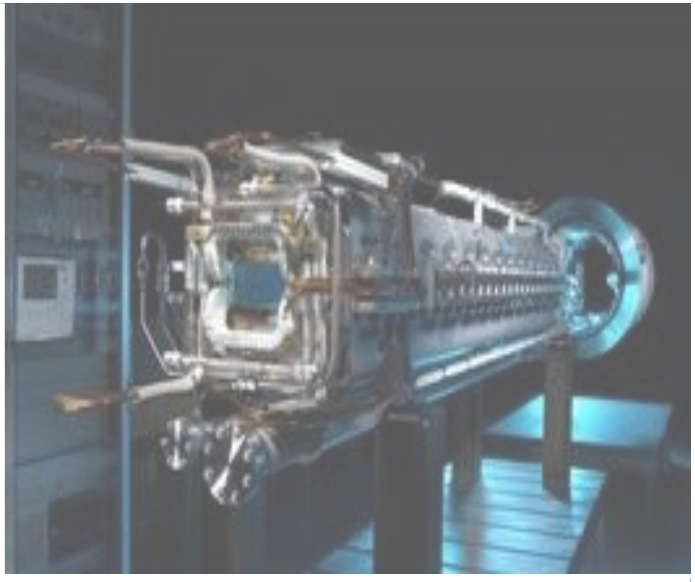




# The NUSTAR Research Programme for Early Science and First Science

Wolfram Korten
IRFU - CEA Paris-Saclay
on behalf of the NUSTAR collaboration

## GSI/FAIR Research Division Retreat

Darmstadt, Germany, February 13-14, 2023

Finland France Germany India Poland Romania Russia Slovenia Sweden UK Czech Republic

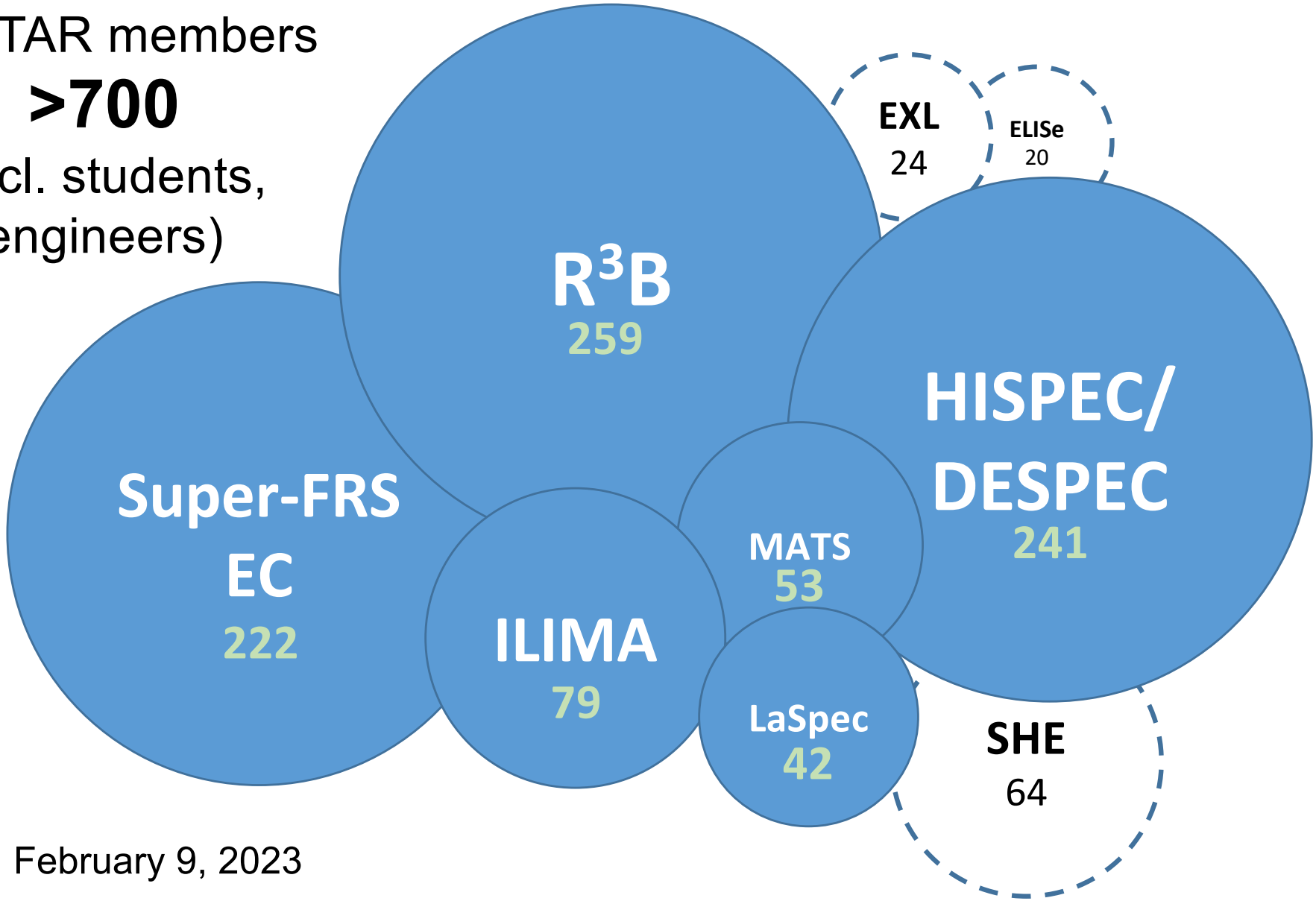
FAIR

# NUSTAR sub-collaborations and members

NUSTAR members

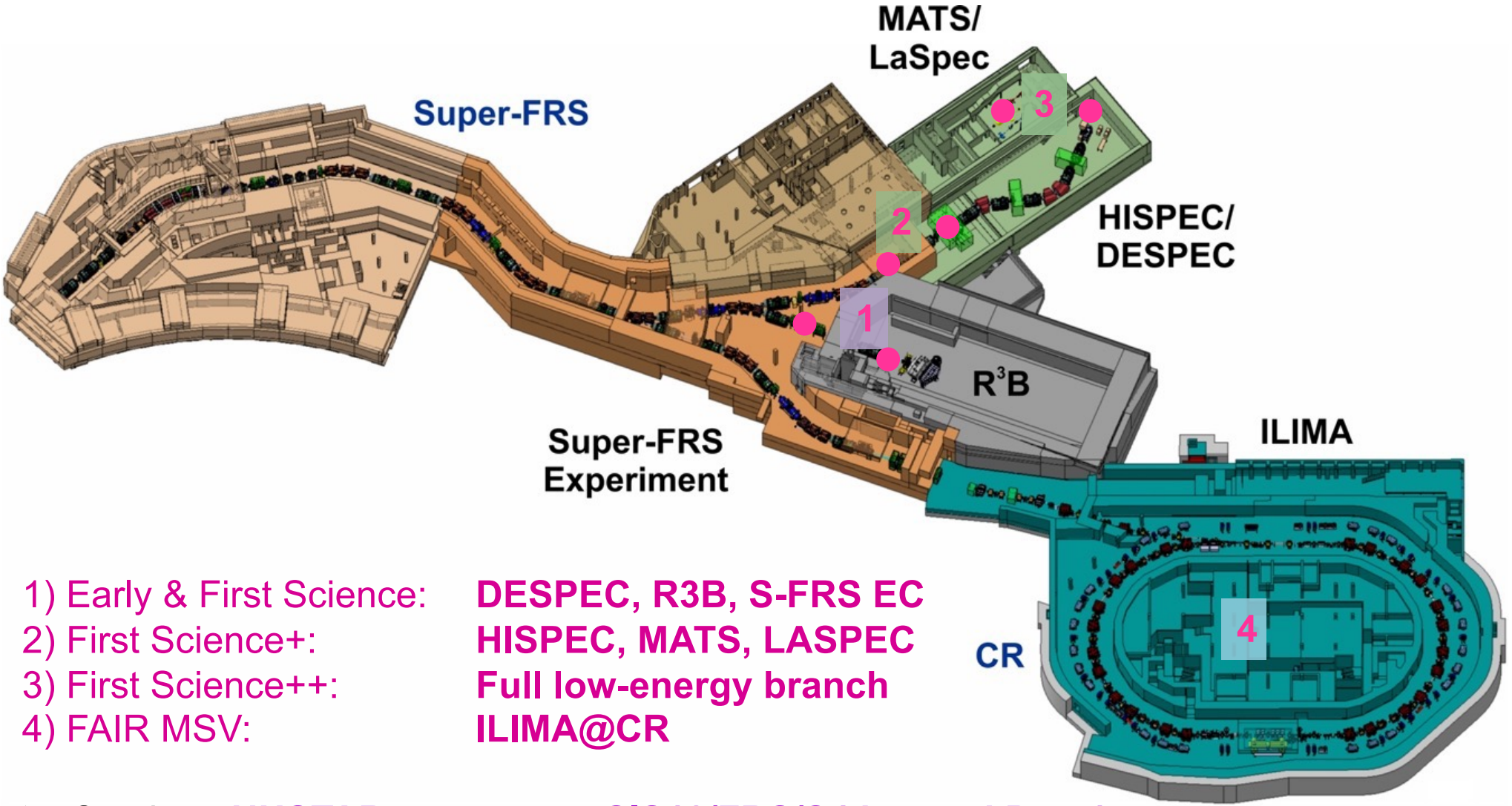
**>700**

(incl. students, engineers)




status: February 9, 2023

# The Super-FRS facility for NUSTAR@FAIR




1) Early & First Science: **DESPEC, R3B, S-FRS EC**
2) First Science+: **HISPEC, MATS, LASPEC**
3) First Science++: **Full low-energy branch**
4) FAIR MSV: **ILIMA@CR**

- Continue **NUSTAR program at SIS18/FRS/S4 beyond Day-1** in particular using ESR and Cryring **until MSV completion**

# NUSTAR requirements from Phase-0 to First Science ++

| Facility status | U beam intensity/spill* at production target (spill length ≥1s) | Luminosity [fb$^{-1}$/week] |
|---|---|---|
| **Phase-0** at GSI with **FRS** | 1...2x10$^{9}$ | **~0.1** |
| | | (x20-50) |
| **Early science** with **Super-FRS** and optimised **UNILAC/SIS18** | 5x10$^{9}$ | **2-5** |
| | | (x4) |
| **First Science+** with **SIS100** (commissioning) | 2x10$^{10}$ | **10-20** |
| | | (x10) |
| **First Science++** with **SIS100** (full intensity) | 3-4x10$^{11}$ | **>100** |

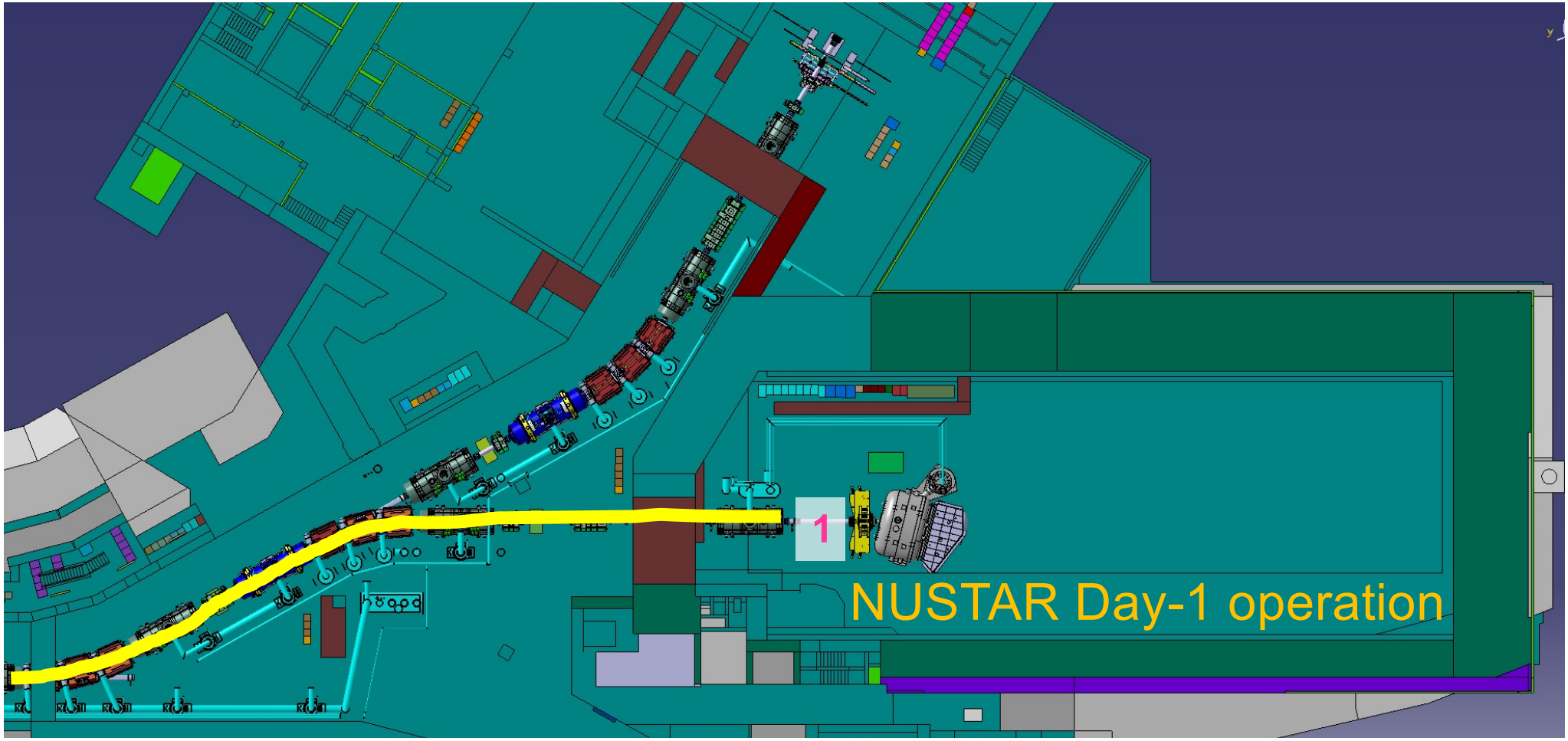
| | | | | |
|---|---|---|---|---|
| **Phase 0** | → | **Early science** | → | **Full MSV** |
| **preparation** | → | **discovery** | → | **detailed studies** |
| • **0.1 fb$^{-1}$** | → | **2-5 fb$^{-1}$** | → | **>100 fb$^{-1}$** |
| • near stability | → | more exotic | → | very exotic nuclei |

# NUSTAR requirements from Phase-0 to First Science ++

1. High intensity for beams on (Super-)FRS target, especially for $^{208}$Pb and $^{238}$U:
   1. Optimizing transmission from UNILAC to SIS (and to FRS target) up to the highest rigidities
   2. Standard operation of the pulsed Hydrogen stripper for experiments
   3. Higher spill rate: 1 per second at 100 ms slow extraction.
2. Improvement to the Micro and Macro spill structure from SIS18 in routine operation for all experiments and beams.
3. Optimizing transmission from FRS to ESR.
4. Installation of the new terminal for the $^{238}$U beam enabling 2.7Hz operation of SIS 100.

# The NUSTAR Science Programme from Early Science to First Science ++

# NUSTAR Early Science in the high-energy cave of the Super-FRS

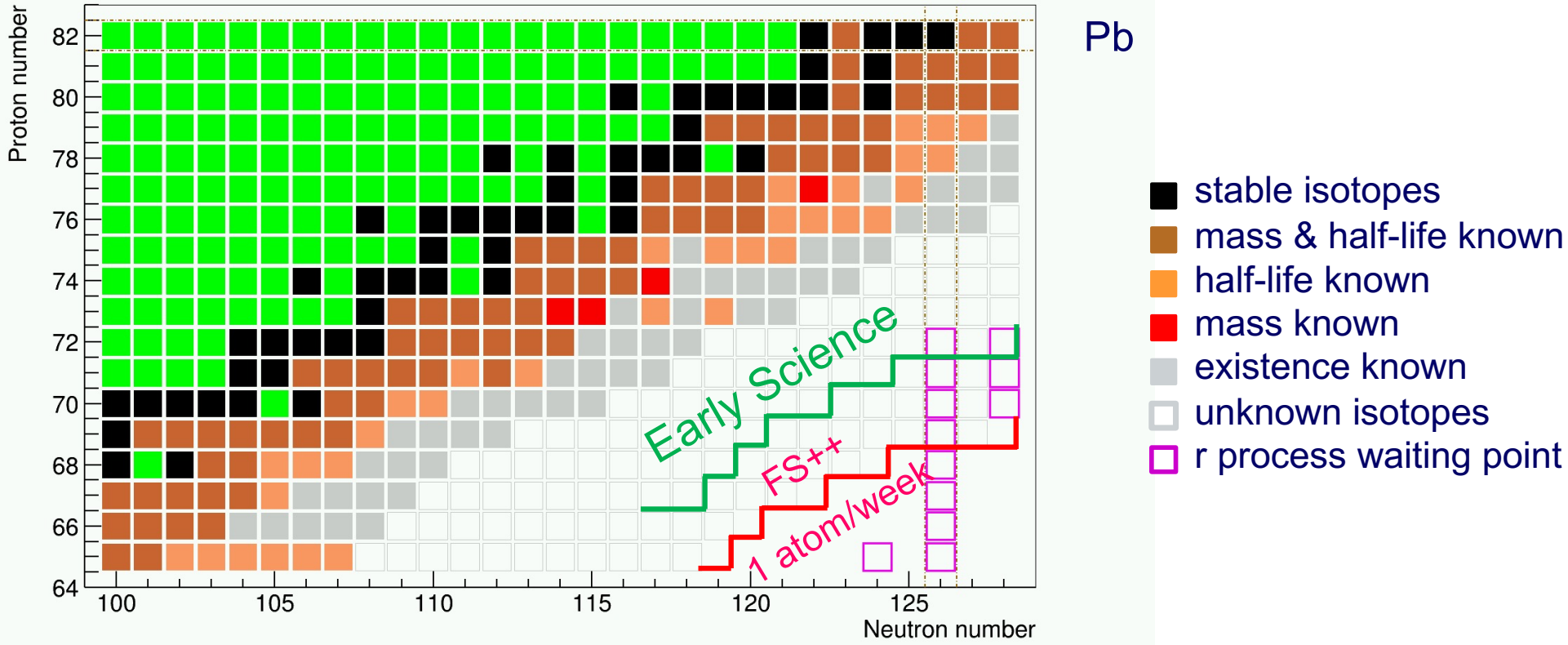



As soon as first Super-FRS beams are available (Q3/2027)

# From Early Science to First Science Plus: Search for new isotopes and their properties

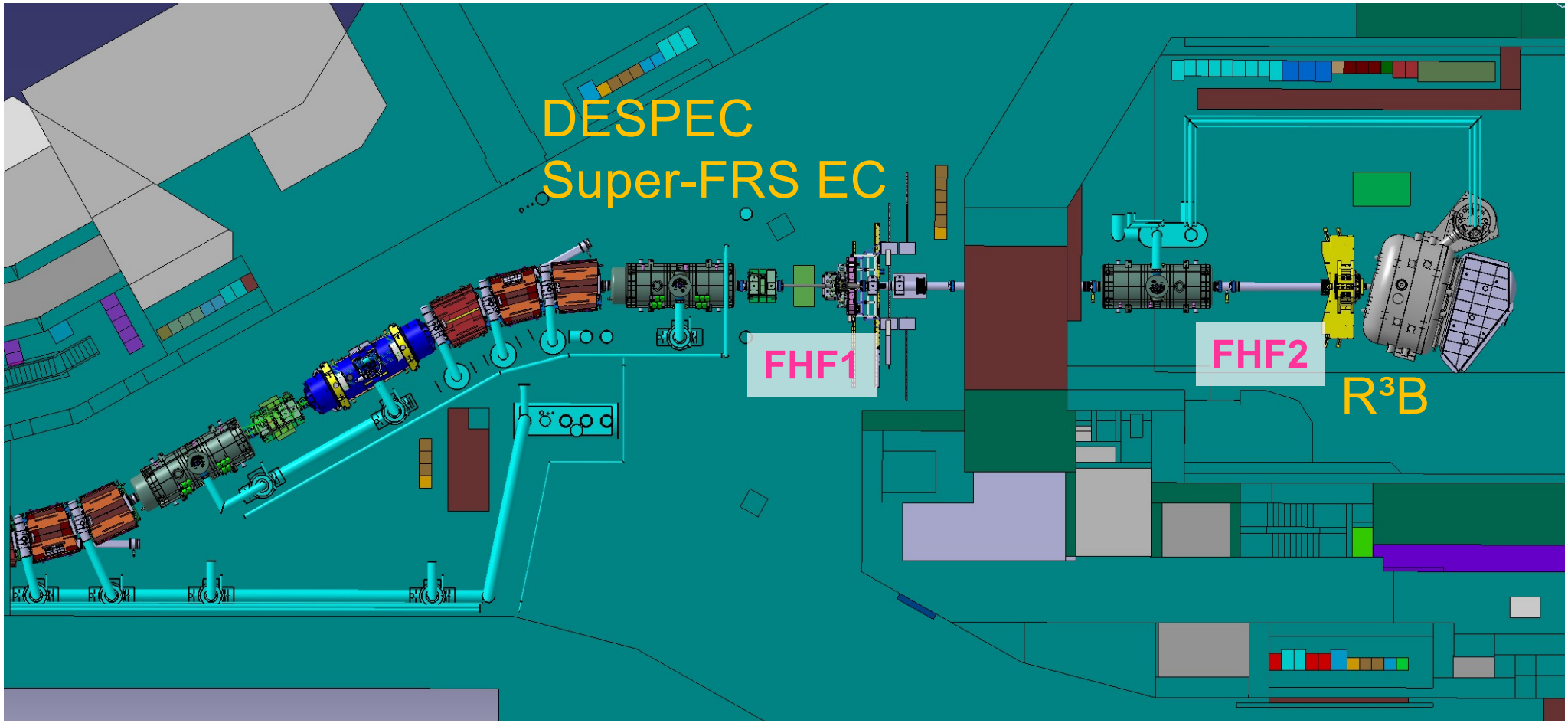
## Towards the r process waiting points at the N=126 shell closure

Understanding the **3rd r-process abundance peak** by studying the ground-state and decay properties of neutron-rich isotopes towards the **N=126 shell closure**



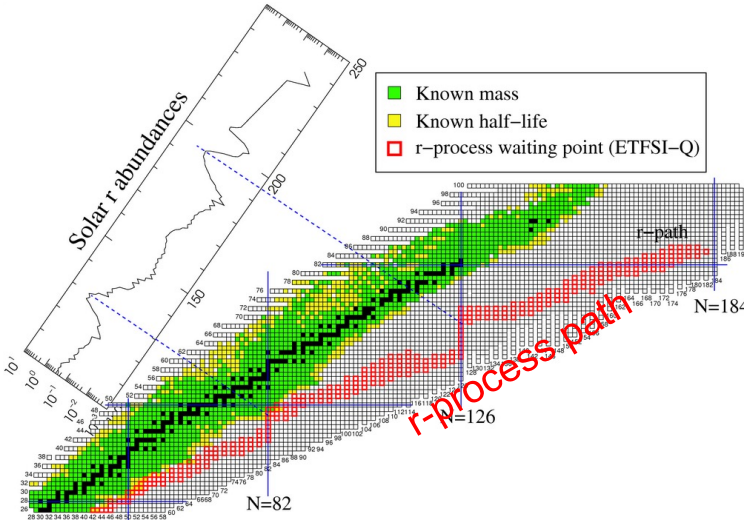

**Each improvement (FRS → Super-FRS; SIS18 → SIS100) will bring us deeper into the r-process path**

# NUSTAR early science with additional option in front of HEC




As soon as Super-FRS is fully commissioned available (2028)

# DESPEC: Complete picture of decay mechanism around N=126: multifaceted approach



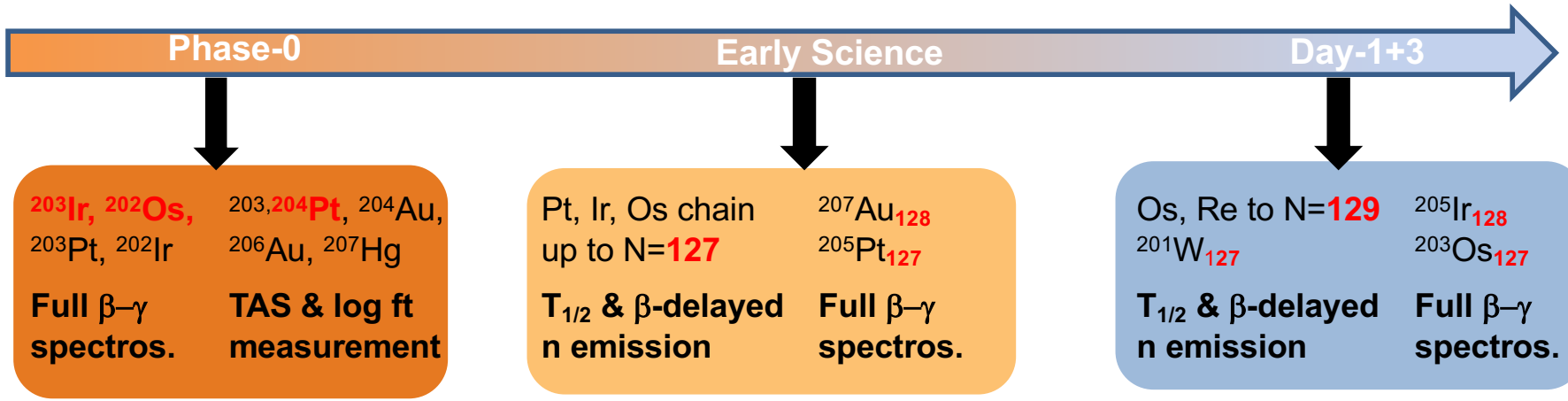

**A~195 r-process abundance peak** fed by **very neutron-rich nuclei around N=126**

- **Half-lifes and $P_n$** values
- Role of **First Forbidden β-decay transitions**
- Access to **GT strength** with Total Absorption Spectroscopy

➔ Measurements possible down to **nb level** and below

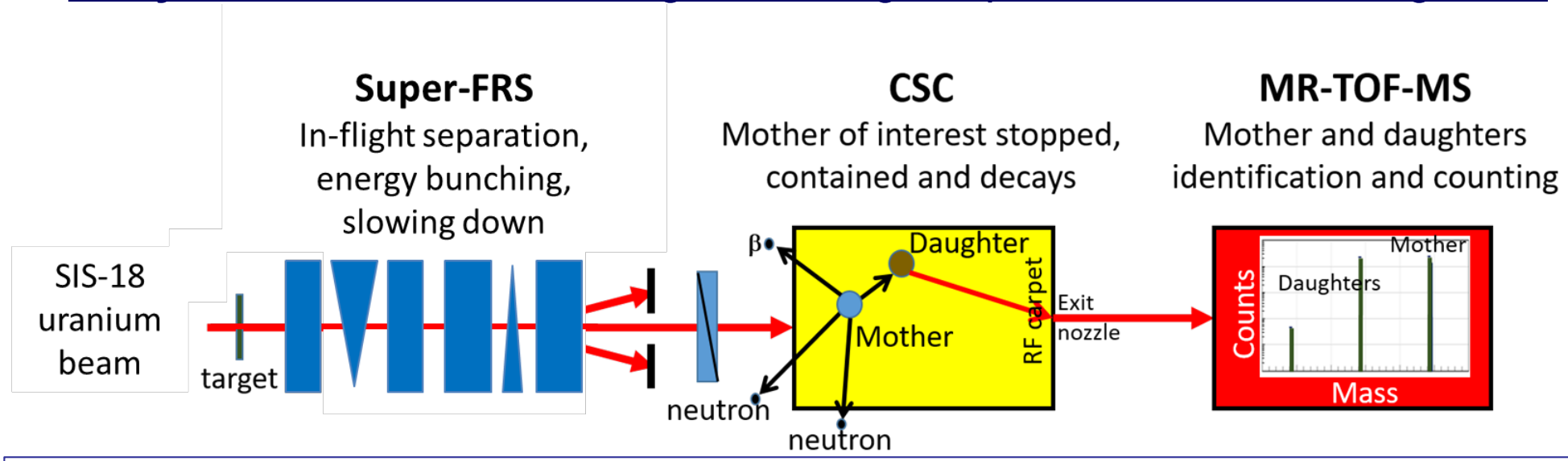
➢ **Early science**: **0.5-1 nb** accessible (**N=127 isotopes**)

➢ **First Science+**: **<0.1 nb** accessible (**N=129 isotopes**)



# Super-FRS EC: Beta-delayed single- and multi-neutron emission probabilities (Mass, $P_{xn}$, $Q_{\beta xn}$, $S_{xn}$ and $T_{1/2}$)

**Early science:** Take advantage of 2-stage separation of fission fragments



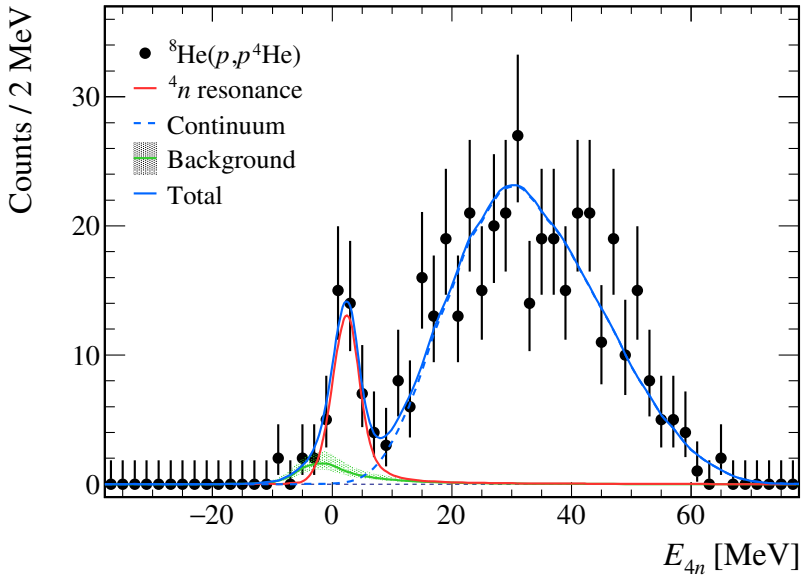

**Step-change and unique feature:**

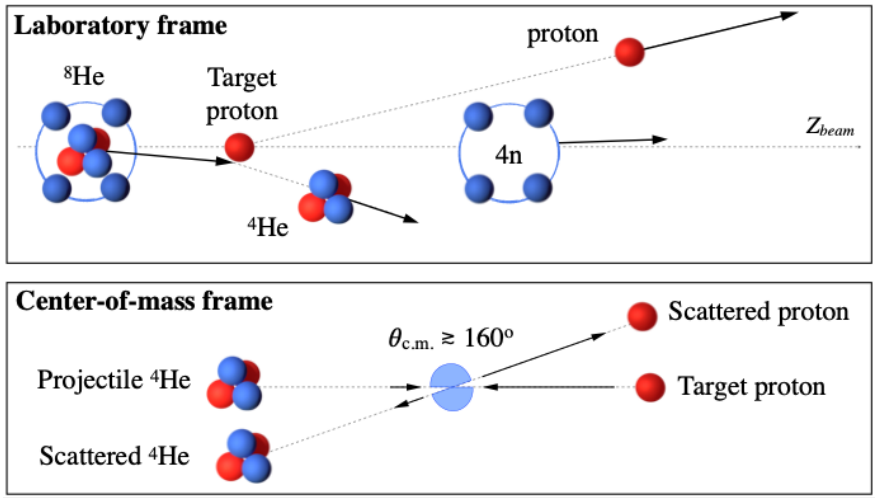
- **Two-stage separation** allow for **increased purity of fission fragment beams**
- Super-FRS provides **10x higher transmission** of fission fragments than FRS
  - **plus SIS-18 intensity increase**
- **Novel instrumentation** (**Super-FRS Ion Catcher**)
  - does not require neutron detection

Super-FRS EC

# R3B: Existence of a resonant “tetra-neutron" state

Strong **4n correlation** observed at RIKEN in a **missing-mass experiment**




The four neutrons could not be measured in coincidence

M. Duer et al., Nature 06/2022, https://doi.org/10.1038/s41586-022-04827-6

## R$^3$B@FAIR Early Science:

- High-intensity $^8$He beam at **high energy**;
- Quasi-elastic $\alpha$ knockout reaction: $^8\mathrm{H}(p,p\alpha)^4\mathrm{n}$ at large momentum transfer
- **NeuLAND**: largest multi-n detection efficiency: **all 4 neutrons** detected

→ Direct measurement of the **correlations among the neutrons** possible

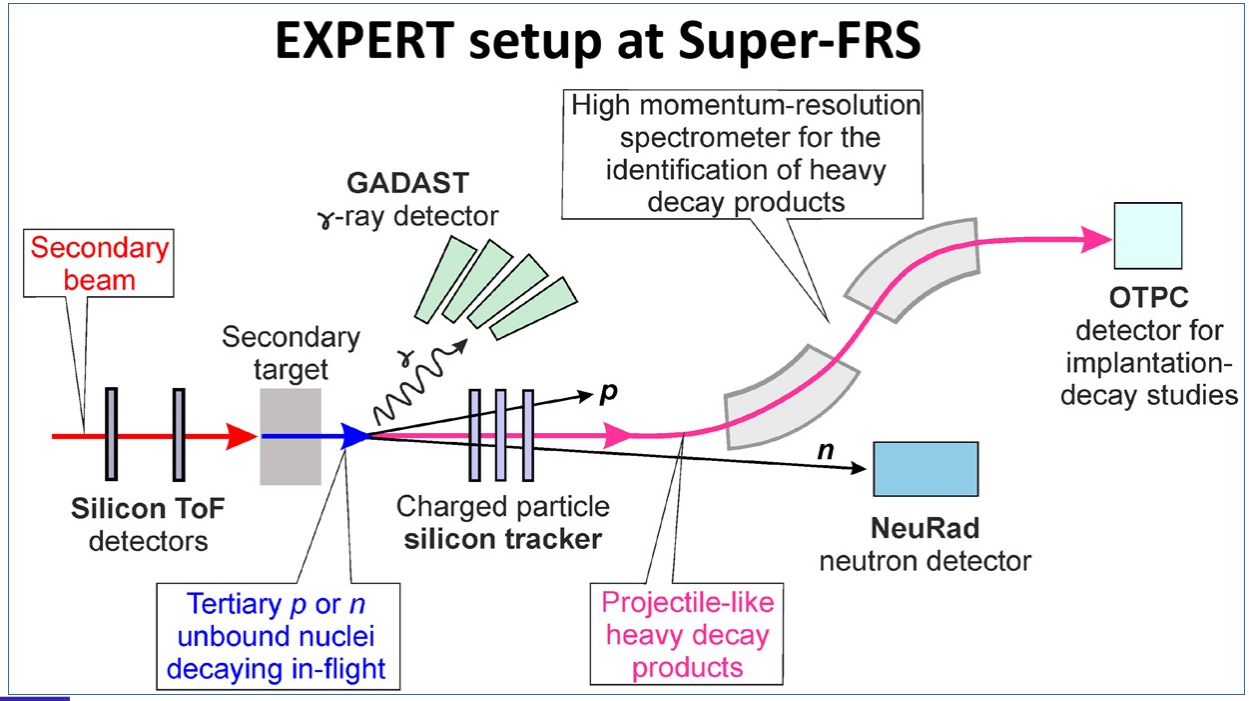
→ **Identification** of the origin of the “4n correlation” observed at RIKEN

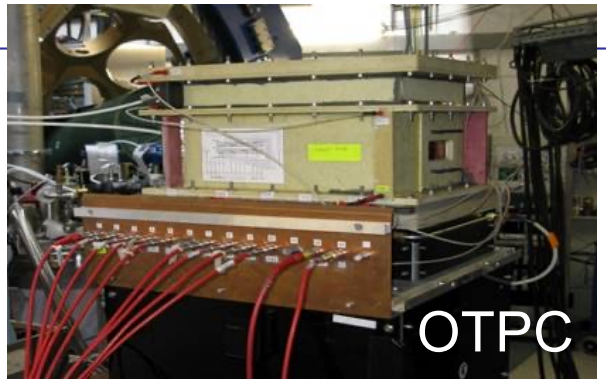
**Unraveling the structure of the elusive "tetra-neutron" state**

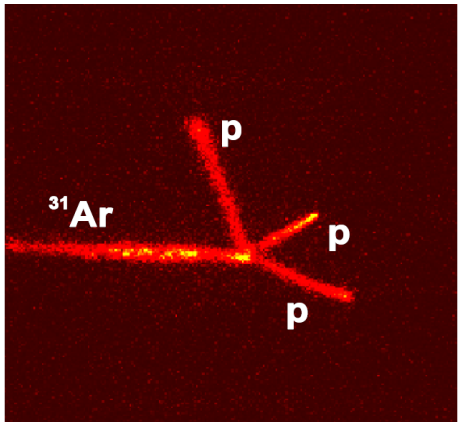
# Nuclear structure beyond the drip-lines: Search for new modes of radioactivity (4p, 2n, 4n, …),

**First Science+:** In-flight decays of medium-heavy (very exotic) drip-line nuclei

- Transmission increase (FRS → Super-FRS) is highest for light and medium heavy projectile fragments
- Ion-optical flexibility: Super-FRS is used as separator (pre-separator) and analyzer (main separator)



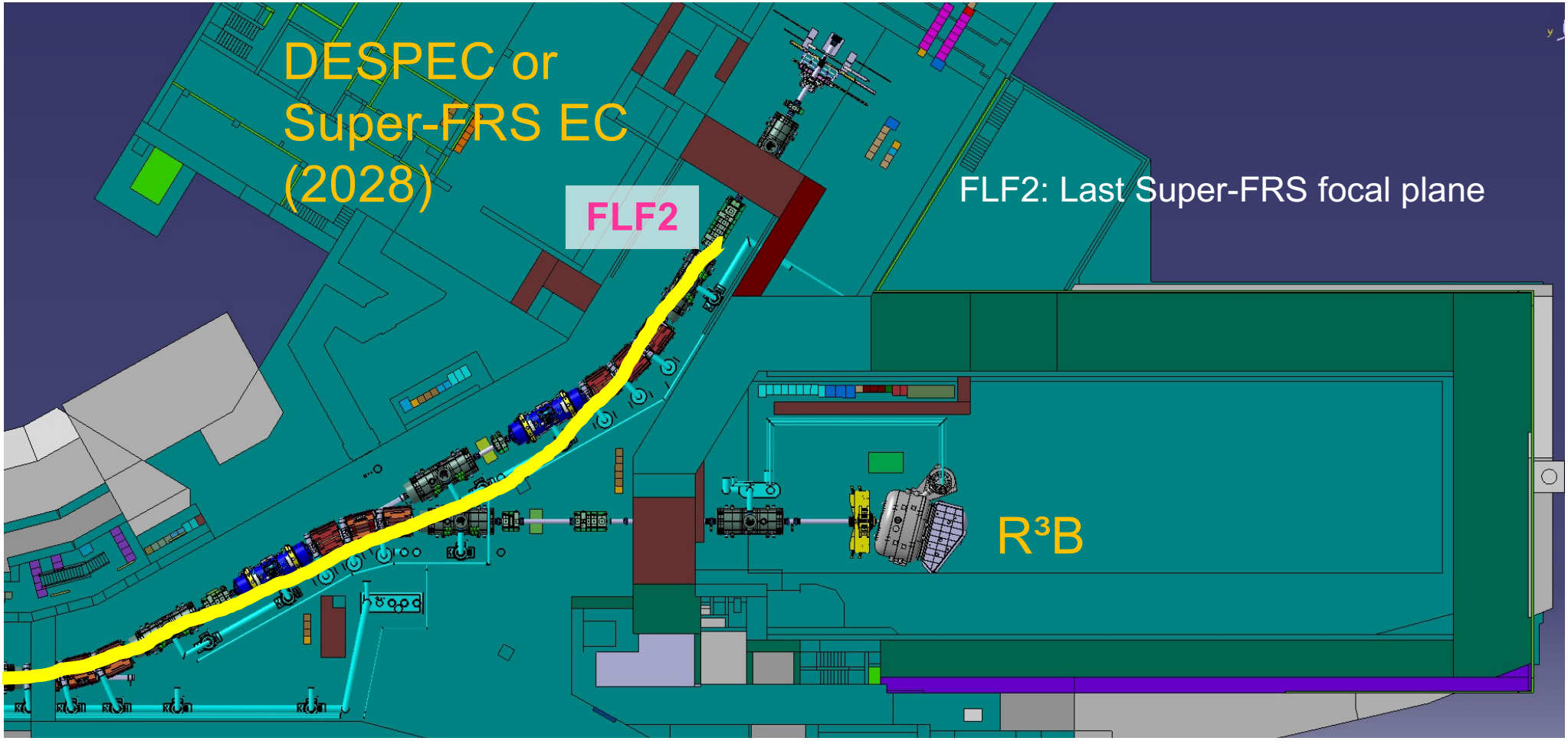




A. Lis et al., PRC 91 (2015) 064309

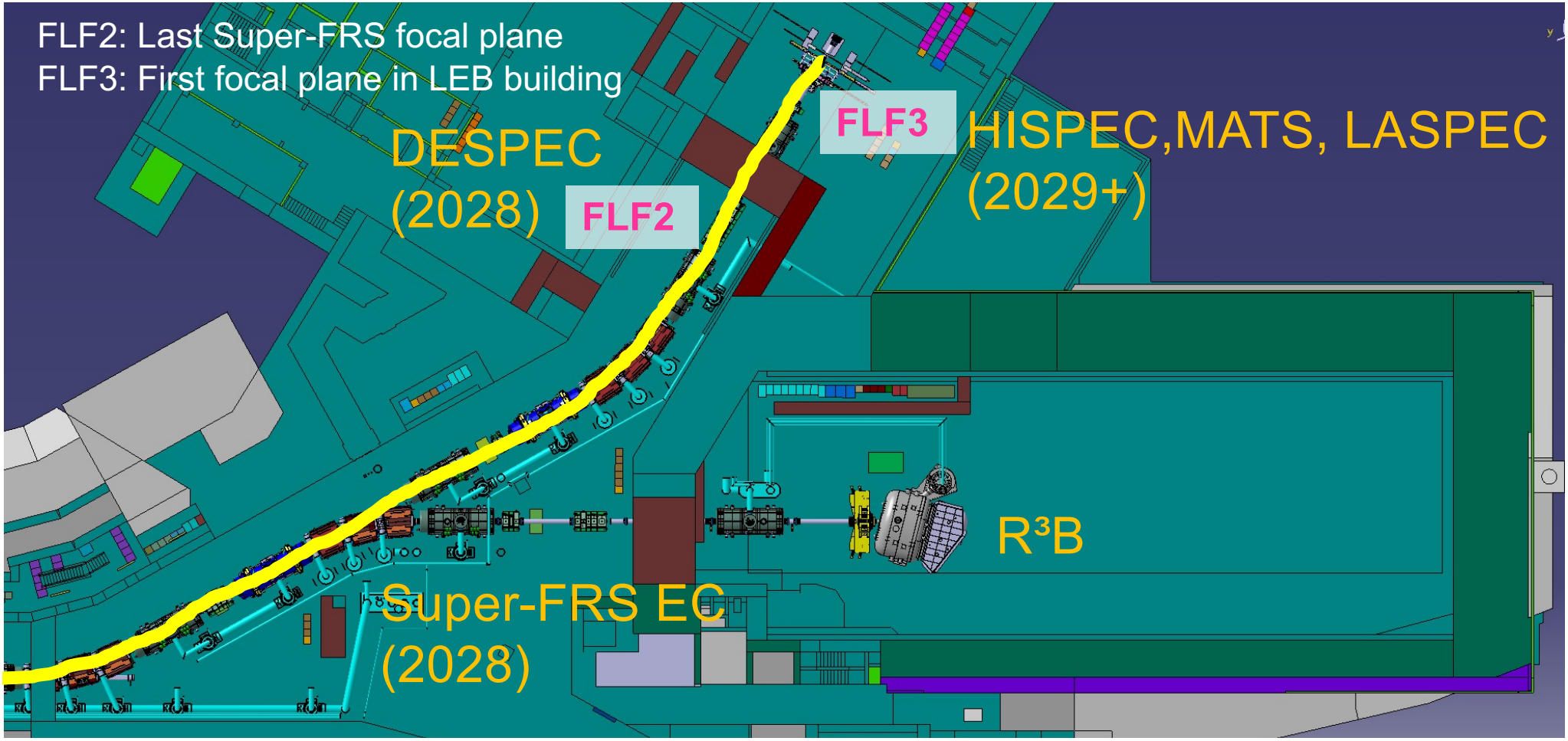
Super-FRS EC

# NUSTAR First Science++ allows two separate areas in the Super-FRS building (FLF2)




Will allow **full parallel operation** of DESPEC, S-FRS EC, R3B:
No loss of operation time for set-up changes if shielded by movable wall

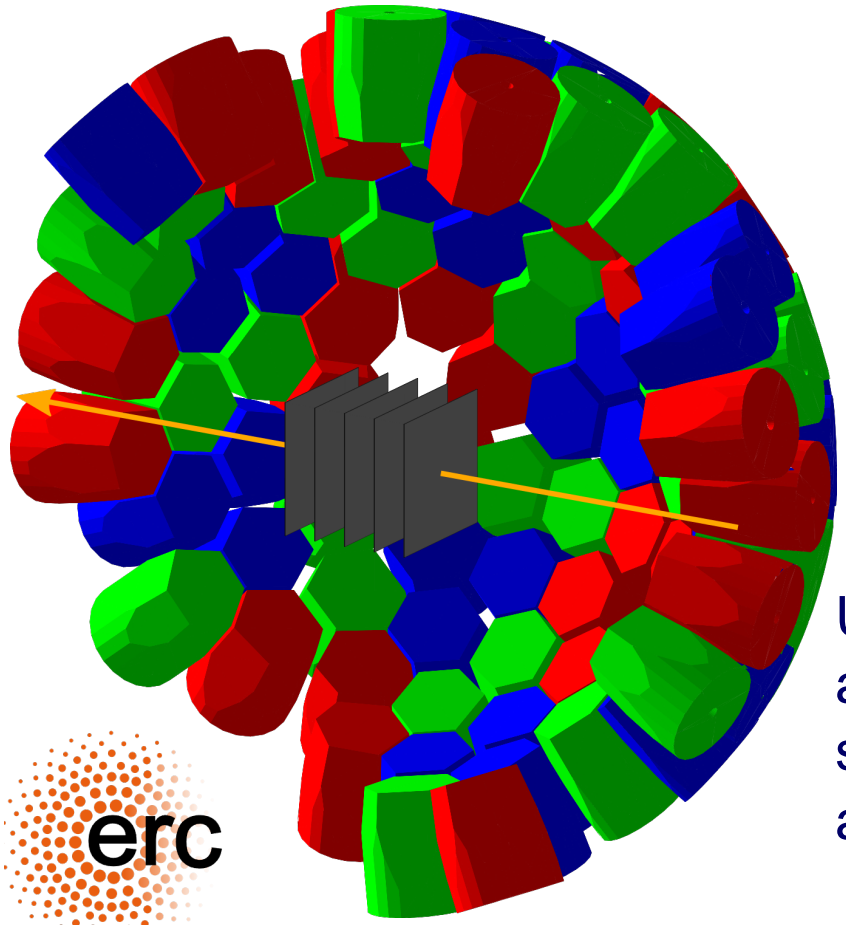
# NUSTAR First Science Plus with additional option(s) in the S-FRS low-energy branch



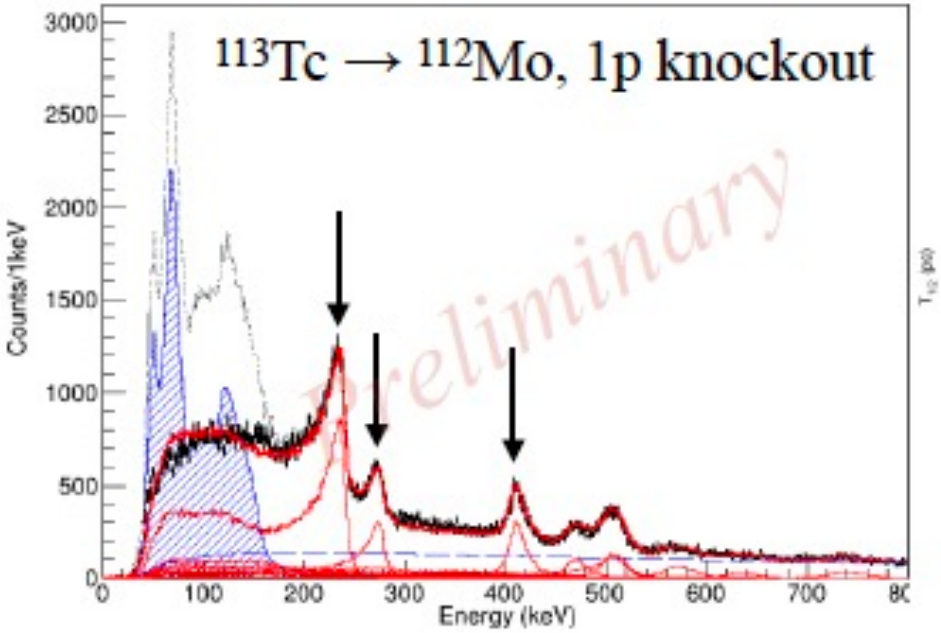

Will allow **full parallel operation** of **HISPEC**, S-FRS EC, R3B:
No loss of operation time for set-up changes

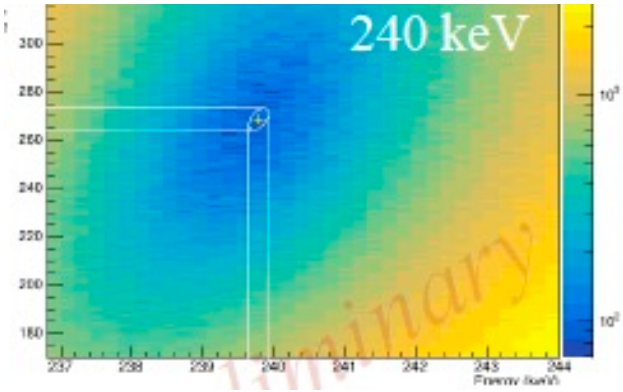
# HISPEC: Picosecond lifetime measurements of exotic nuclei with AGATA

LISA: Compact array of **active target detectors** inside **AGATA** to determine interaction position



Pilot experiment: Picosecond lifetimes with the Miniball Ge detectors at RIBF

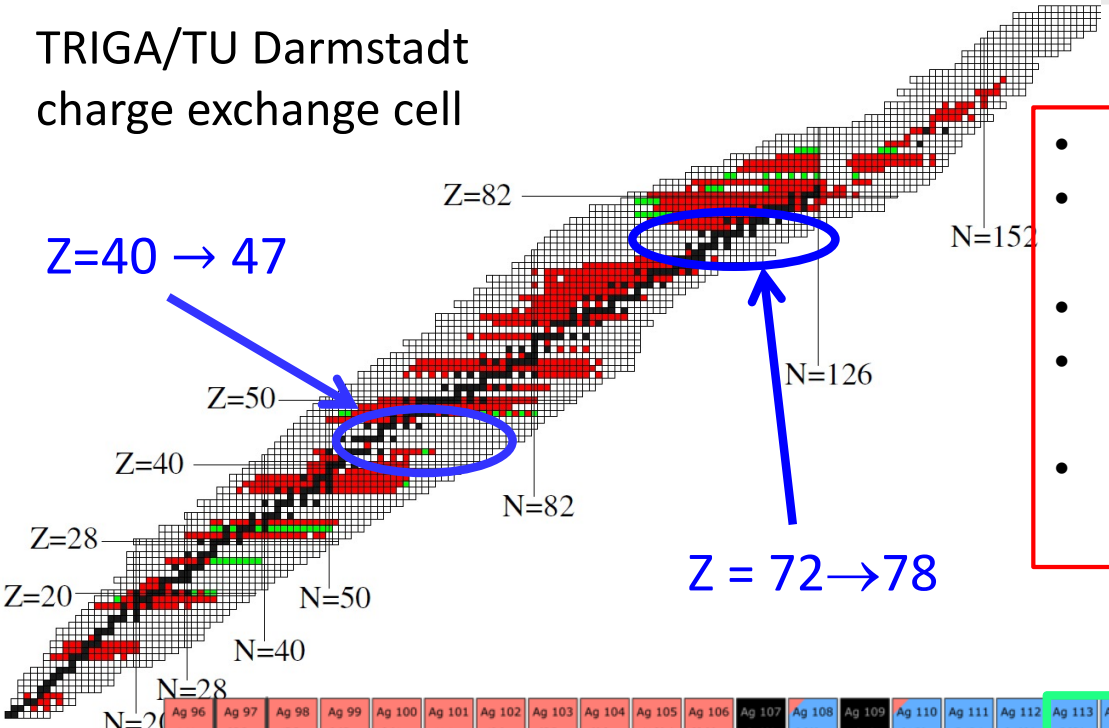


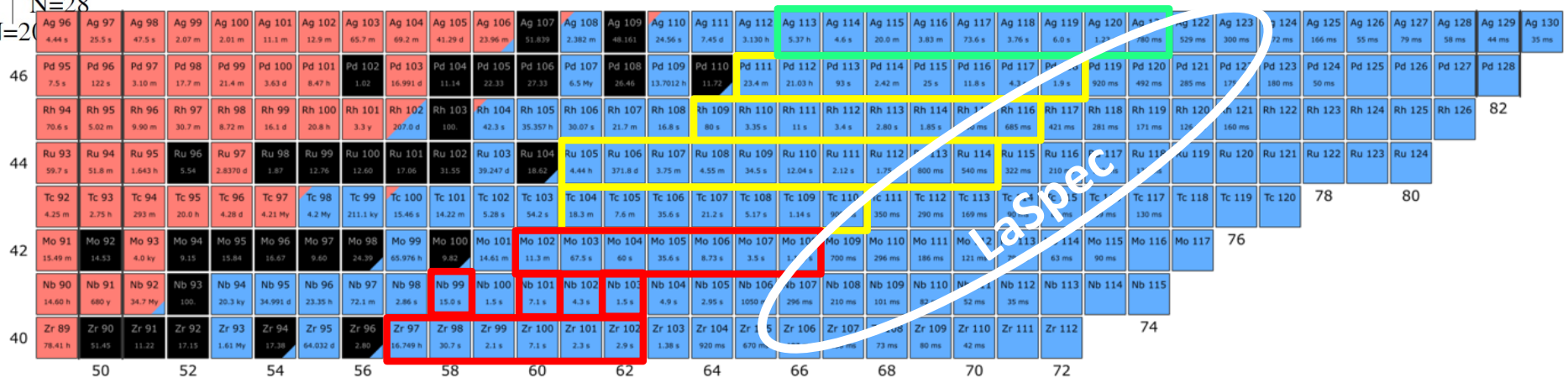

Unknown energies and lifetimes simultaneously accessible

# MATS& LASPEC: mass and laser spectroscopy on refractory elements

TRIGA/TU Darmstadt
charge exchange cell




- Spectroscopy on $^{113\text{-}121}$Ag at JYFL (green)
- Fission yield predictions >5000 ions/s at JyFL (yellow)
- Zr, Nb, Mo from JYFL (red)
- Day-1+3y: Spectroscopy of $^{106}$Zr and beyond and in the Pt region across N=126 shell closure
- Day-1+8y: CRIS developments lead to 1-2 isotopes further



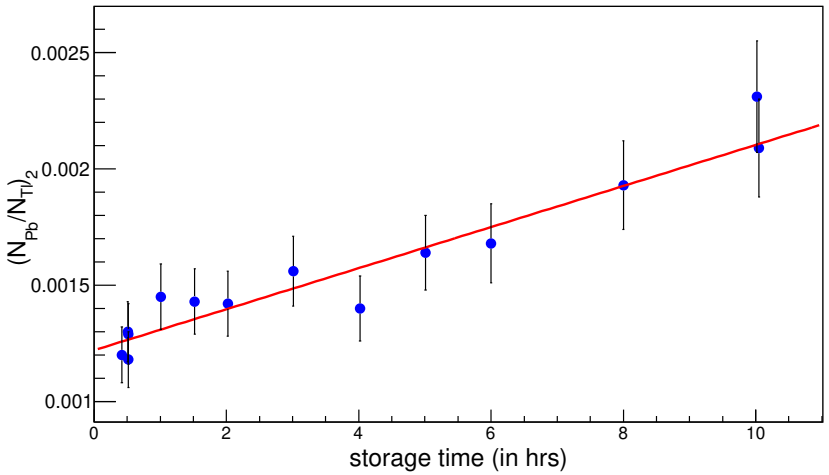
# ILIMA Early Science (still at the ESR): Rare decays (limited to nuclei near stability)

## Measurement of the bound-state beta decay of bare $^{205}$Tl ions

### Lifetime of Highly-Charged Ions

- Accumulation and cooling of secondary beam from FRS
- Long storage times
- Gas jet stripper
- In-ring Particle detector


$^{205}$Tl: Stable in neutral atoms
Radioactive in bare ions

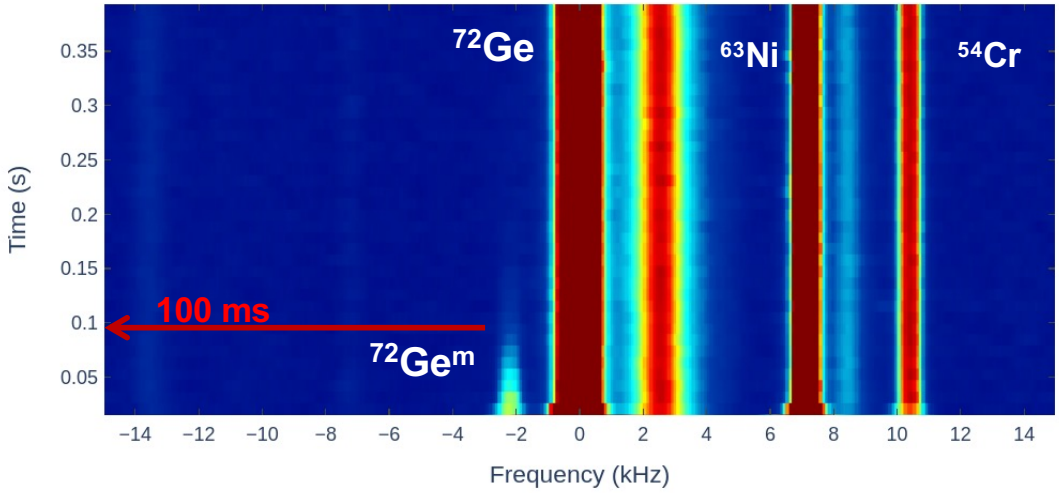



- LOREX project: new solar neutrino detector
- Cosmochronometer of the s-process

## Search for the nuclear two-photon decay in fully-stripped ions

### Isochronous Schottky Mass Spectroscopy

- Mass resolution ~$10^{-6}$
- High precision isochronous condition
- Single-ion sensitivity of new Schottky det.



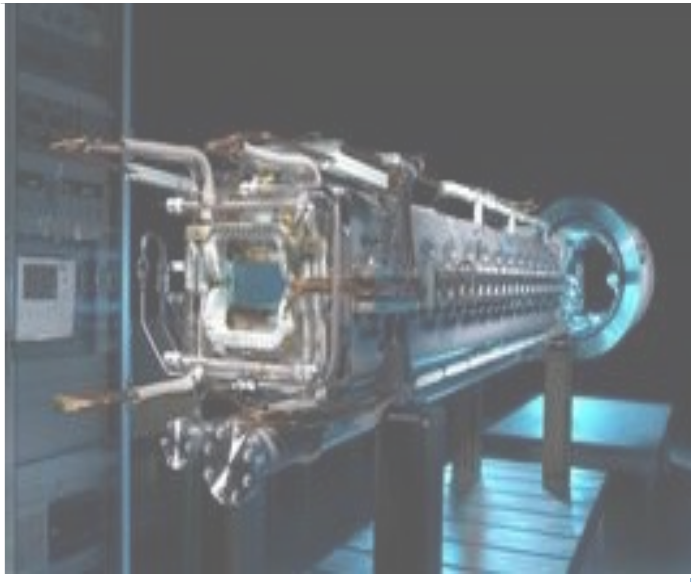

$^{72}$Ge$^{m}$: $0^+ \rightarrow 0^+$ (single $\gamma$ emission forbidden)

New tool to search for $0^+$ isomers in exotic nuclei
$0^+ \rightarrow 0^+$ decays as laboratory for BSM physics

# NUSTAR Perspectives up to FS++

| NUSTAR Experiment | | Originally planned FAIR location | Operable at planned FAIR phase/stage | Currently operated |
|---|---|---|---|---|
| AIC | *anti-proton Ion collisions with rare isotopes* | Beyond MSV | none | no |
| **DESPEC** | *$\gamma$-, $\beta$-, $\alpha$-, p-, n-decay spectroscopy* | LEB Cave | (ES/FS) | FRS |
| ELISE | *elastic, inelastic, and quasi-free e--A scattering* | Beyond MSV | none | no |
| EXL | *light-ion scattering reactions in invere kinematics* | Beyond MSV | (MSV?)* | no |
| **HISPEC** | *in-beam $\gamma$ spectroscopy at low and intermediate energy* | LEB Cave | (FS?)FS++* | (ext.) |
| **ILIMA** | *masses and lifetimes of nuclei in ground and isomeric states* | MSV | CR | ESR |
| **LASPEC** | *Laser spectroscopy* | LEB MATS / LASPEC Area | (FS?)FS++* | (ext.) |
| **MATS** | *in-trap mass measurements and decay studies* | LEB MATS / LASPEC Area | (FS?)FS++* | (ext.) |
| **R3B** | *kinematically complete reactions at high beam energy* | HEB Cave | ES | FRS |
| **Super-FRS EC** | *RIB production, identification and spectroscopy* | Super-FRS and Caves | (ES/FS) | FRS |
| **SHE** | *Nuclear physics and chemistry of super-heavy elements* | n.a. | n.a. | UNILAC / (CW-Linac) |

* too late if >2030



# Thank you very much for your attention

Finland France Germany India Poland Romania Russia Slovenia Sweden UK Czech Republic

FAIR