A detailed wireframe model of a particle accelerator, showing a large, oval-shaped ring structure with various internal components and smaller structures extending from the main ring.

Exploring the extremes with NUSTAR

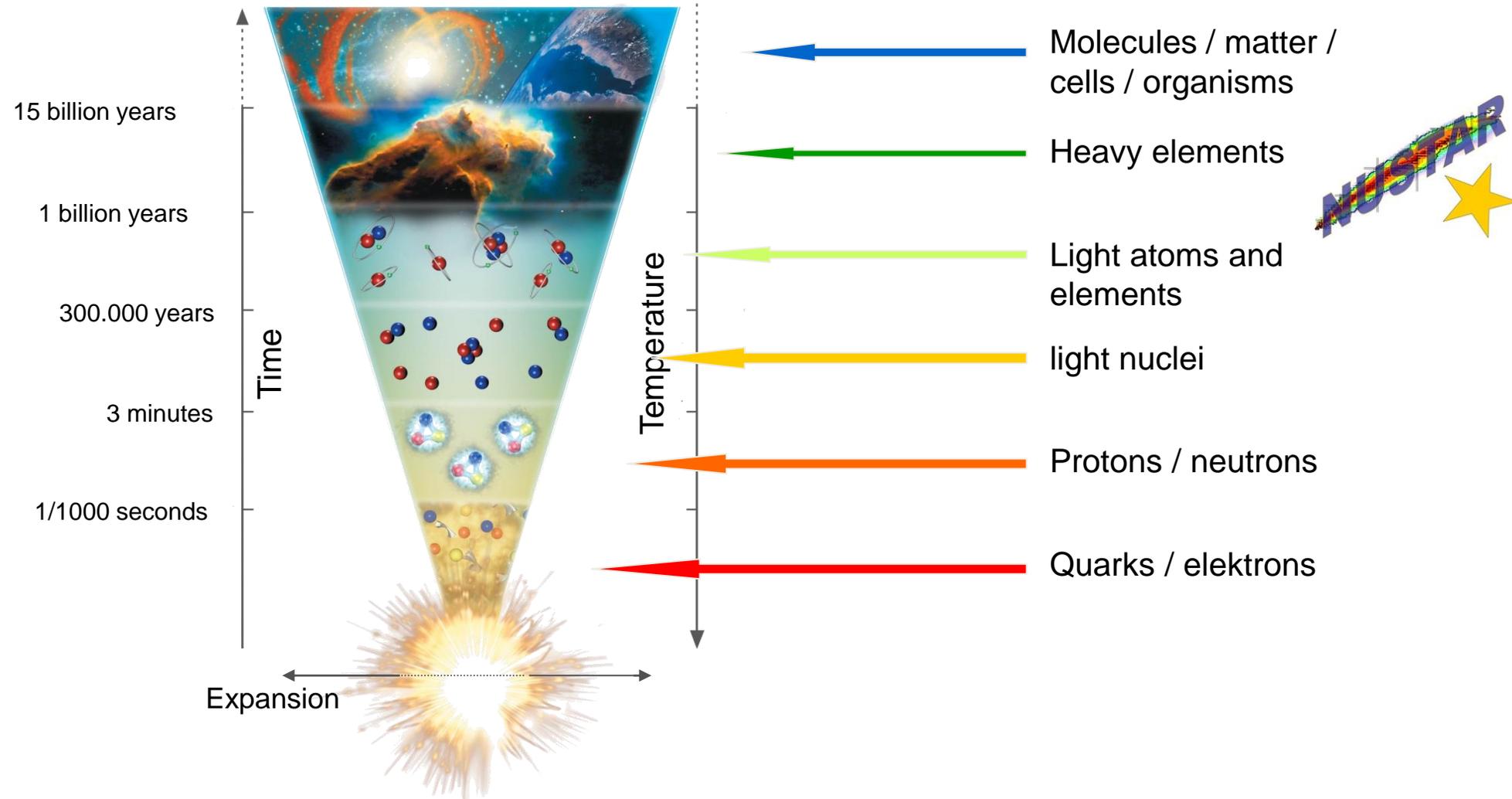
Alexander Herlert (FAIR/GSI)

Theme Meeting on FAIR-Science

Panjab University, Chandigarh, India

April 23, 2025

Understanding the universe



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?

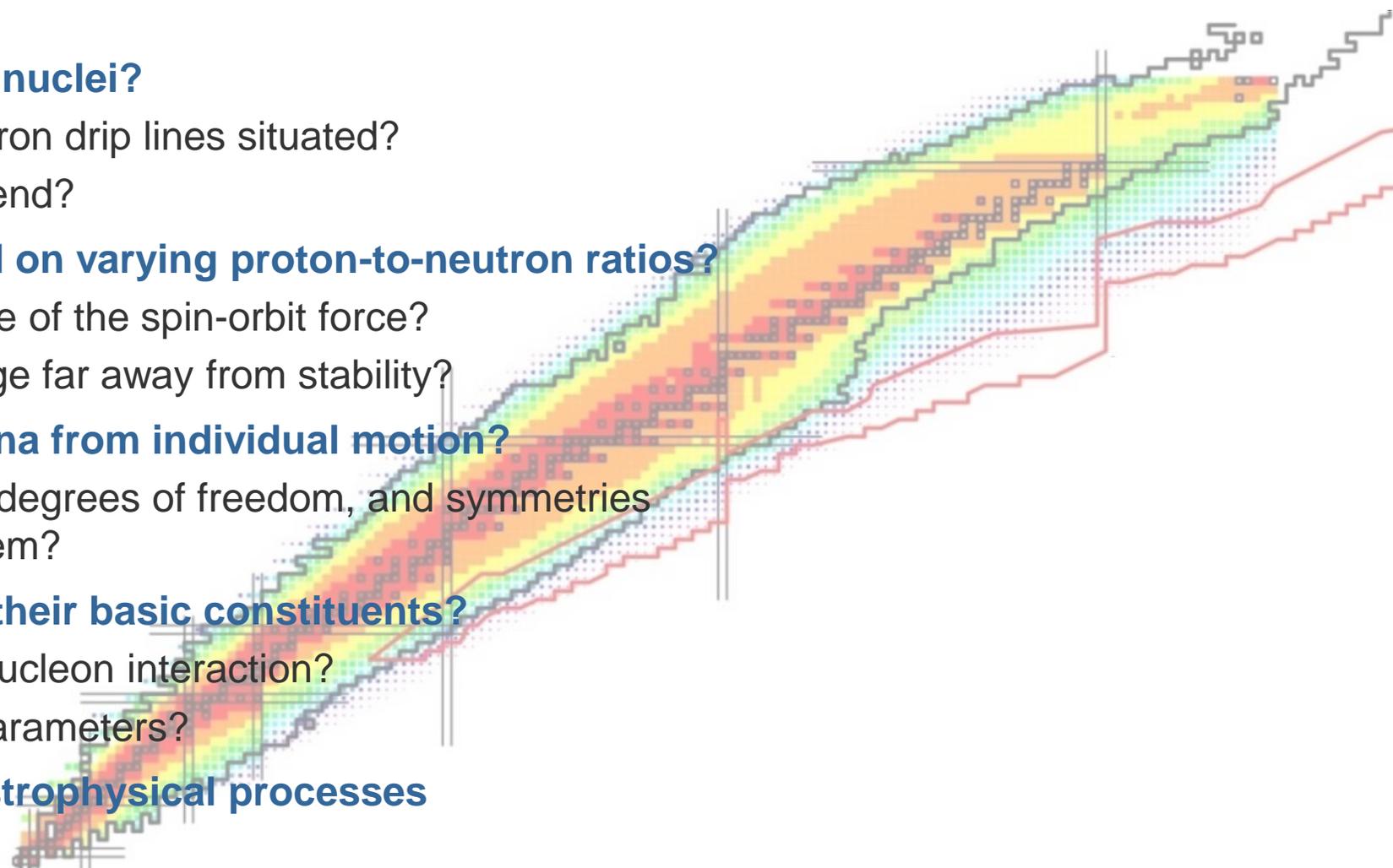
- What are the phases, relevant degrees of freedom, and symmetries of the nuclear many-body system?

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?



Reactions in stellar environments

Equation of State

Limits of existence

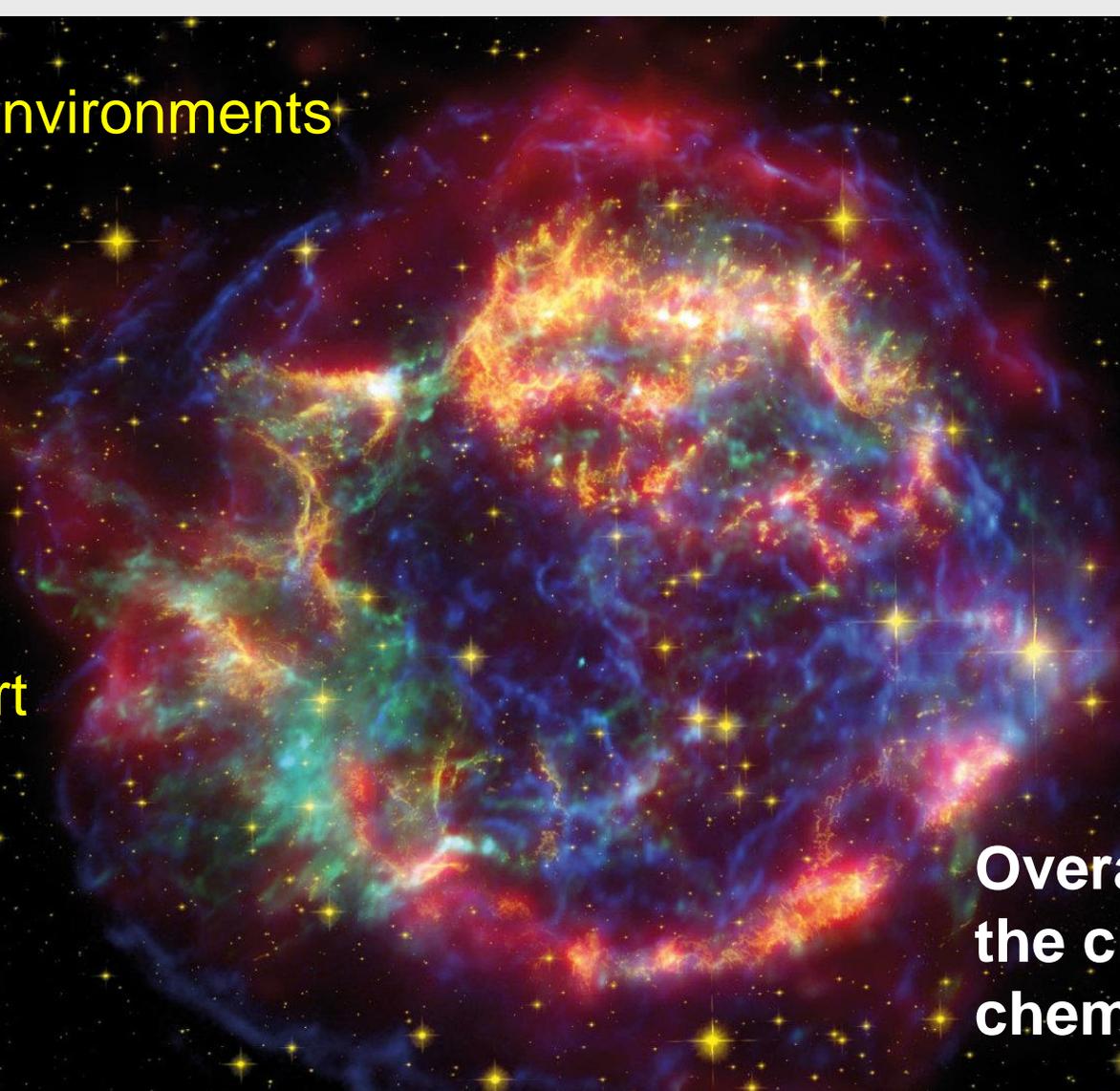
Lifetimes

Masses

P_{xn} values

Fission

... with theory support
for impact



**Overarching physics case:
the creation of the (heavy)
chemical elements**



... requiring information



Reactions in stellar environments

Equation of State

Limits of existence

Lifetimes

Masses

P_{xn} values

Fission

... with theory support
for impact



**Overarching physics case:
the creation of the (heavy)
chemical elements**

Experiment	Description
HISPEC/ DESPEC	In-beam γ -spectroscopy at low and intermediate energy, n-decay, high-resolution γ -, β -, α -, p-, spectroscopy
MATS	In-trap mass measurements and decay studies
LaSpec	Laser spectroscopy
R ³ B	Kinematically complete reactions with relativistic radioactive beams
ILIMA	Large-scale scans of mass and lifetimes of nuclei in ground and isomeric states
Super-FRS EC	High-resolution spectrometer experiments
SHE	Synthesis and study of super-heavy elements
ELISE(*)	Elastic, inelastic, and quasi-free e ⁻ -A scattering
EXL(*)	Light-ion scattering reactions in inverse kinematics

(*) **NESR required** – alternative/intermediate “operation” within MSV under discussion.
SHE at GSI



The NUSTAR toolbox – a complementary approach

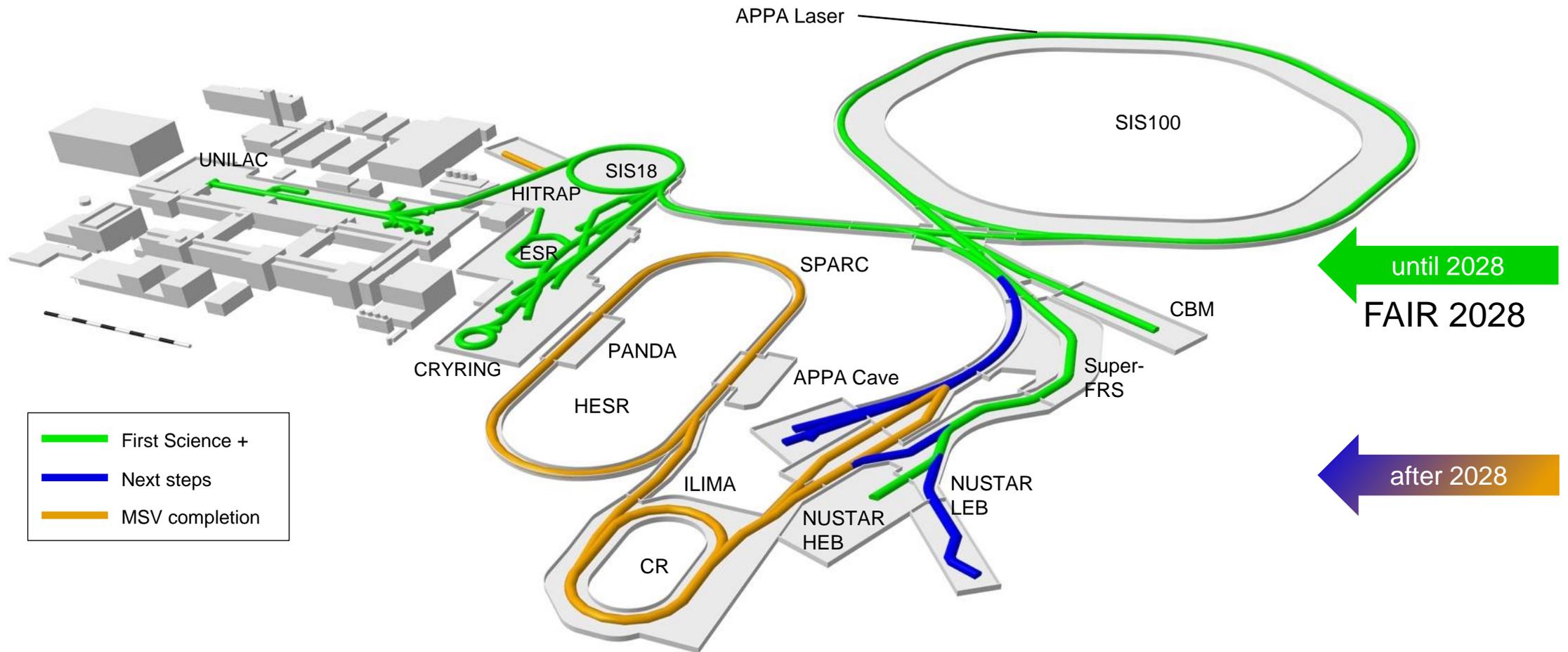


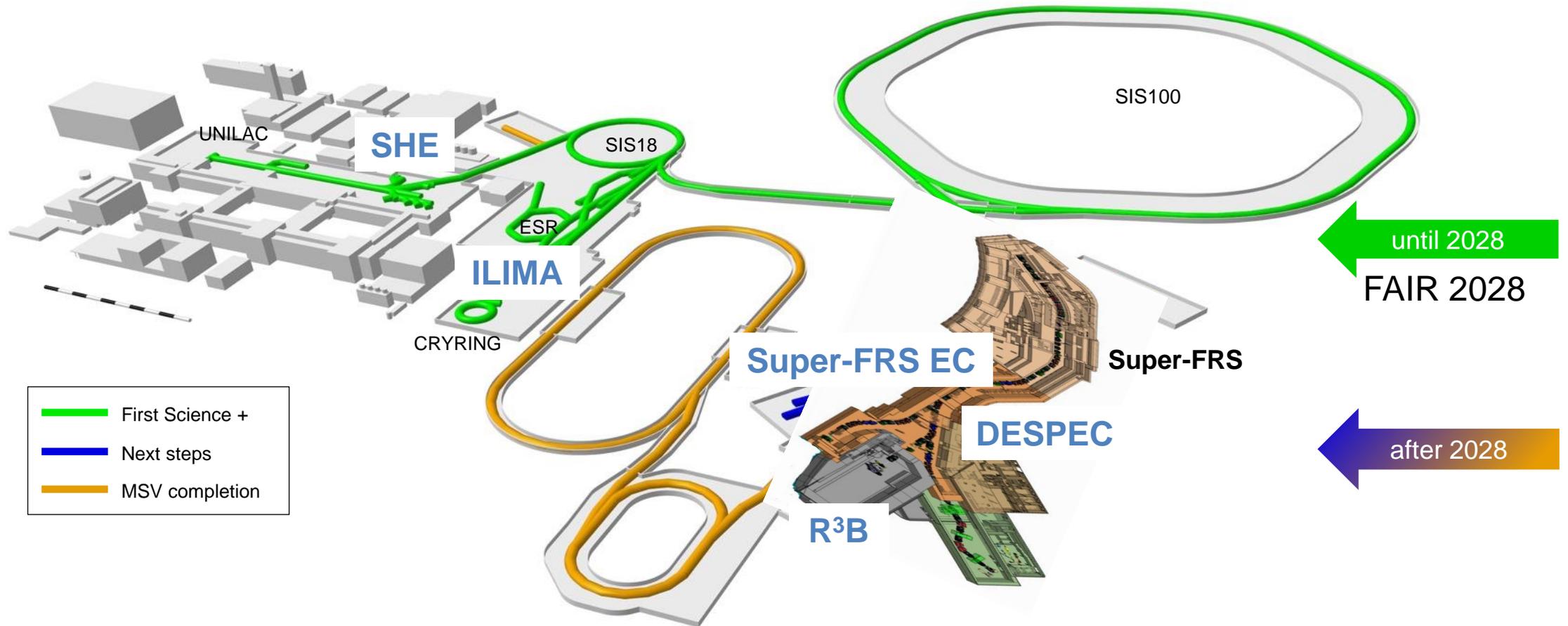
	Super-FRS EC	HISPEC/DESPEC	LaSpec	MATS	R ³ B	ILIMA	SHE
Masses		Q-values, isomers		dressed ions, highest precision	unbound nuclei	bare ions, mapping study	precision mass of SHEs
Half-lives	ps...ns-range	ground state and isomers μs...s			resonance width, decay up to 100ns	bare ions, ms...years	μs...days
Matter radii	interaction x-section				interaction cross sections		
Charge radii	charge-changing cross sections		mean square radii		charge-changing cross sections		mean square radii
Single-particle structure	high resolution, angular momentum	high-resolution particle and γ-ray spectroscopy	magnetic moments, nucl. spins	evolution of shell str., pairing int., valence nucl.	quasi-free knockout, short-range & tensor correlations	evolution of shell closures, pairing corr.	shell structure of SHEs
Collective behavior		electromagnetic transition strength	quadrupole moments	halo structure	dipole response, fission	changes in deformation	
EoS					polarizability, neutron skin		
Exotic Systems	bound mesons, hypernuclei, nucleon resonances	rare and exotic e.m. and particle decays			n-rich hypernuclei	exotic decay modes	



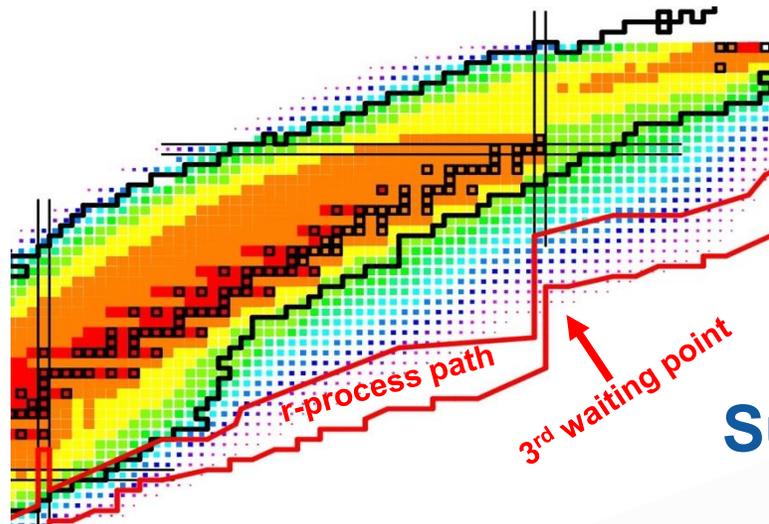


FAIR – 2028 and beyond



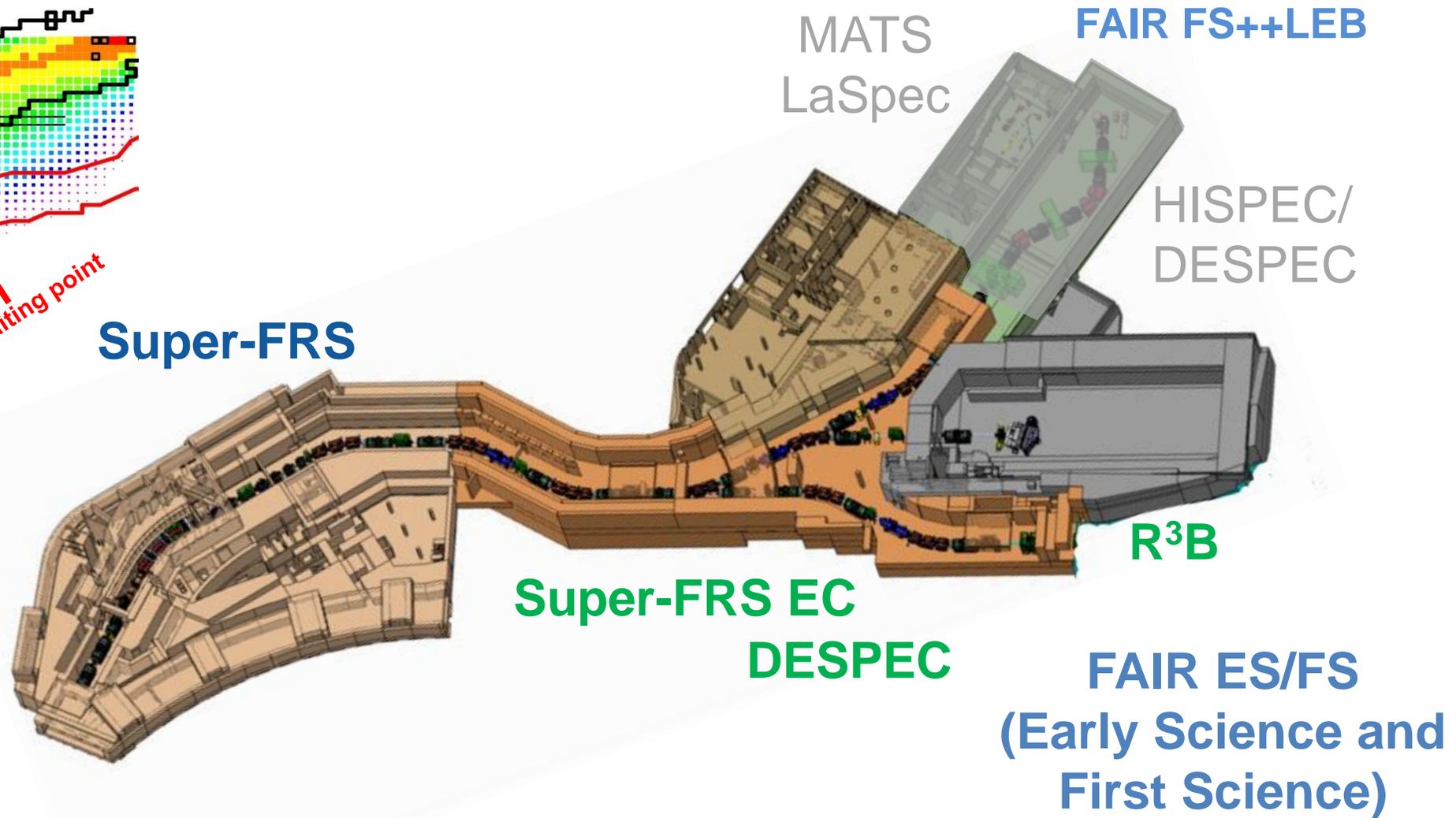


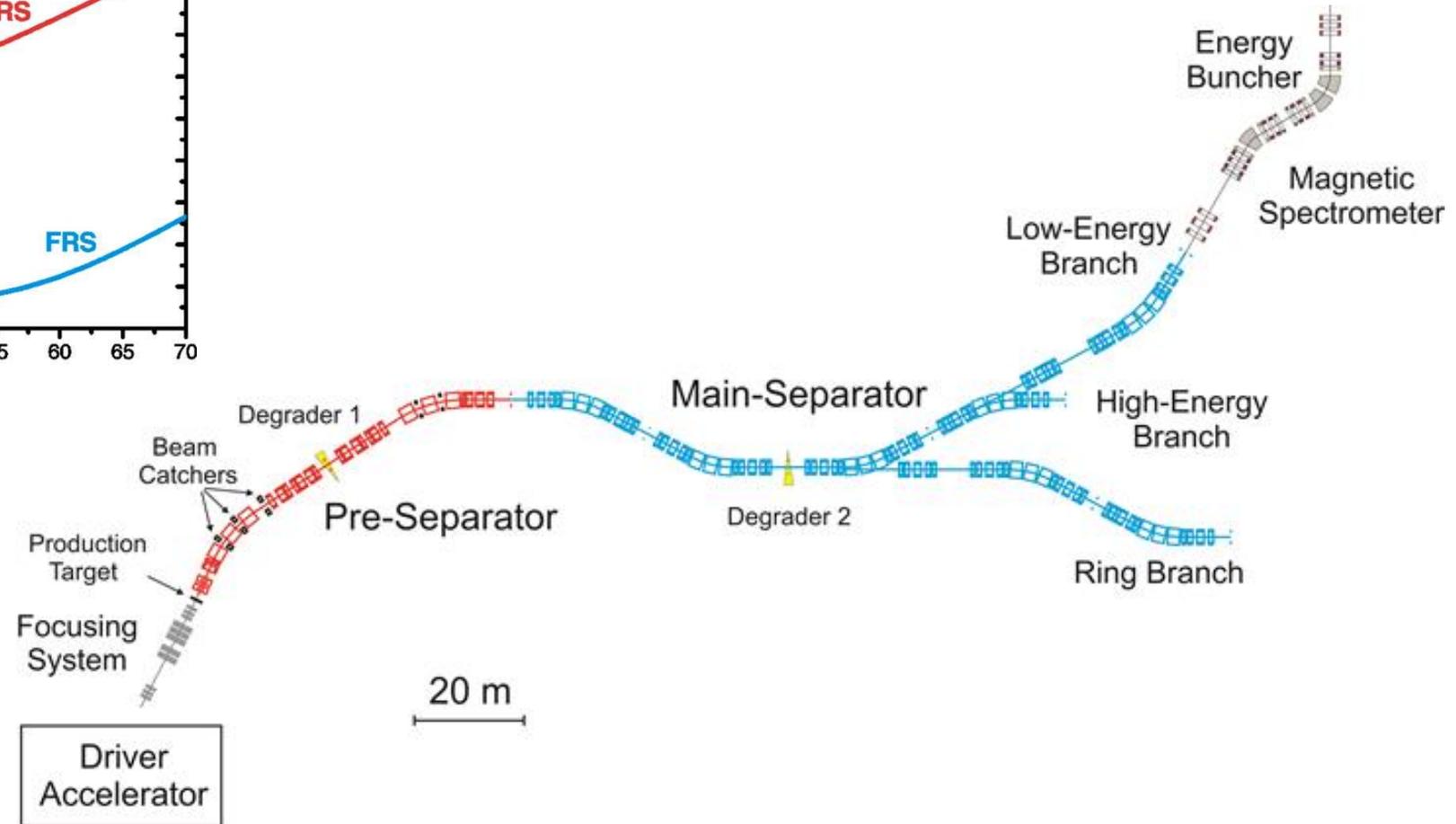
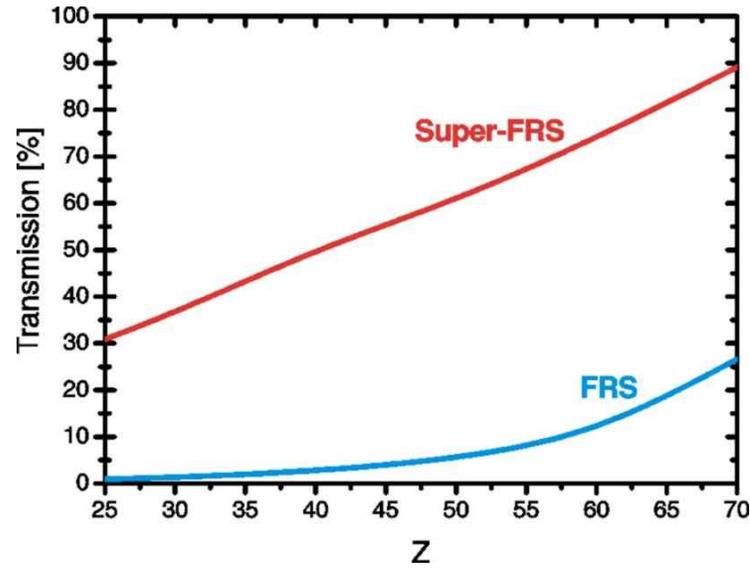
NUSTAR at the **Super-FRS** (**R³B**, **Super-FRS EC** and **DESPEC**) with **SIS100** beams, plus **SHE** experiments at UNILAC and **ILIMA** at the low-energy rings of GSI

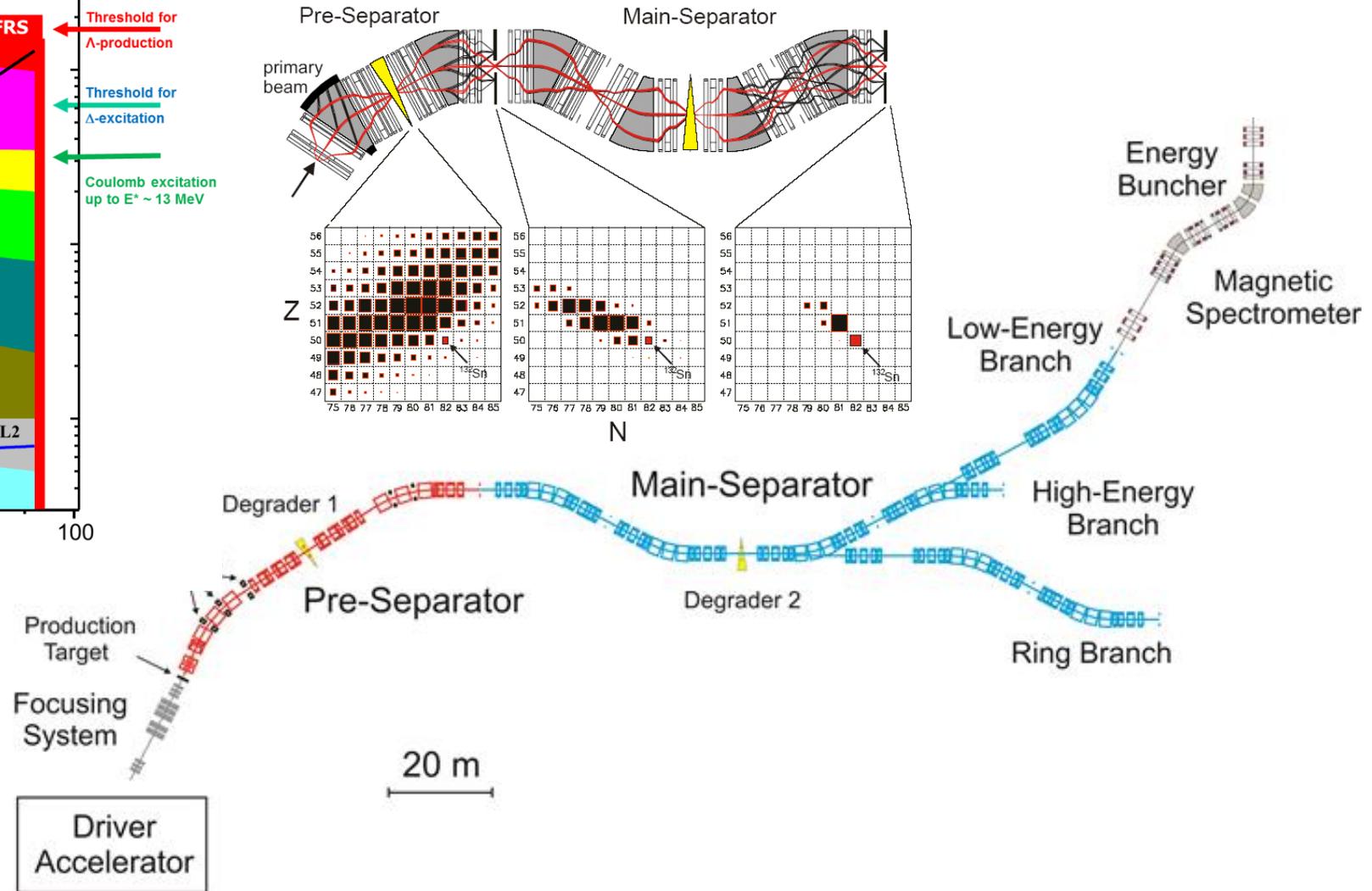
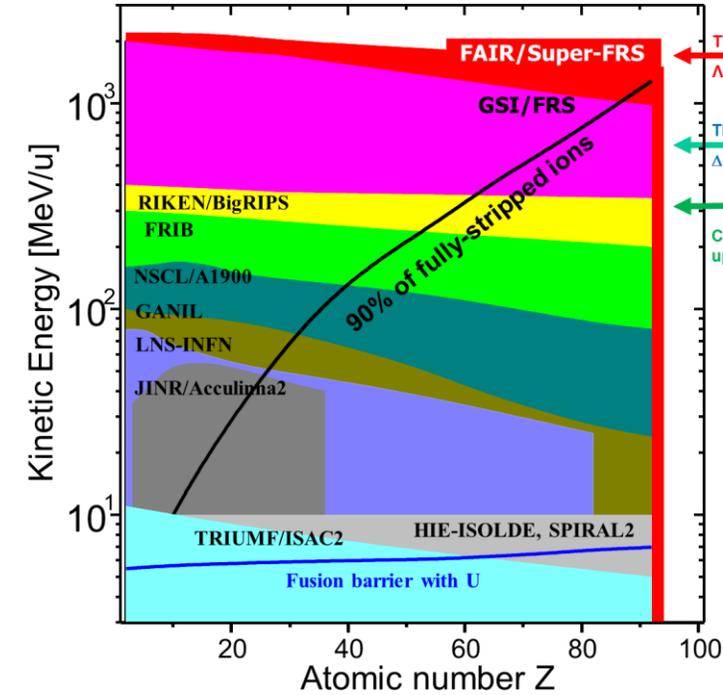


Super-FRS

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





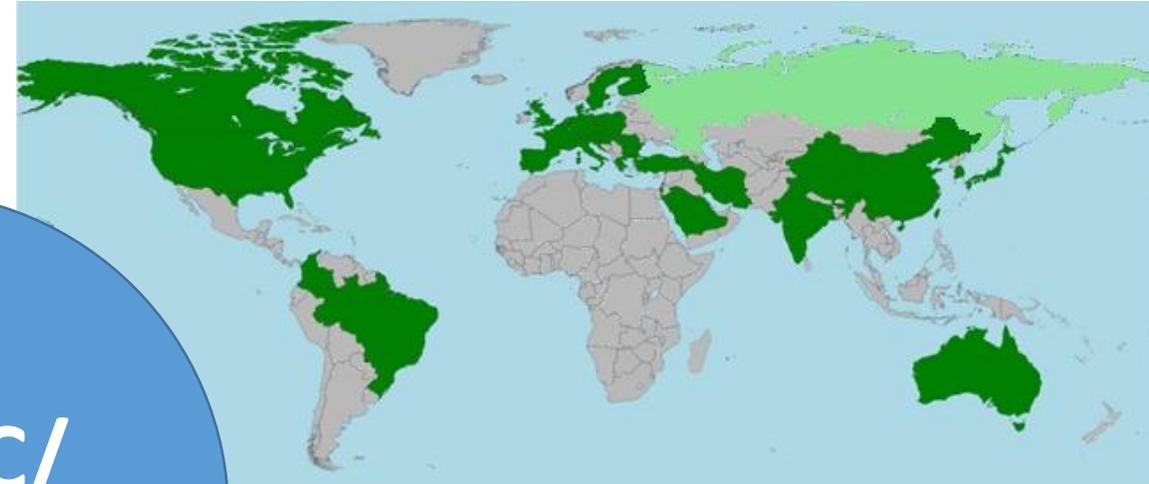
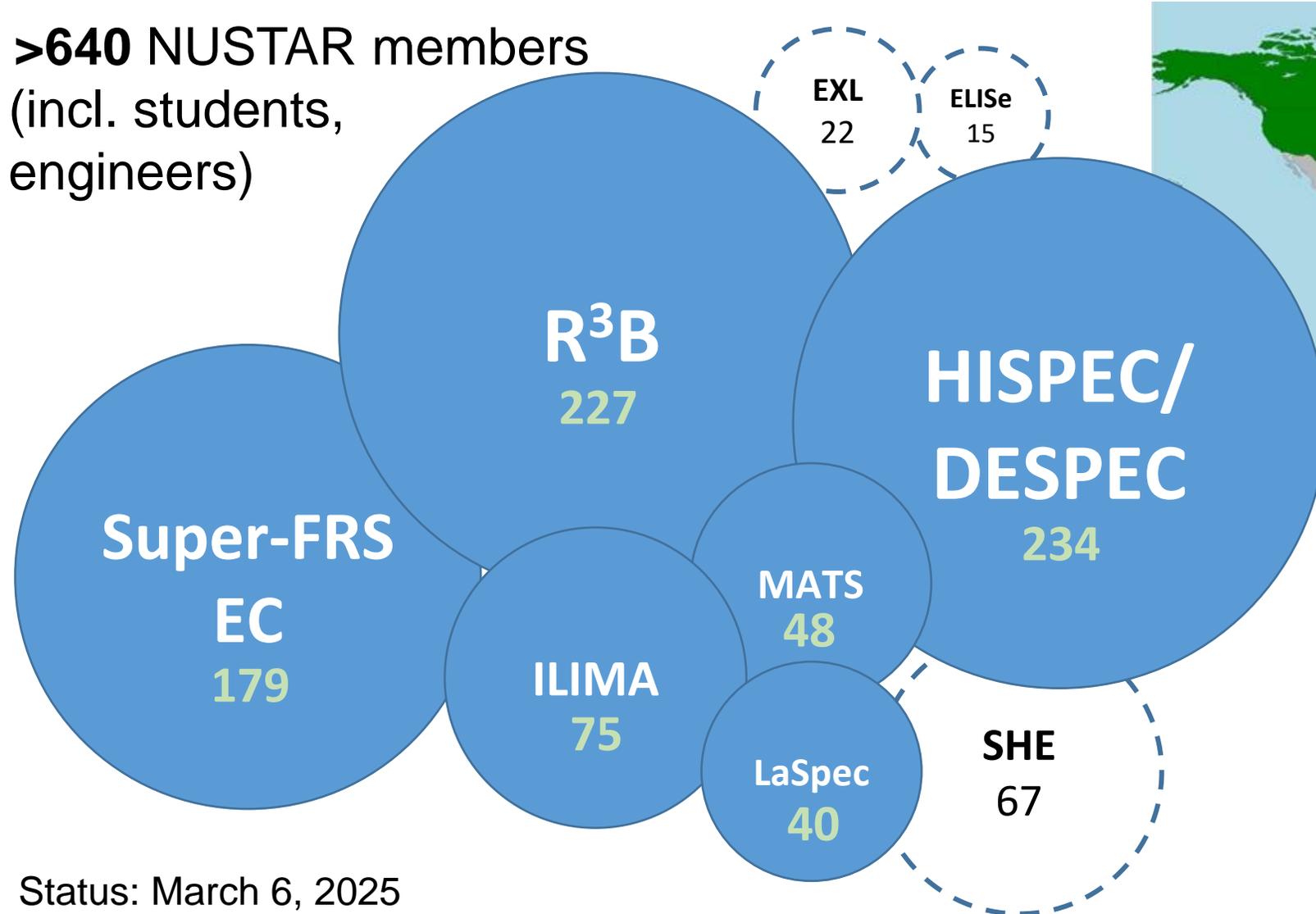




NUSTAR sub-collaborations and members



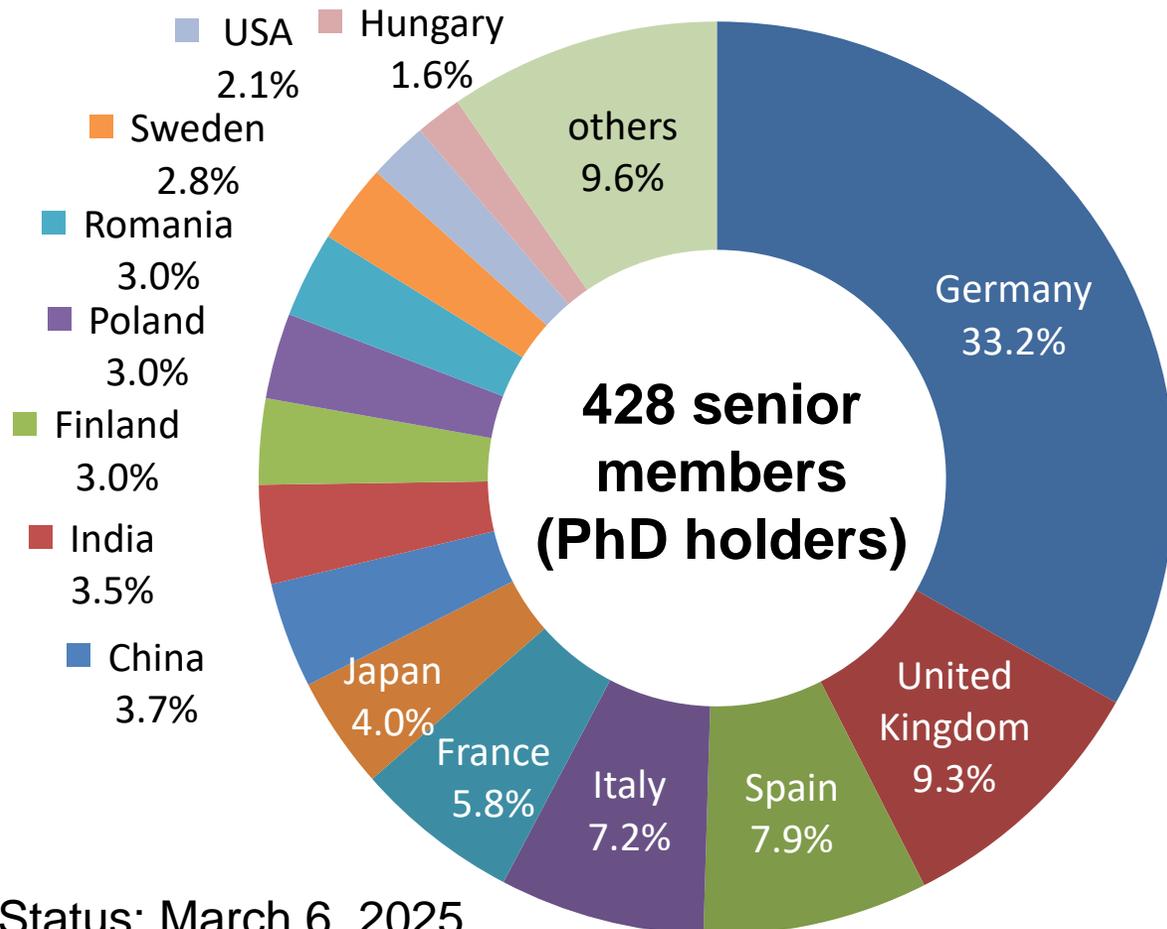
>640 NUSTAR members
(incl. students,
engineers)



- > 1000 listed “interested” scientists
- > 640 registered members (incl. students, etc.)
- ~ 428 senior members (PhD holders w/o Russia)
- > 140 institutes from 35 countries

Status: March 6, 2025

NUSTAR collaboration senior members (PhD holders **without Russia) for collaboration common fund from HISPEC/DESPEC, MATS, LaSpec, R3B, ILIMA, Super-FRS EC**



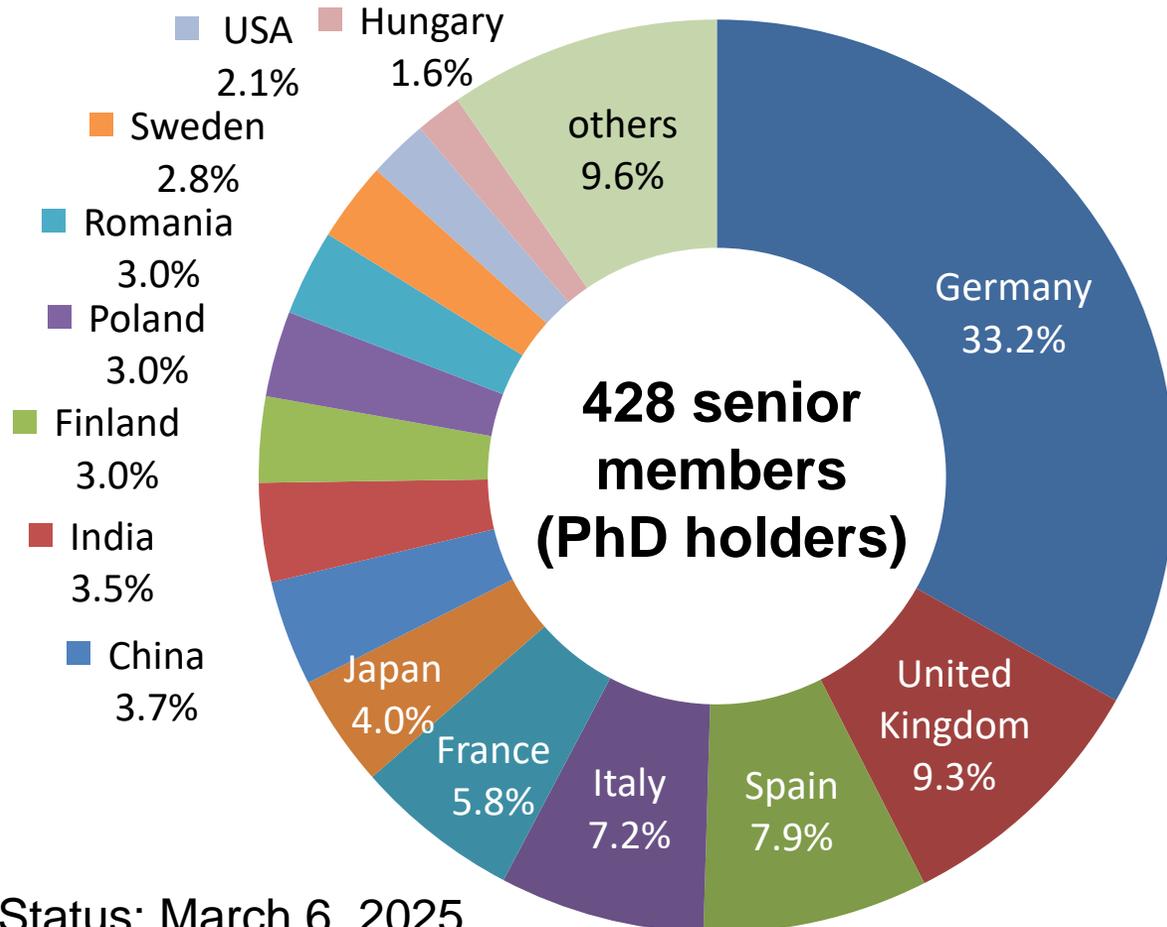
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Secured funding and expression of interest in funding **from 22 countries (incl. Russia)** (incl. 10 FAIR partner countries)



Status: March 6, 2025

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Secured funding and expression of interest in funding **from 22 countries (incl. Russia)** (incl. 10 FAIR partner countries)



Indian partner institutes:
 BARC Mumbai, IIT (ISM) Dhanbad,
 IIT Roorkee, IIT Ropar, IUAC Delhi,
 PU Chandigarh, TIFR Mumbai,
 Univ. Delhi, VECC Kolkata

Status: March 6, 2025



Board of Representatives (elected by Collaboration Board)



Giovanna Benzoni
(INFN Milano)



Michael Block
(GSI/HIM/Mainz,
**Deputy
Spokesperson**)



Lola Cortina
(IFIC Valencia)



Timo Dickel
(GSI)



Zsolt Podolyak
(Univ. Surrey,
Spokesperson)

**Technical
Coordinator**



Helena Albers (GSI/FAIR)

**Resource
Coordinator**



Alexander Herlert (GSI/FAIR)

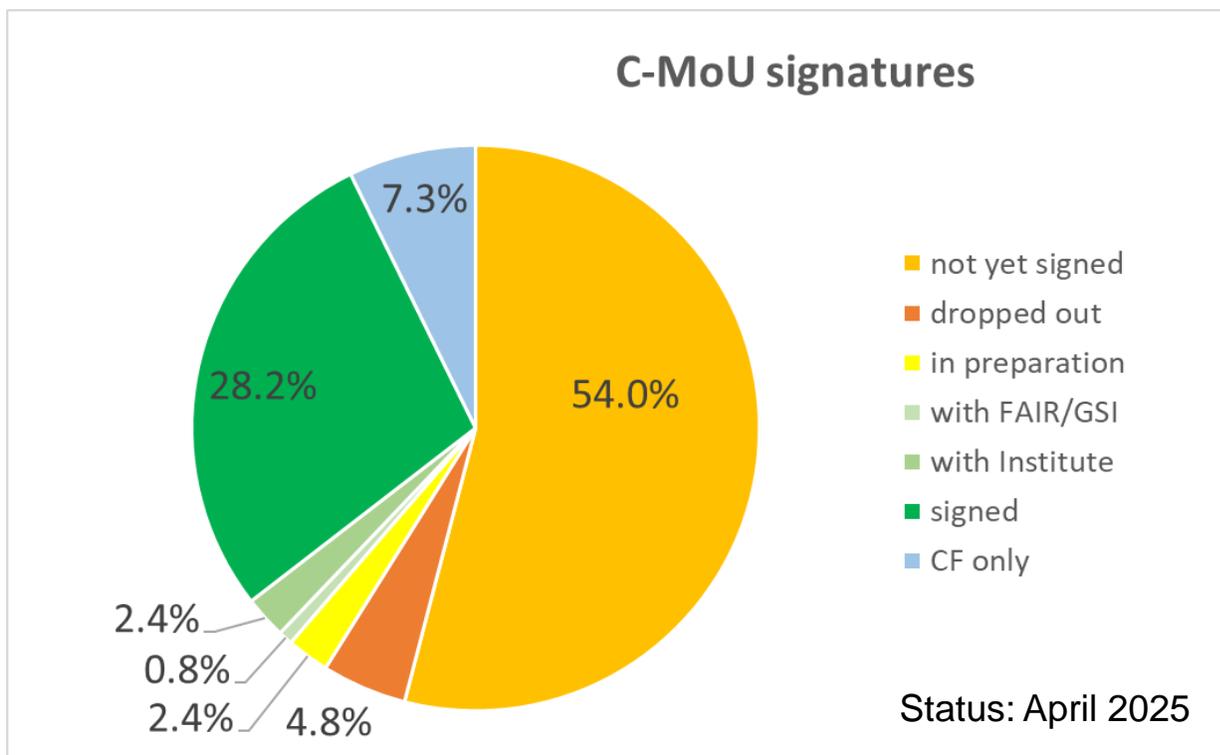


NUSTAR project status (score card)



	NUSTAR sub-system	TDR	Cost [k€ 2005]	Funding	Construction	Date completion	Test/Commissioning
	Early and First Science (ES / FS)						
ES / FS	Cave infrastr.	<div style="width: 100%; height: 15px; background-color: green;"></div>	1,618	<div style="width: 95%; height: 15px; background-color: green; border: 1px solid yellow;"></div>	<div style="width: 0%; height: 15px; background-color: green;"></div>	12/2026	<div style="width: 0%; height: 15px; background-color: gray;"></div>
	HISPEC/DESPEC	<div style="width: 98%; height: 15px; background-color: green; border: 1px solid yellow;"></div>	11,153	<div style="width: 95%; height: 15px; background-color: green; border: 1px solid yellow;"></div>	<div style="width: 25%; height: 15px; background-color: green;"></div>	11/2025	<div style="width: 15%; height: 15px; background-color: gray;"></div>
	MATS	<div style="width: 100%; height: 15px; background-color: green;"></div>	462	<div style="width: 100%; height: 15px; background-color: green;"></div>	<div style="width: 100%; height: 15px; background-color: green;"></div>	08/2024	<div style="width: 20%; height: 15px; background-color: gray;"></div>
	LaSpec	<div style="width: 100%; height: 15px; background-color: green;"></div>	67	<div style="width: 100%; height: 15px; background-color: green;"></div>	<div style="width: 100%; height: 15px; background-color: green;"></div>	06/2021	<div style="width: 100%; height: 15px; background-color: gray;"></div>
	R3B	<div style="width: 100%; height: 15px; background-color: green;"></div>	18,462	<div style="width: 95%; height: 15px; background-color: green; border: 1px solid yellow;"></div>	<div style="width: 40%; height: 15px; background-color: green;"></div>	09/2027	<div style="width: 10%; height: 15px; background-color: gray;"></div>
	ILIMA	<div style="width: 100%; height: 15px; background-color: green;"></div>	424	<div style="width: 100%; height: 15px; background-color: green;"></div>	<div style="width: 10%; height: 15px; background-color: green;"></div>	12/2026	<div style="width: 5%; height: 15px; background-color: gray;"></div>
	Super-FRS EC	<div style="width: 80%; height: 15px; background-color: green; border: 1px solid orange;"></div>	568	<div style="width: 80%; height: 15px; background-color: green; border: 1px solid yellow;"></div>	<div style="width: 20%; height: 15px; background-color: green;"></div>	12/2025	<div style="width: 10%; height: 15px; background-color: green;"></div>
		98.4% <i>value weighted</i>	32,754	95.4% <i>secured</i>	64.6% <i>value weighted</i>		57.2% <i>value weighted</i>
Change since report 2024 II		+ 0.0%	+ 15.0	+ 0.0%	+ 2.1%		+ 0.3%

- Version from July 1, 2024
 - Final version – endorsed by funding agencies at 13th FAIR-RRB meeting
 - Collection of signatures in progress



NUSTAR Collaboration

Memorandum of Understanding

Memorandum of Understanding

for the Collaboration in the Construction of the Nuclear Structure, Astrophysics, and Reactions (NUSTAR) Experiments at FAIR

between

the Facility for Antiproton and Ion Research in Europe GmbH, hereinafter referred to as "FAIR GmbH",

and

the member institutions of the NUSTAR Collaboration, hereinafter referred to as "Member Institutions",

together with the corresponding *Funding Agencies*

Preamble

- (a) The *Member Institutions* of the NUSTAR Collaboration and FAIR GmbH agree to collaborate in order to perform experiments and thus to study fundamental aspects of nuclear structure physics, nuclear astrophysics, and nuclear reaction physics. The NUSTAR experiments shall be jointly constructed by the *Member Institutions* and established at FAIR. Within NUSTAR, several sub-collaborations have been formed, which are responsible for experimental components as described in the corresponding work packages.
- (b) FAIR GmbH and the GSI Helmholtzzentrum für Schwerionenforschung GmbH, hereinafter referred to as "GSI GmbH", jointly represent the *Host Laboratories*.
- (c) This MoU covers the construction period of the NUSTAR experiments and is labelled as "C-MoU" in the following.
- (d) The Technical Design Reports (TDRs) document the basis for the construction of the NUSTAR experiments. The TDRs are subject of approval by the FAIR management, following the recommendation of the FAIR Expert Committee Experiments (ECE). Moreover, FAIR monitors the construction costs of the NUSTAR experiments and their funding together with the *Funding Agencies* via the Resources Review Boards (RRBs).
- (e) In 2007, an Interim MoU was signed by some of the *Member Institutions* to plan the construction of the NUSTAR experiments. It was updated in 2011 with a Pre-Construction MoU in order to affirm the intention of the *Member Institutions* to build the NUSTAR experiments and, in particular, to declare the responsibilities for the construction of the different NUSTAR experimental



NUSTAR Construction MoU – final version



- Version from July 1, 2024
 - Final version – endorsed by funding agencies at 13th FAIR-RRB meeting
 - Collection of signatures in progress

country	share (senior members)	comment / status	
Germany	32.3%	BMBF signed	wait for details for some institutes (one signed)
United Kingdom	9.0%	UKRI-STFC signed	
Spain	7.8%	wait for details	
Italy	7.4%	INFN signed	
France	5.7%	CNRS signed	CEA: wait for details
USA	4.0%	mostly no signature or CF contribution	
Japan	3.8%	wait for details (two signed)	
China	3.6%	wait for details	
India	3.3%	wait for details	
Poland	3.3%	wait for details	
Finland	3.1%	HIP signed	
Sweden	3.1%	VR signed	wait for details for some institutes (one signed)
Romania	2.6%	ISS: signed	IFIN-HH: signed IFA: wait for signature

NUSTAR Collaboration Memorandum of Understanding

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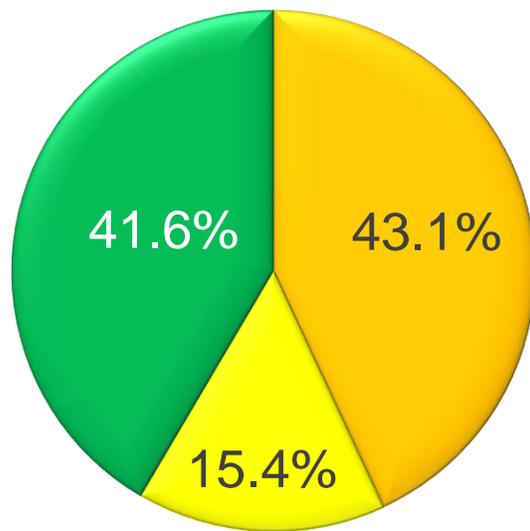
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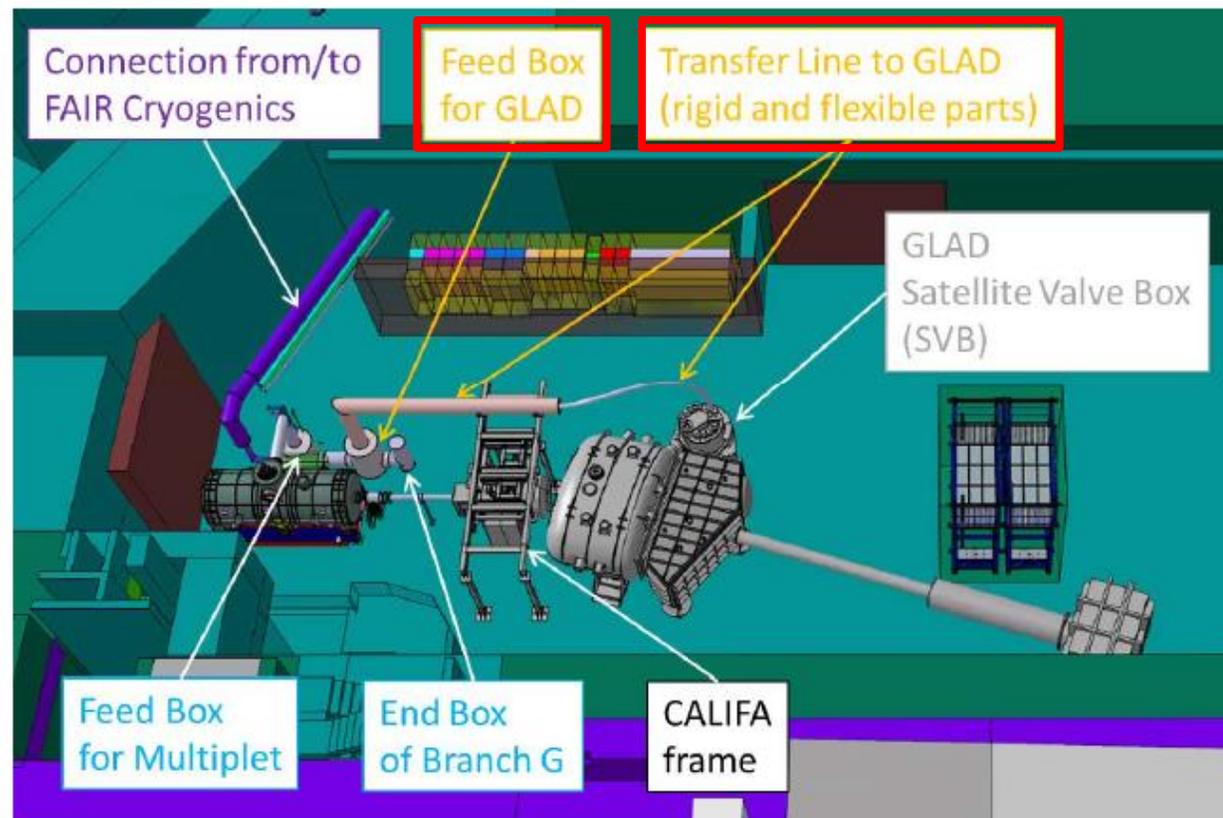
NUSTAR C-MoU
1/11
July 1, 2024

- About **2 MEUR** to be collected for **cave infrastructure** components
 - **Call for Funds in progress**

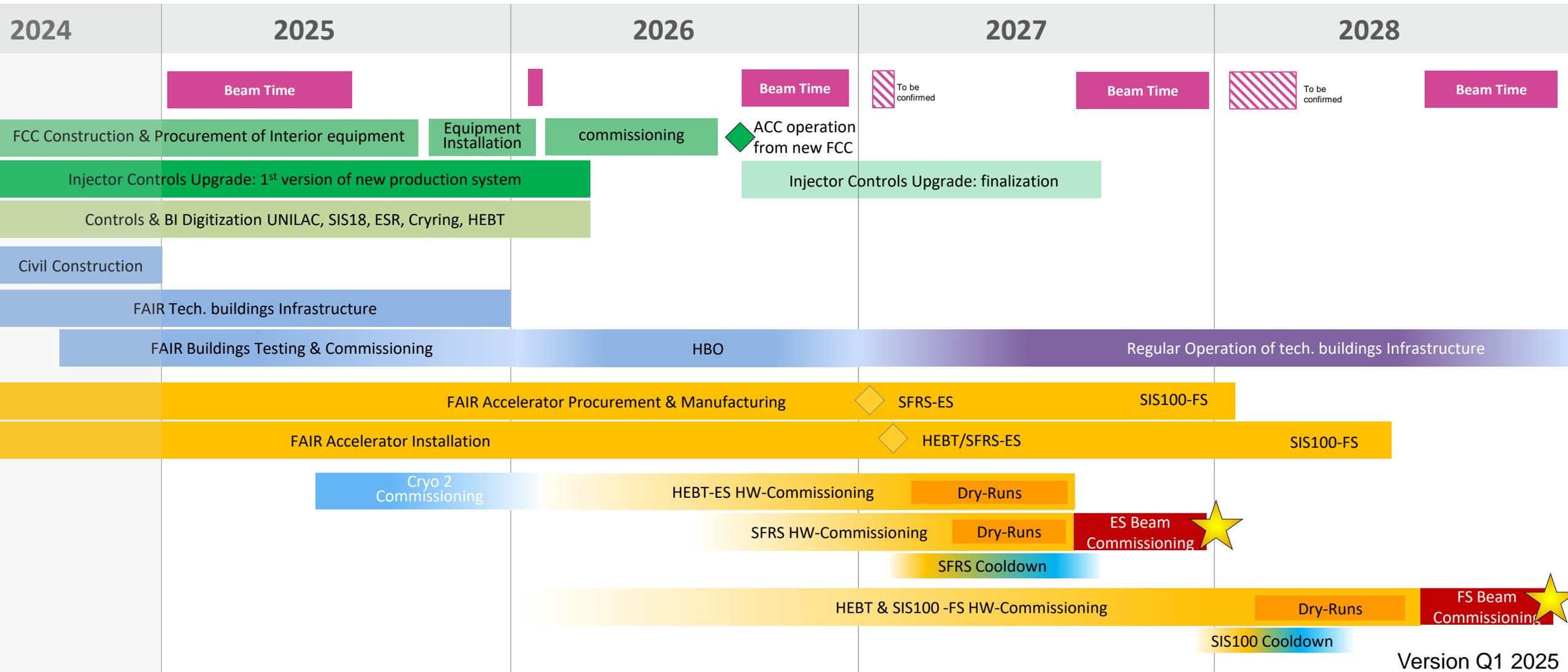


- still required
- in the pipeline
- available

Example: Infrastructure for local cryogenics in HEC

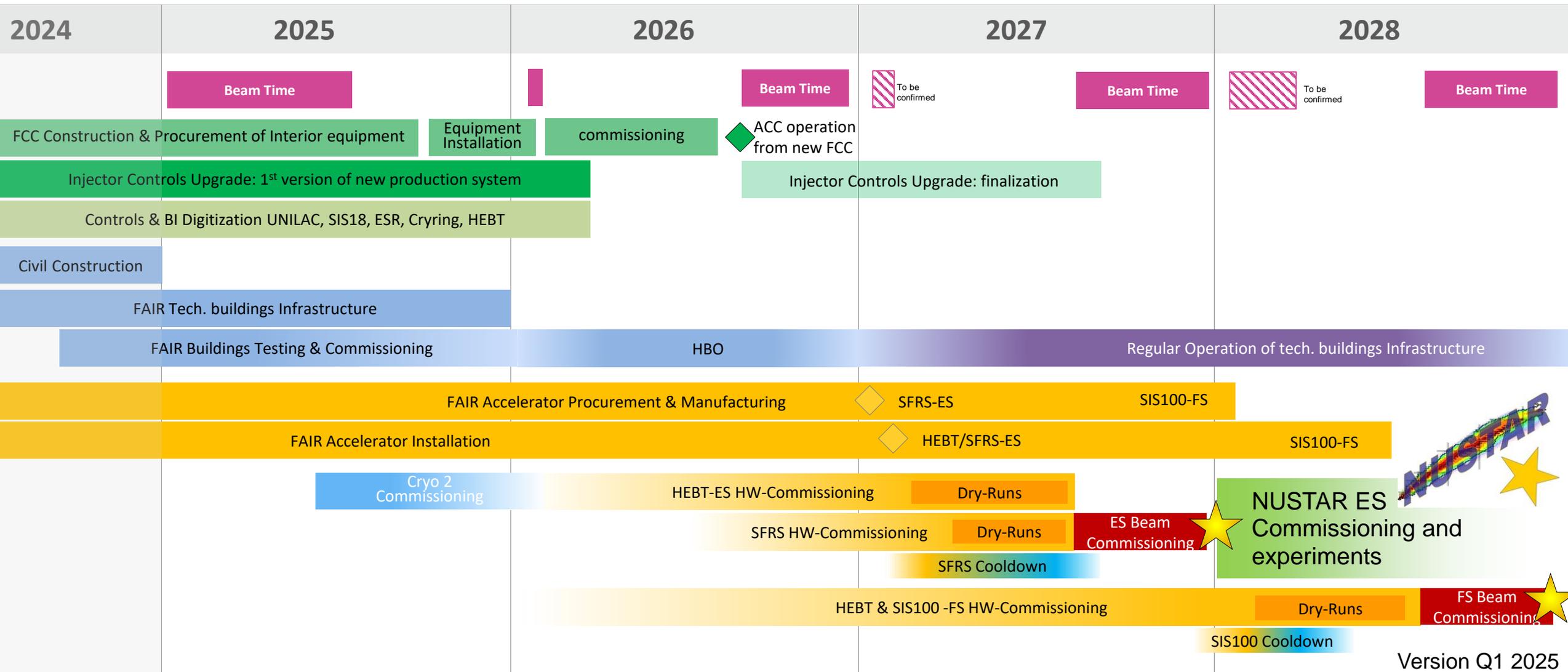


FAIR & GSI Integrated Schedule



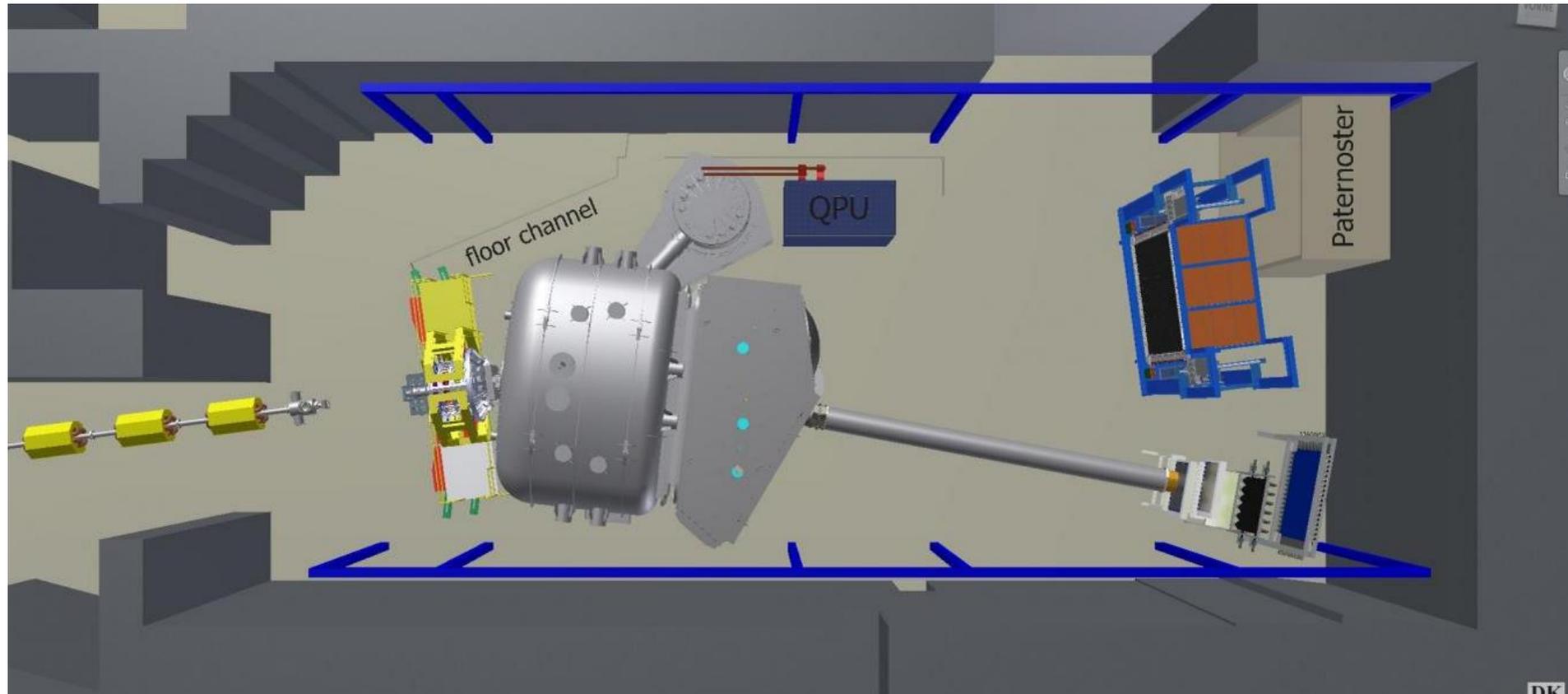
Version Q1 2025

FAIR & GSI Integrated Schedule

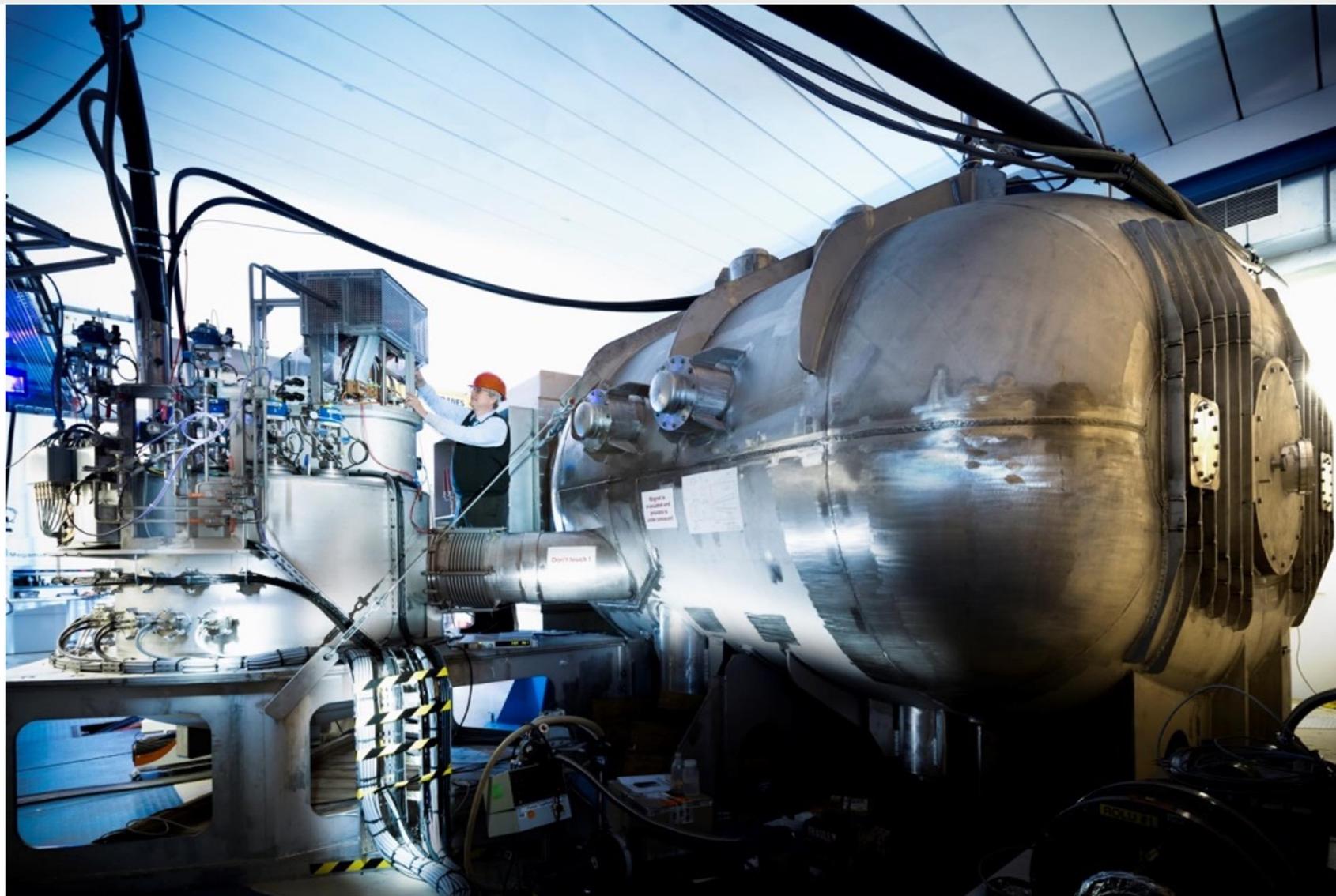


Version Q1 2025

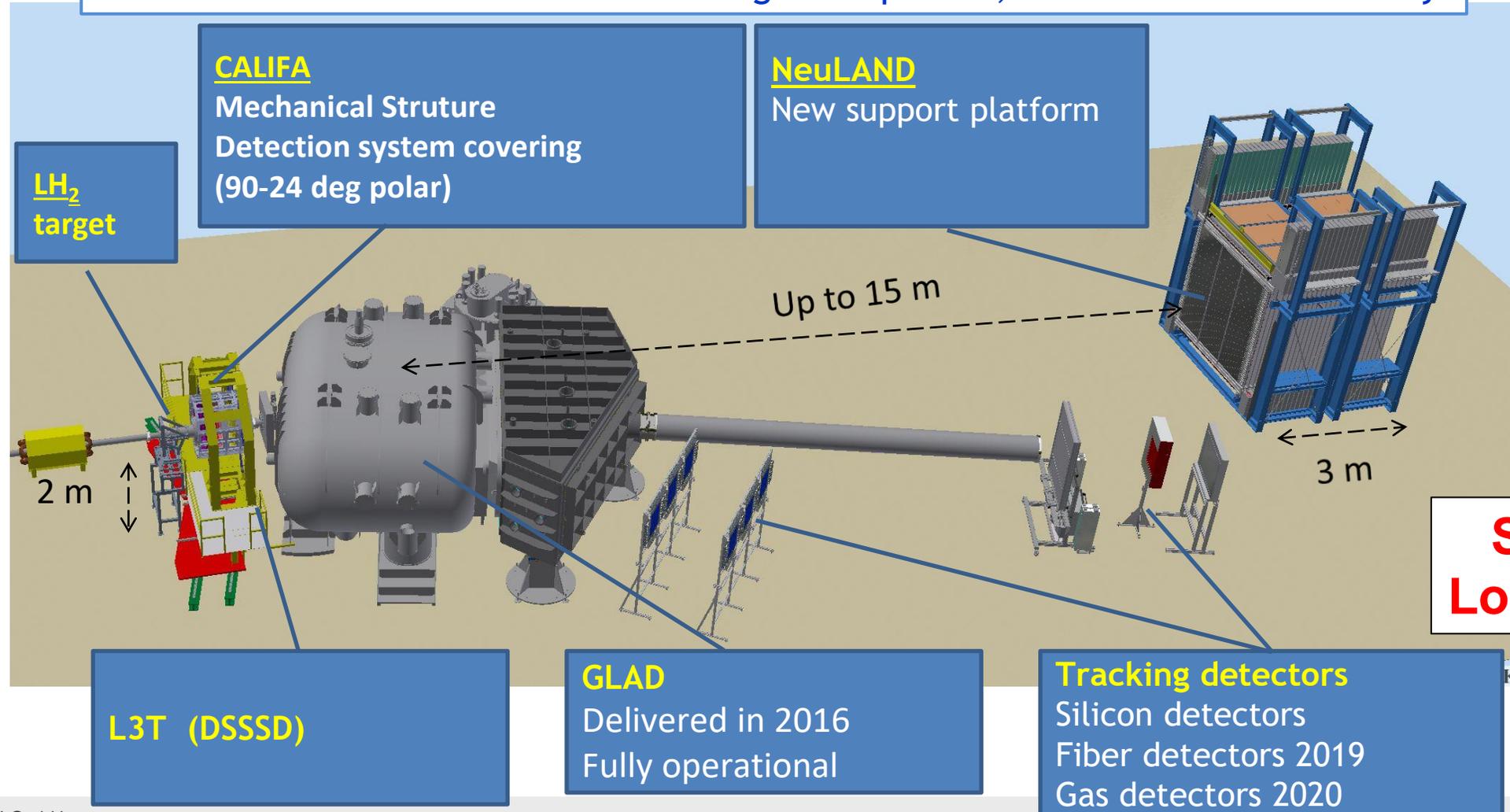
R³B



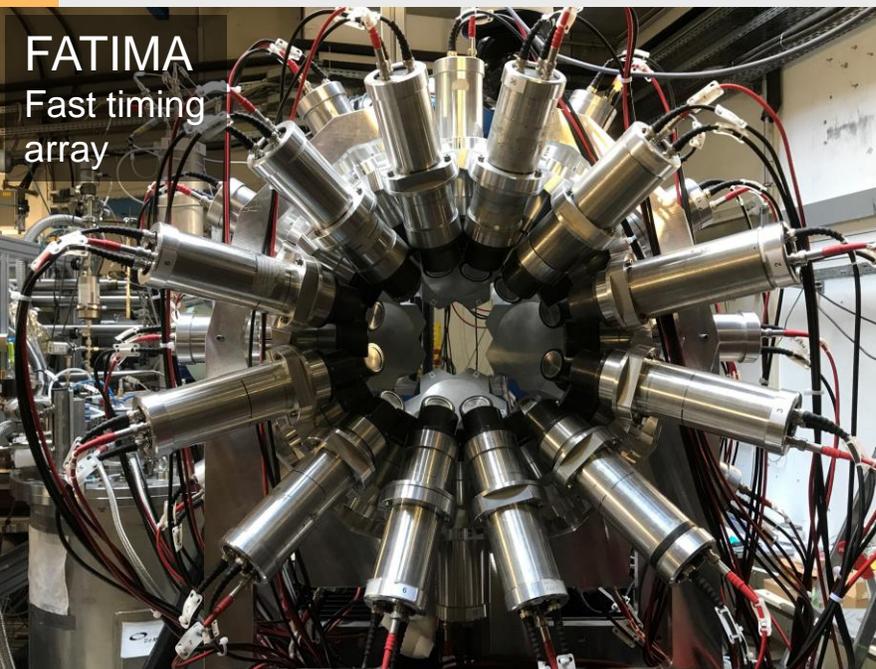
- Full integration test and experiment runs in Cave-C
- Move fully commissioned systems to FAIR High-Energy Cave



Complete kinematics, fixed target experiment to study **R**eactions with **R**elativistic **R**adioactive **B**eams with high acceptance, resolution and efficiency



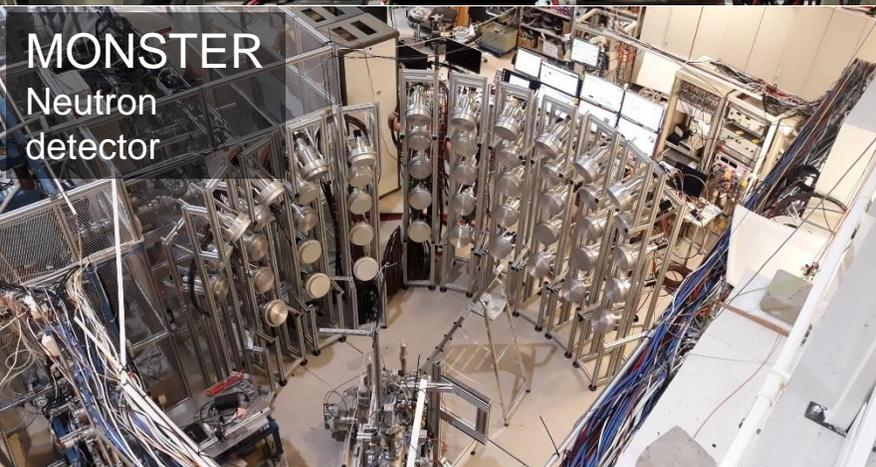
**See talk:
Lola Cortina**



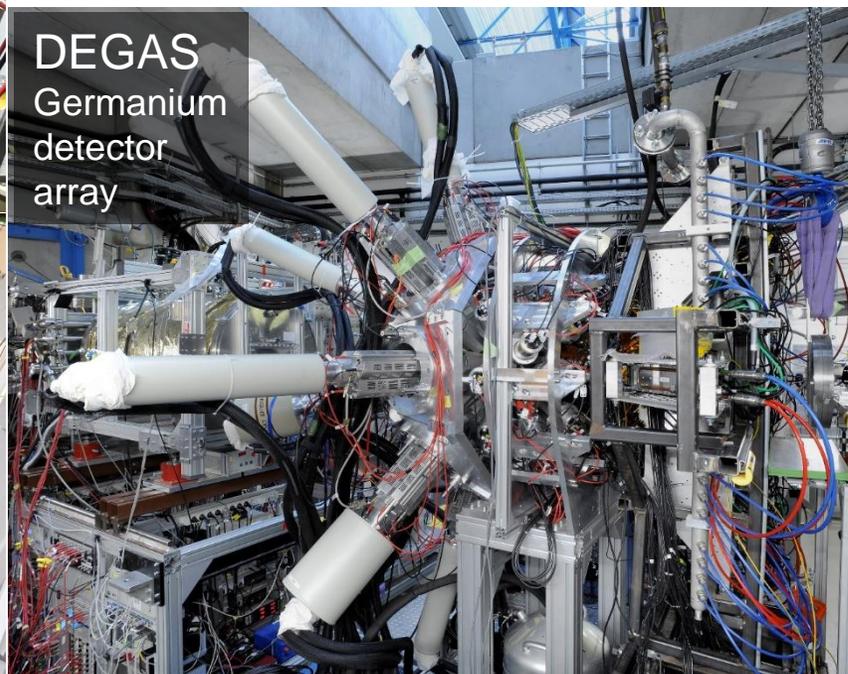
FATIMA
Fast timing
array



**High-resolution in-flight
and decay spectroscopy**



MONSTER
Neutron
detector

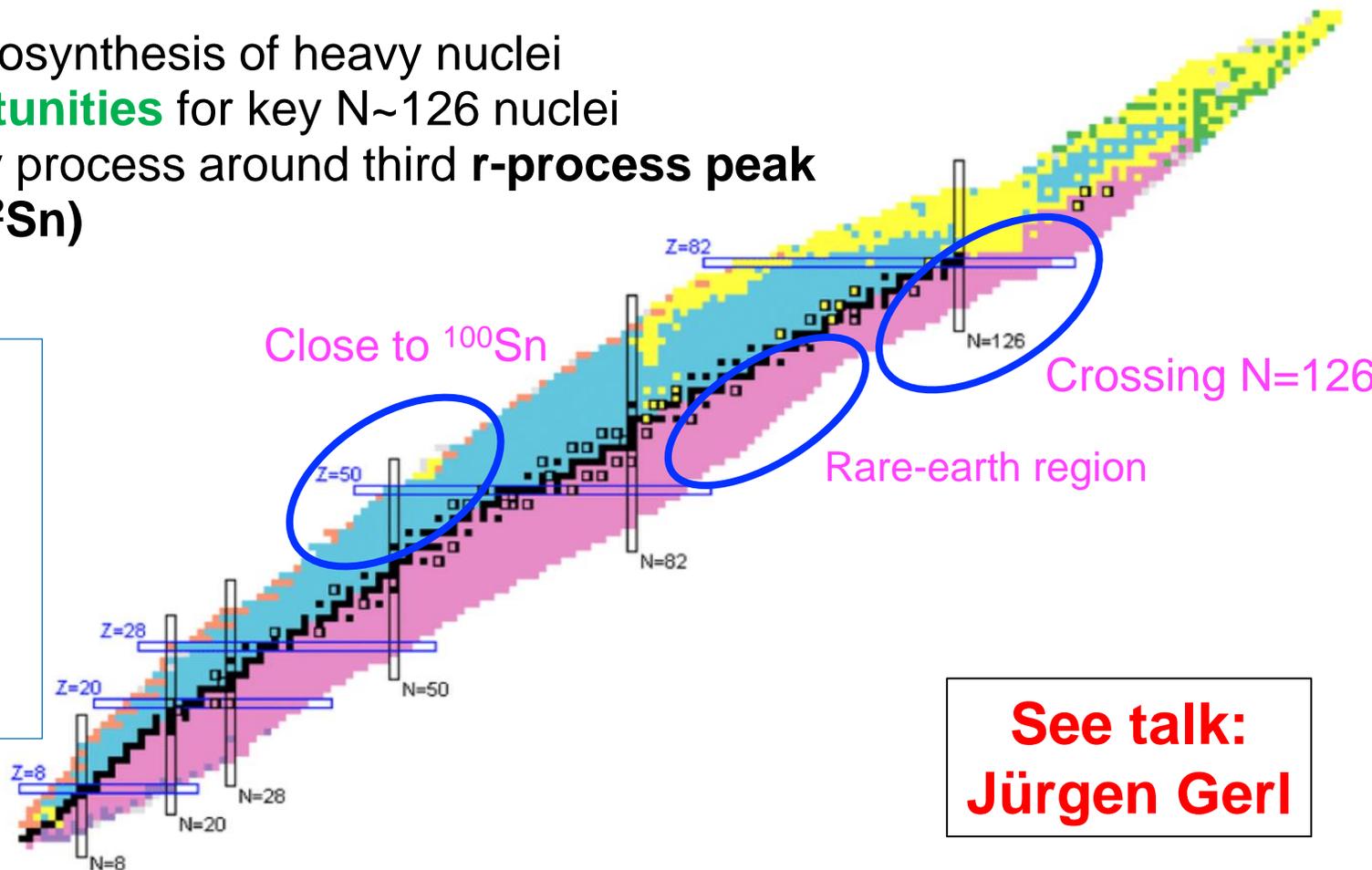


DEGAS
Germanium
detector
array

- The experiments - various configurations of **state-of-the-art detector systems** - will address multiple questions in **nuclear structure, reactions, and astrophysics**.
- Complementary information will be obtained by means of **high-resolution in-flight spectroscopy (HISPEC)** and **stopped-beam decay spectroscopy (DESPEC)** at the FRS of GSI and at the Super-FRS facility at FAIR.

- Shedding light on the evolution of shell structure and exotic nuclear shapes in **uncharted nuclear territory**
- Spectroscopic information for the nucleosynthesis of heavy nuclei
 - GSI/FAIR provides **unique opportunities** for key N~126 nuclei
- Towards a full picture of the beta-decay process around third **r-process peak**
- Nuclear structure around ^{100}Sn (and ^{132}Sn)

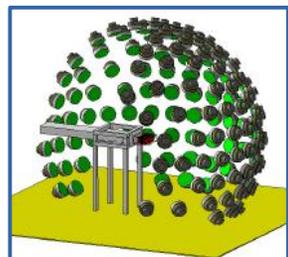
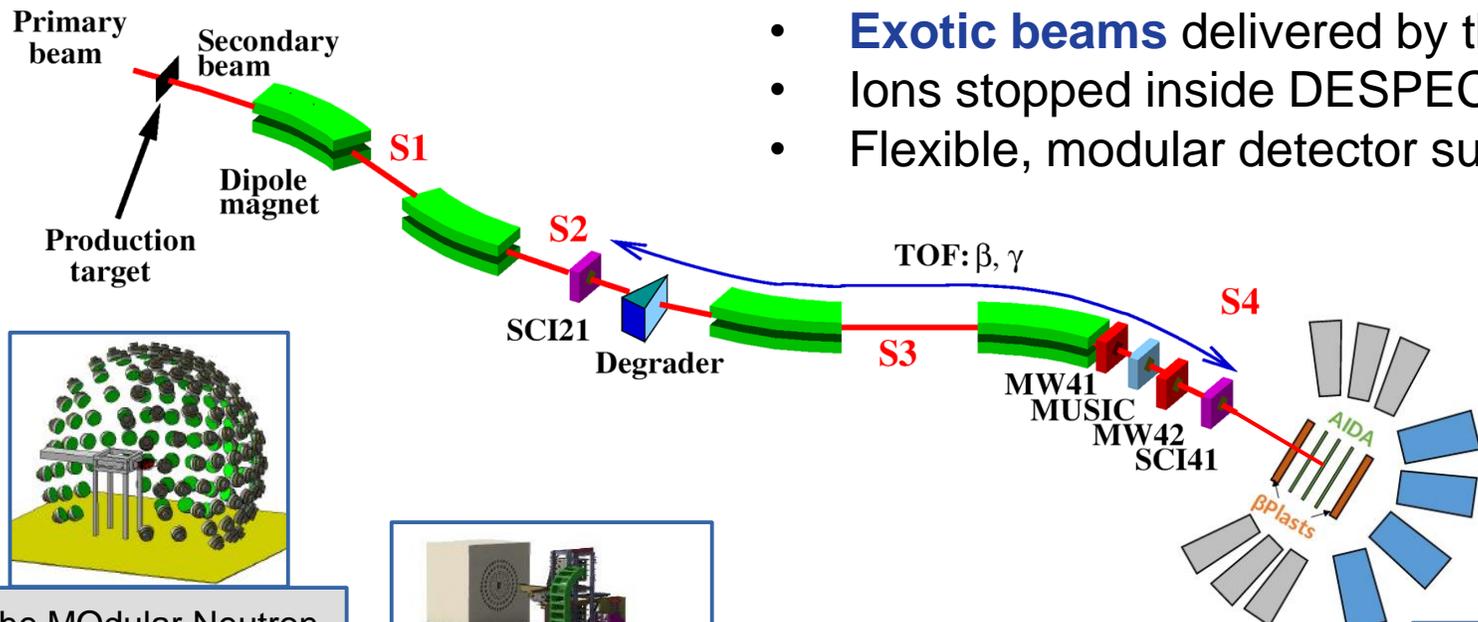
- Comprehensive decay information from key nuclei at secondary beam yields as low as
 - ✓ **one ion per hour**
- Sensitive to nuclear lifetimes spanning
 - ✓ **13 orders of magnitude** (10ps-100s)
- Measurement of
 - ✓ **any mode of nuclear decay**



**See talk:
Jürgen Gerl**

- **Exotic beams** delivered by the FRagment Separator (FRS)
- Ions stopped inside DESPEC setup
- Flexible, modular detector suite **tailored to physics goals**

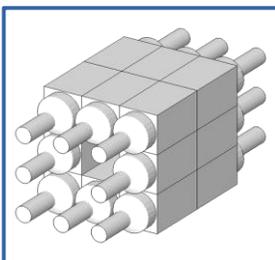
A.K. Mistry *et al.*, The DESPEC setup for GSI and FAIR, NIM A, 166662 (2022)



The MOdular Neutron SpectromETER (MONSTER)



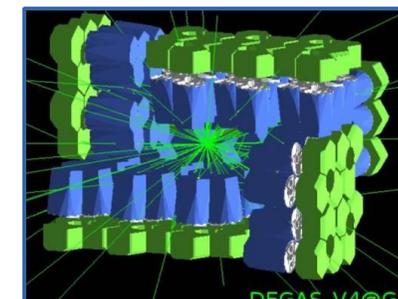
BEta-deLayEd Neutron detector (BELEN)
48 ^3He cylindrical counters



Decay Total Absorption γ -ray Spectrometer (DTAS)
NaI(Tl) modules



FAst TIMing Array $\text{LaBr}_3(\text{Ce})$ modules (FATIMA)



DESPEC Ge Array Spectrometer (DE GAS)

Technological challenge:

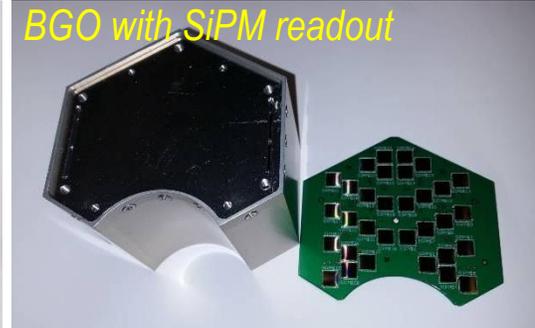
- Encapsulated HPGe crystals in a cryostat with electrical cooling.
- Minimal thermal losses
- High vacuum
- Integrated front-end and
- Imaging capability
- ...



Complex components



Pre-amp + HV unit



BGO with SiPM readout

GSI - Germany
 TIFR/Univ. Delhi - India
 JSI - Slovenia



MONSTER for DESPEC@ FAIR

- 100 (8"×2") Liquid scintillator based ToF detectors
- Excellent time resolution
- Versatile mechanical set-up
- 15 detector units made by VECC and in use

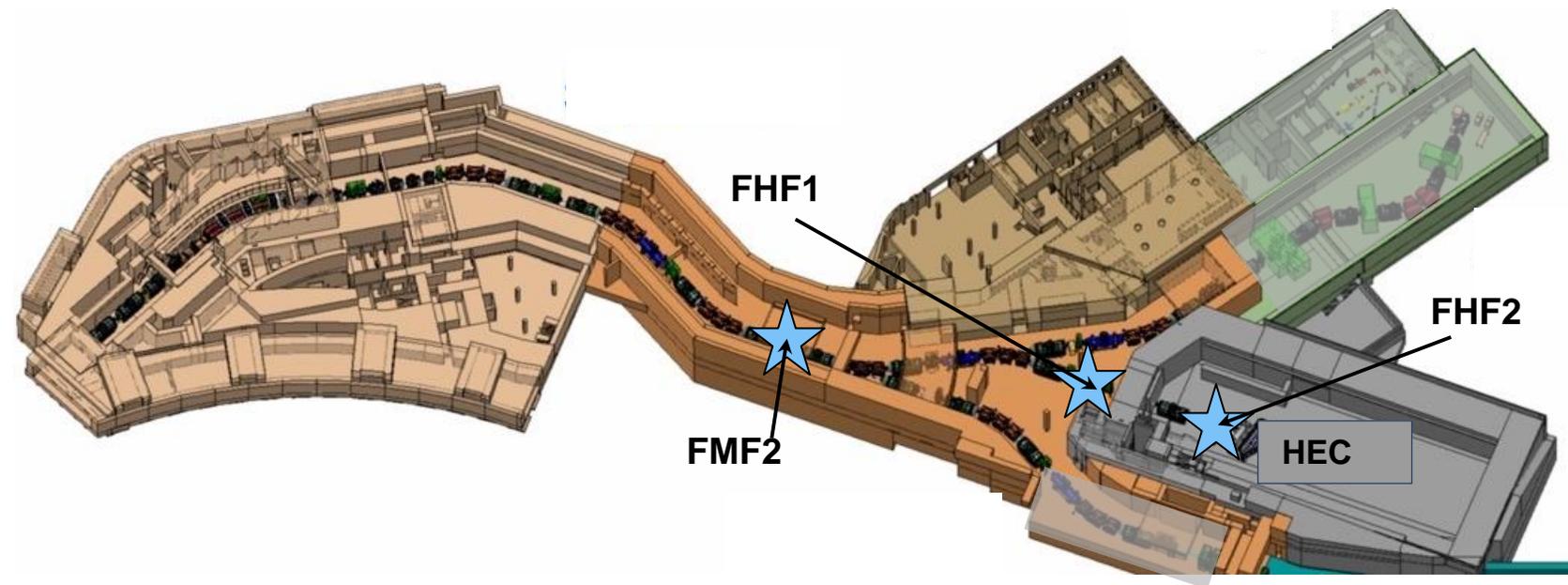


CIEMAT - Spain
 VECC Kolkata – India
 Univ. Valencia – Spain
 JYFL Jyväskylä - Finland

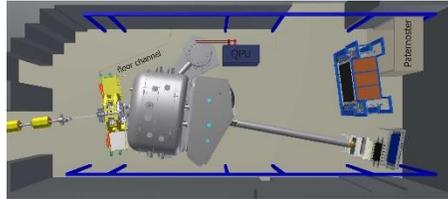


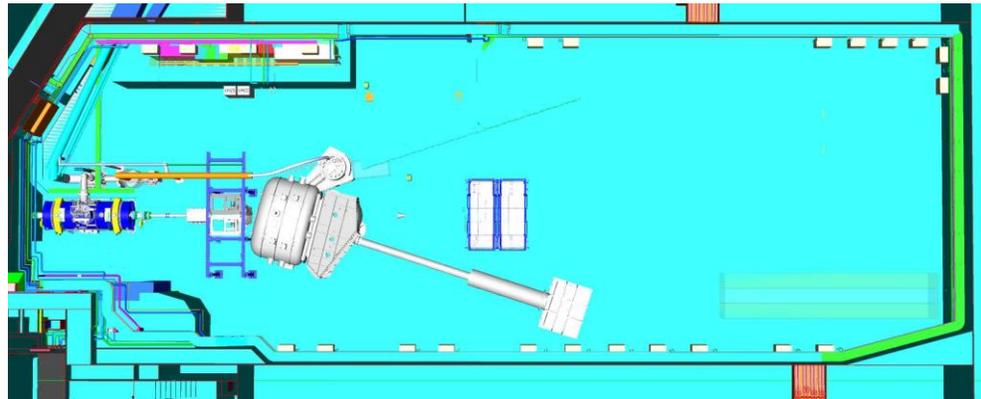
Goal: Energy spectra of β -delayed neutrons using β - γ -n coincidences in most exotic nuclei

- **Key focal planes of the Super-FRS:**
 - **FMF2** mid-point of Super-FRS main separator
 - **FHF1** (Super-FRS tunnel)
 - and **FHF2** (HEC) along high-energy branch



Cave C at GSI
25m x 10m = 250 m²

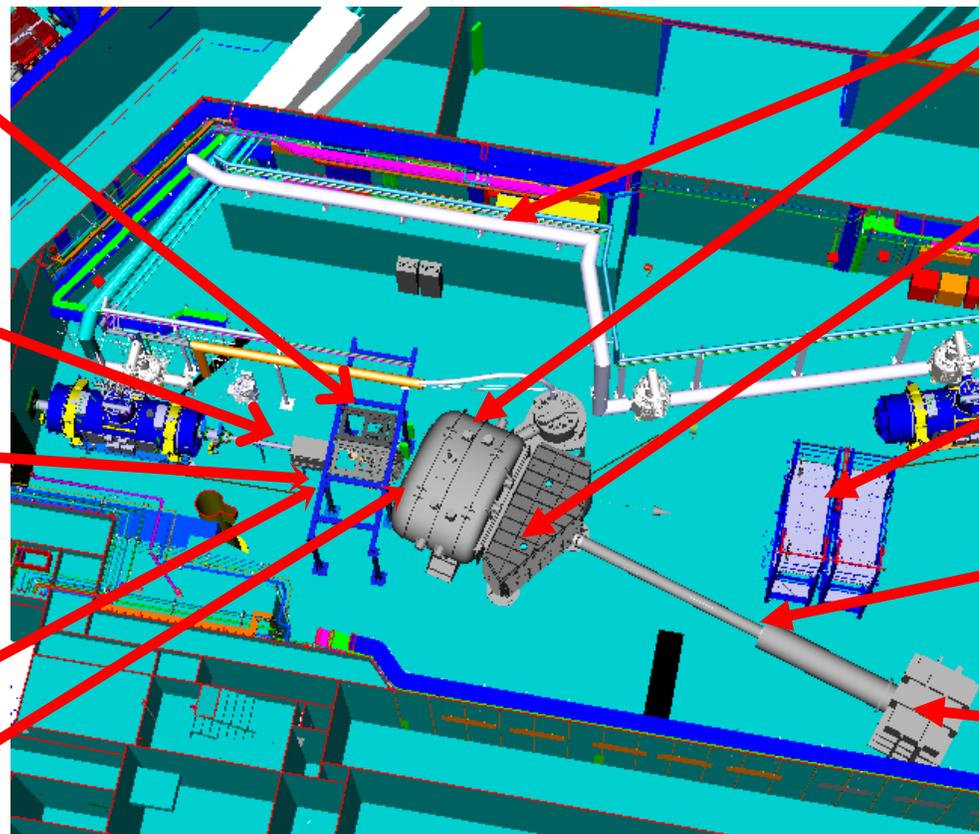




HEC at FAIR
60m x 20m = 1200 m²



R³B



CALIFA with 832 new crystals in the Backward Barrel

New beam diagnostic

LH₂-target with different piping and safety system

TRT with new barrel geometry and 4 x more acceptance

FOOT in-beam tracker with new electronics

GLAD with new control system

PAS with full angular coverage and operation in vacuum

NeuLAND significantly more double-planes

New HI Fiber tracker

TOF-D with a new in vacuum operation

Courtesy: R. Gernhäuser, R³B

Handover "cave ready for installation"

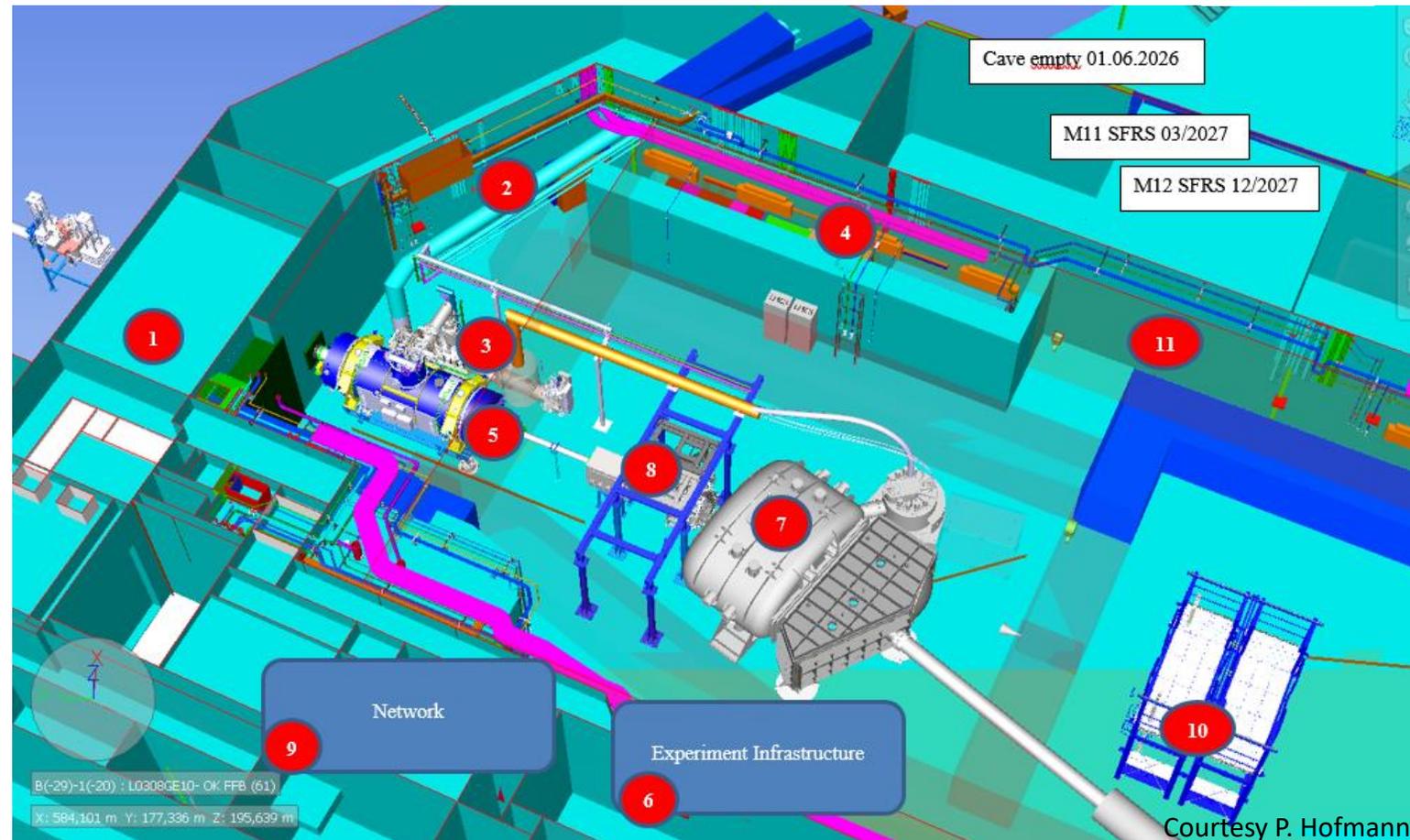
HE Cave Handover from Super-FRS

As soon as HEB cave is "empty", handover MS from Super-FRS, installation of R³B can start

NUSTAR Strategy towards Early Science

- 1) Mobile wall
- 2) Cryo Distribution Line
- 3) Local Cryo
- 4) Racks and cables (machine)
- 5) Multiplet (inc. connections to media)
- 6) Experiment Infrastructure
- 7) GLAD
- 8) CALIFA
- 9) Network
- 10) NEULAND
- 11) Closing of outside wall

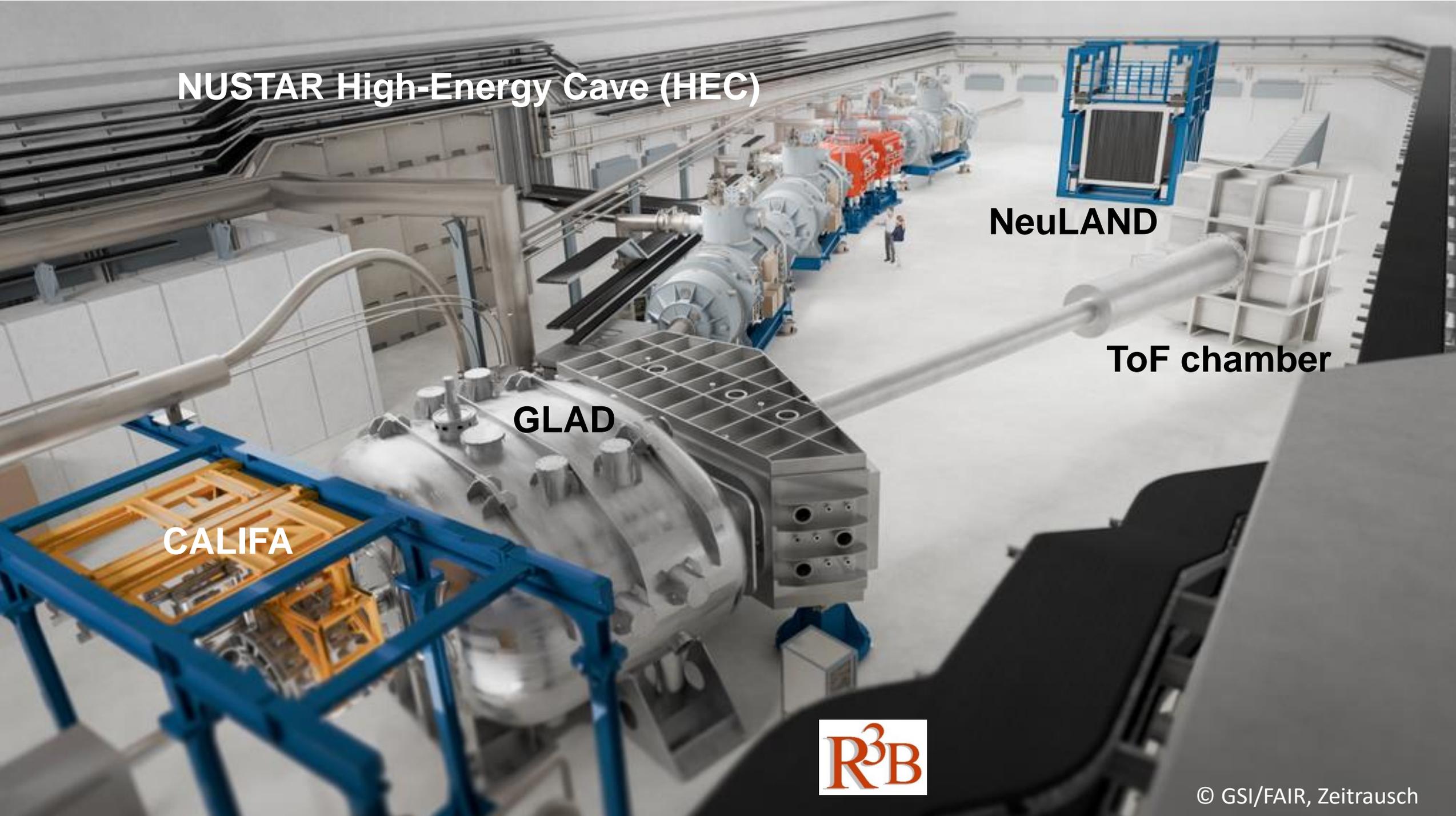
Relocation of GLAD to High-Energy Cave takes ~ 12 months



Courtesy P. Hofmann

**Estimated dates - details being worked out in LCM Workshops*

NUSTAR High-Energy Cave (HEC)



NeuLAND

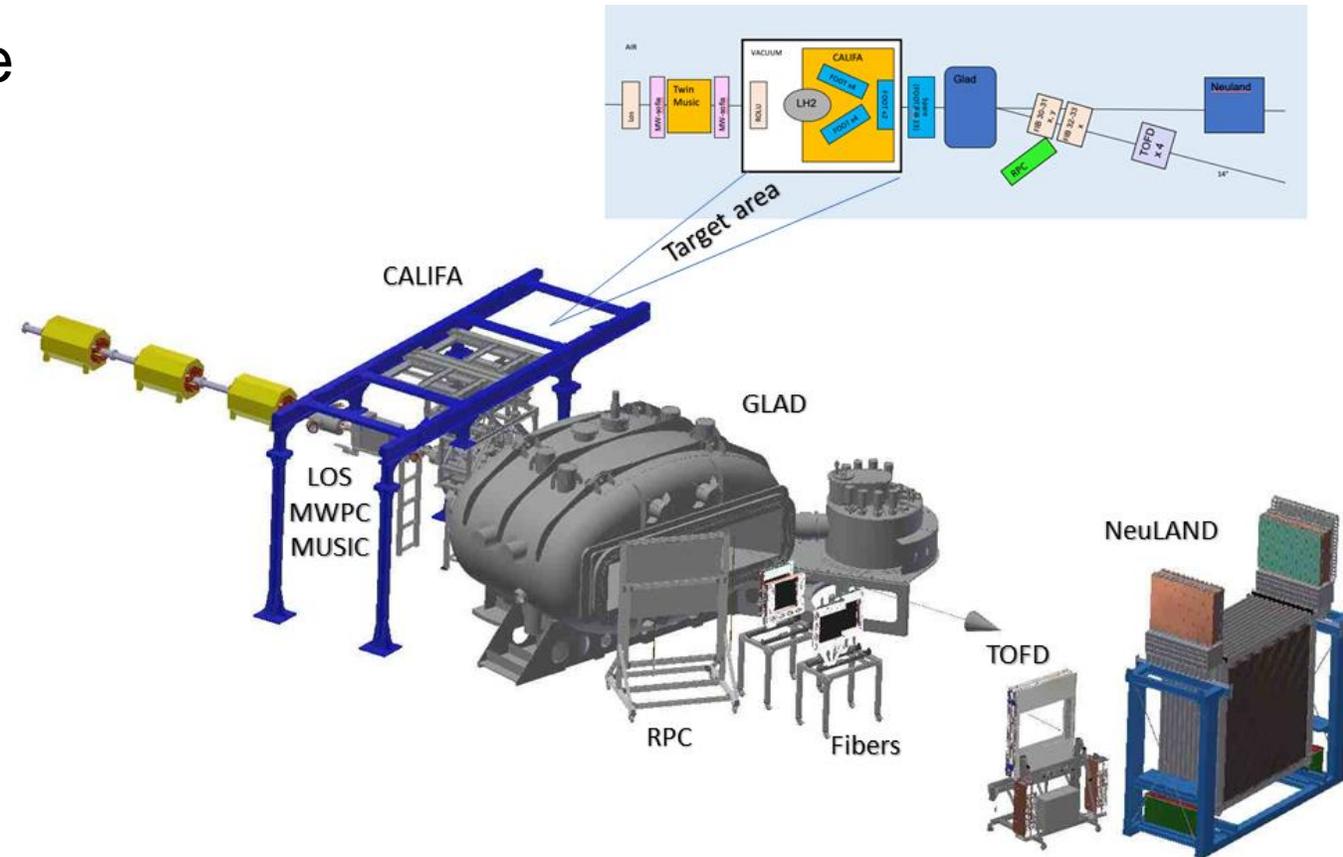
ToF chamber

GLAD

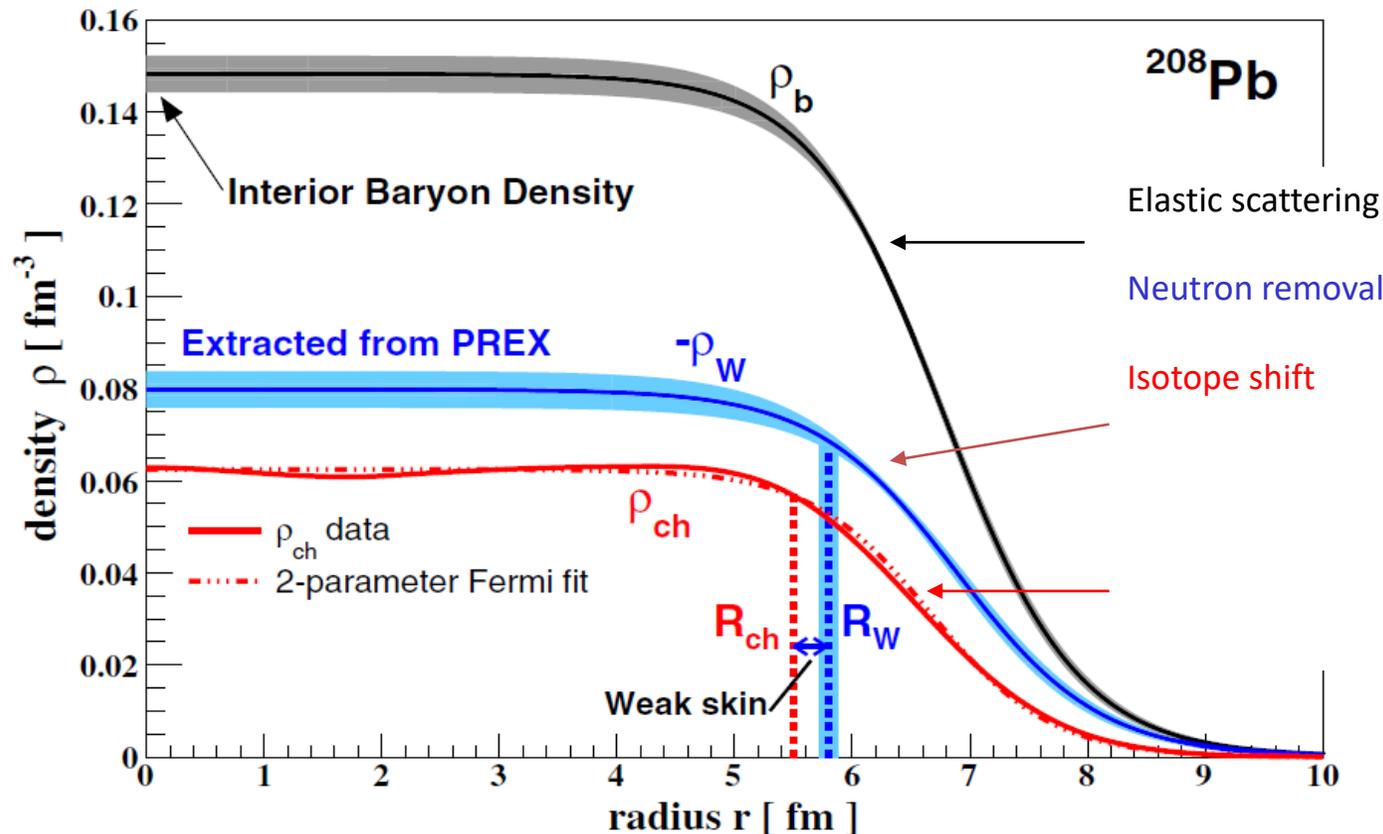
CALIFA



- R³B setup in the high-energy cave
- Focusing on:
 - Neutron skin measurements
 - Fission
- Make use of improvements:
 - Super-FRS transmission
 - Maximum gain for light to medium-heavy nuclei
 - Cleaner beams
- R³B specific improvements
 - longer TOF => identification to high mass
 - better angular resolution



Most precise constraints on the neutron pressure around saturation density from measurements of **neutron skins** and **dipole polarizabilities**



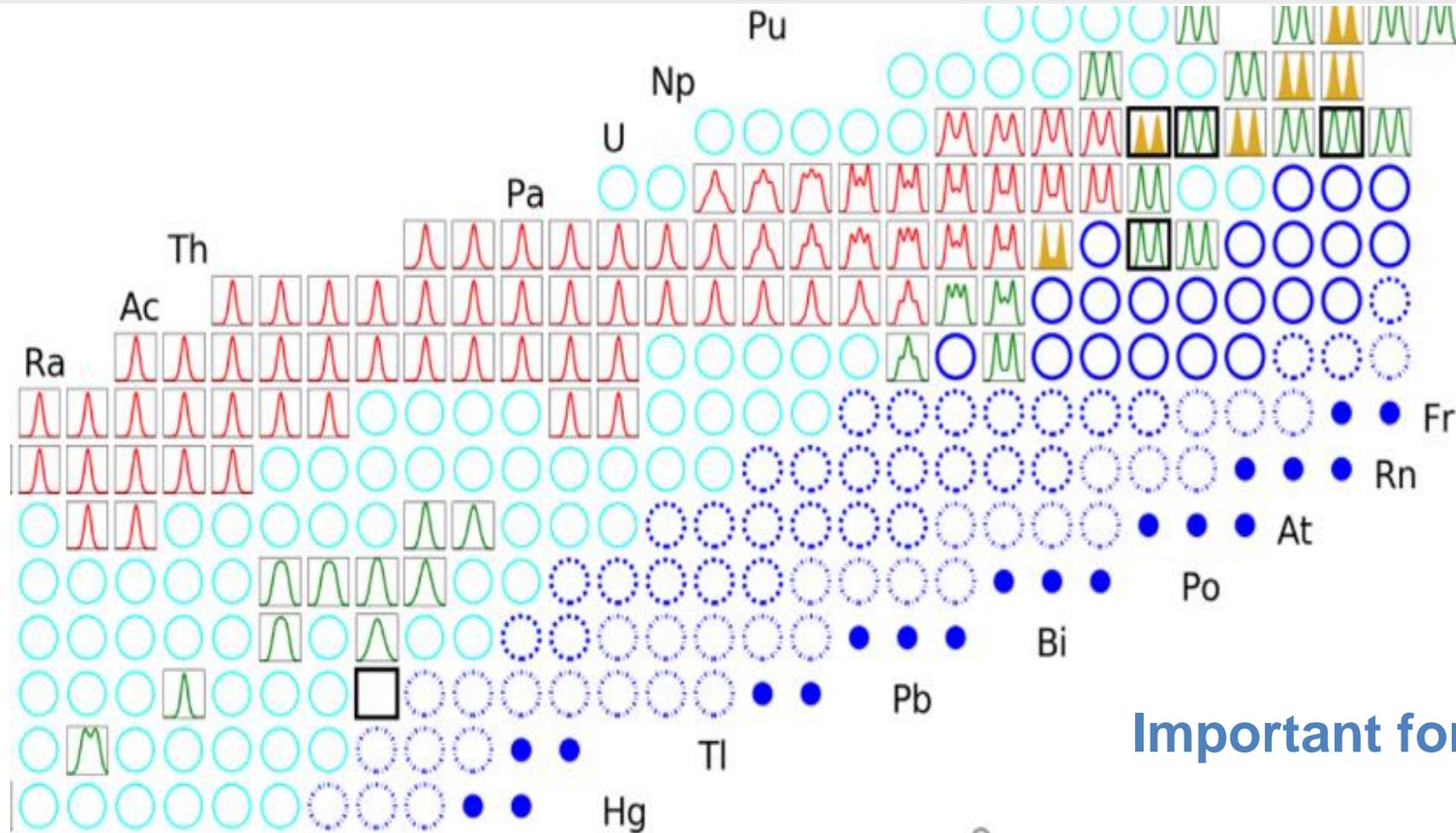
Relatively low ^{238}U intensity needed
 -> sufficient for $\sim ^{132}\text{Sn}$

Important for the Understanding of neutron stars

PHYSICAL REVIEW LETTERS **126**, 172502 (2021)

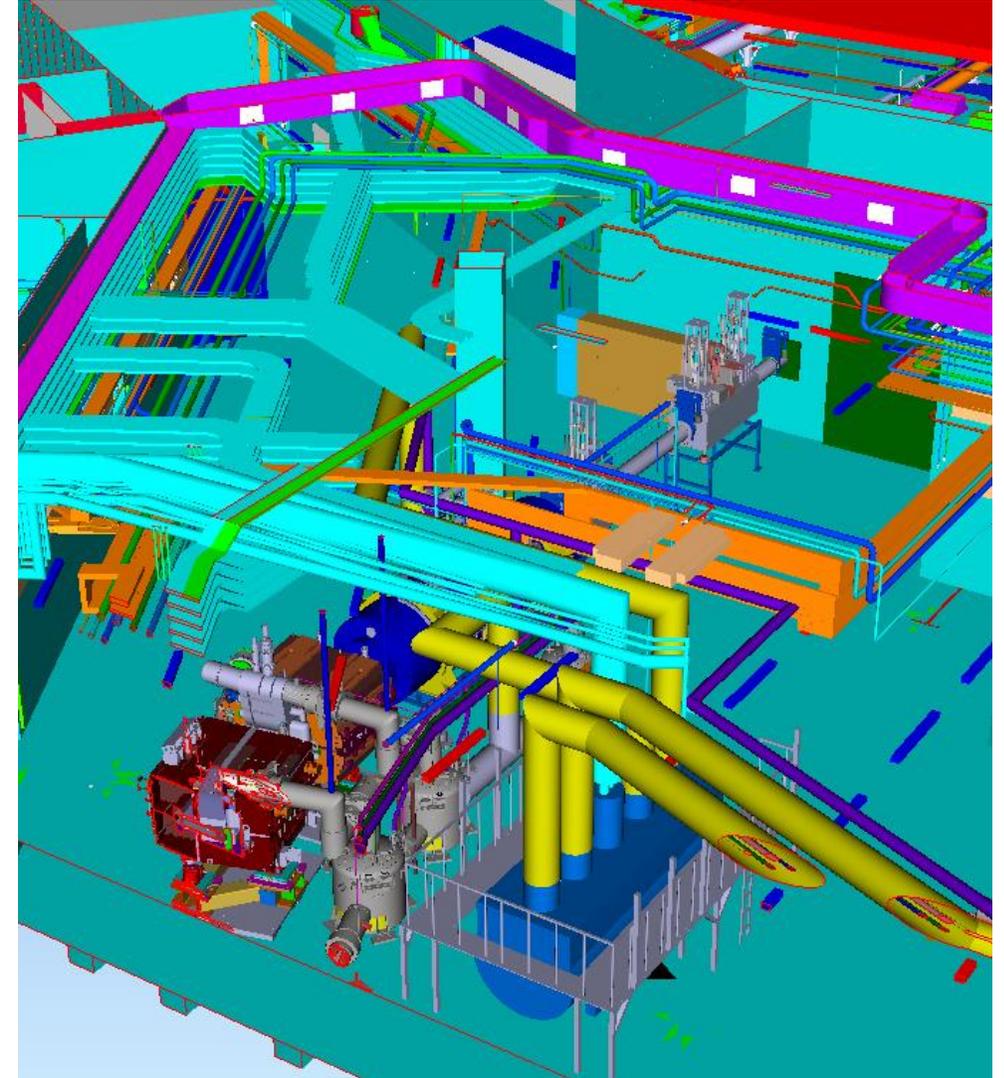
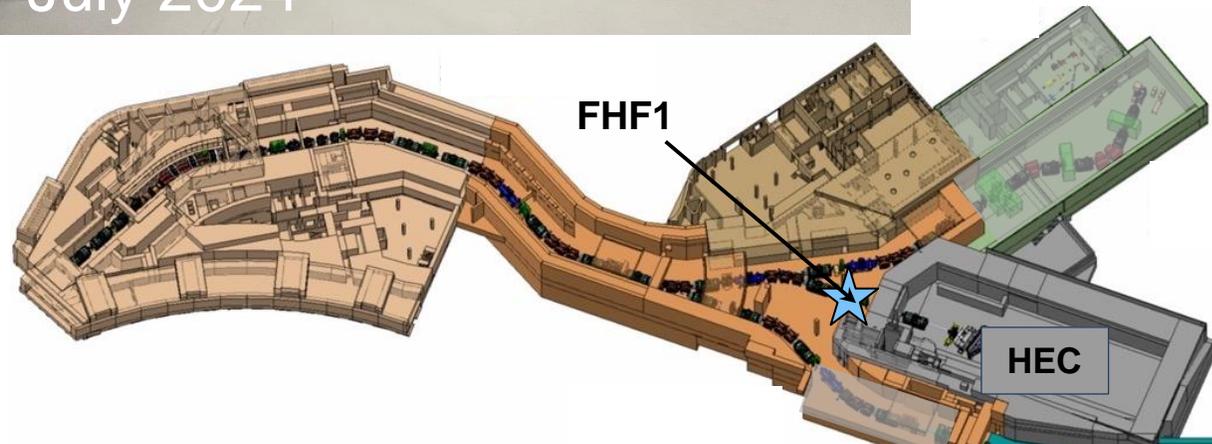


Fission



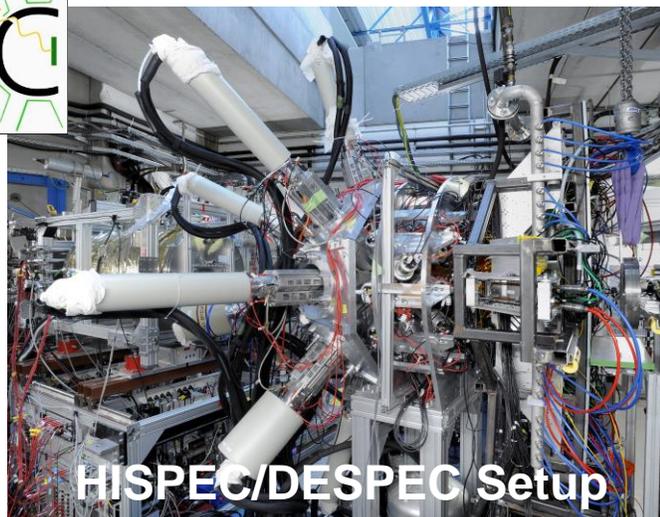
Important for r process

measured Z (red) and A (green) fission yields in actinides and pre-actinides together with the neutron-rich (dark blue circles and dots) and other nuclei (light blue circles) that can be investigated at FAIR





Early Science: Compact setups FHF1/FMF2

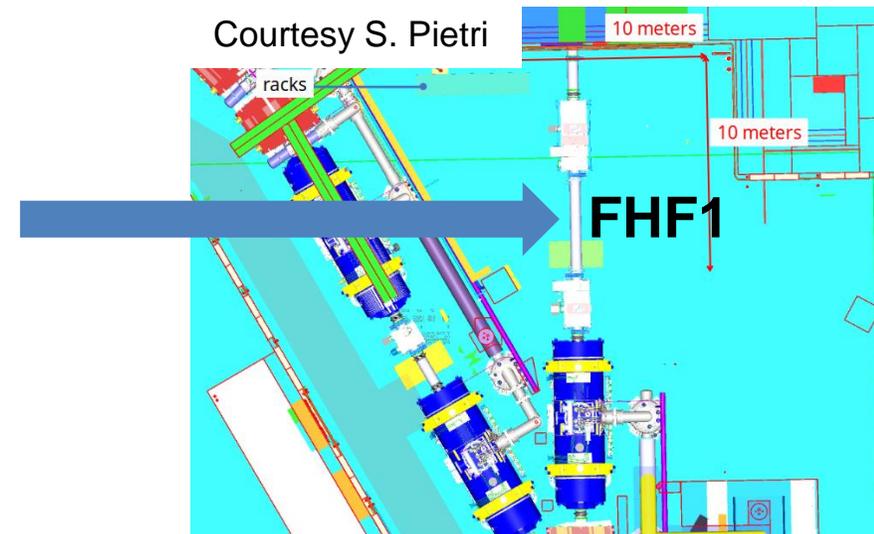


HISPEC/DESPEC Setup



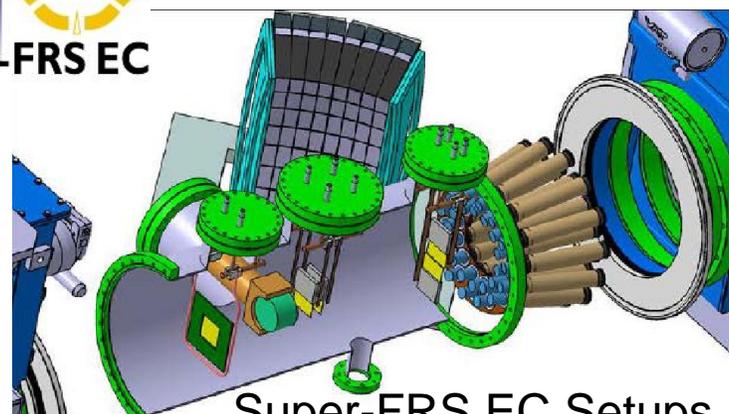
Super-FRS EC Ion Catcher

MR-TOF multi-reflection time-of-flight mass spectrometer



Courtesy S. Pietri

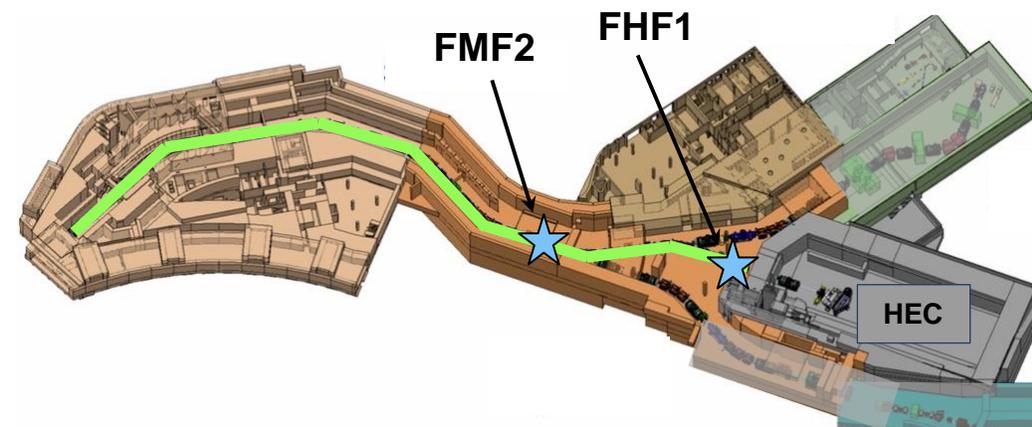
FHF1



Super-FRS EC Setups



FMF2



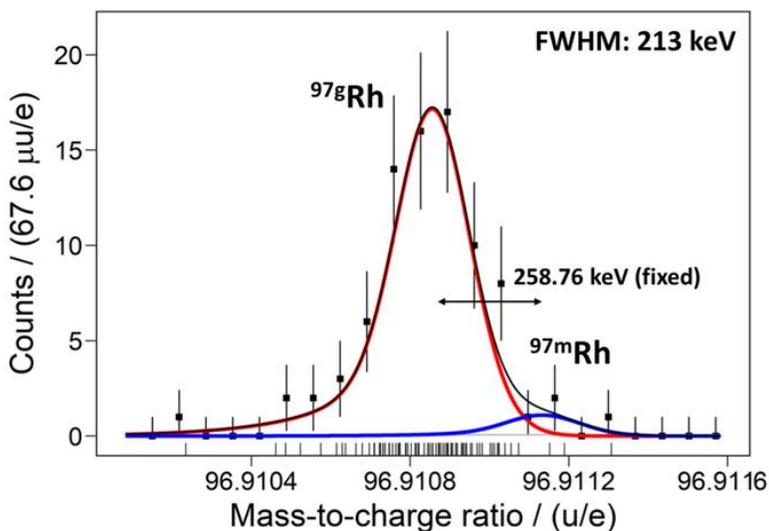
FMF2

FHF1

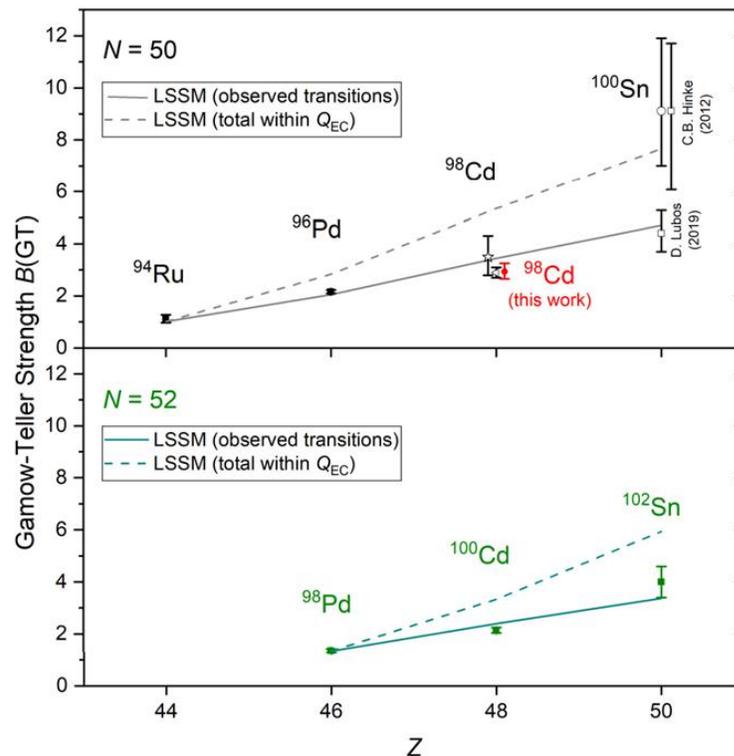
HEC



- First direct mass measurements of ^{98}Cd and ^{97}Rh with the FRS Ion Catcher



A. Mollaebrahimi *et al.*, Physics Letters B 839 (2023) 137833



Overall situation unclear, further experiments required

^{100}Sn mass:

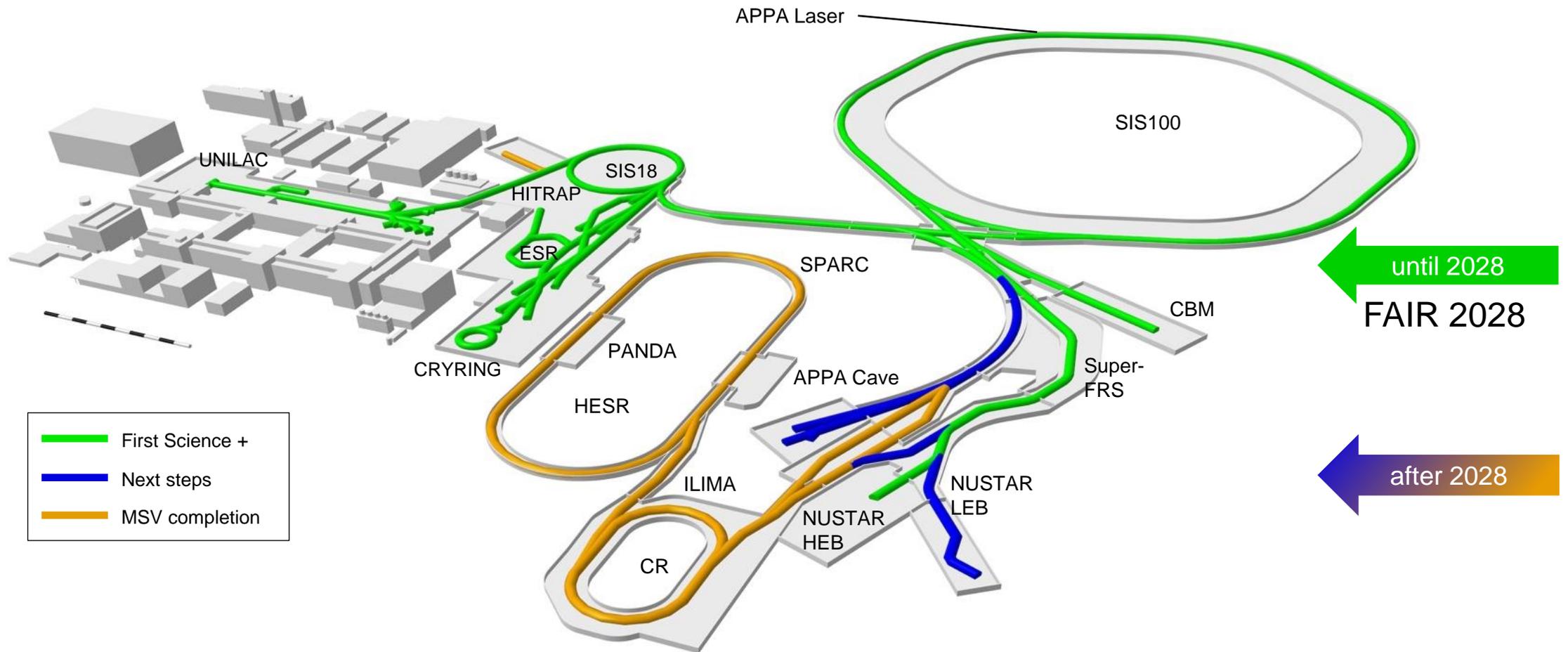
- New results on discrepancy of ^{100}Sn Q_{EC} values (Hinke *et al.* [1] and Lubos *et al.* [2])
 - In recent work, Mougeot *et al.* [3] derive the mass of ^{100}Sn from mass measurements of $^{99-101}\text{In}$ and published ^{100}Sn QEC values
 - value of Hinke *et al.* is favored
- This work:** Evolution of shifted two-neutron shell gap at N=50:
 - Value of Hinke *et al.* [1] is favored.
 Evolution of Gamov-Teller Strength at N=50:
 - Value of Lubos *et al.* [2] is favored.

[1] C.Hinke *et al.*, Nature 486 (2012) 341

[2] D.Lubos *et al.*, PRL 122 (2019) 222502

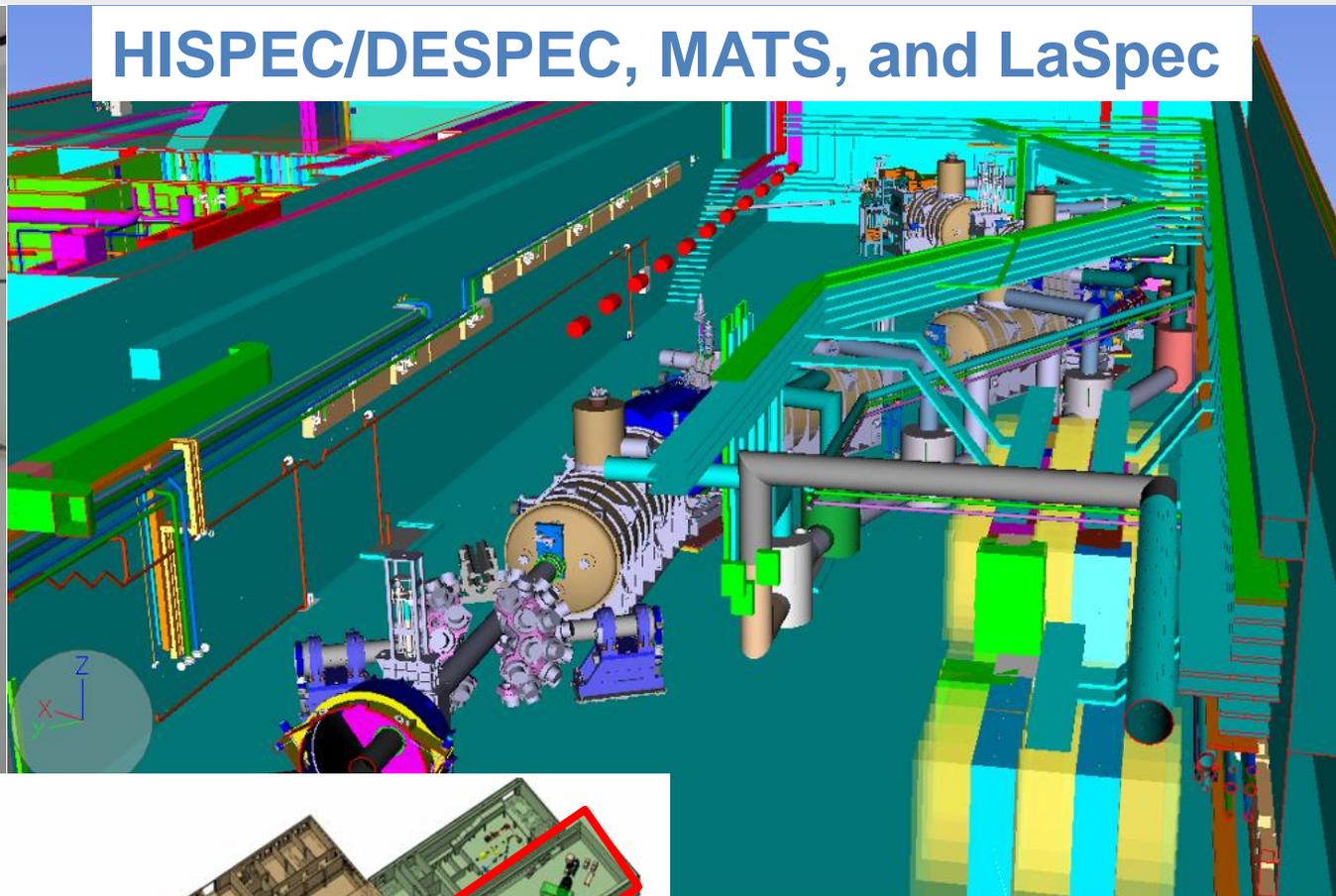
[3] M.Mougeot *et al.*, Nature Phys. 17 (2021) 1099

Next steps and MSV completion ...





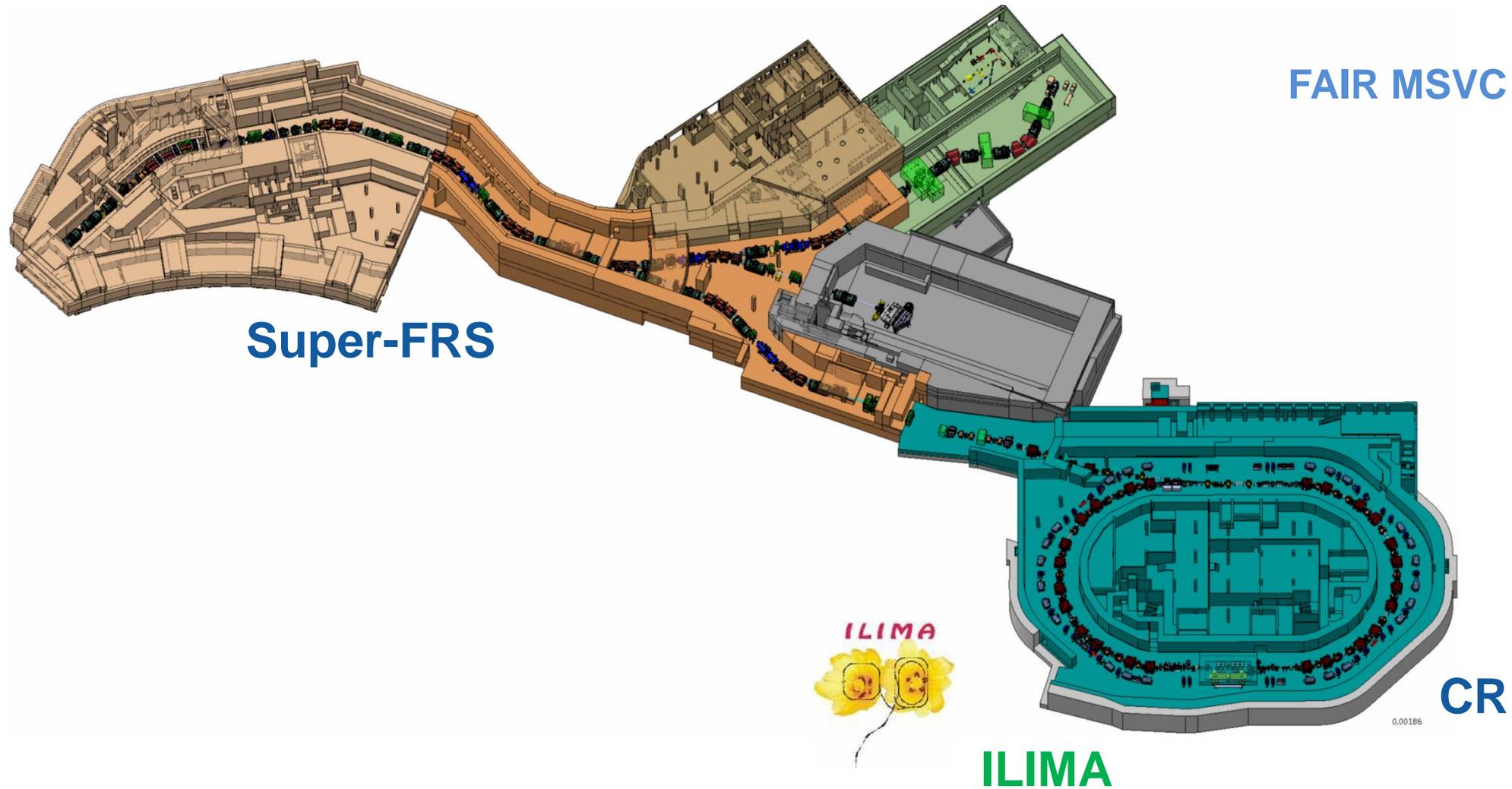
HISPEC/DESPEC, MATS, and LaSpec



January 2025

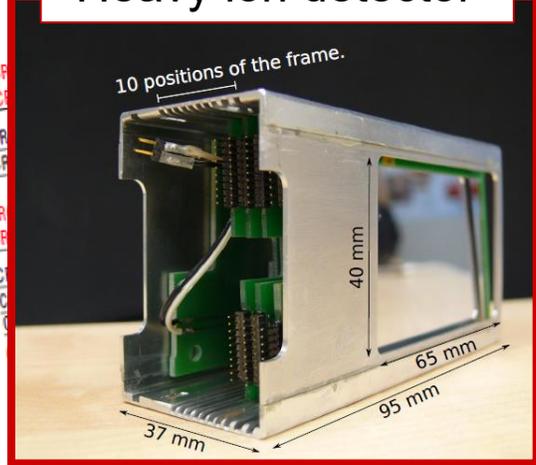


LEB cave



“Schottky pickups”

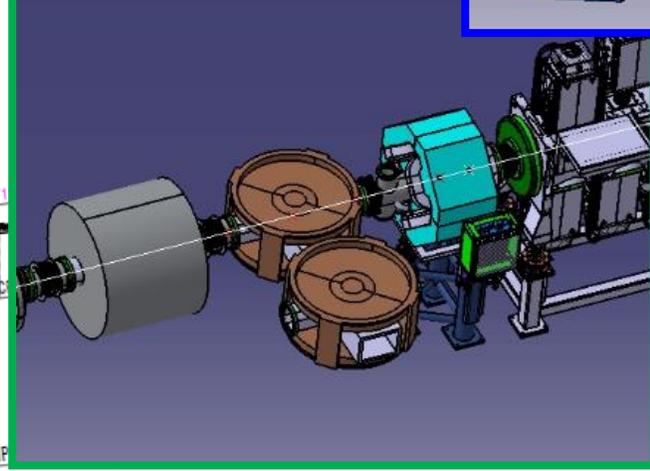
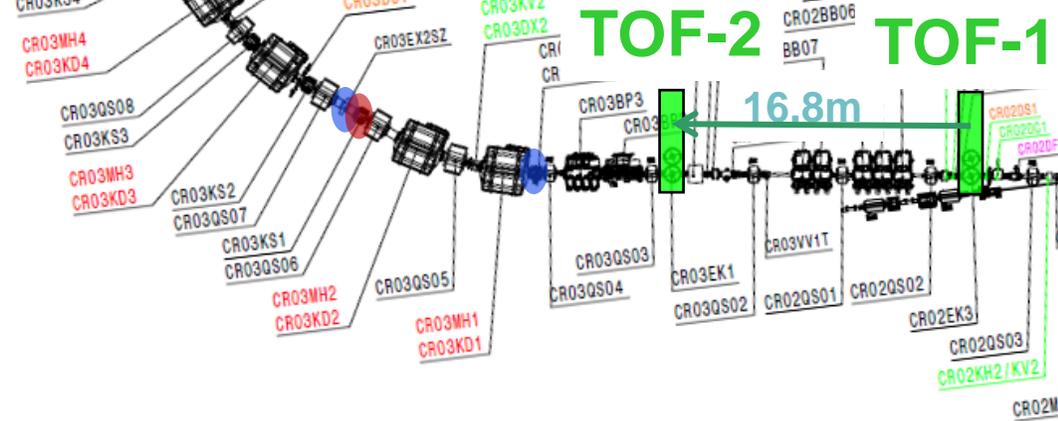
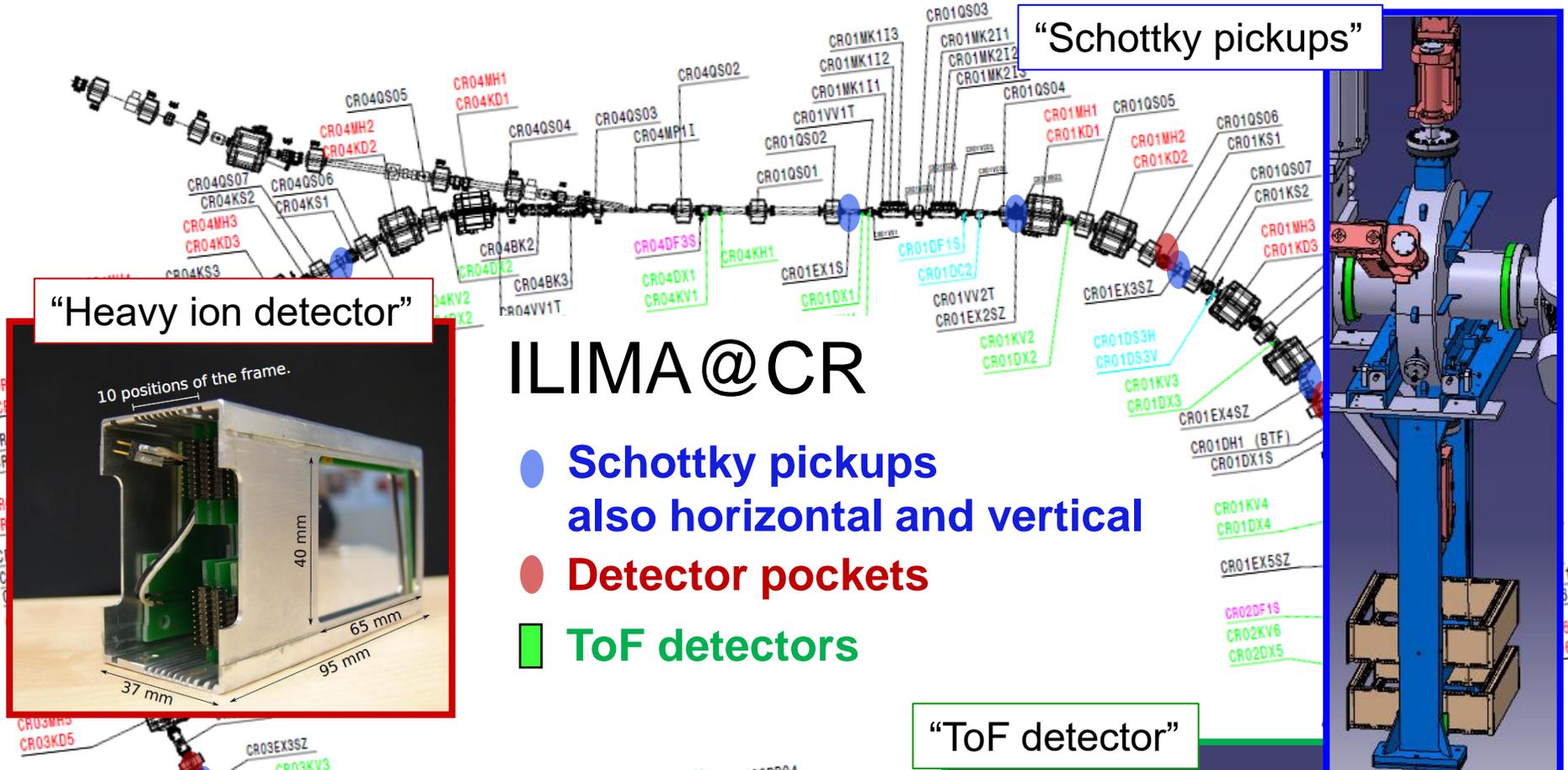
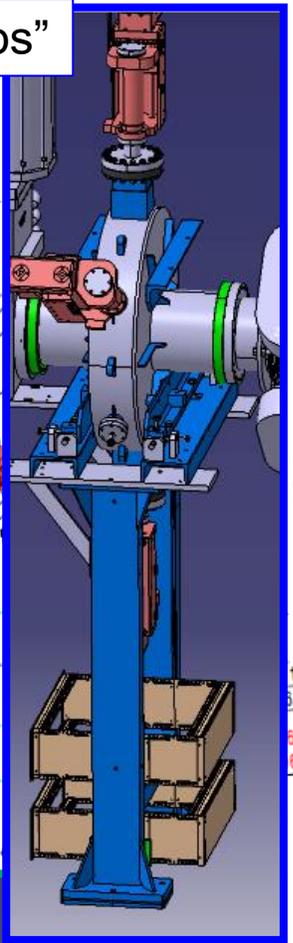
“Heavy ion detector”



ILIMA@CR

- Schottky pickups also horizontal and vertical
- Detector pockets
- ToF detectors

“ToF detector”



stand: 12.02.2016

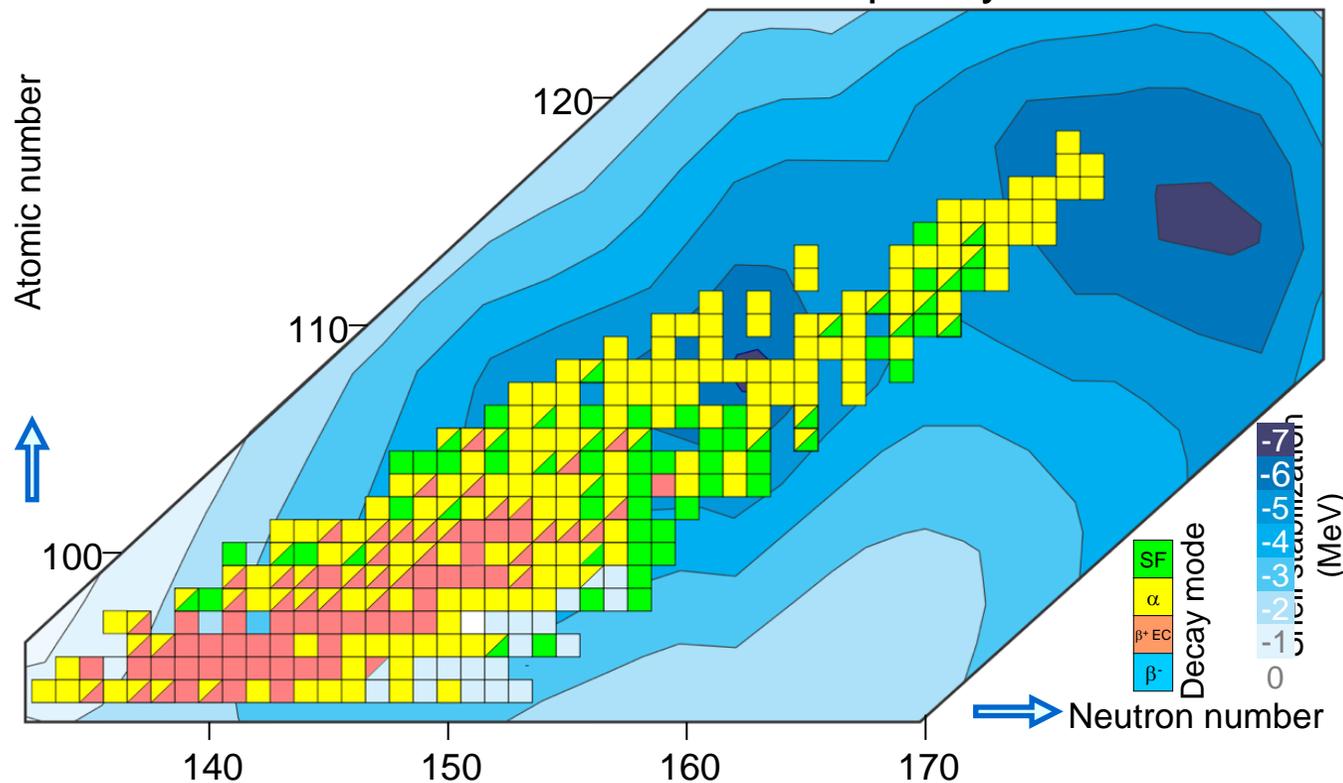




Superheavy elements (SHE) at GSI/UNILAC



- What are the **limits of atomic nuclei and of the periodic table** of the element?
- Does **the structure of the periodic table** hold in the heaviest elements?
 - Comprehensive investigation of **production** and of **atomic, chemical, and nuclear properties** of “accelerator-only” elements **Z ~ 100 – 118**.
- Detailed studies of and with macroscopically available actinide elements with **Z ≈ 90 – 100**

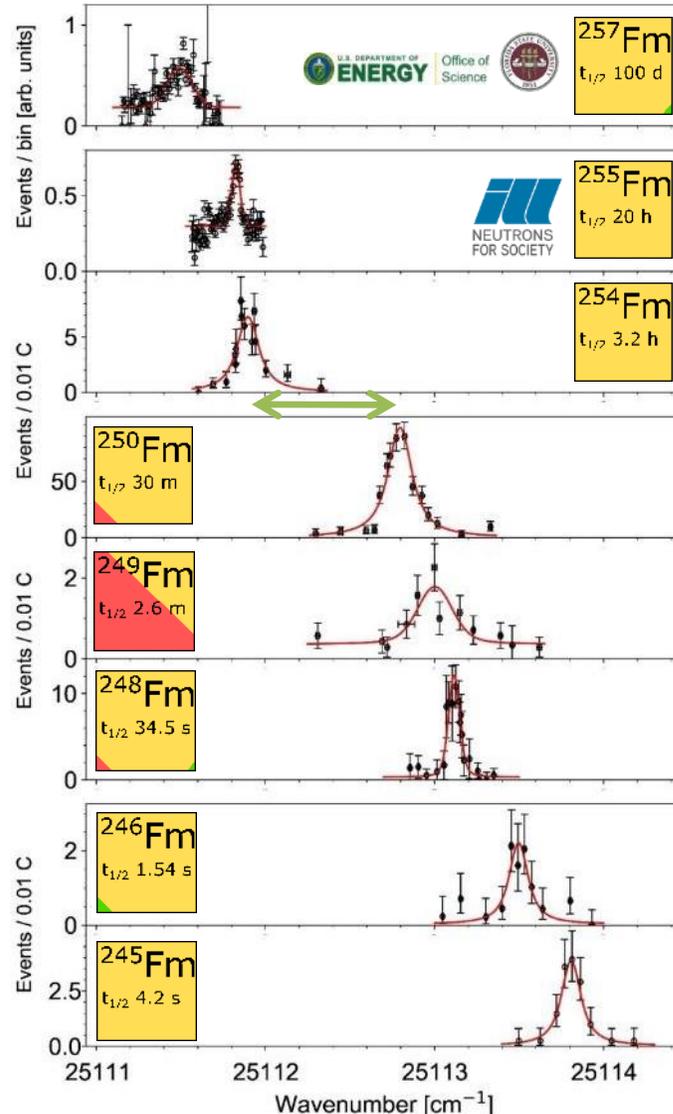


1	2											18											
1																		2					
H																		He					
3	4											13	14	15	16	17	18						
Li	Be																	B	C	N	O	F	Ne
11	12											13	14	15	16	17	18						
Na	Mg																	Al	Si	P	S	Cl	Ar
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36						
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr						
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54						
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe						
55	56	57-71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86						
Cs	Ba	La-Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn						
87	88	89-103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118						
Fr	Ra	Ac-Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og						

*	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
**	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr



Laser Spectroscopy of Fermium Isotopes

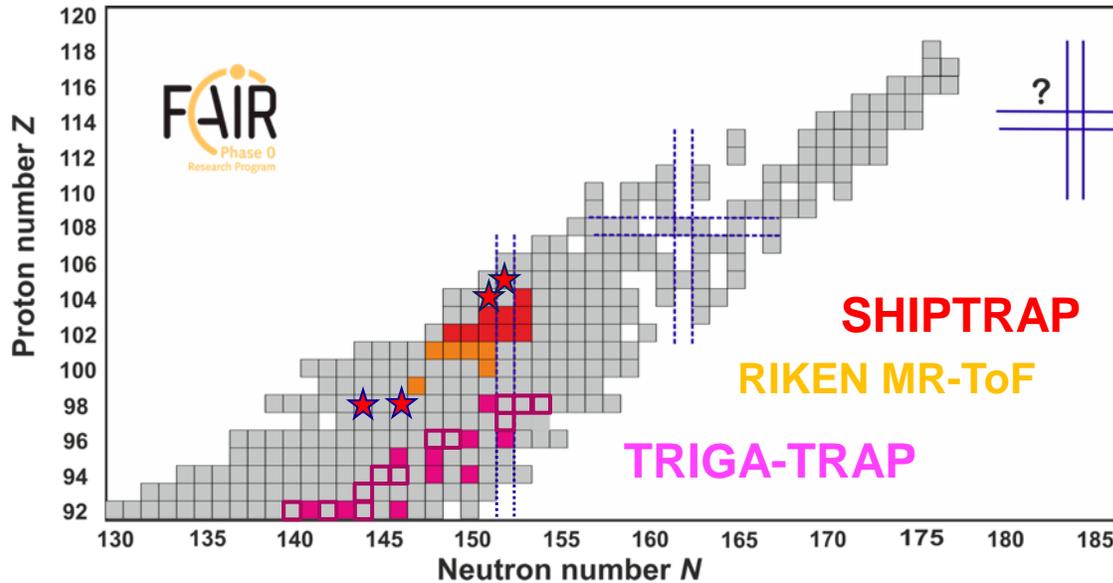


- new methods developed for laser spectroscopy of the heaviest elements in gas cells
- obtained **change in nuclear charge radii** for 8 fermium (Z=100) isotopes from **isotope shifts** measured by laser spectroscopy at GSI/ SHIP and JGU Mainz

$$\delta\langle r^2 \rangle^{AA'} = \left(\Delta v^{AA'} - \frac{A - A'}{AA'} M \right) \frac{1}{F}$$

- comparison with theory calculations: smooth trend in charge radii without signatures of nuclear shell effects

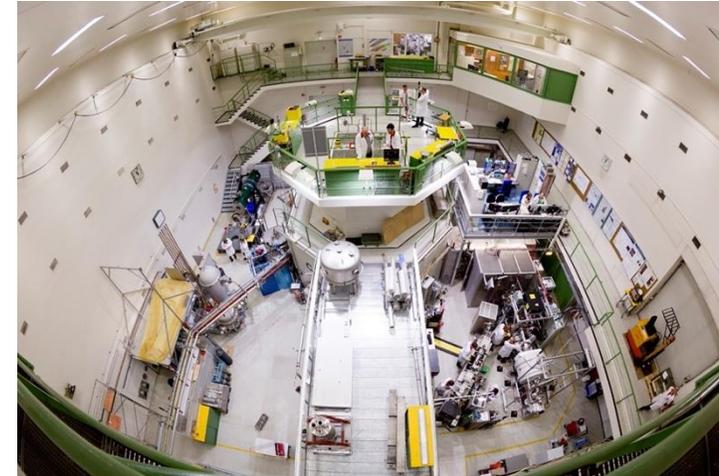
J. Warbinek et al., Nature 634 (2024) 1075 **nature**



SHIPTRAP



TRIGA-TRAP



Direct mass spectrometry beyond $Z = 92$ to map nuclear shell structure evolution

- Online with **SHIPTRAP** at **GSI** and offline with **TRIGA-TRAP** at **Mainz**
- TRIGA-TRAP will move to Super-FRS-LEB at FAIR -> **MATS**



- **NUSTAR core components are in operation** (e.g. at GSI) as part of **FAIR Phase-0**
 - Scientific results, further tests and commissioning, and training (e.g. of PhD students)
- Installation and commissioning of NUSTAR components at FAIR **in detailed planning**
 - **Move and installation of equipment to start soon**
- **Further funding of cave and common infrastructure required**
 - Collection of funds or in-kind via **NUSTAR Construction MoU**
- **Start of FAIR (Early Science)** with SIS18 beam to Super-FRS target **at the end of 2027**
 - First experiment campaigns in 2028 (**R³B, DESPEC, Super-FRS EC**)
- **Additional activities at ESR (ILIMA) and UNILAC (SHE) of GSI**

NUSTAR Week 2025



- Prague, Czech Republic
- September 29th – October 2nd 2025
- More information soon via NUSTAR mailing list



