New perspectives for studies of the collectivity of neutron-rich nuclei at GSI/FAIR

CWAN‘23

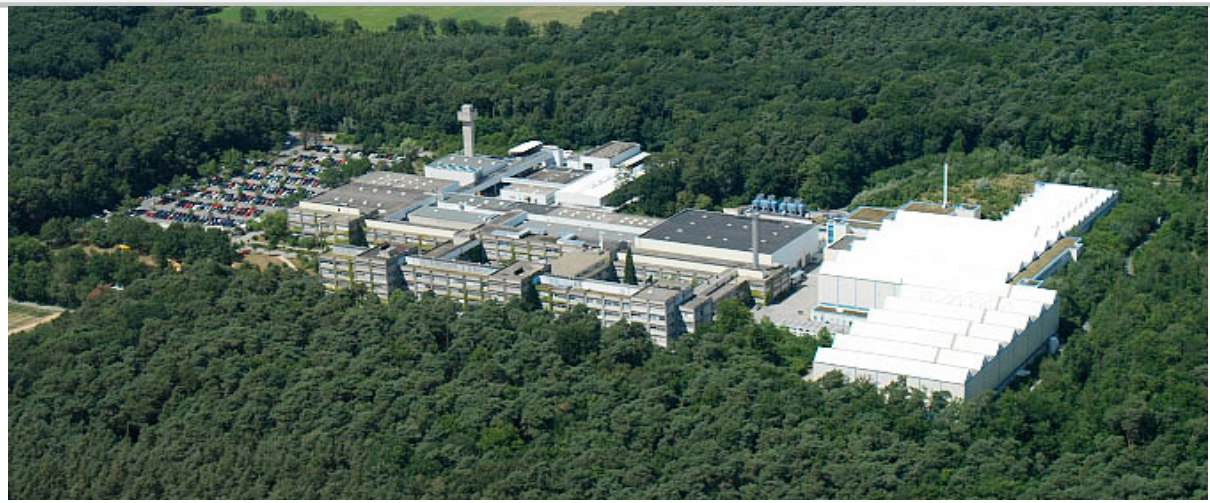
J. Gerl
for the DESPEC collaboration

July 13, 2023

Huizhou, China

GSI – The Laboratory

- German National Lab
- 1600 employees
- 1000 guest scientists



Heavy ion accelerators:

- p …U;
- 14 A·MeV … 2·AGeV

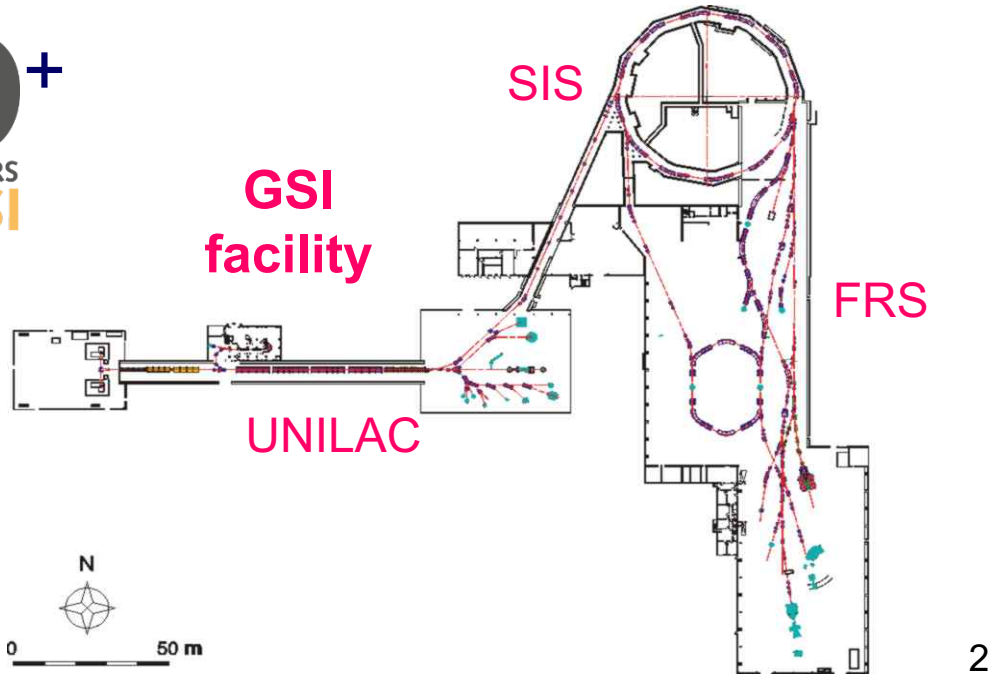
Research areas:

- Nuclear physics
- Atomic physics
- Biophysics/Medicine
- Materials research
- Instrumentation and applications

Future megascience project:

- FAIR, >2 Billion €
- Multi-national Lab

50+ YEARS GSI



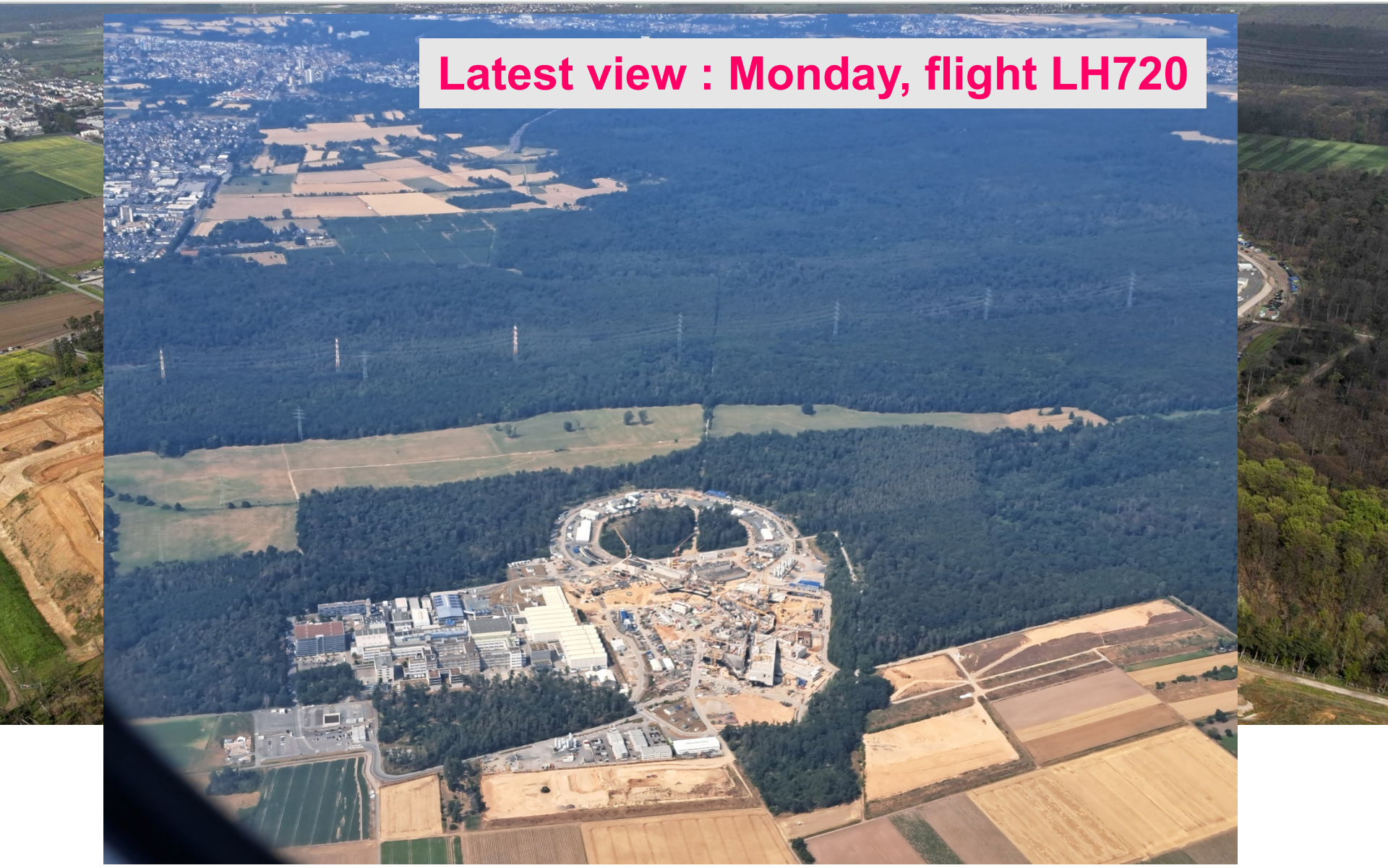
FAIR – the future facility at GSI

- **20 accelerator and experiment buildings** laboratories and supply buildings
- **Underground accelerator ring** with a circumference of ca. 1.100 m
- **About 150.000 m² total** area

FAIR Construction

Central site April 2023

FAIR Construction



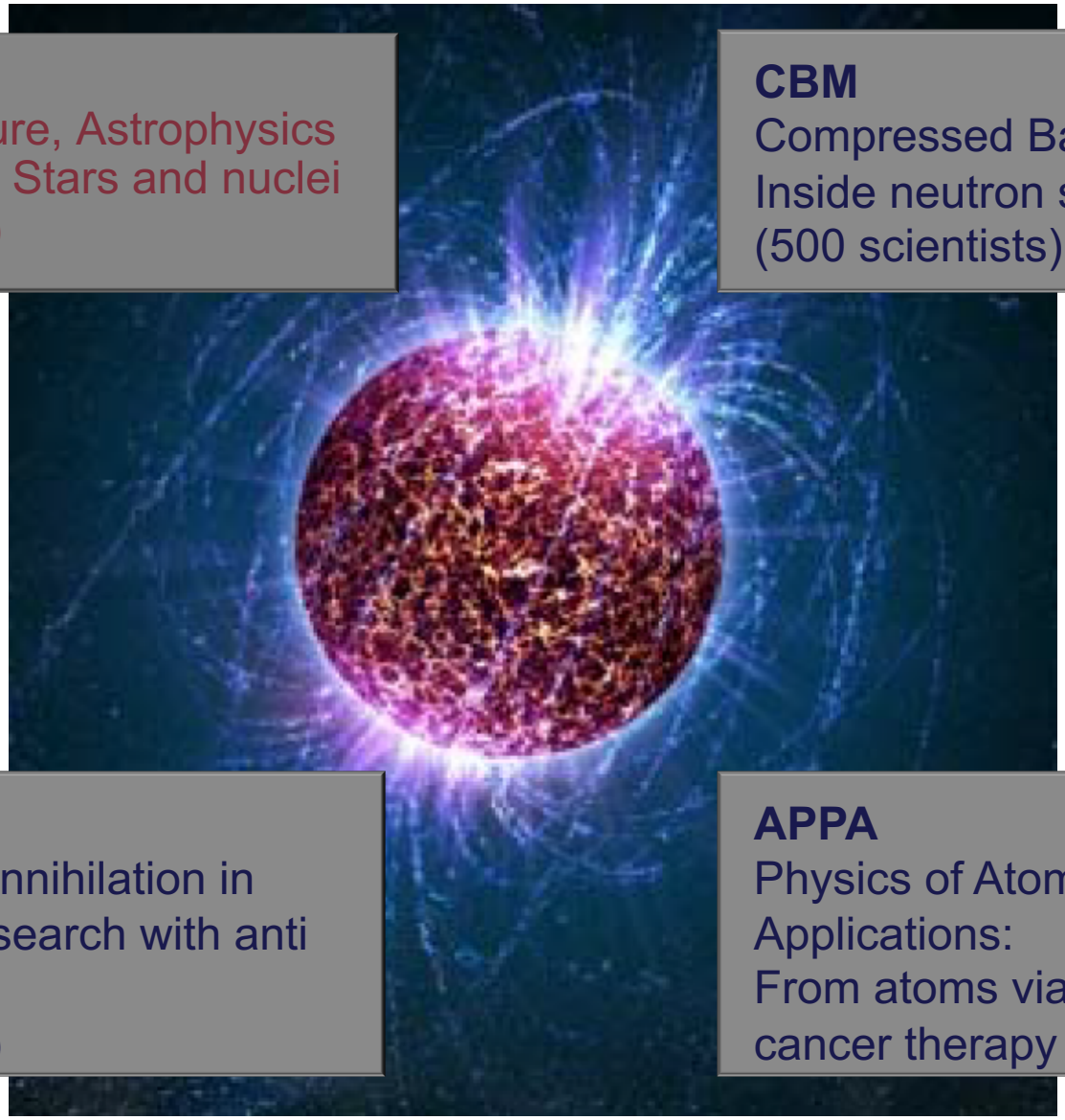
FAIR Construction

Do you see the essential difference to FAIR?

The four scientific pillars of FAIR

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)

NUclear STructure Astrophysics and Reactions

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?

NUSTAR - The Project

DESPEC	γ-, β-, α-, p-, n-decay spectroscopy
ELISE	elastic, inelastic, and quasi-free e^--A scattering
EXL	light-ion scattering reactions in invere 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

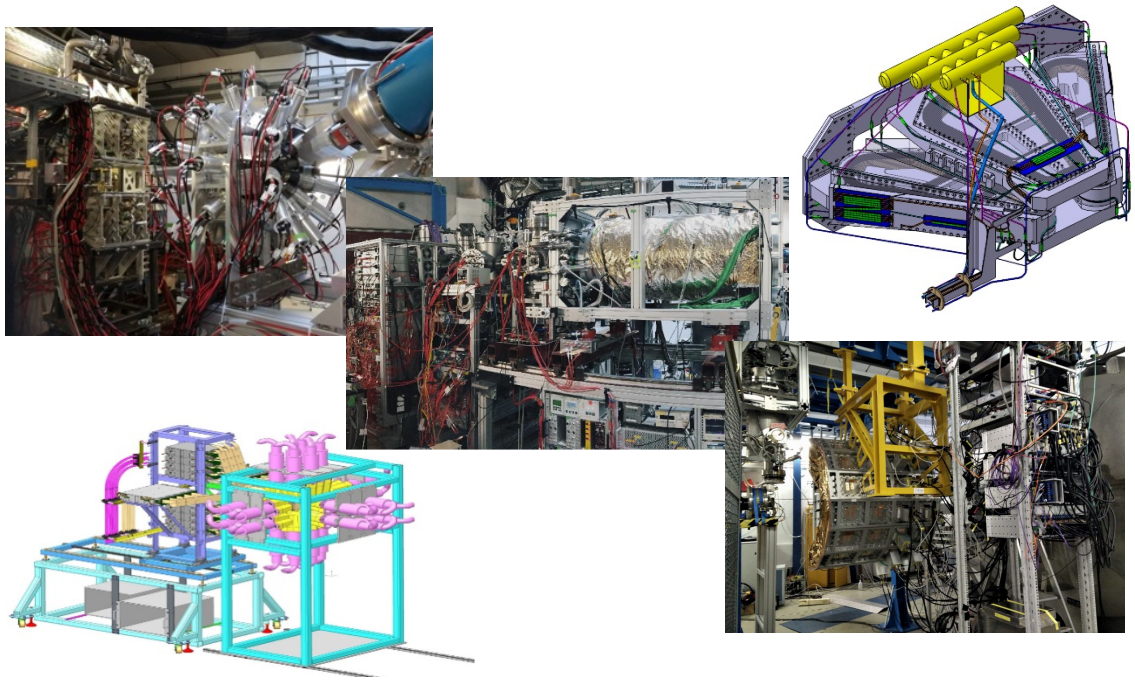
184 institutes

39 countries

NUSTAR - The Project

Evolutionary approach:

Advancing instrumentation by continuous development and gaining experience by physics exploitation



The Approach

Complementary measurements leading to consistent answers

The Collaboration

> 850 scientists

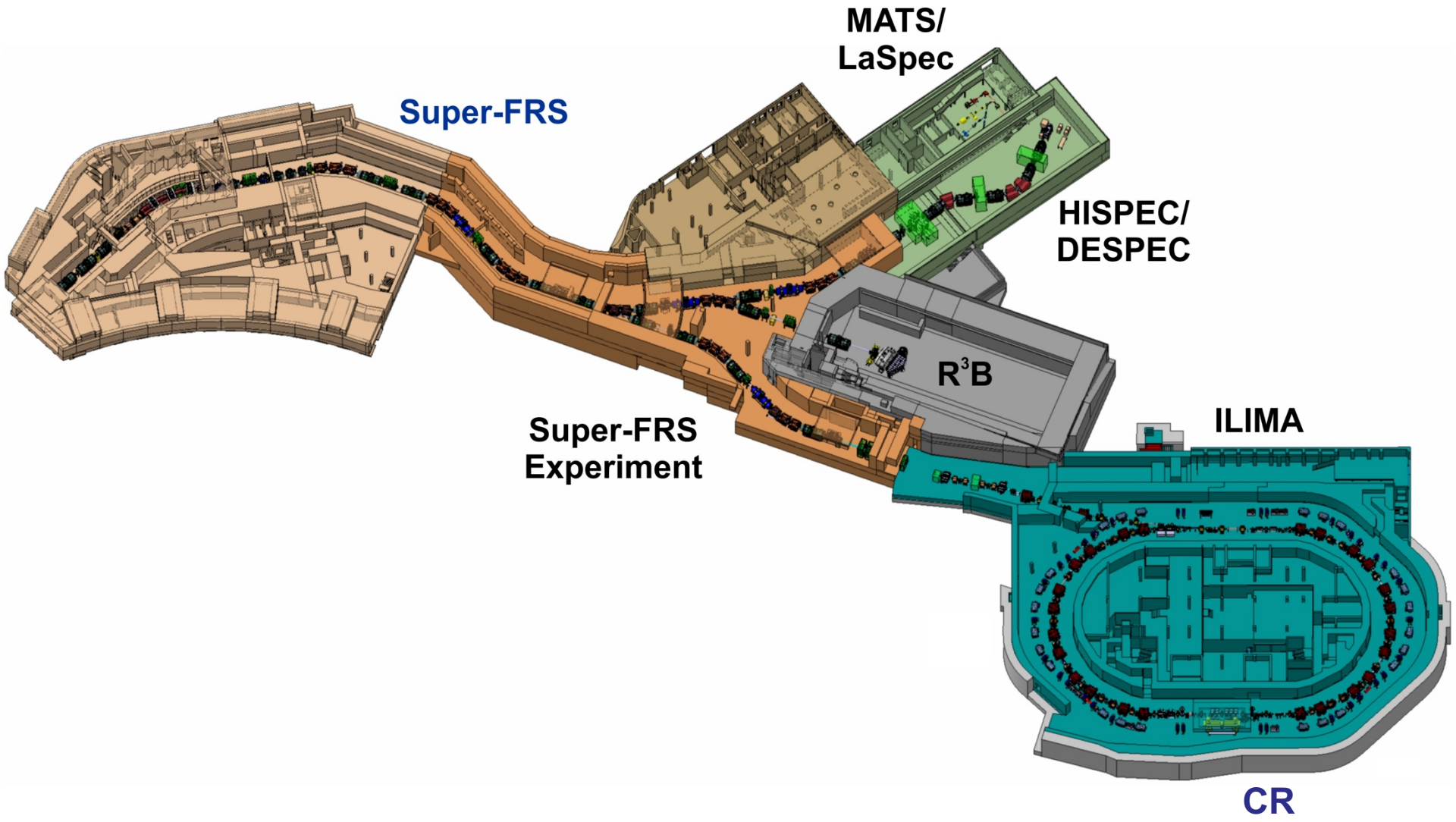
184 institutes

39 countries

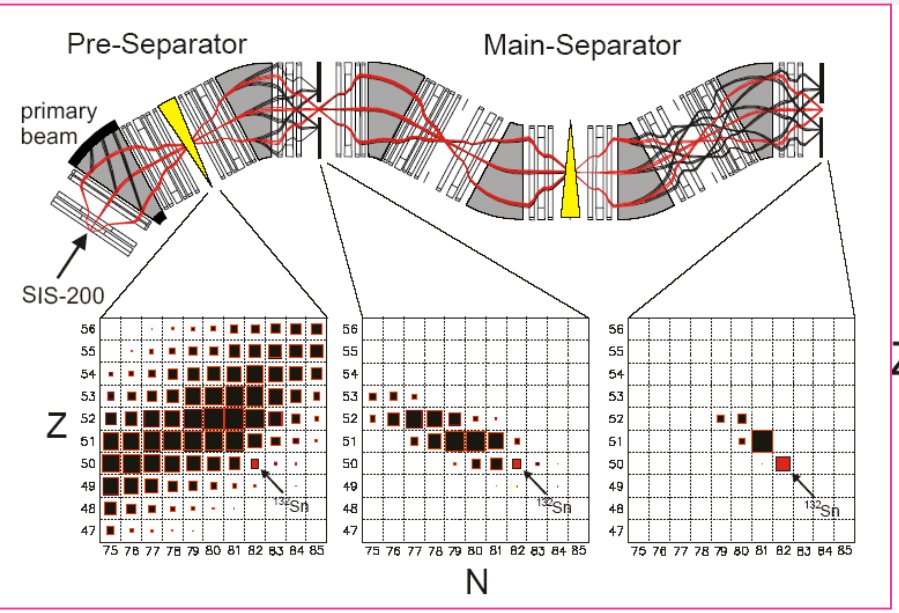
>50 instrumentation sub-projects (MSV)

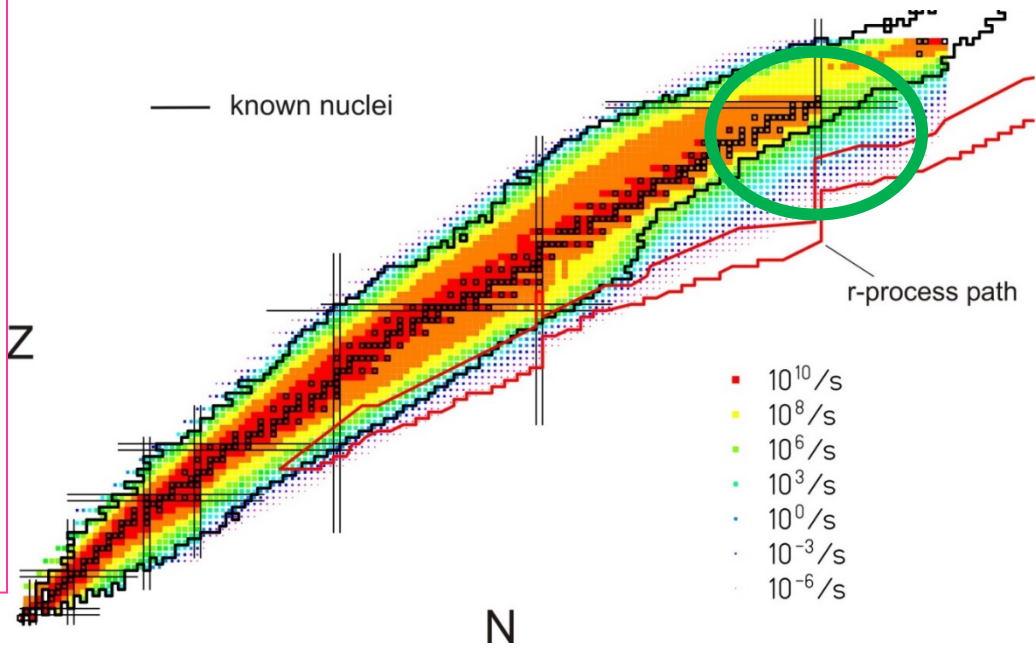
several 1000 major components

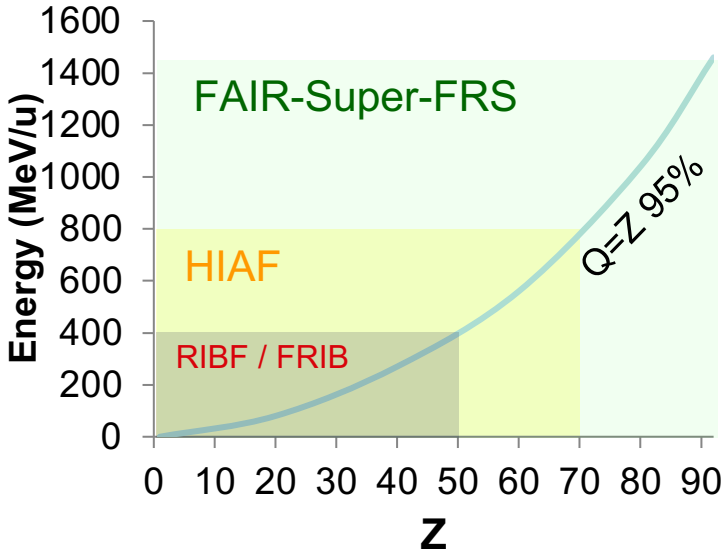
NUSTAR at the FAIR facility



Super-FRS Uniqueness and Competitiveness



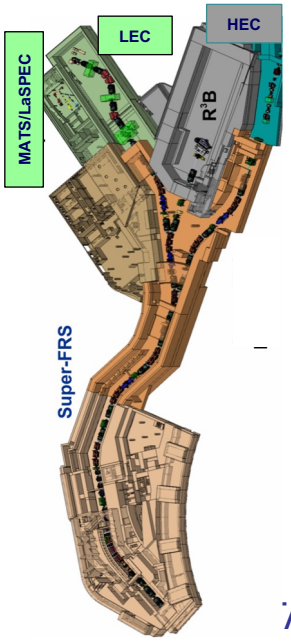


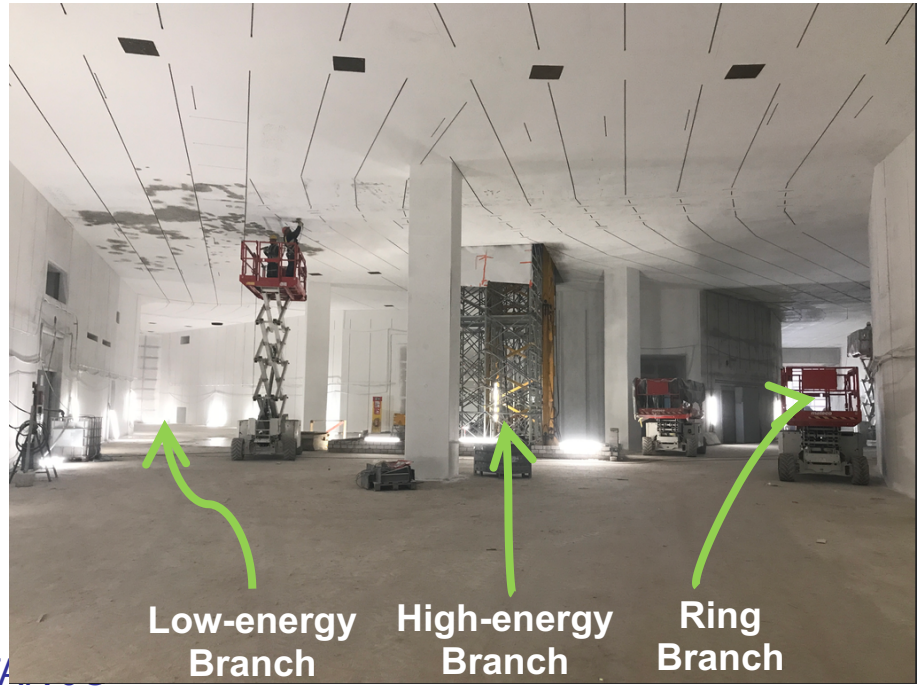


High energies for unique separation and unique experiments
Competitive intensities throughout the periodic table

Facility	U beam int. per spill at production target
previously at GSI	1...2x10^{9}
after the SIS18 upgrade at GSI	8x10^{9}
commissioning phase SIS100	2x10^{10}
final full intensity with SIS100	3x10^{11}

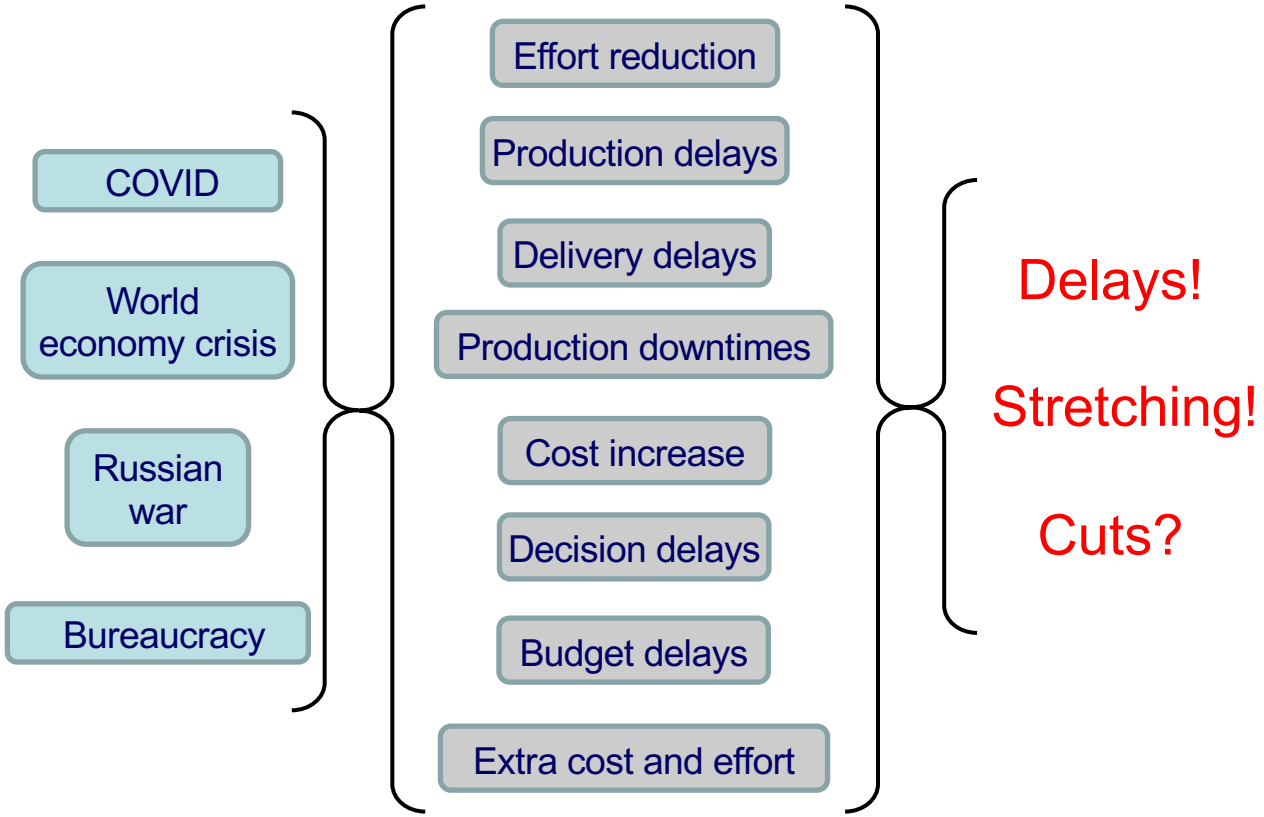
Recent construction highlights



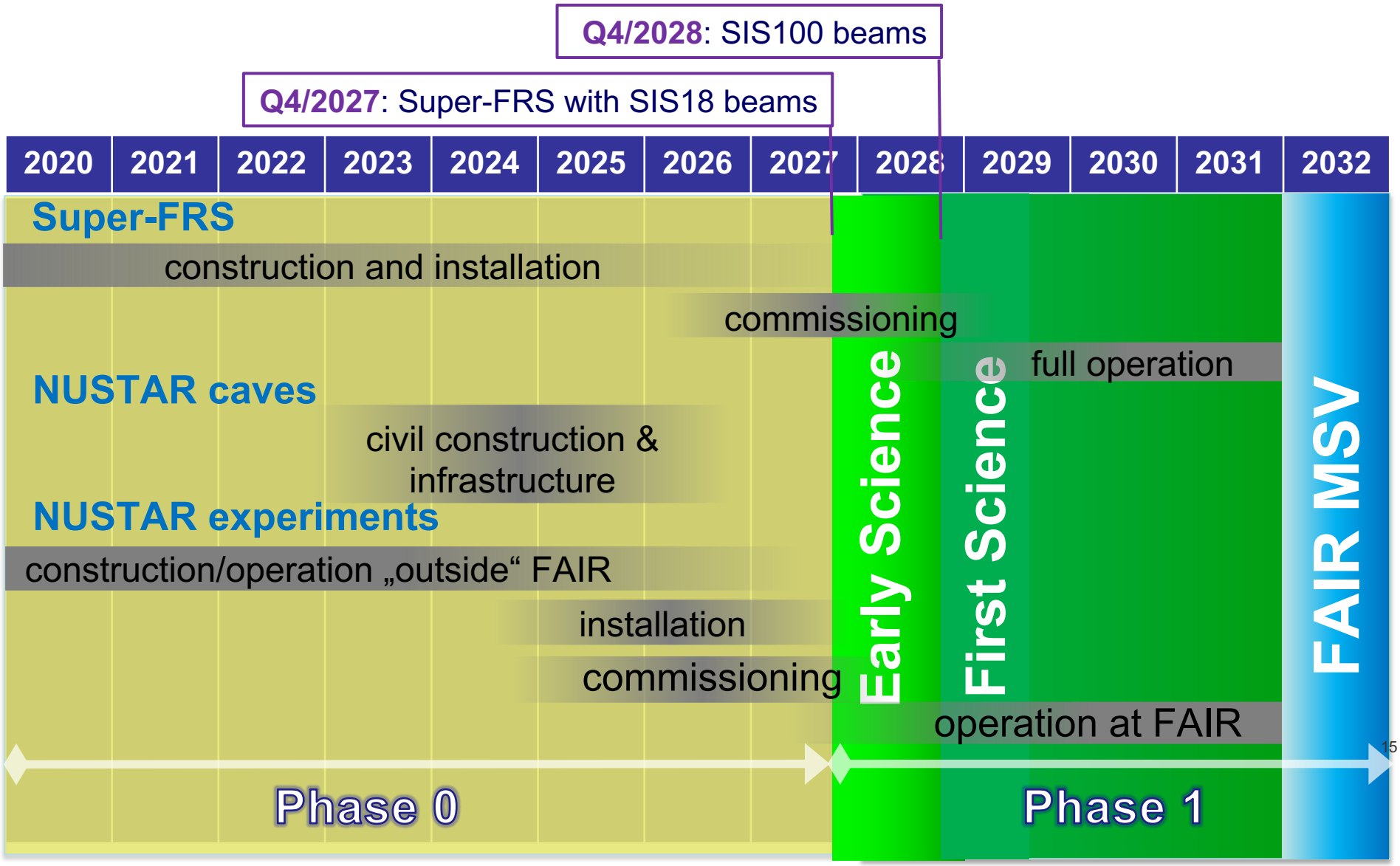


NUSTAR buildings in April

Challenges 2020 … 2022

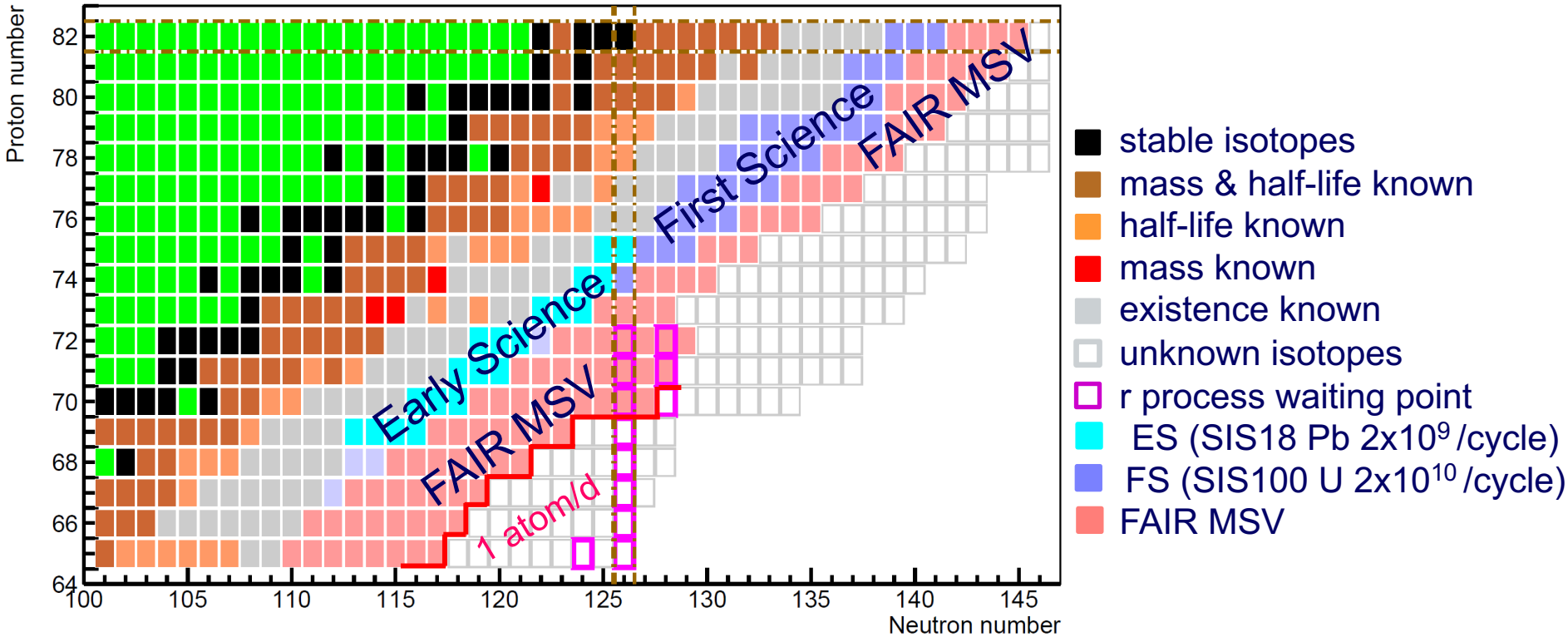


NUSTAR Overall Schedule



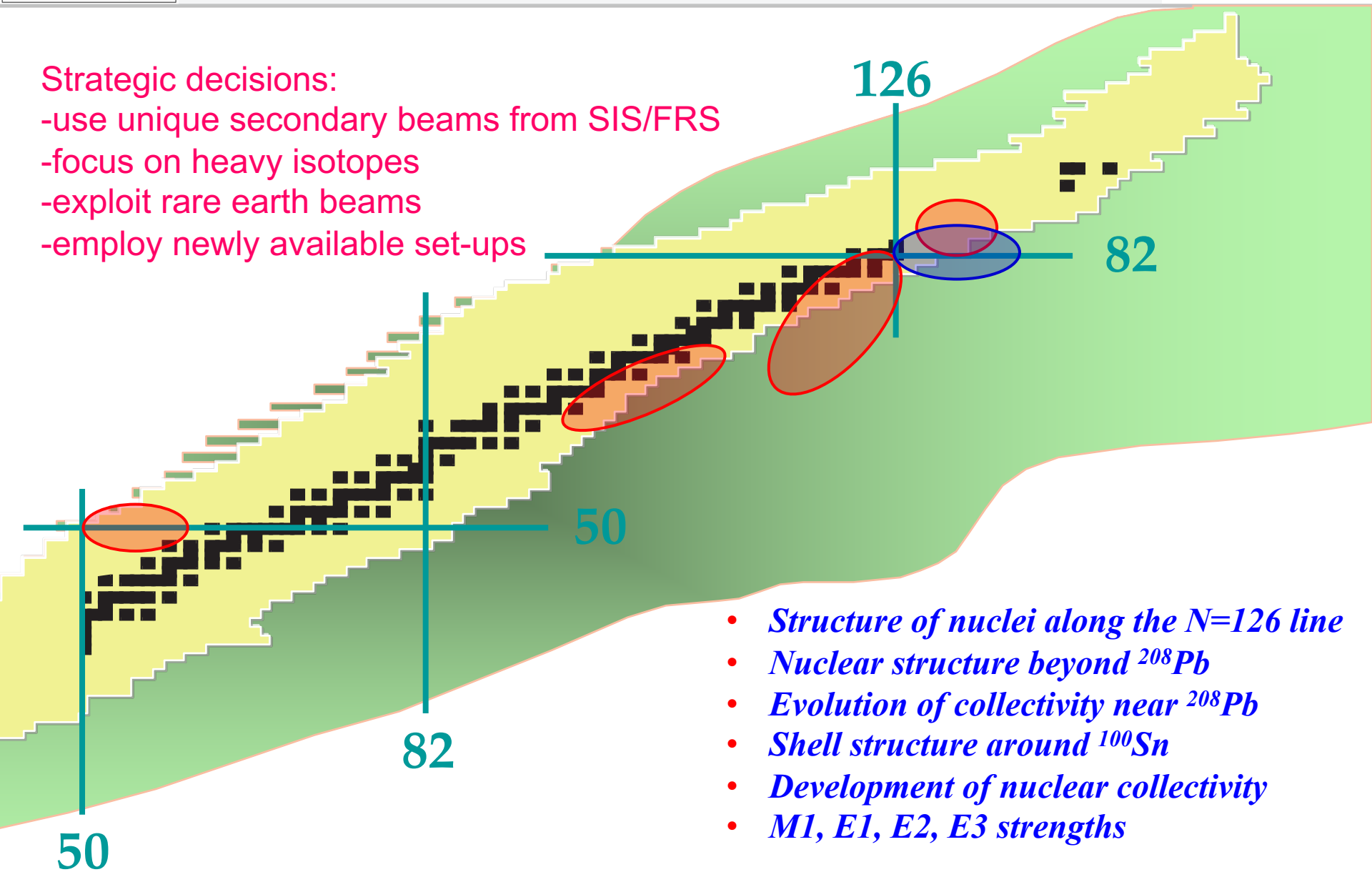
NUSTAR Early Science: New isotopes towards the r-process waiting points at the N=126 shell closure

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**



DESPEC Phase-0 Physics Programme

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

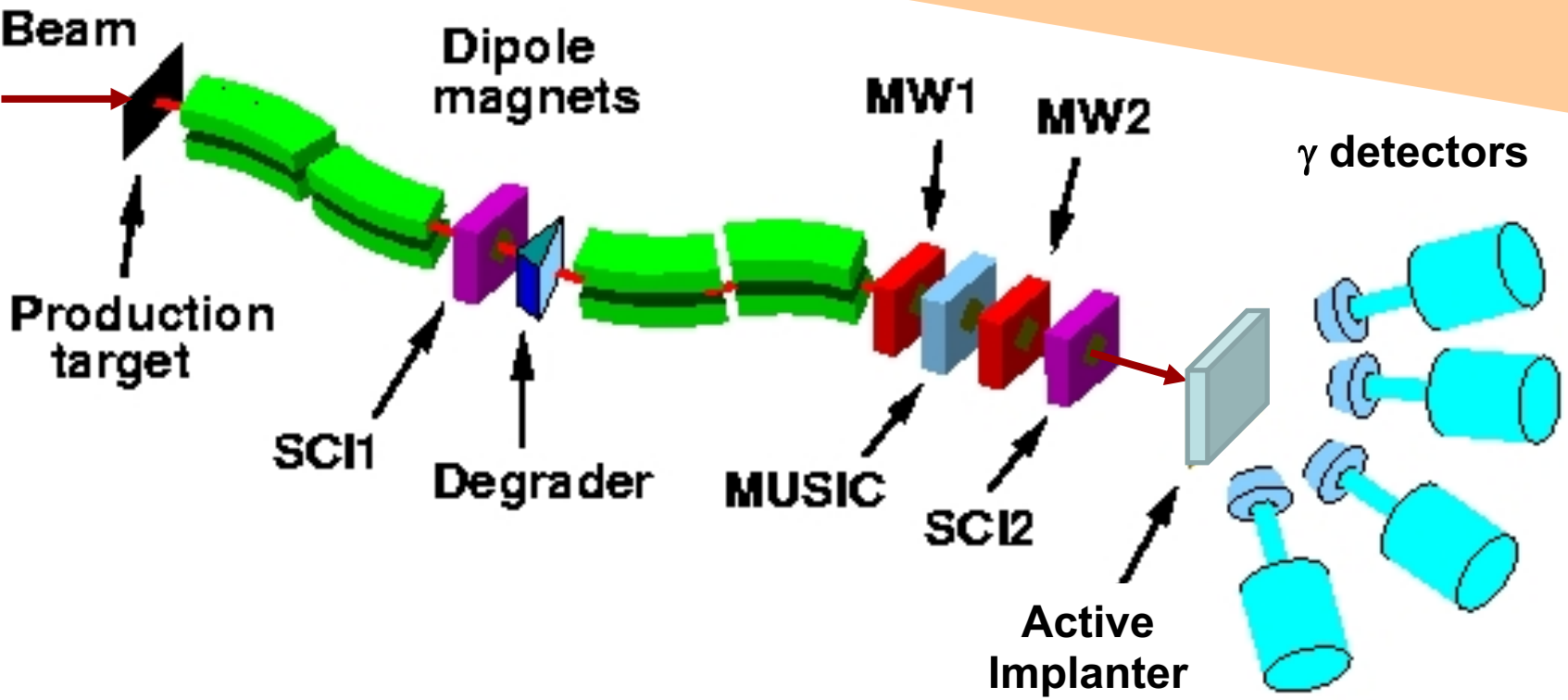
production

selection

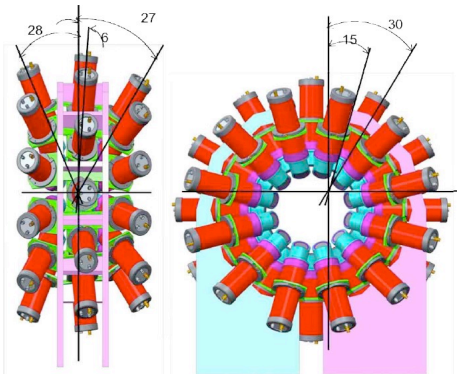
identification

implantation

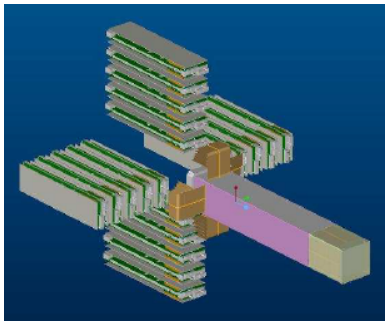
spectroscopy



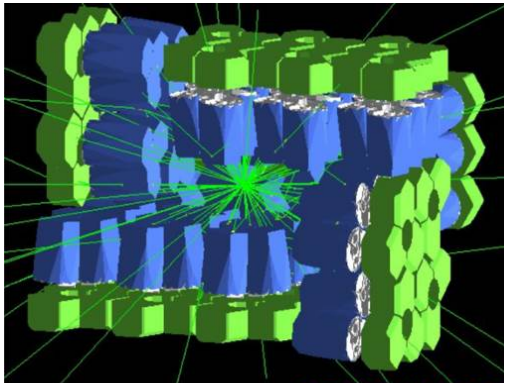
Exploitation plan for Phase-0

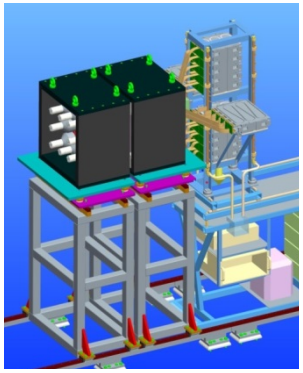


AIDA (narrow config.) used at RIKEN, served as initial implanter in 2020 and 2021. AIDA (wide config.) has been commissioned for 2022 and later.



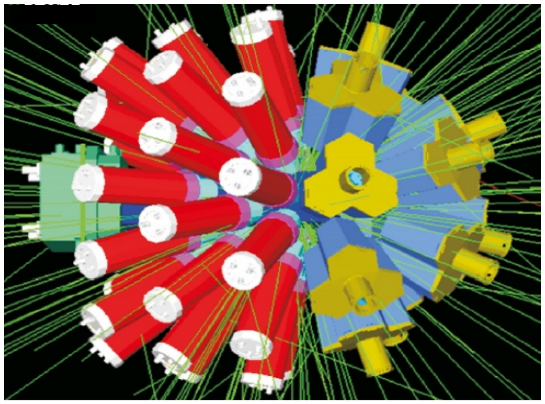
FATIMA used at IFIN-HH, RIKEN and GANIL, has been used for the 1. set-up in 2020/21





DEGAS is under construction and has been commissioned and used for the 2. setup in 2022.

DTAS used at JYFL and RIKEN, was used for the 3. set-up in 2022.

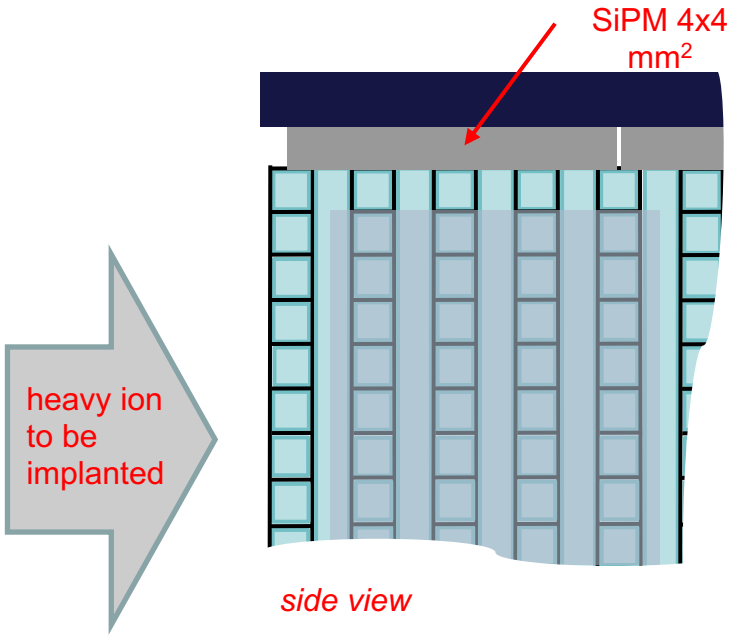


A combined FATIMA+DEGAS setup is planned to be used in 2024

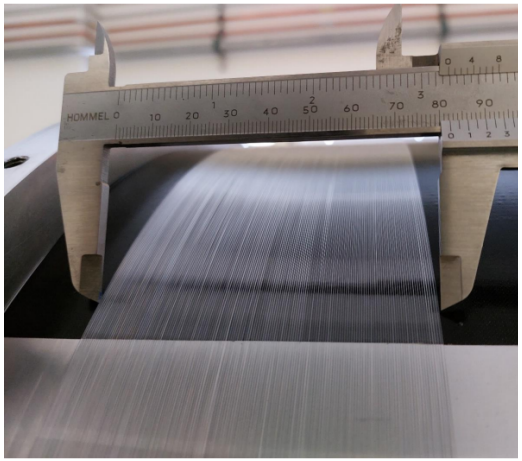
Novel active implanter FIMP complementing AIDA

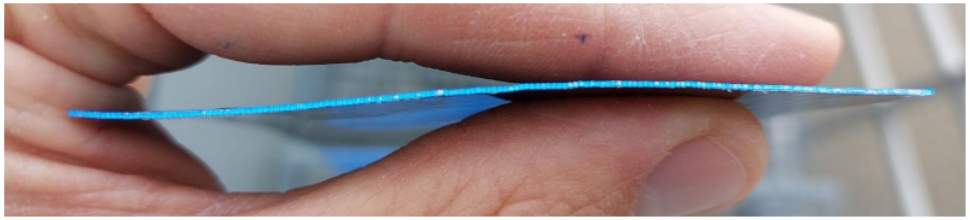
Fiber IMPlanter – FIMP

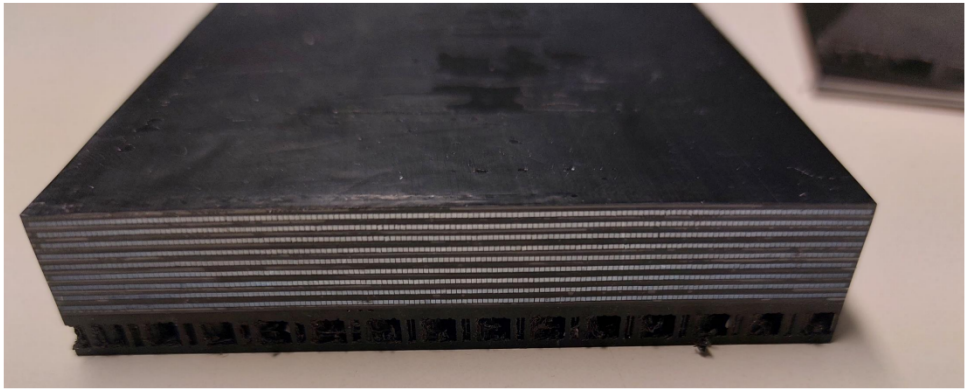
Collaboration with **IMP-CAS Guang-shun Li** and JSI Jelena Vesic



Fibers:
St. Gobain cross section 0.5x0.5 mm²
scintillating core 0.4x0.4 mm²
cladding 0.05 mm



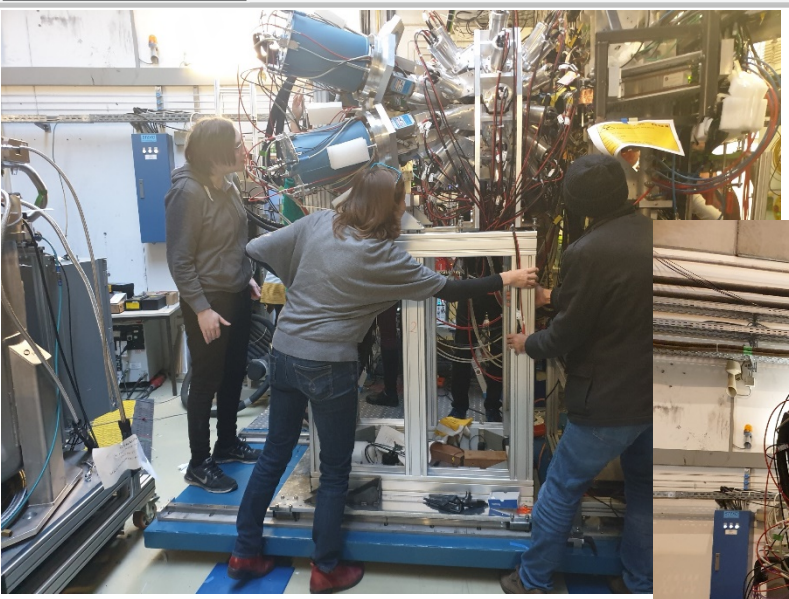


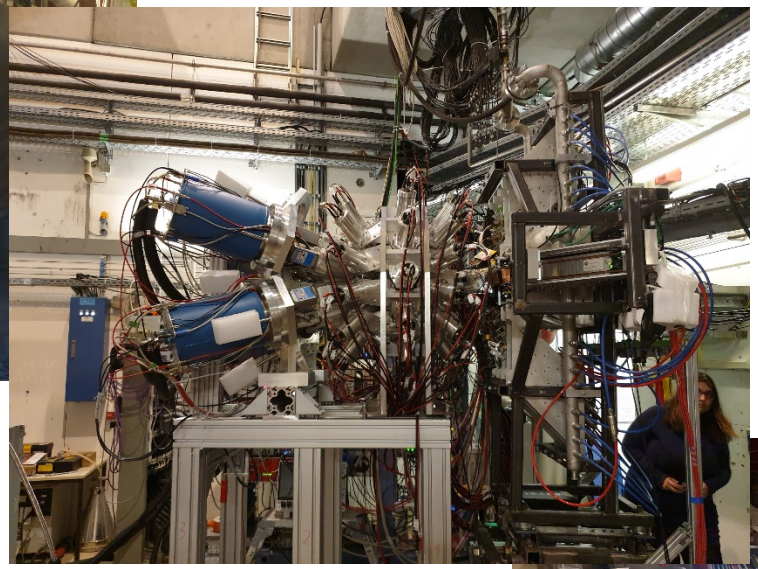


Each SiPM reads 4x8 fibers
Fibers are read on both ends with interleaved SiPMs
This results in 2x2x2 mm³ voxels (granularity 9600)

Expected specs:
-Efficiency: >80% at $E_\beta \geq 500$ keV
-Time resolution: <500 ps at $E_\beta \geq 500$ keV
-Energy resolution: <20% at $E_\beta = 1000$ keV

DESPEC Commissioning beam time





Accelerator Engineering Runs
11.-12-2019

Initial DESPEC Set-up
AIDA + FATIMA +
GALILEO/DEGAS
incl. bPlast and Finger

The NUSTAR answer to Covid-19 from 2020 on: Remote Operation and Cooperative Working

The Virtual Messhütte has been established

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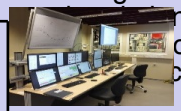

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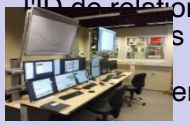
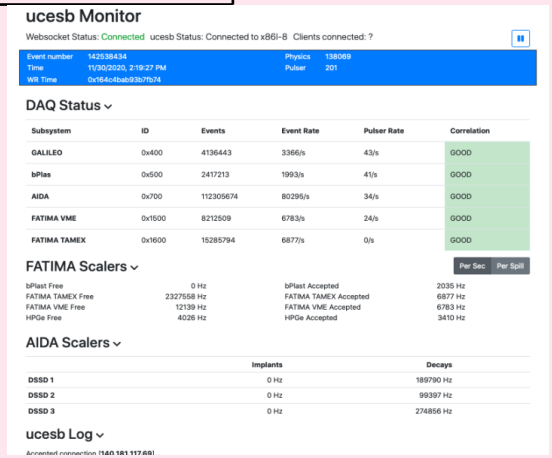
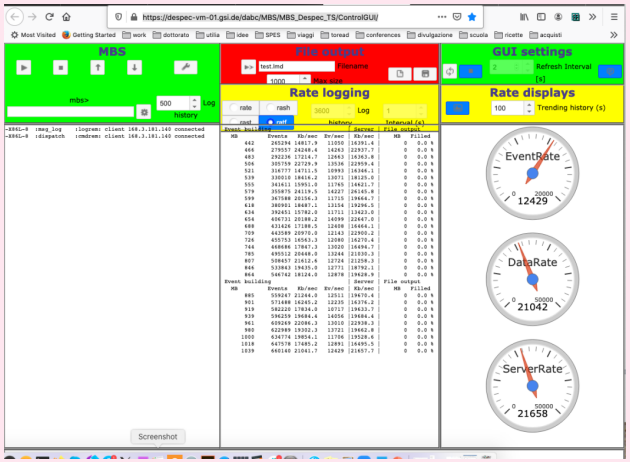


- Remote monitoring and control of detectors/DAQs
- 24/h Zoom sessions with breakout rooms
- E-LOG
- Instant messaging platforms

Experiment control

DAQ rates monitoring
Time sorter control
Time machine correlations
UCESB
FRS scalers
Go4 Online monitoring
Nearline histogramming
Remote oscilloscope
Grafana
Autofill
…





First “real” DeSpec experiment

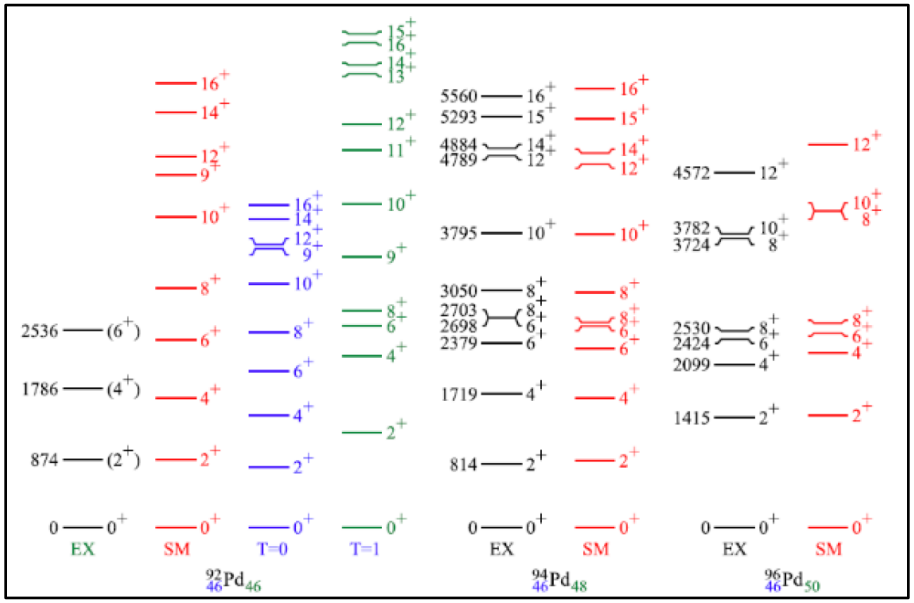
S480 ^{124}Xe beam 9 – 15 March 2020:

Structure of the heaviest N=Z nuclei: Seniority Transitions in ^{94}Pd

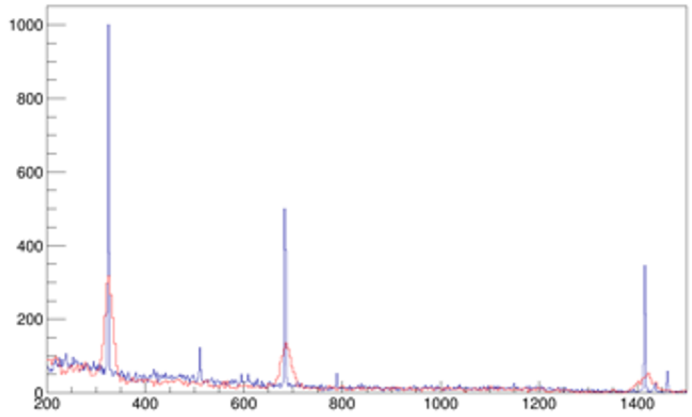
Spokespersons: P. Regan, M. Gorska, B. Cederwall

→ New lifetimes in the ps-to-ns regime

Level schemes of ^{92,94,96}Pd

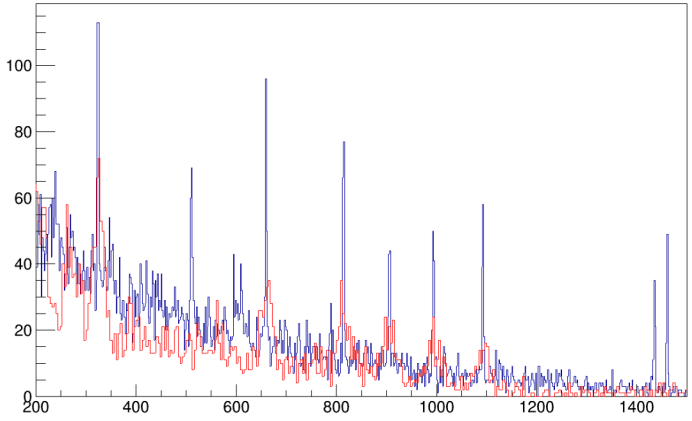


Reference nucleus ^{96}Pd

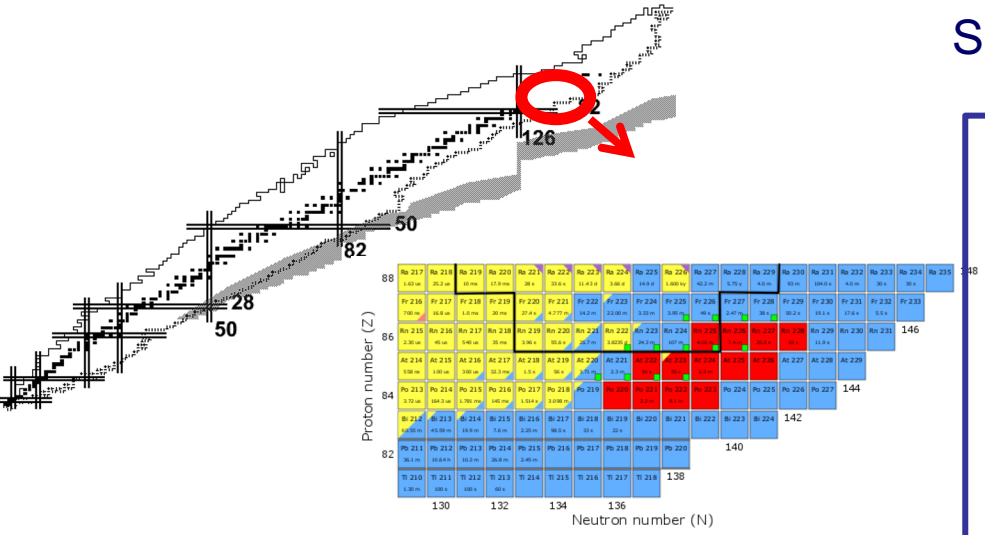


Galileo and FATIMA isomer spectra

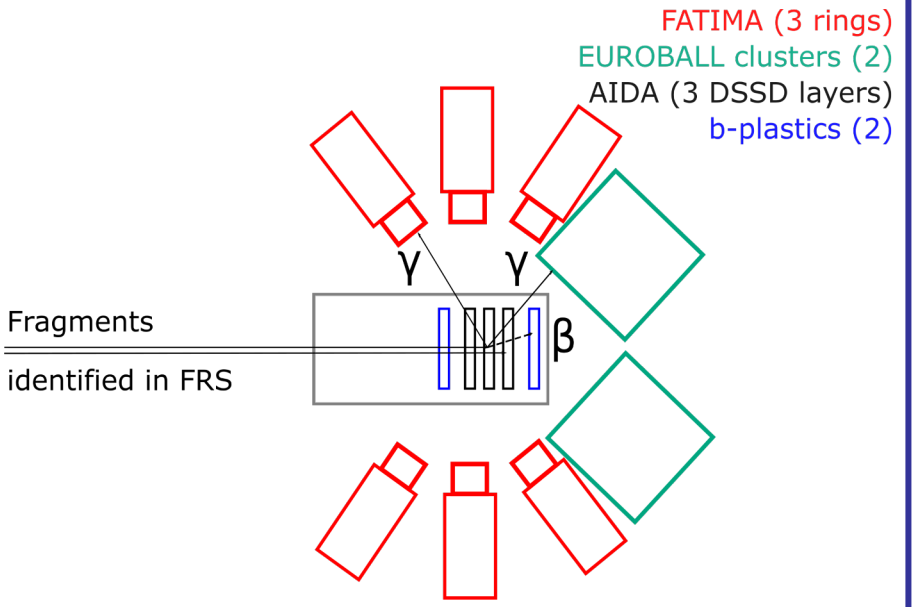
^{94}Pd



S460 Investigation of the A~225 island of octupole deformation



Spokesperson: *G. Benzoni*



1. Octupole deformation around A~225: Study the octupole degree of freedom and quadrupole-octupole correlations at the far end of the IOD

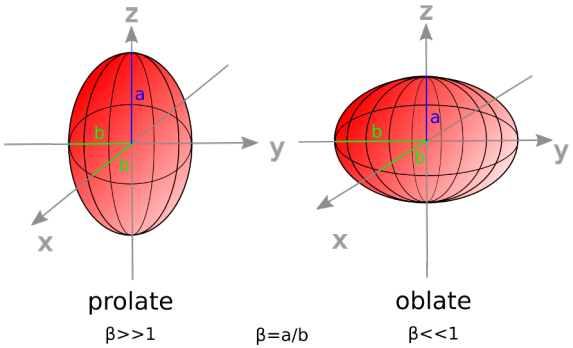
2. Test of nuclear models for r-process: Obtain new beta-decay information beyond N=126

3. Shape isomers in ^{220,222}Po: Prove the existence of super-deformed bands at low excitation energies

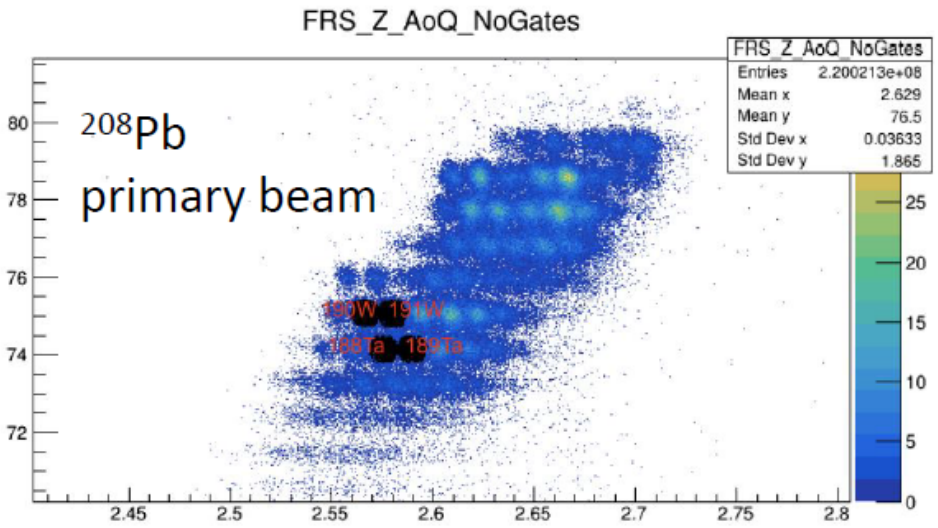
The fragments are implanted in AIDA, the β particles emitted by the β-decays are detected by both AIDA and the two b-plastic scintillators. The γ rays are detected by the FATIMA array and two EUROBALL clusters.

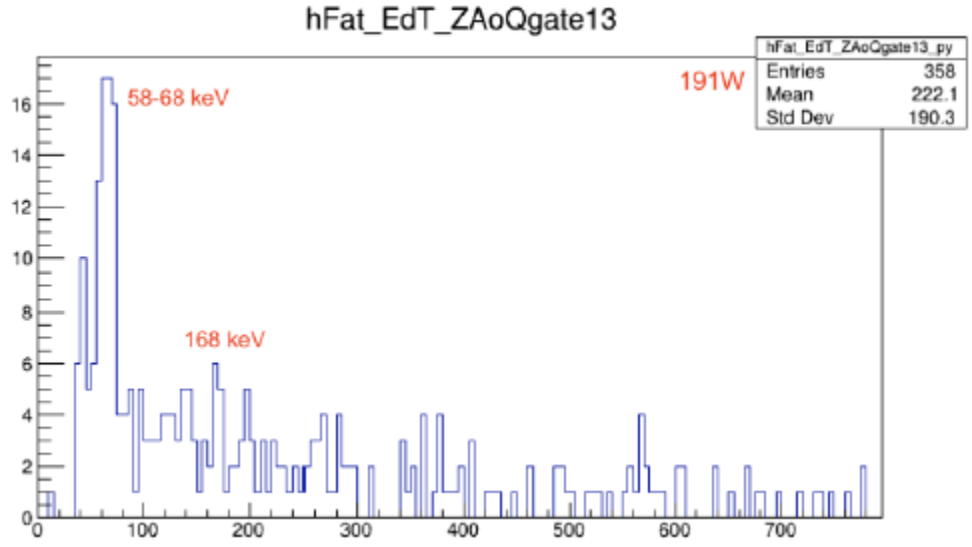
S452 Shape evolution in the Hf-W-Os region

Spokespersons: *V. Werner, P. Regan*



- Shape evolution in the Hf-W-Os region toward magic number N=128
- Transition from prolate to oblate nuclear shapes
- Isomerism and underlying structure relevant for nuclear synthesis and astrophysics
- Beta- and isomer-delayed fast-timing measurements, gamma-ray spectroscopy





DESPEC Phase-0 programme 2022

May 2022: -wide AIDA+DEGAS Set-up

-S450 - Study of N=126 nuclei

γ spectroscopy after isomer and β decay

June 2022: -narrow AIDA+DTAS Set-up

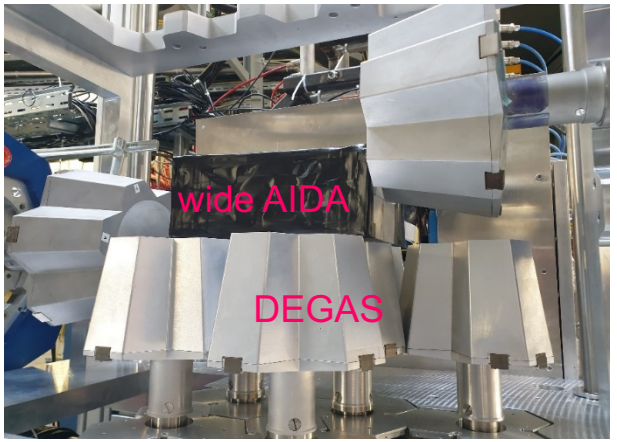
S505 - beta-strength crossing N=126

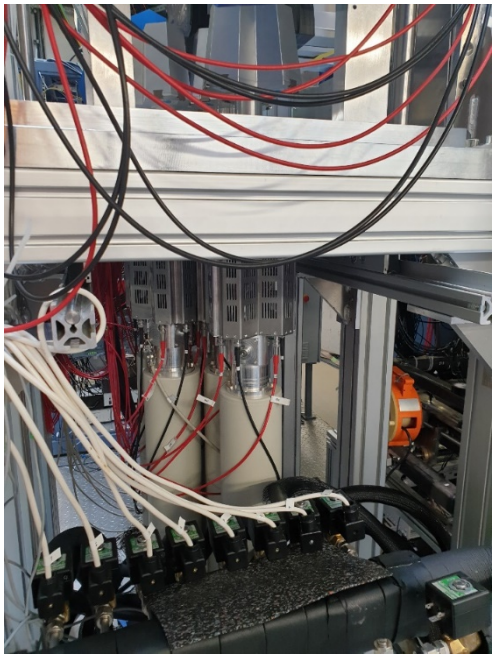
total absorption sprectroscopy

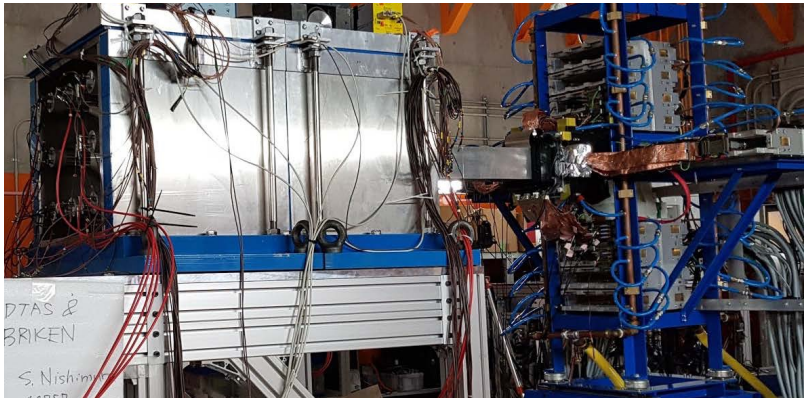
-test and commissioning runs

S497 – DEGAS-10 Slowdown beam setup

S506 – Planar Ge implanter



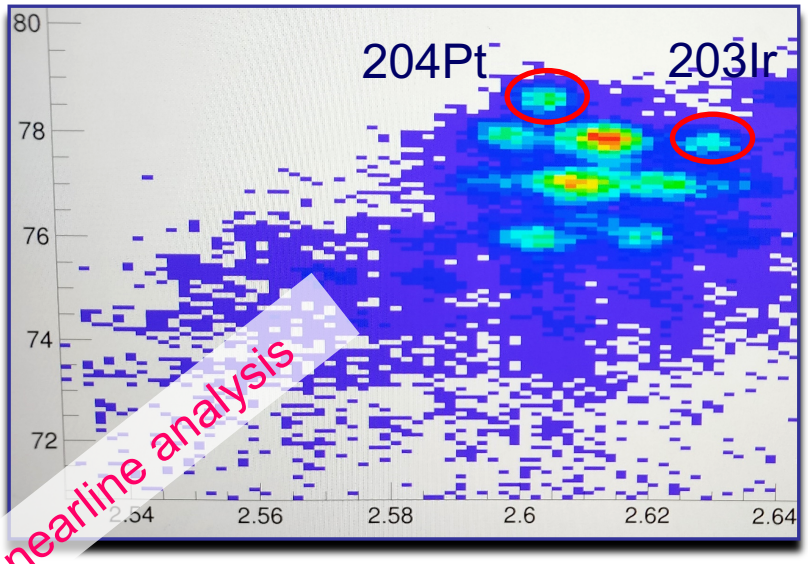




S450 Study of N=126 nuclei: isomeric and beta decays in 202Os and 203Ir

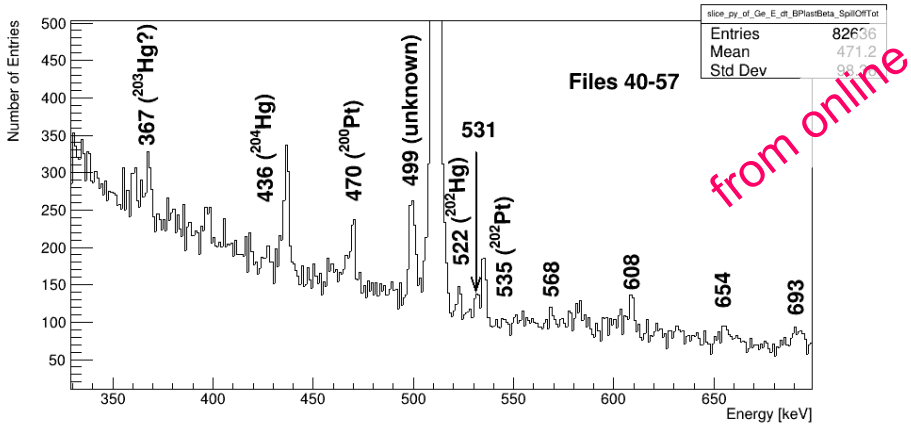
- 10^+, 7^-, 5^- isomers are predicted in ^{202}Os, while a longlived $11/2^-$ is predicted in ^{203}Ir.
- β decay half-lives will be determined and information on excited states in their daughter nuclei ^{202}Ir and ^{203}Pt will be obtained.
- The gained information is important both for our understanding of the shell evolution at N=126 and to provide more robust theoretical predictions on the properties of the r-process path N~126 nuclei.

Spokesperson: *Zs. Podolyak*

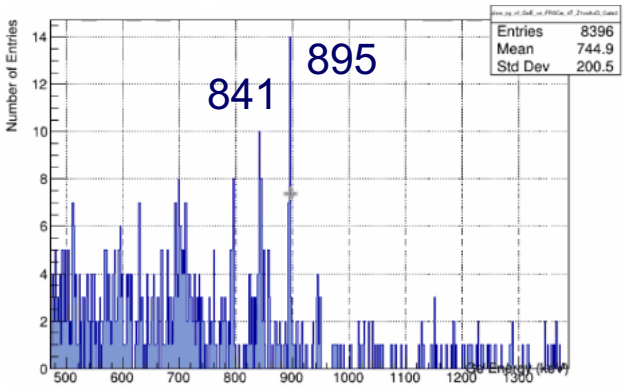


^{203}Ir: 36k (8k in 2006)

from online and nearline analysis



γ spectrum in coincidence with β particles (in bplast)



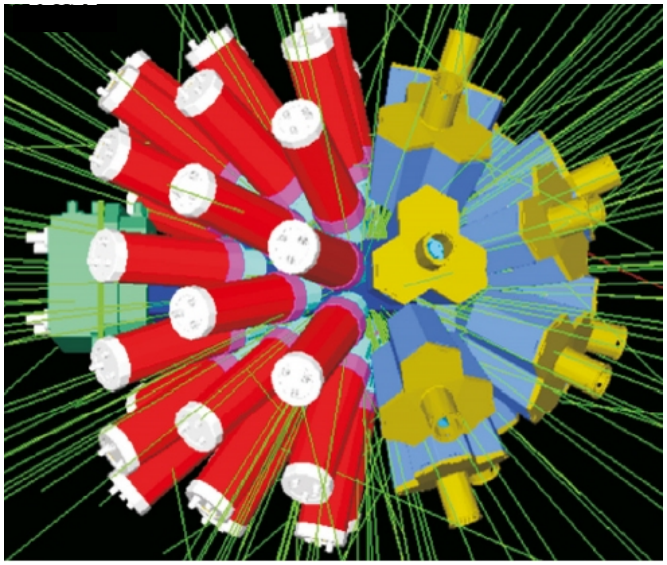
^{203}Ir isomer spectrum

First run in 2024: Structure of neutron-rich rare-earth nuclei far from stability

Spokespersons: H.M. Albers (GSI), T. Grahn (JYFL), C.M. Petrache (Paris), V. Werner (TUD)

- Rare-earth nuclei with N~100 are highly collective
- Many interesting phenomena are to be expected

Perform Spectroscopy and Lifetime (B(E2)) measurements

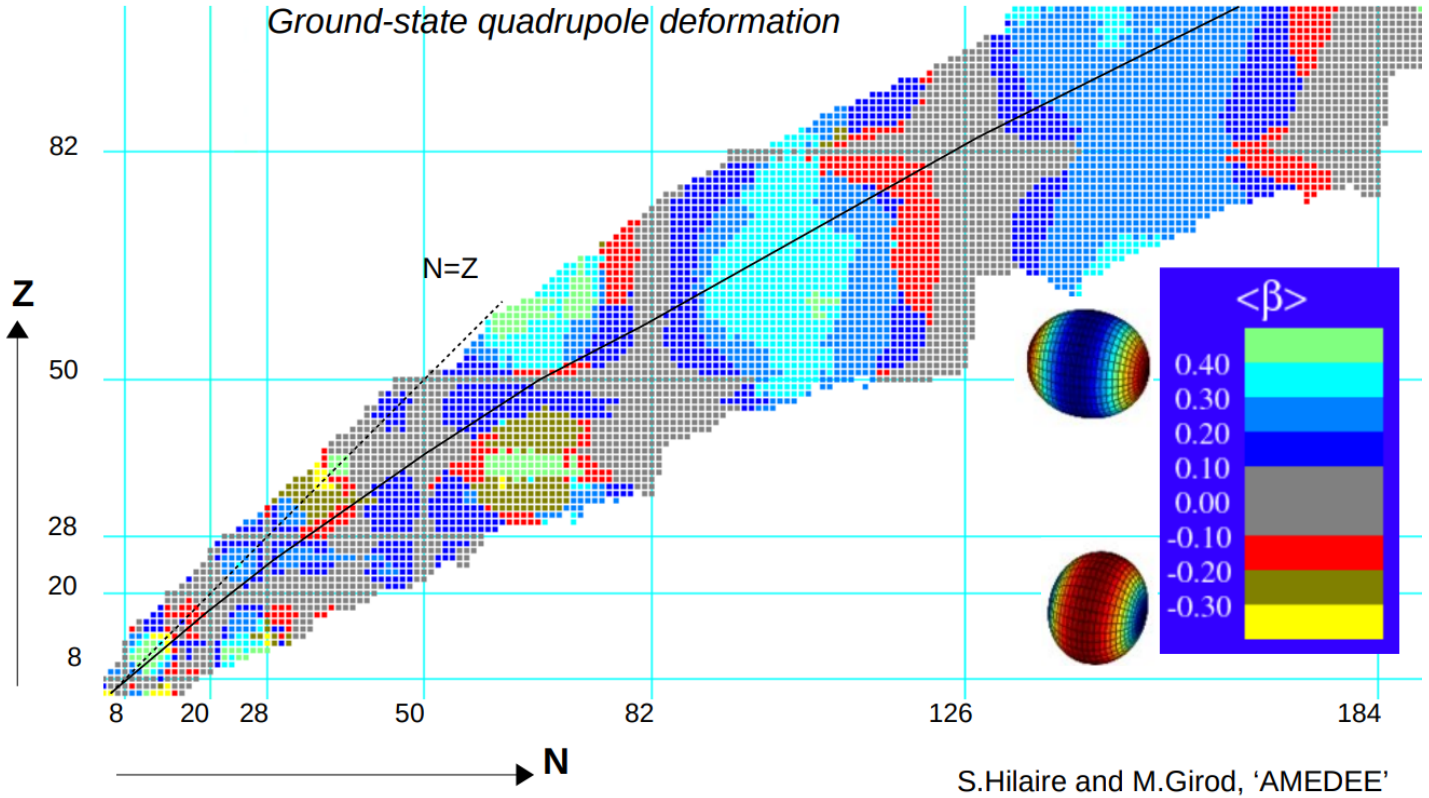


- Unique High-energy ^{170}Er primary beam,
- Clean ion-by-ion separation with FRS
- **New DESPEC hybrid γ-ray array**
- 12 DEGAS HPGes for **high-precision spectroscopy**
  + 36 FATIMA $LaBr_3$ for **fast-timing measurements**

Deformation across the nuclear landscape

Phenomena away from stability

- Exotic decay modes
- Disappearance of magic numbers
- New magic numbers
- Islands of inversion
- Shape transitions
- Shape coexistence
- Exotic shapes
- ...



S.Hilaire and M.Girod, 'AMEDEE'

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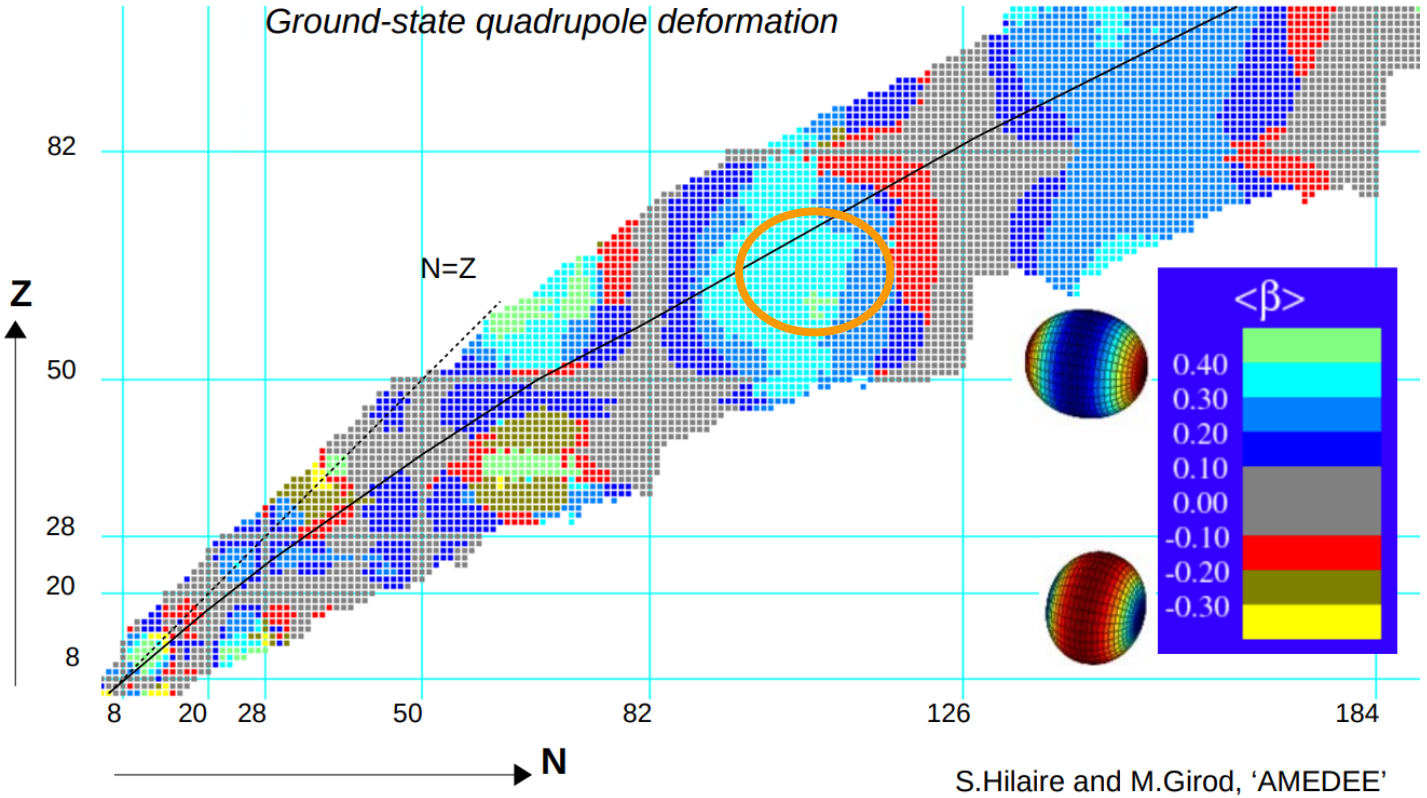
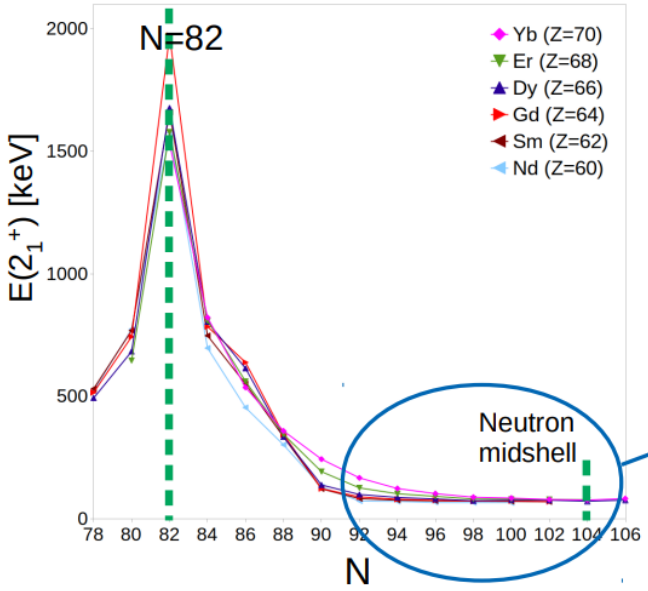
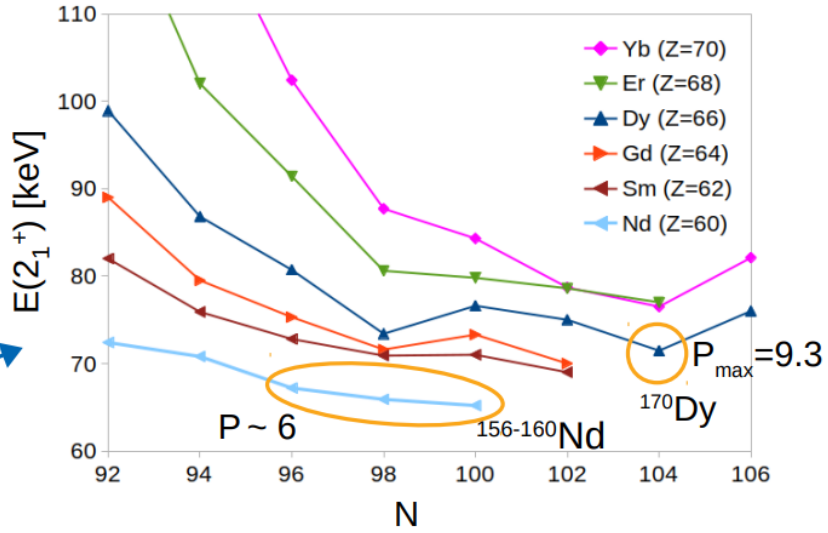


S.Hilaire and M.Girod, 'AMEDEE'

Energy systematics Nd (Z=60) to Er (Z=70)

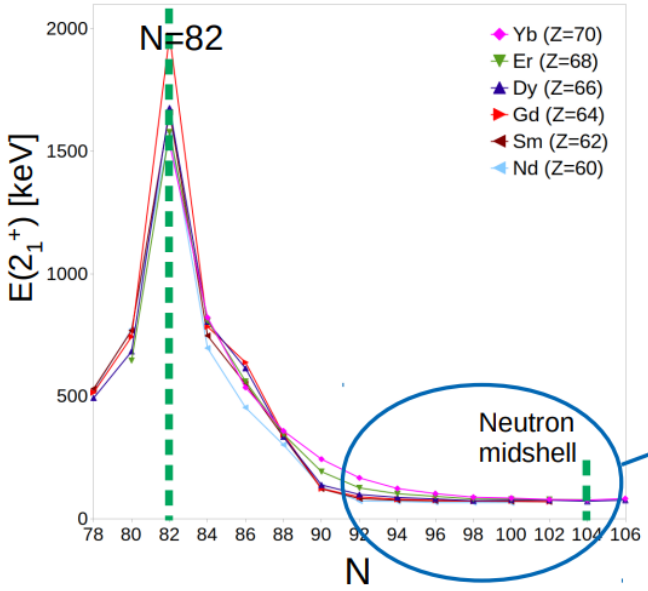


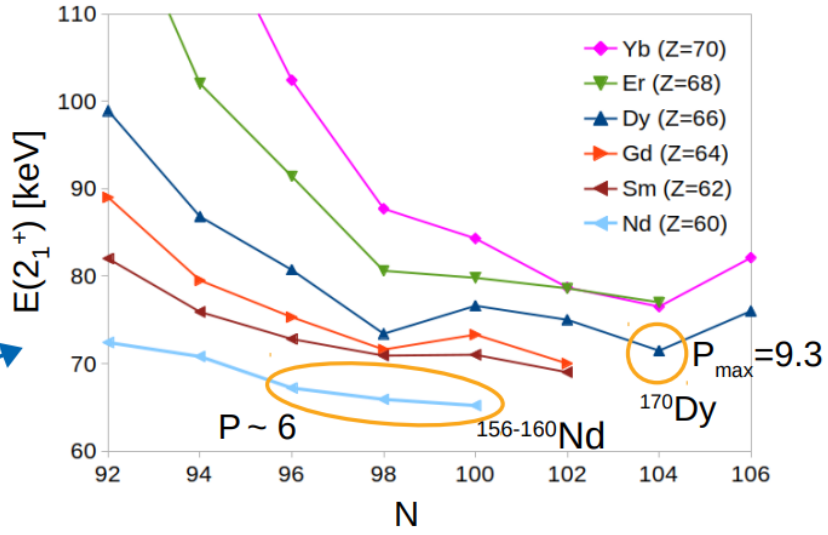


- E(2$_1^+$) ~ J, depends to first order on **deformation** and **pairing**
- **'P-factor'** P = $N_\pi N_\nu/(N_\pi+N_\nu)$ measure of deformation
- Spherical to deformed transition at P~5

- ^{170}Dy equidistant from closed neutron (N=82,126) and proton (Z=50,82) shells, P > 9
- Drop in E(2$_1^+$) approaching mid-shell with increasing $N_\pi N_\nu$ not smooth → **discontinuities**
- Macroscopic properties can be influenced by **'deformed shell gaps'** → **stabilize high deformation**

Energy systematics Nd (Z=60) to Er (Z=70)





- E(2$_1^+$) ~ J, depends to first order on **deformation** and **pairing**
- **'P-factor'** P = $N_\pi N_\nu/(N_\pi+N_\nu)$ measure of deformation
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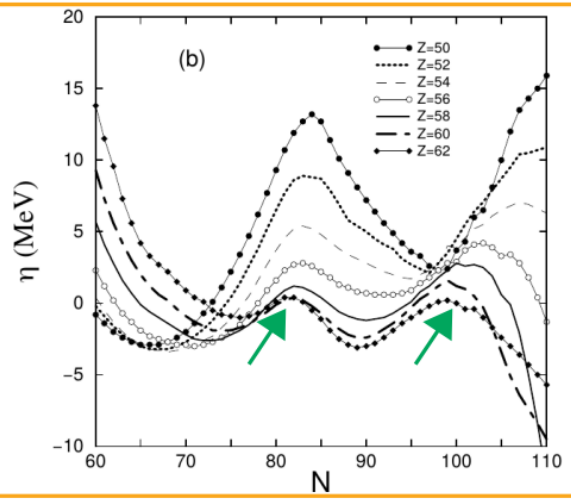
- ***Are deformed subshell closures present?***
- ***Where are they located and what is their nature?***
- ***Where is the highest deformation, and why?***

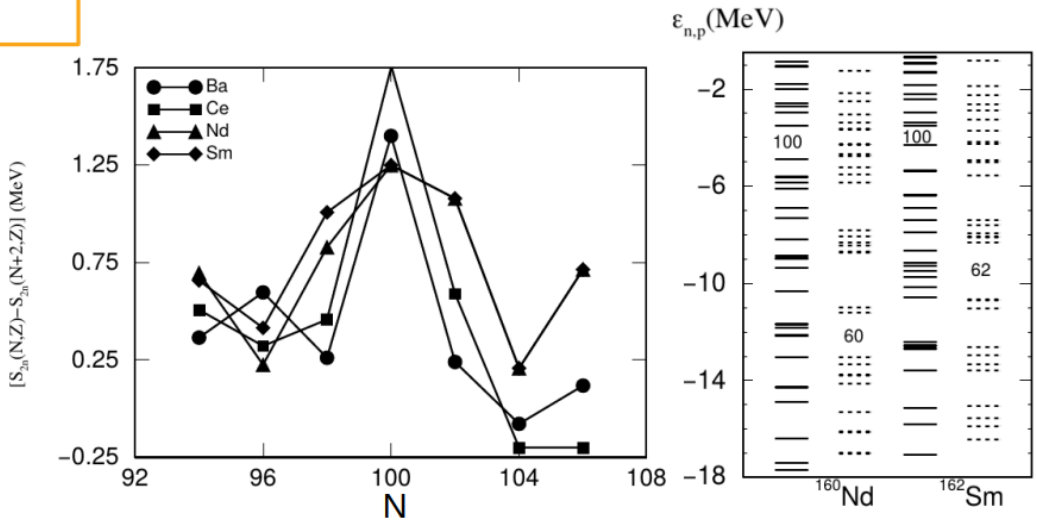
Early predictions of new magic number at N=100

- Infinite nuclear matter (INM) model
- Satpathy *et al.*, J. Phys. G: Nucl. Part. Phys. 30, 771 (2004)
  - Ground state considered as perfect sphere plus residual 'local energy' η
  - η represents energy due to **shell correction, deformation,** diffuseness, Coulomb exchange



- Height and width of Gaussian is measure of magicity
- **New island of stability** at (N,Z) = (100,62)

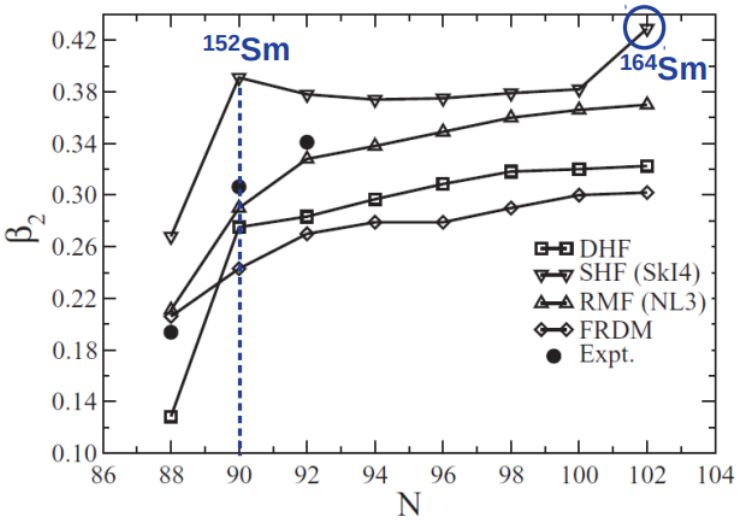
- Relativistic Mean Field (RMF) calculations, same work
- Varied number of harmonic oscillator shells and deformation parameter β_0 + BCS pairing



- S_{2n} and single-particle spectra → **shell gap at N=100**

Sm (Z=62) isotopic chain

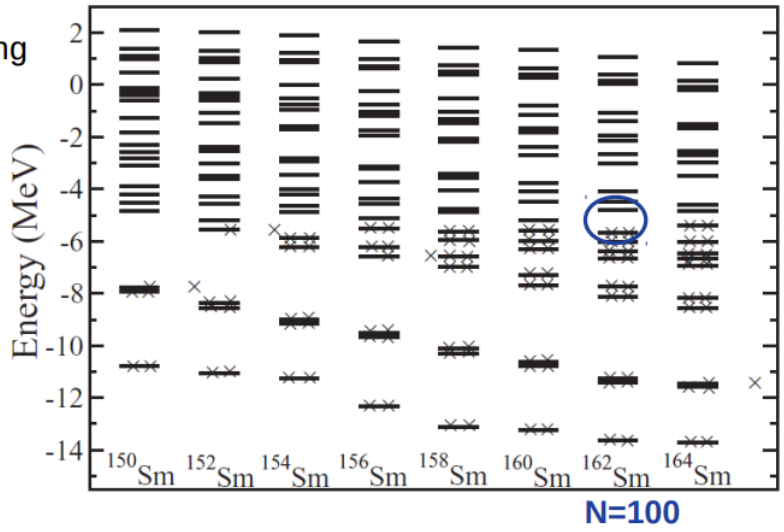
- Quadrupole deformation calculated within self-consistent mean-field models for neutron-rich Sm isotopes, S.K. Ghorui *et al.*, Phys. Rev. C 85, 064327 (2012)
  - → DHF (deformed Hartree-Fock) with surface delta interaction
  - → Skyrme Hartree-Fock (SHF) using SkI4 parameters with BCS pairing
  - → RMF (Relativistic Mean Field) with NL3 parameter set
  - → plus FRDM (Finite Range Droplet Model)



- → Sudden increase of β_2 at N=88-90
- → SHF predicts jump at ^{164}Sm
- → No experimental data beyond N=92

S.K. Ghorui *et al.*, Phys. Rev. C 85, 064327 (2012)

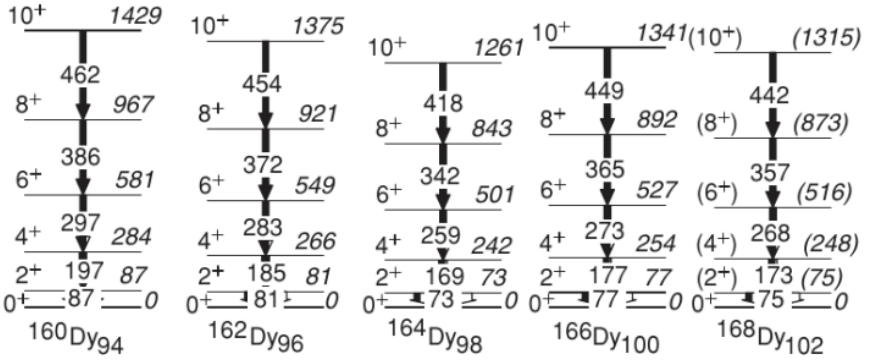
Prolate-deformed neutron orbits

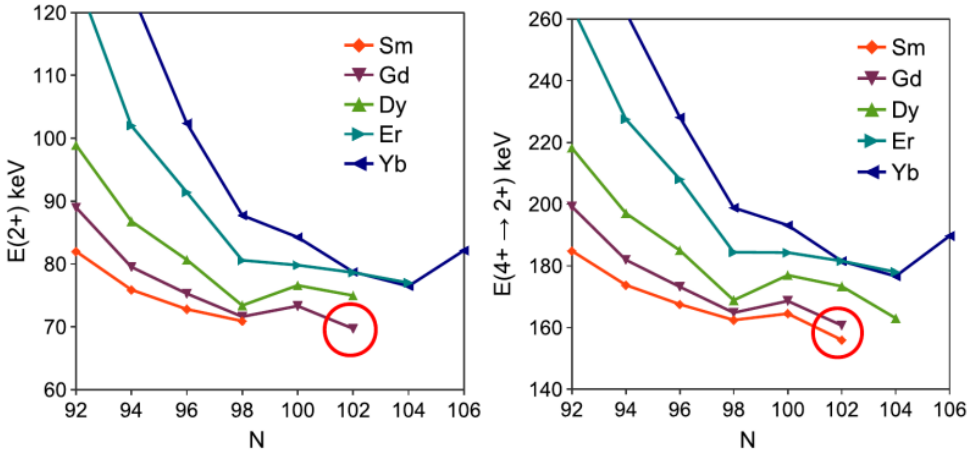


- → Larger gap in neutron Fermi surface for ^{162}Sm compared to N=98 and N=102 neighbours
- **Indication of deformed shell gap at N=100**

Yrast states in N=102 isotones

- Yrast band in ^{168}Dy identified at LNL
- P.-A. Söderström *et al.*, Phys. Rev. C 81, 034310 (2010)
- Multinucleon transfer reaction products identified using PRISMA, ^{82}Se beam impinging on ^{170}Er target
- γ transitions measured with CLARA array (25 HPGe Clovers)
- → **discontinuity persists to high spin**





- N=102 isotones ^{164}Sm and ^{166}Gd studied at RIKEN
- Z. Patel *et al.*, Phys. Rev. Lett. 113, 262502 (2014)
- In-flight fission of ^{238}U beam on ^{9}Be target
- PID → BigRIPS and ZeroDegree spectrometers
- γ rays measured using EURICA (84 HPGe)
- Low-lying transitions in ^{164}Sm and ^{166}Gd observed depopulating (6-), 600- and 950-ns isomers
- Increase in ground-band energies for ^{164}Gd and ^{162}Sm → **evidence for N=100 deformed shell gap**

Astrophysical r-process

- About 50% of nuclei with Z>26 produced in *r*-process nucleosynthesis
- Formation of peak at A~160 area of active research

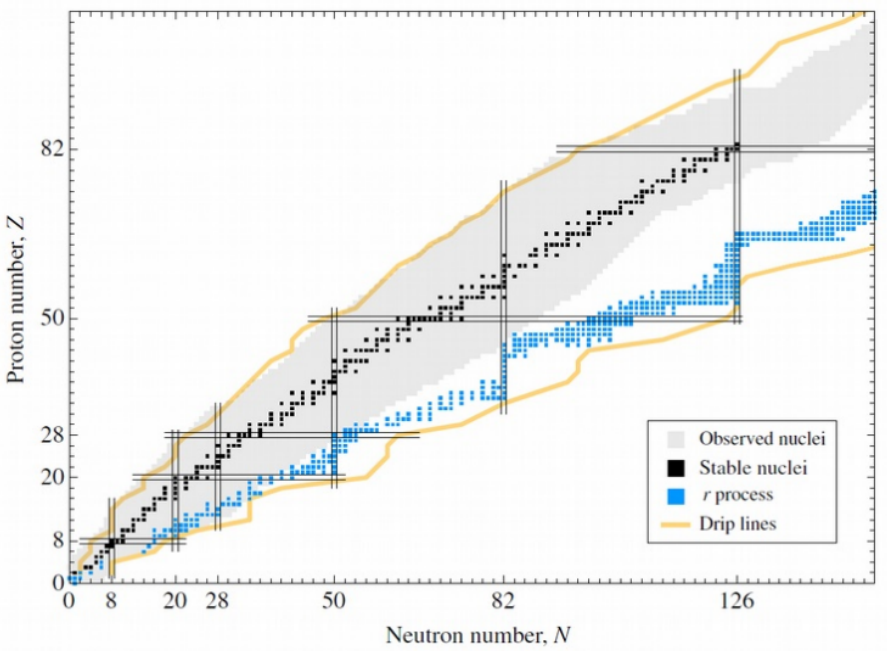
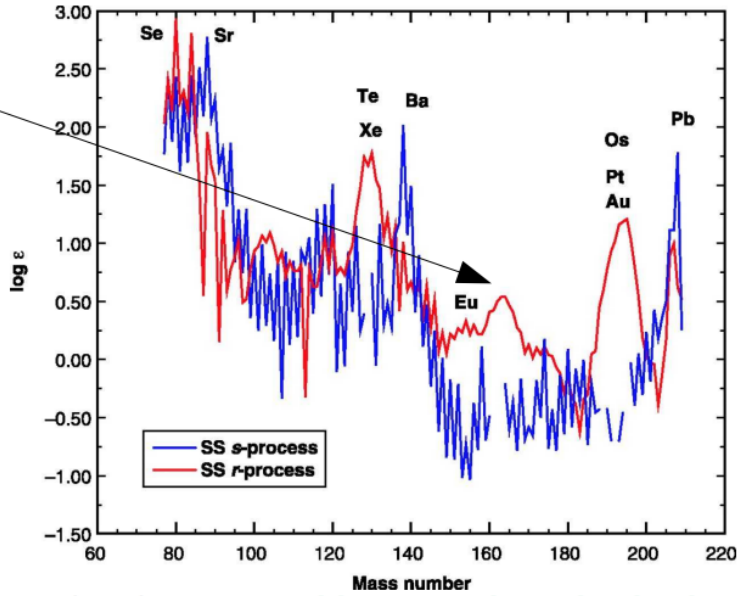


Figure adopted from Tang *et al.*, Phys. Rev. Lett. 124, 062502 (2020)
r-process nuclei: Mumpower *et al.*, Astrophys. J. 869, 14 (2018)

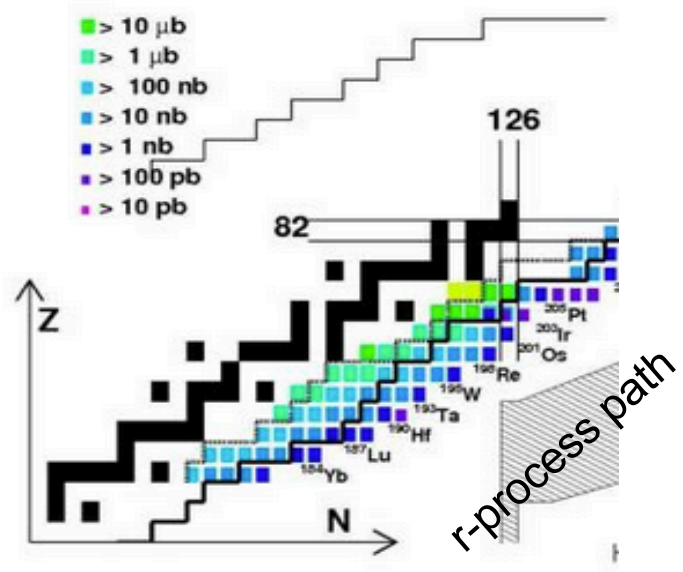
Sneden and Cowan, Science 299, 5603 (2003)



- *r*-process abundances **sensitive to nuclear physics input**
  - Masses, β-decay rates, n-capture rates,...
    (e.g. Arcones and Martínez-Pinedo, Phys. Rev. C 83, 045809 (2011), M.R. Mumpower *et al.*, Phys. Rev. C 85, 045801 (2021))
- **Unknown region of nuclear chart!**

Phase-0 strategy for N=126

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

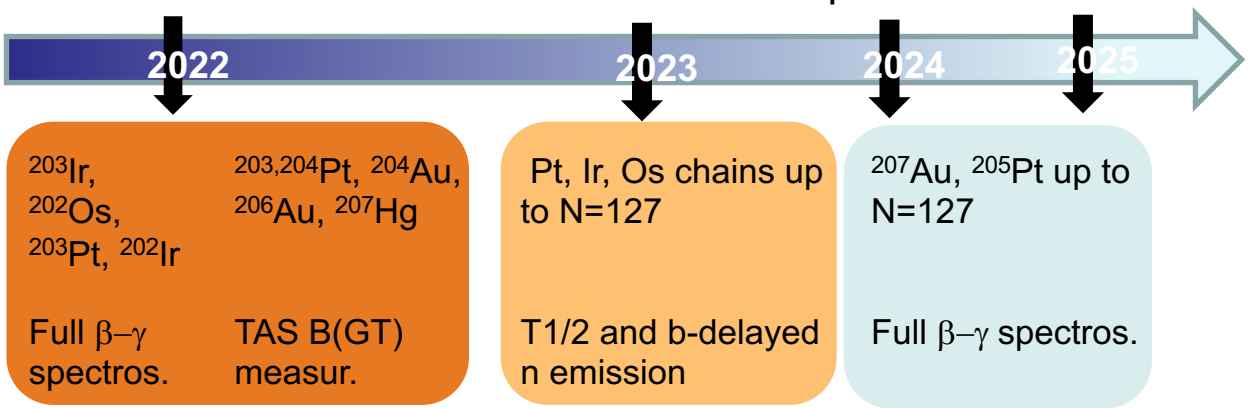


N=125-127 isotones are at reach

R-process A~195 abundance peak fed by nuclei lying around N=126

- Exact **astrophysical location** of the r-process path depends on parameters such as number of available neutrons and lifetimes
- Required input to constrain theory:

- Half-lifes and Pn values determination
  ➔ Measurements possible down to nb level
- Role of First Forbidden transitions
  ➔ Spectroscopy details required
  ➔ Accessible at present at 10 nb level
- Access to B(GT)
  ➔ Accessible at present at 10 nb level



Conclusions

- NUSTAR/DESPEC at GSI/FAIR enables unique and important contributions to our understanding of the atomic nucleus
- Planned and available instrumentation is state-of-the-art
- Execution of DESPEC Phase-0 experiments at GSI has started recently (hindered but not stopped by the corona pandemic)
- A strong experiment programme emphasizing on heavy exotic nuclei is planned for the coming years at GSI until the early implementation of FAIR will start

Be happy: A new golden era of nuclear structure physics is starting with FRIB in the US, RAON in Korea, HIAF in China and FAIR in Germany

Thank You

Thanks to:

G. Aggez, H. Albers, S. Alhomaidhi, T. Arici, M. Armstrong, A. Banerjee, G. Bartram, G. Benzoni, B. Cederwall, Zh. Chen, M. Chishti, B. Das, T. Davinson, M. Gorska, O. Hall, P. Herrmann, D. Hien, S. Jazrawi, P.R. John, C. Jones, R. Kern, I. Kojouharov, P. Koseoglou, G. Kosir, N. Kurz, G.-s. Li, M. Mikolajczuk, A.K. Mistry, B.S. Nara Singh, N. Hubbard, Zs. Podolyak, M. Polettini, P. Regan, M. Rudigier, E. Sahin, H. Schaffner, A. Sharma, A. Sood, J. Vesic, J. Wiederhold, K. Wimmer, A. Yaneva, G. Zhang

...and many more from the **DESPEC Collaboration, FRS Group and NUSTAR Beam Team**