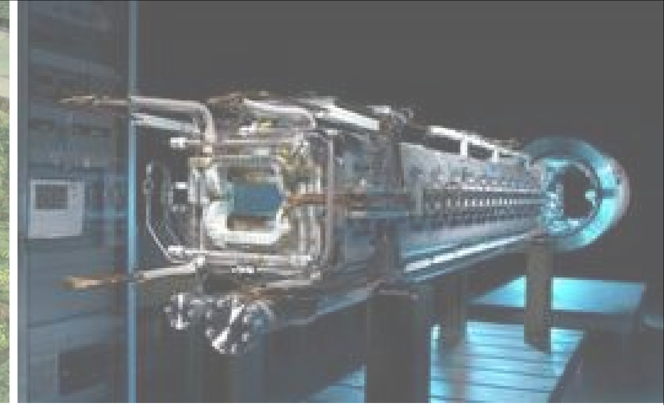




Exploring the extremes with NUSTAR @ FAIR

Nasser Kalantar-Nayestanaki
ESRIG/University of Groningen

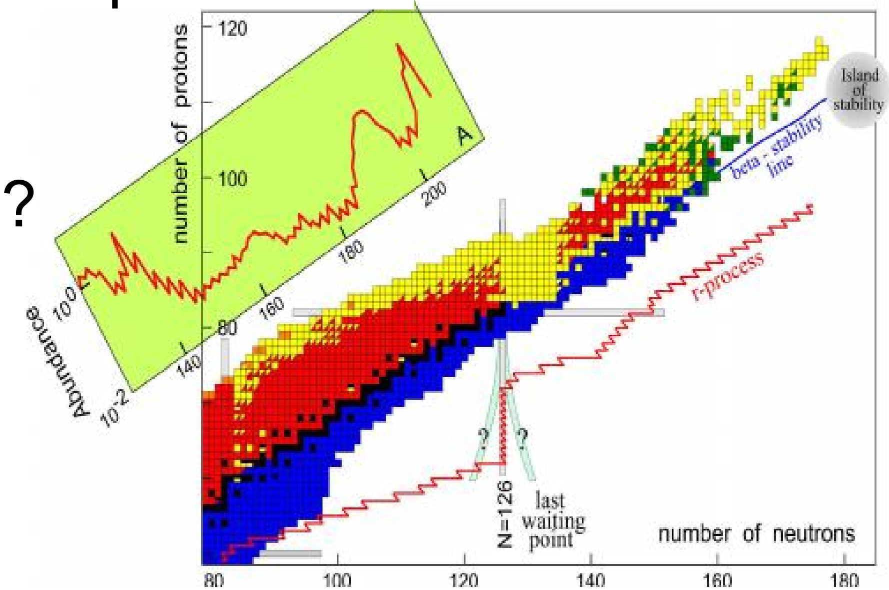
On behalf of NUSTAR Coll.
(Spokespers.: Zsolt Podolyak

LASNPA XIV/2024

Mexico City, Mexico, June 18, 2024

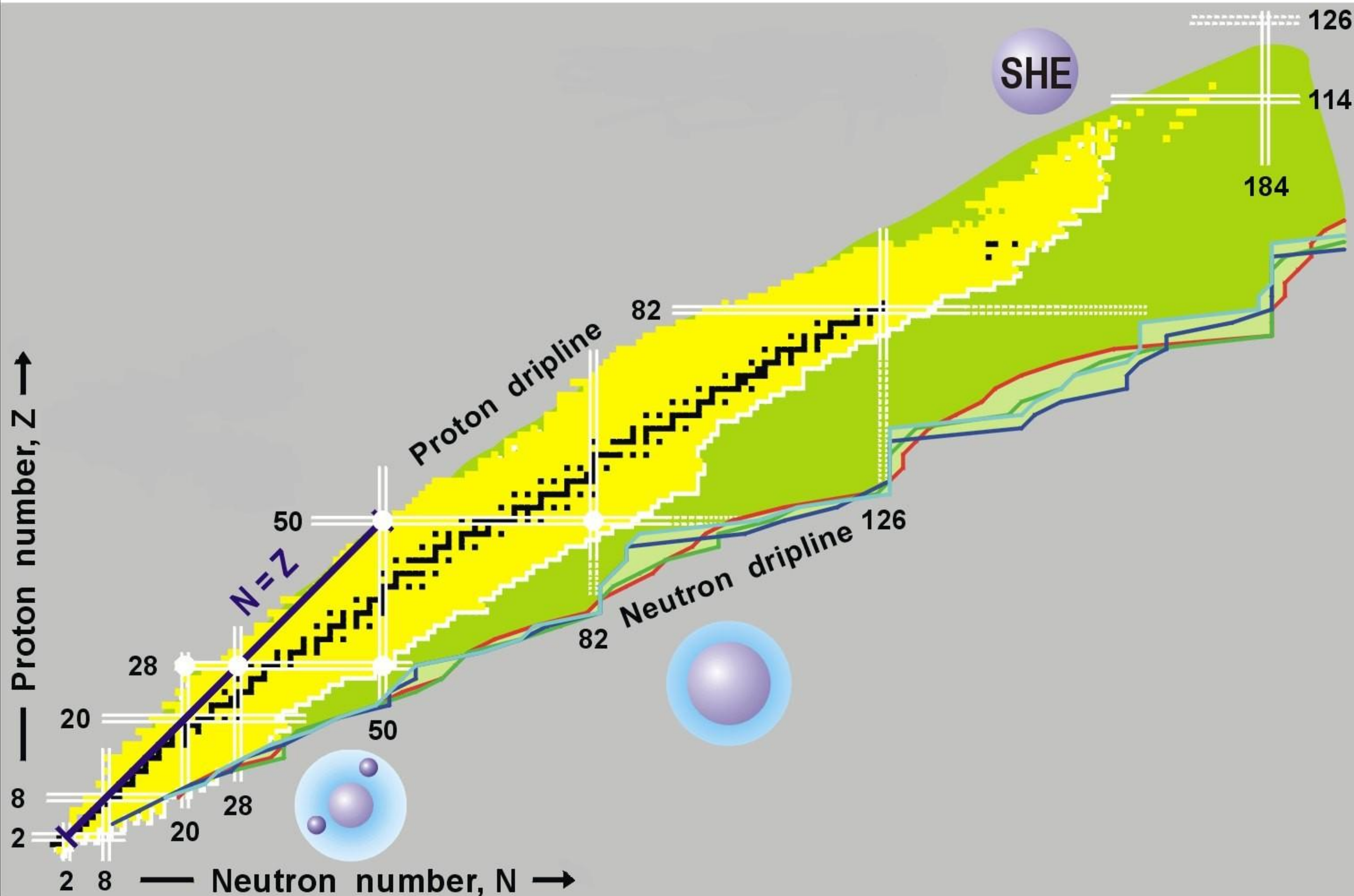
The 11 Greatest Unanswered Questions of Physics

1. What is dark matter?
2. What is dark energy?
3. **How were the heavy elements from iron to uranium made?**
4. Do neutrinos have mass?
5. Where do ultrahigh-energy particles come from?
6. Is a new theory of light and matter needed to explain what happens at very high energies and temperatures?
8. Are protons unstable?
9. What is gravity?
10. Are there additional dimensions?
11. How did the universe begin?

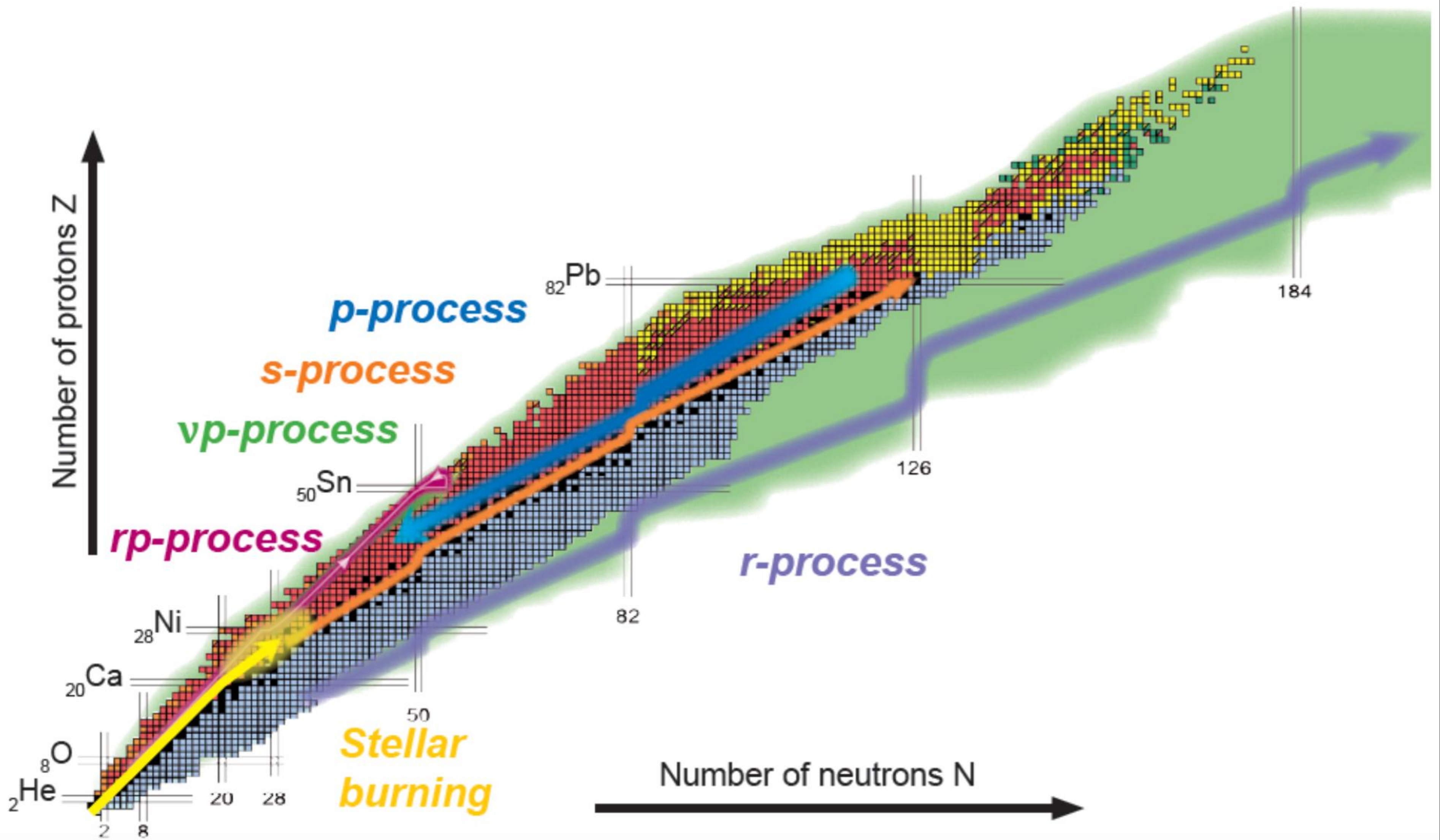


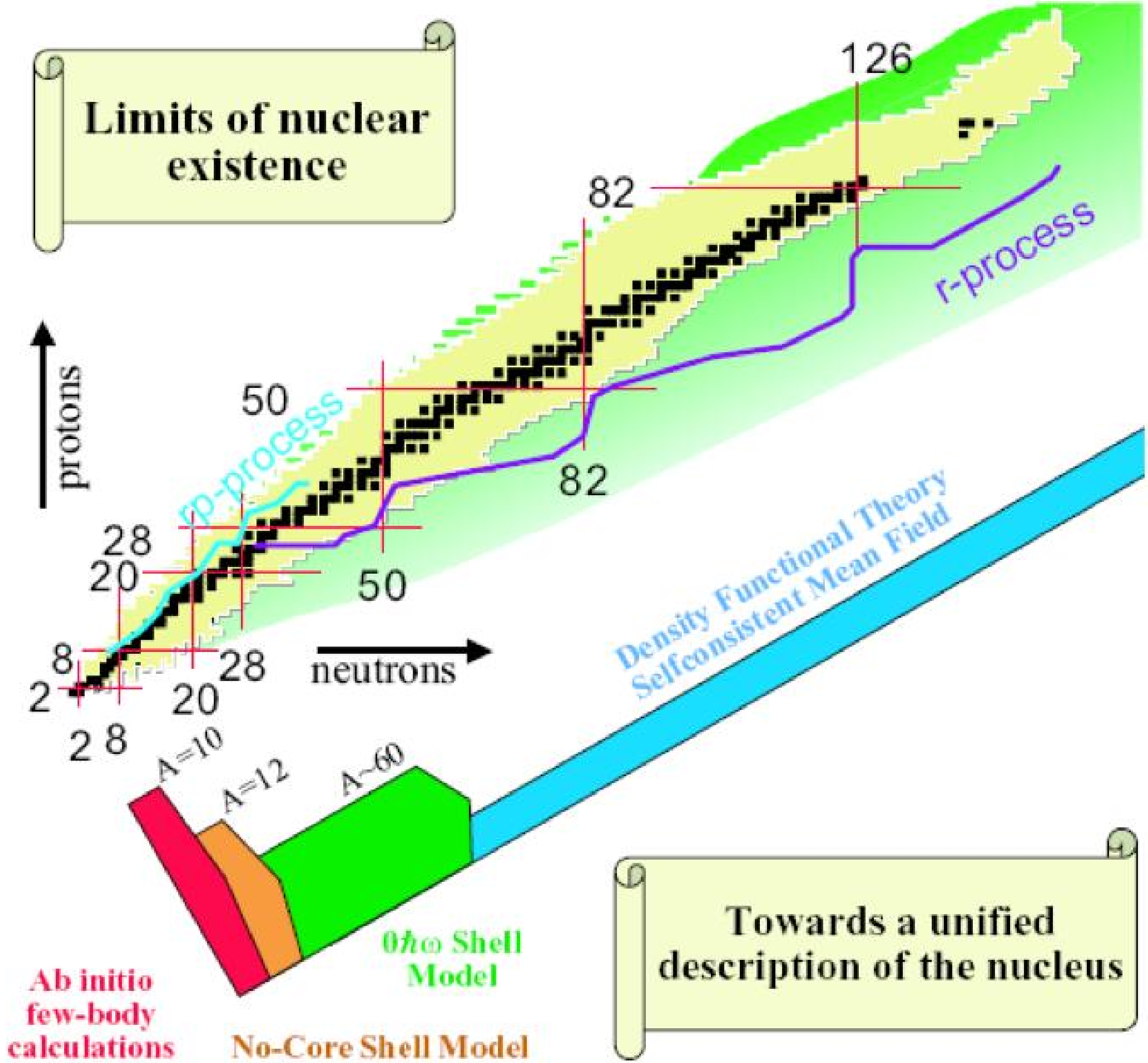
https://www.discovermagazine.com/the-sciences/the-11-greatest-unanswered-questions-of-physics

Snapshot of the nuclear landscape



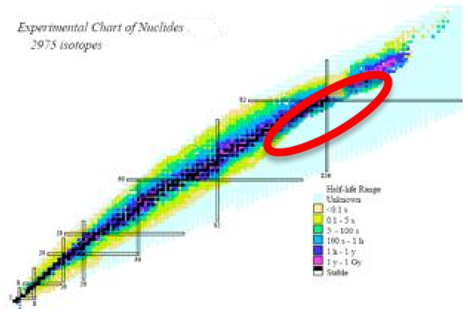
Nuclear and astrophysics meet



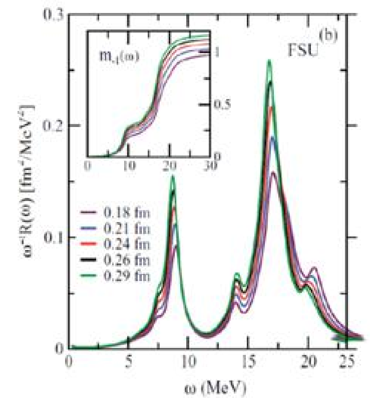

Limits of nuclear existence
126
82
50
28
20
8
2
protons
neutrons
rp-process
r-process
82
50
28
20
2 8
Density Functional Theory
Selfconsistent Mean Field
A=10
A=12
A~60
Ab initio
few-body
calculations
No-Core Shell Model
0ħω Shell
Model
Towards a unified
description of the nucleus

Spear points of NUSTAR Phase 1

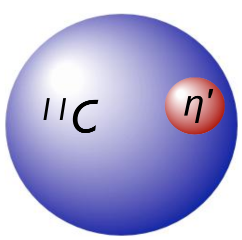
- Heavy nuclei, 3rd r-process peak

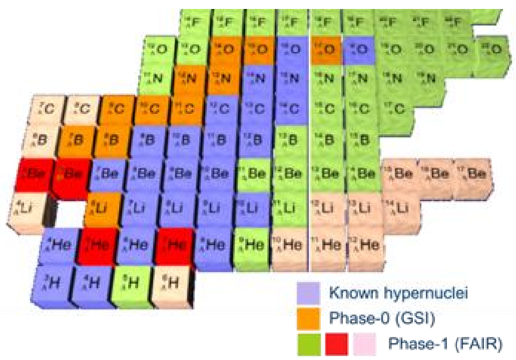


- High excitation energies



- Study of exotics

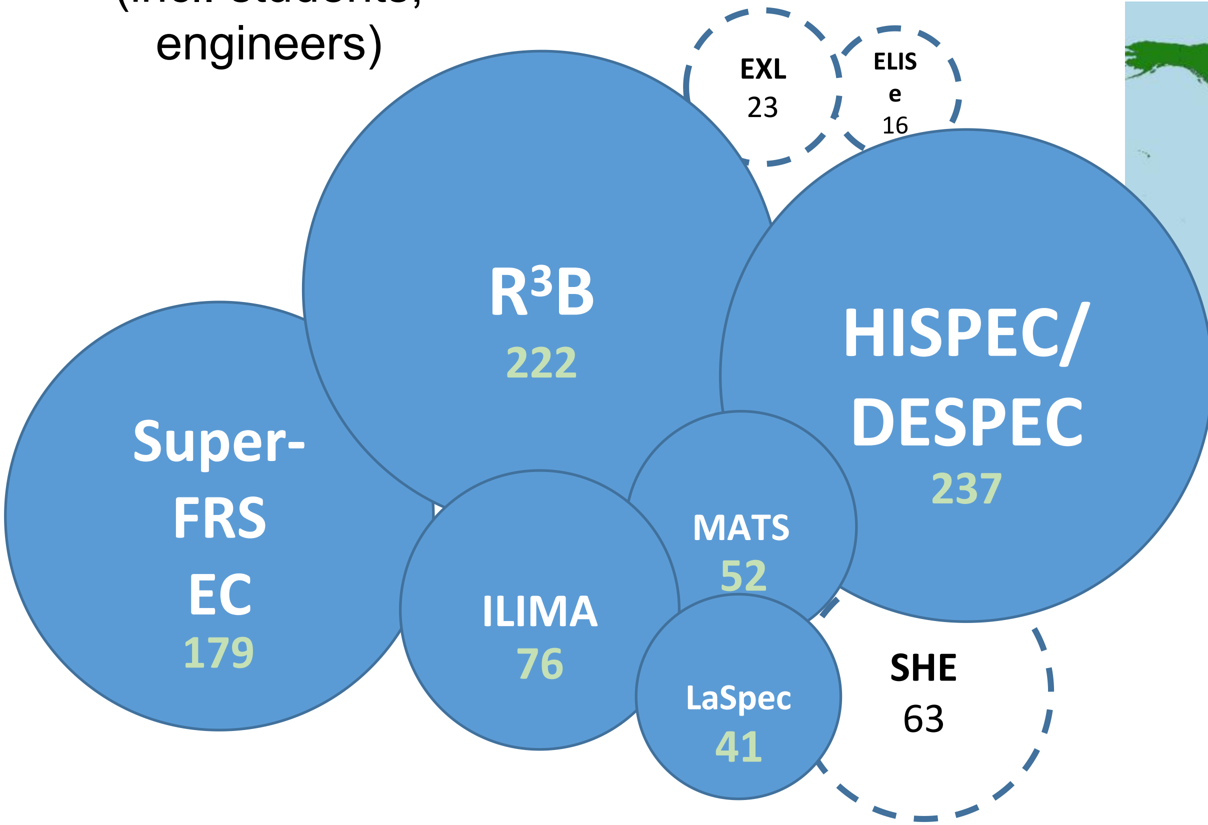


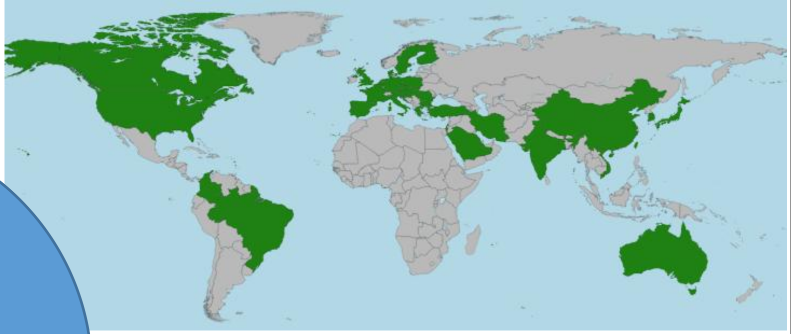


NUSTAR collaboration

NUSTAR – a collaboration of collaborations
One science, different observables, instrumentations

>630 NUSTAR members (incl. students, engineers)





> 1000 listed "interested" scientists

- **> 630 registered members (incl. students, etc.)**
- **~ 420 senior members (PhD holder w/o Russia)**
- **> 150 institutes from 36 countries**

Status: October 8, 2023

NUSTAR – The project 1.2

	Super-FRS	RIB production, separation, and identification
PSP	**Experiment**	**Description**
1.2.2	**HISPEC/ DESPEC**	In-beam γ-spectroscopy at low and intermediate energy, n-decay, high-resolution γ-, β-, α-, p-, spectroscopy
1.2.3	**MATS**	In-trap mass measurements and decay studies
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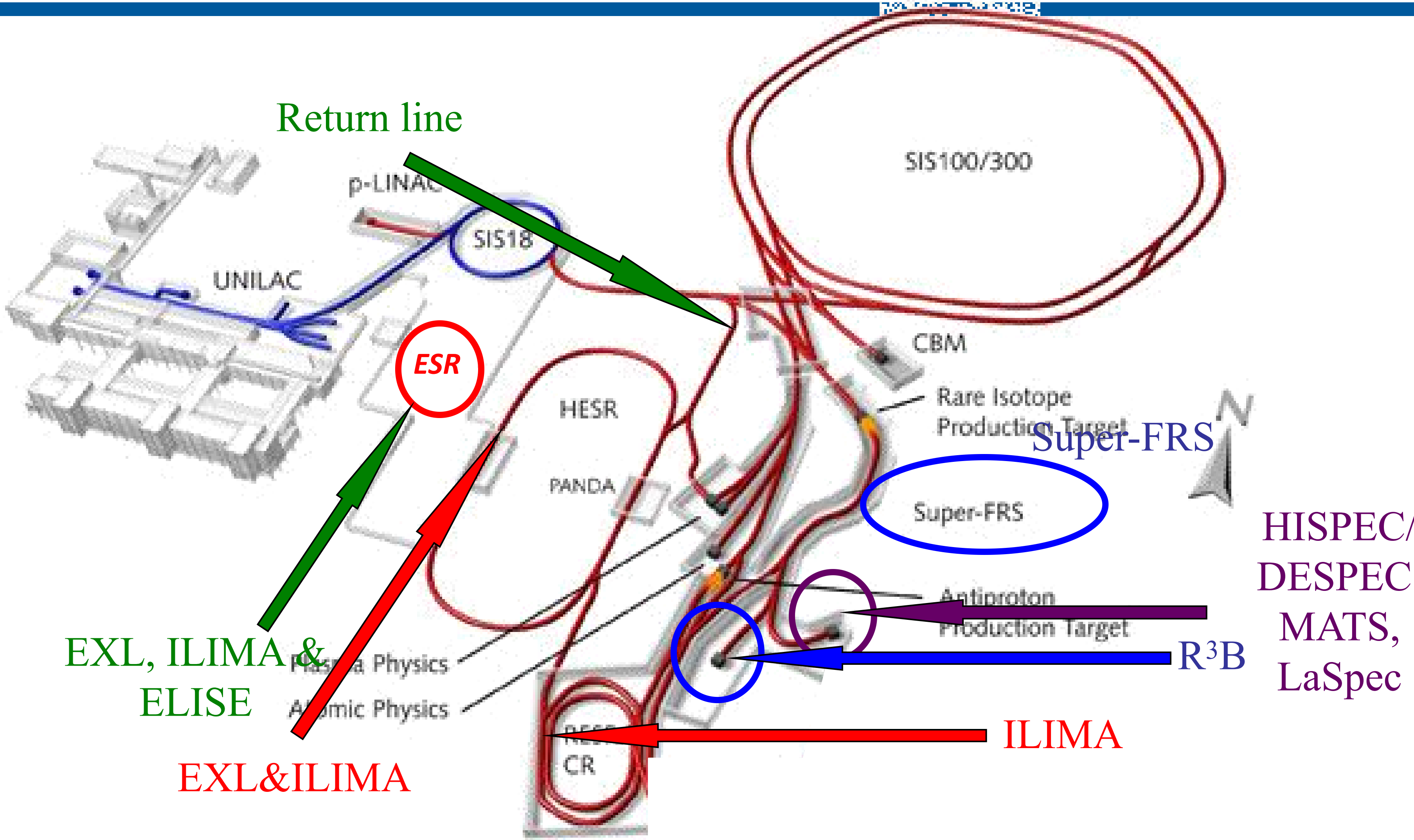
1.2.8	**ELISe(*)**	Elastic, inelastic, and quasi-free e$^-$-A scattering
1.2.9	**EXL(*)**	Light-ion scattering reactions in inverse kinematics

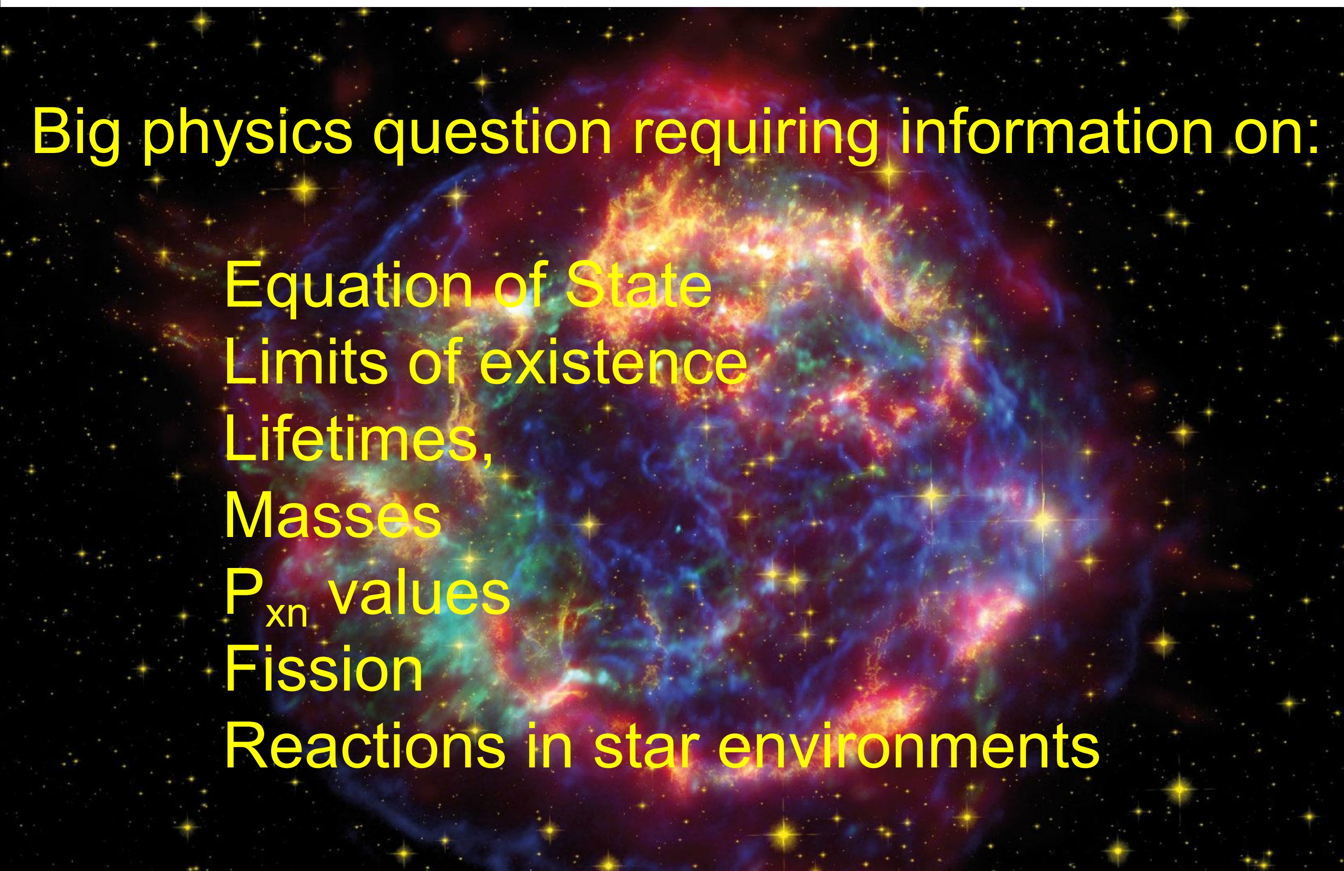
(*) NESR required – alternative/intermediate “operation” within MSV under discussion.
SHE physics case to be evaluated.

MSV and plans of NUSTAR



The Physics Program

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

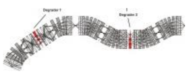


Big physics question requiring information on:

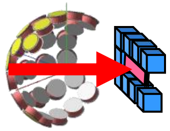
- Equation of State
- Limits of existence
- Lifetimes,
- Masses
- P_{xn} values
- Fission
- Reactions in star environments

Complementarity of NUSTAR experiments

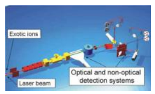
Super-FRS



HISPEC/ DESPEC

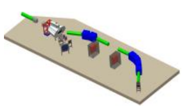


LASPEC

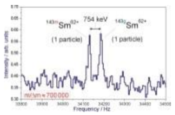


MATS

R3B

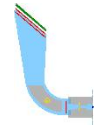


ILIMA



SHE

ELISE



EXL

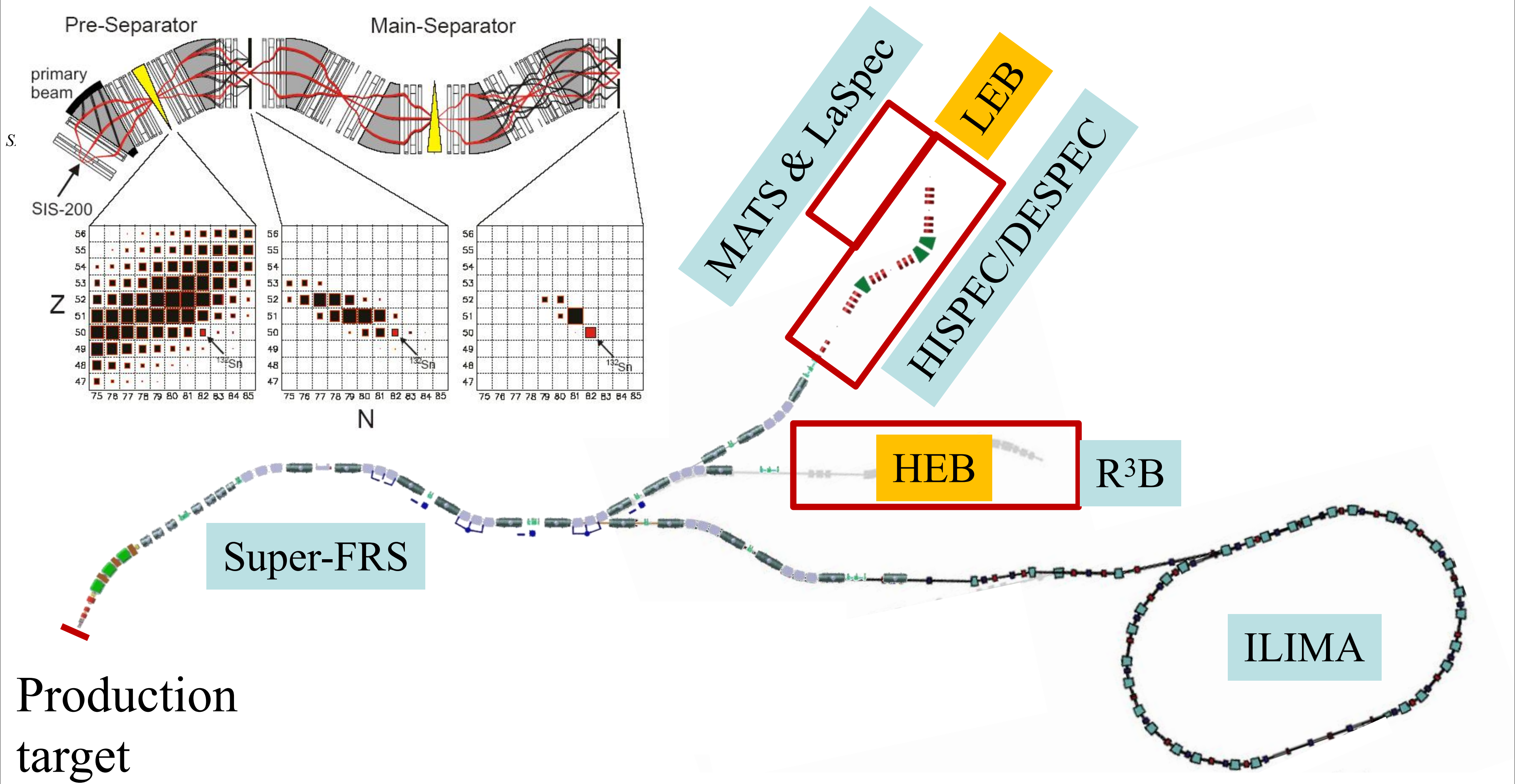
	Super-FRS	HISPEC/DESPEC	LASPEC	MATS	R3B	ILIMA	SHE	ELISe	EXL
Masses	Precision meas.	Q-values, isomers		dressed ions, highest precision	unbound nuclei	bare ions, mapping study	precision mass of SHEs		
Half-lives	ps...ns-range	dressed ions, µs...s			resonance width, decay up to 100ns	bare ions, ms…years	µs...days		
Matter radii	interaction x-section				interaction x-section				matter densitiy 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 and tensor	evolution of shell closures, pairing corr.	shell structure of SHEs		low momentum transfers
Collective behavior		electromag. transitions	quadrupole moments	halo structure	dipole response	changes in deformation		electromag. transitions	monopole resonance
EoS					polarizability, neutron skin			neutron skin ➔	neturon skin, Compressibility
Exotic Systems	bound mesons, hypernuclei, nucleon res.								

What are the highlights of FAIR Phase 1 program?

- Understanding the 3rd r-process peak by means of comprehensive measurements of masses, lifetimes, neutron branchings, dipole strength, and 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 tin isotopes with N larger than 82 (in combination with the results of the first highlight);
- Exotic hypernuclei with very large N/Z asymmetry.

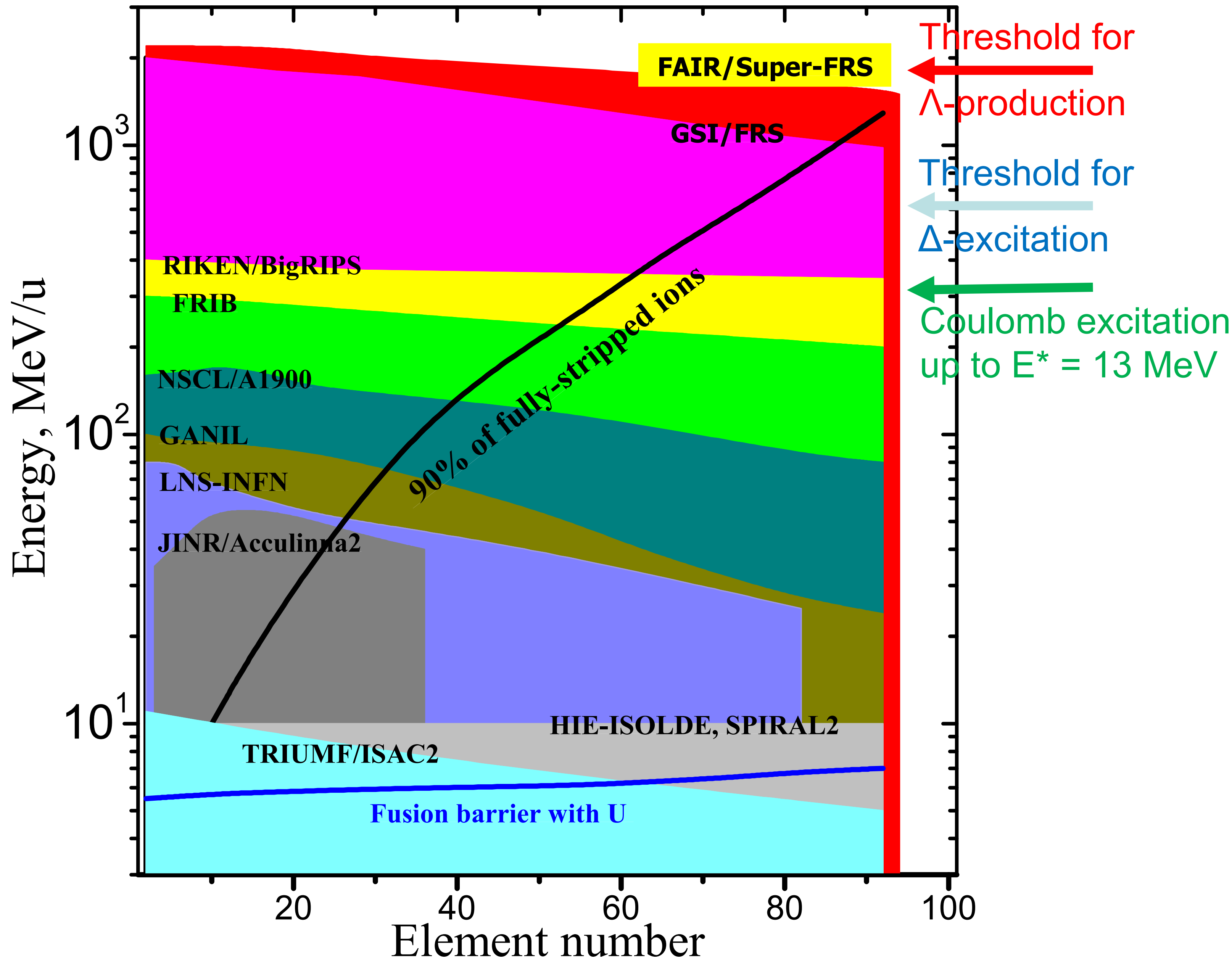
“PARTS” needed

NUSTAR experimental areas, ESSENTIAL to run!



Rich program due to approximately 2000 h beam time for NUSTAR experiments per year!

RARE-ISOTOPE BEAM FACILITIES

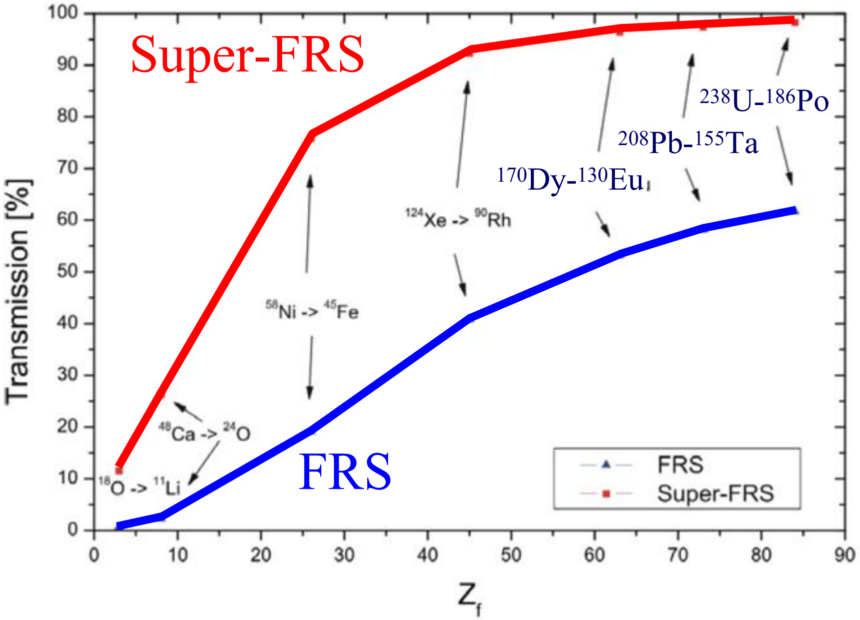


Improvements of Radioactive Ion Beam (RIB) production with the Super-FRS at NUSTAR

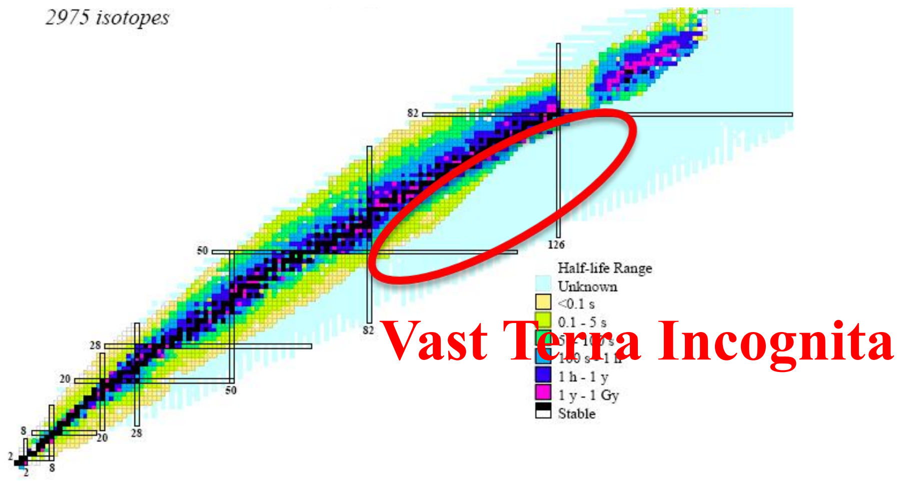
Super-FRS will provide

- Higher yields
  larger transmission (and thicker targets)
- Higher count-rate capabilities
  better suppression (two-stage separation)
- access to short (μs) lifetimes

Higher transmission



from Super-FRS TDR



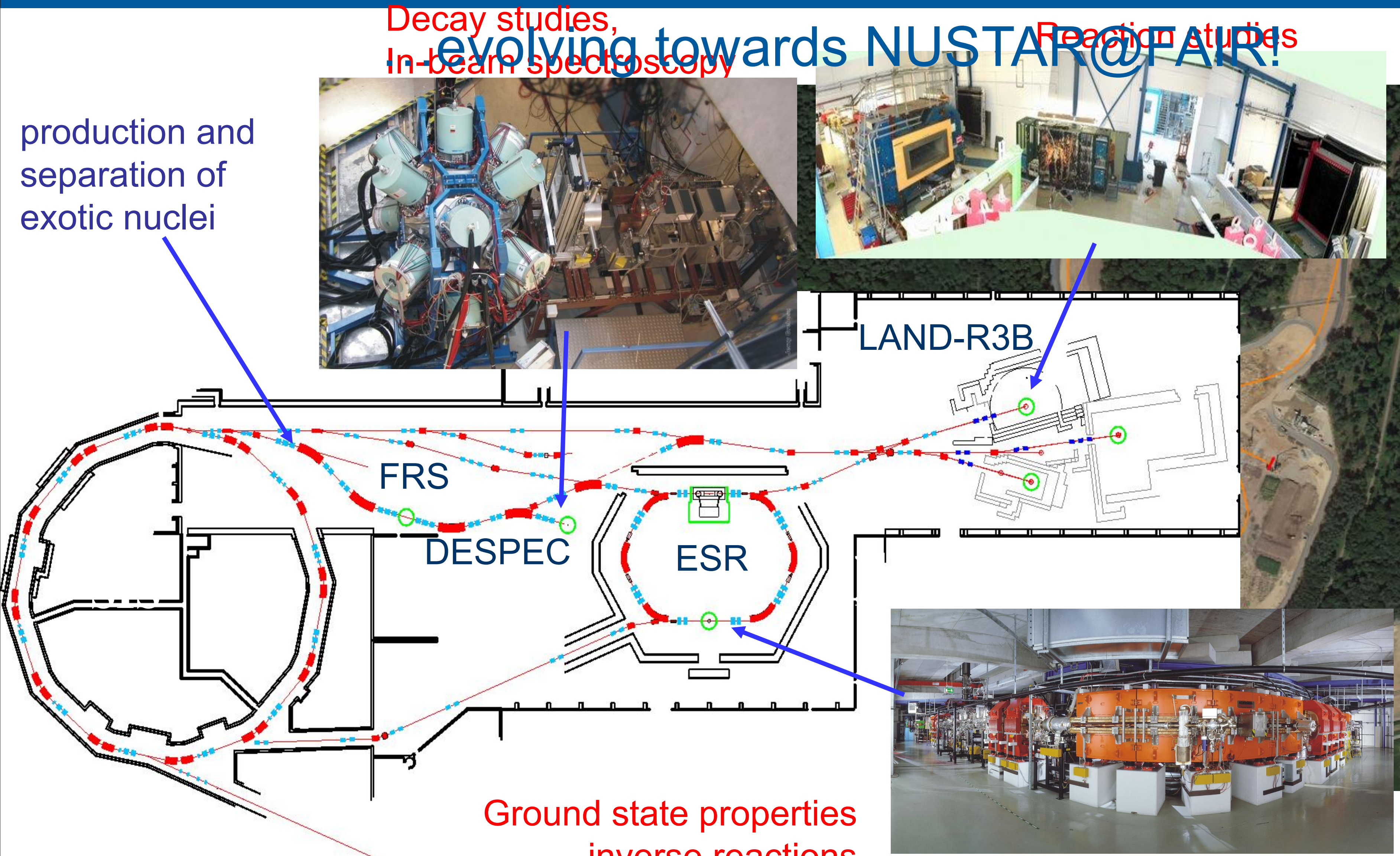
Strategy

Definition of NUSTAR experiment phases

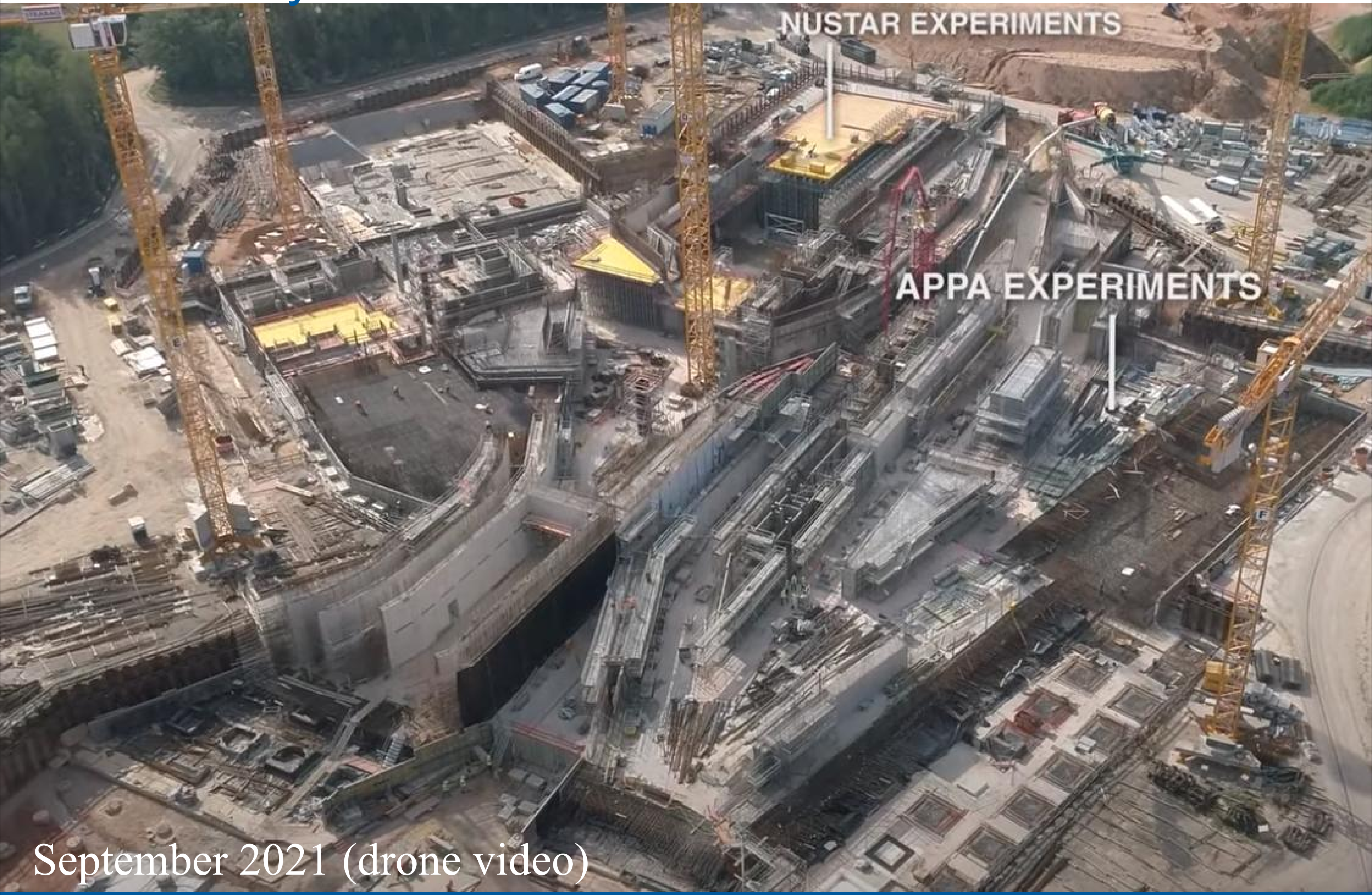
- **Phase 0**
  - R&D and experiments to be carried out with present facilities and FAIR/NUSTAR equipment
- **Phase 1**
  - Core detectors and subsystems completed
  - First measurements with FAIR/Super-FRS beams
  - ➢ **Carry out experiments with highest visibility as part of the core program and within the FAIR MSV**
- **Phase 2**
  - FAIR evolving towards full power
  - Completion of experiments within MSV
  - ➢ **Essentially the full program of MSV can be performed**
- **Phase 3**
  - Moderate projects, which have been initiated on the way (outside MSV) can be included (e.g. experiments related to return line for rings)
- **Phase 4**
  - Major new investments and upgrades for all experiments

Phase 1

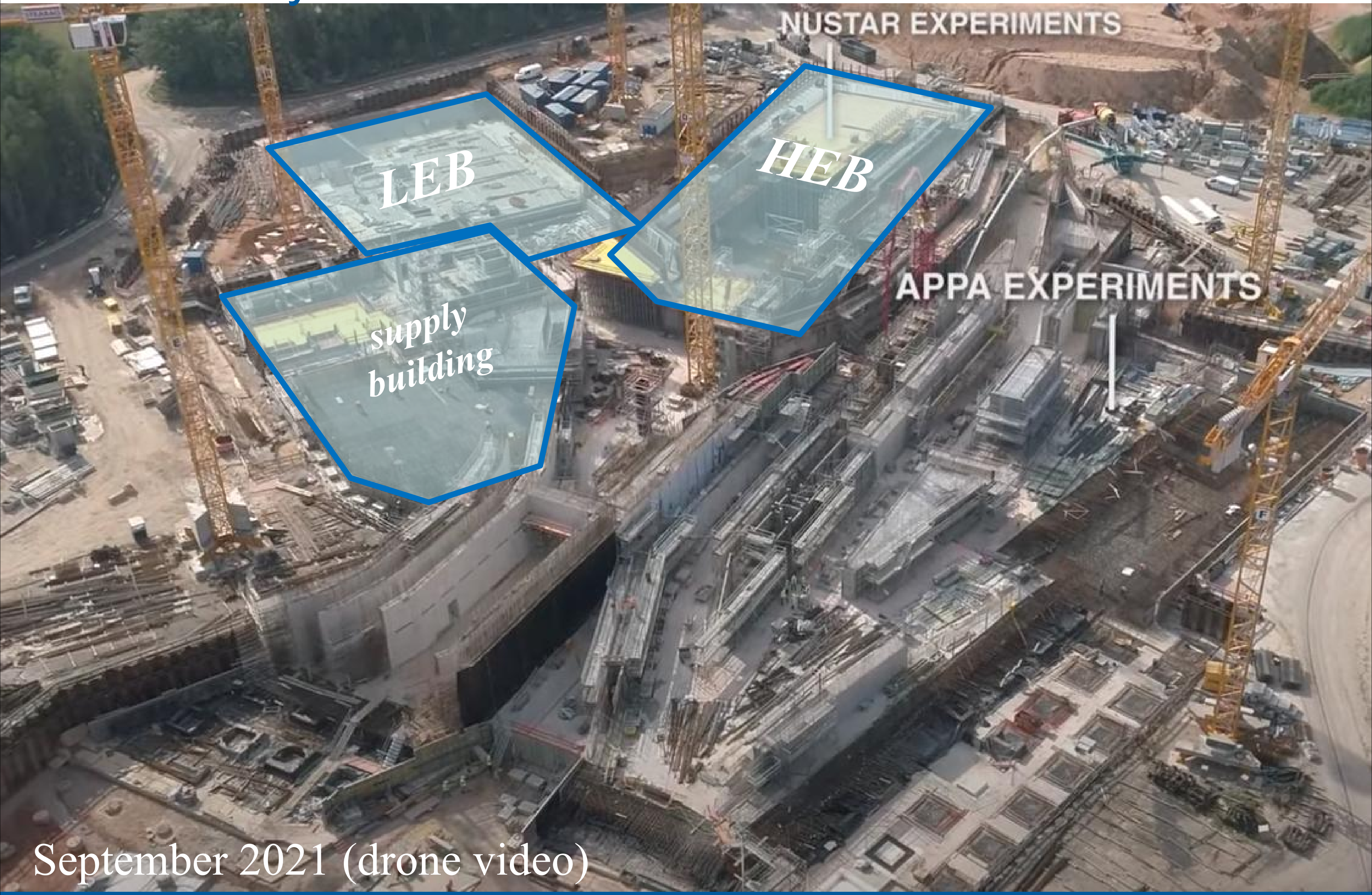
...evolving towards NUSTAR@FAIR!



… to reality

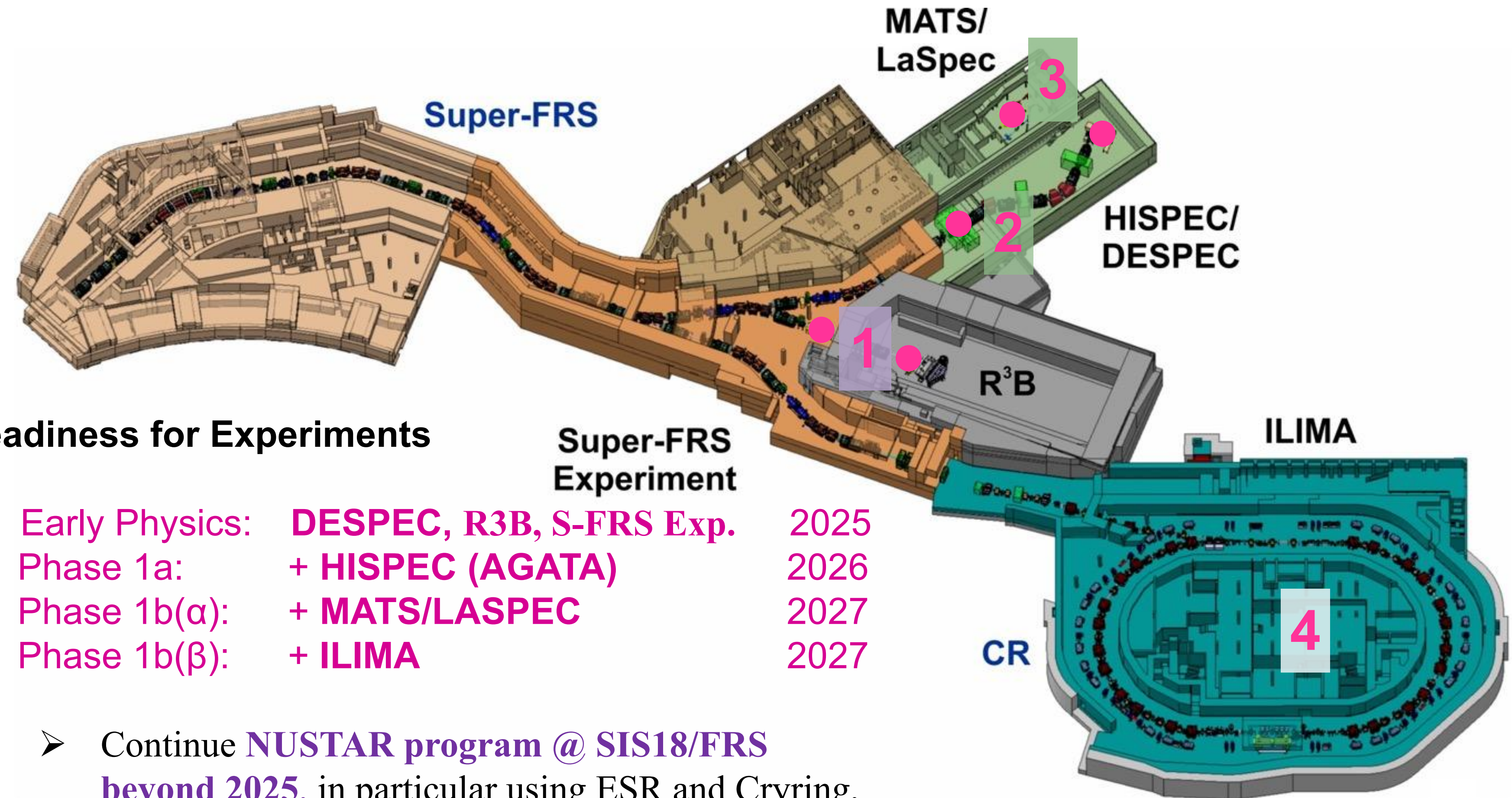

NUSTAR EXPERIMENTS
APPA EXPERIMENTS
September 2021 (drone video)

… to reality


NUSTAR EXPERIMENTS
LEB
HEB
supply building
APPA EXPERIMENTS
September 2021 (drone video)

And in April 2024

NUSTAR Physics start up at FAIR



Readiness for Experiments

1	Early Physics:	**DESPEC, R3B, S-FRS Exp.**	2025
2	Phase 1a:	+ **HISPEC (AGATA)**	2026
3	Phase 1b(α):	+ **MATS/LASPEC**	2027
4	Phase 1b(β):	+ **ILIMA**	2027

- Continue **NUSTAR program @ SIS18/FRS beyond 2025**, in particular using ESR and Cryring, but not exclusively

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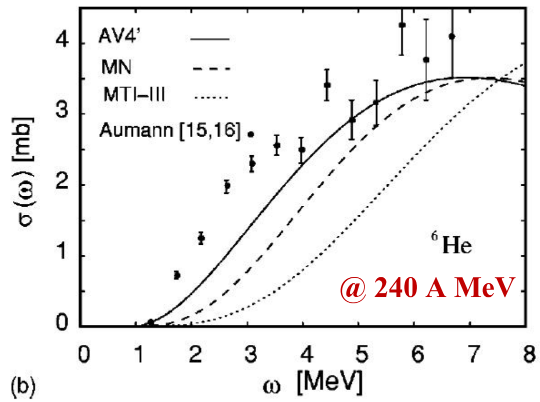
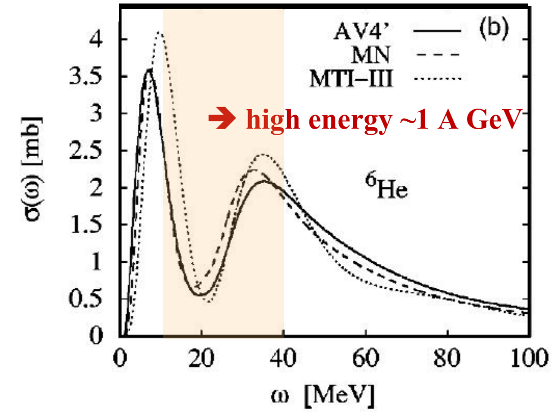
R^3B

Phase 1 Physics with R3B setup:

Dipole strength Distributions in heavy neutron-rich nuclei

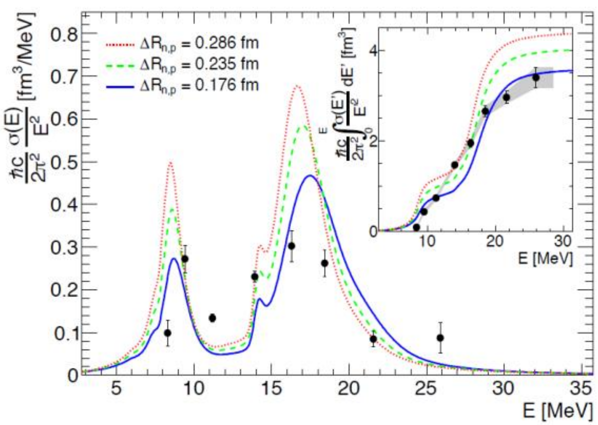
- core vs. neutron skins & halos → density / asymmetry





S. Bacca et al.
PRL **89** (2002) 052502
PRC **69** (2004) 057001

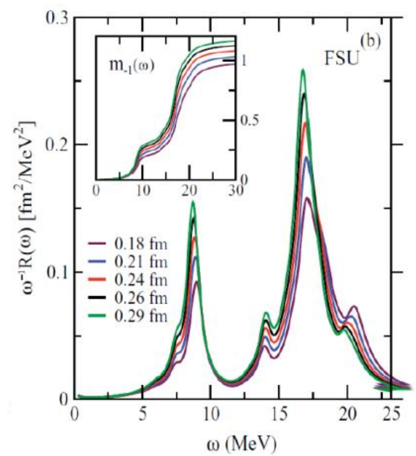
- access to EoS (e.g. neutron star) & low lying E1 strength (r-process)



$$\alpha_D = \frac{\hbar c}{2\pi^2}\int_0^\infty \frac{\sigma(E)}{E^2}dE$$

D. Rossi et al.
PRL **111** (2013) 242503

skin thickness ^{68}Ni
0.175(21) fm



Pb chain & N=126 isotones

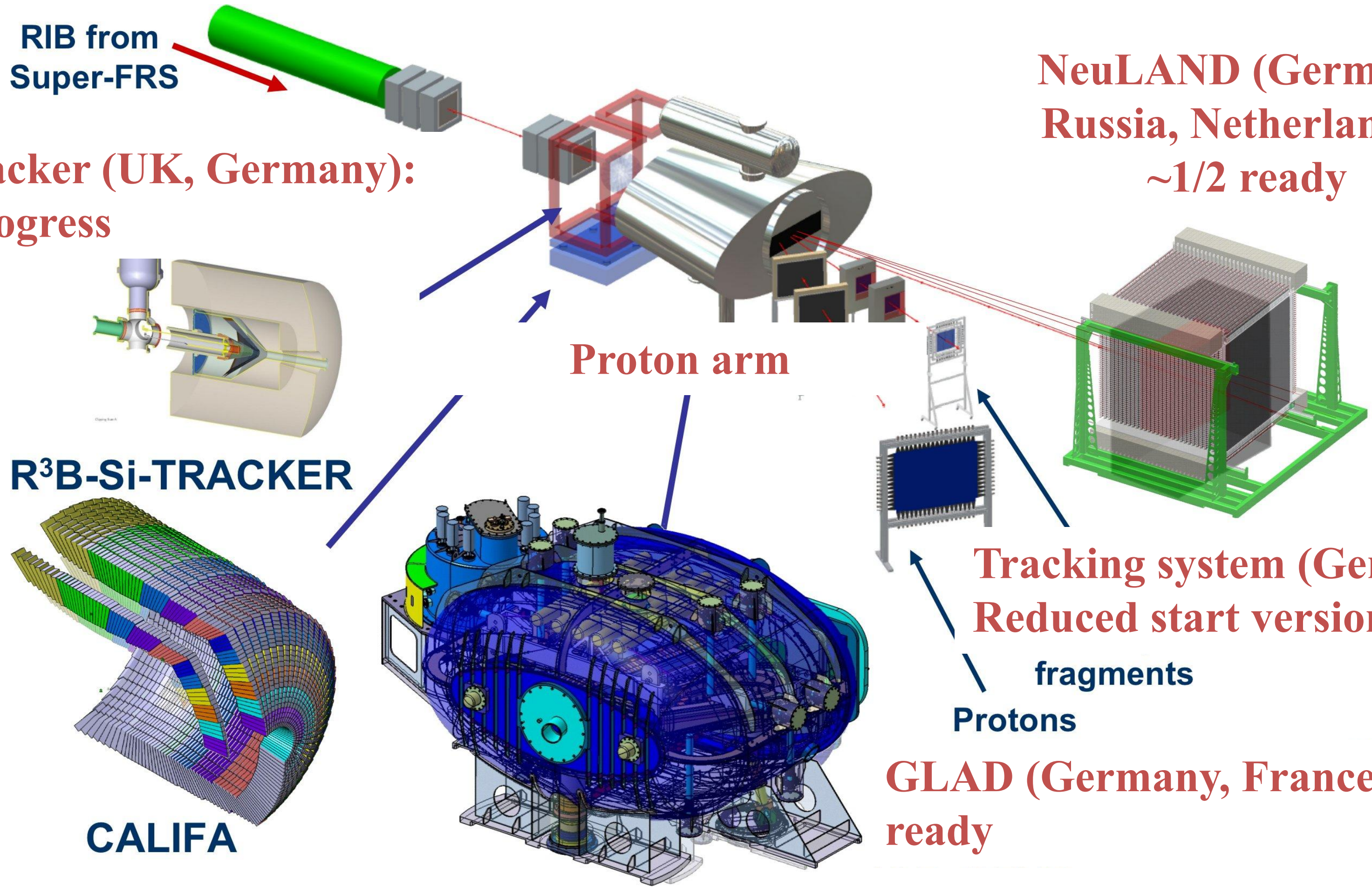
~1 A GeV →
bare ions
Fragment identification

J. Piekarewicz, PRC **83** (2011) 034319

Start version for Phase 0

Si tracker (UK, Germany): in progress

NeuLAND (Germany, Russia, Netherlands): ~1/2 ready



Tracking system (Germany): Reduced start version ready

GLAD (Germany, France): ready

CALIFA (Sweden, Spain, Germany, Russia): Barrel without backward part ready

FAIR Phase-0: $^{12}C+^{12}C$ benchmark case

A benchmark case to provide very precise data that minimize the uncertainty associated to the reaction models

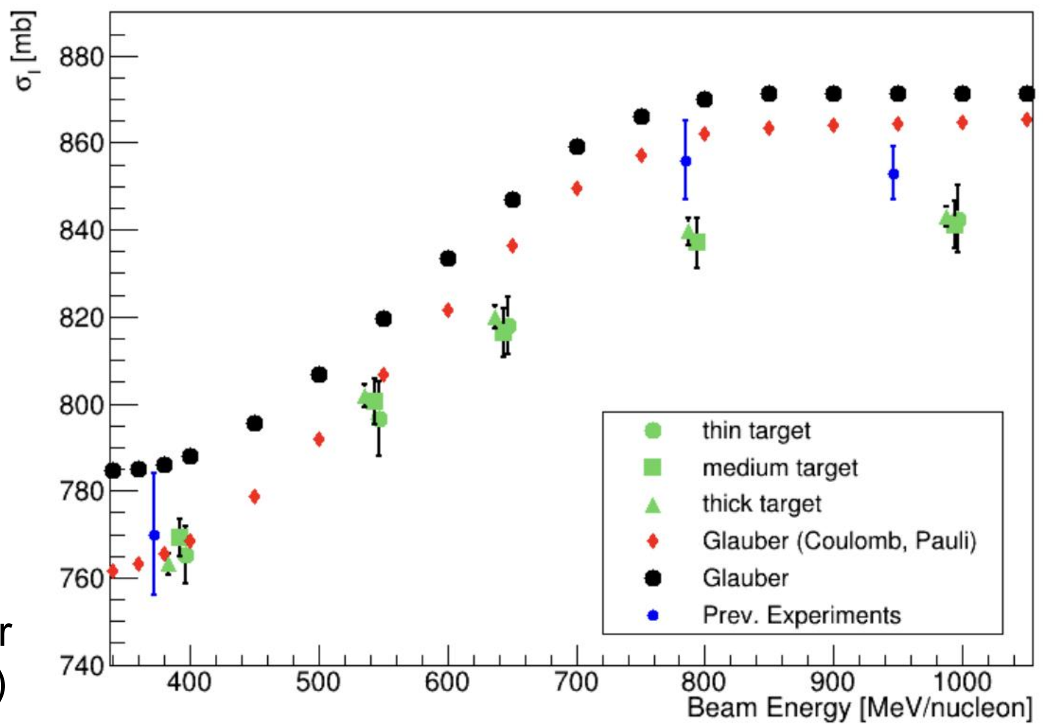
Exp. precision +-0.387%

Determined by the so-called Transmission method

$$\sigma_R = \sigma_{inel} + \sigma_I$$

$$\sigma_R = -\frac{1}{N_t} ln\left(\frac{R_i}{R_o}\right)$$

$R_{i/o}$ is the ratio of non-interacting nuclei after target and incoming nuclei for target in (out)

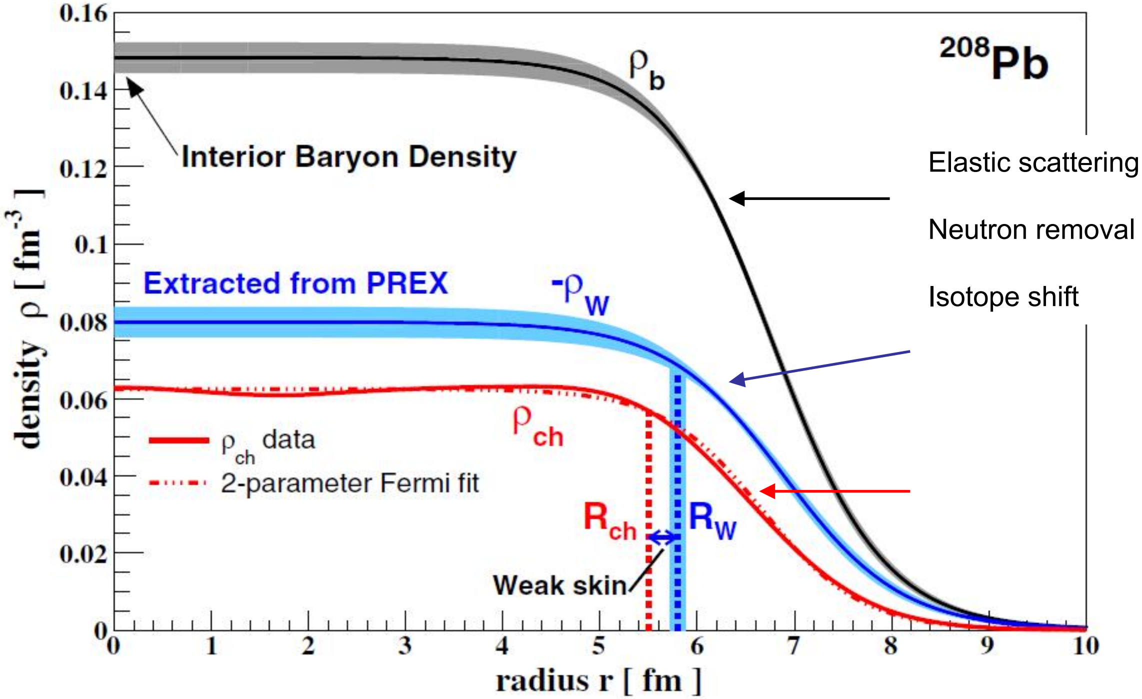


L. Ponath et al., submitted to PLB

Precision of +-0.387% achieved, while the **Glauber model** including in-medium effects of Pauli blocking, Fermi motion, higher-order Eikonal corrections, Coulomb repulsion, and nuclear excitation of giant resonances **overestimates** the cross section **by around 2.5%** at higher beam energies.

ES and FS: neutron skin, polarizability

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

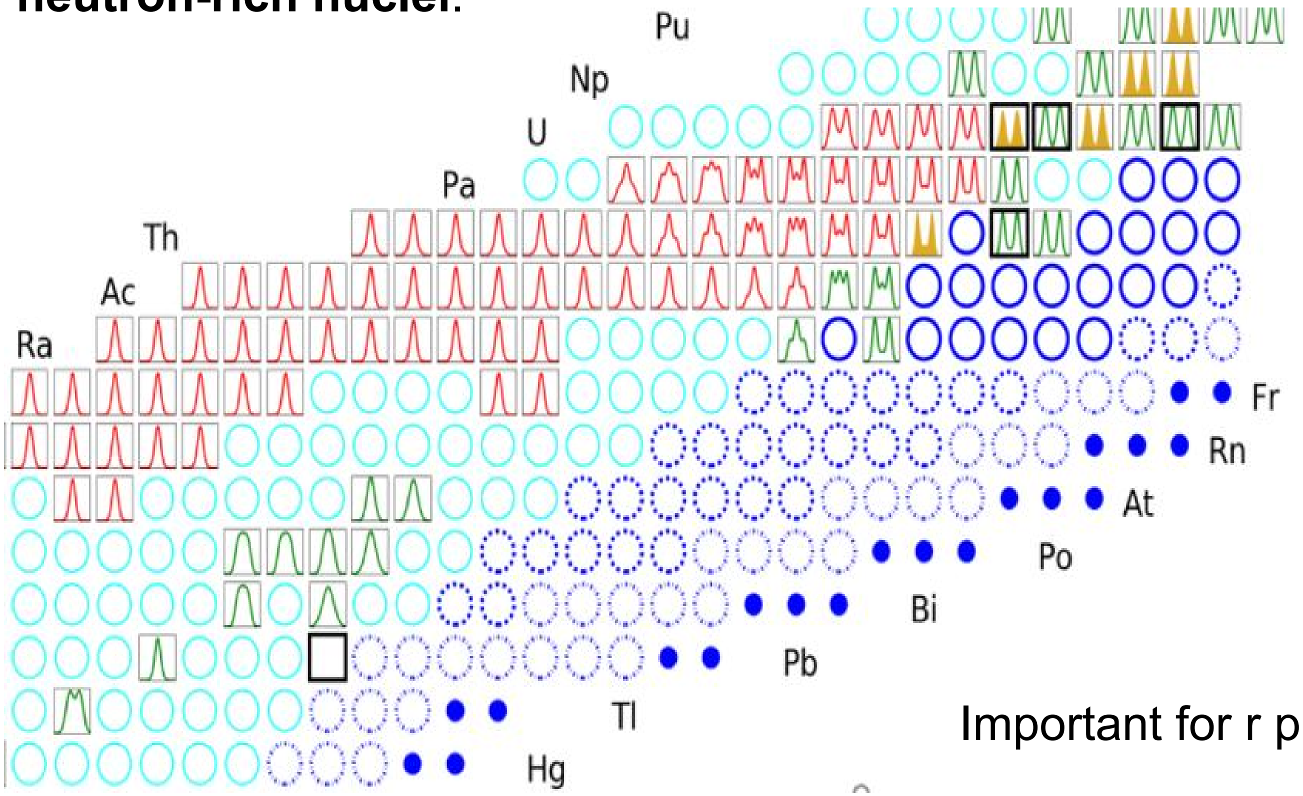


PHYSICAL REVIEW LETTERS **126,** 172502 (2021)

Relatively low ^{238}U intensity needed, enough for ~^{132}Sn

ES and FS: fission

First results on **fission Z/A** and **fission barriers** of **heavy neutron-rich nuclei**.

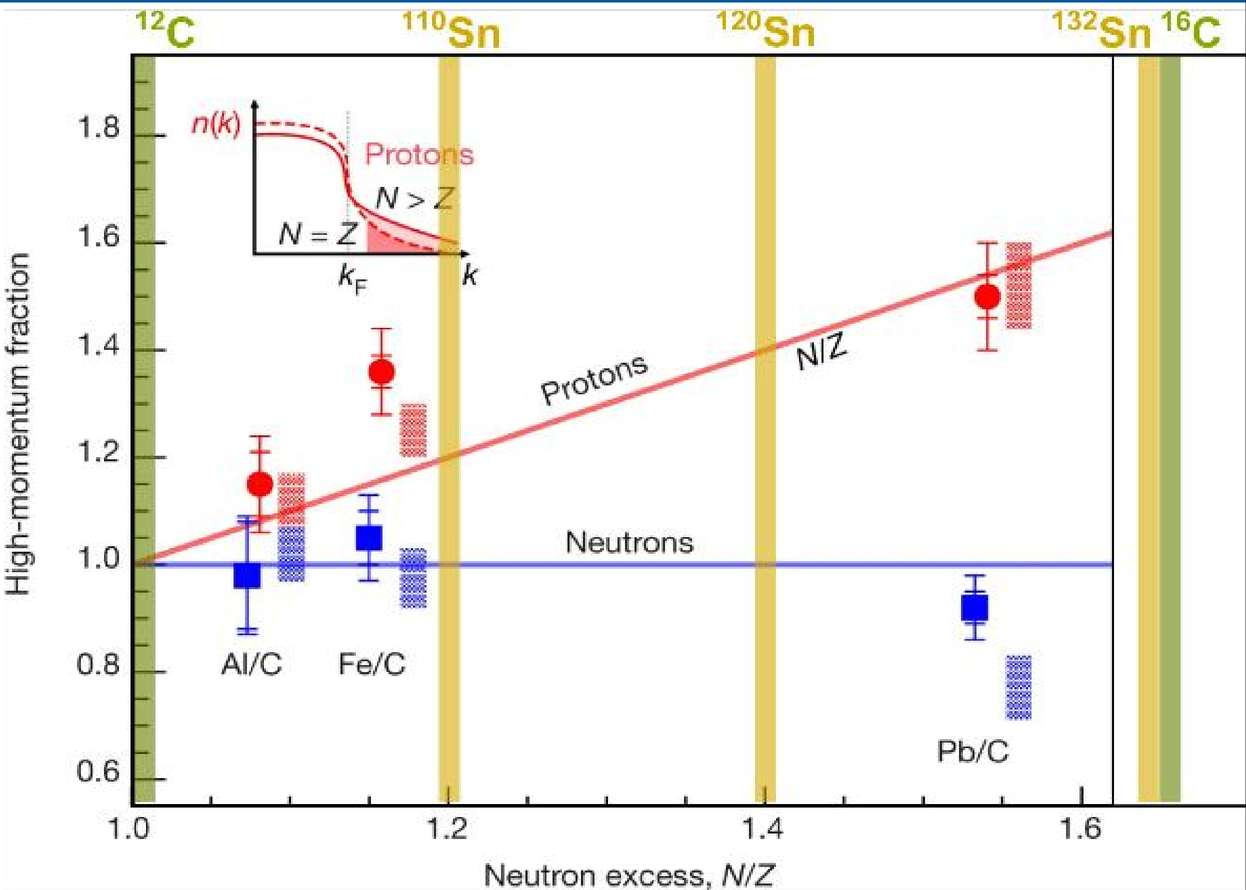


Important for r process

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.

ES and FS: short range correlations

N/Z dependence of
short-range correlations
for light and heavy nuclei.



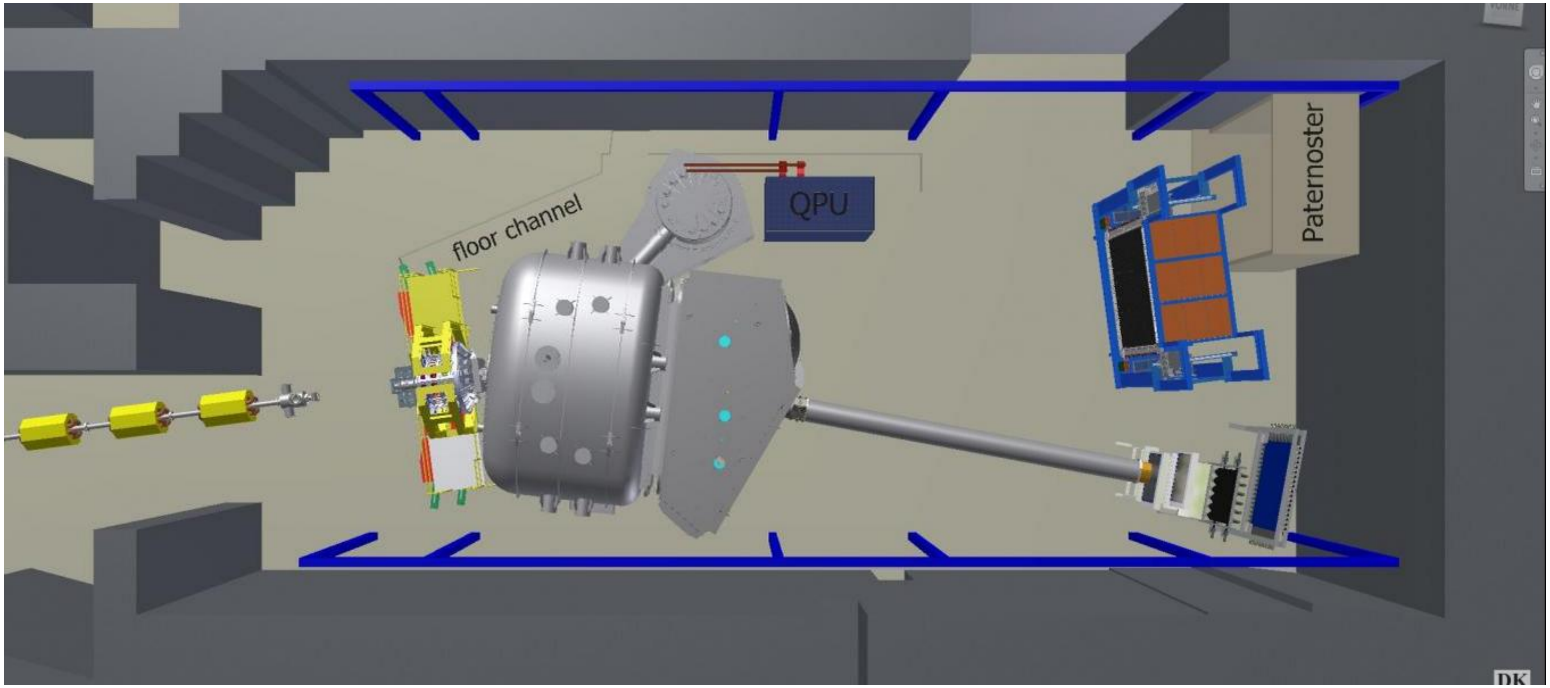
M. Duer et al. (CLAS Collaboration), Nature, 560:617, 2018

Double ratio of high-to-low momentum protons (neutrons) in nucleus A with respect to carbon are marked with dot (squares), and corresponding calculations with rectangles.

Recent Achievements

Modifications in Cave C to accomodate R³B equipment for FAIR Phase-0

- Target area (CALIFA+ LT3)
- GLAD (including Vacuum chamber)
- NeuLAND
- Tracking detectors (beampipe)

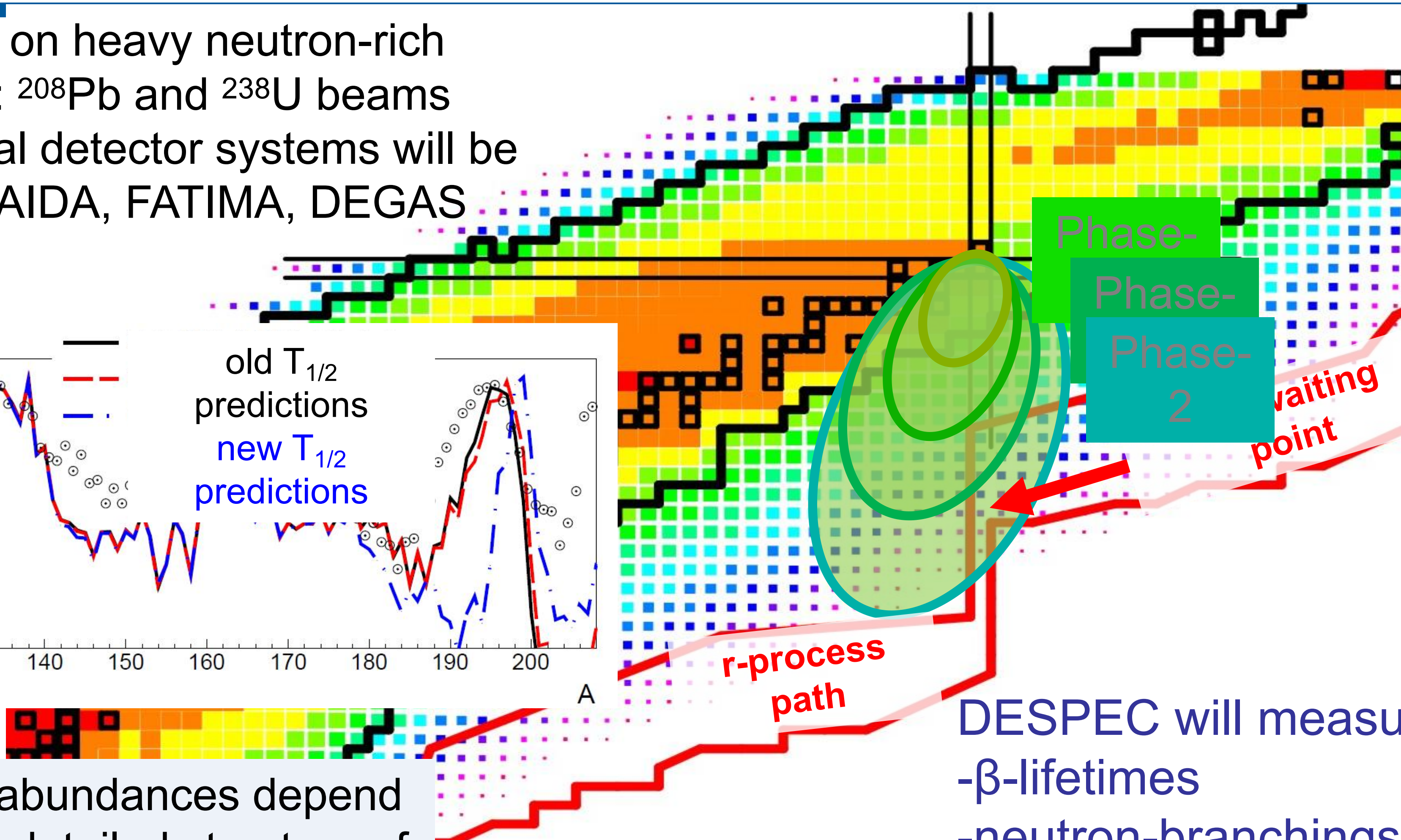


Many experiments approved by GSI-PACs have been running since 2017 with different parts installed.

HISPEC/DESPEC

DESPEC

Focus on heavy neutron-rich nuclei: ^{208}Pb and ^{238}U beams
Several detector systems will be used: AIDA, FATIMA, DEGAS



Mass abundances depend on the detailed structure of N=126 nuclei around the 3rd r-process waiting point

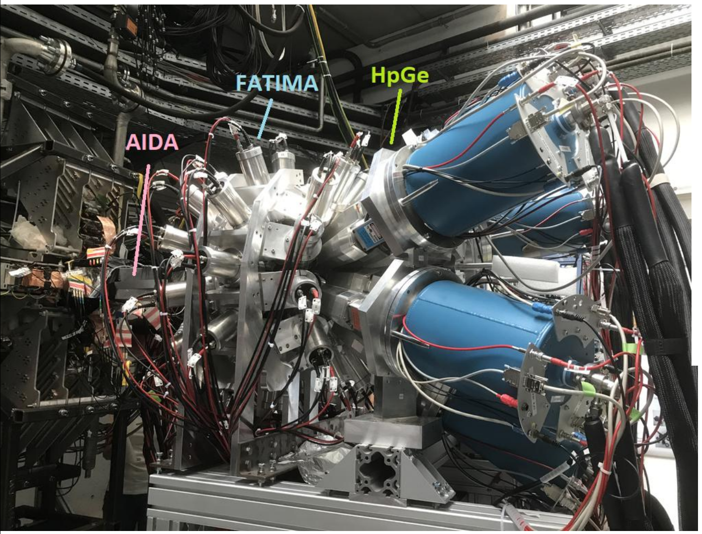
DESPEC will measure:
- β-lifetimes
- neutron-branchings
- strength distributions
- level structure

DESPEC (FAIR Phase-0) campaign at other labs

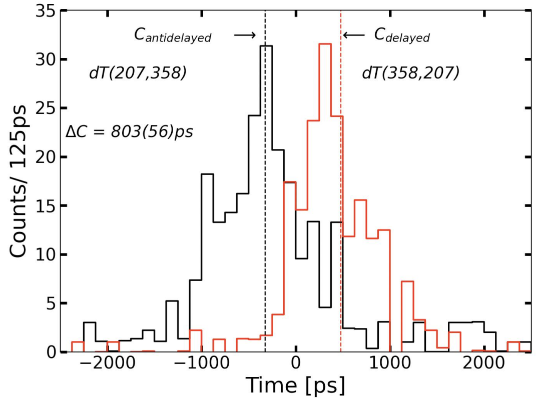
FATIMA fast-timing array in GANIL and Orsay, France

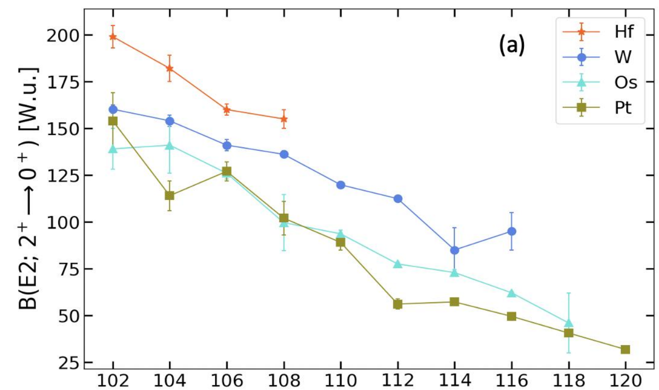
AIDA implantation and decay detector
&
BELEN neutron counter
in RIKEN, Japan

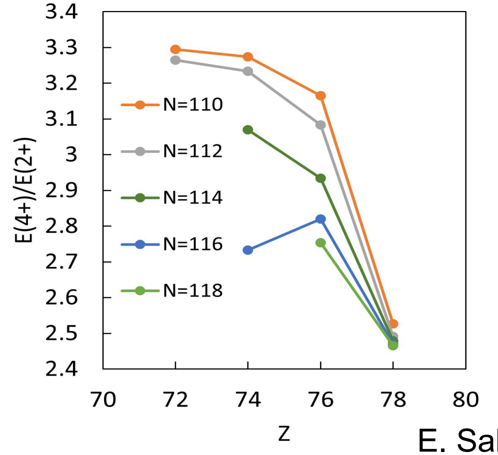
FAIR-0: Prolate-oblate shape transition at $^{190}W_{116}$

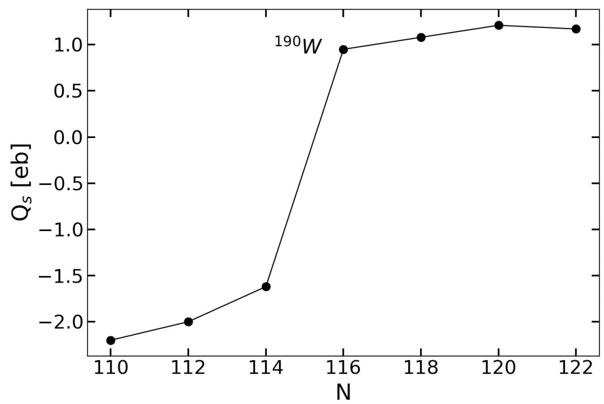


Hybrid array for fast-timing measurements



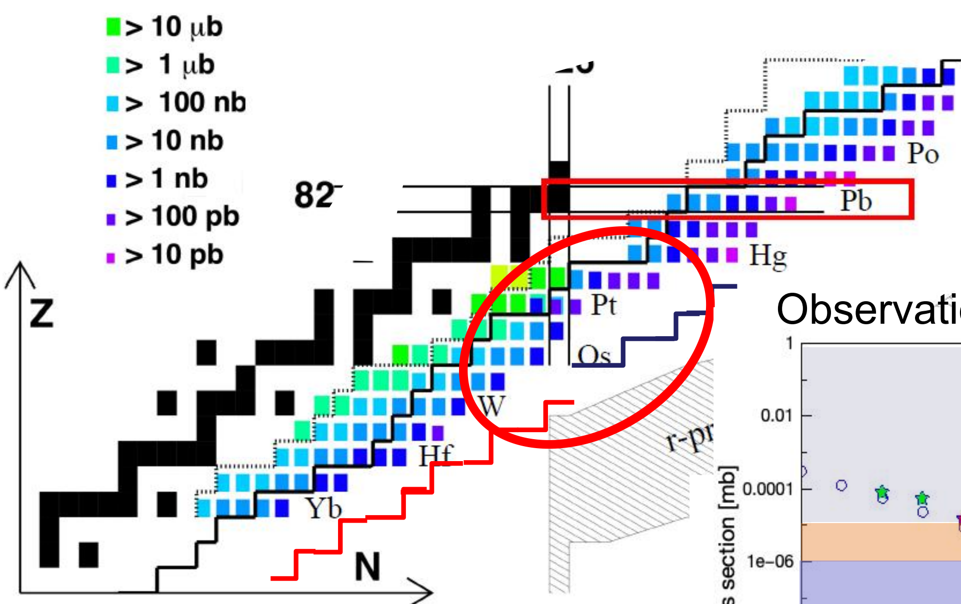






E. Sahin, V. Werner et al., manuscript submitted to PLB

ES and FS:
Structure of N~126 nuclei to elucidate the r-process path



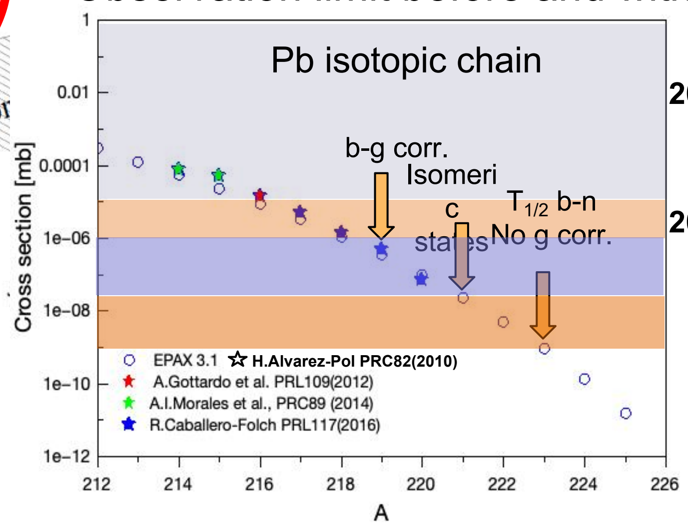
10^{-10} mb limit

10^{-9} mb limit

Evolution of single-particle orbitals
First-forbidden beta decay

=> improved mass and $T_{1/2}$ predictions for the r-process

Observation limit before and with DESPEC



2009 RISING campaign e_g = 16.2%

2022 DESPEC@Phase0 e_g = 21.2%

Early Science

First Science

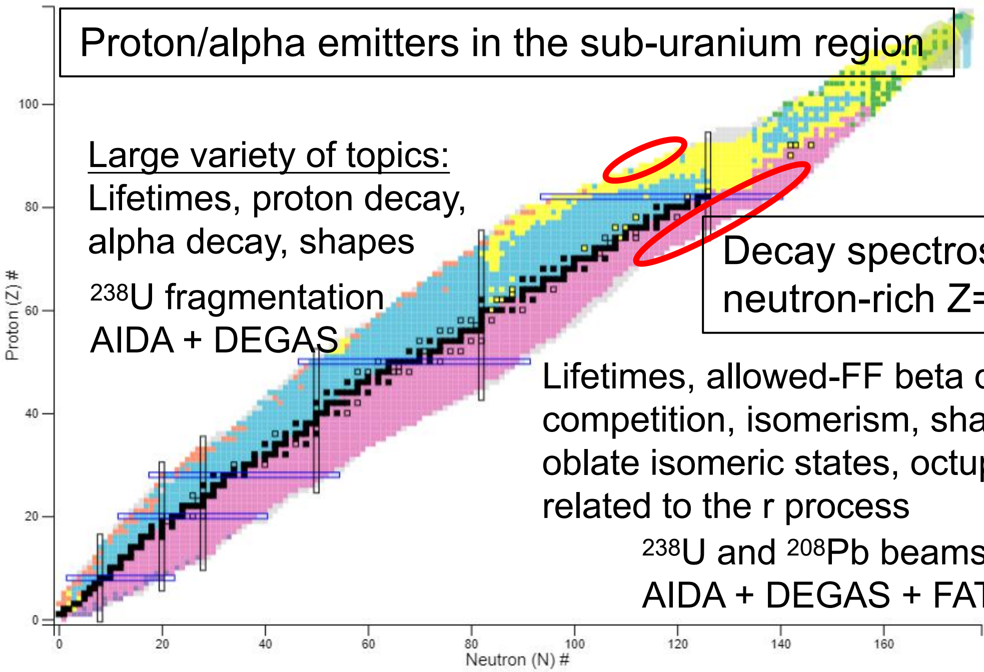
Improved transmission and separation from Super-FRS

Improved g efficiency

Faster DAQ

ES and FS: Summary for DESPEC

- Evolution of the shell structure & exotic nuclear shapes in **uncharted nuclear territory**
- Spectroscopic information for the **nucleosynthesis of heavy nuclei**
- Comprehensive decay information at **beam yields** as low as **one ion per hour**
- Primary focus on **GSI-FAIR uniqueness** for nuclei around **N~126**, while providing **competitive data** on key nuclei also in other regions of the nuclear chart: around ^{100}Sn and ^{132}Sn, rare earth nuclei, …



Proton/alpha emitters in the sub-uranium region

Large variety of topics:
Lifetimes, proton decay, alpha decay, shapes

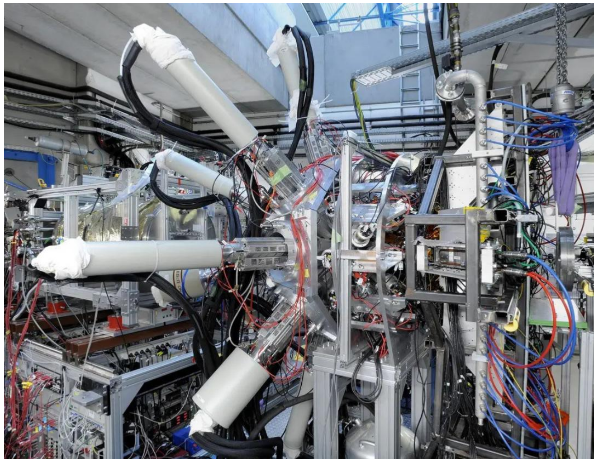
^{238}U fragmentation
AIDA + DEGAS

Decay spectroscopy of neutron-rich Z=64-86 nuclei

Lifetimes, allowed-FF beta decay competition, isomerism, shape evolution oblate isomeric states, octupole collectivity related to the r process

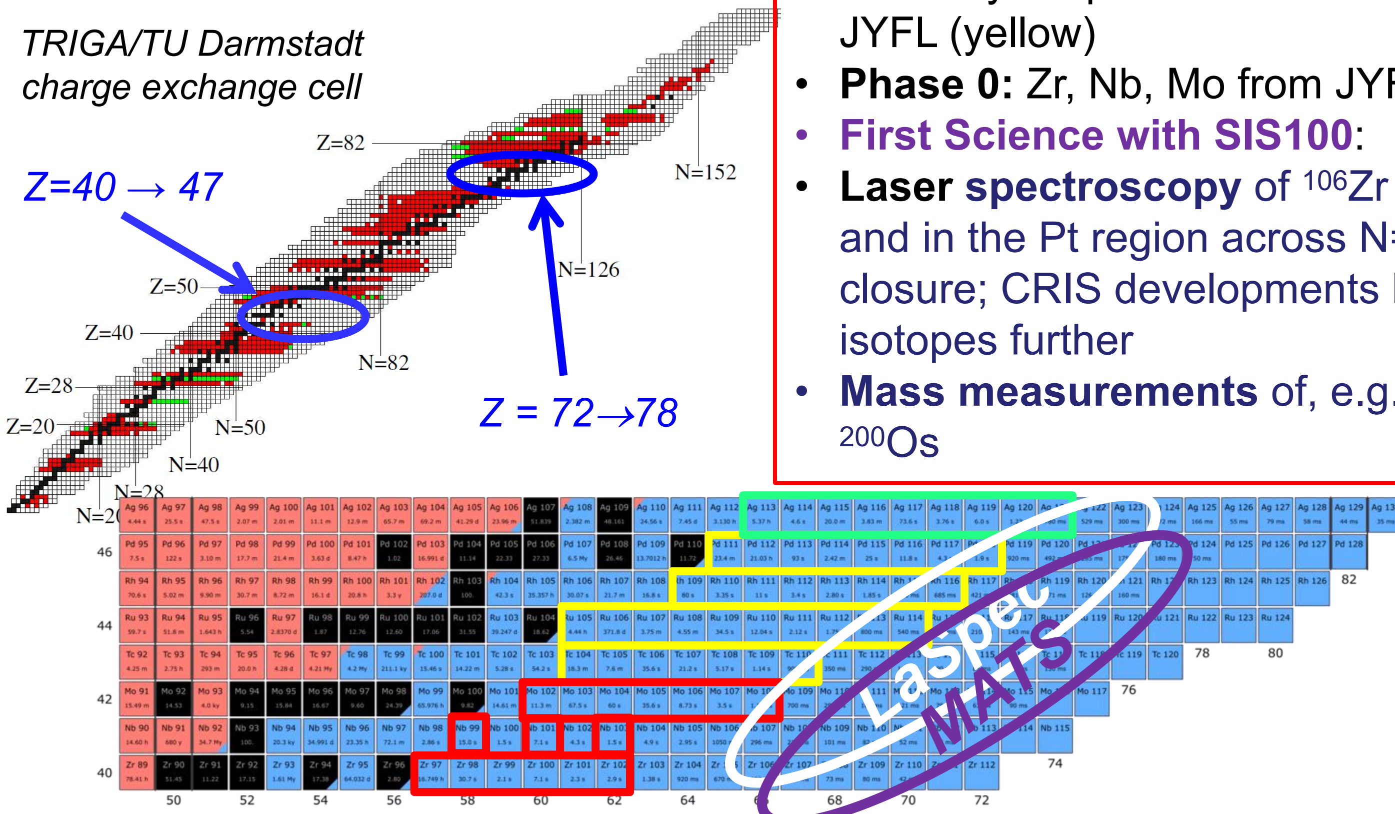
^{238}U and ^{208}Pb beams
AIDA + DEGAS + FATIMA

New Hybrid Ge-LaBr3 array in operation from April 2024



MATS + LaSpec

First Science ++: MATS & LASPEC: Mass and Laser Spectroscopy on refractory elements



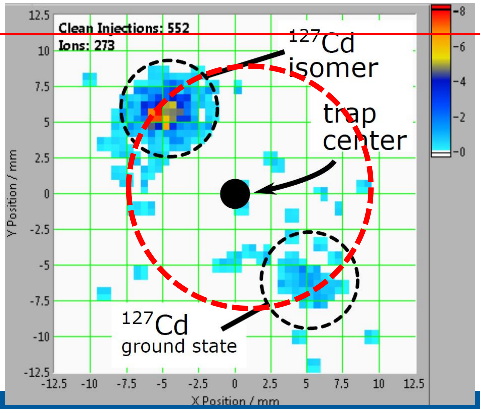
- Spectroscopy on $^{113-121}$Ag at JYFL (green)
- Fission yield predictions >5000 ions/s at JYFL (yellow)
- **Phase 0:** Zr, Nb, Mo from JYFL (red)
- **First Science with SIS100**:
- **Laser spectroscopy** of ^{106}Zr and beyond and in the Pt region across N=126 shell closure; CRIS developments lead to 1-2 isotopes further
- **Mass measurements** of, e.g., ^{110}Zr, ^{126}Pd, ^{200}Os

Needs the low-energy cave

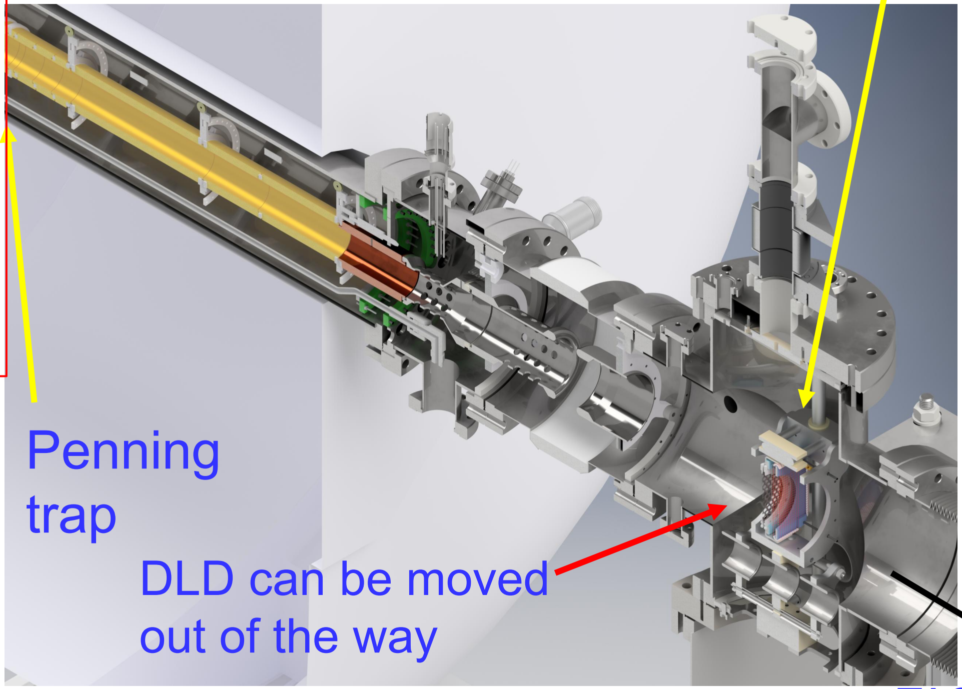
Resolving isomers with ion motional phases in a Penning trap

Demonstration of isomeric cleaning with the novel phase-sensitive PI-ICR technique at JYFLTRAP. Isomerically clean beam of ^{127}Cd provided to post-trap TASISPEC decay setup.

^{127}Cd and ^{127m}Cd: ~280 keV mass difference ($T_{1/2}$ ~300 ms). With 250 ms excitation pattern, a maximal 180° separation achieved. With subsequent excitation, the state of interest is centered while unwanted ones are pushed further out.



Roentdek DLD40 MCP with delay-line anode

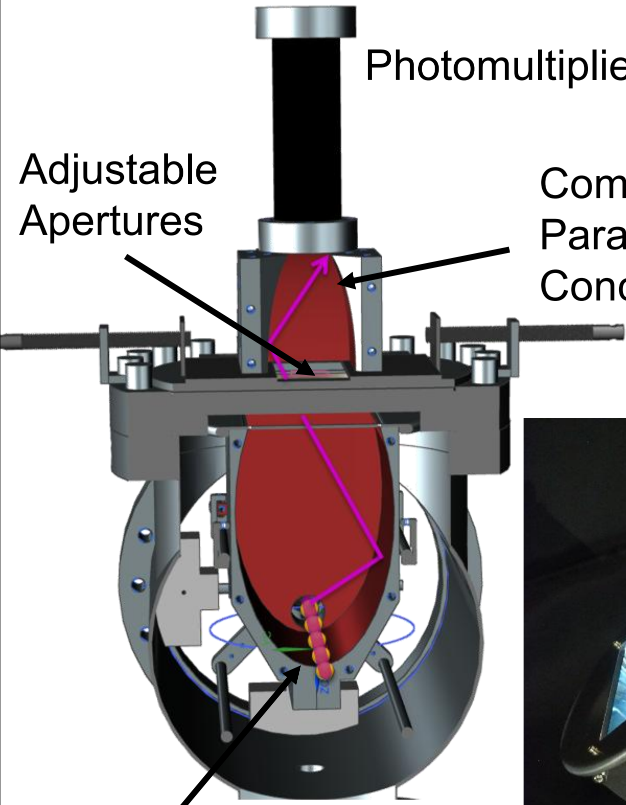


TASISPEC

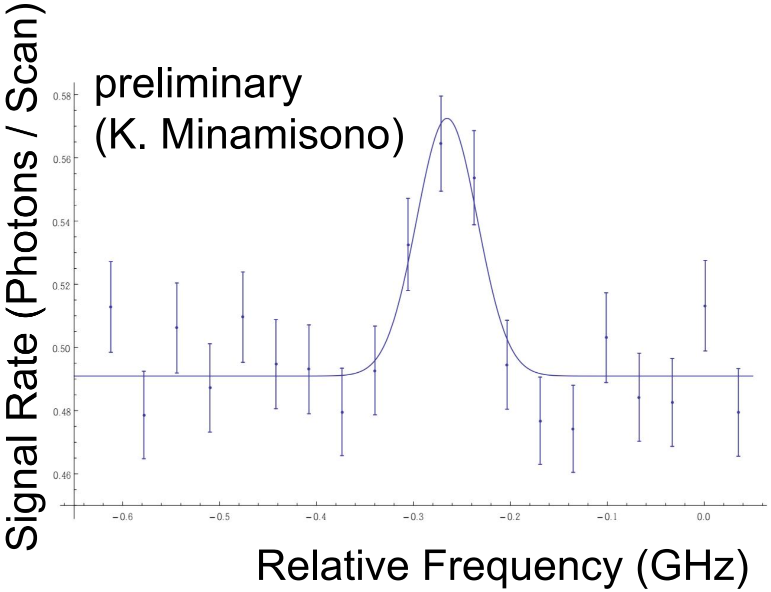
LUND UNIVERSITY

UNIVERSITY OF JYVÄSKYLÄ

First online application of LaSpec's new detection region



Resonance Signal of ^{36}Ca, taken at NSCL

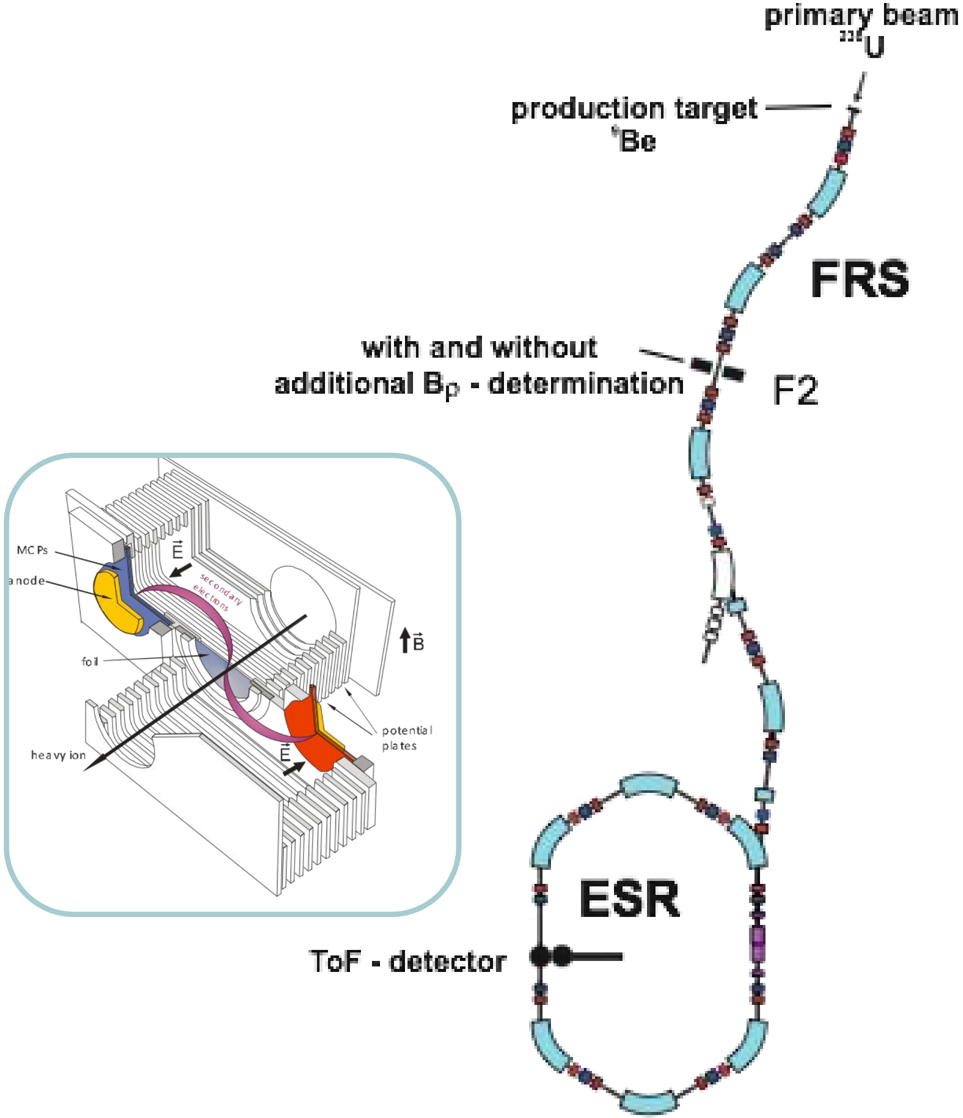


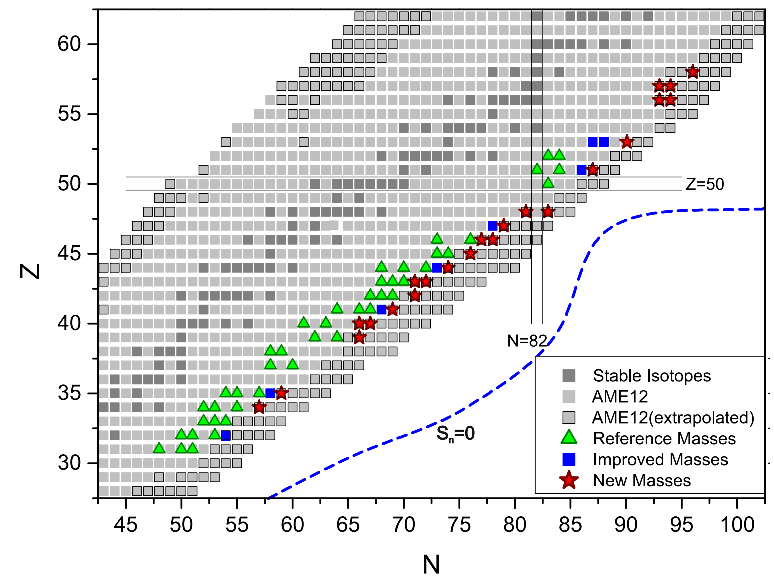
Signal recorded with ≈ 25 ions/sec

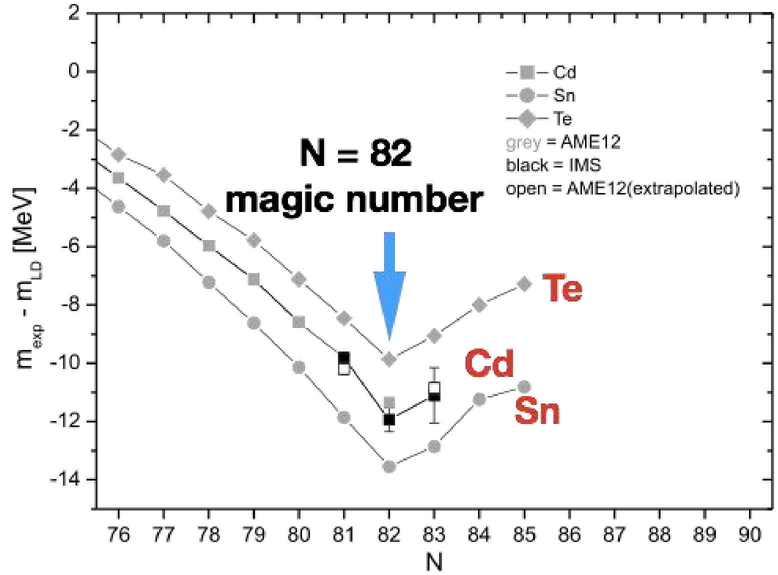
GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung
HIC for FAIR
Helmholtz International Center
SFB 1245
DFG Deutsche Forschungsgemeinschaft

ILIMA

New masses around N=82



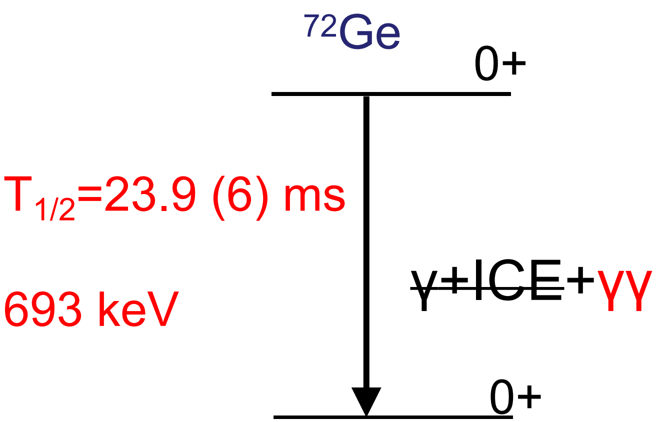


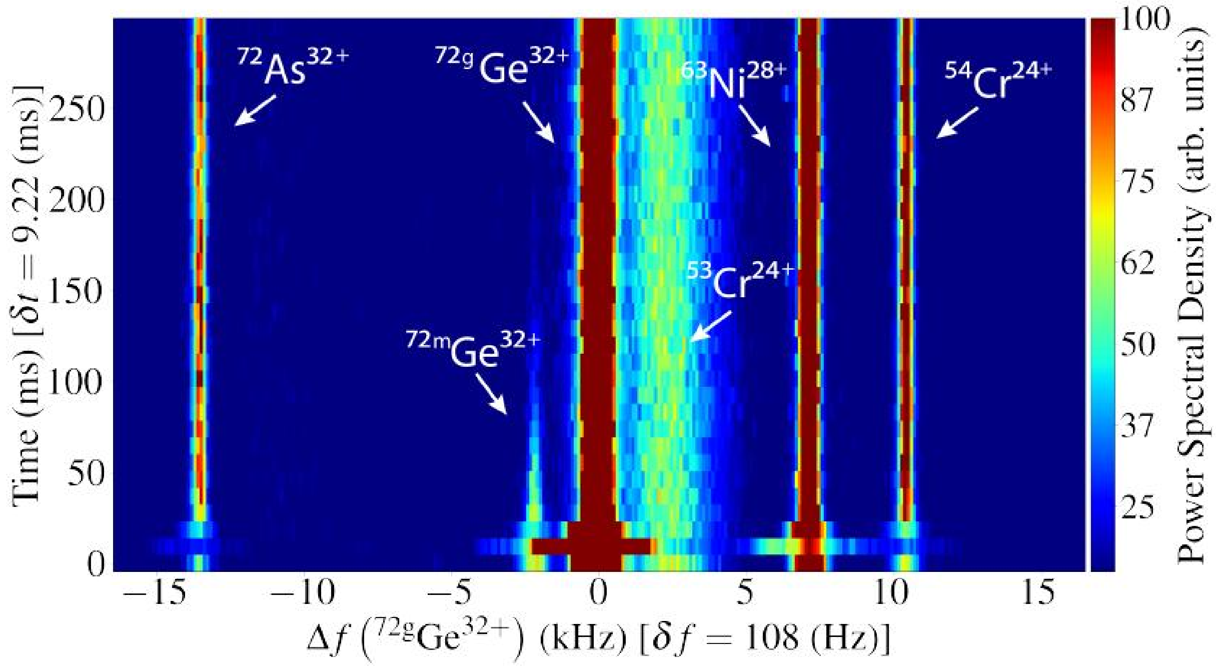


Knöbel et al. EPJ A52 (2016) 138; PLB 754 (2016) 288

FAIR Phase-0: Two-phonon decay
Combined Schottky + Isochronous Mass Spectromet

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





Excitation energies down to ~ 100 keV
and half-lives as short as ~ 10 ms

D. Freire-Fernandez, W. Korten et al.
arXiv:2312.11313v1

Next exp. (^{98}Mo and ^{98}Zr) in May 2024

ES and FS: ILIMA
Continuation at the ESR and Cryring

Isochronous mass measurements

- Neutron-rich heavy nuclei
  - Recently-developed **Schottky detection in isochronous optics**
  - Fast measurement with high resolution (10^{-6}) → access to extremely short-lived nuclei (few 10ms)
- Beta-delayed neutron probabilities
  - Neutron-rich iodine isotopes (proof of principle)

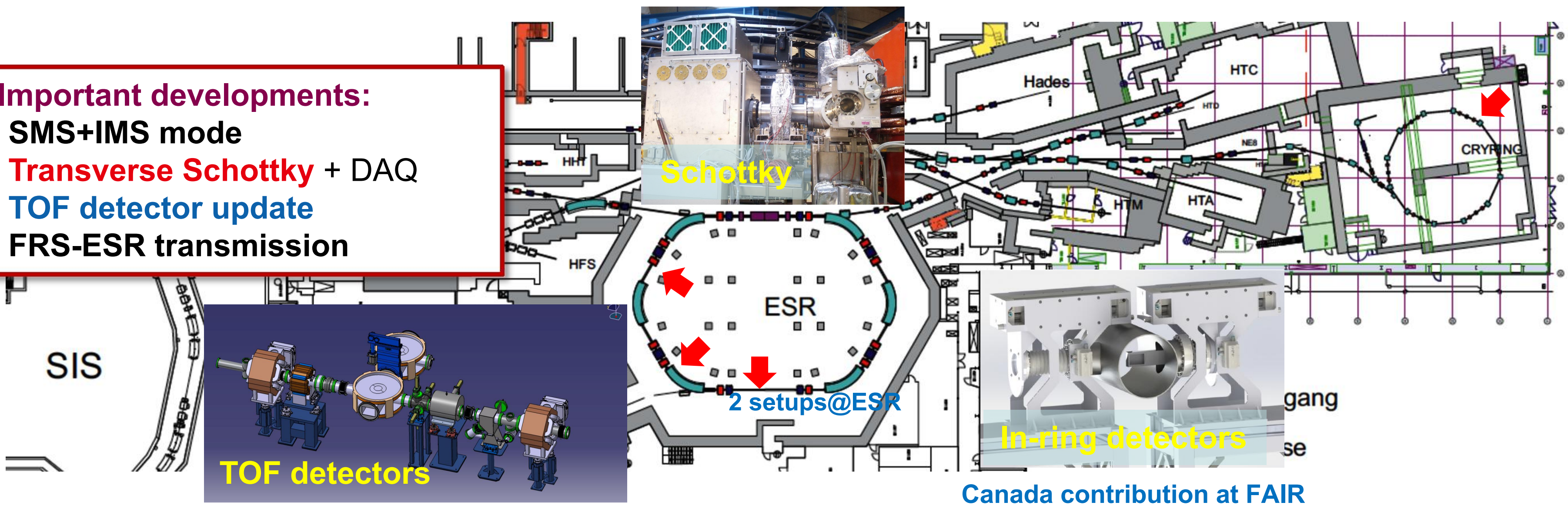
Investigations of exotic radioactive decays

- Hyperfine-resolved electron capture decays
  - ^{111}Sn few electron system becomes allowed or forbidden decay
- NEEC (Nuclear excitation by electron capture)

In cooperation with SPARC!

Important developments:

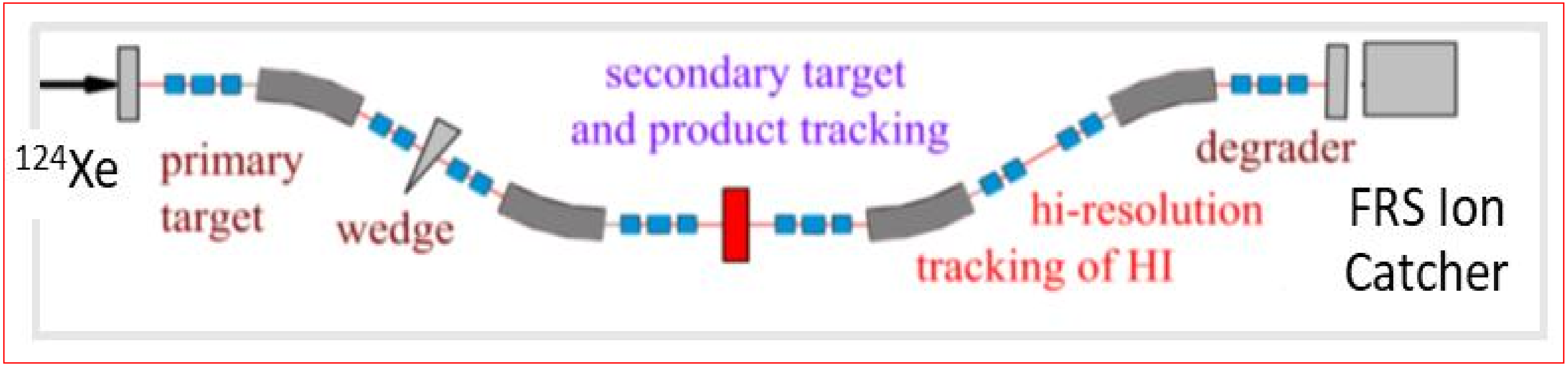
- **SMS+IMS mode**
- **Transverse Schottky** + DAQ
- **TOF detector update**
- **FRS-ESR transmission**



Canada contribution at FAIR

Super-FRS

EXPERT Layout at FRS

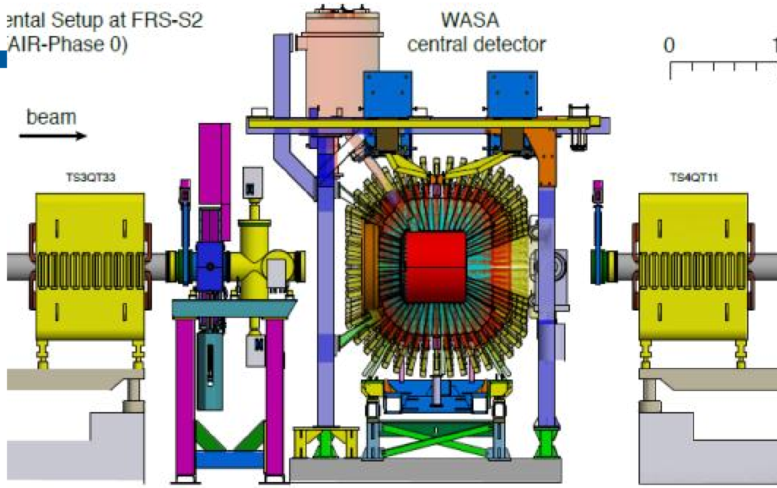


Secondary reactions

$^{70}\mathrm{Br} \rightarrow {}^{69}\mathrm{Br} \rightarrow {}^{68}\mathrm{Se}+p$

$^{74}\mathrm{Rb} \rightarrow {}^{73}\mathrm{Br} \rightarrow {}^{72}\mathrm{Kr}+p$

WASA@FAIR (installed first at FRS-S2)

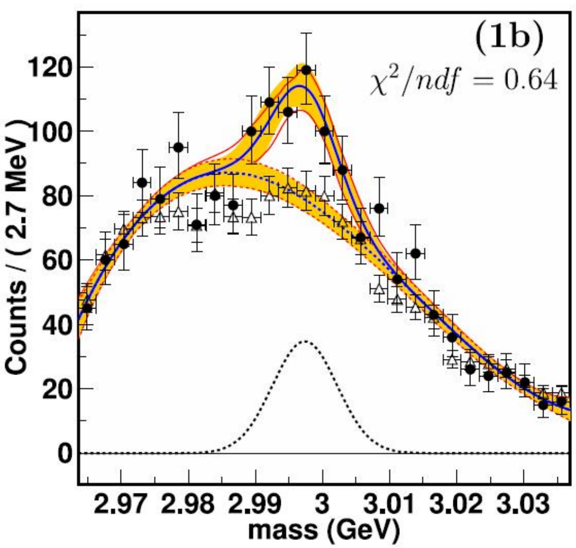


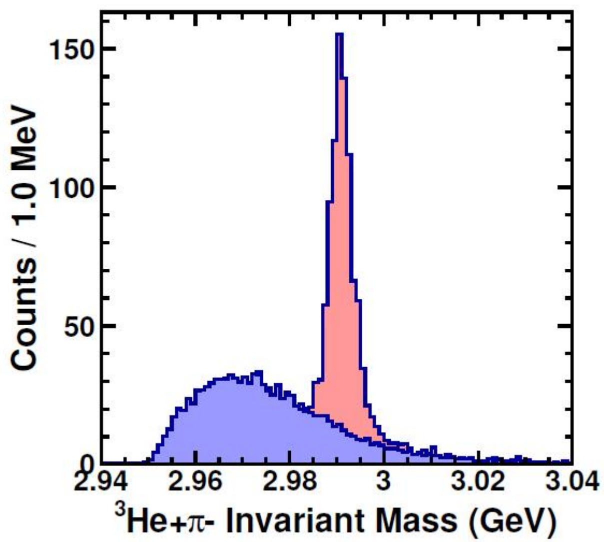
Combination of WASA with FRS provides unique setup for exclusive measurements:

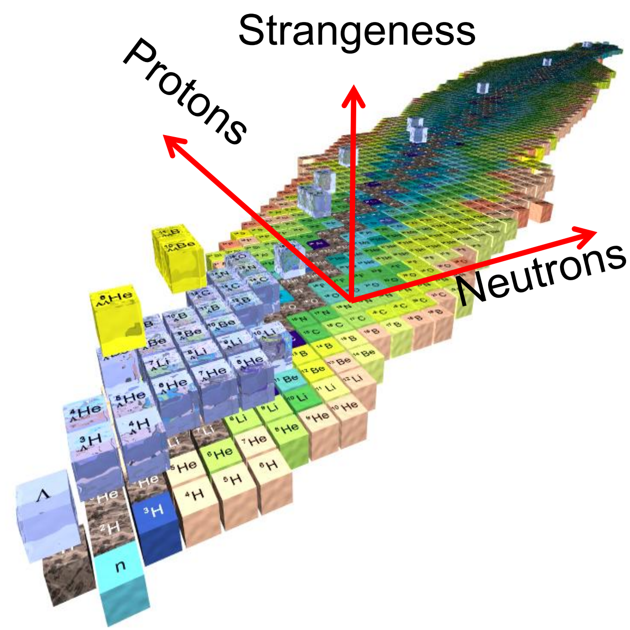
- FRS for high resolution spectroscopy of forward particles
- WASA for decay particles

<u>Hypernuclei:</u>

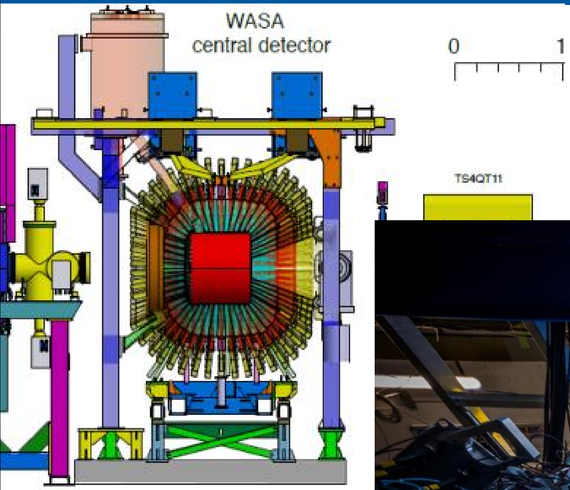
Goals: Short lifetime of $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$
Solve puzzle of nnΛ state

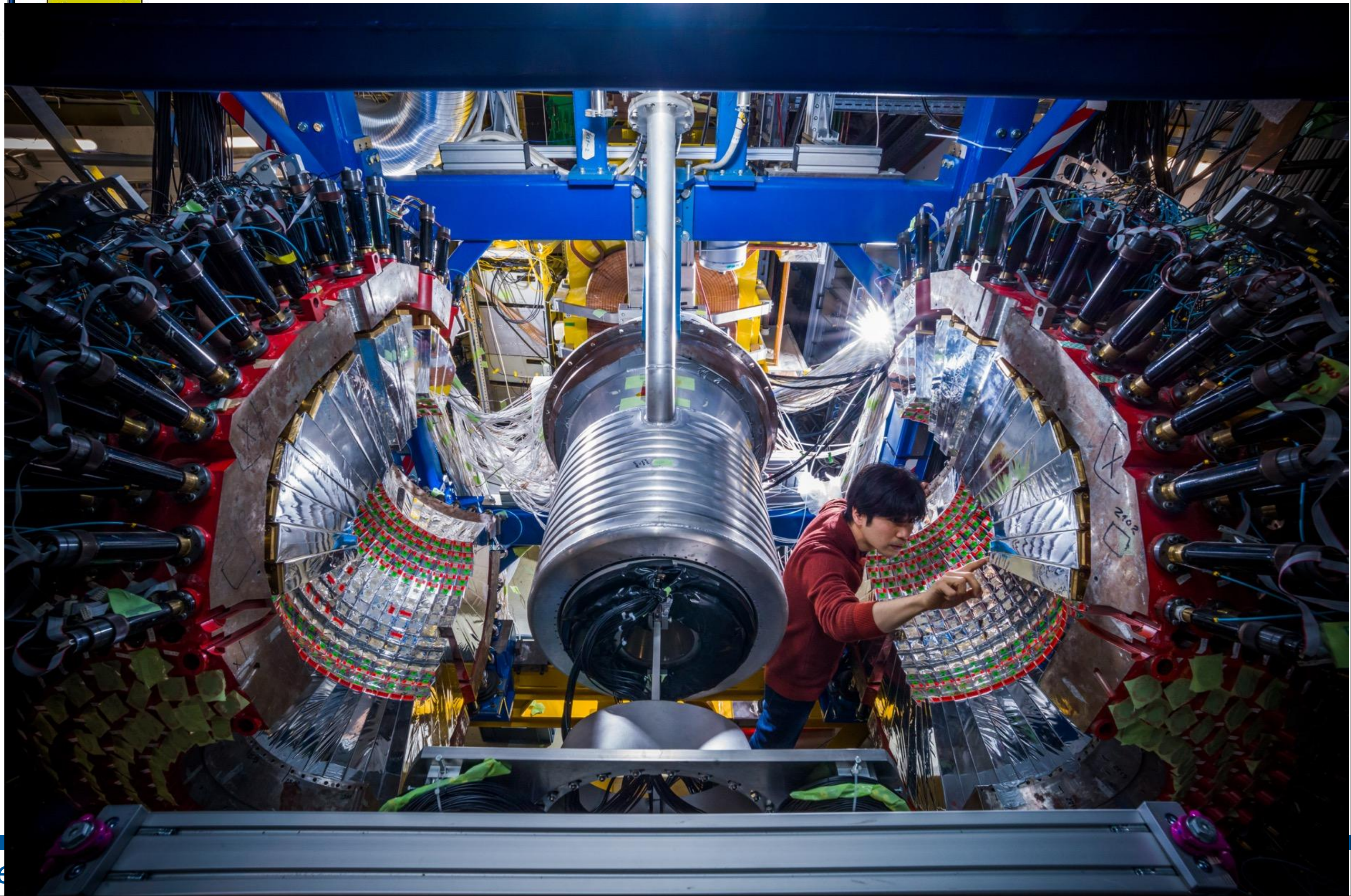




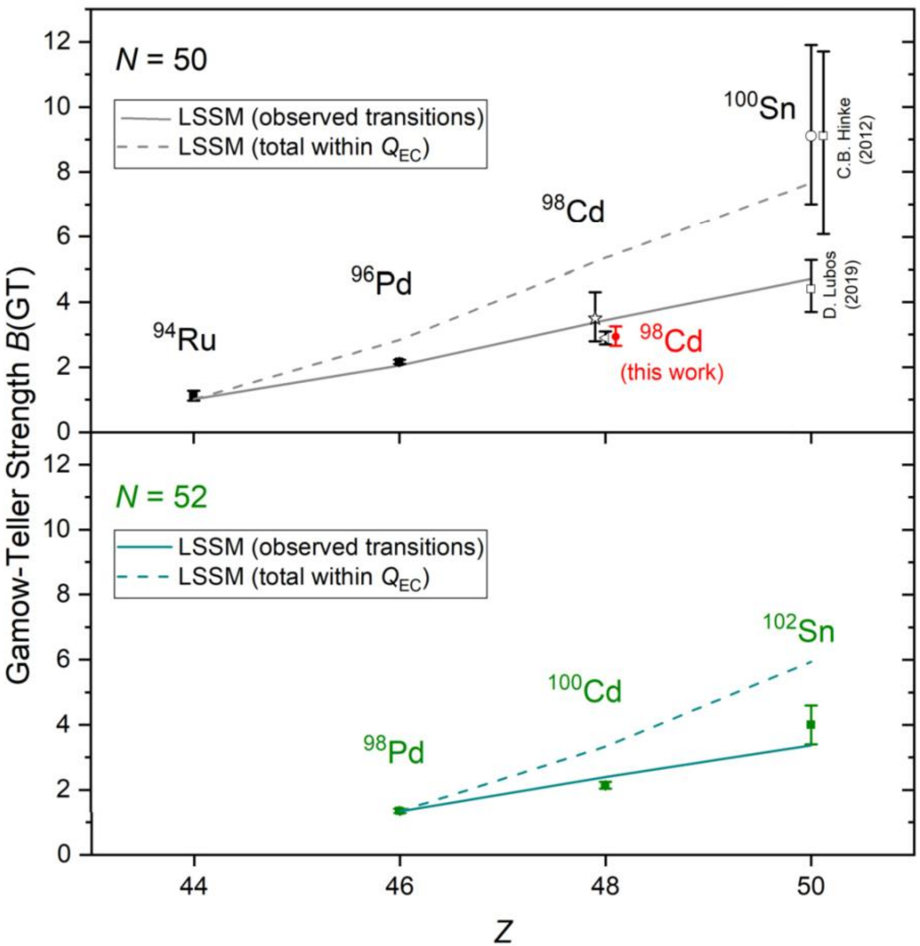


WASA@FAIR (installed first at FRS-S2)





FAIR-0: Gamow-Teller Strength at N=50 and the puzzle of ^{100}Sn mass



A. Mollaebrahimi et al., Phys.Lett. B 839, 137833 (2023)

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

^{100}Sn mass:

New results in 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 ^{101}In and published ^{100}Sn Q_{EC} values 99-
  → 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 Gamow-Teller Strength at N=50:
  → *v*alue of Lubos et al. [2] is favored.

Overall situation unclear, further experiments required.

*[1] C.Hinke et al., Nature **486** (2012) 341*
*[2] D.Lubos at al., PRL **122** (2019) 222502*
*[3] M.Mougeot et al., Nature Phys. **17** (2021) 1099*

Quasi-real-time range monitoring in hadron therapy using positron emitters of carbon and oxygen

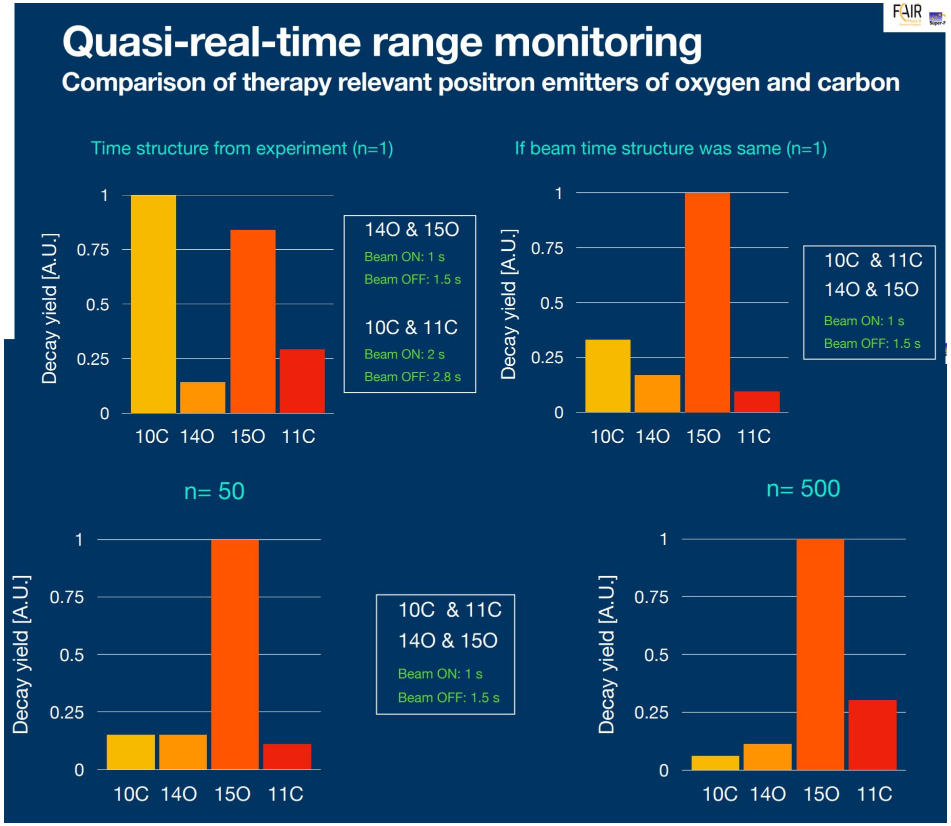
Best candidate?

^{16}O beam -> ^{15}O 43 mb 122 s

^{14}O 1.2 mb 71s

^{12}C beam -> ^{11}C 47 mb 1221 s

^{10}C 4.3 mb 19 s

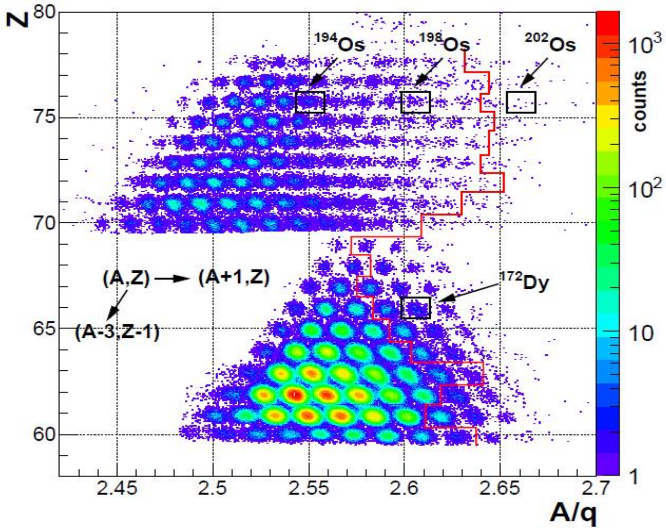


Sivaji Purushothaman et al., Sci Rep 13, 18788 (2023)
Quasi-real-time range monitoring by in-beam PET:
a case for ^{15}O

BIOMAT

(also hadron therapy with ^{11}C on mouse in Feb. 2024)

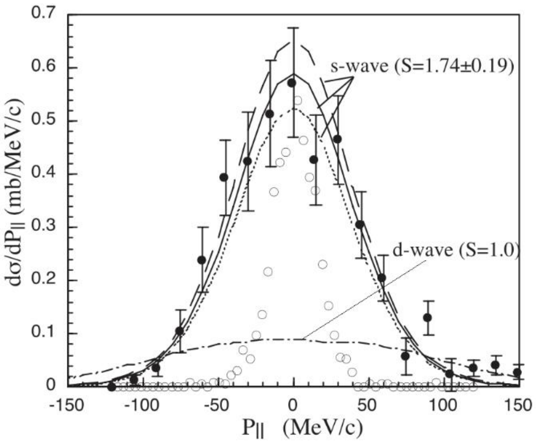
ES and FS: new isotopes, radii and momentum distributions



Search for new isotopes

Longitudinal momentum distribution $P_{||}$

→ Evolution of nucleon orbitals, evolution of shell structure, spectroscopic information for *r*-process



Reaction cross section (σ_R) → matter radius

Charge changing cross section (σ_{CC}) → proton

→Identifying skins (or halos) in heavy nuclei, test of models

Neutron skin systematics

→ EoS of asymmetric nuclear matter

ES, FS: focus on N~82, 126 in heavy neutron-rich nuclei

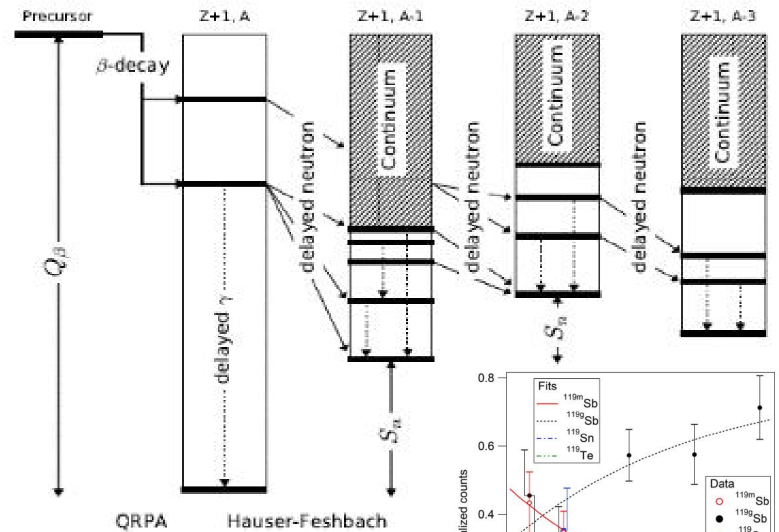
ES and FS: Beta-delayed single- and multiple-neutron emission probabilities (P_{xn})

Important for:

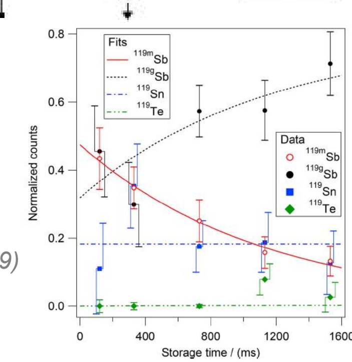
- r-process nucleosynthesis
- nuclear structure
- nuclear reactor safety

Novel method for measuring $\mathbf{P_{xn}}$, simultaneously with **mass**, $\mathbf{Q_{bxn}}$, $\mathbf{S_{xn}}$ and $\mathbf{T_{1/2}}$

Complementary to worldwide programs, especially suited for **multi-neutron** emission

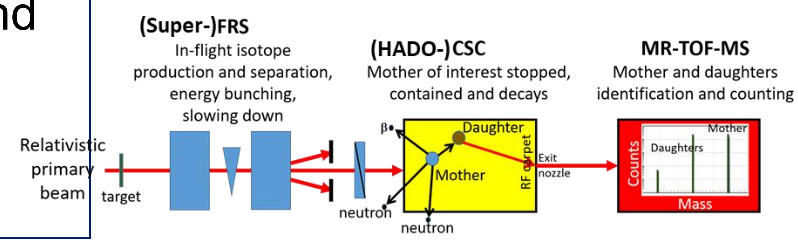


EPJA 55, 148 (2019)



Enhanced transmission and separation of Super-FRS + new CSC increases P_{2n} sensitivity by **more than 2 orders of magnitude(!)**, while reducing background by order(s) of magnitude

→ ≈30…40 P_{2n} measurements expected during Early Science



FS: MNT reaction studies with radioactive beams

SHE

Superheavy elements: “Island of Enhanced Stability”

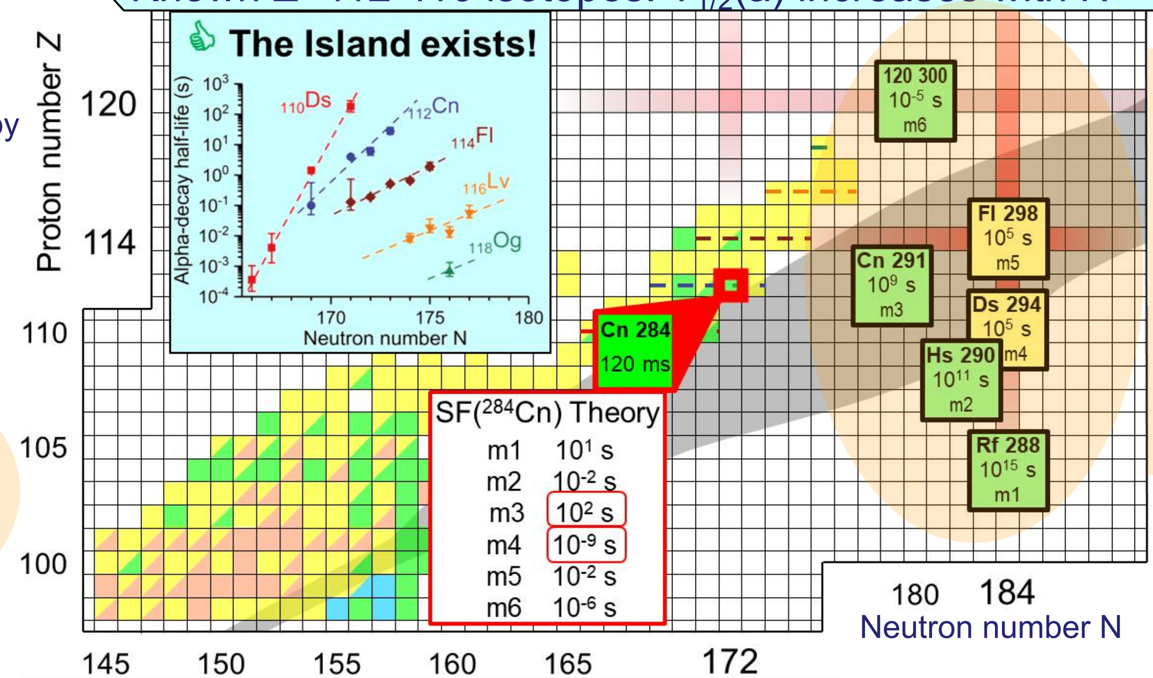
See Next Talk

Message ❶:
Known Z=112-116 isotopes: $T_{1/2}$(a) increases with N

b-stability line
Often predicted spherical shells

Known nuclei decaying by
- a-decay
- b⁻-decay
- b⁺/EC-decay
- SF

Predicted longest-lived nuclei decaying by
- a-decay
- b⁻-decay



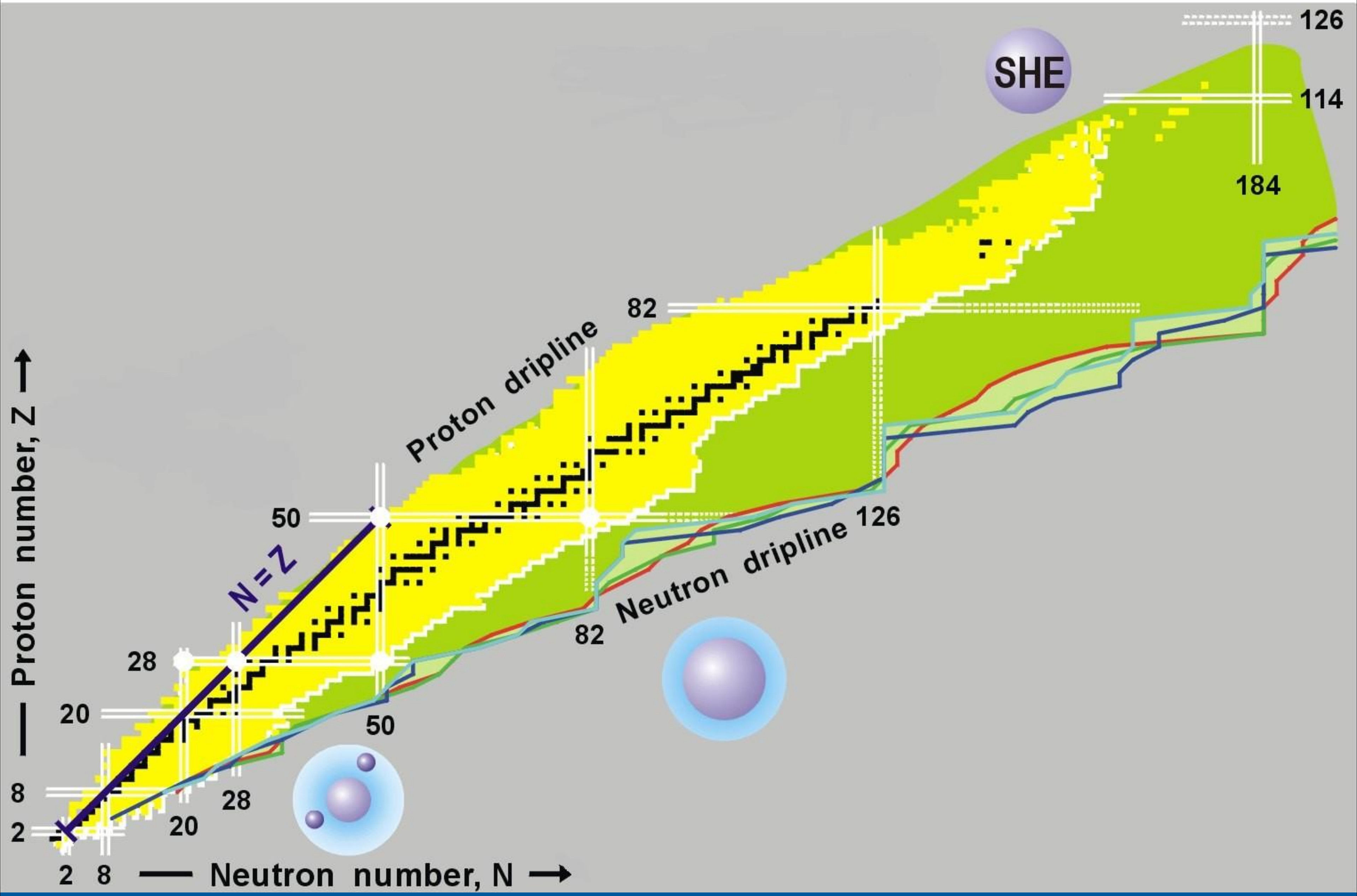
Message ❷:

Predictions from six models (m1-m6) on longest-lived nuclide differ massively in
- Z and A
- its half-life
- its decay mode

O. Smits, Ch.E.Düllmann et al.
Nat. Rev. Phys. 6 (2024) 86

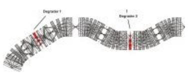
Message ❸:
Theory differs by 11 orders in describing $T_{1/2}$ of known ^{284}Cn

Snapshot of the nuclear landscape

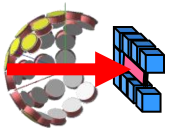


Complementarity of NUSTAR experiments

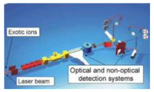
Super-FRS



HISPEC/ DESPEC

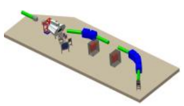


LASPEC

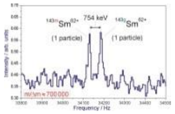


MATS

R3B

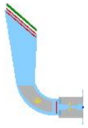


ILIMA



SHE

ELISE



EXL

	Super-FRS	HISPEC/DESPEC	LASPEC	MATS	R3B	ILIMA	SHE	ELISe	EXL
Masses	Precision meas.	Q-values, isomers		dressed ions, highest precision	unbound nuclei	bare ions, mapping study	precision mass of SHEs		
Half-lives	ps...ns-range	dressed ions, μs...s			resonance width, decay up to 100ns	bare ions, ms…years	μs...days		
Matter radii	interaction x-section				interaction x-section				matter densitiy 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 and tensor	evolution of shell closures, pairing corr.	shell structure of SHEs		low momentum transfers
Collective behavior		electromag. transitions	quadrupole moments	halo structure	dipole response	changes in deformation		electromag. transitions	monopole resonance
EoS					polarizability, neutron skin			neutron skin →	neturon skin, Compressibility
Exotic Systems	bound mesons, hypernuclei, nucleon res.								

Thank you!

Conclusions

NUSTAR is ready to GO!

Phase 0 at GSI experiments approved for 2018-19 and 2020-2022

R^{3}B, DESPEC, ILIMA, SuperFRS, EXL, SHE experiments at GSI

Phase 0 MATS, LaSpec experiments at Argonne, Jyväskylä etc.

Day 1:

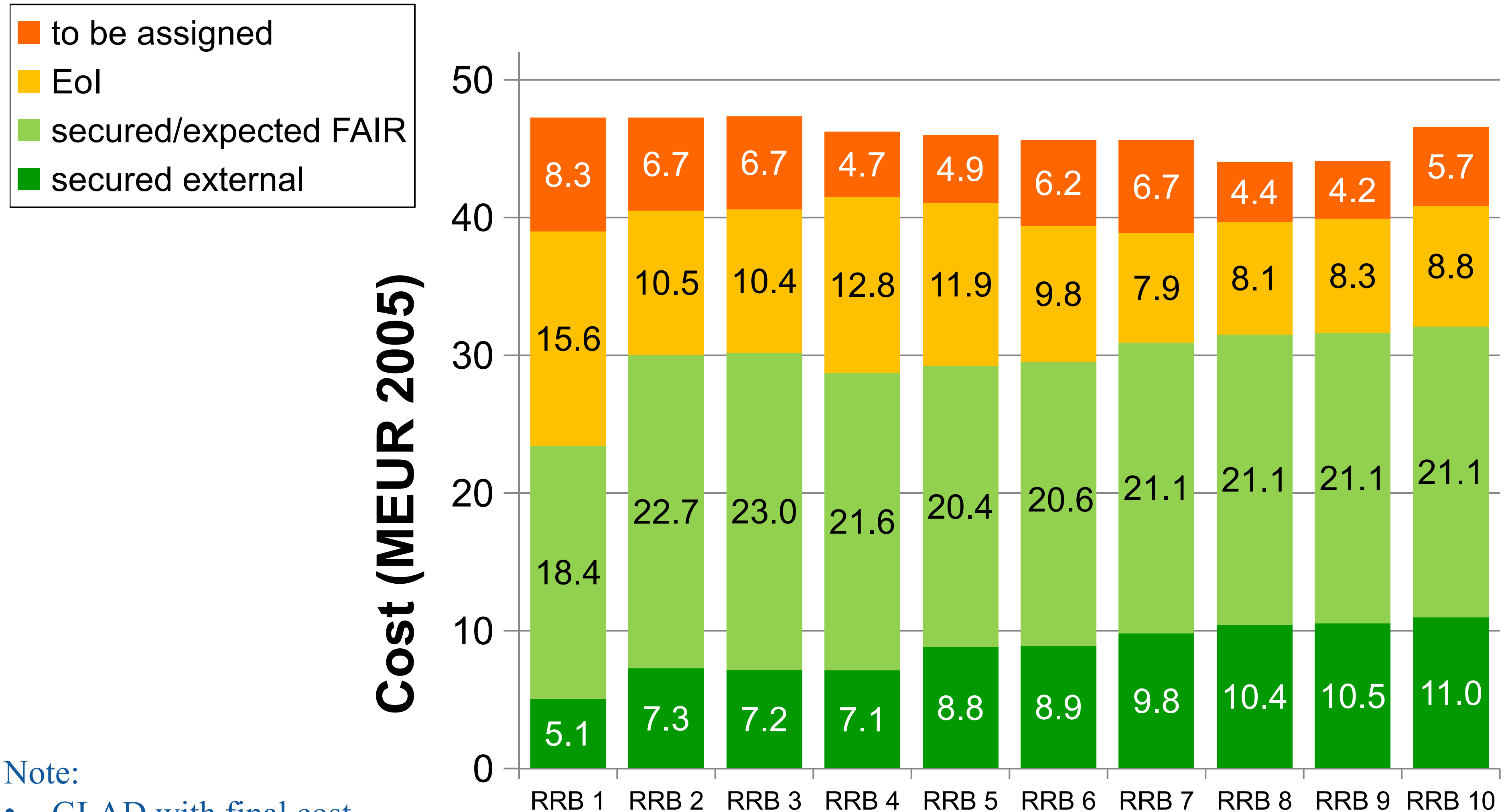
higher beam intensities (more exotic nuclei)
higher energies: high-energy reactions, ‘exotics’

Phase 1: Starts with “Early Start” and ends with reaching the design goals.

Physics case based on uniqueness/strengths of FAIR

Funding

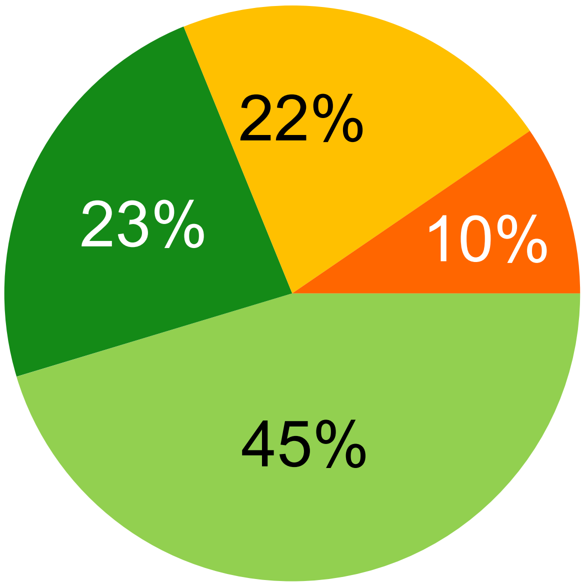
Evolution of NUSTAR project funding



Note:
- GLAD with final cost
- UK included in FAIR

NUSTAR MSV – funding status

46.5 MEUR



- secured/expected FAIR
- secured external
- EoI
- to be assigned

- funding (secured and expected) from: (**FAIR funding** in bold face)

- Australia
- Belgium
- Bulgaria
- Canada
- China
- Czech Republic
- **Finland**
- **France**
- **Germany**
- Hungary
- **India**
- Israel
- Japan
- Netherlands
- **Poland**
- **Romania**
- **Russia**
- Slovenia
- Spain
- **Sweden**
- Turkey
- **United Kingdom**

Status: March, 2021

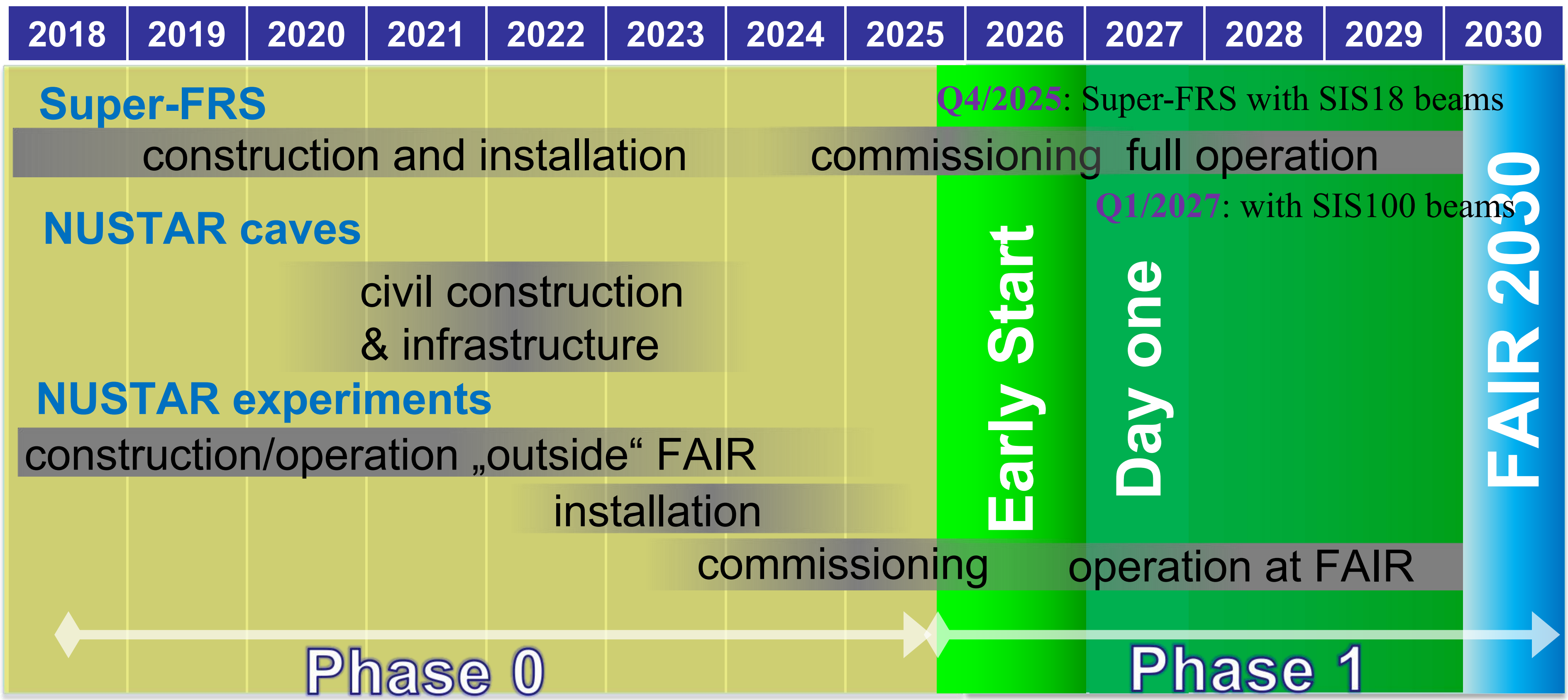
NUSTAR experiment funding (**Day one**)

	NUSTAR sub-system	TDR	Cost [k€ 2005]	Funding	Construction	Date completion	Test/ Commissioning
Day 1	LEB infrastr.		2,109			07/2025	
	HISPEC/DESPEC		10,781			09/2024	
	MATS		1,173			08/2024	
	LaSpec		253			05/2024	
	R3B		17,800			07/2024	
	ILIMA		1,101			07/2025	
	Super-FRS Exp		398			12/2023	
		91.1% *value weighted*	33,615	93.4% *secured*	59.9% *value weighted*		43.9% *value weighted*
Change since report 2021-I		**0.0%**	**0.0**	**0.0%**	**+ 0.3%**		**+ 1.6%**

Status: March 2021

Timeline

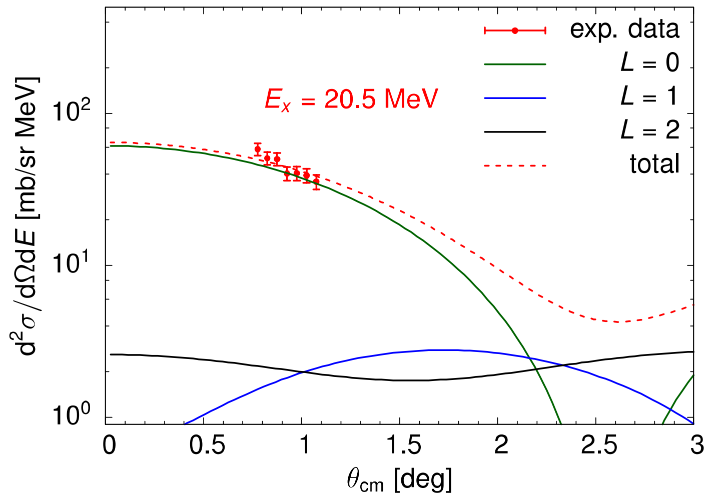
NUSTAR Overall schedule: From Phase-0 to FAIR MSV

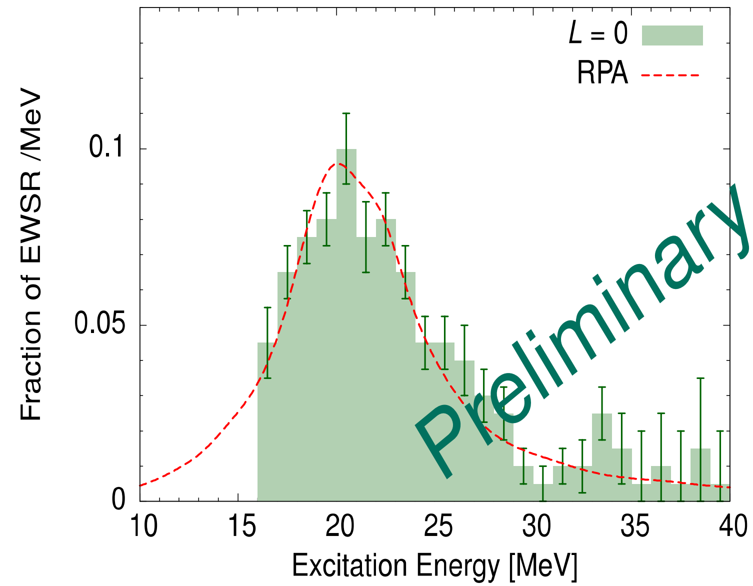


EXL

Recent highlight: Inelastic alpha scattering off ^{58}Ni (100 MeV/u)

Giant Monopole Resonance of ^{58}Ni





First ExL pilot experiment at ESR sets the world records:

- Lowest c.m. angle measured in inverse kinematics
- Most accurate extraction of monopole strength in inverse kinematics

With only one detector !!!

centroid [MeV]	EWSR [%]	
20.5(6)	79^{+12}_{-11}	present data
$21.5^{+3.0}_{-0.3}$	74^{+22}_{-12}	PRC **61**, 067307 (2000)
$20.8^{+0.9}_{-0.3}$	85^{+13}_{-10}	PRC **73**, 014314 (2006)
21.1	94	RPA calculation [4]

[4] G. Colò et al, Comput. Phys. Commun. 184 (2013)

Published Oct. 2016: J.C. Zamora et al., Phys. Lett. B 763 (2016) 16

ExL Phase 0 program (2018/19)

Giant Monopole Resonance of ^{56}Ni

Upgrade of detection system:

- Three more detectors plus new readout
- Closer geometry
- Detection system for recoil

➔ Increase of solid angle substantially

➔ Further reduced background

➔ First measurement of the Giant Monopole Resonance in an unstable nucleus will be possible already in 2018!