

# Exploring the extremes with NUSTAR @ FAIR

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**NUSTAR week**

Ljubljana, Slovenia, September 27, 2017



Finland



France



Germany



India



Poland



Romania



Russia



Slovenia



Sweden



UK



# NUclear STtructure Astrophysics and Reactions

## How are complex nuclei built from their basic constituents?

- What is the effective nucleon-nucleon interaction and how does QCD constrain its parameters?
- How does the three-nucleon force modify the picture?

## How does the effective 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 from stability?
- How does the role of N-N correlations in nuclei and nuclear matter change with isospin?

## How to explain collective phenomena from individual motion?

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

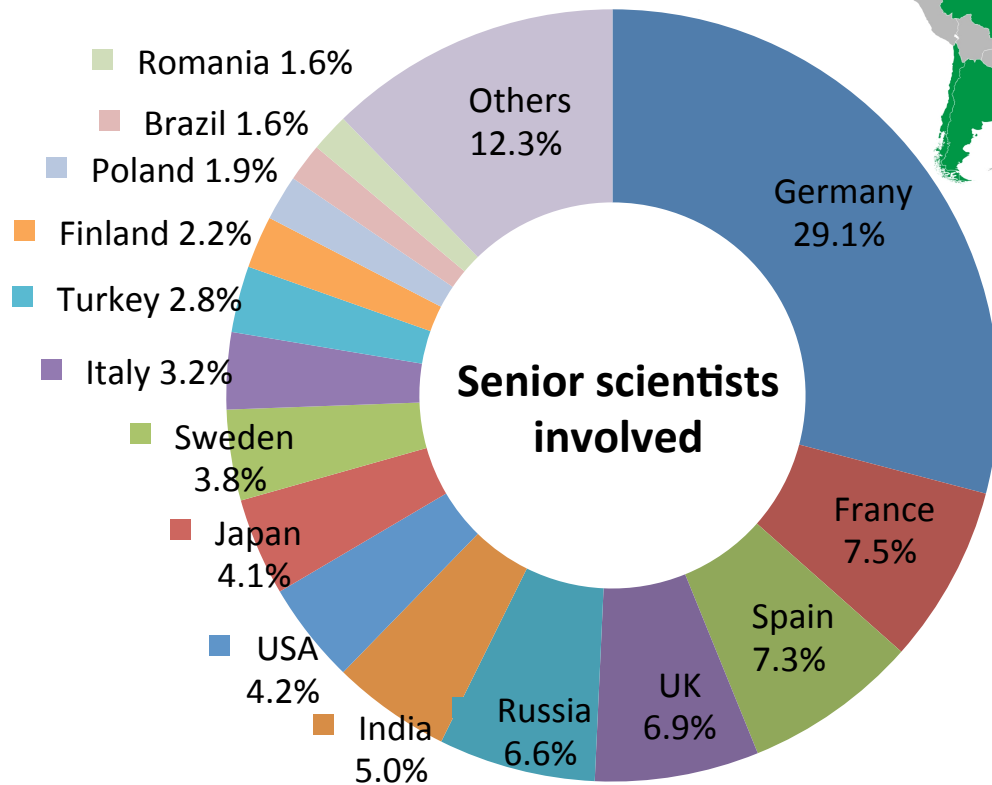
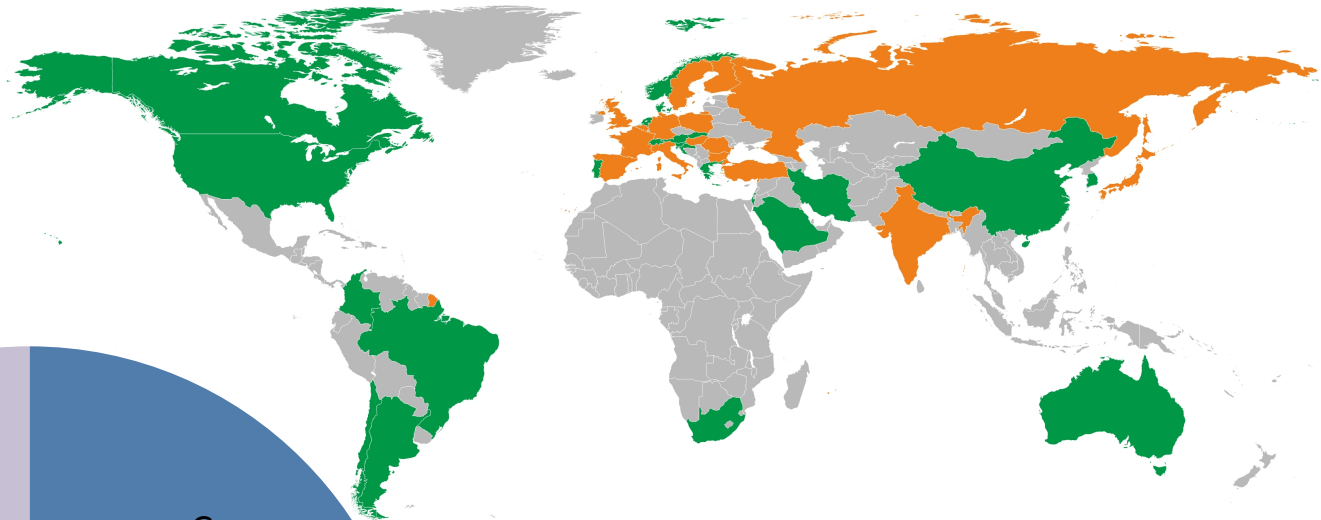
## What are the limits of existence of nuclei?

- Where are the proton and neutron drip lines situated?
- What are the heaviest elements?

## How does the equation of state of nuclear matter change with neutron-to-proton asymmetry?

- How large is the symmetry energy and its density dependence?
- What are the properties of neutron-rich matter?

## Which nuclei are relevant for astrophysical processes, what are their properties and what is their impact on nucleosynthesis modeling?



> 800 registered “interested” scientists in the NUSTAR data-base  
39 countries  
more than 180 institutes

Secured funding and expression of interest in funding  
(status: January 2016)

16 countries (incl. 9 FAIR partner countries)

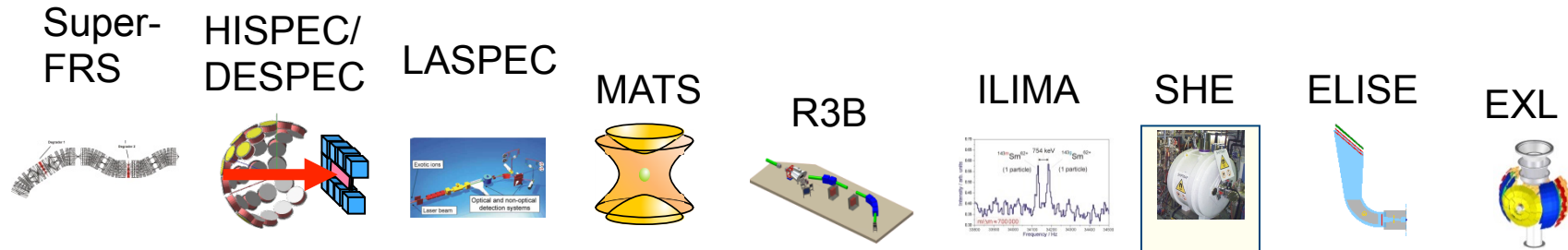
# NUSTAR – The project 1.2



	<b>Super-FRS</b>	RIB production, separation, and identification
<b>PSP</b>	<b>Experiment</b>	<b>Description</b>
1.2.2	<b>HISPEC/ DESPEC</b>	In-beam $\gamma$ -spectroscopy at low and intermediate energy, n-decay, high-resolution $\gamma$ -, $\beta$ -, $\alpha$ -, p-, spectroscopy
1.2.3	<b>MATS</b>	In-trap mass measurements and decay studies
1.2.4	<b>LaSpec</b>	Laser spectroscopy
1.2.5	<b>R<sup>3</sup>B</b>	Kinematical complete reactions with relativistic radioactive beams
1.2.6	<b>ILIMA</b>	Large-scale scans of mass and lifetimes of nuclei in ground and isomeric states
1.2.10	<b>Super-FRS</b>	High-resolution spectrometer experiments
1.2.11	<b>SHE</b>	Synthesis and study of super-heavy elements
1.2.8	<b>ELISe(*)</b>	Elastic, inelastic, and quasi-free e <sup>-</sup> -A scattering
1.2.9	<b>EXL(*)</b>	Light-ion scattering reactions in inverse kinematics

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

# Complementarity of NUSTAR experiments



	Super-FRS	HISPEC/DESPEC	LASPEC	MATS	R3B	ILIMA	SHE	ELISE	EXL
<b>Masses</b>		Q-values, isomers		dressed ions, highest precision	unbound nuclei	bare ions, mapping study	precision mass of SHEs		
<b>Half-lives</b>	ps...ns-range	dressed ions, $\mu$ s...s			resonance width, decay up to 100ns	bare ions, ms...years	$\mu$ s...days		
<b>Matter radii</b>	interaction x-section				interaction x-section				matter density distribution
<b>Charge radii</b>	charge-changing cross sections		mean square radii		charge-changing cross sections			charge density distribution	
<b>Single-particle structure</b>	high resolution, angular momentum	high-resolution particle and $\gamma$ -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
<b>Collective behavior</b>		electromag. transitions	quadrupole moments	halo structure	dipole response	changes in deformation		electromag. transitions	monopole resonance
<b>EoS</b>					polarizability, neutron skin			neutron skin $\rightarrow$	neutron skin, Compressibility
<b>Exotic Systems</b>	bound mesons, hypernuclei, nucleon res.								

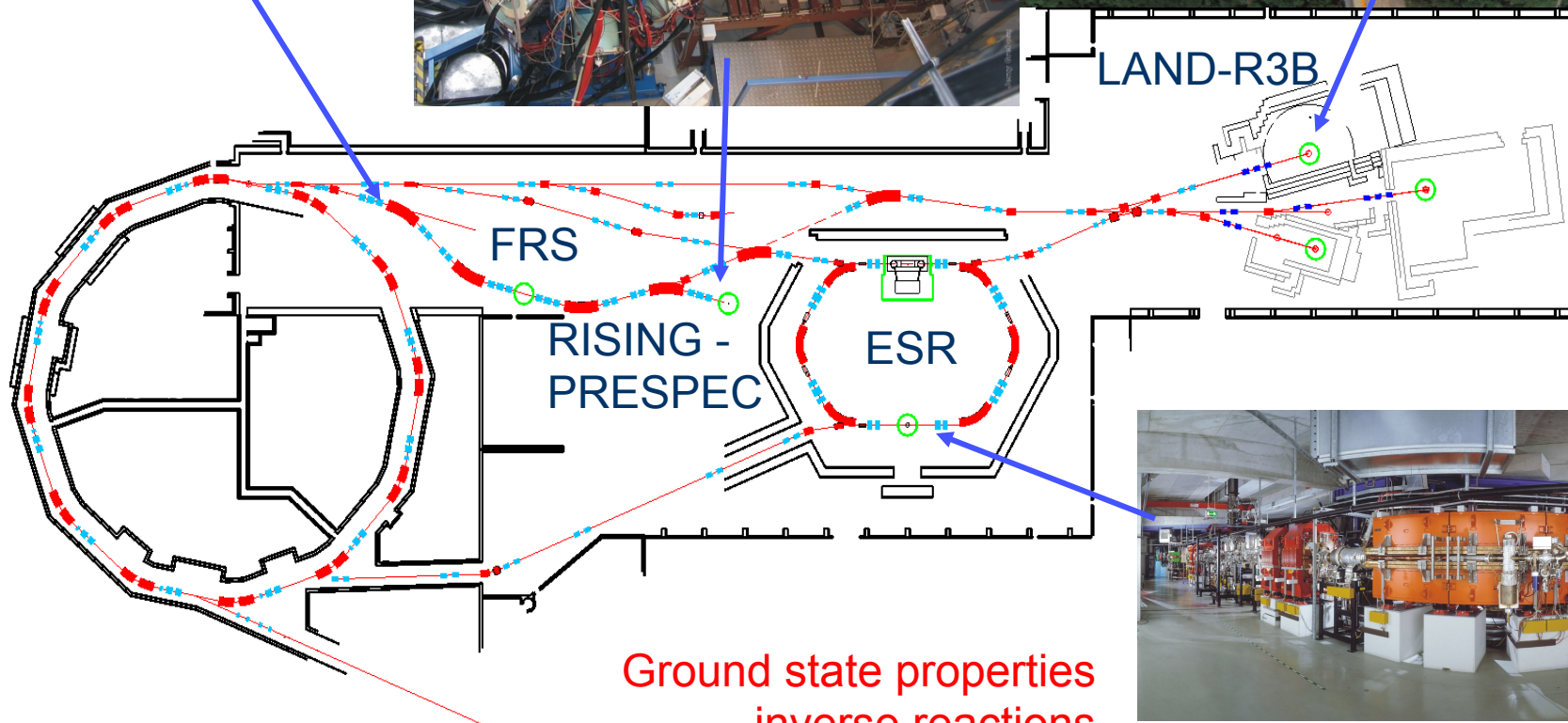
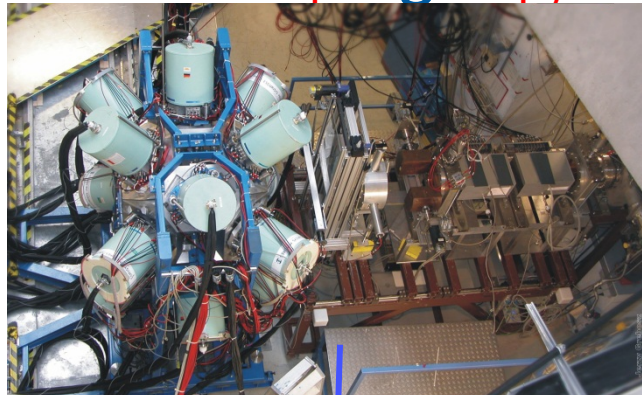
# Existing research opportunities at GSI



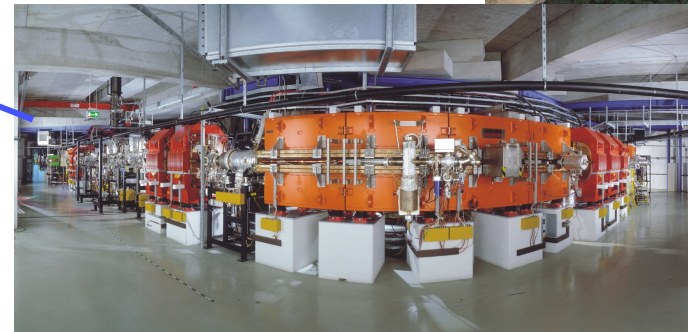
Decay studies,  
In-beam spectroscopy

Reaction studies

production and  
separation of  
exotic nuclei



Ground state properties  
inverse reactions



# Definition of NUSTAR experiment phases

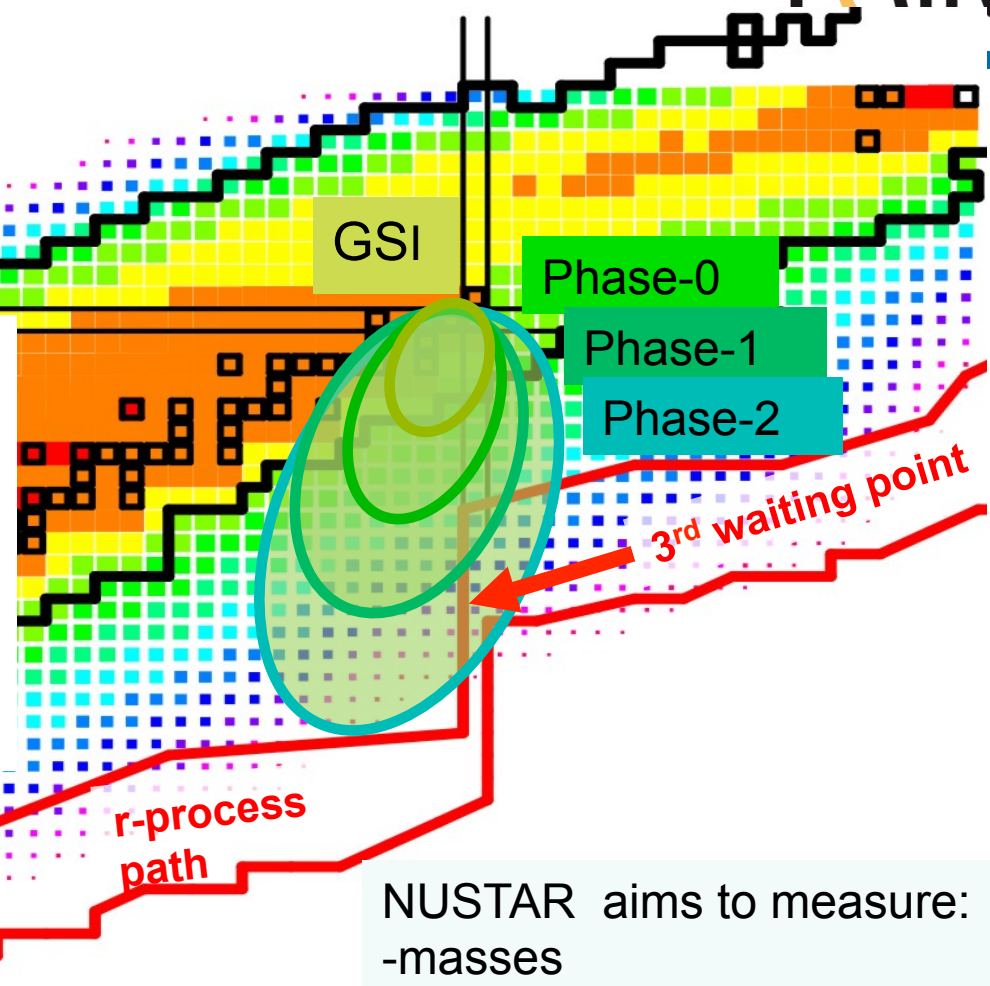
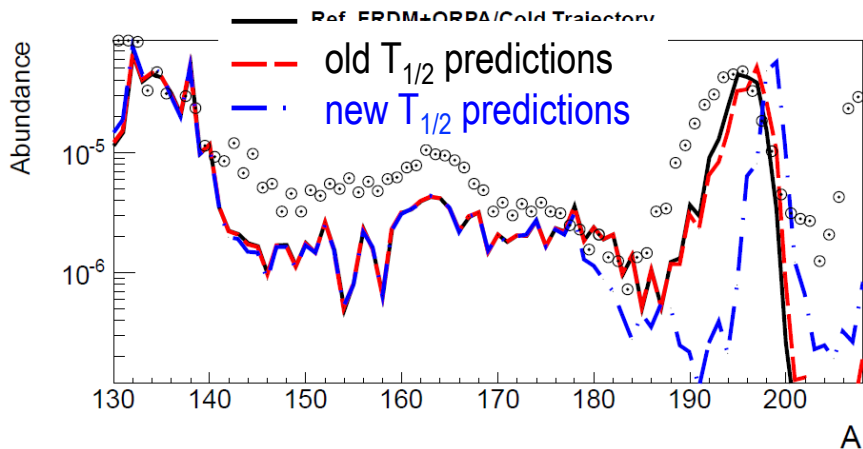


- **Phase 0** **2018/2019 and further**
  - R&D and experiments to be carried out with present facilities and FAIR/NUSTAR equipment
- **Phase 1** **2024/2025**
  - Core detectors and subsystems completed
  - First measurements with FAIR/Super-FRS beams
  - **Carry out experiments with highest visibility as part of the core program and within the FAIR MSV**
- **Phase 2** **Beyond 2025**
  - 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 Physics with HISPEC/DESPEC: r-process nuclei at N=126

Previous GSI measurements contradict earlier lifetime predictions!

→ Mass abundances not understood!



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

- NUSTAR aims to measure:
- masses
  - $\beta$ -lifetimes
  - neutron-branchings
  - strength distributions
  - level structure

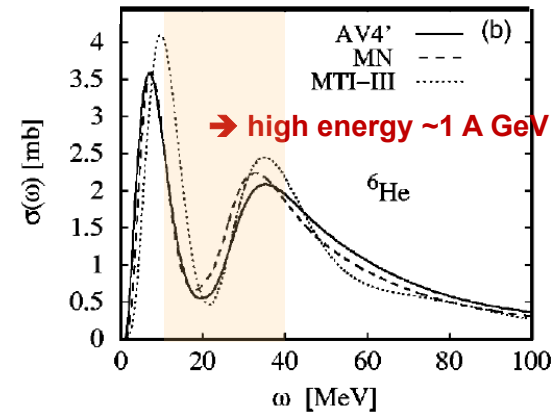
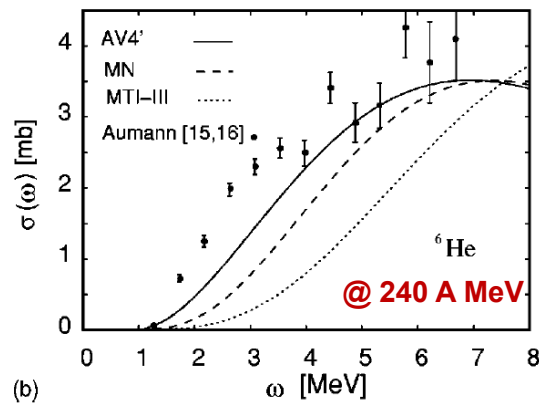


# Phase 1 Physics with R3B setup:

## Dipole strength Distributions in heavy neutron-rich nuclei

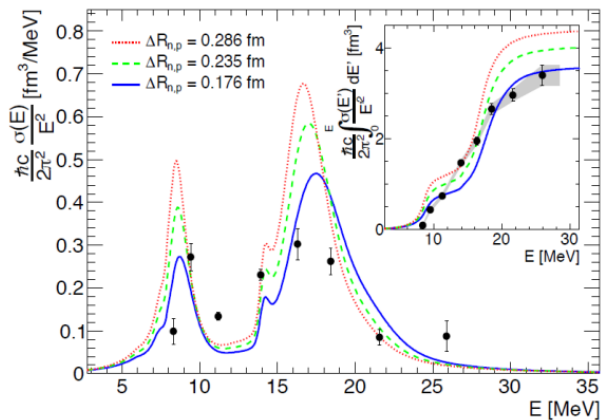


- core vs. neutron skins & halos → density / asymmetry



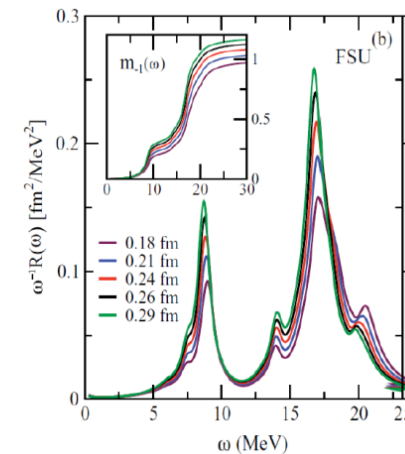
S. Bacca et al.  
PRL **89** (2002) 052502  
PRC **69** (2004) 057001

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



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

skin thickness <sup>68</sup>Ni  
0.175(21) fm



**Pb chain & N=126 isotones**

~1 A GeV →  
bare ions  
Fragment  
identification

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

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

# Exotic (n-rich) hypernuclei and their properties

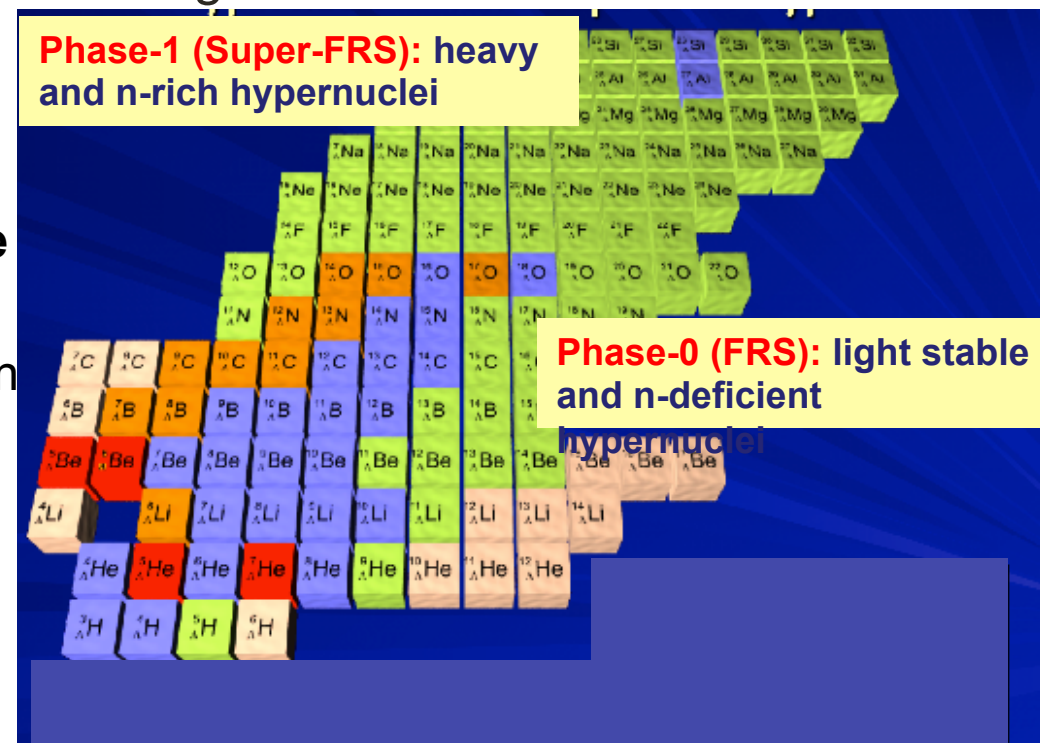
- Production of hypernuclei at high-energy ( $>1.2$  GeV/u) in peripheral collisions of heavy ions has large cross sections (micro-barn).
- The method is also suitable for determination of lifetimes of hypernuclei via weak decay channel ( $\Lambda_{\text{free}} \rightarrow p\pi^-$  or  $n\pi^0$ ,  $\tau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

- **Pilot experiments at GSI (HypHI) show evidence of  ${}^3_{\Lambda}\text{H}$ ,  ${}^4_{\Lambda}\text{H}$ ,  ${}^3_{\Lambda}\text{n}$ .**
- **FRS experiments provide precise binding energies and lifetimes.**
- Super-FRS will provide identification of heavy nuclei and explore the strange sector in very exotic nuclei.

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

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

## Strangeness sector of nuclear chart



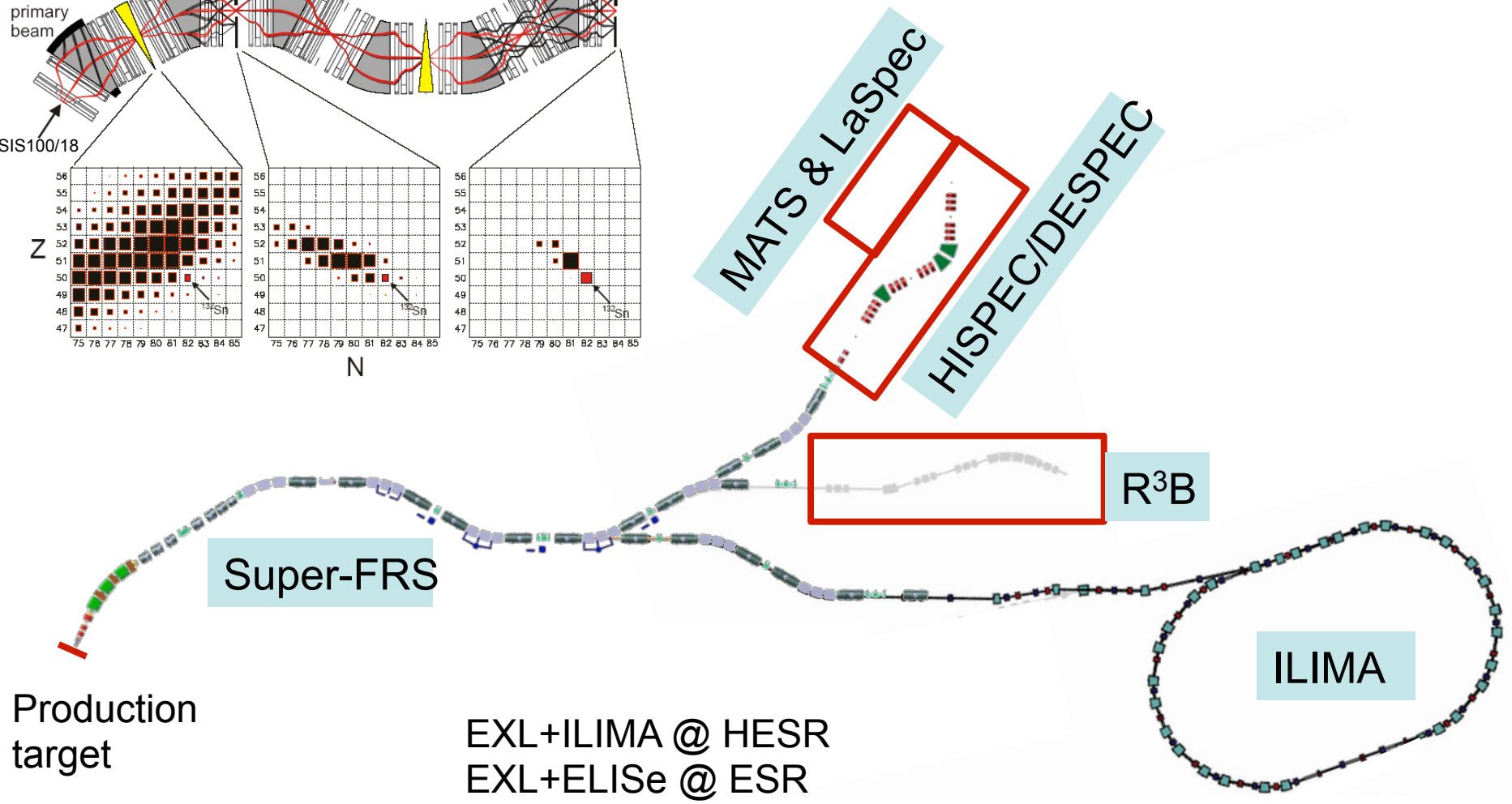
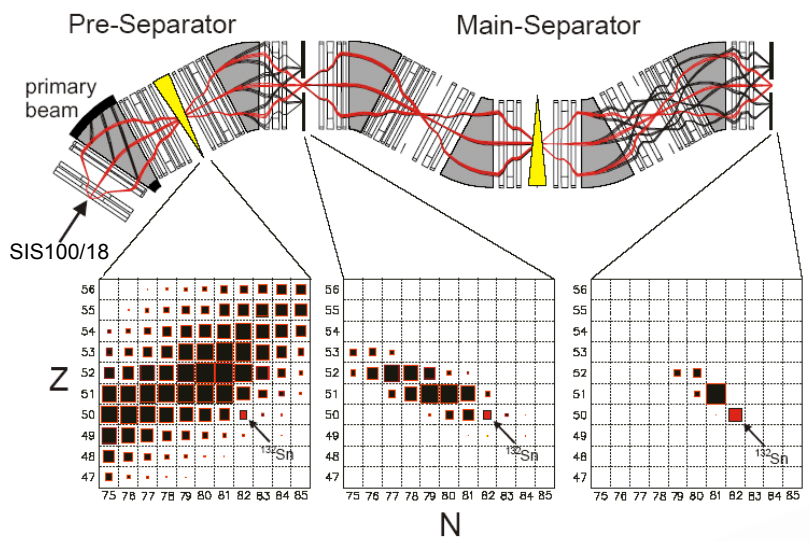
# What are the highlights of MSV Phase 1 program?



- Understanding the 3<sup>rd</sup> 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! FAIR

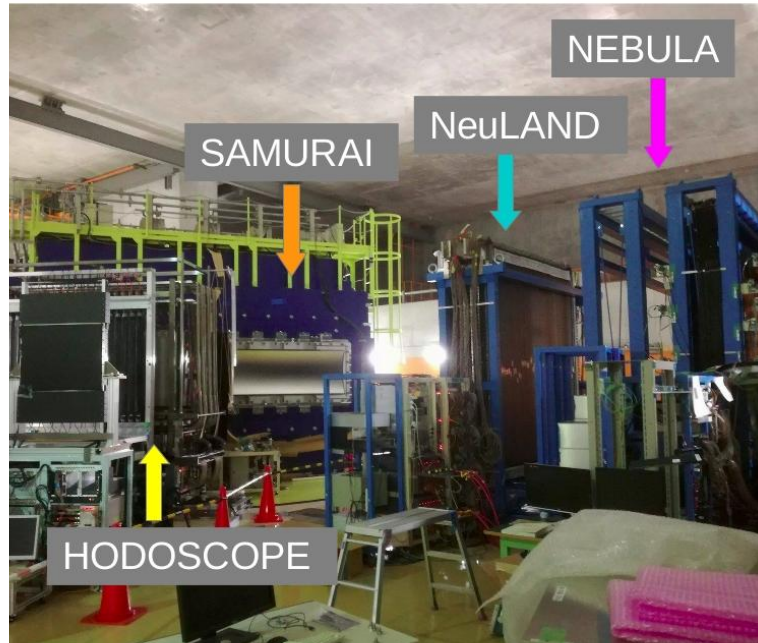


Production target

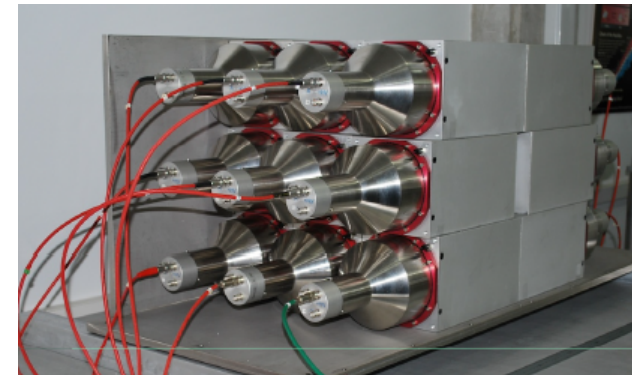
EXL+ILIMA @ HESR  
EXL+ELISe @ ESR

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

# Recent progress (...examples only)



NEULAND in operation at RIKEN

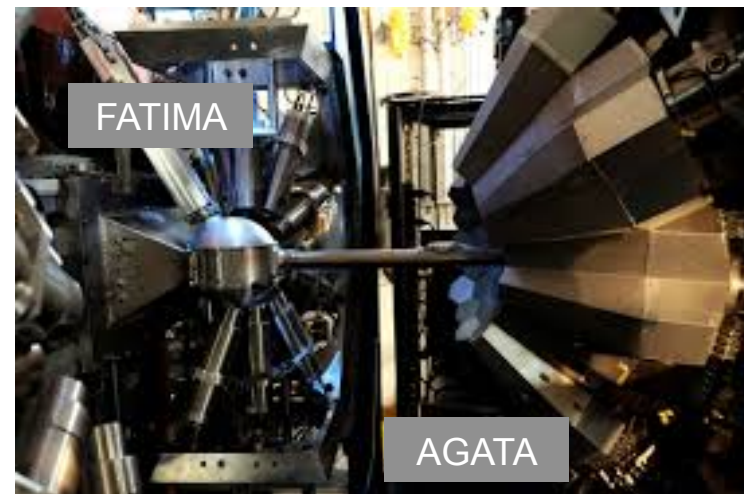


DTAS in operation at JYFL

FATIMA in operation at GANIL



O-TPC ready to use



## FAIR days in Tehran



## FAIR days in Paris





Joint Science Council meeting (June 19-20)

## **Phase-0 and Phase-1 funding**

## Ground-breaking ceremony, July 4



## Ground-breaking ceremony, July 4



# FAIR construction



# FAIR construction



## G-PAC meeting, September 19-21

### NUSTAR: R3B

S444	SIS18	Gernhäuser, Roman	TU-München Physik-Department ZTL	Simon, Haik	R3B - 2018 COMMISSIONING (CALIFA, L3T, GLAD, NeuLAND & Tracking)	25	5	2018	A	16	19
S465	SIS18	Aumann, Thomas	TU Darmstadt Inst. für Kernphysik Schlossgartenstr. 9	Simon, Haik	Dipole response of the drip-line nuclei ${}^6\text{He}$ and ${}^{22,24}\text{O}$	39	-	2018 /19	A	12	0
S442	SIS18	Sorlin, Olivier	GANIL, 15 Bd Henri	Simon, Haik	Study of multi-neutron configurations in atomic nuclei towards the drip line	22	-	2019	A	22	0
S467	SIS18	Paschalis, Stefanos	University of York, U	Simon, Haik	Single-particle structure of neutron-rich Ca isotopes: shell evolution along Z=20	14	-	2019	A	14	0
S455	SIS18	Taieb, Julien	CEA DAM IdF Bruyeres le Chatel 92297 Arnaion	Simon, Haik	Fission investigated with relativistic-radioactive beams and the advanced SOFIA@R3B setup	30	15	2018	A	21	15

### NUSTAR: S-FRS

S447	SIS18	Saito, Takehiko	GSI, Planckstrasse 1	Scheidenberger, Christoph	Studies of the $d + \pi$ signal and lifetime of the ${}^3_{\Lambda}\text{H}$ and ${}^6_{\Lambda}\text{H}$ hypernuclei by new spectroscopy techniques with FRS	36	- (18)	2019	A	27	18
S474	SIS18	Plass, Wolfgang	GSI Helmholtz Cent	Scheidenberger, Christoph	Detector tests with the prototype of the CSC for the Super-FRS and direct mass measurements of neutron-deficient nuclides below 100-Sn	21	-	2018 /19	A	21	0
S468	SIS18	Pietri, Stephane	GSI	Scheidenberger, Christoph	Search for new neutron-rich isotopes and exploratory studies in the element range from terbium to rhenium	27	-	2018	A	14	8
S469	SIS18	Purushothaman, Sivaji	GSI Helmholtzzentrum für	Scheidenberger, Christoph	Accurate slowing-down measurements of heavy ions in gases and solids in the kinetic energy range of (30 to 300) MeV/u with the high-resolution magnetic spectrometer FRS	9	18	2018	A	0	12

### NUSTAR: DESPEC

S452	SIS18	Witt, Waldemar		Gerl, Jürgen	The Oblate-Prolate Shape Transition around A~190	48	-	2018 /19	A	24	0
S460	SIS18	Morales López, Ana Isabel	Instituto de Física Corpuscular (CSIC-Universidad de	Gorska-Ott, Magdalena	Investigation of 220-A-230 Po-Fr nuclei lying in the south-east frontier of the A~225 island of octupole deformation	16	-	2018 /19	A	16	0
S450	SIS18	Podolyak, Zsolt	Department of Physics University of	Gorska-Ott, Magdalena	Study of N=126 nuclei: isomeric and beta decays in ${}^{202}\text{Os}$ and ${}^{203}\text{Ir}$	18	6	2019	A	18	6
S470	SIS18	Pietri, Stephane	GSI	Gerl, Jürgen	Test of an HISPEC TEGIC detector for Low Energy Branch experiments	0	6	2018	A	0	6
S451	SIS18	Katrik, Peter	GSI Planckstrasse 1 64291 Darmstadt	Scheidenberger, Christoph	Depth profiling of activity induced by lost heavy ions	0	10	2018 /19	A	0	10

### UNILAC / SHE

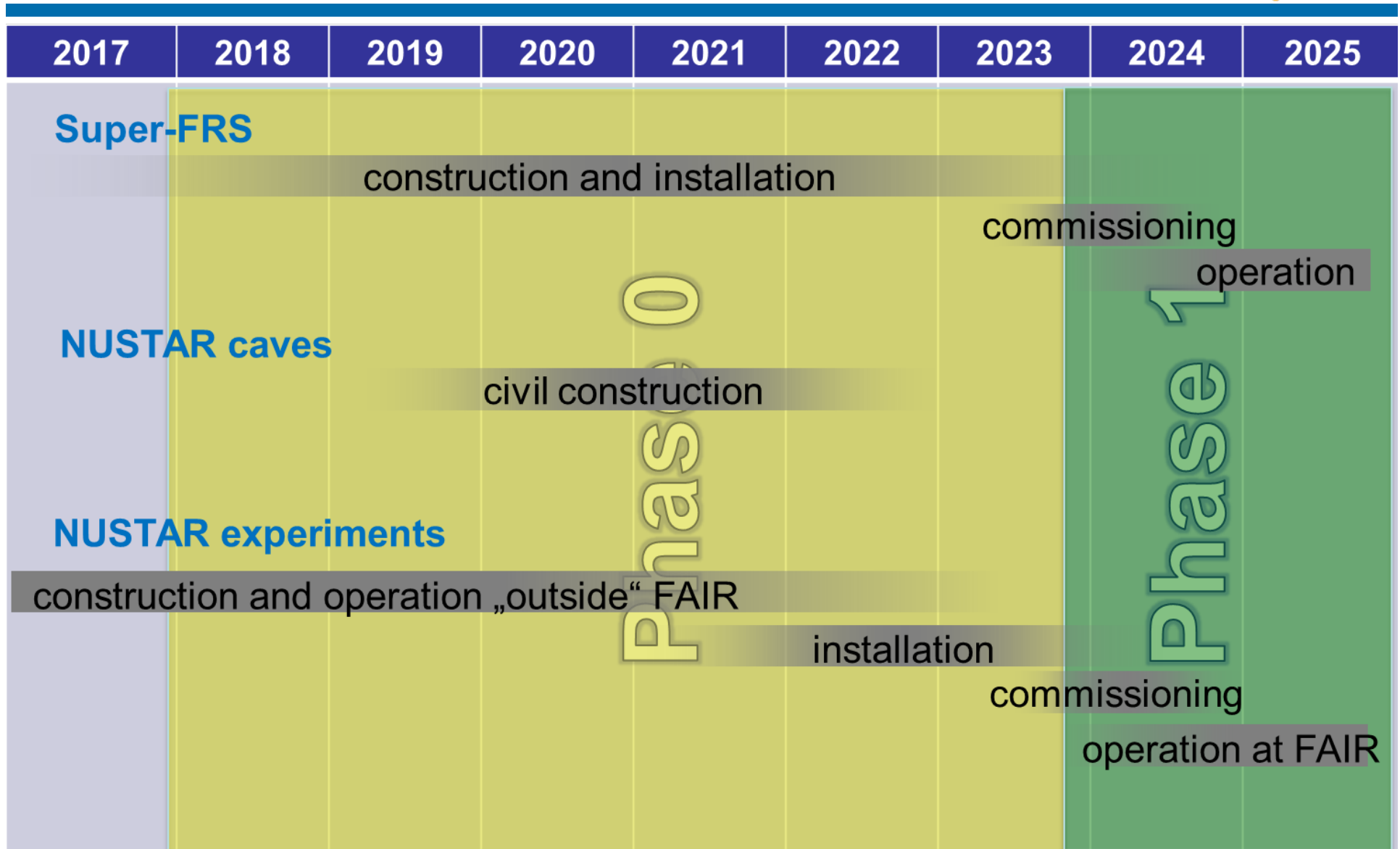
U308	UNILAC	Yakushev, Alexander	GSI Helmholtzzentrum für	Yakushev, Alexander	First chemical study of element 113 behind TASCA	84	72	2018: 72 paras. beam	A	84	72
U310	UNILAC	Rudolph, Dirk	Department of Physics Lund University	Yakushev, Alexander	Spectroscopy of Flerovium Decay Chains & Discovery of ${}^{290}\text{Fl}$	75	24	2018 /19	A	42	24
U312	UNILAC	Block, Michael	GSI	Block, Michael	Direct mass measurements and investigations of isomeric states in Lr and Rf isotopes around the deformed neutron shell closure at N = 152 with SHIPTRAP	42	30	2018 /19	A	42	30
U313	UNILAC	Laatiaoui, Mustapha	KU Leuven, IKS, Celestijnenlaan 200d	Block, Michael	Laser spectroscopy of nobelium and lawrencium	84	-	2018 /19	A	84	0
U314	UNILAC	Raeder, Sebastian	GSI Helmholtzzentrum für	Block, Michael	High-resolution laser spectroscopy of nobelium isotopes and isomers	42	21	2019	A	42	21
U316	UNILAC	Kraft-Bermuth, Saskia	I. Physics Institute Justus-Liebig-Universitaet	Gerl, Jürgen	Test of calorimetric low-temperature detectors (CLTDs) for detection of HI at low and inter-mediate ion energies for application in NUSTAR	-	27	2018 /19	A	0	27

## G-PAC meeting, September 19-21

Experiment	proposals	UNILAC Shifts	SIS18/FRS Shifts	FRS/ESR Shifts
R3B	11 (5)		248 (85+34)	
DESPEC	9 (4)		228 (58+22)	
Super-FRS	12 (4)		260 (62+38)	
ILIMA	2 (1)			42 (21)
SHE	7 (5)	564 (294+147)		
	<b>41 (20)</b>	<b>564 (294+147)</b>	<b>778 (205+94)</b>	<b>42 (21)</b>

*The present G-PAC call for 2018/19 offers approx. 600 shifts for UNILAC, 400 shifts for SIS18 and 170 shifts for ESR/Cryring.*

# NUSTAR timeline





**Thanks!**