Swift heavy ions, ices and astrophysics

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Ices?

Ions? In space, in the lab (GANIL) and in matter.

Laboratory simulations :
Several examples

Water : compaction and amorphisation

Role of CR : CO ice

Jovian moon, magnetosphere
and sulfur implantation : exogenic production?

Gaz mixture, UCAMMs, complex molecules…

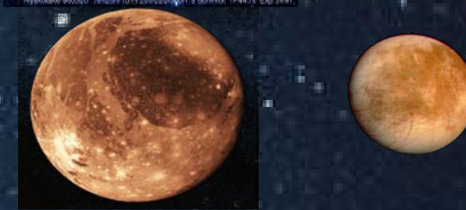
Perspectives : IGLIAS

Astrophysical Ices ...

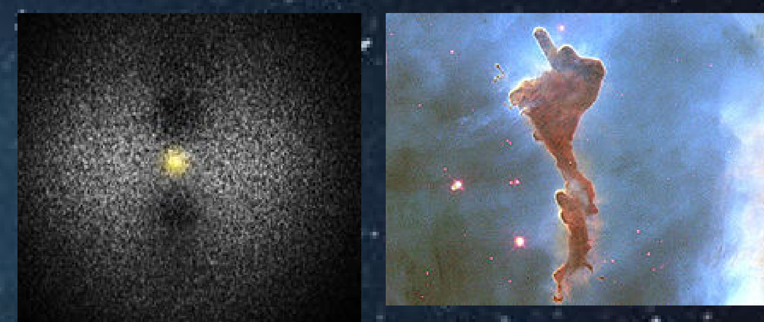
→ Comets

→ Giant Planet's Moons

(Europa, Ganymede, ...)



→ Dust Grains

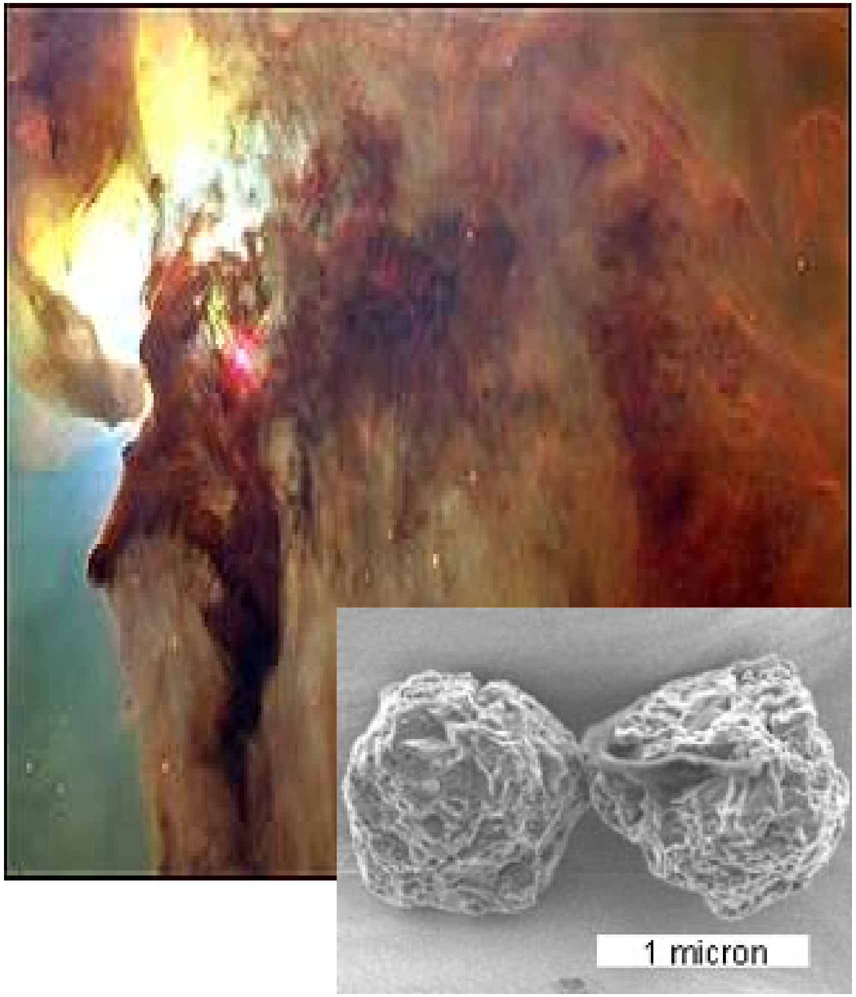


Rings

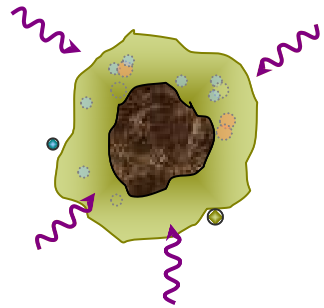
Dense Interstellar Clouds

(birthplaces of suns and planets)

Interstellar dust grains (dense molecular clouds)

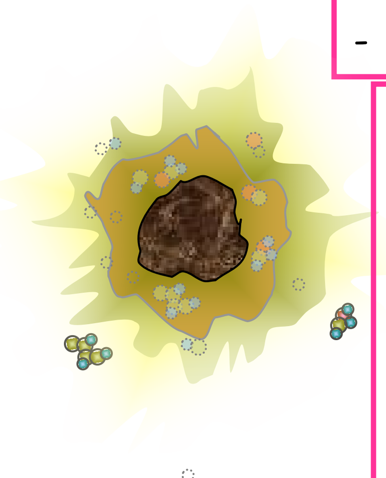


... covered with thin layers of ices (H_2O, CO, NH_3, ...)



are exposed to

- cosmic rays; (protons, helium, heavy ions)
- stellar wind (H, He, C, O, S ...)
- UV photons
- electrons



irradiation leads to ...

Radiolysis

fragmentation/destruction

formation of molecules (radiation chemistry)

Desorption / Sputtering

Compactation / Amorphization

What are Cosmic Rays ?

- Primary Cosmic Rays are very energetic (10^3 to 10^{22} eV) charged particles that traverse outer space

↓

1 kJ

- Basically, they are:

  - light ions: protons + deuterons (87%) and α particles (11%)

  - heavy 4n ions : ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{40}Ar, ^{40}Ca and ^{56}Fe (Ni)

  - electrons (~1%)

  [unstable ions or neutrals are excluded: neutrons, neutrinos, X-rays, γ rays]

- After collision with interstellar matter and atmosphere,

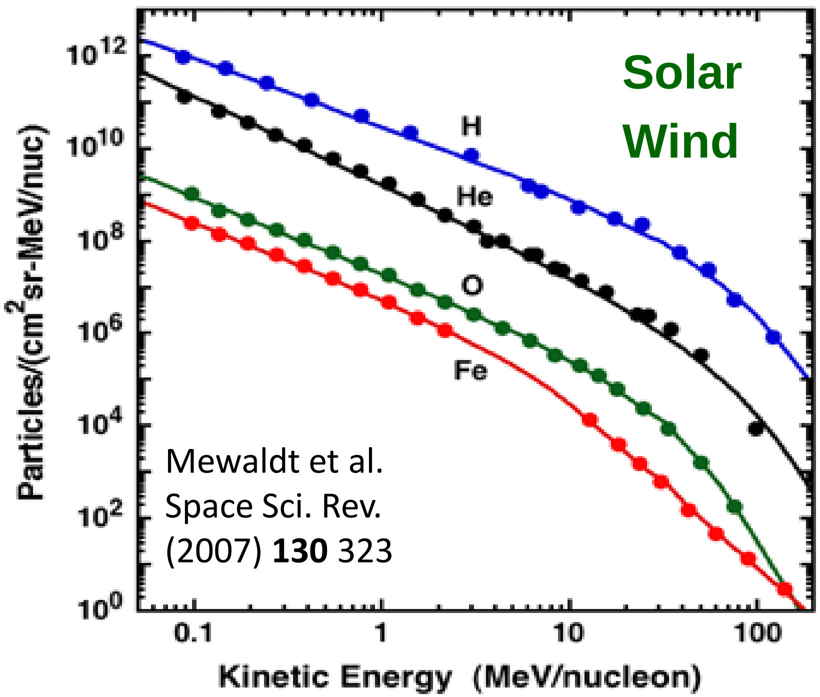
  Secondary Cosmic Rays are formed. They are constituted by:

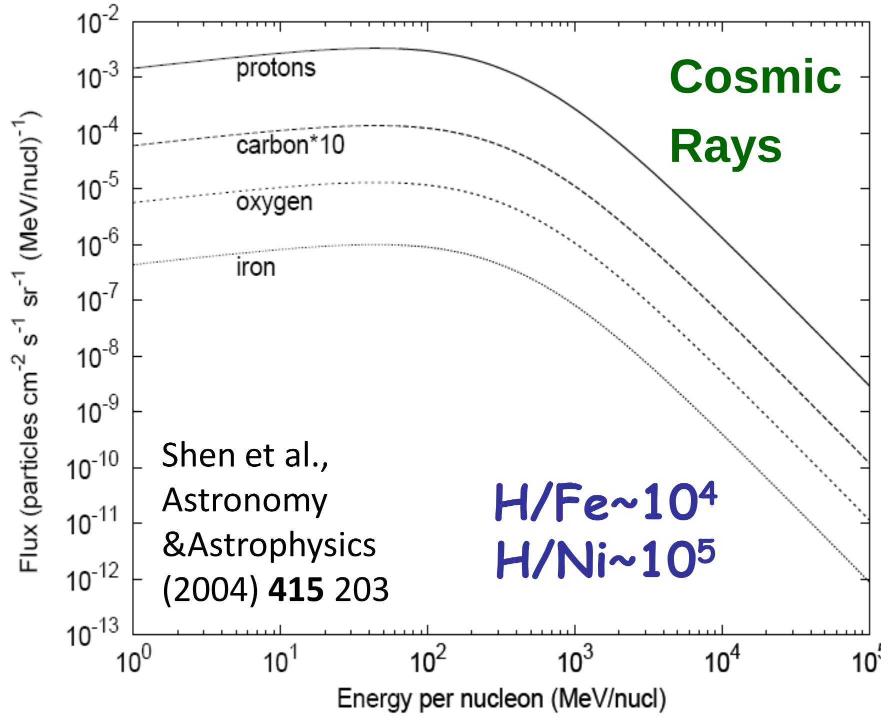
  - Li, Be, B, neutrons (formed by spallation)

  - pions, kaons, mesons, positrons and γ rays

Thanks to Enio

Concerning heavy ions in space:

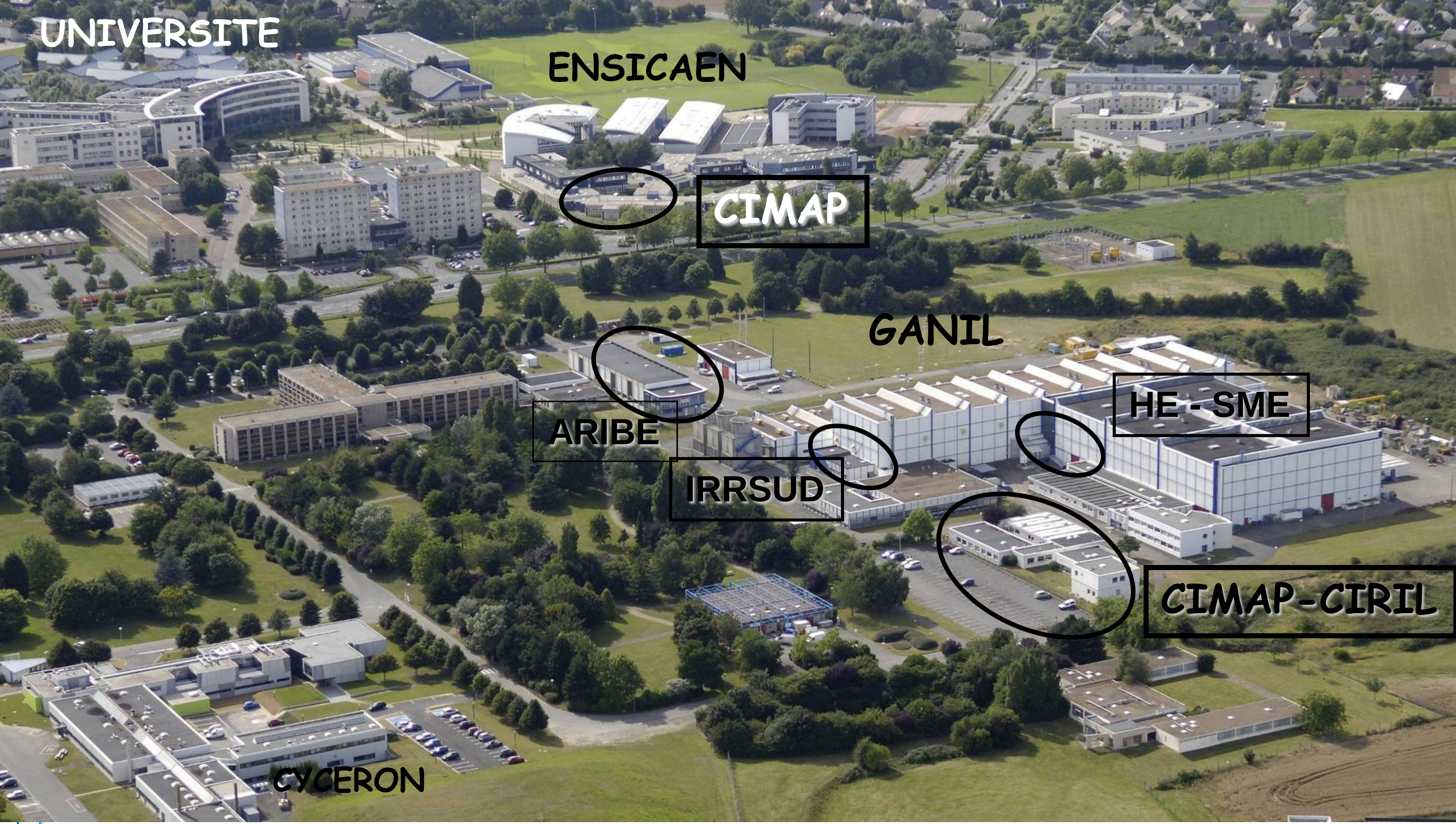




Heavy multiply charged Ions:

- Large electronic energy loss S_e
- Scaling laws: S_e^n with n ≈ ½,1,$^3/_2$,**2**, ... 4)
- Unexplained findings (gas phase CO in dense clouds...), few data
- Astrochemistry: origin of CO_2 and H_2SO_4 on Europa, implantation.
- Shorter time for experiments…

Caen: a big accelerator of particles, GANIL



Du carbone à l'uranium, de l'eV au GeV

From Carbon to Uranium, from eV to GeV

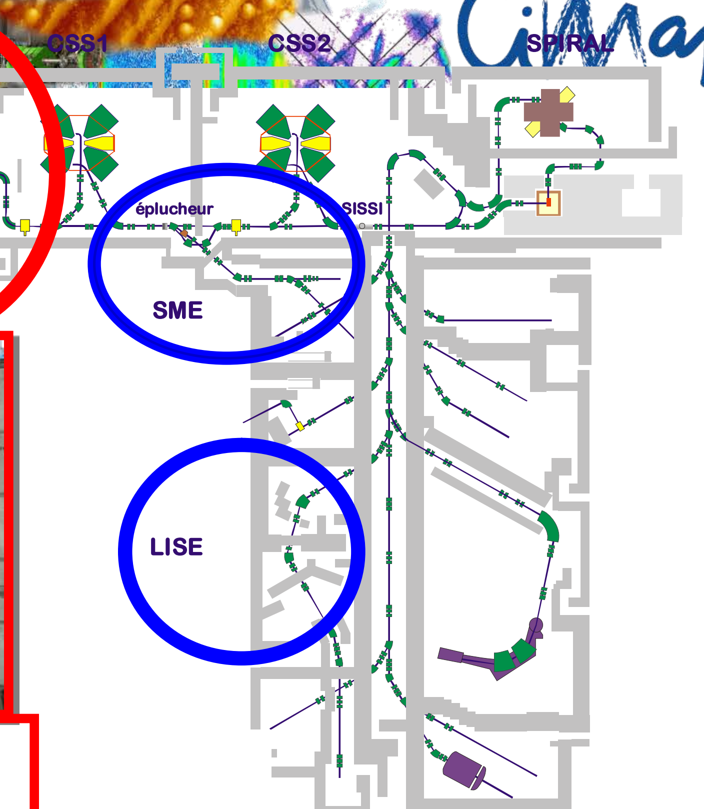
Centre de Recherch

nom

GANIL

CIMAP

HE, SME, IRRSUD



+ARIBE low energy

multiply charged ions

He, C, O, S, Ar, Xe:

q keV

IRRSUD

O, Ni, Xe, Ta, Pb:

0.5 to 1 A MeV

High Energy: LISE

Fe, Ni: 70 A MeV

Medium Energy: SME

O, Fe, Ni, Kr: 5-13 A MeV

3 GeV for iron ion!

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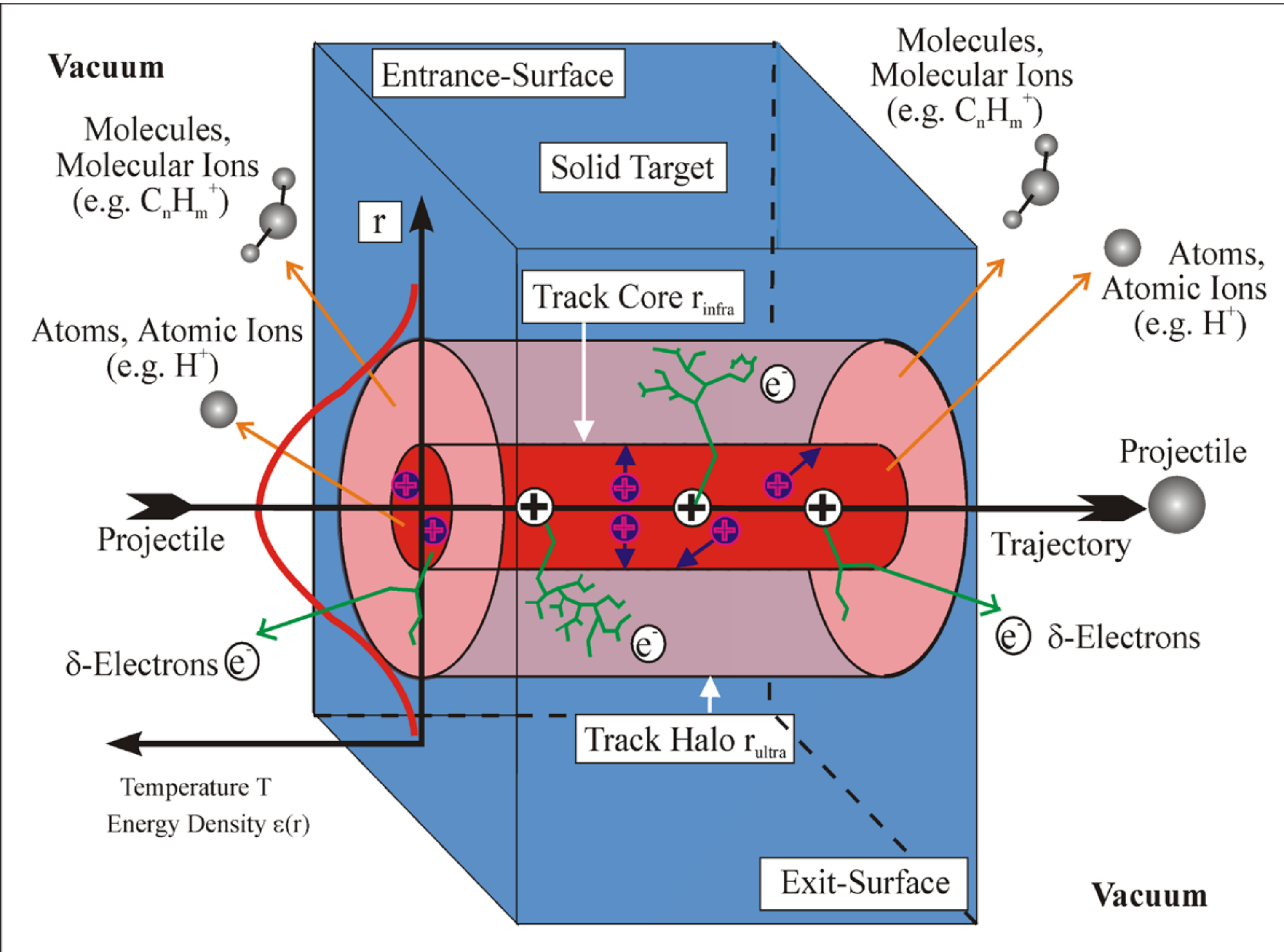
ions in condensed matter: nuclear tracks



Fast process
10^{-15}s

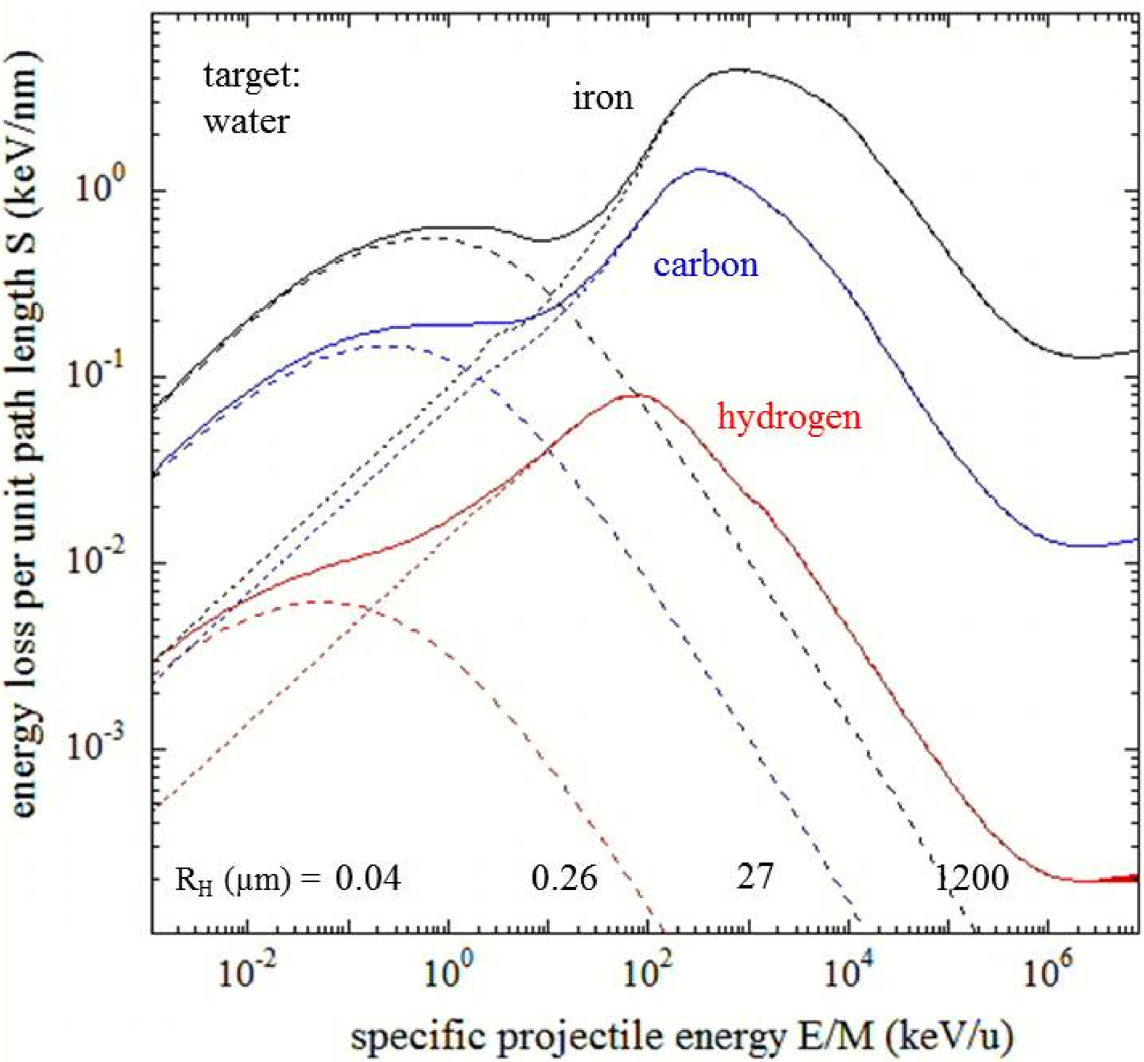
1-30 MeV/µm
(1-30 KeV/nm)
V_e: 0 to $2V_p$

-Radicals

20000 K for
Picoseconde

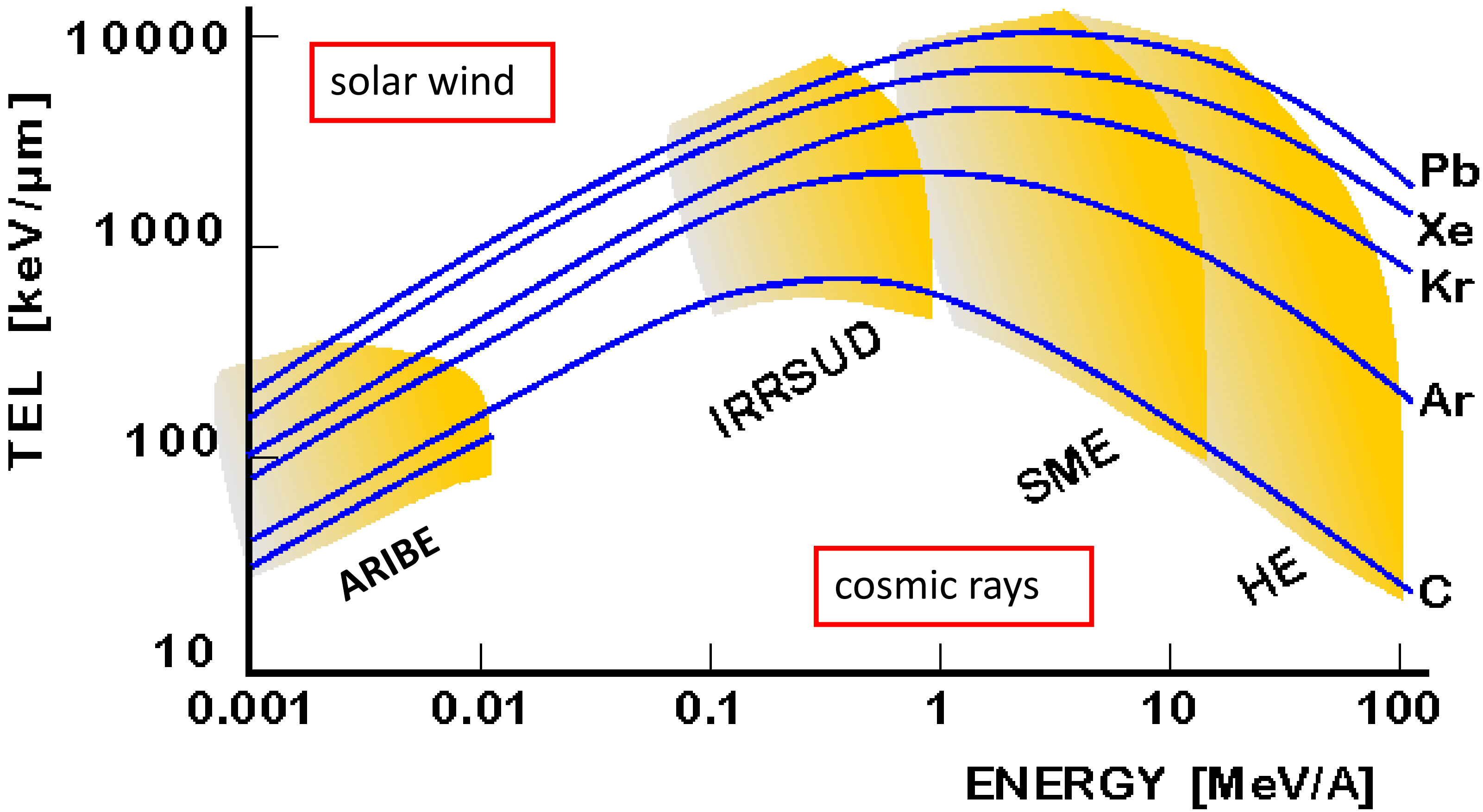
Ysput :
10^4-10^5

For the incoming projectile:
The stopping power dE/dx :
Energy loss per lenght unit



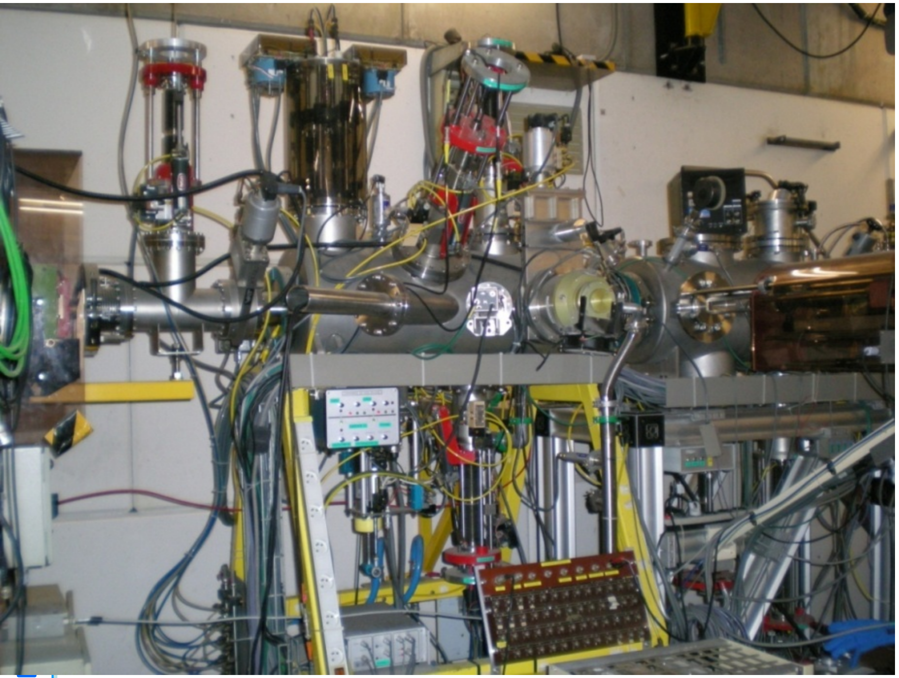
Projectile	Se (keV/nm)
$^{58}Ni^{13+}$	3.0
$^{58}Ni^{11+}$	2.9
$^{64}Ni^{24+}$	2.0
$^{20}Ne^{6+}$	0.92
$^{16}O^{2+}$	0.79
$^{16}O^{5+}$	0.67

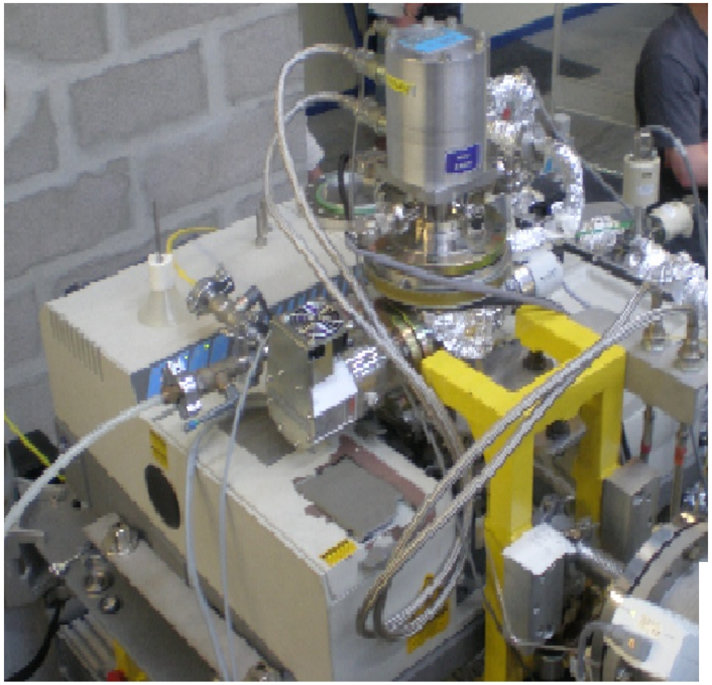
H^{+}(100keV) S_e=0,08 KeV/nm



S_e: 3 orders of magnitude

experimental set-up CASIMIR:
FTIR of condensed gases at 14 K





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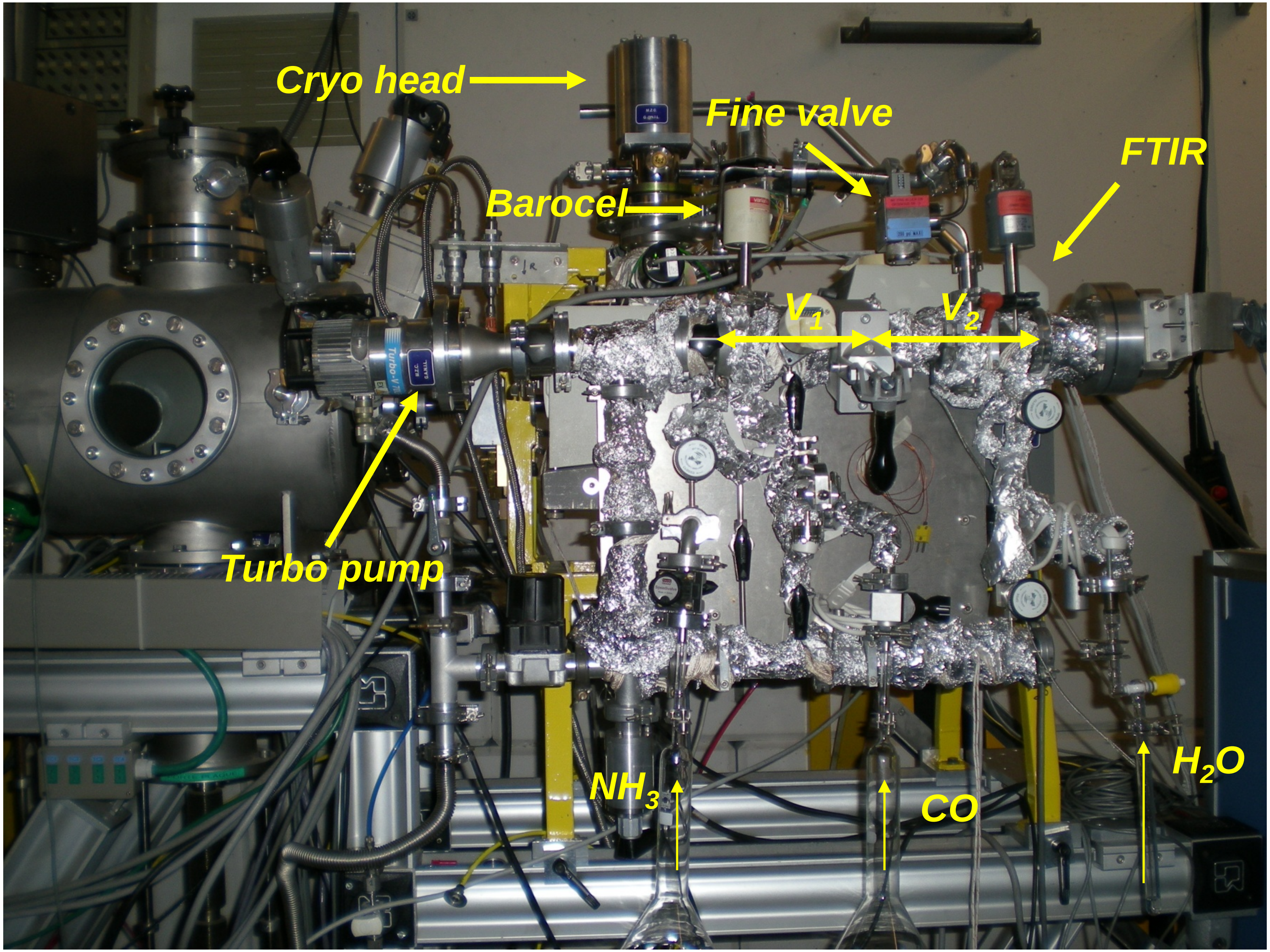
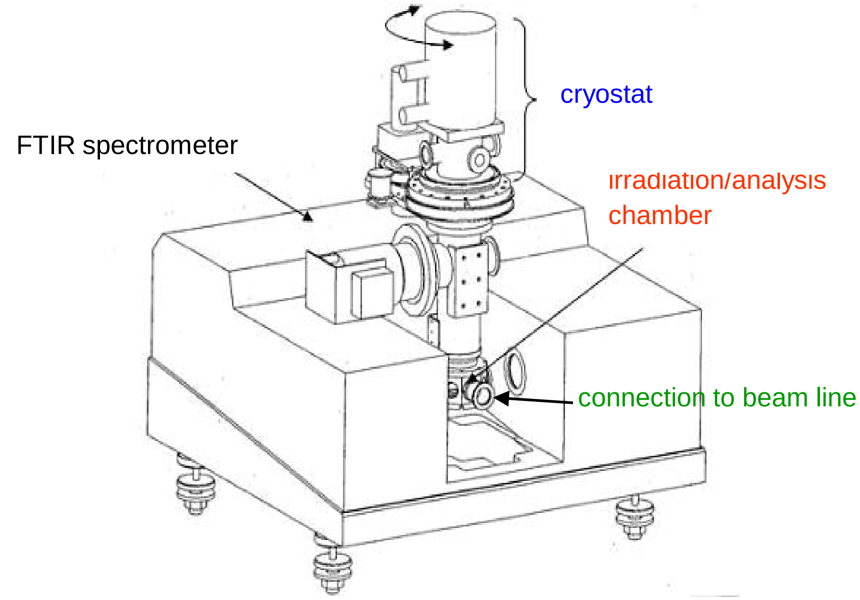
the "gas mixing and deposition machine"



Experimental details



Pressure in irradiation chamber

~2x10^{-8} mbar (14 K)

Substrate

CsI, ZnSe windows

Temperature

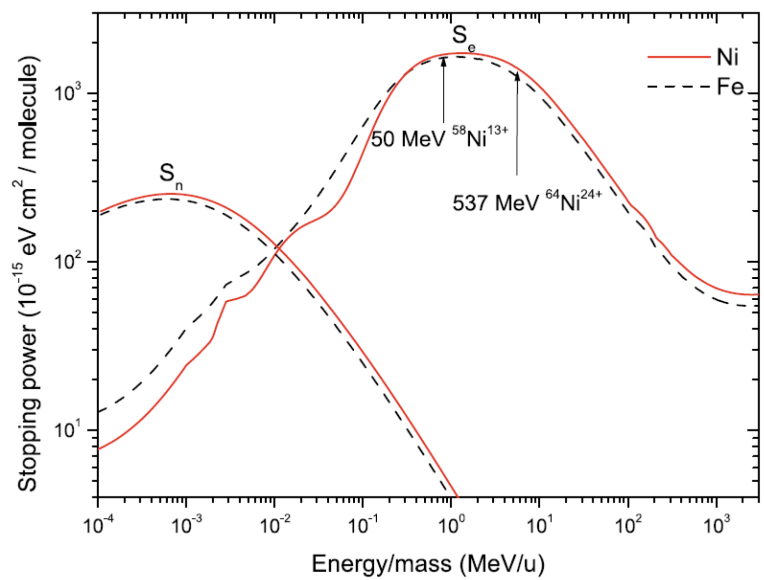
13 K < **T** < 300 K

Samples (ices)

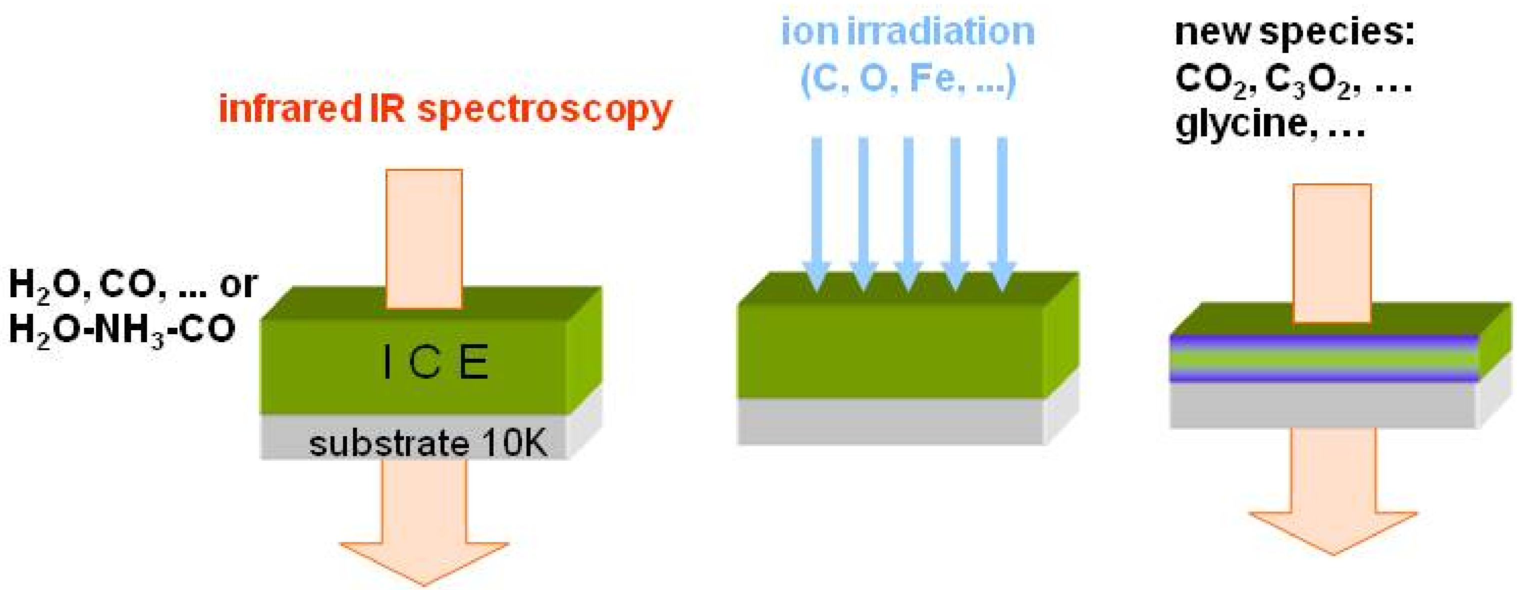
- in situ gas deposition
- thickness ~0.1 - 2 μm (10^{17}-10^{18} molecules/cm^2)
- ion penetration depth > ice thickness (HE exp.)
- ion implantation (Low E exp.)

Ion beam (Grand Accélérateur National d`Ions Lourds, Caen, France)

- 50 MeV $^{58}Ni^{13+}$, 537 MeV $^{64}Ni^{24+}$
- flux ~10^9 ion/cm^2 s
- fluence upto 2x10^{13} ion/cm^2 (typically 4 hours)



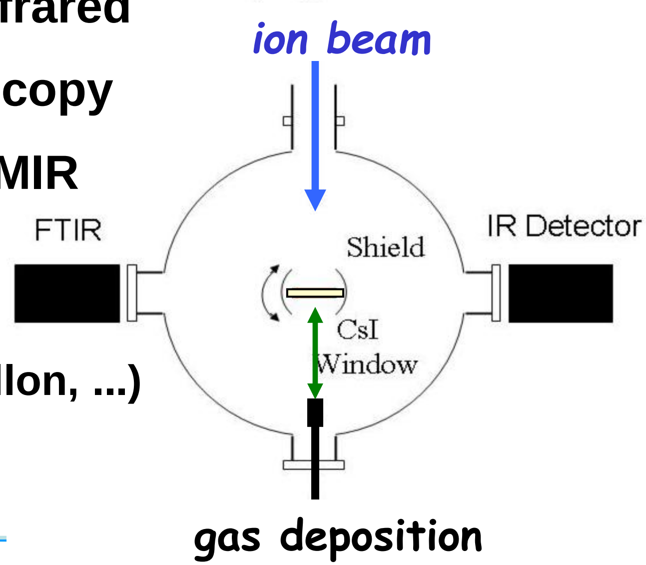
Centre de Recherche ...ons, les Matériaux et la Photonique

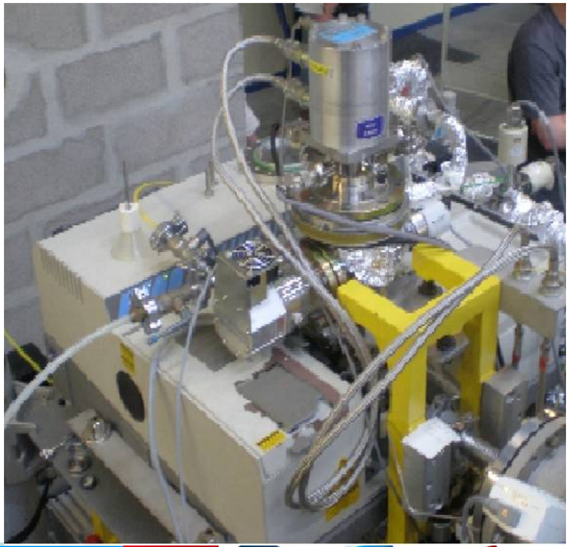


Fourier Transform Infrared Absorption Spectroscopy

FTIR @CIMAP: CASIMIR

(E. Balanzat, J.M. Ramillon, ...)

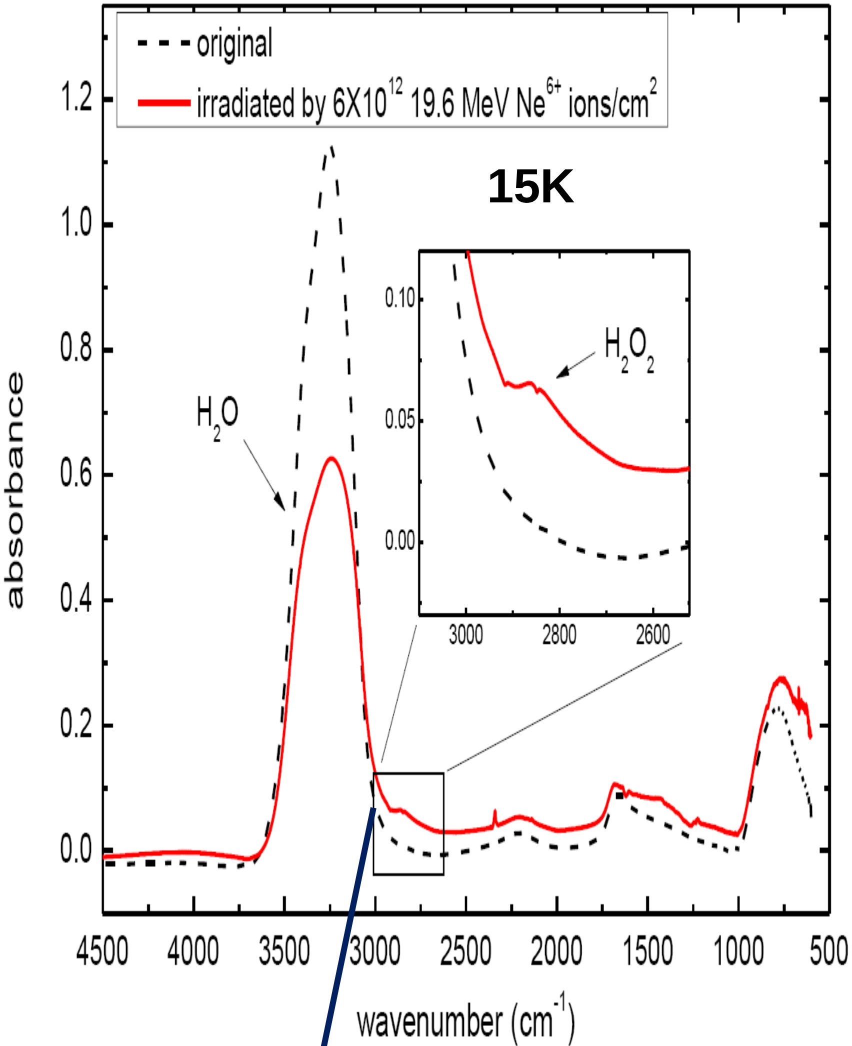




Water ice:
Compaction
and
Amorphization

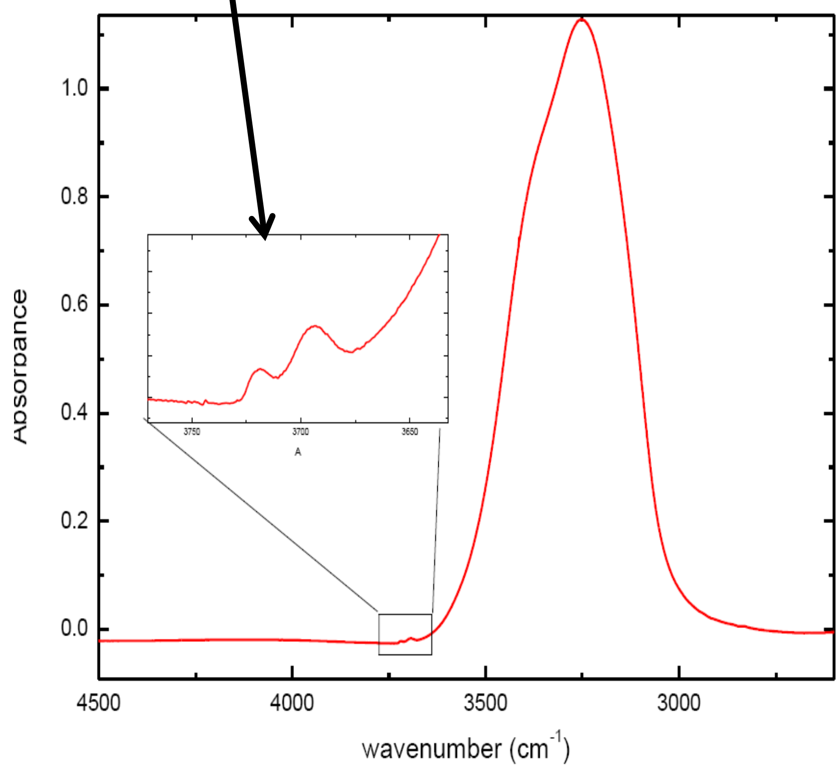
The most abundant molecule in interstellar ices:

Water H_2O



Irradiation of H_2O ice: formation of H_2O_2

Porosity: OH dangling bonds



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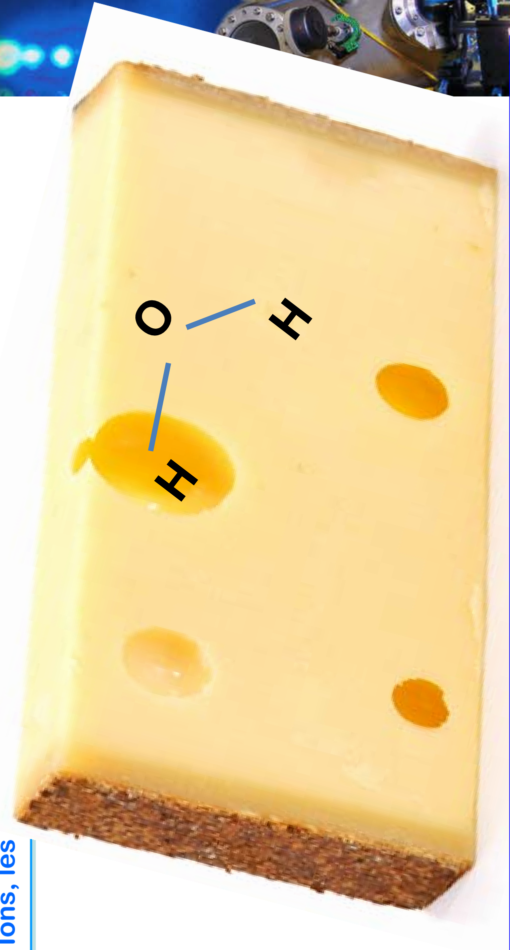
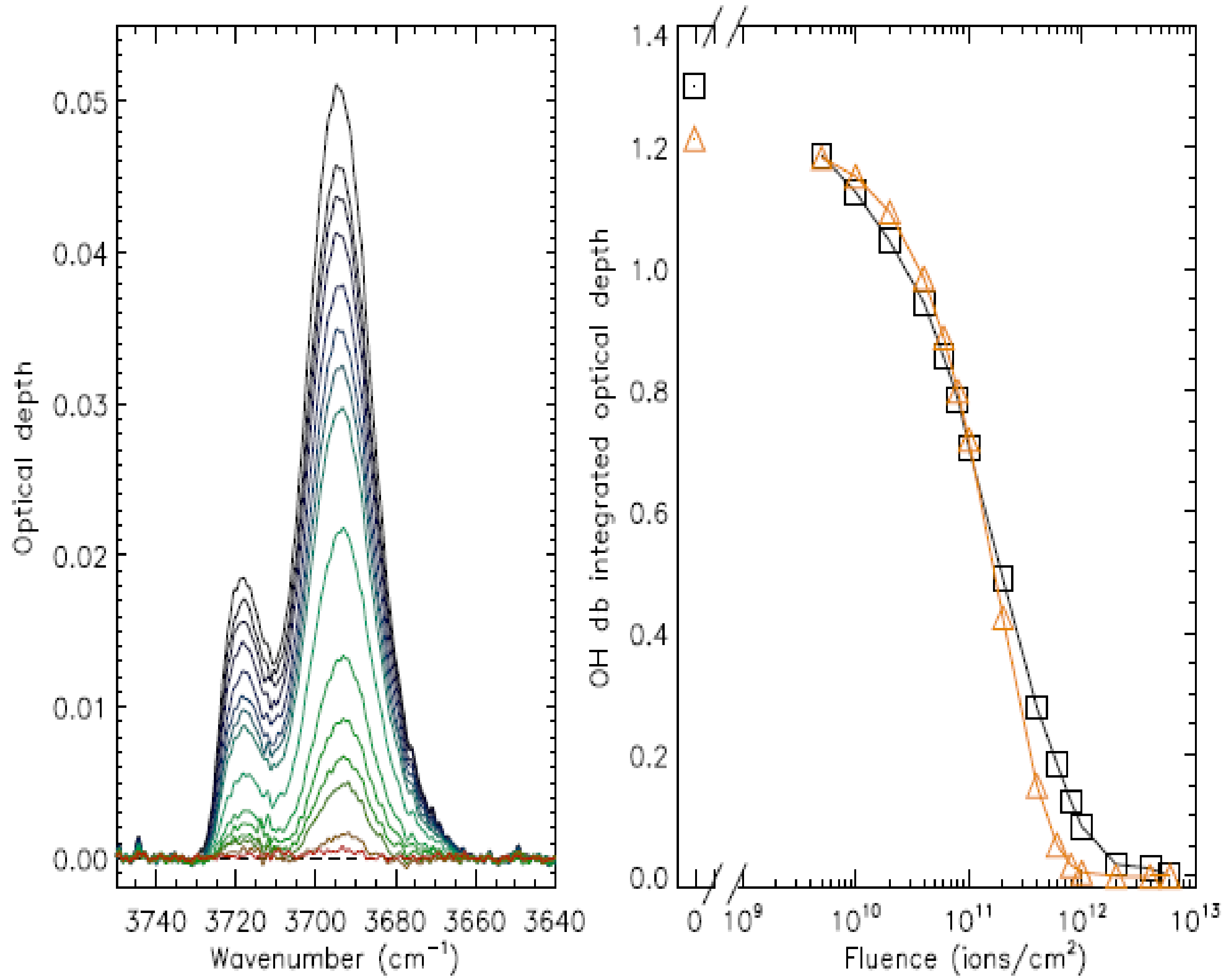
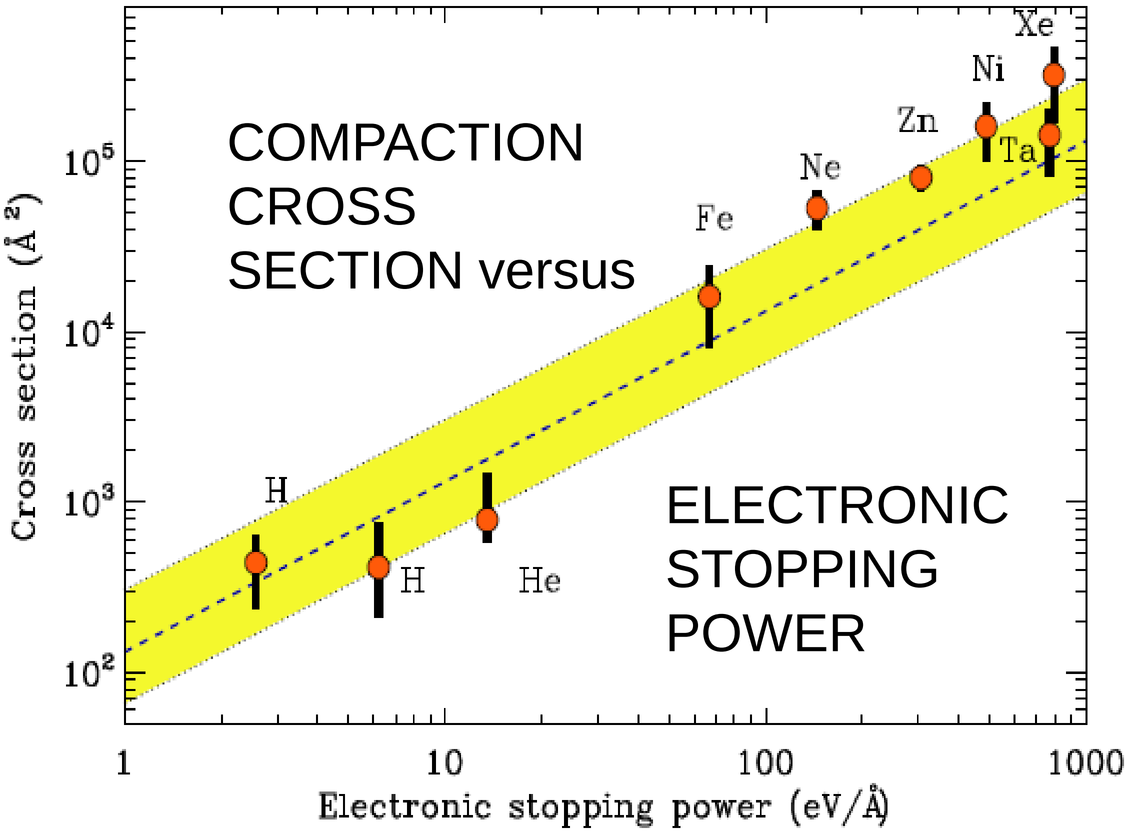




compaction "dose": 1 eV/molecule



$\sigma_c = A\, S_e^{\,n}$ with
n=1,0±0,2

$t_{comp} = 1 \times 10^5$ to 2×10^6 years

small compared
to cloud lifetimes

Indeed **no**
OH dangling bonds
observed by
ISO in ISM

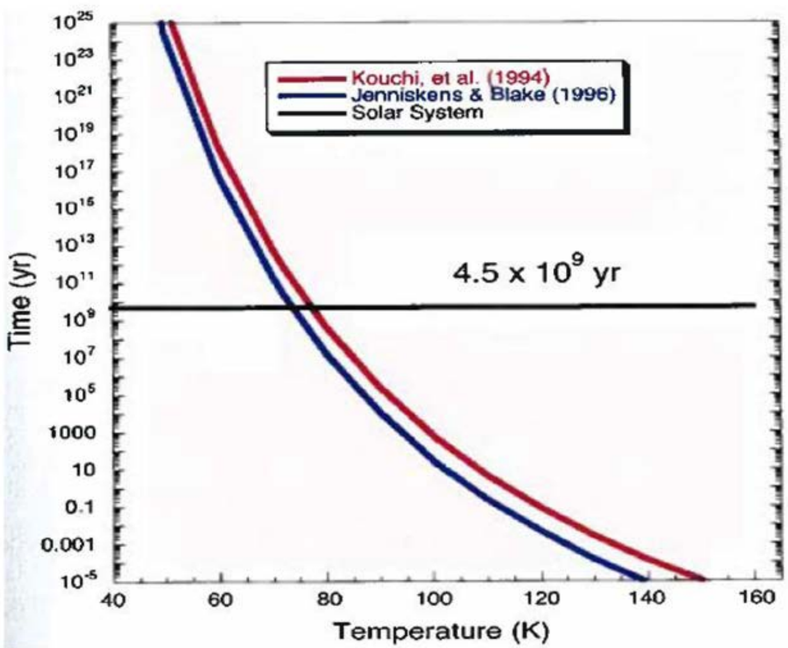
Compaction of Water Ice by Cosmic Rays: Experiment 2012 GANIL-LISE

E. Dartois, J.J. Ding, A.L.F. de Barros, P. Boduch, R. Brunetto, M. Chabot, A. Domaracka, M. Godard, X.Y. Lv, C.F. Mejia Guaman, T. Pino, H. Rothard, E.F. da Silveira, J.C. Thomas

Swift heavy ion irradiation of water ice at MeV to GeV energies: approaching true cosmic ray compaction

Astronomy & Astrophysics 557 (2013) A97

Crystal versus amorphous ice: a competition



Mastrapa et al, 2013

$$f = A_c \times f_c + A_a \times f_a$$

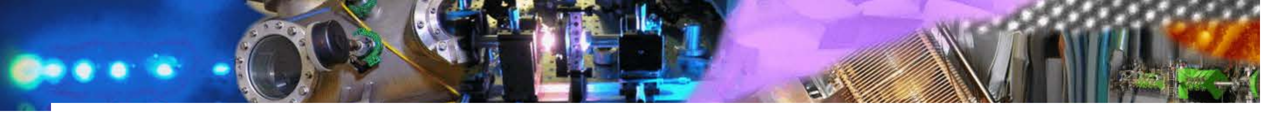
Thermal induced transition:

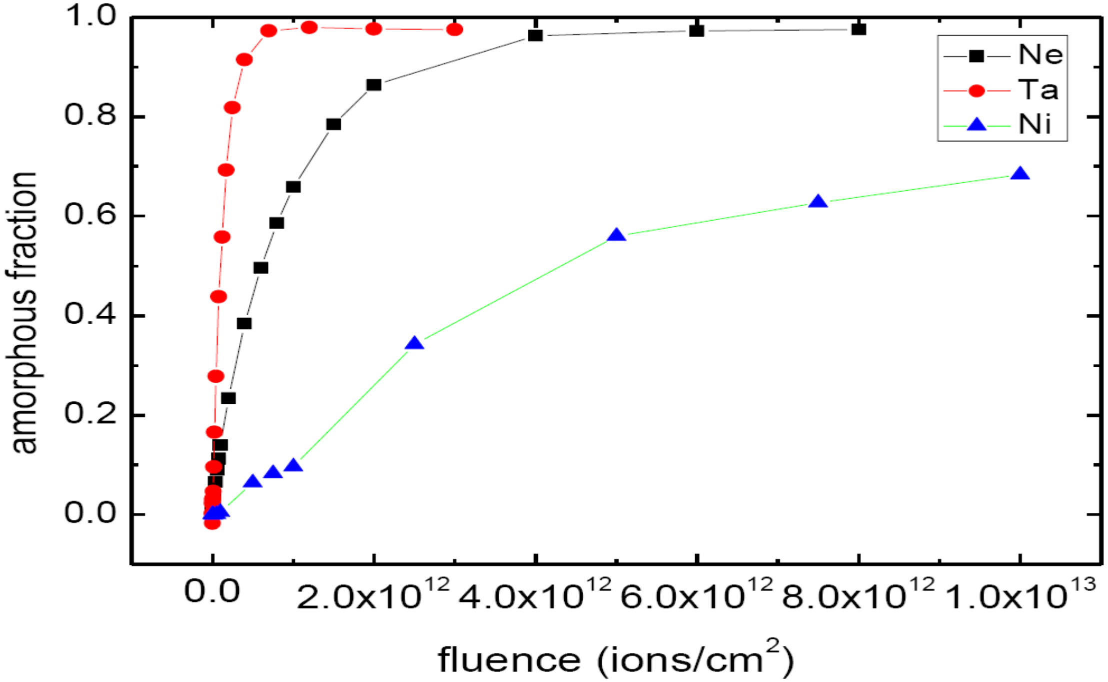
- At 100K amorphous ice converted in crystal in about 10^3 years.

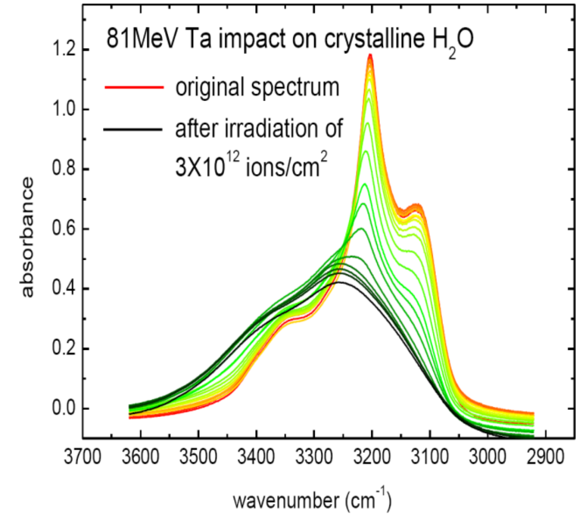
Irradiation : it induces amorphization.

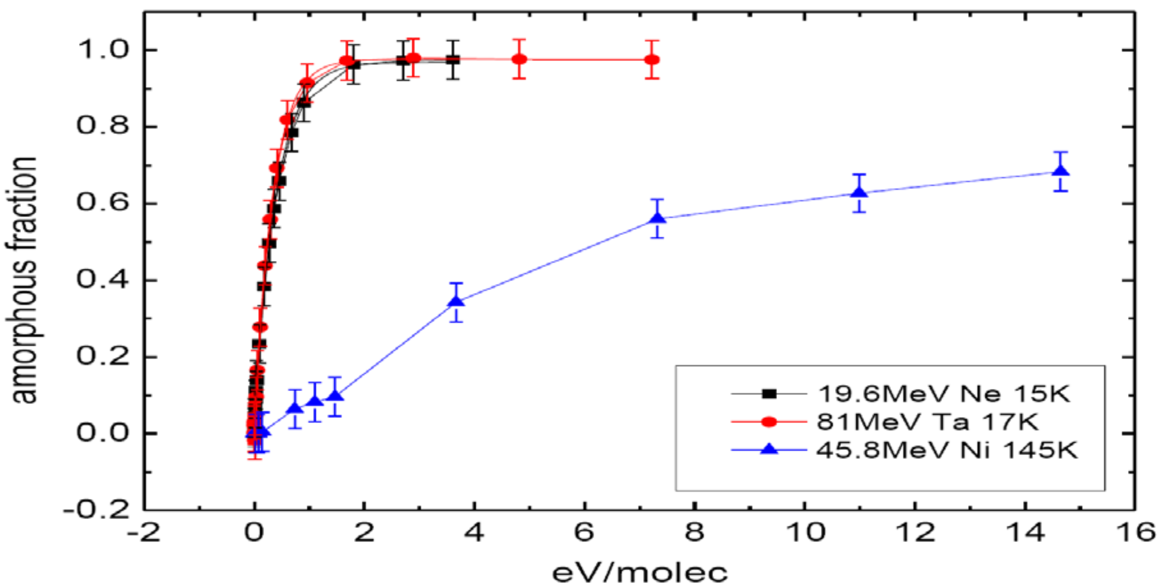
Table3-2: Ions used for irradiation, their electronic stopping power S_e, their nuclear stopping power S_n, and the irradiation temperature.

	Energy (MeV)	Irradiation temperature	S_e (eV/Å)	S_n (eV/Å)
Ne	19.6	15K	143	0.2
Ta	81	17K	757	12.7
Ni	46	145K	460	1.4









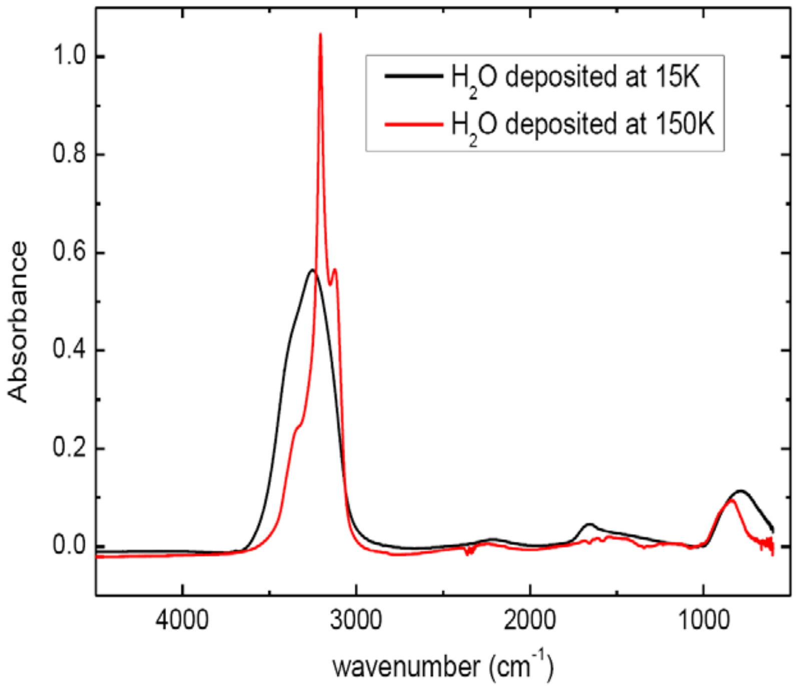
Local dose: the key parameter!

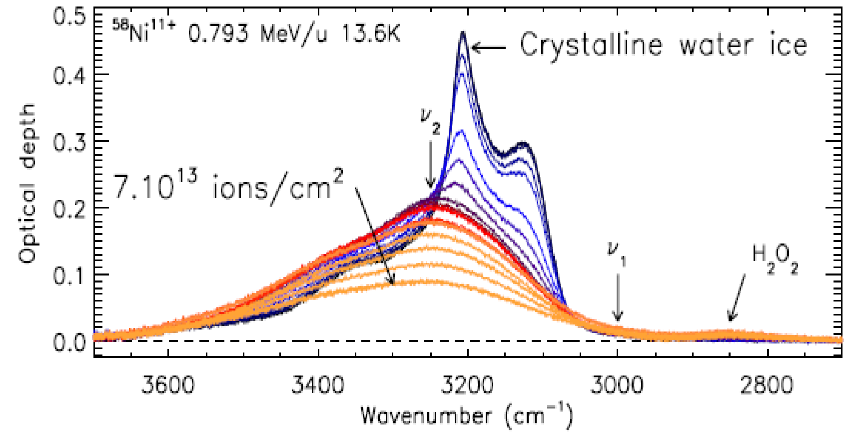
95% at 1,4 eV @15K

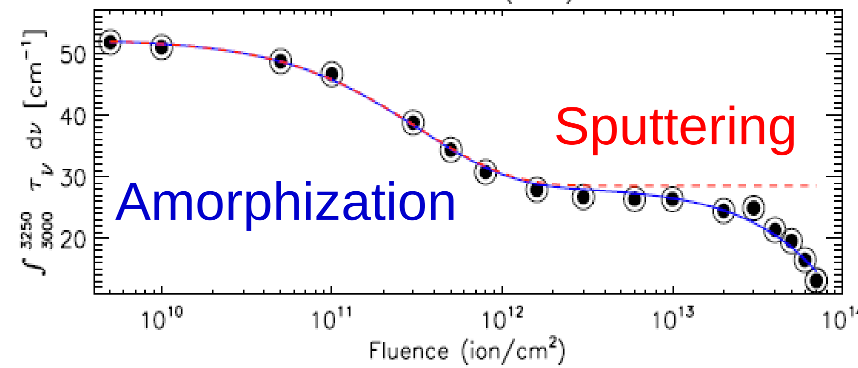
Around 3eV for 100%

At 145 K, much longer due to the thermal crystallization

Thesis JJ Ding







Total Amorphisation dose:
3 eV/molecule

Ion irradiation 3 times more efficient for compaction vs. amorphization
Water ice resilient to phase transition

End point:
amorphous compact ice

E. Dartois, B. Augé, P. Boduch, R. Brunetto, M. Chabot, A. Domaracka, J.J. Ding, O. Kamalou, X.Y .Lv, H. Rothard, E.F. da Silveira, J.C. Thomas
Heavy ion irradiation of crystalline water ice -Cosmic ray amorphization cross-section and sputtering yield
Astronomy & Astrophysics 576 (2015) A126

Carbon Oxide CO,

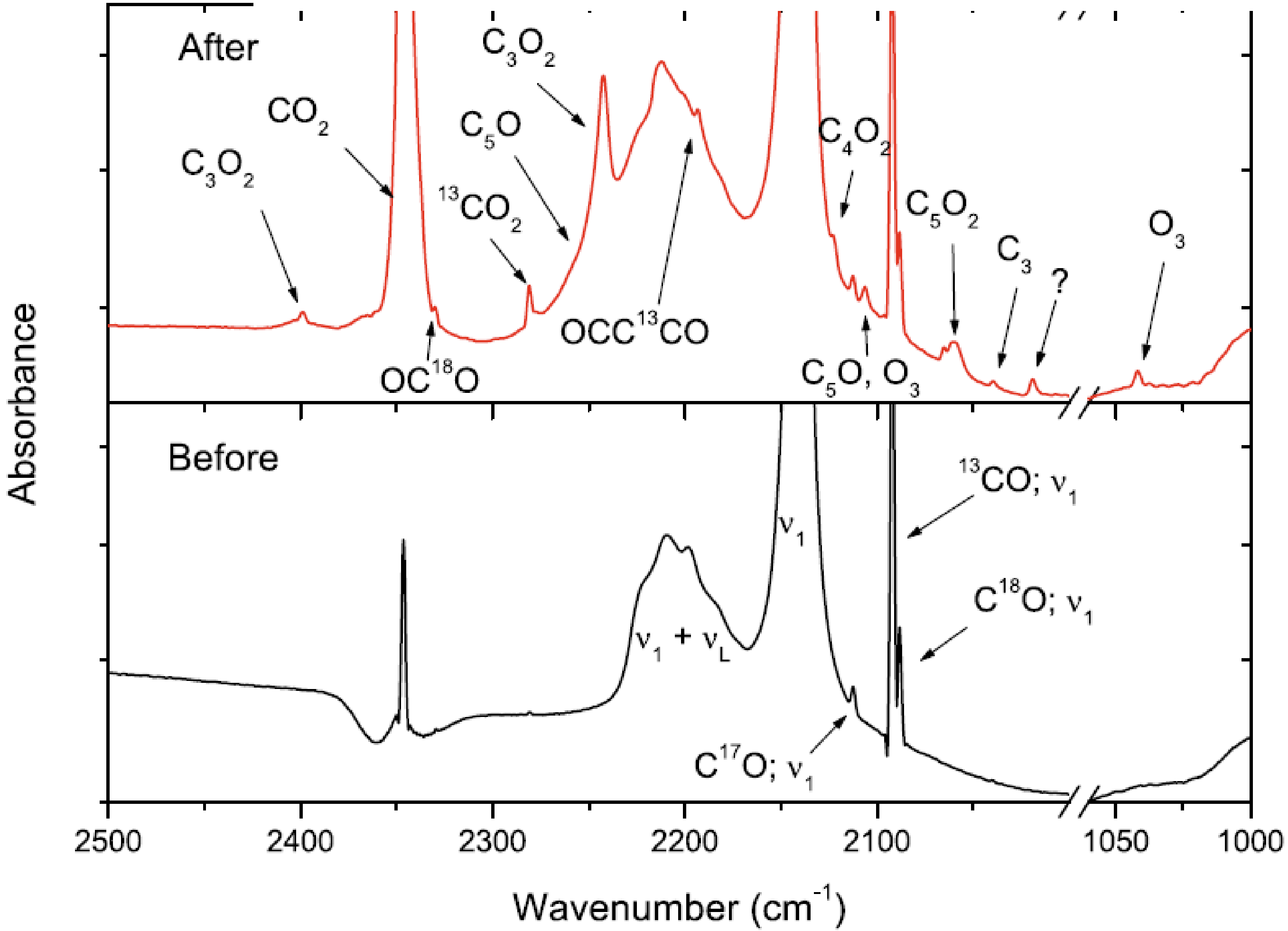
dense molecular clouds,

and cosmic rays.

The starting point: the Eduardo's thesis, cotutella with Enio.

Second example: CO ice

(the second most abundant molecule in space ices after H_2O)



Infrared spectrum of CO ice before and after 50 MeV $^{58}Ni^{11+}$ irradiation with a fluence of 1.0×10^{12} cm^{-2}.

CO destruction

Production of CO_2, O_3, C_x and C_xO_y

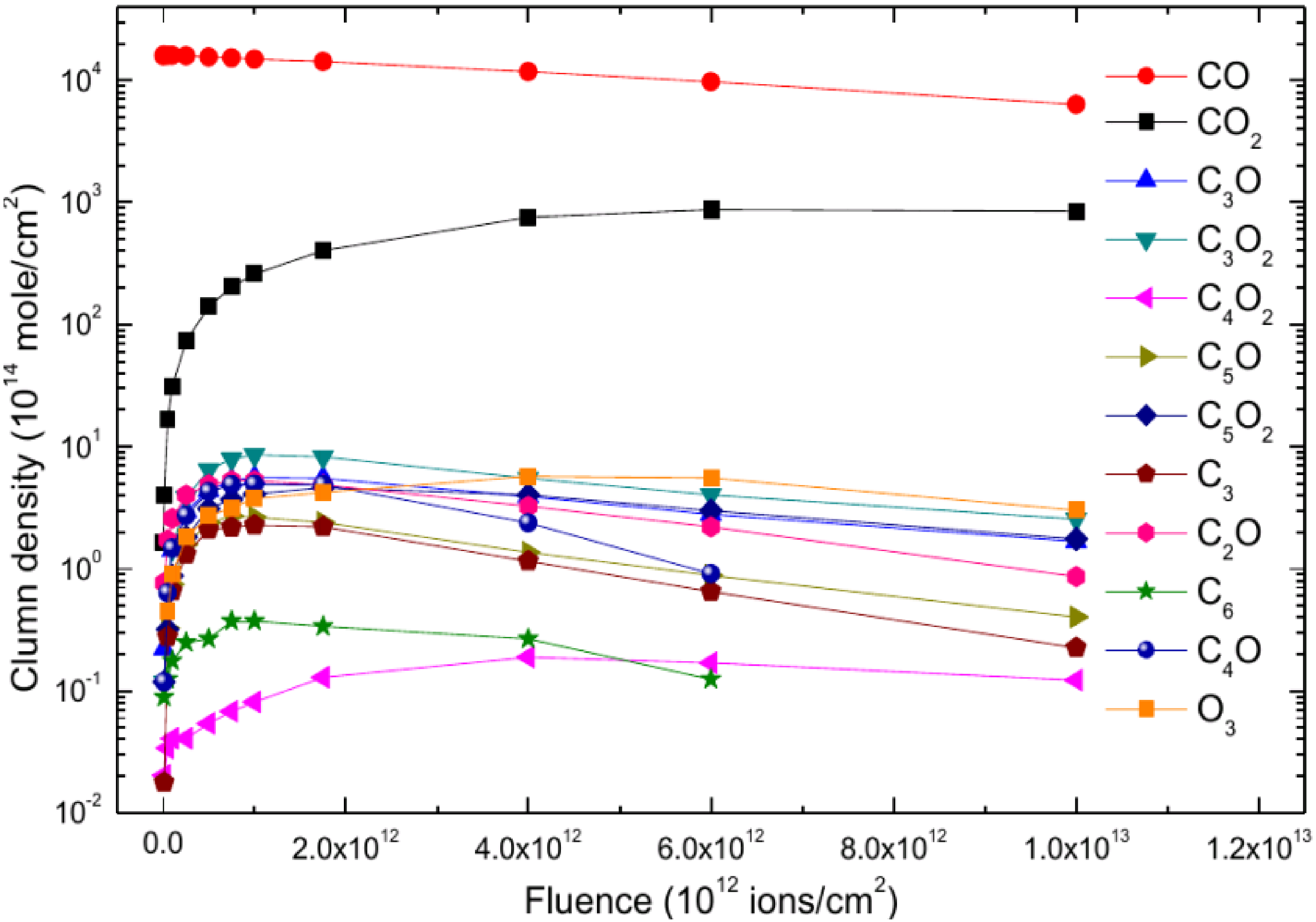
Main « observable » daugther: CO_2

ion	E_0	S_e	S_n	P_d	ℓ_0	N_0
$^{16}O^{7+}$	220	94	0.04	812	0.41	7.16
$^{16}O^{5+}$	16	385	0.4	25	0.39	6.78
$^{16}O^{2+}$	6	452	1.0	11	0.53	9.22
$^{64}Ni^{24+}$	537	1136	0.7	226	0.39	6.88
$^{70}Zn^{26+}$	606	1255	0.7	228	0.74	12.86
$^{56}Fe^{24+}$	270	1318	1.0	112	0.24	4.15
$^{58}Ni^{11+}$	46	1690	5.5	29	0.85	14.8
$^{58}Ni^{13+}$	52	1706	4.9	31	0.54	9.45
$^{58}Ni^{13+}$	52	1706	4.9	31	0.66	11.5
$^{86}Kr^{31+}$	774	1731	1.1	233	0.05	0.83

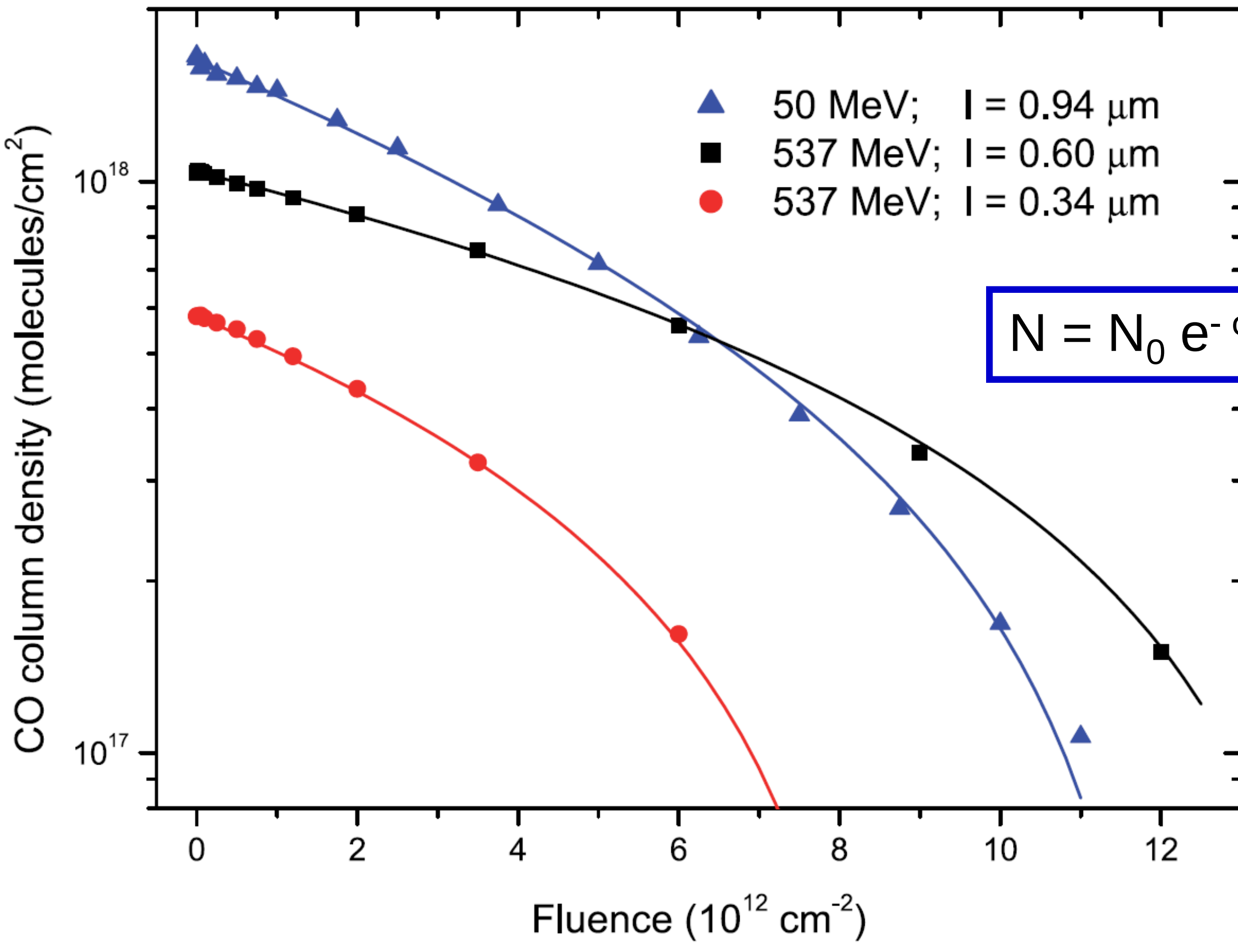
Sputtering yield , destruction and formation cross sections…

… as a function of Se, the electronic stopping power

CO ice: formation of new molecular species



CO ice: disappearence of CO Molecules during Nickel Ion Irradiation:



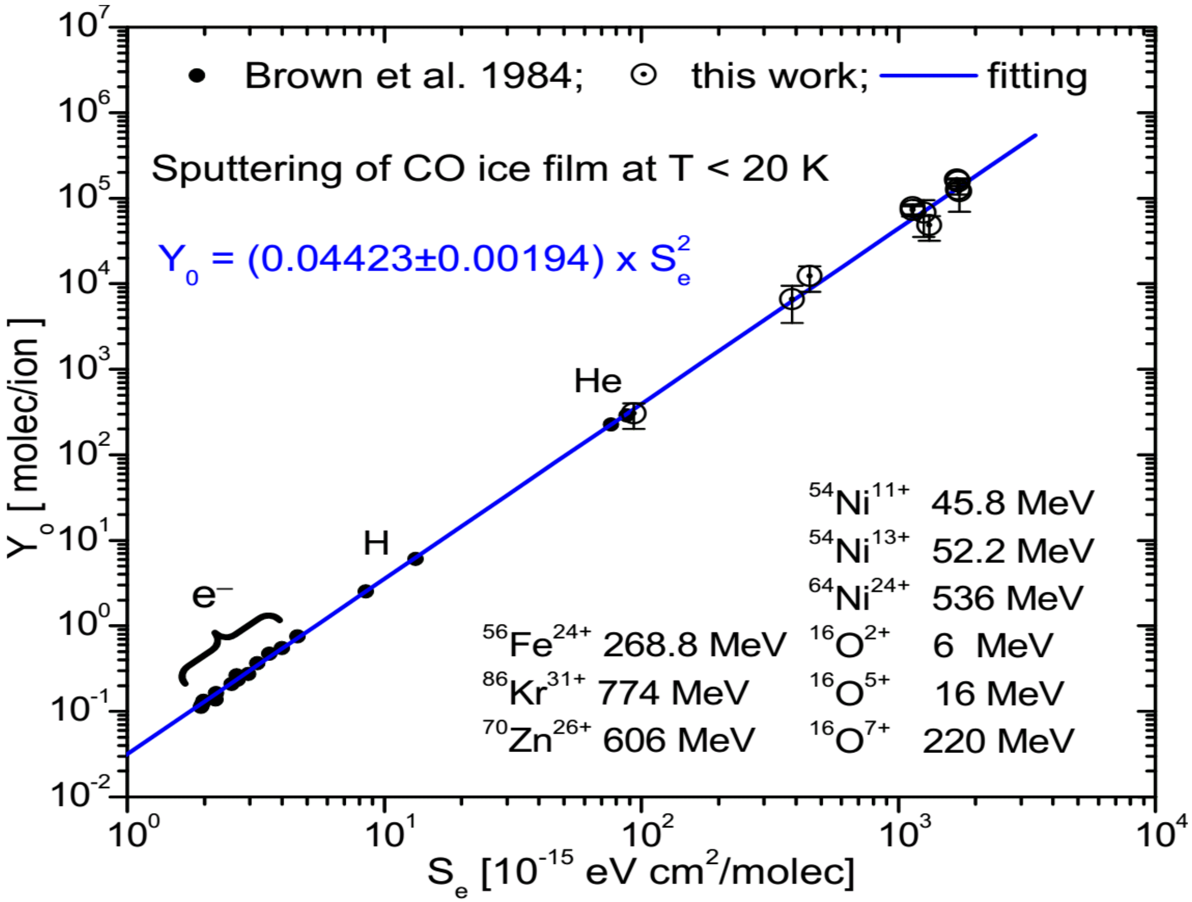
$$N = N_0 e^{-\sigma_d F} - (Y/\sigma_d)(1 - e^{-\sigma_d F})$$

deduced quantities:

Destruction Cross Section σ_d

Sputtering Yield Y

CO ice: Ion induced Sputtering Yield



$Y \sim S_e^2$

$S_e \sim Z_P^2$

$Y \sim S_e^2$

$Y \sim Z_P^4$

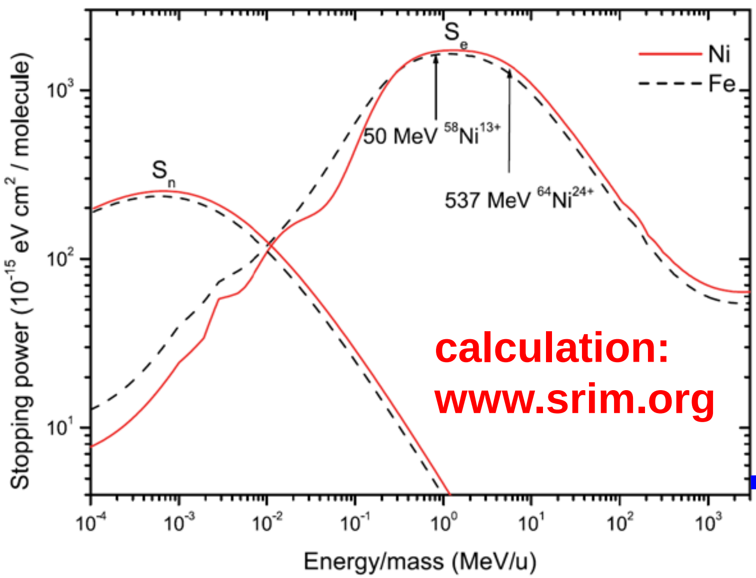
very strong dependence!

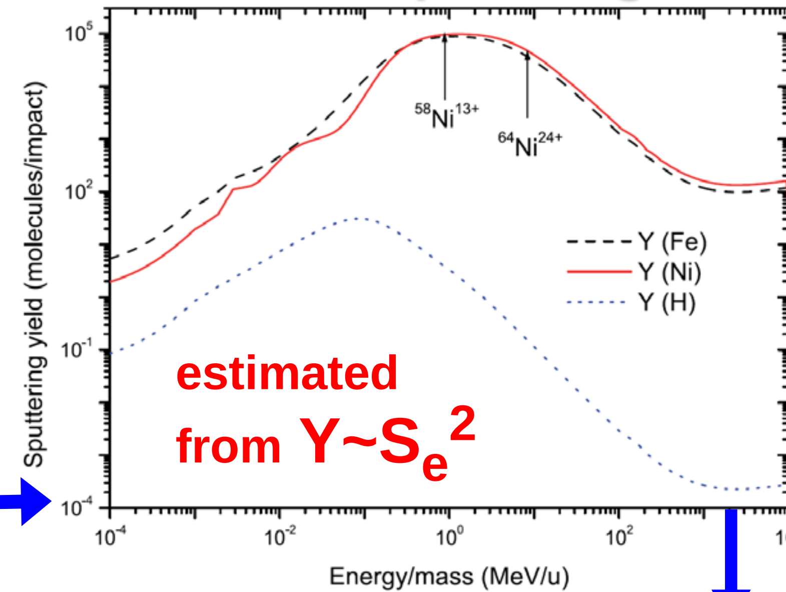
W.L. Brown, W.M. Augustyniak, K.J. Marcantonio, E.H. Simmons, J.W. Boring, R.E. Johnson, C.T. Reimann, Nucl. Instrum. Meth. B1 (1984) 307

E. Seperuelo Duarte, A. Domaracka, P. Boduch, H. Rothard, E. Dartois, E.F. da Silveira Astronomy & Astrophysics 512 (2010) A71

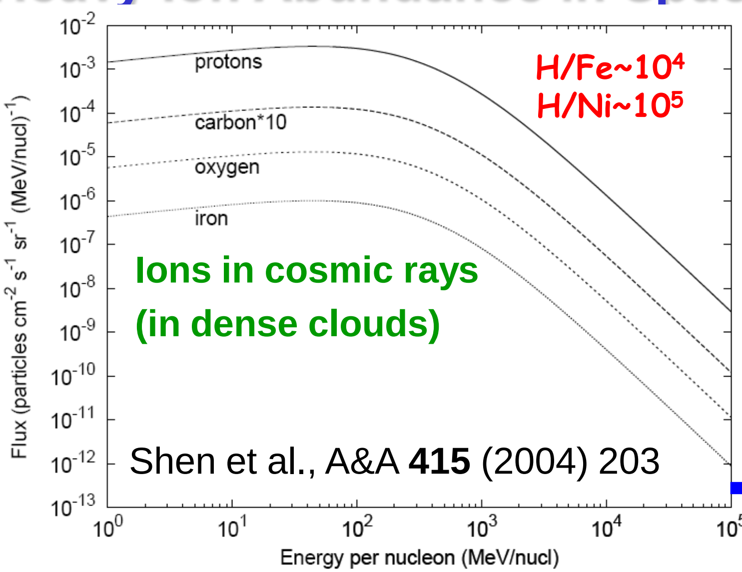
Electronic Energy Loss in CO

CO Sputtering Yield





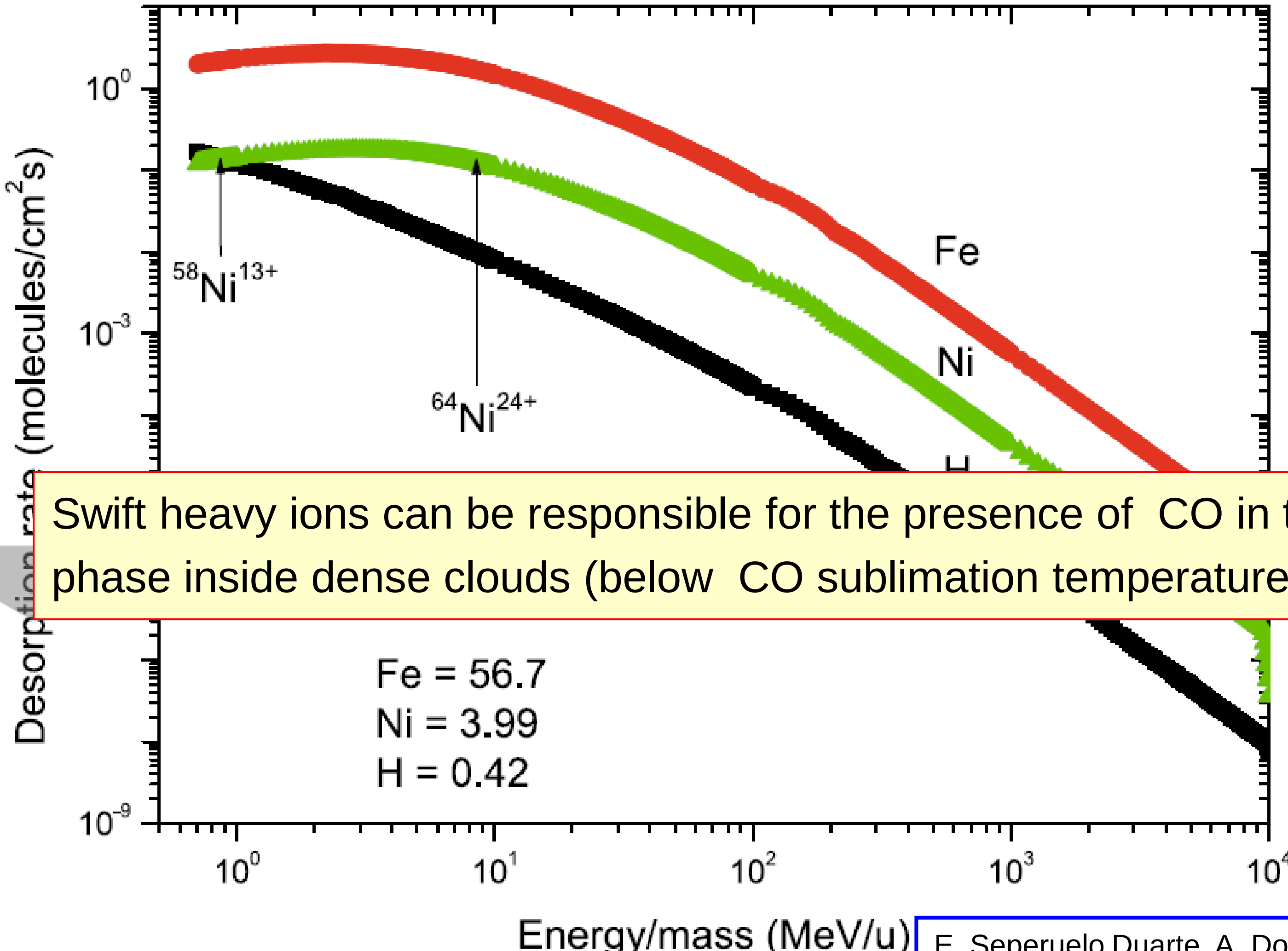
Heavy Ion Abundance in Space



astrophysical application:

presence of CO in the gas phase in “dense” (10^4–10^6 molecules cm^{-3}) molecular clouds **?**

Astrophysical implication

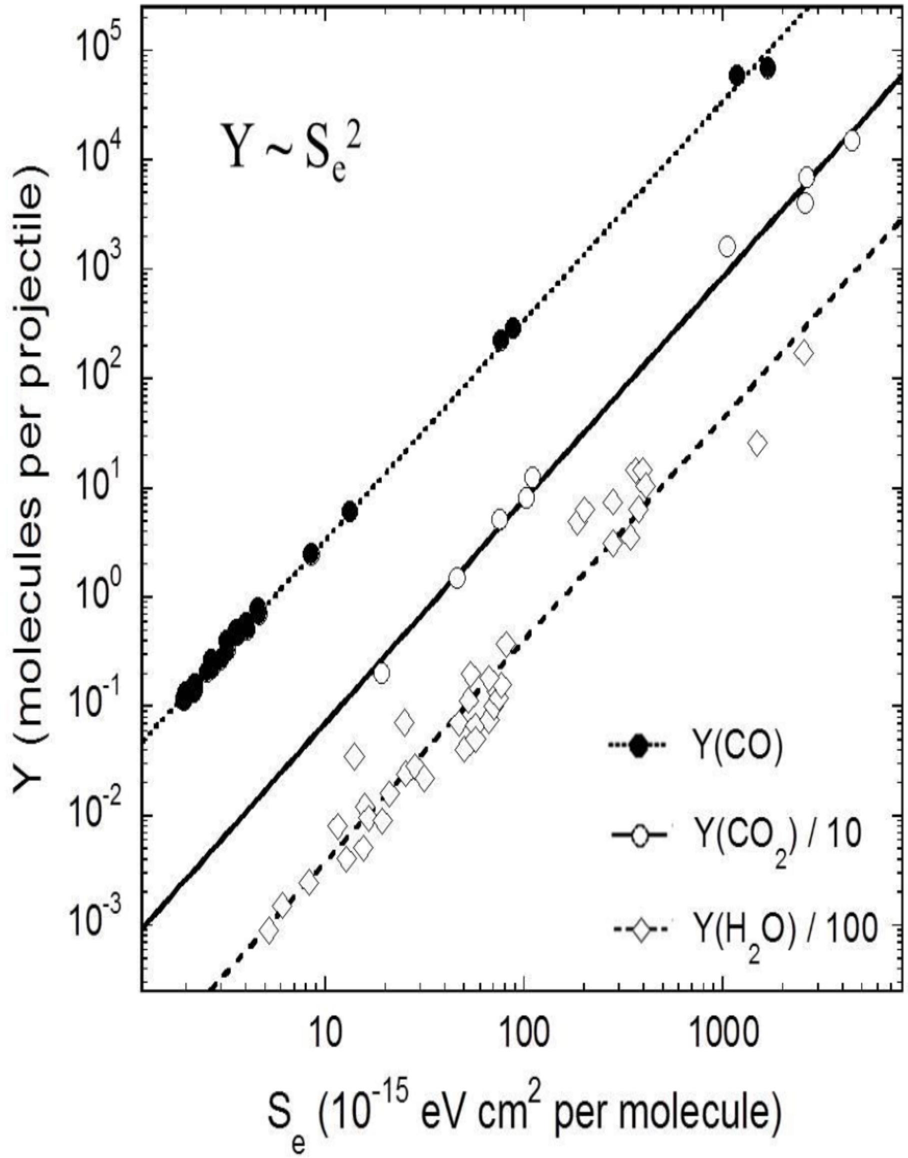


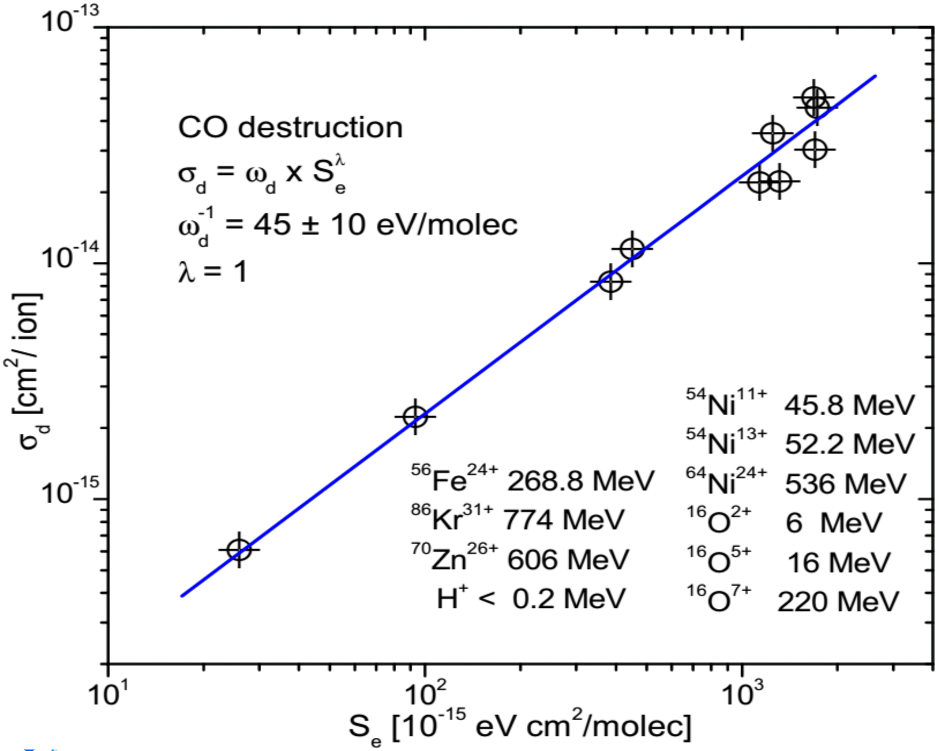
Swift heavy ions can be responsible for the presence of CO in the gas phase inside dense clouds (below CO sublimation temperature,10 K).

E. Seperuelo Duarte, A. Domaracka, P. Boduch, H. Rothard,E. Dartois, E.F. da Silveira
Laboratory simulation of heavy ion cosmic ray interaction with condensed CO
Astronomy & Astrophysics 512 (2010) A71

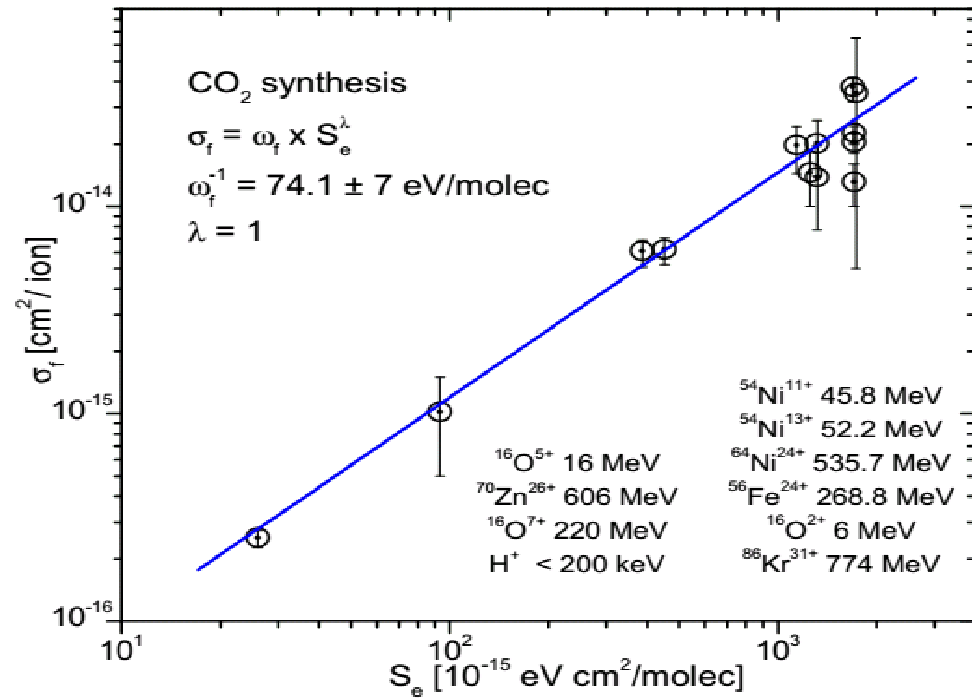
The same results for:

CO, CO_2 and H_2O





$\sigma_{d\,(CO)} \;\alpha\; S_e$



$\sigma_{f\,(CO_2)} \;\alpha\; S_e$

Destruction and formation

Formation proportional to destruction

CO ice-different projectiles: destruction/formation cross sections

Comparison with "other projectiles"

Molecules	Projectile	σ (10^{-15} cm^2)	Reference
CO	50 MeV Ni^{13+}	100	This work
destruction	537 MeV Ni^{24+}	30	This work
	200 keV H^+	0.28	Loeffler et al. (2005)
	10.2 eV photons	0.0003	Loeffler et al. (2005)
	>6 eV photons	<0.000001	Cottin et al. (2003)
	>6 eV photons	<0.00008	Gerakines et al. (1996)
CO_2	50 MeV Ni^{13+}	20	This work
formation	537 MeV Ni^{24+}	18	This work
	200 keV H^+	6	Loeffler et al. (2005)
	10.2 eV photons	0.017	Loeffler et al. (2005)
	>6 eV photons	0.000013	Gerakines et al. (1996)

Astron.Astrophys. **512** (2010) A71

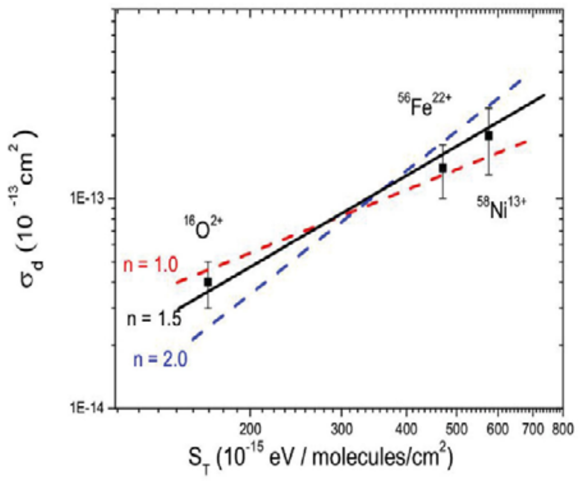


Figure 6. The dependence of the HCOOH destruction cross-section on the total stopping power. Data are for 6 MeV (O), 52 MeV (Ni; in preparation) and 267 MeV (Fe; the results of the current work). The lines correspond to the function $\sigma_d \sim S_e^n$, for $n = 3/2$ (solid line).

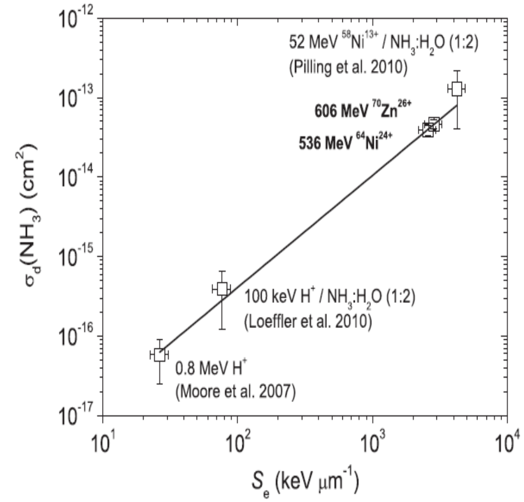


Figure 16. Destruction cross-section (σ_d) and stopping power (S_e) relationship The power law $\sigma_d(NH_3) \propto S_e^{1.4\pm0.1}$ is derived from $\sigma_d(NH_3)$ obtained in thi work and those compiled from the literature. See details in the text.

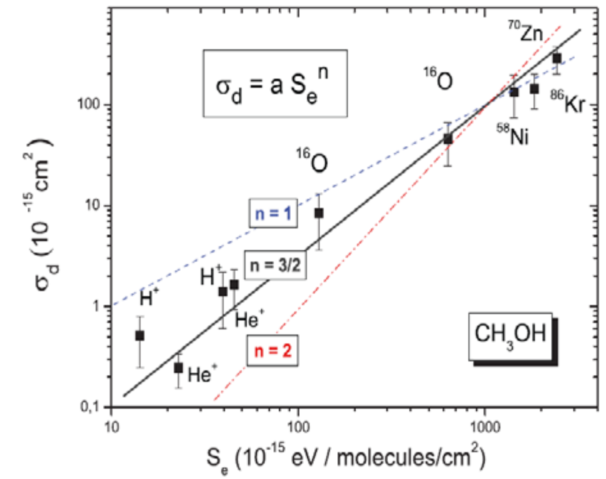


Figure 8. The dependence of CH_3OH destruction cross-section on the electronic stopping power. Data for 16- and 220-MeV O, Zn and Kr are results of the current work; Gerakines et al.(2001), Brunetto et al. (2005) and Baratta et al.(2002). The lines correspond to the function $\sigma_d \sim S_e^n$, for $n = 1$, 3/2 (solid line) and 2.

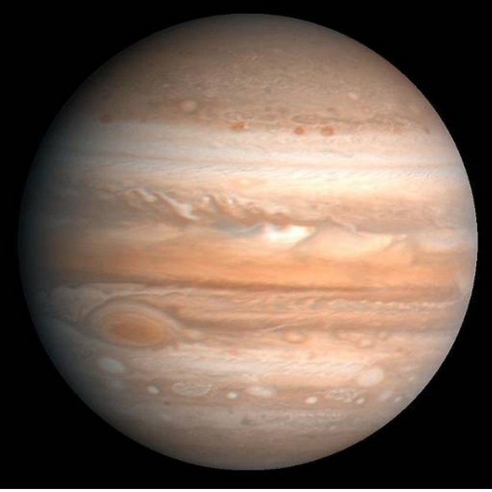
Diana P. P. Andrade et al(MNRAS 2013)	Vinicius Bordalo et al (Astro. Journal (2013)	Ana L, F, de Barros et al (MNRAS 2011)
n=1,5 for formic acid	n=1,4 for ammonia	n=1.5 for methanol

Conclusion: for the destruction, always between 1 and 1,5 for simple molecules

Galilean moons,

Jupiter’s magnetosphere,

sulfur cycles.



Jupiter, NASA's spacecraft *GALILEO*, and the Galilean Moons Io, Europa, Ganymede, Callisto

Io: SO_2 ice dominant

Europa, Callisto, Ganymede: H_2O ice dominant

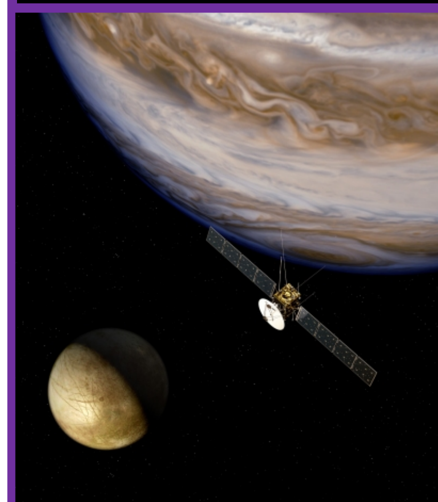
Europa: significant quantities of magnesium, sodium sulfate Na_2SO_4, carbonate hydrates

Other absorption features and prime candidates:

3.4 μm	(~2940 cm^{-1})	C-H
3.5 "	(~2857 cm^{-1})	H_2O_2
3.88 "	(~2580 cm^{-1})	S-H, H_2CO_3
4.05 "	(~2470 cm^{-1})	SO_2
4.25 "	(~2350 cm^{-1})	CO_2
4.57 "	(~2190 cm^{-1})	CN

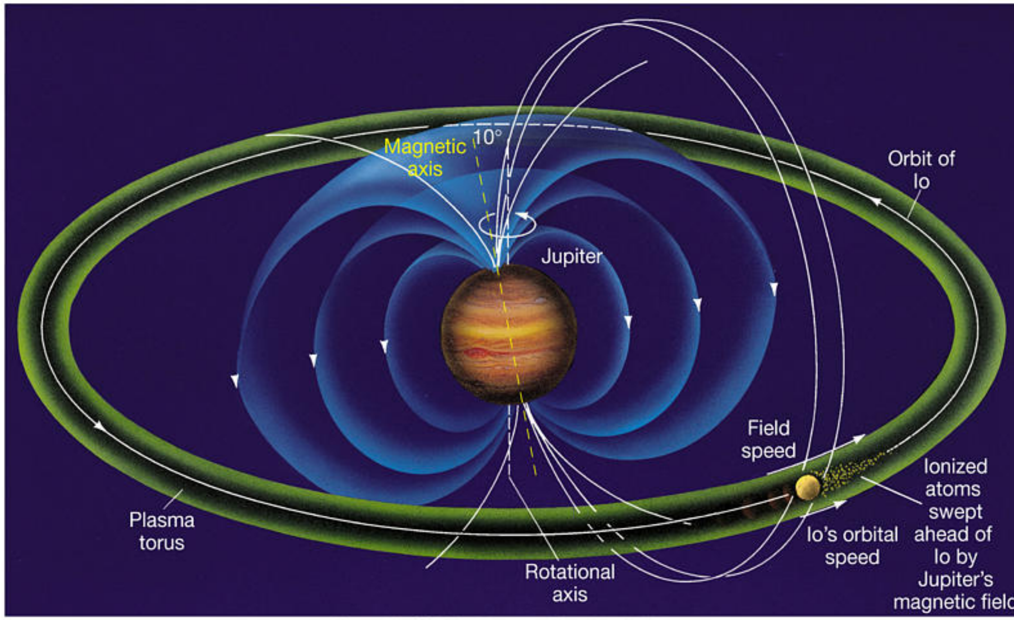
Open question: are these species **native** from the satellites or **synthesized** by **exogenic processes** e.g. ion implantation **?**

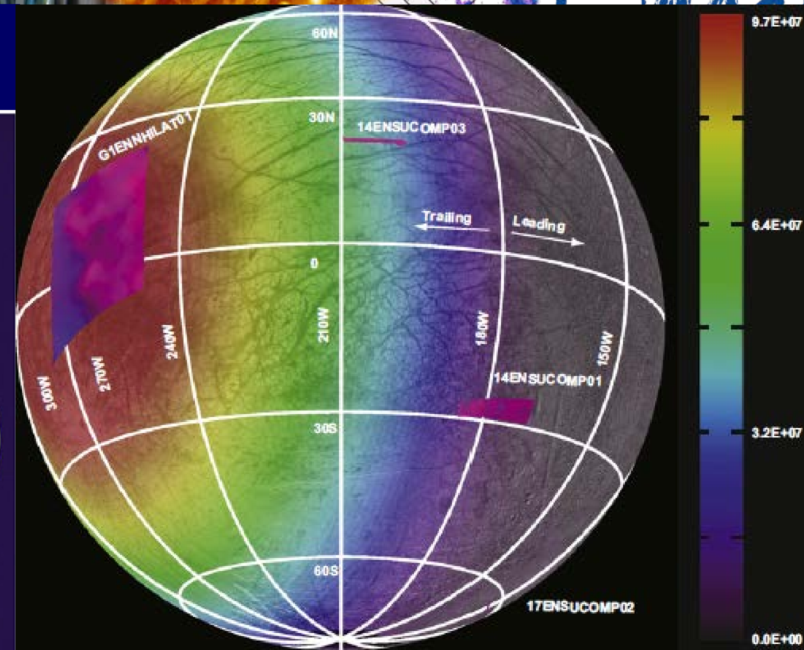
JUICE **2022 - 2033**
ESA Cosmic Vision



Centre de Recherche sur les Ions, les Matériaux et la Photonique

The Jovian Magnetosphere





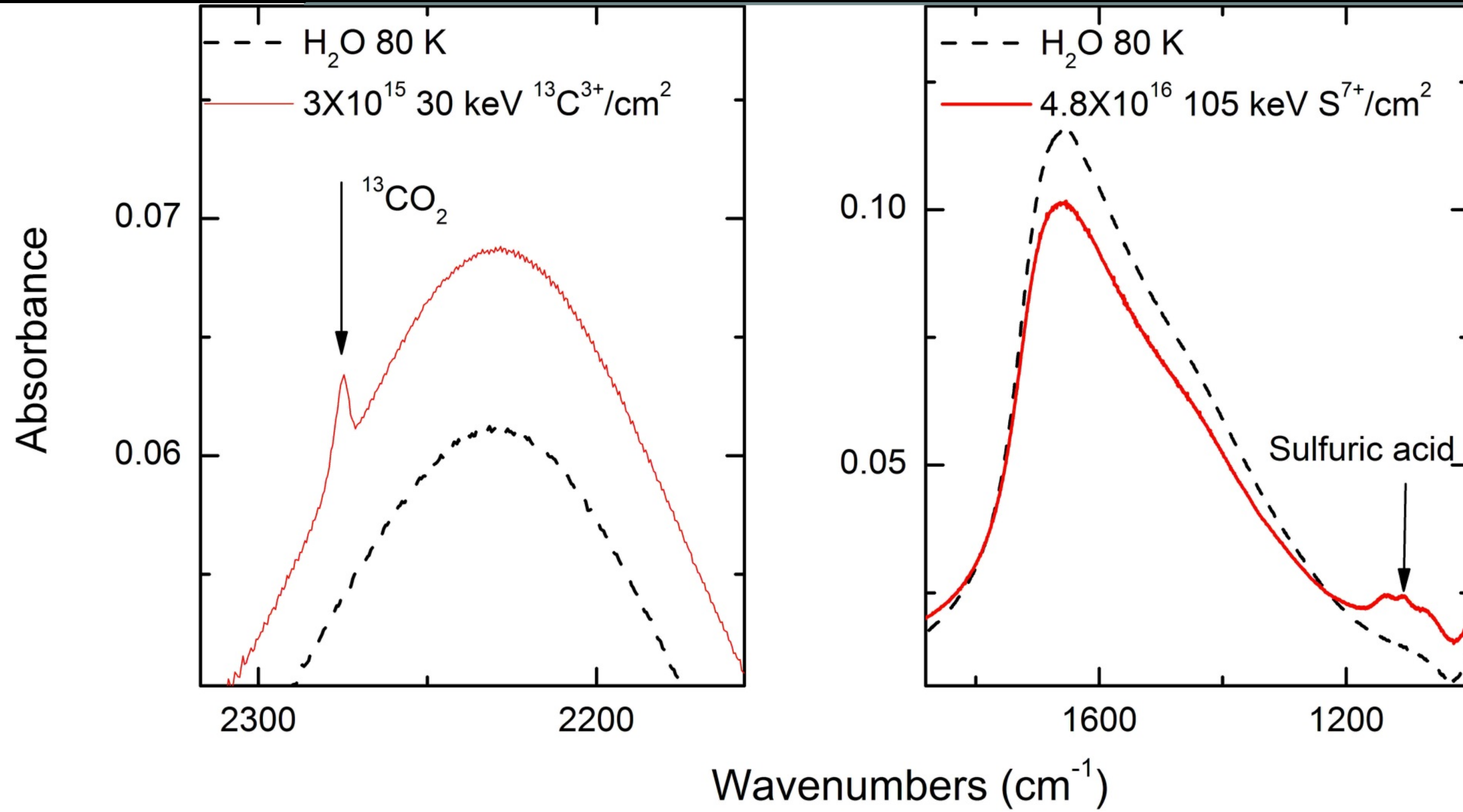
E U R O P A : Sulfur Ion Flux

J.B. Dalton III, T. Cassidy, C. Paranicas,
J.H. Shirley, L.M. Prockter, L.W. Kamp
Planetary and Space Science 77 (2013) 45

Flux of sulfur ions: up to 9,7 10^7 s^{-1} cm^{-2}
It depends on the « region »

Implantation experiments

What can we do in the laboratory?
we can measure formation yields of carbon dioxide and sulfuric acid

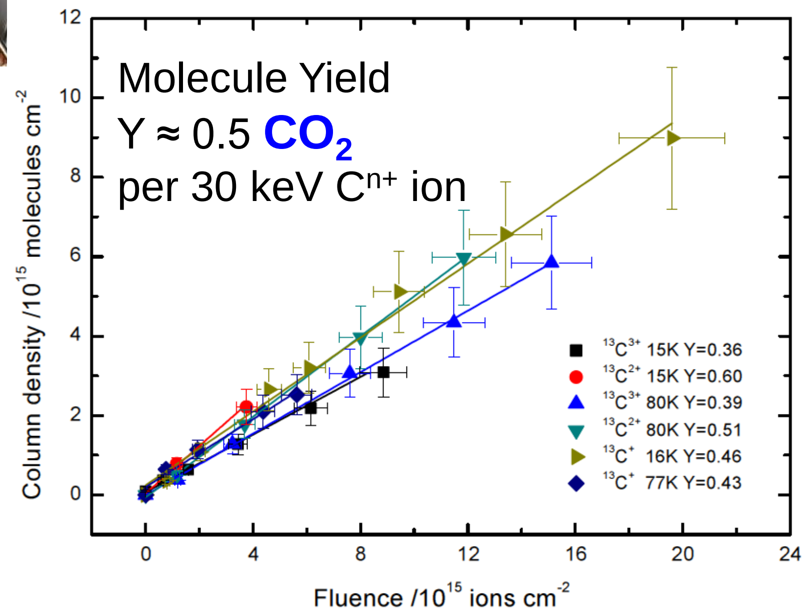


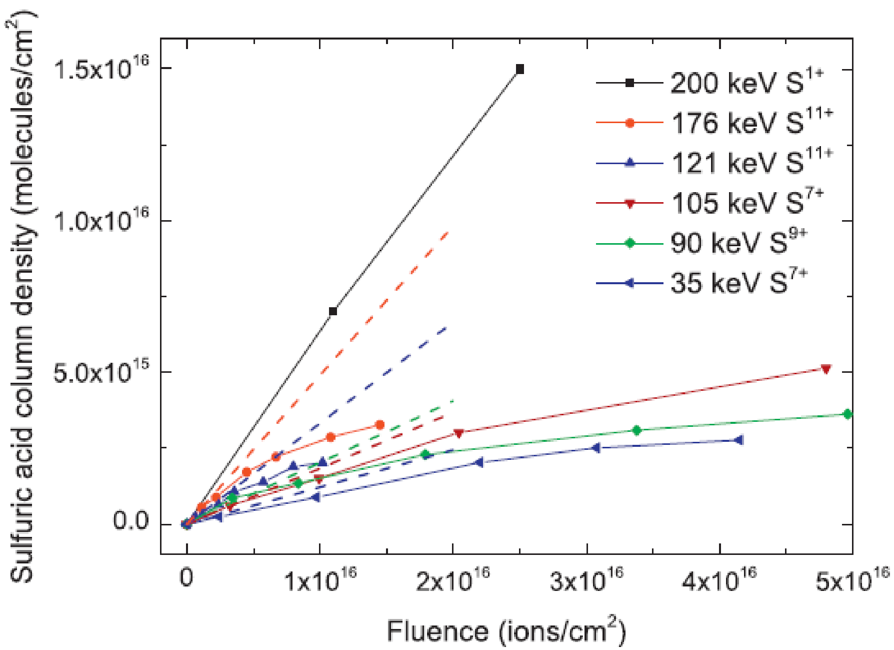
IR spectra of water ice before and after implantation of carbon and sulfur ions

X.Y. Lv, A L F. de Barros, P. Boduch, V. Bordalo,
E.F. da Silveira, A. Domaracka, D. Fulvio,
C. A.Hunniford, T. Langlinay, N.J. Mason,
A.R. W. McCullough, M.E. Palumbo,
A.S. Pilling, H. Rothard, G. Strazzulla

Implantation of multiply charged
Carbon Ions in Water Ice

Astronomy & Astrophysics 546 (2012) A81





Molecule Yield
Y(H_2SO_4) ≈ 0.12 (35 keV)
≈ 0.64 (200 keV)
per S^{n+} ion

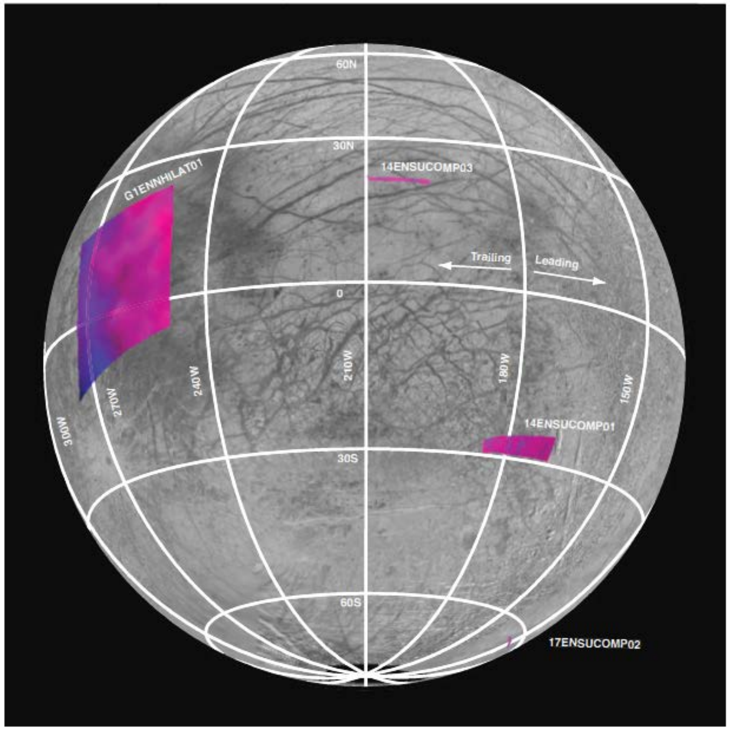
J. J. Ding, P. Boduch, A. Domaracka,
S. Guillous, T. Langlinay, X.Y. Lv, M.E. Palumbo,
H. Rothard, G. Strazzulla

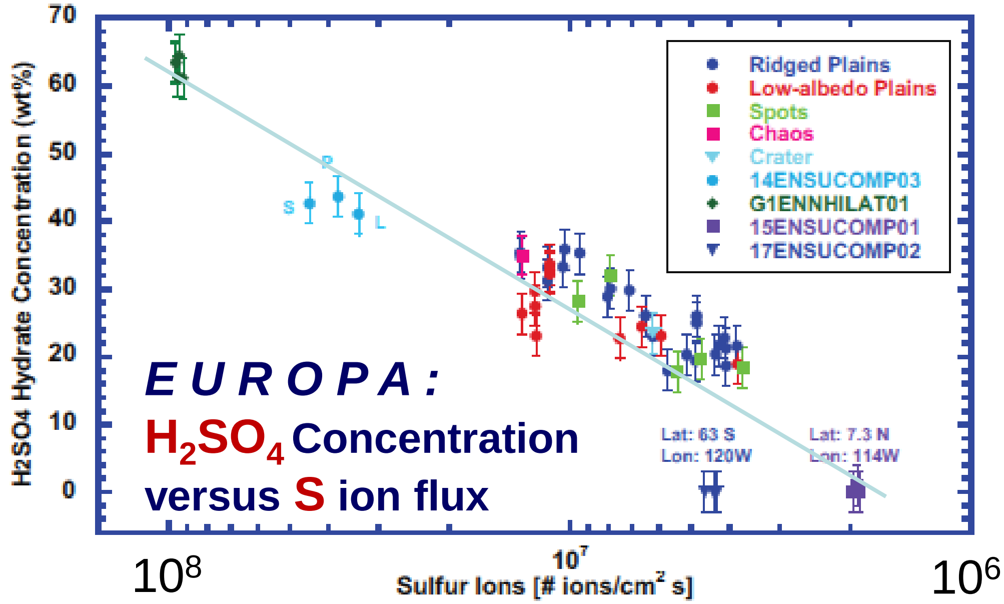
Implantation of Multiply Charged
Sulfur Ions in Water Ice

Icarus 226 (2013) 860–864

Table 4-3: Fluxes of sulfur ions estimated for some regions of the surface of Europa and times necessary to produce $3 \times 10^{19}/cm^2$ of hydrated sulfuric acid. The highest flux has been measured for NIMS observations of a region (G1ENNHILQT01) of the trailing hemisphere, the lowest for a region in the leading hemisphere (15ENSUCOMP01).

Flux of S-ions (cm^{-2} s^{-1})	Time (years) Using Y=0.12	Time (years) Using Y=0.64
2×10^6	4×10^6	7×10^5
1×10^8	9×10^4	1.4×10^4





J.B. Dalton III et al.,
Planetary and Space Science 77 (2013) 45:

Correlation of H_2SO_4 hydrate concentration with sulfur ion flux

Ding et al., Icarus 336 (2013) 860:

Concentration compatible with measured Molecule Yield from Implantation!

but ... C implantation in water ice does not explain observed CO_2 concentration.

and ... no evidence (yet) for production of SO_2 or H_2S in *water ice ...*

Sulfur implantation in CO and CO_2 ices

X. Y. Lv[1,2*], P. Boduch[2], J. J. Ding[2], A. Domaracka[2], T. Langlinay[2], M. E. Palumbo[3], H. Rothard[2] and G. Strazzulla[3†]
[1] *School of Nuclear Science and Technology, Lanzhou University, Lanzhou 730000, China*
[2] *Centre de Recherche sur les Ions, les Matériaux et la Photonique (CEA/CNRS/ENSICAEN/UCBN), CIMAP–CIRIL–GANIL, Boulevard Henri Becquerel, BP 5133, F–14070 Caen Cedex 05, France*
[3] *INAF–Osservatorio Astrofisico di Catania, Catania, Italy*

Monthly Notices of the Royal Astronomical Society (2013)

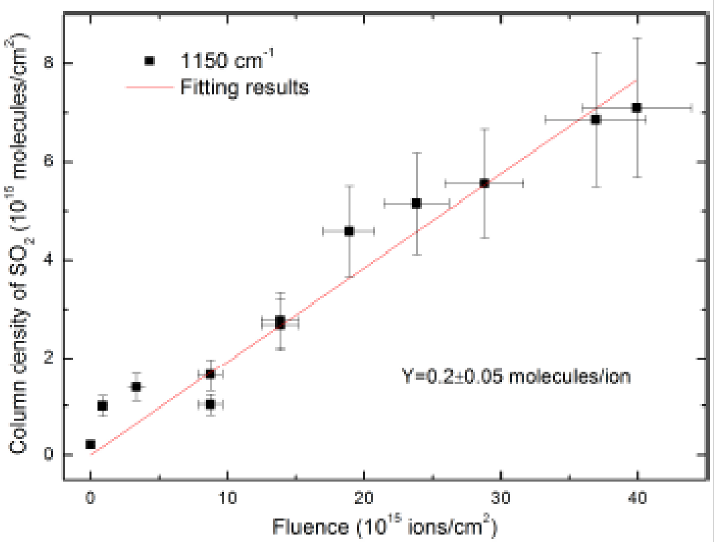


Figure 4. Column density of SO_2 produced after 176-keV S^{11+} implantation in CO ice, as a function of ion fluence. The error bar is about 10 per cent for fluence and 20 per cent for column density.

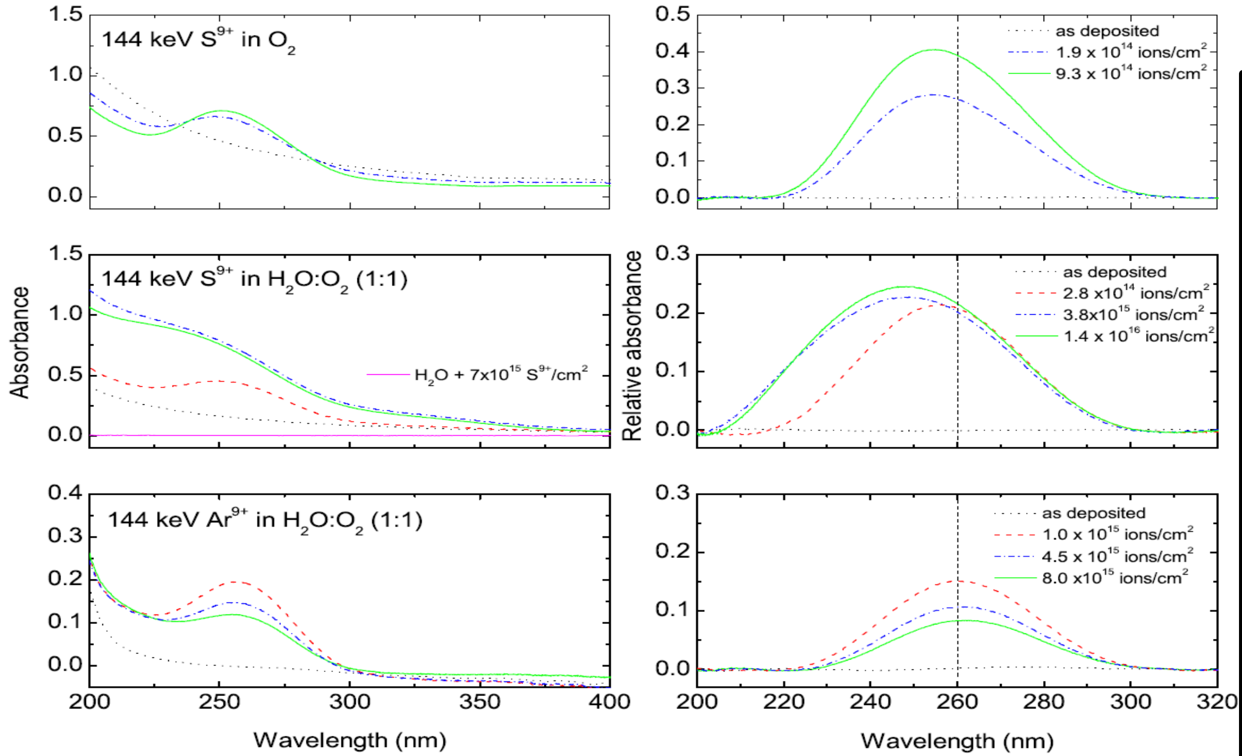
S implantation in CO and CO_2:

Y(**SO_2**) = 0.20 ± 0.05 molec./ion at 176 keV in **CO**
Y(**SO_2**) = 0.38 ± 0.02 molec./ion at 90 keV in **CO_2**

and ... **CS_2** produced in **CO_2** and **OCS** in **CO**

Europa: time to produce observed amount of **SO_2** depends strongly on CO_2 concentration:
200 years ... up to 20000 years

Star forming regions: strong flux of stellar wind from young stars (T-Tauri phase) interacts with CO_2 rich dust, later incorporated in comets



Targets representative of parents molecules for SO_2 and O_3

No SO_2 formed (280 nm)

O_3 efficiency formed at 260 nm with S and Ar

New band at 255 nm not existing with Ar

Appearance at 255nm for H_2O-O_2 then shifted at 247nm for higher S fluence

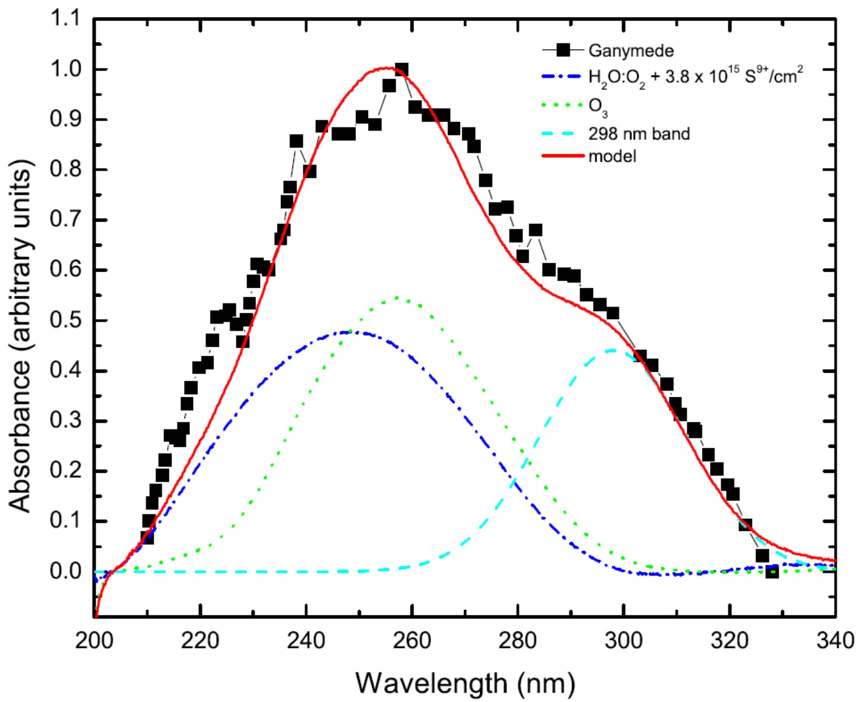
Formation of SO_3^- and HSO_3^-

Complementary experiments in the UV domain:

Ar^{q+} and S^{q+} on O_2, H_2O+O_2 (1:1)

No effect of implantation for Ar^{q+}

Icarus, accepted 2016



Ozone at 260 nm
HSO3 at 247 nm

And 298 nm????

Figure 7: The absorption band observed on Ganymede (Noll et al., 1996) is fitted by using three components as indicated in the figure (see details in the text).

Mixtures and complex organic molecules

High energy ion versus UV irradiation of methanol:ammonia ice

Formation of common organic products

G. M. Muňoz Caro, E. Dartois, P. Boduch, H. Rothard, et al. (A&A, 2013)

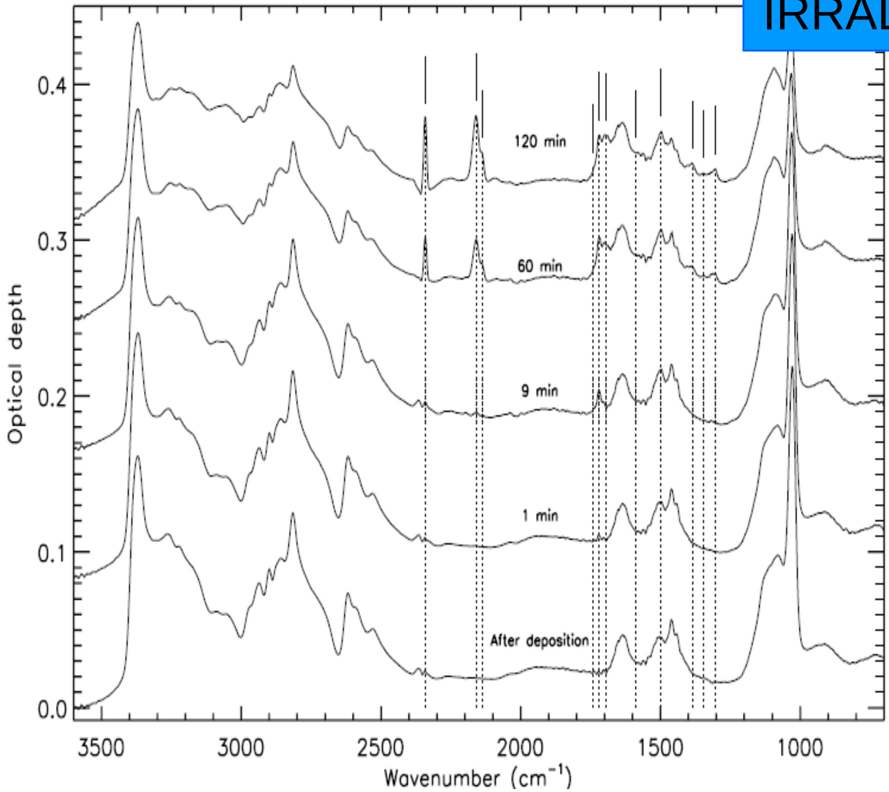
NH_3:CH_3OH ice

CASIMIR@GANIL:
Zn (SME), Ne (IRRSUD)

2,5 10^{14} photons/cm^2/s (10eV) versus Zn^{26+} at 620 MeV (flux 10^9 ions/cm^2/s

Local dose up to 30 eV/molecule

IRRADIATION



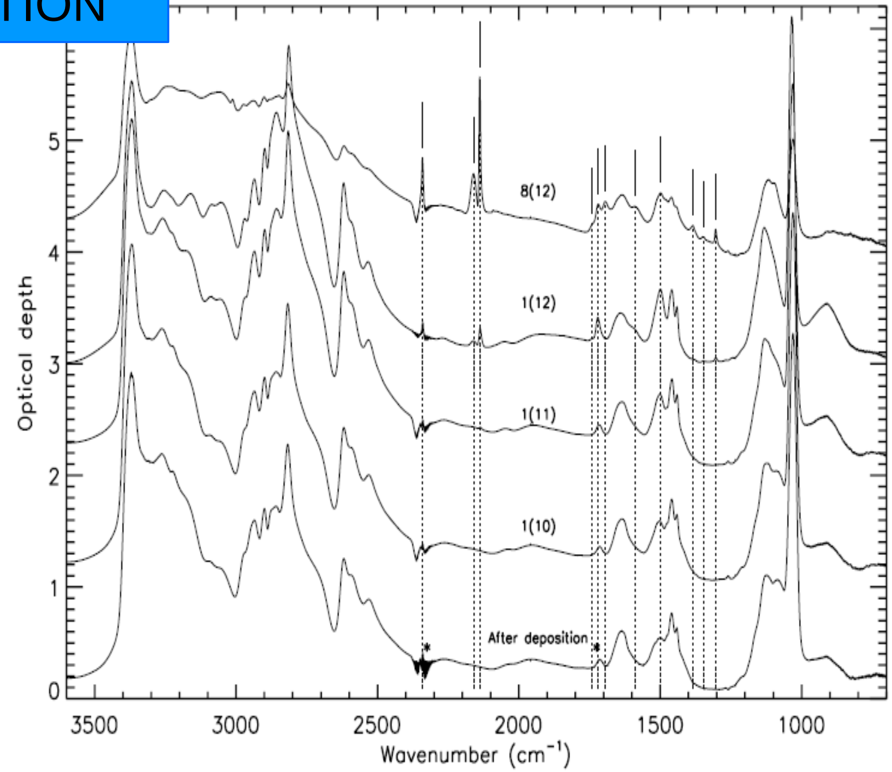


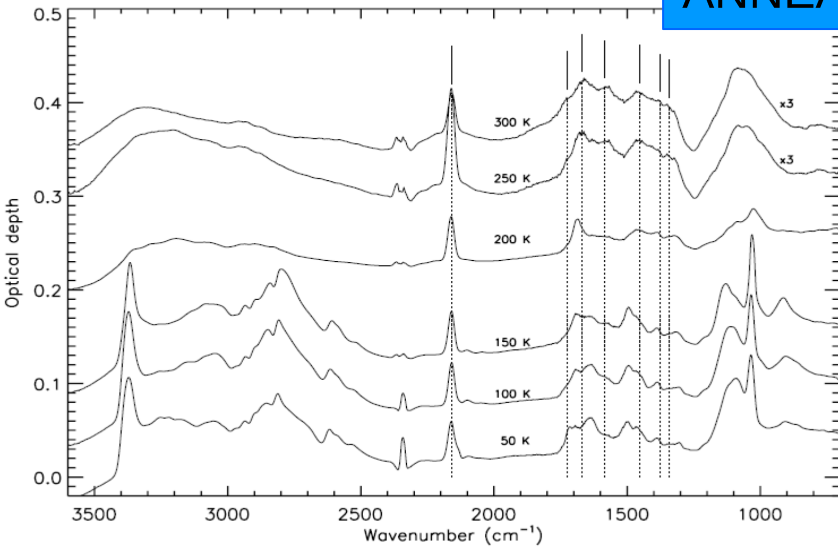
Table 1. New bands attributed to irradiation products

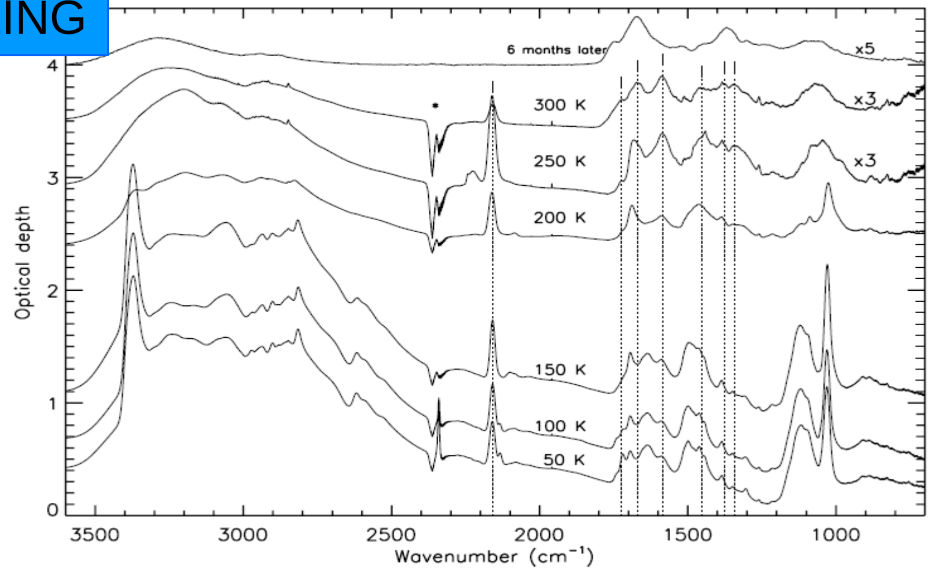
position[a] (cm^{-1})	Assignment	vibration mode	UV after dep.	Zn (620 MeV)
2340	CO_2	CO str.	×	×
2160	OCN^-	CN str.	×	×
2138	CO	CO str.	×	×
1740	C=O ester/aldehyde	CO str.	×	×
1720	H_2CO	CO str.	×	×
1694	$HCONH_2$?	CO str.	×	×
1587	COO^- in carb. ac. salts[b,c]	COO^- asym. str.	×	×
1498	H_2CO	CH_2 scis.	×	×
1385	CH_3 groups	CH_3 sym. def.	×	×
1347	COO^- in carb. ac. salts[b,c]	COO^- sym. str.	×	×
1303	CH_4	def.	×	×

[a] Position varies sligthly due to interaction of species within the matrix; [b] Muñoz Caro & Schutte (2003) ; [c] Nuevo et al. 2006.

Same « products » for both experiments!

ANNEALING





Ph

Table 2. Assigned feature carriers of the IR residue spectrum formed by UV irradiation of NH_3:CH_3OH = 1:1 ice.

Position cm^{-1}	Assignment	Vibration mode	UV after dep.	Zn (620 MeV)
3600-2300	R-COOH, alcohols, NH_4^+	OH str., NH str.	×	×
2930?confirm	-CH_2OH[b]	$2\nu_{19}$ antisym. -CH_2 str.	×	×
2875?confirm	-CH_2OH[b], NH_4^+[a]	ν_{18} sym. CH_2 str., $2\nu_4$ of NH_4^+[a]	×	×
2160	OCN^-	CN str.	×	×
1723	Aldehydes	C=O str.	×	×
1670	Amides	C=O str.	×	×
1586	COO^- in carboxylic acid salts [c,d]	COO^- antisym. str.	×	×
1454	NH_4^+[a]	ν_4[a]	×	×
1378	CH_3 groups	CH scissoring [a]	×	×
1342	COO^- in carboxylic acid salts [c,d]	COO^- sym. str.	×	×
1050	CH2-OH in primary alcohols	C-O str.	×	×

[a] Wagner & Hornig (1950)
[b] Muñoz Caro & Dartois (2009)
[c] Muñoz Caro & Schutte (2003)
[d] Nuevo et al. 2006

Same residues for both experiments!

nom

Conclusion :

- Same local dose (eV/molecule)
- Formation : the same species
- Residues very similar
- Rich in organic molecules.

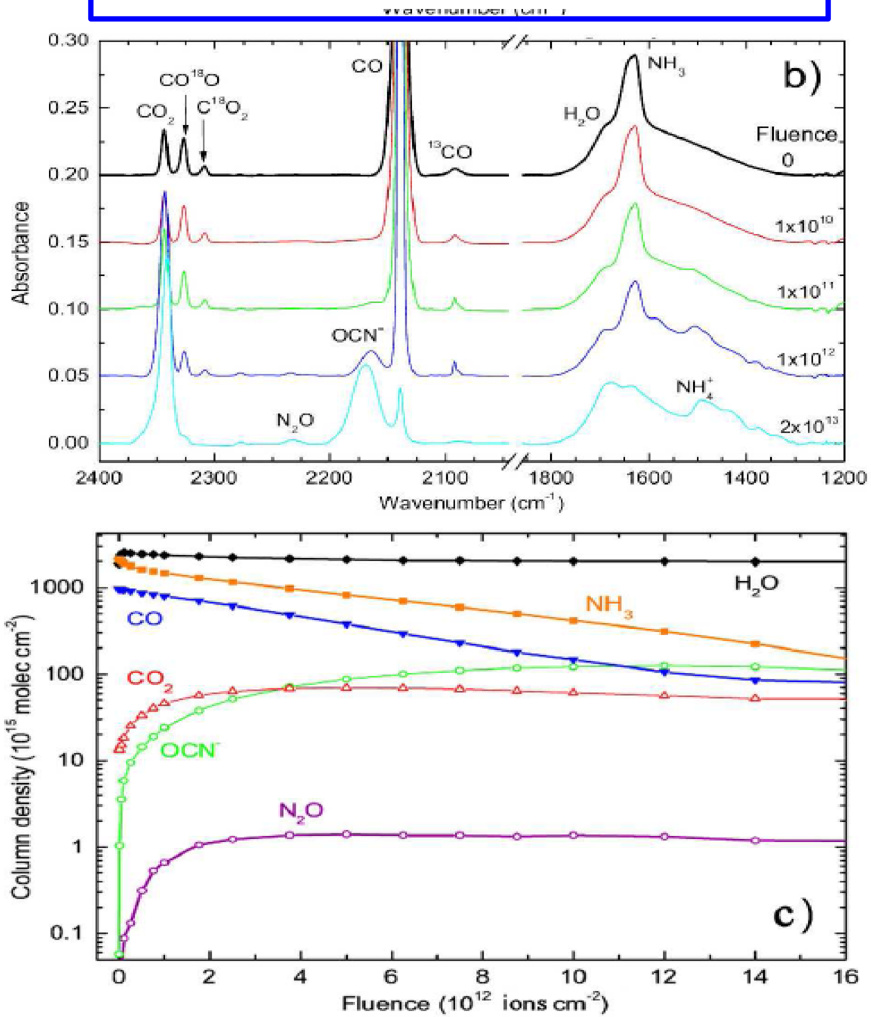
- Sputtering of HCI very strong vs UV
- G values are different, higher for HCI.

• Projected range: Higher for ions

- Thicker sample
- Better for other analysis…

H_2O – CO - NH_3 ice

46 Mev $^{58}Ni^{13+}$



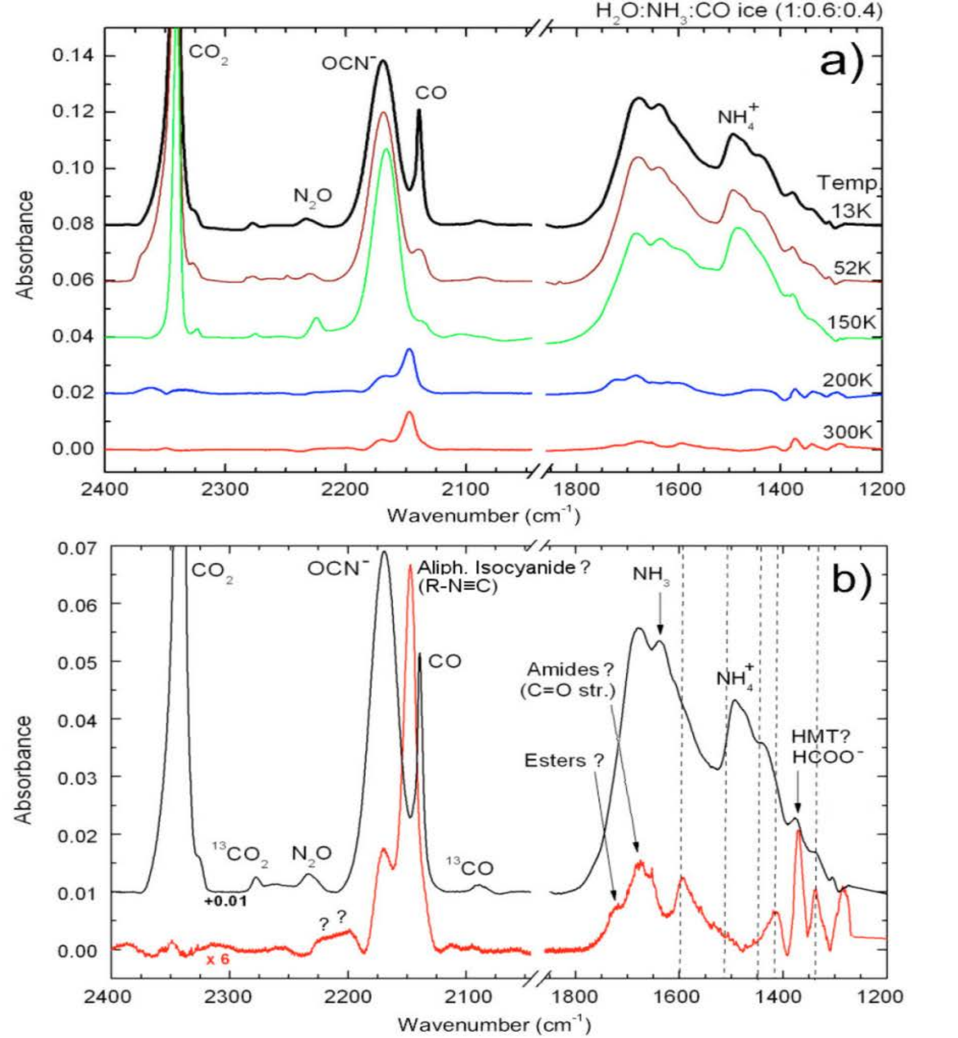


Fig. 6. **a)** Infrared spectra of $H_2O:NH_3:CO$ ice (1:0.6:0.4) from 2400 to 1200 cm^{-1} during heating to room temperature. The sample temperature of each spectrum is given. Each spectrum has an offset of 0.02 for clearer visualization. **b)** Comparison between the irradiated ice at 13 K (top spectrum) and the 300 K residue (bottom spectrum). Vertical dashed lines indicate the frequencies of some vibration modes of zwitterionic glycine ($NH_3^+CH_2COO^-$).

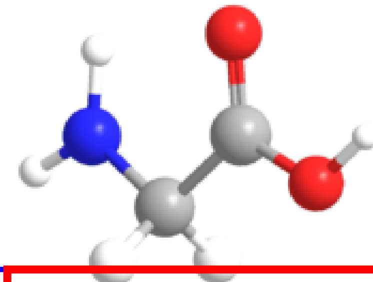
S. Pilling et al.Astronomy & Astrophysics 509 (2010) A87

Frequency (cm^{-1})	Wavelength (μm)	Temp. (K)	Molecule
2233	4.48	13	N_2O
2218–2200	4.51-4.54	300	nitriles†
2168	4.61	13, 300	OCN^-
2147	4.66	300	aliph. isocyanide†
~2112	4.73	300	$NCO_2^{\dagger}$
1725	5.80	300	ester†
1683	5.94	300	amides†
1652	6.05	300	asym-$N_2O_3^{\dagger}$
1637	6.11	13	?
1593	6.28	300	$NH_3^+CH_2COO^{-\dagger}$
1558	6.42	300	?
1533	6.52	300	?
1506	6.64	300	$NH_3^+CH_2COO^{-\dagger}$
~1490	6.71	13	NH_4^+
1474	6.78	13	$NO_3^{\dagger}$
1440	6.94	13	$NH_3^+CH_2COO^{-\dagger}$
1415	7.07	300	$NH_3^+CH_2COO^{-\dagger}$
~1370	7.30	13, 300	HMT† $HCOO^-$
~1338	7.47	13, 300	$NH_3^+CH_2COO^{-\dagger}$ $NH_2CH_2COO^{-\dagger}$ $HCOO^-$
1305	7.66	13	$N_2O_3^{\dagger}$; $N_2O_4^{\dagger}$
1283	7.80	300	$N_2O^{\dagger}$

S. Pilling, E. Seperuelo Duarte, E. F. da Silveira, E. Balanzat, H. Rothard, A. Domaracka, P. Boduch
Radiolysis of ammonia-containing ices by energetic, heavy and highly charged ions inside dense astrophysical environments, Astronomy & Astrophysics 509 (2010) A87

H_2O - CO - NH_3 ice

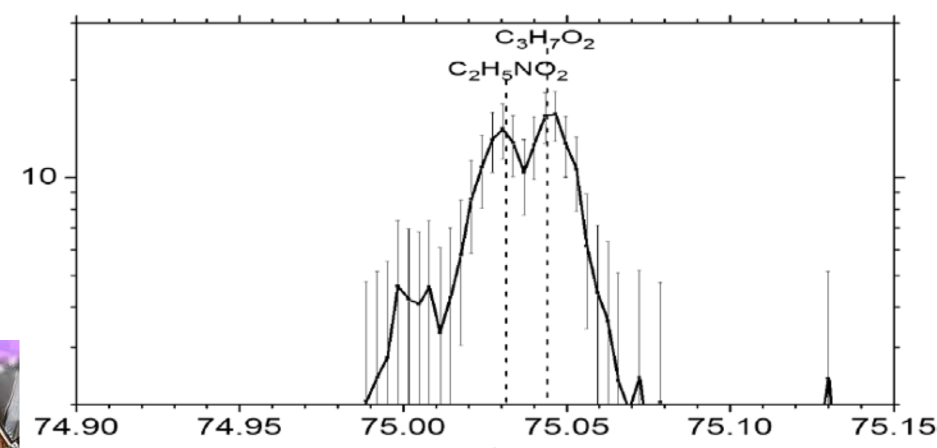
⇒ glycine (amino acid)



Analysis of the Residues by Chromatography?

The amount of residue?

Prebiotic chemicals
amino acid in the coma of
comet 67P/Churyumov-Gerasimenko

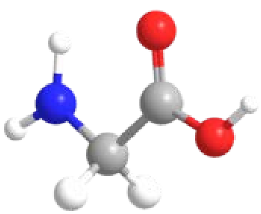


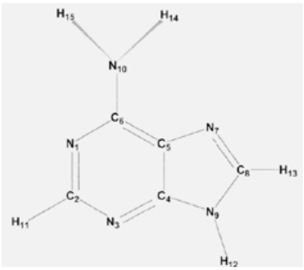
Kathrin Altwegg et al, Space sciences, 2016.

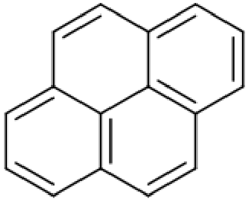
Radiation resistance of organic molecules

⇒ **Irradiation of ices containing complexe molecules**

e.g. glycine, adenine, PAH (Polycyclic aromatic hydrocarbons)







other materials:
carbonaceous, silicates
chemistry at interfaces?

Swift heavy ion irradiation on frozen N_2-CH_4 ices relevant to surfaces of Oort Cloud objects : toward understanding formation of UltraCarbonaceous Antarctic MicroMeteorites

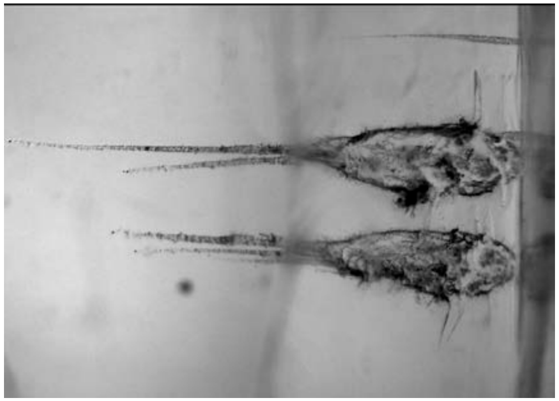
UCAMMs

AUGÉ Basile's thesis

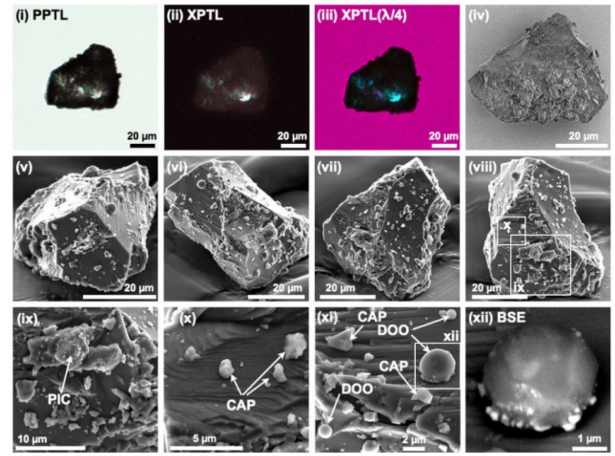
auge@ganil.fr

de Recherche sur les Ions, les Matériaux et la Photonique

Extraterrestrial Matter on Earth



Impacts from comet 81P/Wild particles (*Stardust*)



Fragments from Itokawa (*Hayabusa 1*)

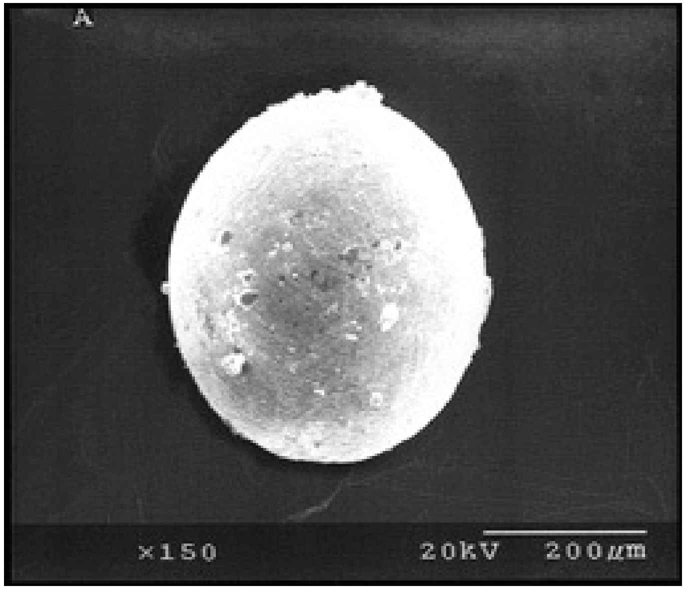
Orgueil Meteorite (Muséum de Montauban)

- Stardust : 7 years in space
- Hayabusa 1 : 7 years in space (5 years late)
- About 40 t of meteorites falling on Earth every year
- Dozens of meteorites collected every year

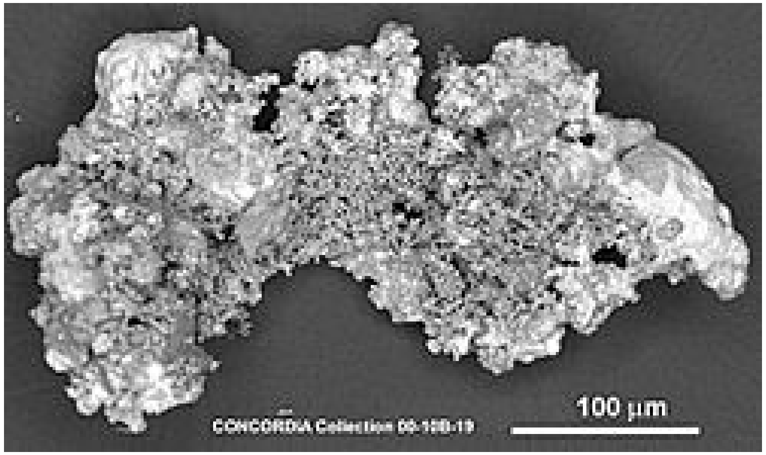
Not enough raw matter

Love et al. 1993

Extraterrestrial Matter on Earth : Micrometeorites



Micrometeorite (Washington State University)

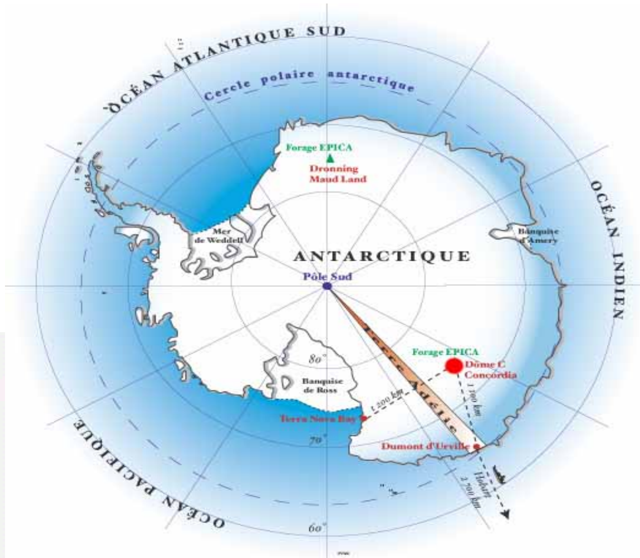


Micrometeorite (CONCORDIA Collection)

- About 40 000 t of mm falling on Earth every year
- About 35 000 impacts by second

Love et al. 1993

Antarctic micrometeorites



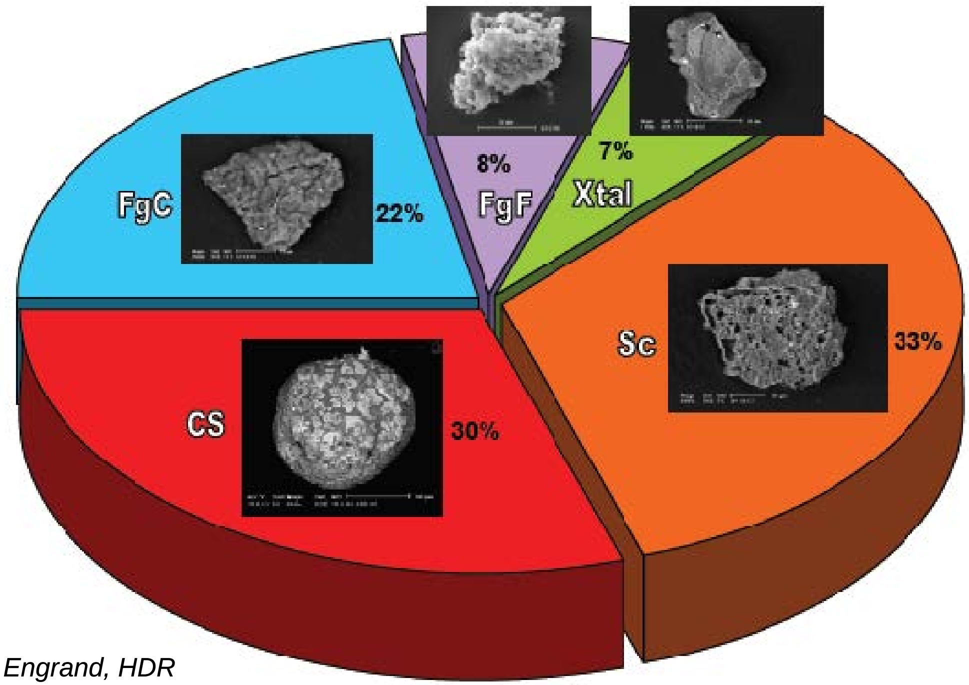
- 1100 km inland, 3200 m elevation
- Katabatic wind
- 3.5 km of ice
- -80°C < T < -30°C

→

- Low human contamination
- Excellent dust conservation
- Ratio ET/T optimal

HIGH DISCOVERY POTENTIAL

Different types of micrometeorites:



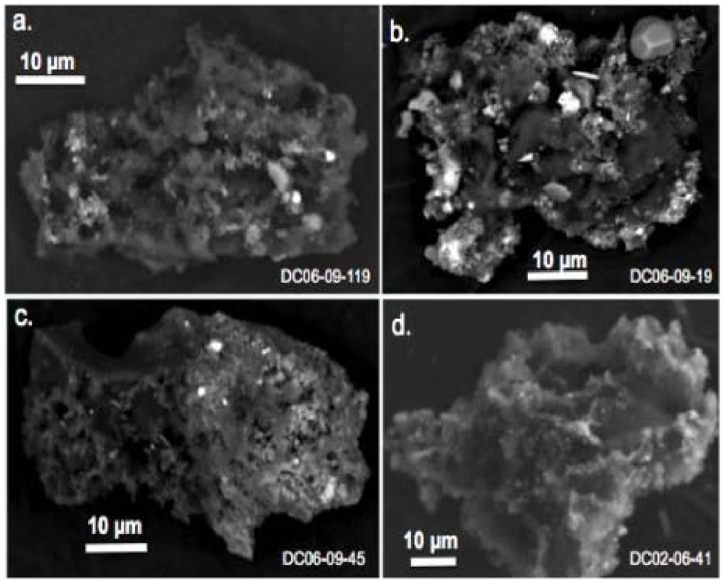
C. Engrand, HDR

- FgC, fined-grained compact
- Xtal, crystalline
- Sc, scorie
- CS, cosmic spherule
- **FgF, fined-grained fluffy**

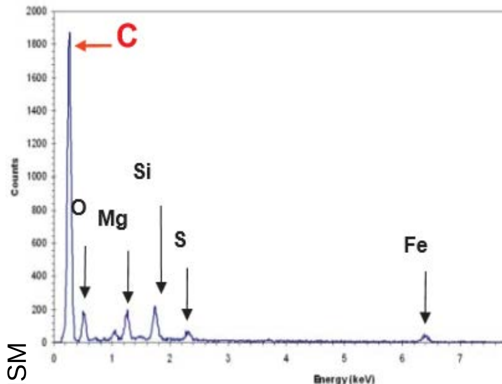
2000 micrometeorites in the CONCORDIA collection

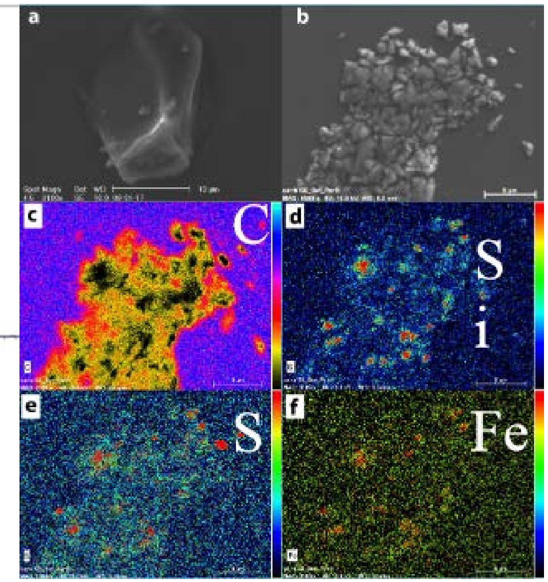
Ultracarbonaceous micrometeorites (2% of the FgF)

UCAMMs (UltraCarbonaceous Antarctic MicroMeteorites)



Concordia CSNSM

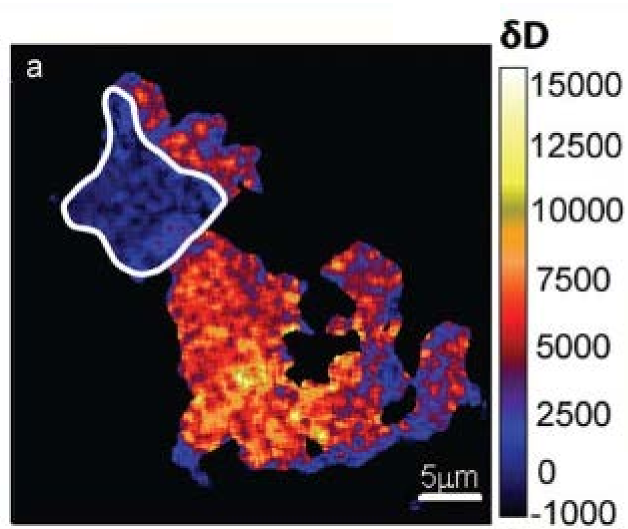




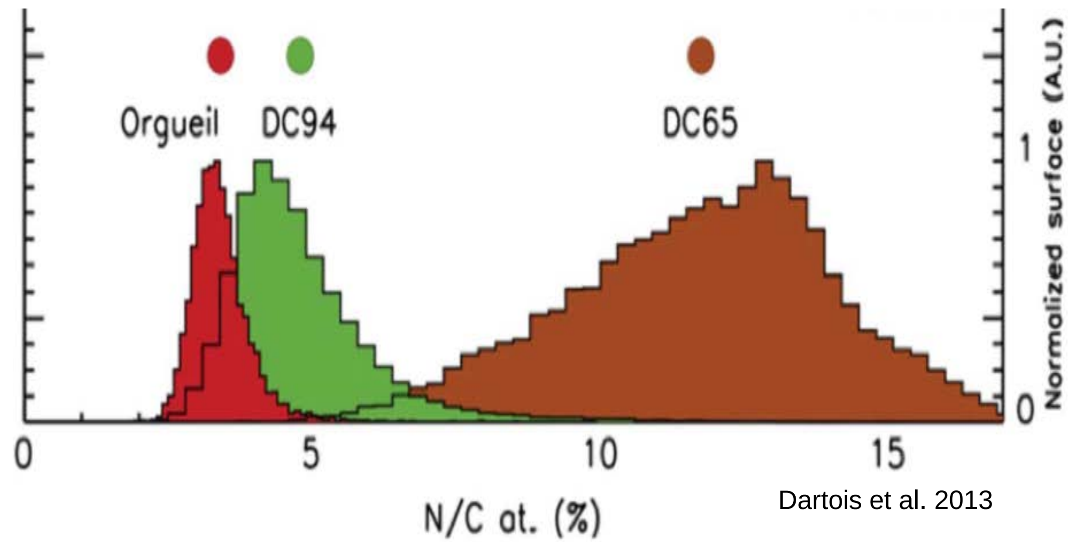
Dartois et al. 2008
Dartois et al. 2013

- Up to 65 w% and 50 vol% of carbonaceous matter (C chondrite : 4w%)

UCAMMs (UltraCarbonaceous Antarctic MicroMeteorites)



Duprat et al. 2010



Dartois et al. 2013

- D/H ~ 10-30 * D/H

Formation in the cold regions of the protoplanetary disk

Bockélé et al. 1998

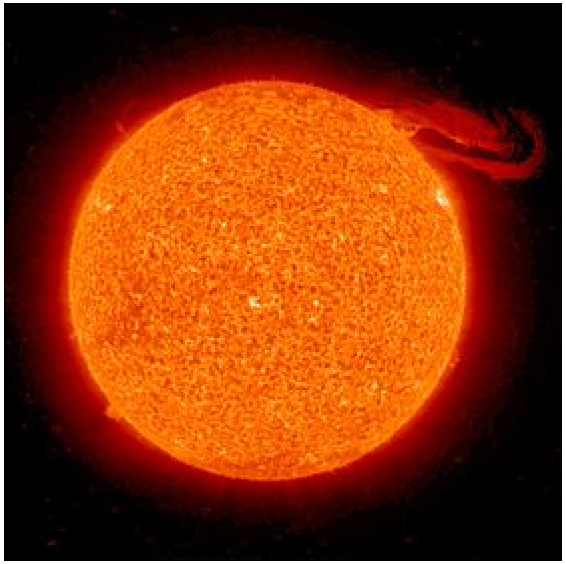
And no Oxygen…

- N-rich matter

Efficient energy source

Gerakines et al. 2001

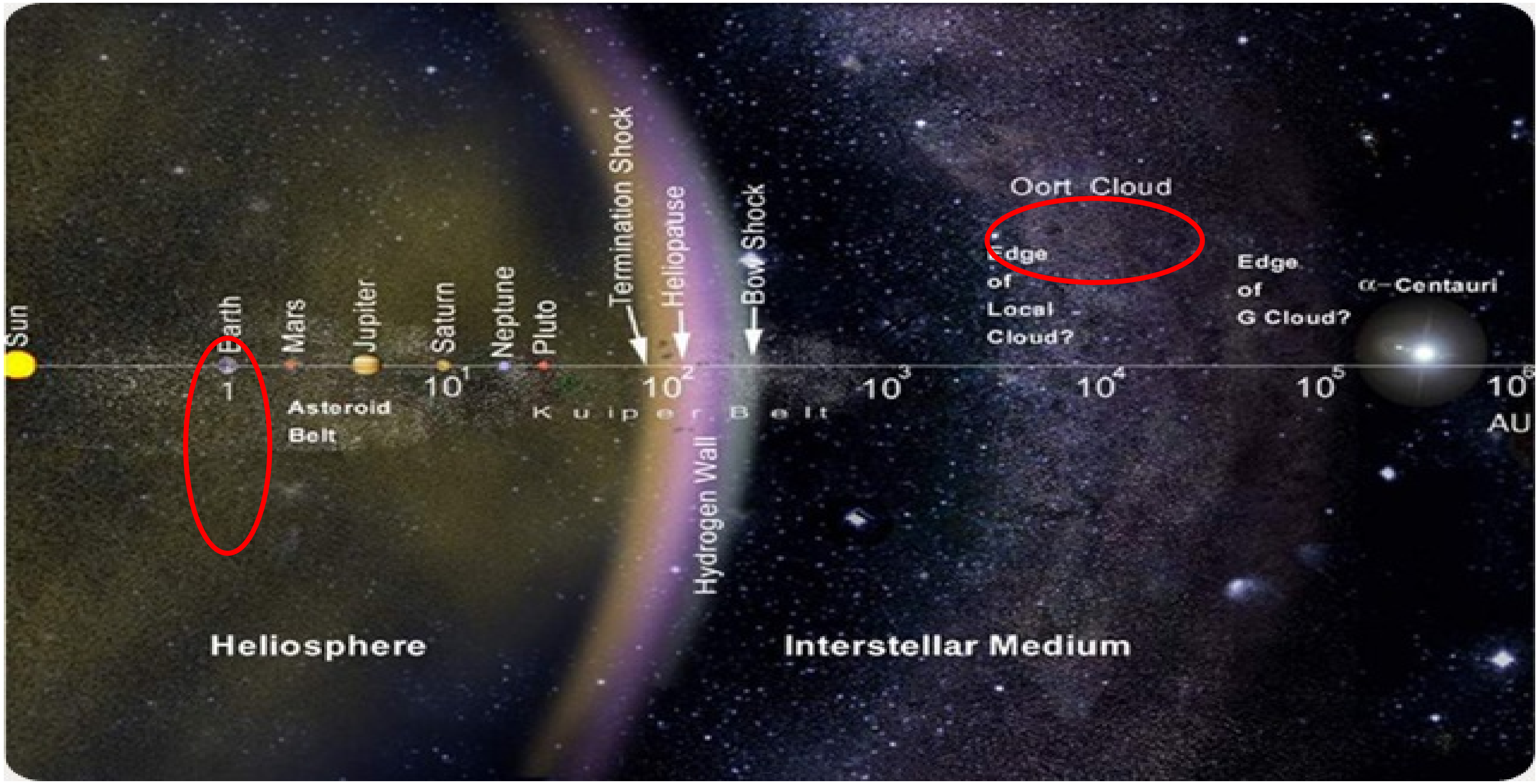
Energy sources in the Solar System



Solar wind

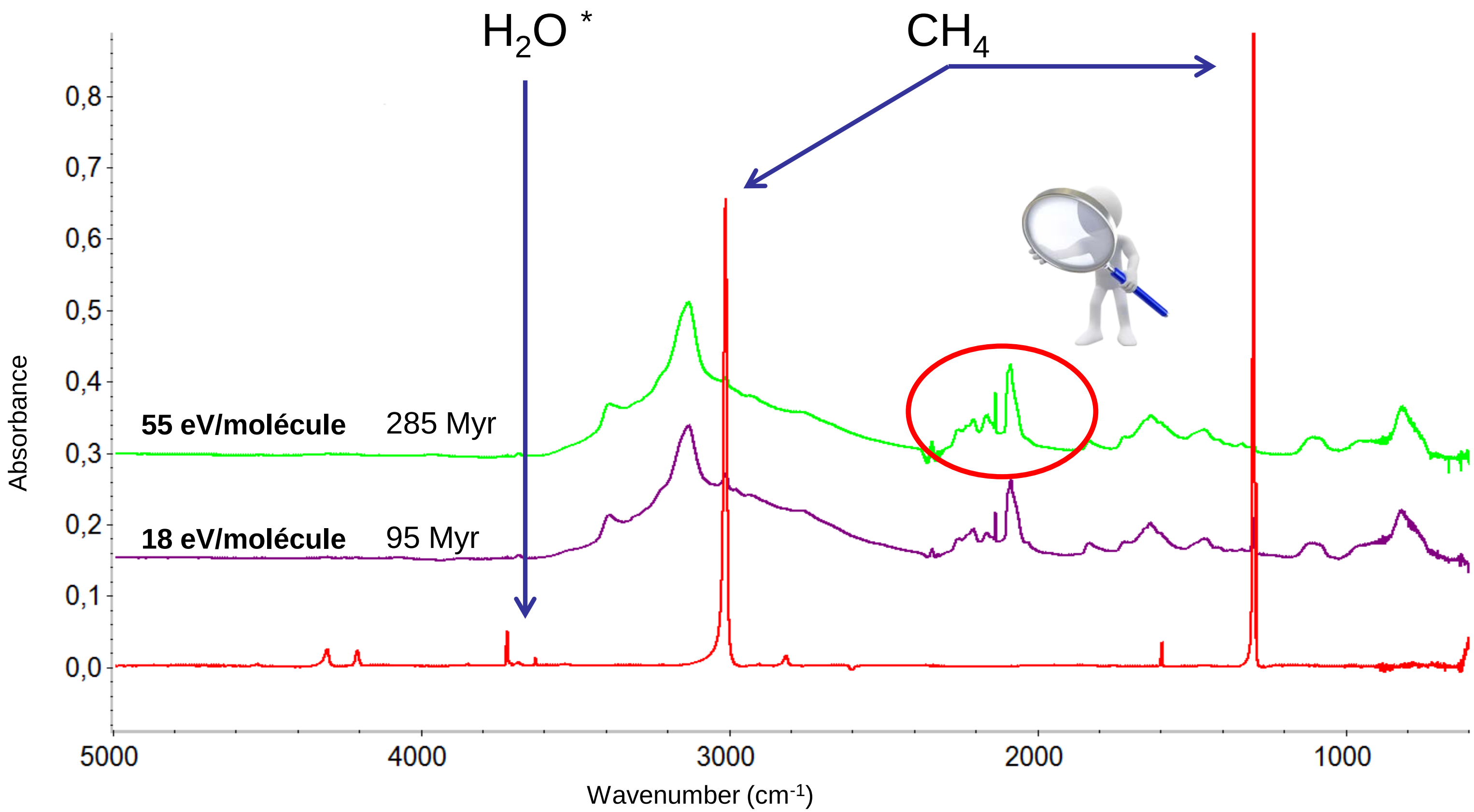
Galactic Cosmic Rays

UCAMMs (UltraCarbonaceous Antarctic MicroMeteorites)



- Production of N_2-CH_4 ices relevant to Oort Cloud objects surfaces
- Irradiation on IRRSUD and SME beam lines to simulate GCR irradiation
- *In-situ* FTIR spectroscopy to monitored ices chemical evolution
- Annealing to obtain solid residues at room temperature
- *Ex-situ* analysis of the residues

N_2-CH_4 (90:10) ices, IRRSUD (Ni^{11+}, 44 MeV)



Basile Augé et al, A&A accepted 2016

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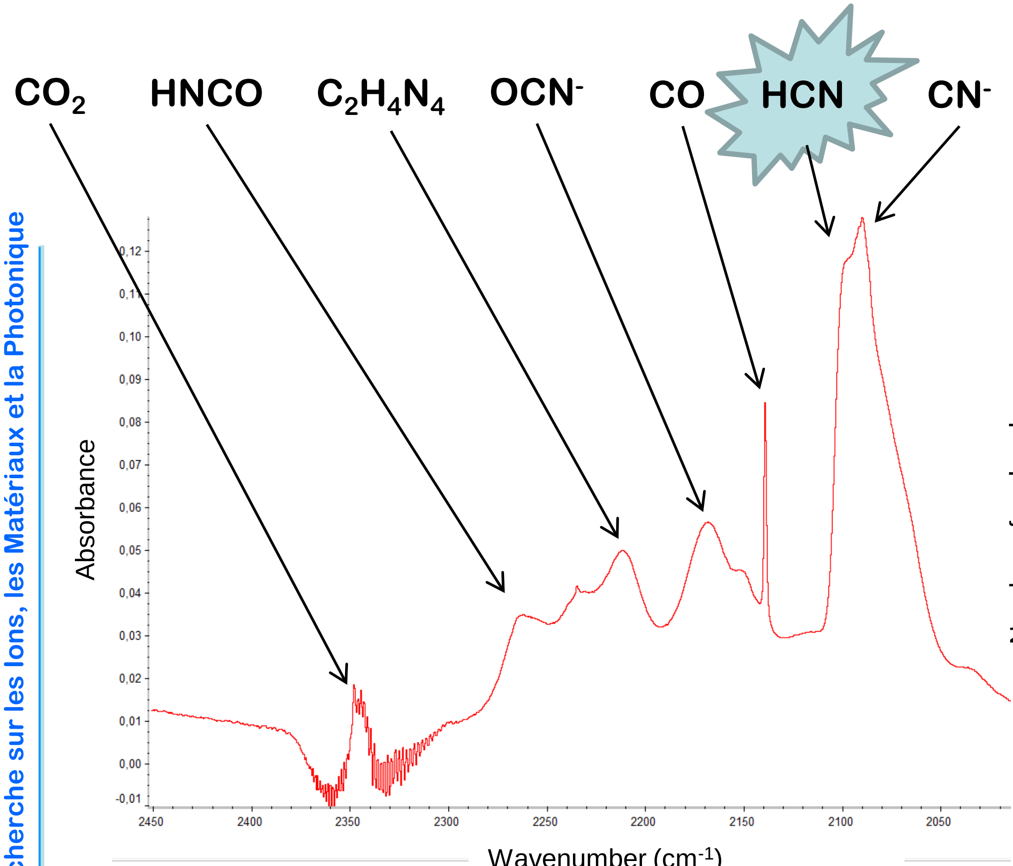
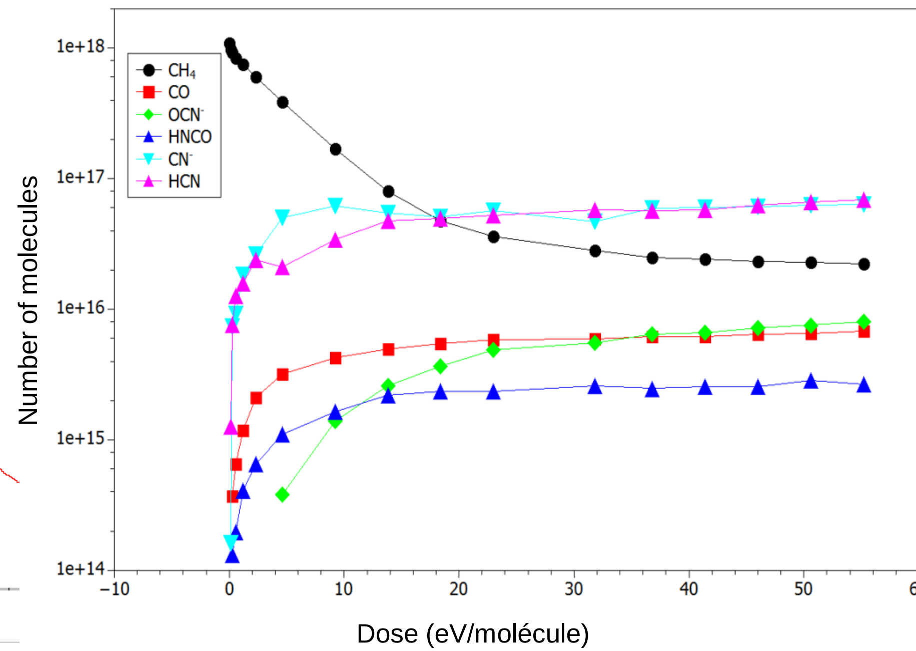
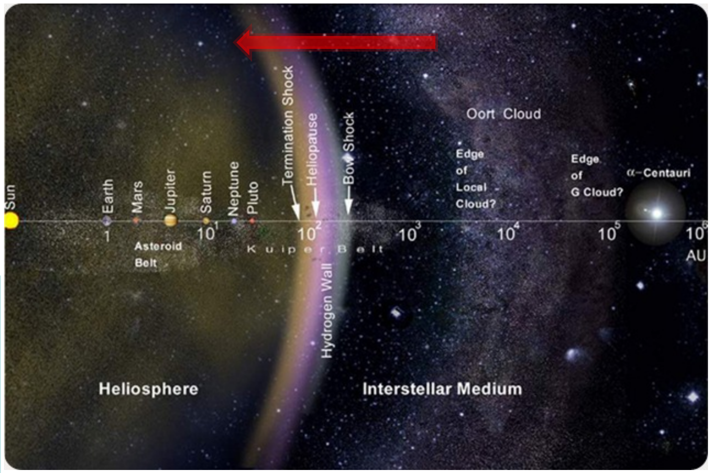
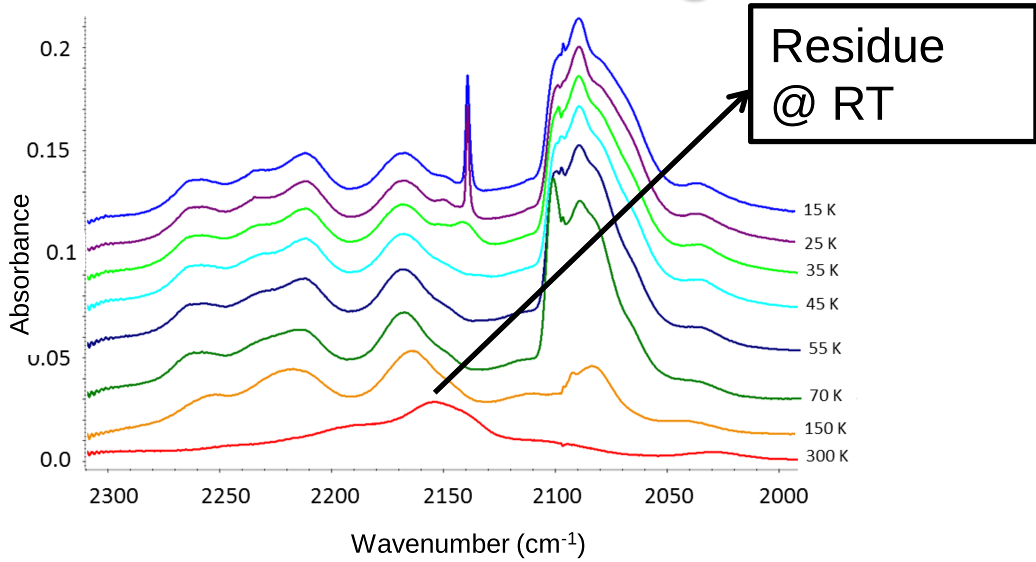
N_2-CH_4 (90:10) ices, IRRSUD (Ni^{11+}, 44 MeV)

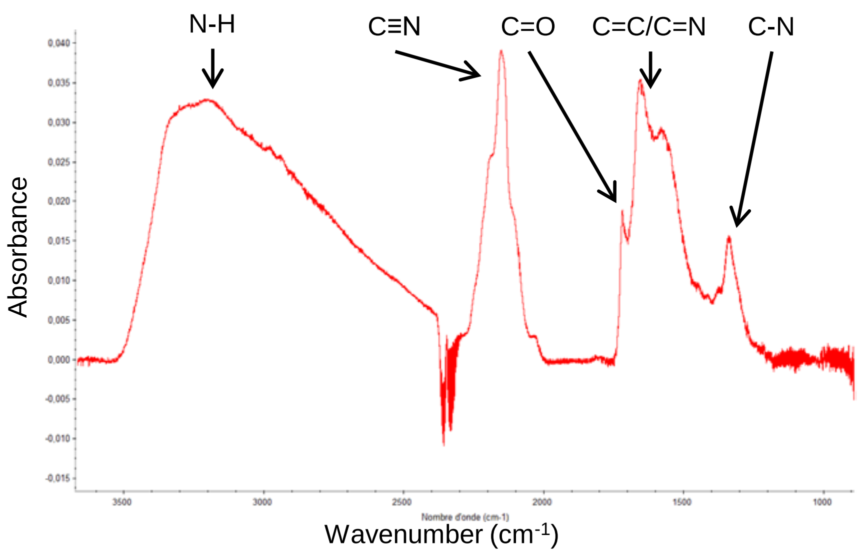


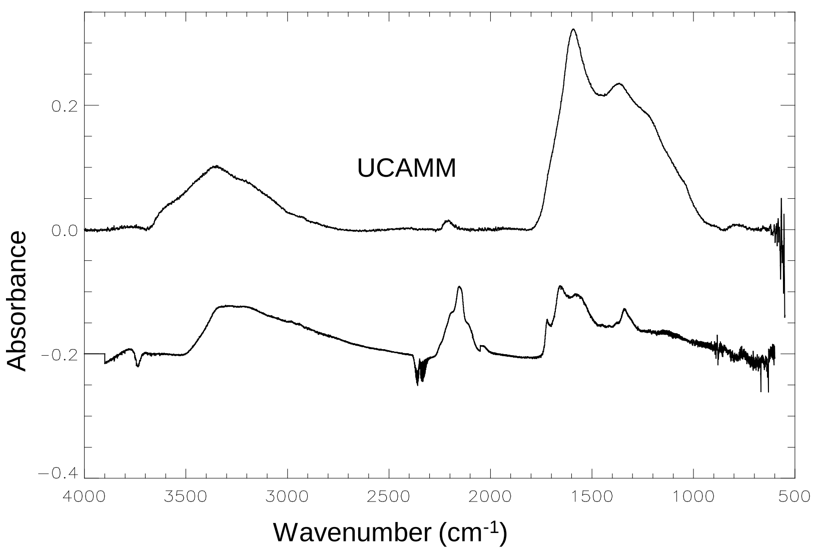


Residue and UCAMM: comparaison after annealing

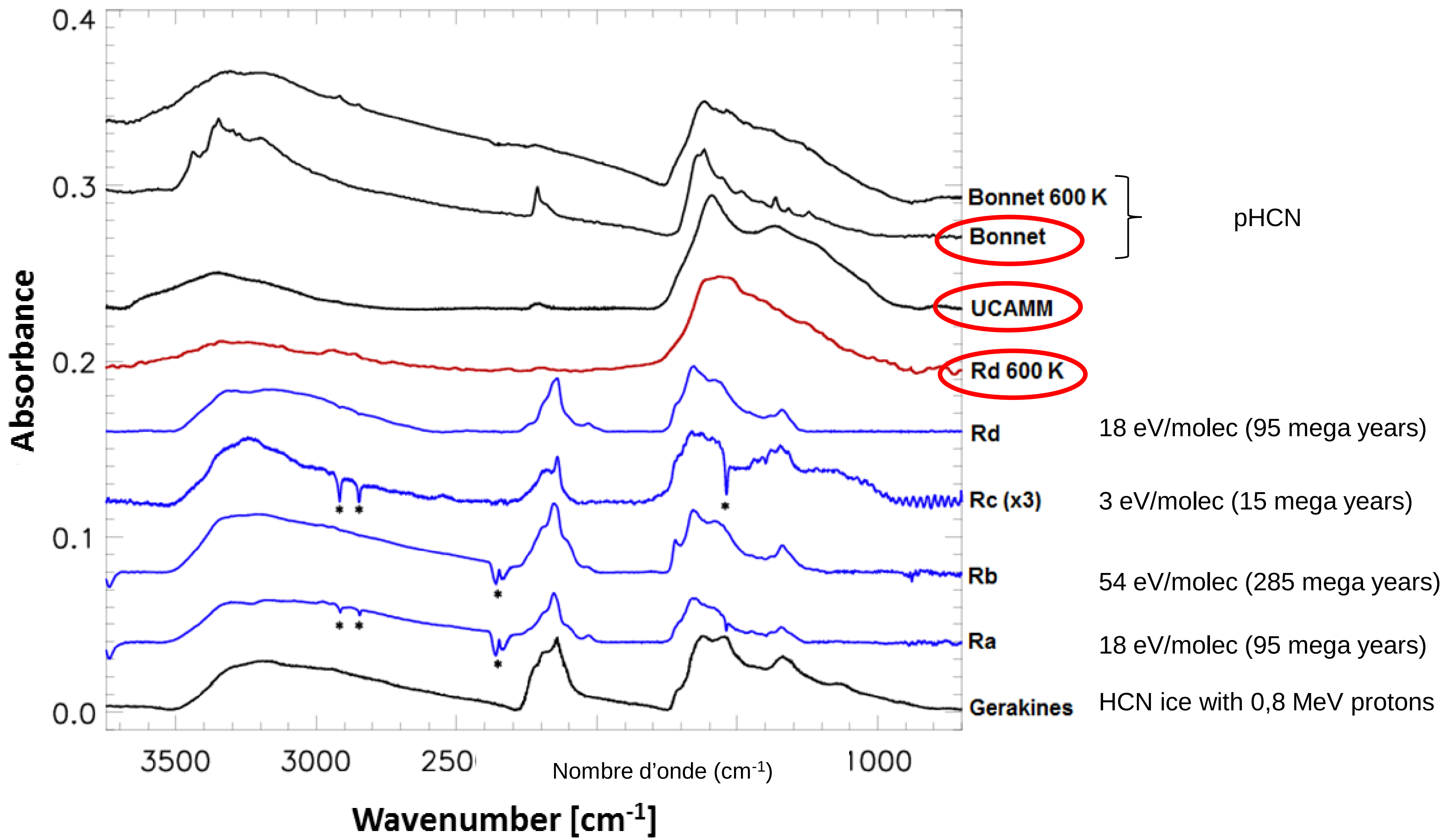








Residues analysis : different proportions, different doses, different T

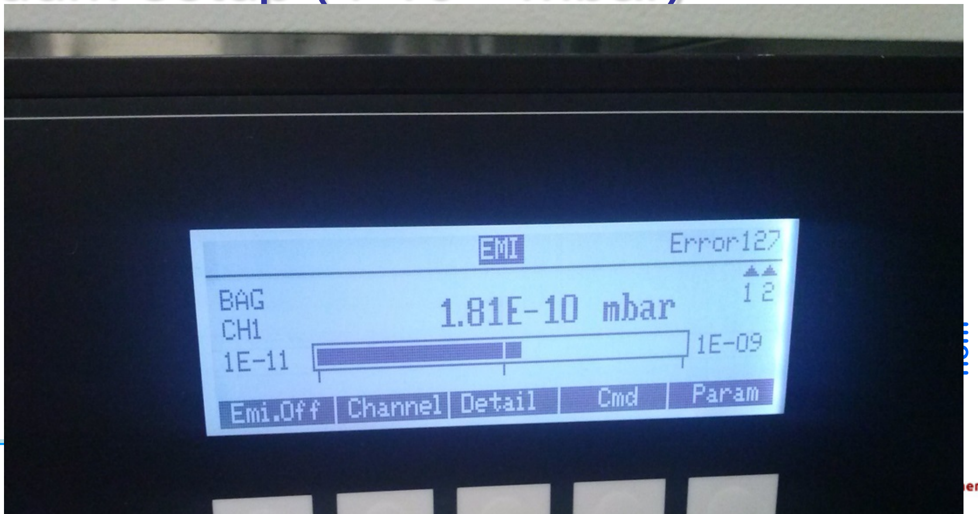


- HCN : the good « material »
- What next ?

→ Longer irradiation (1 Gy) (nitrile band?)

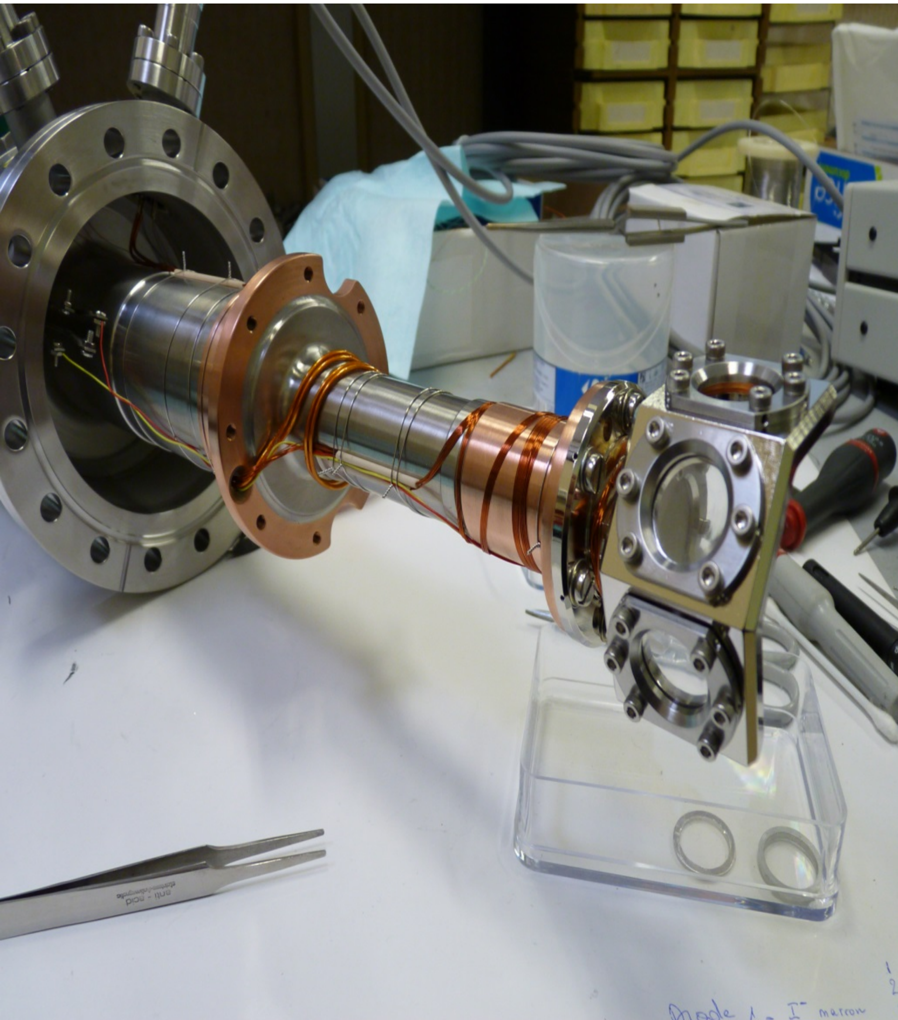
- With no redeposition of water : (No R-C=O band)

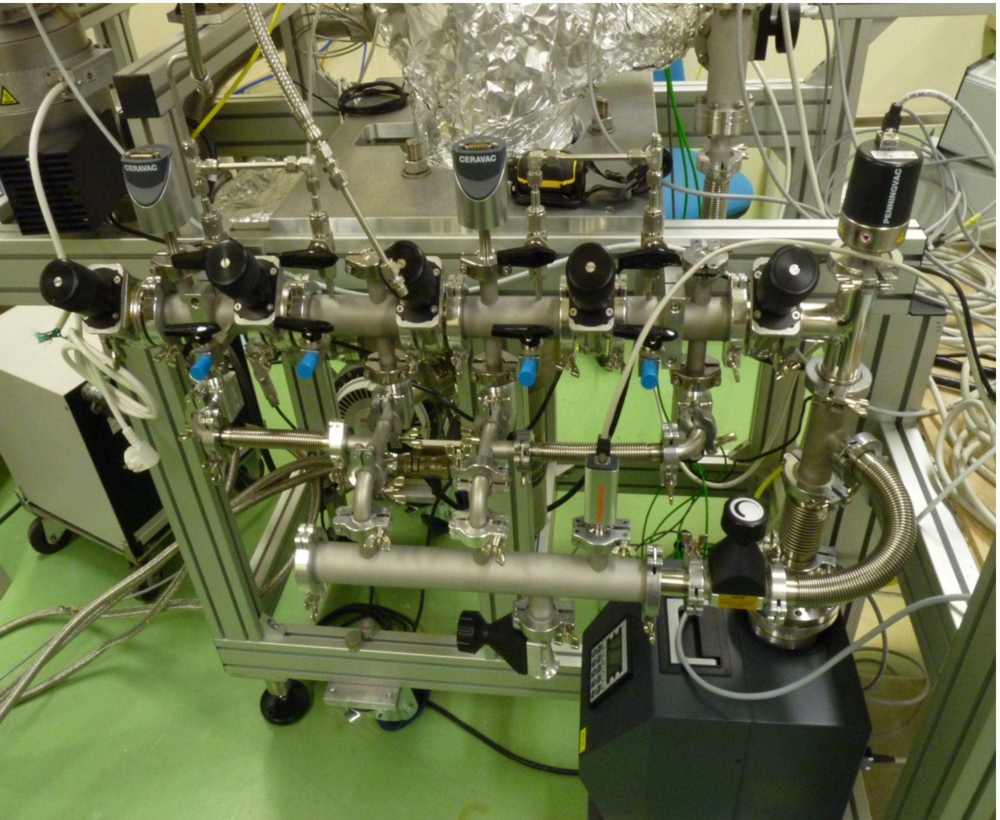
- IGLIAS : new ultra high vacuum setup (1 10^{-10}mbar)

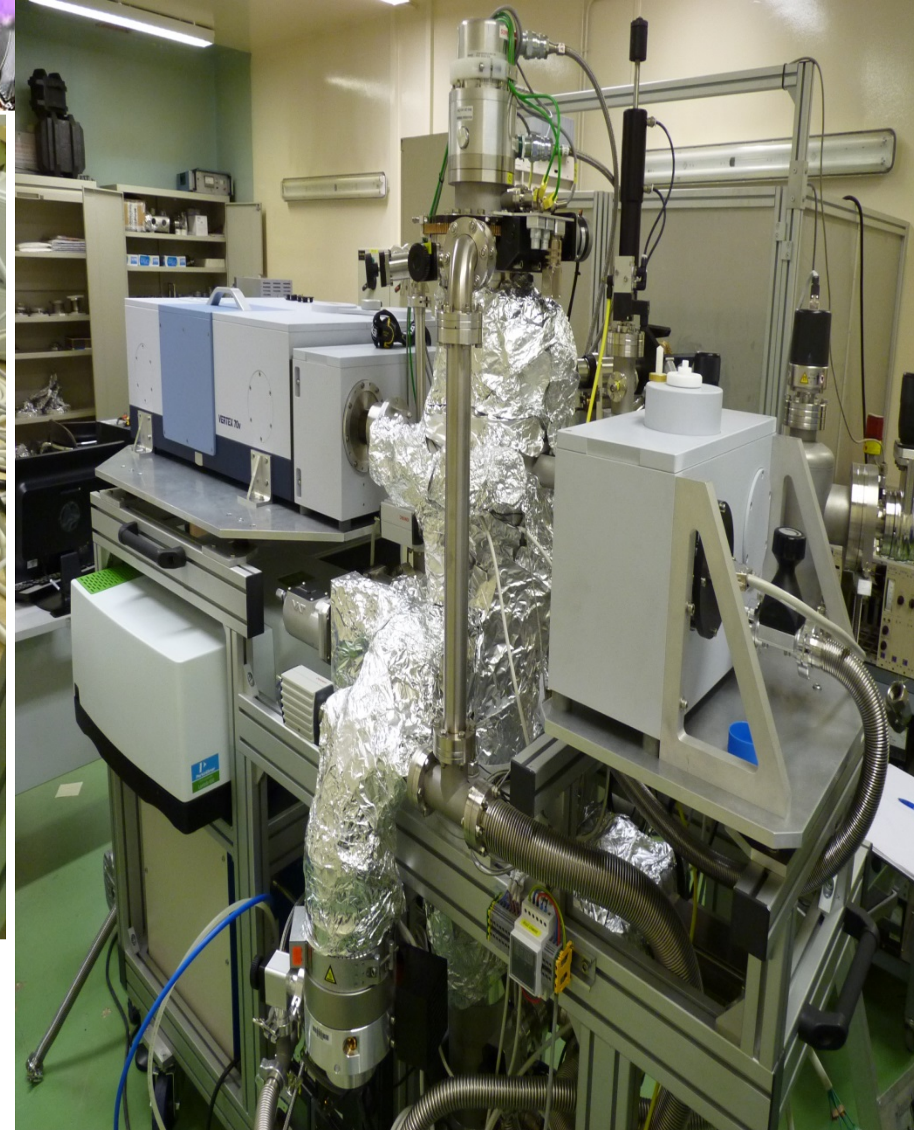


- New system :
- 1 10^{-10} mbar (1 ML of water per hour)
- Online device with two spectrometers:
    - - IR Bruker V70 (under primary vaccum, (500-6000 cm^{-1})
    - - UV visible Perkin (200-800 nm, transmission, optical fiber).
    - - for samples: 3 windows, 20 mm diameter (bigger residues).
    - Up to 4 gas for the deposition, co deposition avalaible.
    - QMS, electron gun.
    - Open to the scientific communitee!

Some pictures:







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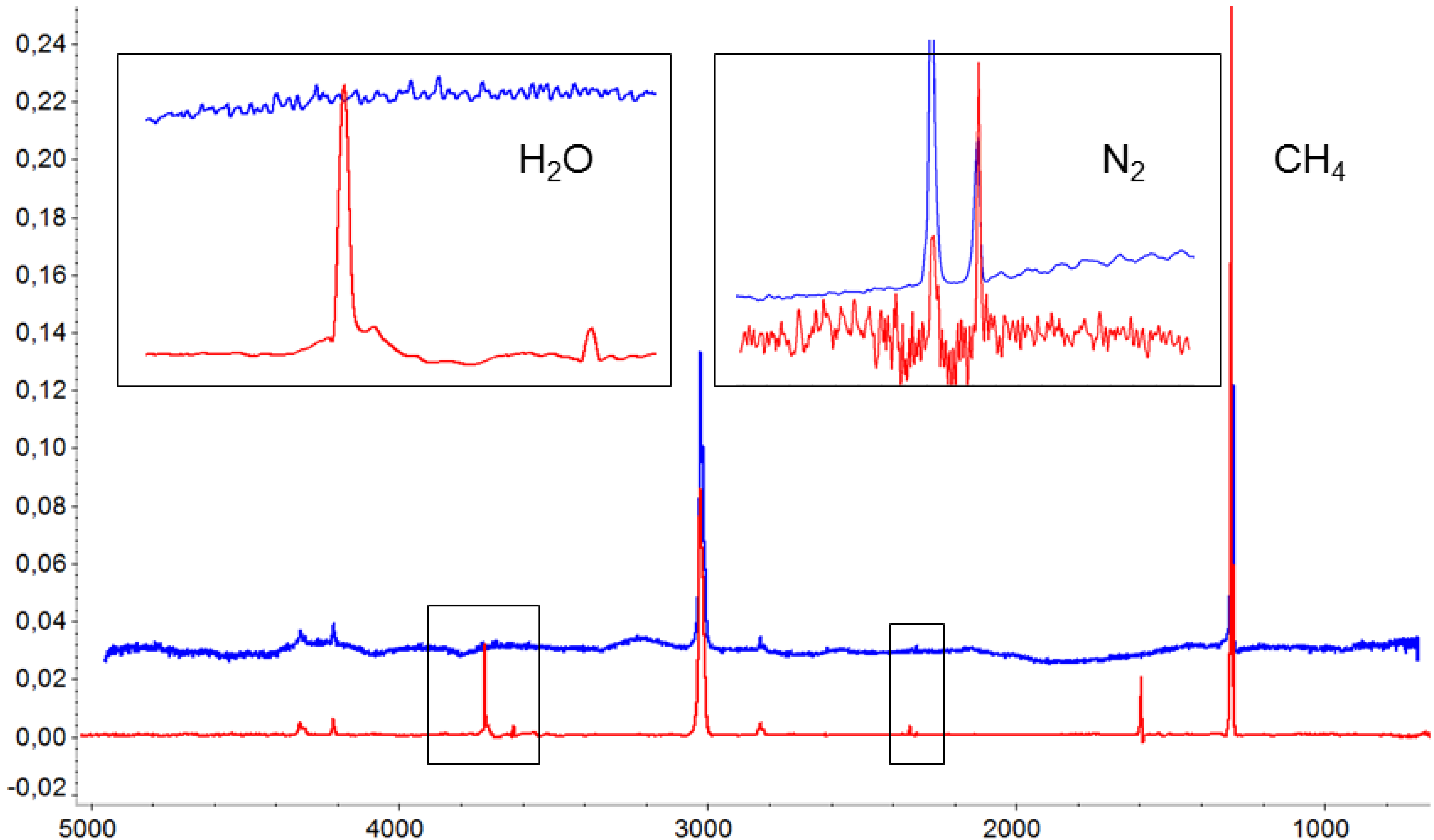
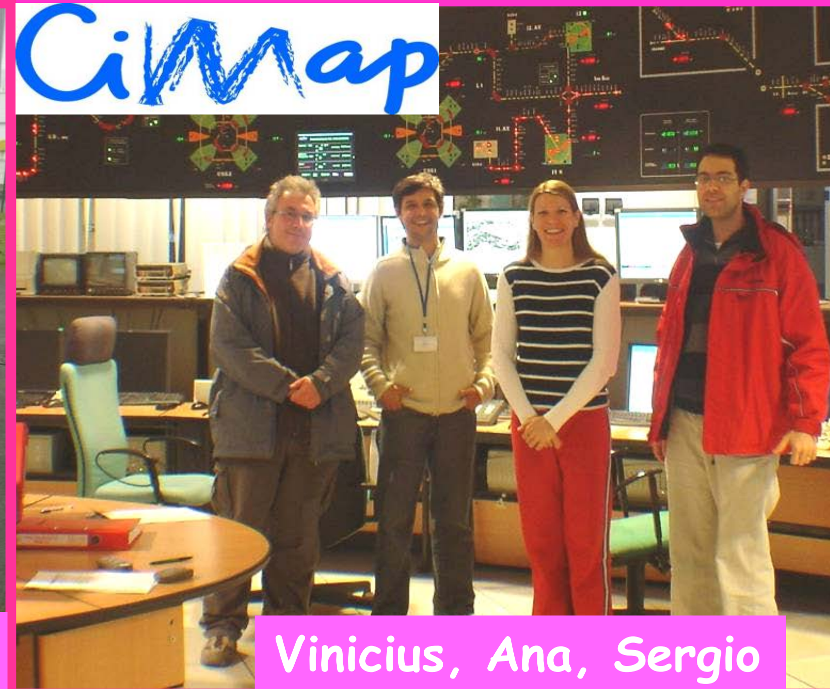
nom

N_2-CH_4 (98:2), CASIMIR and IGLIAS



Thank you

Jingjie, Xueyang, Gianni, Thomas, Hermann, Philippe, Stéphane



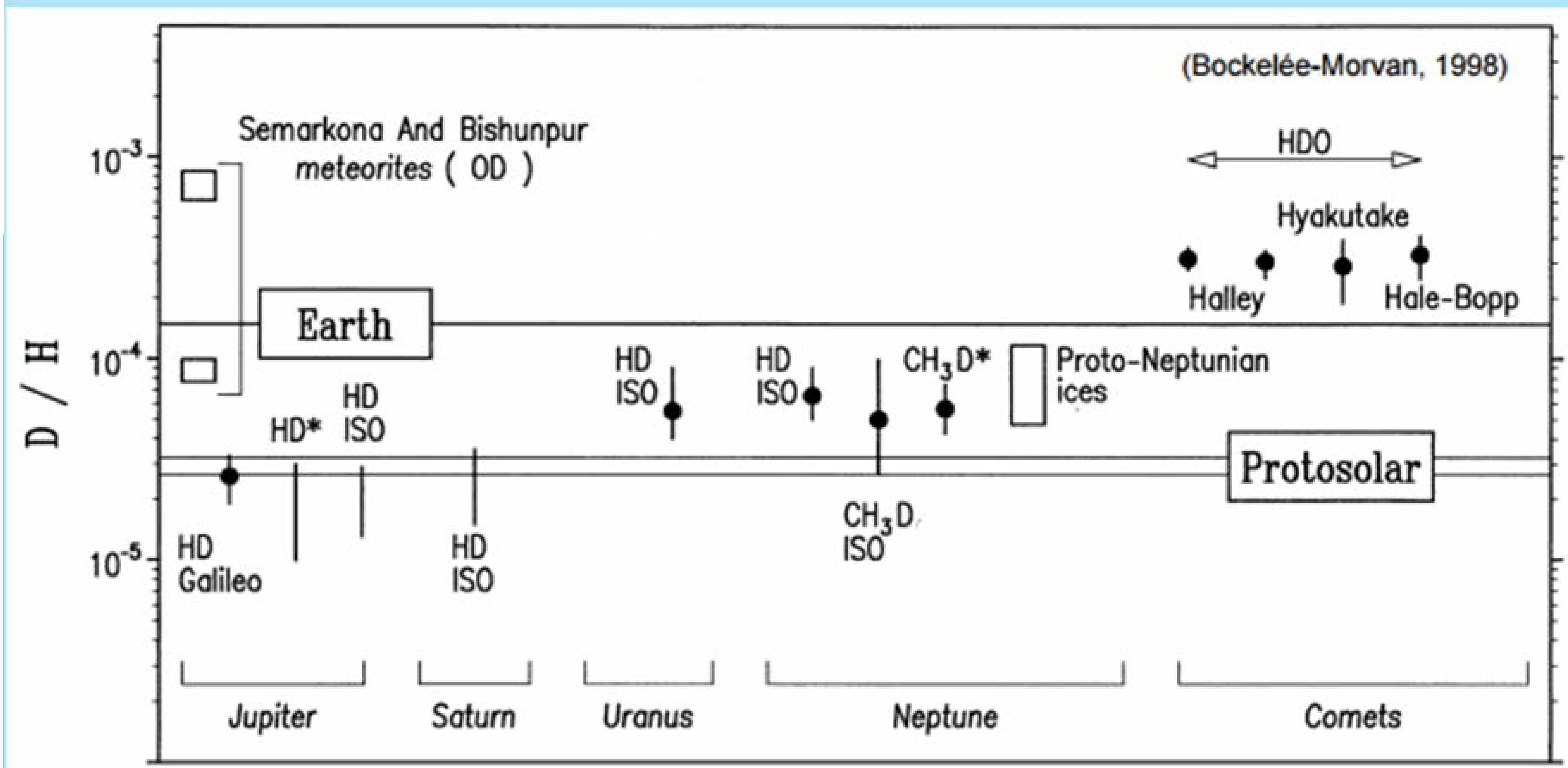
Vinicius, Ana, Sergio

Hussein+Enio

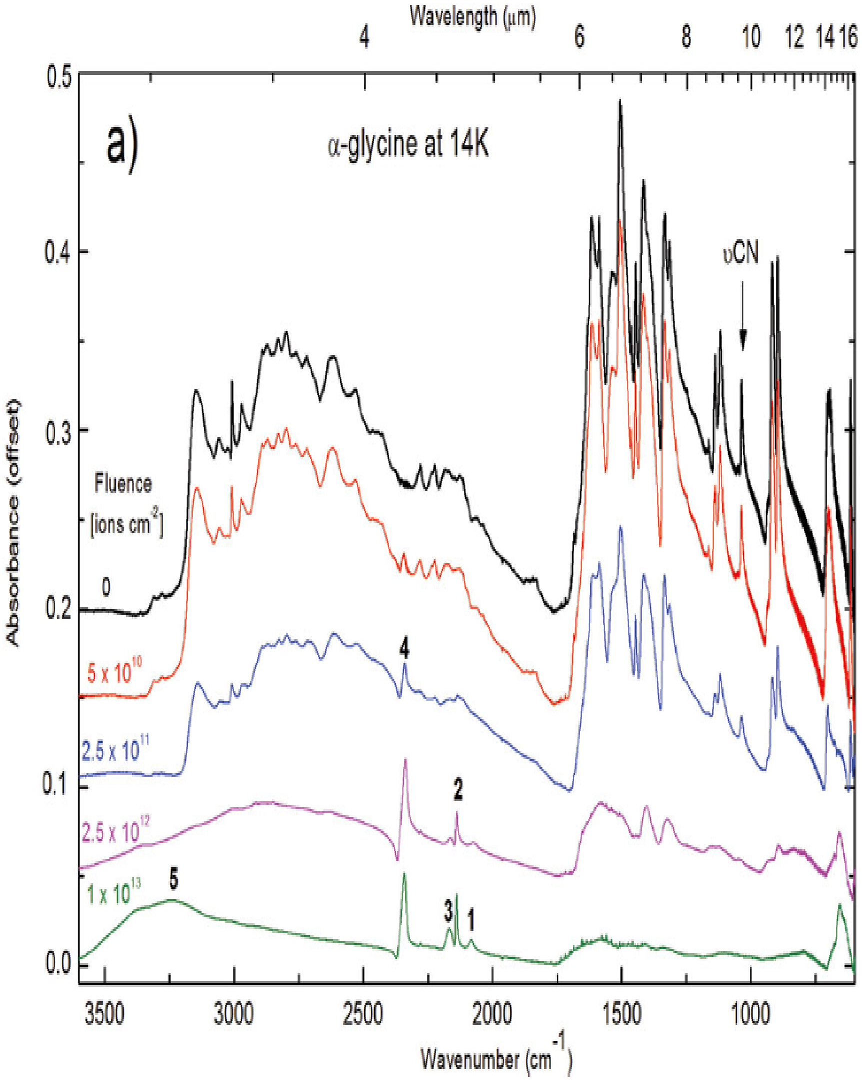
Eduardo

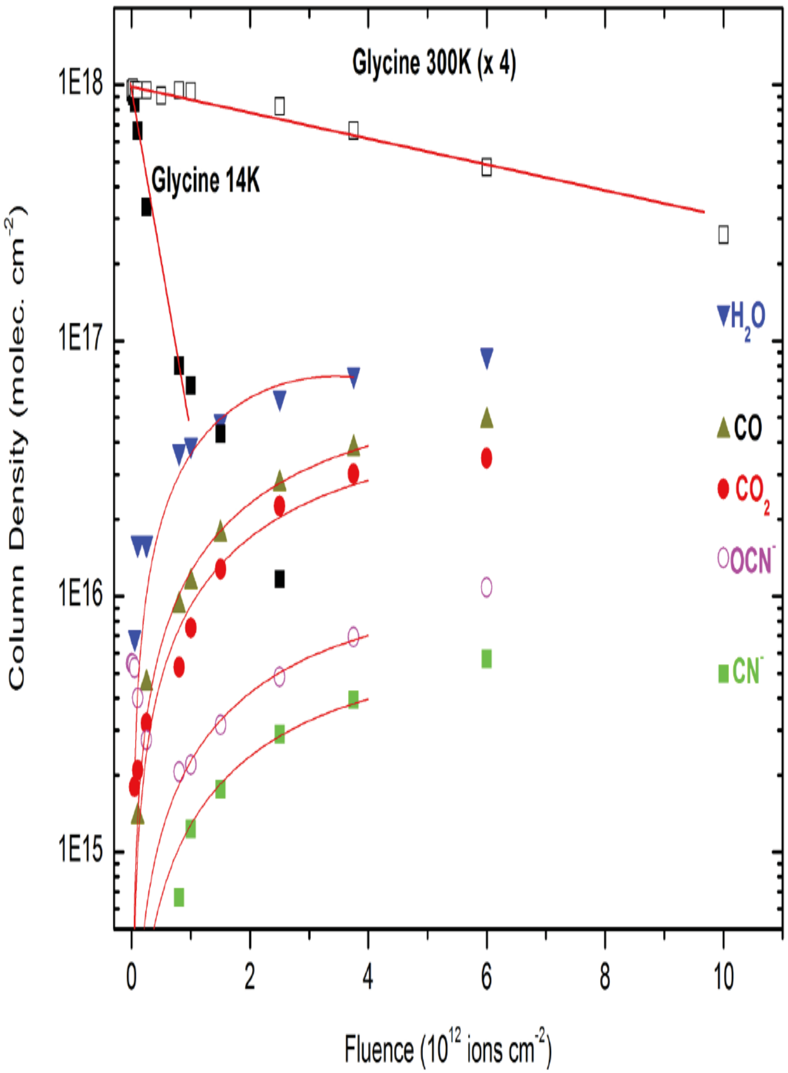
Emmanuel

Alicja


(Bockelée-Morvan, 1998)
Semarkona And Bishunpur
meteorites (OD)
HDO
Hyakutake
Halley
Hale-Bopp
Earth
D / H
10^-3
10^-4
10^-5
HD
ISO
HD
ISO
CH3D*
Proto-Neptunian
ices
HD*
HD
ISO
Protosolar
HD
Galileo
HD
ISO
CH3D
ISO
Jupiter
Saturn
Uranus
Neptune
Comets

Glycine at 14K and 300 K $^{58}Ni^{11+}$@ 46MeV





Destruction cross section:

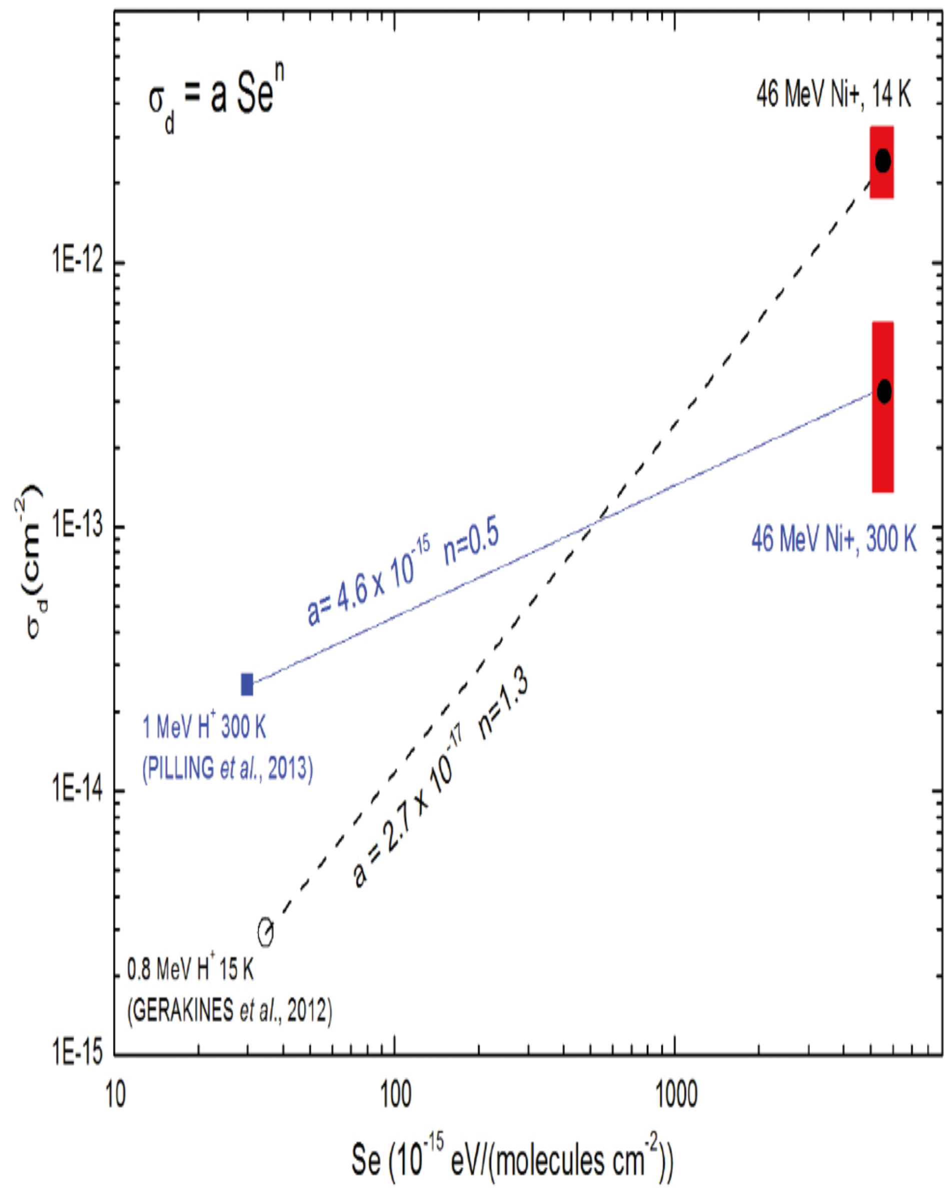
$\sigma=2,4\ 10^{-12}\ cm^2$ @ 14K

$\sigma=3,4\ 10^{-13}\ cm^2$ @ 300K

Temperature effect

$$\sigma=AS_e^n$$

Temperature (K)	n
14	1.3
300	0.5



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