Highly charged radioactive ions – the intersection of nuclear structure, atomic physics and astrophysics

Yury A. Litvinov

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

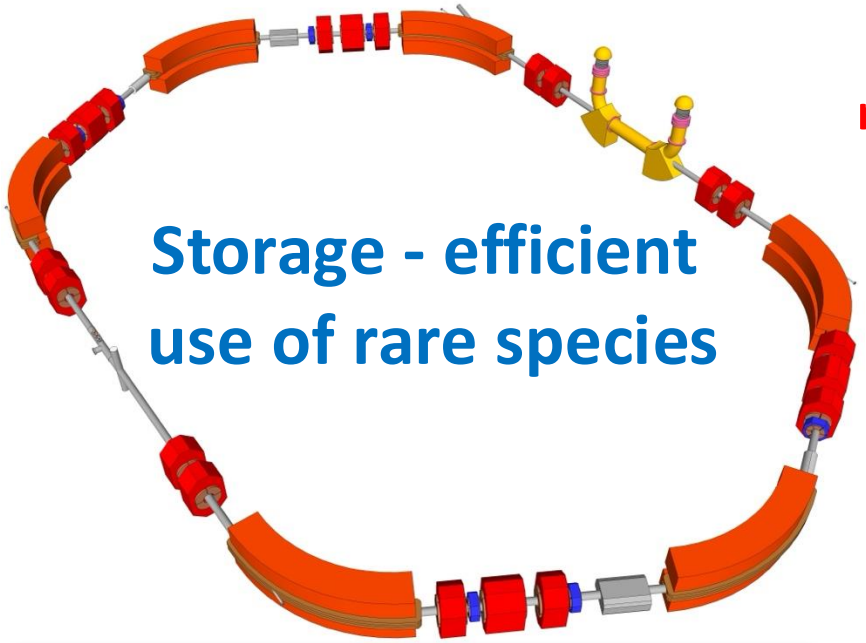
GSI

EMMI Workshop and International Workshop on Nucleosynthesis of Heavy Elements: r-process
19-25 January 2025, Darmstädter Haus, Hirschegg, Kleinwalsertal, Austria.

www.gsi.de/astrum

Heavy-Ion Storage Rings - Versatile Instruments

Dedicated beam preparation and manipulation techniques



Storage - efficient use of rare species

A huge trap – more than 100 m circumference, aperture size – 25 cm

Nuclear reaction inevitably leads to large momentum spread of the secondary beam

Beam cooling - high quality beams

Isochronous mode – high mass resolution

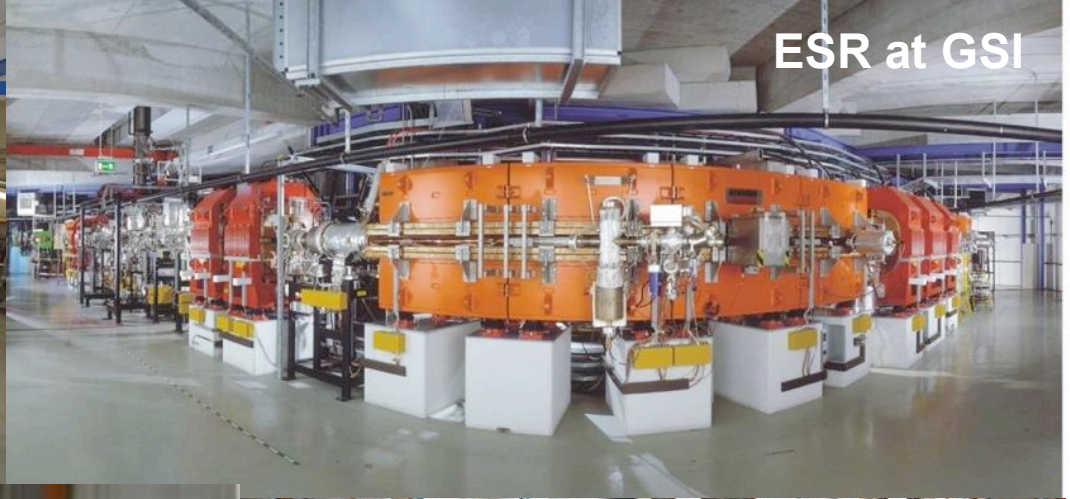
Small production rates of secondary beams

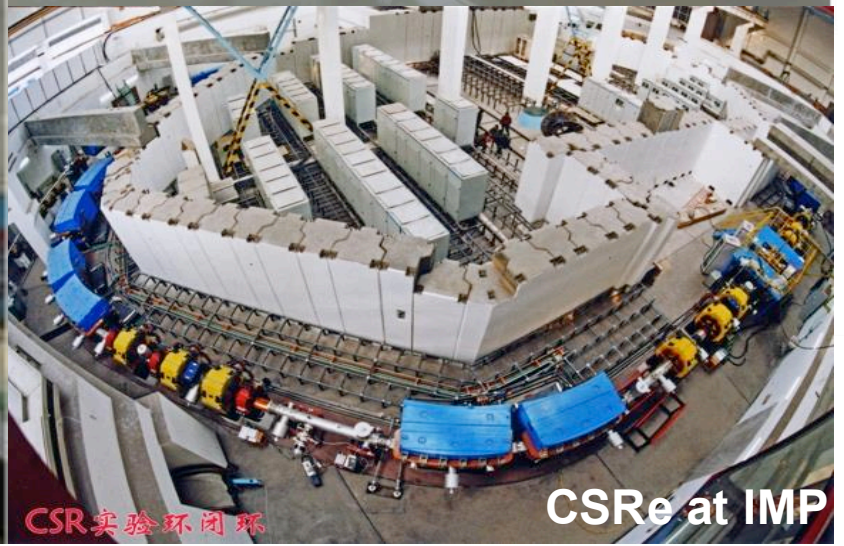
Accumulation techniques

Single-particle sensitivity detection

Short-lived species

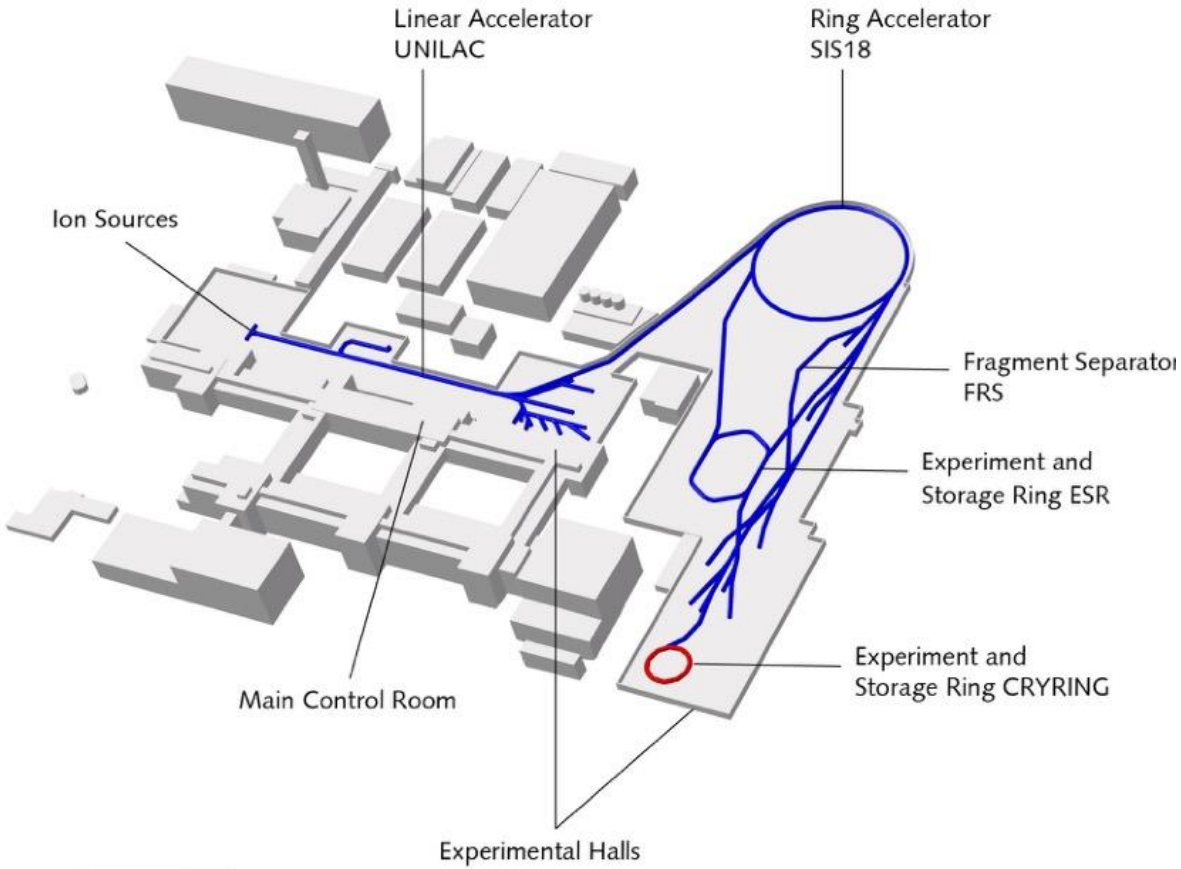
Instantaneous detection

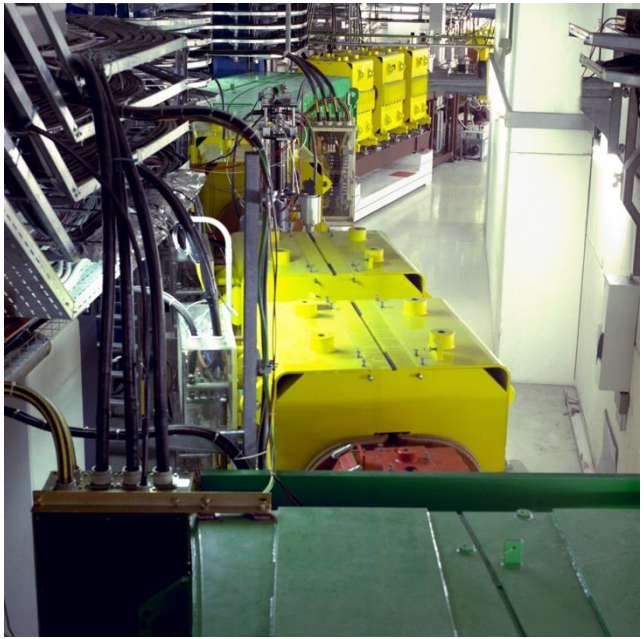




Photos: M. Lestinsky, A. Zschau, GSI; IMP Lanzhou; RIKEN

Radioactive Ion Beam Facility at GSI





GSI FAIR Phase-0 Research Program

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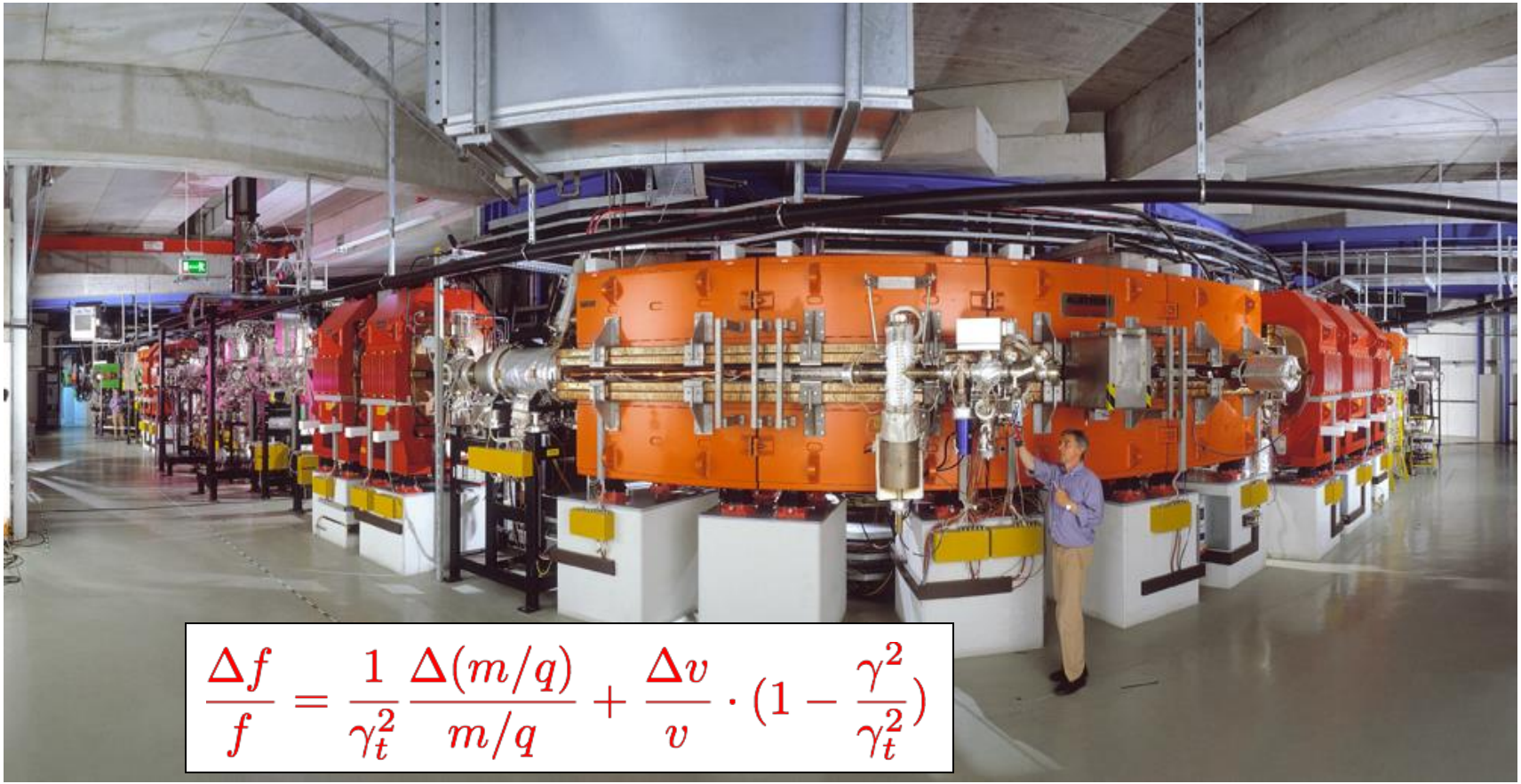
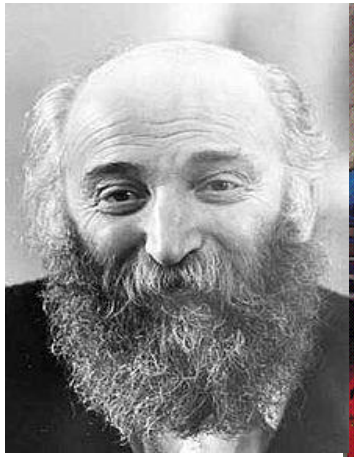
Picture: GSI, Darmstadt

The Experimental Storage Ring

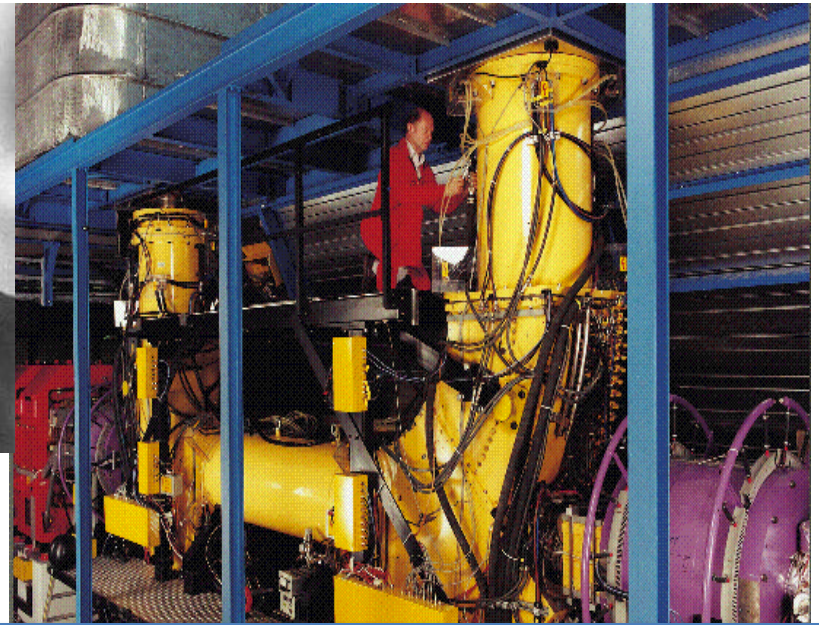


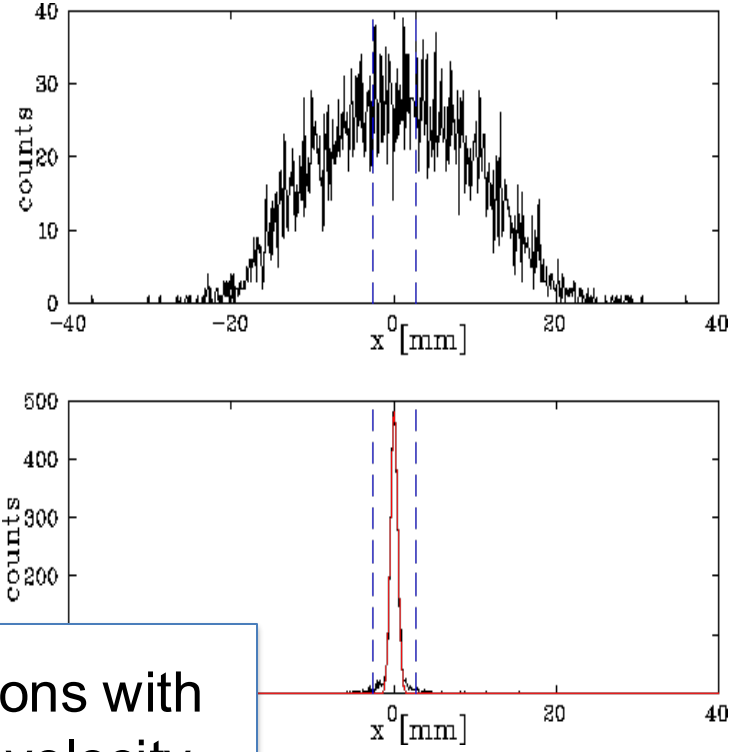
$$\frac{\Delta f}{f} = \frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\cdot\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

Electron Cooling of Secondary Beams



Gersh I. Budker
1918 - 1977





The cross-section for recombination of electrons with highly-charged ions diverges at zero relative velocity. Why stored ions do simply not recombine and get lost from the ring?

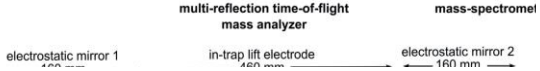
$$\frac{\Delta v}{v} \approx 1 \cdot 10^{-7}$$

Direct Mass Measurements on the Chart of the Nuclides

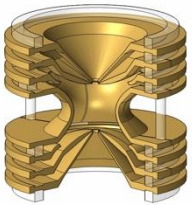
Where do we stand?

About 7000 nuclei are expected to exist

Masses of about 2300 have been measured



Multi-Reflection ToFs



Penning Traps

R3
Storage
Ring

Storage Rings

K. Blaum et al., 100 Years Mass Spectrometry [Int. J. Mass Spectr. 349-350 (2013)]

T. Yamaguchi et al., Prog. Part. Nucl. Phys. 120, 103882 (2021)

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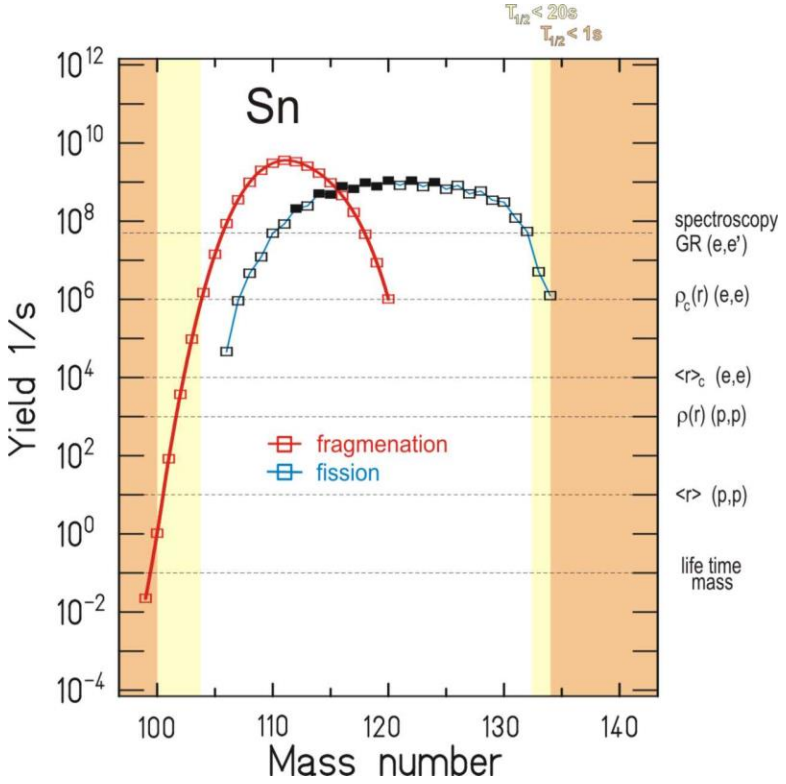
Characteristics of mass spectrometry techniques

Why do not we measure them all?

Mass spectrometry techniques:
- Bandwidth
- Resolving power
- Speed
- Sensitivity

Ultimate goal to combine all 4 characteristics



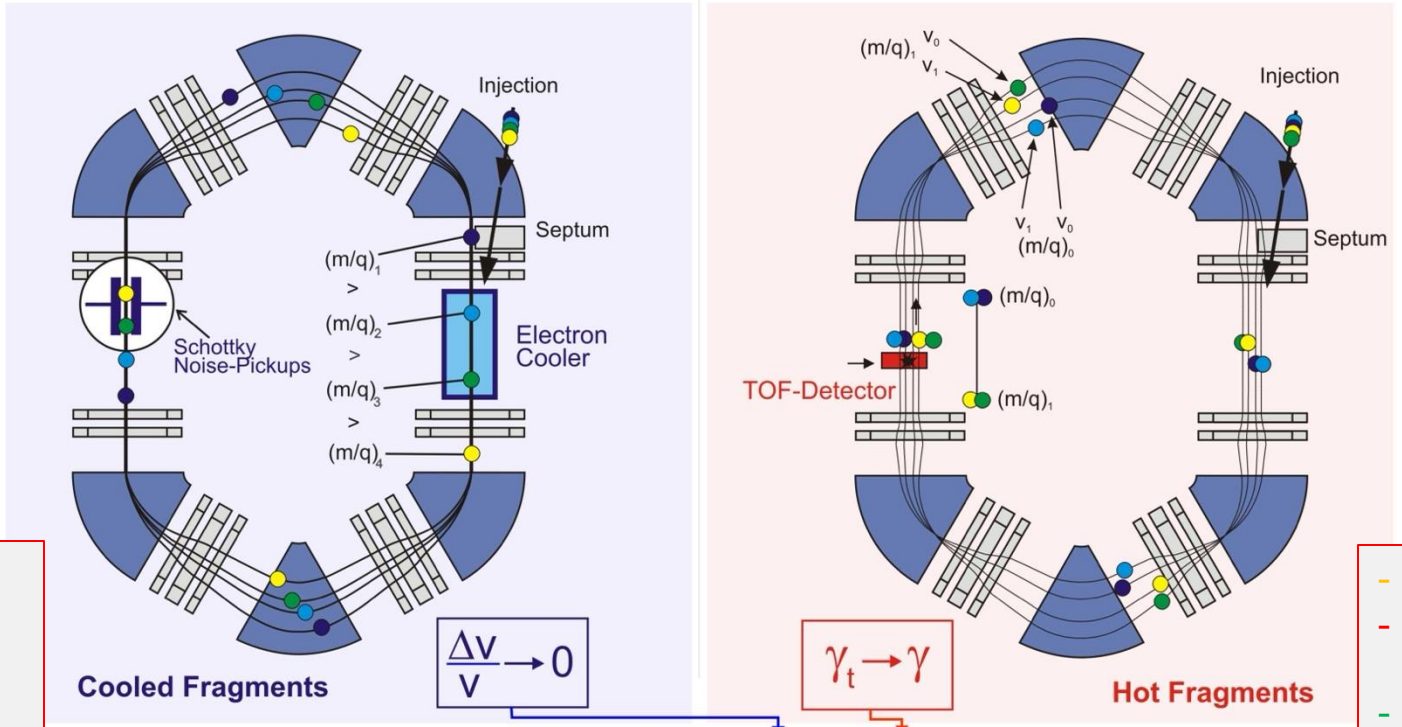
Schottky and Isochronous Storage Ring Mass Spectrometry

Cooling: Takes time

Non-Destructive Detection (Schottky detectors)

Destructive Detectors (foil-based Secondary electron detectors)

No cooling



$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

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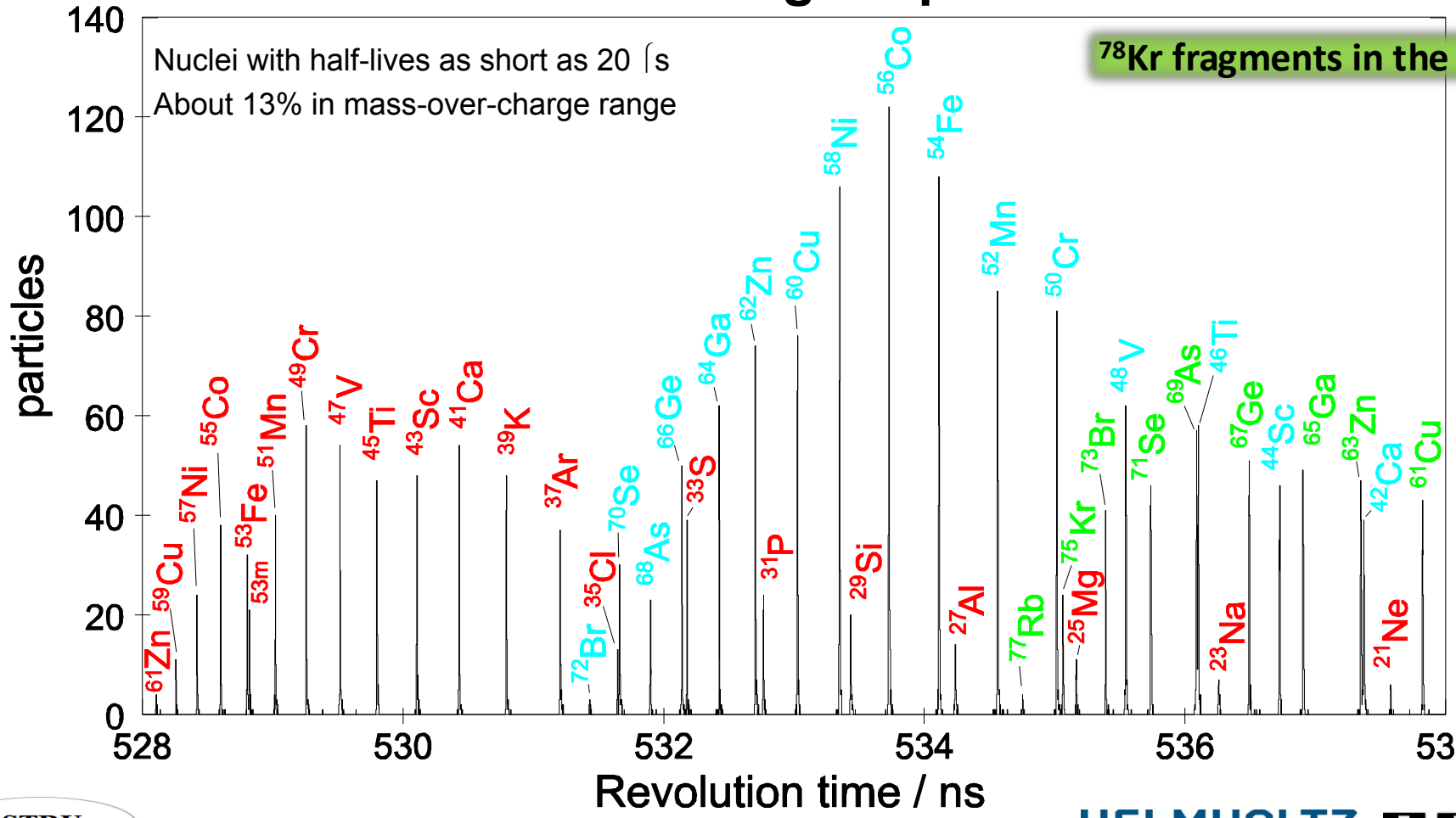
IMS: Time-of-Flight Spectra



M. Hausmann et al., Hyperfine Interactions 132 (2001) 291

IMS: Isochronicity Window

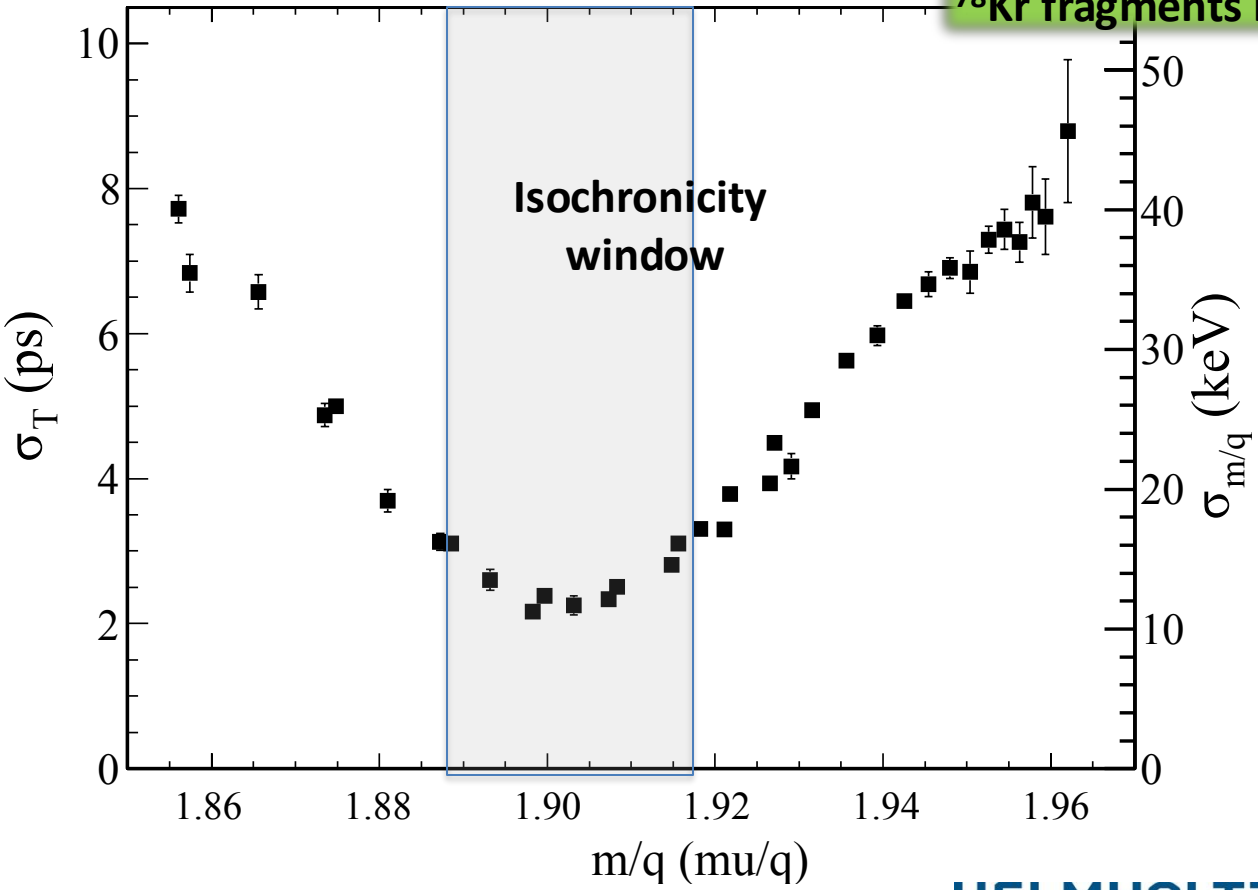
$$B\rho = \frac{m}{q} v\gamma$$

$$\frac{\delta m/q}{m/q} \propto 13\%$$

$$\gamma \neq \gamma_t$$

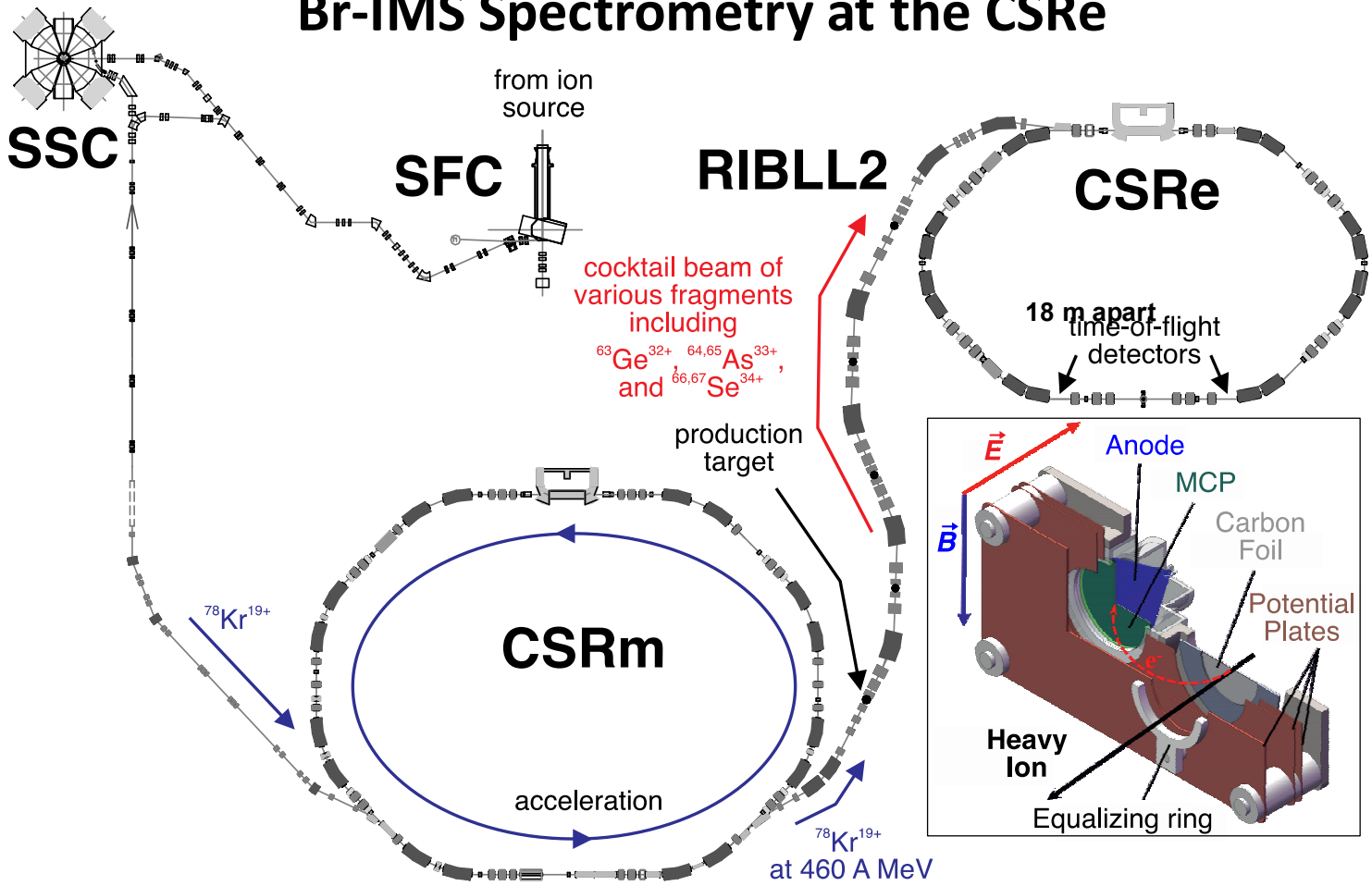
- Bandwidth
- Resolving power
- Speed
- Sensitivity

^{78}Kr fragments in the CSRe



M. Wang et al., Physical Review C 106 (5) (2022) L051301

Br-IMS Spectrometry at the CSRe



Br-IMS Spectrometry at the CSRe

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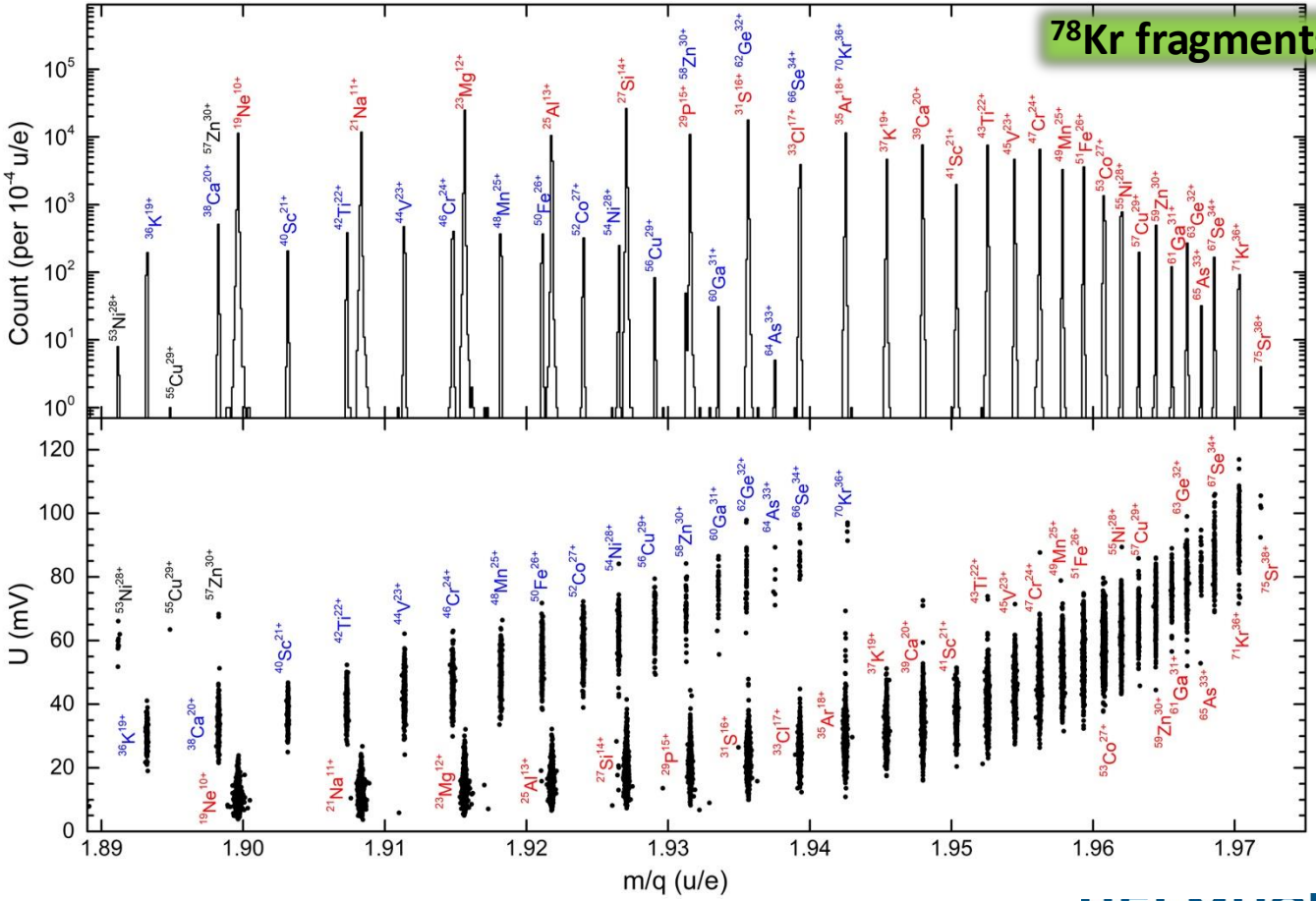

M. Wang et al., Physical Review Letters 130 (2023) 192501

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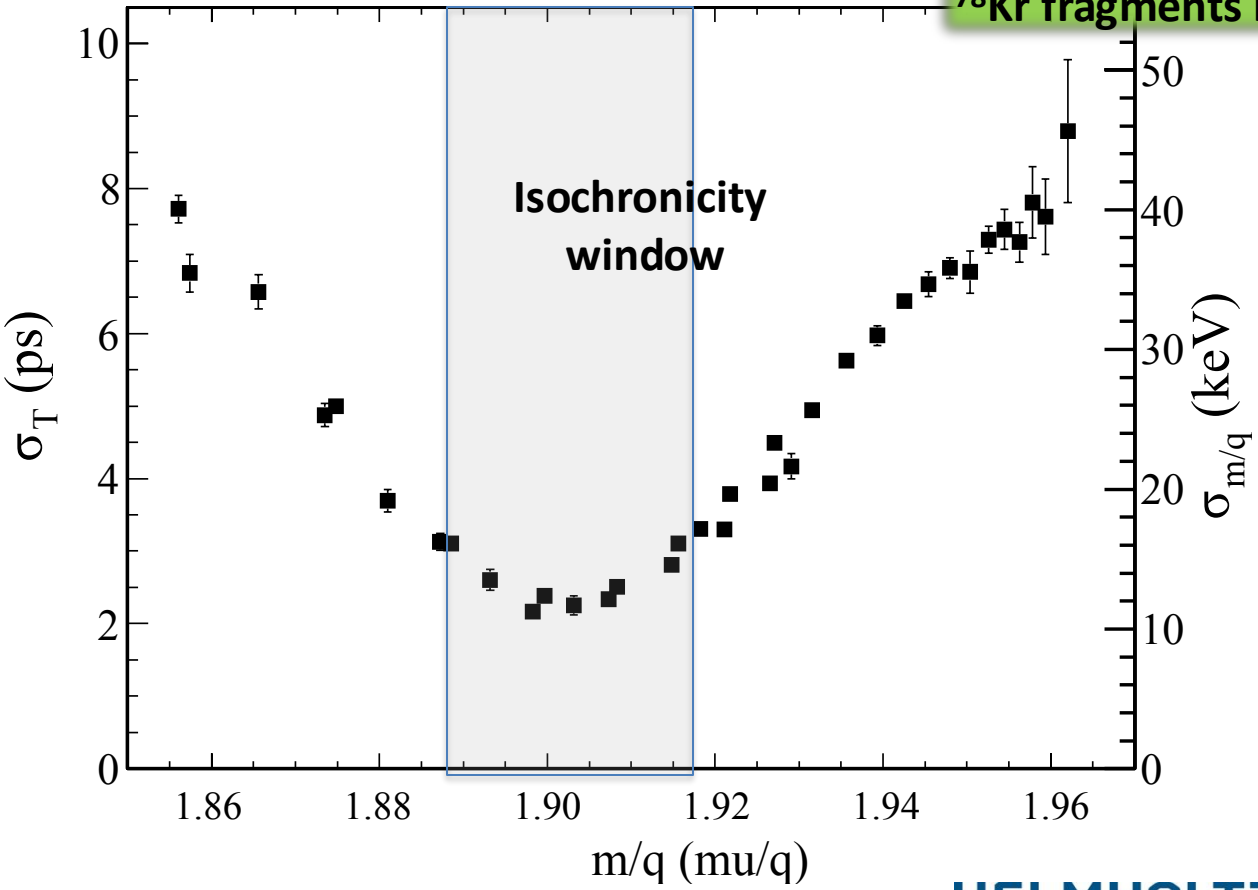

M. Wang et al., Physical Review C 106 (5) (2022) L051301

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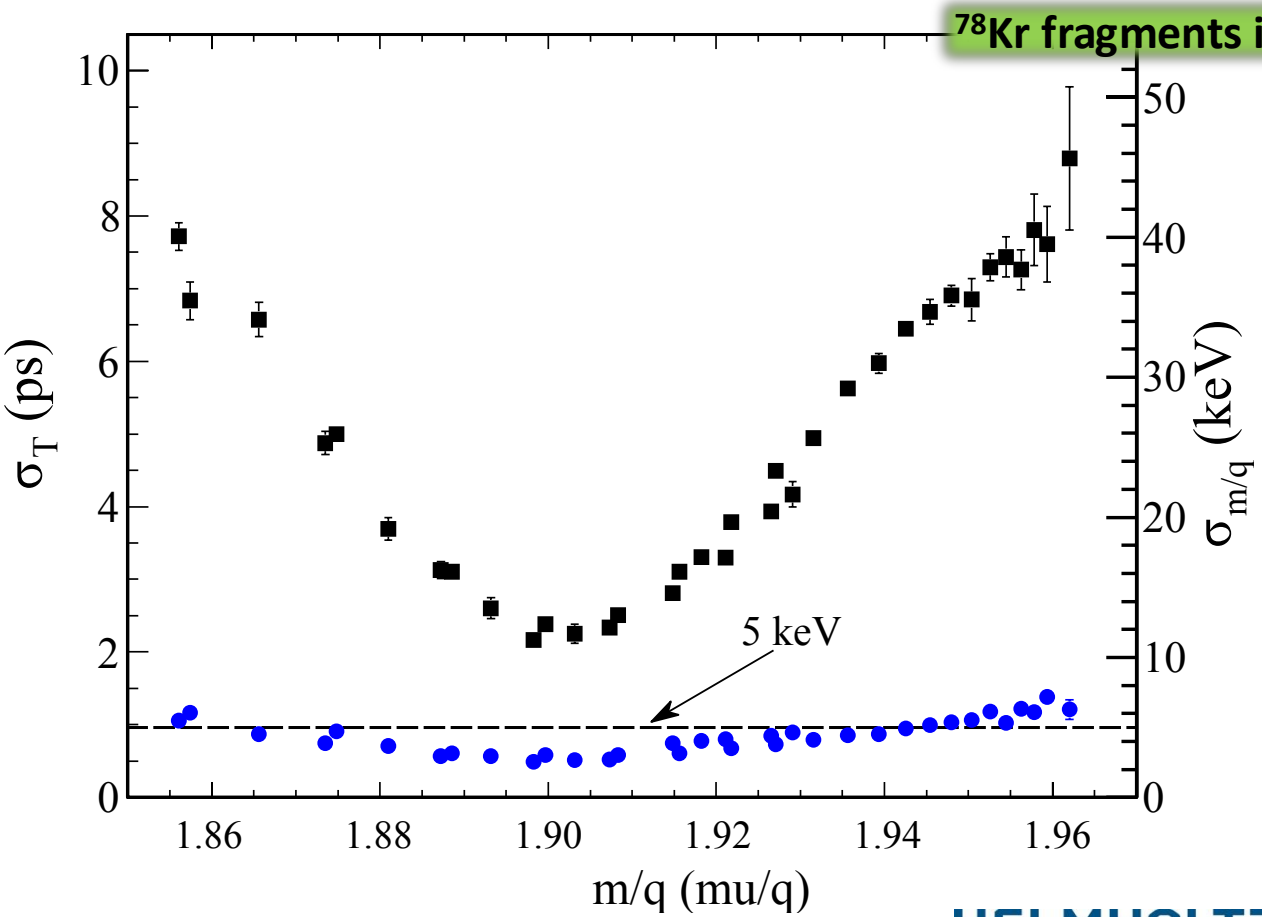


- Bandwidth
- Resolving power
- Speed
- Sensitivity

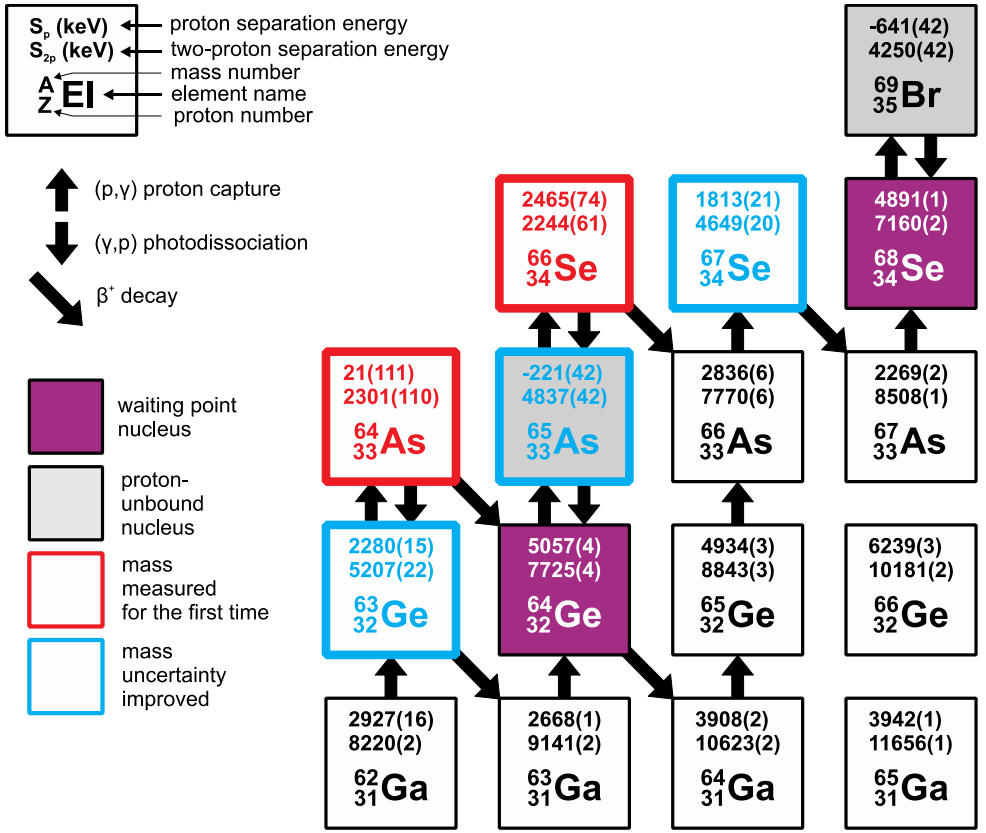
M. Wang et al., Physical Review C 106 (5) (2022) L051301

Rp-process nucleosynthesis at ^{64}Ge

Rate of the most exotic species is 6 ions in 2 weeks, which is sufficient for the mass measurement with relative precision of 1.7 10^{-6}

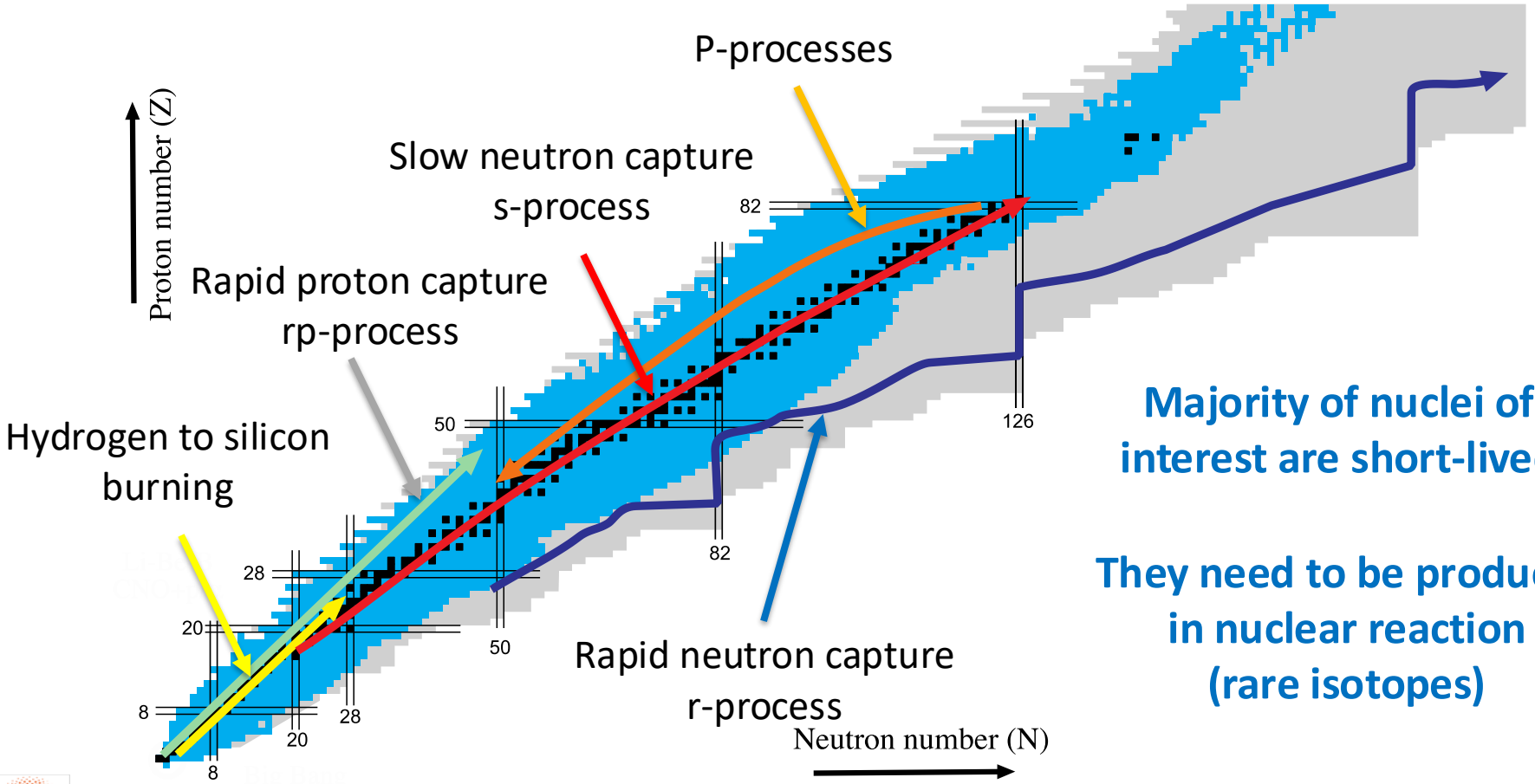
^{65}As is less bound

^{66}Se is more bound



X. Zhou et al., Nature Physics 2023

Nucleosynthesis Processes



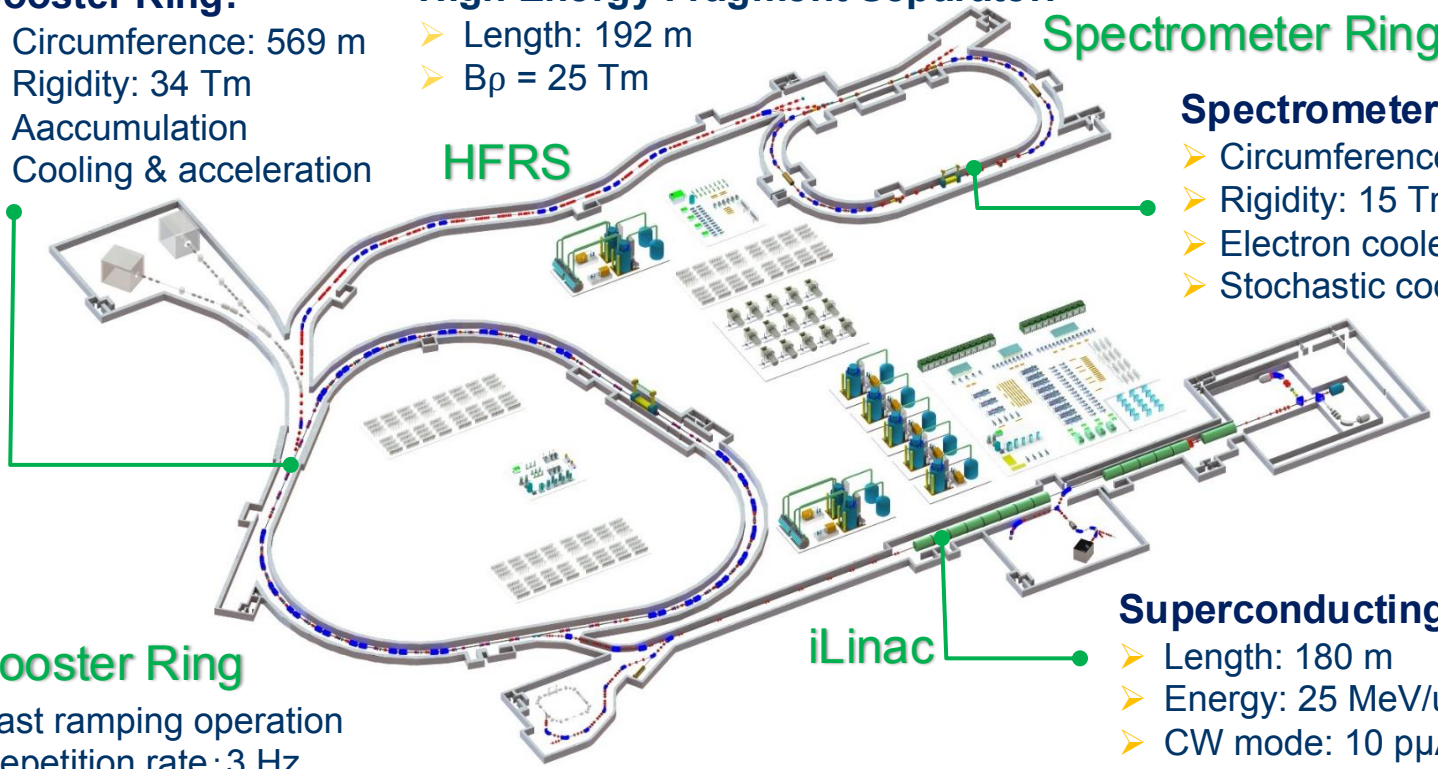
Majority of nuclei of interest are short-lived

They need to be produced in nuclear reaction (rare isotopes)

Accelerator Complex

Booster Ring:
- Circumference: 569 m
- Rigidity: 34 Tm
- Aaccumulation
- Cooling & acceleration

High Energy Fragment Separator:
- Length: 192 m
- Bρ = 25 Tm



Spectrometer Ring:
- Circumference: 277.2 m
- Rigidity: 15 Tm
- Electron cooler
- Stochastic cooler

Ion Sources:
- a 45 GHz FECR
- a 28 GHz SECRAL
- a 2.45 GHz ECR

Fast ramping operation
Repetition rate：3 Hz

Superconducting Ion Linac:
- Length: 180 m
- Energy: 25 MeV/u ($^{238}U^{34+}$)
- CW mode: 10 pμA with A/Q=2~5
- Pulse mode: 1.0 emA with A/Q=2~7

Schottky and Isochronous Storage Ring Mass Spectrometry

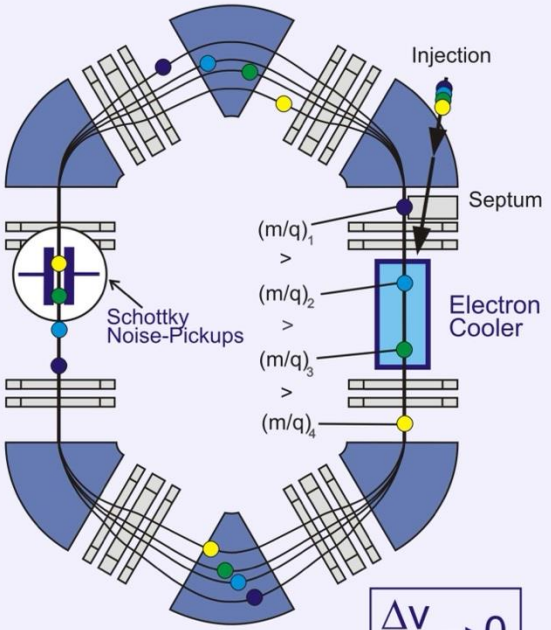
Cooling: Takes time

Non-Destructive Detection (Schottky detectors)

Destructive Detectors (foil-based Secondary electron detectors)

No cooling

SCHOTTKY MASS SPECTROMETRY

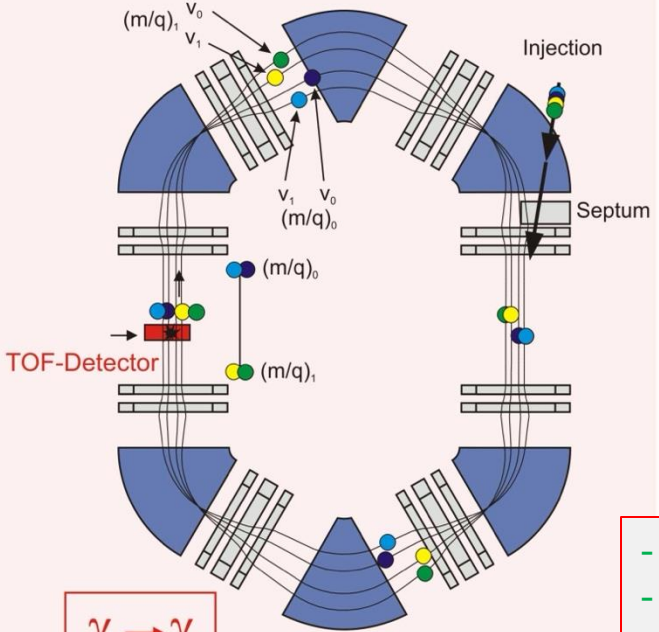


Cooled Fragments

$\frac{\Delta v}{v} \rightarrow 0$

- Bandwidth
- Resolving power
- Speed
- Sensitivity

ISOCHRONOUS MASS SPECTROMETRY



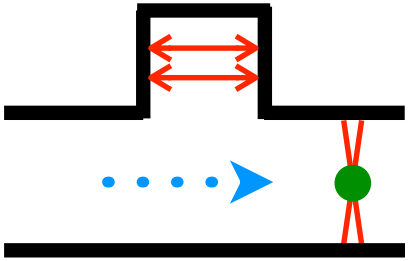
Hot Fragments

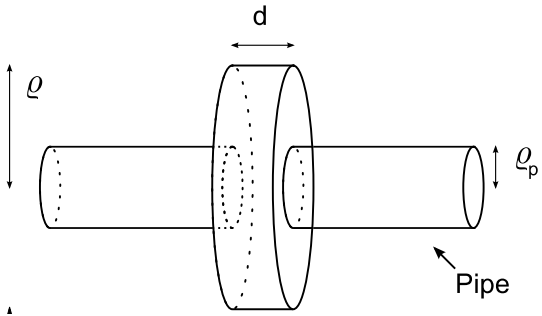
$\gamma_t \rightarrow \gamma$

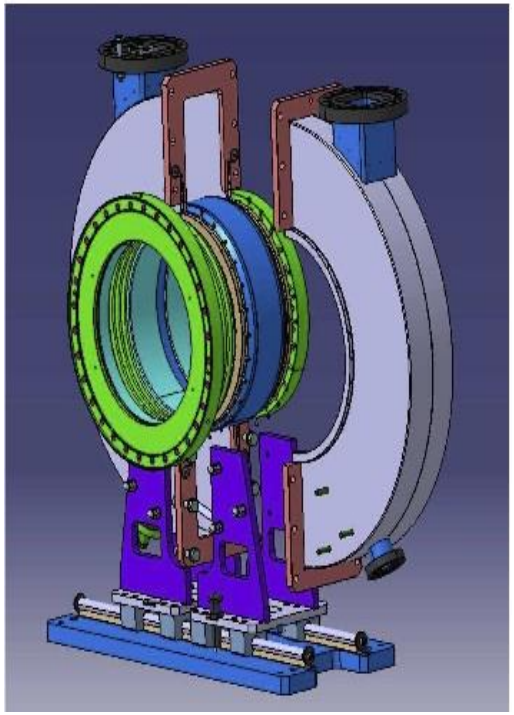
- Bandwidth
- Resolving power
- Speed
- Sensitivity

$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t^2}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1-\frac{\gamma^2}{\gamma_t^2}\right)$$

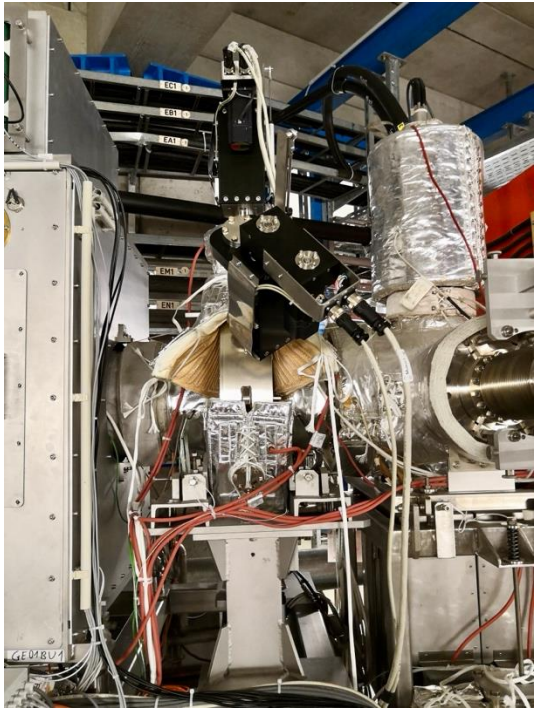
Non-Destructive Particle Detection







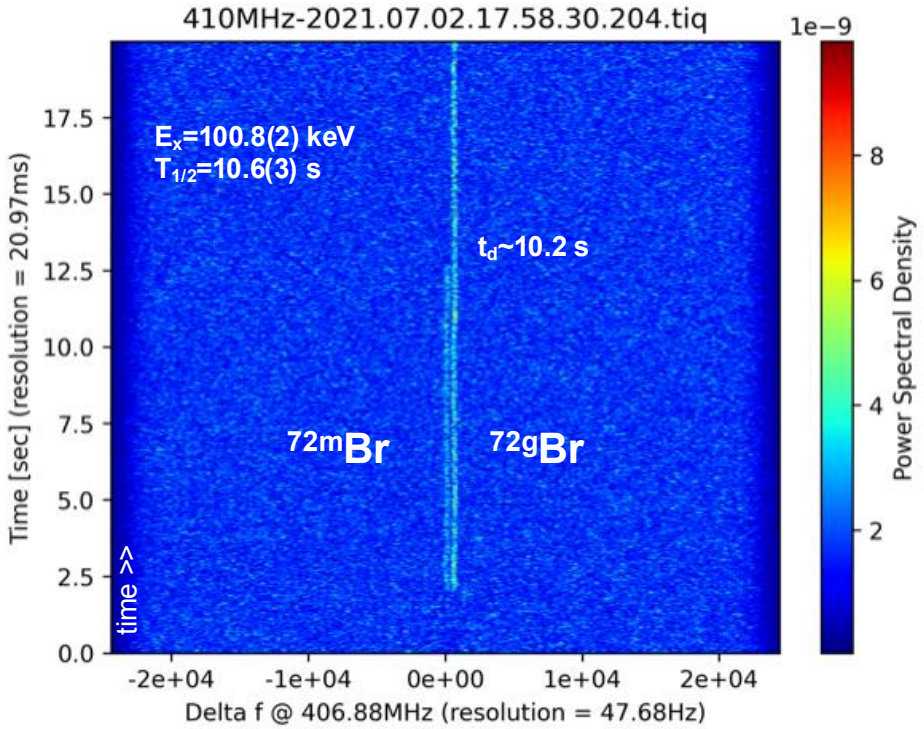
F. Nolden et sl., Nucl. Instr. Meth. A (2011)



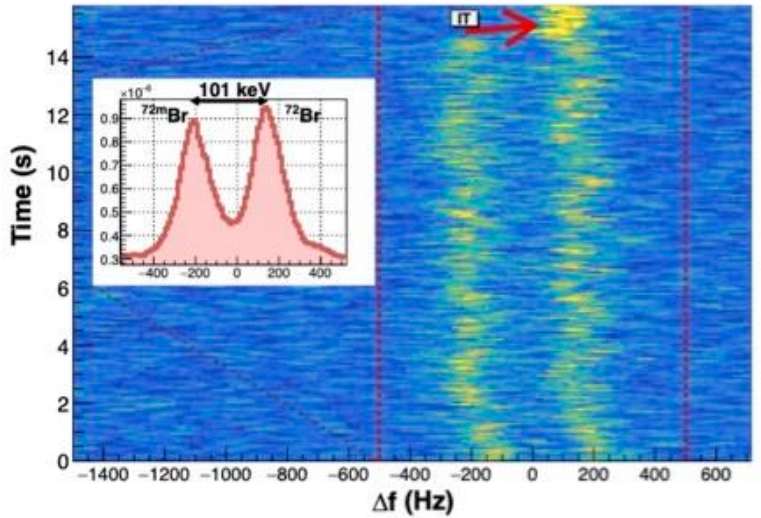
S. Sanjari et al., Rev. Sci. Instr. (2020)

The goal: to measure non-destructively the revolution frequency of a single ion within a few miliseconds

Combined Isochronous+Schottky Mass Spectrometry



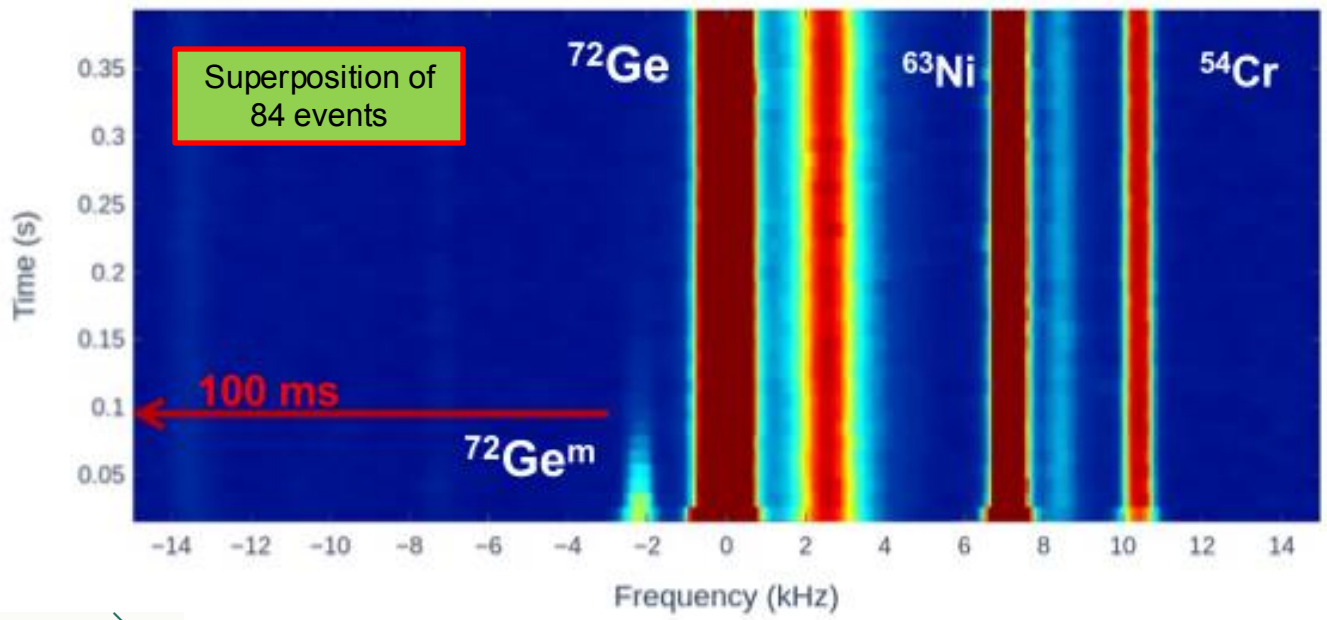
Schottky spectra of single events
Separation of the 101 keV isomer in ^{72}Br



→ $\Delta m/m < 10^{-6}$

Courtesy W. Korten and D. Fernandez

Combined Isochronous+Schottky Mass Spectrometry



^{72}Ge^{m}: $0^{+}\rightarrow 0^{+}$ (single γ emission forbidden)

New tool to search for 0^{+} isomers in exotic nuclei

Joint PhD Position

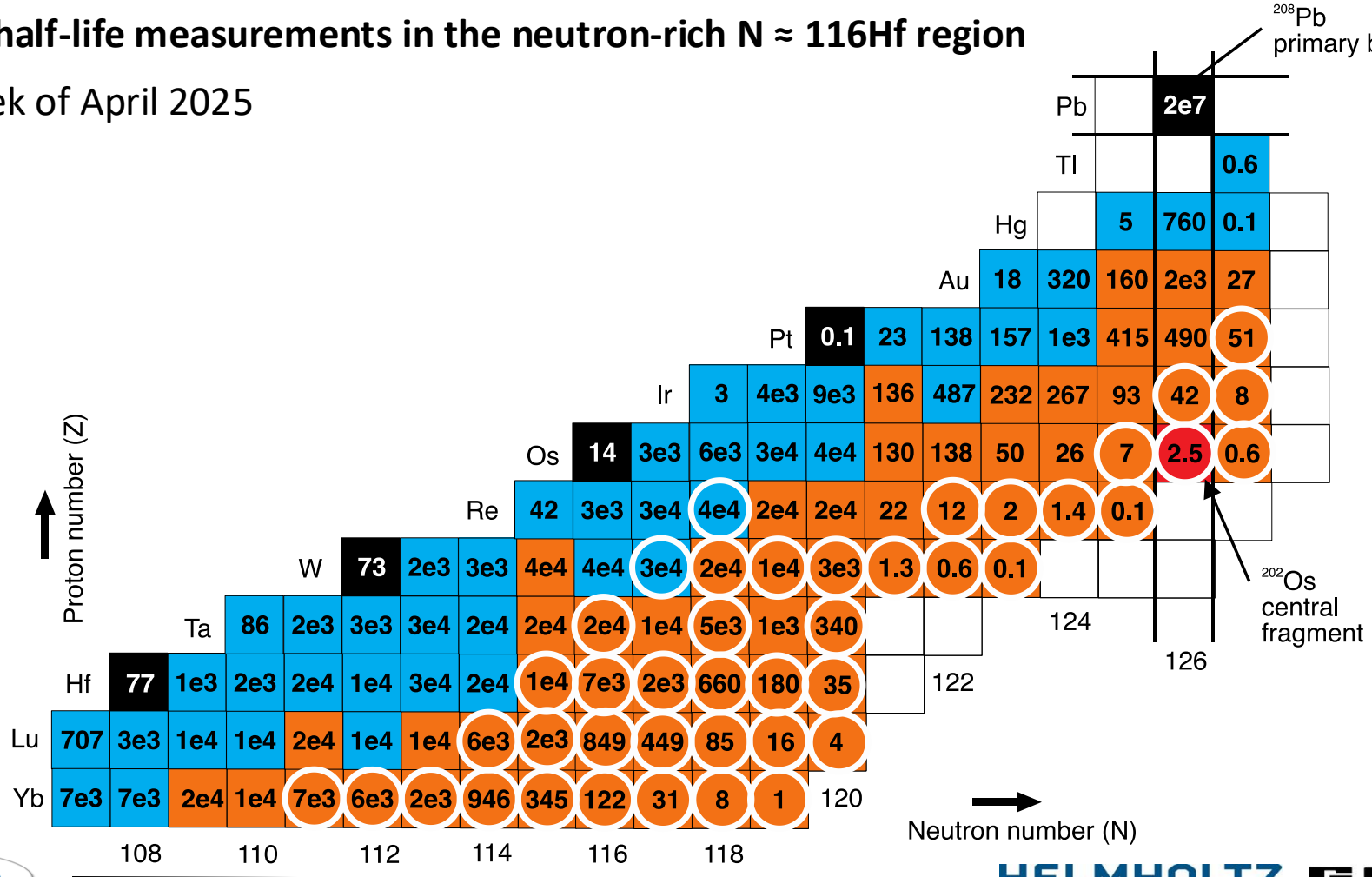
CEA Saclay
GSI Darmstadt
MPIK Heidelberg

David
Freire Fernández

Courtesy: D. Fernandes and W. Korten

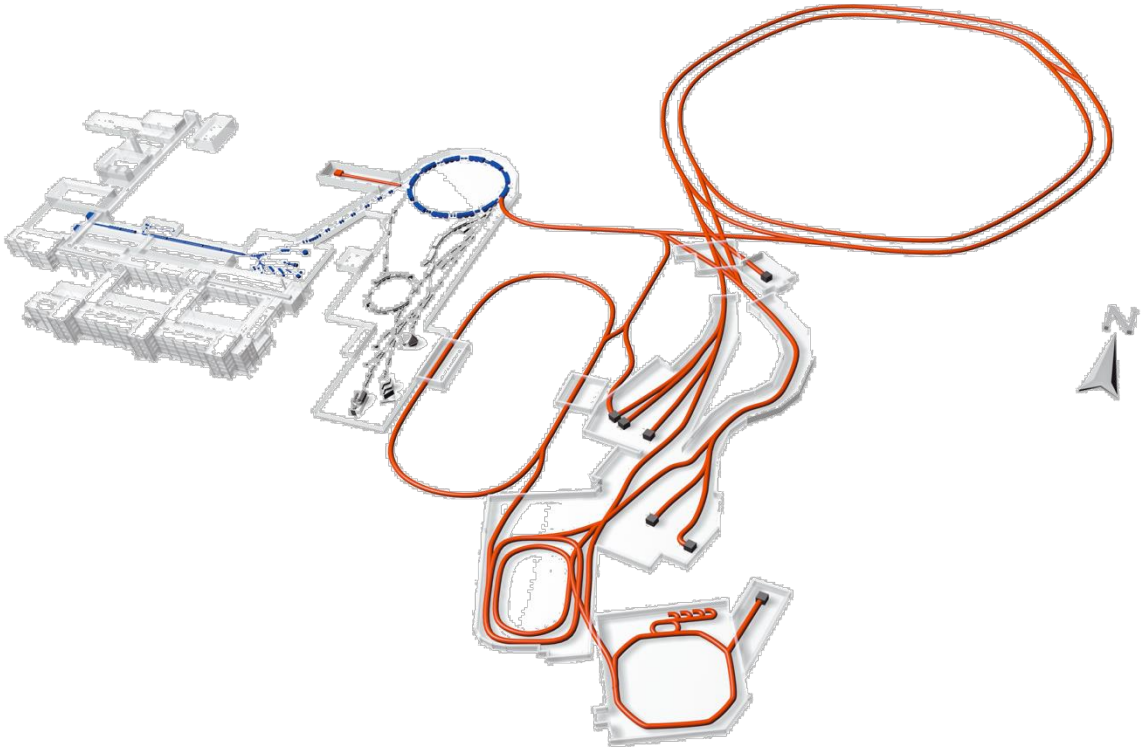
Mass & half-life measurements in the neutron-rich N ≈ 116Hf region

First week of April 2025



Heavy-ion storage rings offer rich, versatile capabilities for the research with radioactive highly charged ions

Masses of exotic nuclei
Isomeric states
Exotic decay modes
Nuclear reactions (high E)
Astrophysical reactions (low E)
Atomic reactions
Laser spectroscopy
Electron spectroscopy



ERC CoG ASTRUm Litvinov
ERC AdG NECTAR Jurado
ERC StG ELDAR Bruno
ERD AdG HITHOR Stöhlker

Many thanks to our collaborators from all over the world !!!

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