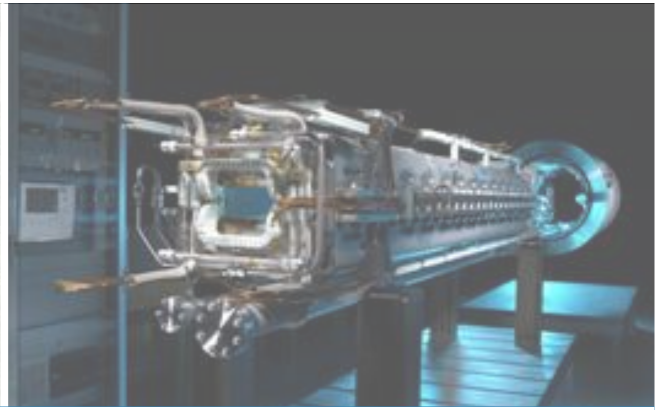


NUclear Structure, Astrophysics and Reactions – NUSTAR

Thomas Nilsson, NUSTAR BR chair

FAIR Science Mini-Workshop – GSI/FAIR 2013-07-02

FAIR

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?

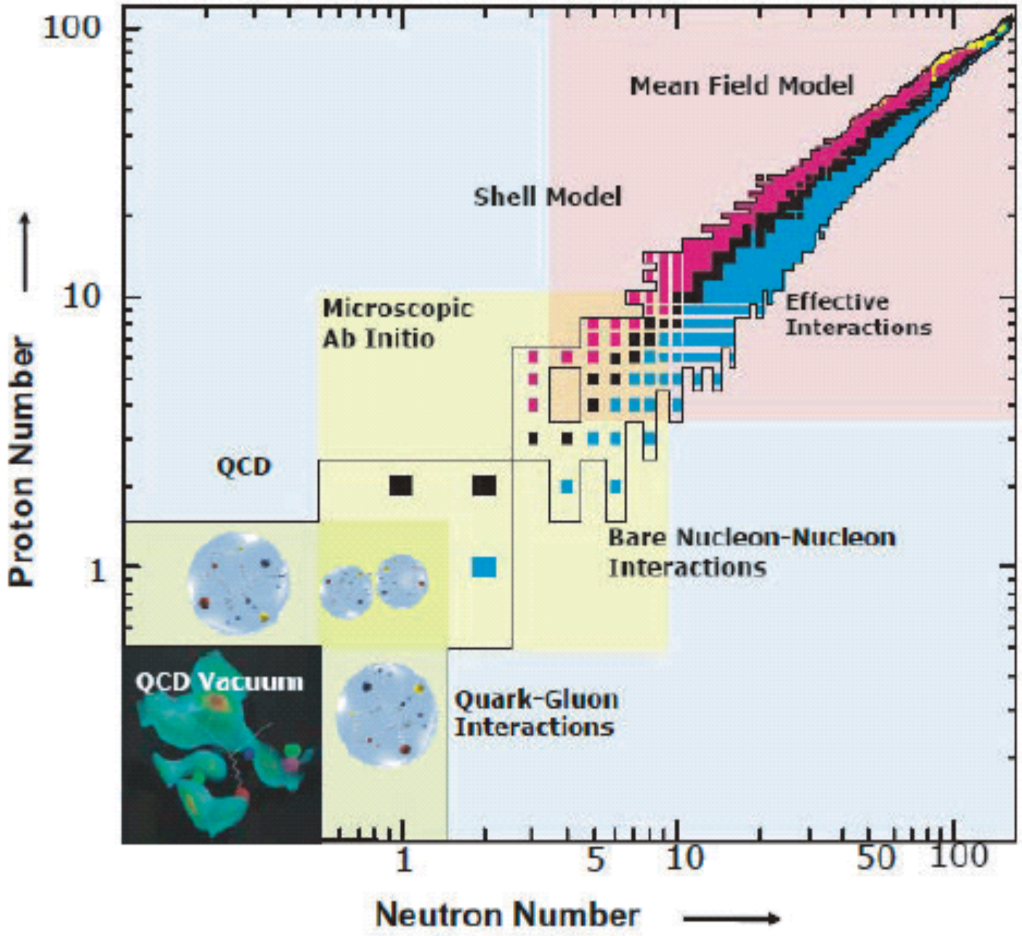
- What is the effective nucleon-nucleon interaction?
- How does QCD constrain its parameters?

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

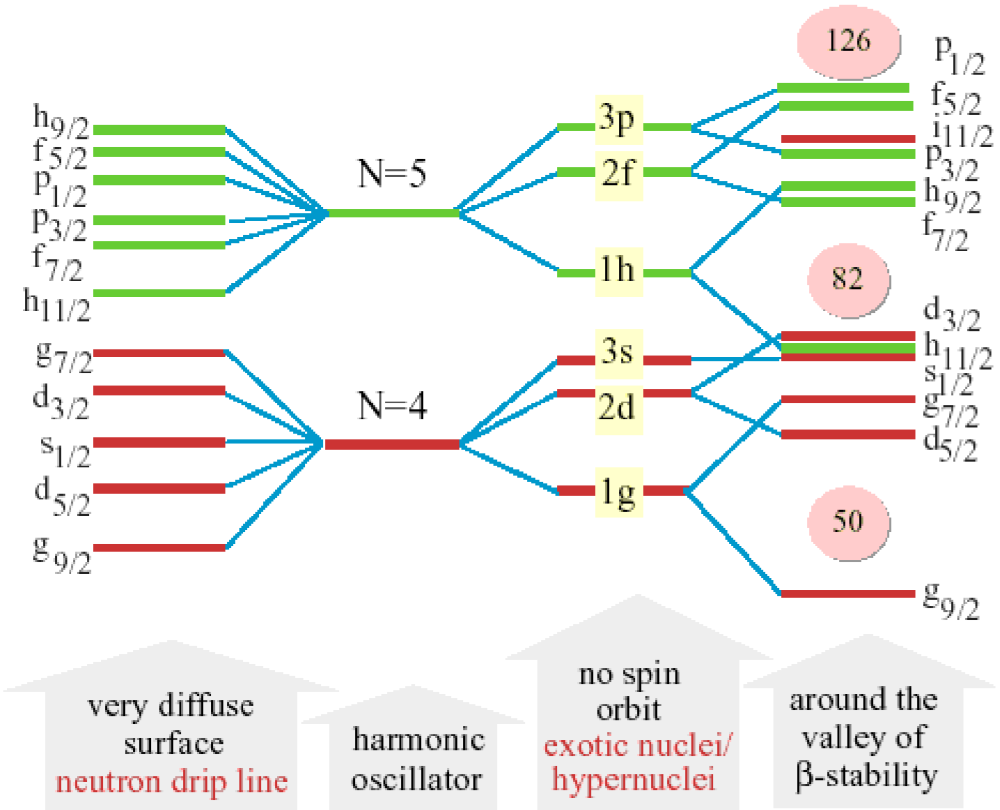
- What is the origin of the heavy elements?

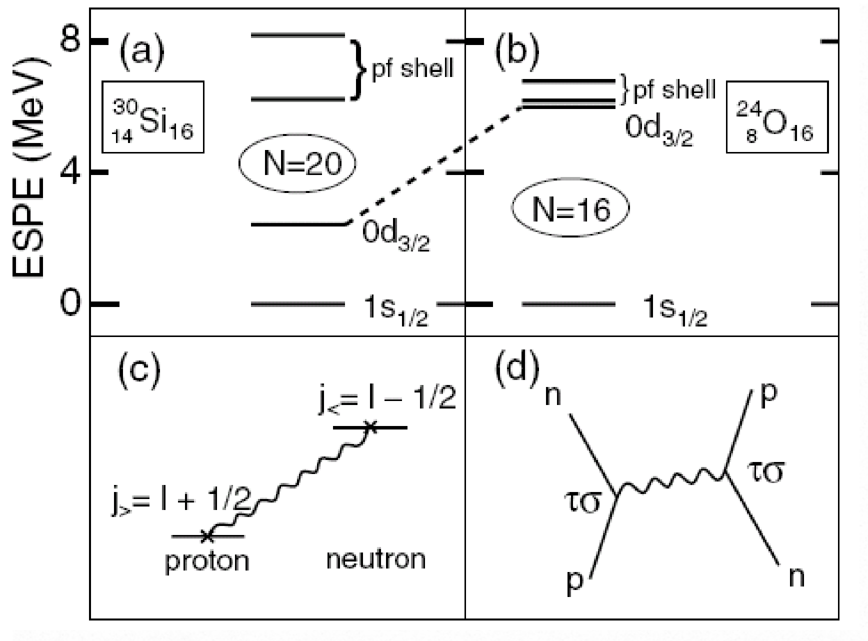
Open questions

- **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?





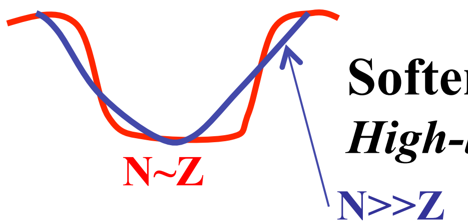
A. Ozawa et al. PRL 84 (2000) 5493

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)



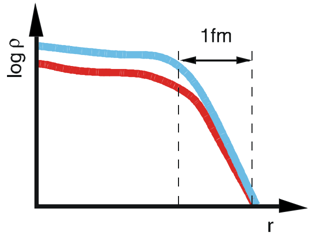
Softening of the nuclear potential:

High-l pushed upward and

Spin-Orbit splitting reduced

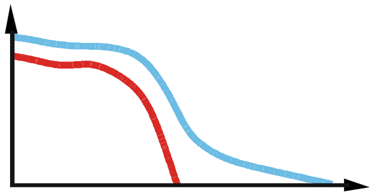
How to explain collective phenomena from individual motion?

stable



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

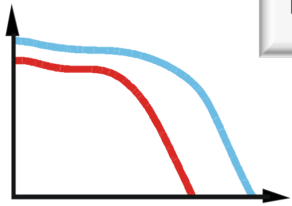
$d_p = d_n = \text{const} \approx 1\text{fm}$



halo

$r_p \neq r_n$

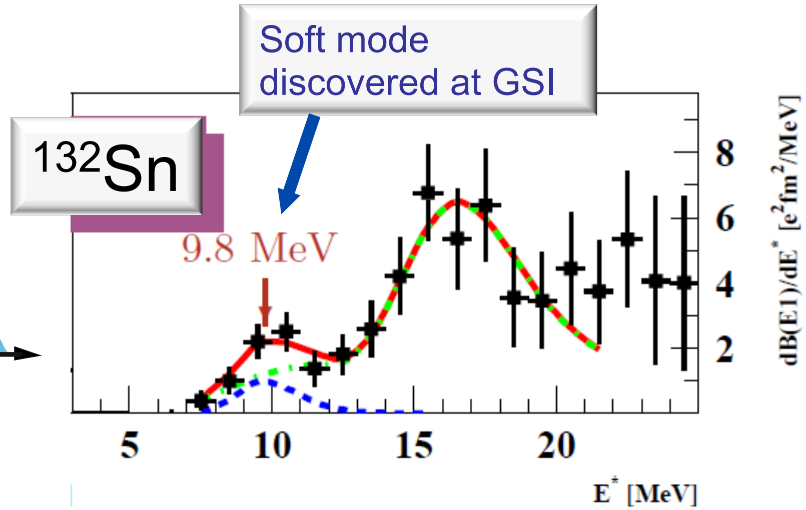
$d_p \neq d_n$



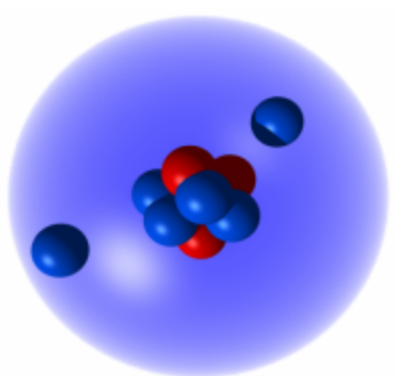
skin

$r_p \neq r_n$

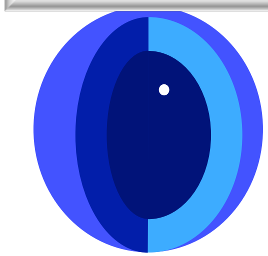
$d_p = d_n$



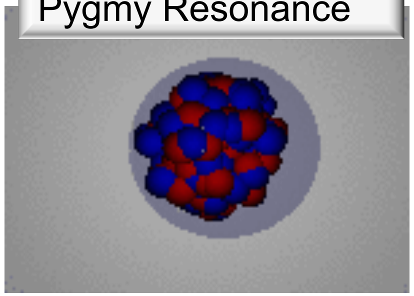
Halos



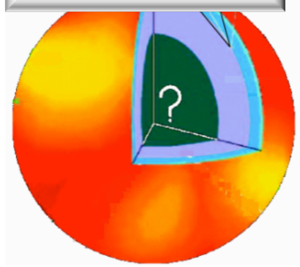
Neutron Skins



Pygmy Resonance



Neutron stars

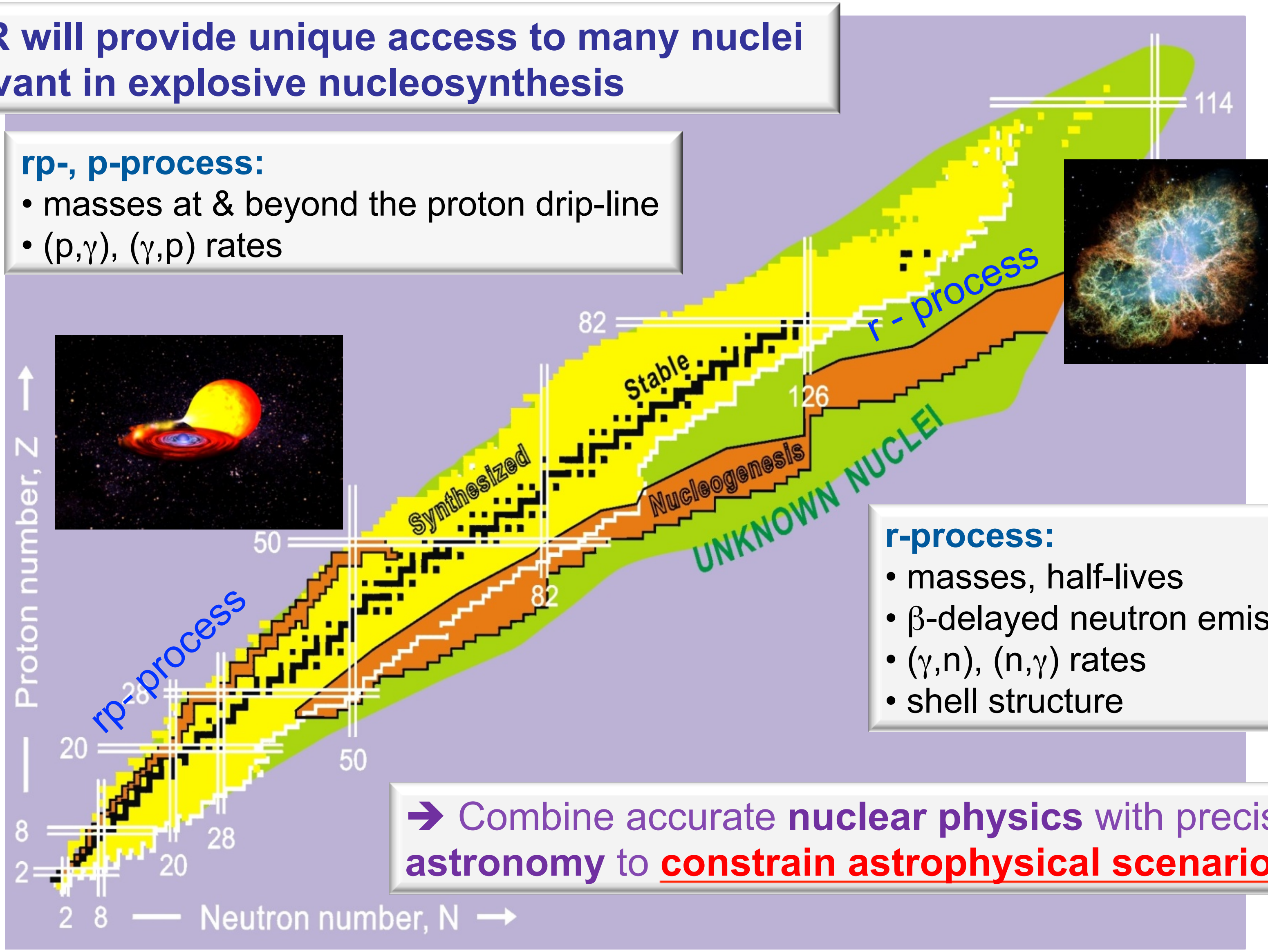


EOS

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

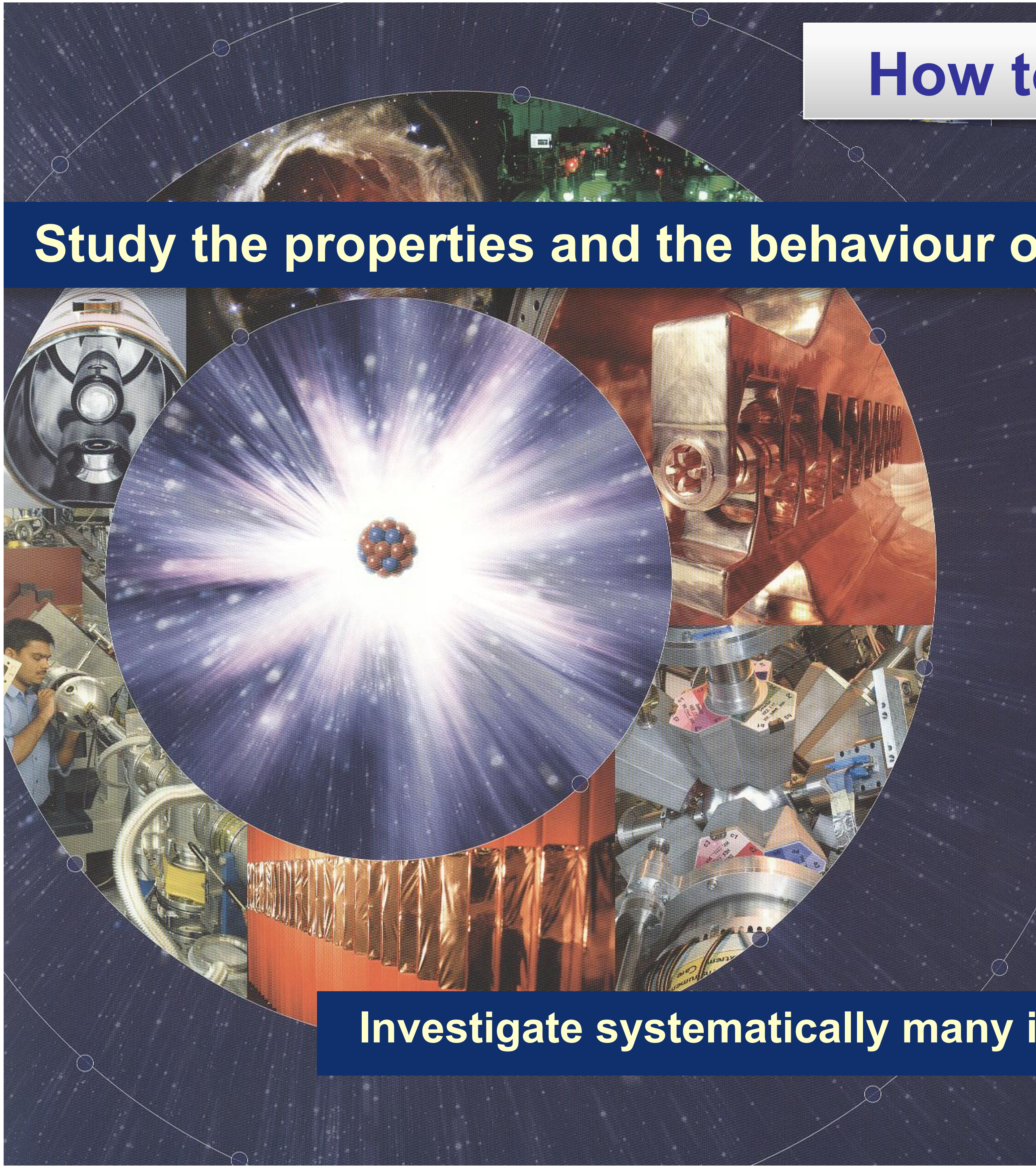


r-process:
- masses, half-lives
- β-delayed neutron emission
- (γ,n), (n,γ) rates
- shell structure

➔ 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 high-resolution 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

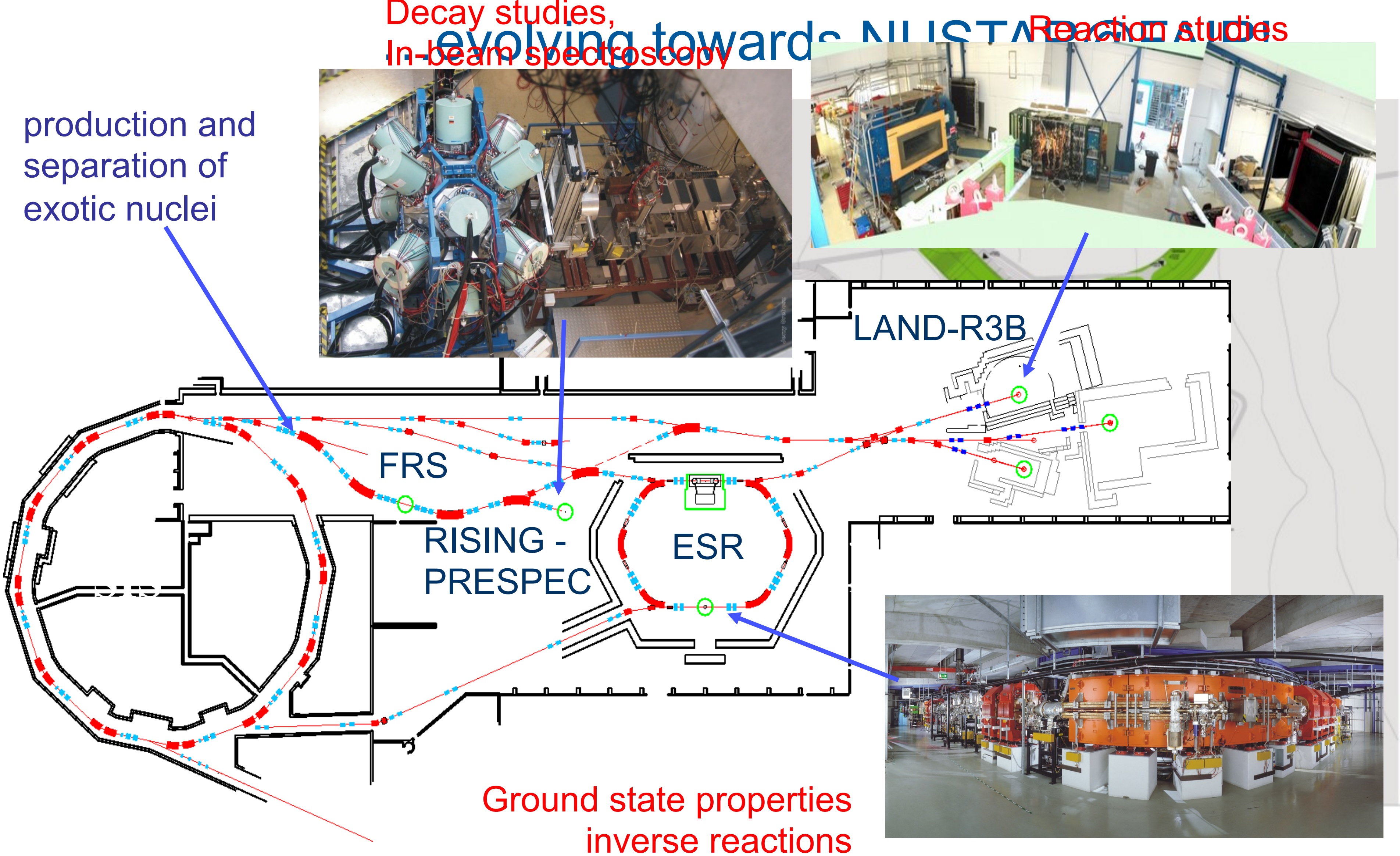
The Investment

82 M€ Super-FRS

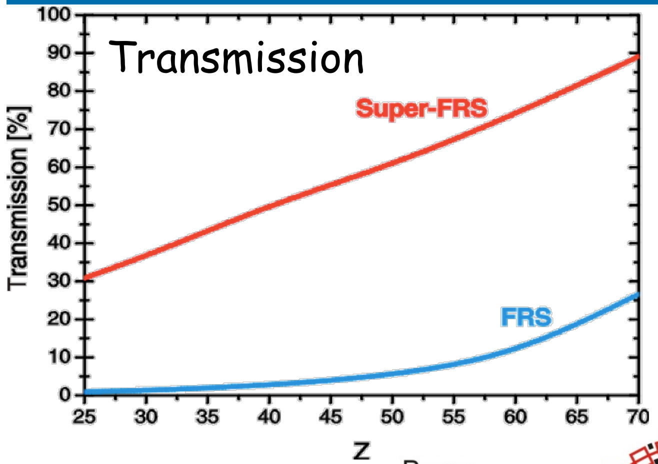
73 M€ Experiments

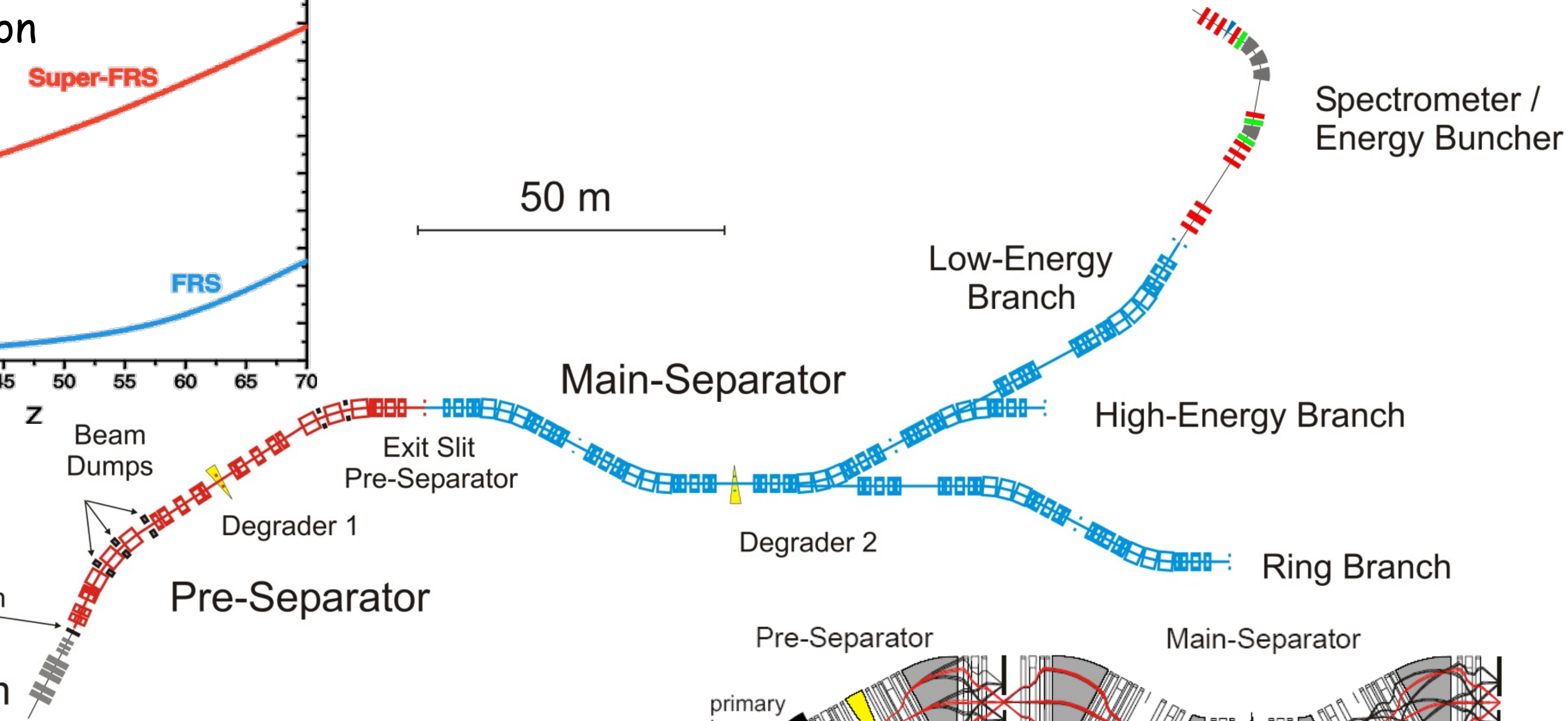
NUSTAR Week Kolkata Oct 2012

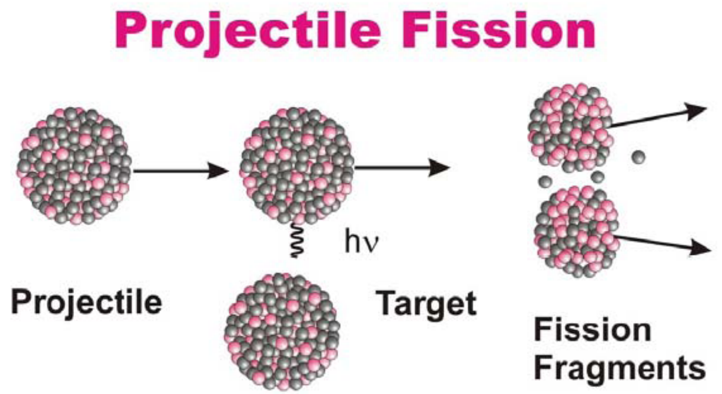
Existing research opportunities at GSI

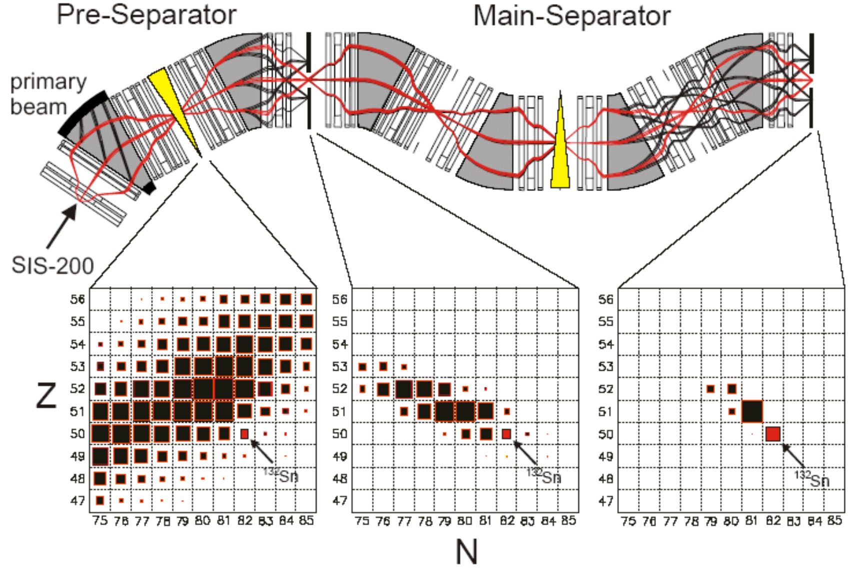


SUPERconducting FRagment Separator

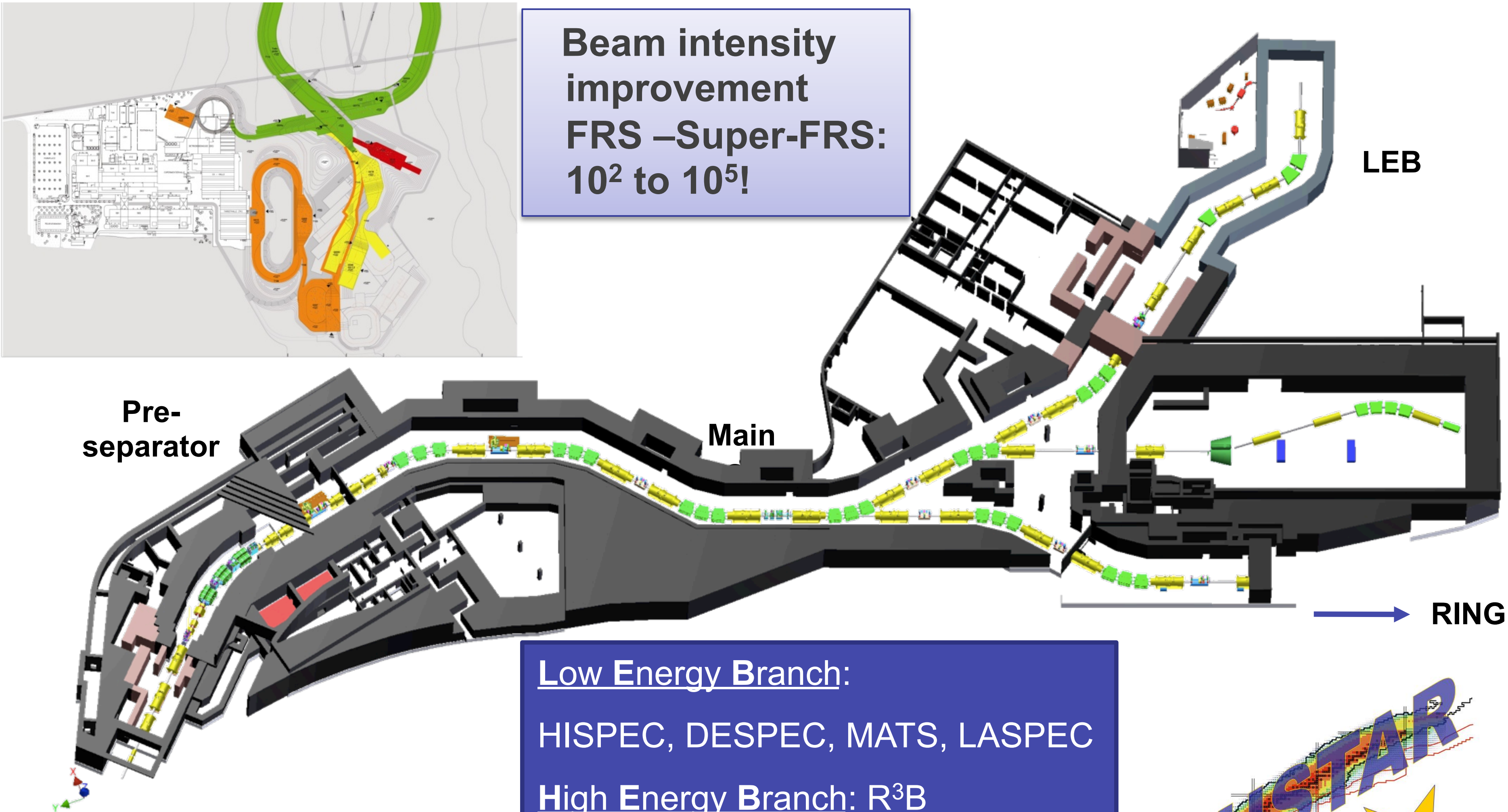








NUSTAR - The Facility



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

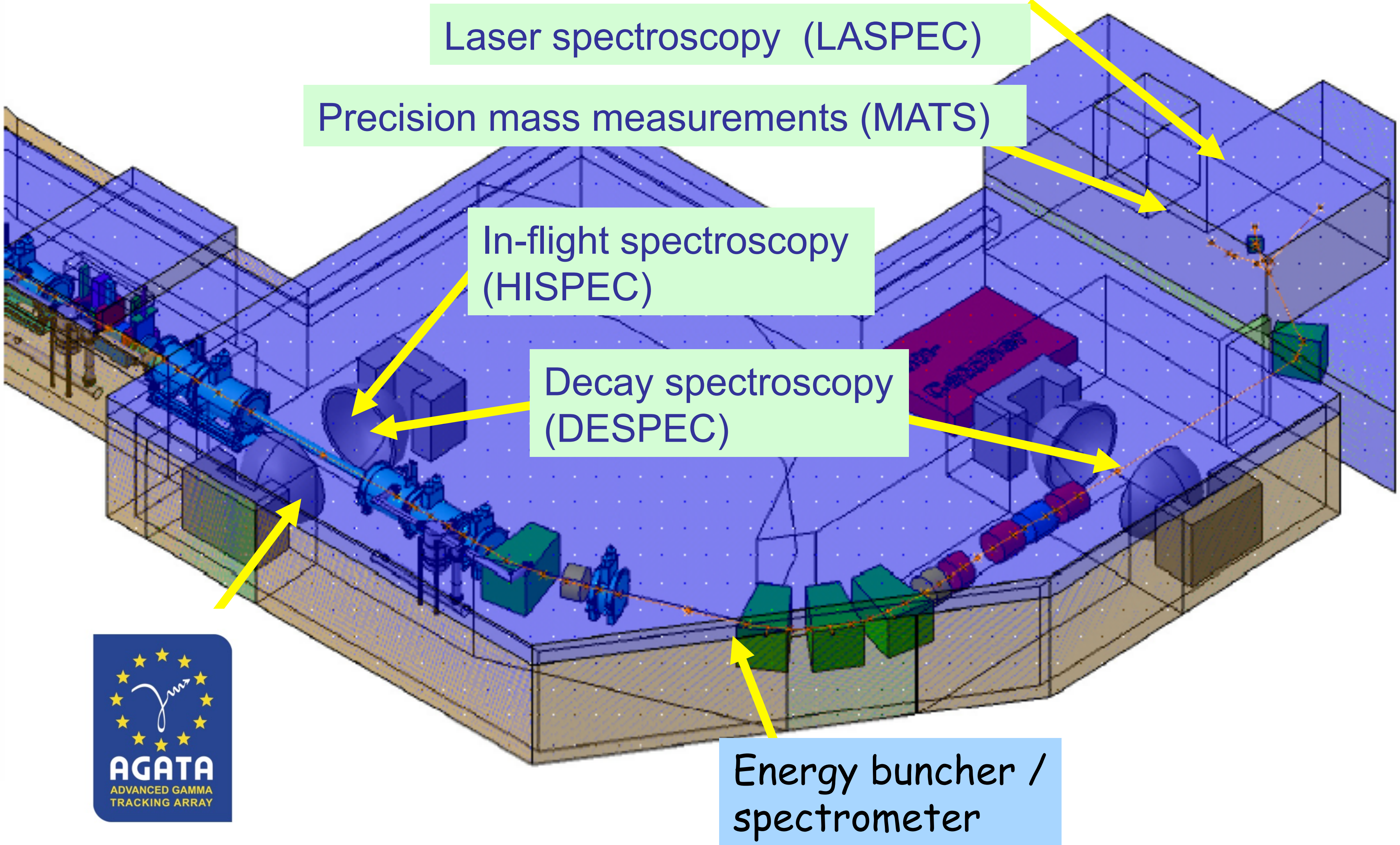
Low Energy Branch:

HISPEC, DESPEC, MATS, LASPEC

High Energy Branch: R³B

Ring Branch: EXL, ILIMA, ELISE

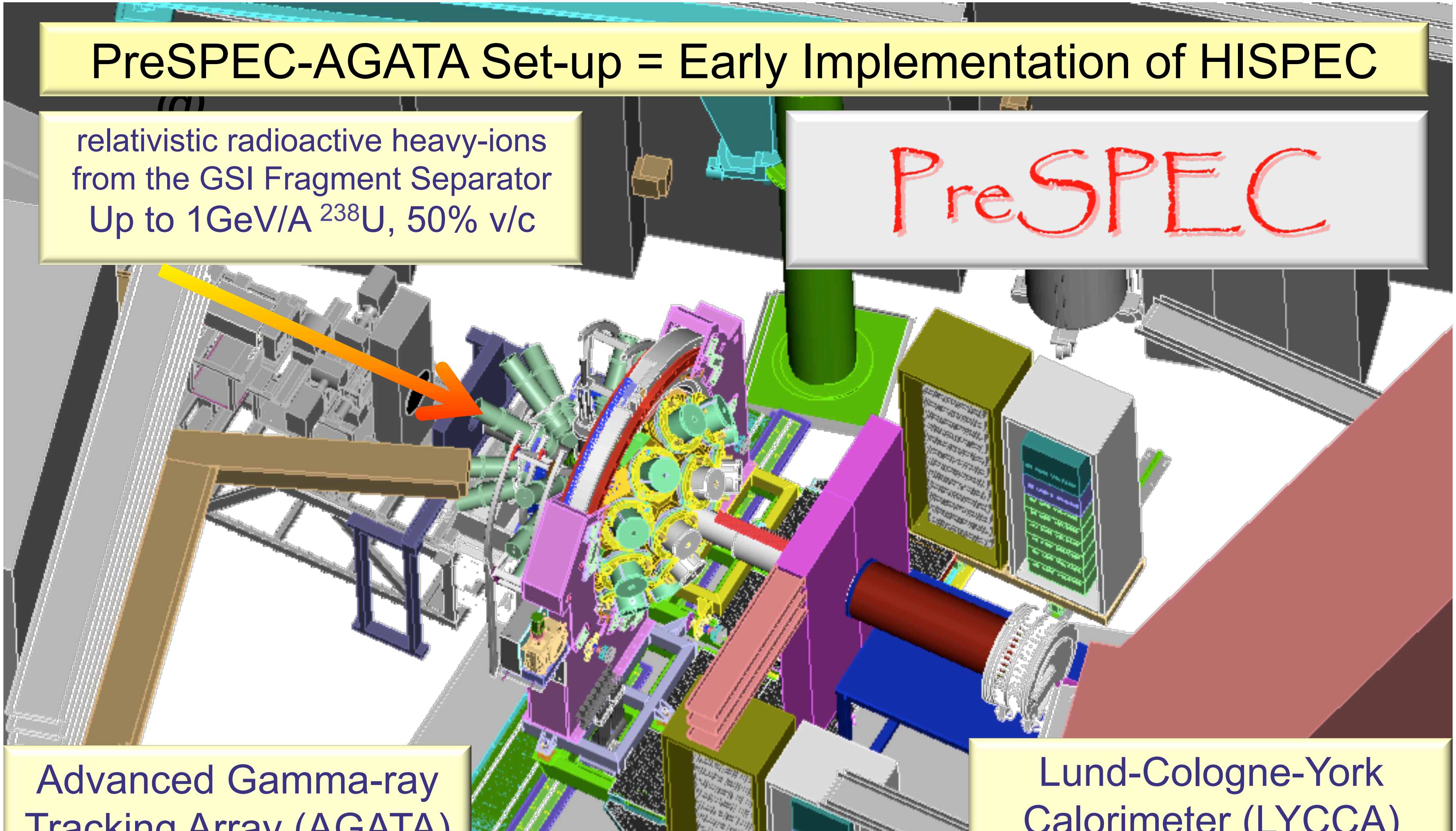
LEB - Experiments with slowed and stopped beams



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



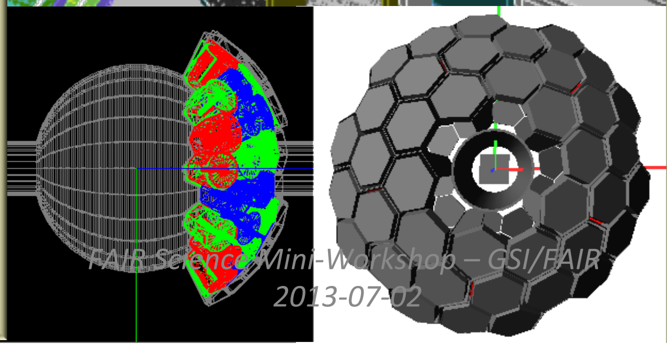
Advanced Gamma-ray Tracking Array (AGATA)

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

d ~ 20 cm

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

$\Delta E \approx 0.4\%$

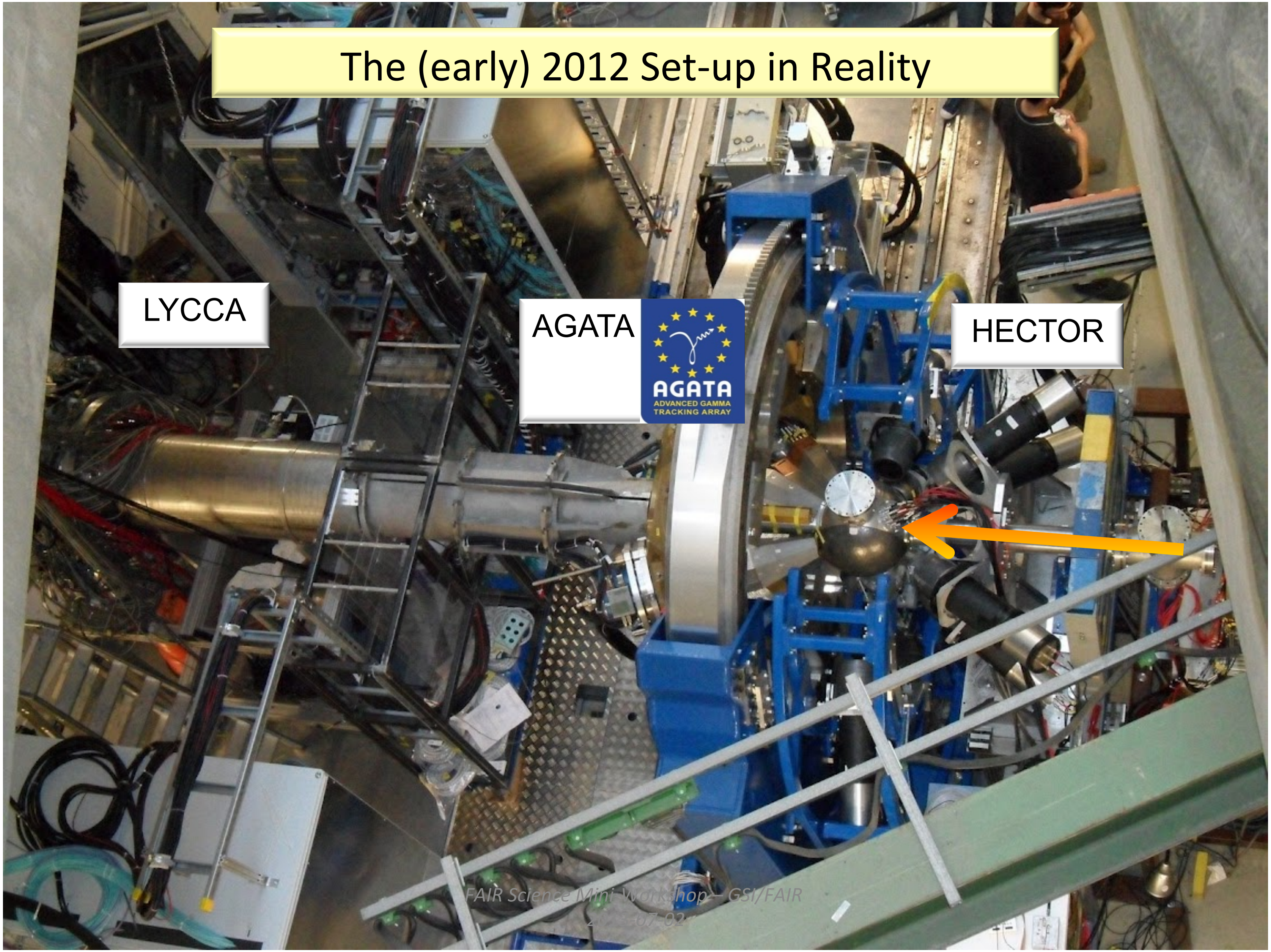


Lund-Cologne-York Calorimeter (LYCCA)

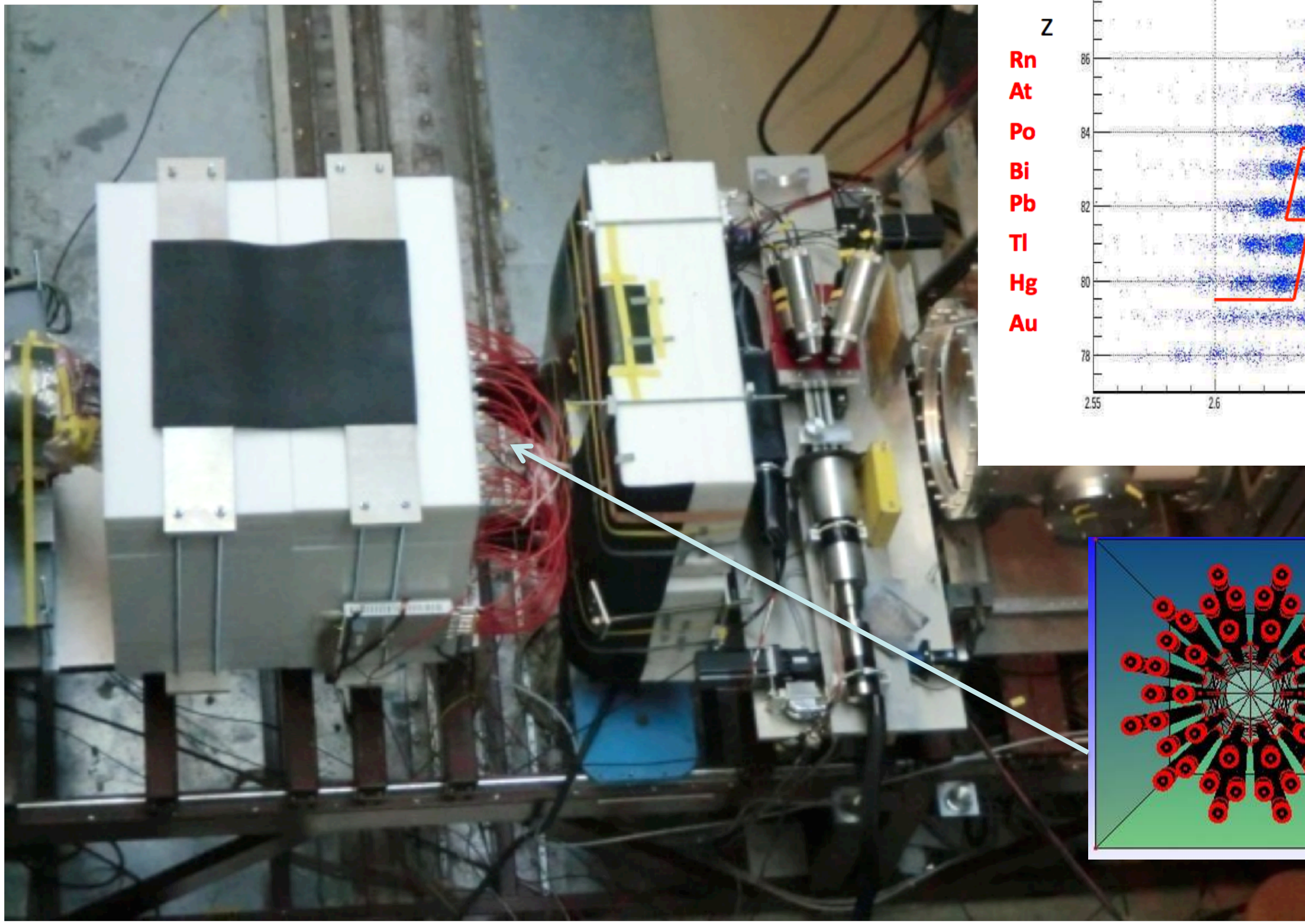
A and *Z* particle-ID after secondary target by means of

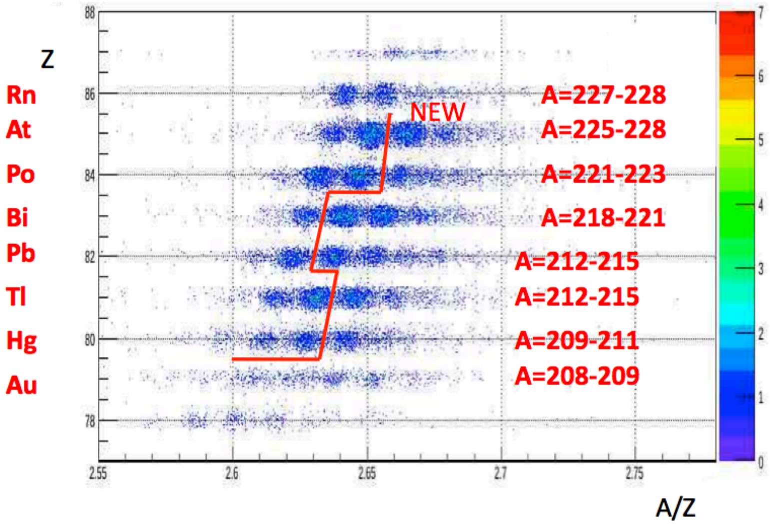
- x,y tracking
- ΔE-E (Si-CsI)
- Δt (plastic)

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.

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

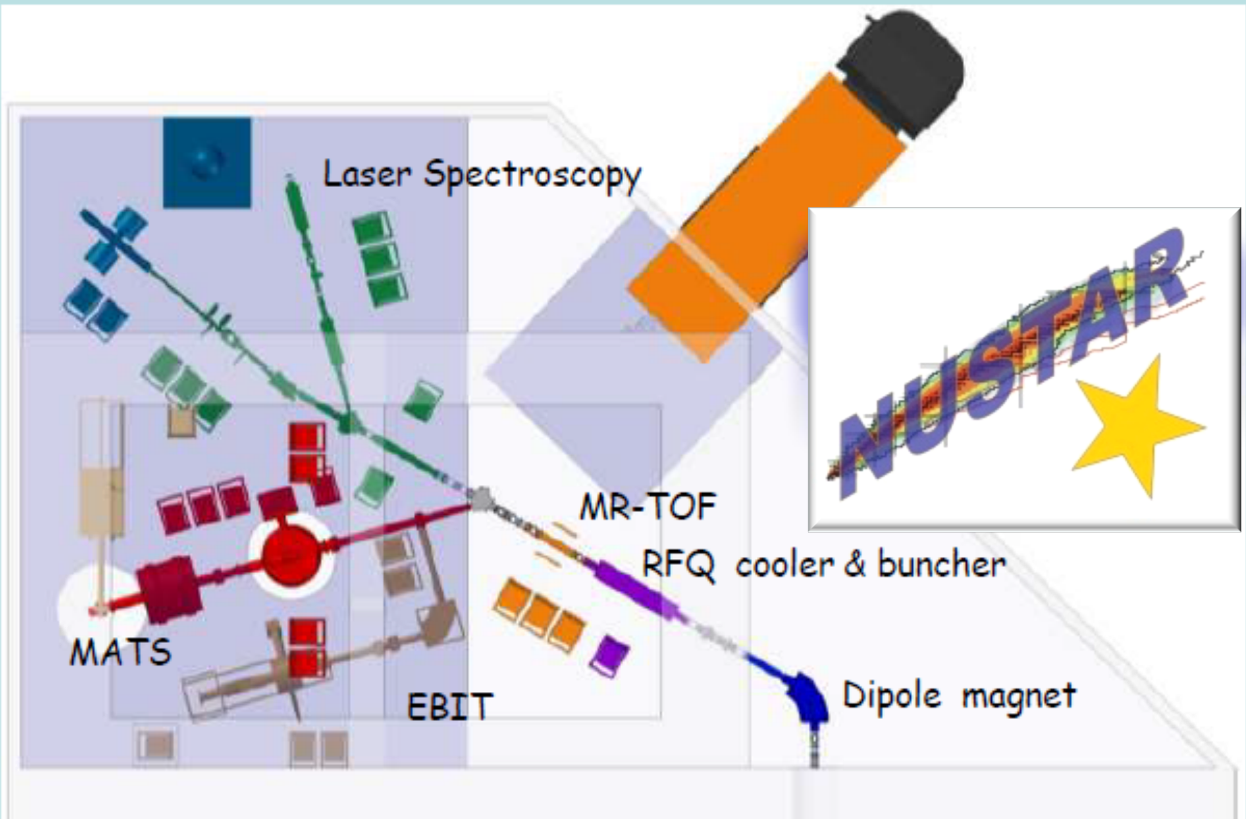
2012-2013: PreSPEC In-Beam phase 2 (= HISPEC-0)

AGATA plus LYCCA-1

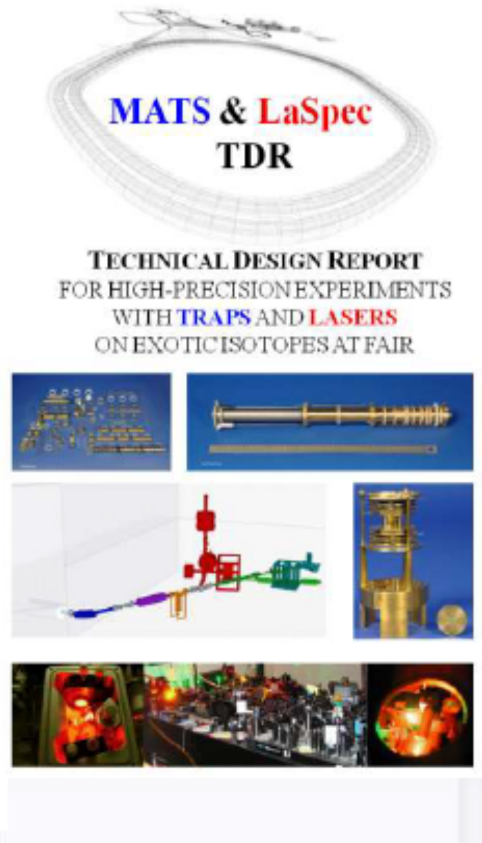
2014-2016: PreSPEC Decay (= DESPEC-0)

2018+: FAIR Facility for Antiproton and Ion Research in Europe GmbH (commissioning) experiments

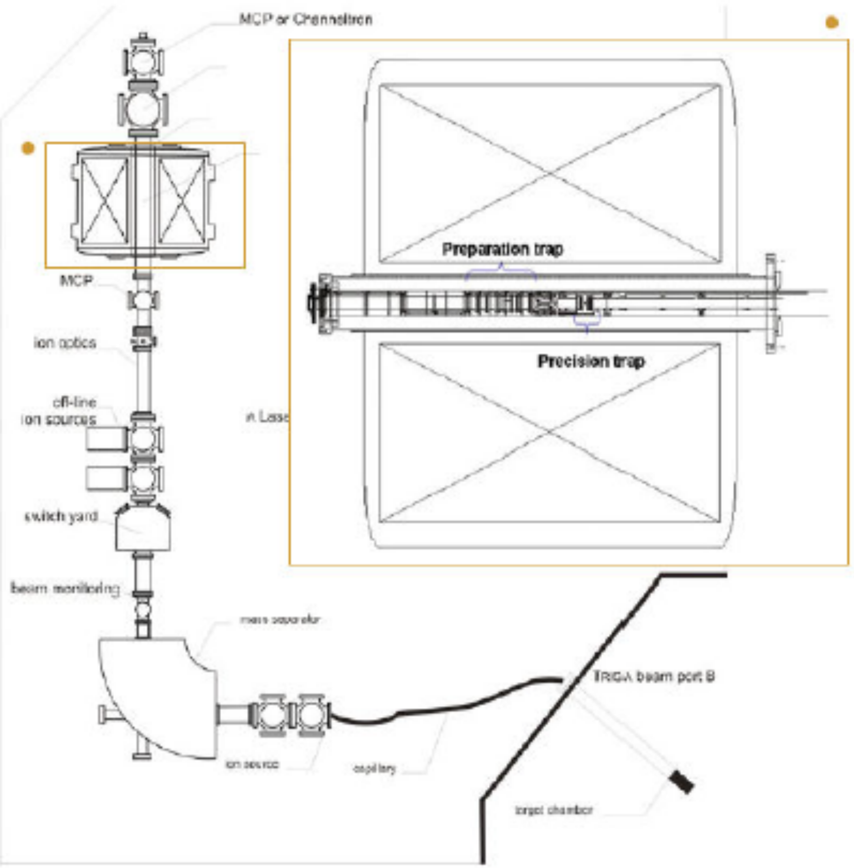
MATS/LASPEC at the LEB

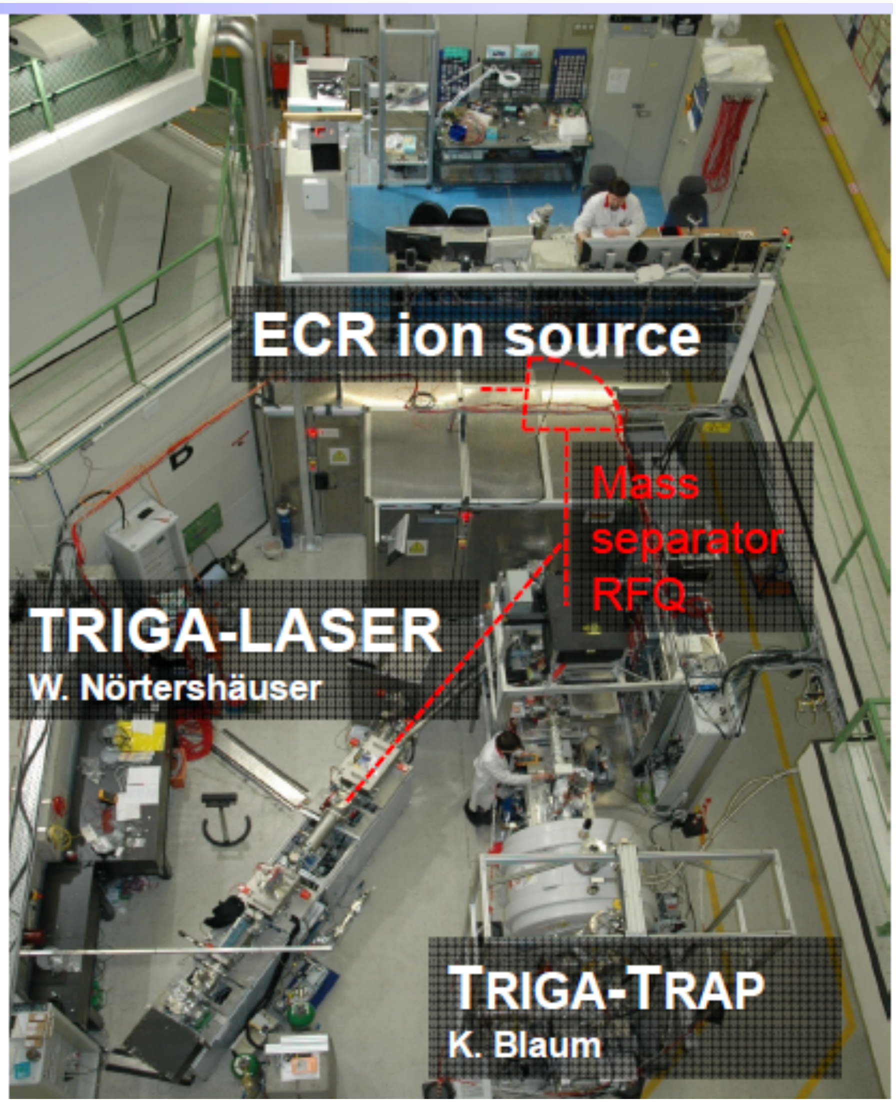


for more information see:
Technical Design Report of MATS & LaSpec:
D. Rodriguez, EPJ Special Topics 183 (2010) 1-123



TRIGAspec





Project start @ TRIGA (Mainz): 01/08

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

Start data taking: 05/09

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

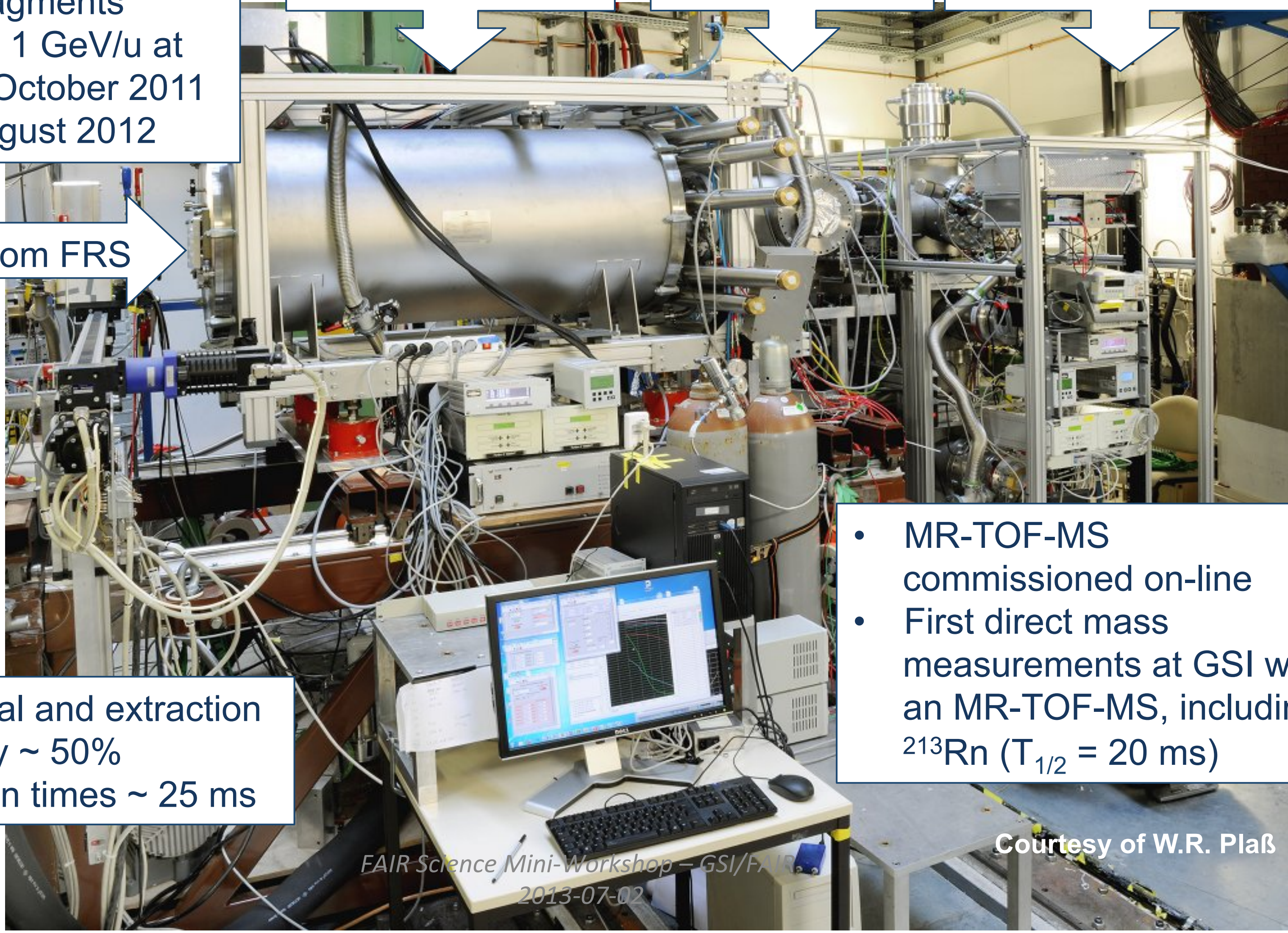
On-line test using ^{238}U projectile fragments produced at 1 GeV/u at the FRS in October 2011 and July/August 2012

Cryogenic stopping cell

Diagnostics unit

Time-of-flight mass spectrometer

Beam from FRS

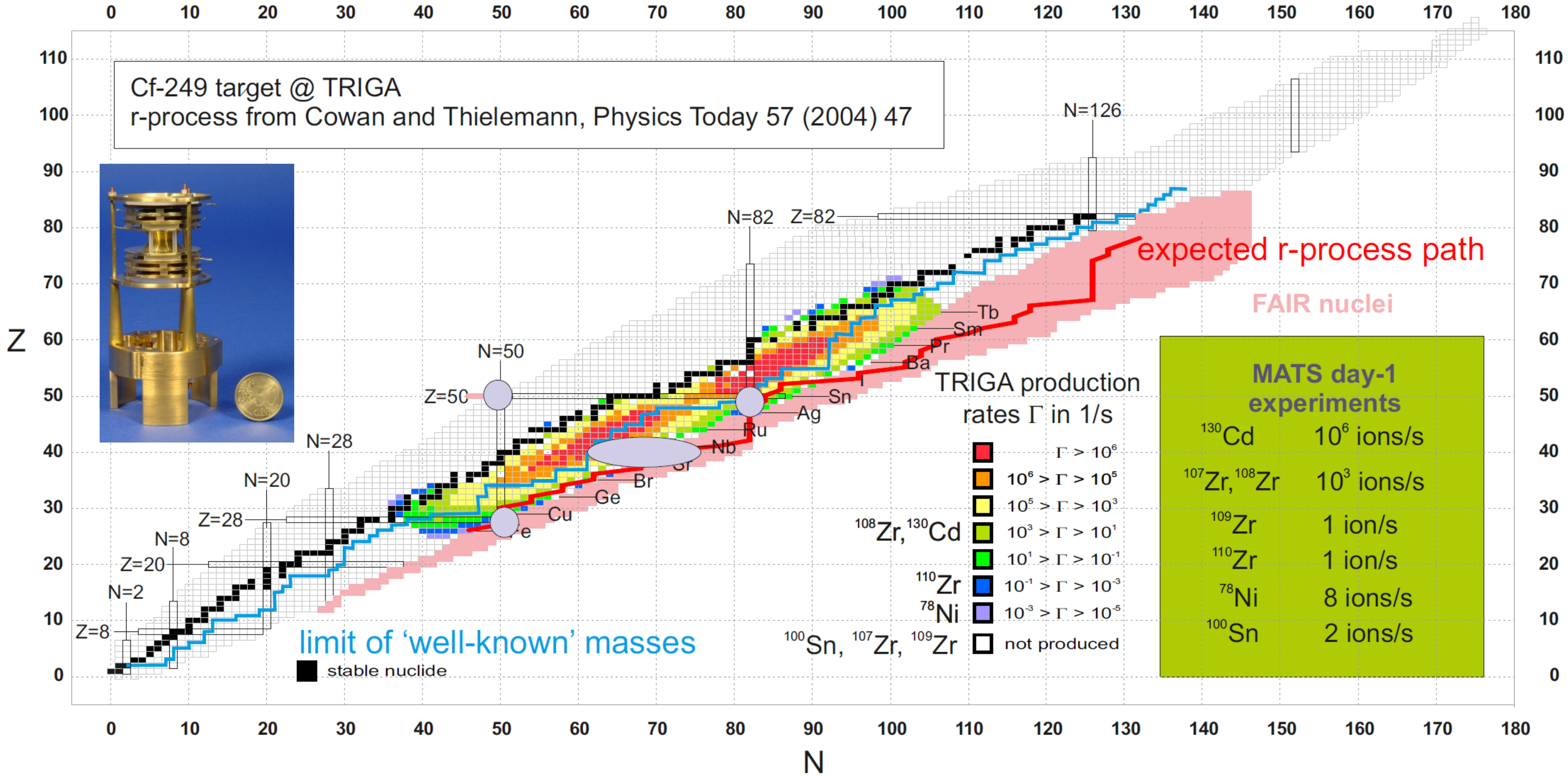


Courtesy of W.R. Plaß

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

- 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)

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

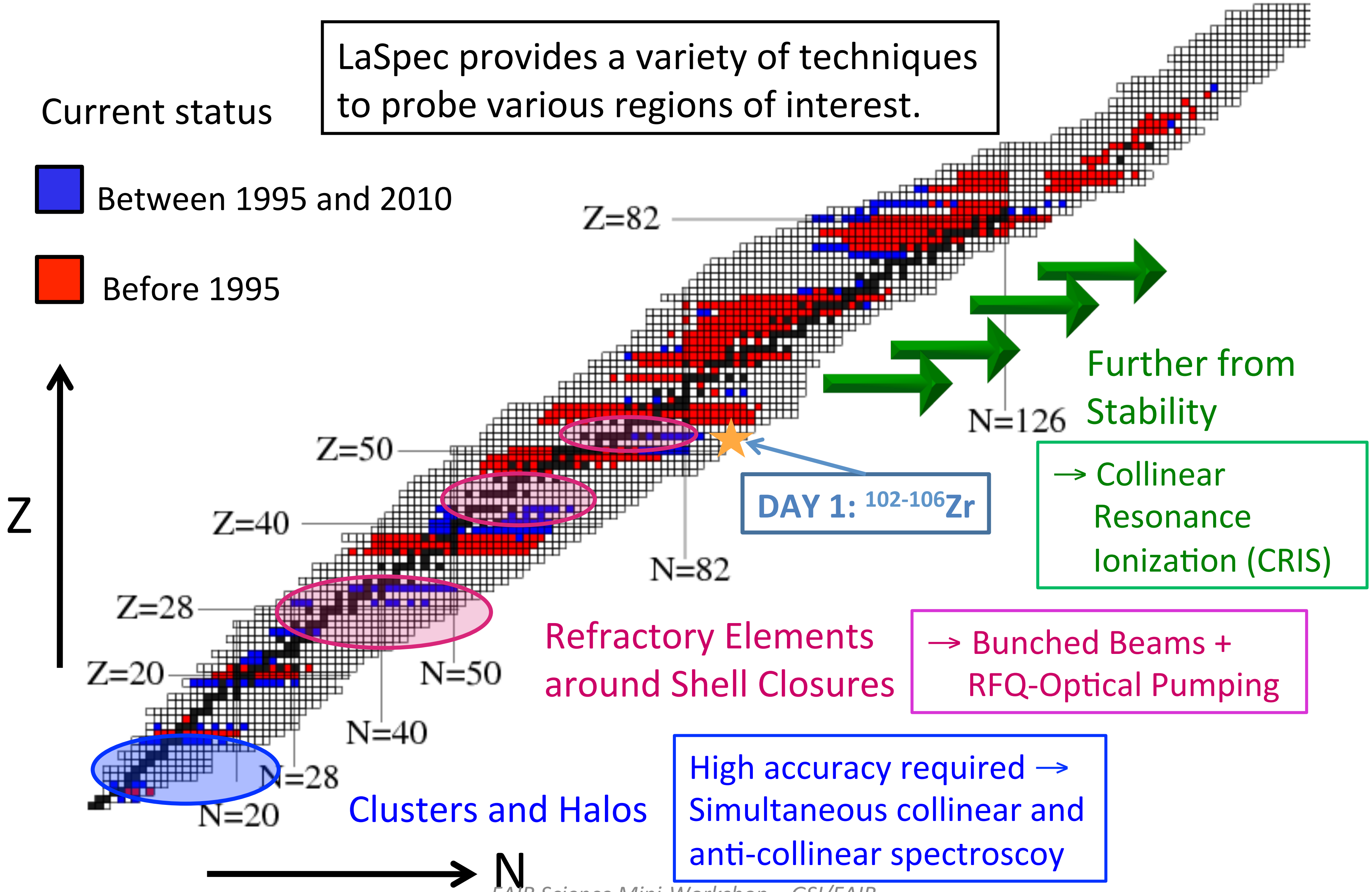
LaSpec at FAIR: future measurements

LaSpec provides a variety of techniques to probe various regions of interest.

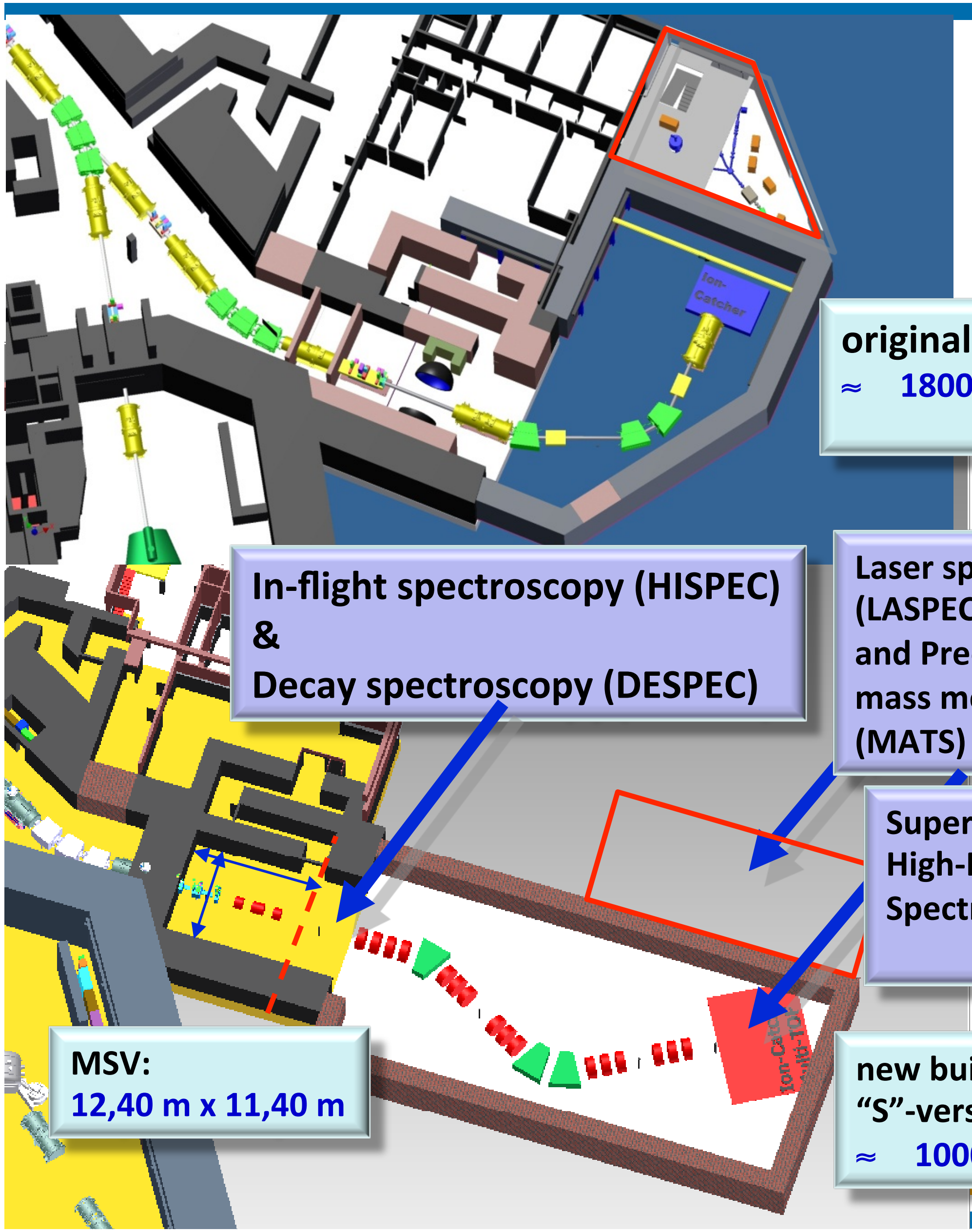
Current status

Between 1995 and 2010

Before 1995



Low Energy Branch - status and perspectives



LEB building not in MSV! (cf. SC report)

Experimental areas required/ foreseen

- HISPEC DESPEC: **$7x8\ m^2$**
- Focal plane of spectrometer: **2.8 m**
- Behind E-buncher: **$10x8\ m^2$**
- MATS and LASPEC: **$30x13\ m^2$**

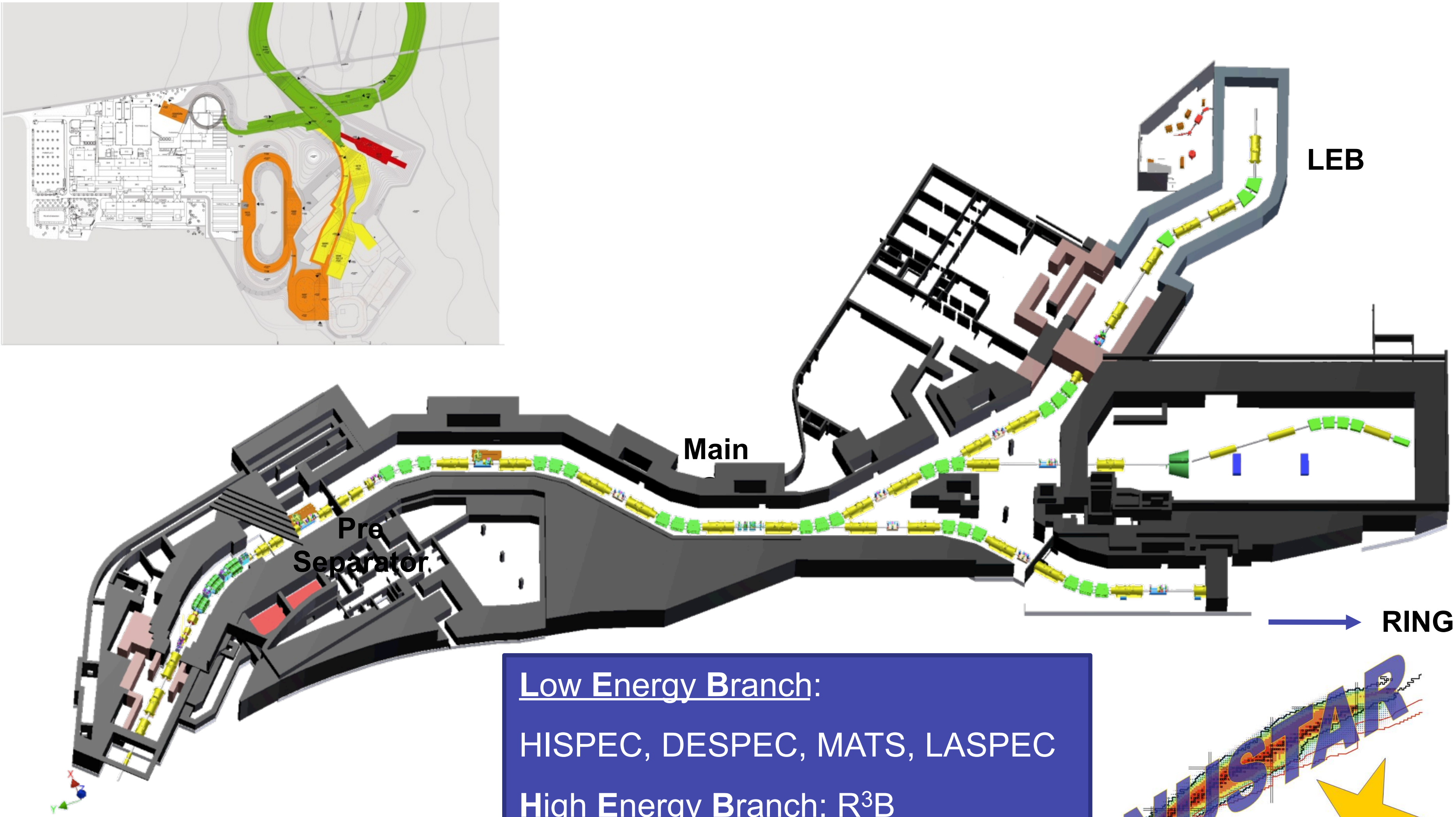
Major improvements to optimize the experimental performance

- 5 more magnets (4 Q-poles, 1 6-pole) additional cost:
  1. ∅ 600 mm → ≈ M€ 1.5 – M€ 2
  2. but ∅ 380 mm (Standard Super-FRS Multipoles → possible savings

  → transmission reduced by 1.8 for E-Buncher

LEB task force formed

NUSTAR - The Facility



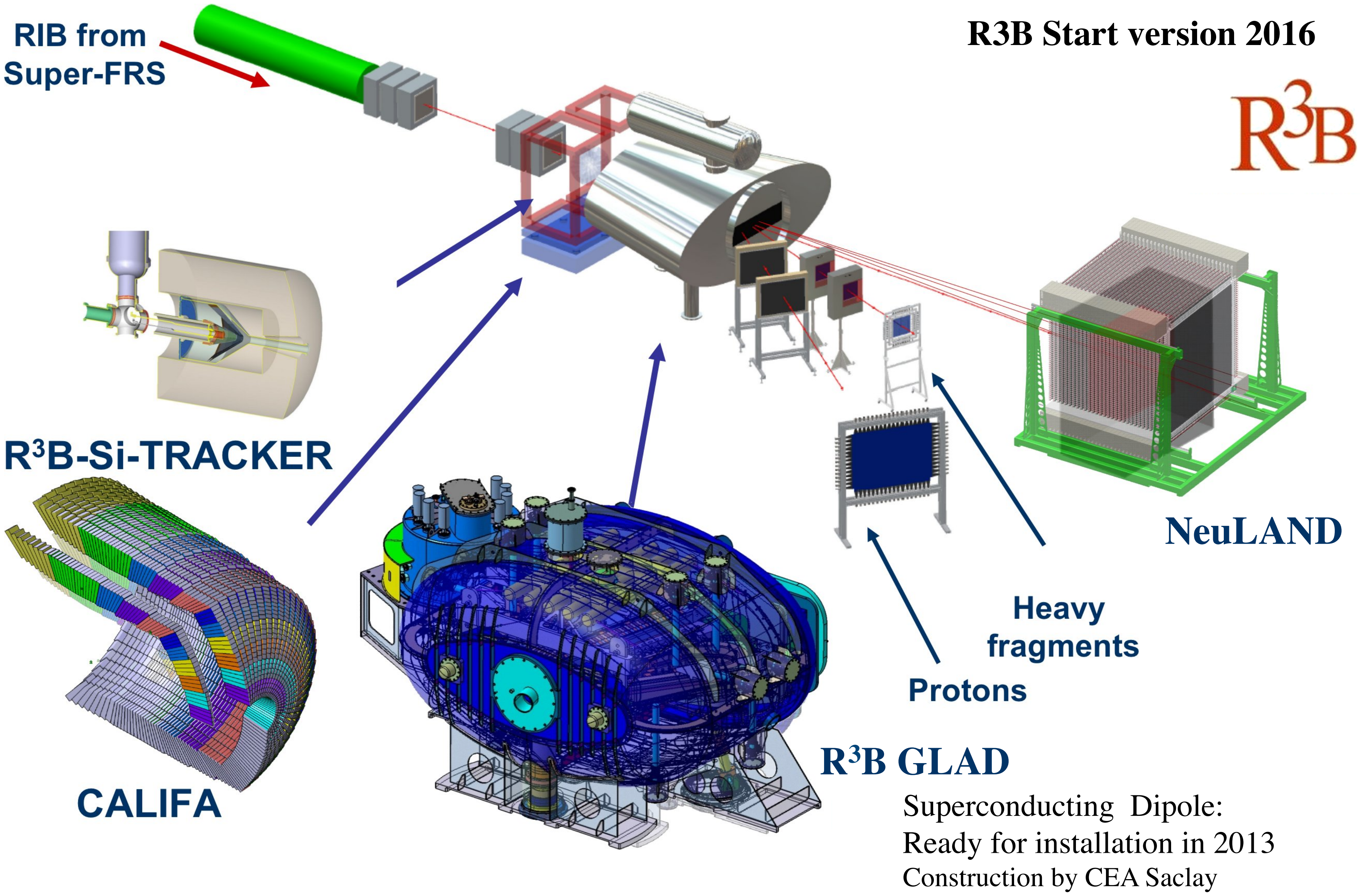
Low **E**nergy **B**ranch:

HISPEC, DESPEC, MATS, LASPEC

High **E**nergy **B**ranch: R^3B

Ring Branch: EXL, ILIMA, ELISE

Reactions with Relativistic Radioactive Beams



Status

Major achievements

Large-acceptance dipole GLAD

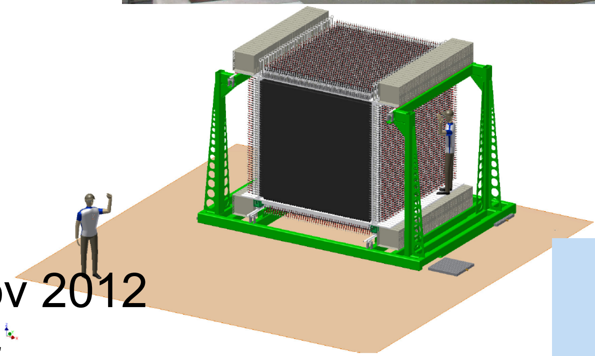
✓ Cold mass ready and inserted in test cryostat at Saclay

✓ Final cryostat in construction

✓ Delivery of magnet to GSI end of 2013

Neutron Detector NeuLAND

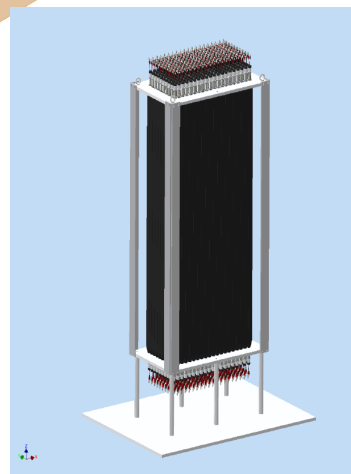
✓ Design finalized
modular active detector of 3000 scintillator bars; $250x250x300cm^3$ active volume



✓ TDR submitted to FAIR and accepted in Nov 2012

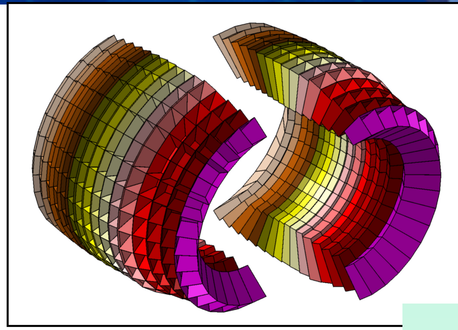
✓ Experiment with mono-energetic neutrons from deuteron breakup performed in Nov 2012:
200 modules (400 PM channels) in final design mounted and tested

✓ Construction of 20% detector for 2014 ongoing
First double-plane ready, material ordered from German contribution



Status

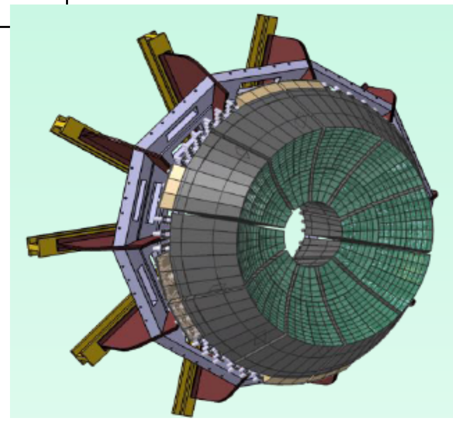
Major achievements



Photon- and particle calorimeter CALIFA

✓ Design of barrel part finalized
1952 CsI crystals with APD readout

✓ TDR submitted to FAIR and accepted in Nov 2012



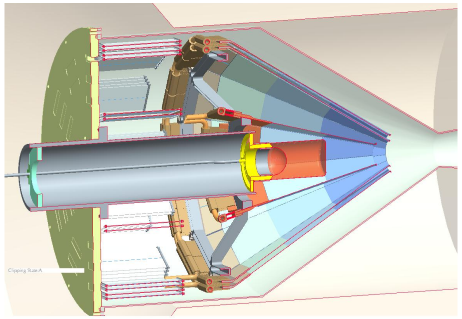
✓ R&D on forward end-cup ongoing
phoswich concept of $LaBr_3$-$LaCl_3$ crystals

Target Recoil Tracking Detector

✓ Design finalized

✓ Construction started

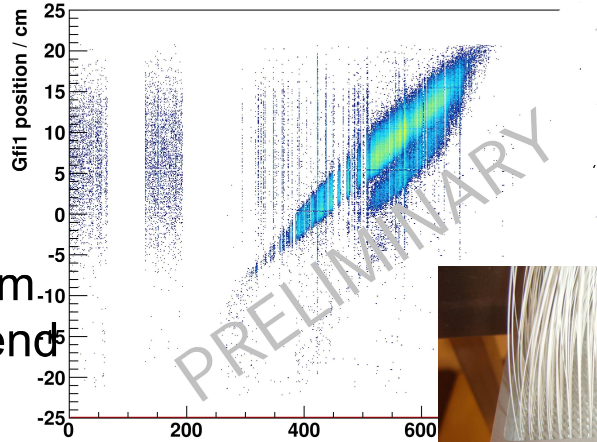
✓ Project fully funded and
lead by UK consortium

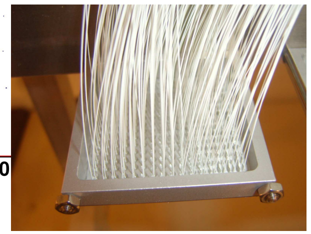


Tracking Detectors

Thin large-area fiber detector: Prototype with 0.25 mm pitch, readout by PSPM and NXCYTER based frontend

✓ Successful test with Sn beam in 2012





Schedule and first experiments

2012 Test of NeuLAND modules with mono-energetic neutrons

2013 Installation of infrastructure in Cave C for GLAD (He cryo-system, power supply)
Delivery and installation of superconducting dipole GLAD (expected Q4/2012)

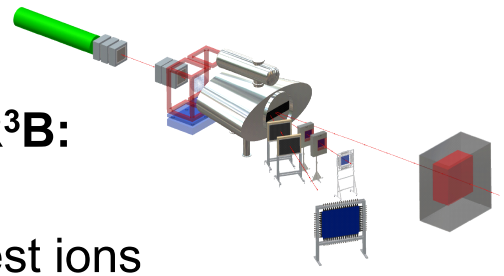
2014 Installation of 20% detectors NeuLAND and CALIFA
Commissioning and physics run expected in Q3/2014

2015 Construction and installation of detector components

2016 Commissioning of full R3B setup and first physics run at GSI

2017 Installation of experimental setup at FAIR site including superconducting triplet

2018 Commissioning and first experiments at Super FRS



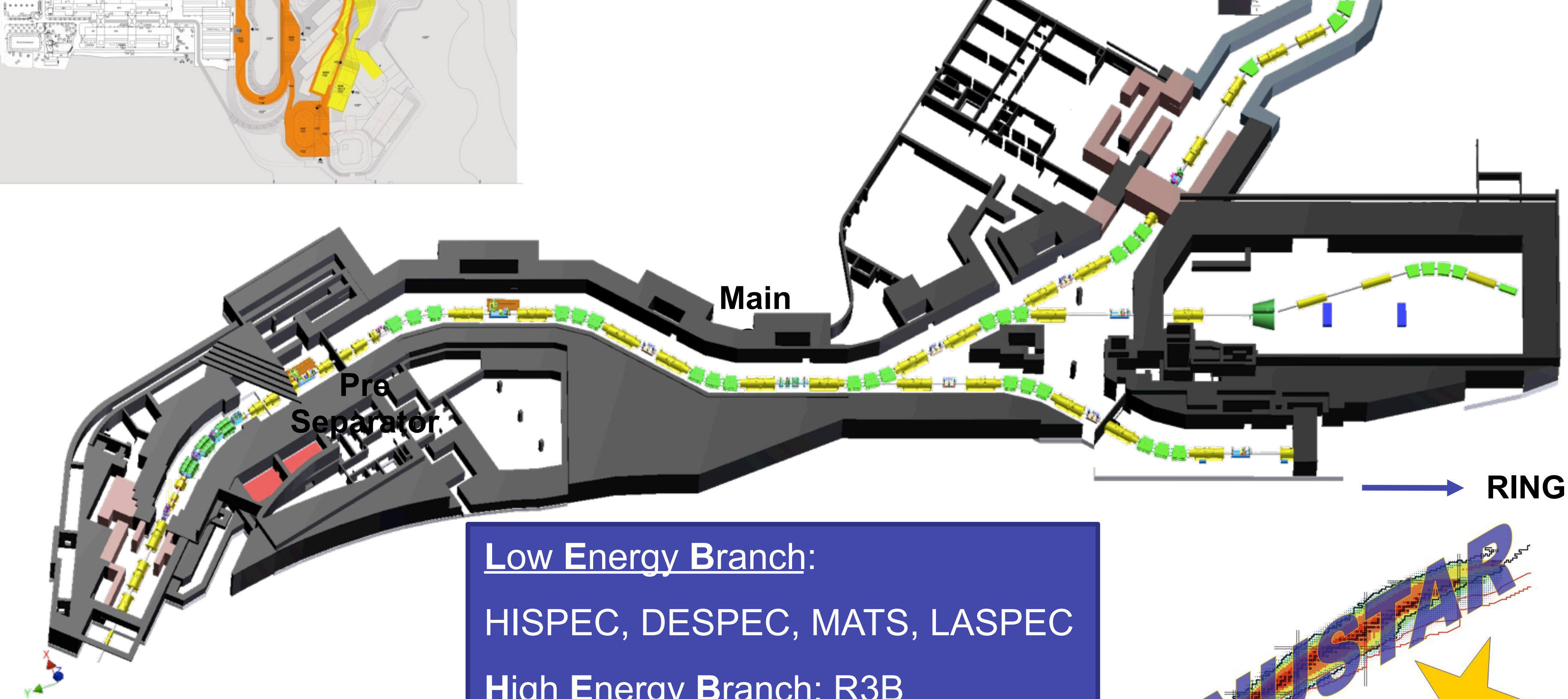
Experiments in 2018 will make use of uniqueness of R^3B:

- 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, and of neutron-rich Pb isotopes

NUSTAR - The Facility



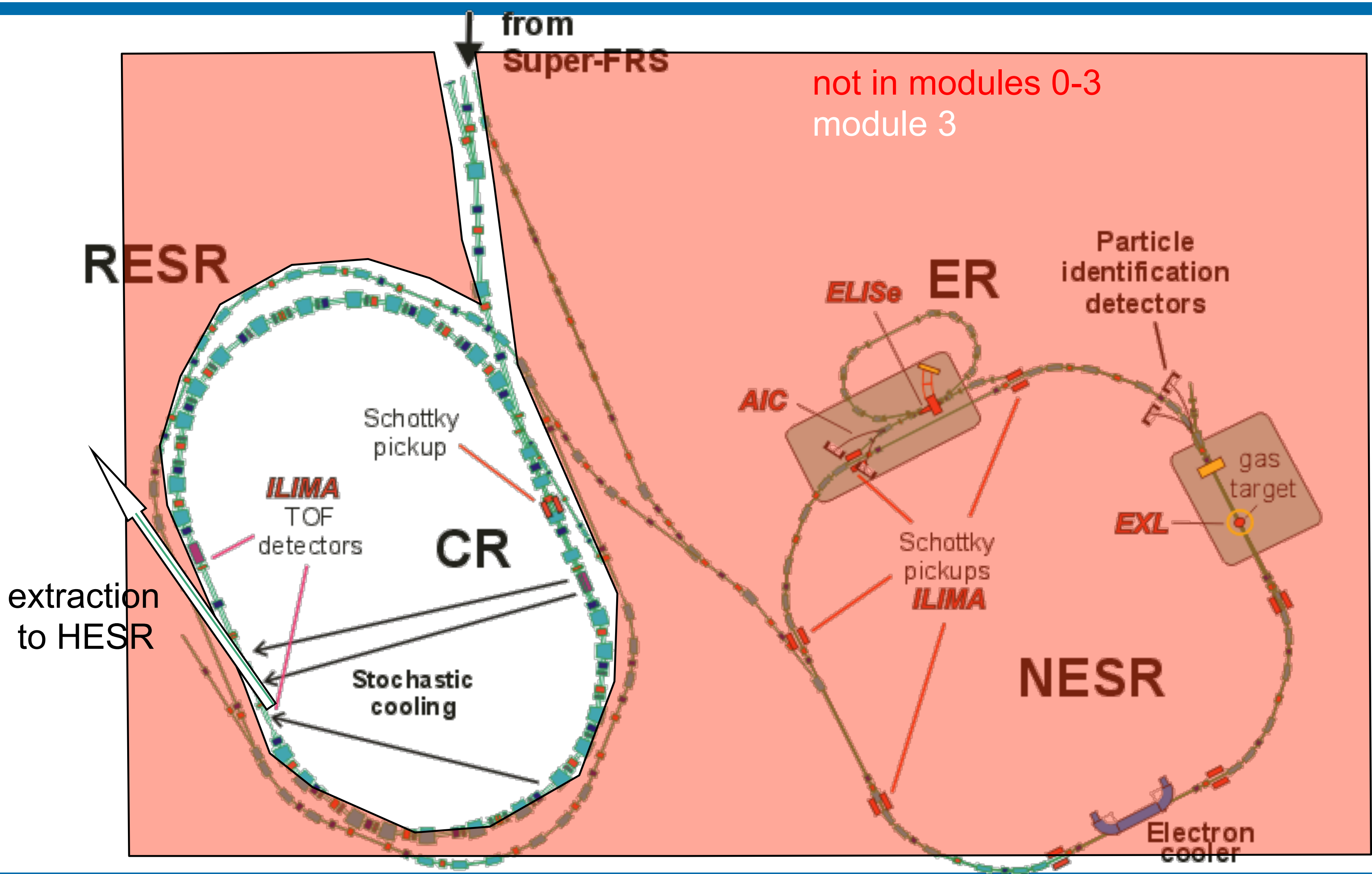
Low Energy Branch:

HISPEC, DESPEC, MATS, LASPEC

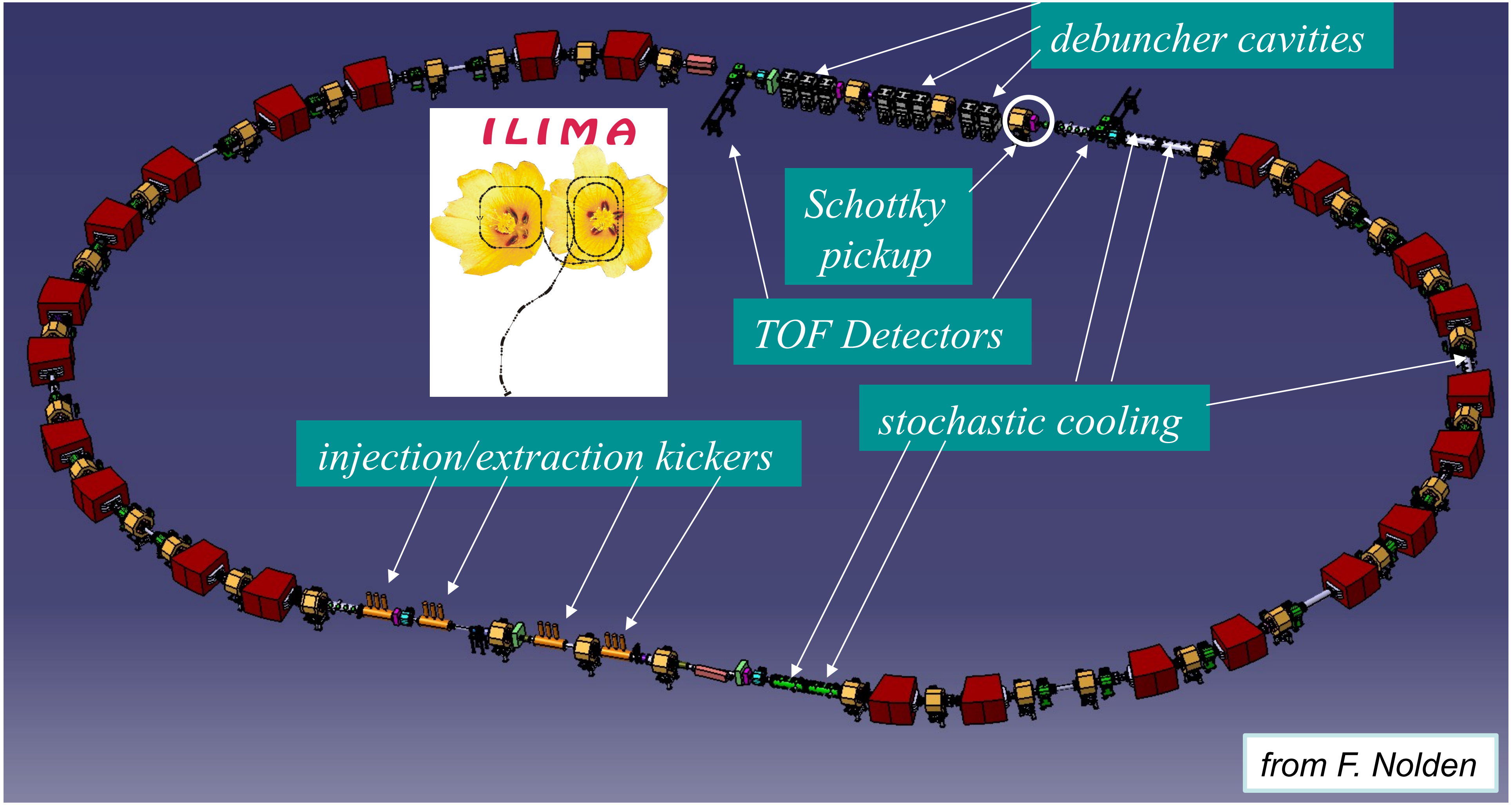
High Energy Branch: R3B

Ring Branch: EXL, ILIMA, ELISE

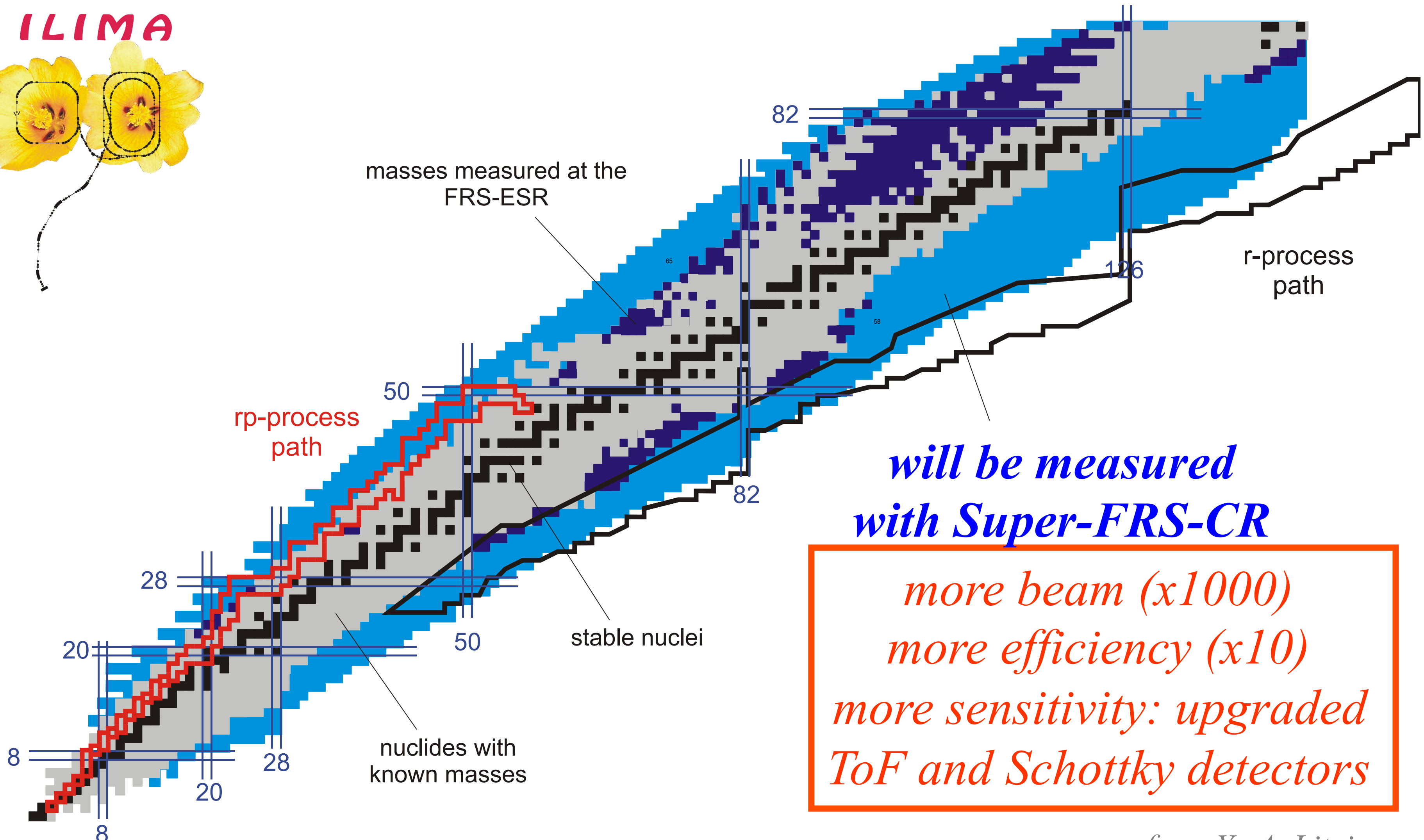
CR, RESR, NESR Storage Rings



CR perspective view



Potential for new masses with ILIMA

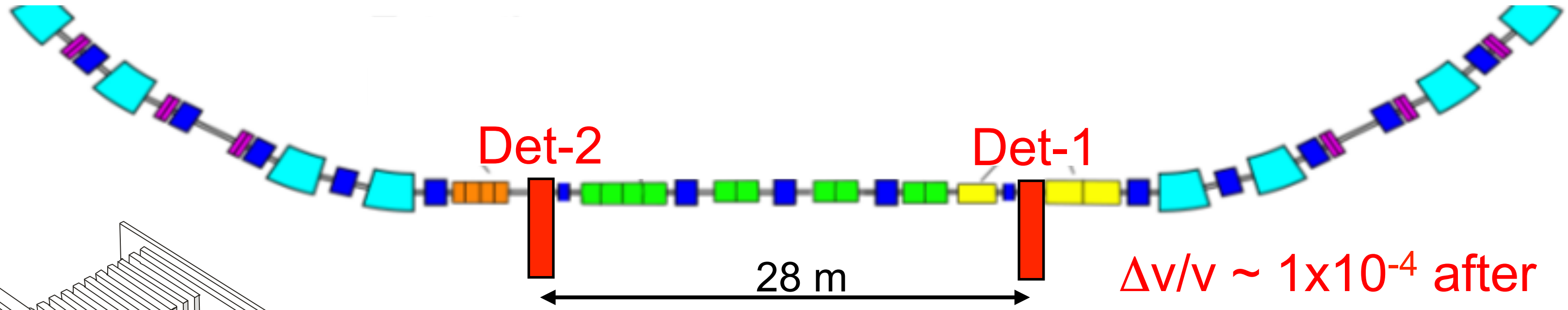


more beam (x1000)
more efficiency (x10)
more sensitivity: upgraded ToF and Schottky detectors

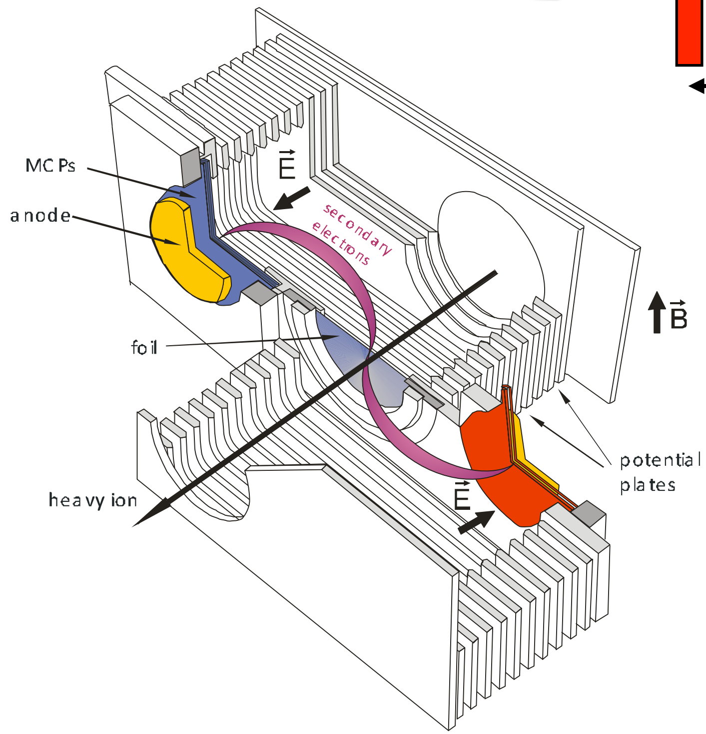
from Yu.A. Litvinov

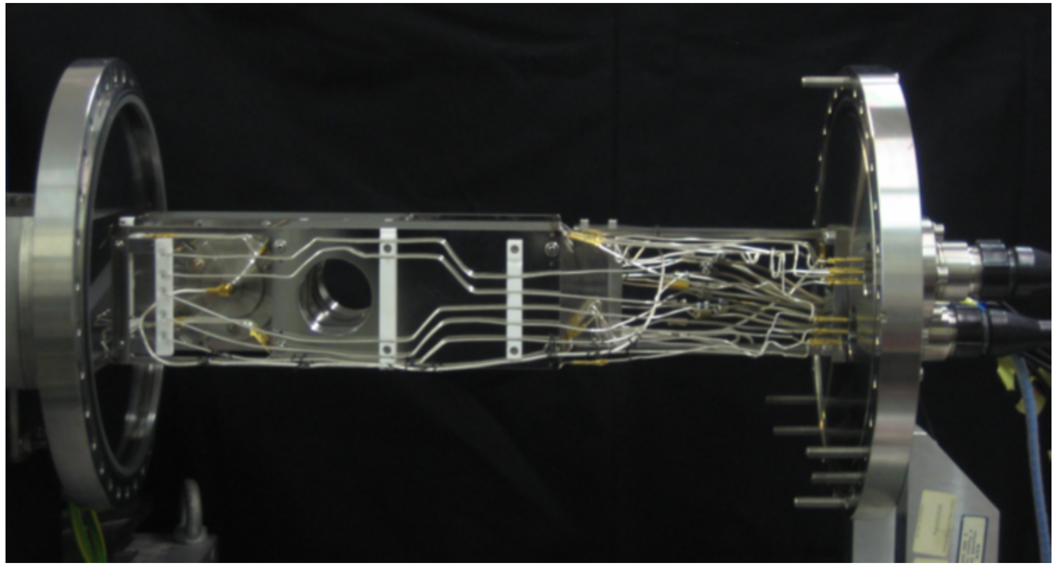
ToF Detection

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



Δv/v ~ 1x10^{-4} after averaging many turns

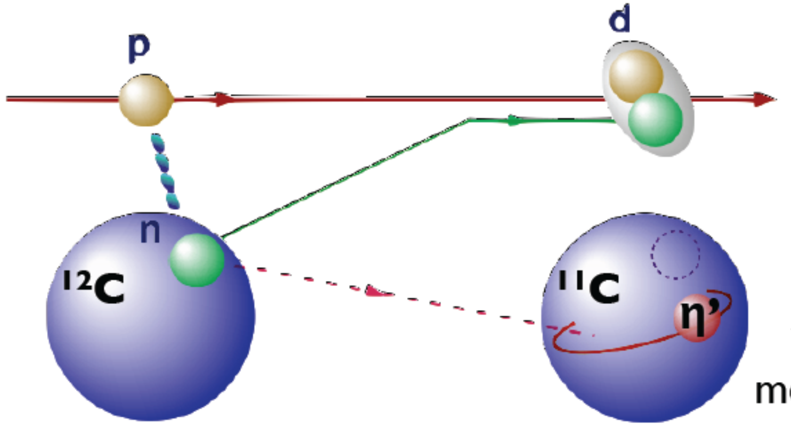




Super-FRS as a high-resolution spectrometer

Example: Chiral symmetry studied using (p,dp) reactions

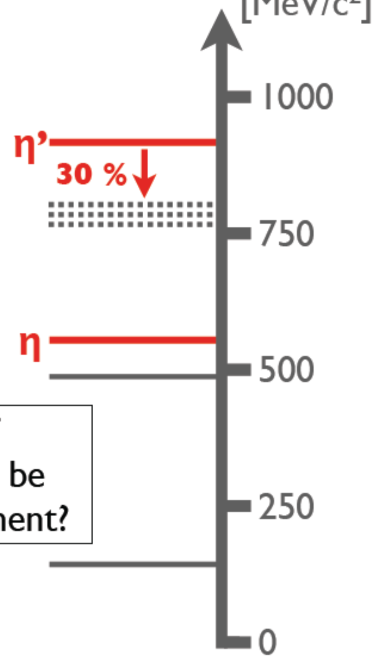
η' transfer reaction + Missing mass measurement

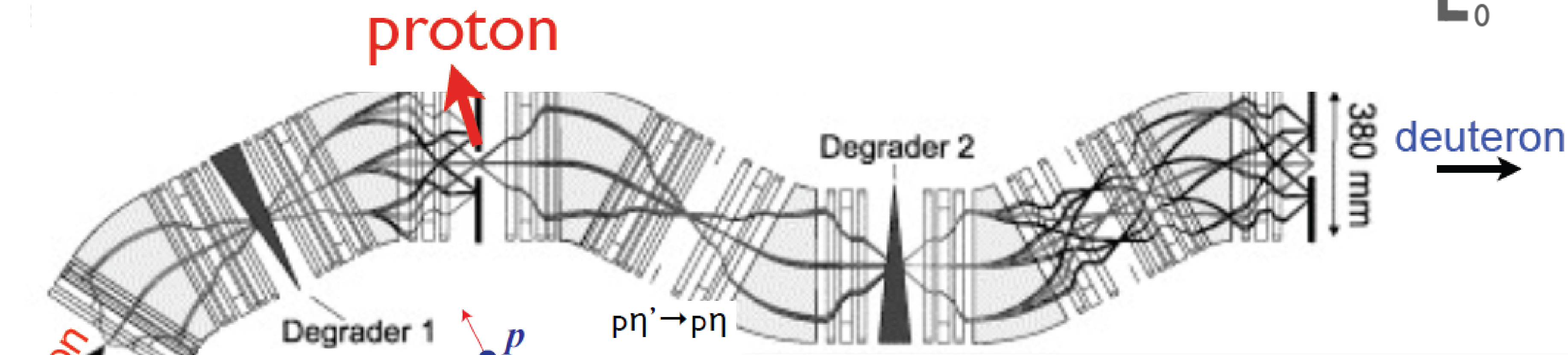


η' × ^{11}C mesic nuclei

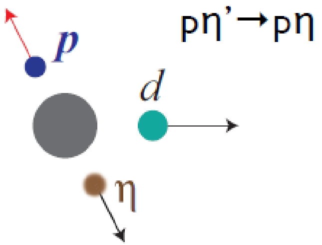
An estimation shows 30% reduction of $|m_{\eta'} - m_\eta|$

Q. Mass shift of ~ 150 MeV/c² can be observed in experiment?





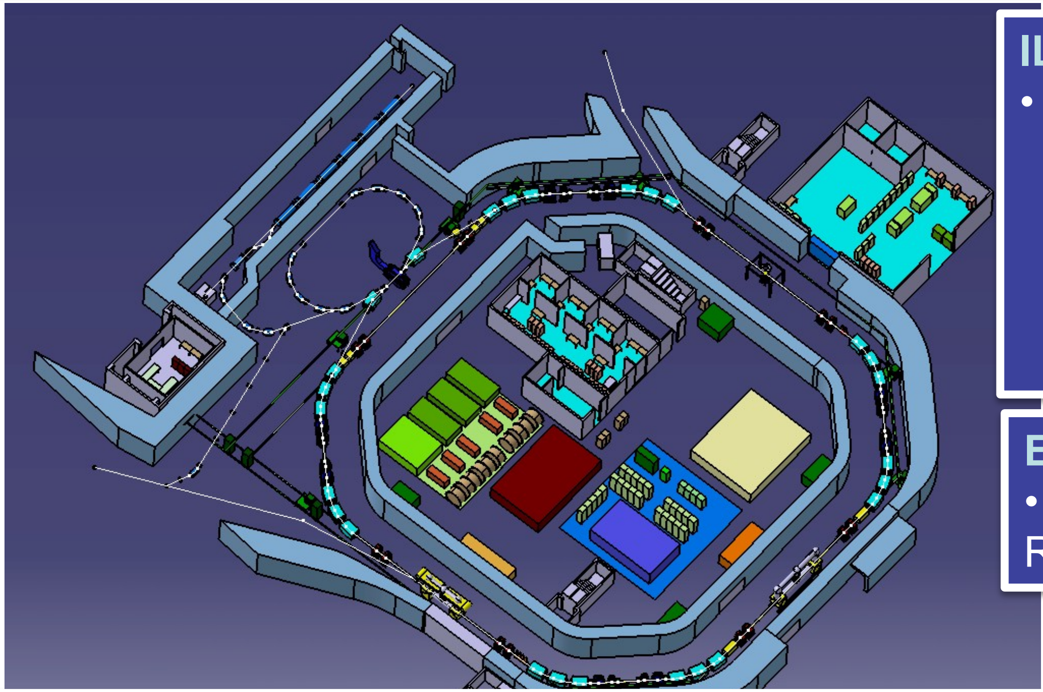
Exclusive measurement



Super-FRS physics collaboration currently being formed

Beyond MSV: NUSTAR programme at the NESR

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



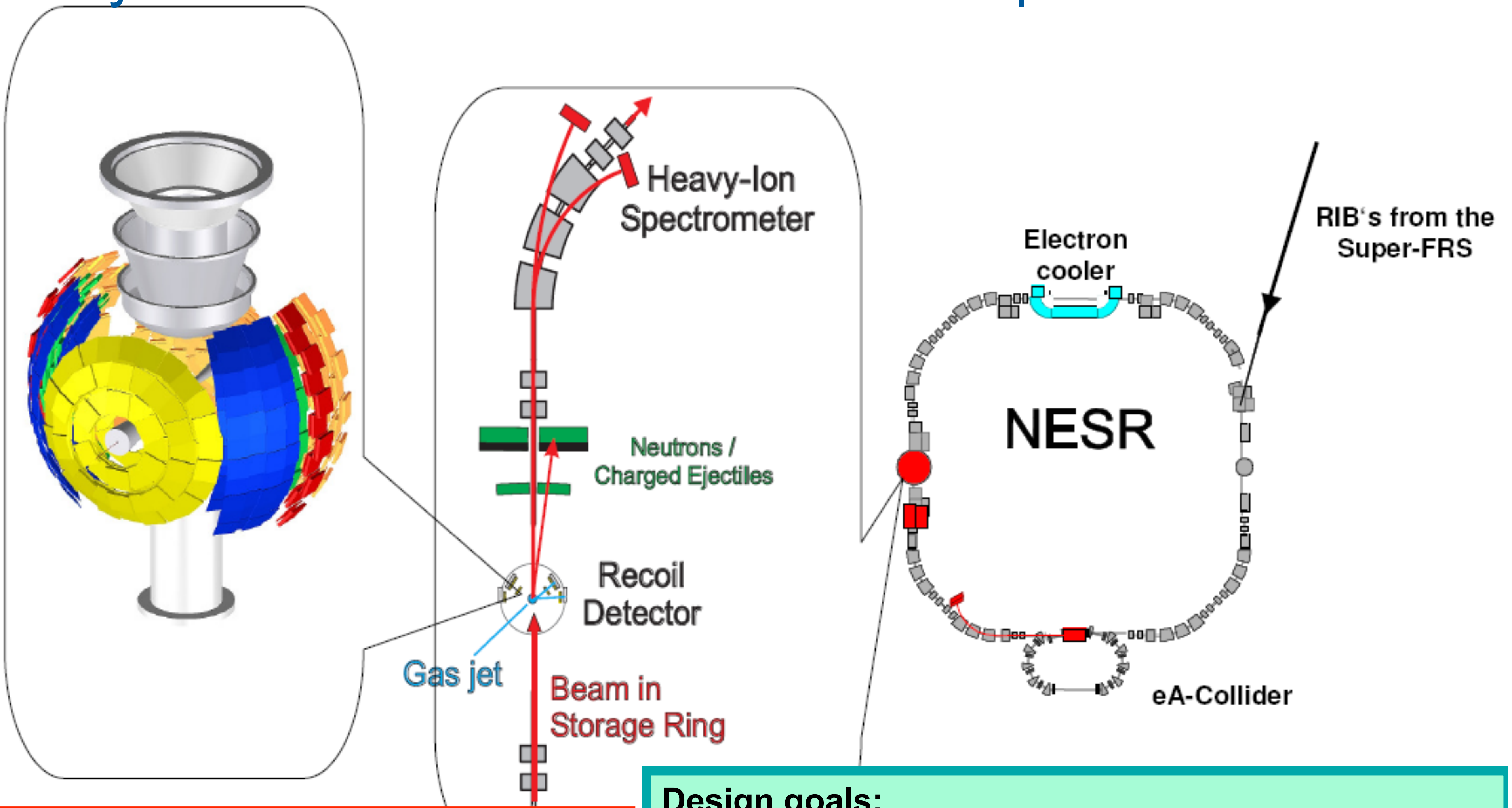
ILIMA
- electron cooled beams needed for
  - higher precision and separation (ground and isomeric states)
  - time-resolved studies (unique decay modes, e.g. bound beta decay)
  - studies with pure isomeric beams

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)

Beyond MSV: Details of the EXL setup

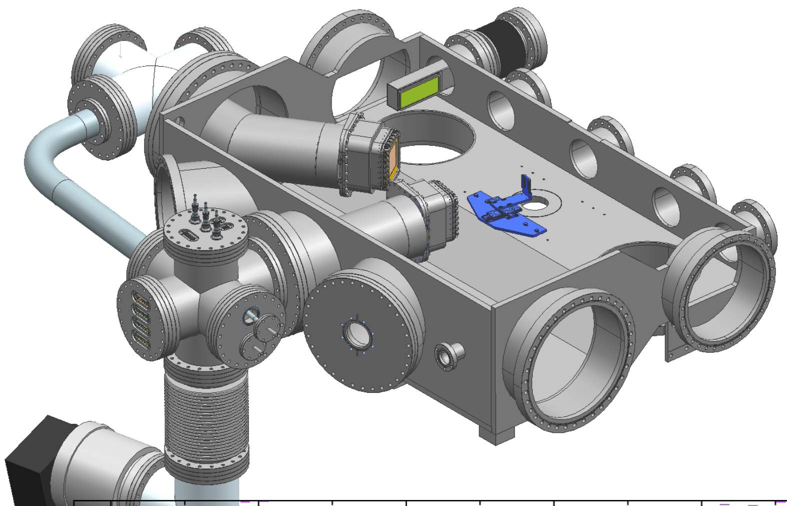


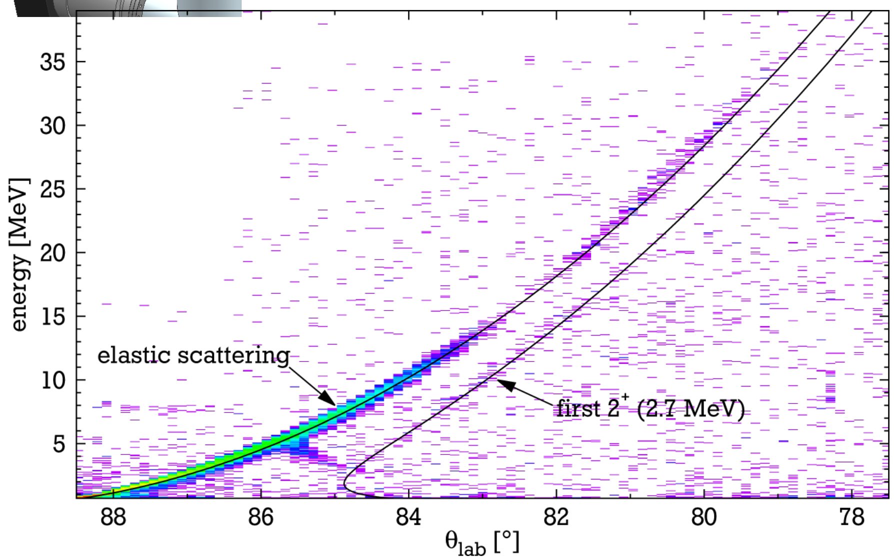
Detection systems for:
- Target recoils and gammas (p,α,n,γ)
- Forward ejectiles (p,n)
- Beam-like heavy ions

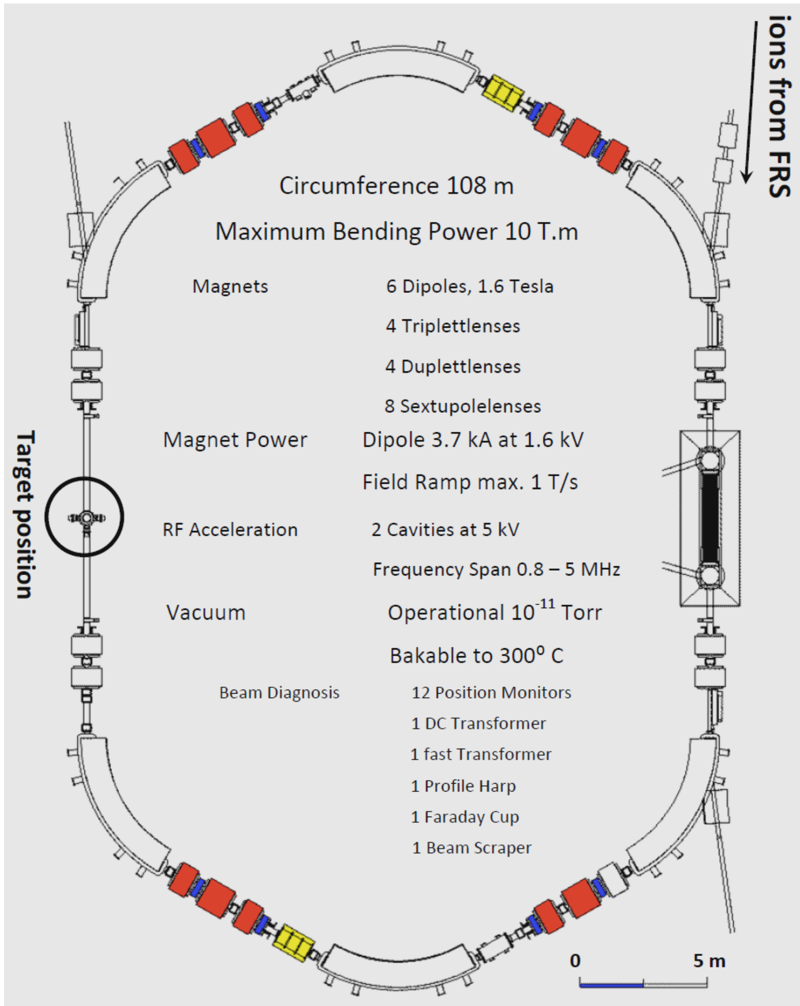
Design goals:
- Universality: applicable to a wide class of reactions
- Good energy and angular resolution
- Large solid angle acceptance
- Specially dedicated for low q measurements with high luminosity (> 10^{28} cm^{-2} s^{-1})

Intermediate storage ring activities@ESR/"Green Paper"

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

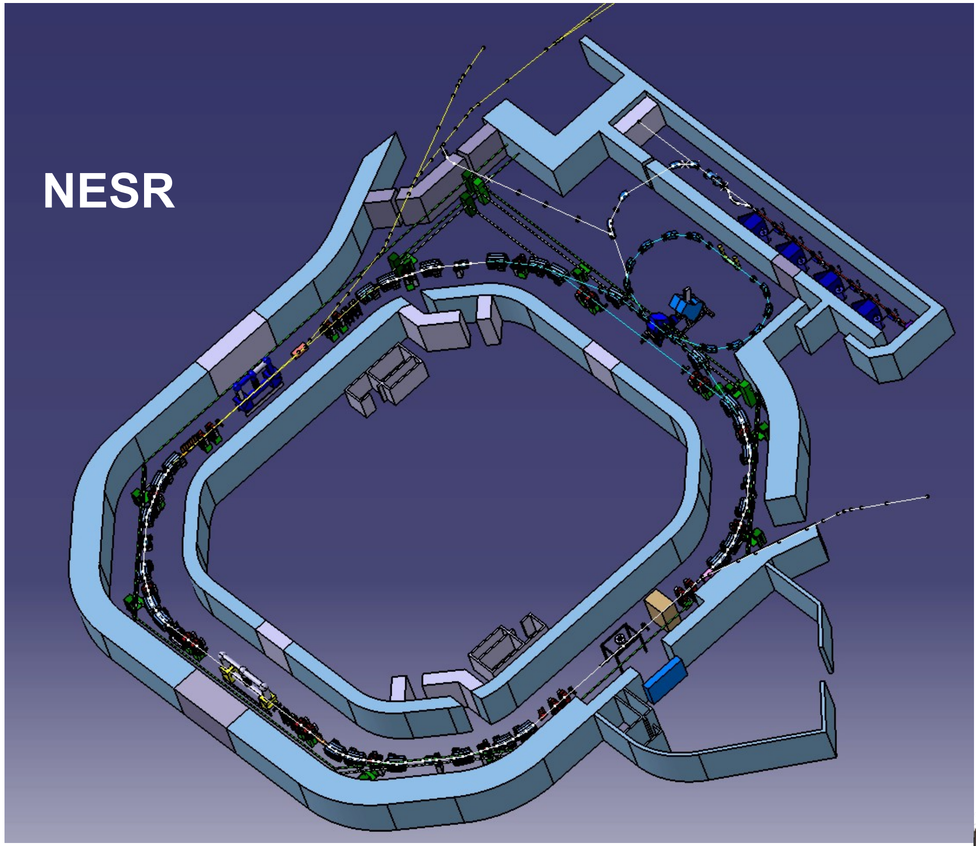






Beyond MSV: **ELISe and AIC**

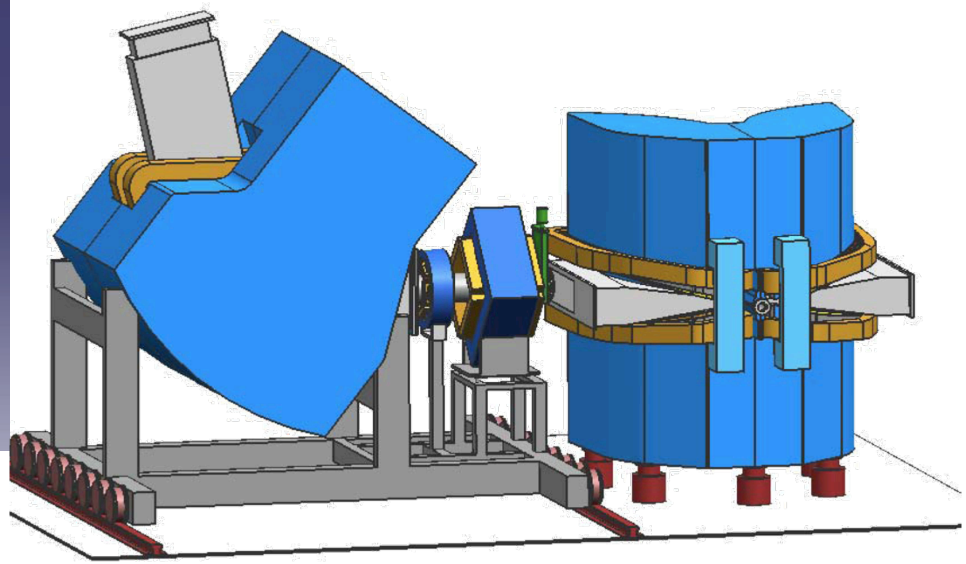
Haik Simon • GSI / Darmstadt



- 125-500 MeV electrons
- 200-740 MeV/u RIBs

➔ up to 1.5 GeV CM energy

- spectrometer setup at the interaction zone & detector system in ring arcs



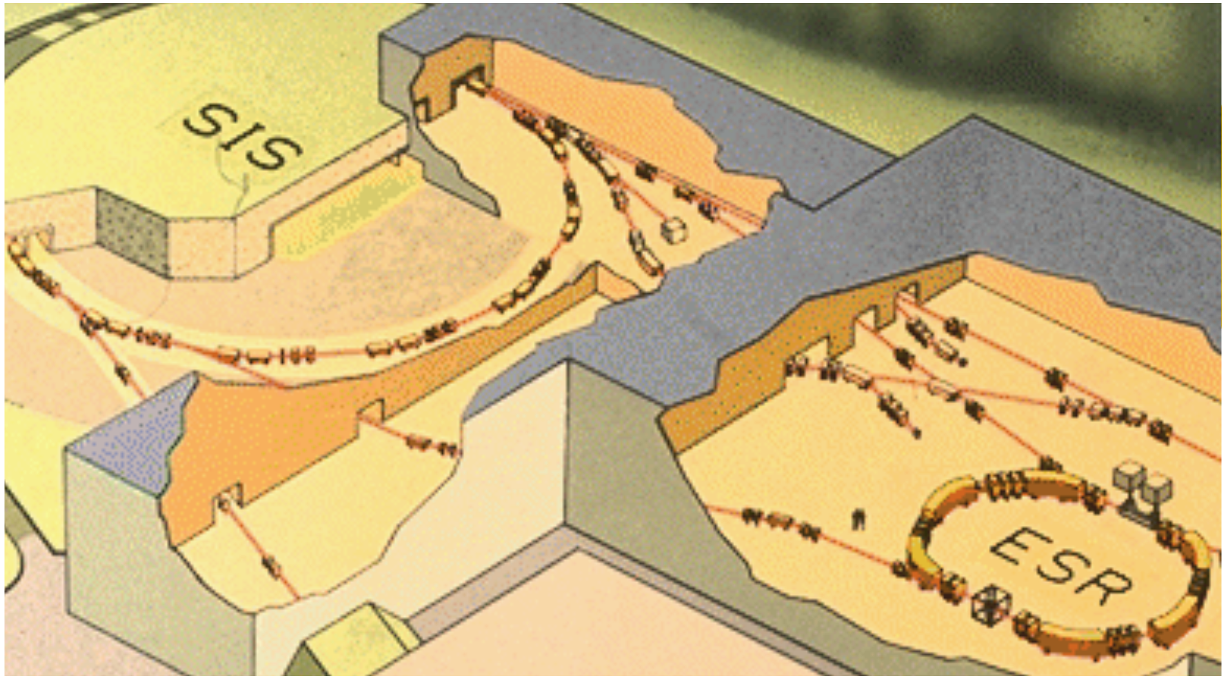
AIC option:

- 30 MeV antiprotons

- detector system in ring arcs
- Schottky probes

A.N. Antonov et al, NIMA 637(2011)60-76
ELISe conceptual design study

Cryring at the ESR



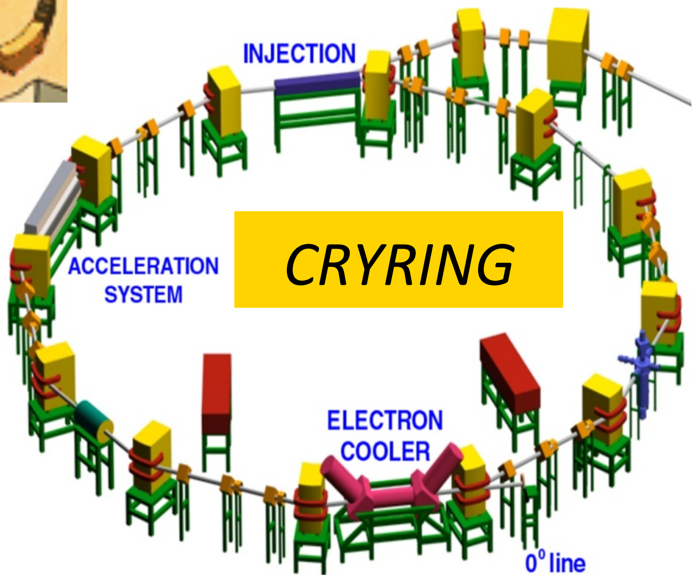
ESR:
Circumference
108 m

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



Uniqueness of NUSTAR@FAIR

Synchrotron-based RIB production for:

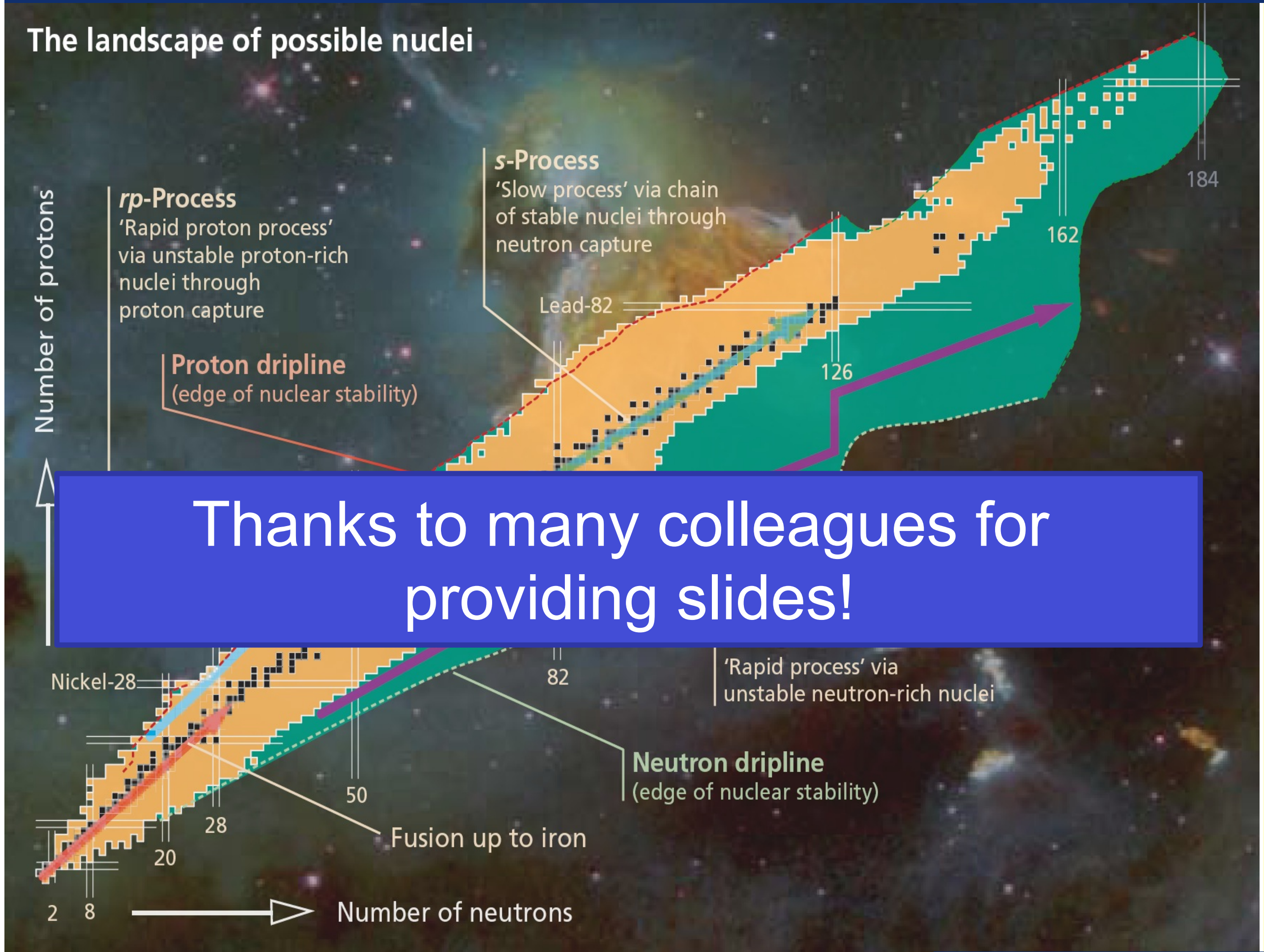
- High-energy Radioactive Beams (≤1.5 GeV/u)
  - Efficient production, separation, transmission and detection aided by Lorentz boost
  - Access to also the heaviest nuclei without charge-state ambiguities
  - Large range of attainable reaction mechanisms
- Storage rings
  - Mass measurements and beam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

Combined with:

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

Status

The NUSTAR Project aims to study exotic nuclei...



Thanks to many colleagues for providing slides!

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