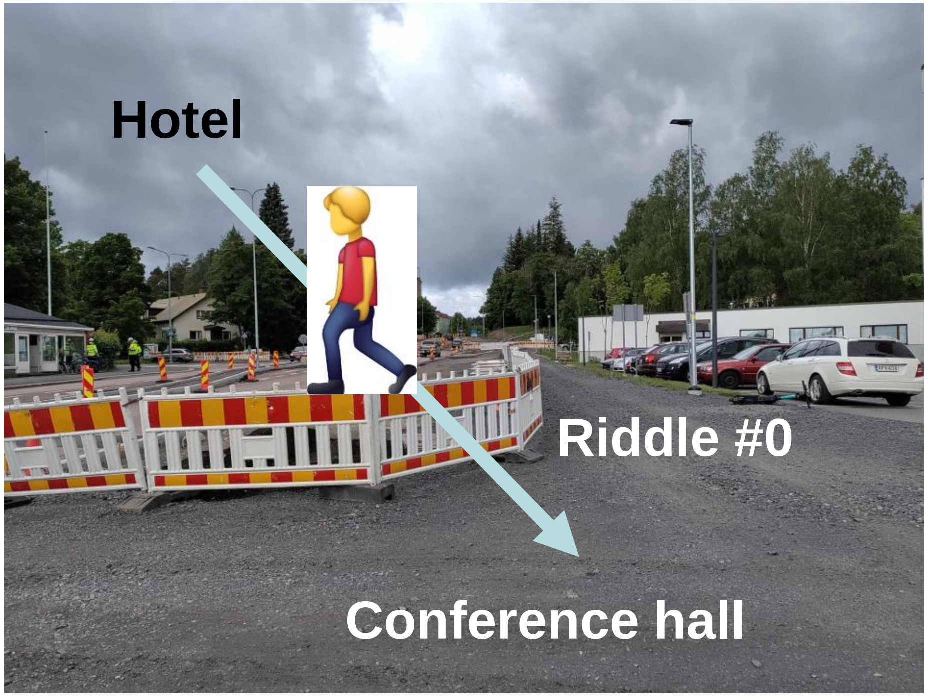
Mass measurements of exotic nuclides in the vicinity of ^{100}Sn and their implications to nuclear structure

Subtitle: Who doesn‘t like a good mistery?

Gabriella Kripkó-Koncz
and the FRS Ion Catcher Collaboration
for the Super-FRS Experiment Collaboration

II. Physikalisches Institut, JLU Gießen, Germany

Mass measurements of exotic nuclides in the vicinity of ^{100}Sn and their implications to nuclear structure



Motivation: the vicinity of ^{100}Sn

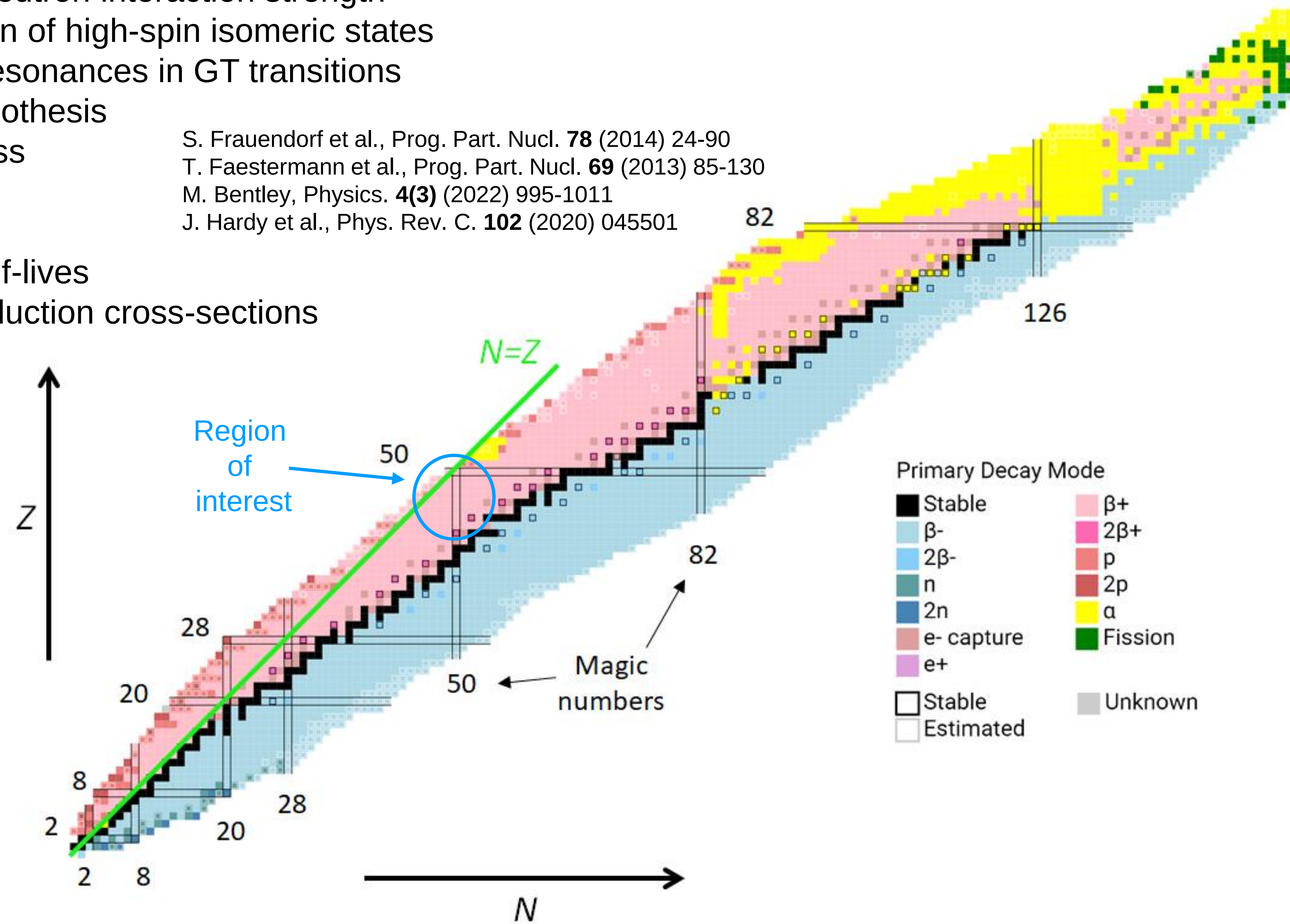
Study of heavy N≈Z nuclei, e.g.:

- Proton-neutron interaction strength
- Formation of high-spin isomeric states
- Strong resonances in GT transitions
- CVC hypothesis
- rp-process

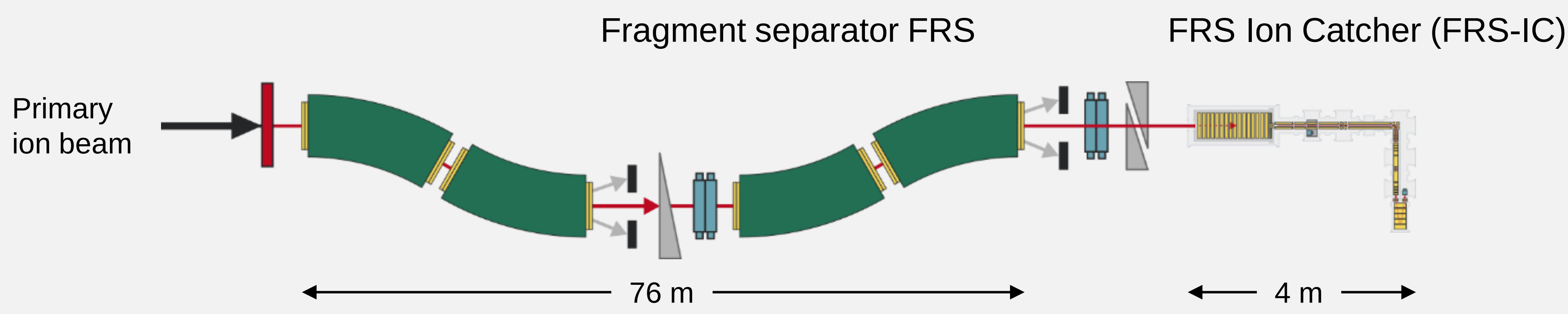
S. Frauendorf et al., Prog. Part. Nucl. **78** (2014) 24-90
T. Faestermann et al., Prog. Part. Nucl. **69** (2013) 85-130
M. Bentley, Physics. **4(3)** (2022) 995-1011
J. Hardy et al., Phys. Rev. C. **102** (2020) 045501

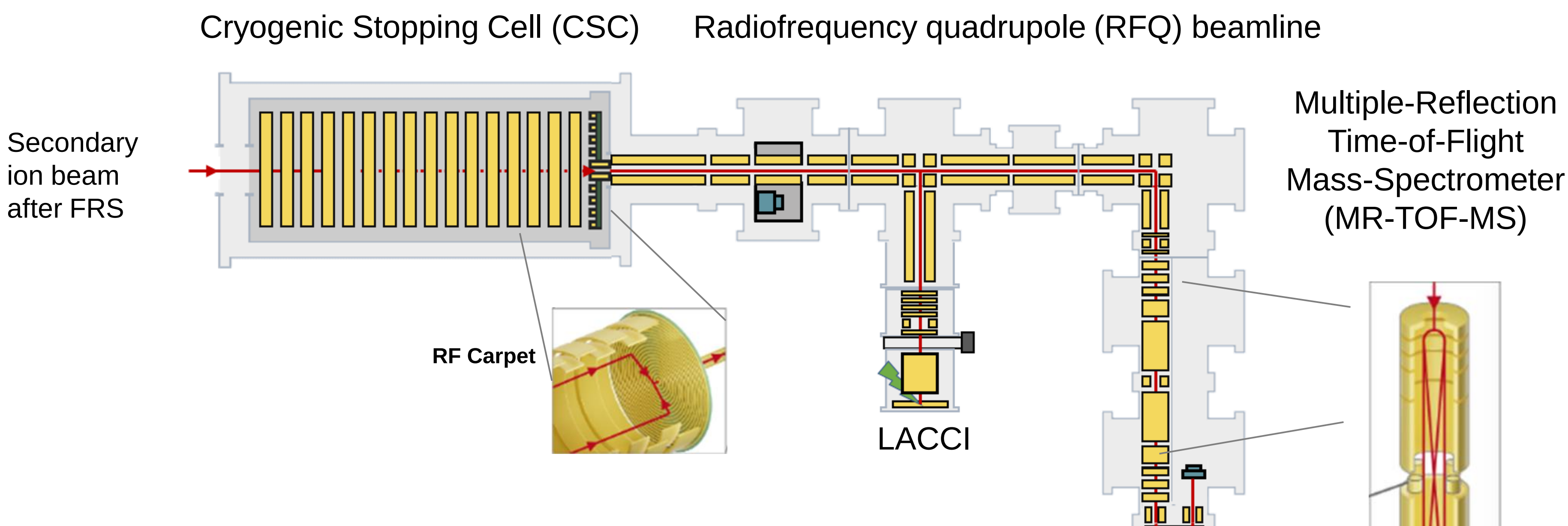
Challenges:

- Short half-lives
- Low production cross-sections



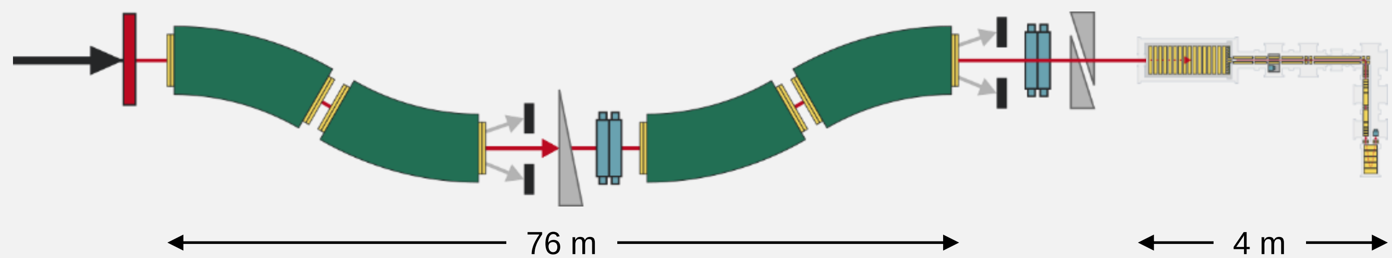
FRS Ion Catcher at GSI

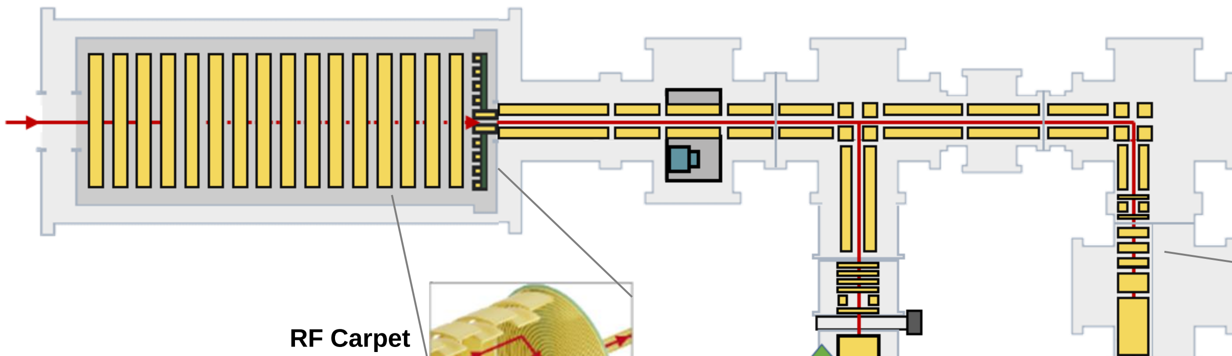


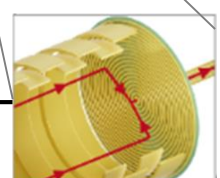


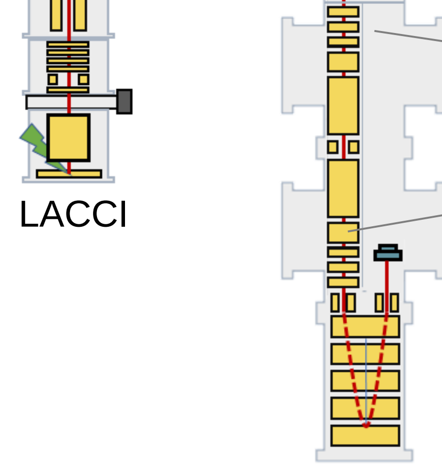
H. Geissel et al., NIM B 70 (1992)
W.R. Plaß et al., Hyperfine Interact 241 (2020)

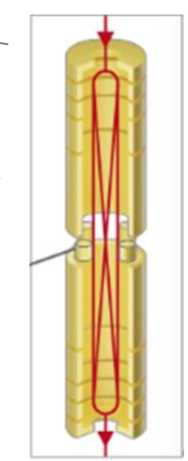
FRS Ion Catcher at GSI







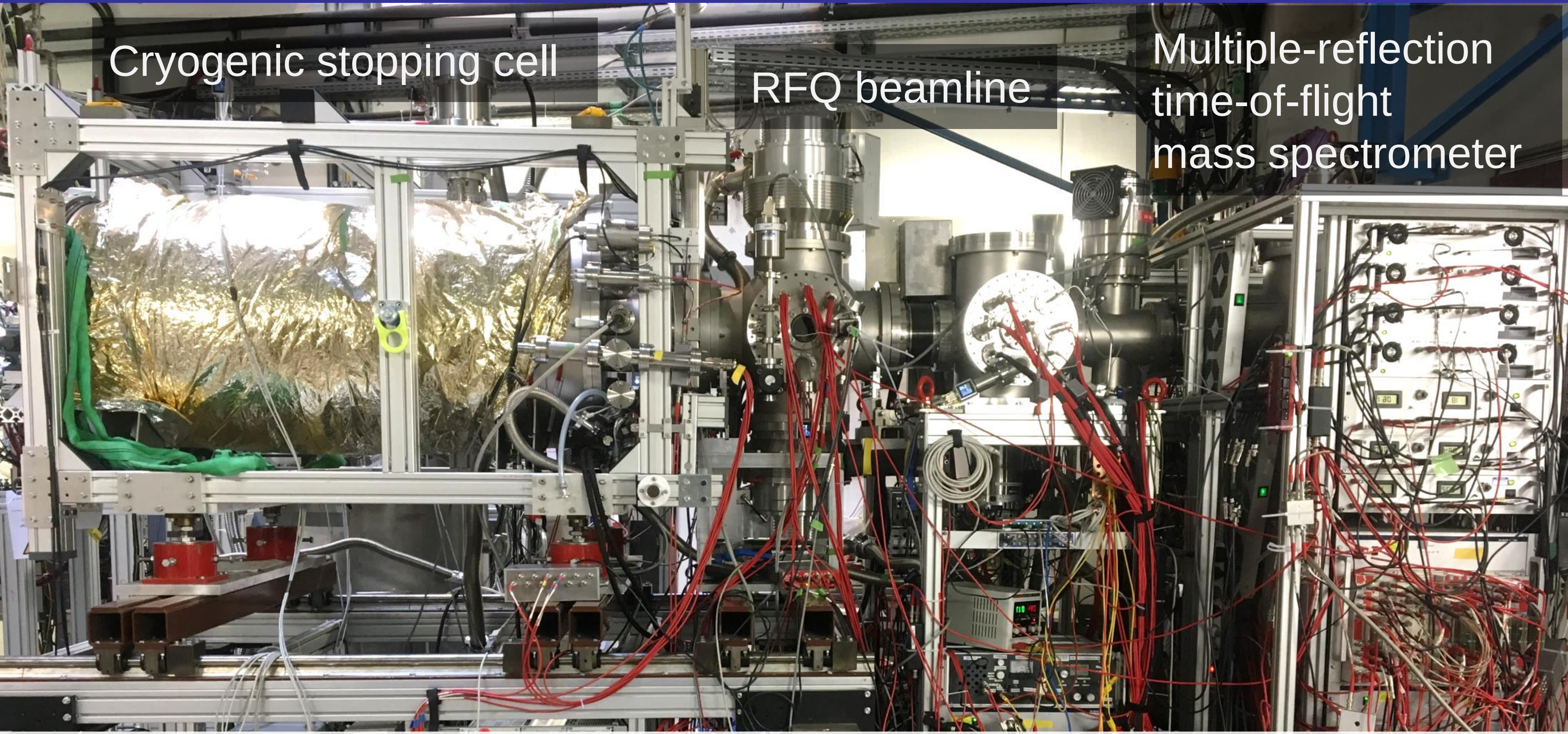




Performance characteristics

- Broad-band mass measurements
- m/Δm up to 1,000,000
- Mass accuracy: down to a few 10^{-8}
- Accessible half-lives: down to a few ms
- Cross sections: down to a few nb (CSC areal density up to 9 mg/cm^2)

FRS Ion Catcher at GSI

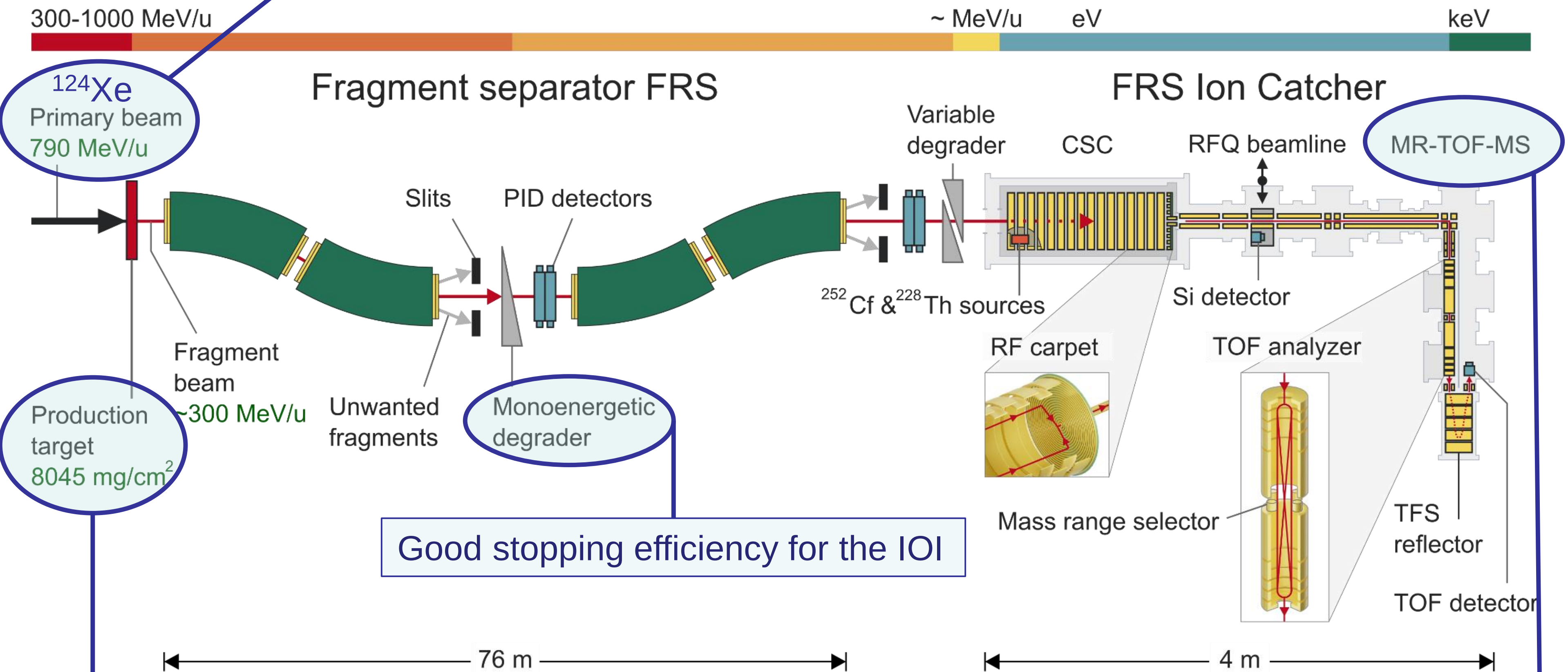


J. Zhao et al., NIM B **547** (2024) 165175
J. Yu et al., NIM A **1064** (2024) 169371
T. Dickel et al., NIM B **541** (2023) 275278
C. Hornung et al., NIM B **541** (2023) 257259
I. Miskun et al., IJMS **459** (2021) 116450
W.R. Plaß et al, Hyperfine Inter. **241** (2020) 1
F. Greiner et al., NIM B **463** (2020) 324
E. Haettner et al., NIM A **880** (2018) 138
Purushothaman et al., IJMS **421** (2017) 245
W. R. Plaß et al., Phys. Scr. **T166** (2015) 014069
M.P. Reiter et al., NIM B **376** (2016) 240
W.R. Plaß et al., Int. J. Mass Spectrometry **394** (2013)
M. Ranjan et al., EPL **96** (2011) 52001
S. Purushothaman et al., EPL **104** (2013) 42001
M. Ranjan et al., NIM A **770** (2015) 87
W.R. Plaß et al., NIM B **266** (2008)

FRS Ion Catcher at GSI and S474 experiment

Efficient data taking (3 isotones)

Challenge: small production cross-sections (few nbarn)



Good stopping efficiency for the IOI

Thicker target

A few events are enough for accurate mass determination.

A. Mollaebrahimi *et al*., PLB **839** (2023) 137833

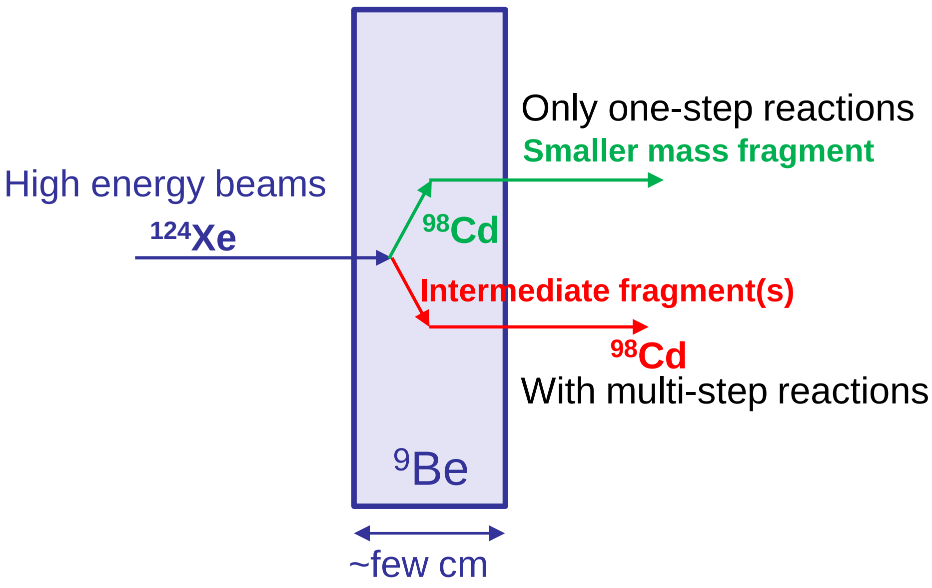
W.R. Plaß *et al*., NIM B 317 (2013) 457

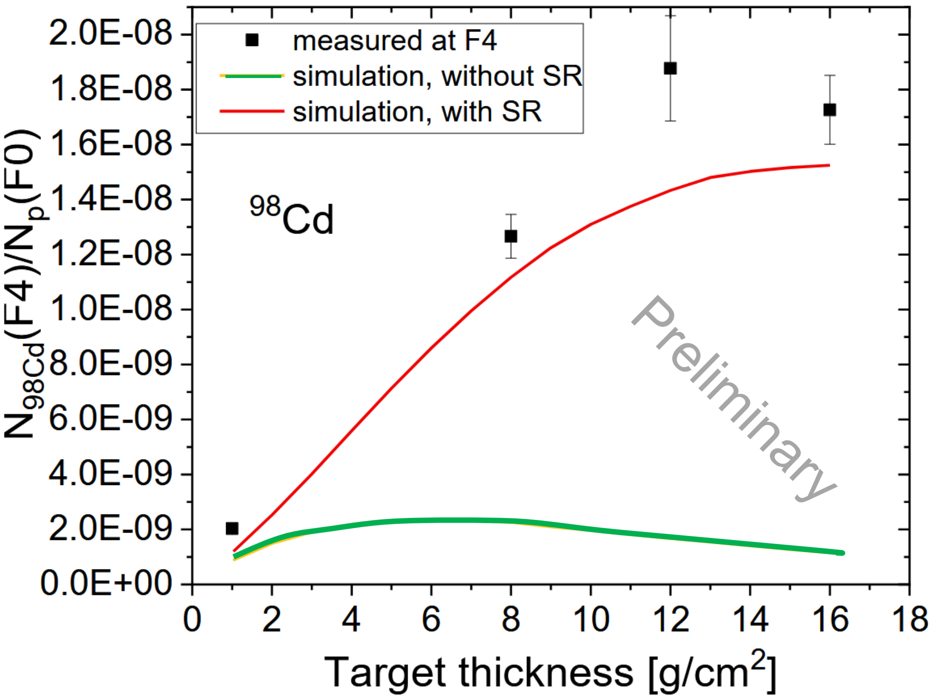
W.R. Plaß *et al*., Int. J. Mass Spectrom. 394 (2013) 134

T. Dickel *et al*., NIM A 777 (2015) 172

Thicker production target

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



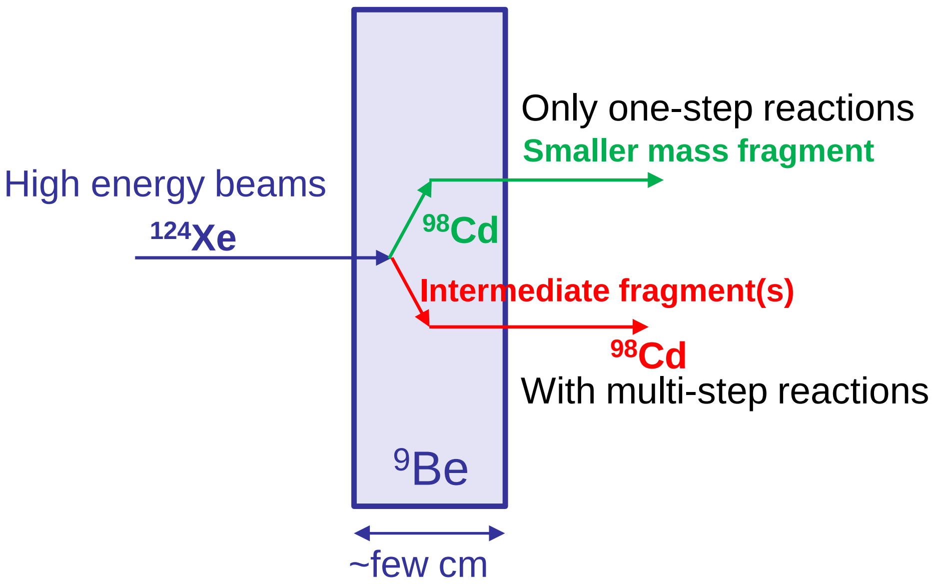


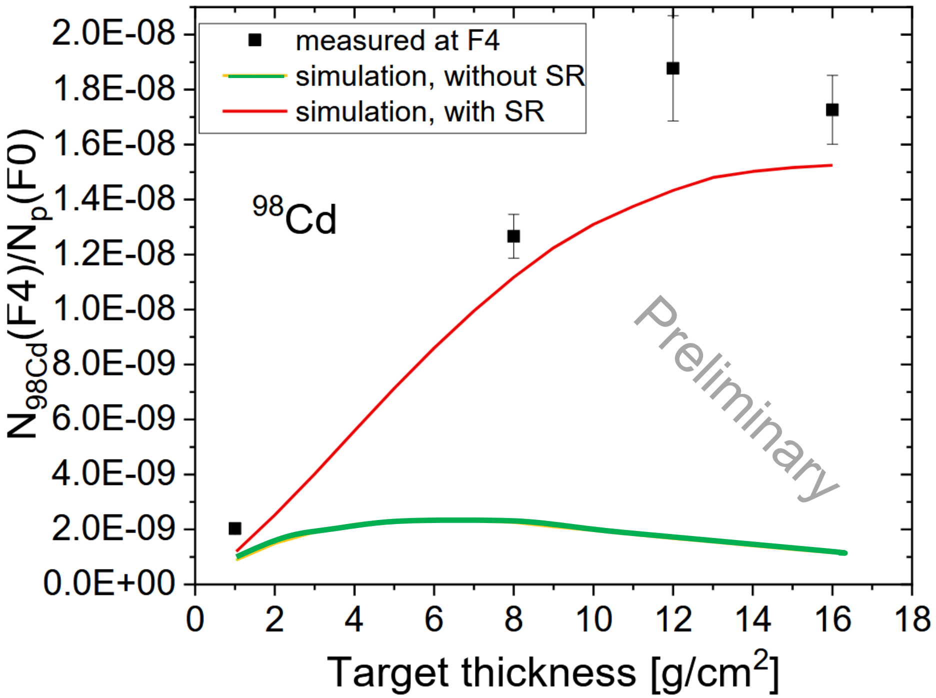
E. Haettner, R. Prajapat, T. Dickel, H. Geissel, C. Hornung, W.R. Plaß, J. Zhao

Thicker production target

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

$\frac{A}{Z^2}(^{124}Xe) \sim \frac{A}{Z^2}(^{98}Cd)$ - minimize location straggling to avoid decreasing the stopping efficiency





E. Haettner, R. Prajapat, T. Dickel, H. Geissel, C. Hornung, W.R. Plaß, J. Zhao

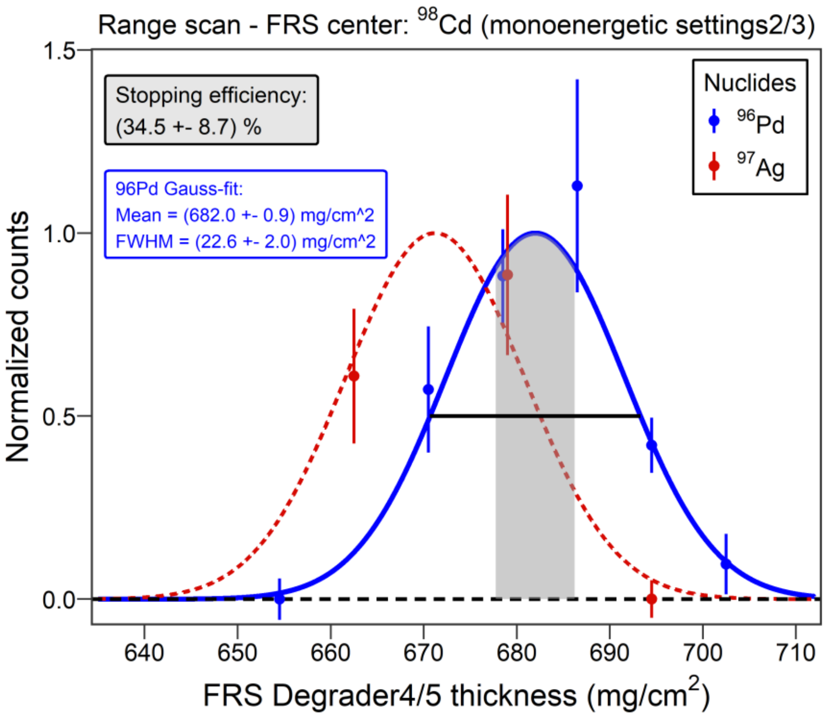
Efficient data taking (3 isotones)

- Monoenergetic ion optics + tune beam energy with synchrotron

3 isotones have the same stopping range in CSC

3 isotones can be measured simultaneously in one settings

N=50 isotones



Mass spectrum – FRS center: ^{93}Pd

N=47 isotones

Contents removed

Proton-separation energies can be directly deduced

Super-FRS EC

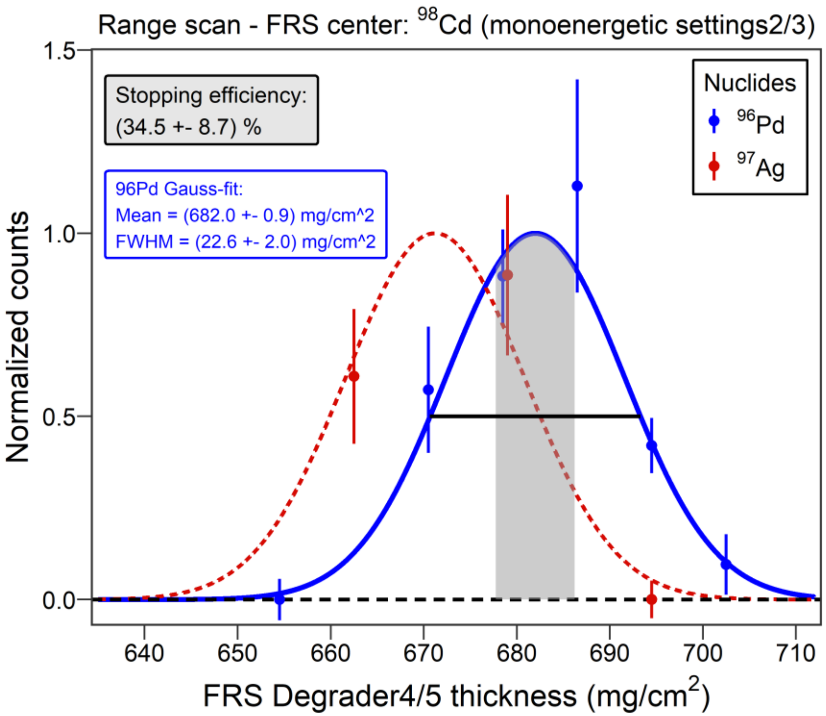
FAIR Phase 0 Research Program FRS

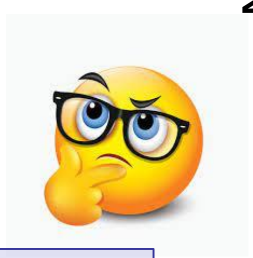
Riddle #1: „unexpected“ isotopes

- Monoenergetic ion optics + tune beam energy with synchrotron

3 isotones have the same stopping range in CSC — 3 isotones can be measured simultaneously in one settings

N=50 isotones





Mass spectrum – FRS center: ^{93}Pd

N=47 isotones

Contents removed

„Unexpected“ isotopes were observed.

Super-FRS EC

FAIR Phase 0 Research Program FRS

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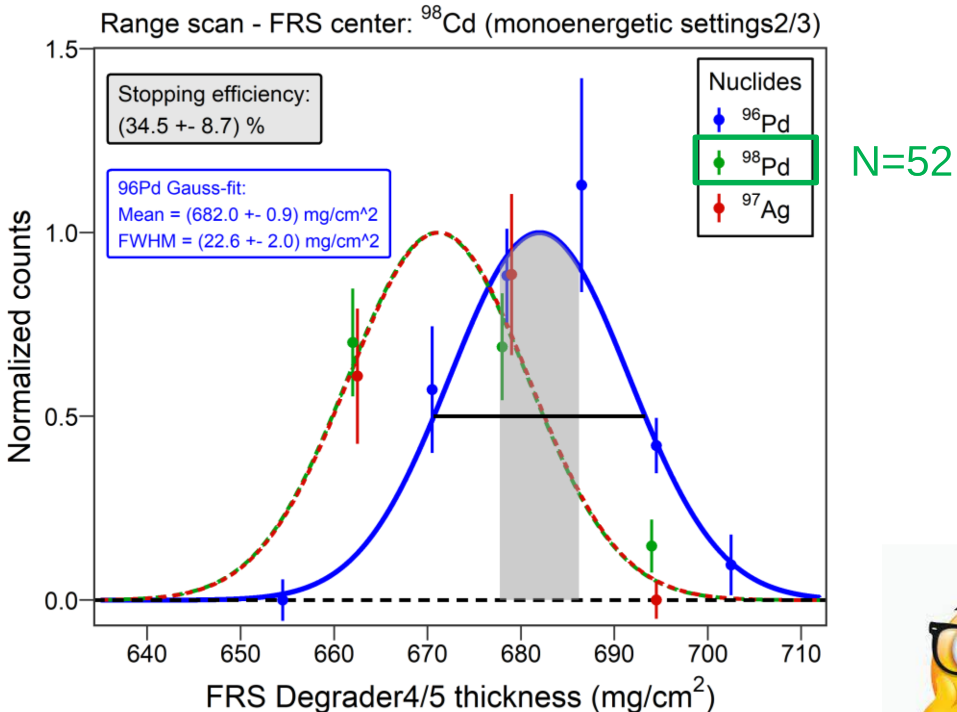

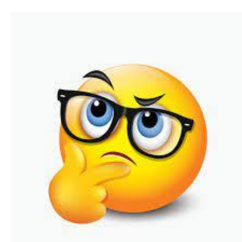

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Super-FRS EC

FAIR Phase 0 Research Program FRS

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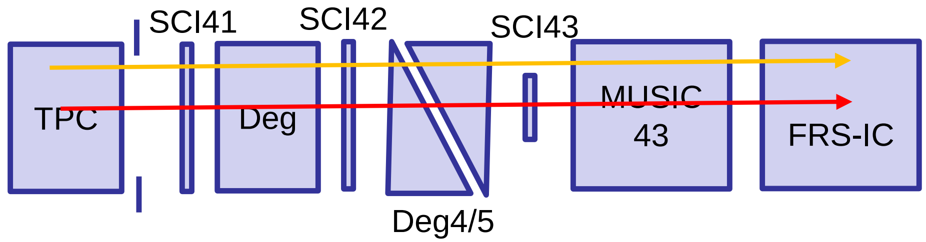
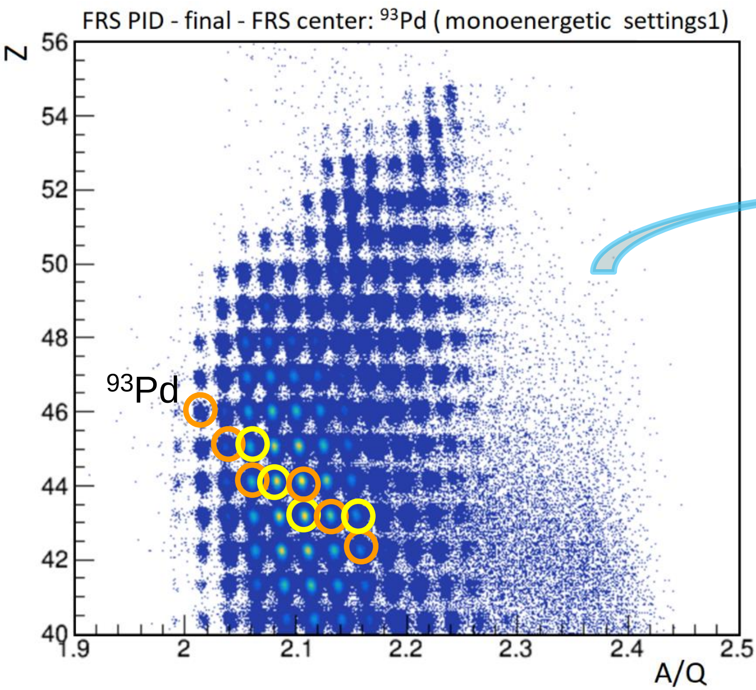


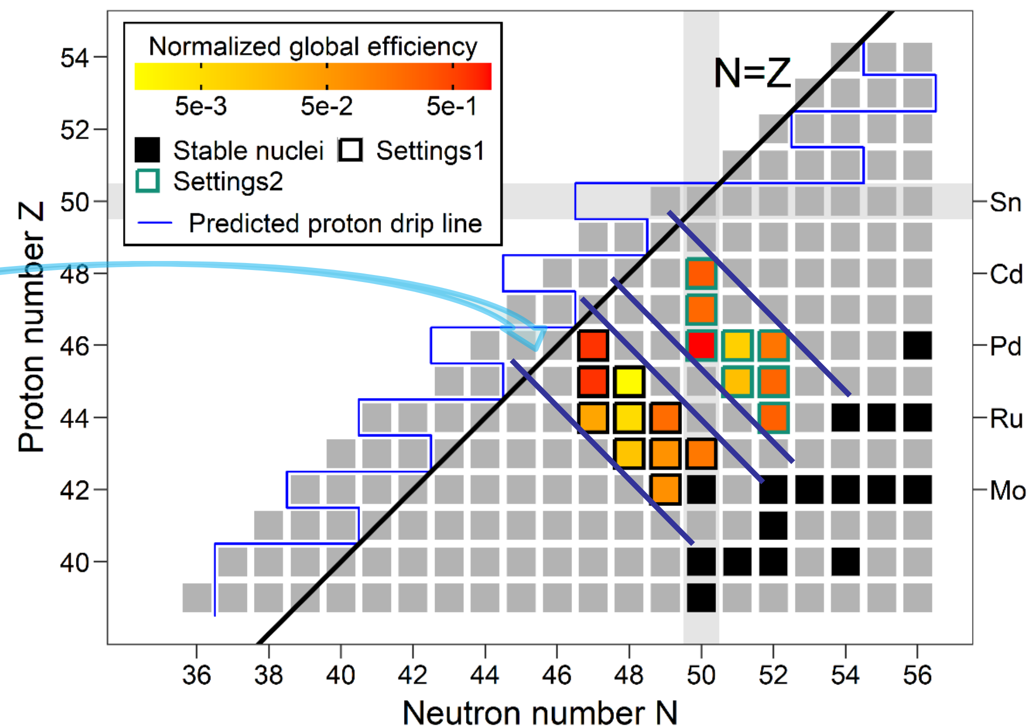
LISE++ simulations

Consistent picture

Yields measured with FRS Ion Catcher

Yields measured by FRS PID detectors





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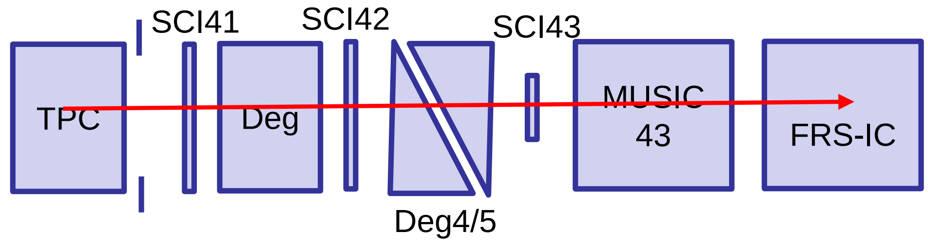

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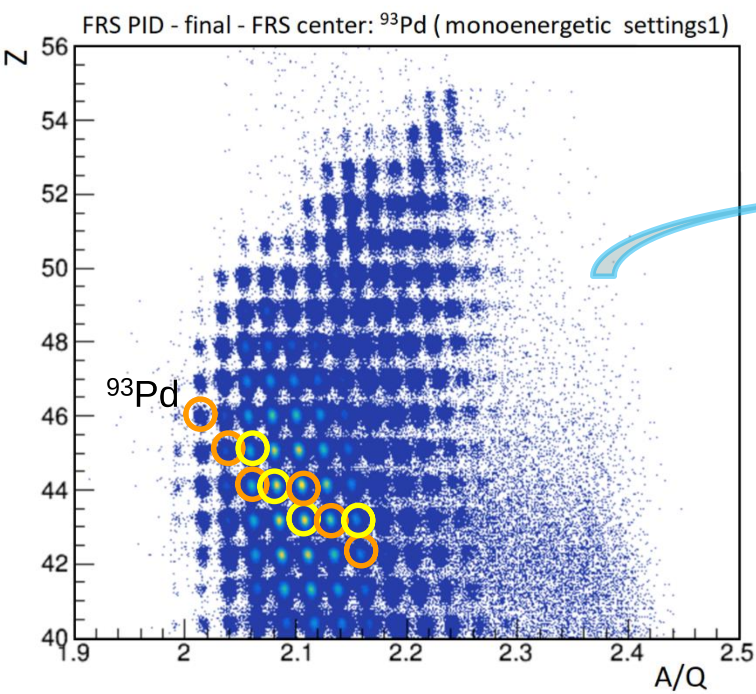

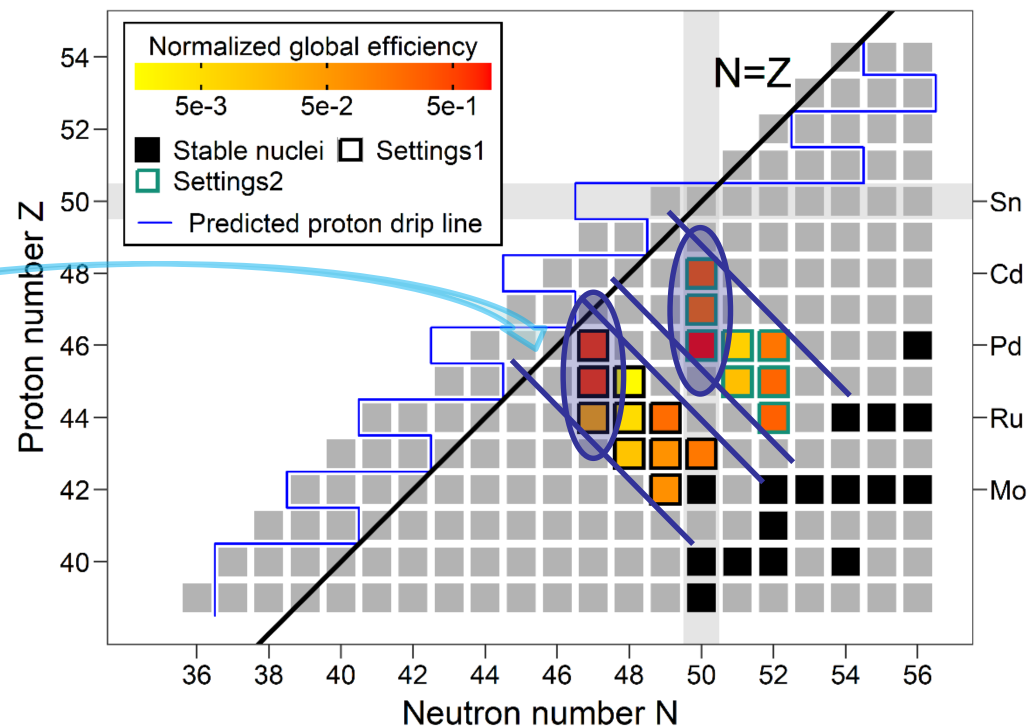

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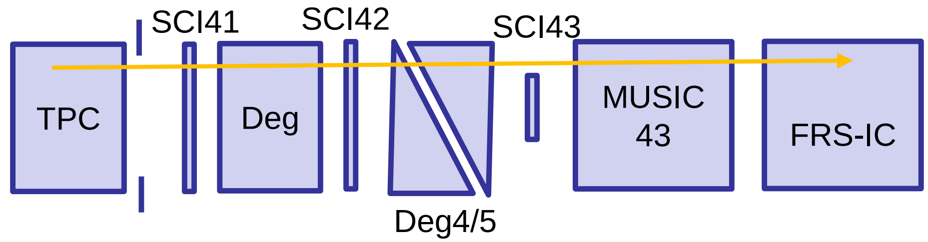

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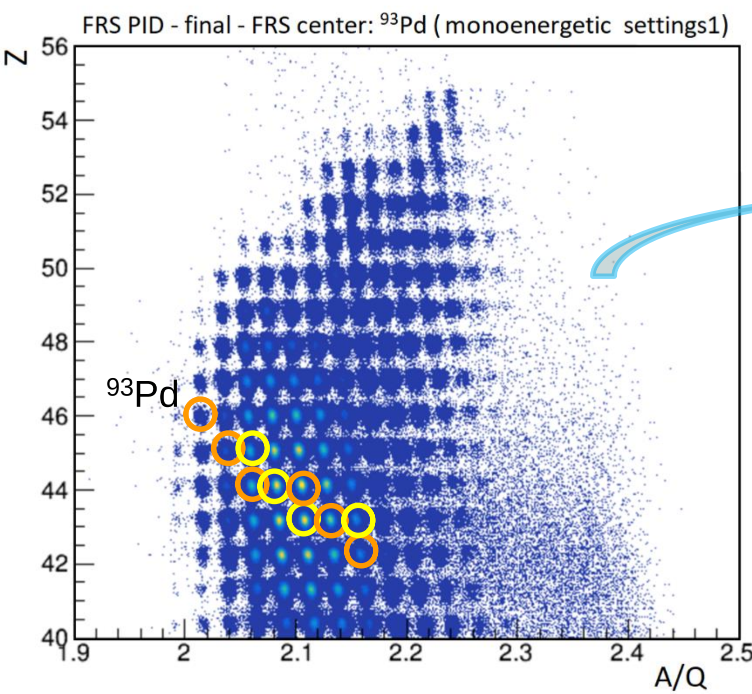
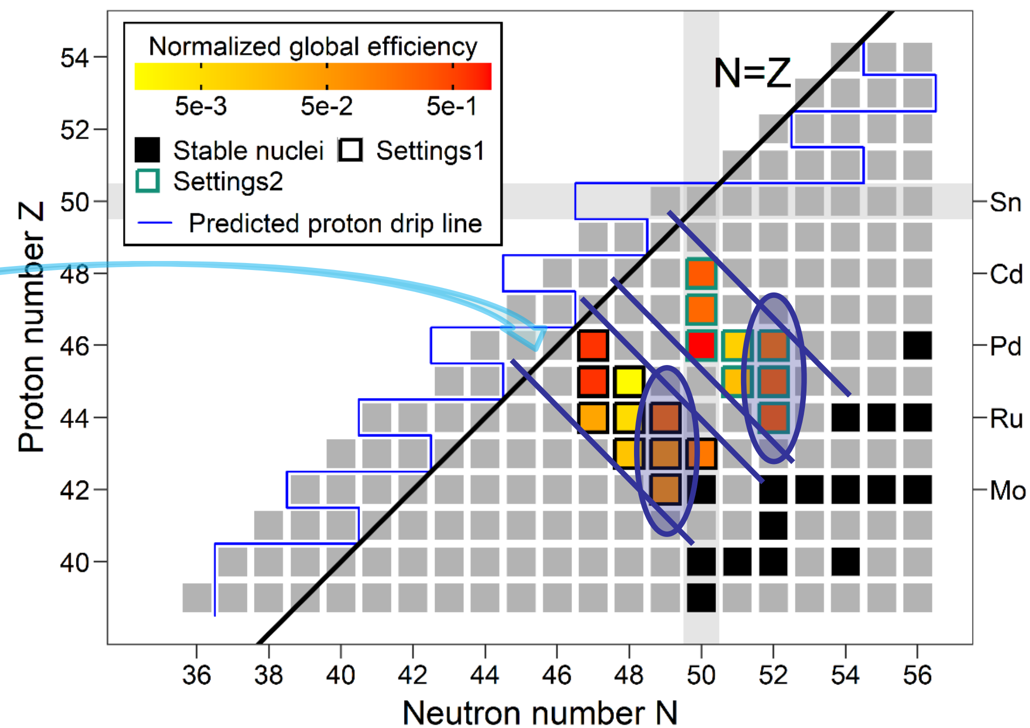
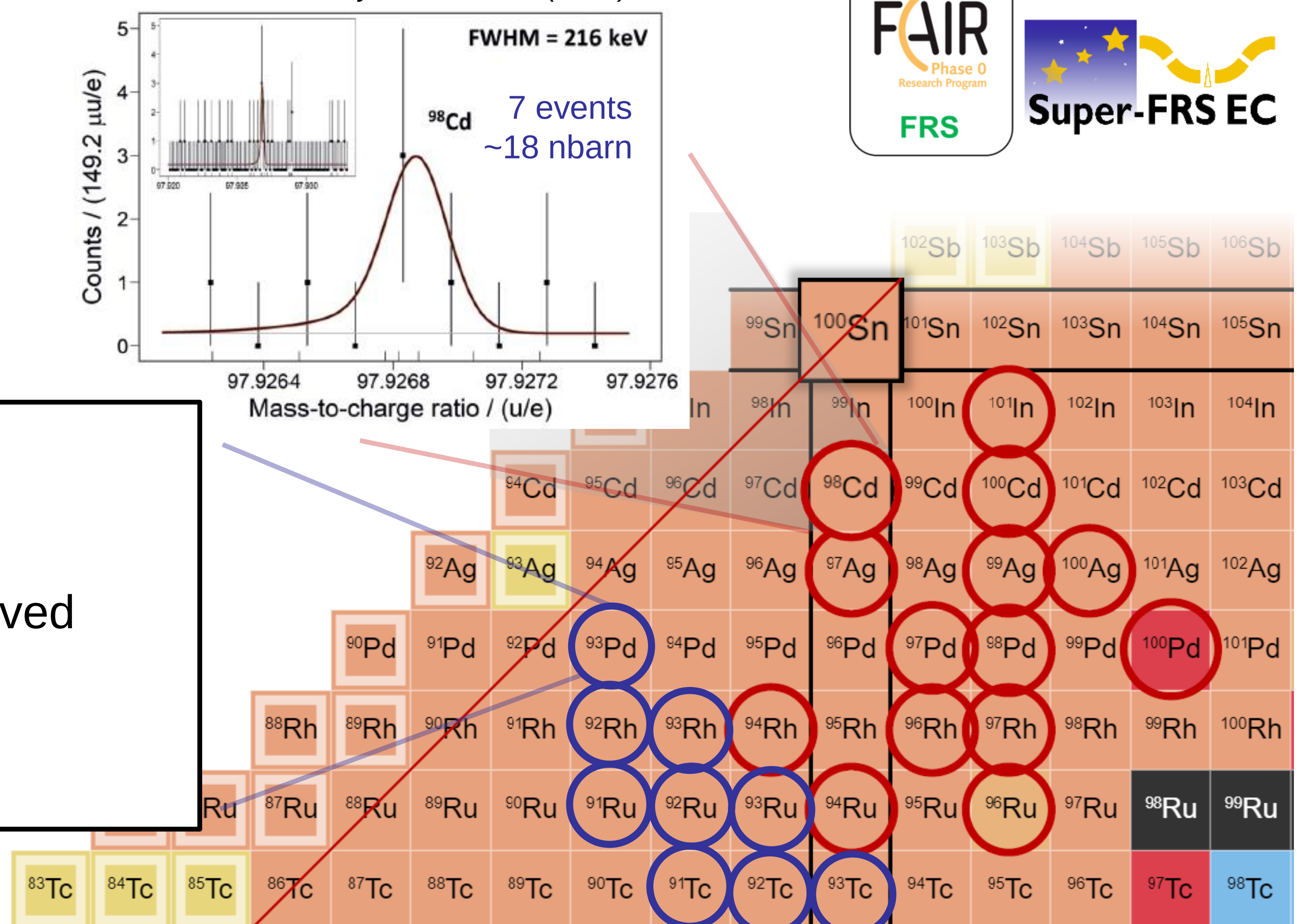




Measured masses in the vicinity of ^{100}Sn

- Direct mass measurements of 24 ground states and 2 isomers
- First direct mass measurements of ^{98}Cd and ^{93}Pd

A. Mollaebrahimi et al., Phys. Lett. B 839 (2023) 137833



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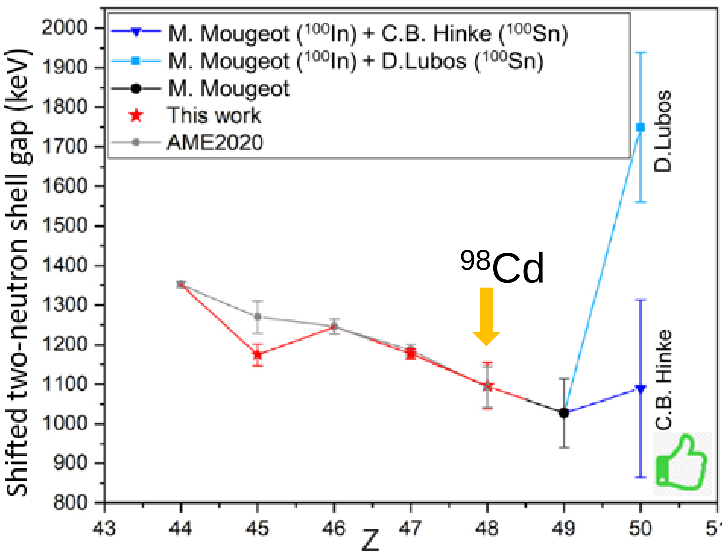
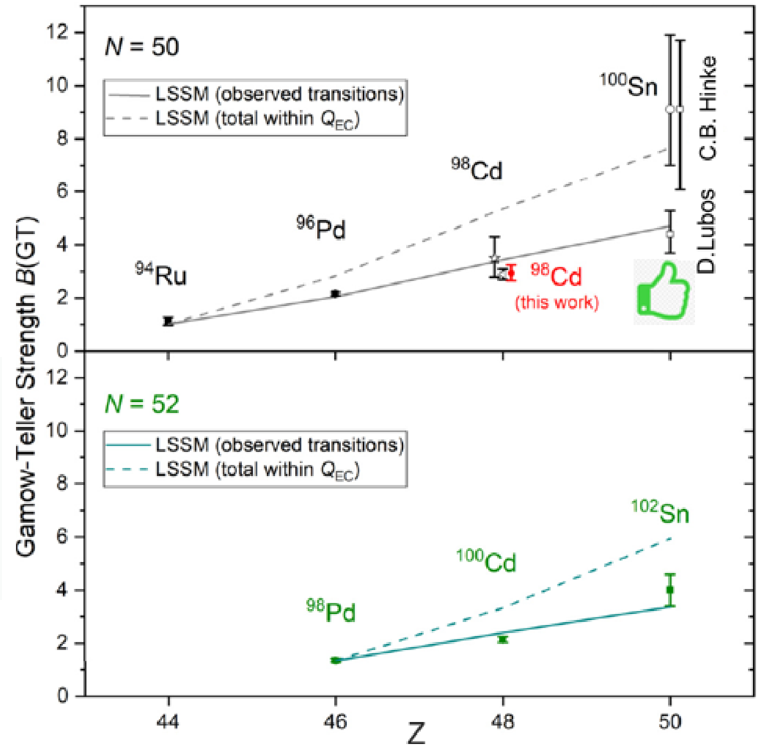
Riddle #2: Controversy around the mass of ^{100}Sn

- The "^{100}Sn mass riddle": measured mass of ^{100}In [M. Mougeot et al.] + two different Q_{EC} values
  - *D. Lubos, et al., Phys. Rev. Lett. 122 (2019) 222502*
  - *C.B. Hinke, et al., Nature 486 (2012) 341*





[C.B. Hinke et al.] was favored in comparison to ab-initio calculation done in [M. Mougeot et al.]

M. Mougeot, et al., Nat. Phys. 17 (2021) 1099

The evolution of B(GT) for N=50 and N=52 isotones in comparison to LSSM **favors [D. Lubos et al.].**

A. Mollaebrahimi et al., Phys. Lett. B 839 (2023) 137833

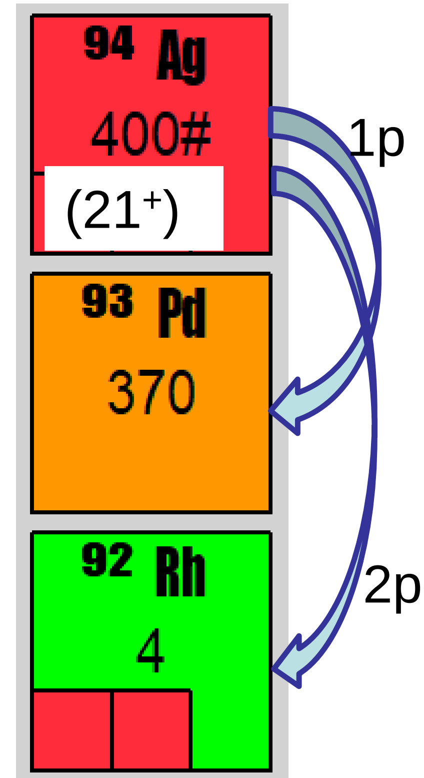
New/improved experiments are needed!

“History” of ^{94}Ag (21$^+$) isomer

The high-spin isomer has been observed to decay via:

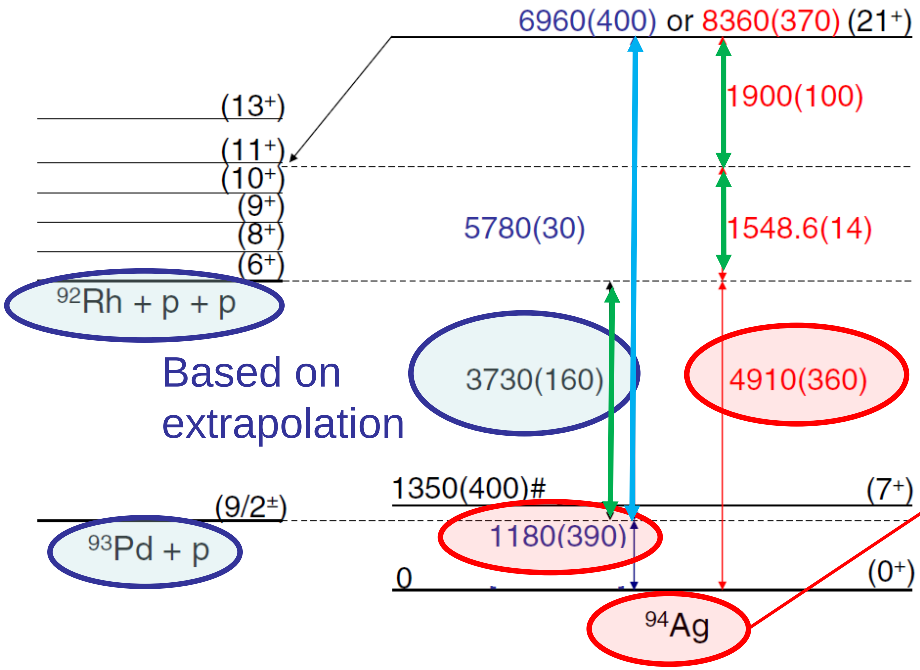
- β-decay C. Plettner et al., Nucl. Phys. A 733, 20 (2004)
- β-delayed proton emission I. Mukha et al., Phys. Rev. C 70, 044311 (2004)
- direct 1p-decay I. Mukha et al., PRL 95 (2005) 022501
- direct 2p-decay I. Mukha et al., Nature 439 (2006) 298

Intense scientific discussions



- O. L. Pechenaya et al., Phys. Rev. C 76, 011304 (2007)
- K. Kaneko et al., Phys. Rev. C 77, 064304 (2008)
- D. G. Jenkins et al., Phys. Rev. C 80, 054303 (2009)
- J. Cerny et al., Phys. Rev. Lett. 103, 152502 (2009)

A. Kankainen et al., PRL 101 (2008) 142503



JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

IGISOL, Jyväskylä – dedicated hot-cavity catcher to measure Ag isotopes

M. Reponen *et al.*, Rev. Sci. Instrum. 86, 123501 (2015)

V. Virtainen (next talk)

Riddle #3: the 1p/2p-decay of ^{94}Ag (21^+) isomer

Measurement yields a mismatch between ME of 21+, when obtaining it from 1p/2p-decay branches.

The theoretical interpretation of our results is ongoing.

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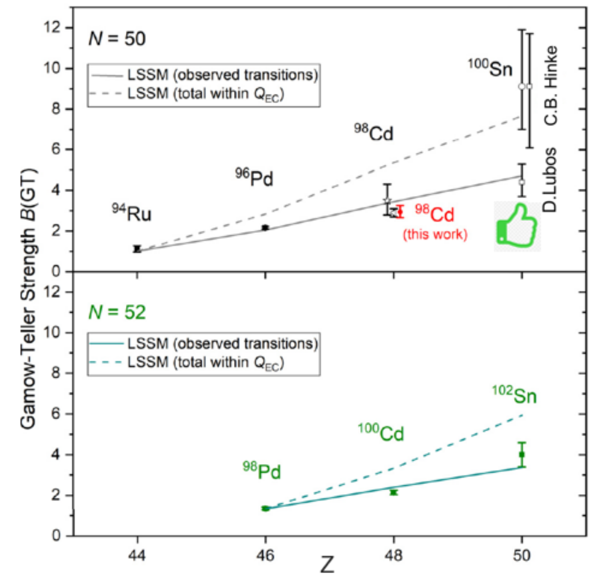
[J. Dudek, I. Dedes, F. Nowacki, A. Blazhev, D. Dao, X. Mougeot, J. Äystö]

G. Kripkó-Koncz et al., in preparation

Summary and Outlook

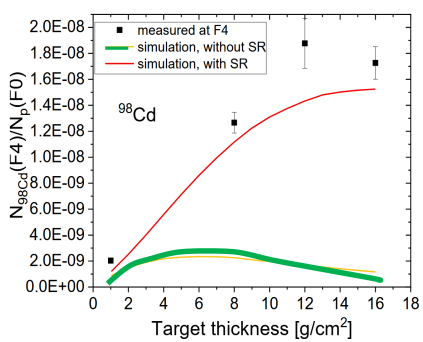
Measurements below ^{100}Sn – S474:

- Coping with very small production cross-sections
  - Thicker targets
  - Efficient data taking (3 isotones)
- Explanation for “unexpected” isotopes
- Implications for the “^{100}Sn mass riddle”
- Implications for the exotic decay modes of the ^{94}Ag (21^+) isomer **V. Virtainen (next talk)**



Outlook:

- The usage of thick targets will be further exploited at FAIR with high energy beams.



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Super-FRS EC

FAIR Phase 0 Research Program FRS

Acknowledgements

Super-FRS Experiment Collaboration

FRS Ion Catcher Collaboration

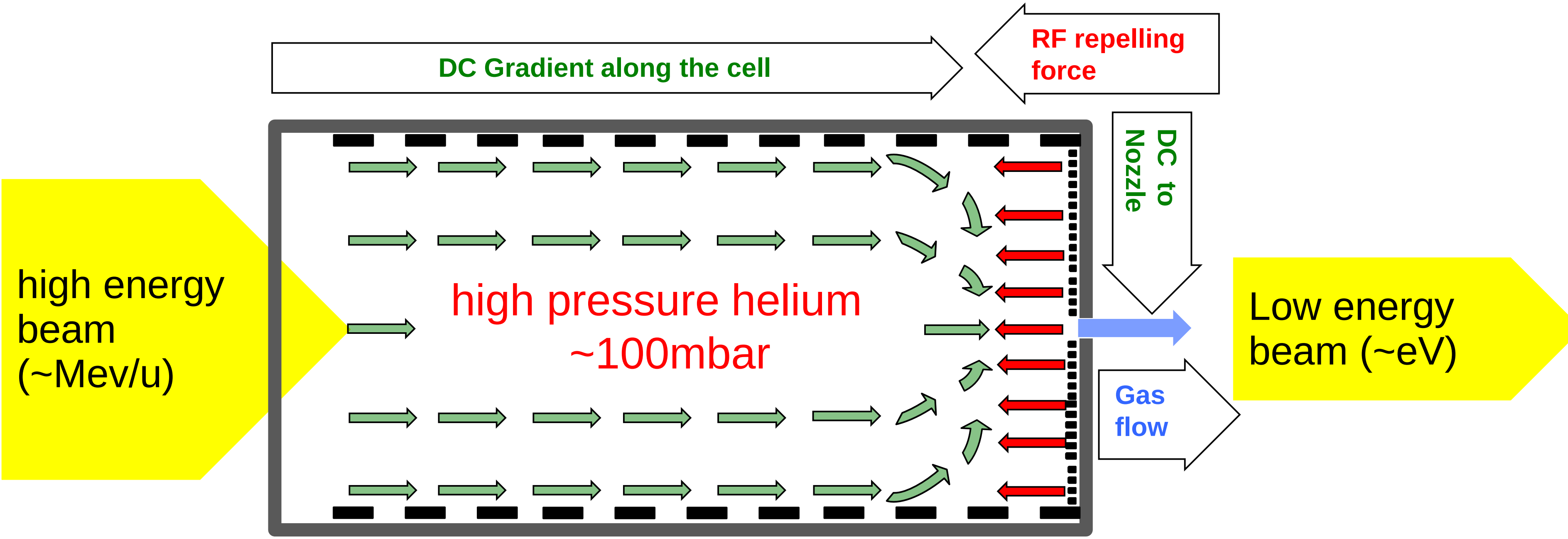
D. Amanbayev, B. Ashrafkhani, O. Aviv, S. Ayet San Andrés, J. Äystö, S. Bagchi, D.L. Balabanski, S. Beck, O. Beliuskina, J. Bergmann, A. Blazhev, Z. Brencic, S. Cannarozzo, O. Charviakova, P. Constantin, D. Curien, I. Dedes, M. Dehghan, T. Dickel, F. Didierjean, G. Duchene, J. Dudek, T. Eronen, T. Fowler-Davis, M. Friedman, Z. Gao, Z. Ge, H. Geissel, S. Glöckner, M. Górska, T. Grahn, F. Greiner, L. Gröf, M. Gupta, E. Haettner, M. Harakeh, C. Hornung, Y. Ito, A. Jaries, A. Jokinen, B. Kaizer, N. Kalantar-Nayestanaki, A. Kankainen, D. Kar, A. Karpov, Y. Kehat, D. Kostyleva, G. Kripkó-Koncz, D. Kumar, K. Mahajan, I. Mardor, A.A. Mehmandoost-Khajeh-Dad, N. Minkov, A. Mollaebrahimi, I. Moore, D. Morrissey, I. Mukha, M. Narang, D. Nichita, Z. Patyk, H. Penttilä, A. Perry, S. Pietri, A. Pikhtelev, W.R. Plaß, I. Pohjalainen, S. Pomp, R.K. Prajapat, S. Purushothaman, M.P. Reiter, M. Reponen, S. Rinta-Antila, H. Rösch, A. Rotaru, J. Ruotsalainen, N. Saadon, C. Scheidenberger, P. Schury, A. Shrayer, M. Simonov, S.K. Singh, A. Solders, A. Spataru, A. State, Y. Tanaka, P. Thirolf, N. Tortorelli, E. Vardaci, L. Varga, M. Vencelj, V. Virtanen, M. Wada, H. Weick, L. Welde, M. Wieser, M. Will, H. Wilsenach, M.I. Yavor, J. Yu, A. Zadvornaya, J. Zhao

The results presented here are based on the experiment S474, which was performed at the FRS at the GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt (Germany) in the context of FAIR Phase-0

Funding: **German Federal Ministry for Education and Research** (05P19RGFN1, 05P21RGFN1), **JLU Giessen and GSI** (JLU-GSI strategic Helmholtz partnership agreement), **Helmholtz Research Academy Hesse for FAIR (HFHF)**, **HGS-HIRe**, **German Research Foundation** (SCHE 1969/2-1), **DAAD** (57610603), **Israel Ministry of Energy** (220-11-052), **Israel Science Foundation** (2575/21), **Romanian Ministry of Research, Innovation and Digitalization** (PN 23 21 01 06), **Polish Minister of Science and Higher Education** (5237/GSI-FAIR/2022/0), **IAEA** (CRP F42007, 24000)

Backup slides

Concept: Cryogenic Stopping Cell (CSC)



IGISOL/Stopping cells:

- **Fast** → access to short-lived exotic nuclides ($T_{1/2}$ ~ ms)
- **Universal** → element-independent
- **Efficient** → highest stopping and extraction efficiency

M. Wada NIM B 317 (2013) 450

Cryogenic Operation

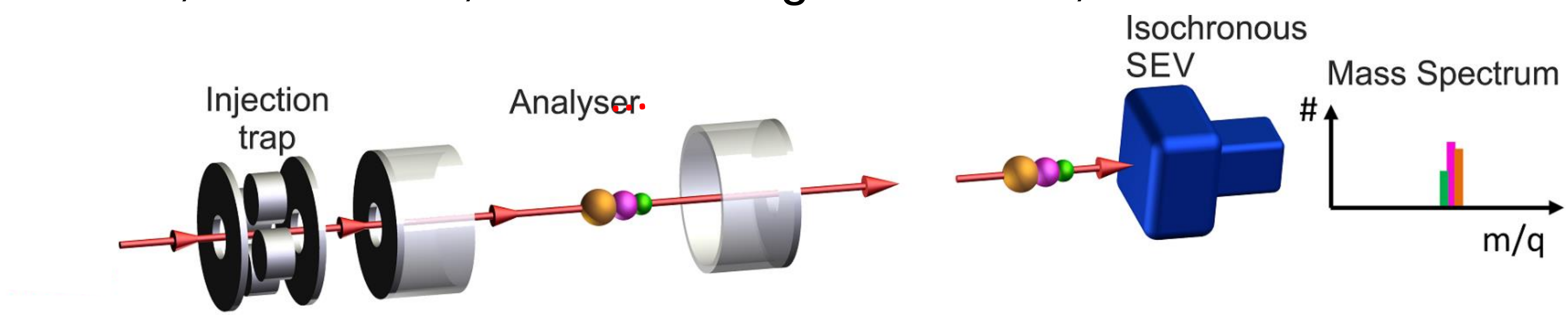
- **Clean** → ion beams of high cleanliness

M. Ranjan *et al.*, Europhys. Lett. 96 (2011) 52001
Purushothaman S. *et al.*, EPL 104 (2013) 42001

Concept: MR-TOF-MS

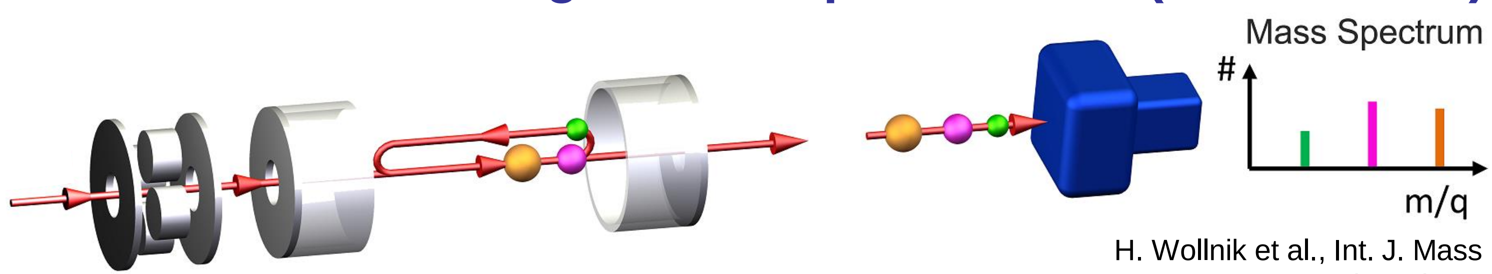
Enables high performance

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



To achieve high mass resolving power and accuracy:

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



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

Applications

- Diagnostics measurements: monitor production, separation and low-energy beam preparation of exotic nuclei — W.R. Plaß et al., Int. J. Mass Spectrom. 394 (2013) 134
- Direct mass measurements of exotic nuclei — C. Scheidenberger et al., Hyperfine Interact. 132 (2001) 531
- High-resolution mass separator — W.R. Plaß et al., NIM B 266 (2008) 4560

Experimental challenges and dealing with them

Experimental Challenges:

- Short half-lives (~ ms)
- Small production cross section (~ pbarn-µbarn)
- Low-lying isomeric states

The setup of the FRS-IC and in particular the MR-TOF-MS enables high performance to deal with such challenges

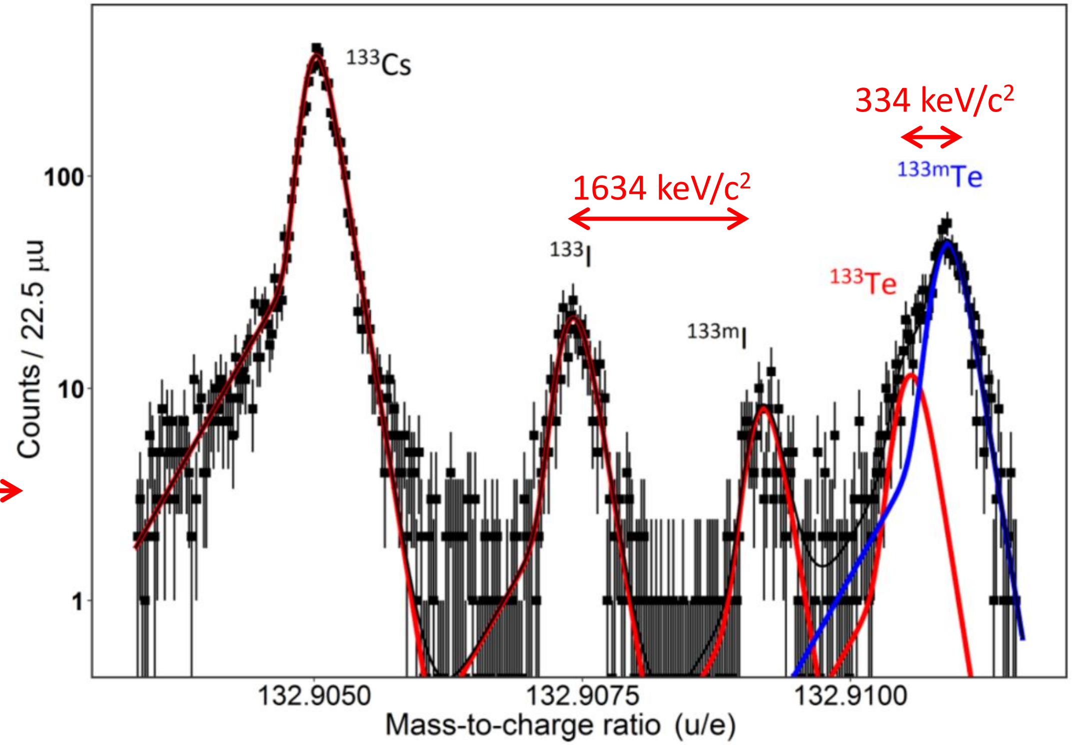
- Fast → access to short-lived ions
- Sensitive, broadband, non-scanning → efficient, access to rare ions
- Enables high mass resolving power and accuracy

Short-lived ions measured at the FRS Ion Catcher:

- With RIB: ^{212}Rn (23.9 ms), ^{213}Rn (19.5 ms), ^{220}Ra (17.9 ms)
- Offline: ^{215}Po (1.8 ms)

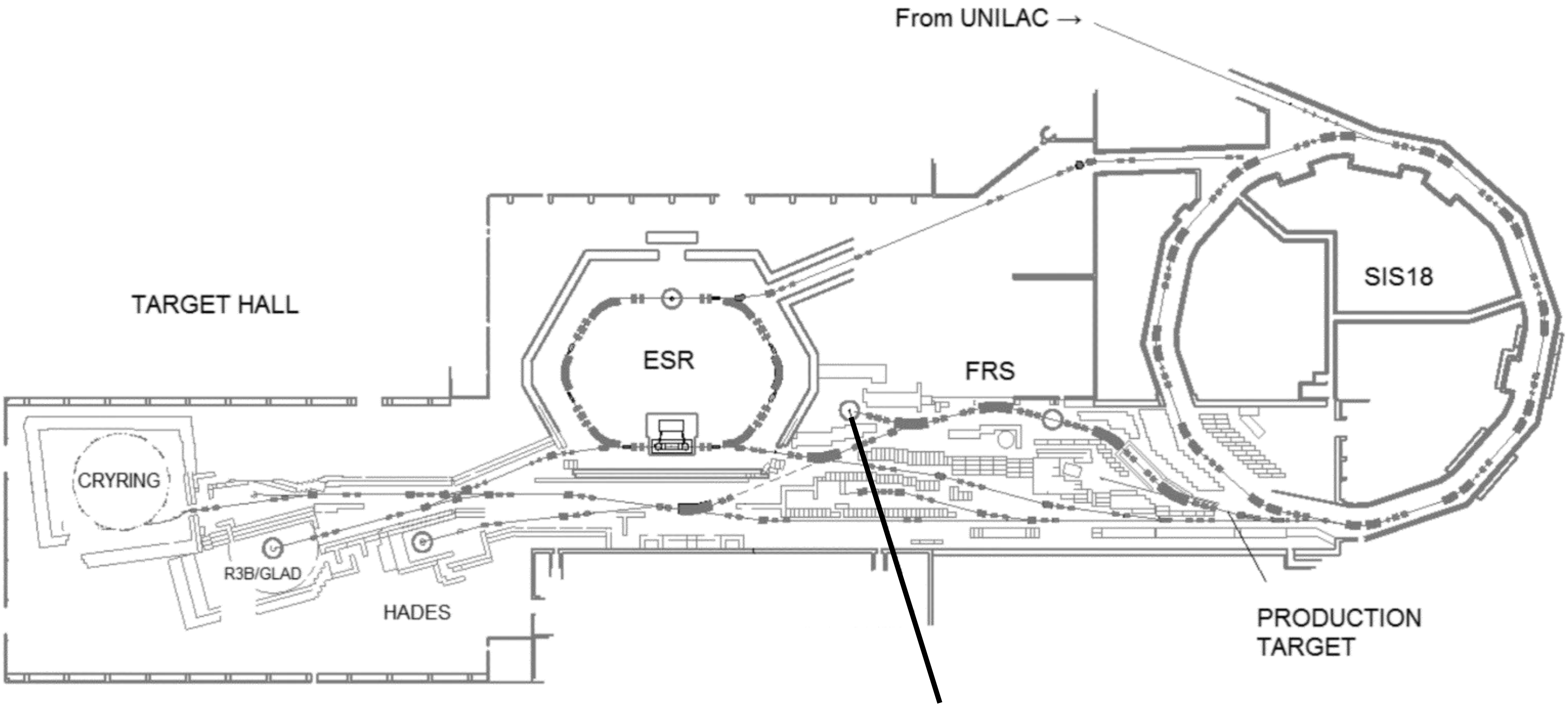
A.-K. Rink, PhD thesis, JLU Gießen (2017)

Resolving power: $m/\Delta m = 410{,}000$



S. Ayet *et al.*, PRC 99 (2019) 064313

The FRS Ion Catcher at GSI



FRS Ion
Catcher

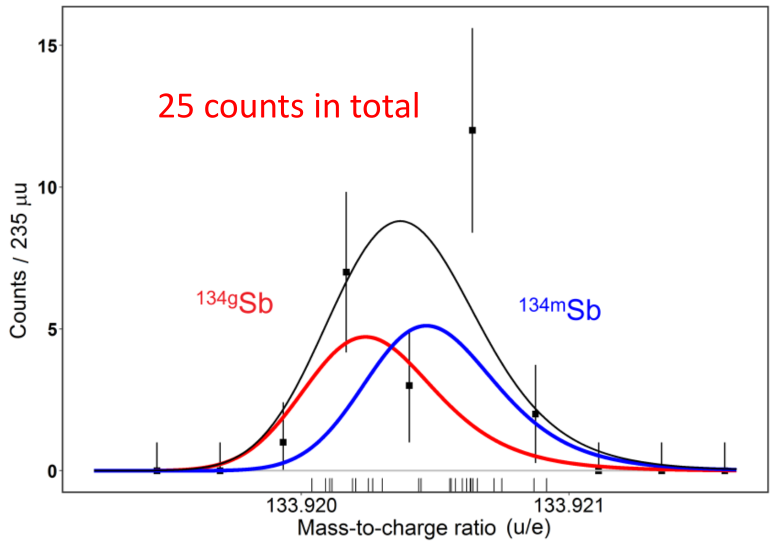
Data analysis procedure

Data-analysis procedure optimized for sensitivity and accuracy:

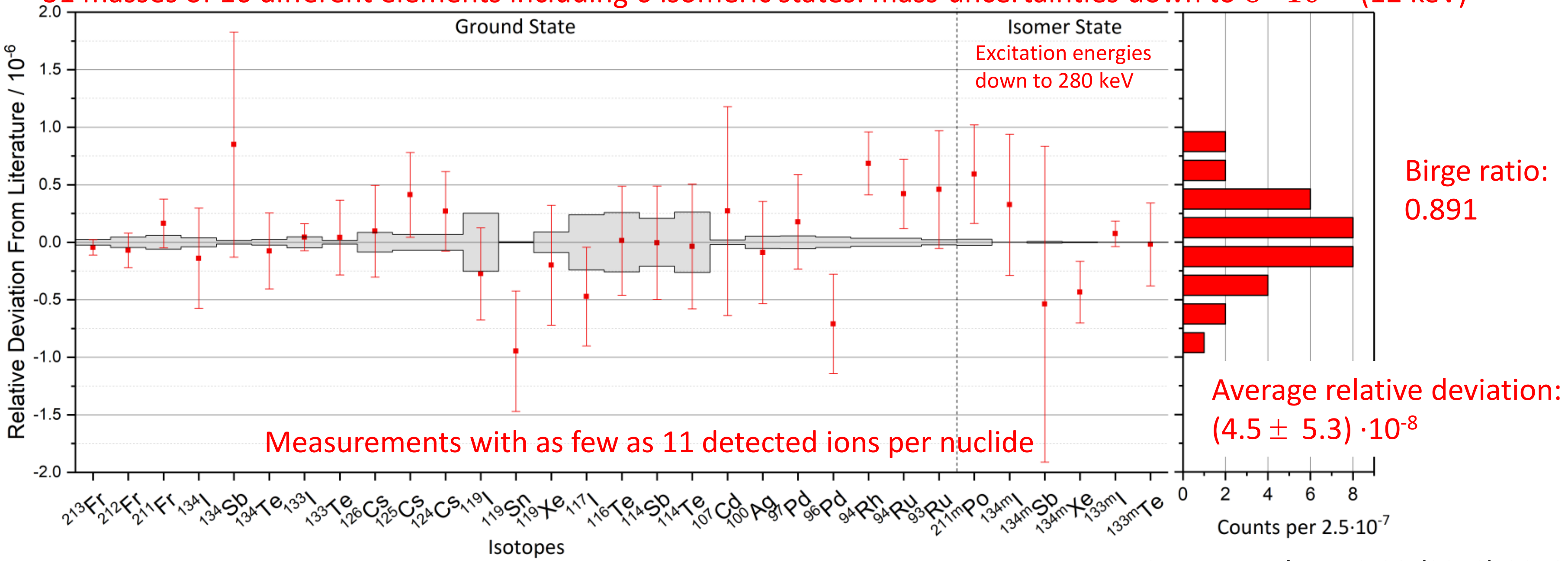
- Data evaluation developed for low statistics and overlapping peaks
- dedicated fit function – Hyper-EMG

  S. Purushothaman *et al.*, IJMS, 421, 245 (2017)

- accurate determination of uncertainties



31 masses of 16 different elements including 6 isomeric states: mass uncertainties down to $6 \cdot 10^{-8}$ (12 keV)



S. Ayet *et al.*, PRC 99 (2019) 064313