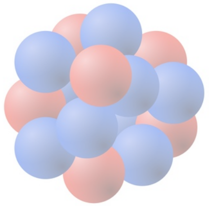
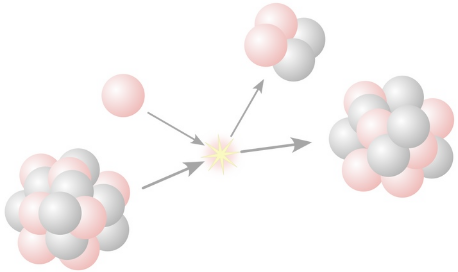
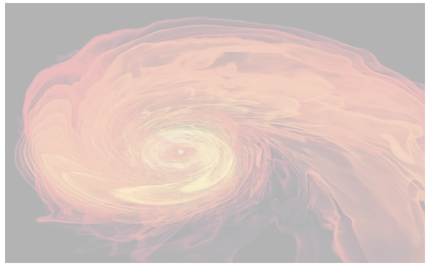
The success and future perspectives for high-precision atomic mass measurements using MRTOF-MS at RIBF

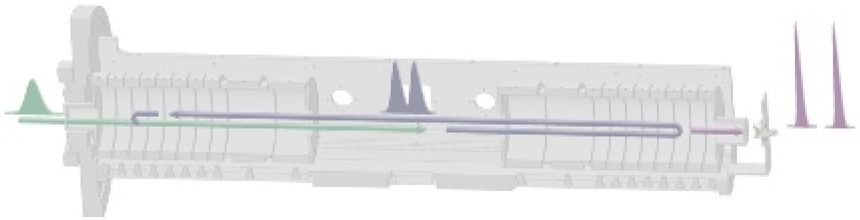


Marco Rosenbusch for RIKEN/SLOWRI and the WNSC-IPNS-KEK collaboration
RIKEN Nishina Center for Accelerator-based Science
2-1 Hirosawa, Wako, Saitama 351-0198, Japan



- **Little starter: a short overview of MRTOF setups at the RIBF facility**
- **MRTOF-MS and the new setup at BigRIPS/SLOWRI**
- **Essential tools to save our bread**
- **Timeline of the ZD MRTOF experiment**
- **Great recent results!**
- **How about future developments?**

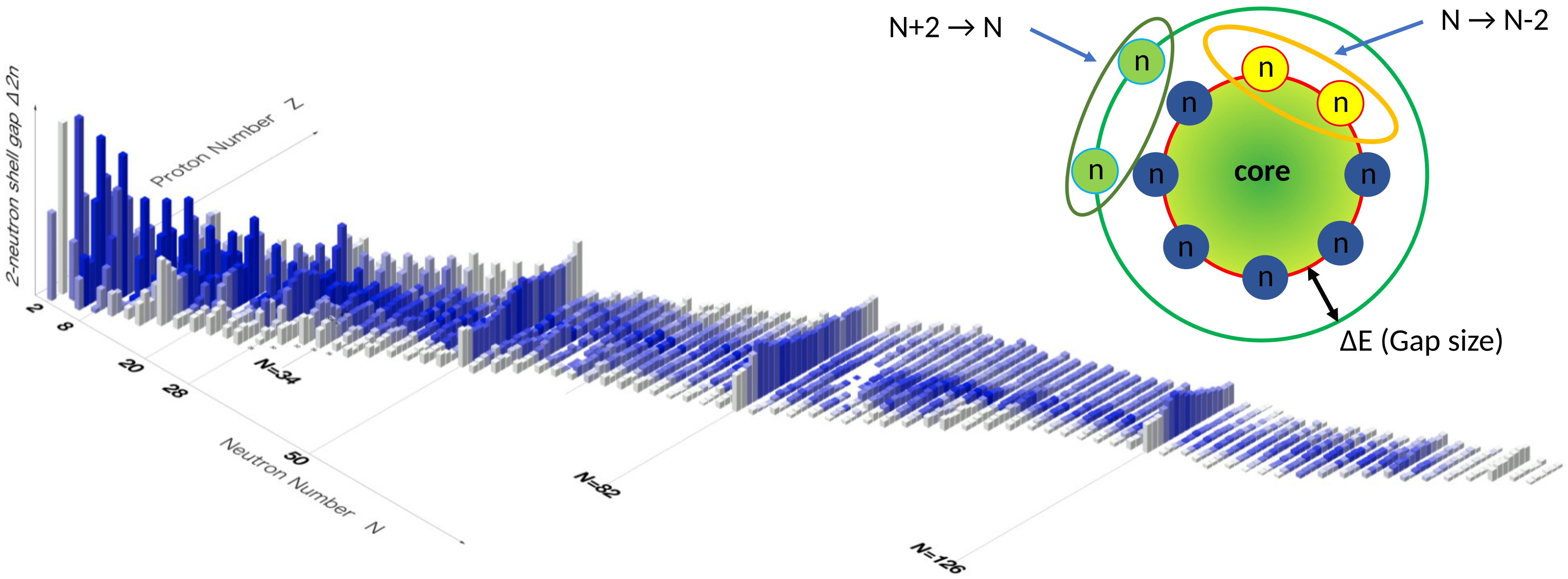




KEK-JAPAN

KEK Wako Nuclear Science Center

Masses for nuclear structure and astrophysics

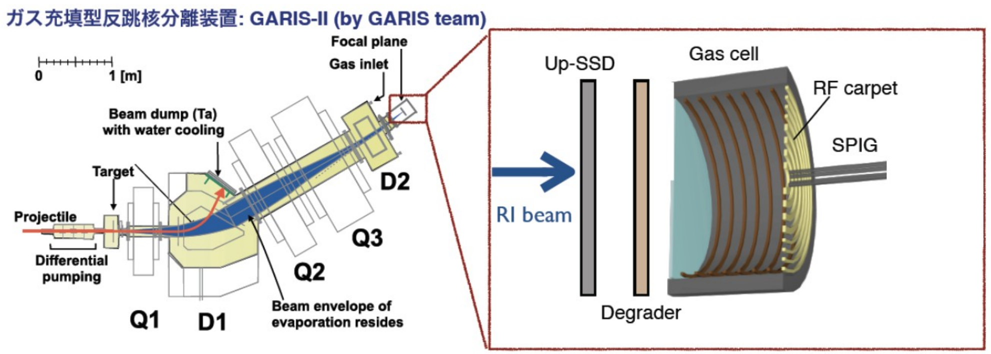


Nuclear structure by finite difference formulae

$$S_{2n}(N,Z) = m(N-2,Z) - m(N,Z) + 2m_n$$

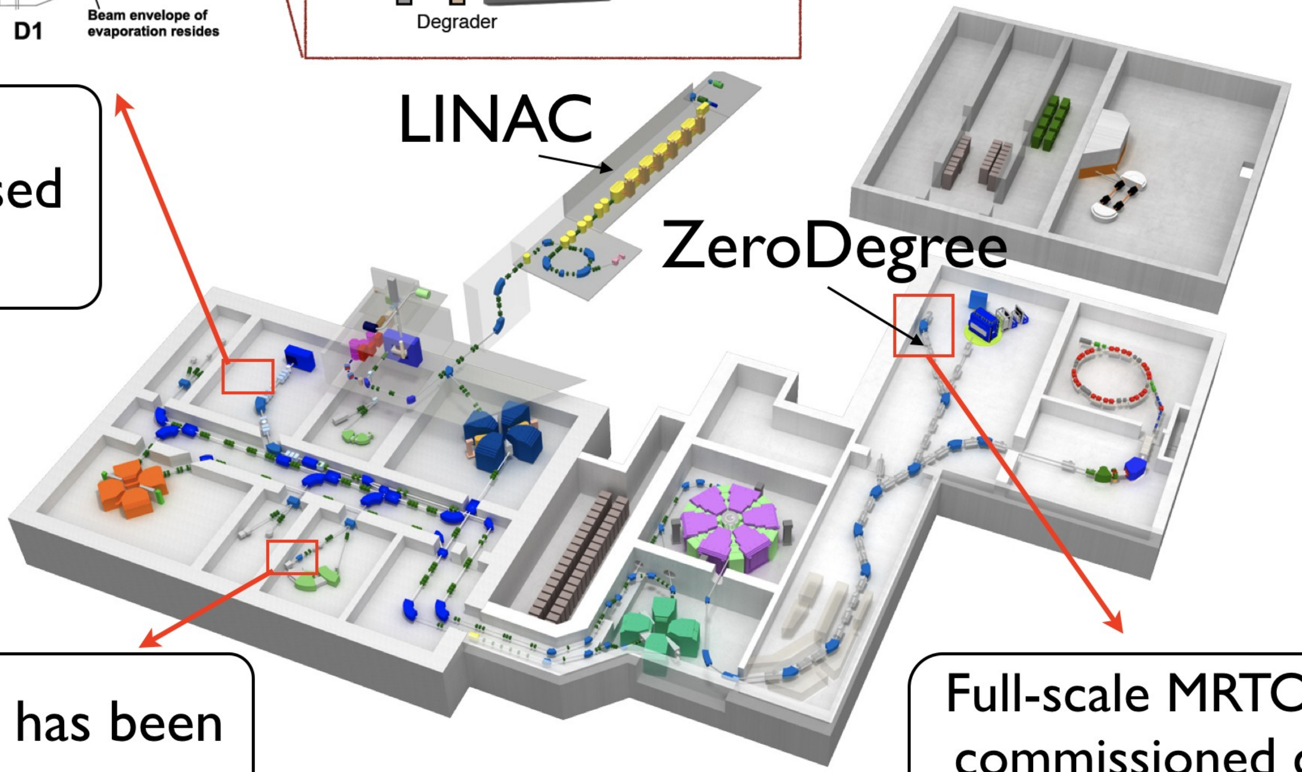
$$\Delta_{2n}(N,Z) = S_{2n}(Z,N) - S_{2n}(Z,N+2)$$

Current MRTOF facilities at RIBF



GARIS-III MRTOF coming soon

Original full-scale MRTOF primarily used for SHE studies



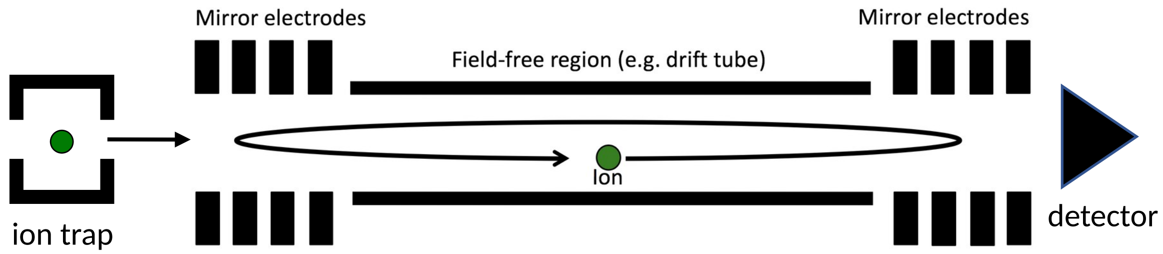
- Full scale = 1m
- Half-scale = 50cm

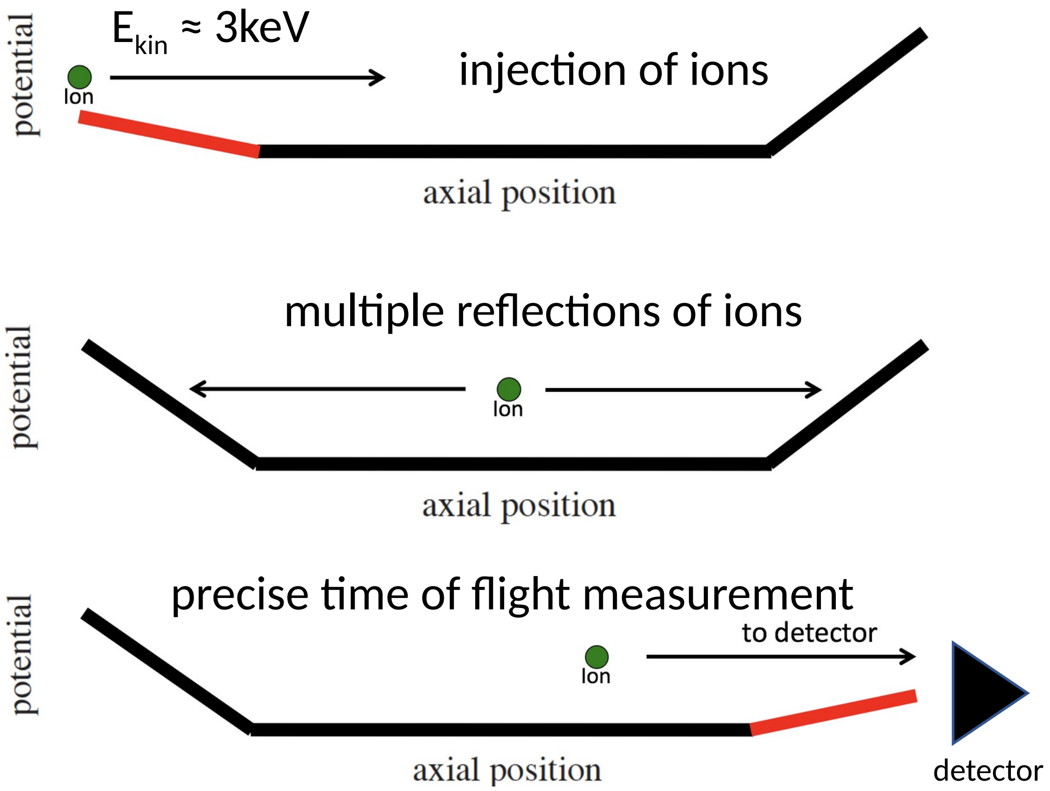
Half-scale MRTOF has been useful in mass-spectroscopy-assisted laser spectroscopy

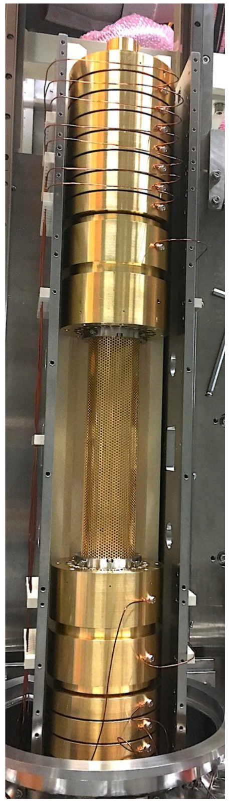
Full-scale MRTOF has been commissioned commensal to in-beam gamma-ray spectroscopy

MRTOF-MS and the new setup at BigRIPS/SLOWRI

H.Wollnik and M. Przewloka, Int. J. Mass Spectrom. Ion Proc. 96, 267 (1990)







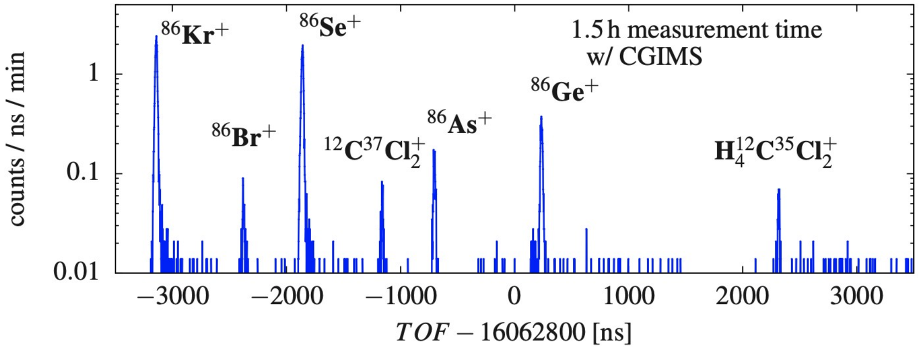
Total time of flight predominantly determined by the electrostatic term of the system

device constant

$$\overline{t(q,m)} = A \cdot \sqrt{\frac{m}{q}}$$

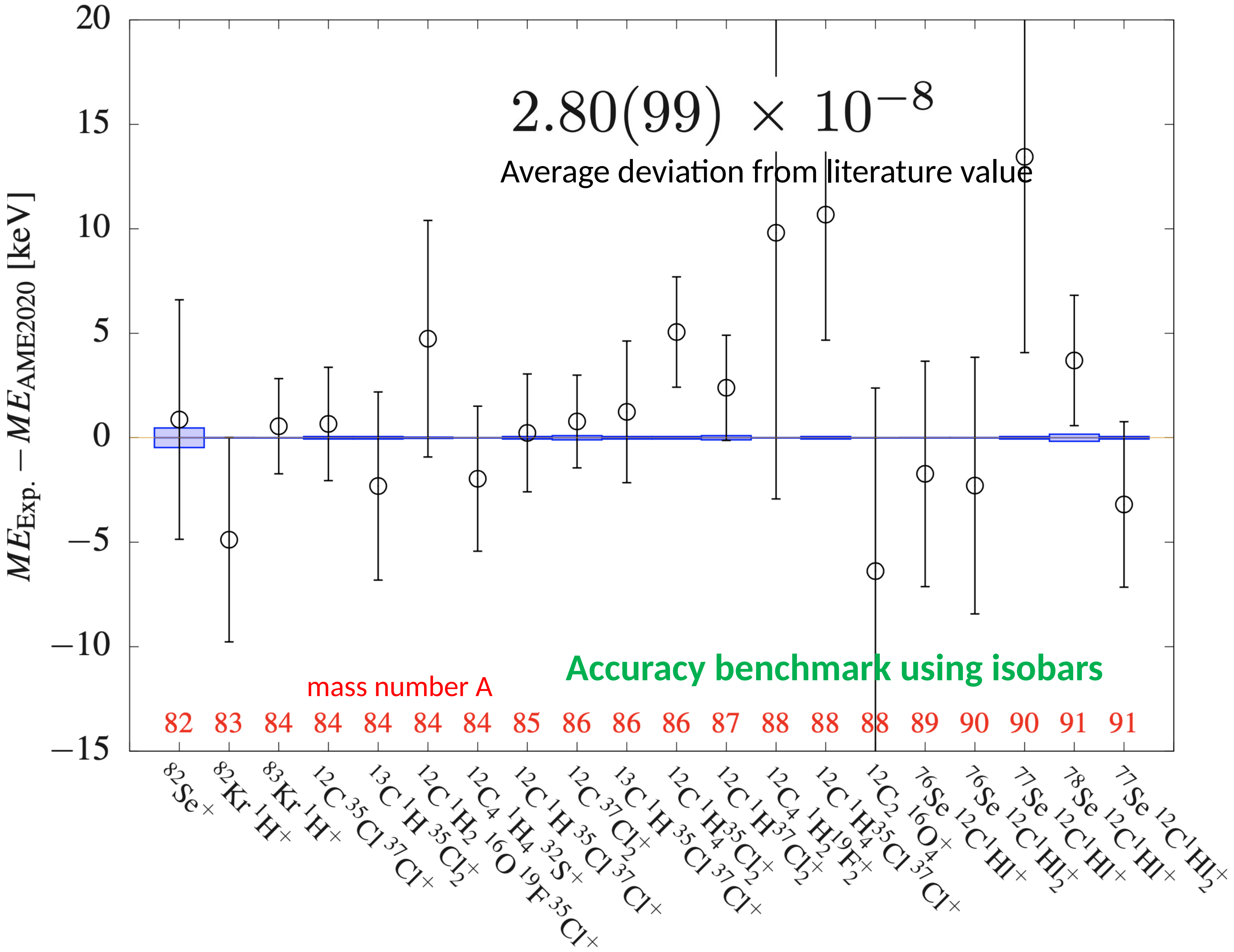
average from ion distribution

electrostatic contribution



- **Flight path of a few kilometers possible**
- **Short measurement time ≈ 10-20 ms**
- **Mass resolving power R_m > 100,000**
- **Relative mass precision $\delta m/m < 10^{-7}$**
- **High accuracy (acceptable syst. effects)**

Mass accuracy study (isobaric referencing):



Wideband mass accuracy?

- Yes, possible and formerly used with dedicated t_0 calibration
- However: we must be aware, MRTOF-MS is not fully electrostatic

device constant

$$\overline{t(q,m)} = A \cdot \sqrt{\frac{m}{q}} + t_0 + t_{\text{NS}}(q,m) + t_{\text{other}}(q,m)$$

average from ion distribution

electrostatic contribution ($A \cdot \sqrt{\frac{m}{q}}$)

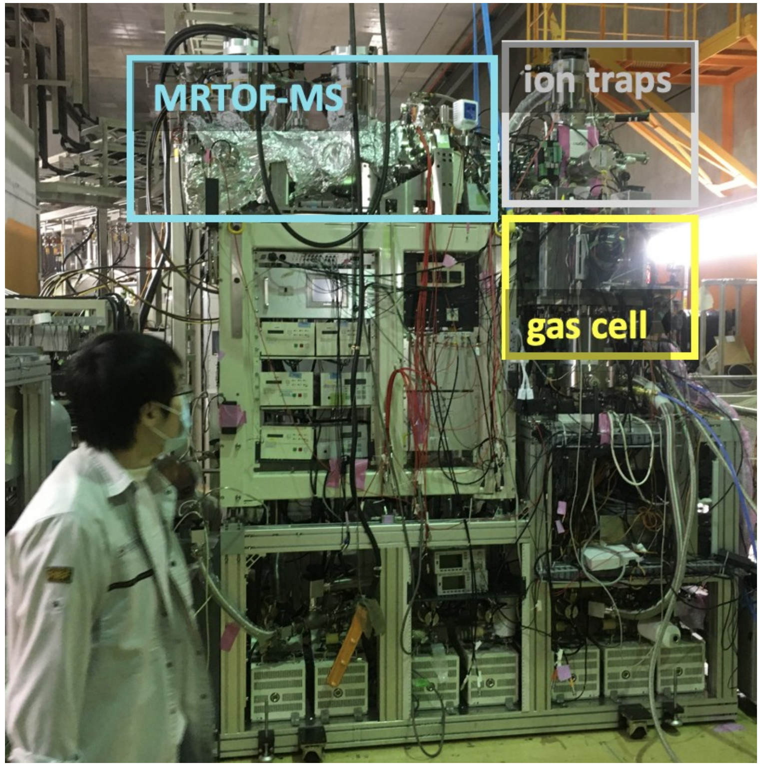
offset time (t_0)

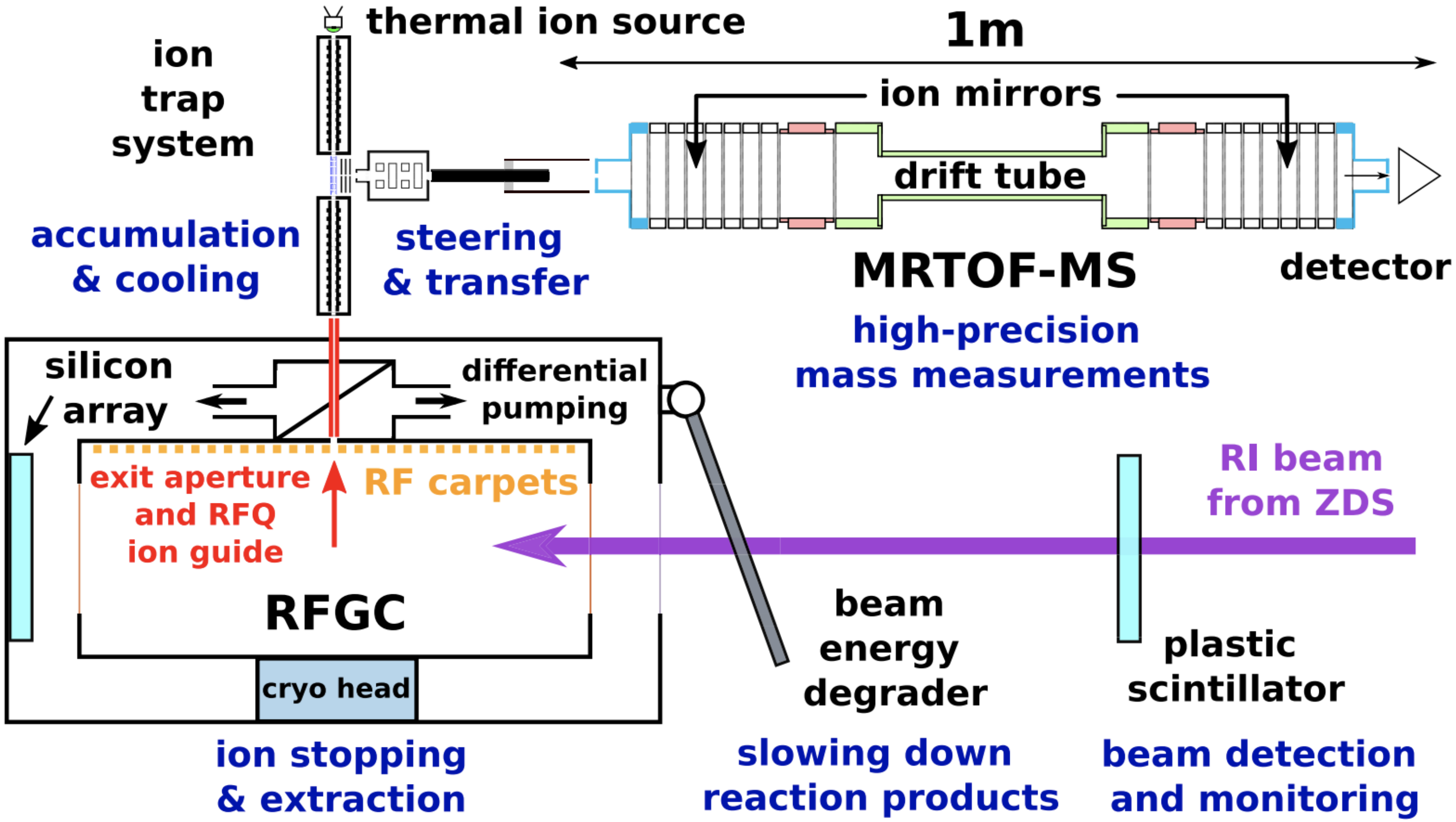
non-static fields ($t_{\text{NS}}(q,m)$)

ion-trap physics and ToF detect. ($t_{\text{other}}(q,m)$)

MRTOF-MS and the new setup at BigRIPS/SLOWRI

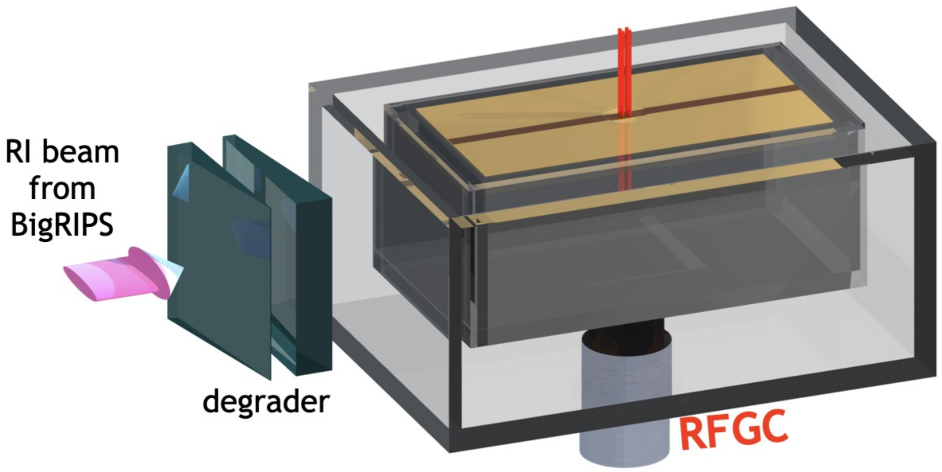
ZD MRTOF-MS overview

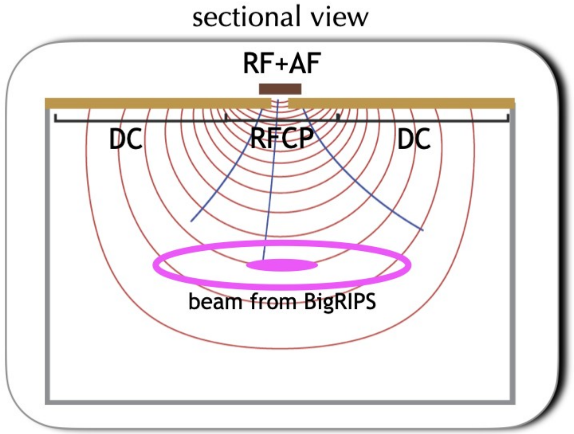


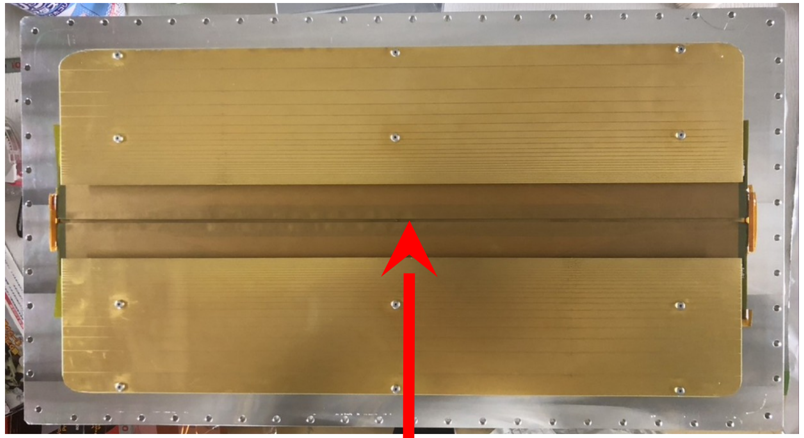


MRTOF-MS and the new setup at BigRIPS/SLOWRI

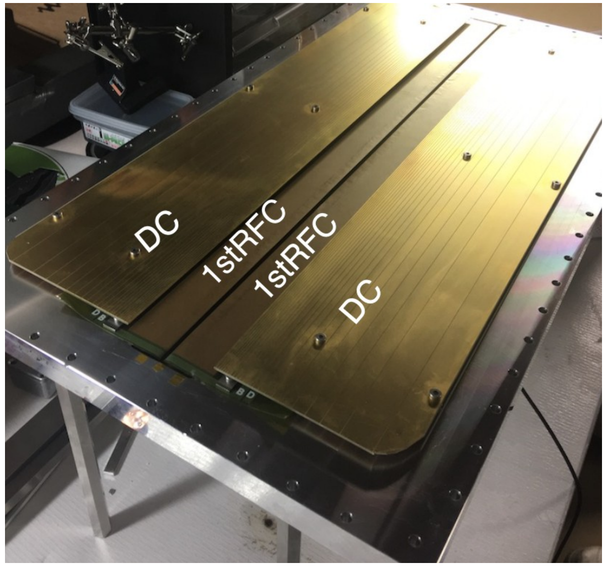
New He gas-filled ion catcher (or also "radiofrequency gas cell" RFGC)

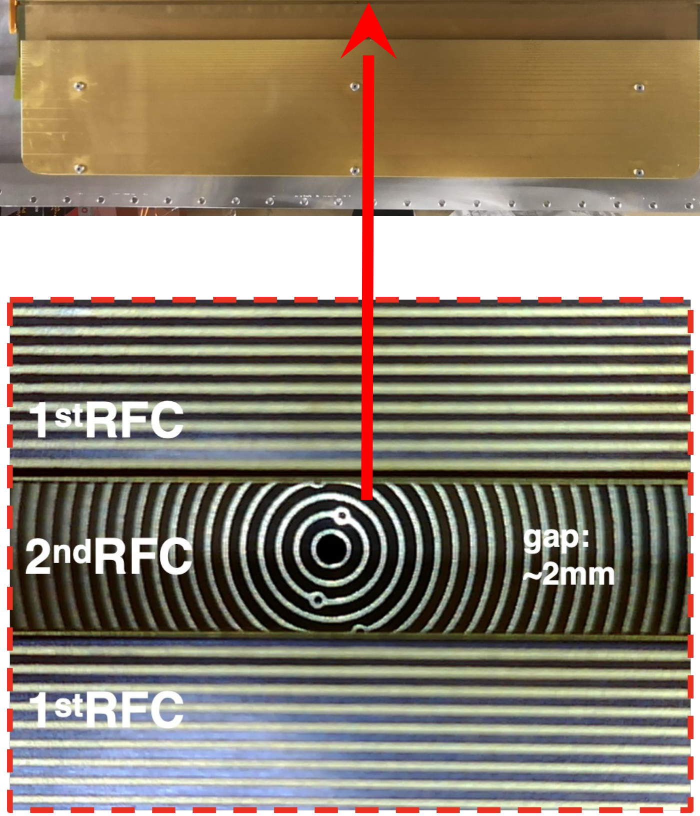




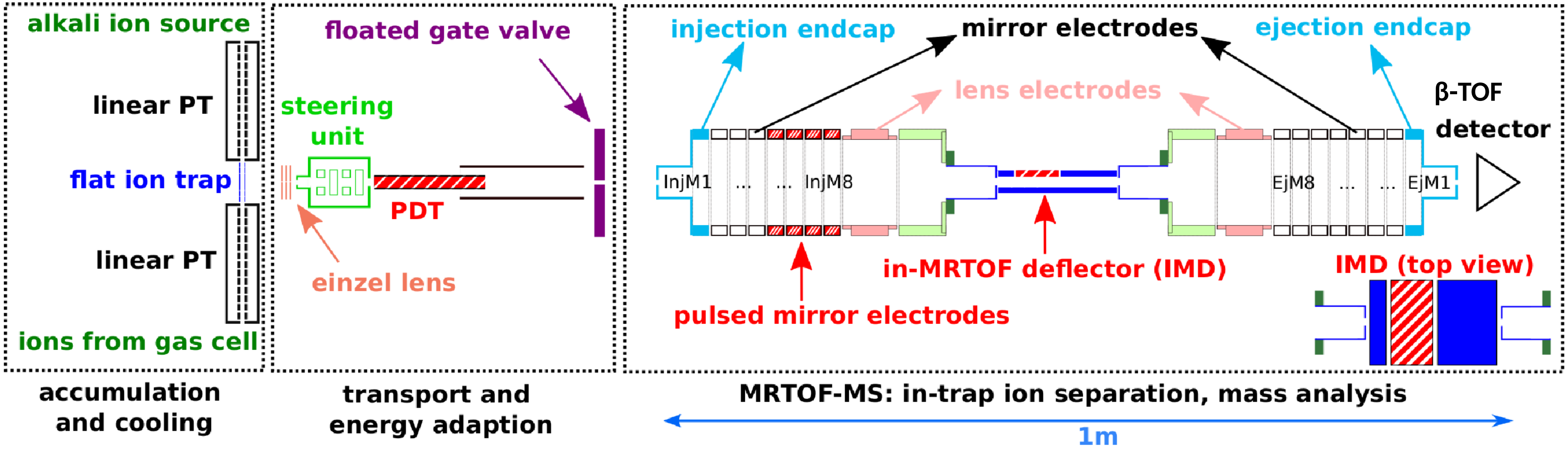


- Beam-energy degrader is used to slow down the beam
- If energy matches the stopping power of the gas, the ions will stop inside the volume



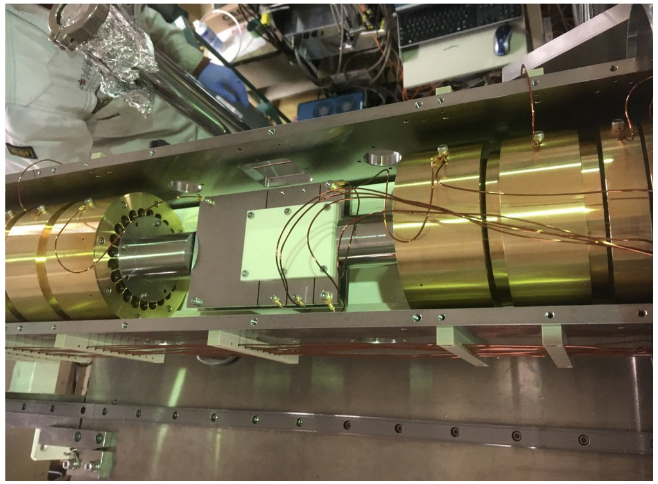


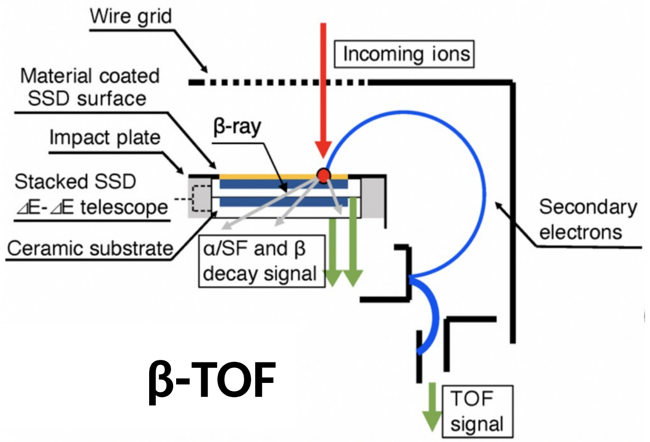
MRTOF-MS and the new setup at BigRIPS/SLOWRI



Essential tools

- Energy adaption available by pulsed drift tube
- In-trap ion separation available (two methods tested)
- Beta-TOF detection available



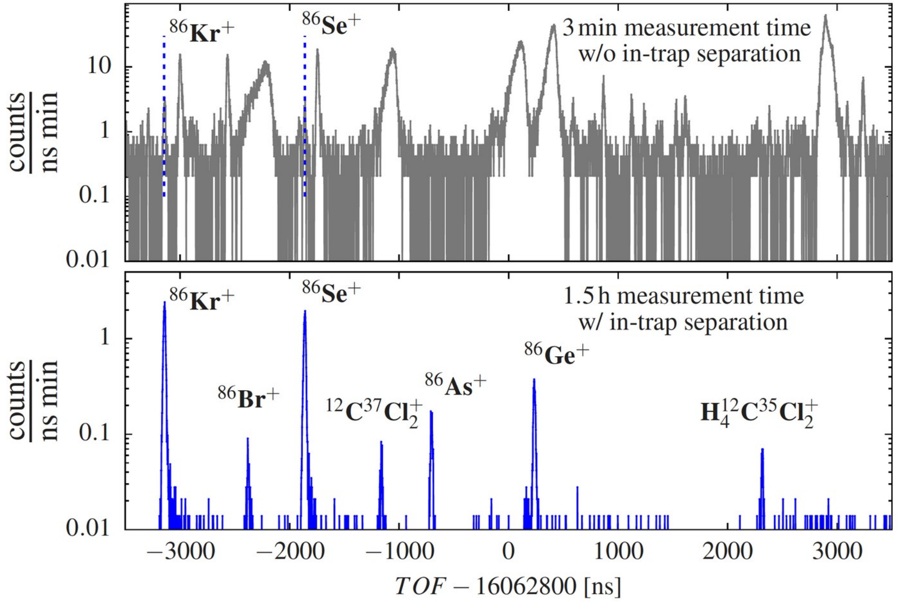


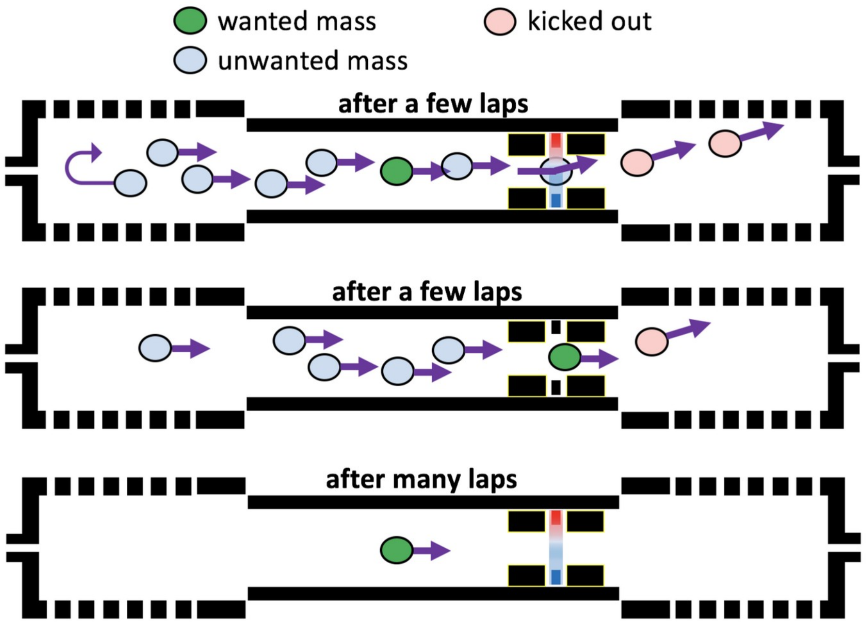
β-TOF

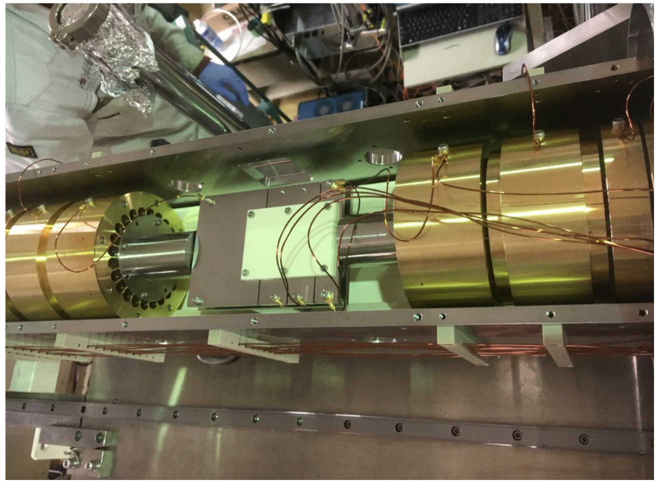
M. Rosenbusch *et al.*, Nucl. Instr. Meth. A 1047, 167824 (2023)

Essential tools: In-MRTOF deflector

- Selective kick-out possible
- **Selective protection of several masses now possible**
- Proper design: Kick out of unwanted ions with weak (20 V) pulse





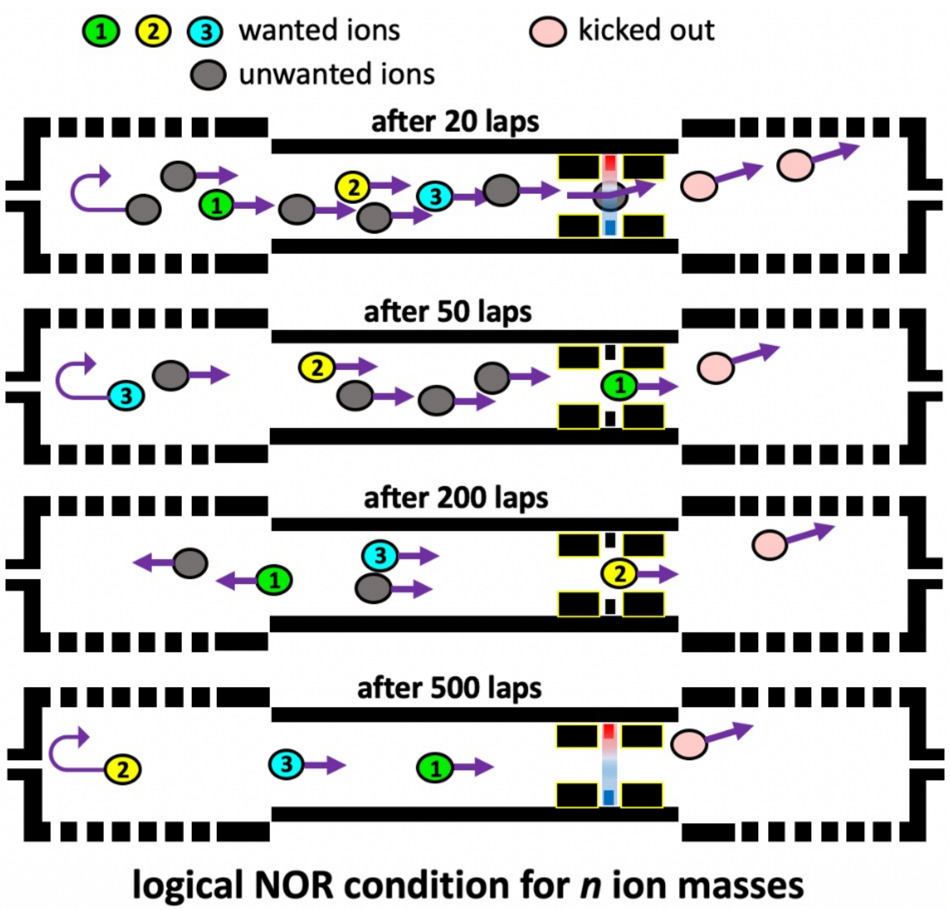


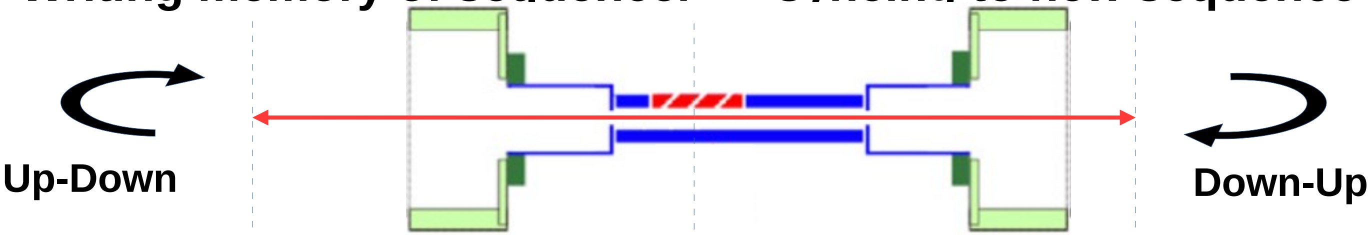
First MRTOF in-trap cleaning with deflector:
Y. Toker *et al.*, J. Instrum. 4, P09001 (2009).

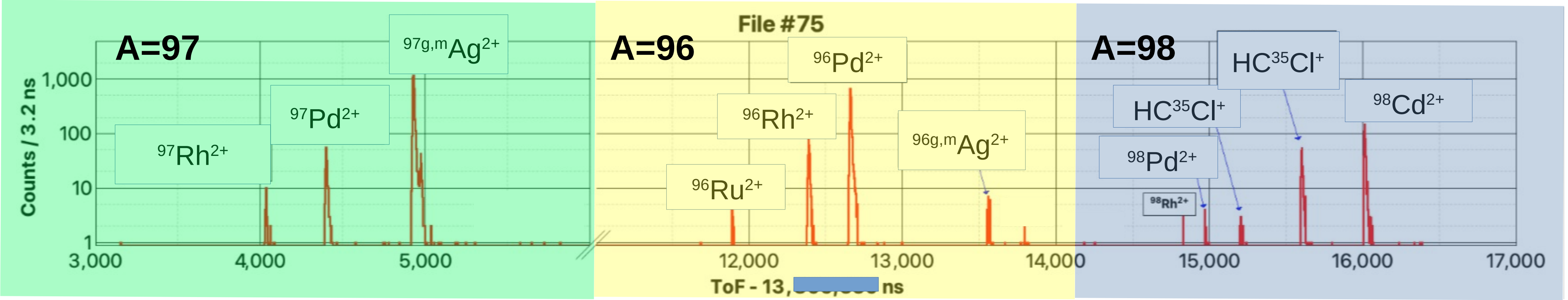
Development of deflectors:
T. Dickel *et al.*, Nucl. Instrum. Meth. 777, 172 (2015).
P. Fischer *et al.*, Rev. Sci. Instrum. 89, 015114 (2018).

Usage of mirror endcaps:
J. T. Johnson *et al.*, Anal. Chem. 91, 8789 (2019).

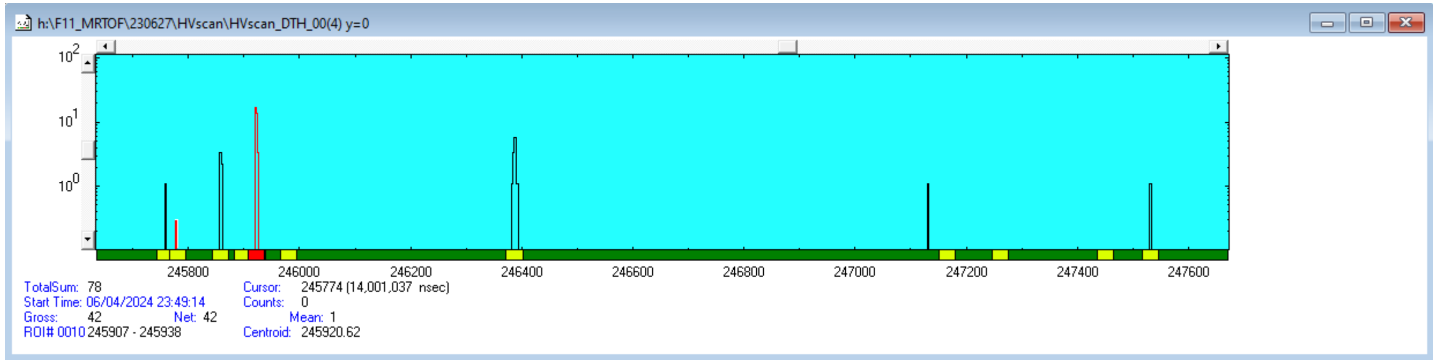
- **Selecting various isobar groups at the same time**
- **Selecting the moments and number of pulses**
- **Calculating crossing time for all selected isotopes**
- **Defining "safety region" (distance from IMD), including asymmetry of motion (Down-Up / Up-Down)**
- **Generating pulse-train sequence**
- **Writing memory of sequencer → syncing to new sequence**



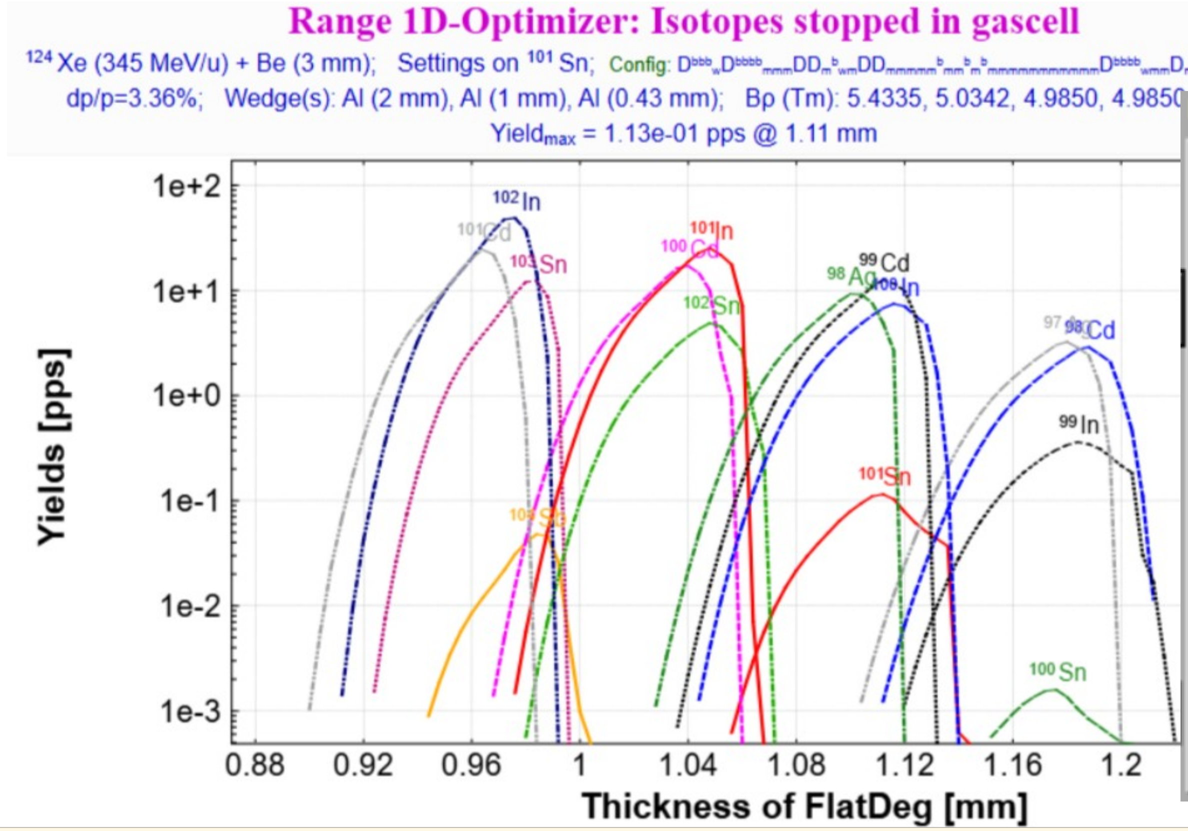


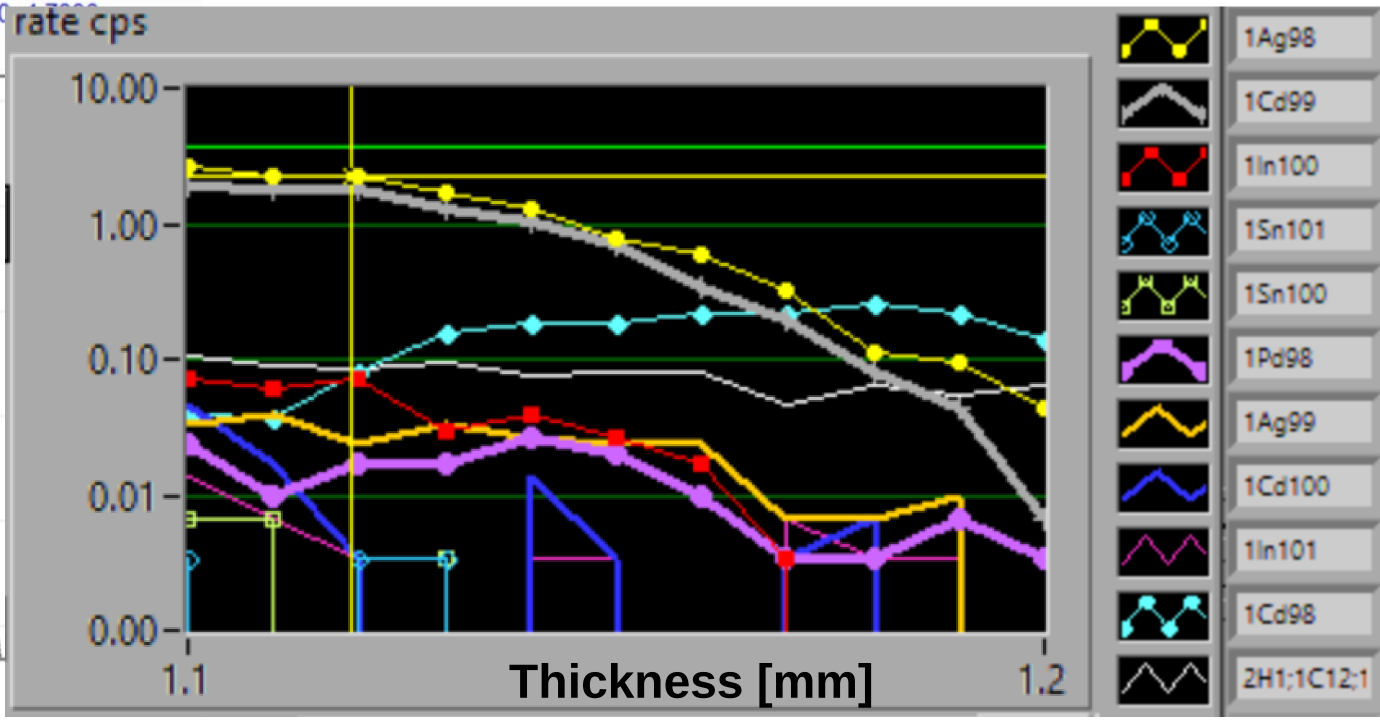


Essential tools: In-MRTOF deflector



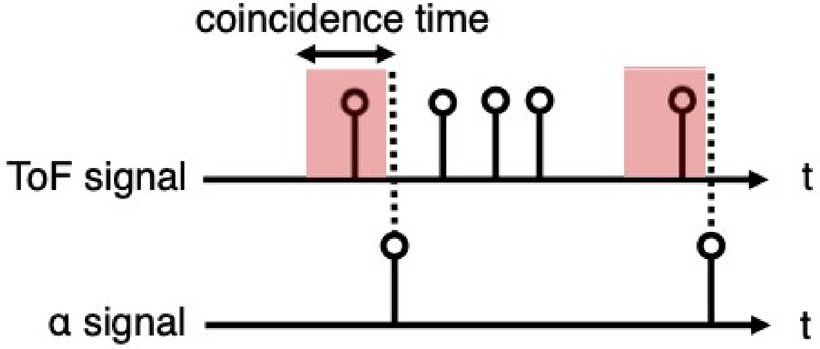
- **Easy-to-go degrader scanning**
- **Focusing on several isotopes simultaneously**
- **Background-free measurement**

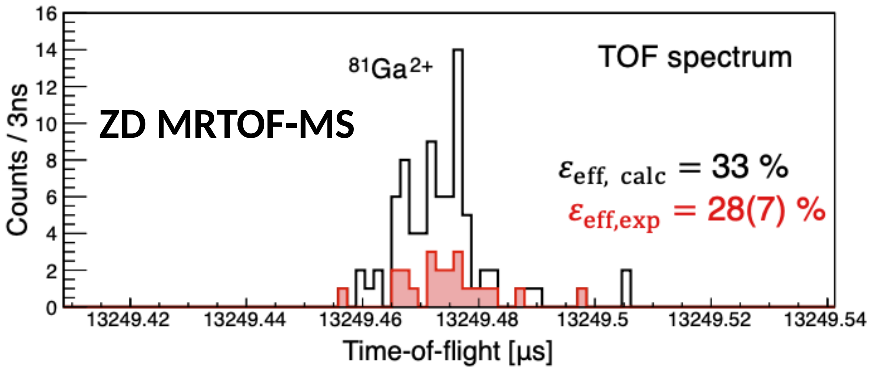


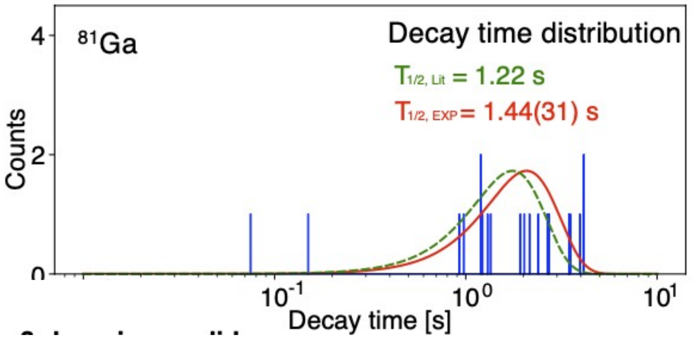


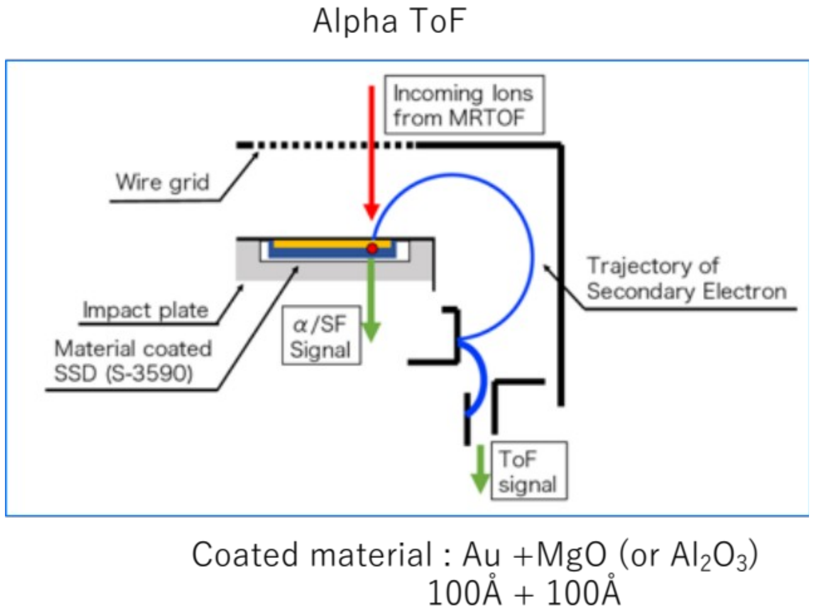
Essential tools: α/β – TOF detector

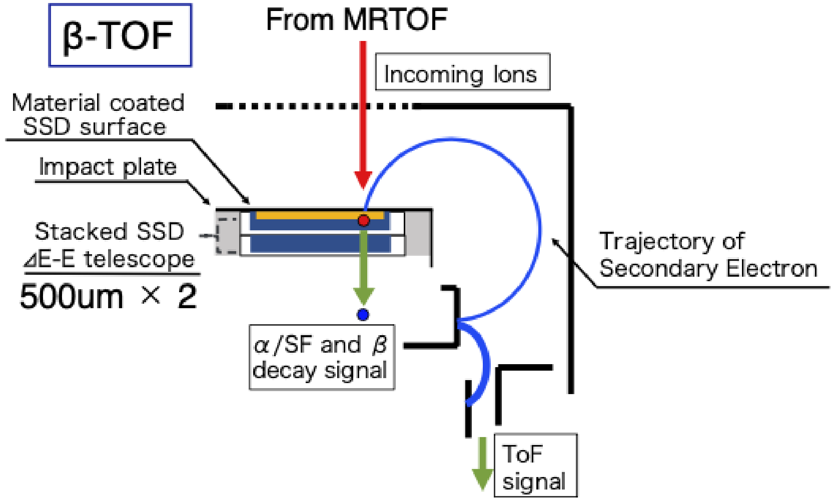
ToF-decay correlated mass spectroscopy



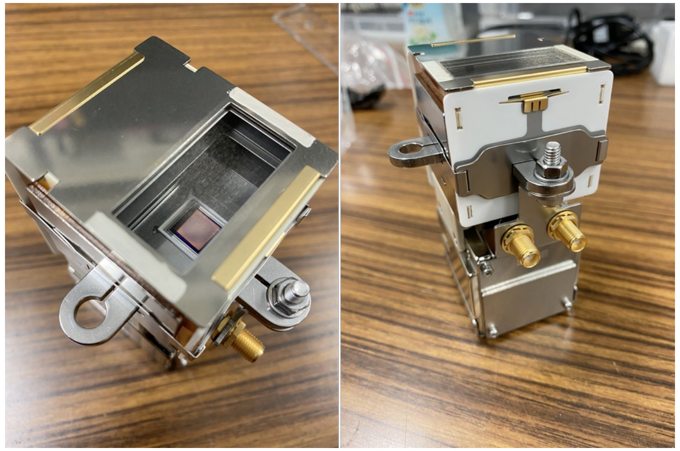








Correlation with TOF and β-signal
(The β-signal is the one passing through the double layered Si.)

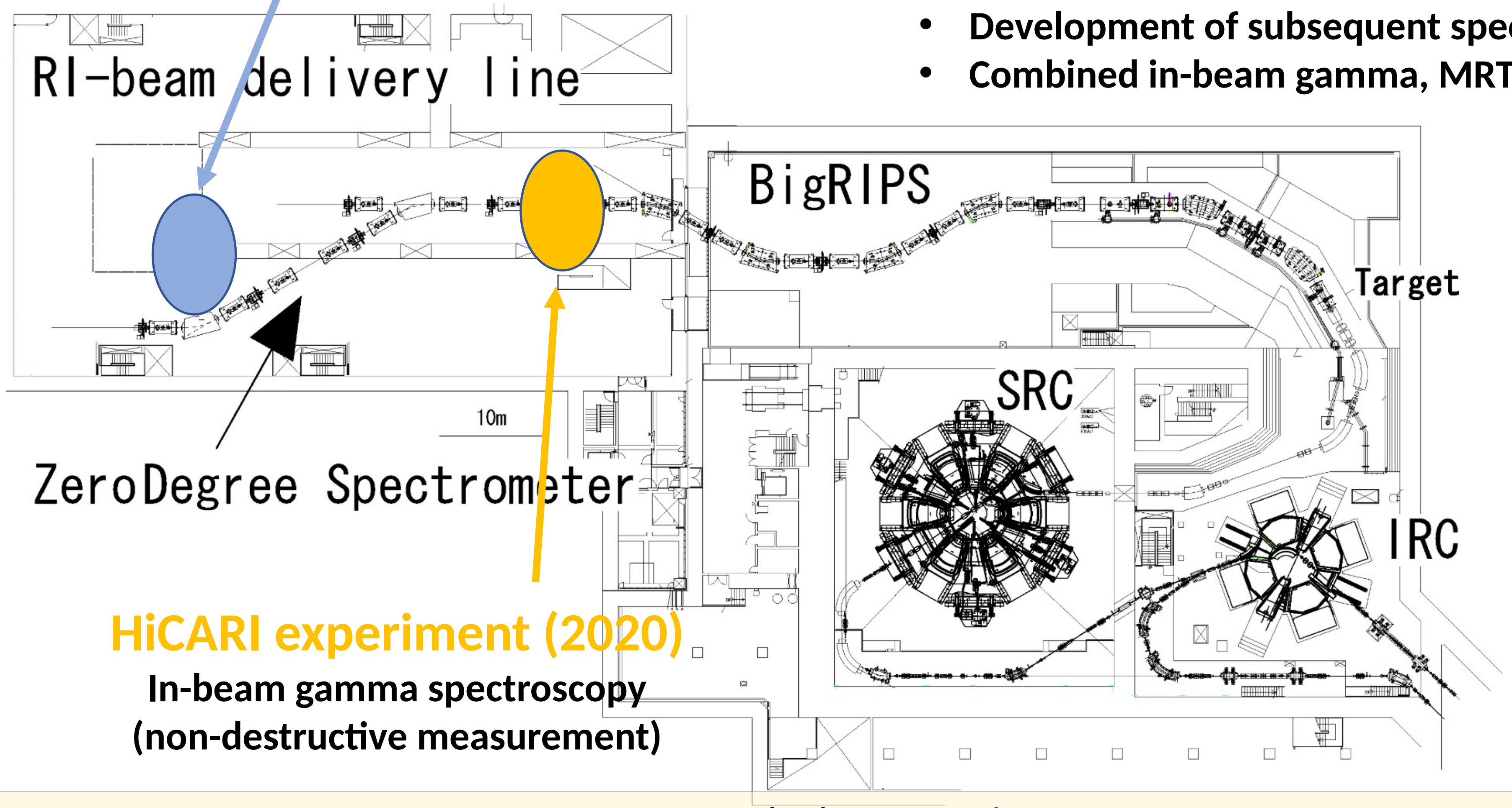


T. Niwase *et al.*, Prog. Theo. Exp. Phys. 2023(3), 031H01 (2023), T. Niwase *et al.*, Phys. Rev. C 104, 044617 (2021), T. Niwase *et al.*, Nucl. Instrum. Meth. A 953, 163198 (2020)

Timeline of the ZD MRTOF experiment

- Basic assembly from 2018
- Starting offline GC development in 2019
- GC coupled to MRTOF-MS spring/summer 2020
- Transport to ZD spectrometer fall 2020
- First commissioning with in-beam gamma in winter 2020
- First dedicated run on Ni isotopes winter 2021 / spring 2022
- Accelerator broken from winter 2022
- Development of subsequent spectroscopy during 2023
- Combined in-beam gamma, MRTOF-MS, and decay spec. 2024

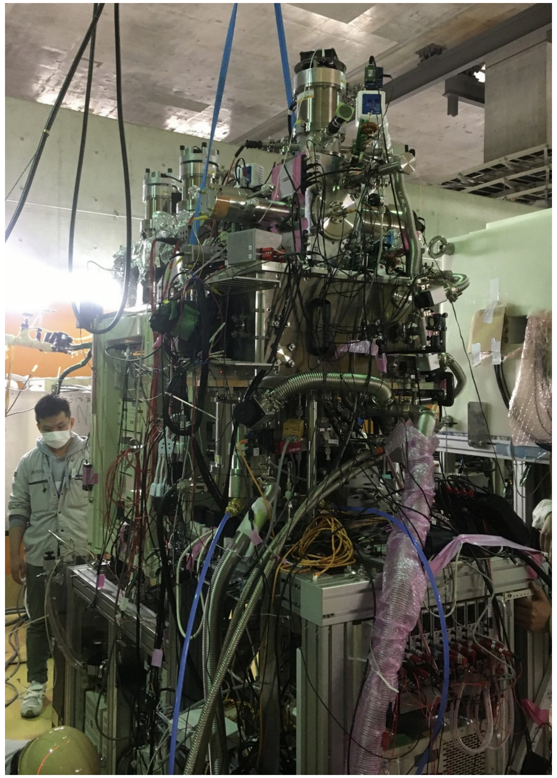
MRTOF-MS setup



HiCARI experiment (2020)

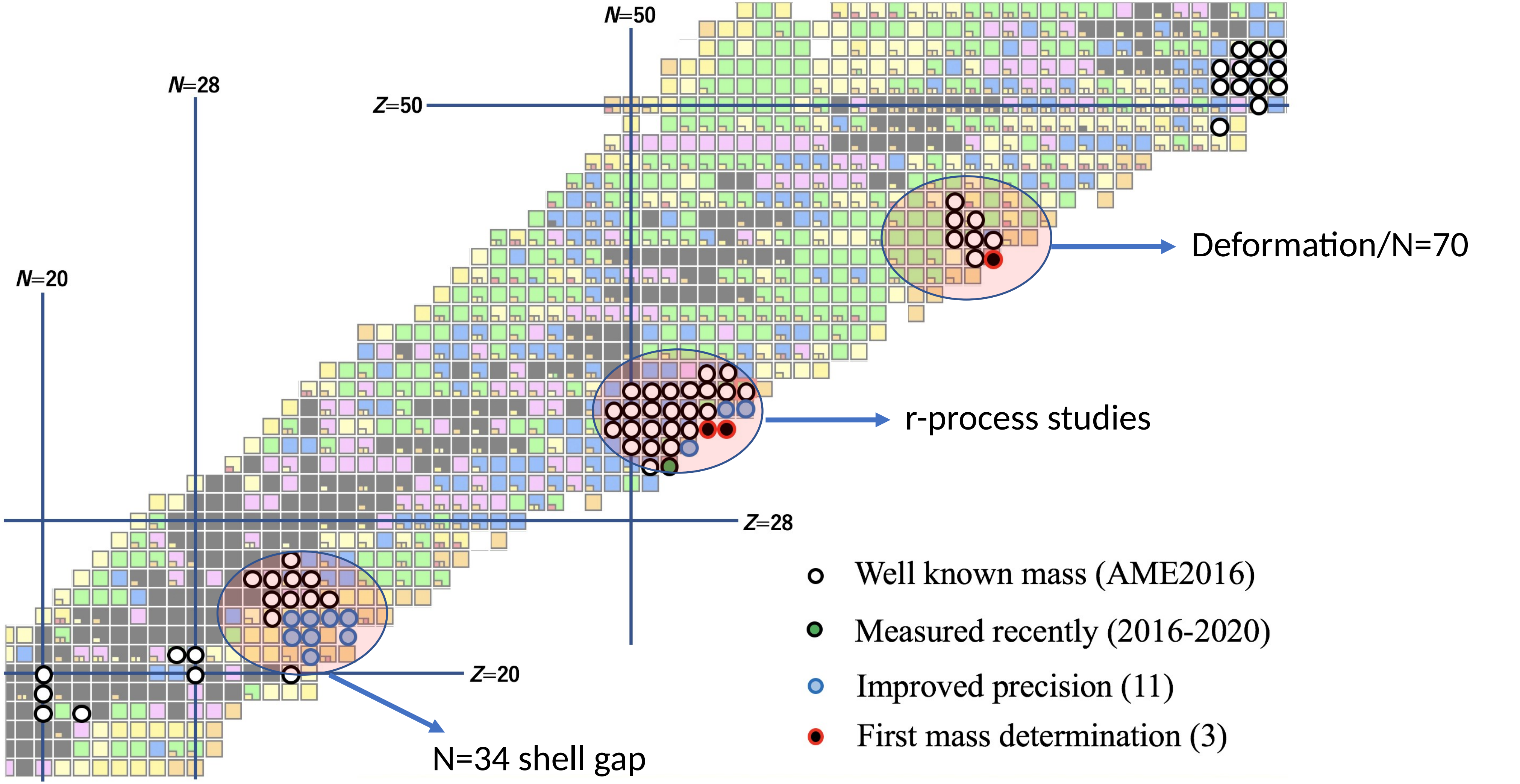
In-beam gamma spectroscopy

(non-destructive measurement)



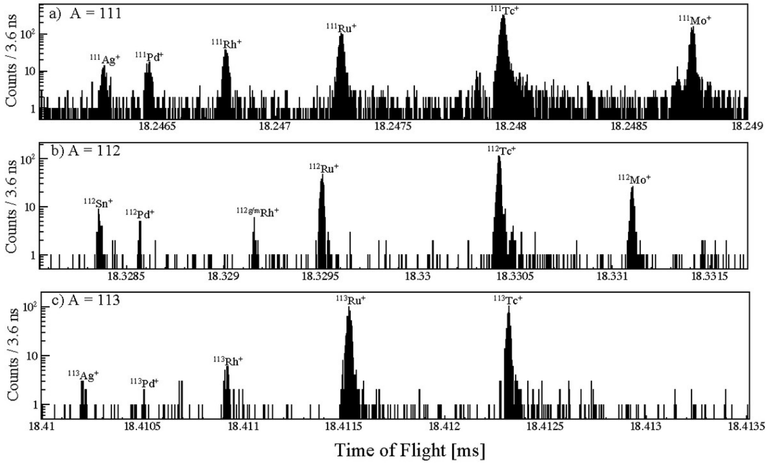
Timeline of the ZD MRTOF experiment

- ~ 70 mass measurements in different regions of the nuclide chart
- Three nuclear masses measured for the first time
- Eleven nuclear masses improved in precision
- Total system efficiency measured (0.3% - 1.5%)



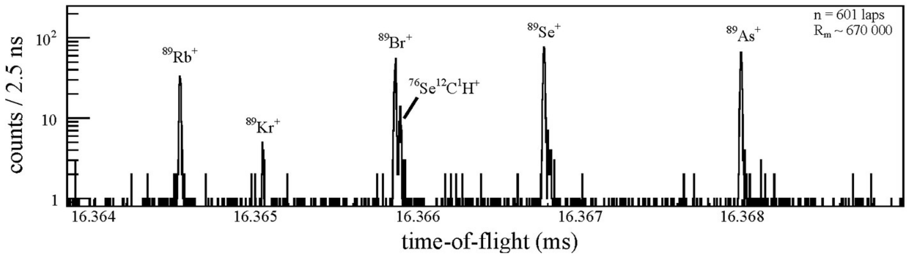
Timeline of the ZD MRTOF experiment

D.S. Hou, A. Takamine et al., Phys. Rev. C 108, 054312 (2023)

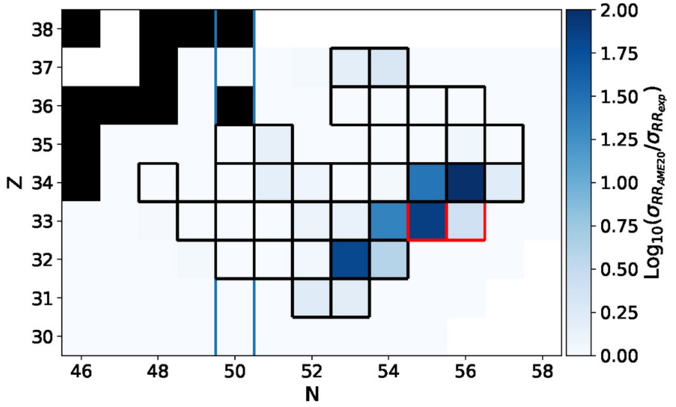


14 isotopes!
New: ^{112}Mo

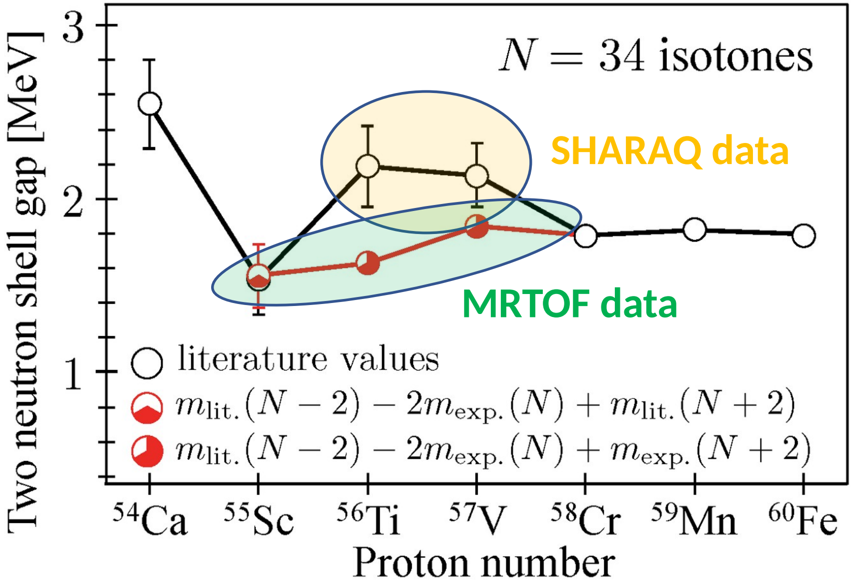
W. Xian, S. Chen et al., Phys. Rev. C 109, 035804 (2024)



35 isotopes!
New: ^{88,89}As

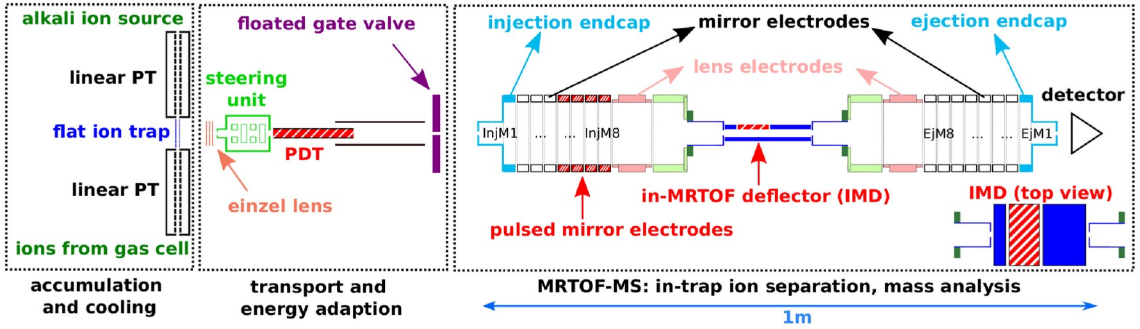


S. Iimura, M. Rosenbusch *et al.*, PRL 130, 012501 (2023)



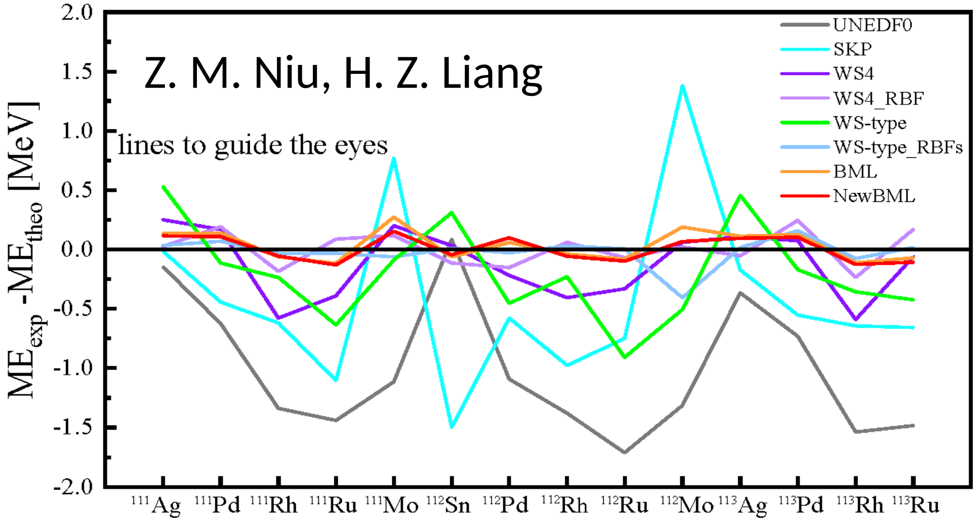
19 isotopes!
New: N=34
shell gap

M. Rosenbusch *et al.*, Nucl. Instr. Meth. A 1047, 167824 (2023)



Timeline of the ZD MRTOF experiment

D.S. Hou, A. Takamine et al., Phys. Rev. C 108, 054312 (2023)



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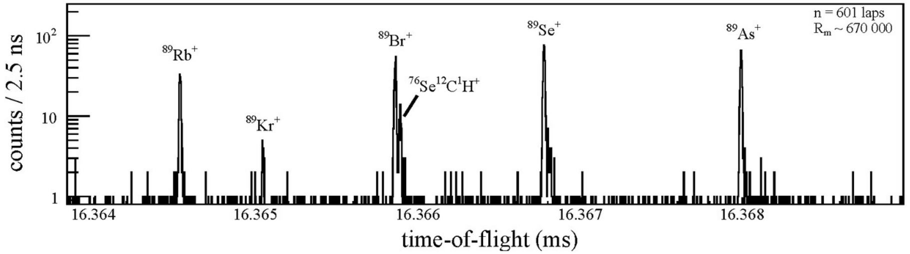
W. Xian, S. Chen et al., Phys. Rev. C 109, 035804 (2024)



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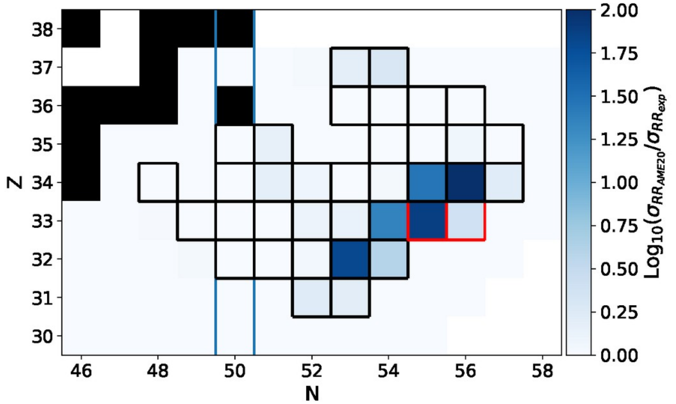
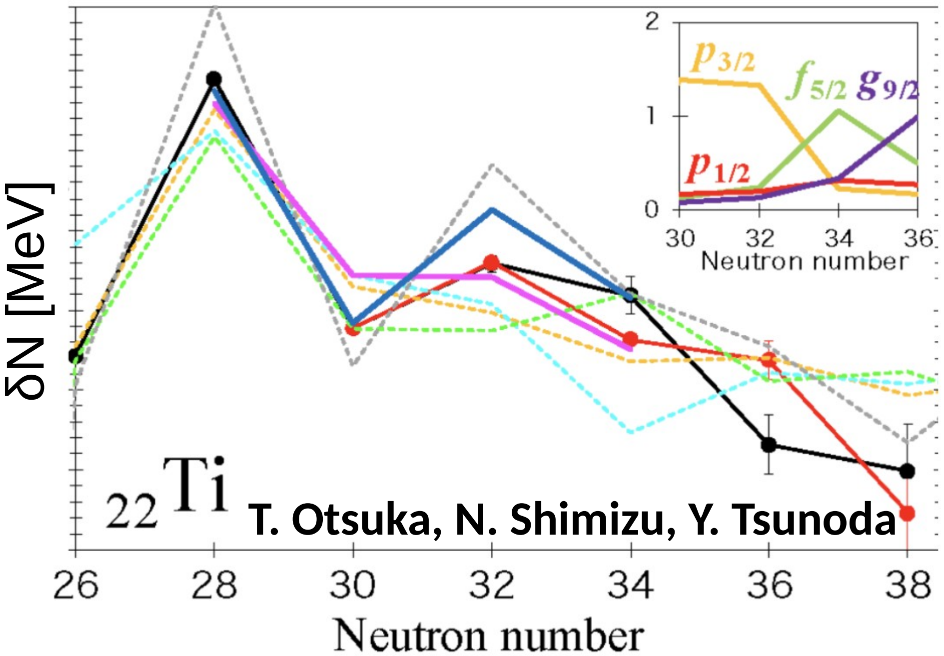
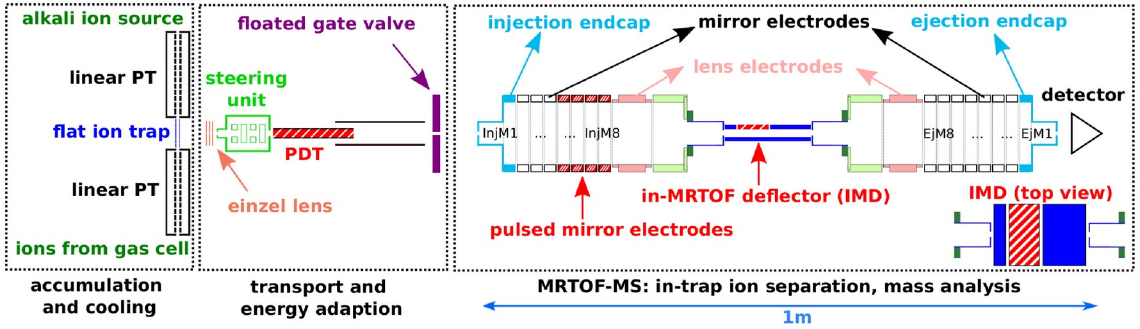


S. Iimura, M. Rosenbusch *et al.*, PRL 130, 012501 (2023)



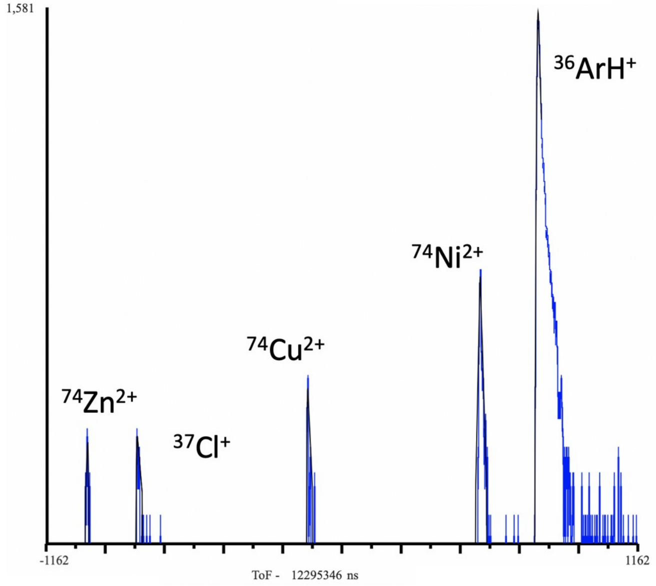
19 isotopes!
New: N=34
shell gap

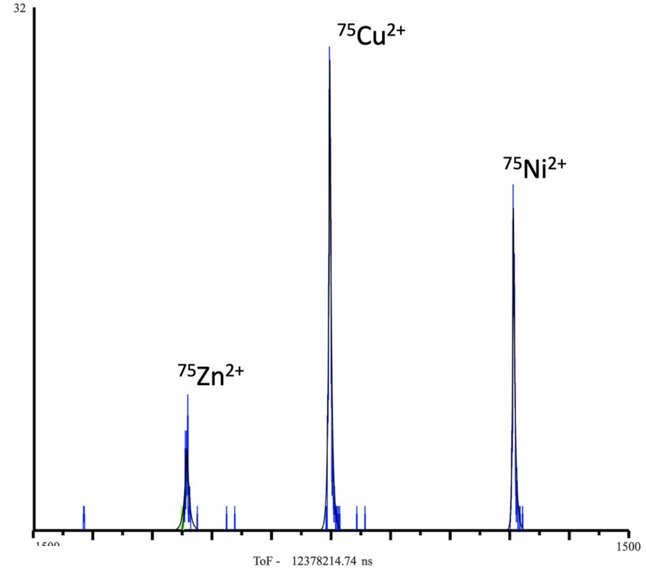
M. Rosenbusch *et al.*, Nucl. Instr. Meth. A 1047, 167824 (2023)

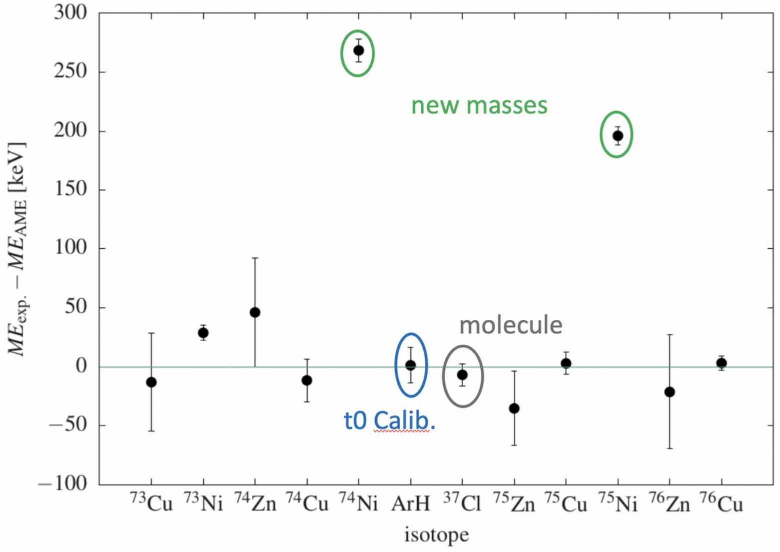


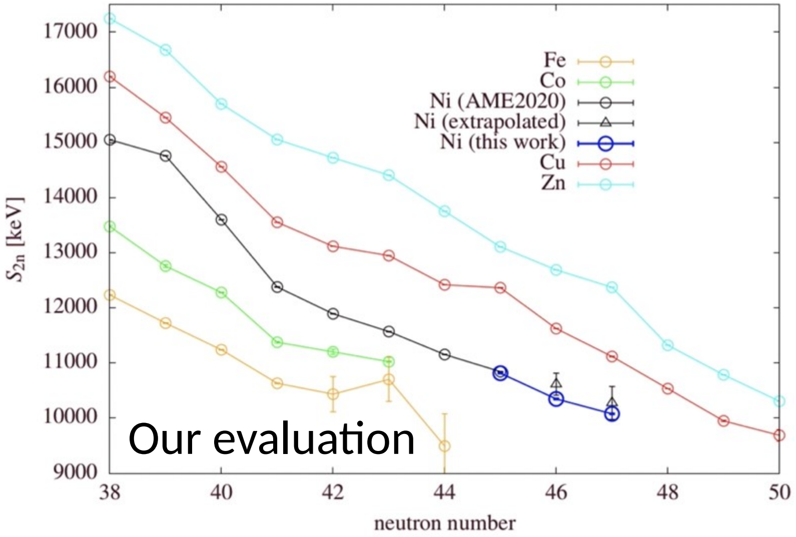
Timeline of the ZD MRTOF experiment

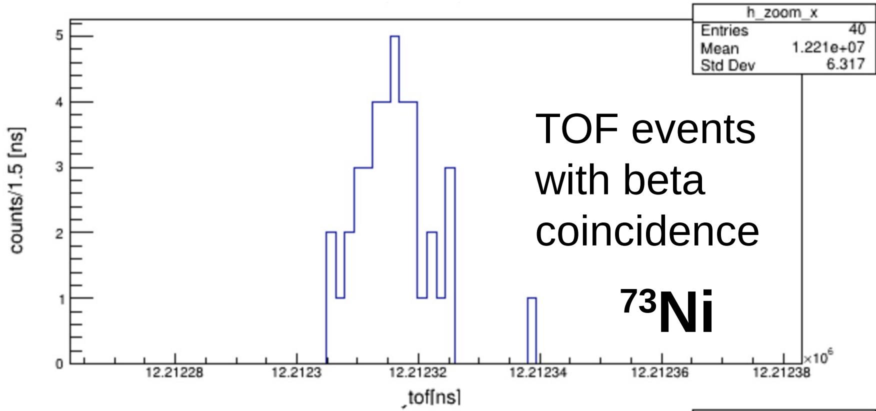
Mass measurements of $^{73-75}Ni$, and beta-TOF POP measurements

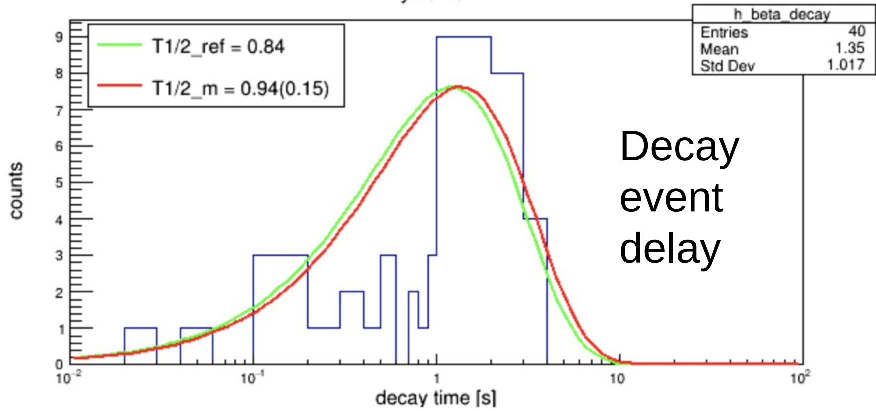








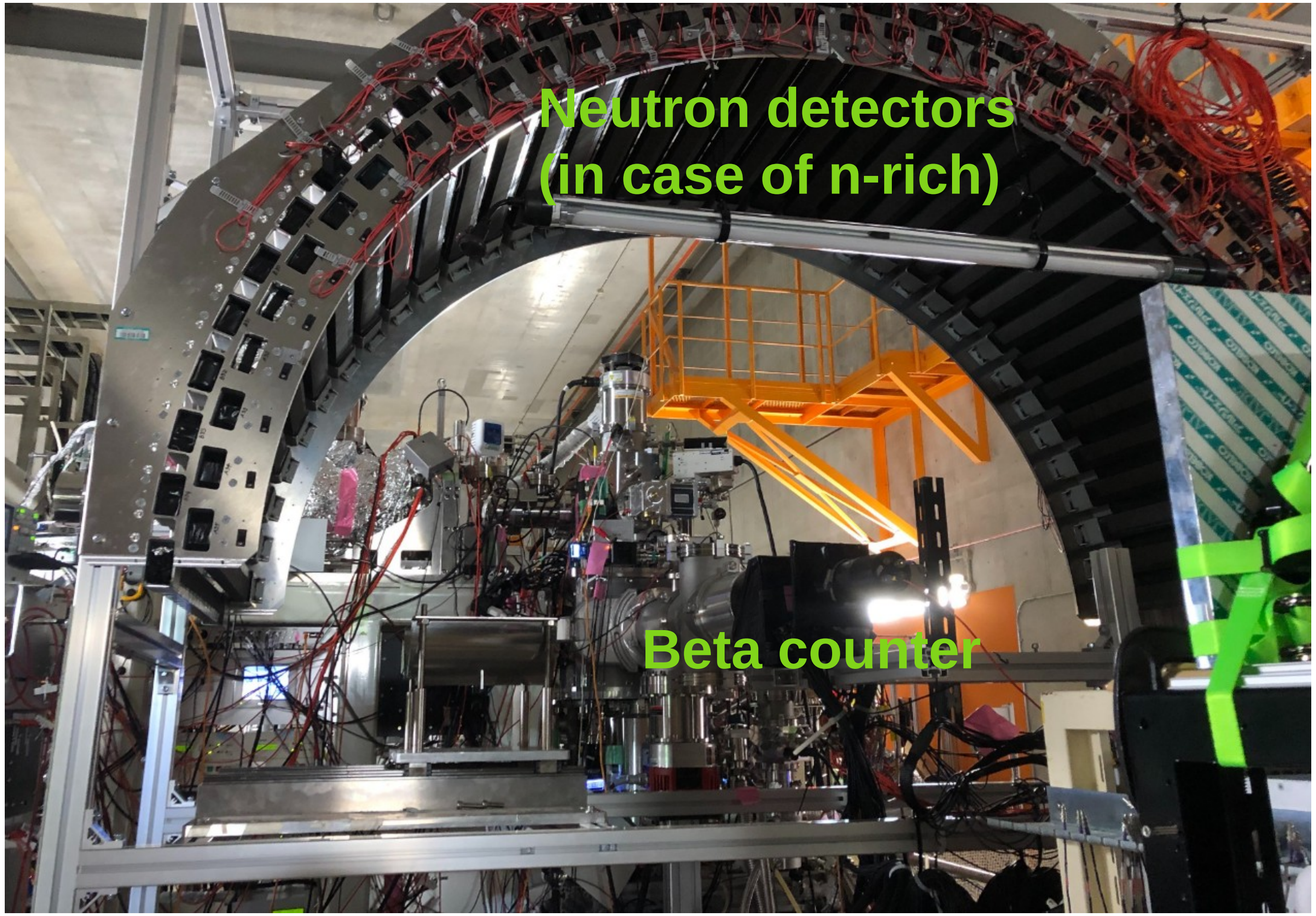


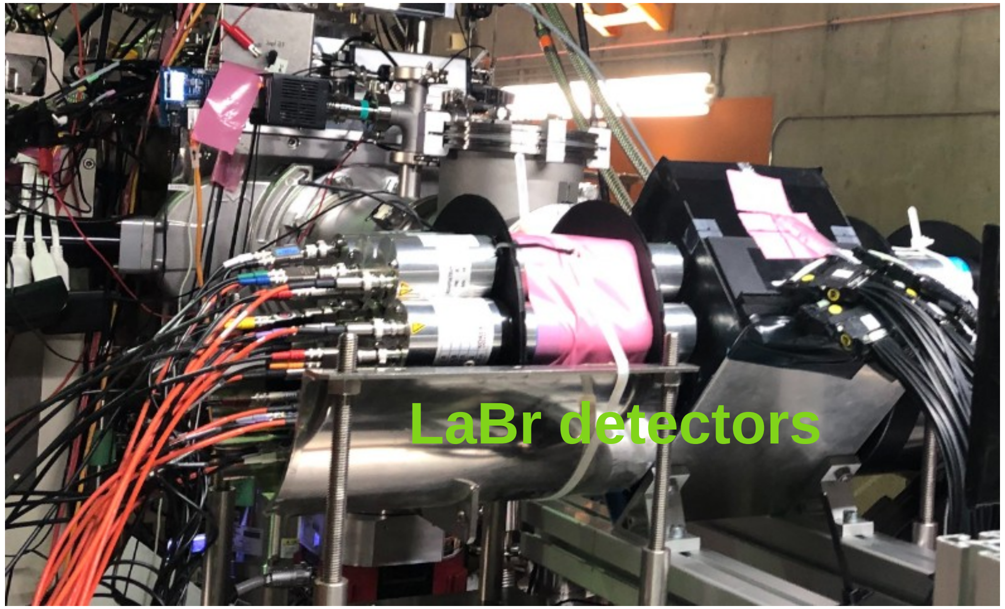


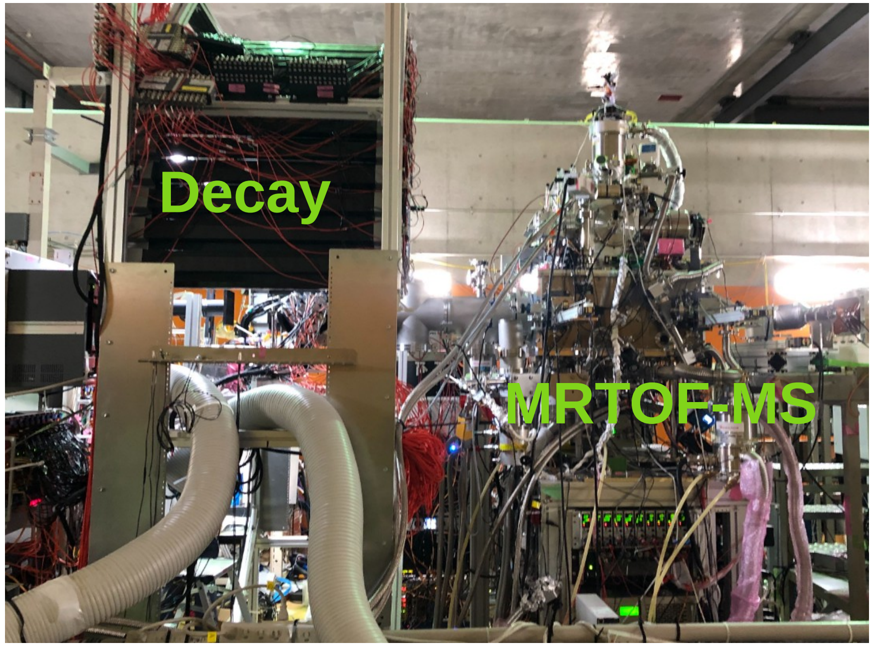
$^{74,75}Ni$ also recently published by JYFLTRAP: S. Giraud *et al.*, Phys. Lett. B 833, 137309 (2022)

Timeline of the ZD MRTOF experiment

2023-2024
Development of a vacuum beam line
for subsequent decay spectroscopy

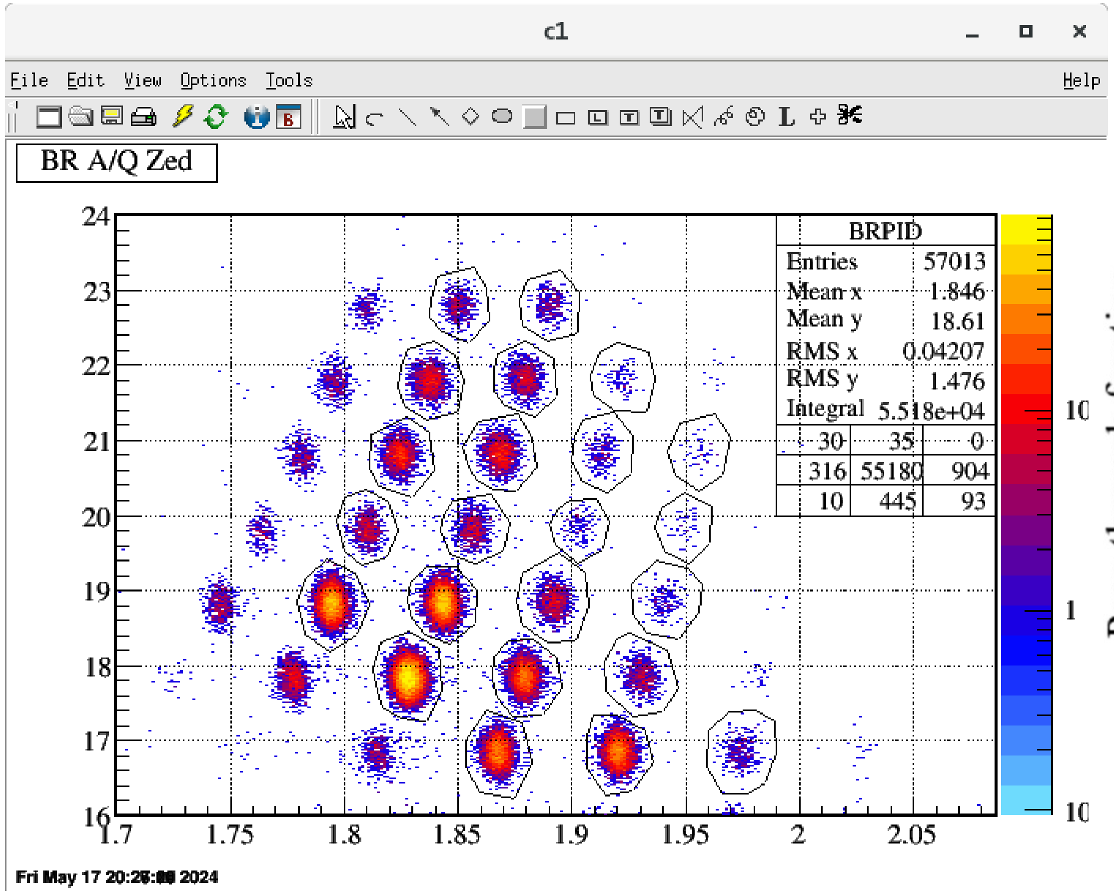


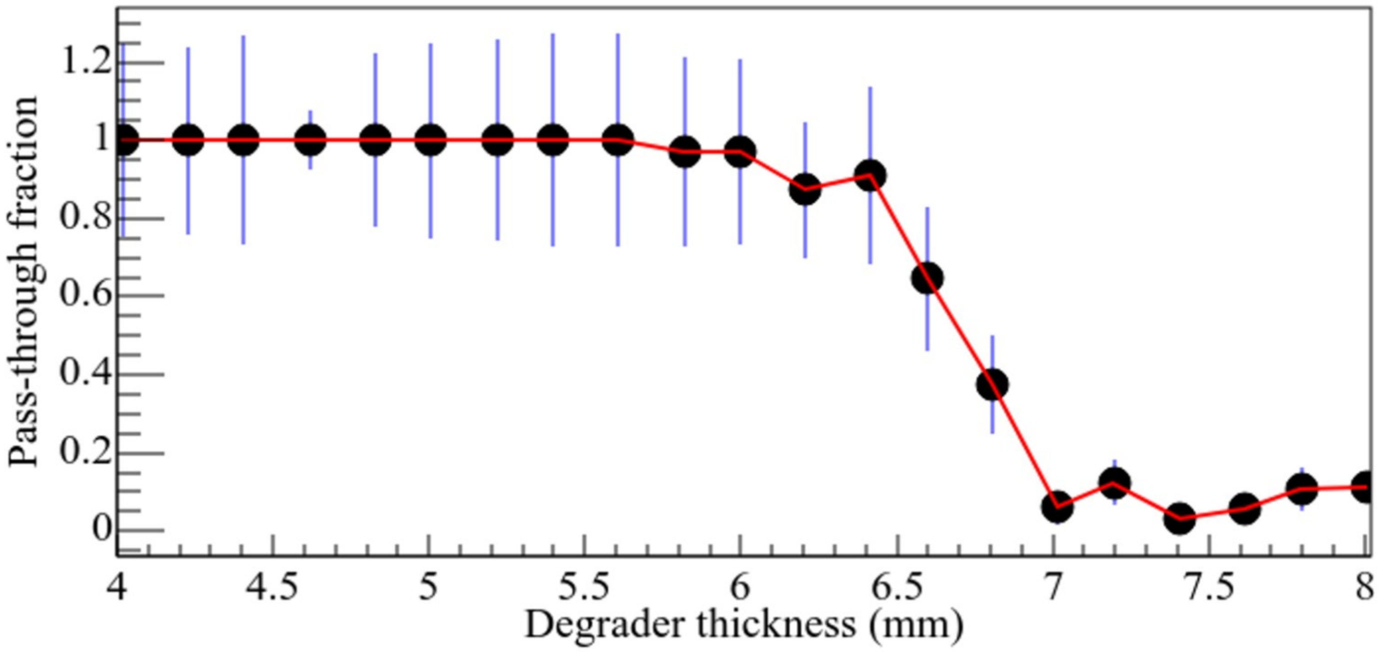




TOF and beta-TOF signal added to same DAQ (CAEN waveform recorders)

Timeline of the ZD MRTOF experiment

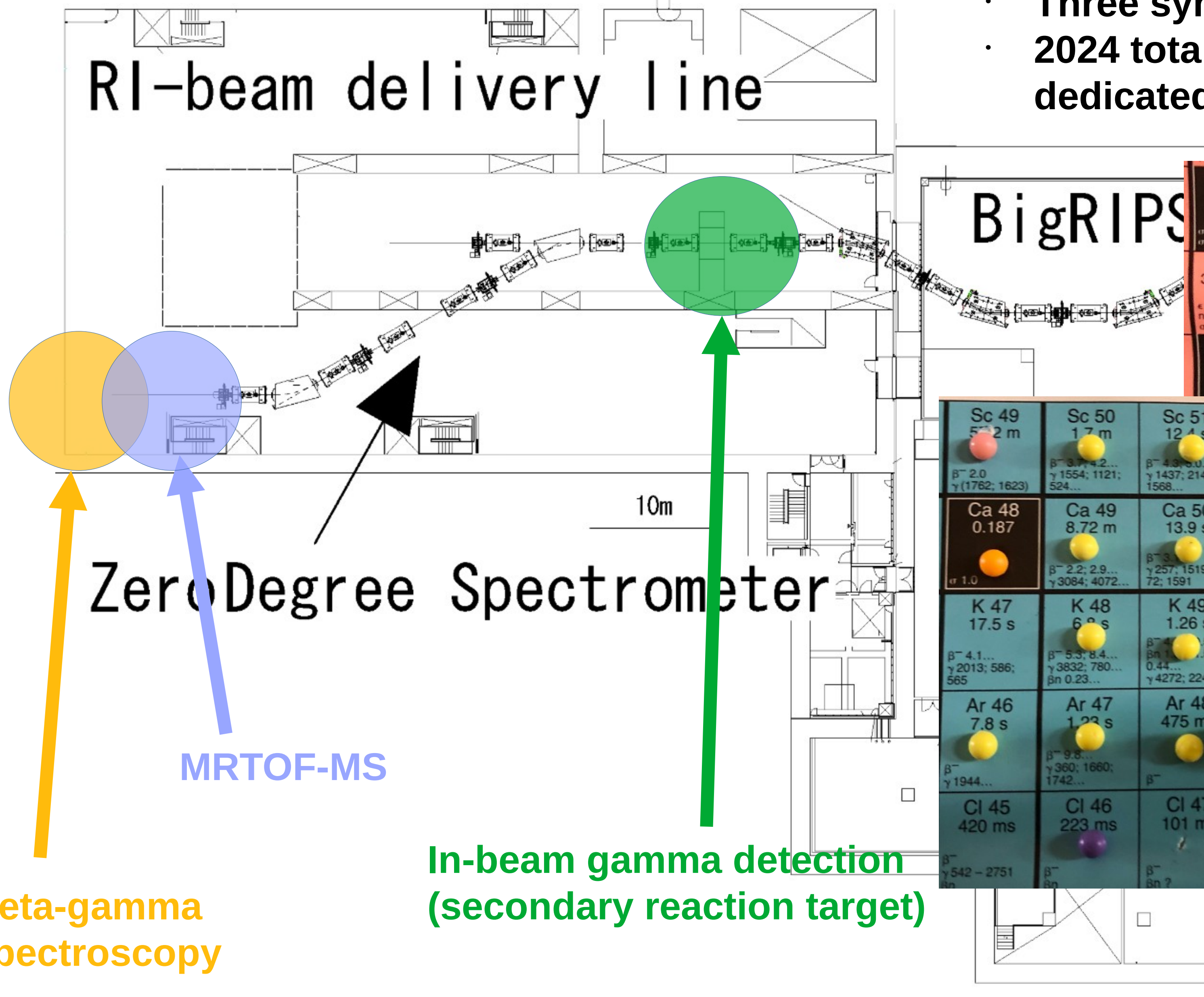


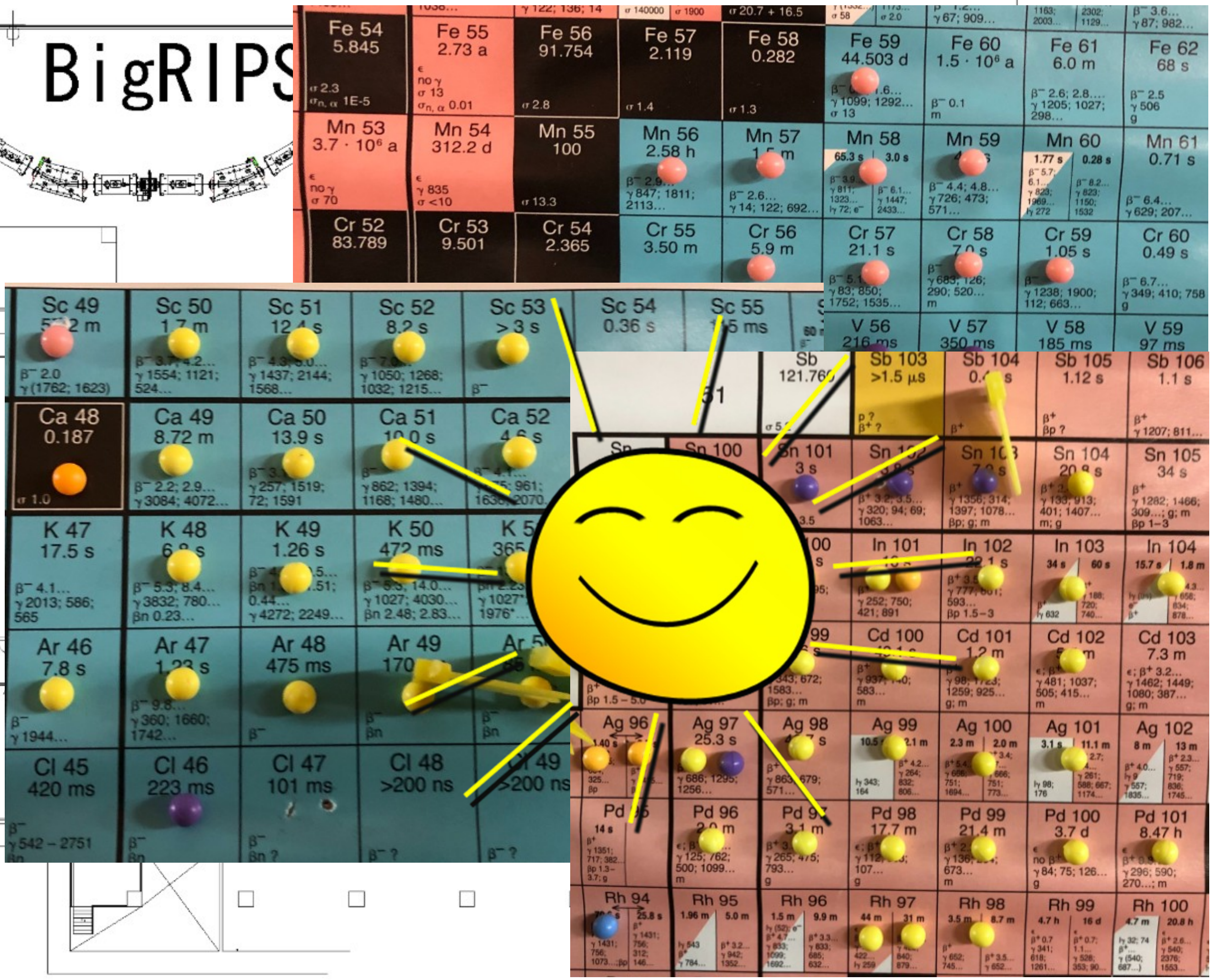


Great recent results!

And it works!

- Three symbiotic experiments with same beam
- 2024 total: three combined runs, and one dedicated beam time for masses

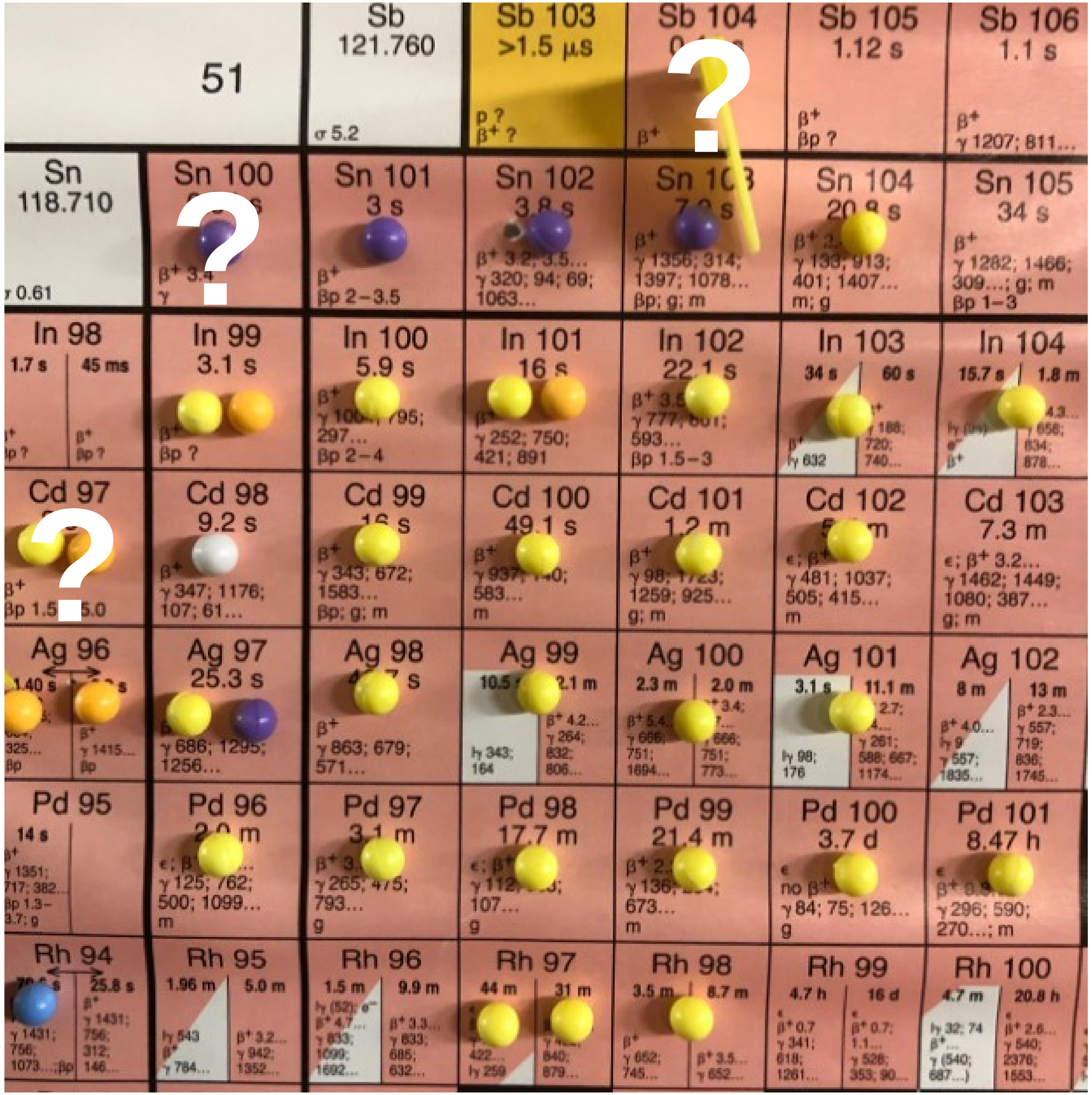




Great recent results!

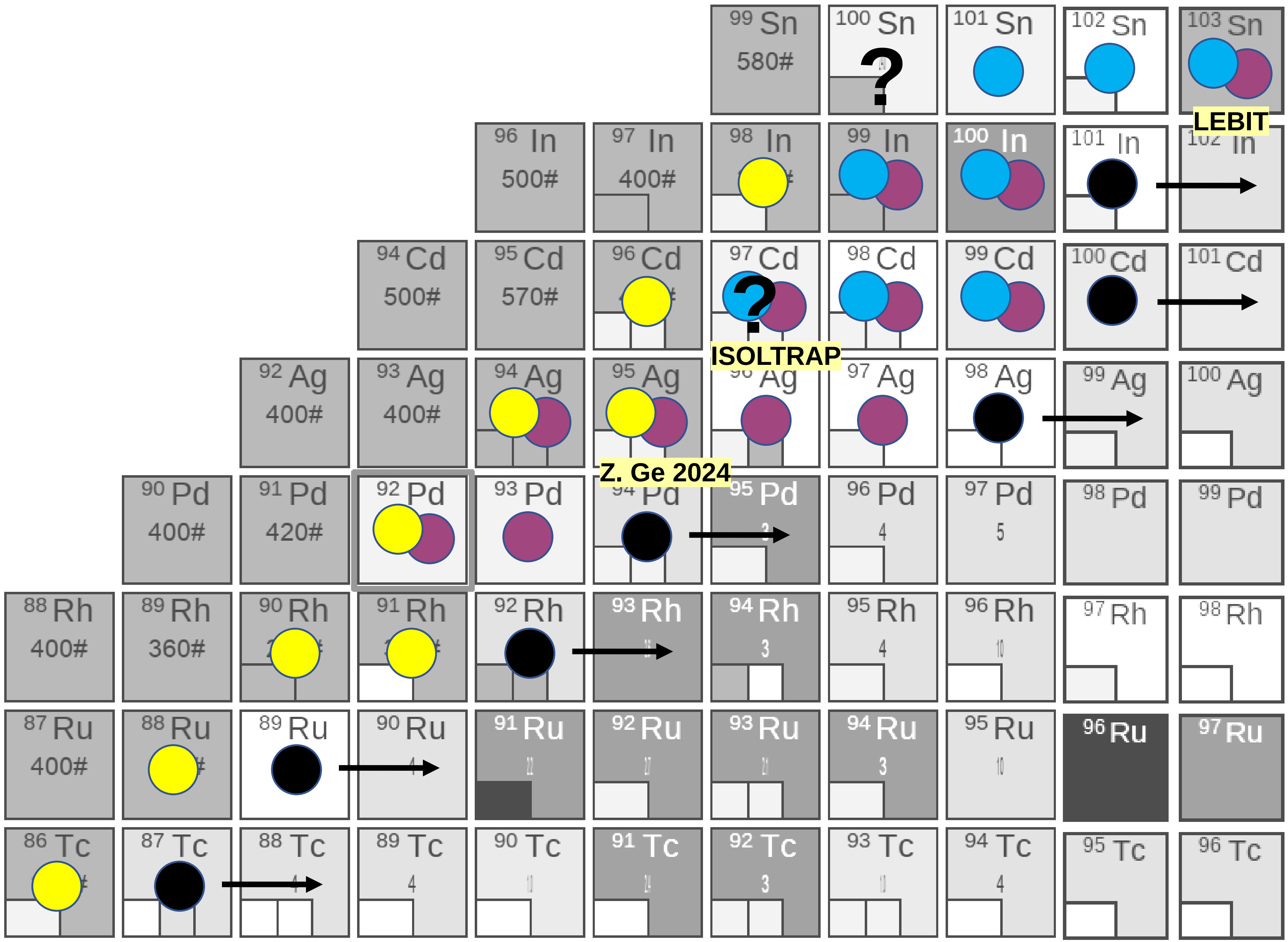
Little disclaimer:

Our pins mean: “Candidates”! They don’t necessarily tell that it is already a proper (publishable) measurement. ;-)



Overview:

High-precision mass measurements of N=Z around ^{100}Sn

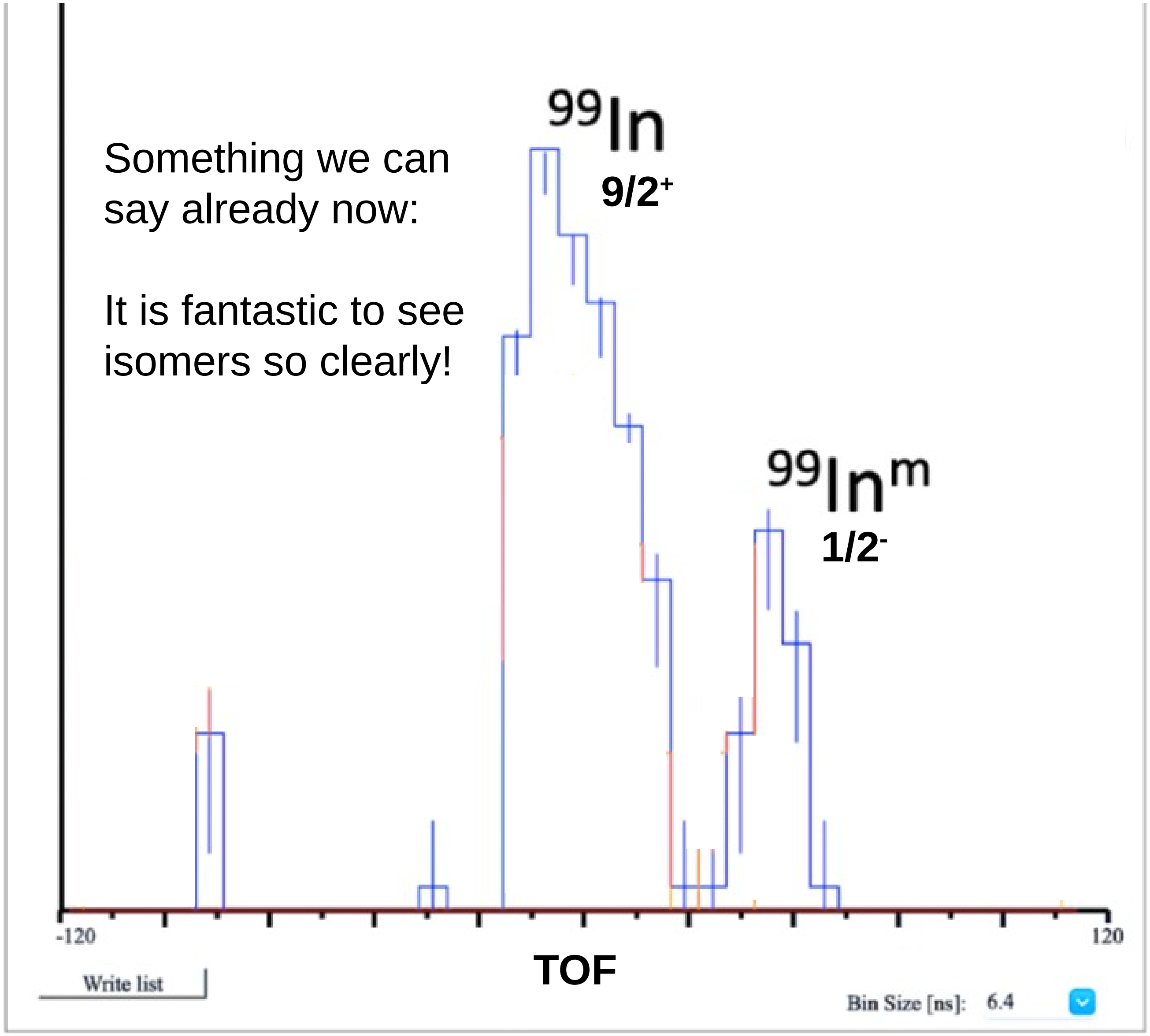


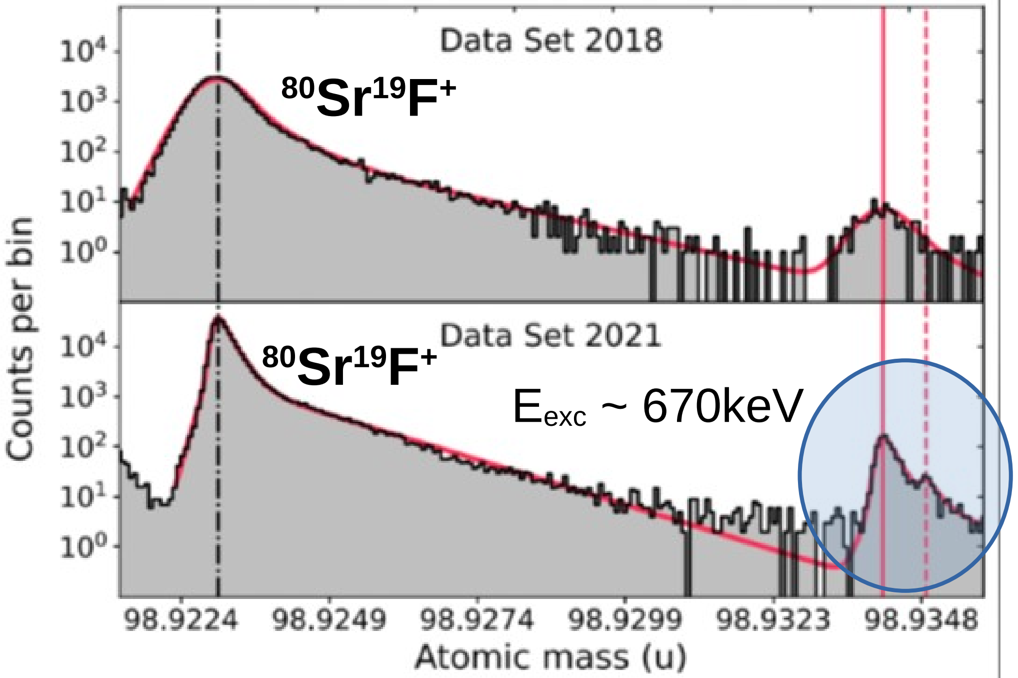
- Accomplished (new or improved)
- Still to do
- Known by other exp.
- Well known

Great recent results!

Something we can say already now:

It is fantastic to see isomers so clearly!

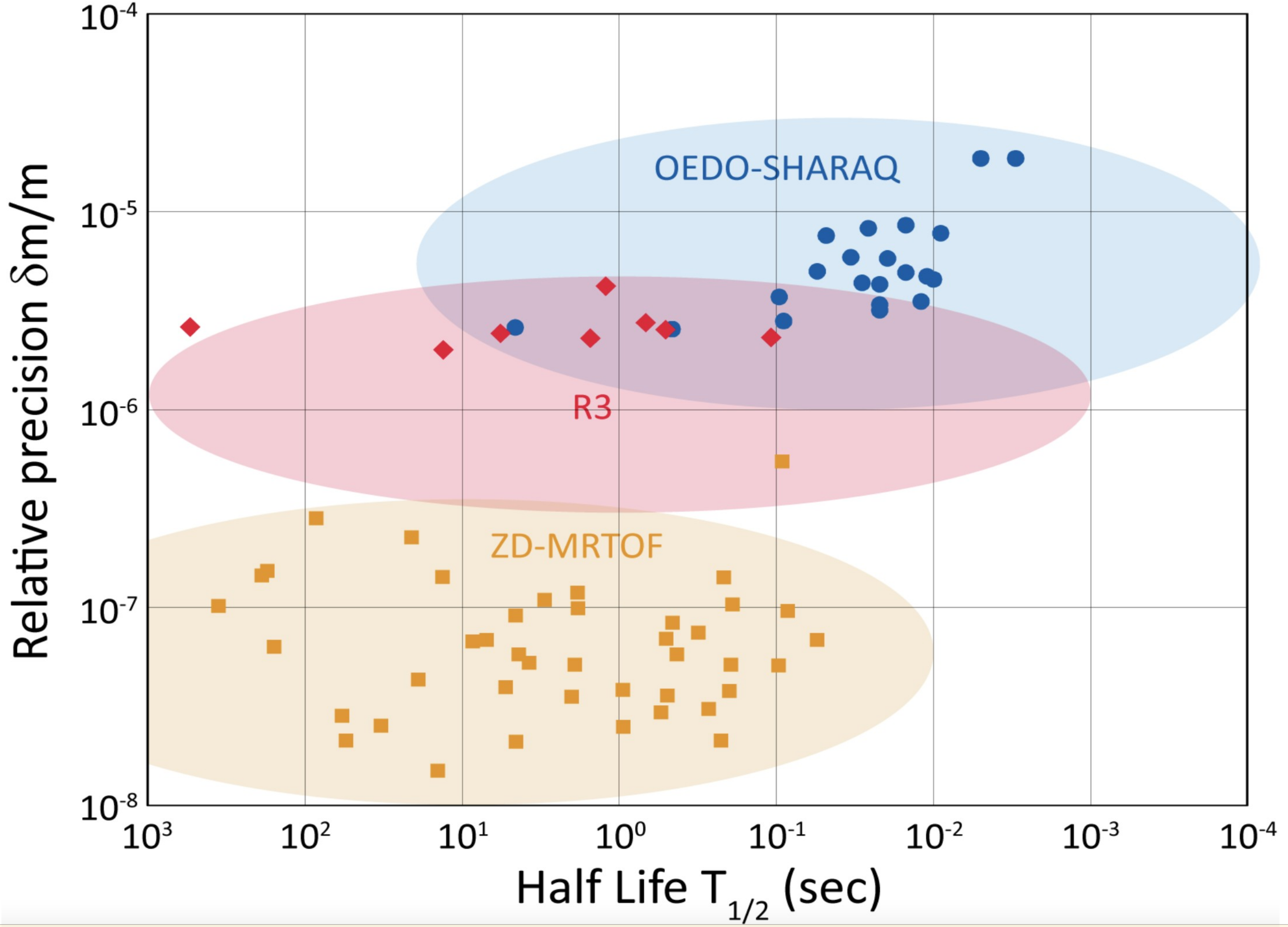




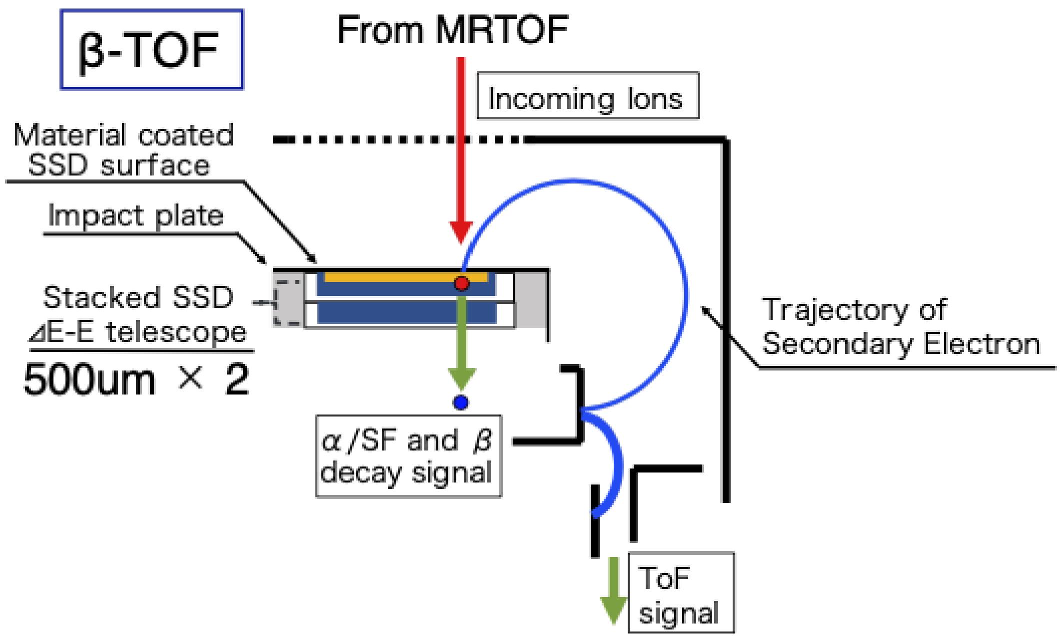
Spectrum from ISOLTRAP MRTOF

L. Nies et al., Phys. Rev. Lett. 131, 022502 (2023)

Published data from RIBF

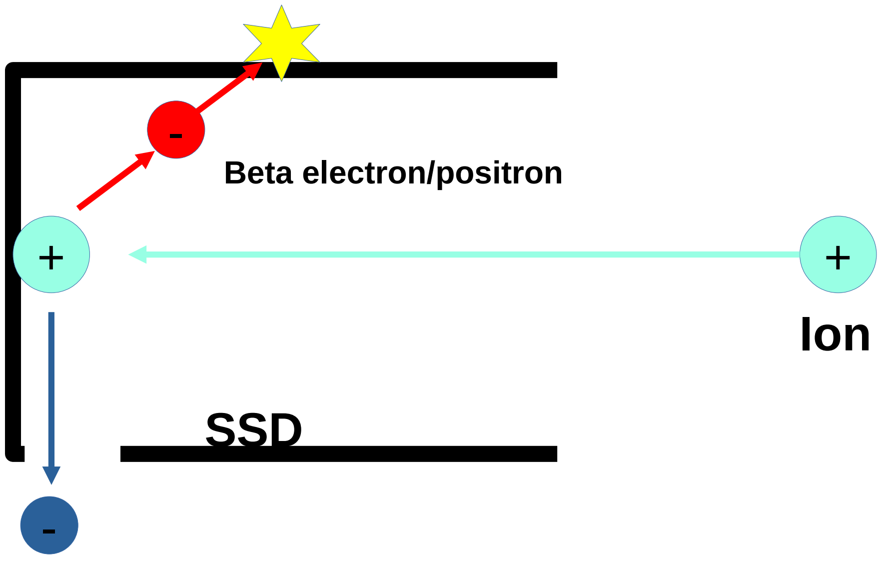


How about future developments?



Correlation with TOF and β-signal
(The β-signal is the one passing through the double layered Si.)

We need to increase the efficiency and quality of beta-TOF detection

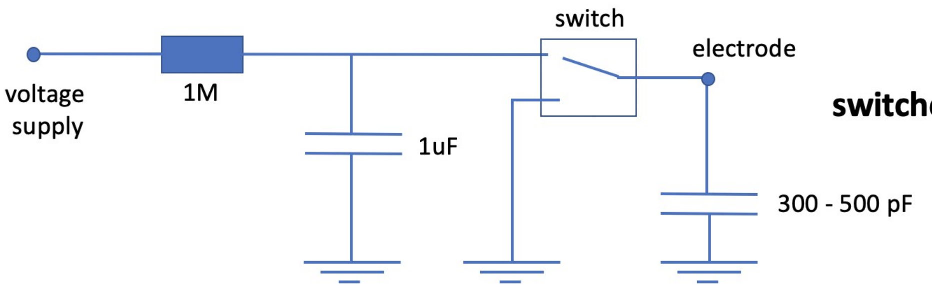


Finding ways for more fruitful decay spectroscopy tagged on masses

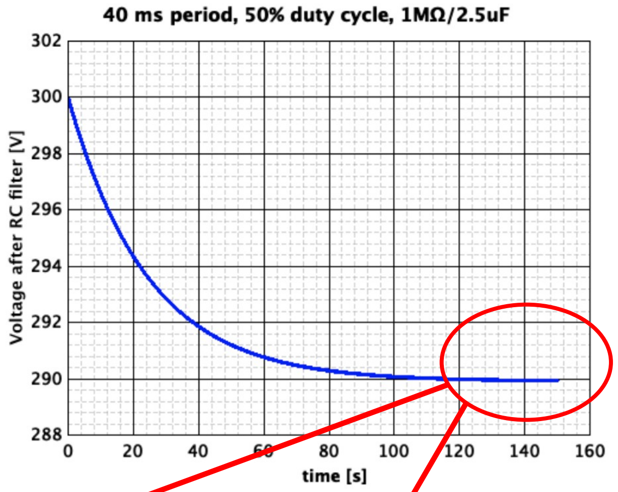
How about future developments?

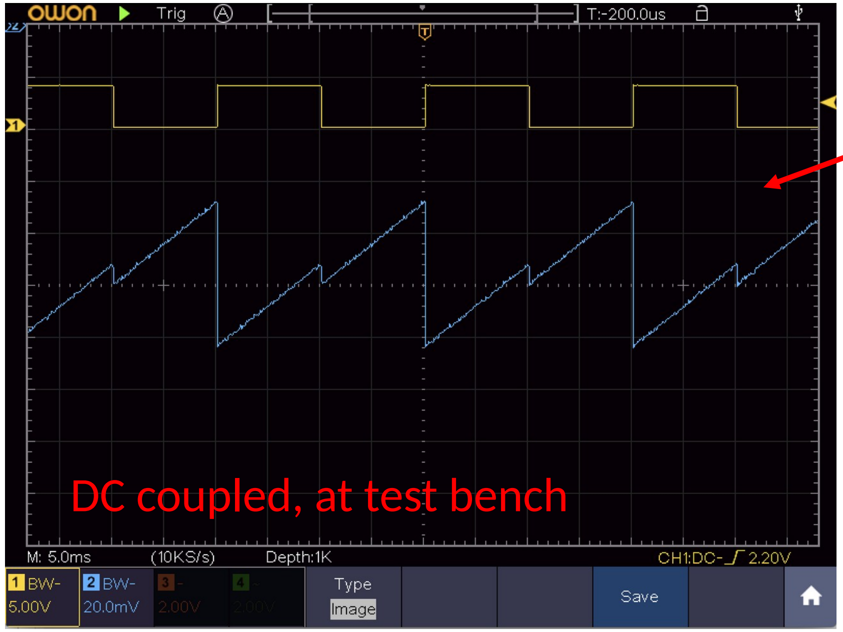
Making the electrostatic system more electrostatic

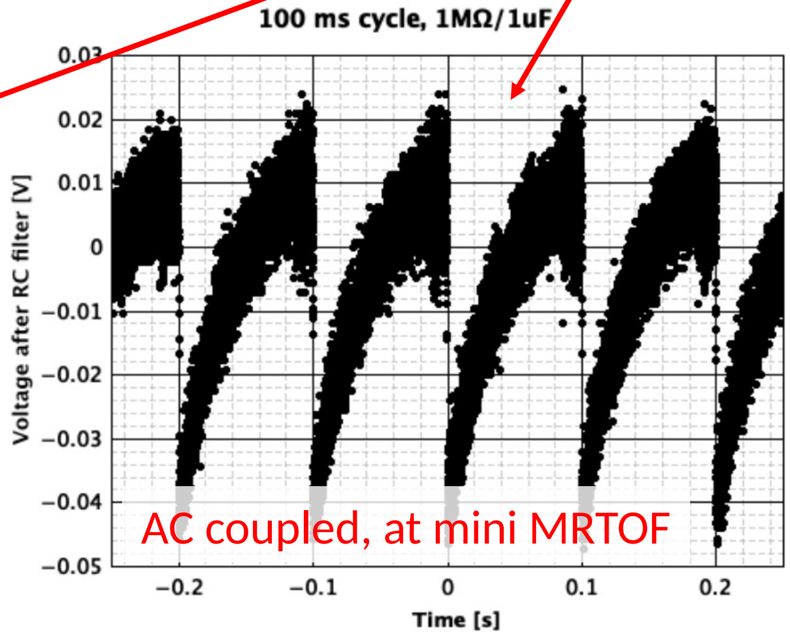
Micro-ramping at the MRTOF mirrors



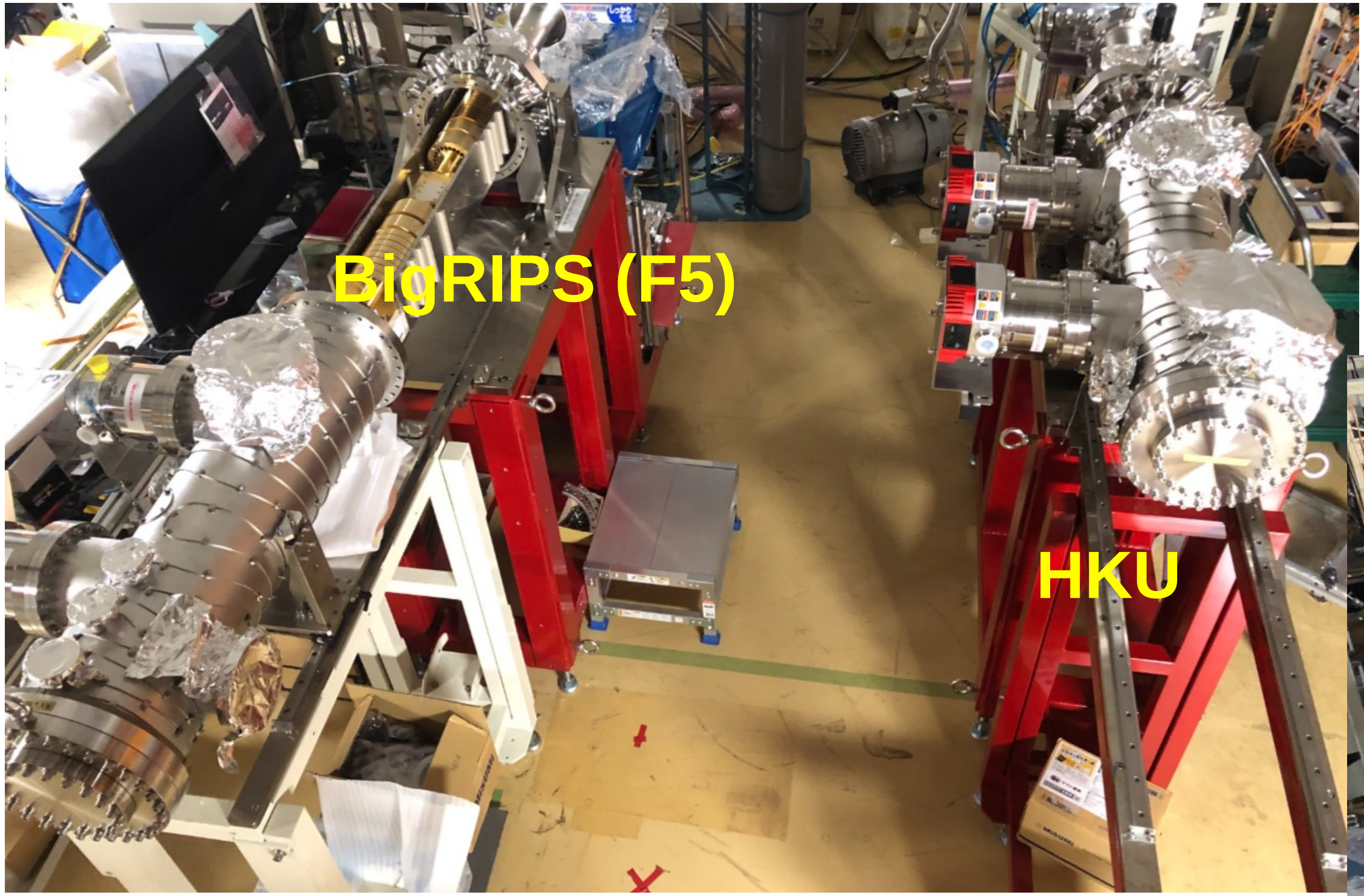
switched electrodes



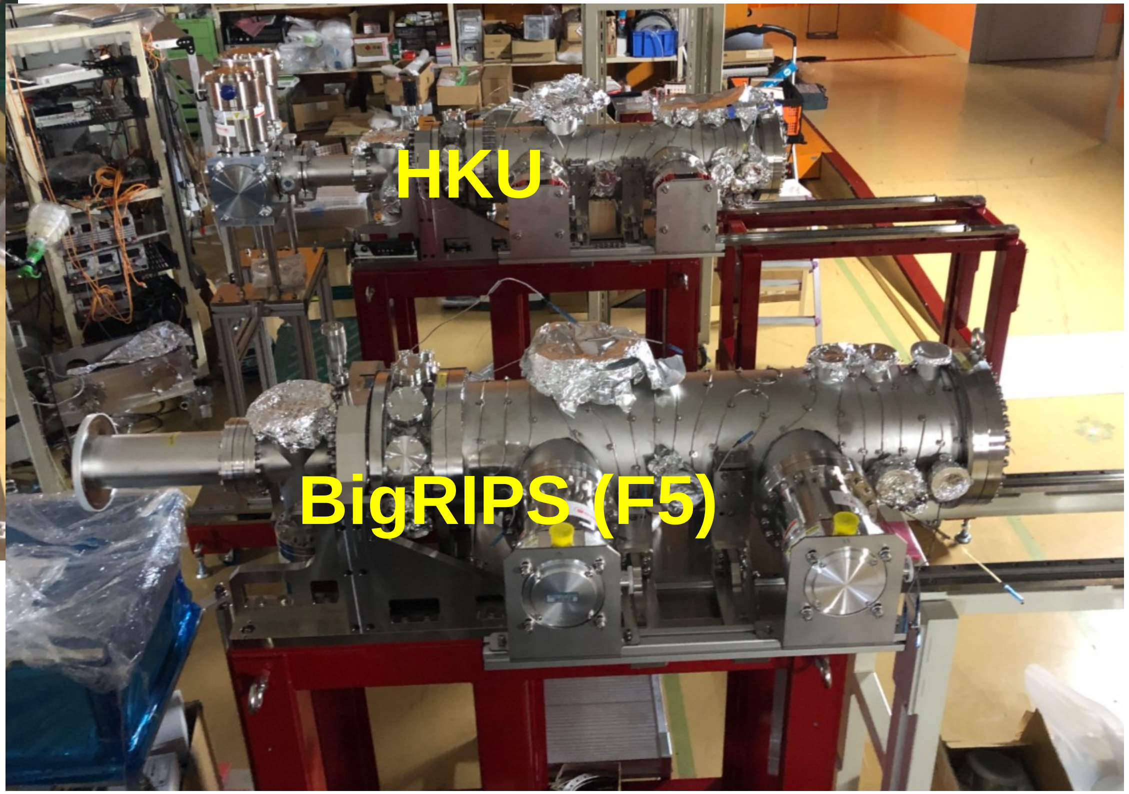




How about future developments?



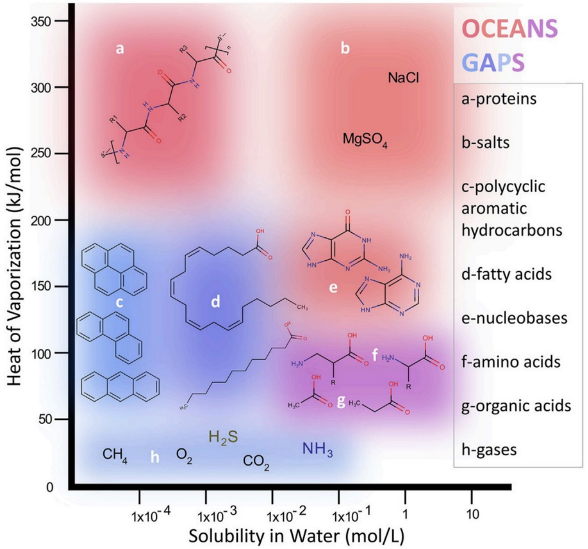
Building new MRTOF spectrometers!

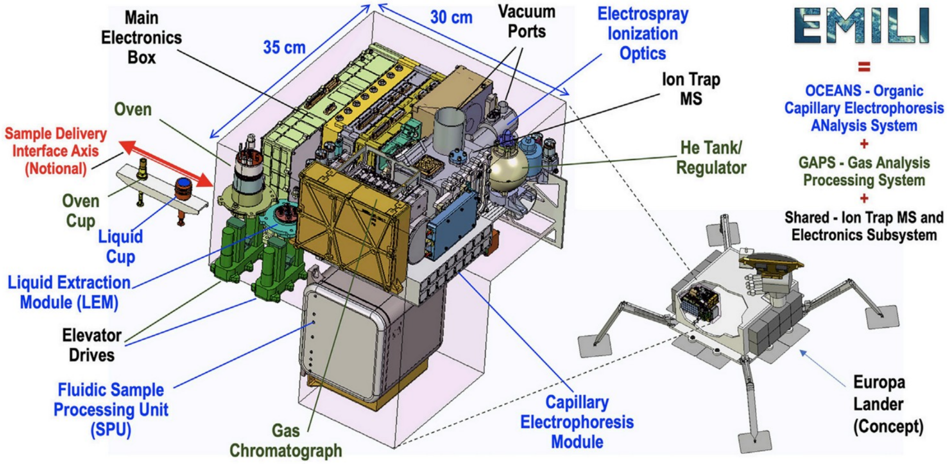


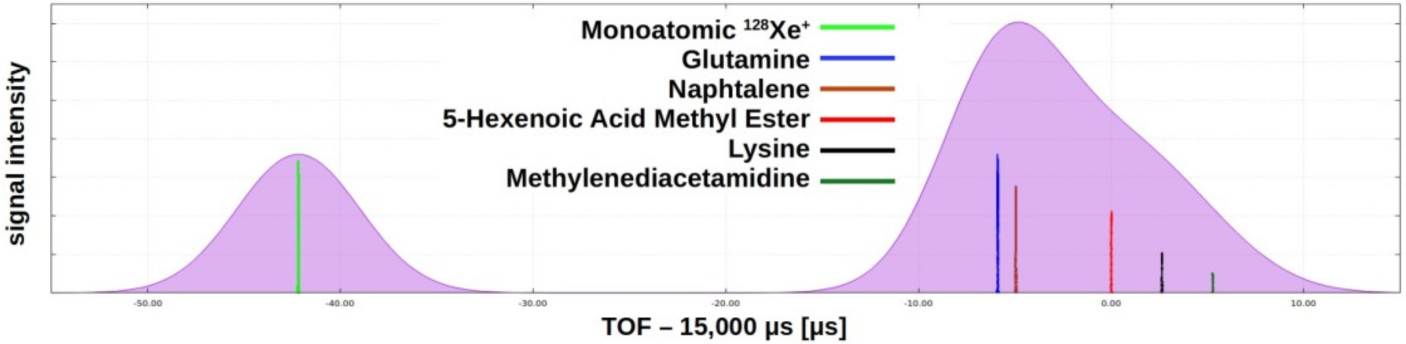
How about future developments?

Outreach: Mass spectrometry in space with NASA

William B Brinckerhoff

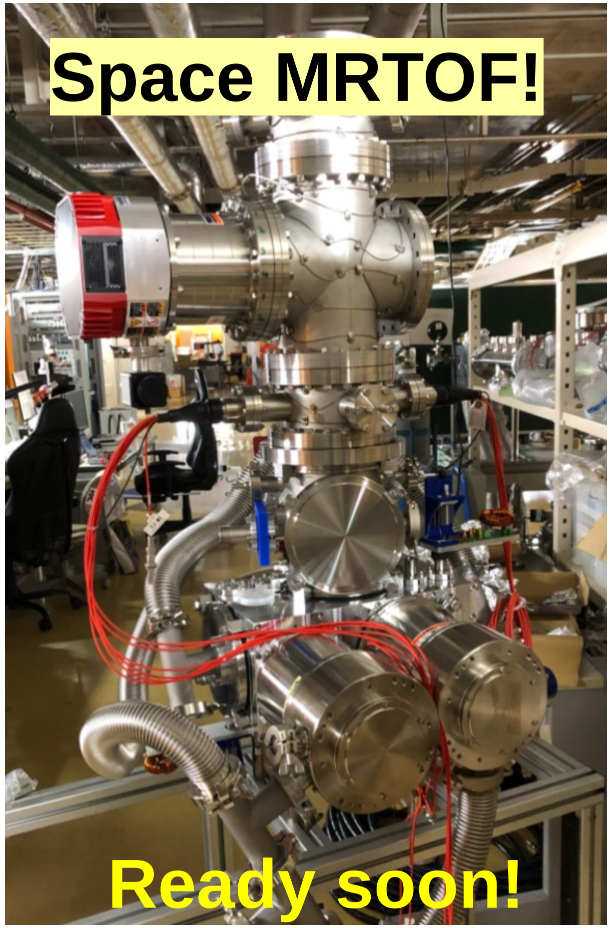


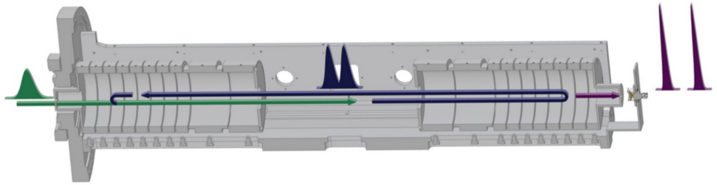




Search for signs of former life:

- Certain molecules can only be formed by living beings
- Identification by mass spectrometers
- MRTOF-MS technology is robust and able to survive in space environments





Summary

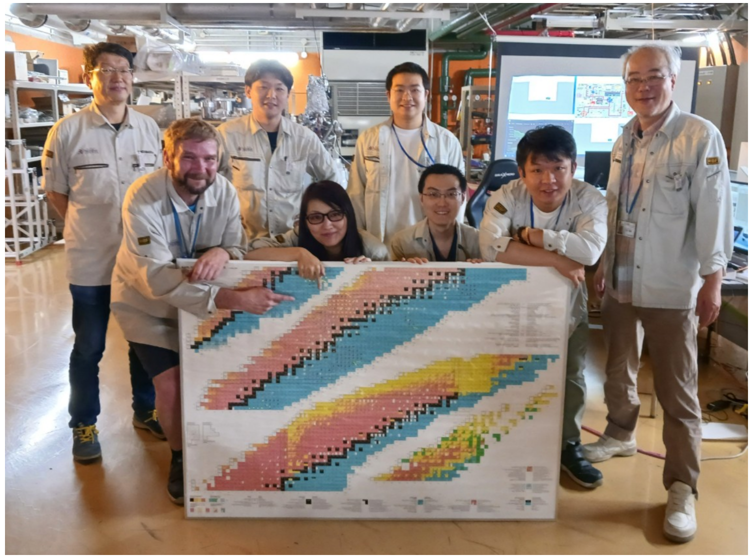
- **The ZD MRTOF-MS became one of the most successful projects for mass measurements of the recent years!**
  ➞ 68 isotopes published!

- **Background problems in case of low production rates are tackled by efficient use of an IMD system, and beta-correlated mass spectroscopy**

- **From test setup to ready-to-use device in about four years of time line**

- **Development of combined runs with in-beam gamma campaigns**
  ➞ powerful proposals

- **Development of through-beam experiments for simultaneous decay spectroscopy**



RIKEN

UNIVERSITY OF SURREY

UNIVERSITY of York

香 港 大 學
THE UNIVERSITY OF HONG KONG

KEK-JAPAN


2020 first ZD MRTOF commissioning

RIKEN NISHINA CENTER

IMP

東京大学
THE UNIVERSITY OF TOKYO

CNS

Thanks to:

- **KISS collaboration**
- **SHE mass collaboration**
- **ZD MRTOF collaboration**

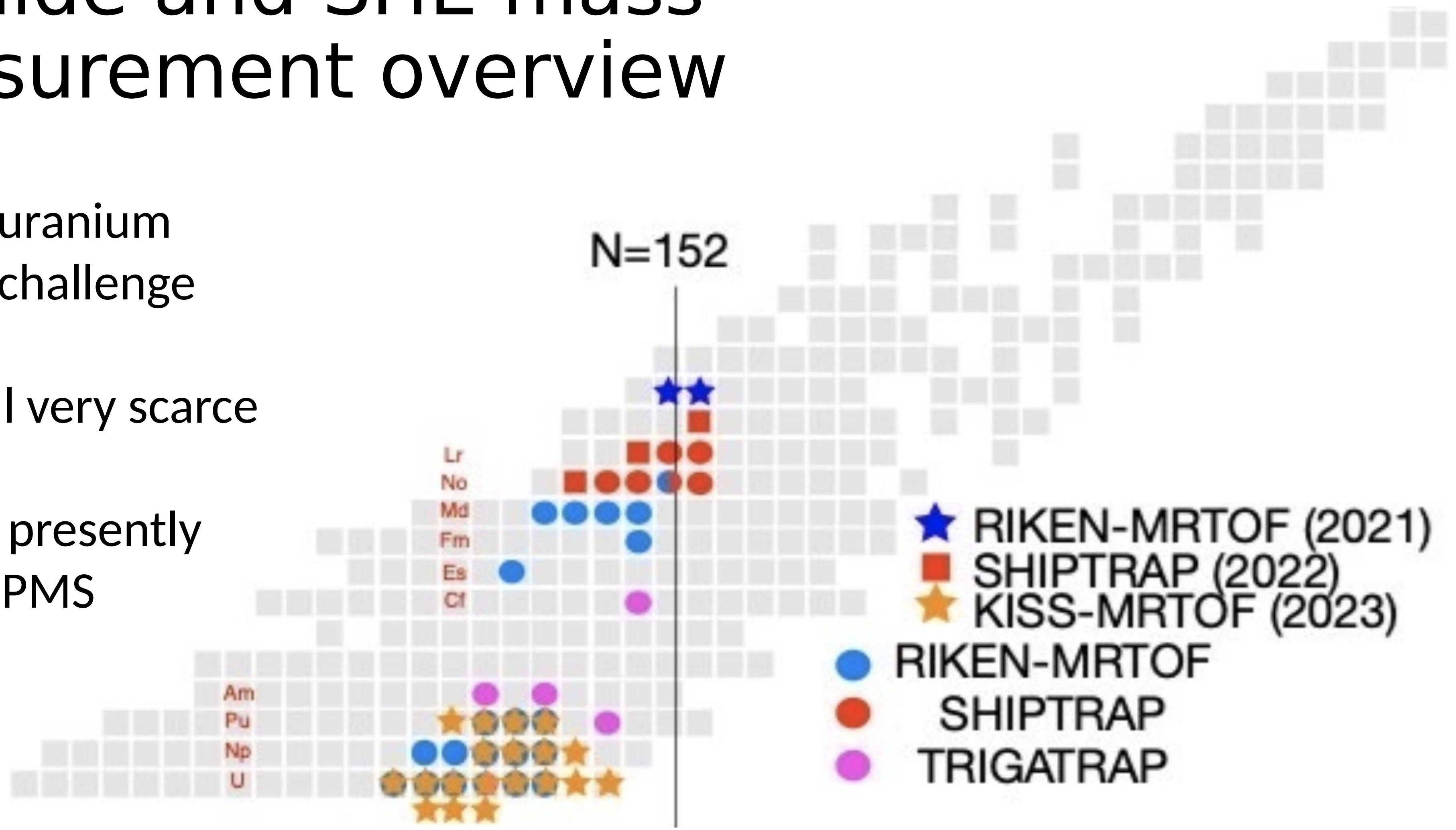
JAEA

IJCLab Irène Joliot-Curie

WNSC
KEK Wako Nuclear Science Center

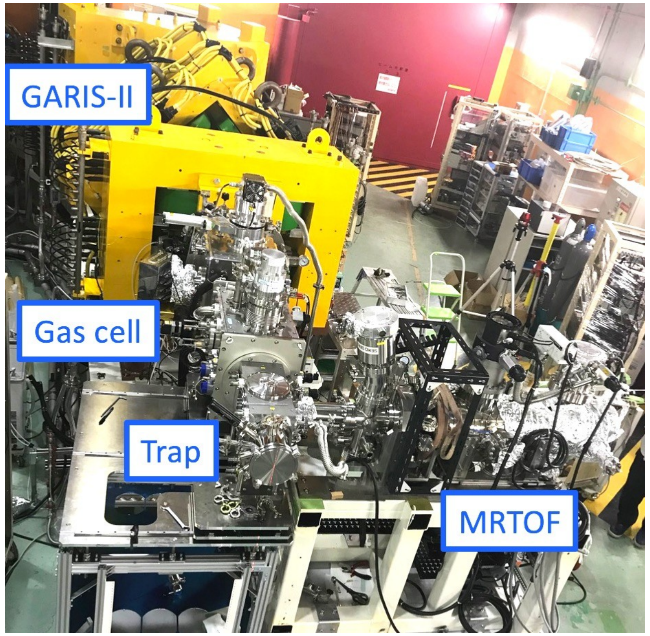
Actinide and SHE mass measurement overview

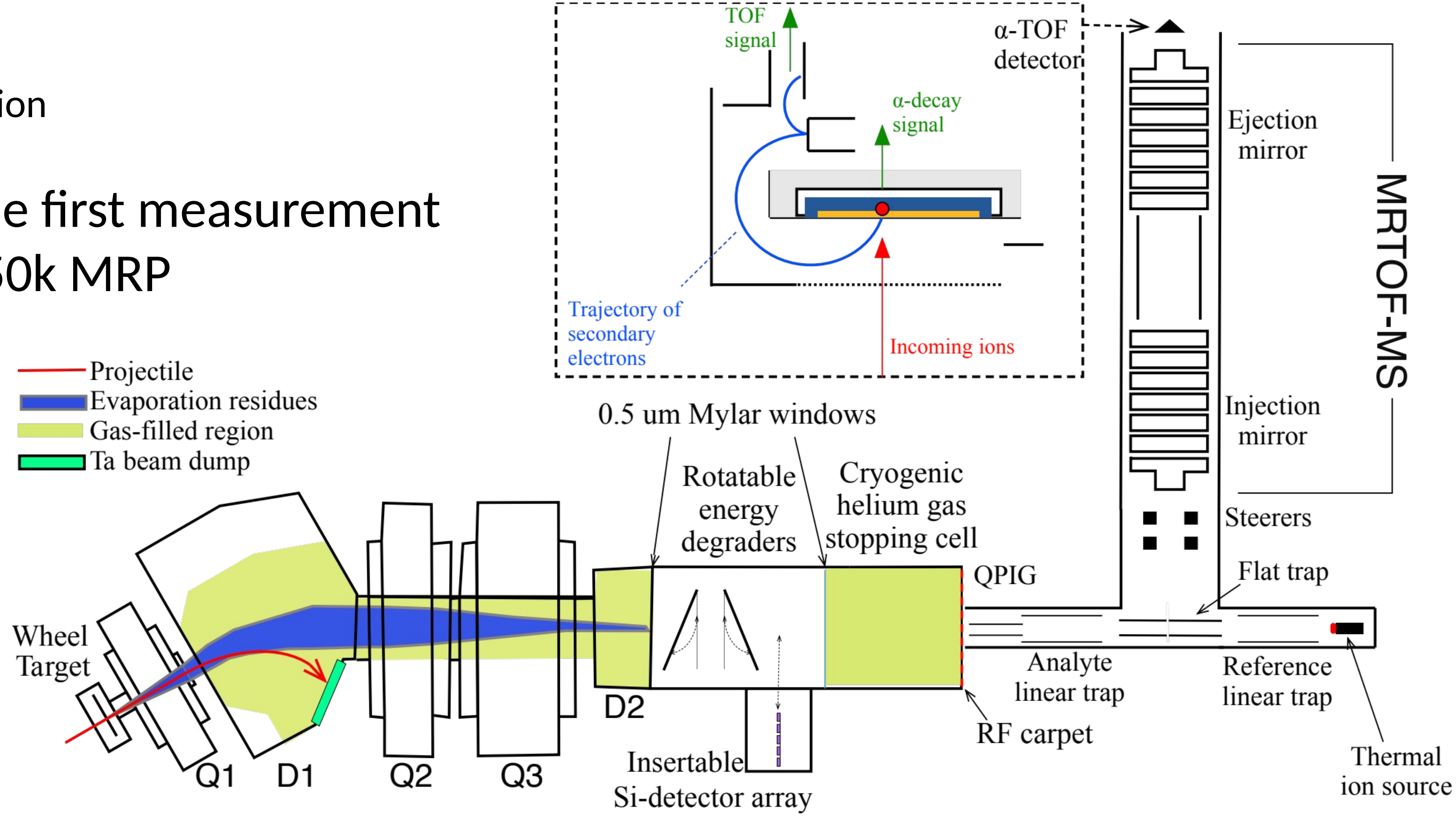
- Production of transuranium isotopes is a major challenge
- Available data is still very scarce
- Only a few projects presently join the efforts of HPMS



SHE-Mass facility overview

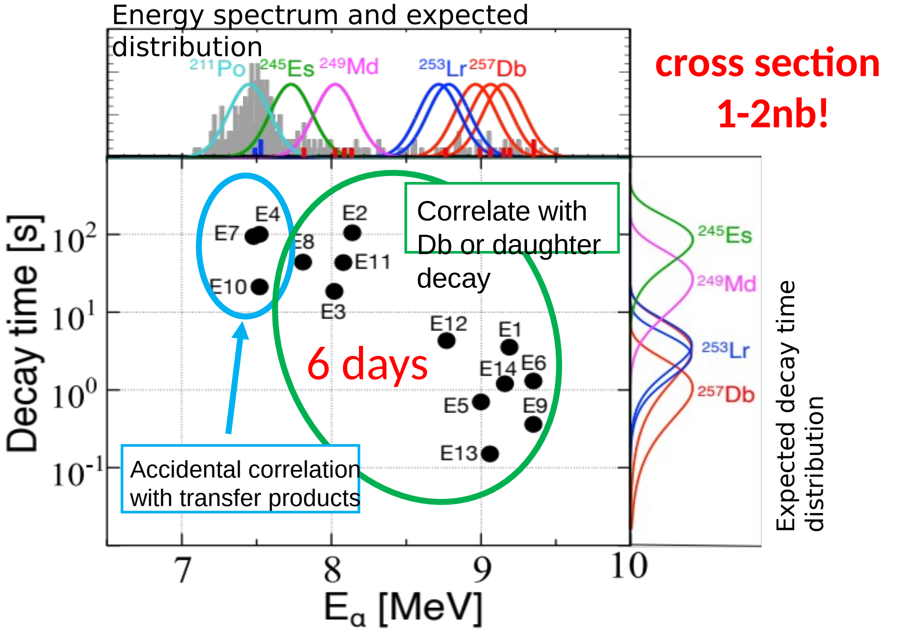
- System efficiency ~5%
  - 25%~30% stopping+extraction
  - ~20% transport
- MRTOF ~300k MRP in the first measurement
- Recently increased to 750k MRP





The SHE Mass facility and status of ^{257,258}Db mass measurements

P. Schury et al,PRC104, L021304 (2021)



First effort: metallic Pb targets

Primary beam of 500 pnA ^{51}V on nat. Pb, 6MeV/u

11 ToF events correlated with α-decays

Mass resolving power limited to $m/\Delta m \approx 300k$

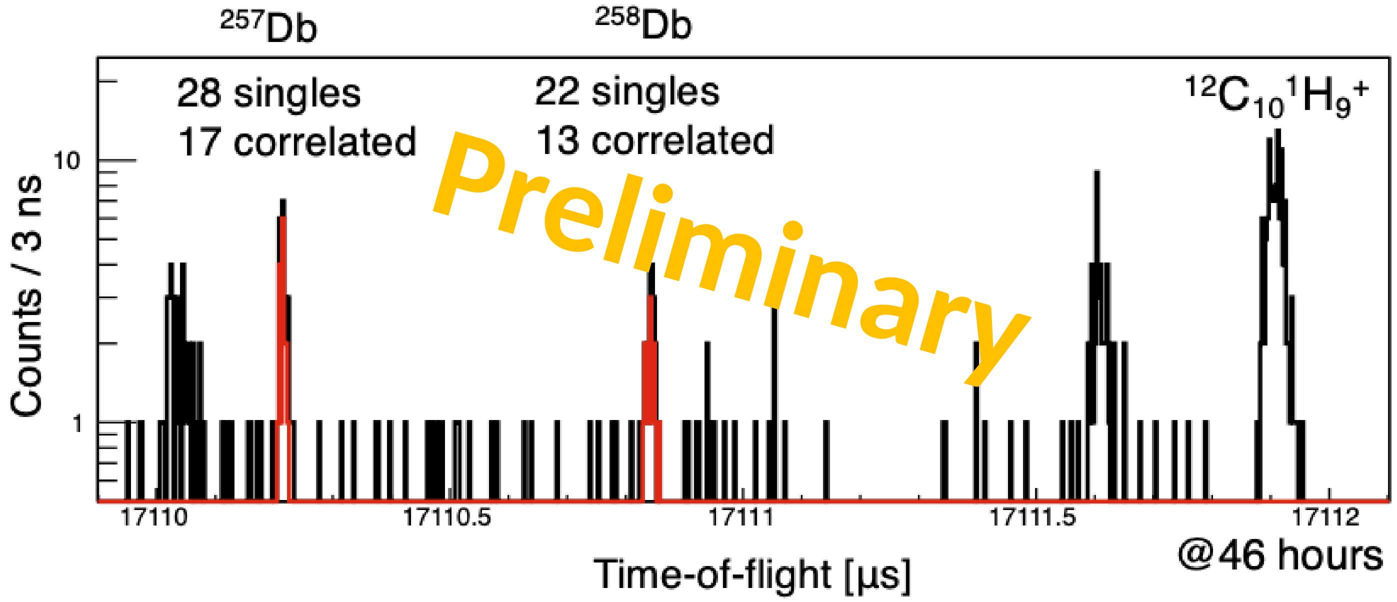
Second effort with **PbS** targets

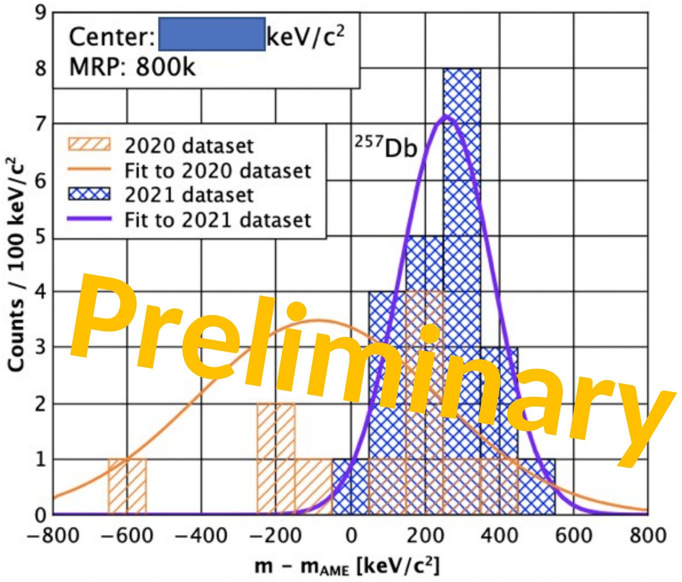
Primary beam intensity up to 2 puA, 6MeV/u possible

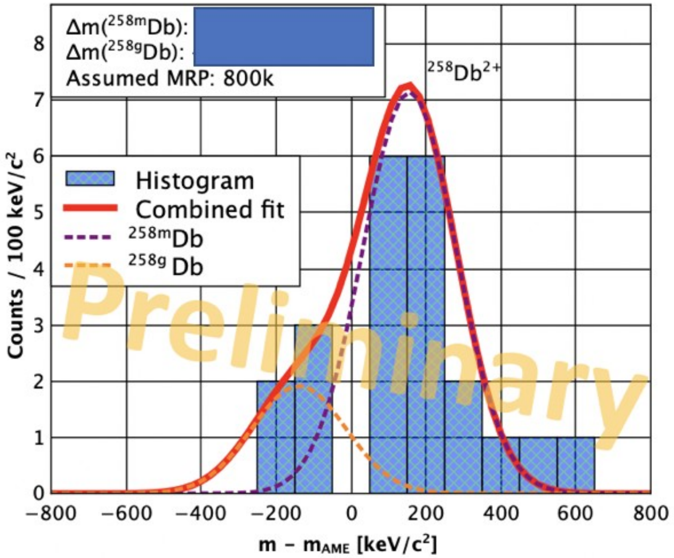
Many more correlated events

Mass resolving power reached $m/\Delta m \approx 750k$

Could exclude $E_{ex}(^{257m}Db) \geq 300$ keV





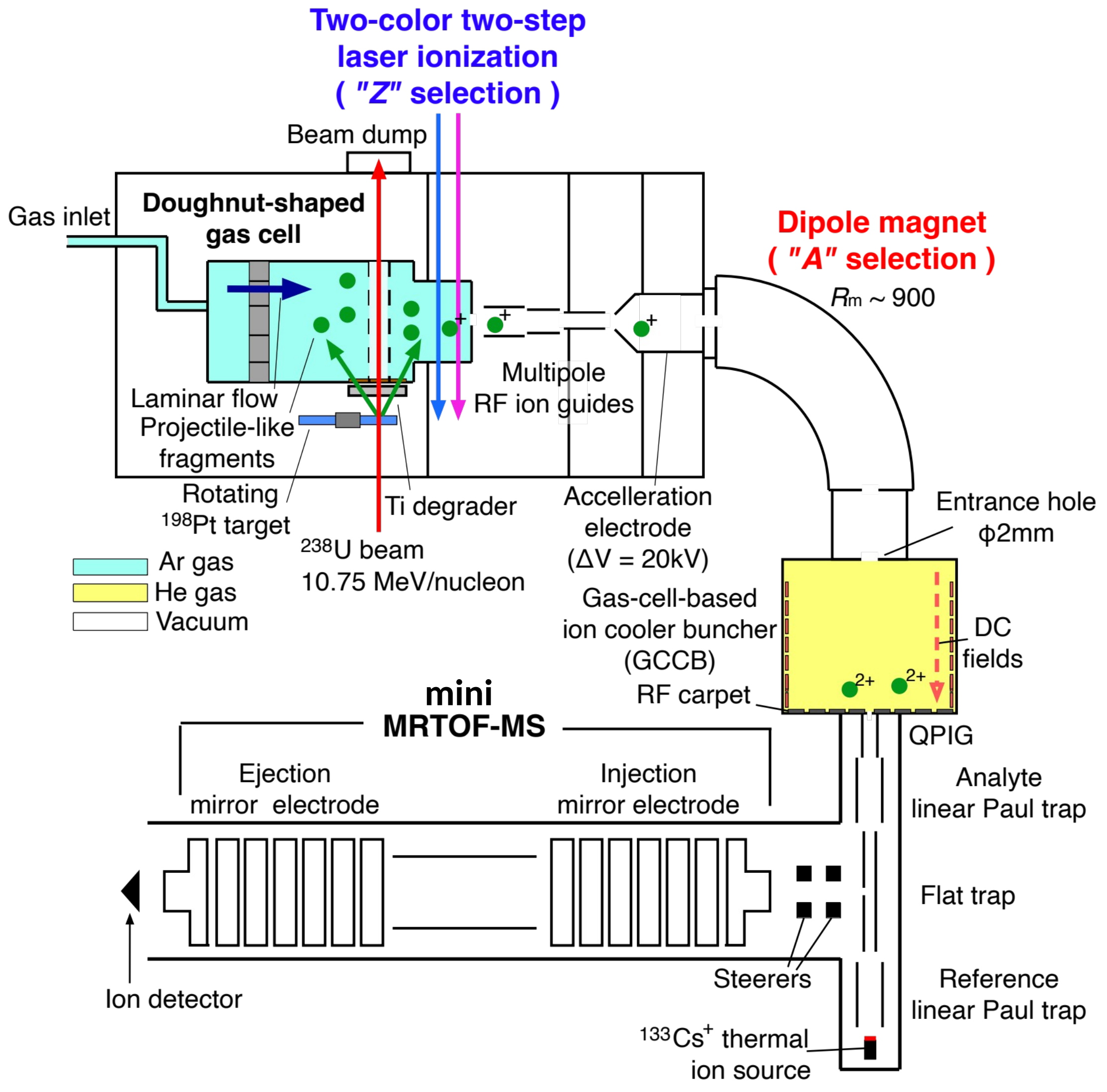


The KISS facility and the discovery of a new uranium isotope

Schematic view of KISS-MRTOF

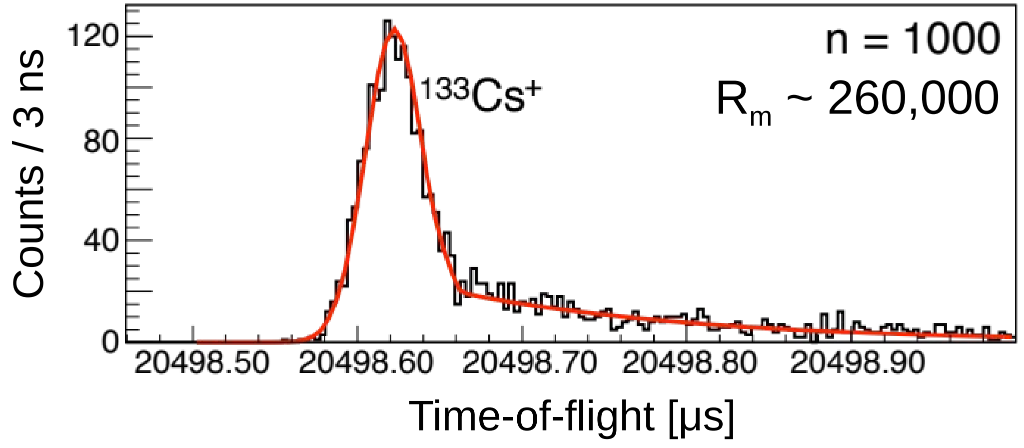
- Beam : ^{238}U 10.75 MeV/nucleon ~30pnA
- Target : ^{198}Pt target (enriched to 91.63%)

~30pnA



① Thermalization of
MNT products in Ar gas
② Selection of **atomic number**
by **laser-ionization** technique
③ Selection of **mass number**
by **dipole magnet**
④ Spectroscopy with pure-beam
(βγ, half-life, mass)

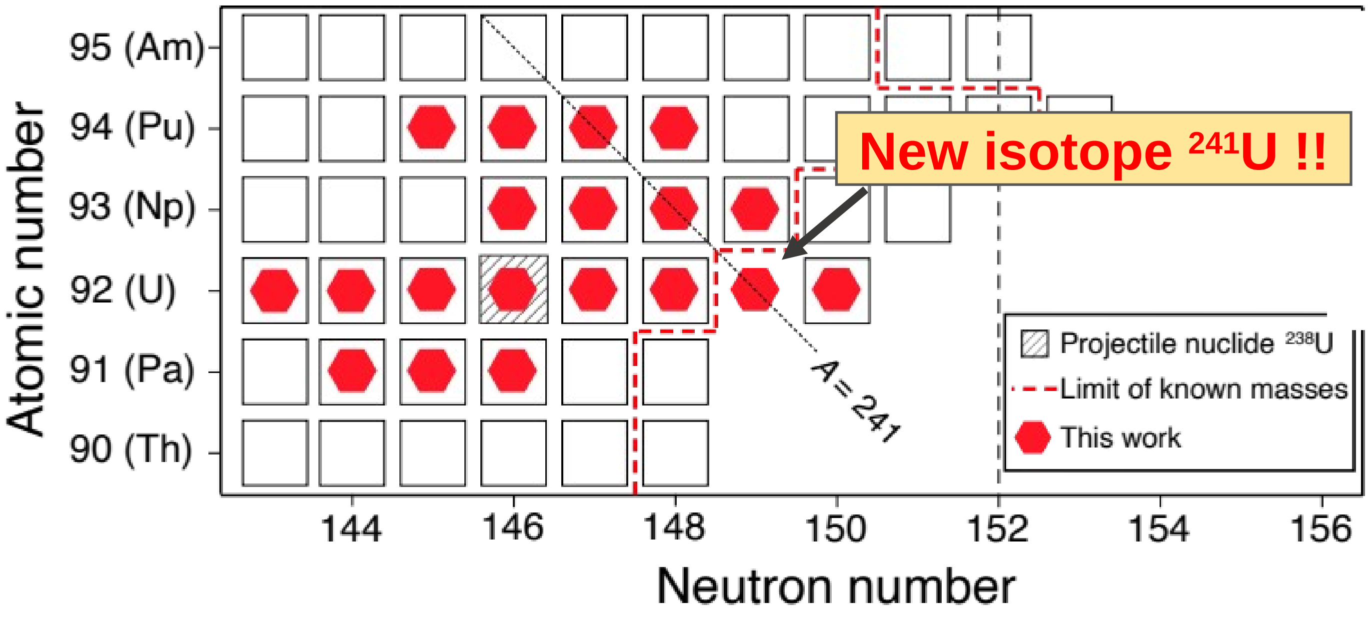
Mass measurement by MRTOF-MS



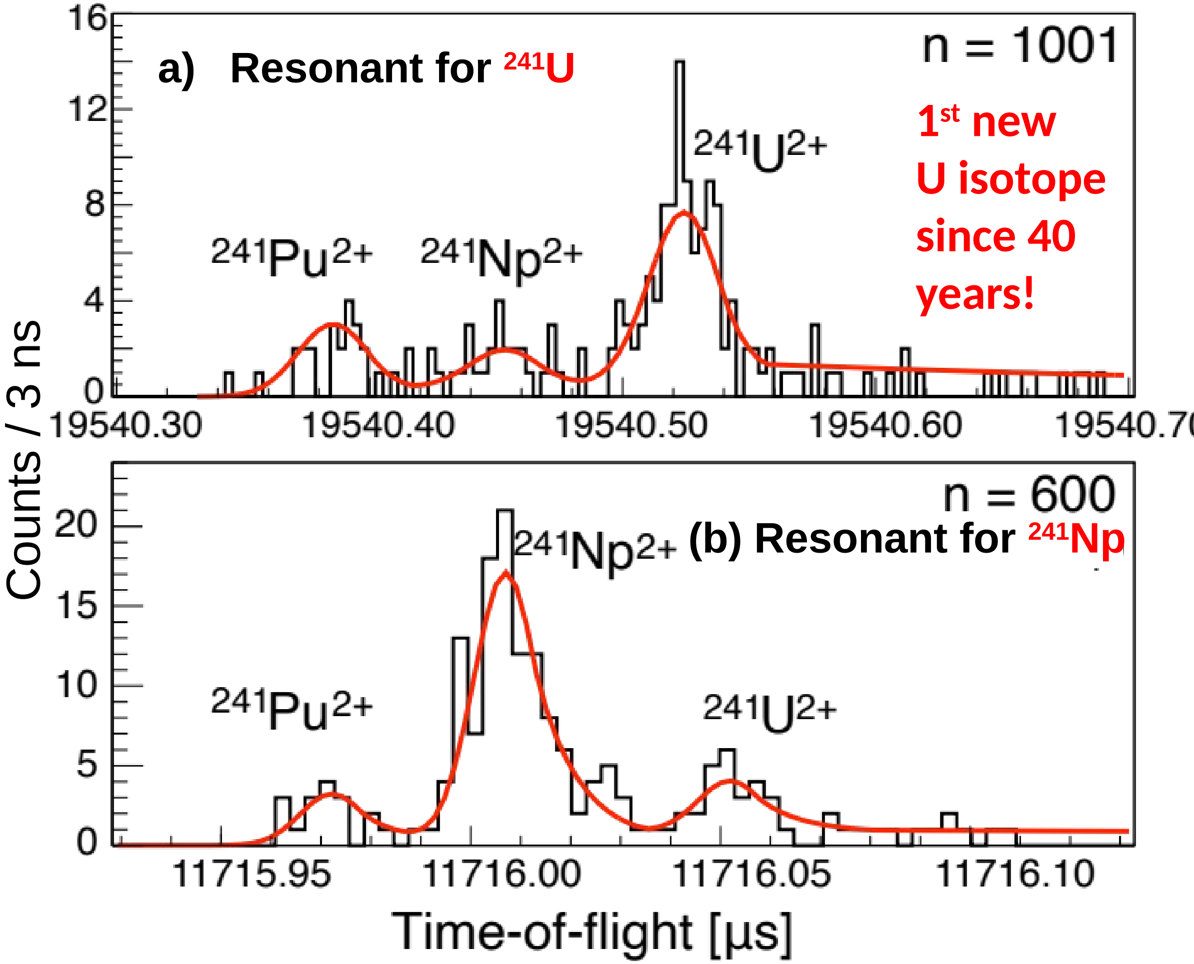
The KISS facility and the discovery of a new uranium isotope

Totally 19 nuclides were measured

$^{235-242}$U, $^{235-237}$Pa, $^{239-242}$Pu, $^{239-242}$Np



TOF spectrum of A = 241 species



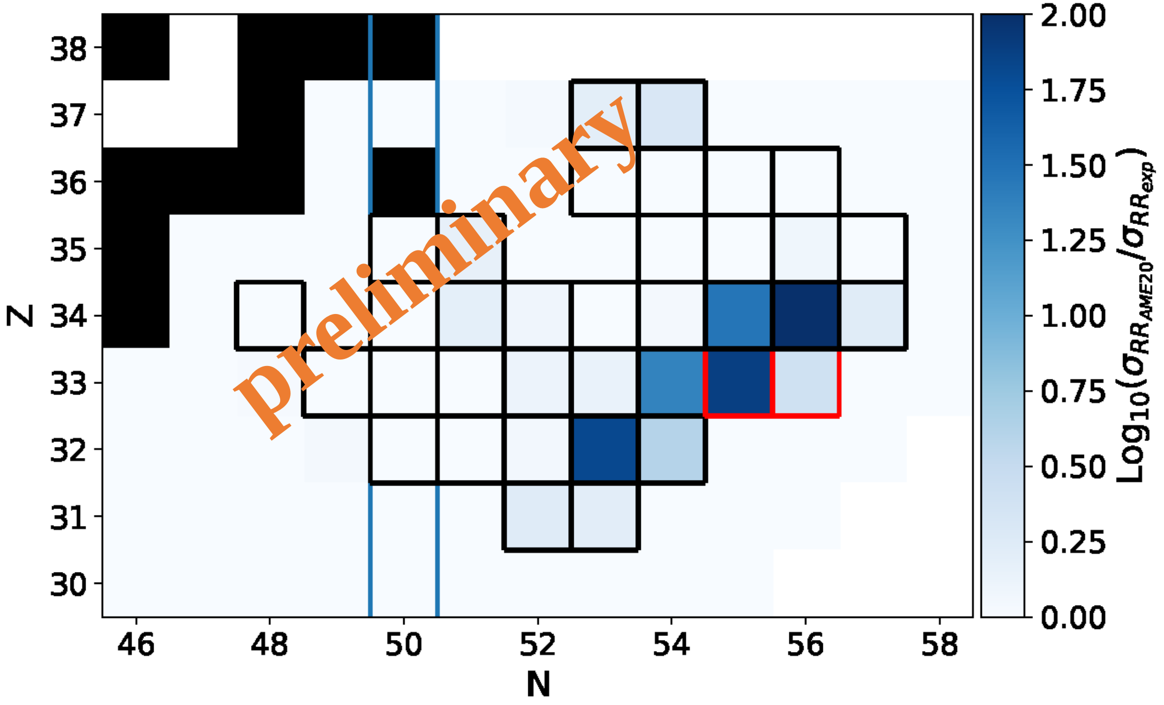
- Beam : ^{238}U 10.75 MeV/nucleon ~30pnA
- Target : ^{198}Pt target (enriched to 91.63%)

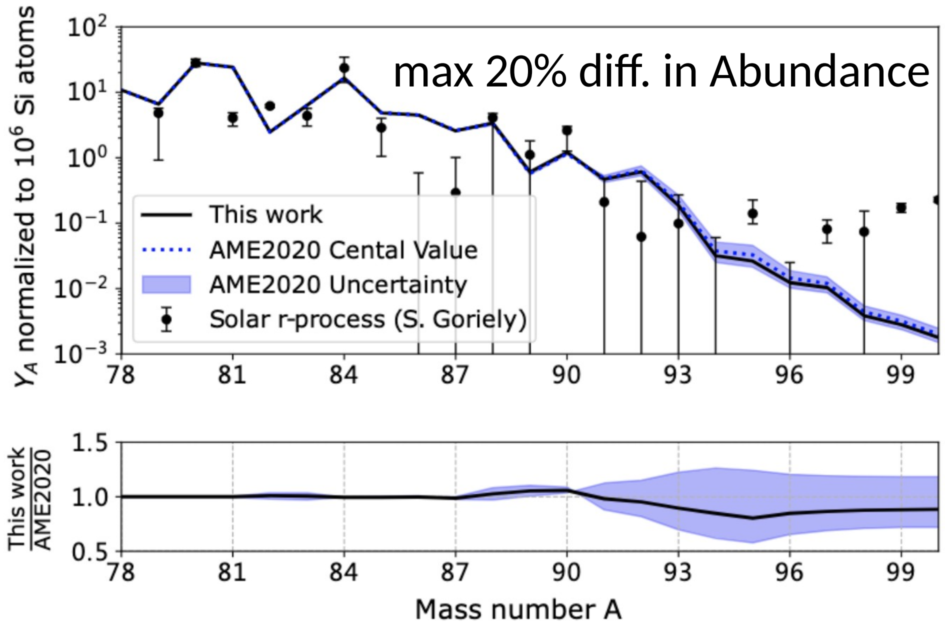
T. Niwase *et al.,* Phys. Rev. Lett. 130, 132502 (2023).
Editors suggestion!

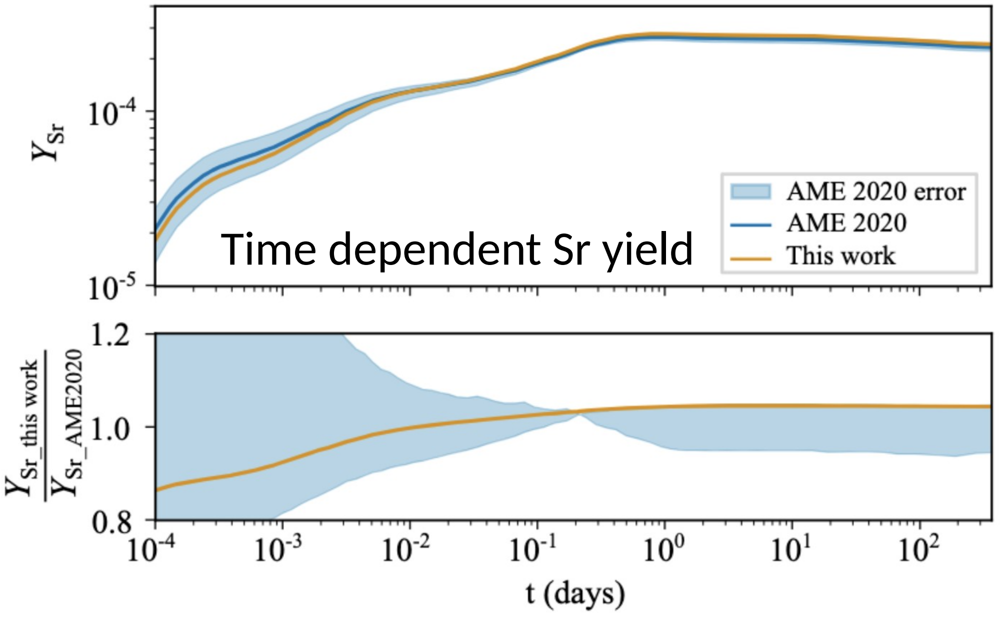
Clearly identified as new isotope ^{241}U

High-precision mass measurements of n-rich Ga-Br isotopes

Astrophysical considerations





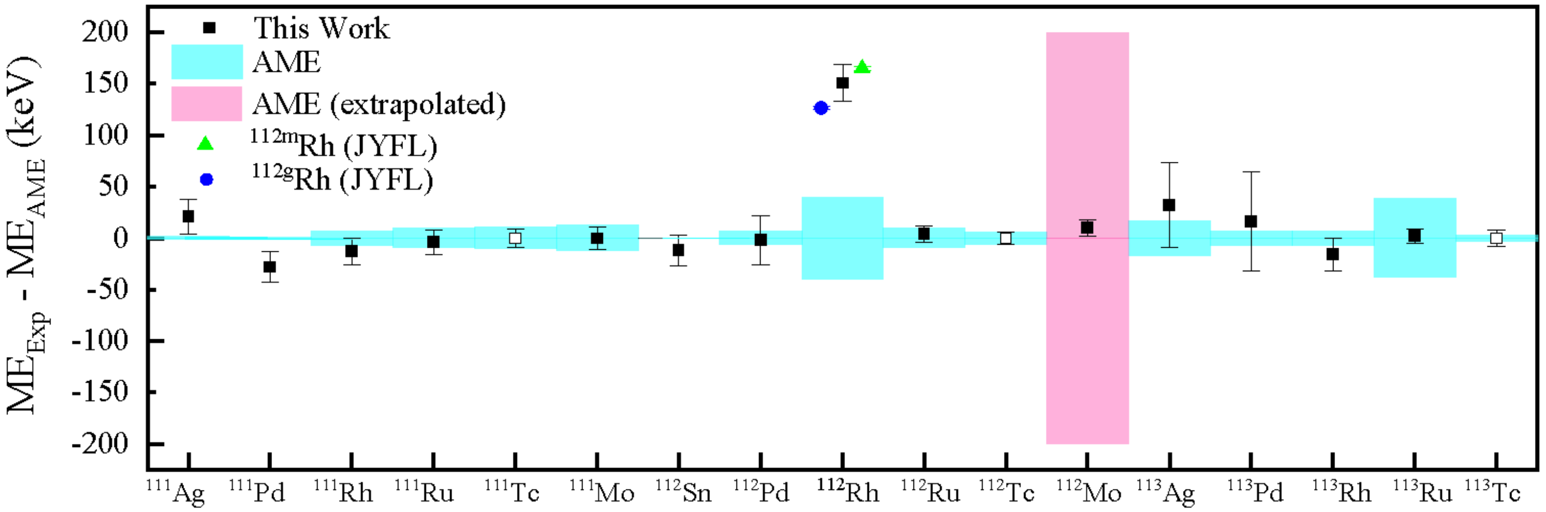


- Theoretical work by S. Nikas
- Pinning down reaction rates for neutron capture
- Comparing r-process abundance using new data
- Dynamic evolution of Sr yield motivated by GW170817

W. Xian, S. Chen *et al.*, under review at PRC

High-precision mass measurements of n-rich Mo isotopes

Parasitic experiment of HiCARI (in-beam gamma) Campaign: W. Korten



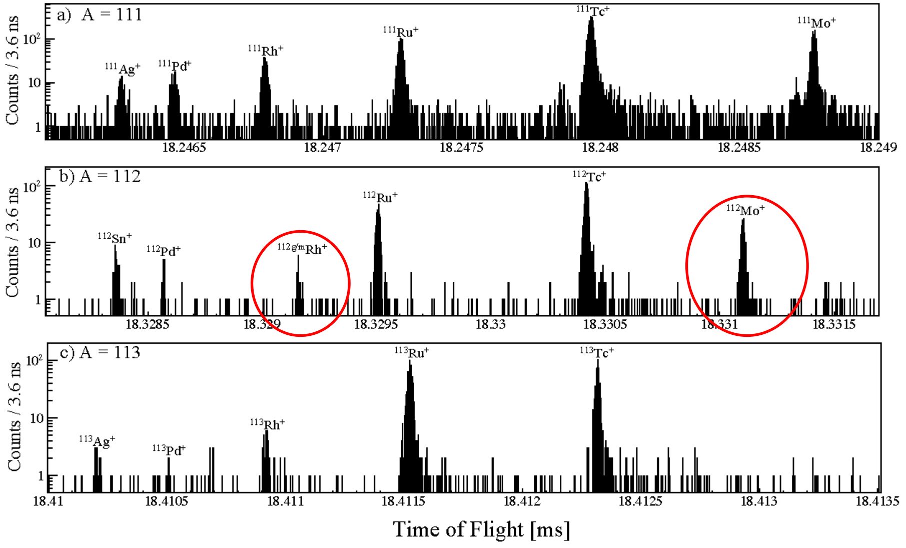


TABLE I. Measured radioactive isotopes, the reference ion, measured mass excess ME_{MRTOF}, mass excess from literature AME2020 ME_{AME2020}, mass deviation calculated as $\Delta m = ME_{\mathrm{MRTOF}}$ - ME_{AME2020}. Extrapolated values of AME2020 are denoted by #, and the total number of the detected ions N_{ion} in this work.

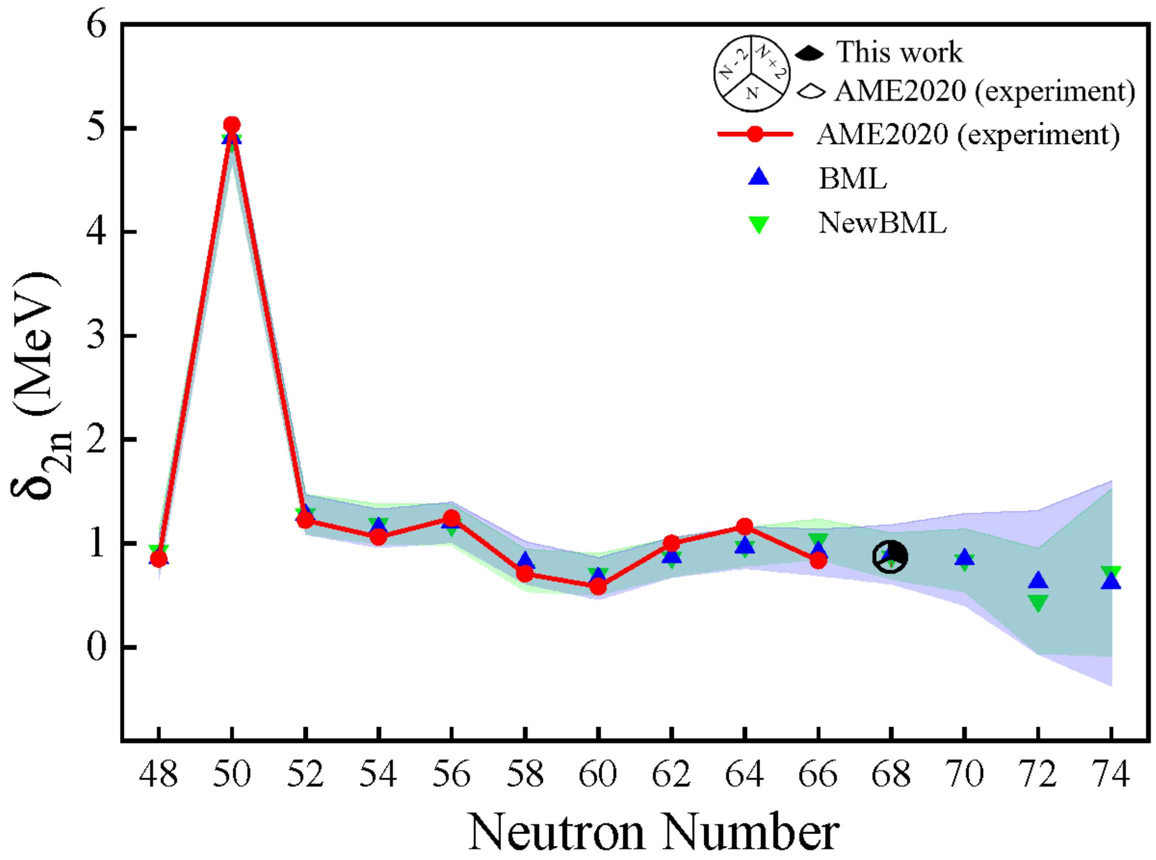
Species	Ref. ion	ME_{MRTOF} (keV/c^2)	ME_{AME2020} (keV/c^2)	Δm (keV/c^2)	N_{ion} (Counts)
^{111}Ag	^{111}Tc	−88195.22(15.40)	−88215.48(1.46)	20.23(15.47)	115
^{111}Pd	^{111}Tc	−86010.80(14.17)	−85985.89(0.73)	−24.91(14.19)	125
^{111}Rh	^{111}Tc	−82318.53(11.28)	−82303.87(6.8[illegible])	−14.66(13.19)	262
^{111}Ru	^{111}Tc	−76791.50(9.16)	−76785.33([illegible])	−6.17(13.33)	743
^{111}Mo	^{111}Tc	−59939.88(8.47)	−5993[illegible](12[illegible]8)	−0.07(15.16)	1300
^{112}Sn	^{112}Tc	−88667.21(14.43)	−8[illegible]5.[illegible]5(0.29)	−12.16(14.44)	83
^{112}Pd	^{112}Tc	−86323.23(23.68)	[illegible]21.04(6.55)	−2.19(24.57)	34
^{112}Ru	^{112}Tc	−75626.83(6.55)	[illegible]5630.87(9.60)	4.05(11.62)	493
^{112}Mo	^{112}Tc	−57469.80(7.51)	−57480.00(200.00)#	10.21(200.14)	283
^{113}Ag	^{113}Tc	−86994.56(40.5[illegible])	−87026.83(16.64)	32.26(43.84)	16
^{113}Pd	^{113}Tc	−83574.42(4[illegible]75)	−83590.50(6.95)	16.08(48.26)	18
^{113}Rh	^{113}Tc	−78783.08(15.9[illegible])	−78766.94(7.13)	−16.13(17.45)	80
^{113}Ru	^{113}Tc	−71866.53(6.33)	−71867.82(38.28)	1.29(38.80)	1051

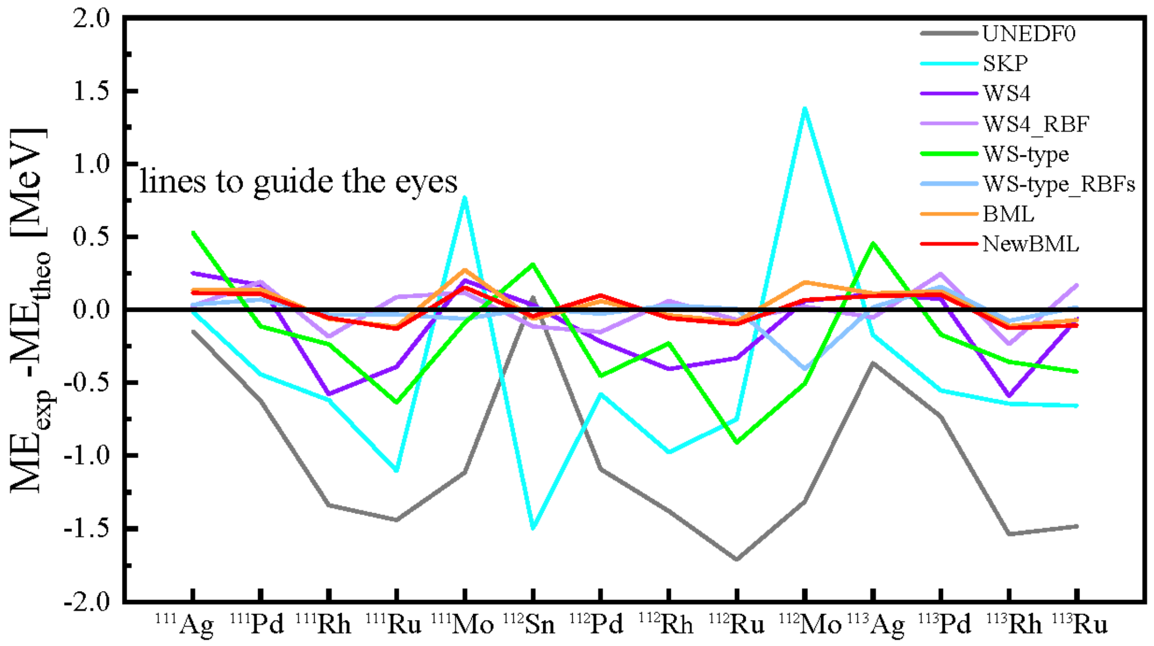
preliminary

D. Hou *et al.*, now accepted by PRC!!!

moderate efficiency: 0.5%

High-precision mass measurements of n-rich Mo isotopes





Co-work with University of Tokyo and IMP:

- BML mass model using machine learning
- New data included into BML code in this study

Learning how to extrapolate…