# AXIS 1: NUCLEAR PHYSICS CENTER

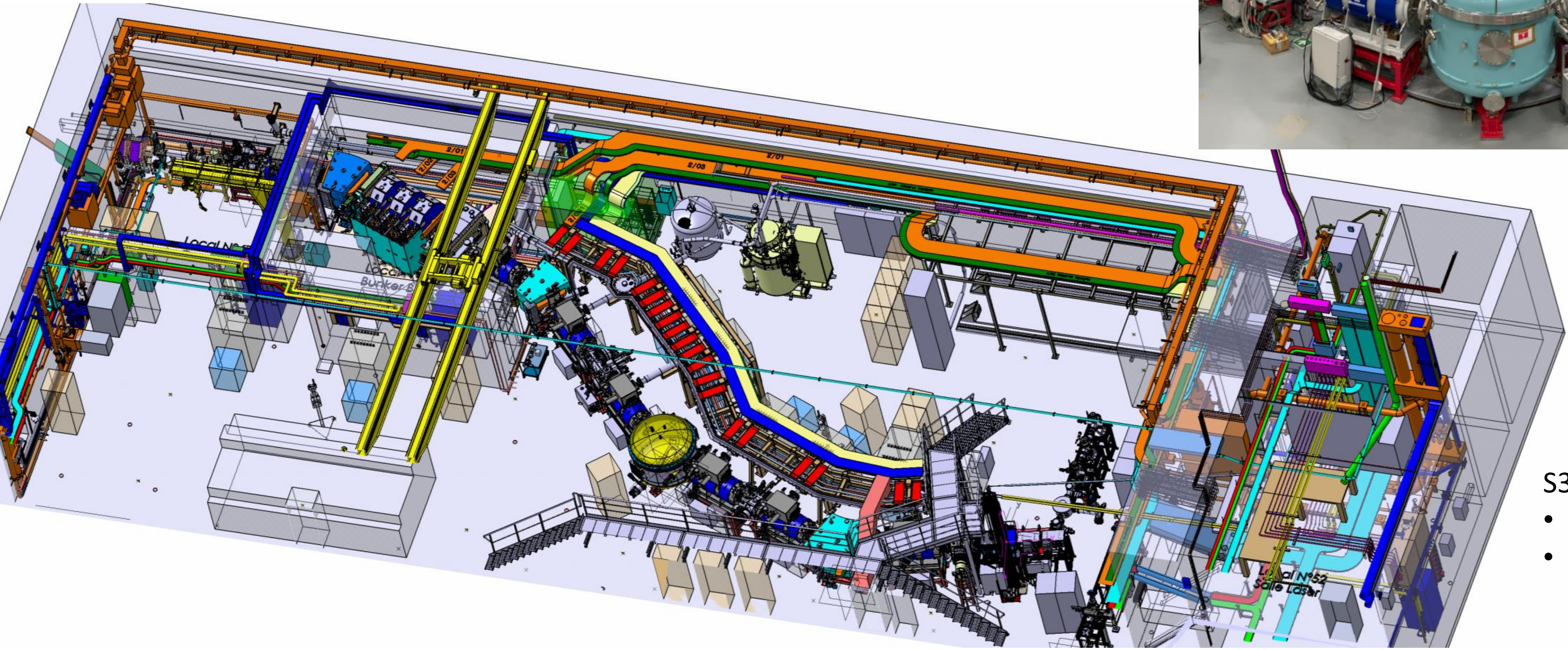
*Scientific Advisory Board: meeting n°1*

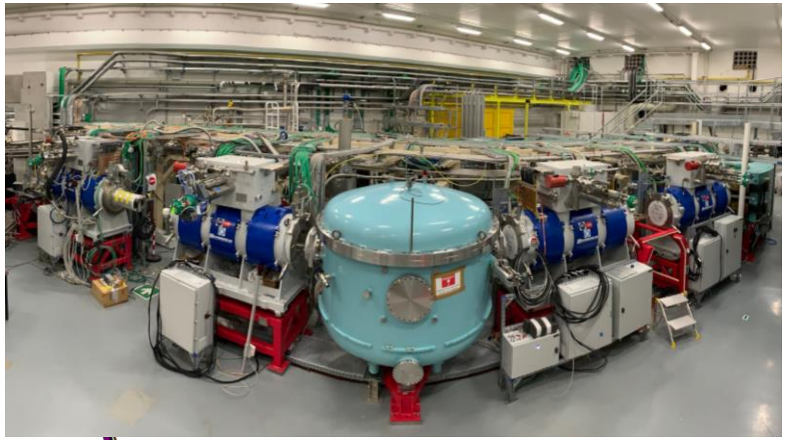
# WP3: PROTON DETECTION AT S3-LEB

*A. de Roubin*

# S3 – SUPER SEPARATOR SPECTROMETER

- Wide range (H to U) of high intensity primary beams (10 $\mu$Amp)
- High primary beam rejection and high acceptance spectrometer



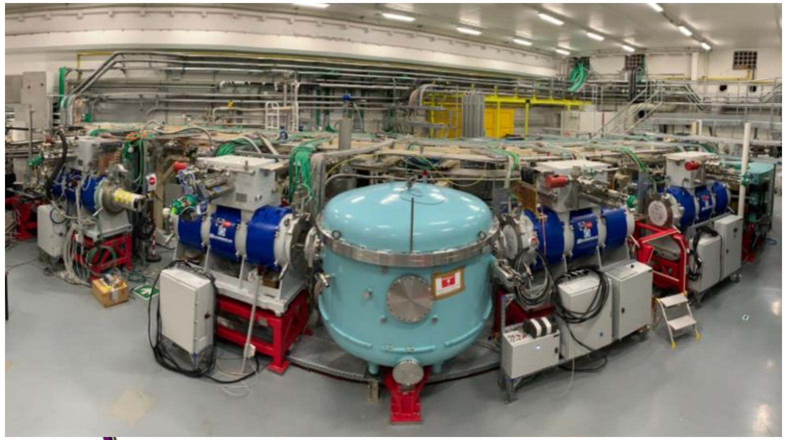


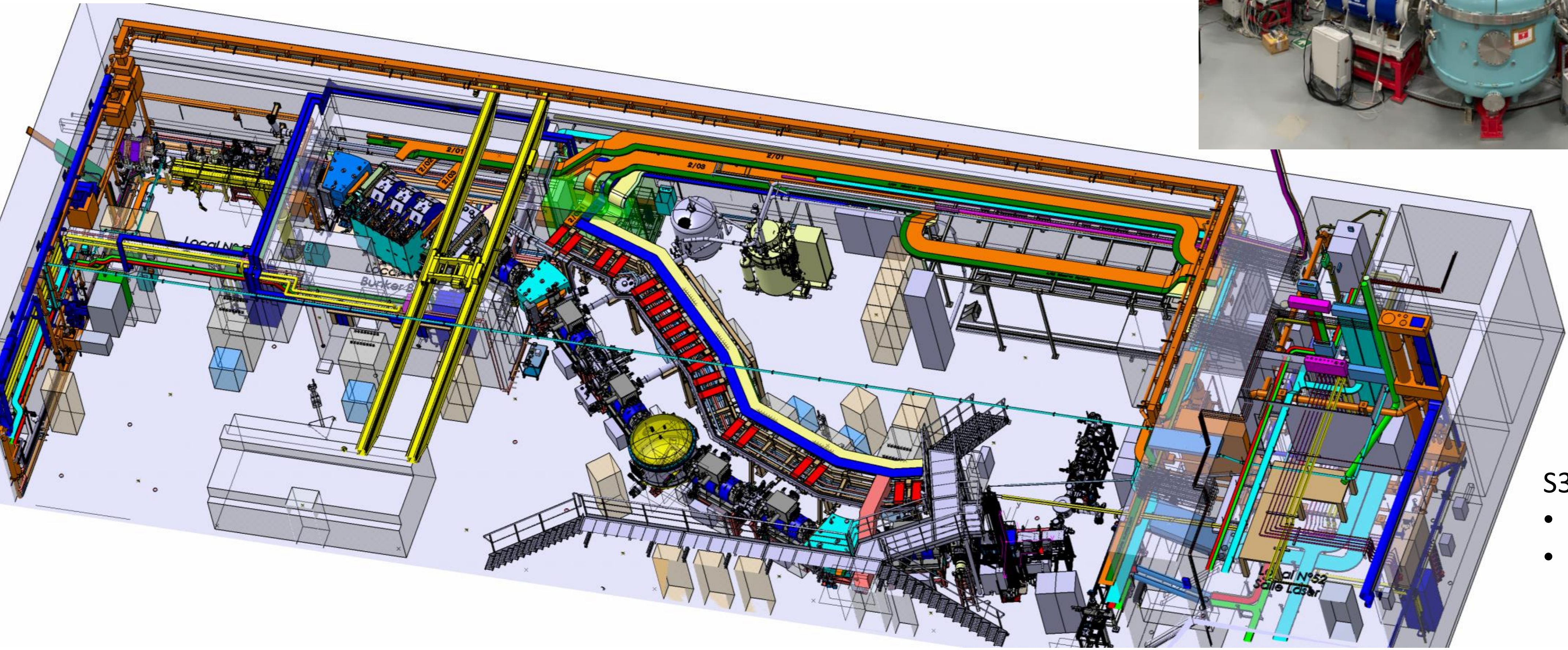
S3 equipex:

- 22 M€
- 400 ETP (12 years)

# S3 – SUPER SEPARATOR SPECTROMETER

- The RIBs are produced by fusion evaporation
- Pre-selected by the in-flight spectrometer S3
- Transported to the gas cell in the converging mode



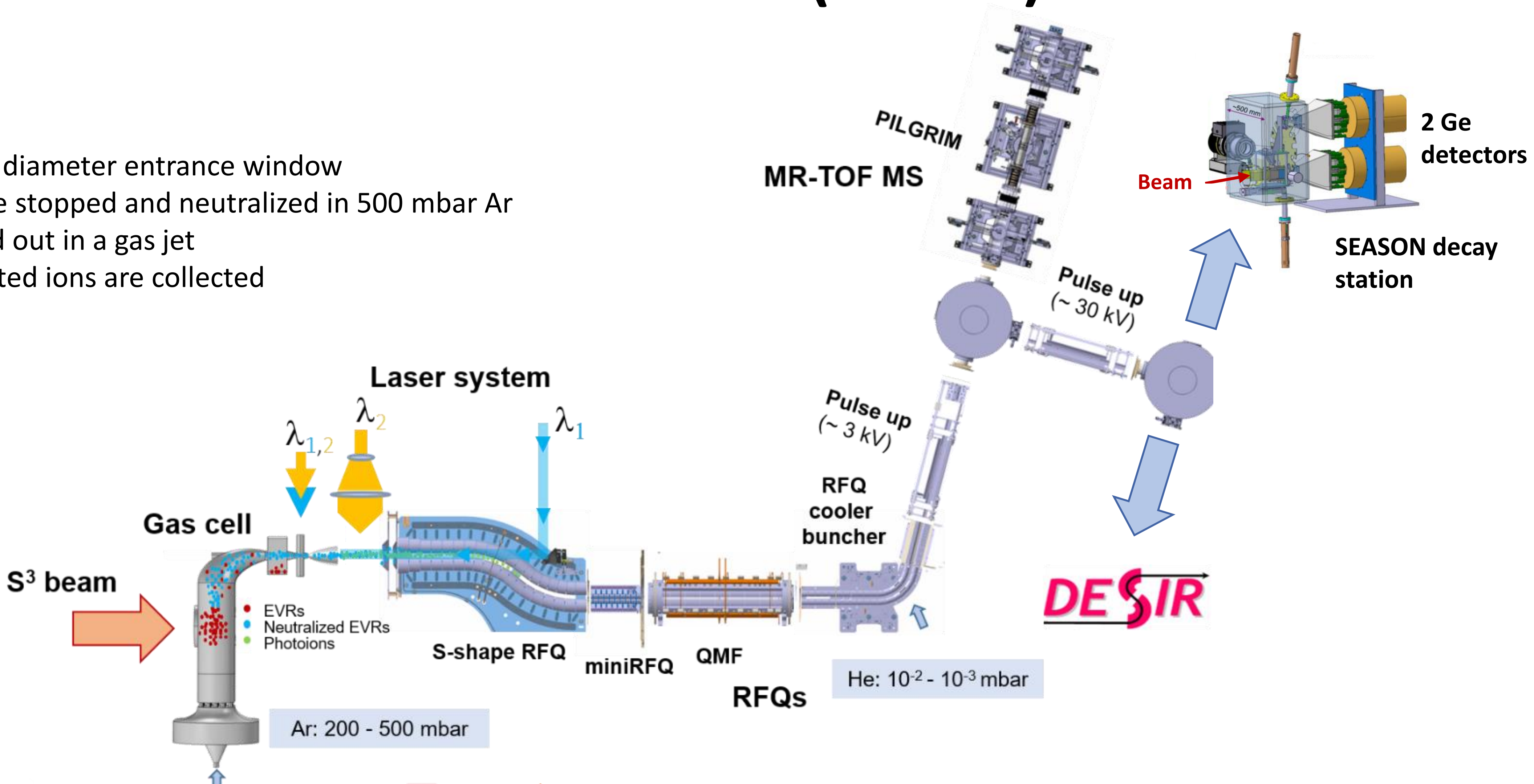



S3 equipex:
- 22 M€
- 400 ETP (12 years)

# S3 LOW ENERGY BRANCH (S3-LEB)

**Gas cell:**

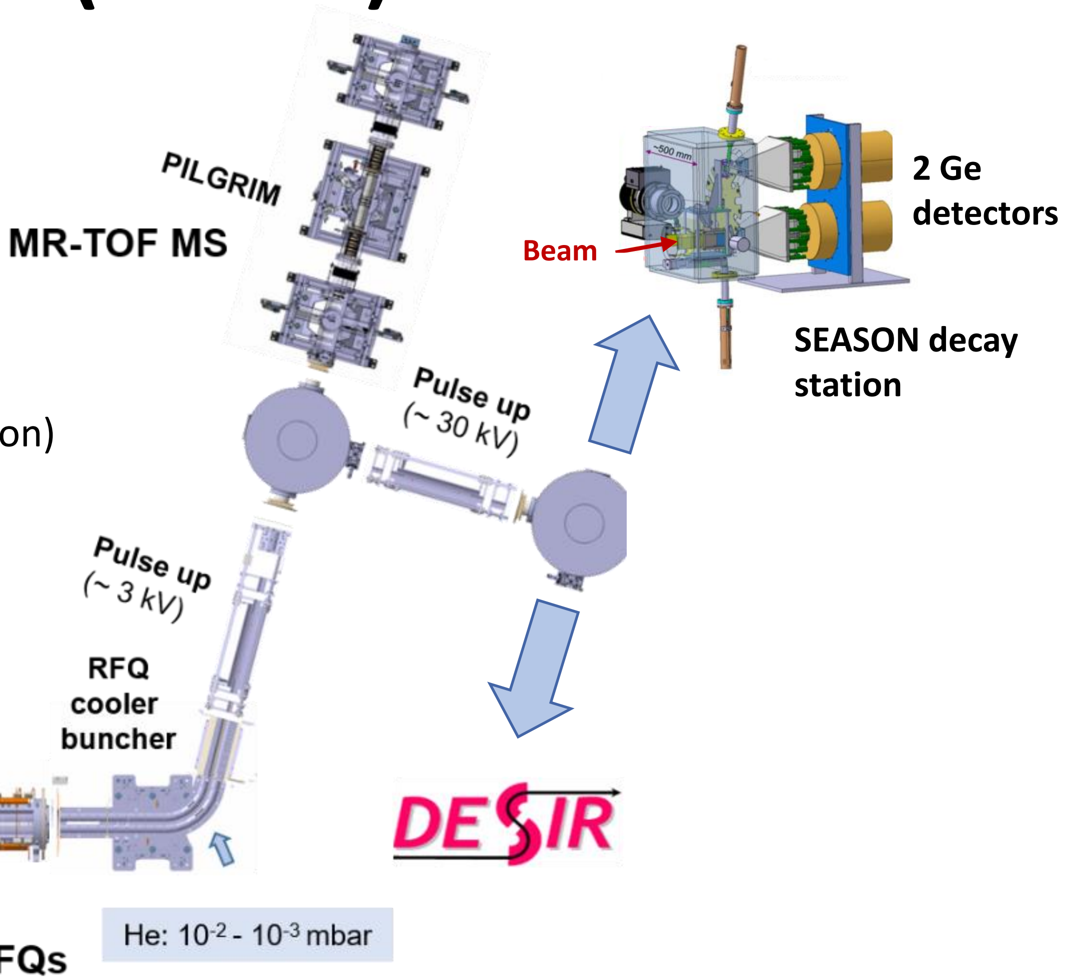
- 50 mm diameter entrance window
- Ions are stopped and neutralized in 500 mbar Ar
- Flushed out in a gas jet
- Unwanted ions are collected

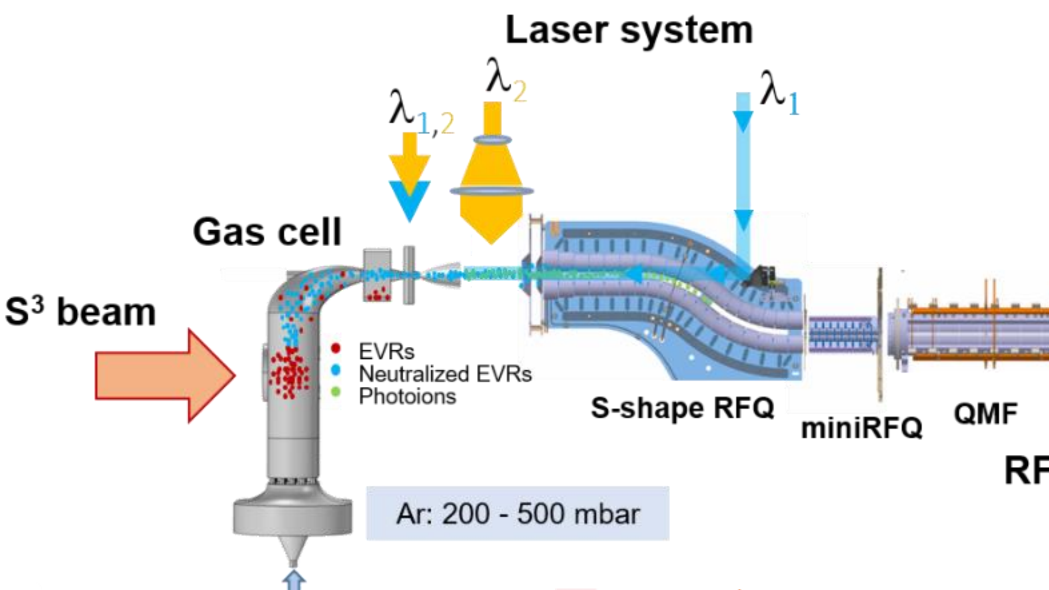


# S3 LOW ENERGY BRANCH (S3-LEB)

**Laser system:**

- Broad band lasers in the gas cell to look for atomic transitions
- Narrow band ionization in the gas jet
  - Low temperature
  - Low pressure
- High resolution spectroscopy (300 MHz resolution, isomer purification)

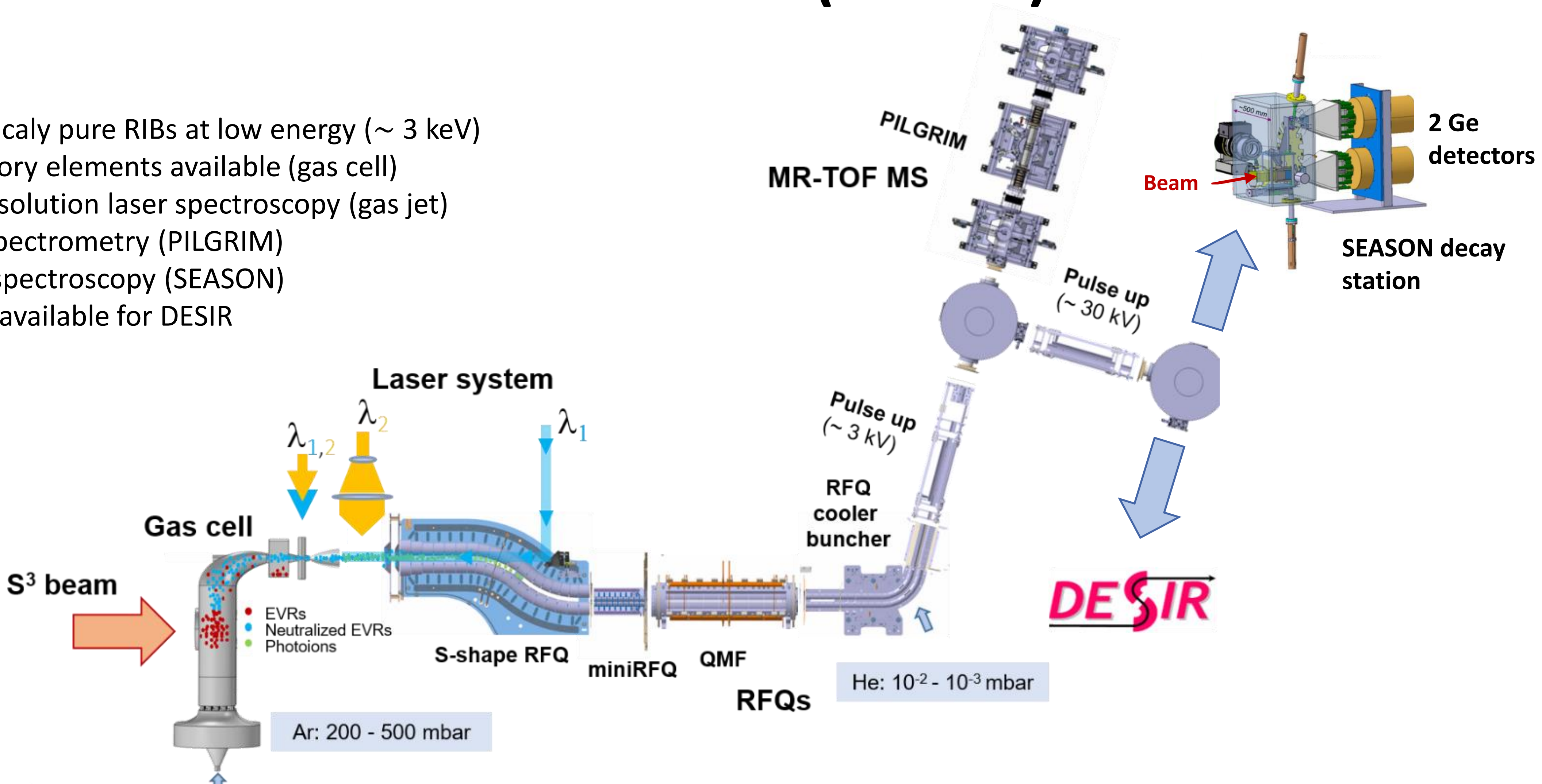



KU LEUVEN · IJCLab Irène Joliot-Curie · LPC Caen · GANIL Spiral2 · Johannes Gutenberg Universität Mainz · University of Jyväskylä · cea

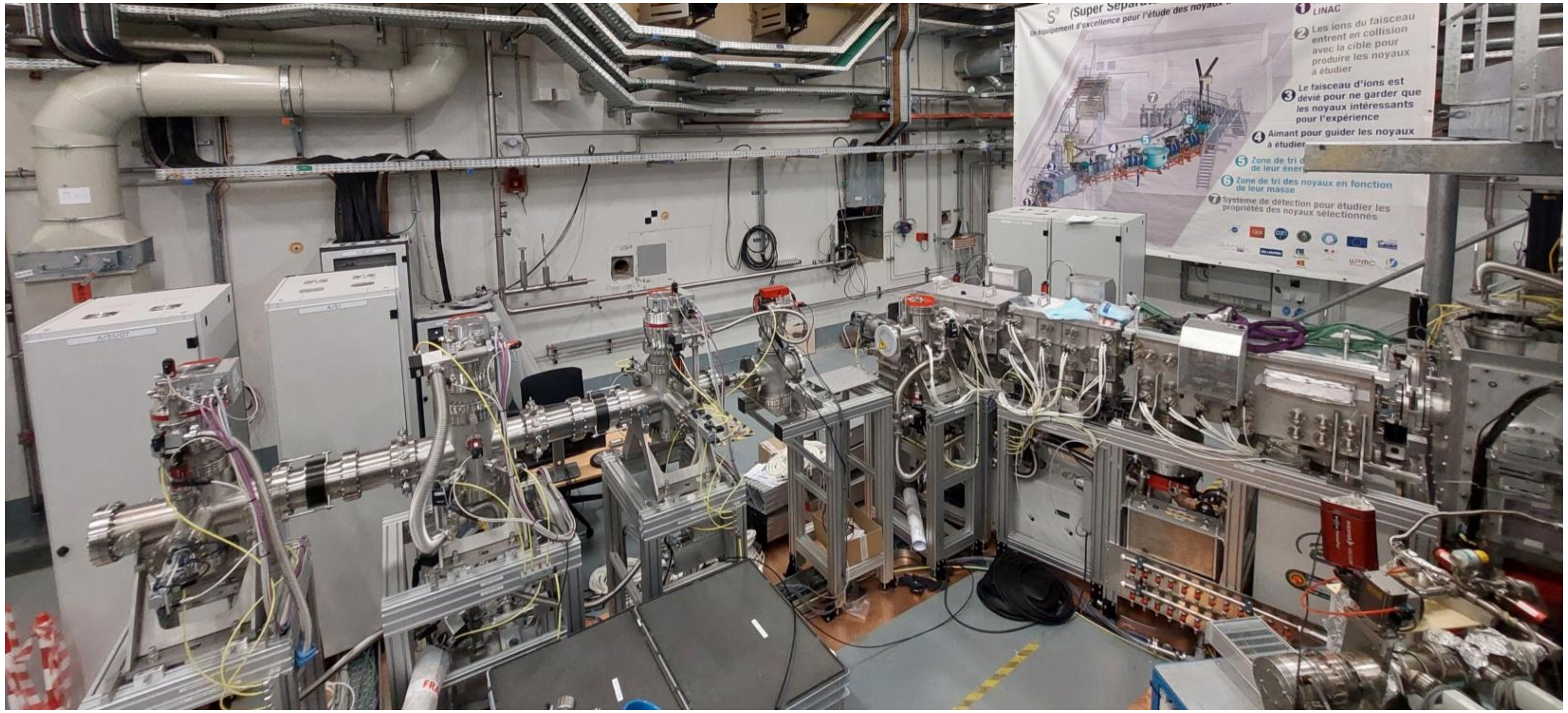
# S3 LOW ENERGY BRANCH (S3-LEB)

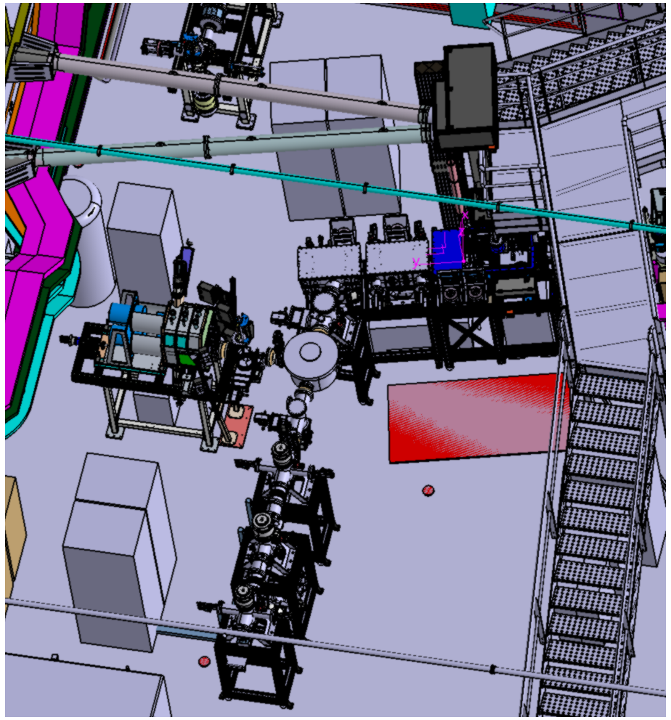
- Isomericaly pure RIBs at low energy (~ 3 keV)
- Refractory elements available (gas cell)
- High resolution laser spectroscopy (gas jet)
- Mass spectrometry (PILGRIM)
- Decay spectroscopy (SEASON)
- Beams available for DESIR



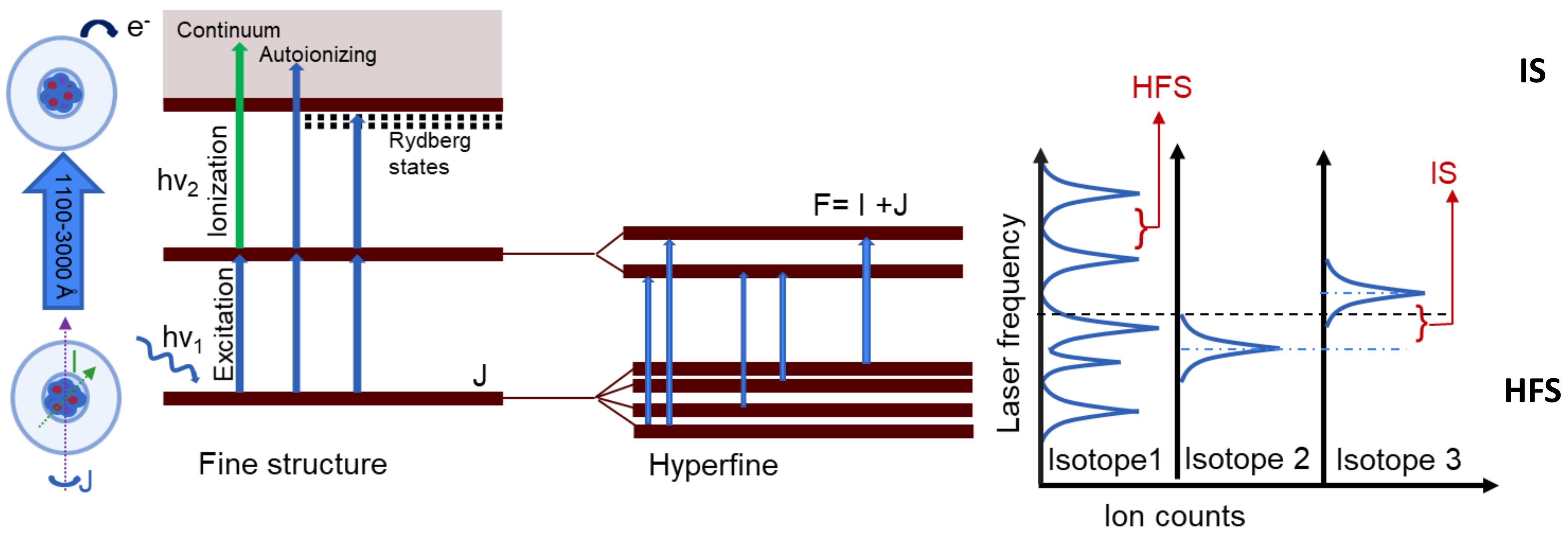
# S3-LEB AT S3

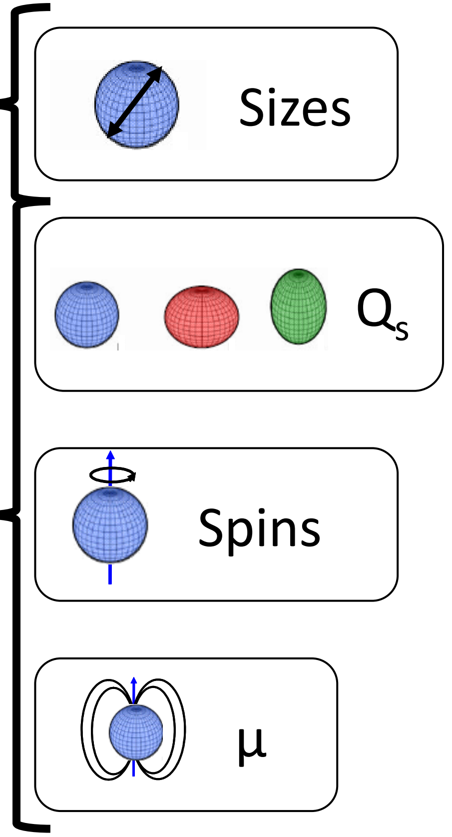
- After 10 years of construction and commissioning at LPC, $S^3$LEB moved to GANIL in March
- Installation at $S^3$:
  - Vacuum and related equipment reconnected and tested
  - HV and RF cabling and final alignments ongoing, water and gas connections to be done
  - Recommissioning to start soon, with e.g. total (gas cell) efficiency tests using a Ra recoil source foreseen



# RESONANT LASER IONIZATION SPECTROSCOPY

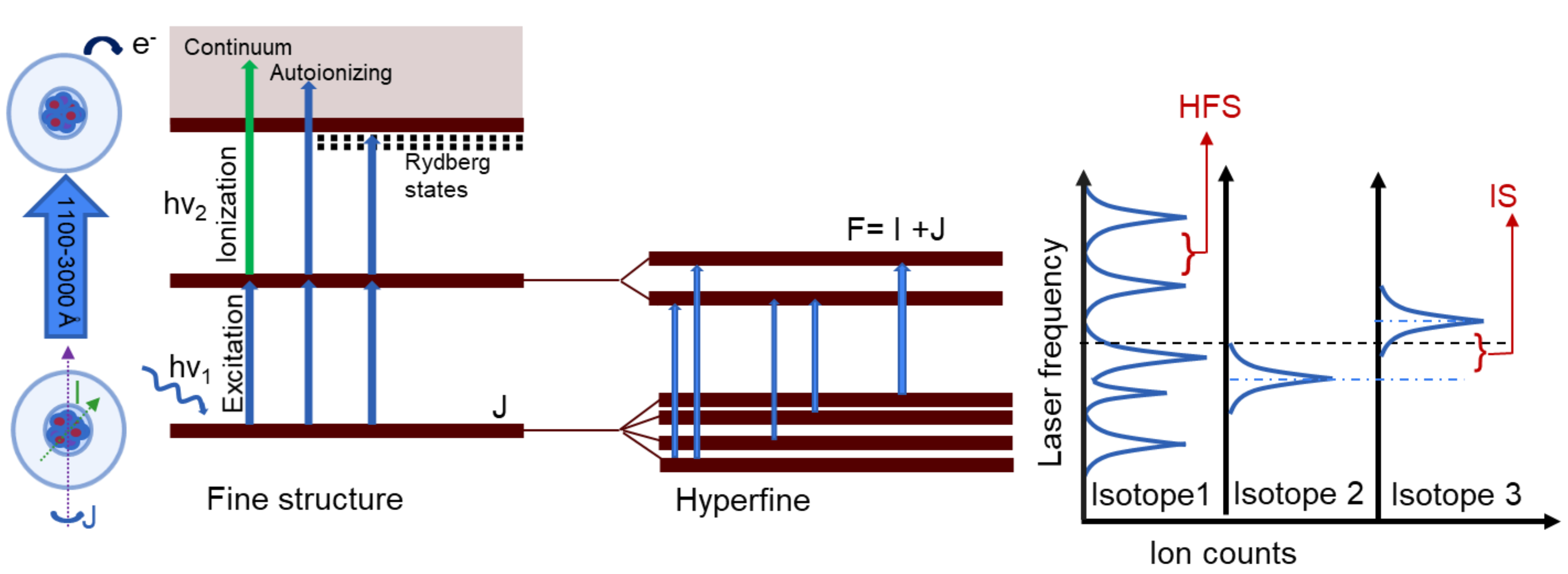


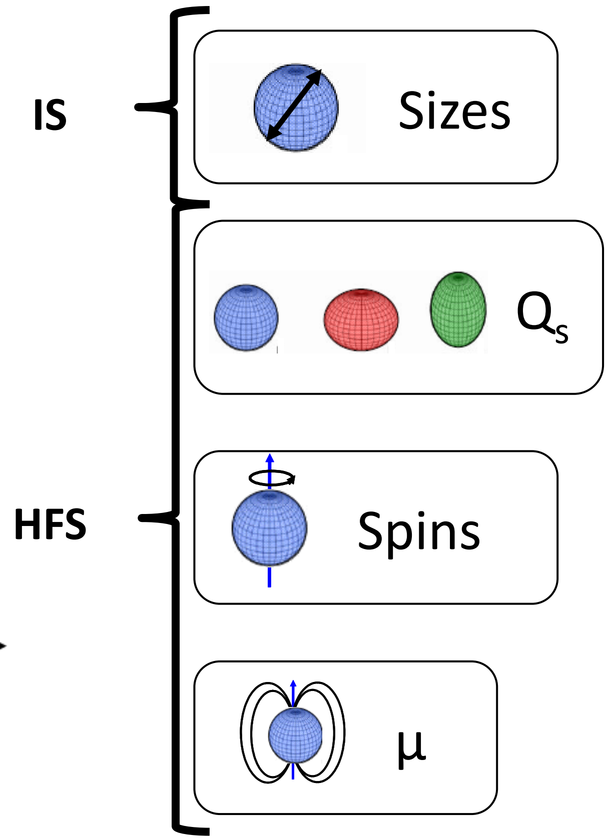




**Resonant Laser Ionization method:**

- Gives an extra selection in Z to the ions of interest
    - Only one given element (isomer) is ionised with the chosen combination of photons.
- Increasing the resolution of the system can give access to the hyperfine structure
    - Due to the coupling of the nucleus with the electronic orbital

# RESONANT LASER IONIZATION SPECTROSCOPY

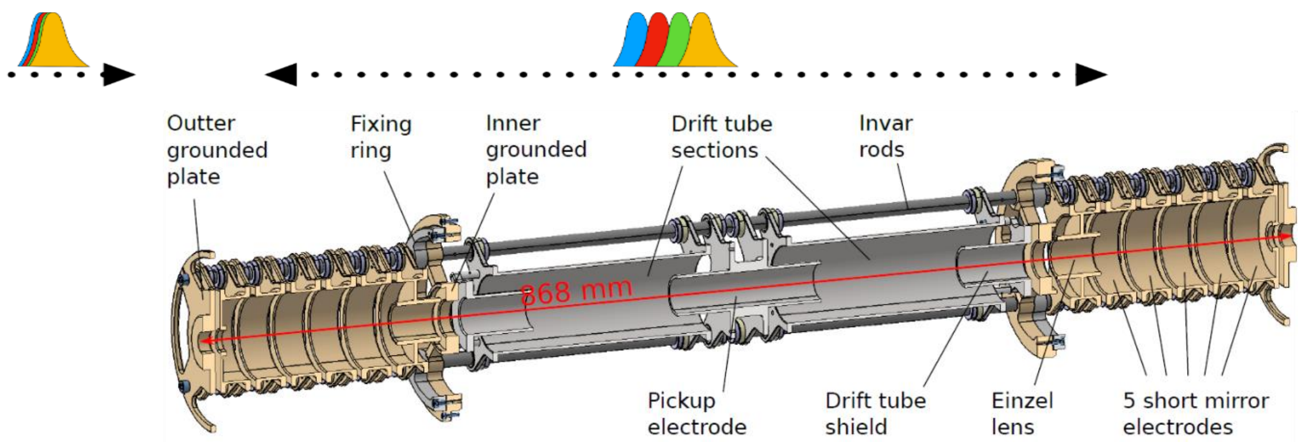


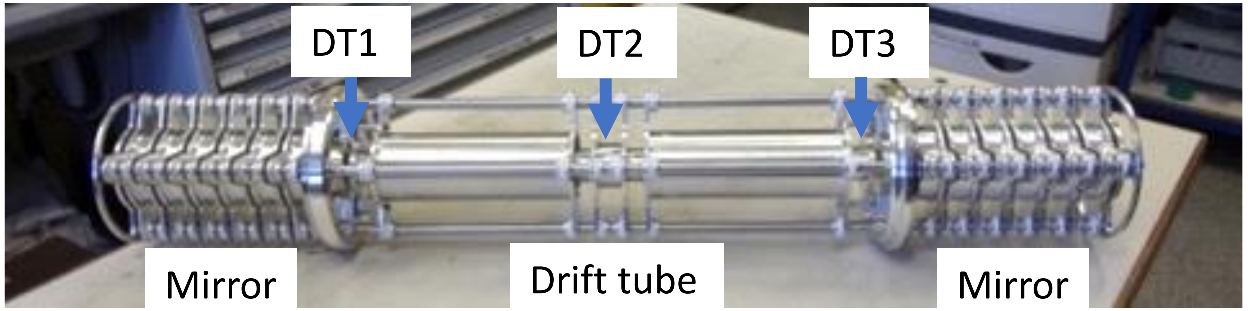



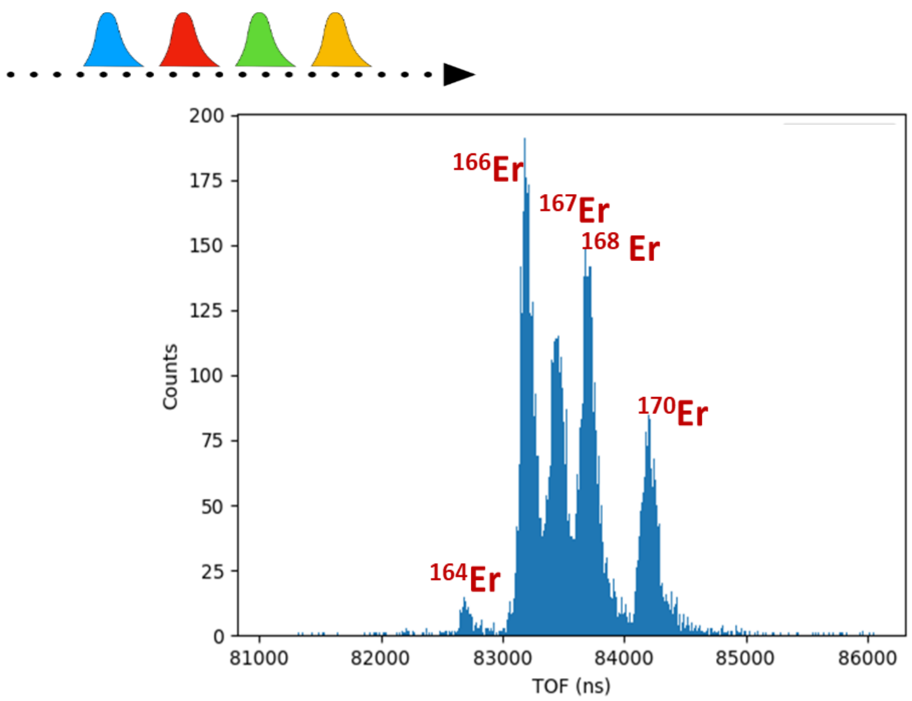

**Resonant Laser Ionization method:**

- Scan the laser frequency of the transition to measure isotope shifts
  - Information on charge radii
- Hyperfine splitting
  - Give access to deformation, spins and magnetic moments

# MASS SPECTROMETRY




- The MR-TOF MS is an electrostatic ion trap
- Increase the TOF by multiple reflections
- Purification and mass measurements

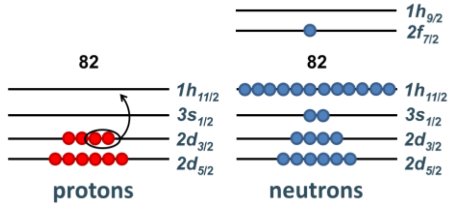
# PERSPECTIVES AND ONLINE COMMISSIONING

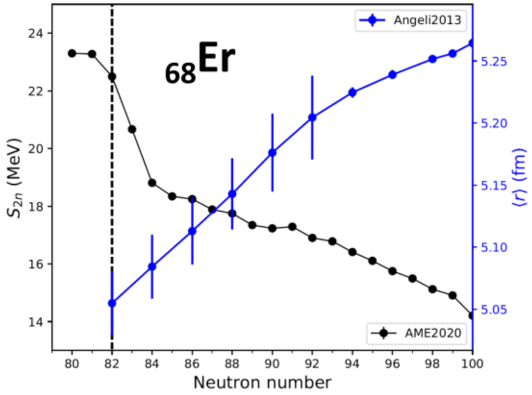
**2026:** Start physics commissioning of $S^3$ with reaction $^{116}Sn(^{40}Ar, 4n)^{151}Er$:

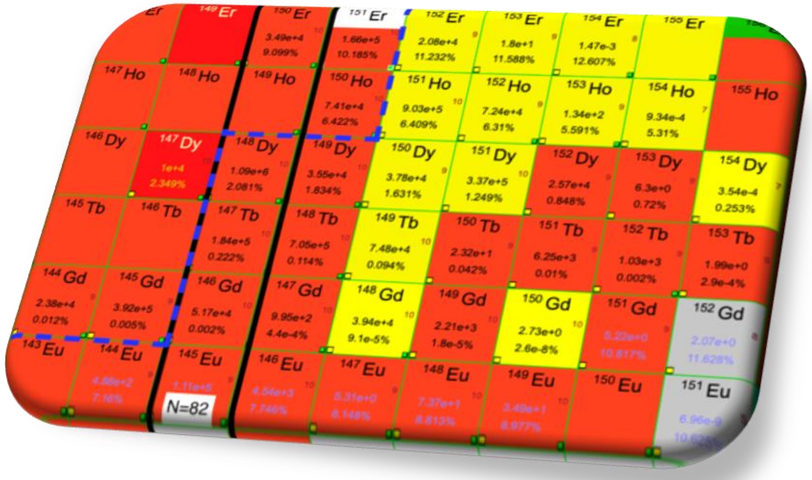
- Opportunity to study the single-particle states and high-spin isomers around the *N = 82* shell closure

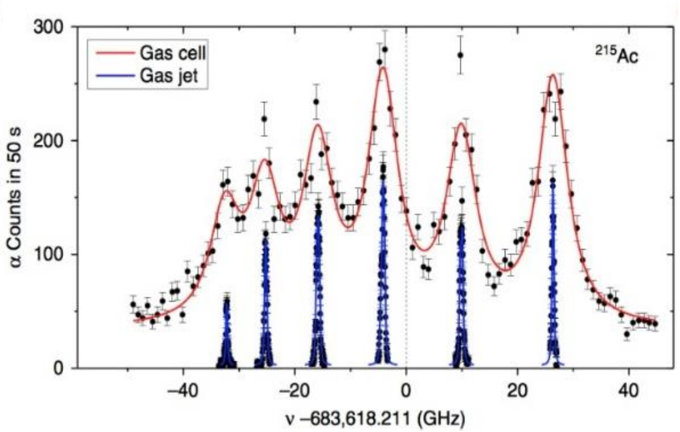
**>2026:**

- Production of actinium by asymmetric reactions ($^{40}Ar + ^{175}Lu$ and $^{20}Ne + ^{197}Au$)
- Production of *N = Z* nuclei ($^{50}Cr + ^{58}Ni$)

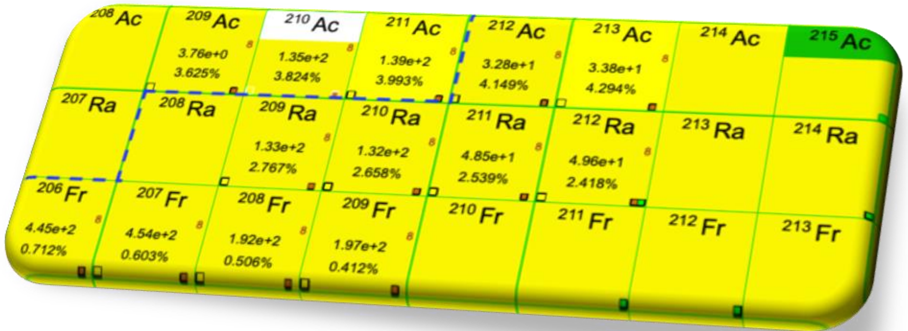


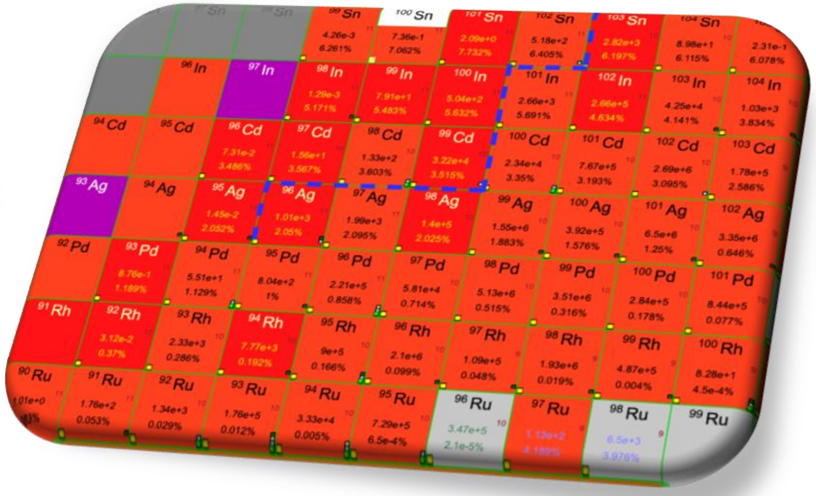




*R. Ferrer, Nature Comm. 8 14520 (2017)*



Courtesy: S. Geldhof



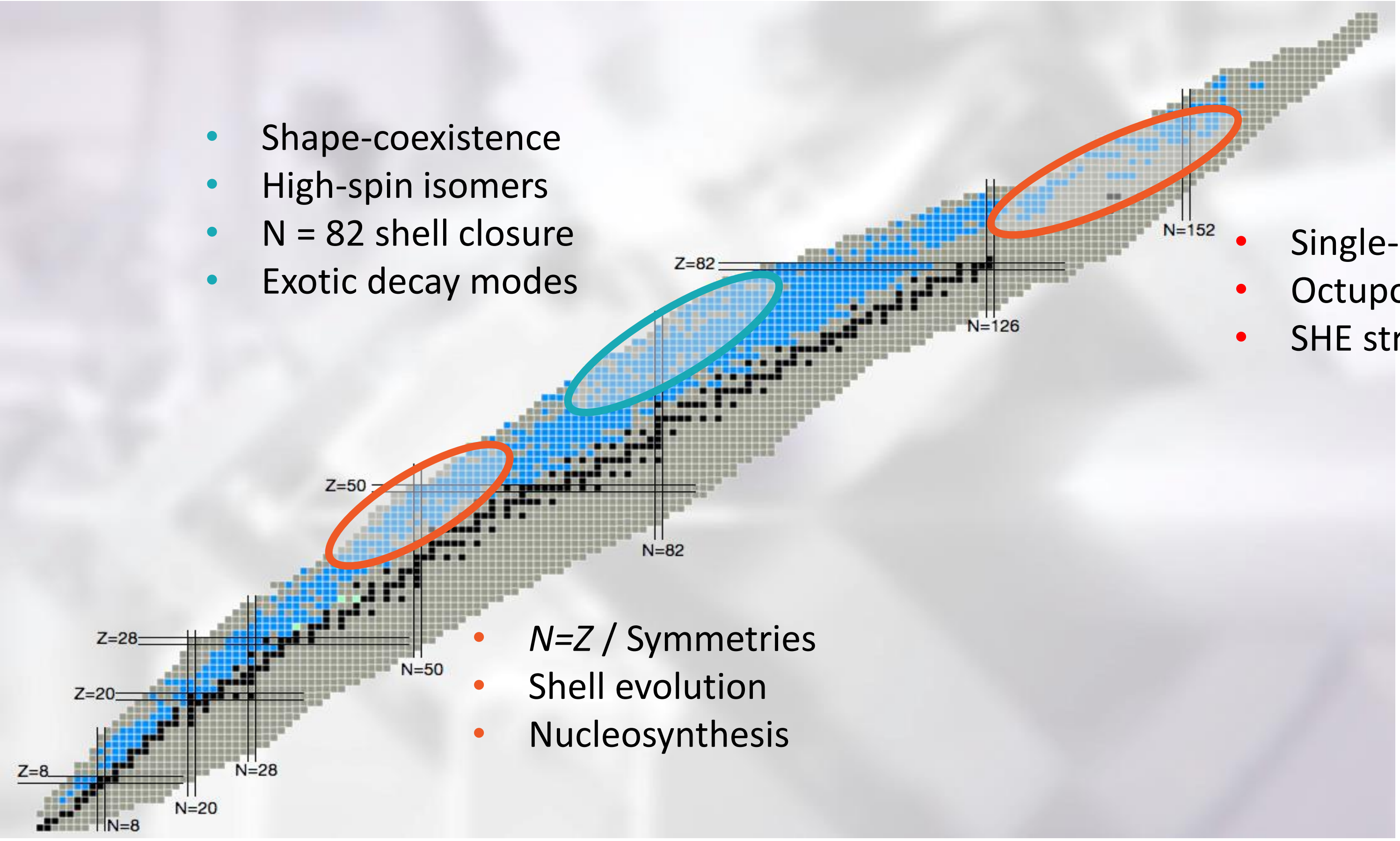
*LISE++ simulations (courtesy H. Savajols)*

# PERSPECTIVES AND ONLINE COMMISSIONING

After online commissioning, start of scientific programme:

- 11 pre-proposals/Letters of Intent prepared for workshop back in 2018, re-discussed in 2022
- Additional abstracts on neutron-deficient (heavy-)medium mass nuclei (*Z = 50* to *Z = 82*) in 2022

Main focus:




- Shape-coexistence
- High-spin isomers
- N = 82 shell closure
- Exotic decay modes

- Single-particle vs deformation
- Octupole deformation
- SHE structure (Fm, No, Lr)

- *N=Z* / Symmetries
- Shell evolution
- Nucleosynthesis

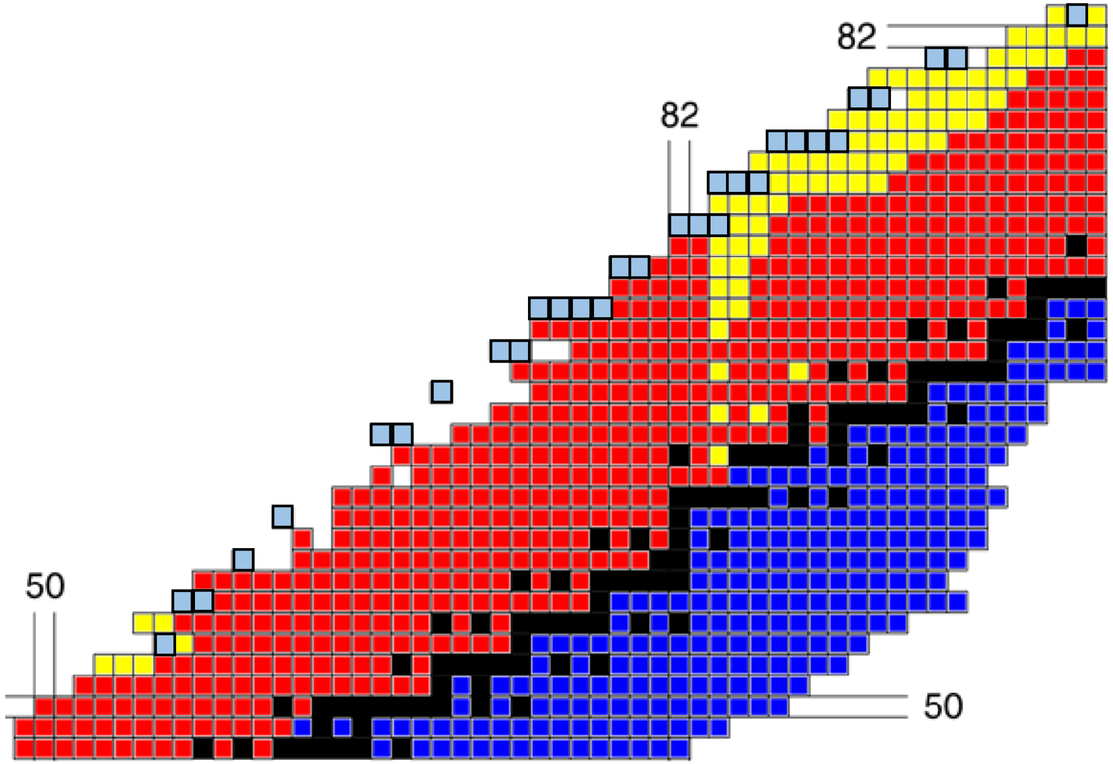
# PROTON RADIOACTIVITY AT LOW ENERGY

- **Proton dripline:**
  - Nuclear interaction is not enough to bind nucleons together
  - Nucleons are bind by coulomb and centrifugal barrier

- **Proton radioactivity:**
  - Separation energy: $S_p < 0$
  - Proton travel through the barriers by quantum tunneling effect
  - The proton has a given half-live

- **Study of the nuclear structure beyond the dripline:**
  - Unique possibility to probe nuclear structure far from stability
  - Determination of individual states for protons and neutrons

- $\sim$ **30 proton emitting nuclei are known with Z > 50:**
  - 20 proton emissions from long-lived excited states
  - From $^{109}_{53}\mathrm{I}$ (lightest) to $^{185}_{83}\mathrm{Bi}$ (heaviest)
  - For most of them the mass has not been measured directly
  - No laser spectroscopy has been done on them



# CHARACTERIZATION OF THE PROTON RADIOACTIVITY

**To fully characterize the proton radioactivity, one needs:**

- Observation of the emitted proton
- The energy released in the decay $Q_p$
- The angular momentum carried by the proton $I_p$
- The probability to find the daughter nucleus in its ground state or in a low-lying excited state
  - This probability is the so-called fine structure effect of the proton emission
  - It depends strongly on the shape of the nucleus.

**The proton radioactivity lifetime depends on these factors:**

- Deformation
- Angular momentum of the emitted proton
- Residual interaction between valence proton and neutron
  - Especially in case of odd-odd nuclei

# CHARACTERIZATION OF THE PROTON RADIOACTIVITY

**To fully characterize the proton radioactivity, one needs:**

- Observation of the emitted proton
- The energy released in the decay $Q_p$
- The angular momentum carried by the proton $I_p$
- The probability to find the daughter nucleus in its ground state or in a low-lying excited state
  - This probability is the so-called fine structure effect of the proton emission
  - It depends strongly on the shape of the nucleus.

**The proton radioactivity lifetime depends on these factors:**

- Deformation
- Angular momentum of the emitted proton
- Residual interaction between valence proton and neutron
  - Especially in case of odd-odd nuclei

**$I_p$ angular momentum:**

- Laser spectroscopy

**$Q_p$ released energy:**

- Mass measurement

**Nuclear deformation:**

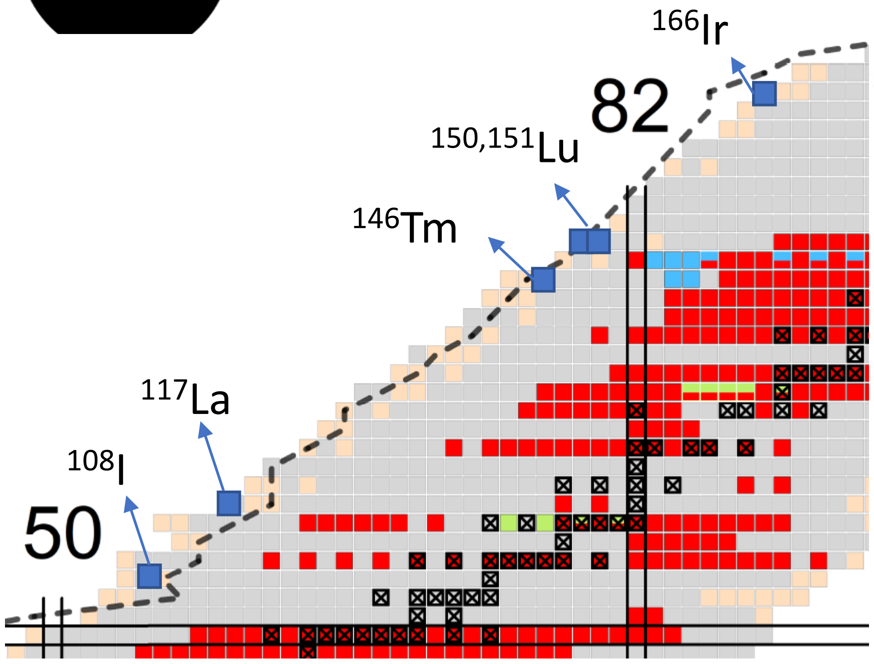
- Laser spectroscopy
- Mass spectrometry

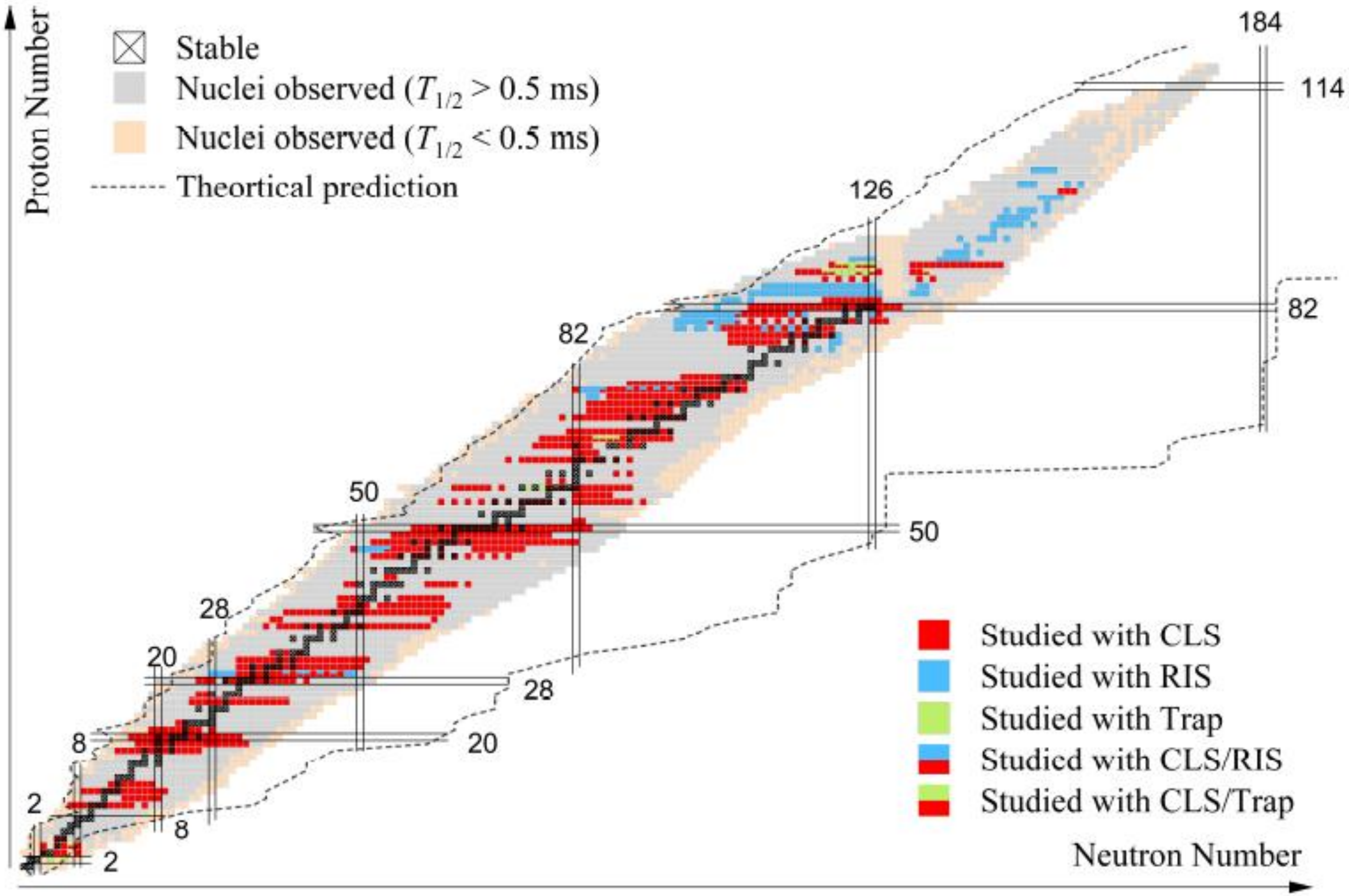
# PROTON EMITTERS ACCESSIBLE AT S3

| | | I S3 (A/Q=3) | AfterLEB | Fast LEB | I S3 (A/Q=7) | AfterLEB | After Fast LEB |
|---|---|---|---|---|---|---|---|
| 108I | 36ms | 23 | 0,00 | 0,35 | 115 | 0,01 | 1,76 |
| 117La | 23,5ms | 4,45E+00 | 0,00 | 0,04 | 22,25 | 0,00 | 0,21 |
| 146Tm | 68ms | 120 | 0,36 | 3,12 | 600 | 1,80 | 15,59 |
| 151Lu | 80,6ms | 1,10E+03 | 3,37 | 28,68 | 5500 | 16,87 | 143,39 |
| 150Lu | 45ms | 160 | 0,06 | 2,97 | 800 | 0,32 | 14,87 |
| 166Ir | 10,5ms | 190 | 0,00 | 0,28 | 950 | 0,00 | 1,42 |

Courtesy: L. Caceres

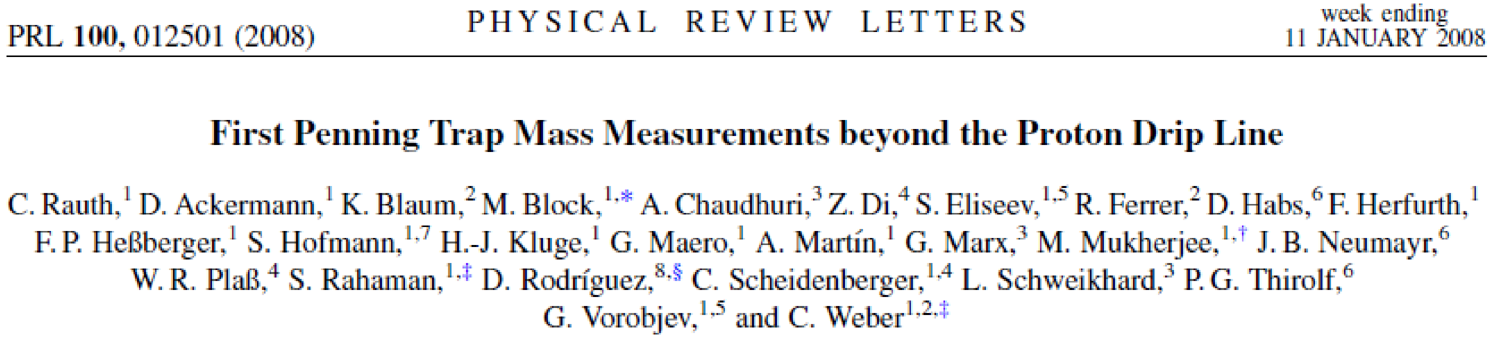
# LASER SPECTROSCOPY BEYOND THE P-DRIPLINE



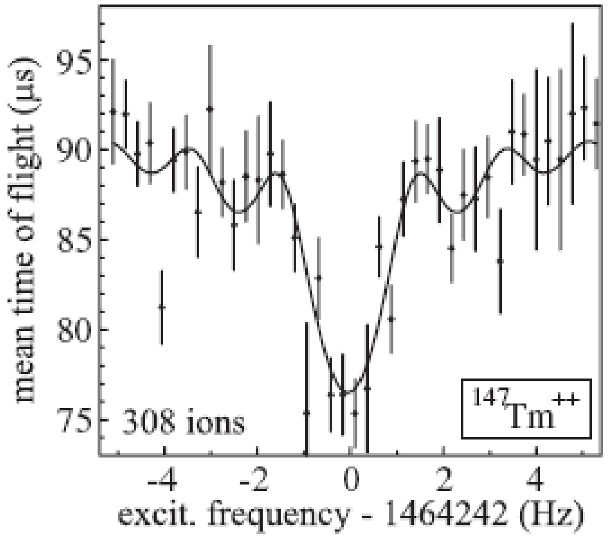

X.F. Yang, S.J. Wang, S.G. Wilkins et al., Laser spectroscopy for the study of exotic nuclei, Progress in Particle and Nuclear Physics (2022)
doi: https://doi.org/10.1016/j.ppnp.2022.104005.

# MASS SPECTROMETRY BEYOND THE P-DRIPLINE


PRL 100, 012501 (2008) PHYSICAL REVIEW LETTERS week ending 11 JANUARY 2008

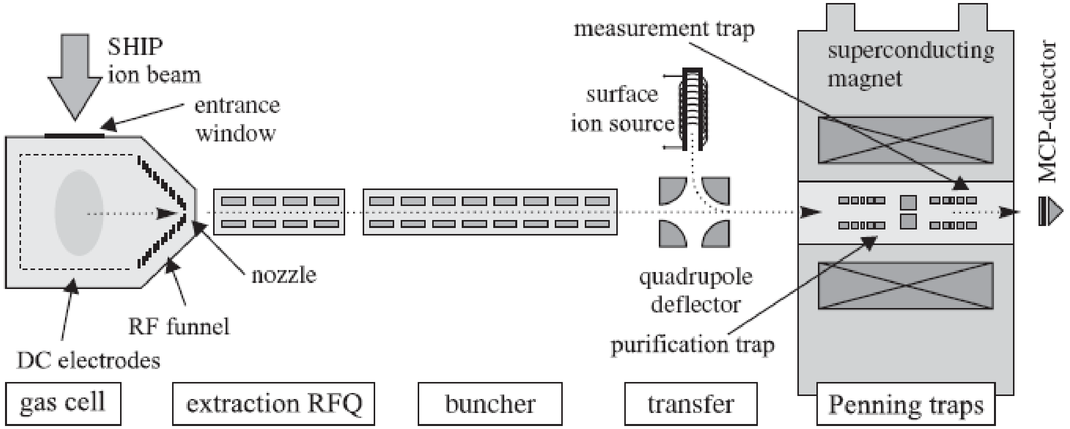
**First Penning Trap Mass Measurements beyond the Proton Drip Line**

C. Rauth,[1] D. Ackermann,[1] K. Blaum,[2] M. Block,[1,*] A. Chaudhuri,[3] Z. Di,[4] S. Eliseev,[1,5] R. Ferrer,[2] D. Habs,[6] F. Herfurth,[1] F. P. Heßberger,[1] S. Hofmann,[1,7] H.-J. Kluge,[1] G. Maero,[1] A. Martín,[1] G. Marx,[3] M. Mukherjee,[1,†] J. B. Neumayr,[6] W. R. Plaß,[4] S. Rahaman,[1,‡] D. Rodríguez,[8,§] C. Scheidenberger,[1,4] L. Schweikhard,[3] P. G. Thirolf,[6] G. Vorobjev,[1,5] and C. Weber[1,2,‡]




- Direct mass measurement of proton emitting nuclei:
  - To test mass models
  - To study competition between α decay and proton emission (also β for some cases)
  - To determine the proton drip line location

- First direct mass measurement of a proton emitter nuclei
  - $^{147}_{69}Tm$ at SHIPTRAP



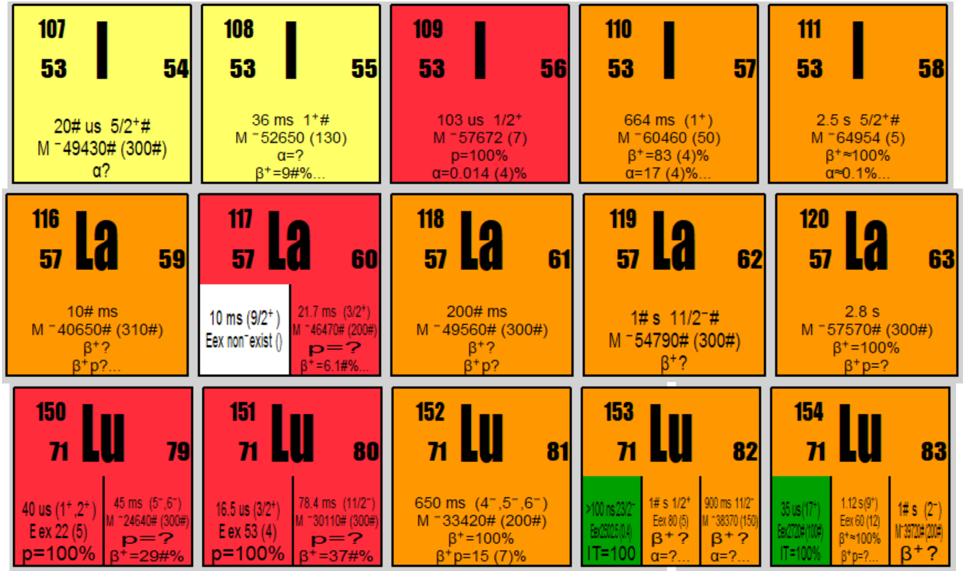
# P-BOX – THE SEARCH FOR NEW P-EMITTING NUCLEI

**Q-values:**

- Play a major role in the evaluation of half-lives
- A small change in the value of 0.1 MeV changes the half-life value of the magnitude of one to two order.

**Search for new proton emitting states:**

- Investigation of the “transition phase” in an isotopic chain
- Fine definition of the dripline




M.G. Srinivas *et al.*, NPA **1036** (2023) 122673
Z.-Q. Sheng, *et al.*, Chin. Phys. C **39** (2015) 024102
J.P. Cui, *et al.*, Phys. Rev. C **101** (2020) 014301
M. Gonçalves, et al., Phys. Lett. B **774** (2017) 14

Table 3
Comparison of evaluated half-lives using present work (PW) for the ground state to ground state transitions with that of theoretical predictions [97–99].

| Reactions | Q MeV | $\log T_{1/2}(s)$ PW | | $\log T_{1/2}(s)$ [97–99] | |
|---|---|---|---|---|---|
| $^{108}I \rightarrow ^{107}Te$ | 0.6 | 0.0912 | 1,23 s | −1.394 | 40 ms |
| $^{118}La \rightarrow ^{117}Ba$ | 0.378 | 5.568 | 1,23 s | 8.407 | 40 ms |
| $^{122}Pr \rightarrow ^{121}Ce$ | 0.526 | 2.0521 | | 3.448 | |
| $^{126}Pm \rightarrow ^{125}Nd$ | 0.759 | −0.611 | | −1.492 | |
| $^{127}Pm \rightarrow ^{126}Nd$ | 0.545 | 2.789 | | 3.795 | |
| $^{130}Eu \rightarrow ^{129}Sm$ | 1.028 | −2.996 | | −4.974 | |
| $^{133}Eu \rightarrow ^{132}Sm$ | 0.675 | 1.369 | | 1.101 | |
| $^{136}Tb \rightarrow ^{135}Gd$ | 0.918 | −1.042 | | −2.784 | |
| $^{137}Tb \rightarrow ^{136}Gd$ | 0.759 | 0.143 | | 0.047 | |
| $^{142}Ho \rightarrow ^{141}Dy$ | 0.554 | 4.88 | | 6.34 | |
| $^{148}Tm \rightarrow ^{147}Er$ | 0.489 | 1.593 | | 9.78 | |
| $^{152}Lu \rightarrow ^{151}Yb$ | 0.833 | 1.9327 | 85 s | 0.827 | 7 s |
| $^{153}Lu \rightarrow ^{152}Yb$ | 0.609 | 4.118 | | 6.384 | |
| $^{162}Re \rightarrow ^{161}W$ | 0.764 | 3.2612 | | 3.831 | |
| $^{163}Re \rightarrow ^{162}W$ | 0.706 | 3.3796 | | 5.278 | |
| $^{169}Ir \rightarrow ^{168}Os$ | 0.621 | 6.1471 | | 8.675 | |
| $^{169}Au \rightarrow ^{168}Pt$ | 1.961 | −6.064 | | −8.808 | |
| $^{170}Au \rightarrow ^{169}Pt$ | 1.474 | −1.262 | | −5.221 | |
| $^{172}Au \rightarrow ^{171}Pt$ | 0.9 | 0.6942 | | 2.411 | |
| $^{173}Au \rightarrow ^{172}Pt$ | 0.992 | 0.708 | | 0.73 | |
| $^{176}Tl \rightarrow ^{175}Hg$ | 1.25 | −1.078 | | −2.32 | |
| $^{178}Tl \rightarrow ^{177}Hg$ | 0.738 | 3.398 | | 6.866 | |
| $^{179}Tl \rightarrow ^{178}Hg$ | 0.727 | 4.462 | | 7.147 | |
| $^{184}Bi \rightarrow ^{183}Pb$ | 1.327 | 1.056 | | −2.675 | |
| [illegible] $\rightarrow ^{185}Pb$ | 1.083 | 2.03 | | 0.546 | |
| [illegible] $\rightarrow ^{186}Pb$ | 1.019 | 2.157 | | 1.579 | |

# P-BOX – THE SEARCH FOR NEW P-EMITTING NUCLEI

**Q-values:**

- Play a major role in the evaluation of half-lives
- A small change in the value of 0.1 MeV changes the half-life value of the magnitude of one to two order.

**Search for new proton emitting states:**

- Investigation of the "transition phase" in an isotopic chain
- Fine definition of the dripline

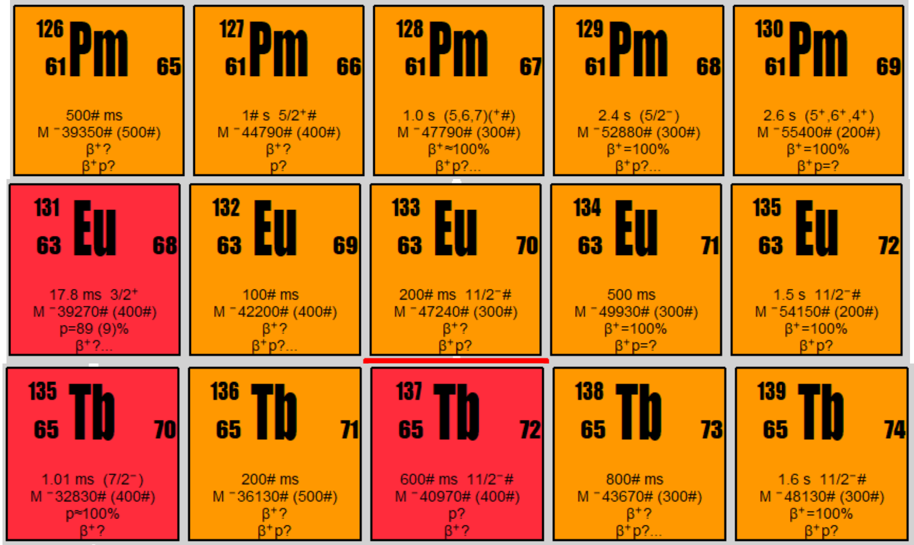



Table 3

Comparison of evaluated half-lives using present work (PW) for the ground state to ground state transitions with that of theoretical predictions [97–99].

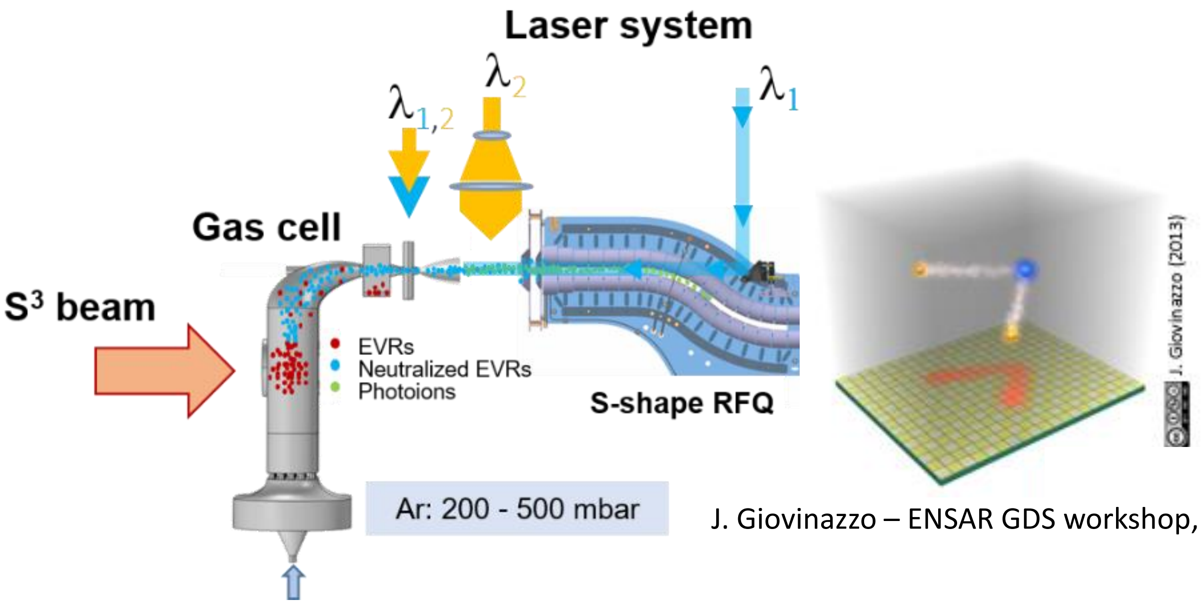
| Reactions | Q MeV | $\log T_{1/2}(s)$ PW | | $\log T_{1/2}(s)$ [97–99] | |
|---|---|---|---|---|---|
| $^{108}I \rightarrow {}^{107}Te$ | 0.6 | 0.0912 | 1,23 s | −1.394 | 40 ms |
| $^{118}La \rightarrow {}^{117}Ba$ | 0.378 | 5.568 | 1,23 s | 8.407 | 40 ms |
| $^{122}Pr \rightarrow {}^{121}Ce$ | 0.526 | 2.0521 | | 3.448 | |
| $^{126}Pm \rightarrow {}^{125}Nd$ | 0.759 | −0.611 | 245 ms | −1.492 | 32 ms |
| $^{127}Pm \rightarrow {}^{126}Nd$ | 0.545 | 2.789 | 615 ms | 3.795 | ~ 1:45 h |
| $^{130}Eu \rightarrow {}^{129}Sm$ | 1.028 | −2.996 | | −4.974 | |
| $^{133}Eu \rightarrow {}^{132}Sm$ | 0.675 | 1.369 | 23 s | 1.101 | 12 s |
| $^{136}Tb \rightarrow {}^{135}Gd$ | 0.918 | −1.042 | 90 ms | −2.784 | 1,6 s |
| $^{137}Tb \rightarrow {}^{136}Gd$ | 0.759 | 0.143 | 1,4 s | 0.047 | 1,1 s |
| $^{142}Ho \rightarrow {}^{141}Dy$ | 0.554 | 4.88 | | 6.34 | |
| $^{148}Tm \rightarrow {}^{147}Er$ | 0.489 | 1.593 | | 9.78 | |
| $^{152}Lu \rightarrow {}^{151}Yb$ | 0.833 | 1.9327 | 85 s | 0.827 | 7 s |
| $^{153}Lu \rightarrow {}^{152}Yb$ | 0.609 | 4.118 | | 6.384 | |
| $^{162}Re \rightarrow {}^{161}W$ | 0.764 | 3.2612 | | 3.831 | |
| $^{163}Re \rightarrow {}^{162}W$ | 0.706 | 3.3796 | | 5.278 | |
| $^{169}Ir \rightarrow {}^{168}Os$ | 0.621 | 6.1471 | | 8.675 | |
| $^{169}Au \rightarrow {}^{168}Pt$ | 1.961 | −6.064 | | −8.808 | |
| $^{170}Au \rightarrow {}^{169}Pt$ | 1.474 | −1.262 | | −5.221 | |
| $^{172}Au \rightarrow {}^{171}Pt$ | 0.9 | 0.6942 | | 2.411 | |
| $^{173}Au \rightarrow {}^{172}Pt$ | 0.992 | 0.708 | | 0.73 | |
| $^{176}Tl \rightarrow {}^{175}Hg$ | 1.25 | −1.078 | | −2.32 | |
| $^{178}Tl \rightarrow {}^{177}Hg$ | 0.738 | 3.398 | | 6.866 | |
| $^{179}Tl \rightarrow {}^{178}Hg$ | 0.727 | 4.462 | | 7.147 | |
| $^{184}Bi \rightarrow {}^{183}Pb$ | 1.327 | 1.056 | | −2.675 | |
| $^{186}$[illegible] $\rightarrow {}^{185}Pb$ | 1.083 | 2.03 | | 0.546 | |
| [illegible] $\rightarrow {}^{186}Pb$ | 1.019 | 2.157 | | 1.579 | |


M.G. Srinivas *et al.,* NPA **1036** (2023) 122673
Z.-Q. Sheng, *et al.,* Chin. Phys. C **39** (2015) 024102
J.P. Cui, *et al.,* Phys. Rev. C **101** (2020) 014301
M. Gonçalves, et al., Phys. Lett. B **774** (2017) 14

# P-BOX – THE SEARCH FOR NEW P-EMITTING NUCLEI

**Investigation of the dripline:**

- High precision Q-values measurements at the dripline
- Finer identification of new proton emitting nuclei
- Observation of the emitted proton
  - Clear definition of the dripline




J. Giovinazzo – ENSAR GDS workshop, Jan. 2019

**P-box:**

- TPC-like detector after the S-shape RFQ
  - Benefit from the laser selection → pure beam
  - TPC is not sensitive to $\beta^+$ → no contaminated spectra
- Gas ionization to see the proton
- No need for the full trace → detector walls made of Si detectors → proton energy measurement

**BUT:** No entrance window

- Need for simulations and preliminary studies for the detector
- **Project for a 2 years postdoc**