High-Resolution Mass Measurements at the FRS Ion Catcher in the Vicinity of ^{100}Sn

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Part of Super-FRS collaboration

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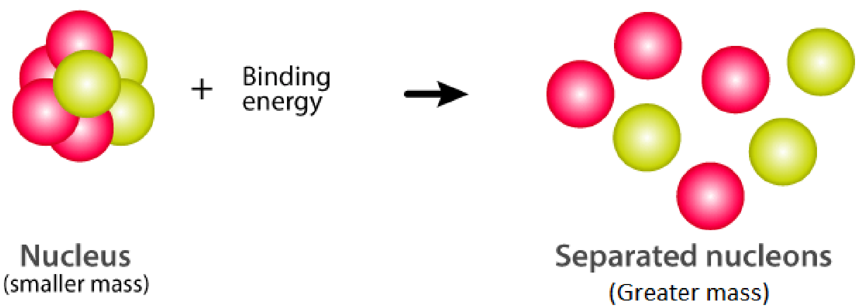
Mass and binding energy

Mass is one of the most fundamental properties of particles which reflects the **binding energy** of a bound system and can reveal information about its properties.



Sensitive prob for studying:

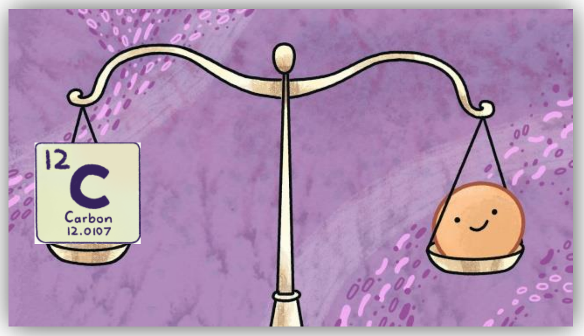
- ✓ Nuclear structure
- ✓ Shell evolutions
- ✓ Nuclear deformations
- ✓ Nucleon interactions
- ✓ Decay properties
- ✓ etc.

The mass of a neutral atom:

$$M = [(Z \times m_p) + (N \times m_n) - B_{nucleus} + (Z \times m_e) - B_{atom}]/c^2$$

Z: number of protons/electrons
N: number of neutrons
m_p and m_n: mass of free protons and neutrons
m_e: mass of free electron
$B_{nucleus}$: binding energy of nucleons
B_{atom}: binding energy of electrons
c: speed of light

Mass

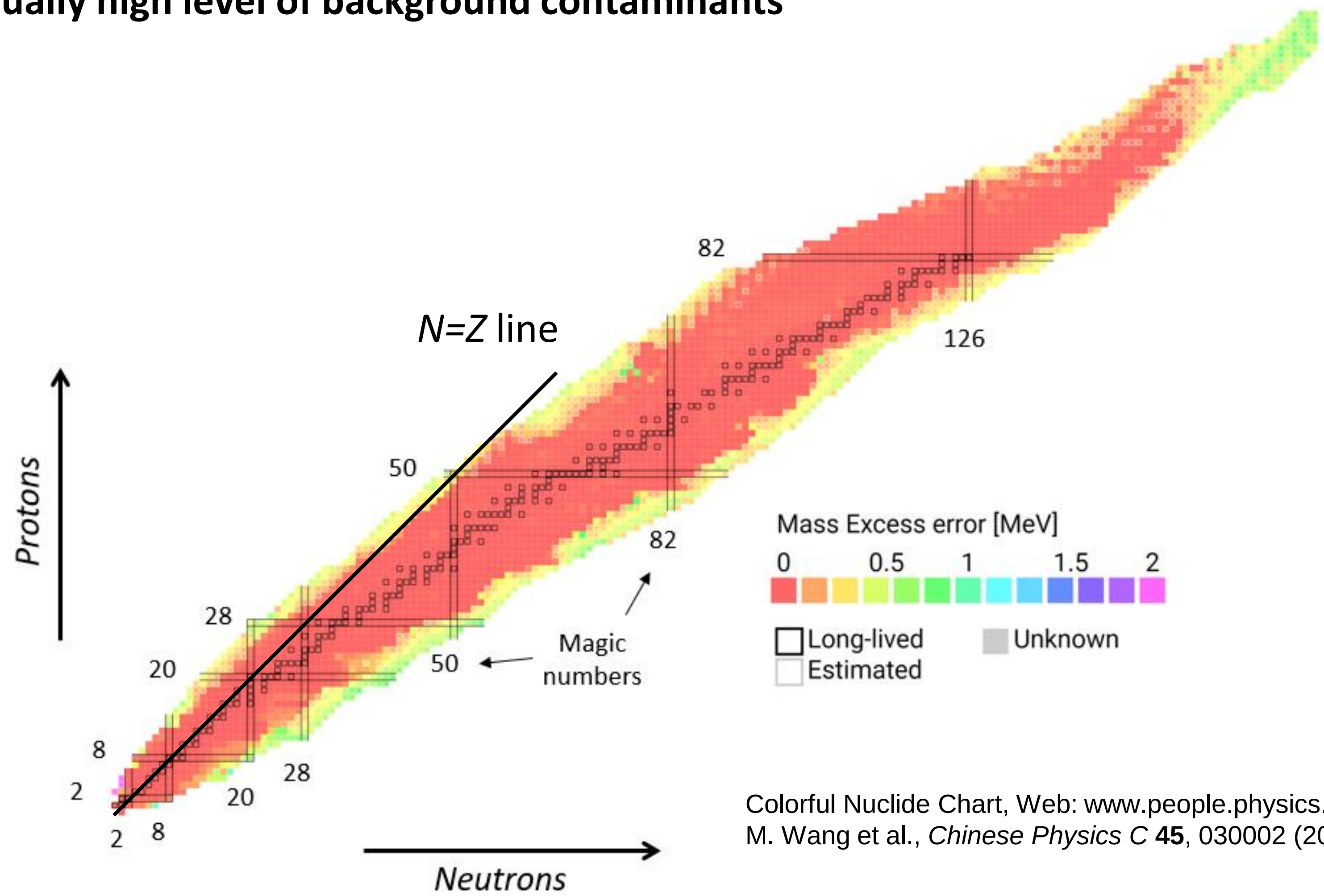


Experimental studies on exotic nuclei

Experimental challenges:

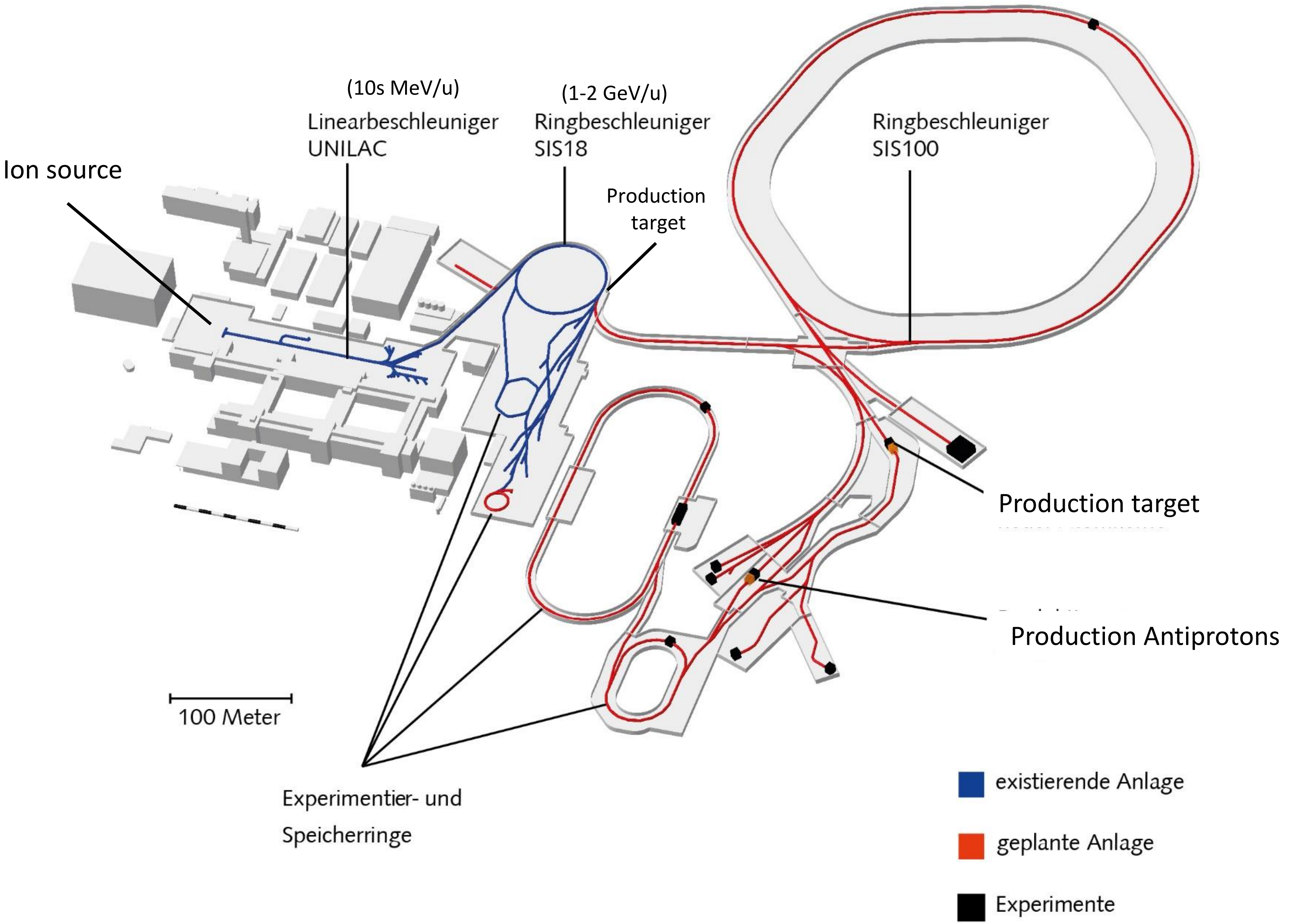
- **Low production cross section**
- **Short half-lives**
- **Usually high level of background contaminants**

need for fast and efficient experimental methods



Colorful Nuclide Chart, Web: www.people.physics.anu.edu.au
M. Wang et al., *Chinese Physics C* **45**, 030002 (2021)

Experimental facility in Germany (GSI/FAIR)



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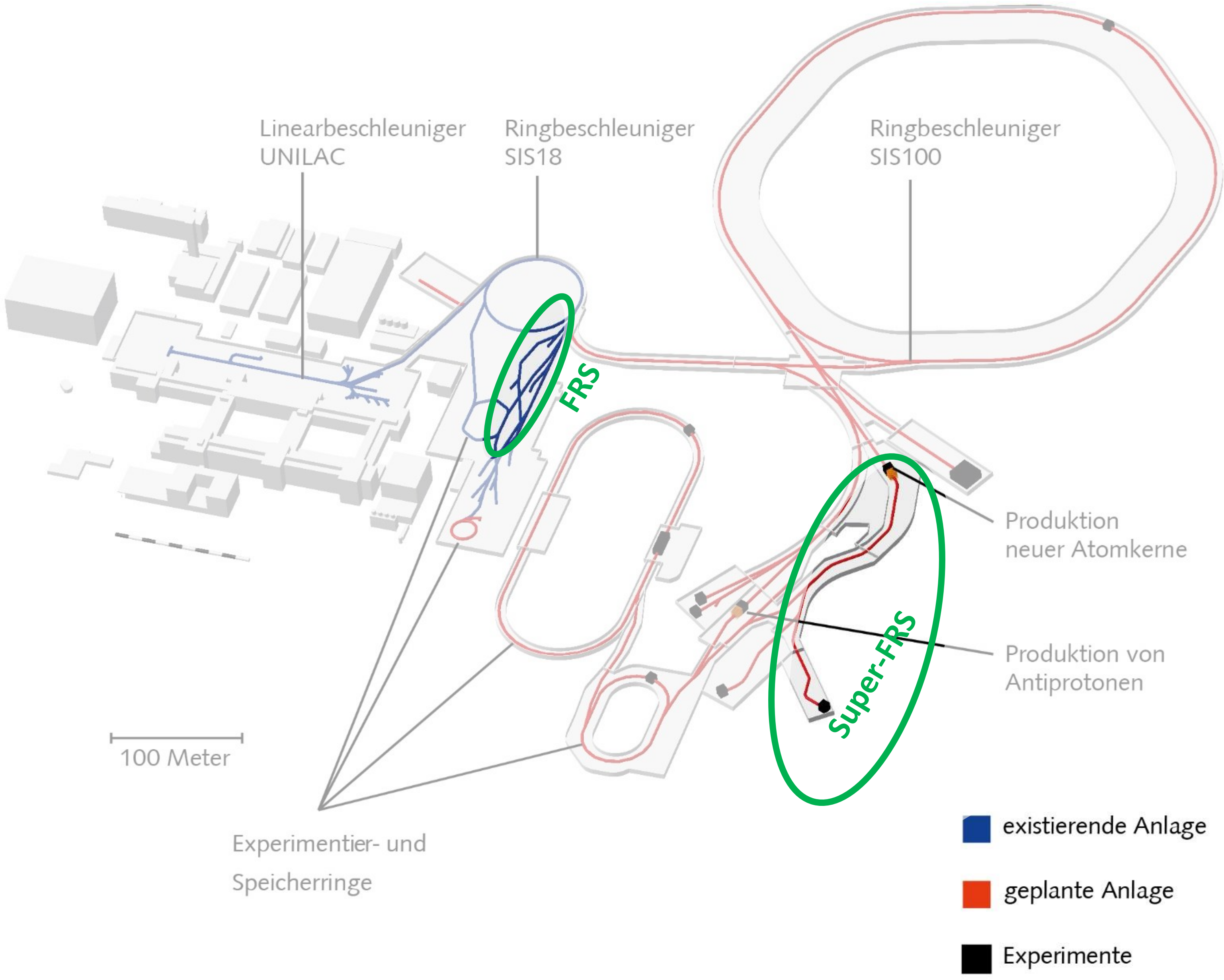
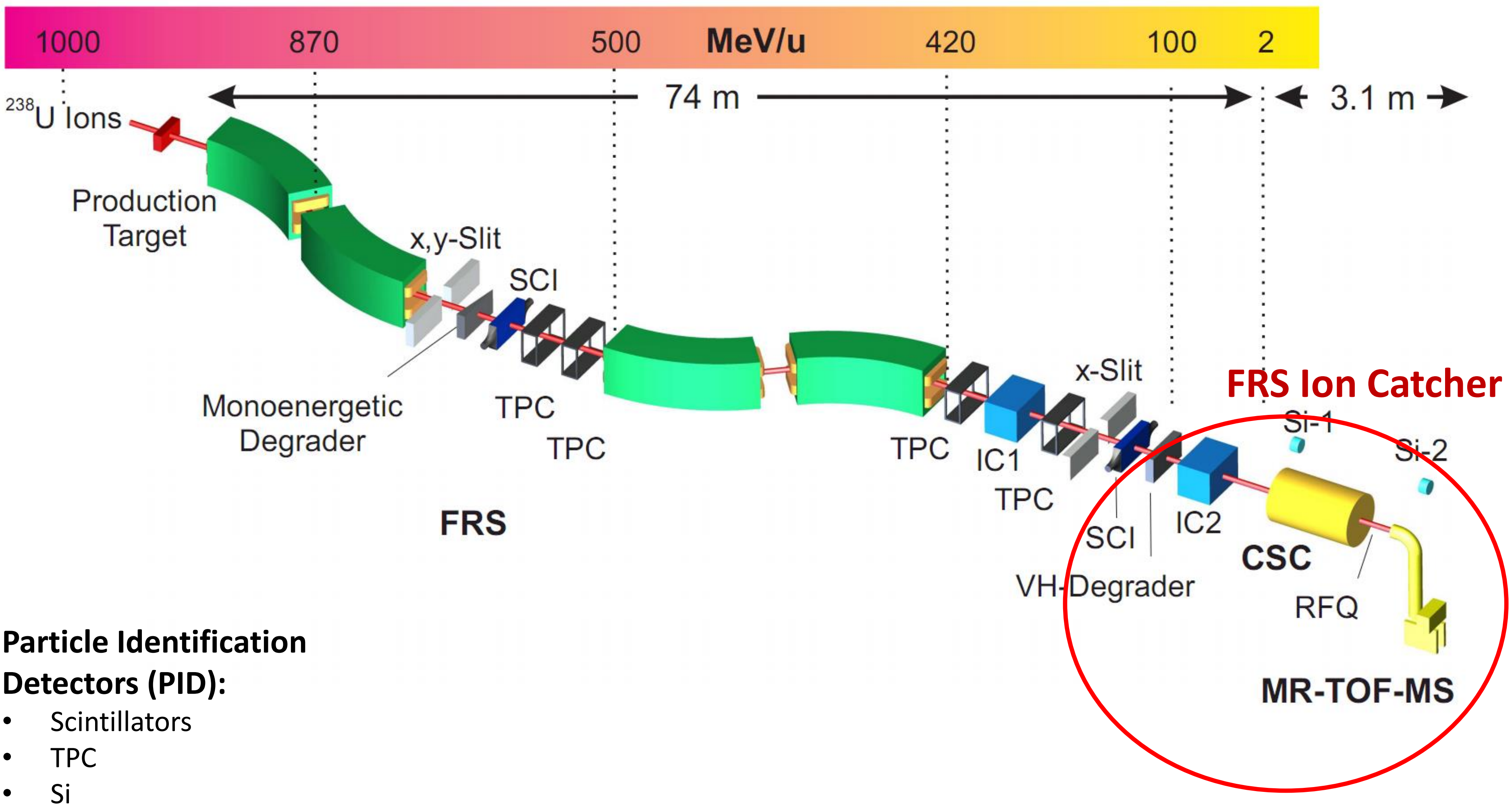


FRagment Separator (FRS)

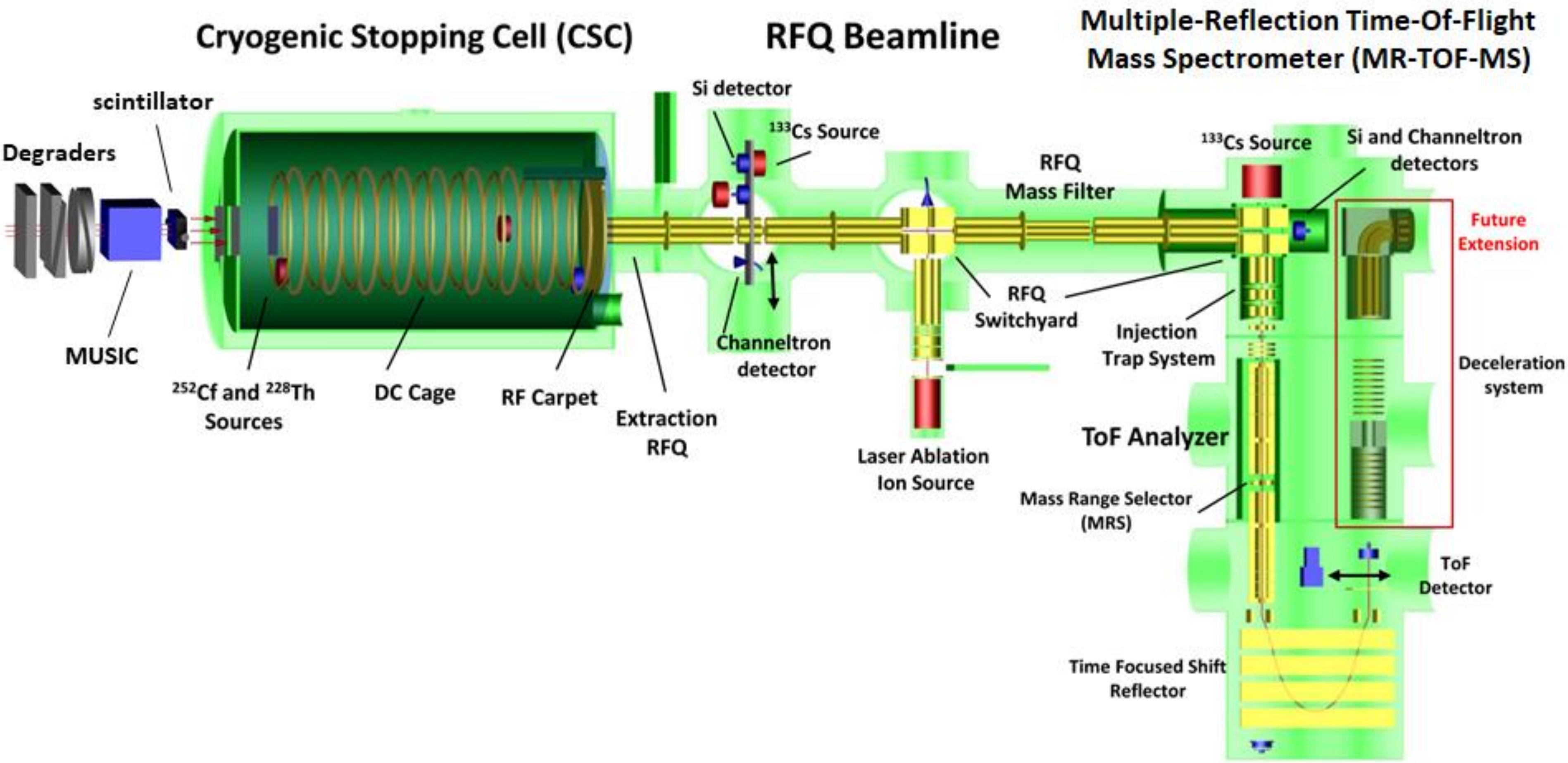
- **In-flight** isotope production and separation.
- High-resolution **mass spectrometer/separator** for the projectile fragmentation/fission products



Particle Identification Detectors (PID):

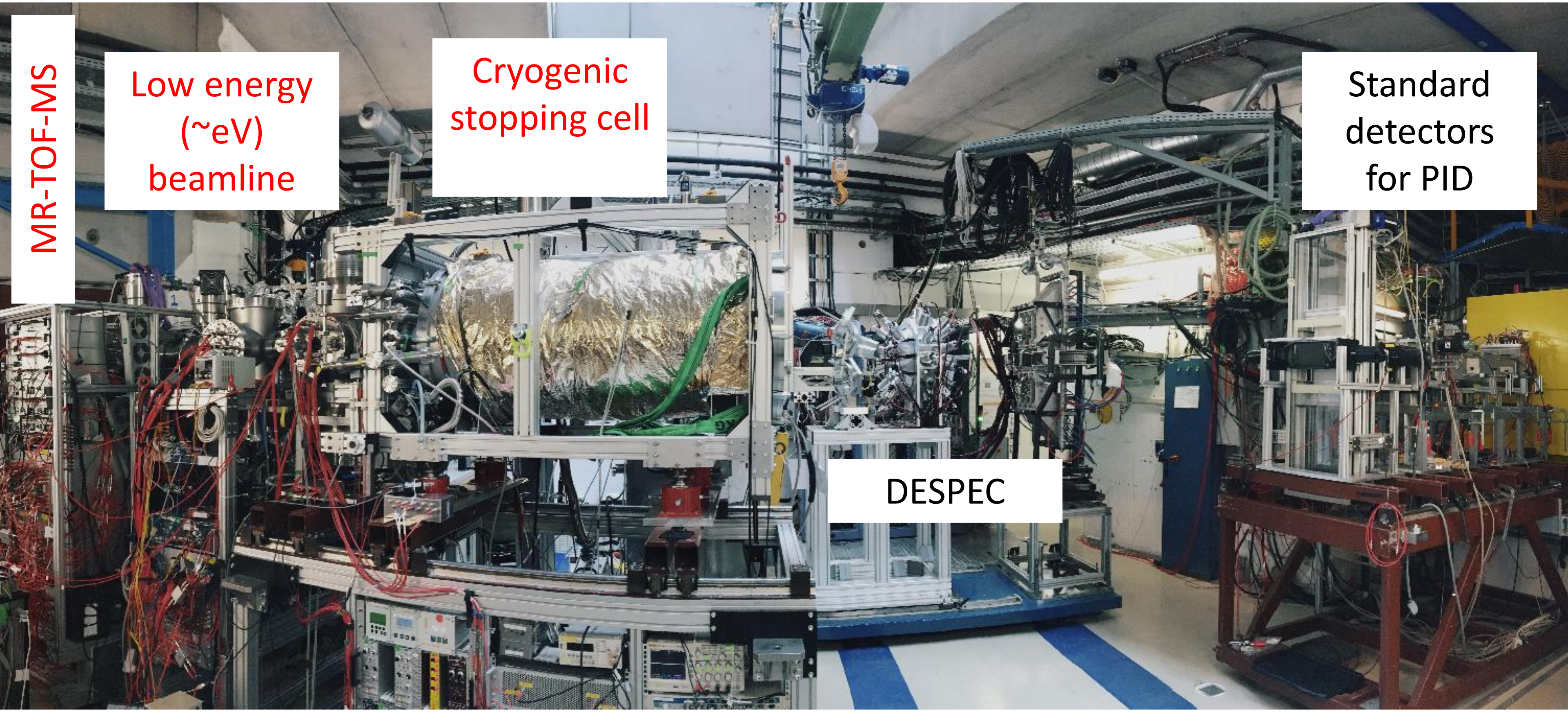
- Scintillators
- TPC
- Si
- MUSIC

FRS Ion Catcher (FRS-IC) setup



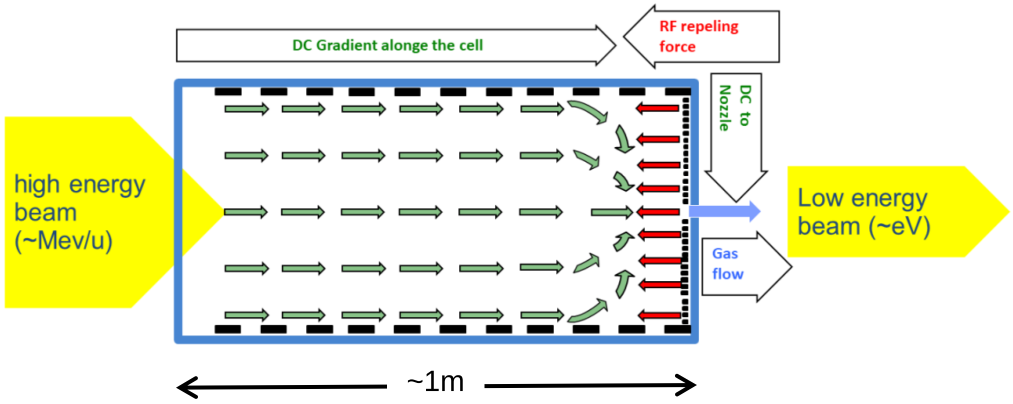
W.R. Plaß et al., NIM B **266** (2008)
W.R. Plaß et al., NIM B **317** (2013)
W.R. Plaß et al., Int. J. Mass Spectrometry **394** (2013)
T. Dickel et al., NIM A **777** (2015)

FRS Ion Catcher (FRS-IC) setup

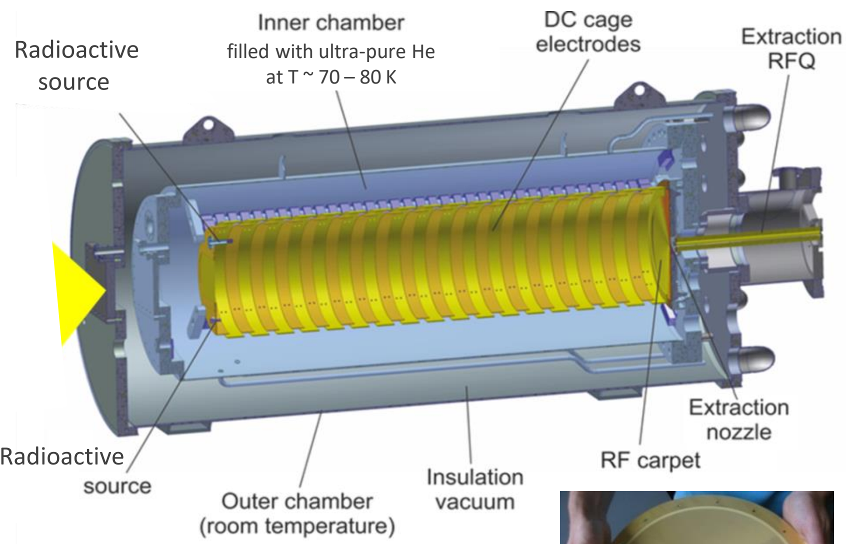


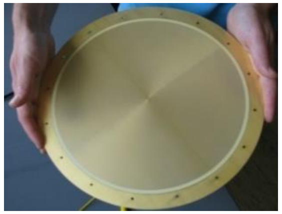
S. Purushothaman et al., IJMS 421 (2017) 245
W.R. Plaß et al, Hypefine Inter. 241 (2020) 1
I. Miskun et al., IJMS 459 (2021) 116450
W. R. Plaß et al., Phys. Scr. T166 (2015) 014069
E. Haettner et al., NIM A 880 (2018) 138
W.R. Plaß et al., Int. J. Mass Spectrometry **394** (2013)
M. Ranjan et al., Europhys. Lett. 96 (2011) 52001
S. Purushothaman et al., EPL 104 (2013) 42001
M. Ranjan et al., NIM A 770 (2015) 87
M.P. Reiter et al., NIM B 376 (2016) 240
F. Greiner et al., NIM B 463 (2020) 324
W.R. Plaß et al., NIM B **266** (2008)

Cryogenic Stopping Cell (CSC)



Stopping
and
thermalization
of ions in gas



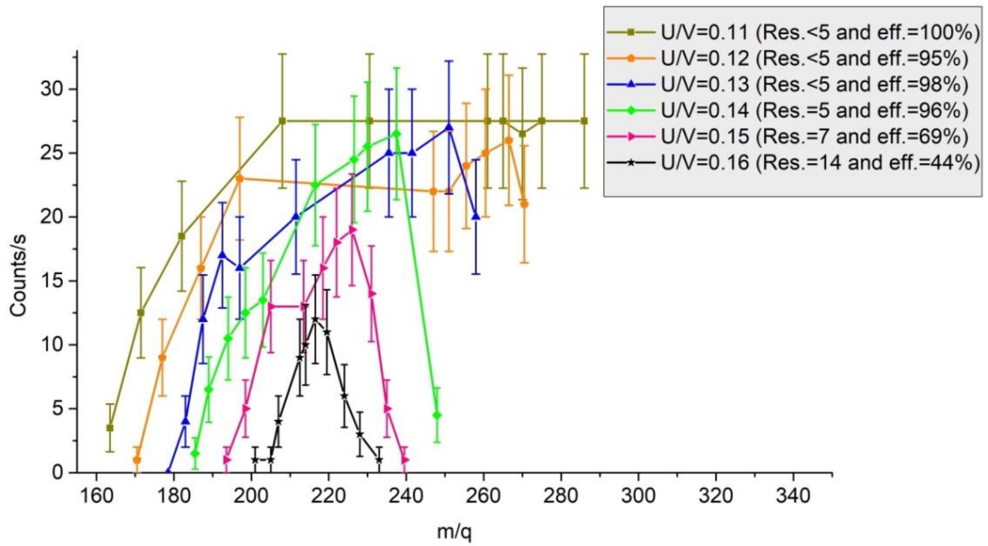


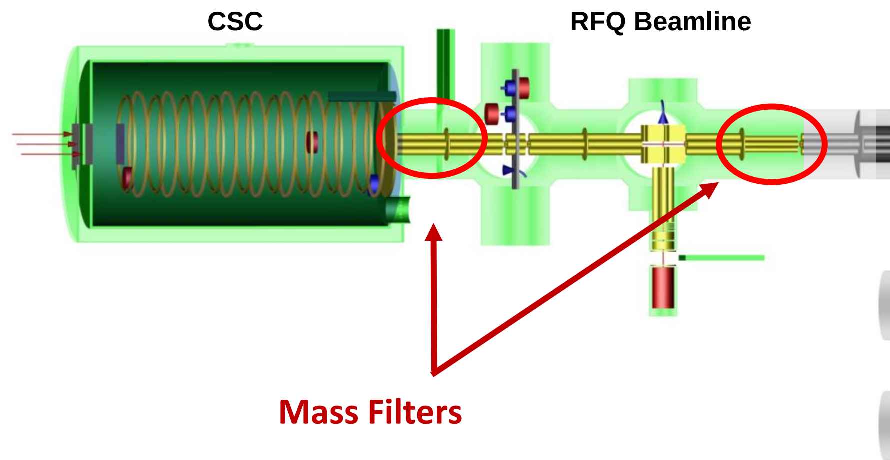
KVI, GSI, JLU

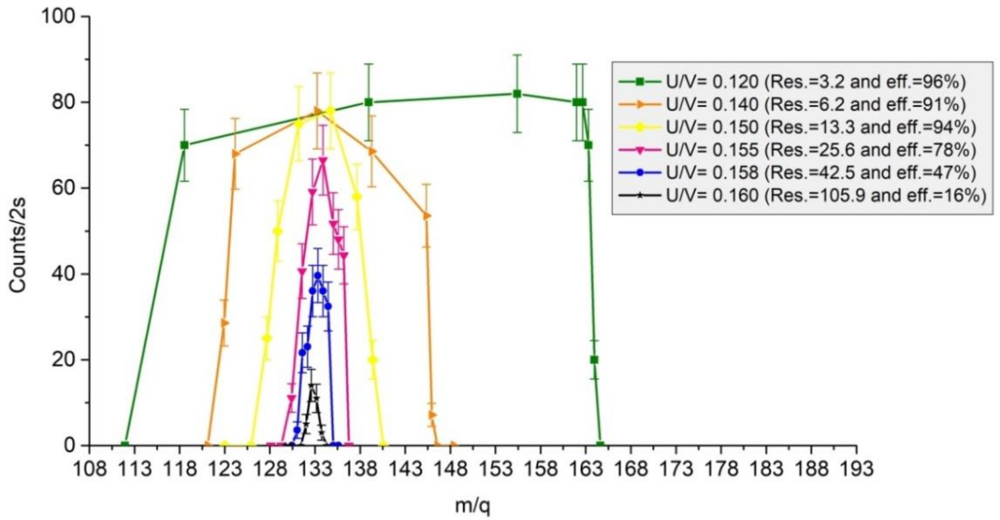
- **Helium-gas at cryogenic temperature**
- **Clean →** cold ion beams of high cleanliness
- **Universal →** element-independent extraction
- **Efficient →** high stopping and extraction efficiency
- **Fast →** access to short-lived exotic nuclides ($T_{1/2}$ ~ ms)

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

RFQ beamline and Mass Filters







- RF Quadrople for low-energy ion transport
- Can be used as a mass filter
- Collision-Induced-Dissociation (CID)
- Isolation-Dissociation-Isolation (IDI) [1]

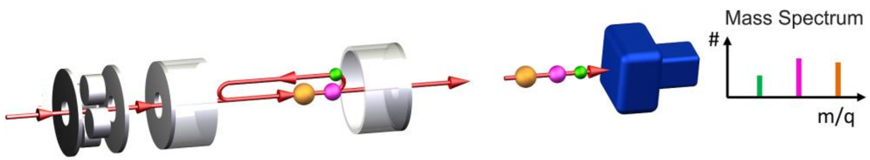
Background Suppression to MR-TOF (molecular and ions)

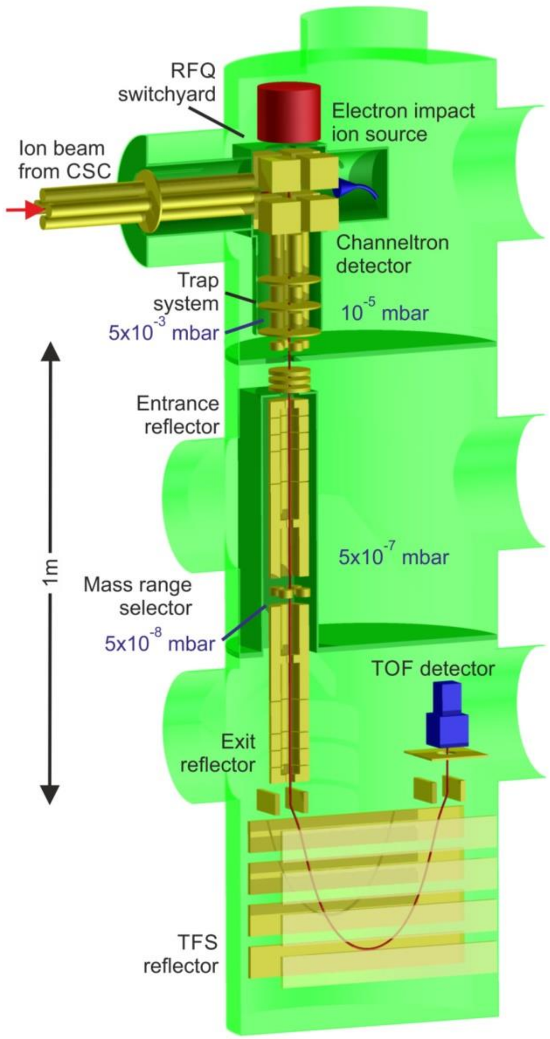
[1] F. Greiner et al., NIM B **463** (2020)

Mass measurement technique (MR-TOF-MS)

Fast, **sensitive**, **accurate**, **broadband** and **non-scanning** operation of MR-TOF-MS [1] suitable for the mass measurements of the most exotic nuclei far away from the valley of stability.

- Resolving power = 1,000,000 [2]
- Mass accuracy = 1.7 × 10^{-8} [2]
- Sensitivity = a few detected ions
- Rate capacity = 10^6 ions/s
- Cycle times = a few ms



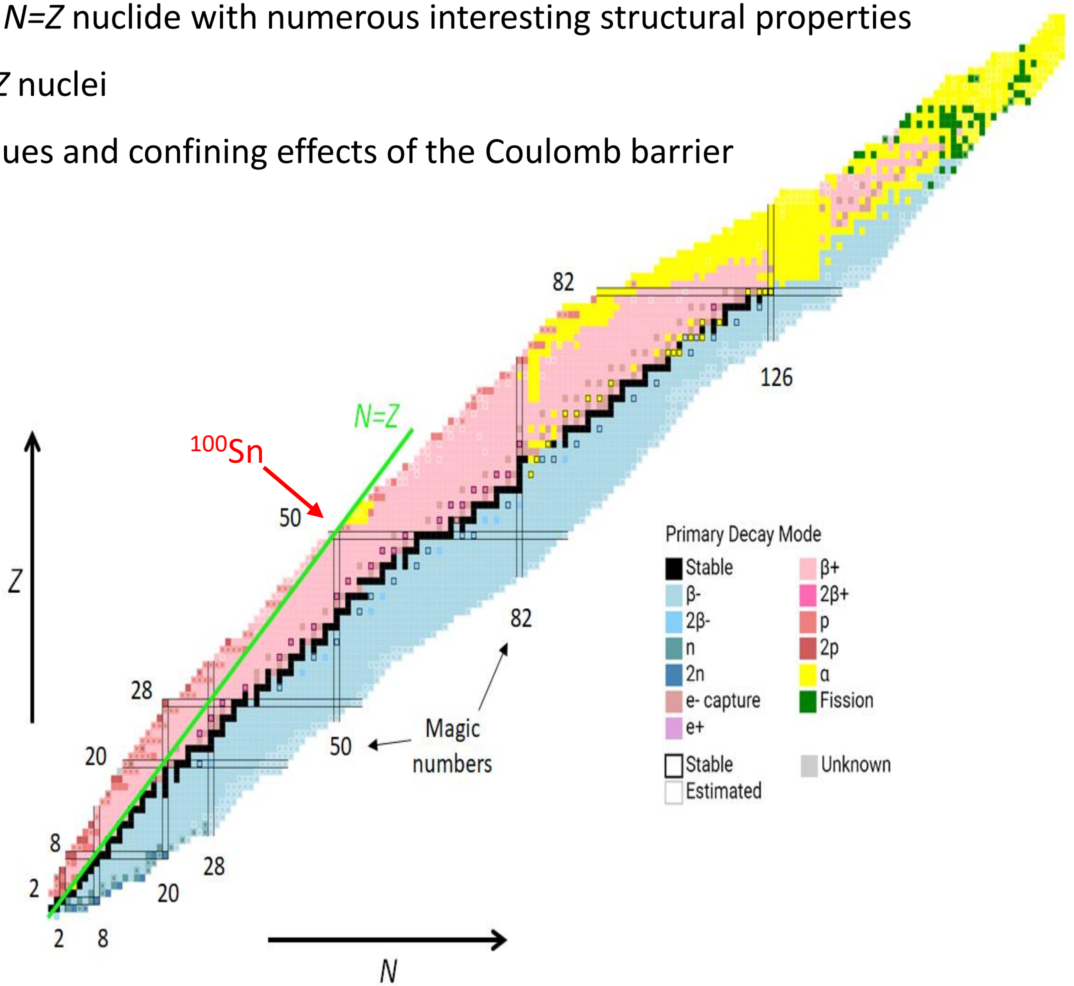


[1] T. Dickel et al., *Nucl. Intr. Meth. B* **376**, 216 (2016)
[2] I. Mardor et al., *PRC* **103**, 034319 (2021)

Mass measurements with MR-TOF-MS

Isotopes in vicinity of *N=Z* and ^{100}Sn

- The proton-neutron (pn) interaction in nuclear structure mechanisms for *N=Z* nuclei
- Light *N=Z* nuclei are better studied (closer to stability, long half-lives or stable)
- Heavy *N=Z* nuclei are challenging (closer to the proton drip-line, short half-lives and low production cross sections)
- Doubly-magic ^{100}Sn as the heaviest self-conjugate *N=Z* nuclide with numerous interesting structural properties
- Beyond ^{100}Sn: lies a region of proton unbound *N=Z* nuclei
- Below ^{100}Sn: shaped by pn-interaction, large Q-values and confining effects of the Coulomb barrier



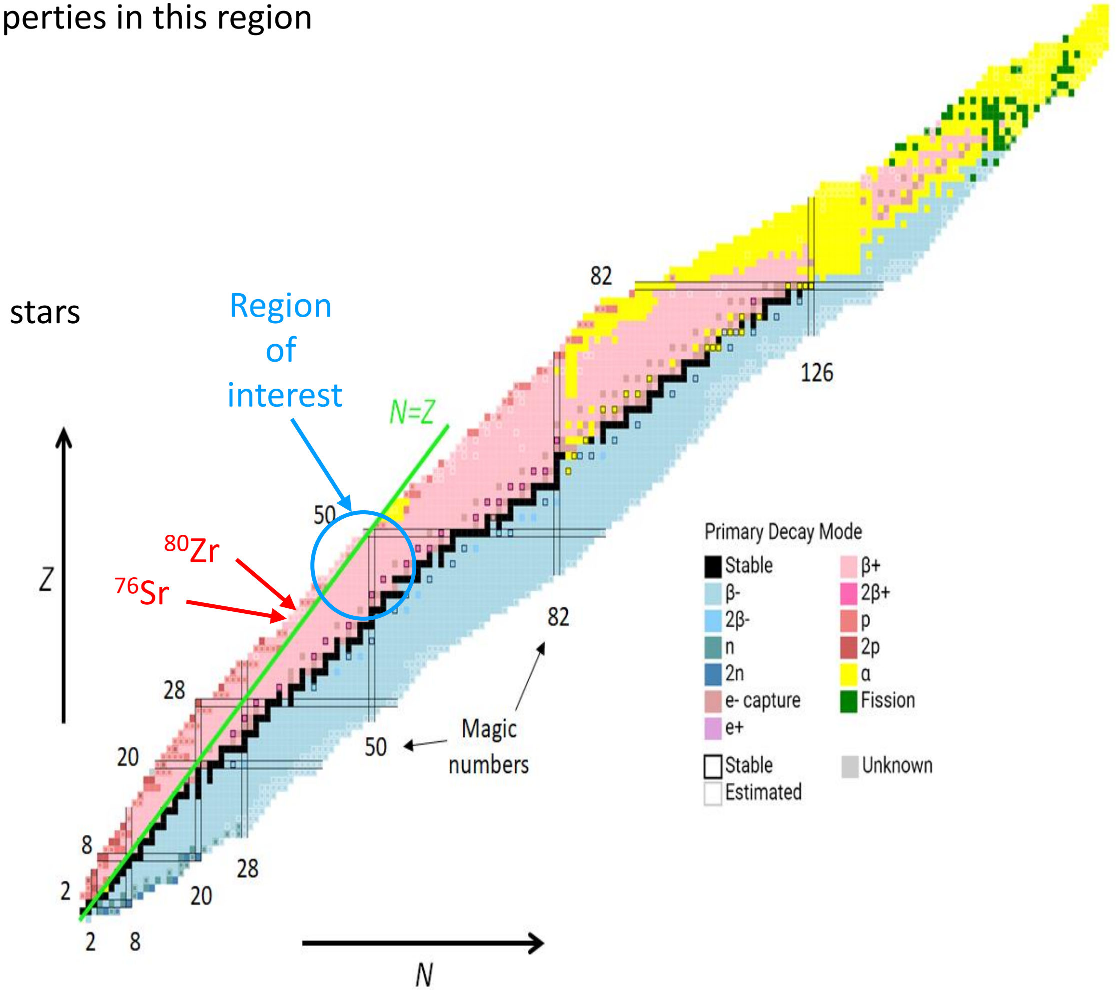
I. Mardor et al., *Physical Review* C **103** (2021)
D. Lubos et al., *Physical Review Letters* **122** (2019)
C. B. Hinke et al., *Nature* **486** (2012)
M. Mougeot et al., *Nature Physics* **17** (2021)
H. Morita et al., *Physical Review* C **98** (2018)

Isotopes in vicinity of *N*=*Z* and ^{100}Sn

- ○ The experimental access to ^{100}Sn is still limited, most of the data obtained originate from nuclei in its vicinity.
- ○ The region to probe the unique properties of doubly-magic ^{100}Sn and heavy *N*=*Z* nuclei
- ○ ^{76}Sr and ^{80}Zr are the heaviest *N*=*Z* mass measured so far (large gap toward closed shell *N*=*Z*=50)

- ○ Shed light on our understanding of nuclear properties in this region and supports the studies for:

- Nuclear structure of *N*=*Z* nuclei
- Wigner energy for *N*=*Z* nuclei
- Challenge the nuclear models in extreme cases
- Beta-delayed proton emission investigations
- X-ray burst studies involved in accreting neutron stars
- etc.



I. Mardor et al., *Physical Review* C **103** (2021)
D. Lubos et al., *Physical Review Letters* **122** (2019)
C. B. Hinke et al., *Nature* **486** (2012)
M. Mougeot et al., *Nature Physics* **17** (2021)
H. Morita et al., *Physical Review* C **98** (2018)

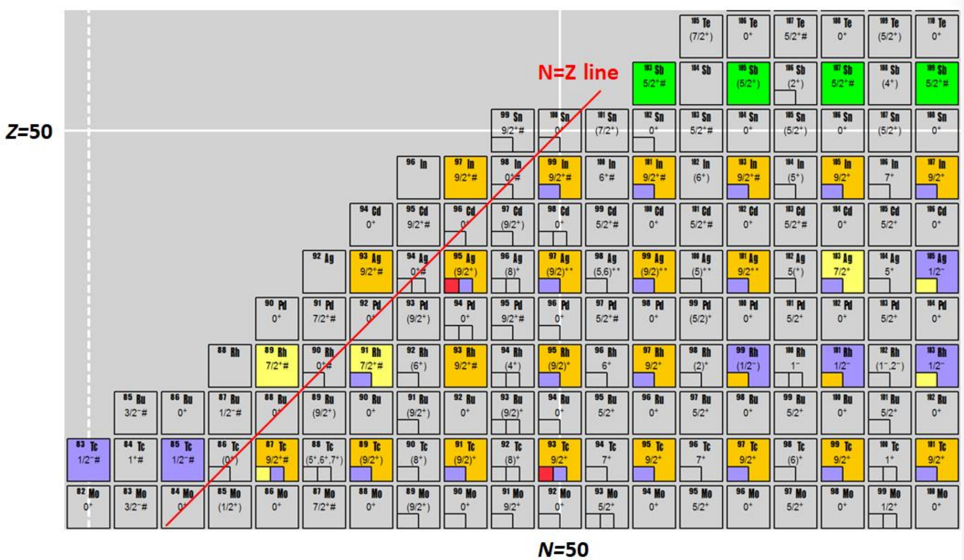
Long-lived isomers in this region

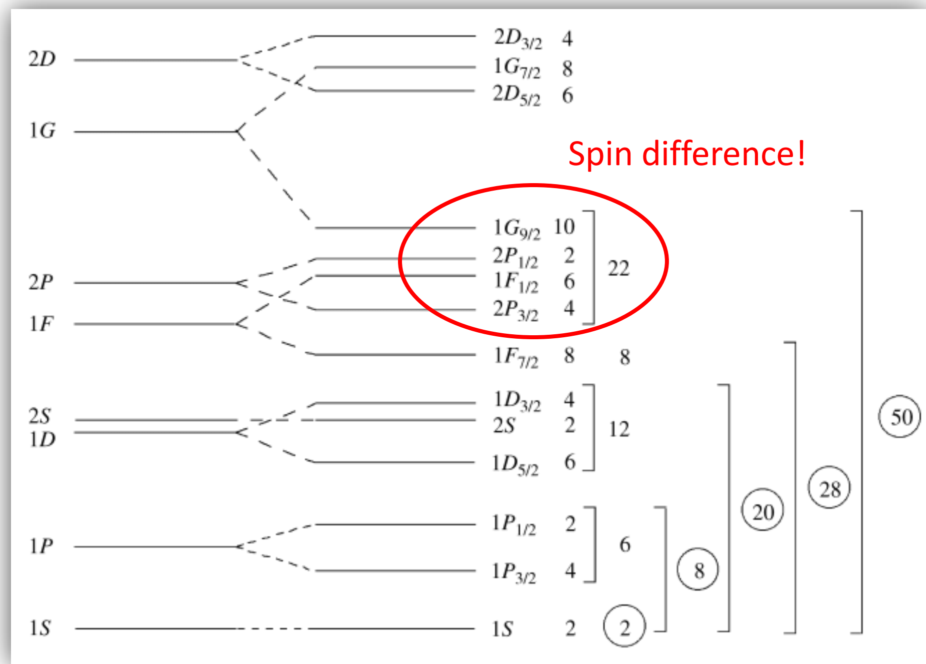
- Existence of nuclear isomers due to the major spin change of 1g9/2 and neighboring shell levels
- Interesting physics cases for understanding of the nuclear structure in this region
- Benchmark nuclear models and shell model calculations

odd-even isotopes :

9/2+ spin at ground state
1/2+ spin for isomers

Nuclear shell model





Isotopes in vicinity of ^{100}Sn at FRS

➢ **Projectile Fragmentation:**

Experiment I

^{124}Xe at 800 MeV/u with $1.5 \cdot 10^{9}$ ions/spill
(3s length, repetition rate 5s)

Beryllium target with 8.045 g/cm^2

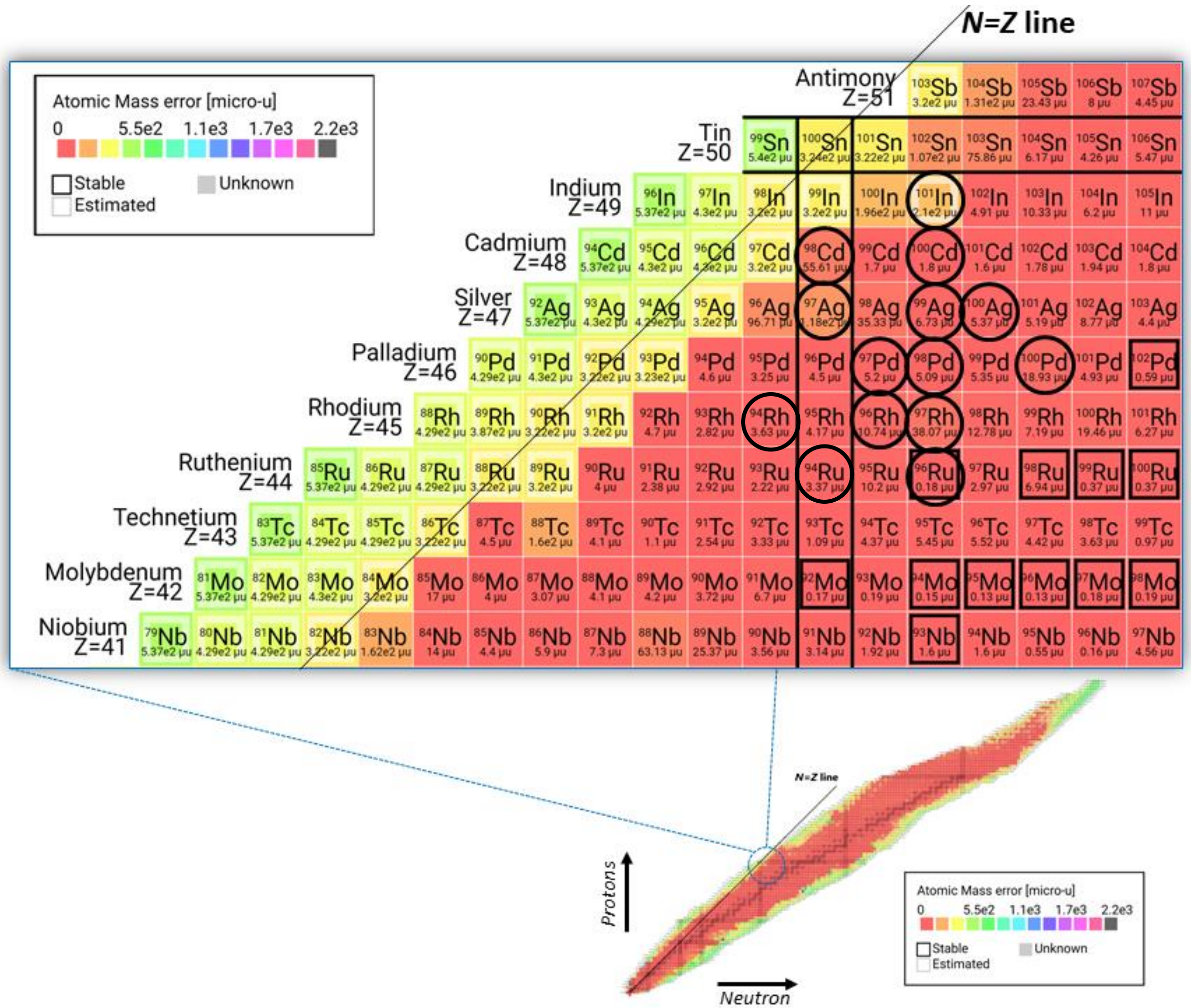
Stopping cell at 6.23 mg/cm^2
(85 K and 110 mbar Helium)

Experiment II

^{124}Xe at 600 MeV/u with $1 \cdot 10^{9}$ ions/spill
(0.5s length, repetition rate 4s)

Beryllium target with 1.622 g/cm^2

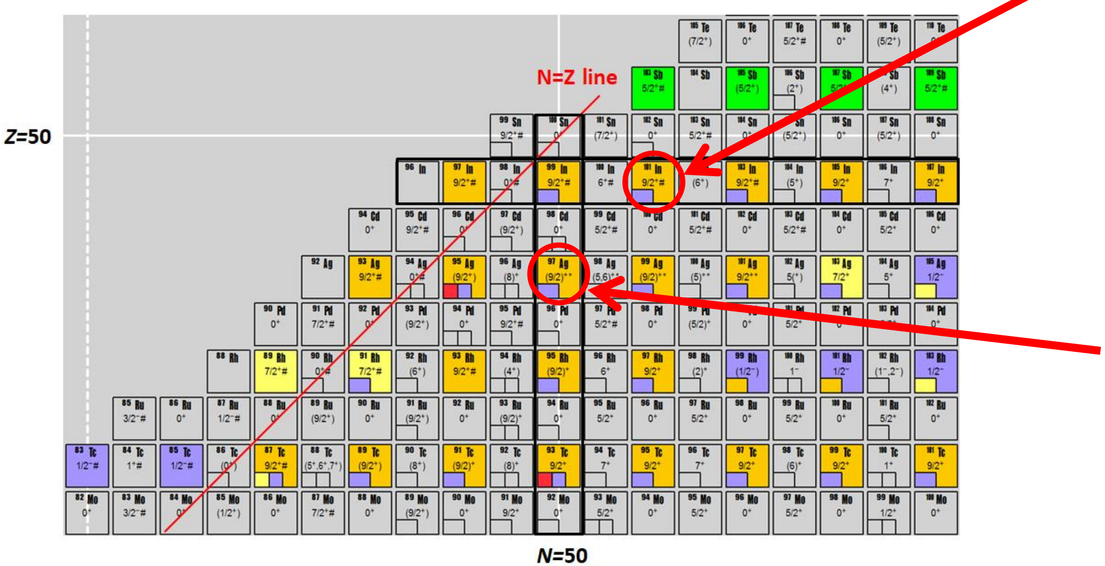
Stopping cell at 4.6 mg/cm^2
(82 K and 75 mbar Helium)

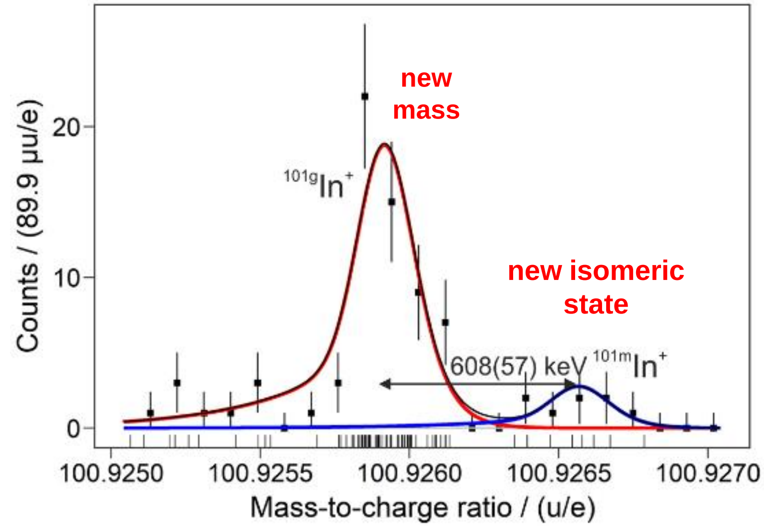


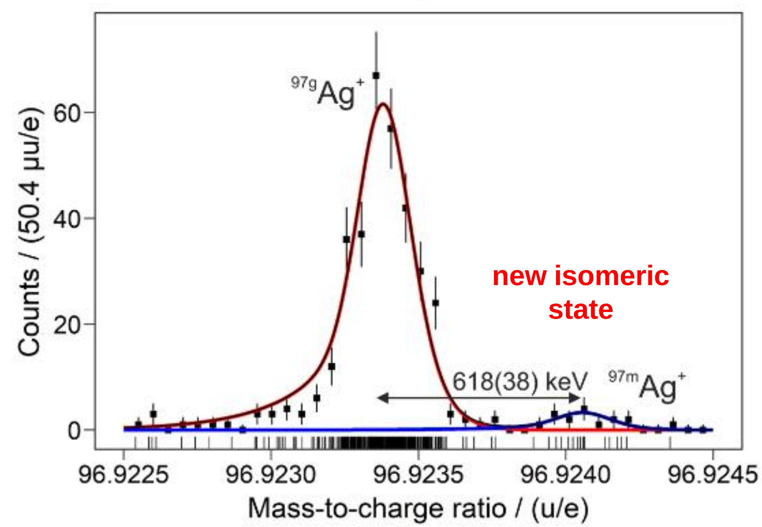
Long-lived isomers in this region

- Discovery of isomer in ^{97m}Ag together with the excitation energy of ^{101m}In
- First measurement of a nuclear isomeric state using MR-TOF-MS technique

Due to the high sensitivity and non-scanning measurement technique, MR-TOF-MS is an ideal device for new isomers search



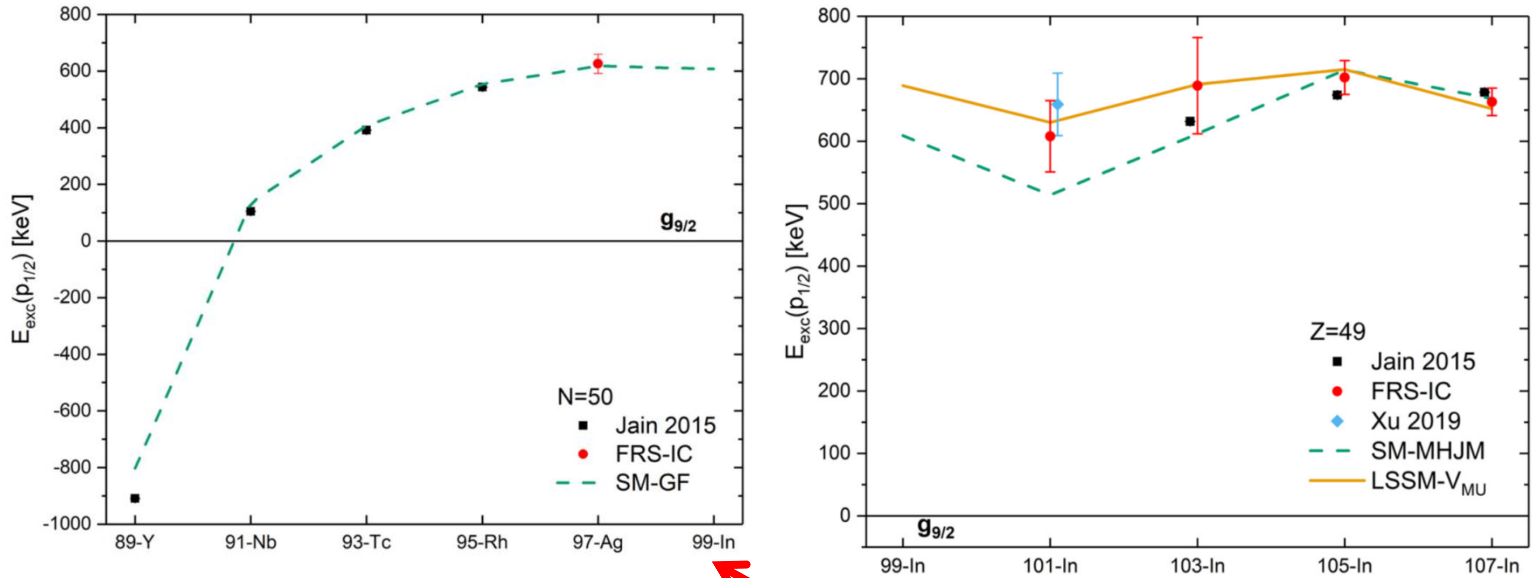


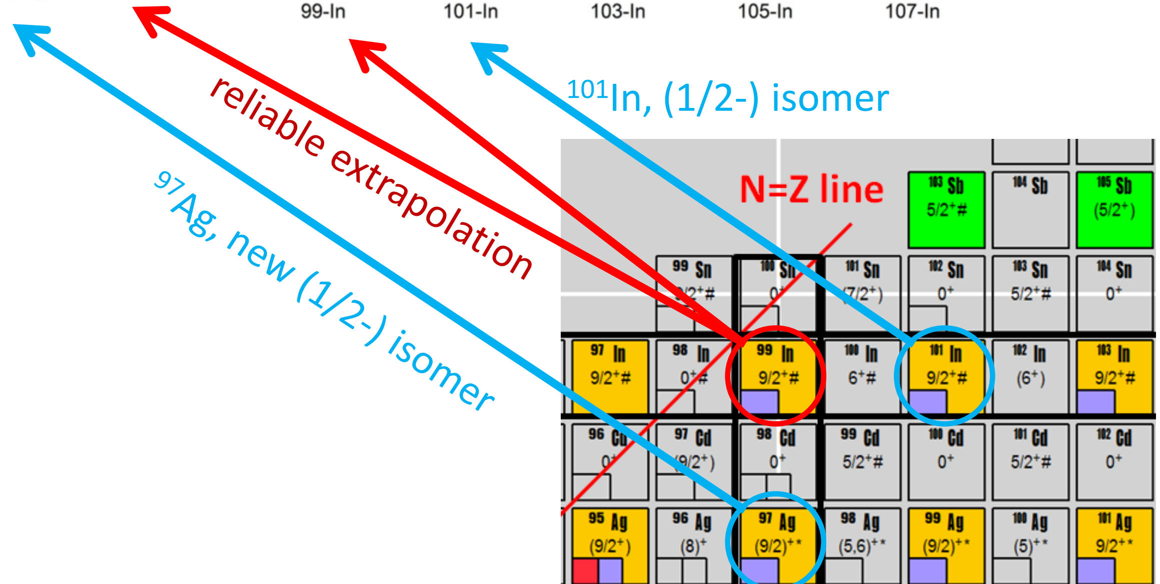


C. Hornung et al., PLB 802 (2020) 135200

Long-lived isomers in this region

- State-of-art theoretical calculations for odd-even nuclei on N=50 isotonic chain ad Z=49 isotopic chain
- Core excitation for the ^{99m}In excitation energy extrapolation (600-700 keV)

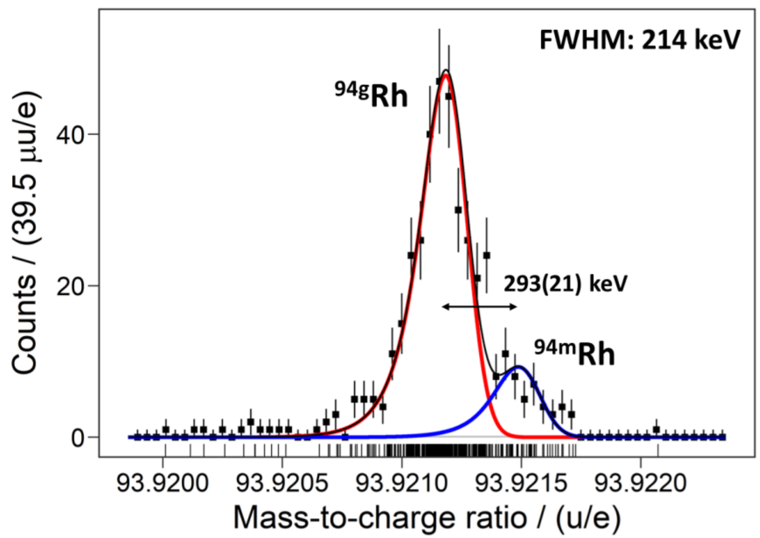




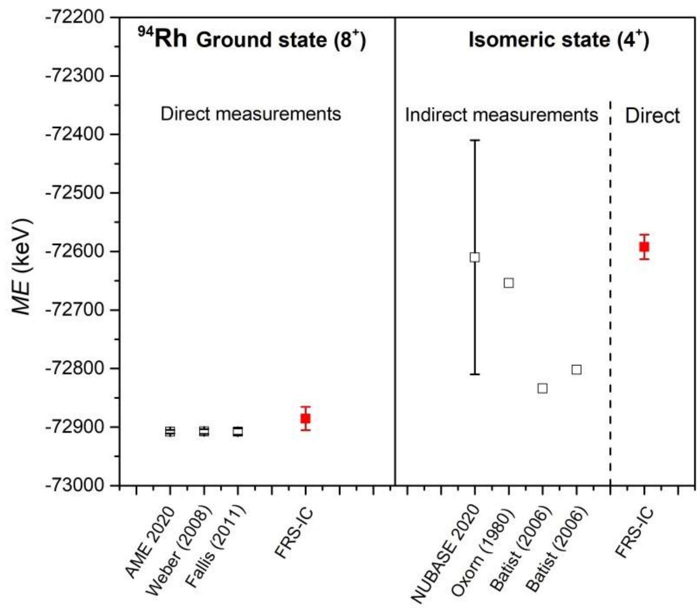
C. Hornung et al., PLB 802 (2020) 135200

^{94}Rh ground state and IS state

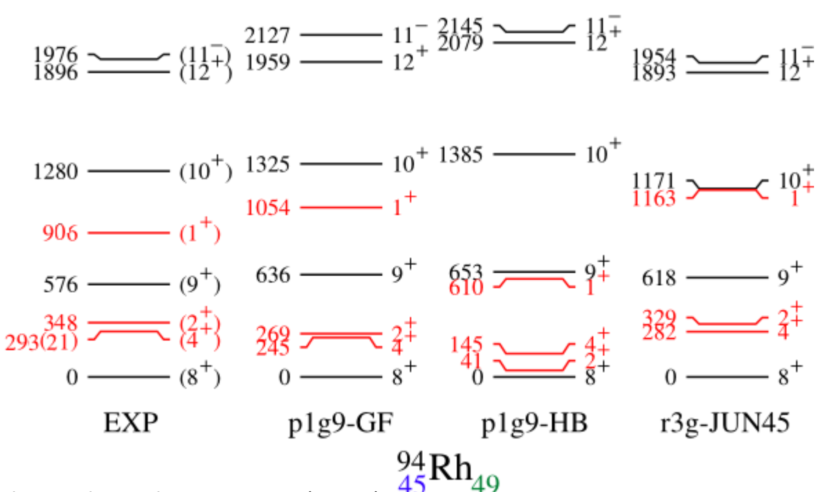
C. Hornung, PhD thesis, University of Giessen (2018)



- **Literature:**
  - two states with half-lives of order of seconds are reported ($t_{1/2}$ =70.6 s and 25.8 s).
  - the relative order of states and assigned spins are under discussion.
- **NUBASE2020:**
  - (4^+) to ground state with 70.6 s
  - (8^+) to isomeric state with 25.8 s and only extrapolated excitation energy (#300±#200 keV)



Shell model calculations



K. Oxorn et al., *Physik A* **294** (1980)
C. Weber et al., *Physical Review C* **78** (2008)
L. Batist et al., *Eur. Phys. Jour. A* **29** (2006)

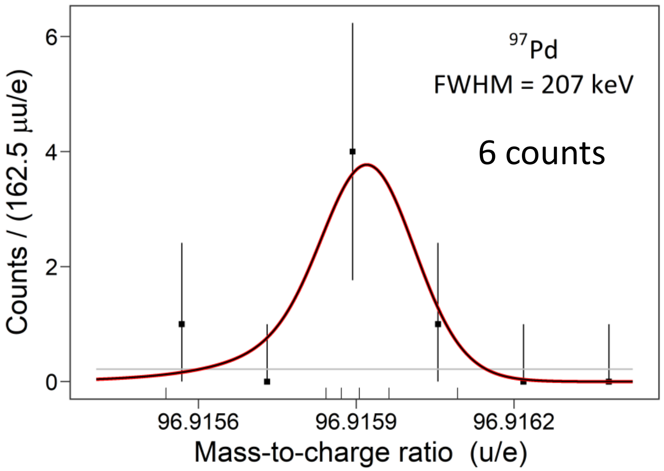
R. Gross et al., *Nuclear Physics A* **267** (1976)
H. Herndi et al., *Nuclear Physics A* **627** (1997)
M. Honma et al., *Physical Review C* **80** (2009)

Hubert Grawe
Magdalena Gorska

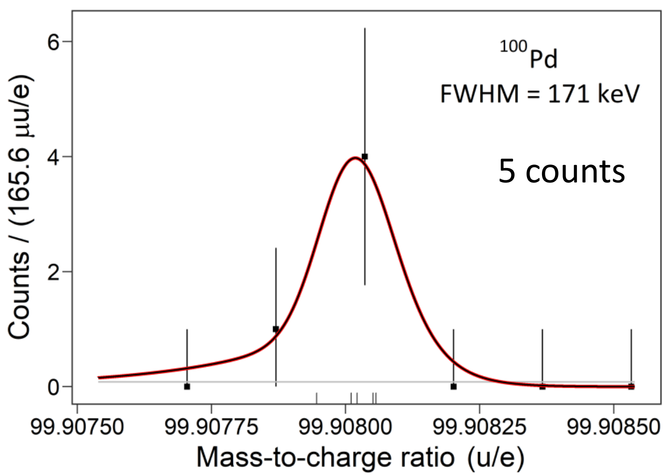
Benchmark of low statistics cases

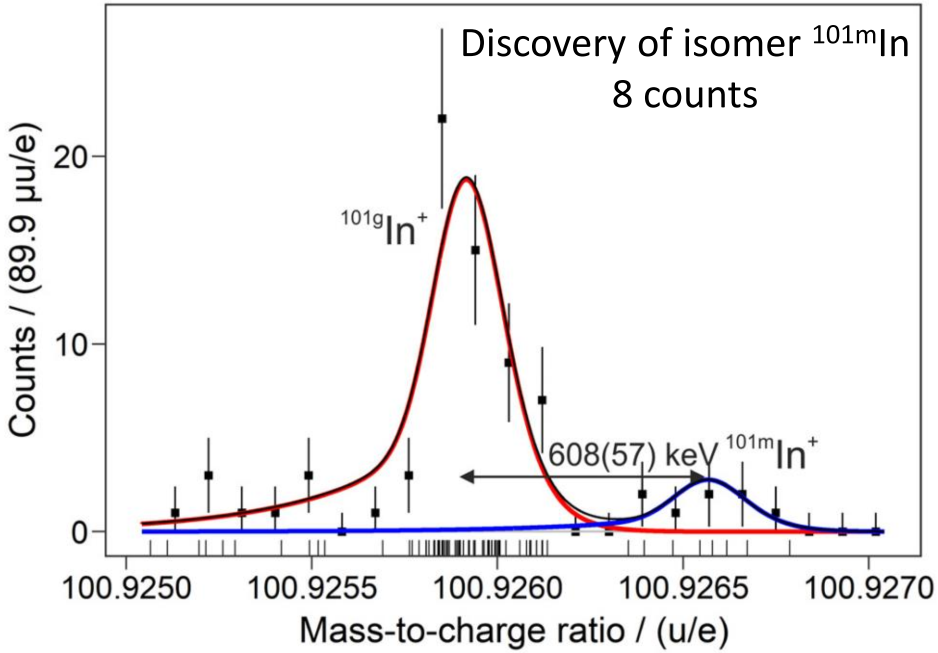
- High sensitivity and reliability of MR-TOF-MS for a very-low number of identified ions

$ME_{\text{FRS-IC}} = -77830 \pm 69$ keV
$ME_{\text{AME20}} = -77806 \pm 5$ keV
$ME_{\text{FRS-IC (old)}} = -77798 \pm 37$ keV



$ME_{\text{FRS-IC}} = -85202 \pm 52$ keV
$ME_{\text{AME20}} = -85213 \pm 18$ keV

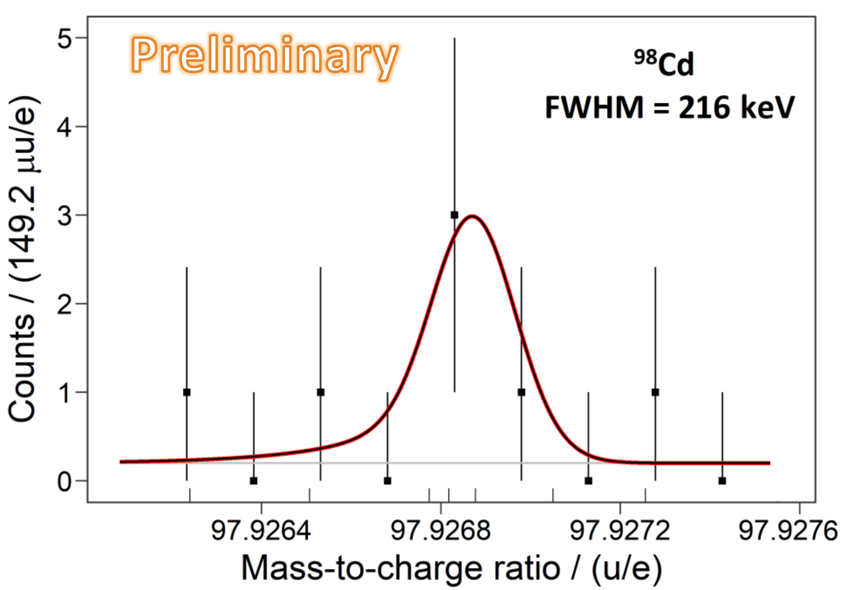


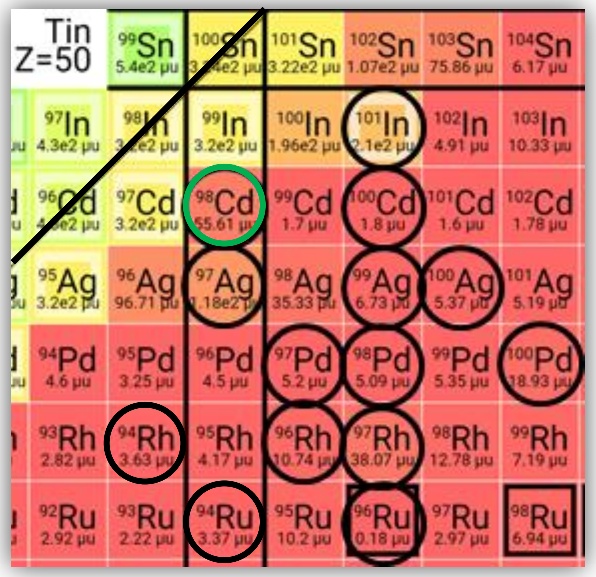


C. Hornung et al., *Physics Letters B* **802** (2020)

First direct mass measurement on ^{98}Cd

- High sensitivity and high accuracy of MR-TOF-MS
- FRS-IC record for the smallest production cross section (18 nbarn)
- Measured in only 2 hours
- Sensitivity among the top sensitive measurements for Projectile-fragmentations





Summary

- Mass measurement of ground states and isomers produced by projectile fragmentation of ^{124}Xe at Fragment Separator (FRS) and FRS-Ion Catcher (FRS-IC)
- First discovery of ^{97m}Ag and excitation energy of ^{101m}In
- First measurement on ^{94m}Rh isomer with an excitation energy of 293(21) keV
- Shell model calculations for understanding the structure of states and spin-parity assignments
- New direct mass measurement of ^{98}Cd
- Sensitivity record for production of ^{98}Cd with cross section of only 18 nbarn in projectile fragmentation
- Goal: Push toward more exotic nuclei for mass measurements of heavy *N=Z* nuclei

Acknowledgements

FRS Ion Catcher Collaboration

D. Amanbayev, B. Ashrafkhani, O. Aviv, S. Ayet San Andrés, J. Äystö, S. Bagchi, D. Balabanski, S. Beck, J. Bergmann, A. Blazhev, Z. Brencic, S. Cannarozzo, O. Charviakova, P. Constantin, D. Curien, D. Das, I. Dedes, M. Dehghan, T. Dickel, J. Dobaczewski, J. Dudek, T. Eronen, T. Fowler-Davis, Z. Gao, Z. Ge, H. Geissel, S. Glöckner, M. Górska, T. Grahn, F. Greiner, L. Gröf, M. Gupta, E. Haettner, O. Hall, M. Harakeh, C. Hornung, J.-P. Hucka, Y. Ito, A. Jokinen, B. Kaizer, N. Kalantar-Nayestanaki, A. Kankainen, A. Karpov, Y. Kehat, L. Kilmartin, D. Kostyleva, G. Kripkó-Koncz, D. Kumar, N. Kuzminchuk, K. Mahajan, I. Mardor, A.A. Mehmandoost-Khajeh-Dad, N. Minkov, A. Mollaebrahimi, D. Morrissey, I. Moore, I. Mukha, G. Münzenberg, T. Murböck, M. Narang, D. Nichita, Z. Patyk, A. Perry, S. Pietri, A. Pikhtelev, W.R. Plaß, I. Pohjalainen, S. Pomp, S. Purushothaman, M.P. Reiter, M. Reponen, S. Rinta-Antila, H. Rösch, A. Rotaru, C. Scheidenberger, T. Schellhaas, P. Schury, A. Shrayer, 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, M. Wasserheß, H. Weick, M. Wieser, M. Will, H. Wilsenach, O. Yaghi, M.I. Yavor, J. Yu, A. Zadvornaya, J. Zhao

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