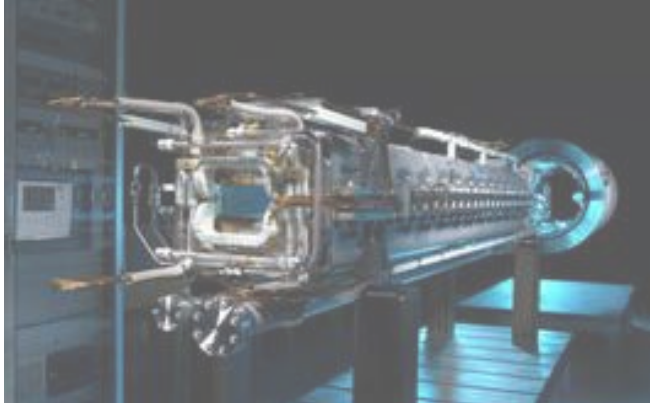




NUSTAR activities at FAIR

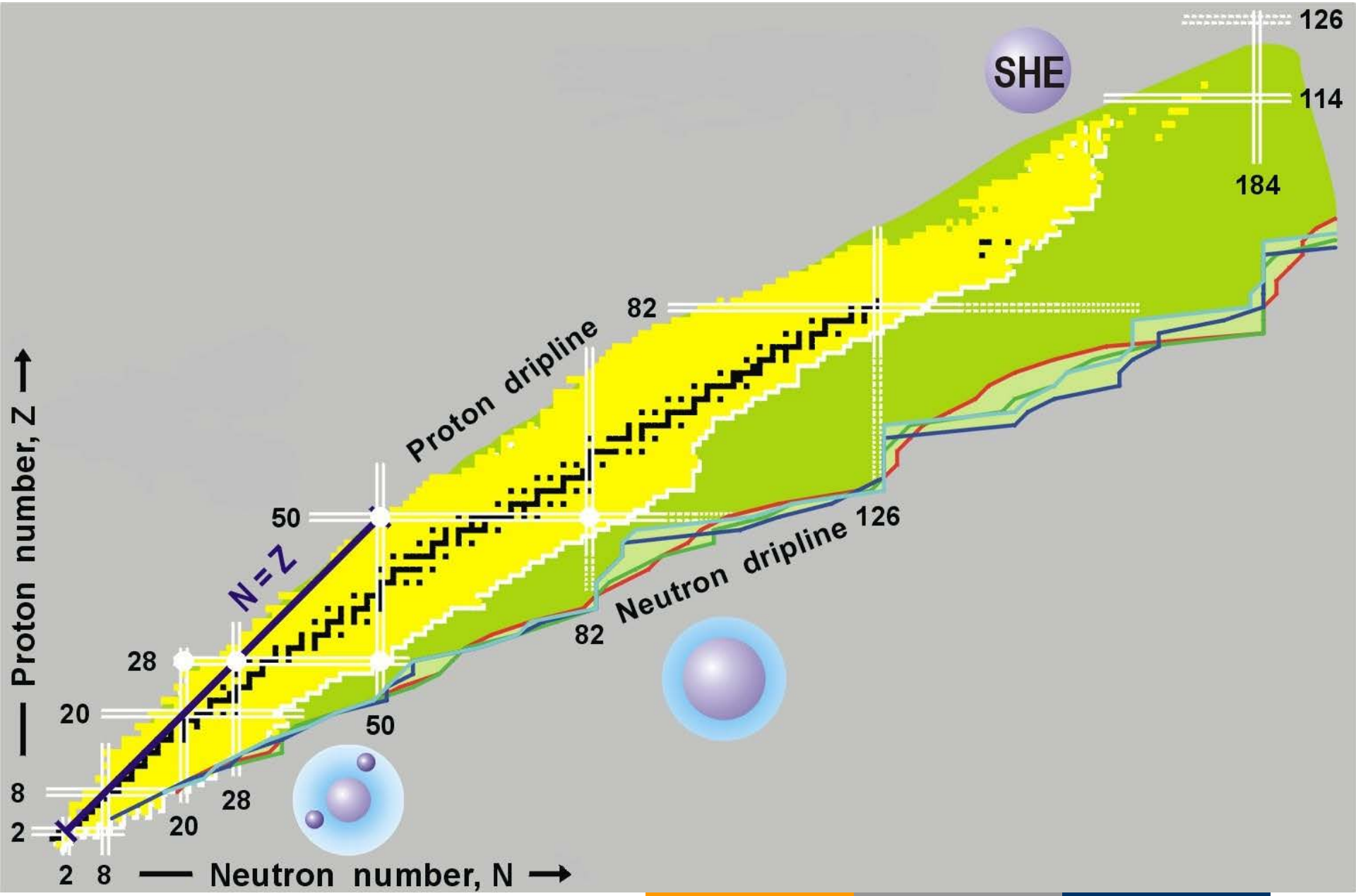
Nasser Kalantar-Nayestanaki
KVI-CART/University of Groningen
on behalf of NUSTAR collaboration

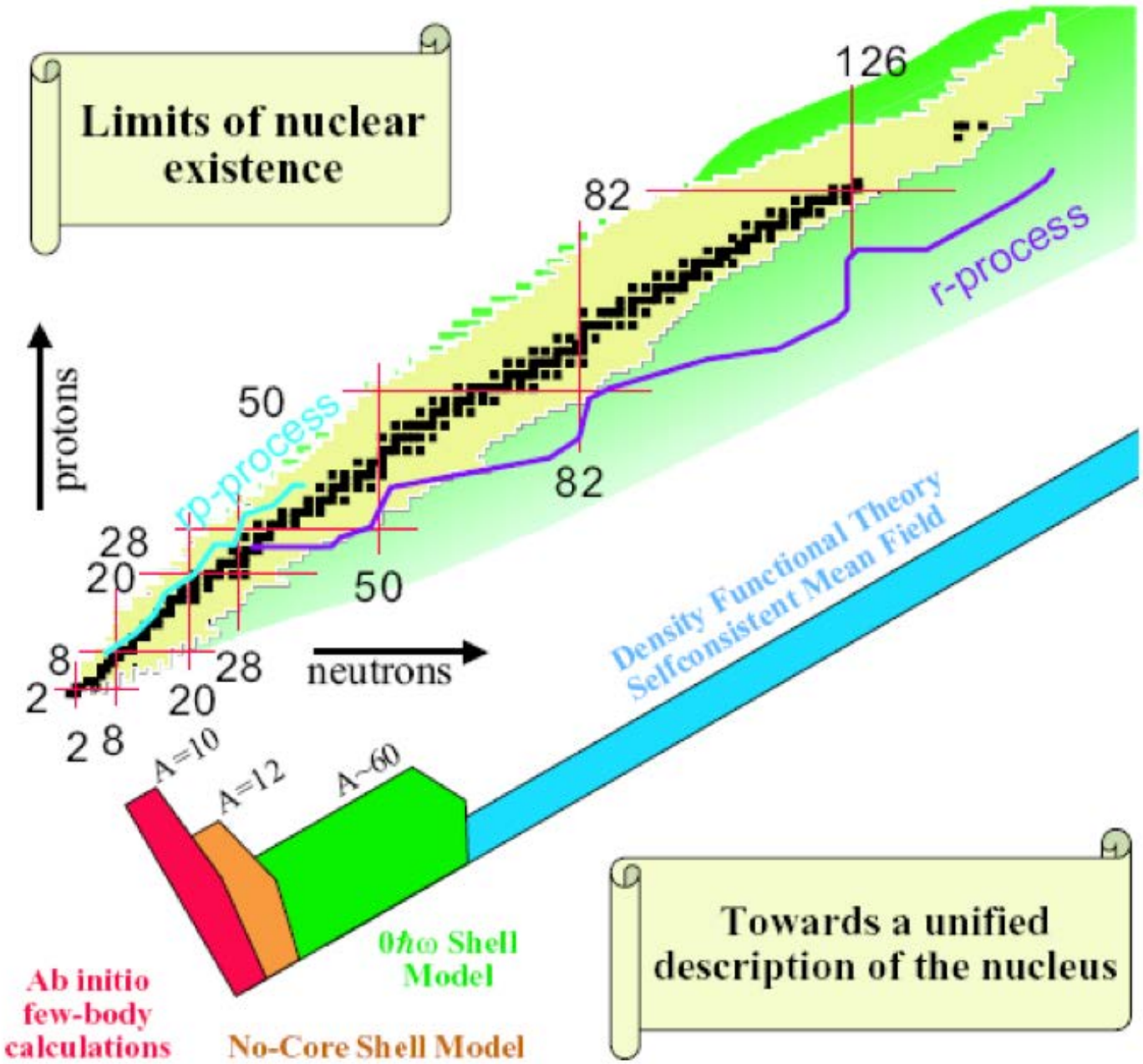
SFAIR meeting

Uppsala, Sweden, November 10, 2014

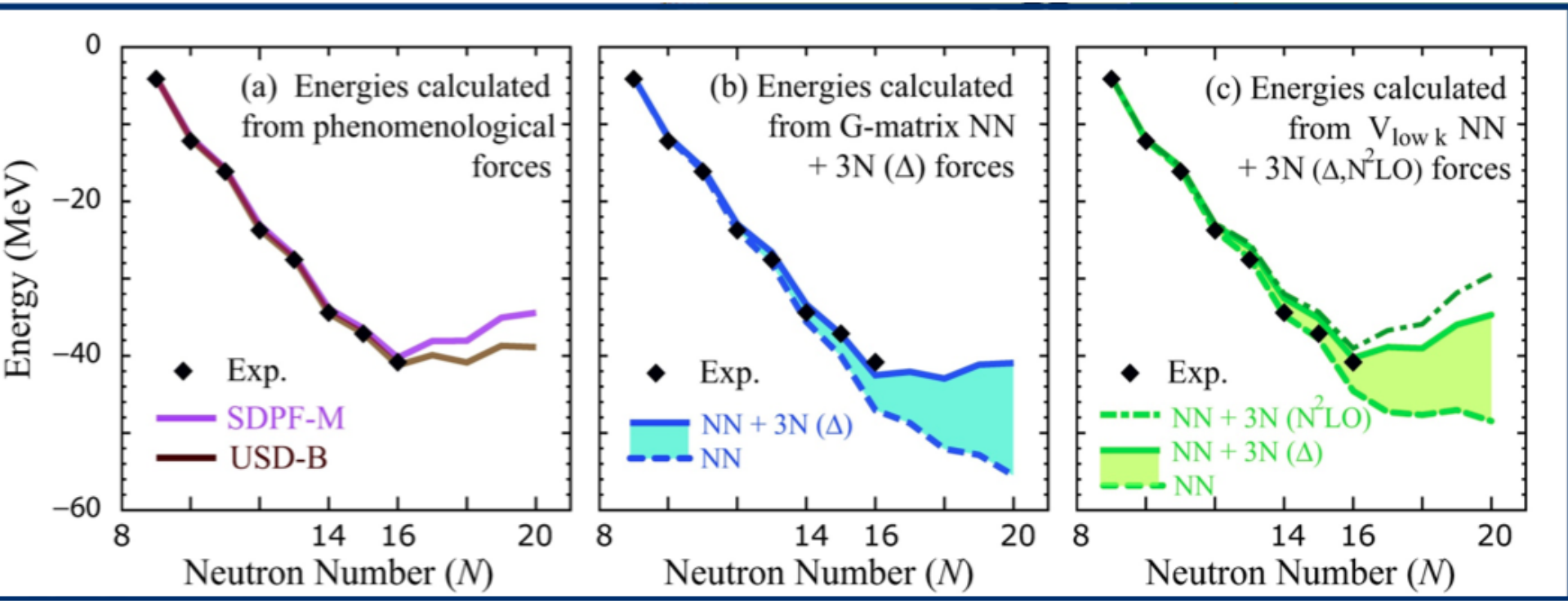
Finland France Germany India Poland Romania Russia Slovenia Sweden UK

Snapshot of the nuclear landscape




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

Binding Energies of Oxygen Isotopes



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

Ground-state energies

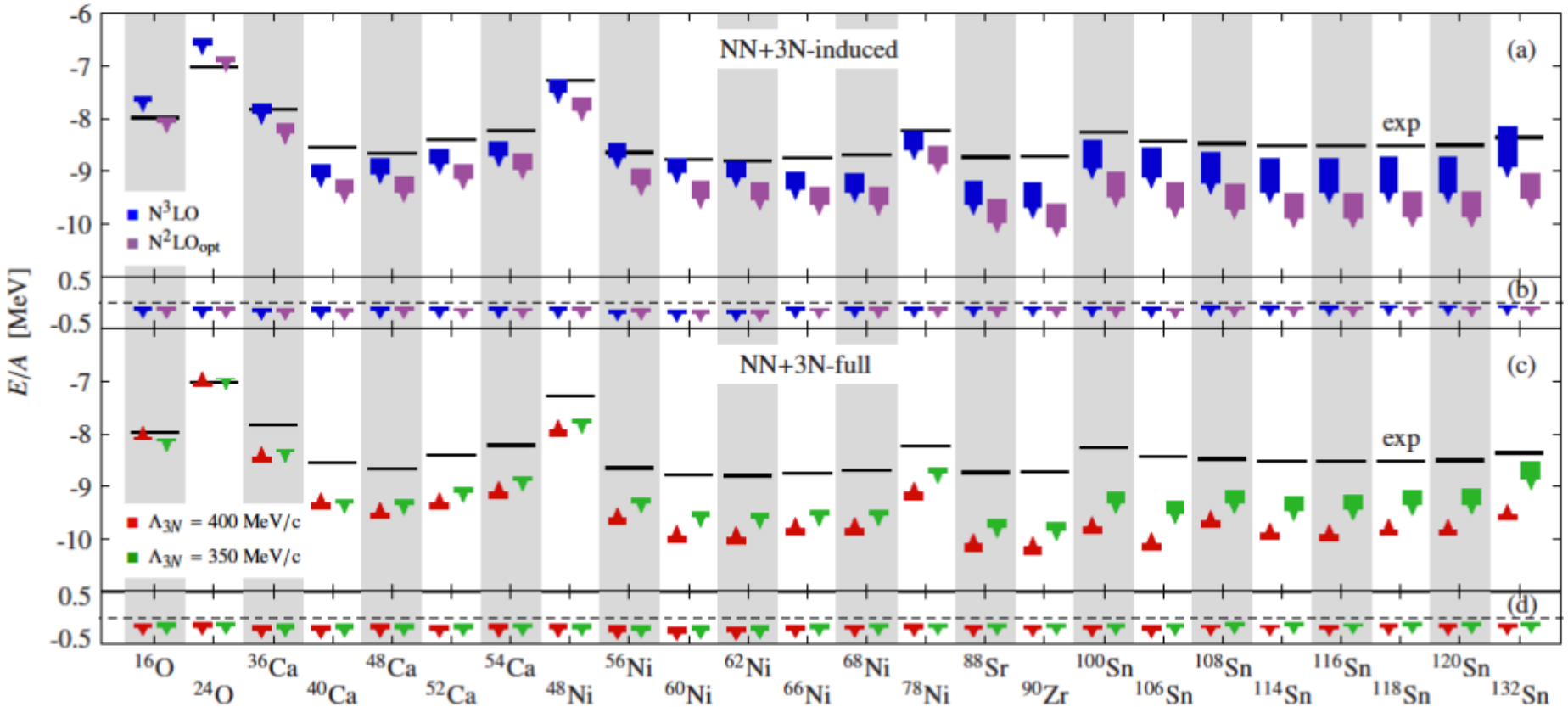


FIG. 5: (Color online) Ground-state energies from CR-CC(2,3) for (a) the NN+3N-induced Hamiltonian starting from the N^{3}LO and N^{2}LO-optimized NN interaction and (c) the NN+3N-full Hamiltonian with Λ_{3N} = 400 MeV/c and Λ_{3N} = 350 MeV/c. The boxes represent the spread of the results from $\alpha = 0.04$ fm^4 to $\alpha = 0.08$ fm^4, and the tip points into the direction of smaller values of α. Also shown are the contributions of the CR-CC(2,3) triples correction to the (b) NN+3N-induced and (d) NN+3N-full results. All results employ $\hbar\Omega$ = 24 MeV and 3N interactions with $E_{3\max}$ = 18 in NO2B approximation and full inclusion of the 3N interaction in CCSD up to $E_{3\max}$ = 12. Experimental binding energies [32] are shown as black bars.

S. Binder et al., Phys. Lett. B 736, 119 (2014), http://arxiv.org/pdf/1312.5685.pdf

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?

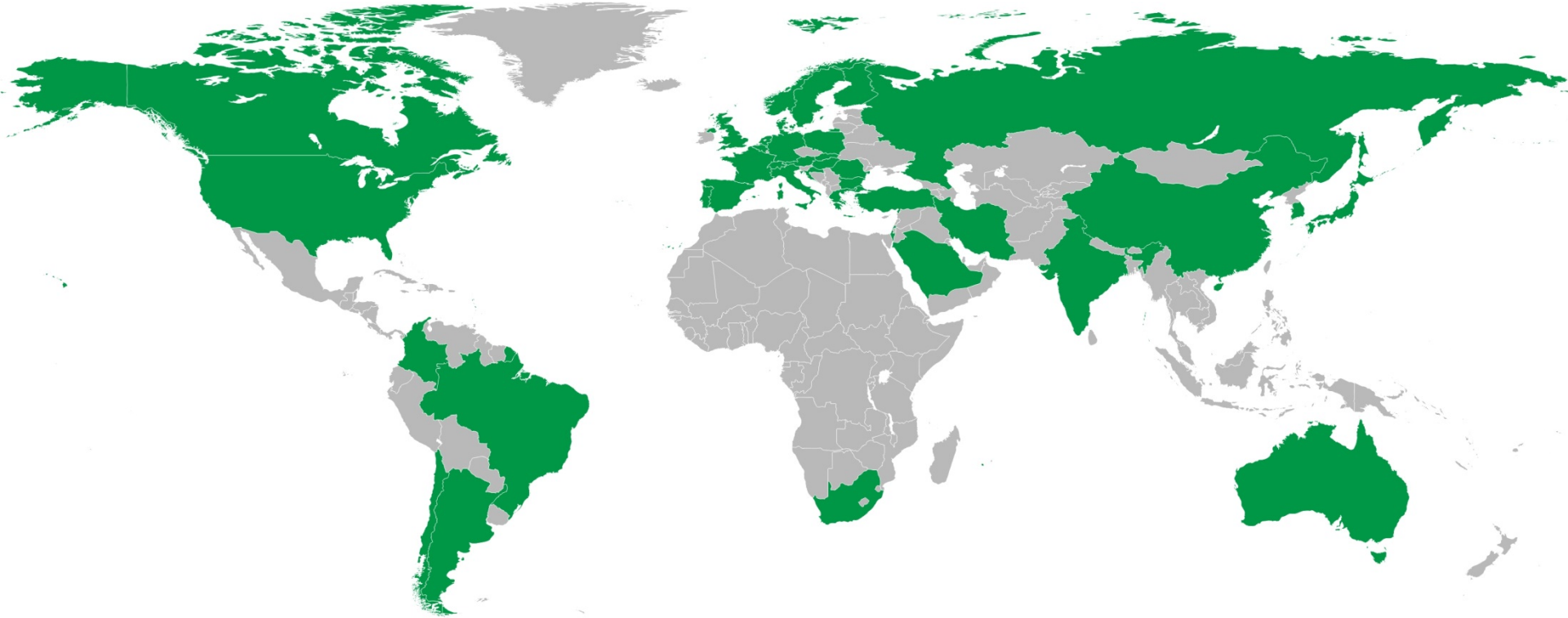
What is the effective nucleon-nucleon interaction?

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 Collaboration



>800 registered NUSTAR members
38 countries
>180 institutes

NUSTAR Week GSI March 2014

NUSTAR - The Project

Super-FRS	RIB production, identification and high-resolution spectroscopy
HISPEC/D ESPEC	in-beam □spectroscopy at low and intermediate energy, γ-, β-, α-, p-, n-decay spectroscopy
ILIMA	masses and lifetimes of nuclei in ground and isomeric states
LASPEC	laser spectroscopy
MATS	in-trap mass measurements and decay studies
R^3B	kinematically complete reactions at high beam energy
Super-FRS	high-resolution studies with high-performance separator
SHE	study of Super-Heavy Elements
ELISE	elastic, inelastic, and quasi-free e^-A scattering
EXL	light-ion scattering reactions in inverse kinematics

The Approach

Complementary measurements leading to consistent answers

The Collaboration

> 800 scientists

> 180 institutes

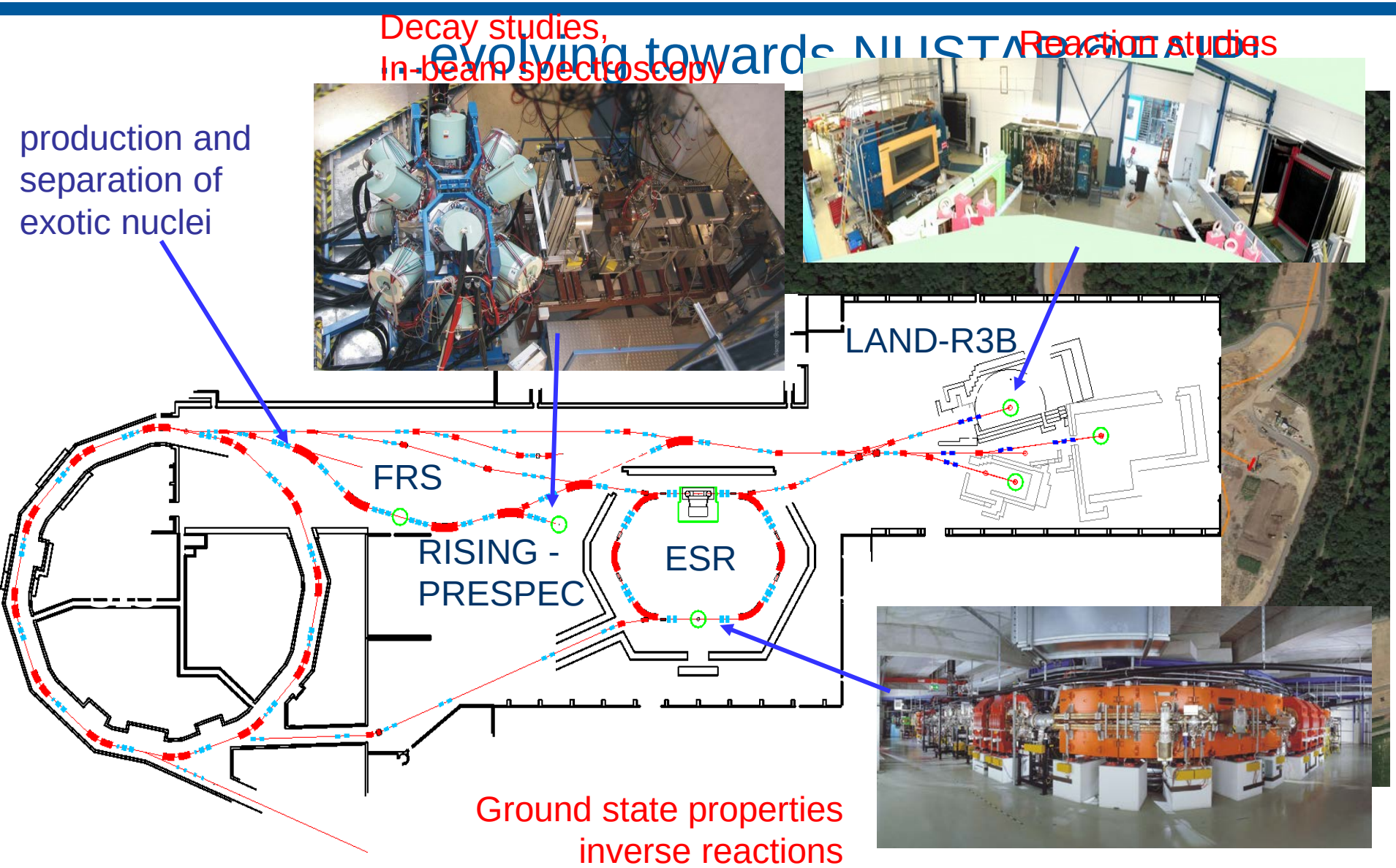
38 countries

The Investment

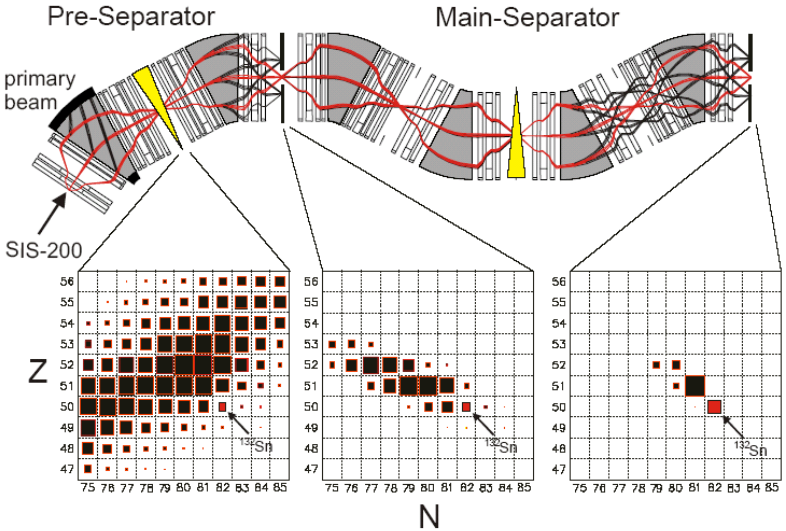
82 M€ Super-FRS

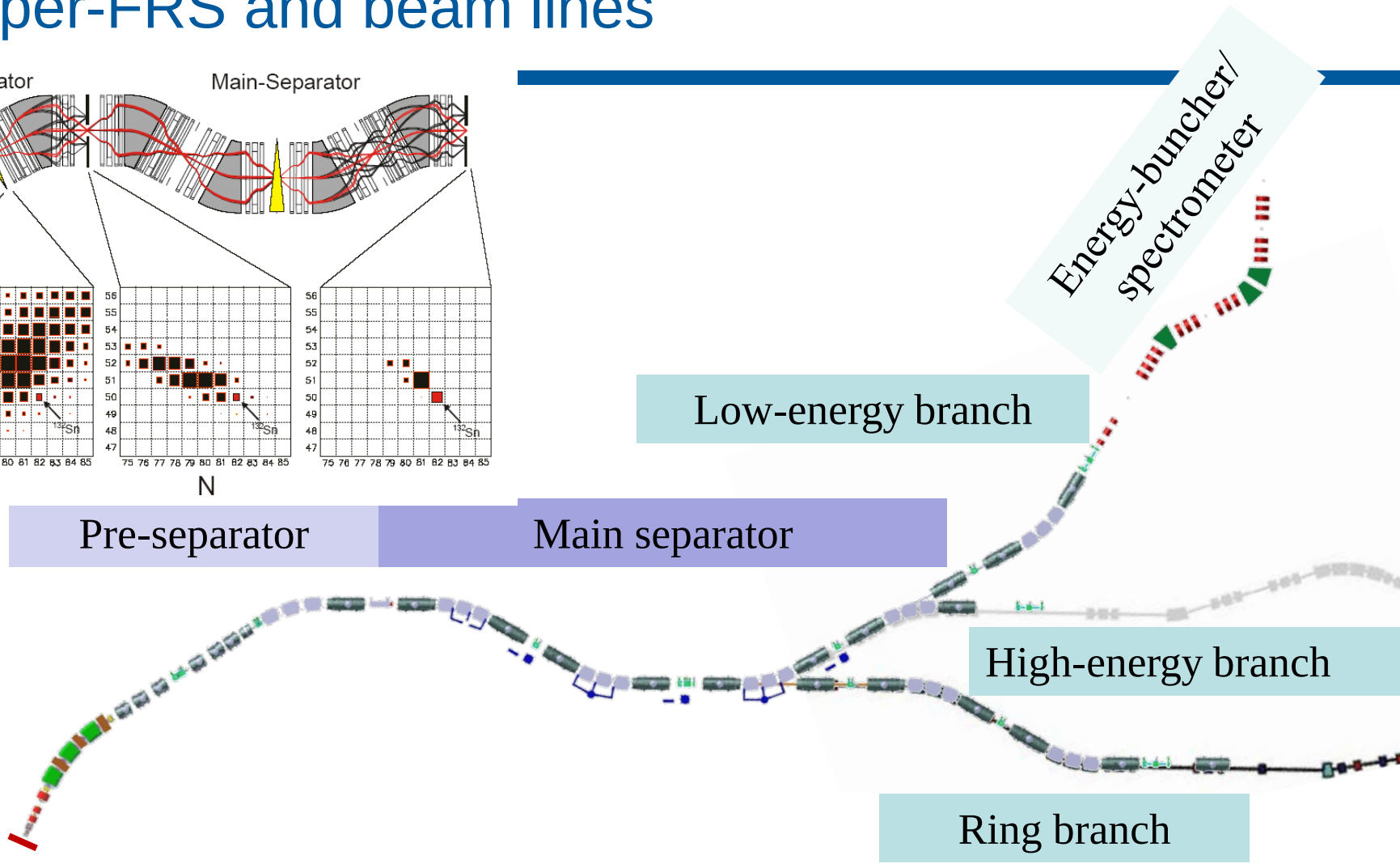
73 M€ Experiments

Existing research opportunities at GSI



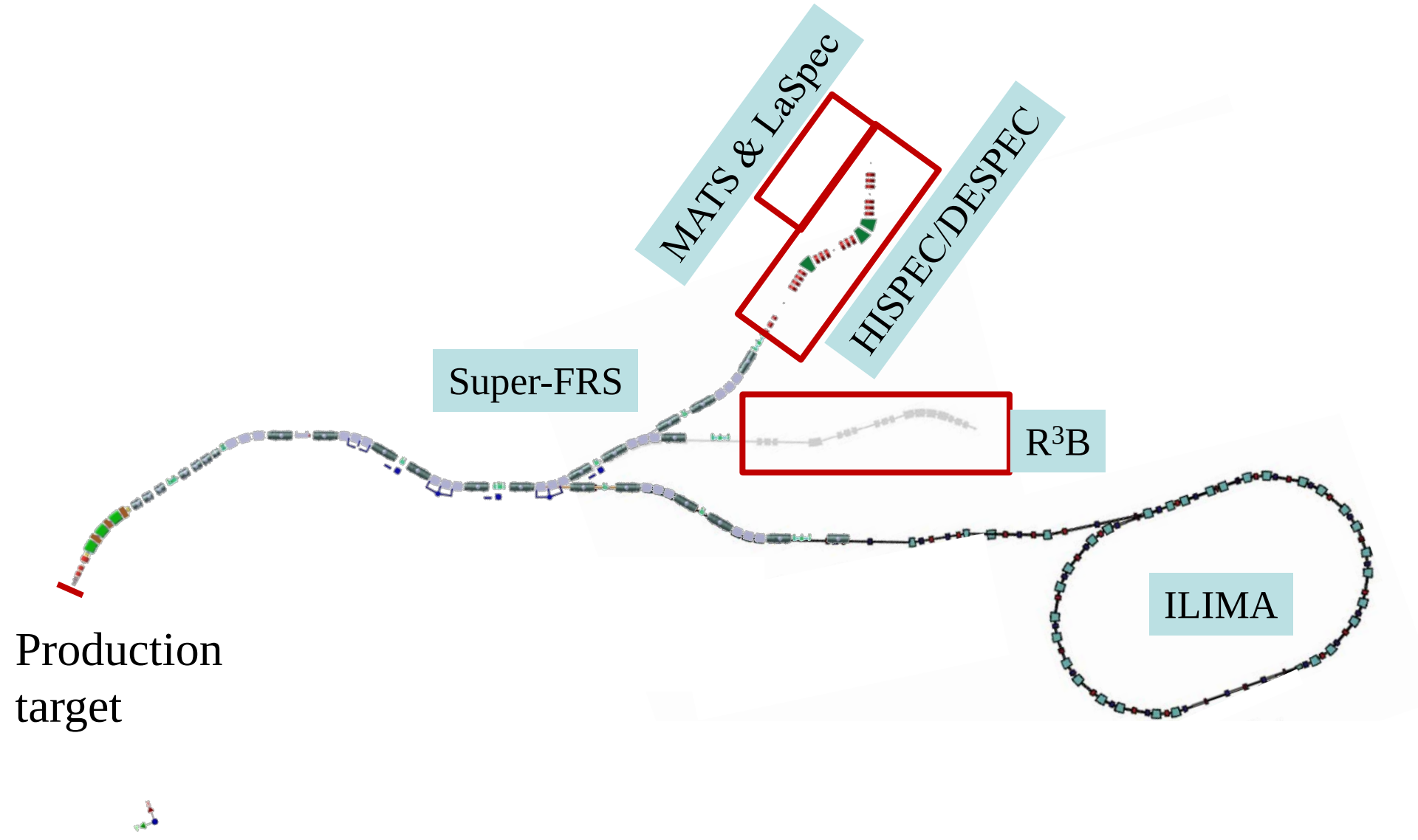
Super-FRS and beam lines



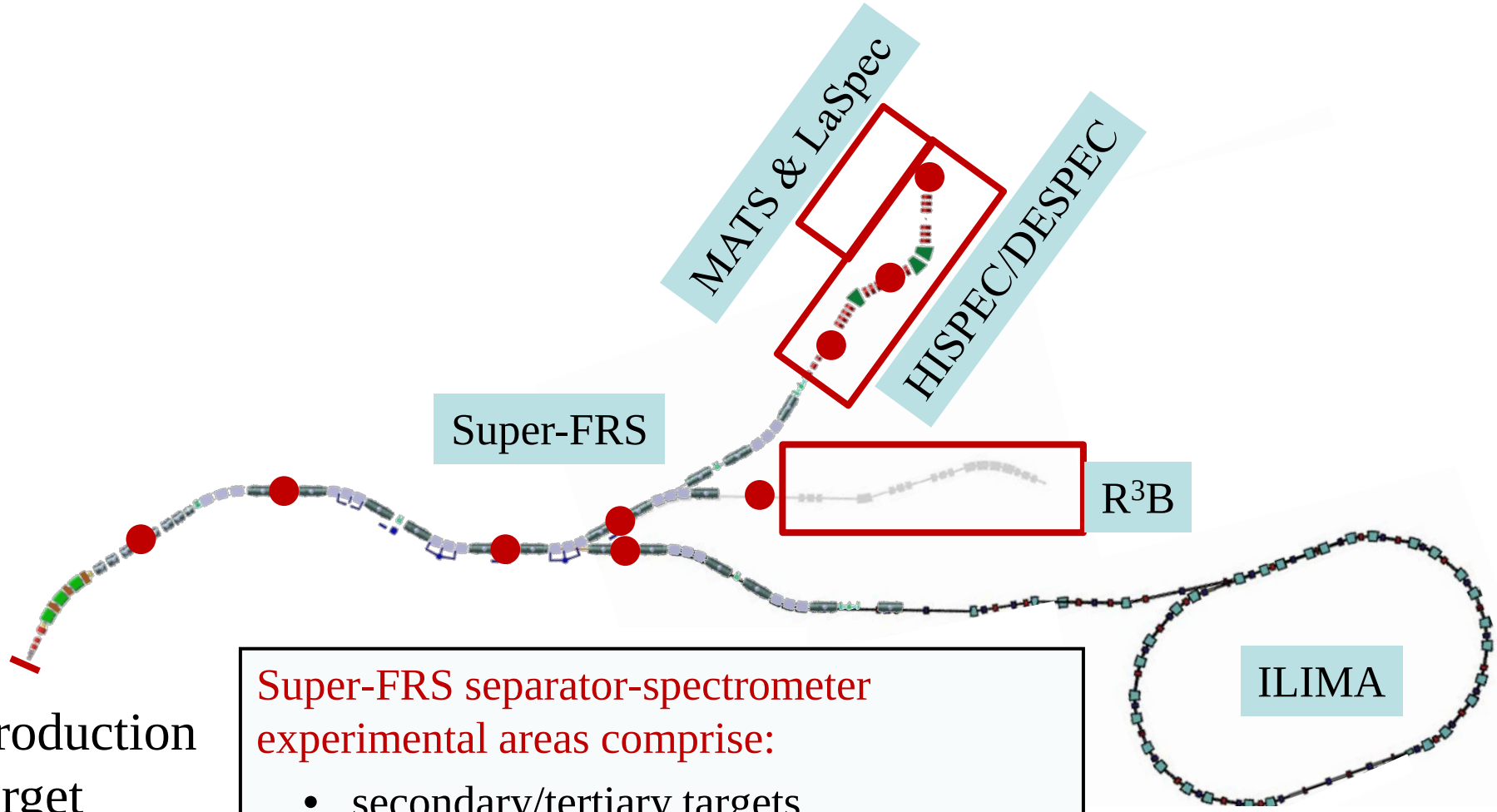


Production target

NUSTAR experimental areas



NUSTAR experimental areas



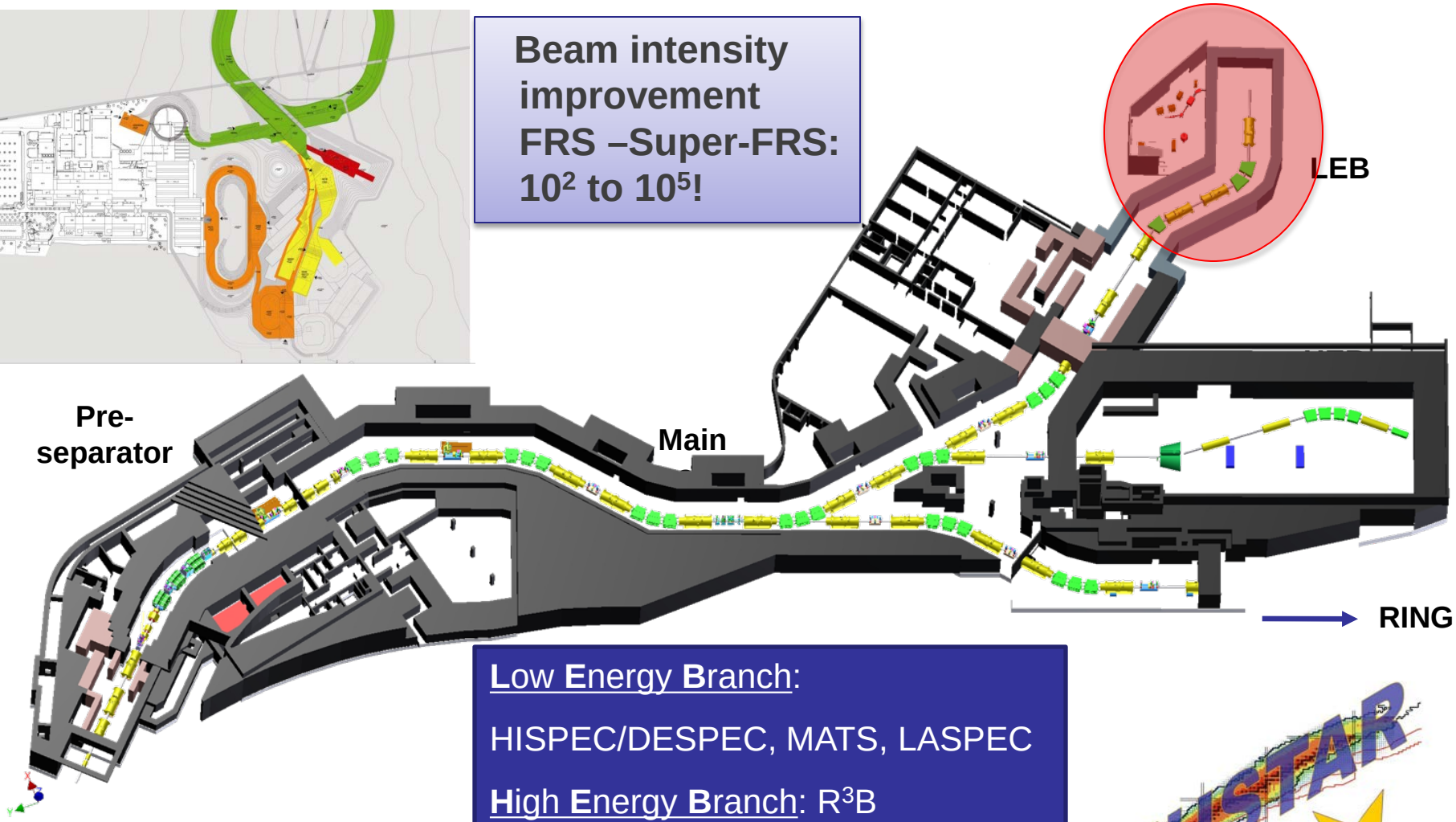
Production target

Super-FRS separator-spectrometer experimental areas comprise:

- secondary/tertiary targets
- degrader stations
- ancillary detectors

NUSTAR - The Facility

Beam intensity improvement FRS –Super-FRS: 10^2 to 10^5!



Low Energy Branch:

HISPEC/DESPEC, MATS, LASPEC

High Energy Branch: R^3B

Ring Branch: EXL, ILIMA, ELISE

Status Technical Design Reports (35 TDRs)

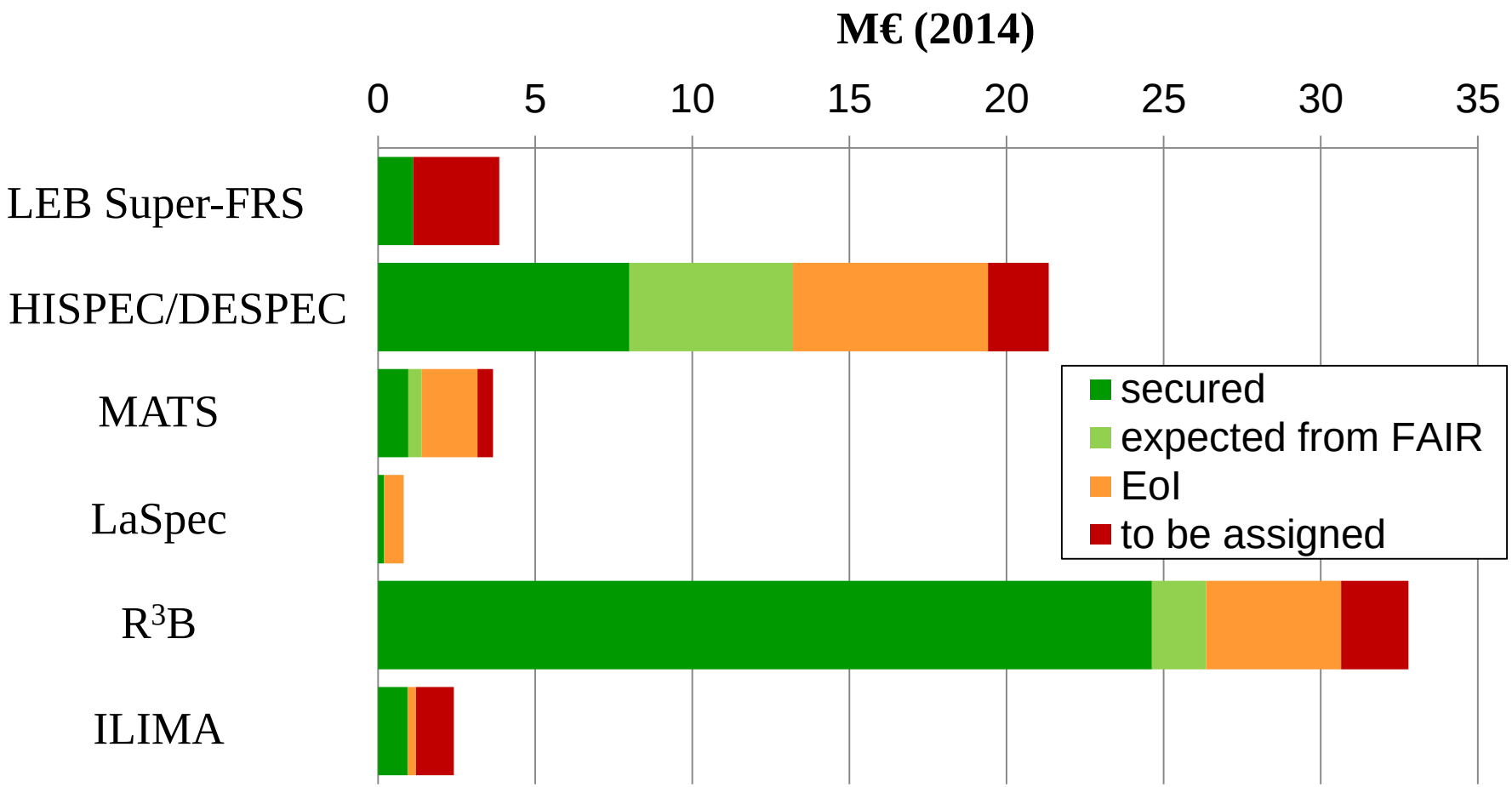
- *Approved TDRs (10):*
  - *HISPEC/DE (6) (LYCCA, Plunger, AIDA, BELEN, MONSTER,D*
  - *MATS + LaSpec ll subsystems – except LD-RIS: no action)*
  - *R^3B (3) (Multiplet, ND, CALIFA-barrel)*

- *Submitted (4):*
  - *HISPEC/DESPEC (AGA GAS, NEDA)*
  - *R^3B (GLAD)*

See the talk by Alex Herlert

TDRs expec (submission profile – 2014)				
2014	2015	2016	2017	
6	12	3	0	0

Status of NUSTAR experiment funding



HISPEC/DESPEC - foreseen instrumentation

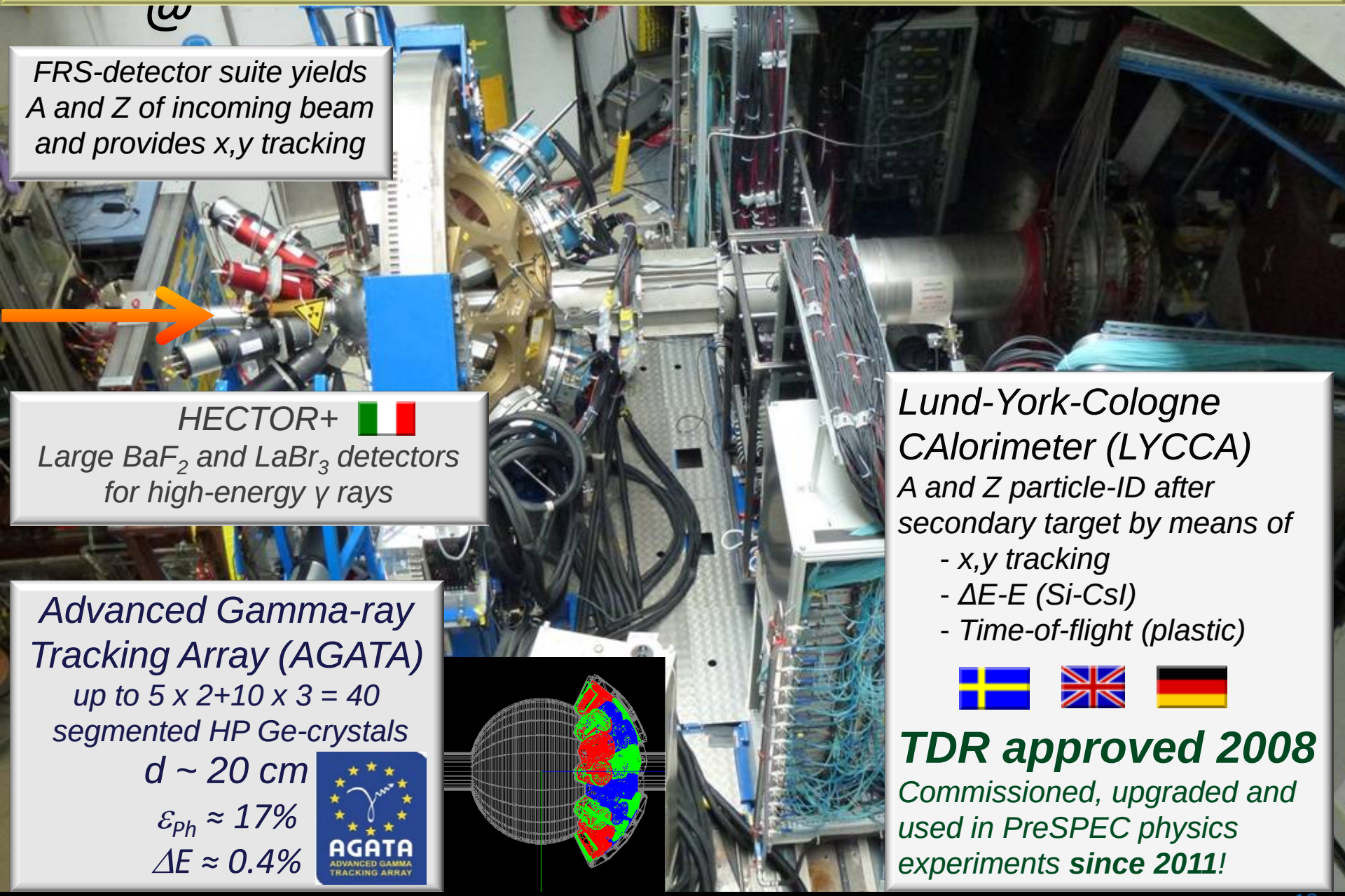
HISPEC

- AGATA gamma-tracking spectrometer
- LYCCA heavy-ion calorimeter with ToF capability (Sweden)
- Plunger nuclear level lifetime measurements
- MINOS Proton target
- NEDA Neutron detector array (Sweden)
- HYDE light charged-particle array

DESPEC

- AIDA active implantation device
- MONSTER neutron ToF array
- BELEN neutron detection array
- DTAS Decay Total Absorption Spectrometer
- DEGAS Ge Array gamma spectrometer (Sweden)
- FATIMA Fast TIMing Array

PreSPEC-AGATA 2012-2014: Early Implementation of HISPEC



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

HECTOR+

Large BaF_2 and $LaBr_3$ detectors for high-energy γ rays

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)

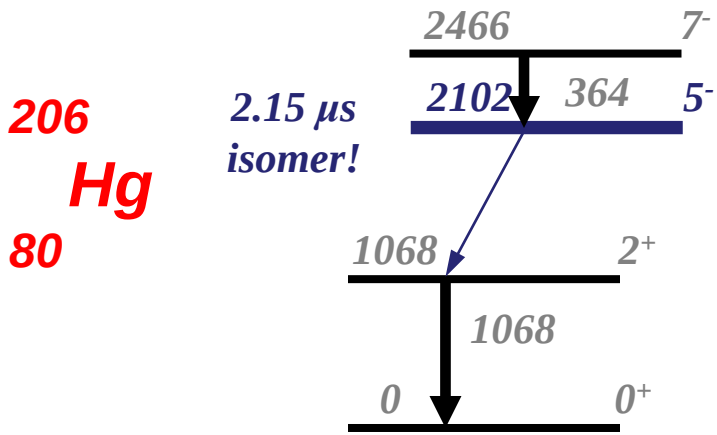
A and Z particle-ID after secondary target by means of

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

TDR approved 2008

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

Phase 0: S429
B(E2;$0^+ \rightarrow 2^+$) transition strengths in the vicinity of ^{208}Pb



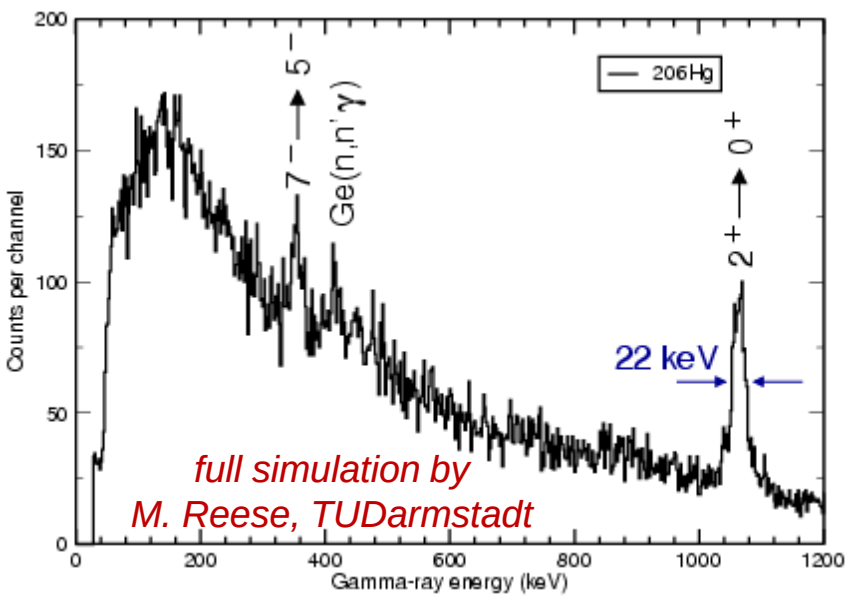
Staged programme:

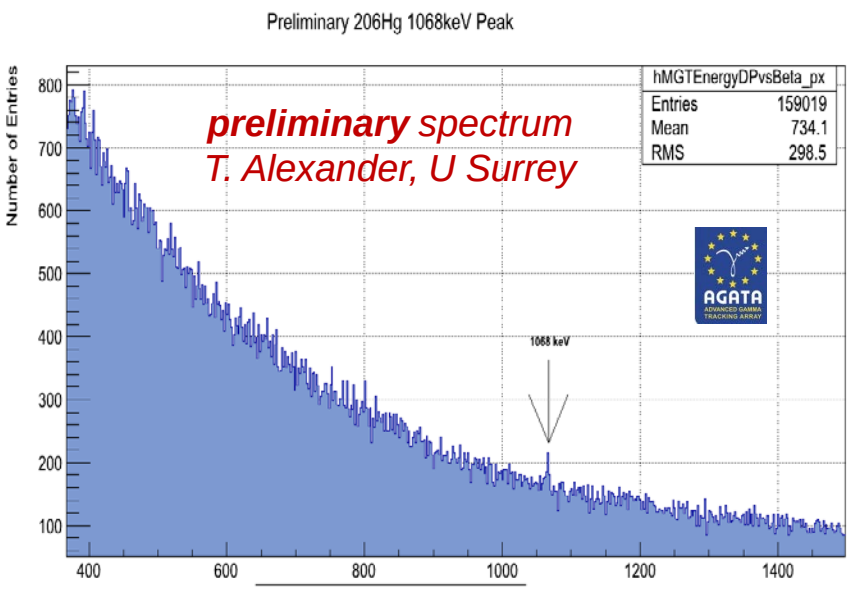
Z=82 and N=126 isomers: **RISING Stopped**

$^{198\text{-}206}$Pb, ^{206}Hg and ^{200,202}Pt: **^{208}Pb beam GSI**

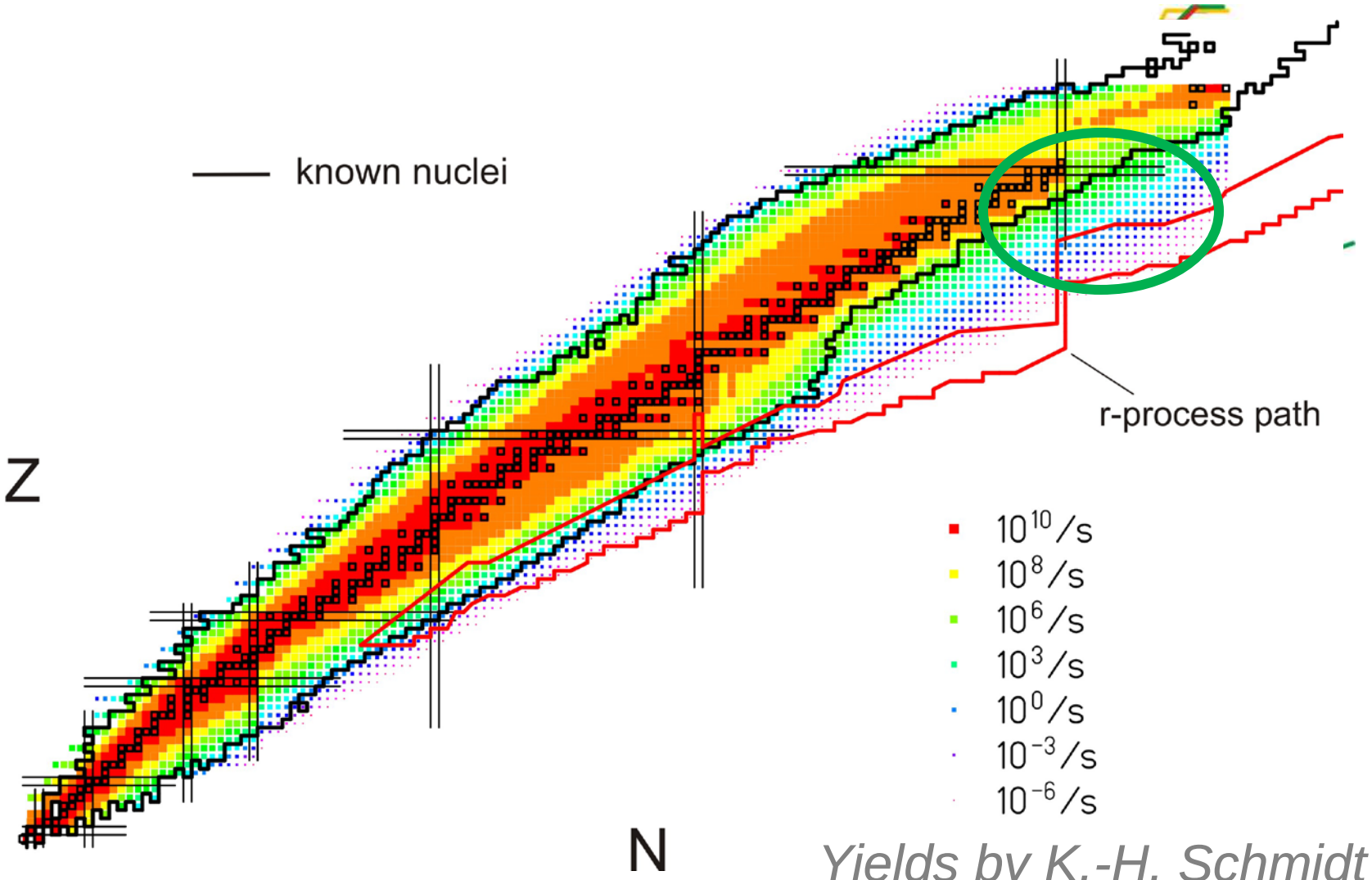
$^{208\text{-}214}$Po, ^{210}Pb: **^{238}U beam GSI**

^{204}Pt, ^{208}Hg, ^{21X}Pb : **^{238}U beam HISPEC-FAIR**



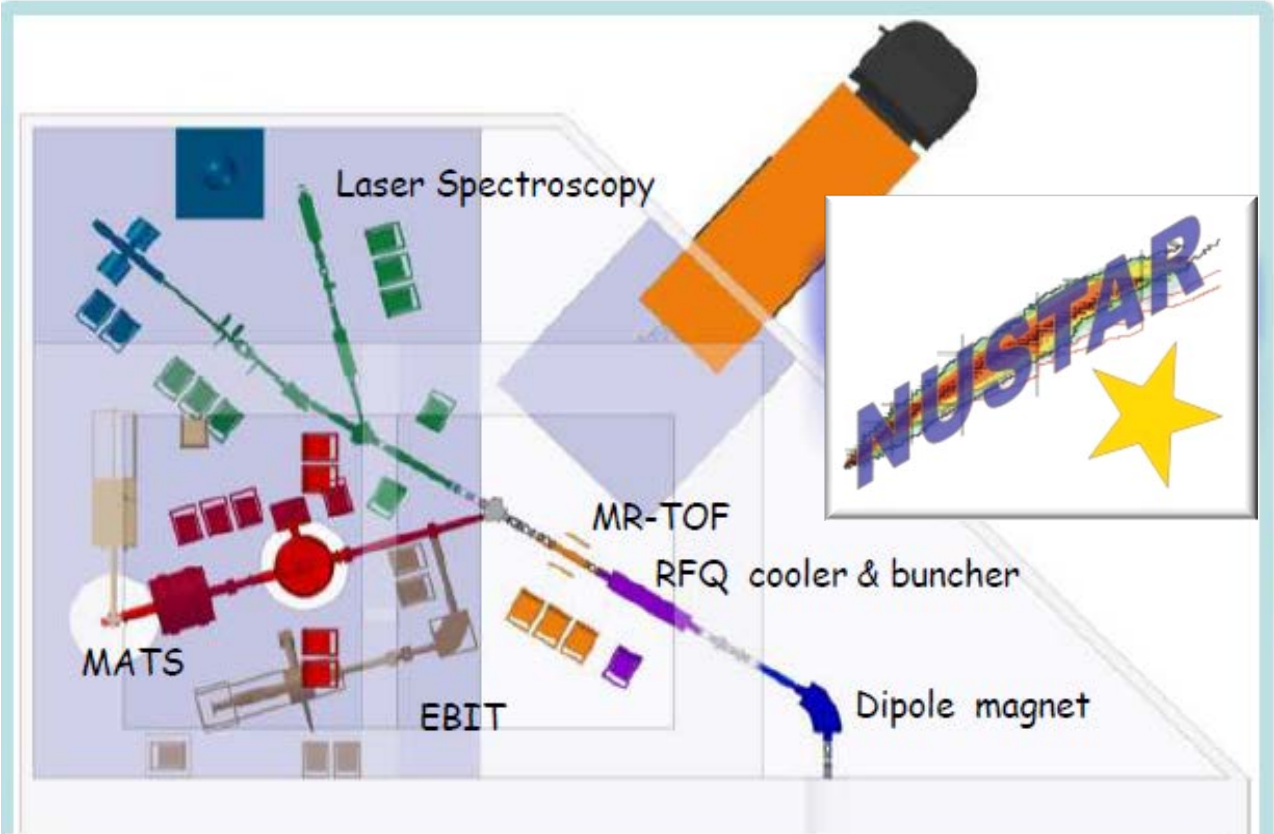


Phase 1 experiments, n-rich Pb



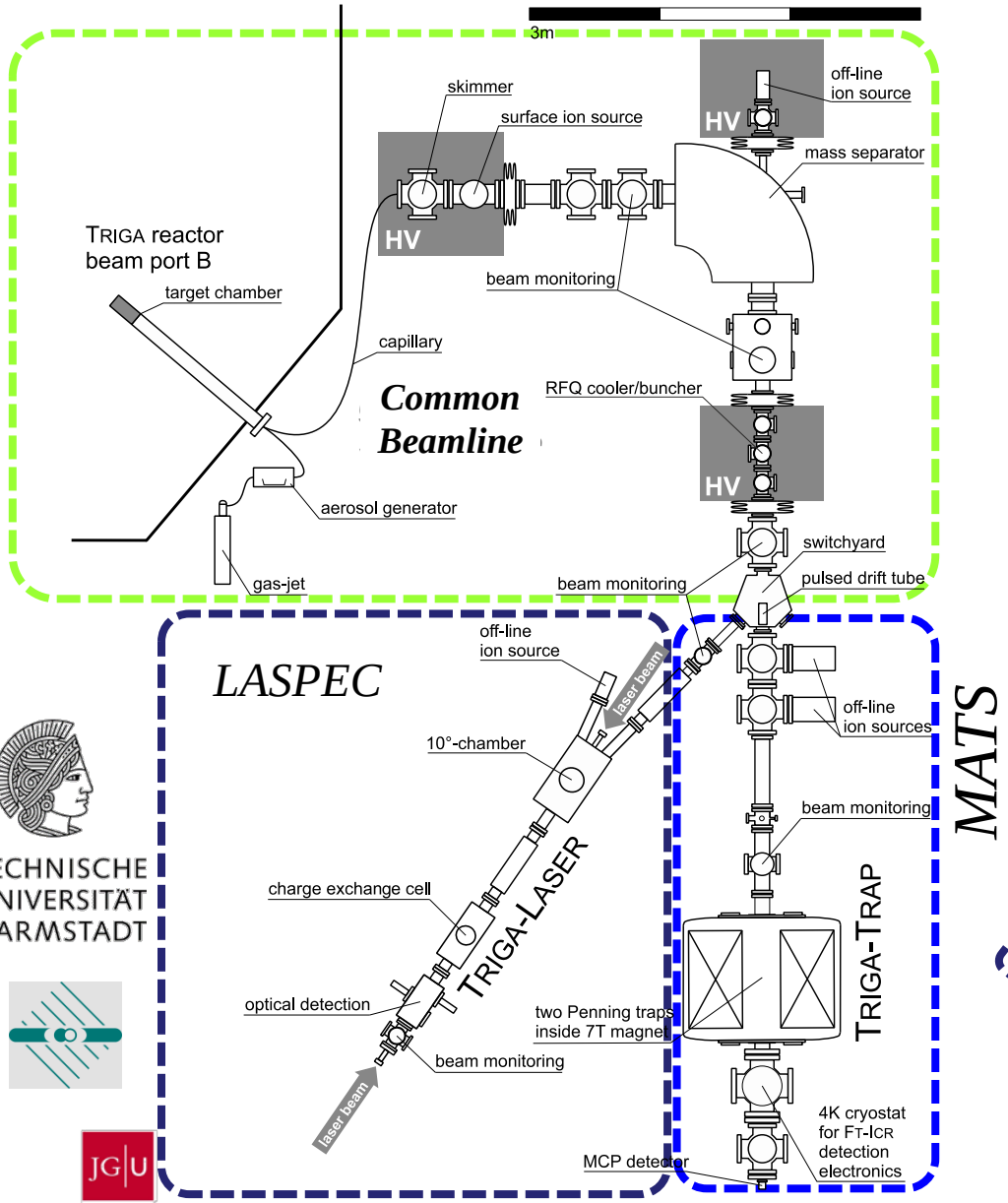
Yields by K.-H. Schmidt

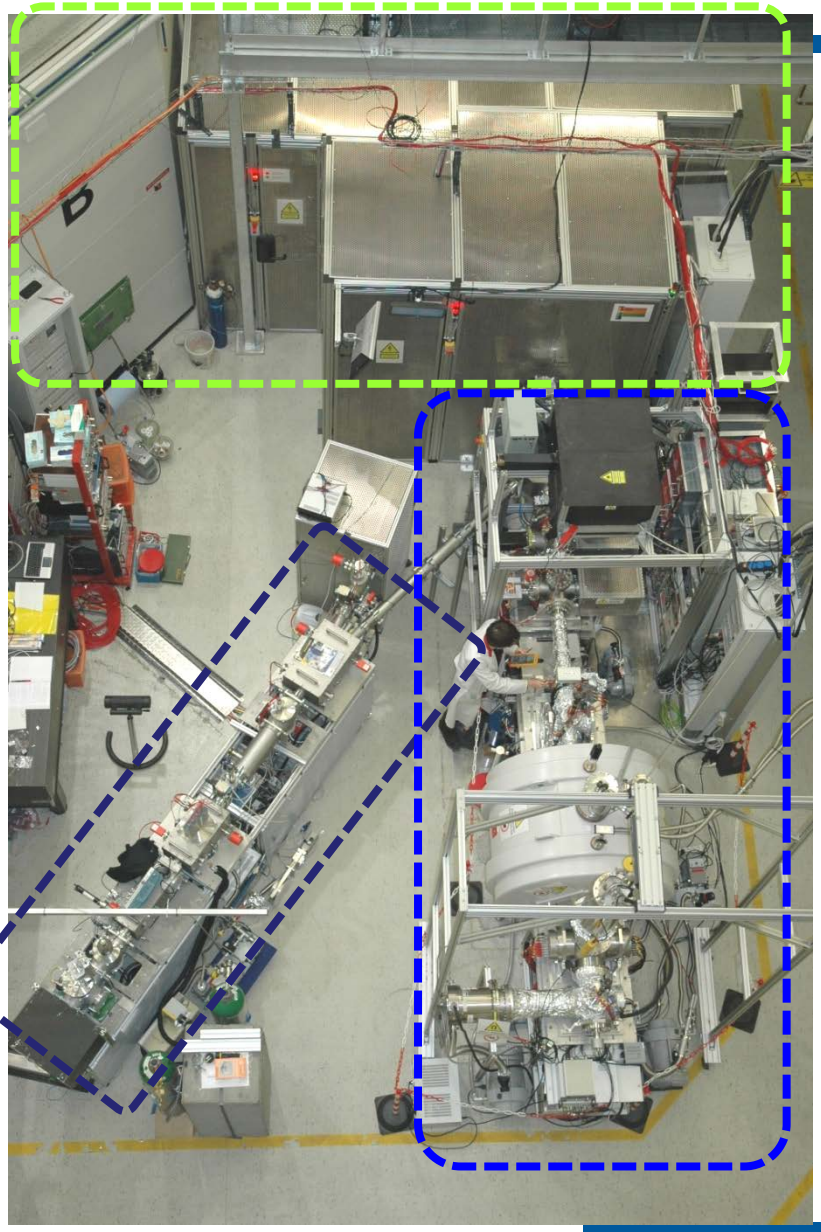
MATS/LASPEC at the Low Energy Branch (LEB)



for more information see:
Technical Design Report of MATS & LaSpec:
D. Rodriguez, EPJ Special Topics 183 (2010) 1-123

TRIGA-SPEC @ Mainz: Prototype of MATS and LASPEC



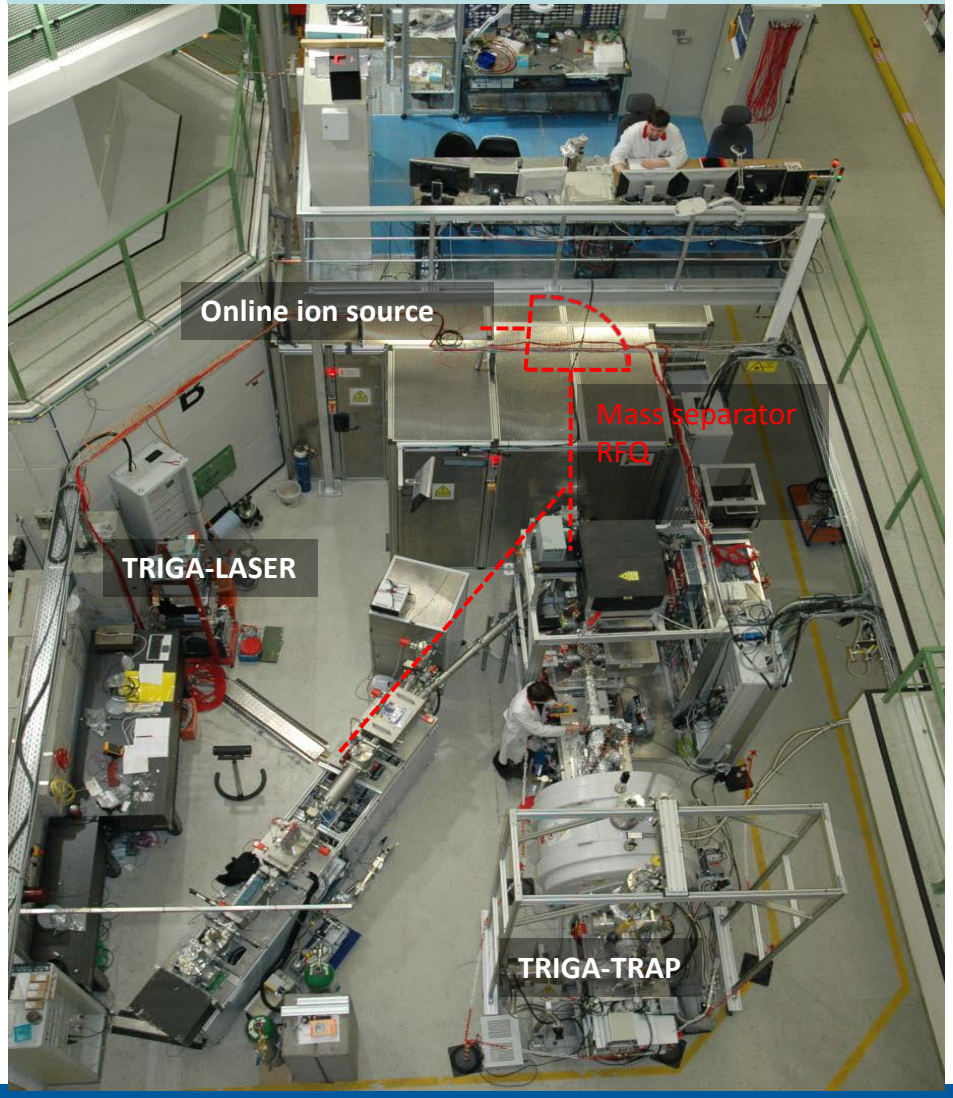


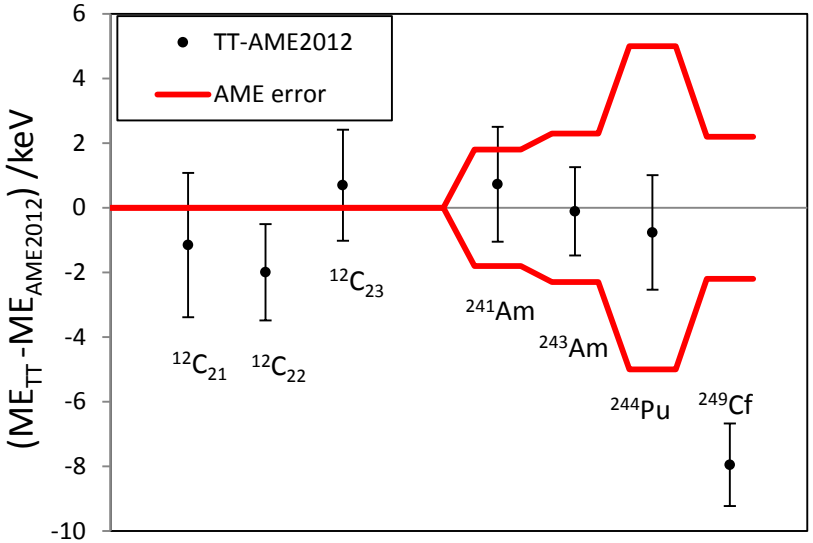
TECHNISCHE UNIVERSITÄT DARMSTADT

JG|U

Mass Measurements at TRIGA-TRAP in 2013
First stage of MATS (View with GSI data)

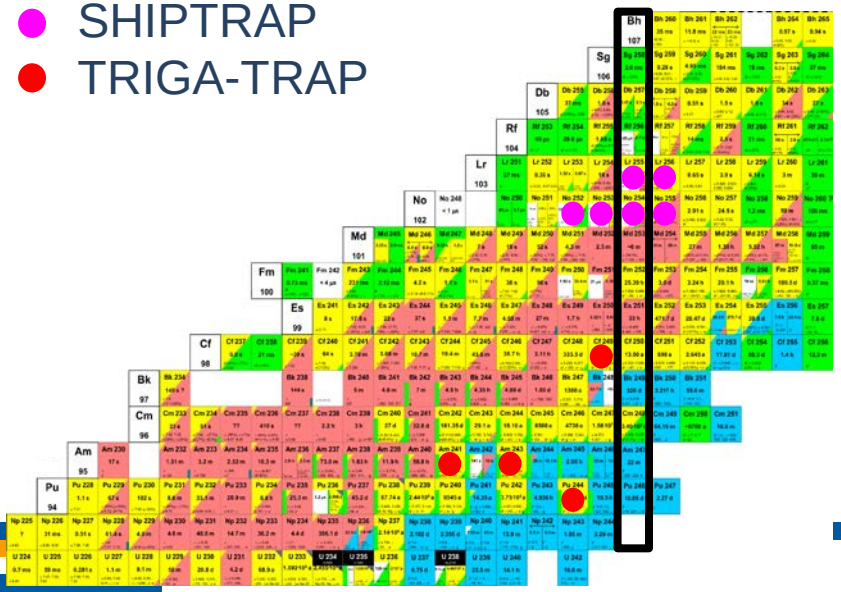
project start @ TRIGA: 01/2008
start data taking: 05/2009



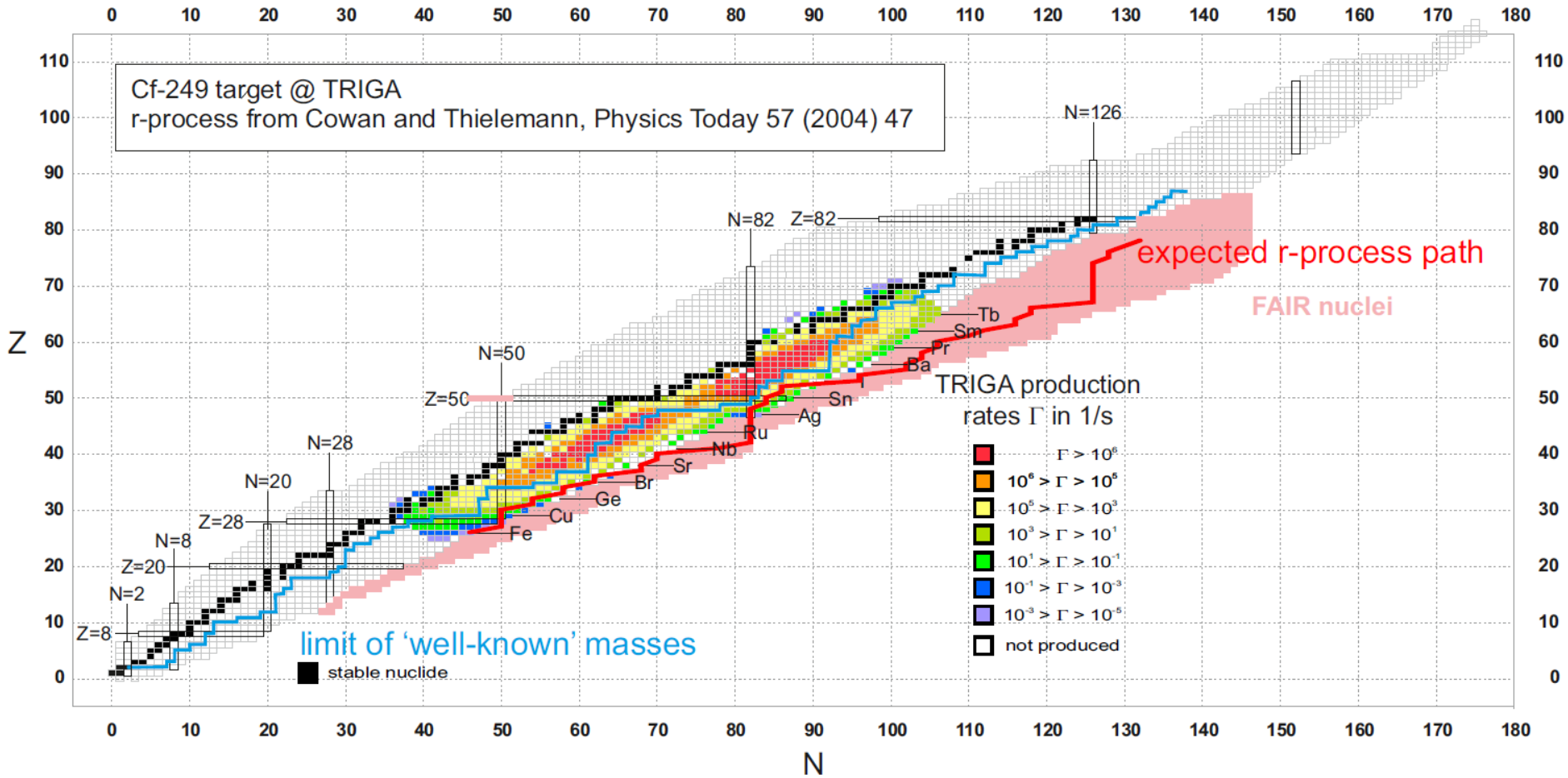


N=152

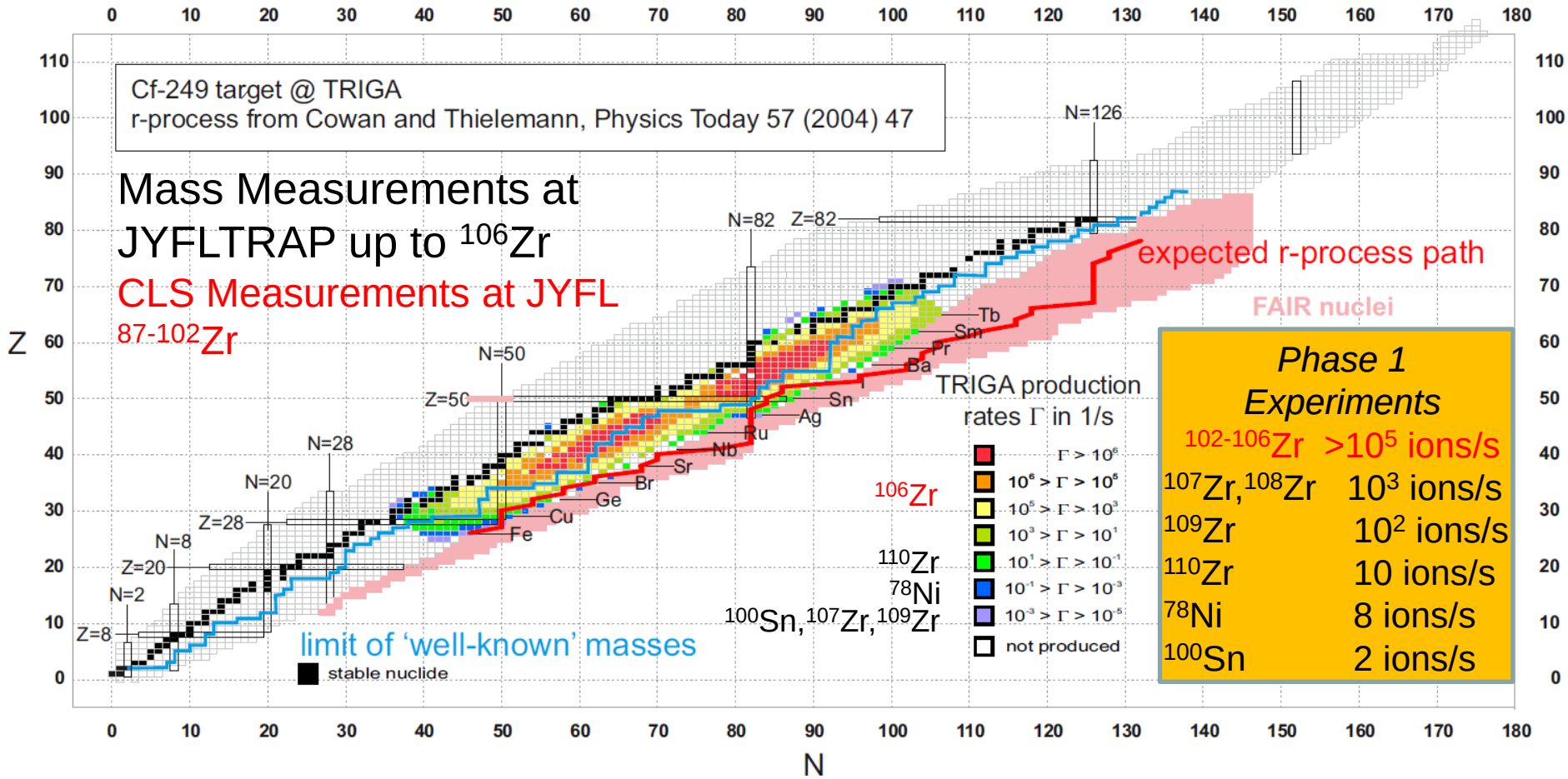
- SHIPTRAP
- TRIGA-TRAP



First experiments with MATS & LaSpec at FAIR
Phase 0 → Phase 1



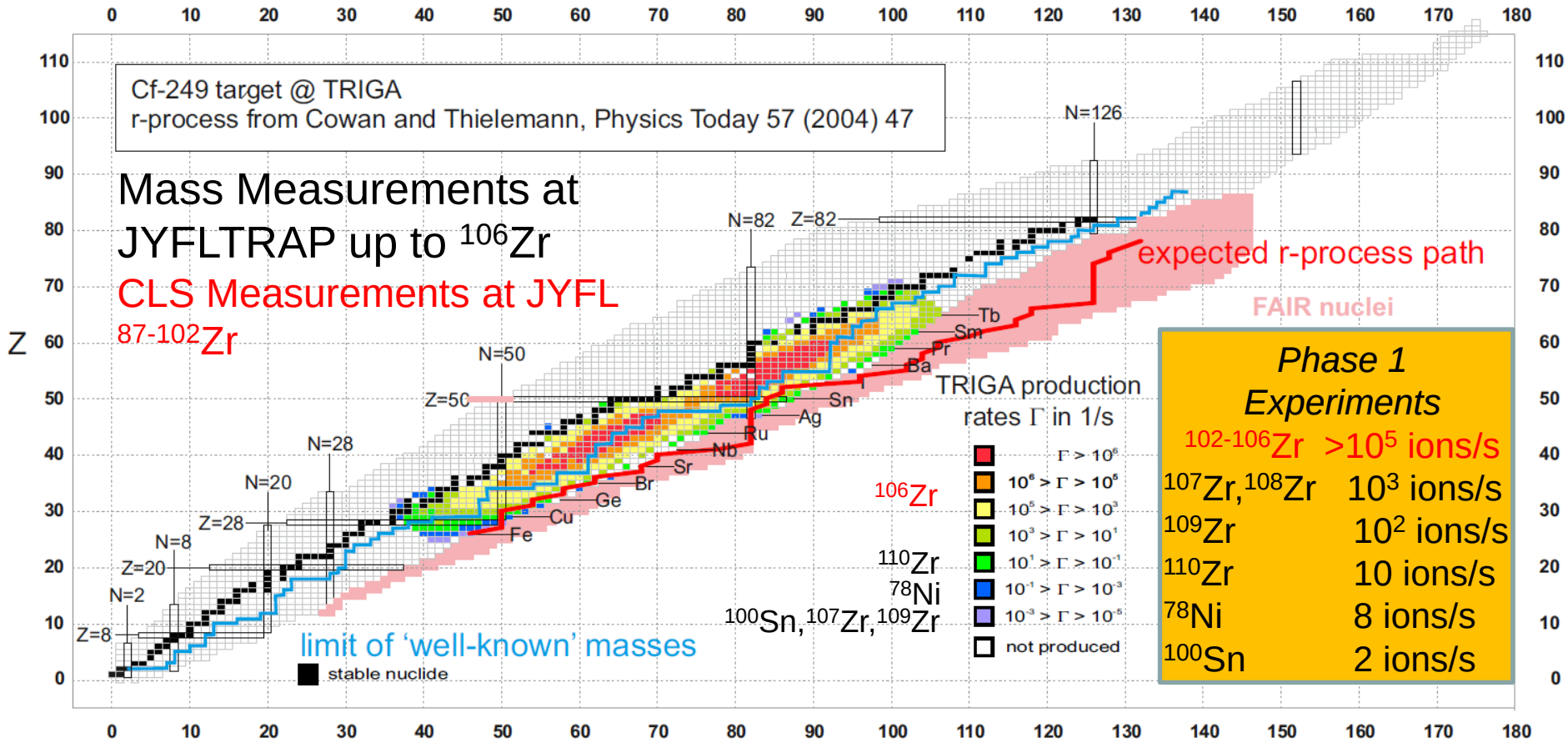
First experiments with MATS & LaSpec at FAIR
Phase 0 → Phase 1



Phase 1 Experiments

$^{102\text{-}106}$Zr	>10^5 ions/s
^{107}Zr,^{108}Zr	10^3 ions/s
^{109}Zr	10^2 ions/s
^{110}Zr	10 ions/s
^{78}Ni	8 ions/s
^{100}Sn	2 ions/s

First experiments with MATS & LaSpec at FAIR
Phase 0 → Phase 1



Phase 1 Experiments

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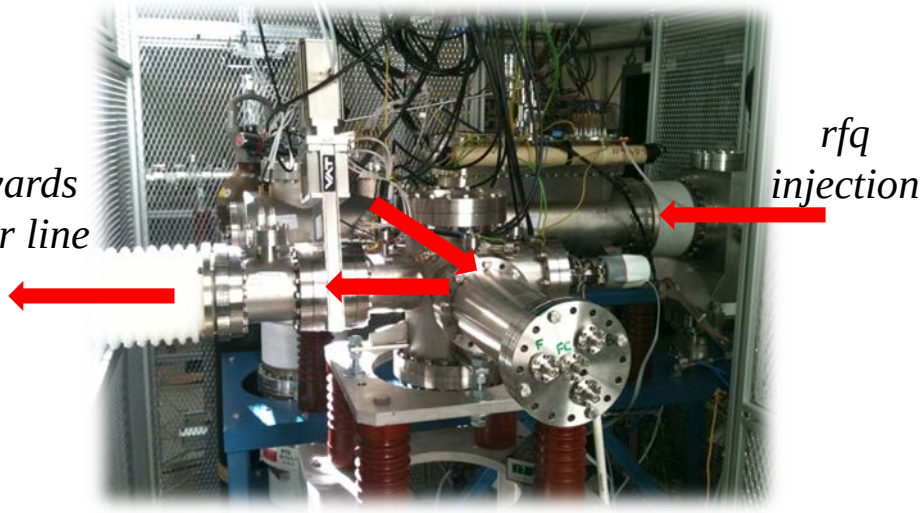
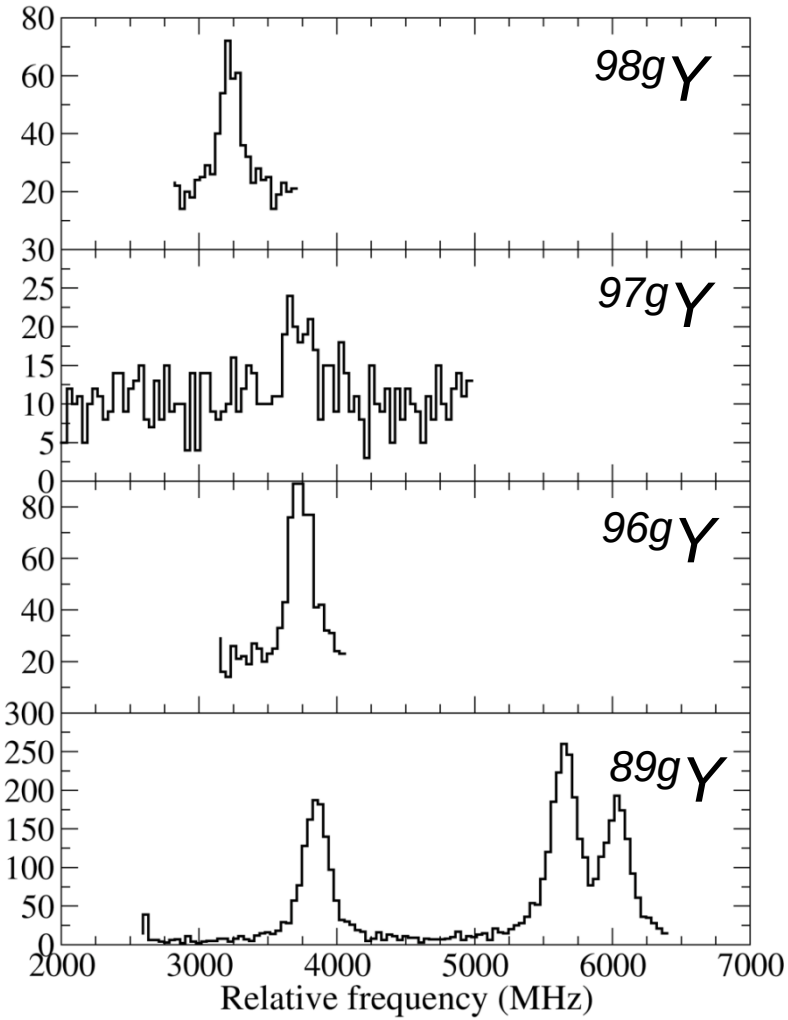
^{107}Zr, ^{108}Zr	10^3 ions/s
^{109}Zr	10^2 ions/s
^{110}Zr	10 ions/s
^{78}Ni	8 ions/s
^{100}Sn	2 ions/s

- The accessibility will depend on the performance of the Super-FRS and the ion-gas catcher (TDR of the ion catcher in preparation)

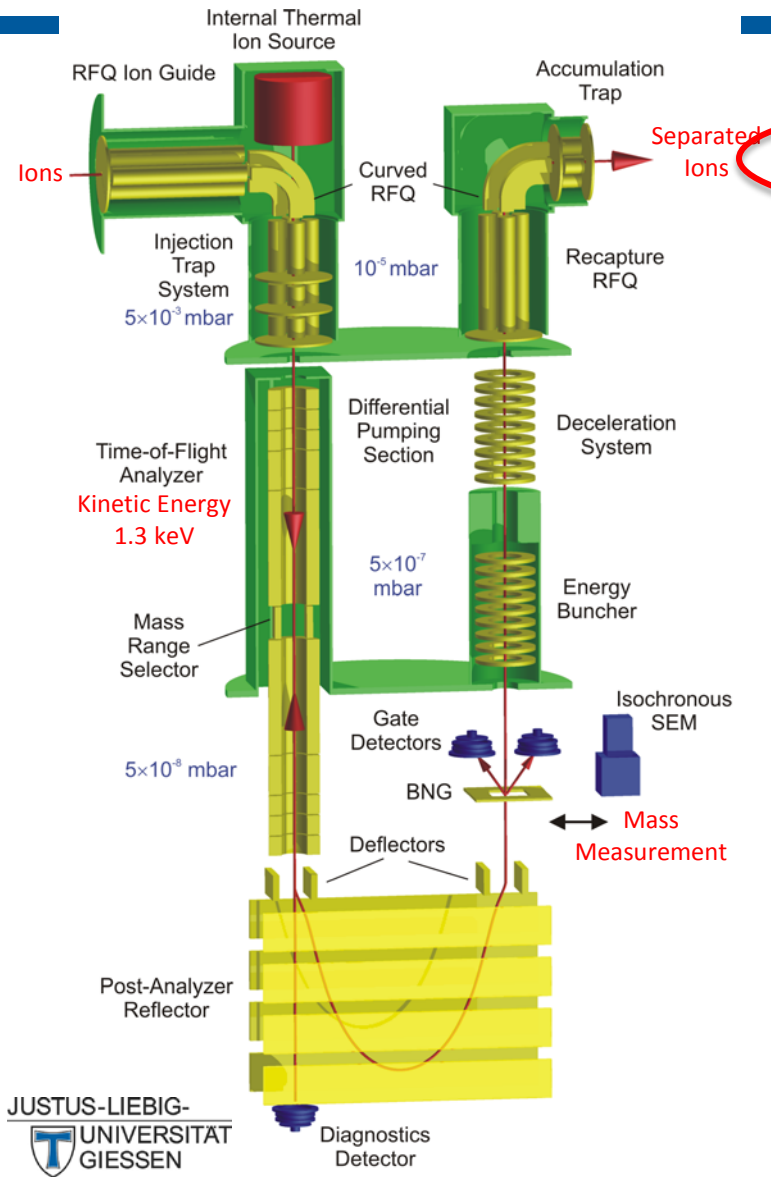
Collinear laser spectroscopy of doubly-charged fission fragments at IGISOL-4





- First spectroscopy on 2^+ charge states
- Optical manipulation in rfq
- s→p transition from metastable state
- Calibrate atomic factors in yttrium

Multi-Reflection Time-Of Flight Mass Spectrometer

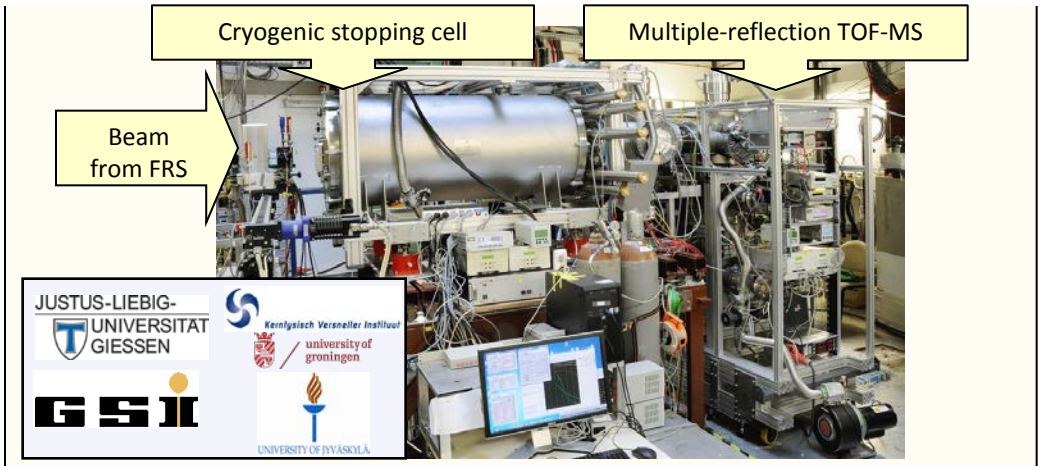


W.R. Plaß et al., NIM B 266 (2008) 4560
W.R. Plaß et al., Int. J. Mass Spectrom. 394 (2013) 134

Mass spectrometer (direct mass measurements, broadband diagnostics) and isobar separator

Features world wide unique performance characteristics:

- Mass resolving power: up to 600,000
- Mass measurement accuracy: down to 10^{-7}
- Measurement duration: ~ few ms
- Repetition frequency: up to 400 Hz
- Transmission efficiency: > 50%
- Ion capacity: up to 10^6 ions/s

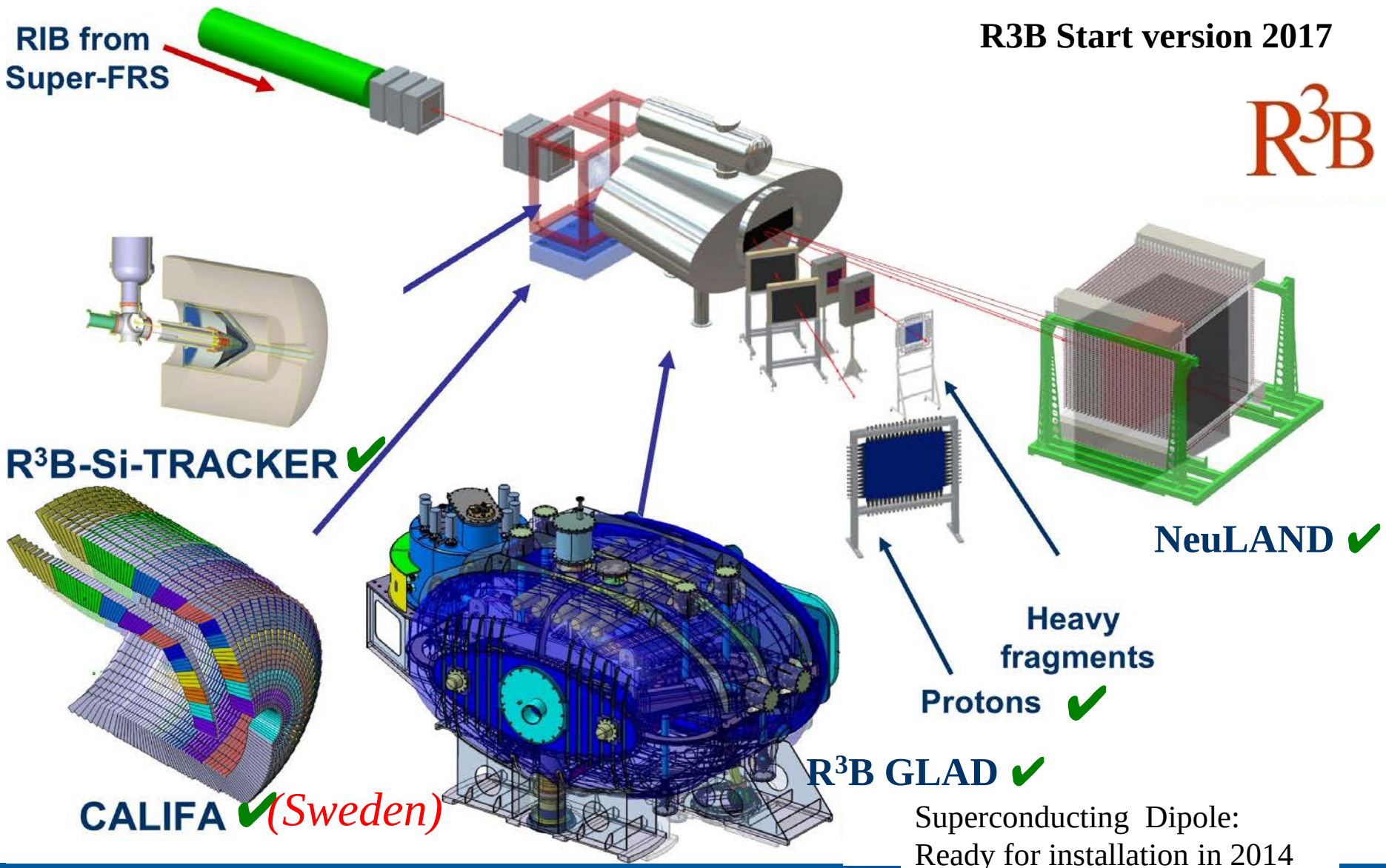


Commissioned online at the FRS Ion Catcher in 2012

- First direct mass measurements of ^{211}Po and ^{211}Rn, ^{213}Rn ($T_{1/2}$ = 19.5 ms!)
- Characterization of stopping cell performance: MR-TOF-MS ideal diagnostics tool for stopping cells

Future work: Implement recapture system / operation as (ultra-)high resolution mass separator

Reactions with Relativistic Radioactive Beams



Superconducting Dipole:
Ready for installation in 2014
Construction by CEA Saclay

Schedule and first experiments

2013 Installation of infrastructure in Cave C for GLAD (He cryo-system, power supply)
Delivery and installation of superconducting dipole GLAD (expected Q4/2014)

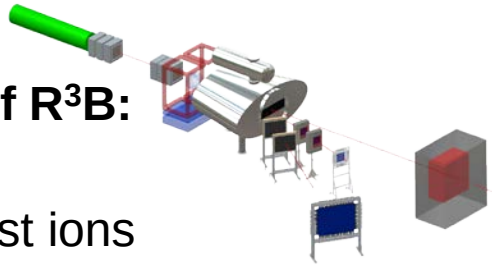
2014 Installation of 20% detectors NeuLAND and CALIFA
Commissioning run in Q3/2014 (This actually happened in Sep./Oct. 2014)

2015/16 Construction and installation of detector components

2017/18 Commissioning of full R3B setup and first physics run at GSI

2019 Installation of experimental setup at FAIR site including superconducting triplet

2020/21 Commissioning and first experiments at Super-FRS



Experiments in 2020/21 will make use of uniqueness of R^{3}B:

- Reactions at high beam energies up to 1 GeV/nucleon
- Tracking and identification capability even for the heaviest ions
- Multi-neutron tracking capability, high-efficiency calorimeter

Experiments possible for the first time:

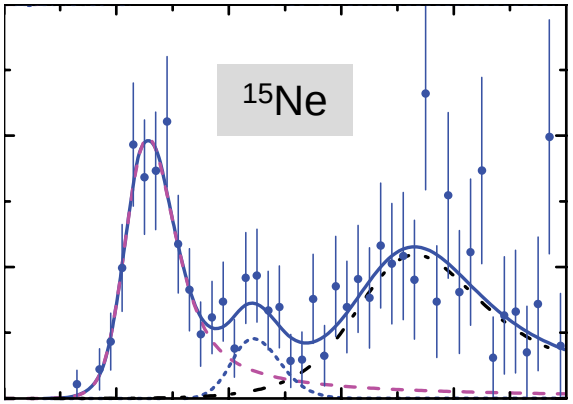
- 4 neutron decays beyond the drip-line and for heavier n-rich isotopes
- Kinematically complete measurements of quasi-free nucleon knockout reactions
- Electric dipole and quadrupole response of Sn nuclei beyond N=82, and of neutron-rich Pb isotopes

Beyond the drip line
First observation of ^{15}Ne ground and excited states

^{15}Ne and daughter nuclei

^{15}Ne 3-body decay

^{16}Ne

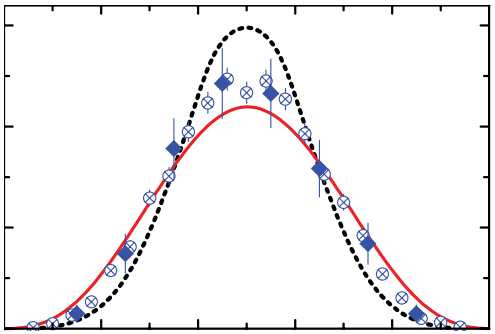


⊗ *^{16}Ne exp data*

◆ *^{15}Ne exp data*

^{16}Ne isotropic 3-body decay

sequential decay via the ^{14}F gs



^{15}Ne ground state unbound by S_{2p} = 2.522(66) MeV

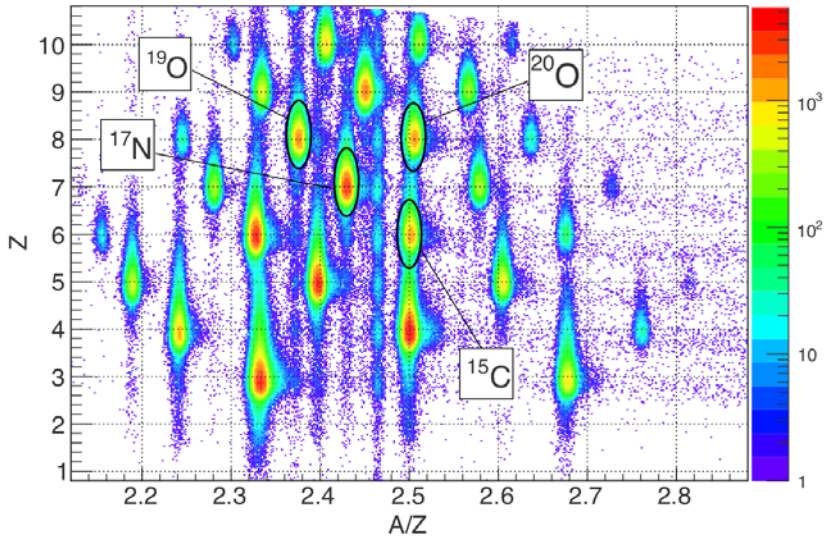
^{15}Ne is (like ^{16}Ne) a true 2p-decay nucleus, (despite available states in ^{14}F)

F. Wamers et al., Phys. Rev. Lett. 112 (2014) 132502

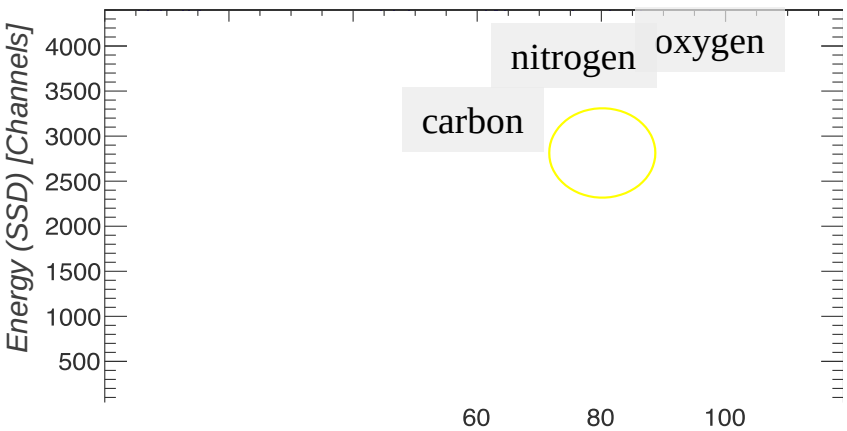
Quasi-free scattering

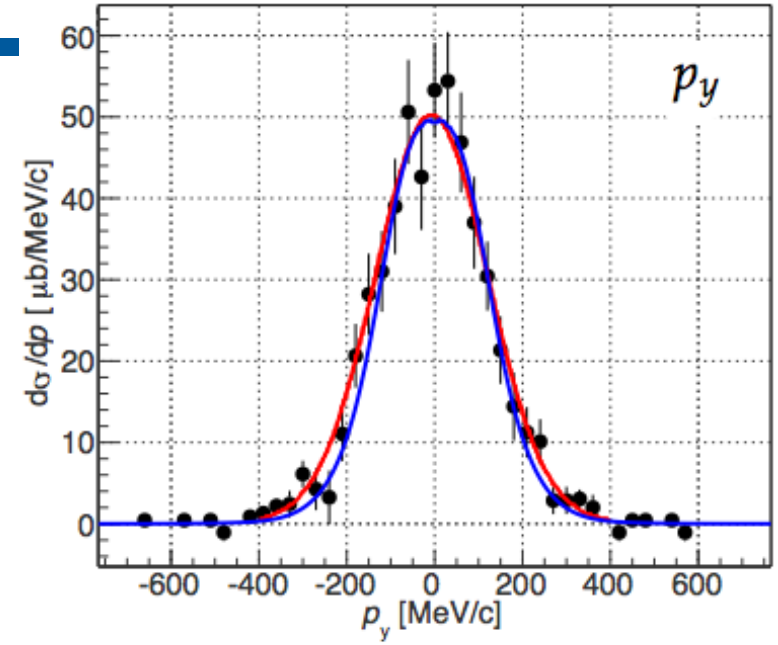
$p(^{20}O, pp^{19}N)$

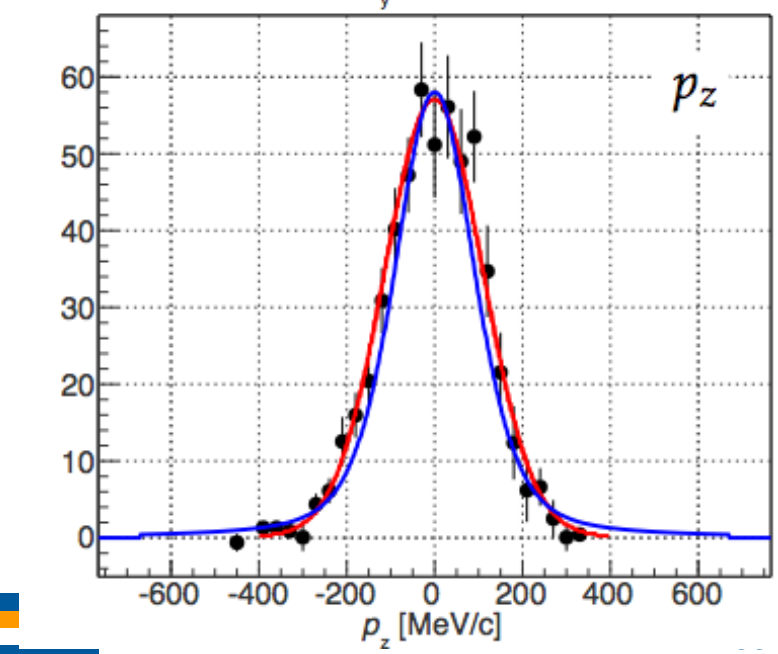
Incoming Particles



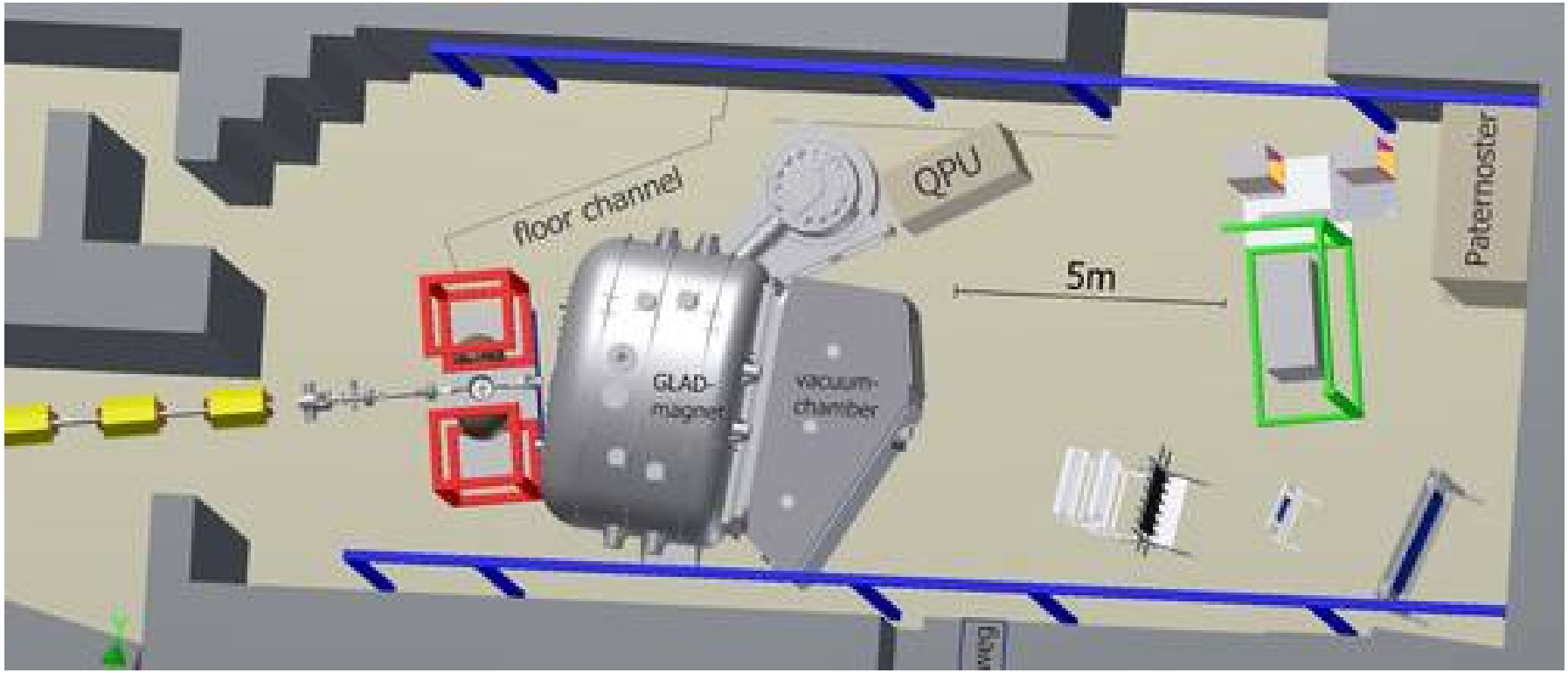
Outgoing Particles







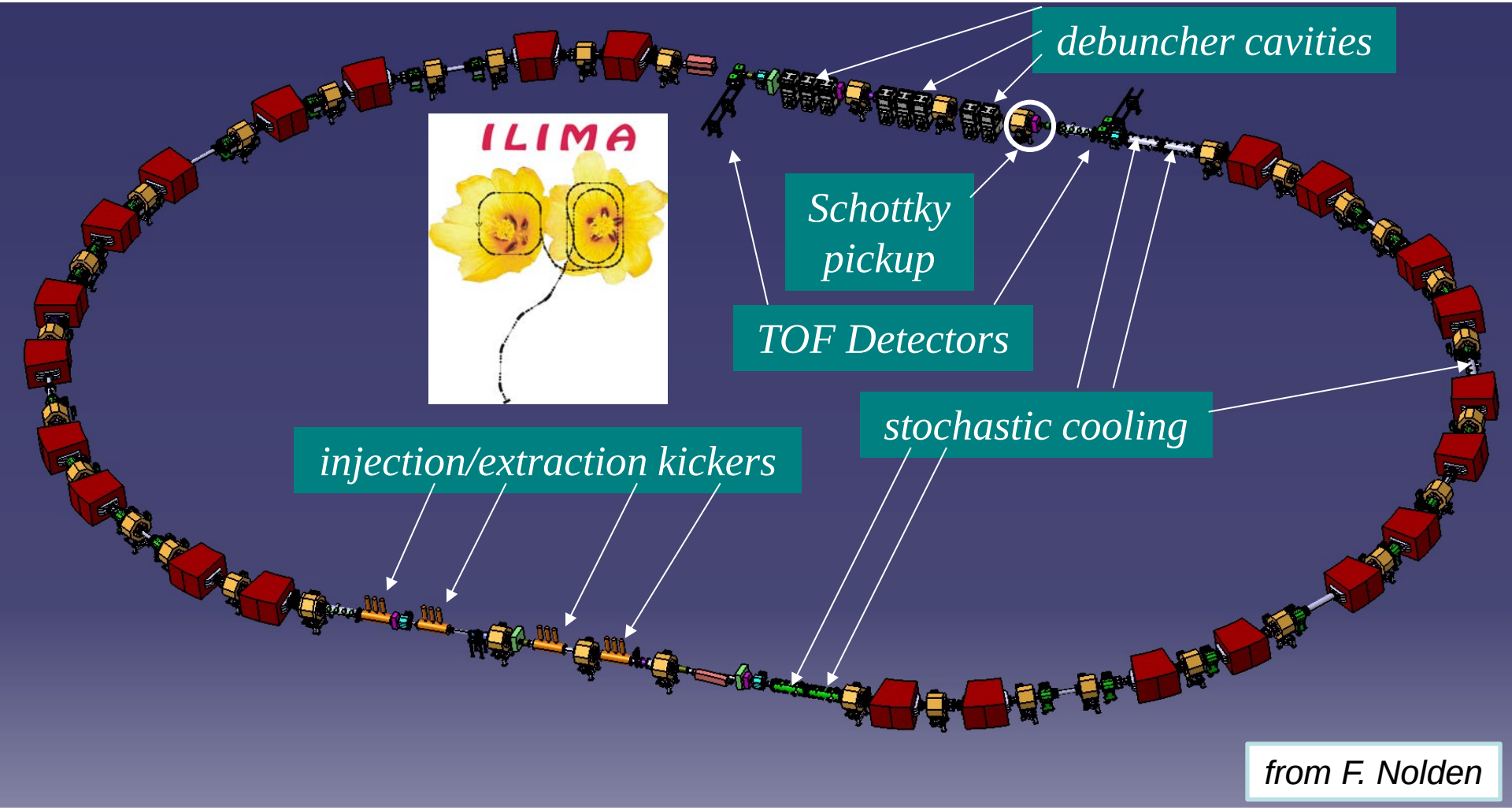
Phase 0: Test Setup@Cave-C – Next steps → Phase 1



- Experiment campaign 2014
- Preparations for GLAD installation
- Full integration test and potential later runs in Cave-C
- Move fully commissioned systems to FAIR high-energy Cave

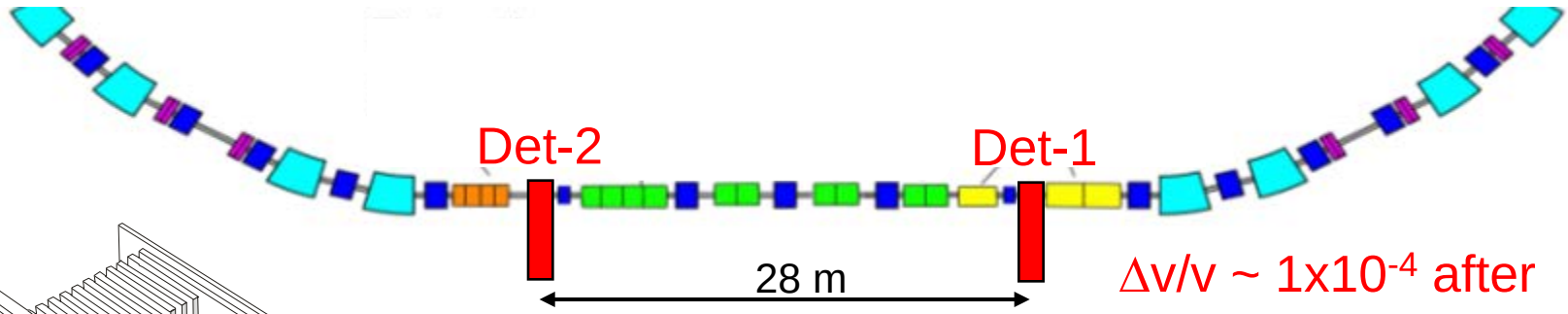
ILIMA – partial program in CR (NESR not in MSV)

CR perspective view

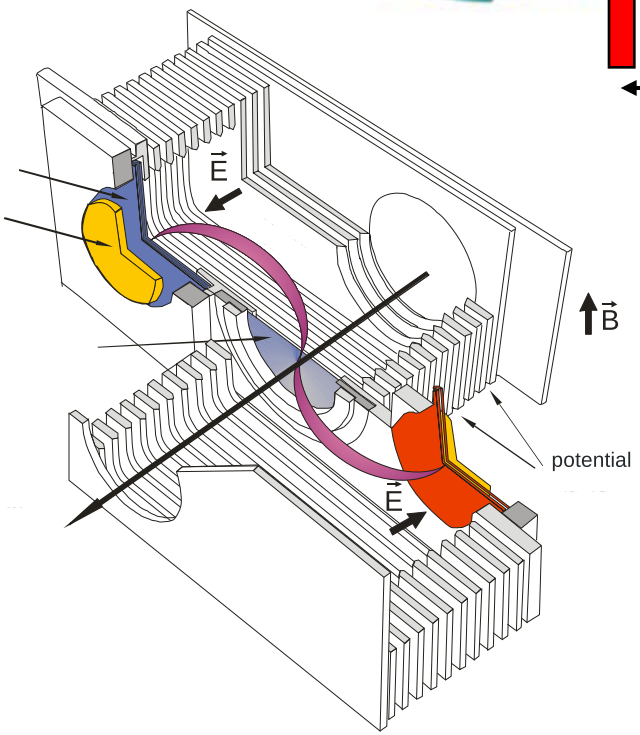


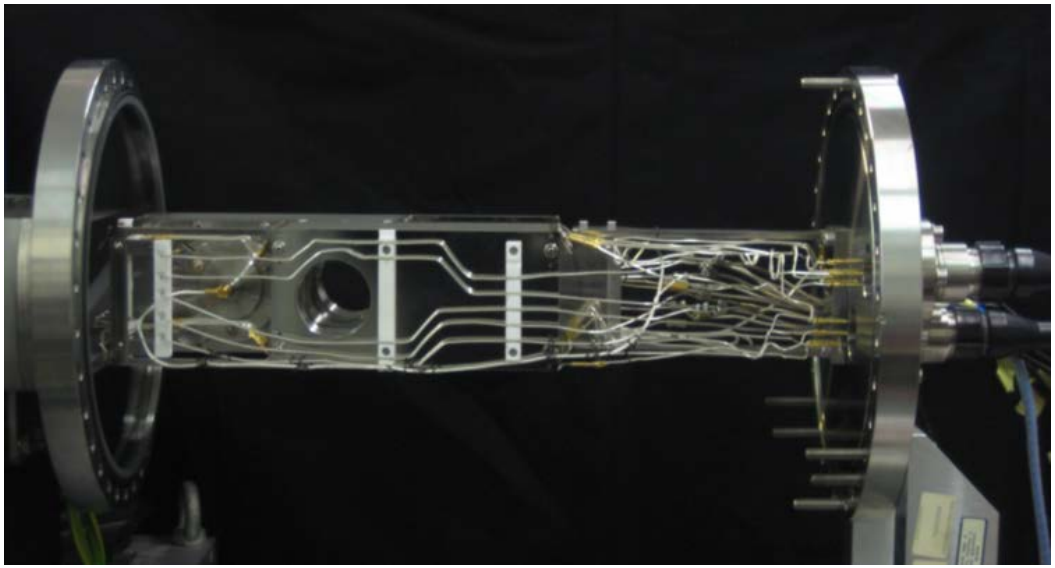
ToF Detection

How to operate in a ring without an electron cooler?
→ Measure velocity and also position simultaneously with two ToF detectors.

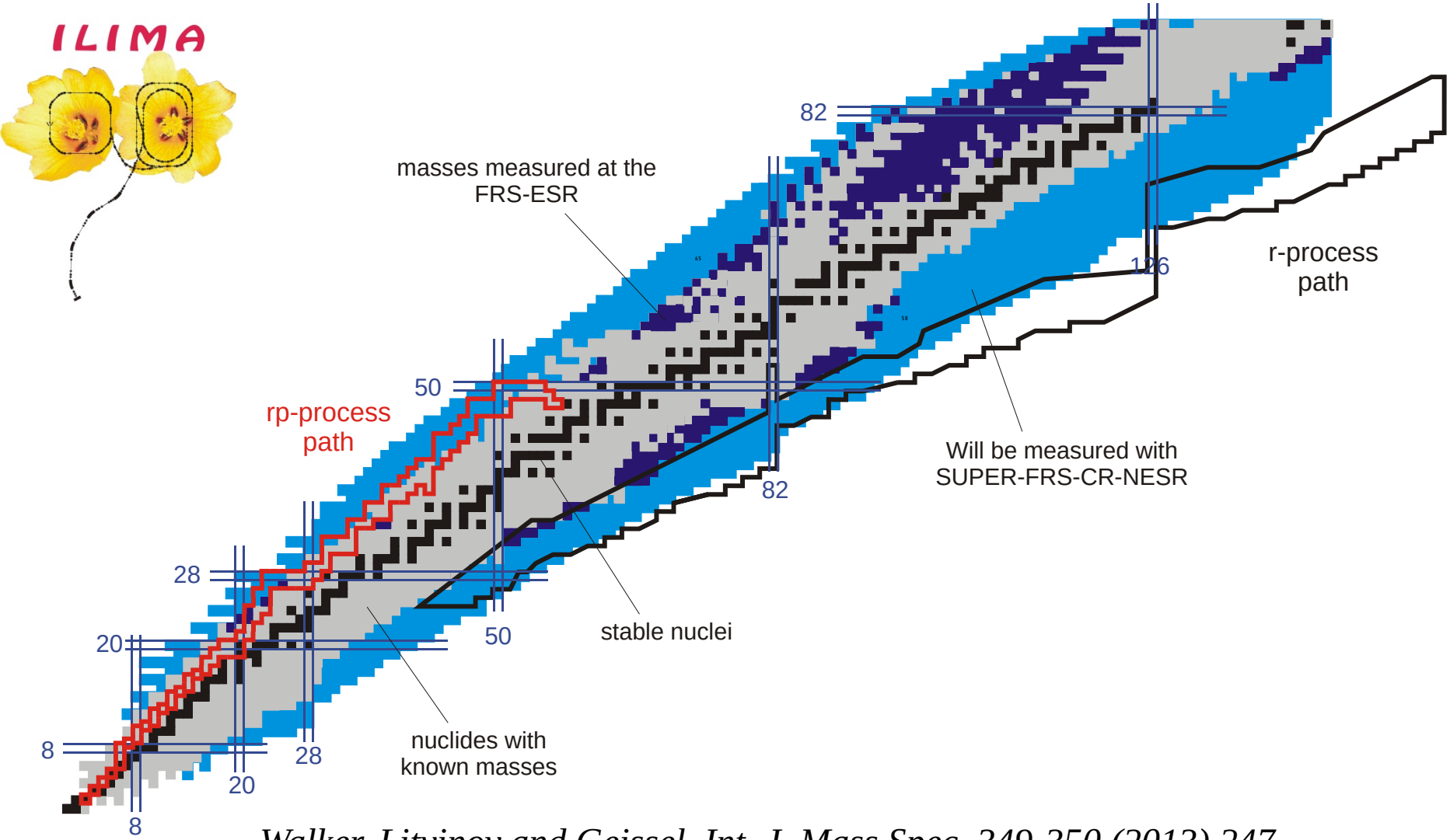


$\Delta v/v \sim 1\times10^{-4}$ after averaging many turns





Potential for new masses with ILIMA



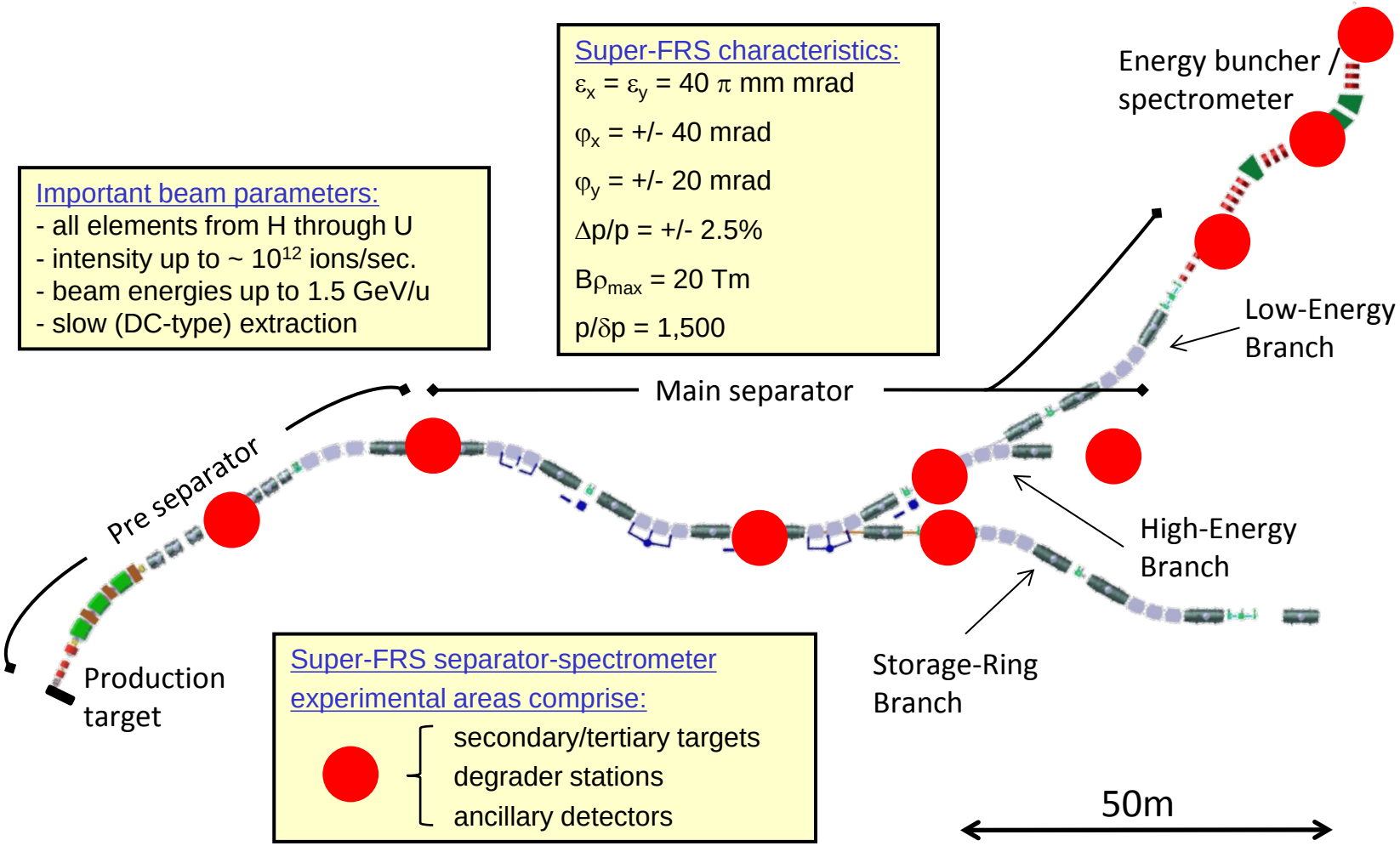
Walker, Litvinov and Geissel, Int. J. Mass Spec. 349-350 (2013) 247

Super-FRS as an experimental setup

High-resolution spectrometer for relativistic beams

Important beam parameters:
- 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

Super-FRS characteristics:
$\varepsilon_x = \varepsilon_y = 40\ \pi$ mm mrad
φ_x = +/- 40 mrad
φ_y = +/- 20 mrad
$\Delta p/p$ = +/- 2.5%
$B\rho_{max}$ = 20 Tm
$p/\delta p$ = 1,500



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

Super-FRS experiments

Super-FRS physics collaboration within NUSTAR formally established

Worldwide unique features:

- energy > 500 MeV/u
- momentum resolution p/Δp ~ 1500 ... 20000
- customized ion-optical modes

Planned experiments will use

- separator stages for high momentum resolution
- intermediate degrader and target stations
- standard equipment + (new) ancillary detectors

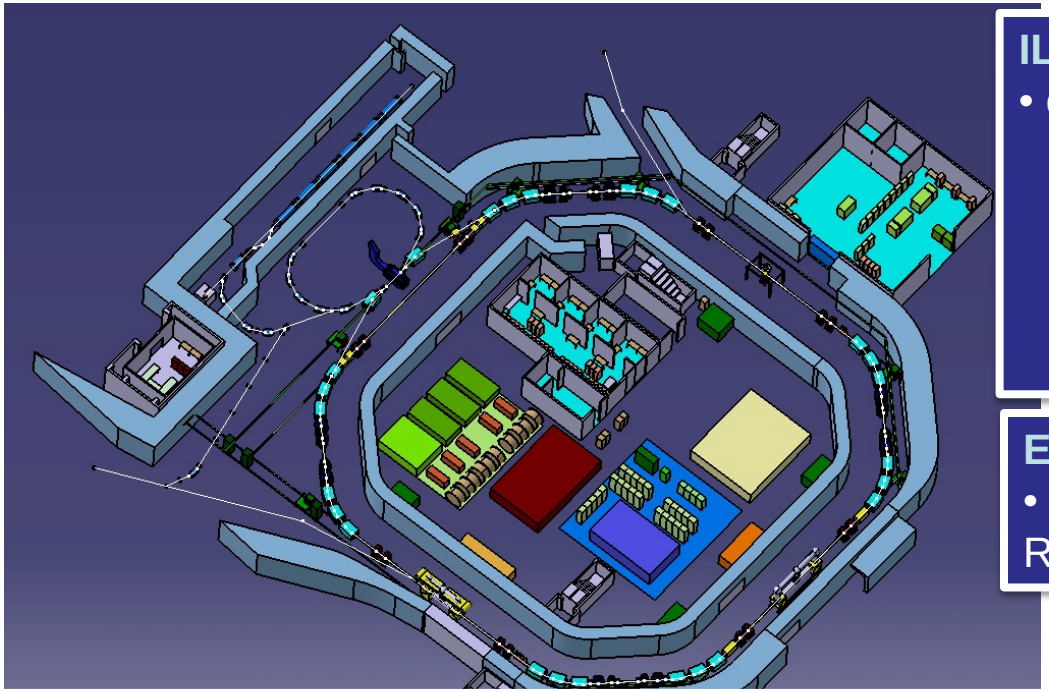
Super-FRS as:

- high-performance separator for mono-isotopic or cocktail beams
- high resolution spectrometer
- RI beam separator plus reaction spectrometer

Science programme compiled, synergies and overlaps identified

Beyond MSV: NUSTAR program at the NESR

Experiments with stored, electron cooled ion beams
- **World-wide unique**
- **Conceptionally new experiments**



ILIMA
- electron cooled beams needed for
  - higher precision and separation (ground and isomeric states)
  - time-resolved studies (unique decay modes, e.g. bound beta decay)
  - studies with pure isomeric beams

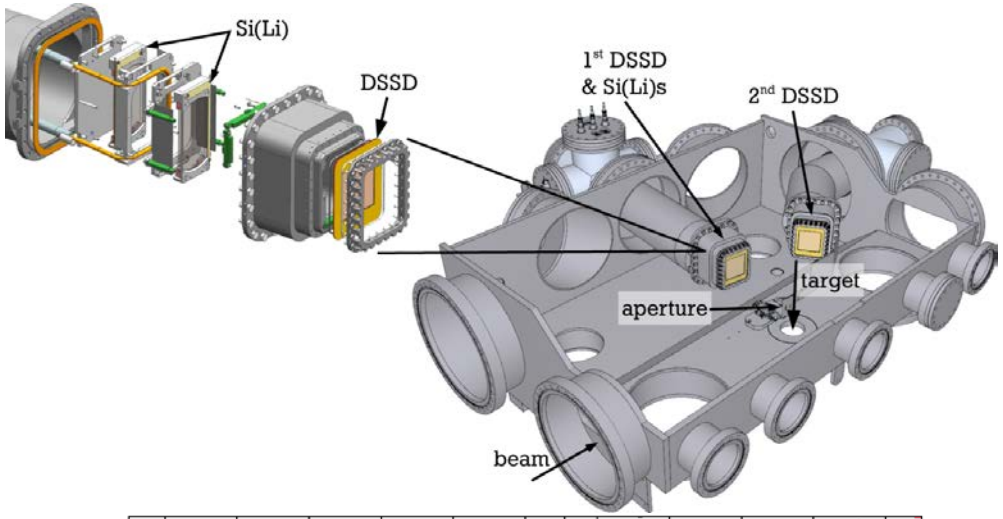
ELISe
- Elastic and inelastic electron scattering on RIBs

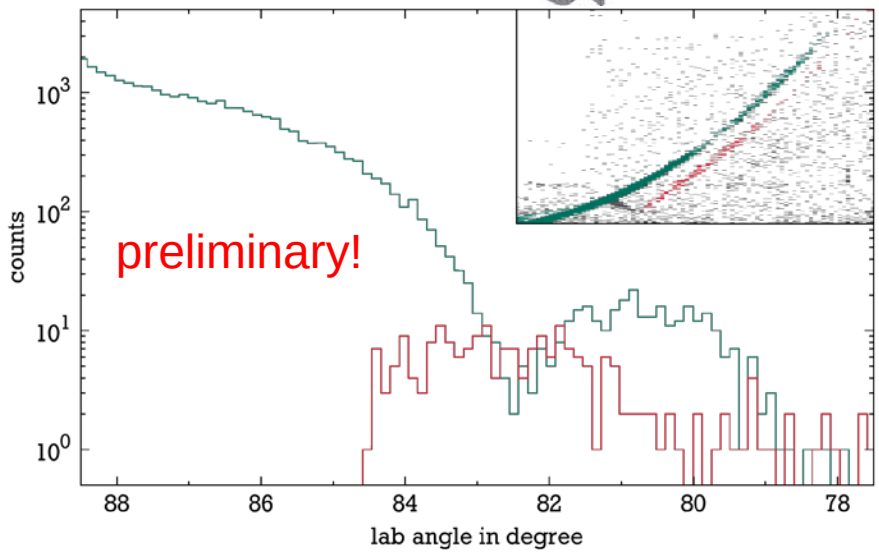
EXL: Elastic and inelastic scattering, reaction with low-momentum transfer
- matter distributions, monopole resonances, capture reactions, charge exchange reactions, transfer, knock-out

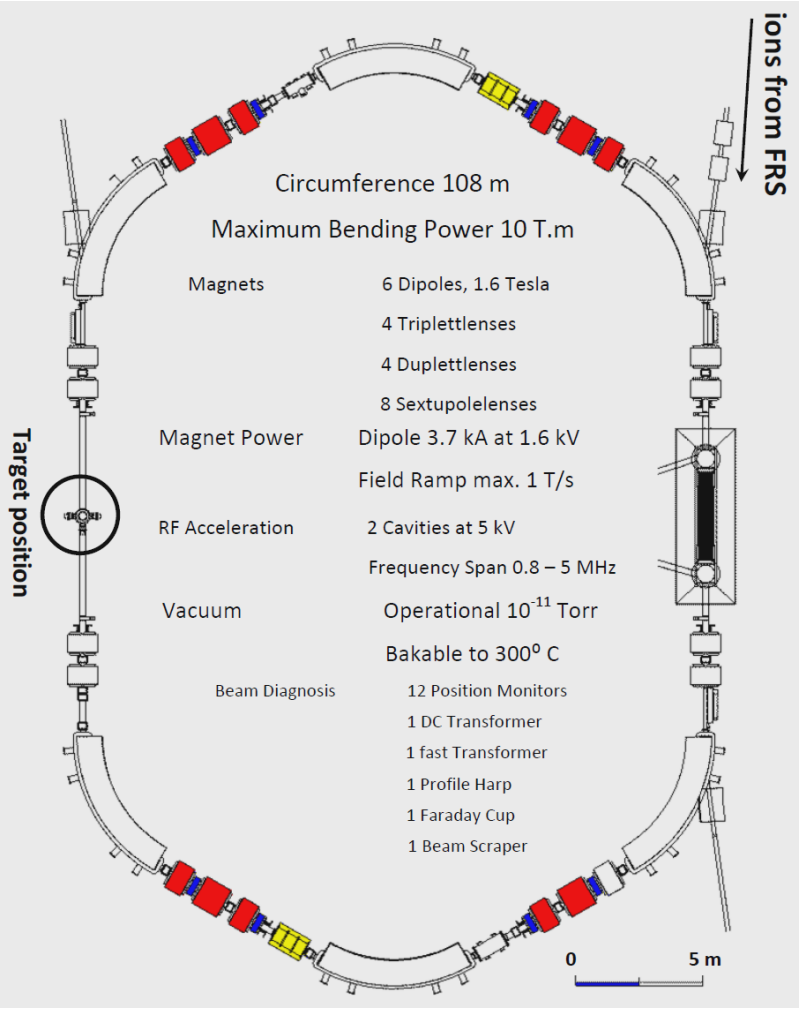
(n-skins, compressibility, GT-strength, shell evolution, nucl. astrophysics reactions)

Intermediate storage ring activities @ ESR

Elastic p-scattering off ^{56}Ni (E105)

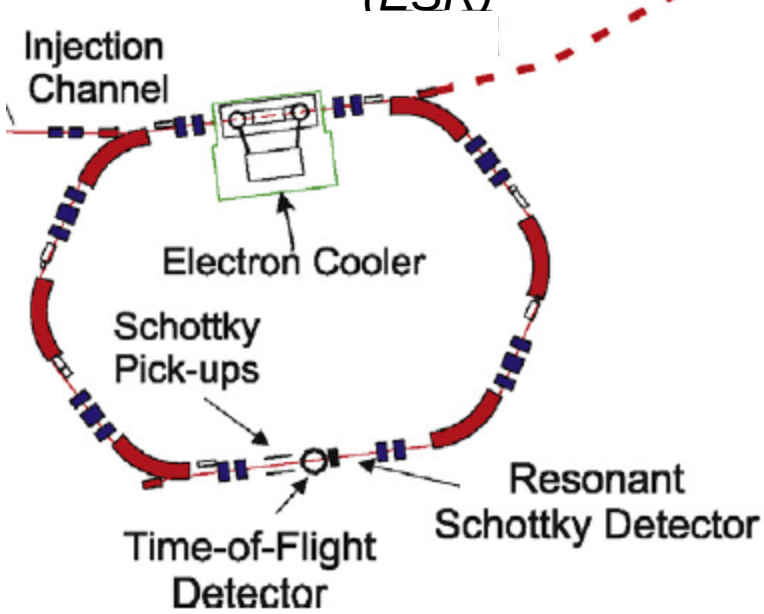




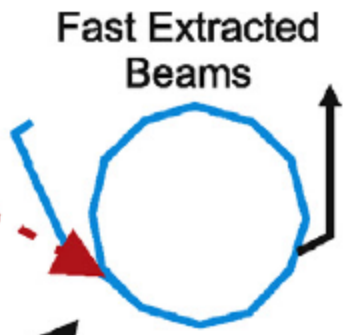


Possibility to prepare <100 keV bare ions

GSI Experimental Storage Ring (ESR)



Slowed-Down Highly-Charged Ions

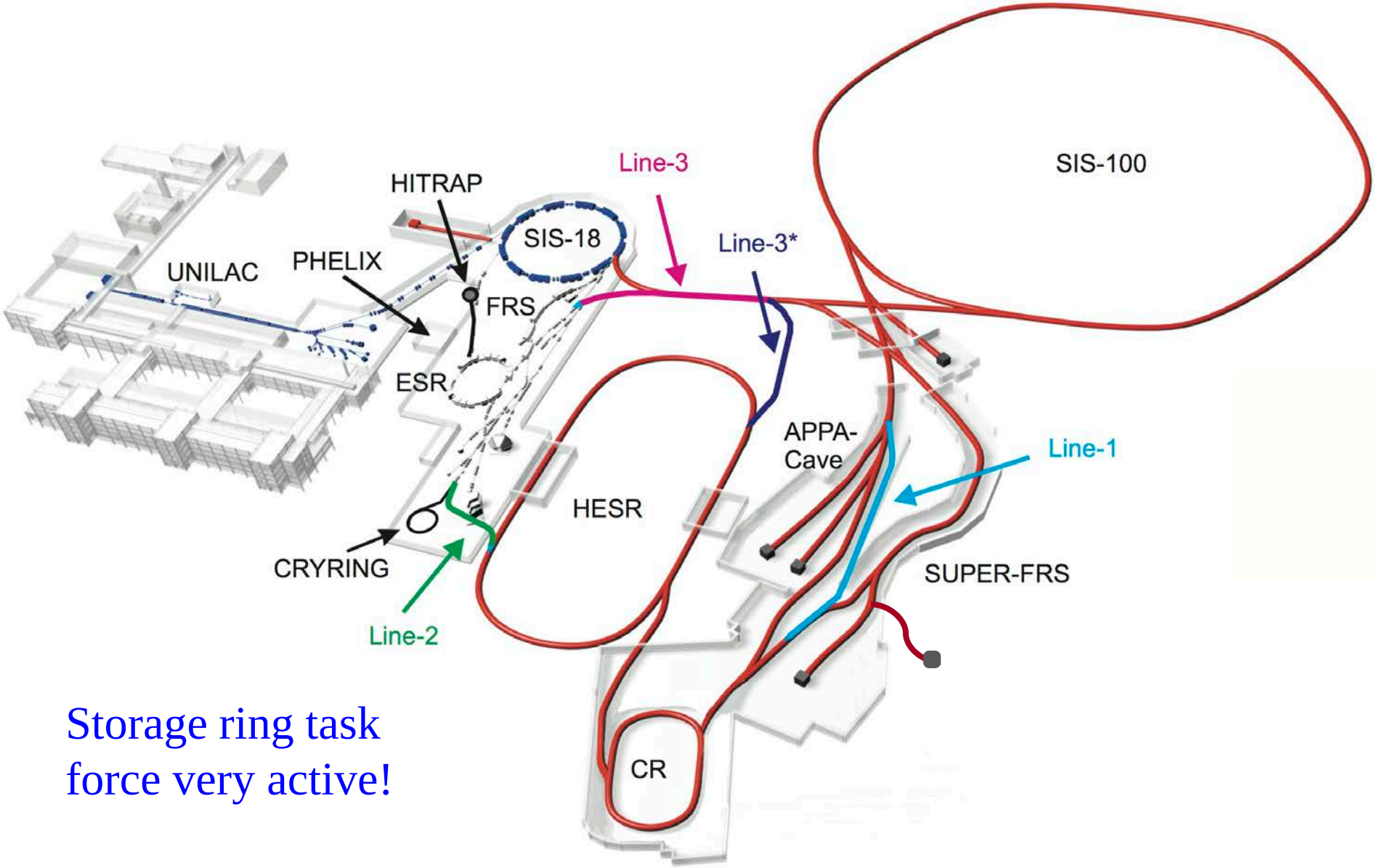


now being installed

CRYRING
Circumference
54 m
Bρ: 1.44 Tm

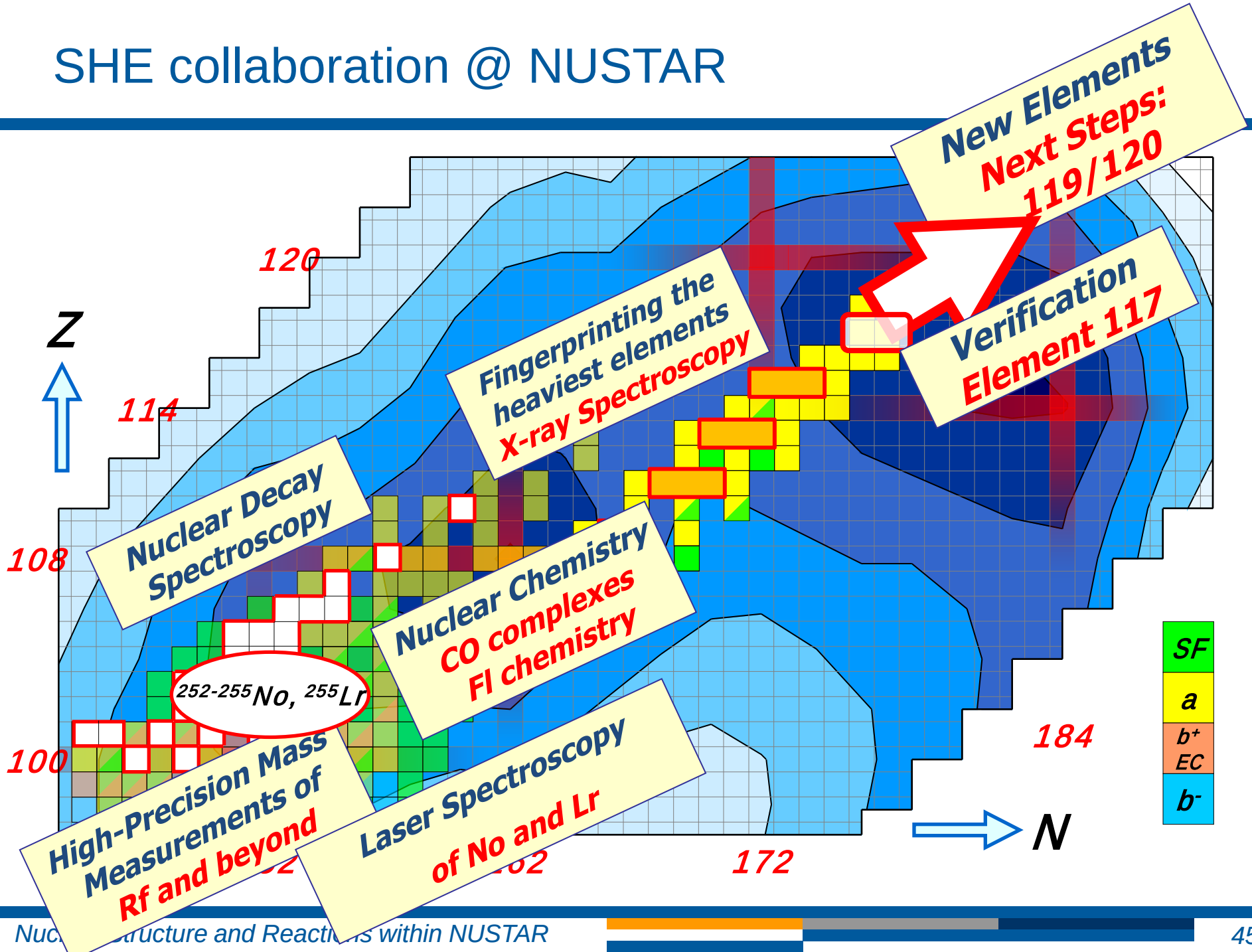
Cryring+ESR: beam energies 0.1-1.0 MeV/u reaction-rates measurements in the Gamow window of the **rp-process**

Transfer line to HESR/ESR/CRYRING



Storage ring task force very active!

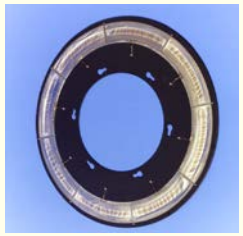
SHE collaboration @ NUSTAR



Unique instrumentation for SHE research at FAIR

ECR/PIG + UNILAC

Beam



Stable targets

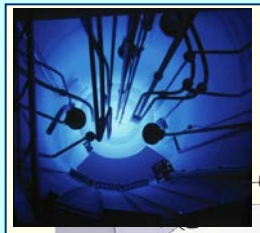
Actinide targets

SHIP

SHIPTRAP

TASCA

TASISpec



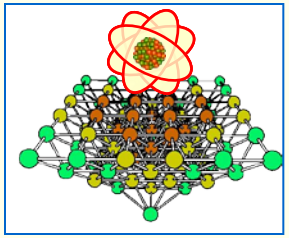
TRIGA-

-LASER

-TRAP

Radiochem. labs

Chemistry



Chemical theory

SHE collaboration @ NUSTAR

SHE research will complement NUSTAR scientific program

- Comprehensive approach to study atomic, chemical, and nuclear properties of the heaviest elements (Z > 100)
- versatile cutting-edge setups such as SHIP, SHIPTRAP, TASCA, TASISpec and more ready for experiments
- steps toward realization of high-intensity CW Linac for SHE research underway: accelerator R&D at HIM/GSI/GUF (“demonstrator” funded)

SHE sub-collaboration is formed following endorsement by the NUSTAR collaboration, science case recently submitted.

Spokesperson:	Rolf-Dietmar Herzberg
Deputy Spokesperson:	Michael Block
Technical Coordinator:	Alexander Yakushev

NUSTAR priorities

The priorities of NUSTAR for major projects:

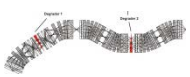
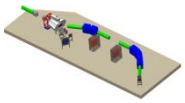
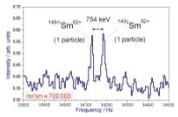
① Realization of Low-Energy Building;

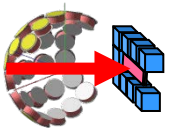
and *beyond the MSV*:

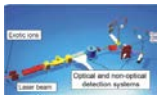
② Realization of the return line from CR to ESR;
③ Modification of ESR and building of the Electron ring.

Complementarity of NUSTAR experiments

Super-FRS *R3B* *ILIMA* *EXL* *ELISE* *AIC* *HISPEC/ DESPEC* *MATS* *LASPEC*



	Super-FRS	R3B	ILIMA	EXL	ELISE	AIC	HISPEC/DESPEC	MATS	LASPEC
Masses			bare ions, mapping study				Q-values, isomers	dressed ions, highest precision	
Half-lives	ps...ns-range		bare ions, s...h				dressed ions, µs...s		
Matter radii	interaction x-sect	matter radii		matter densitiy distributions		matter radii from absorption			
Charge radii					charge density distribution				mean square radii
Single-particle structure	high resolution, angular momentum	complete kinematics, neutron detection	Stored isomers	low momentum transfers			high-resolution spectroscopy		Magnetic moments
Collective behavior		dipole resonance		Monopole resonance	Elelctromag. Transitioins				Quadrupole moments

NUSTAR@FAIR

World-wide unique synchrotron-based RIB production for:

- High-energy Radioactive Beams (≤1.5 GeV/u)
  - Efficient production, separation, transmission and detection aided by Lorentz boost
  - Access to the heaviest nuclei without charge-state ambiguities
  - Large range of attainable reaction mechanisms
- Storage rings
  - Mass measurements and beam preparation/manipulation
  - Isomeric beams
  - Novel experimental tools (beyond MSV/with CRYRING, ESR and HESR)

Combined with:

- Wide range of state-of-the-art instrumentation – *not monolithic!*
  - Strong evolution from existing programs
  - Dynamic progress in terms of TDRs/construction/operation
  - Some NUSTAR FAIR experiments could already start in 2017/2018

→ ***Comprehensive map of nuclear landscape***

Thank you!