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Broadband Mass Measurements in Storage Rings

Yuri A. Litvinov

**EMMI Workshop: Neutron Matter in Astrophysics:
From Neutron Stars to the R-Process
15-18 July 2010, GSI, Darmstadt, Germany**

Max-Planck-Institut
für Kernphysik

Masses: Fundamental Properties of Atomic Nuclei

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- ➢ **Binding energies**
- • **Mass models**
- • **Shell structure**

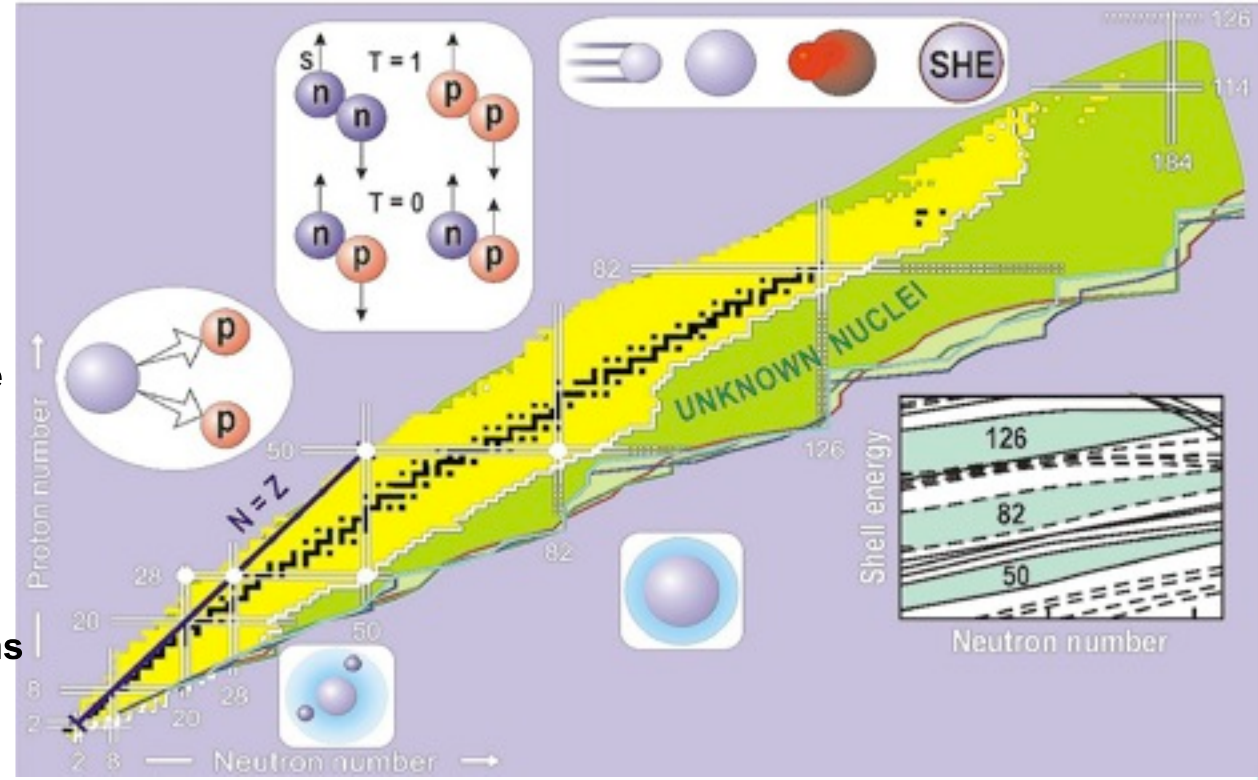
- ➢ **Correlations**
- • **pairing**

- ➢ **Reaction phase space**
- • **Q-values**
- • **Reaction probabilities**

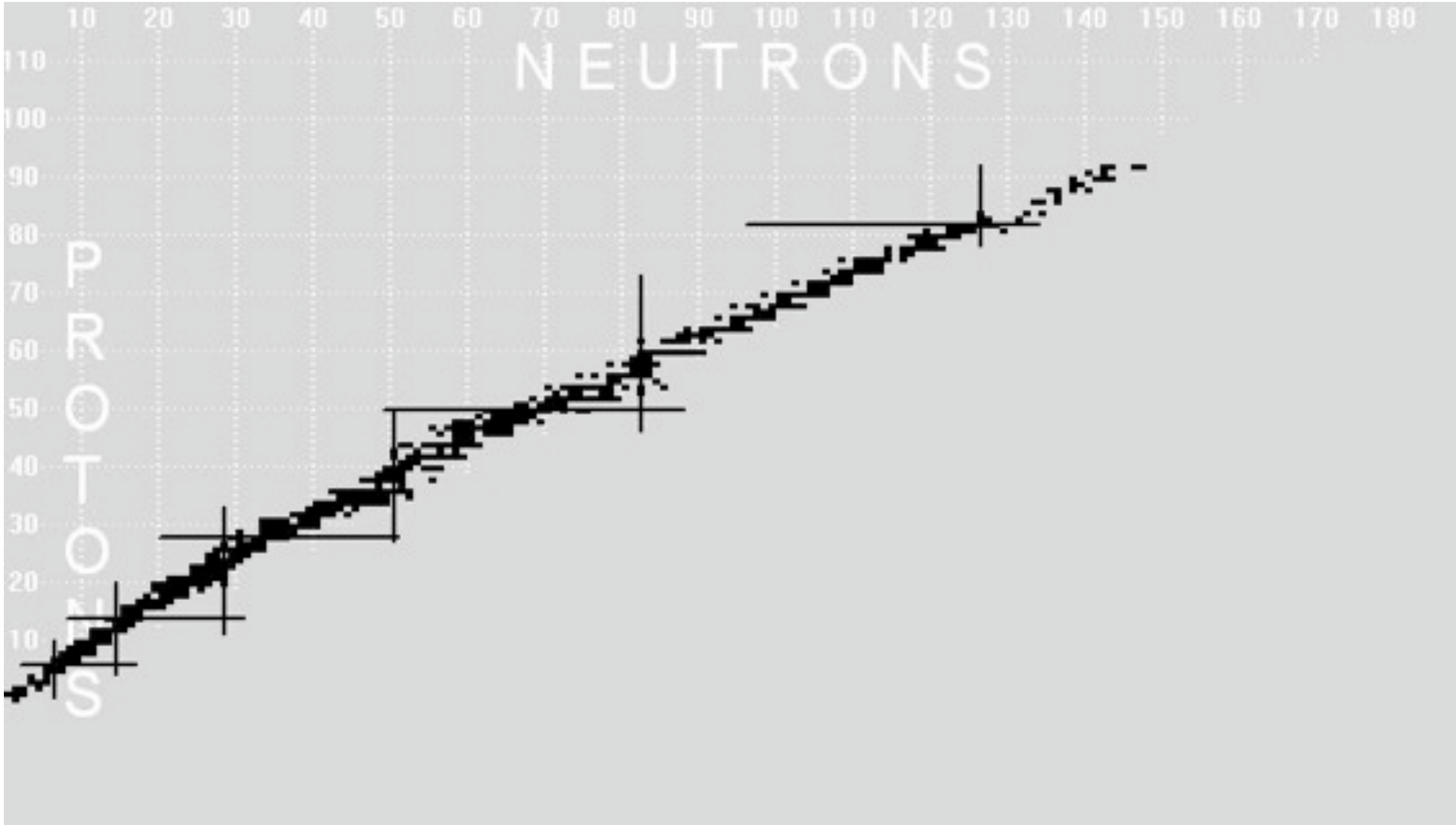
- ➢ **The reach of nuclei**
- • **Drip lines**
- • **Specific configurations and topologies**

- ➢ **Nuclear astrophysics**
- • **Paths of nucleosynthesis**

- ➢ **Fundamental symmetries**
- ➢ **Metrology**
- ➢ **…..**



History of Mass Exploration



Up to 1940!

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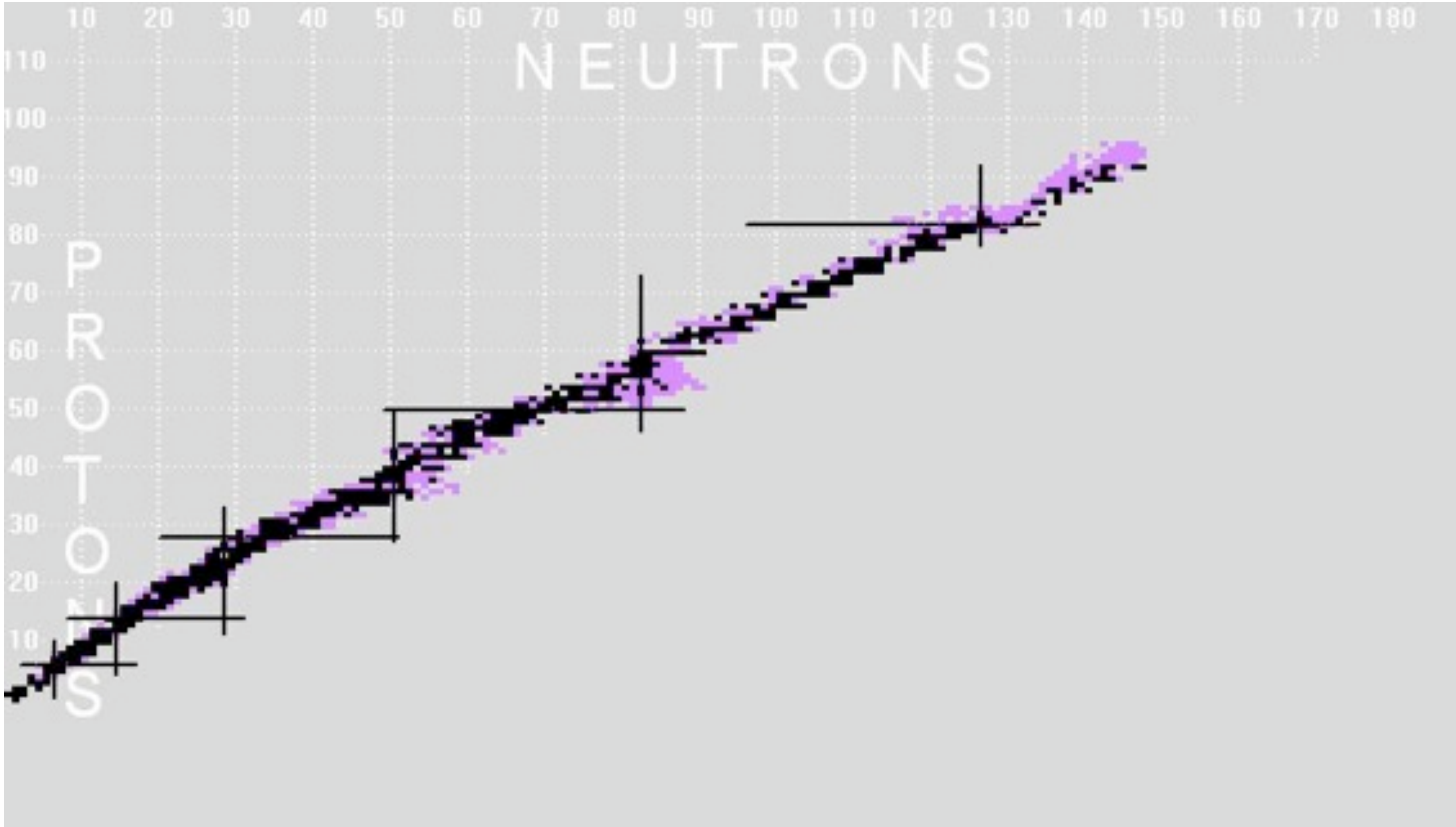
History of Mass Exploration



Up to 1948!

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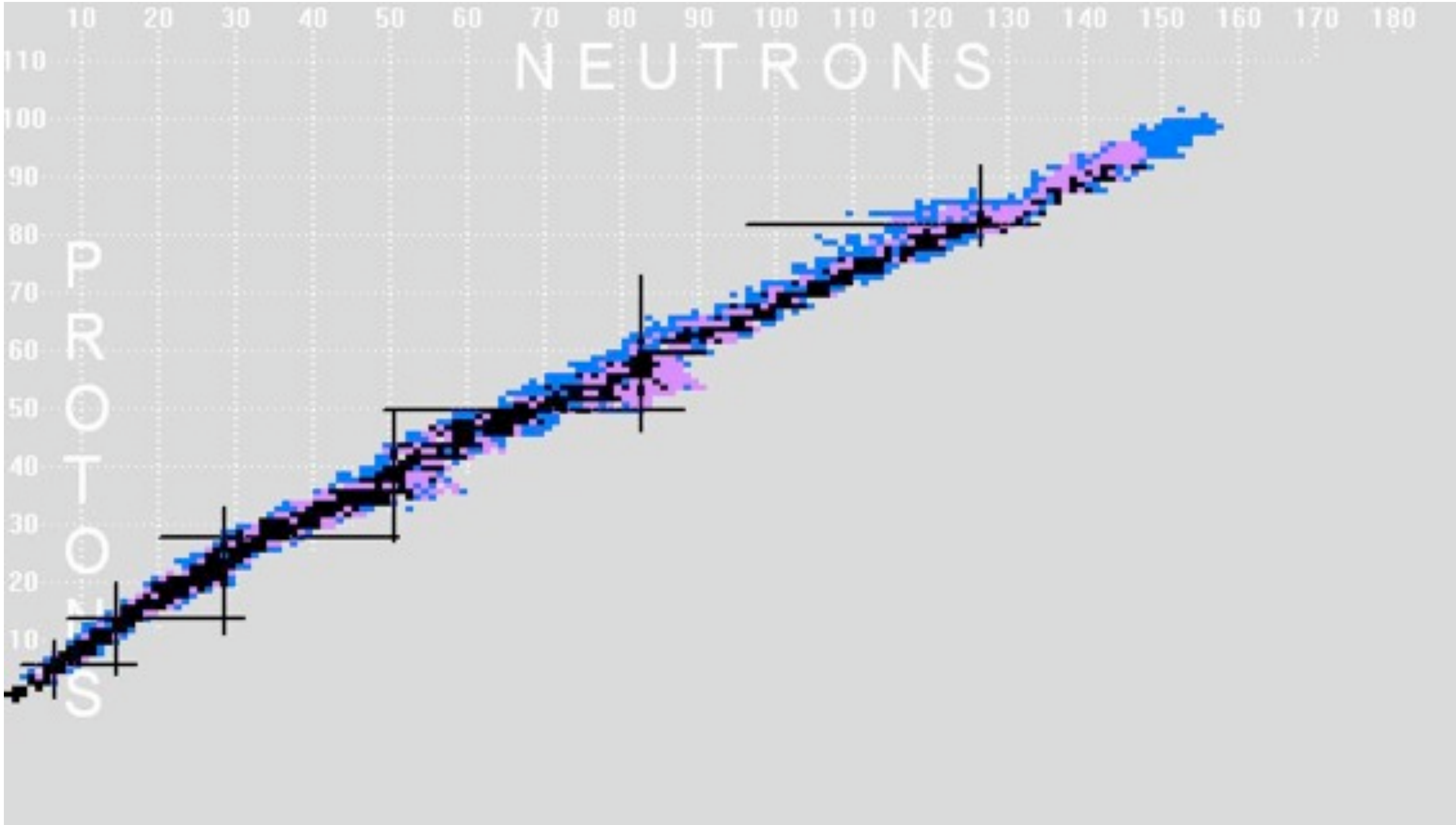
History of Mass Exploration



Up to 1958!

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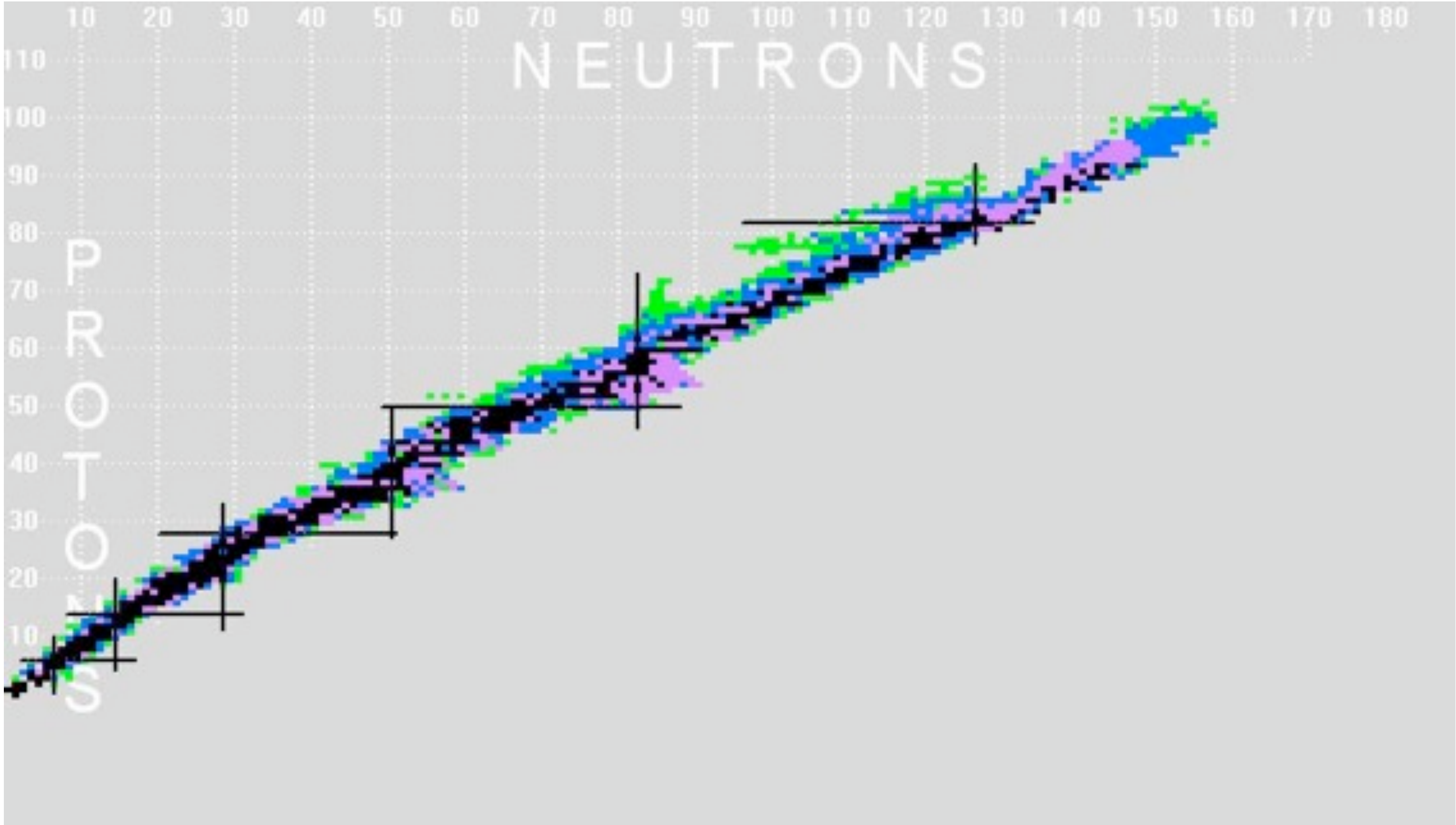
History of Mass Exploration



Up to 1968!

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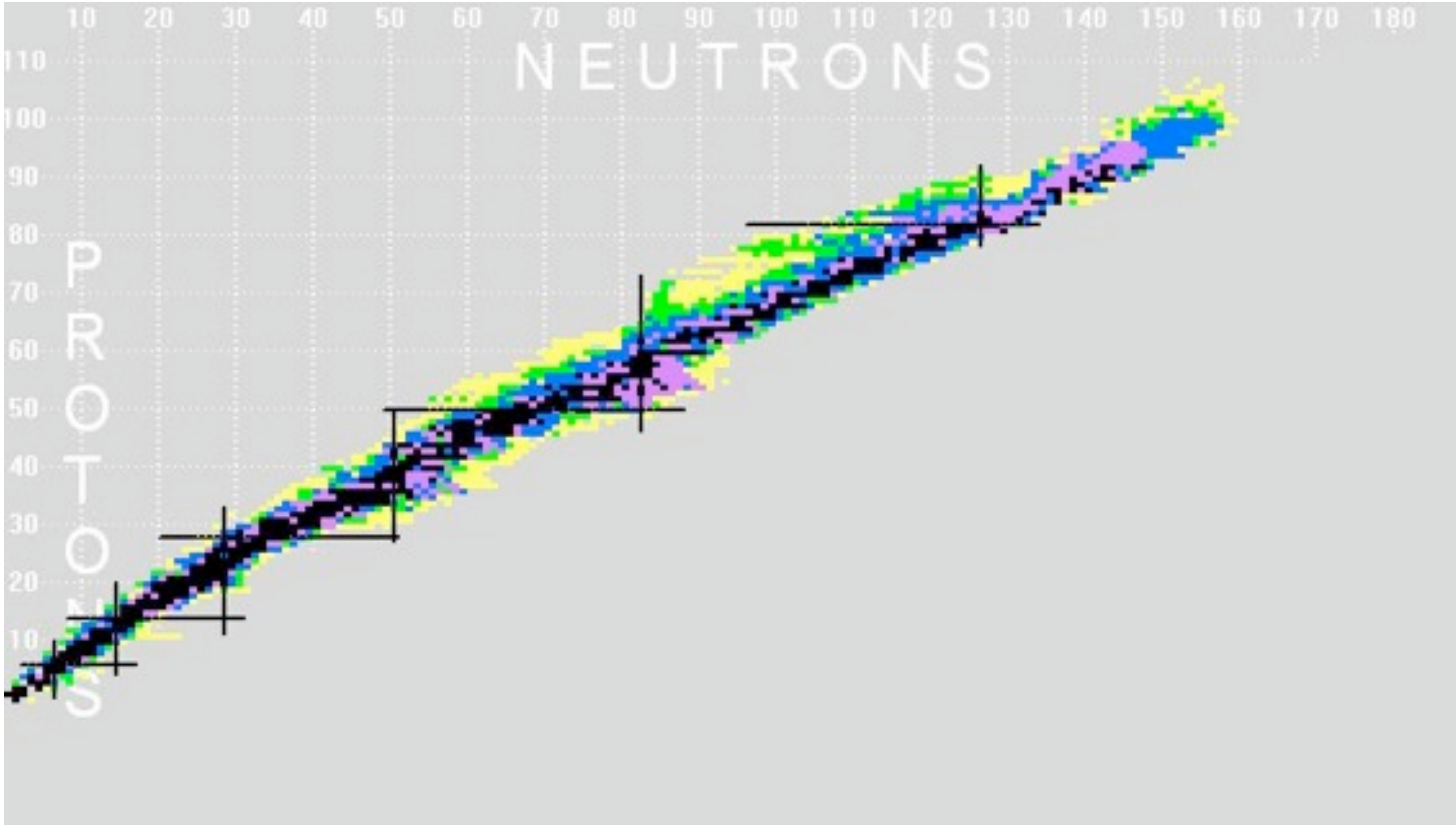
History of Mass Exploration



Up to 1978!

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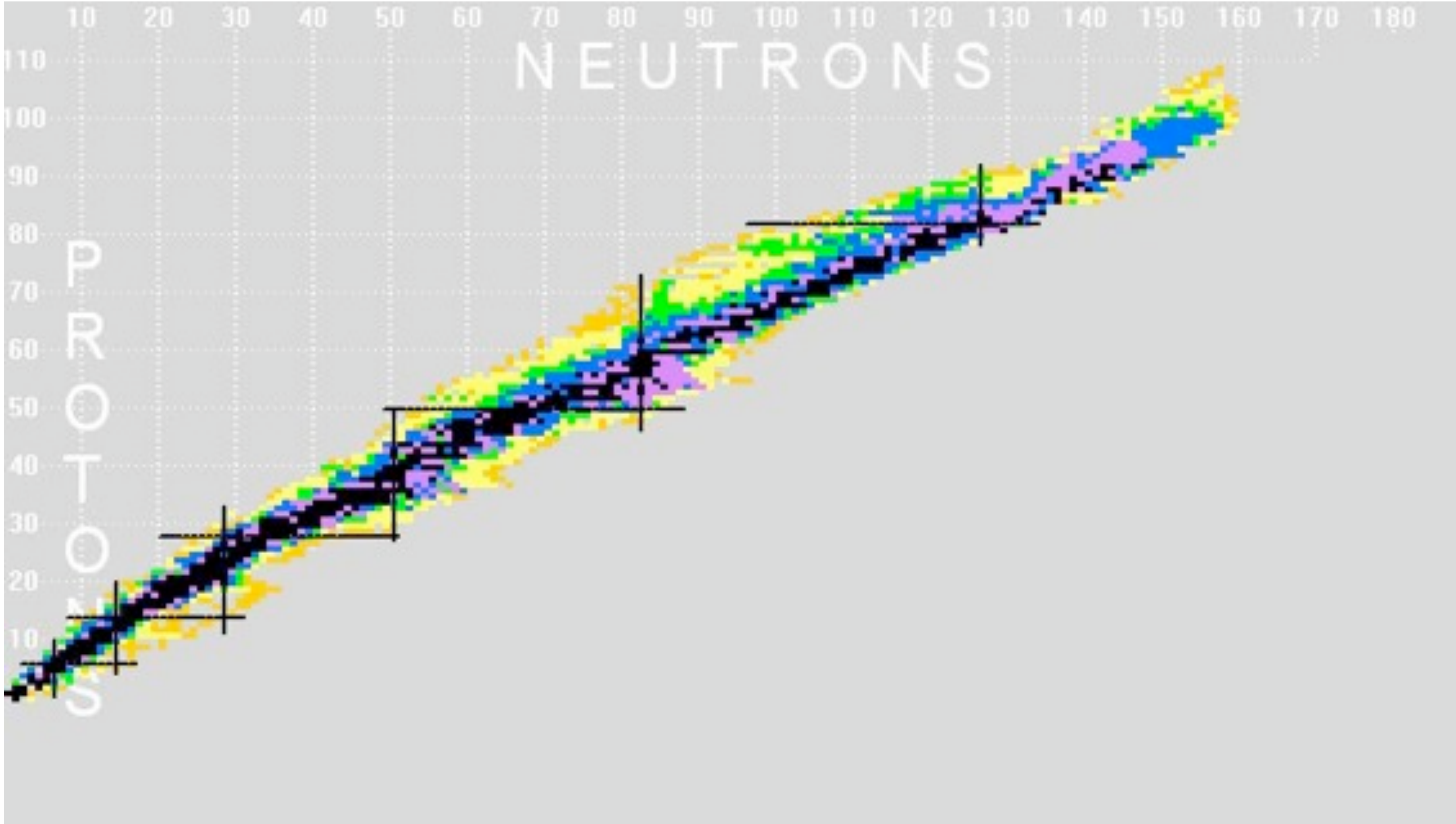
History of Mass Exploration



Up to 1988!

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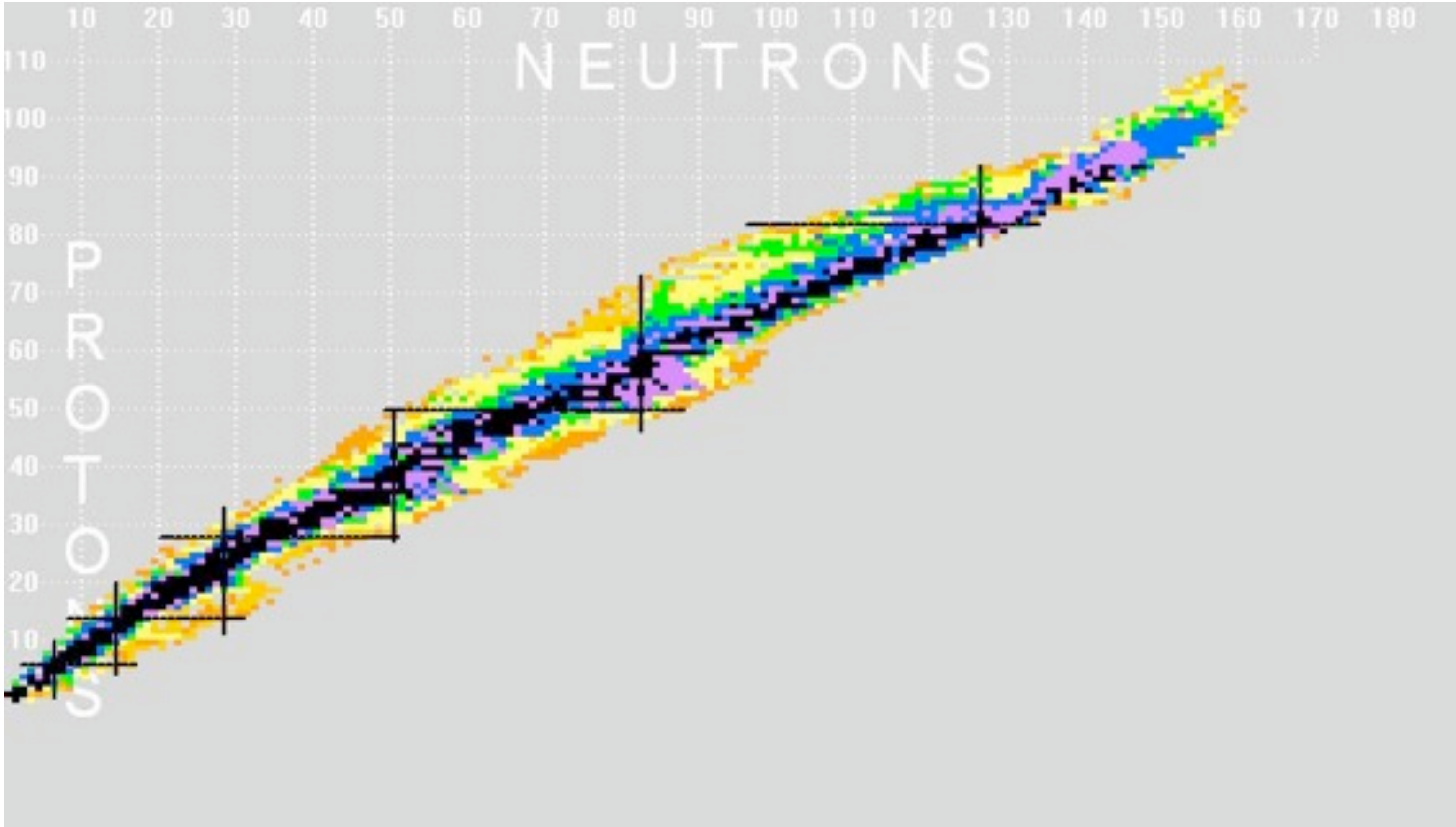
History of Mass Exploration



Up to 1994!

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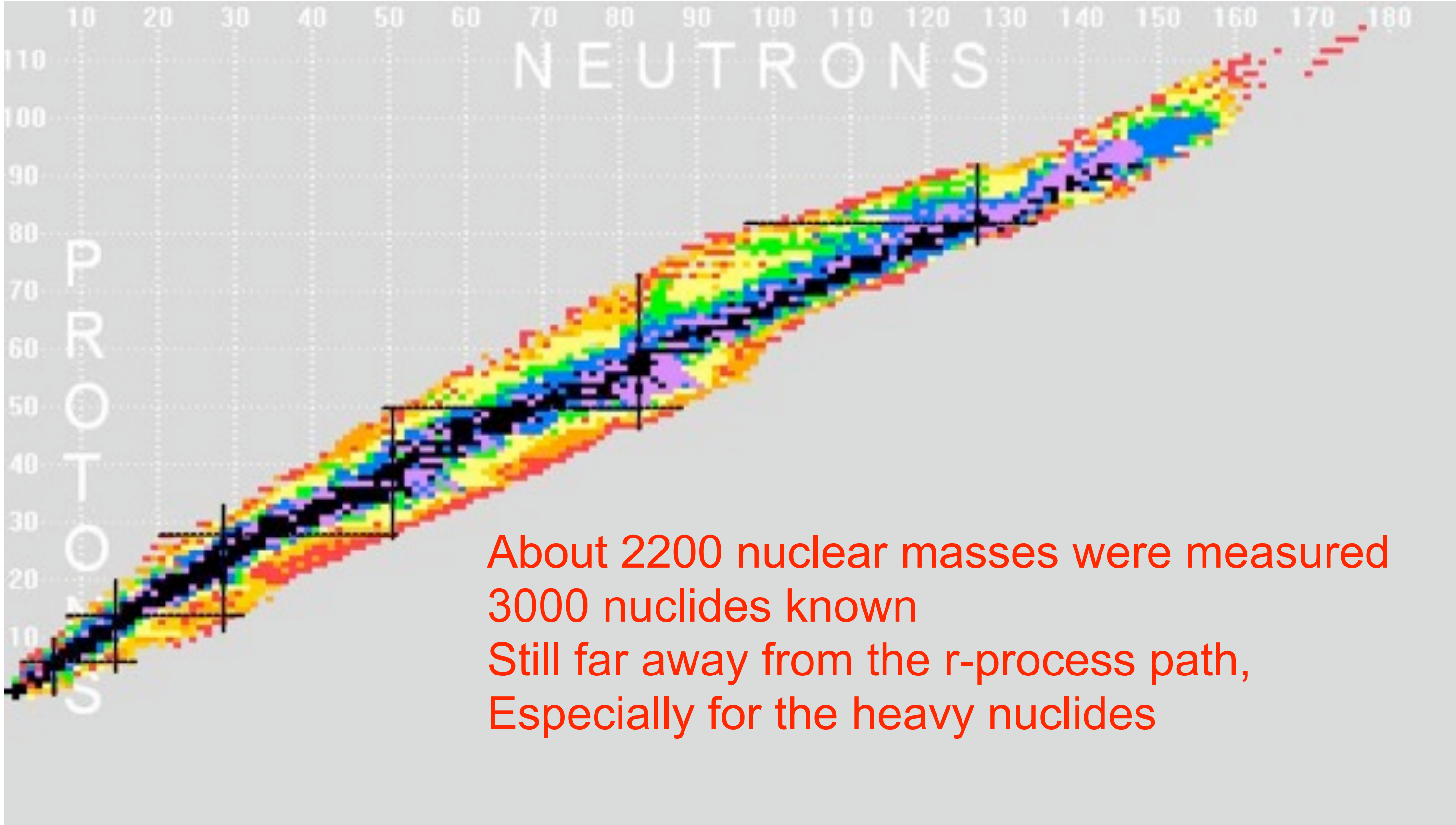
History of Mass Exploration



About 2200 nuclear masses were measured
3000 nuclides known
Still far away from the r-process path,
Especially for the heavy nuclides

Up to 2004!

G. Audi et al., Nucl. Phys. **A565**, 1(1993); A 595, 409 (1995), A729, 337(2003)

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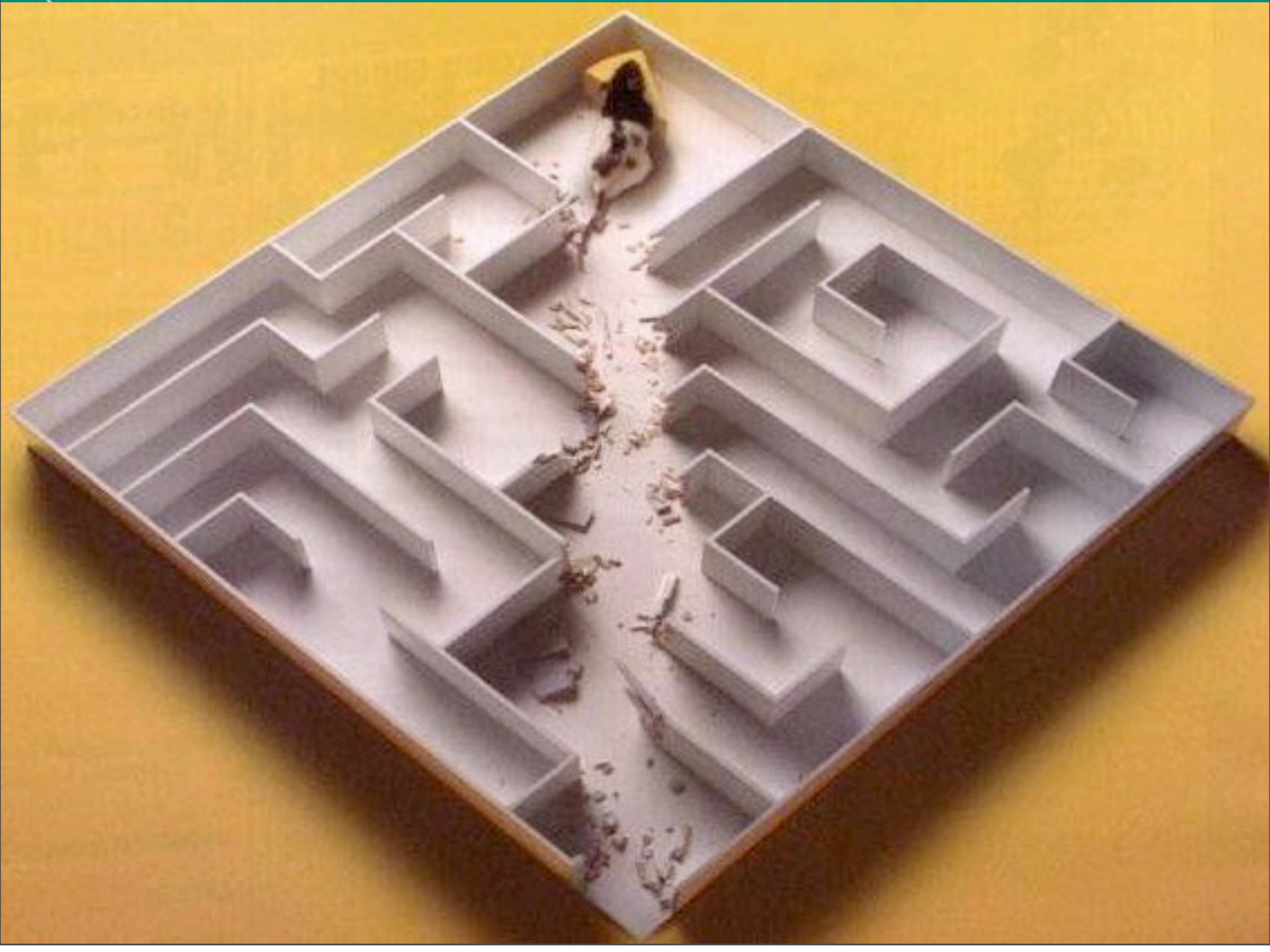
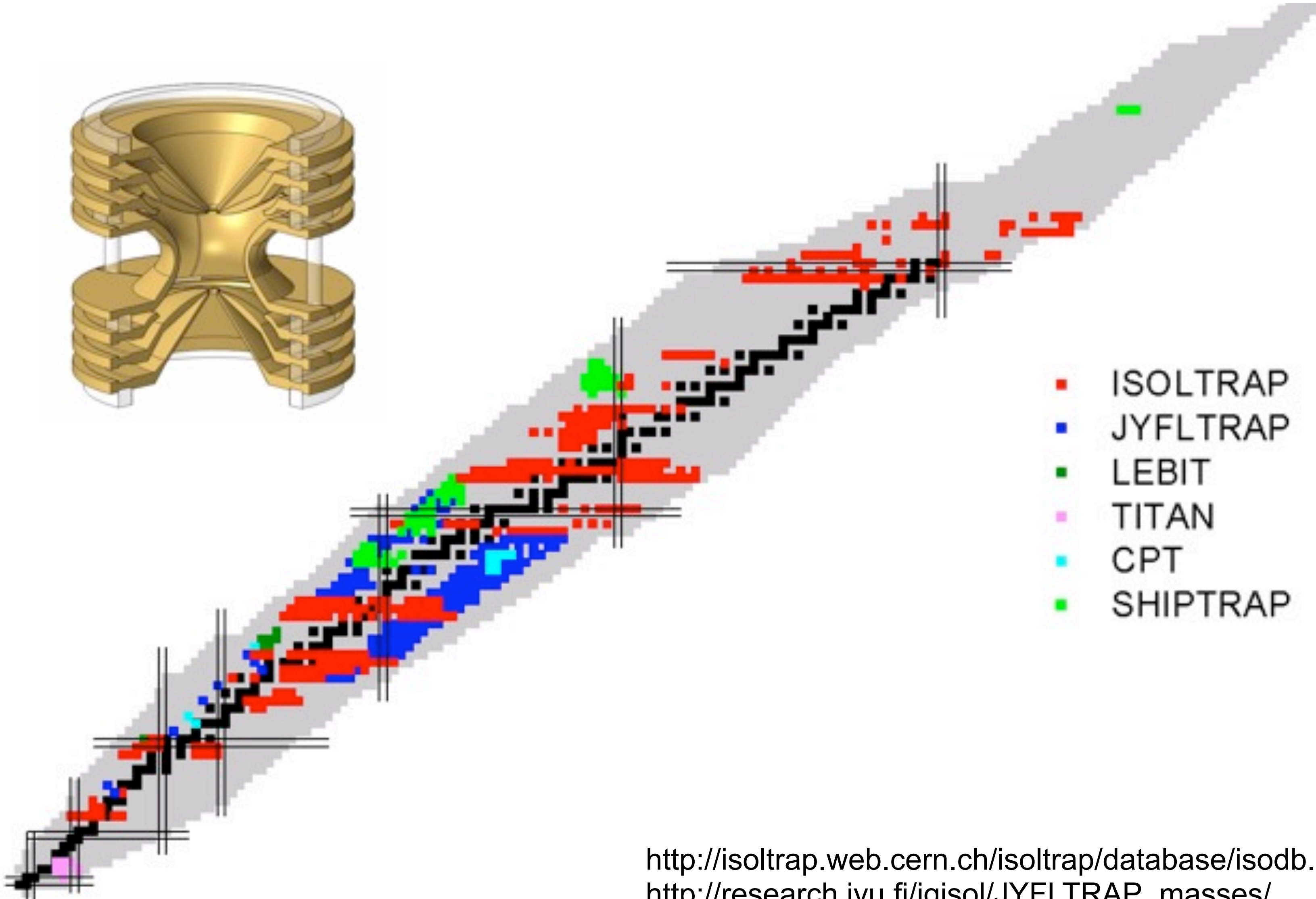


Penning Trap Mass Measurements



http://isoltrap.web.cern.ch/isoltrap/database/isodb.asp
http://research.jyu.fi/igisol/JYFLTRAP_masses/

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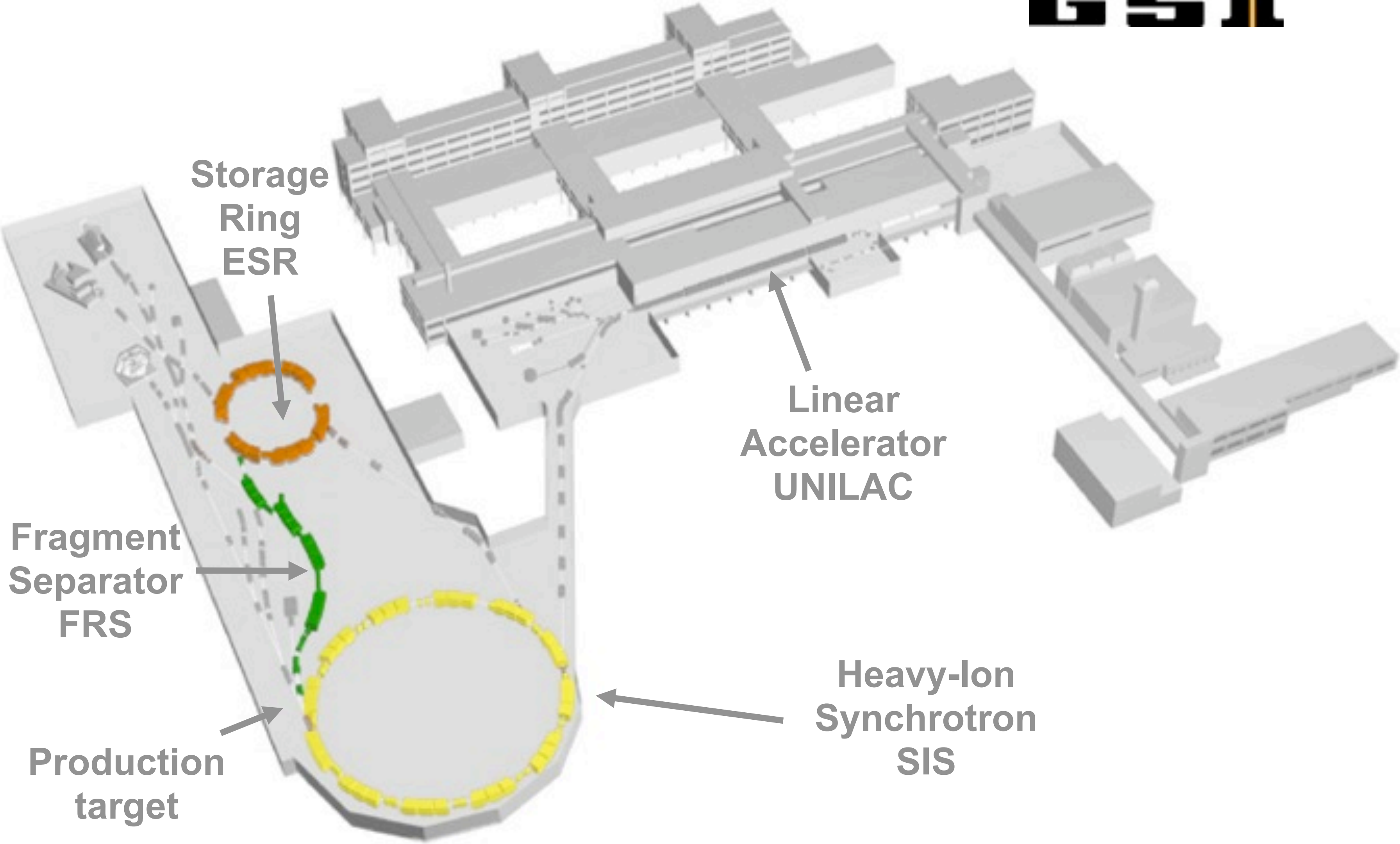
Secondary beam facility at GSI



A glance on the SIS

Circumference = 216 m, E_{max} (U) = 1 GeV/u, q = 78^{+}

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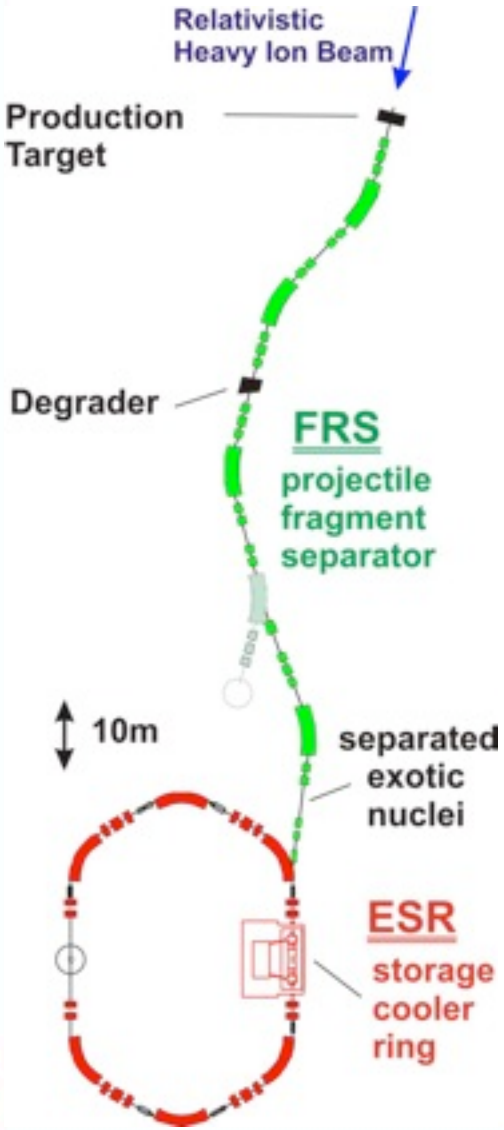
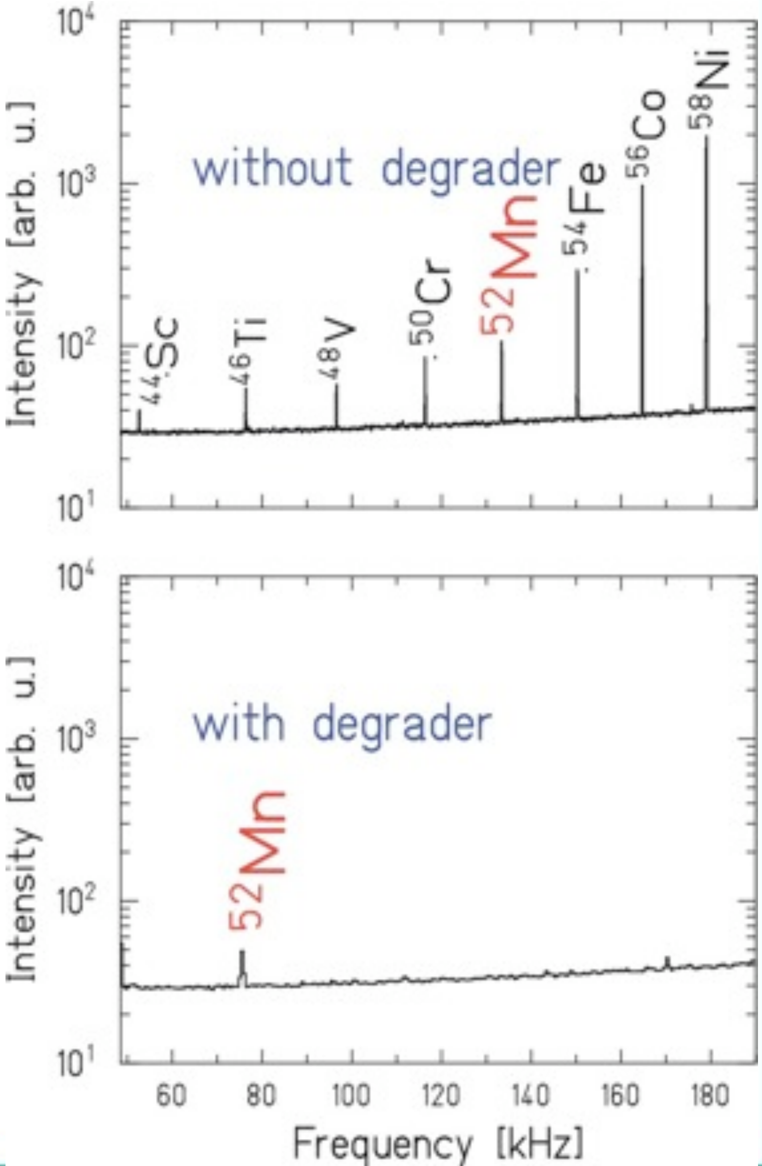
Separation and Storage

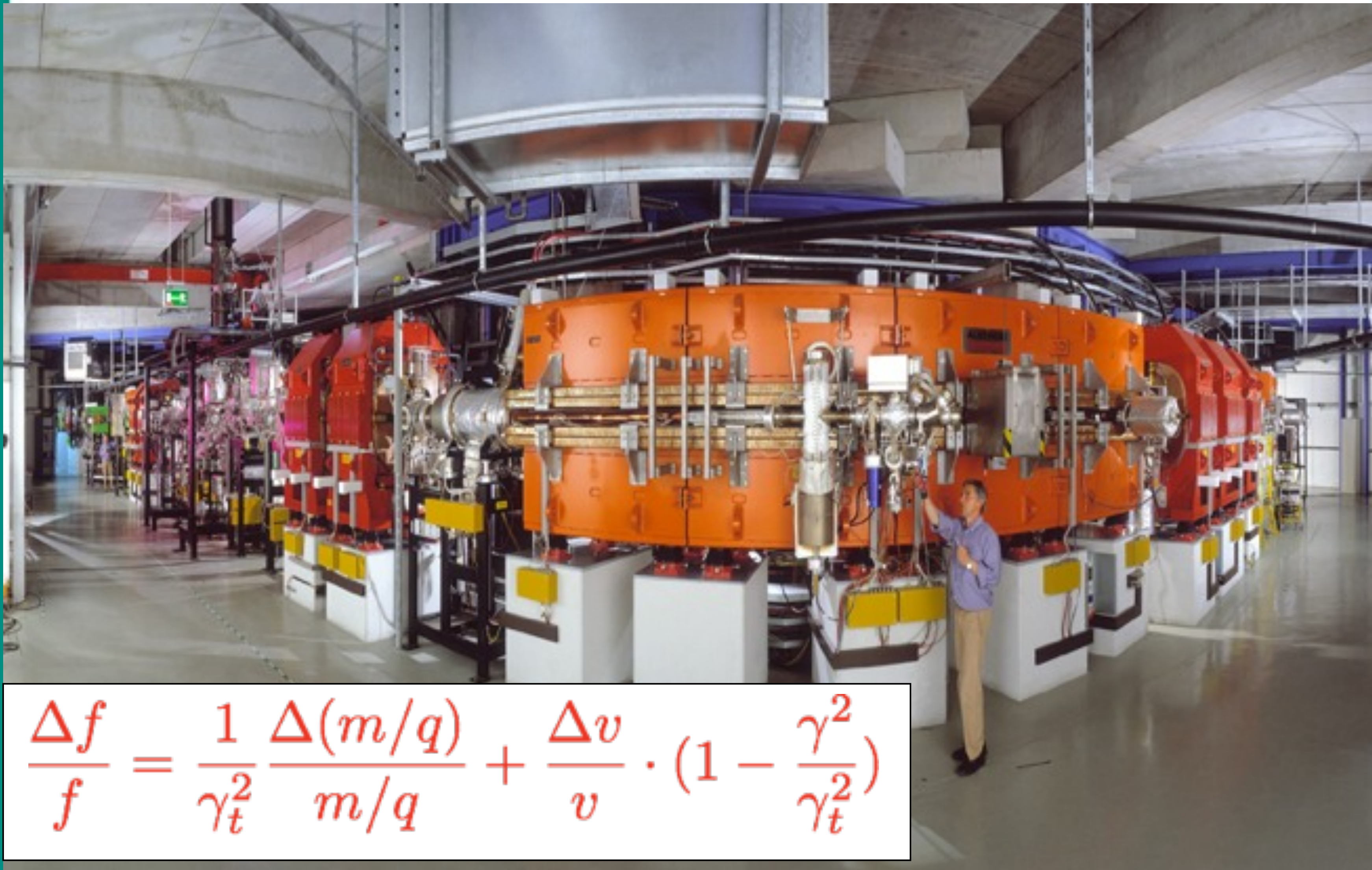


- Highly-charged ions
- In-Flight separation
- Cocktail or mono-isotopic beams

- Circumference: 108 m
- Vacuum :10^{-11} mbar
- Revolution frequency: 2 MHz @ E= 400 MeV/u
- Stochastic and electron cooling



Experimental Storage Ring at GSI



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

ESR: B. Franzke, NIM B 24/25 (1987) 18

Stochastic cooling: F. Nolden et al., NIM B 532 (2004) 329
Electron cooling: M. Steck et al., NIM B 532 (2004) 357

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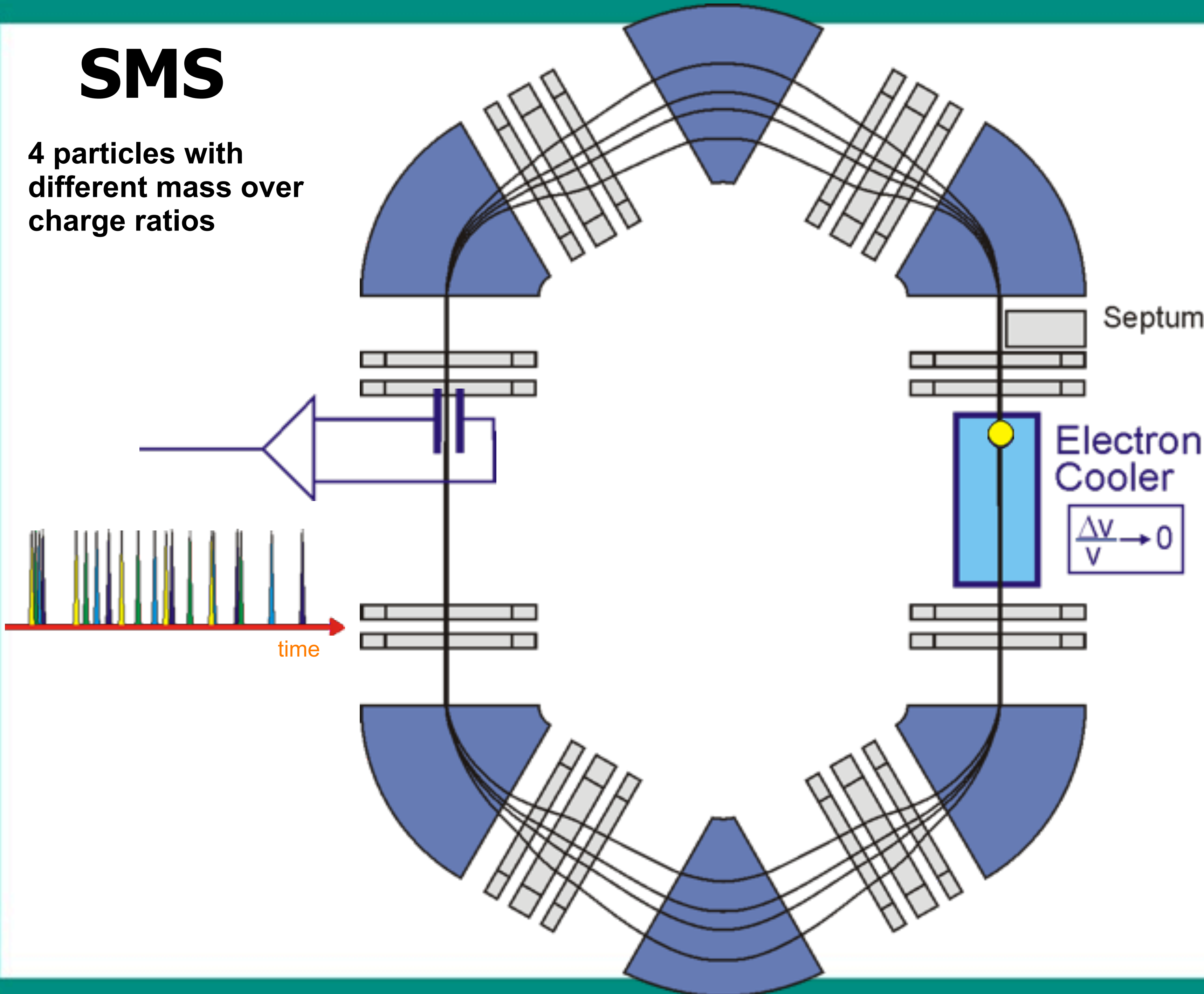
SMS

4 particles with different mass over charge ratios



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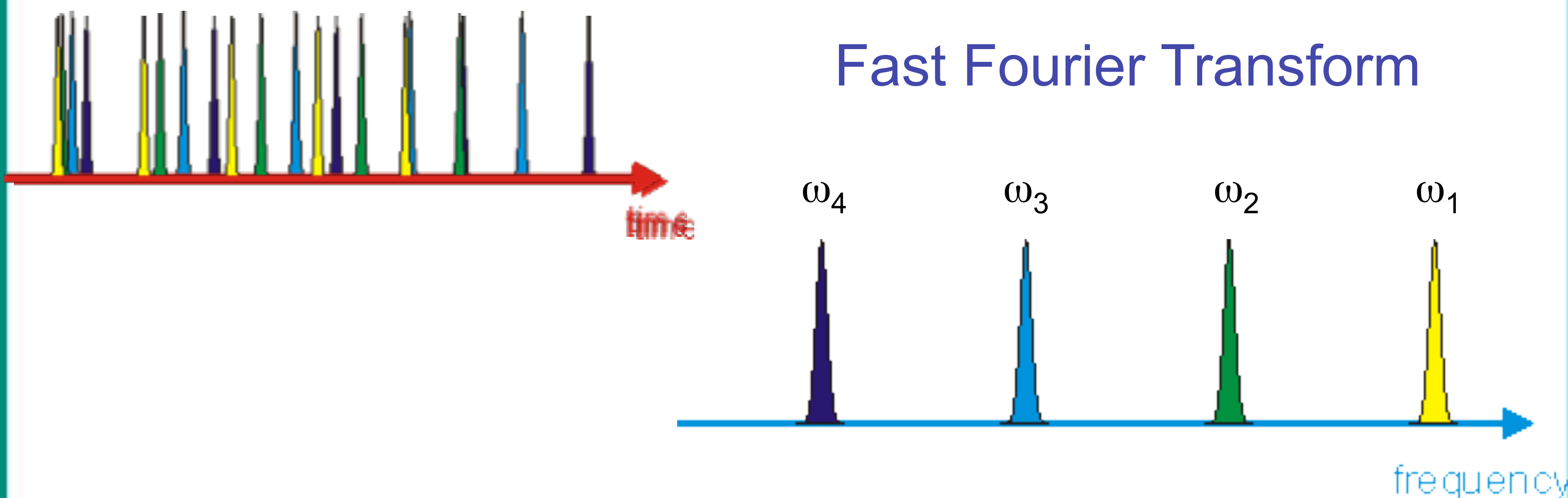
SMS



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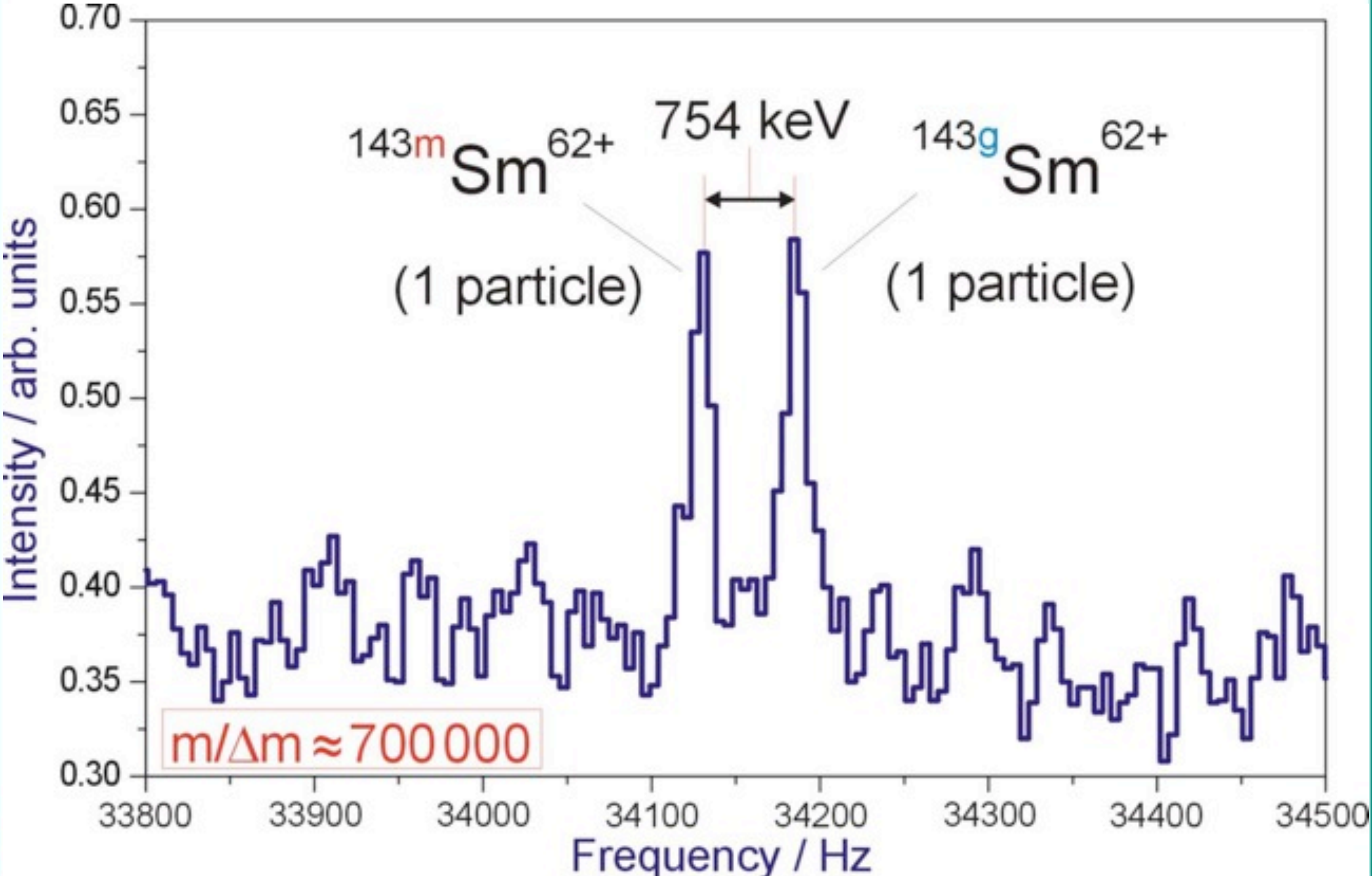
Broad-Band Schottky Frequency Spectra



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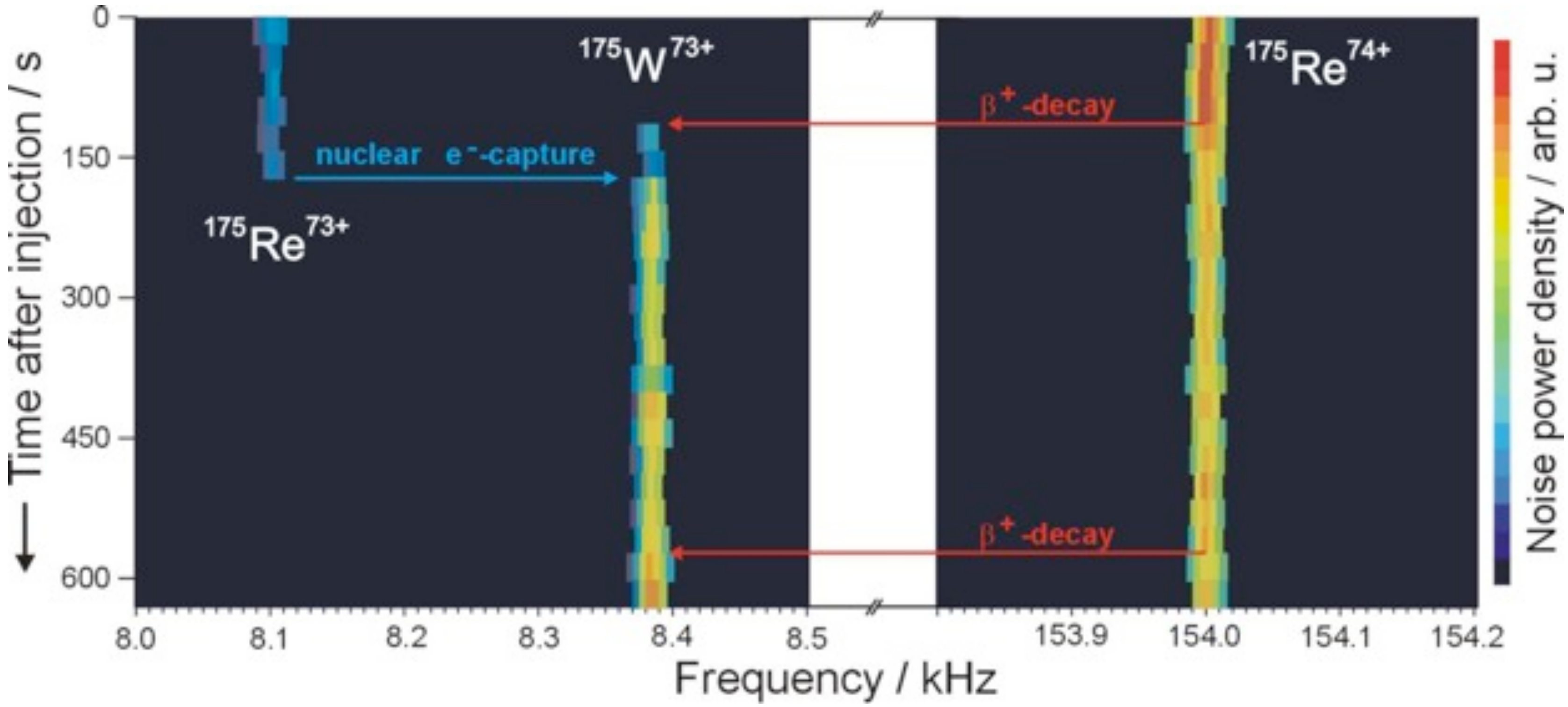
Nuclear Decays of Stored Single Ions

Time-resolved SMS is a perfect tool to study decays in the ESR



EC, β+,β-, bound-state β, and IT decays were observed

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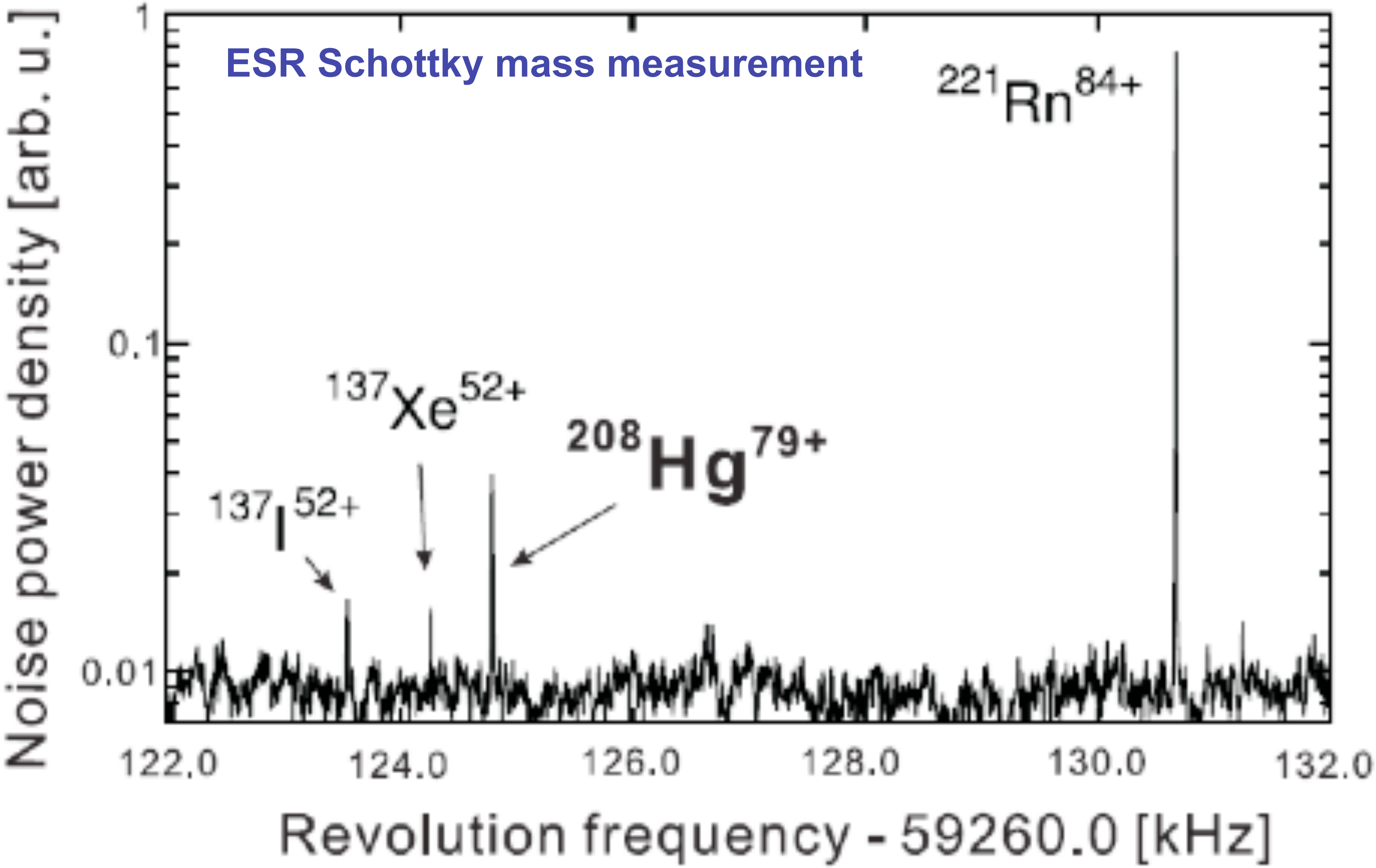
Experimental proton-neutron interaction



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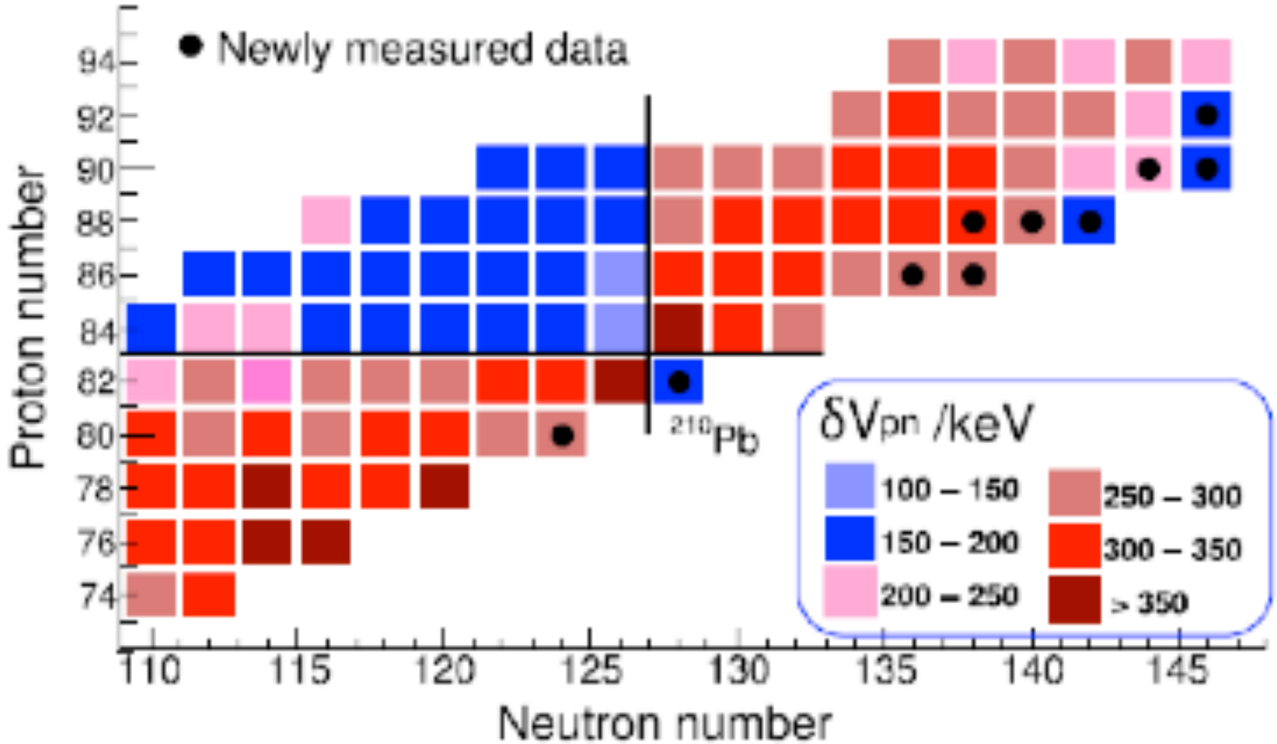
Experimental proton-neutron interaction



For even-even nuclei

$$\delta V_{pn}(Z,N) = \frac{1}{4}[\{B(Z,N)-B(Z,N-2)\}-\{B(Z-2,N)-B(Z-2,N-2)\}]$$

L. Chen *et al.*, Phys. Rev. Lett. 102, 122503 (2009)

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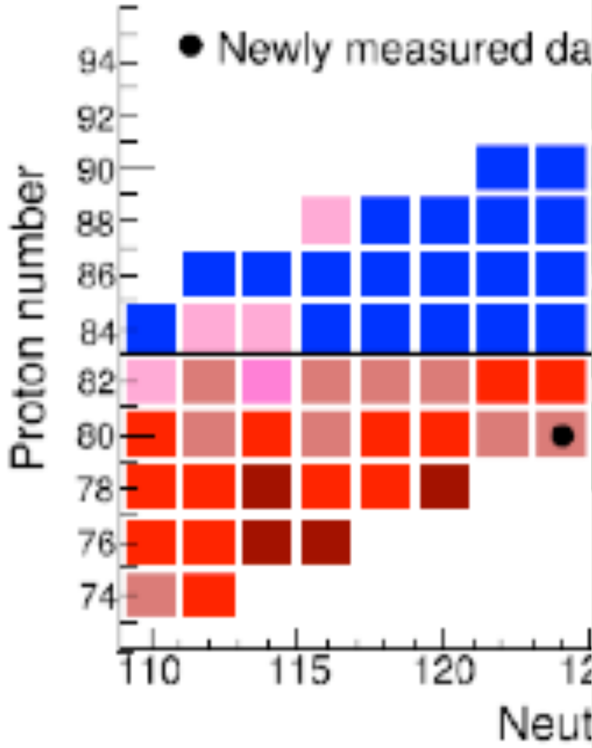
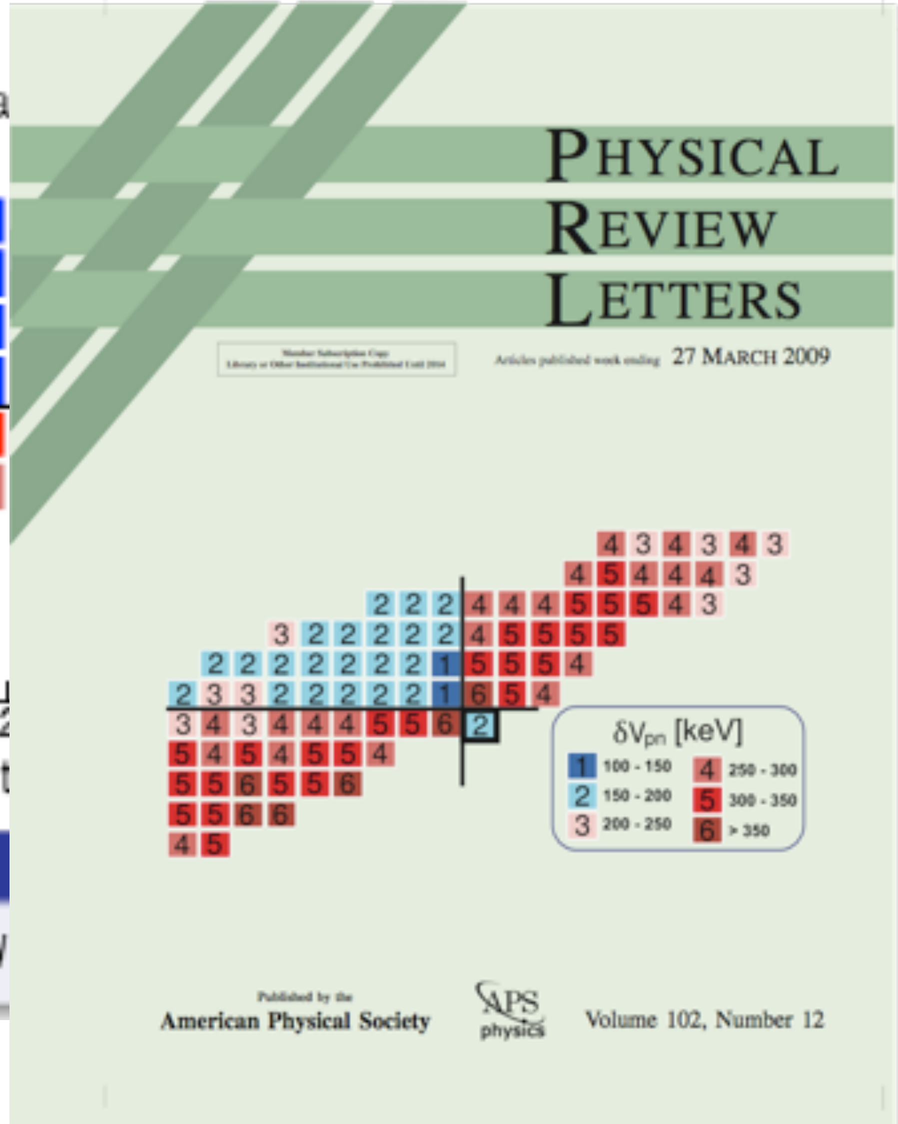
Experimental proton-neutron interaction





For even-even nuclei

$\delta V_{pn}(Z,N) = \frac{1}{4}[\{B(Z,N) - B(Z,N$

L. Chen *et al.*, Phys. Rev.

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Fragmentation of ^{197}Au

187Au 8.4 M ε: 100.00% α: 3.0E-3%	188Au 8.84 M ε: 100.00%	189Au 28.7 M ε: 100.00% α < 3.0E-5%	190Au 42.8 M ε: 100.00% α < 1.0E-6%	191Au 3.18 H ε: 100.00%	192Au 4.94 H ε: 100.00%	193Au 17.65 H ε: 100.00%	194Au 38.02 H ε: 100.00%	195Au 186.098 D ε: 100.00%	196Au 6.1669 D ε: 93.00% β-: 7.00%	197Au STABLE 100%
186Pt 2.08 H ε: 100.00% α≈ 1.4E-4%	187Pt 2.35 H ε: 100.00%	188Pt 10.2 D ε: 100.00% α: 2.6E-5%	189Pt 10.87 H ε: 100.00%	190Pt 6.5E+11 Y 0.014% α: 100.00%	191Pt 2.83 D ε: 100.00%	192Pt STABLE 0.782%	193Pt 50 Y ε: 100.00%	194Pt STABLE 32.967%	195Pt STABLE 33.832%	196Pt STABLE 25.242%
185Ir 14.4 H ε: 100.00%	186Ir 16.64 H ε: 100.00%	187Ir 10.5 H ε: 100.00%	188Ir 41.5 H ε: 100.00%	189Ir 13.2 D ε: 100.00%	190Ir 11.78 D ε: 100.00%	191Ir STABLE 37.3%	192Ir 73.827 D β-: 95.13% ε: 4.87%	193Ir STABLE 62.7%	194Ir 19.28 H β-: 100.00%	195Ir 2.5 H β-: 100.00%
184Os >5.6E+13 Y 0.02% α	185Os 93.6 D ε: 100.00%	186Os 2.0E+15 Y 1.59% α: 100.00%	187Os STABLE 1.6%	188Os STABLE 13.29%	189Os STABLE 16.21%	190Os STABLE 26.36%	191Os 15.4 D β-: 100.00%	192Os STABLE 40.93%	193Os 30.11 H β-: 100.00%	194Os 6.0 Y β-: 100.00%
183Re 70.0 D ε: 100.00%	184Re 38.0 D ε: 100.00%	185Re STABLE 37.40%	186Re 3.7186 D β-: 92.53% ε: 7.47%	187Re 4.12E+10 Y 62.60% β-: 100.00% α < 1.0E-4%	188Re 17.003 H β-: 100.00%	189Re 24.3 H β-: 100.00%	190Re 3.1 M β-: 100.00%	191Re 9.8 M β-: 100.00%	192Re 16 S β-: 100.00%	193Re
182W >8.3E+18 Y 26.50% α	183W >1.3E+19 Y 14.31% α	184W >2.9E+19 Y 30.64% α	185W 75.1 D β-: 100.00%	186W >2.7E+19 Y 28.43% α	187W 23.72 H β-: 100.00%	188W 69.78 D β-: 100.00%	189W 10.7 M β-: 100.00%	190W 30.0 M β-: 100.00%	191W >300 NS β-	192W >300 NS β-
181Ta STABLE 99.988%	182Ta 114.43 D β-: 100.00%	183Ta 5.1 D β-: 100.00%	184Ta 8.7 H β-: 100.00%	185Ta 49.4 M β-: 100.00%	186Ta 10.5 M β-: 100.00%	187Ta ≈2 M β-	188Ta ≈20 S β-	189Ta 3 S β-	190Ta 0.3 S β-	
180Hf STABLE 35.08%	181Hf 42.39 D β-: 100.00%	182Hf 8.90E+6 Y β-: 100.00%	183Hf 1.067 H β-: 100.00%	184Hf 4.12 H β-: 100.00%	185Hf 3.5 M β-: 100.00%	186Hf 2.6 M β-: 100.00%	187Hf 30 S β-	188Hf 20 S β-		

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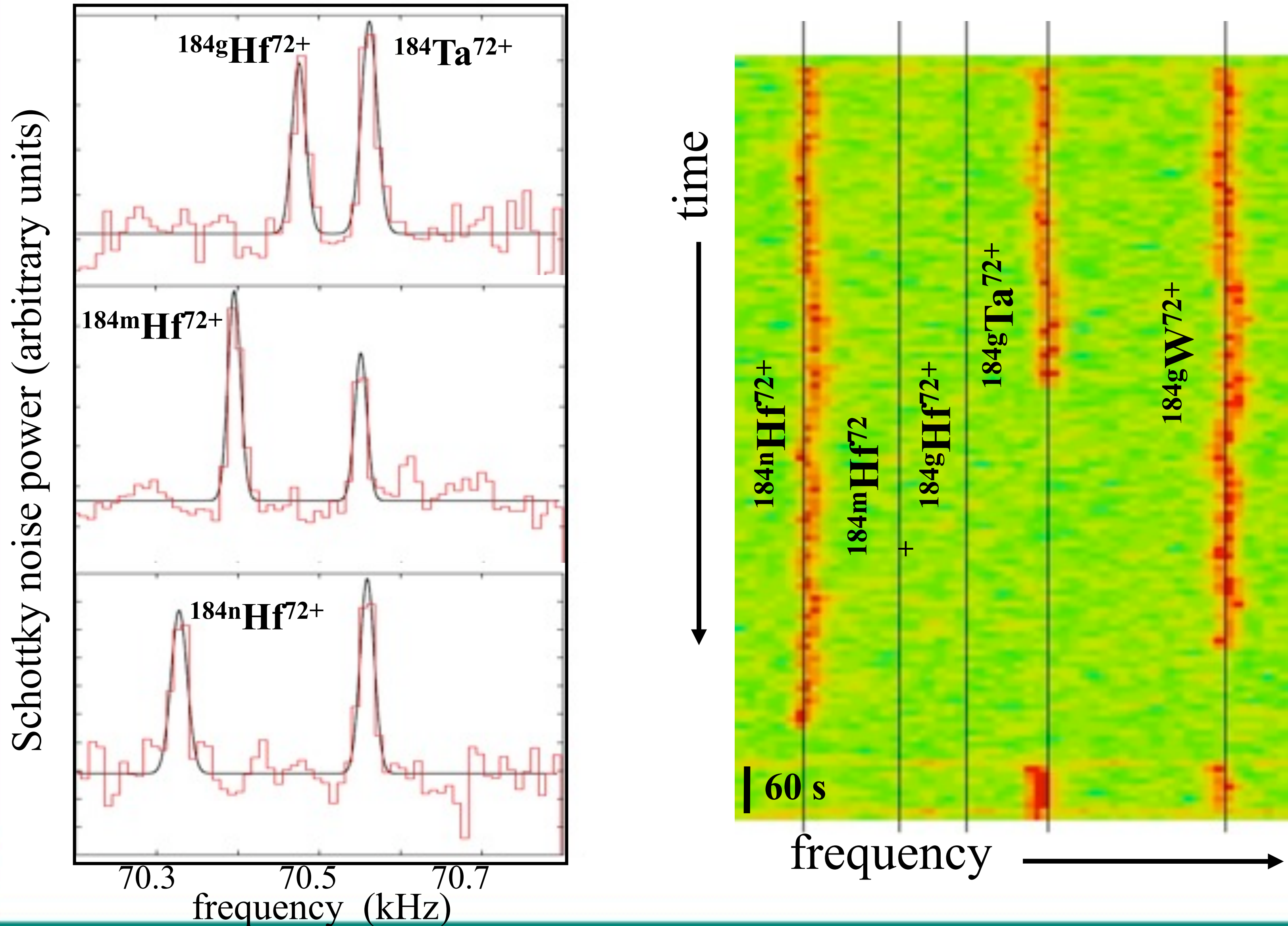
Discovery of ^{184n}Hf Isomer



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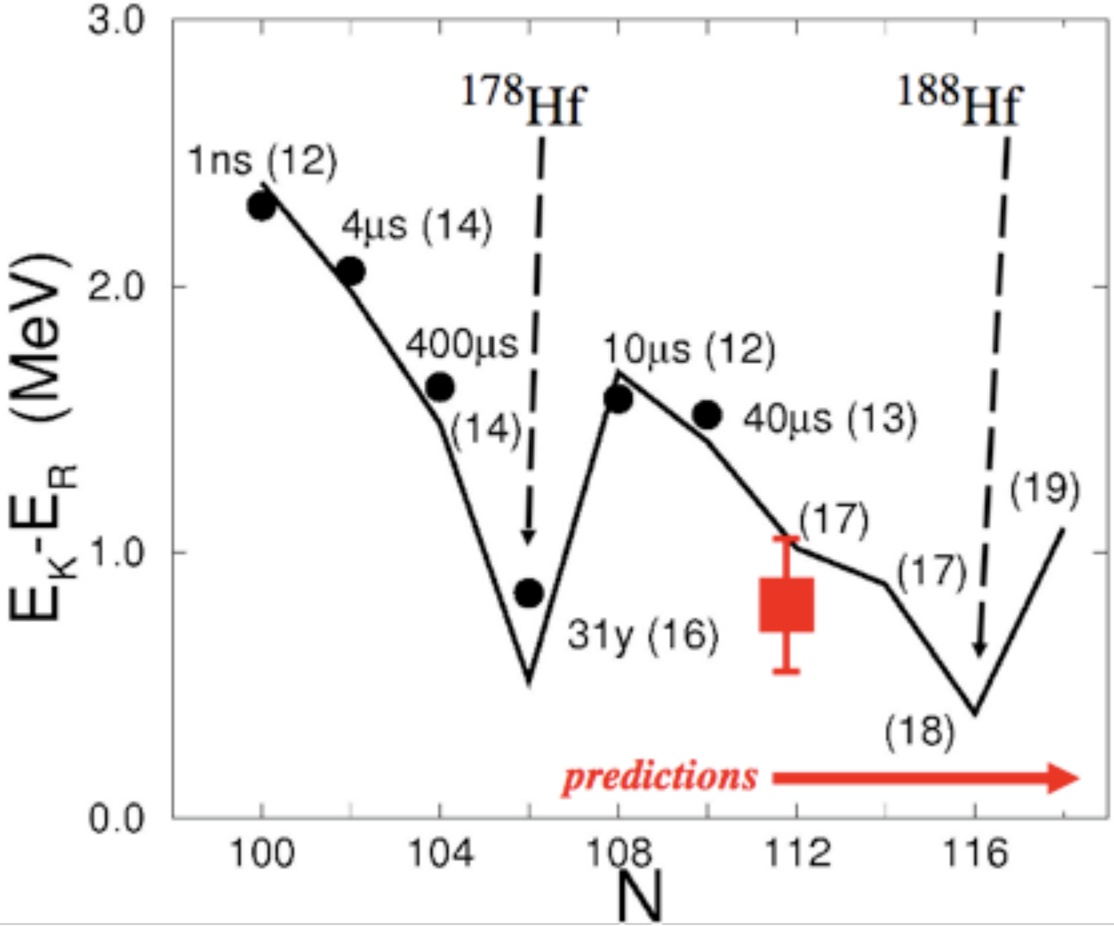
Discovery of ^{184n}Hf Isomer



calculation

experiment

New ESR data ^{184}Hf

Isochronous Mass Spectrometry

1985 - H. Wollnik, Y. Fujita, H. Geissel, G. Münzenberg, et al.

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

$$\gamma_t \rightarrow \gamma$$

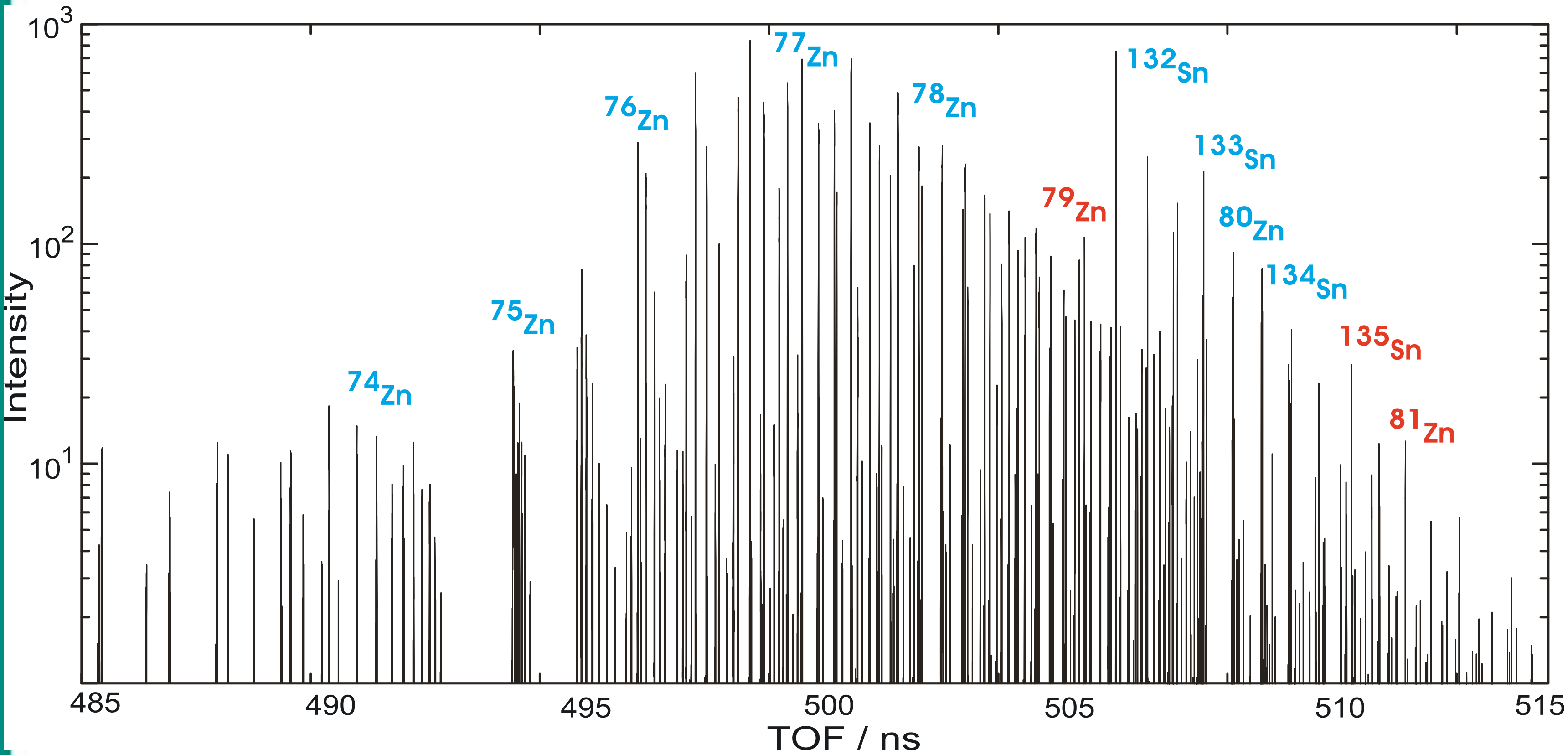
ims_basic2.swf

IMS: Time-of-Flight Spectra

Nuclei with half-lives as short as 20 μs

About 13% in mass-over-charge range

m/q range: 2.4-2.7



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

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IMS: Time-of-Flight Spectra

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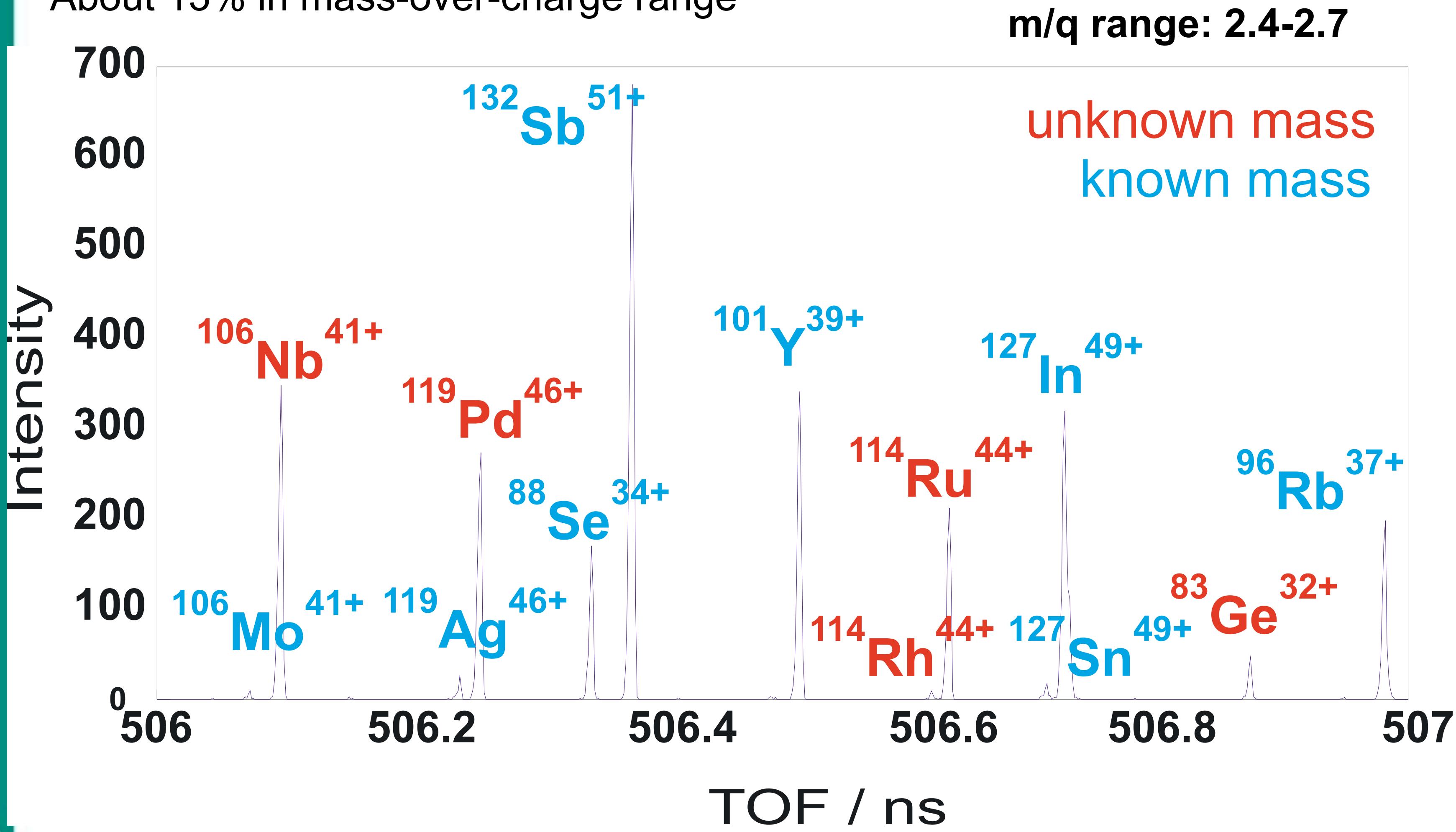

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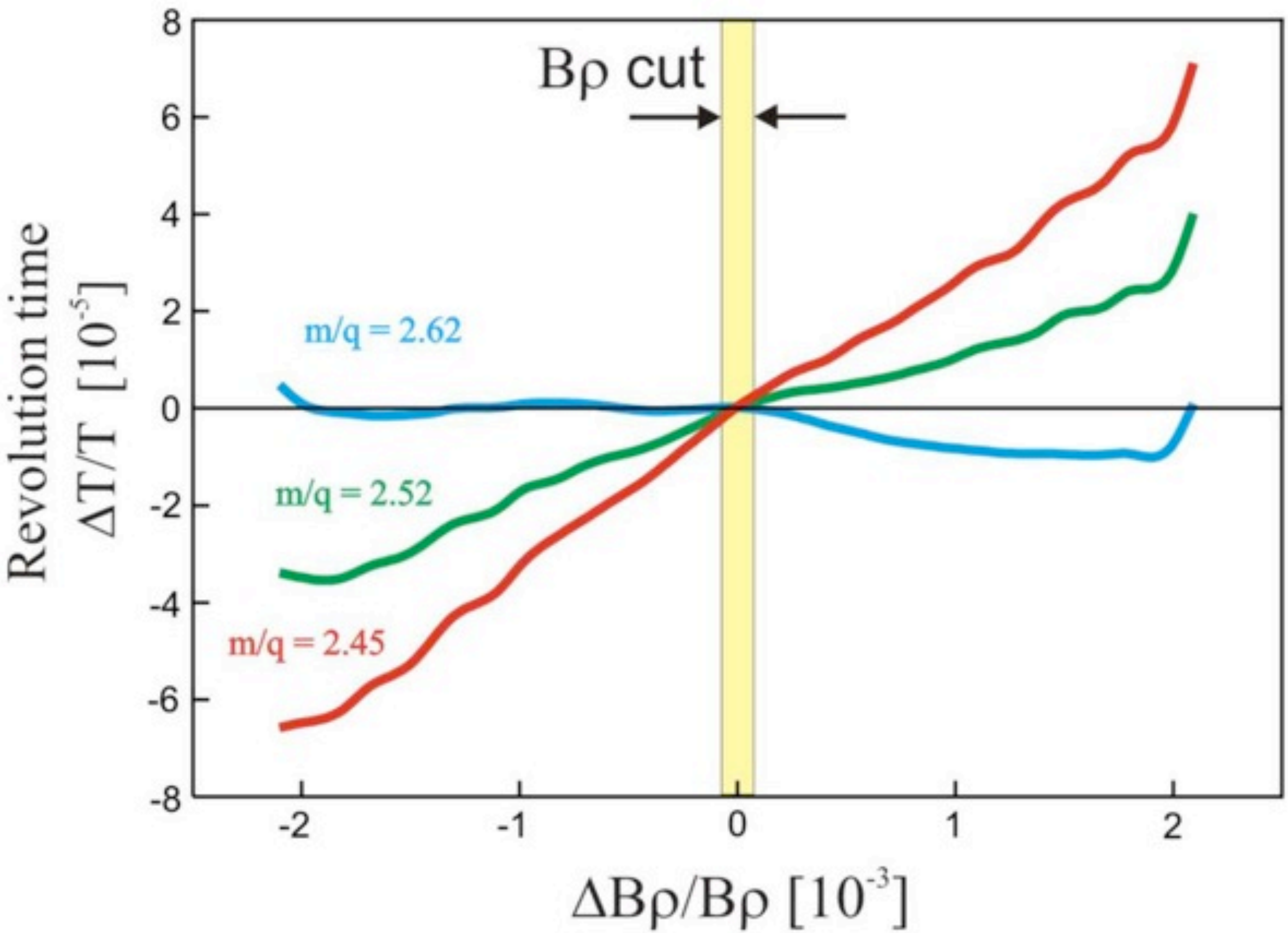
Isochronicity conditions



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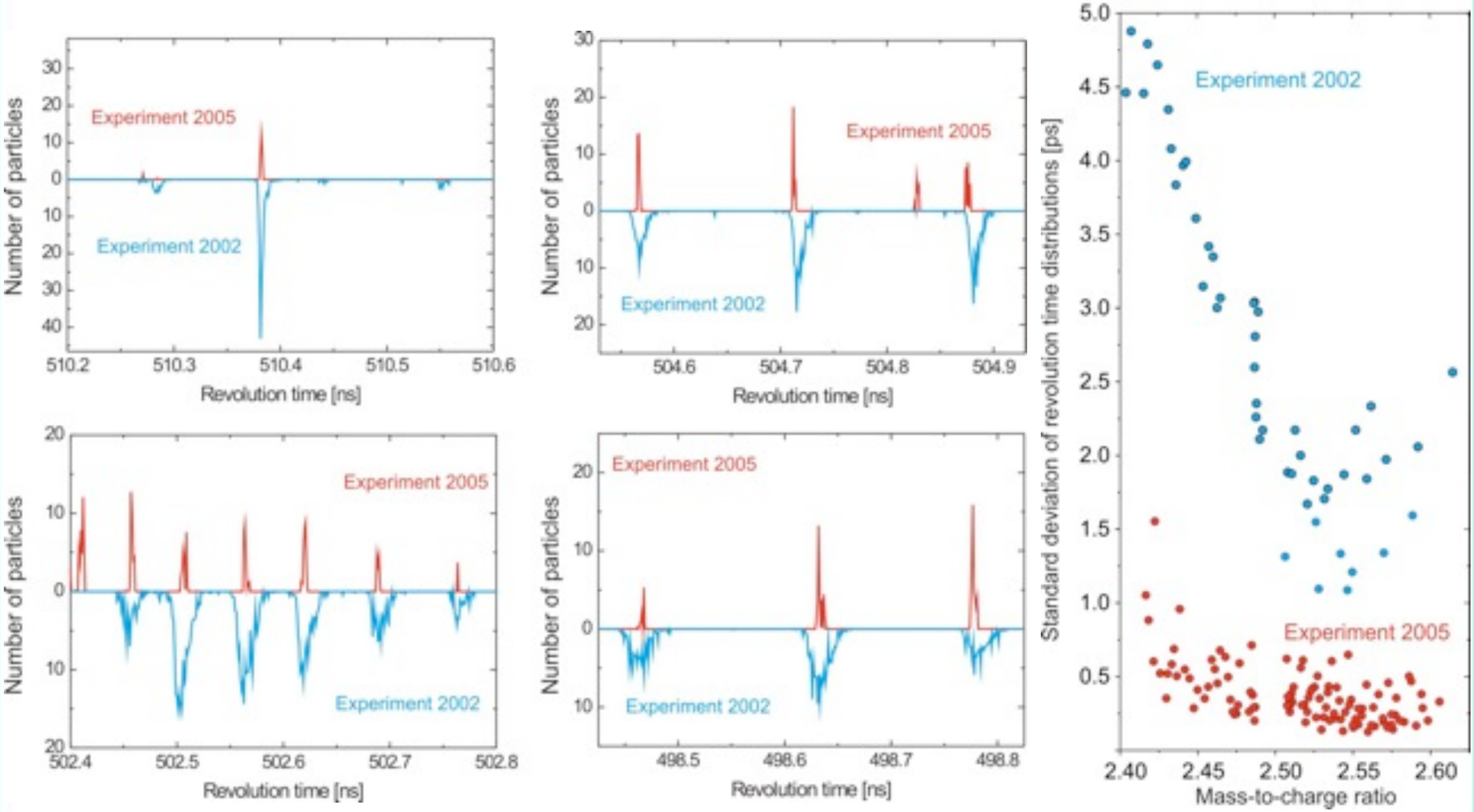
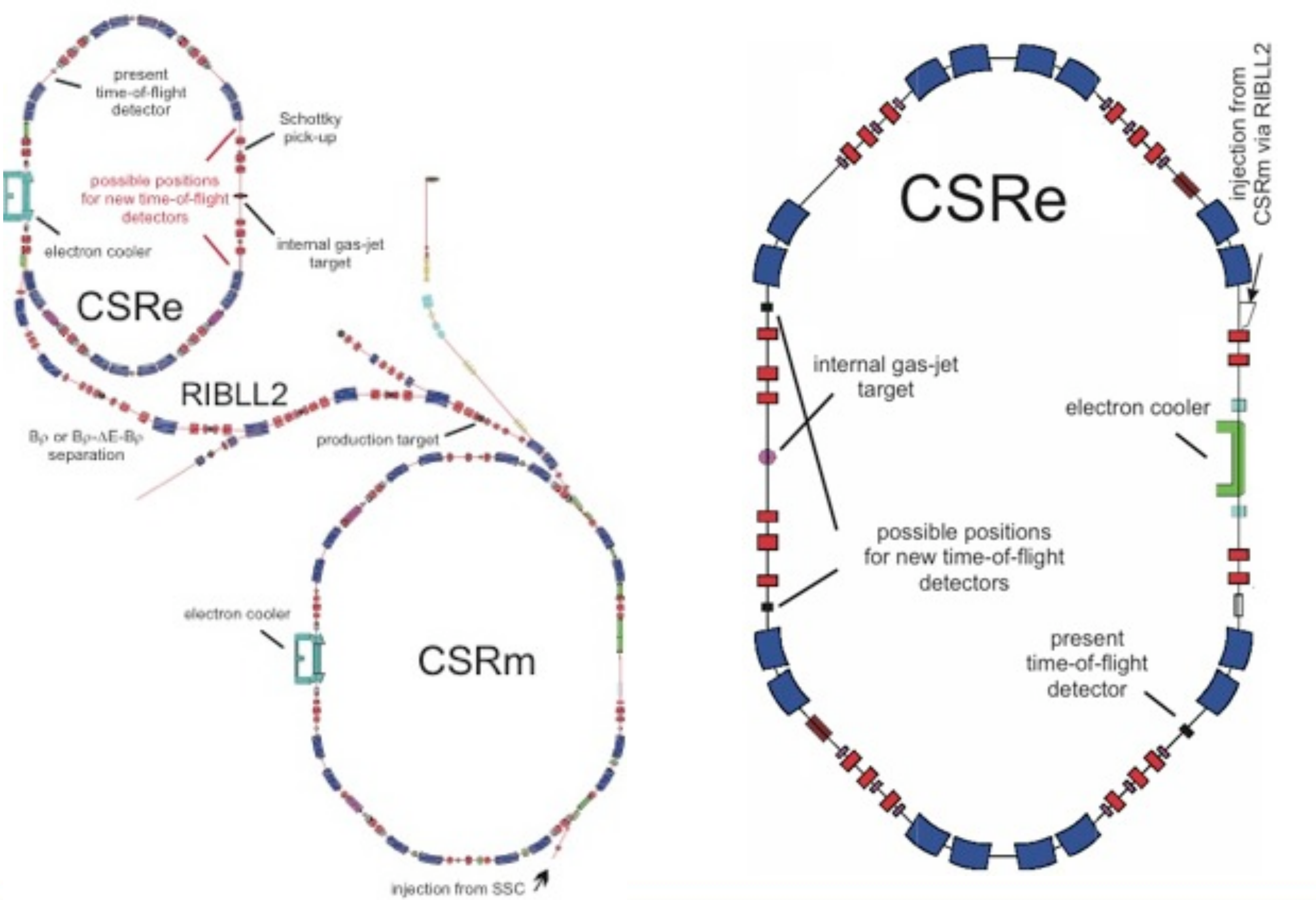
IMS: Bρ Tagging



Good isochronous conditions are fulfilled only in a small range

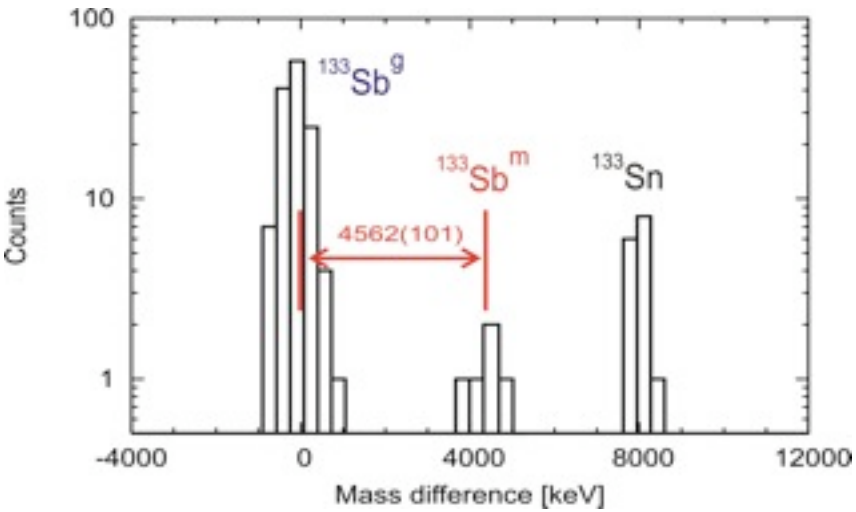
Solution: measurement of *B*ρ or *v* in addition

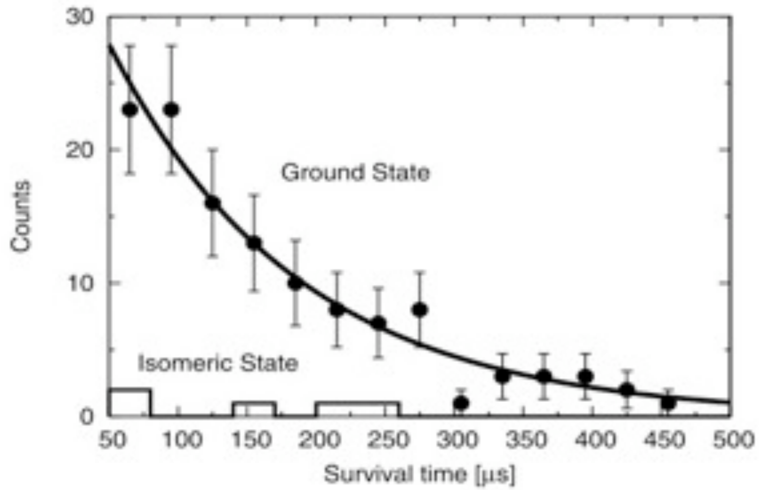
CSRm-CSRe Complex at IMP Lanzhou



Observation of ^{133m}Sb isomeric state

17 μs isomeric state in neutral ^{133}Sb





R_{IMS}=200 000

Expected half-live of bare isomer: ~ 17 ms, α_t~991

A new half-live domain for storage-ring experiments

B. Sun et al., PLB 688 (2010) 294

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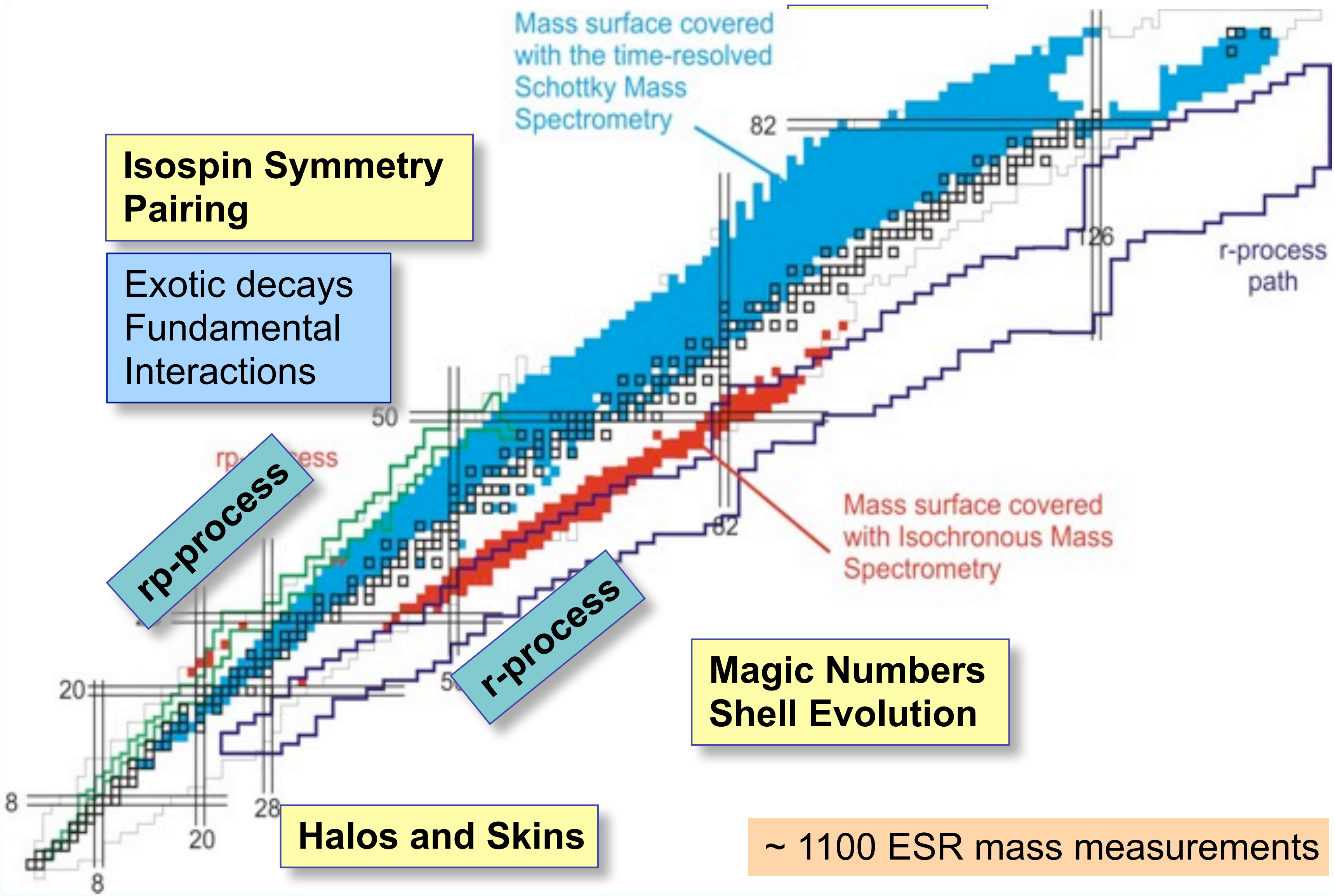
Nuclear structure studies



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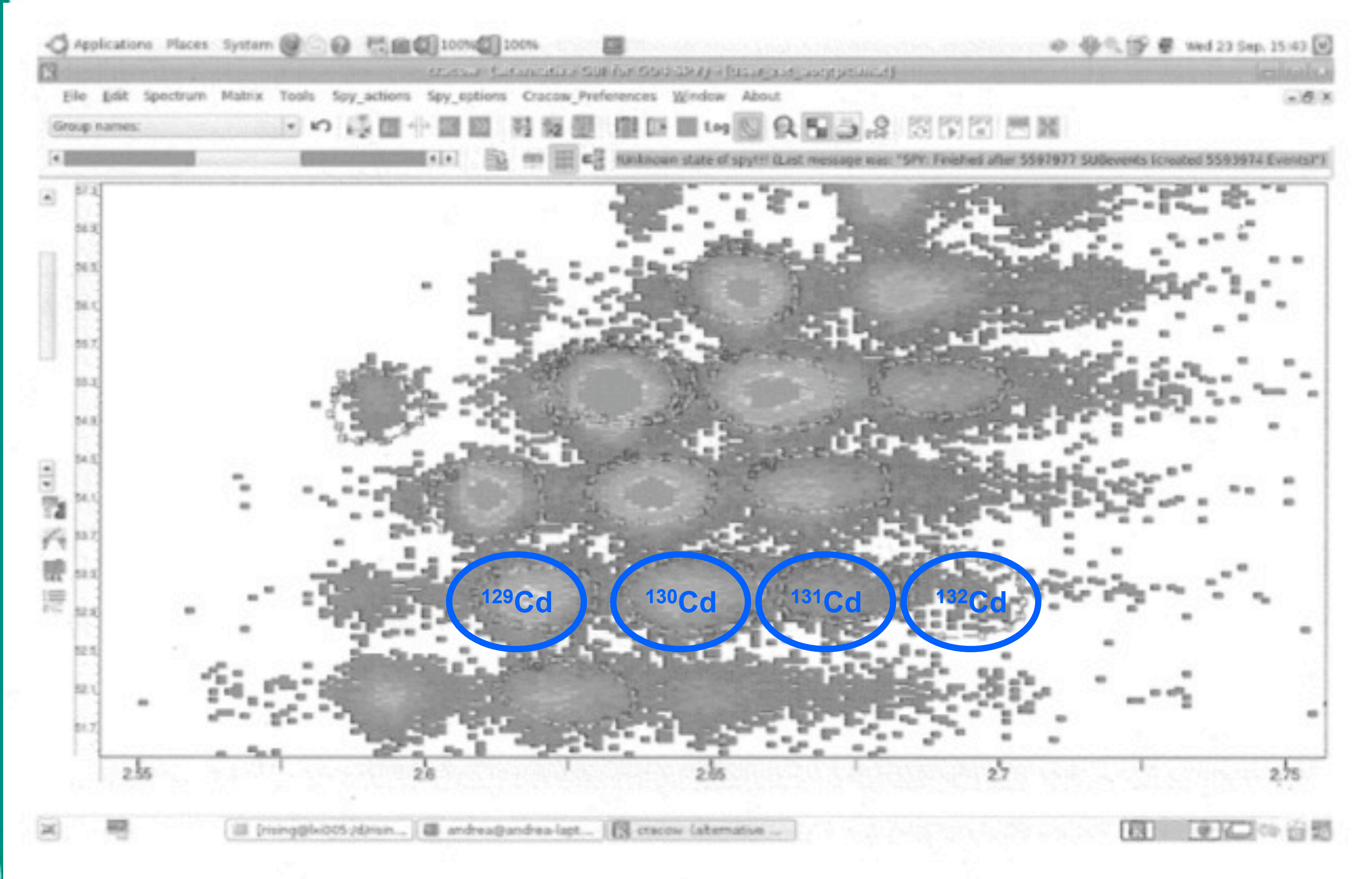
Masses of $^{129-132}$Cd (new experiment)



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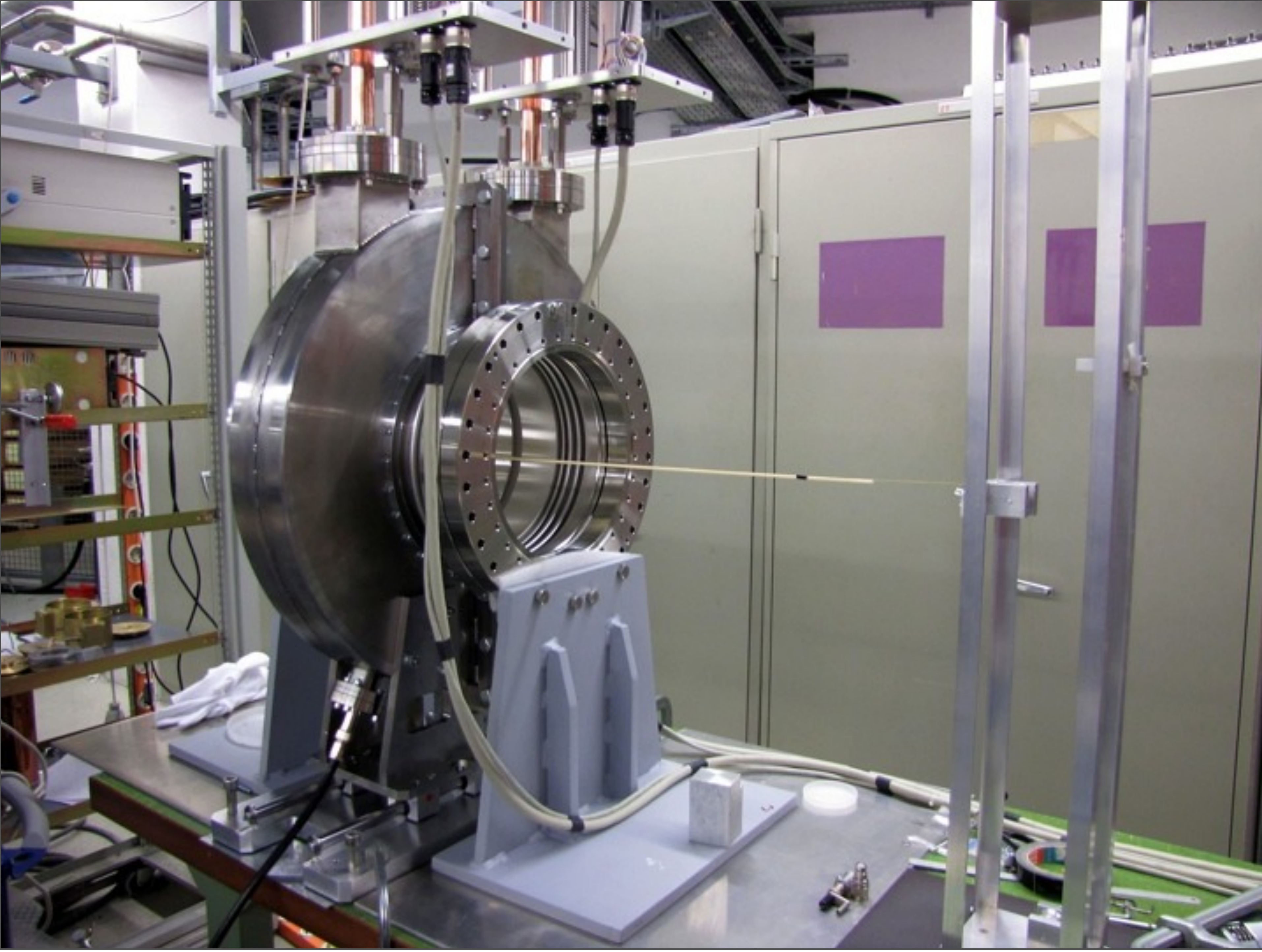
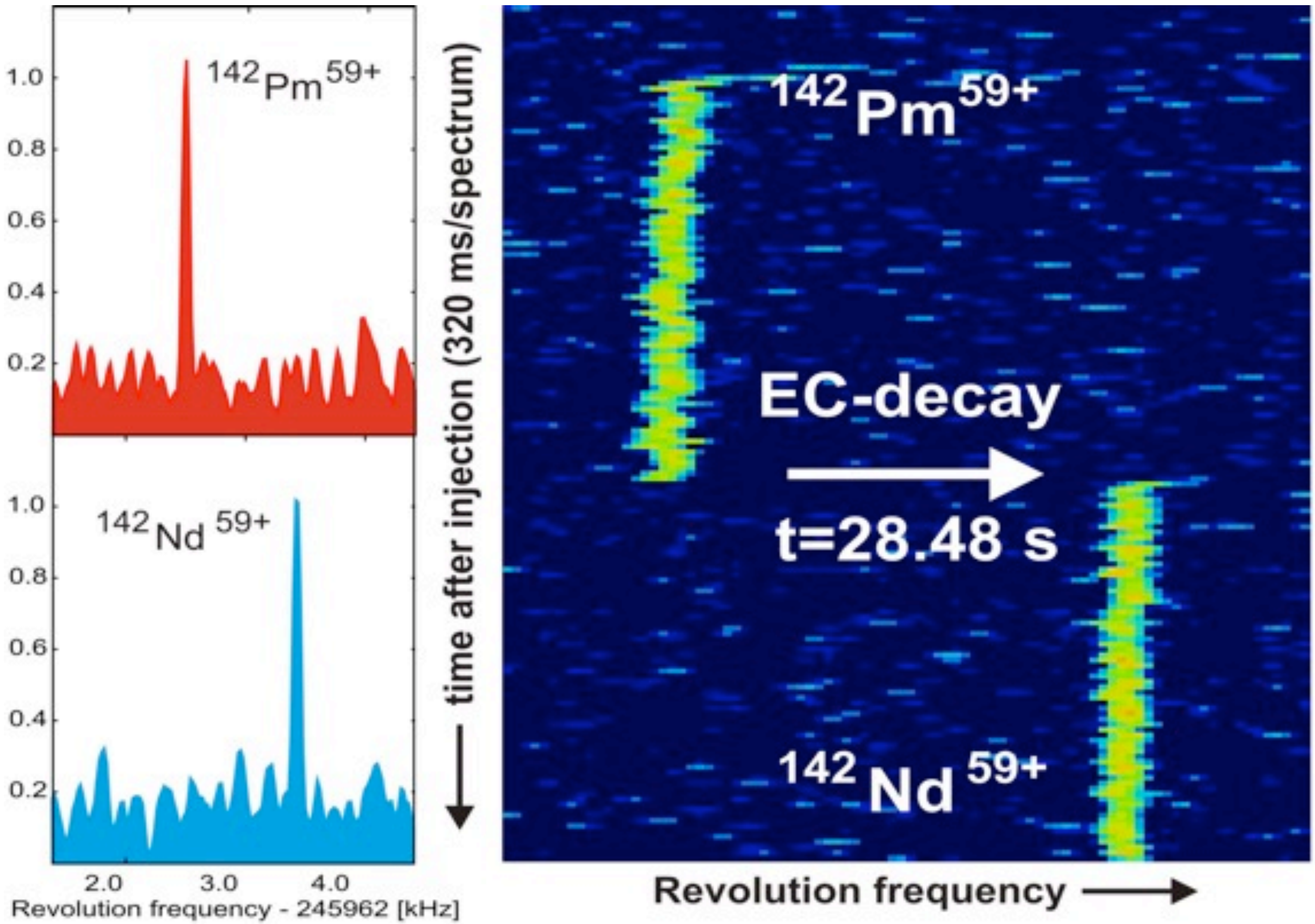


Single ion sensitivity



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Experimental Collaboration

D. Atanasov, D. Balabanski, K. Blaum, F. Bosch, D. Boutin, C. Brandau, L. Chen, Ch. Dimopoulou, H. Essel, Th. Faestermann, H. Geissel, E. Haettner, M. Hausmann, S. Hess, V. Ivanova, P. Kienle, Ch. Kozhuharov, R. Knöbel, J. Kurcewicz, S.A. Litvinov, Yu.A. Litvinov, X. Ma, L. Maier, M. Mazzocco, W. Meng, F. Montes, A. Musumarra, G. Münzenberg, C. Nociforo, F. Nolden, T. Ohtsubo, A. Ozawa, W.R. Plass, A. Prochazka, R. Reuschl, S. Sanjari, Ch. Scheidenberger, D. Shubina, U. Spillmann, M. Steck, Th. Stöhlker, B. Sun, T. Suzuki, S. Torilov, X. Tu, H. Weick, M. Winkler, N. Winckler, D. Winters, N. Winters, T. Yamaguchi, G. Zhang

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MICHIGAN STATE UNIVERSITY

GSI

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