Future projects in nuclear physics

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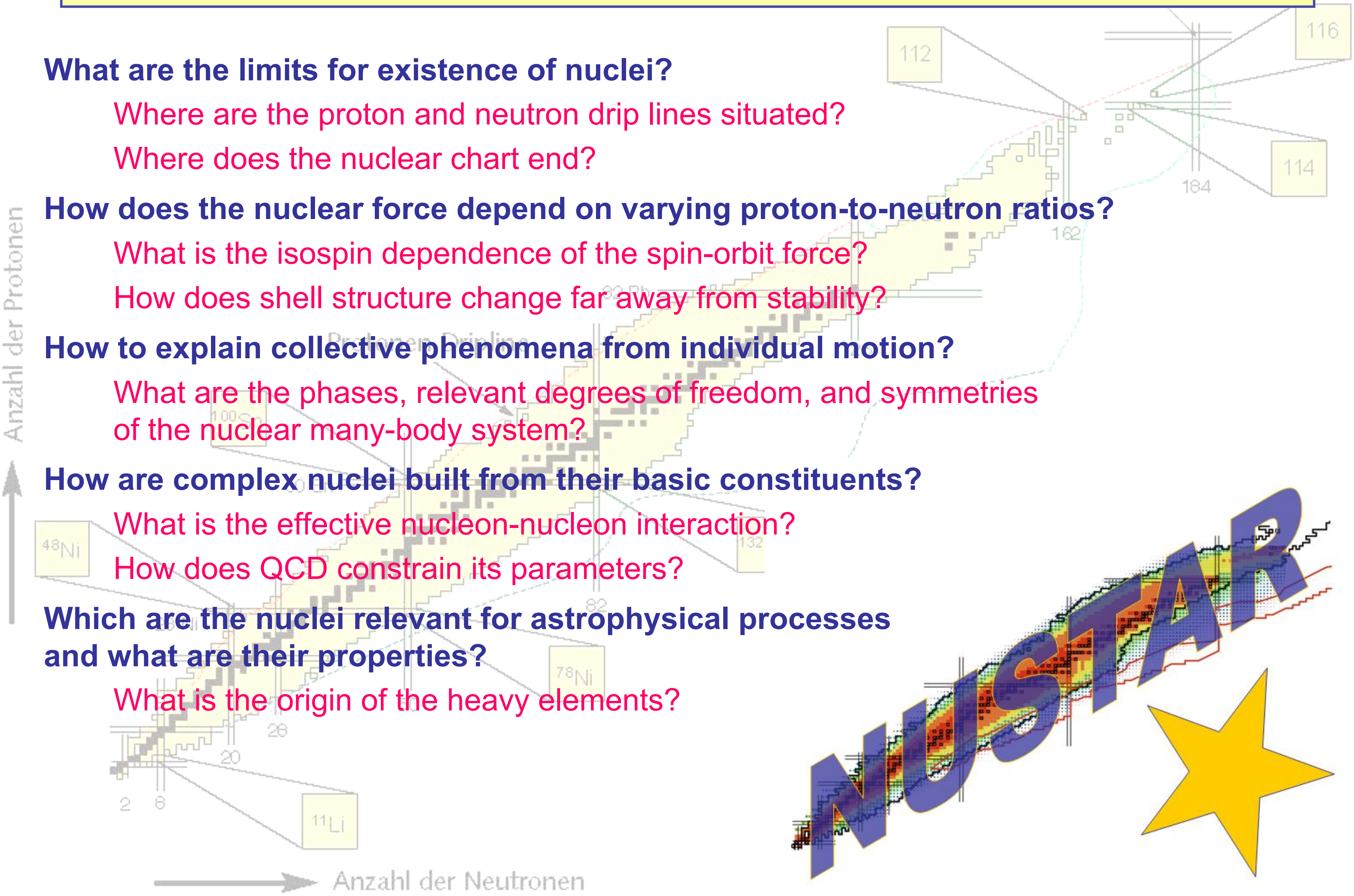
The Future of Non-Collider Physics
HIM, Mainz, Germany
April 2017

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?

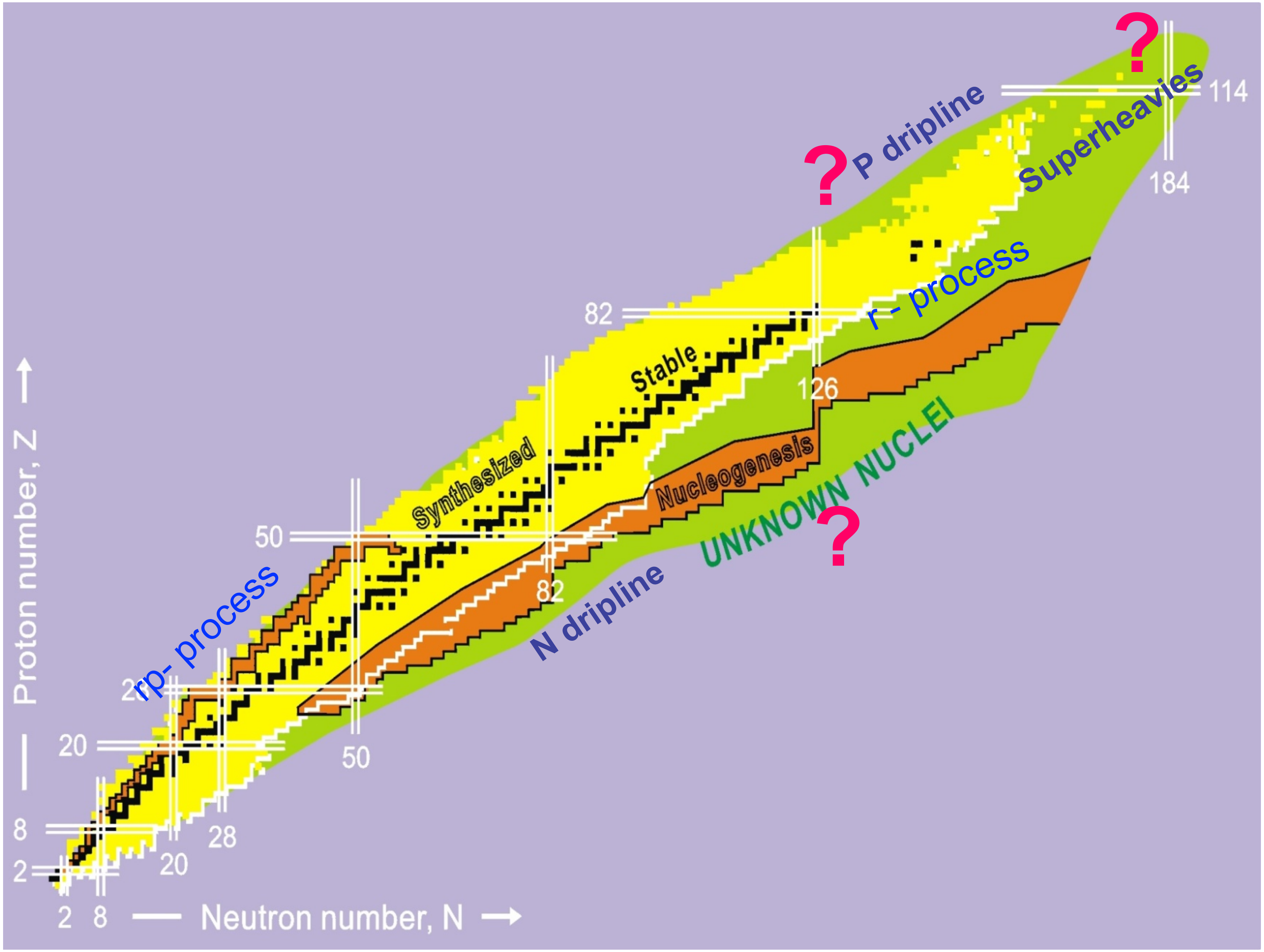
What is the effective nucleon-nucleon interaction?

How does QCD constrain its parameters?

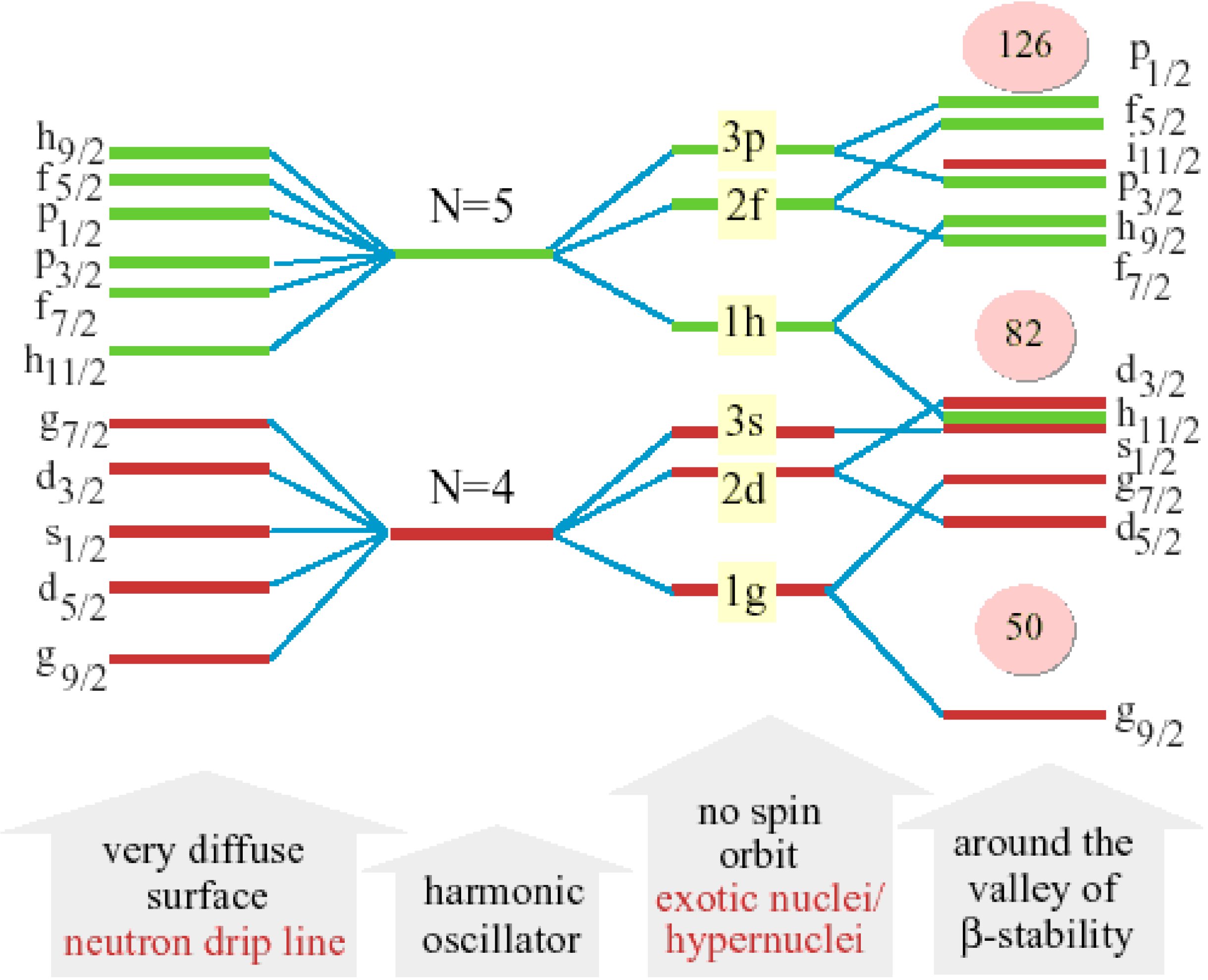
Which are the nuclei relevant for astrophysical processes and what are their properties?

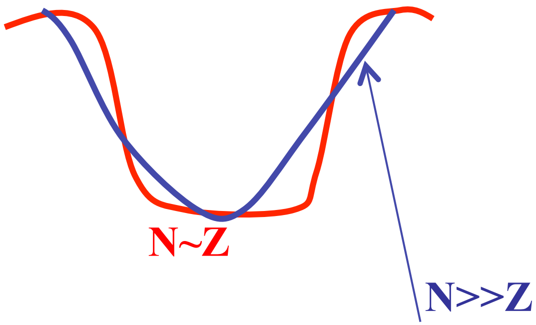
What is the origin of the heavy elements?

What are the limits of existence of atomic nuclei?



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



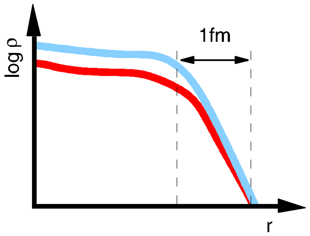


Softening of the nuclear potential:
High-l pushed upward and Spin-Orbit splitting reduced

Shell quenching and reordering:
Transition from SO gaps (50,82,126) to HO gaps (40,70,112)

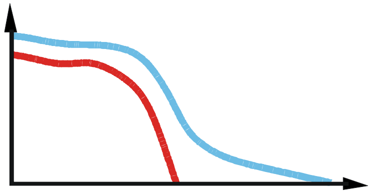
How to explain collective phenomena from individual motion?

stable



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

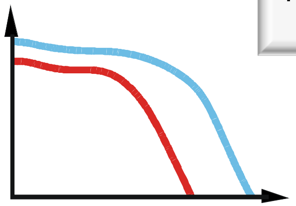
$d_p = d_n = \text{const} \approx 1\text{fm}$



halo

$r_p \neq r_n$

$d_p \neq d_n$



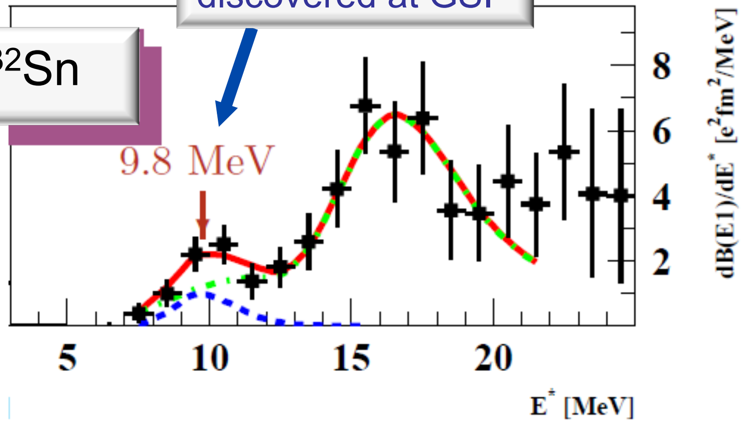
skin

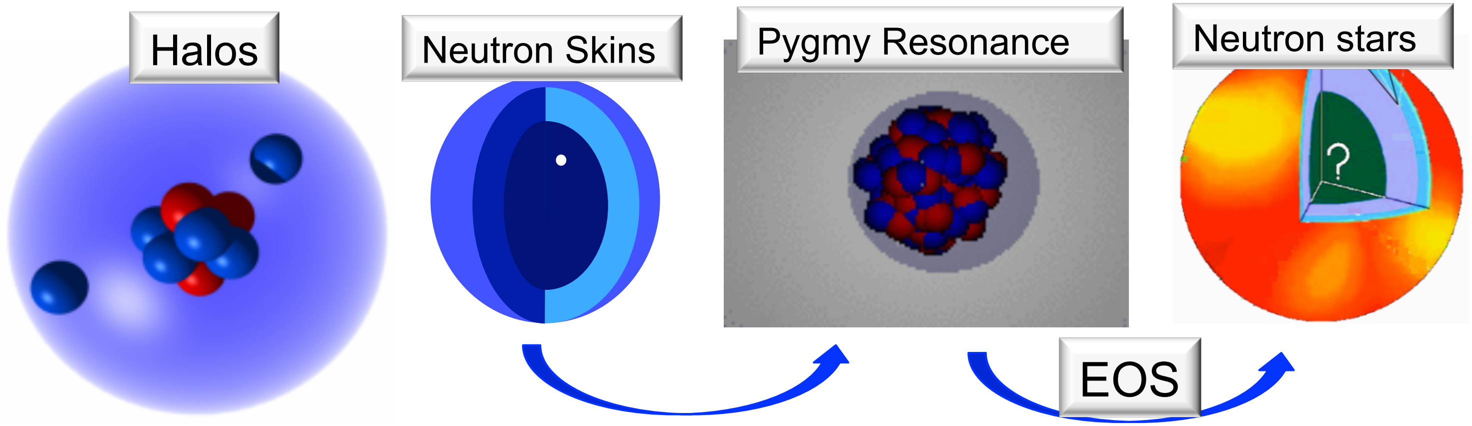
$r_p \neq r_n$

$d_p = d_n$

^{132}Sn

Soft mode discovered at GSI





Halos

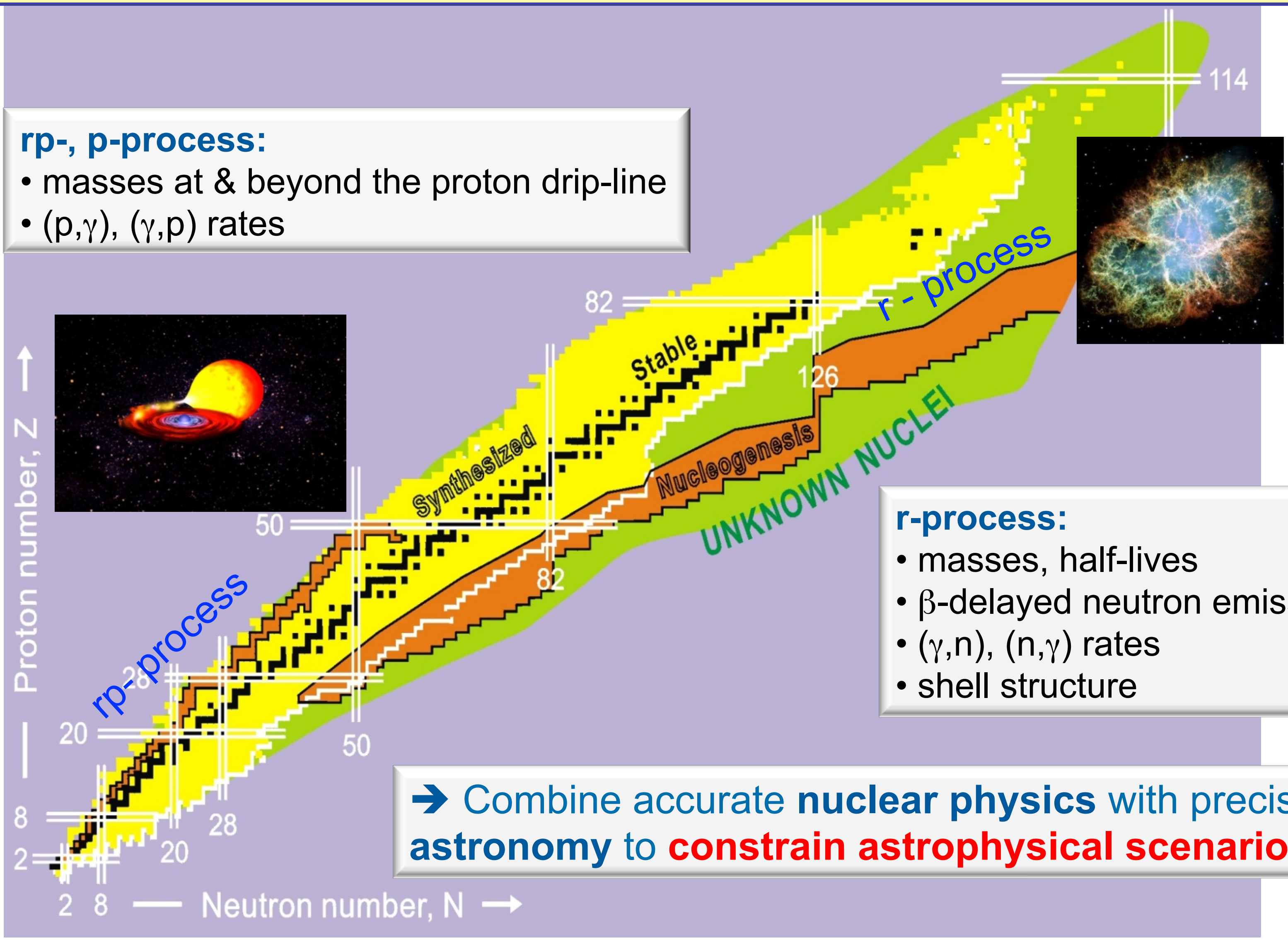
Neutron Skins

Pygmy Resonance

Neutron stars

EOS

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



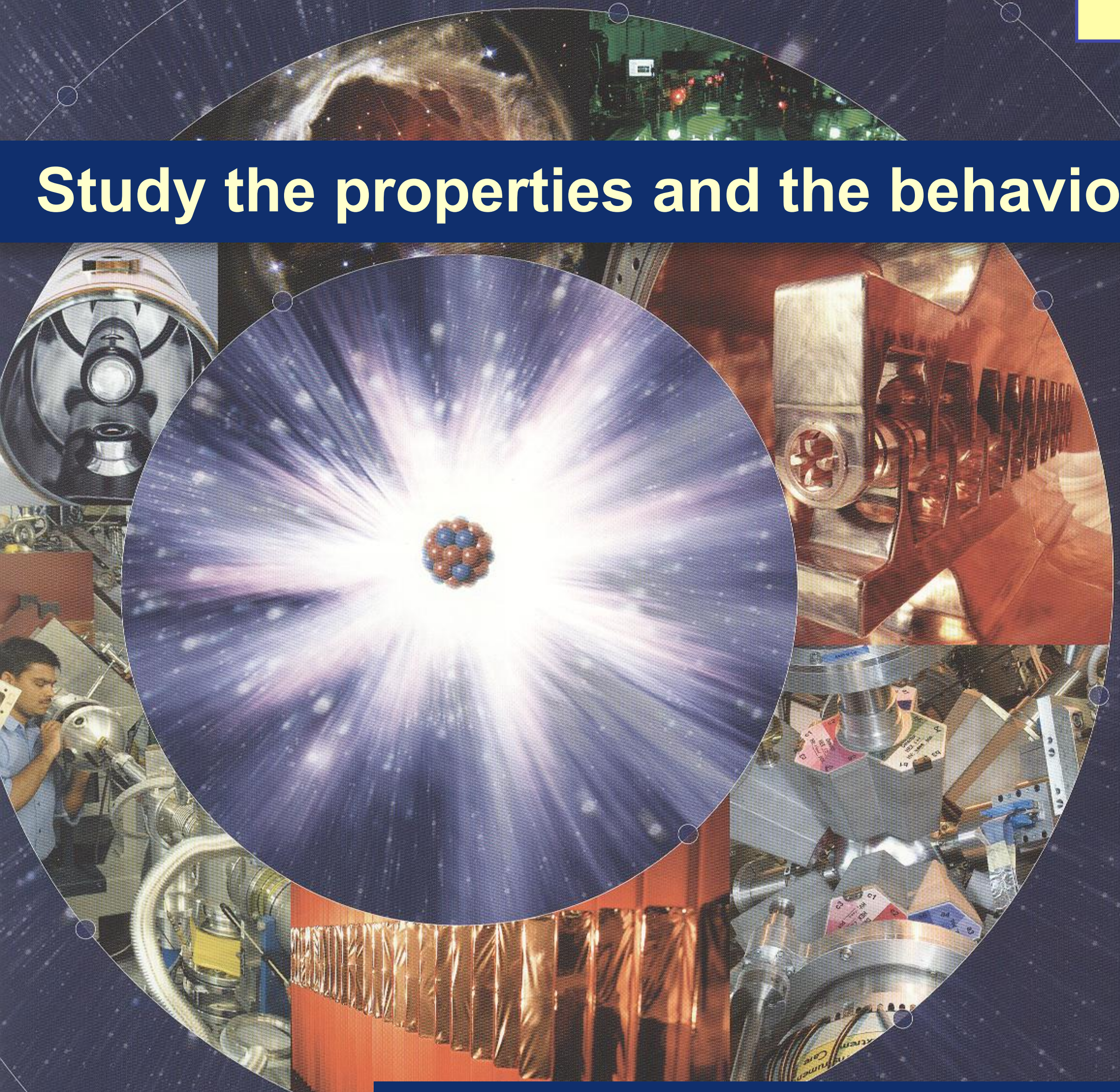
rp-, p-process:
- masses at & beyond the proton drip-line
- (p,γ), (γ,p) rates

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

What do we need to make experiments?

Particle accelerators

Ion beams from all stable isotopes from H to U
and
radioactive ion beams of all isotopes accessible
with energies
0.1 MeV/u to 10 MeV/u
and
0.1 GeV/u to 2 GeV/u
and
highest intensity possible

Electron beams
with energies
2 MeV to 200 MeV
and
highest intensity possible

Instrumentation

Light charged particle detectors

Heavy ion detectors

Neutron detectors

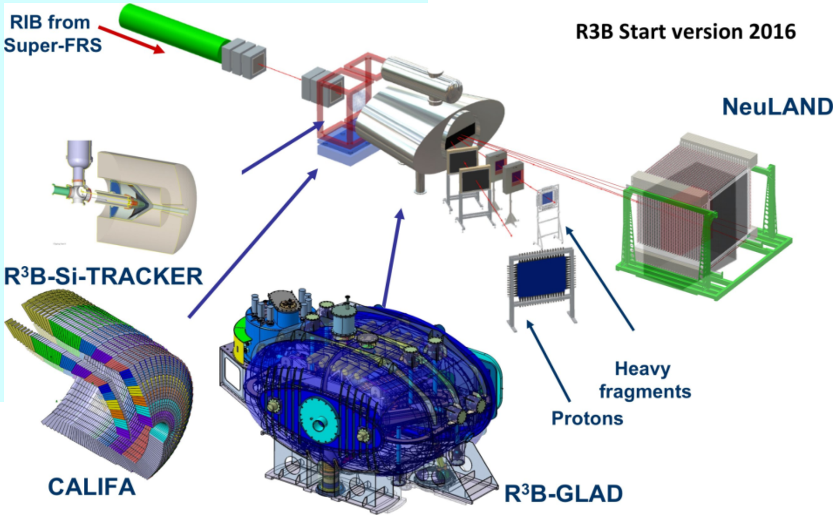
γ-detectors

Spectrometer

Separators

Calorimeter

EDAQ



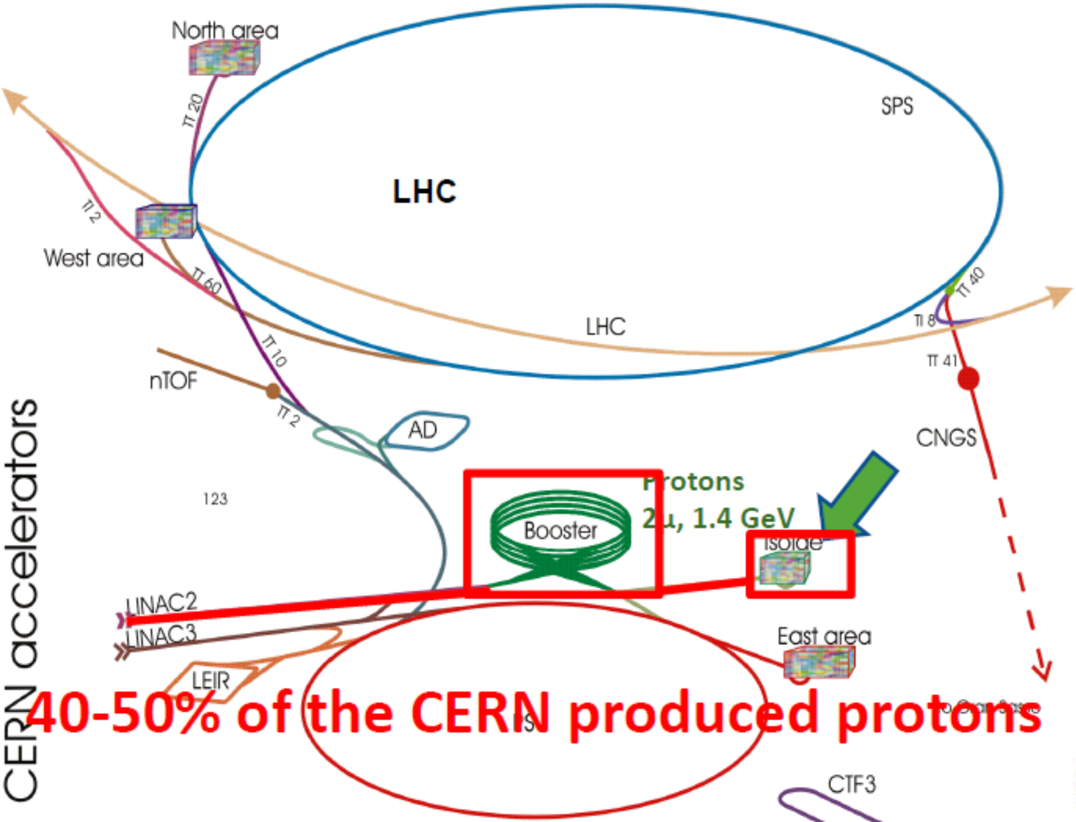
ISOLDE at CERN

ISOLDE is the CERN radioactive beam facility (operative since 1967)

ISOLDE provides low energy (10-60 keV) and post-accelerated beams

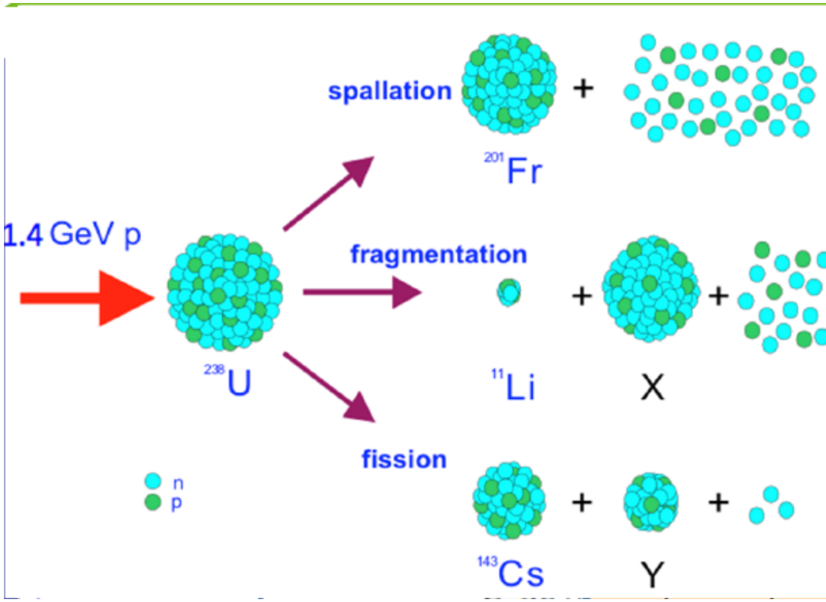
It is run by a collaboration of 16 countries

> 800 Users from 200 Institutions, 50 experiments / year



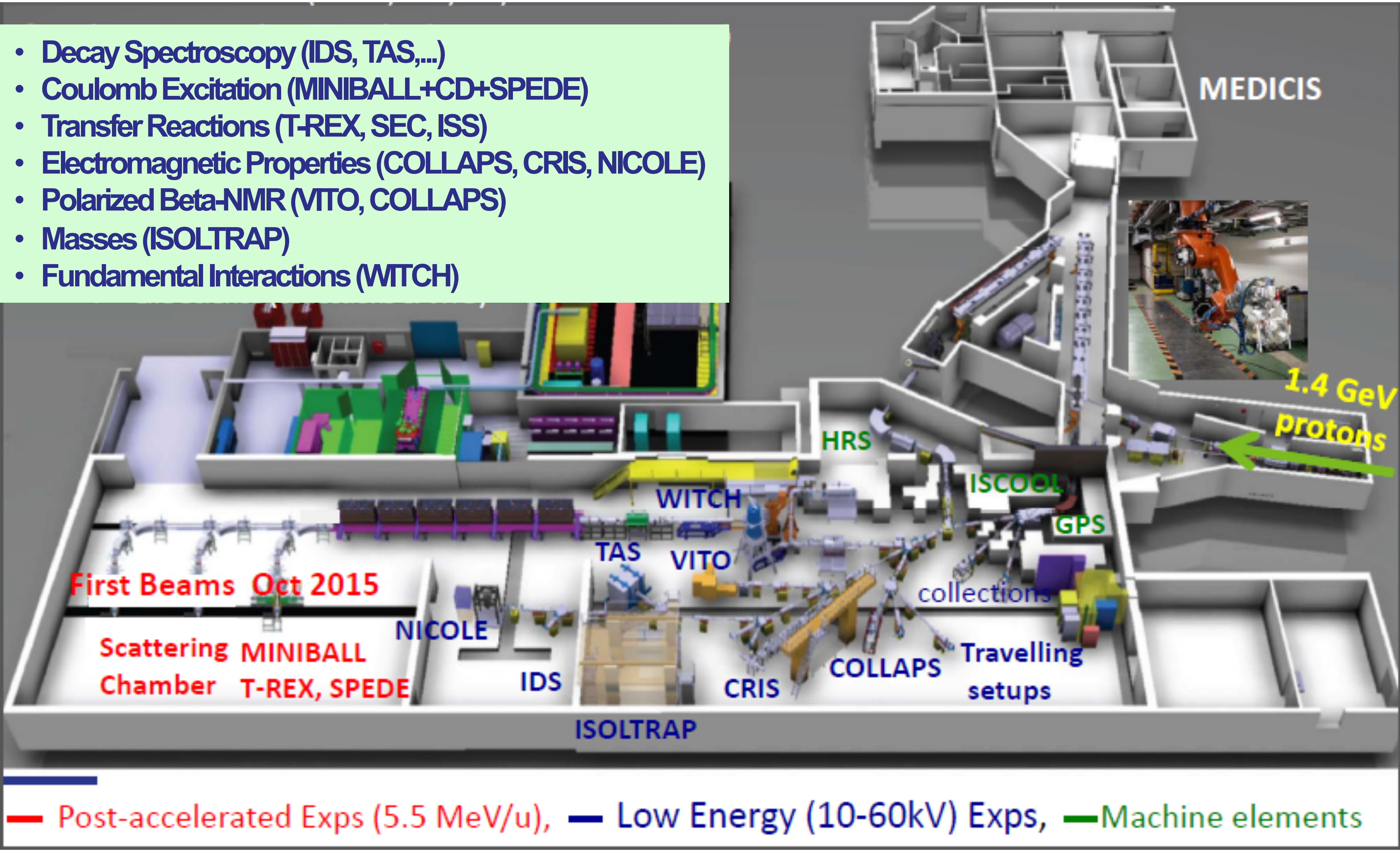
40-50% of the CERN produced protons

ISOL based RIB production

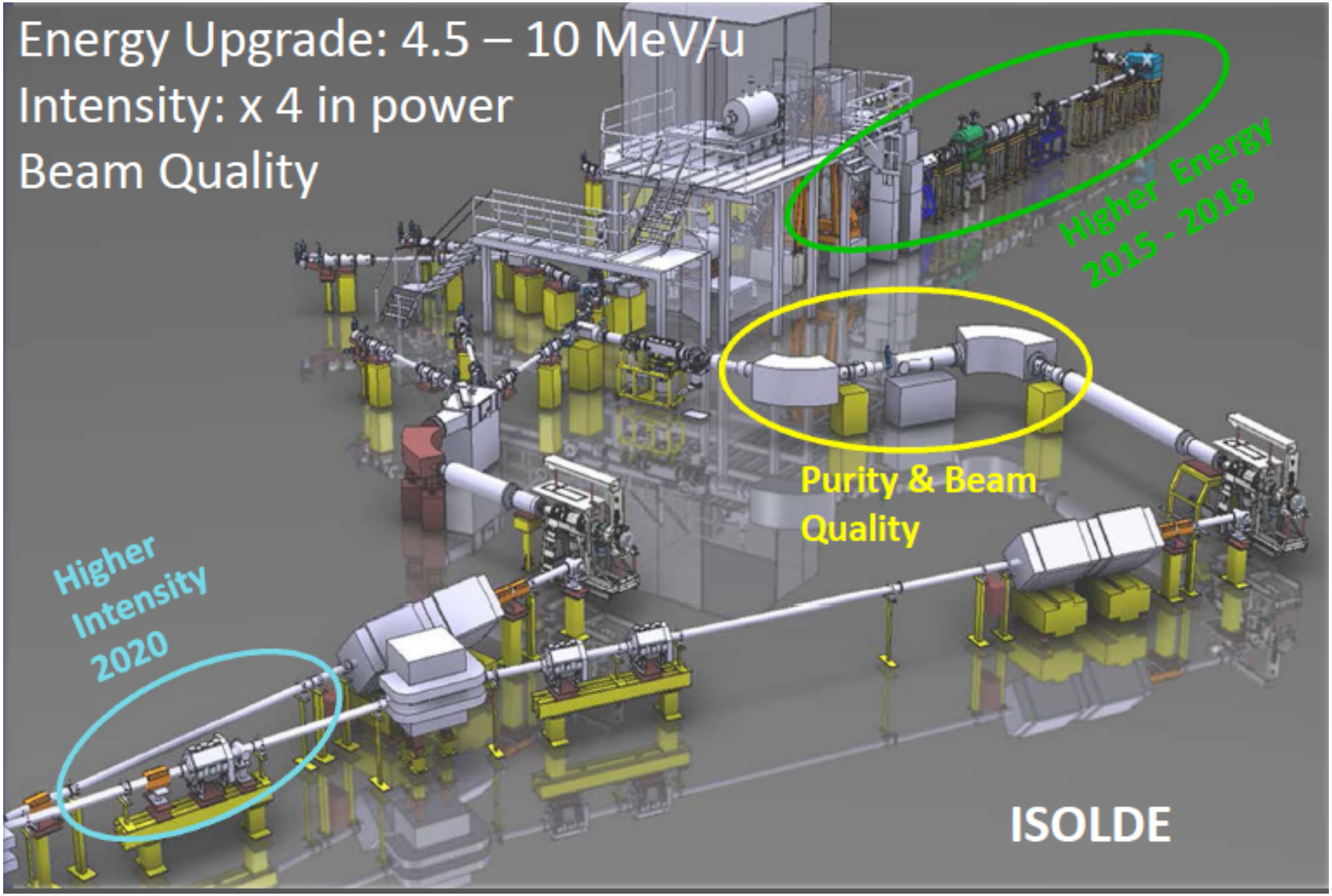


ISOLDE Facility

- Decay Spectroscopy (IDS, TAS,...)
- Coulomb Excitation (MINIBALL+CD+SPEDE)
- Transfer Reactions (T-REX, SEC, ISS)
- Electromagnetic Properties (COLLAPS, CRIS, NICOLE)
- Polarized Beta-NMR (VITO, COLLAPS)
- Masses (ISOLTRAP)
- Fundamental Interactions (WITCH)



HIE-ISOLDE Project



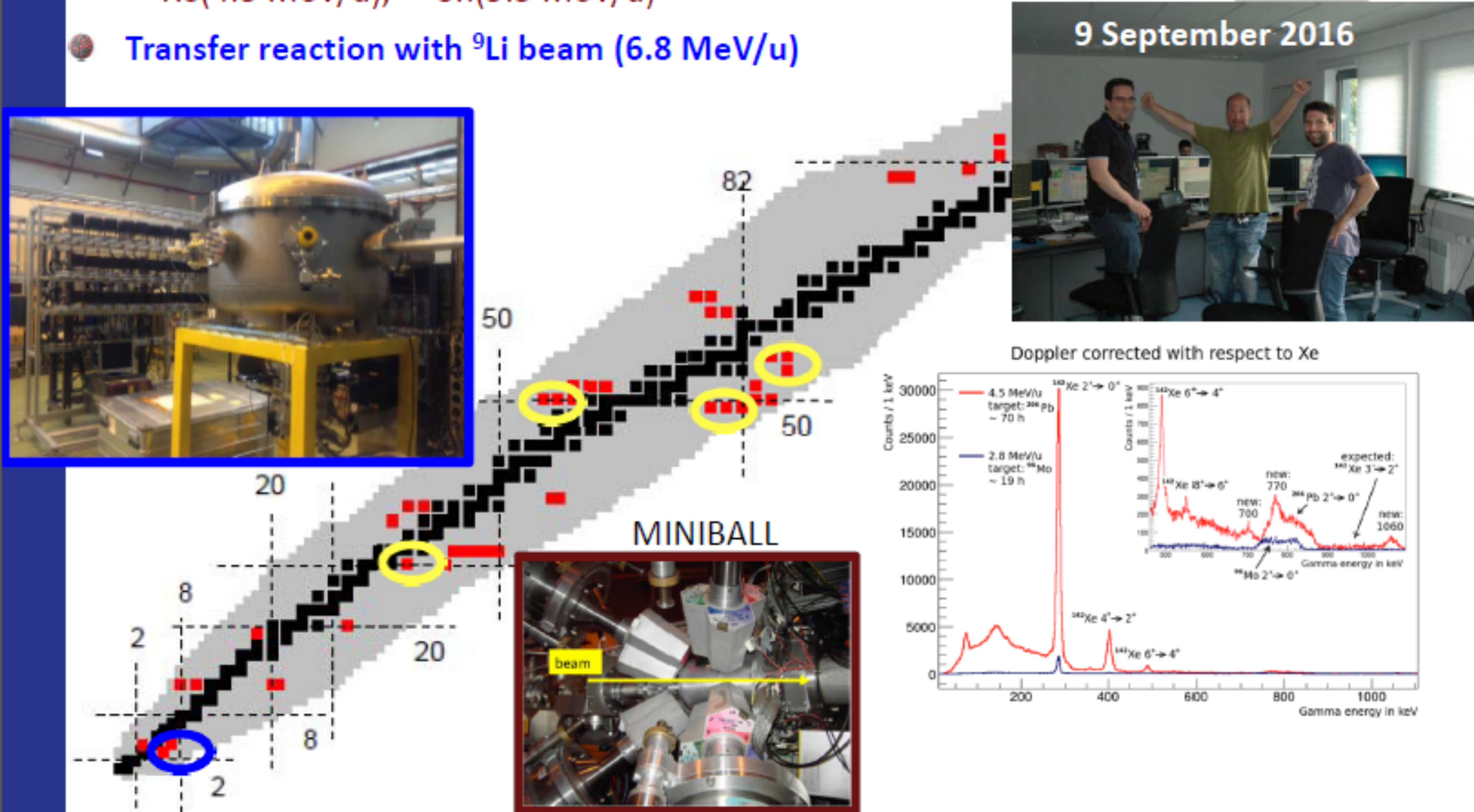
Energy Upgrade: 4.5 – 10 MeV/u

Intensity: x 4 in power

Beam Quality

HIE-ISOLDE @ 5.5 MeV/u

- HIE-ISOLDE producing physics: beams @ 4.3 MeV/u in 2015 and 5.5 MeV/u in 2016.
- Coulomb excitation of ^{74,76,78}Zn (4.3 MeV/u), ^{110}Sn(4.5 MeV/u), ^{142}Xe(4.5 MeV/u), ^{132}Sn(5.5 MeV/u)
- **Transfer reaction with ^{9}Li beam (6.8 MeV/u)**

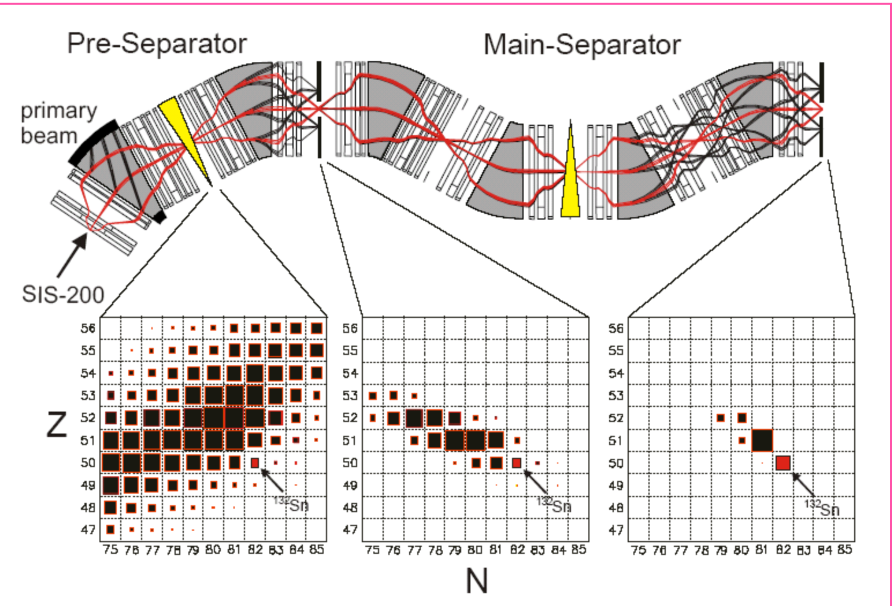


9 September 2016

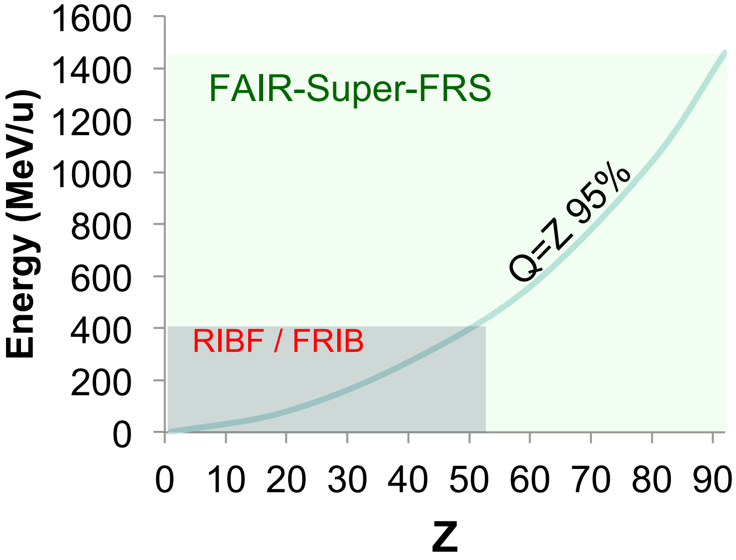
MINIBALL

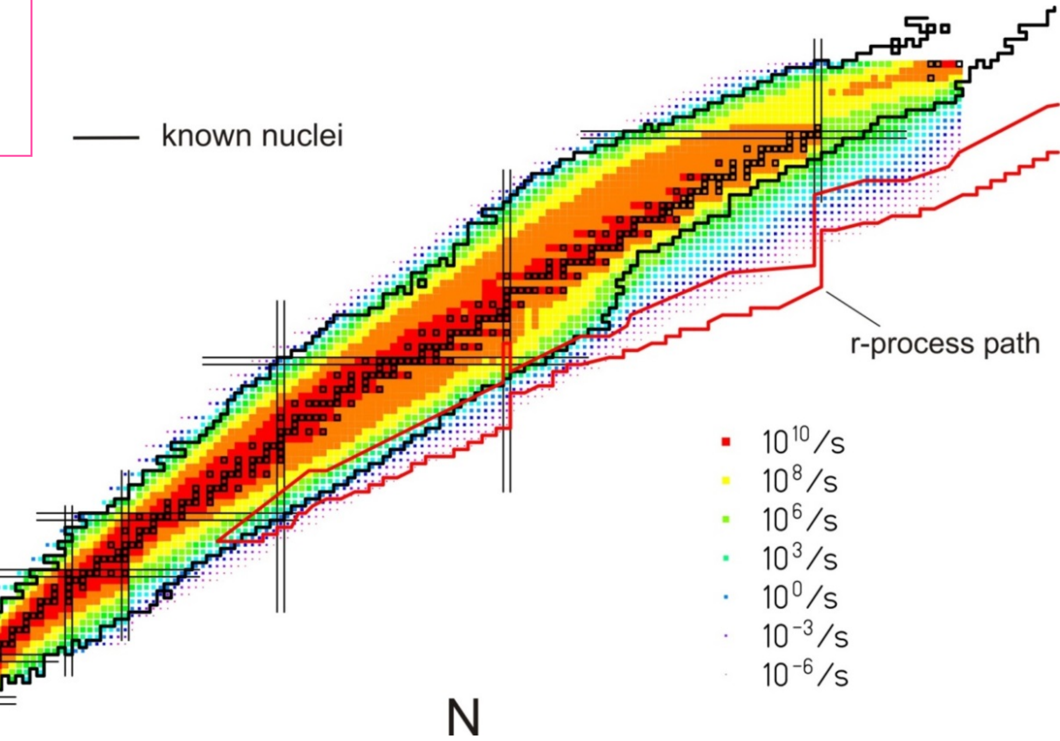
Doppler corrected with respect to Xe

HE RIBs by Fragmentation at GSI/FAIR

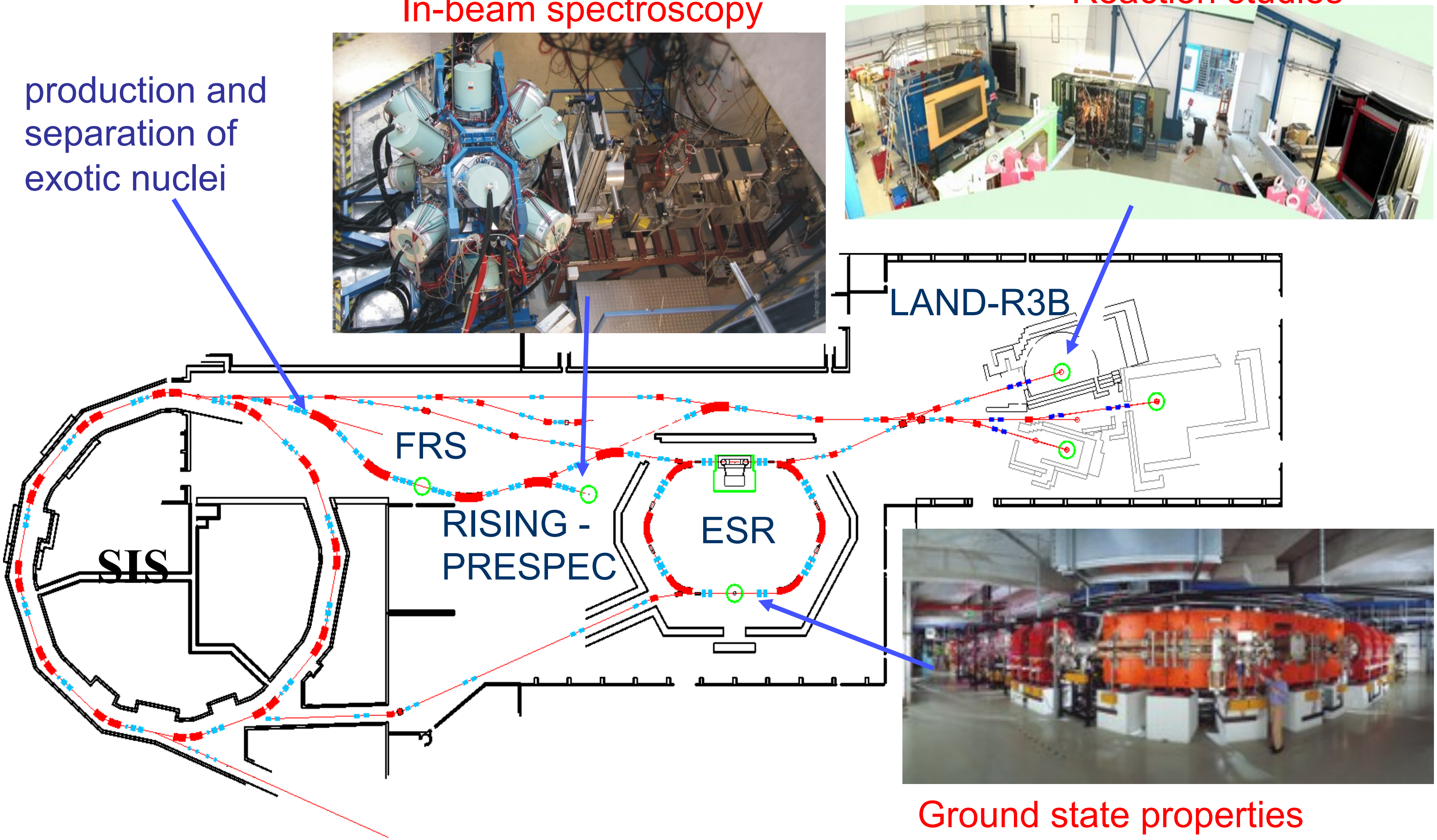


- High energies for unique separation and unique experiments
- Competitive intensities throughout the periodic table





From existing research opportunities at GSI...



production and separation of exotic nuclei

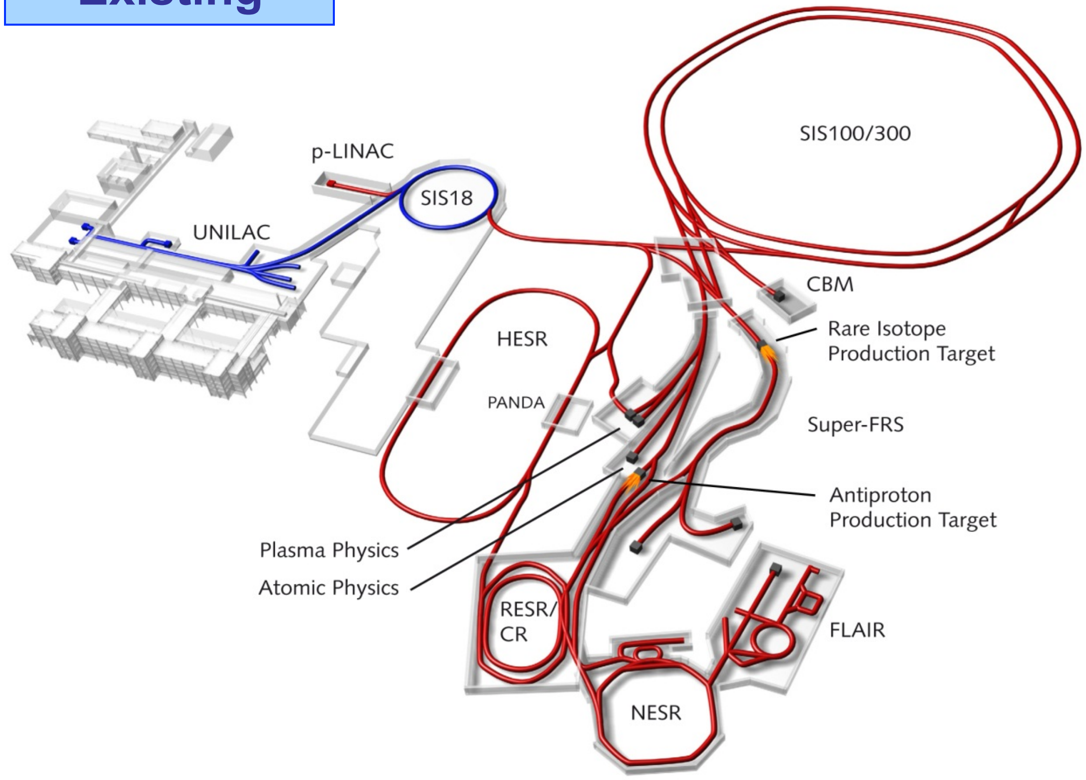
Decay studies,
In-beam spectroscopy

Reaction studies

Ground state properties
inverse reactions

… to the Facility for Antiproton and Ion Research

Existing



To be built

Primary beams

- Faster cycling (3Hz instead of 0.3Hz)
- 10^{12}/s 1.5-2 GeV/u $^{238}U^{28+}$
- 10^{10}/s 35 GeV/u $^{238}U^{73+}$

Secondary beams

- 1.5-2 GeV/u
- Beam intensity improvement FRS – Super-FRS: 10^2 to 10^5

NUSTAR at GSI/FAIR - 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

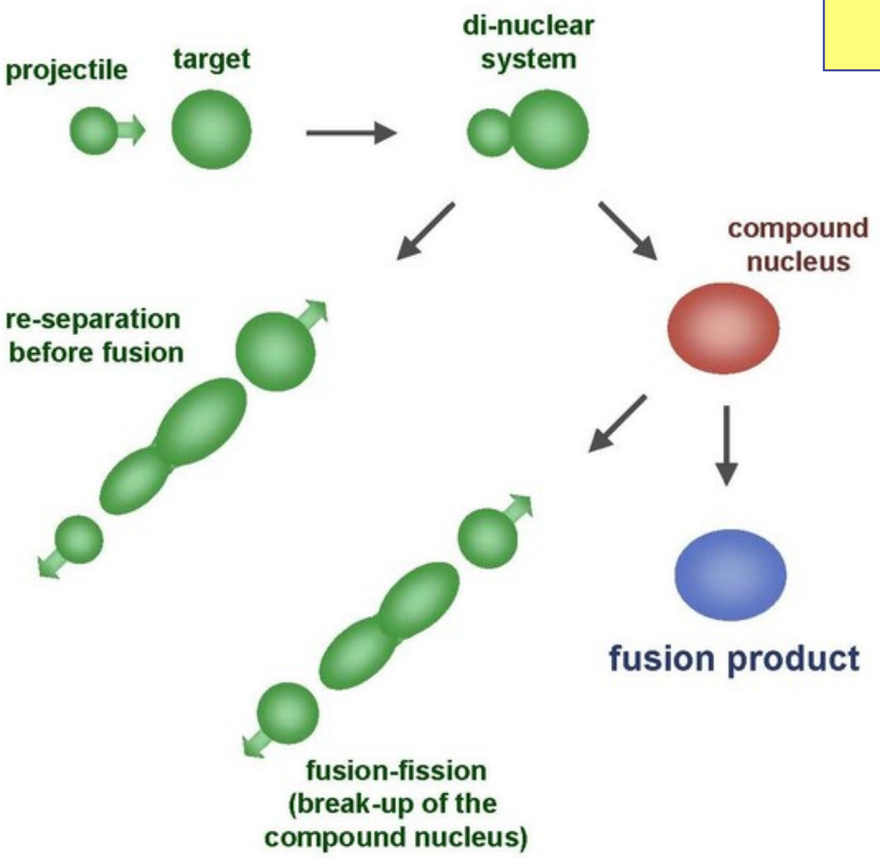
The Collaboration

> 850 scientists

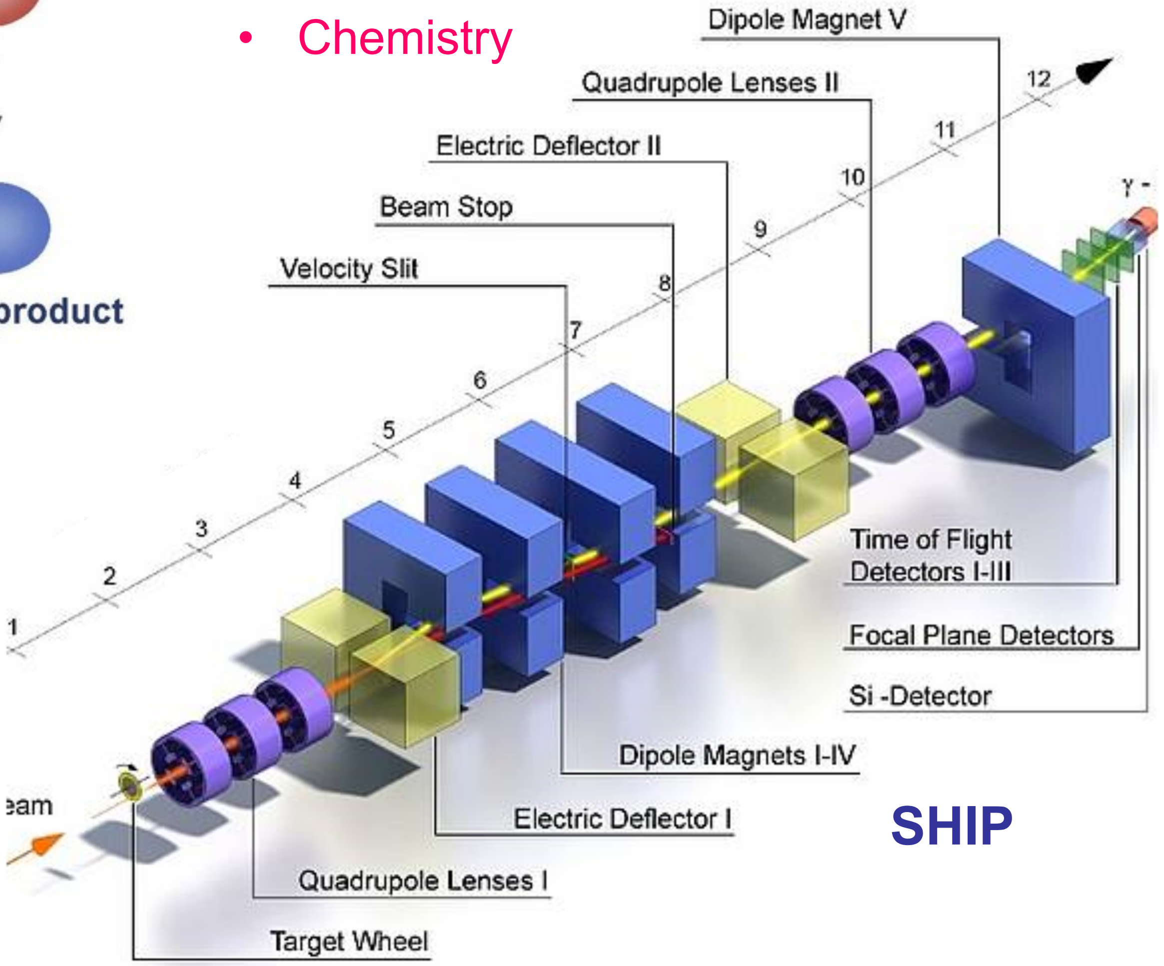
184 institutes

39 countries

Superheavy elements



- Production
- Mass measurements
- Spectroscopy
- Reaction studies
- Chemistry



SHIP

Production of Superheavies by hot or cold fusion reactions at the UNLIAC at GSI

SHE Strategy

UNILAC not suited for simultaneous FAIR and SHE operation

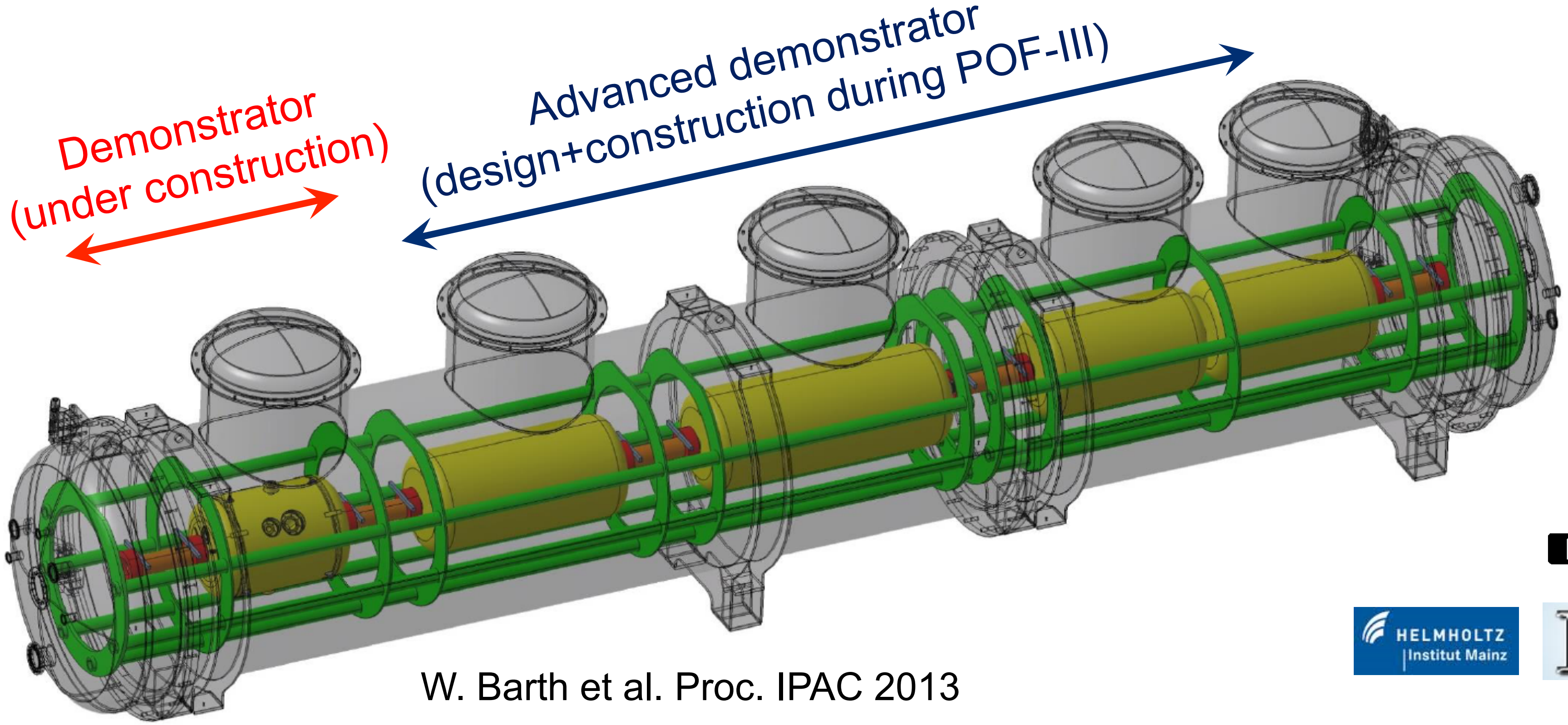
→ **Dedicated CW linac required**

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



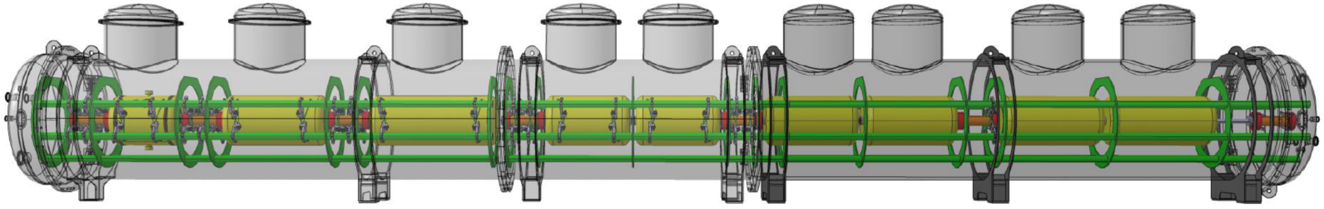
W. Barth et al. Proc. IPAC 2013

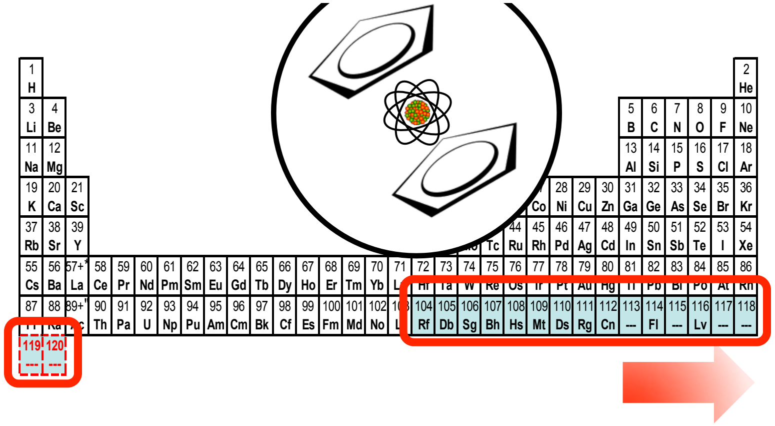
SHE research 2020+

New cw linac

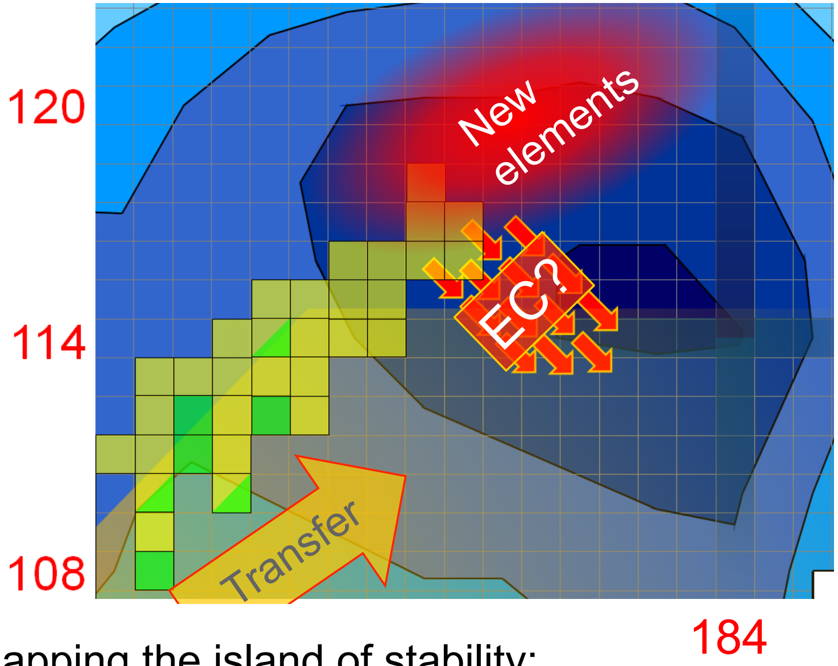
E_{Beam} up to 7.3 MeV/u

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:

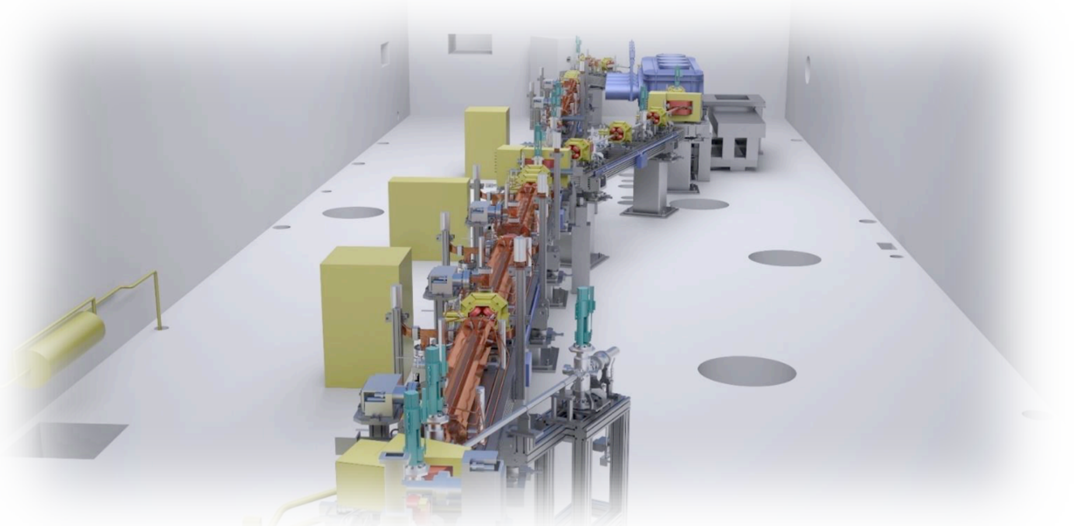
- New elements with Z>118
- Neutron-rich isotopes in transfer reactions
- Weak EC decay channels towards center of island
- Direct mapping of shell evolution towards N=184

Extreme Light Infrastructure
Nuclear Physics (ELI-NP)

-High-Power-Lasersystem **HPLS**,
2 x 10 PW Maximum

-Intense γ beam **GBS**,
E_γ = 0,2-19,5 MeV Laser-Compton-Backscattering

-Eight experimental stations



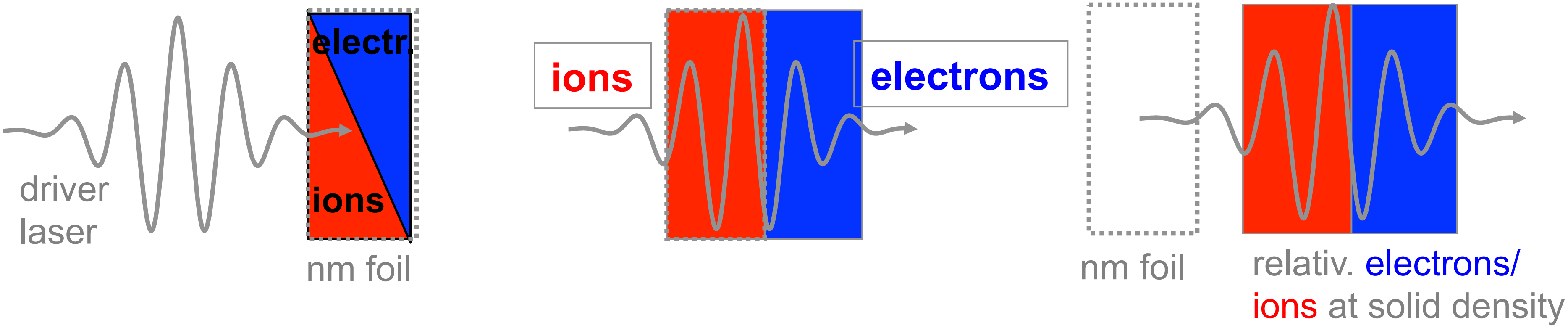
2018 Commissioning of HPLS and GBS; 2019 operation and Day 1 experiments

Futuristic ideas: Radiation Pressure Ion Acceleration

Suggested by P. Thirolf, LMU München

- high-power (100 TW – PW), short-pulse (few fs) lasers
- focused intensity on target: $10^{20} – 10^{24}$ W/cm^2
- accelerating field: ~ TV/m

- high-intensity driver laser + thin solid target foil:



- cold compression of electron sheet, followed by electron breakout
- dipole field between electrons and ions
- ions + electrons accelerated as neutral bunch (avoid Coulomb explosion)
- solid-state density: 10^{22} - 10^{23} e/cm^3

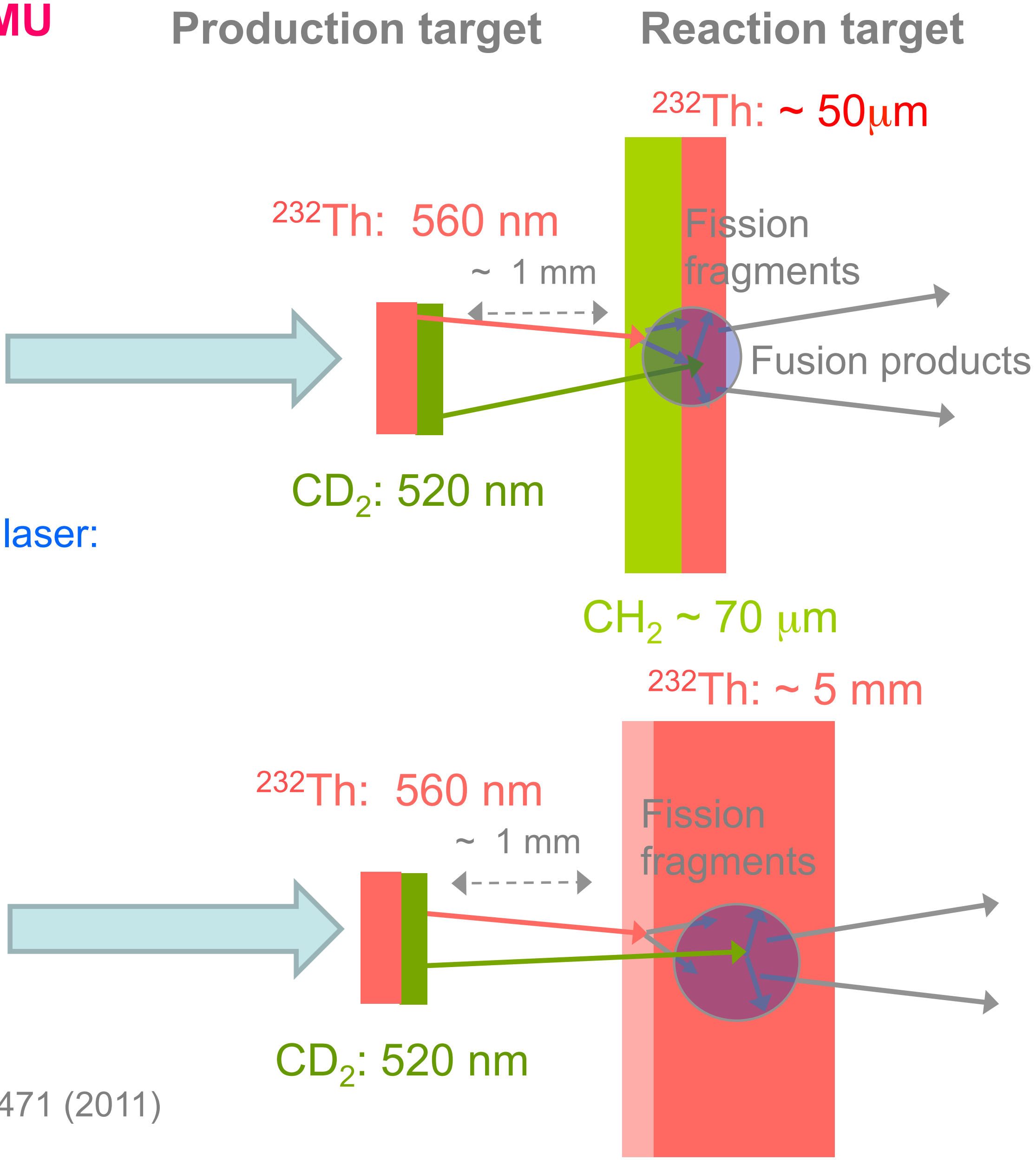
  'classical' bunches: 10^8 e/cm^3

$$E_{\text{ion}} \propto I_{\text{Laser}}$$

→ ~ 10^{14} x density of conventionally accelerated ion beams

Futuristic ideas: Exp. Scheme for “Fission-Fusion”

Suggested by P. Thirolf, LMU



conventional stopping:

high-power, high-contrast laser:
300 J, 30 fs (10 PW)

ca.·10^{23} W/cm^2

focal diam. ~ 3 µm

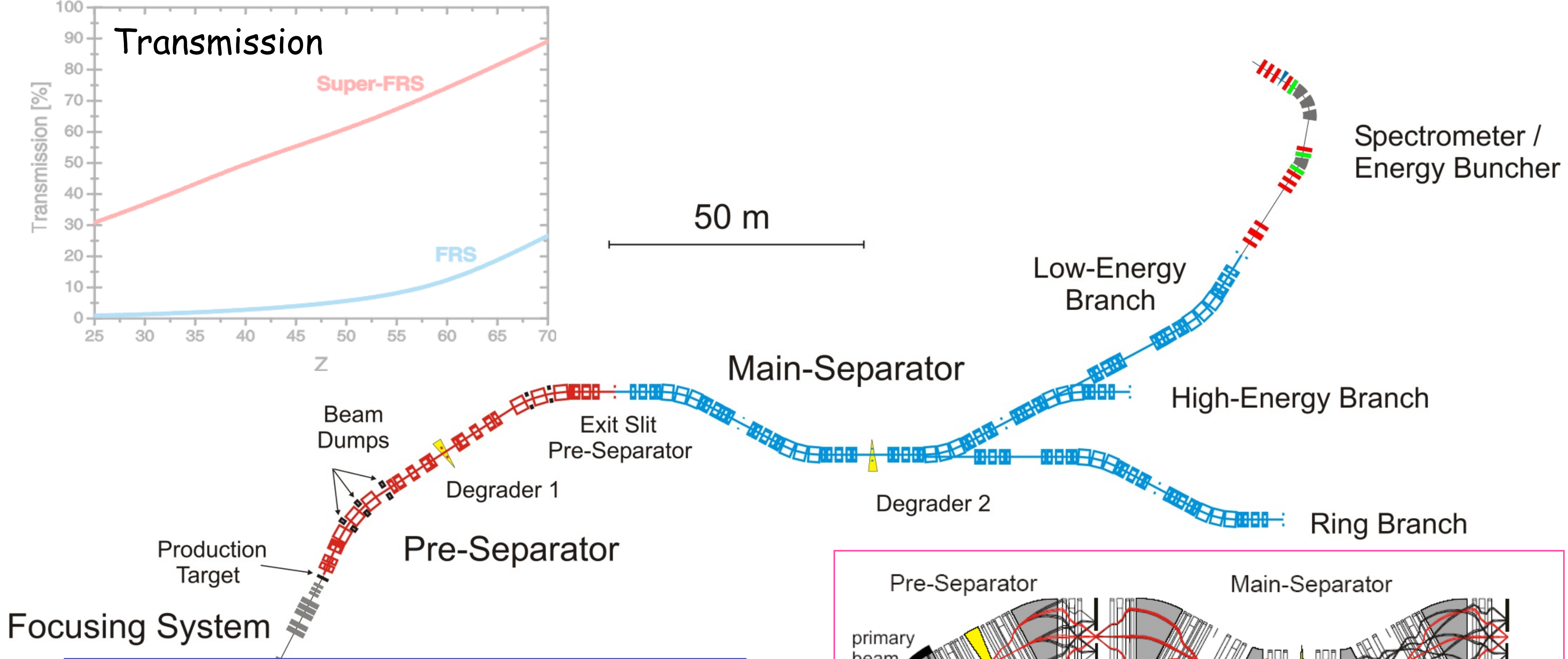
collective stopping:

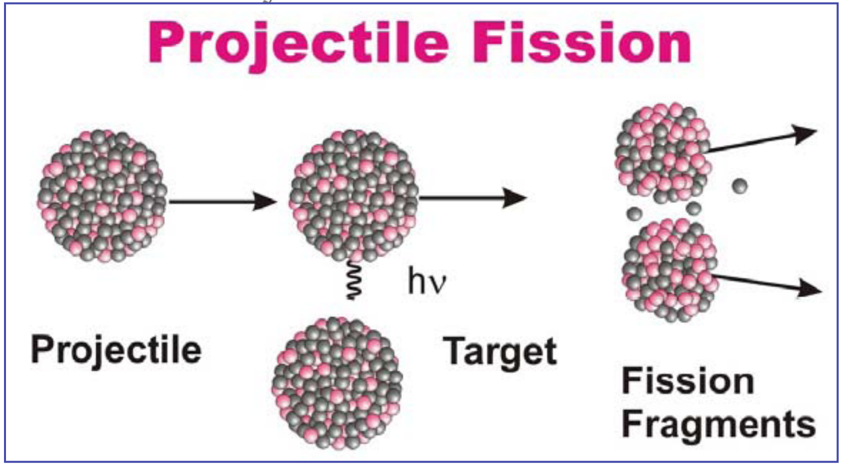
D. Habs, PT et al., Appl. Phys. B 103, 471 (2011)

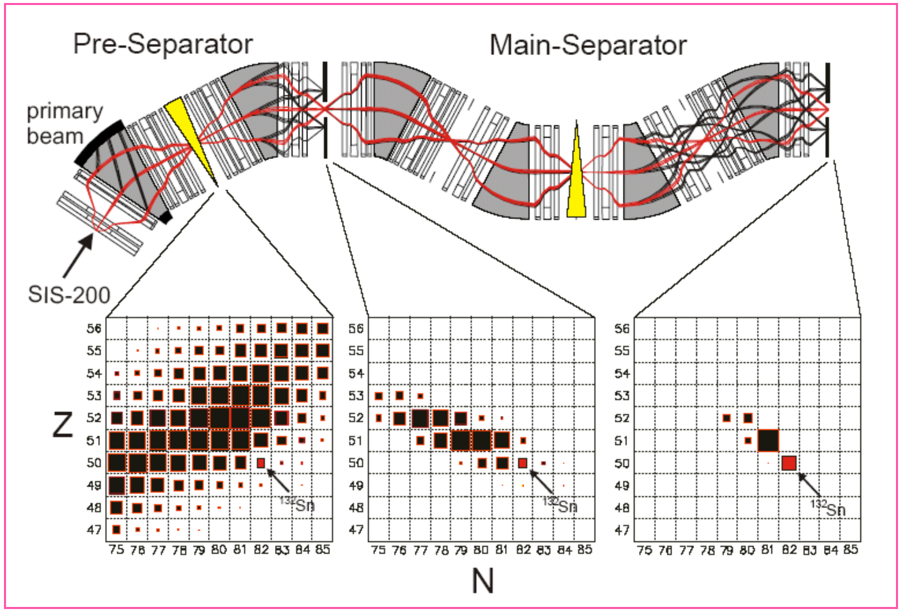
Concluding remarks

- Powerful ISOL and In-flight RIB facilities are key to further advancements of experimental Nuclear Physics
- In addition stable heavy ion beam accelerators are needed e.g. for SHE research
- Further improvements in beam intensities and beam quality are requested
- To reach the boundaries of nuclear stability most likely novel acceleration (and measurement) concepts will be needed
- The beam time demand of the community cannot be satisfied with existing and planned facilities.
- There are too few „simple“ facilities available for the training of students and young researchers and for testing equipment

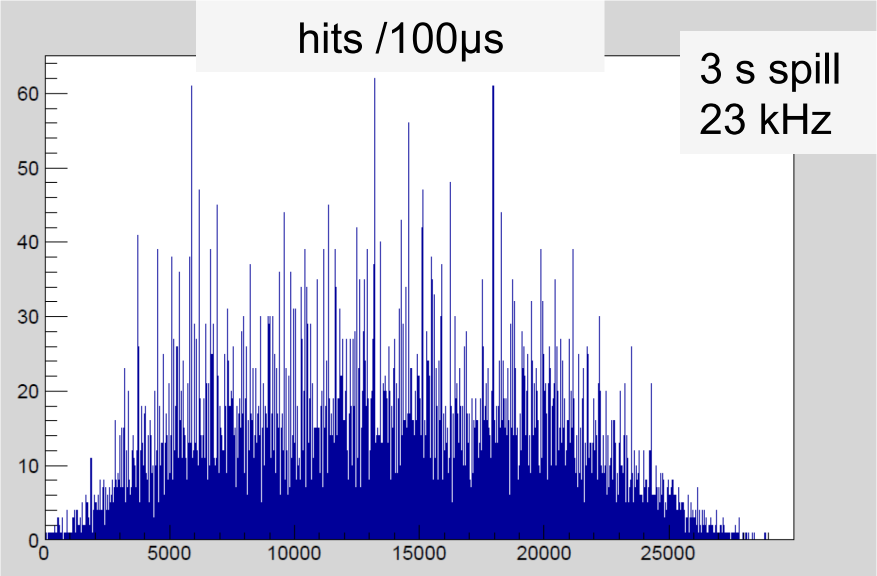
SUPERconducting FRagment Separator





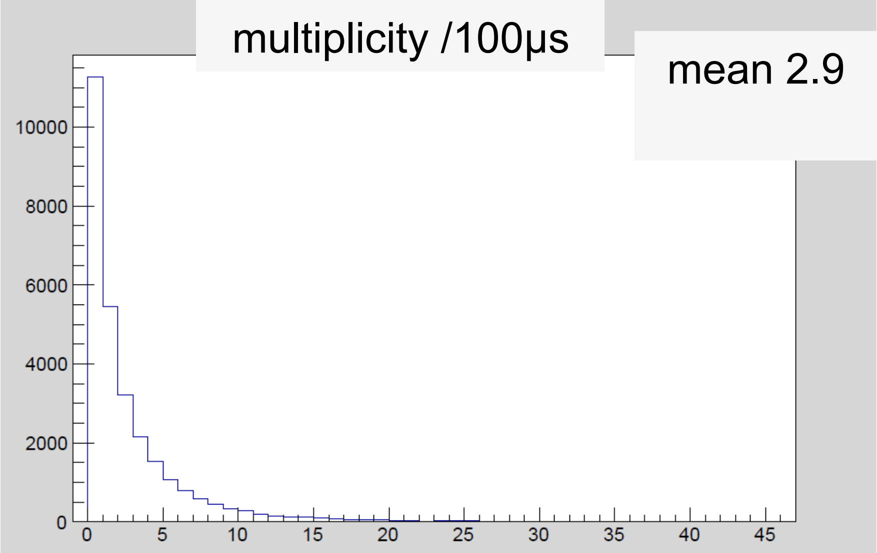


Coarse Spill Structure at FRS S4



Coarse spikes with up to 100x hits compared to the mean value per 100 us interval.

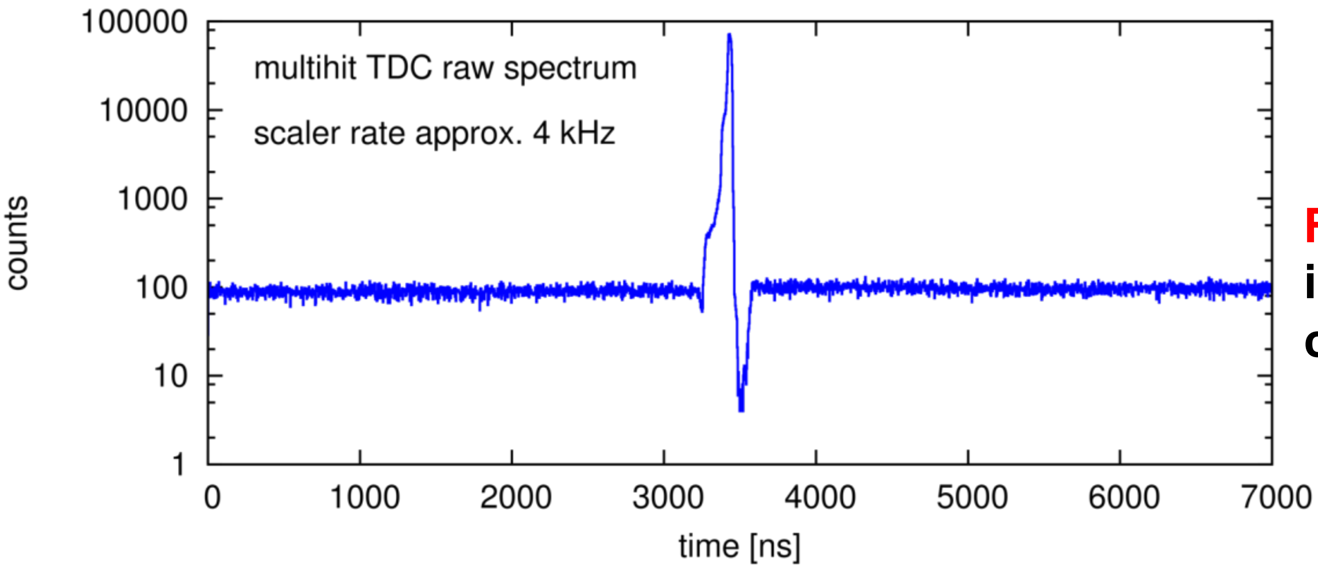
Voids with up to 50% empty time intervals.



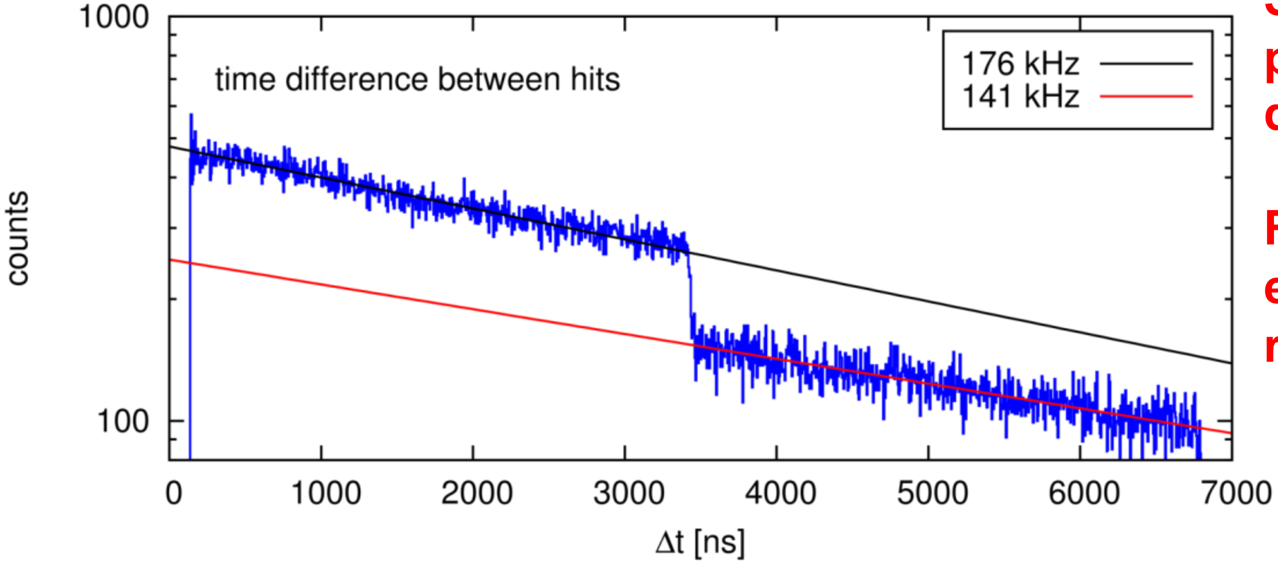
DAQ processing time: ≈ 100µs
→ Only 1 hit /100µs contributes.

Spikyness reduces data acceptance by up to a facotor of 3 !!!!

Fine Spill Structure at FRS S4



Fine spikes **with up to 50x instantaneous rate compared to mean rate.**



Severe overloading of particle tracking detectors!!!!

Reduced detection efficiency and reduced resolution!!!!