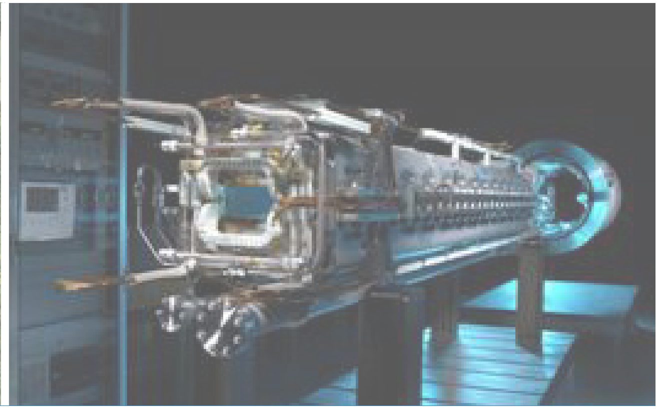




Overview of NUSTAR

Thomas Nilsson, NUSTAR BR chair
ECE Meeting – 2012-11-19

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?

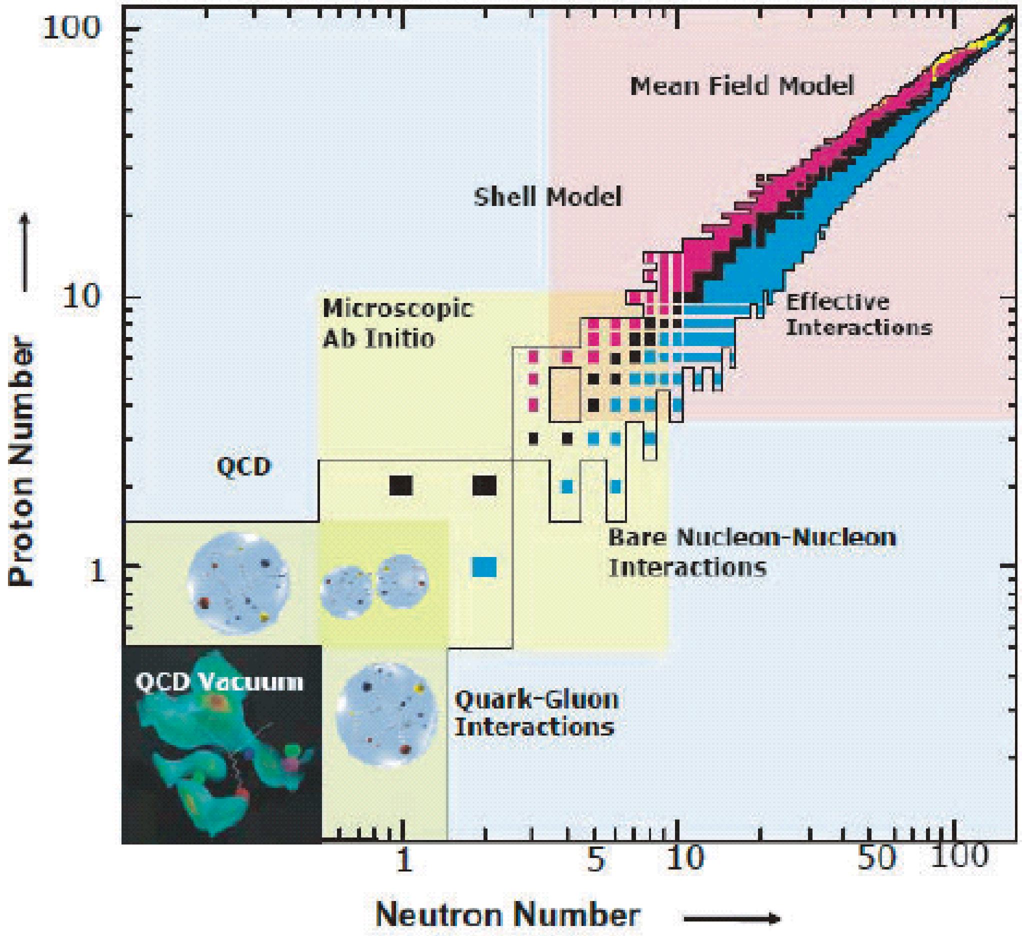
- What is the effective nucleon-nucleon interaction?
- How does QCD constrain its parameters?

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

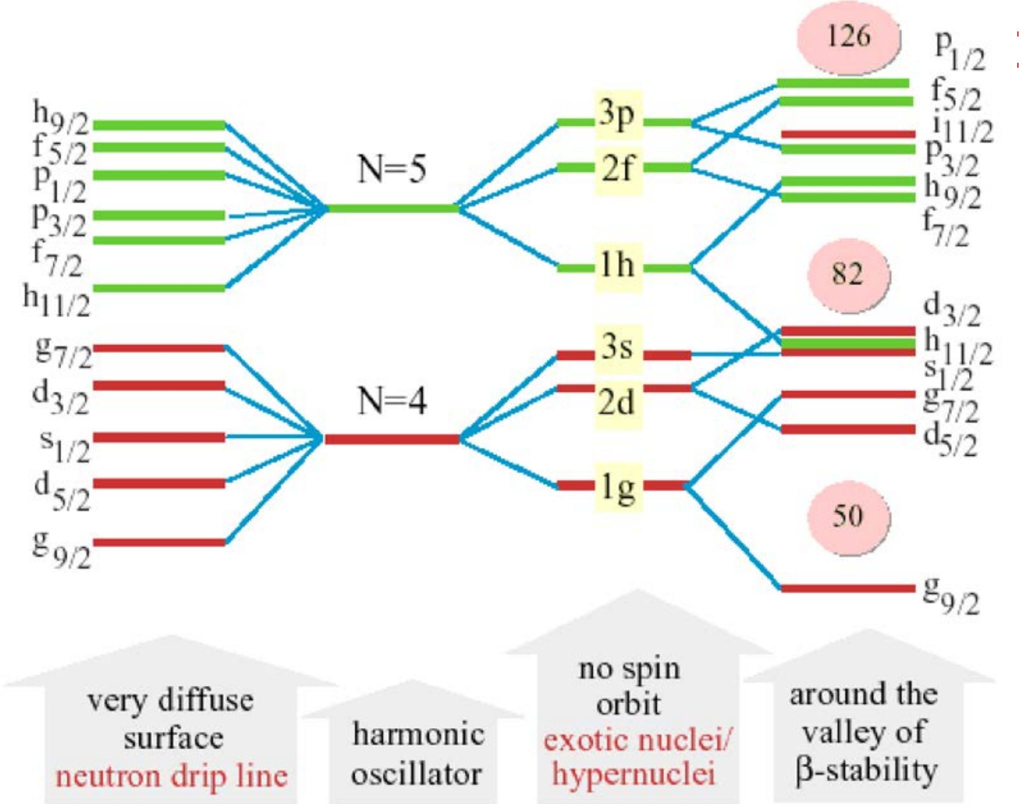
- What is the origin of the heavy elements?

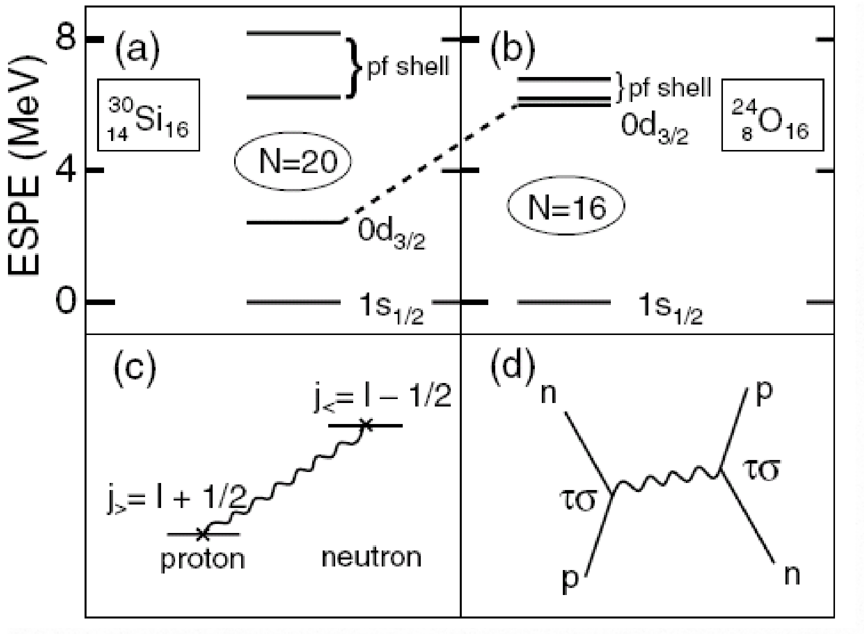
Open questions

- **What are the limits for existence of nuclei?**
  - **Where are the proton and neutron drip lines situated?**
  - **Where does the nuclear chart end?**
- **How are complex nuclei built from their basic constituents?**
  - **What is the effective nucleon-nucleon interaction?**
  - **How does QCD constrain its parameters?**



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





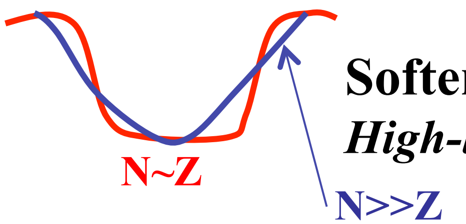
A. Ozawa et al. PRL 84 (2000) 5493

T. Otsuka et al., PRL 87(2001)082502

Shell quenching and reordering:

Transition from SO gaps (50,82,126)

to HO gaps (40,70,112)



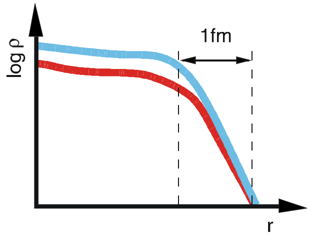
Softening of the nuclear potential:

High-l pushed upward and

Spin-Orbit splitting reduced

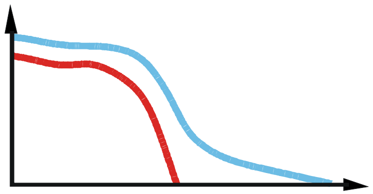
How to explain collective phenomena from individual motion?

stable



$r_p = r_n, \quad \rho_0 = 0.17\text{fm}^{-3}$

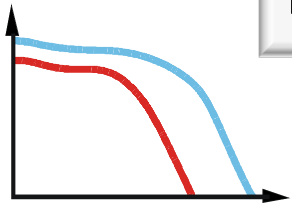
$d_p = d_n = \text{const} \approx 1\text{fm}$



halo

$r_p \neq r_n$

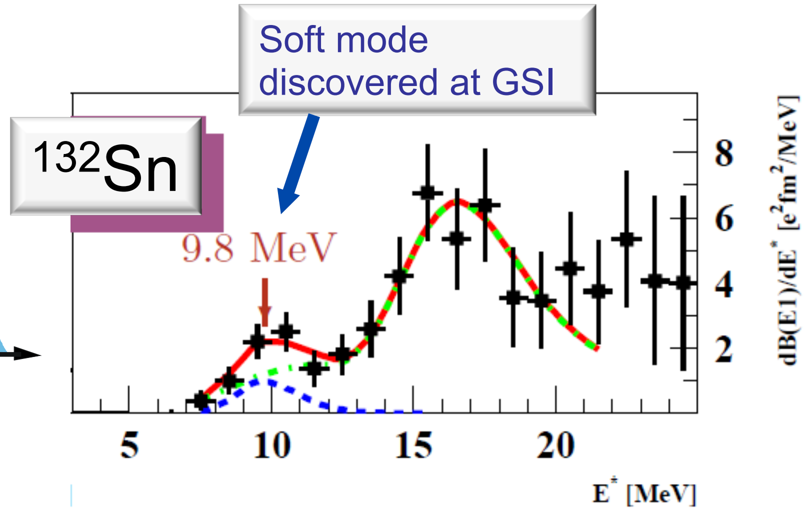
$d_p \neq d_n$



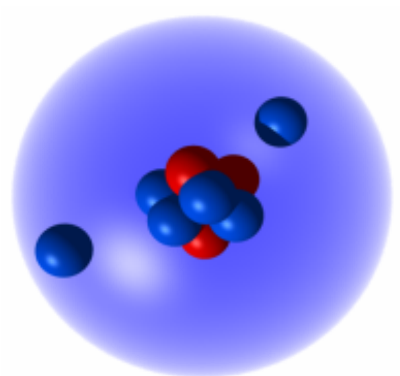
skin

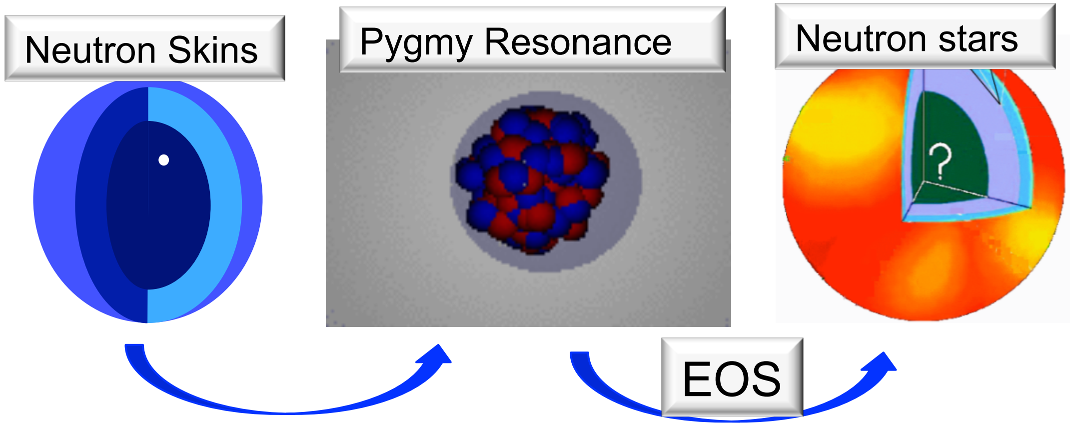
$r_p \neq r_n$

$d_p = d_n$



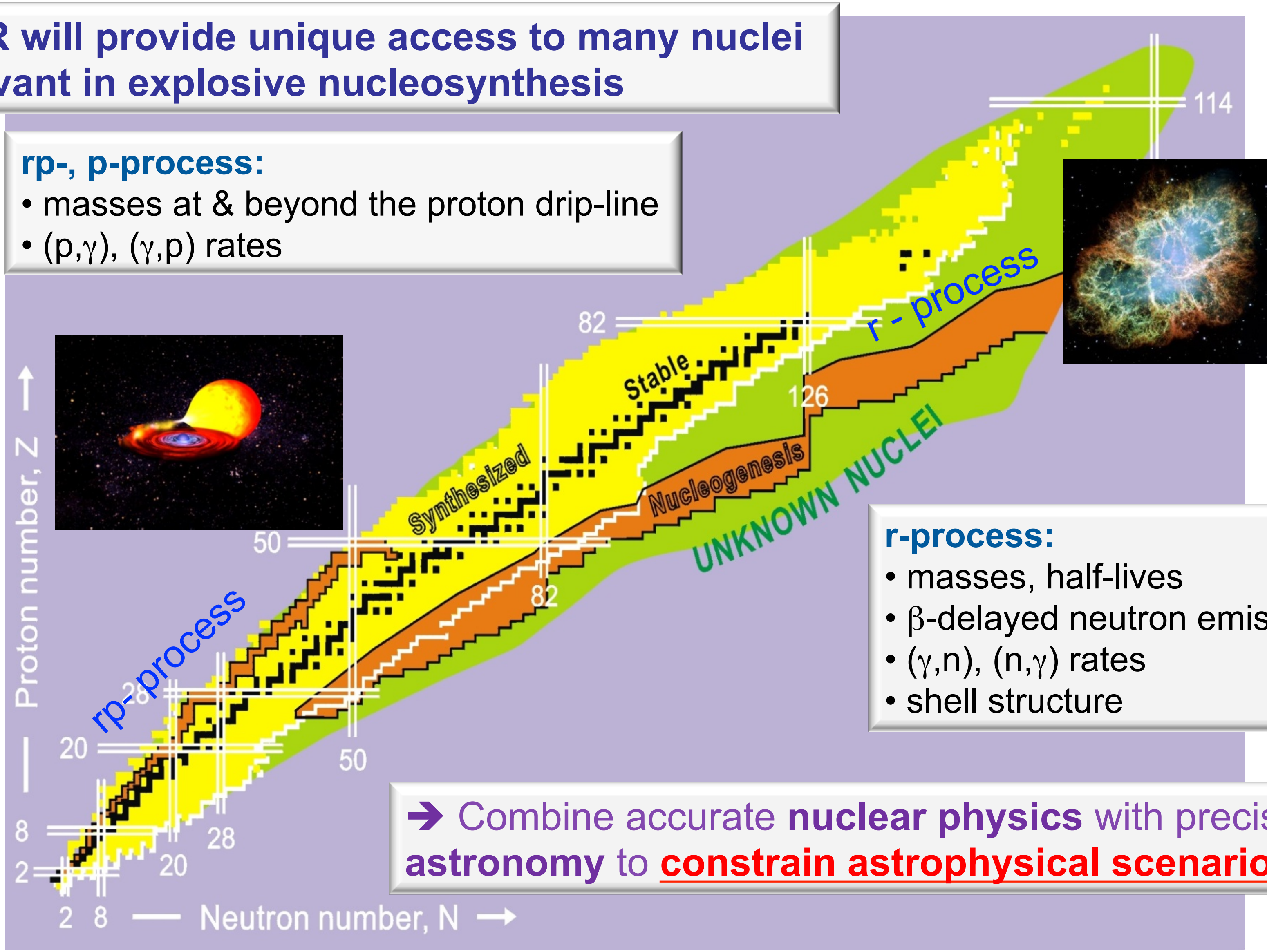
Halos





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

FAIR will provide unique access to many nuclei relevant in explosive nucleosynthesis



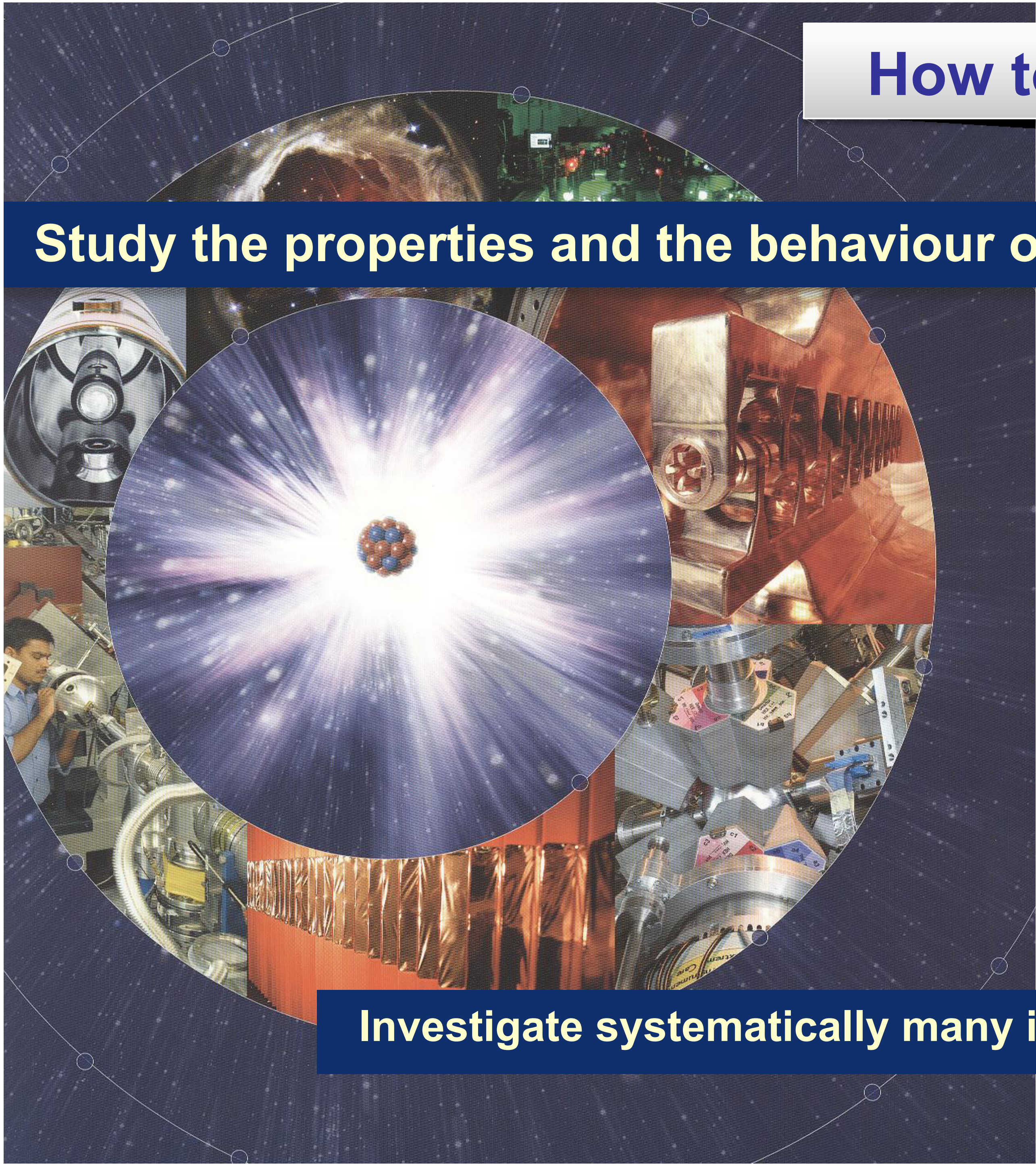
rp-, p-process:
- masses at & beyond the proton drip-line
- (p,γ), (γ,p) rates

r-process:
- masses, half-lives
- β-delayed neutron emission
- (γ,n), (n,γ) rates
- shell structure

➔ Combine accurate **nuclear physics** with precision **astronomy** to **constrain astrophysical scenarios**

How to get answers?

Study the properties and the behaviour of exotic nuclei!



Ground state

mass, binding energy, spin, parity...

Excited states

energy, spin, moments, transition probability...

Decay

lifetime, energy, modes...

Reaction

kinetics, energy, constituents...

Investigate systematically many isotopes far off stability

NUSTAR - The Project

Super-FRS	RIB production, identification and spectroscopy
DESPEC	γ-, β-, α-, p-, n-decay spectroscopy
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
R^3B	kinematically complete reactions at high beam energy
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

146 institutes

38 countries

The Investment

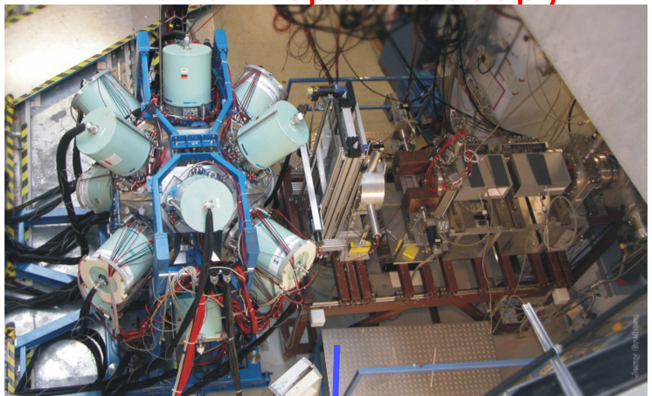
82 M€ Super FRS

73 M€ Experiments

NUSTAR Week Kolkata Oct 2012

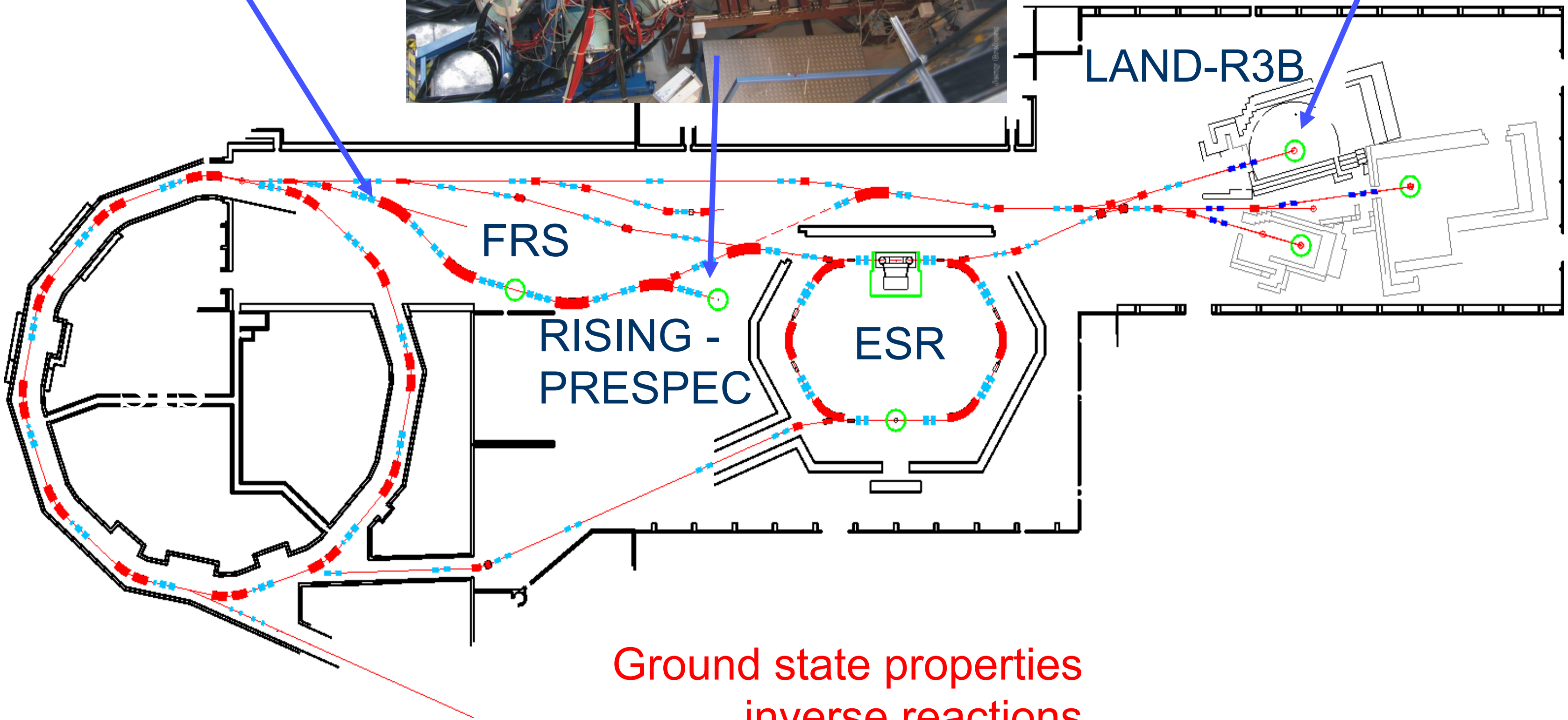
Existing research opportunities at GSI

Decay studies,
In-beam spectroscopy



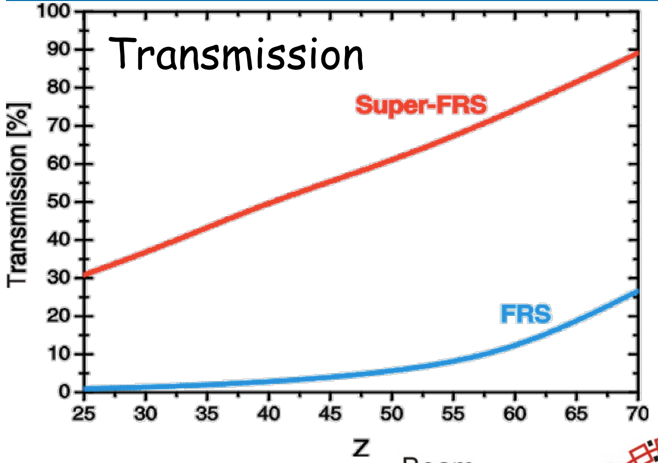
Reaction studies

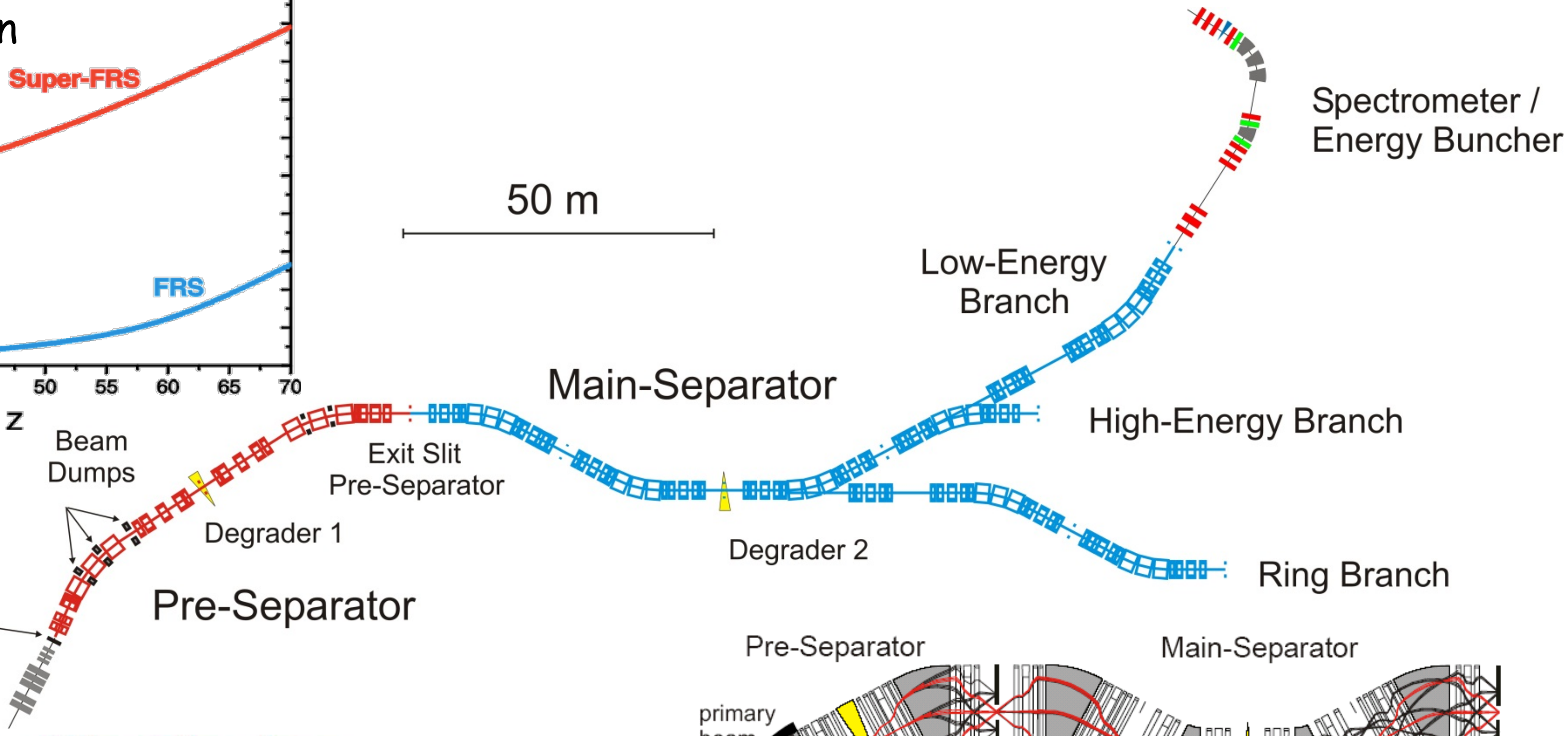
production and
separation of
exotic nuclei

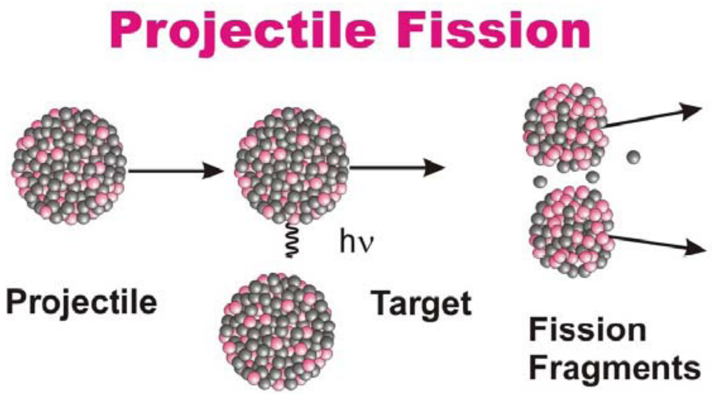


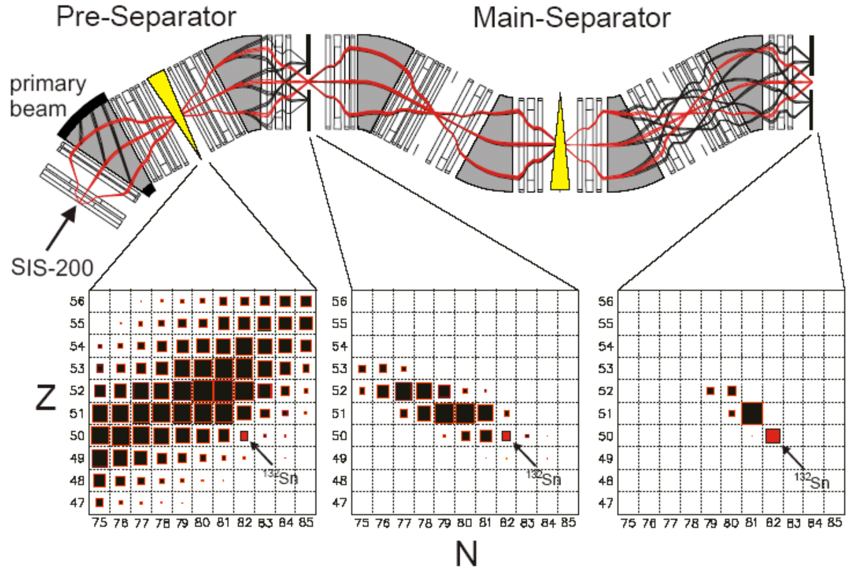
Ground state properties
inverse reactions

SUPERconducting FRagment Separator



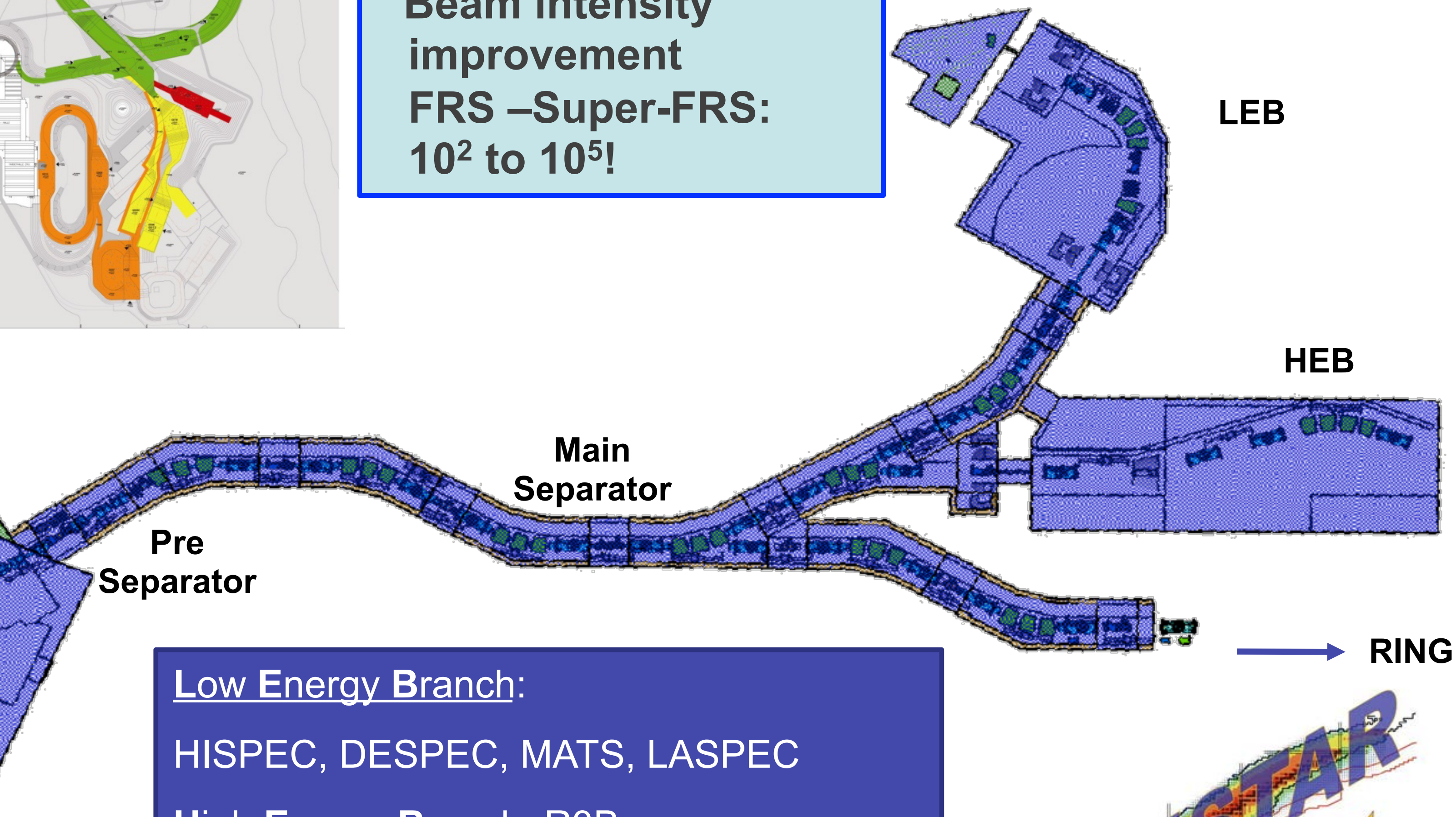






NUSTAR - The Facility

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



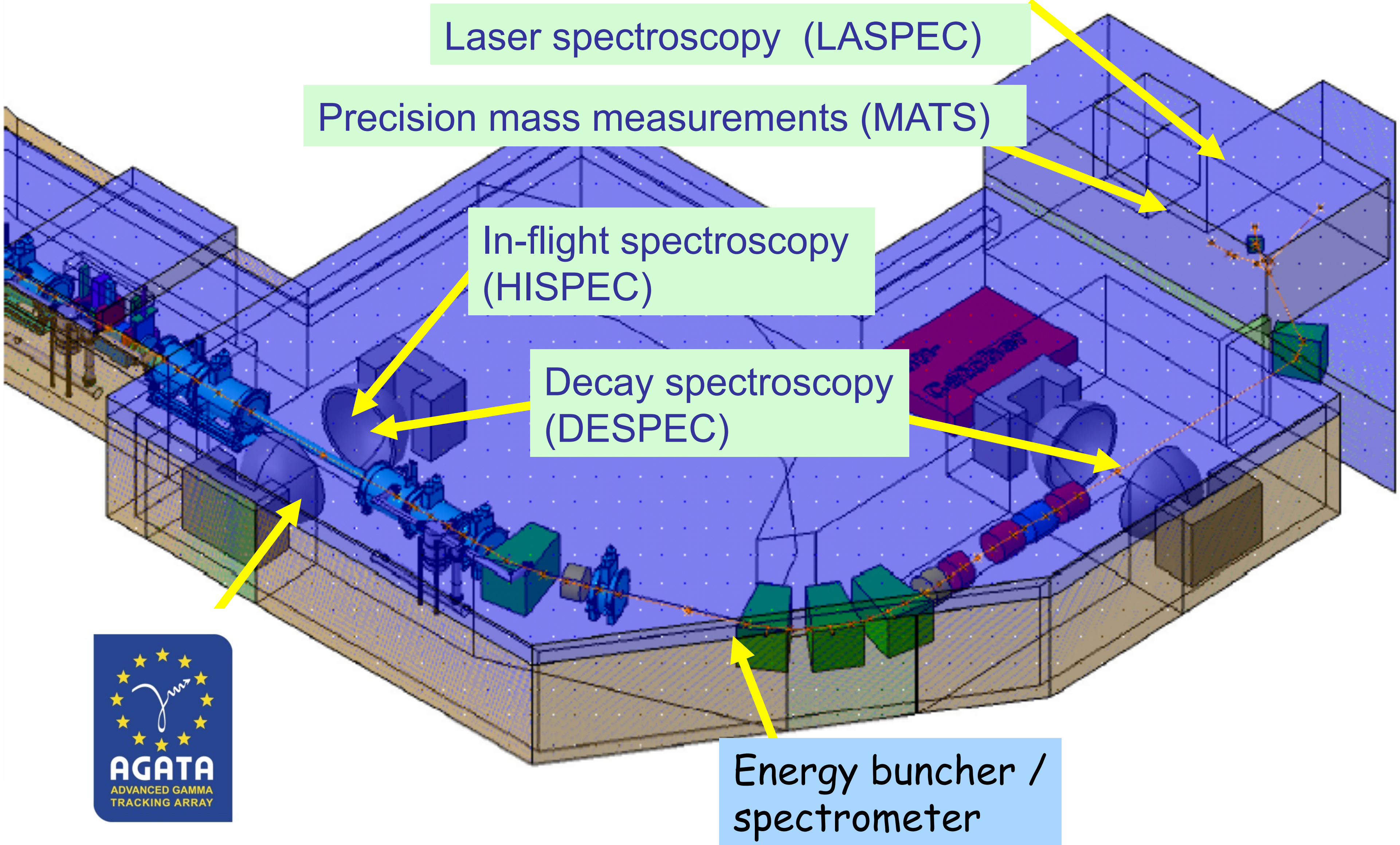
Low Energy Branch:

HISPEC, DESPEC, MATS, LASPEC

High Energy Branch: R3B

Ring Branch: EXL, ILIMA, ELISE

LEB - Experiments with slowed and stopped beams



HISPEC/DESPEC - foreseen instrumentation

HISPEC

- LYCCA heavy ion calorimeter with ToF capability
- AGATA gamma spectrometer
- HYDE light particle array
- NEDA Neutron detector array
- EDAQ dedicated electronics and DAQ based on several branches

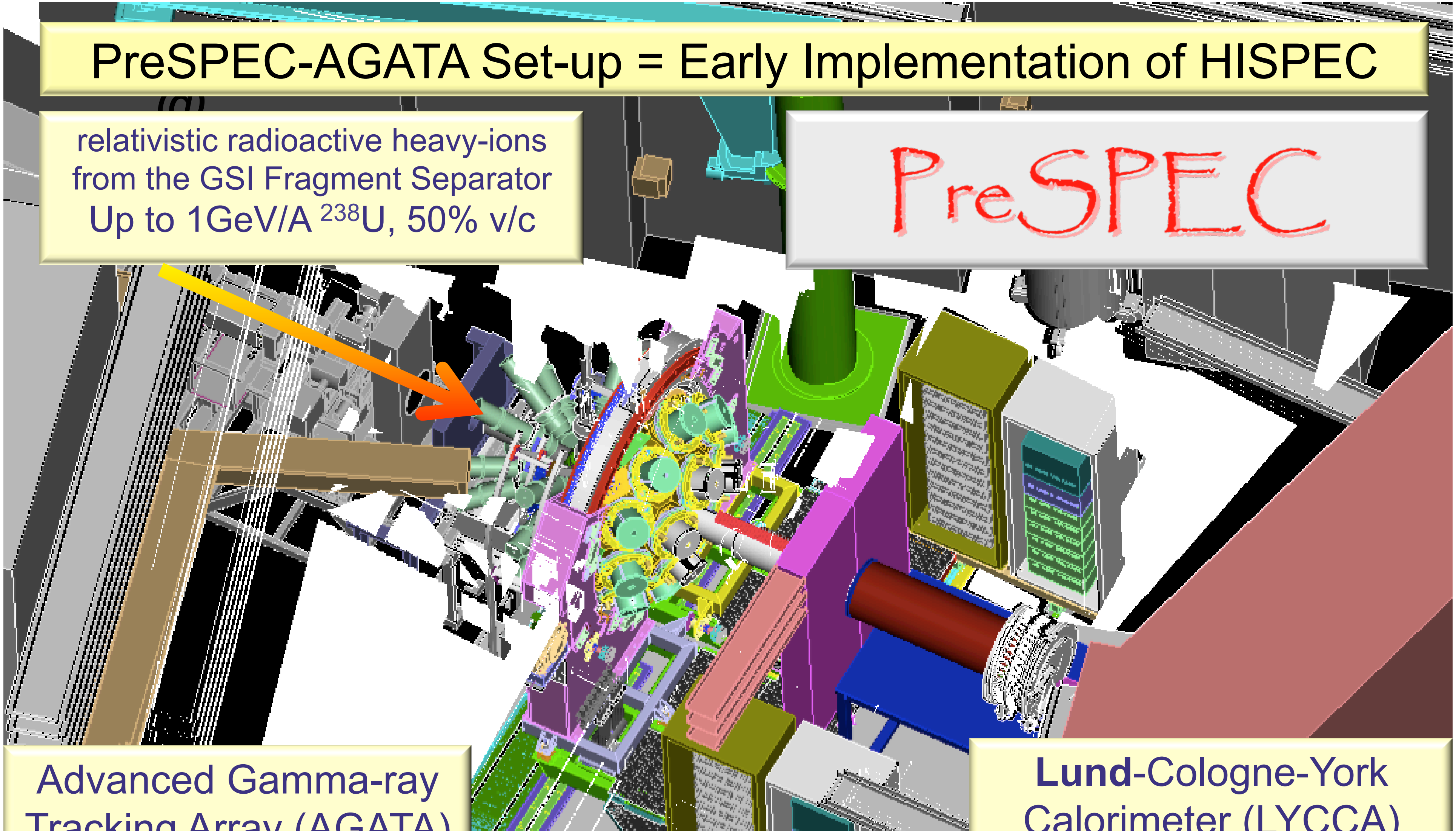
DESPEC

- AIDA active implantation device
- MONSTER neutron ToF array
- BELEN neutron detecion array
- DTAS   Decay Total Absorption Spectrometer
- DESPEC Ge Array gamma spectrometer
- FATIMA Fast timing array

PreSPEC-AGATA Set-up = Early Implementation of HISPEC

relativistic radioactive heavy-ions
from the GSI Fragment Separator
Up to 1GeV/A ^{238}U, 50% v/c

PreSPEC



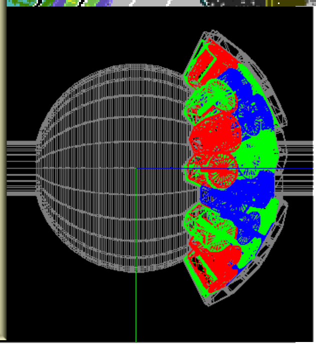
Advanced Gamma-ray Tracking Array (AGATA)

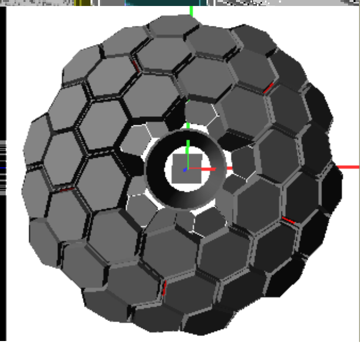
up to 5 x 2+10 x 3 = 40
segmented HP Ge-crystals

d ~ 20 cm

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

$\Delta E \approx 0.4\%$



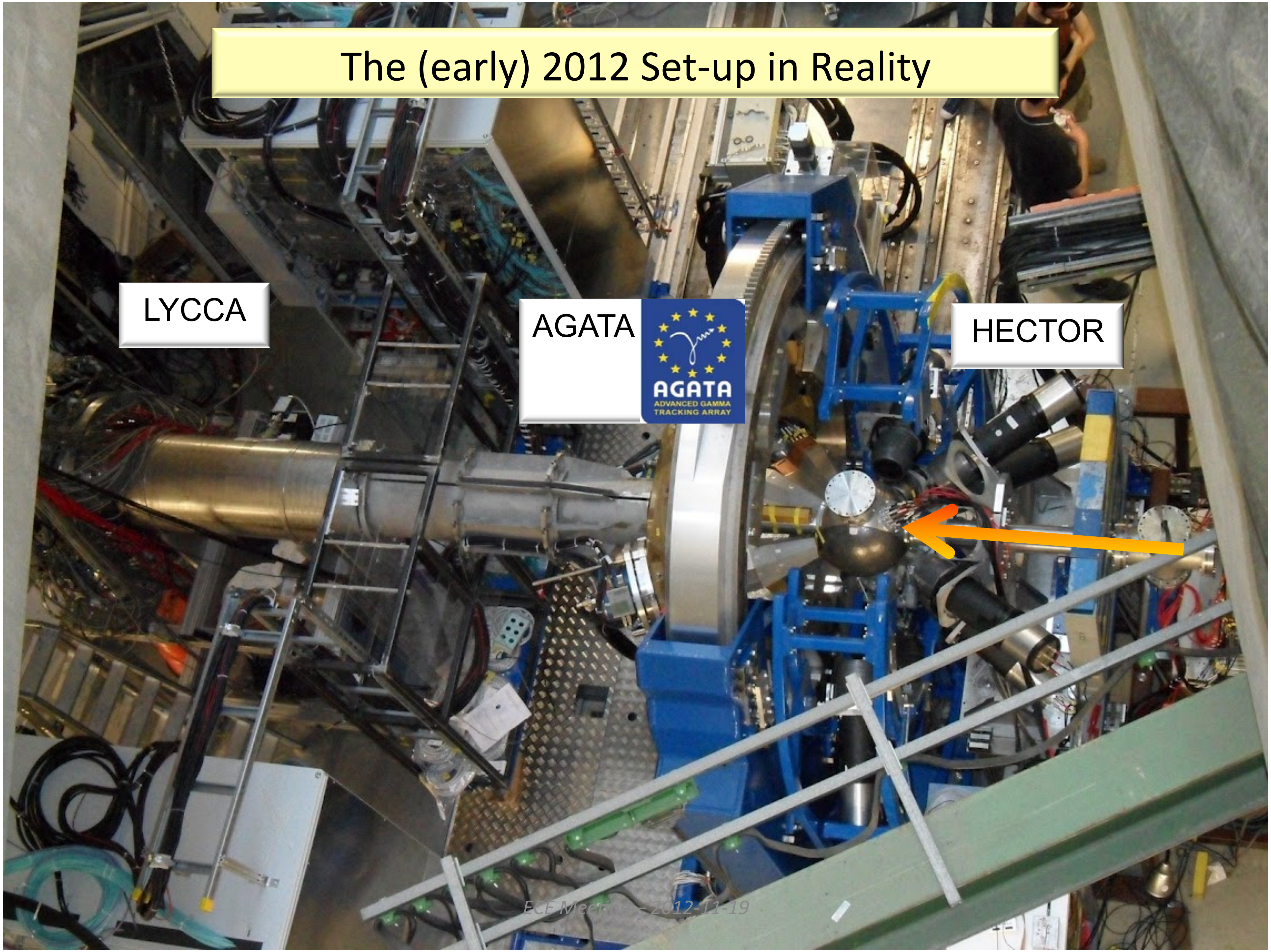


Lund-Cologne-York Calorimeter (LYCCA)

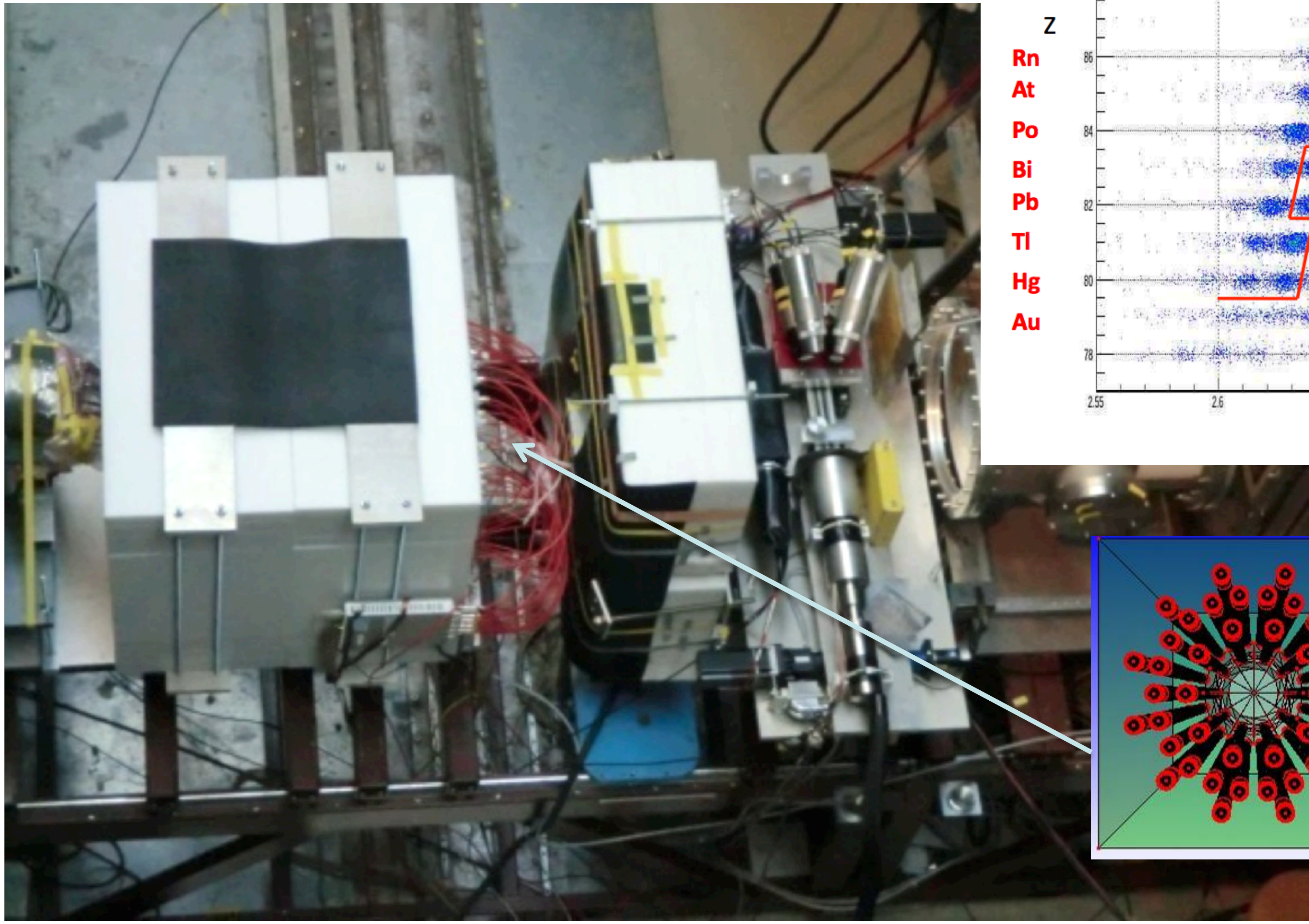
A and *Z* particle-ID after secondary target by means of

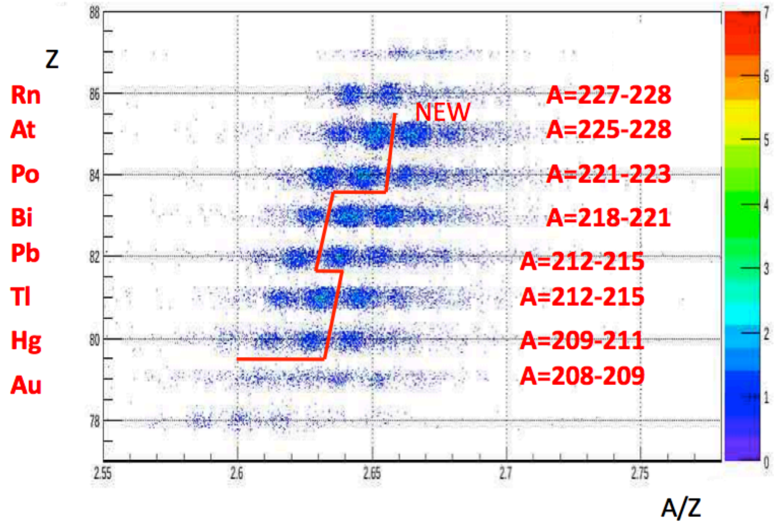
- x,y tracking
- ΔE-E (Si-CsI)
- Δt (plastic)

The (early) 2012 Set-up in Reality



Last DESPEC setup (2011): BELEN 4π neutron detector:

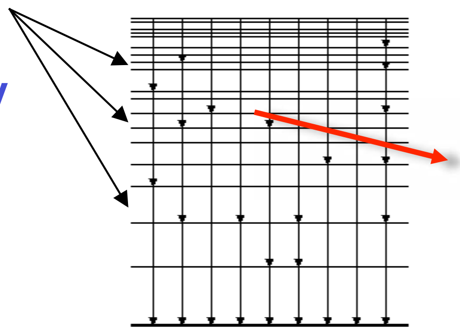




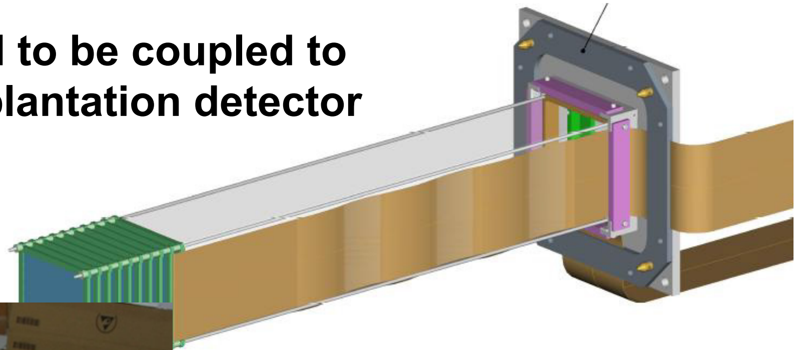
C. Domingo-Pardo et al, "Measurement of β-delayed neutrons around the 3rd r-process peak".
Newly identified nuclei for beta delayed neutron branch determination
Schematic view of the ^{3}He counters of BELEN.

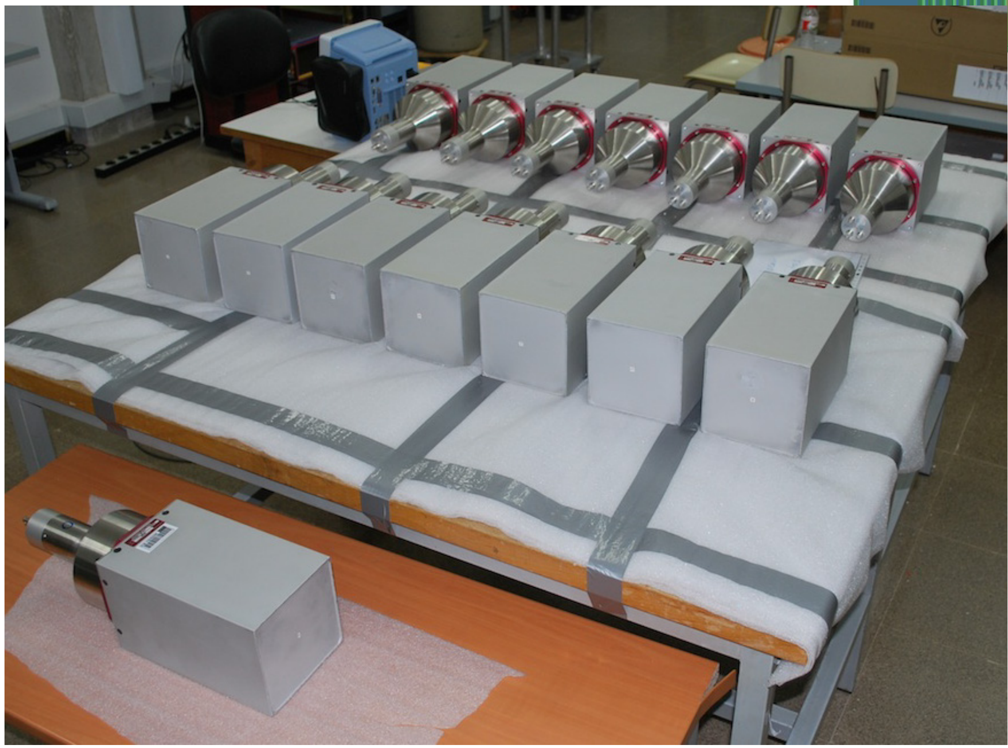
Decay Total Absorption Spectrometer (DTAS)

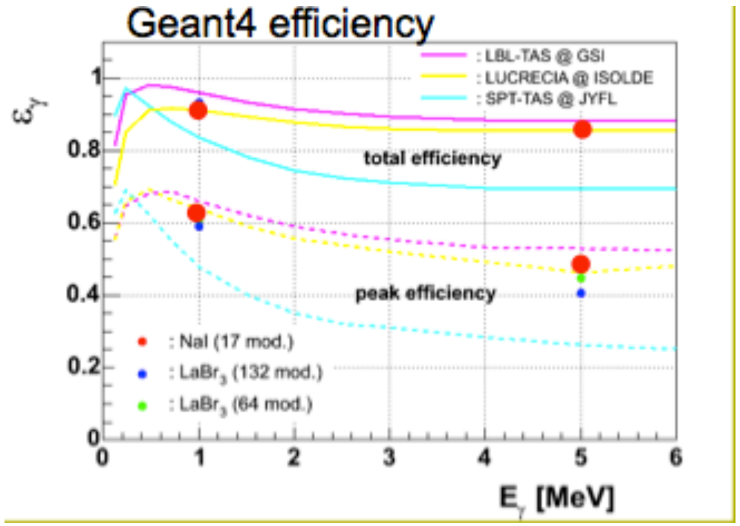
β-decay



Designed to be coupled to AIDA implantation detector







Information on the multiplicity of the gamma cascade

HISPEC/DESPEC Evolutionary timeline

2004-2005: RISING In-Beam

EUROBALL Cluster plus small Si-CsI array

2006-2009: RISING Stopped Beam

EUROBALL Cluster (plus active Si-stopper)

2010-2011: PreSPEC In-Beam phase 1

EUROBALL Cluster plus LYCCA-0

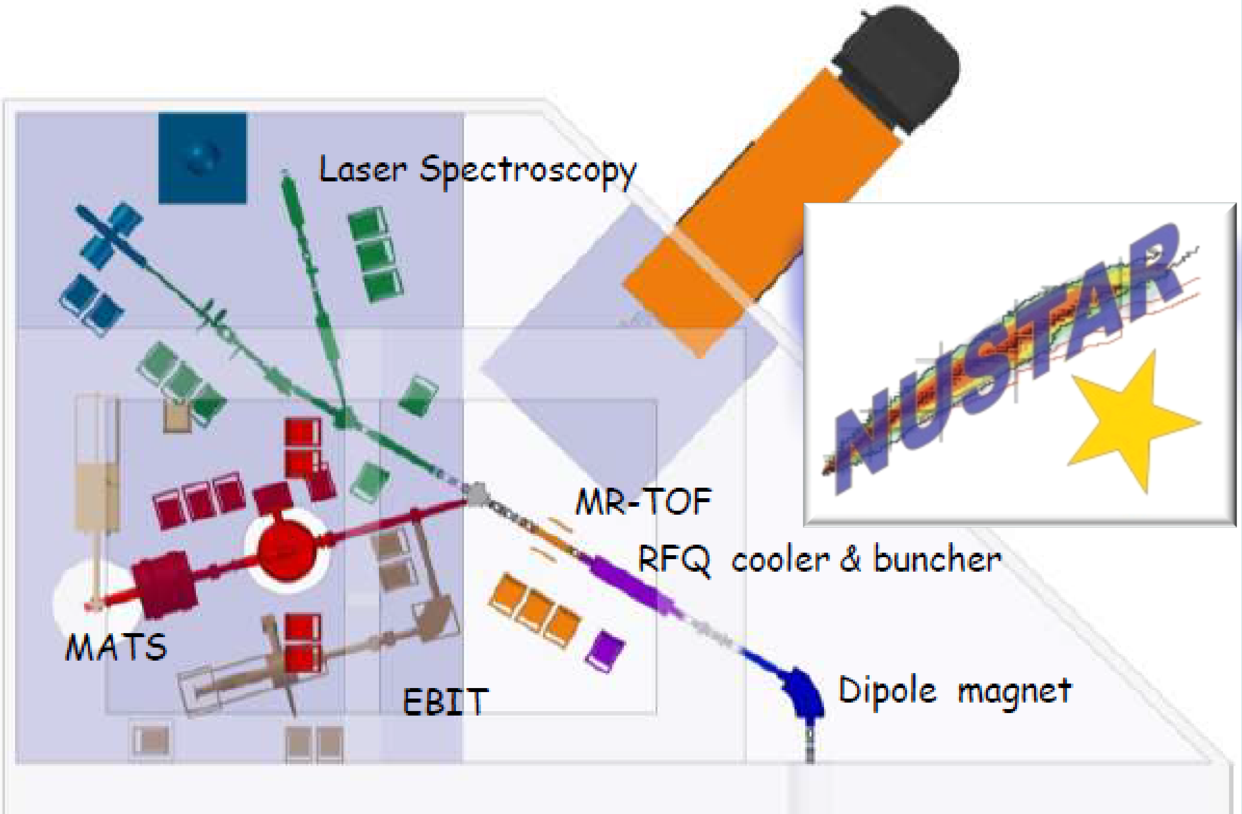
2012-2013: PreSPEC In-Beam phase 2 (= HISPEC-0)

AGATA plus LYCCA-1

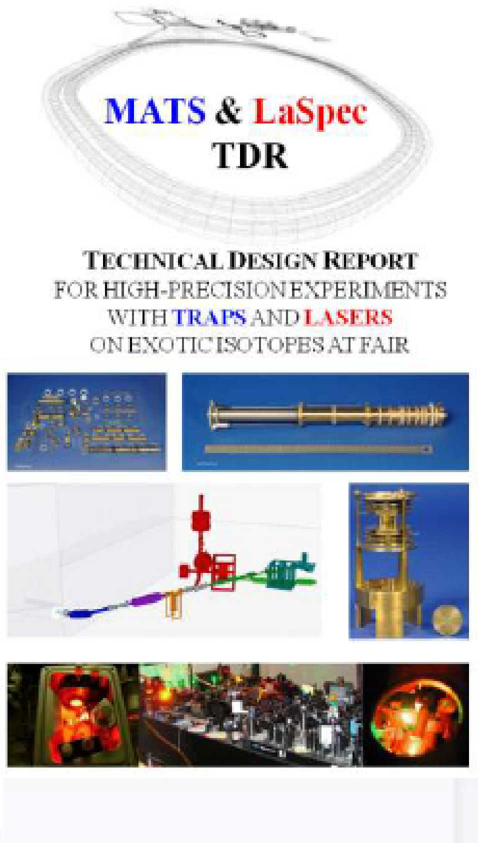
2014-2016: PreSPEC Decay (= DESPEC-0)

2017+: FAIR Facility for Antiproton and Ion Research in Europe GmbH (commissioning) experiments

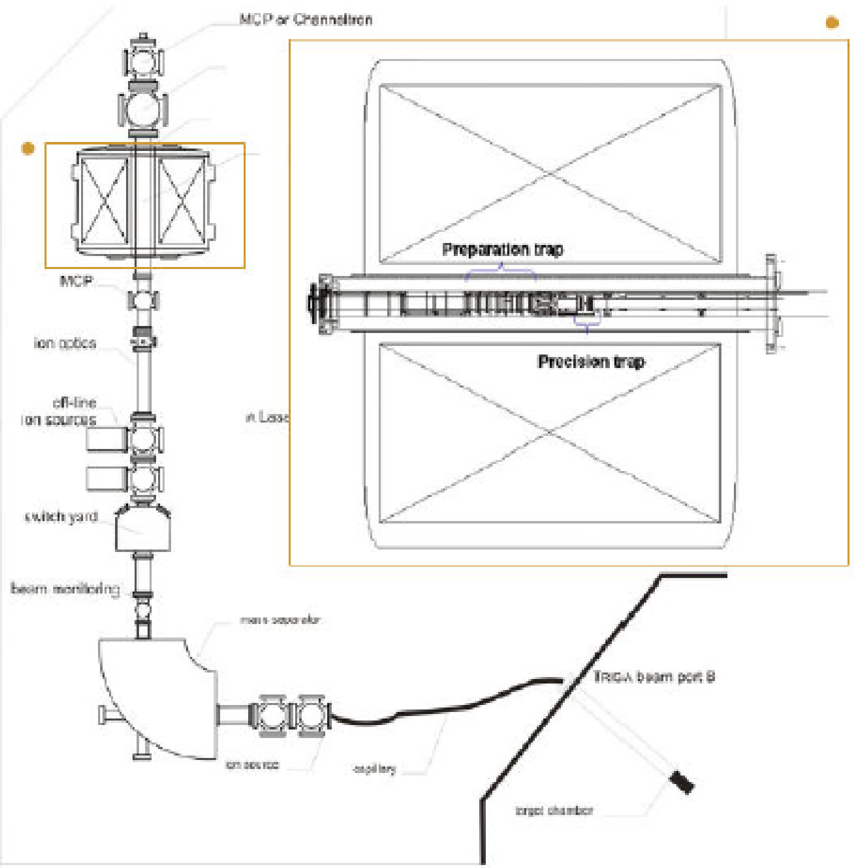
MATS/LASPEC at the LEB

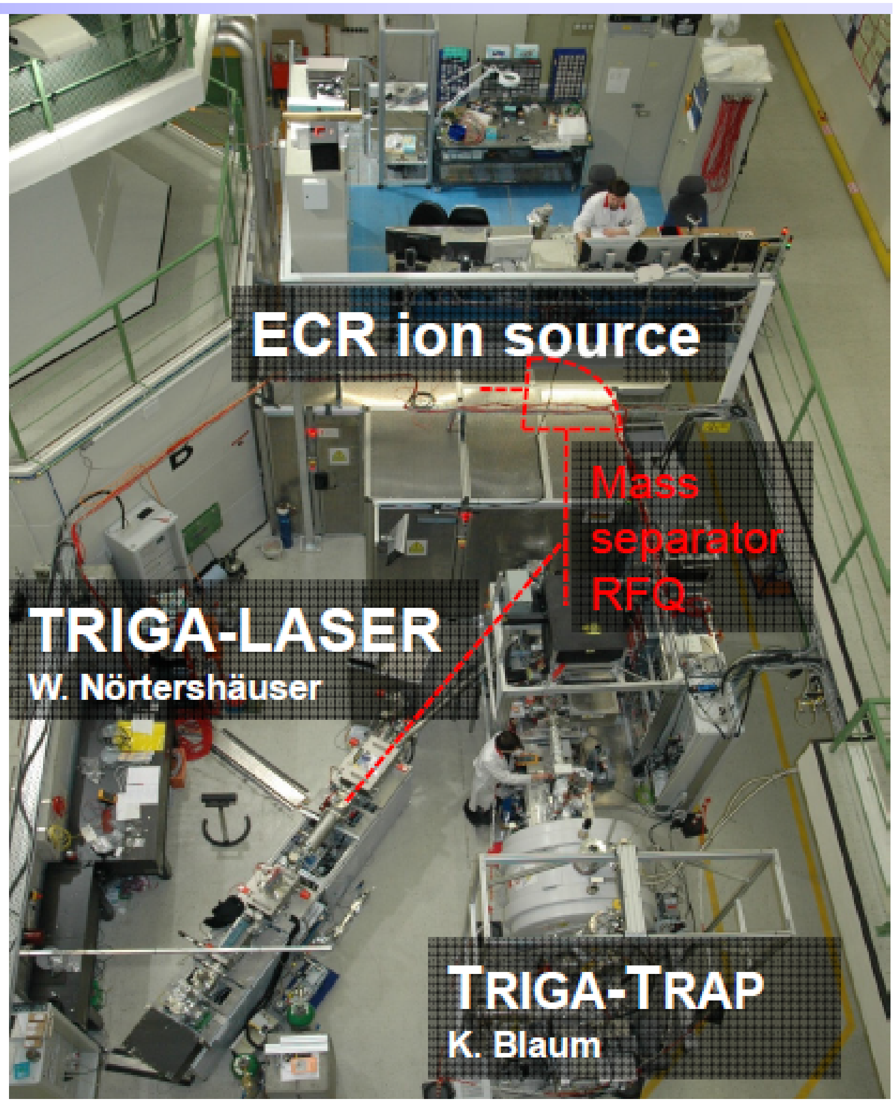


for more information see:
Technical Design Report of MATS & LaSpec:
D. Rodriguez, EPJ Special Topics 183 (2010) 1-123



TRIGAspec



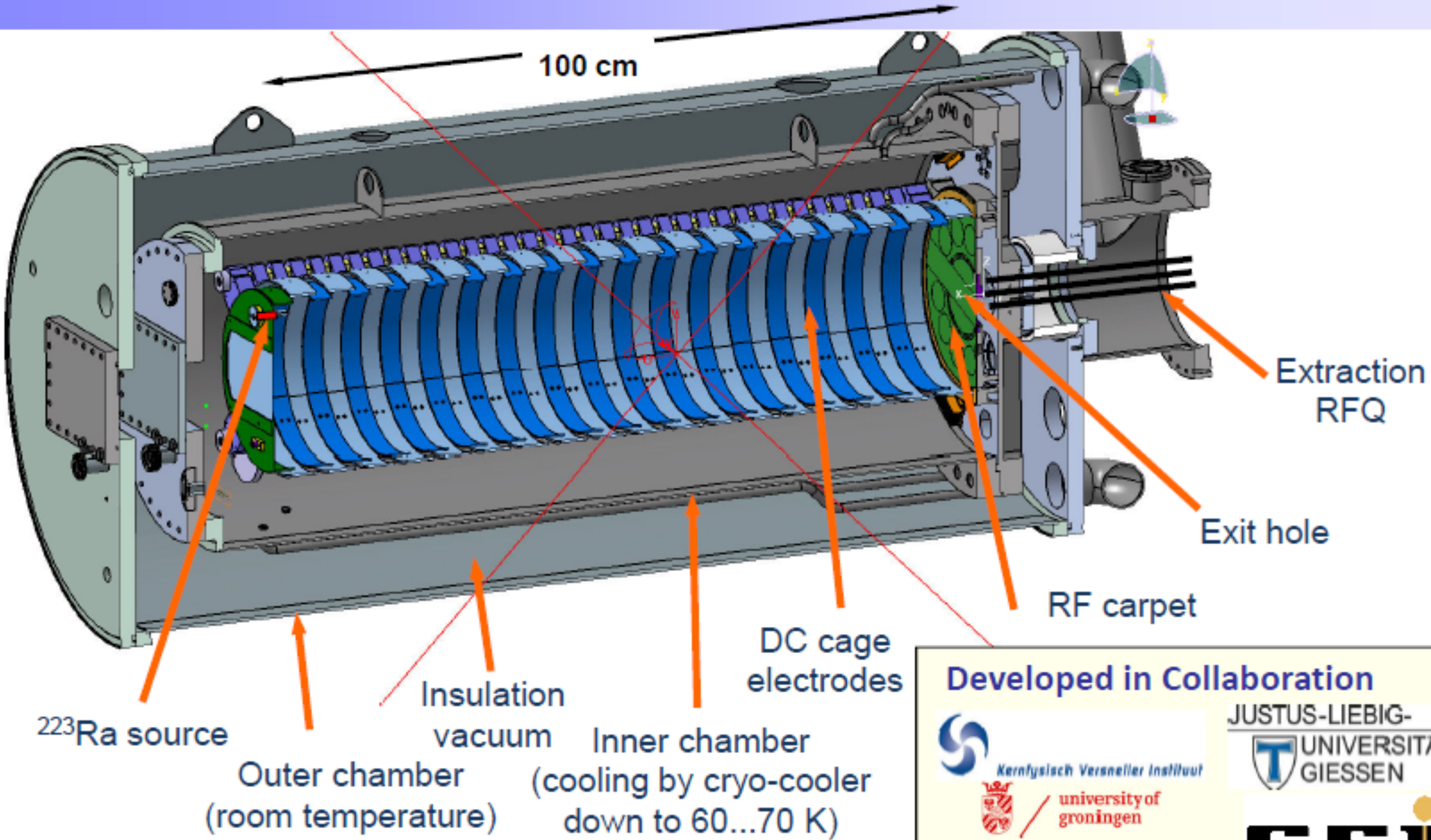


Project start @ TRIGA (Mainz): 01/08

J. Ketelaer *et al.*, Nucl. Instrum. Methods A 594, 162 (2008)

Start data taking: 05/09

The cryogenic stopping cell for the LEB



Developed in Collaboration

Kernfysisch Versneller Instituut

university of groningen

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

GSI

M. Ranjan et al., Europhys. Lett. 96 (2011) 52001

M. P. Reiter, Master Thesis, Justus-Liebig-Universität Gießen (2011)

Common beam line for MATS/LaSpec
Commissioning of the gas cell at the FRS (GSI)

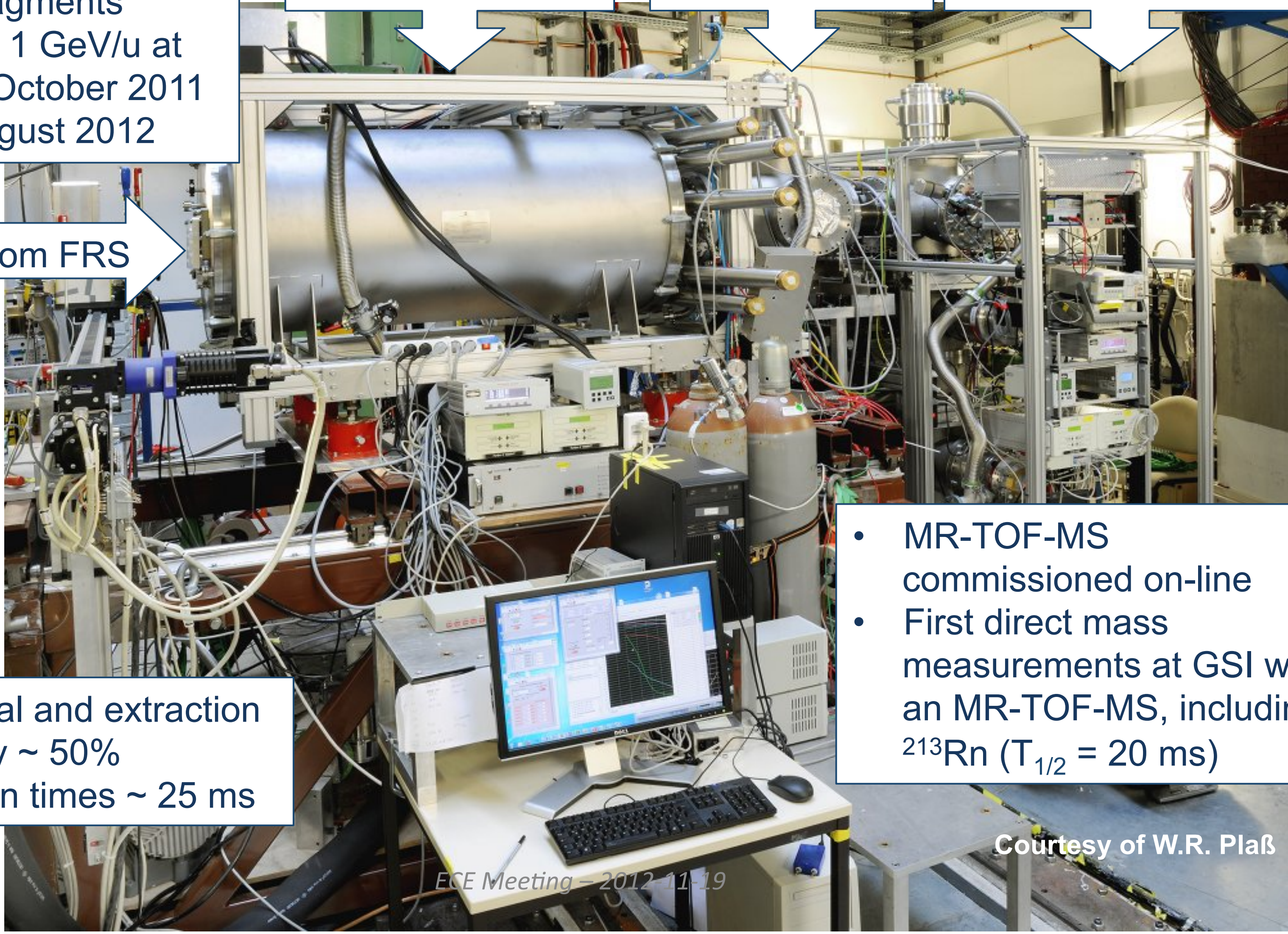
On-line test using ^{238}U projectile fragments produced at 1 GeV/u at the FRS in October 2011 and July/August 2012

Cryogenic stopping cell

Diagnostics unit

Time-of-flight mass spectrometer

Beam from FRS

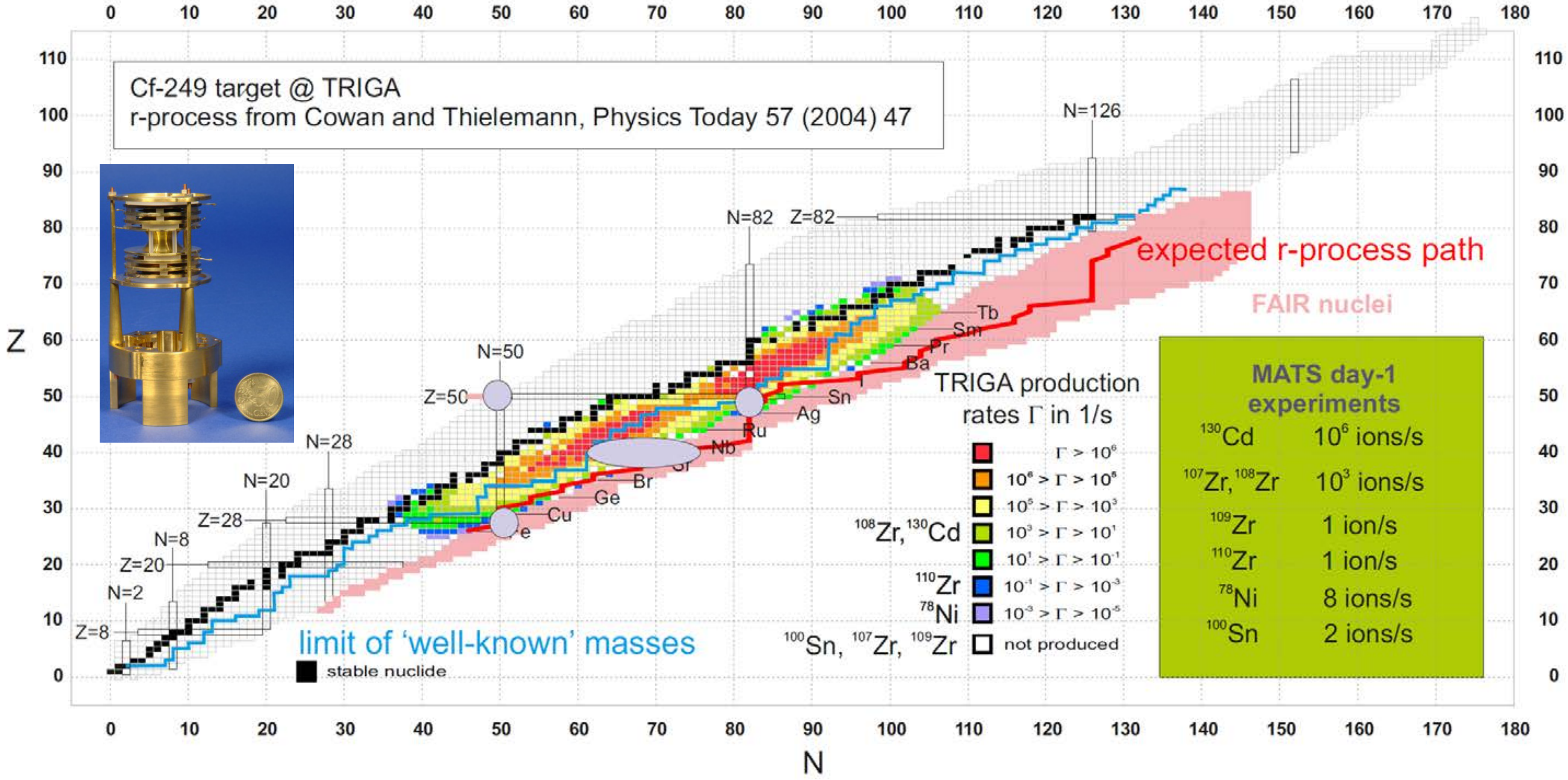


Courtesy of W.R. Plaß

- MR-TOF-MS commissioned on-line
- First direct mass measurements at GSI with an MR-TOF-MS, including ^{213}Rn ($T_{1/2}$ = 20 ms)

- Ion survial and extraction efficiency ~ 50%
- Extraction times ~ 25 ms

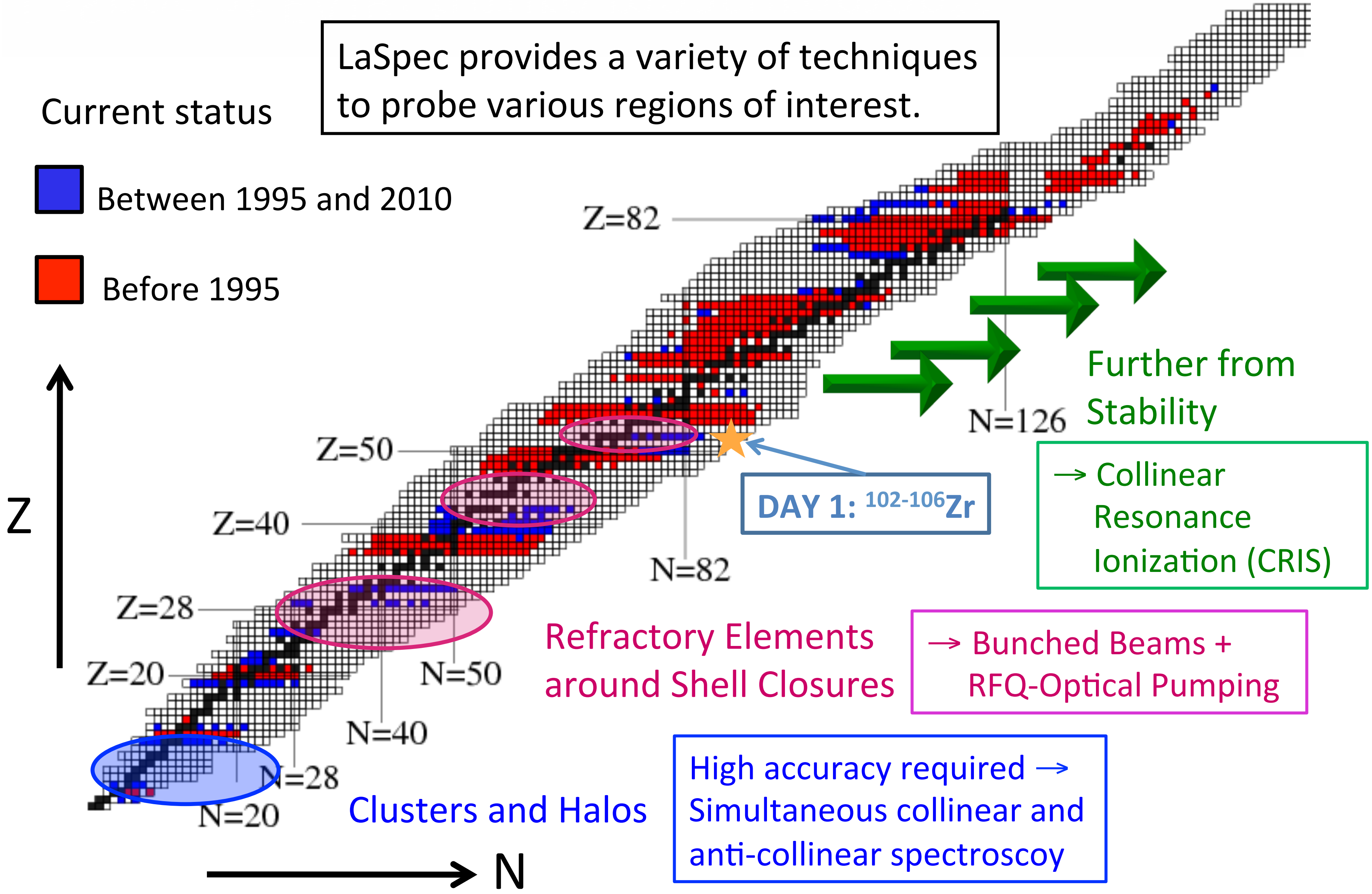
MATS day-1 experiments
Comparison with TRIGA-TRAP



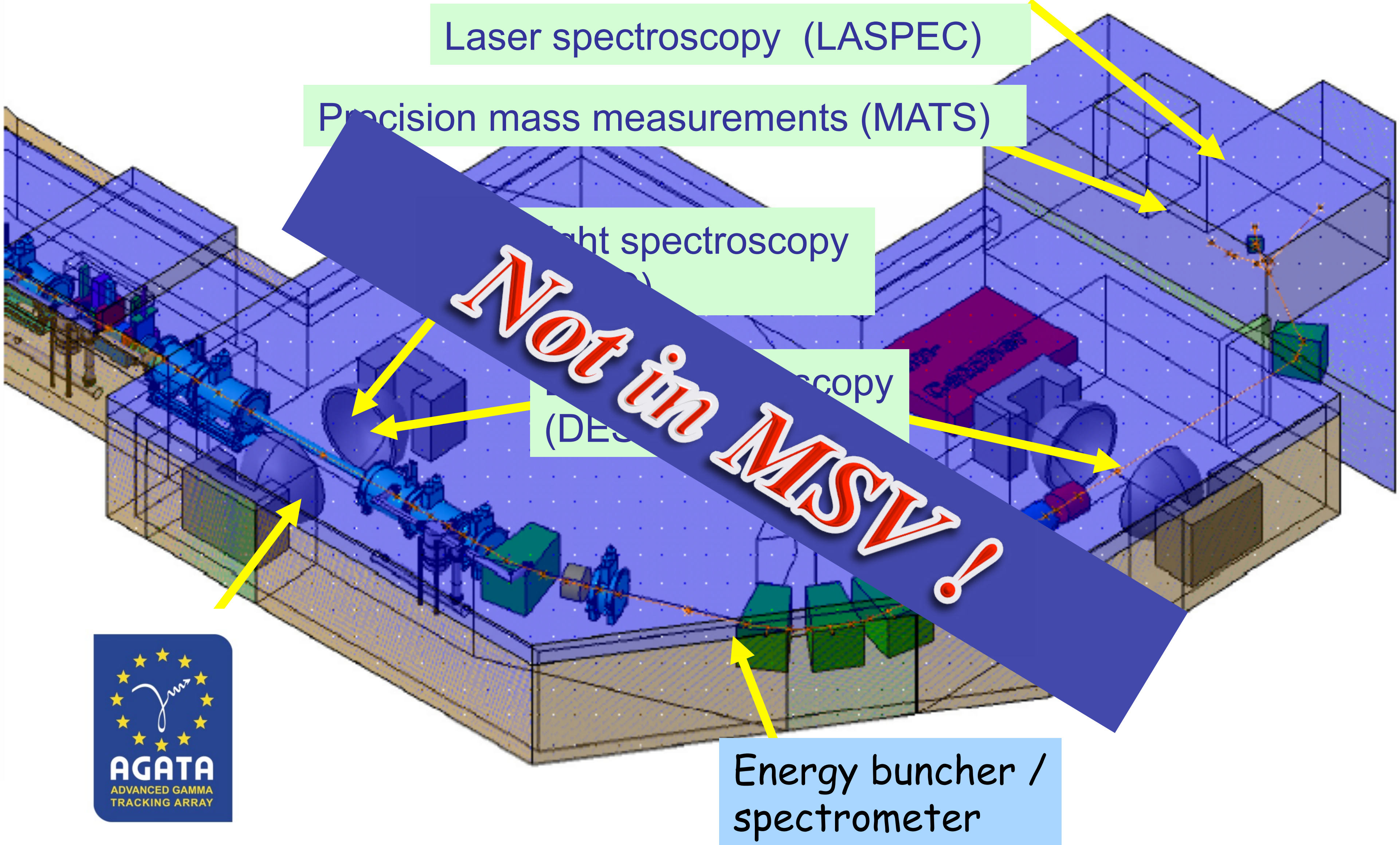
ISOLTRAP: up to ^{128}Cd **JYFLTRAP: up to ^{106}Zr** **TITAN: highly-charged ions**

D. Rodríguez et al., Eur. Phys. J. Special Topics, 183 (2010) 1-123

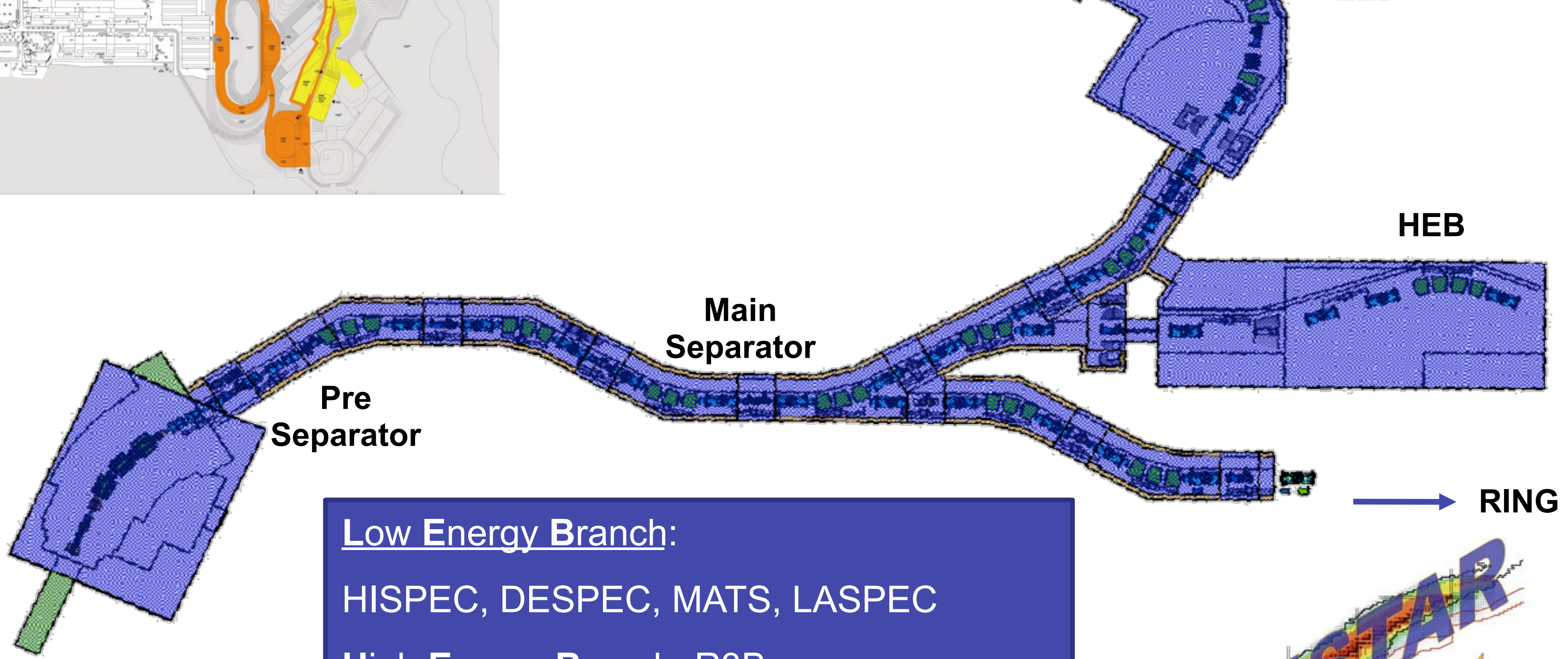
LaSpec at FAIR: future measurements



Experiments with slowed and stopped beams



NUSTAR - The Facility



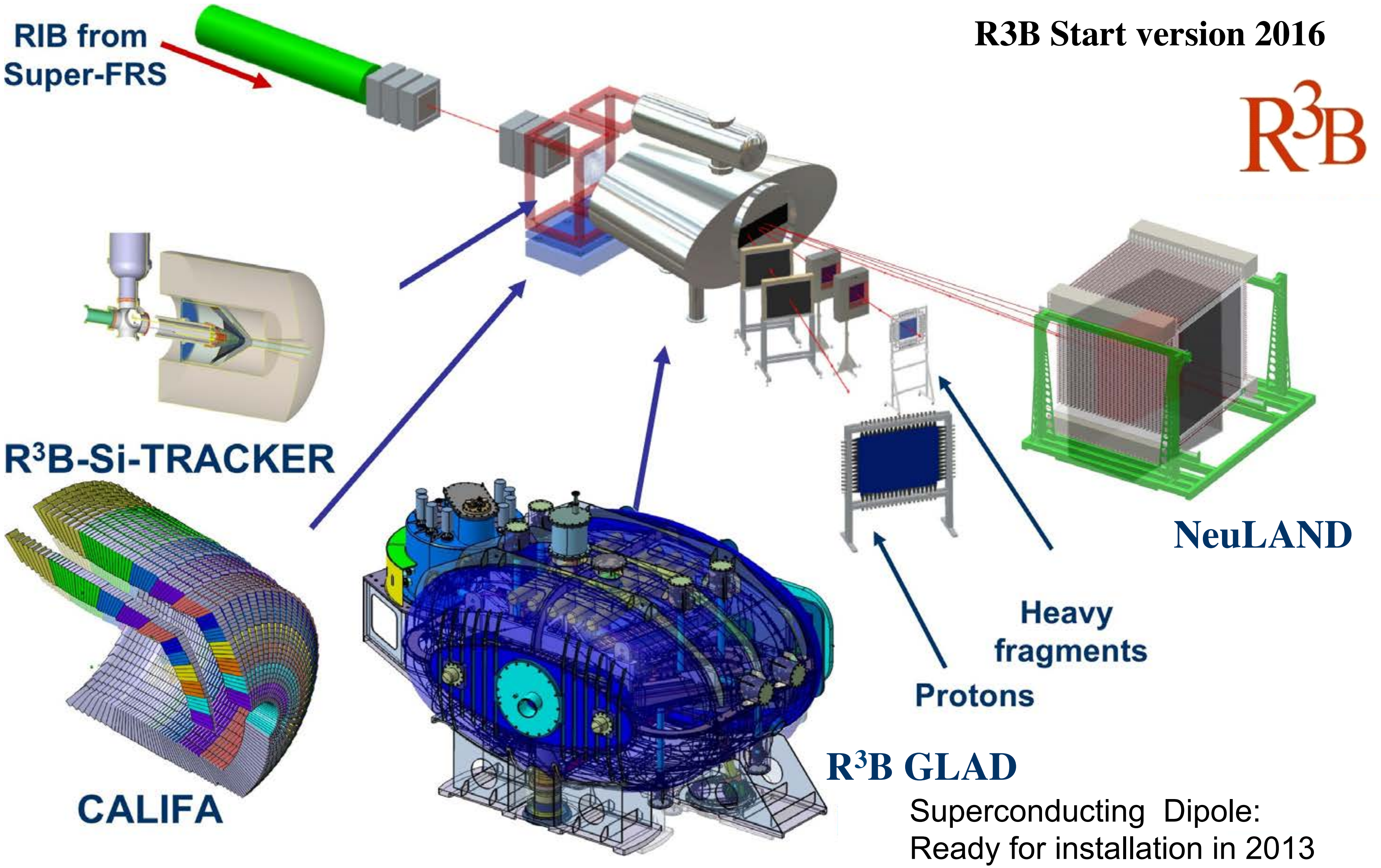
Low Energy Branch:

HISPEC, DESPEC, MATS, LASPEC

High Energy Branch: R3B

Ring Branch: EXL, ILIMA, ELISE

Reactions with Relativistic Radioactive Beams



Status

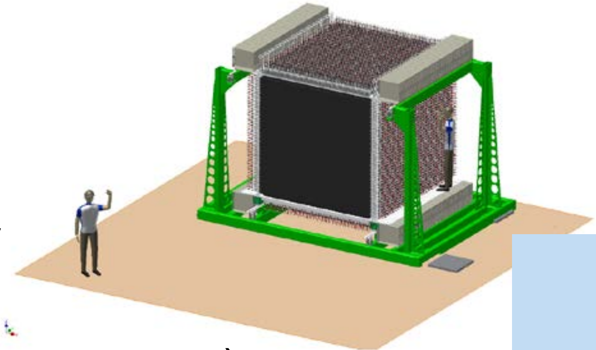
<u>Major achievements</u>

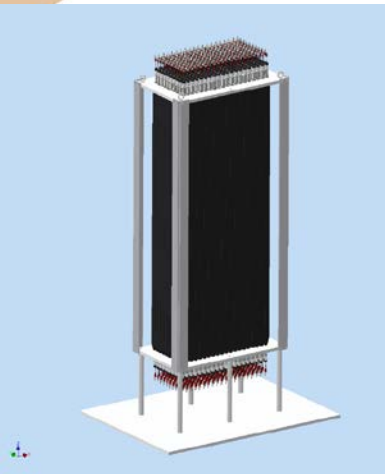
Large-acceptance dipole GLAD

- Cold mass ready and inserted in test cryostat at Saclay
- Final cryostat in construction
- Delivery of magnet to GSI end of 2013

Neutron Detector NeuLAND

- Design finalized
  modular active detector of 3000 scintillator bars; 250x250x300cm^3 active volume
- TDR submitted to FAIR in Nov 2011 (in review process)
- Experiment with mono-energetic neutrons from deuteron breakup in Nov 2012:
  200 modules (400 PM channels) in final design mounted
- Construction of 20% detector in 2013/2014

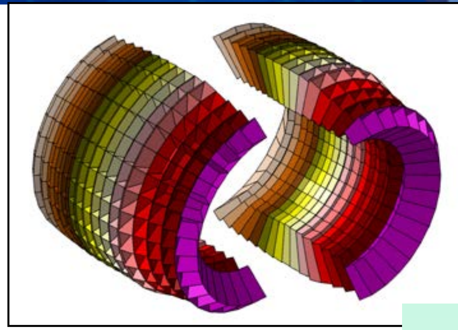


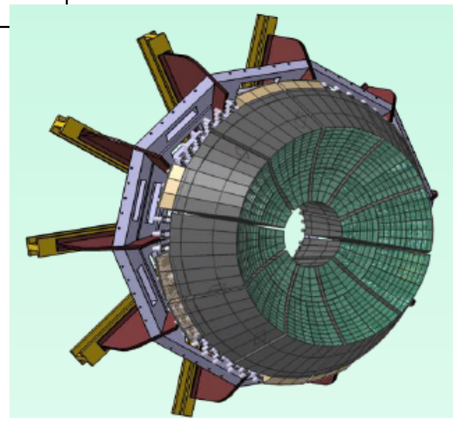


Status

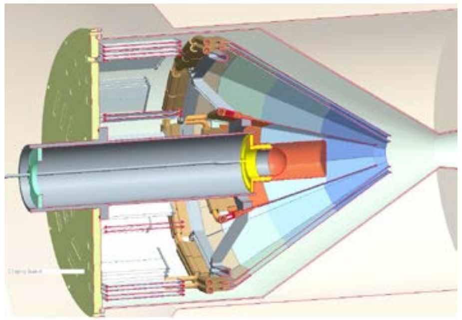
<u>Major achievements:</u>

Photon- and particle calorimeter CALIFA
- Design of barrel part finalized
  1952 CsI crystals with APD readout
- TDR submitted to FAIR Nov 2011 (in review process)
- R&D on forward end-cap ongoing
  phoswich concept of $LaBr_3$-$LaCl_3$ crystals

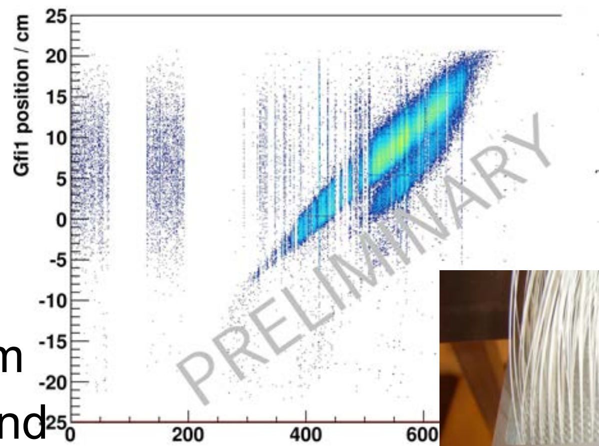


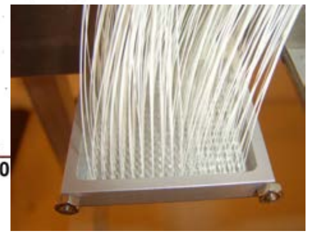


Target Recoil Tracking Detector
- Design finalized
- Construction started
- Project fully funded and
  lead by UK consortium



Tracking Detectors
Thin large-area fiber detector: Prototype with 0.25 mm pitch, readout by PSPM and NXCYTER based frontend successfully tested with Sn beam in 2012





Schedule and first experiments

2012	Test of NeuLAND modules with mono-energetic neutrons Installation of infrastructure in Cave C for GLAD (He cryo-system, power supply)
2013	Delivery and installation of superconducting dipole GLAD
2014	Installation of 20% detectors NeuLAND and CALIFA Commissioning and physics run
2015	Construction and installation of detector components
2016	Commissioning of full R3B setup and first physics run
2017	Installation of experimental setup at FAIR site including superconducting triplet
2018	Commissioning and first experiments at Super FRS

Experiments in 2018 will make use of uniqueness of R^{3}B:

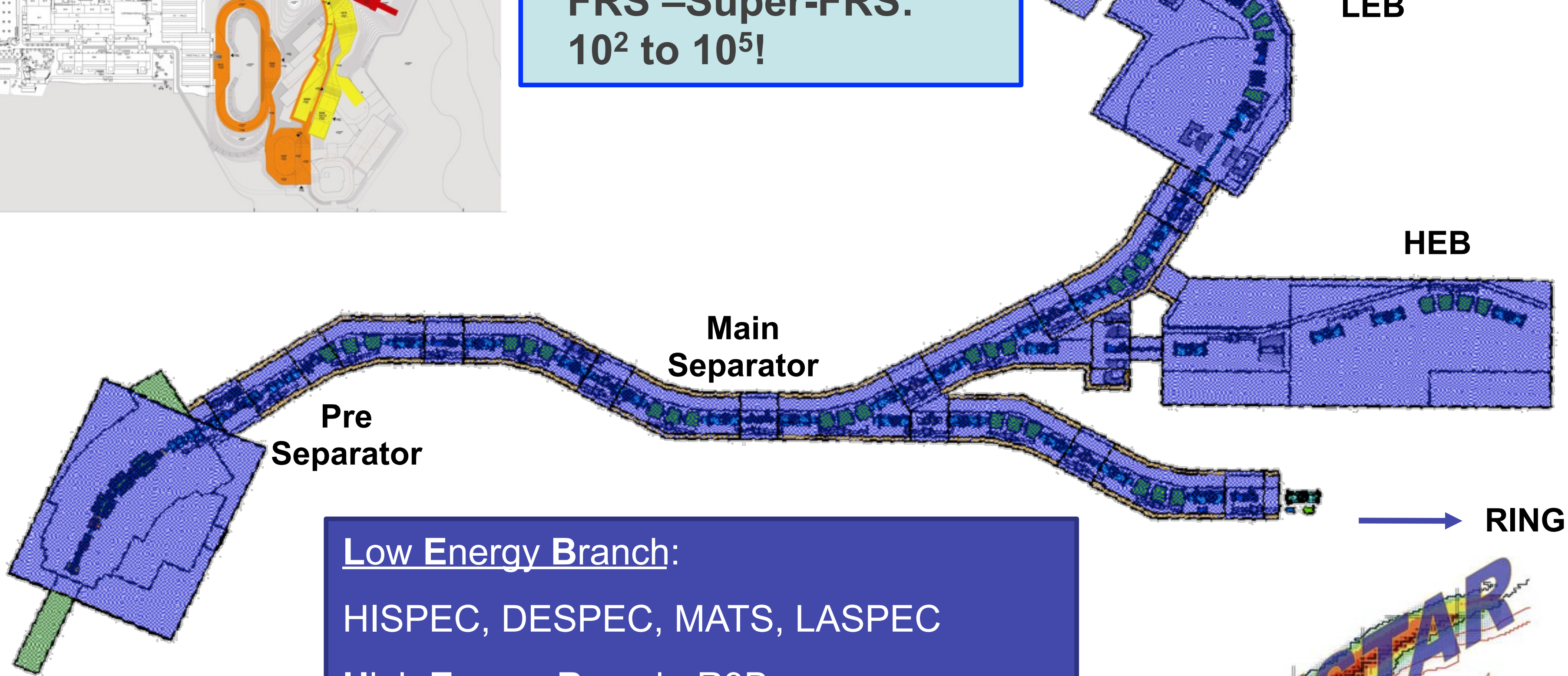
- Reactions at high beam energies up to 1 GeV/nucleon
- Tracking and identification capability even for the heaviest ions
- Multi-neutron tracking capability, high-efficiency calorimeter

➡ **Experiments possible for the first time:**

- 4 neutron decays beyond the drip-line: e.g. ^{4}n, ^{28}O
- Kinematically complete measurements of quasi-free nucleon knockout reactions
- Electric dipole and quadrupole response of Sn nuclei beyond N=82
- Electric dipole and quadrupole response of neutron-rich Pb isotopes

NUSTAR - The Facility

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



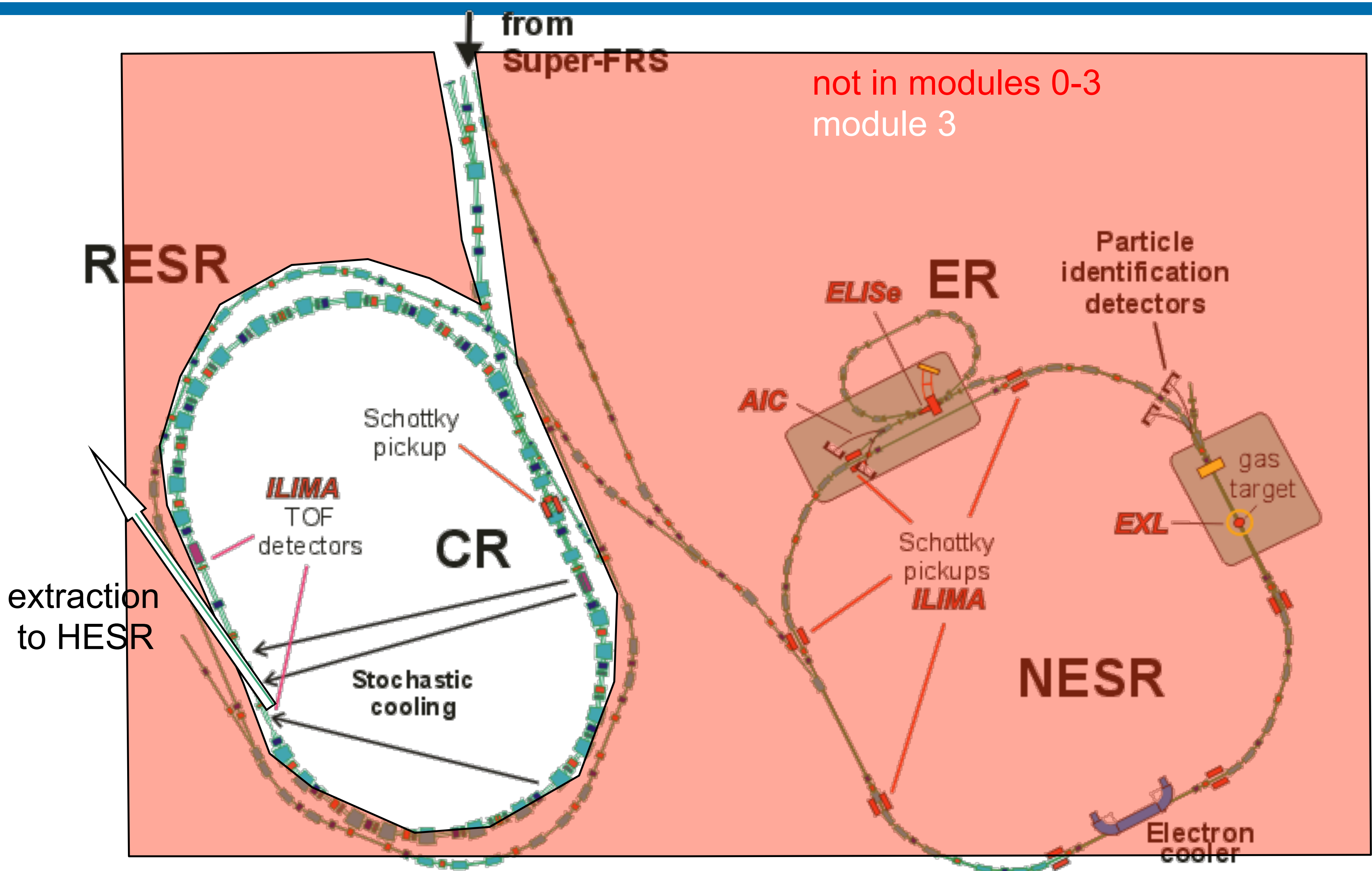
Low Energy Branch:

HISPEC, DESPEC, MATS, LASPEC

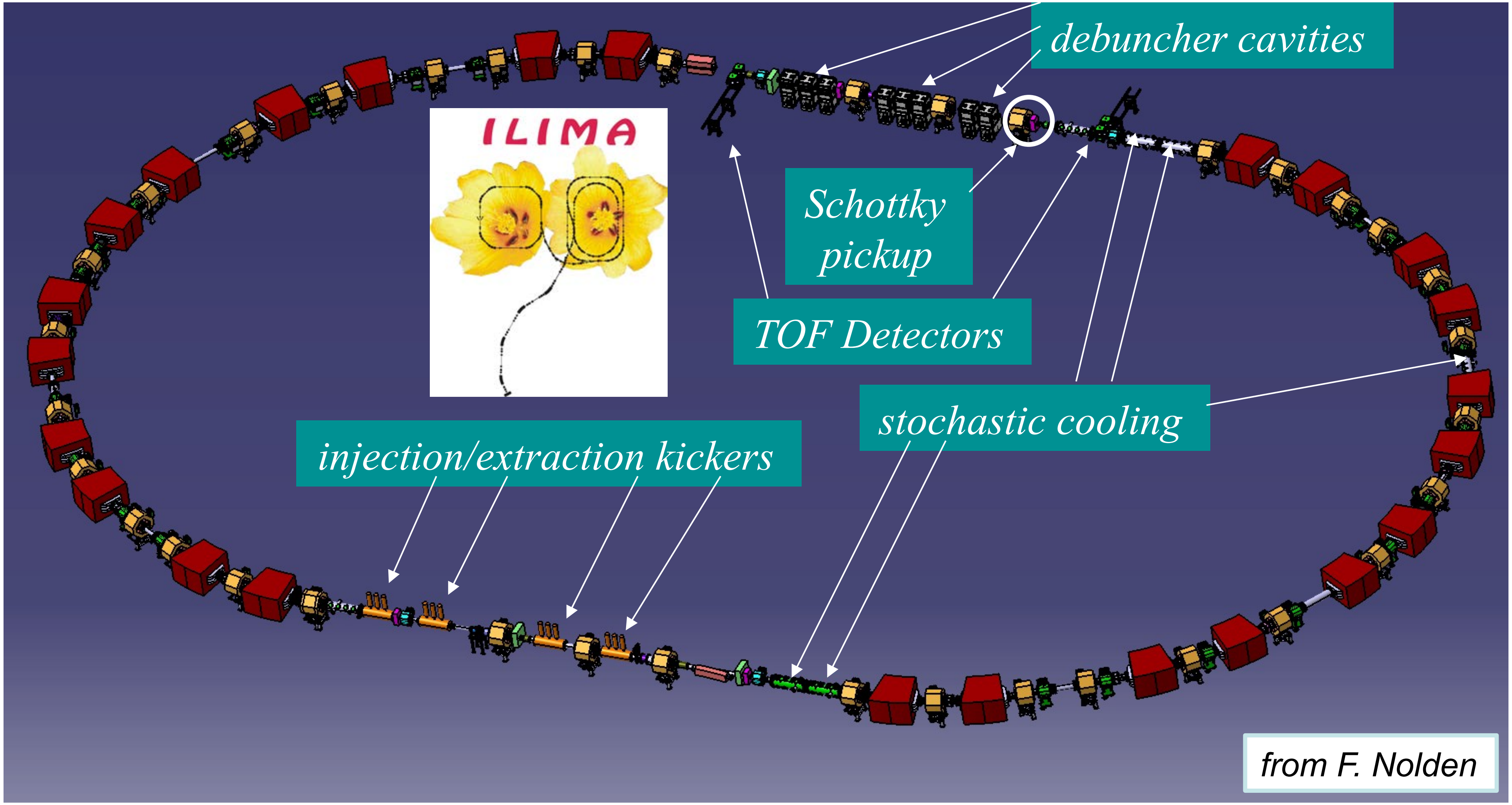
High Energy Branch: R3B

Ring Branch: EXL, ILIMA, ELISE

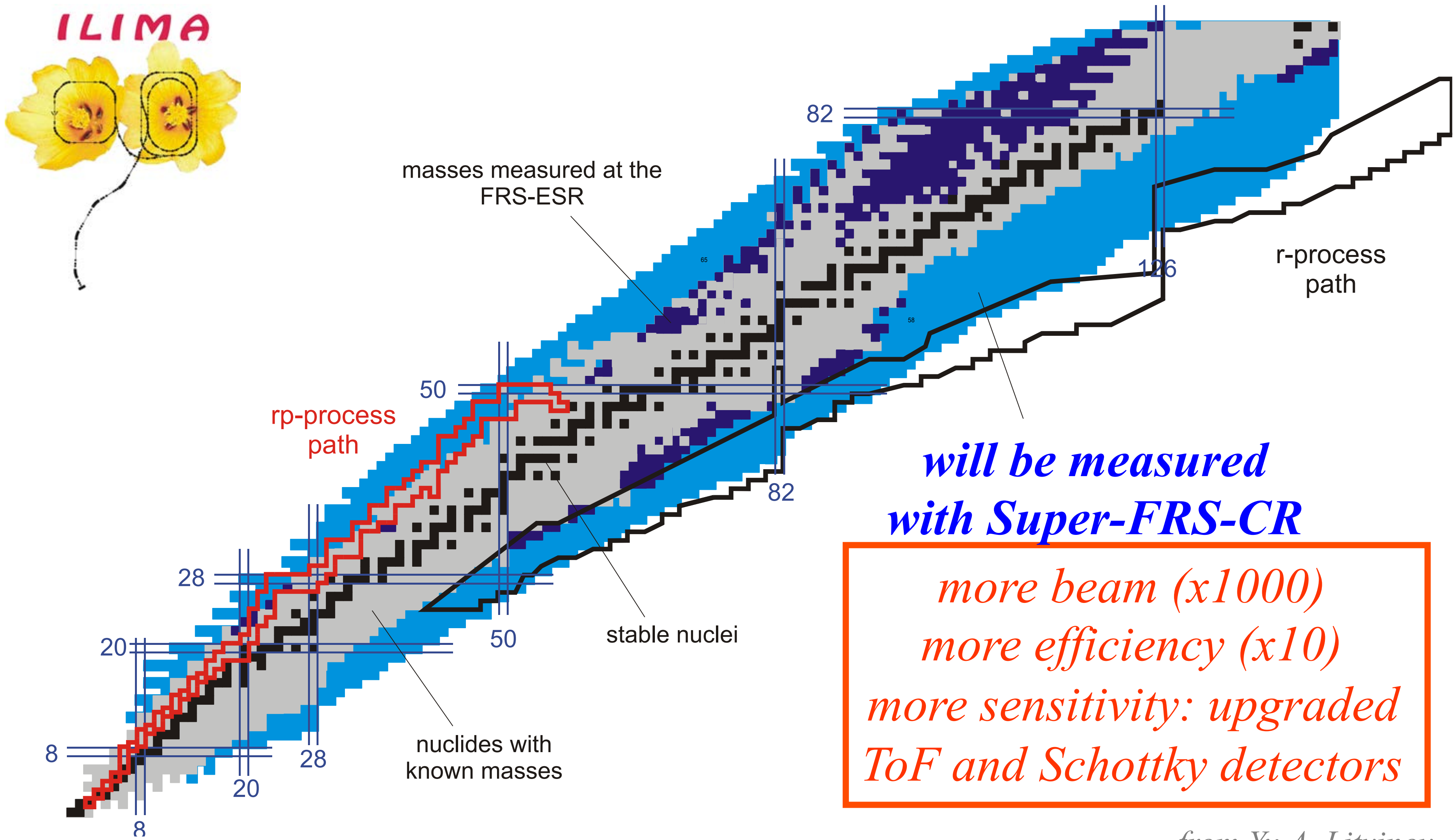
CR, NESR Storage Rings



CR perspective view



Potential for new masses with ILIMA

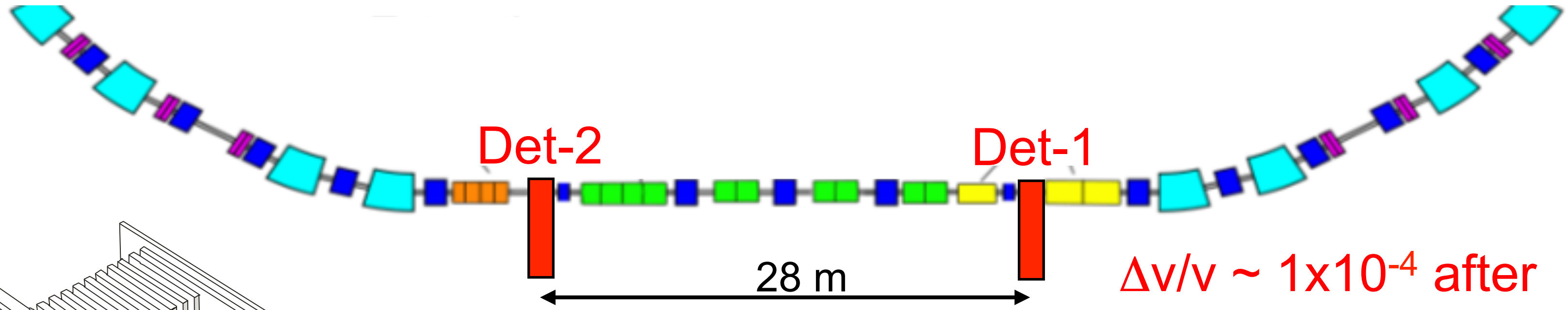


more beam (x1000)
more efficiency (x10)
more sensitivity: upgraded ToF and Schottky detectors

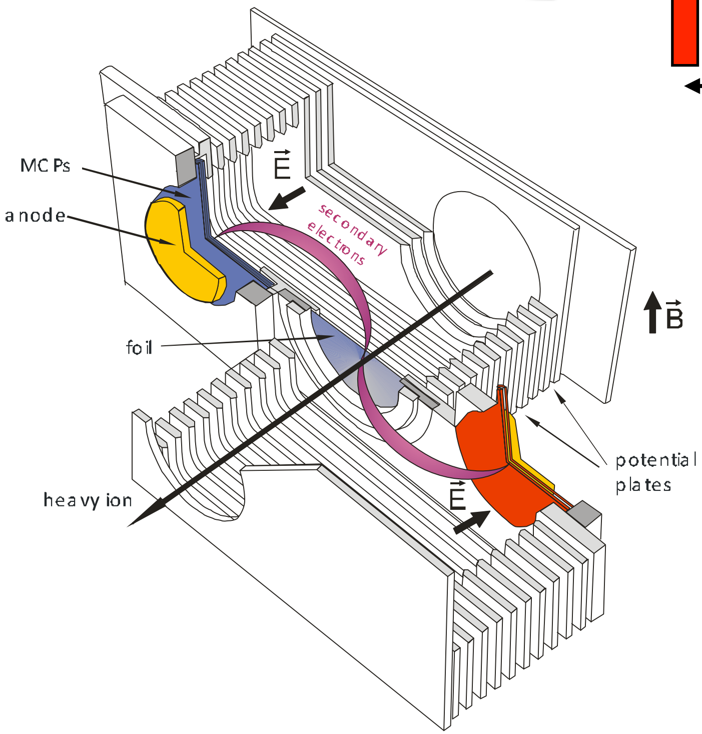
from Yu.A. Litvinov

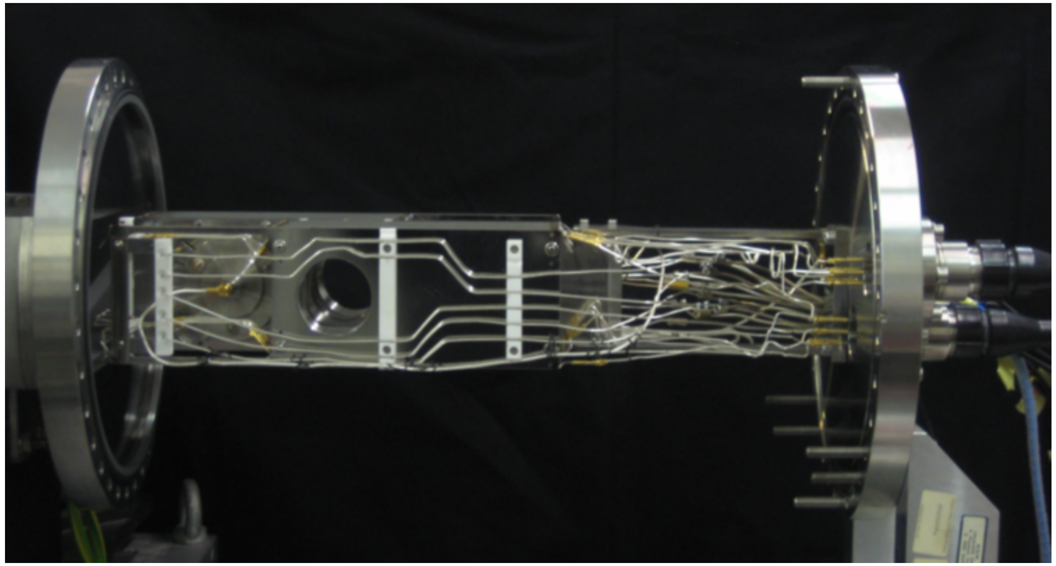
ToF Detection

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





Status NUSTAR TDRs

PSP-code	Description	Status	expected
LEB Super-FRS			
1.2.1.1	Slow beamline and spectrometer		06/2015
1.2.1.2	Stopping cell, extraction, cooling, beam-distribution system, and electrostatic beamlines		06/2015
1.2.1.3	Laser ion source		06/2015
HISPEC/DESPEC			
1.2.2.9	HYDE charged particle detectors for reaction studies (HISPEC)		12/2012
1.2.2.10	LYCCA charged particle detector (50-200 A·MeV) (HISPEC)	approved	
1.2.2.11	Plunger (HISPEC)		12/2012
1.2.2.13	DSSD implantation and decay detector (AIDA) (DESPEC)	approved	
1.2.2.14	DESPEC high resolution g-detector		01/2013
1.2.2.15	Fast timing (FATIMA)		12/2014
1.2.2.16.1	BELEN (DESPEC)		12/2012
1.2.2.16.2	MONSTER		12/2012
1.2.2.16.3	NEDA		12/2012
1.2.2.17	Total absorption spectrometer (DTAS) (DESPEC)	submitted	

Status NUSTAR TDRs (cont)

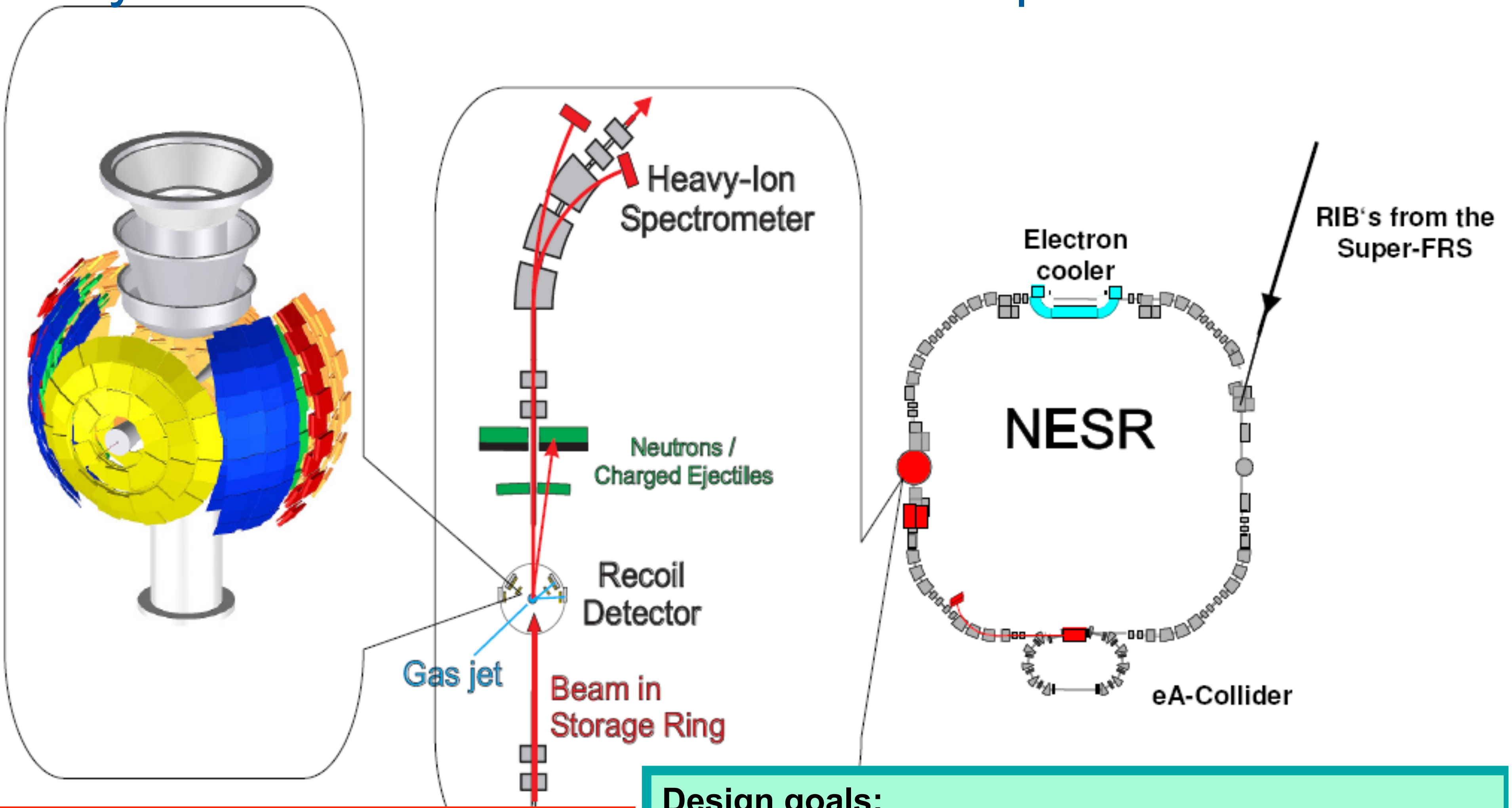
MATS			
1.2.3.1	Beamline	approved	
1.2.3.2	Off-line ion source		
1.2.3.3	RFQ and switchyard		
1.2.3.4	EBIT		
1.2.3.5	q/A selection		
1.2.3.6	Preparation Penning Trap		
1.2.3.7	Precision Penning Trap		
1.2.3.8.1	Detectors TOF-MS		
1.2.3.8.2	Detectors FT-ICR-MS		
1.2.3.8.3	In-trap conversion electron spectroscopy		
1.2.3.9	Control system		
1.2.3.10	General Control and safety equipment		
1.2.3.11	Spares		
1.2.3.12	Tape station		
1.2.3.13	MR-TOF-MS		
LaSpec			
1.2.4.1	Switchyard	approved	
1.2.4.2	Collinear Ion Beamline		
1.2.4.3	Optical Pumping		
1.2.4.4	b-NMR		
1.2.4.5	RILIS		
1.2.4.7	Laser Housing		
1.2.4.8	Data Acquisition		

Status NUSTAR TDRs (cont)

R^3B			
	R3B Phase 1		
1.2.5.1.1.1	Quadrupole triplet	approved	
1.2.5.1.1.2	Large-acceptance dipole	approved	
1.2.5.1.2.1	Tracking detectors		06/2013
1.2.5.1.2.2	Large-area ToF wall		12/2013
1.2.5.1.2.3.1	Gamma spectrometer - barrel (CALIFA)	submitted	
1.2.5.1.2.3.2	Gamma spectrometer - forward endcap (CALIFA)		12/2014
1.2.5.1.2.4	Target recoil detector		12/2012
1.2.5.1.2.5	Neutron ToF spectrometer (NeuLAND)	submitted	
1.2.5.1.3	Vacuum systems (beam pipes, detector chambers, big chamber behind magnet, pumps)		12/2012
1.2.5.1.4	DAQ electronics (VME systems, computers and cables)		12/2012
1.2.5.1.5	Infrastructure		12/2016
	R3B Phase 2		
1.2.5.2.1	Spectrometer		03/2016
1.2.5.2.2	Tracking detectors for spectrometer		03/2016
1.2.5.2.3	Active target		09/2013
ILIMA			
1.2.6.3	Schottky pick-ups		01/2014
1.2.6.4	Time-of-flight detectors		01/2015
1.2.6.5	Decay detectors		01/2015

NUSTAR funding for MSV: 85% (secured+applied+EOI)

Beyond MSV: Details of the EXL setup



Detection systems for:

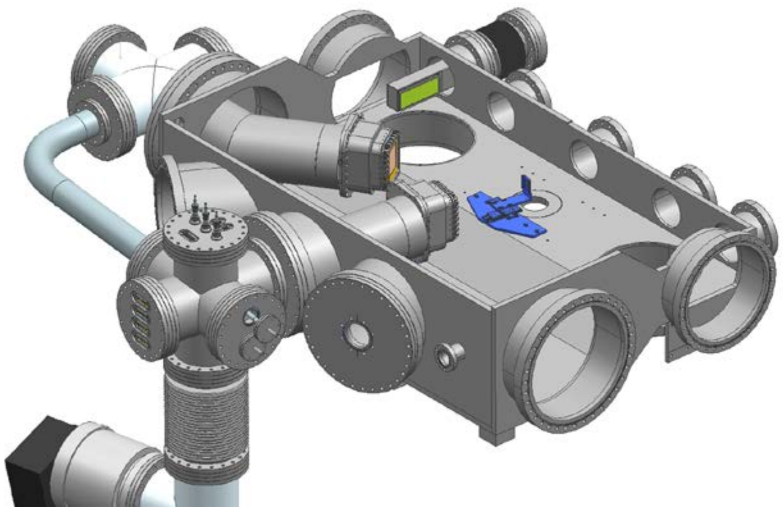
- Target recoils and gammas (p,α,n,γ)
- Forward ejectiles (p,n)
- Beam-like heavy ions

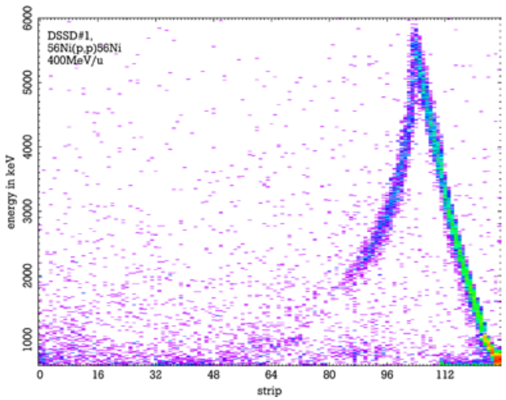
Design goals:

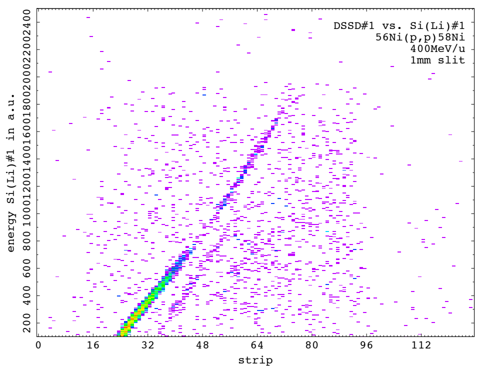
- Universality: applicable to a wide class of reactions
- Good energy and angular resolution
- Large solid angle acceptance
- Specially dedicated for low q measurements with high luminosity (> 10^{28} cm^{-2} s^{-1})

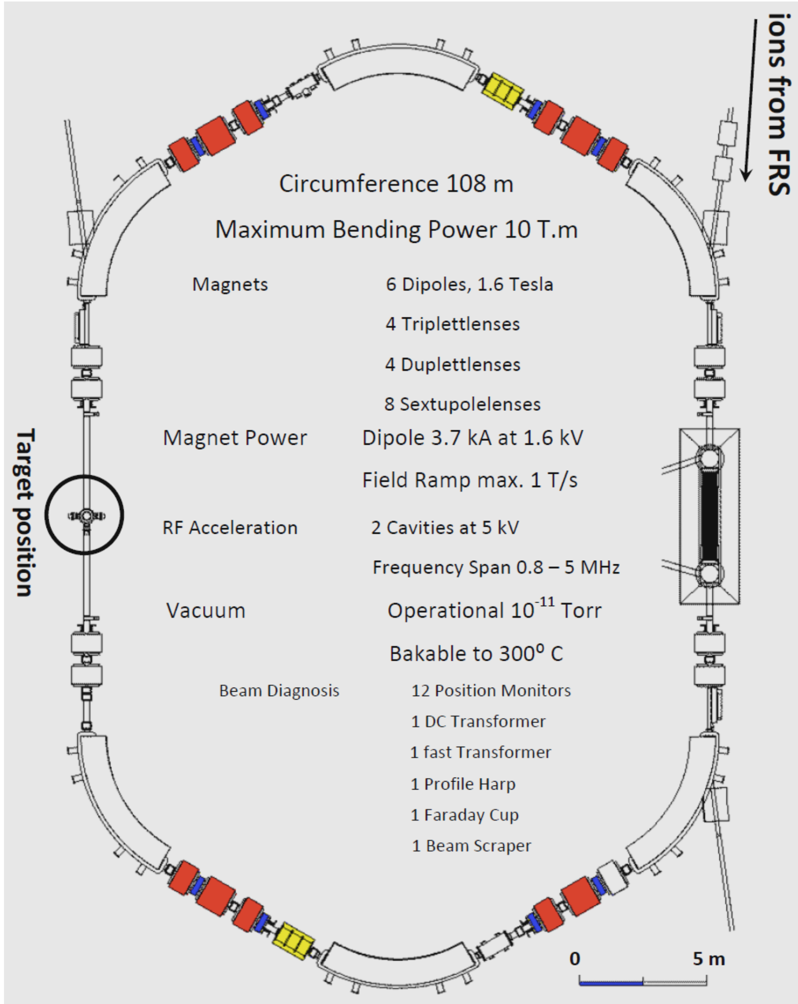
Intermediate storage ring activities/“Green Paper”

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

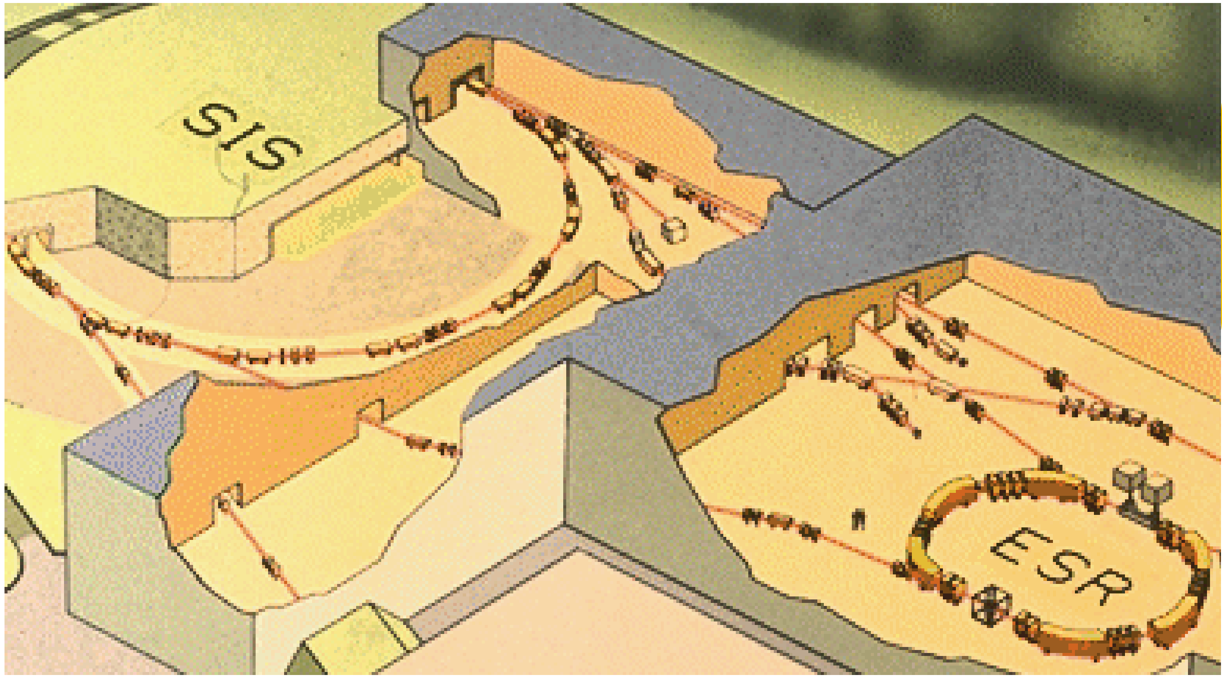








Cryring at the ESR



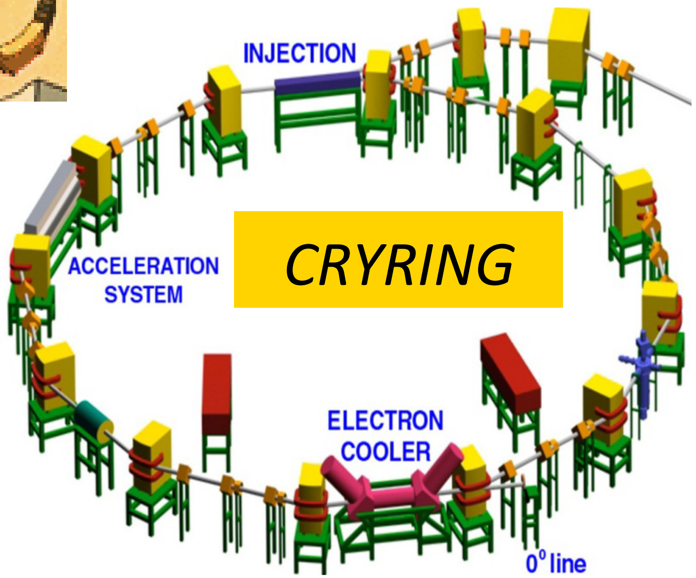
ESR: Circumference 108 m

Bρ: 10 Tm

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

Cryring Circumference 54 m

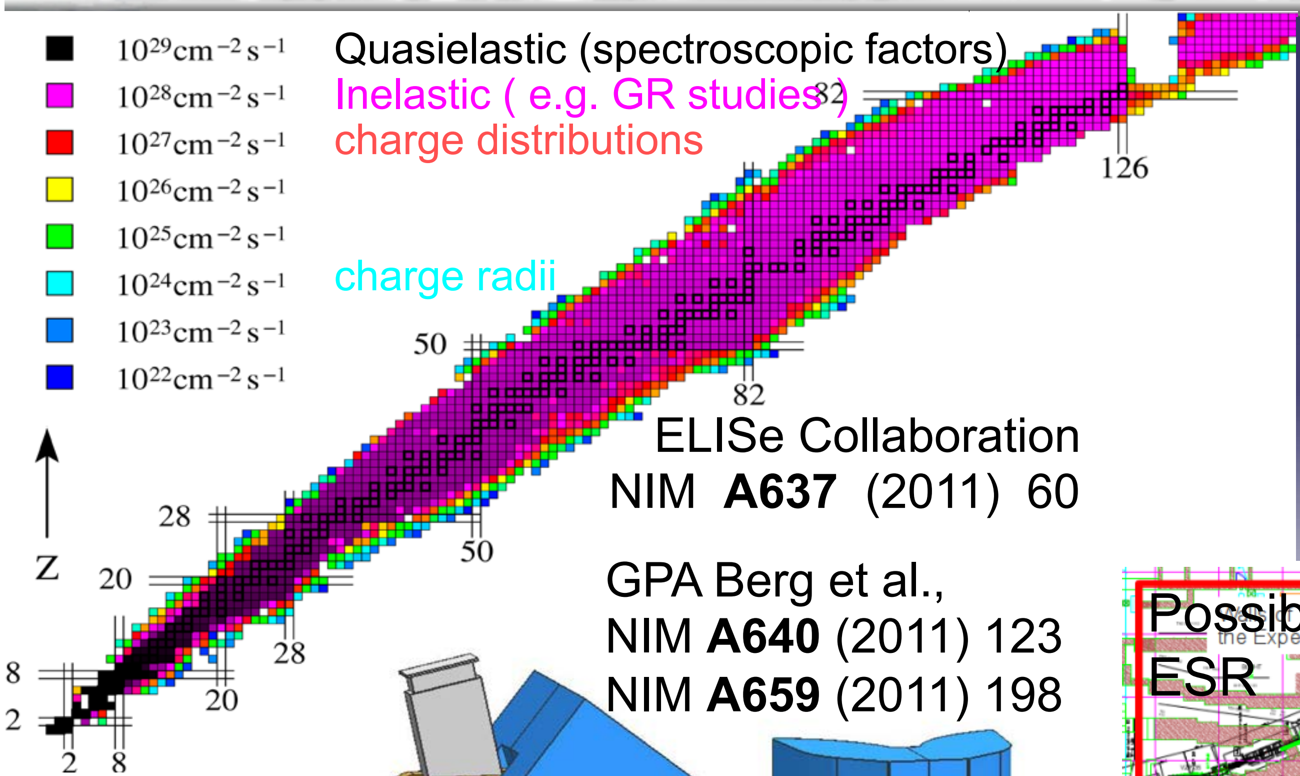
Bρ: 1.44 Tm



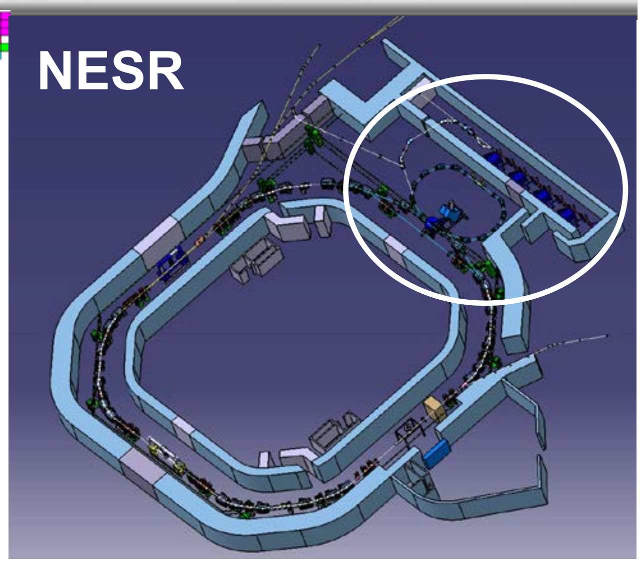
Realization of an RIB electron collider setup

The **ELISe** experiment

Haik Simon • GSI / Darmstadt

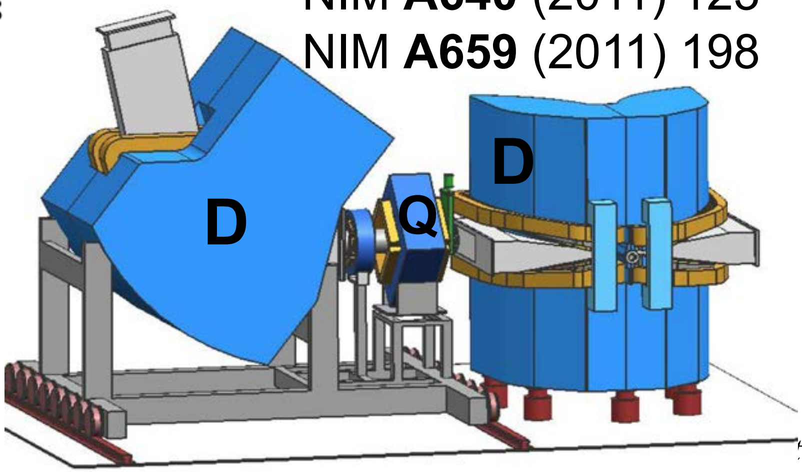


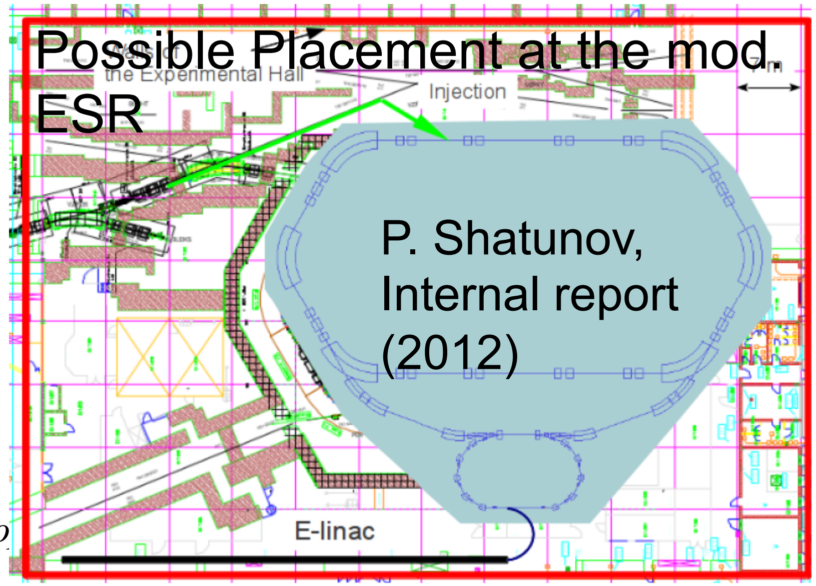
Quasielastic (spectroscopic factors)
Inelastic (e.g. GR studies)
charge distributions
charge radii



ELISe Collaboration
NIM **A637** (2011) 60

GPA Berg et al.,
NIM **A640** (2011) 123
NIM **A659** (2011) 198





P. Shatunov,
Internal report
(2012)

Uniqueness of NUSTAR@FAIR

Synchrotron-based RIB production for:

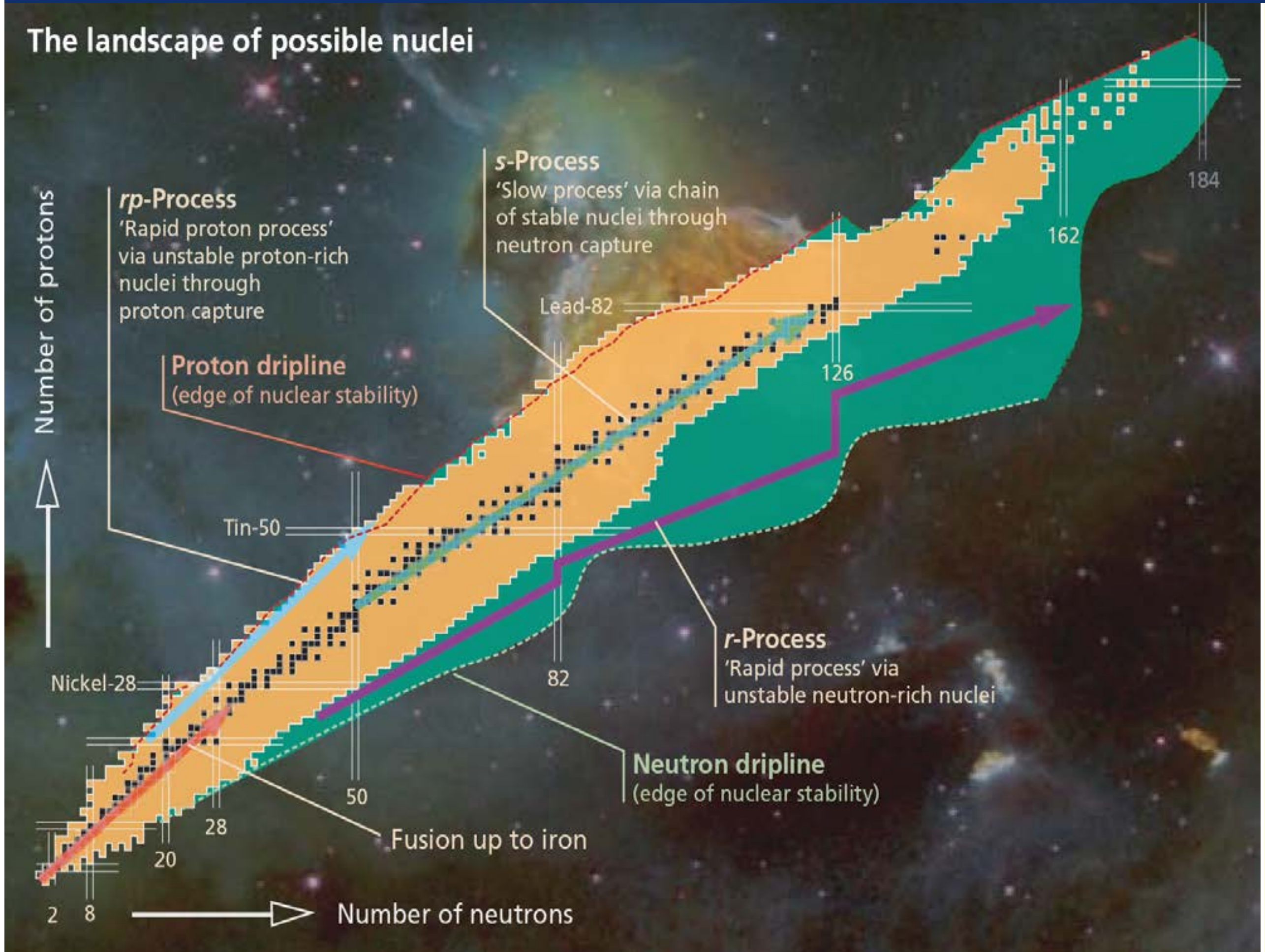
- High-energy Radioactive Beams (≤1.5 GeV/u)
  - Efficient production, separation, transmission and detection aided by Lorentz boost
  - Access to also the heaviest nuclei without charge-state ambiguities
  - Large range of attainable reaction mechanisms
- Storage rings
  - Mass measurements and beam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

Combined with:

- Wide range of state-of-the-art instrumentation
  - Strong evolution from existing programmes

Status

The NUSTAR Project aims to study exotic nuclei...



Physics subject

to understand the formation of the elements and to finally describe the atomic nucleus

Instrumentation

a multitude of novel particle and radiation detectors and set-ups with sophisticated EDAQ systems are being prepared

Perspective

First experiments in early implementations are already operational at GSI and other labs.

NUSTAR will be in time to produce first results at FAIR!

...and is well under way