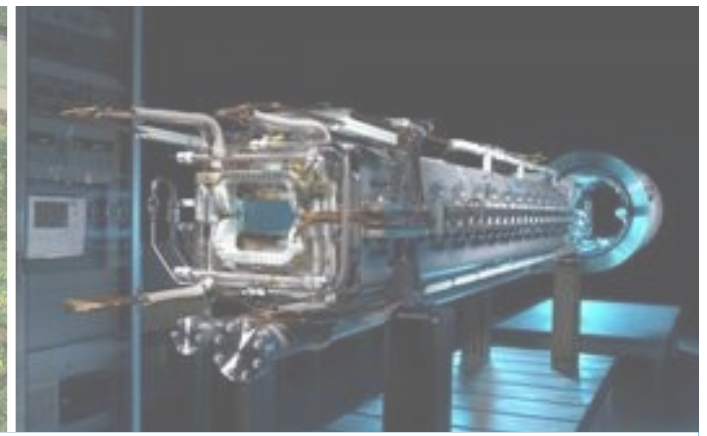




From Atomic Nuclei to Stars: Exploring the Extremes with NUSTAR at FAIR

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

FAIR Seminar at Jagiellonian University and Institute of Nuclear Physics PAN
February 4th, 2021



Finland



France



Germany



India



Poland



Romania



Russia



Slovenia



Sweden

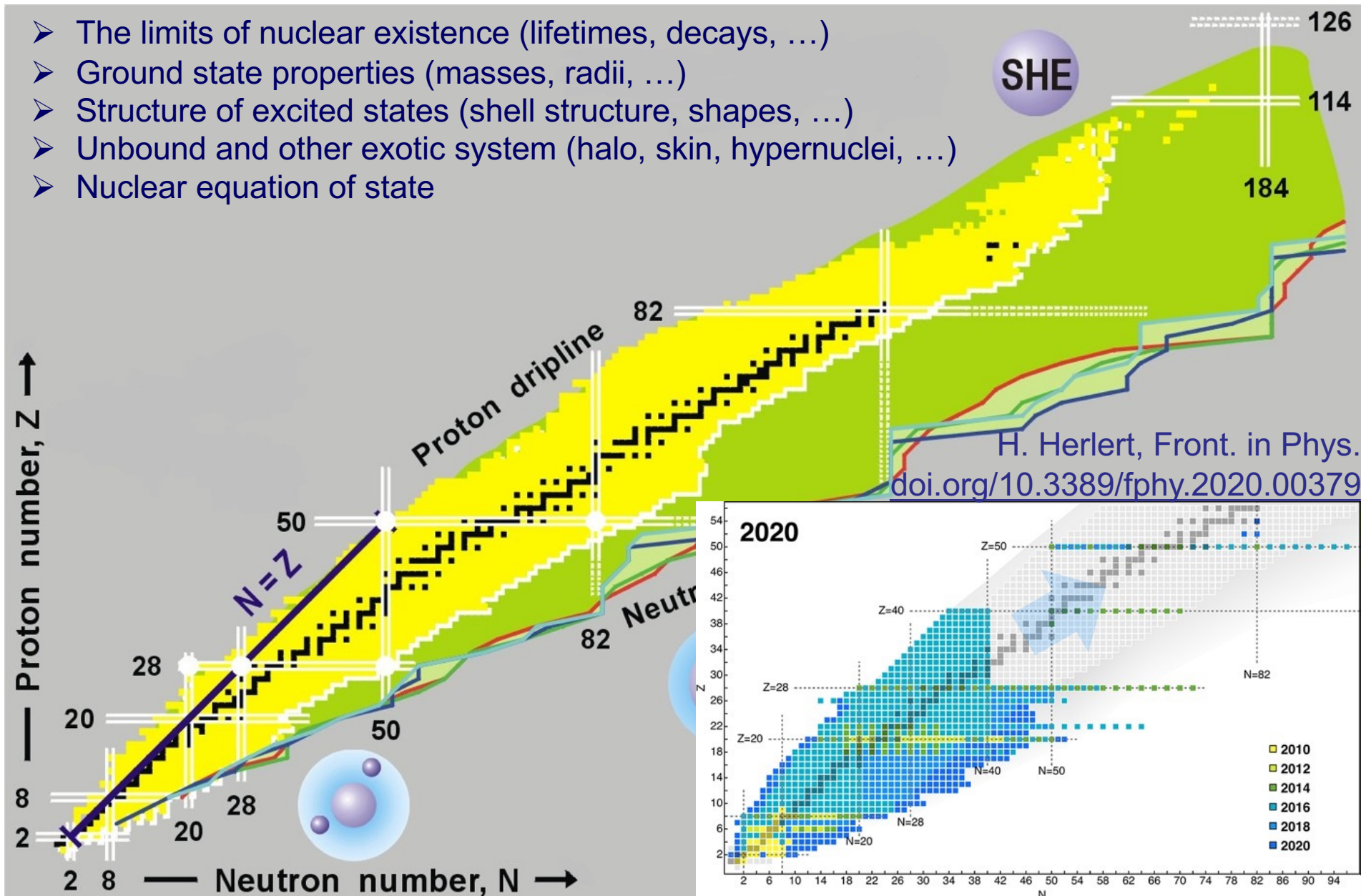


UK

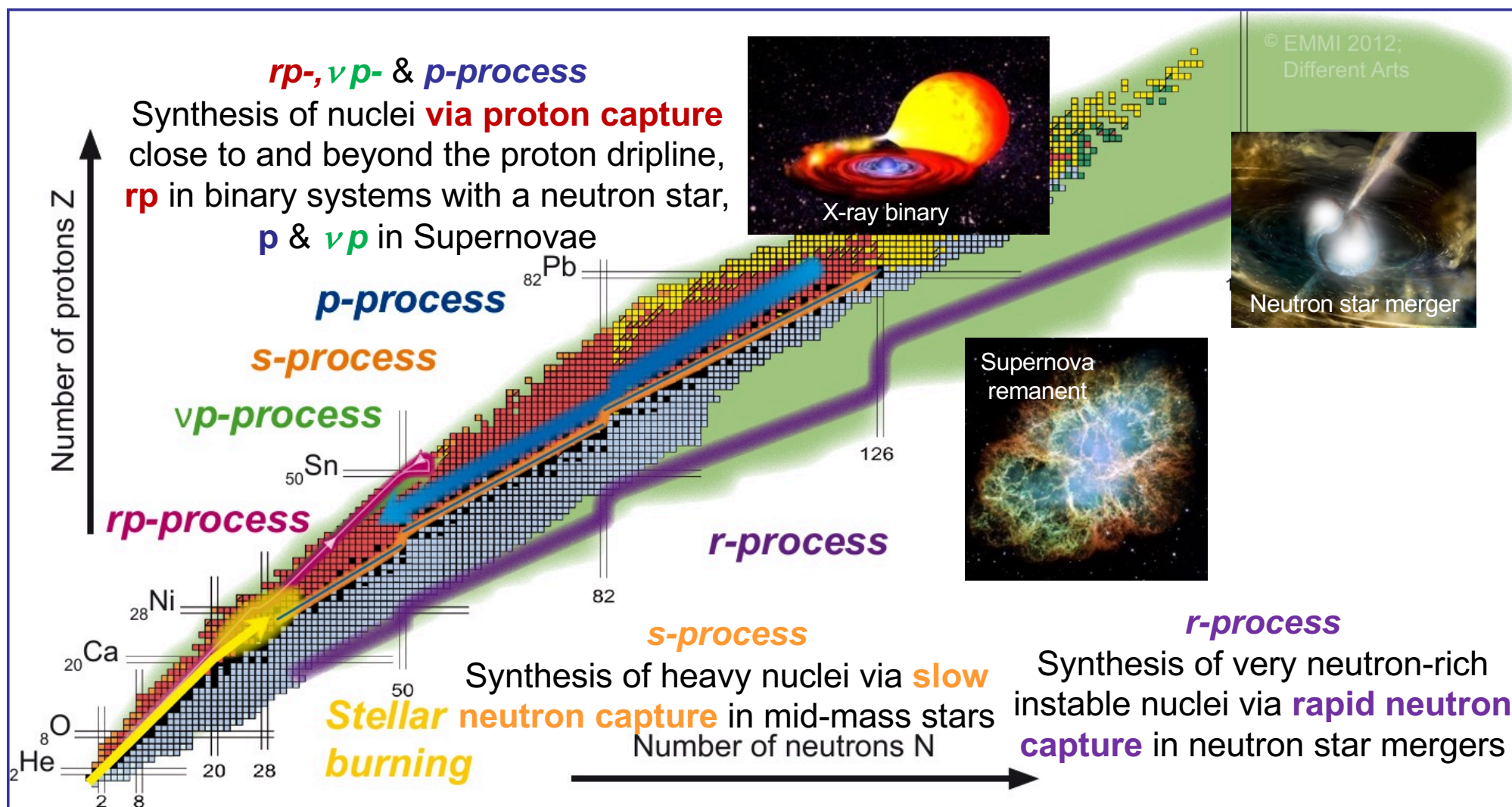


- The Physics Program of the FAIR collaboration on ***NUclear STtructure Astrophysics and Reactions***
- The **Super-FRS Radioactive Ion Beam facility** for NUSTAR@FAIR
- The **NUSTAR Day-1 Program** at the Super-FRS
- Status of the NUSTAR experiment and first results from research in **FAIR phase-0**

- The limits of nuclear existence (lifetimes, decays, ...)
- Ground state properties (masses, radii, ...)
- Structure of excited states (shell structure, shapes, ...)
- Unbound and other exotic system (halo, skin, hypernuclei, ...)
- Nuclear equation of state

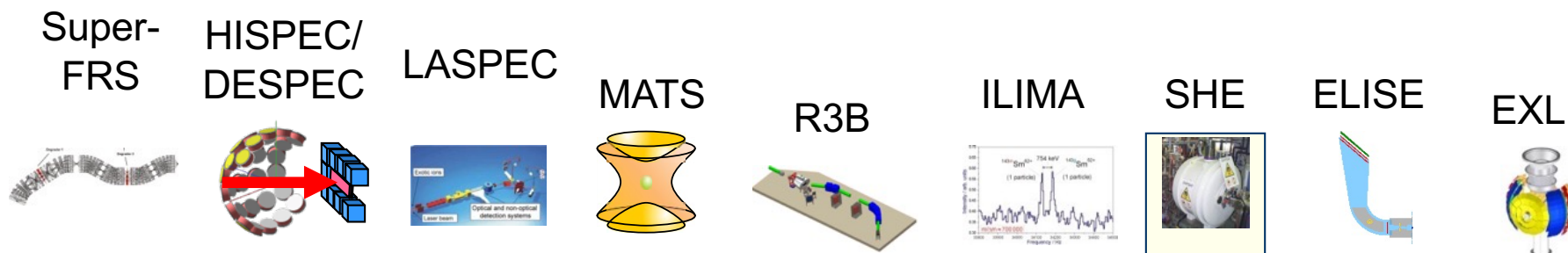


Measurements in the laboratory: Mass, lifetime, decay channels, structure of very rare (neutron- or proton-rich) nuclei far from the valley of stability



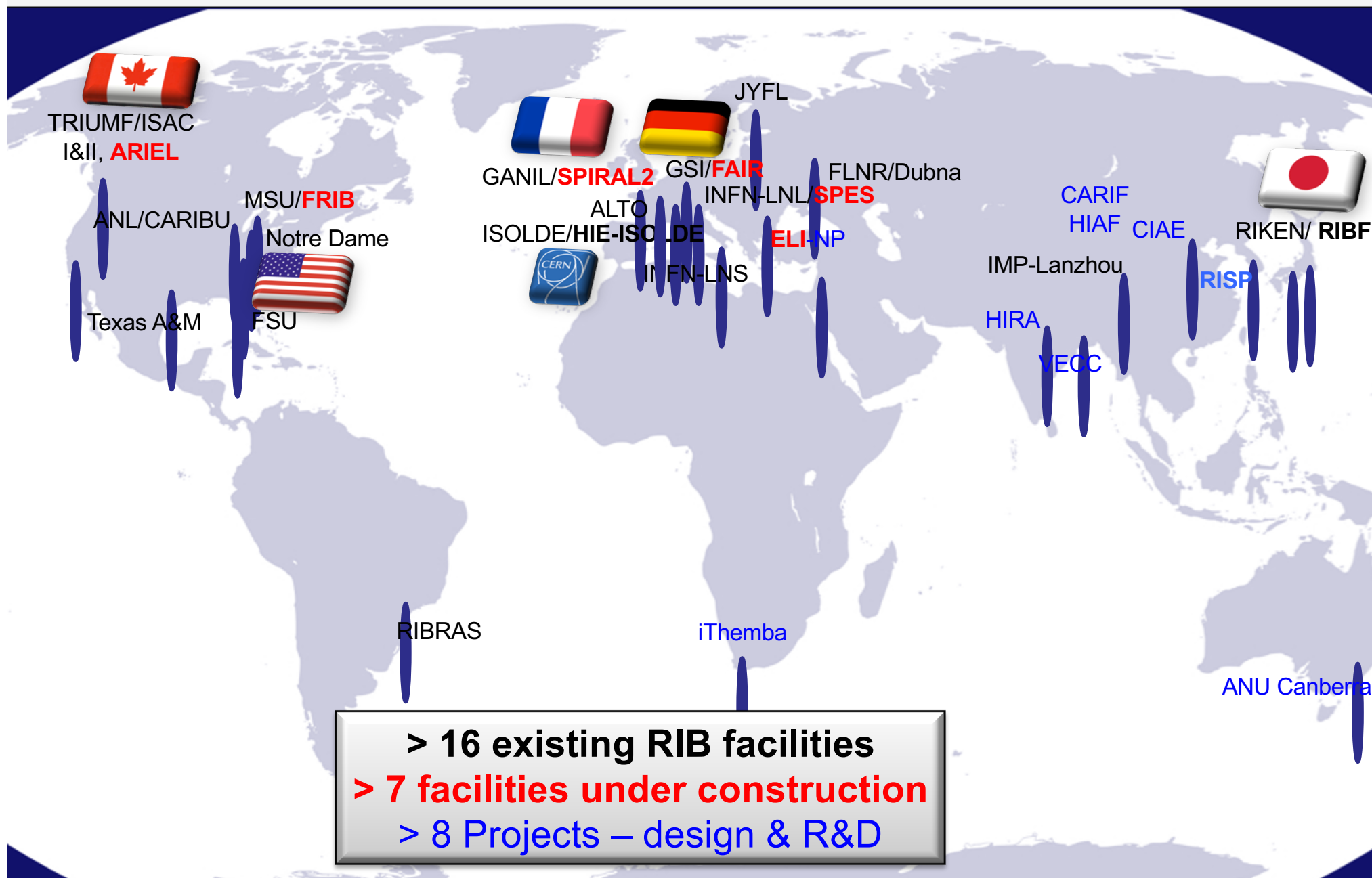
Super-FRS	Production, separation, and identification of rare isotopes
HISPEC/ DESPEC	In-beam γ-spectroscopy at low and intermediate energy, Decay spectroscopy: high-resolution γ -, β -, α -, p, n-decay
MATS	In-trap mass measurements and decay studies
LaSpec	Laser spectroscopy
R³B	Kinematical complete reactions with relativistic radioactive beams
ILIMA	Large-scale scans of mass and lifetimes of nuclei in ground and isomeric states in storage rings
Super-FRS experiments	High-resolution spectrometer experiments, exotic nuclear matter
SHE	Synthesis and study of super-heavy elements
ELISE(*)	Elastic, inelastic, and quasi-free e-A scattering in storage rings
EXL(*)	Light-ion scattering reactions in inverse kinematics in storage rings

(*) NESR required – alternative/intermediate solution under consideration.

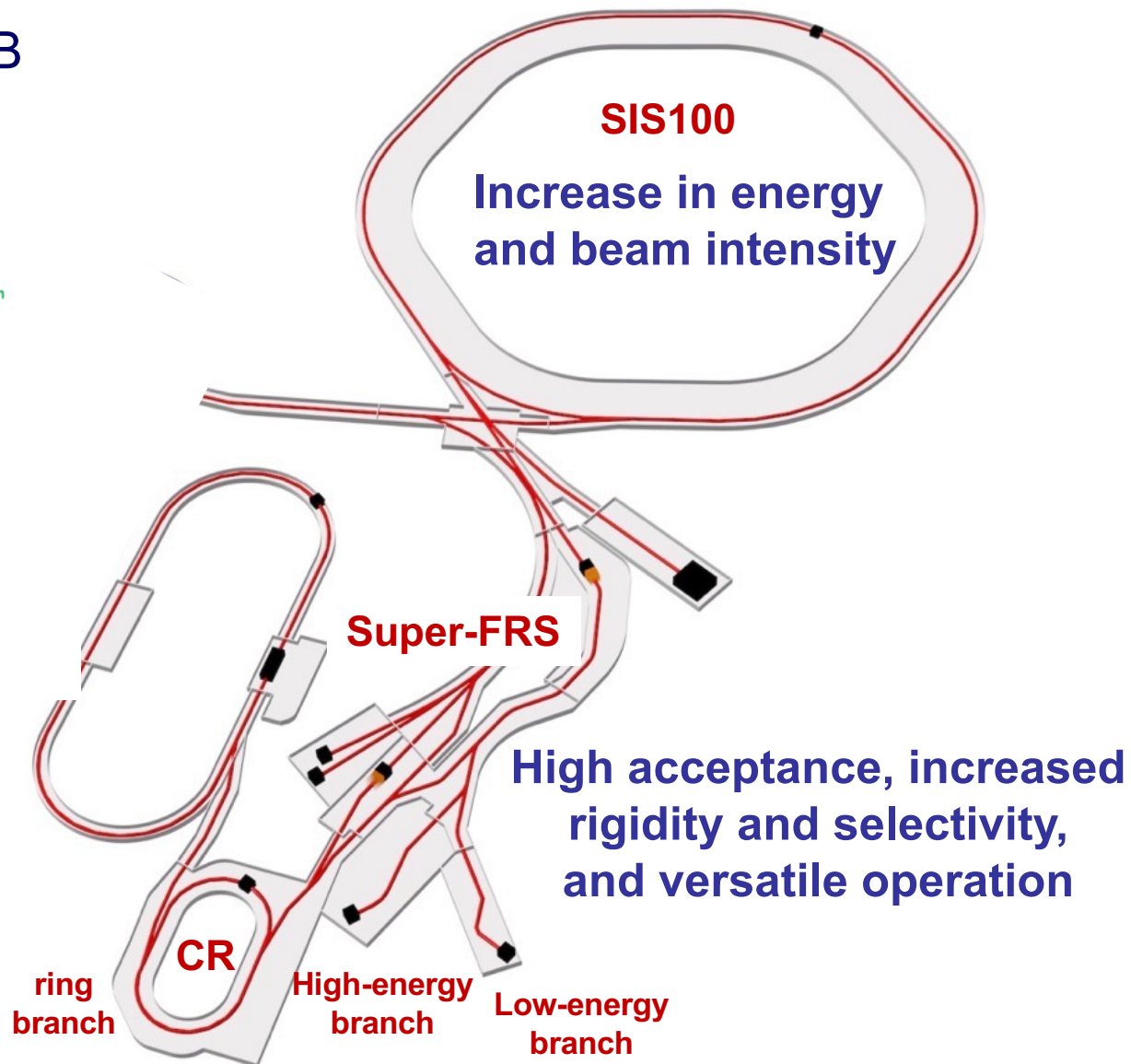
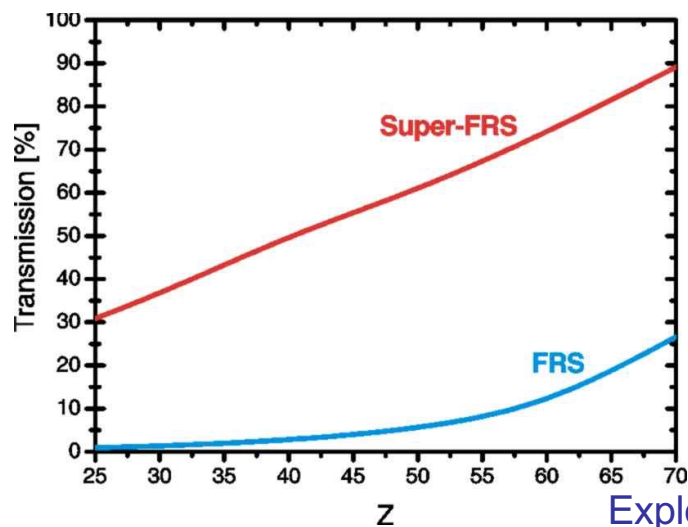
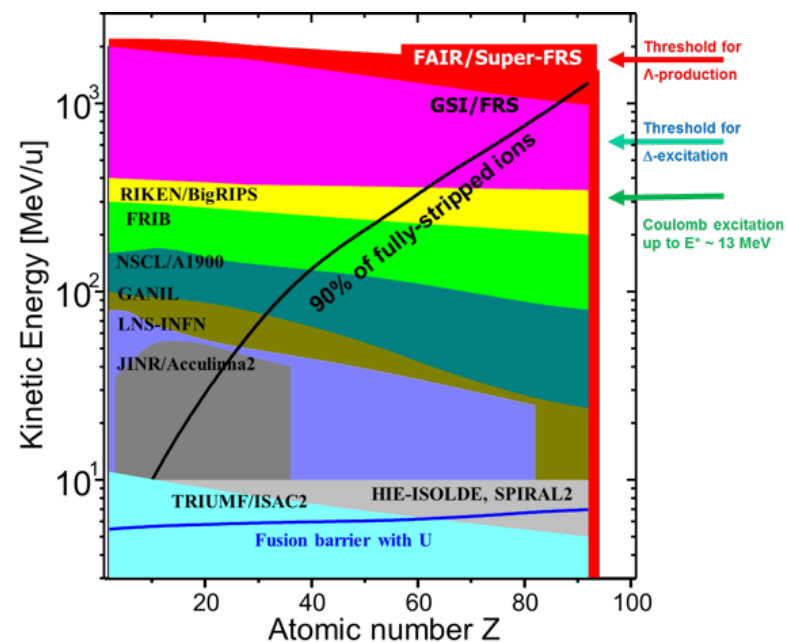


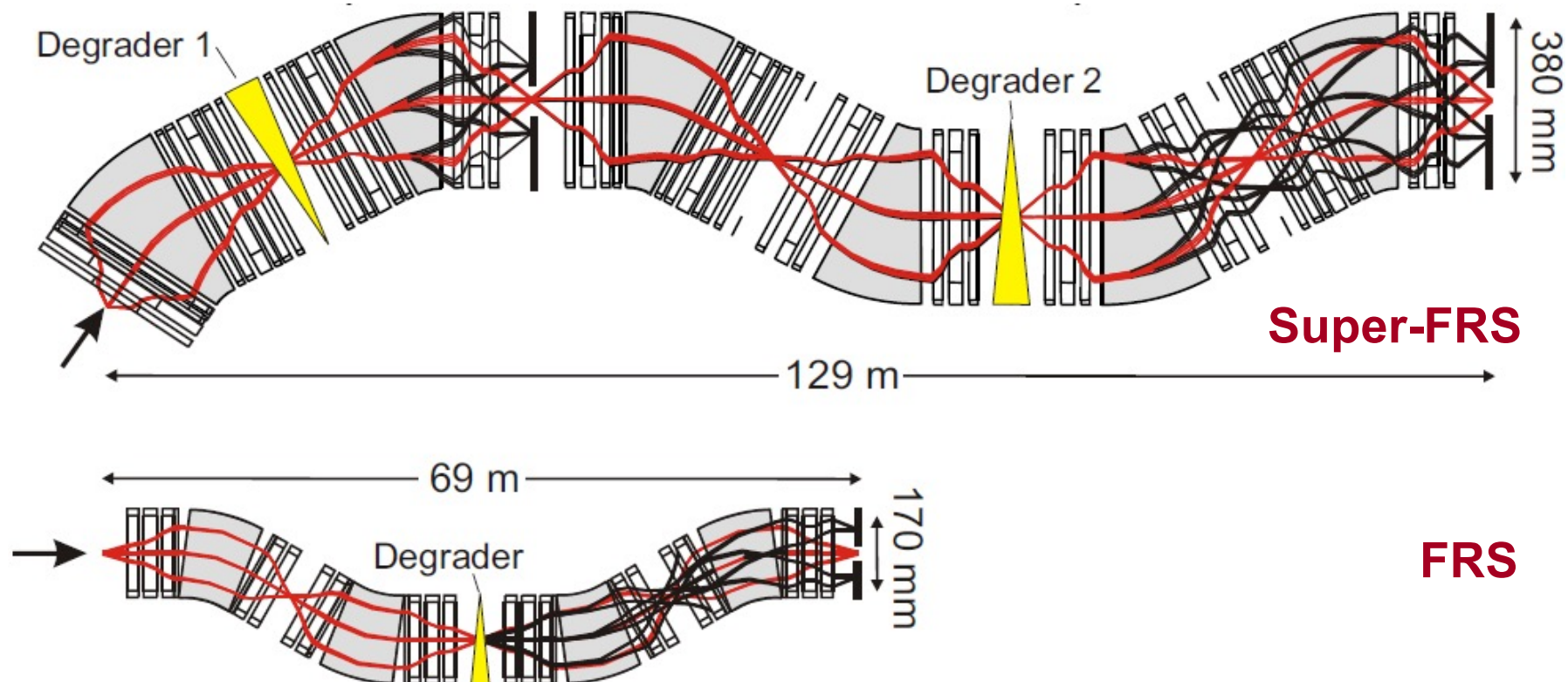
	Super-FRS	HISPEC/DESPEC	LASPEC	MATS	R3B	ILIMA	SHE	ELISE	EXL
Masses		Q-values, isomers		dressed ions, highest precision	unbound nuclei	bare ions, mapping study	precision mass of SHEs		
Half-lives	ps...ns-range	ground state and isomers μ s...s			resonance width, decay up to 100ns	bare ions, ms...years	μ s...days		
Matter radii	interaction x- section				interaction cross sections				matter density distribution
Charge radii	charge- changing cross sections		mean square radii		charge-changing cross sections			charge density distribution	
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		low momentum transfers
Collective properties		electromagnetic transition strength	quadrupole moments	halo structure	dipole response, fission	changes in deformation		electromagnetic transition strength	monopole resonance
Equation of State (EoS)					polarizability, neutron skin			neutron skin	neutron skin, compressibility
Exotic nuclear Systems	hypernuclei, bound mesons, nucleon reson.	rare and exotic e.m. and particle decays			n-rich hypernuclei	exotic decay modes			

The Super-FRS Radioactive Ion Beam facility for NUSTAR@FAIR



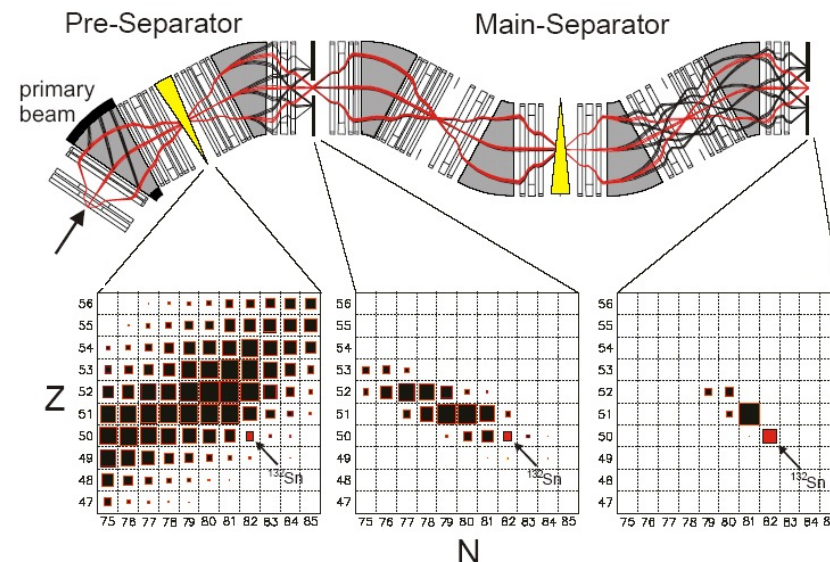
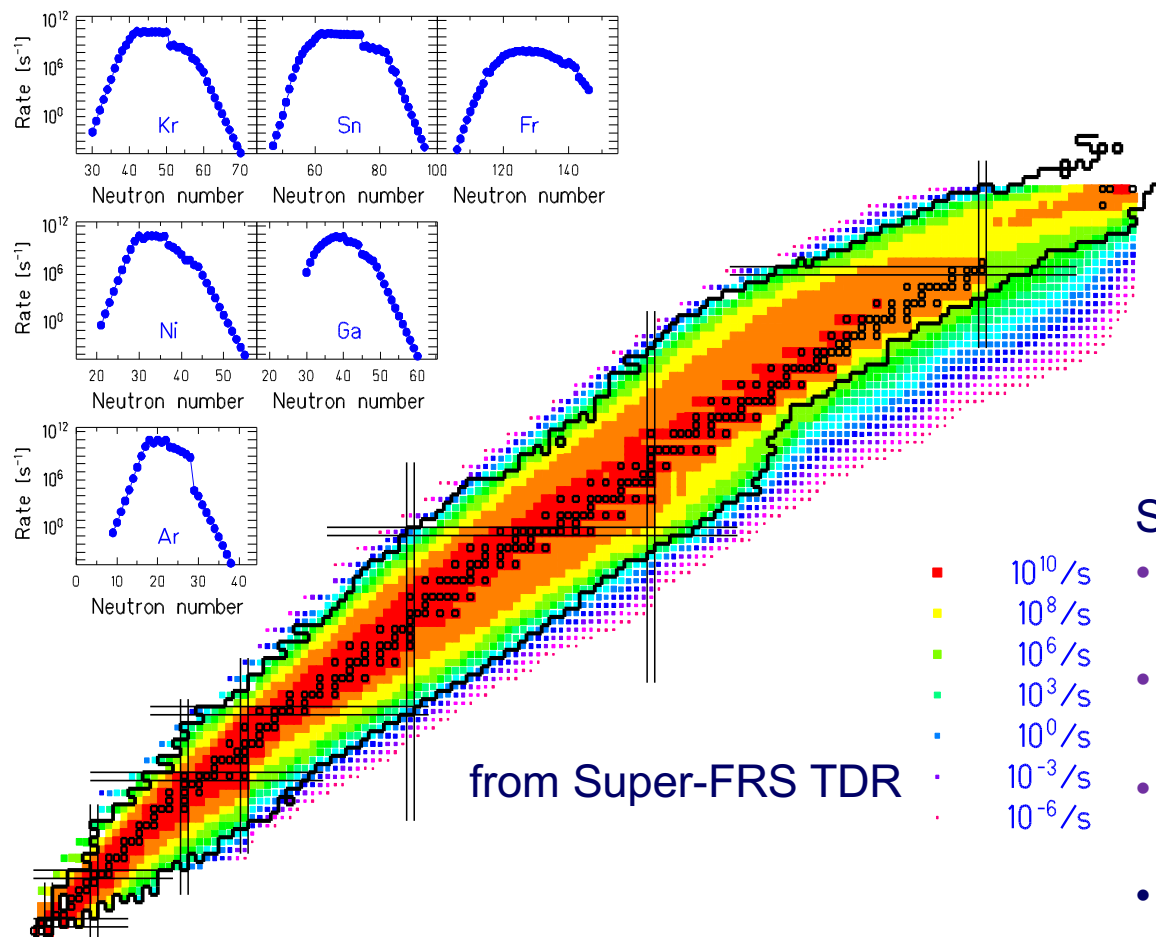
World-wide highest energy RIB





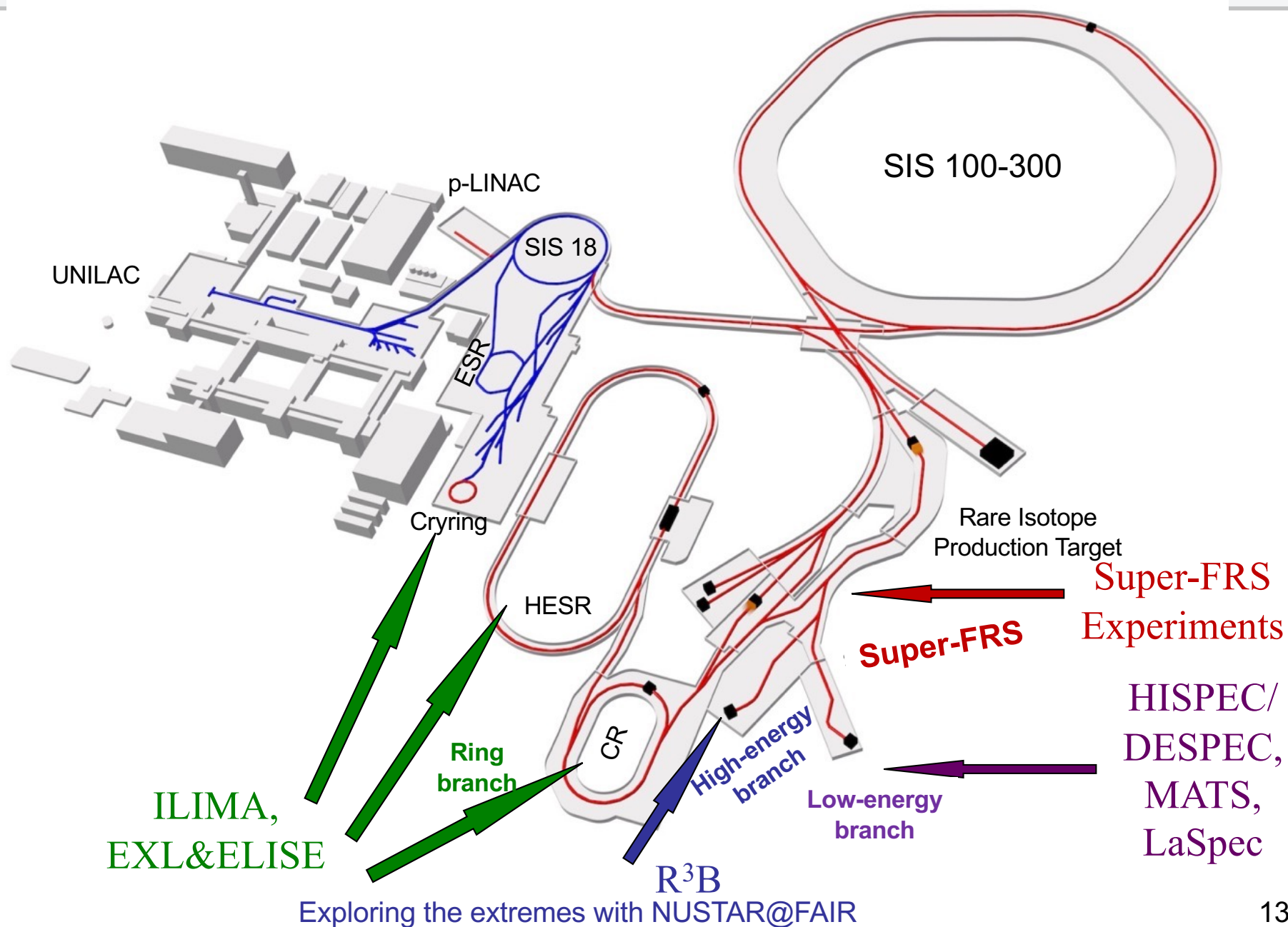
	$B\rho_{\max}$	$\Delta p/p$	$\Delta\Phi_x, \Delta\Phi_y$	resolving power	gain factor	
					^{19}C	^{132}Sn
FRS	18 Tm	1.0 %	$\pm 13, \pm 13$ mrad	1500	1	1
Super-FRS	20 Tm	2.5 %	$\pm 40, \pm 20$ mrad	1500	5	10
				including primary rate	1000	7500

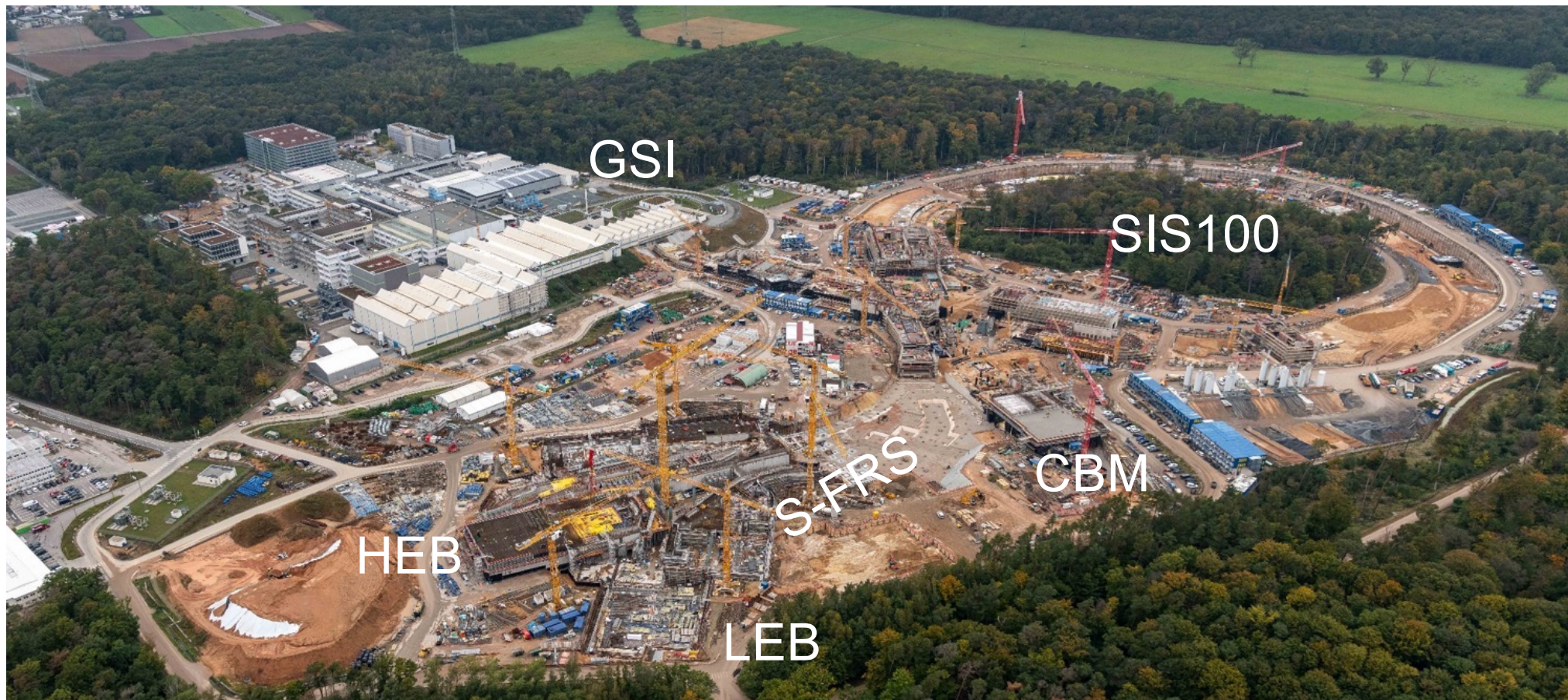
Projectile fragmentation and fission of primary beams with $E < 1.5$ GeV/u



Super-FRS performance:

- **Highest energy RIBs** (fully stripped up to $Z=92$)
- **Higher production rates** (thicker targets and higher transmission)
- **Isotopically pure and isomeric beams** (access to **short lived nuclei** (ns- μ s))
- Study of **new excitation modes**



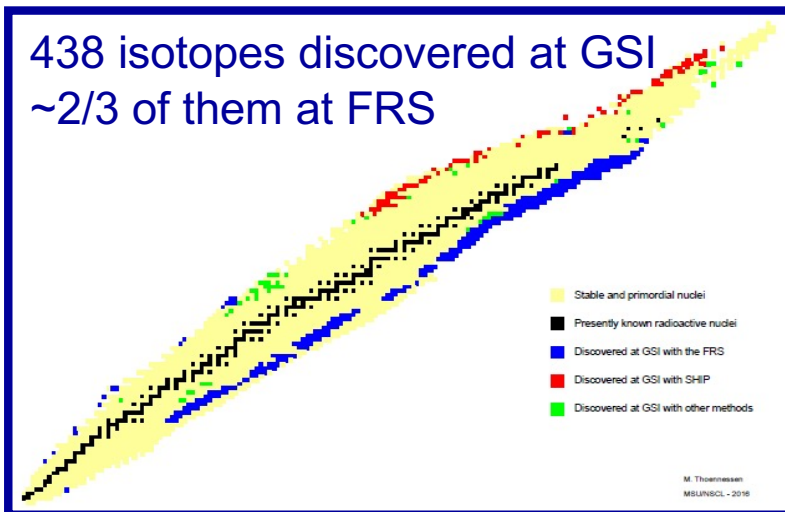


Civil construction progressing well, concrete works of underground ringtunnel completed in May 2021.
Manufacturing of accelerator and experiment components by all partner countries ongoing worldwide.
Many accelerator and experiment components are delivered and tested ready for installation

The NUSTAR Day-1 Program at the Super-FRS

- **Understanding the 3rd r-process peak** by means of comprehensive measurements of lifetimes, masses, neutron branching ratios, dipole strength, and the level structure along the **N=126 isotones**;
- **Equation of State (EoS) of asymmetric matter** by means of measuring the dipole polarizability and neutron-skin thicknesses of **heavy neutron-rich isotopes** (in combination with the results of the first highlight);
- **Exotics: Hypernuclei** with large N/Z asymmetry and **nucleon excitations** in nuclei

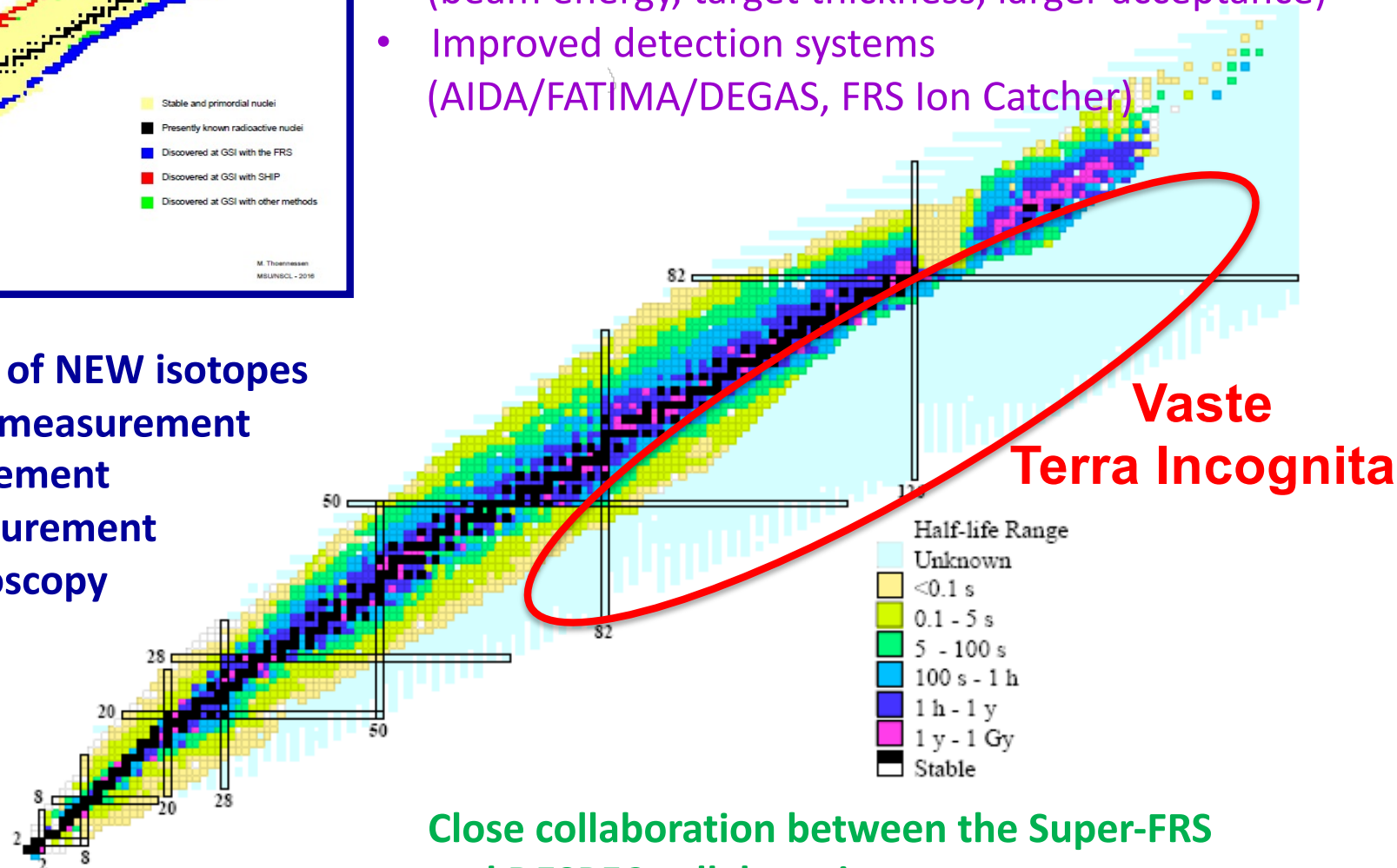
438 isotopes discovered at GSI
~2/3 of them at FRS



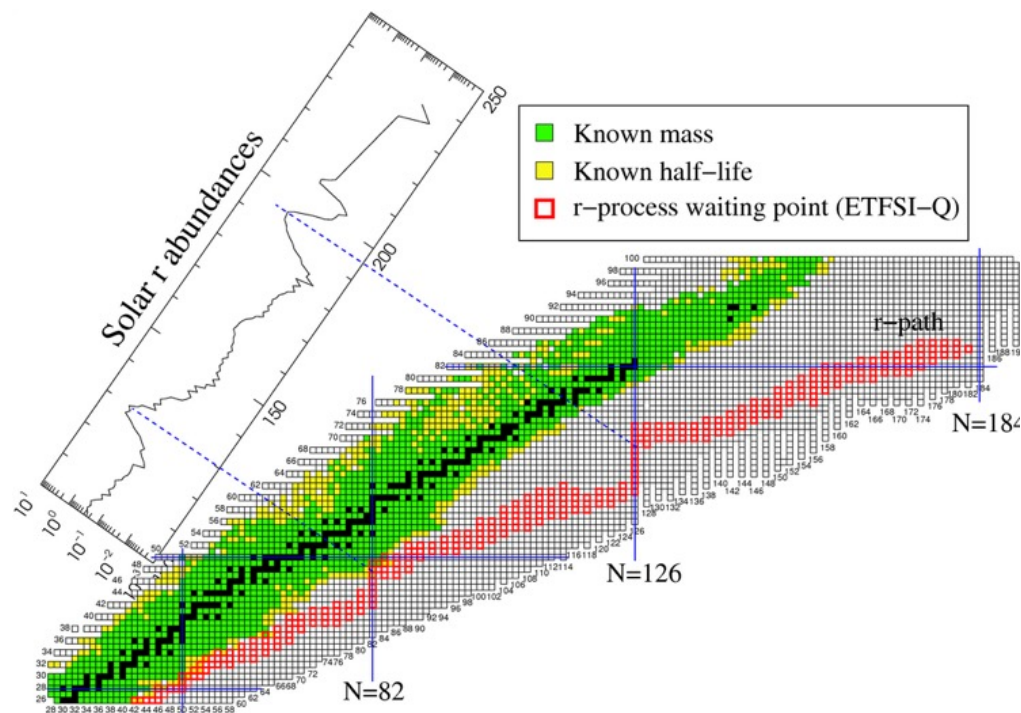
Rich harvest expected, due to:

- Higher intensities
(beam energy, target thickness, larger acceptance)
- Improved detection systems
(AIDA/FATIMA/DEGAS, FRS Ion Catcher)

- identification of NEW isotopes
- cross section measurement
- mass measurement
- half-life measurement
- decay spectroscopy

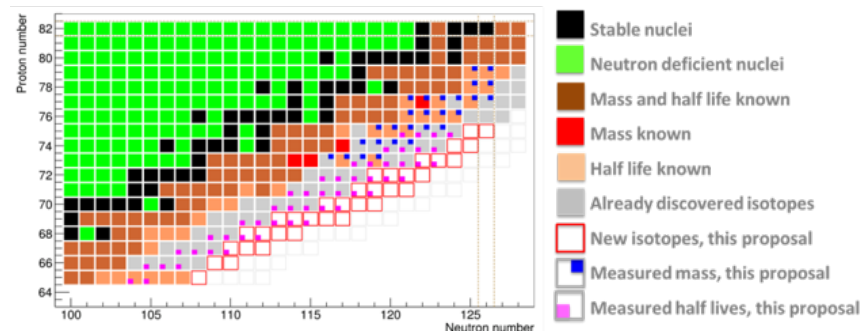


**Close collaboration between the Super-FRS
and DESPEC collaborations**



- Ground-state properties (half-life, masses) and decay studies (β -decay, isomers)
- Spectroscopic information for the **nucleosynthesis of heavy nuclei** (for RIB yields as low as one ion per hour)
- Evolution of the shell structure and exotic nuclear shapes near the **limits of nuclear existence**

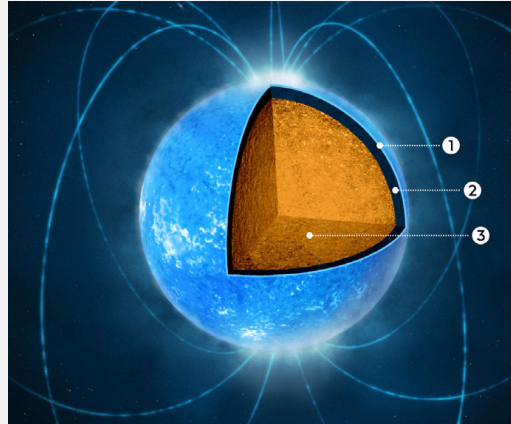
Understand the **3rd r-process abundance peak** by studying neutron-rich isotopes of elements ^{65}Re to ^{75}Tb and measure ground-state properties



Each improvement (FRS $\rightarrow$ Super-FRS; SIS18 $\rightarrow$ SIS100) will bring us deeper into the unknown territory

Neutron star: very neutron-rich,
wide density range, but the radius
dominantly determined by
neutron pressure L (at ρ_{sat})

$$S(\rho) \approx J + L\epsilon(\rho) + \frac{1}{2}K_{\text{sym}}\epsilon^2(\rho)$$



Comprehensive program foreseen at FAIR:

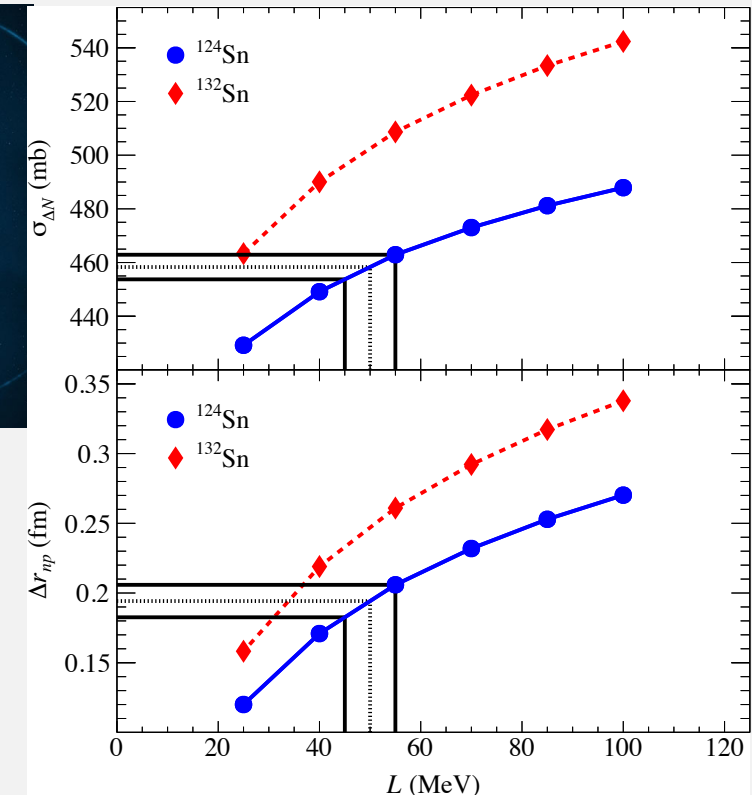
Sensitive nuclear observables: n-skin, dipole polarizability

Phase 0: Accurate measurement of cross sections:

- Total n-removal cross sections (n-skin)
- Total Coulomb cross sections (polarizability)
- Short-range correlations in neutron-rich nuclei

Phase 1: - elastic p scattering (HESR) + Laser → **neutron radius**

- dipole response of heavy neutron-rich nuclei → **polarizability**
- Giant Monopole Resonance by α, α' at ESR → **incompressibility K_{sym}**
- heavy-ion collision at 400-1000 MeV/u with n-rich beams (ρ : $1\rho_{\text{sat}} - 3\rho_{\text{sat}}$)



T. Aumann et al., PRL**119** (2017)
RMF Theory: S. Typel, PRC **89** (2014)

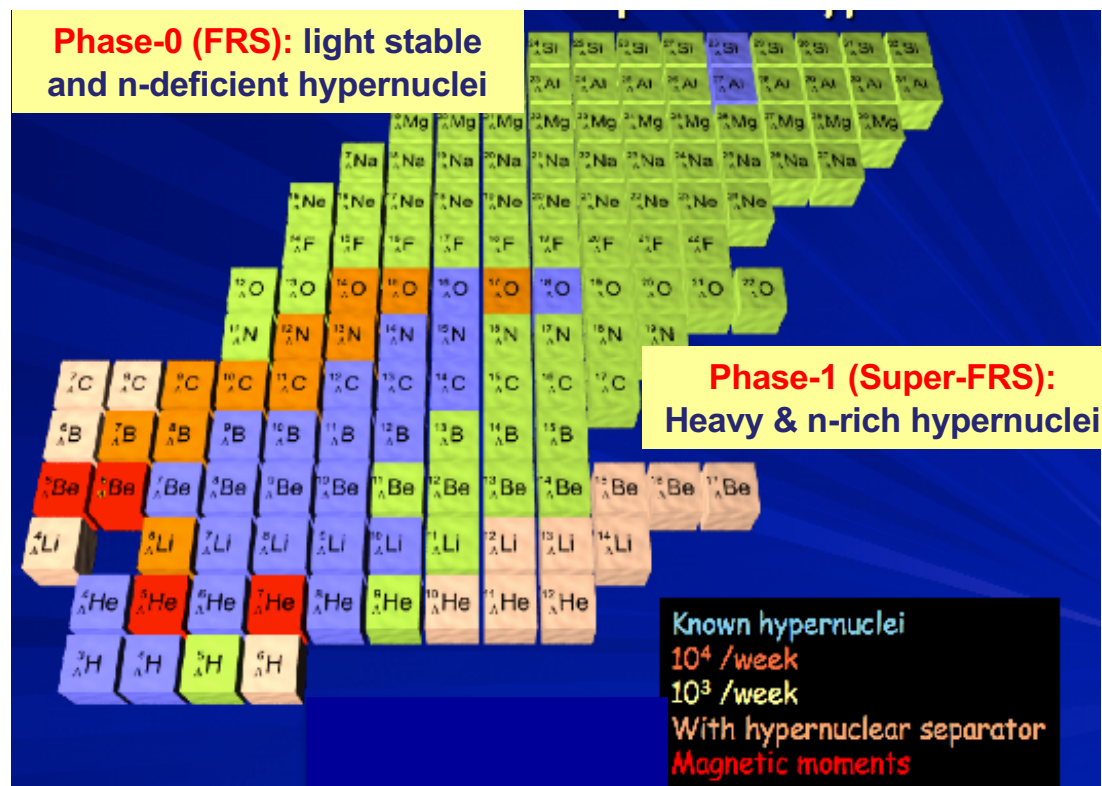
- Production of hypernuclei at high-energy ($>1.2A$ GeV) heavy-ions peripheral collision is expected to have large cross sections.
- The method is also suitable for determination of lifetimes of hypernuclei via weak decay channel ($\Lambda_{\text{free}} \rightarrow p\pi^-$ or $n\pi^0$, $\tau \sim 0.26$ ns).
(Lorentz factor on lifetime !)

Strangeness sector of nuclear chart

- **Pilot experiment at GSI (HypHI): Evidence of ${}^3_{\Lambda}\text{H}$, ${}^4_{\Lambda}\text{H}$, 3_{Λ}n**
- Lifetimes have been determined.
- Next goals: binding energies via **invariant mass spectroscopy**
- **Super-FRS in high-resolution mode** will lead to $\Delta E \sim 1\text{MeV}$

C.Rappold et al., Phys. Rev. C 88(2013) 041001

A.Botvina et al., Phys Rev C 88(2013) 054605

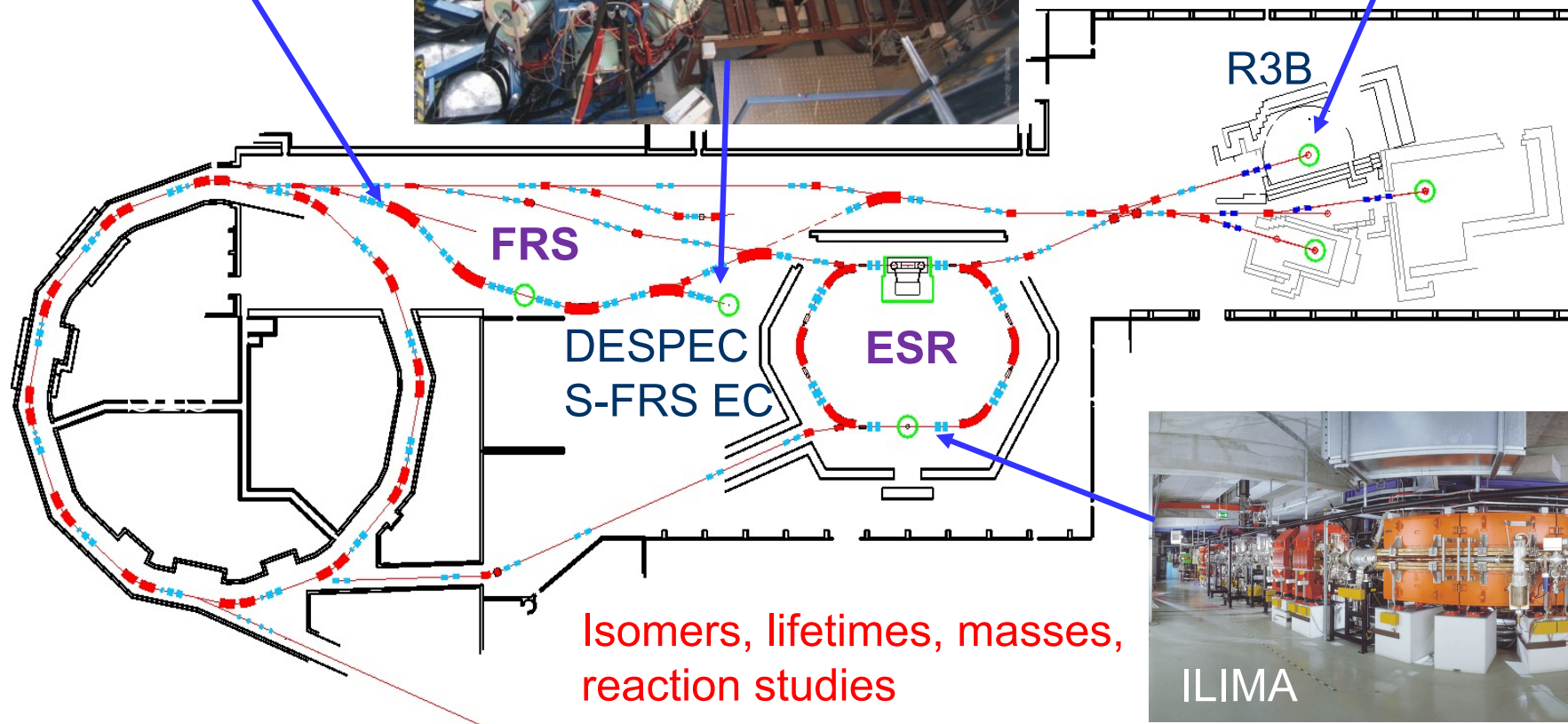
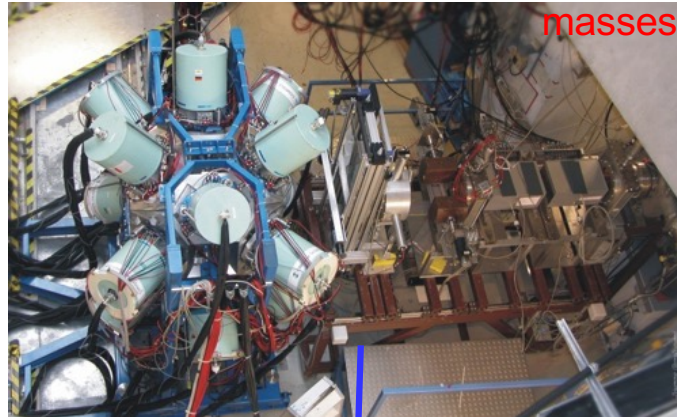


Status of NUSTAR experiments and research in FAIR Phase-0 (at GSI)

FAIR Phase 0

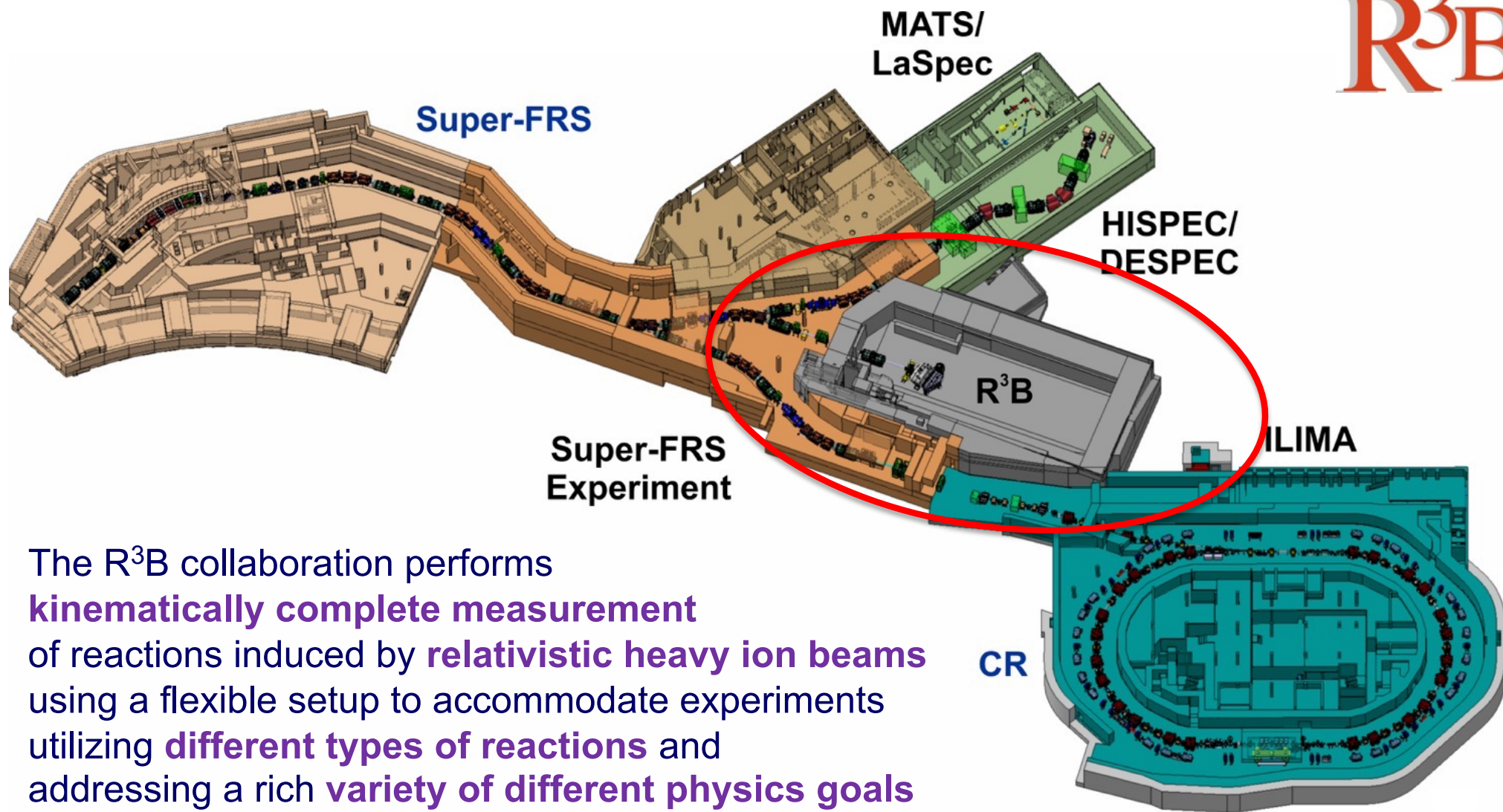
production and separation of exotic nuclei

Isotope search, decay spectroscopy, masses



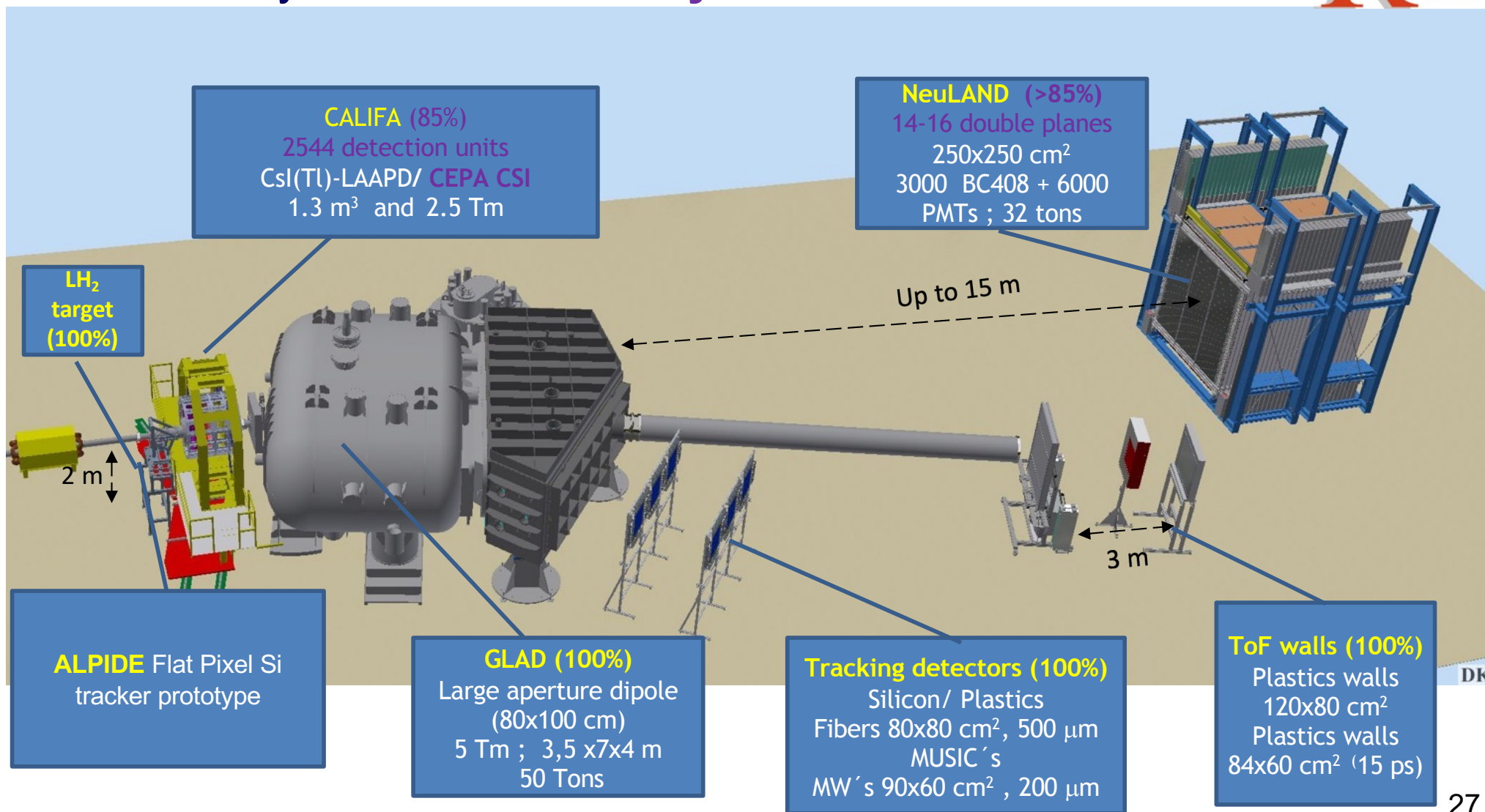
Isomers, lifetimes, masses, reaction studies





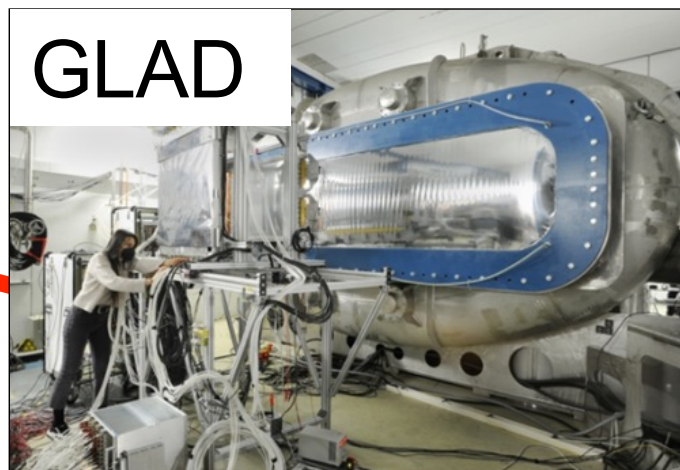
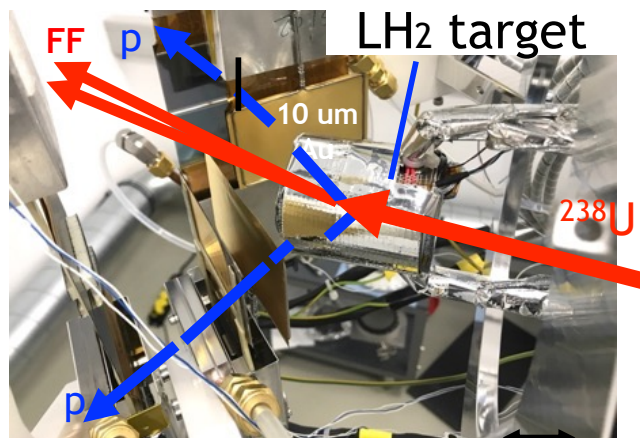
The R³B collaboration performs **kinematically complete measurement** of reactions induced by **relativistic heavy ion beams** using a flexible setup to accommodate experiments utilizing **different types of reactions** and addressing a rich **variety of different physics goals**

Kinematically complete measurement of reactions induced by relativistic heavy ion beams

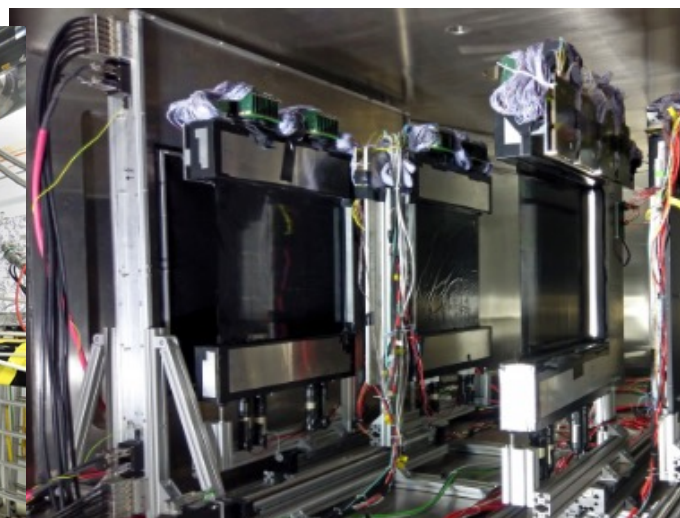
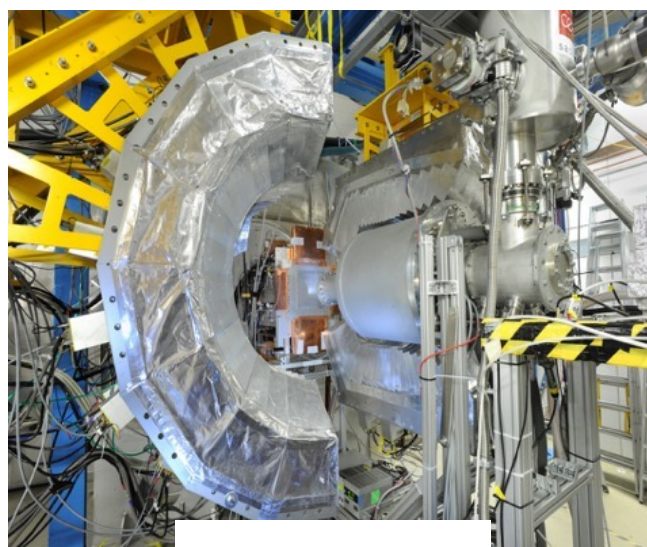


Reaction studies with relativistic radioactive beams

R³B



NeuLAND



CALIFA

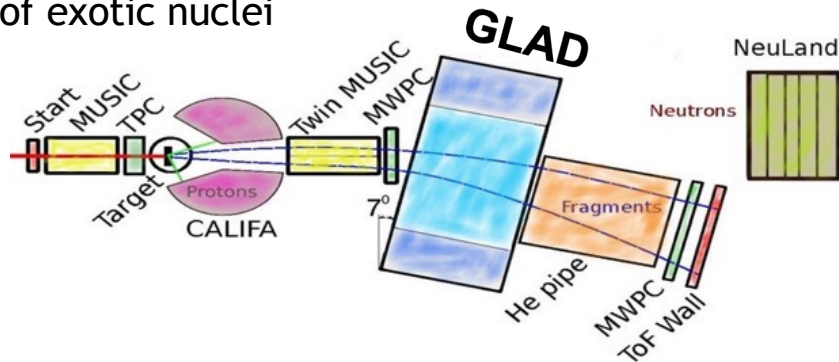
Tracking detectors

Exploring the extremes with NUSTAR@FAIR

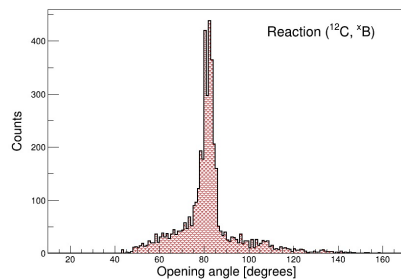
Proof of concept for (p,2pf)

$^{238}\text{U} + \text{p} @ 500 \text{ A MeV (p,2pf)}$

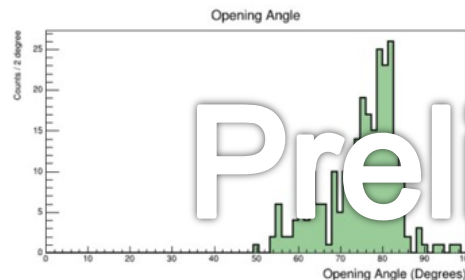
First step towards fission barrier measurements of exotic nuclei



CALIFA proton opening angle



^{12}C beam on a CH_2 target
inverse kinematics



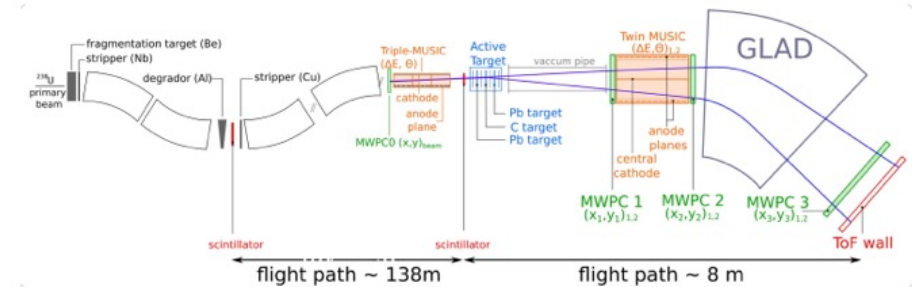
^{238}U beam on a LH_2 target
inverse kinematics

Fission yields of n-deficient actinides

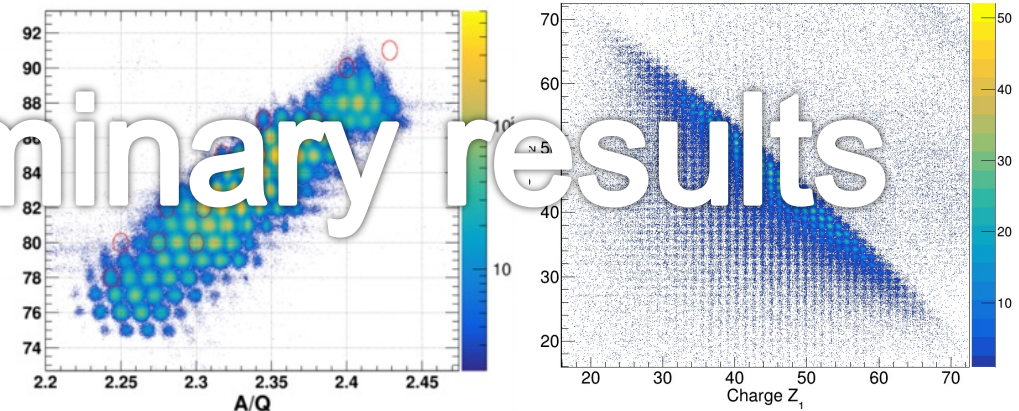
$^{238}\text{U} + \text{Be} @ 700 \text{ A MeV} \rightarrow \text{R3B Coulex on Pb}$

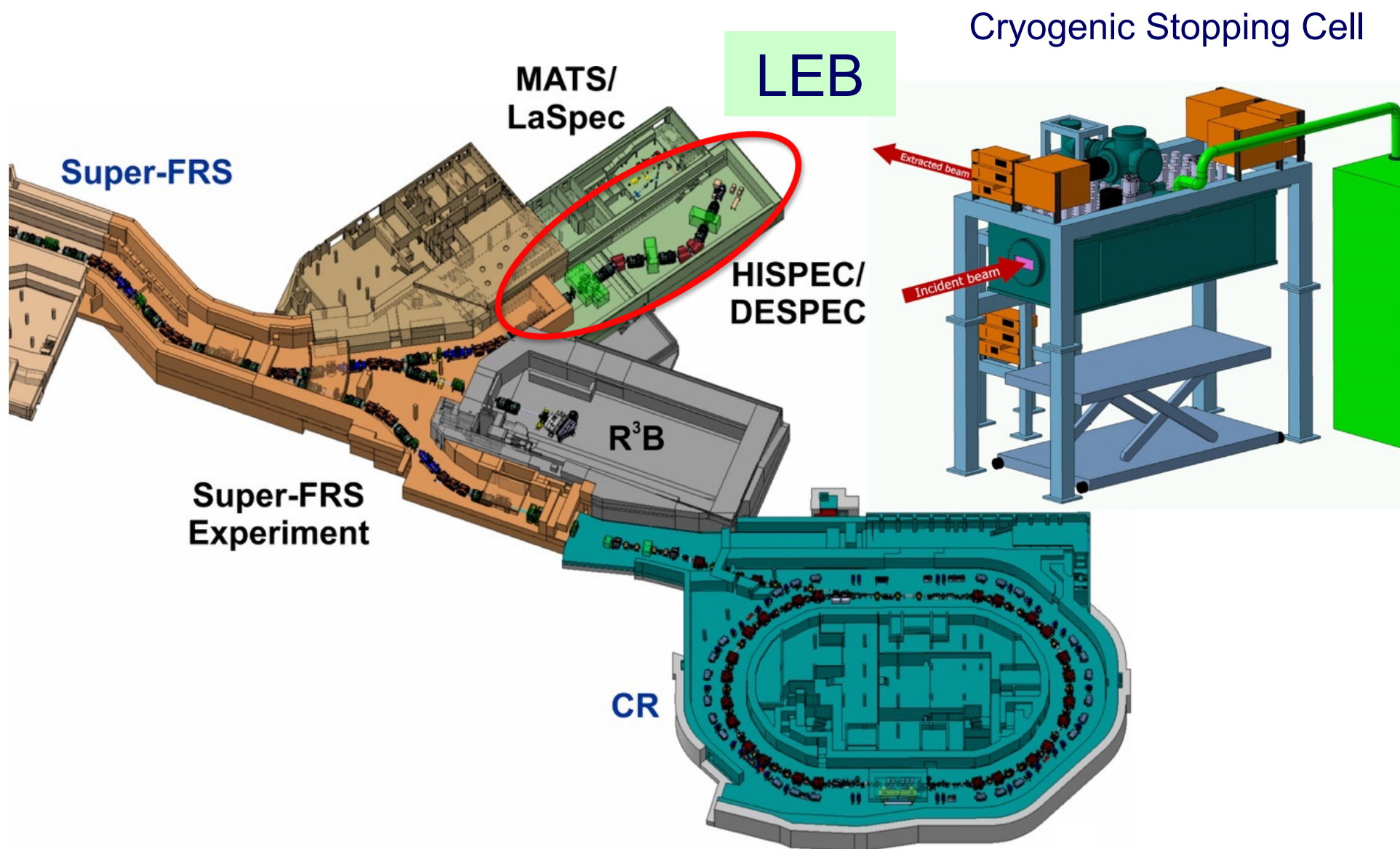
Investigation of new fission modes

- Excellent ID of fission fragments
- Full kinematics detection



Preliminary results





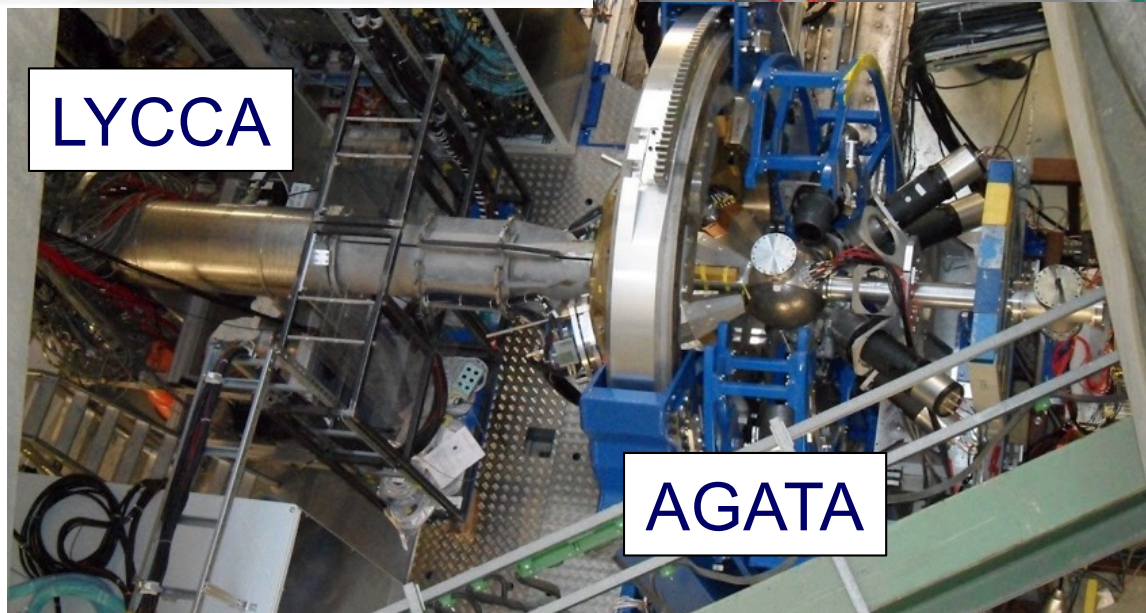
BELEN



DTAS

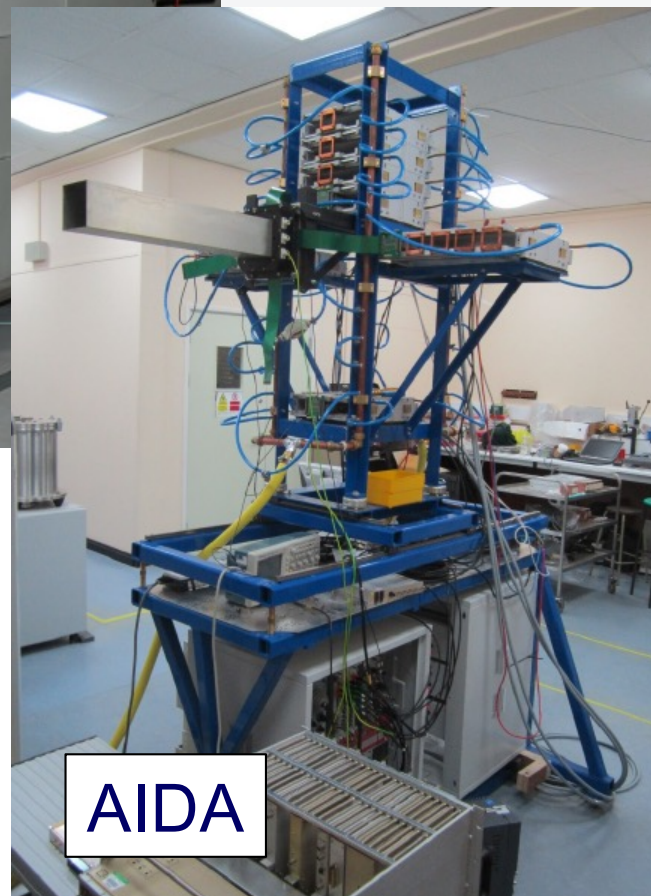


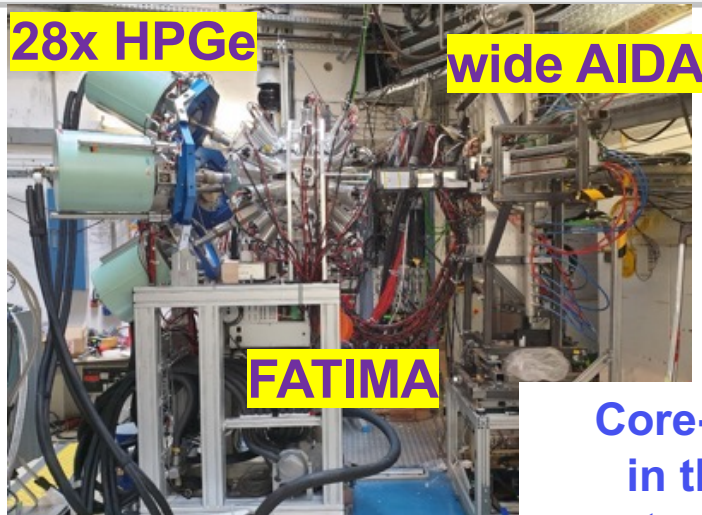
LYCCA



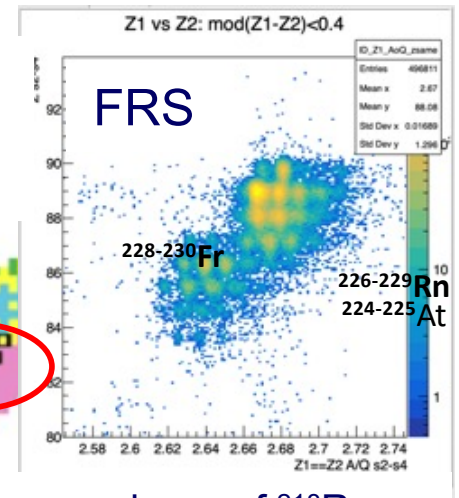
AGATA

AIDA

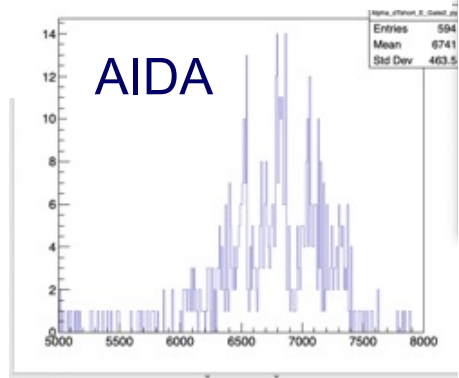




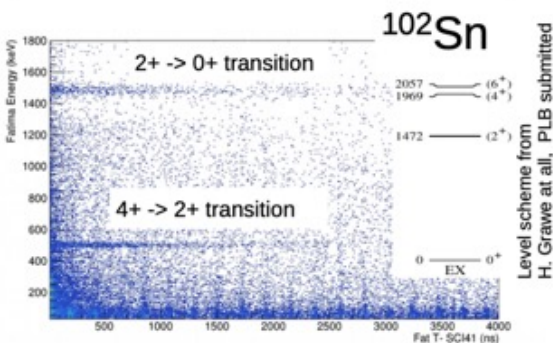
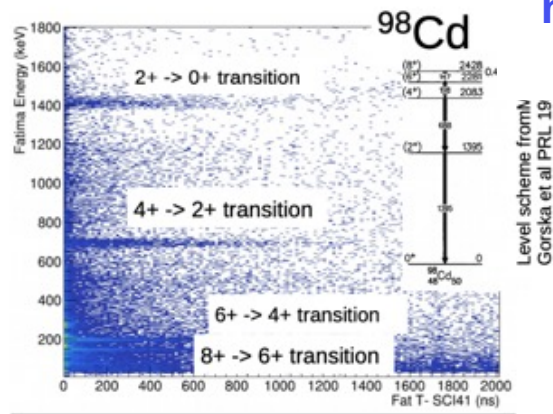
Investigation the south-east frontier of the $A \sim 225$ island of octupole deformation



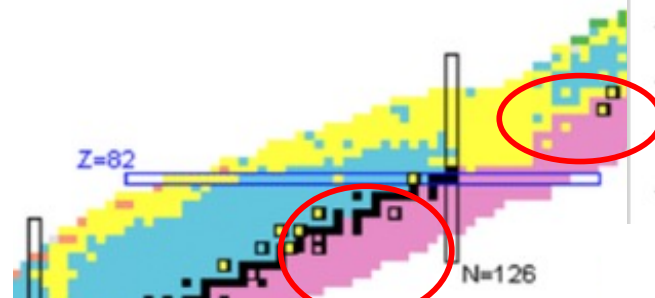
α decay of ^{218}Rn calibration nucleus



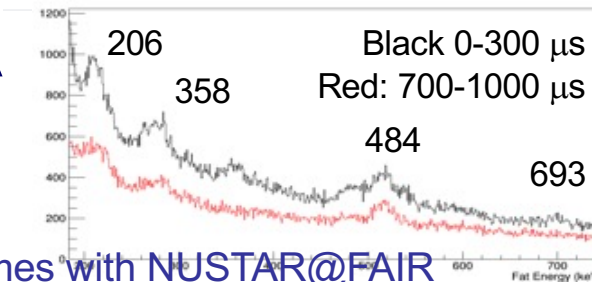
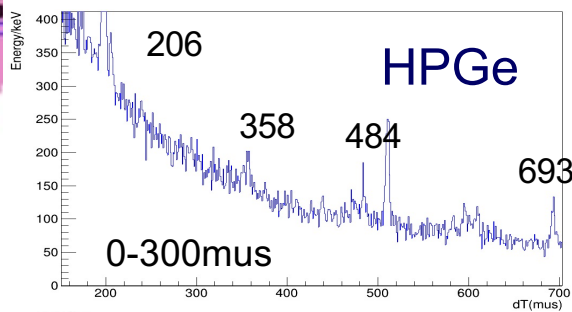
Core-breaking in the most neutron-deficient Tin isotopes



FATIMA
(LaBr_3)

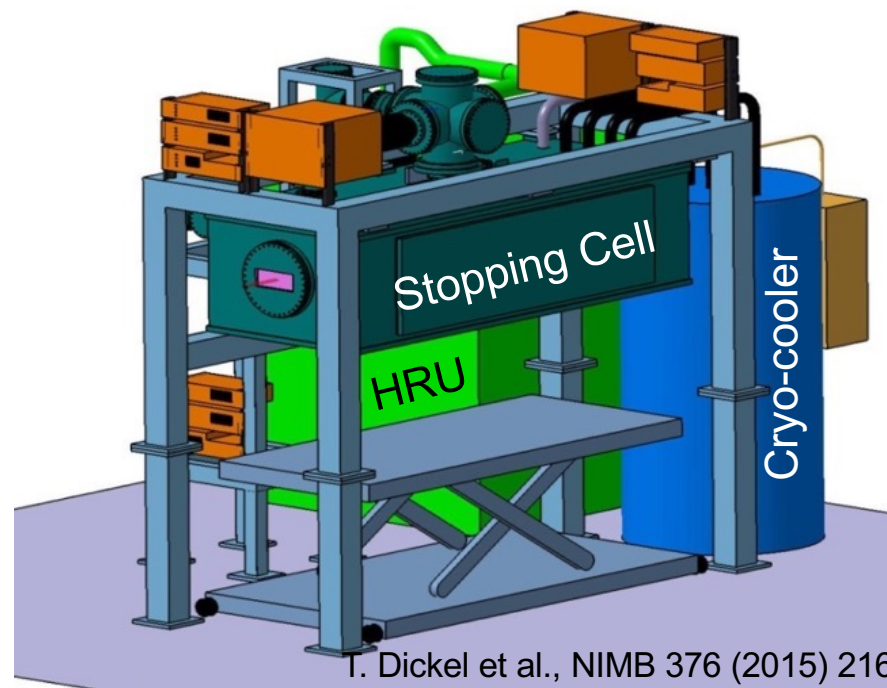
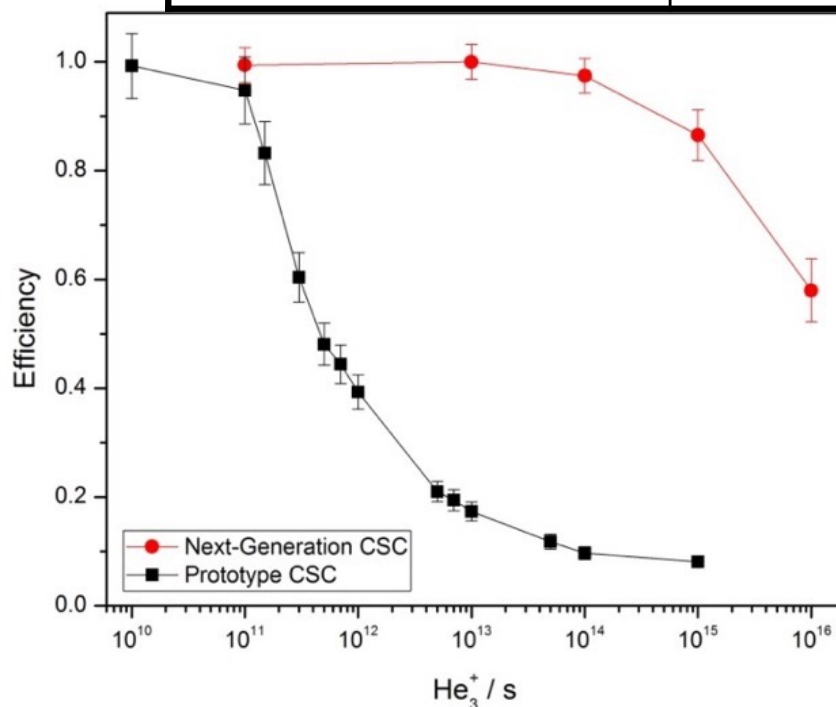


Shape Evolution in neutron-rich $A \sim 190$ nuclei



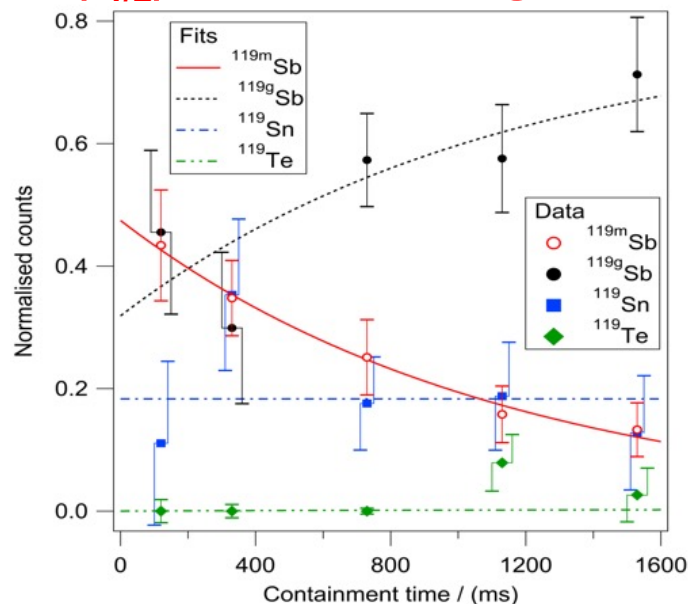
Exploring the extremes with NUSTAR@FAIR

	Prototype CSC	Design Goals LEB CSC
Areal density (He)	6 mg/cm ²	20...40 mg/cm ²
Extraction time	25 ms	5...10 ms
Rate capability	10 ⁴ /s	10 ⁷ /s



I. Dickel et al., NIMB 376 (2015) 216

Simultaneous measurement of mass, halflife ($t_{1/2}$) and branching ratio



Mass/ E_{ex}

$(2799 \pm 30) \text{ keV}$

$t_{1/2}$

Measured

$776 \pm 181 \text{ ms}$

Literature

$850 \pm 90 \text{ ms}$

Branching
Ratio (BR)

γ

1

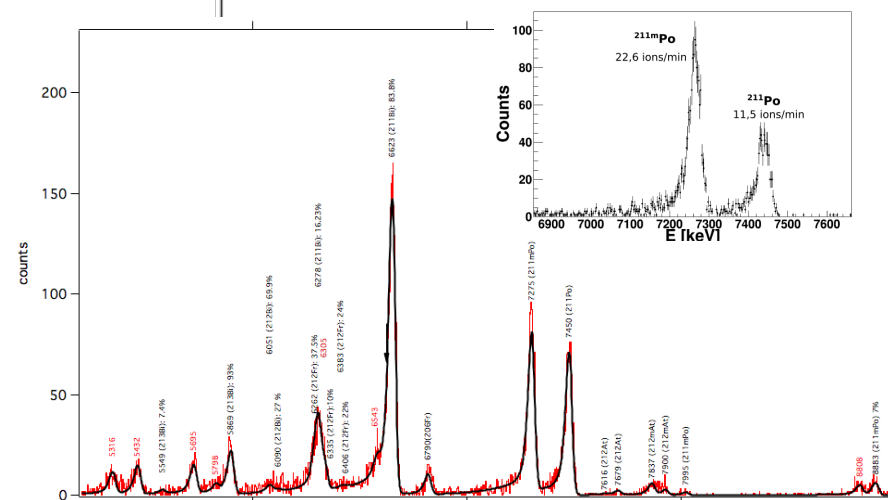
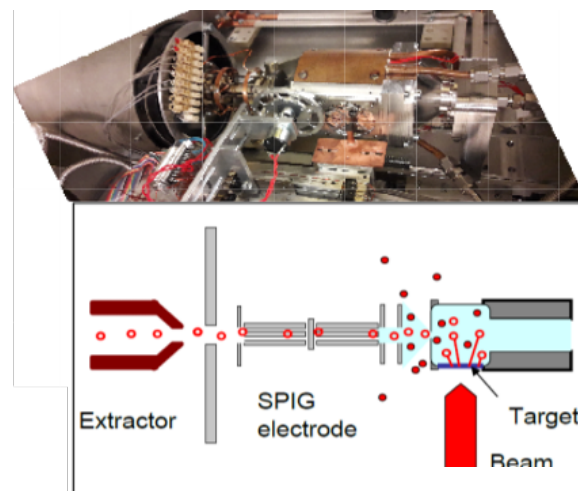
β^-

0

β^+

0

IGISOL @ Jyväskylä (Multi-nucleon transfer $^{136}\text{Xe} + ^{209}\text{Bi}$)

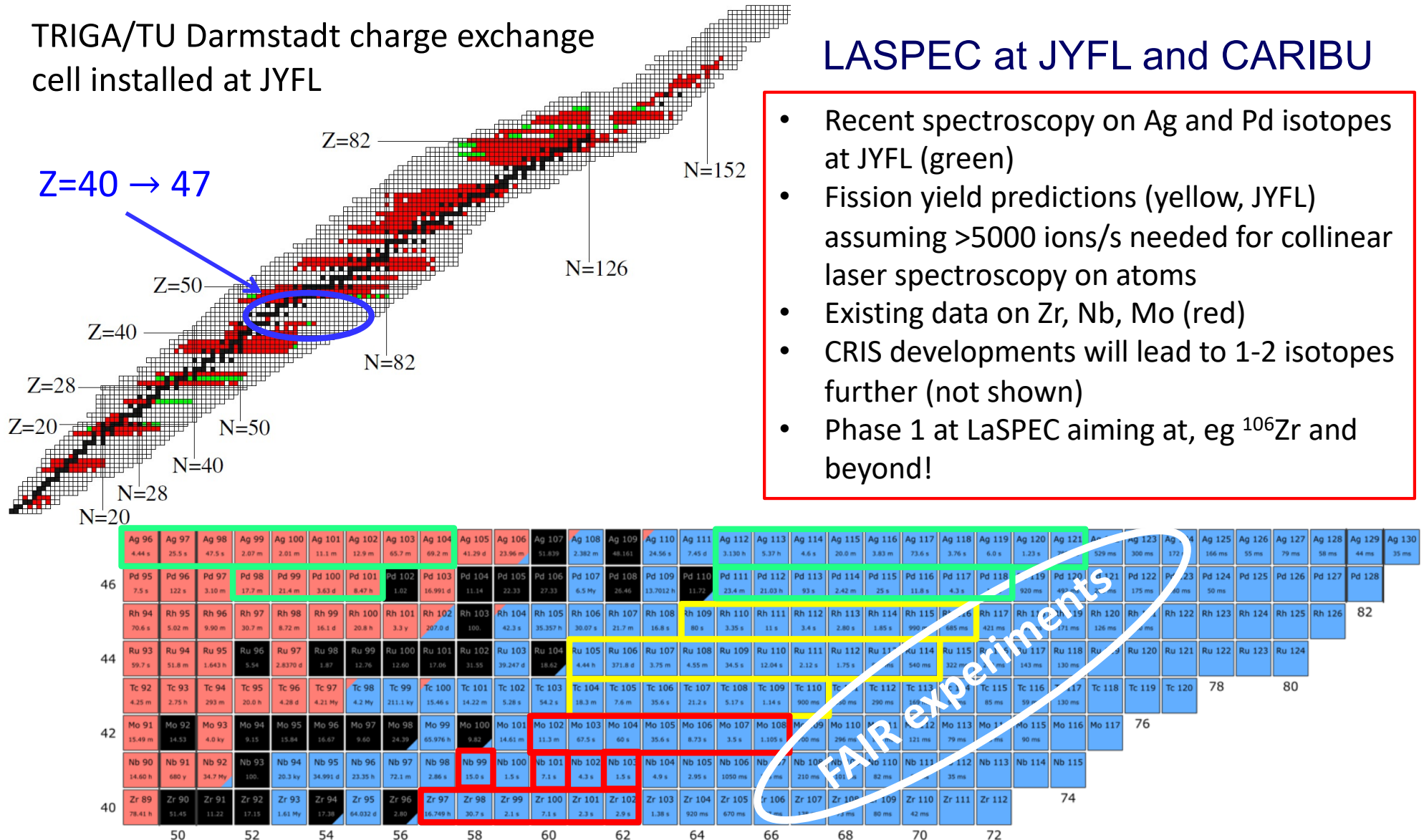


α -Spectroscopy for $^{136}\text{Xe} (945 \text{ MeV}) + ^{209}\text{Bi}$

TRIGA/TU Darmstadt charge exchange
cell installed at JYFL

LASPEC at JYFL and CARIBU

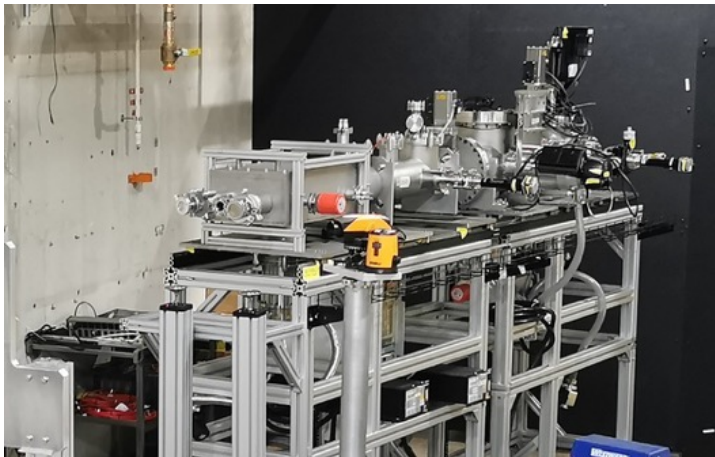
- Recent spectroscopy on Ag and Pd isotopes at JYFL (green)
- Fission yield predictions (yellow, JYFL) assuming >5000 ions/s needed for collinear laser spectroscopy on atoms
- Existing data on Zr, Nb, Mo (red)
- CRIS developments will lead to 1-2 isotopes further (not shown)
- Phase 1 at LaSPEC aiming at, eg ^{106}Zr and beyond!



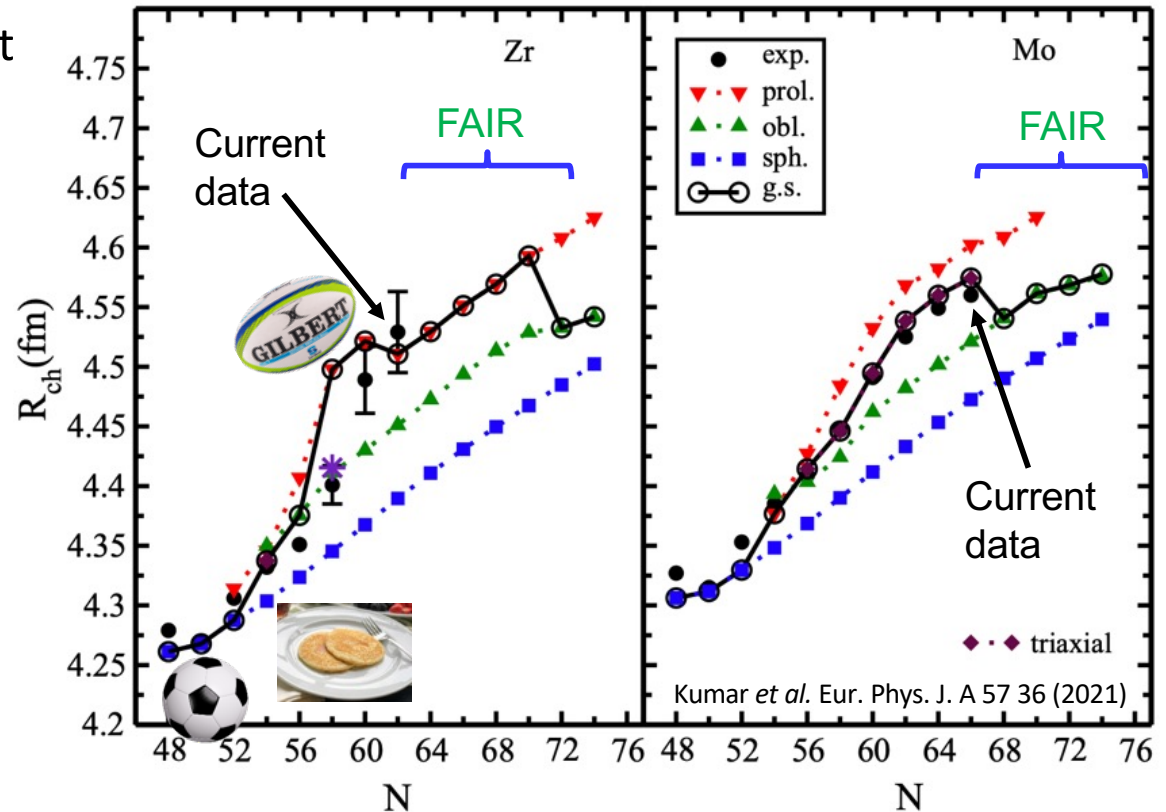
Exotic nuclei can exhibit many different shapes, especially those made at FAIR.

At LaSpec we will measure the charge radius of the nucleus, R_{ch} , for different isotopes and reveal the changing size and shape, with neutron number.

Shape coexistence is where a single nucleus can exhibit multiple shapes.



LASPEC beamline, installation @ CARIBU
Photo: B.Maaß



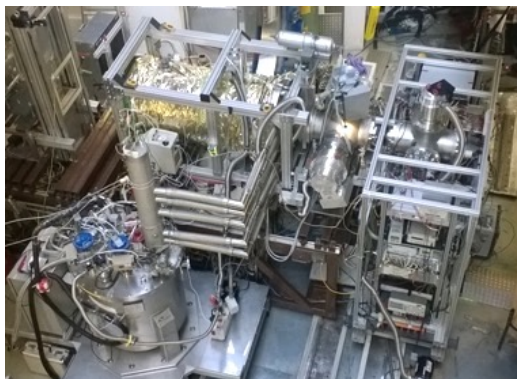
This will challenge state-of-the-art theories.

The experimental apparatus, which uses laser spectroscopy, has been developed at TU Darmstadt and is currently on tour making measurements at the Argonne National Lab.

High-resolution spectrometer experiments at the border line of nuclear, atomic and hadron physics

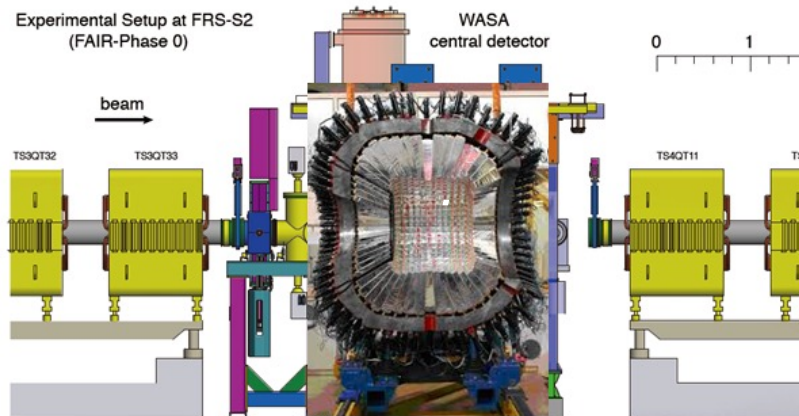
(Super-)FRS as multiple-stage magnetic system (separator, analyser, spectrometer, energy buncher) combined with ancillary detectors, e.g. with:

FRS Ion Catcher

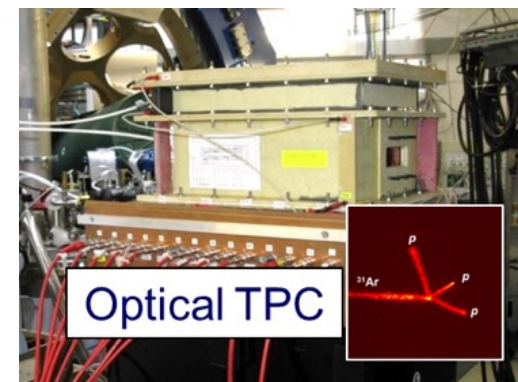


→ **Cryogenic Stopping Cell**

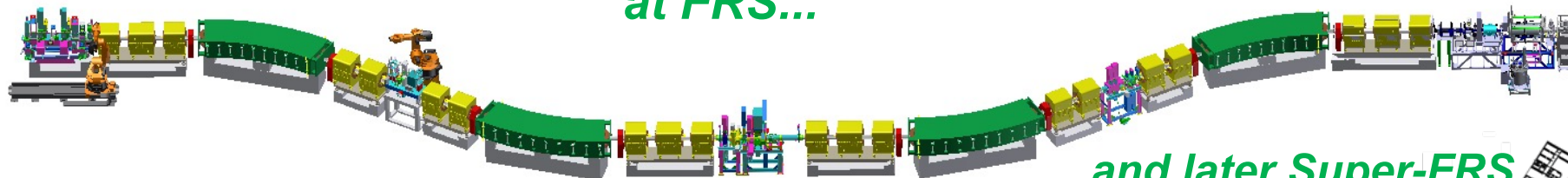
WASA



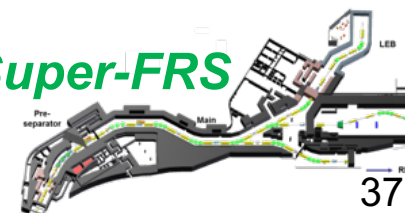
EXPERT



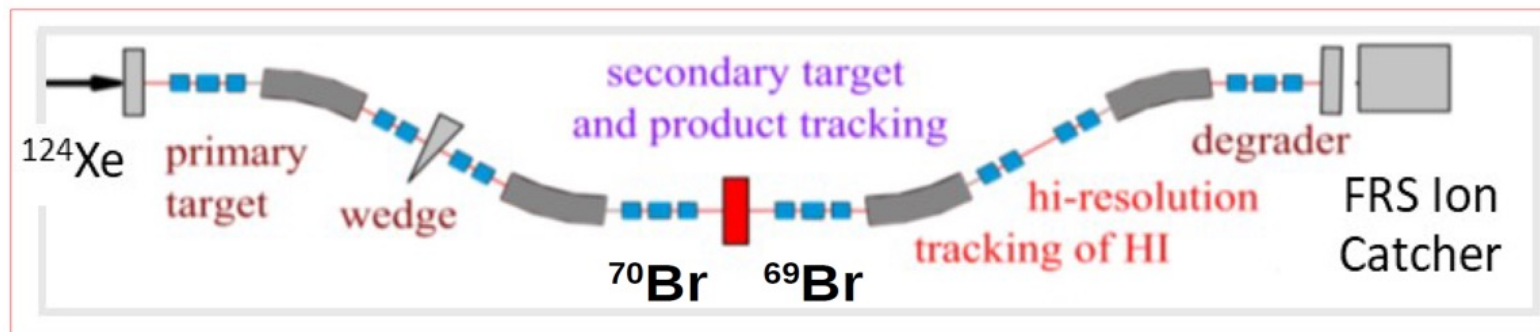
at FRS...



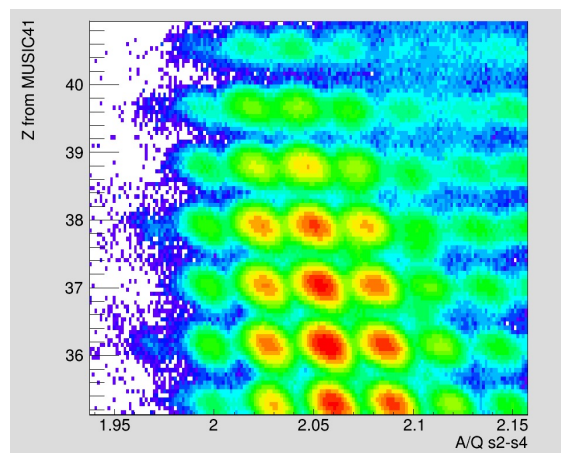
...and later Super-FRS



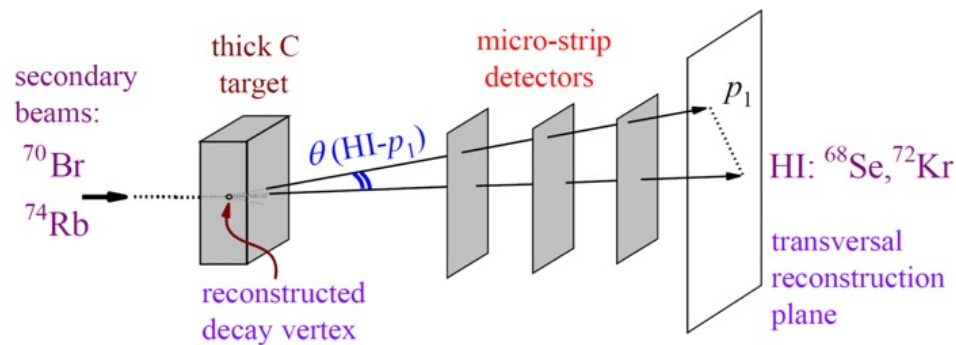
In-flight decay spectroscopy of proton-unbound Br and Rb nuclei



Identification matrix



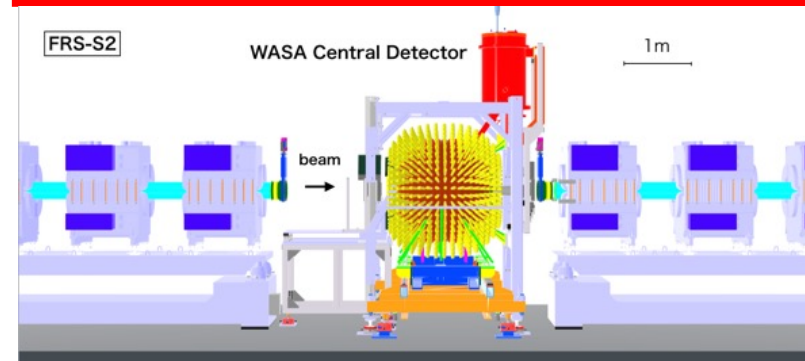
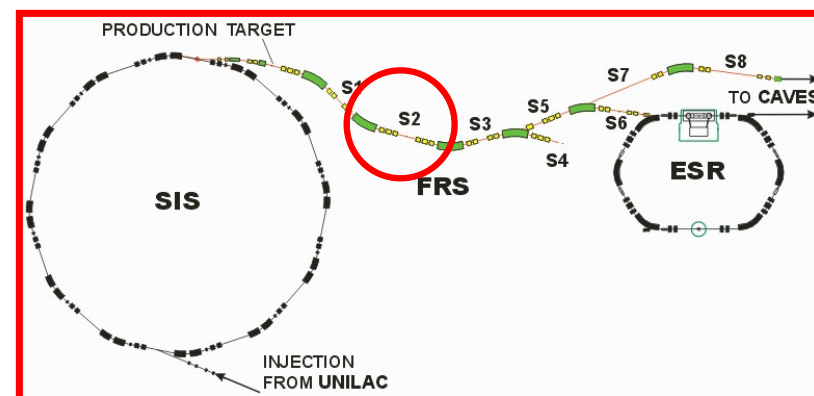
EXPERT detectors



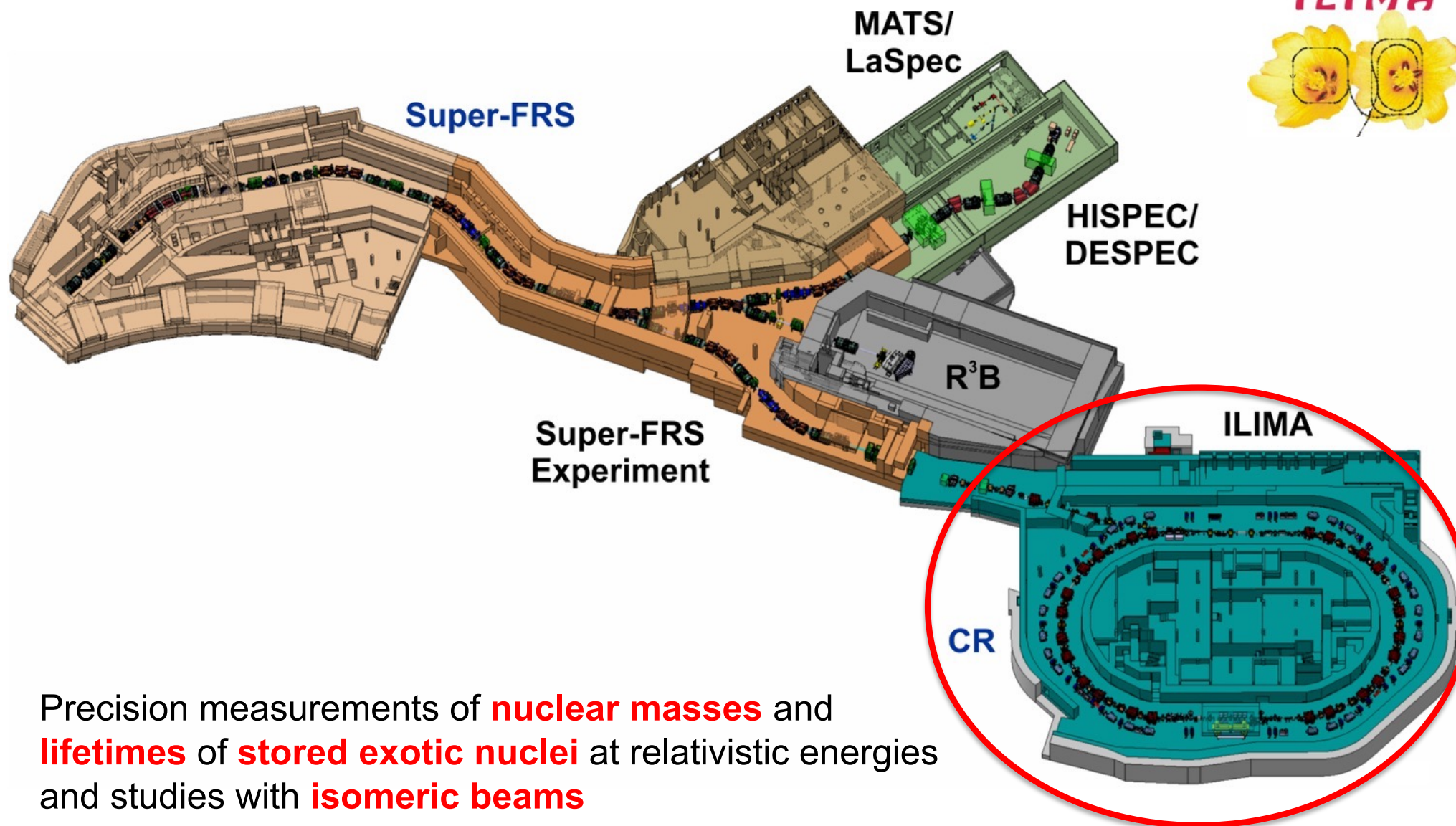
- Successful tests of new microstrip tracking detectors produced by Perugia University

Experiments scheduled in February – March, 2022

- Hypernuclear studies: Lifetime of ${}^3_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{H}$ and confirmation of $nn\Lambda$
- Search for the eta'-meson-nucleus bound system



The ILIMA experiment in the Collector Ring (CR)



Precision measurements of **nuclear masses** and **lifetimes** of **stored exotic nuclei** at relativistic energies and studies with **isomeric beams**

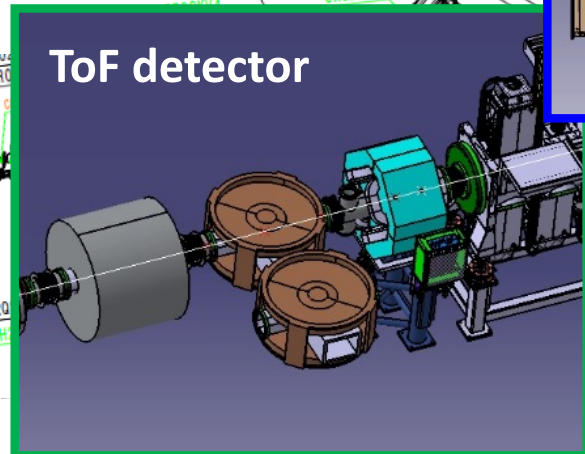
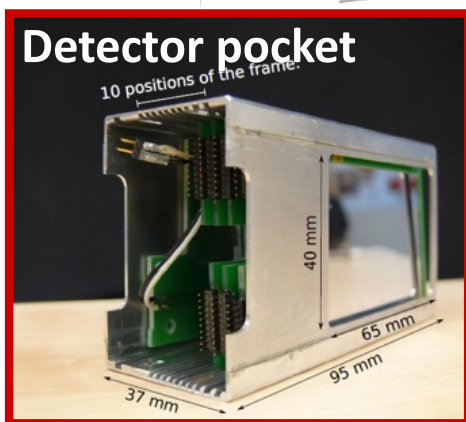
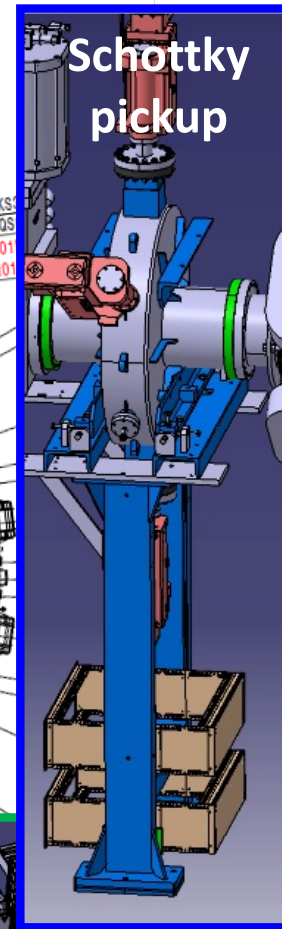
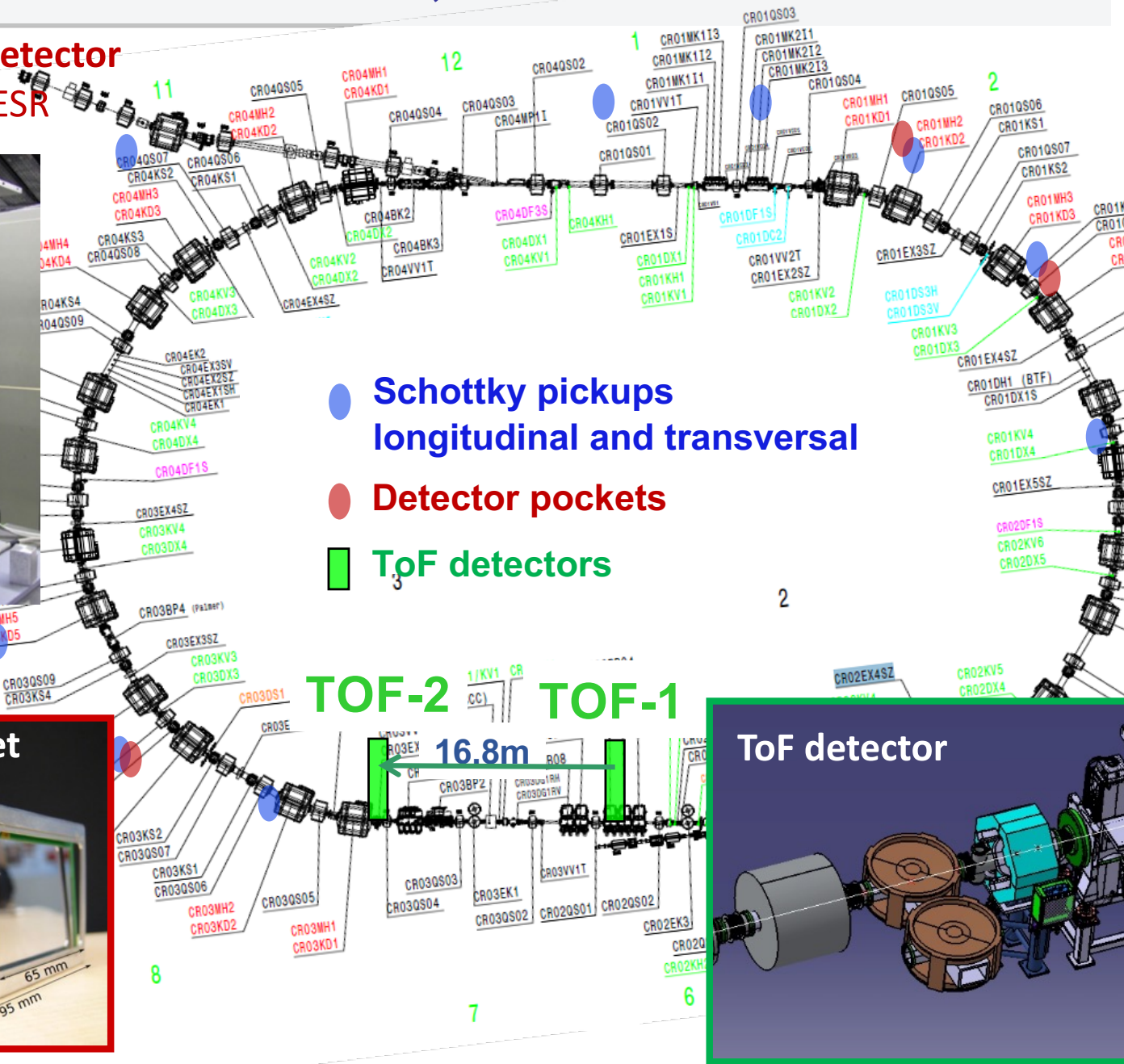


ILIMA Phase1@CR

Isomeric beams, Lifetimes and Masses



New Schottky detector
In operation at ESR



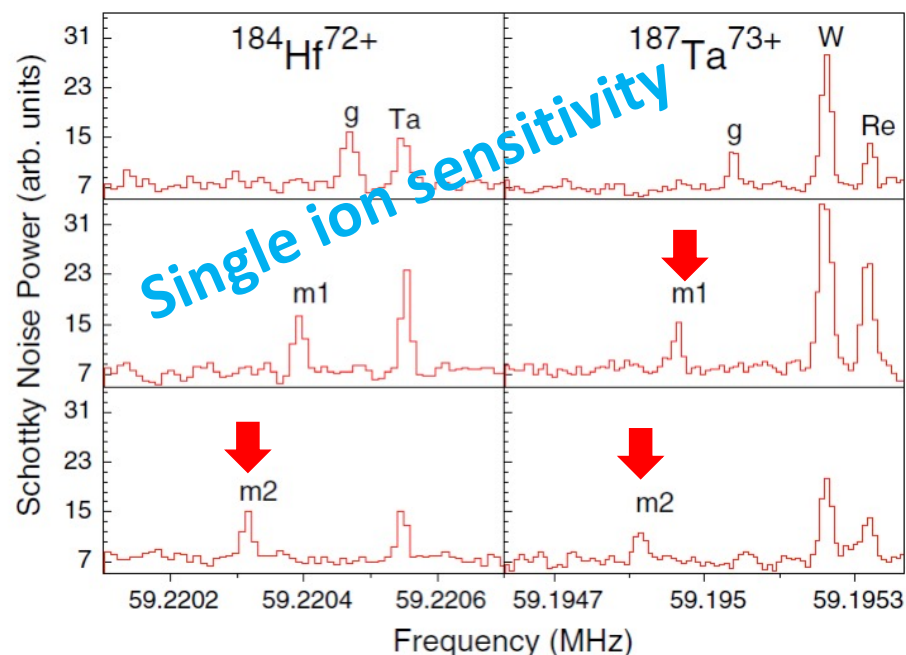
Stand: 12.02.2016

Pos.	Detektor	Hersteller	Modell	Typ	Material	Farbe	Größe	Gewicht	Preis	Stand
1	CR04KS1	CR	CR04KS1	KS	St	Gr	100 mm	100 g	100 €	12.02.2016
2	CR04KS2	CR	CR04KS2	KS	St	Gr	100 mm	100 g	100 €	12.02.2016
3	CR04KS3	CR	CR04KS3	KS	St	Gr	100 mm	100 g	100 €	12.02.2016
4	CR04KS4	CR	CR04KS4	KS	St	Gr	100 mm	100 g	100 €	12.02.2016
5	CR04KS5	CR	CR04KS5	KS	St	Gr	100 mm	100 g	100 €	12.02.2016
6	CR04KS6	CR	CR04KS6	KS	St	Gr	100 mm	100 g	100 €	12.02.2016
7	CR04KS7	CR	CR04KS7	KS	St	Gr	100 mm	100 g	100 €	12.02.2016
8	CR04KS8	CR	CR04KS8	KS	St	Gr	100 mm	100 g	100 €	12.02.2016
9	CR04KS9	CR	CR04KS9	KS	St	Gr	100 mm	100 g	100 €	12.02.2016
10	CR04KS10	CR	CR04KS10	KS	St	Gr	100 mm	100 g	100 €	12.02.2016



Long-lived isomers in the Experimental Storage Ring: Study of $^{186-188}\text{Hf}$ (search for new K-isomers)

Successful results of previous E048: **new isomers**



M.W. Reed et al., PRL105 (2010) 172501

M.W. Reed et al., PRC86 (2012) 054321

Masses of more than 1000 in a single exp

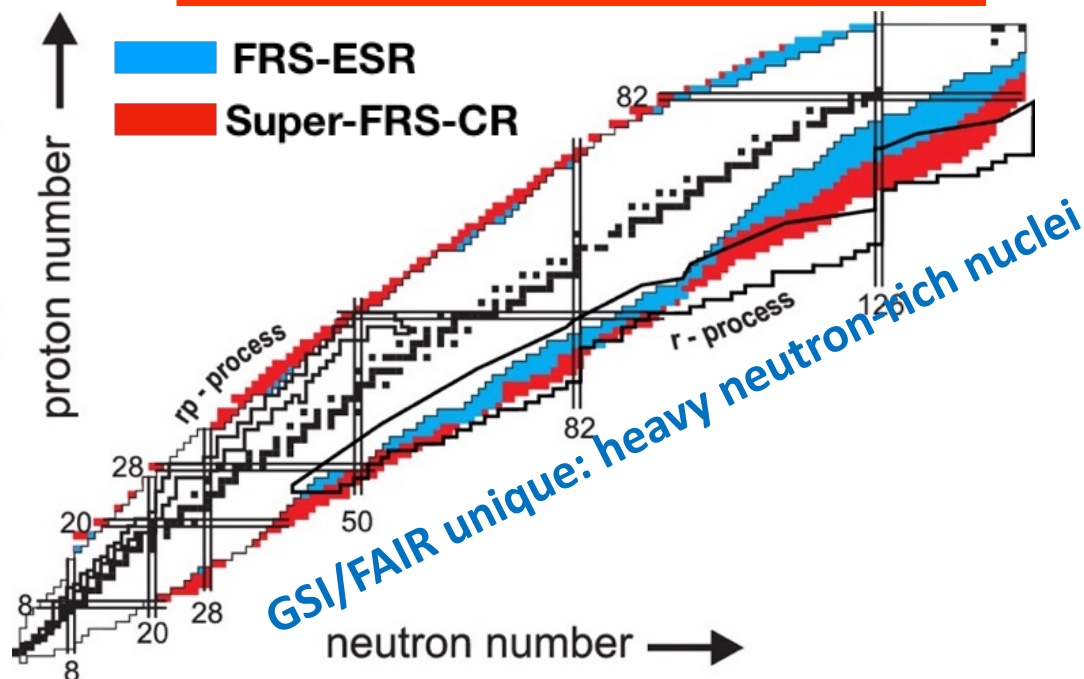
Mass accuracy: $1.5 \cdot 10^{-7}$

Mass resolving power: $2 \cdot 10^6$

Results:

more than 300 new masses

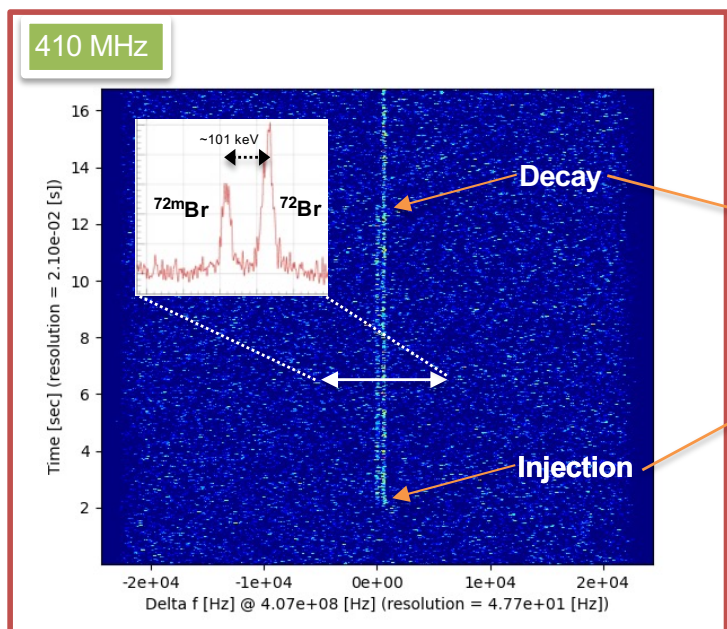
more than 300 improved masses



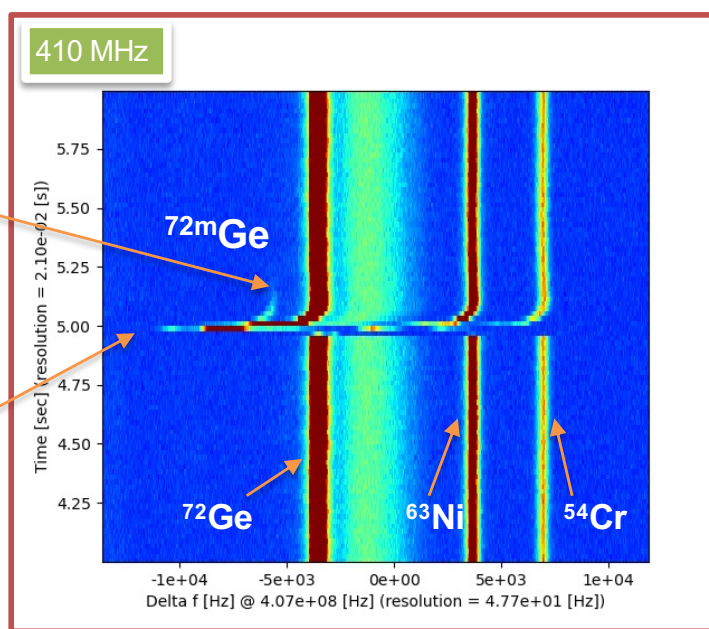
Combining **Schottky Mass Spectroscopy** and the **isochronous mode** of the **ESR**

- **Access to short-lived isomers (ms)**
- **High-resolution mass spectroscopy ($< 10^{-6}$)**
- **Higher sensitivity from new 410 MHz resonator**

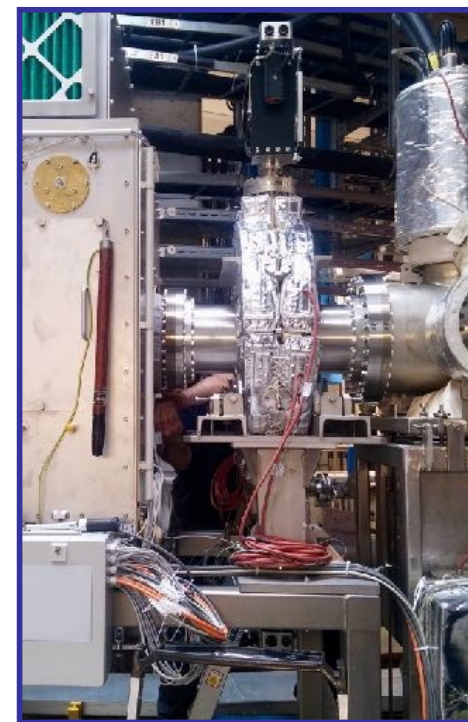
S.Sanjari et al.,
Rev. Sci. Instr. 91, 083303 (2020)

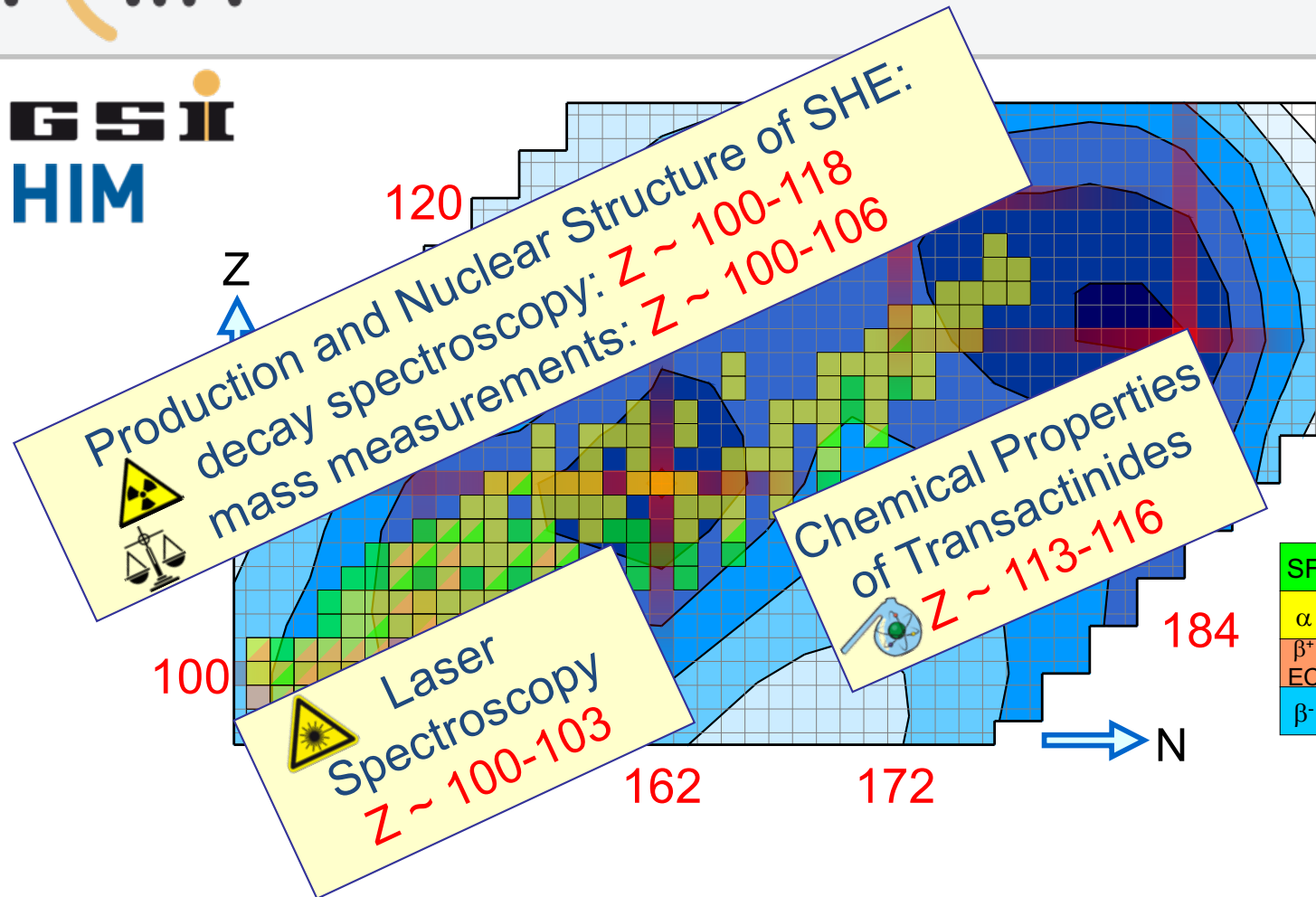


Isomer detection
well below 100 keV

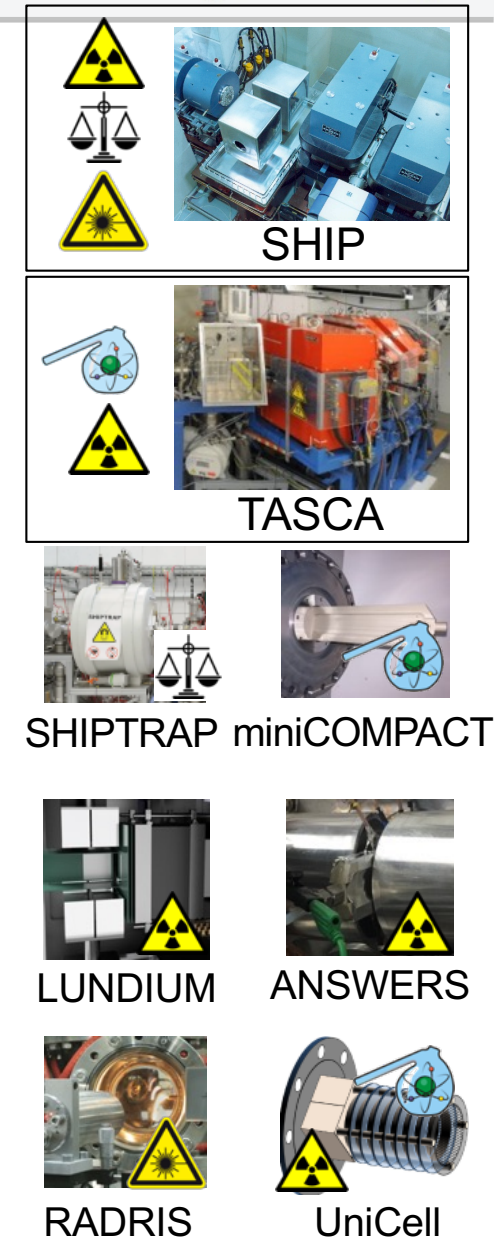


Two-photon decay of
0+ isomer in ^{72}Ge





Comprehensive investigation of **production** and of **atomic, chemical and nuclear properties** of elements $Z \sim 100 - 118$ using **novel techniques** and **GSI-unique suite** of experimental setups around recoil separators SHIP and TASCA



Ongoing technical developments will yet broaden the suite of available setup **GSI**

HIM

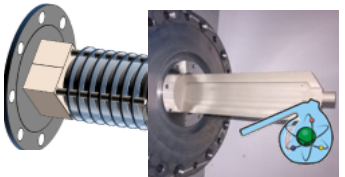
LUNDIUM decay station nearing completion

- will see a physics-driven commissioning 2022 (U319)
- novel detector setup for high alpha-photon coincidence efficiency (FI & L/K x-rays)



ANSWERS prototype for α/β /fission spectroscopy is in operation

- upgrade to state-of-the-art detectors started
- successfully commissioned with No and Rf nuclei (U328)
- next steps include neutron-rich superheavy nuclei



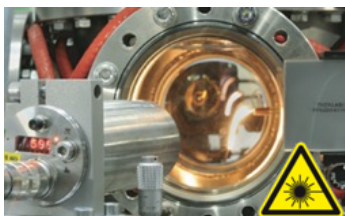
UniCell construction starts, **miniCOMPACT** is in operation

- UniCell will allow extraction of short-lived isotopes with <0.1 s lifetimes
- access to $_{116}\text{Lv}$ and $_{117}\text{Ts}$ with miniCOMPACT



SHIPTRAP in “production” mode

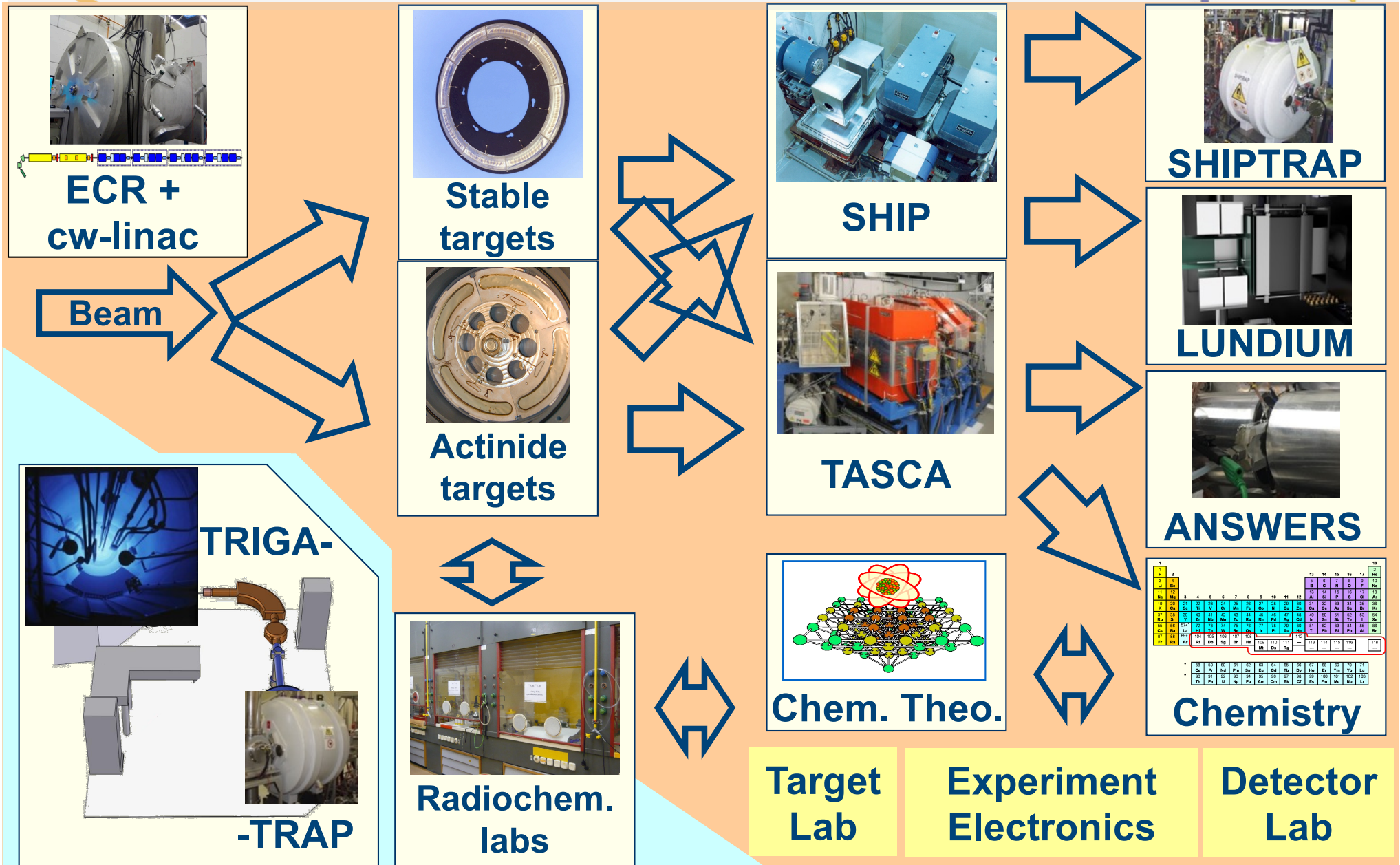
- mass measurements of ground states, e.g. ^{255}Rf , ^{257}Db
- study isomeric states, e.g. $^{257\text{m}}\text{Db}$ and $^{258\text{m}}\text{Db}$
- access heavier elements such as ^{261}Sg

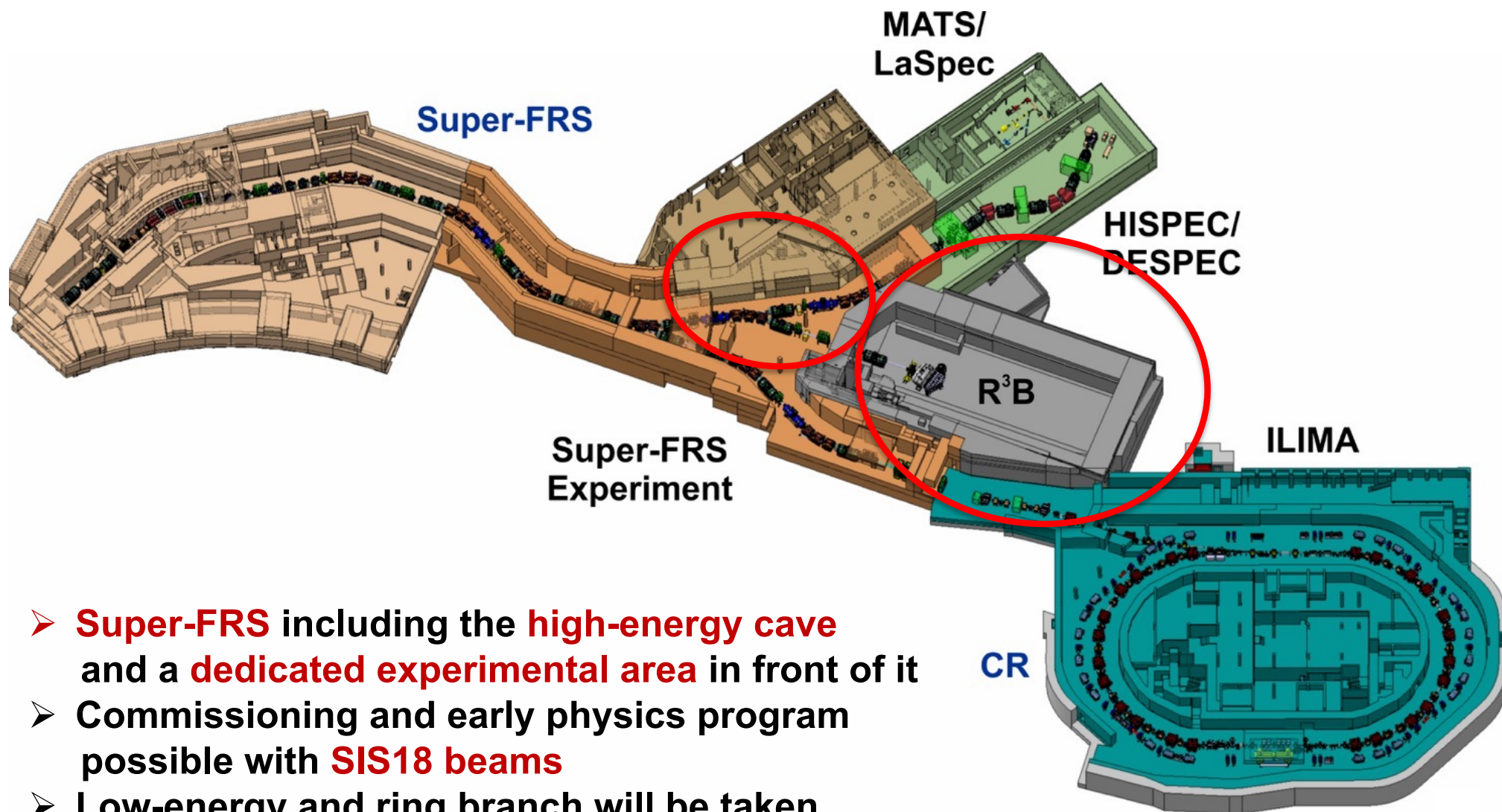


Laser spectroscopy – more exotic nuclides & higher precision

- gas-jet for improved resolution and accessing shorter lived nuclei
- measurements of hyperfine structures, e.g., $^{254\text{m}}\text{No}$ and beyond

Unique combination of equipments for SHE studies

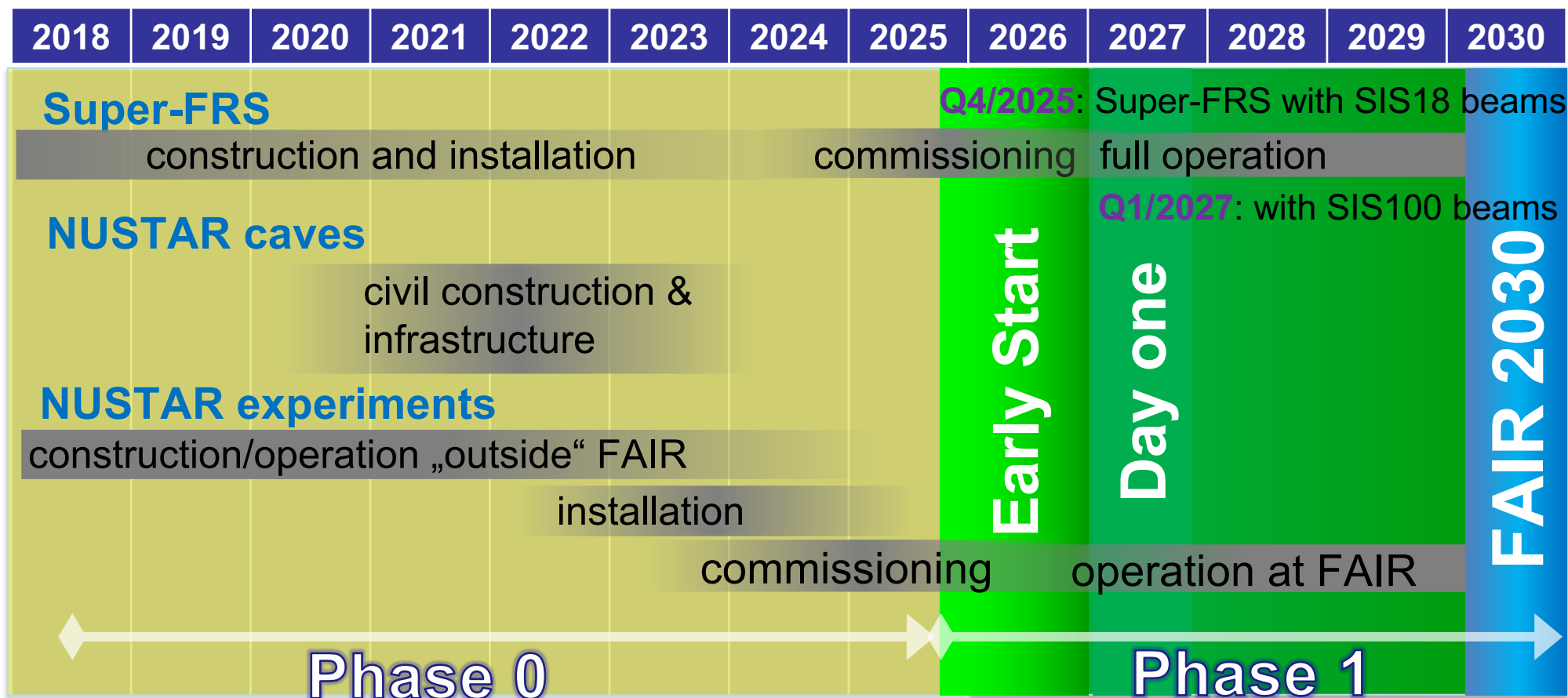




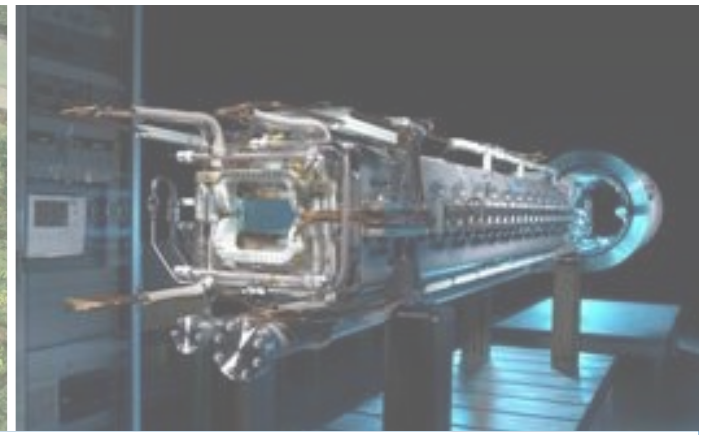
- **Super-FRS** including the **high-energy cave** and a **dedicated experimental area** in front of it
- Commissioning and early physics program possible with **SIS18 beams**
- Low-energy and ring branch will be taken consecutively into operation, but should not be delayed

Facility	U beam intensity/spill at production target		Luminosity [fb ⁻¹]
previously at GSI (Phase 0)	1...2x10 ⁹	gain factor	
after the SIS18 upgrade at GSI	5x10 ⁹	~5	0,1
commissioning phase SIS100	2x10 ¹⁰	~4	5
final full intensity with SIS100	3-5x10 ¹¹	~20	100

Phase 0 (2019/20)	→	Day-1 (2024)	→	Full MSV (202x)
preparation	→	discovery	→	detailed studies
• 0.1 fb ⁻¹	→	2-5 fb ⁻¹	→	100 fb ⁻¹
• (near)stability	→	exotic	→	very exotic nuclei



- The **NUSTAR** collaboration at FAIR covers all aspects of nuclear structure, reactions and astrophysics with dedicated equipment
- The **NUSTAR** experiments will make use the unique properties of the **accelerators** (energy, intensity), the **Super-FRS** (transmission, rejection, resolution) and the **new instrumentation**
- **FAIR Phase-0** currently under way **at GSI** for commissioning of the equipment and first physics results
- **NUSTAR Day-1 experiments** using SIS18 beams as soon as **first beams from the Super-FRS** will become available (Q4/2025) will allow to start a viable NUSTAR physics program (DeSpec, R3B, Super-FRS)
- The low-energy (MATS & LASPEC) and storage ring experiments (ILIMA) require the operation of the **full Super-FRS facility**



Thank you for your attention

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