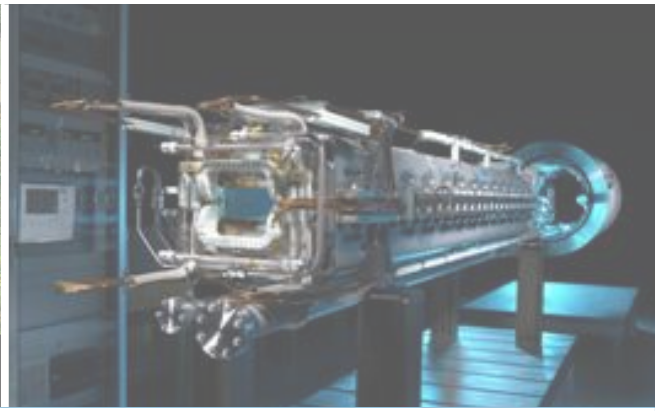




Radioactive Beams at FAIR - the NUSTAR programme

NUclear STructure, Astrophysics and Reactions

Thomas Nilsson

Chalmers University of Technology, Sweden

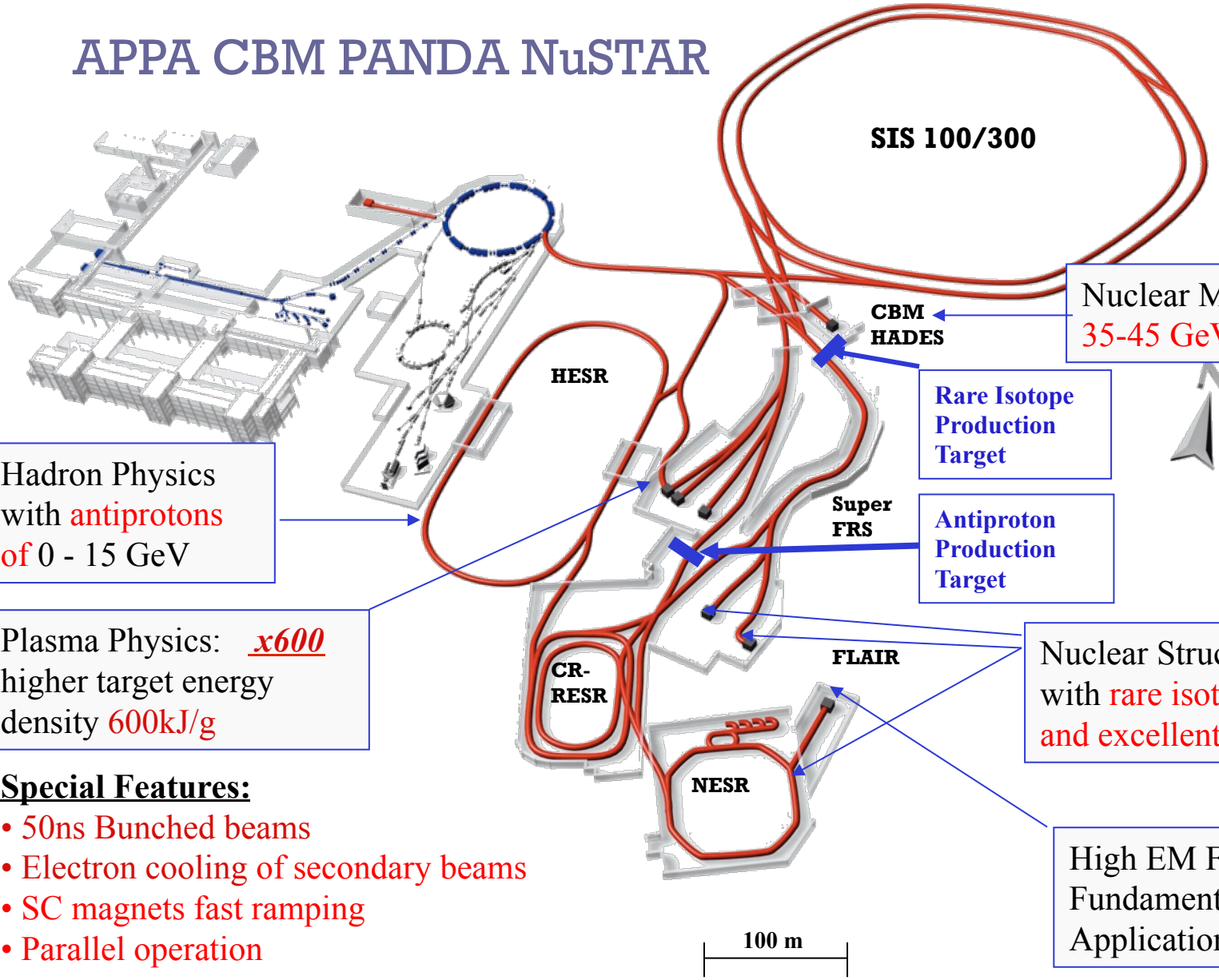
NUSTAR Board of Representatives/Board of FAIR Collaborations

EURORIB'12

Abano Terme May 20-25, 2012

Research Communities at FAIR

APPA CBM PANDA NuSTAR



Nuclear Matter Physics with 35-45 GeV/u HI beams, ***x1000***

Rare Isotope Production Target

Antiproton Production Target

Hadron Physics with antiprotons of 0 - 15 GeV

Plasma Physics: ***x600*** higher target energy density 600kJ/g

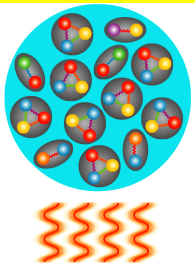
Nuclear Structure & Astrophysics with rare isotope beams, ***x10 000*** and excellent cooling

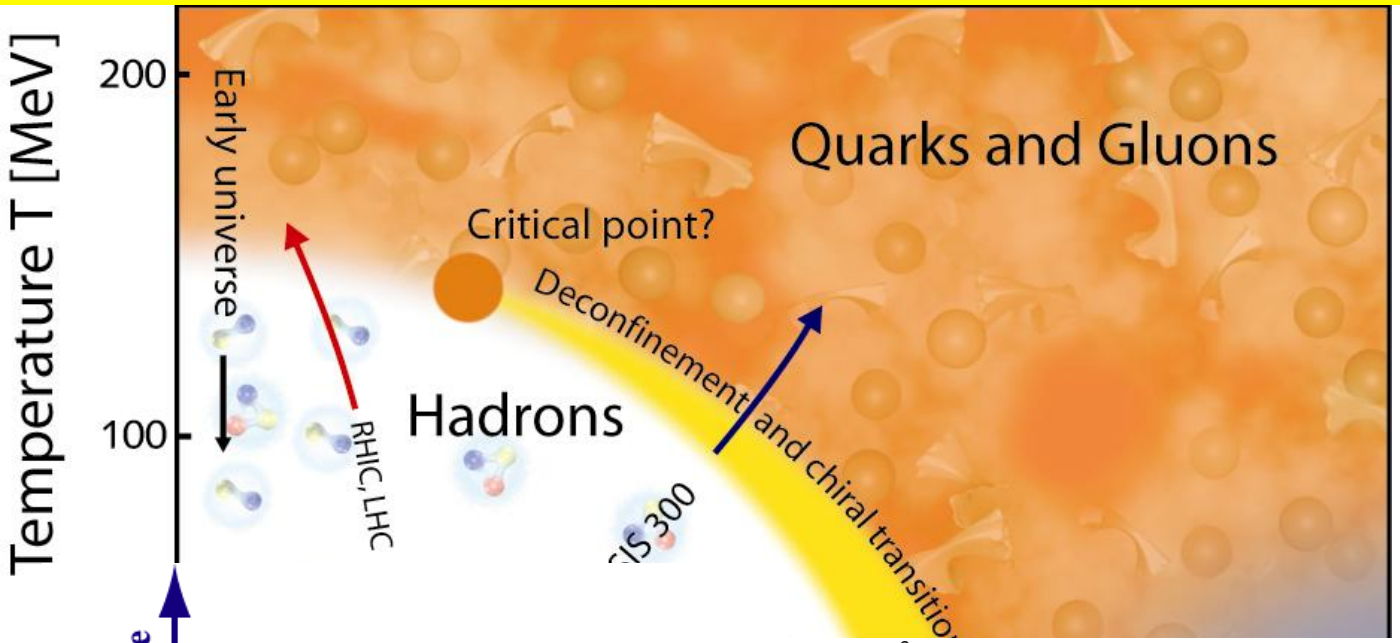
High EM Field (HI) _
Fundamental Studies(HI & p)
Applications (HI)

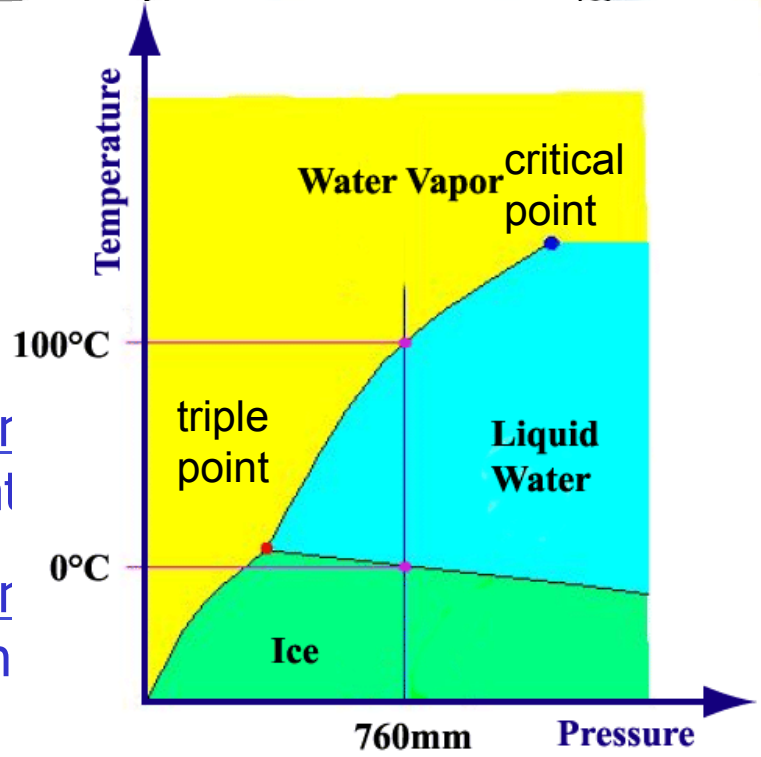
Special Features:

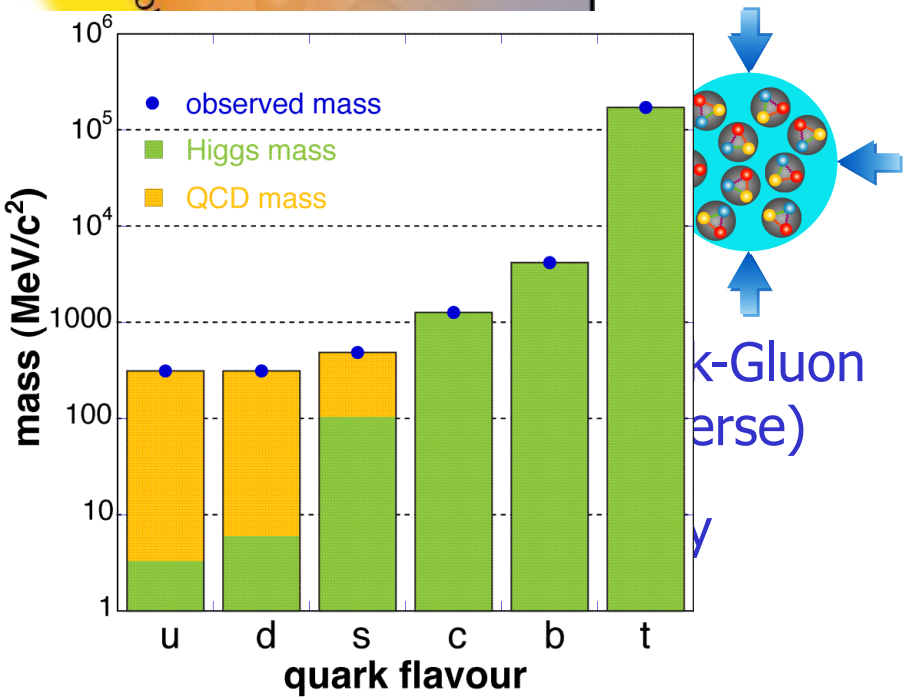
- 50ns Bunched beams
- Electron cooling of secondary beams
- SC magnets fast ramping
- Parallel operation

The phase diagram of strongly interacting matter







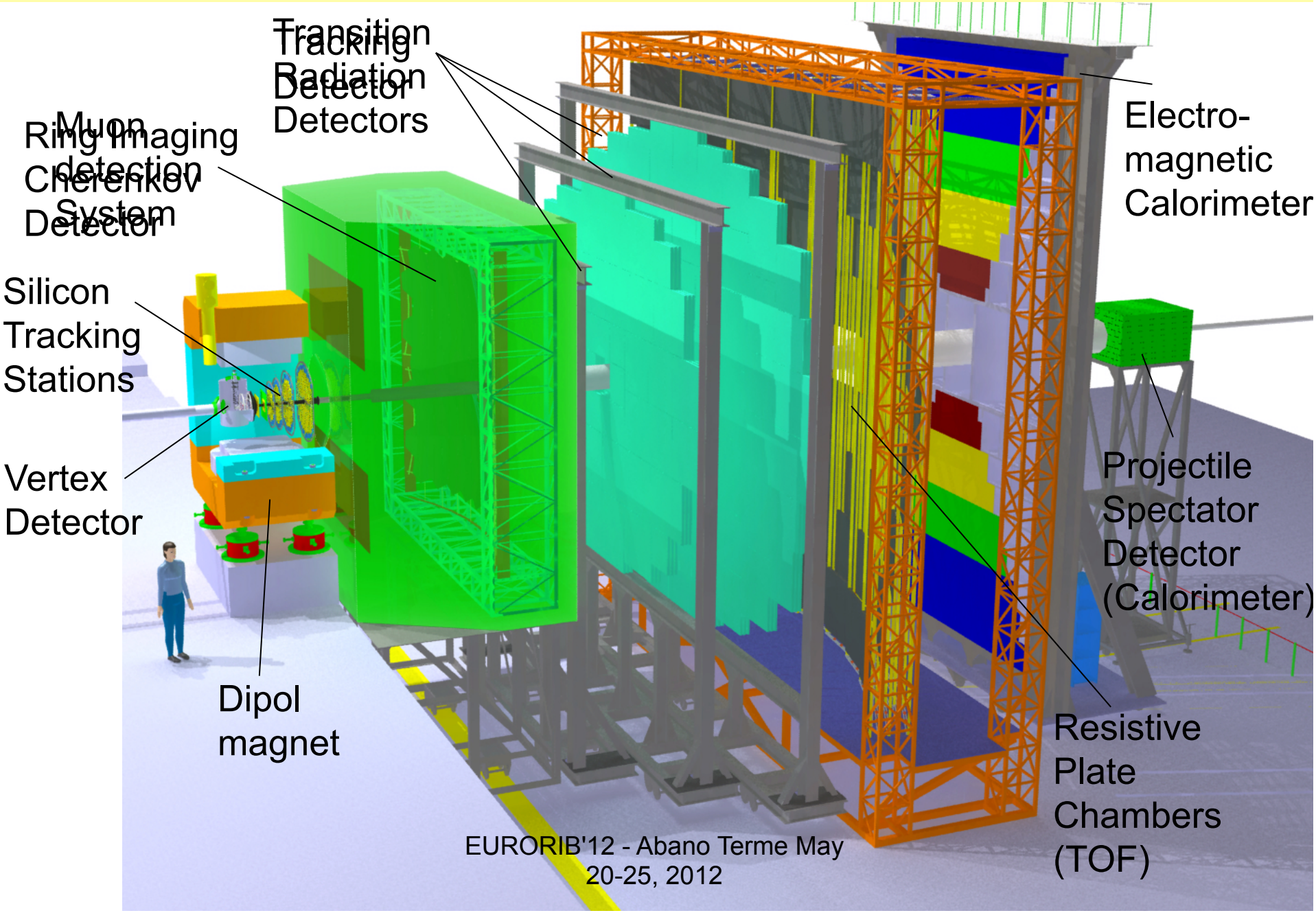


Heavy-ior
Plasma at

Heavy-ior
interactin

k-Gluon
erse)
y

The Compressed Baryonic Matter Experiment



PANDA - Hadron Spectroscopy

Spectroscopy with antiprotons

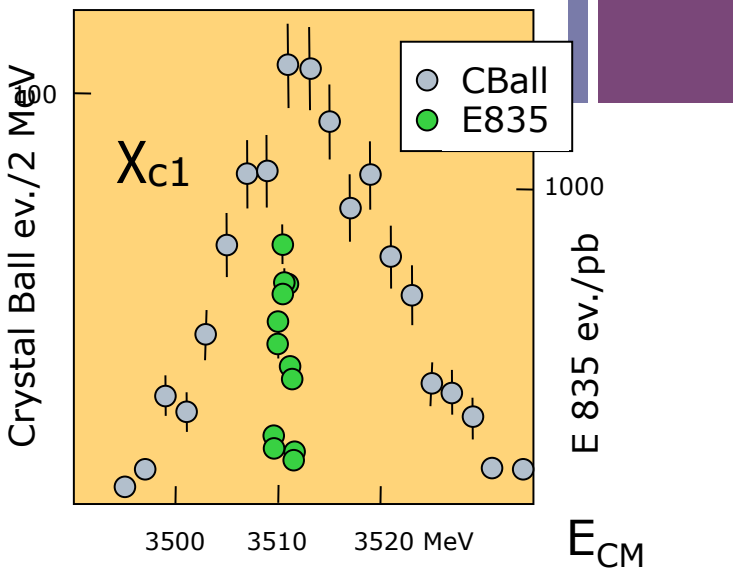
- $p\bar{p}$ machine allows $\Delta E \sim 100$ keV vs. $\Delta E \sim 10$ MeV in e^+e^-

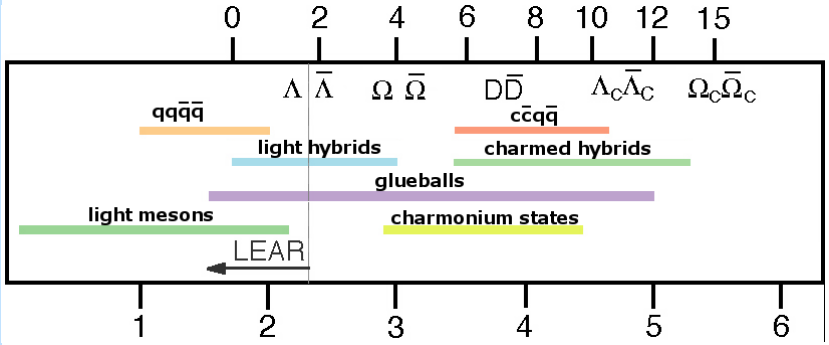
➔obtain m and Γ with high precision

- e^+e^- directly produces only $J^{PC} = 1^{--}$ (γ)
- pp accesses all states

Charm spectroscopy

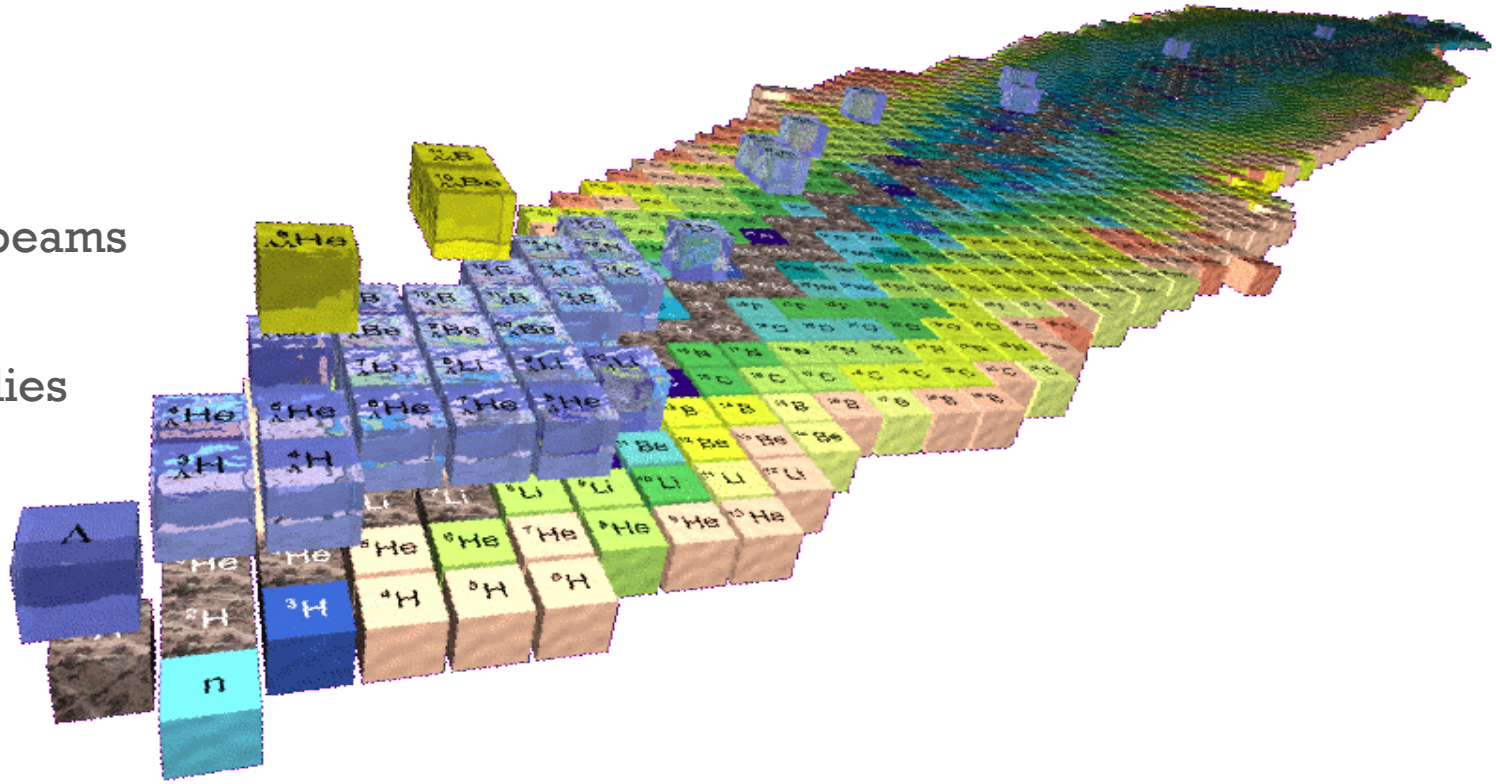
- Charmonium: Positronium of QCD
- Charm hybrids
  - c-states narrow, understood
  - Little interference between $c\bar{c}g$ and $c\bar{c}$-states
  - Mass 4–4.5 GeV, $c\bar{c}$ g narrow,
  - ~ $\sigma(p\,\bar{p} \rightarrow c\,\bar{c})$
- Charm meson spectroscopy



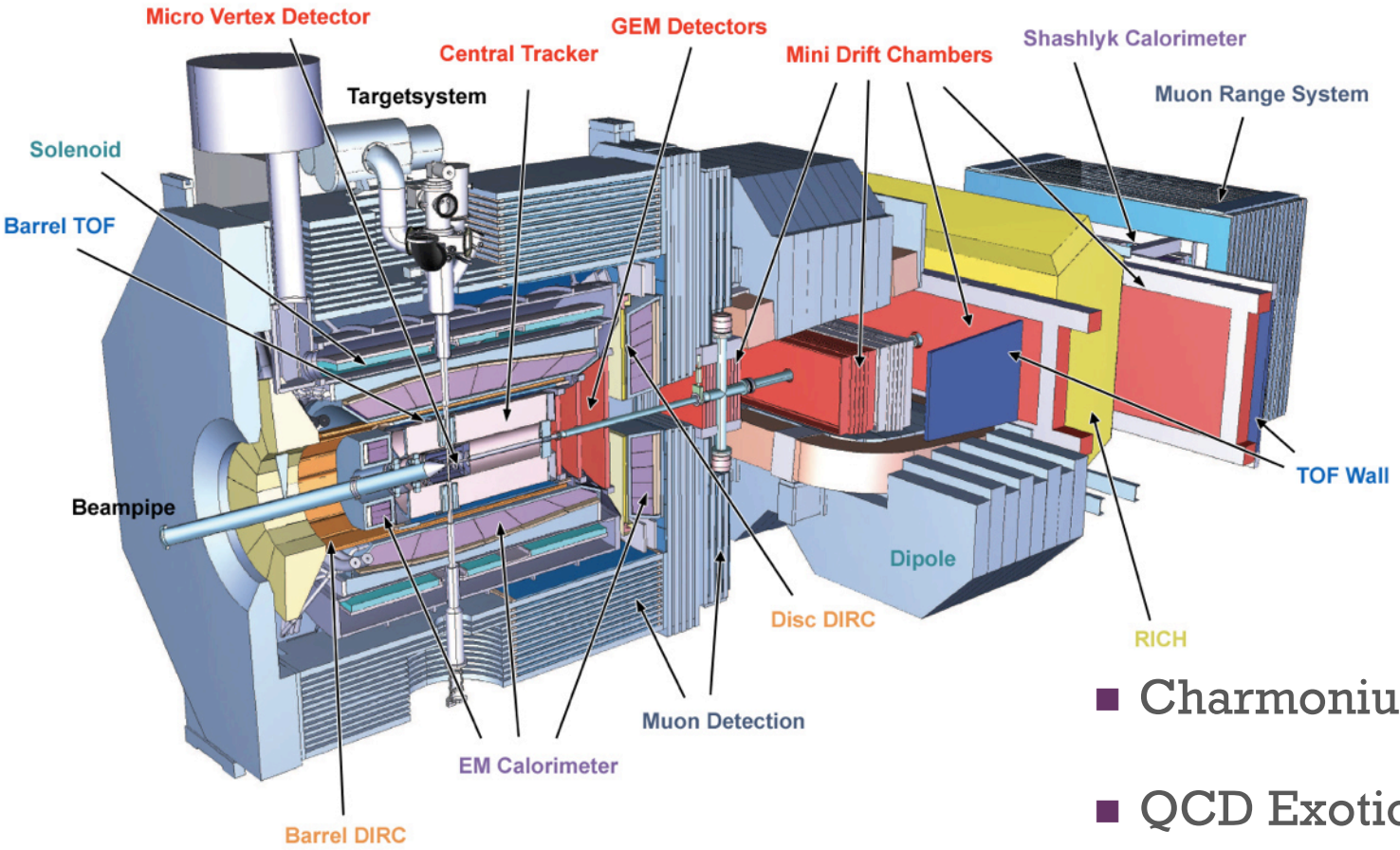


Extending the nuclear chart@FAIR

- Panda
  - Nucleon structure
  - Hypernuclei – strangeness dimension
  - …
- NUSTAR
  - Radioactive beams
    - Reactions
    - Decay studies

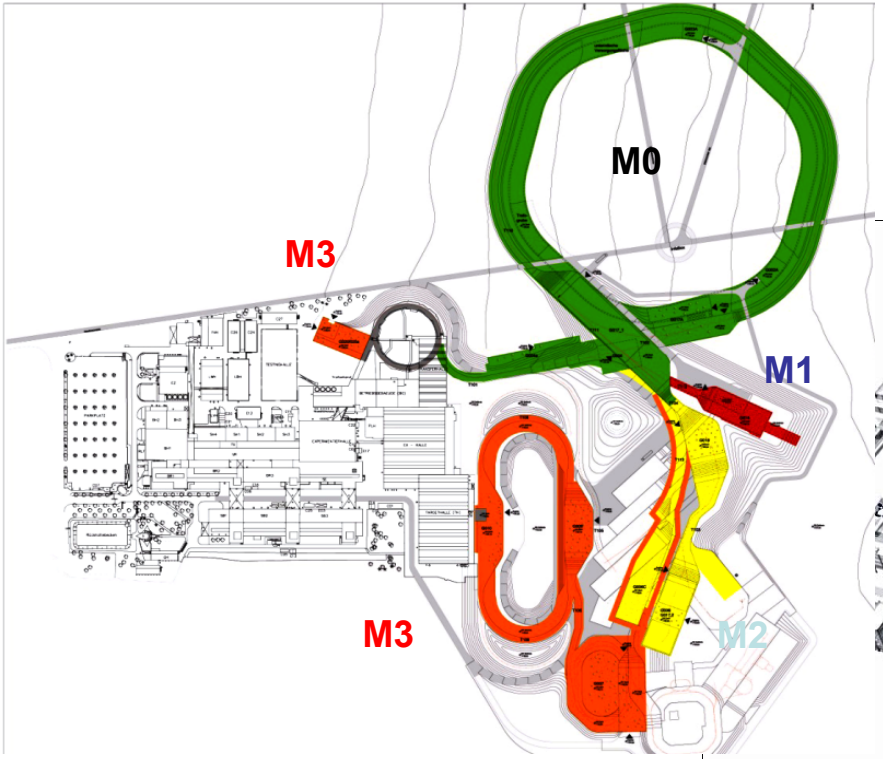


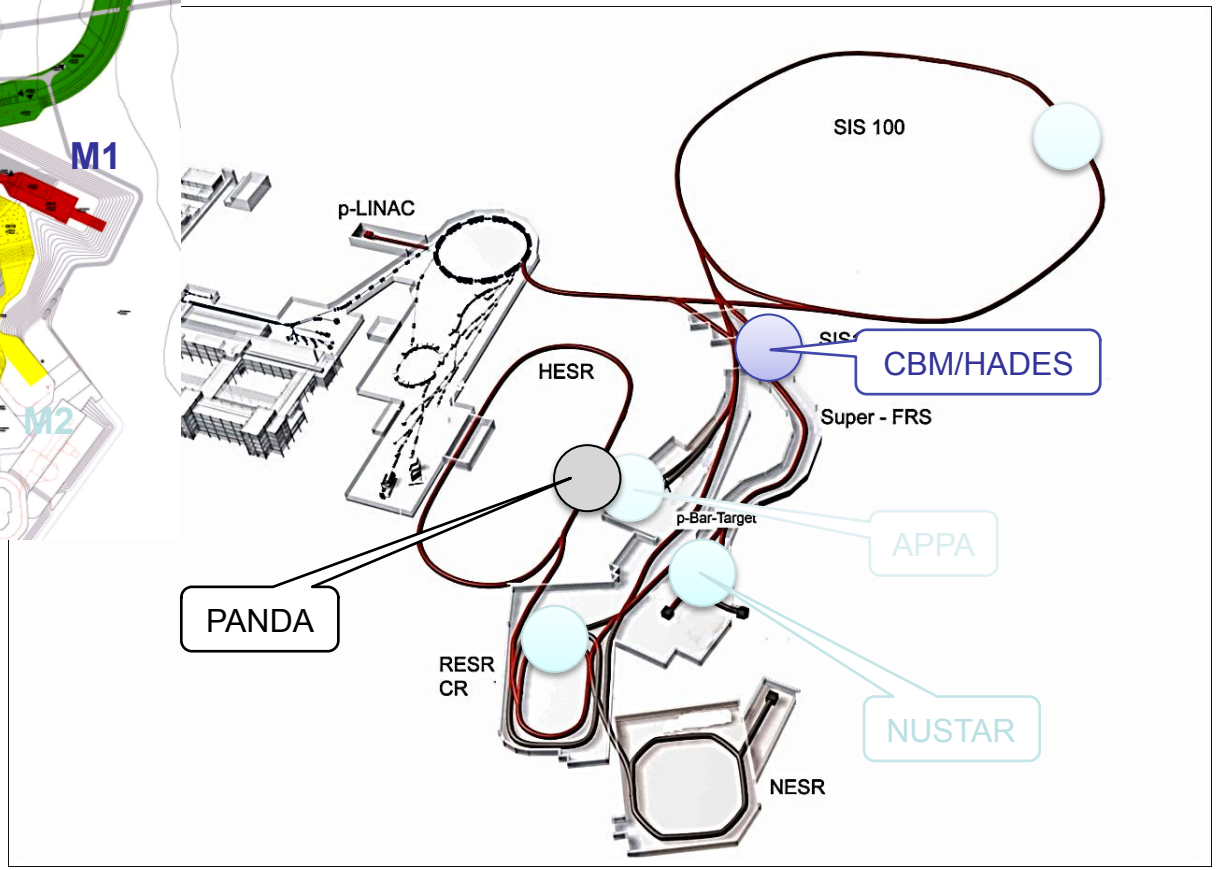
Panda



- Charmonium Spectroscopy
- QCD Exotics
- Hypernuclear physics
- Charm in nuclear matter

Modularised Start Version





Experiments

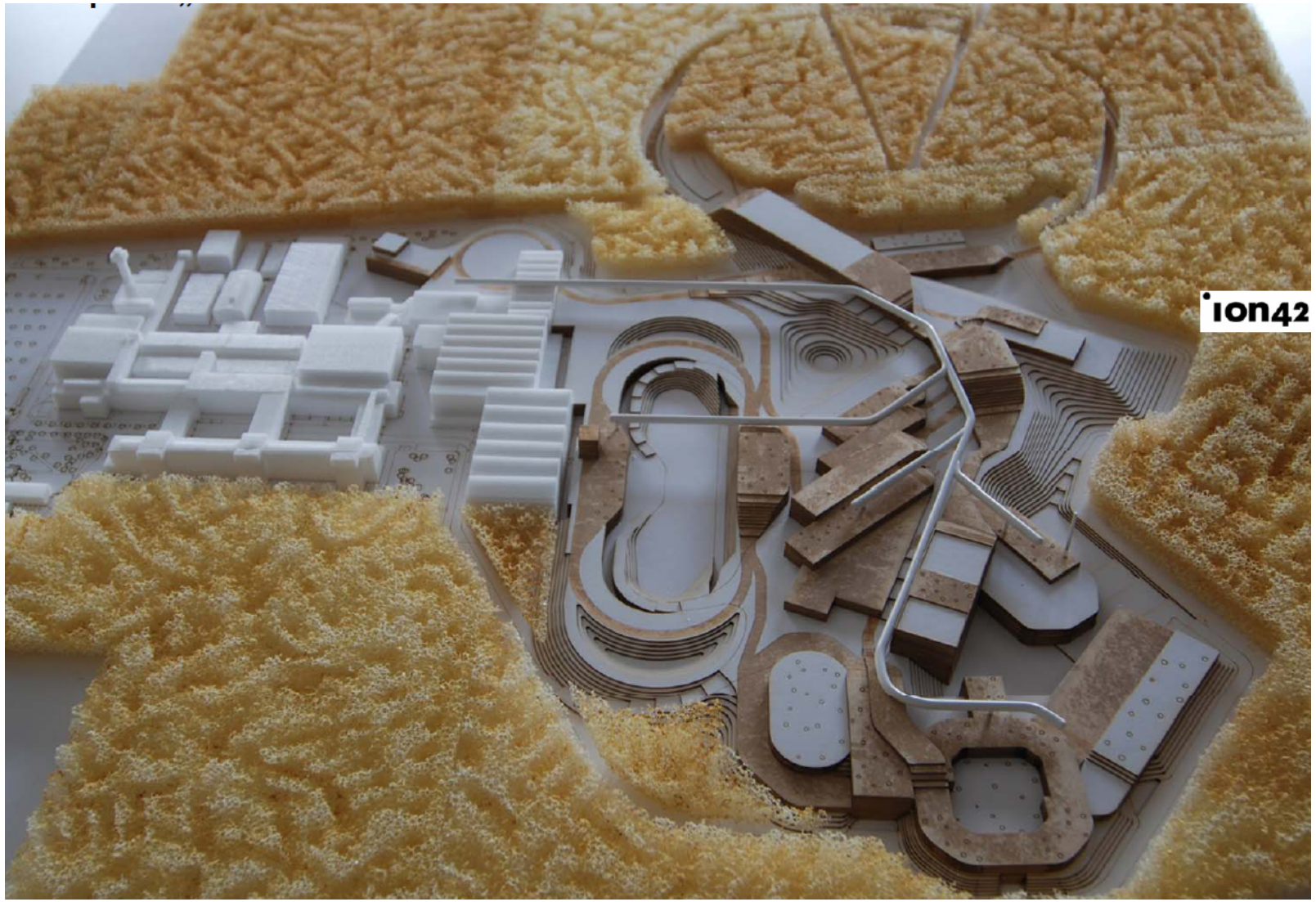
M1: APPA

M1: CBM/HADES

M2: NUSTAR

M3: PANDA

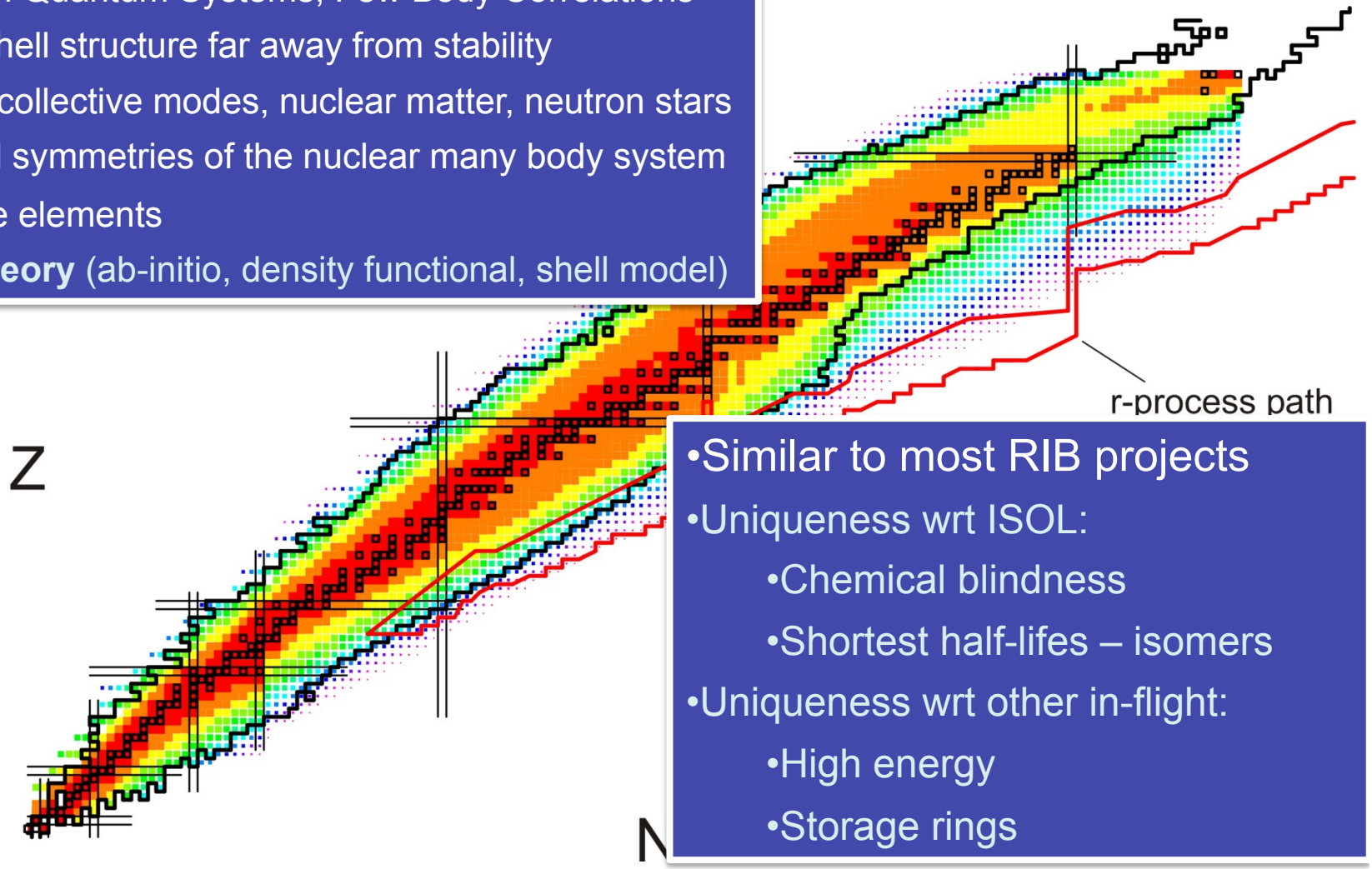
Civil Construction



Central Topics for NUSTAR at FAIR

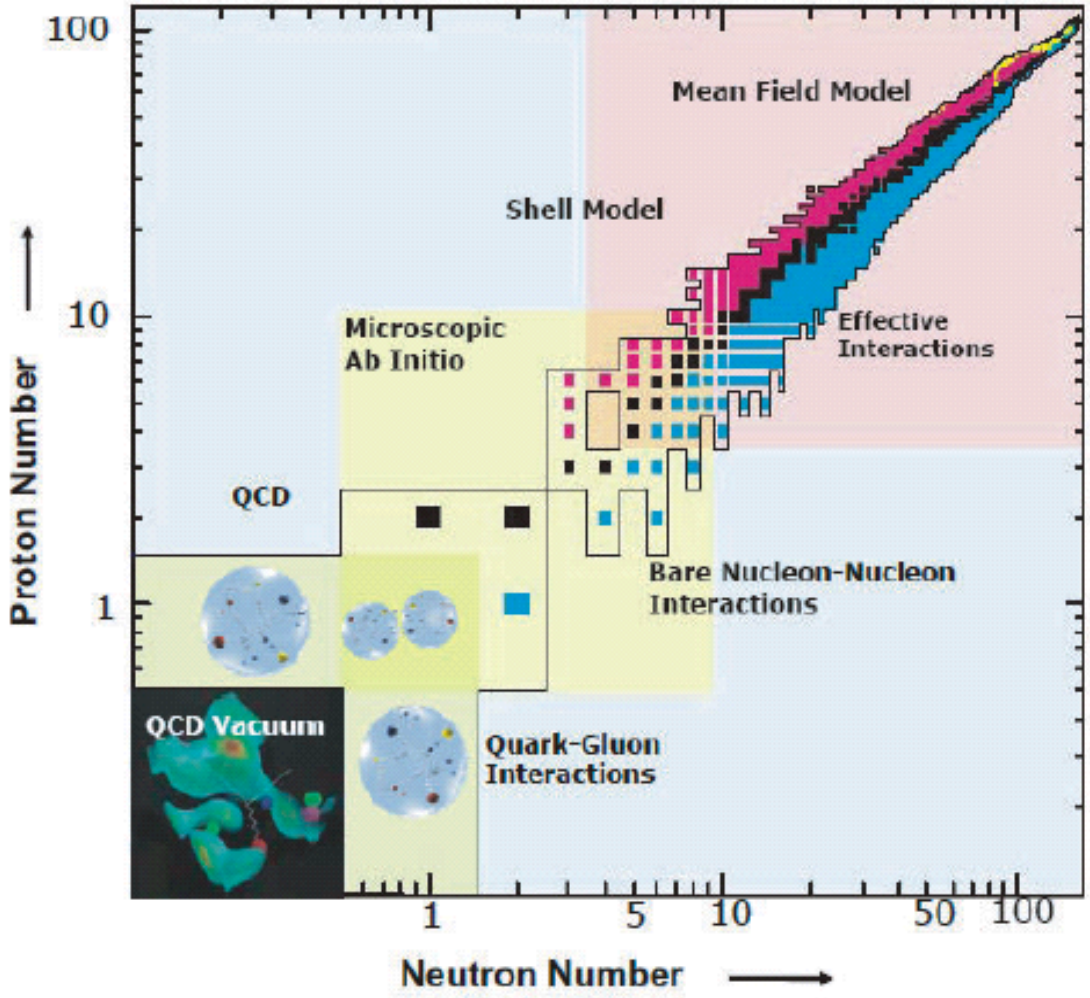
- Quest for the limits of existence
- Halos, Open Quantum Systems, Few Body Correlations
- Changing shell structure far away from stability
- Skins, new collective modes, nuclear matter, neutron stars
- Phases and symmetries of the nuclear many body system
- Origin of the elements

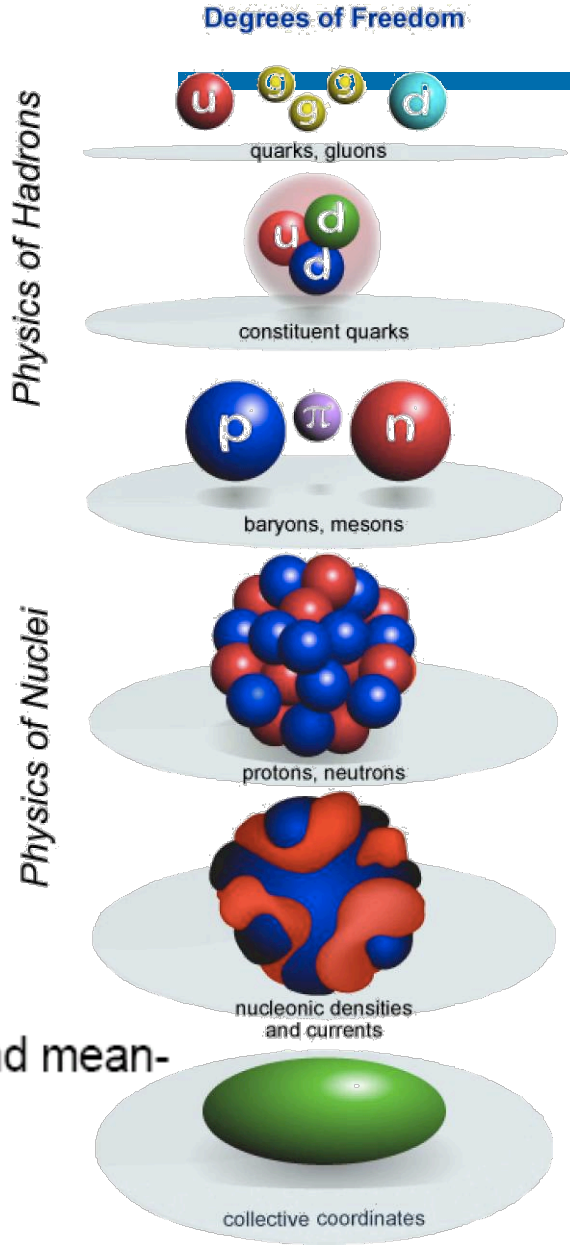
➔ **unified theory** (ab-initio, density functional, shell model)



- Similar to most RIB projects
- Uniqueness wrt ISOL:
  - Chemical blindness
  - Shortest half-lifes – isomers
- Uniqueness wrt other in-flight:
  - High energy
  - Storage rings

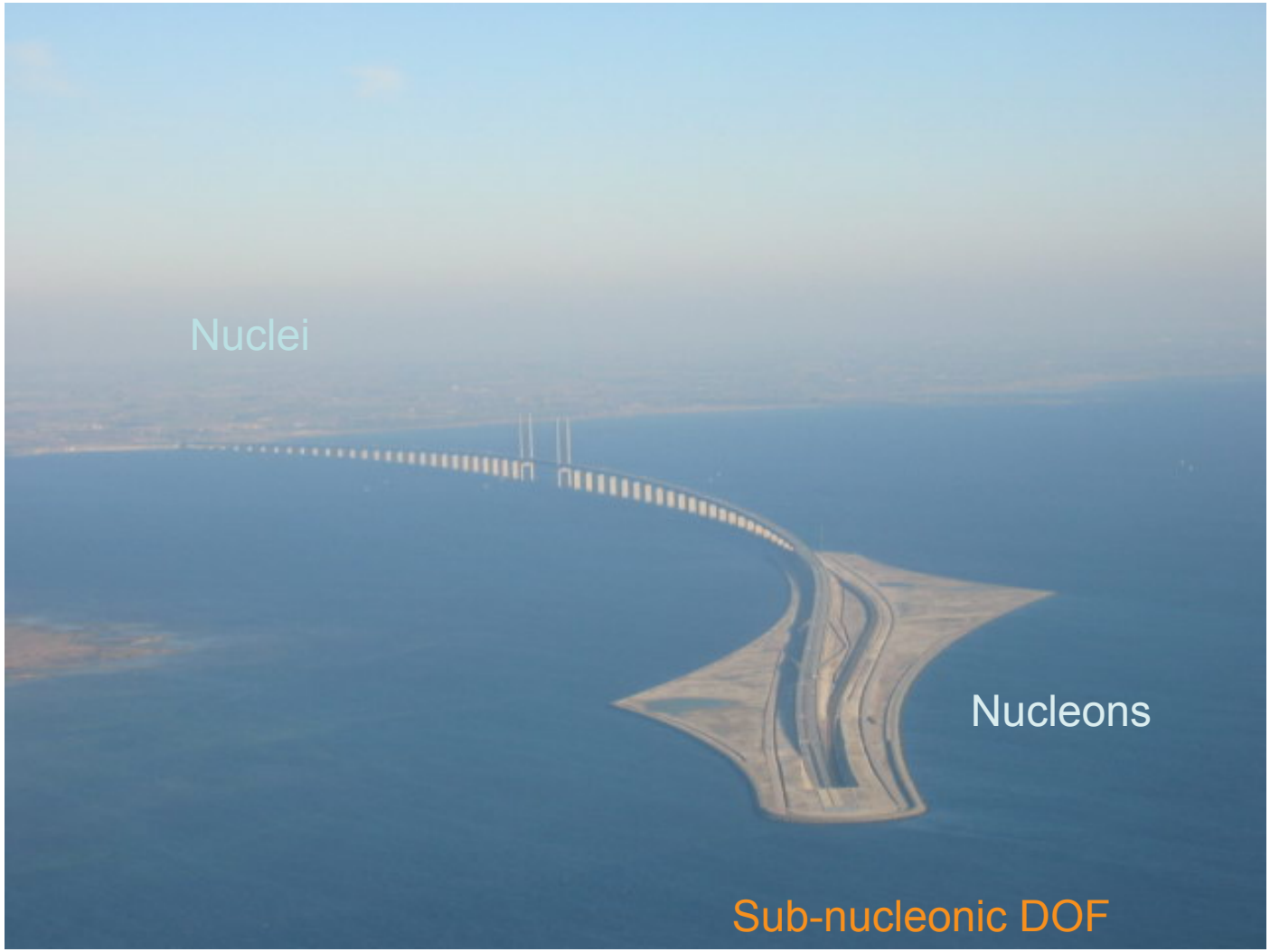
The chart of nuclei – a theoretical perspective



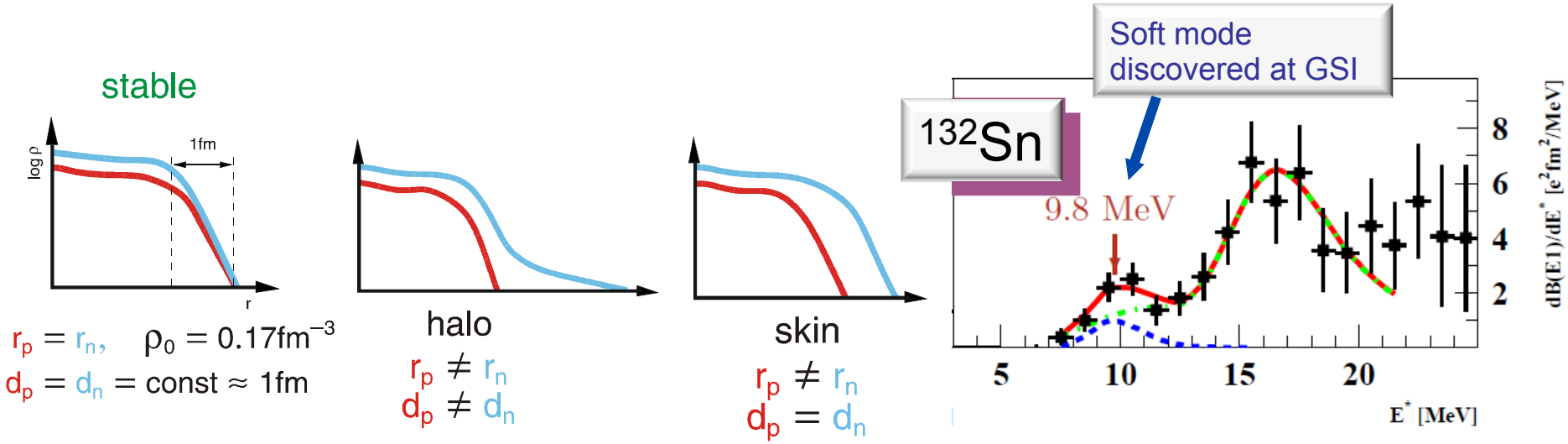


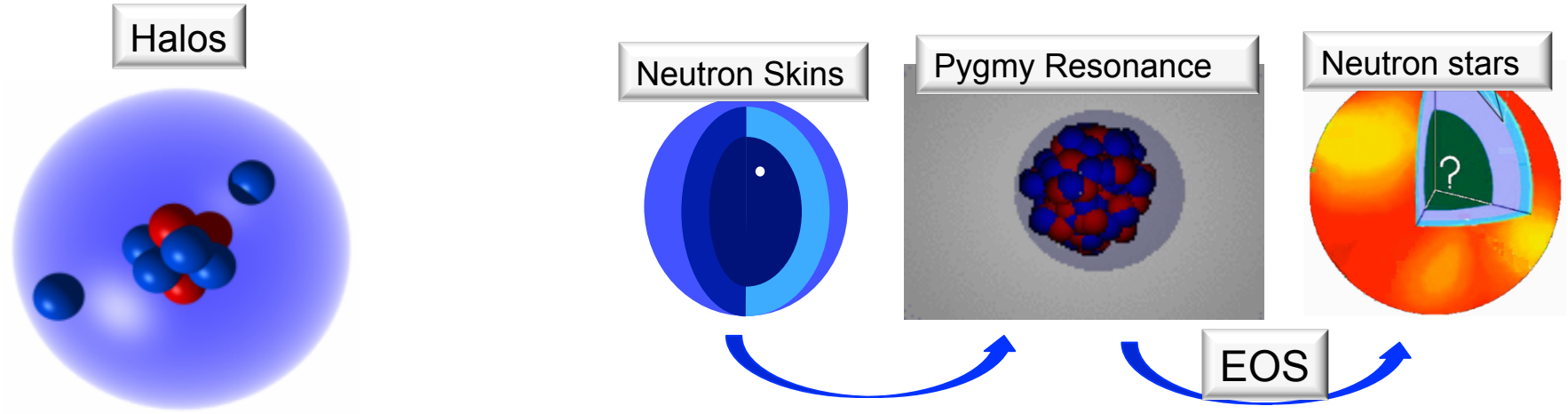
From QCD → effective field theories → nucleon-nucleon forces and mean-field models with effective interactions: small and tedious steps

Bridges?

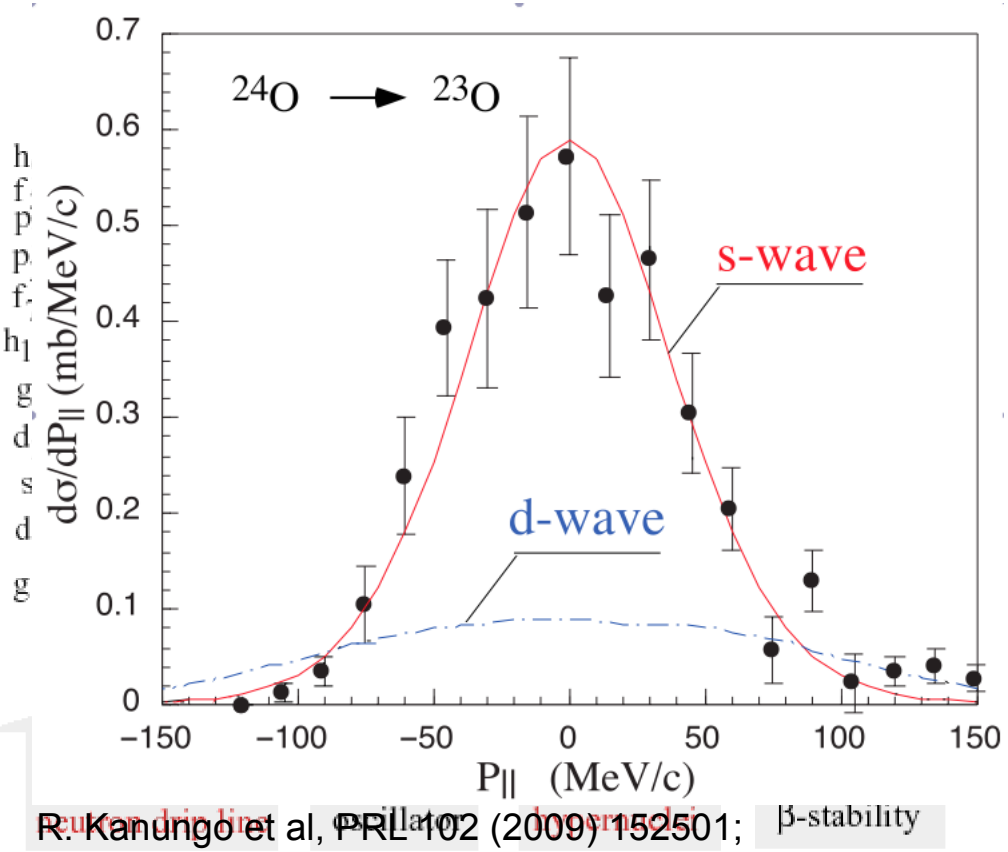


Neutron halos, skins – collective modes

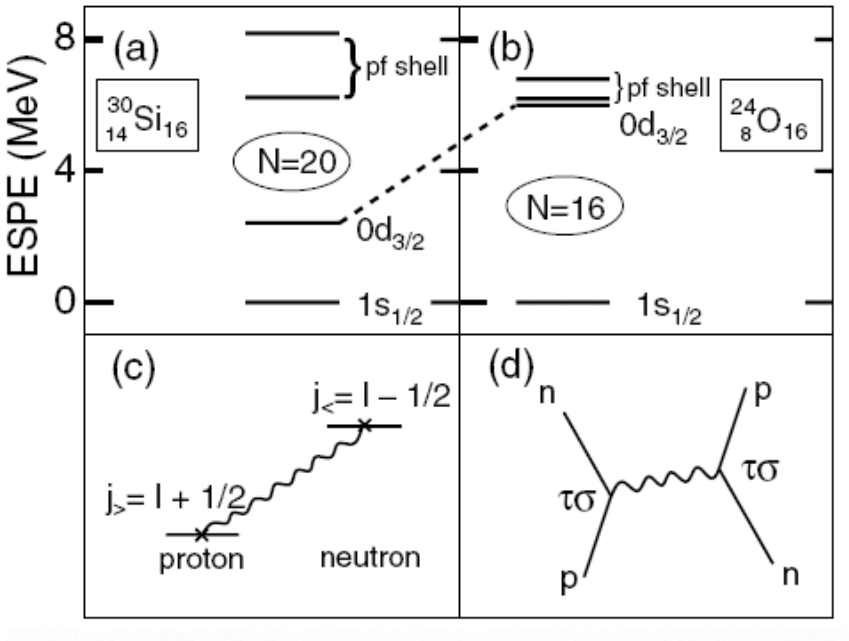




Drastic Changes in Shell Structure far from stability



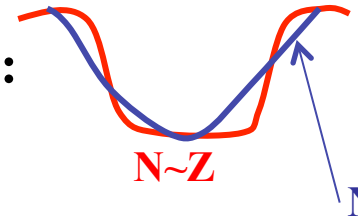
R. Kanungo et al, PRL 102 (2009) 152501;
R. V. F. Janssens, Nature 459 (2009) 1069



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

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

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

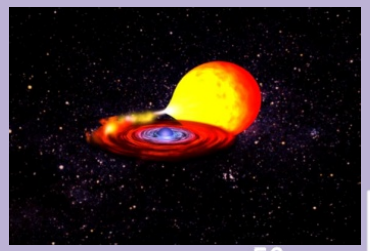


Shell quenching and reordering:
Transition from SO gaps (50,82,126)
to HO gaps (40,70,112)

Nuclear Astrophysics at FAIR

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

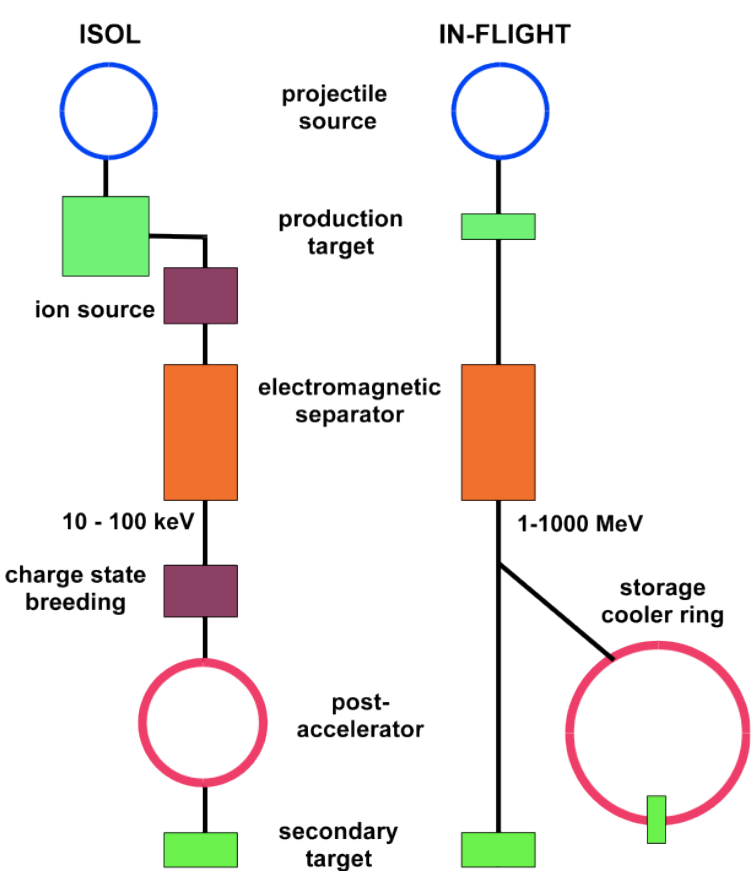


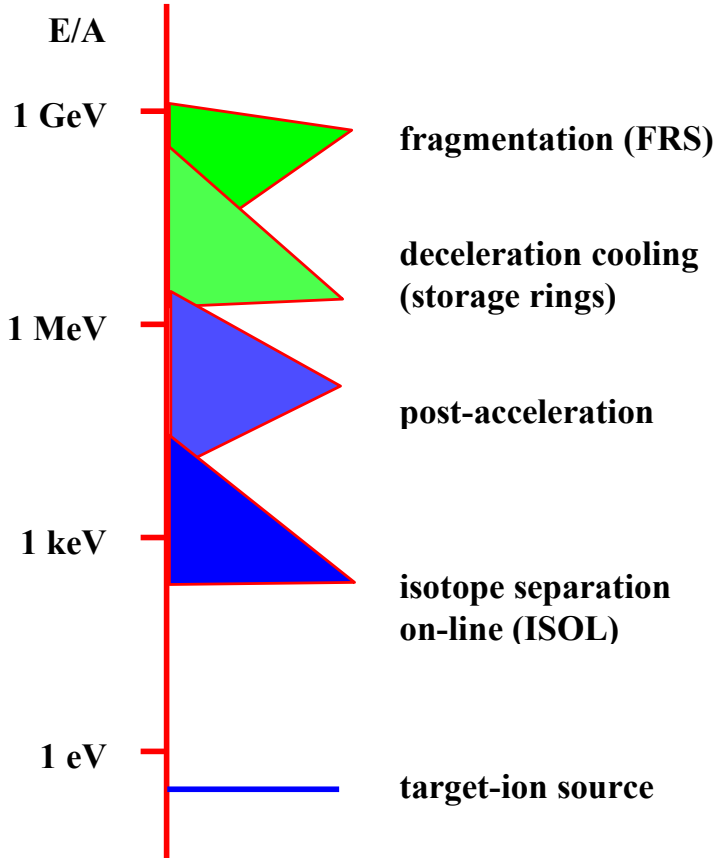
➔ **Session tomorrow**

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**

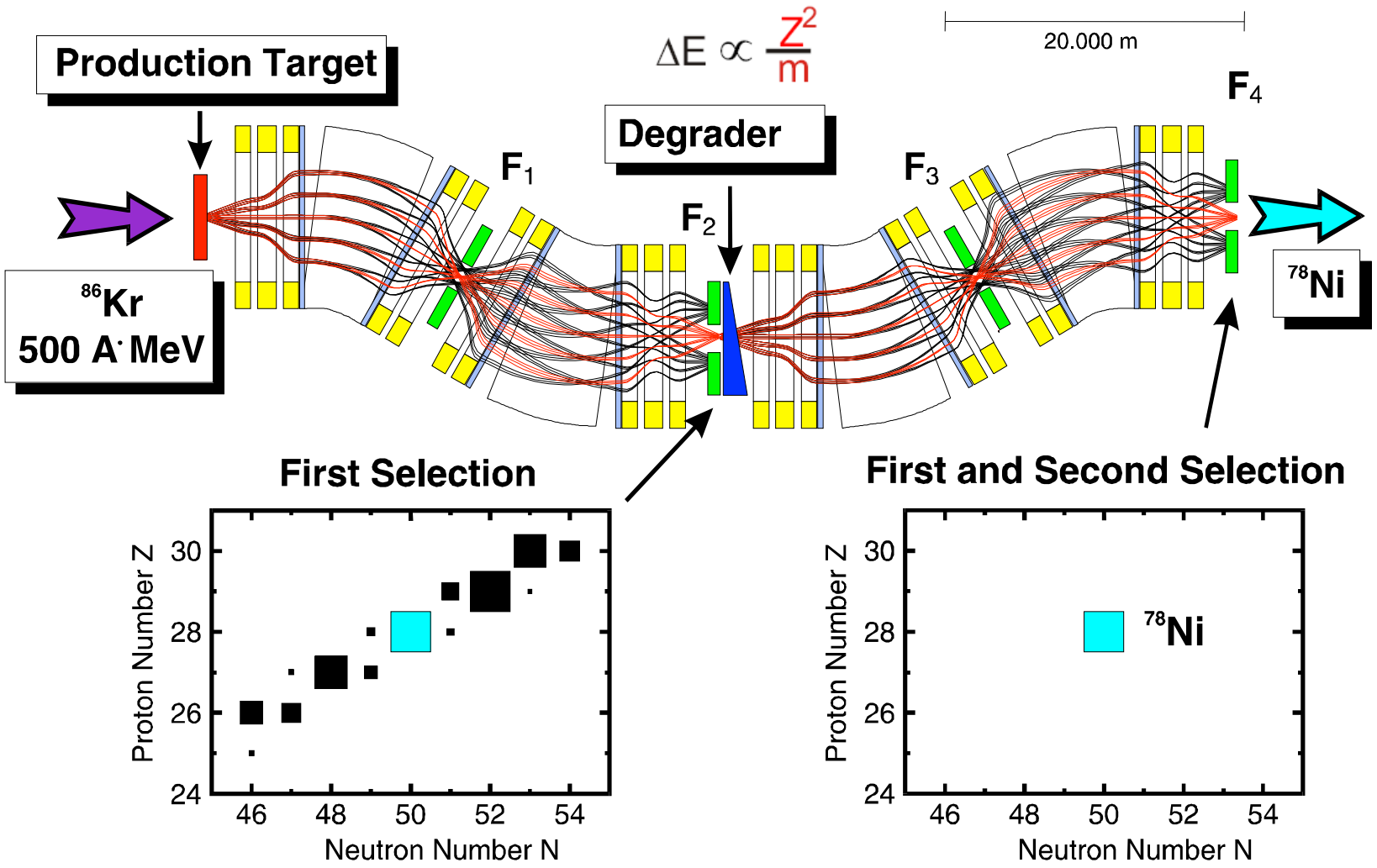
Radioactive beams – production and separation





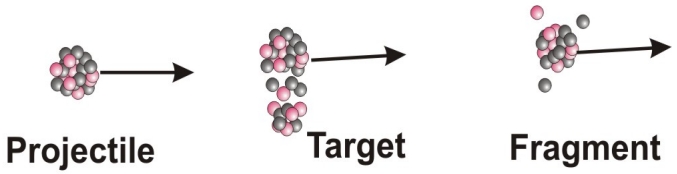
➔ **Previous + current session**

FRS@GSI Bρ - ΔE – Bρ separation Method



Production of exotic nuclei at relativistic energies

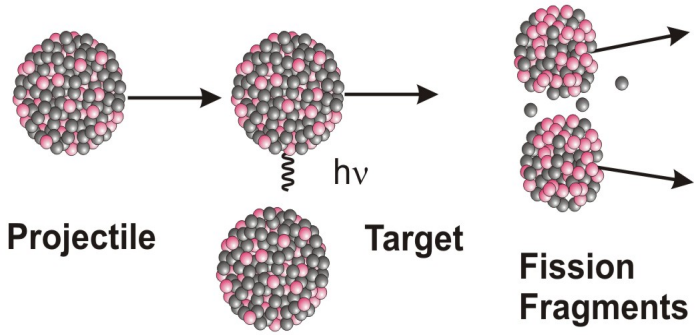
Projectile Fragmentation



Nucleon-nucleon collisions, abrasion, ablation

$$\vec{v}_f \approx \vec{v}_p$$

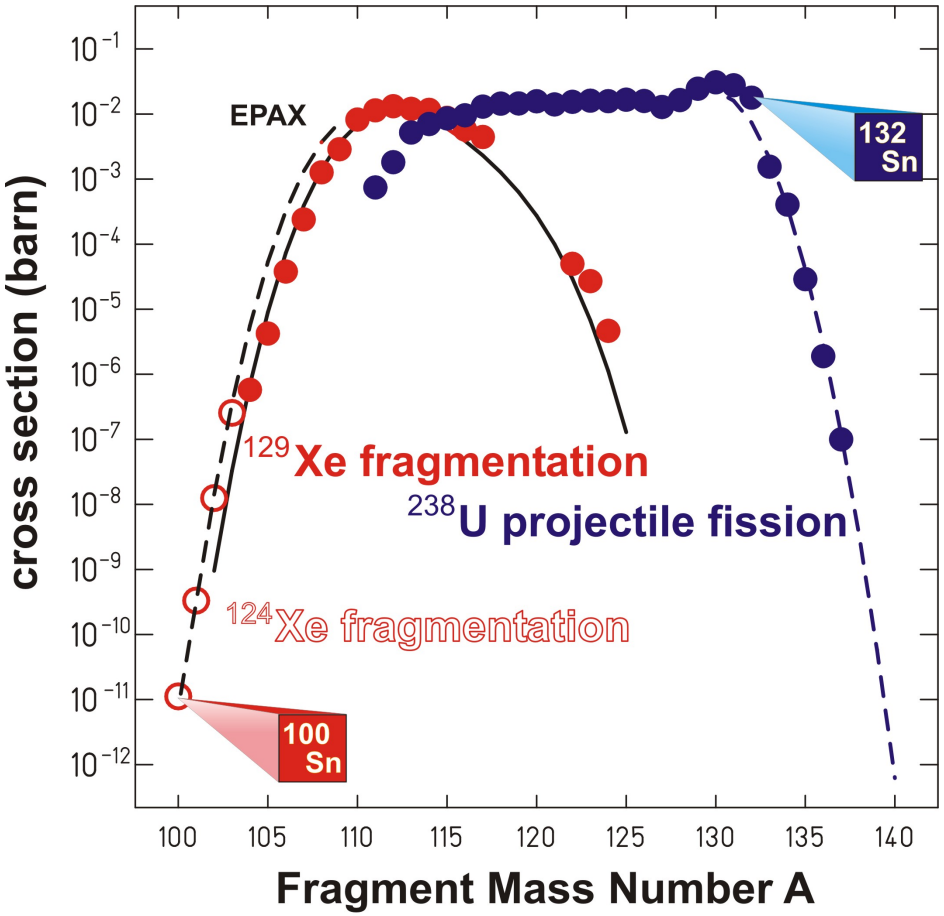
Projectile Fission



Electromagnetic excitation, fission in flight

$$\vec{v}_f \approx \vec{v}_p + \vec{v}_{fission}$$

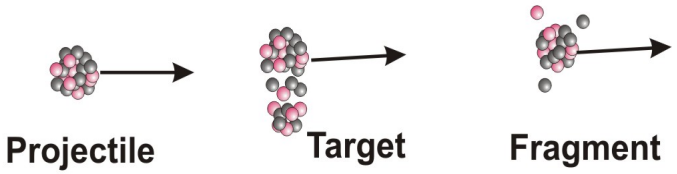
Sn isotope production



K.Sümmerer

Production of exotic nuclei at relativistic energies

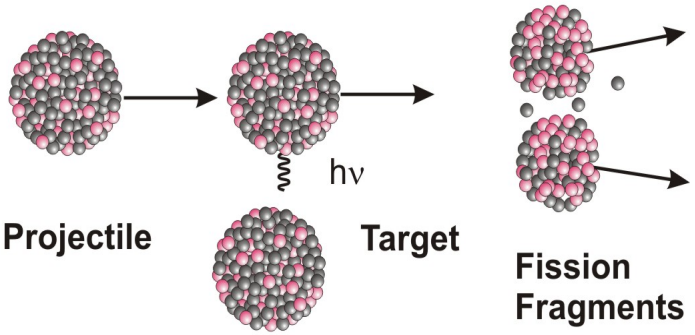
Projectile Fragmentation



Nucleon-nucleon collisions, abrasion, ablation

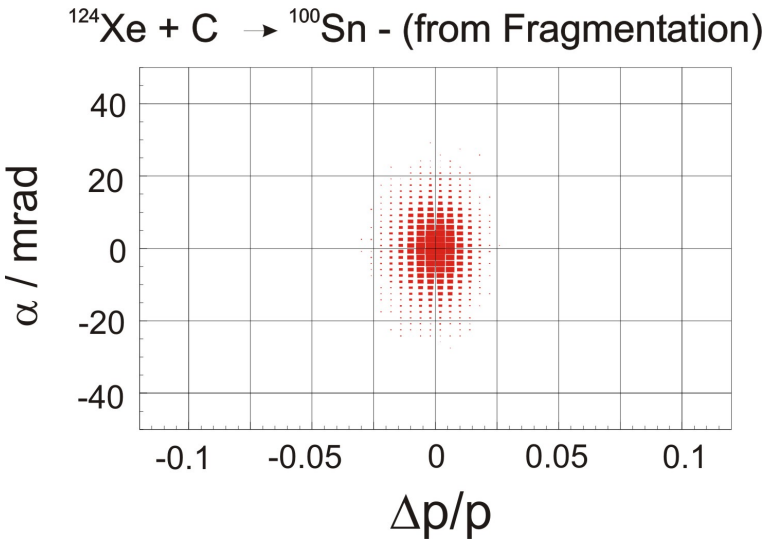
$$\vec{v}_f \approx \vec{v}_p$$

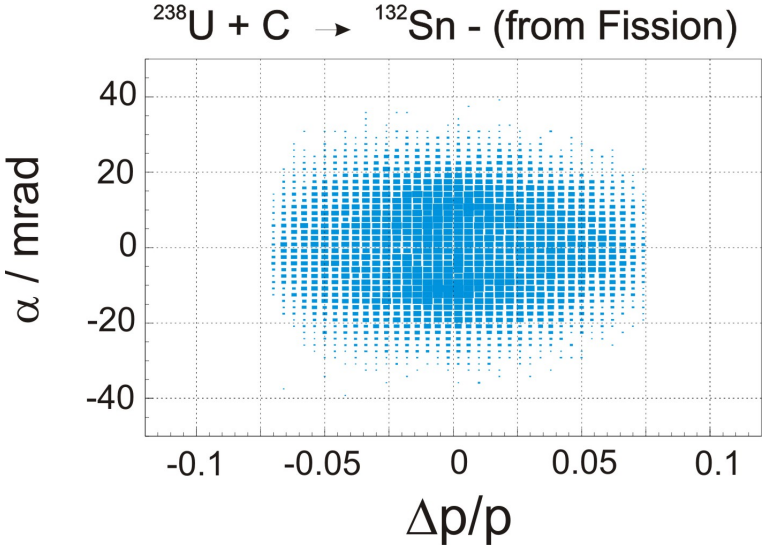
Projectile Fission



Electromagnetic excitation, fission in flight

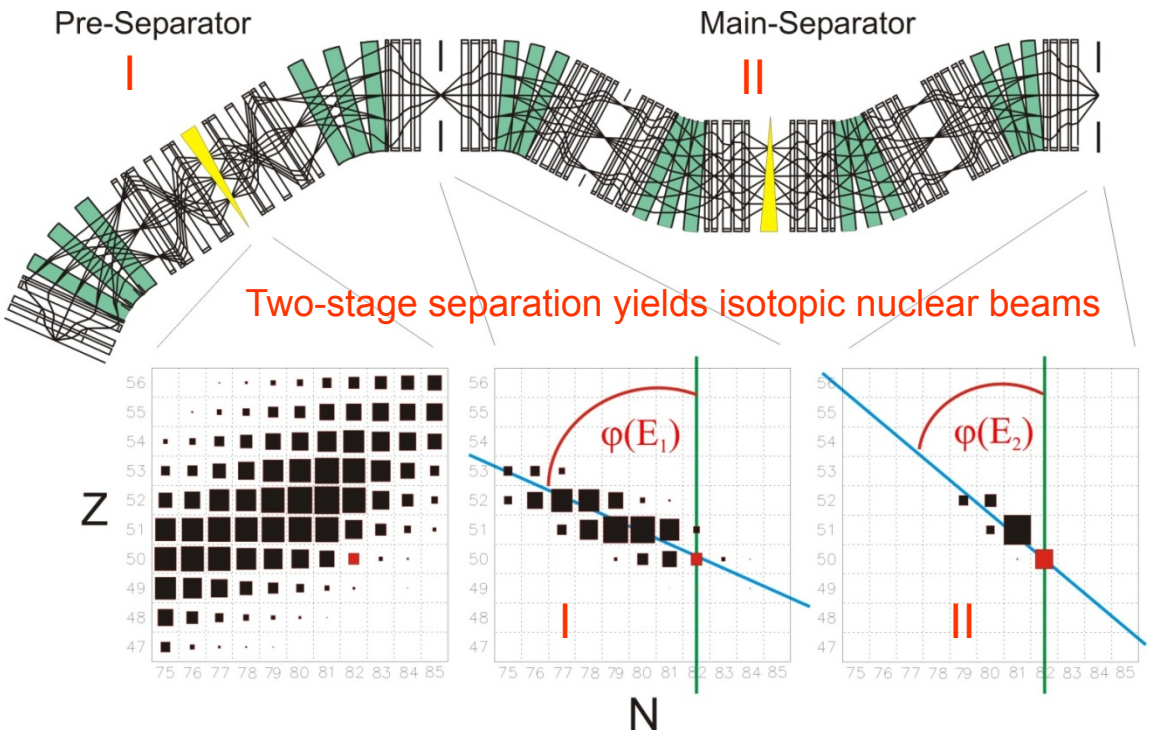
$$\vec{v}_f \approx \vec{v}_p + \vec{v}_{fission}$$

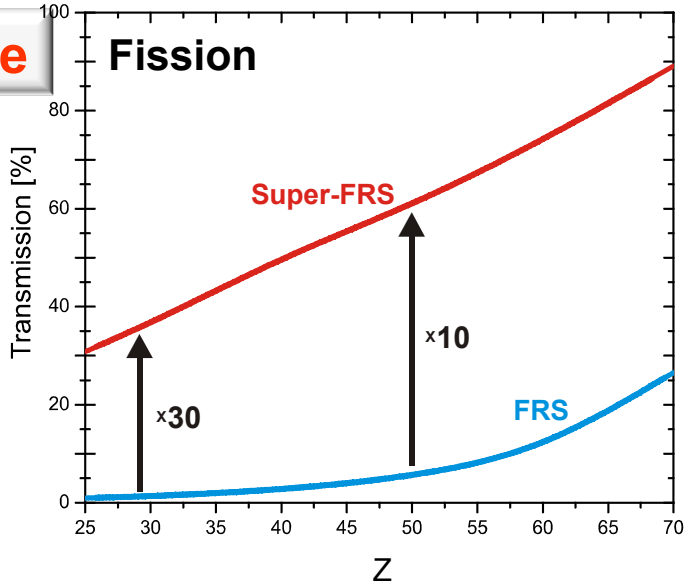


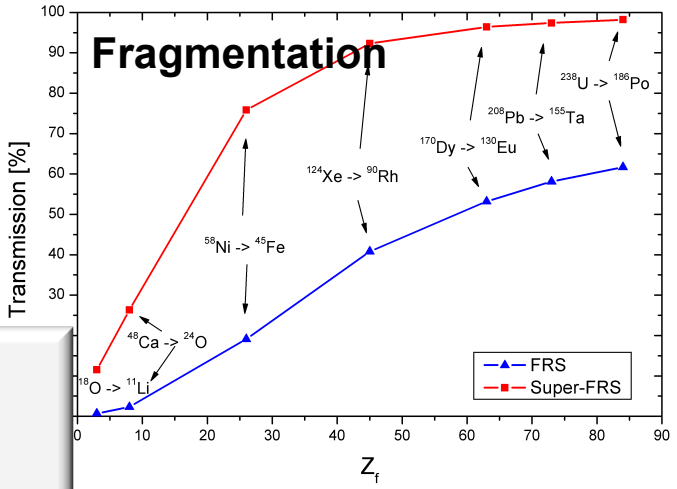


The Super-FRS

Central instrument for the NUSTAR programme



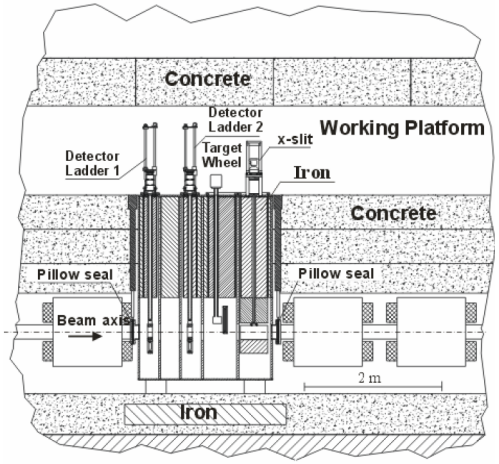




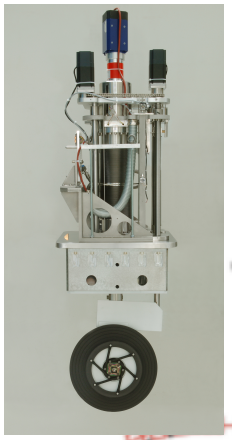
- High acceptance for projectile fragments and fission products
- Two-stage separation absolutely needed for clean beams
- **More than one order of magnitude transmission gain relative to FRS**

Super-FRS - Technical Challenges

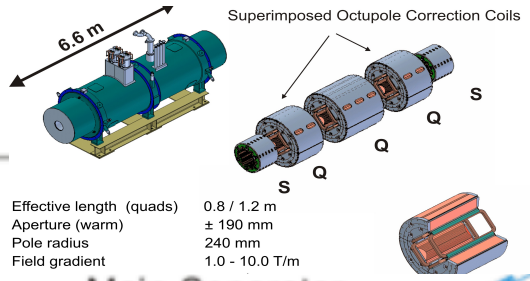
Remote Handling



Target & Beam Catcher

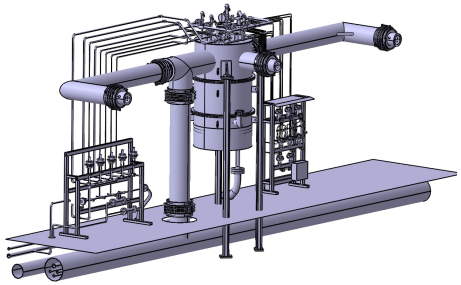


SC Multiplets



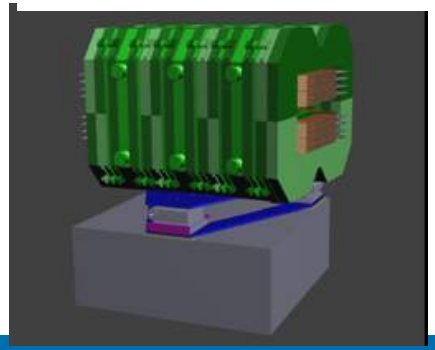
Effective length (quads)	0.8 / 1.2 m
Aperture (warm)	± 190 mm
Pole radius	240 mm
Field gradient	1.0 - 10.0 T/m

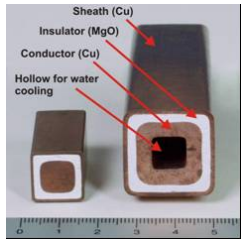
Cryogenics



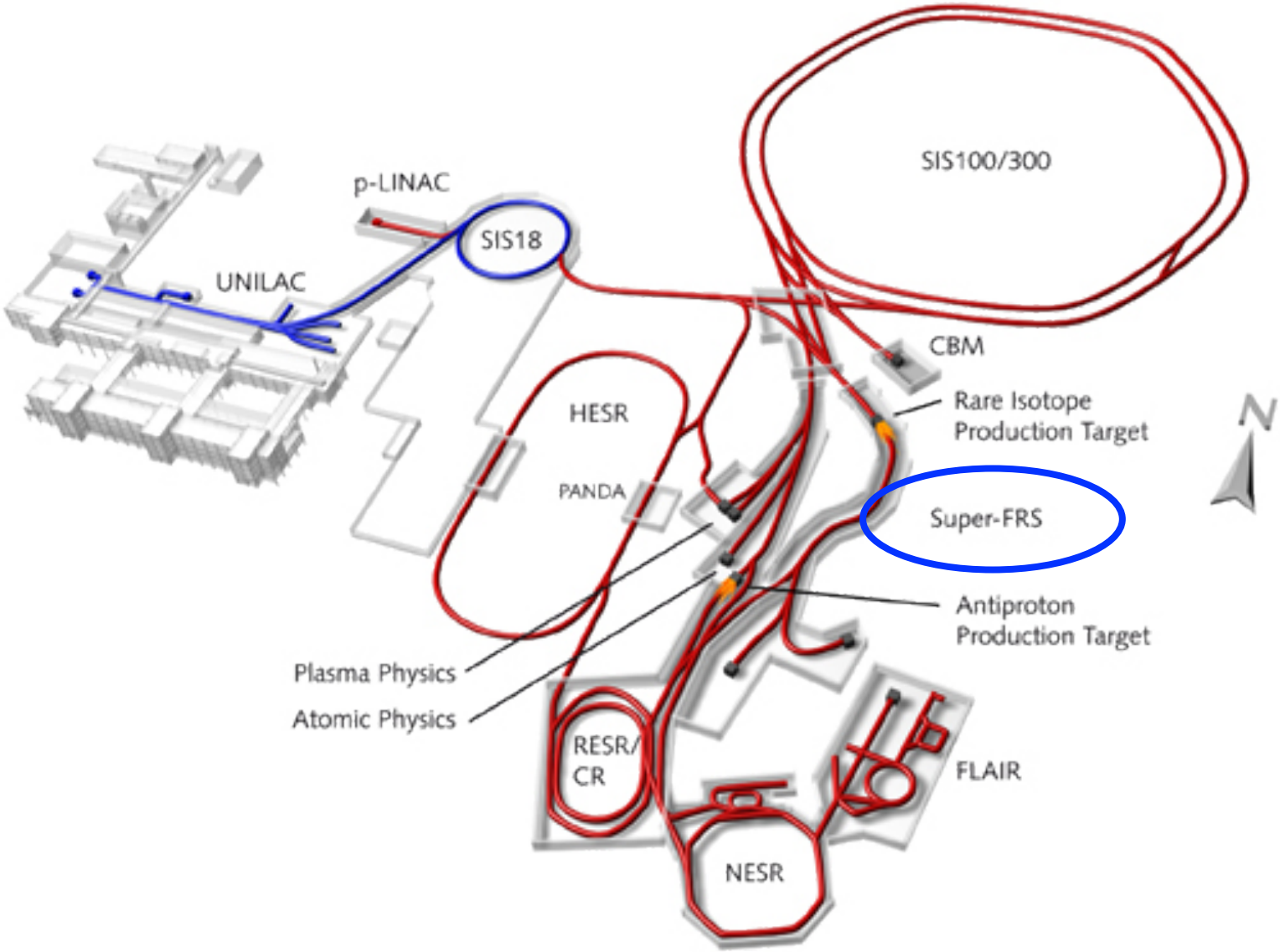
SC Dipoles

Radiation Resistant Magnets

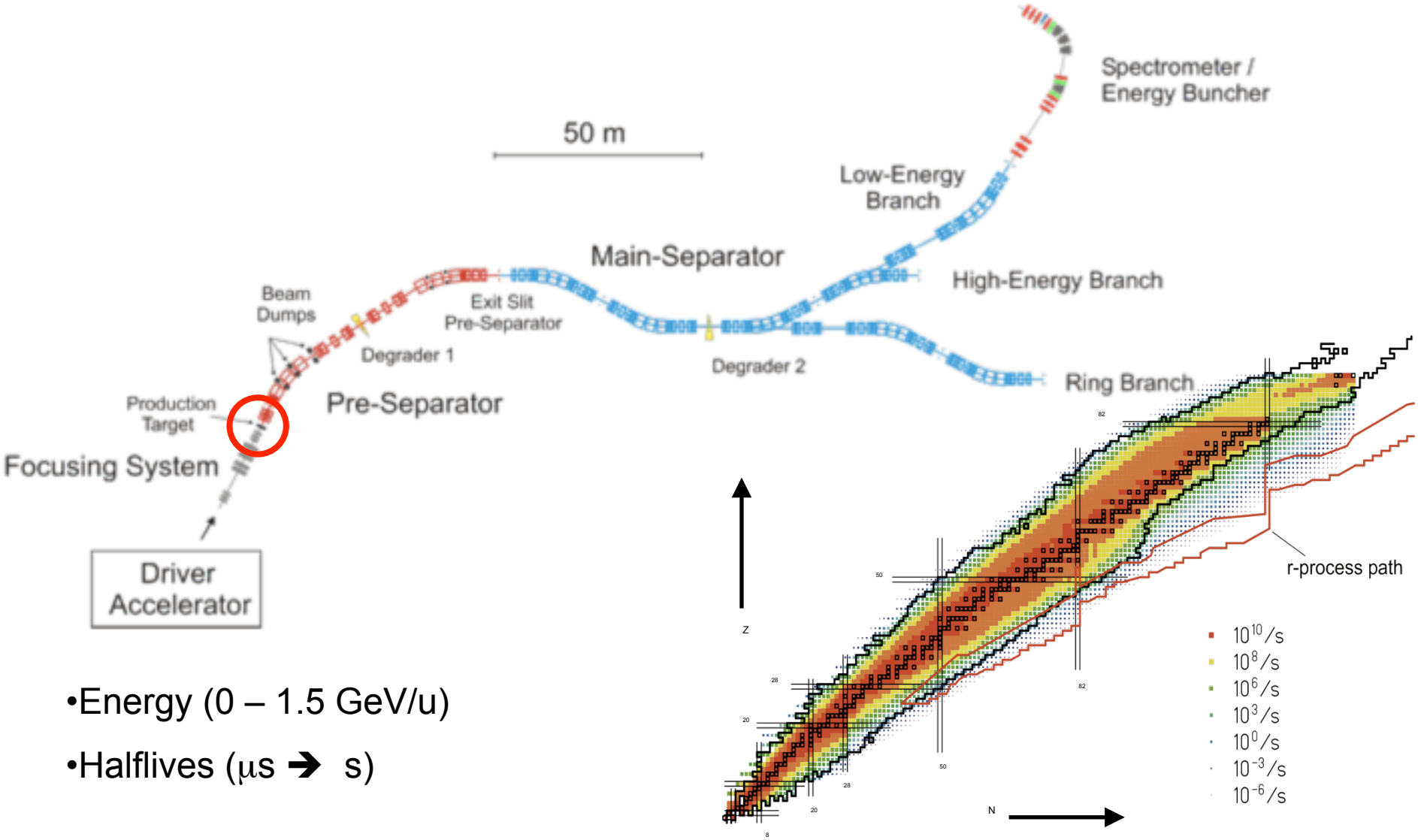




Facility for Antiproton and Ion Research



Super-FRS – radioactive beams at FAIR



- Energy (0 – 1.5 GeV/u)
- Halflives (μs ➔ s)

NUclear STructure, Astrophysics and Reactions

> 800 members from 37 countries and 146 institutions

Annual NUSTAR Collaboration Meeting@GSI Feb 29- March 2 2012

NUSTAR Experiments in the MSV

Nuclear reactions

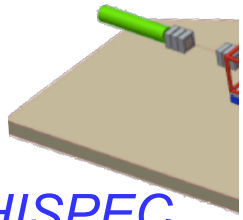
- Relativistic energies *R³B*
- High-res. spectroscopy *HISPEC*

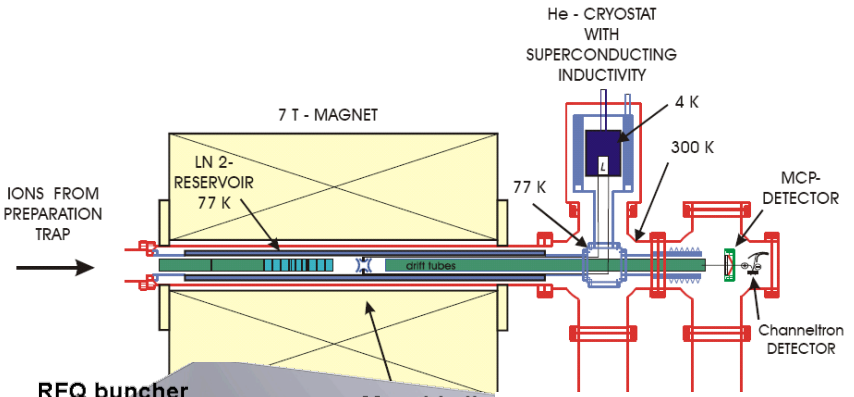
Decay properties

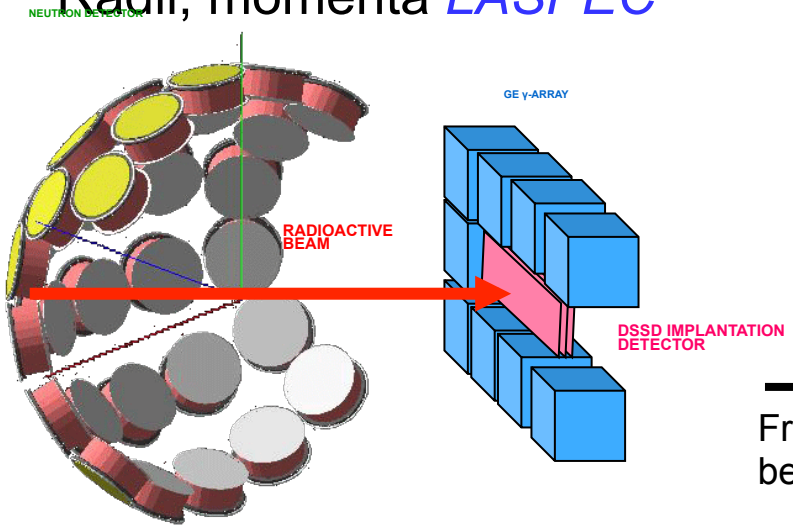
- Stopped beams *DESPEC*

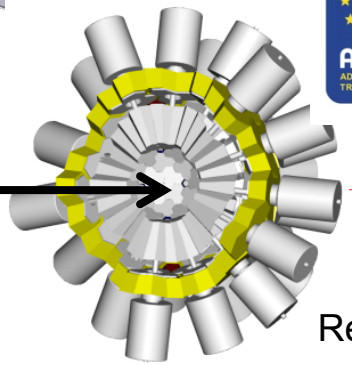
Ground state properties

- Masses *MATS, ILIMA*
- Radii, momenta *LASPEC*

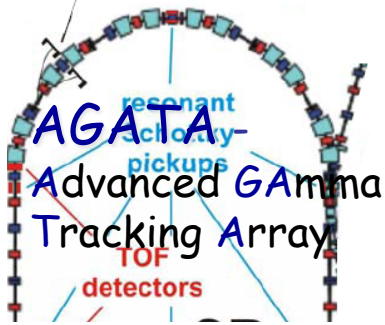


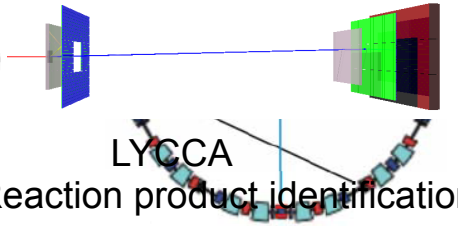






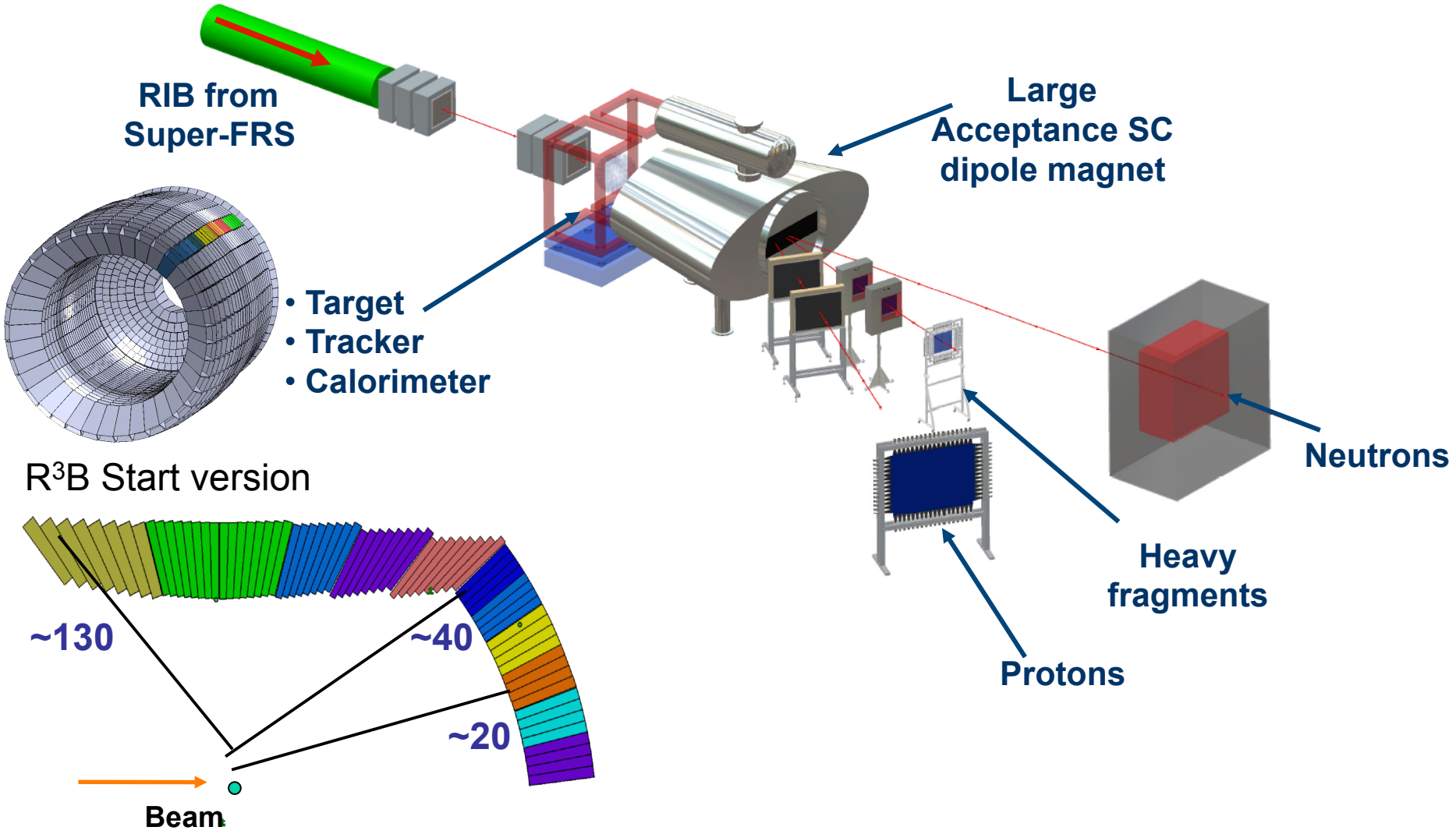
Fragment beam





LYCCA
Reaction product identification

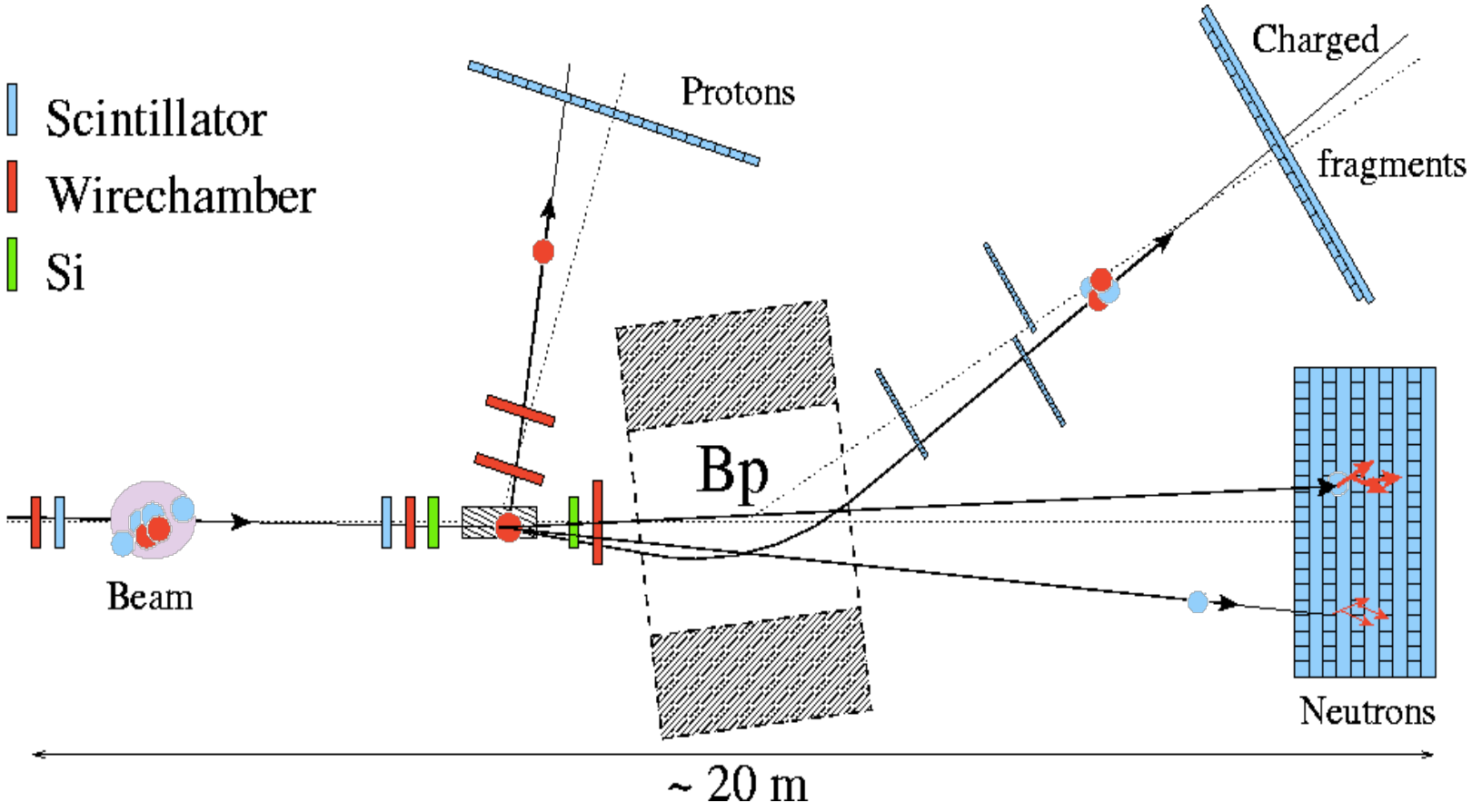
Reactions with Relativistic Radioactive Beams



R^3B reaction types

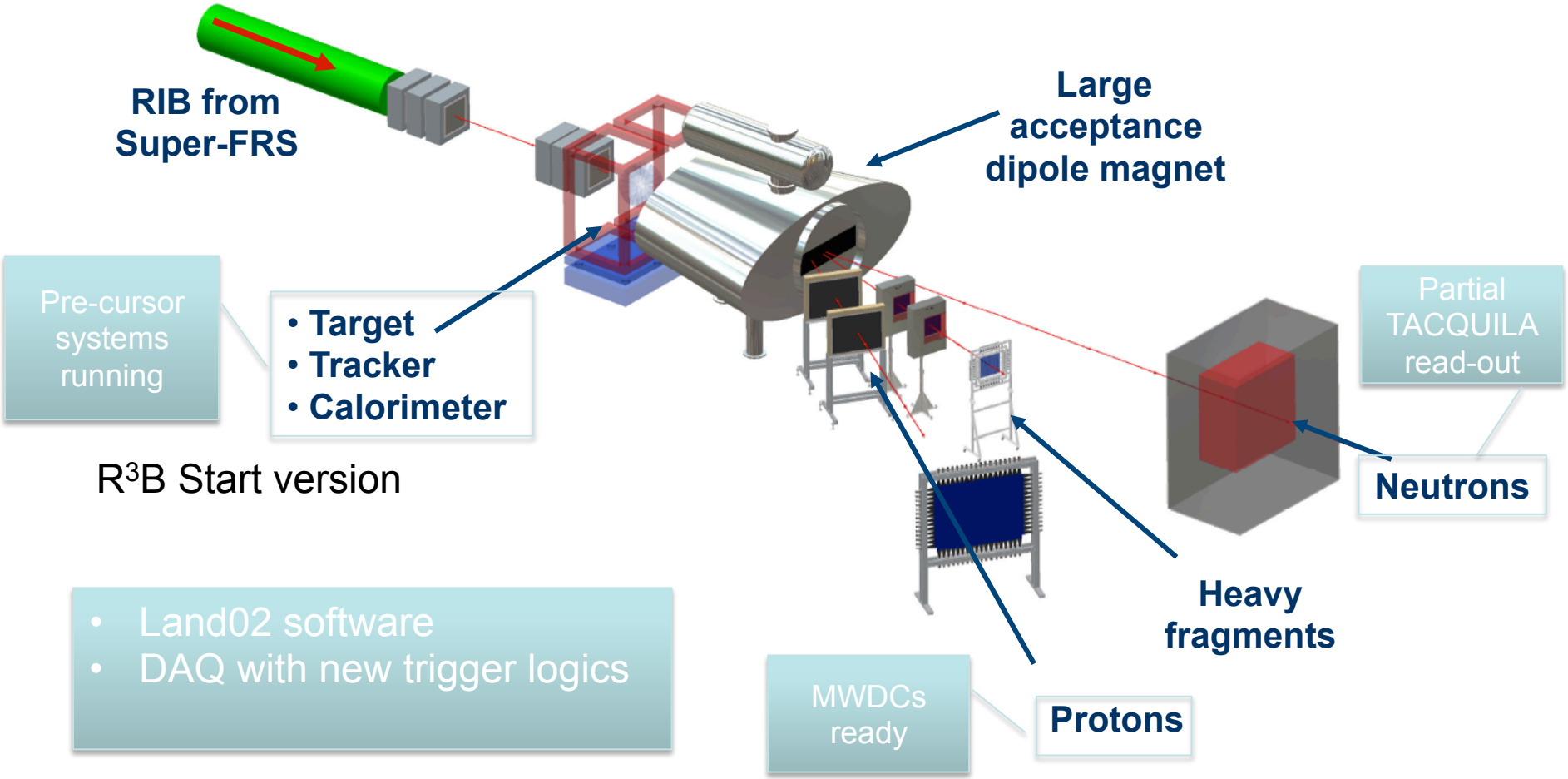
Reaction type	*Physics goals*
Knockout	Shell structure, valence-nucleon wave function, many-particle decay channels unbound states, nuclear resonances beyond the drip lines
Quasi-free scattering	Single-particle spectral functions, shell-occupation probabilities, nucleon-nucleon correlations, cluster structures
Total-absorption measurements	Nuclear matter radii, halo and skin structures
Elastic p scattering	Nuclear matter densities, halo and skin structures
Heavy-ion induced electromagnetic excitation	Low-lying transition strength, single-particle structure, astrophysical S factor, soft coherent modes, low-lying resonances in the continuum, giant dipole (quadrupole) strength
Charge-exchange reactions	Gamow-Teller strength, soft excitation modes, spin-dipole resonance, neutron skin thickness
Fission	Shell structure, dynamical properties
Spallation	Reaction mechanism, astrophysics, applications: nuclear-waste transmutation, neutron spallation sources
Projectile fragmentation and multifragmentation	Equation-of-state, thermal instabilities, structural phenomena in excited nuclei, γ-spectroscopy of exotic nuclei

Precursor activities with ALADIN/LAND@GSI



Data-taking since 1990

Reactions with Relativistic Radioactive Beams

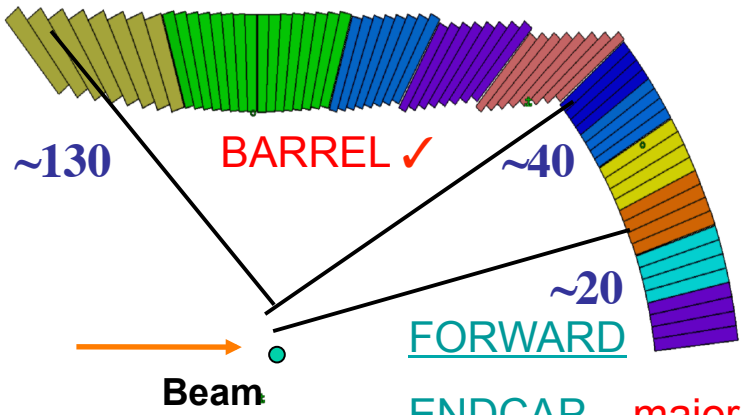


R^3B Start version

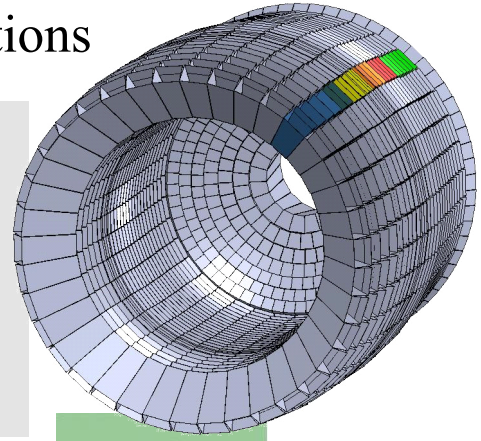
- Land02 software
- DAQ with new trigger logics

CALIFA/R³B R&D

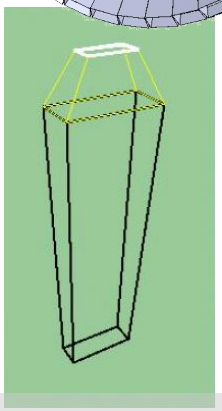
General design of the detector based on kinematical considerations



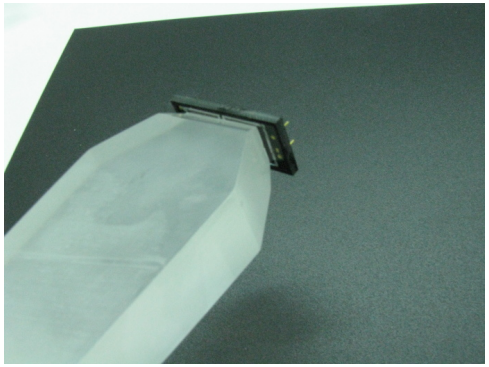
- "Egg" shape
- Highly segmented
- Thick detection volume
- Scintillation based
- Performant photo-sensors



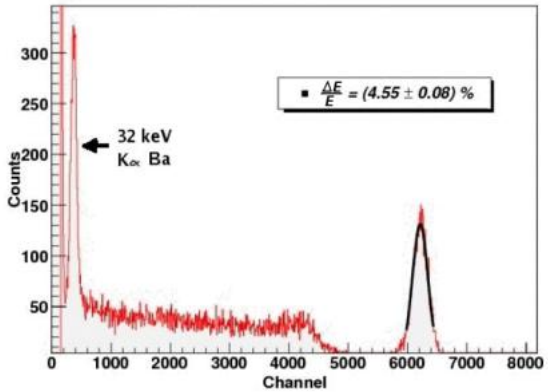
ENDCAP – major challenge!
LaBr/LaCl Phoswich?



Crystal and photosensors
Barrel → CsI+APD



1cm³ and 662 keV γ



Real shape, 1MeV γ

→ ΔE/E ~ 5 %

TDR submitted, evaluation ASAP

WG Coordinator: Dolores Cortina-Gil, Univ. Santiago de Compostela

Neutron detector NeuLAND

Working group coordinator: K. Boretzky (GSI)

Existing LAND detector:

- $\sigma_t < 250$ ps
- $\sigma_{x,y,z} \approx 3$ cm
- Size: 2 x 2 x 1 m^3
- Plastic scintillator / Fe converter sandwich structure

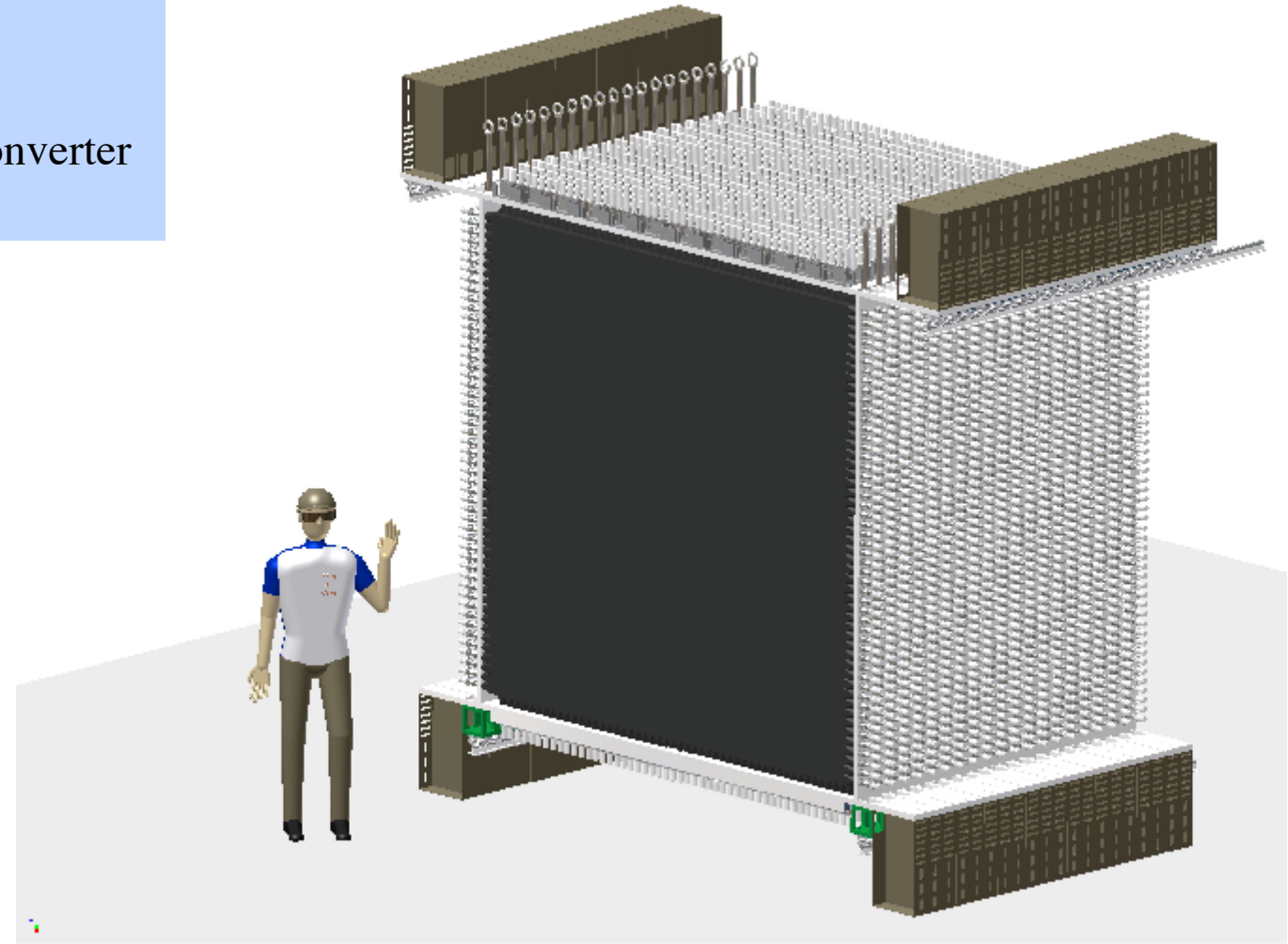
NeuLAND :

20 XY-Planes

2000 Paddles

4000 Photomultiplier

Weight: ca. 19000 kg

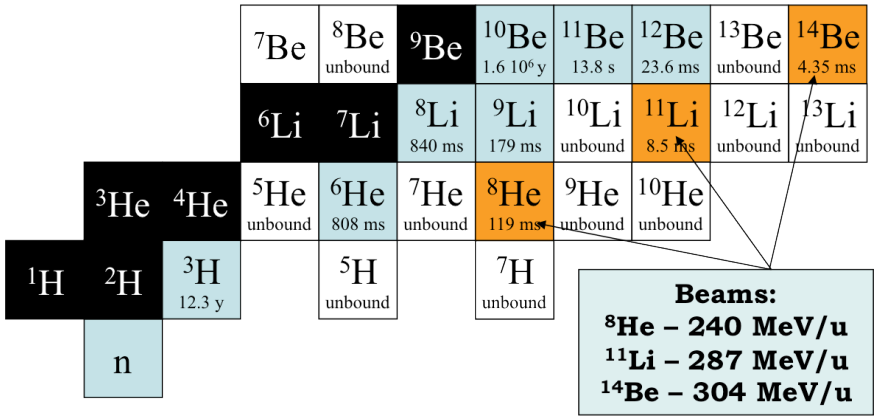


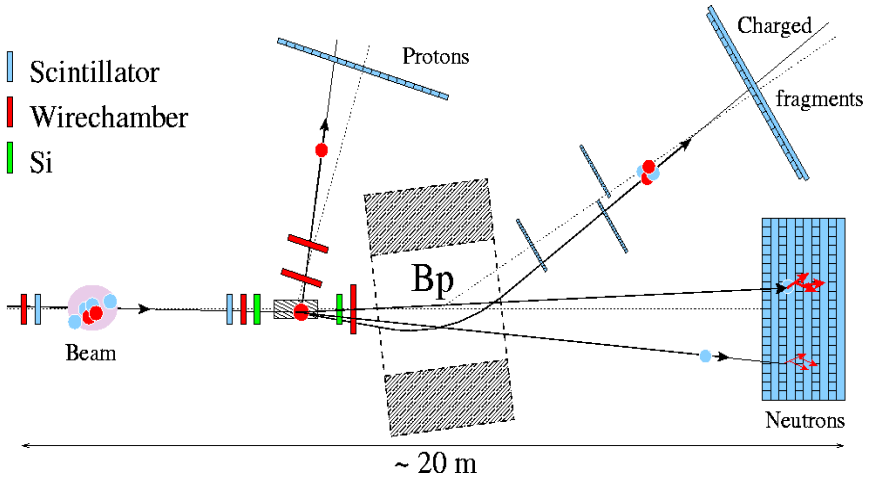
Improvement of multi-n recognition

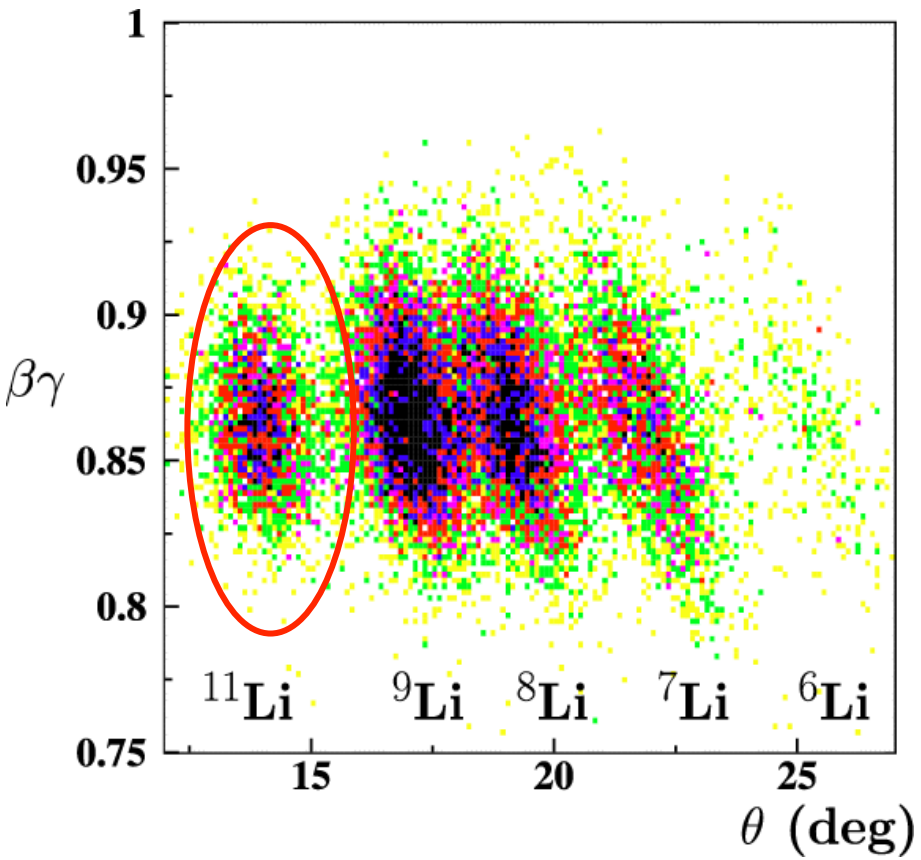
TDR submitted, evaluation ASAP

Proton knockout from 304 MeV/u ^{14}Be

S245@GSI

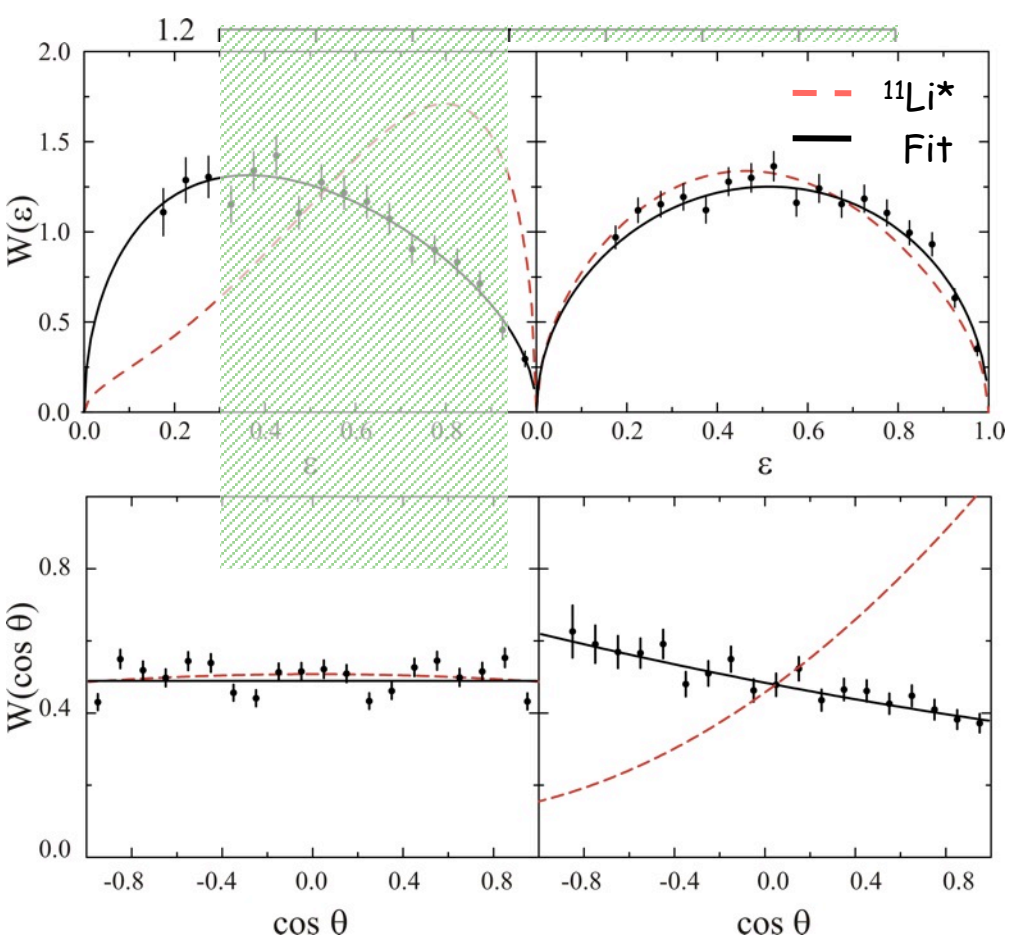


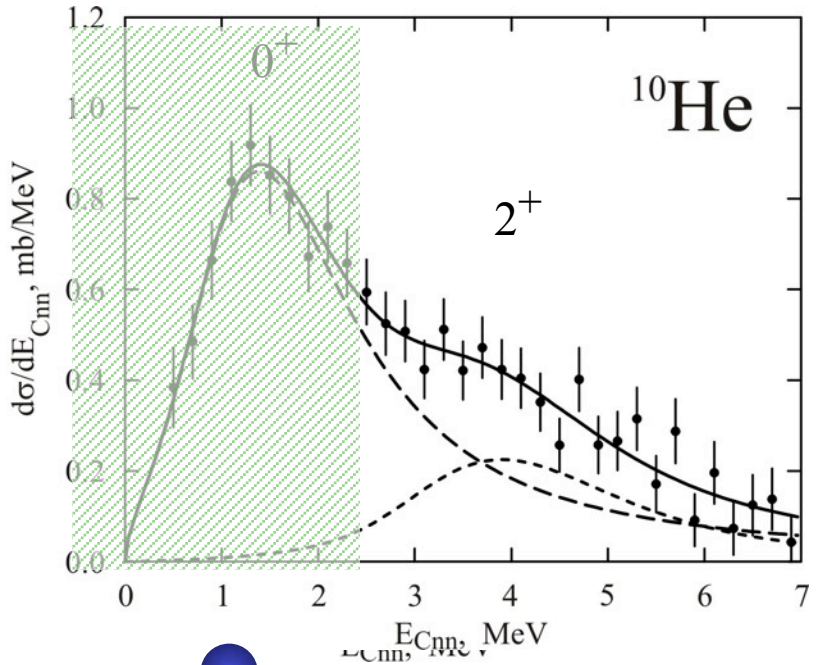


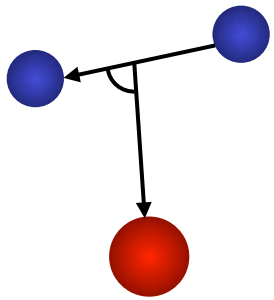


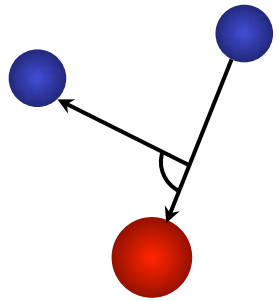
Yu. Aksyutina *et al*. PLB 666(2008)430

Relative-energy spectrum of $^{1}H(^{11}Li,2p)^{10}He$









H.T. Johansson et al, Nucl. Phys. A847(2010)66-88, doi:10.1016/j.nuclphysa.2010.07.002

➔ talk by H. Simon

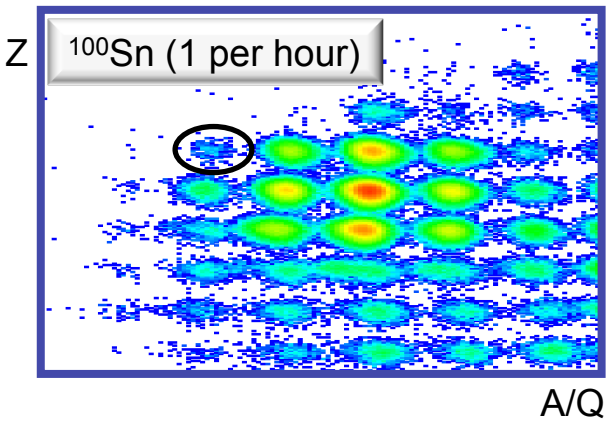
Yu. Aksyutina

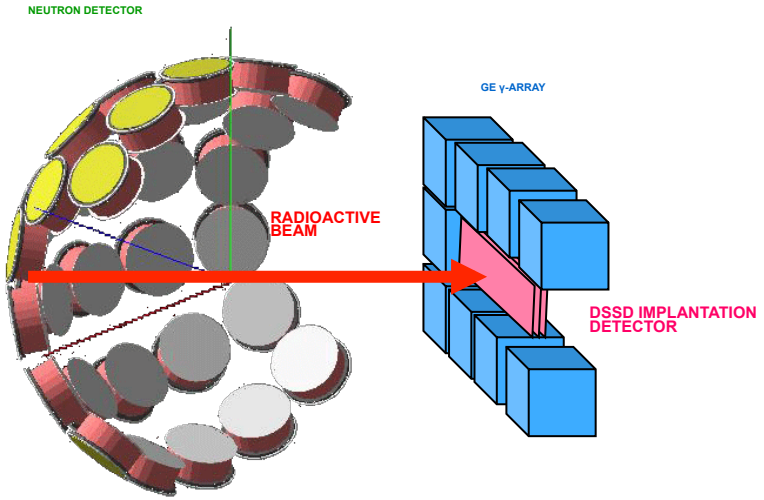
DESPEC

DESPEC: decay spectroscopy using gamma-ray spectroscopy and neutron detection following isomeric or beta-decay of very exotic nuclei

- Gamow Teller strength (short range correlations, nucleosynthesis, supernovae)
- Structure along the proton drip-line (proton radioactivity, rp-process)
- Structure of r-process nuclei (shell evolution, r-process path)
- g-factors and lifetimes of isomers (evolution of shells and collectivity, nuclear shapes)

- **Experiments possible with stopped beams & production rates down to 1 isotope per hour**
- **farthest reach towards the drip lines**





HISPEC

HISPEC: high resolution in-flight gamma-spectroscopy

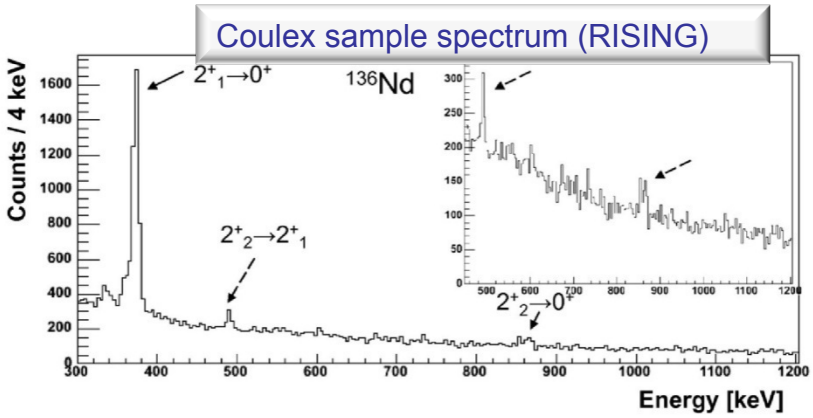
- Excited states in exotic nuclei
  - Inelastic excitation (EM, hadronic), secondary fragmentation, knock-out
- Lifetimes and g-factors of short-lived excited states

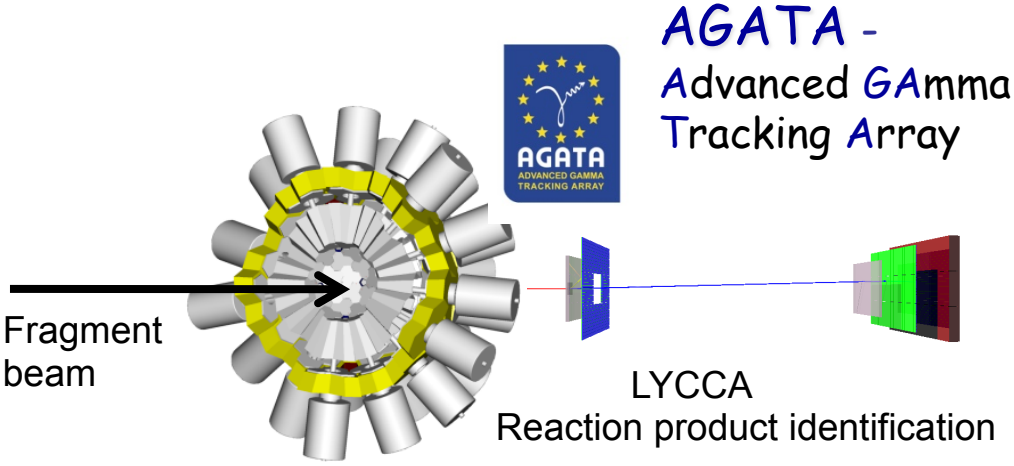
(evolution of shells and collectivity)

(phase-/shape-transitions & shape coexistence)

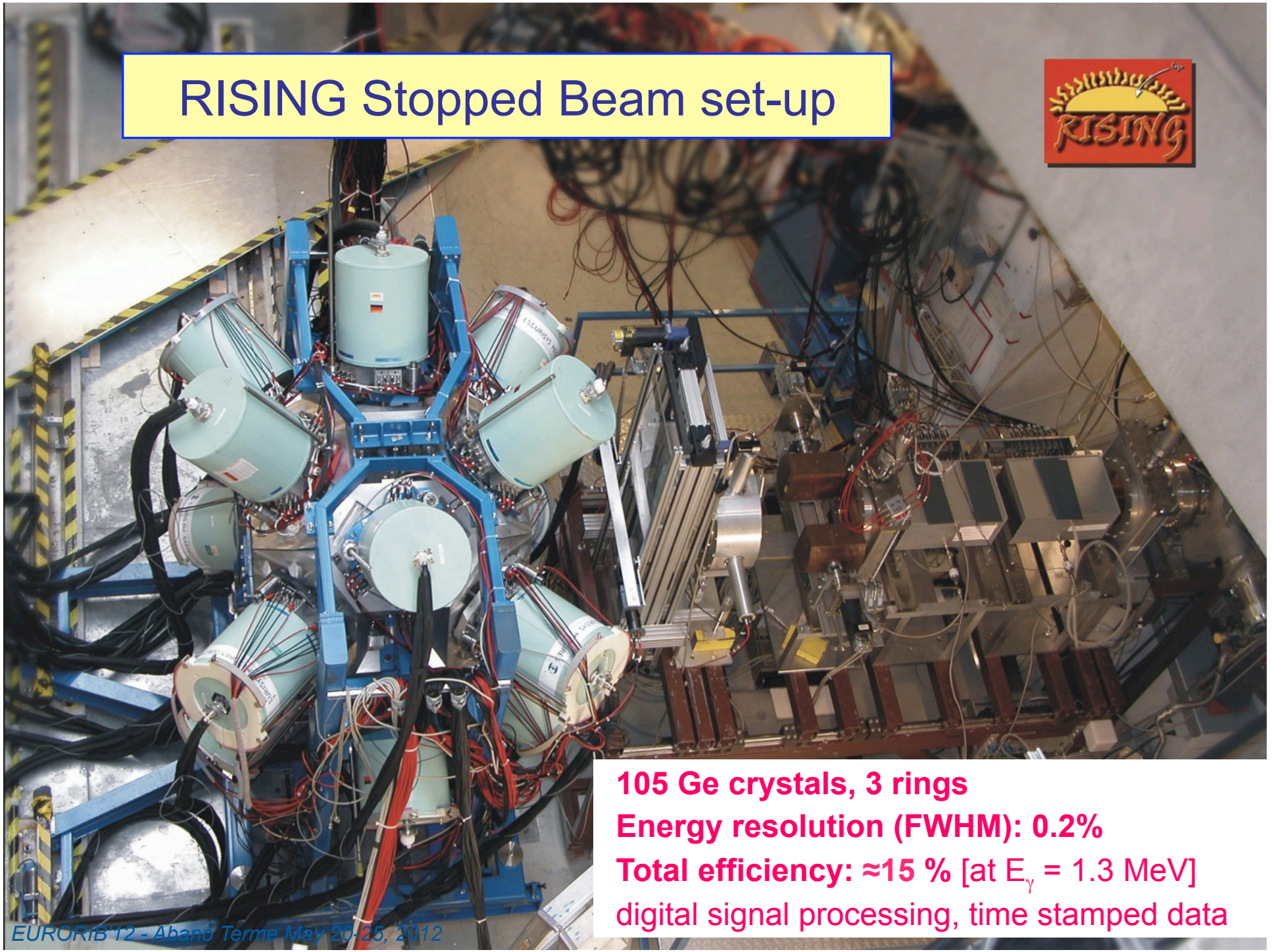
(isospin symmetry, pn-pairing)

- **Experiments possible with medium-energy beams (50-100 AMeV)**
- **Broad program for nuclei with A up to ~100**





RISING Stopped Beam set-up

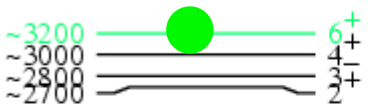


105 Ge crystals, 3 rings

Energy resolution (FWHM): 0.2%

Total efficiency: ≈15 % [at E_γ = 1.3 MeV]

digital signal processing, time stamped data

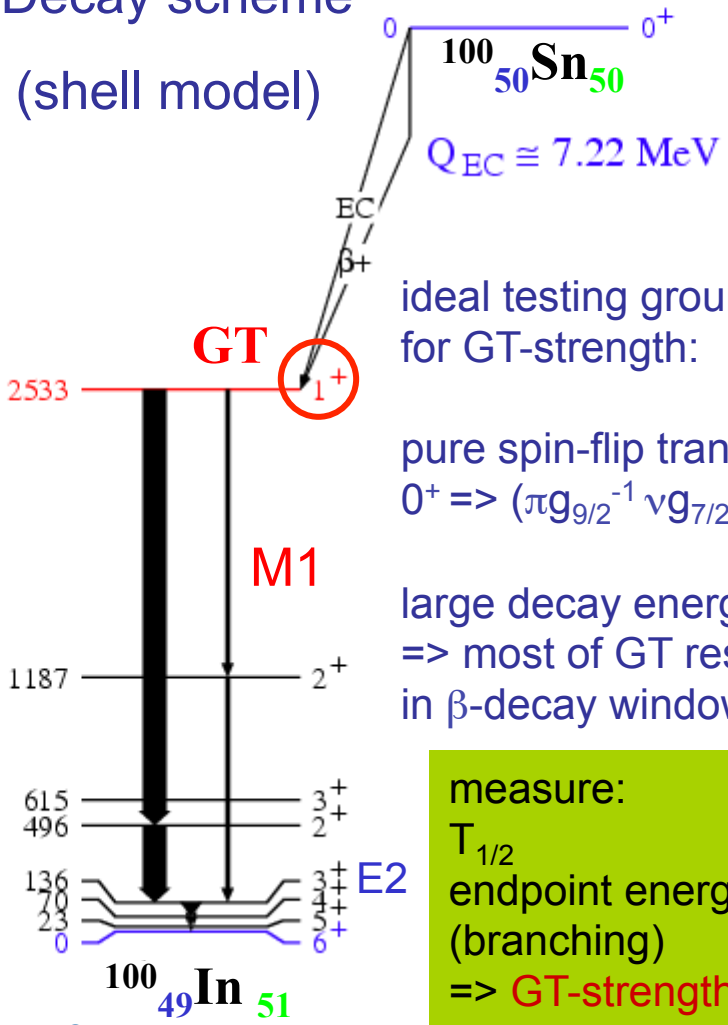


^{100}Sn

- GT strength in the decay
- rp process end point
- 6$^+$ spin gap isomer
- particle stability of neighbours

Decay scheme

(shell model)



ideal testing ground for GT-strength:

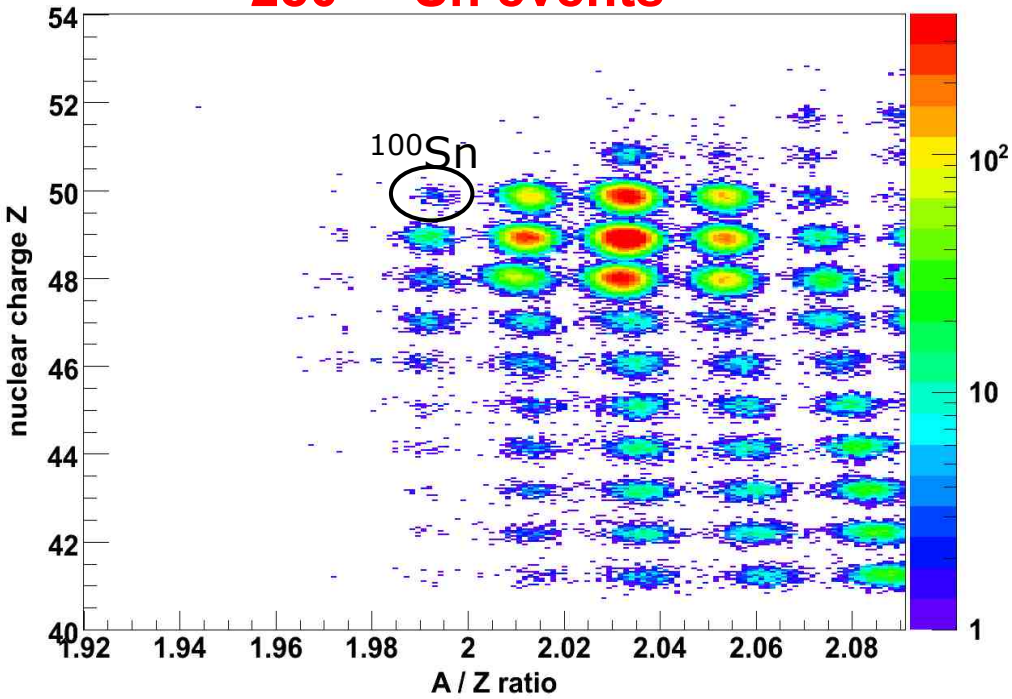
pure spin-flip transition
$0^+ \Rightarrow (\pi g_{9/2}^{-1}\, \nu g_{7/2})1^+$

large decay energy
=> most of GT resonance in β-decay window

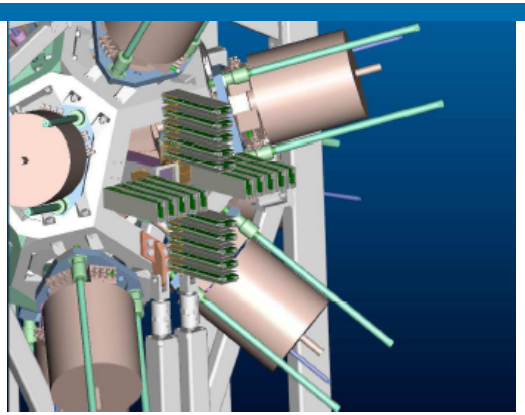
measure:
$T_{1/2}$
endpoint energy
(branching)
=> GT-strength

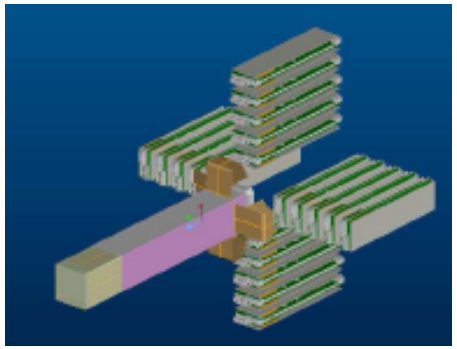
^{124}Xe fragmentation, 1 evt/h

≈280 ^{100}Sn events

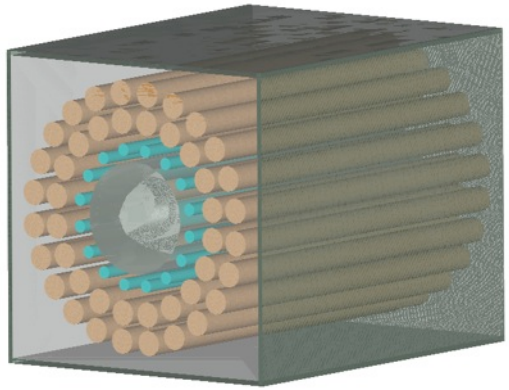


Instrumentation developments

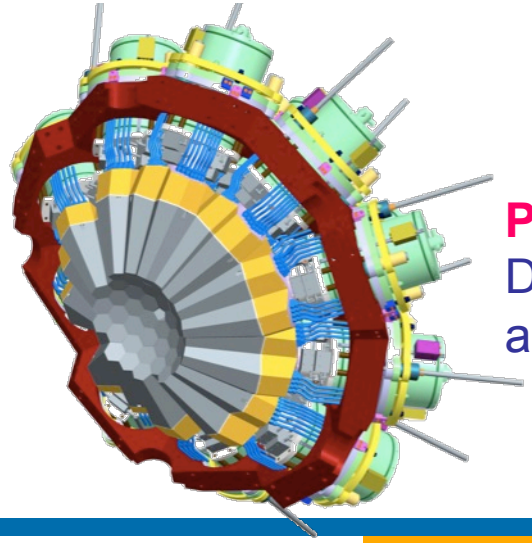




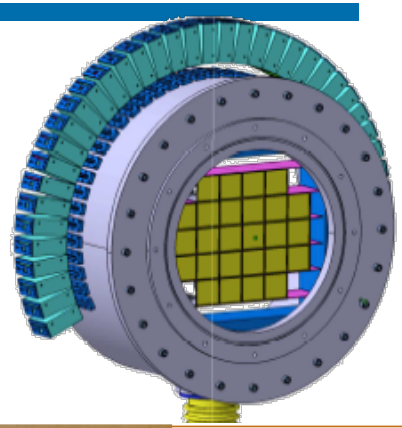
AIDA

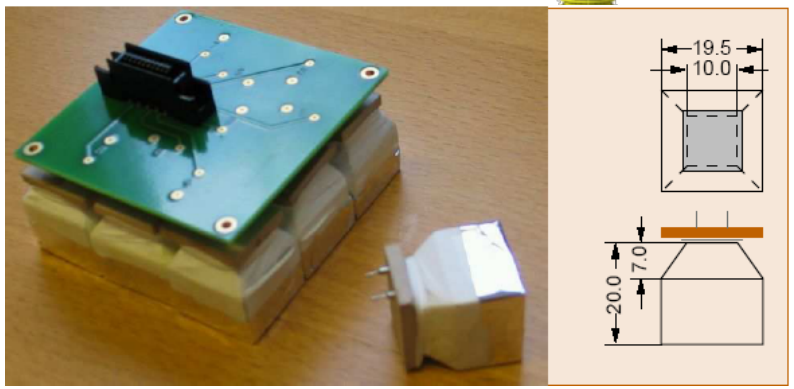


4π Neutron Array
development on-going



LYCCA
TDR accepted,
LYCCA-0
operational





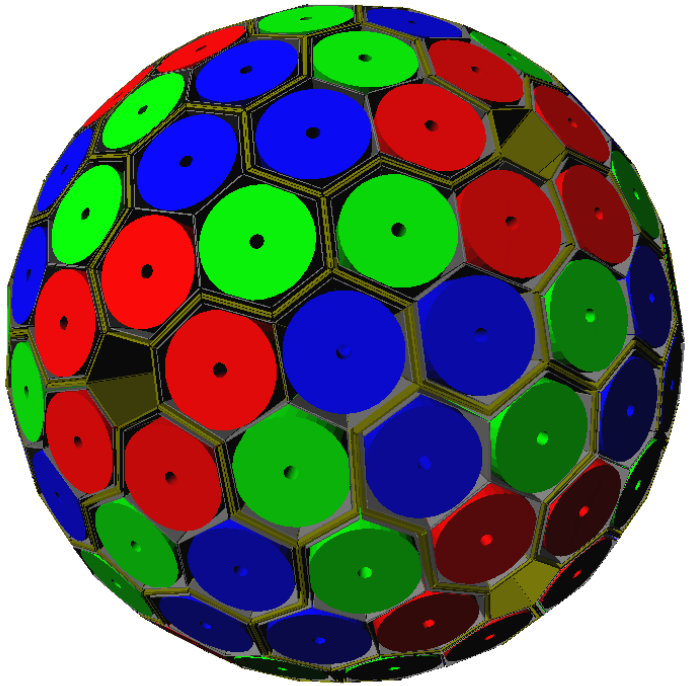
AGATA
➔ *J. Valiente Dobon*
➔ *PRESPEC@GSI*

Plunger
Device operational,
adaptation ongoing

AGATA

(Advanced GAmma Tracking Array)

4π γ-array for Nuclear Physics Experiments at European accelerators providing radioactive (FAIR, SPIRAL-2, EURISOL) and high-intensity stable beams



Main features of AGATA

Efficiency: 40% (M_γ =1) 25% (M_γ =30)
today's arrays ~10% (gain ~4) 5% (gain ~1000)

Peak/Total: 55% (M_γ=1) 45% (M_γ=30)
today ~55% 40%

Angular Resolution: ~1° →
FWHM (1 MeV, v/c=50%) ~ 6 keV !!!
today ~40 keV

Rates: 3 MHz (M_γ=1) 300 kHz (M_γ =30)
today 1 MHz 20 kHz

- 180 large volume 36-fold segmented Ge crystals in 60 triple-clusters
- Digital electronics and sophisticated Pulse Shape Analysis algorithms allow

Operation of Ge detectors in position sensitive mode → γ-ray tracking

MATS and LASPEC

MATS and LASPEC: **ground state properties using high-precision techniques**

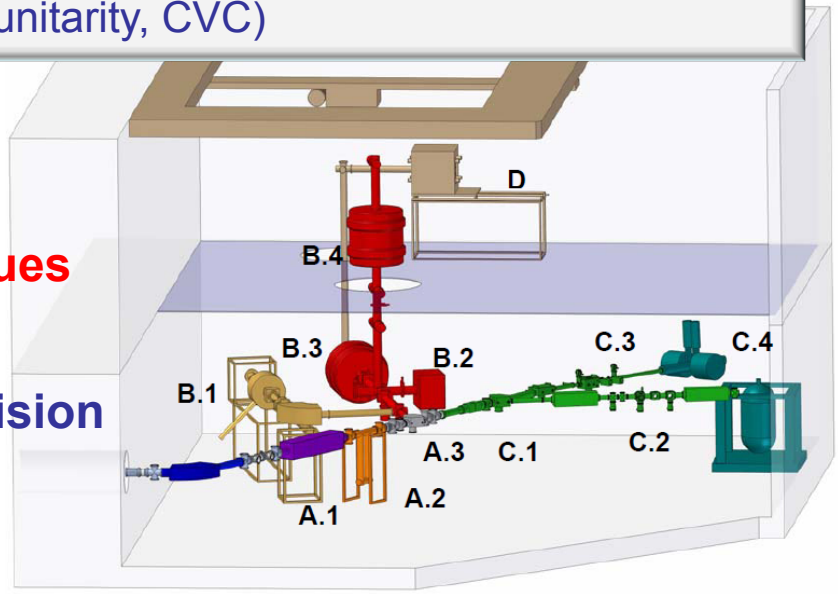
- Penning trap system (MATS)
  - High-precision masses for highly charged ions
  - Trap-assisted and in-trap spectroscopy
- Laser spectroscopy (LASPEC)
  - Ground state spins, moments, isotope shifts from laser spectroscopy

    (evolution of shells and nuclear shapes)

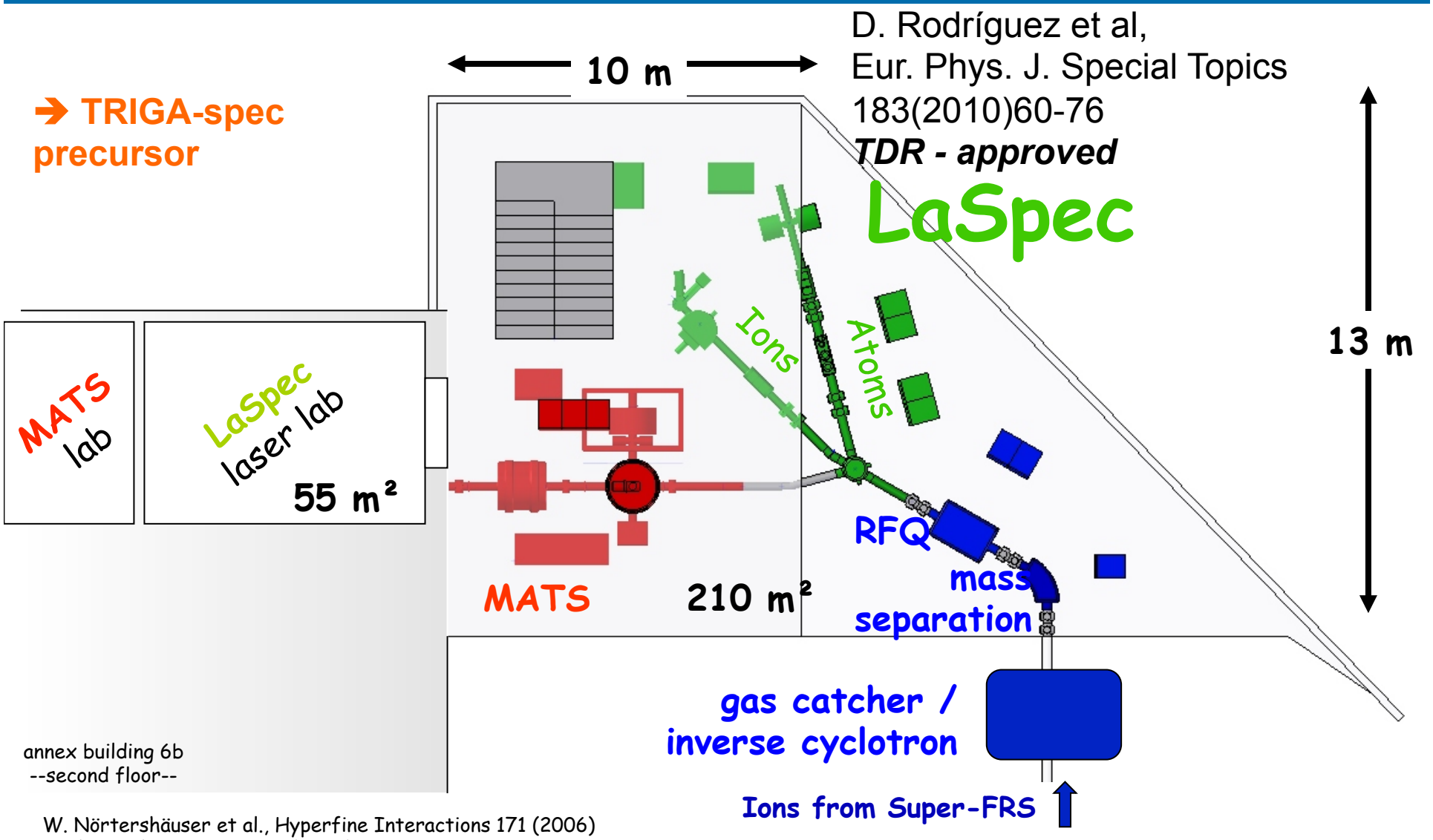
    (nuclear astrophysics input: masses, EC rates, GT strength)

    (test of fundamental symmetries: CKM unitarity, CVC)

- **Stopping in and extraction from gas-cell**
- **charge breeding & non-destructive techniques**
- **half-life limit ~10ms**
- **Access to refractory elements, highest precision**



LaSpec & MATS @ FAIR



W. Nörtershäuser et al., Hyperfine Interactions 171 (2006)
K. Blaum, Phys. Rep. 425, 1 (2006)

NUSTAR Experiments in Modularized Start Version

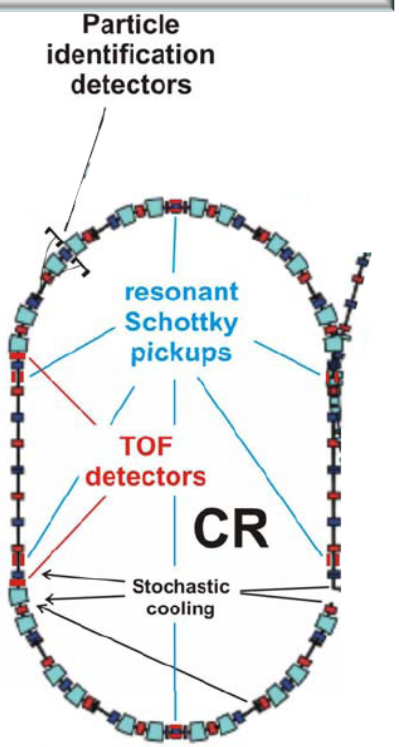
ILIMA in CR: mass measurements of nuclei with half-lives in the ms region

- Masses of very exotic nuclei using isochronous mode & TOF technique
- Half-lives via detection of decay products with particle detectors
- Study of isomeric states

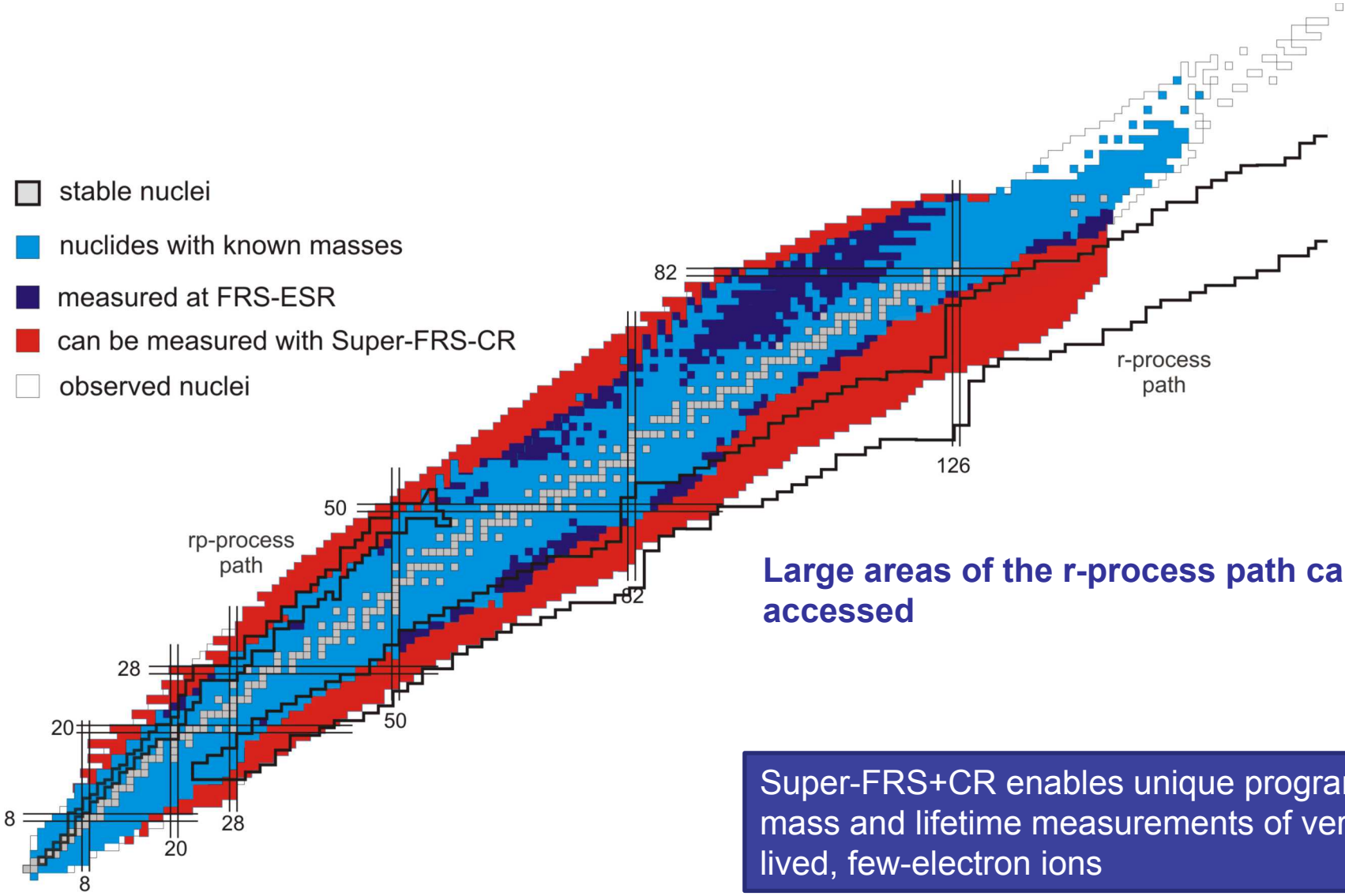
(shell evolution, effective interaction)

(nuclear astrophysics input: masses, half-lives)

- **Masses with precision ~50 keV**
- **Many masses at same time**
- **access to nuclei with half-lives shorter than cooling times**



ILIMA in CR

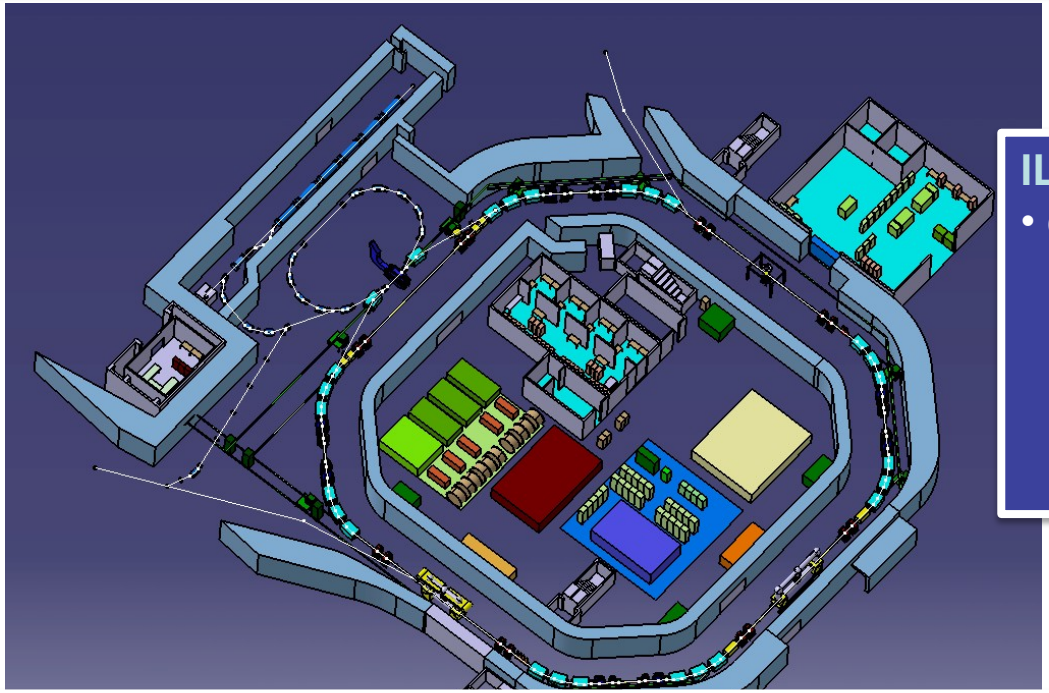


Large areas of the r-process path can be accessed

Super-FRS+CR enables unique program for mass and lifetime measurements of very short lived, few-electron ions

NUSTAR programme at the NESR

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



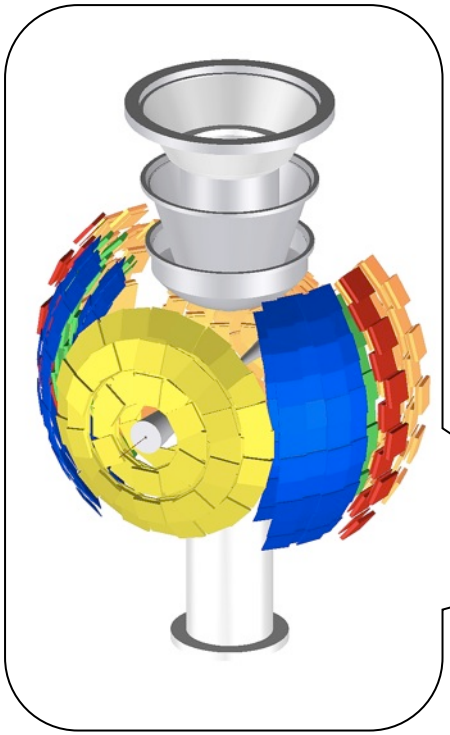
ILIMA
- electron cooled beams needed for
  - higher precision and separation (ground and isomeric states)
  - time-resolved studies (unique decay modes, e.g. bound beta decay)
  - studies with pure isomeric beams

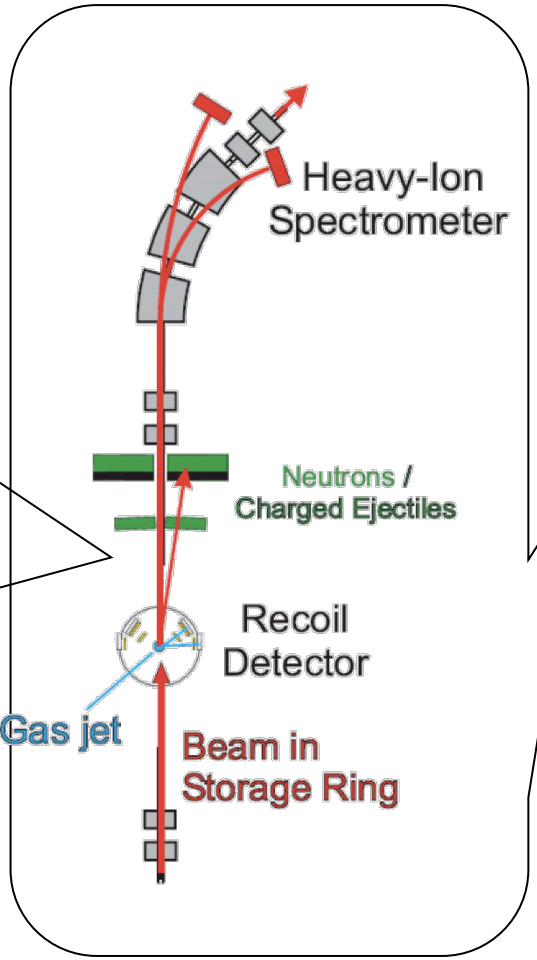
EXL: Elastic and inelastic scattering, reaction with low-momentum transfer
- matter distributions, monopole resonances, capture reactions, charge exchange reactions, transfer, knock-out

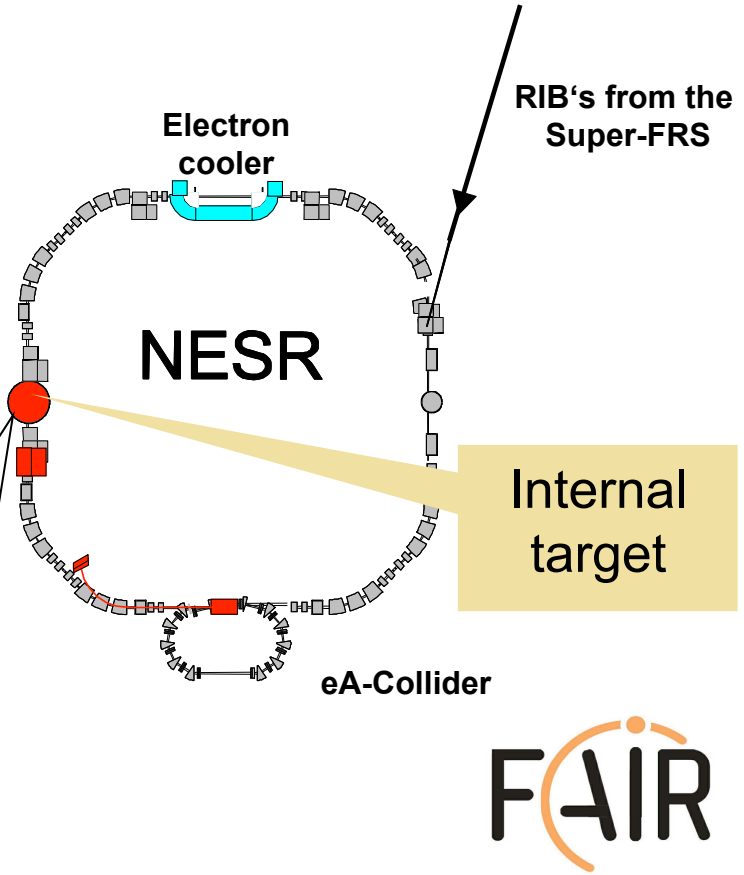
(n-skins, compressibility, GT-strength, shell evolution, nucl. astrophysics reactions)

The EXL experiment

EXotic Nuclei Studied in Light-Ion Induced Reactions at the NESR Storage Ring







Target-Recoil and Gamma Detector around internal target

Light-ion scattering in the storage ring (EXL)

Scattering in inverse kinematics

Low-momentum transfer region often most important, e.g.,

- giant monopole excitation
- elastic scattering

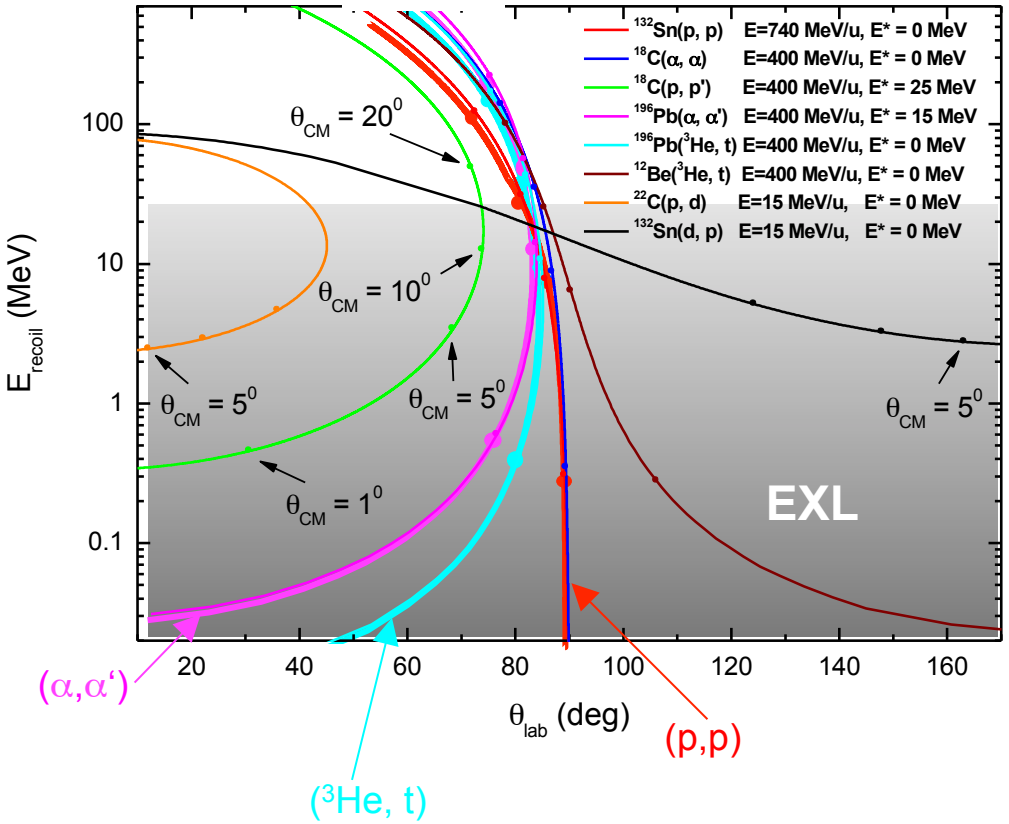
Experimental difficulty

- low recoil energies
- thin targets (low luminosity)

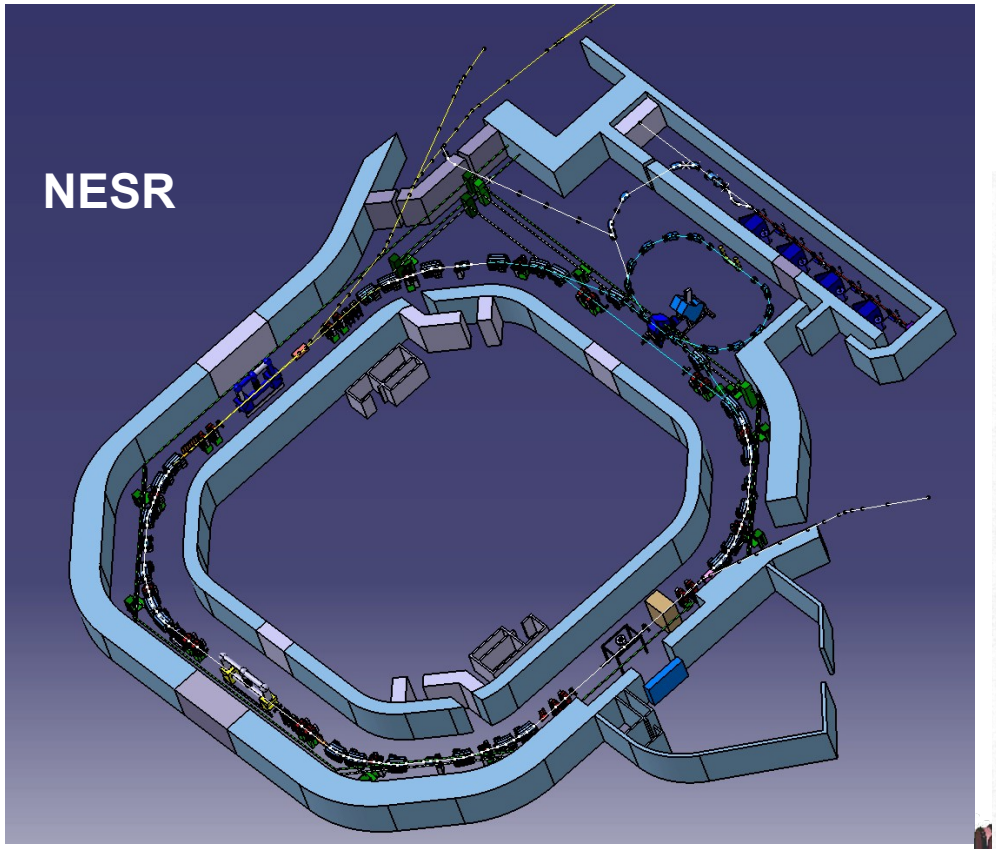
EXL solution:

in-ring scattering at internal gas-jet targets

gaining back luminosity due to circulation frequency of ~ 10^6

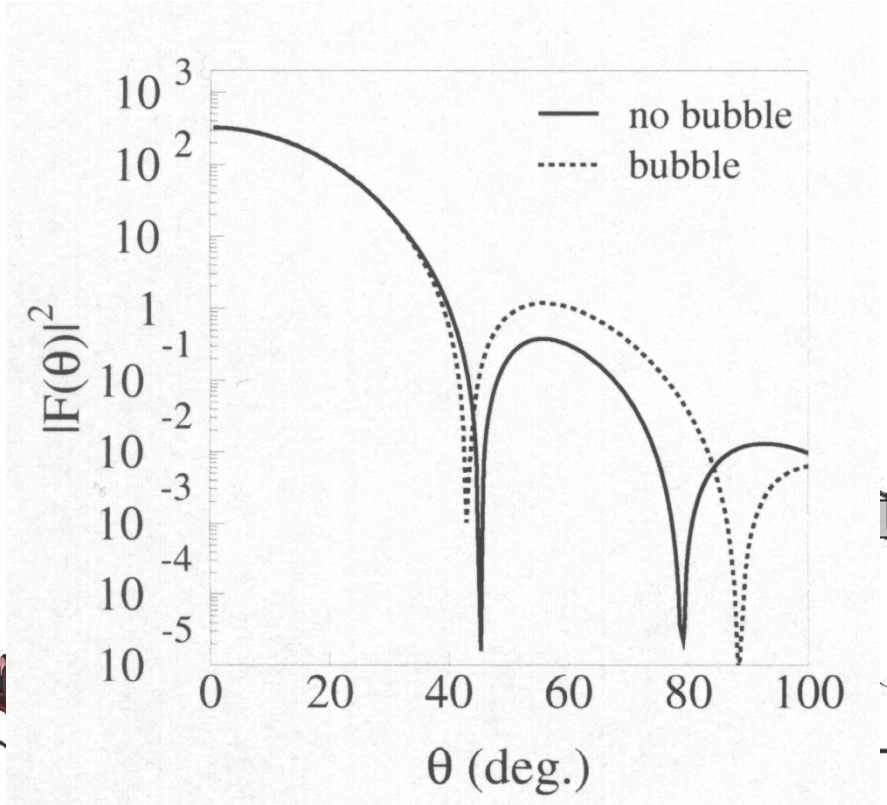


Long-term – **ELISe and AIC**



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

➔ up to 1.5 GeV CM energy



AIC option:

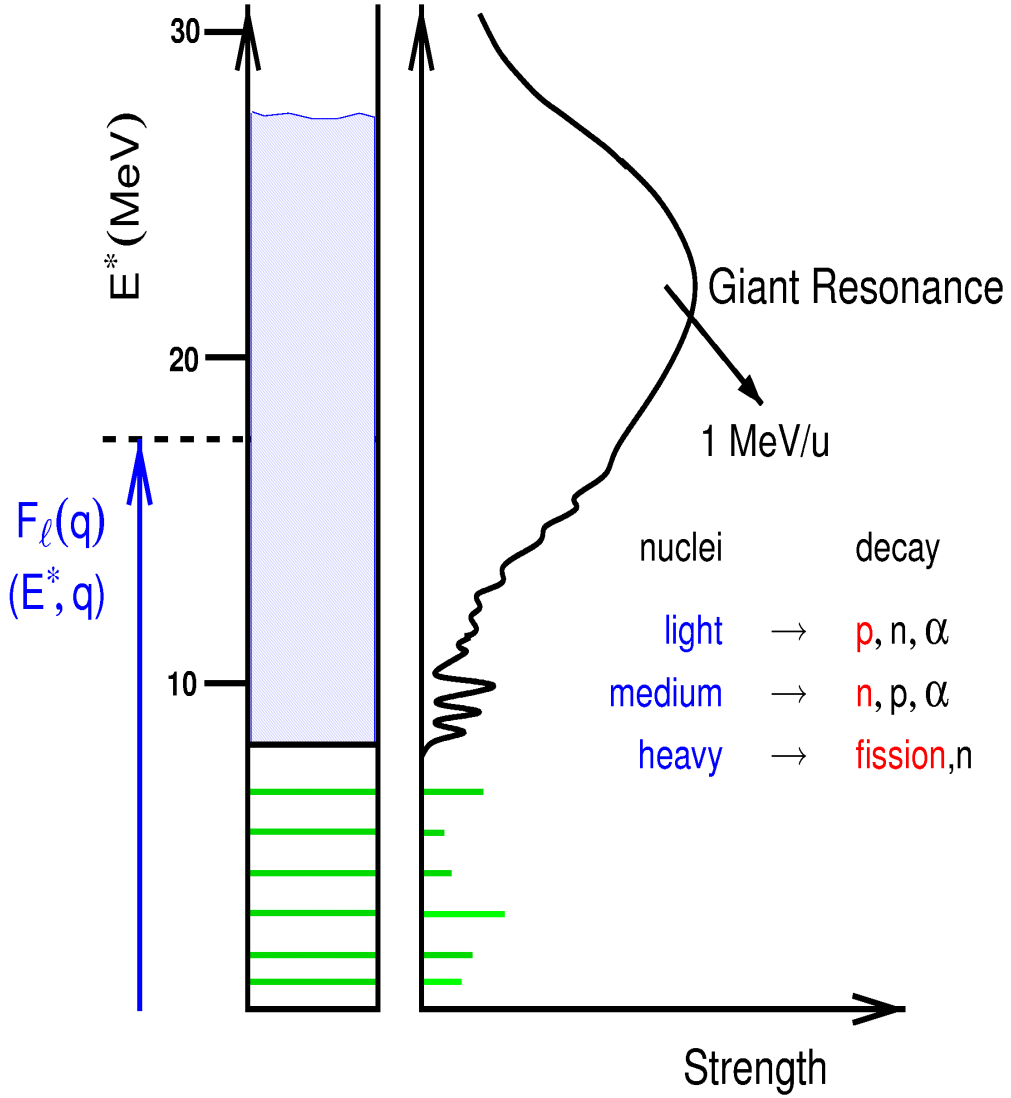
- 30 MeV antiprotons

- detector system in ring arcs
- Schottky probes

A.N. Antonov et al, NIMA 637(2011)60-76

ELISe conceptual design study

Inelastic scattering in the eA collider



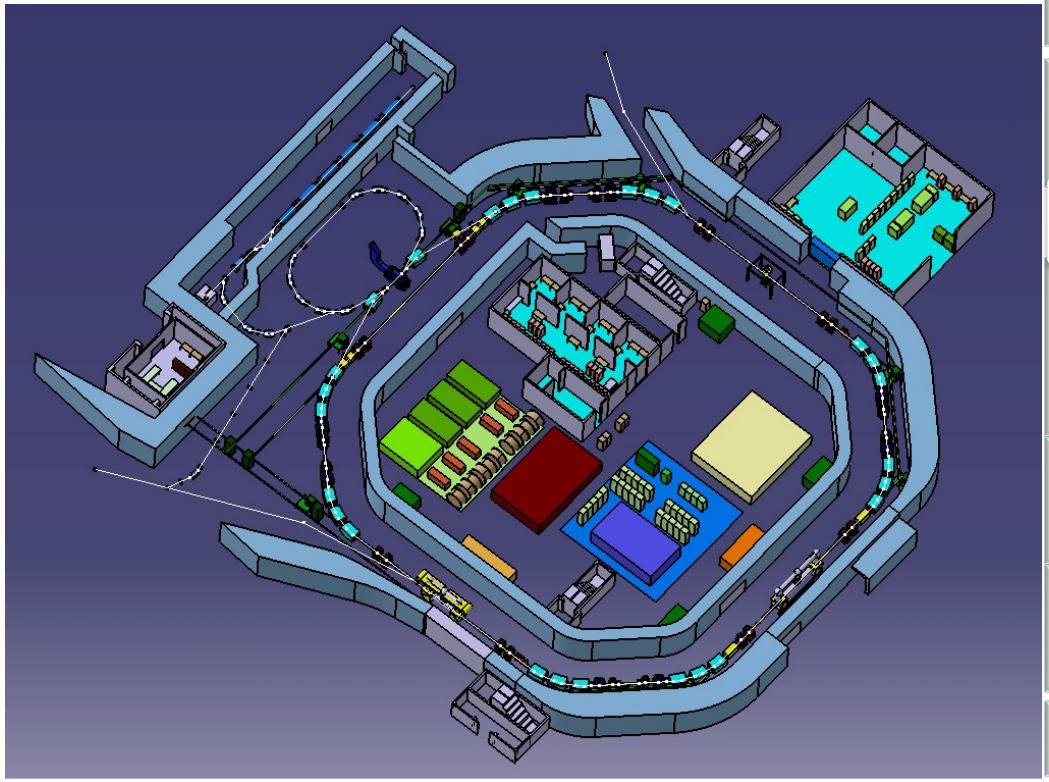
- Excitation energy is measured directly (below and above particle tresh.)
- momentum transfer dependence ➔ multipolarity of transition can be determined
- final state identification with unprecendented efficiency (e,e'X) ➔ (e,e' A') ➔ suppression of elastic radiative tail (no background)

➔ Low lying strength (structure)
E.g.: E1-Soft-Dipole mode:
transition density peaks in the interior.

Sagawa, Esbensen, NUPA693(2001)448

NESR (Module 4)

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



APPA

SPARC: Precision Studies of the Quantum Dynamics of Atomic Systems

FLAIR: Atomic Physics with slow p-bars

NUSTAR

ILIMA: High-precision mass measurements, isomeric beams – also in CR

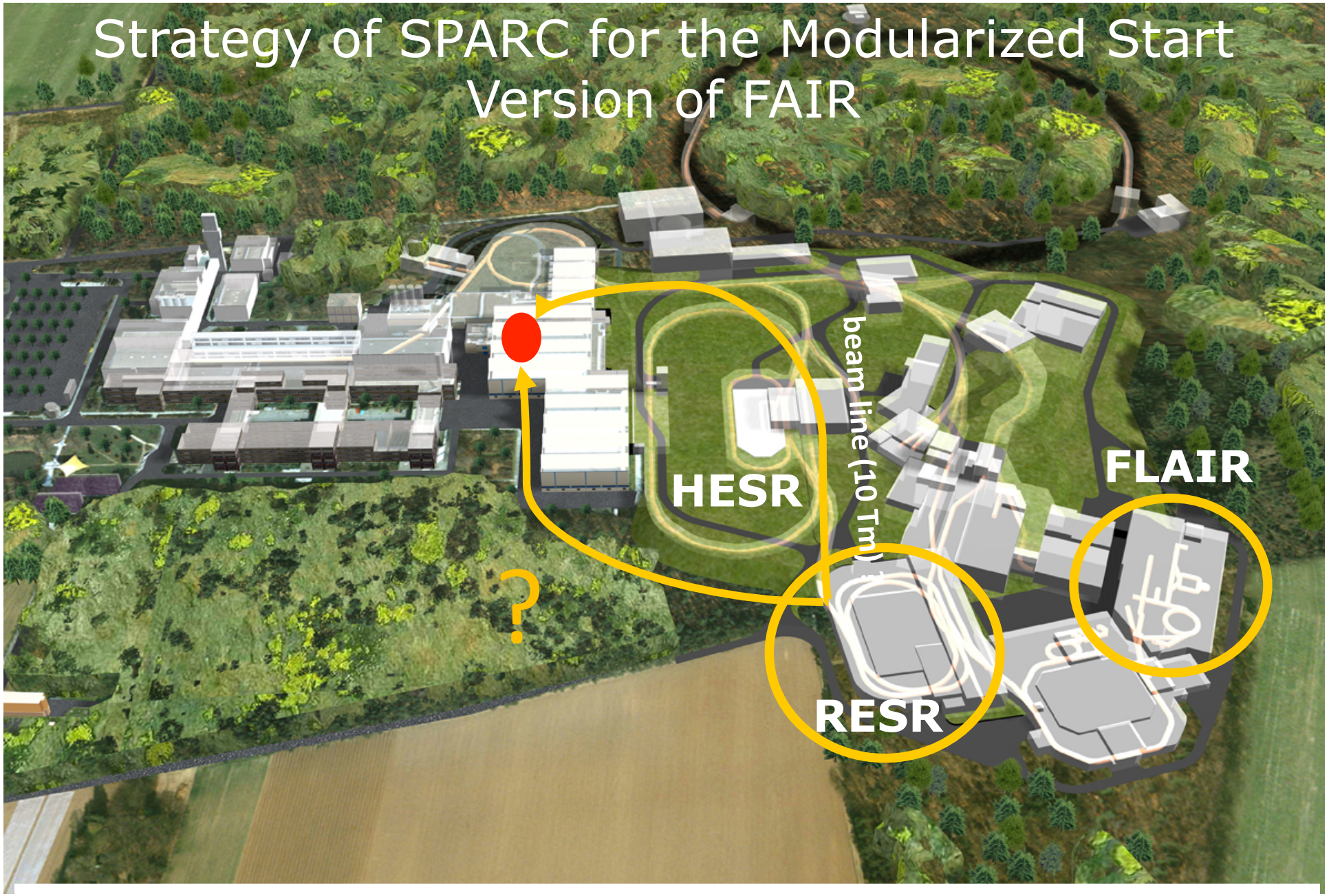
EXL: Elastic and inelastic scattering, reaction with low-momentum transfer

ELISe: Elastic and inelastic electron scattering on RIBs

AIC: p-bar annihilation on RIBs

SPARC initiative: move parts or whole APPA and NUSTAR ring programmes to the HESR/ ESR

Strategy of SPARC for the Modularized Start Version of FAIR



CN DE ES FI FR GB GR IN IT PL RO RU SE

Th. Stöhlker

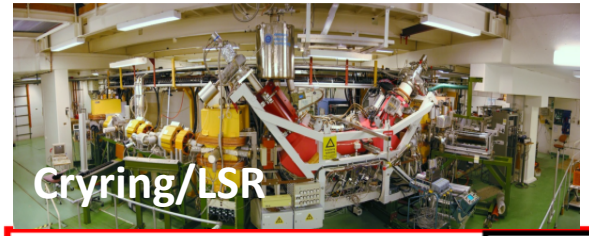
Highly-Charged Ions at Low Energies

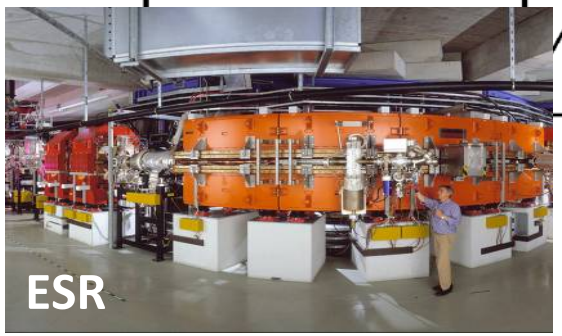
- **Spectroscopy for tests of QED**
  - High-precision x-ray spectroscopy
    - 1s-Lamb-Shift
    - Two-Electron-QED
  - Recoil ion momentum spectroscopy
    - Highly-excited stated
  - Laser Spectroscopy
  - Recombination Spectroscopy with high resolution
- **Atomic collisions**
  - Sub-femtosecond correlated dynamics
  - Unexplored regime: strong perturbation Q/v
- **Nuclear Physics at Low-Energies**
  - Similar to TSR@ISOLDE (➔ **R. Raabe Tuesday**)

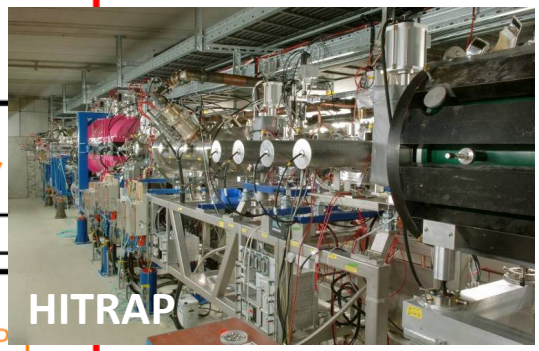
Features@Cryring

- Low-energy and electron cooled beams
- Electron cooling with adiabatic expansion
- Slow extraction
- High-luminosity for in-ring experiments
- Very fast deceleration 7 T/s
- Internal jet target

FLAIR-Facility & SIS18







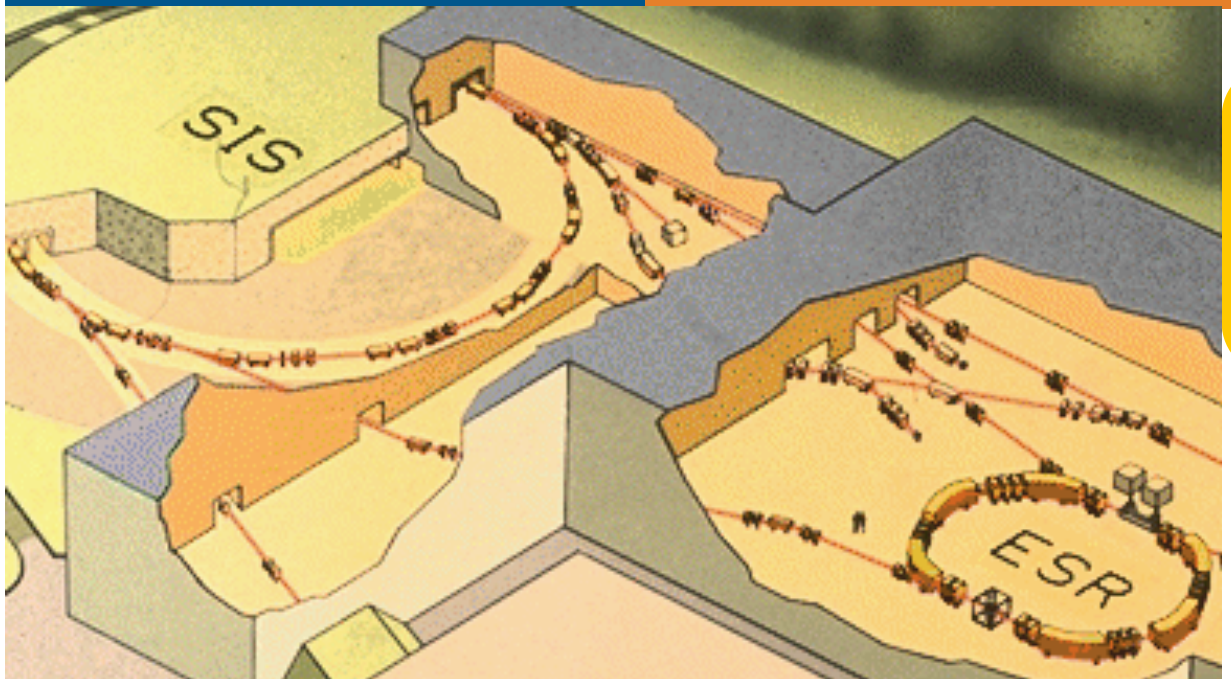
For ions, this can already realized at the current SIS18.

Unique physics opportunities !!!

For pbars, at the very first moment pbars will be available, the complete FLAIR facility is in operation.

Unique physics opportunities !!!

Cryring at the ESR

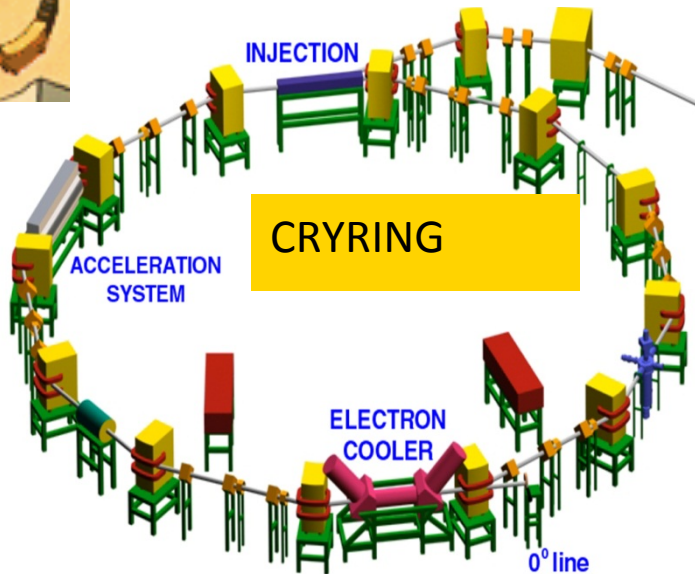


ESR:
Circumference
108 m

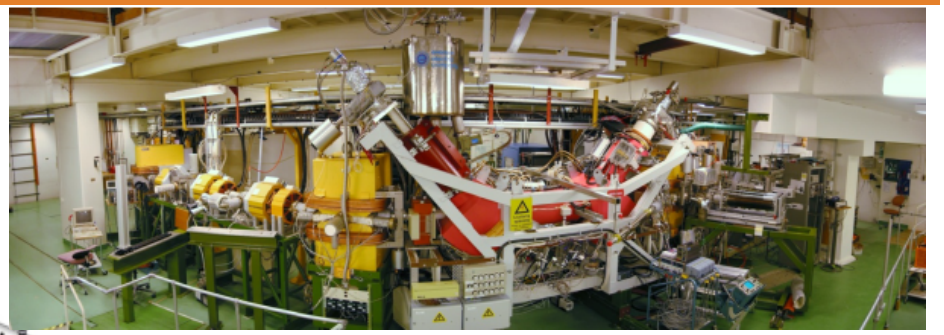
Bρ: 10 Tm

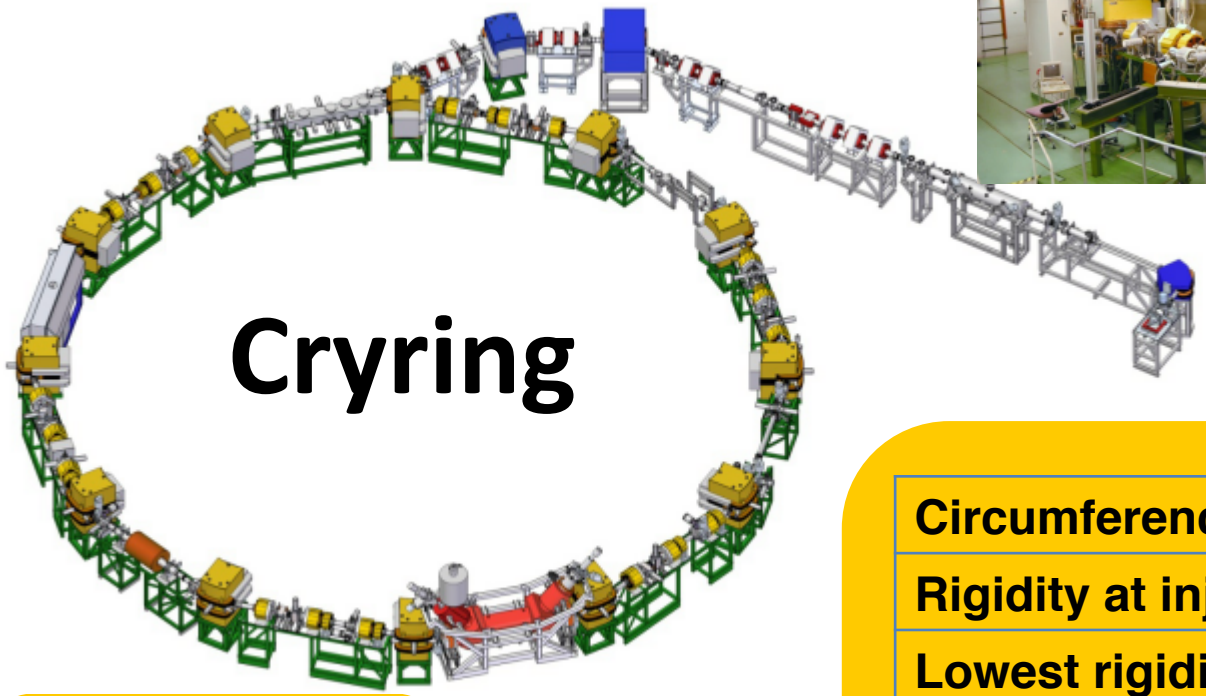
Cryring
Circumference
51.6 m

Bρ: 1.44 Tm



Cryring





Electron cooling
Collinear laser spectroscopy
Internal target

Circumference:	51.63 m
Rigidity at injection	0.88 Tm (1.44 Tm)
Lowest rigidity	0.054 Tm
Lowest energy	Charge exchange limited
Magnet ramping	7 T/s; 1 T/s
Vacuum system	10^{-11} -10^{-12} bar
Slow extraction	

Conclusions

- The FAIR facility will open up unique possibilities in large realms of Radioactive Beam Physics
  - "Chemical blindness" of production
  - Exotic nuclei will be studied with a range of methods
- R^3B - Reactions with relativistic radioactive beams yield exceptional prospects for studies of nuclear systems at the extremes, based on a generic fixed-target set-up
  - Fully adapted to Super-FRS production method
- Highest achievable resolution experiments with fast and stopped beams with HISPEC and DESPEC
  - AGATA – most advanced gamma detector existing
- MATS/LaSPEC/ILIMA studies of ground-state properties (masses, moments) at highest precision and shortest half-lives
- Exciting future prospects with EXL, ELISe, AIC when going towards full facility
  - Ring branch unique for FAIR
  - Intermediate programme with CRYRING@ESR?

THANKS to all NUSTAR colleagues for providing slides!