Ion irradiation affects the composition of frozen surfaces in space

Riccardo G. Urso

INAF-Osservatorio Astrofisico di Catania

Institut d’Astrophysique Spatiale, Université Paris-Saclay, Orsay, France

Dep. of Physics, Freie Universität Berlin, Germany

INAF ISTITUTO NAZIONALE DI ASTROFISICA OSSERVATORIO ASTROFISICO DI CATANIA

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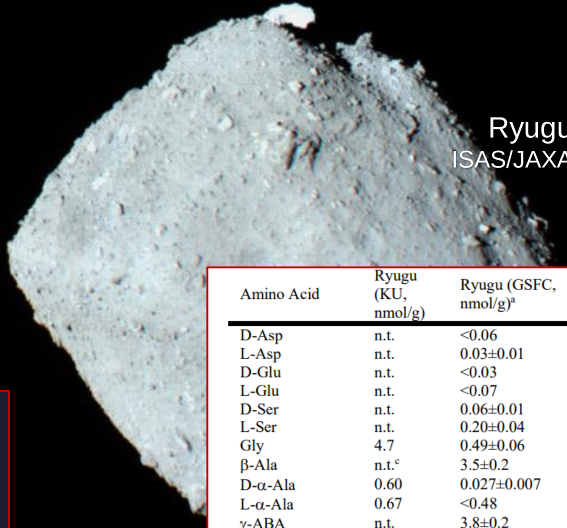
IAS Orsay

Freie Universität Berlin

Astrophysical context

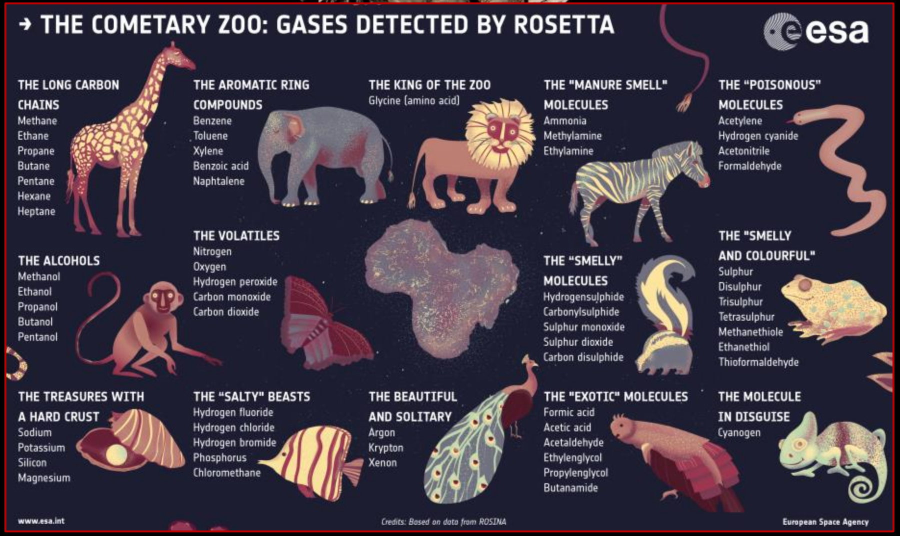
Atmosphere-less surfaces in the Solar System

67P/C-G
ESA/Rosetta/MPS



Ryugu
ISAS/JAXA

Arrokoth
NASA/J. Hopkins Univ. R. Tkachenko



Credits ESA

Amino Acid	Ryugu (KU, nmol/g)	Ryugu (GSFC, nmol/g)[a]	CI1 Orgueil[b] (GSFC, nmol/g)
D-Asp	n.t.	<0.06	0.41±0.23
L-Asp	n.t.	0.03±0.01	0.14±0.21
D-Glu	n.t.	<0.03	0.32±0.11
L-Glu	n.t.	<0.07	0.56±0.15
D-Ser	n.t.	0.06±0.01	<0.01
L-Ser	n.t.	0.20±0.04	<0.01
Gly	4.7	0.49±0.06	11.5±6.0
β-Ala	n.t.[c]	3.5±0.2	30.6±7.6
D-α-Ala	0.60	0.027±0.007	0.90±0.19
L-α-Ala	0.67	<0.48	1.1±0.25
γ-ABA	n.t.	3.8±0.2	2.7±1.3
D-β-AIB	n.t.	0.22±0.02	c[d]
L-β-AIB	n.t.	0.18±0.02	
D-β-ABA	n.t.	0.35±0.01[e]	2.1±1.1
L-β-ABA	n.t.	0.35±0.01[e]	1.8±0.6
α-AIB	n.t.	0.41±0.03	3.3±1.4
D-α-ABA	0.091	<0.01	0.69±0.48[d]
L-α-ABA	0.095	<0.01	
D-Val	0.022	<0.08	0.19±0.05
L-Val	0.047	<0.07	0.48±0.02
D-Nva	0.014	<0.04[e]	0.23±0.02[d]
L-Nva	0.014	<0.04[e]	
D-Iva	0.044	<0.06	0.31±0.03
L-Iva	0.039	<0.05	0.42±0.02
D,L-β-APA	n.t.	<0.15	1.6±0.1
δ-AVA	n.t.	1.3±0.1[e]	1.2±0.2
D,L-3-A-2-MBA	n.t.	c	0.55±0.03
3-A-3-MBA	n.t.	c	<0.26
3-A-2,2-DMBA	n.t.	0.060±0.002[e]	0.59±0.03
D,L-3-A-2-EPA	n.t.	c	1.5±0.1
D,L-γ-APA	n.t.	c	2.4±0.2
D,L-4-A-2-MBA	n.t.	<0.19	1.5±0.1
D,L-4-A-3-MBA	n.t.	c	2.8±0.1

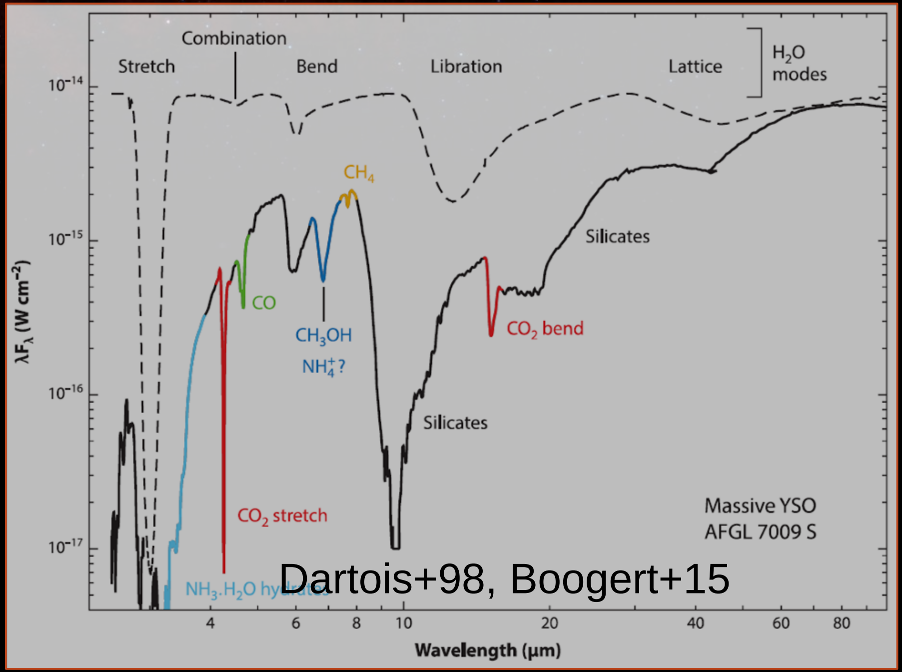
Parker et al. LPSC 2022

Astrophysical context

- Icy grain mantles in the interstellar medium

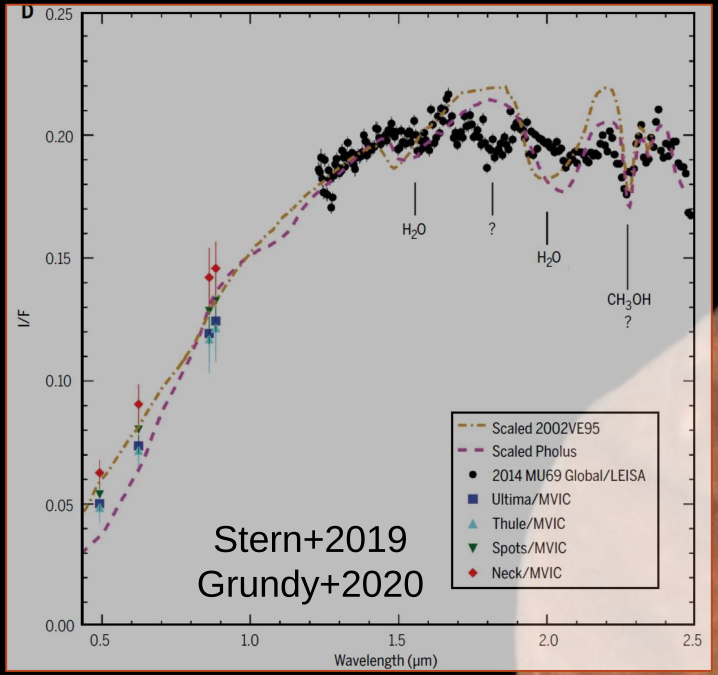
Simple frozen volatile compounds

e.g., H_2O, CH_3OH, NH_3 (e.g. Barucci + 2011)



Dartois+98, Boogert+15

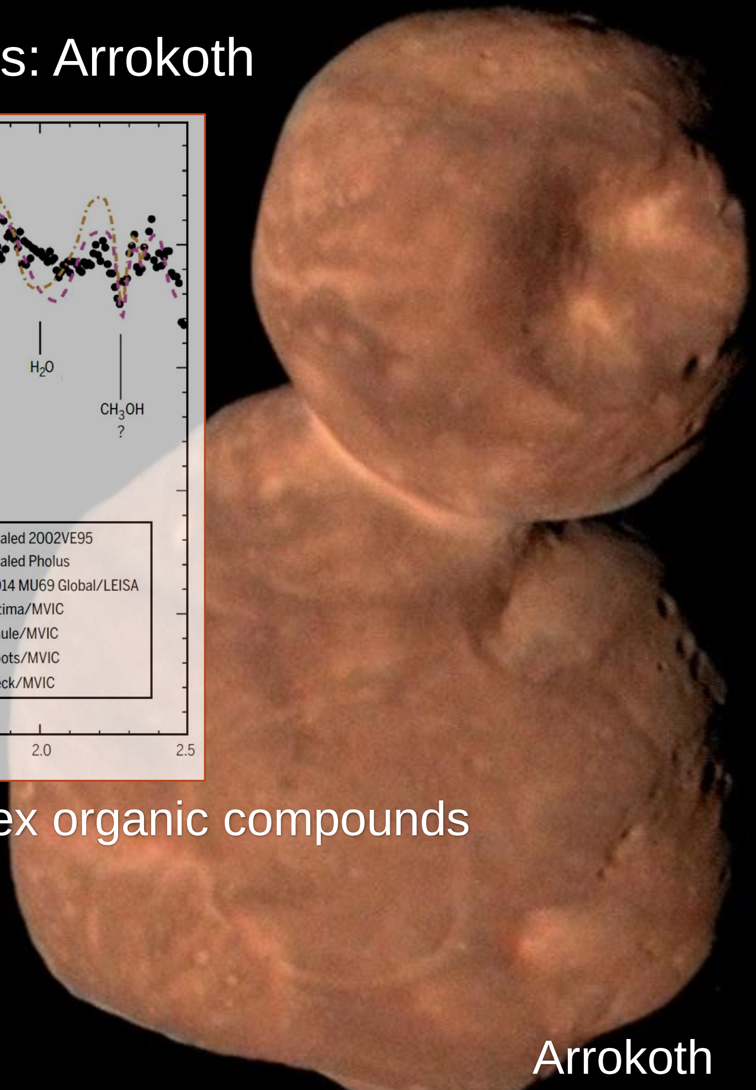
- Kuiper-belt objects: Arrokoth



Stern+2019
Grundy+2020

VIS-NIR red slopes: complex organic compounds

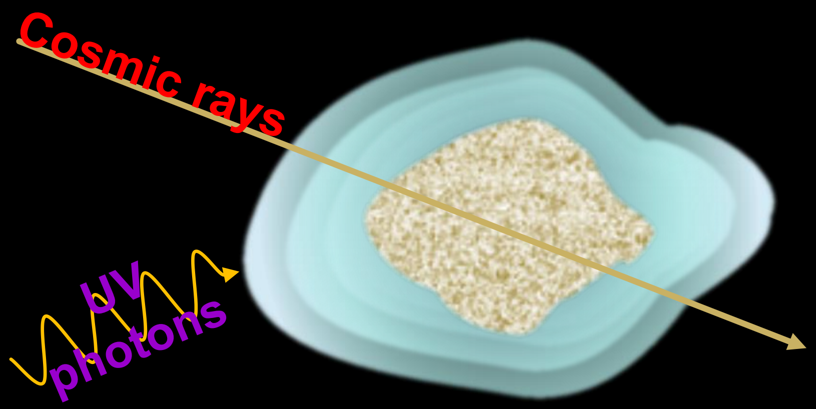
(e.g. Dalle Ore + 2011)



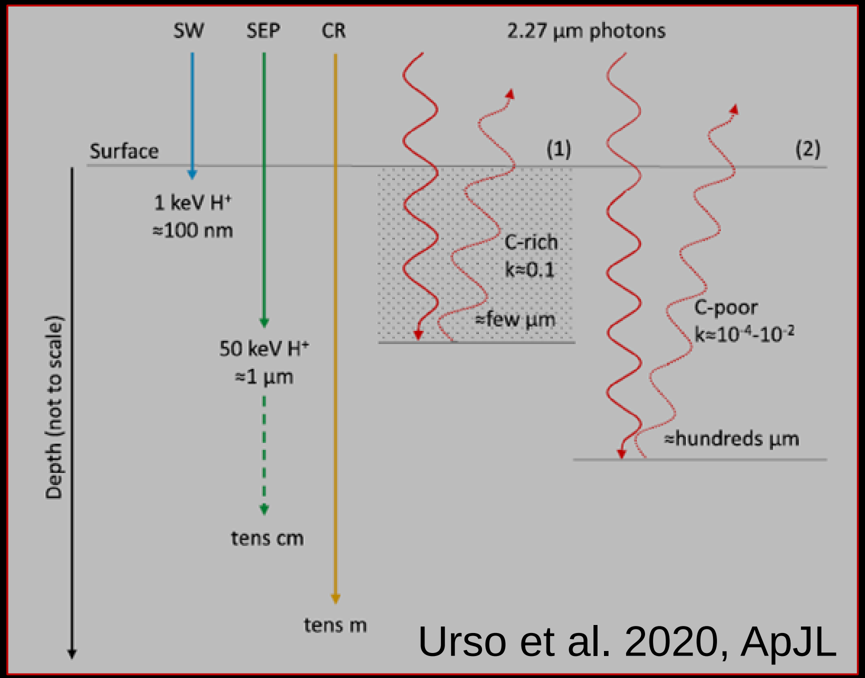
Arrokoth
NASA/J. Hopkins Univ. R. Tkachenko

Ion irradiation in space

Icy grain mantles
In young star-forming regions

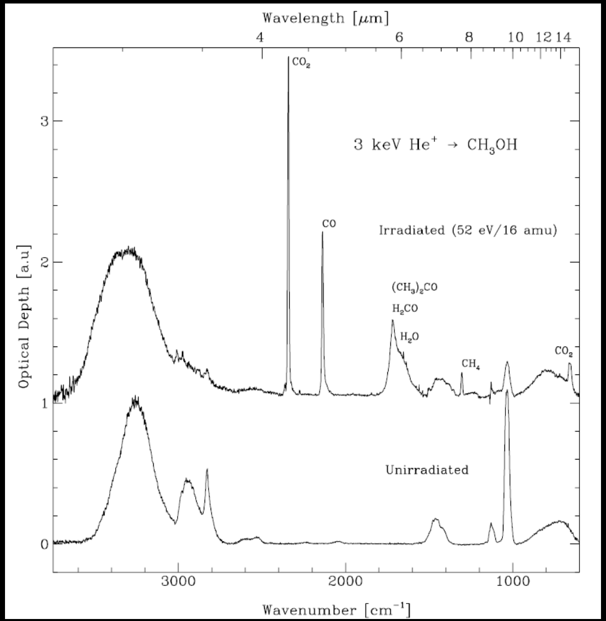


Atmosphere-less surfaces
in the outer Solar System

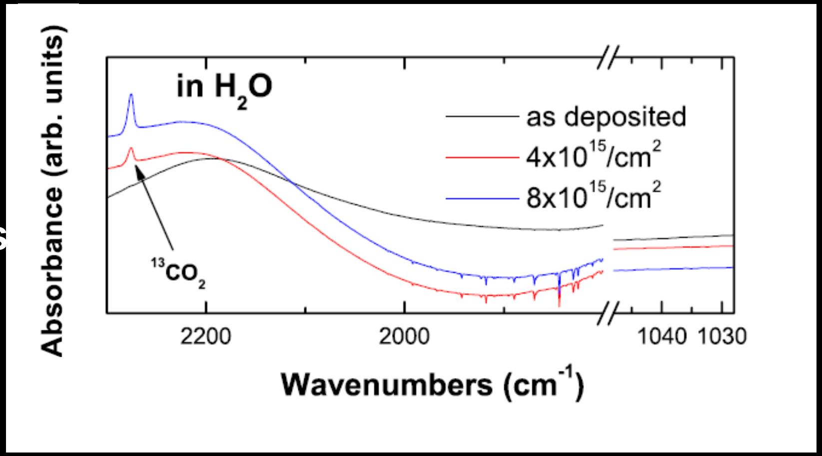


Ion irradiation in space

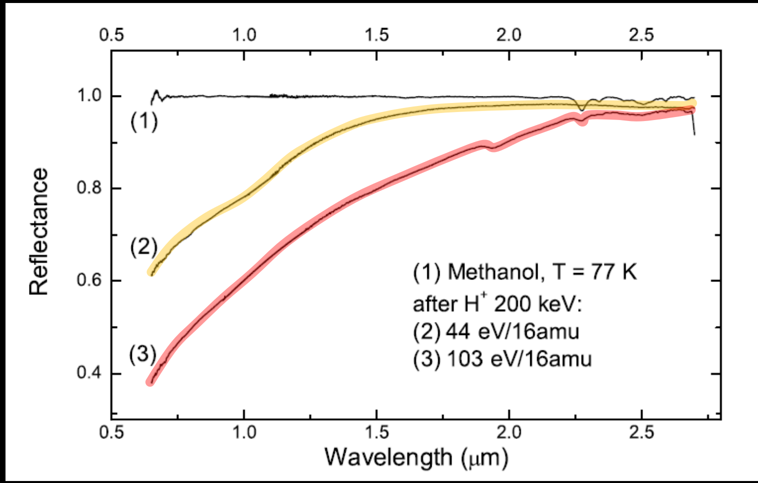
chemical changes
energy transfer
Palumbo+99



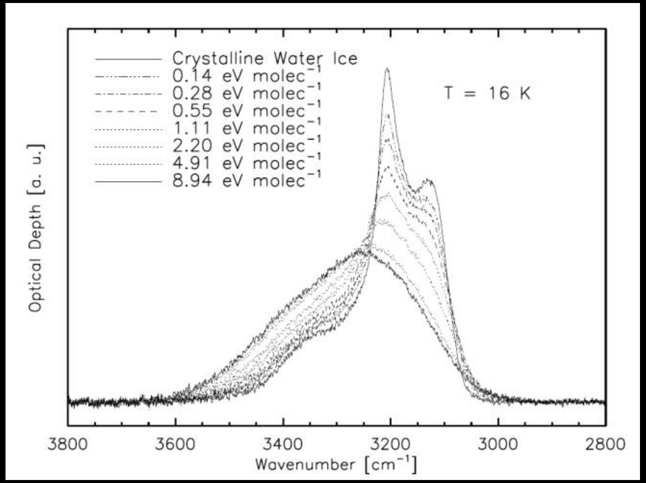
chemical changes
implantation
Boduch+13



Reddening
Brunetto+06
Poston+18
Hénault+in prep.

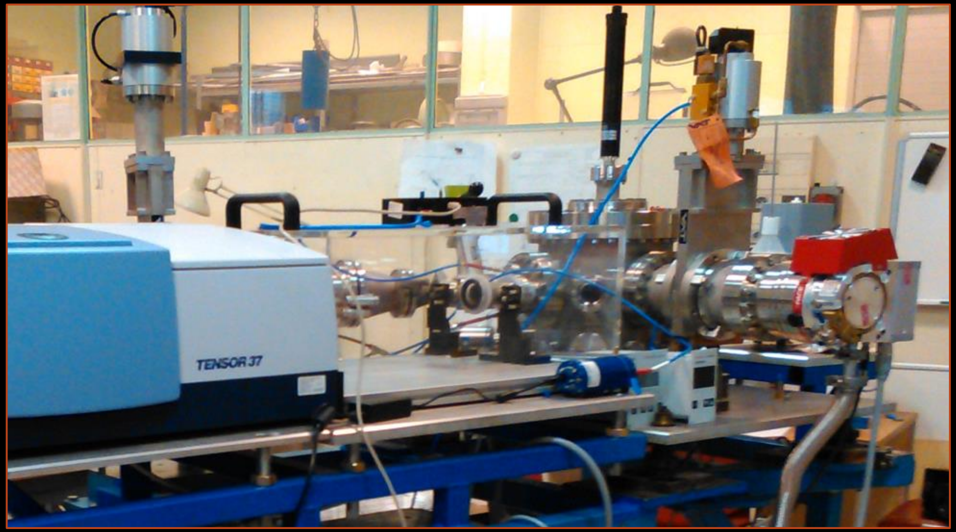


Structural changes
Leto & Baratta 03
Mastrapa & Brown 06
Dartois+15

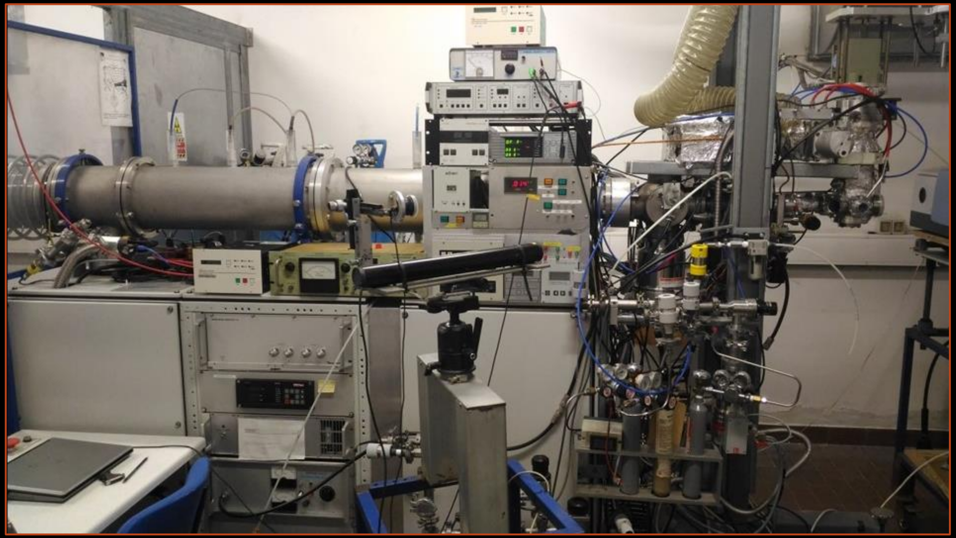


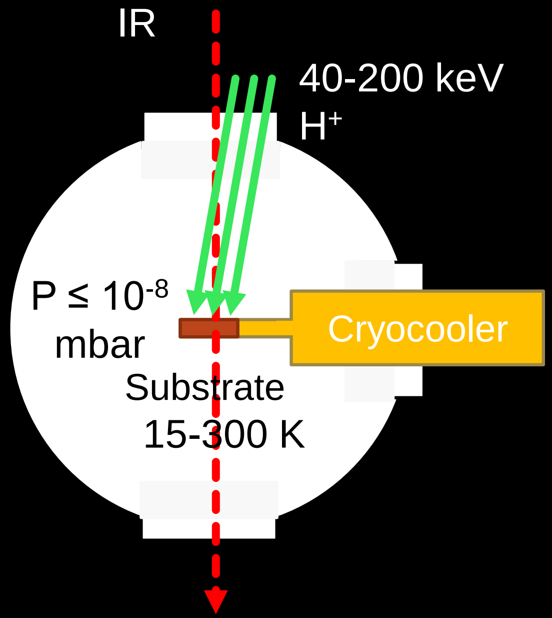
Laboratory experiments

INGMAR-T
IAS-IJCLab,
Orsay, France



LASp
INAF-OACT,
Catania, Italy

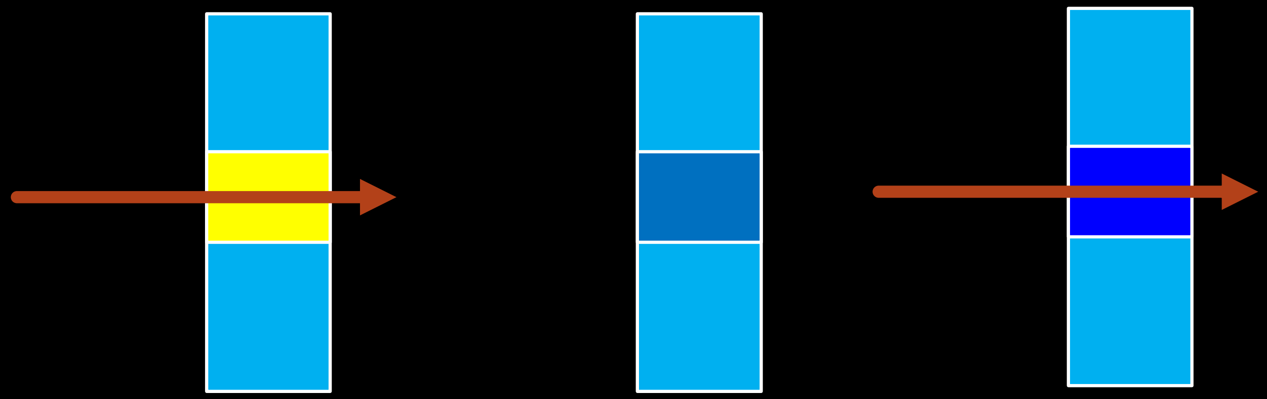




1. $H_2O:CH_3OH:NH_3$ ices
2. Irradiation with 40-200 keV H^+
3. in-situ infrared spectroscopy
4. warm-up to 300 K

Laboratory Experiments

- Temperature: ≥10 K, 40 K, heating possible
- Pressure: 10^{-9} – 10^{-8} mbar
- Ion source: 40 keV – 200 keV H^+ → High energy loss in the sample thicknesses
- Low ion-beam current: hundreds of nA to 1 µA

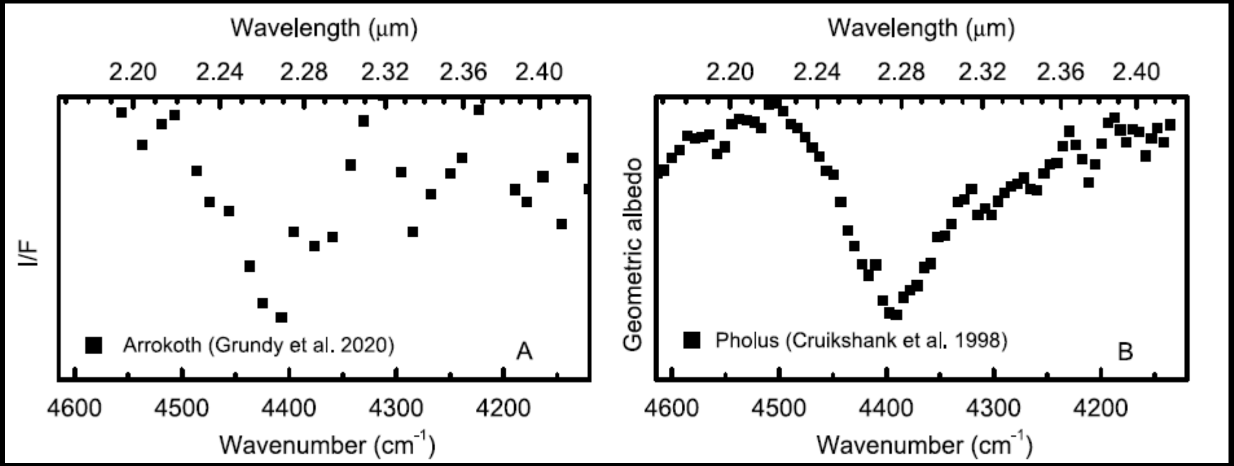


Excitation and recombination along the ion track: **≤10^{-12} s** (1 picosecond)

Time needed for another ion to hit the same spot: **1.6×10^{-2} s**

ions travel in non-excited volumes of target ice

Spectral changes induced by irradiation

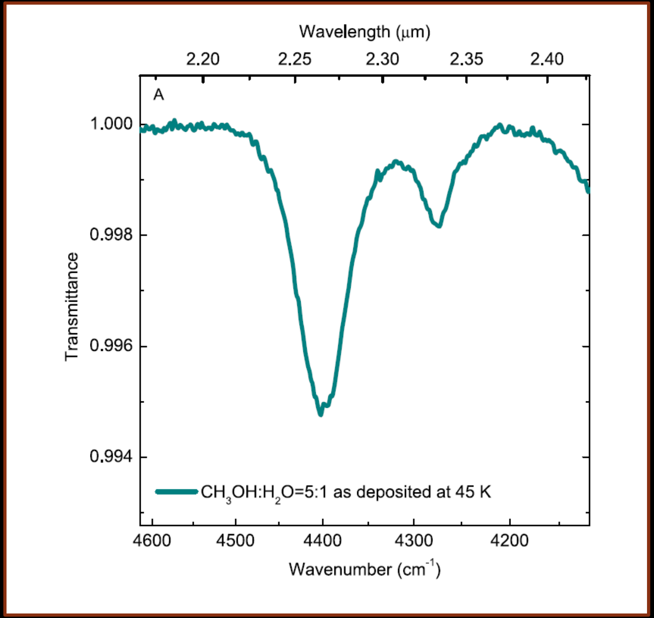


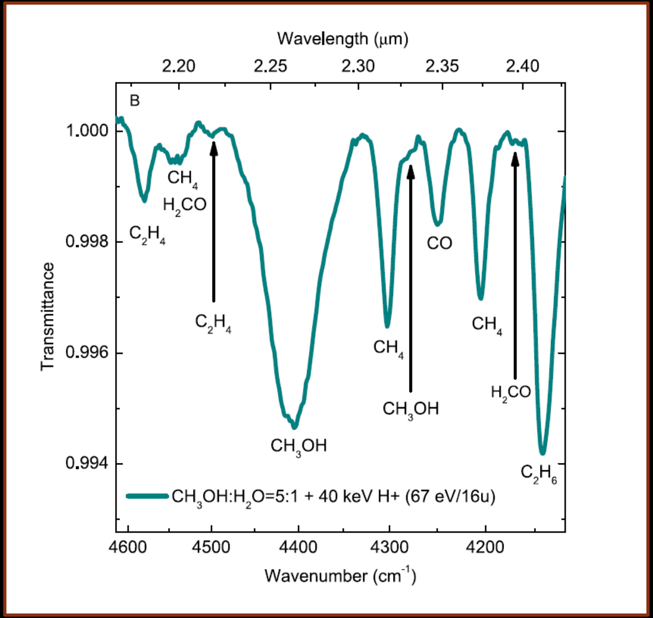
Production of new compounds

(e.g. Palumbo+1999, Hudson & Moore 2000)

Decrease of the 2.34 μm band (Brunetto+2005)

NIR methanol bands
2.27, 2.34 μm

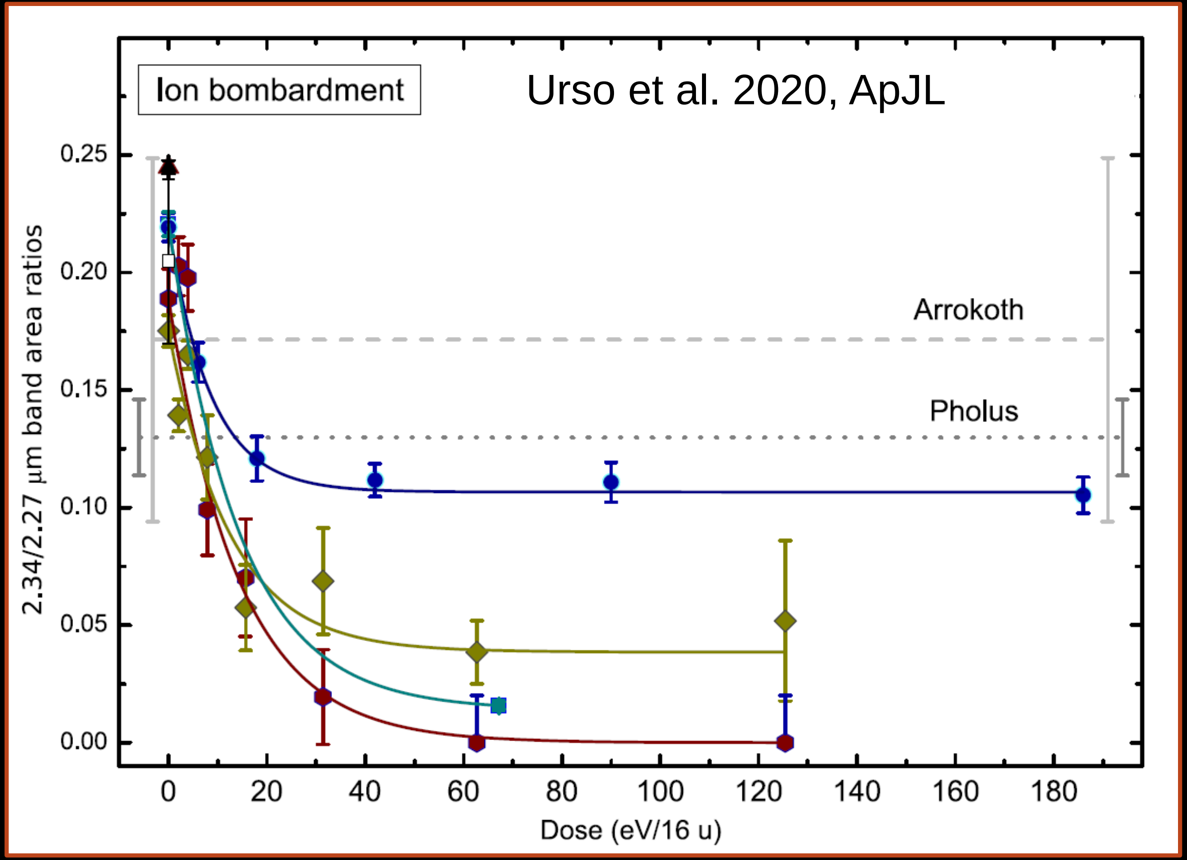


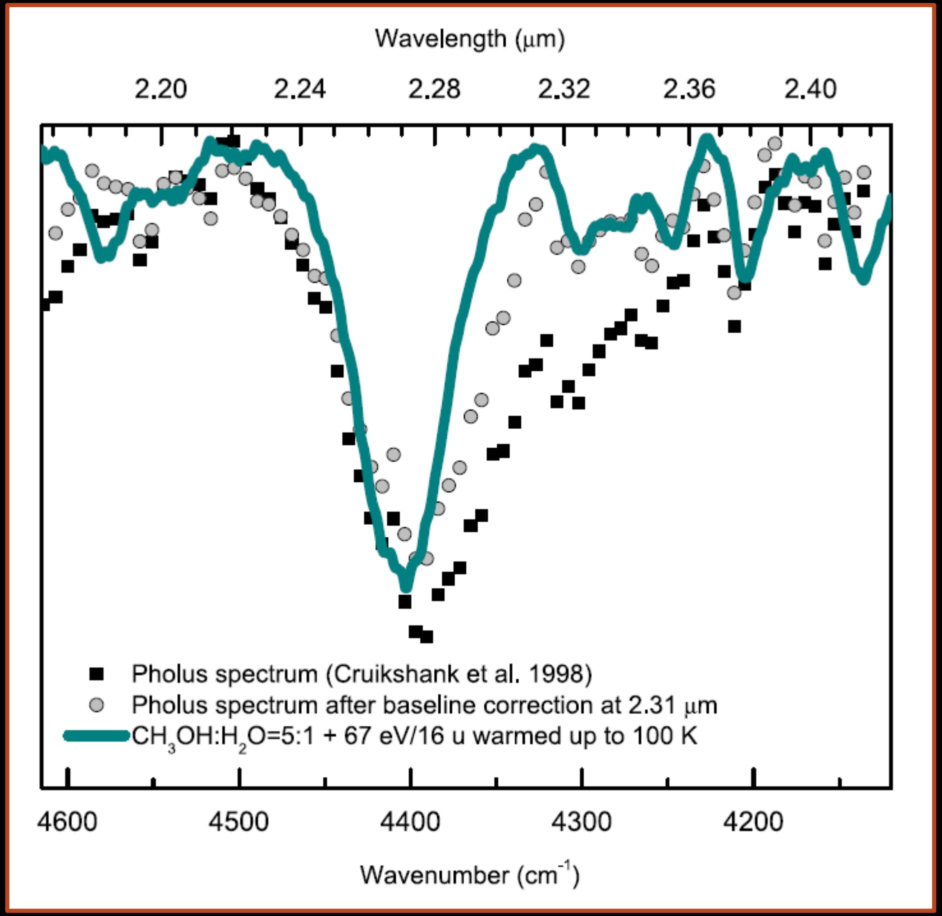


Urso et al. 2020, ApJL

Spectral changes induced by irradiation

Testing the 2.34/2.27 µm band ratio as a probe of irradiation



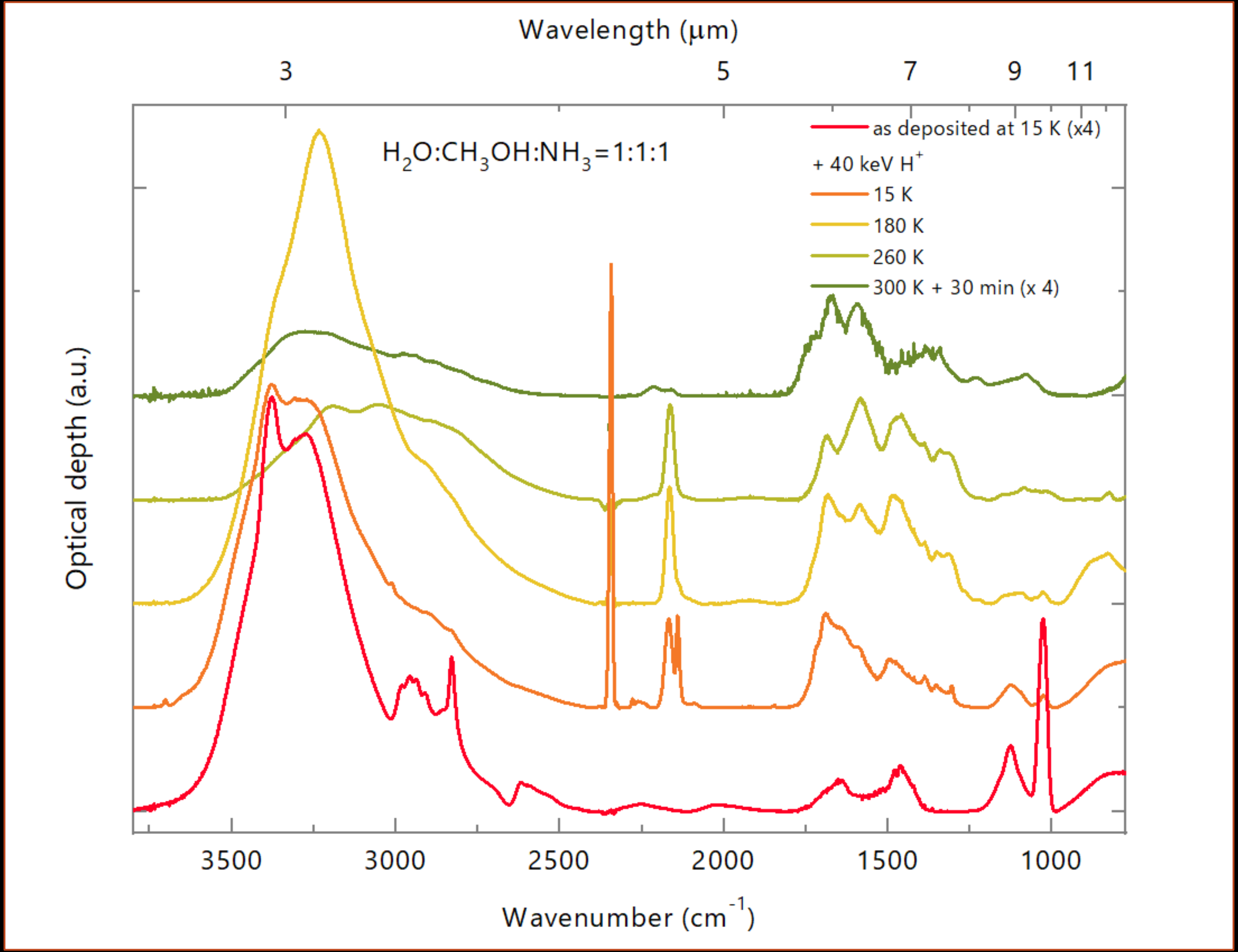


Timescales of irradiation at 20-40 AU: $4\text{-}8\times10^9$ years by CR
$6\text{-}30\times10^6$ years by SEP

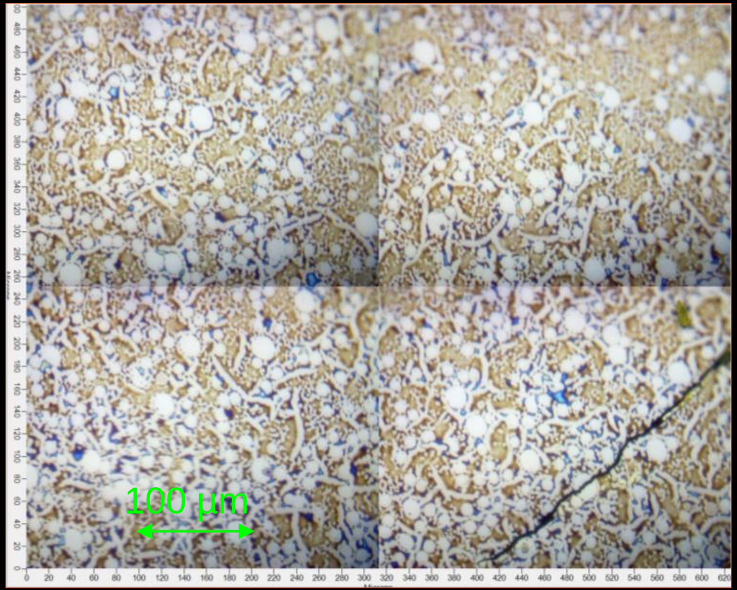
Formation of complex organics

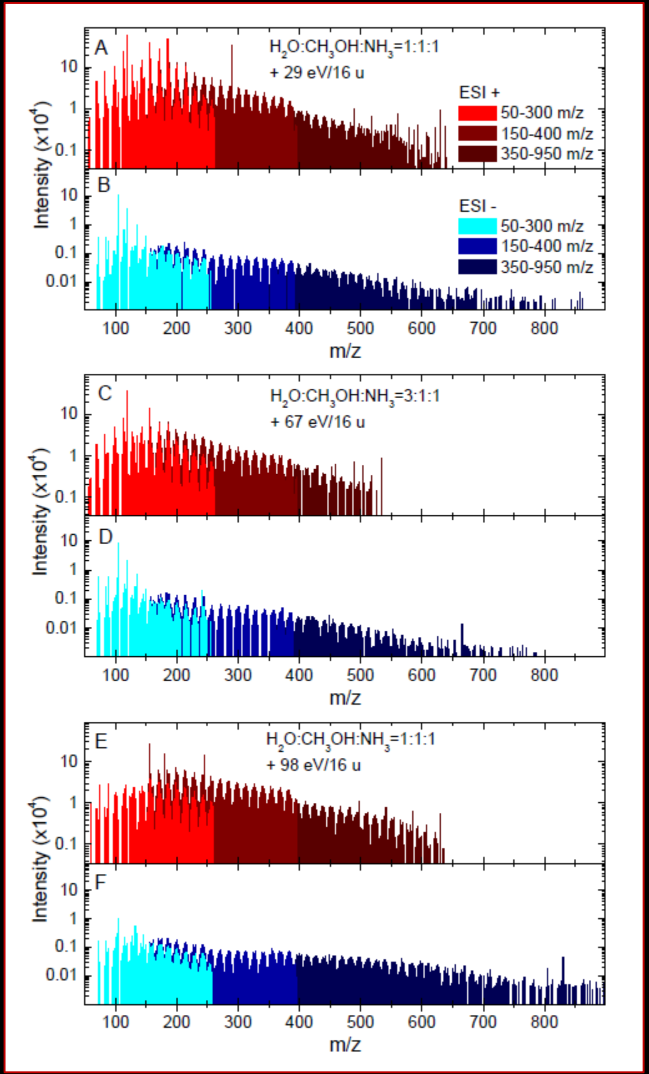
Ion irradiation
+
Heating

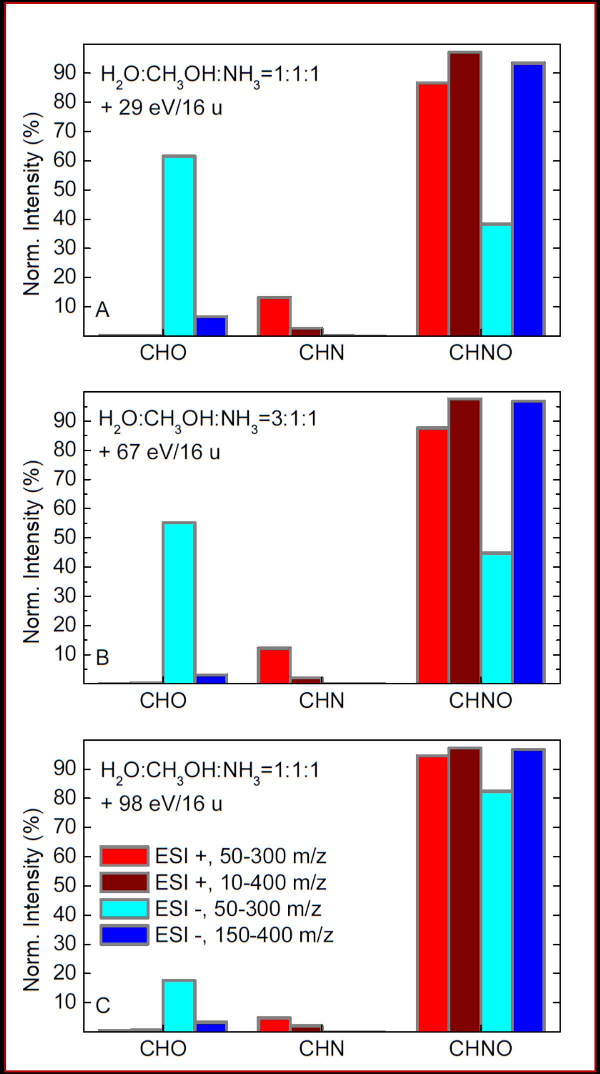
sublimation of volatiles and diffusion



Formation of complex organics







LTQ-Orbitrap
IPAG (Grenoble, France)

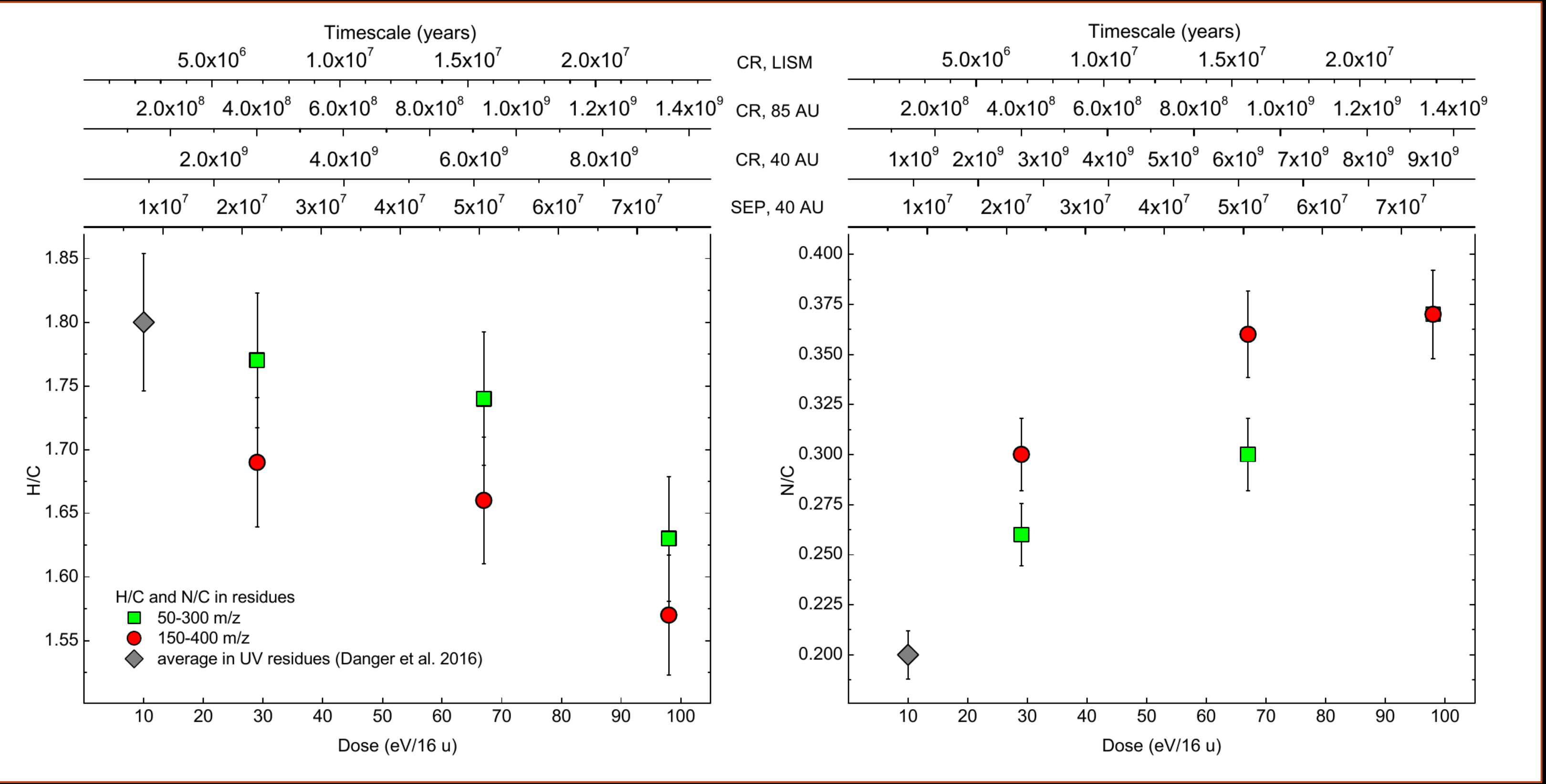
More than 3000 molecular fragments in each sample

Urso, R. G. et al. 2020, A&A

Mass spectra 50-950 m/z

Abundance of molecular groups

Formation of complex organics



Urso, R. G. et al. 2020, A&A

Isomers of amino acids:

Histidine, Glutamine, Threonine, Proline, Amino isobut. Acid, Alanine, Glycine

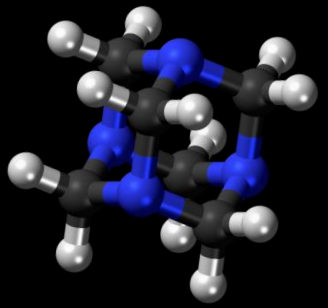
Isomers of nucleobases:

Thymine, Cytosine, Uracil

Formation of complex organics

Hexamethylenetetramine (HMT)

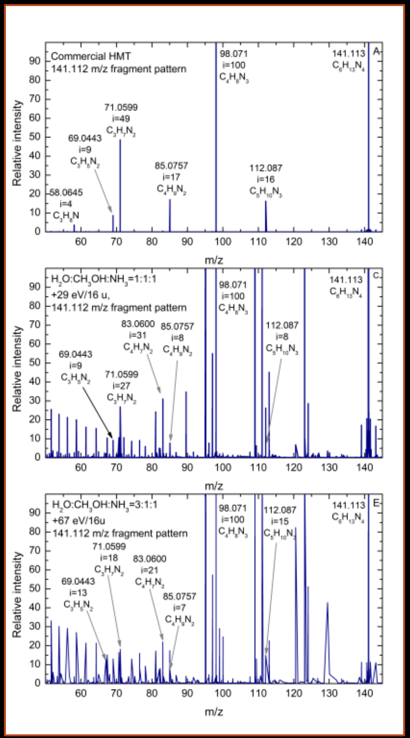
precursor of amino acids and
N-heterocycles



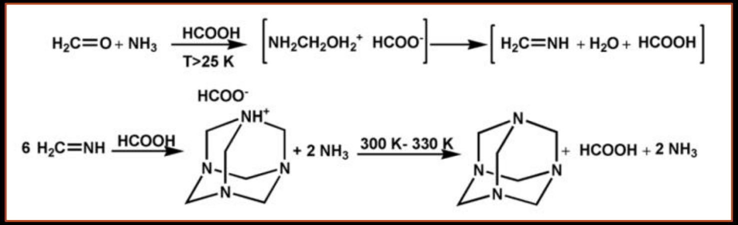
Revealed in carbonaceous chondrites (Oba+2020)

Revealed in laboratory samples

HMT decreases with increasing dose

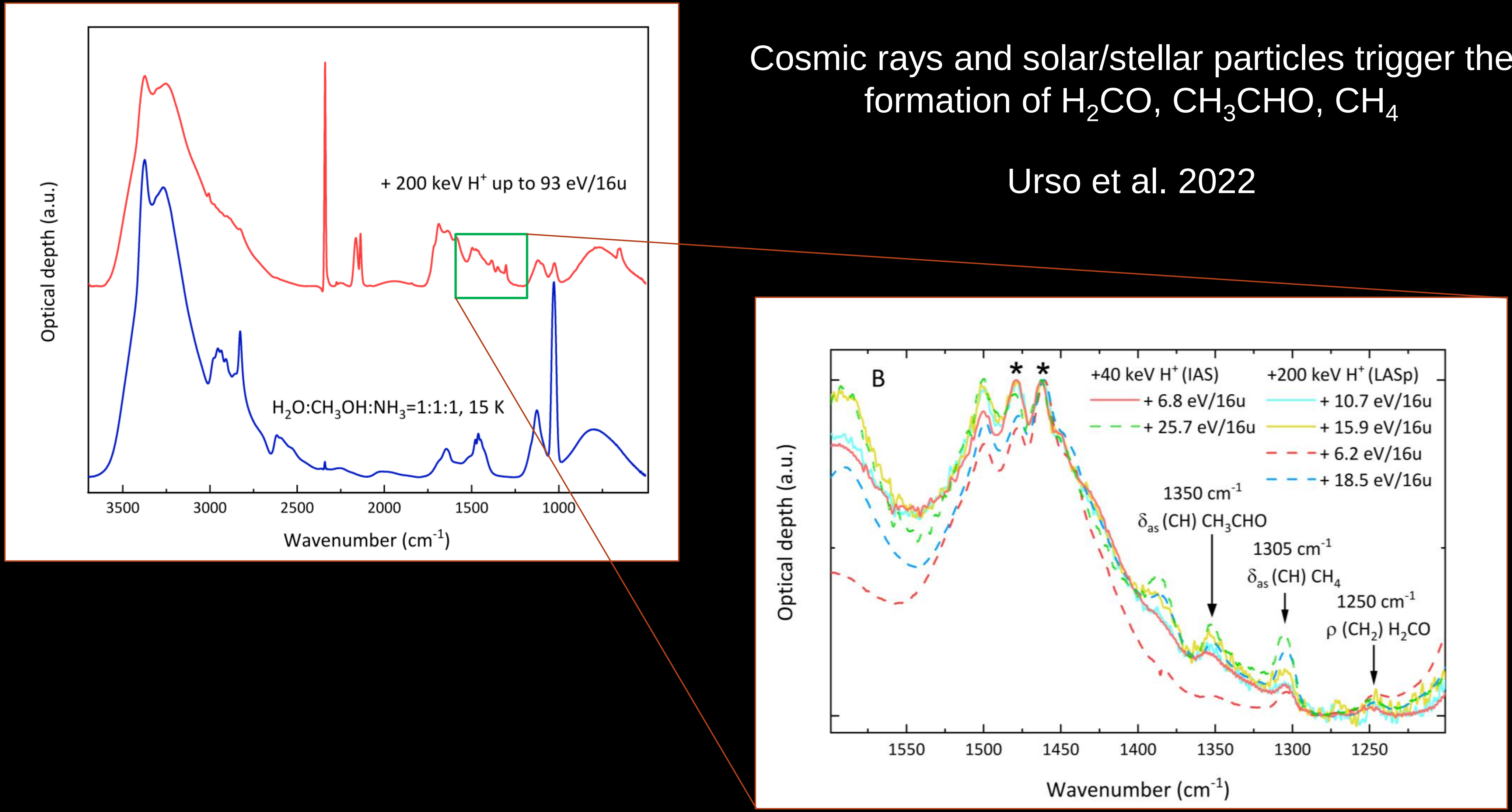


Urso+20, A&A



(Vinogradoff + 2012)

Precursors of complex organics in ices



Cosmic rays and solar/stellar particles trigger the formation of H_2CO, CH_3CHO, CH_4

Urso et al. 2022

Precursors of complex organics in irradiated ices

Why does the composition of refractory organics depend on the irradiation dose?

Formation/destruction of complex organic precursors in the ice

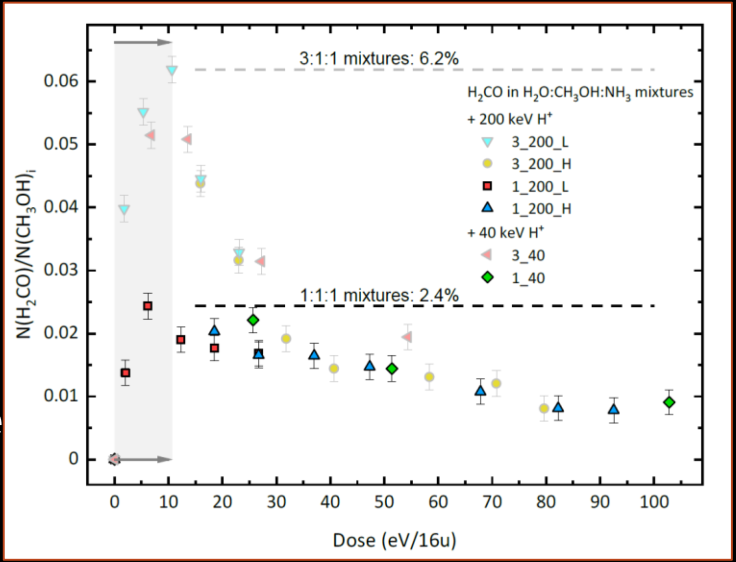
Timescales of formation: 10^6 -10^8

Doses > 10 eV/molecule determine H_2CO destruction

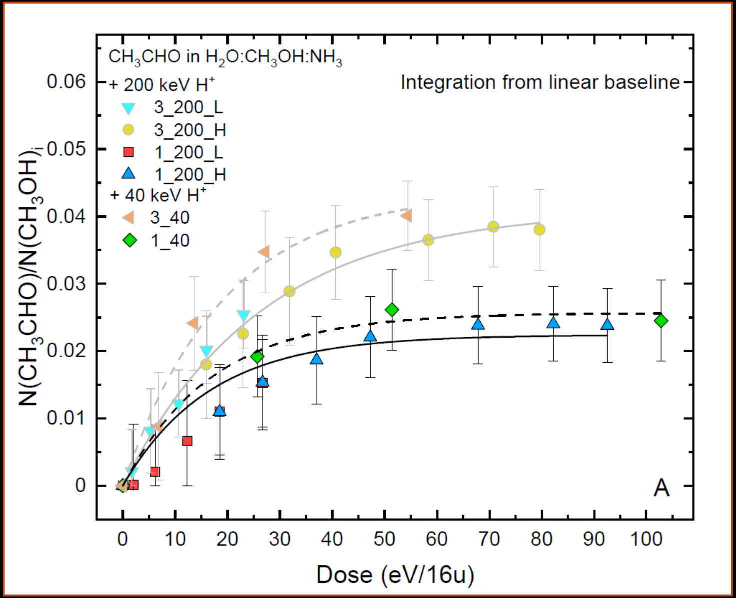
- Lower quantities of Hexamethylenetetramine can form

Urso et al. 2022

Formaldehyde

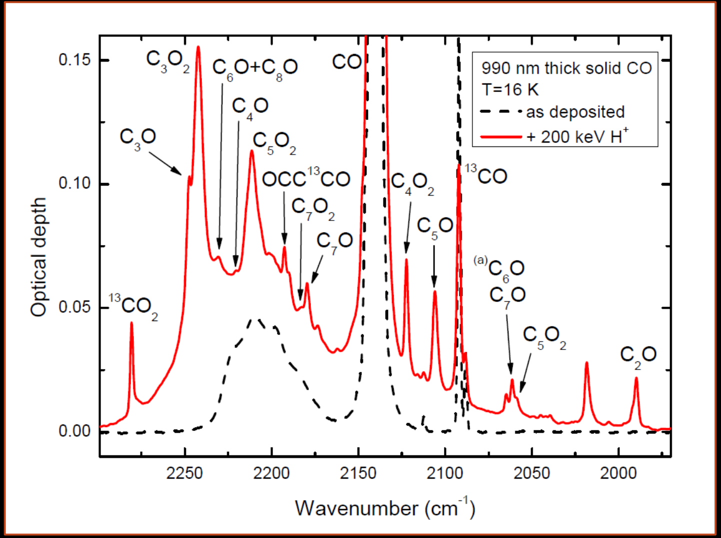


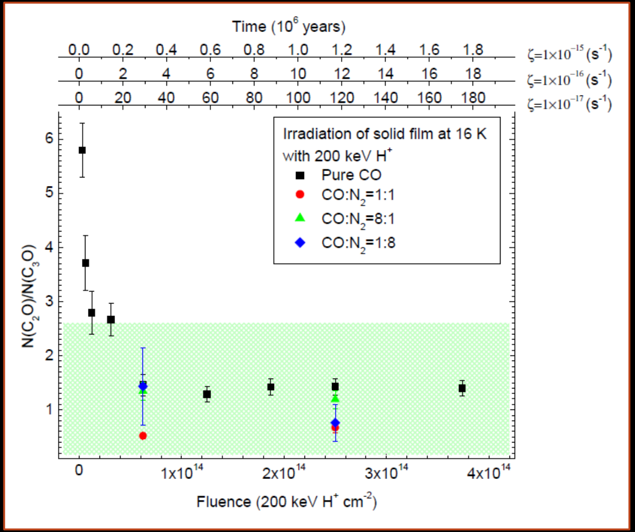
Acetaldehyde



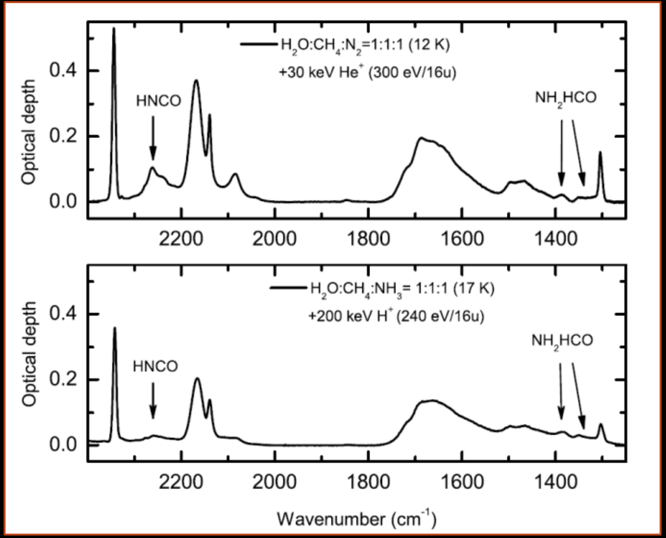
Other species in irradiated ices

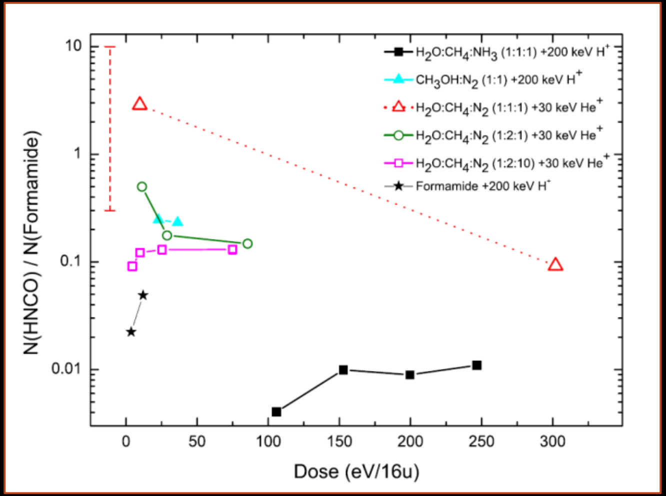
C_2O and C_3O Palumbo+08, Urso+19





Formamide Kanuchova+16, Urso+17





Many other compounds could be present

!!!

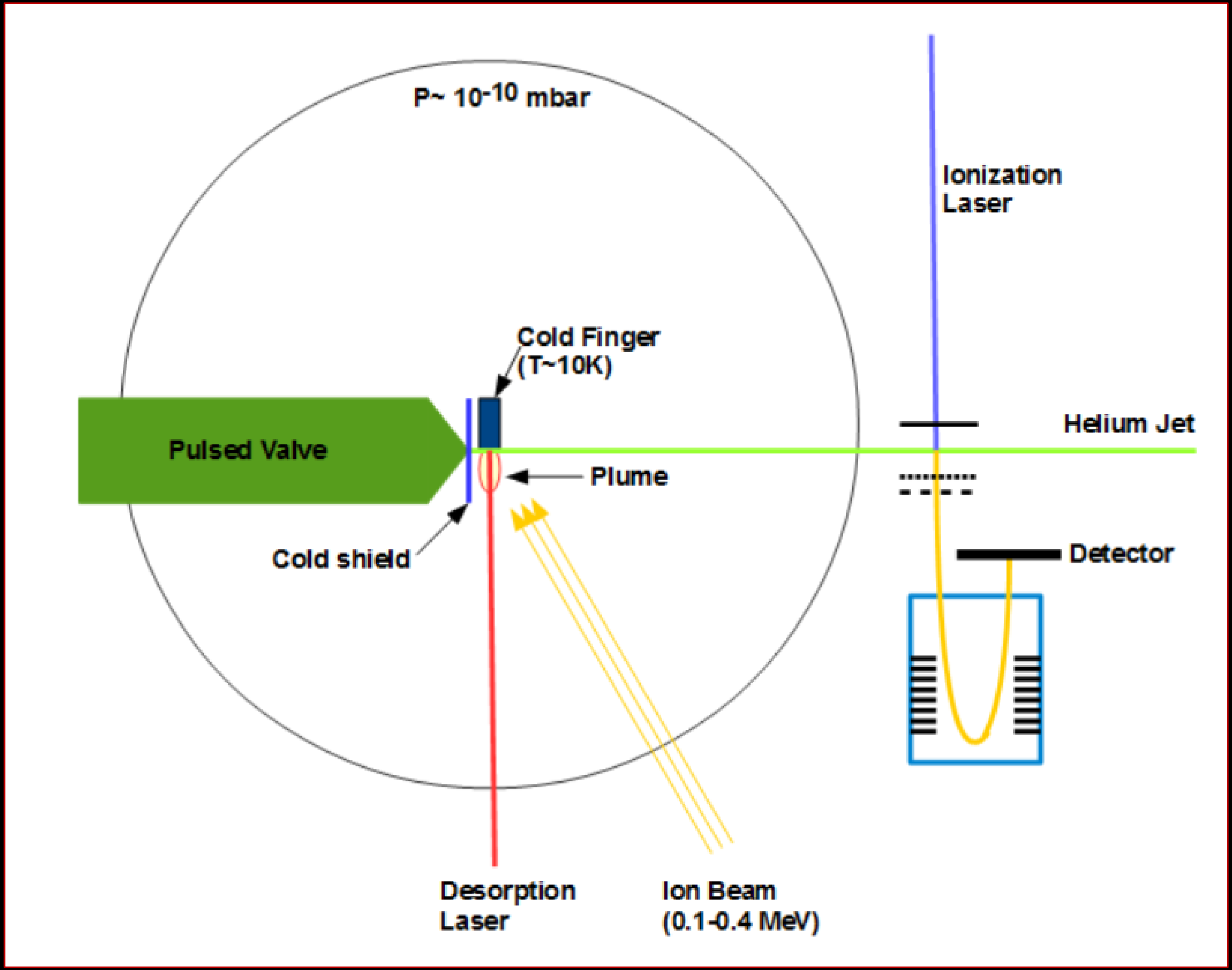
Intrinsic limits of IR spectroscopy

Combining different techniques

Perspectives and conclusions

Need for more sensitive techniques to detect molecules formed after ion irradiation of ices

In-situ mass spectrometry at INAF-OACT



Irradiation-induced alteration of complex organics

Freie Universität Berlin

EINSTEIN Foundation.de

He Cryocooler (10-350 K)
5 keV electron gun
Mid-IR, Uv-vis spectroscopy
TPD

OREOcube

Astrochemistry, Carbon- and Photochemistry, Life Detection, Planetary Environments, Meteoritics

Exocube

Astrobiology, Radiation Biology, Extreme Life, Life Support, Biocontamination

P.I. A. Elsaesser (FUB, Berlin)

Conclusions

- Cosmic rays and solar ions alter frozen surfaces
- NIR methanol band ratio as a spectroscopic probe of irradiation
- Formation of complex organics: dependence on the irradiation dose
- Astrobiologically-relevant compounds: HMT, isomers of amino acids, and nucleobases
- High doses destroy the precursors of complex organics

Thank you!