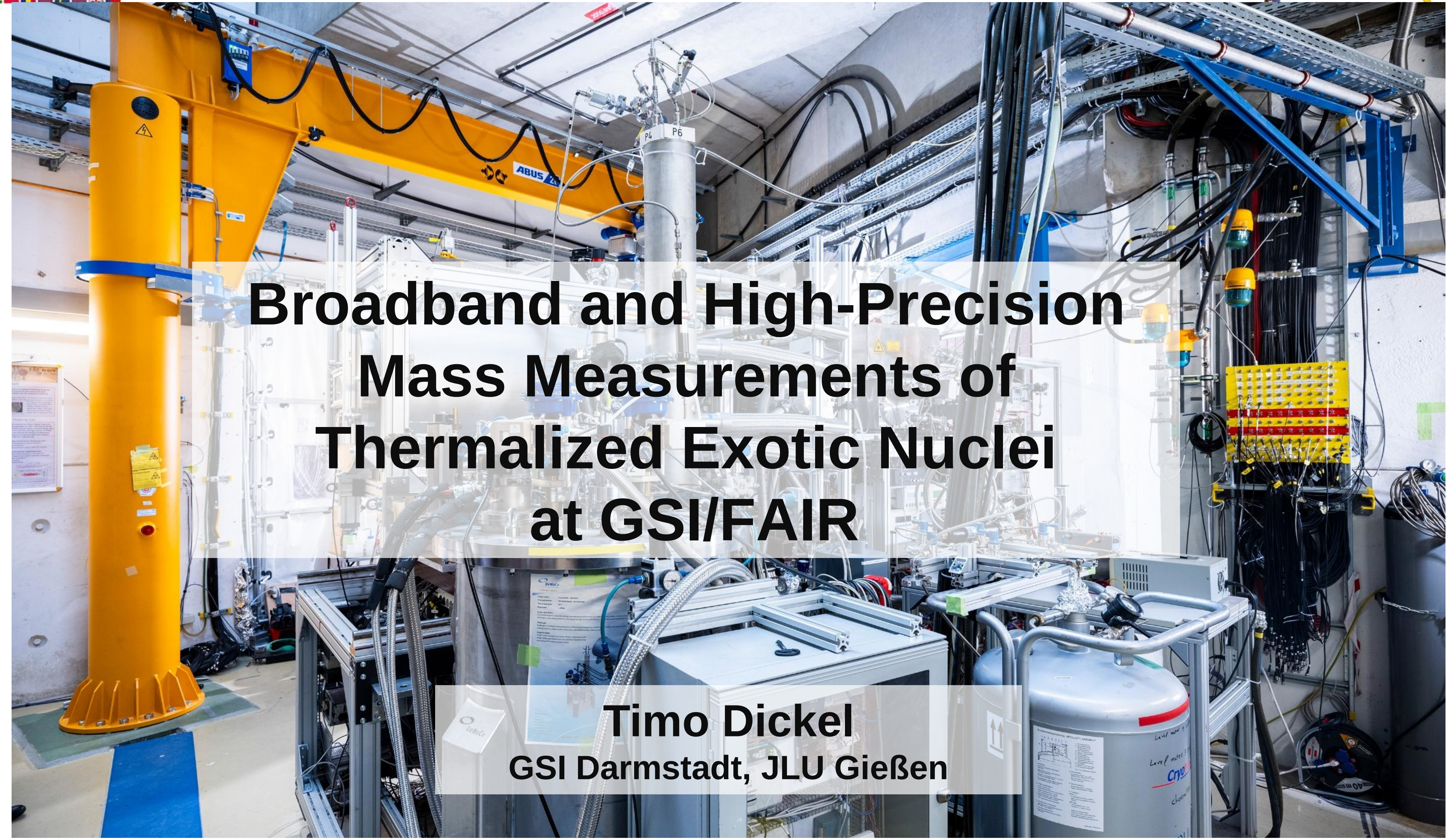


Broadband and High-Precision Mass Measurements of Thermalized Exotic Nuclei at GSI/FAIR

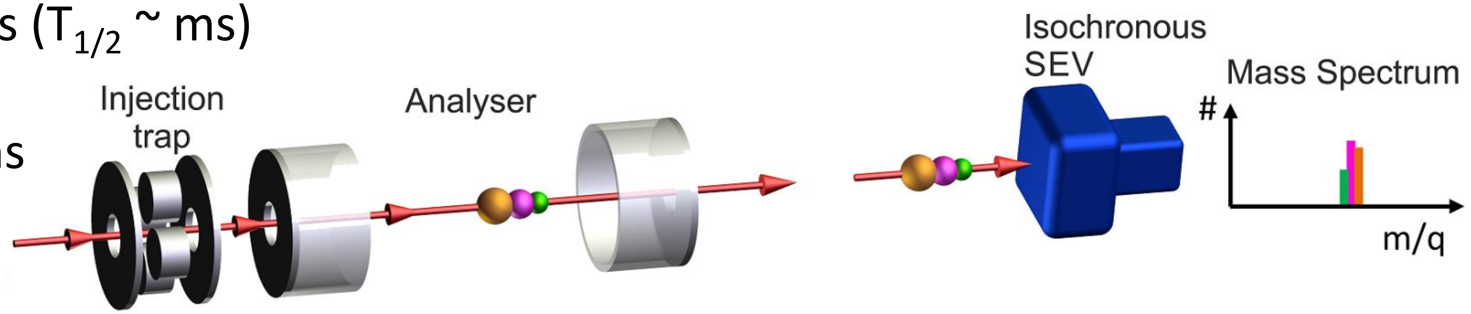
Timo Dickel
GSI Darmstadt, JLU Gießen

Time-of-flight mass spectrometry

- Higher precision
- Faster measurement
- Higher sensitivity
- Higher rate capability

Enables high performance

- Fast $\rightarrow$ access to very short-lived ions ($T_{1/2}$ ~ ms)
- Sensitive, **broadband,** non-scanning
  $\rightarrow$ efficient, access to rare ions



$$R_m = \frac{TOF}{2\,\Delta(TOF)}$$

↑ Long flight path: km → ~20ms

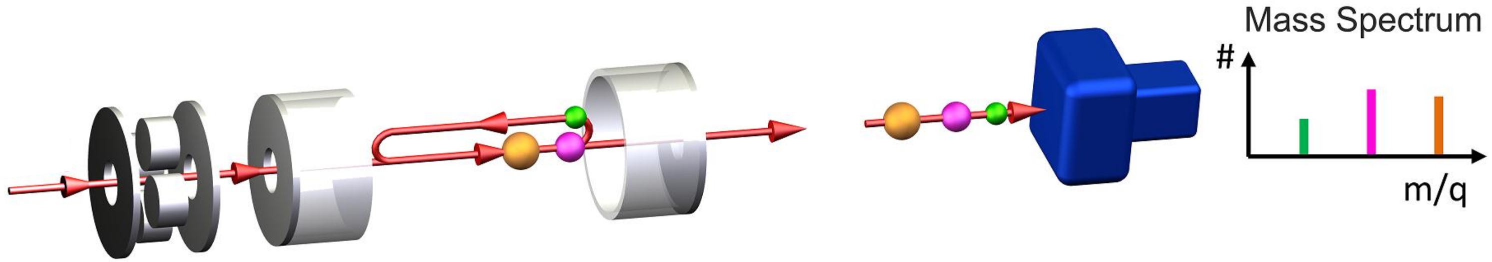
↓ Cooling: ~5 ns

To achieve high mass resolving power and accuracy:

Multiple-reflection time-of-flight mass spectrometer (**MR-TOF-MS**)

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

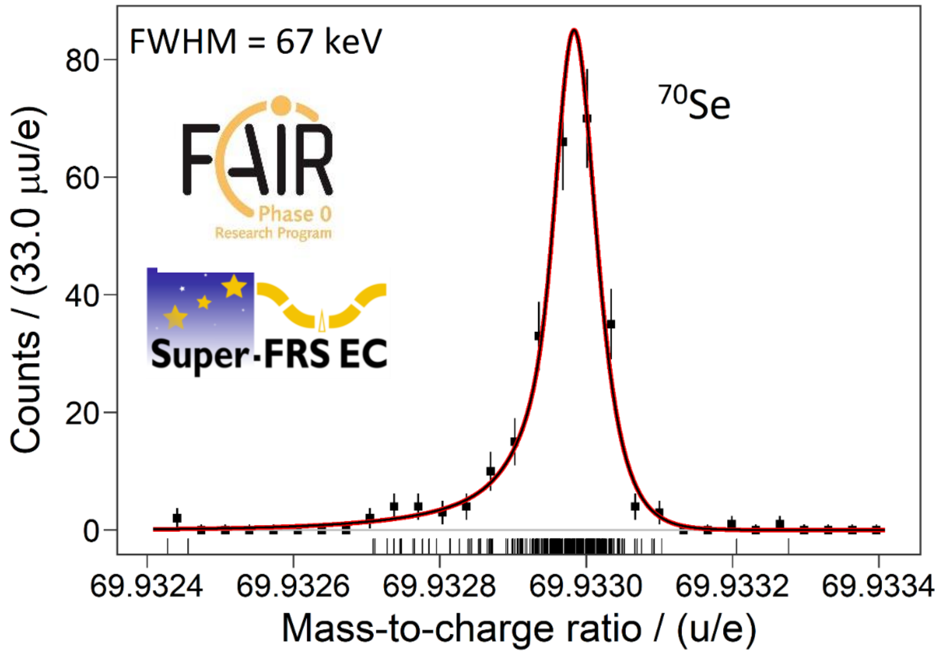
Experimental Physics II



H. Wollnik et al., Int. J. Mass Spectrom. Ion Processes 96 (1990) 267

Performance of MR-TOF-MS: Mass resolving power and accuracy

FRS-IC Mass resolution and accuracy

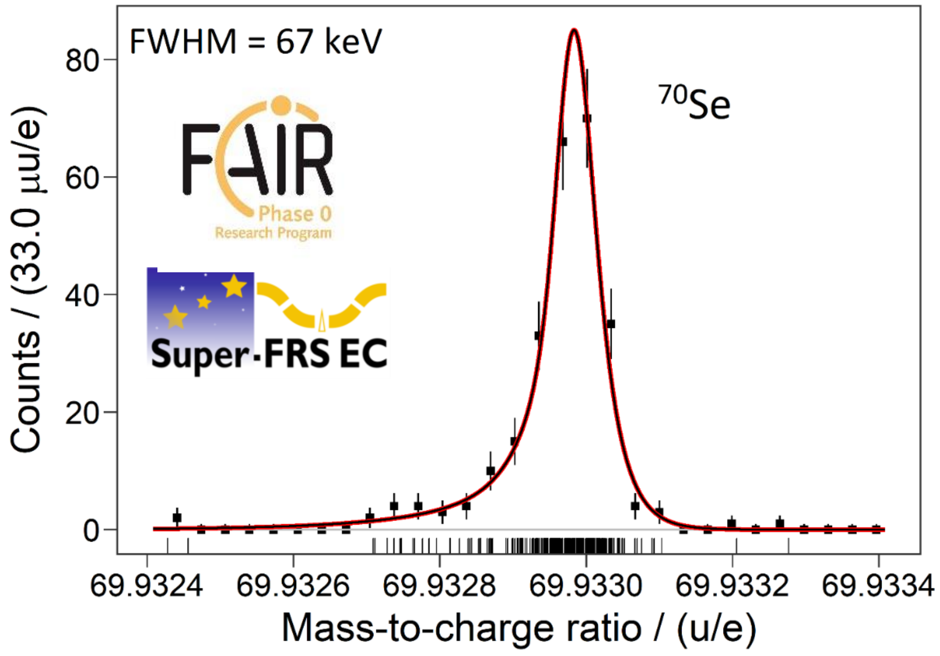


I. Mardor et al., PRC 103, 034319 (2021)

Mass accuracy down to $1.7 \cdot 10^{-8}$
MRP of 1,000,000 @ TOF of ~23 ms

Performance of MR-TOF-MS: Mass resolving power and accuracy

FRS-IC Mass resolution and accuracy



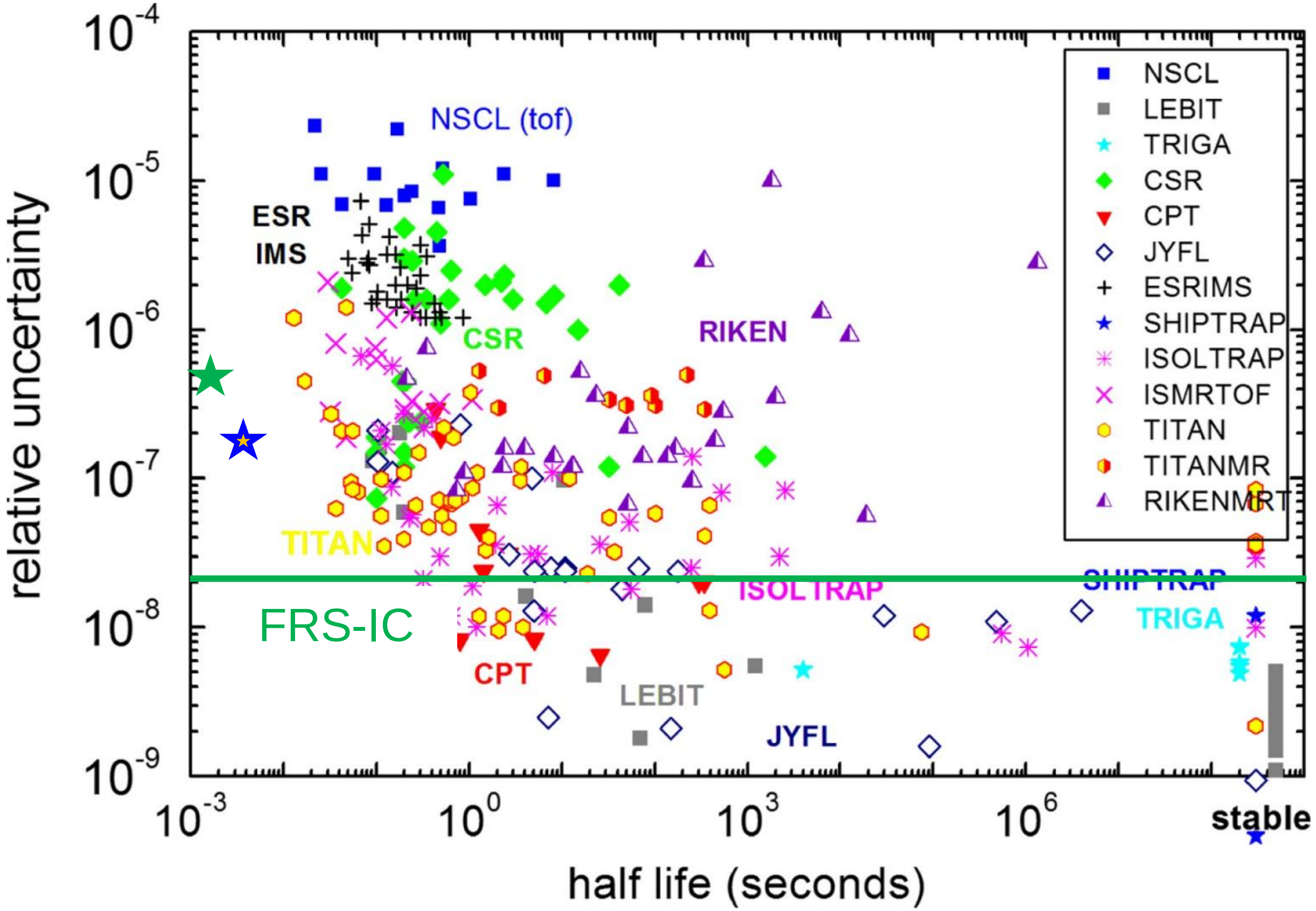
I. Mardor et al., PRC 103, 034319 (2021)

Mass accuracy down to $1.7 \cdot 10^{-8}$

MRP of 1,000,000 @ TOF of ~23 ms

Comparison with other mass measurement techniques

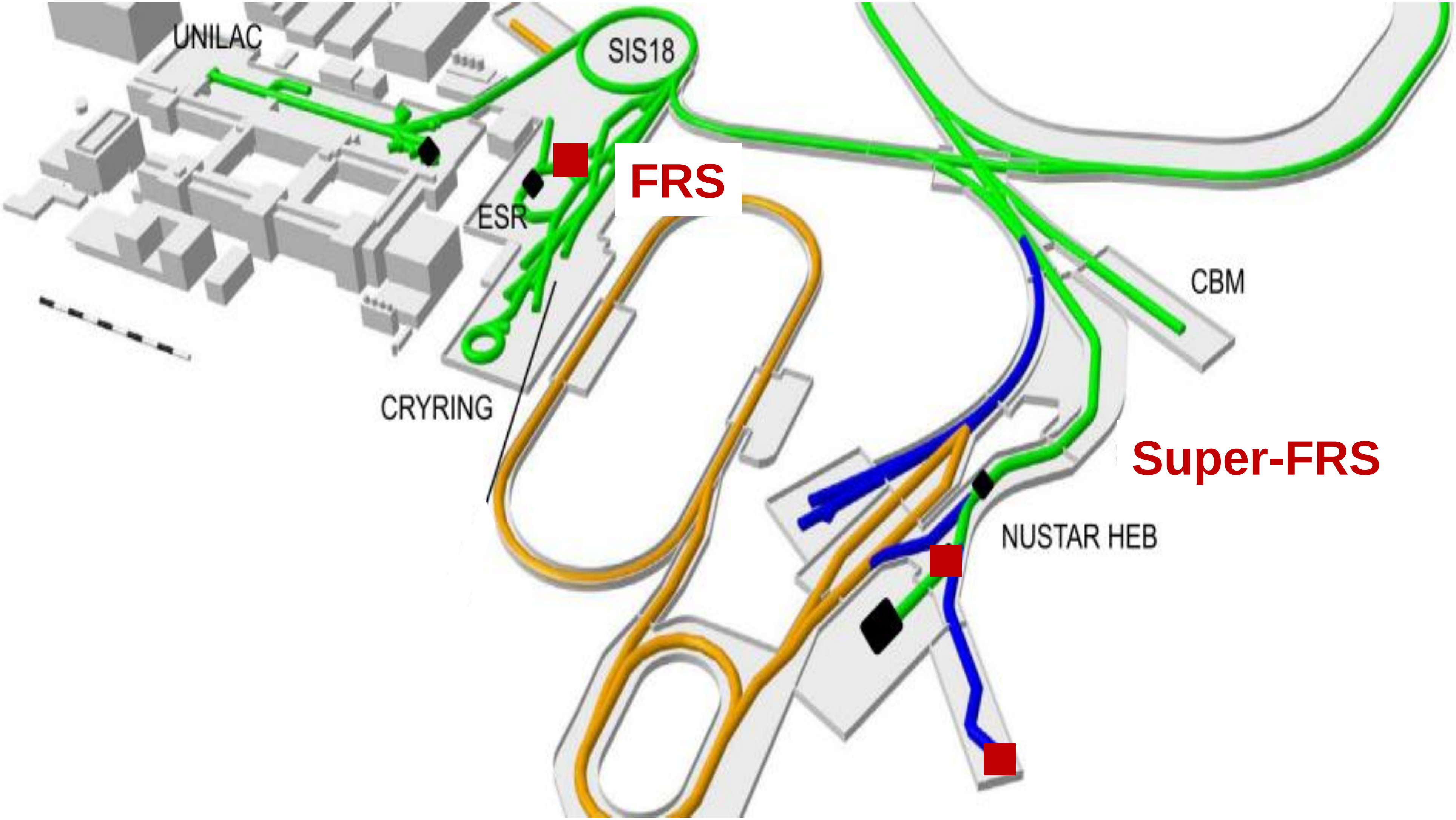
T. Yamaguchi et al. PPNP 120/2021) 103882



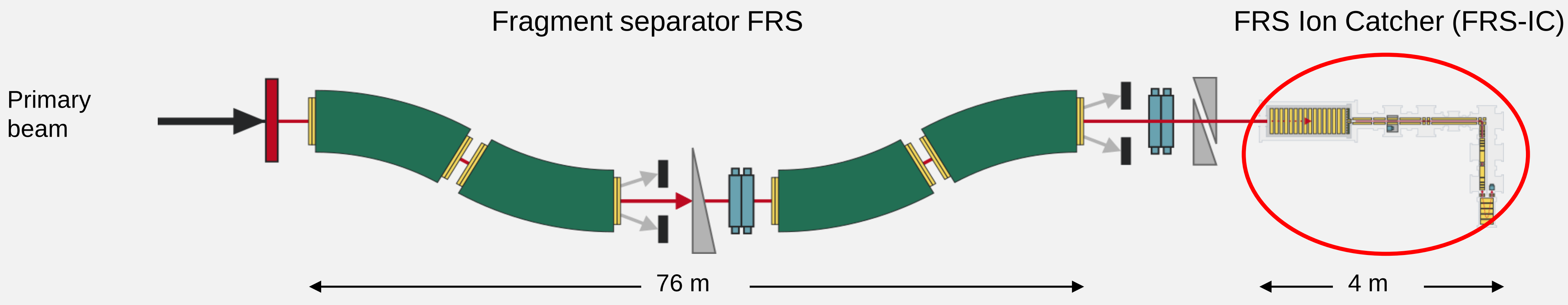
A.-K. Rink, PhD thesis, JLU Gießen (2017)

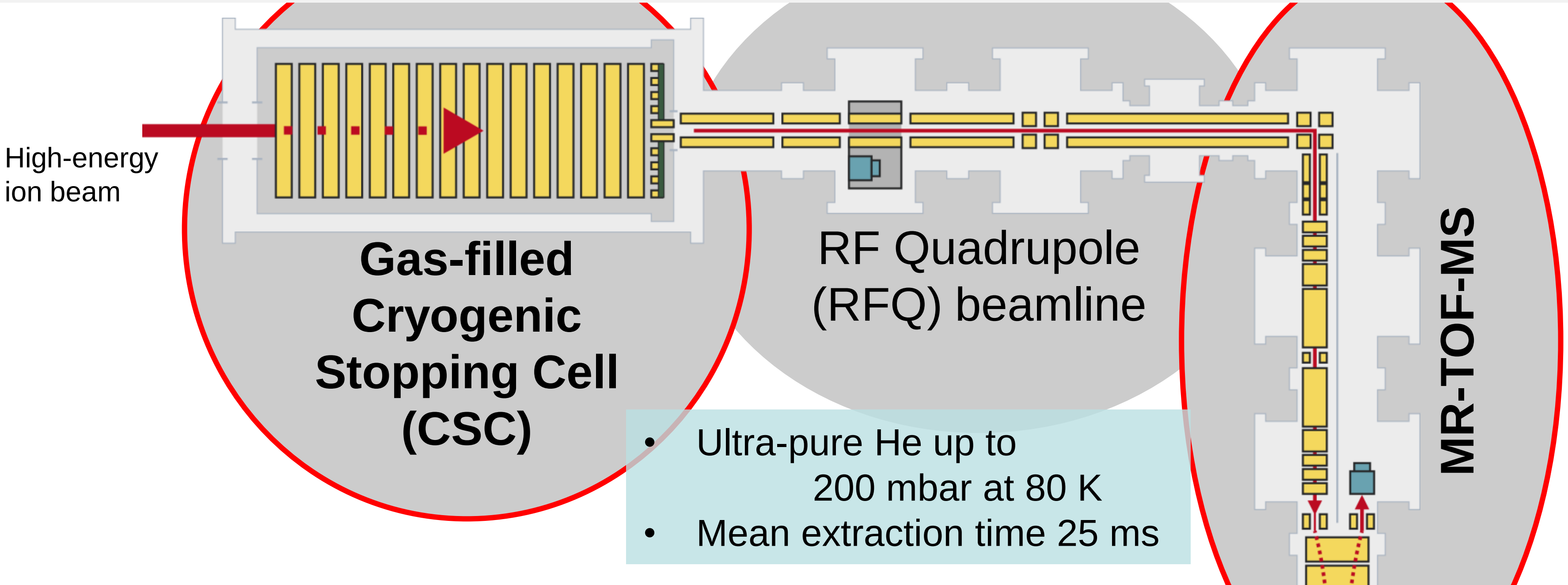
E. M. Lykiardopoulou et al., PRL 134, 052503 (2025)

The FRS and Super-FRS Ion Catcher at GSI/FAIR



The FRS Ion Catcher at GSI

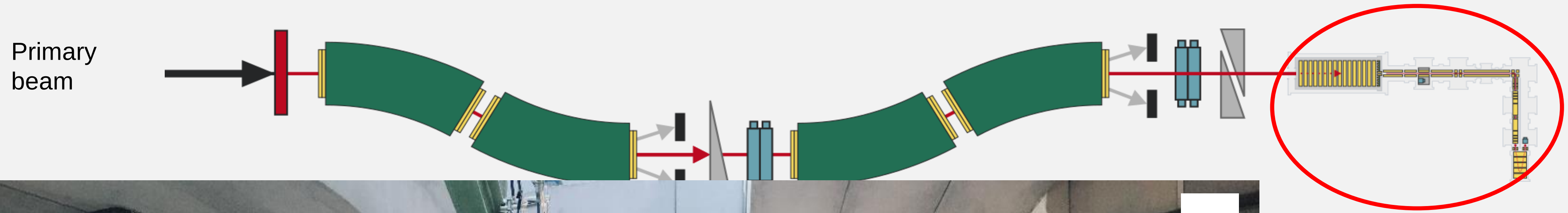


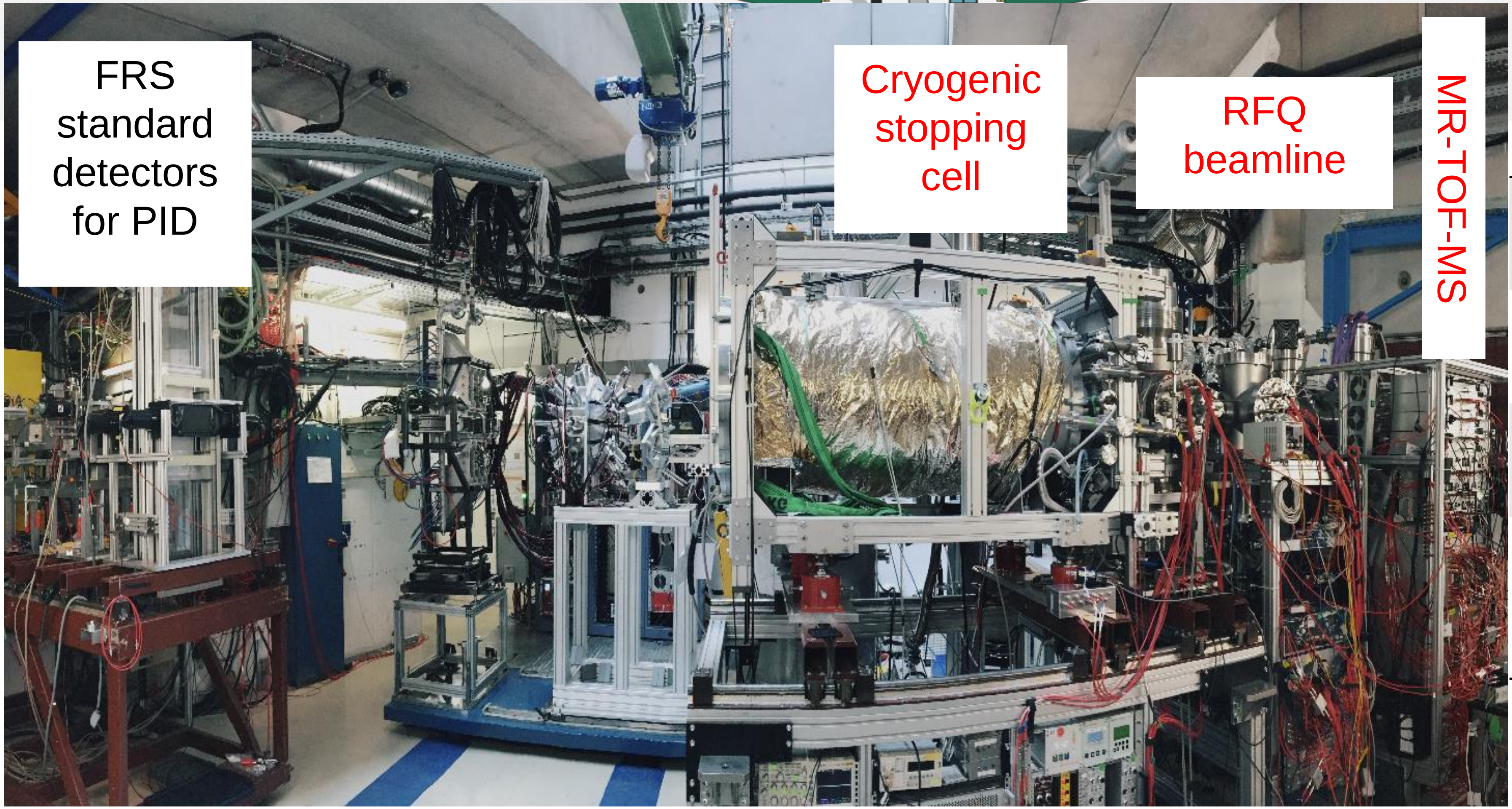


Thick CSC	Stopping of relativistic nuclei
Clean and sensitive	low production cross section
Fast	short-lived ions with $T_{1/2}$ ~ms
Broadband & non-scanning MR-TOF-MS	Effective way of collecting data

Fragment separator FRS: *H. Geissel et al., NIM B 70 (1992)*
The FRS Ion Catcher: *W.R. Plaß et al., NIM B 317 (2013)*
Coupling of FRS and FRS IC: *T. Dickel et al., Atoms (2024), 12, 52*

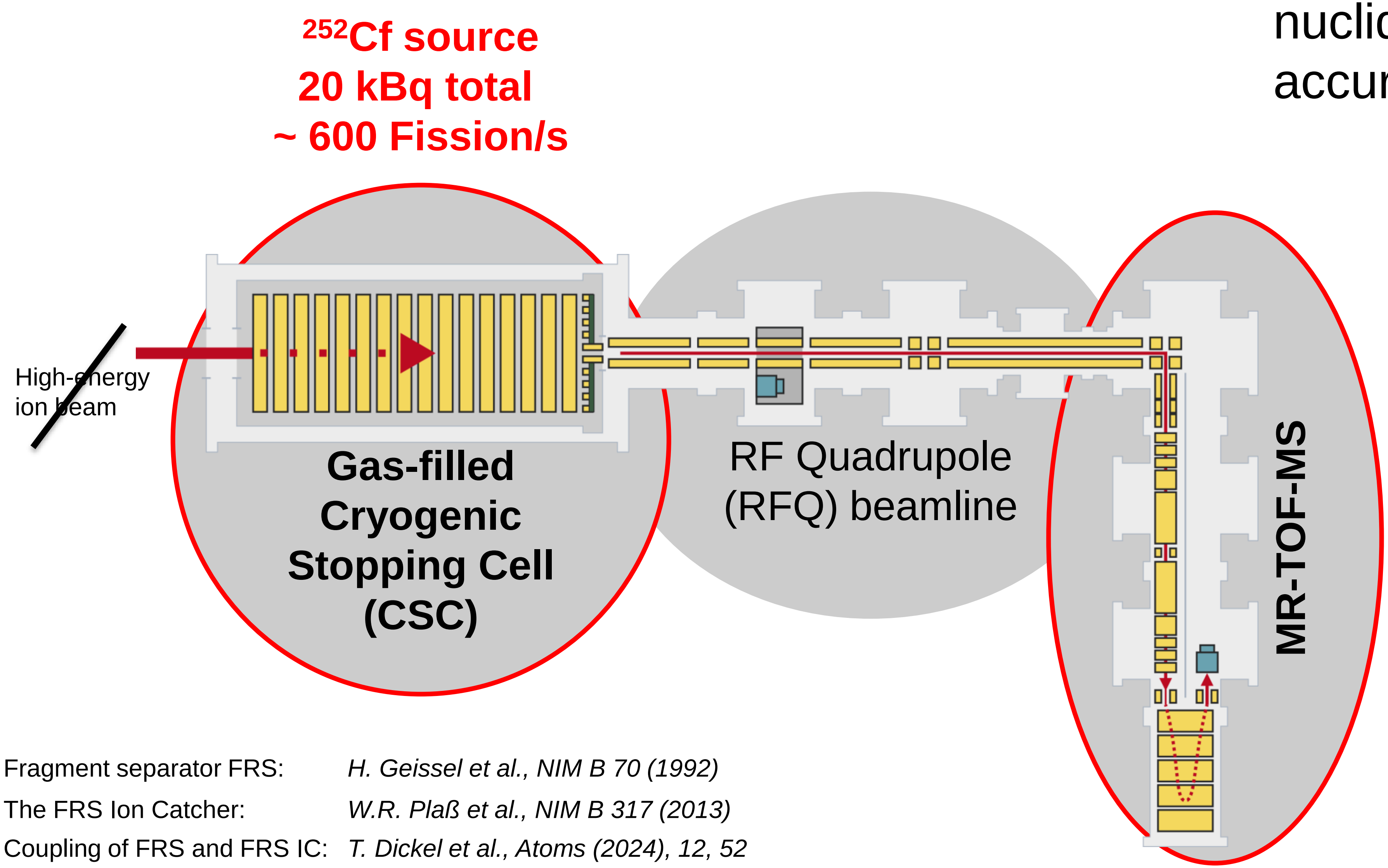
The FRS Ion Catcher at GSI





Thick CSC	Stopping of relativistic nuclei
Clean and sensitive	low production cross section
Fast	short-lived ions with $T_{1/2}$ ~ms
Broadband & non-scanning MR-TOF-MS	Effective way of collecting data

The FRS Ion Catcher at GSI offline



Mapping a large region of nuclide chart with high accuracy

Ingredients for absolute IIFY measurement:

- Fast, clean, non-scanning and broadband experimental setup
- Quantification of all correction factors

Fragment separator FRS: *H. Geissel et al., NIM B 70 (1992)*

The FRS Ion Catcher: *W.R. Plaß et al., NIM B 317 (2013)*

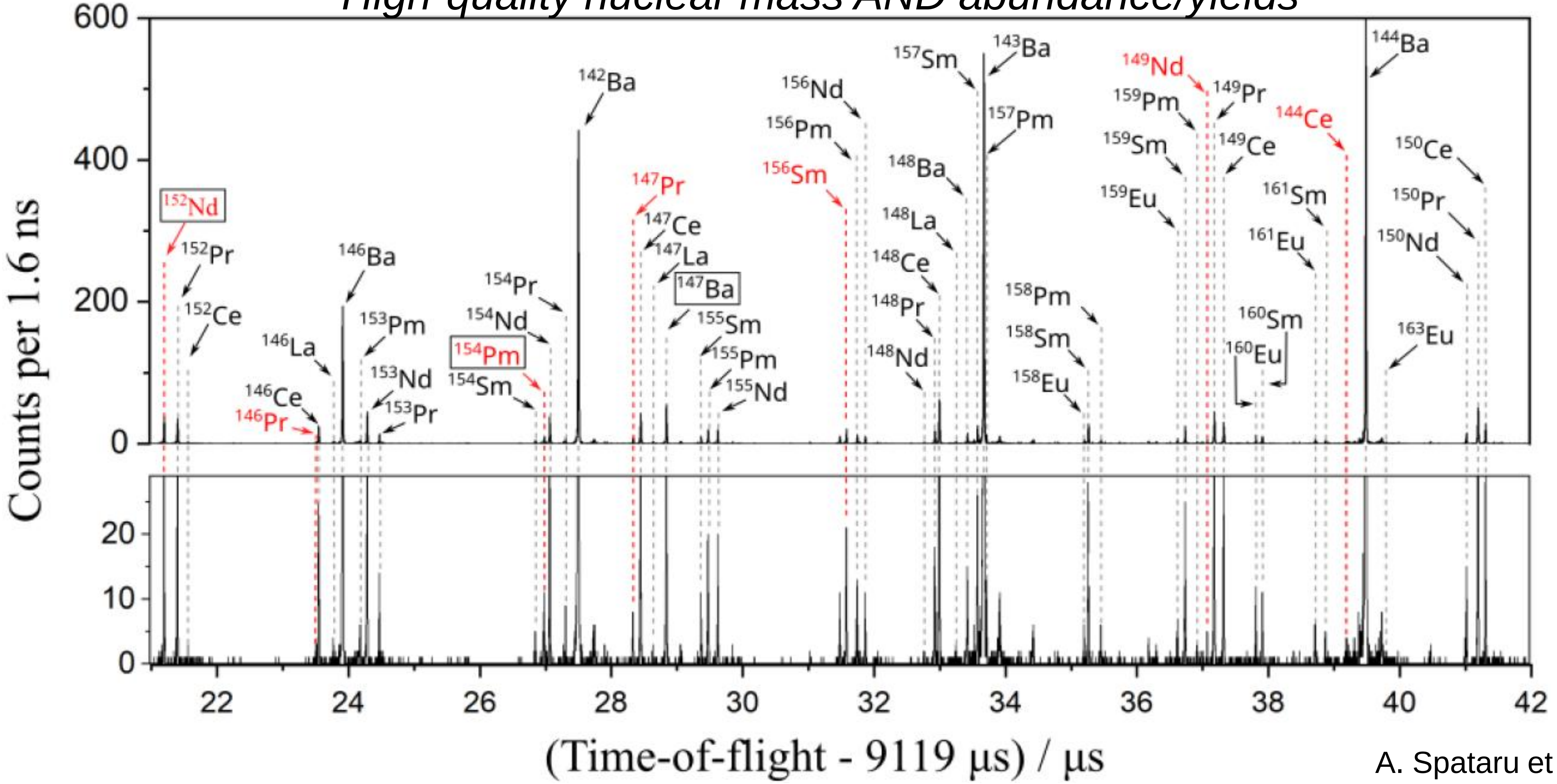
Coupling of FRS and FRS IC: *T. Dickel et al., Atoms (2024), 12, 52*

Broadband measurement of ^{252}Cf spontaneous fission products

Example of the MR-TOF-MS spectrum:

- Spans over ~20 mass numbers
- Mass resolving power (FWHM) of up to 450,000 (flight time ~9 ms)

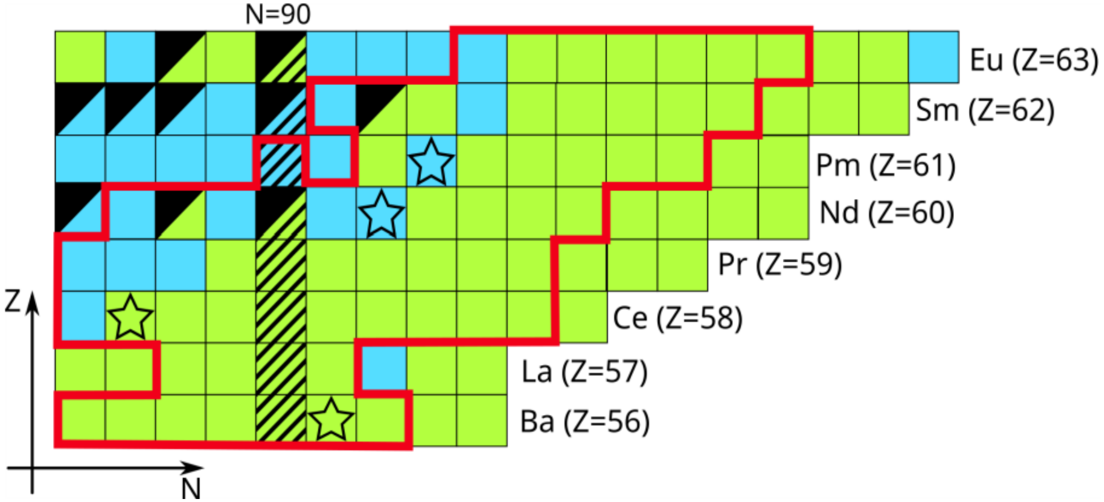
High-quality nuclear mass AND abundance/yields



A. Spataru et al., PRC 111 (2025)

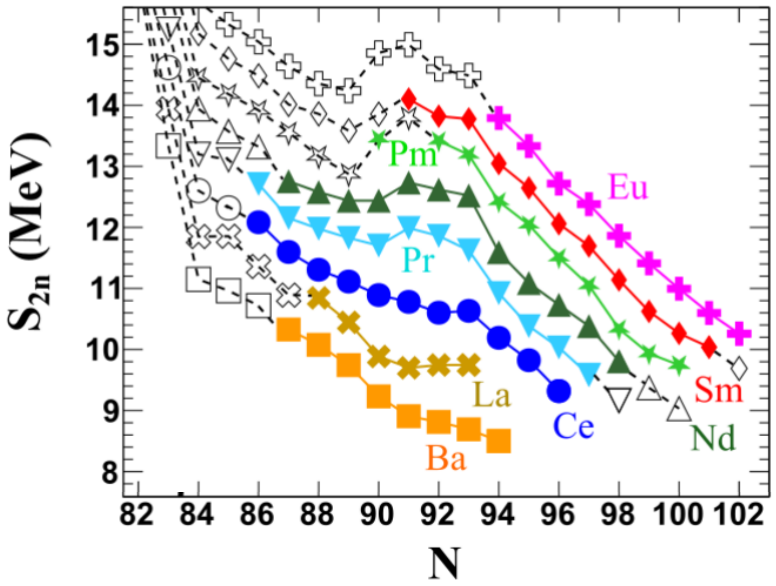
Mapping a mass surface

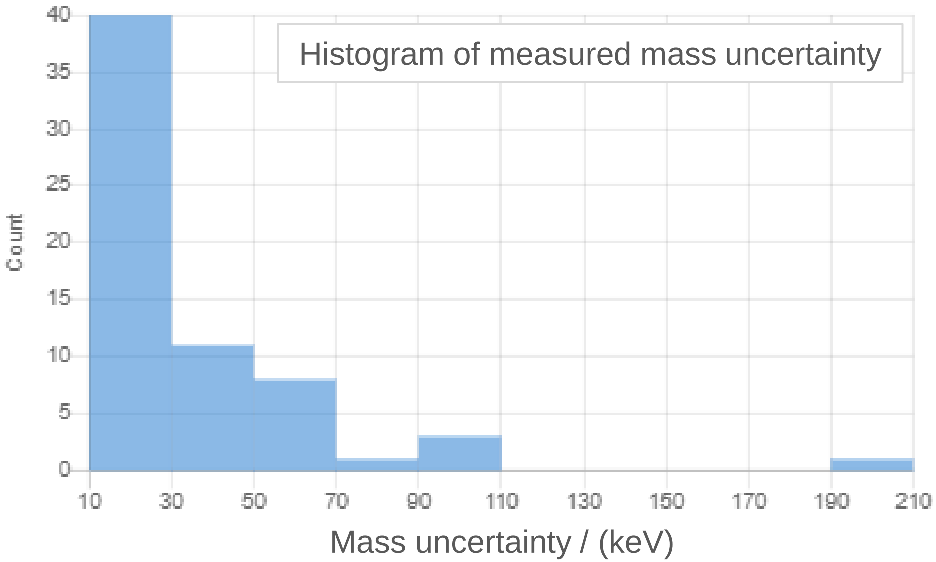
- Heavy fission peak - mid-shell region of rare-earth nuclei (Z>50, N~90)
- Most masses measured with an uncertainty better than 30 keV
- Data confirms behaviour of S2n at shape phase transition at N=90



Previous direct ( ) and indirect ( ) mass measurements
Data from [AME2020, R.Orford et al., PRC105, L052802 (2022)]

FRS-IC (this work) improved mass uncertainty





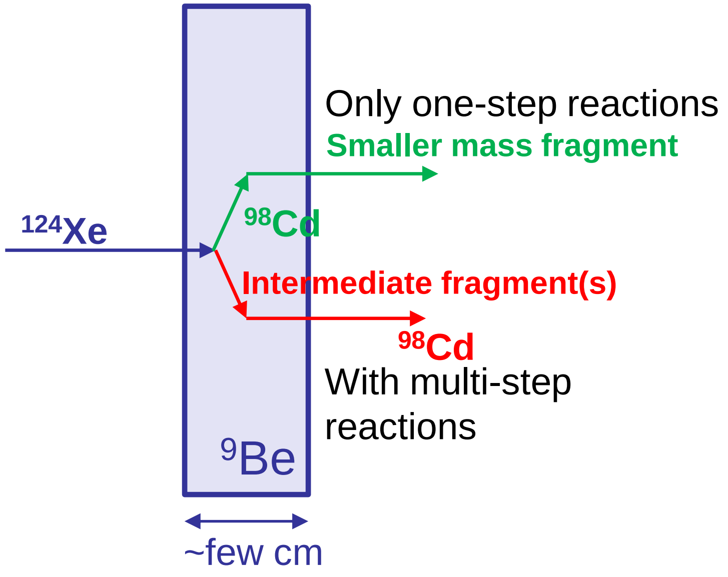
A. Spataru et al., PRC 111 (2025)

Recent developments for stopped beams

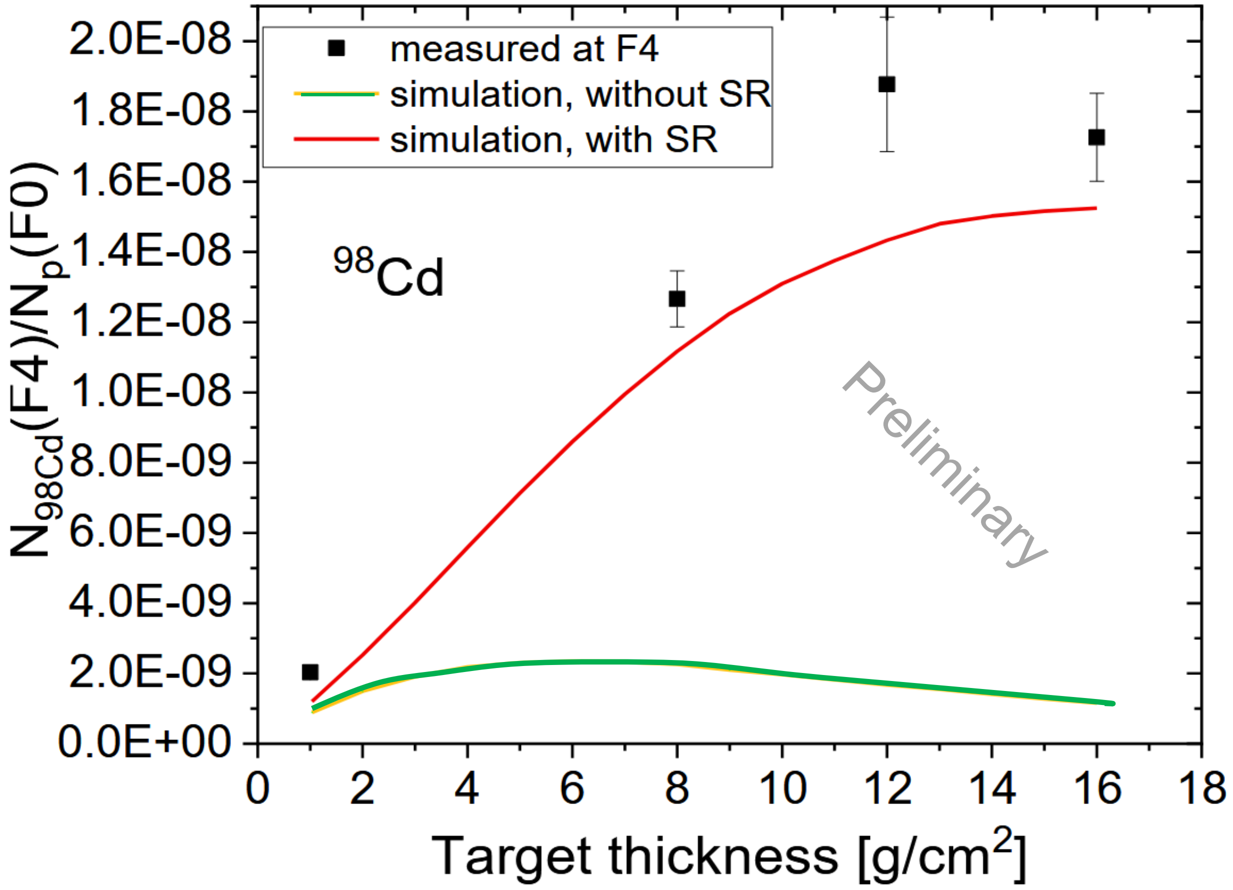
- Thicker targets (up to 16 g/cm^2)
  → secondary (multi-step) reactions start to contribute

$$\frac{A}{Z^2}\left({}^{124}Xe\right) \sim \frac{A}{Z^2}\left({}^{98}Cd\right)$$

minimize location straggling to avoid decreasing the stopping efficiency



E. Haettner, et al.

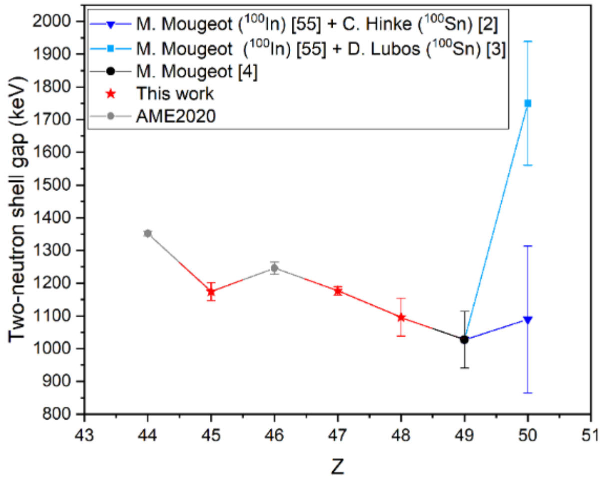


A. Mollaebrahimi *et al.*, *Phys. Lett. B* **839** (2023) 137833
G. Zhang, et al., *Phys. Lett. B* **863** (2025) 139378

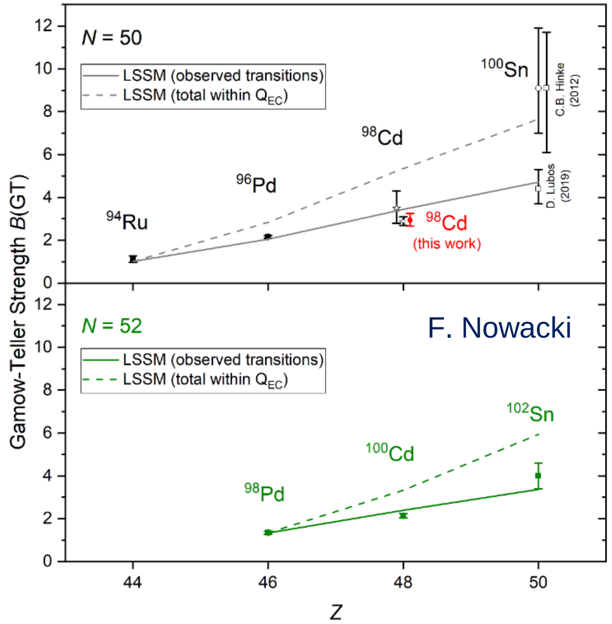
First direct mass measurements of ^{98}Cd and ^{97}Rh with the FRS Ion Catcher

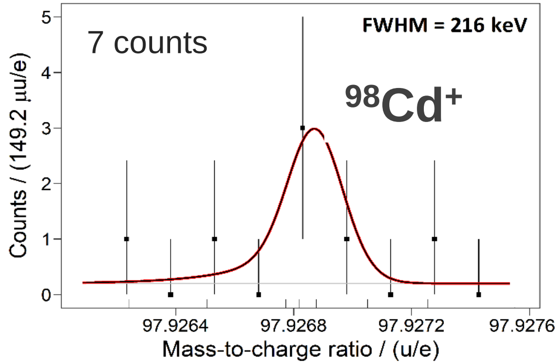
Shell Gap and Gamov-Teller Strength at *N*=50 and the puzzle of ^{100}Sn mass

N+2 two-neutron shell gap at N=50



Gamov-Teller Strength at N=50, 52





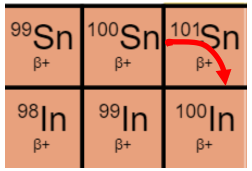
A. Mollaebrahimi *et al.*,
Phys. Lett. B **839** (2023) 137833
PhD thesis, University of Groningen (2021)

^{100}Sn mass:

New results on discrepancy of **^{100}Sn Q_{EC} values** (Hinke et al. [1] and Lubos et al. [2])

- In recent work Mougeot et al. [3] derive the mass of ^{100}Sn from mass measurements of $^{99-101}$In and published ^{100}Sn Q_{EC} values → value of Hinke et al is favored
- **This work**:
  Evolution of two-neutron shell gap at N=50: Value of Hinke et al. [1] is favored.
  Evolution of Gamov-Teller Strength at N=50: Value of Lubos et al. [2] is favored.

→ **Overall situation unclear, further experiments required**



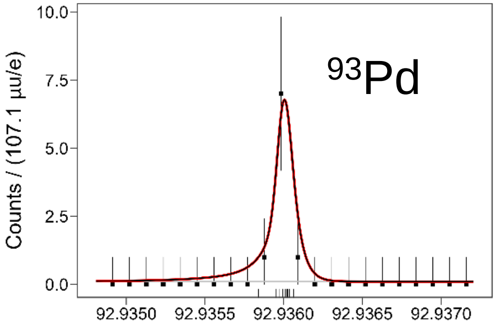
Super-FRS EC

FAIR Phase 0 Research Program

[1] C.Hinke *et al.*, Nature **486** (2012) 341 [2] D.Lubos *at al.*, PRL **122** (2019) 222502 [3] M.Mougeot *et al.*, Nature Phys. **17** (2021) 1099

Optimal stopping in an ultra thin stopper

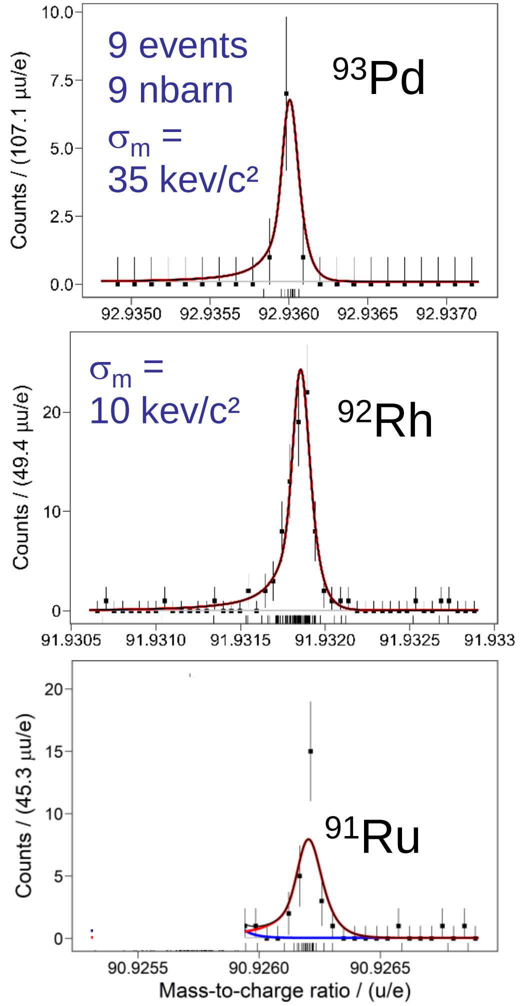
max. stopping efficiency for single isotopes



Optimal stopping in an ultra thin stopper
+ optimize beam energy

max. stopping efficiency for single isotopes

N=47 isotones

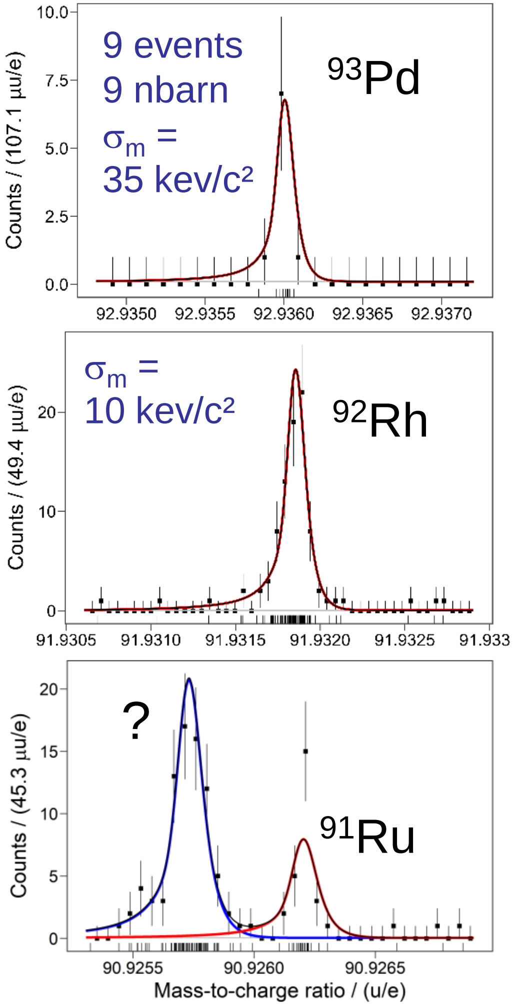


FRS and FRS Ion Catcher: Efficient measurement schemes

Optimal stopping in an ultra thin stopper
+ optimize beam energy

max. stopping efficiency for single isotopes

N=47 isotones

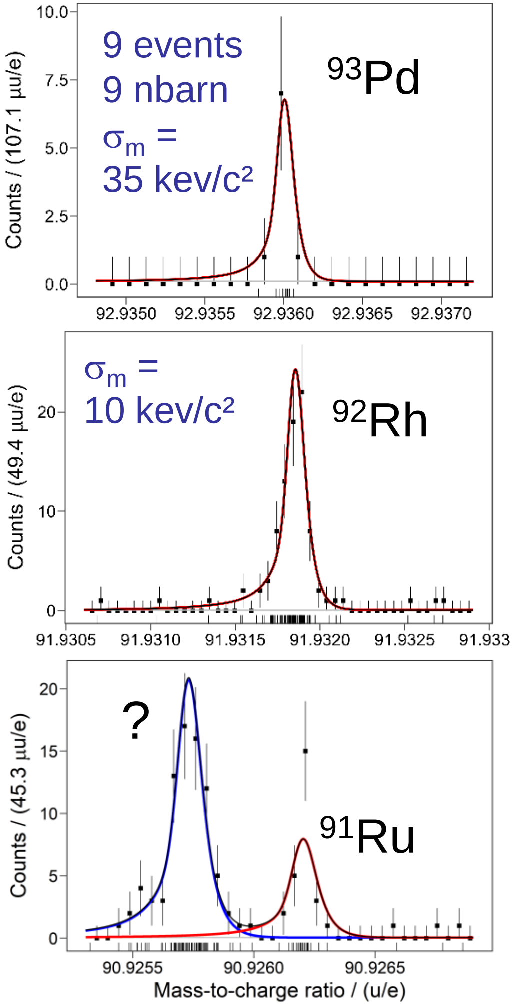


The ^{94}Ag riddle

Optimal stopping in an ultra thin stopper
+ optimize beam energy

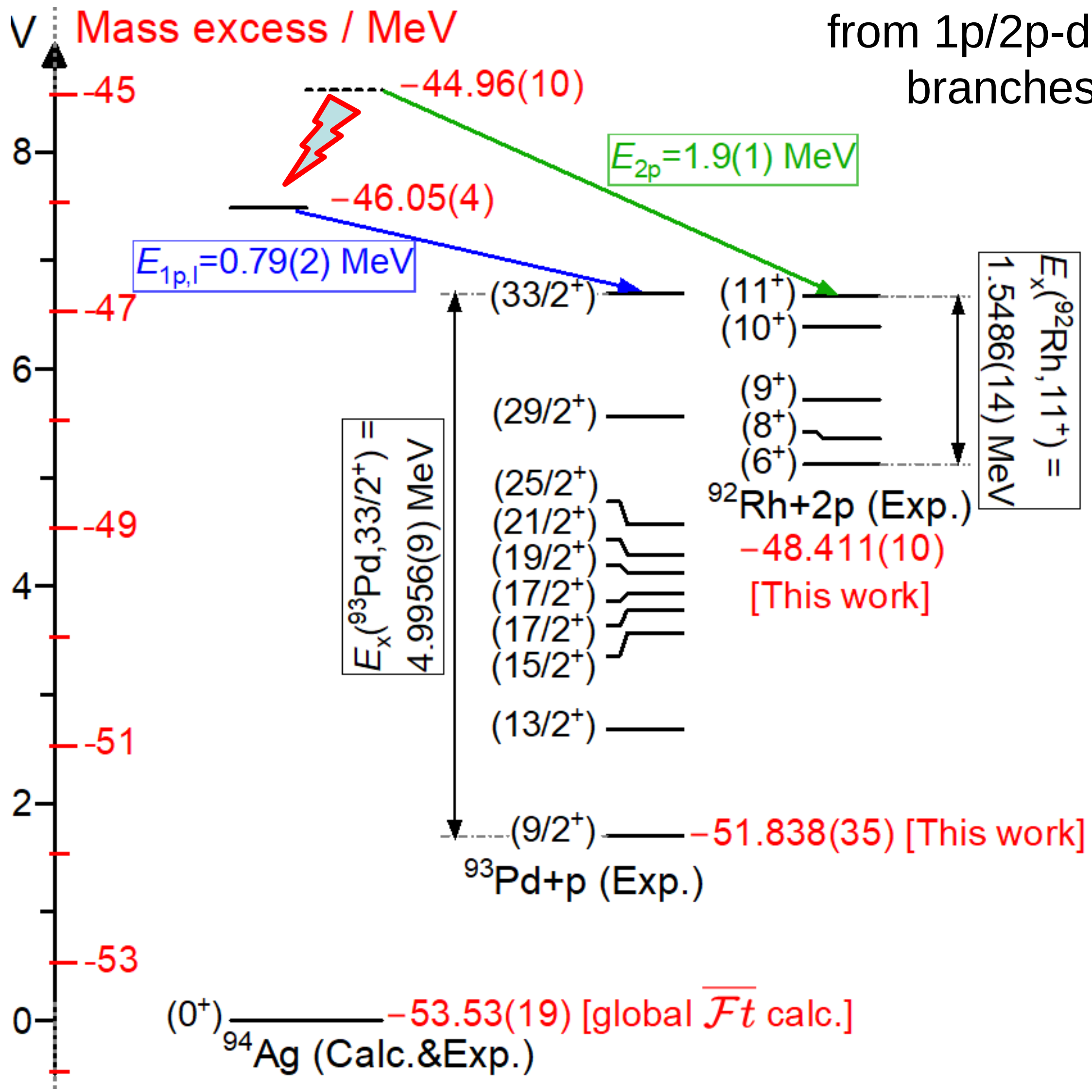
max. stopping efficiency for single isotopes

N=47 isotones



G. Kripkó-Koncz *et al.*,
PRR accepted

~10σ mismatch
between ME of 21+
from 1p/2p-decay
branches.

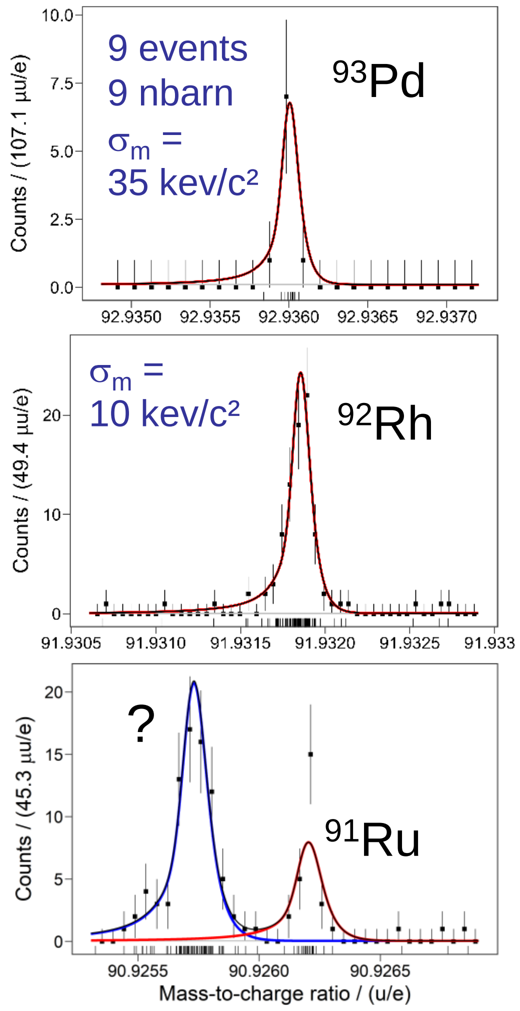


FRS and FRS Ion Catcher: Efficient measurement schemes

Optimal stopping in an ultra thin stopper + optimize beam energy

max. stopping efficiency for single isotopes

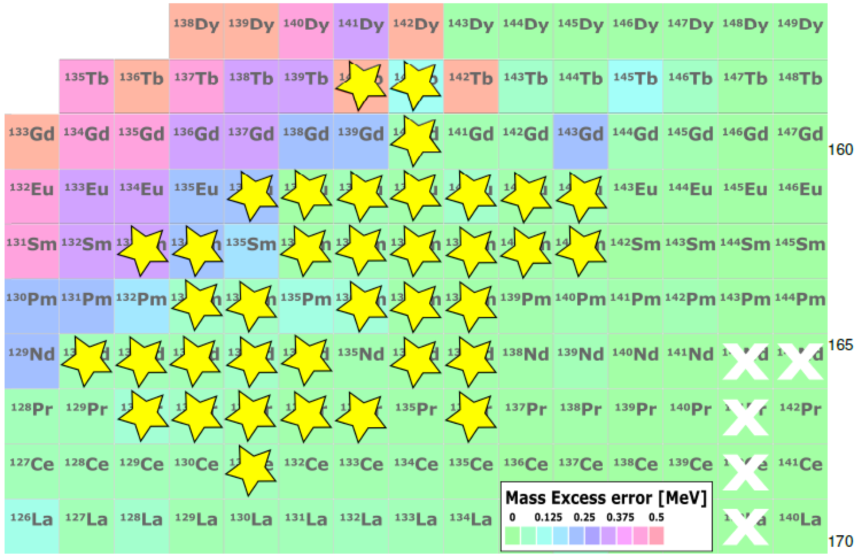
N=47 isotones



Mean Range Bunching (MRB)

Simultaneous stopping of many isotopes

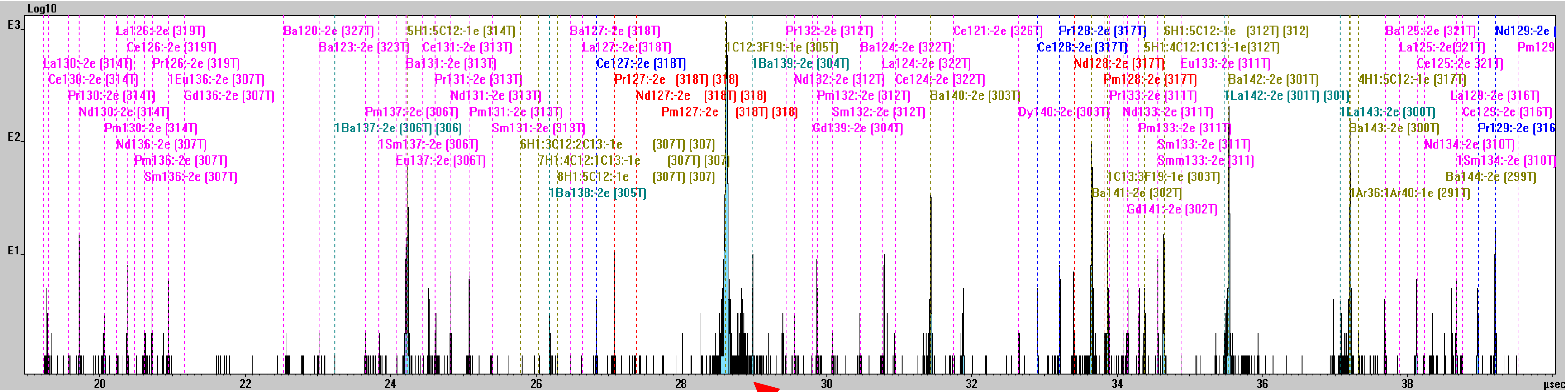
(at slightly reduced efficiency for single isotopes)



35 nuclides in one(!) FRS / MR-TOF-MS setting

T. Dickel et al., NIM B 541 (2023) 275-278

MR-TOF-MS enable broadband mass measurements



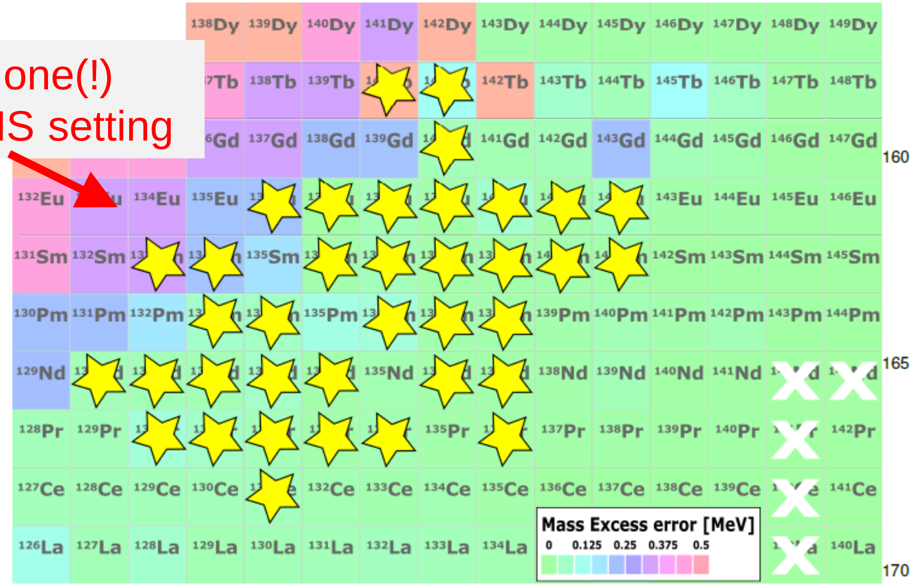
35 nuclides in one(!)
FRS / MR-TOF-MS setting

Super-FRS EC

FAIR Phase 0 Research Program

MR-TOF-MS data covering a large mass range (>10u/e) with high MRP (>350k)

Mapping large parts of the nuclear chart in one single setting



T. Dickel et al., NIM B 541 (2023) 275-278

How to measure neutrons with a mass spectrometer?

How to measure PXN with a mass spectrometer?

Challenge: Detect neutrons

Solution: Measure mass change instead

FRS/Super-FRS

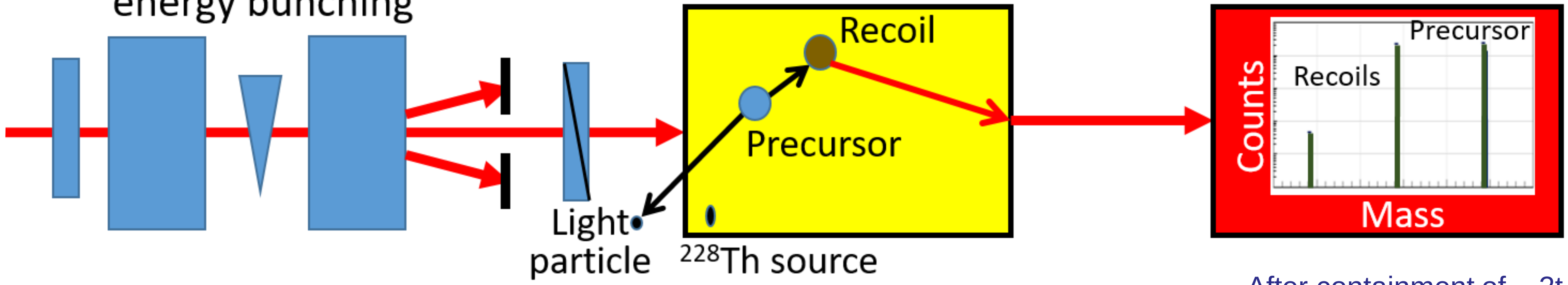
In-flight isotope production and separation, energy bunching

CSC

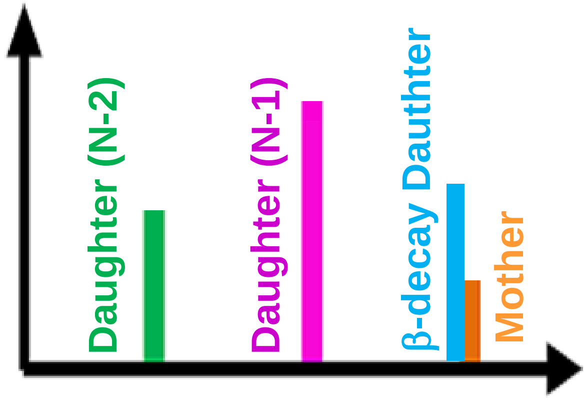
Required precursors stopped, contained and decay

MR-TOF-MS

Precursor and recoils identification and counting



After containment of ~ $2t_{1/2}$

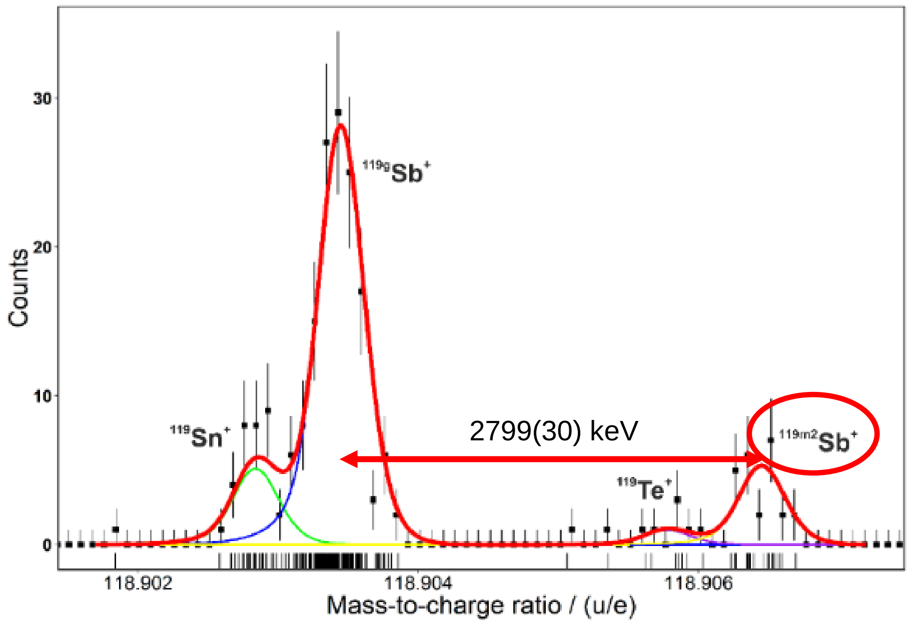


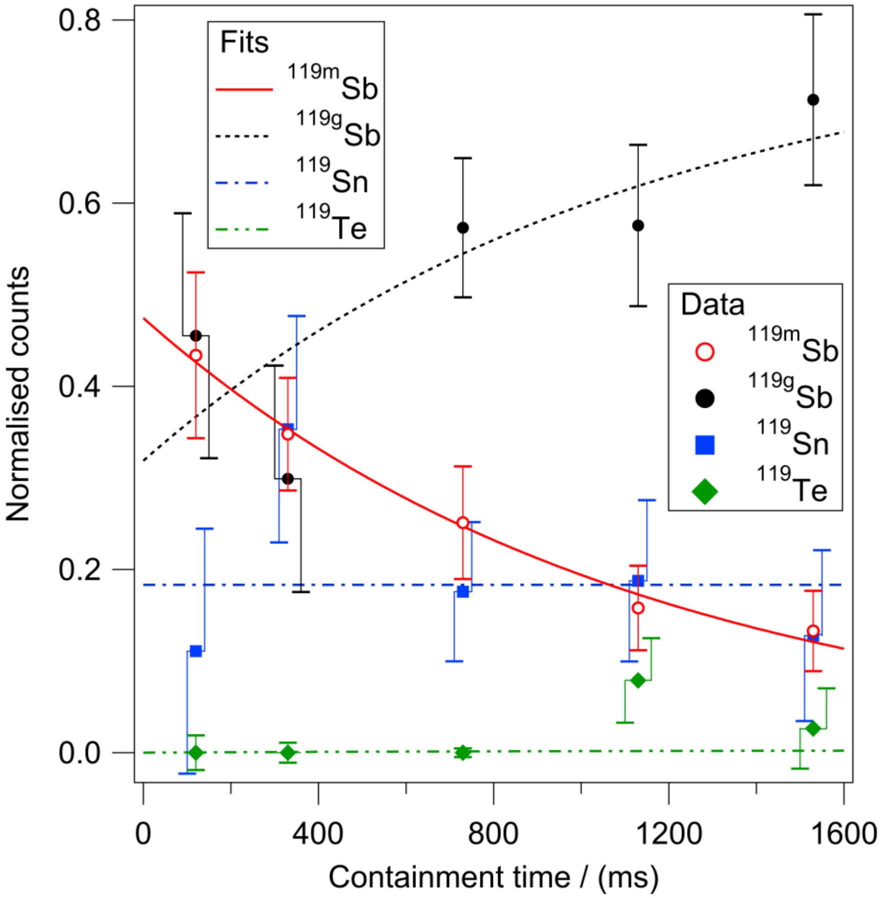
Production of exotic nuclei

Stopping cell → Ion trap

Simultaneous measurements of Pxn, half-lives, masses, Q-values, isomer excitation energies

Proof-of-concept: Novel method for half-lives and branching ratios (e.g., P_{xn})





Fits based on solution of radioactive decay laws

First experimental proof that ^{119m}Sb decays only via isomeric transition

Measured branching

Isomer Transition	β-	β+
1	0	0

Half-life

Measured value	Literature value
776 ± 181 ms	850 ± 90 ms

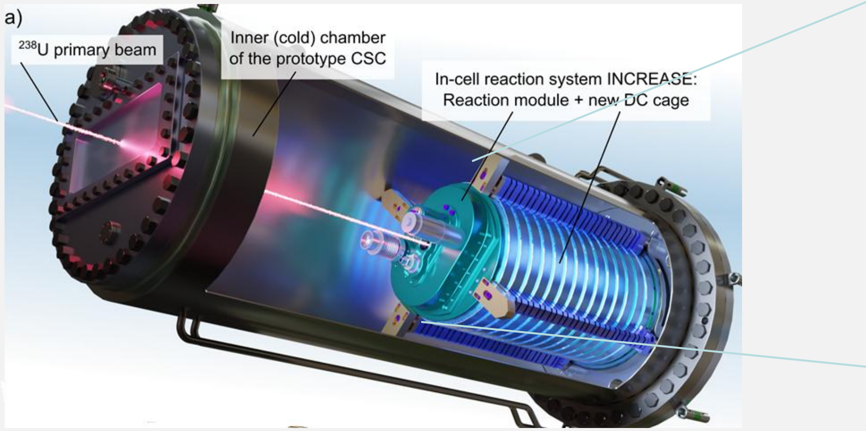
I. Miskun et al., EPJA (2019) 55: 148

End of June '25 test experiment with ^{135}Sb

MNT: proof-of-principle experiments at GSI

MNT with secondary beams = Accelerate to relativistic energy + Slow down to Coulmb barrier

in-cell MNT reaction

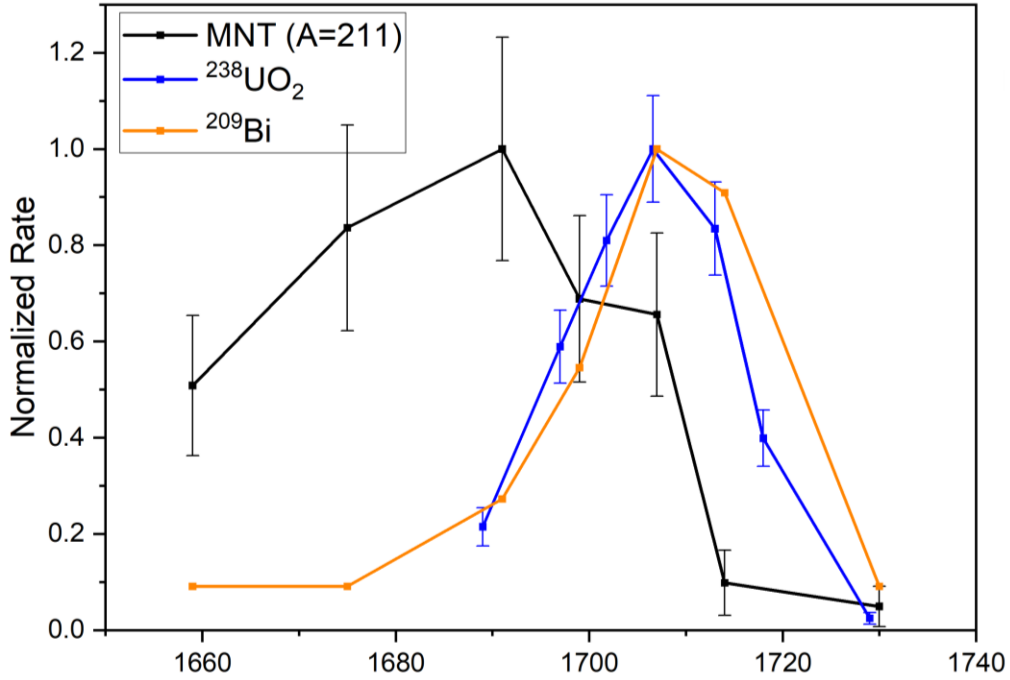


T. Dickel et al., J. Phys.: Conf. Ser. 1668 (2020)

MNT with primary beam of ^{238}U + ^{209}Bi

- **500 MeV/u** initial energy
- **< 1 x 10⁶ ions/s** on target

Development for **secondary** beams at the Super-FRS (intensity will be comparable or higher)



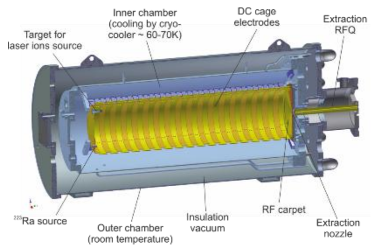
A. Mollaebrahimi et al., NPA 1057 (2025) 123041

- Identification of MNT products with a **relativistic beam** slowed down to Coulomb barrier energies
- **less than 10^6 ions per second** (~100pfA) on target

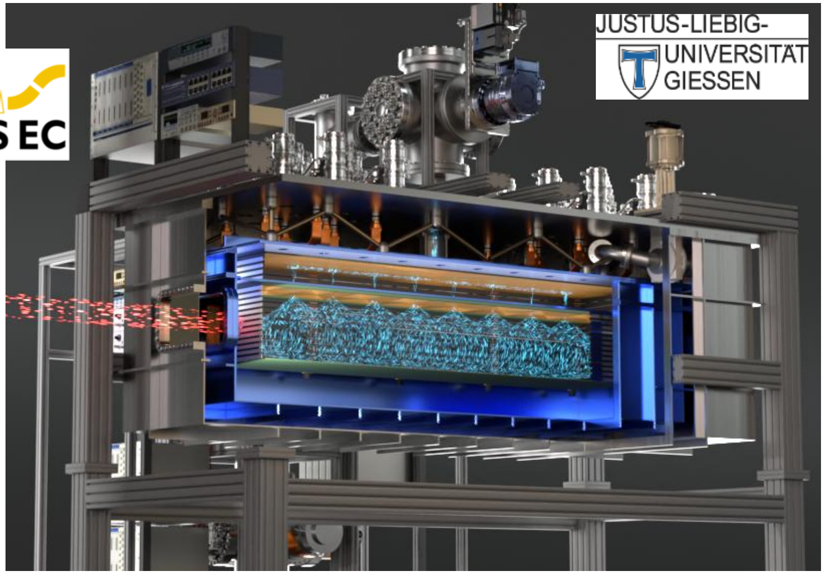
→ method applicable for **secondary beams**

From FRS to Super-FRS Ion Catcher

From FRS-Ion CSC **to** **Super-FRS Ion CSC**



Super-FRS EC



T. Dickel et al., NIM B 317 (2016) 216-220

New scientific opportunities:

- MNT reactions with secondary beams
- β-delayed neutron emission and half-lives
- Mass measurements of more exotic species
- and more…

Almost all that is needed for r-process

	FRS-IC CSC	Super-FRS IC CSC
Areal density (He)	6 mg/cm^2	20…40 mg/cm^2
Extraction time	25 ms	5…10 ms
Rate capability	10^4/s	10^7/s

- More efficient → Higher sensitivity
- Faster → Access to shorter lived nuclei
- Higher rate capability → New class of experiments

Low-energy ion beam with and for
Super-FRS EC / MATS / LaSpec collaborations

J. Äystö et al., NIM B 376 (2016) 111 D. Rodriguez et al., IJMS 255 (2013) 349 W. Nörtershäuser et al., Hyperfine Interact. 171 (2006) 149

Beam intensities: From Phase-0 to Early and First Science

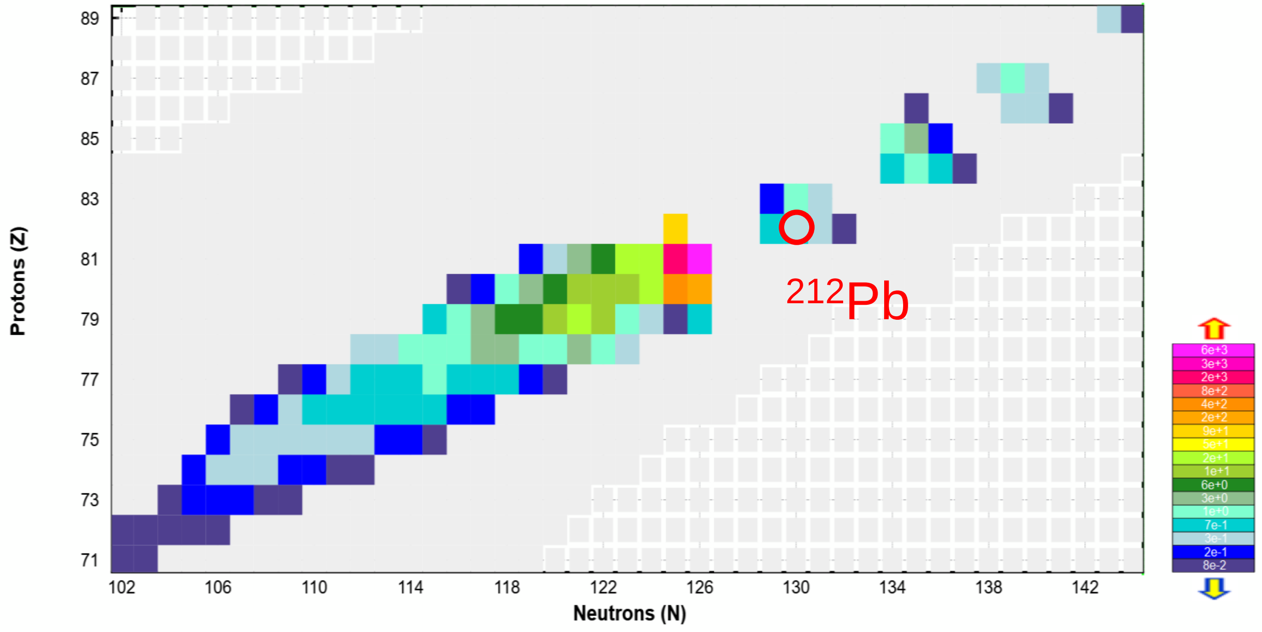
Facility	**U beam intensity/spill at production target**	If spill = 2 s
Today at GSI with **FRS** (Phase 0)	$1...2 \times 10^{9}$	
Early science with **Super-FRS** and **UNILAC/SIS18**	$2...5 \times 10^{9}$	0.2-0.4 pnA
First Science with **SIS100** (after commissioning)	2×10^{10}	1.6 pnA
First Science with **SIS100** (full intensity)	$3…4 \times 10^{11}$	32 pnA

Simulation comparison FRS vs Super-FRS

Production of 212Pb

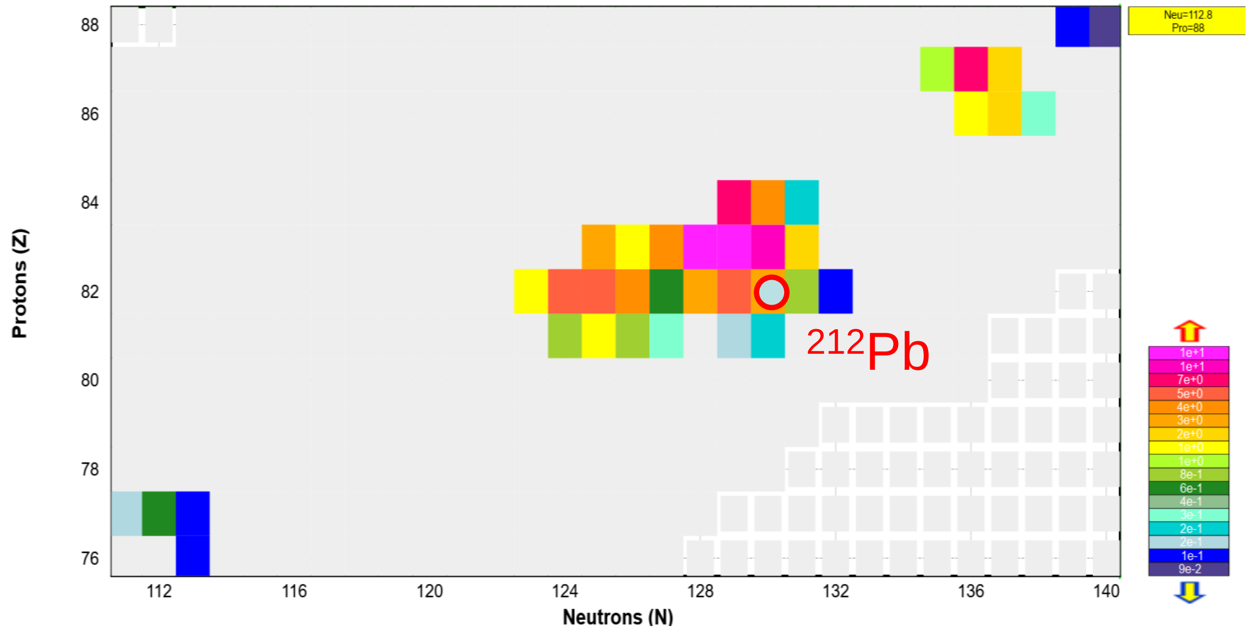
FRS

- 5E8 ^{238}U@1 GeV/u (2E9 per spill, 2s on / 2s off)
- Charge states → closed slits → limited transmission
- Total Rate at mid focus ~2x10^7 per second
- Total Rate at final focus **~1x10^4 per second**
- ^{212}Pb rate ~1 pps, in reality more like **0.3pps**



Super-FRS + SIS18

- 1E9 ^{238}U@1 GeV/u (4E9 per spill, 2s on / 2s off)
- Charge states no issue due to pre separator
- Total Rate at mid focus ~3x10^2 per second
- Total Rate at final focus **~1x10^2 per second**
- ^{212}Pb rate **~ 3pps**



Simulation comparison FRS vs Super-FRS

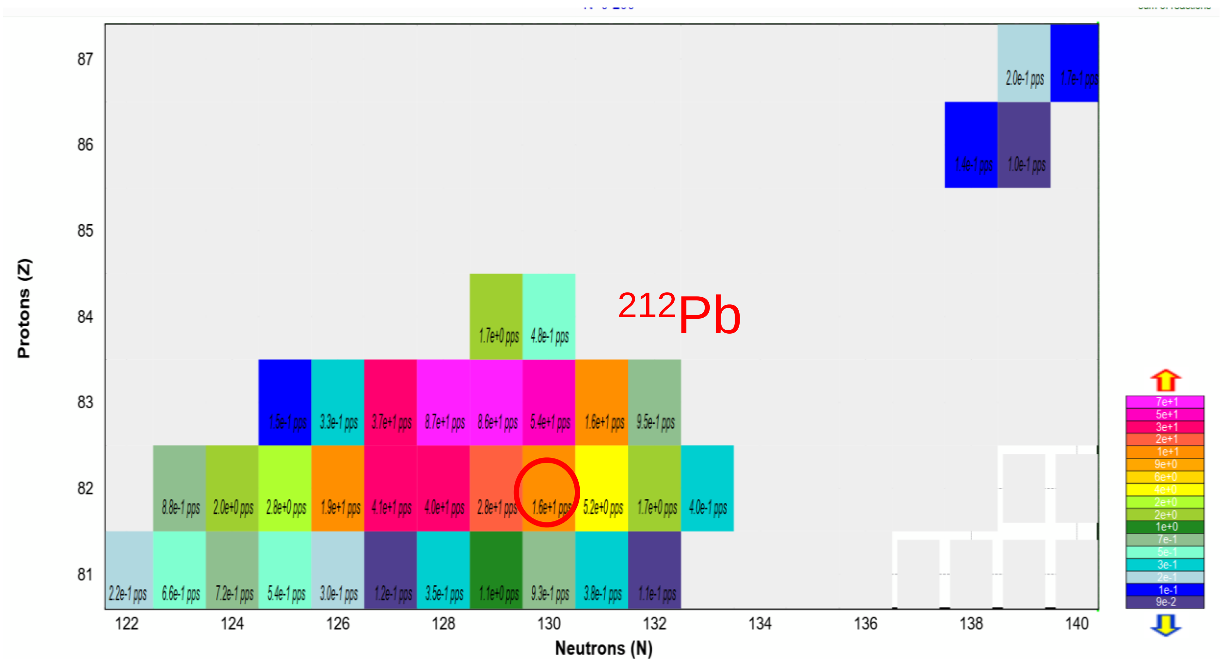
Production of 212Pb

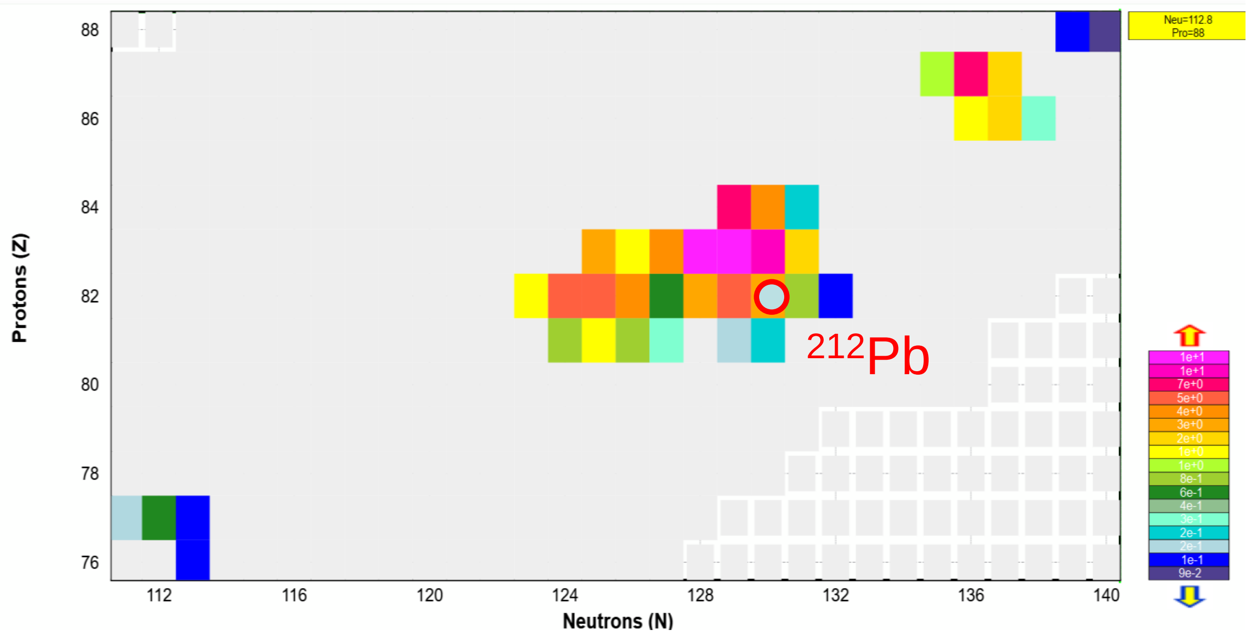
Super-FRS + SIS100

- 5E9 ^{238}U@1.5 GeV/u (2E10 per spill, 2s on / 2s off)
- Charge states no issue due to pre separator
- Total Rate at mid focus ~2x10^3 per second
- Total Rate at final focus **~4x10^2 per second**
- ^{212}Pb rate **~15 pps → 300 pps** @ full intensity

Super-FRS + SIS18

- 1E9 ^{238}U@1 GeV/u (4E9 per spill, 2s on / 2s off)
- Charge states no issue due to pre separator
- Total Rate at mid focus ~3x10^2 per second
- Total Rate at final focus **~1x10^2 per second**
- ^{212}Pb rate **~ 3pps**



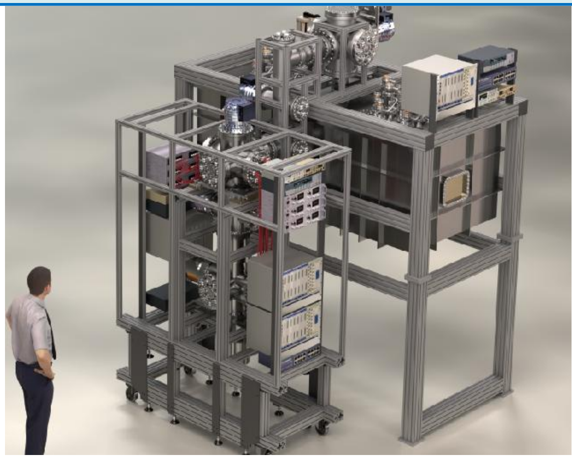


Summary and Outlook

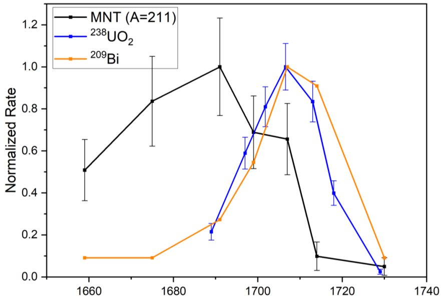
Experiment in 26/27
Neutron-rich isotopes above fission peaks

Experiment in 28 and beyond
Super-FRS:
Higher intensities and cleaner conditions
→ most exotic cases
FRS:
Test, Developments and special cases

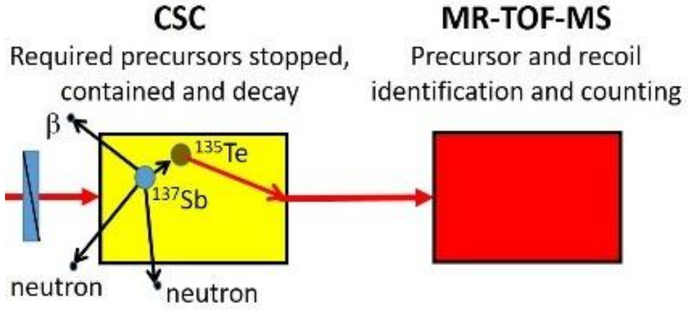
New Instrumentation



New production methods
MNT reaction studies with secondary beams



Mass spectrometry for other astrophysic data



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