

NUSTAR Physics Opportunities

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GSI/FAIR
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Theme Meeting on FAIR Science, Chandigarh, 24 April 2025



Finland



France



Germany



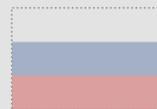
India



Poland



Romania



Russia



Slovenia



Sweden



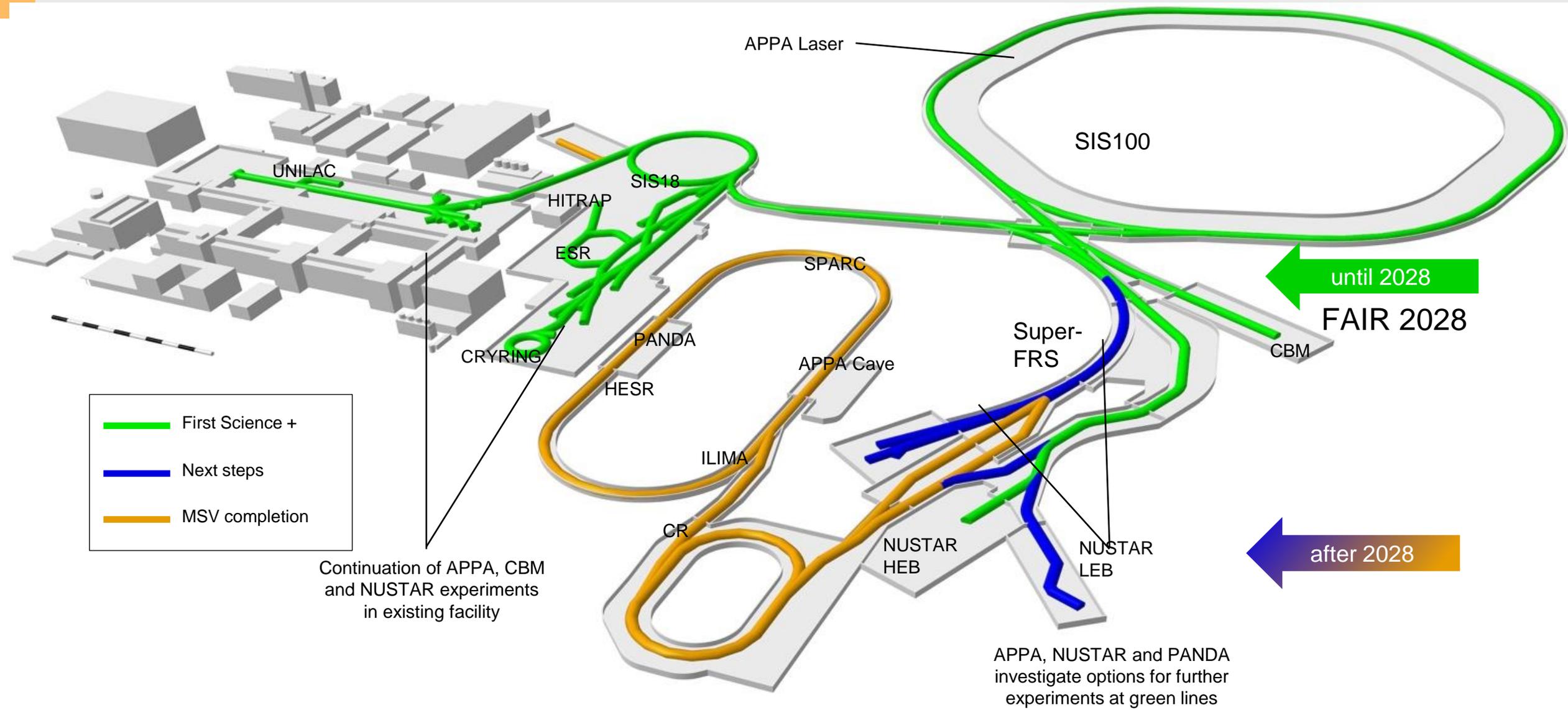
UK



Czech Republic



THE GSI/FAIR facility



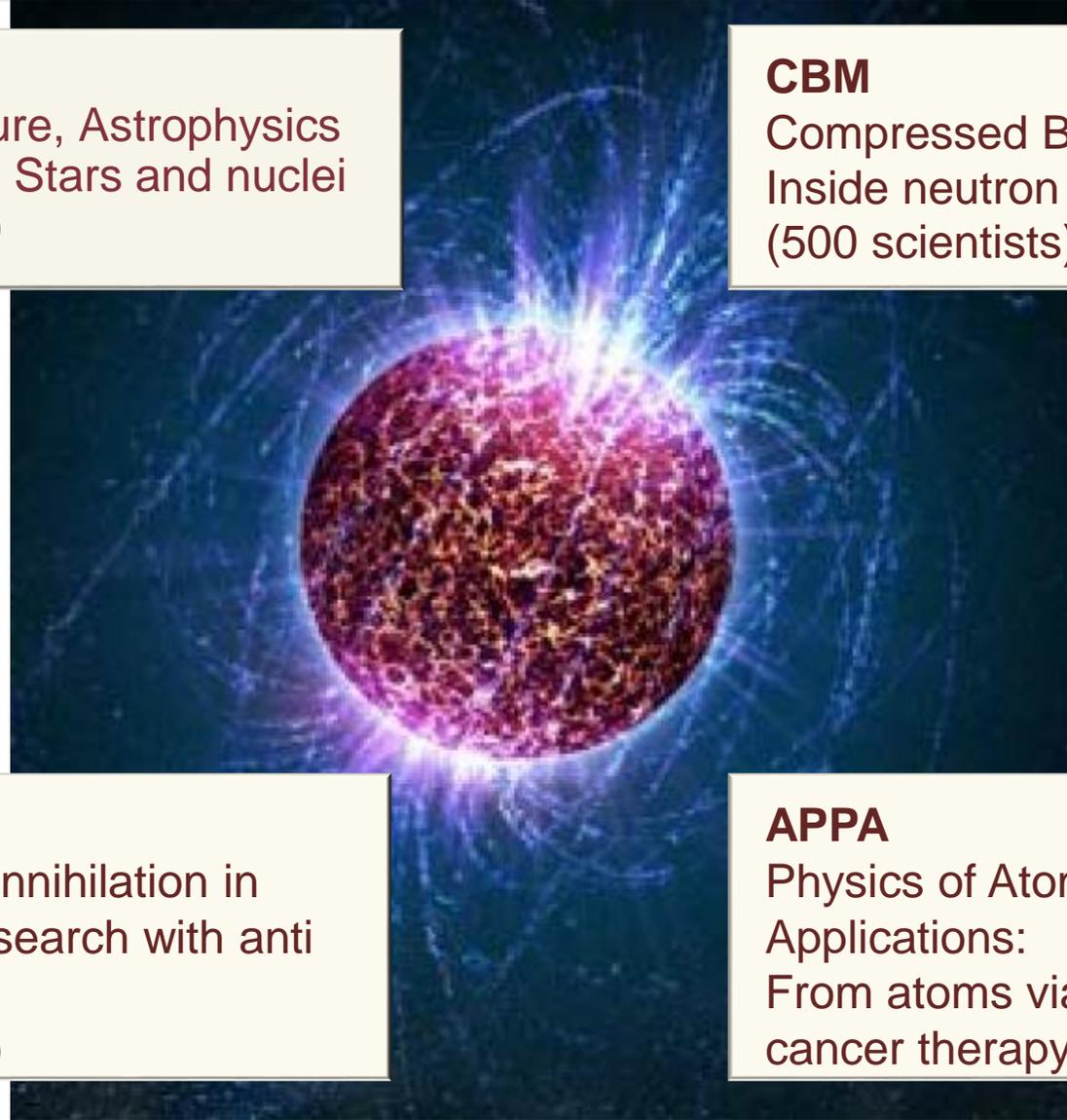
FAIR Scientific Pillars

NUSTAR

Nuclear Structure, Astrophysics and Reactions: Stars and nuclei (900 scientists)

CBM

Compressed Baryonic Matter: Inside neutron stars (500 scientists)



PANDA

Antiprotonen-Annihilation in Darmstadt: Research with anti matter (500 scientists)

APPA

Physics of Atoms, Plasma and Applications: From atoms via planets to cancer therapy (720 scientists)

What are the limits for existence of nuclei?

Where are the proton and neutron drip lines situated?

Where does the nuclear chart end?

How does the nuclear force depend on varying proton-to-neutron ratios?

What is the isospin dependence of the spin-orbit force?

How does shell structure change far away from stability?

How to explain collective phenomena from individual motion?

What are the phases, relevant degrees of freedom, and symmetries of the nuclear many-body system?

How are complex nuclei built from their basic constituents?

What is the effective nucleon-nucleon interaction?

How does QCD constrain its parameters?

Which are the nuclei relevant for astrophysical processes and what are their properties?

What is the origin of the heavy elements?

The Universe in the Lab

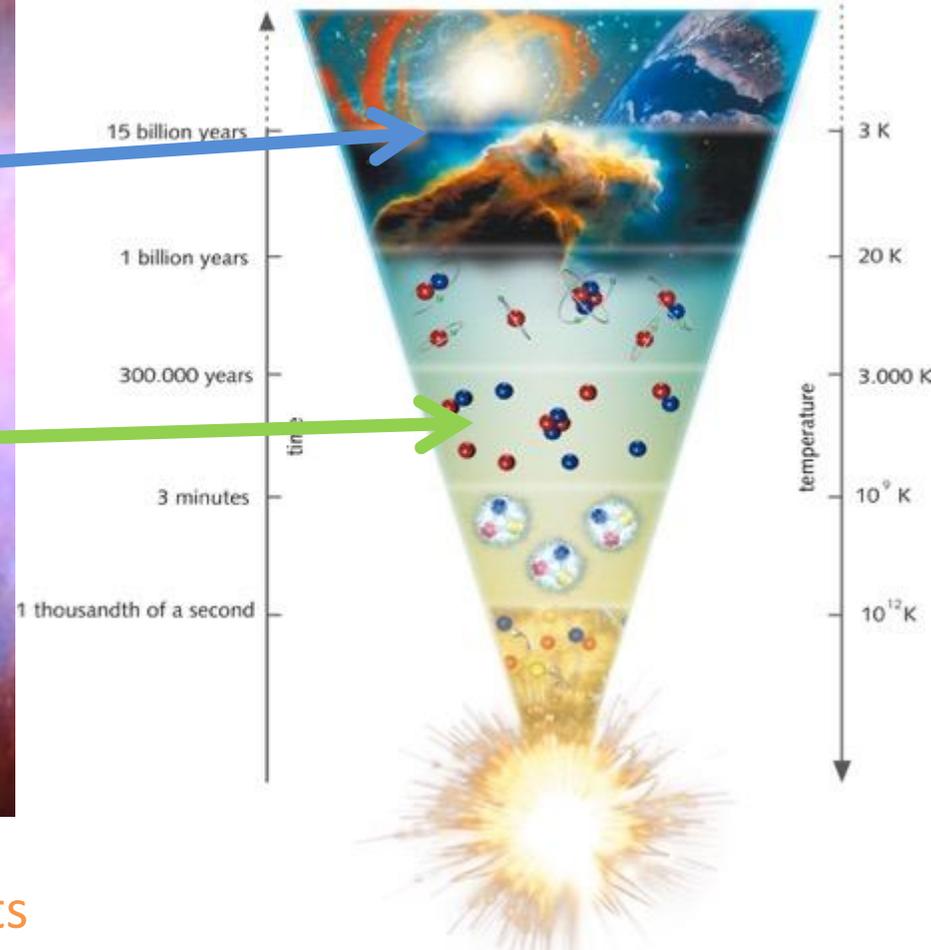
Example: Synthesis of the chemical elements

Periodic Table of the Elements

H	He																	
Li	Be	B	C	N	O	F	Ne											
Na	Mg	Al	Si	P	S	Cl	Ar											
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe	
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn	
Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Uuq	Uup	Uuh	Uus	Uuq	
Lanthanide Series		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu		
Actinide Series		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr		

Periodic Table of the Elements

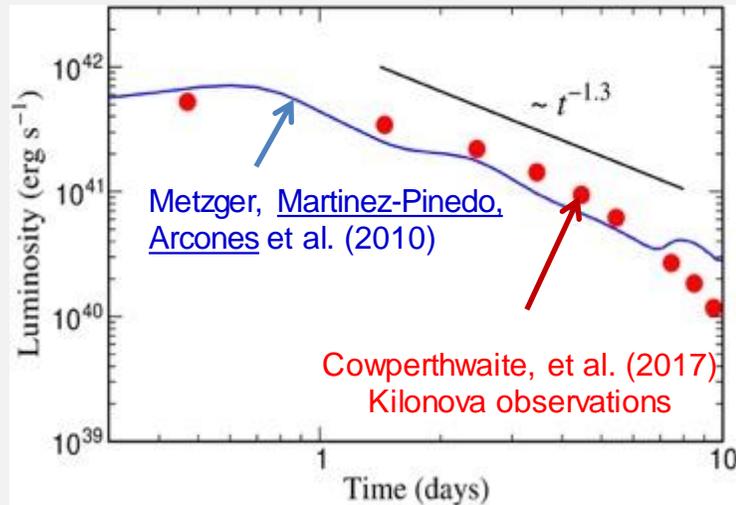
H	He
Li	



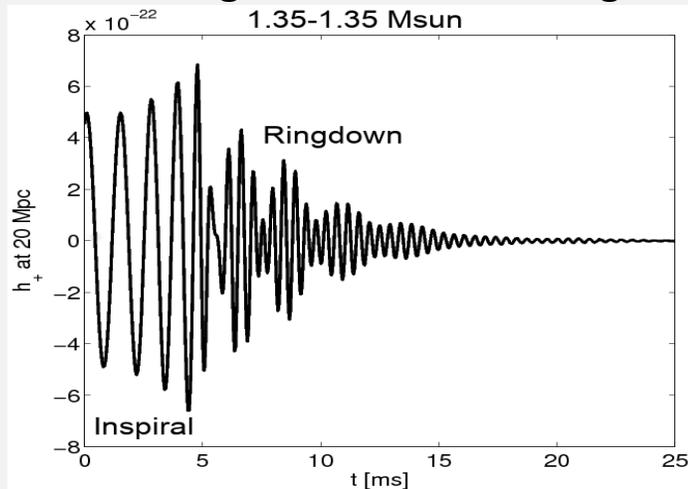
Where and how were the heavy elements made in the universe? ← *belongs to the top unanswered questions in physics*

Further push of FAIR science motivation

... by multimessenger study of a neutron-star merger in summer 2017



Electromagnetic “Kilonova” Signal



Gravitational Wave Signal

Theoretical prediction by GSI researchers (2010):

Neutron star mergers are the astrophysical site of the r-process producing the very heavy elements like Pt, Au and beyond, **thereby exhibiting a characteristic electromagnetic “Kilonova” signal.**

Confirmation by Ligo, Virgo and other astronomer groups (2017)

via detection of both **gravitational and electromagnetic waves emerging from such an event.**

FAIR was designed to study the properties of neutron star matter and to trace back the production paths of the heavy elements!

Big physics question requiring information on:

Equation of State

Limits of existence

Lifetimes

Masses

P_{xn} values

Fission

Reactions in star environments

with theory support for impact



DESPEC	γ -, β -, α -, p-, n-decay spectroscopy
ELISE	elastic, inelastic, and quasi-free e ⁻ -A scattering
EXL	light-ion scattering reactions in inverse kinematics
HISPEC	in-beam γ spectroscopy at low and intermediate energy
ILIMA	masses and lifetimes of nuclei in ground and isomeric states
LASPEC	Laser spectroscopy
MATS	in-trap mass measurements and decay studies
R3B	kinematically complete reactions at high beam energy
Super FRS	RIB production, identification and spectroscopy
SHE	Nuclear physics and chemistry of super-heavy elements

The Approach

Complementary measurements leading to consistent answers

The Collaboration

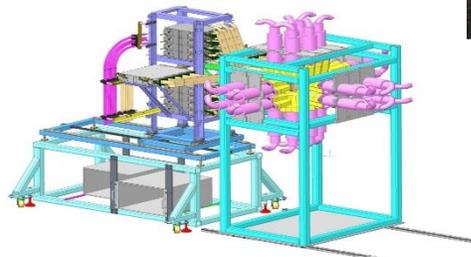
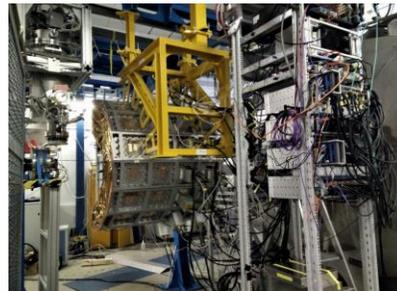
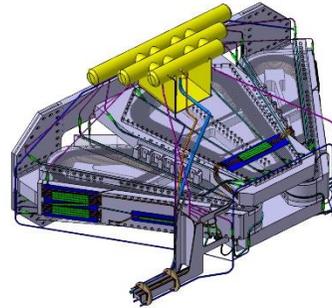
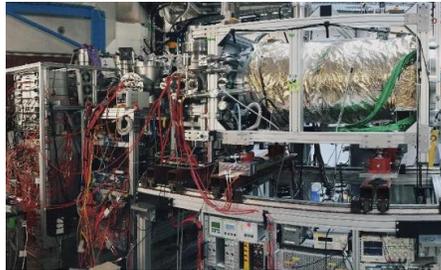
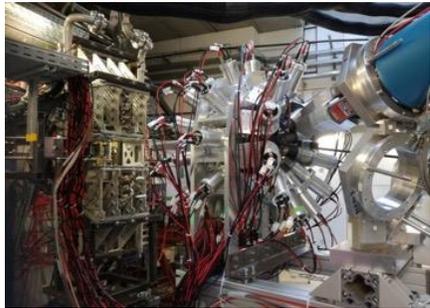
> 850 scientists

184 institutes

39 countries

Evolutionary approach:

Advancing instrumentation by continuous development and gaining experience by physics exploitation



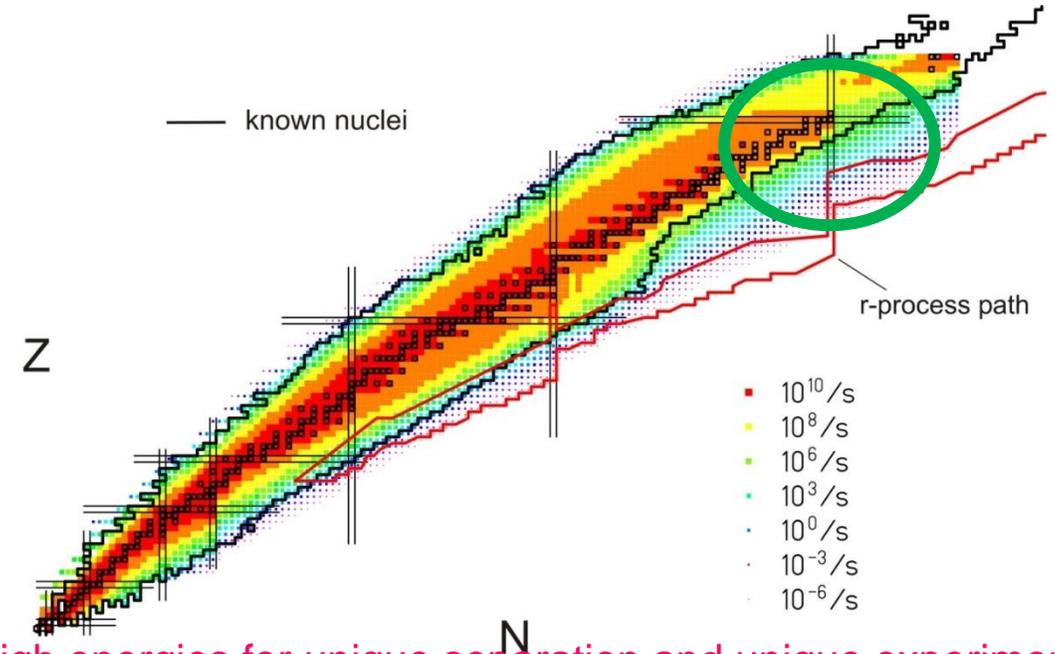
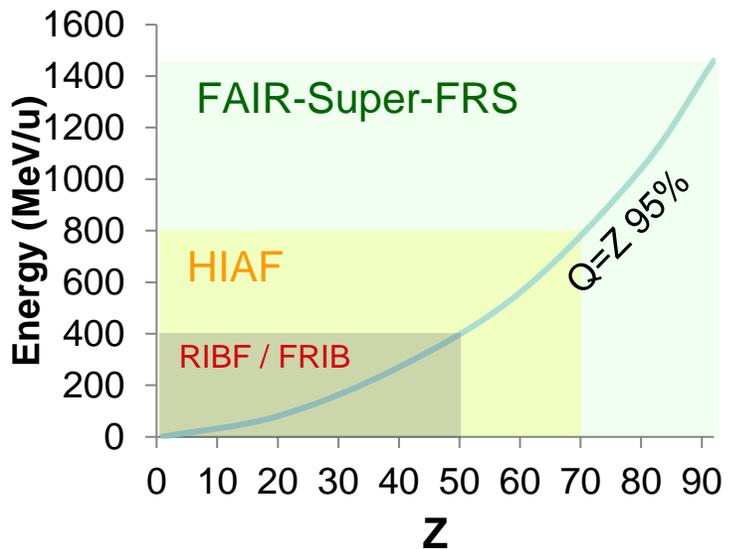
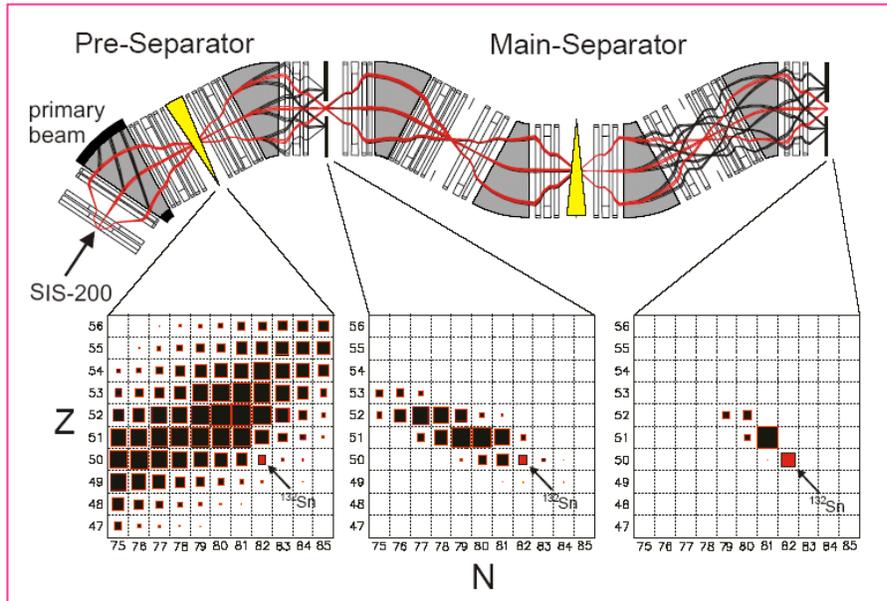
>50 instrumentation sub-projects (MSV)
several 1000 major components

The Approach

Complementary measurements leading to consistent answers

The Collaboration

> 850 scientists
184 institutes
39 countries



High energies for unique separation and unique experiments
Competitive intensities throughout the periodic table

Facility	U beam int. per spill at production target
previously at GSI	$1 \dots 2 \times 10^9$
after the SIS18 upgrade at GSI	8×10^9
commissioning phase SIS100	2×10^{10}
final full intensity with SIS100	3×10^{11}

2021-2022 FAIR-0 experiments (with equipment built for FAIR)

2023 No experiments (but there were tests)

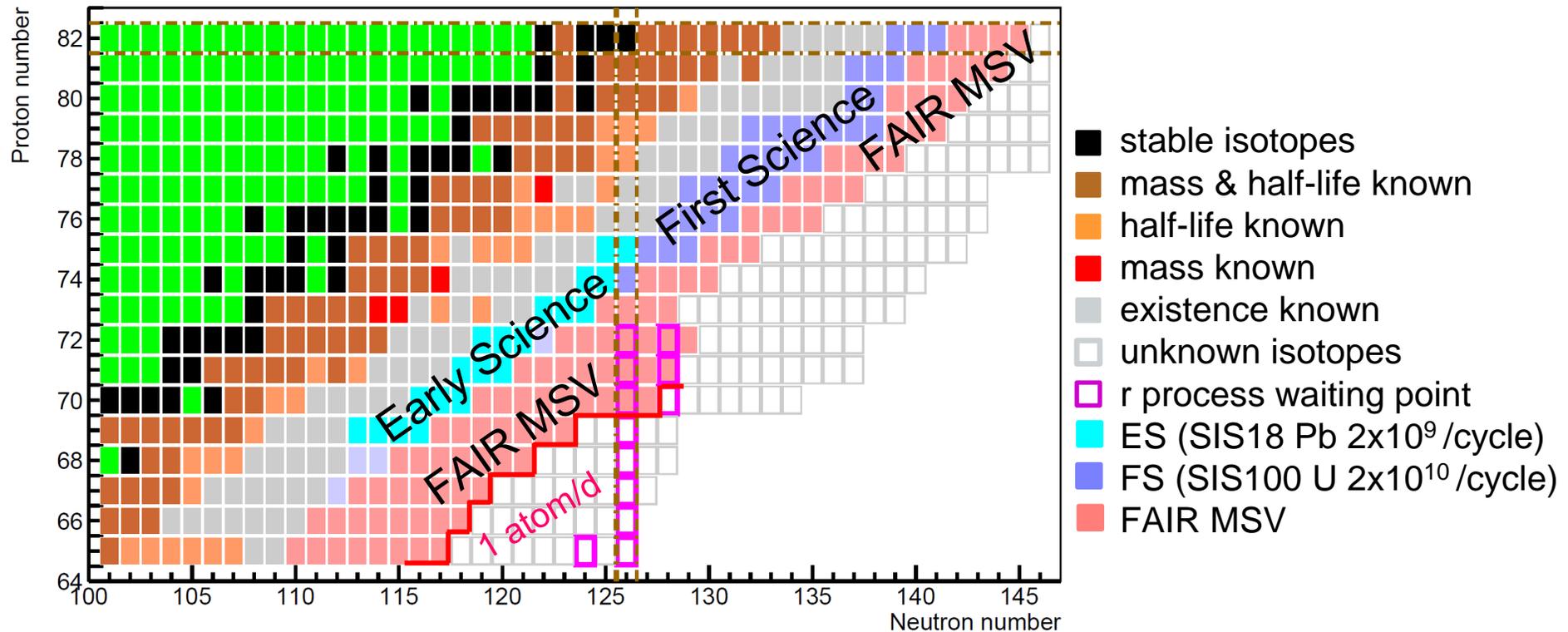
2024-2025 FAIR-0 experiments

2026-2027 FAIR-0 experiments (G-PAC in Feb. 2025)

End 2027 -> **Early Science (with SuperFRS)**

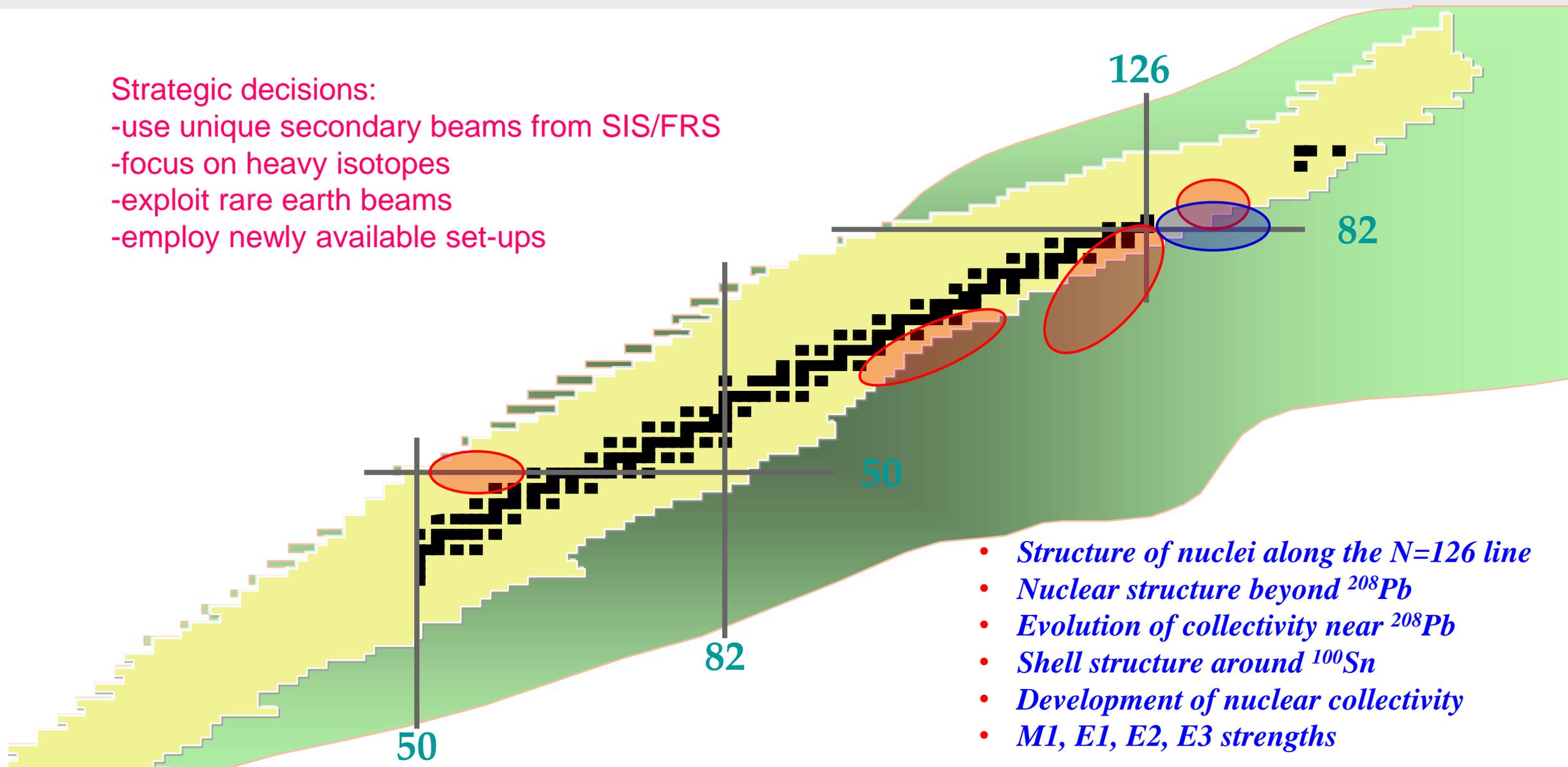
End 2028 -> **First Science (with SuperFRS and SIS100)**

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



Strategic decisions:

- use unique secondary beams from SIS/FRS
- focus on heavy isotopes
- exploit rare earth beams
- employ newly available set-ups



- *Structure of nuclei along the N=126 line*
- *Nuclear structure beyond ^{208}Pb*
- *Evolution of collectivity near ^{208}Pb*
- *Shell structure around ^{100}Sn*
- *Development of nuclear collectivity*
- *M1, E1, E2, E3 strengths*

DESPEC: Decay Spectroscopy

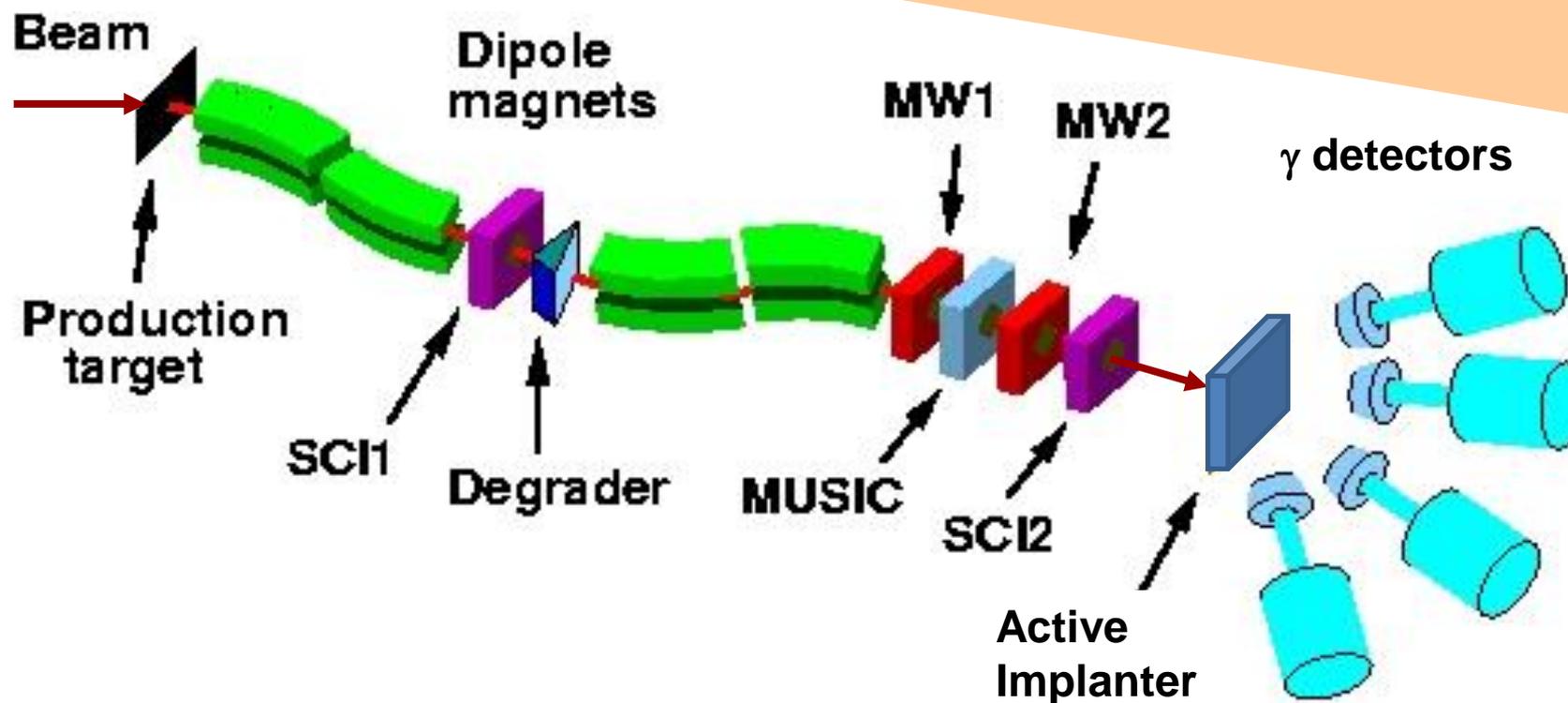
production

selection

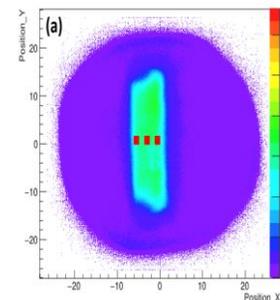
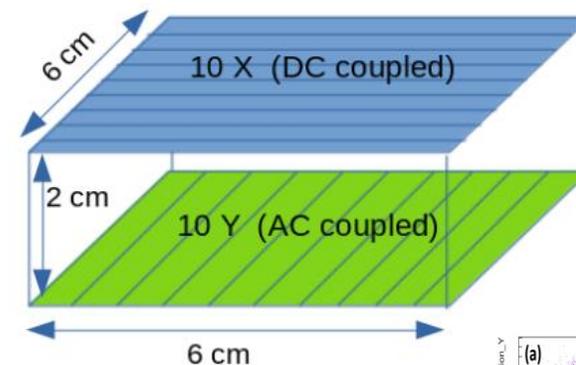
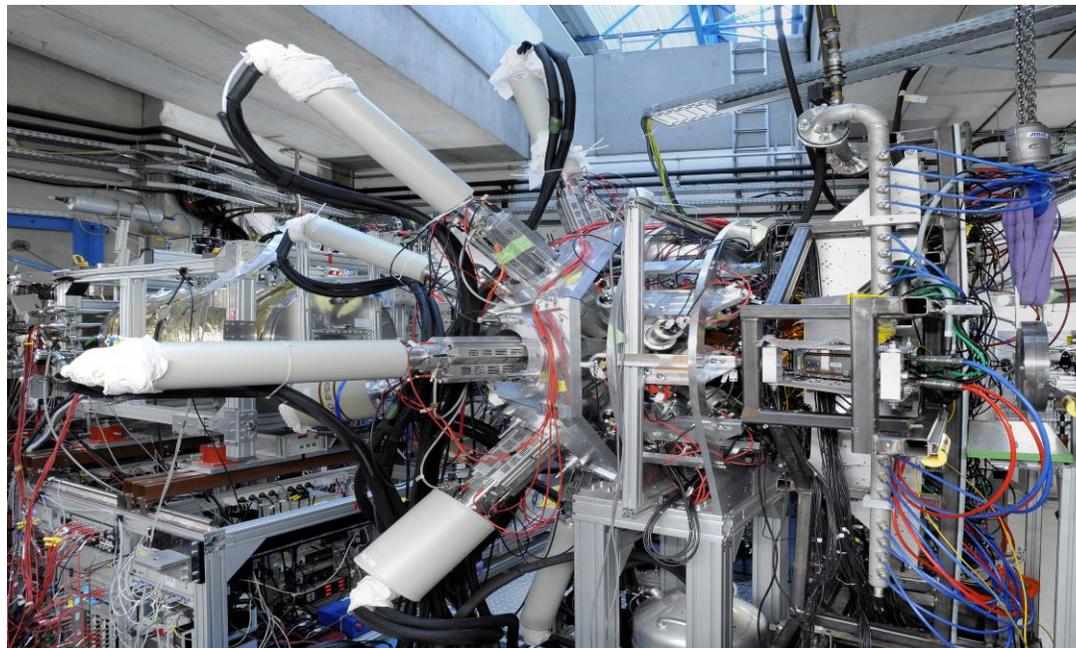
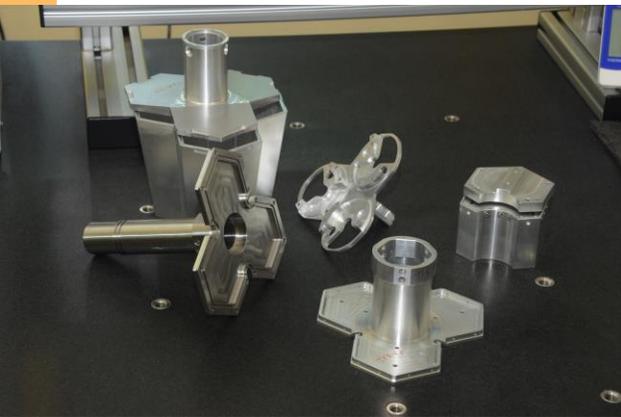
identification

spectroscopy

implantation

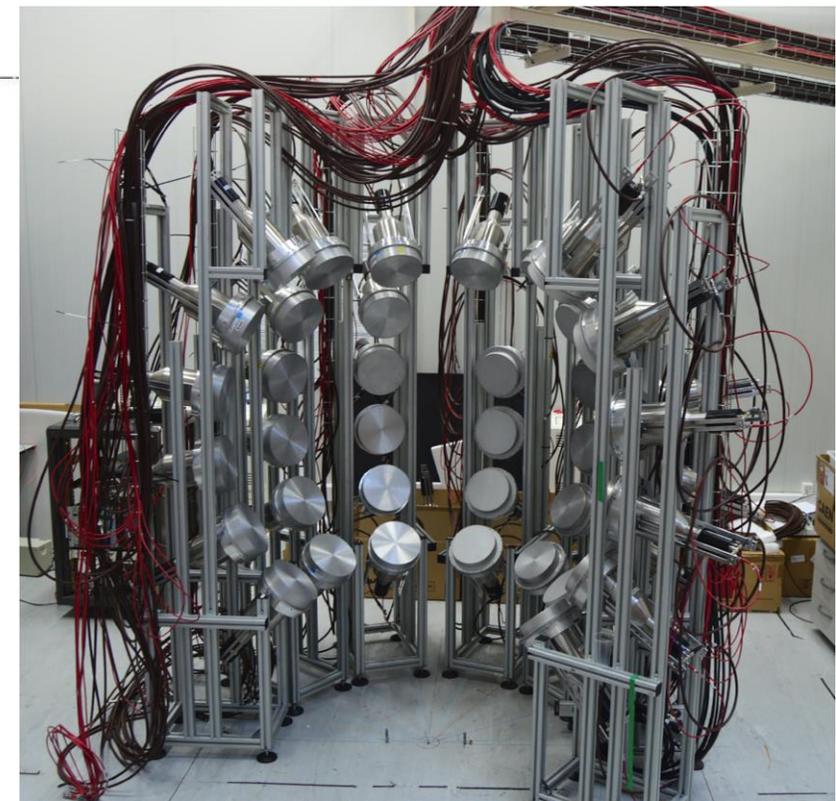
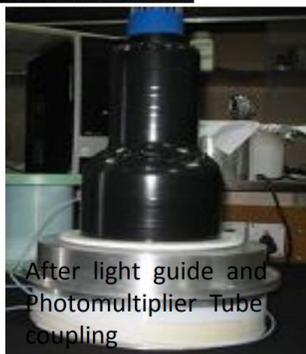
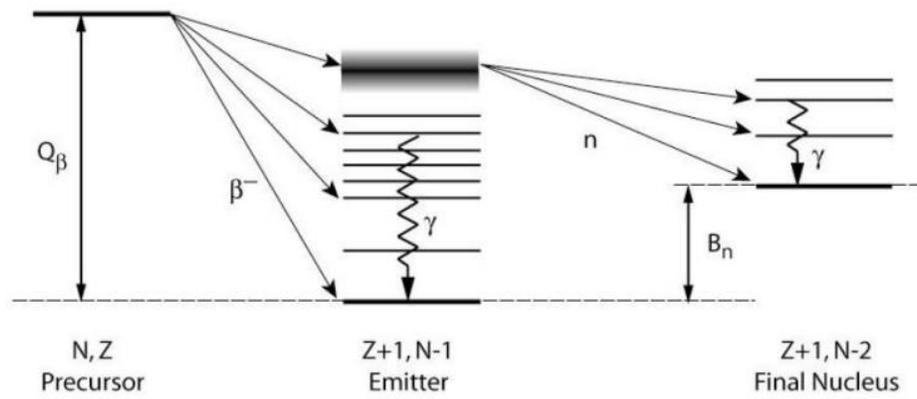
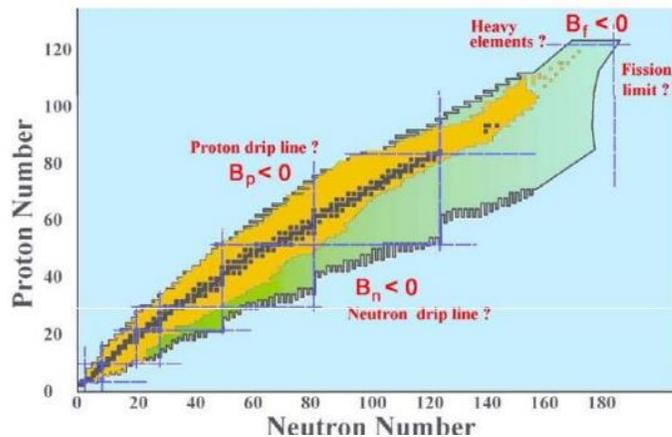


DESPEC: DEGAS γ spectroscopy array



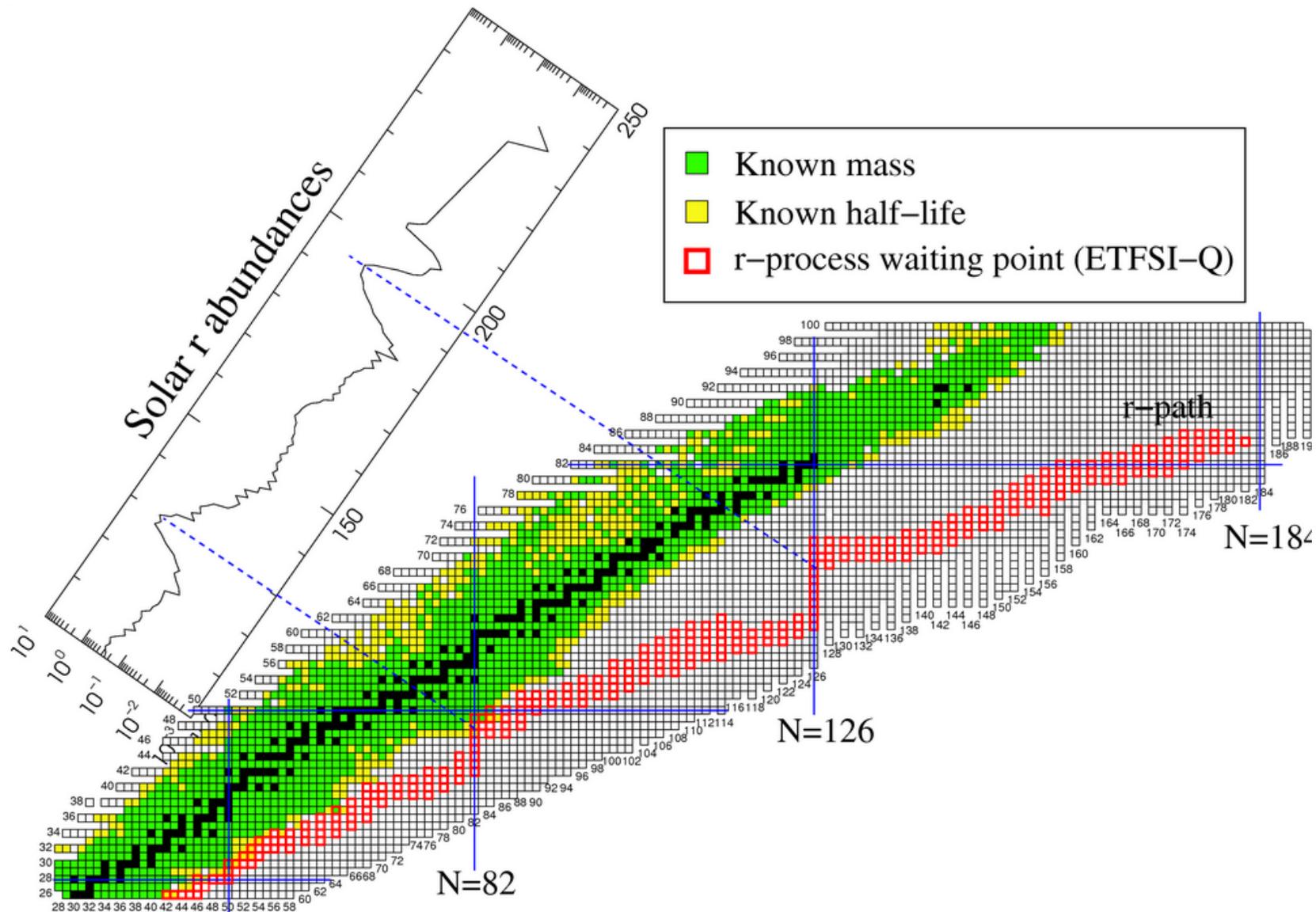
- A prototype of DEGAS mechanics made in India has been approved
- DEGAS mechanics fabricated in India are used in the Experiment at FAIR
- An Implant HPGe Double Sided Strip Detector was used in an experiment at GSI/FAIR
- Geant4 Simulation for DEGAS
- Several Ph.D students are being trained in R&D related to DEGAS
- Active contribution in experiments of DESPEC Collaboration

*major contribution
TIFR, Univ. Delhi*



*major contribution
VECC*

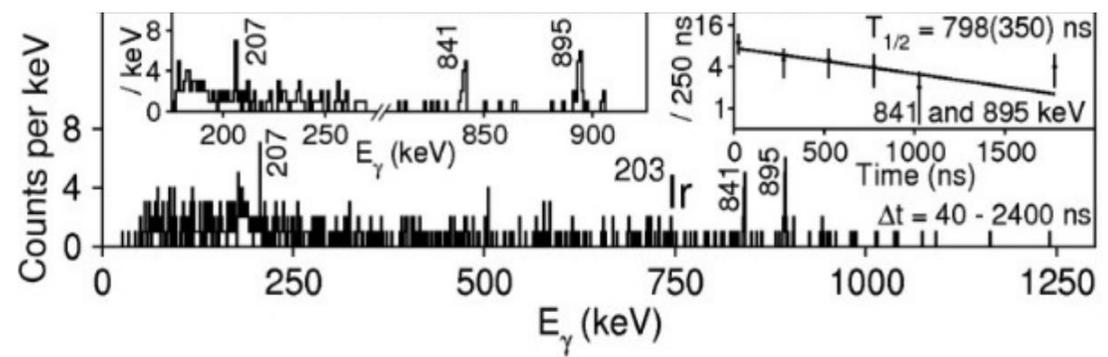
N=126 nuclei and the r-process



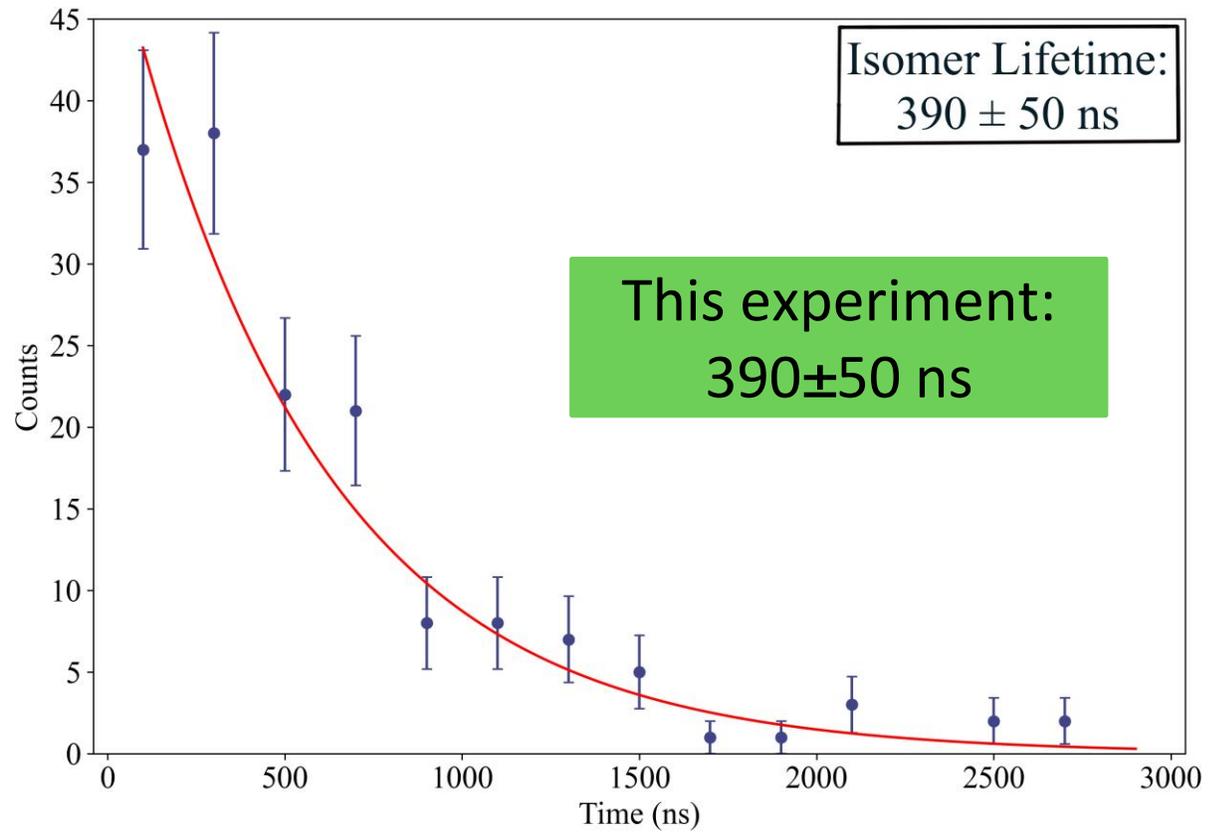
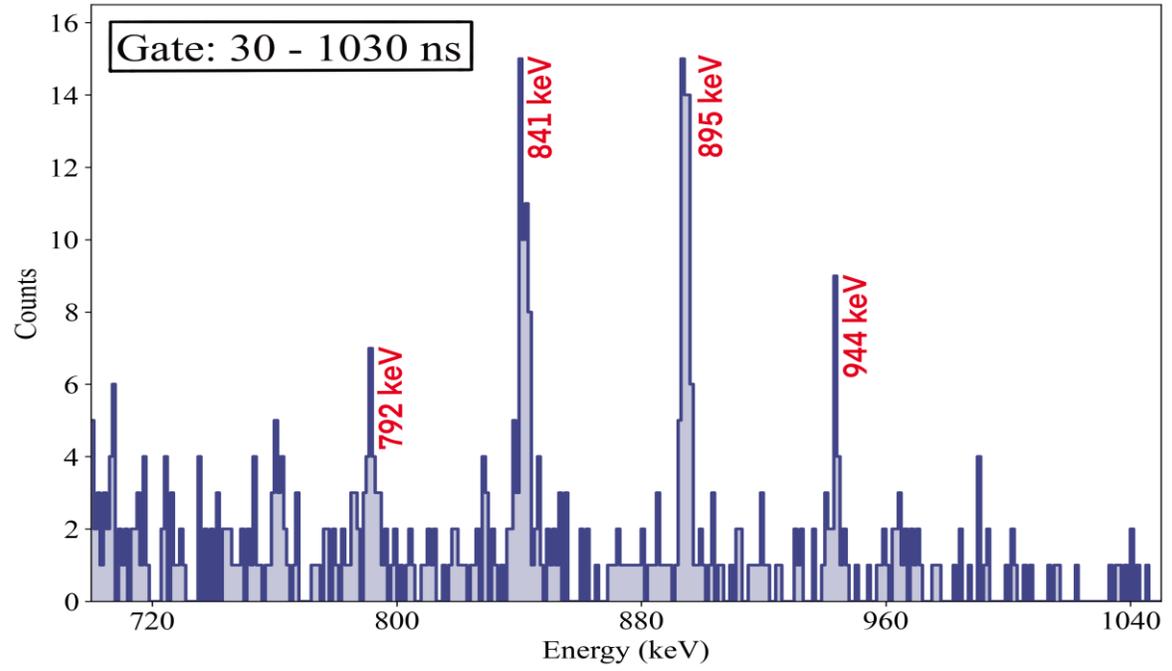
Needed:

- Masses
- Half-lives
- Excited states
- Decay properties

DESPEC Experiment in 2022: ^{203}Ir isomeric decay

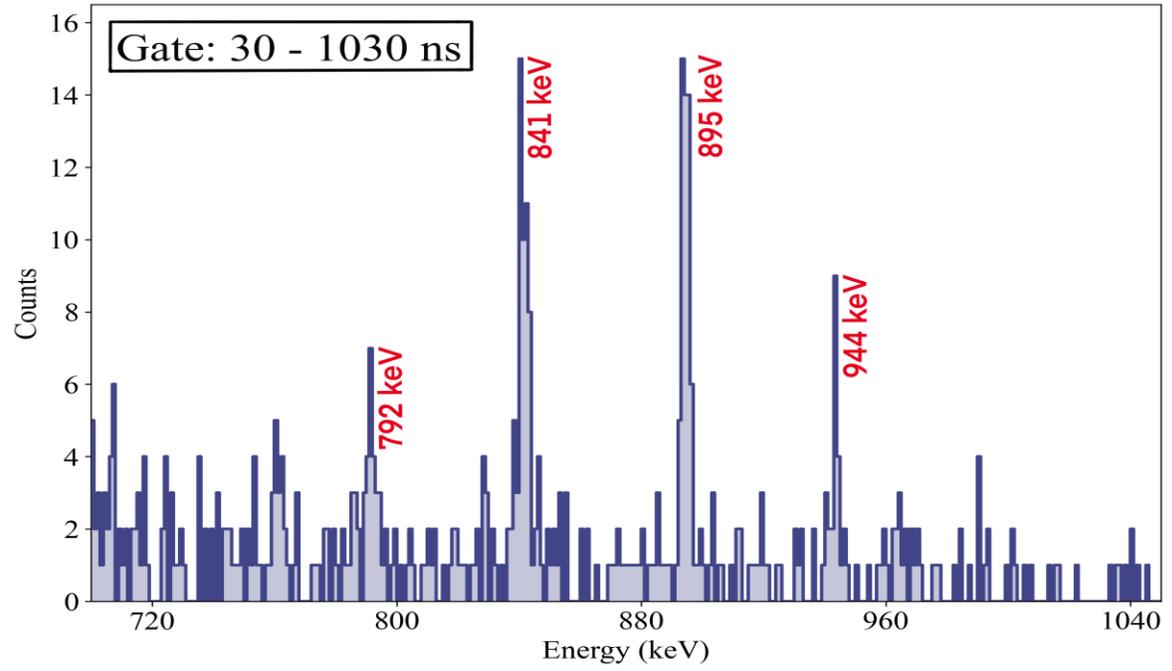
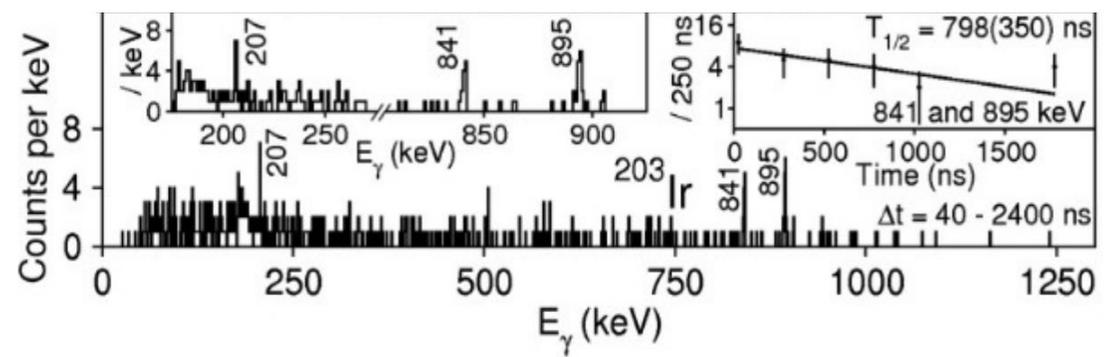


old
**S. Steer (2010):
 798 ± 350 ns**



**This experiment:
 390 ± 50 ns**

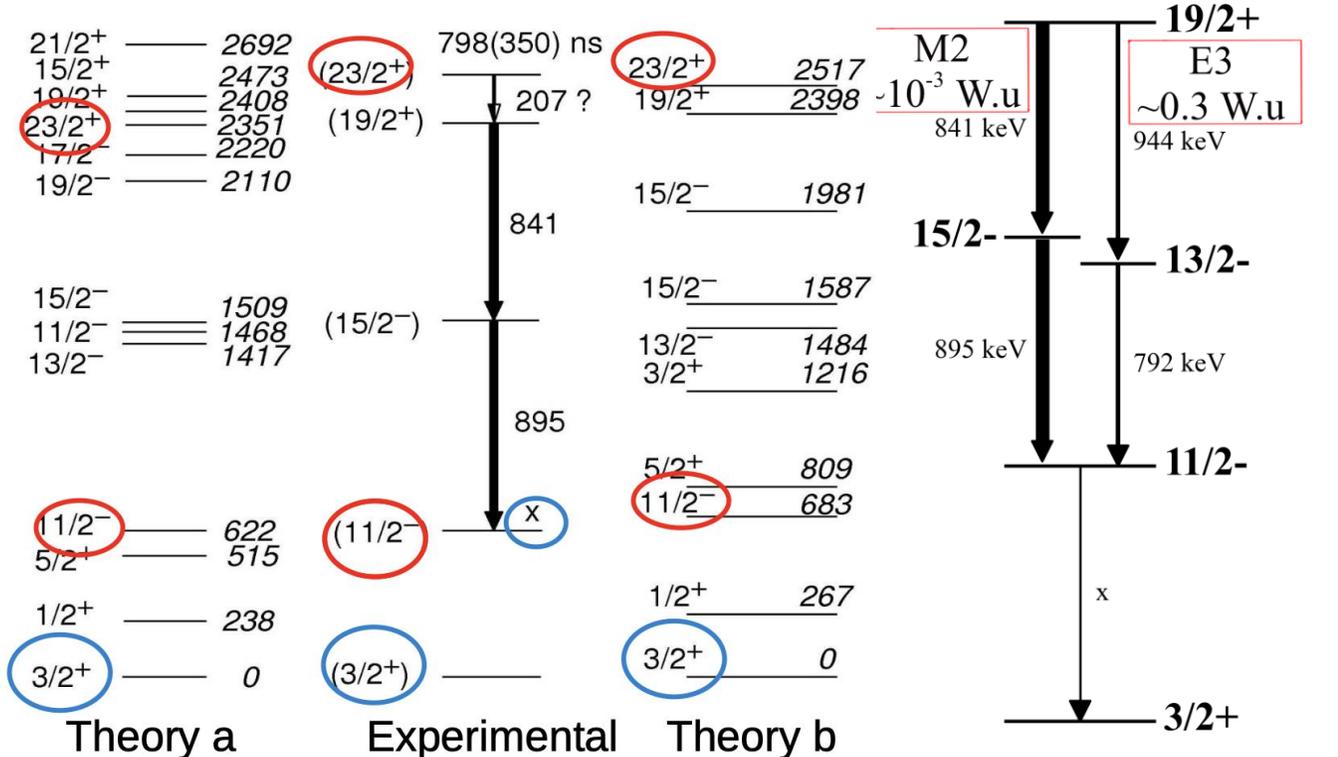
DESPEC Experiment in 2022: ^{203}Ir isomeric decay



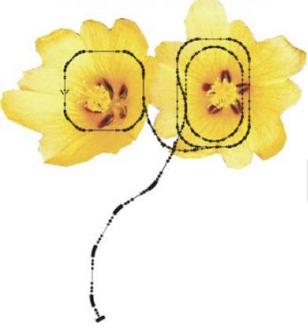
old

S. Steer (2010):

Updated:



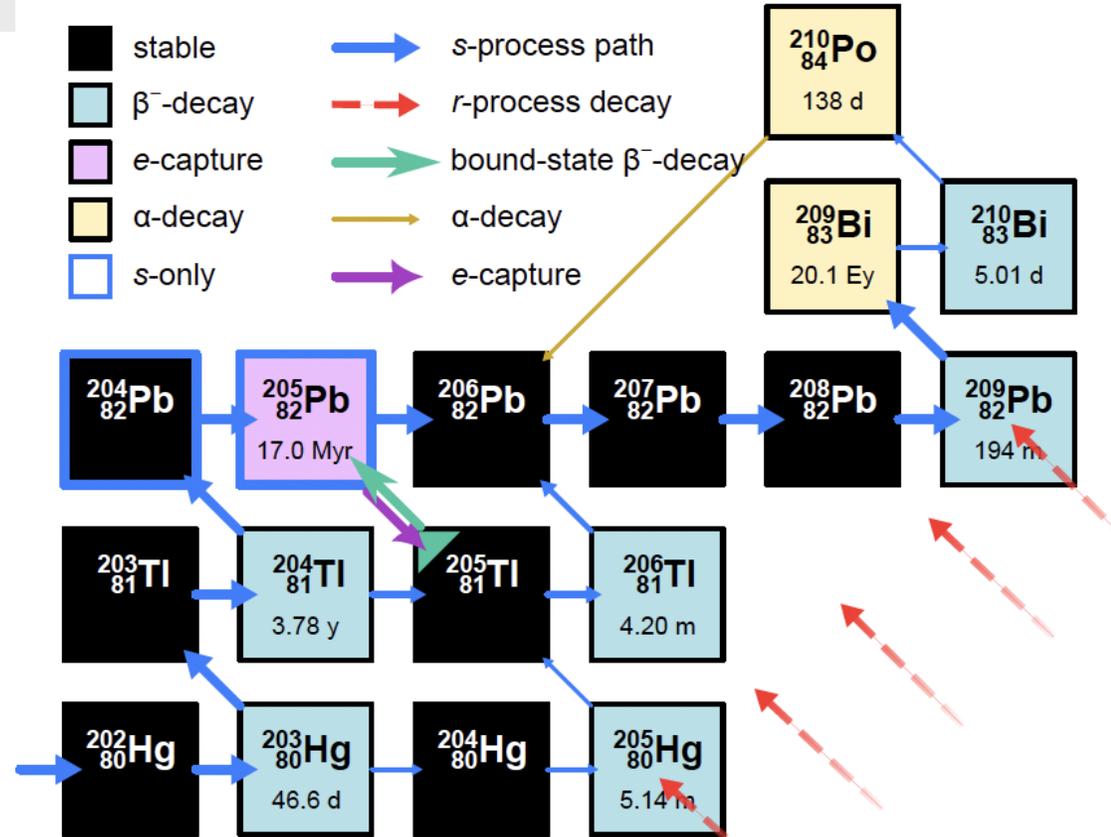
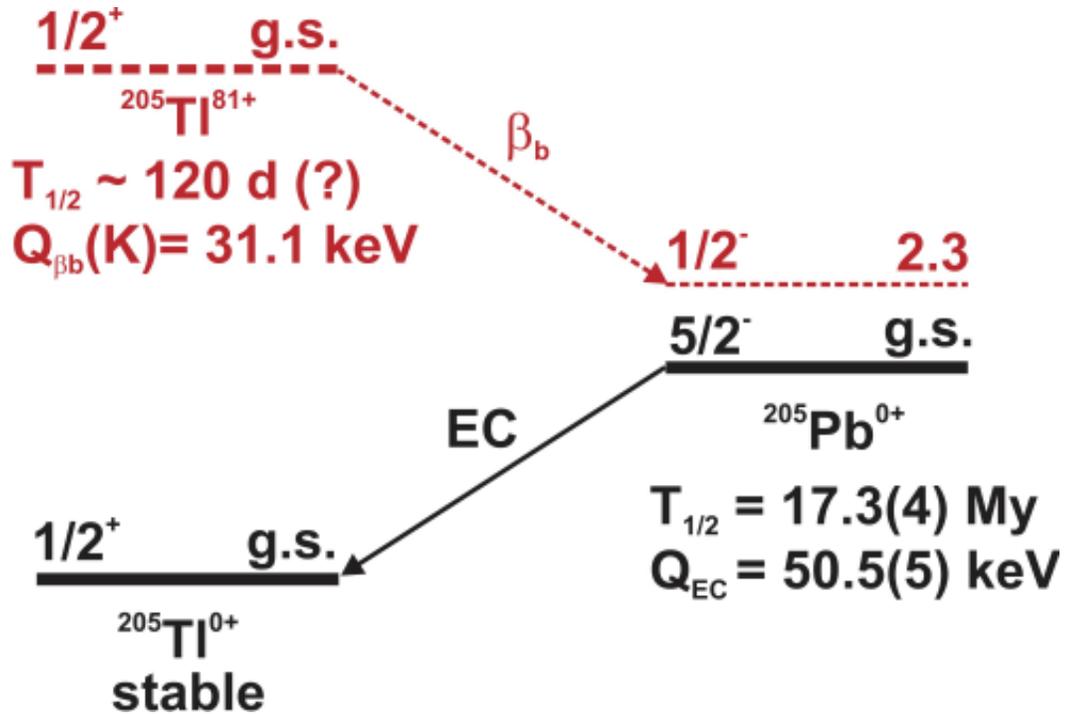
○ isomeric decay ○ beta decay



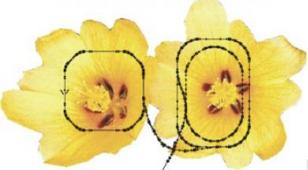
Bound-State Beta Decay of ^{205}Tl



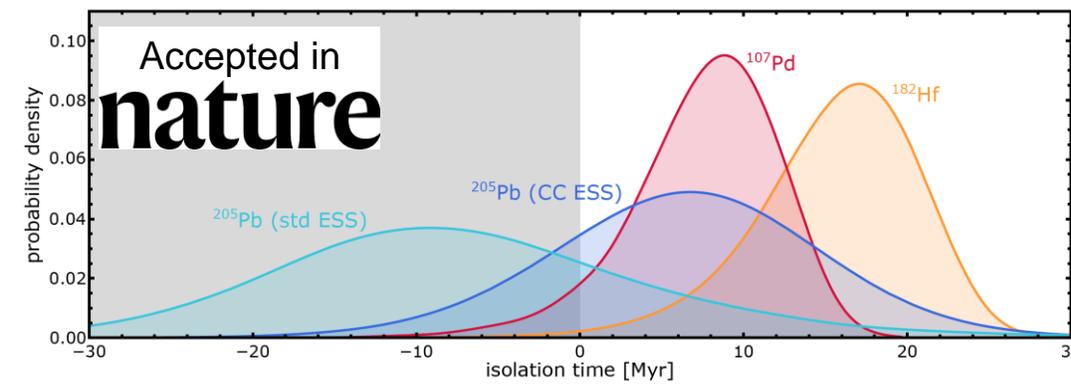
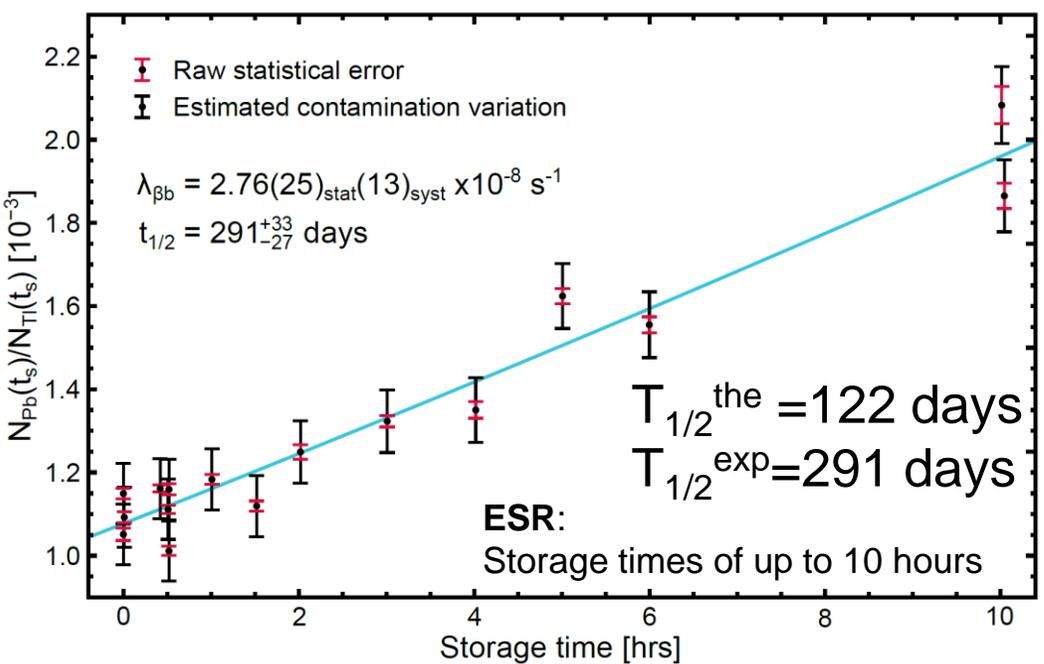
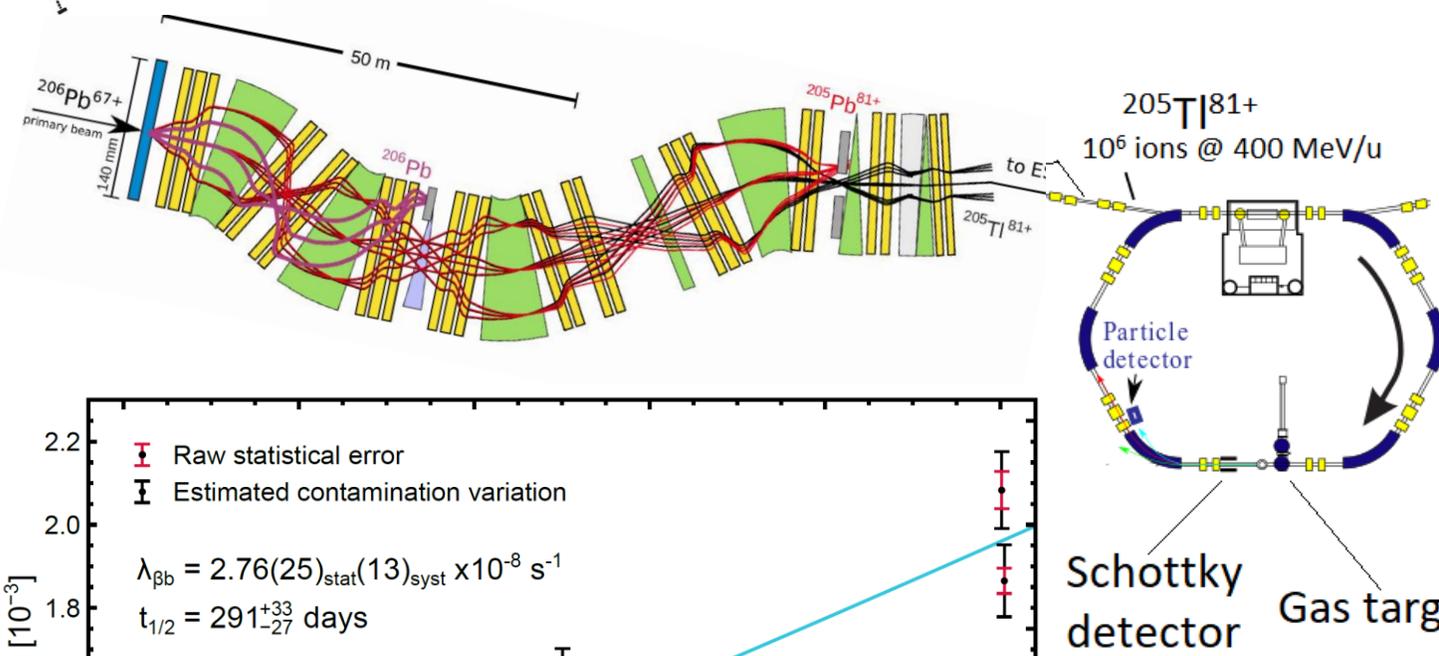
^{205}Tl : Stable in neutral atoms
Radioactive in bare ions
 Cosmochronometer of the s-process



Neutrino energy threshold 53 keV!
 LOREX project: new solar neutrino detector



Bound state beta decay of $^{205}\text{Tl}^{81+}$



Combined with meteoritic data, new ^{205}Pb and ^{205}Tl decay rates in plasmas, and astrophysical simulations, the isolation time of the solar matter from the last synthesis of ^{205}Pb is for the first time positive!

G. Leckenby et al., Nature 635, 321 (2024)

Combined with new neutrino capture rates, the new ^{205}Tl decay constant sets precise constraints on the production of ^{205}Pb by solar pp neutrinos, and thus for the LOREX project aiming at measuring ^{205}Pb in lorandite minerals

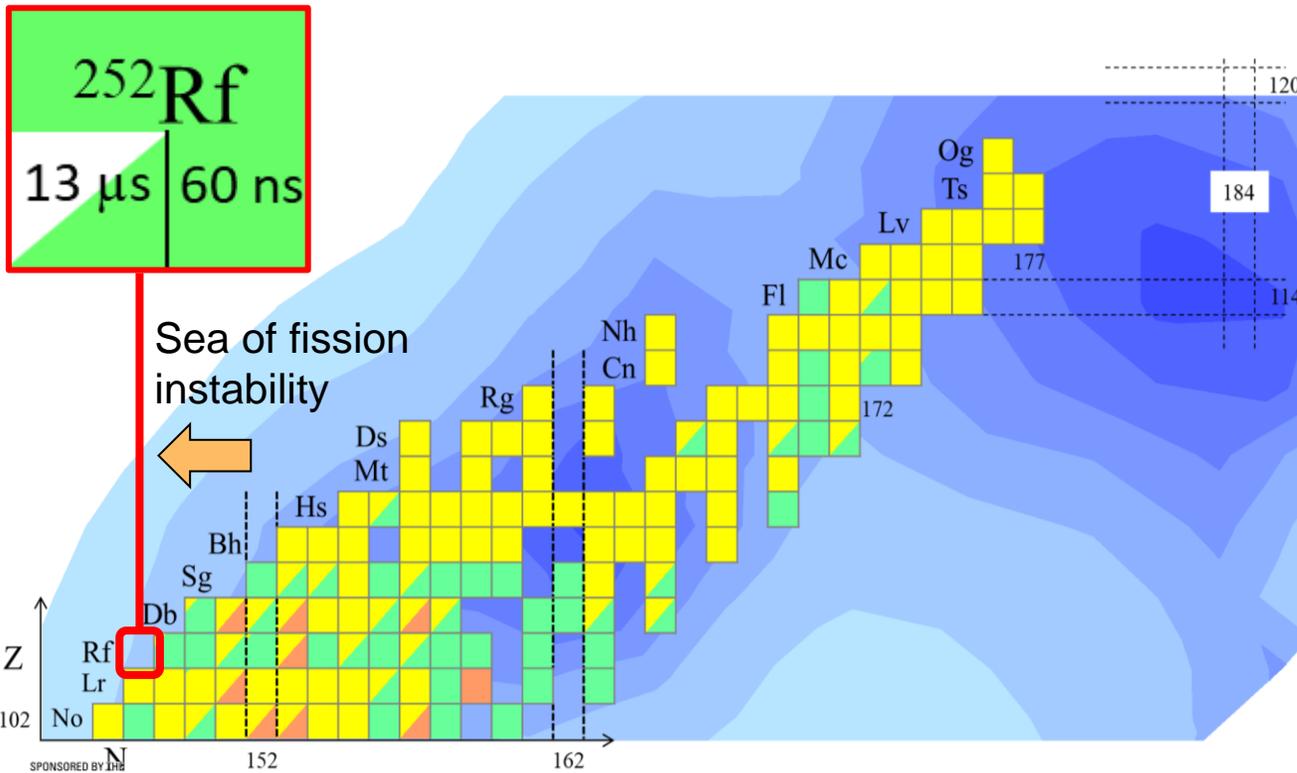
R. S. Sidhu et al., Phys. Rev. Lett. 133, 232701 (2024)



Discovery of 60-ns ²⁵²₁₀₄Rf: Marking the shoreline of the Island of Stability

J. Khuyagbaatar, P. Mosat et al., Phys. Rev. Lett. 134, 022501 (2025)
Editors' Suggestion / Featured in Physics

- Shoreline towards the Sea of Fission Instability is reached in the new ²⁵²Rf
- Detection only possible thanks to longer-lived high-*K* state



Prediction: “**Clouds of stability**” of superheavy nuclei

K-isomeric state (Rf-252m): 50 μs

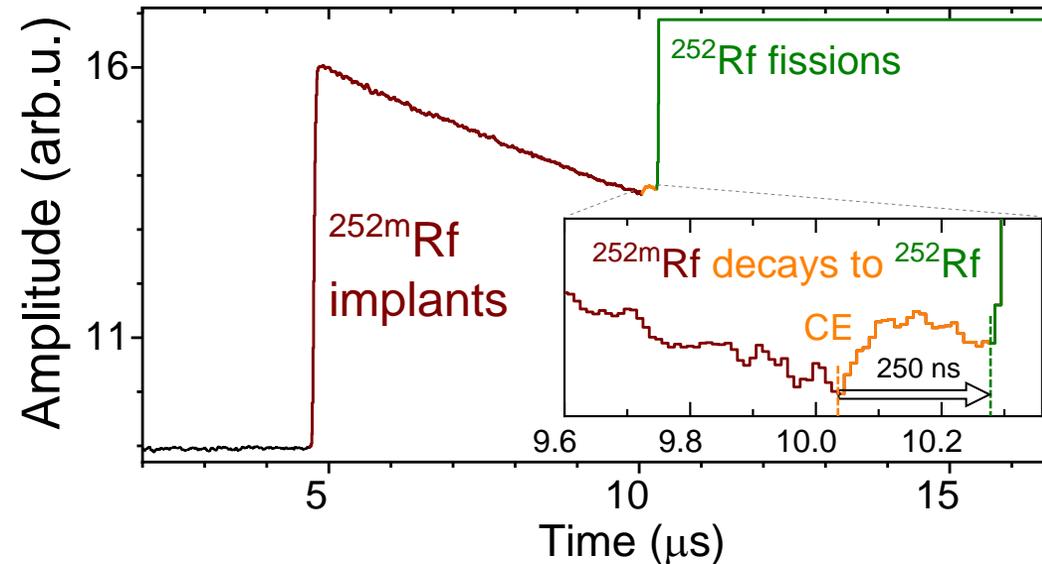
Ground state (Rf-252): 100 ns

J. Khuyagbaatar, Eur. Phys. J. A 58, 243 (2022).

Experiment: ⁵⁰Ti+²⁰⁴Pb @ **TASCA**

K-isomeric state (Rf-252m): 13 ⁺⁴/₋₃ μs

Ground state (Rf-252): 60 ⁺⁹⁰/₋₃₀ ns



Experiments running at FRS

Creation of the chemical elements

^{205}Tl bound-state beta decay

SHE; hadron therapy

shape evolution at $N \sim 126$; $N = 126$ nuclei

Early Science (with SuperFRS)

increased transmission; better detection systems

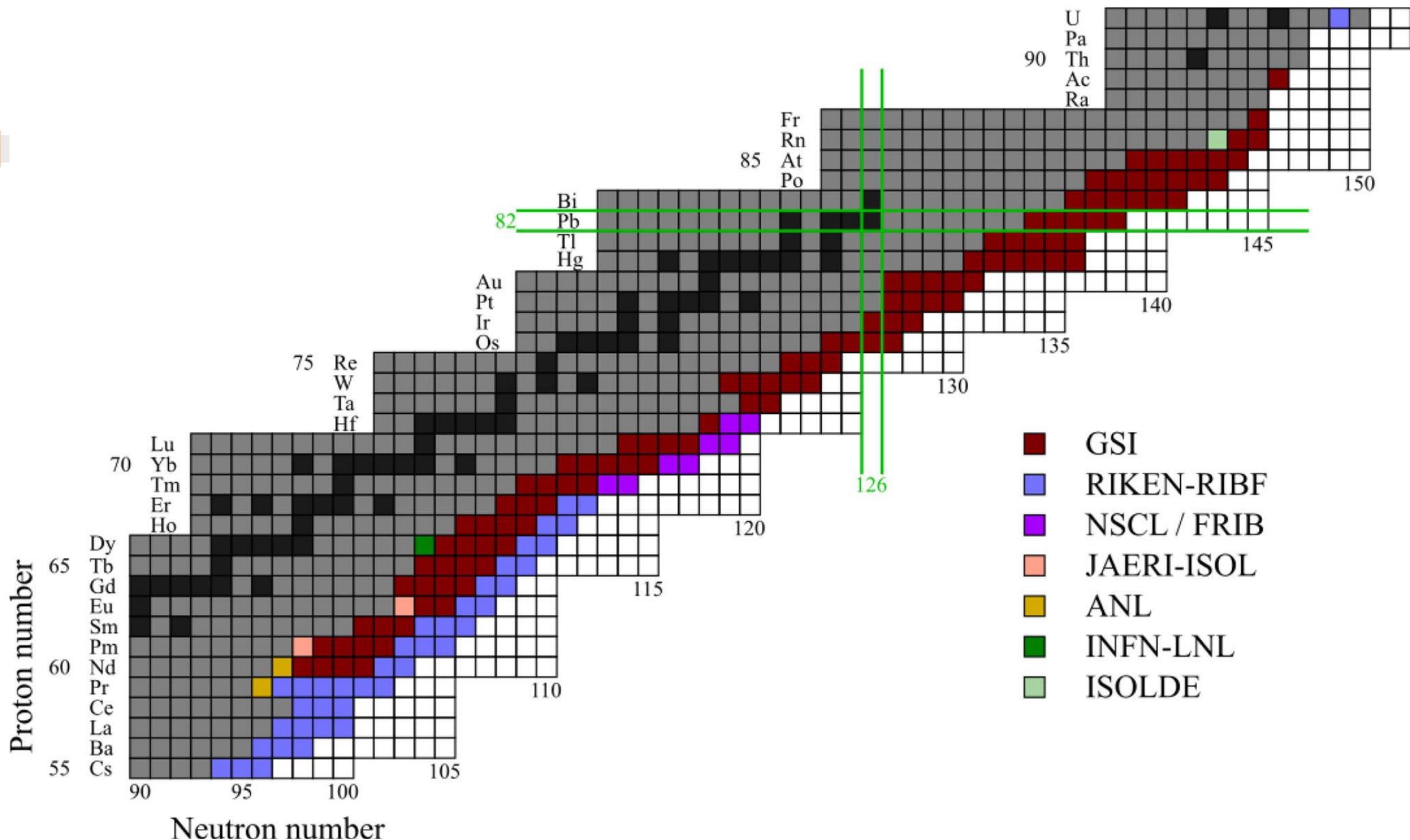
from end of 2027

First Science (with SIS100)

increased primary beam intensity

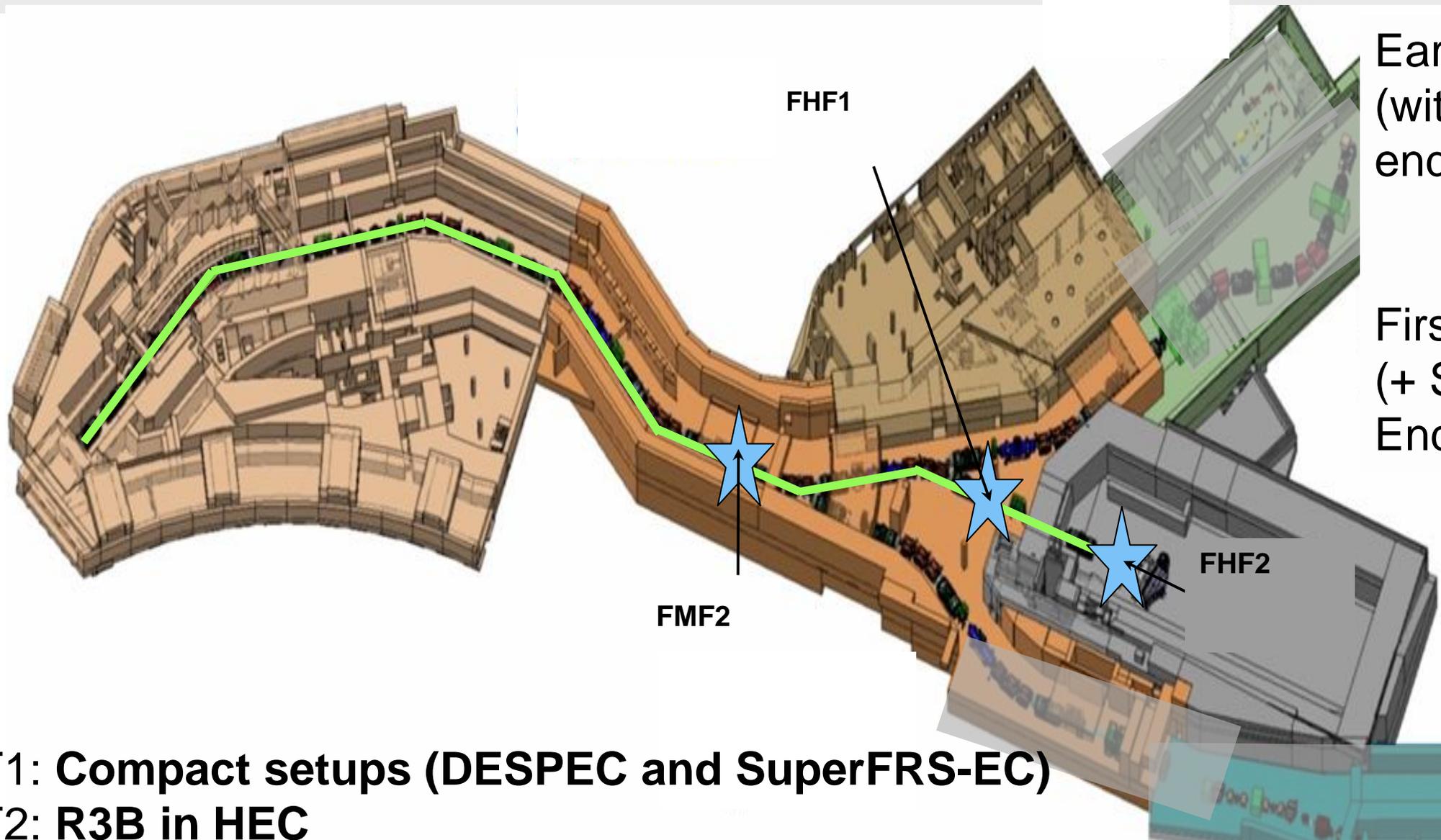
from end of 2028





Part of the Segrè chart, highlighting the isotopes first identified since 2010.

G.G. Kiss, Zs. P., Eur. Phys. J. A 60, 175 (2024)



Early Science
(with SuperFRS)
end of 2027 ->

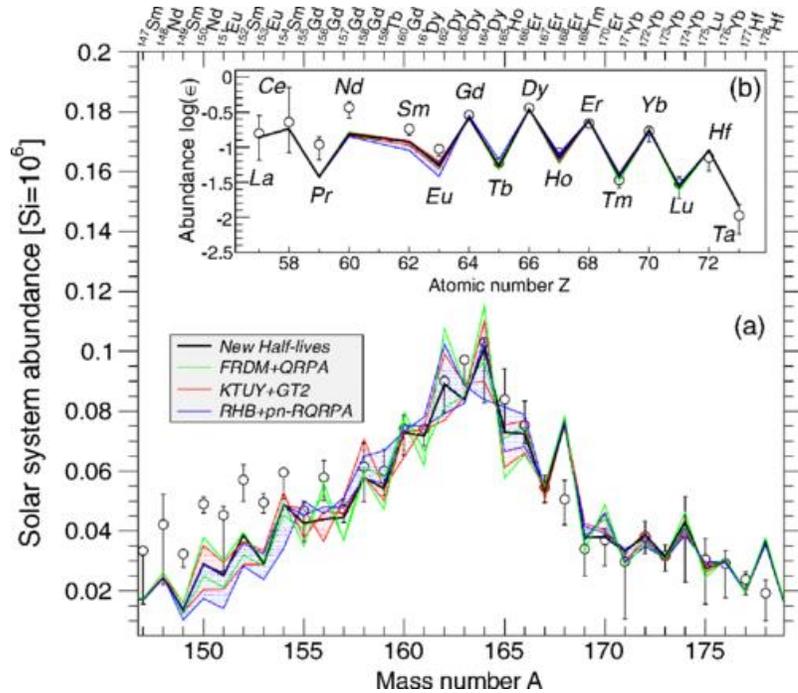
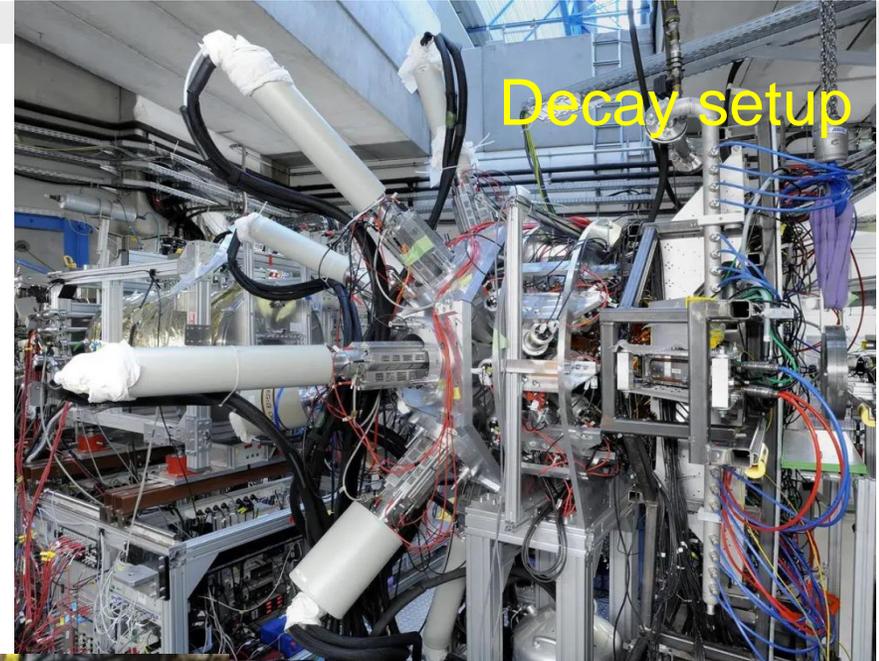
First Science
(+ SIS100)
End of 2028 ->

FHF1: Compact setups (DESPEC and SuperFRS-EC)

FHF2: R3B in HEC

- Production of exotic neutron-rich isotopes
- Measurement of their beta-decay lifetimes
 - Measurement of their masses

Astro impact, based on theory



FAIR/GSI strategic operation scenario: ES, FS, towards FS+

