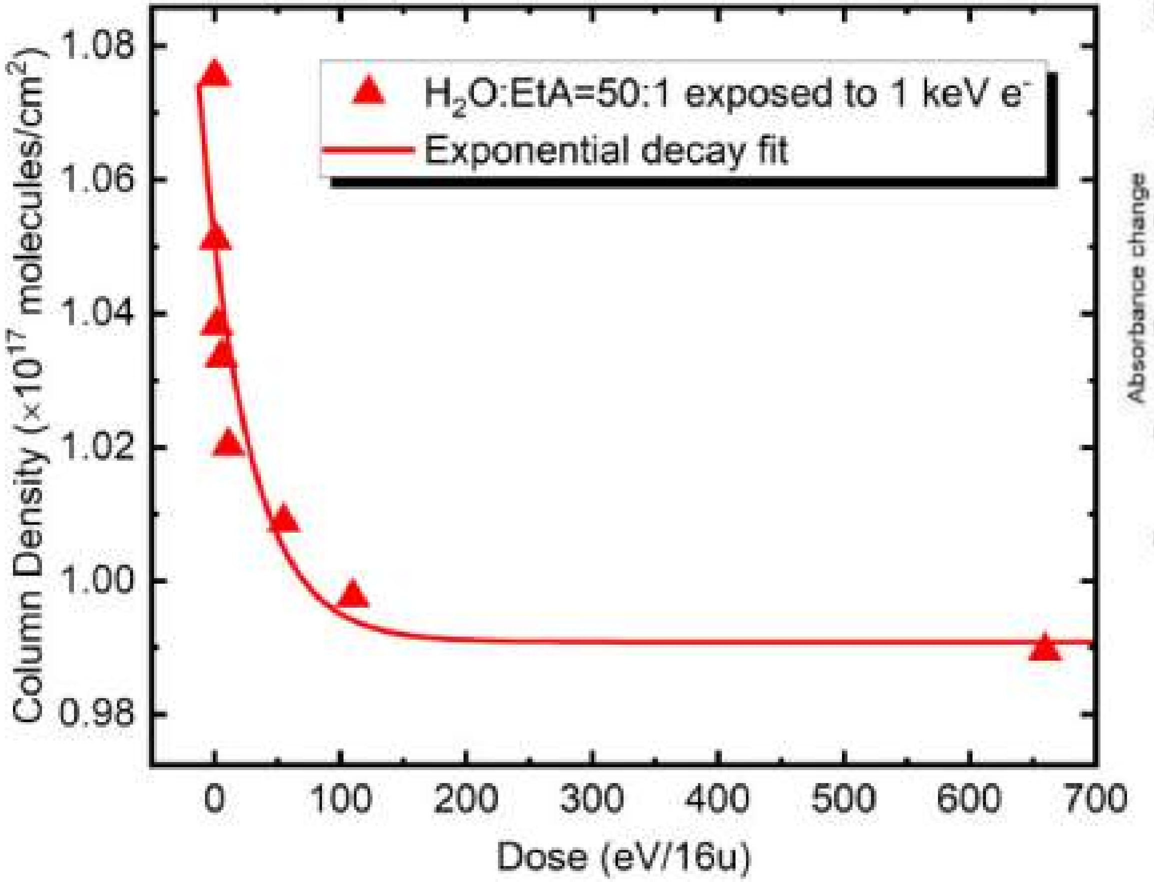
IR and VUV spectroscopic investigation of ion, electron, and thermally processed EtA ice

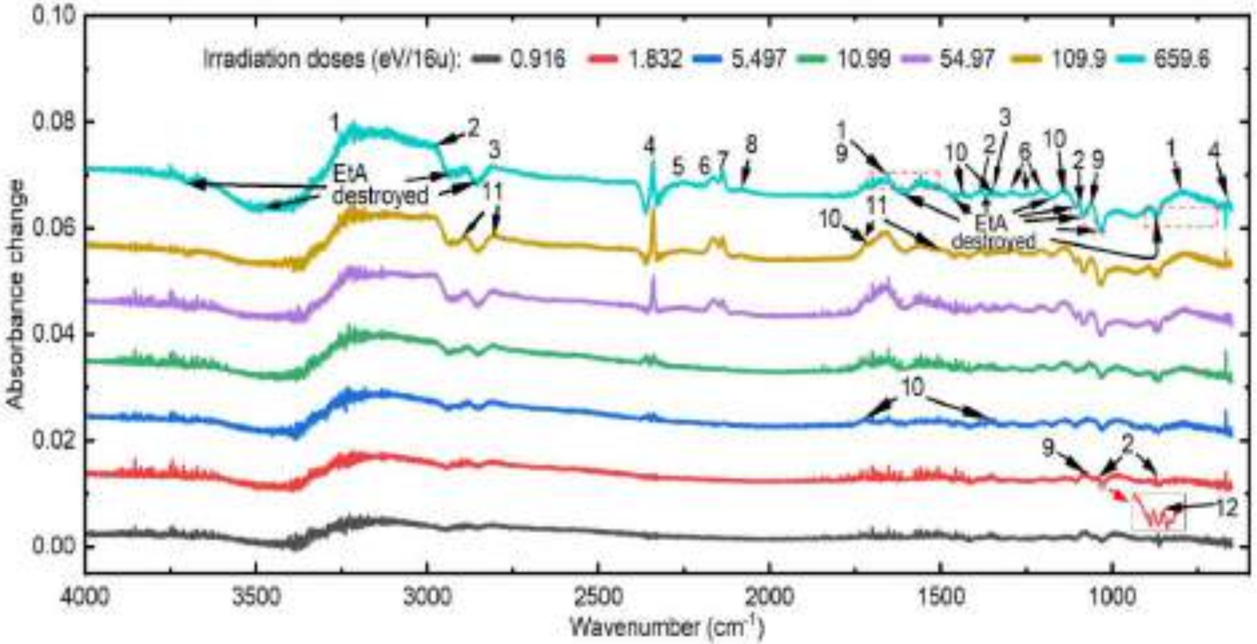




H_2O, H_2O_2, CO_2, OCN^-, CO, CN^-, $HCHO$, C_2H_4, C_2H_5OH, NH_3, CH_3OH

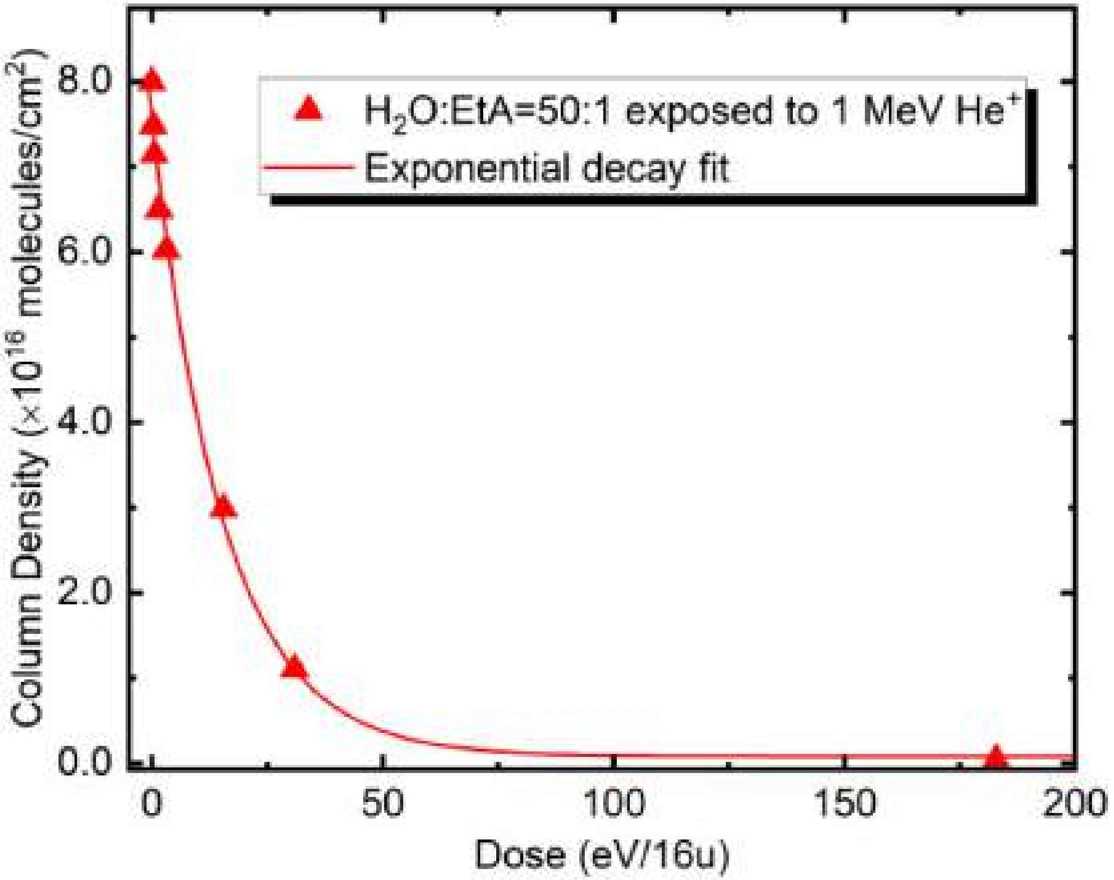
IR and VUV spectroscopic investigation of ion, electron, and thermally processed EtA ice

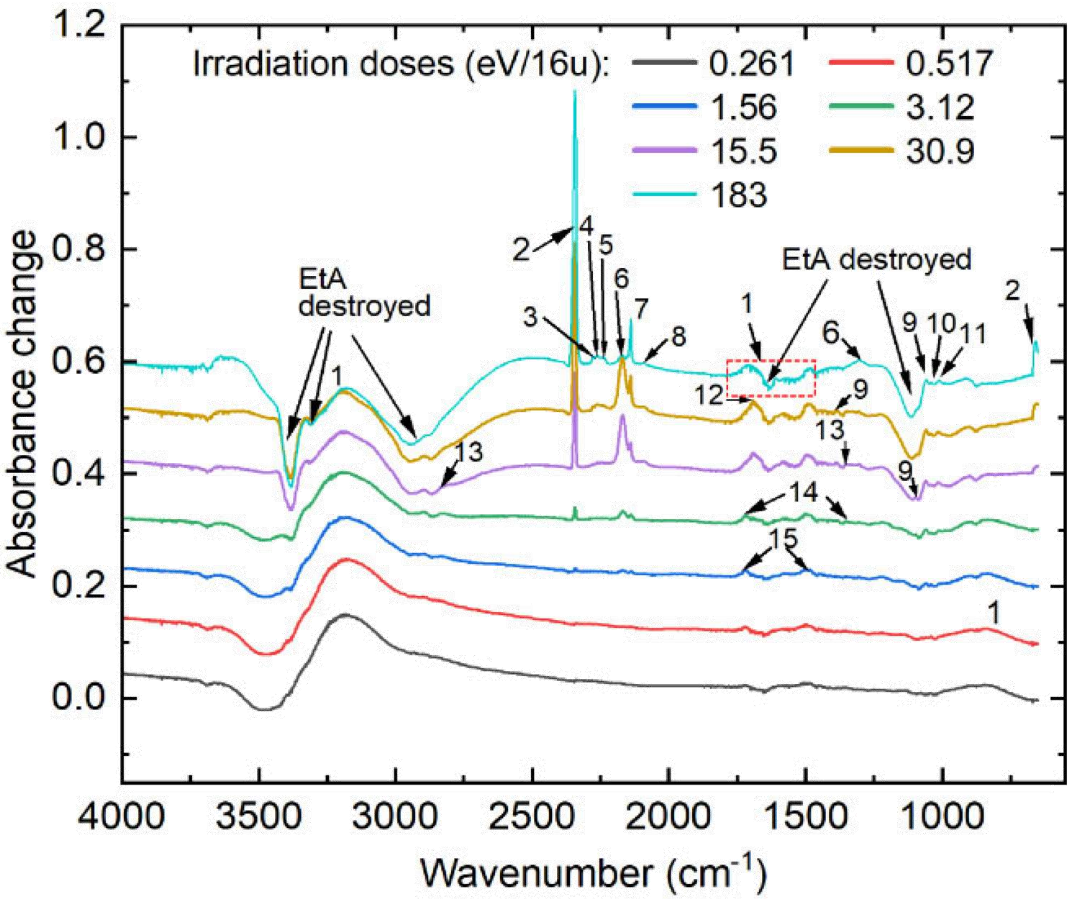




H_2O, H_2O_2, CO_2, OCN^-, HNCO, CO, CN^-, HCHO, CH_3CHO, C_2H_5OH, NH_3, CH_3OH

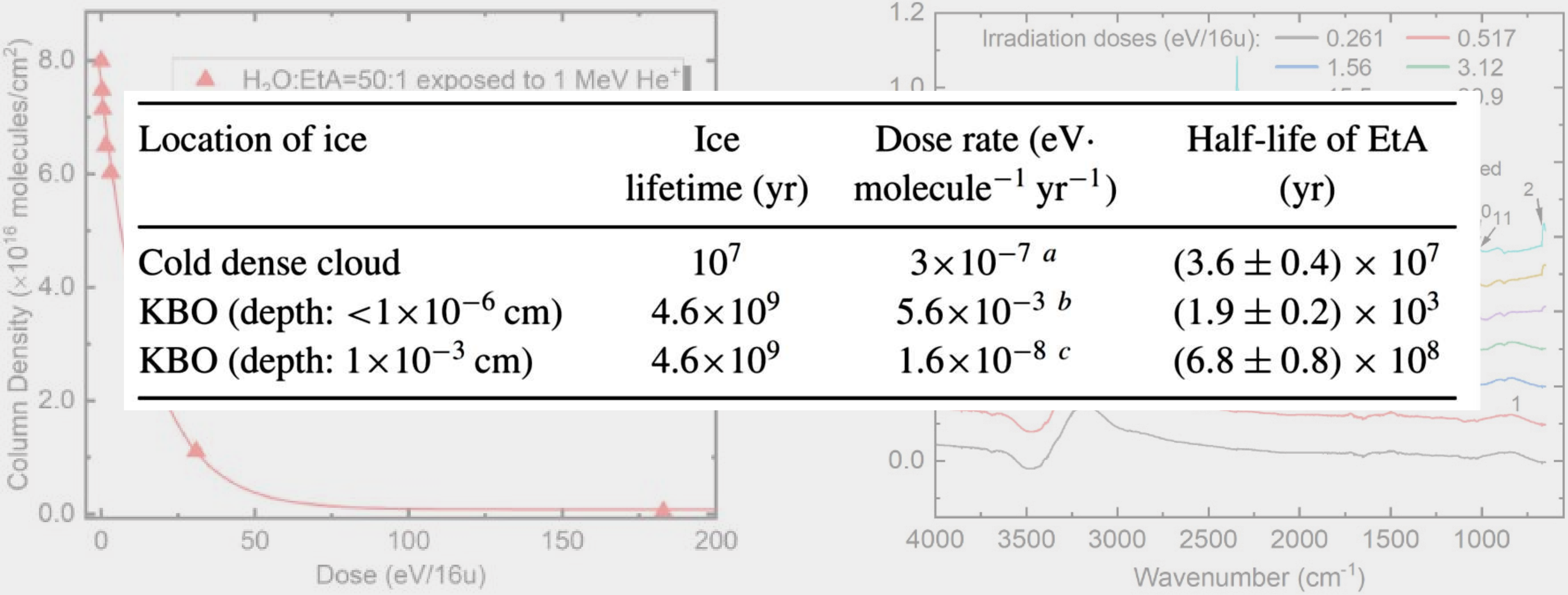
IR and VUV spectroscopic investigation of ion, electron, and thermally processed EtA ice





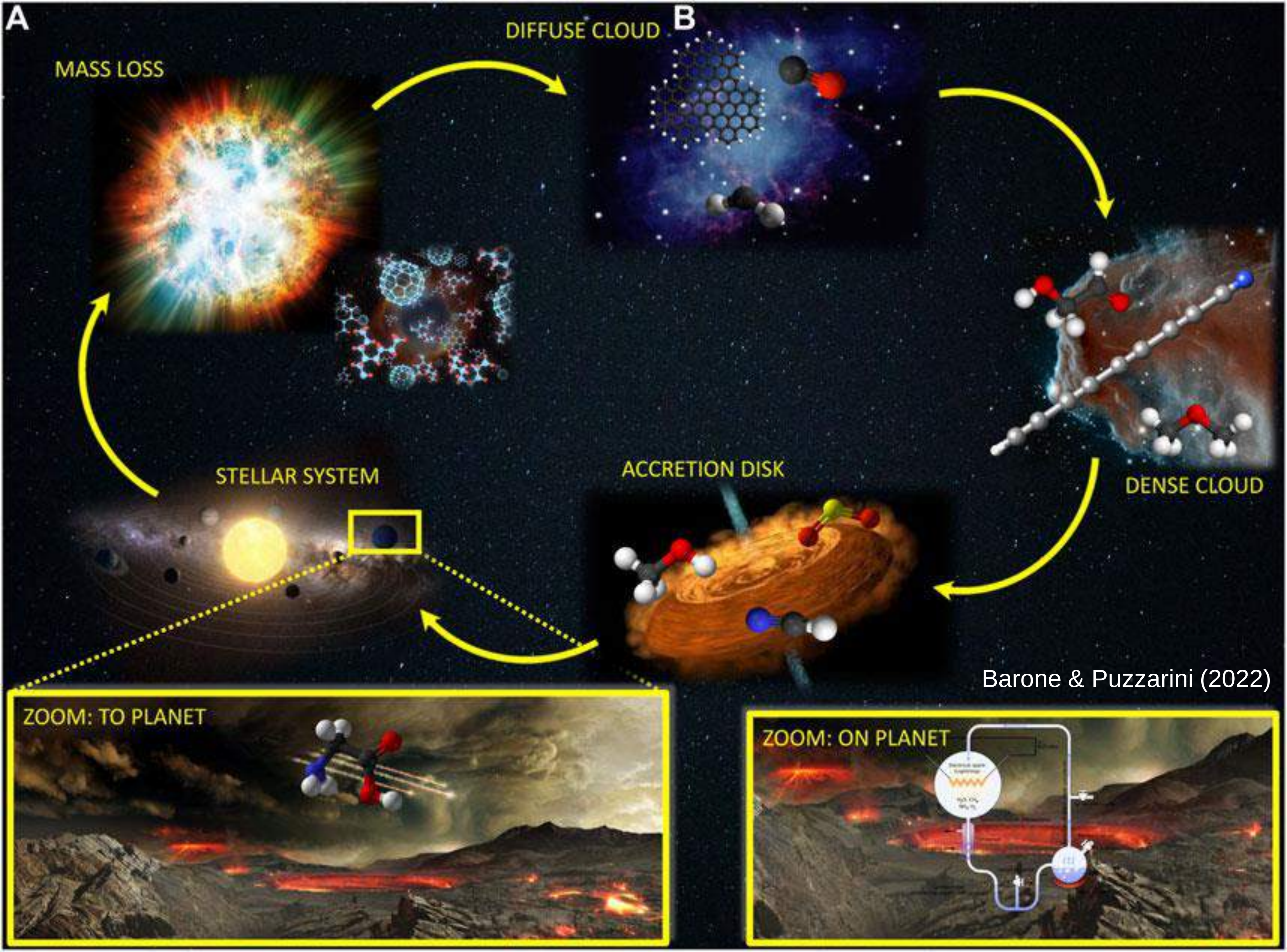
H_2O, H_2O_2, CO_2, $^{13}CO_2$, OCN^-, N_2O, CO, CN^-, HNCO, O_3, HCHO, NH_2CHO, C_2H_5OH, CH_3CHO, CH_3OH

IR and VUV spectroscopic investigation of ion, electron, and thermally processed EtA ice



Location of ice	Ice lifetime (yr)	Dose rate (eV· molecule^{-1} yr^{-1})	Half-life of EtA (yr)
Cold dense cloud	10^7	3×10^{-7} [a]	$(3.6 \pm 0.4) \times 10^7$
KBO (depth: $<1\times10^{-6}$ cm)	4.6×10^9	5.6×10^{-3} [b]	$(1.9 \pm 0.2) \times 10^3$
KBO (depth: 1×10^{-3} cm)	4.6×10^9	1.6×10^{-8} [c]	$(6.8 \pm 0.8) \times 10^8$

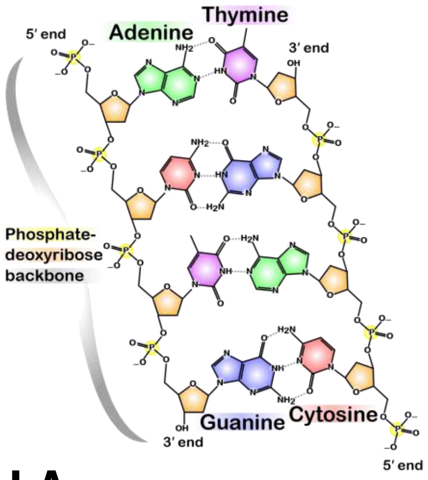
H_2O, H_2O_2, CO_2, $^{13}CO_2$, OCN^-, N_2O, CO, CN^-, HNCO, O_3, HCHO, NH_2CHO, C_2H_5OH, CH_3CHO, CH_3OH



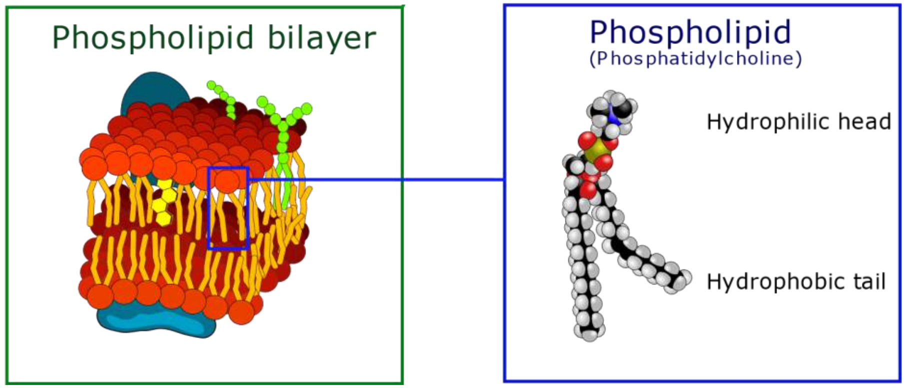
Barone & Puzzarini (2022)

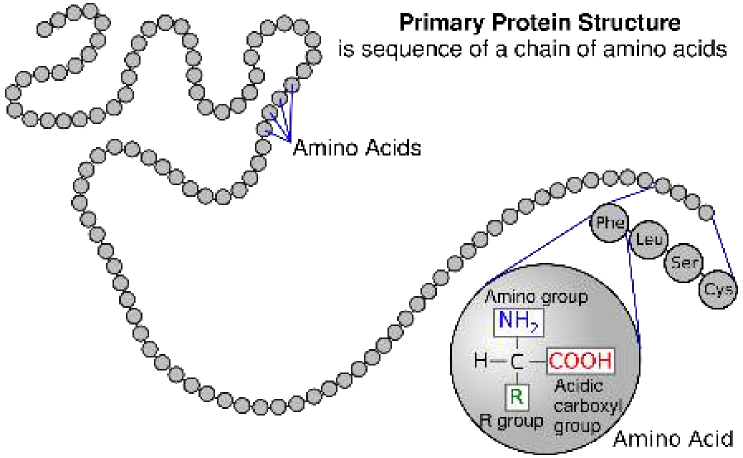
Does Surface Chemistry drive the formation of the building blocks of cells?

VS

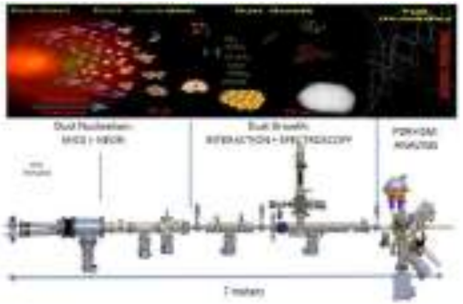


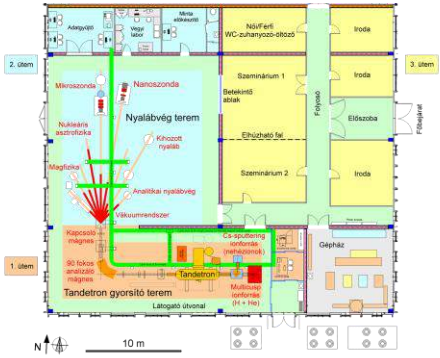
RNA or DNA Worlds

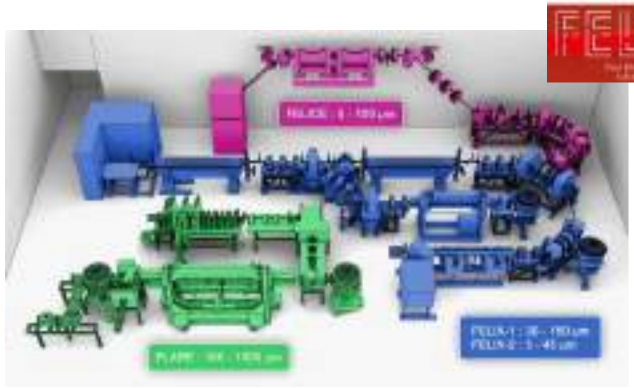




Astrochemistry at Large-Scale Facilities

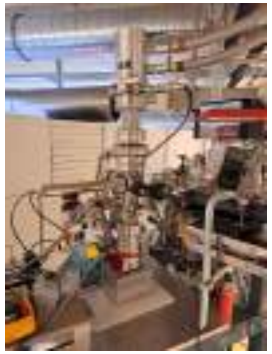






STARDUST MACHINE

ICE CHAMBER



ICA

AQUILA

LISA

Summary

- Simple and complex organic molecules formed on dust grains via Dark Chemistry
- UV, CR, electrons, and heat change the physicochemical composition of ice grains
- Building blocks of life can survive star formation process
- Laboratory Astrochemistry needs to strengthen link to Astrobiology

QUESTIONS

WEBB
SPACE TELESCOPE