How to **simulate cosmic ray** and **solar wind** interaction with **astrophysical materials** in the **laboratory**

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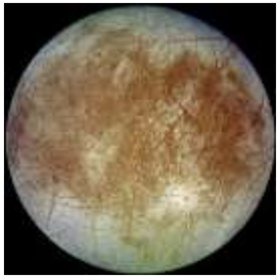
Boulevard Henri Becquerel, BP 5133, F-14070 Caen Cedex 05, France

astrophysical materials:

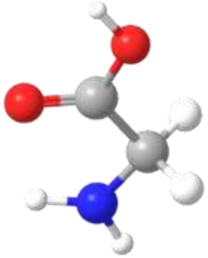
carbonaceous, **Silicates**, and **Ices**



laboratory simulation:

solar wind, ions trapped in magnetospheres,
and ***cosmic rays***

at heavy **ion accelerators**
GANIL Aribe, Irrsud, SME, HE
+ GSI Unilac: from **keV** to **GeV**



Infrared absorption spectroscopy FTIR
TOF-SIMS, QMS, QCM

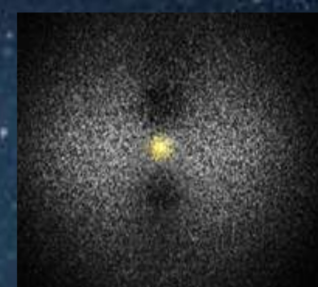
CiMap

Radiation effects (ices, silicates)

→ Comets

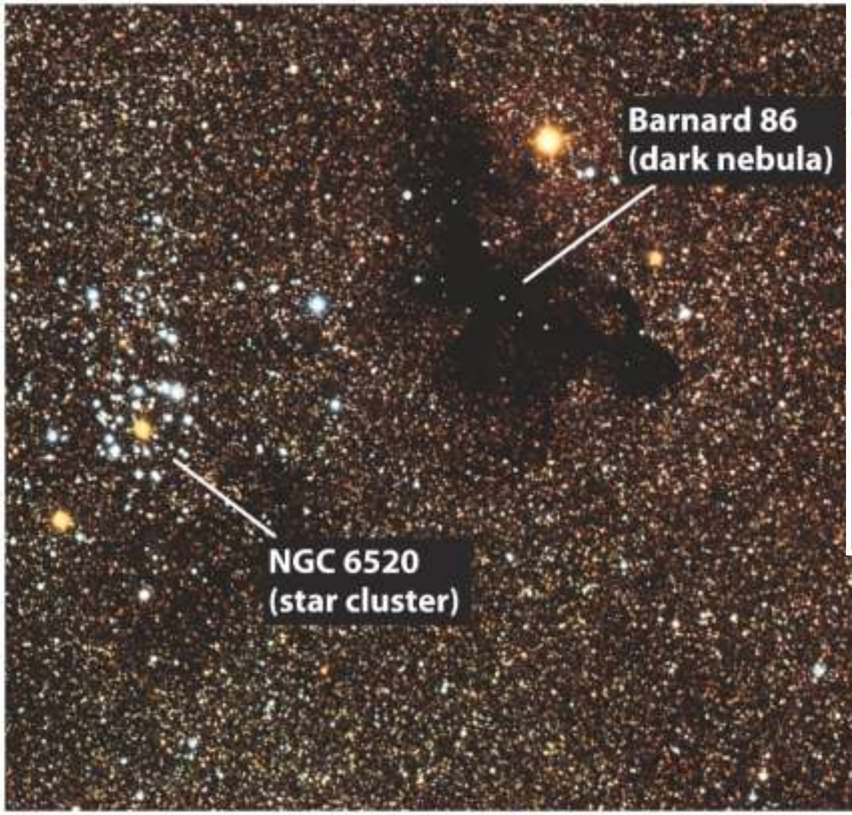
→ Satellites of giant planets
(Europa, Ganymed, Titan…)

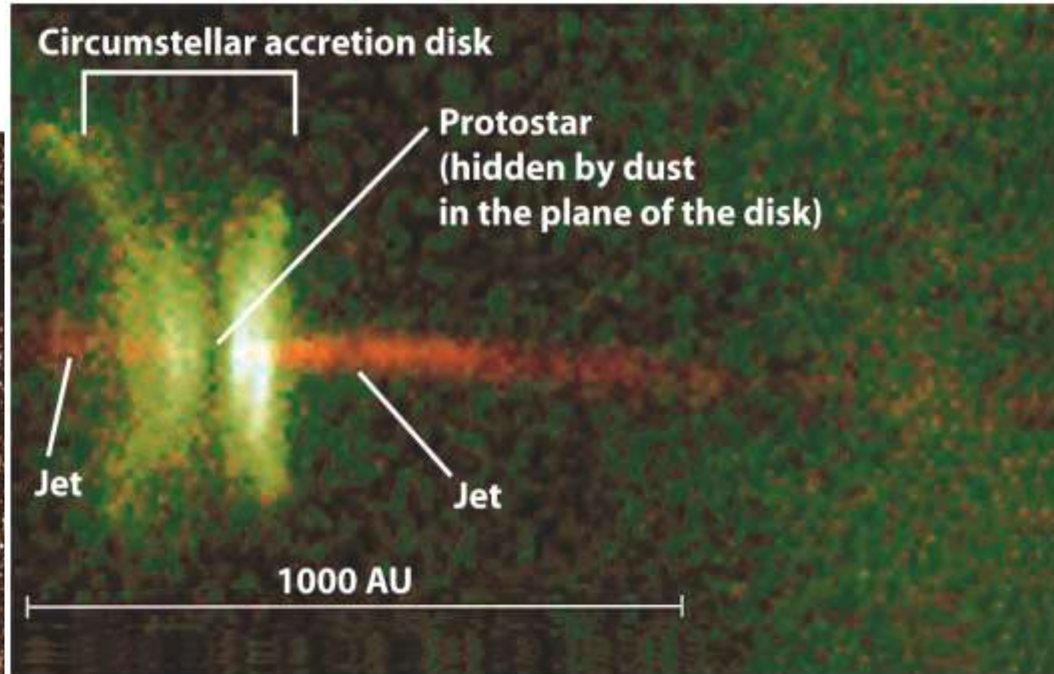
→ Dust grains

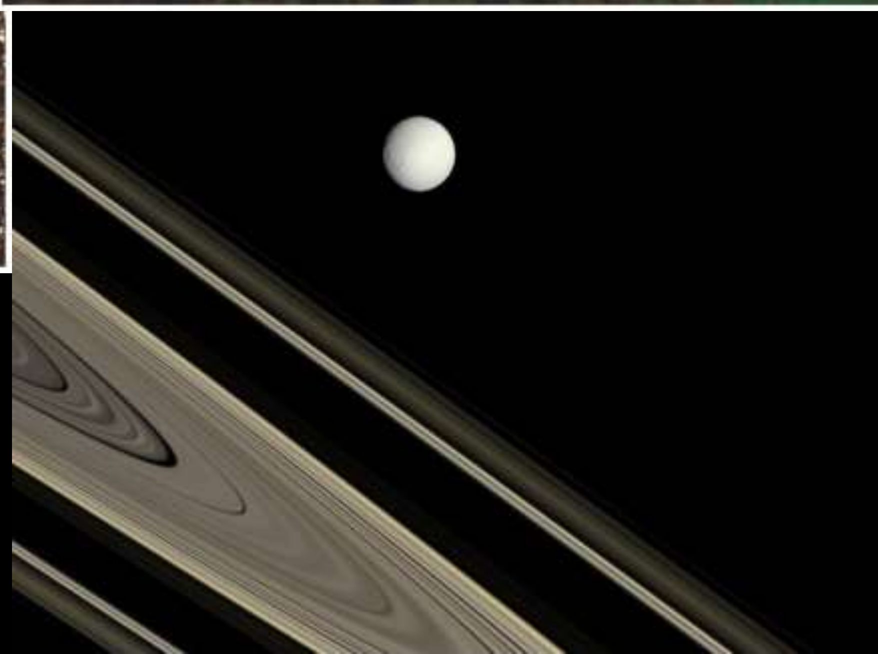


Solar wind, cosmic rays, planetary magnetic fields

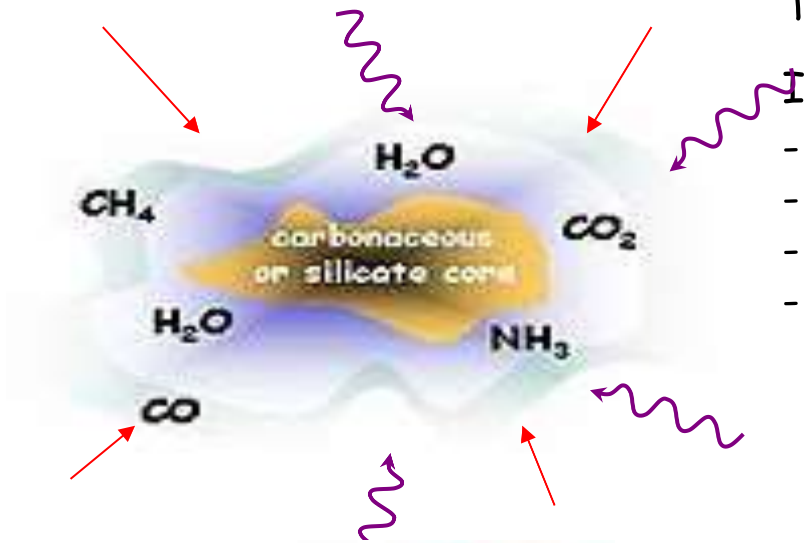
Astrophysical ices







Radiation Processing of Astrophysical ices



Thermal processes

Irradiation with:

- cosmic rays;
- stellar (solar) wind;
- UV radiation;
- magnetosphere (high and low-energy).

Irradiation induced physical-chemical modification within ice and also desorption of species from ice

Missions of CIMAP

« **Laboratoire d'Accueil** » for ***interdisciplinary research***
at GANIL (Grand Accélérateur National d'Ions Lourds)

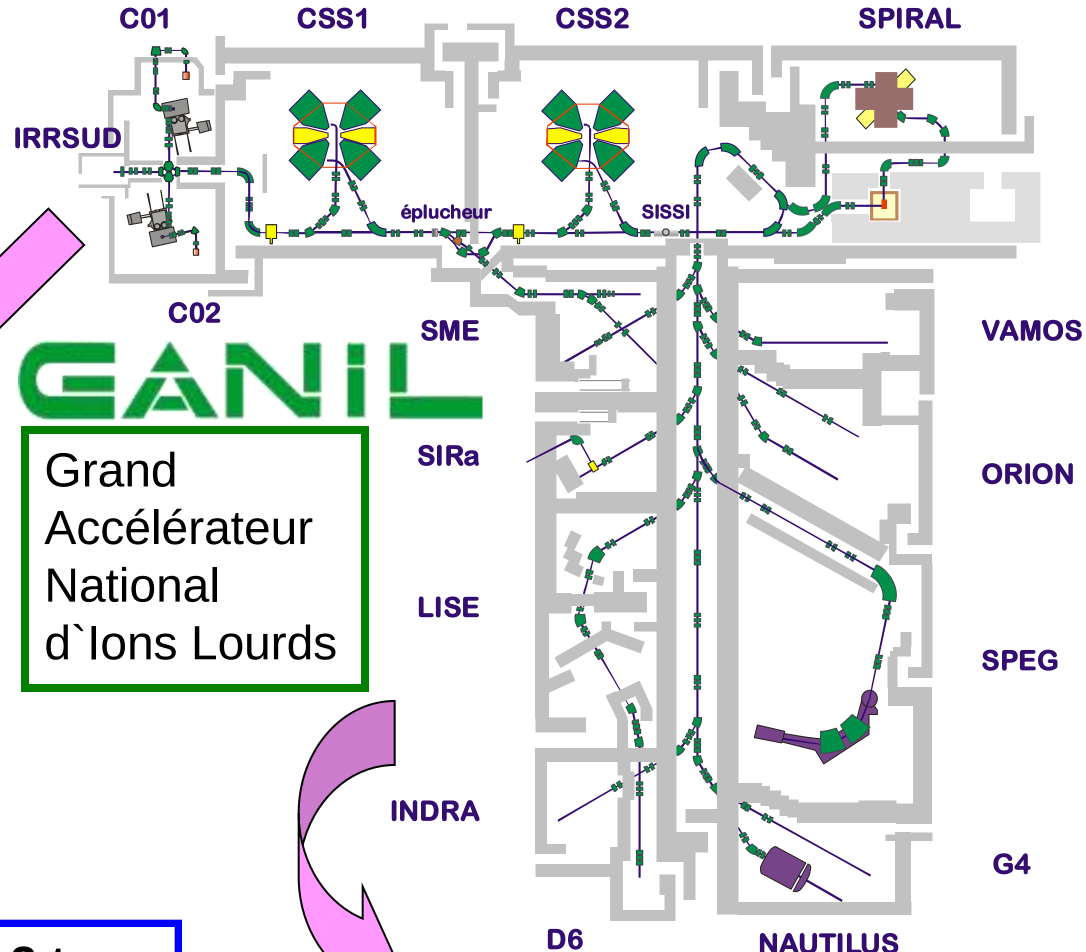
Teaching (University, ENSI engineering school;
Master + Ph. students, postdocs, visitors, ...)

Scientific Animation (organization of conferences, seminars, workshops; interdisciplinary Programm Advisory Committee iPAC; user meetings; networks …)

Research:

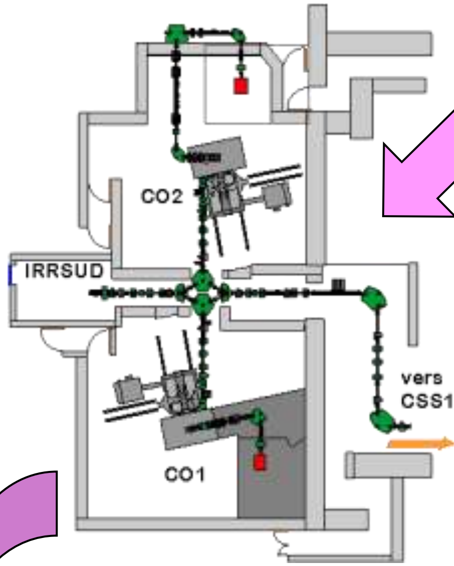
Matériaux, Lasers et Instrumentation

Interaction Ion - Matière



GANIL

Grand Accélérateur National d`Ions Lourds



0.3 to

1 MeV/u

IRRSUD

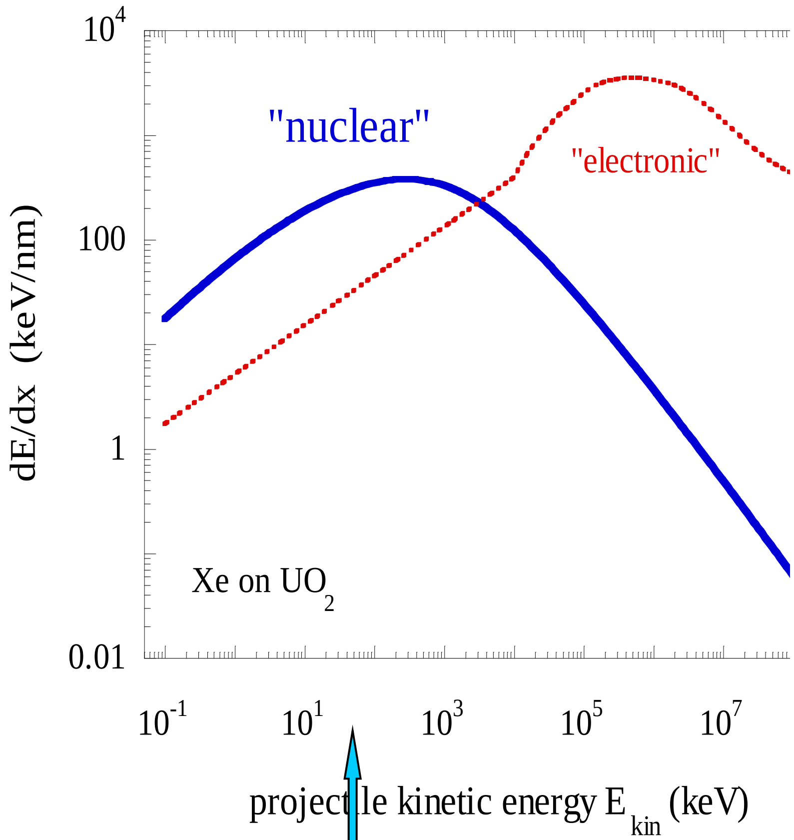
C to U

4 à 95 MeV/u

IRABAT

IRASME

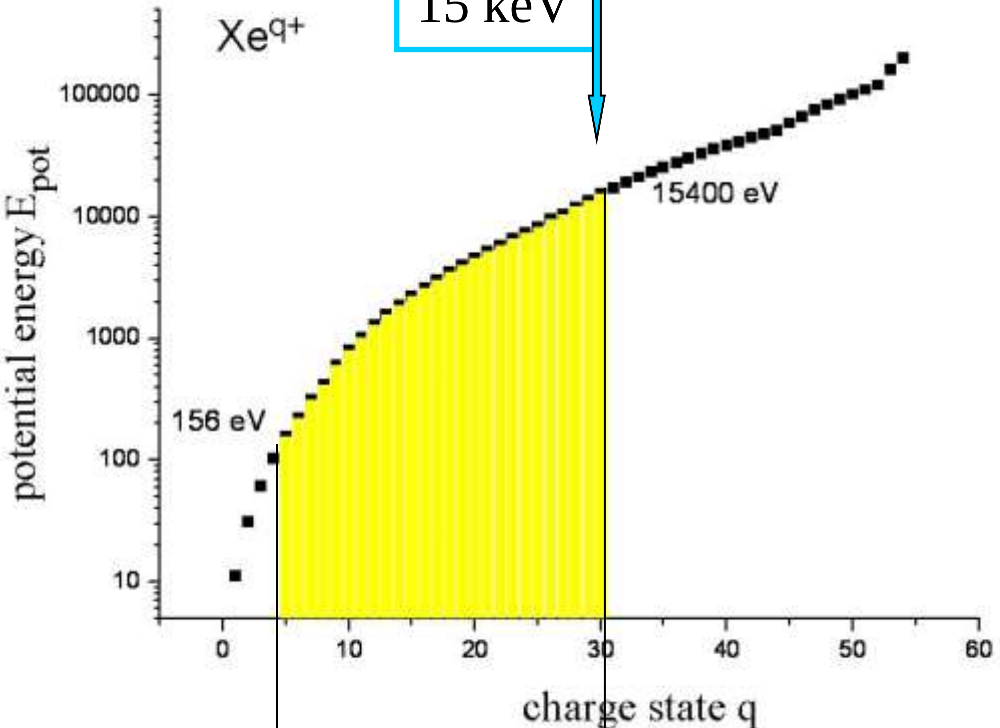
NUCLEAR vs. ELECTRONIC STOPPING: Xe → UO_2

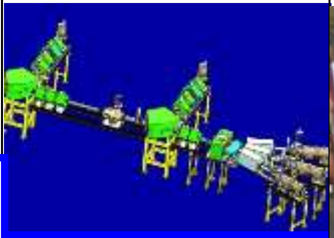


80 keV

Potential Energy

15 keV

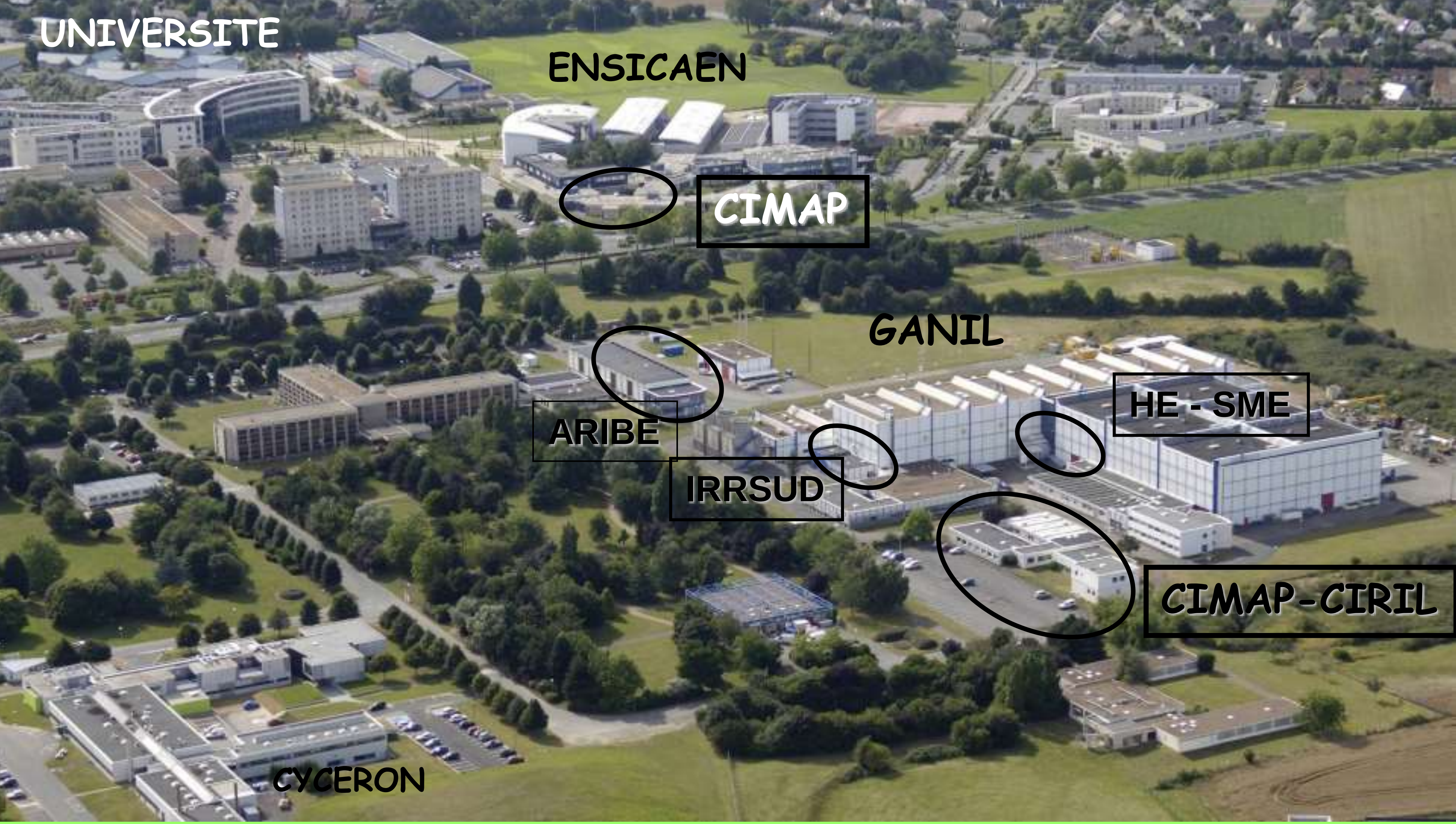




Very low energy

q keV … q eV

A R I B E


UNIVERSITE
ENSICAEN
CIMAP
GANIL
HE - SME
ARIBE
IRRSUD
CIMAP-CIRIL
CYCERON


CiMap

Some

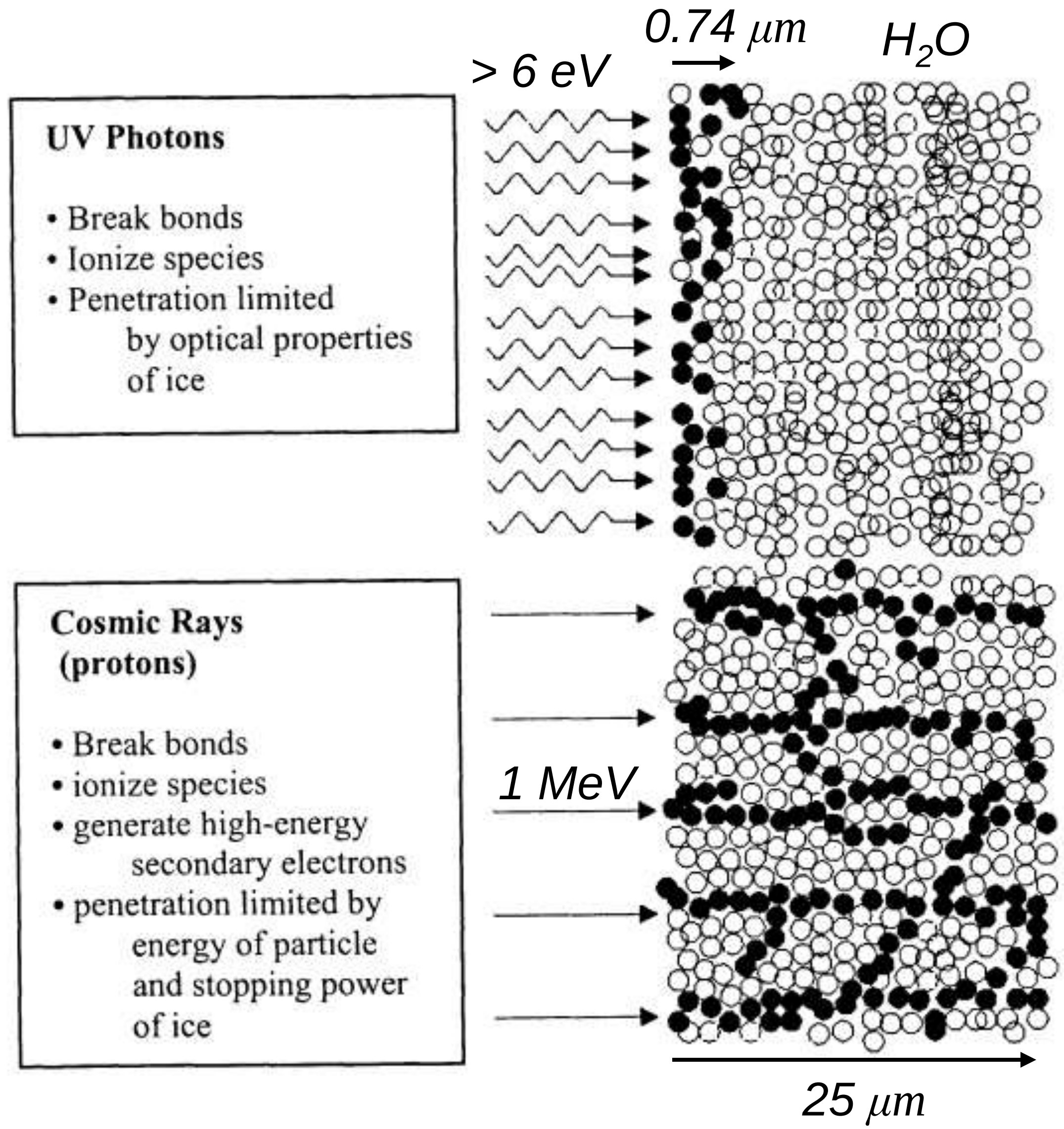
Physics

Ice-processing effects caused by UV and cosmic rays

UV PHOTONS

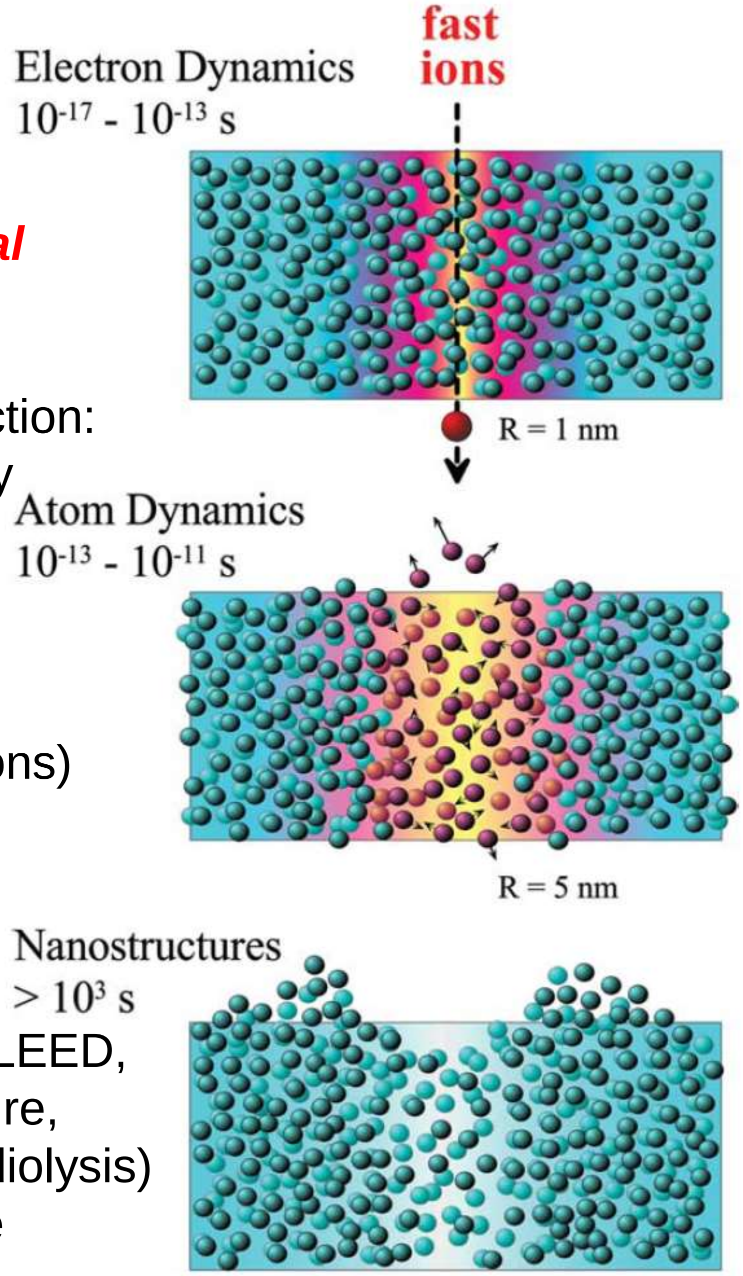
Laboratory simulations of relevant targets bombarded with fast charged particles and photons.

Cosmic Rays (MeV-GeV Ions)



Gerakines et al. J. Geo. Res. (2001) **106** 381

Experimental Probe:



Electron Ejection: Spectroscopy

Sputtering (Neutrals, Secondary Ions)

Microscopy, LEED, FTIR (structure, chemistry,radiolysis) + many more

Coulomb Explosion ?

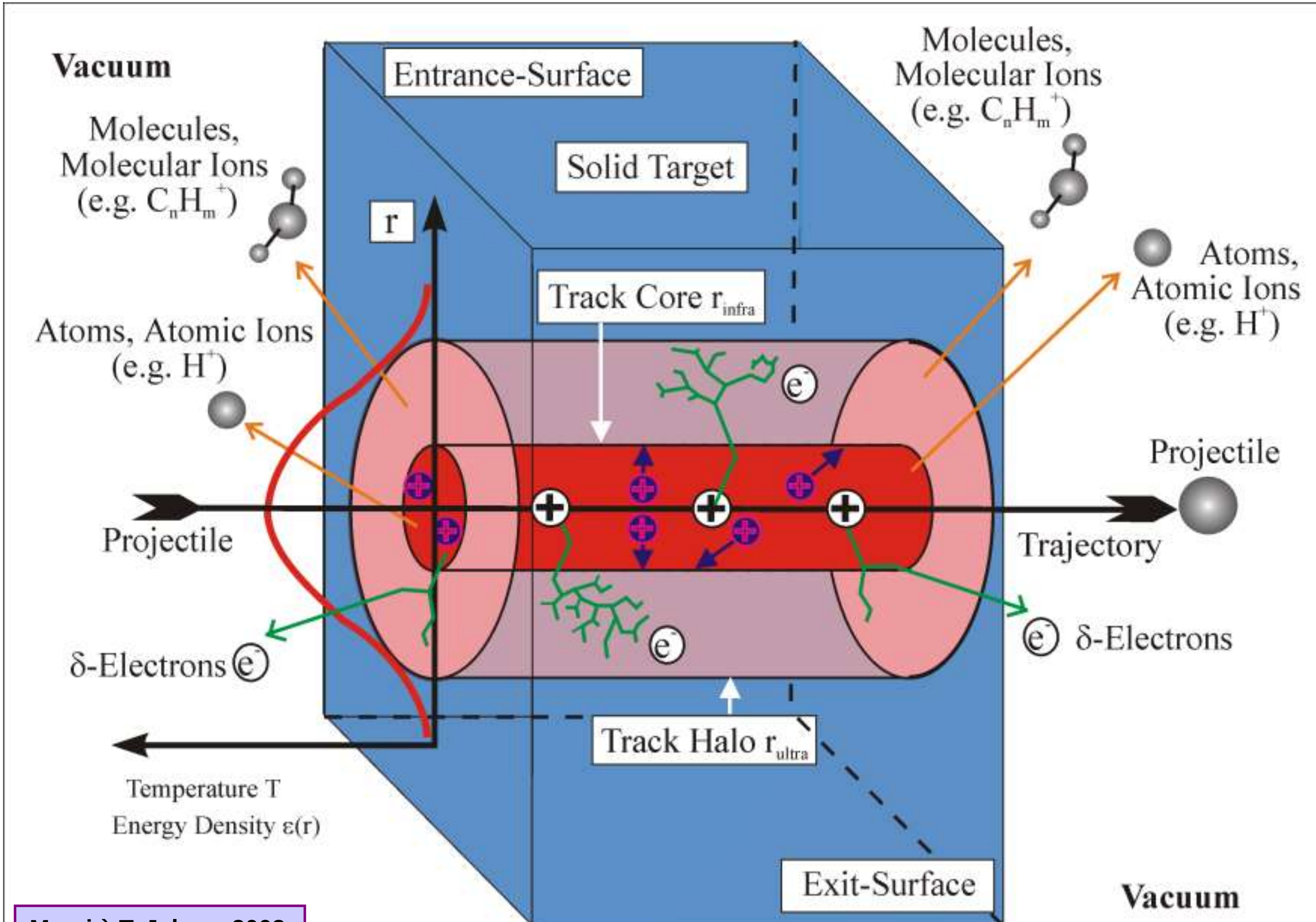
Thermal Spike ?
M.Toulemonde et al. NIMB 212 (2003) 346

(Excitons ?)

(non-) linear cascade

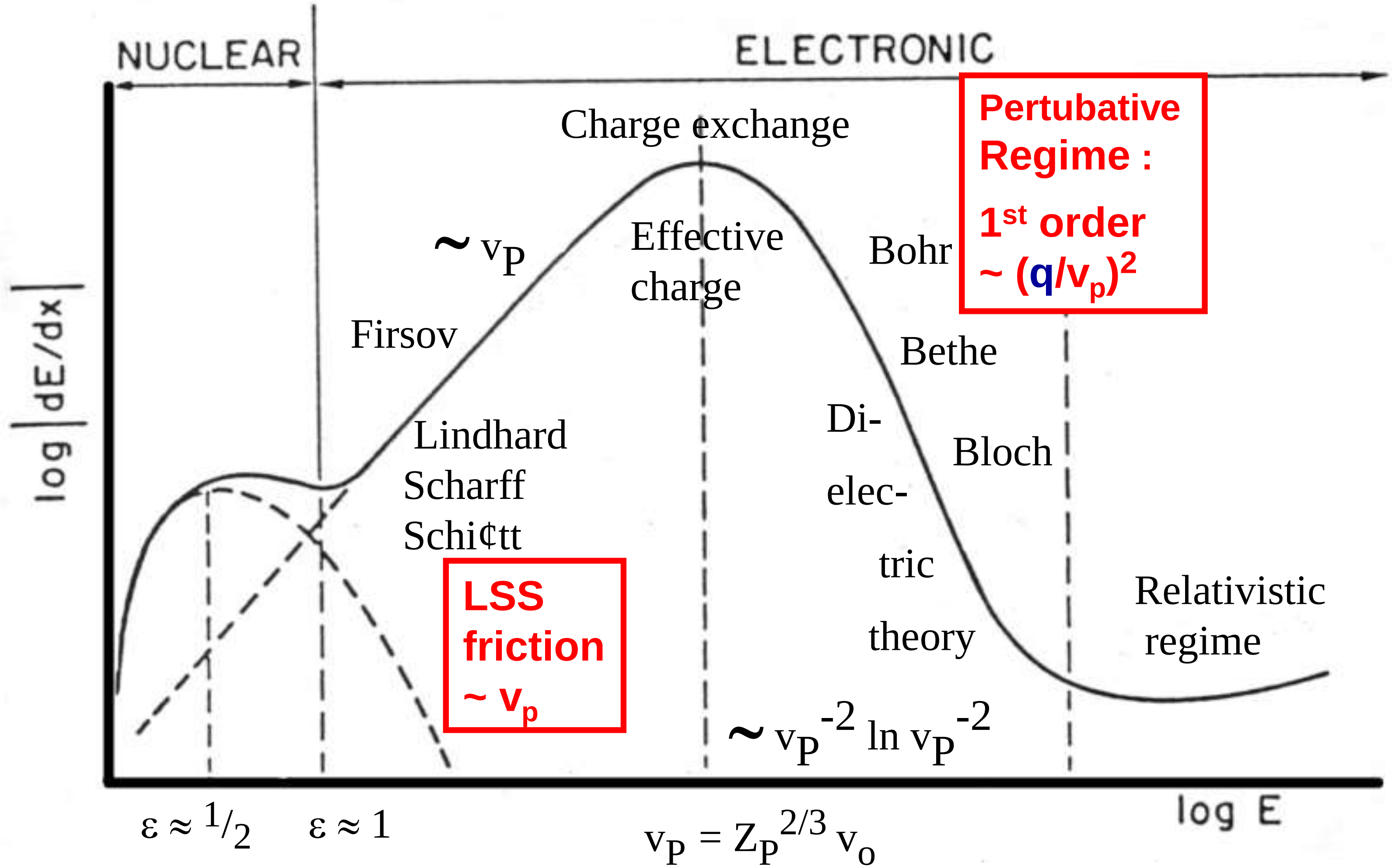
G. Schiwietz, K. Czerski, M. Roth, F. Staufenbiel, P.L. Grande

NIM B226 (2004) 683



Merci à T. Jalowy 2003

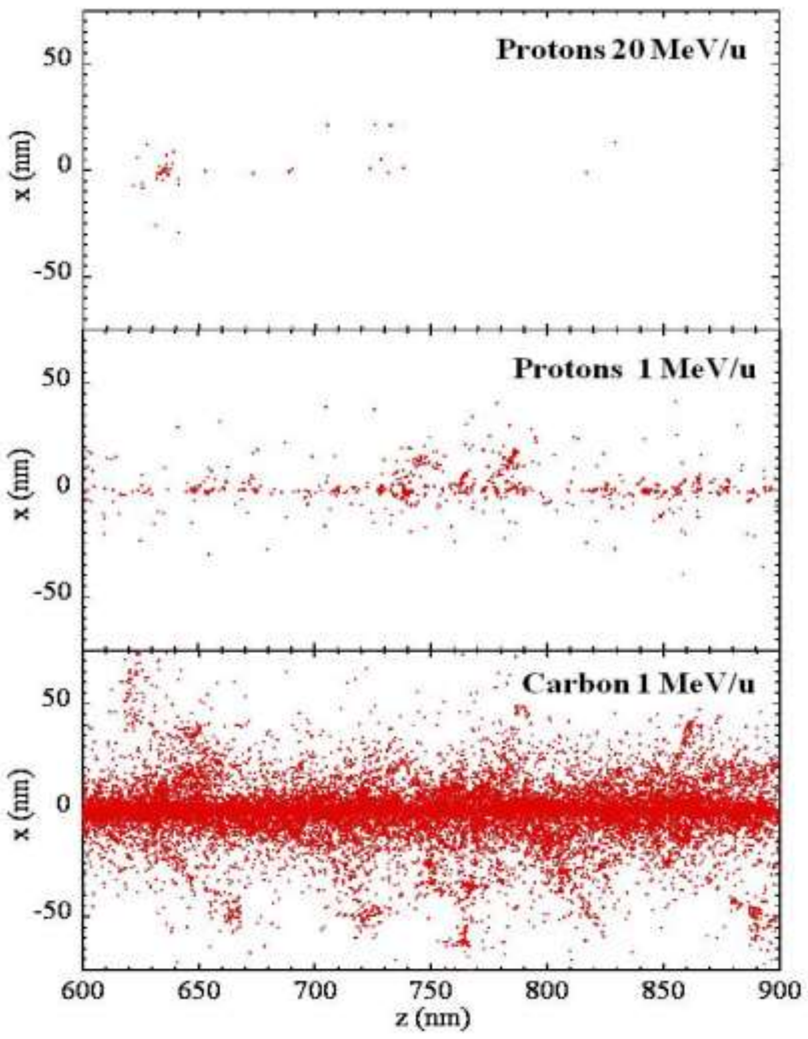
Energy loss as a function of projectile energy



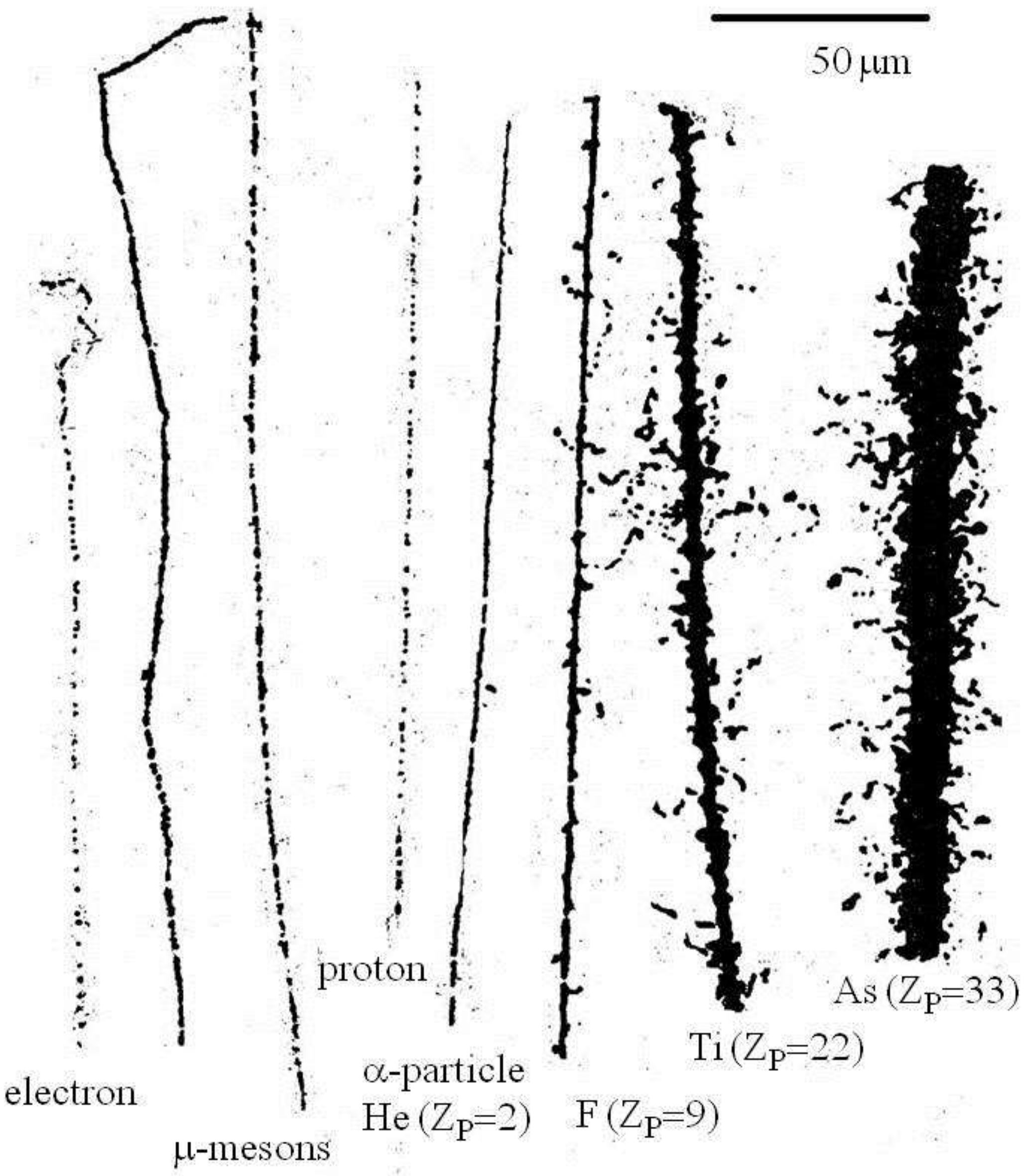
solar/stellar wind

cosmic rays

Ion Nuclear Tracks



Particle Tracks (≈ 10 MeV/u) in photographic Emulsion



merci à B. Gervais

Ion beam

Secondary particle emission → analysis

Neutrals (atoms, molecules, cluster…)

Ions

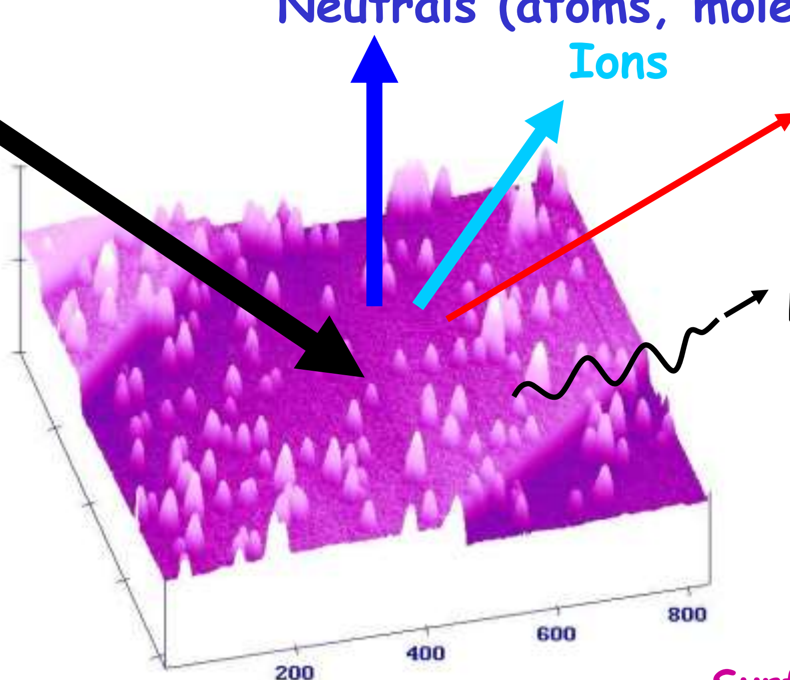
Electrons

Energy deposition

(energy loss)

↓

Strong electronic excitation



Photons

Sputtering

(particle ejection)

Tracks

(bulk,

surface)

chemistry e.g. FTIR

Surface Modification

Bulk: quasi one-dimensional nanostructure

Defects
Radiolysis

Experimental approaches

FTIR infrared absorption spectroscopy: ice bulk analysis based on the infrared absorptions due to molecular vibrations.

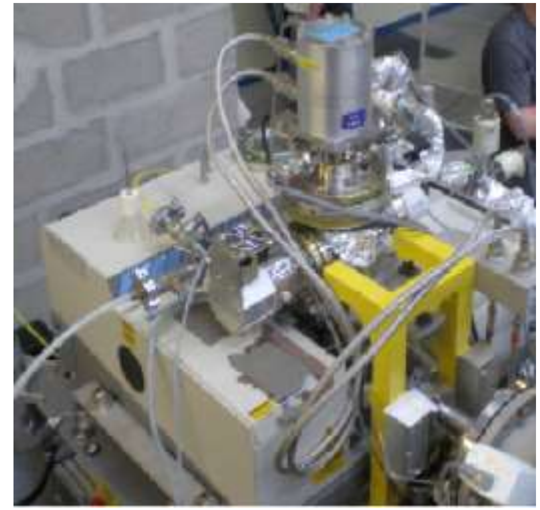
TOF-SIMS mass spectrometry:

surface analysis via the desorbed ions by measuring their time-of-flight from the target to the detector

QMS mass spectrometry

QCM (quartz crystal microbalance)

and many more ...



Complementary and Emerging Techniques for Astrophysical Ices Processed in the Laboratory

M.A. Allodi · R.A. Baragiola · G.A. Baratta · M.A. Barucci · G.A. Blake · P. Boduch · J.R. Brucato · C. Contreras · S.H. Cuylle · D. Fulvio · M.S. Gudipati · S. Ioppolo · Z. Kaňuchová · A. Lignell · H. Linnartz · M.E. Palumbo · U. Raut · H. Rothard · F. Salama · E.V. Savchenko · E. Sciamma-O'Brien · G. Strazzulla

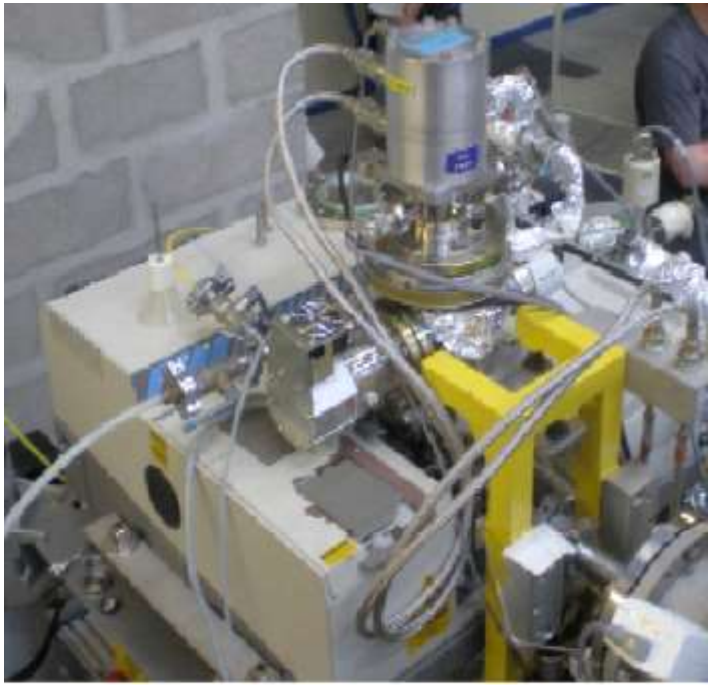
Space Science Review (2013)180:101-175

Spectroscopy: Raman
UV-visible
THz
Luminescence

Chromatography (organics)

Fourier Transform Infrared Specroscopy

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

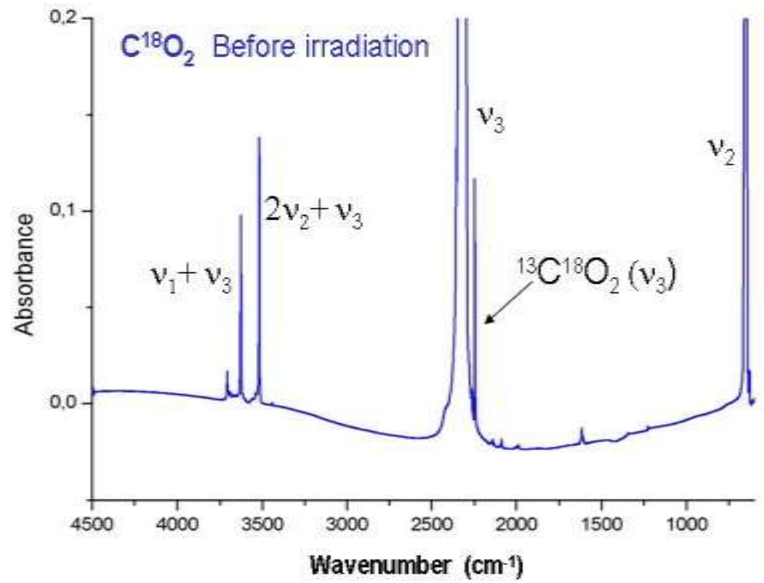


FTIR Fourier Transform Infrared Absorption Spectroscopy: molecular vibrations

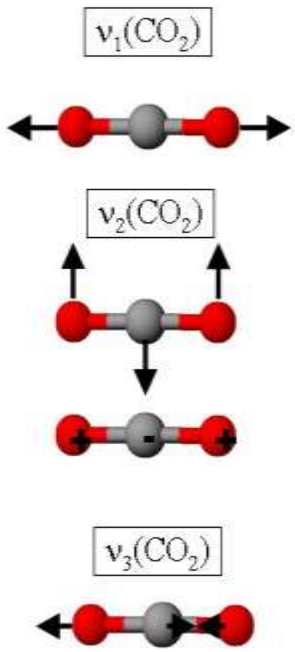
plenty of information:

Absorption Line Position + Shape:
identification of molecules,
environment ("dangling bonds": porosity ...)
structure (crystalline, amorphous)

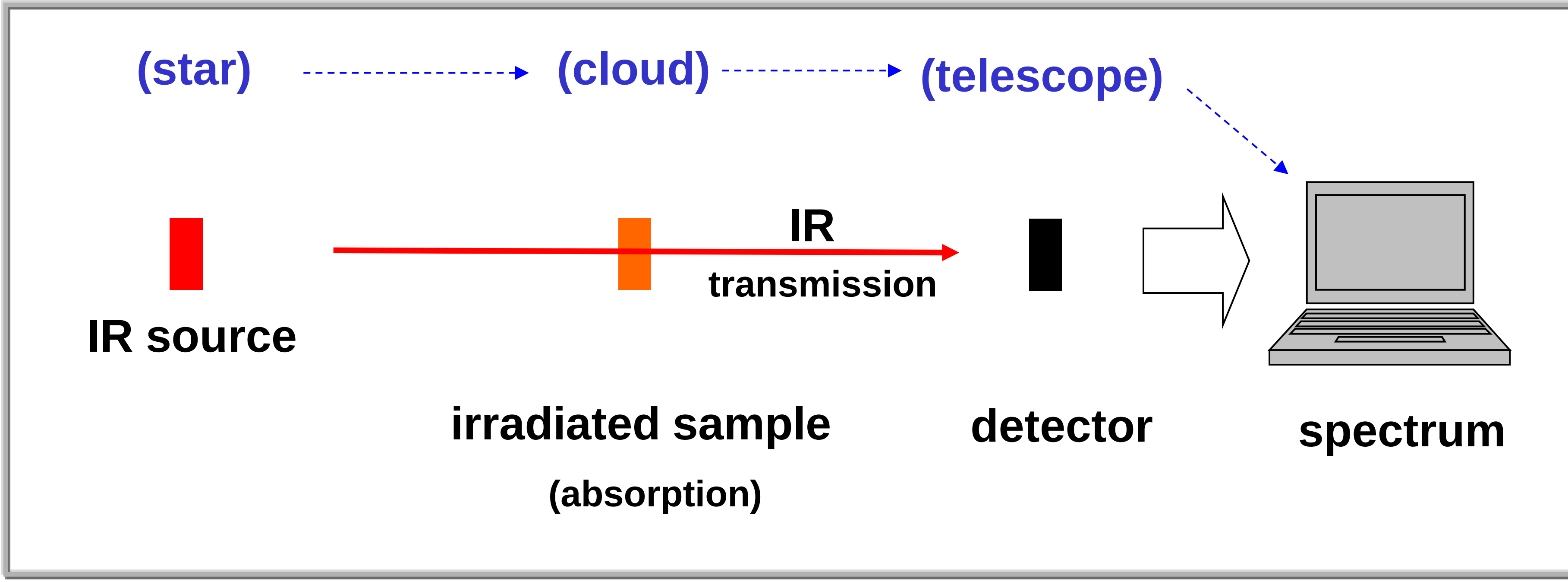
Integral (Surface)
columnar density (thickness)
evolution with projectile fluence: disappearance and synthesis of molecules

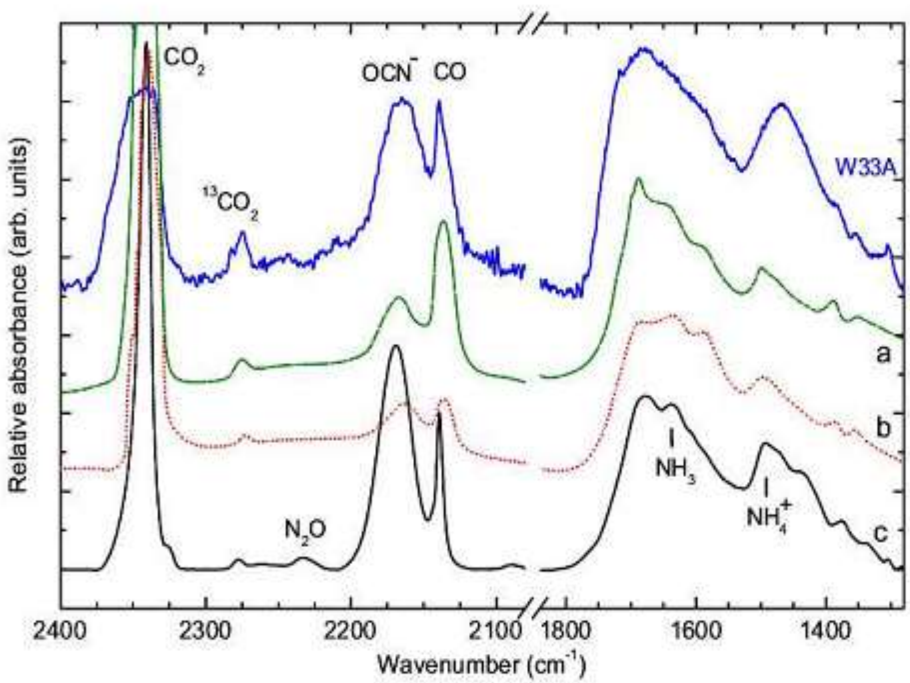


FTIR spectrum of $C^{18}O_2$ ice at 15 K



but:
detection of symmetric molecules (O_2, N_2 ...) difficult





Space observation:

ISO Infrared Space Observatory, protostellar source W33a

Laboratory simulation:

UV photons

protons

heavy ions

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

CASIMIR @ IRRSUD and SME

Ion beam (Grand Accélérateur National d`Ions Lourds)

- 46 MeV $^{58}Ni^{11+}$, 50 MeV $^{64}Ni^{13+}$, 537 MeV $^{64}Ni^{24+}$
- ion penetration depth > ice thickness
- flux ~10^9 ions / (cm^2 s)
- fluence up to 1.5×10^{13} ion/cm^2

Substrate

CsI

Temperature

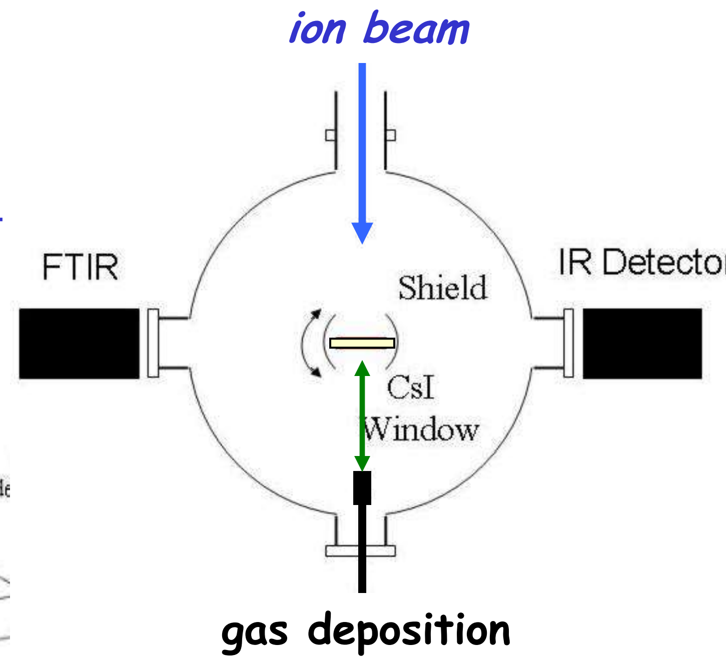
13 K < T < 300 K

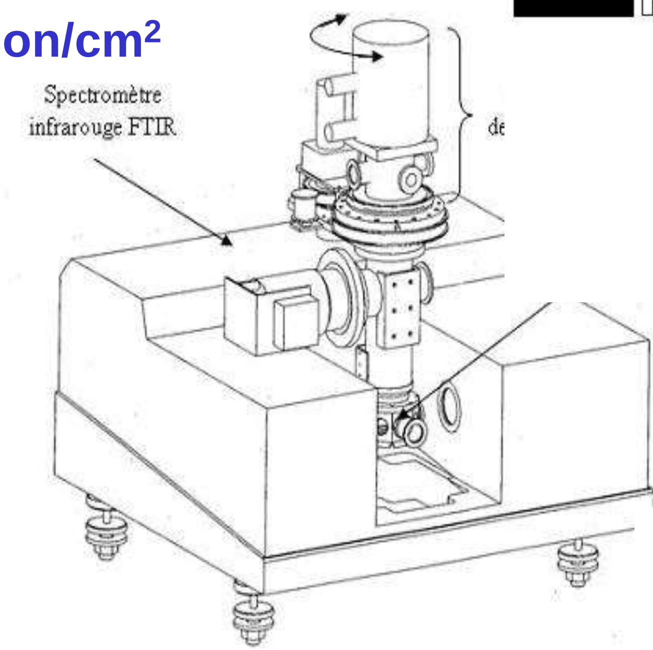
Samples (ices)

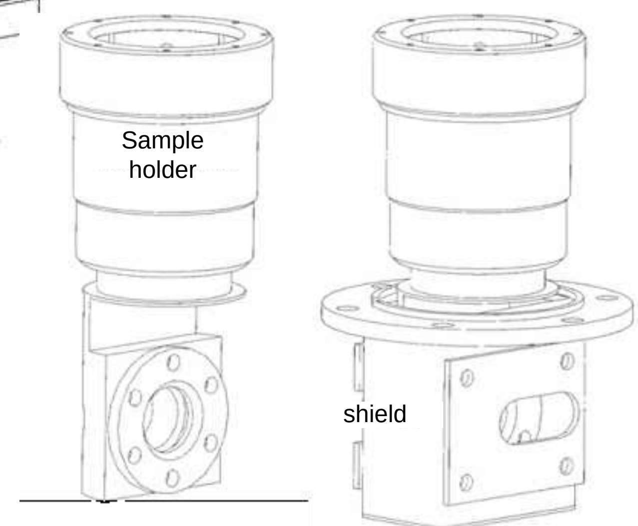
- *in situ* gas deposition
- thickness ~0.1 - 2 μm

Pressure in irradiation chamber

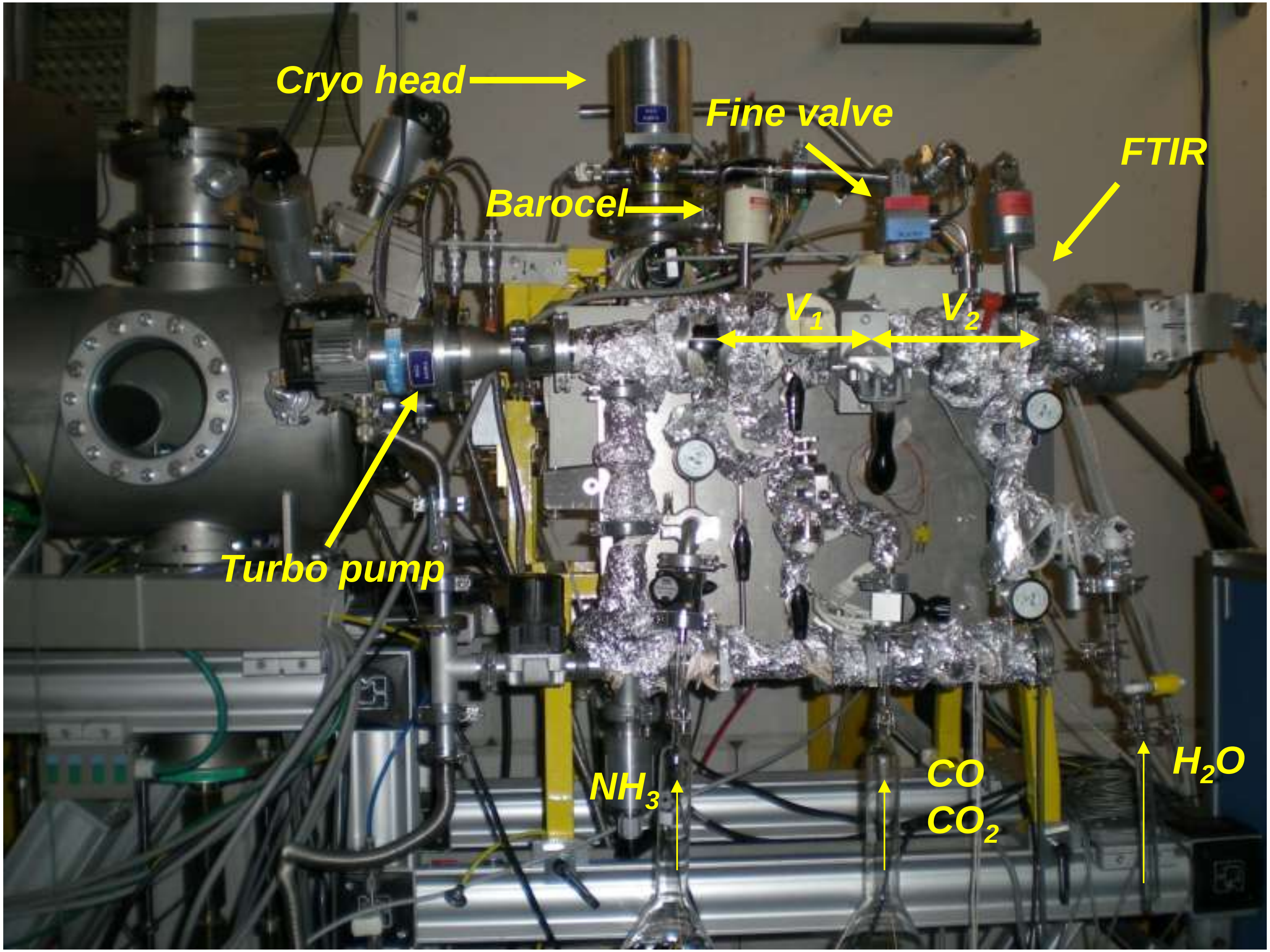
~$2\text{-}5 \times 10^{-8}$ mbar (13 K)





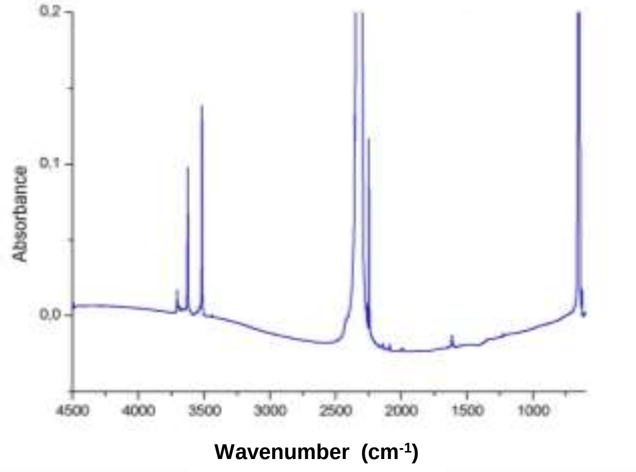


the "gas mixing and deposition machine"

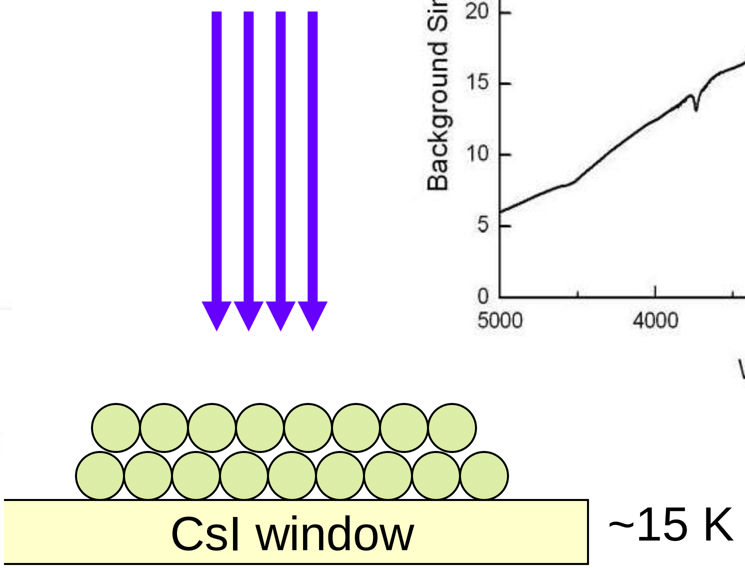


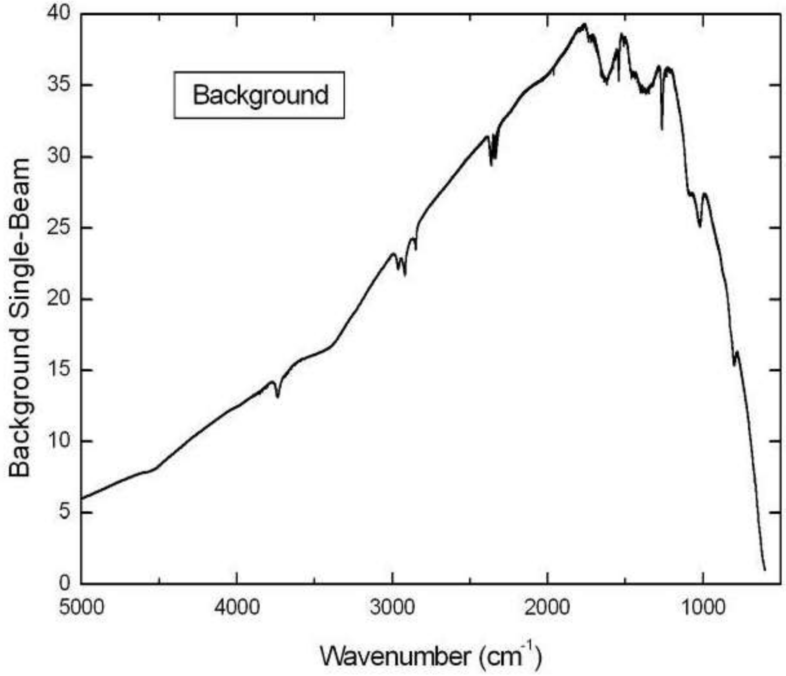
Experimental procedure

$C^{18}O_2$ Before irradiation

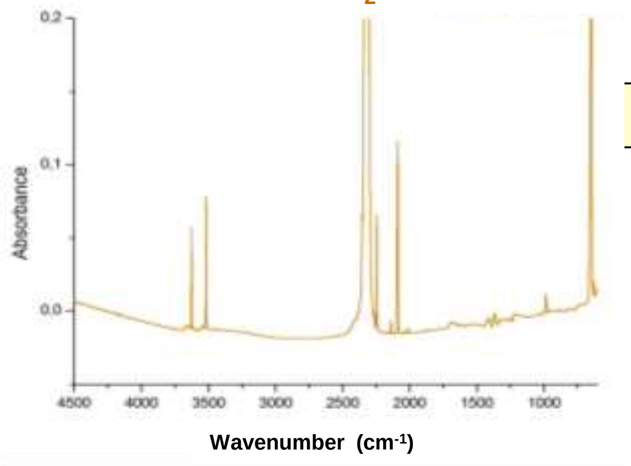


heavy ion beam

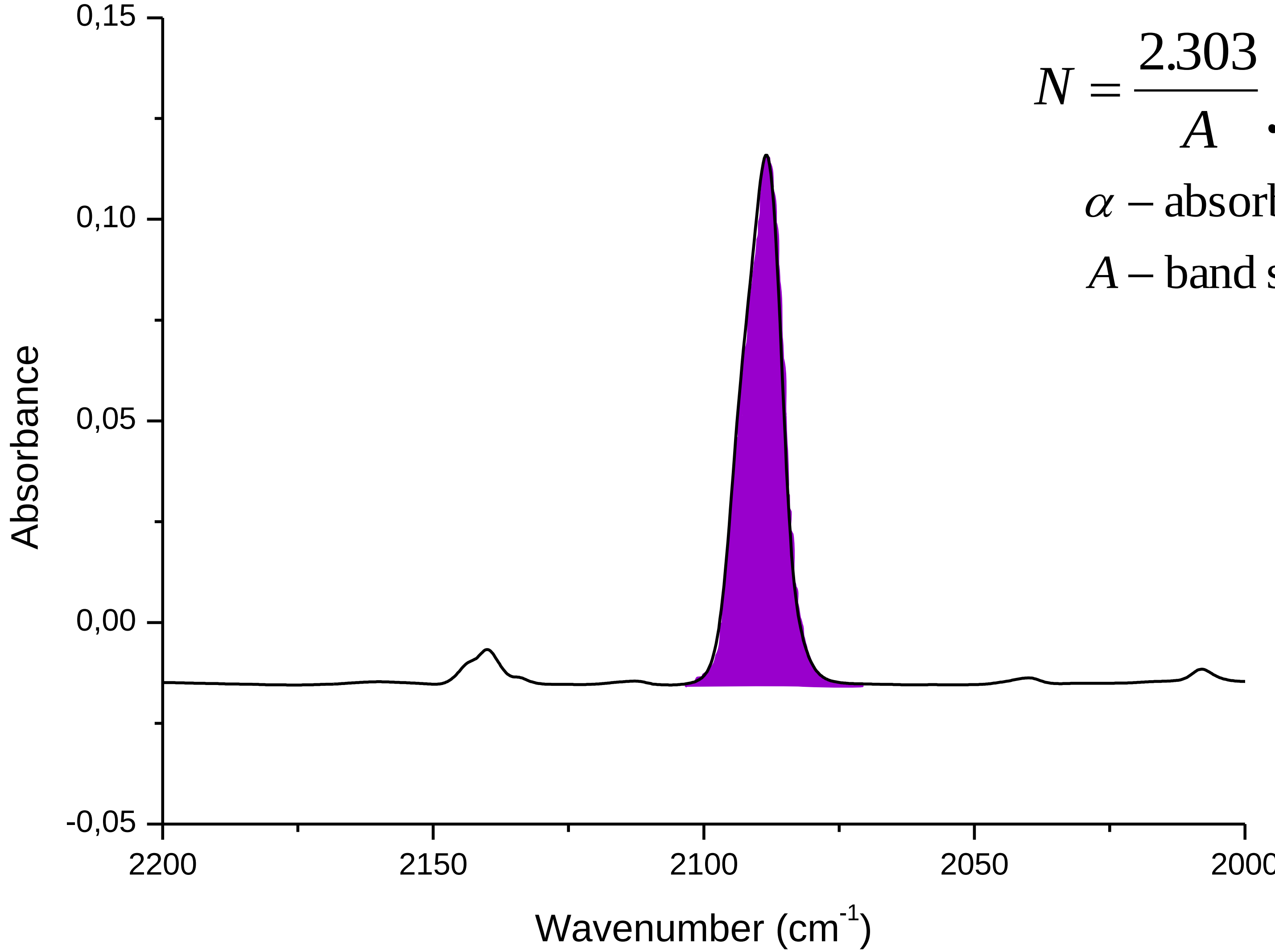




$C^{18}O_2$ After irradiation



FTIR spectrum: Measuring the column density

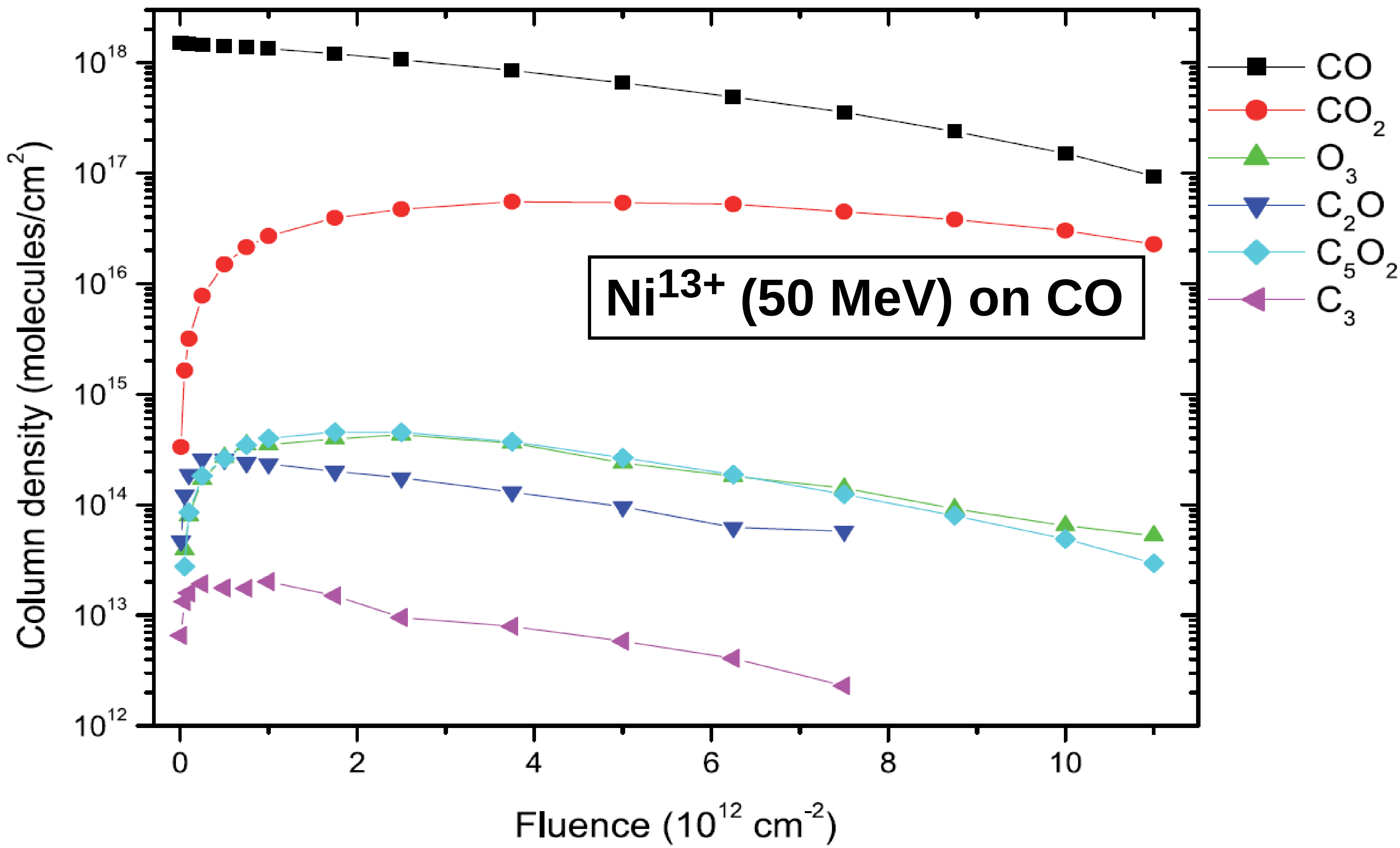


$$N = \frac{2.303}{A} \int \alpha \, d\kappa$$

α – absorbance

A – band strength

Evolution of Column density with projectile fluence



Synthesis of Molecules by Heavy Ion Irradiation:

CO_2 ice: CO, CO_3, O_3, C_3

CO ice: CO_2, O_3, C_3O_2, C_5O_2, C_2O, C_3, C_4O_2 / C_7O_2

Comparison to proton / UV photon irradiation:

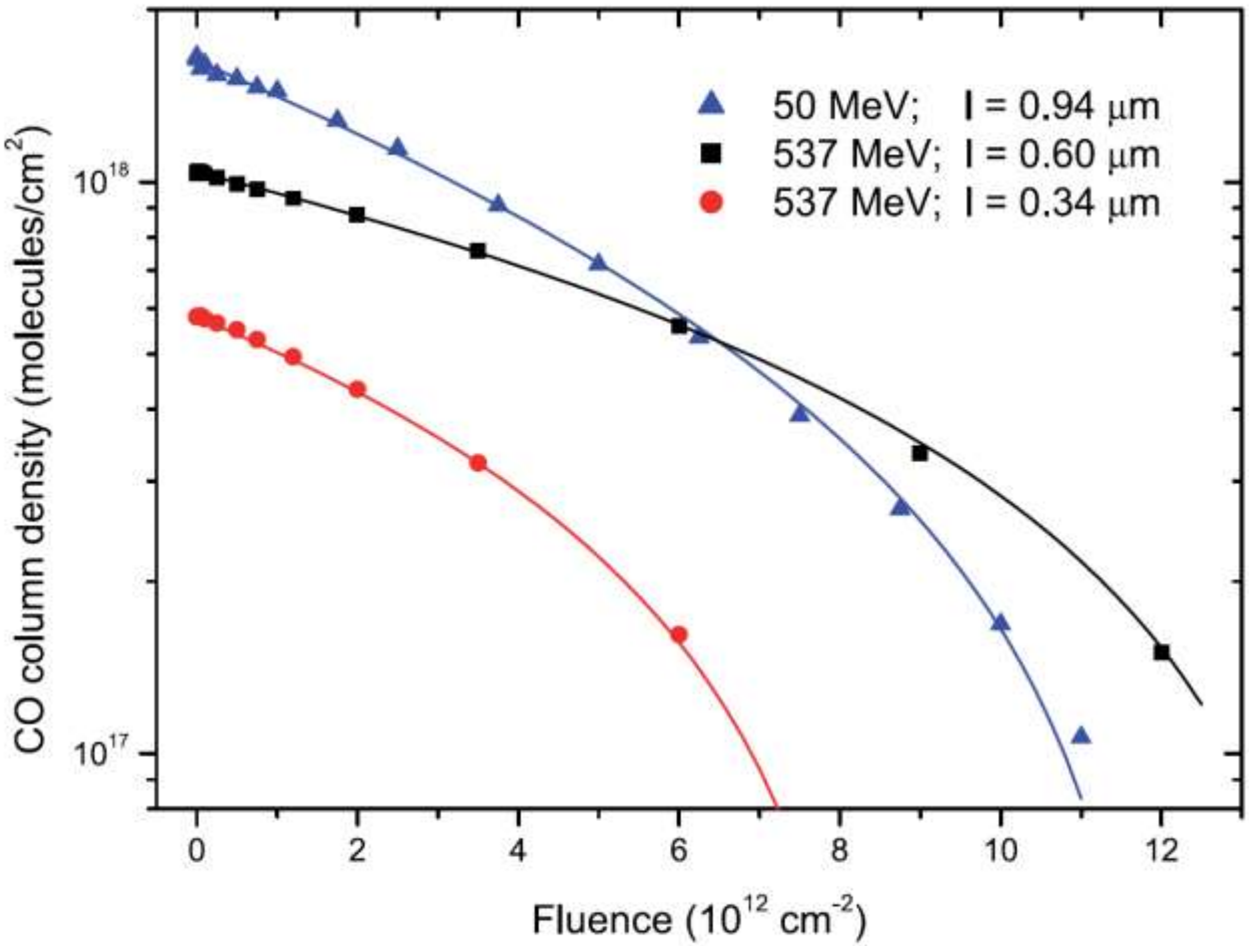
Destruction / Formation Cross Sections σ_d / σ_f

Radiochemical Yield

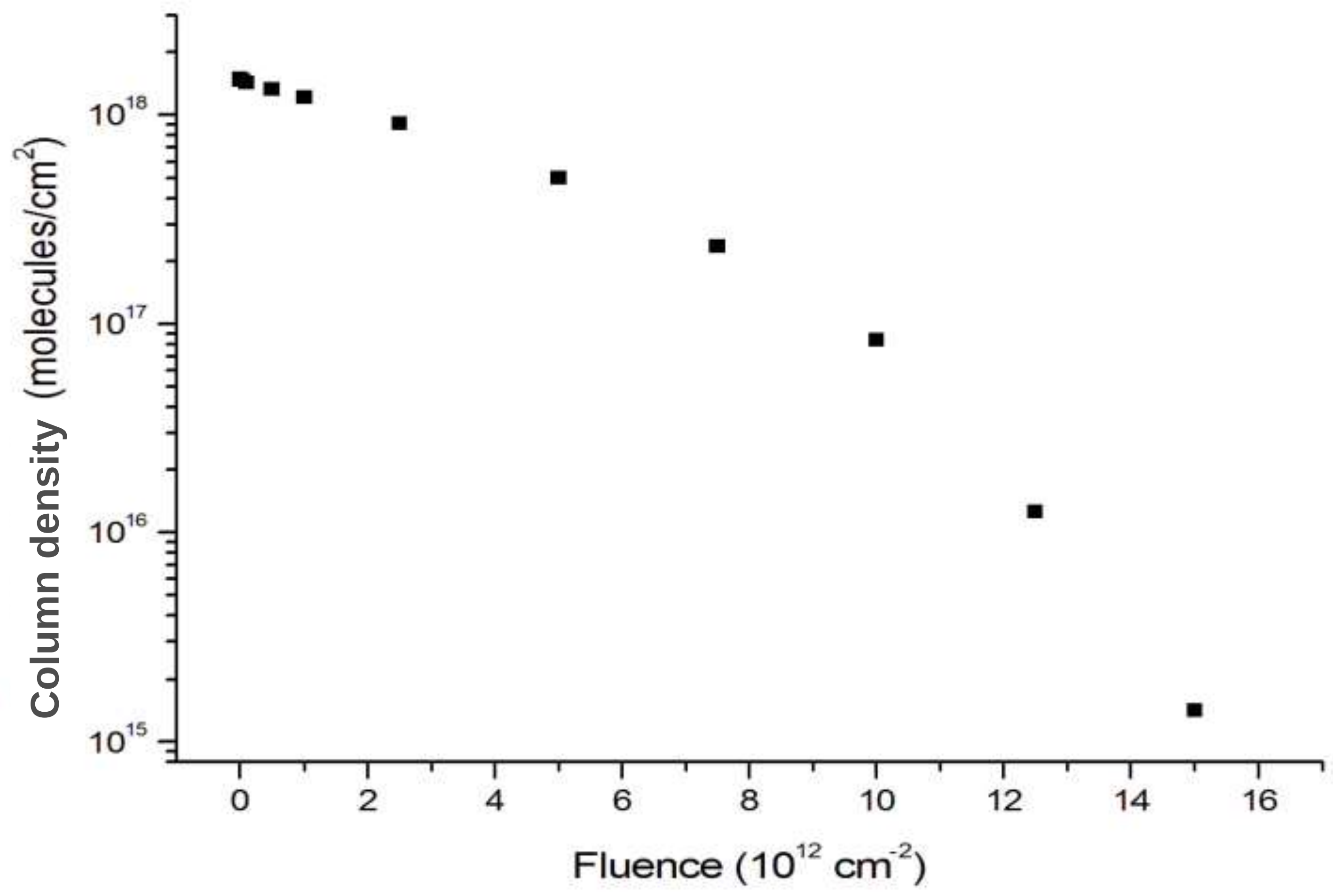
$$G = 100 \frac{\sigma_d}{S_e}$$

Molecule	Projectile	σ (10^{-15} cm^2)	*G*	Reference
CO	50 MeV Ni^{13+}	100	–5.9	Seperuelo et al. A&A (2010)
	537 MeV Ni^{24+}	30	–2.5	
	200 keV H^+	0.28	–0.79	Loeffler, Baratta, Palumbo, Strazulla, Baragiola A&A (2005) **435** 587
	10.2 eV photons	0.0003		Loeffler et al. (2005)
CO_2	50 MeV Ni^{13+}	20	1.2	Seperuelo et al. A&A (2010)
	537 MeV Ni^{24+}	18	1.5	
	200 keV H^+	6	0.62	Loeffler et al. (2005)
	10.2 eV photons	0.017	0.59	Loeffler et al. (2005)
C_3O_2	50 MeV Ni^{13+}	3	0.18	Seperuelo et al. A&A (2010)
	537 MeV Ni^{24+}	25	2.2	
	200 keV H^+		0.14	Palumbo [private communication, see ApJ (2008) **685** 1033]
C_2O	50 MeV Ni^{13+}		0.12	Seperuelo et al. A&A (2010)
	200 keV H^+		0.37	Palumbo [private communication, see ApJ (2008) **685** 1033]

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



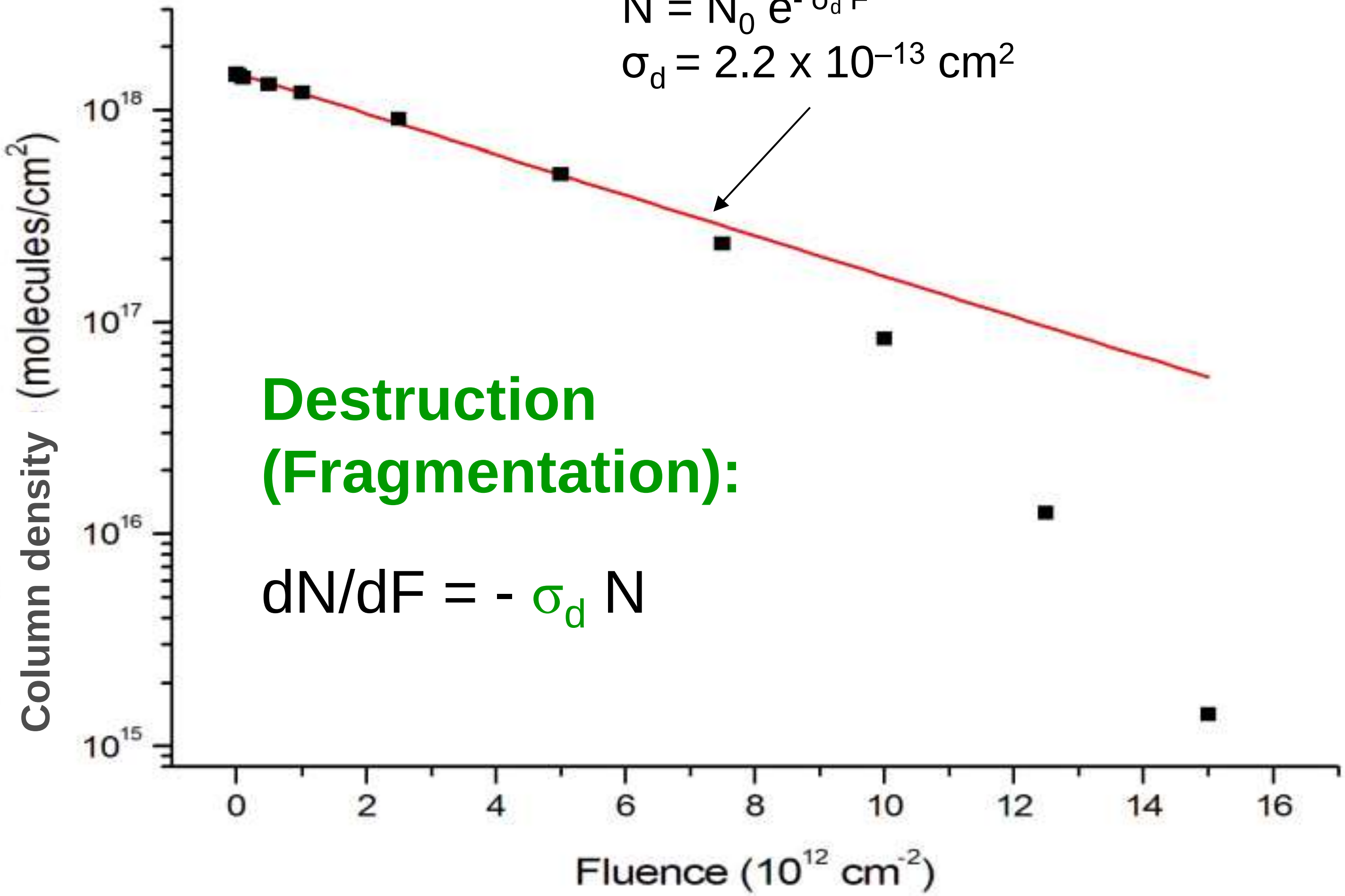
Another example: 46 MeV 58Ni^{11+} → CO_2



Another example: 46 MeV 58Ni^{11+} → CO_2

$N = N_0 e^{-\sigma_d F}$

$\sigma_d = 2.2 \times 10^{-13}$ cm^2



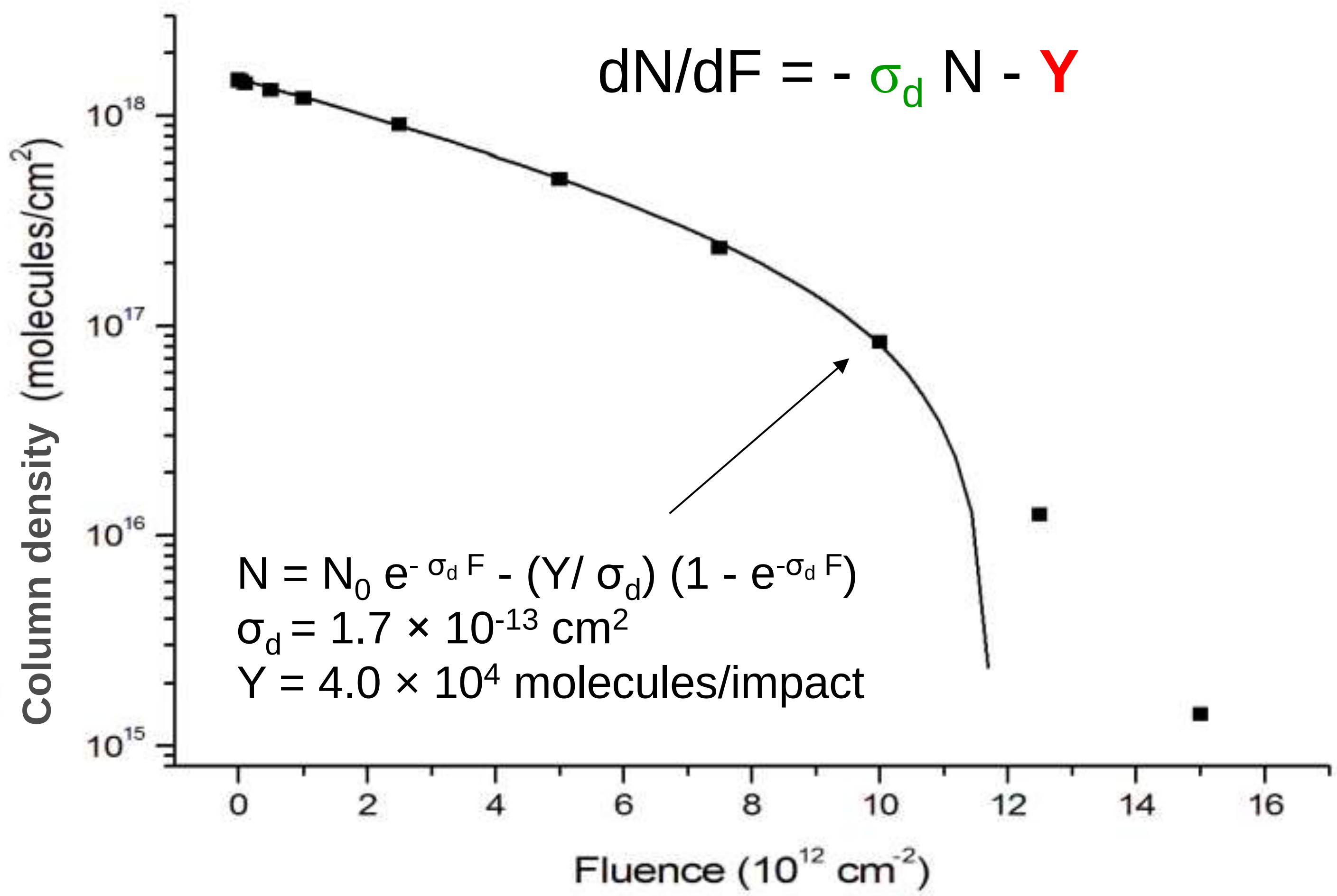
Destruction (Fragmentation):

$dN/dF = -\sigma_d N$

Another example: 46 MeV 58Ni^{11+} → CO_2

Destruction plus Sputtering:

$$dN/dF = -\sigma_d N - Y$$

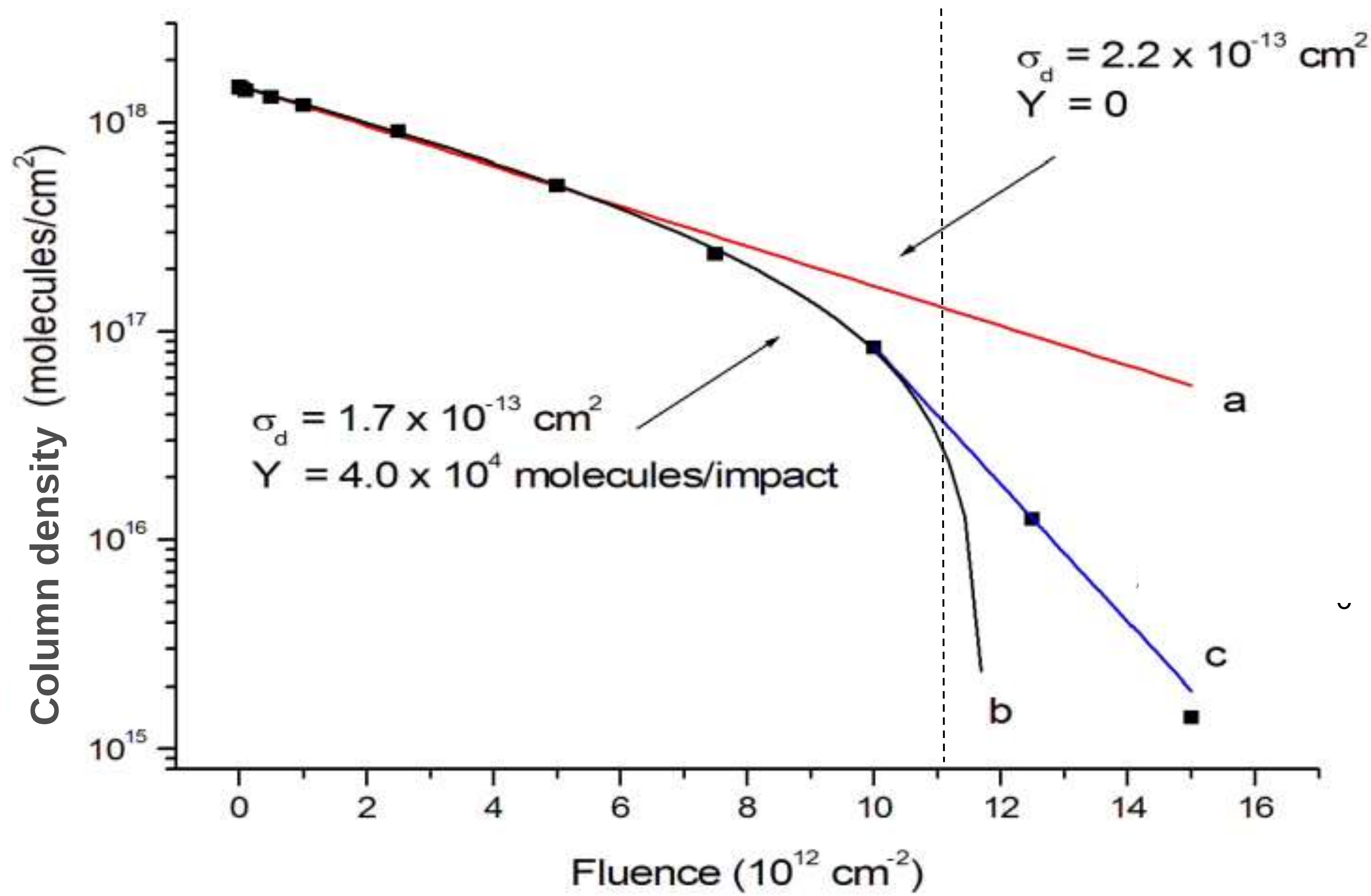


$$N = N_0 e^{-\sigma_d F} - (Y/\sigma_d)(1 - e^{-\sigma_d F})$$

$\sigma_d = 1.7 \times 10^{-13}\ cm^2$

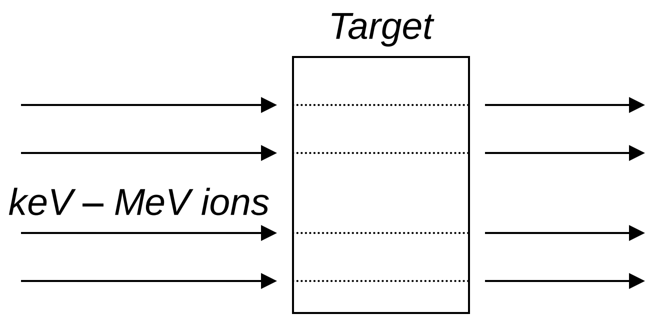
$Y = 4.0 \times 10^4$ molecules/impact

Another example: 46 MeV $58Ni^{11+} \rightarrow CO_2$



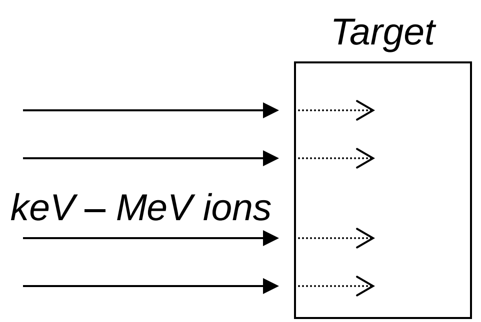
Ion-target interaction

Irradiation experiment



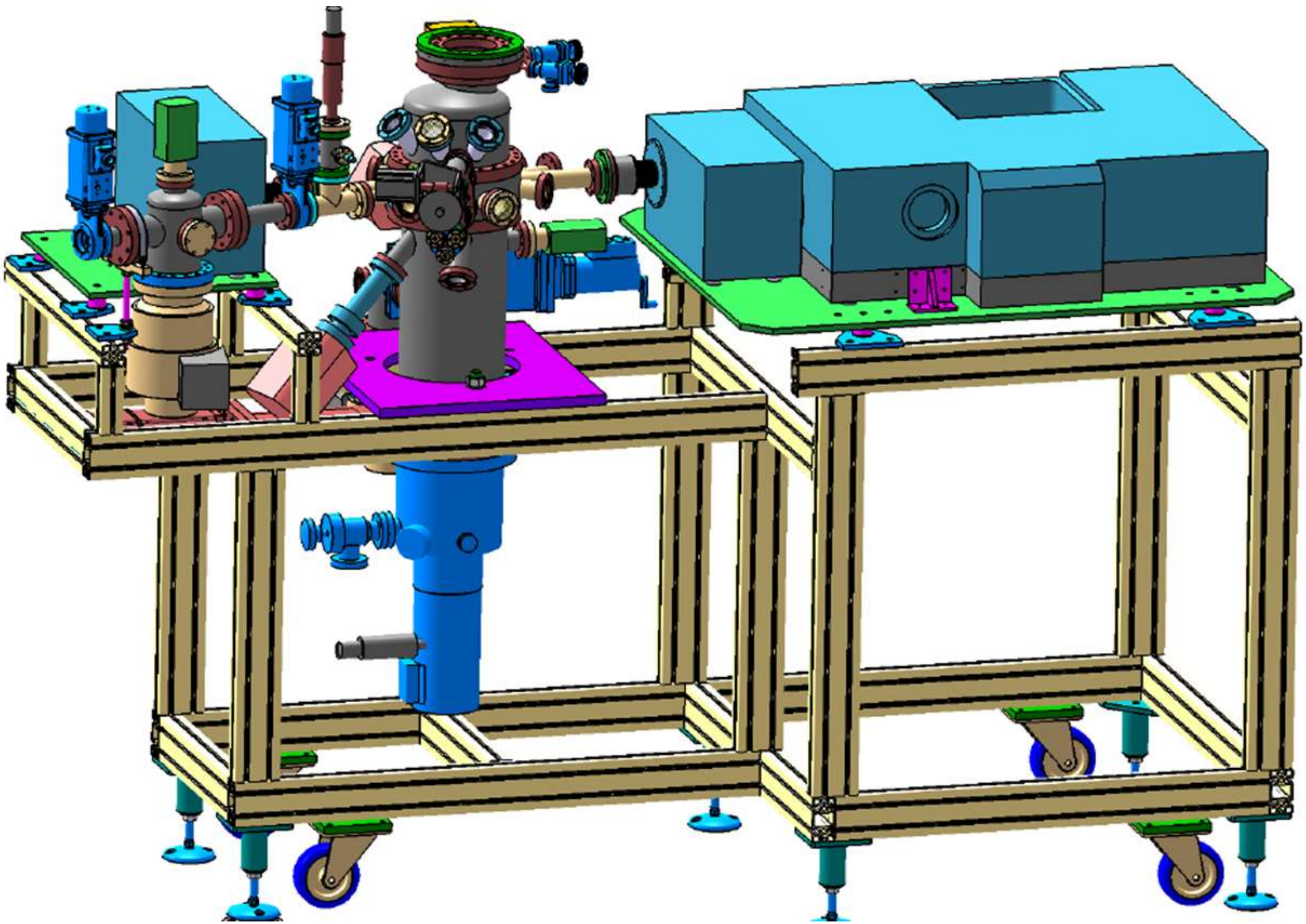
Ions pass through the target

Implantation experiment



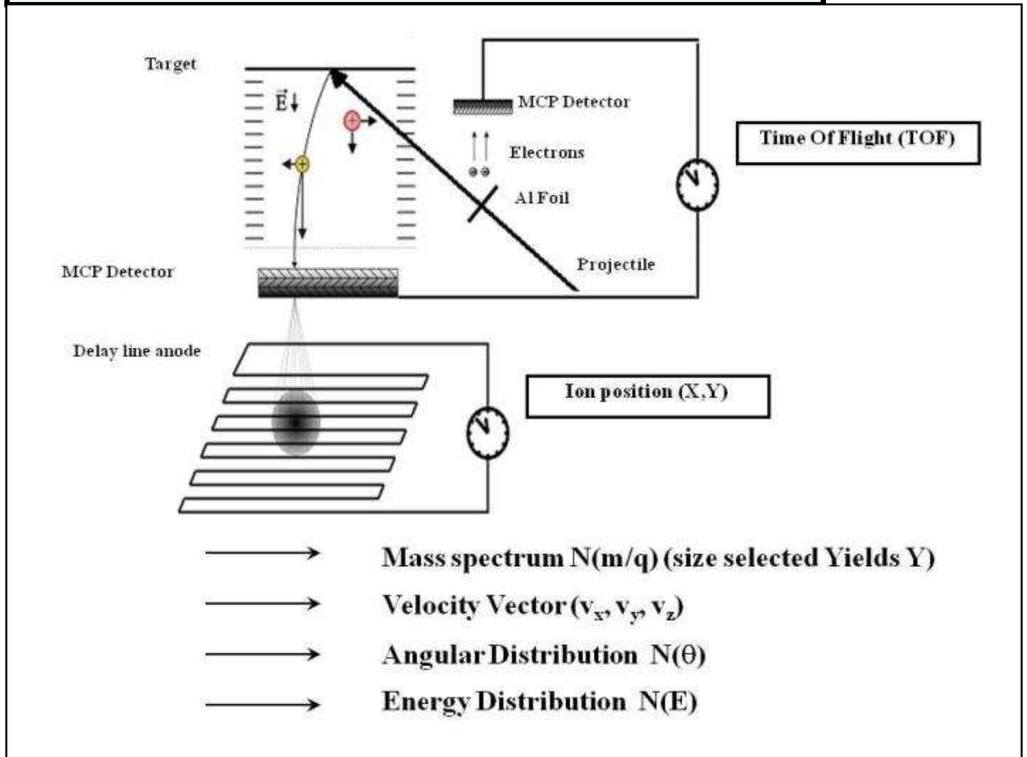
Ions are stopped in the target

ANR IGLIAS   P. Boduch CIMAP/Caen   E. Dartois IAS/Orsay

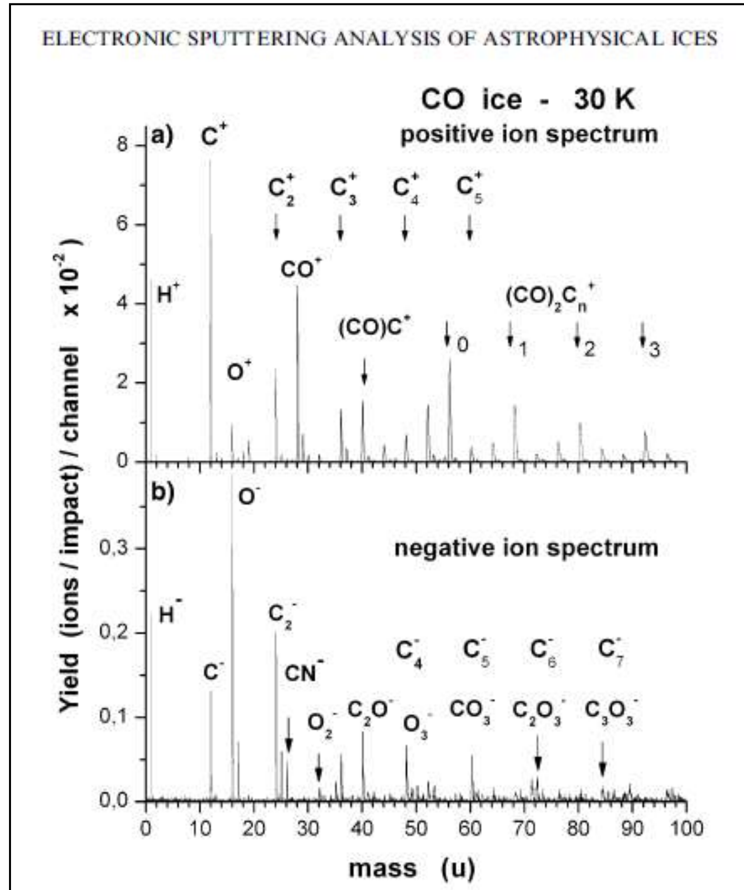


TOF-SIMS

XY-time of flight–secondary ion mass spectroscopy TOF-SIMS

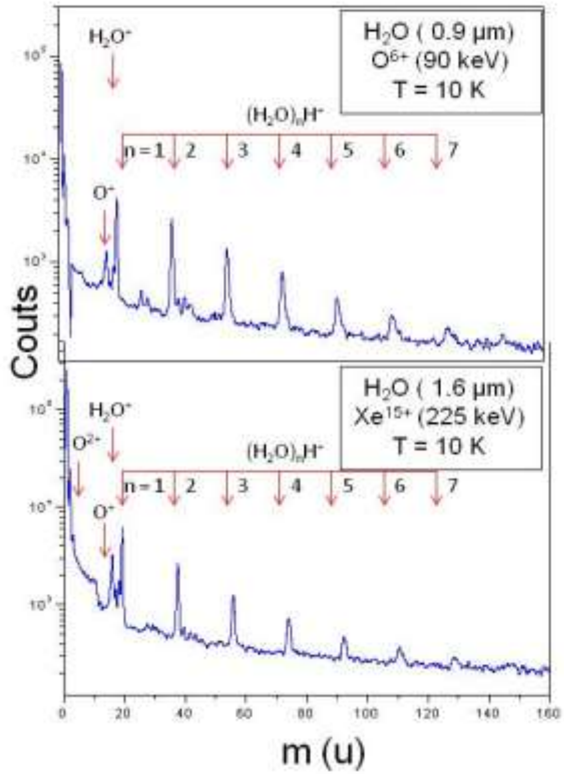


H. Hijazi et al., Nucl. Instr. Meth. B269 (2011) 1003;
Eur. Phys. J. D66 (2012) 68; Eur. Phys. J D68 (2014) 185



L.S. Farenzena, P. Iza, R. Martinez, F.A. Fernandez-Lima, E. Seperuelo Duarte, G.S. Faraudo, C.R. Ponciano, E.F. da Silveira, M.G.P. Homem, A. Naves de Brito, K. Wien
Electronic Sputtering Analysis of Astrophysical Ices,
Earth, Moon, and Planets 97 (2005) 311

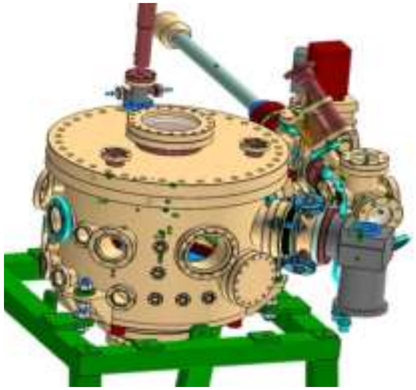
AODO : ionic part of the sputtering

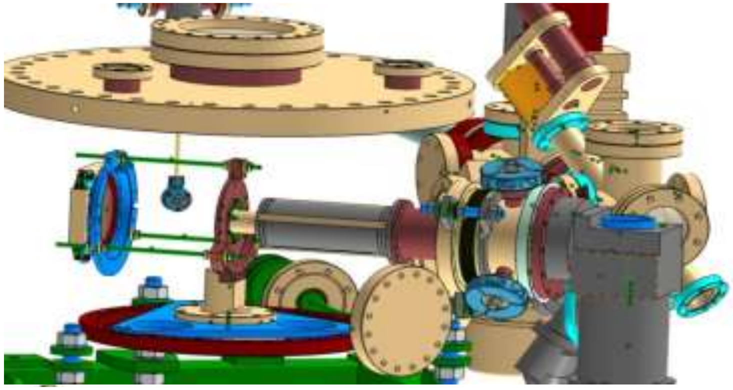


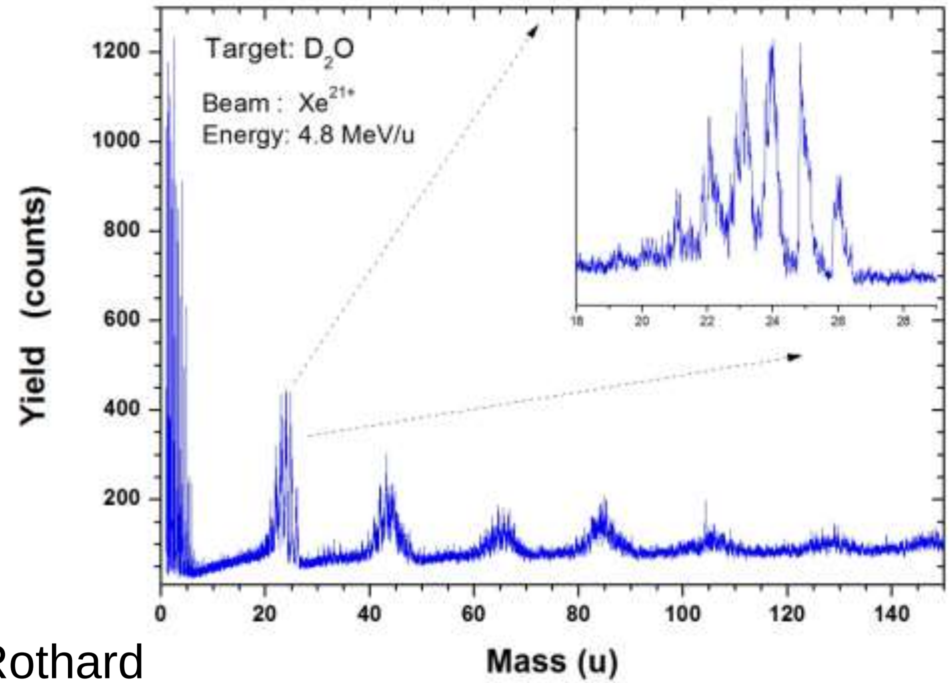
Complementary results…

XY-TOF-SIMS with cold head

designed by J.M. Ramillon (CIMAP)







GSI Unilac M1 (2014)

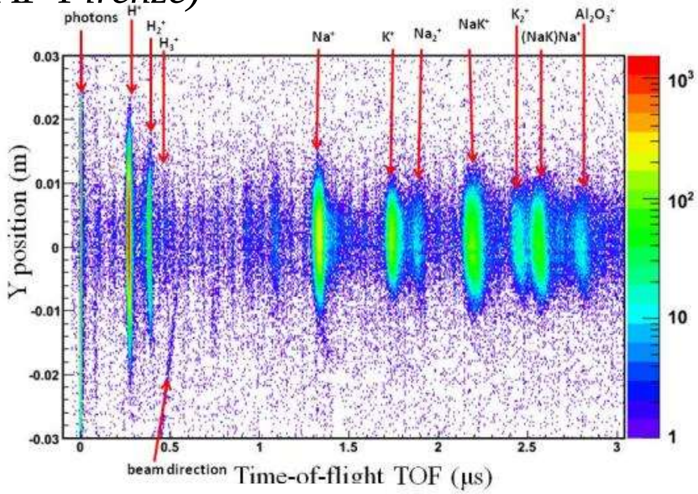
Rafael Martinez, A. Domaracka, H. Rothard (CIMAP),Lars Breuer (Univ. Duisburg-Essen), M. Bender, D. Severin (GSI)

thanks to A. Wucher (Univ. Duisburg-Essen)

Materialforschung

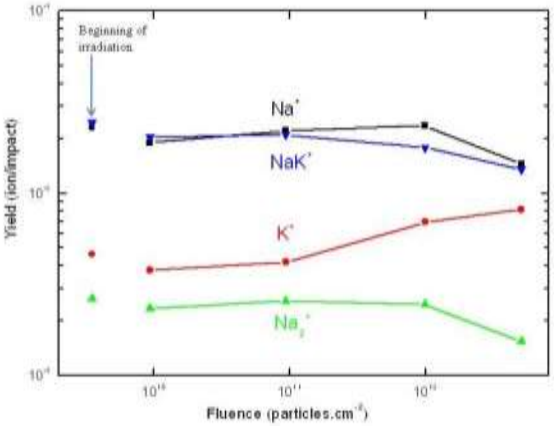
Astrophysical Application: *silicates* exposed to ***solar wind*** and ***cosmic rays***

T. Langlinay, P. Boduch, H. Rothard (CIMAP Caen),
G. Strazzulla, M.E. Palumbo (INAF Catania),
J.R.Brucato (INAF Firenze)

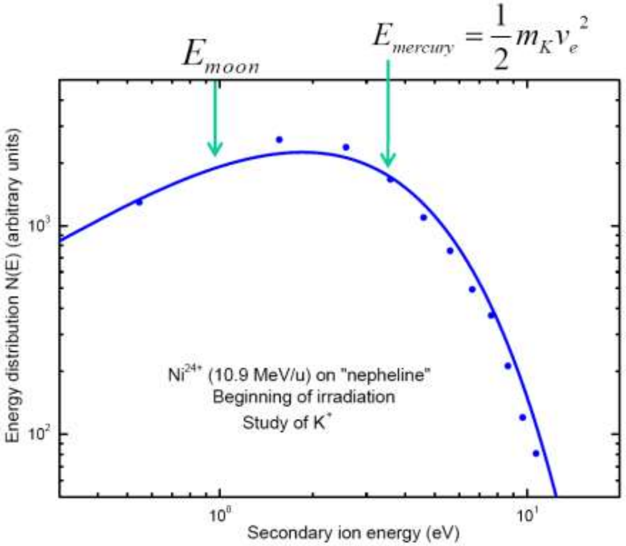


Nepheline (Na,K)$AlSiO_4$
model for rocks on surfaces of moons + planets (e.g. mercury)

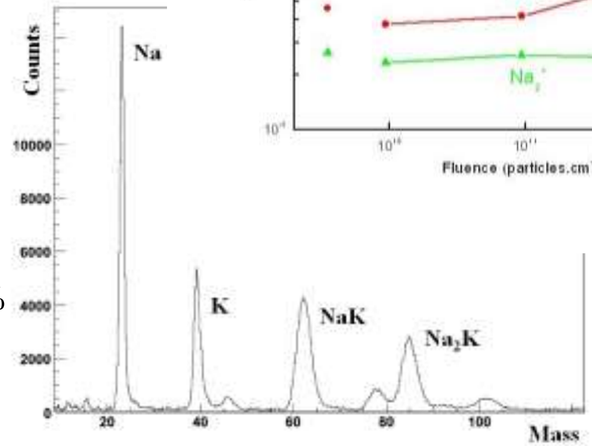
Evolution of surface + sputter yields with heavy ion fluence (irradiation time)



- Energy distribution of K^+:



Escaping particles: Mercury: ≈ 50 %
Moon: ≈ 80 %



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Région Basse Normandie

Calvados