Kickoff meeting of the CNRS-MSU International Research Laboratory on Nuclear Physics and Nuclear Astrophysics

laboratoire commun CEA/DSM CNRS/IN2P3

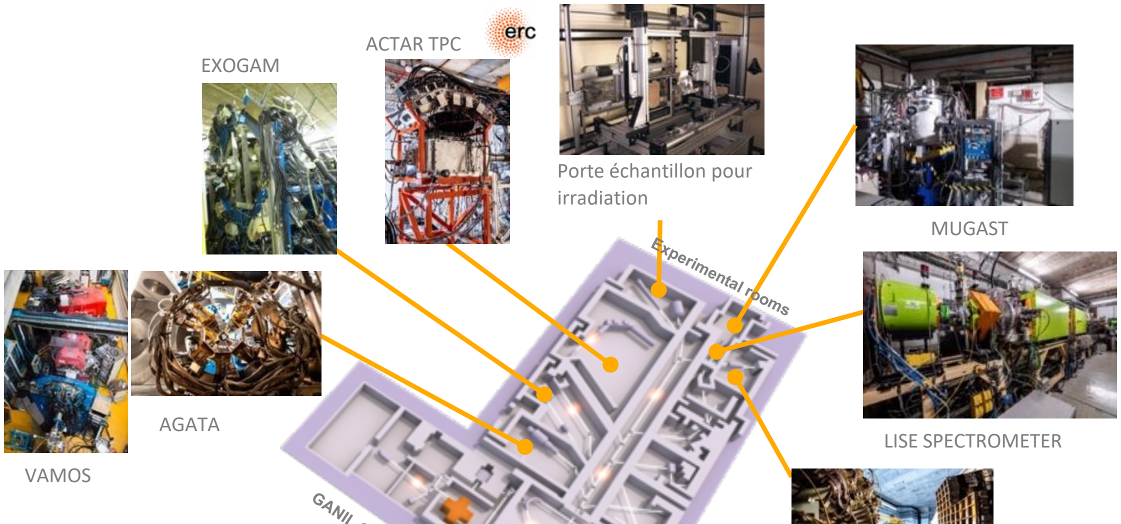
Instrumentation GANIL/SPIRAL2

Hervé Savajols (GANIL/France)

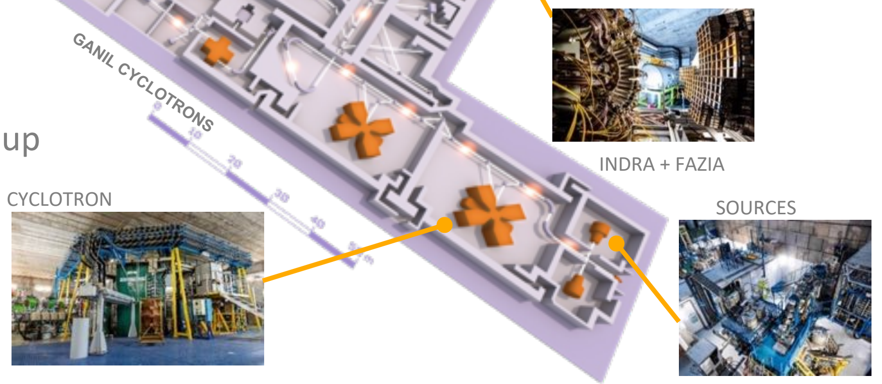
Not exhaustive list

GANIL – SPIRAL2

Cyclotrons and their experimental equipment



- Beams : ^{12}C up to U
- Energy : from <1 MeV up to 95 MeV/nucleon
- Up to 3 parallel experiments



Large variety spectrometers/detectors :

- VAMOS++ and the fission revival
- LISE and the « tandem » mode

- MUST2/MUGAST
- ACTAR-TPC active target
- INDRA+FAZIA
- EXOGAM (AGATA)
- PARIS
- NEDA, …

New SPIRAL1 beams
New stable beams in future : Th & ^{235}U

AGATA@GANIL.1

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2015-2017

AGATA coupled to VAMOS, FATIMA, PARIS

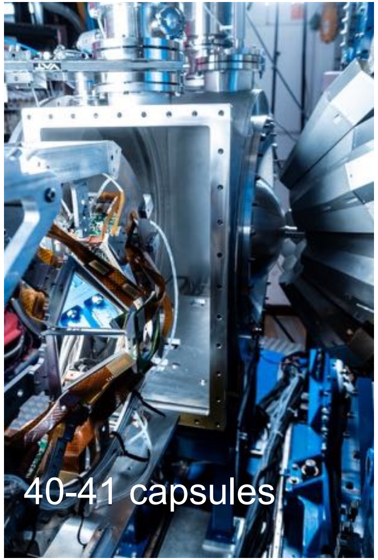
Exotic nuclei spectroscopy by MNT transfer and fission reaction

2018

AGATA coupled to NEDA-DIAMANT

N~Z nuclei spectroscopy fusion evaporation

2019-2021



AGATA coupled to VAMOS MUGAST

Exotic nuclei spectroscopy by transfer reaction using RIB

2021

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

Exotic nuclei spectroscopy MNT transfer

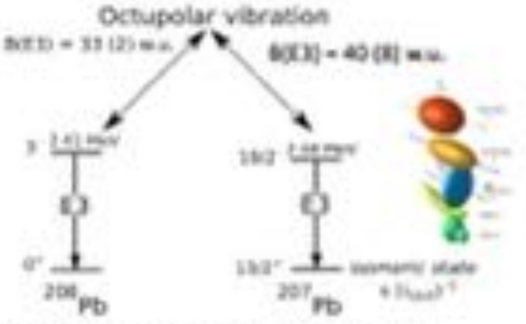
- 2π system by the end of the LNL campaign (~2025-2026)
- 3π array in 2030

AGATA back @ GANIL in 2026 ?

821 UT have been performed over 29 experiments

Some highlights of AGATA@GANIL.1

Evidence of octupole-phonon at high spin in ^{207}Pb: Study of the octupole phonon in the ^{208}Pb region.

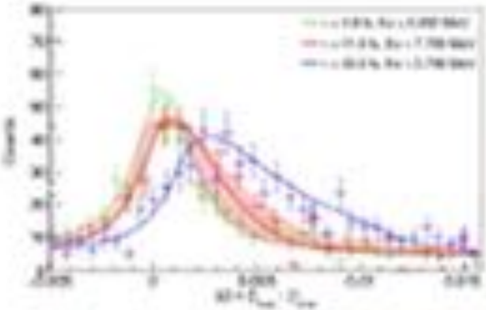


D. Ralet et al Phys.Lett. B 797, 134797 (2019).

1st AGATA Nature paper

Search for ^{22}Na in novae supported by a novel method for measuring femtosecond nuclear lifetimes

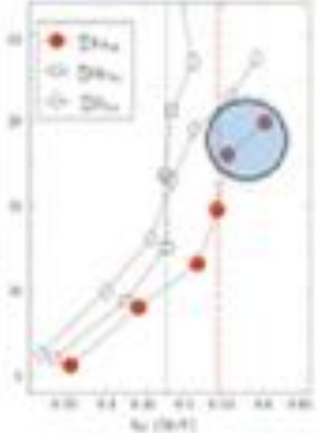
Constraining the ^{22}Na$(p,\gamma)^{23}$Mg reaction from the spectroscopy of the 7785.0(7) keV resonance in ^{23}Mg.

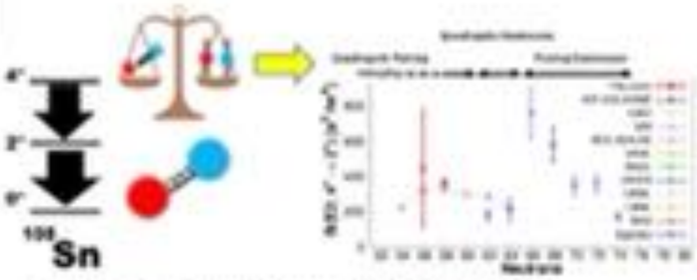


Ch. Fougère et al Nature Communications volume 14, 4536 (2023)

Direct observation of a "delayed" rotational alignment in a deformed N = Z nucleus (^{88}Ru), in agreement with theoretical predictions related to the presence of strong isoscalar neutron-proton pair correlations.

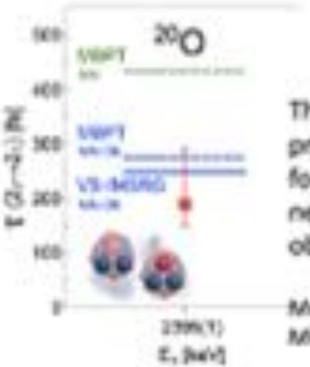
B. Cederwall et al, Phys. Rev. Lett. 124,062501 (2020)





M.Siciliano et al, Physics Letters B 806 (2020) 135474

- 2+ wave function is dominated by the p-n quadrupole interaction
- 4+ wave function is a balance between p-n quadrupole and pairing interactions
- Revisit our predictions on the ^{100}Sn structure to be investigated at S3



The achieved results agree well with predictions from MBPT and ab initio VS-IMSRG for ^{20}O, showing that 3N interactions are needed to accurately describe electromagnetic observables in neutron-rich nuclei.

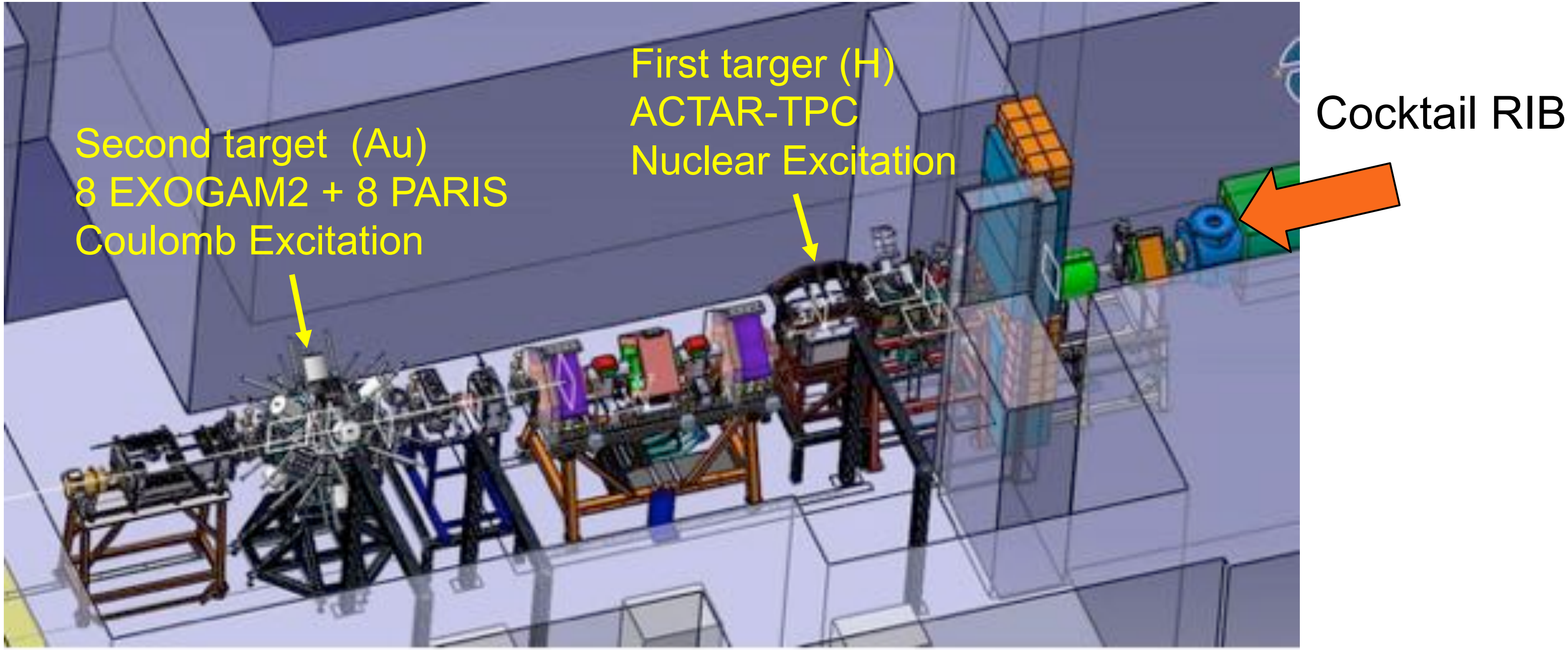
More accurate and holystique description from MUGAST-AGATA data, I. Zanon (LNL) submitted to PRL

M. Ciemala et al, Phys. Rev. C101, 021303(R) (2020)

LISE 2022

« Tandem » mode with ACTAR-TPC and EXOGAM-PARIS-ZDD: a world premiere with heavy ions

Simultaneous measurement of Coulomb and nuclear excitation for neutron-rich isotopes of Si and S



LISE 2022

Cocktail RIB

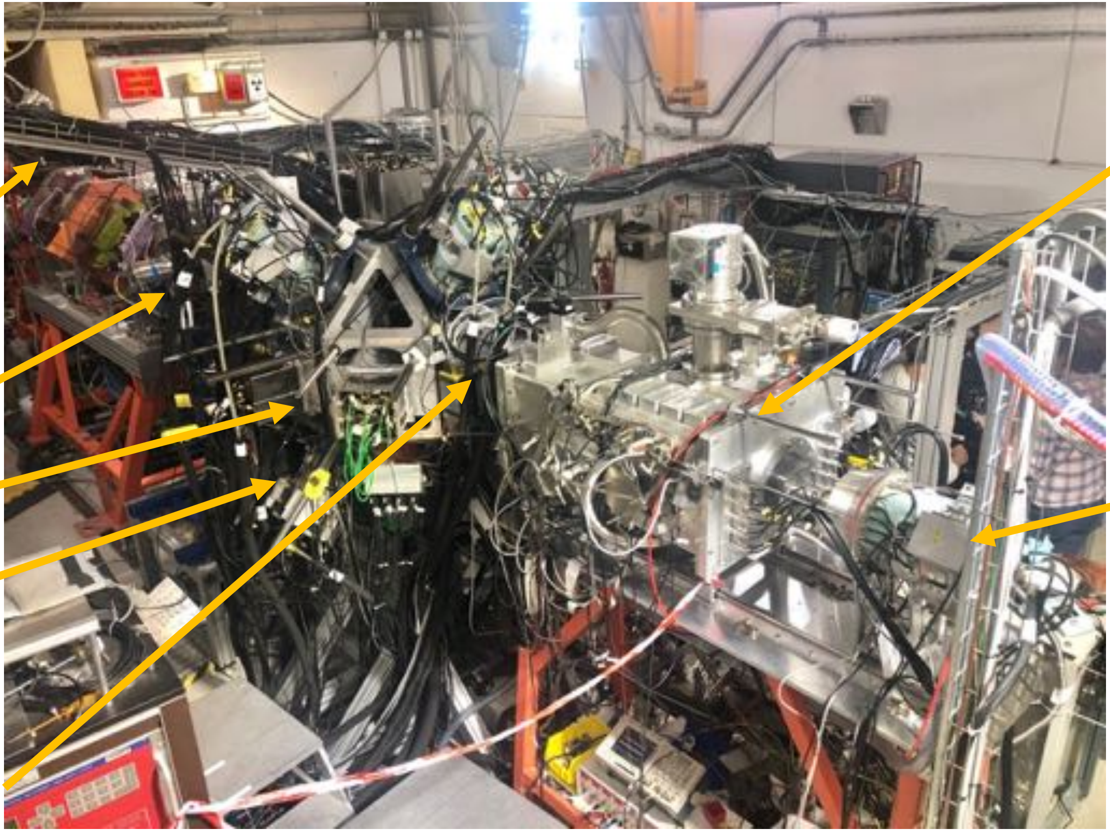
ACTAR TPC

CATS

8 PARIS

8 EXOGAM

Annular Silicon detectors

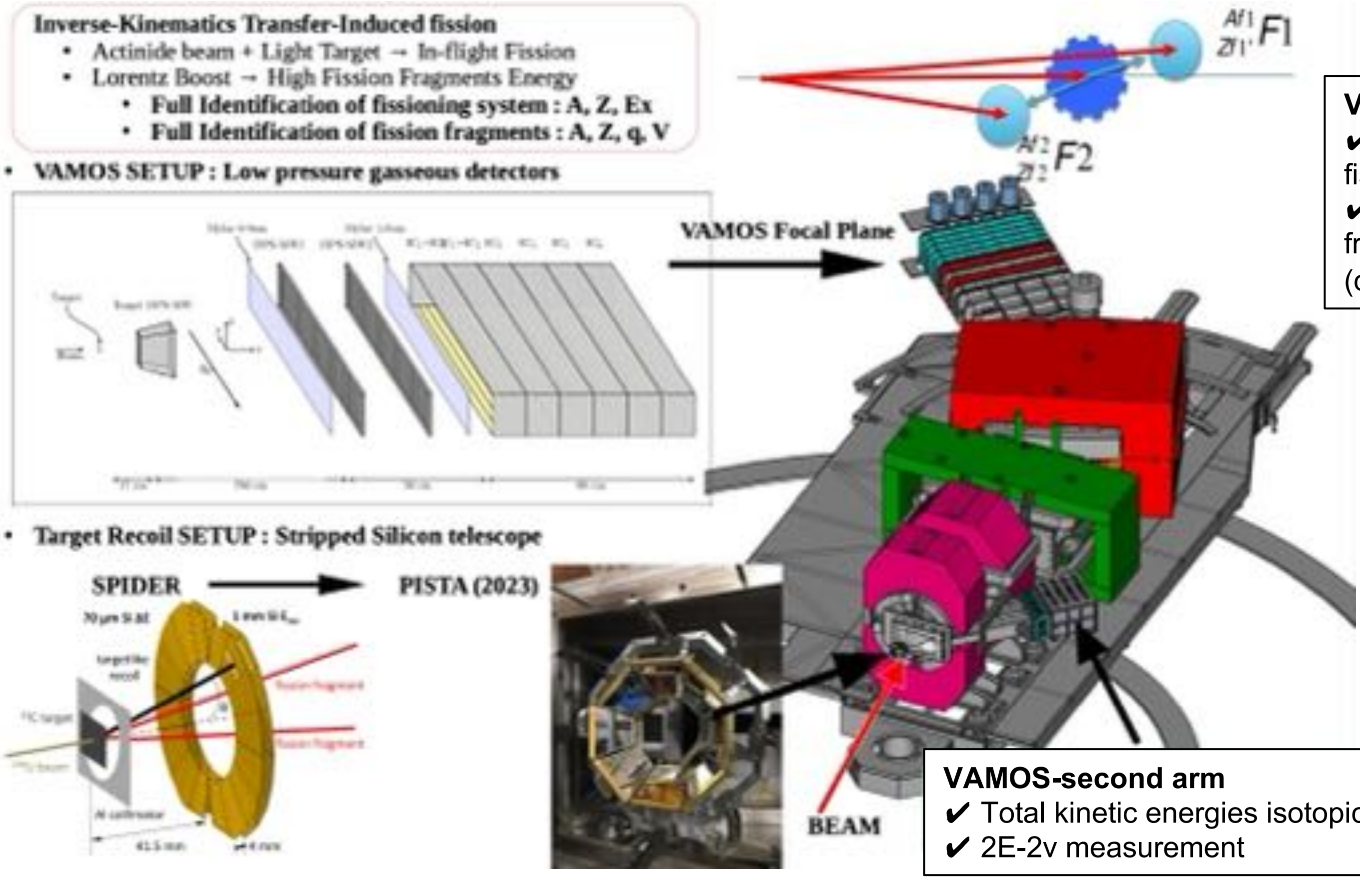


Zero Degree Detection

EXOGAM 0°

Data analysis is under progress

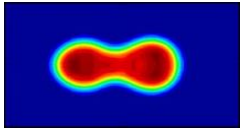
Fission studies at VAMOS++



VAMOS
✔ Direct and complete isotopic fission fragments yields Y(A,Z)
✔ Precise center-of-mass fission fragment velocities isotopically (due to Coulomb barrier energies)

SPIDER → PISTA
✔ A
✔ Z
✔ (Elab,θlab) → E*

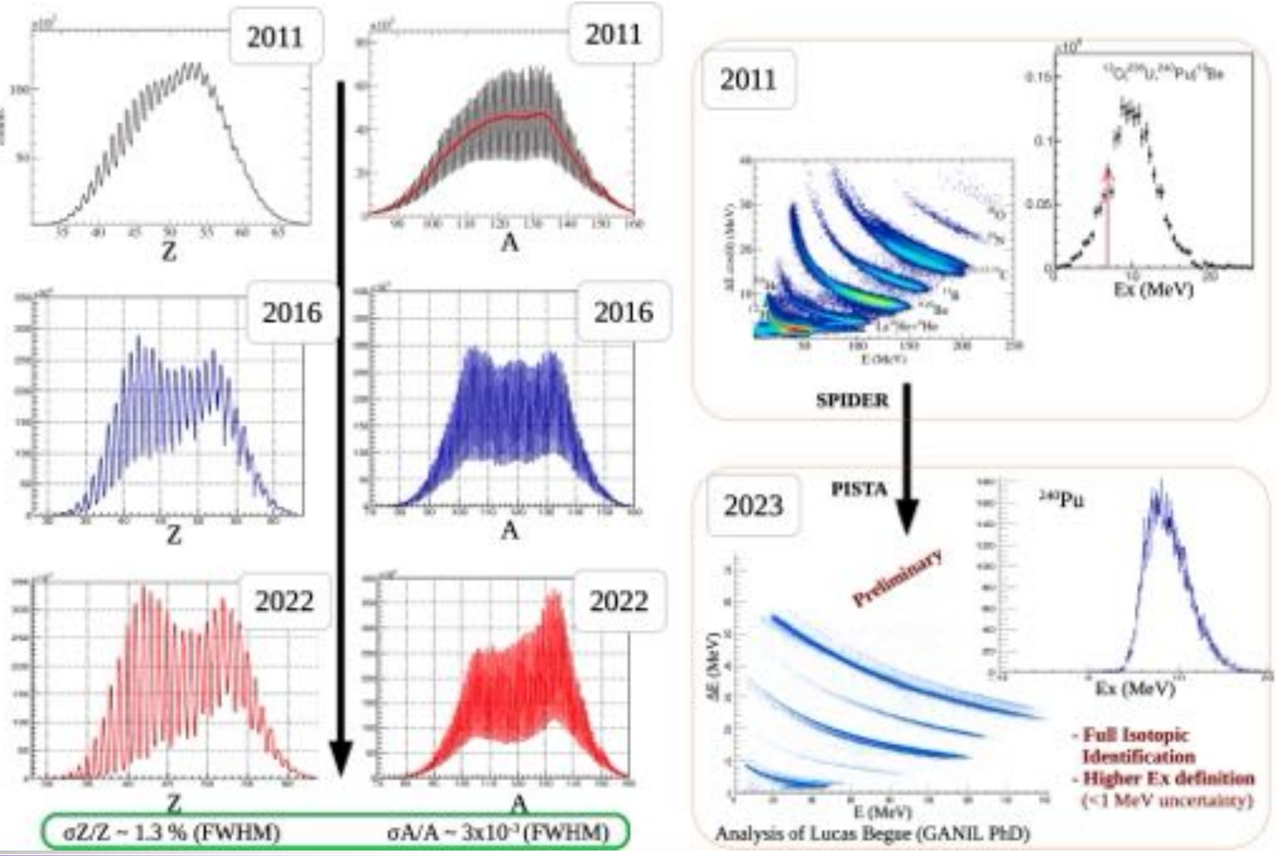
VAMOS-second arm
✔ Total kinetic energies isotopically
✔ 2E-2v measurement



Fission studies at VAMOS++

Evolution of the VAMOS detection setups

Mass of the fission fragments



Selection of the fissioning system : ^{240}Pu

ACTAR TPC : Design

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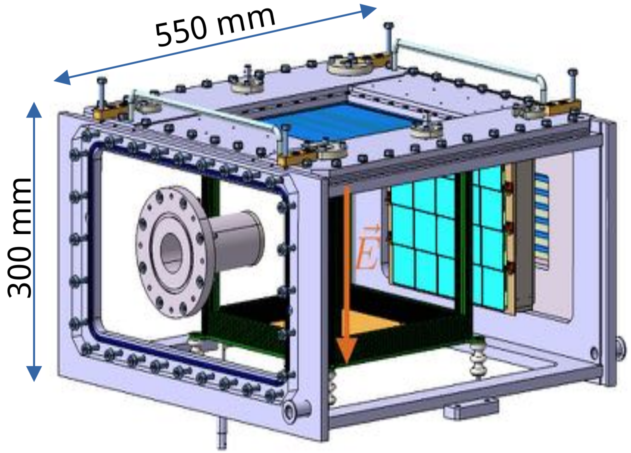
Active target: (Gaseous) detector in which the atoms of the gas are used as a target



✓ Drift region: principle

- Transparent to particles on 4 sides

→ Wire field cage

- Homogeneous vertical drift electric field

→ Double wire field cage: 2 mm/1 mm pitch

✓ Amplification region: principle

- Bulk Micromegas (CERN PCB workshop)
- Local gain reduction via pad polarization

✓ Segmented pad plane

- Micromegas

→ transverse multiplicity ≈ electron straggling: 2x2 mm^2 pads

- 16384 pads with very high density: challenge!

→ Two solutions investigated

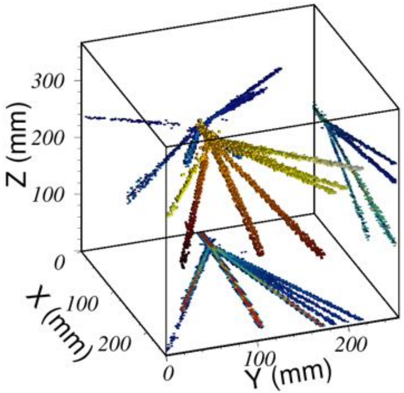
✓ Electronics: GET

GET electronics:

- 512 samples ADC readout depth x 16384 pads

→ volume sampling in 8 Mega voxel

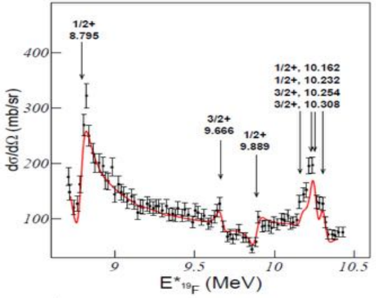
- adjustable gain, peaking time, individual trigger: pad per pad



Physics cases addressed and performances

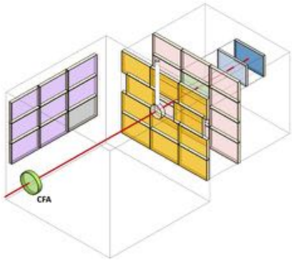
- **Study of excitation functions (resonant scattering, etc...)**

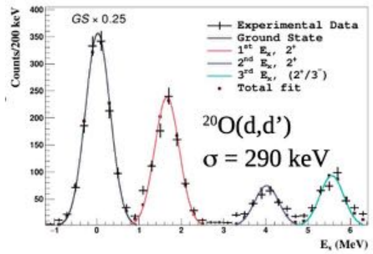
→ thick target, need to differentiate the reactions channels
→ Commissioning experiment: $^{18}O(p,p)$ and $^{18}O(p,\alpha)$ excitation functions
→ E_{cm} resolution dominated by the angular straggling of the ions in the gas: optimum with H_2 gas for proton target



- **Reactions with very negative Q-value in inverse kinematics**

→ recoil stops inside the target
→ Study of GMR and Soft compression modes in $^{58,68}Ni$ through (α,α') reaction
→ Access to center-of-mass angles below 3°
→ Resolution in E* dominated by the straggling in range, no possible amelioration



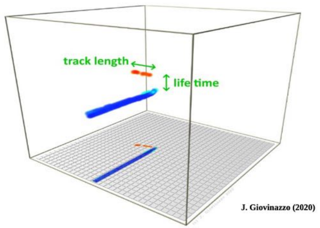


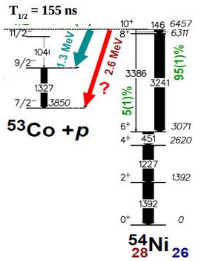
- **Reactions with (very) low intensity beams**

→ thick target, no loss of resolution due to the target thickness
→ Measurement of the $^{19}N(d,^{3}He)$ reaction with $D_2(90)+iC_4H_{10}(10)$ gas @ 1 bar: equivalent 11 mg/cm^2 CD_2

- **Time Projection Chamber mode**

→ Ideal for implantation/decay studies
→ Study of the proton decay branches of the ^{54m}Ni and ^{53m}Co & study of the ^{48}Ni 2-proton radioactivity
→ Validation of the techniques for lifetimes from ~100 ns to more than 100 ms





INDRA + FAZIA

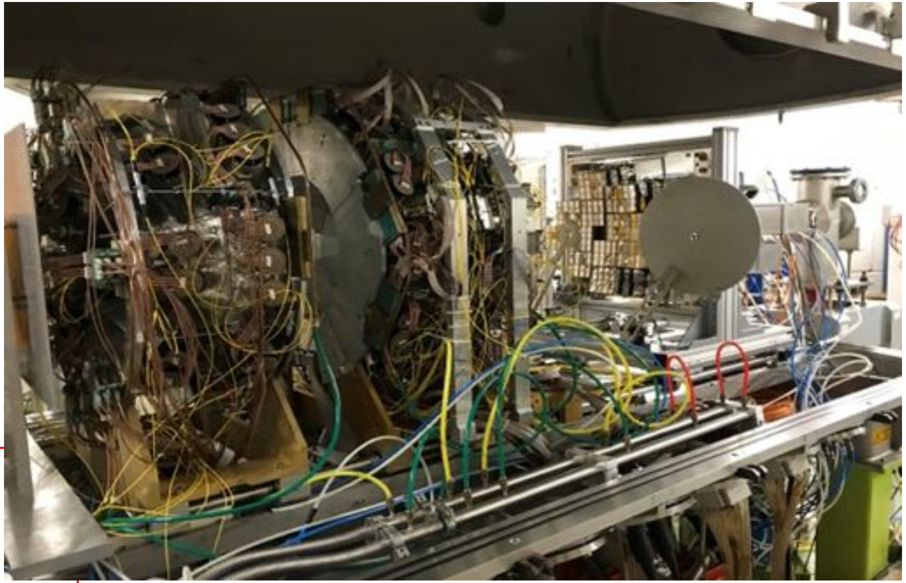
Full 4π set-up with high quality A & Z identification and E measurements

Already two campaigns performed at GANIL:

- 2019: E789
- 2022: E818

Two others to come 2025-

- E881 and E884



INDRA FAZIA

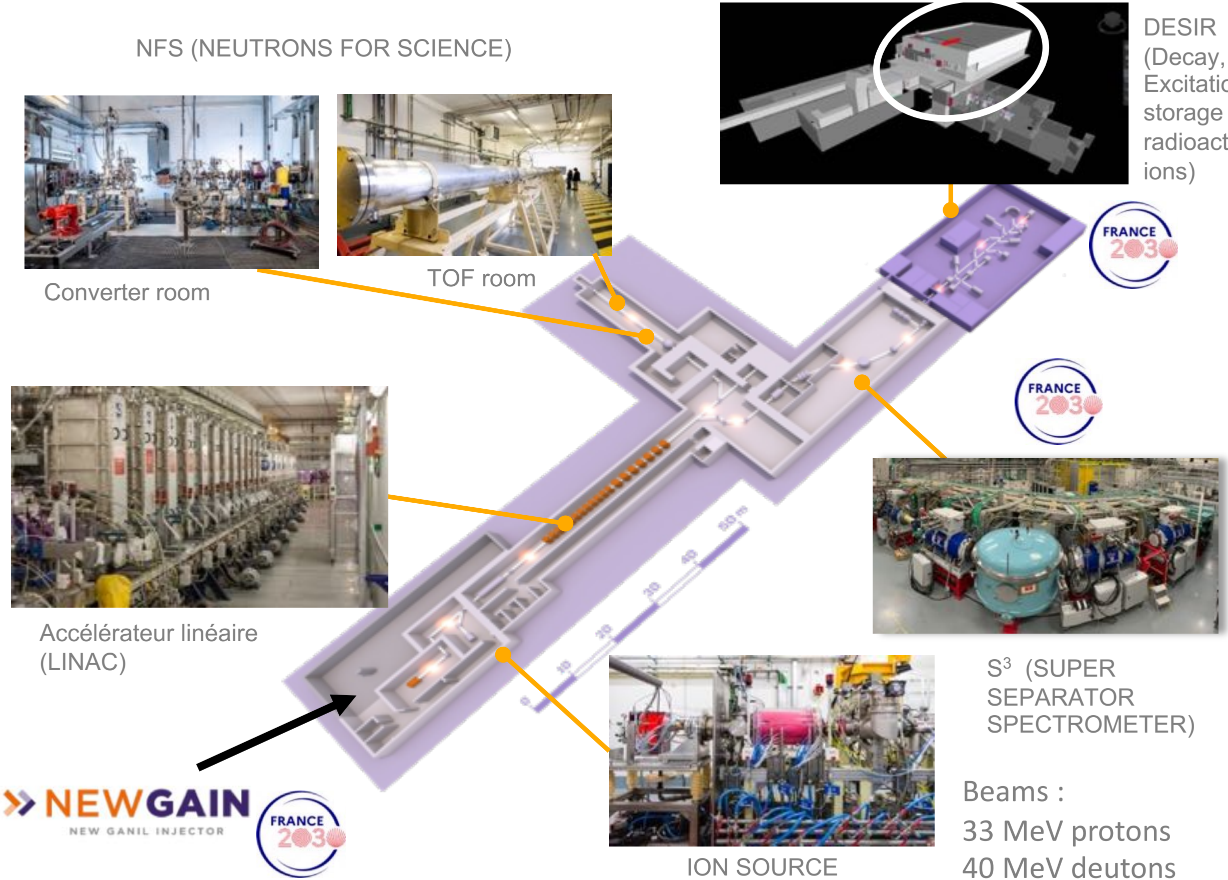
FAZIA:

12 blocks 1,8° -13,5°
192 telescopes Si-Si-CsI(Tl)
Z identification 1-54
A resolution Z~20 PSA Z~25 ΔE-E

INDRA:

12 rings 14° -176°
240 CsI(Tl)
96 Si detectors
Z identification 1-54
A resolution Z=1-4 CsI, Z=1-6 Si-CsI

SPIRAL2 and the new experimental rooms



Beams :
33 MeV protons
40 MeV deutons
<14,5 MeV/nucleon ions lourds

A new accelerator ramping up:

-First operation experimental area and the first neutrons at GANIL/SPIRAL2: NFS first campaigns and results

-Super Separator Spectrometer

-DESIR project

-Second injector (NEWGAIN)

Few data available in the fast neutron energy domain

Physics of the fission process and characterization of fission products of actinides

Fundamental physics

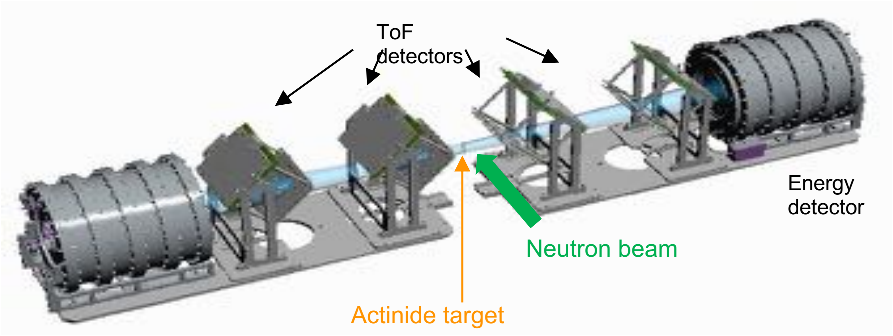
- Excitation energy sharing
- Deformation at scission
- Role of the structure effects

Nuclear application

- Characterization of fission products of actinides

Experimental goals are to:

- detect both fragments in coincidence
- measure their kinetic energy
- identify their mass pre & post evaporation
- provide information on their nuclear charge



Fission fragment detection based on low-pressure gaseous detectors

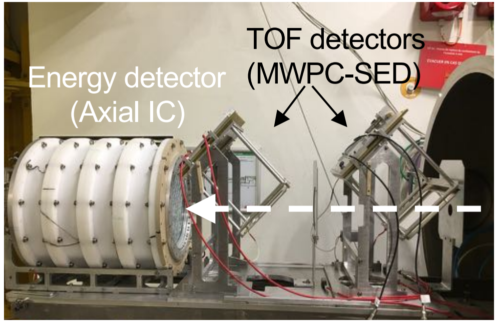
- SED-MWPC detectors : s(t) = 120 ps & s(xy) = 2 mm
- Axial Ionisation chamber: s(E)/E ~ 1 %

Pre-evap. fragment masses (2V): σ(A) ~1 uma
Post-evap. fragment masses (EV): σ(A) ~2 uma

Falstaff

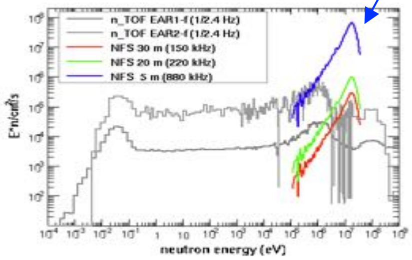
laboratoire commun CEA/DSM CNRS/IN2P3

E814 experiment: *^{235}U Fission fragment study with FALSTAFF at NFS*

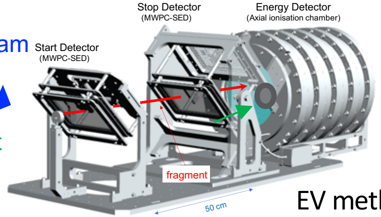


One arm experiment

Neutron beam

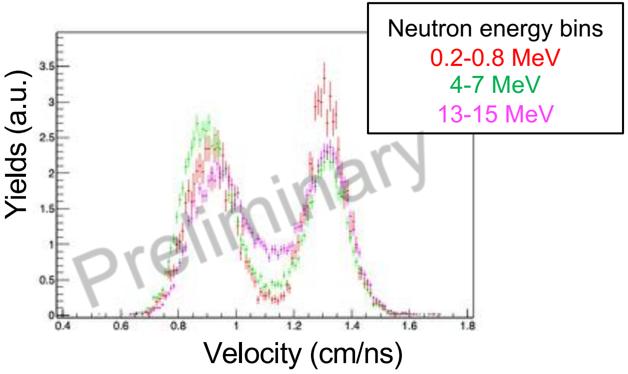


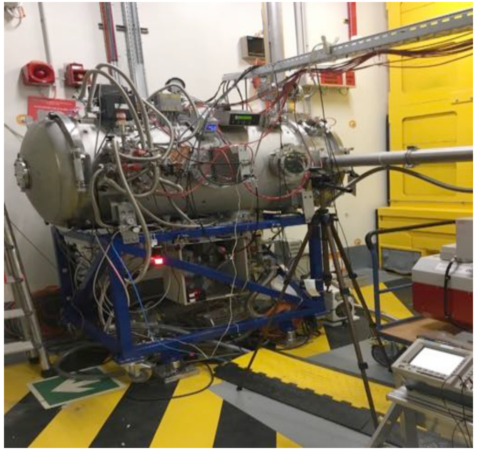
^{235}U target



EV method
- Post-evaporation fragment mass

+2 LaBr3 detectors (Subatech, Nantes) close to the target





Future:
- NFS experiment in 2024 : ^{237}Np
- Second arm in construction
- First experiment with two arms at NFS expected in 2025

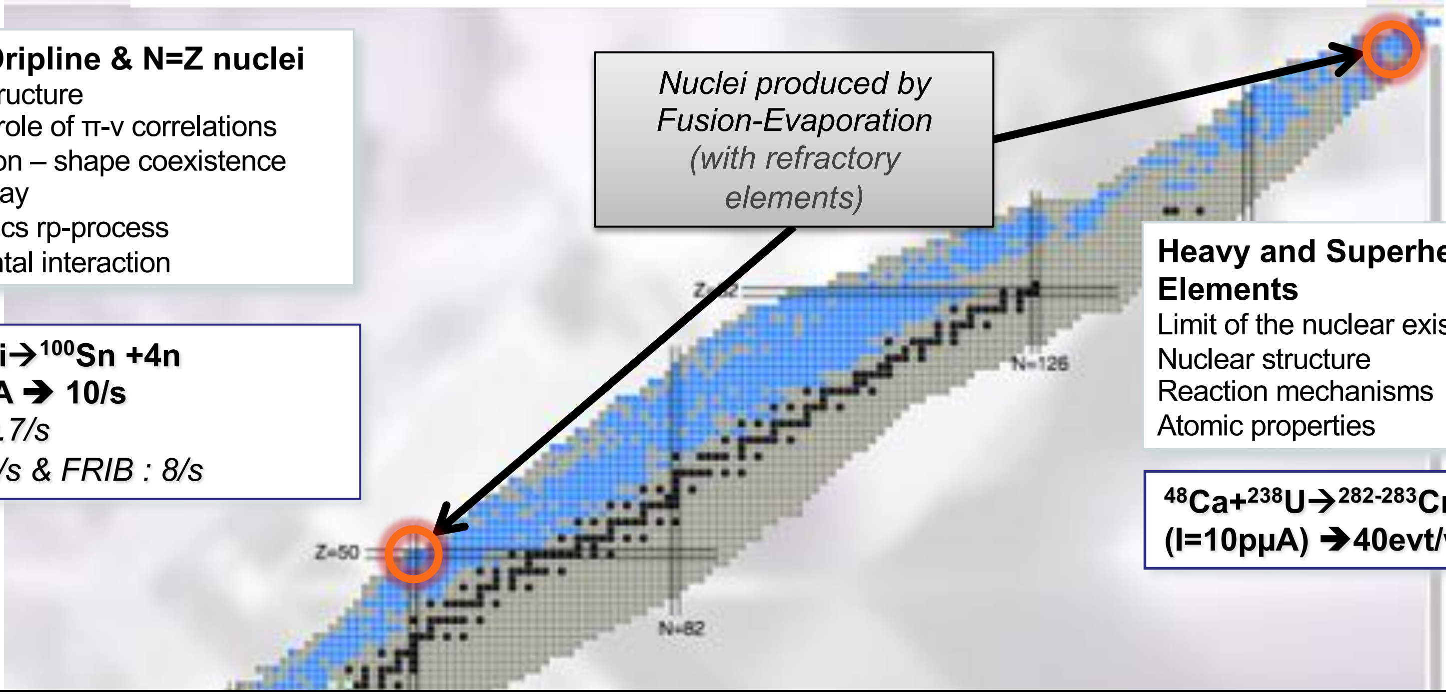
S³ Super Separator Spectromer

Study of rare events in nuclear and atomic physics

Proton Dripline & N=Z nuclei
Nuclear structure
Study the role of π-ν correlations
Deformation – shape coexistence
Exotic decay
Astrophysics rp-process
Fundamental interaction

$^{58}Ni+^{46}Ti \rightarrow ^{100}Sn$ +4n
I=10pμA ➔ 10/s
RIBF : 0.7/s
FAIR : 2/s & FRIB : 8/s

Nuclei produced by Fusion-Evaporation (with refractory elements)



Heavy and Superheavy Elements
Limit of the nuclear existence
Nuclear structure
Reaction mechanisms
Atomic properties

$^{48}Ca+^{238}U \rightarrow ^{282-283}Cn$+3,4n
(I=10pμA) ➔40evt/week

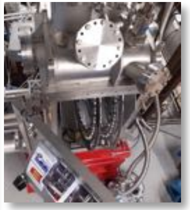
- **Develop a comprehensive model of atomic nuclei** – How do we understand the structure and stability of atomic nuclei?
- **Understand the origin of elements**
- **Use of atomic nuclei to test fundamental symmetries and properties**

http://u.ganil-spiral2.eu/chartbeams/

Super Separator Spectrometer

Main equipment and detection setups

Target system



High power rotating targets

3 × M-dipoles

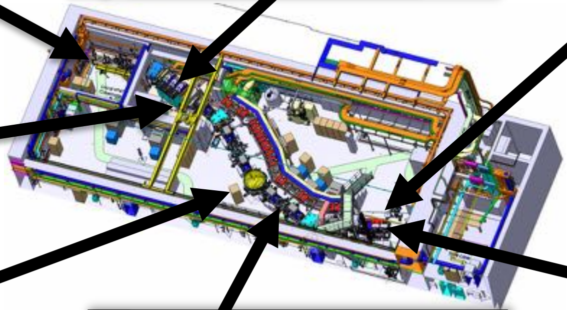
Large H & V gaps

E-Dipole

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

Dispersive zone

Open RT magnet & beam dump & Movable fingers



SC Multipoles

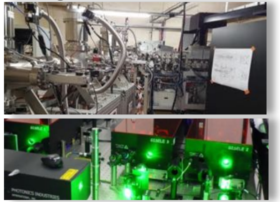
SMT, PSS, Coldbox & LTC

Infra / Interface

Lot C68, Cooling system, Laser room

LEB

LEB @ LPC & GISELE Laser Lab



SIRIUS

DSSD, SSD, FEE/BEE, DAQ & Diagbox

- High selectivity > 10^{13} - High efficiency 50% - In flight mass separation > 1/450
- Versatility & unique instrumentation (SIRIUS – LEB)

Optics and performances

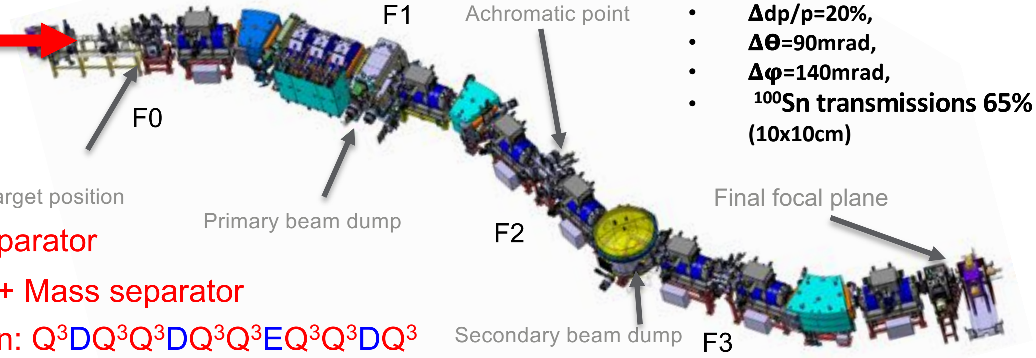
laboratoire commun CEA/DSM CNRS/IN2P3

Basic properties and functionalities

Reference beam :
A=100, Q=24+, σ_p = 3.7%, σ_θ = 18mrad

High beam intensity

High power target: >> 1pμA (= 6.10^{12}p/s)



Versatile multistep separator

Momentum achromat + Mass separator

Ion optics configuration: $Q^3DQ^3Q^3DQ^3Q^3EQ^3Q^3DQ^3$

F1 : R16=1.15cm/%, F2/F4 : R16 = R26 = 0, F3 : R16 = -1.73 cm/% / -1.59 cm/%

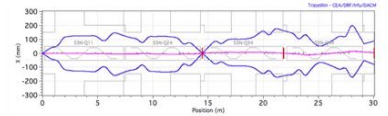
Two basic optical modes of operation:
High transmission vs high mass resolution
→ The momentum achromat (MA) optic is common to all modes

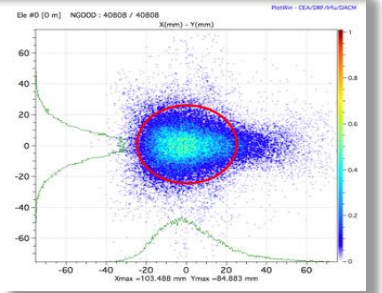
In future :

- Online optics Bayesian optimization
- Implementation of machine learning

Convergent Mode (CM)

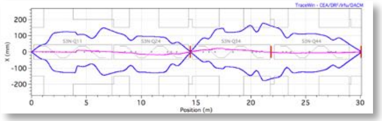
- **No mass resolution**
- **6 charge states**
- **Δdp/p=20%,**
- **Δθ=90mrad,**
- **Δφ=140mrad,**
- **^{100}Sn transmissions 65% (10x10cm)**

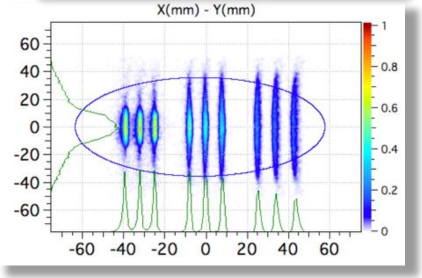




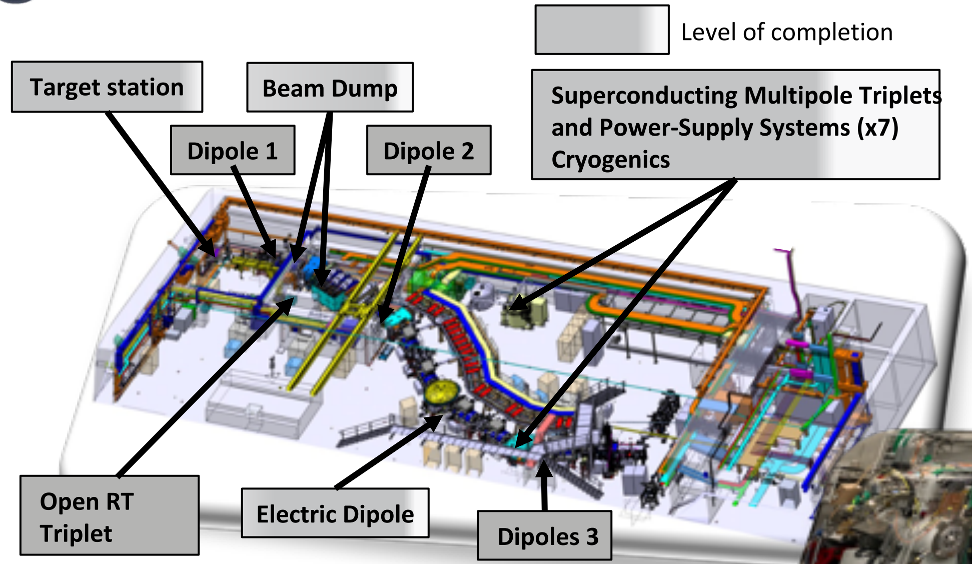
High Resolution Mode (HRM)

- **m/q dispersion = 8 mm/%**
- **3 charge states & M/ΔM = 500**
- **Δdp/p=16%**
- **Δθ=45mrad**
- **Δφ=140mrad)**
- **^{100}Sn transmissions 40% (10x10cm)**

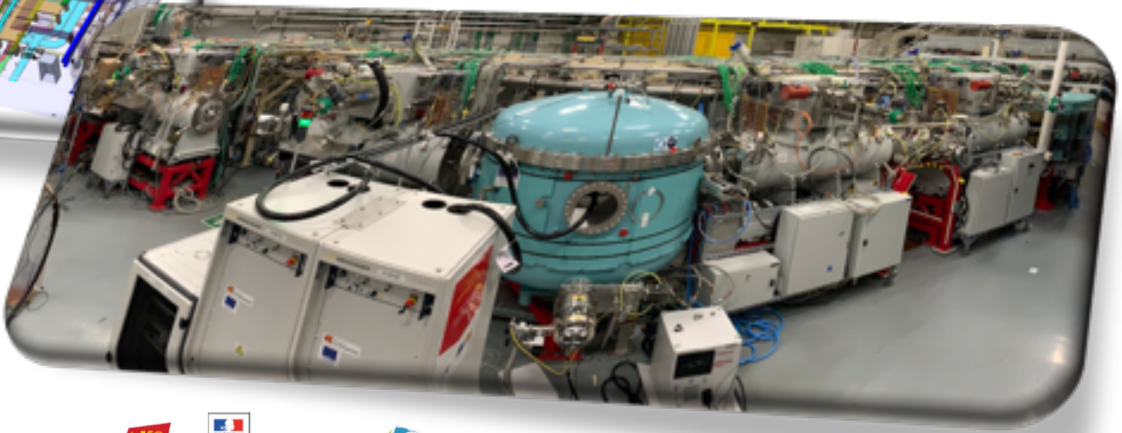




Status of the beamline



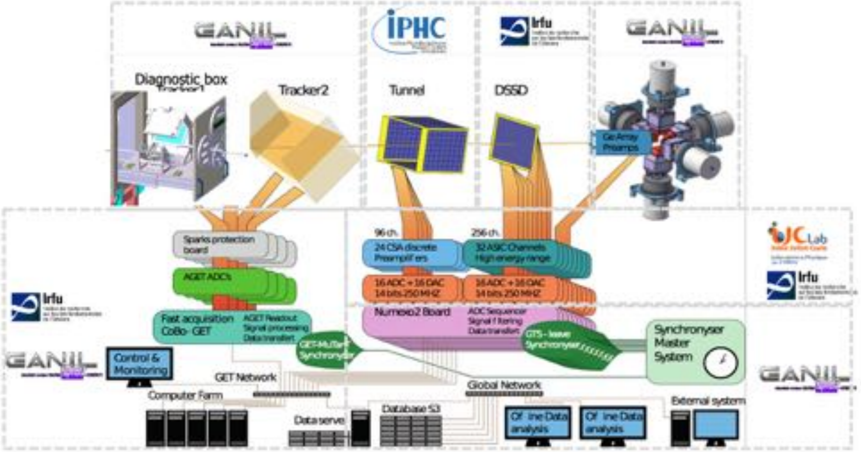
➢ Ready for beam commissioning 2025

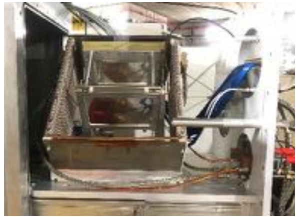


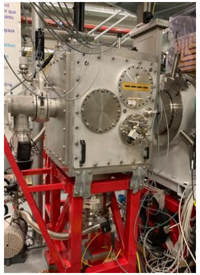
Level of completion ≈ 85 %

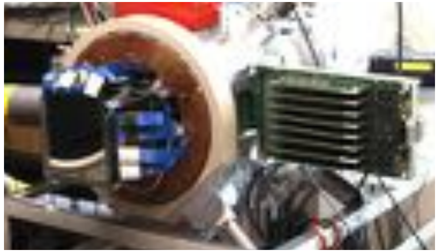
SIRIUS *(Spectroscopy & Indentification of Rare Ions Using S^3)*

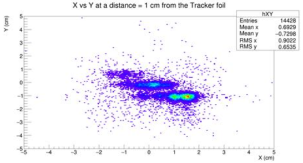
Decay spectroscopy of VHE/SHE

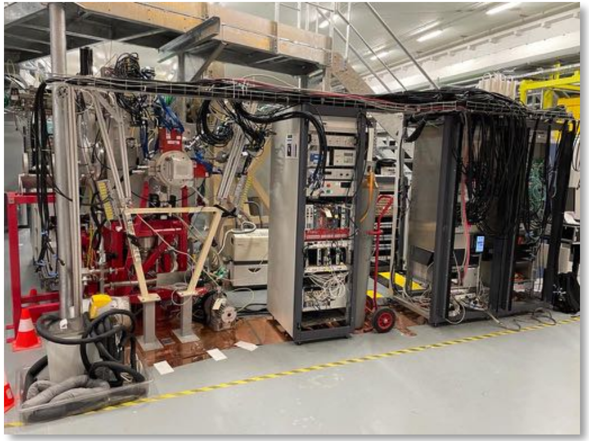












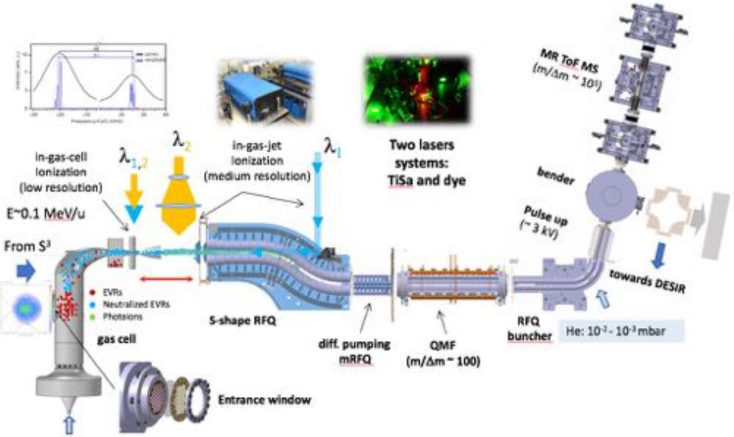
α, SF, e^-, γ decay spectroscopy

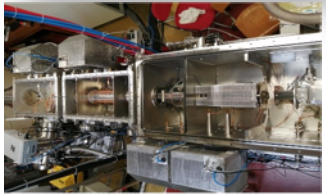
- Time of flight (Δt < 1ns) and tracking (Δx) <0.5mm) of (super)heavy ions
- Implantation decay correlation (10x10cm2, 128x128ch DSSD)
- Digital electronics for fast decays (low gain/high gain switching) ΔE_α <20keV

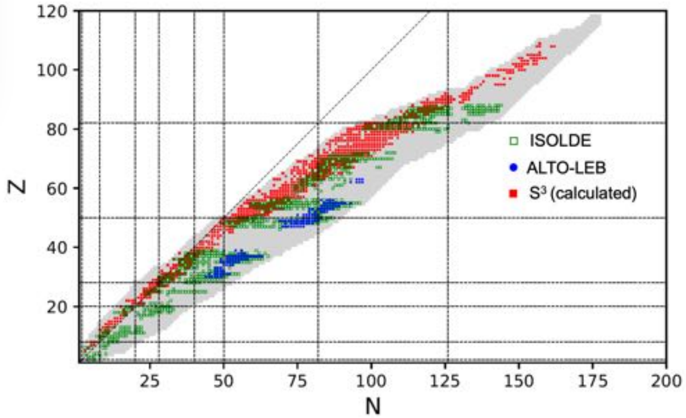
LEB (Low Energy Branch)

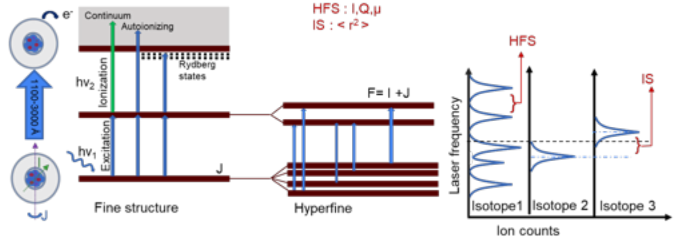
Laser, decay spectroscopy & Mass measurement

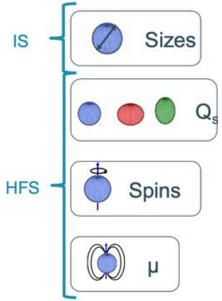
- Pure & low energy beams
- Species not available by other techniques











- Nuclear Moments / Charge radii / Spin
- Mass
- Decay spectroscopy

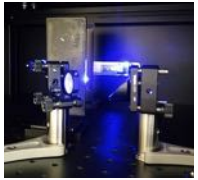
LEB commissioning

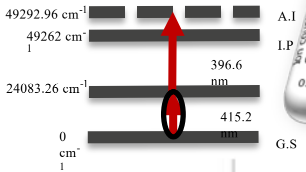
First high resolution laser spectroscopy and mass measurement of stable erbium isotopes

- In gas jet saser spectroscopy : 200 MHz resolution (FWHM)
- Mass resolving power : R ~120.000

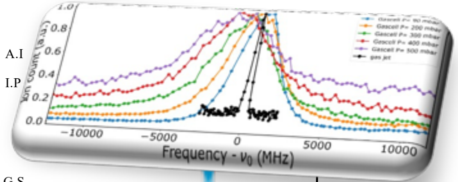
A. Ajayakumar et al. NIMB 539 (2023)102

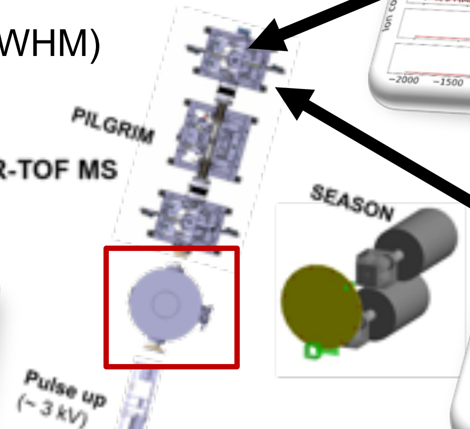
Ionisation laser scheme

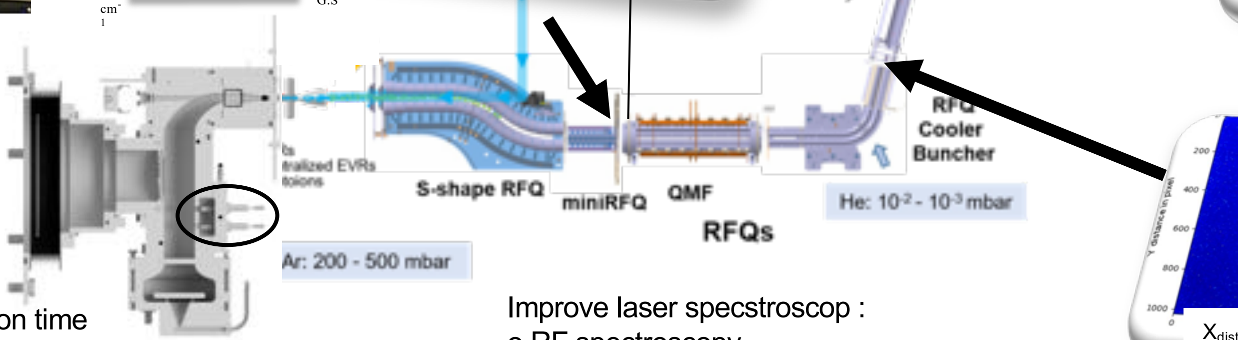




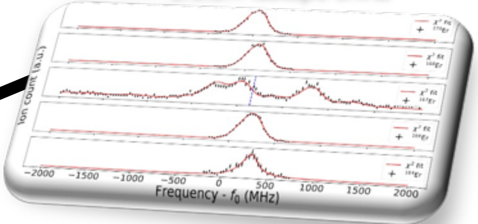
jet/gas spectral resolution



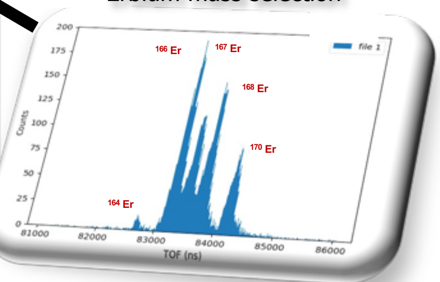




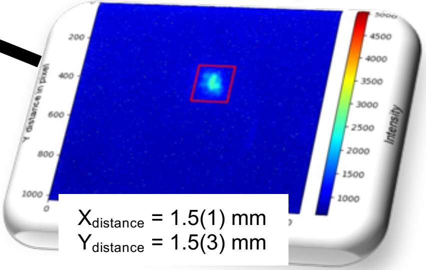
Erbium isotope shifts



Erbium mass selection



Ion bunch image



New gas cell:
- o Reduce extraction time
- o Improve neutralization efficiency

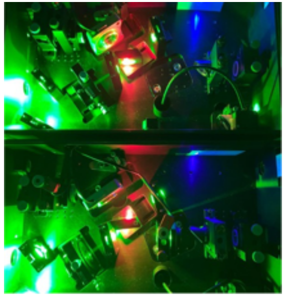
Improve laser specstroscop :
- o RF spectroscopy

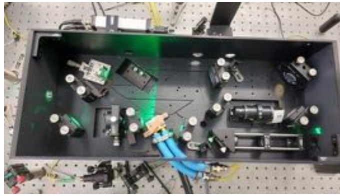
LEB – Laser developments GISELE @ GANIL

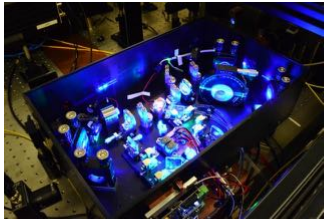
laboratoire commun CEA/DSM CNRS/IN2P3

Development of laser spectroscopy methods
System of different linewidths available

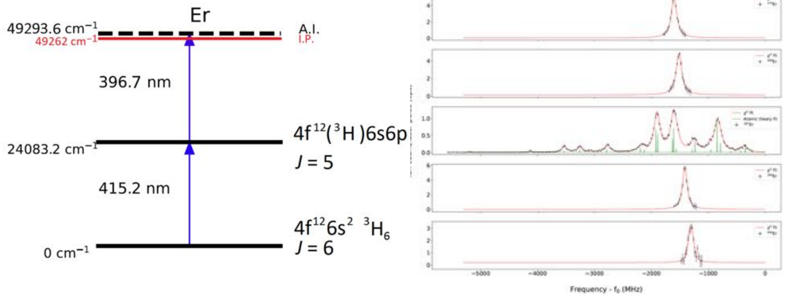
- New injection-locked Ti:sa cavity in collaboration with JGU Mainz ($\Delta\lambda$ < 50 MHz)
- New continuous wave Ti:sa laser in collaboration with Uni. Nagoya
- Day-1 laser spectroscopy developments : Er, Sn, Pd



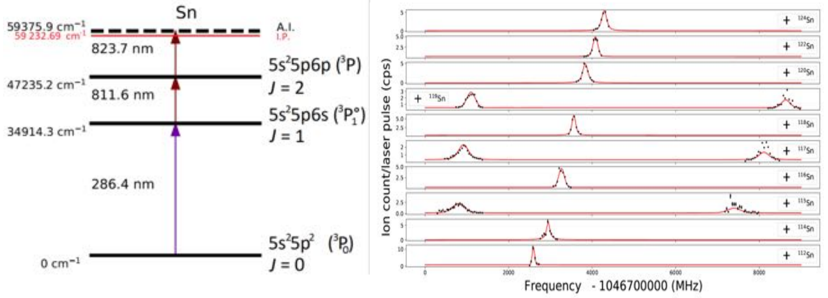




162,164,166,167,168-170Er isotope shifts



112,114,115,116,117,118,119,120,122-124Sn isotope shifts



J. Romans, NIMB 536 (2023) 72   *A. Ortiz-Cortes, PhD defense, 26/01/2023*

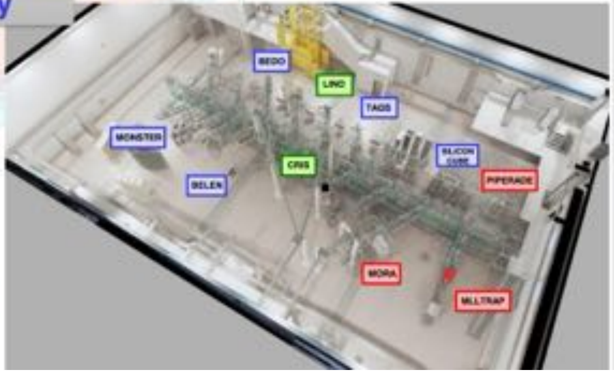
DESIR

Low energy (< 60 keV) 1^+ RIBs from SPIRAL1 and S^3

- Collinear laser-spectroscopy — **LUMIERE**
- Laser polarisation (LINO)
- Paul trap (MORA) — **DETRAP**
- Penning traps (PIPERADE, MLLTrap) — **BESTIOL**
- (Trap-assisted) decay spectroscopy

Dedicated workshops in 2024/25
→ LOI
→ Day 1 proposals

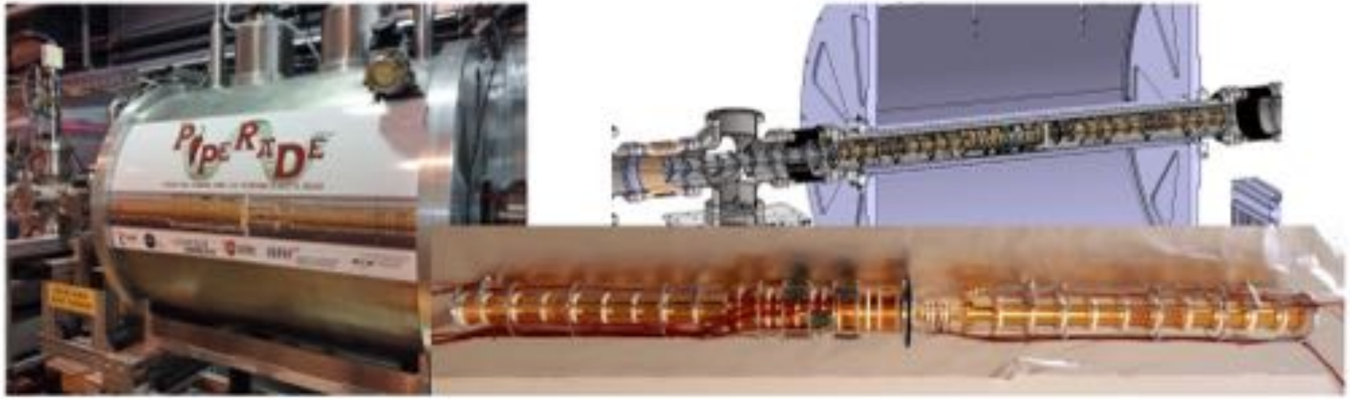
LP2i, lpc, GANIL, LPC, GSI, IPHC, LMU, IFIC, KU LEUVEN, MANCHESTER



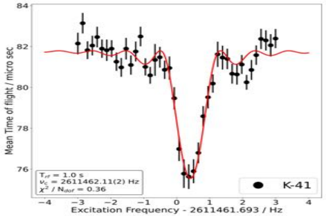
PIPERADE

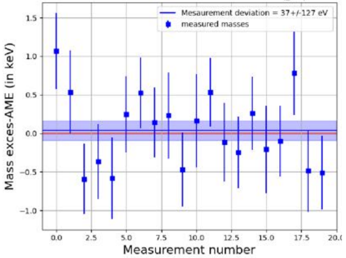
laboratoire commun CEA/DSM CNRS/IN2P3

Purification and mass measurements



^{41}K vs $^{39}K \sim 3.10^{-9}$

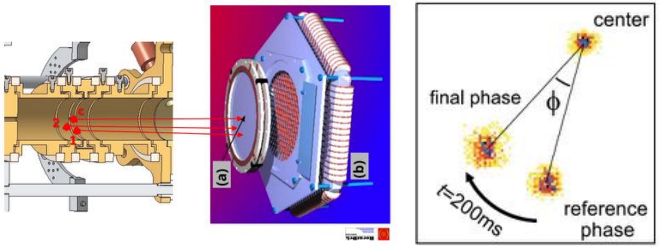




Double penning trap

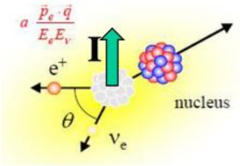
- Purification : 10^5 ions/bunch, 2-20 Hz
- Mass measurements TOF-ICR and PI-ICR (10^{-8} – 10^{-9} precision)

Next steps



Search for new physics via the *D* correlation measurement

THE MORA PROJECT
MATTER'S ORIGIN FROM RADIOACTIVITY



A non-zero *D* can arise from CP violation

$$D\frac{\langle\vec{J}\rangle}{J}\cdot\left(\frac{\vec{p}_e}{E_e}\times\frac{\vec{p}_\nu}{E_\nu}\right)$$

T reversal odd

D correlation measurement in ^{23}Mg, ^{39}Ca decays to the 10^{-5} level with some beam, laser and trapping R&D

- Ion cooling and trapping originally developped for

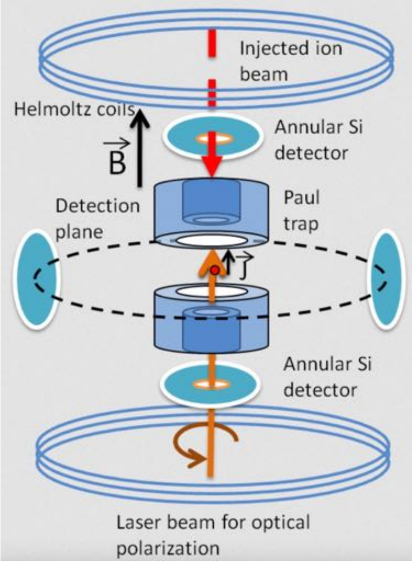
LPCTrap

New trap and new detection setup:

off-line commissioning at

Completed in automn 2021

- Theoretical studies with state-of-the-art EFTs



- Innovative laser polarisation techniques at

MORA installation at JYFL/IGISOL (completed!)

Proof of principle of polarization
First *D* measurement
Started in Feb 2022

With experts from:

KU LEUVEN NUCLEAR AND RADIATION PHYSICS
MANCHESTER 1824 The University of Manchester

Back to GANIL/DESIR, making use of the intense and purified ISOL beams from SPIRAL 1/ S3-LEB: **2027**

anr agence nationale de la recherche AU SERVICE DE LA SCIENCE

RÉGION NORMANDIE

Conclusion

- **Large variety of spectrometers and detectors**
  - VAMOS++ and the new Super Separator Spectrometer
  - MUGAST-GRIT, INDRA FAZIA, PISTA, SIRIUS
  - ACTAR-TPC
  - FALSTAFF

- **The rise of low/thermal energy physics has trigged new developments**
  - Gas-cell technology (S^3-LEB, FRIENDS^3 R&D, …)
  - Laser spectroscopy techniques (in gas jet, collinear, …)
  - Trap devices (MR-ToF-MS, double Penning trap, …)
  - Trap assisted decay spectroscopy (under development with MLLTrap)
  - Ion trap-based device (MORA)

- **Next generation of electronics and DAQ**

Examples where synergies between the IRL partners are possible (not exhaustive list)