Programs and projects at GANIL-SPIRAL2

A brief history of GANIL

1976 Creation of GANIL
(Grand Accélérateur national d'ions lourds)

1983 First experiment

2001 SPIRAL1 exotic beams

2006 SPIRAL2 Project signature of convention for construction
Inclusion on European Strategy Forum for Research Infrastructures (ESFRI) roadmap

2016 SPIRAL2 ESFRI Landmark

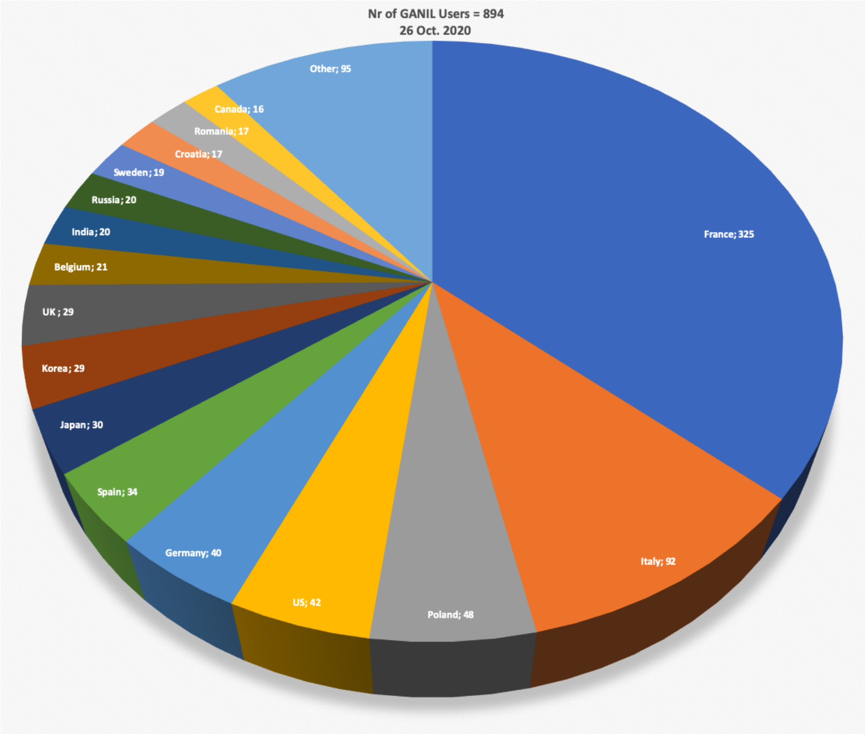
2019 Start of the commissioning of SPIRAL2

2020 First neutron beams

2021 First NFS experiments (Neutron For Science)

Some numbers

• 230 permanent staff members (CEA and CNRS researchers, engineers, technicians) + 40 temporary staff (15 PhD, 5 postdocs)
+ CIMAP = 24 permanent staff + 15 PhD + 8 postdocs
• An international scientific community of ≈ 1000 members



France
Italie
Pologne
USA
Allemagne
Espagne
Japon
Corée
Royaume Uni
Belgique
Inde
Russie
Suède
Roumanie
Canada

A major facility for heavy ions in the world

with GSI/FAIR (Germany), RIBF/RIKEN (Japan), FRIB/MSU (USA), ISOLDE (CERN)…

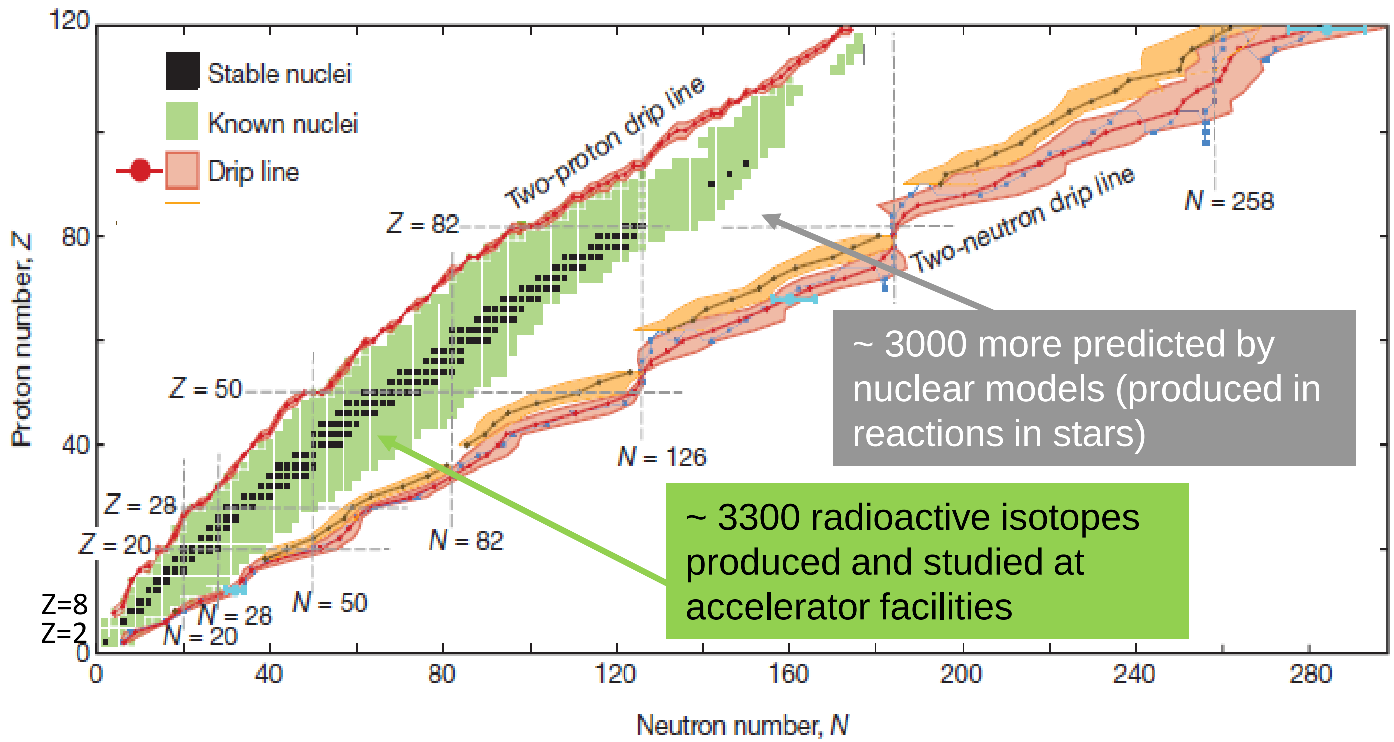
Programs at GANIL-SPIRAL2

GANIL: a multidisciplinary and multi-users laboratory

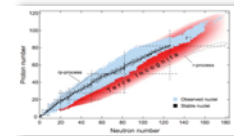
Nuclear Physics@GANIL: study of exotic nuclei

Main questions to be answered :

- What are the limits of existence of nuclei ?
- What are the underlying fundamental interactions ?
- How regular patterns emerge in the intrinsic structure of complex many body nuclei ?



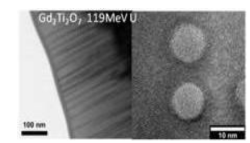
Nuclear Physics



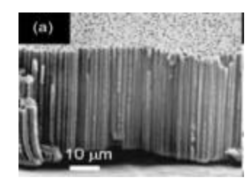
Nuclear Astrohysics

Astrochemistry

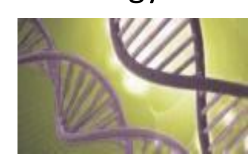
Materials under irradiation



Nanostructuration



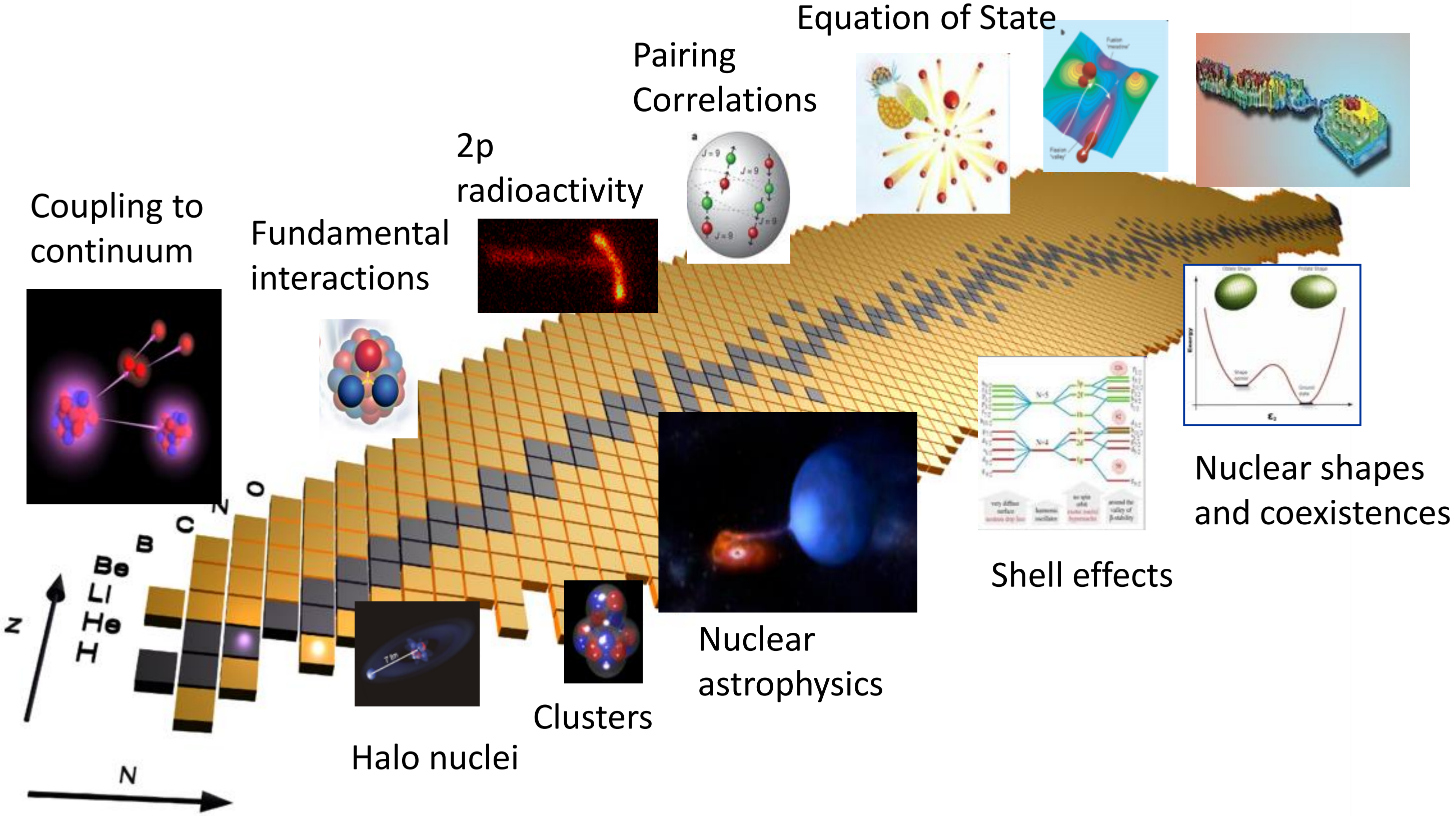
Radiobiology



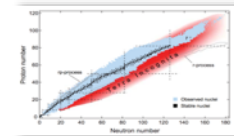
GANIL: a multidisciplinary and multi-users laboratory

Nuclear Physics@GANIL: study of exotic nuclei

- ➢ Are there more unexpected new phenomena to be discovered ?
  - ✓ Shell structure modification and new magic numbers
  - ✓ Halo nuclei
  - ✓ New radioactivities
  - ✓ ????



Nuclear Physics



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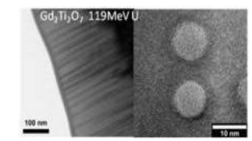
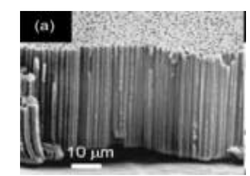
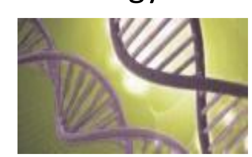


Nanostructuration

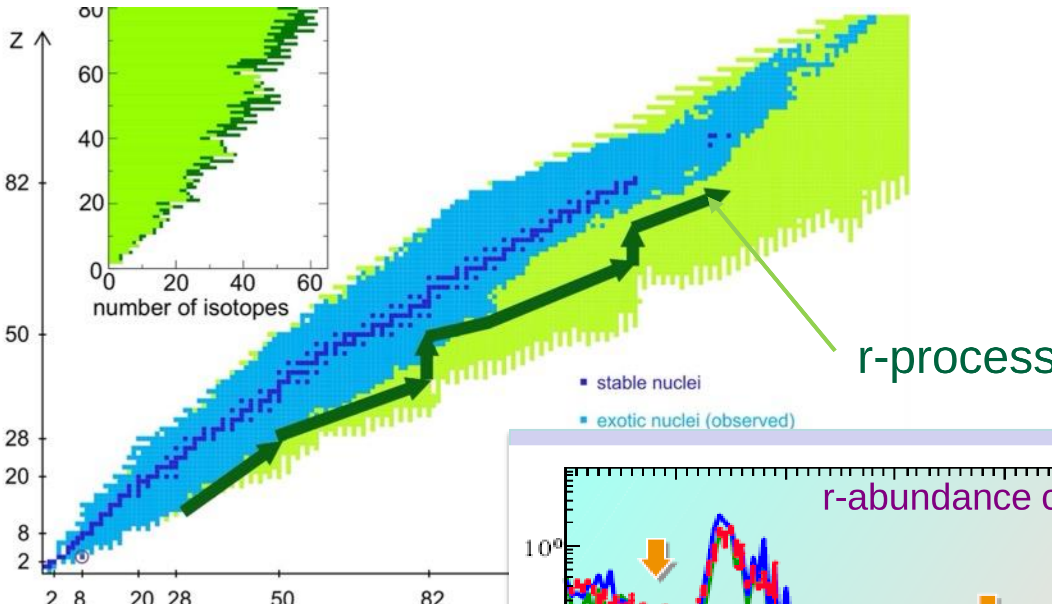


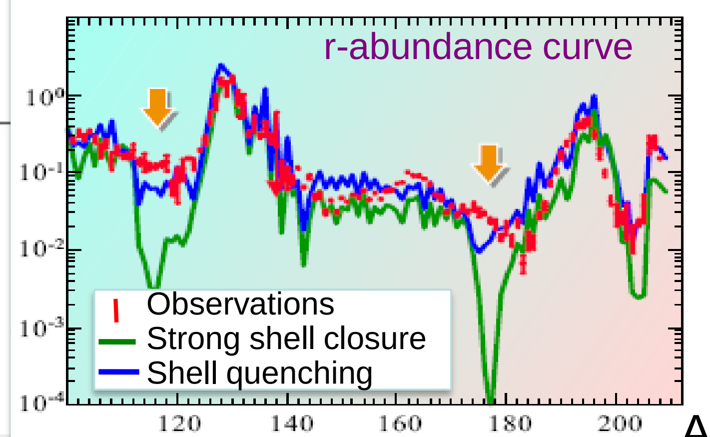
Radiobiology



GANIL: a multidisciplinary and multi-users laboratory

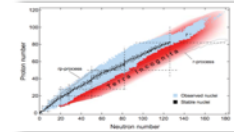
Nuclear astrophysics:
How nuclei have participated and still participate in the creation of elements in the universe?
Renewed interest since the discovery of gravitational waves : EM counterpart of GW170817 is the strongest evidence of heavy elements nucleosynthesis through the r-process.





B. Pfeiffer, et al., NPA 693 (2001) 282

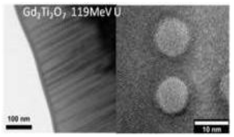
Nuclear Physics



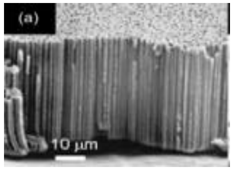
Nuclear Astrohysics

Astrochemistry

Materials under irradiation



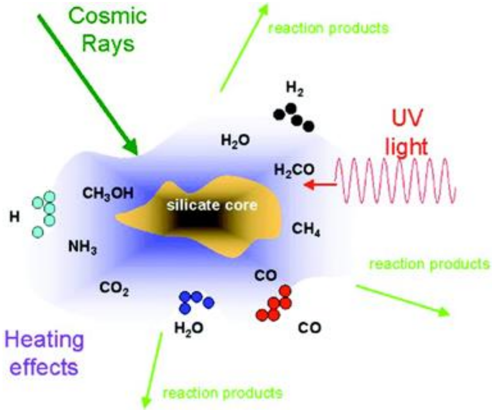
Nanostructuration



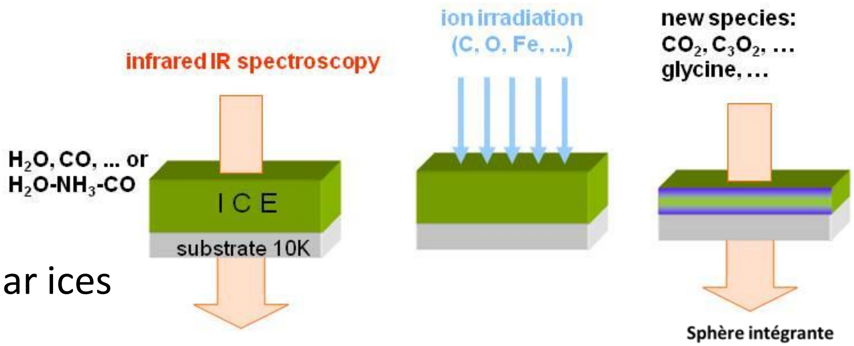
Radiobiology

GANIL: a multidisciplinary and multi-users laboratory

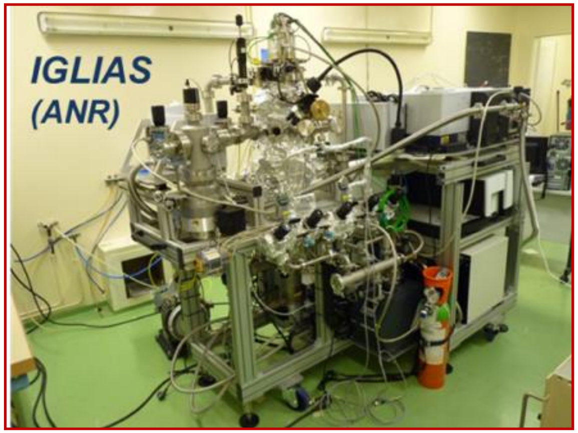
Astrochemistry:
Role of cosmic rays and stellar winds on ices for the appearance of molecules in the universe

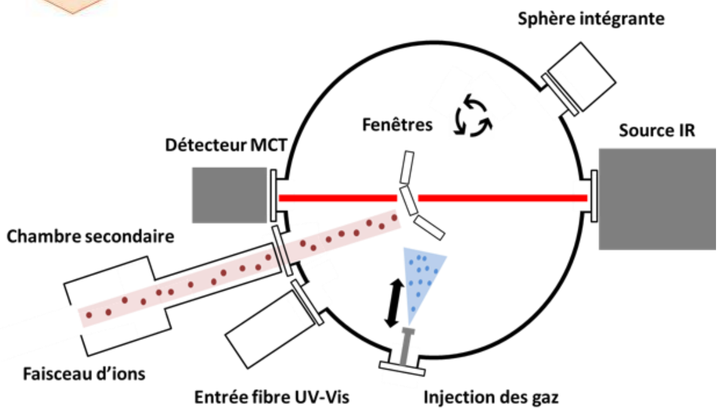


fragmentation/destruction
formation of molecules
Desorption / Sputtering /implantation



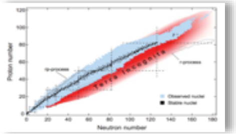
IGLIAS setup to mimic interstellar ices exposed to radiation





In-situ gas deposition
3 spectrometers (UV-visible, FTIR, QMS)

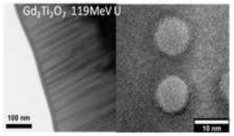
Nuclear Physics



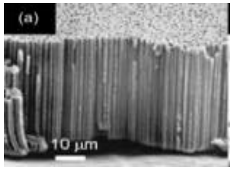
Nuclear Astrohysics

Astrochemistry

Materials under irradiation



Nanostructuration

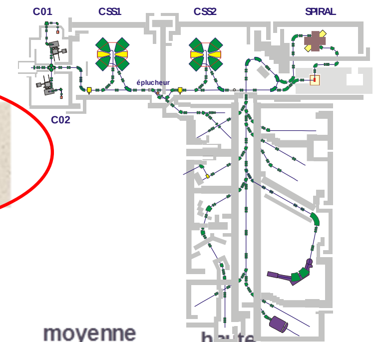


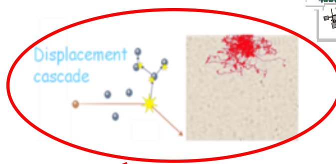
Radiobiology

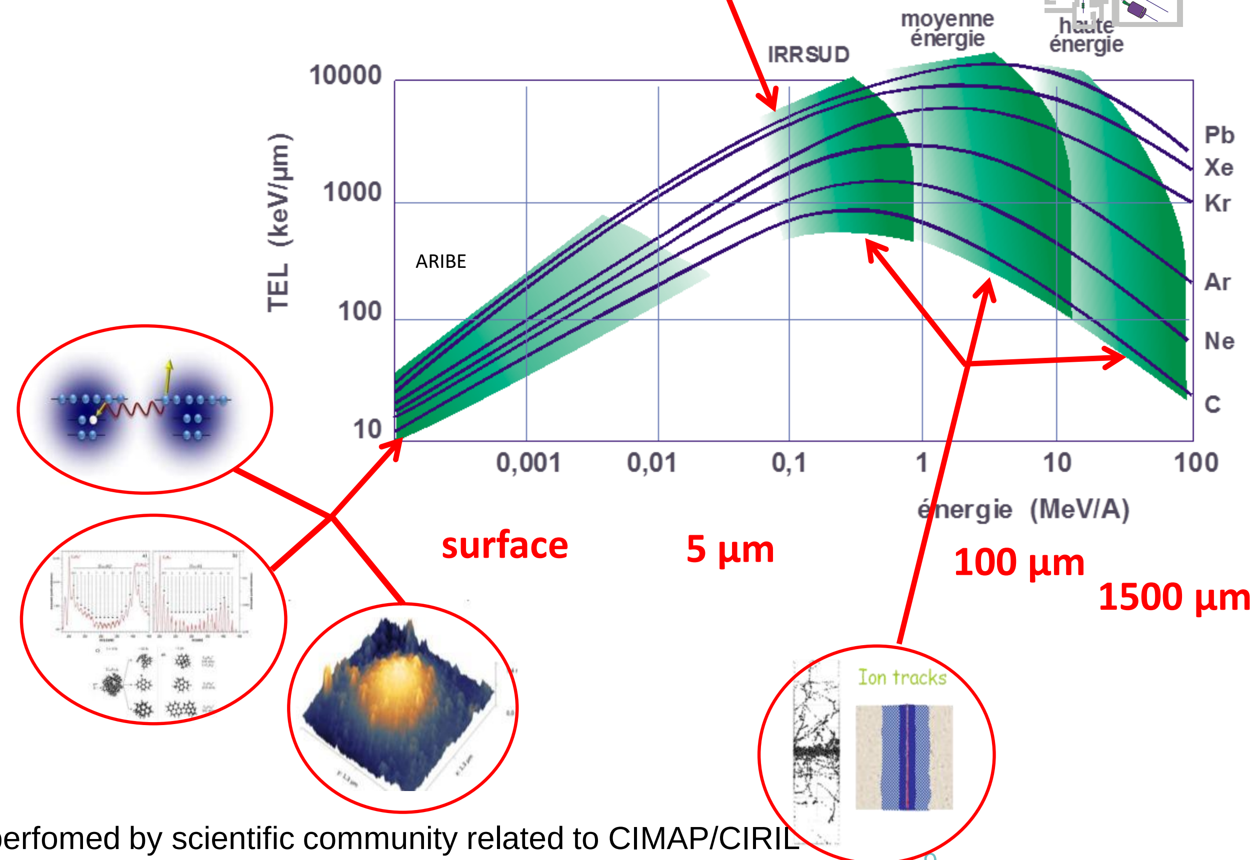
GANIL: a multidisciplinary and multi-users laboratory

Materials under irradiation/Nanostructuration

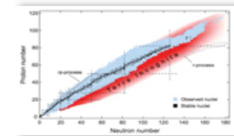
- Materials study
- Contribution to improving the nuclear power plants safety (fuel tubes, nuclear packaging)







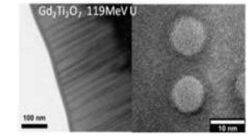
Nuclear Physics



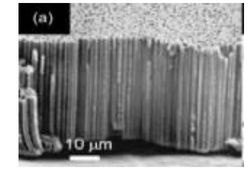
Nuclear Astrohysics

Astrochemistry

Materials under irradiation



Nanostructuration



Radiobiology

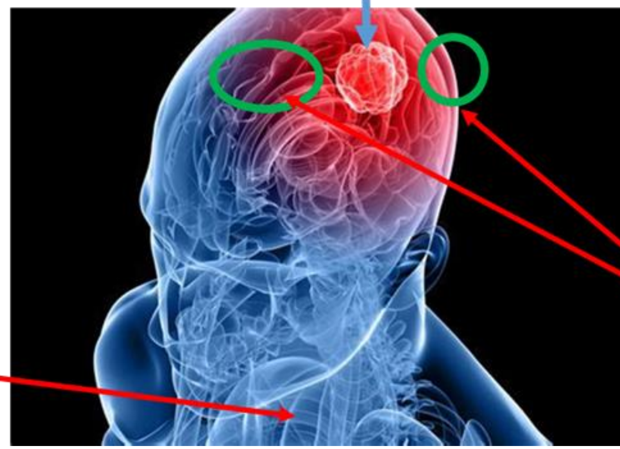
Studies perfomed by scientific community related to CIMAP/CIRIL

GANIL: a multidisciplinary and multi-users laboratory

Radiobiology

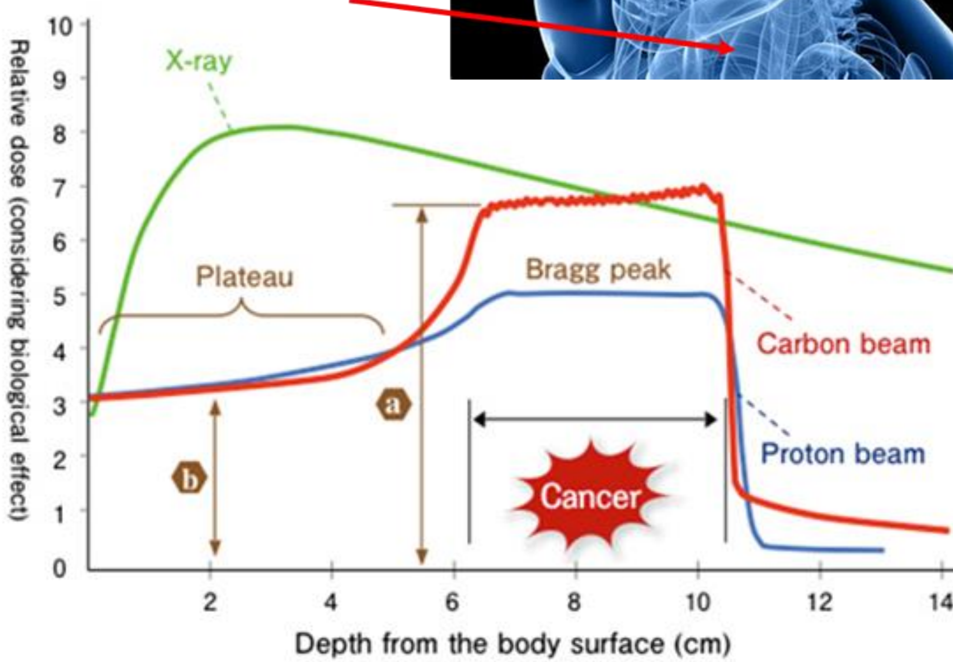
- New radioisotopes for medicine (^{211}At)
- pre-clinical studies and innovative methods for hadrontherapy

Tumor effects



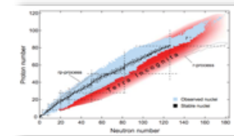
normal tissues

Non-targeted effects



New hadrontherapy center nearby GANIL

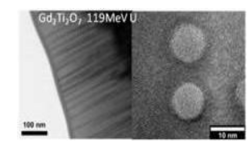
Nuclear Physics



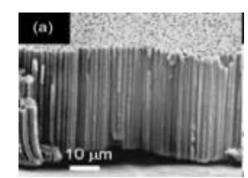
Nuclear Astrohysics

Astrochemistry

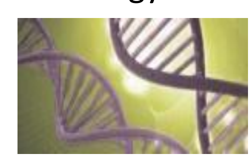
Materials under irradiation



Nanostructuration

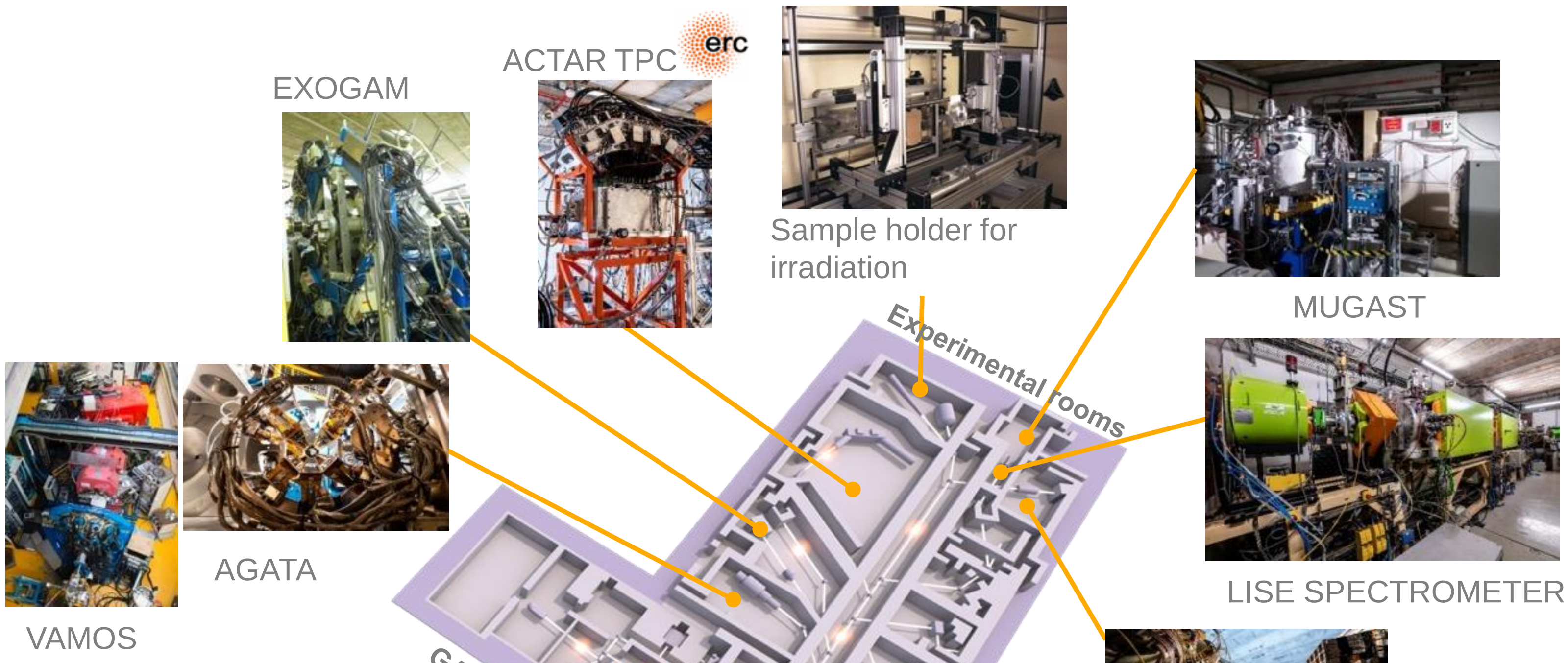


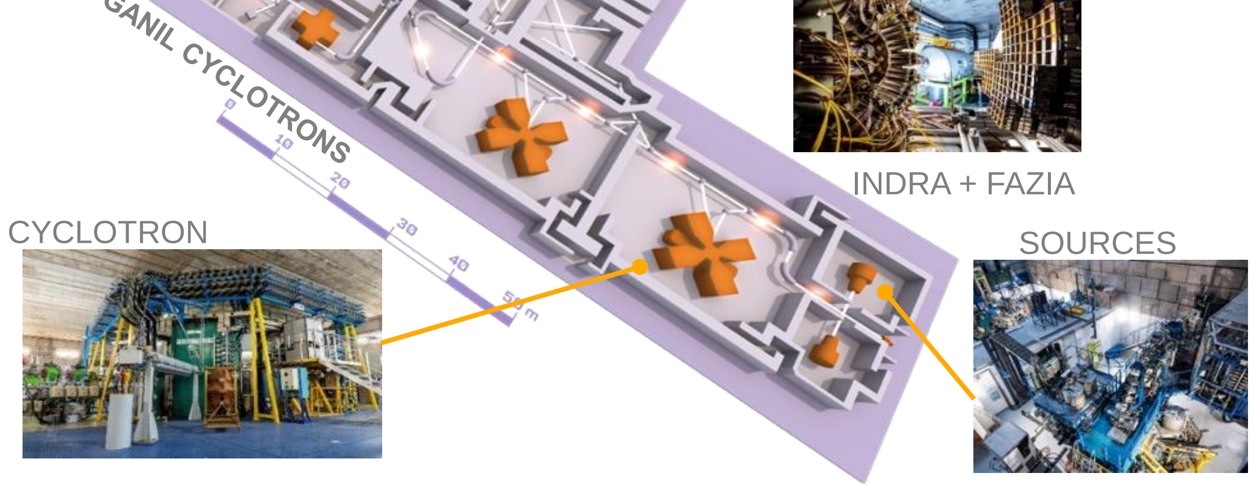
Radiobiology



GANIL-SPIRAL2 Facility

GANIL Cyclotrons and experimental equipment





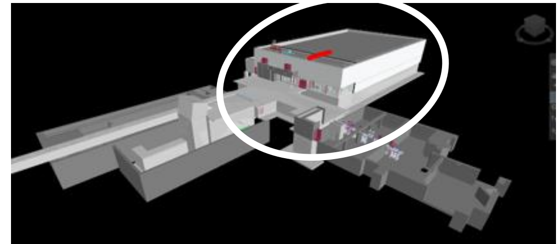
- Beams : ^{12}C to U
- Energy : from <1 MeV up to 95MeV/nucleon
- Up to 4 experiments in parallel

SPIRAL2 and the new experimental rooms

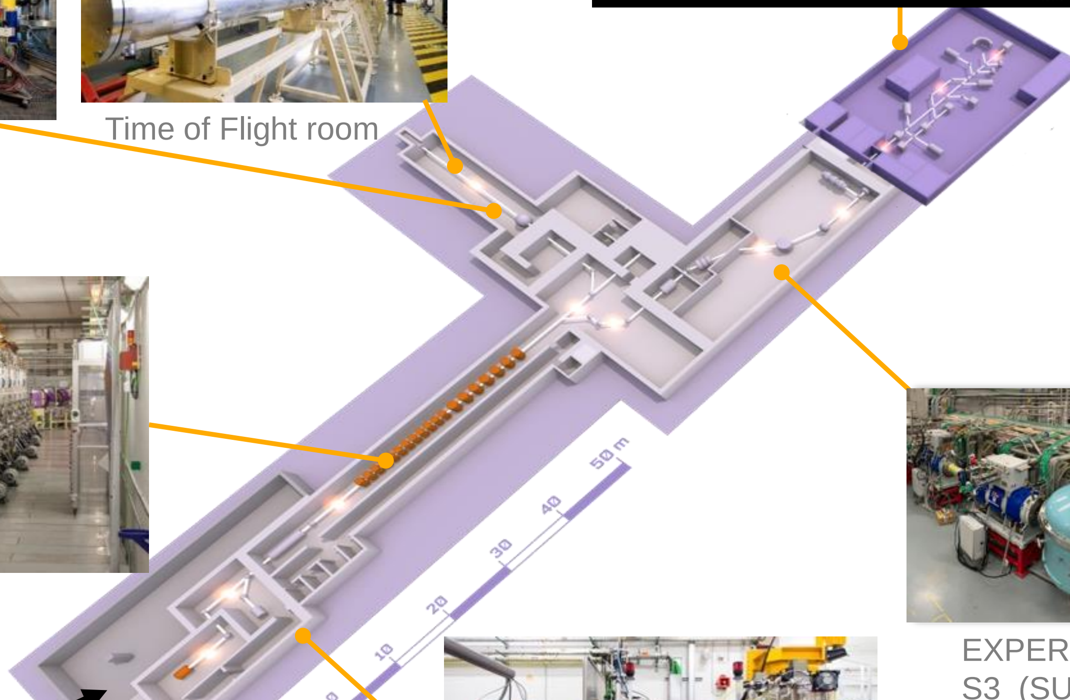
EXPERIMENTAL ROOM NFS (NEUTRONS FOR SCIENCE)

Convertor room

Time of Flight room

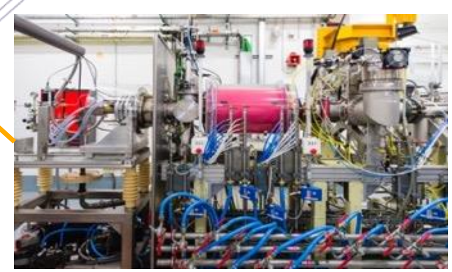


EXPERIMENTAL ROOM DESIR (Desintegration, Excitation and Storage of Radioactive Ions)



LINEAR accelerator (LINAC)

NEWGAIN
NEW GANIL INJECTOR



ION SOURCE

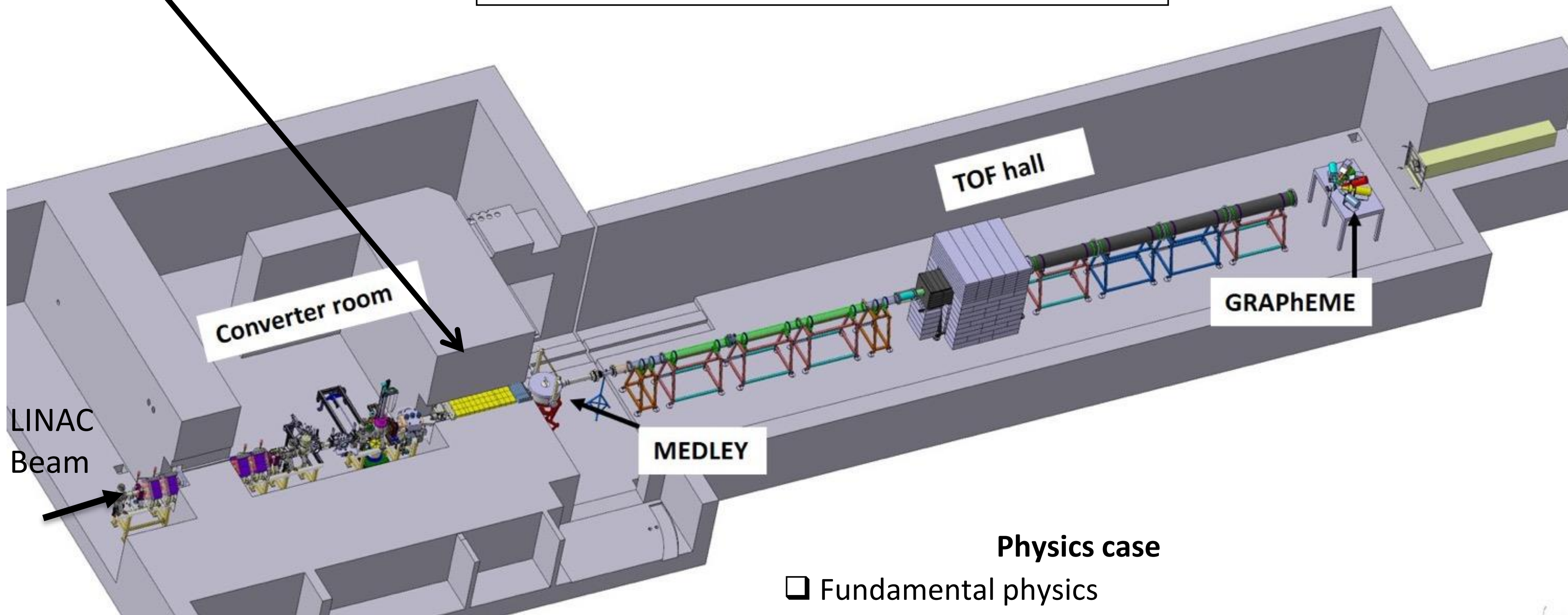
EXPERIMENTAL ROOM S3 (SUPER SEPARATOR SPECTROMETER)

Beams :
33 MeV protons
40 MeV deutons
<14,5 MeV/A heavy ions

New experimental room : Neutron for Science

Collimator

- Ion and neutron induced reactions
- Irradiation station (n, p, d)



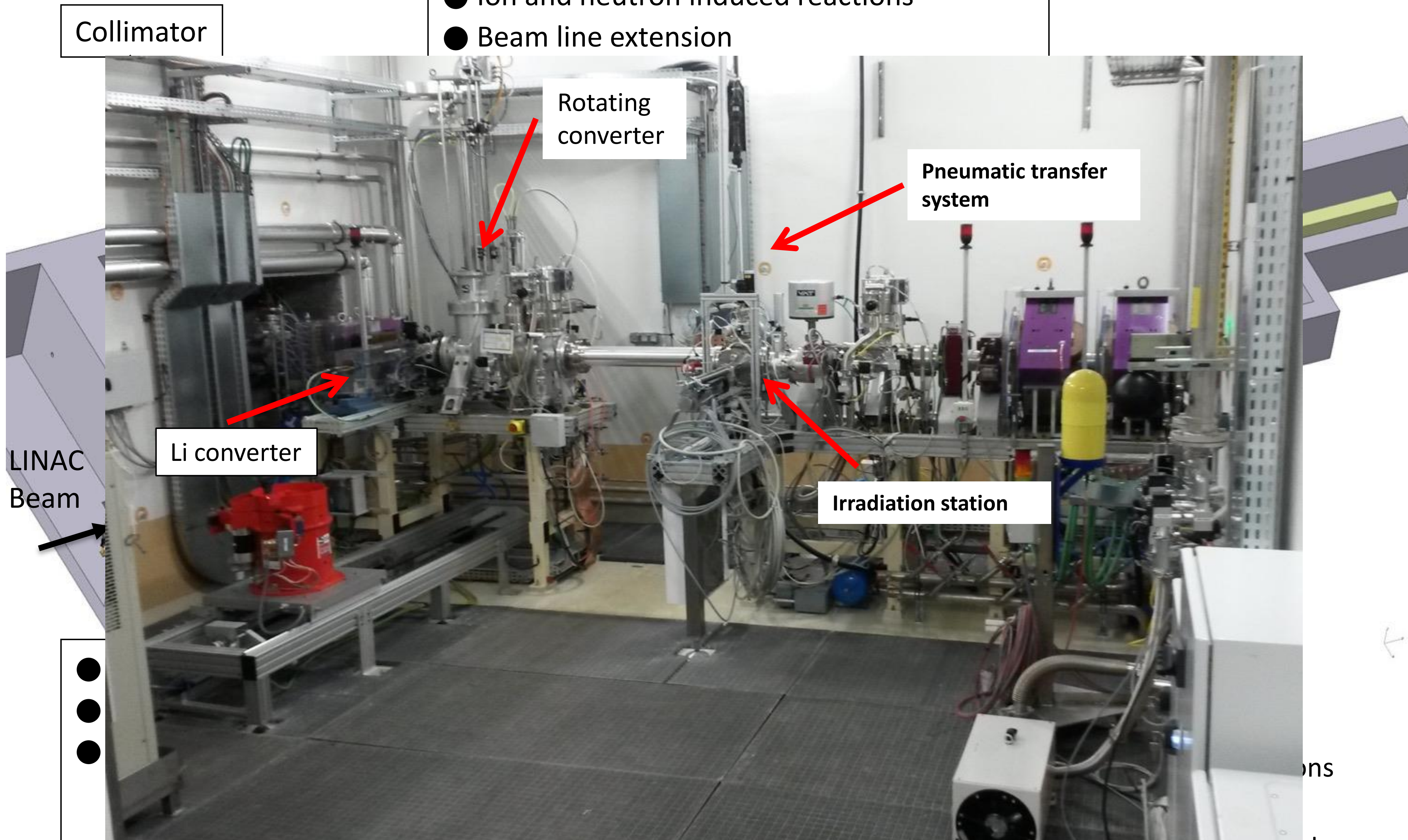
- Neutron Beam at 0°
- Collimator   beam quality
- Size (L x l) ≃ (28m x 6m)
    - TOF measurements
    - free flight path

Physics case

- ❑ Fundamental physics
- ❑ Astrophysics
- ❑ New generation of reactor
- ❑ Fusion technology
- ❑ Radioisotopes production for medical applications
- ❑ Biology (cells irradiation..)
- ❑ Development and characterization of new detectors
- ❑ Study of the single-event upsets

New experimental room : Neutron for Science

- Ion and neutron induced reactions
- Beam line extension



- ❑ Development and characterization of new detectors
- ❑ Study of the single-event upsets

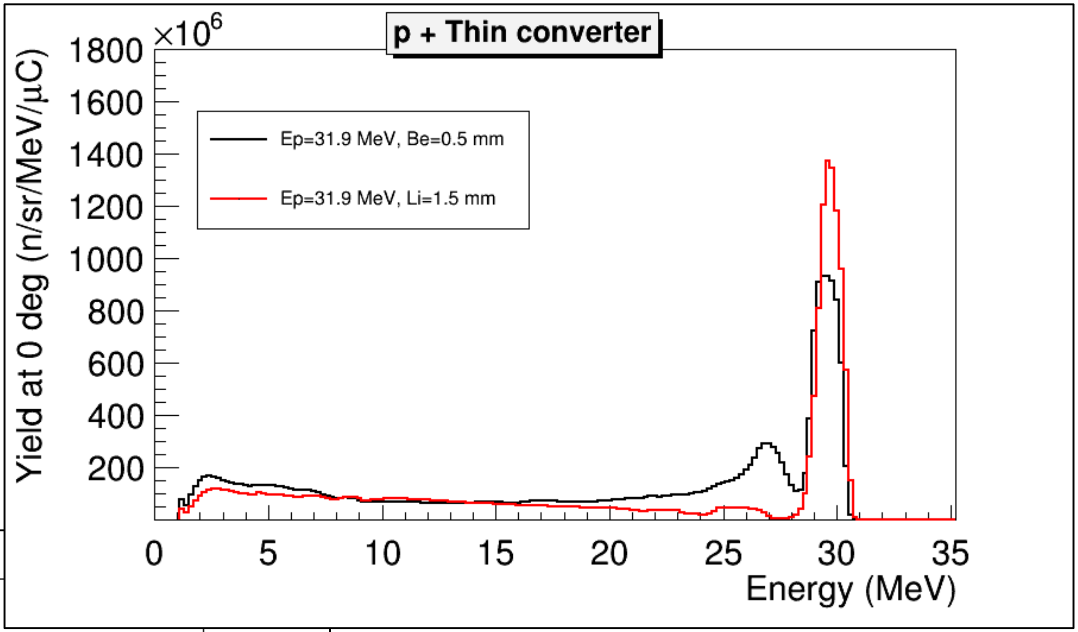
New experimental room : Neutron for Science

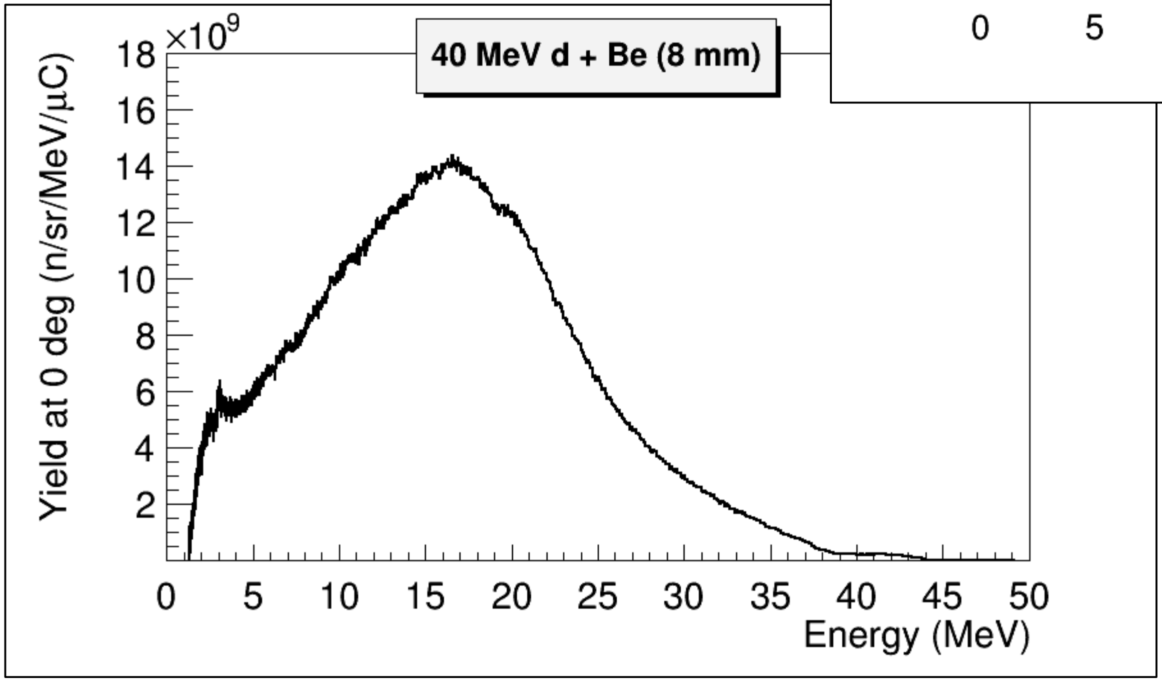
LINAC
Beam

s

- ❑ Study of the single-event upsets

Neutrons beams





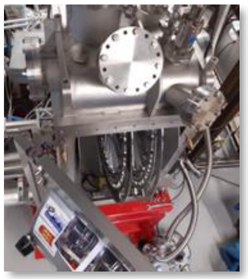
Flux at 5 meters :
8.10^7 n/s/cm^2
at 15 MeV : 5.10^6 n/s/cm^2/MeV
at 30 MeV : 6.10^5 n/s/cm^2/MeV

S³ : the Super Separator Spectrometer

Fundamental research in **Nuclear & Atomic physics**

- High selectivity > 10^{13} beam rejection
- High efficiency 50%
- Mass resolution > 350
- Versatility : high resolution, high transmission, high beam rejection modes…
- Unique instrumentation : SIRIUS for p, α, electron and γ spectroscopy, and S3-LEB with gas catcher, RFQ and MR-ToF-MS

Target system



High power rotating targets

3 × M-dipoles

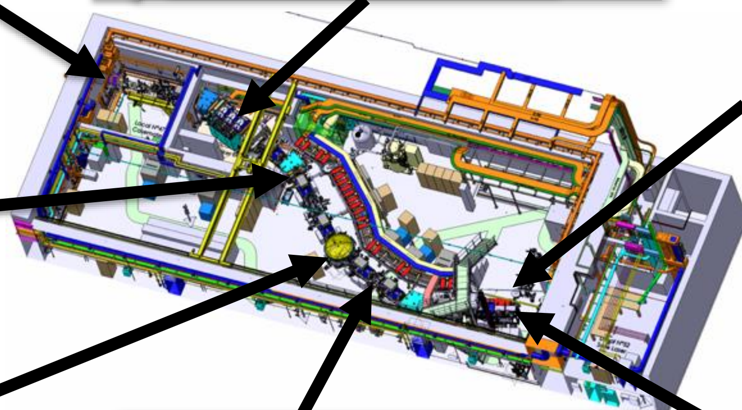
Large H & V gaps

E-Dipole

20 cm gap & +/- 300 kV
Open slit in the anode

Dispersive zone

Open RT magnet & beam dump & Movable fingers



SC Multipoles

SMT, PSS, Coldbox & LTC

Infra / Interface

Cooling system, Laser room …

LEB

LEB @ LPC & GISELE Laser Lab

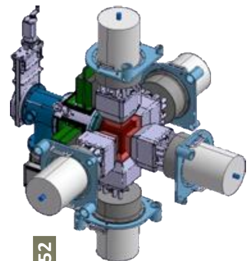
SIRIUS

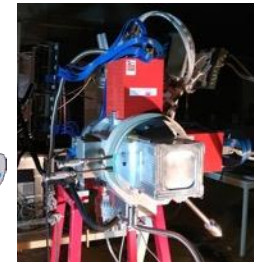
DSSD, SSD, FEE/BEE, DAQ & Diagbox

S^3-SIRIUS day 1 pre-proposals

SIRIUS: Spectroscopy and Identification of Rare Isotopes Using S3

- tracking detector
- Si detector box
- Ge detectors





K-isomers
Single particle states
New isotopes – limits of stability
Odd-Z nuclei
Reaction mechanism
N=152, 162

Very heavy and super heavy nuclei

- Limit of the nuclear existence
- Shell correction effects
- Reaction mechanisms

Isomers
^{254}Rf, ^{260}Sg

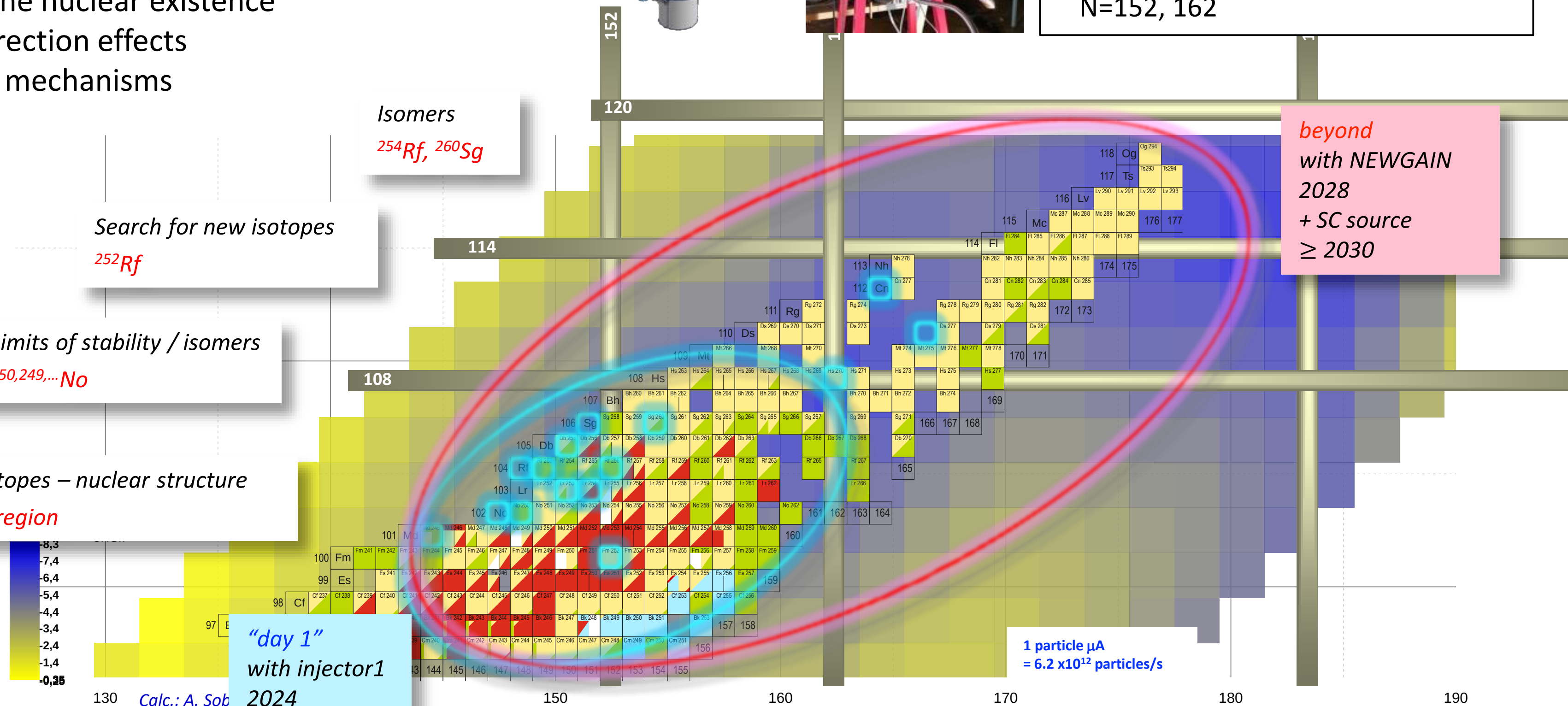
Search for new isotopes
^{252}Rf

Limits of stability / isomers
$^{250,249,...}$No

Odd Z isotopes – nuclear structure
fermium region

beyond
with NEWGAIN
2028
+ SC source
≥ 2030

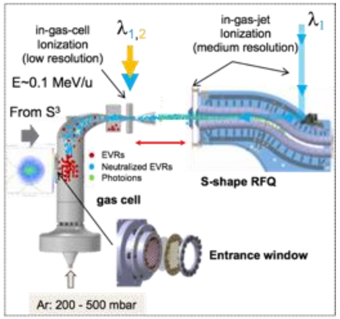
"day 1"
with injector1
2024



S^3-LEB day 1 pre-proposals

REGLIS^3

Observables :
- Nuclear magnetic dipole moment
- Nuclear Electric quadrupole moment
- Mean charge radii
- Spin

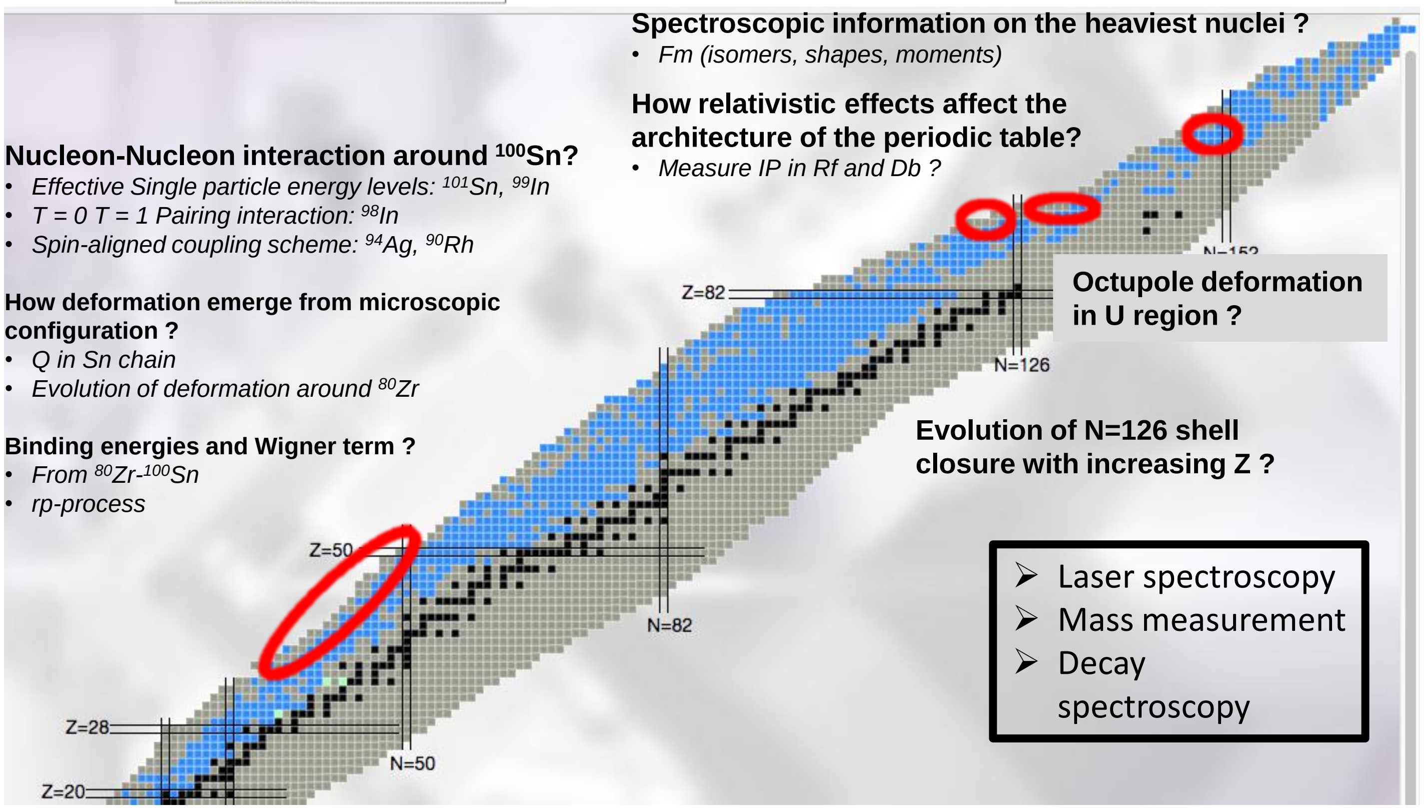


PILGRIM (MR-Tof-MS)

Observables :
- Mass (100keV)

Tape station

Observables :
- Decay spectroscopy
- Half-life



Spectroscopic information on the heaviest nuclei ?
- *Fm (isomers, shapes, moments)*

How relativistic effects affect the architecture of the periodic table?
- *Measure IP in Rf and Db ?*

Nucleon-Nucleon interaction around ^{100}Sn?
- *Effective Single particle energy levels: ^{101}Sn, ^{99}In*
- *T = 0 T = 1 Pairing interaction: ^{98}In*
- *Spin-aligned coupling scheme: ^{94}Ag, ^{90}Rh*

How deformation emerge from microscopic configuration ?
- *Q in Sn chain*
- *Evolution of deformation around ^{80}Zr*

Binding energies and Wigner term ?
- *From ^{80}Zr-^{100}Sn*
- *rp-process*

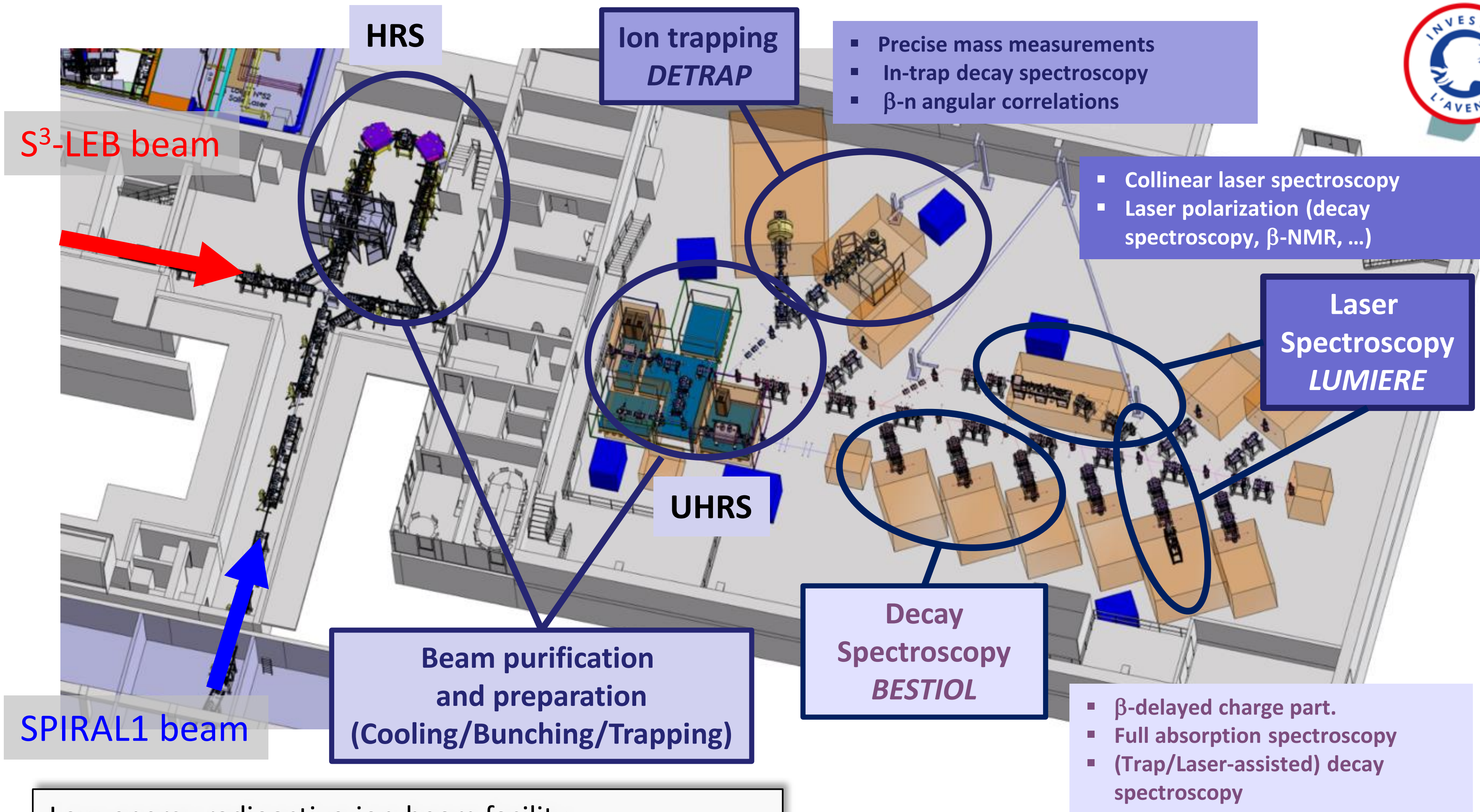
Octupole deformation in U region ?

Evolution of N=126 shell closure with increasing Z ?

- ➢ Laser spectroscopy
- ➢ Mass measurement
- ➢ Decay spectroscopy

- ◎ N=Z region: shell evolution, nucleosynthesis, symmetries
- ◎ Heavy neutron-deficient refractory elements: shapes/shape coexistence, exotic decay modes
- ◎ Heavy and Super Heavy Element region: single-particle versus deformation, atomic physics

Experimental room under project: DESIR



Low-energy radioactive-ion-beam facility

- Beams from SPIRAL1 and S^3
- Important beam preparation and purification capabilities
- High resolution/precision experiments

Construction will start after « Modification autorisation » procedure (ASN, MSNR) and public inquiry => Spring-summer 2023

First beams: 2027

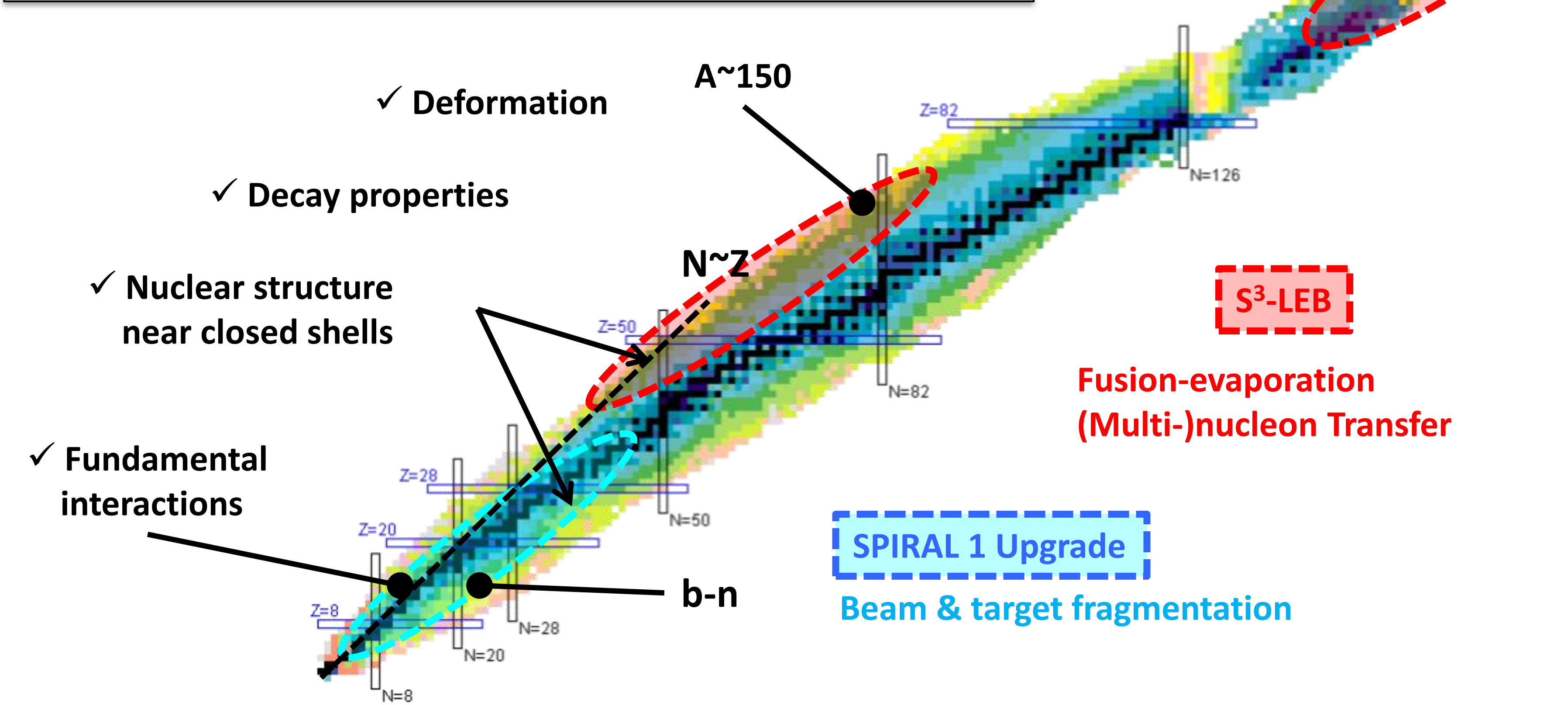
Scientific Program

- Collinear laser spectroscopy
- β-delayed γ spectroscopy
- β-n angular correlation
- Mass measurement
- β-delayed charge part., β-n emission
- (Trap-assisted) β-decay, full absorption spectroscopy

LUMIERE

DETRAP

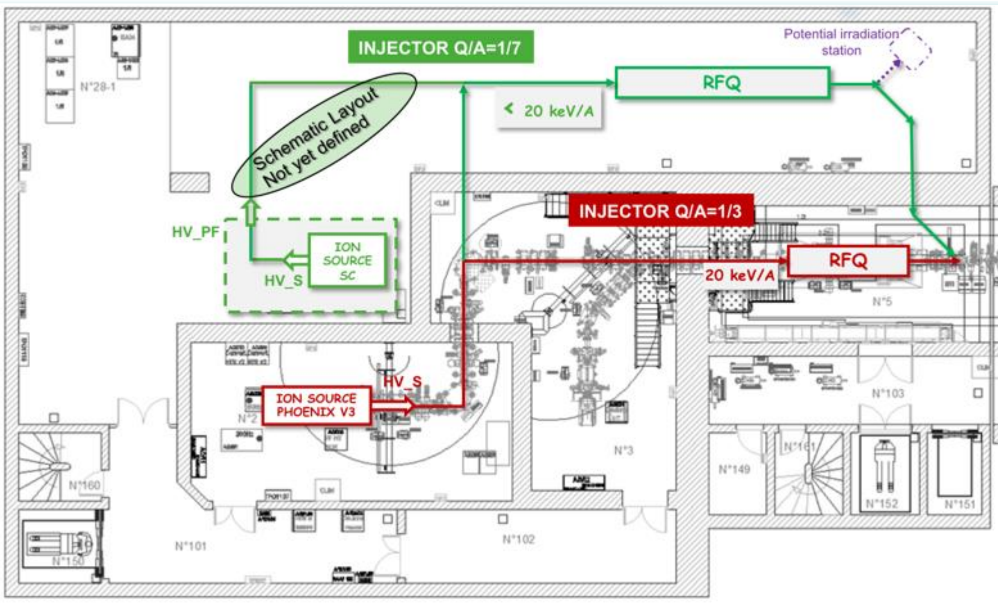
BESTIOL



New injector for SPIRAL2: NEWGAIN

NEWGAIN
NEW GANIL INJECTOR

Floorplan, design intensities and time line



Ions	*beam intensities* — *injector1* *2023* Intensity (pμA) Phoenix V3 RFQ A/Q≤3	NEWGAIN (injector2) *2028* Intensity (pμA) Phoenix V3 RFQ A/Q≤7	NEWGAIN (injector2) *≥ 2030* Intensity (pμA) SC Ion Source RFQ A/Q≤7
^{18}O	80	*	375
^{19}F	>15	>40	>40
^{36}Ar	16	70	45
^{40}Ar	3.6	70	45
^{36}S	2.3	*	*
^{40}Ca	2.9	10	20
^{48}Ca	1.2	10	20
^{58}Ni	1.1	4	**8**
^{84}Kr	0.1	10	**20**
^{139}Xe	0.001	7	**>10**
^{238}U	<<0.001	0.1	**6**

Measured | Estimated

* -> no estimation

NEWGAIN *White Book*

https://www.ganil-spiral2.eu/scientists/ganil-spiral-2-facilities/accelerators/newgain/

NEWGAIN *time line*

2020	2021	2022	2023	2024	2025	2026	2027	2028

Study Phase → Construction Phase → ***first beam***

GANIL-SPIRAL2
medium/long term perspectives

Vision for the future of GANIL: Expert Committee report

GANIL spiral2 laboratoire commun CEA/DRF CNRS/IN2P3

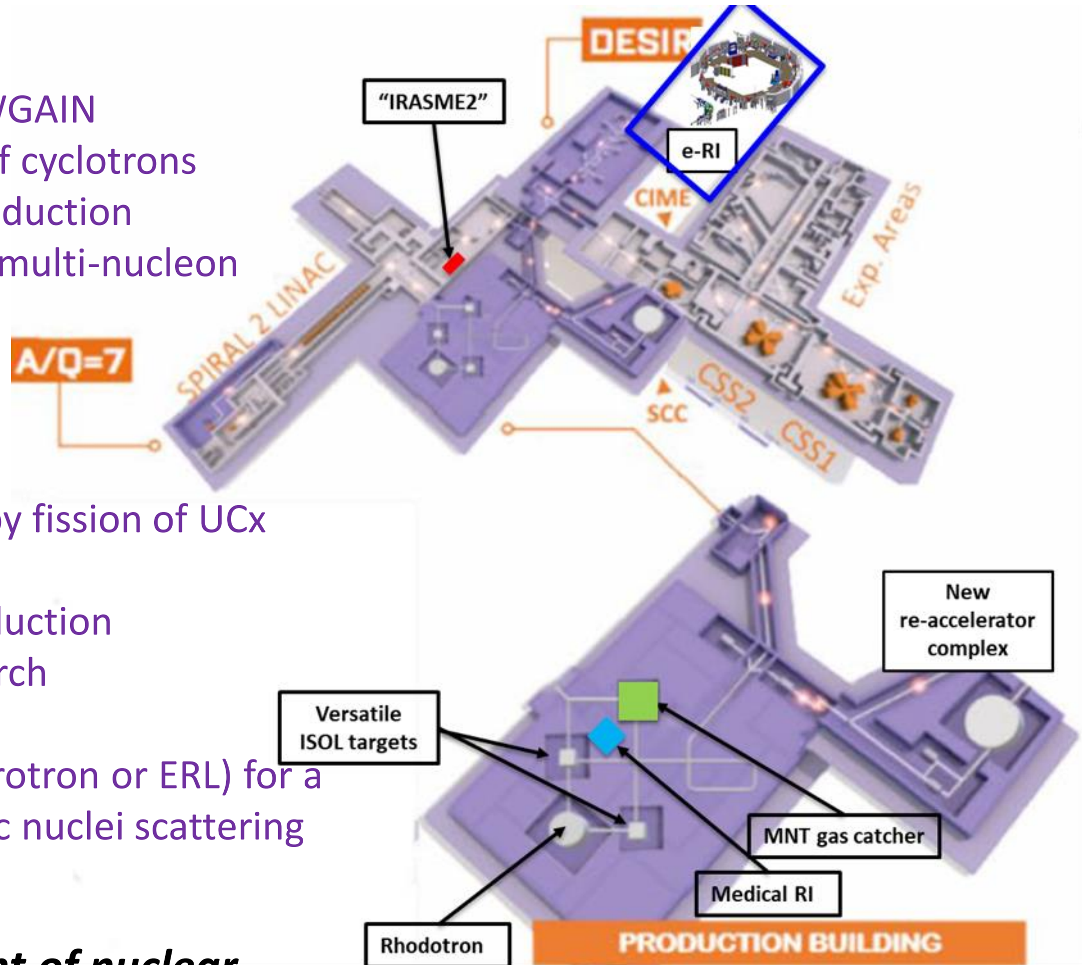
Expert committtee Chair : Michel Spiro
Members: Maria Jose Garcia Borge (CSIC), Paolo Giubellino (FAIR), Ulli Köster(ILL), Hiroyushi Sakurai (RIKEN), Boris Sharkov (JINR), Brad Sherill (MSU), Johanna Stachel (Univ. Heidelberg)

Three steps for the future of GANIL

1) Until 2030:
-finalisation of ongoing projets : S3, DESIR, NEWGAIN
-cyclotrons and LINAC operation, refurbishing of cyclotrons
-new target station for test of radioisotopes production
-test gas cell for fragment production via MNT (multi-nucleon transfer)

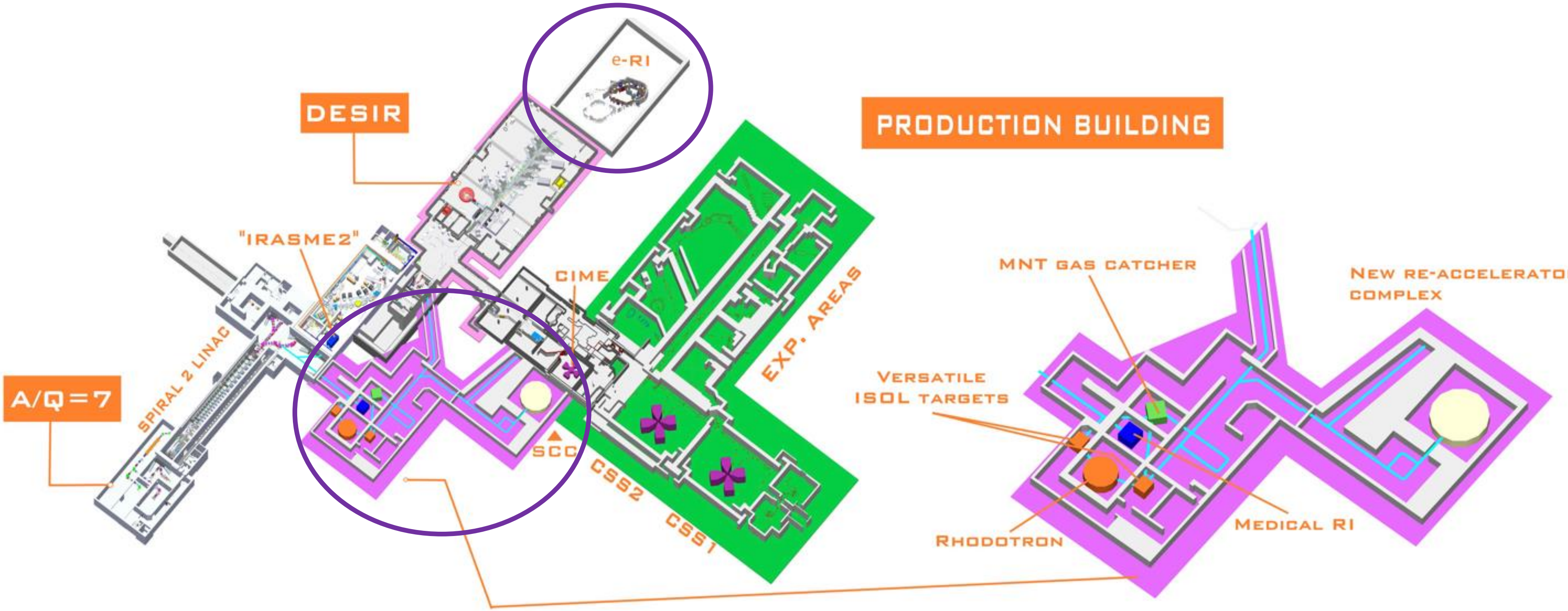
2) Until 2035
-renovation or replacement of CIME cyclotron to reach 100 MeV/nucleon
-building for production of n-rich exotic nuclei by fission of UCx target.
-Dedicated target station for radioisotopes production
-Dedicated beam line for pluridisciplinary research

3) Until 2040
-Construction of an electron accelerator (synchrotron or ERL) for a new generation of experiments : electron-exotic nuclei scattering



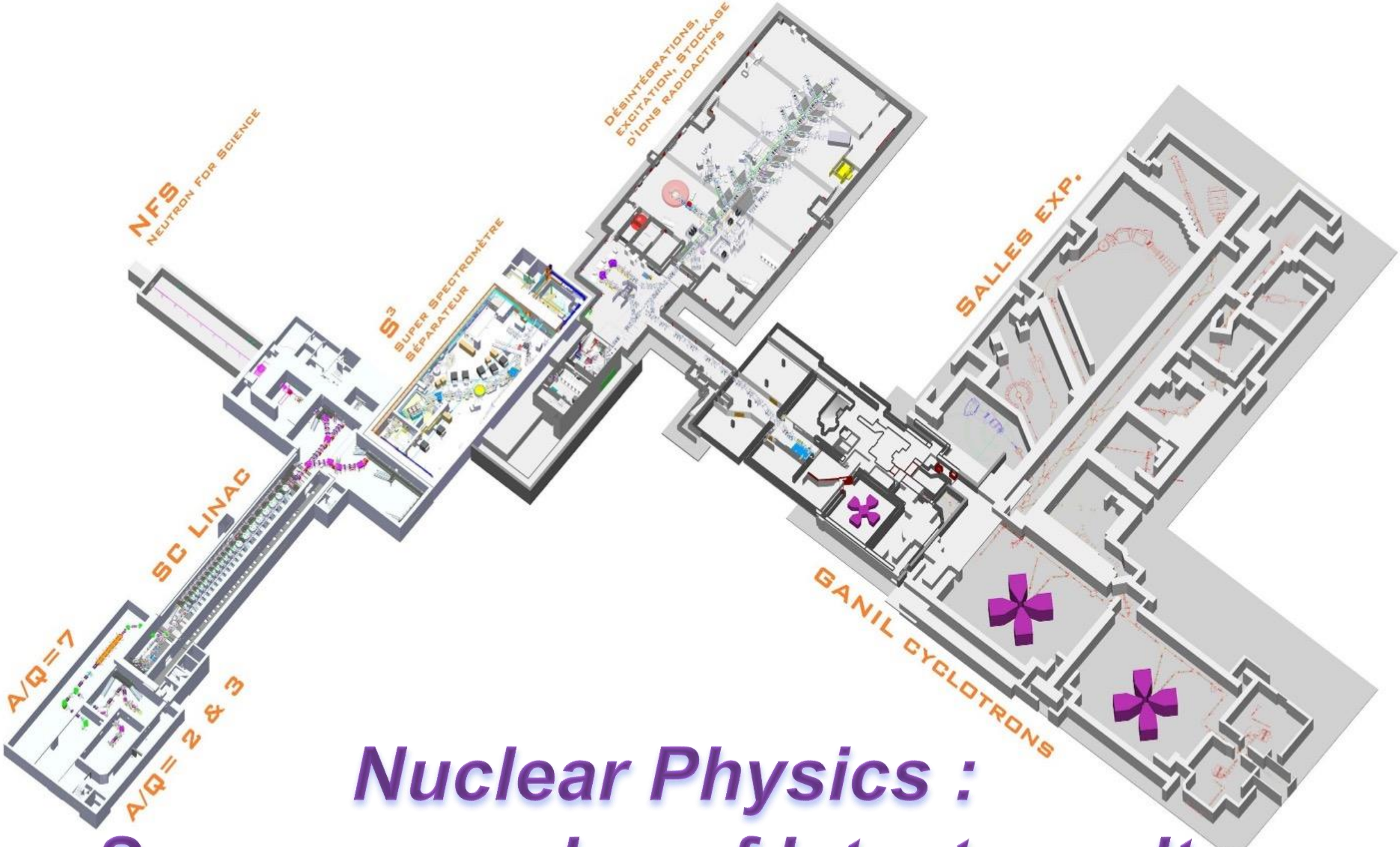
« Vision to keep GANIL at the forefront of nuclear science globally for many decades to come »

GANIL 2040 ????


e-RI
DESIR
PRODUCTION BUILDING
"IRASME2"
CIME
EXP. AREAS
MNT GAS CATCHER
NEW RE-ACCELERATOR COMPLEX
SPIRAL 2 LINAC
A/Q=7
SCC
CSS2
CSS1
VERSATILE ISOL TARGETS
MEDICAL RI
RHODOTRON

Thank you
for your attention

Back up slides

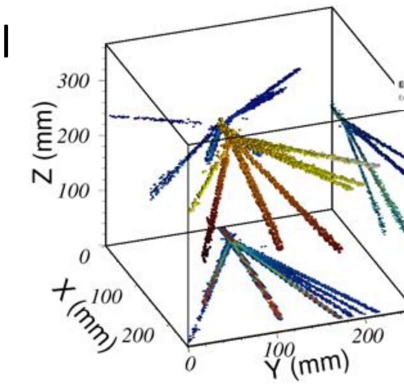


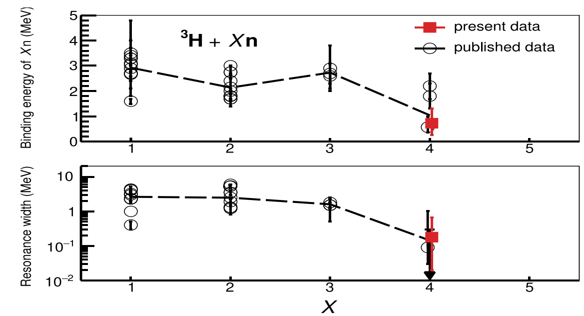
Nuclear Physics :
Some examples of latest results

Study of very neutron rich light nuclei : ^{7}H

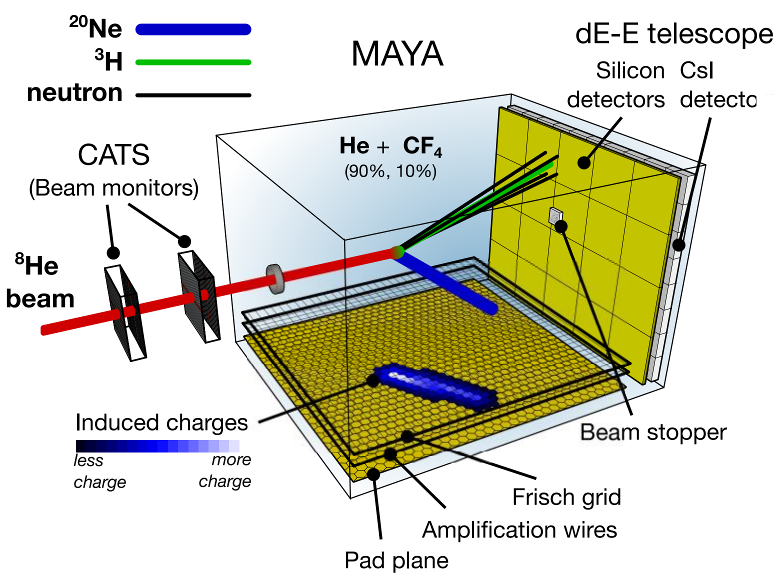
ACTAR active target : the detector gas constitutes the target material

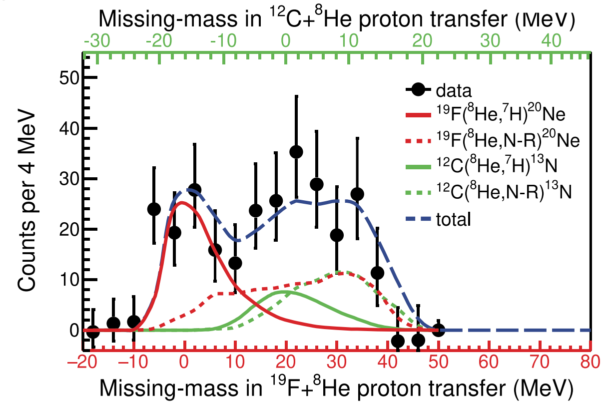
- ⇒ Thick target to compensate for low beam intensity
- ⇒ Vertex and energy measurement
- ⇒ Low particle thresholds
- ⇒ Large range of center of mass angles
- ⇒ Very high efficiency
- ⇒ Excitation function





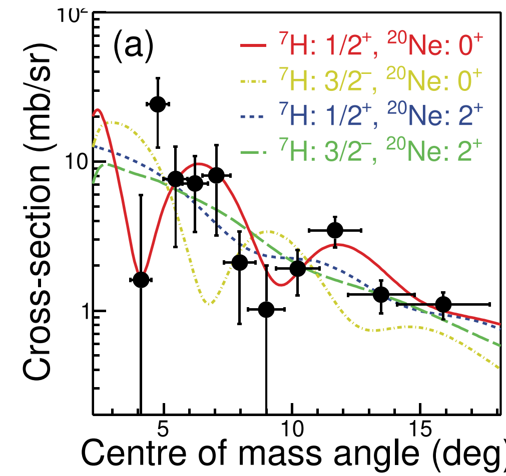
Application to ^{7}H ground state properties investigation by missing mass method M. Caamano et al, Phys. Lett B829 (2022)





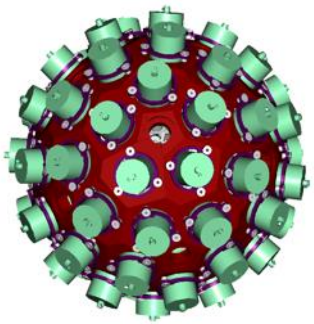
$$E_R = 0.73^{+0.58}_{-0.47}\ \text{MeV}$$

$$\Gamma_R = 0.18^{+0.47}_{-0.16}\ \text{MeV}$$



½+ ground state

The AGATA project : THE ultimate spectrometer



- 180 (60 triple-clusters) 36-fold segmented crystals
- Amount of germanium: 362 kg
- Solid angle coverage: 82 %
- Singles rate >50 kHz
- Efficiency: 43% (M_γ=1) , 28% (M_γ = 30)
- Peak/Total: 58% (M_γ=1), 49% (M_γ = 30)
- Angular Resolution: ~1º

The project timeline is to complete the 4π by 2030

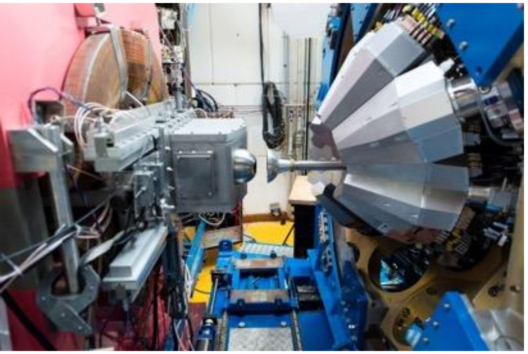
Combination of:

- ❑ segmented detector
- ❑ pulse-shape analysis
- ❑ tracking the γ rays
- ❑ digital electronics

S. Akkoyun *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A 668, 26 (2012).
E. Clément *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A 855, 1 (2017).

AGATA@GANIL: many sub-campaigns

2015-2017

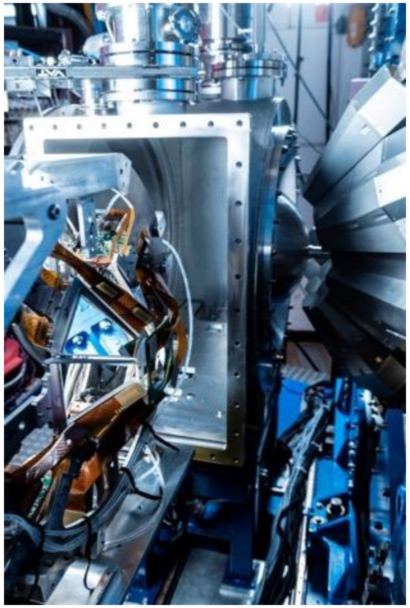


AGATA coupled with
VAMOS, FATIMA, PARIS

2018

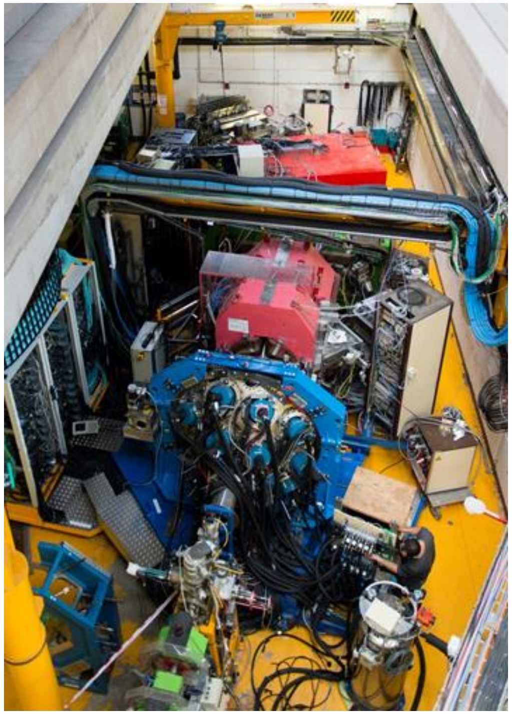
AGATA coupled with
NEDA- DIAMANT

2019-2021



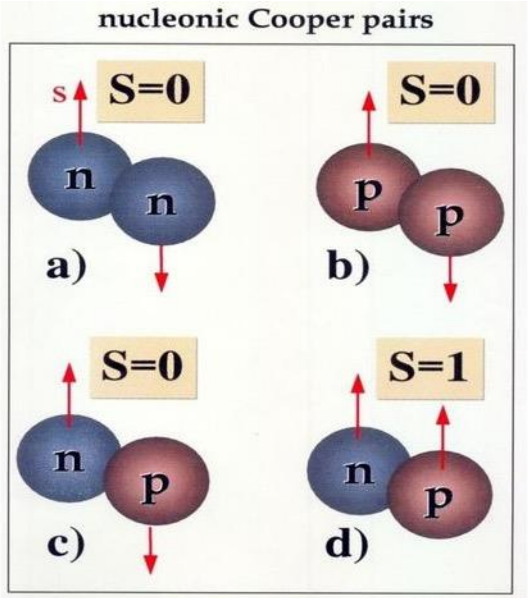
AGATA coupled with
VAMOS MUGAST

2021



AGATA coupled with
VAMOS, EXOGAM,
2nd Arm, LEPS

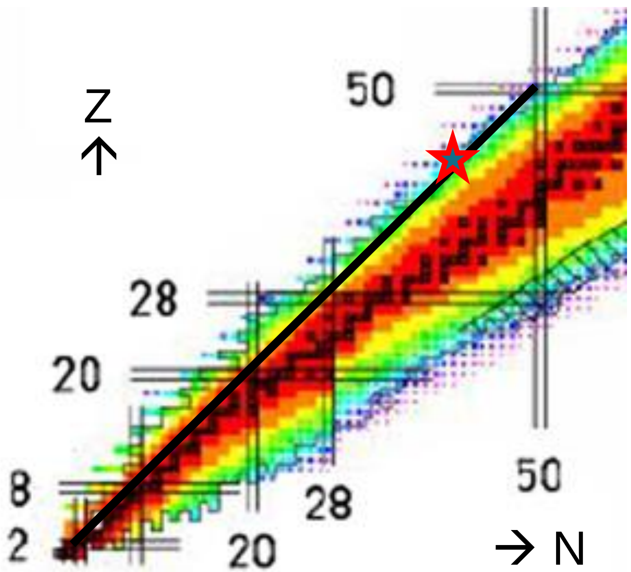
N=Z isotopes: study p-n (iso-scalar) pairing correlations

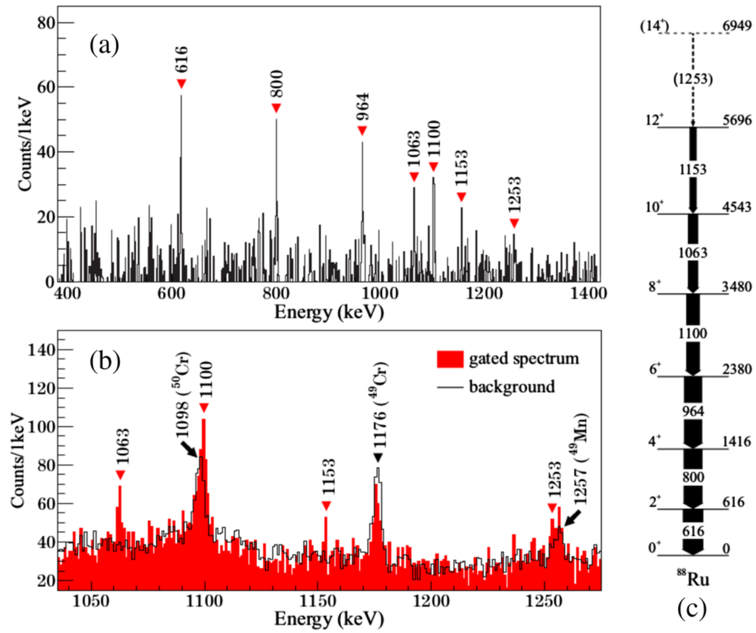


Nucleons can form strongly correlated pairs which impact strongly on nuclear structure.

Only in N=Z nuclei will the p-n (isoscalar) pairing be important, as protons and neutrons occupy the same orbit.

★ ^{88}Ru: 44 protons and 44 neutrons (near proton dripline)





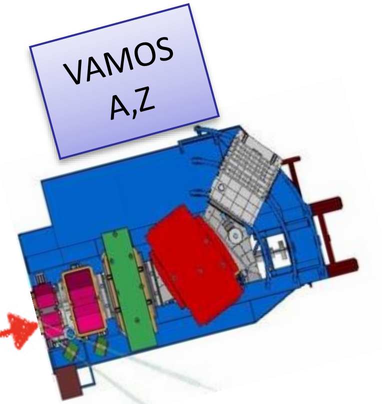
Rotating deformed nucleus with strong ISO-SCALAR p-n pairing !

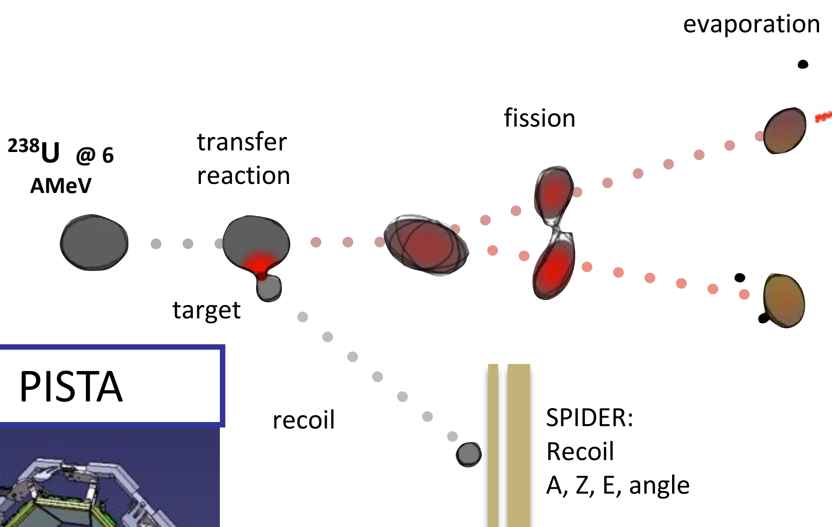
B. Cederwall et al., PRL 124, 062501 (2020)

Fission Studies in inverse kinematics @ VAMOS

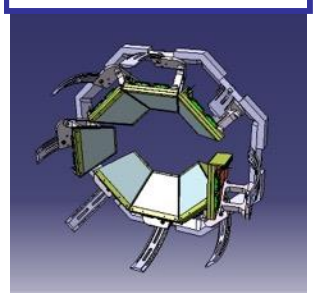
Inverse Kinematics using beams of ^{238}U around Coulomb Barrier

Access to « exotic » fissionning systems heavier than ^{238}U



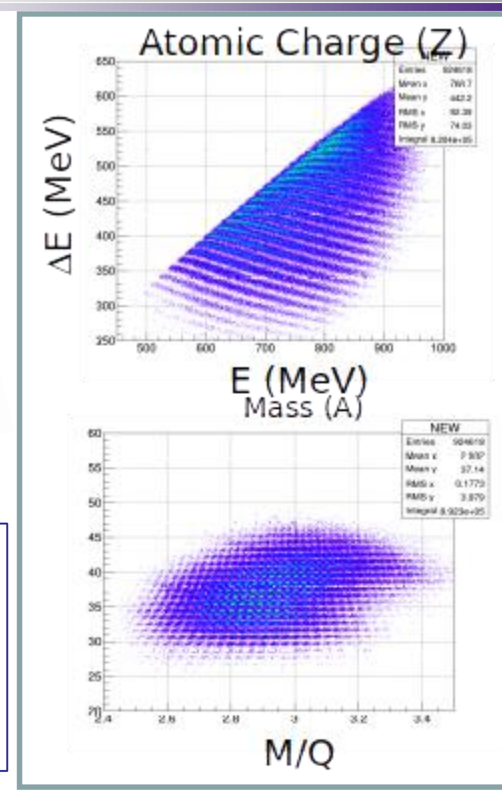


PISTA



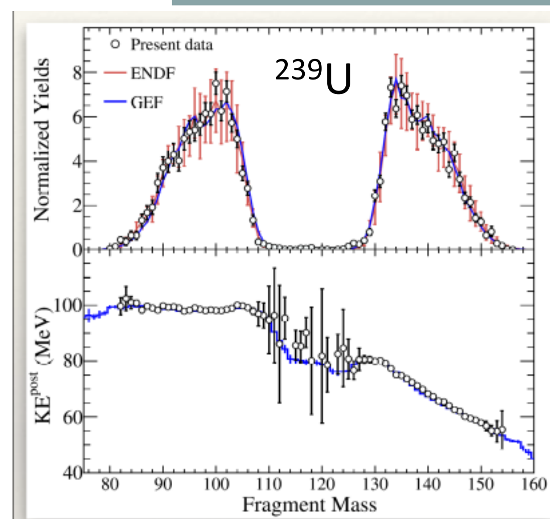
VAMOS Magnetic Spectrometer

Direct and Complete isotopic fission fragment yields

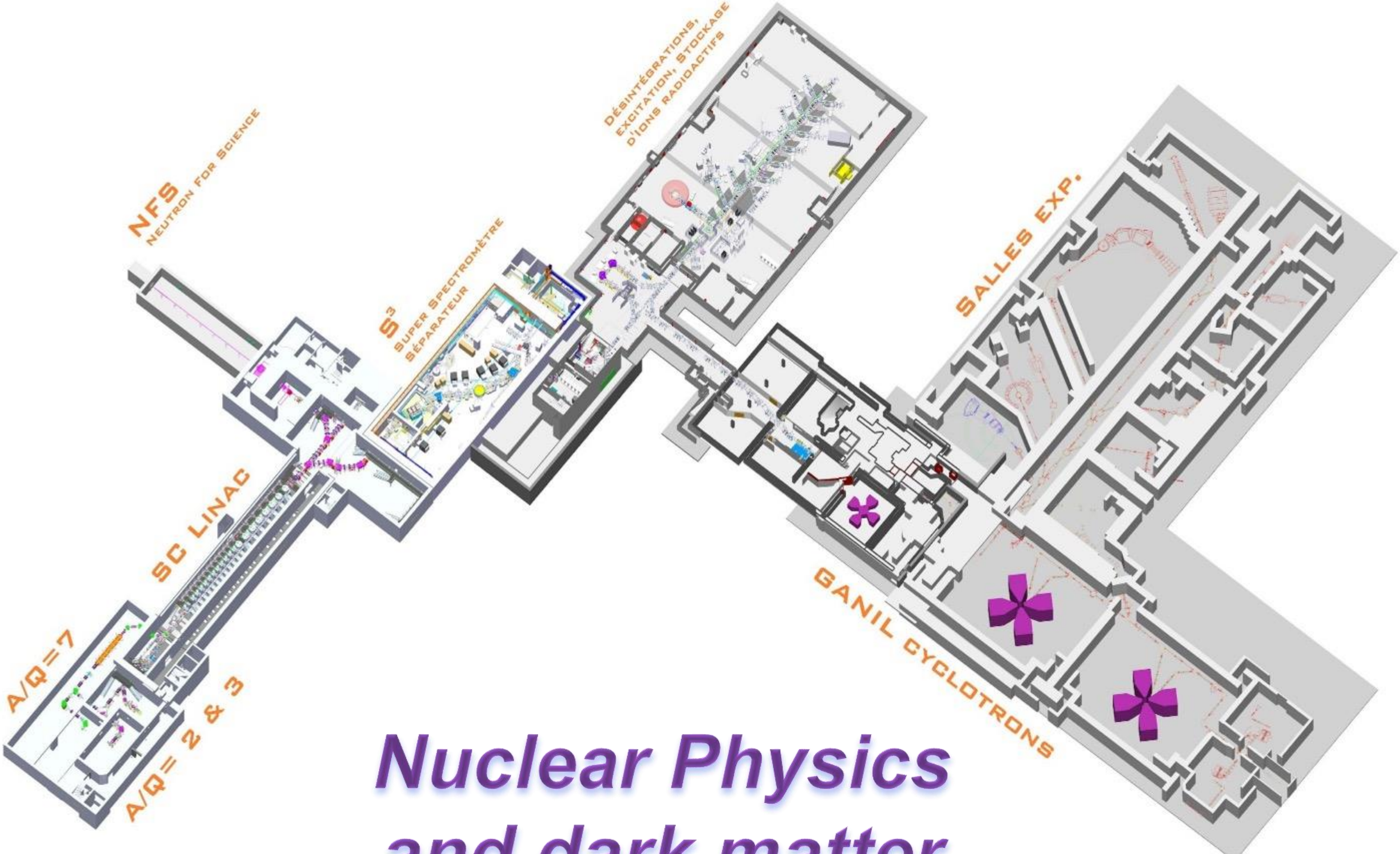


Surrogate reactions (transfer induced fission)

- Selection of the fissionning system
- Measurement of the excitation energy

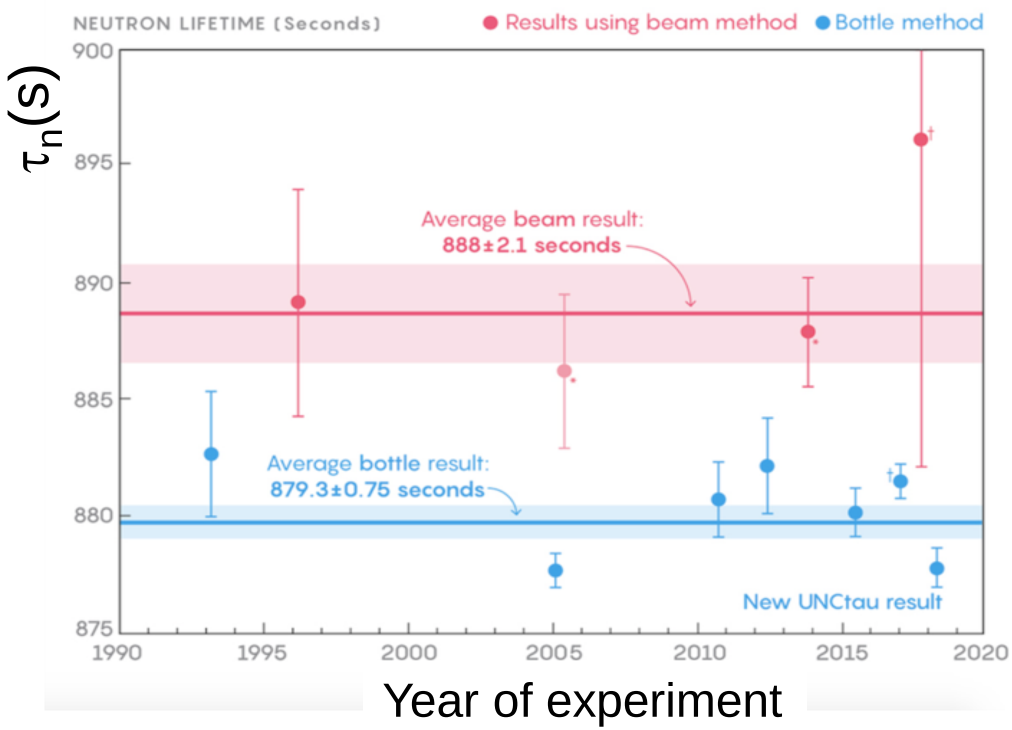


D. Ramos et al PRL (2019)



Nuclear Physics and dark matter

The neutron lifetime puzzle



W. Pattie et al, Science 360 (2018) 6389

Counting emitted protons :

$$\tau_n^{beam} = 888.0 \pm 2.1\ s$$

Counting remaining neutrons :

$$\tau_n^{bottle} = 879.3 \pm 0.75\ s$$

Discrepancy $\frac{\Delta\tau_n}{\tau_n} \approx 1\%$

How could the remaining 1% be explained ?

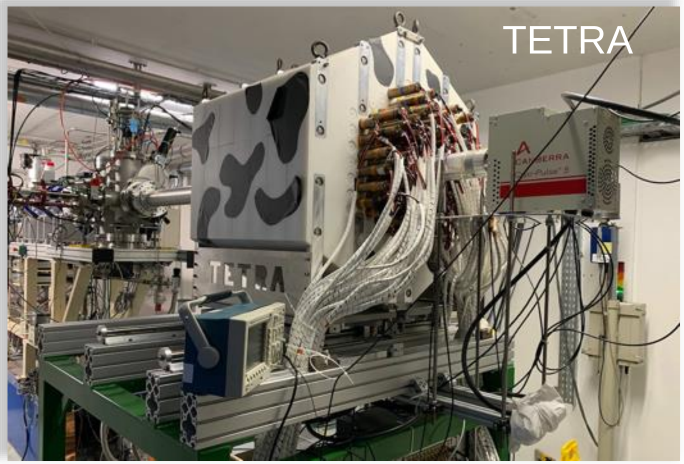
- Decay of neutron into particles of Standard Model (other than *p*) : excluded
- **n → dark matter :** *Fornal and Grinstein, PRL120(2018)191801 -> shortening of the apparent lifetime in the bottle*

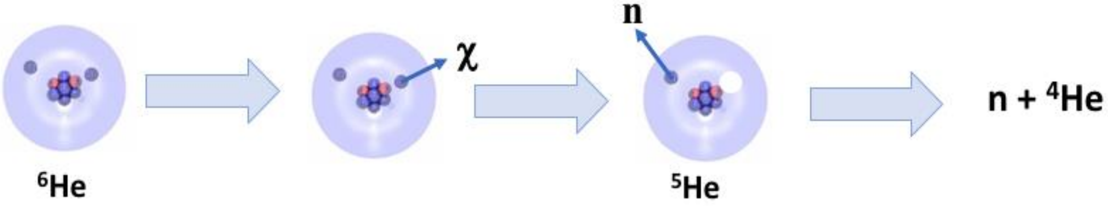
  n → dark particle(s) to be searched for

Neutrons loosely bound in nuclei may also decay by the dark channel, if allowed by energy conditions

Search for dark decay of neutrons in ^{6}He

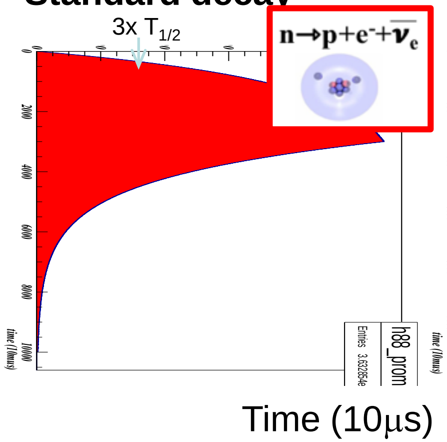
(H. Savajols et al. June 2021)



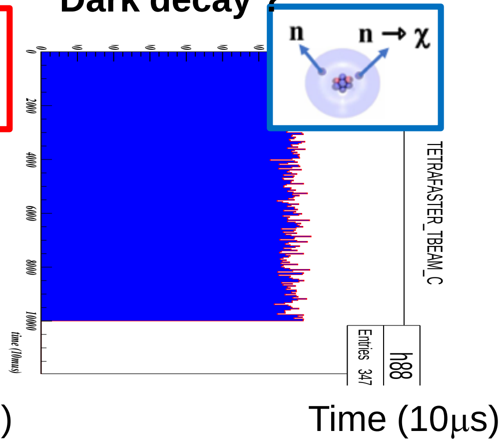


Branching ratio estimate from bottle/inflight decays **$B_\chi = 1.2 \times 10^{-5}$**
Allowed energy window : **M_χ < Mn - 975.45 keV**
Combining other results **937.992 MeV < M_χ < 938.589 MeV**
Pfutzner and Riisager, PRC 97, 042501(R) (2018)

Standard decay



Dark decay ?

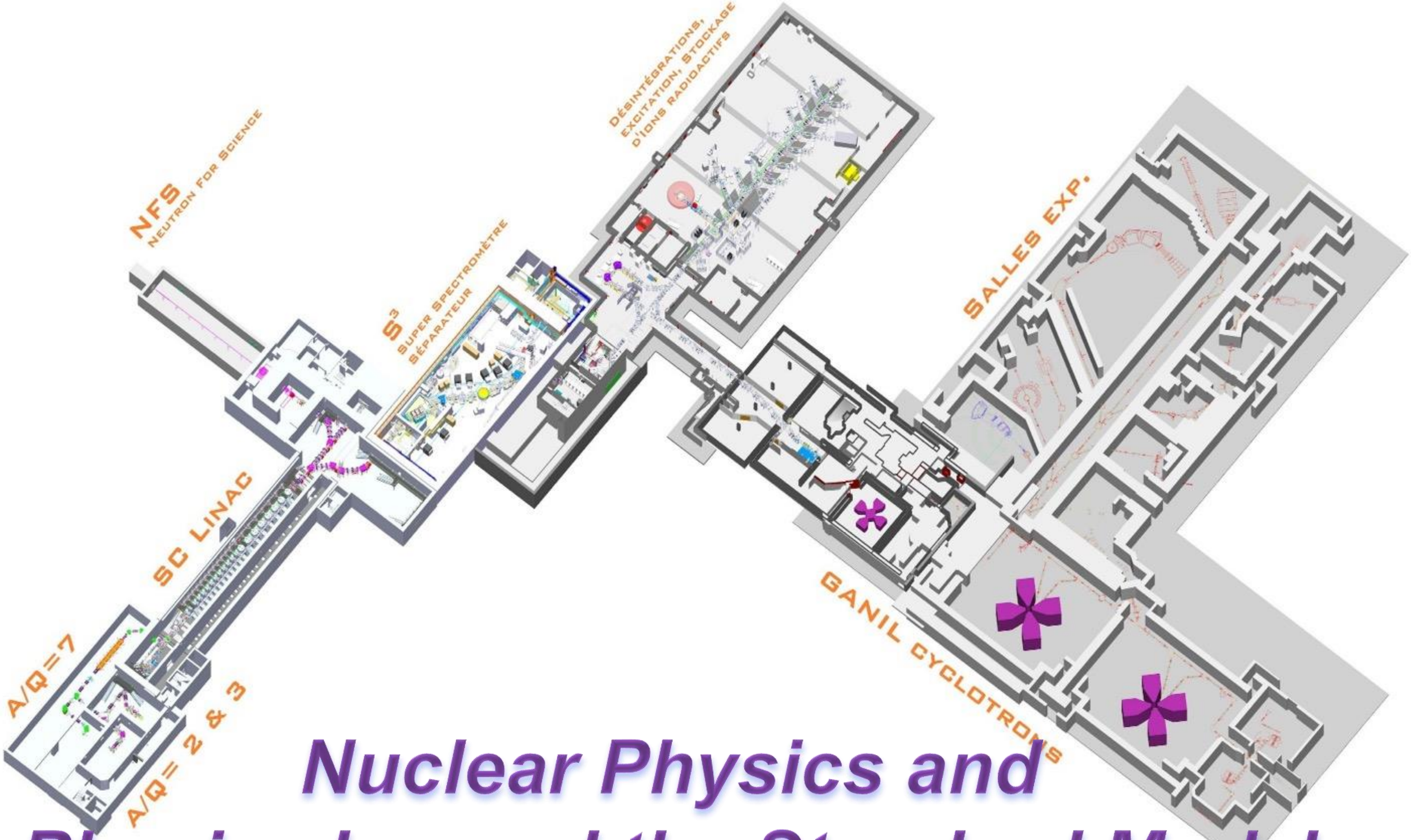


$^6He^{1+}$ SPIRAL1 world-record intensity (2×10^8 pps)

Neutron multidetector TETRA with 50% efficiency

Search of an excess of neutrons in the decay of ^{6}He

➔ The final analysis provides a stringent upper limit for this dark decay



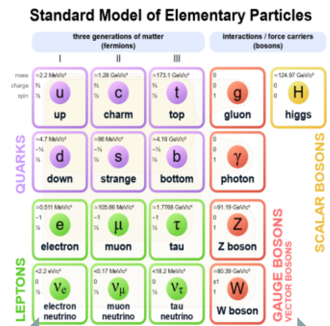
Nuclear Physics and Physics beyond the Standard Model

Nuclear beta decay as a laboratory for weak interaction

- **Two complementary approaches:**

High energy frontier

« Direct » observation of new particles at high energy colliders (LHC)



Linked through EFT

Precision/intensity frontier

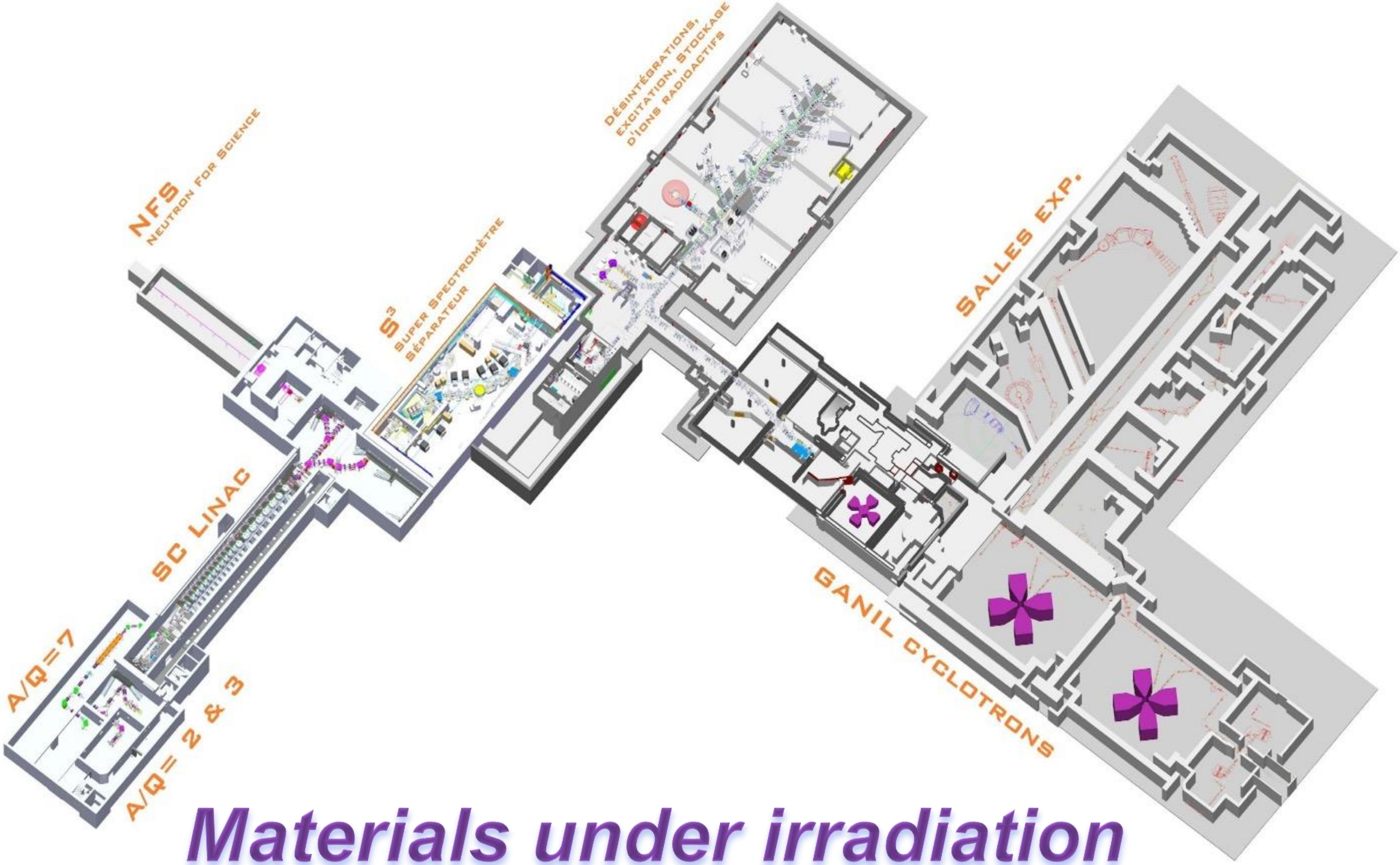
Look for tiny deviations from SM predictions

- Non zero EDMs
- ν oscillations
- Search for WIMPs
- Dark decay of neutron
- …
- **Correlation measurements in nuclear beta decay**
  → exotic couplings of electroweak interaction

- *b*: Search for Tensor Interactions in nucLear bEta Decay (bSTILED)
  Searching for exotic tensor currents via a *b* correlation measurement to the 10^{-4} level

- Matter's Origin from RadioActivity (MORA)
  searching for CP violation in nuclear β-decay via a *D* correlation measurement to the 10^{-5} level

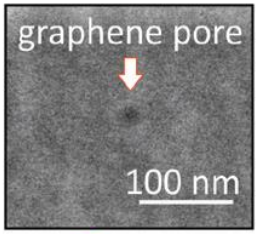
- Measurement of Ft values (half-lifes, branching ratios) of superallowed decays for tests of CVC to the 10^{-4} level and the search for exotic scalar currents

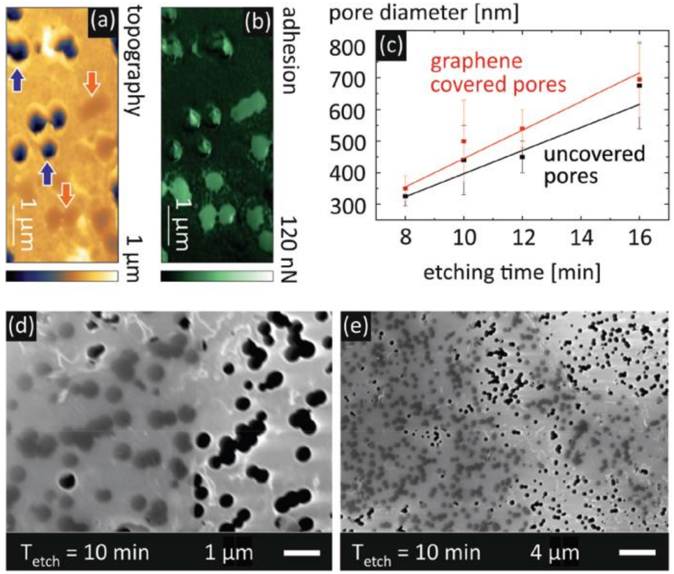


Materials under irradiation

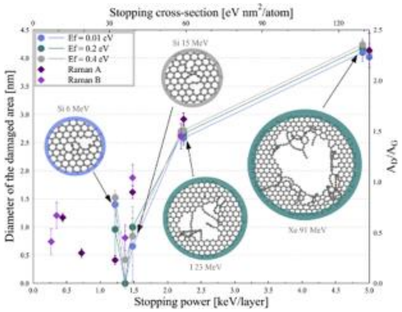
Graphene/polymer nanoporous membranes

Experiment

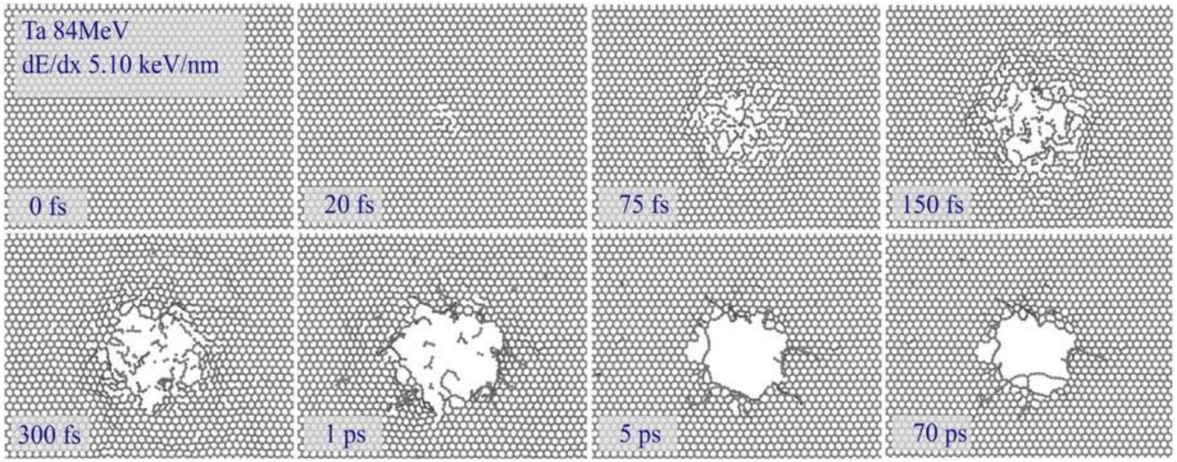




Simulation
Pore diameter as a function of stopping power



Pores diameter as a function of time



Collaboration:

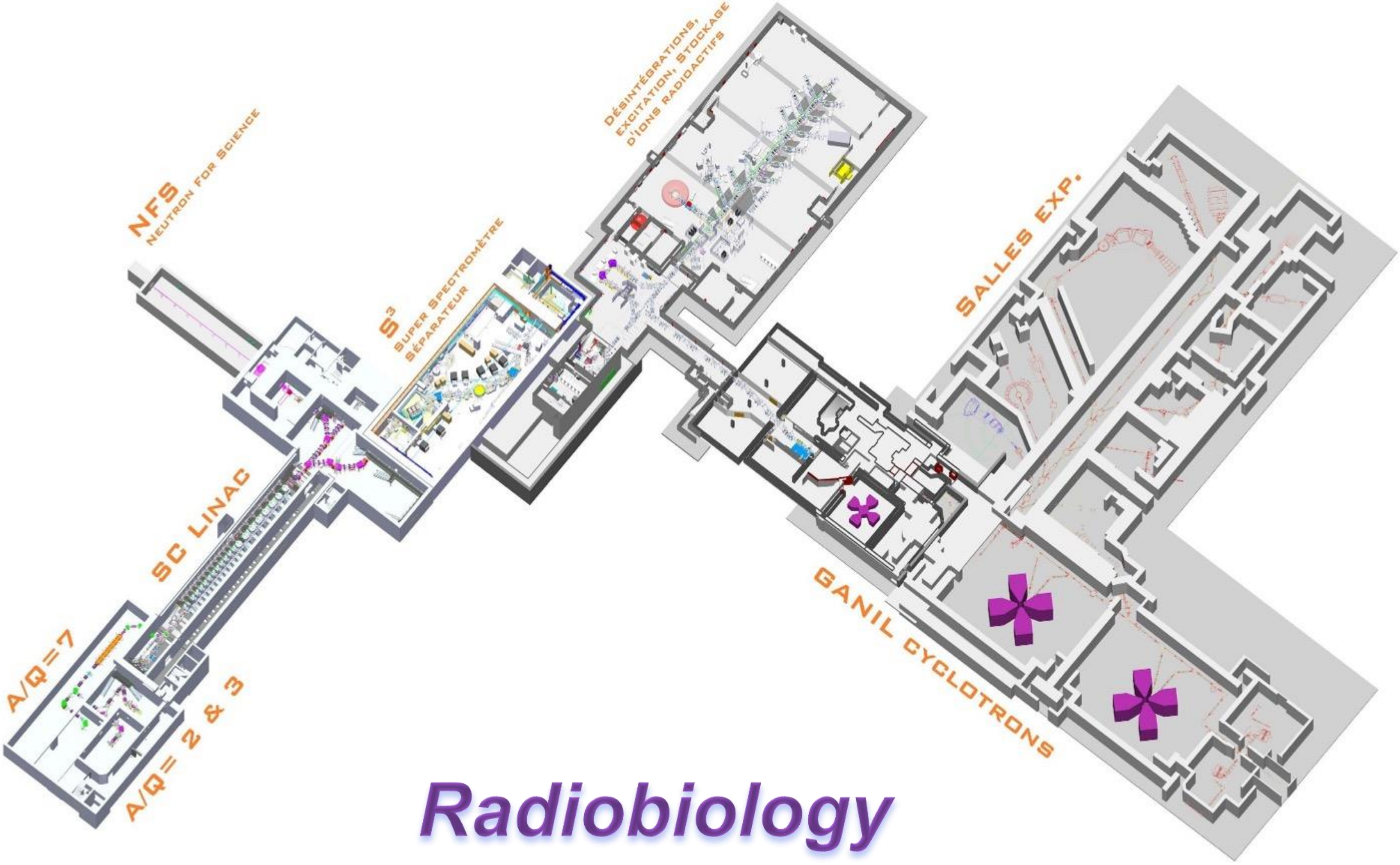
Universities of
Helsinki and Aalto, Finland
Nottingham, UK
Duisburg-Essen, Germany
Wien, Austria
Science and Technology MISiS, Russian Federation

CIMAP, France
Ruder Boskovic Inst., Croatia
Helmholtz-Zentrum Dresden-Rossendorf, Germany

Application:
Desalination of sea water
Project NU TEGRAM
Flagship Graphene

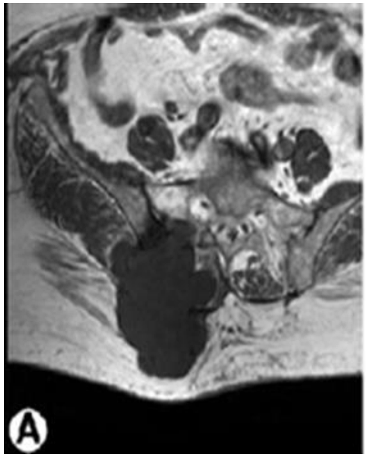
H. Vázquez *et al.*
Carbon 114 (2017) 511

L. Madauß *et al.*
Nanoscale 9 (2017) 10487

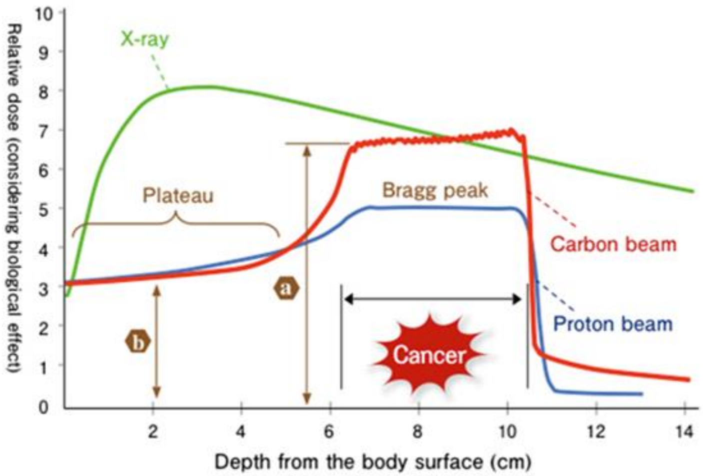


Radiobiology

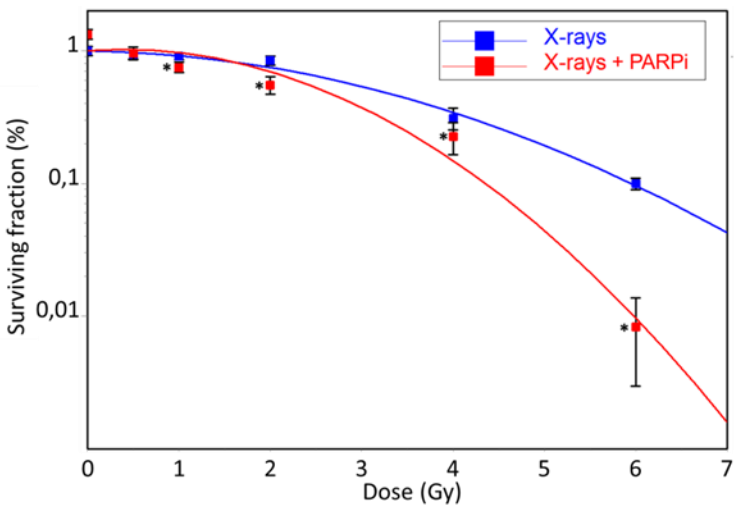
Chondrosarcoma / pre-clinical experiments

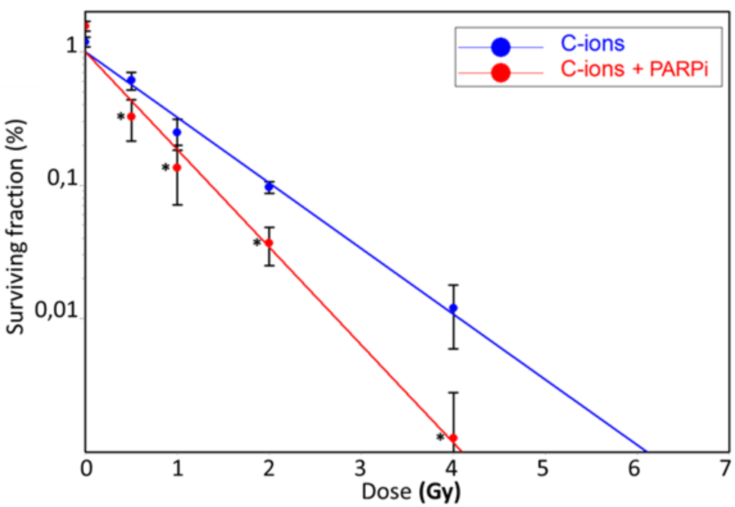


Chondrosarcoma
malignant tumor of cartilage with bad prognostic - highly radio-resistant => use of hadrontherapy ?



Clonogenic assays: comparison between X-rays and C-ions (+/- PARPi)

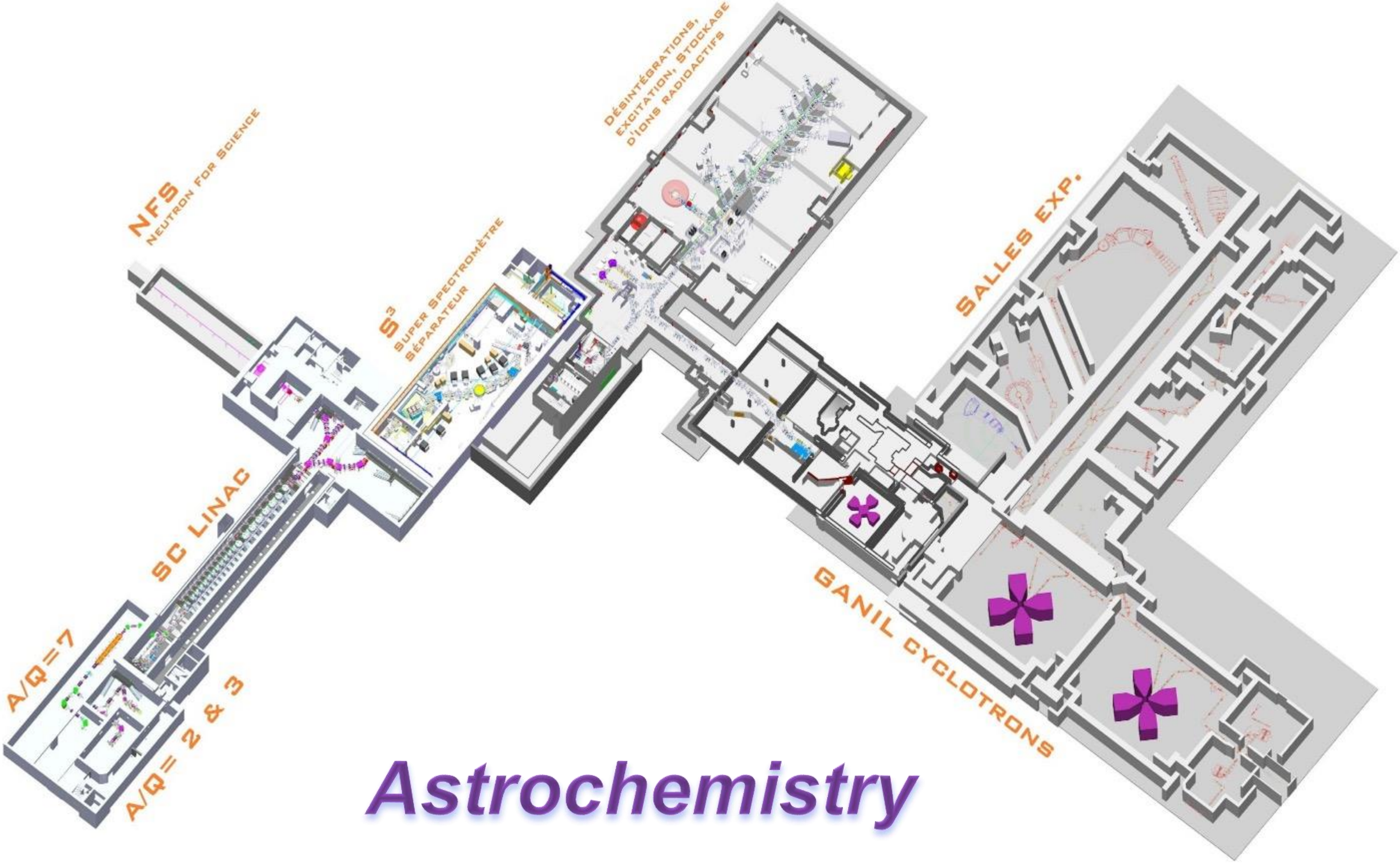




Cell survival (%) is a mean +/- SD of 3 independent experiments performed in triplicate

Comparison of C-ions and X-rays: Relative Biological Effectiveness 2,95

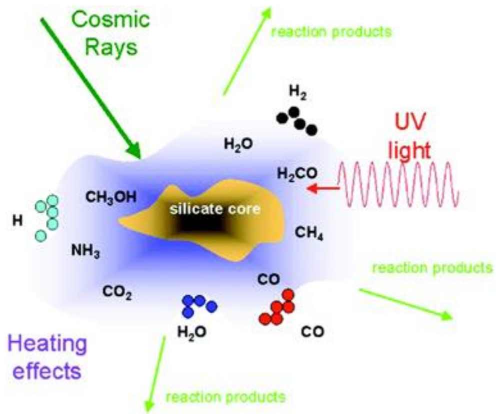
M. Cesaire, J. of bone oncology 17 (2019) 100246



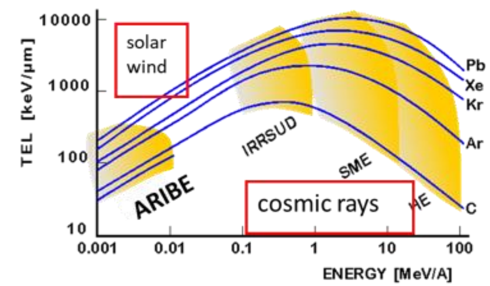
Astrochemistry

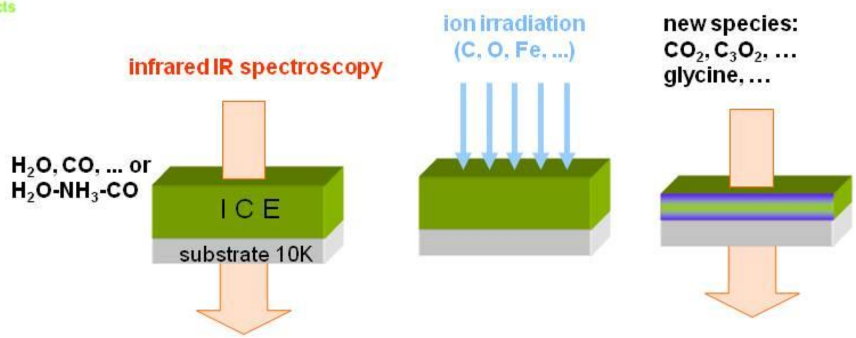
Role of cosmic rays and stellar winds on ices for the appearance of molecules in the universe

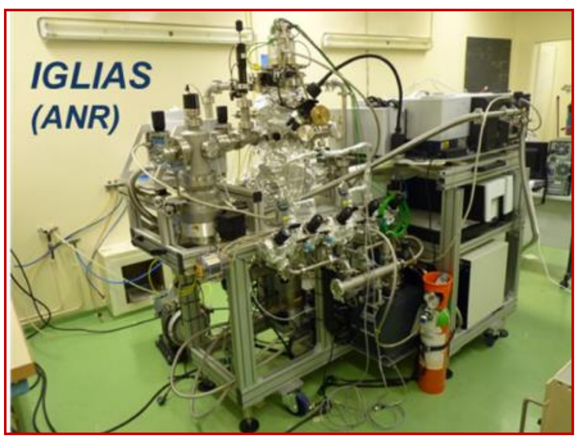
IGLIAS setup to mimic interstellar ices exposed to radiation

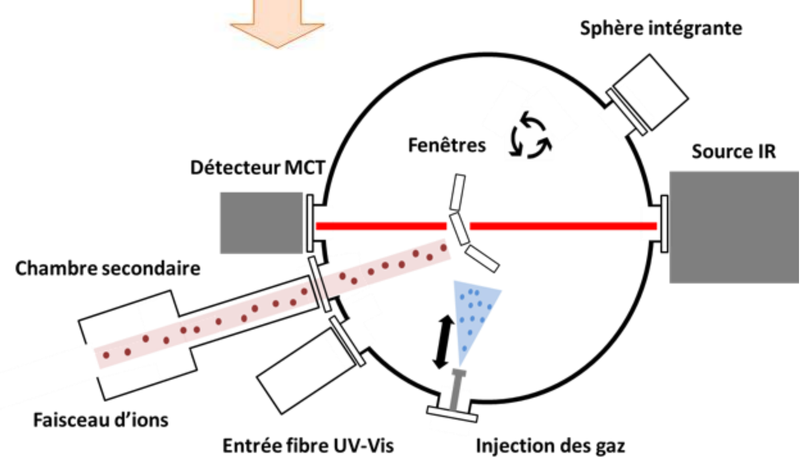


fragmentation/destruction
formation of molecules
Desorption / Sputtering /implantation
Compactation / Amorphization









In-situ gas deposition
3 spectrometers (UV-visible, FTIR, QMS)