Multiple-beam irradiation platform to investigate the origin and evolution of organic matter of the Solar System (MIRRPLA)

PEPR Origins

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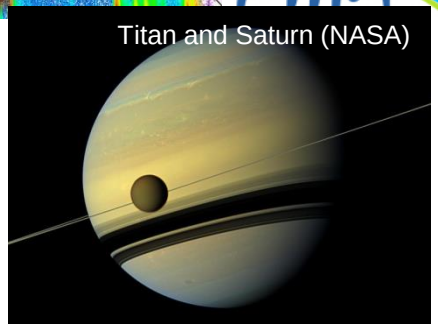
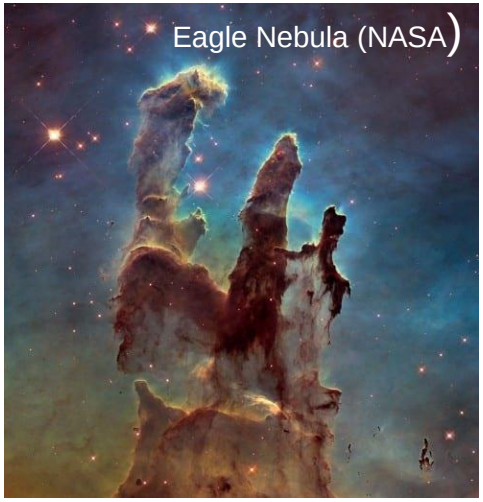
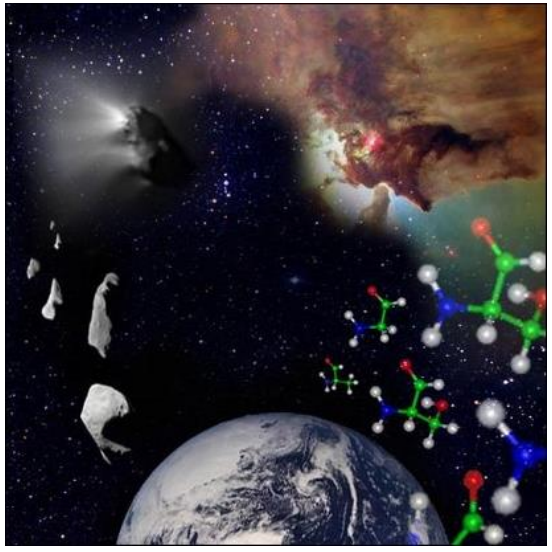
Outline

- General context and motivation
- PEPR Origins
- Ions in space
- MIRRPLA platform
  (scientific and technical challenges)
- Summary and perspectives


Titan and Saturn (NASA)


Eagle Nebula (NASA)

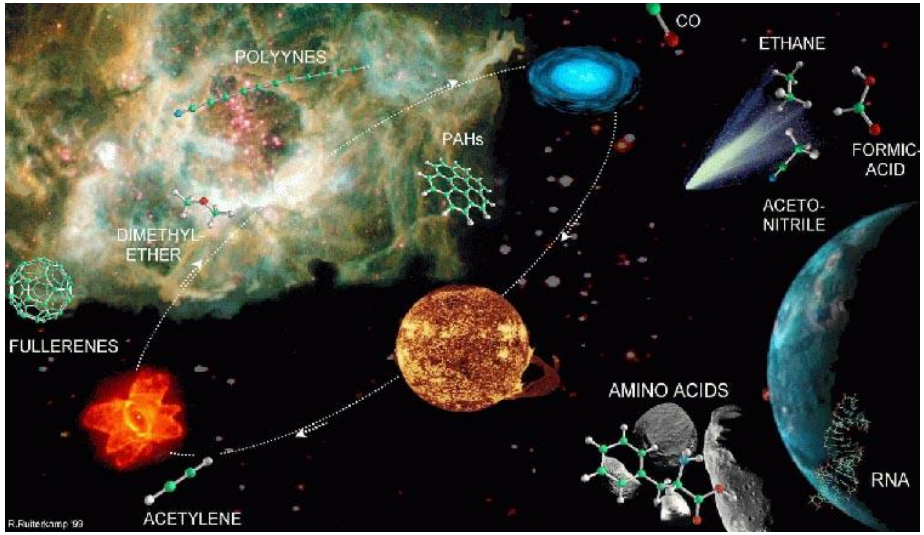



Jupiter and the Galilean satellites (NASA)

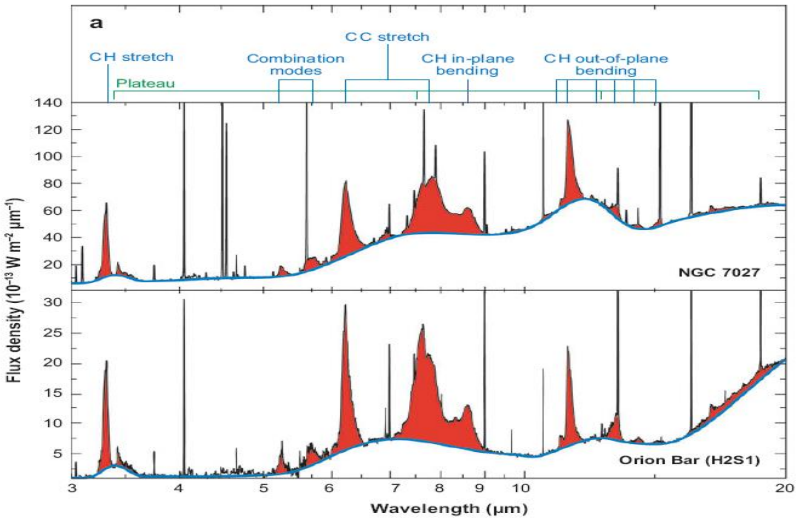
Motivation: molecular diversity in space

In interstellar medium, more than 250 molecules have been indentified,

e. g. large carbonaceous molecules like PAHs and fullerenes, COMs…



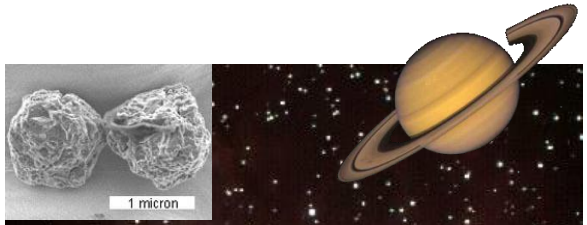
http://www.eana-net.eu

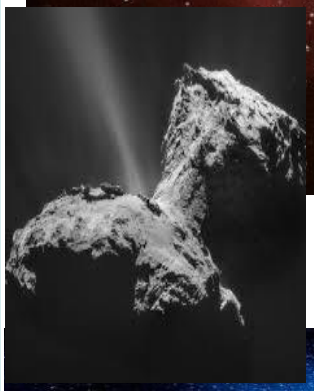


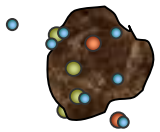
E. Peeters et al. *Astron. Astrophys.* **390** (2002) 1089

Laboratory studies (quantum chemistry, experiments…) are needed in order to understand the physical and chemical processes leading to such rich chemical inventory.

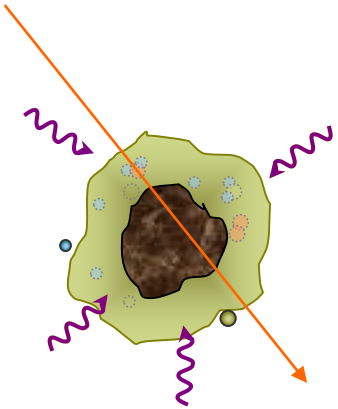
Astrophysical ices



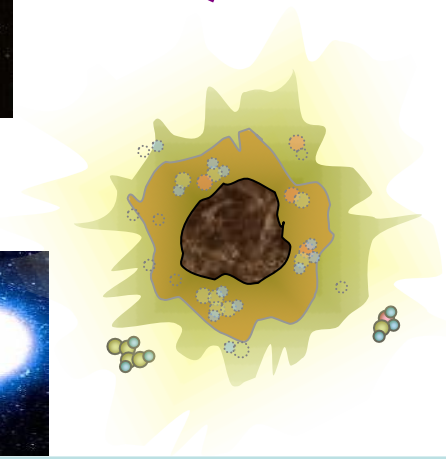




Icy mantles are formed from simple molecules (H_2O, CO, CO_2, NH_3, CH_4, etc).

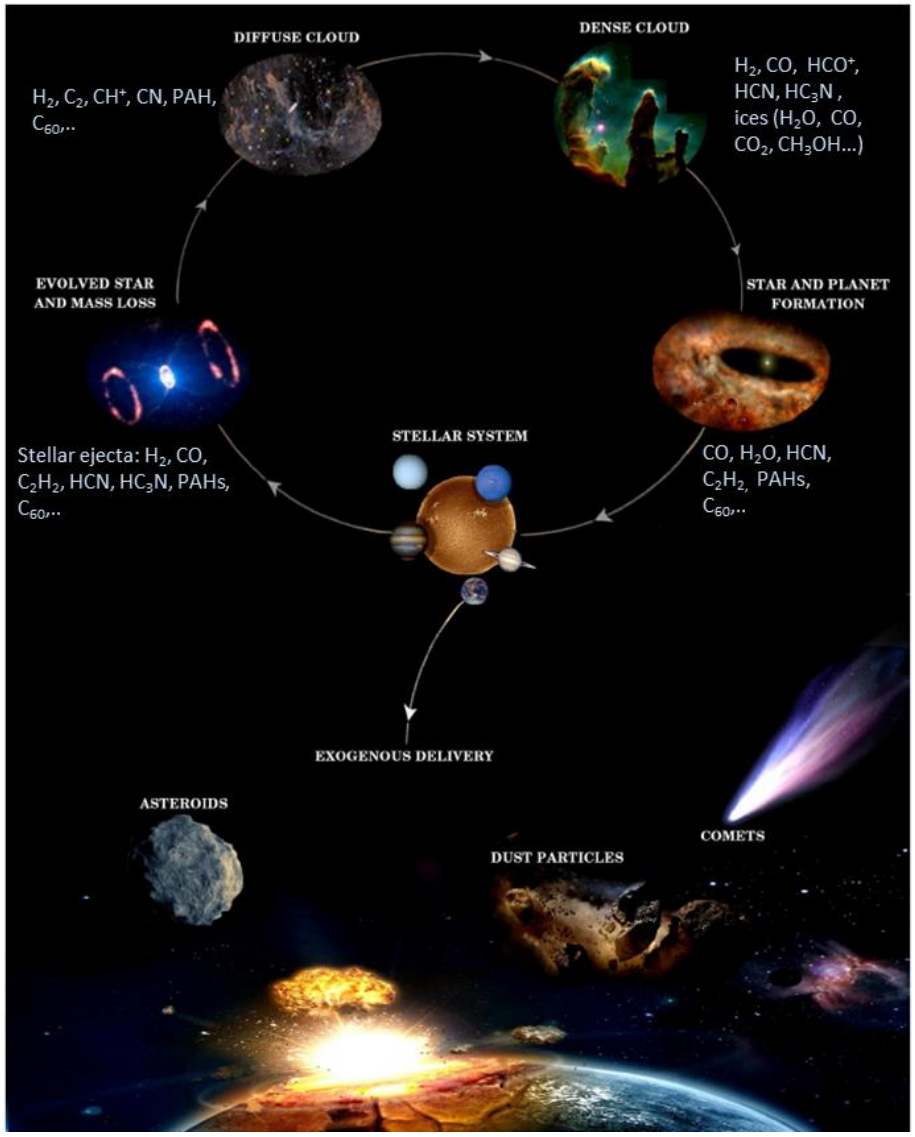


Energetic processing by:
- photons (including UV and X-rays),
- electrons (high and low-energy),
- ions (cosmic rays, solar wind, magnetosphere).



Irradiation leads to:
- ice structural changes,
- desorption/sputtering,
- radiolysis (fragmentation) and formation of new molecular species.

The life cycle of the interstellar matter



Complex organic molecules (COMs) and prebiotic molecules

- Formation mechanisms?
- Stability under ionizing radiation?
- Origin of life?

astrochemistry/astrobiology

PEPR Origins

PI: Alessandro Morbidelli, Laboratoire Lagrange

Origins, from planets to life - technological, societal and epistemic breakthroughs

Objectives: Understanding the origin of life, discovering and characterizing other Earths

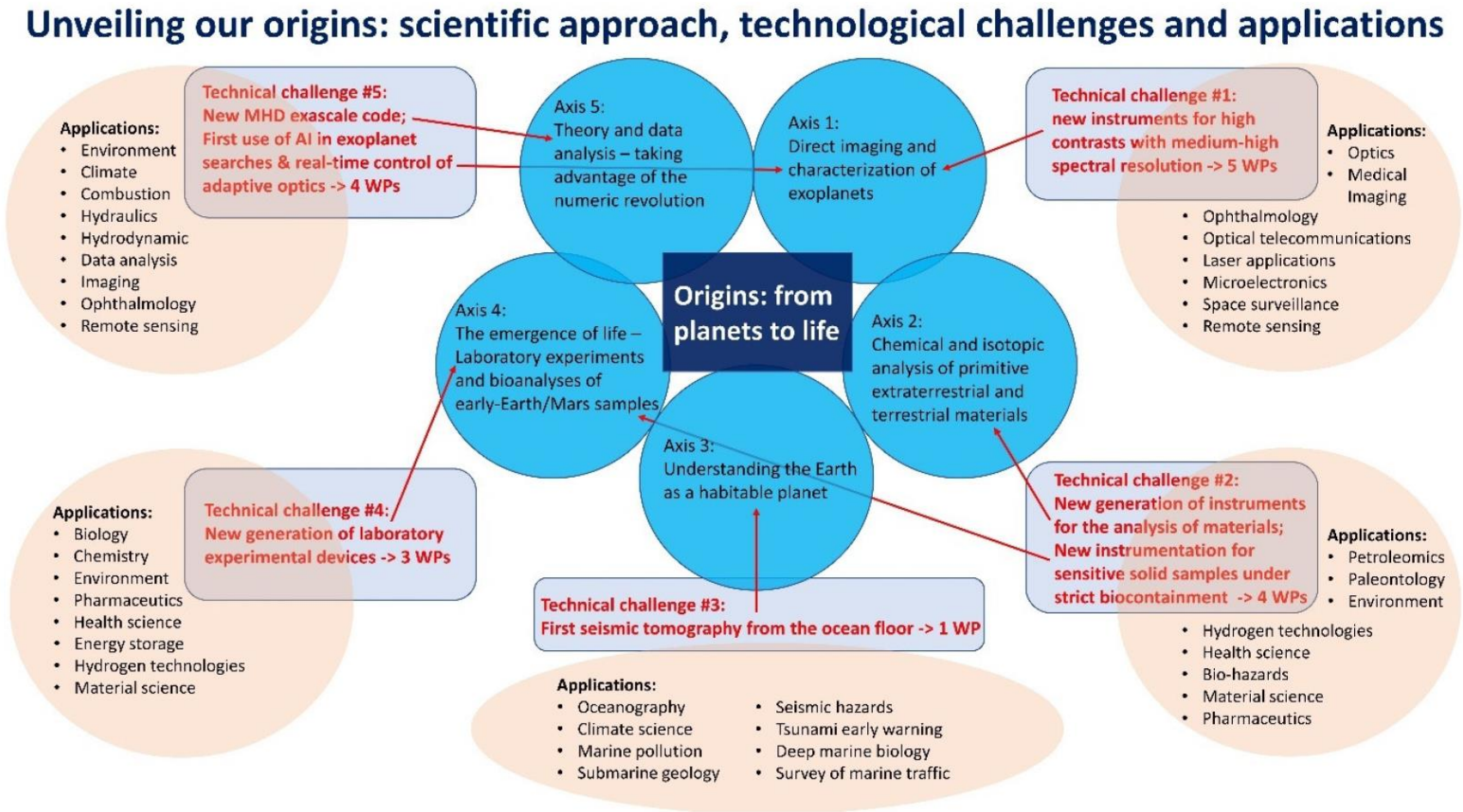


Fig. 1: Structure of our project (technological part): main research axes, technological challenges and potential applications

PEPR Origins in numbers

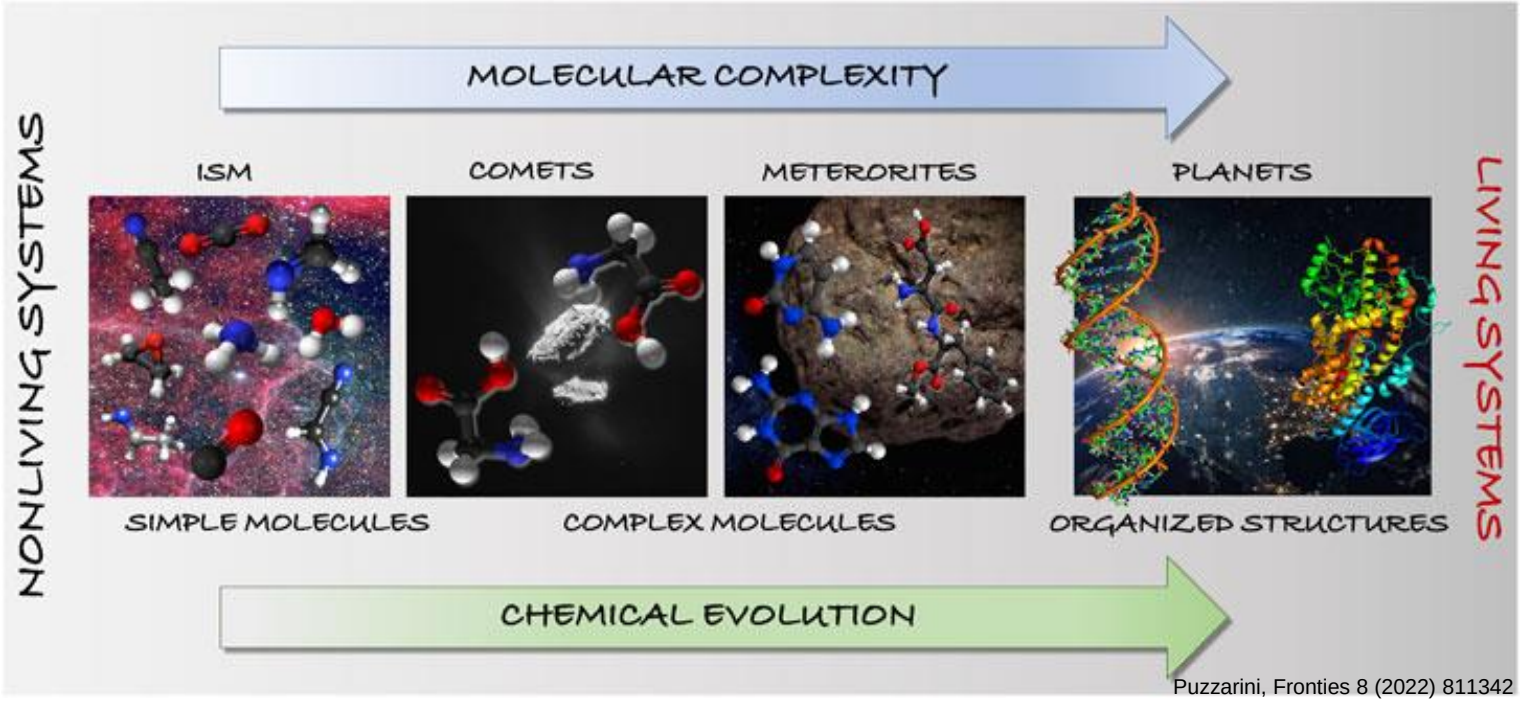
Origins, from planets to life - technological, societal and epistemic breakthroughs

Objectives: Understanding the origin of life, discovering and characterizing other Earths

- 28 national organizations
- development of 17 instruments
  (e.g. Platform MIRRPLA: axis 4)
- 45,5 M€ for 7 years

The location of the institutions participating to this project (pins). In blue, those involved in focused projects (WPs). The colored lines highlight collaborations in each of the research axes.

MIRRPLA: Multiple-beam irradiation platform
to investigate the origin and evolution of organic matter of the Solar System



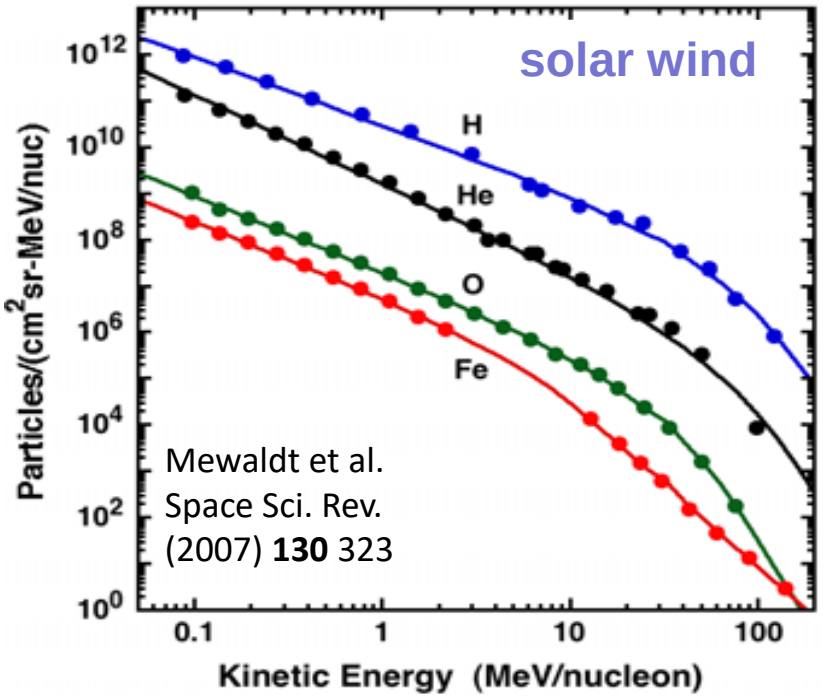
Puzzarini, Fronties 8 (2022) 811342

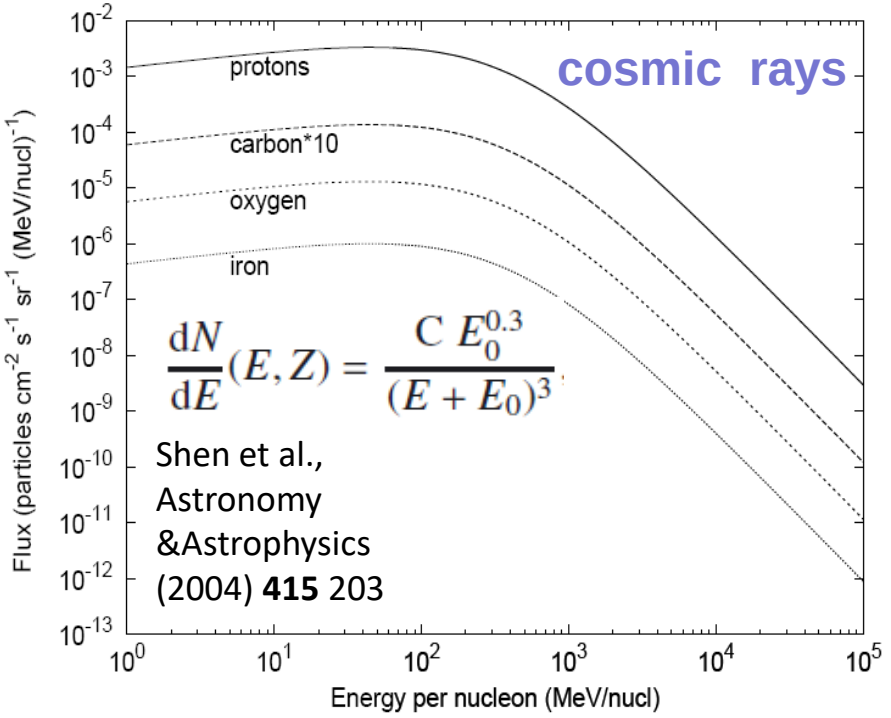
Molecular systems in space are processed by several sources of radiation:

- photons (including UV and X-rays);
- electrons;
- ions.

→ ionisation, fragmentation, desorption/sputtering, reactivity,...

Ions in space

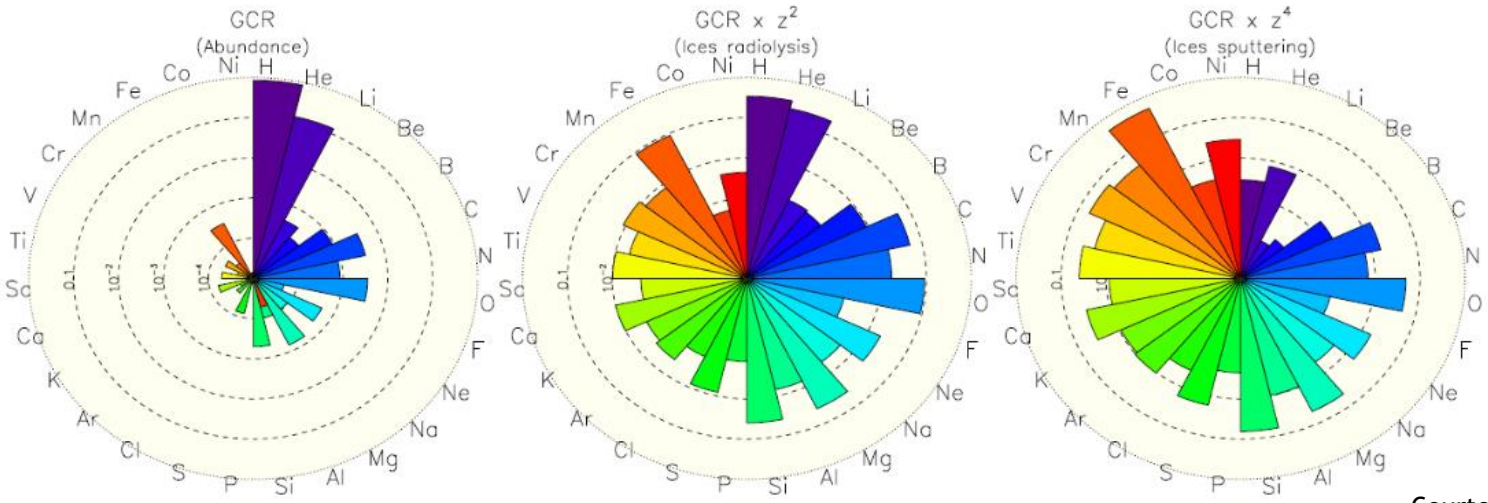




H/Fe~10^4
H/Ni~10^5

Heavy ions: why ?

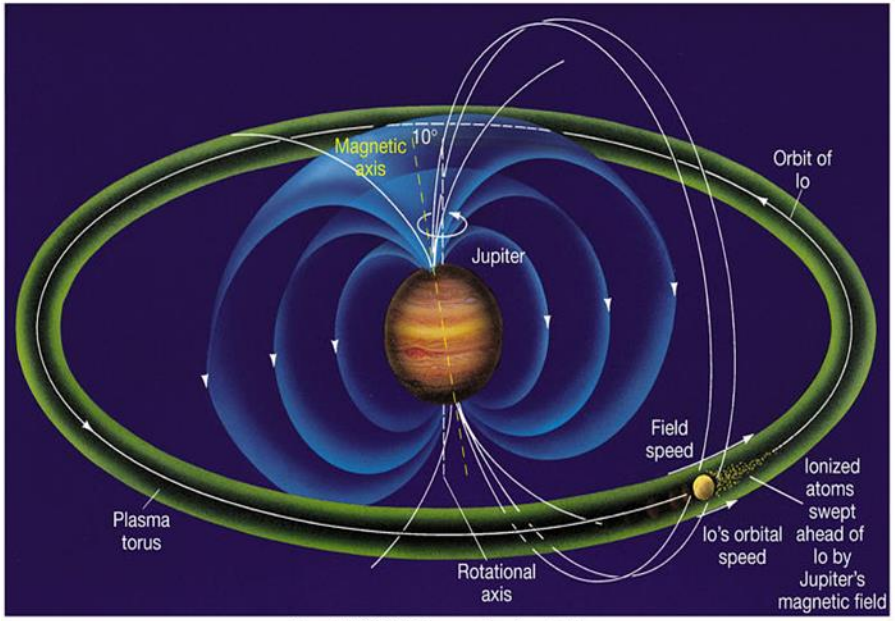
- large electronic energy loss S_e
- scaling laws: S_e^n with n ≈ ½,1,$^3/_2$,2, ... 4)



Courtesy of E. Dartois

- *Unexplained findings (gas phase molecules in dense clouds...e.g. CO...)*

Jupiter's magnetosphere



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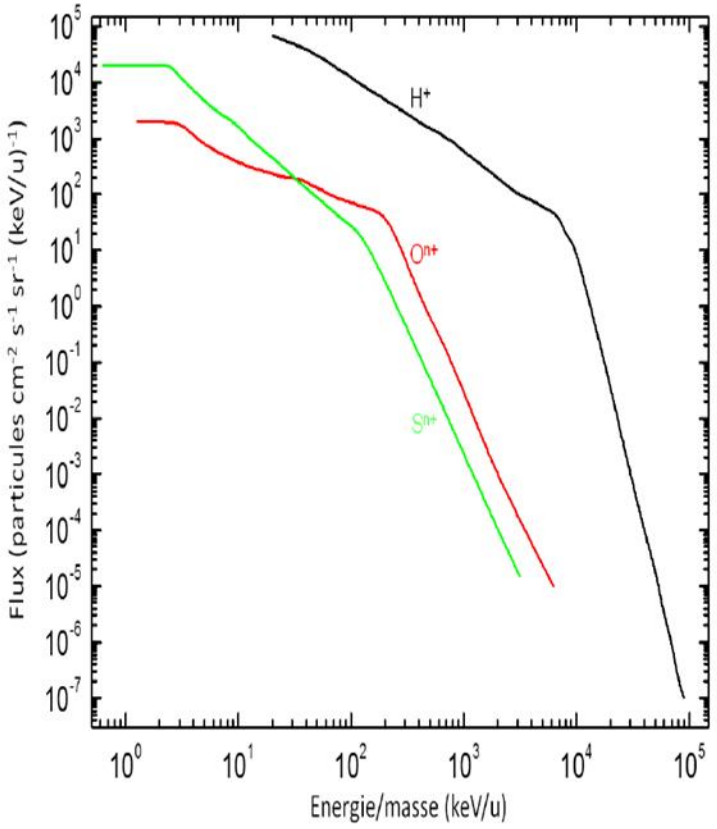
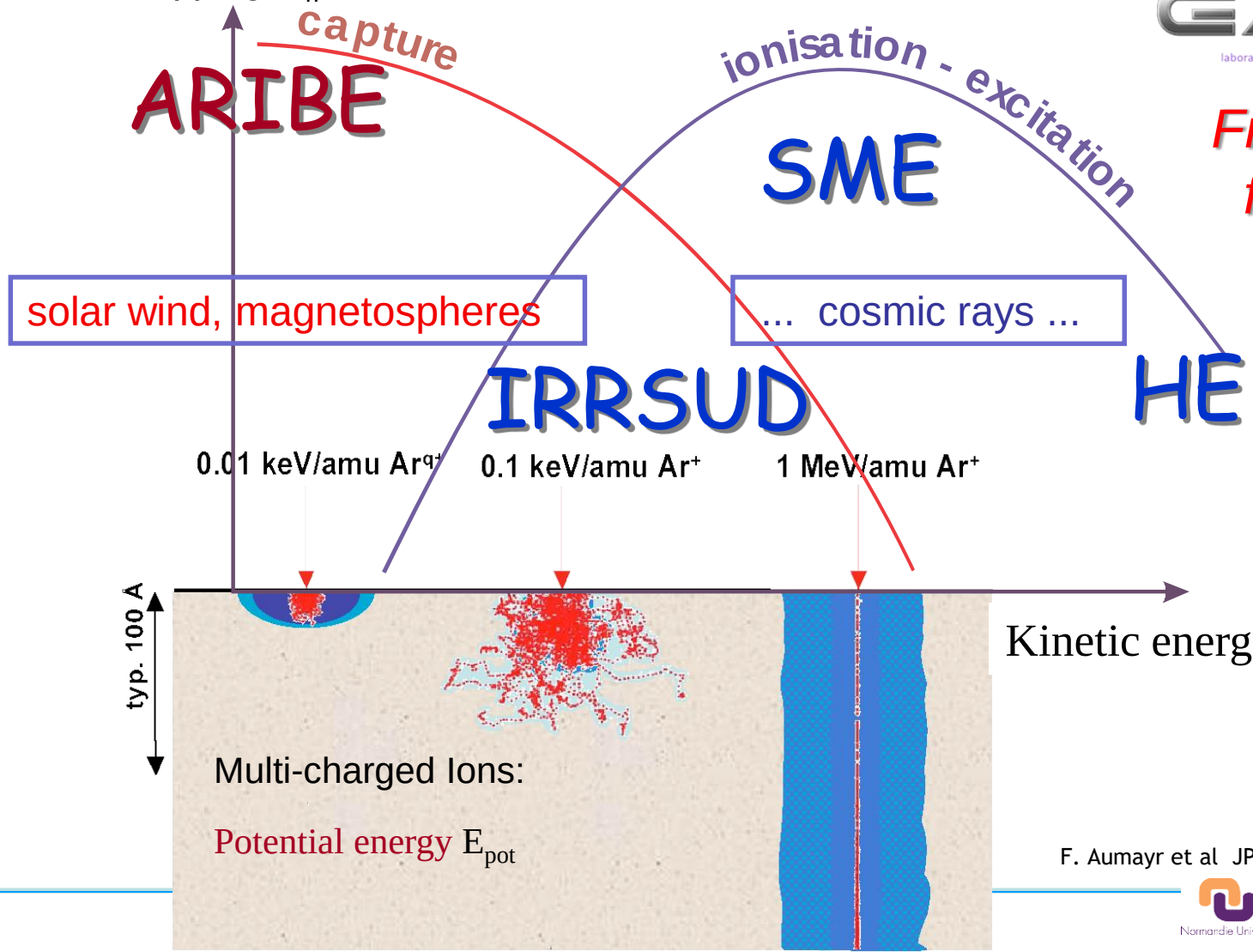


- *Astrochemistry: origin of CO_2 and H_2SO_4 on Europe, organic molecules*

Basic processes in ion collisions

Elastic collisions: ion -nucleus
"nuclear stopping" S_n

Inelastic collisions: ion – target electron
"electronic stopping" S_e



From He to U, from keV to GeV

F. Aumayr et al JPCM **23** (2011) 393001

Astrophysics + chemistry @CIMAP

Targets:

Pure ices of small molecules (H_2O, CO, CO_2, NH_3, CH_4 etc.), mixed ices, COMs

- **Structure**: amorphous vs. cristalline, porous vs. compact (H_2O)
- **Radiolysis**: radiation resistance and survival times of molecules
- Formation of **new molecular species** (irradiation / implantation)
- Increasing chemical complexity: **emergence of life**?
- **Sputtering**: origin of gas phase molecules

Solid materials (silicates, nepheline etc): sputtering

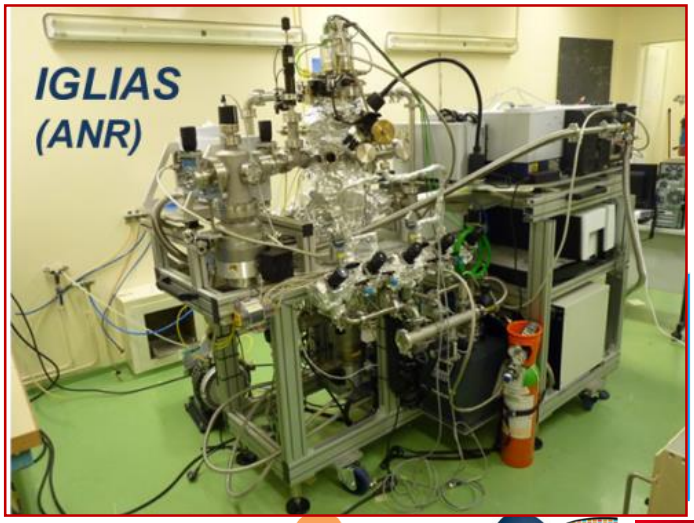
Methods:

infrared absorption spectroscopy (FTIR), UV-vis, QMS

Aim:

- input to astrochemical models
  (cross sections, yields: scaling laws)
- comparison to space observations

about 40% i-PAC beam time is allocated to astrophysics;
since 2009: >80 publications; > 40 invited talks



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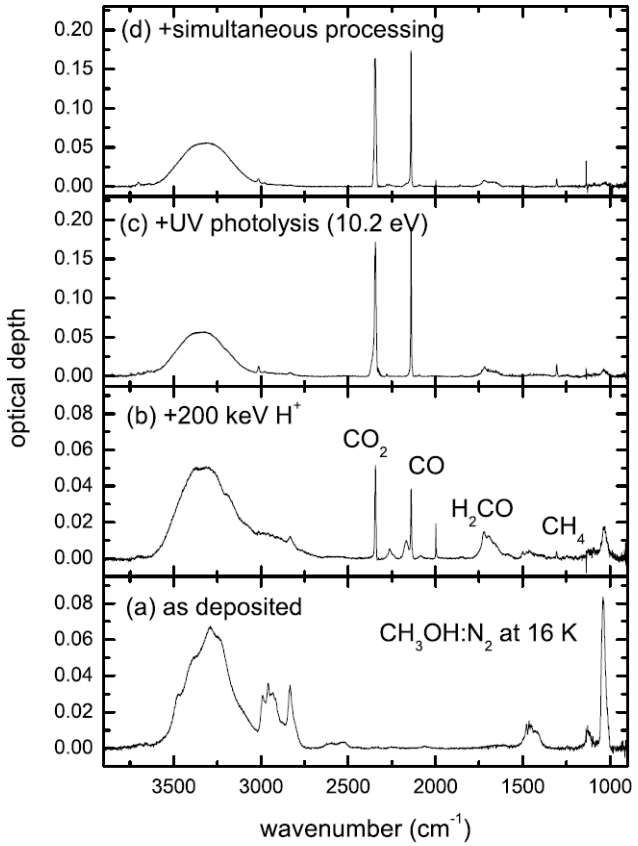
Radiation field in space: complex!

"real" conditions: simultaneous irradiation with ions, photons and electrons
-> radiation synergies effects?



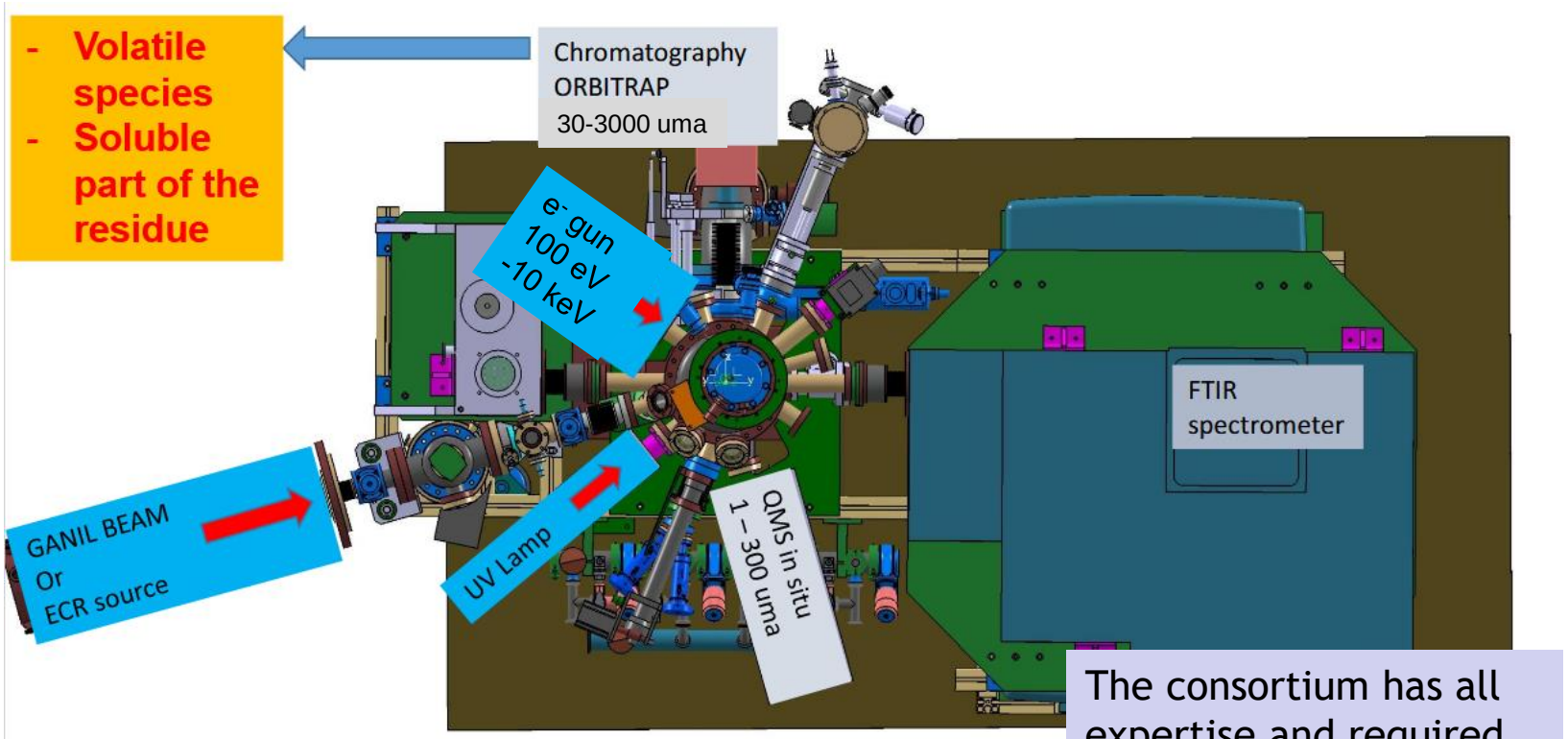
Simultaneous UV- and ion processing of astrophysically relevant ices
The case of CH_3OH:N_2 solid mixtures
F. Islam, G. A. Baratta, and M. E. Palumbo
AA 561, A73 (2014)

"....from a quantitative point of view the behavior of newly formed molecules can in some instances significantly depend on the UV/ions dose ratio. Hence the effects of simultaneous processing on other astrophysically relevant mixtures should be experimentally investigated to better understand the chemical evolution of solid phase molecules in space."

Investigations on synergy effects on simultaneous energetic processing of ices are needed.
(no data in astrobiology context yet!)

MIRRPLA: a new platform

1st objective: to design and build an ultrahigh vacuum chamber equipped with a cold head for sample preparation and multiple-beam irradiation with UV photons, electrons and ions



The consortium has all expertise and required skills to carry out the project.

Competences:
CIMAP: ion irradiation, FTIR, QMS
PIIM: photon and electron irradiation, FTIR, GC-Orbitrap

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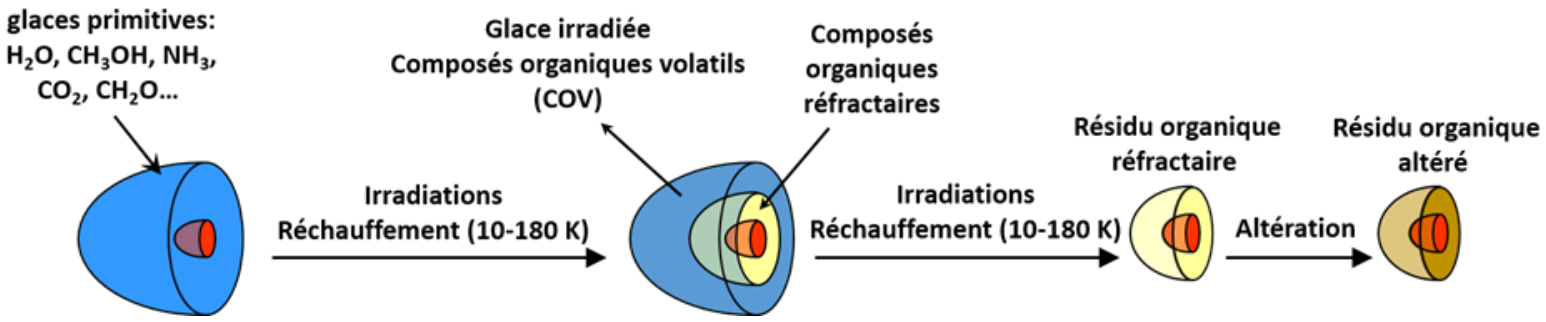
MIRRPLA: investigation synergy effects

2nd objective: to use the novel multiple-beam irradiation platform to investigate irradiation synergy effects on formation and destruction of complex organic matter/prebiotic species in a wide range of kinetic energies of the projectile (from keV to GeV) in combination with UV photon (~10eV) and electron irradiation (100 eV-10keV).



Courtesy
G. Danger

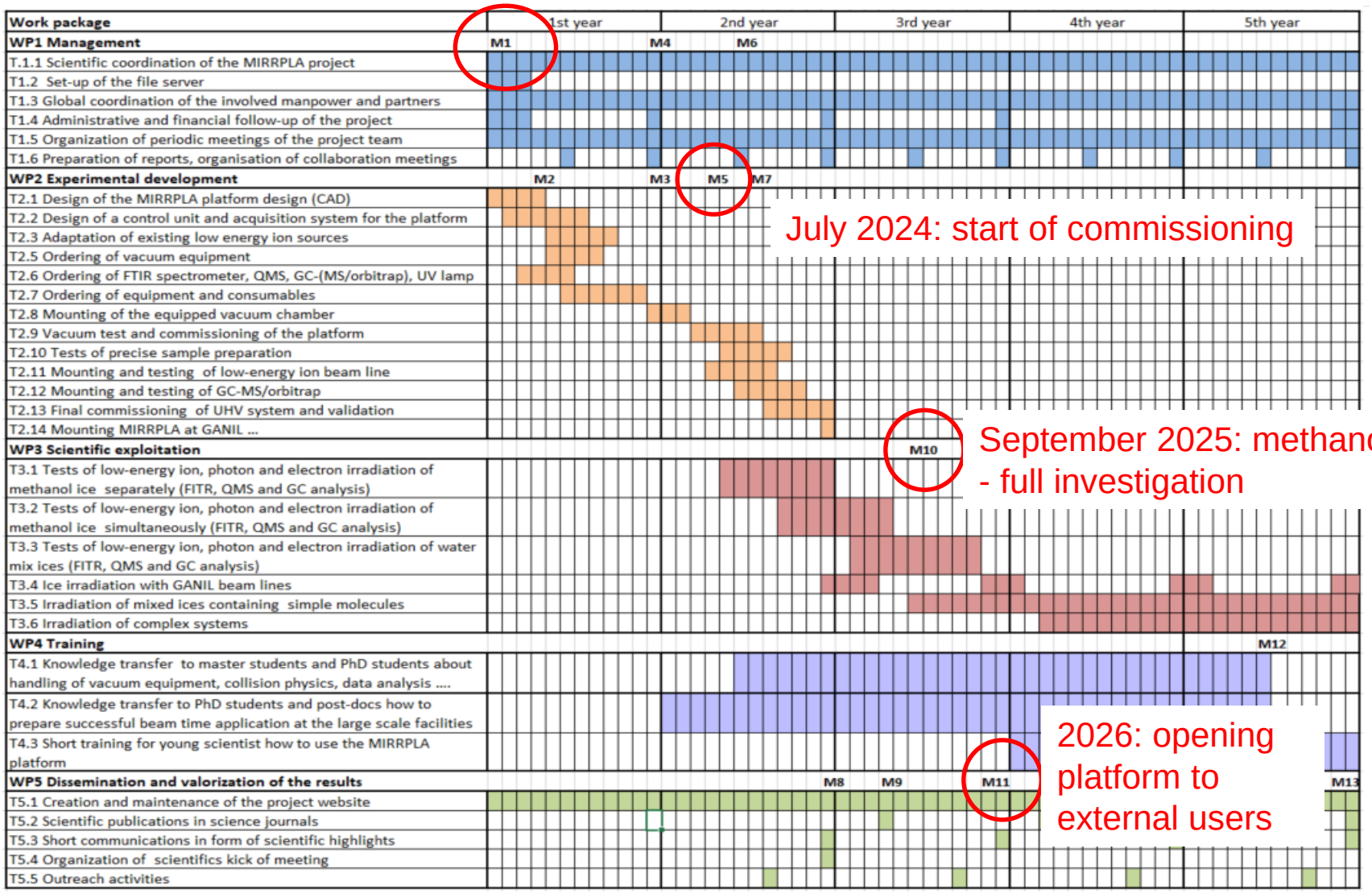
Analysis: in-situ FTIR, QMS, GC-orbitrap, ex-situ SIMS, HRMS

First samples: CH_3OH, H_2O:NH_3:CH_3OH

Organic residues: ” **primary material**” to investigate its further chemical evaluation/complexification under different environmental conditions
PEPR Origins WP2.4 *Microfluidic platforms for investigating matter complexification towards the origins of life*

Timeline: key dates

Start: March 2023



July 2024: start of commissioning

September 2025: methanol ice - full investigation

2026: opening platform to external users

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MIRRPLA: budget

Equipment: ~800 k€

- UHV chambers, turbo-and cryo-pumps, cold head, QMS
- FTIR spectrometer under vacuum
- GC-Orbitrap contacted to UHV chamber
- UV lamp with differential pumping stage, dosimetry system
- electron gun (100eV-10 keV), optics:
- adaptation of low-energy ion source to cover low-energy solar wind ions, sweeping device

Personnel: ~270 k€

- 1 PhD student (3 years)
- Post-doc- 24 months

100% funded
in the frame of PEPR Origins

Summary

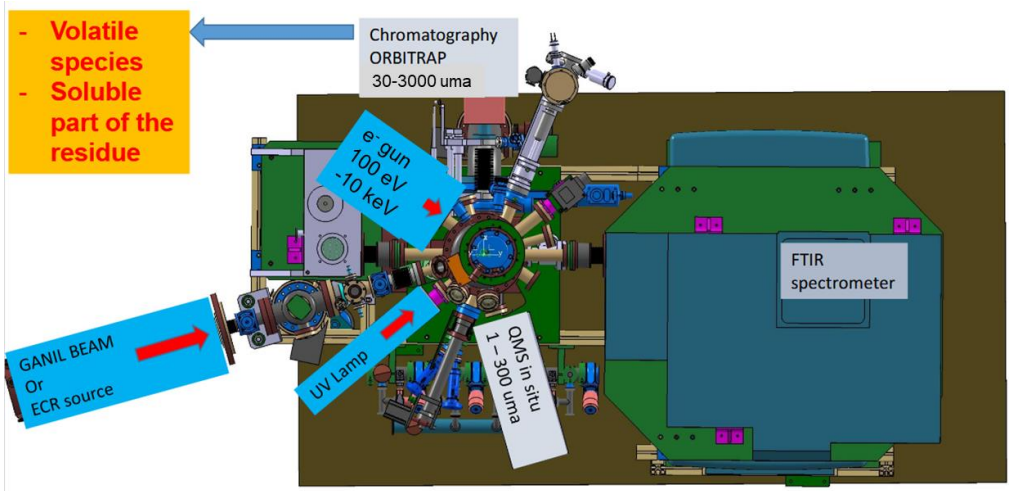
MIRRPLA: an unique worldwide multi-beam platform

Irradiation: UV photons, 100eV-10keV electrons, keV-GeV ions

Samples: 10-300K (ices/films)

Analysis: in-situ FTIR, QMS, CG-orbitrap

Location: GANIL room D2 (new layout is needed!)



Impact beyond the origins of life

The platform will be open to the whole scientific community via GANIL-CIMAP-CIRIL user's facility.

- ***Health***: unique opportunity to investigate fundamental processes at the molecular level by mixed irradiation of biomolecules and DNA fragments to develop new cancer treatment models. Another connected field the exposure of living beings to the complex radiation field in space (space missions).
- ***Environmental science***: evolution under ionizing radiation of air pollutants like polycyclic aromatic hydrocarbons (PAHs), soot particles
- ***Material science***: to develop, characterize and optimize design a new generation of polymer materials; radiation effects on materials used in spacecraft