# NUSTAR Overview

J. Gerl

HIC4FAIR Workshop Detectors & Accelerators

Hamburg, Germany

July 2015

# NUclear STructure Astrophysics and Reactions

**What are the limits for existence of nuclei?**

- Where are the proton and neutron drip lines situated?
- Where does the nuclear chart end?

**How does the nuclear force depend on varying proton-to-neutron ratios?**

- What is the isospin dependence of the spin-orbit force?
- How does shell structure change far away from stability?

**How to explain collective phenomena from individual motion?**

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

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

- What is the effective nucleon-nucleon interaction?
- How does QCD constrain its parameters?

**Which are the nuclei relevant for astrophysical processes and what are their properties?**

- What is the origin of the heavy elements?

# NUSTAR - The Project

| | |
|---|---|
| **DESPEC** | γ-, β-, α-, p-, n-decay spectroscopy |
| **ELISE** | elastic, inelastic, and quasi-free $e^-$-A scattering |
| **EXL** | light-ion scattering reactions in invere kinematics |
| **HISPEC** | in-beam γ spectroscopy at low and intermediate energy |
| **ILIMA** | masses and lifetimes of nuclei in ground and isomeric states |
| **LASPEC** | Laser spectroscopy |
| **MATS** | in-trap mass measurements and decay studies |
| **R3B** | kinematically complete reactions at high beam energy |
| **Super FRS** | RIB production, identification and spectroscopy |
| **SHE** | Nuclear physics and chemistry of super-heavy elements |

**The Approach**

Complementary measurements leading to consistent answers

**The Collaboration**

> 850 scientists

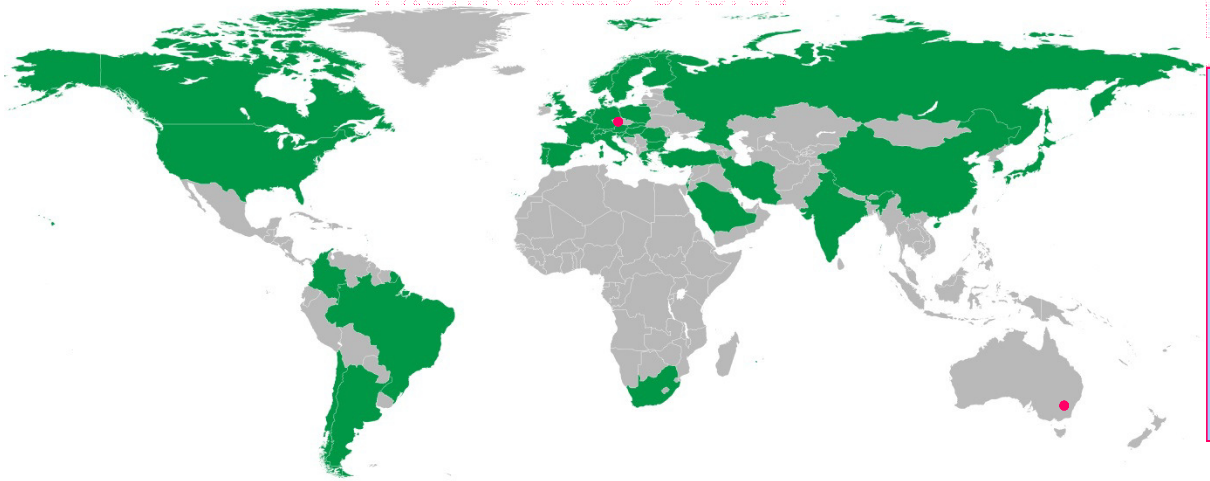
184 institutes

39 countries

# NUSTAR - The Project

**Evolutionary approach:**

**Advancing instrumentation by continuous development and gaining experience by physics exploitation**



**The Approach**

Complementary measurements leading to consistent answers

**The Collaboration**

> 850 scientists

184 institutes

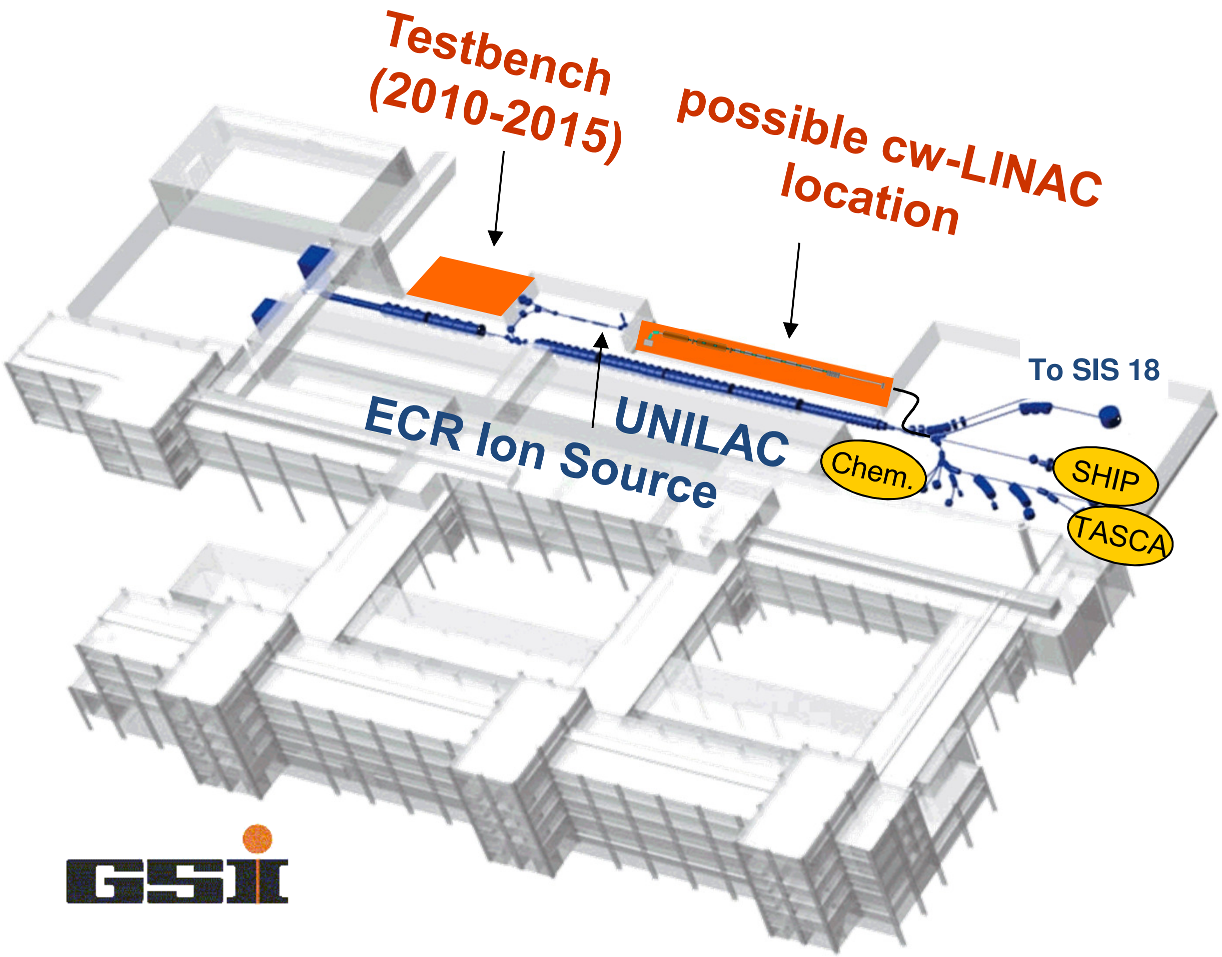
39 countries

**>50 instrumentation sub-projects (MSV)**

**several 1000 major components**

# SHE @ GSI: Toward a Dedicated cw LINAC

**UNILAC not suited for simultaneous**
- **FAIR (A>180, ≤3 Hz, 100 μs pulses)**
- **SHE operation (A<80, long duty cycle)**




**Paving the way for dedicated superconducting cw-LINAC:**

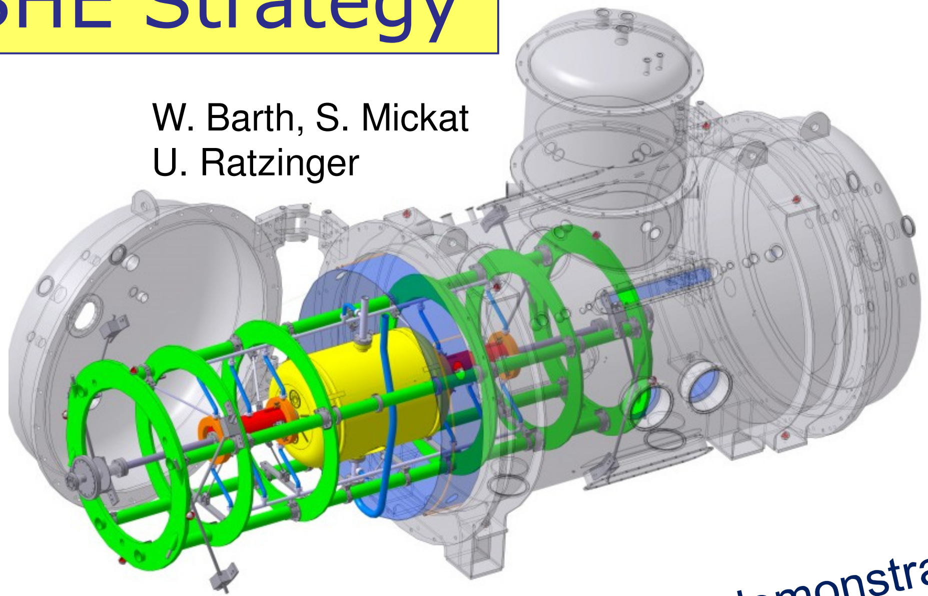
**Energy: 3.5-7.5 MeV/u**

**Uncertainty: <3 keV/u**

**Duty cycle: 100%**

# SHE Strategy

W. Barth, S. Mickat
U. Ratzinger



**Staged approach:**

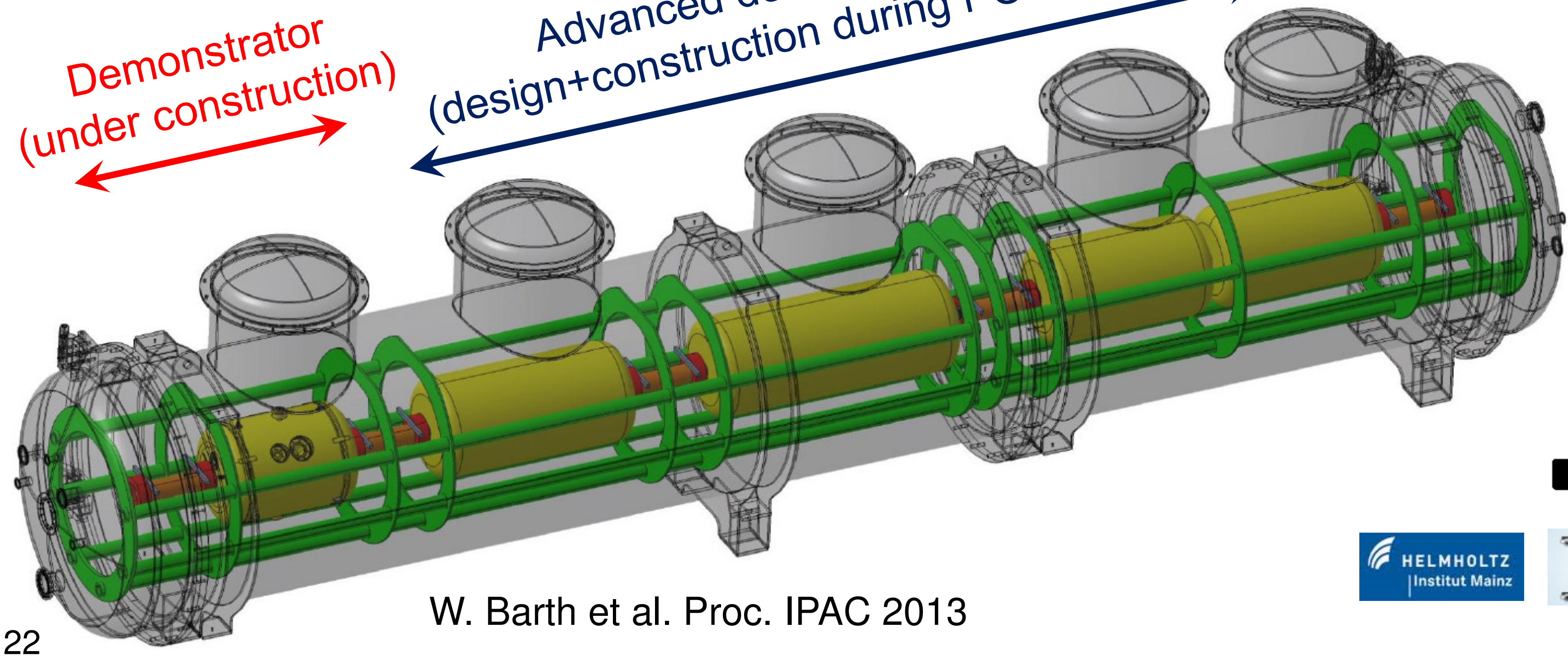
**1.** Construct first cavity as a prototype to demonstrate feasibility.
Commissioning: 2015

**2.** Construct multicell string during POF 3 (2015-2019)
Useful for SHE research, synergies for FAIR!

**3.** Construct full linac

Demonstrator (under construction)

Advanced demonstrator (design+construction during POF-III)

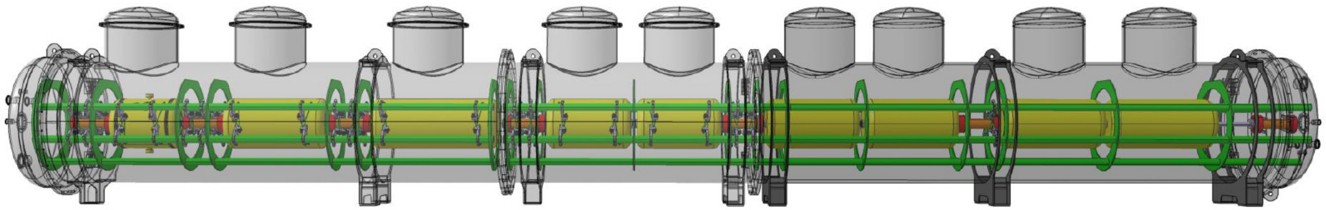


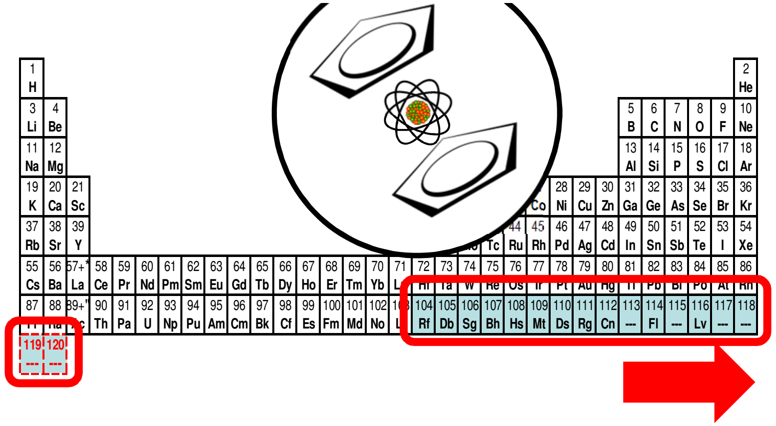
W. Barth et al. Proc. IPAC 2013

# SHE research 2020+

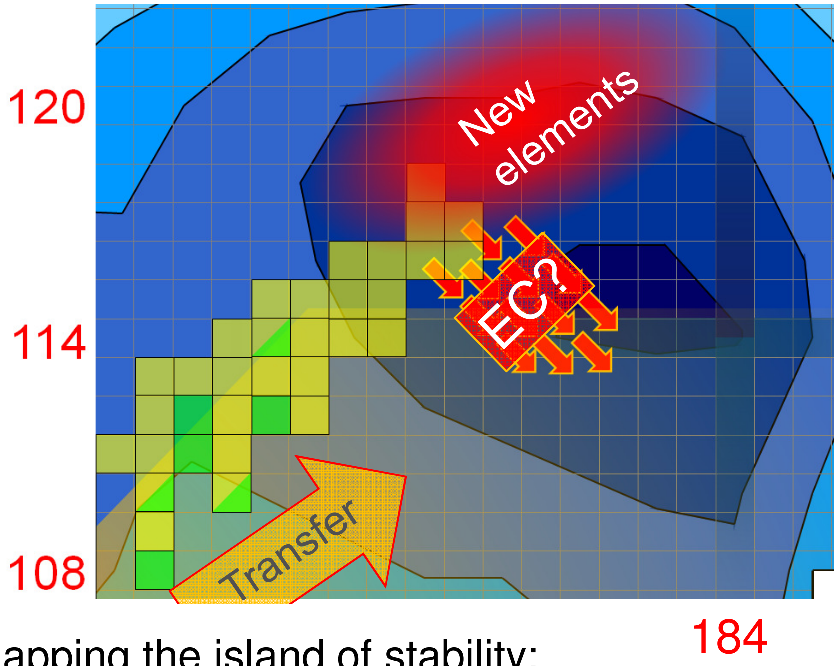
## New cw linac

**$E_{Beam}$ up to 7.3 MeV/u**
**Length: 13.5 m**





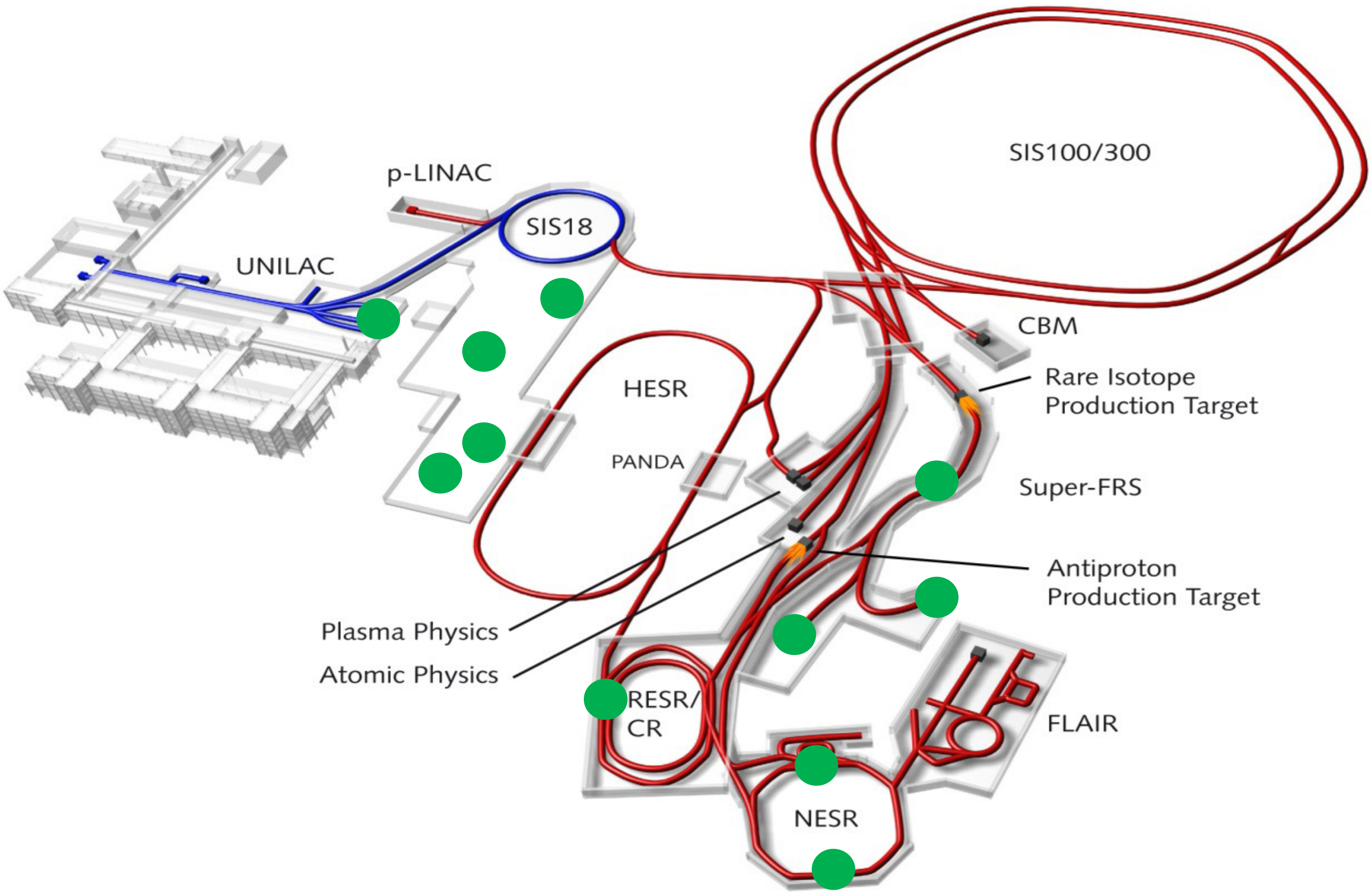
- Atomic structure beyond No (Z=102)
- Experiments with single SHE-ions (e.g. chemistry + mass spec)
- Chemical studies towards Eka-Rn
- New SHE molecules, their stability, formation kinetics
- New period in the periodic table



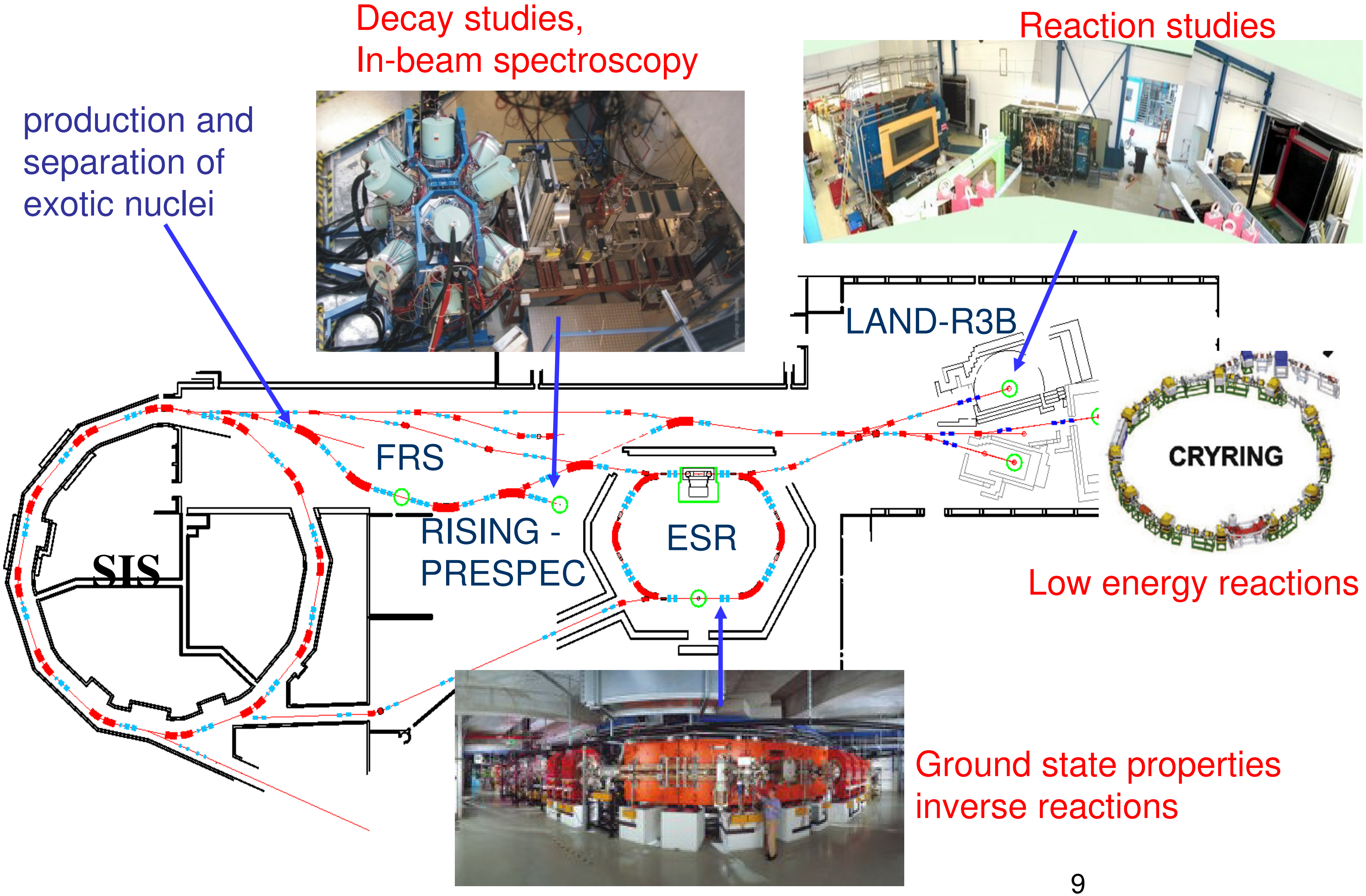

Mapping the island of stability:

- New elements with Z>118
- Neutron-rich isotopes in transfer reactions
- Weak EC decay channels towards center of island
- Direct mapping of shell evolution towards N=184

# NUSTAR uses GSI and FAIR



# Existing and new research opportunities at SIS/FRS/ESR



# NUSTAR - The Facility

**Low Energy Branch**:

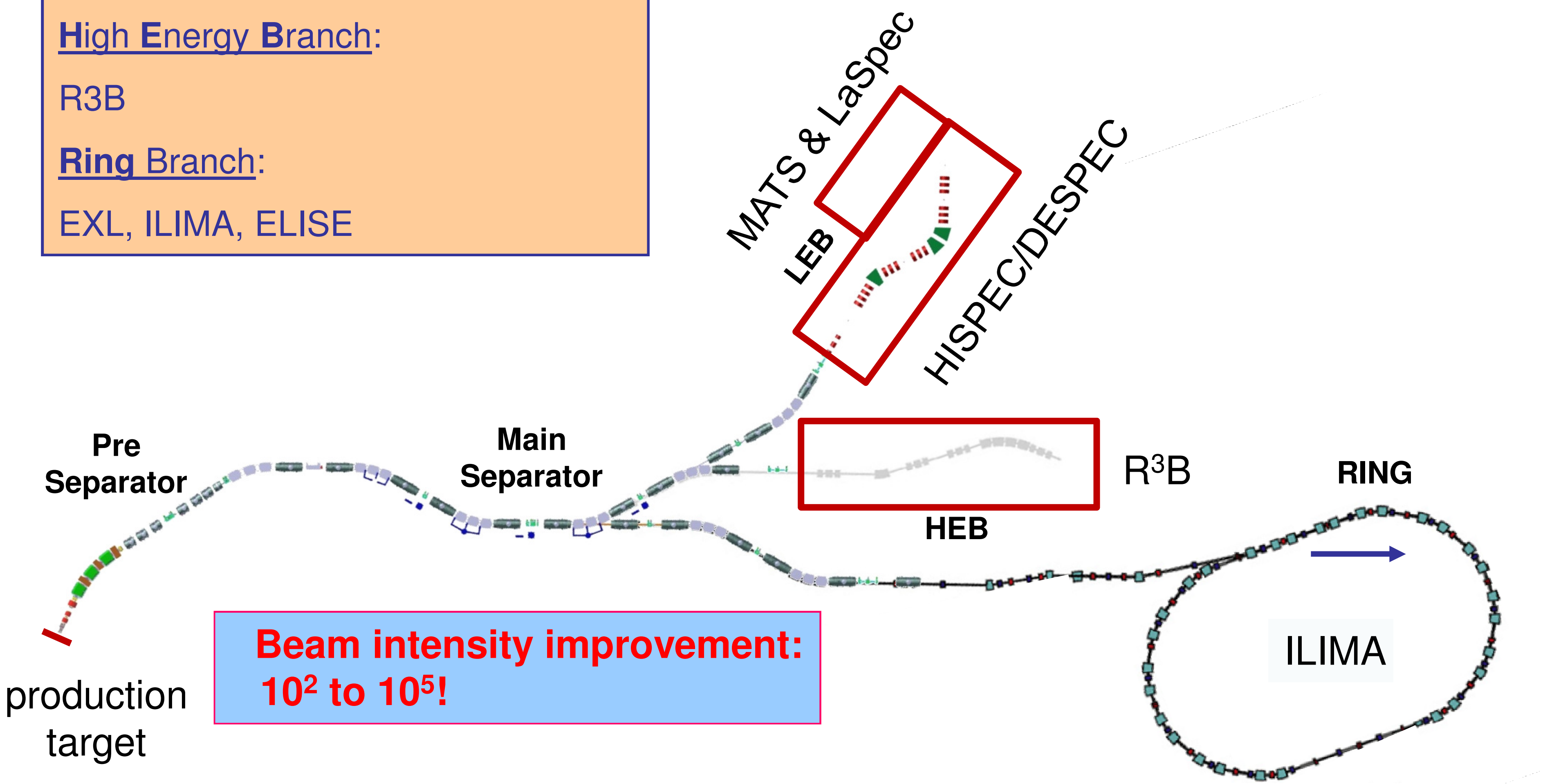
HISPEC, DESPEC, MATS, LASPEC

**High Energy Branch**:

R3B

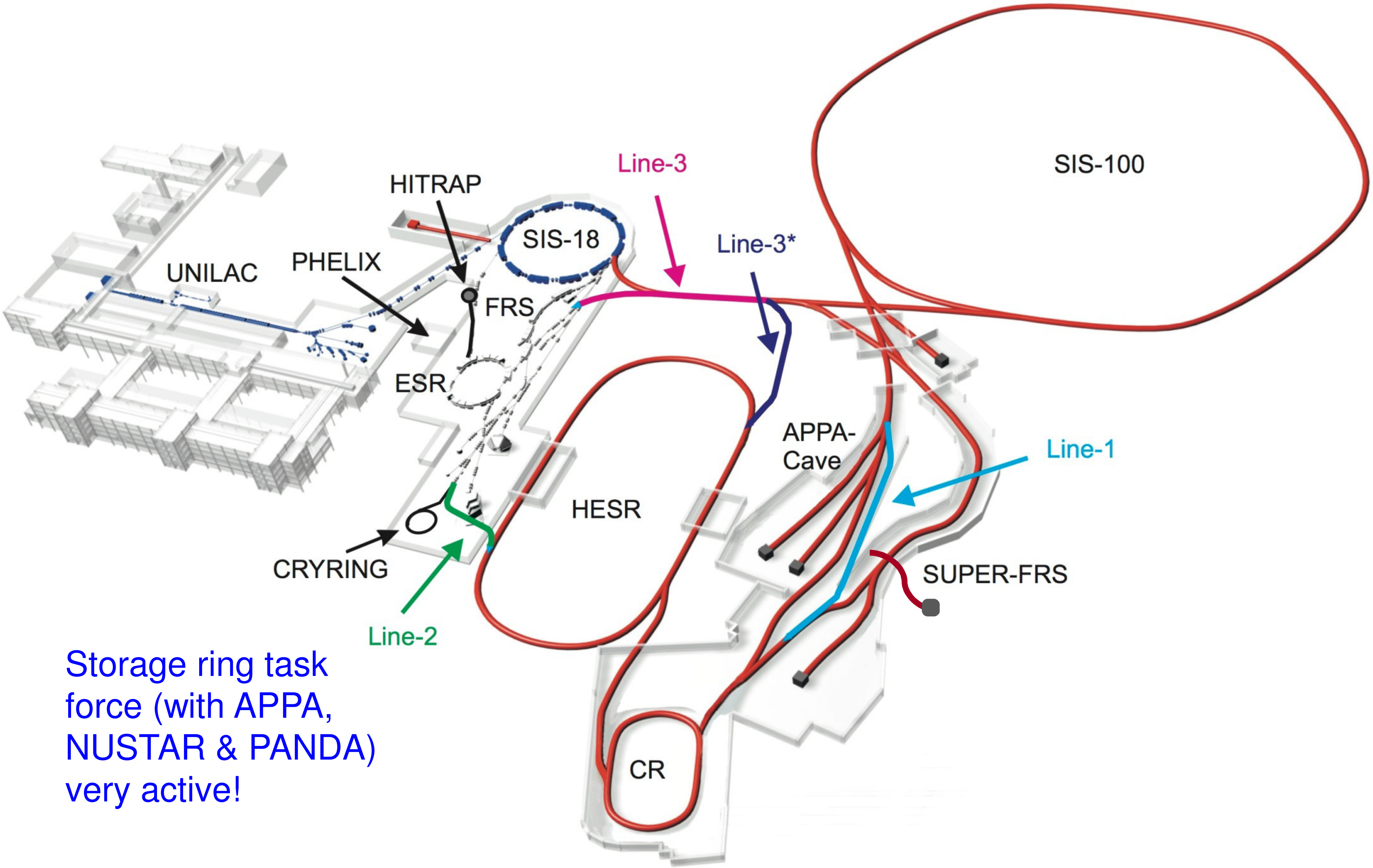
**Ring Branch**:

EXL, ILIMA, ELISE




**Beam intensity improvement: $10^2$ to $10^5$!**

# Future transfer line to HESR/ESR/CRYRING




Storage ring task force (with APPA, NUSTAR & PANDA) very active!

# Super-FRS as an experimental setup

## High-resolution spectrometer for relativistic beams

<u>Important beam parameters:</u>
- all elements from H through U
- intensity up to ~ $10^{12}$ ions/sec.
- beam energies up to 1.5 GeV/u
- slow (DC-type) extraction

<u>Super-FRS characteristics:</u>

$\varepsilon_x = \varepsilon_y = 40\ \pi$ mm mrad

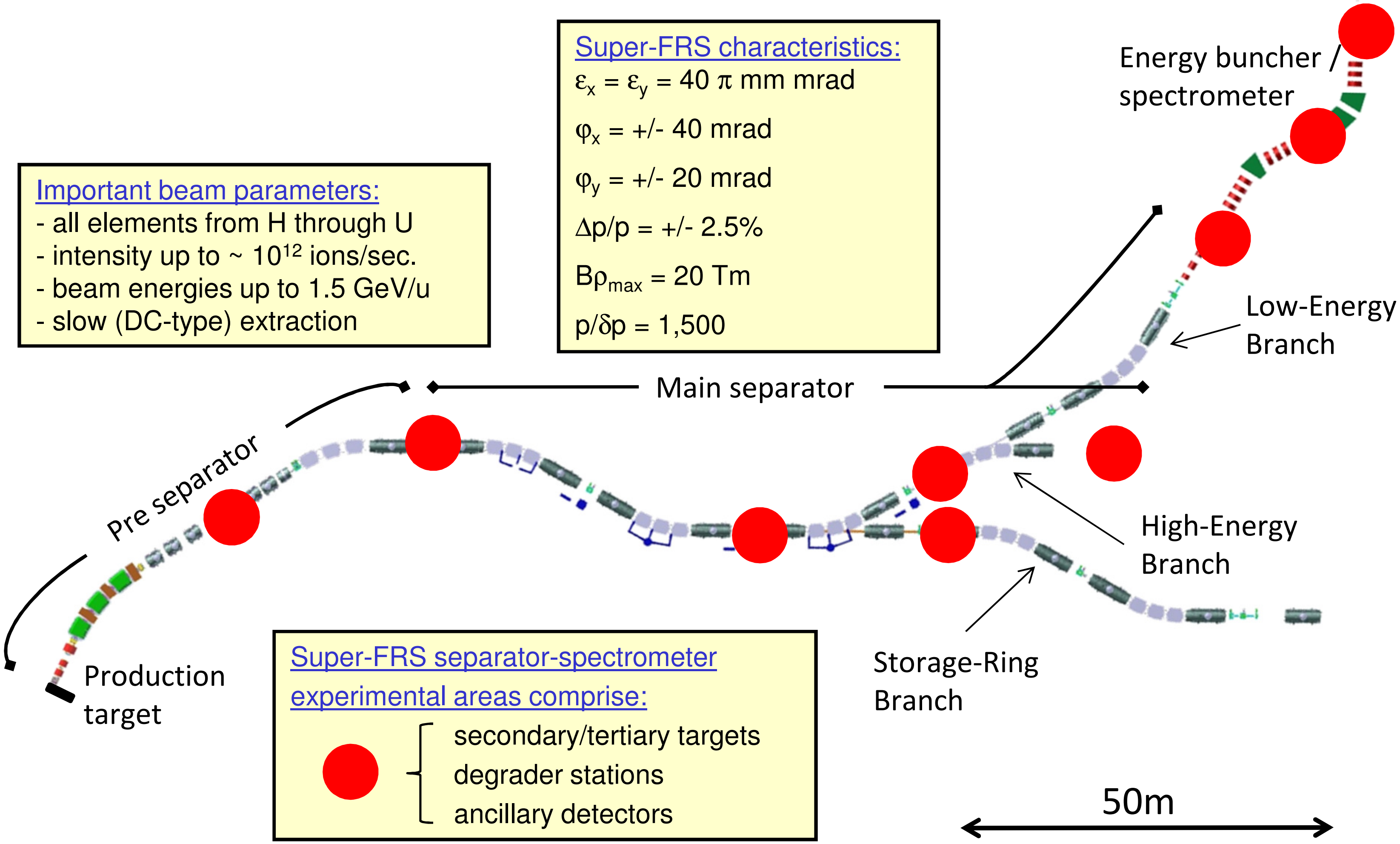
$\varphi_x$ = +/- 40 mrad

$\varphi_y$ = +/- 20 mrad

$\Delta p/p$ = +/- 2.5%

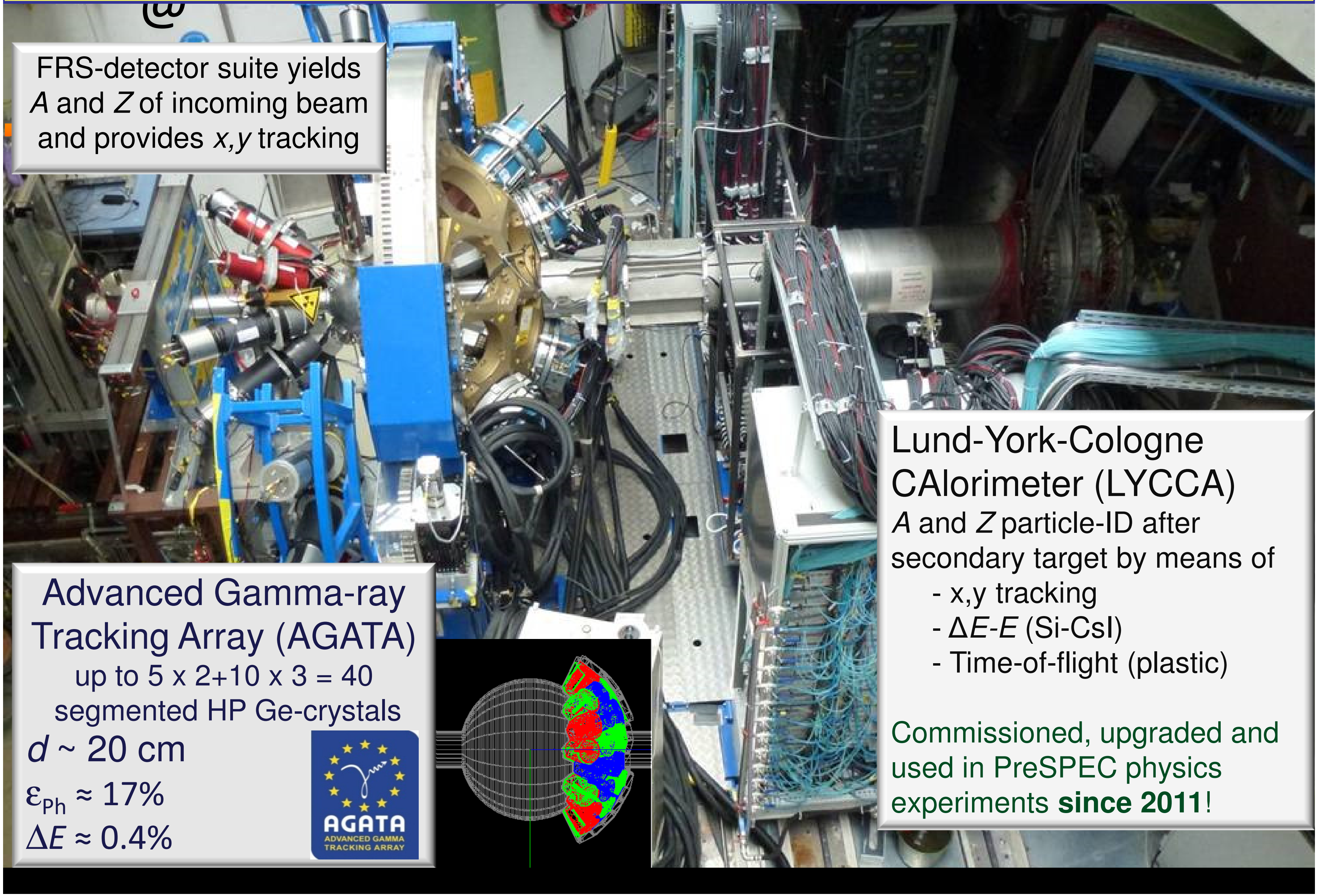
$B\rho_{max}$ = 20 Tm

$p/\delta p$ = 1,500




<u>Super-FRS separator-spectrometer experimental areas comprise:</u>
- secondary/tertiary targets
- degrader stations
- ancillary detectors

# PreSPEC-AGATA 2012-2014: Early Implementation of HISPEC



FRS-detector suite yields *A* and *Z* of incoming beam and provides *x,y* tracking

## Advanced Gamma-ray Tracking Array (AGATA)

up to 5 x 2+10 x 3 = 40 segmented HP Ge-crystals

$d$ ~ 20 cm

$\varepsilon_{Ph} \approx 17\%$

$\Delta E \approx 0.4\%$

## Lund-York-Cologne CAlorimeter (LYCCA)

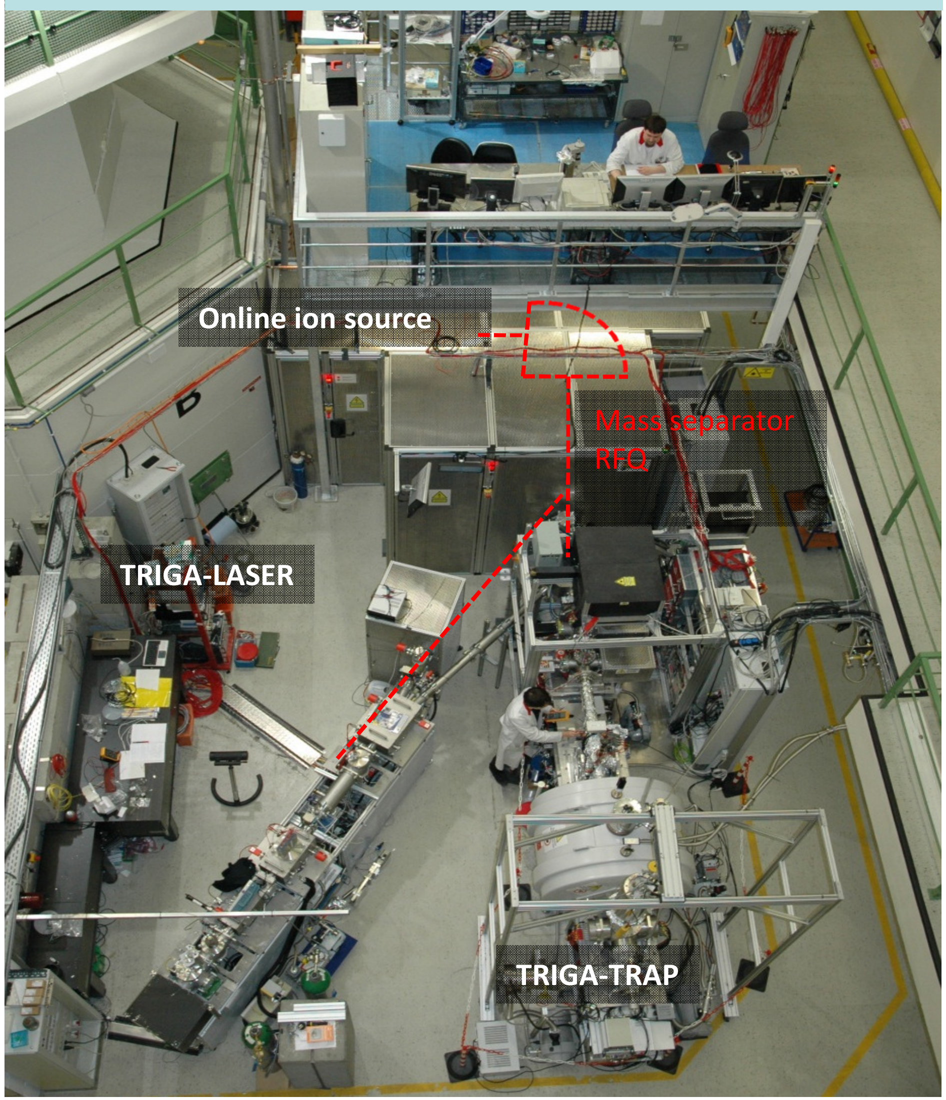
*A* and *Z* particle-ID after secondary target by means of

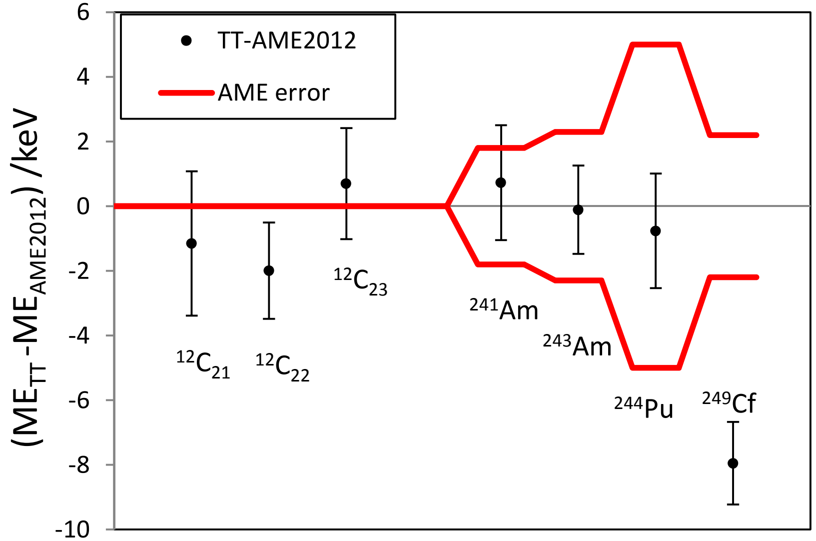
- x,y tracking
- Δ*E*-*E* (Si-CsI)
- Time-of-flight (plastic)

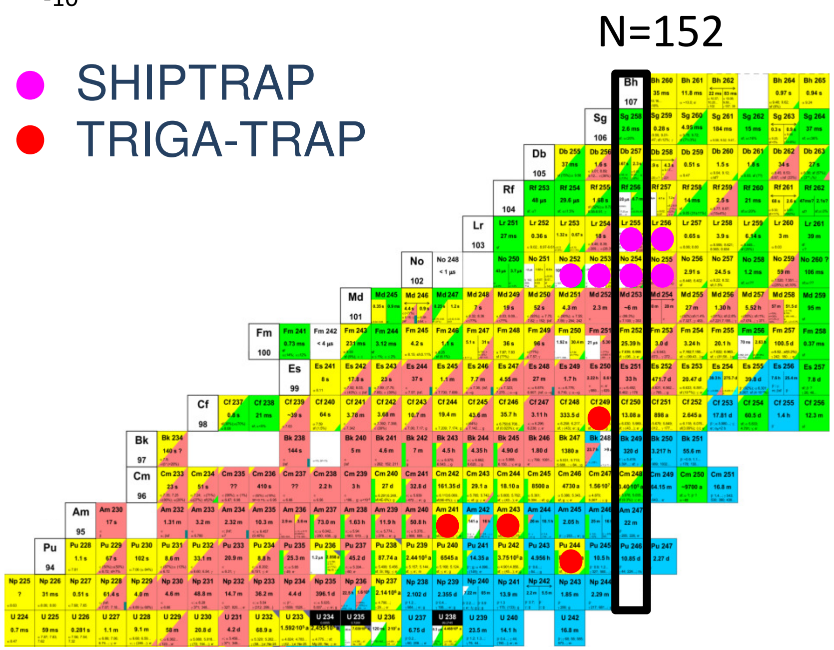
Commissioned, upgraded and used in PreSPEC physics experiments **since 2011**!

# Mass Measurements at TRIGA-TRAP in 2013
# Phase 0 of MATS

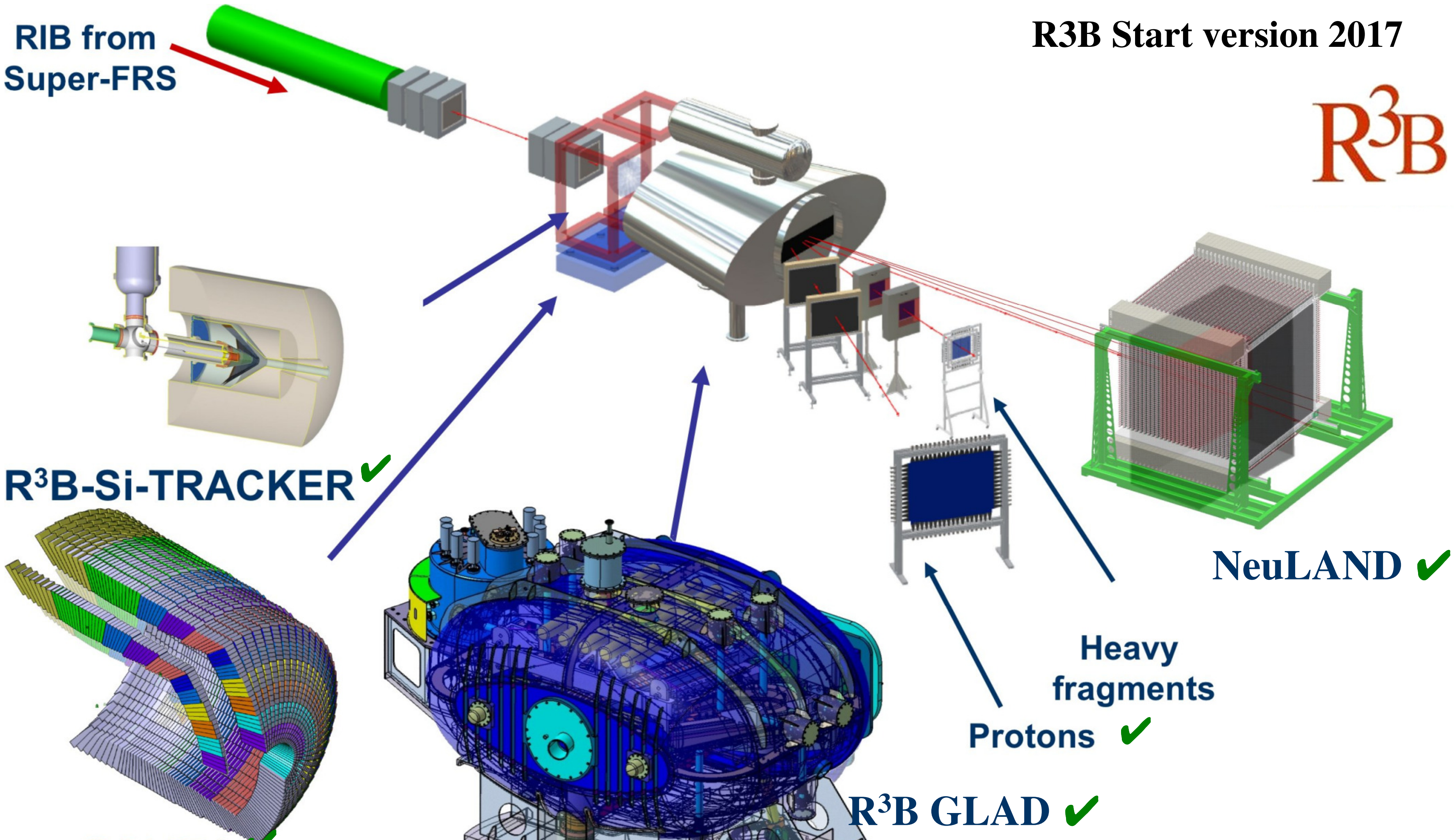
**project start @ TRIGA: 01/2008**
**start data taking: 05/2009**



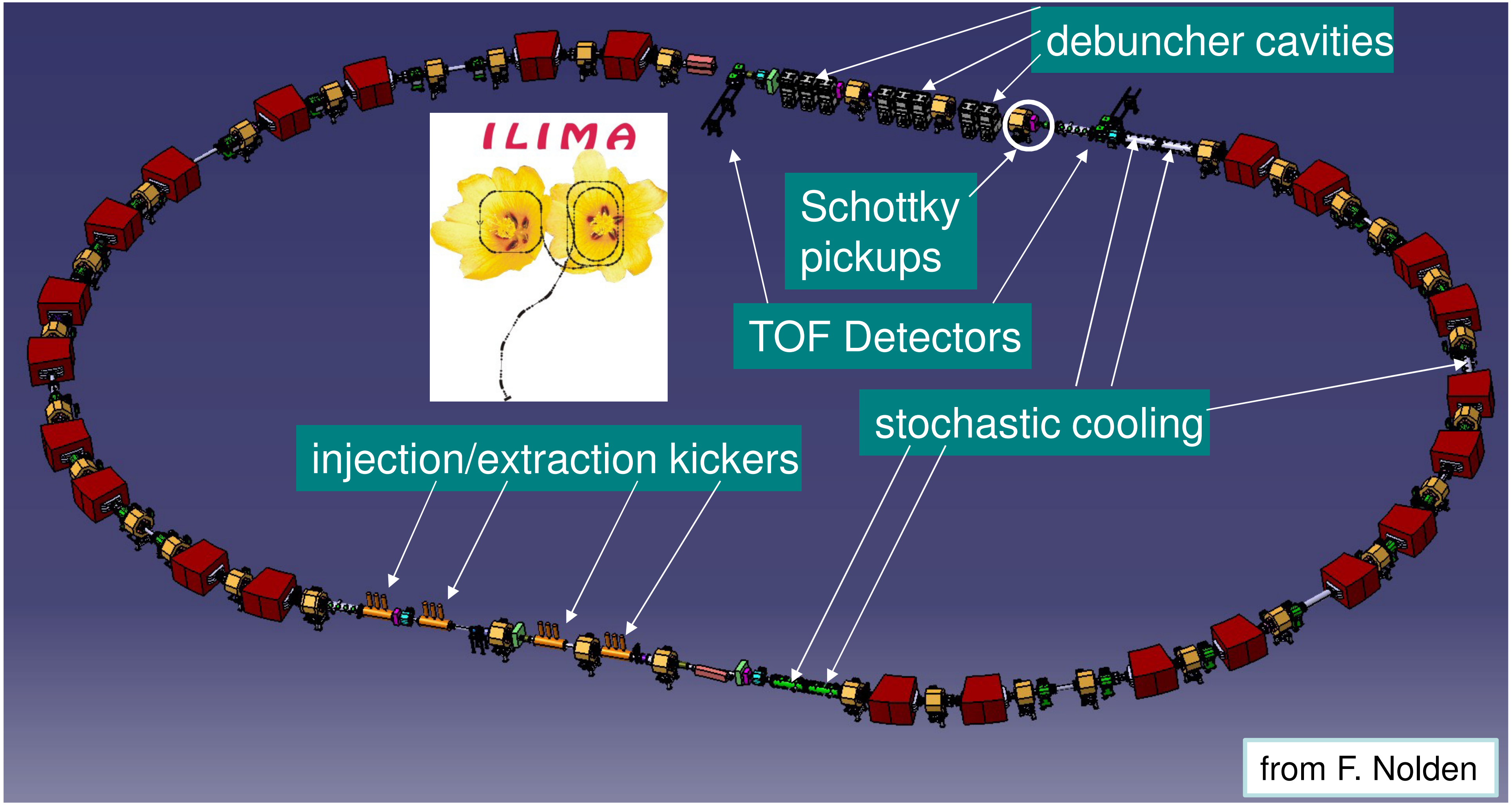
# Reactions with Relativistic Radioactive Beams R³B




Superconducting Dipole:
Ready for installation in 2015
Construction by CEA Saclay

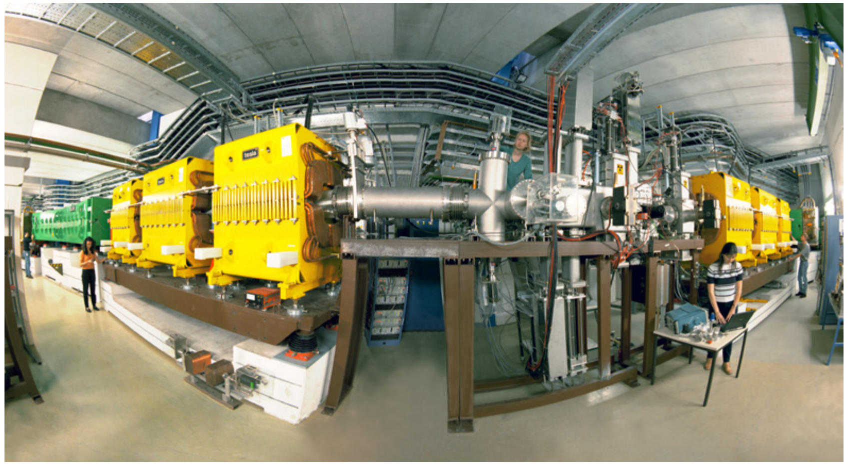
# ILIMA – partial program in CR (NESR not in MSV)

## CR perspective view

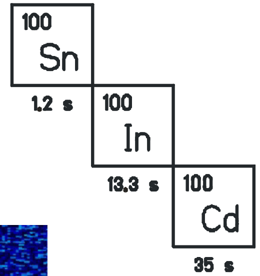


# Selectivity and Sensitivity

- Highest selectivity
  - FRS: $1:10^{13}$
  - Super-FRS: $< 1:10^{17}$



- Ultimate sensitivity
  - FRS: spectroscopy with 1 atom/day
  - ESR: mass and decay measurements with 1 single atom

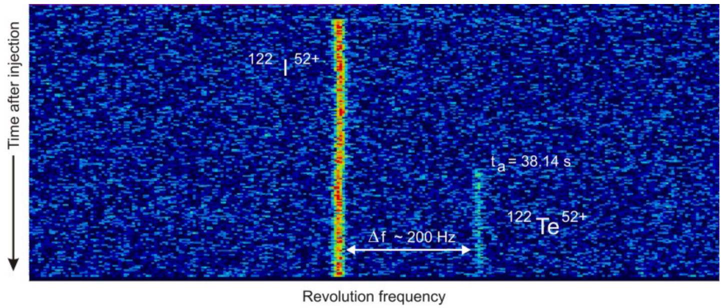



$T_{1/2} = (0.94\ ^{+0.54}_{-0.27})$ s

$Q_\beta = (3.4\ ^{+0.7}_{-0.3})$ MeV

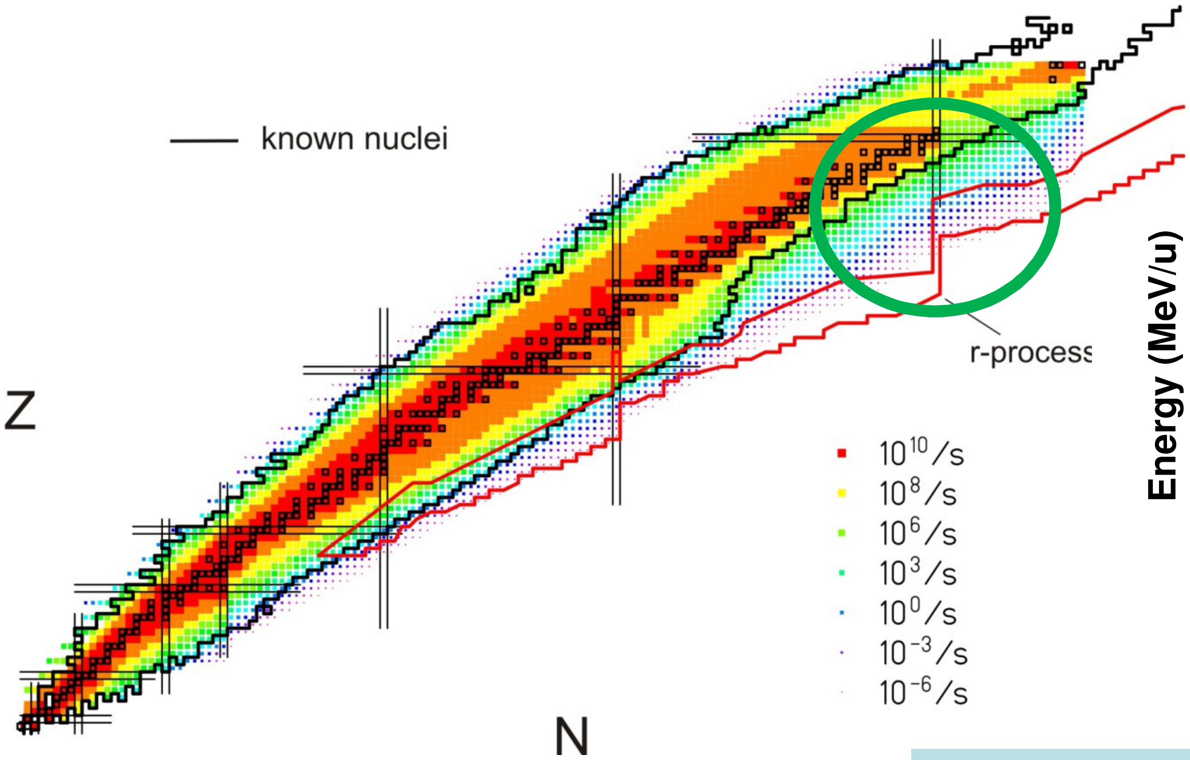
$\sigma = 11$ pb

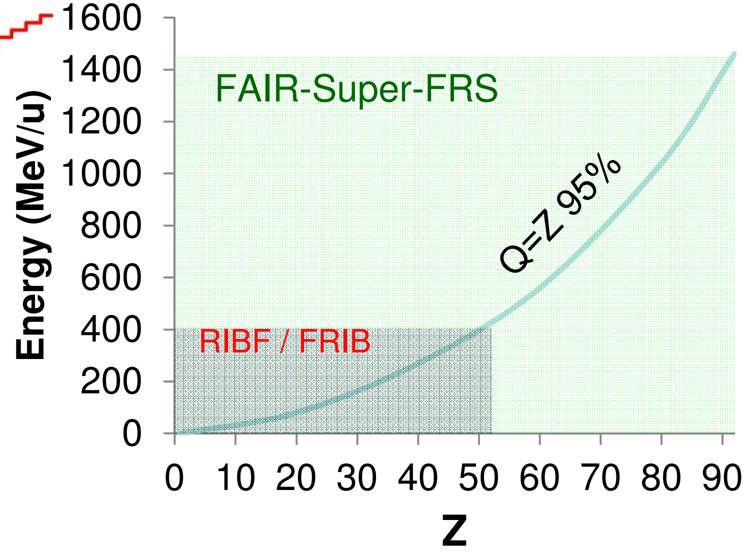
(7 atoms)




R. Schneider et al.
Z. Phys. (1995)

# Uniqueness and Competitiveness

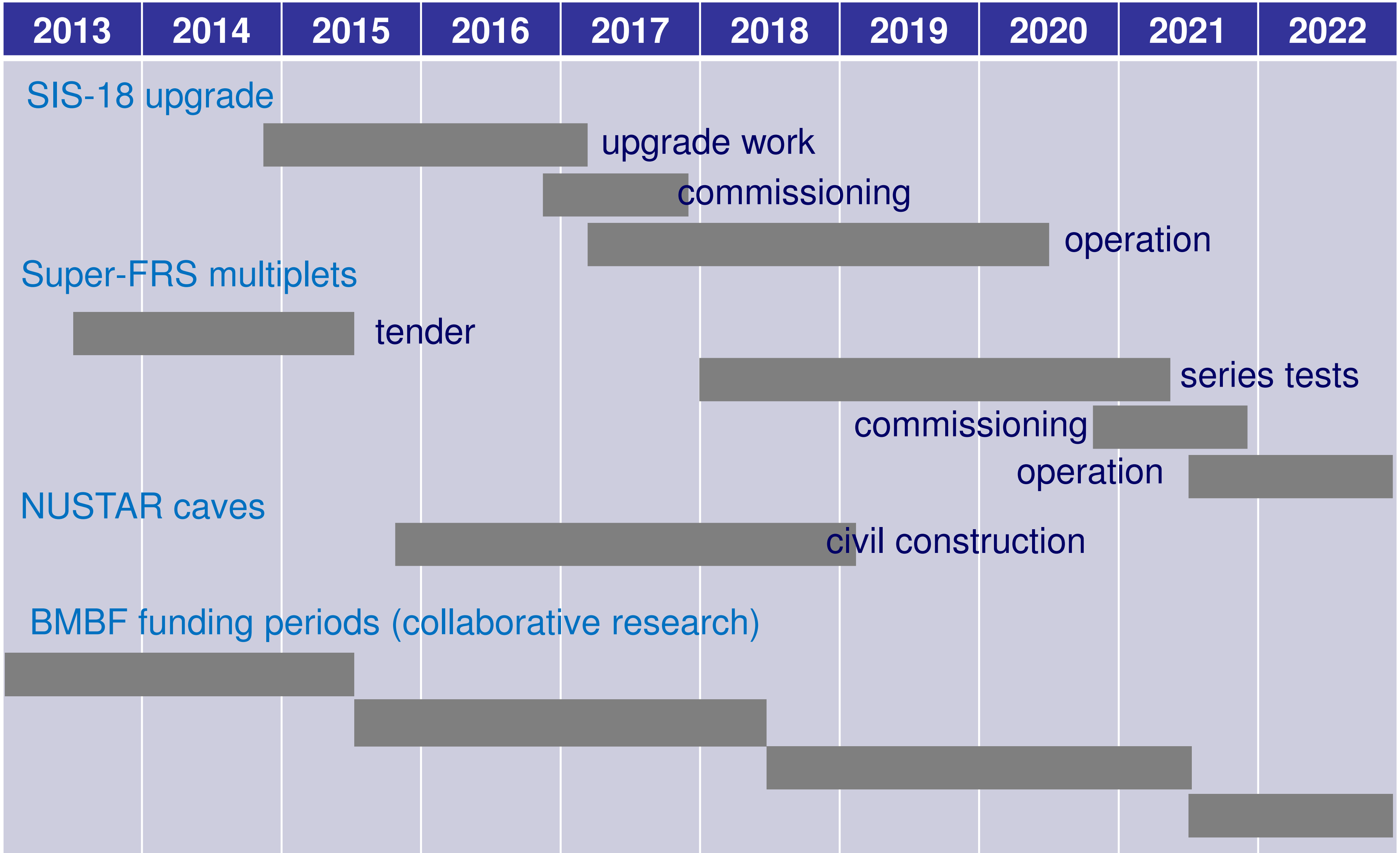


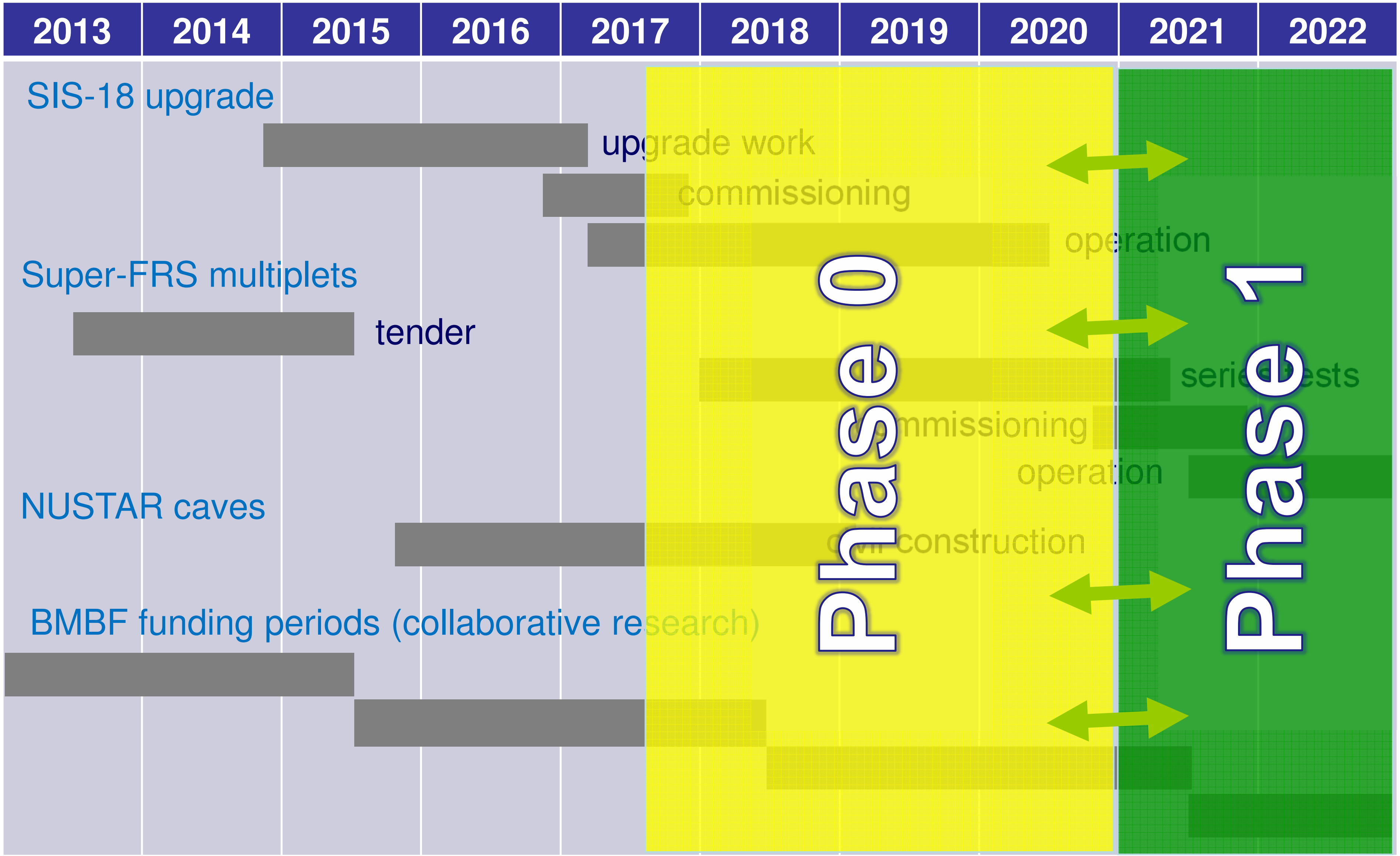

- High energies for unique separation and unique experiments
- Competitive intensities throughout the periodic table

| Facility | U beam int. per 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 | $3x10^{11}$ |

# Time Lines


2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
SIS-18 upgrade
upgrade work
commissioning
operation
Super-FRS multiplets
tender
series tests
commissioning
operation
NUSTAR caves
civil construction
BMBF funding periods (collaborative research)

# Initial NUSTAR Phases



# NUSTAR - Phases

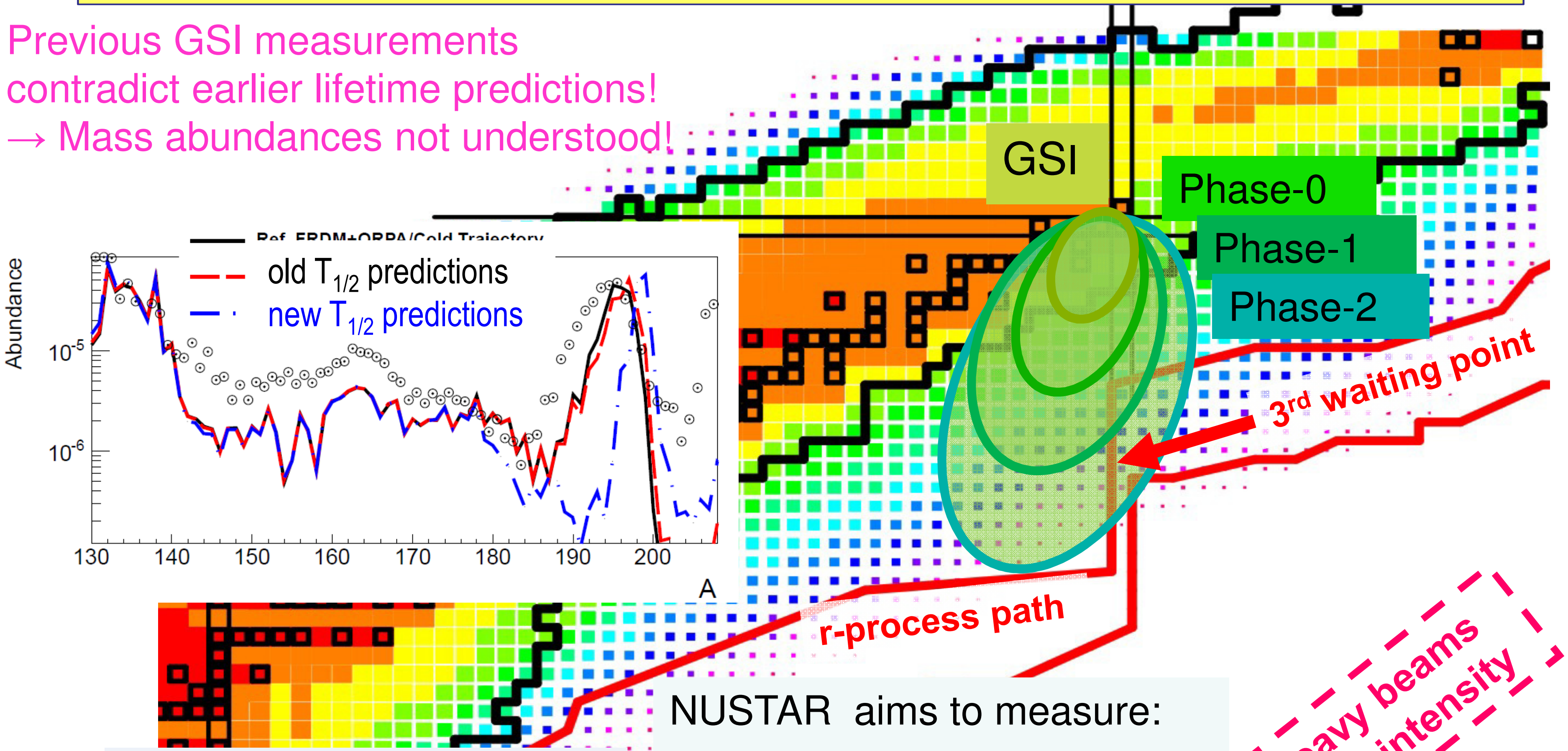
- **Phase 0**
  - R&D and experiments to be carried out with present facilities (GSI and others) and FAIR/NUSTAR equipment (basic set-ups)
- **Phase 1**
  - Core detectors and subsystems completed
  - First measurements with FAIR/Super-FRS beams
  - ➢ **Carry out experiments with highest visibility as part of the core program and within the FAIR MSV (“day-1”)**
- **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 or $R^3B$ spectrometer)
- **Phase 4**
  - Major new investments and upgrades for all experiments

# Highlights of the initial Phase – 1 programme

- 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 to the results of the first highlight);
- Exotic hypernuclei with very large N/Z asymmetry.

# The N=126 Physics case

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



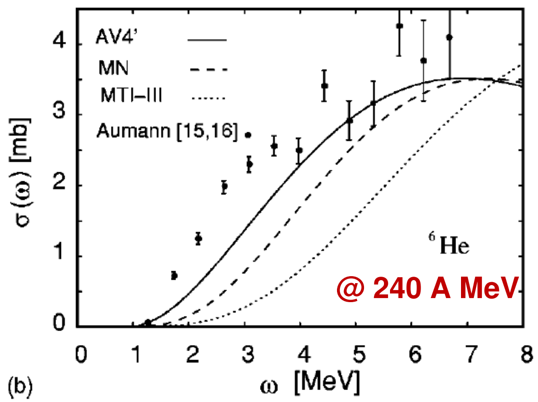

Mass abundances depend on the detailed structure of N=126 nuclei around the 3rd r-process waiting point

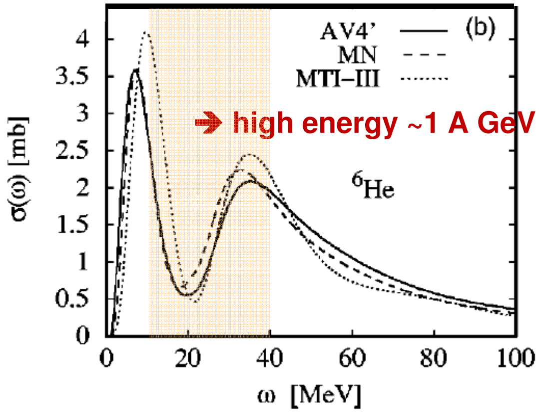
NUSTAR aims to measure:
- masses
- β-lifetimes
- neutron-branchings
- strength distributions
- level structure

Very heavy beams at highest intensity

# Phase 1 Physics with R3B setup

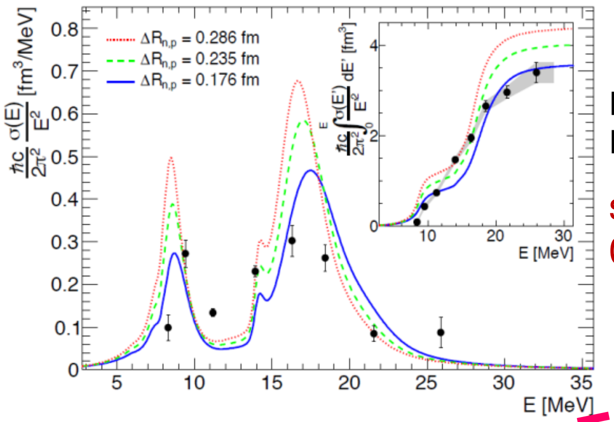
- core vs. neutron skins & halos → density / asymmetry




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

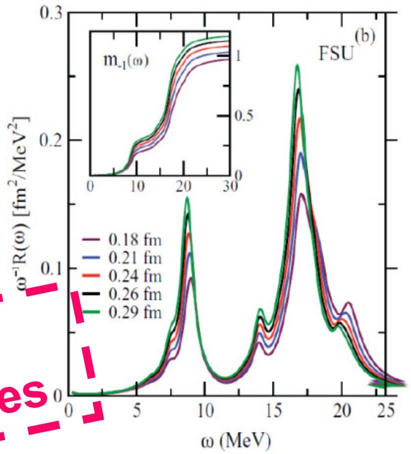
- access to EoS (e.g. neutron star) & low lying E1 strength (r-process)




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

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

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



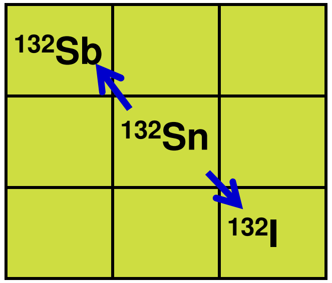

**Pb chain &**
**N=126 isotones**

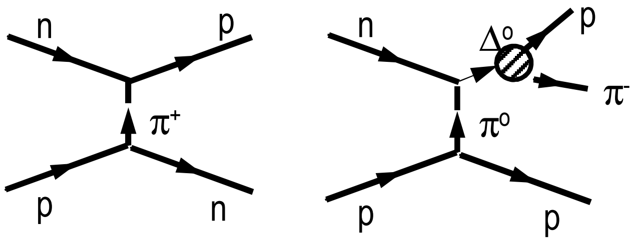
**~1 A GeV** →
bare ions
Fragment
identification

Light to heavy beams
at high energies and intensities

# Physics with S-FRS as high-resolution spectrometer

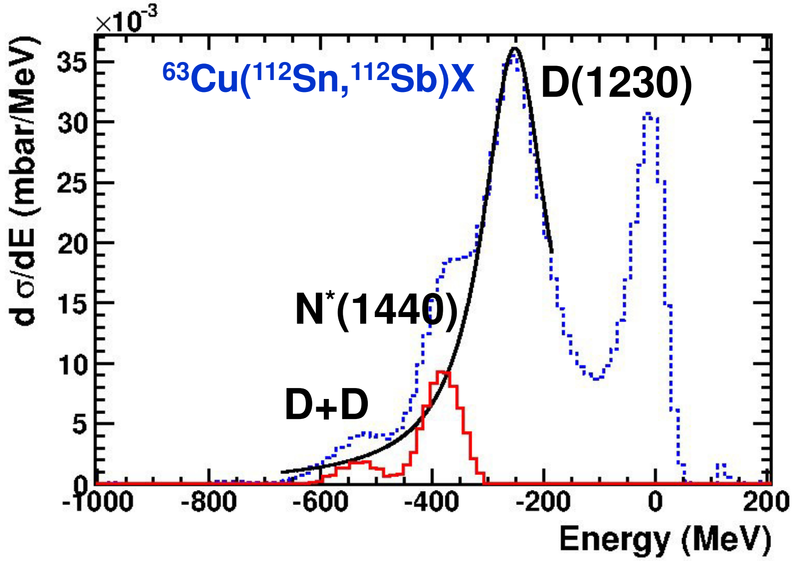
## Isobaric charge exchange reactions




quasi-elastic    inelastic

Relativistic neutron-rich projectiles (>600 MeV/u)
High-resolving power spectrometer
→ Pilot experiments with stable beams at FRS/GSI in 2017+
→ Experiments with asymmetric nuclear beams at Super-FRS/FAIR



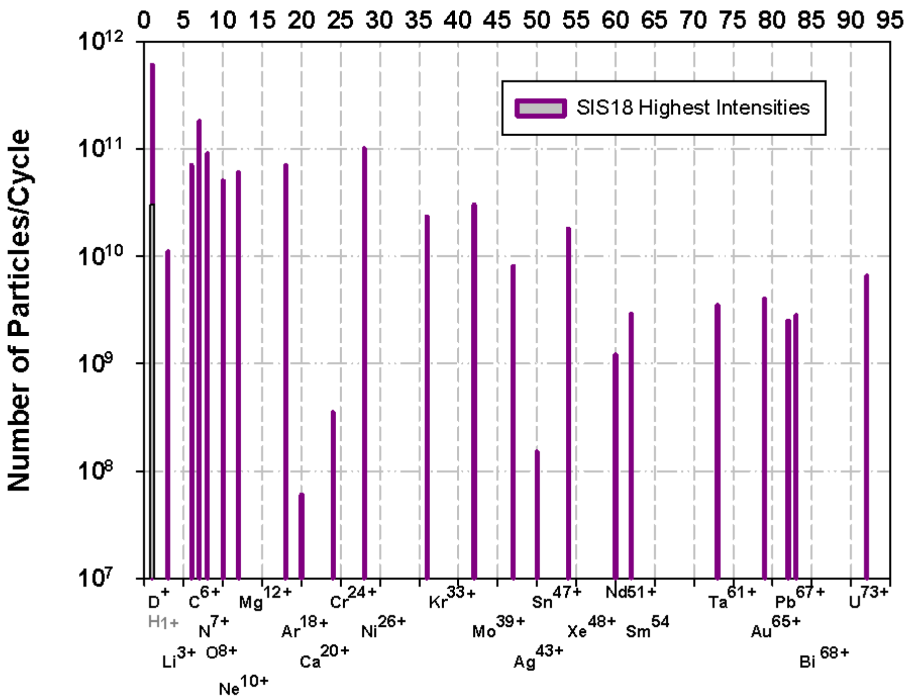

The momentum recoil induced by the pion emission proves the excitation of the resonances

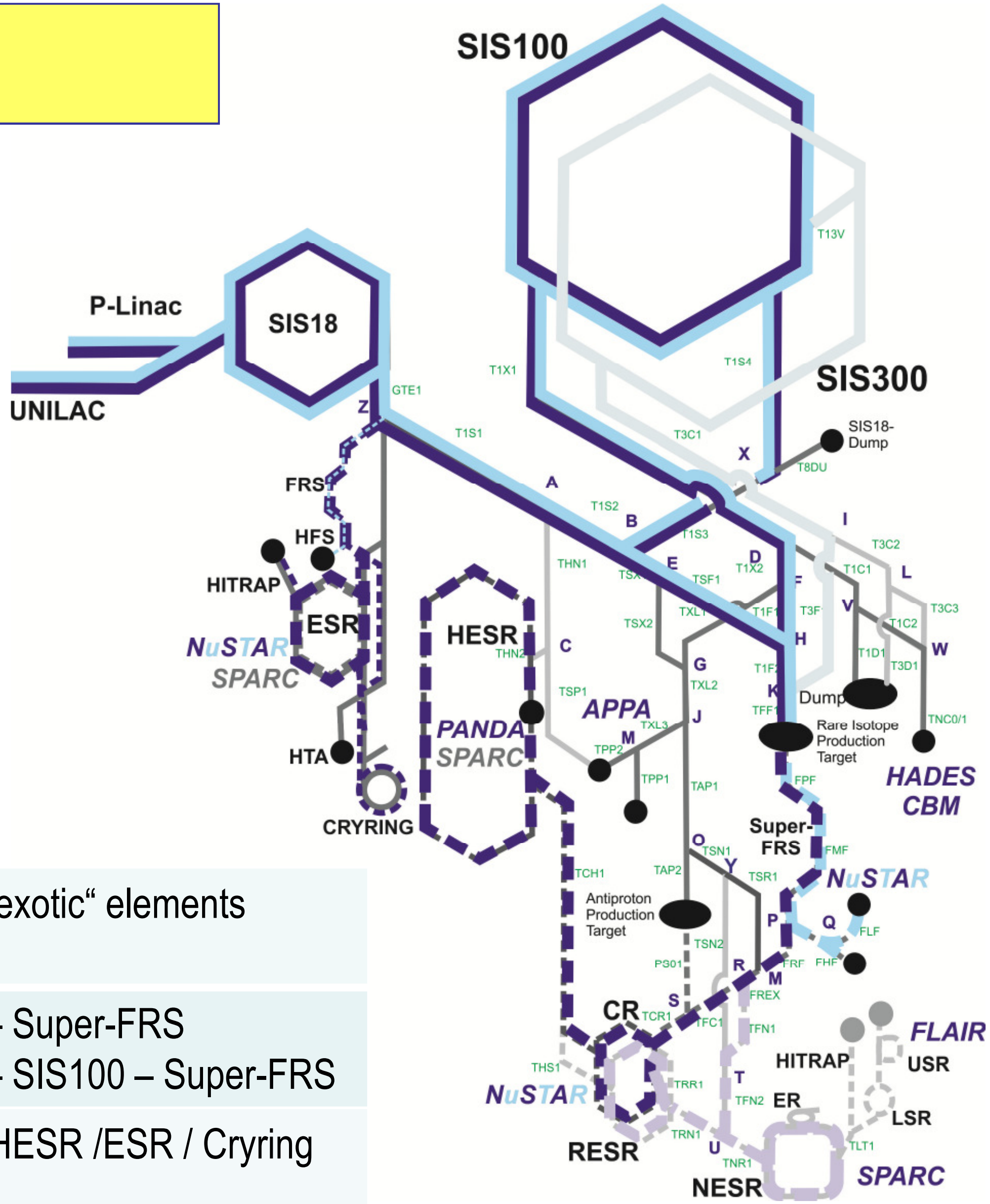
## Physics case

- ✓ Nuclear Structure Physics with the excited nucleon.
- ✓ In-medium baryon resonances.
- ✓ Role of nucleon excitations in massive neutron stars.
- ✓ Constraining the symmetry energy s(n,p)/s(p,n)

**Medium heavy beams at highest energies**

# MSV Beam Options

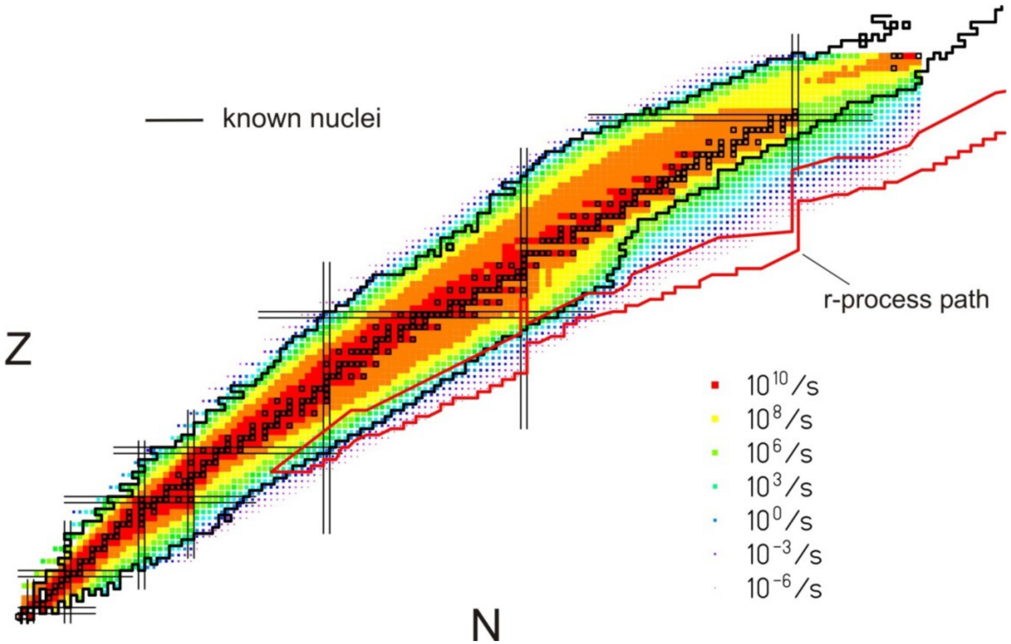


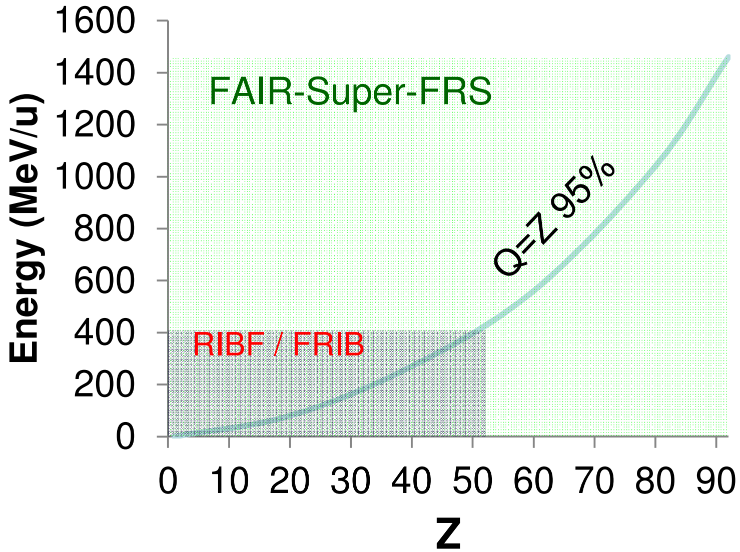




| | |
|---|---|
| Optimal production of RIBs from a multitude of primary beams | From H to U incl. “exotic“ elements |
| Versatile operation modes for enhanced parallel beam usage | UNILAC – SIS18 – Super-FRS<br>UNILAC – SIS18 – SIS100 – Super-FRS |
| Fast beam tuning and switching between NUSTAR experiments | LEB / HEB / CR / HESR /ESR / Cryring |

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

# Beam requirements




NUSTAR is potentially interested in any isotope and thus any primary beam possible!

The experiments will focus on the use of heavy beams (Z>50) with U and Pb covering maybe 50%.

Beam energy depends on Z and must be large enough to keep the ions fully stripped.

Beam intensity needs usually to be as high as possible (statistic counts)!

Spill length may vary between 0.5 s and 10 s, and fast extraction mainly for Ring experiments

Spill uniformity without intensity spikes is essential for most experiments.

# Concluding remarks

- NUSTAR has an excellent science case which will still be valid in 202x for NUSTAR/Super-FRS@FAIR.
- The critical path is the readiness of Super-FRS.
- The NUSTAR equipment/end stations will be ready well in time for Super-FRS beams.
- NUSTAR has an intermediate plan, and pursues an evolutionary approach: perform unique and exciting pilot experiments at GSI with the available new equipment for FAIR (phase 0)
- A wide variety of high intensity beams is required
- A uniform spill structure without spikes and voids is important

# Status of the Demonstrator

## Cavity

## Cryostat

## New HIM Building

Helmholtz-Institut Mainz

**Hi-Bay** Labs Offices

Available Q1/2016

## Cave near the ECR ion source