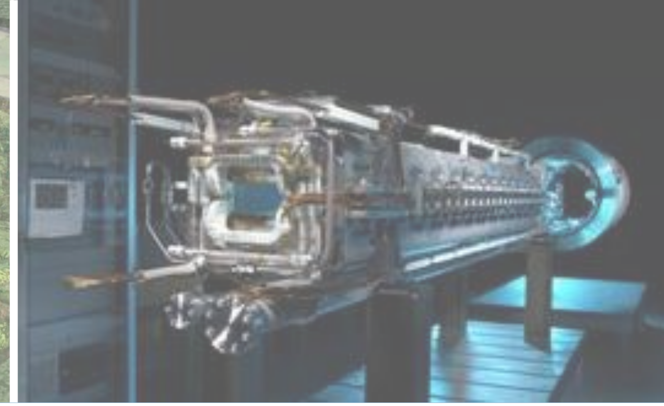


Exploring the extremes with NUSTAR @ FAIR

Nasser Kalantar-Nayestanaki
KVI-CART/University of Groningen

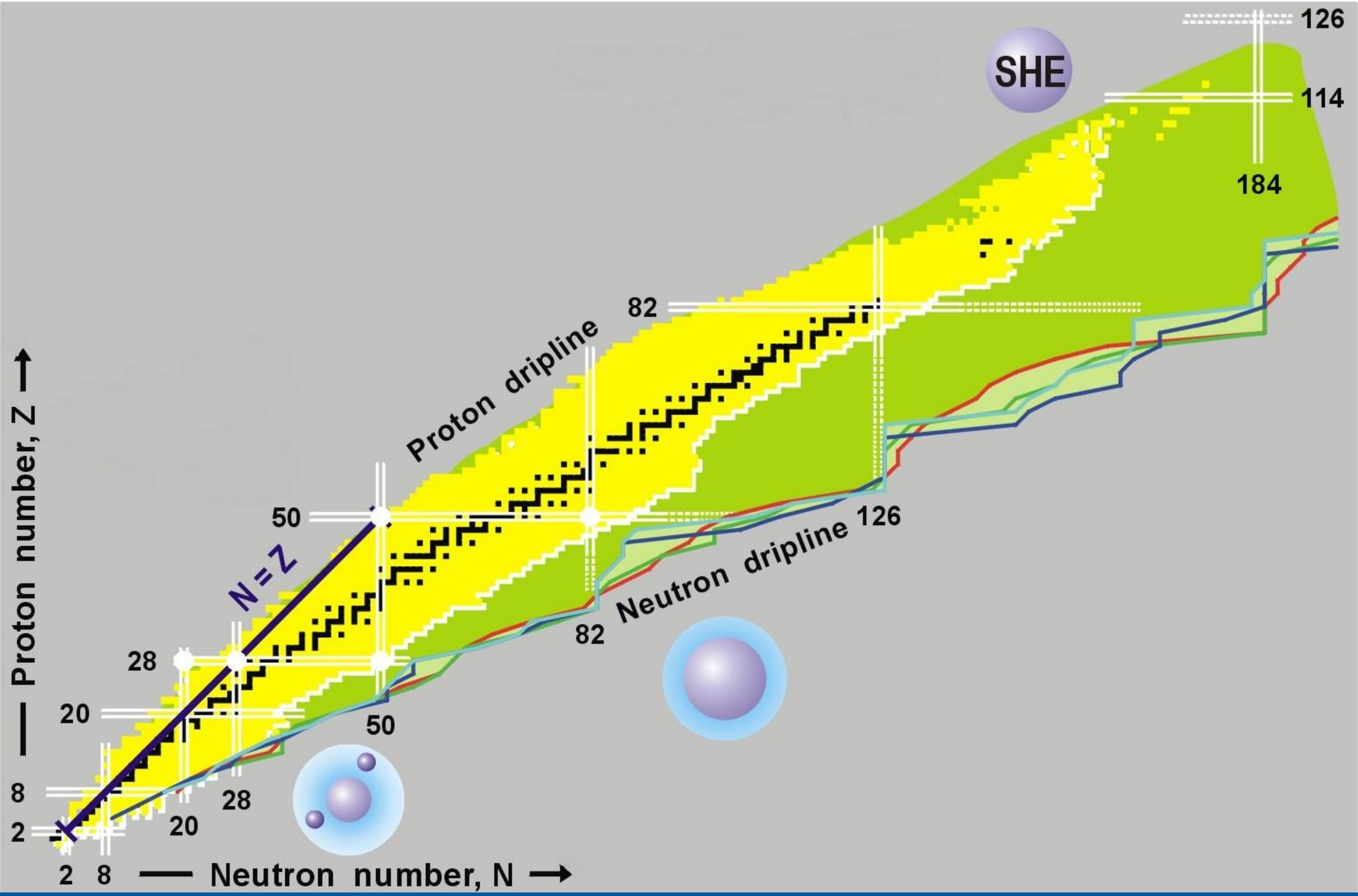
Journées FAIR-France

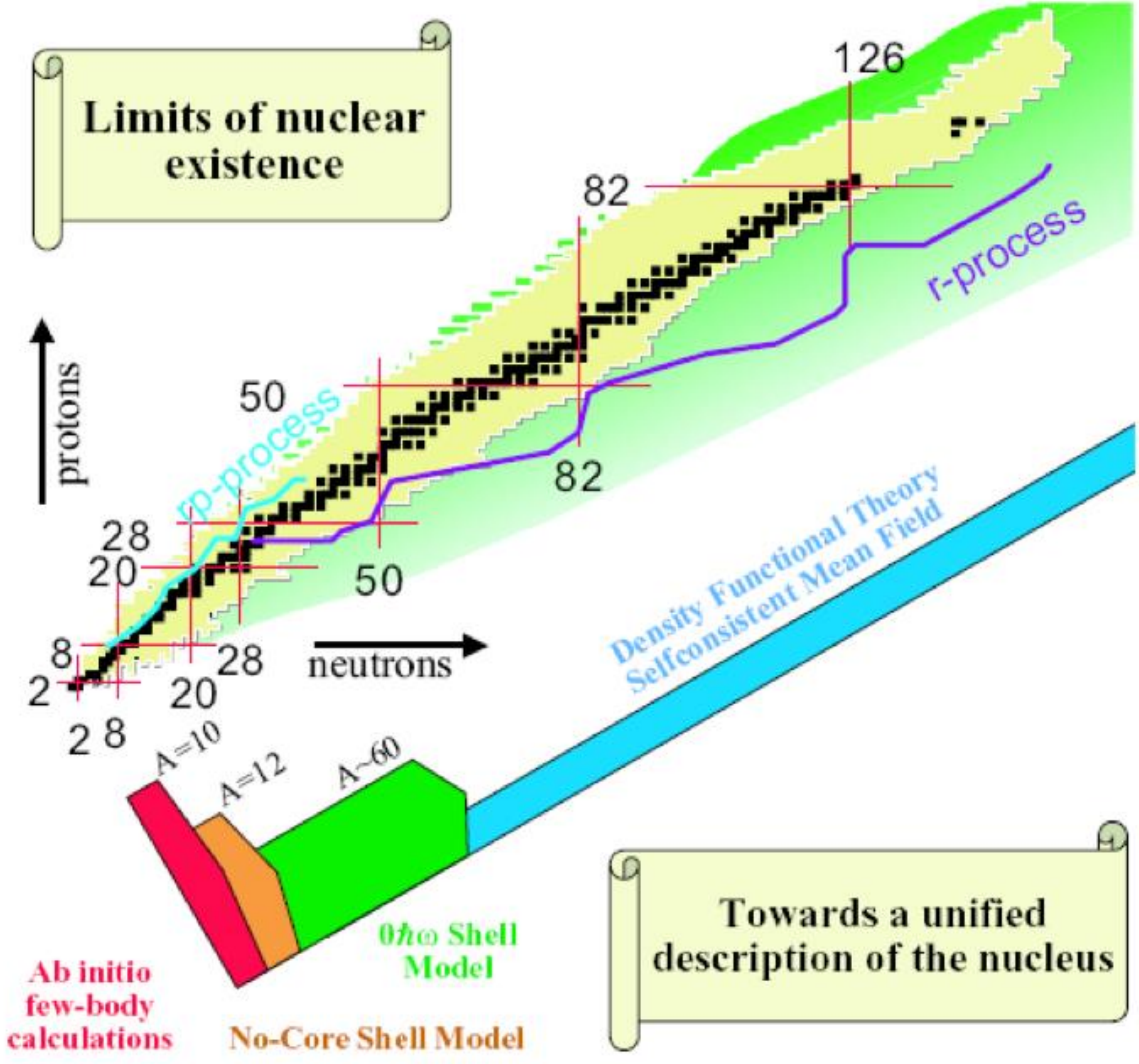
Orsay, France, May 18, 2017

Finland France Germany India Poland Romania Russia Slovenia Sweden UK

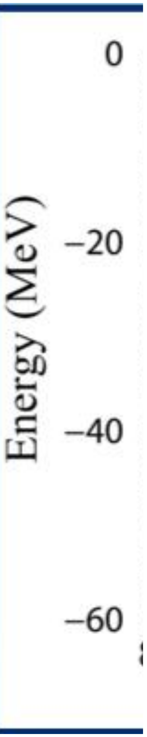
FAIR

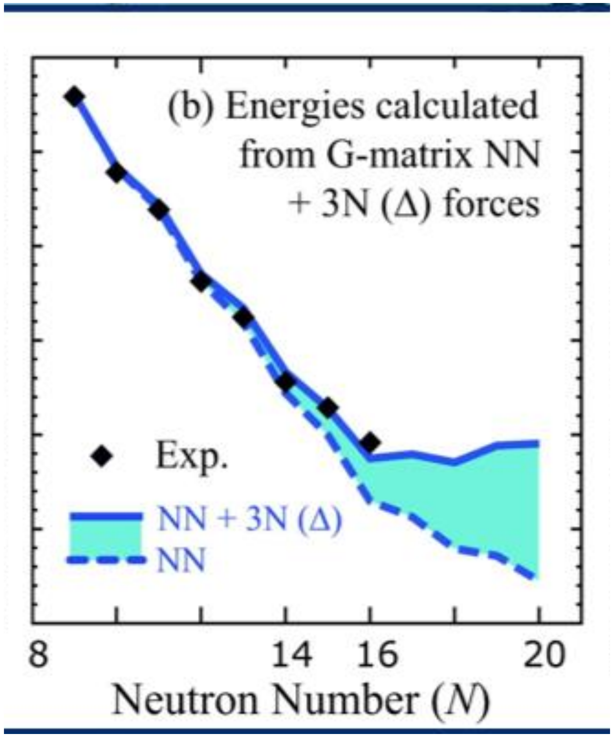
Snapshot of the nuclear landscape




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

Binding Energies of Oxygen Isotopes





Otsuka, Suzuki, Holt, Schwenk, Akaishi, PRL 105, 032501 (2010)

NUclear STructure 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?

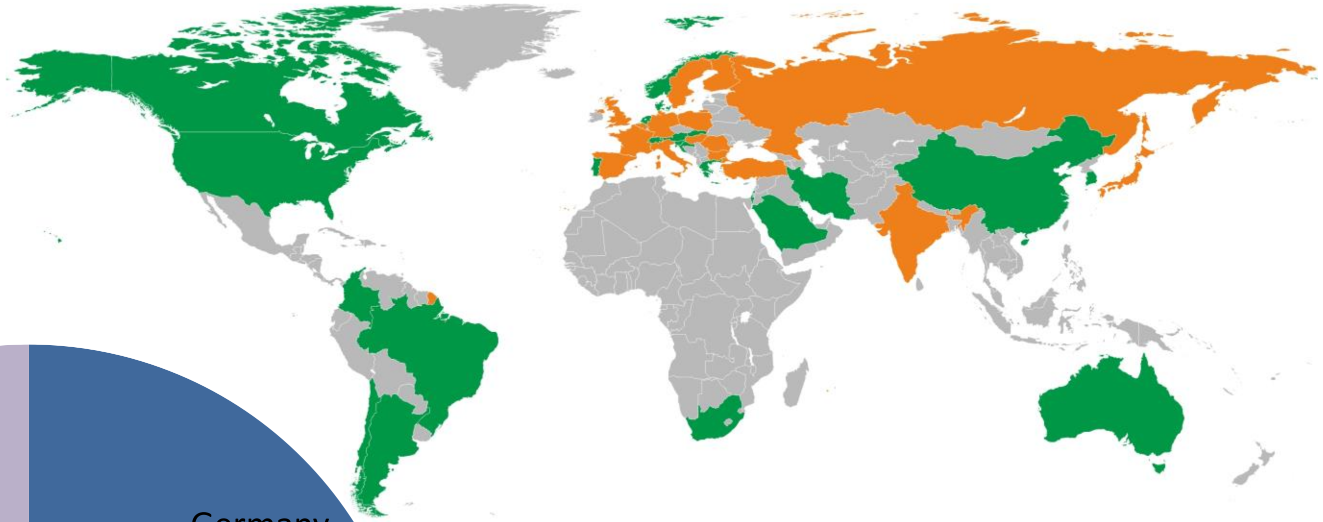
- *Where are the proton and neutron drip lines situated?*
- *What are the heaviest elements?*

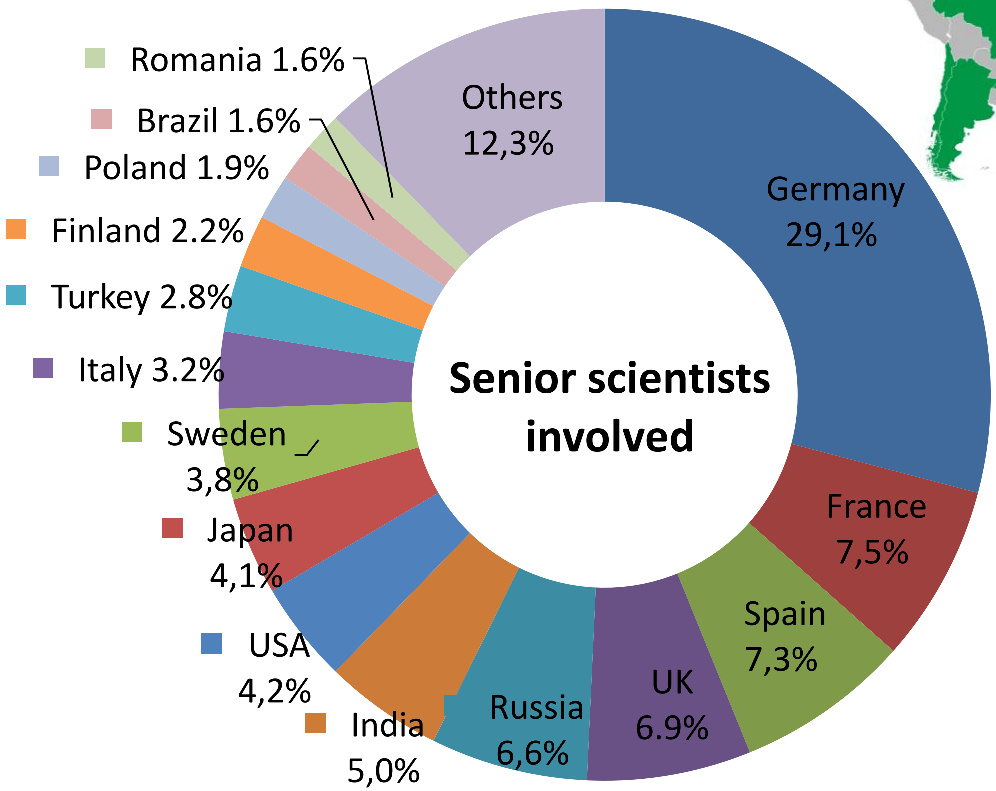
How does the equation of state of nuclear matter change with neutron-to-proton asymmetry?

- *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?

NUSTAR Collaboration





> 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)

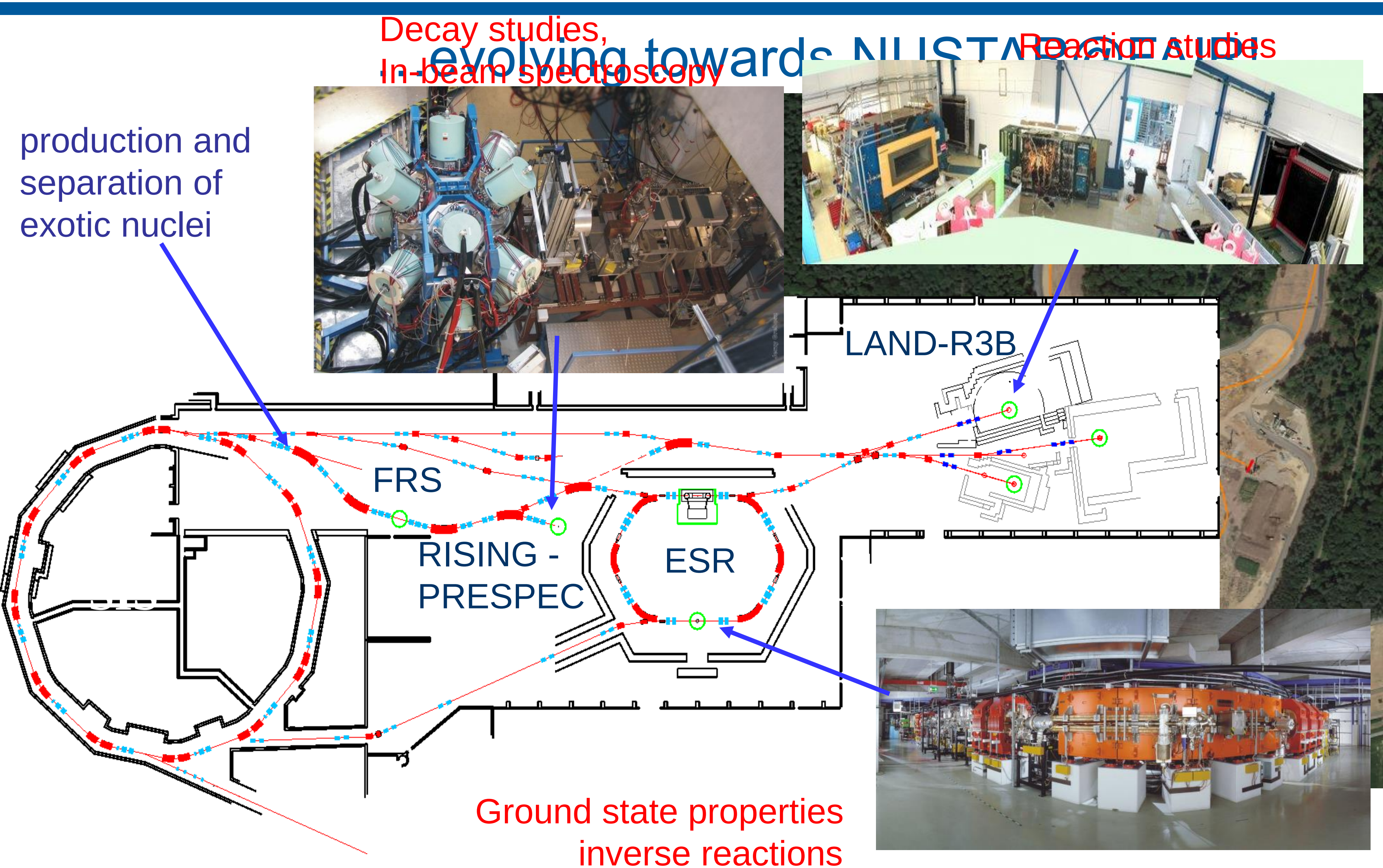
NUSTAR – The project 1.2

	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
1.2.4	**LaSpec**	Laser spectroscopy
1.2.5	**R^3B**	Kinematical complete reactions with relativistic radioactive beams
1.2.6	**ILIMA**	Large-scale scans of mass and lifetimes of nuclei in ground and isomeric states
1.2.10	**Super-FRS**	High-resolution spectrometer experiments
1.2.11	**SHE**	Synthesis and study of super-heavy elements
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 by ECE.

Existing research opportunities at GSI

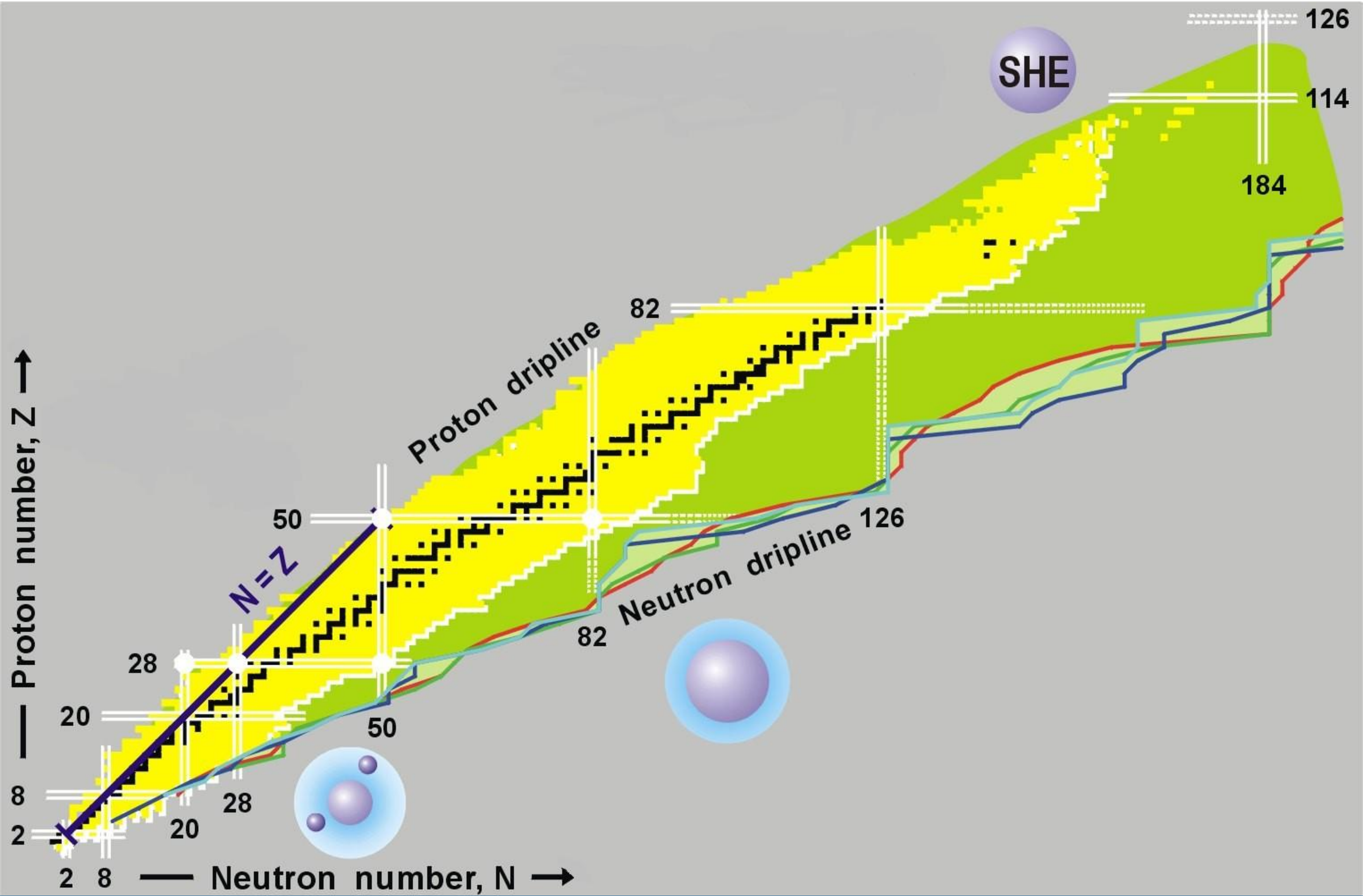
evolving towards



Definition of NUSTAR experiment phases

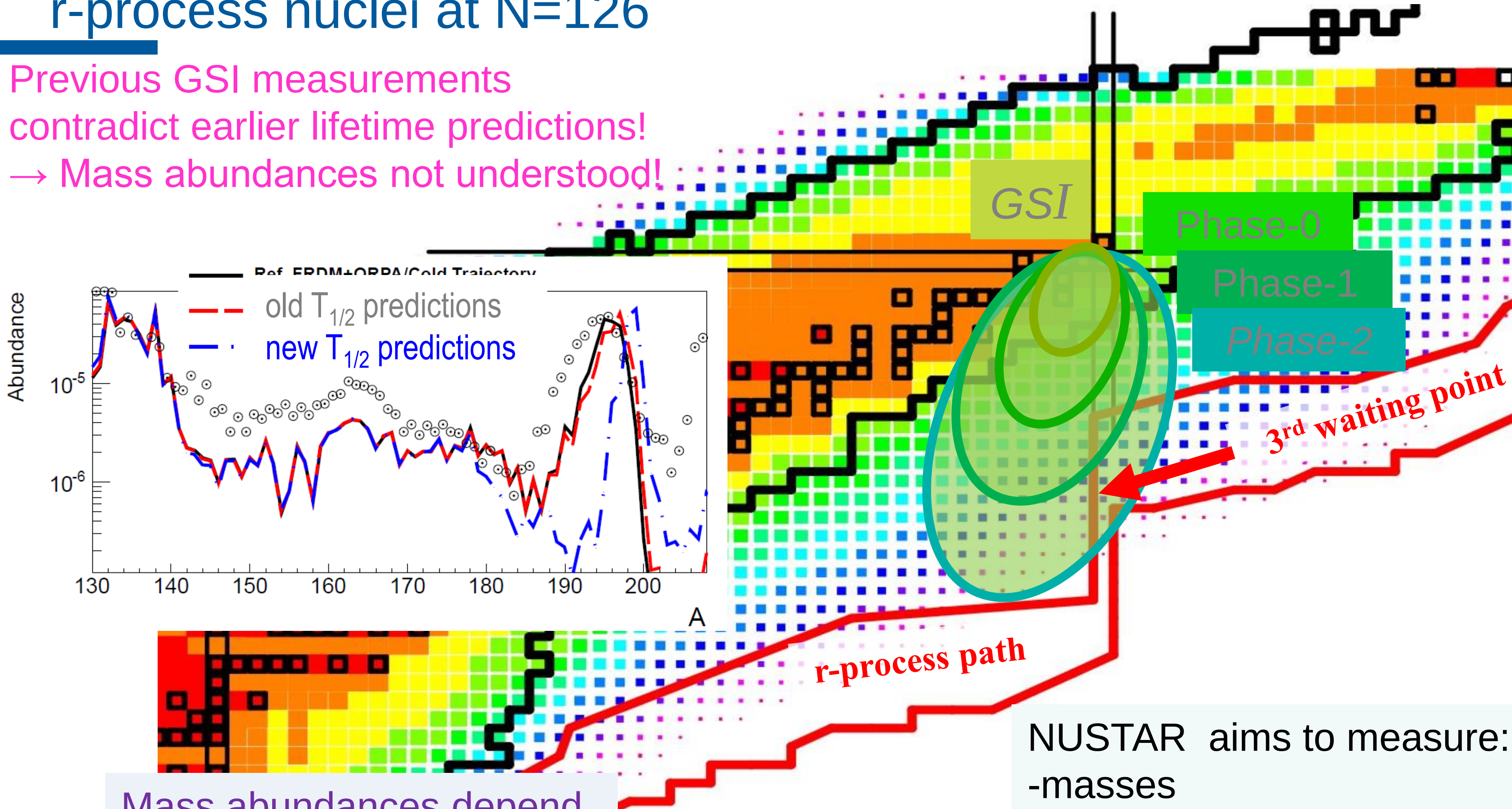
- **Phase 0** **2018/2019 and further**
  - R&D and experiments to be carried out with present facilities and FAIR/NUSTAR equipment
- **Phase 1** **2024/2025**
  - Core detectors and subsystems completed
  - First measurements with FAIR/Super-FRS beams
  - **Carry out experiments with highest visibility 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

Snapshot of the nuclear landscape



Phase 1 Physics with HISPEC/DESPEC:
r-process nuclei at N=126

Previous GSI measurements contradict earlier lifetime predictions!
→ Mass abundances not understood!



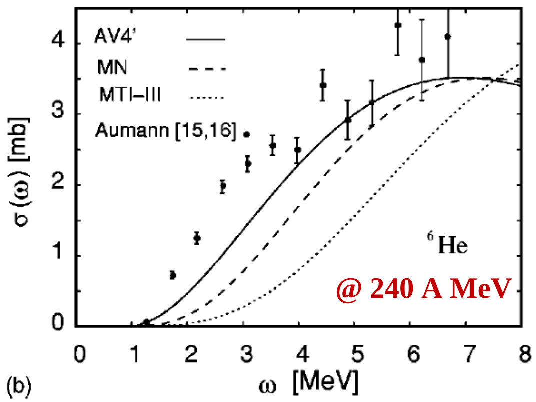
Mass abundances depend on the detailed structure of N=126 nuclei around the 3rd r-process waiting point

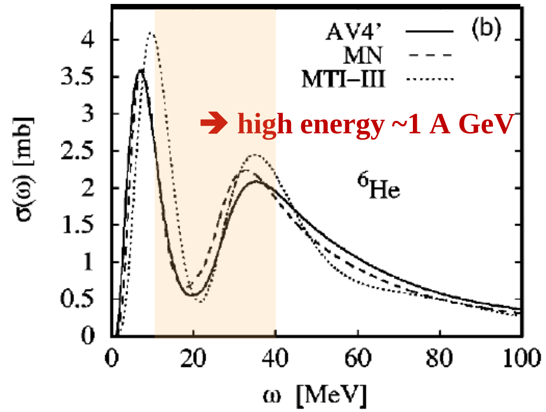
NUSTAR aims to measure:
- -masses
- -β-lifetimes
- -neutron-branchings
- -strength distributions
- -level structure

Phase 1 Physics with R3B setup:

Dipole strength Distributions in heavy neutron-rich nuclei

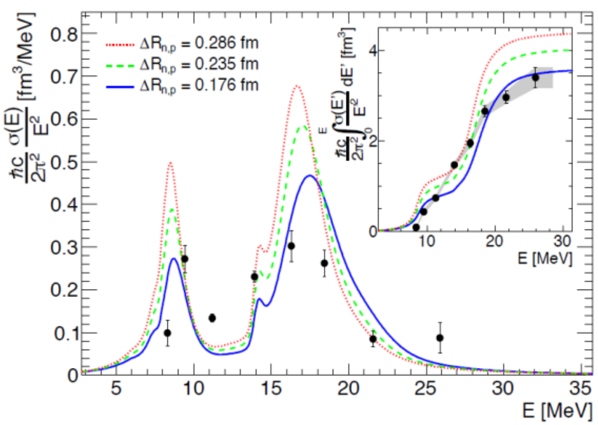
- core vs. neutron skins & halos → density / asymmetry





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

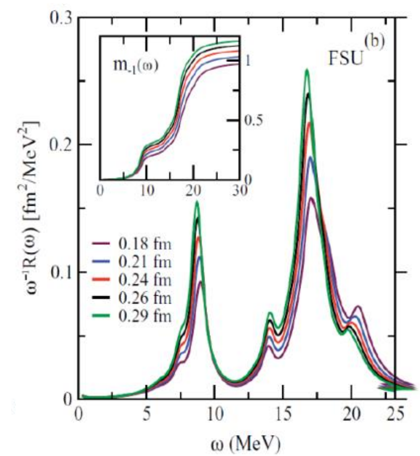
- access to EoS (e.g. neutron star) & low lying E1 strength (r-process)



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

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

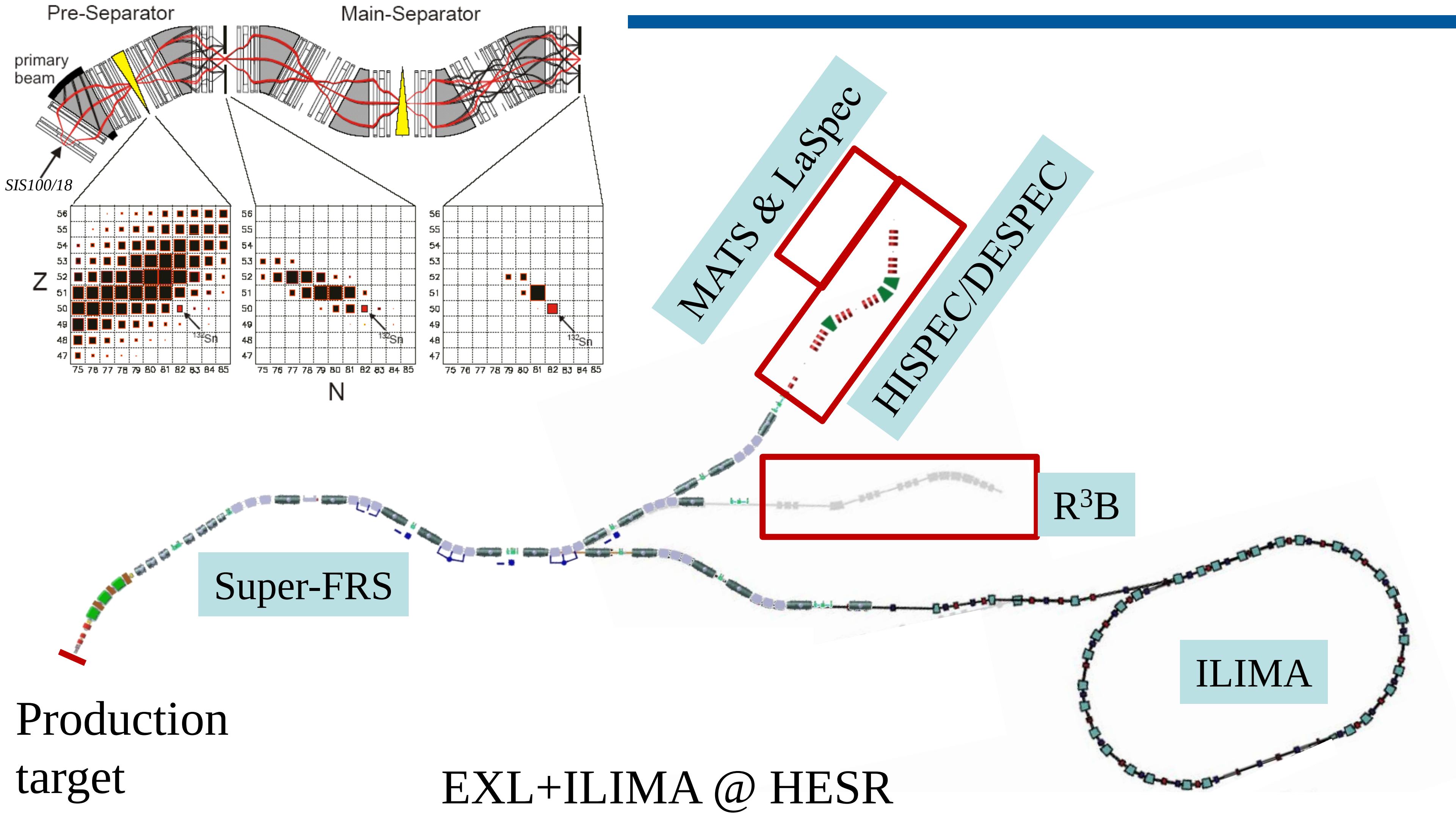
J. Piekarewicz, PRC **83** (2011) 034319

What are the highlights of MSV 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!



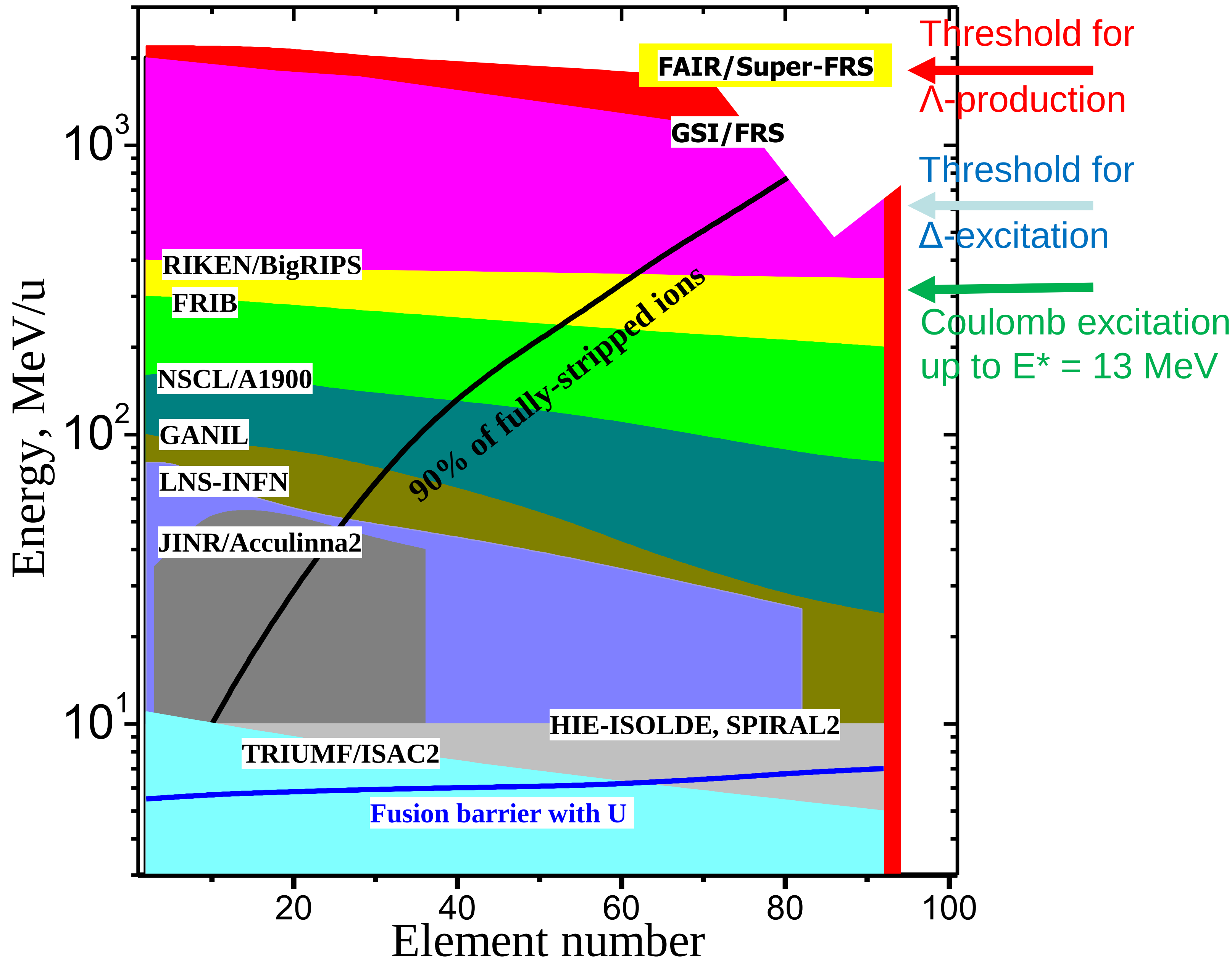
Rich program due to approximately 2000 h beam time for NUSTAR experiments per year!

SIS100 essential!

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

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

RARE-ISOTOPE BEAM FACILITIES



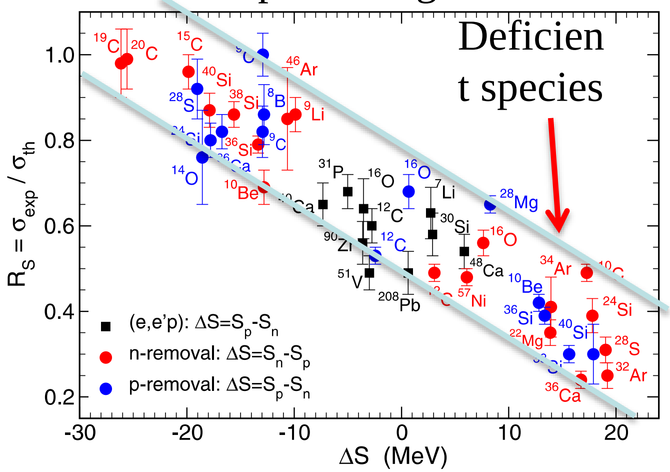
Recent highlights

R^3B

Recent highlight: Quenching of single-particle strength - Dependence on neutr

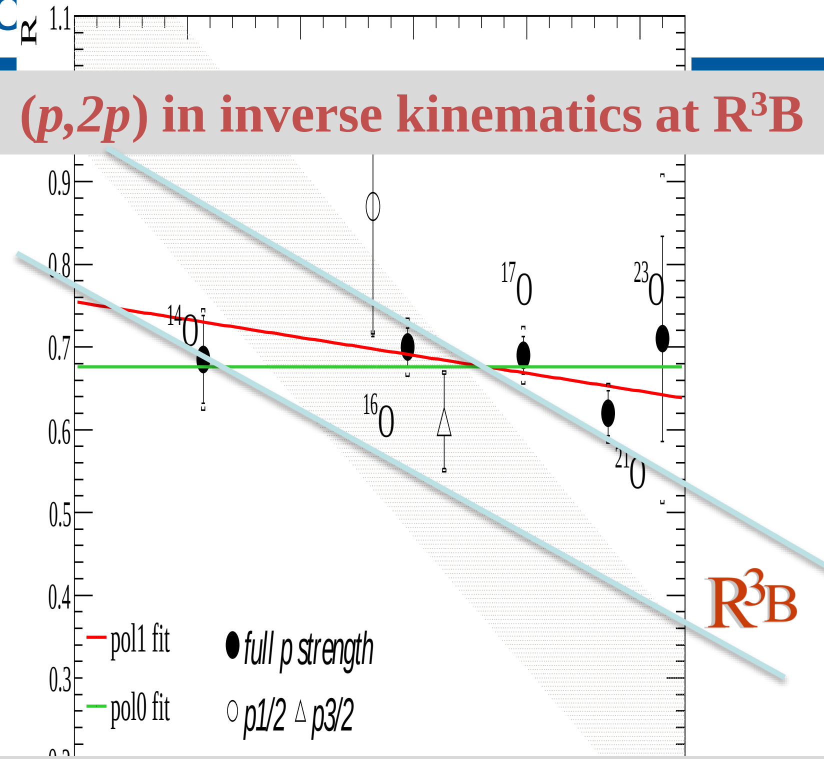
The Puzzle

Results from knockout experiments using extended composite targets at 50-100 MeV/u



J.A. Tostevin and A. Gade, PRC 90 (2014) 057602

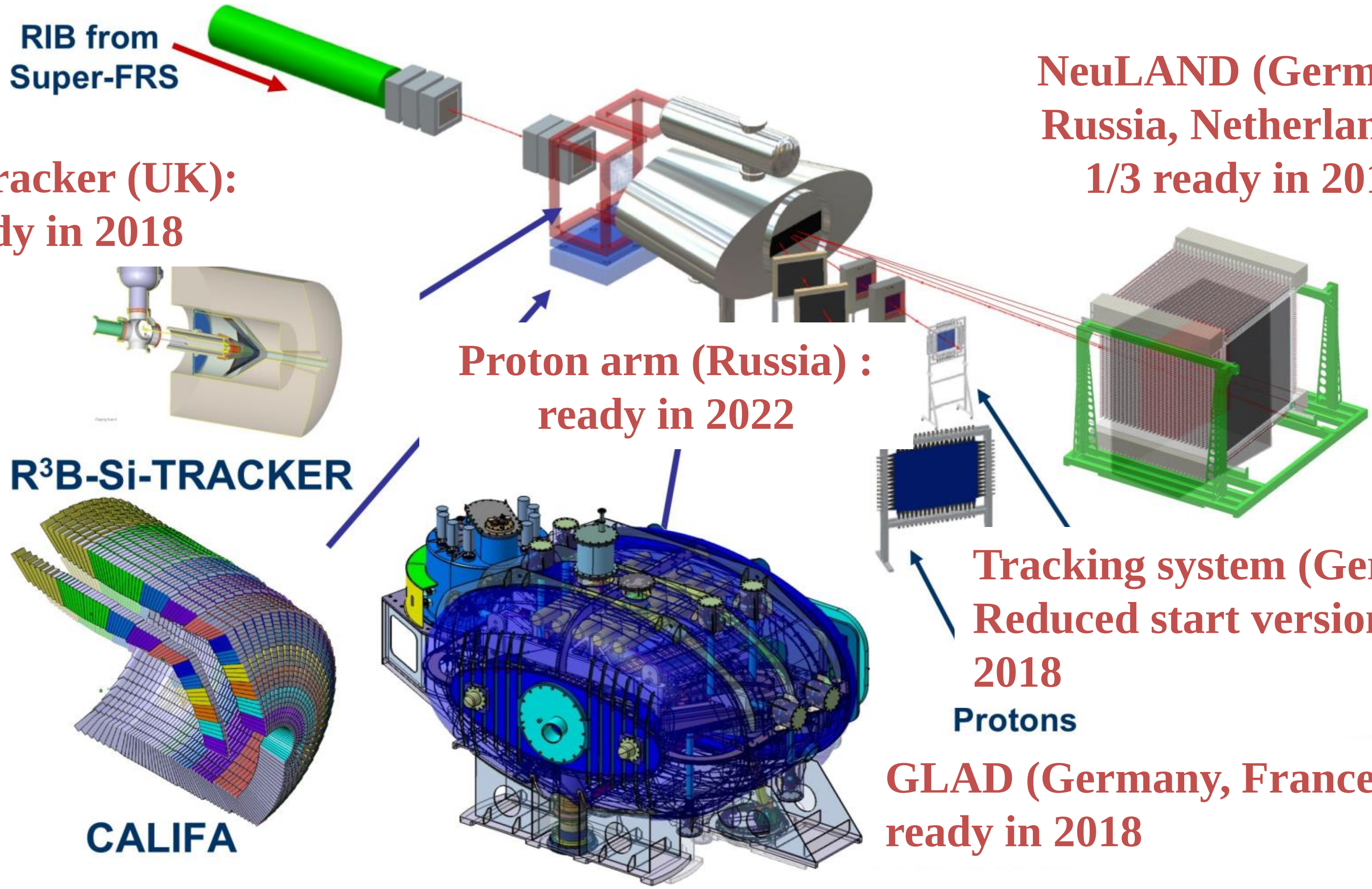
(p,2p) in inverse kinematics at R[3]B



L. Atar et al. (R[3]B collaboration), publication in preparation

- ✓ Quantitative benchmark experiment against ^{12}C(*e,e'p*) successfully accomplished
- ✓ First exclusive large-acceptance (*p*,2*p*) experiment with radioactive beams accomplished
- ✓ Clean reaction mechanism, quantitative reaction theory developed and tested
- ✓ Wide range in asymmetry (S_p-S_n) covered
- ➔ **Only weak dependence on asymmetry observed!**
- ➔ Long-standing puzzle might have been clarified
- ➔ Reason for systematic change of cross sections for conventional knockout to be clarified

Start version for Phase 0 (Status 2018)



Si tracker (UK):
ready in 2018

NeuLAND (Germany, Russia, Netherlands):
1/3 ready in 2018

Proton arm (Russia) :
ready in 2022

Tracking system (Germany):
Reduced start version ready in 2018

GLAD (Germany, France):
ready in 2018

CALIFA (Sweden, Spain, Germany, Russia):
Barrel without backward part ready in 2018
Frontcap missing! -> part of the program delayed

GLAD magnet (November 2015, GSI)

Phase 0 physics program in 2018/19 (green/orange)

R^3B program will strongly benefit from the availability of 1 GeV/nucleon beams (installation and commissioning of GLAD will be finished in 2017).

➔ Large fraction of the physics program can be started with partly completed detection systems in 2018:

- Dipole response of neutron-rich nuclei: partly possible for light nuclei already 2018 ✓
- Dipole strength of halo nuclei up to 30 MeV excitation energy (reduced n efficiency) ✓
- Pygmy and Giant Resonances, Dipole polarizability (EoS of asymmetric nuclear matter): needs CALIFA; delayed until construction accomplished (2020 depending on funding) No
- (*p,2p*) – single-particle and shell structure: possible to start already 2018 ✓
- (*p,2pN*) – *NN* tensor short-range correlations: needs CALIFA; delayed to 2020 No
- (*p,2p*) fission - fission barriers: possibly already in 2018 ✓
- Fission (elm. excitation) - nuclear structure: possible (reduced information on neutrons) ✓
- Light drip-line nuclei: up to *2n* decays possible (reduced NeuLAND efficiency) ✓
- Beyond neutron drip-line: up to *2n* decays possible (reduced NeuLAND efficiency) ✓
- Pure neutron systems, multi-neutron (>4) decays: (needs NeuLAND completion) No
- Spectroscopy of 2^+ states of heavy neutron-rich nuclei ✓
- Elastic and inelastic scattering using the active target (smaller prototype available) (✓)
- Nuclei at and beyond the proton drip-line (needs PAS, ready only in 2022) No

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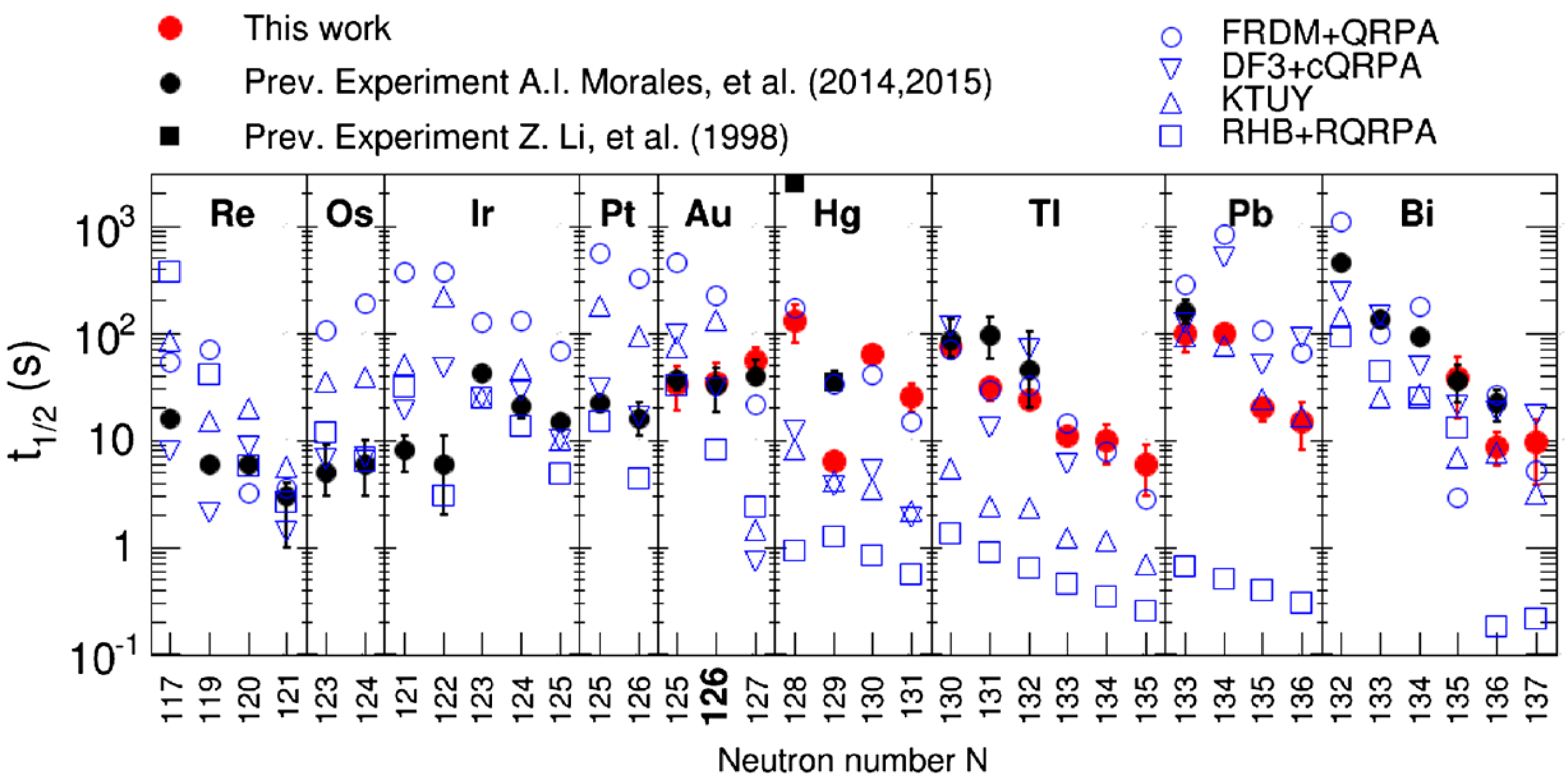
HISPEC/DESPEC

PRL 117, 012501 (2016) PHYSICAL REVIEW LETTERS week ending 1 JULY 2016

First Measurement of Several β-Delayed Neutron Emitting Isotopes Beyond $N = 126$

R. Caballero-Folch,[1,2] C. Domingo-Pardo,[3,*] J. Agramunt,[3] A. Algora,[3,4] F. Ameil,[5] A. Arcones,[5] Y. Ayyad,[6] J. Benlliure,[6] et al.

Relevant for the nucleosynthesis of heavy elements



BELEN neutron counter used; DESPEC experiment at GSI

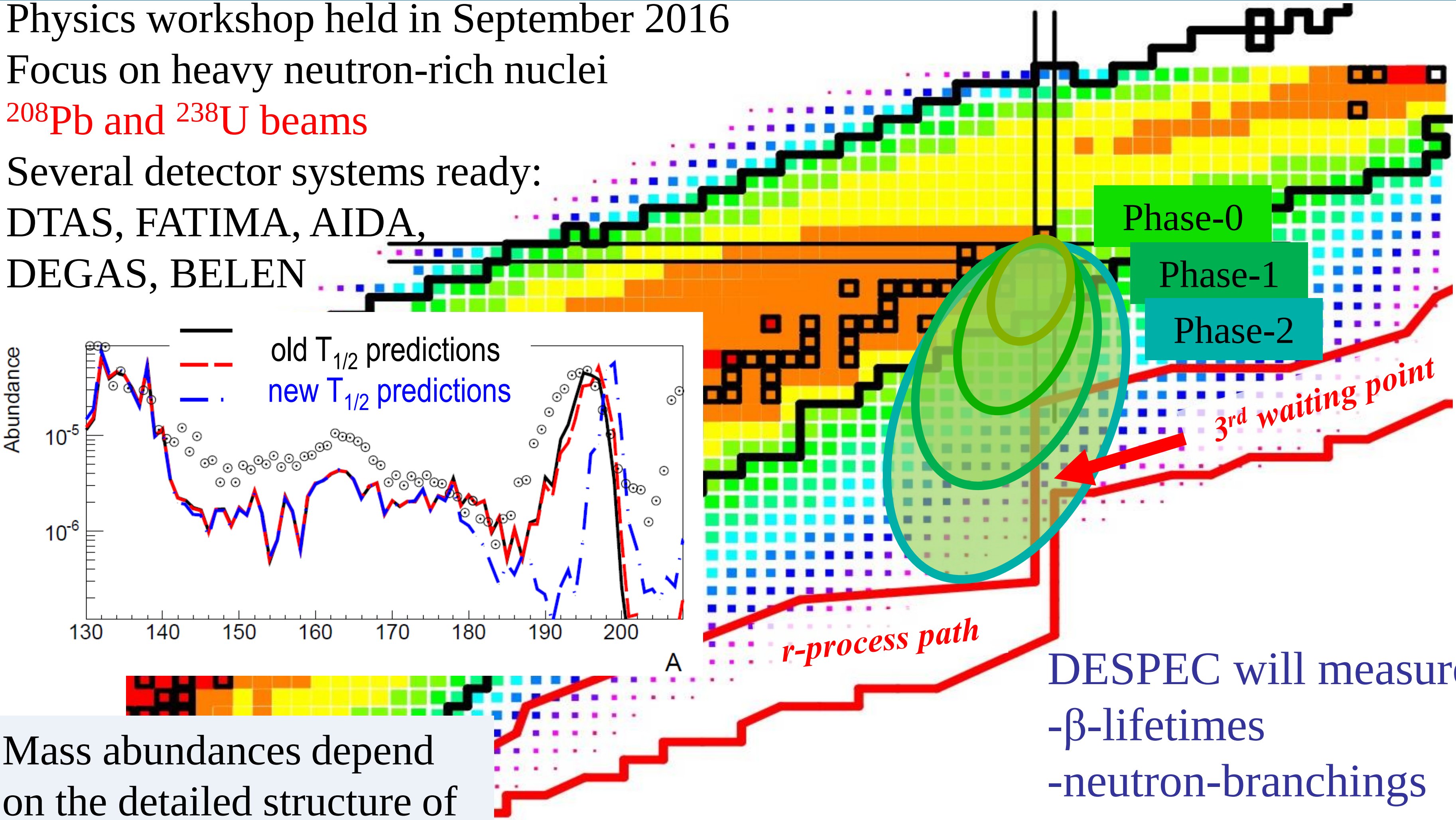
DESPEC in 2018-2020 (Phase 0)

Physics workshop held in September 2016

Focus on heavy neutron-rich nuclei

^{208}Pb and ^{238}U beams

Several detector systems ready:
DTAS, FATIMA, AIDA,
DEGAS, BELEN



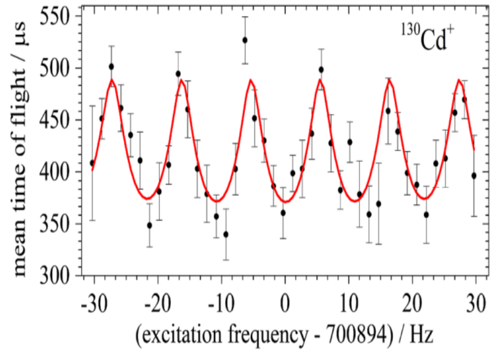
Mass abundances depend on the detailed structure of N=126 nuclei around the 3rd r-process waiting point

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

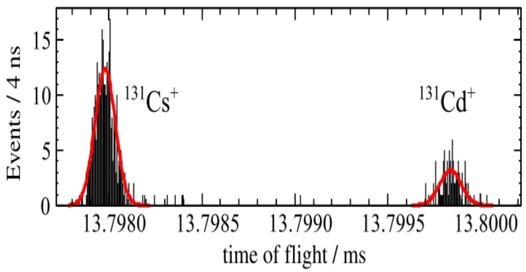
MATS

MATS Phase 0: Developments for mass measurements of n-rich nuclides

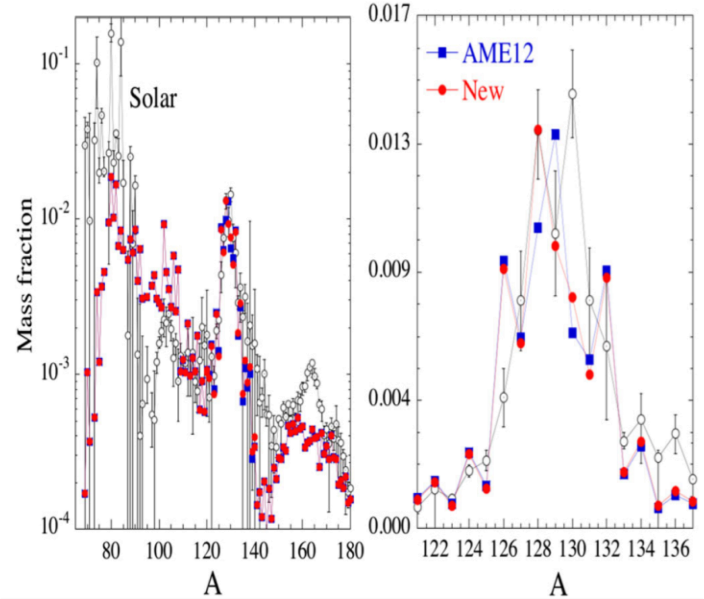
Masses of n-rich Cd isotopes around A=132 measured with ISOLTRAP at CERN



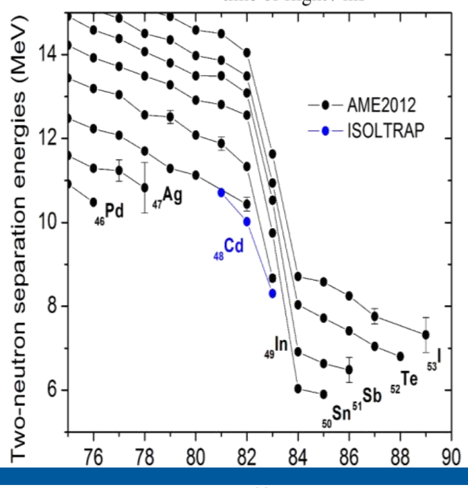
Penning trap



MR-ToF



D. Atanasov et al., PRL 115, 232501 (2015)

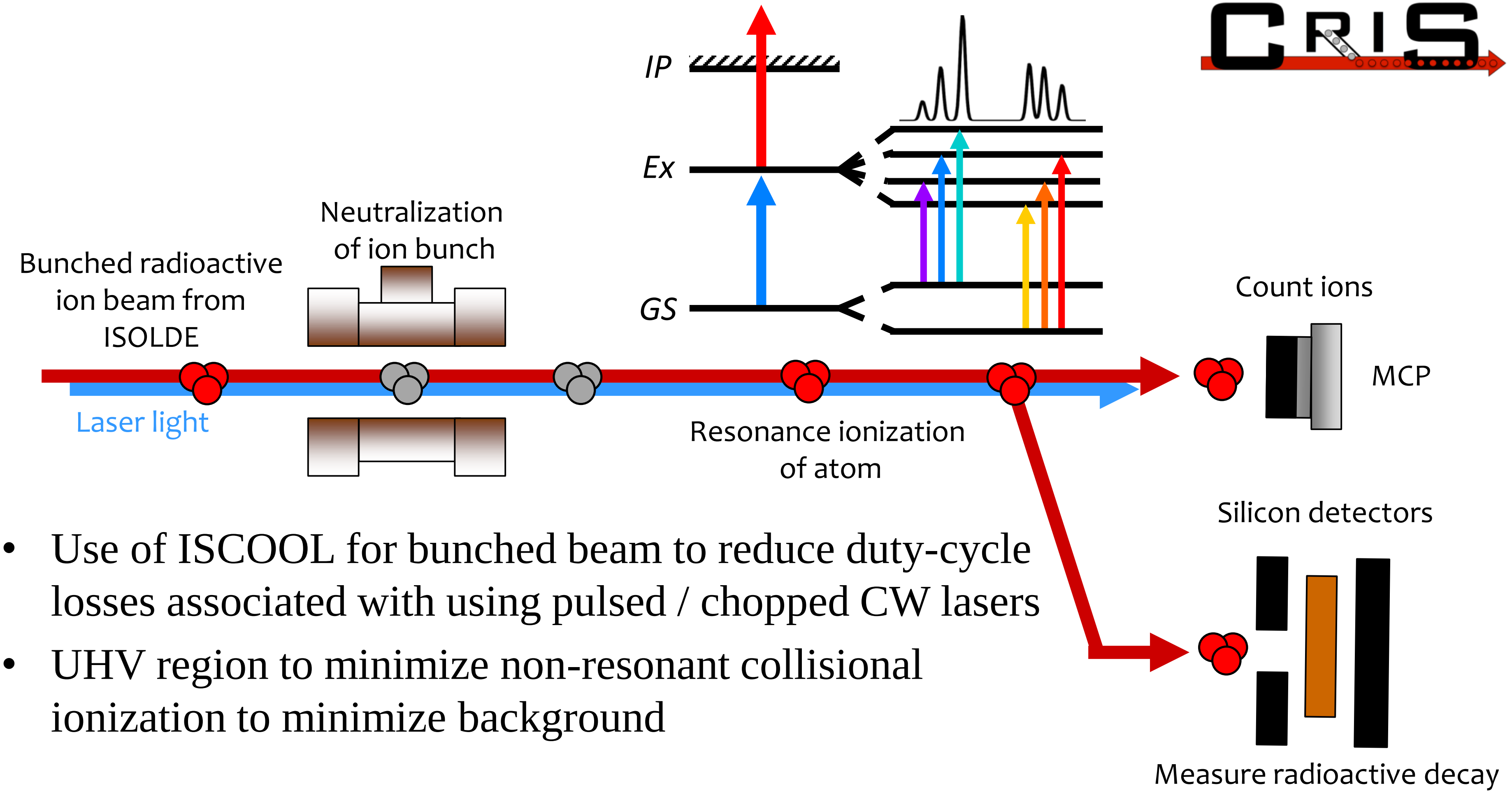


- New mass values show deviation from Atomic Mass Evaluation 2012
- Astrophysical network calculations with new data result in better agreement with the solar abundances in A=132 region
- High-precision mass measurements of additional *n*-rich nuclides accessible at FAIR important to support r-process studies

LaSpec

LaSpec – The CRIS technique

At LaSpec we endeavour to adapt and implement new techniques of laser spectroscopy of exotic radioactive nuclei. One such technique is CRIS, Collinear Resonance Ionization Spectroscopy.



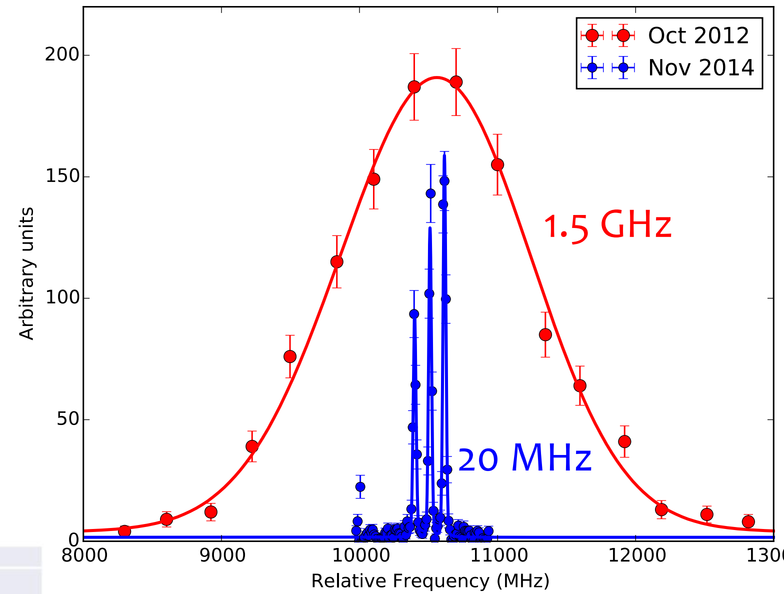
- Use of ISCOOL for bunched beam to reduce duty-cycle losses associated with using pulsed / chopped CW lasers
- UHV region to minimize non-resonant collisional ionization to minimize background

CRIS development

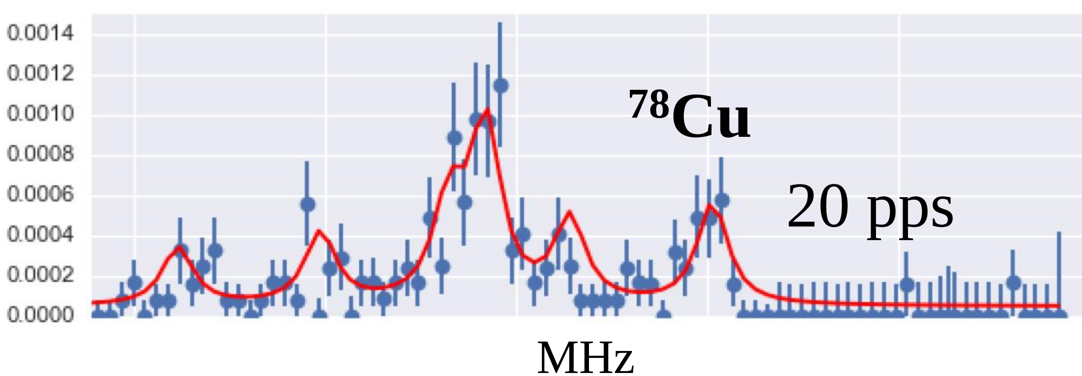
In 2015, a new method of chopped CW delayed ionization RIS was demonstrated that measured ^{219}Fr ($t_{1/2}$ = 20 ms) with a linewidth of 20(1) MHz.

This year, the CRIS experiment introduced an injection-seeded laser system (on loan from JYFL) to test 249 nm and measured ^{78}Cu with a yield of 20 pps as part of the ERC funded FNPMLS project.

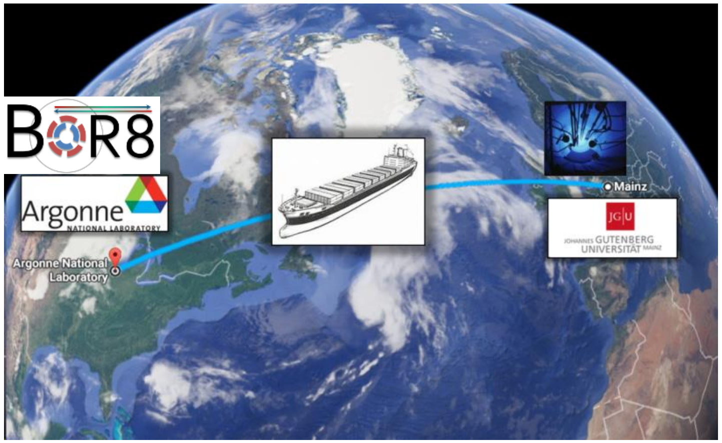
Background rate of 1 count every 400 s
Total experimental efficiency of ~1%

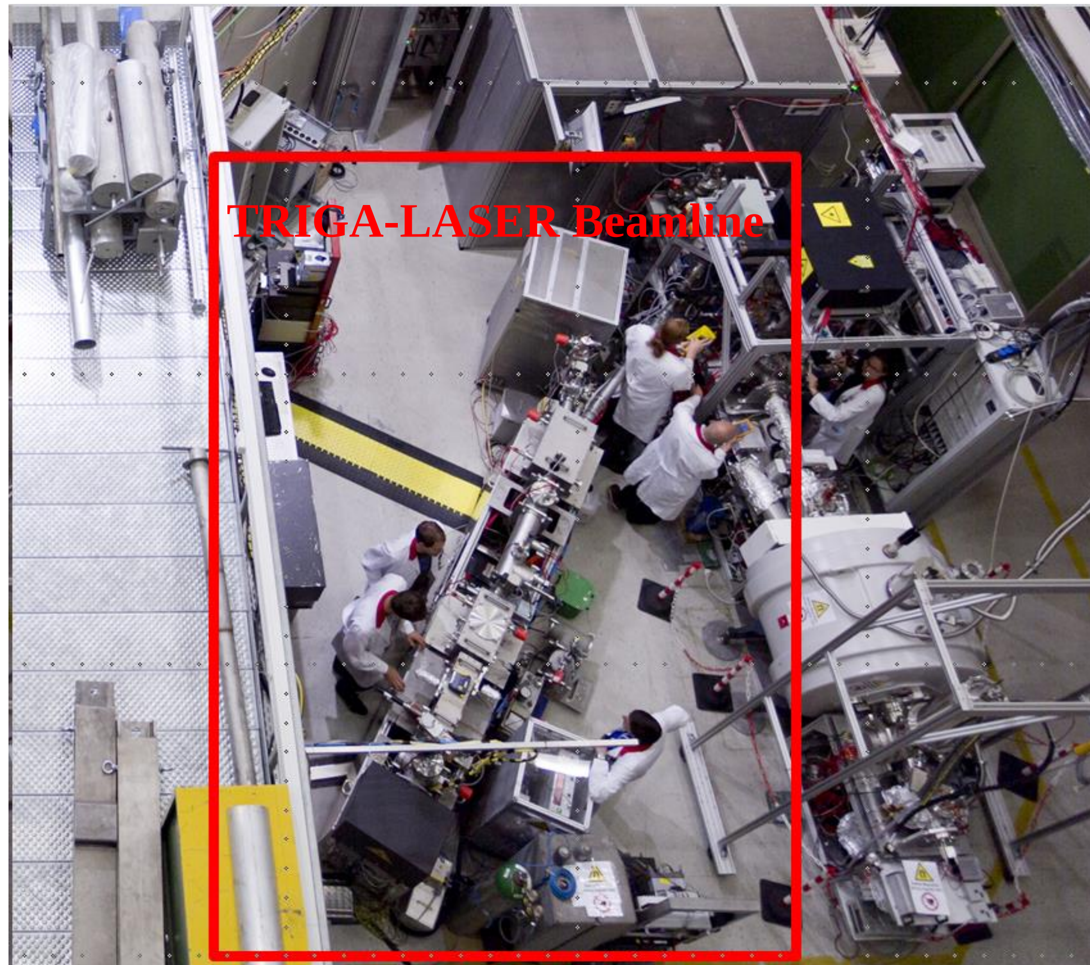


R. de Groote et al, Phys. Rev. Lett. 115, 13250 (2015)



LaSpec Phase 0



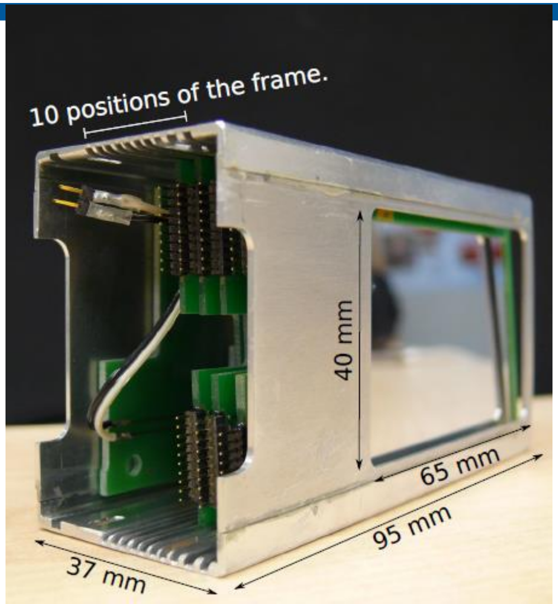


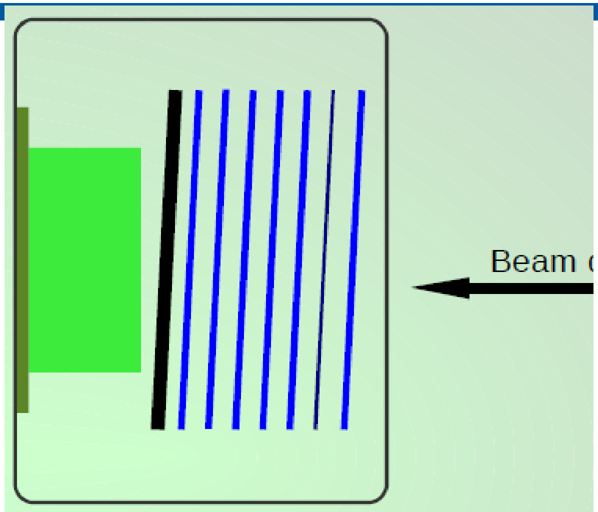
ATLAS & CARIBU:
Conditions comparable to LEB
(Beams at 5 kV)

→ Perfect place to test and optimize the new prototypes
→ Flagship experiment: charge radius of proton halo ^{8}B
→ CARIBU: many isotopes available from ^{252}Cf fission
→ 2021/22: Return to FAIR

ILIMA

ILIMA: CsISiPHOS detector for in-ring decay



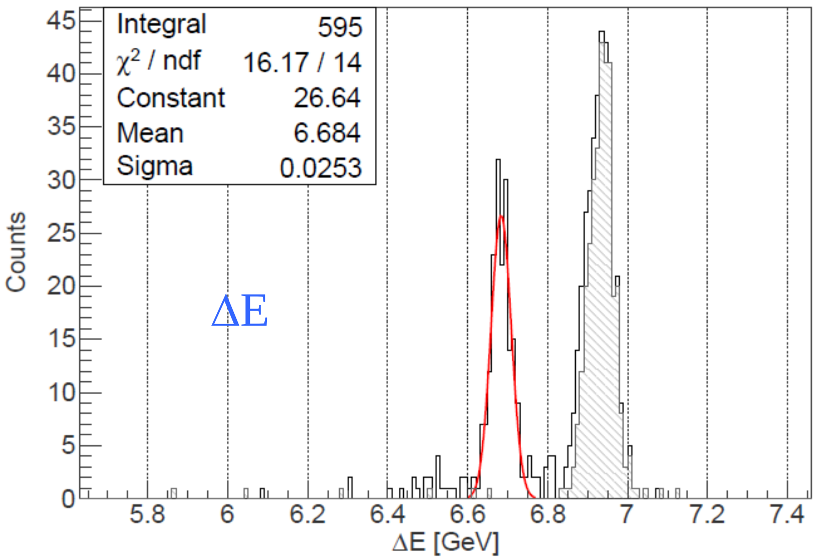


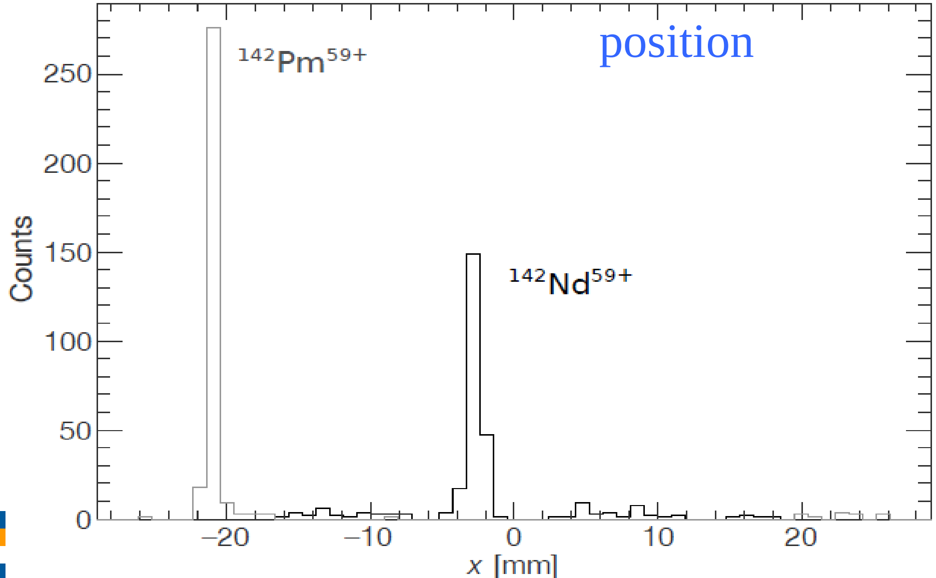
DSSD stack for ΔE-E active area 40mm x 60mm also with CsI calorimeter + Si photo-diode, to identity Z and A.

Prototype tested in the ESR:

Najafi et al., NIM A836 (2016) 1

β^+ decay: $^{142}Pm^{60+} \rightarrow {}^{142}Nd^{59+}$, atomic electron capture $\rightarrow {}^{142}Pm^{59+}$





ILIMA: Phase 0

- **Mass, isomer and lifetime measurements will be done for heavy neutron-rich nuclei, especially in the region of the nuclear chart between ^{208}Pb and the r-process path.**

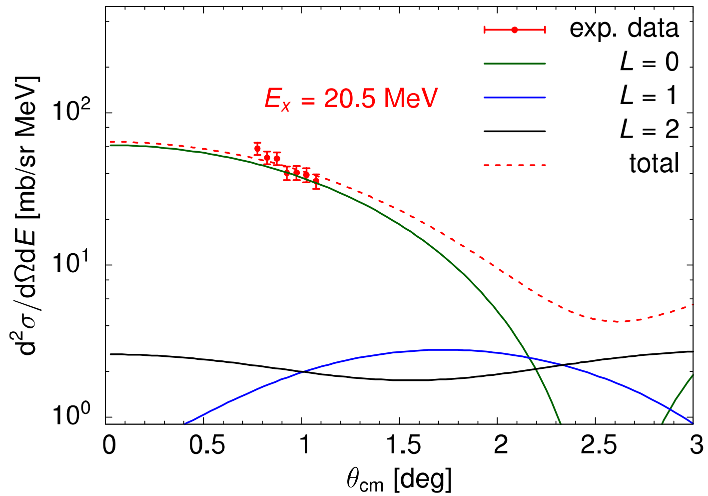
- **These measurements would be done at the ESR by employing an improved time-of-flight detector as well as novel non-destructive highly-sensitive Schottky detectors.**

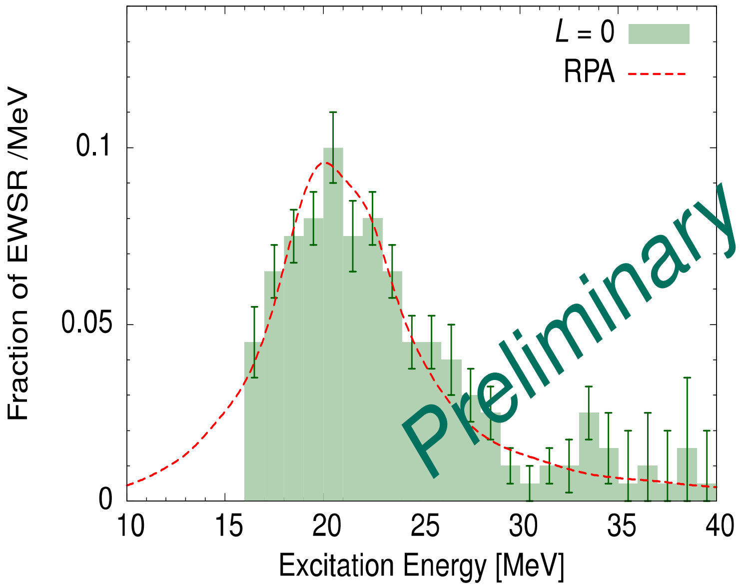
- **Experiments addressing the influence of atomic shells on nuclear decay rates will be conducted at lowest energies at CRYRING.**

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

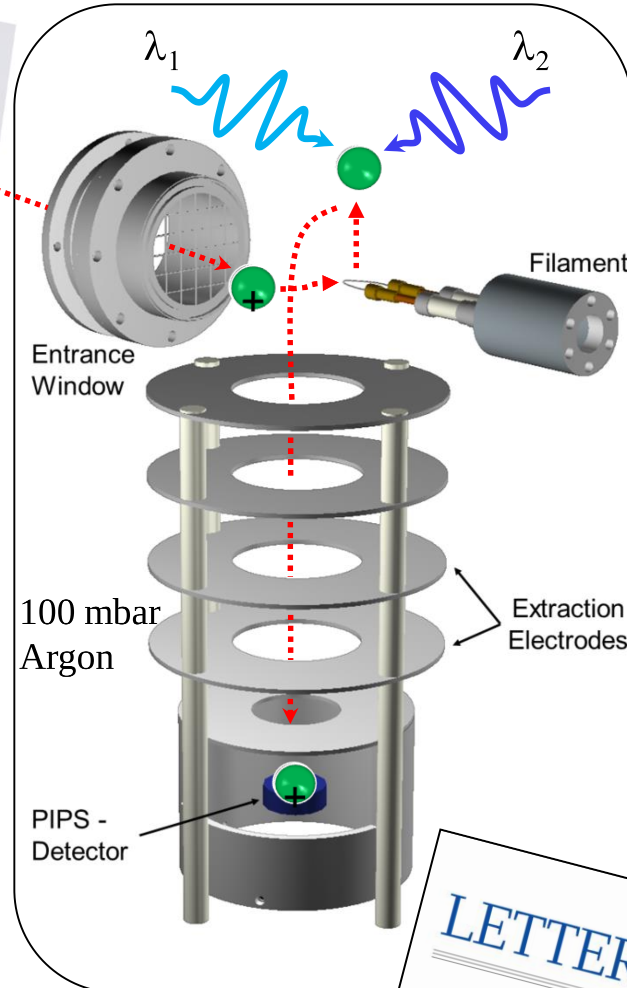
➔ Further reduced background

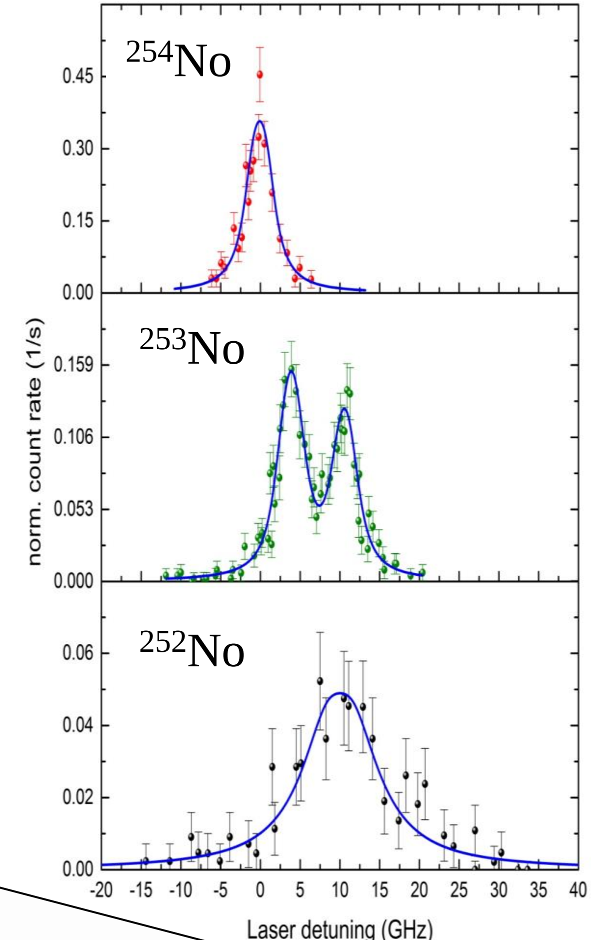
➔ First measurement of the Giant Monopole Resonance in an unstable nucleus will be possible already in 2019!

SHE

Super Heavy Elements (SHE):

First Spectroscopic Investigation of Nobelium (Z=102)





Achievements:

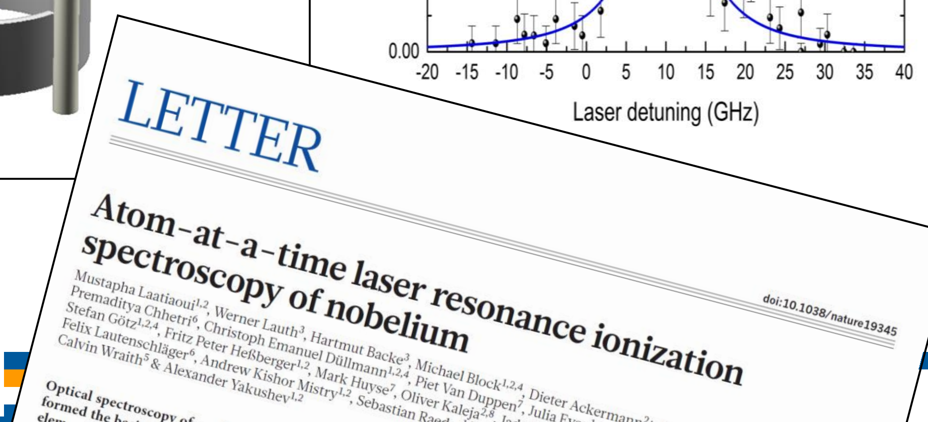
➔ First ever successful laser spectroscopy beyond fermium

➔ Production rates: ~ 1 atom/s

➔ Overall efficiency up to 10%

➔ First ionization potential of nobelium precisely measured

➔ Nuclear spin and moments extracted for the isotope ^{253}No



LETTER

doi:10.1038/nature19345

Atom-at-a-time laser resonance ionization spectroscopy of nobelium

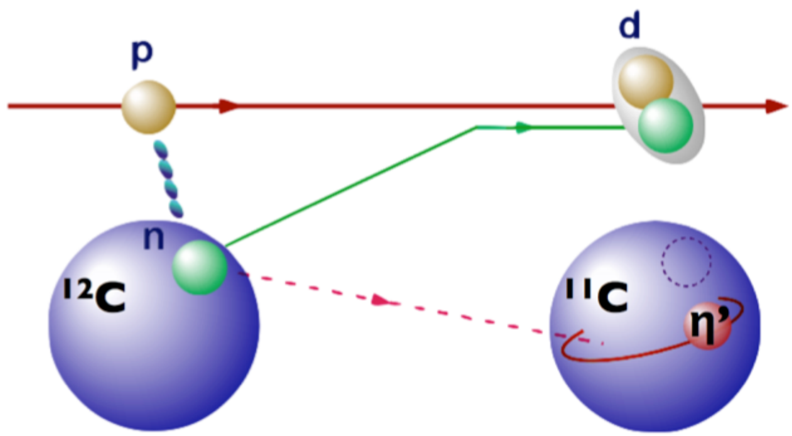
Mustapha Laatiaoui[1,2], Werner Lauth[3], Hartmut Backe[3], Michael Block[1,2,4], Dieter Ackermann
Premaditya Chhetri[6], Christoph Emanuel Düllmann[1,2,4], Piet Van Duppen[7], Julia Ev
Stefan Götz[1,2,4], Fritz Peter Heßberger[1,2], Mark Huyse[7], Oliver Kaleja
Felix Lautenschläger[6], Andrew Kishor Mistry[1,2], Sebastian Raed
Calvin Wraith[5] & Alexander Yakushev[1,2]

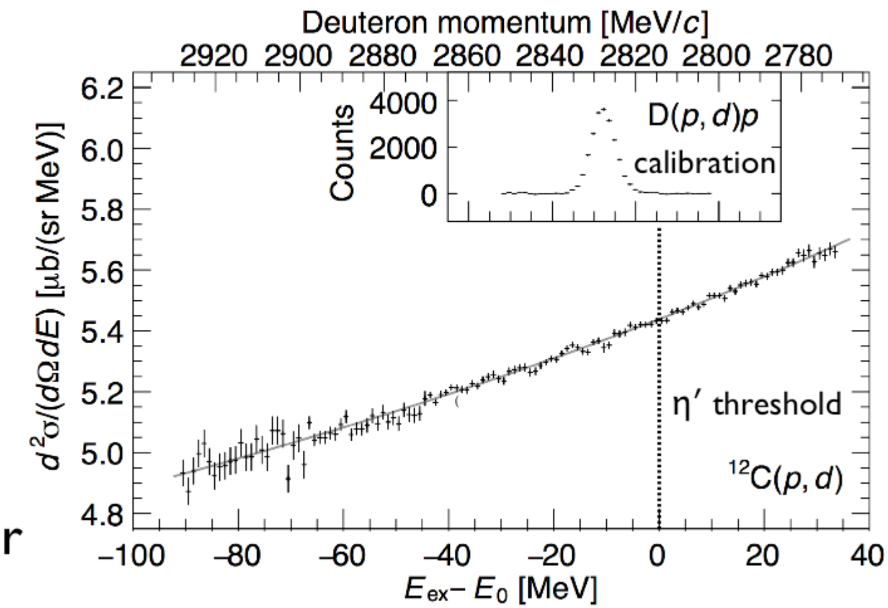
Optical spectroscopy of
formed the b

Media coverage

Super-FRS

Search for η′ mesic nuclei by spectroscopy of $^{12}C(p,d)$ reaction with FRS





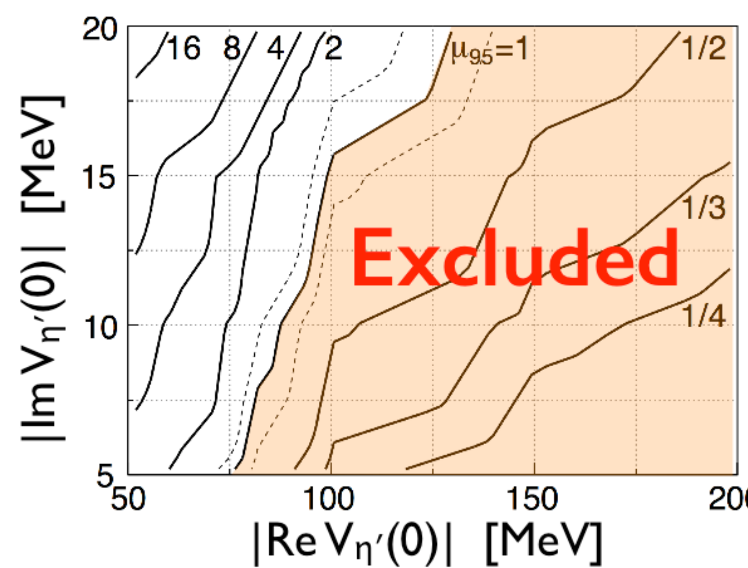
- ◇ FRS used as high-resolution spectrometer
- ◇ extremely good statistics achieved
- ◇ stringent constraints on η′-nucleus potential

PRL 117, 202501 (2016) PHYSICAL REVIEW LETTERS week ending 11 NOVEMBER 2016

Measurement of Excitation Spectra in the $^{12}C(p, d)$ Reaction near the η' Emission Threshold

Y. K. Tanaka,[1,*] K. Itahashi,[2,†] H. Fujioka,[3,‡] Y. Ayyad,[4] J. Benlliure,[5] K.-T. Brinkmann,[6] S. Friedrich,[6] H. Geissel,[6,7] J. Gellanki,[8] C. Guo,[9] E. Gutz,[6] E. Haettner,[7] M. N. Harakeh,[8] R. S. Hayano,[1] Y. Higashi,[10] S. Hirenzaki,[10] C. Hornung,[6] Y. Igarashi,[11] N. Ikeno,[12] M. Iwasaki,[2] D. Jido,[13] N. Kalantar-Nayestanaki,[8] R. Kanungo,[14] R. Knöbel,[6,7] N. Kurz,[7] V. Metag,[6] I. Mukha,[7] T. Nagae,[3] H. Nagahiro,[10] M. Nanova,[6] T. Nishi,[2] H. J. Ong,[4] S. Pietri,[7] A. Prochazka,[7] C. Rappold,[7] M. P. Reiter,[7] J. L. Rodríguez-Sánchez,[5] C. Scheidenberger,[6,7] H. Simon,[7] B. Sitar,[15] P. Strmen,[15] B. Sun,[9] K. Suzuki,[16] I. Szarka,[15] M. Takechi,[17] I. Tanihata,[4,9] S. Terashima,[9] Y. N. Watanabe,[1] H. Weick,[7] E. Widmann,[16] J. S. Winfield,[7] X. Xu,[6,7] H. Yamakami,[3] and J. Zhao[9]

(η-PRiME/Super-FRS Collaboration)



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 ($\Lambda_{free} \rightarrow p\pi^-$ or $n\pi^0$, $\tau \sim 0.26$ ns)

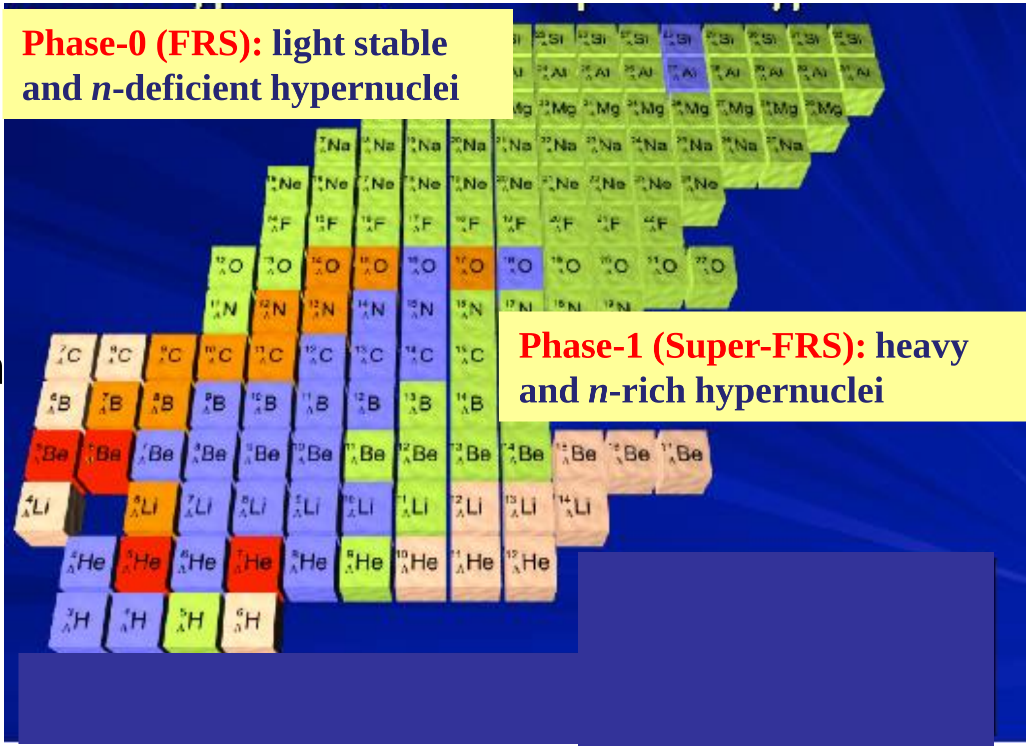
  (Lorentz factor on lifetime!)

- **Pilot experiments at GSI (HypHI) show evidence of $^3_\Lambda$H, $^4_\Lambda$H, $^3_\Lambda$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)

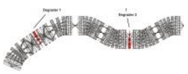
A. Botvina et al., Phys Rev C 88, 054605 (2013)

Strangeness sector of nuclear chart

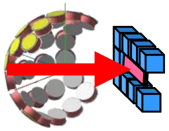


Complementarity of NUSTAR experiments

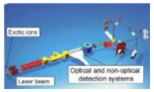
Super-FRS



HISPEC/ DESPEC

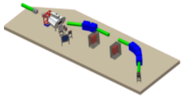


LASPEC

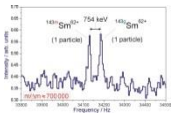


MATS

R3B

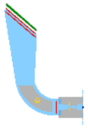


ILIMA



SHE

ELISE

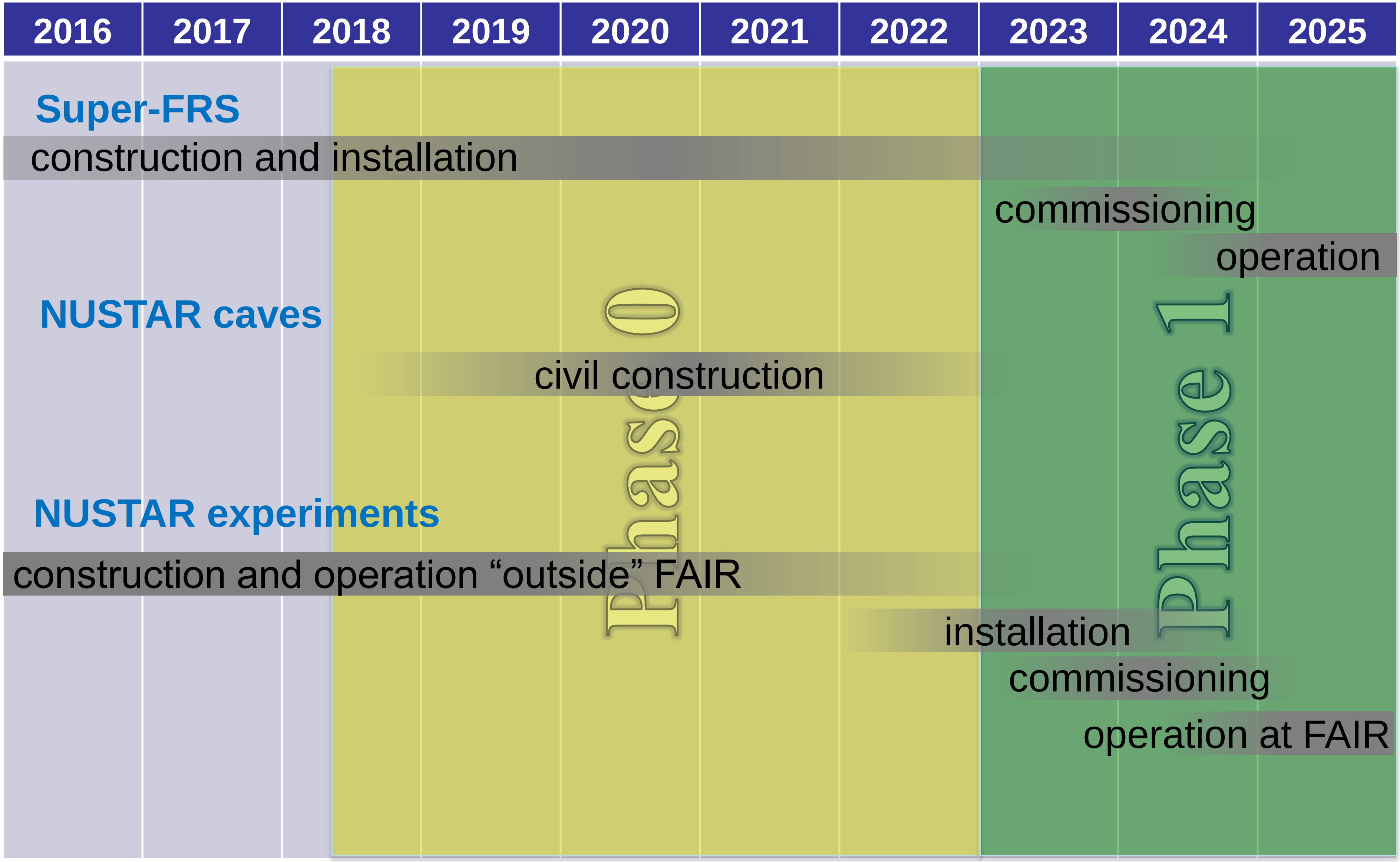


EXL

	Super-FRS	HISPEC/DESPEC	LASPEC	MATS	R3B	ILIMA	SHE	ELISe	EXL
Masses		Q-values, isomers		dressed ions, highest precision	unbound nuclei	bare ions, mapping study	precision mass of SHEs		
Half-lives	ps...ns-range	dressed ions, ms...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.								

Timeline

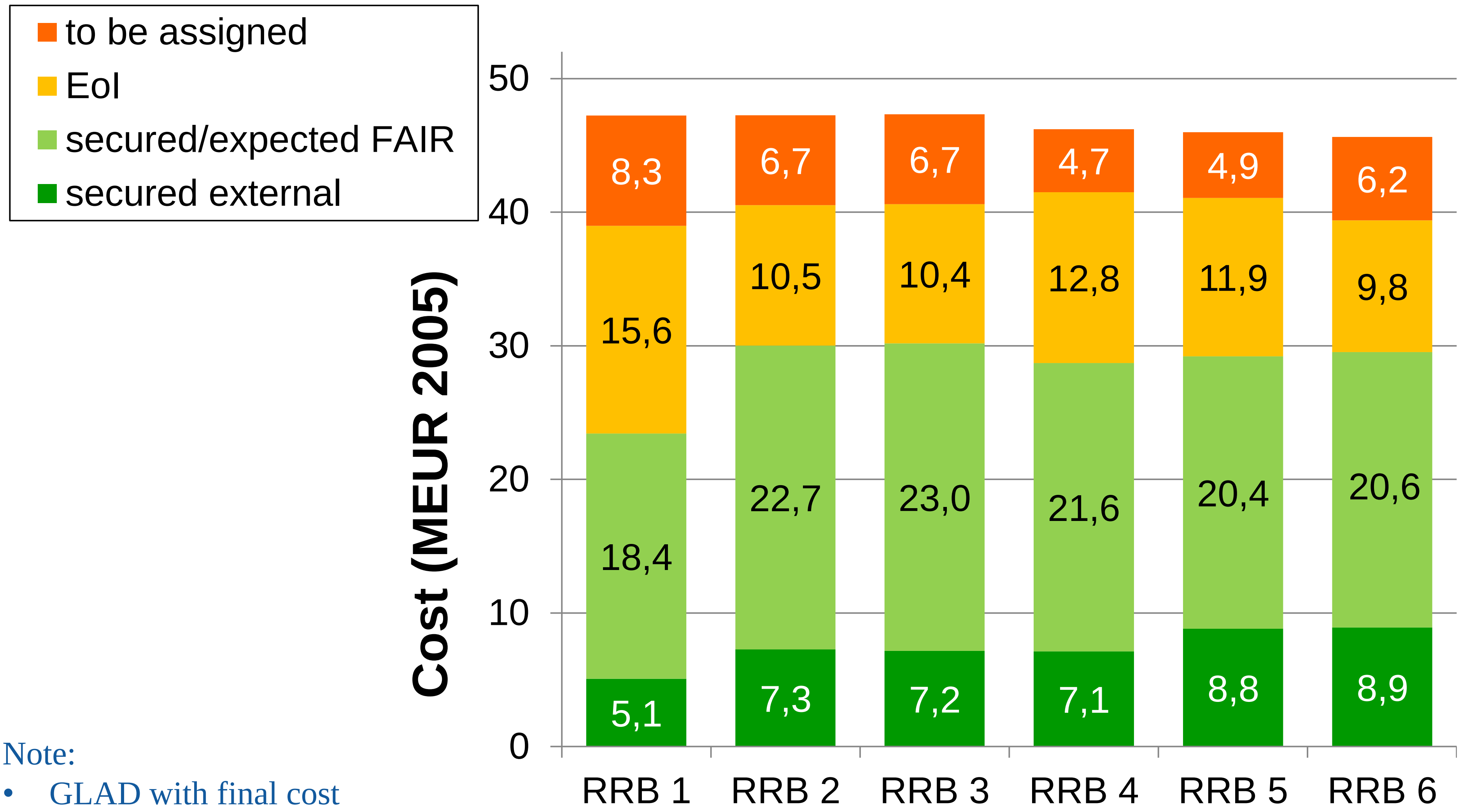
Scenario for NUSTAR Phase 0 and 1



Thank you!

Funding and TDRs

Evolution of NUSTAR project funding



Note:

- GLAD with final cost
- UK included in FAIR

Status of NUSTAR experiment funding