Storage Ring Mass Spectrometry

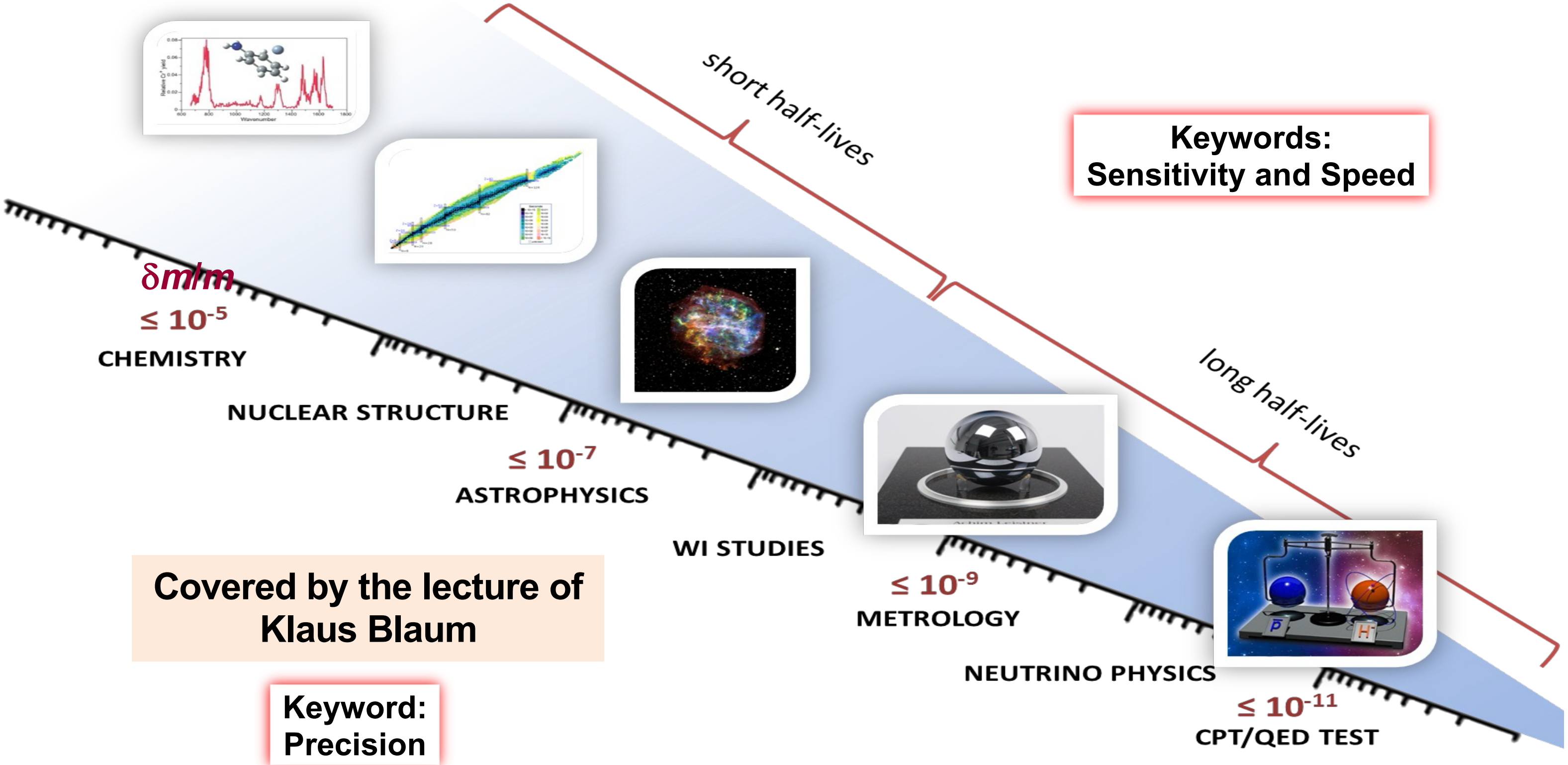
Yury A. Litvinov

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

GSI

EMMI Workshop
“Nuclear masses in astrophysics for the next 25 years”
18-22 August 2025, Darmstadt, Germany

Precision regimes



Keywords: Sensitivity and Speed

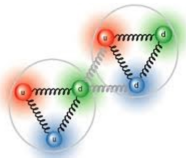
Covered by the lecture of Klaus Blaum

Keyword: Precision

Fundamental Interactions

What is so exciting about atomic nuclei?



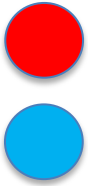



Electromagnetic

Weak

Strong

Q: Is our Sun still burning?

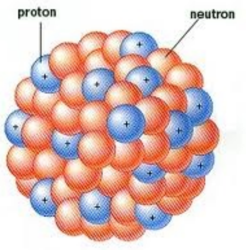


Protons

Neutrons

<u>Nucleons</u>

Fermions

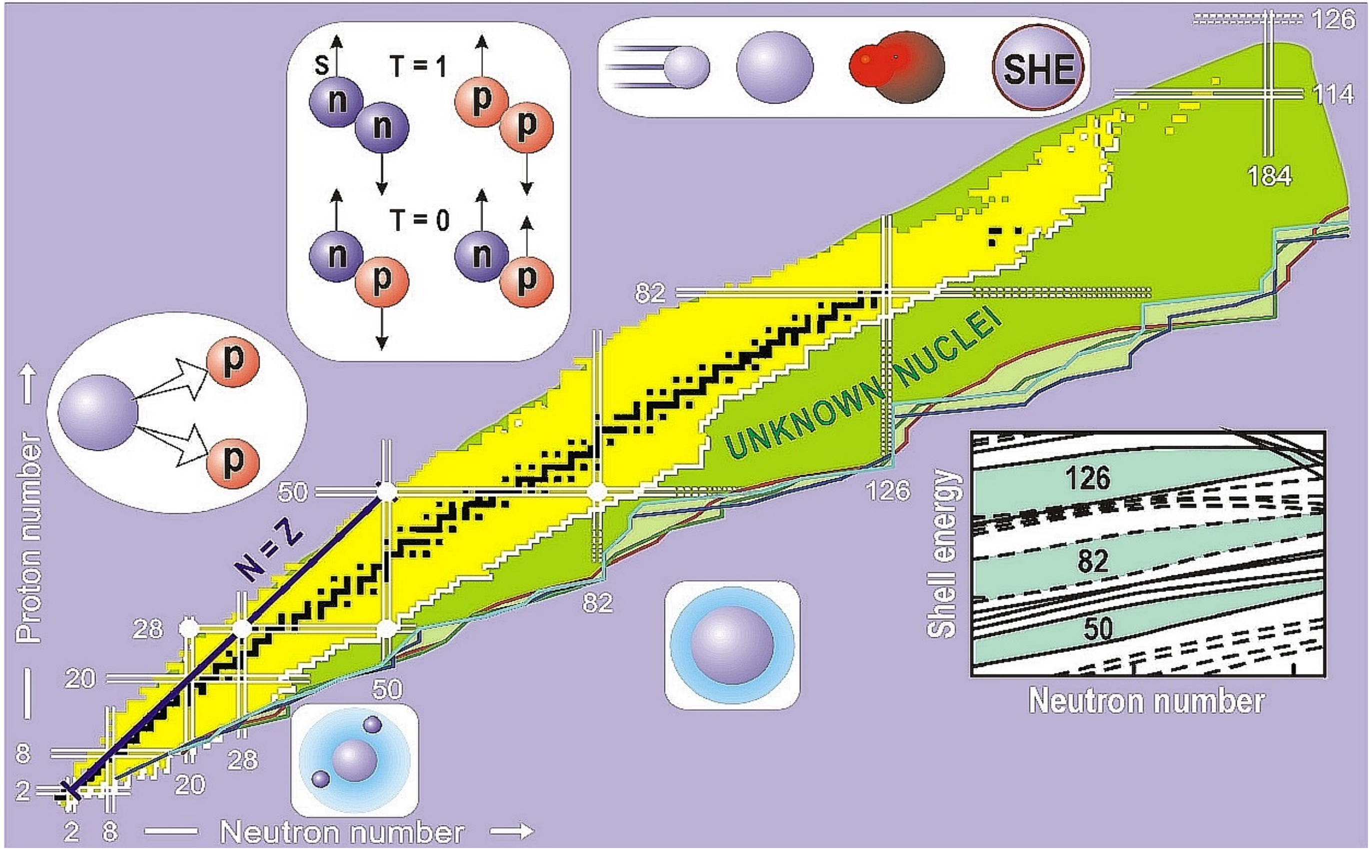


Atomic nuclei – natural results of the complex "game" of complex interactions in a complex quantum many-body system composed of two types of fermions

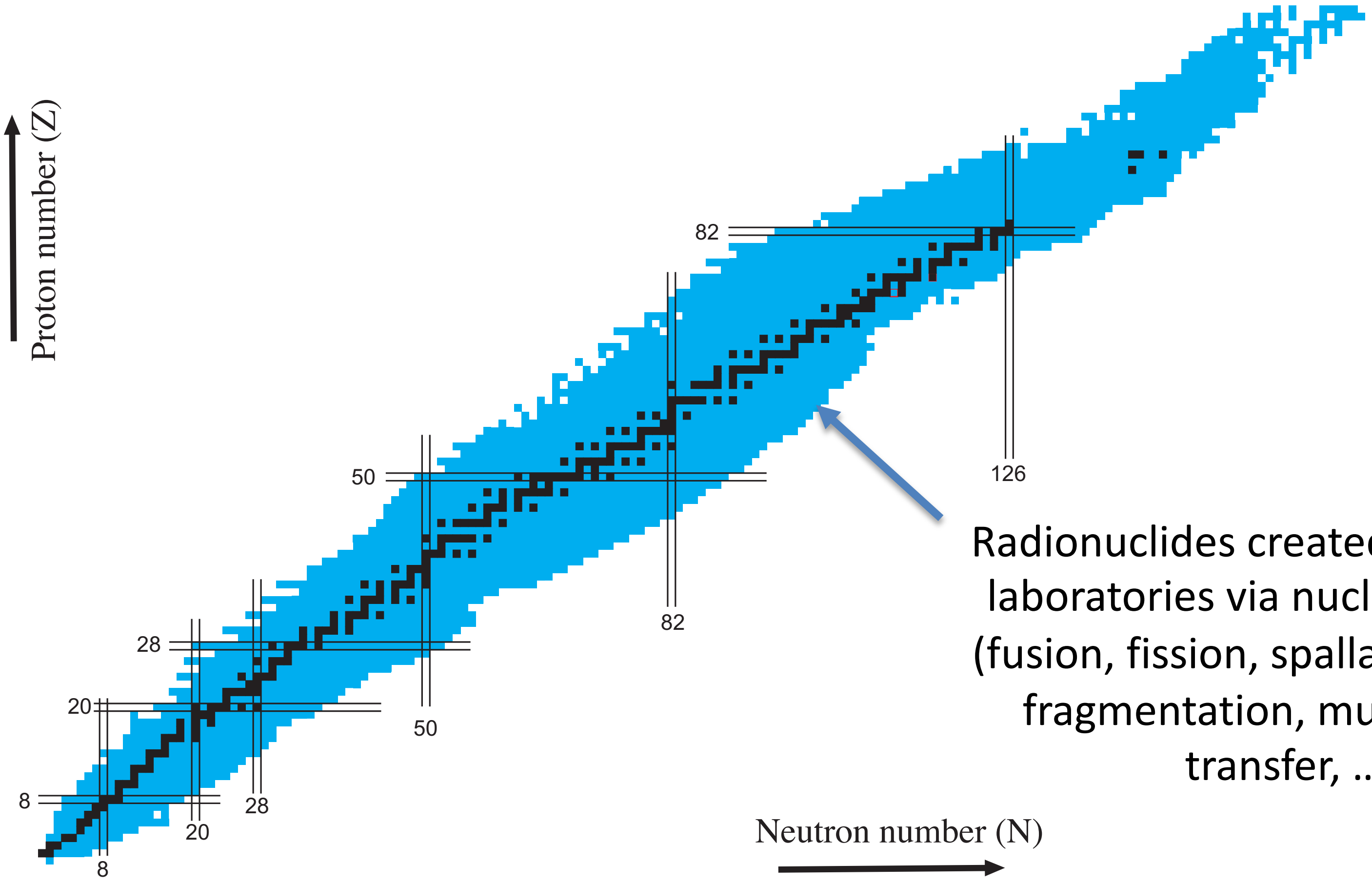
Properties of Atomic Nuclei

- Limits of existence
- Shell structure
- Shapes
- Correlations
- Decays and reactions
- Fundamental symmetries

Total energy of the system

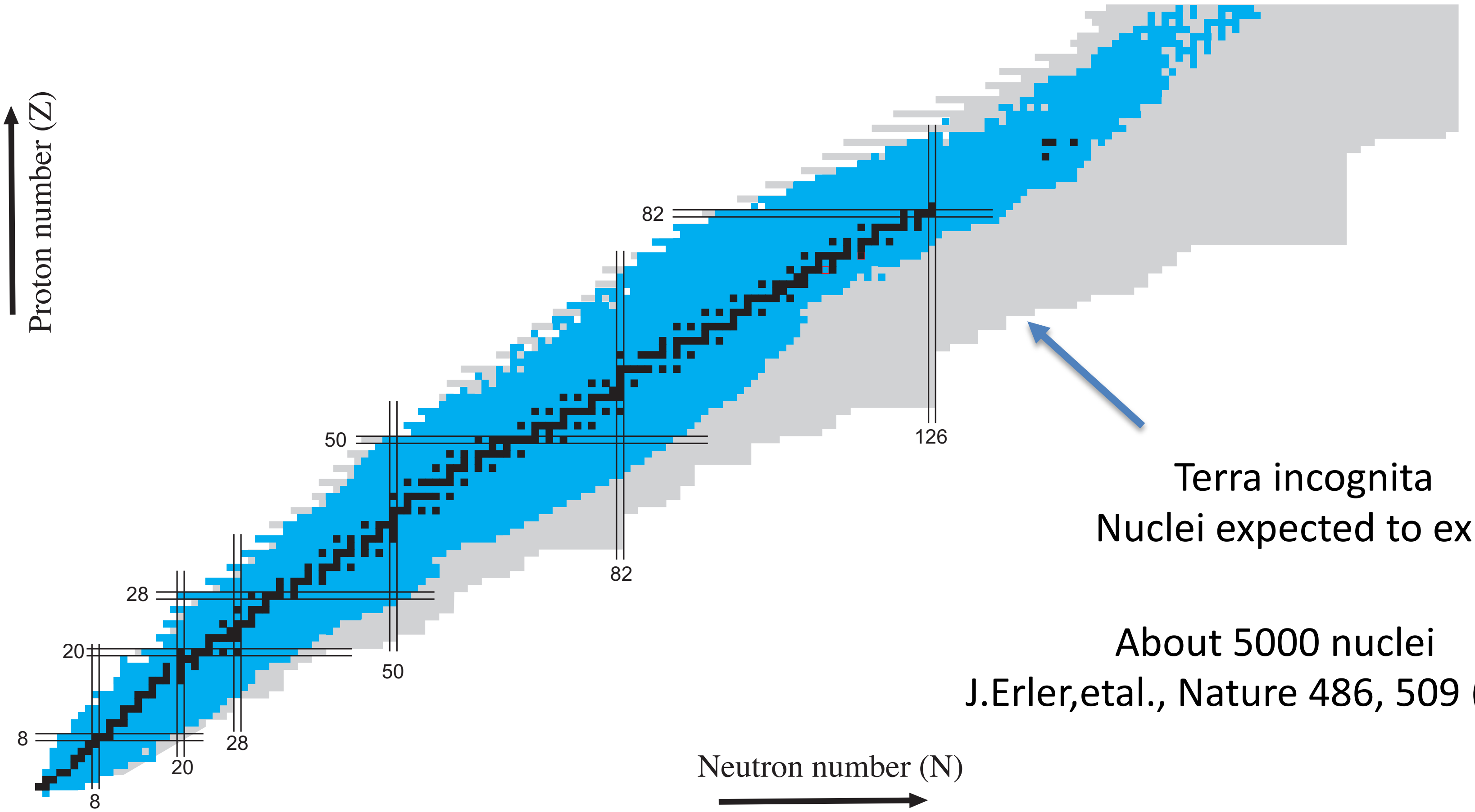


Nuclear Chart: Known nuclides



Radionuclides created in terrestrial laboratories via nuclear reactions (fusion, fission, spallation, transfer, fragmentation, multi-nucleon transfer, ….)

Nuclear Chart: What is not yet known?



Terra incognita
Nuclei expected to exist

About 5000 nuclei
J.Erler,etal., Nature 486, 509 (2012)

Nucleosynthesis Processes (best known)

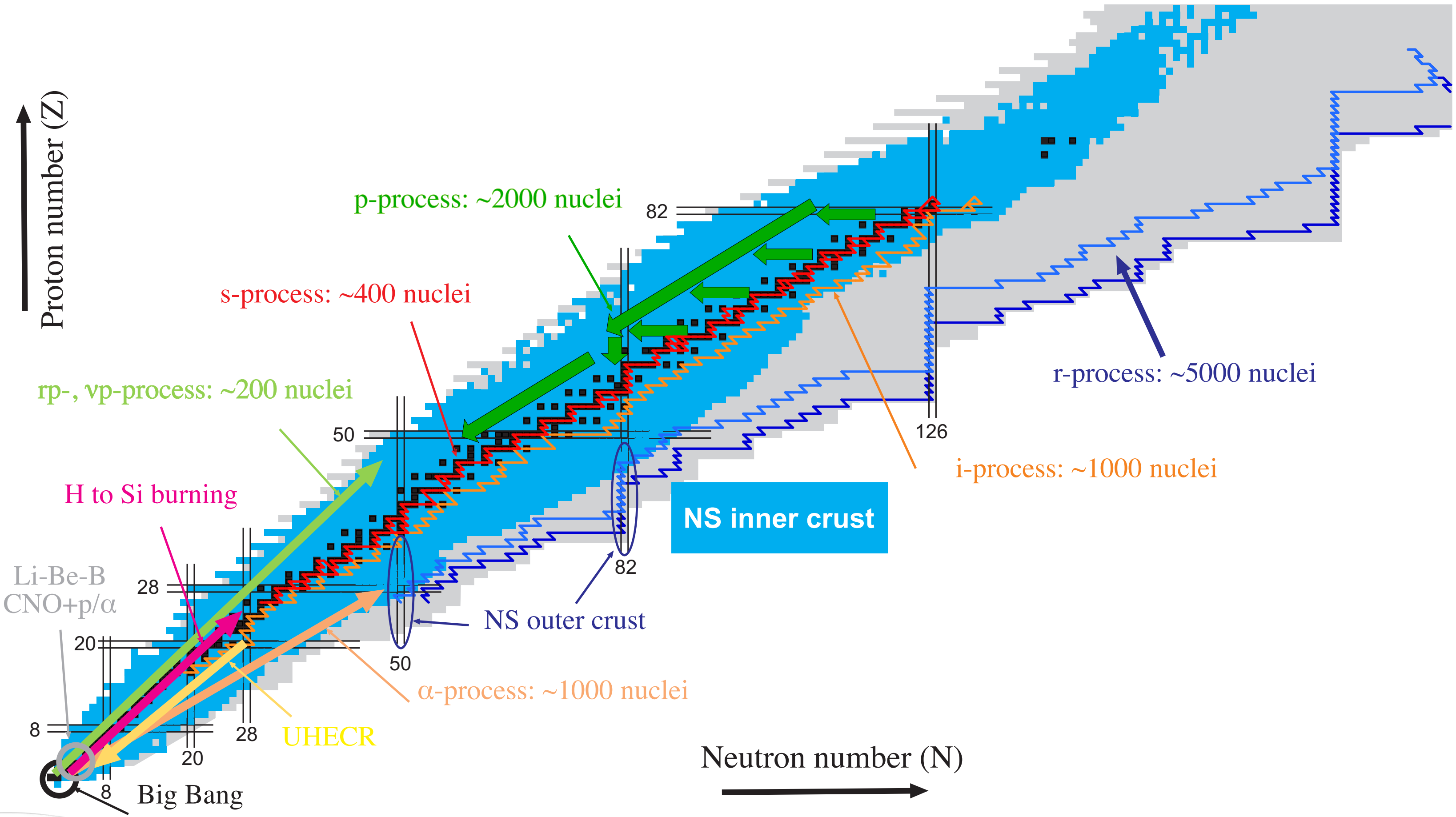
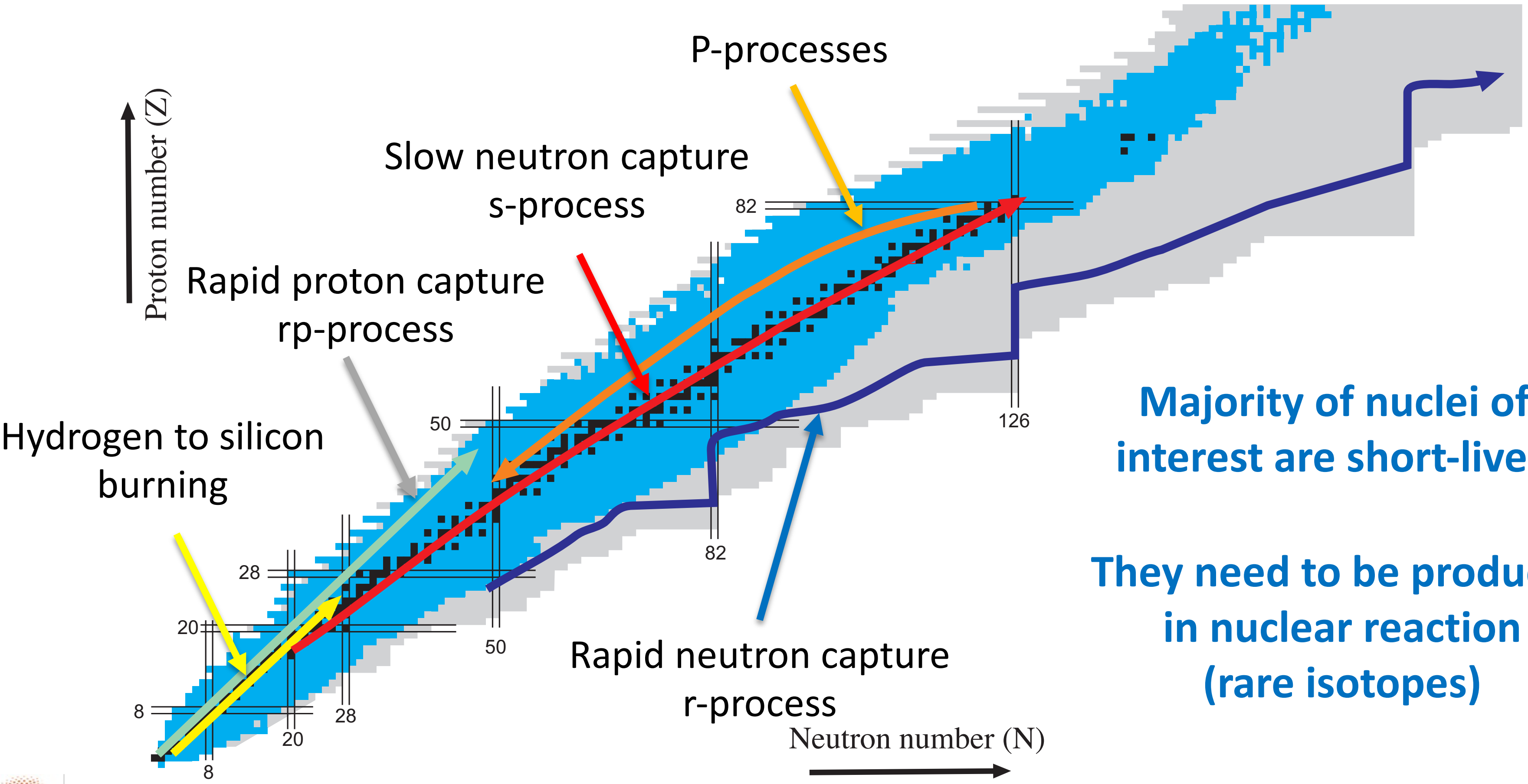


Figure: NuPECC Long Range Plan 2024

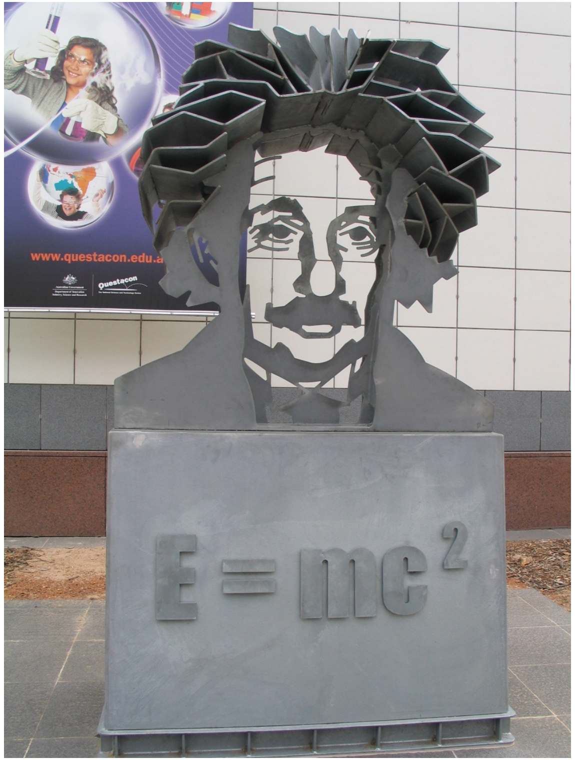
Nucleosynthesis Processes

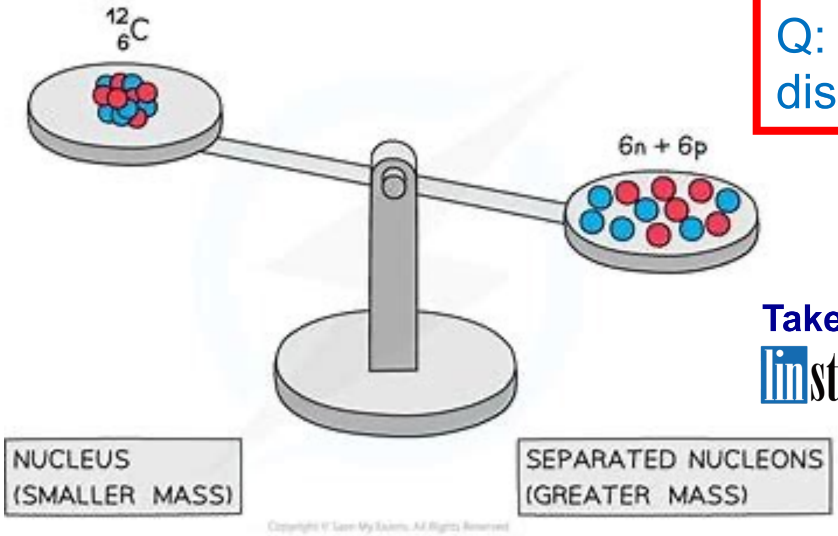


Majority of nuclei of interest are short-lived

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

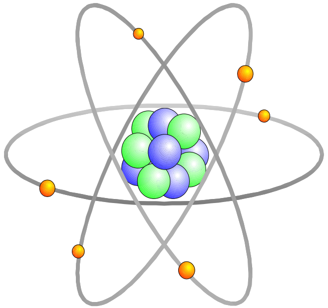
Atomic Mass – Fundamental Property of Atomic Nucleus





Q: Who has discovered?

Taken from linstitute 翰林



= N · (neutron) + Z · (proton) + Z · (electron)

\- binding energy

1935-1936 H.A. Bethe, C.F. von Weizsäcker

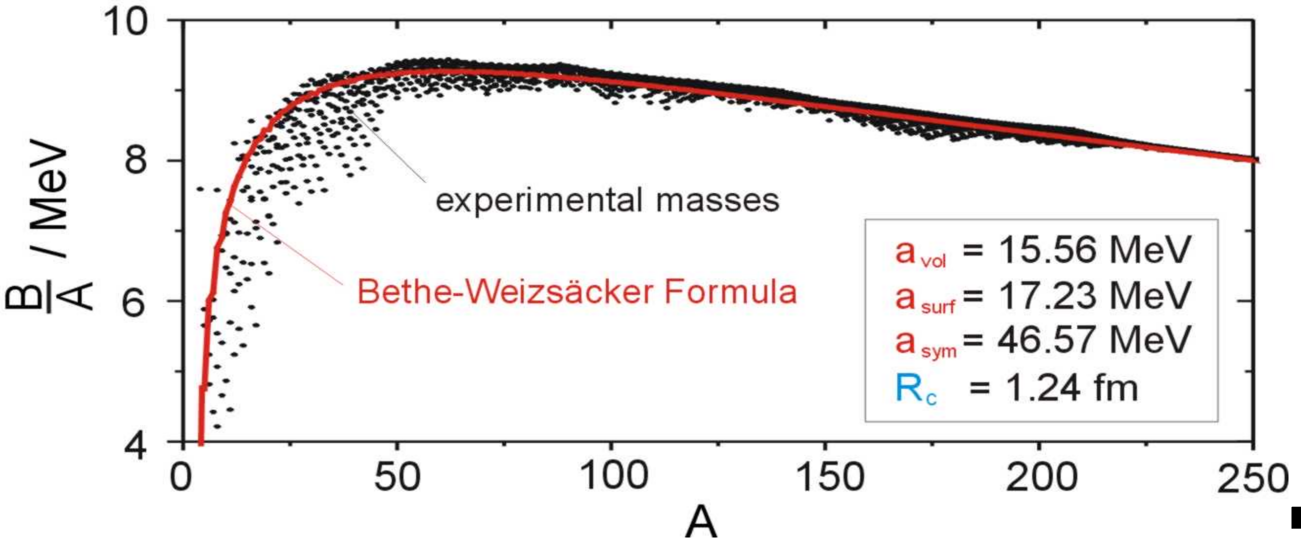
Nuclei are treated as a classical liquid drop

Bethe-Weizsäcker Formula (1935):

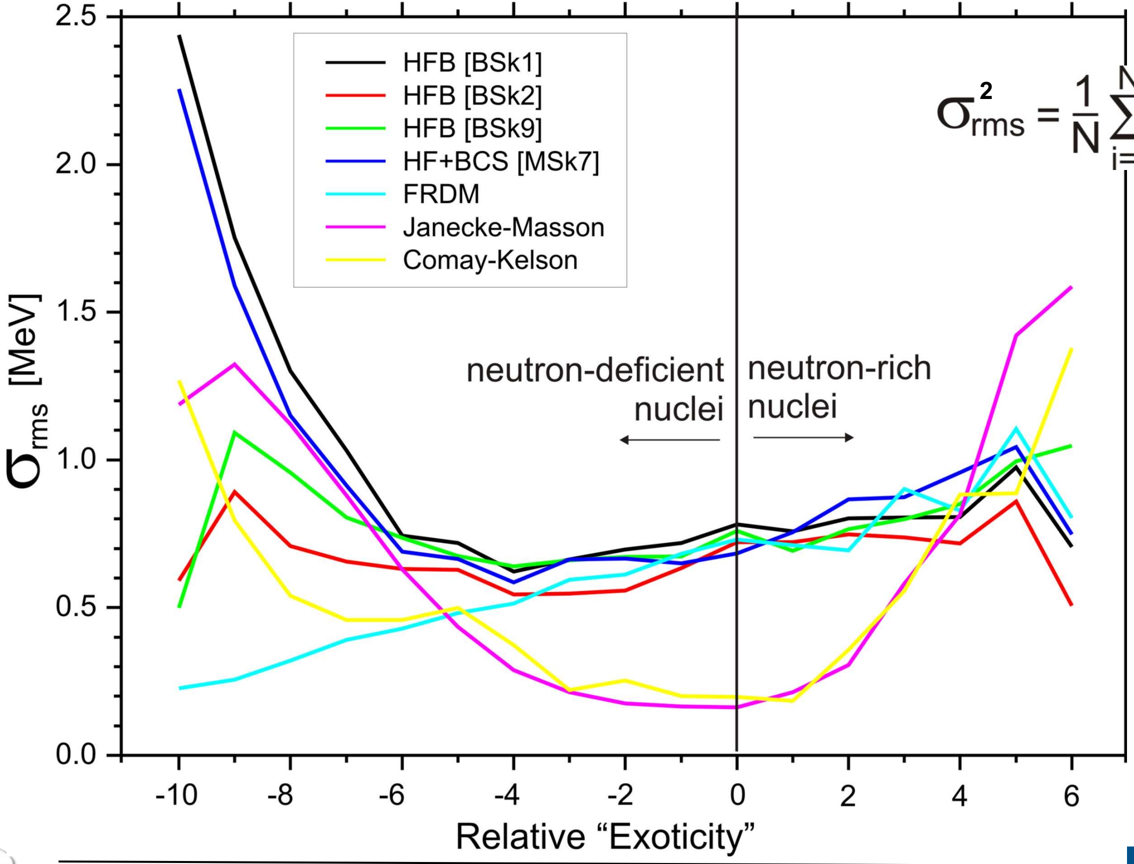
$$B(N,Z) = a_{vol} A - a_{surf} A^{2/3} - \frac{1}{2} a_{sym} \frac{(N-Z)^2}{A} - \frac{3}{5} \frac{Z^2 e^2}{R_c}$$

deformation dependent

Accuracy is better than 1 % !!!

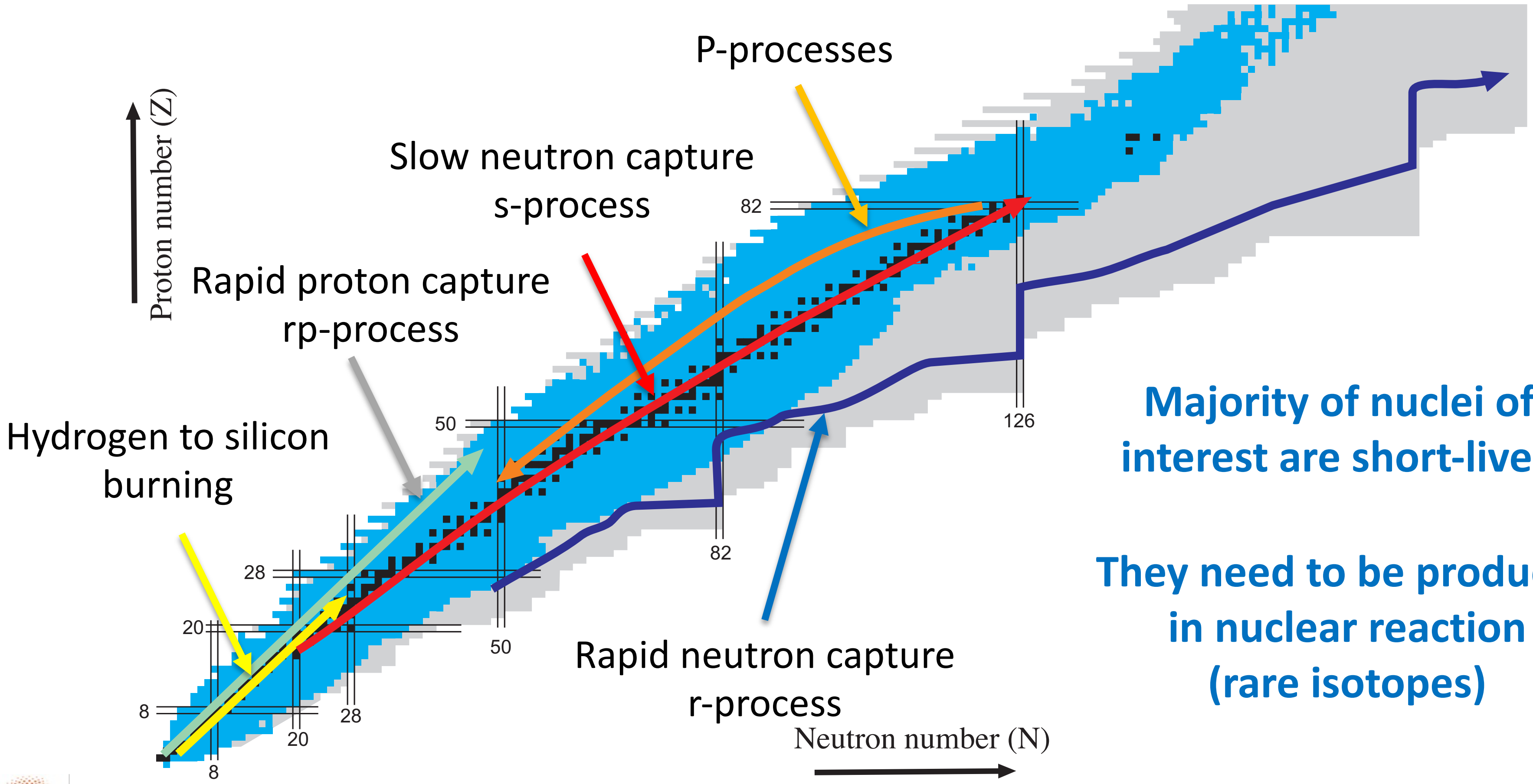


Predictive Powers of Mass Models



$$\sigma_{rms}^2 = \frac{1}{N}\sum_{i=1}^{N}(m_i^{exp} - m_i^{theory})^2$$

Nucleosynthesis Processes



Majority of nuclei of interest are short-lived

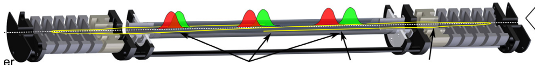
They need to be produced in nuclear reaction (rare isotopes)

Direct Mass Measurements on the Chart of the Nuclides

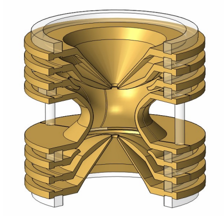
Where do we stand?

About 7000 nuclei are expected to exist

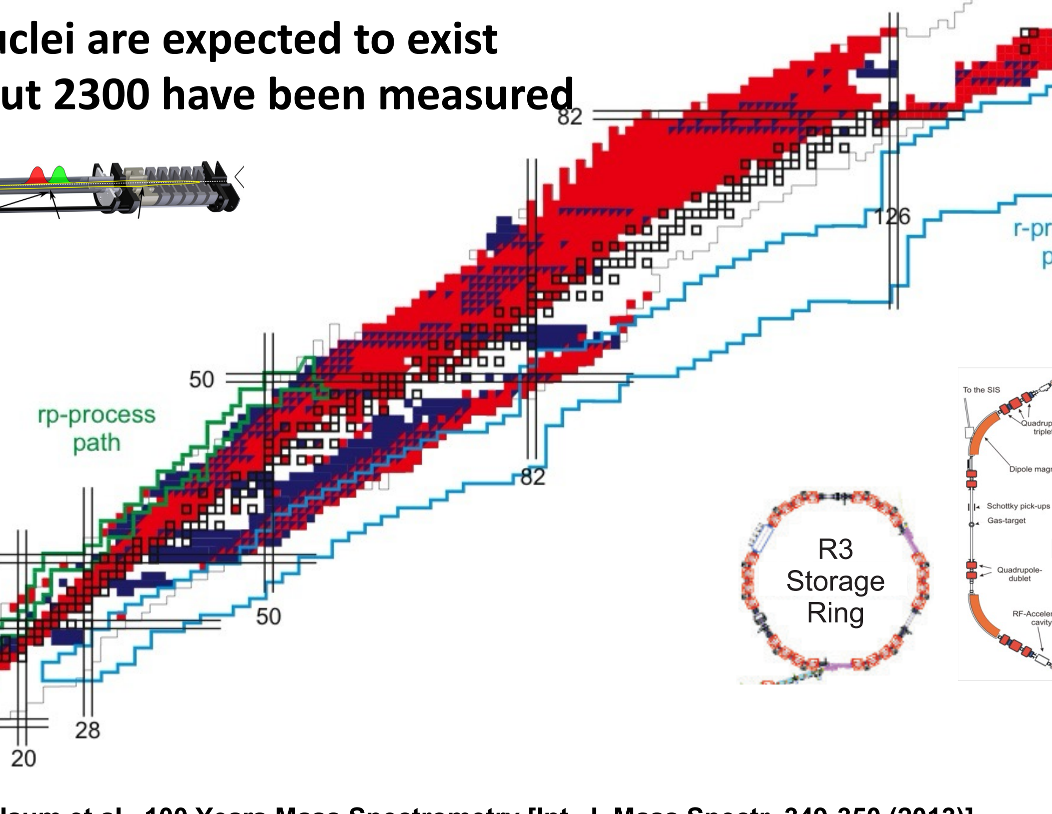
Masses of about 2300 have been measured

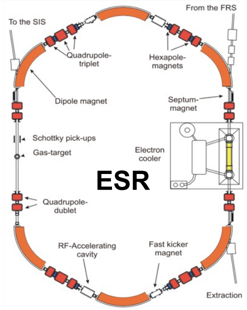


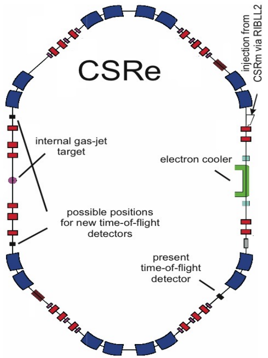
Multi-Reflection ToFs



Penning Traps







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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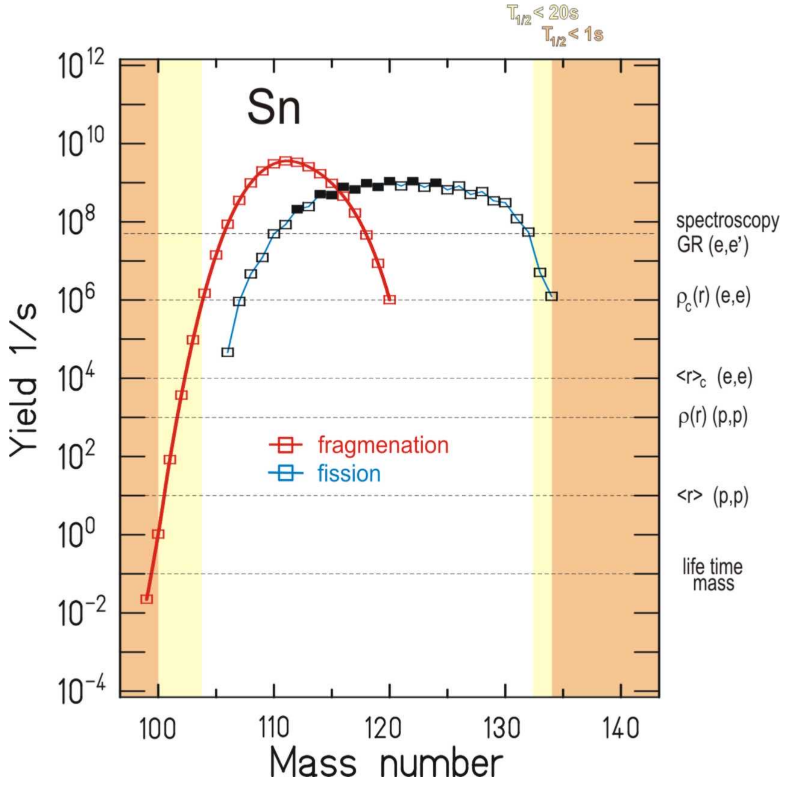
Characteristics of mass spectrometry techniques

Why do not we measure them all?

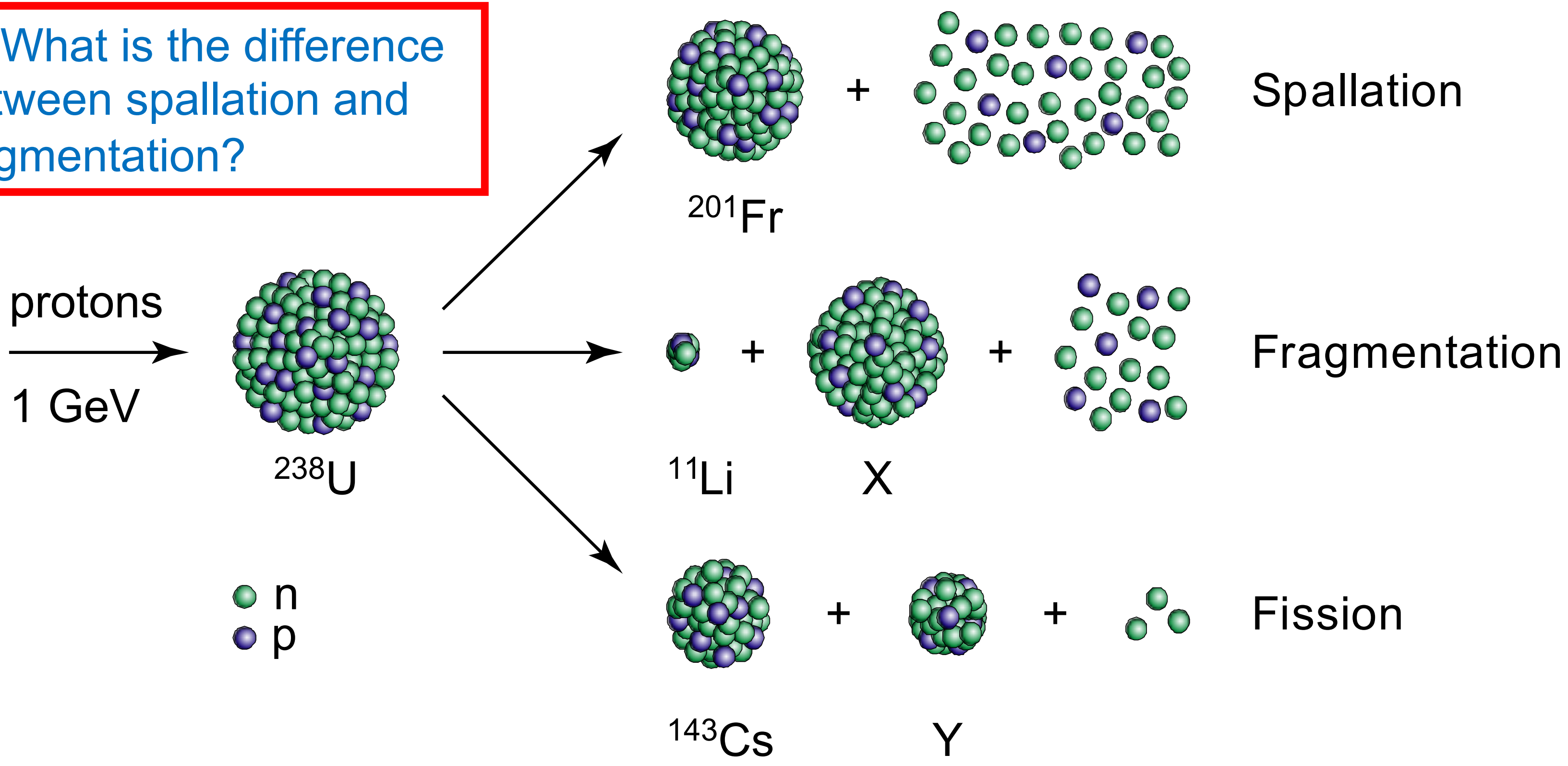
Mass spectrometry techniques:
- Bandwidth
- Resolving power
- Speed
- Sensitivity

Ultimate goal to combine all 4 characteristics

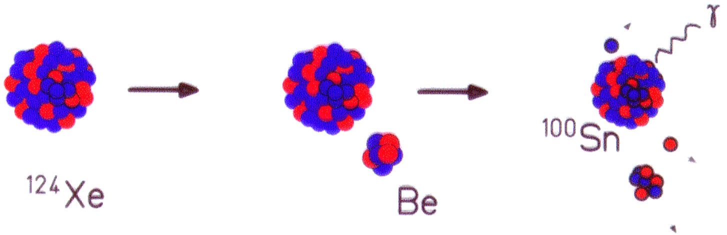


Proton-induced reactions

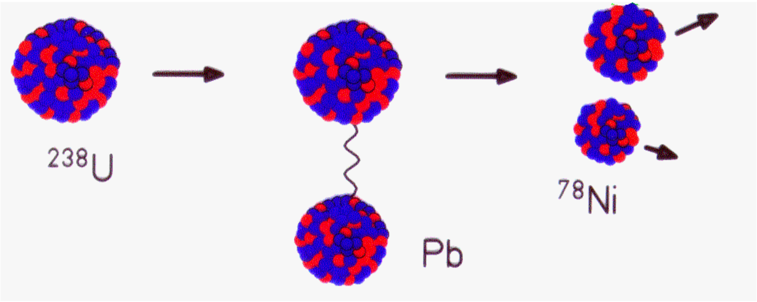
Q: What is the difference between spallation and fragmentation?



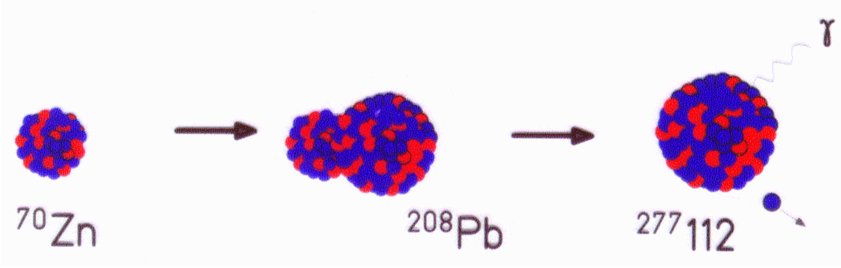
Heavy-ion-induced reactions



Projectile Fragmentation



Coulomb Fission / Coulomb dissociation



Fusion

Charged Particle Motion in Magnetic Field

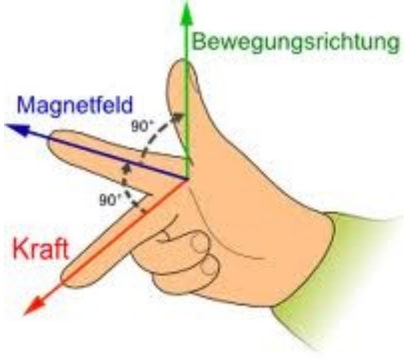
Centrifugal Force

$$F_c = \frac{m \cdot v^2}{r}$$

$$F_L = q \cdot v \cdot B$$

$$\frac{m \cdot v}{q} = B \cdot r$$

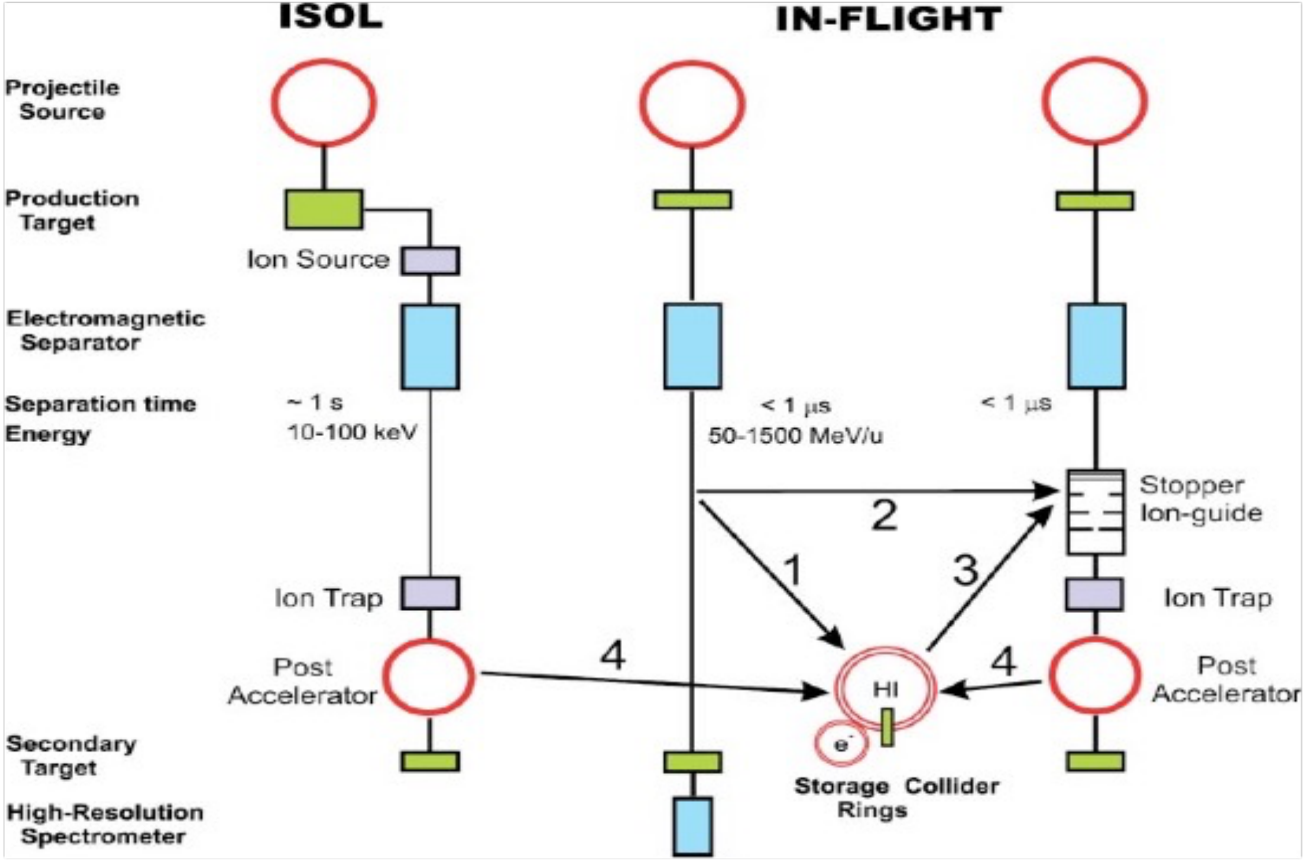
Velocity!!!



Lorentz Force

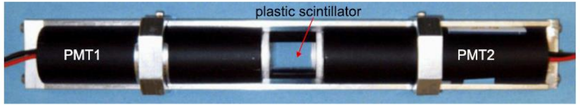
r - Radius
q - Charge
v - Velocity
m - Mass
B – Magnetic induction

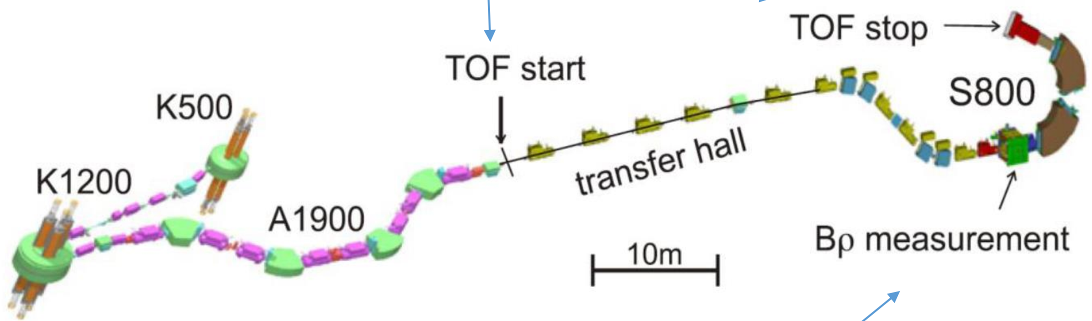
Production and separation of exotic nuclei

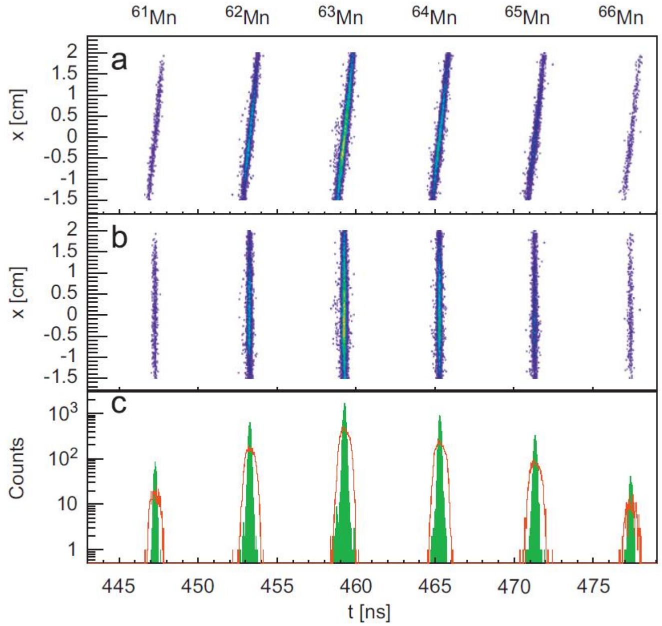


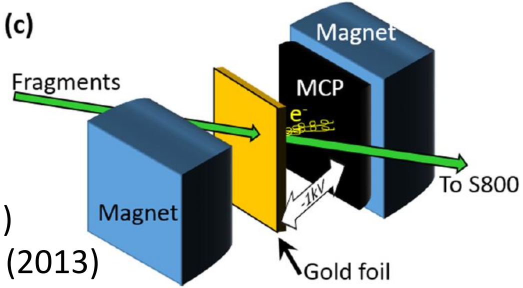
TOF-Bρ experiments at NSCL

(Stolen from Alfredo)









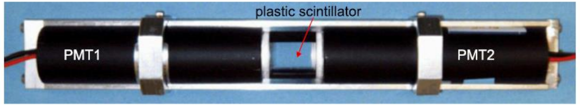
$$\frac{\delta m}{m} \approx 2 \times 10^{-4}$$

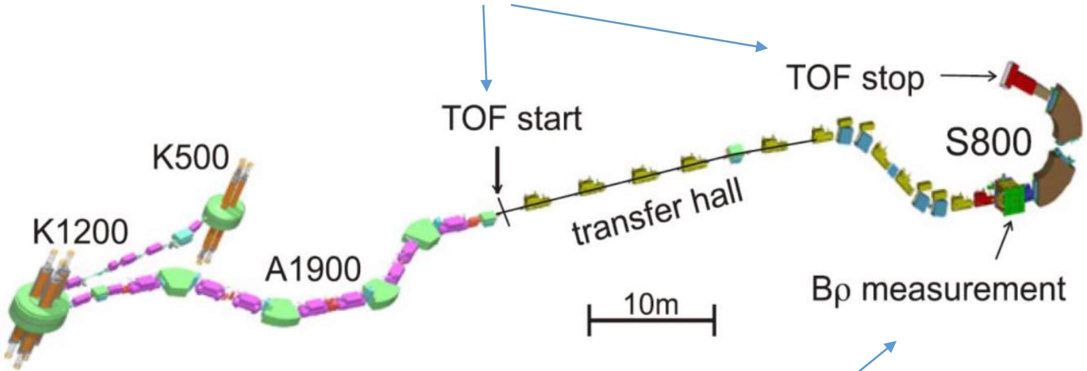
Matos et al , NIMA (2012)
Meisel and George, IJMS (2013)

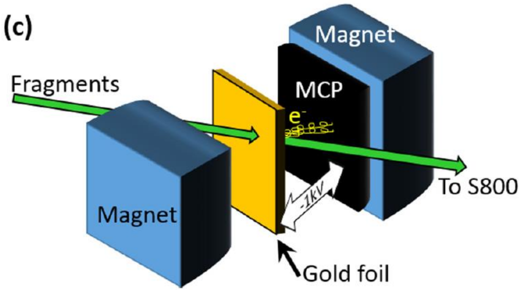
Note: technique pioneered at GANIL (SPEG), currently also an active program at RIKEN (e.g. Michimasa et al, PRL 2018)

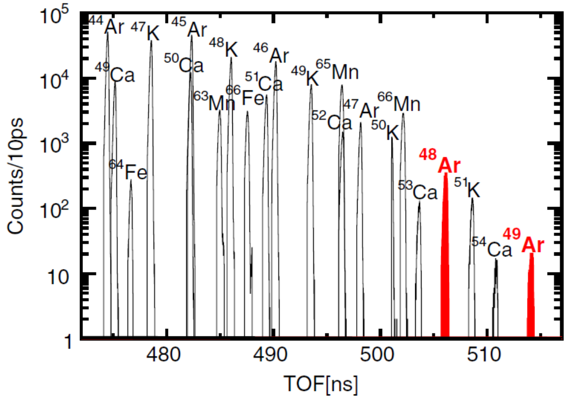
(Stolen from Alfredo)

TOF-Bρ experiments at NSCL: mass calibration

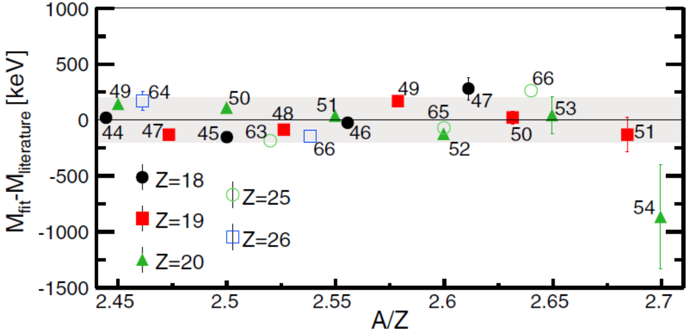






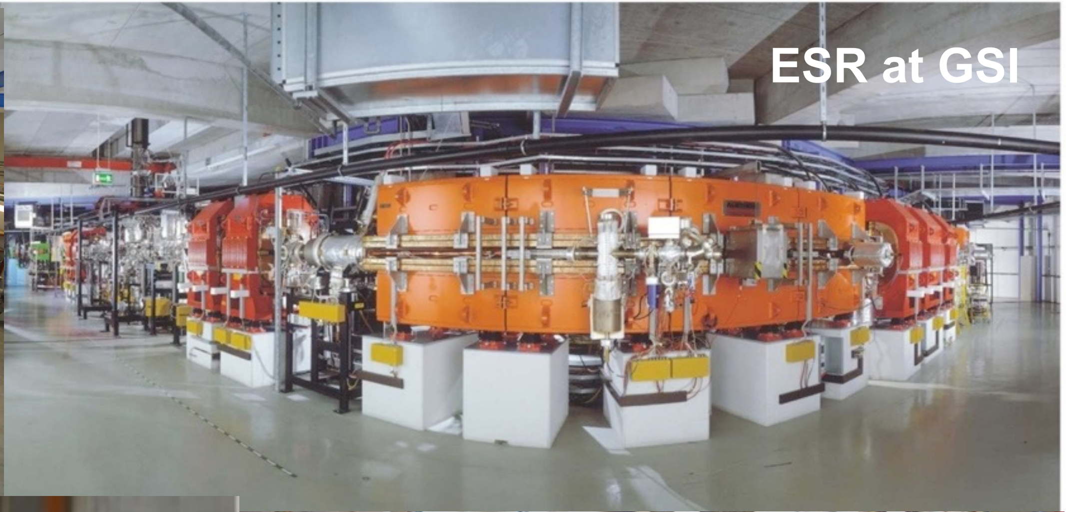


$$\frac{m}{q} = f(TOF_{B\rho}, Z)$$



- Bandwidth
- Resolving power
- Speed
- Sensitivity

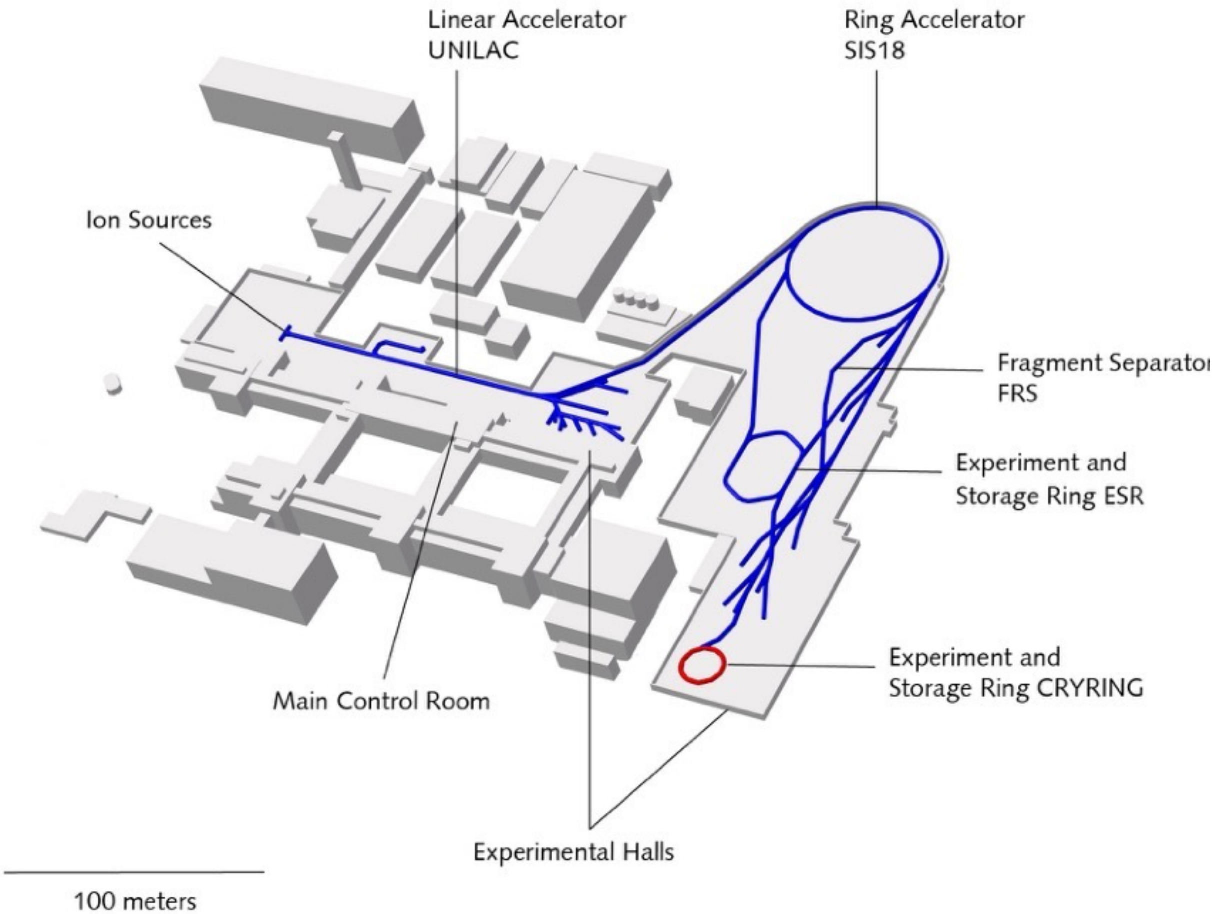

CRYRING at GSI

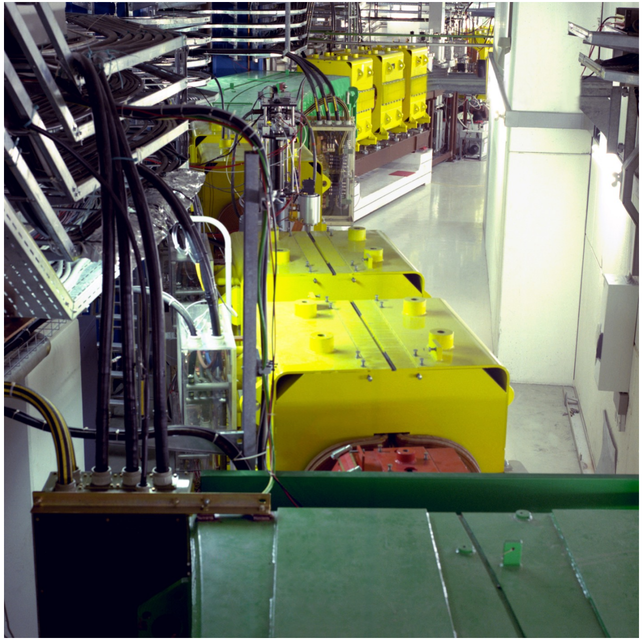

ESR at GSI


R3 at RIKEN


CSR实验环闭环
CSRe at IMP

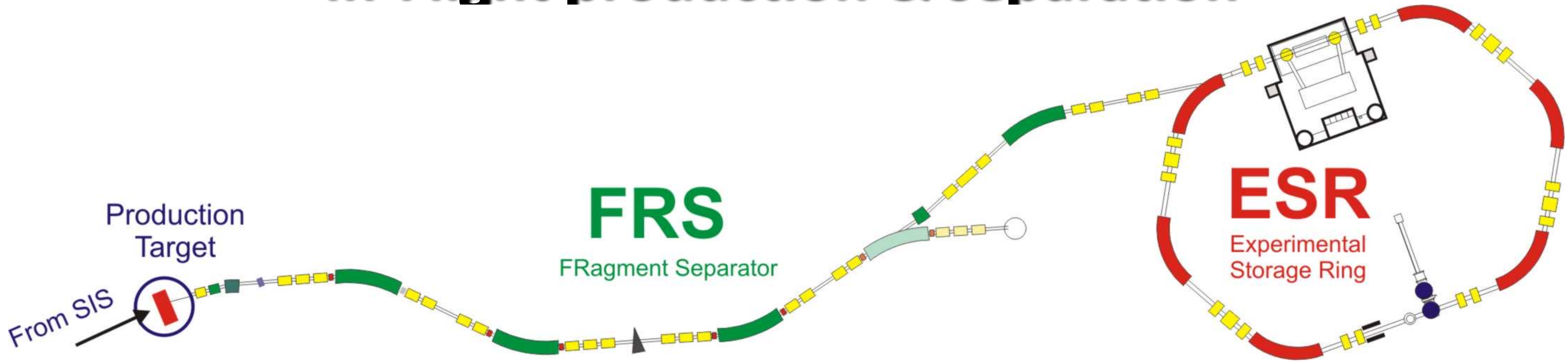
Radioactive Ion Beam Facility at GSI





Picture: GSI, Darmstadt

In-Flight production & separation



Primary beams @ 400-1000 MeV/u

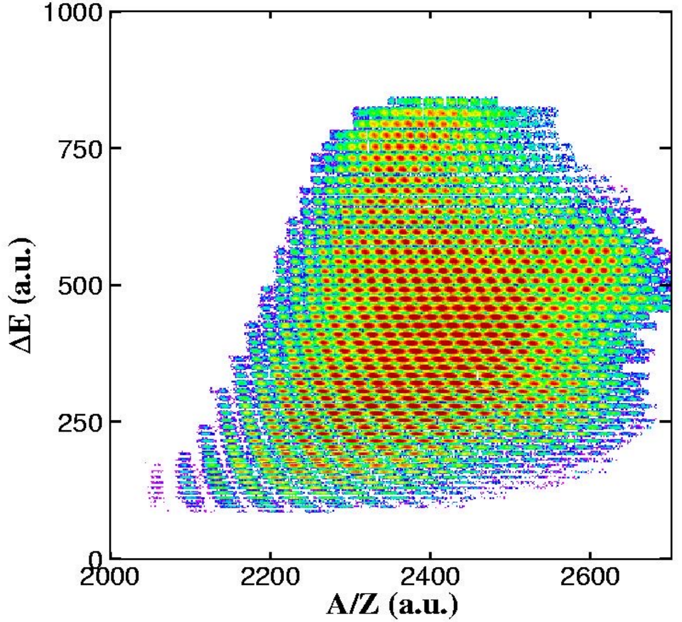
Highly-Charged Ions (0, 1, 2 … bound electrons)

In-Flight separation within ~ 150 ns

Cocktail or mono-isotopic beams

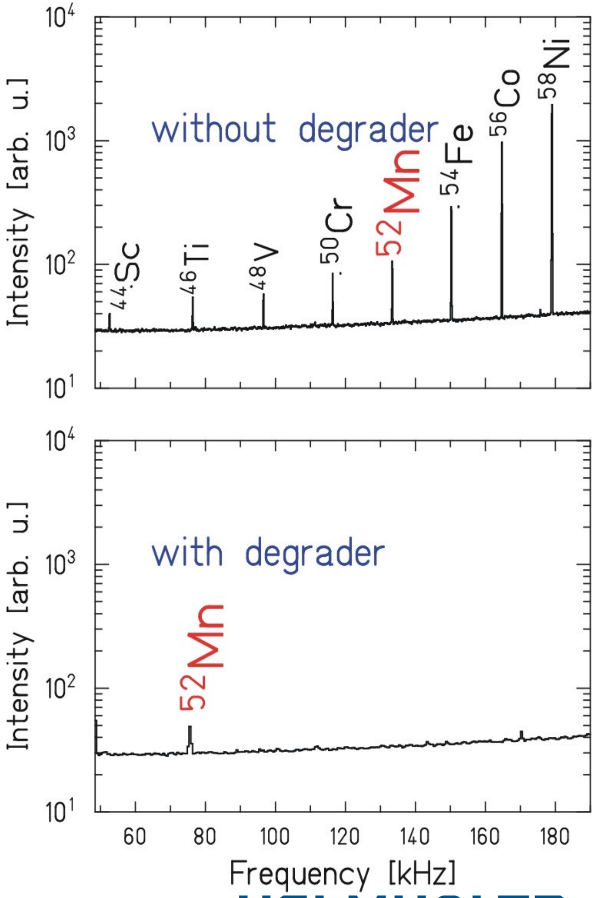
In-Flight production & separation

About 1000 nuclear residues identified



A/Z-resolution ~10^{-3}

J. Pereira et al., PRC (2007)



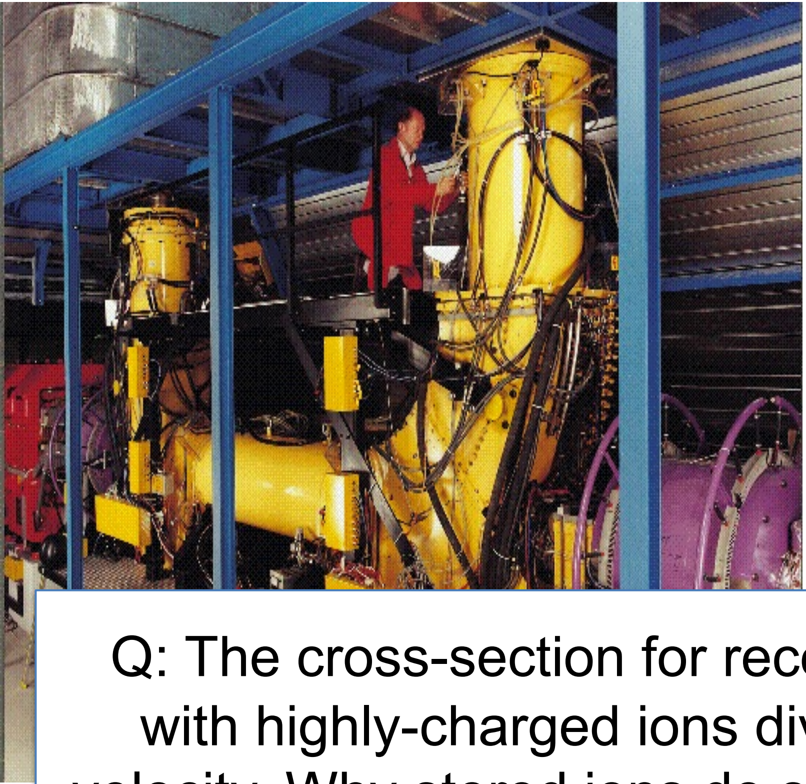
Experimental Cooler-Storage Ring in Lanzhou, China

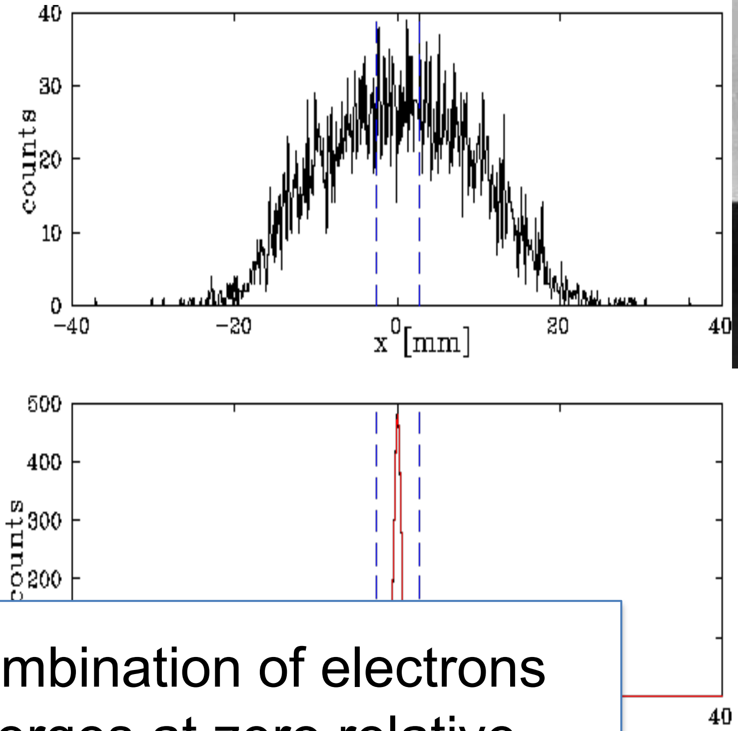
Photos: A. Zschau, GSI; IMPCAS Lanzhou

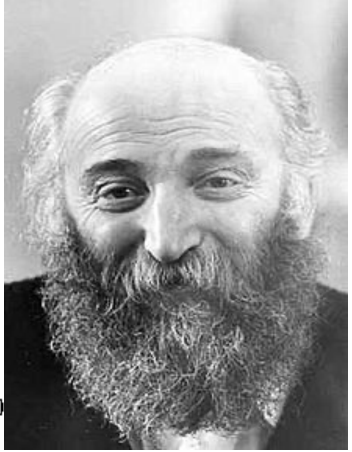
Experimental Storage Ring ESR in Darmstadt, Germany

Photos: A. Zschau, GSI; IMPCAS Lanzhou

Electron Cooling of Secondary Beams





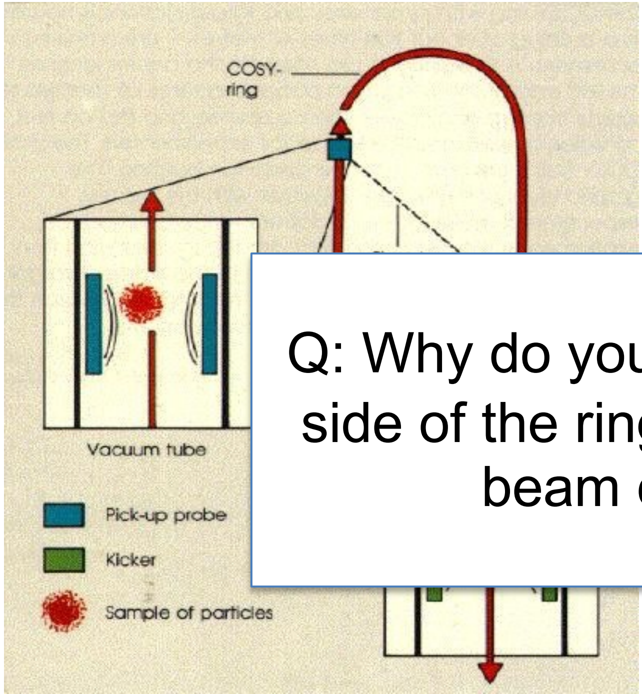


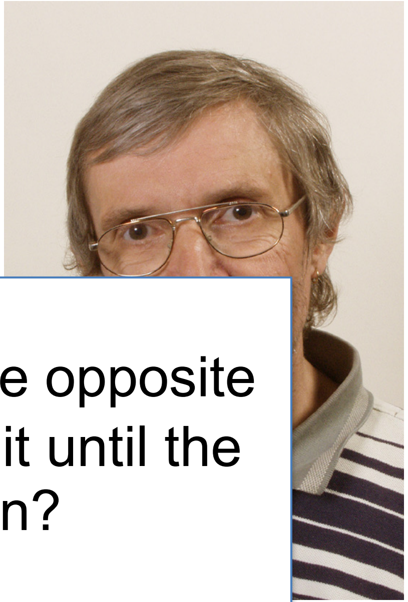
Gersh I. Budker
1918 - 1977

Markus Steck 2025+

Q: 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?

Stochastic Cooling (self-correction of trajectory)





Q: Why do you need to send the signal to the opposite side of the ring? Why cannot one simply wait until the beam comes back after full revolution?

Simon van der Meer
1925 - 2011

Fritz Nolden
2023+

Nobel prize 1984:
S. van der Meer
and C. Rubbia

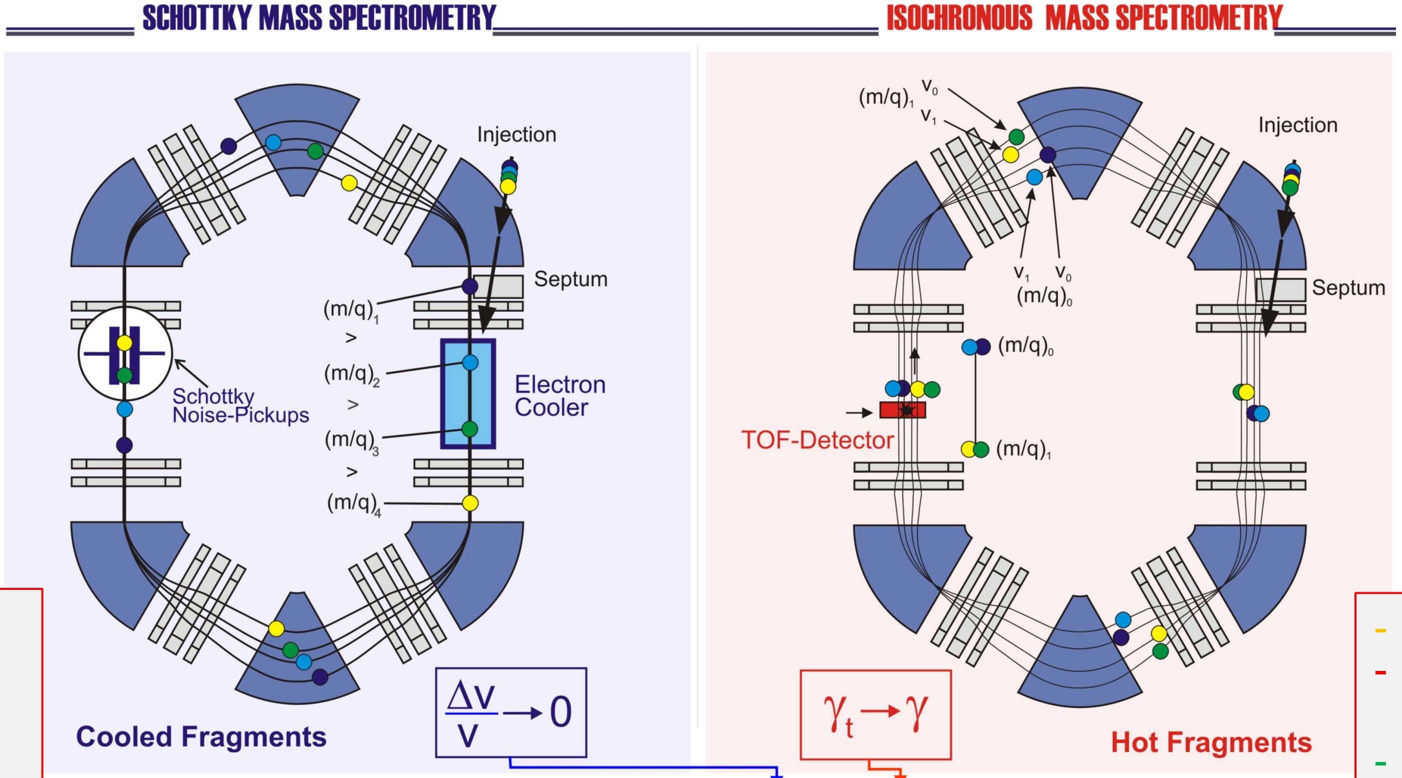
Photos from the Nobel Foundation archive.

Schottky and Isochronous Storage Ring Mass Spectrometry

Cooling: Takes time

Non-Destructive Detection (Schottky detectors)

- Bandwidth
- Resolving power
- Speed
- Sensitivity



Destructive Detectors (foil-based Secondary electron detectors)

No cooling

- Bandwidth
- Resolving power
- Speed
- Sensitivity

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

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B. Franzke, H. Geissel, G. Münzenberg, Mass Spectr. Rev. 27 (2008)

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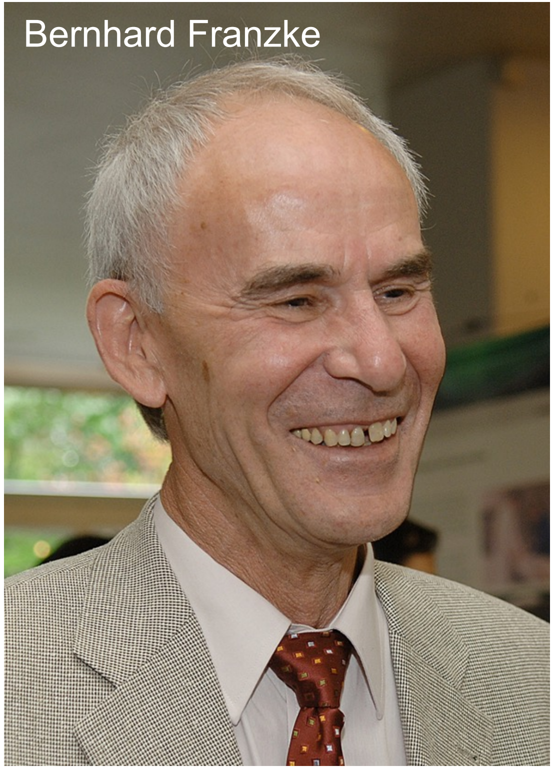
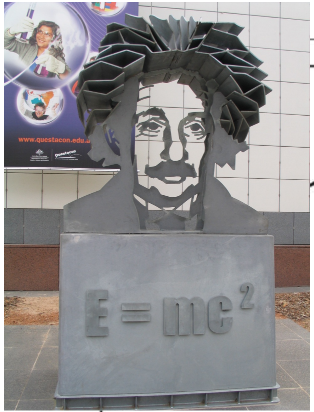
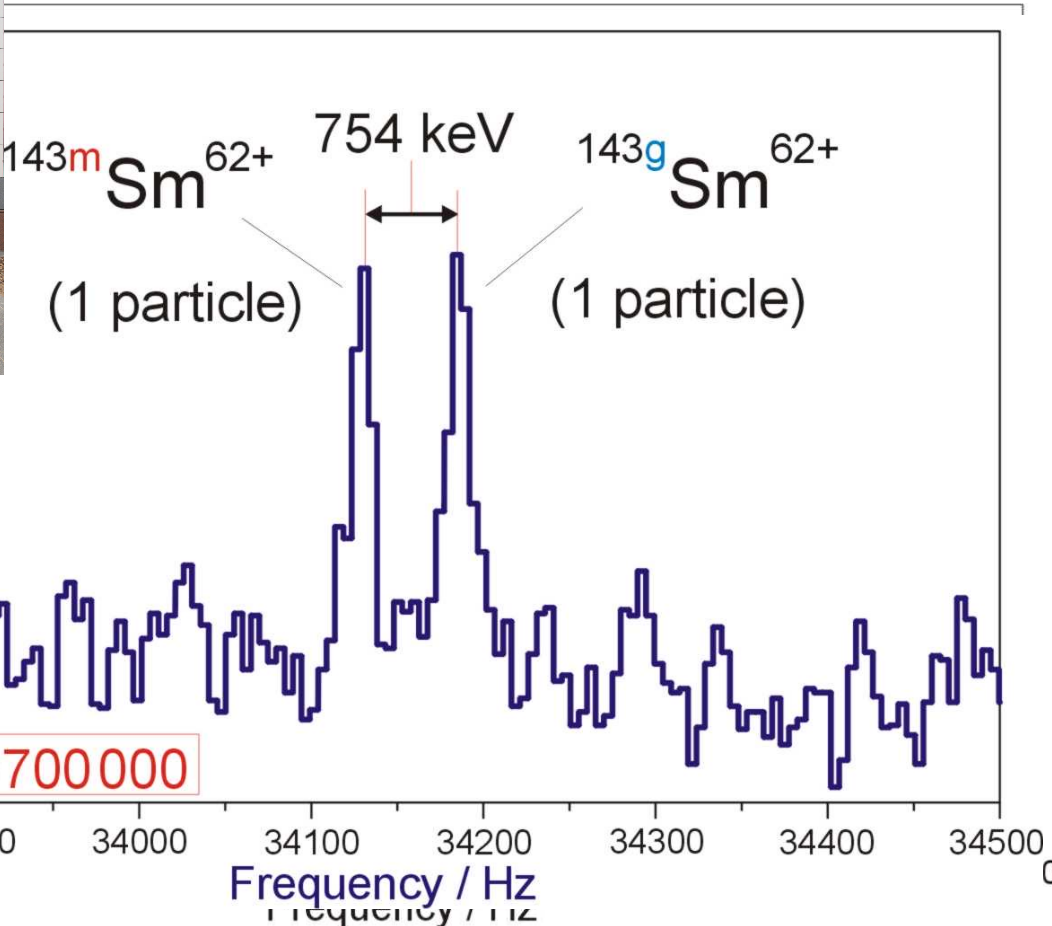
1985: Proposal for Schottky Mass Spectrometry at the ESR



B. Franzke, H. Geissel, G. Münzenberg, Mass Spectr. Rev. 27 (2008)

SMS: Broad Band Frequency Spectra





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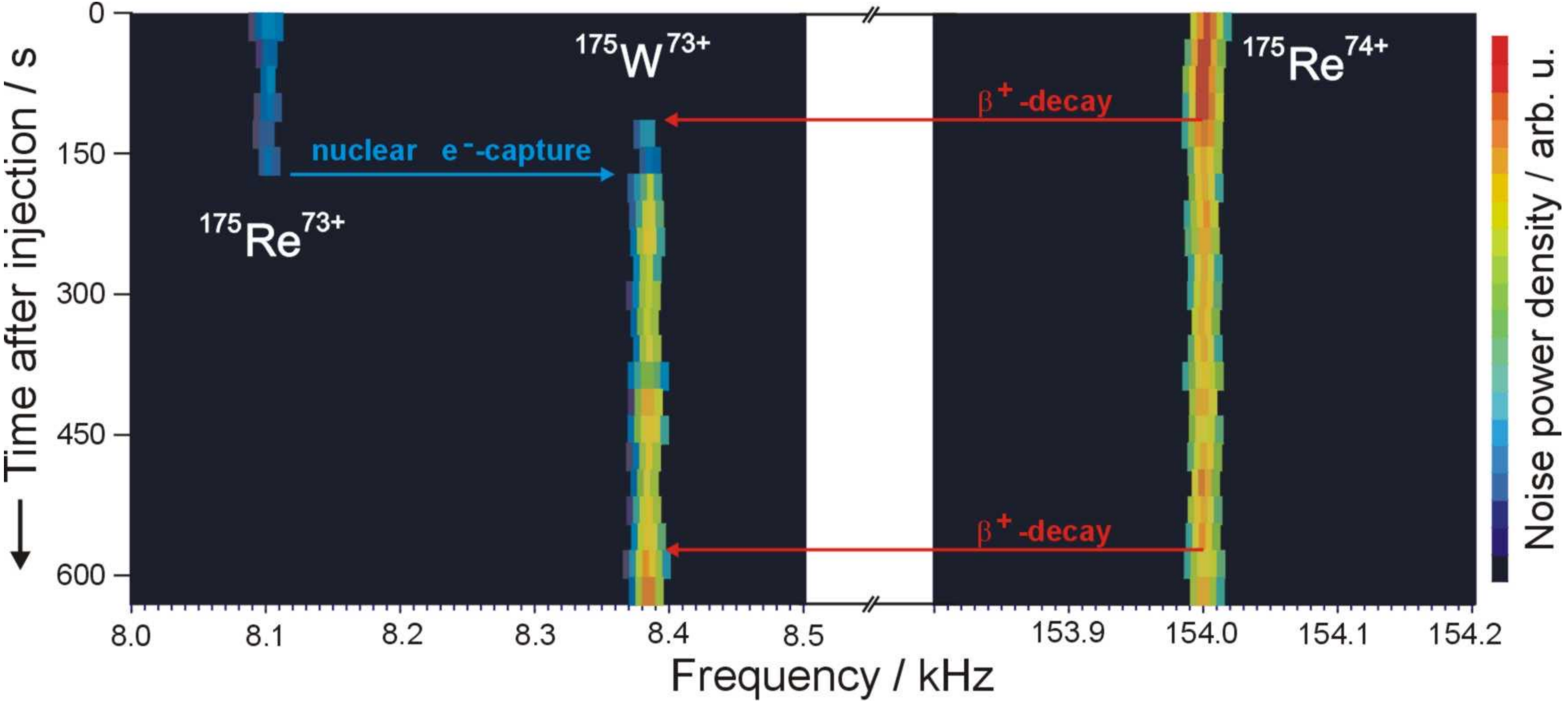
Nuclear Decays of Stored Single Ions



Schottky and Isochronous Storage Ring Mass Spectrometry

Cooling: Takes time

Non-Destructive Detection (Schottky detectors)

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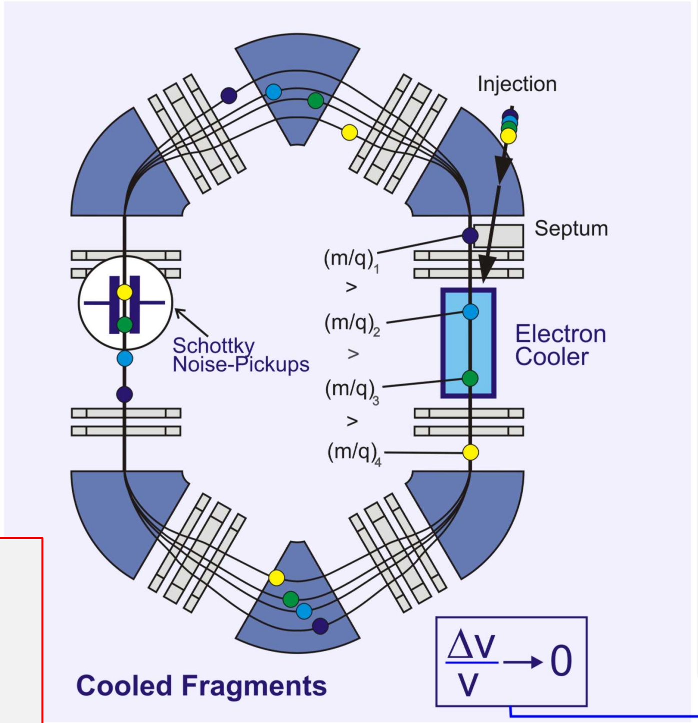
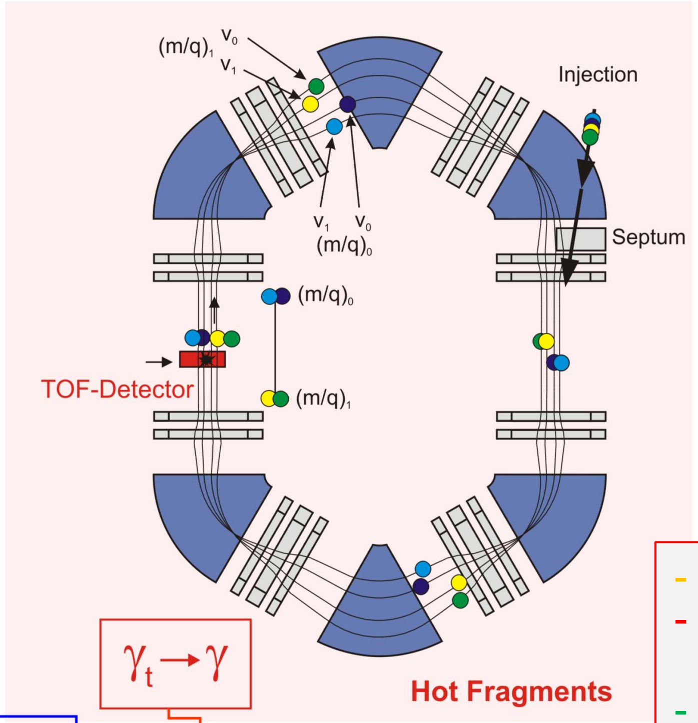
SCHOTTKY MASS SPECTROMETRY



ISOCHRONOUS MASS SPECTROMETRY



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B. Franzke, H. Geissel, G. Münzenberg, Mass Spectr. Rev. 27 (2008)

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International Journal of Mass Spectrometry 349–350 (2013) 38–46

Contents lists available at ScienceDirect

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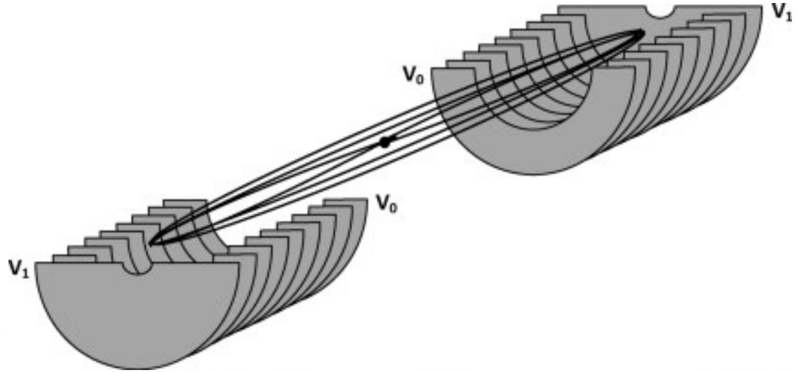
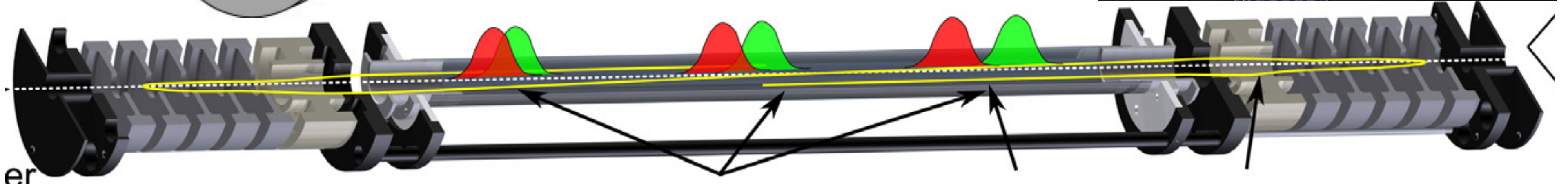
journal homepage: www.elsevier.com/locate/ijms

History of mass measurements in time-of-flight mass analyzers

Hermann Wollnik*

Physikalisches Institut, Universität Giessen in Giessen, Germany





International Journal of Mass Spectrometry and Ion Physics, 48 (1983) 411—414
Elsevier Scientific Publishing Company, Amsterdam — Printed in The Netherlands

Time-of-Flight Mass Spectrometry for Ions of Large Energy Spread

W.Gohl, R.Kutscher, H.J.Laue and H.Wollnik
2. Phys. Institut, Univ. of Giessen, 63 Giessen, Germany

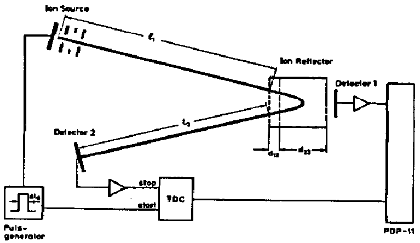


Fig.1 Principle of a TOF-MS with a double stage ion-reflector and a total drift length $l=l_1+l_2$.

In an ion reflector the ions of higher energy penetrate deeper than those of lower energy which causes for the faster more energetic ions a longer flight time in the reflector than for the slower less energetic ions. On the other hand the higher energetic ions need less flight time in the drift tube of the TOF-MS than the lower energetic ions. Thus the overall flight time is widely independent of the kinetic energy of the ions and depends only on the particle mass /1/.

Nuclear Instruments and Methods in Physics Research A240 (1985) 77–90
North-Holland, Amsterdam

OPTICAL DESIGN OF THE TOFI (TIME-OF-FLIGHT ISOCHRONOUS) SPECTROMETER FOR MASS MEASUREMENTS OF EXOTIC NUCLEI

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Los Alamos National Laboratory, Los Alamos, NM 87545, USA

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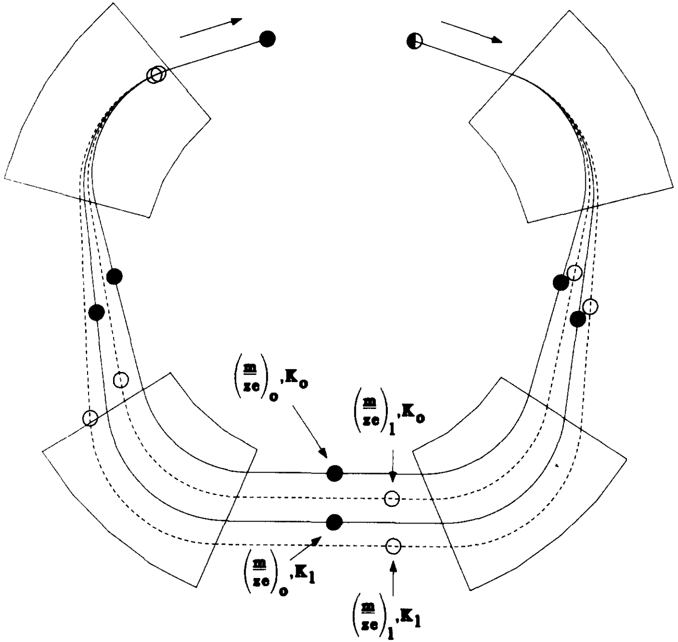
Massachusetts Institute of Technology, Cambridge, MA 02139, USA

K.L. BROWN
Stanford Linear Accelerator Center, Stanford, CA 94305, USA

Received 4 March 1985



2. TOFI – a time-of-flight isochronous spectrometer

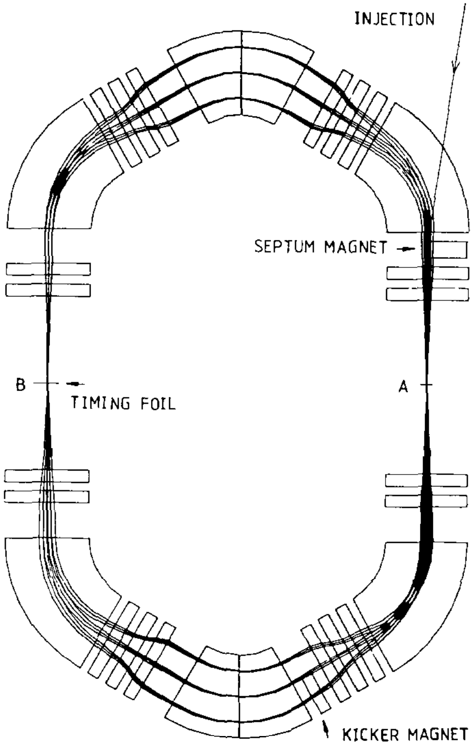
Our approach to a recoil time-of-flight spectrometer is to employ an isochronous design, which makes the transit time of a particle with a given mass-to-charge ratio passing through the spectrometer independent of the particle velocity (see fig. 1). This condition is achieved by an arrangement of sector

1987: Proposal for Isochronous Mass Spectrometry at the ESR

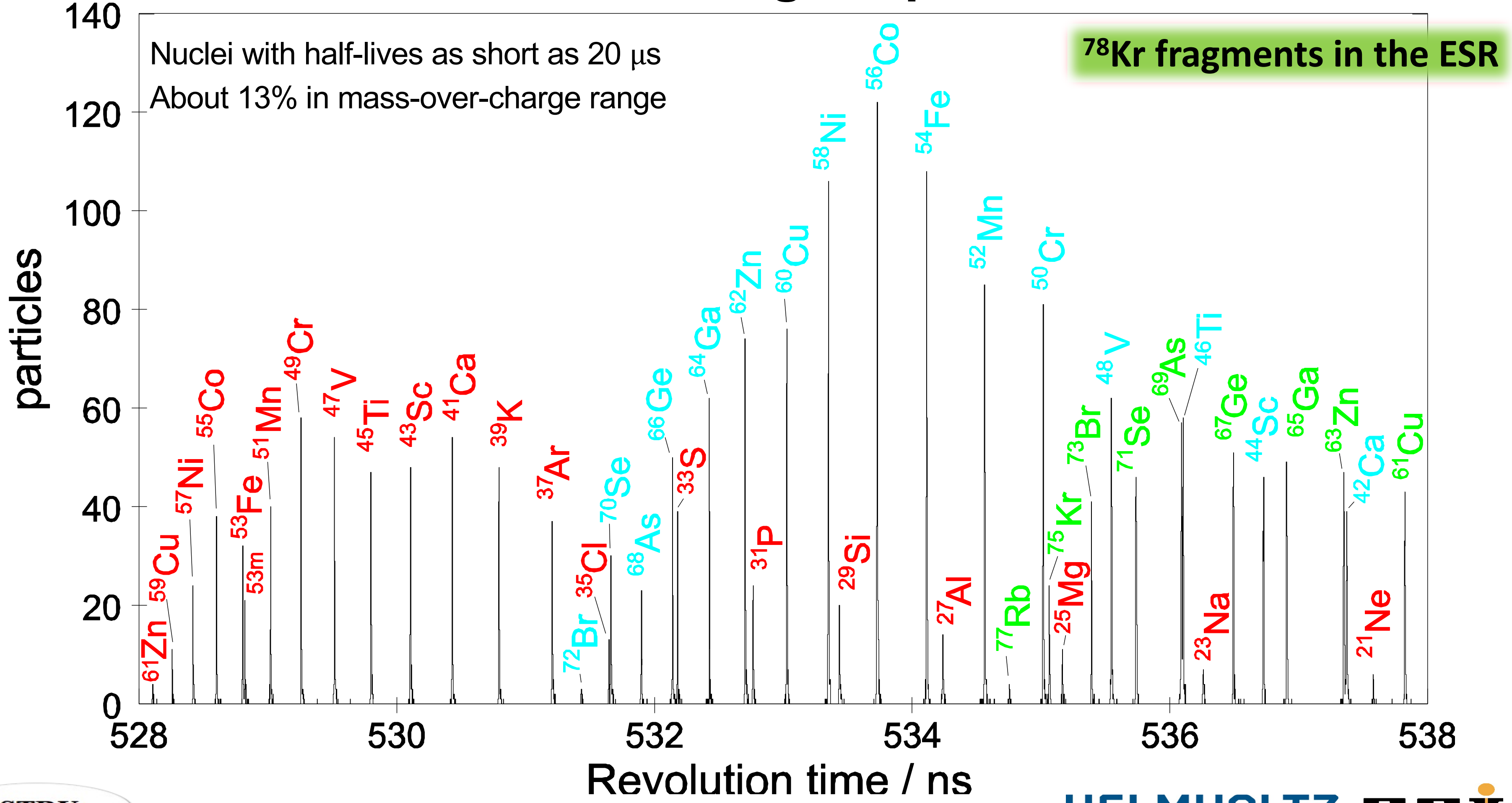
PROPOSAL FOR GSI SIS/ESR

Wollnik H, Schwab T, Berz M, Seifert H, Münzenberg G, Geissel H, Löbner KEG, Vieira DJ, Wouters JM, Kraus RH, Matsuda H.

Direct mass measurements of exotic nuclei at SIS/ ESR.
GSI-Report GSI-87-7, ISSN 0171-4546, 1987



IMS: Time-of-Flight Spectra



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

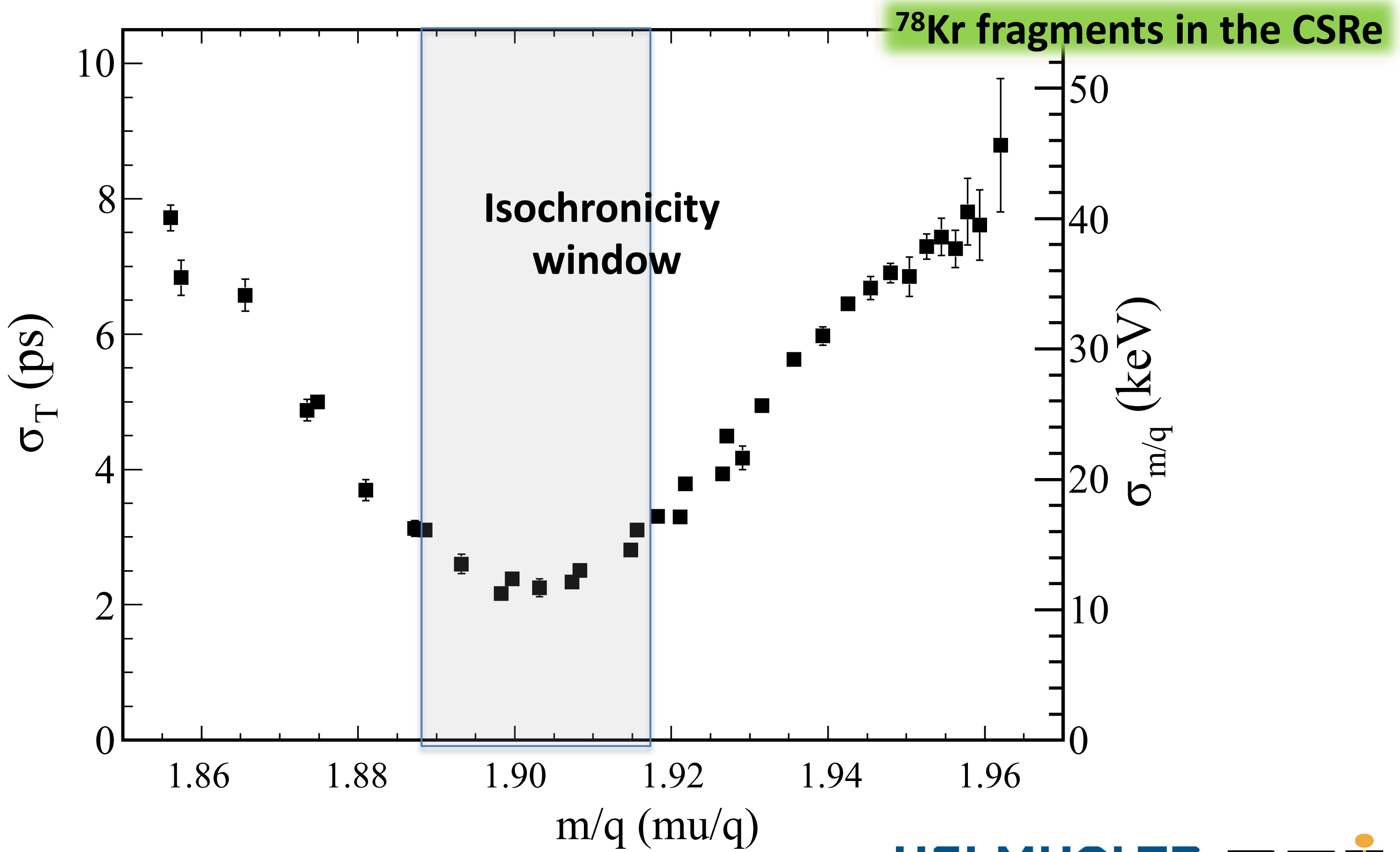
IMS: Isochronicity Window

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

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

$$\gamma \neq \gamma_t$$

- Bandwidth
- Resolving power
- Speed
- Sensitivity

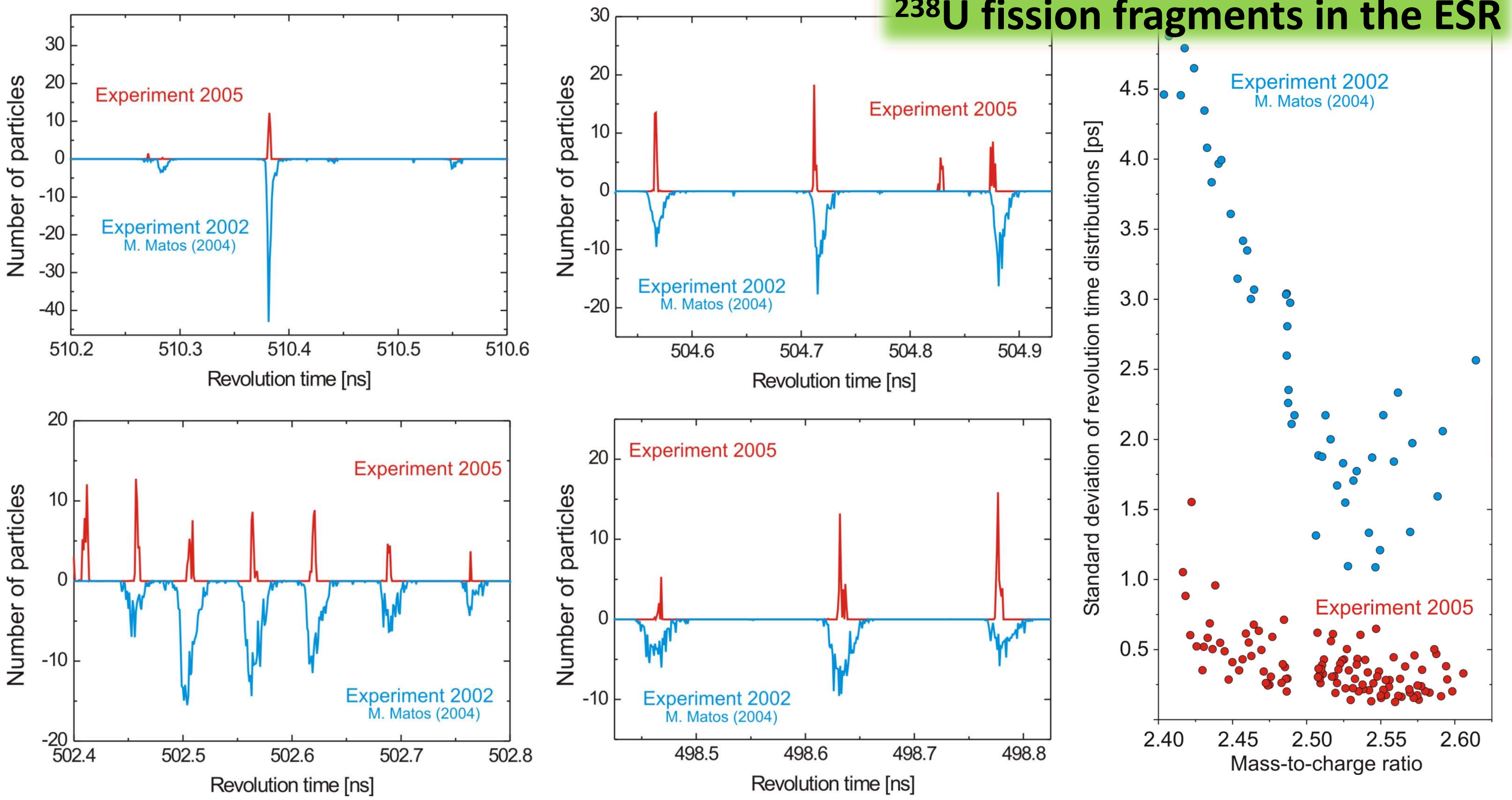


M. Wang et al., Physical Review C 106 (5) (2022) L051301

Br-Tagging IMS Spectroscopy

^{238}U fission fragments in the ESR

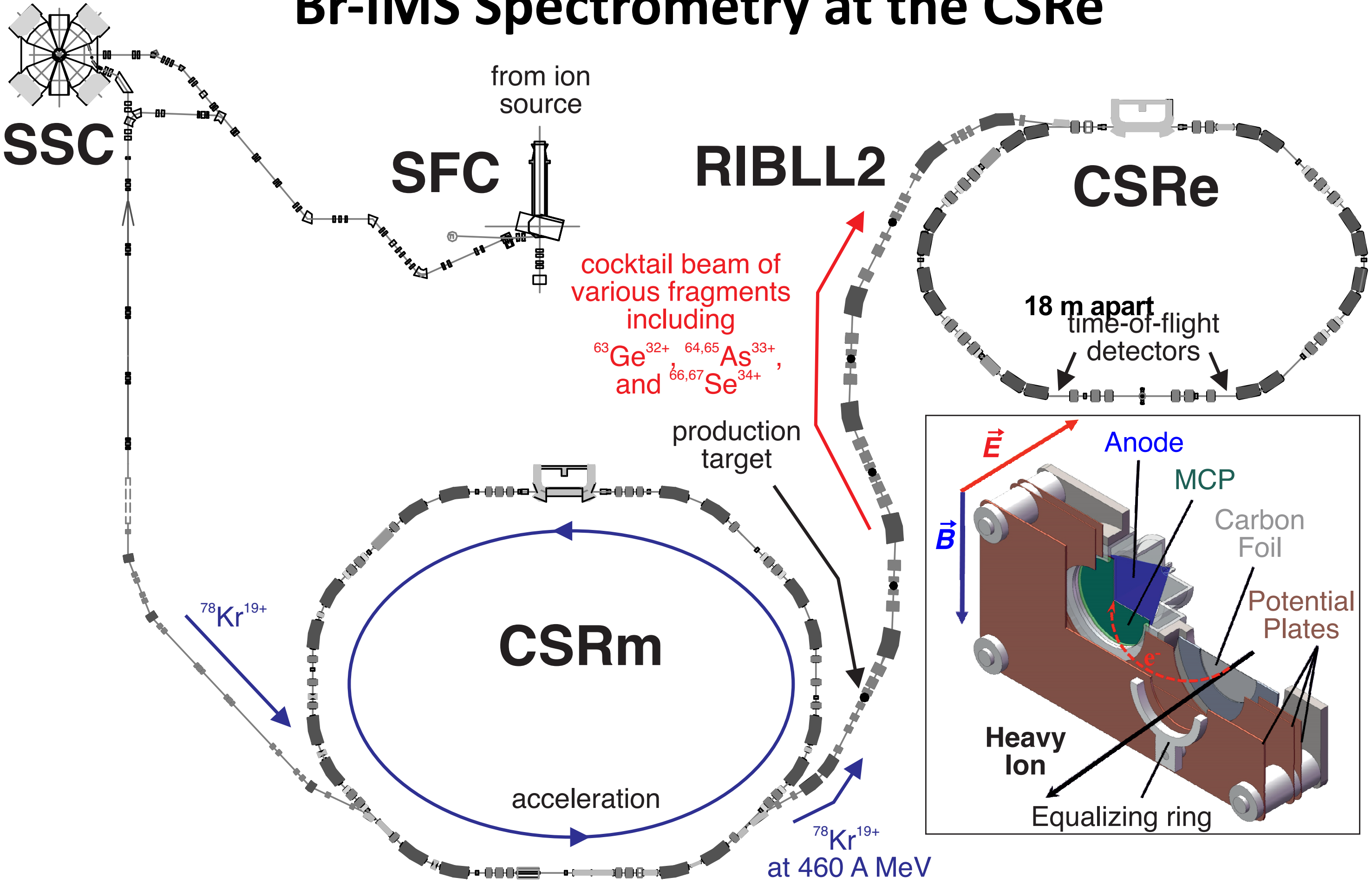
- **Bandwidth**
- **Resolving power**
- **Speed**
- **Sensitivity**



H. Geissel et al., J. Phys. G (2005)

H. Geissel et al., Hyp. Interactions 173 (2006)

Br-IMS Spectrometry at the CSRe

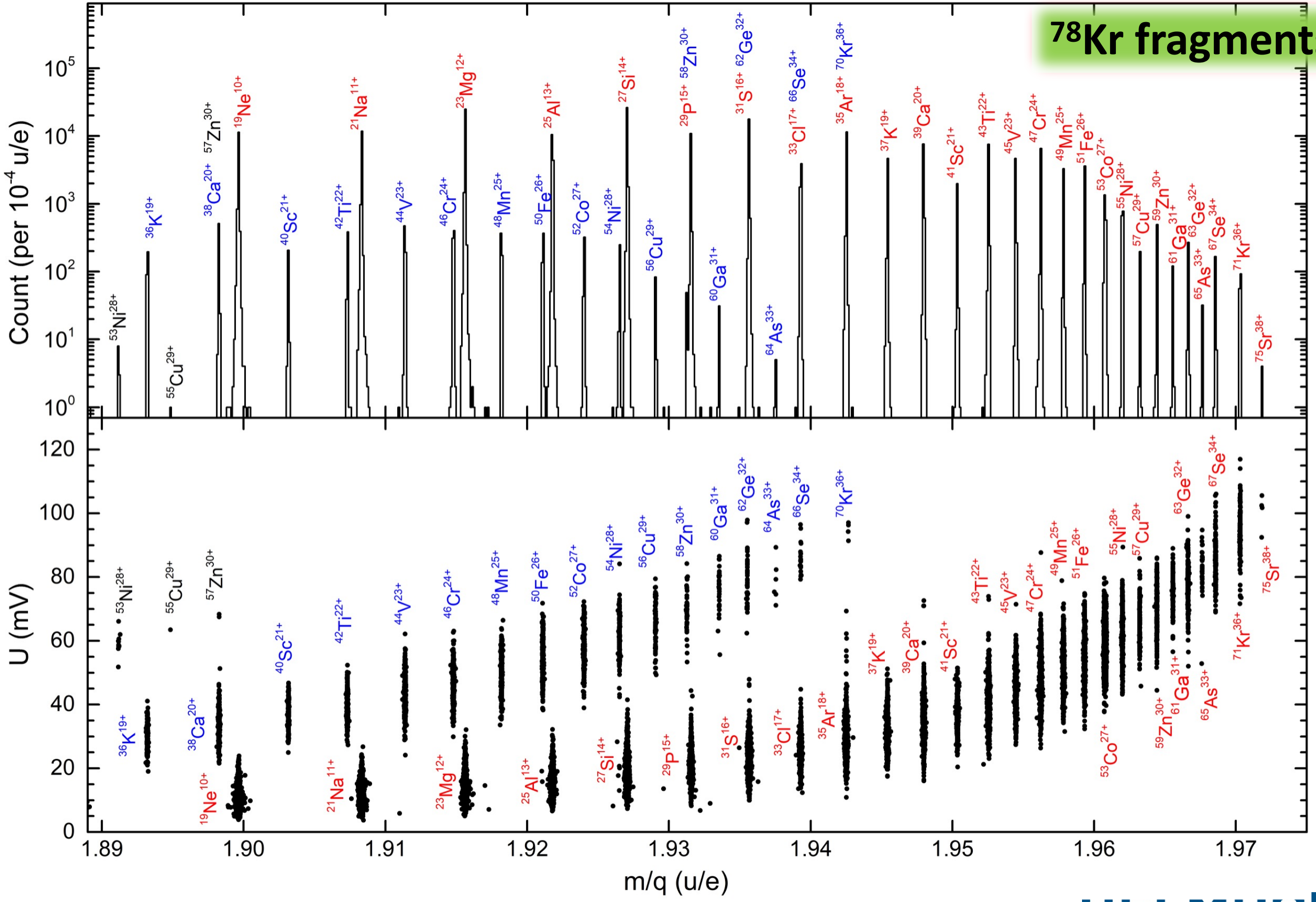


erc ASTRUm

X. Zhou et al., Nature Physics 2023

HELMHOLTZ GSI

Br-IMS Spectrometry at the CSRe



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

IMS: Isochronicity Window

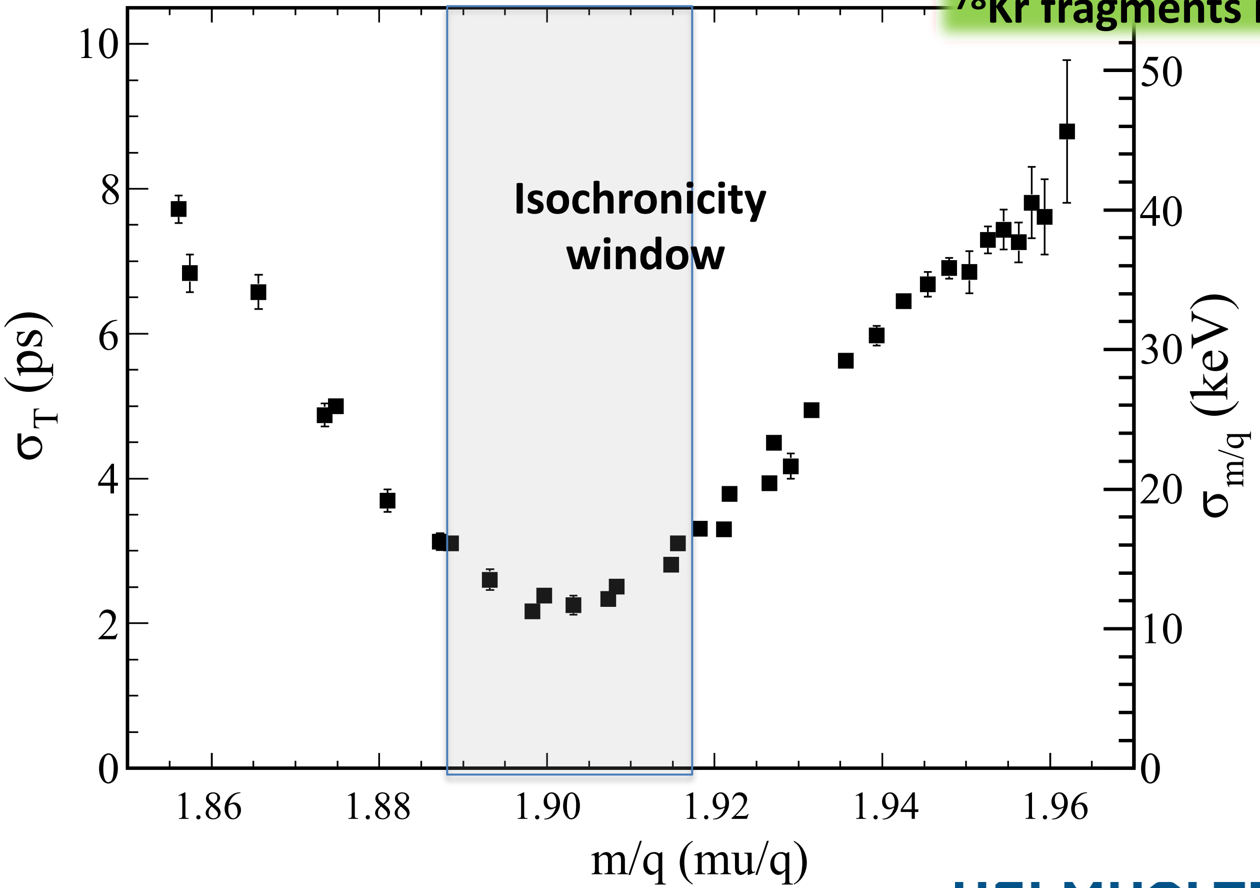
$$B\rho = \frac{m}{q} v\gamma$$

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

$$\gamma \neq \gamma_t$$

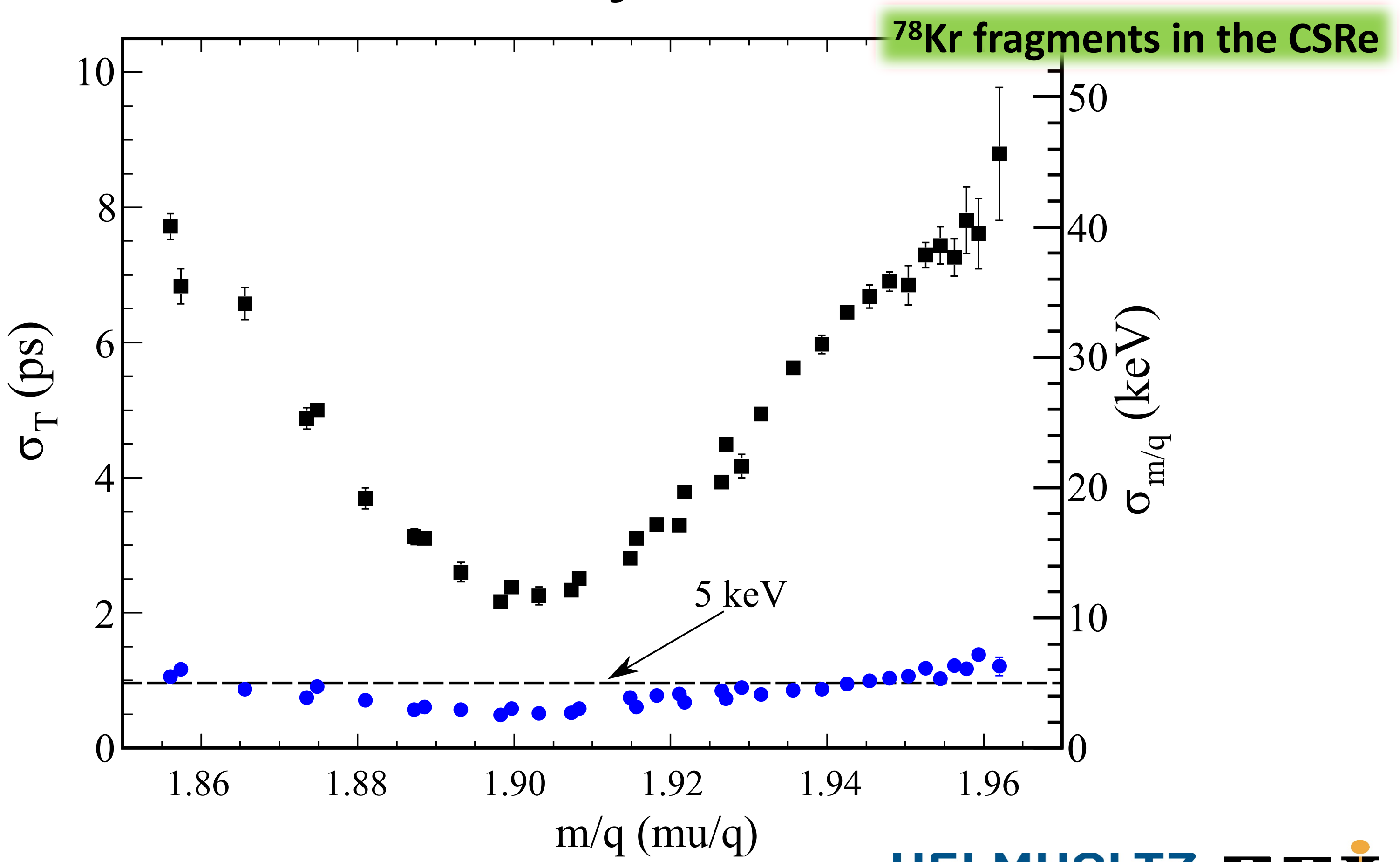
- Bandwidth
- Resolving power
- Speed
- Sensitivity

^{78}Kr fragments in the CSRe



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

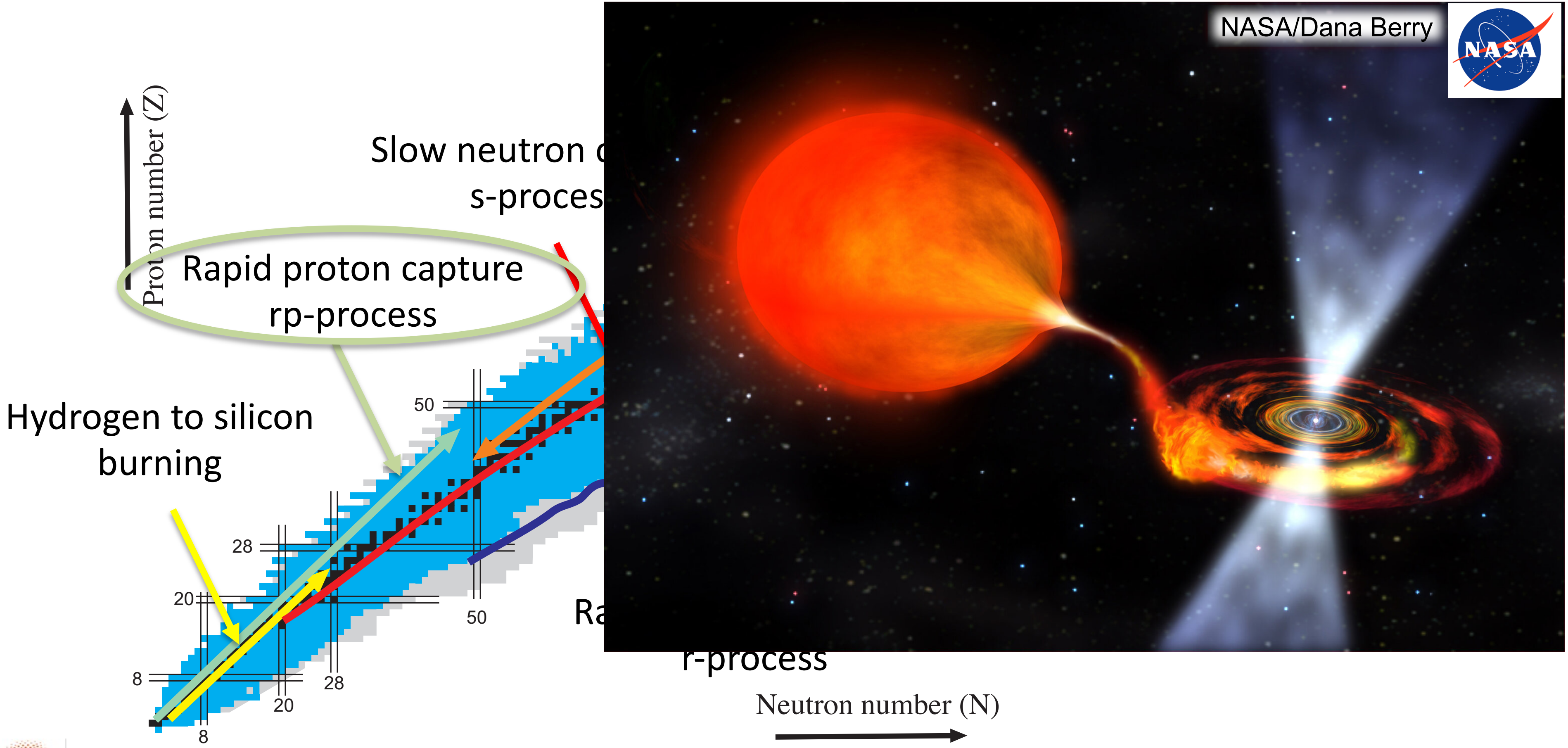
IMS: Isochronicity Window



- Bandwidth
- Resolving power
- Speed
- Sensitivity

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

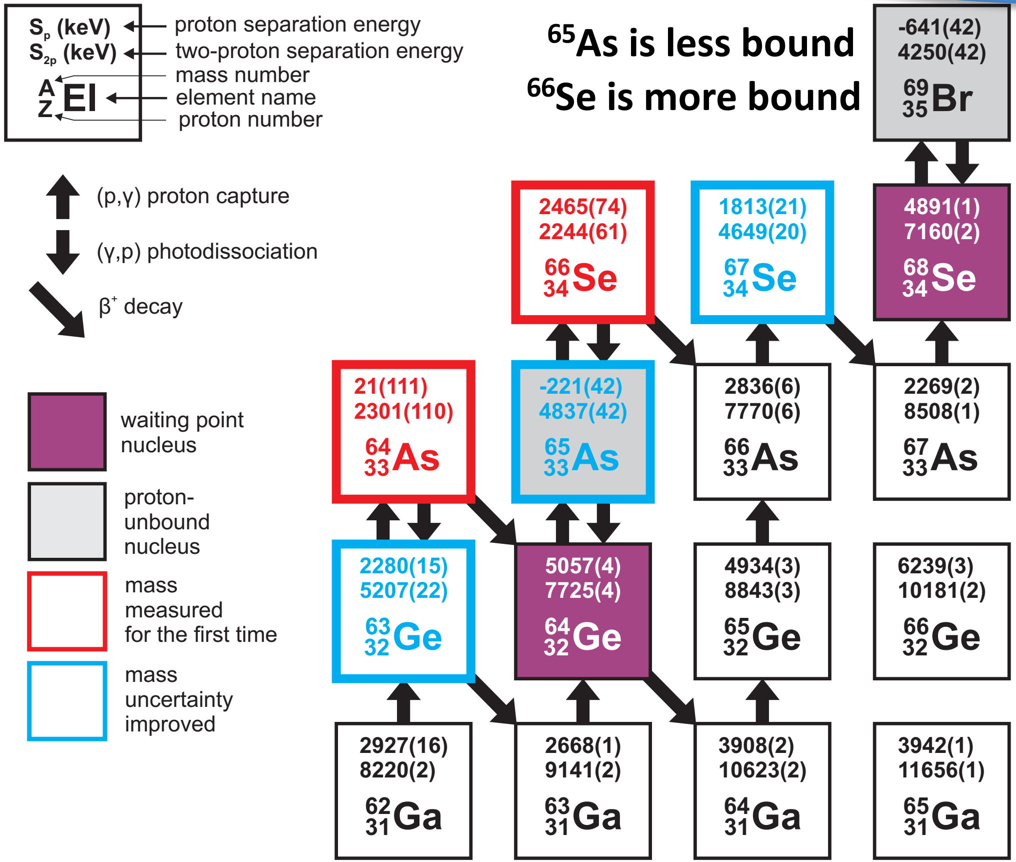
Nucleosynthesis Processes



Rp-process nucleosynthesis at ^{64}Ge

nature physics

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}

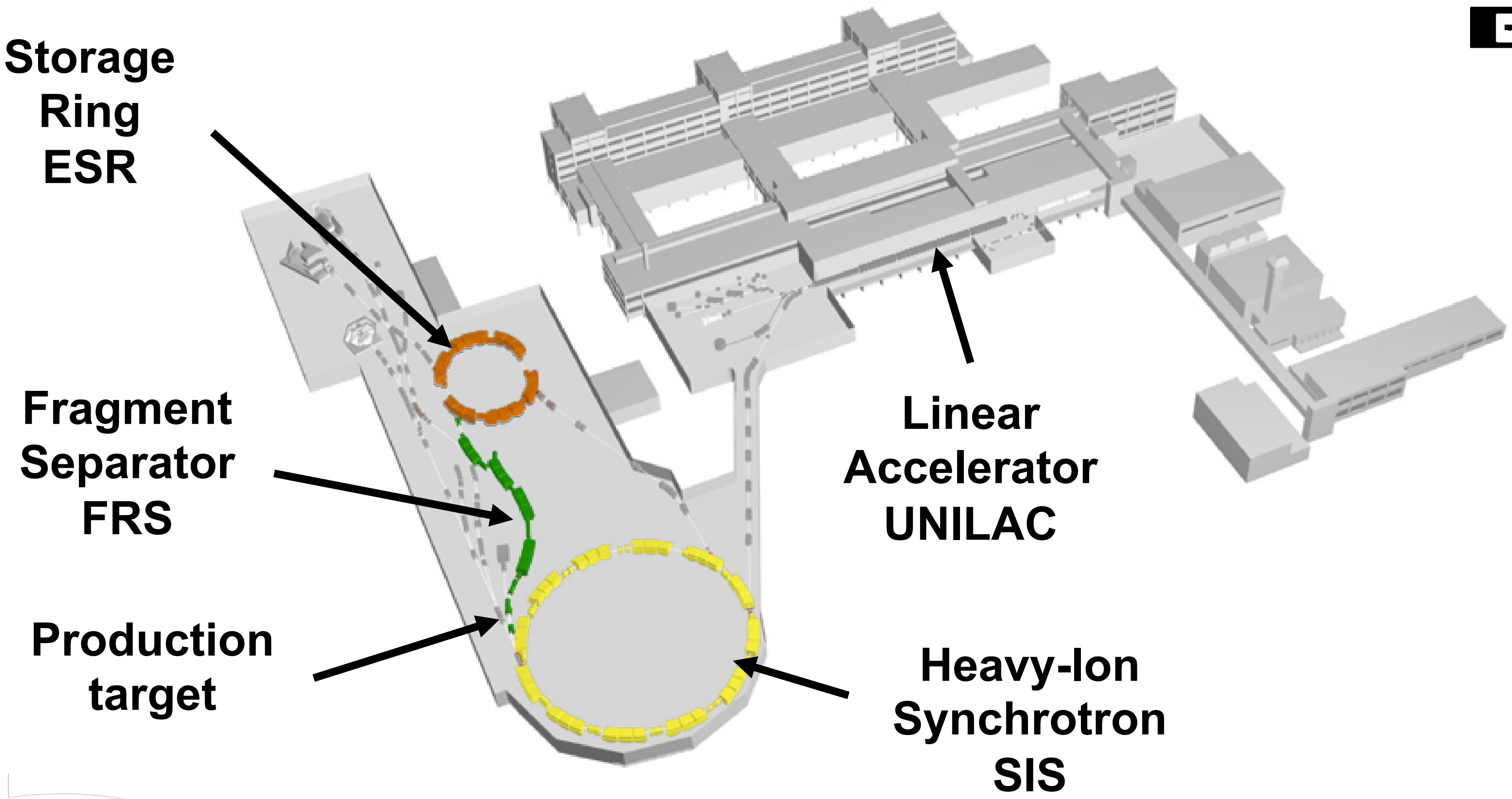


erc ASTRUm

X. Zhou et al., Nature Physics 19 (2023) 1091–1097

HELMHOLTZ GSI

Radioactive Ion Beam Facility at GSI

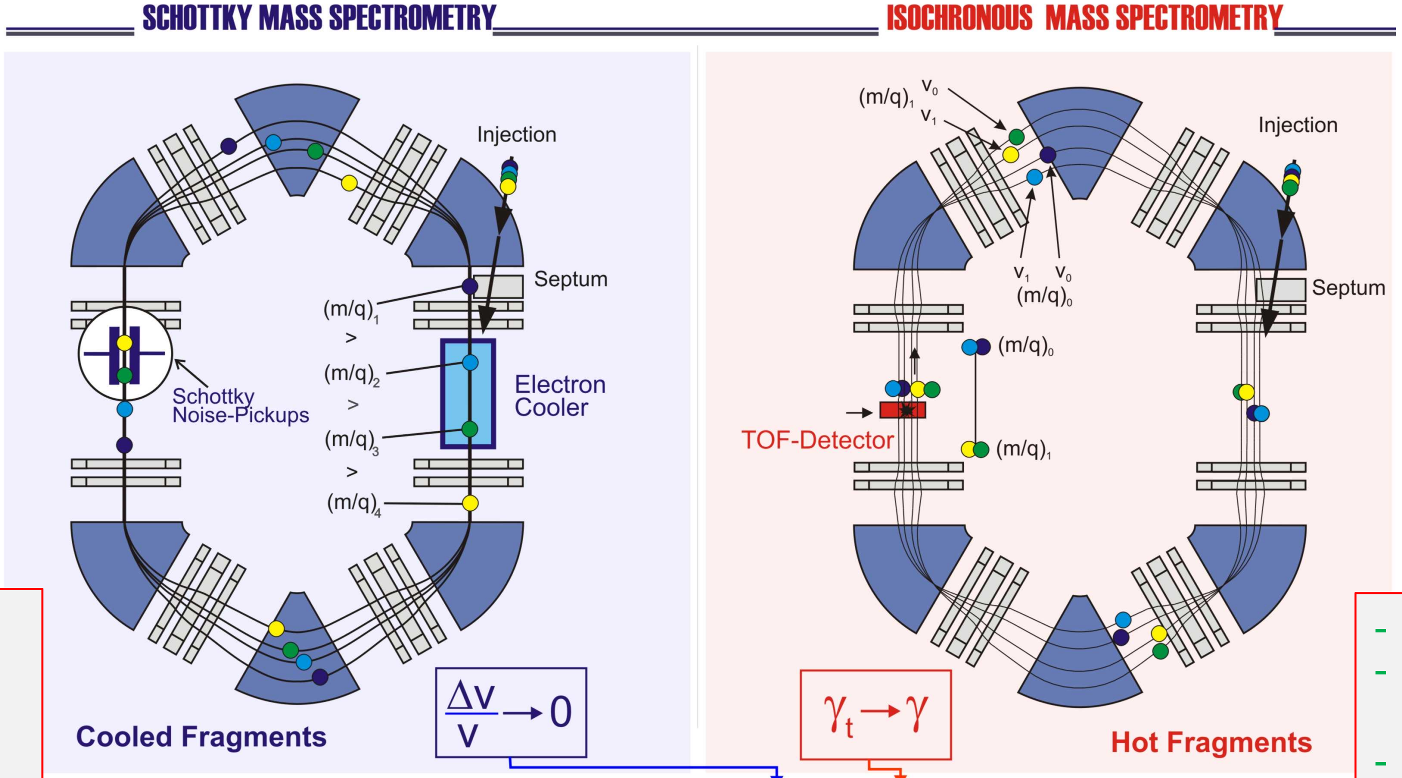


Picture: GSI, Darmstadt

Schottky and Isochronous Storage Ring Mass Spectrometry

Cooling: Takes time

Non-Destructive Detection (Schottky detectors)



Destructive Detectors (foil-based Secondary electron detectors)

No cooling

- Bandwidth
- Resolving power
- Speed
- Sensitivity

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

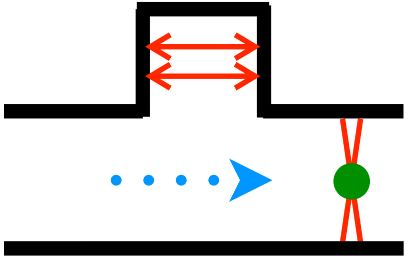
- Bandwidth
- Resolving power
- Speed
- Sensitivity

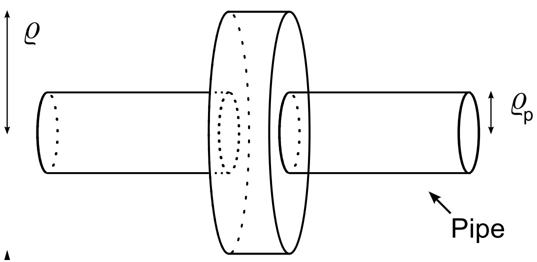
erc ASTRUm

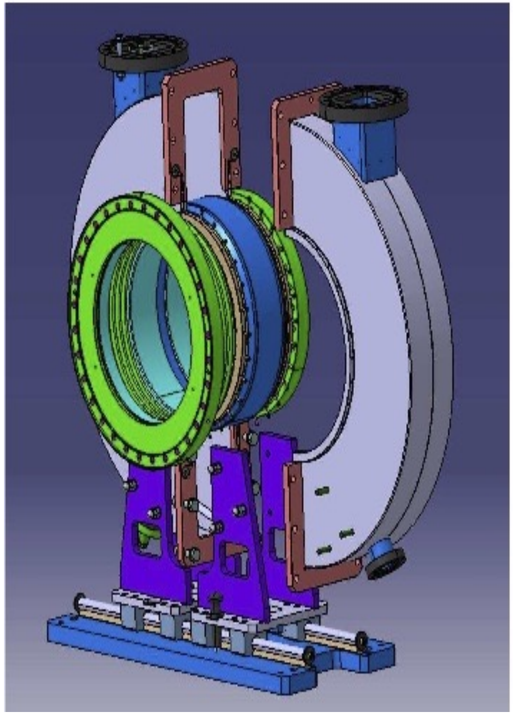
HELMHOLTZ GSI

B. Franzke, H. Geissel, G. Münzenberg, Mass Spectr. Rev. 27 (2008)

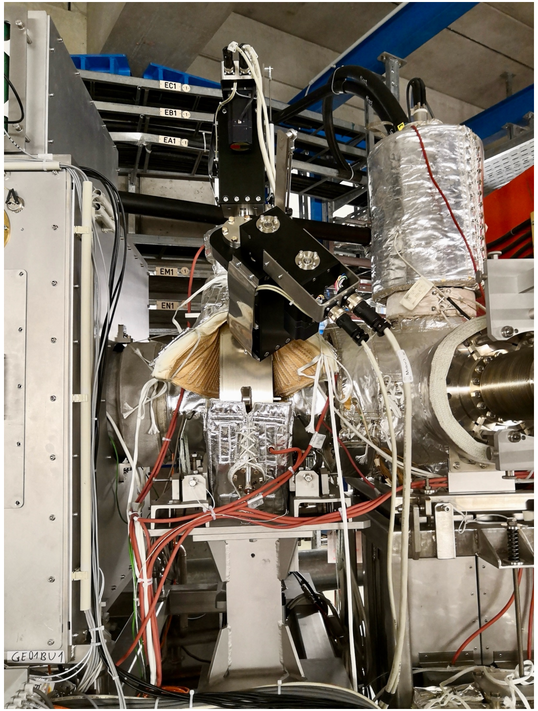
Non-Destructive Particle Detection







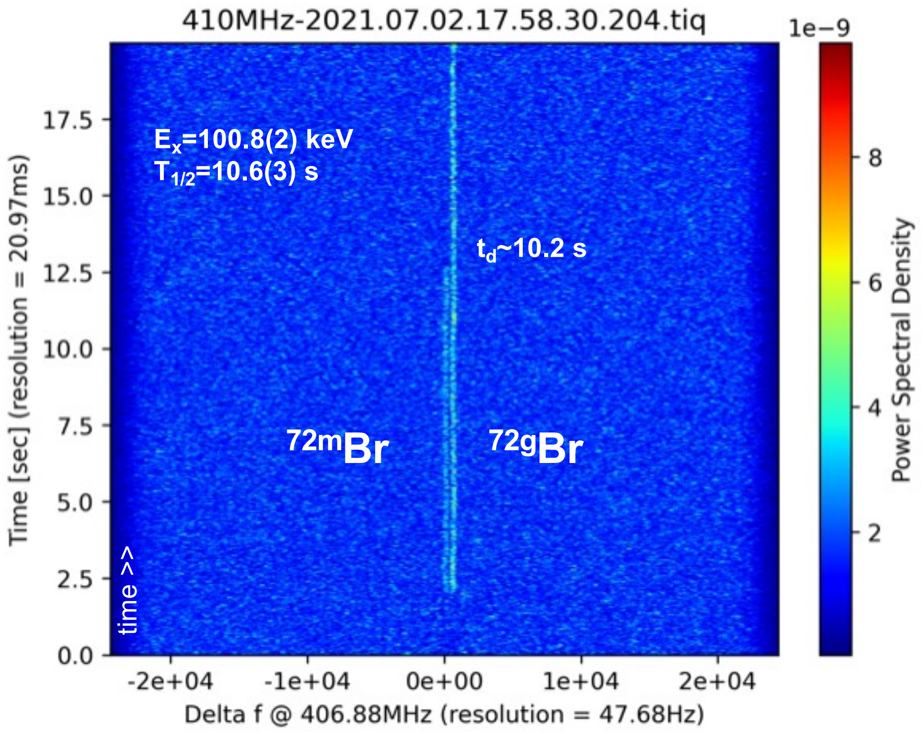
F. Nolden et sl., Nucl. Instr. Meth. A (2011)



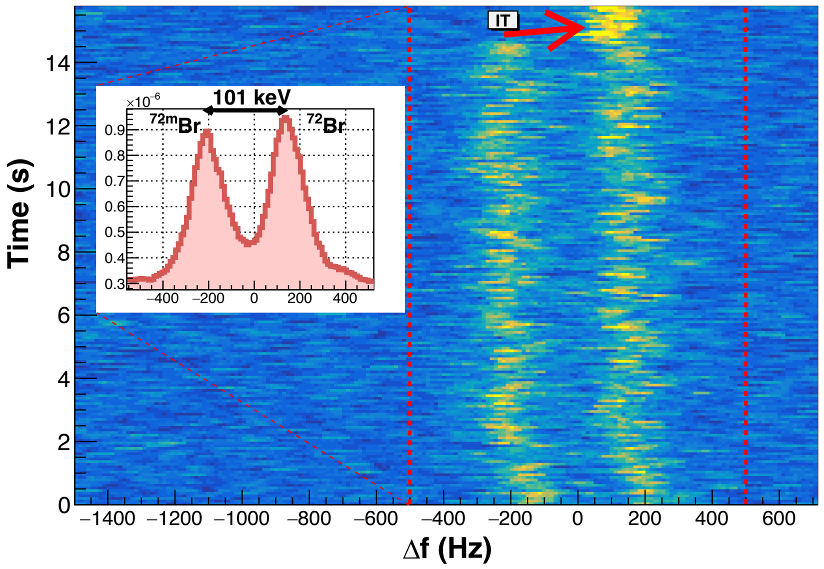
S. Sanjari et al., Rev. Sci. Instr. (2020)

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

Combined Isochronous+Schottky Mass Spectrometry



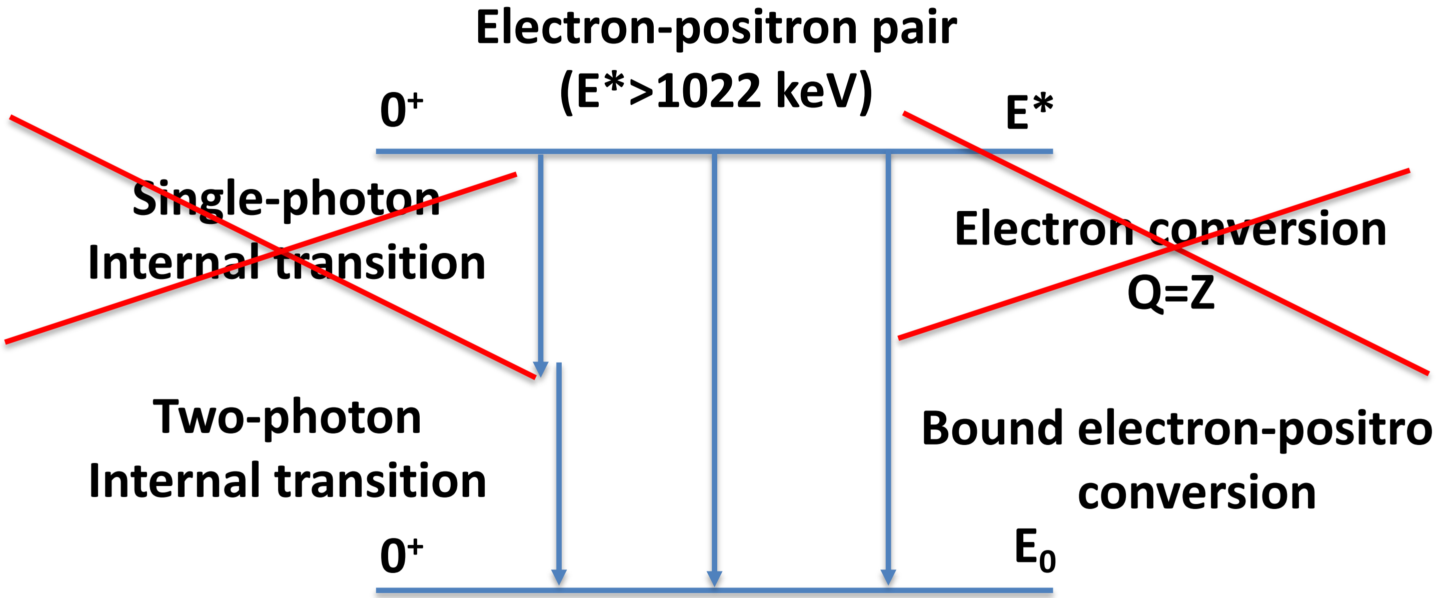
Schottky spectra of single events
Separation of the 101 keV isomer in ^{72}Br



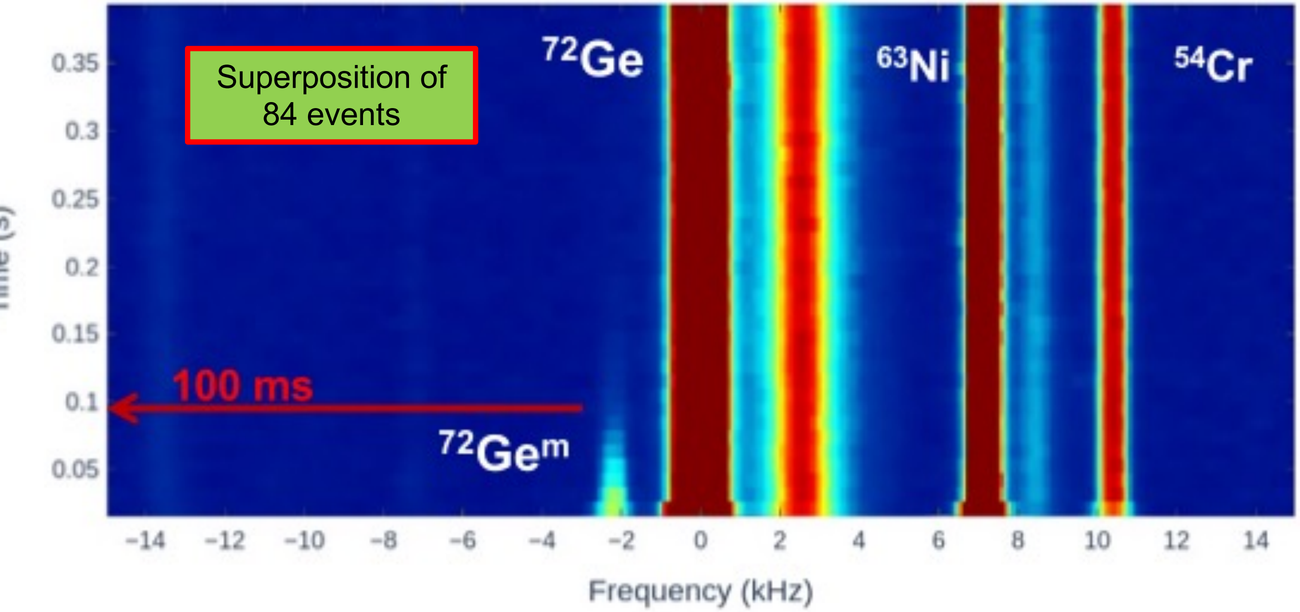
→ $\Delta m/m < 10^{-6}$

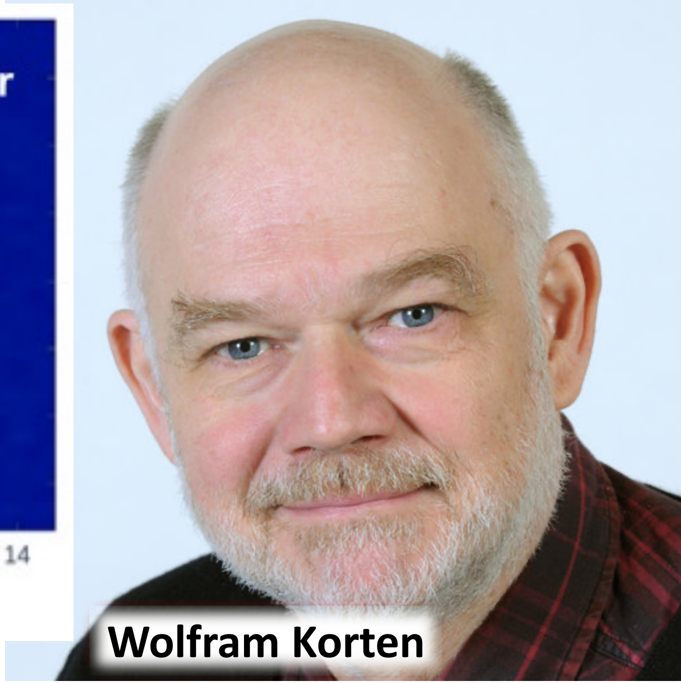
Courtesy W. Korten and D. Fernandez

Electromagnetic decays in bare nuclei



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
$0^{+} \rightarrow 0^{+}$ decays as laboratory for BSM physics

Courtesy: D. Fernandes and W. Korten

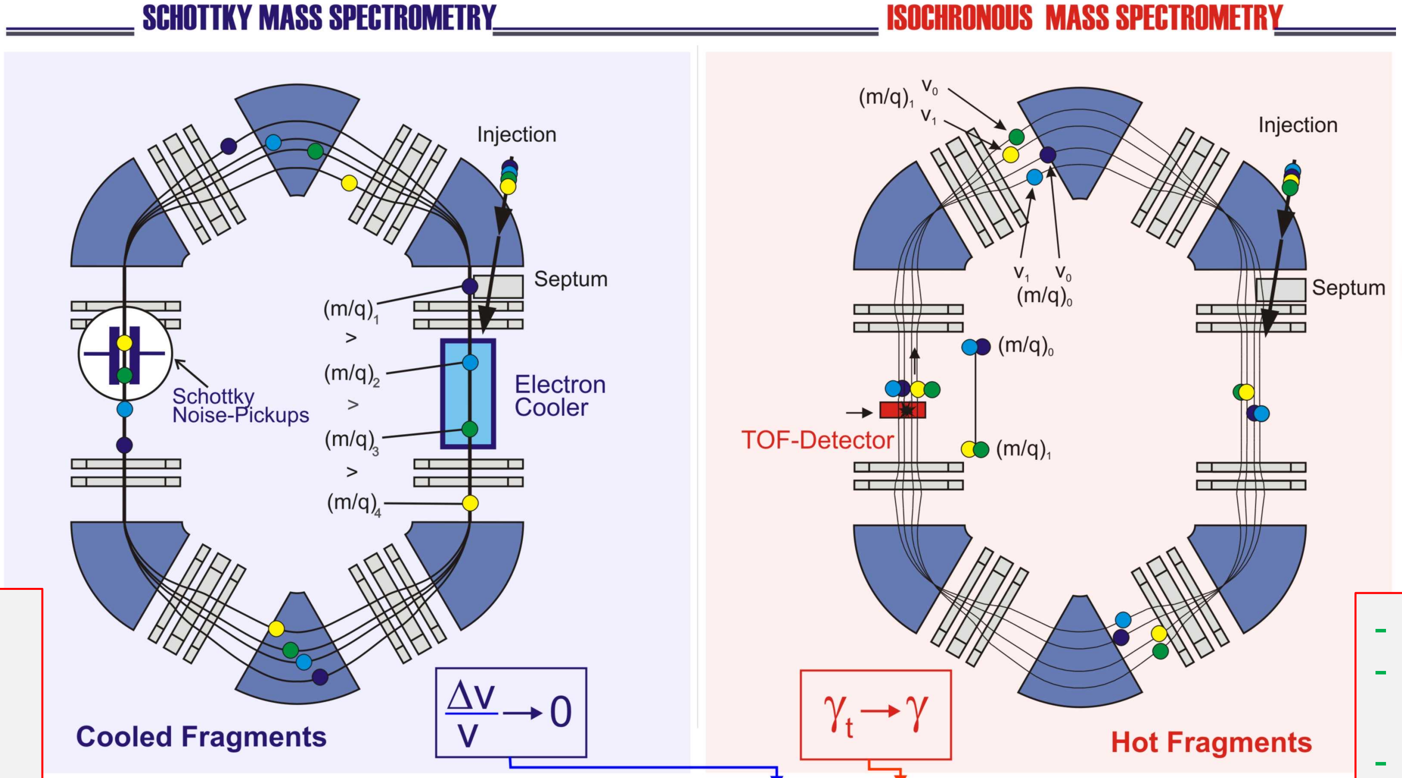
Schottky and Isochronous Storage Ring Mass Spectrometry

Isochronous mode

No cooling

Non-Destructive Detection (Schottky detectors)

- Bandwidth
- Resolving power
- Speed
- Sensitivity



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

Isochronous mode

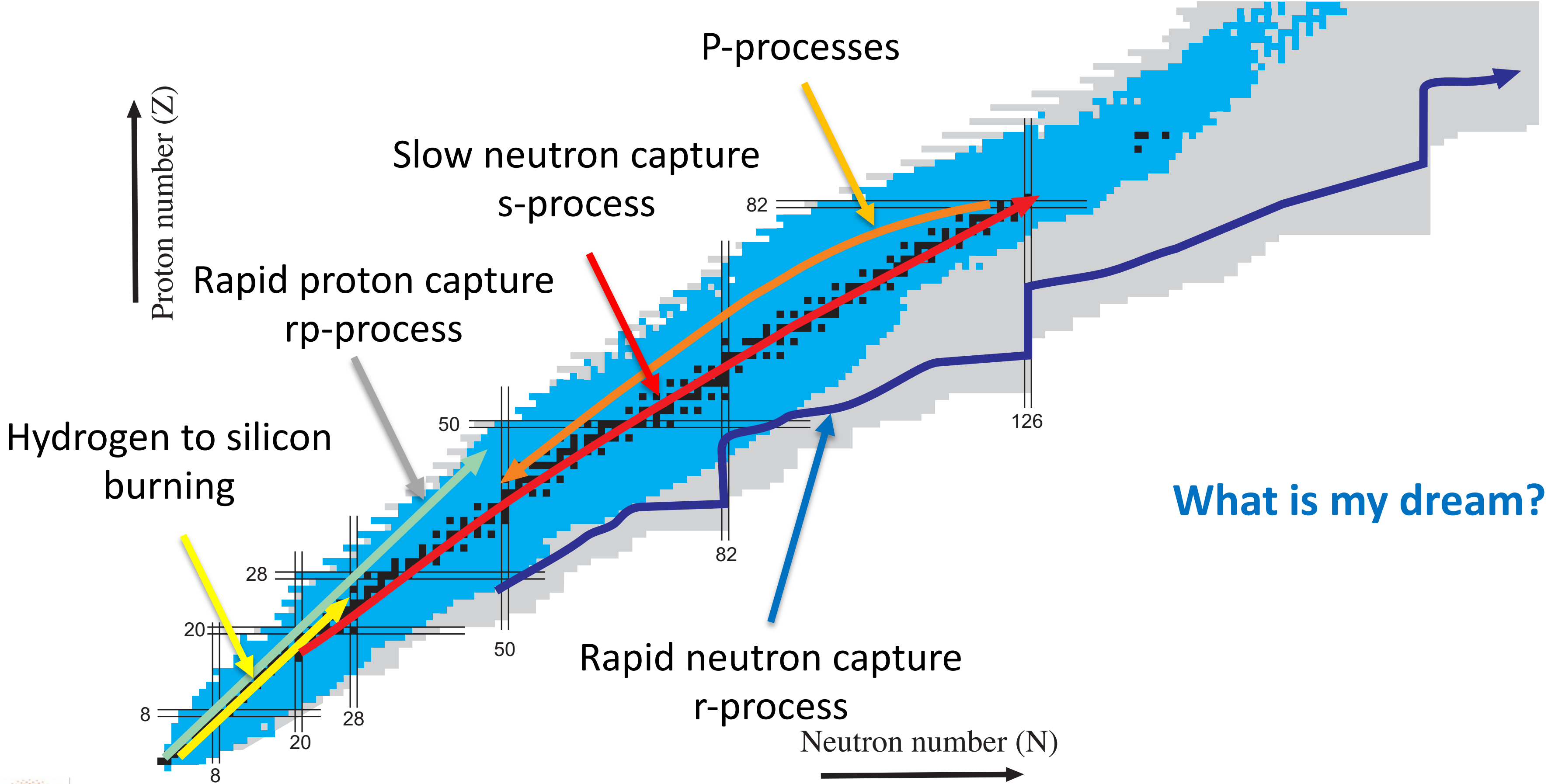
No cooling

Velocity measurement

- Bandwidth
- Resolving power
- Speed
- Sensitivity

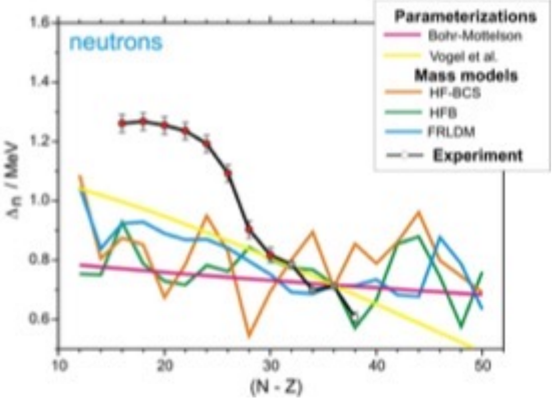
B. Franzke, H. Geissel, G. Münzenberg, Mass Spectr. Rev. 27 (2008)

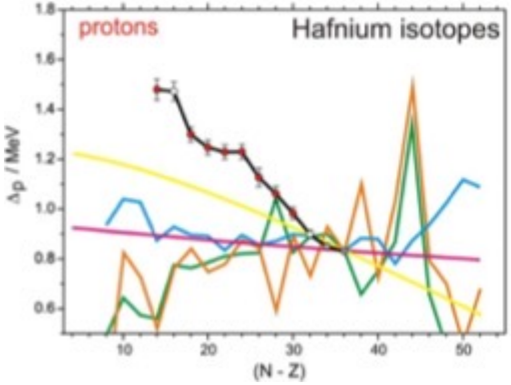
Nucleosynthesis Processes

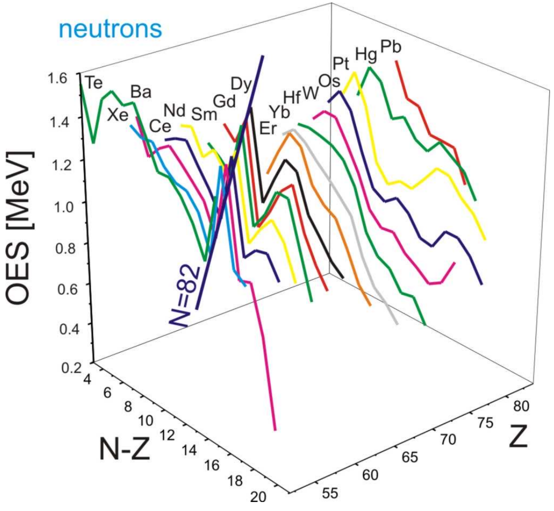


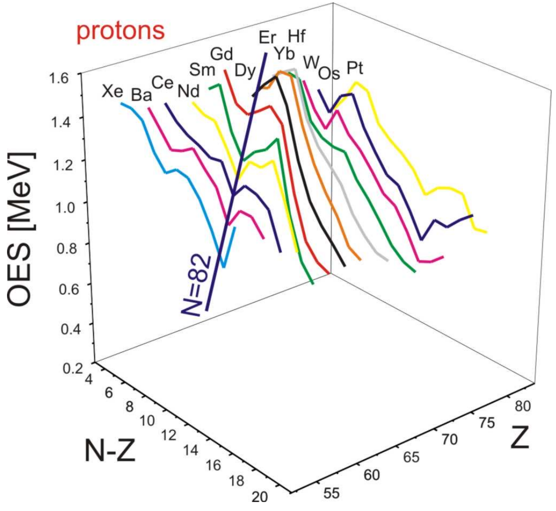
What is my dream?

Nucleon-Nucleon Correlations









Neutrons

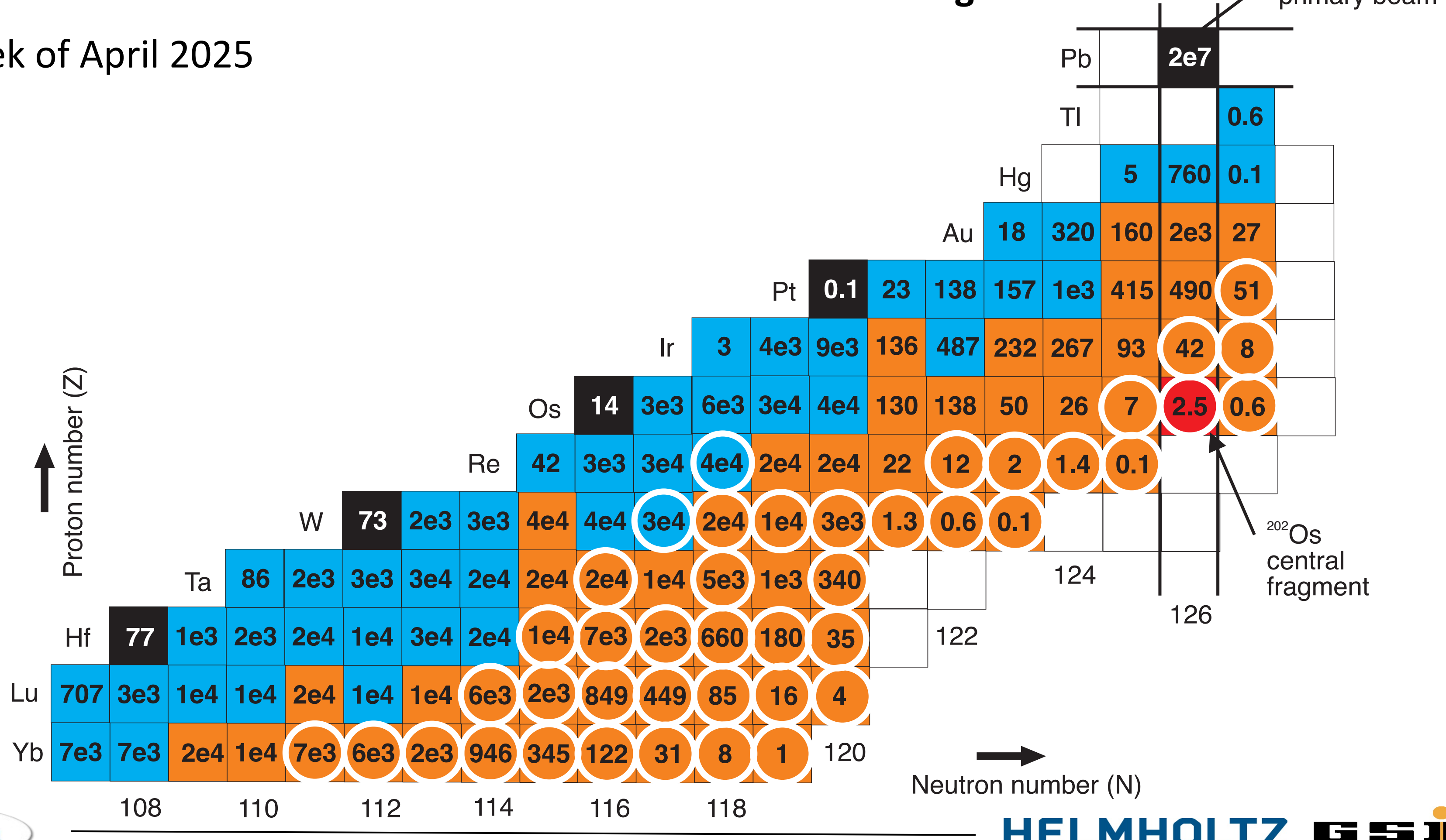
$$\Delta_{n5} = \frac{1}{8}\big(m(Z,N+2) - 4(Z,N+1) + 6m(Z,N) - 4m(Z,N-1) + m(Z,N-2)\big)\cdot c^2$$

Protons

$$\Delta_{p5} = \frac{1}{8}\big(m(Z+2,N) - 4(Z+1,N) + 6m(Z,N) - 4m(Z-1,N) + m(Z-2,N)\big)\cdot c^2$$

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

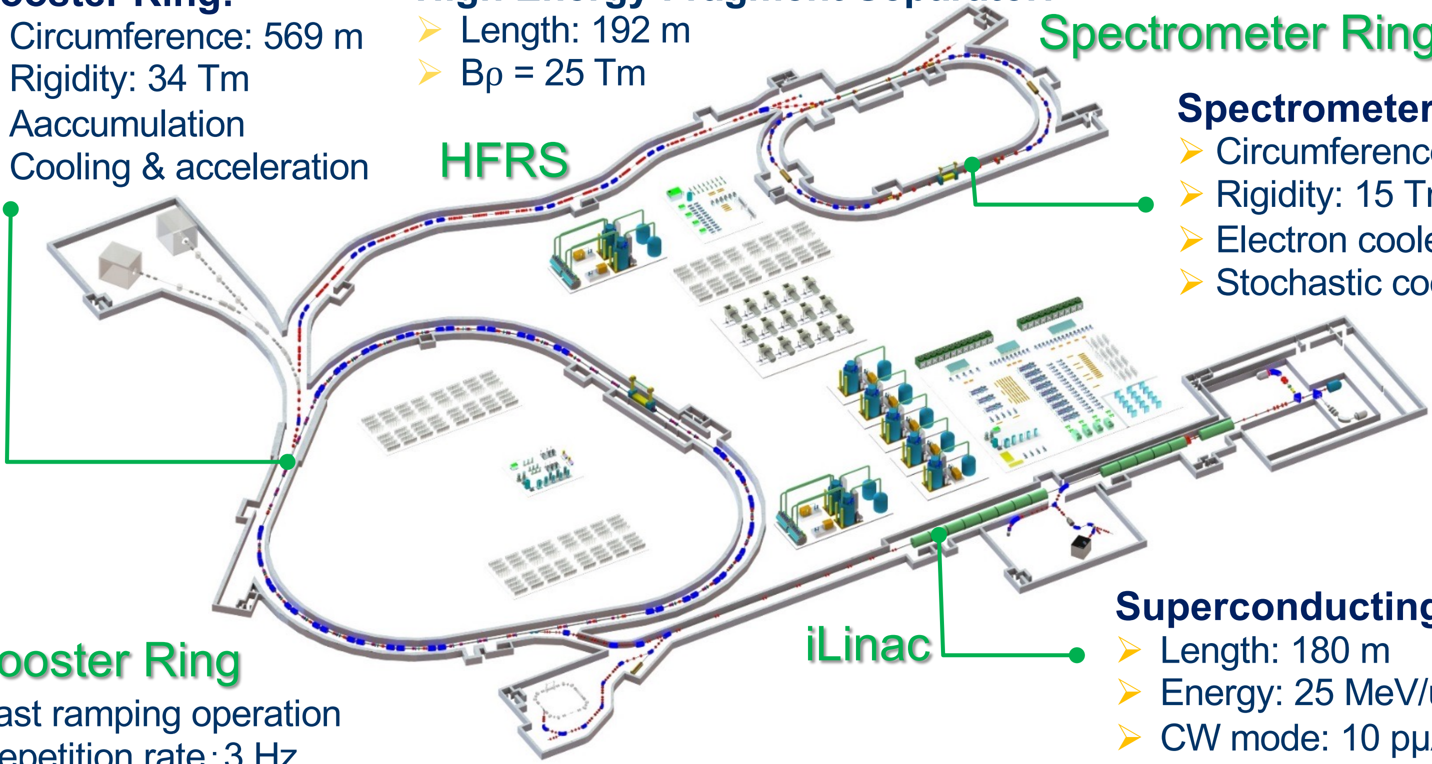
First week of April 2025



Accelerator Complex

Booster Ring:
- Circumference: 569 m
- Rigidity: 34 Tm
- Aacumulation
- 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

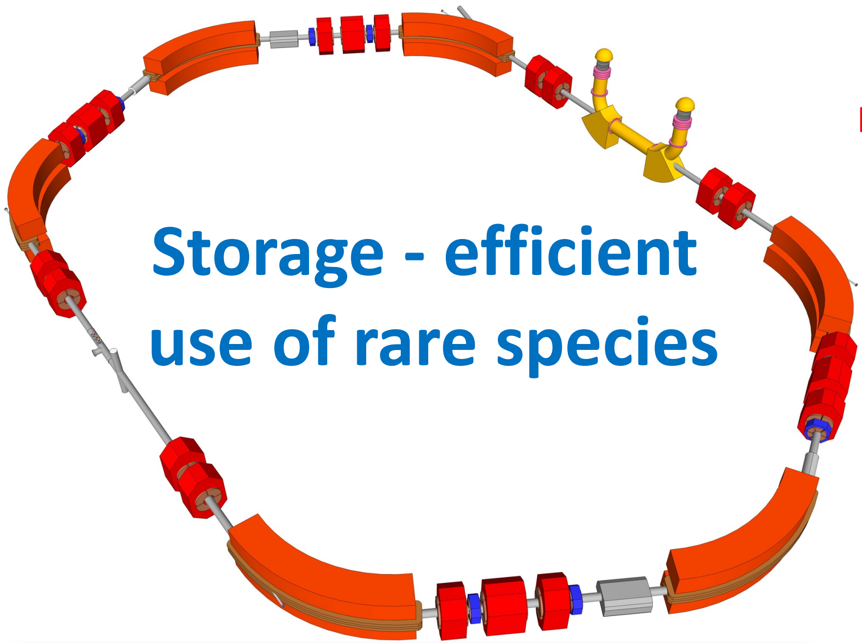
Ion Sources:
- a 45 GHz FECR
- a 28 GHz SECRAL
- a 2.45 GHz ECR

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

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

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

NucAR

sparc

Stored Particles Atomic Physics Research Collaboration

NUSTAR

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THE UNIVERSITY OF EDINBURGH

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

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