JYVÄSKYLÄN YLIOPISTO
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Recent advances in mass spectrometry of radioactive nuclei

Tommi Eronen

Outline

- Mass measurement techniques with “stopped” ions
  - Penning trap mass spectrometry (PTMS)
  - Multi-reflection time-of-flight mass spectrometry (MR-TOF-MS)

- Some insights to used ion manipulation methods
  - In-trap decay
  - Retrapping, stacking

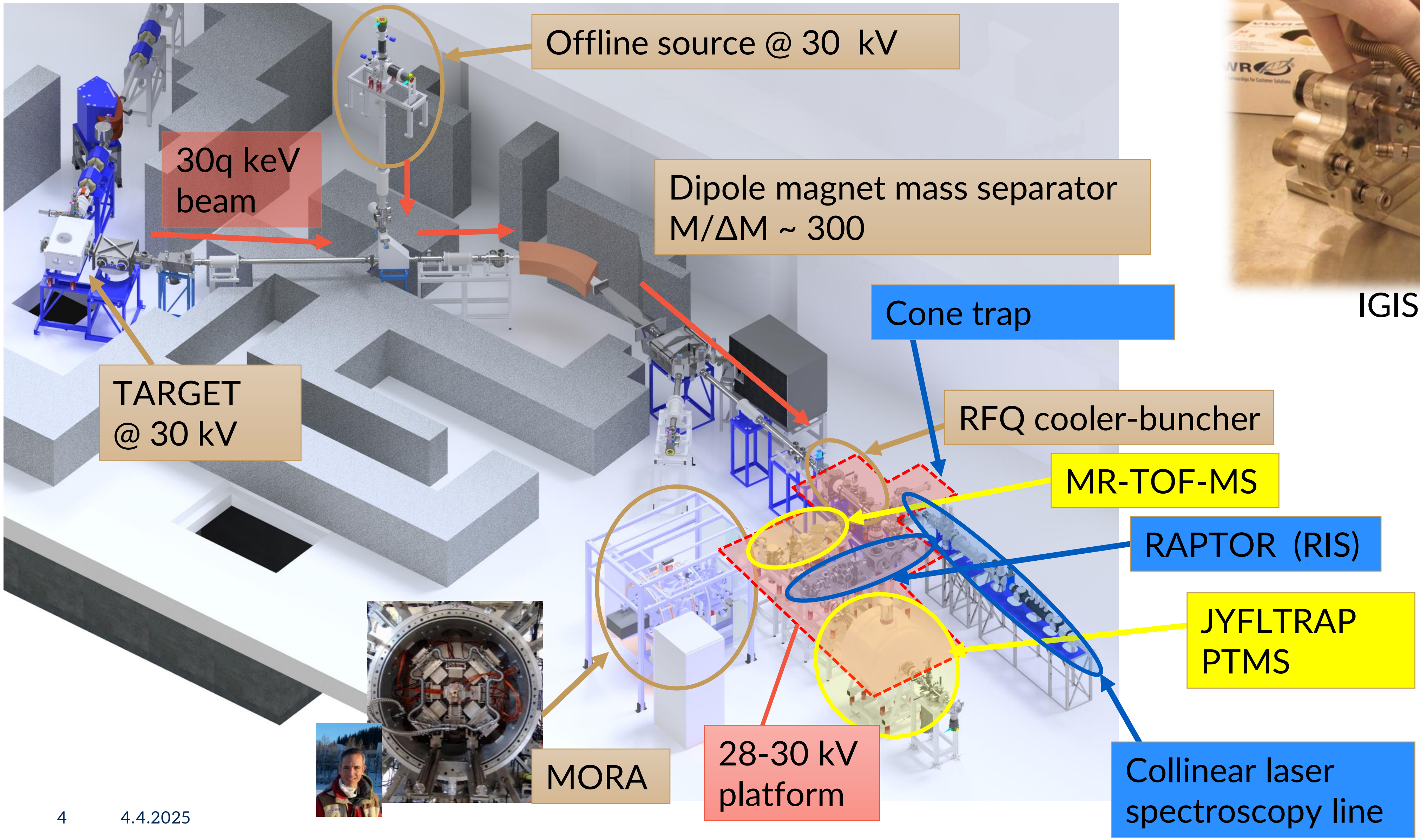
- Glimpse to potential new techniques

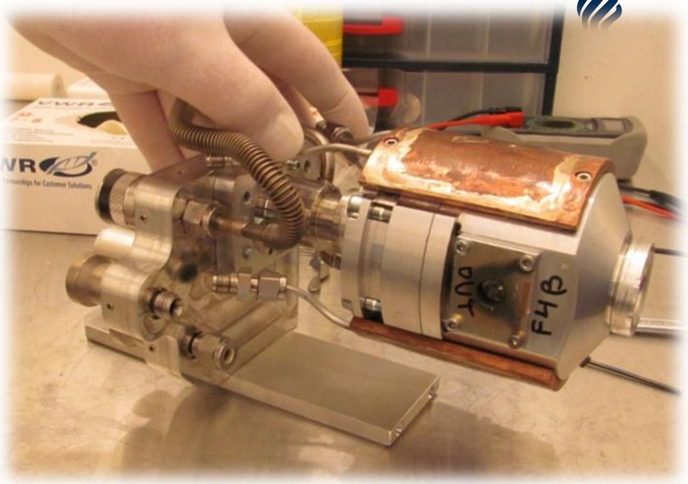
Atomic mass spectrometry at low energy facilities

- Radioactive beam production at high voltage 5...100 kV platform
  - This is the transfer potential
- and then slowed down with near-same potential to be trapped
- Transfer inside with
  - Low E (1-5 kV)
  - Pulsed drift tubes

- Atomic mass spectrometry with stored ions
  - Penning traps (100 V)
  - MR-TOFS (few kV)

IGISOL facility



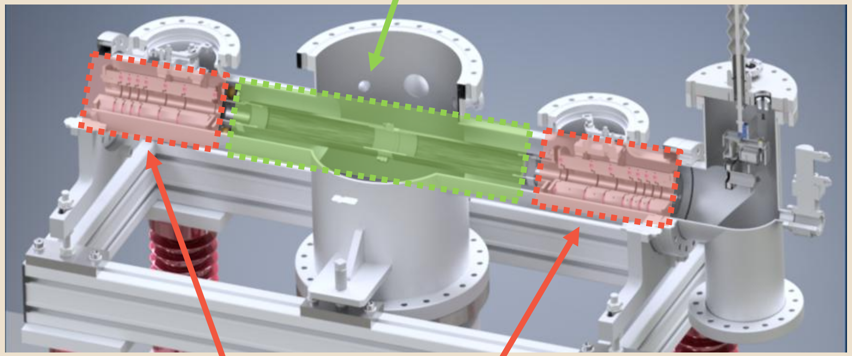


IGISOL fission ion guide

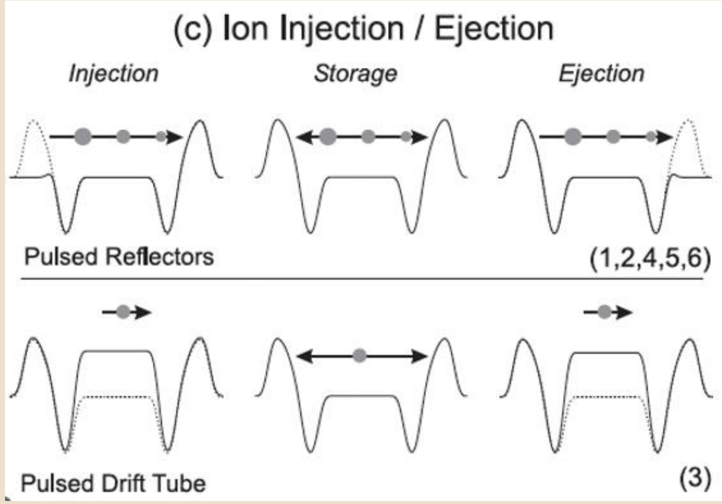
MR-TOF-MS

- Separation of mass in time-of-flight
- Same E_{kin} for all ions, masses separate in time-of-flight (TOF)
  - $t = a\sqrt{m/q} + b$
- Mass resolving power $R = \frac{M}{\Delta M} = \frac{t}{2\Delta t}$ (= 0.5 ... 10 x 10^5)
- Trapping
  - Switch mirrors or in-trap lifting

Drift tube



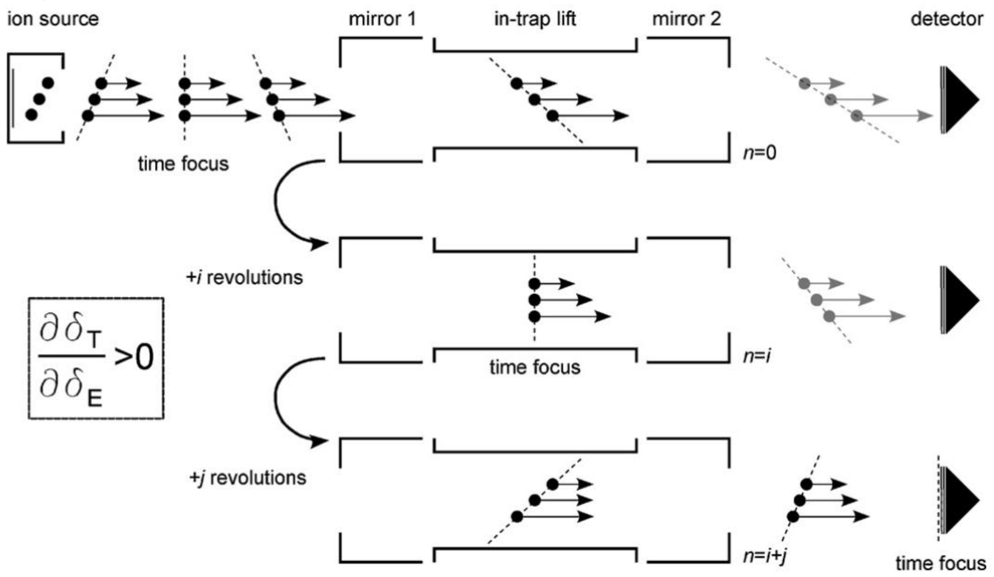
- **Mirror electrodes**



Time-focus considerations

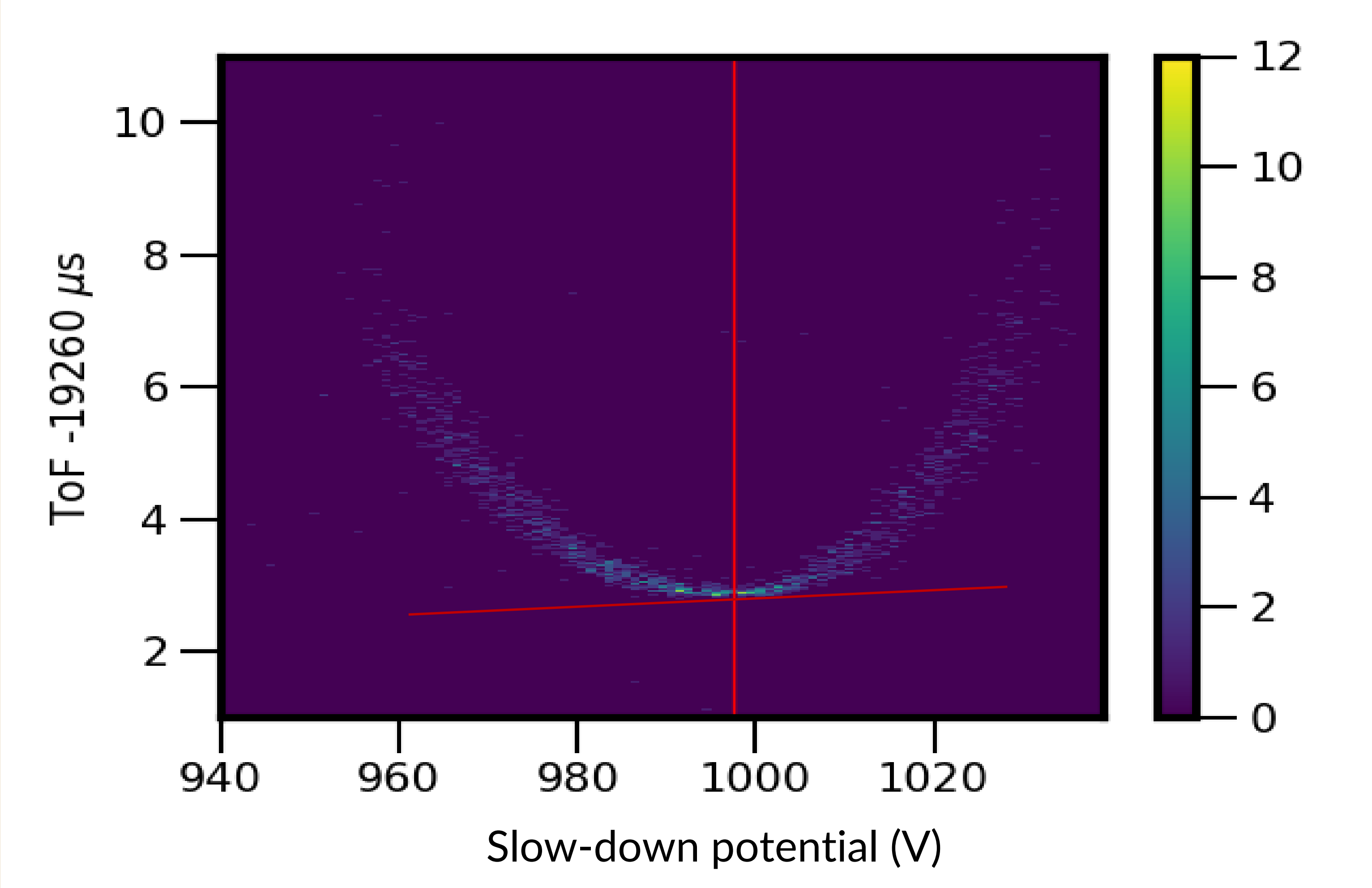
- Aim: time focus at detector
- From RFQ buncher: push-pull creates too early time focus
- Tune spectrometer to focus
  - Ions with higher *E* have increased *t*
- Turn-number dependent
  - $\frac{\partial \delta_T}{\partial \delta E}$ tunable by changing ions *E* inside MRTOF

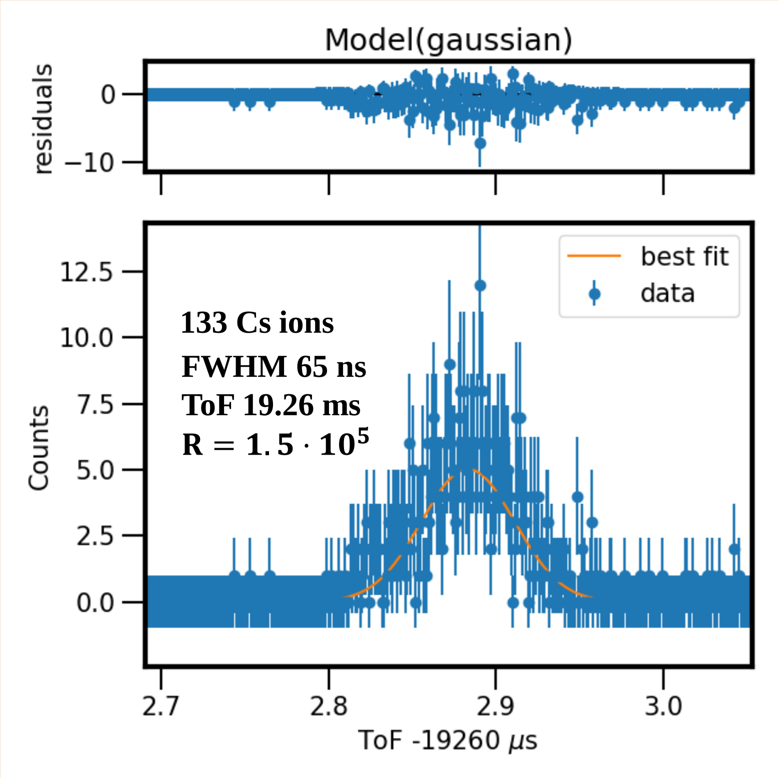
RFQ CB push-pull extraction



R. N. Wolf et al., IJMS 313, 8 (2012)

Time-focus tuning for certain turn number

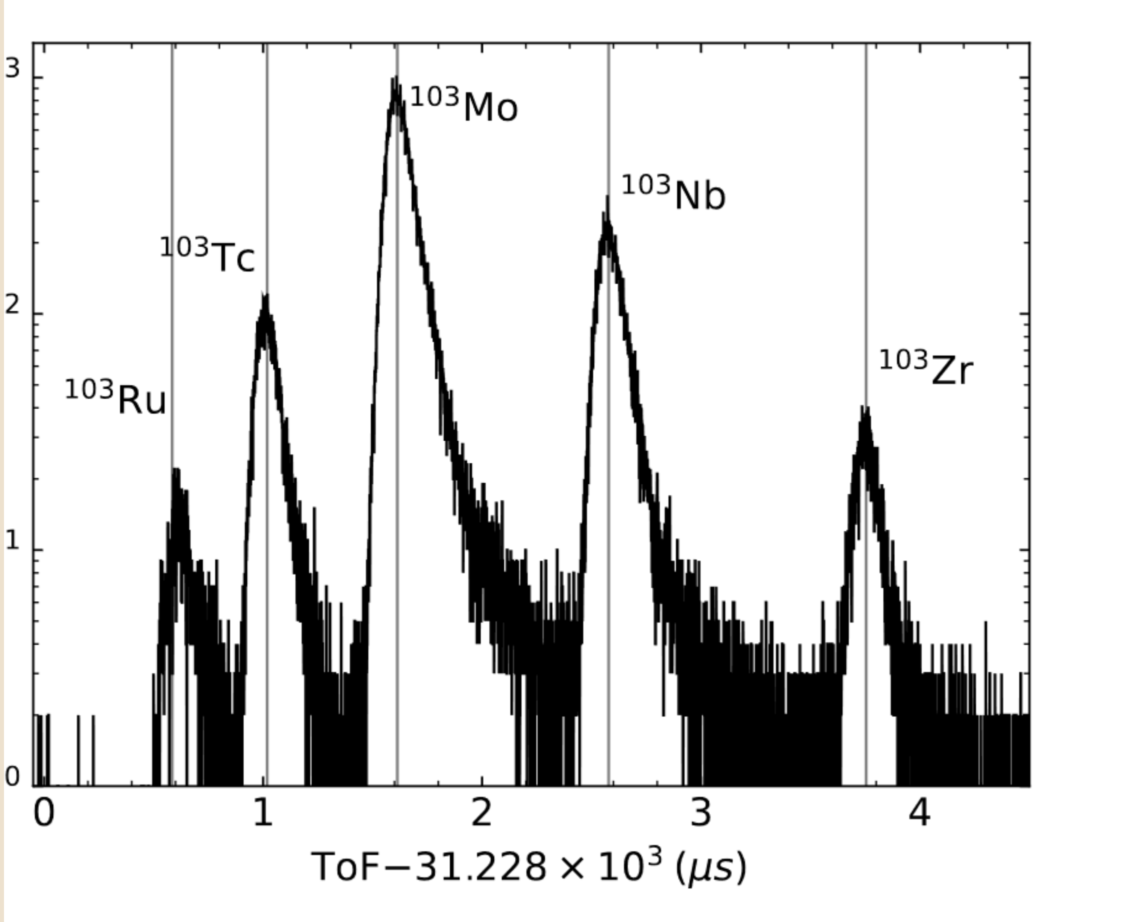




E_{kin} in MR-TOF

MR-TOF spectrum

- $R = \frac{M}{\Delta M} = \frac{t}{2\Delta t}$
- Non-scanning



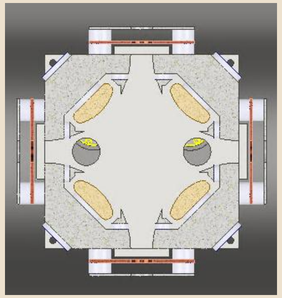
Jyväskylä Buncher + MRTOF

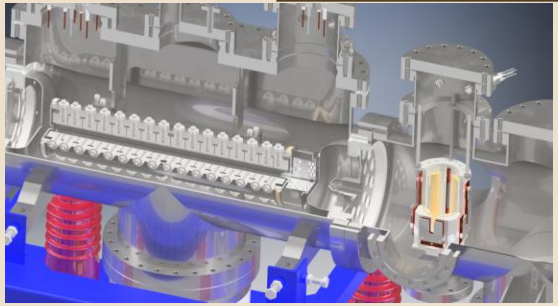
30 kV

Buncher

2 kV

4-pole bender





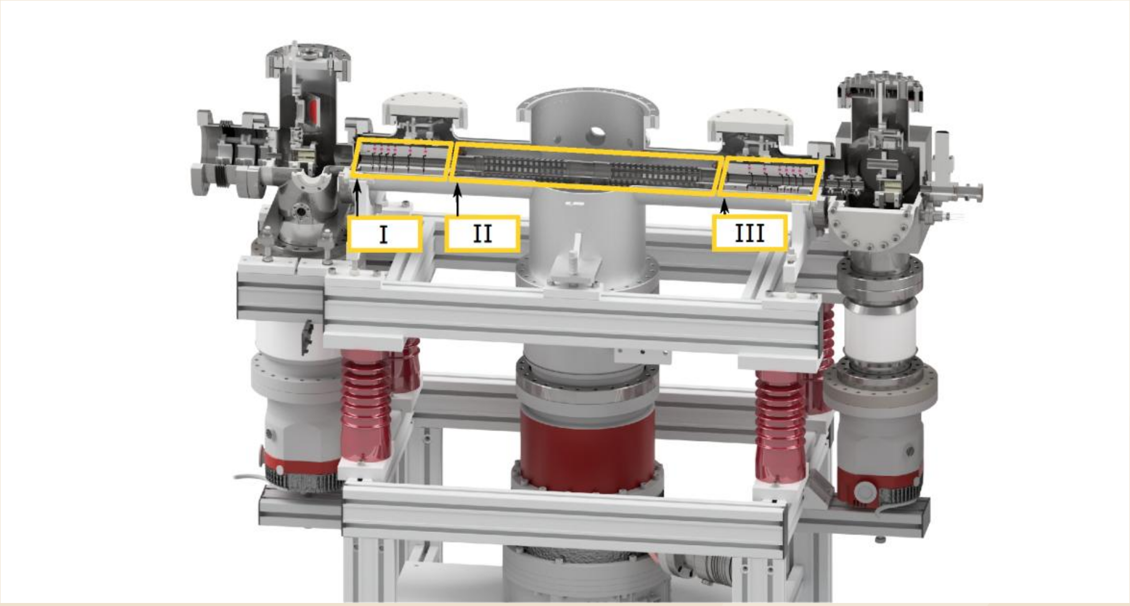
2 kV

MRTOF

1 kV trapped

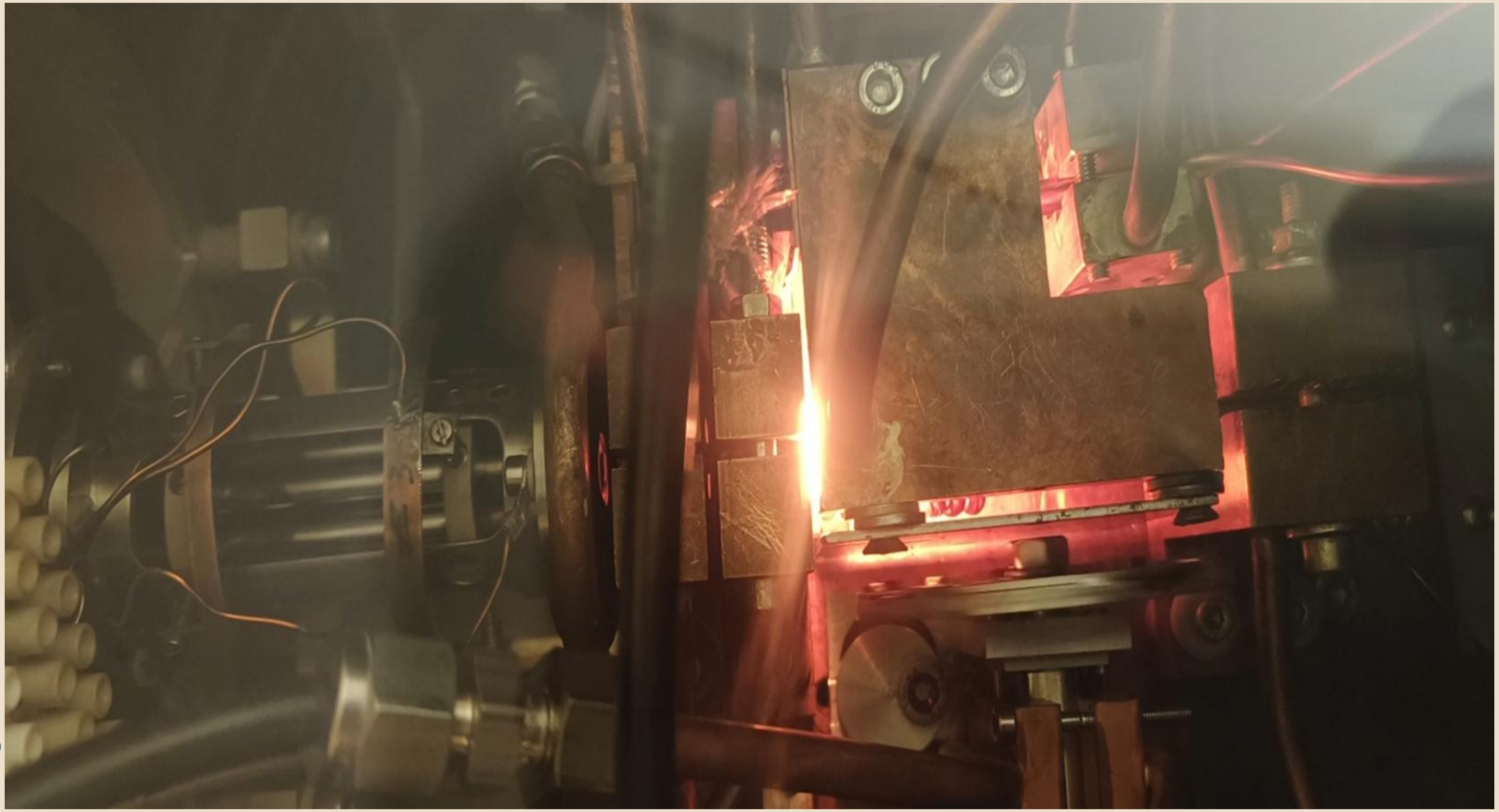
2 kV

MagneTOF ion detector



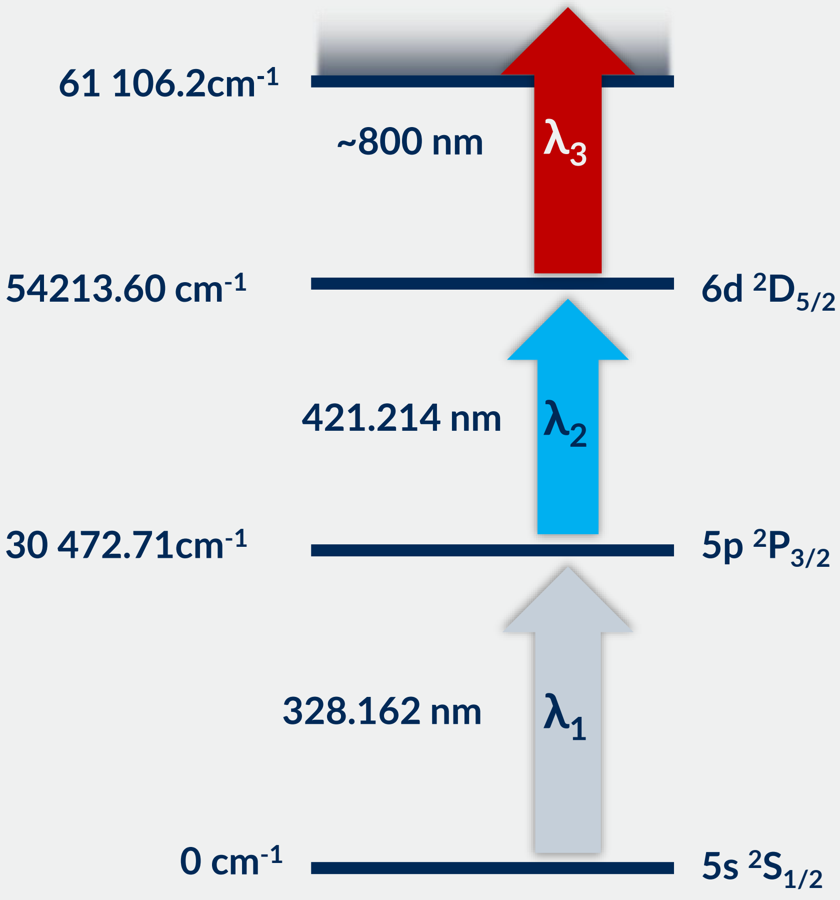
Mass measurement of state of ^{94}Ag

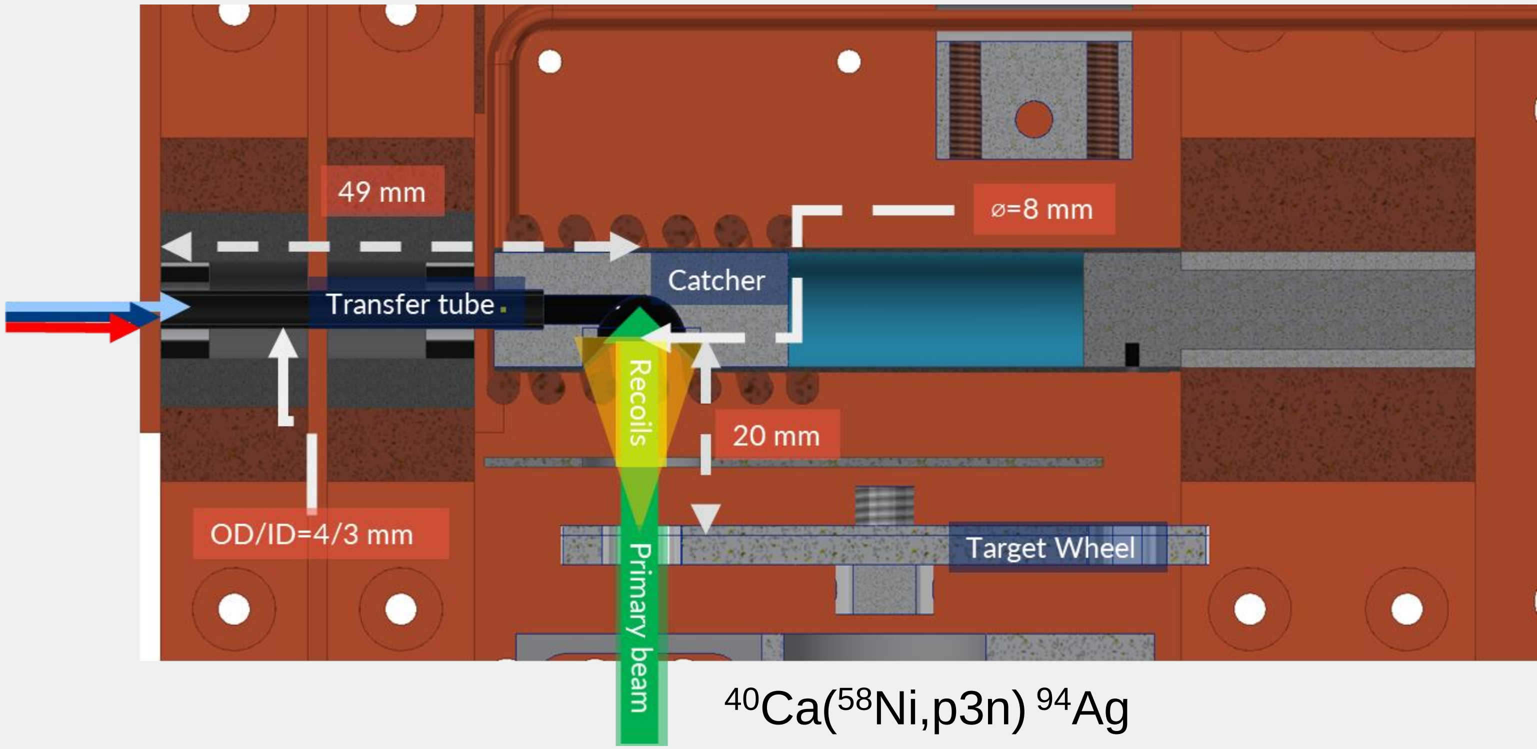
- Hot-cavity ion source "ISOL with heavy-ion fusion evaporation reaction"
  - Mikael Reponen et al.



Inductively Heated Hot Cavity Cather Laser Ion Source

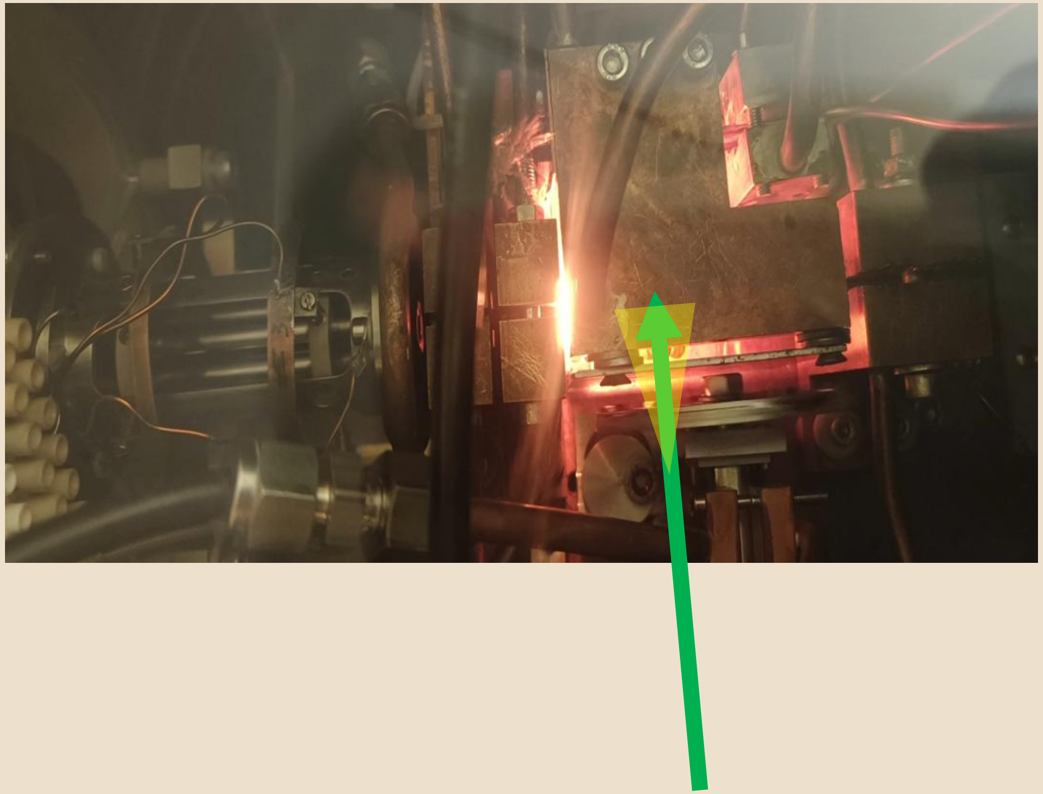
IGISOL typically: Gas cell. This time no buffer gas in chamber: reaction products caught in graphite catcher.

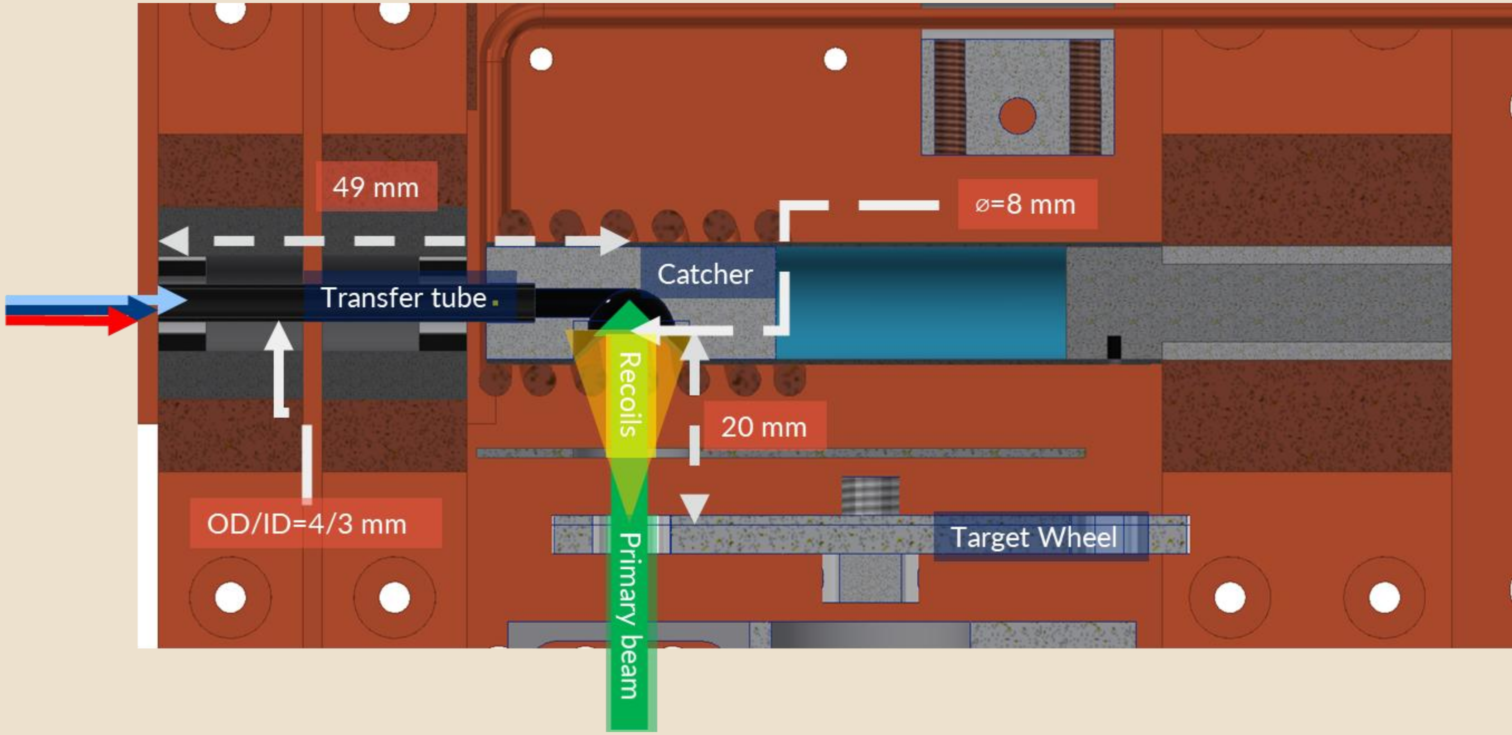




^{40}Ca(^{58}Ni,p3n) ^{94}Ag

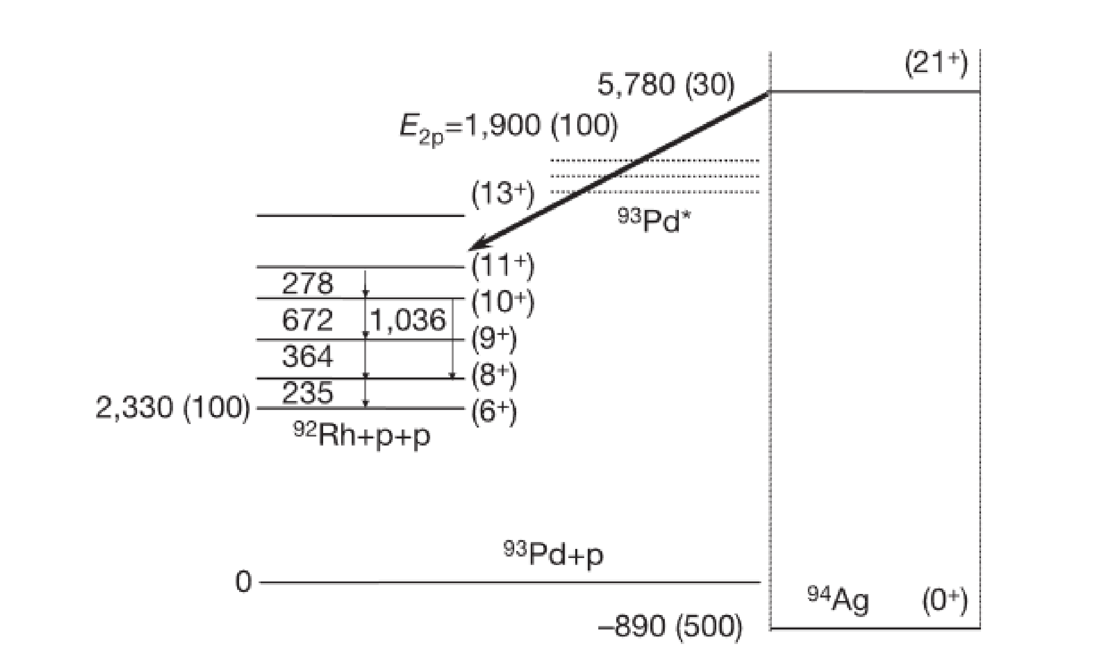
- A target ion source system for fusion-evaporation reactions
  - Efficient: ~10 % for Ag, few % for Pd
  - Fast: ~8 ms for Ag, < 1 s for Pd

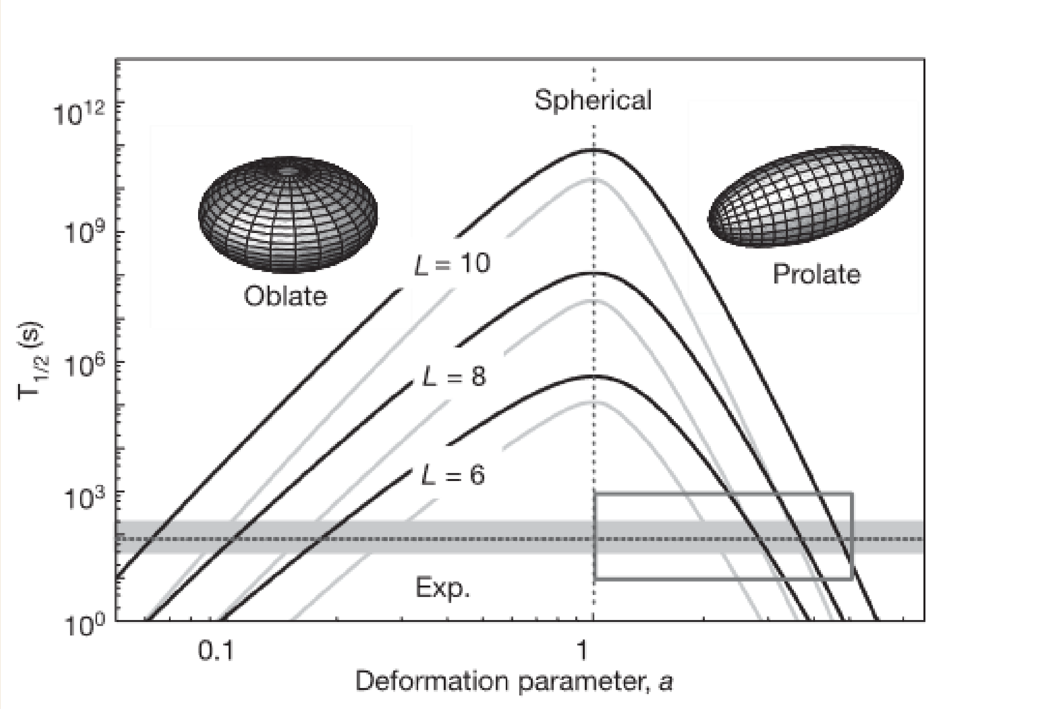


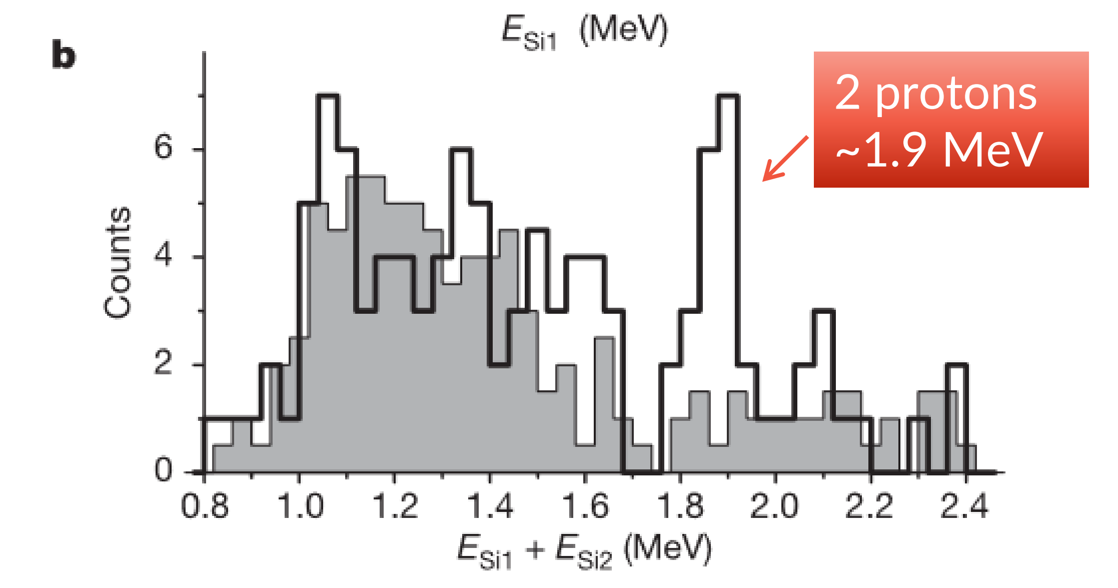

49 mm
⌀=8 mm
Catcher
Transfer tube
Recoils
20 mm
OD/ID=4/3 mm
Target Wheel
Primary beam

^{94}Ag

- N=Z nucleus, N=Z=47, has 21$^+$, 7$^+$ and 0$^+$ gs
- 21$^+$ state is p- and 2p emitter
- 21$^+$ state decay:

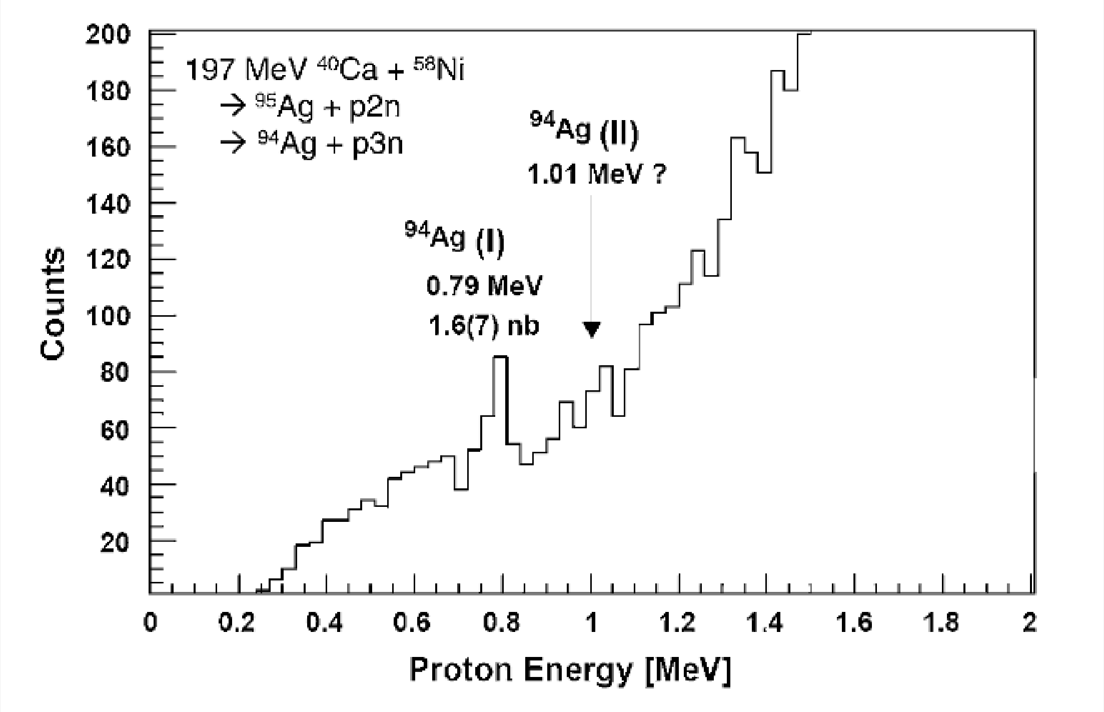


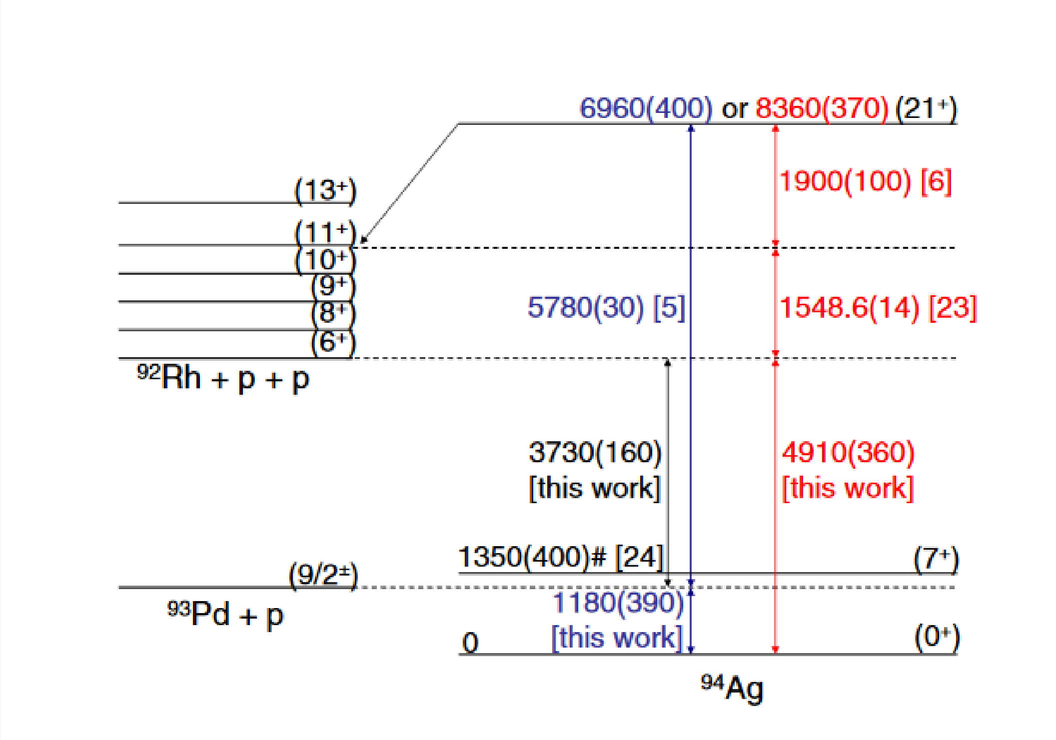




I. Mukha et al. Nature 439 (2006) 298.

(Non-existence?) of two-proton radioactivity in ^{94}Ag 21+ state



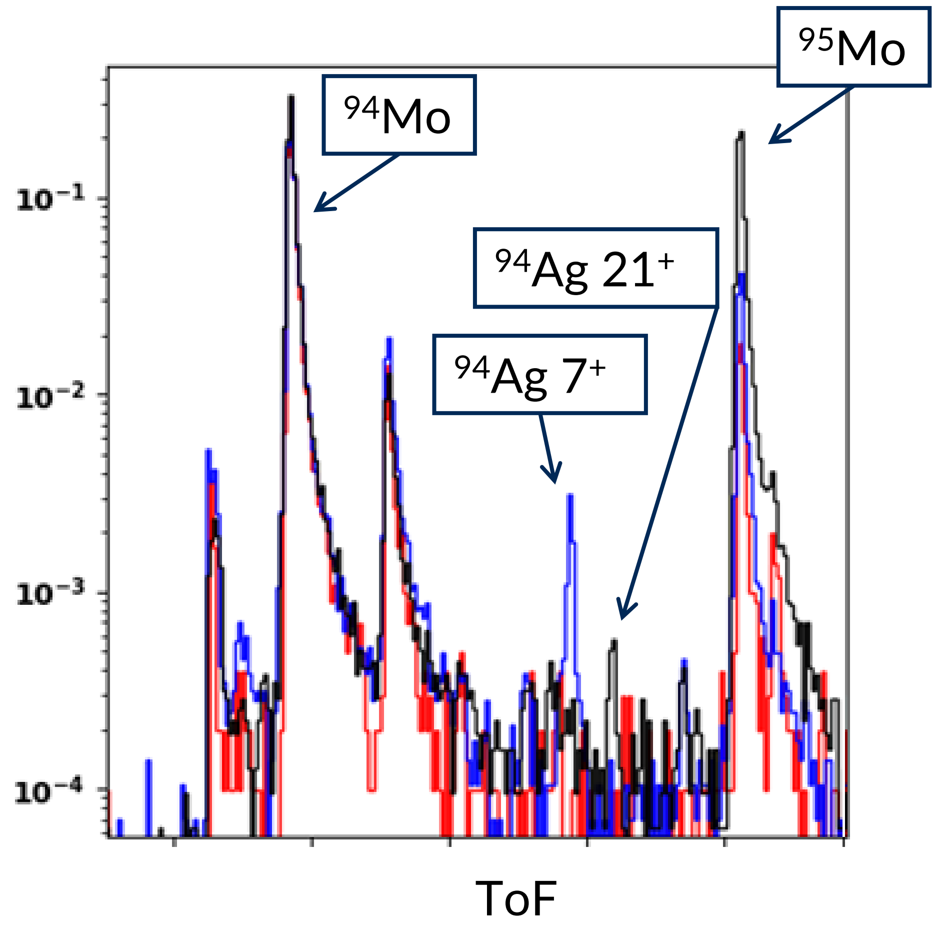


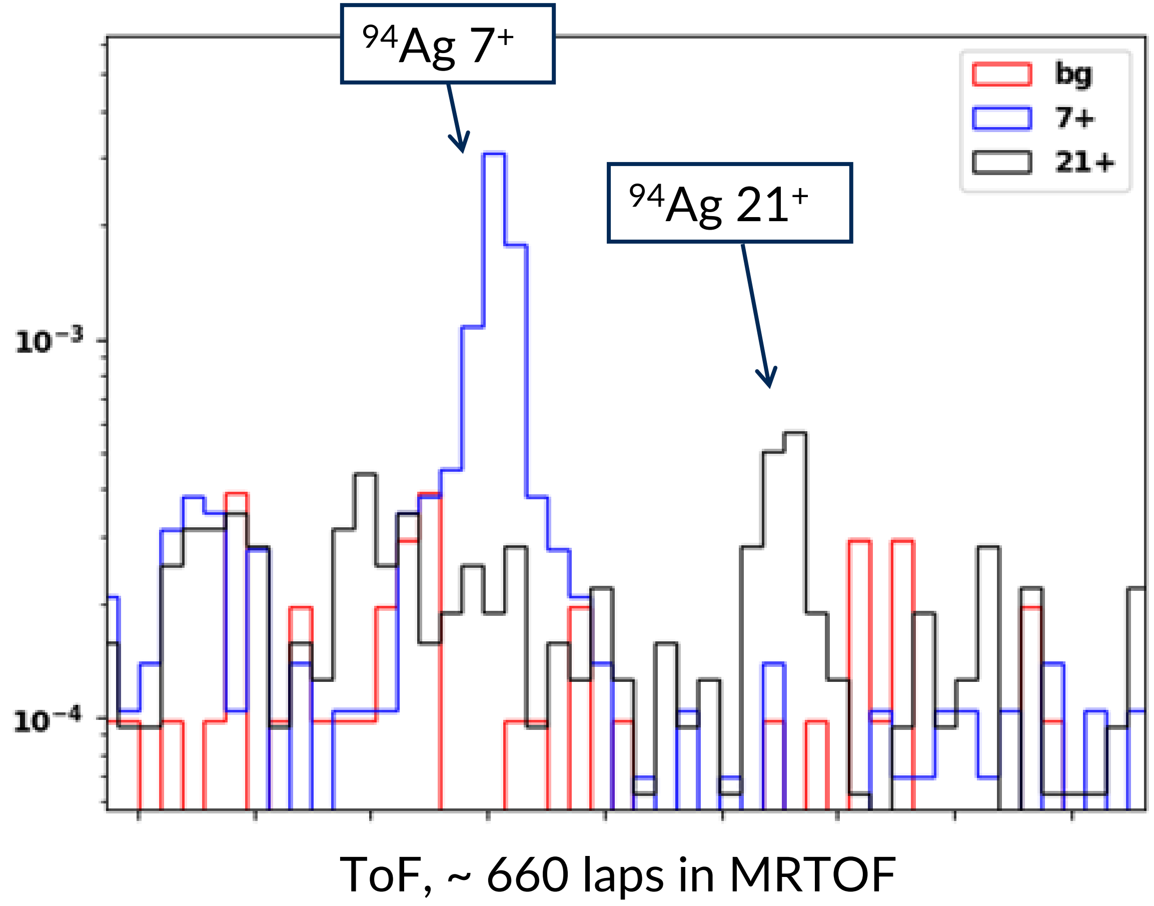
- Subsequent study by Cerny et al. confirmed the 0.79 MeV proton, but saw no evidence for two-proton decay or the other 1.01 MeV single proton

J. Cerny PRL 103, 152502 (2009) A. Kankainen et al. PRL 101, 142503 (2008)

Mass measurement of 21^{+} and 7^{+} ^{94}Ag states

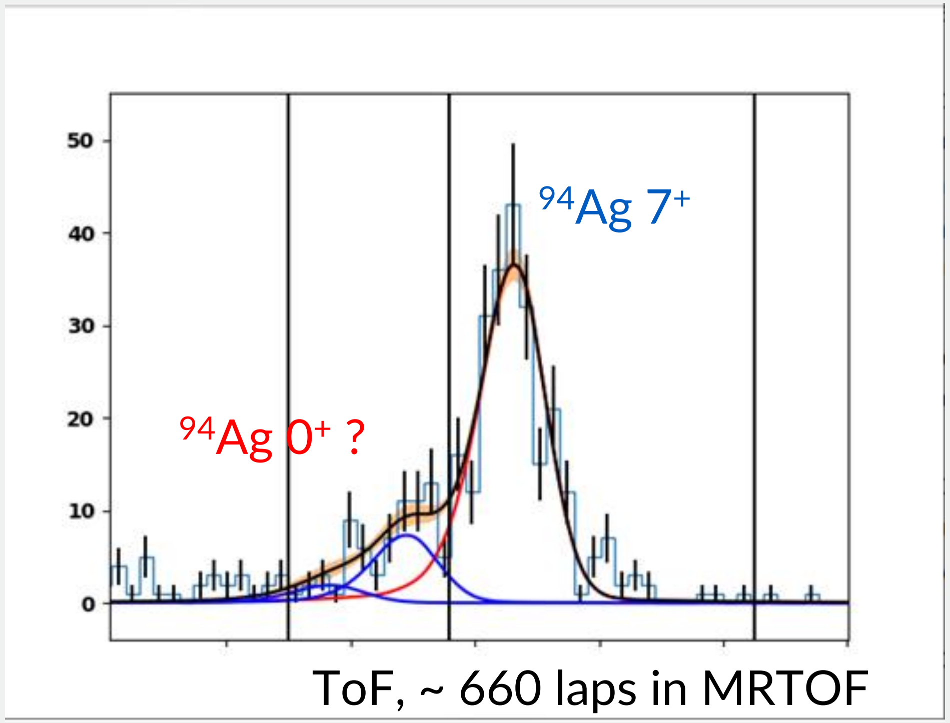
Laser 1st step used to select the state to be ionized



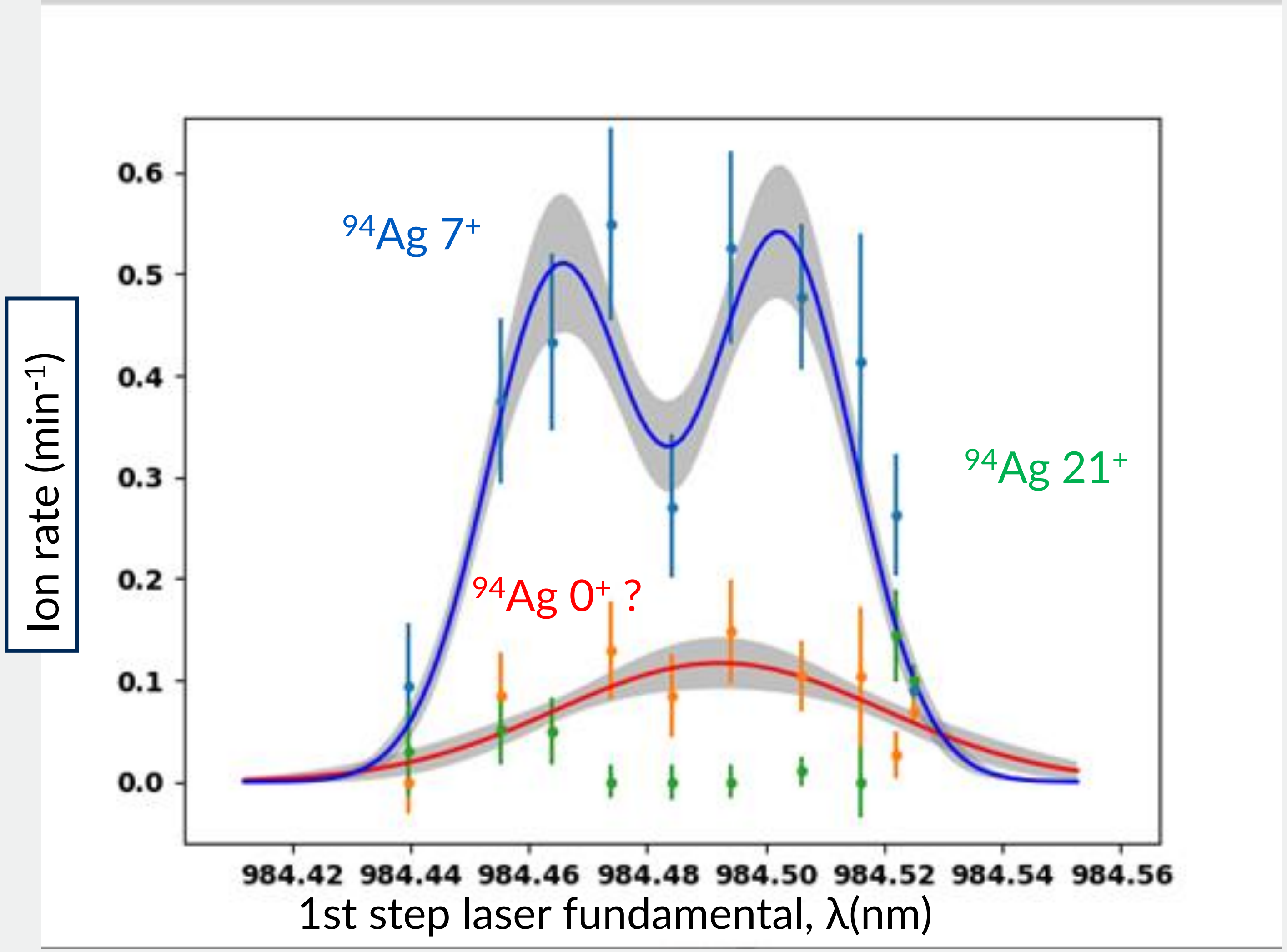


How about 0^+ ground state?

Rates of
R(7+)   = 0.55/min
R(21+) = 0.15/min



Laser frequency scan



^{94}Ag measurements conclusion

- Mukha measured: E_{2p} = ~1.9 MeV
- Our measurement:
  - 94Ag(21+) to ^{92}Rh ground state $Q_{2p}\,(94\mathrm{Ag}\,(21+) \rightarrow 92\mathrm{Rh}(\,6+)) < 1.9\ \mathrm{MeV}$

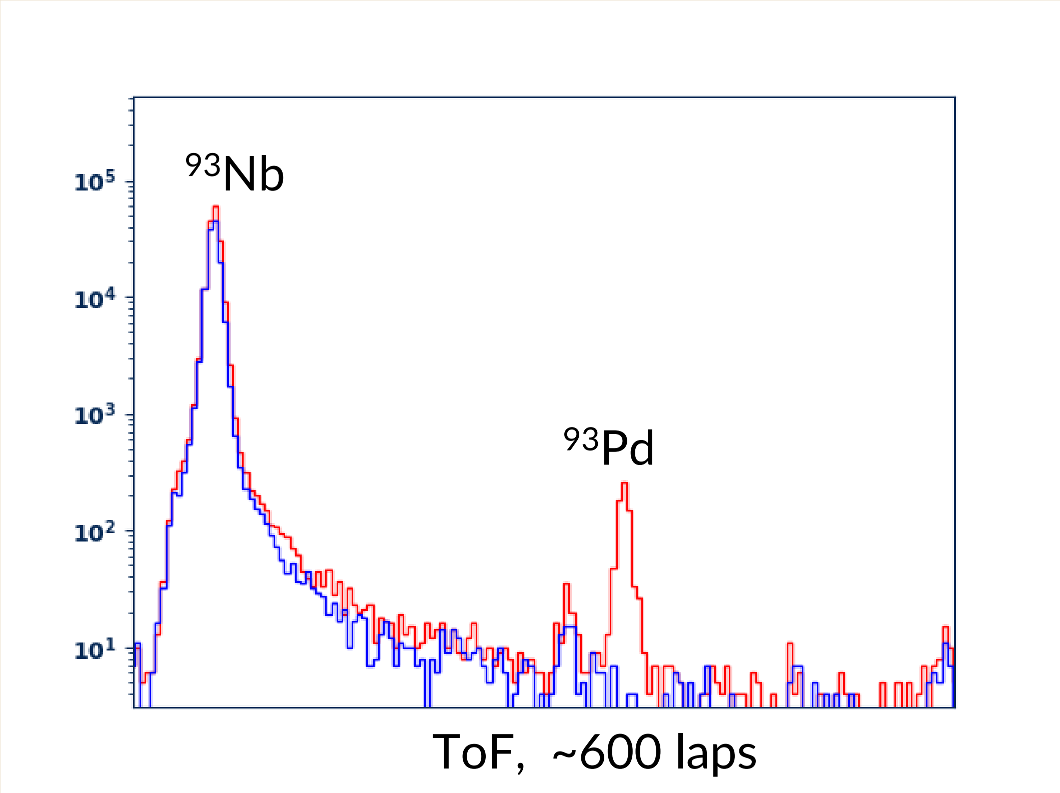
- **2p decay not energetically possible**

M. Reponen and V. Virtanen et al. (to be published) 2025

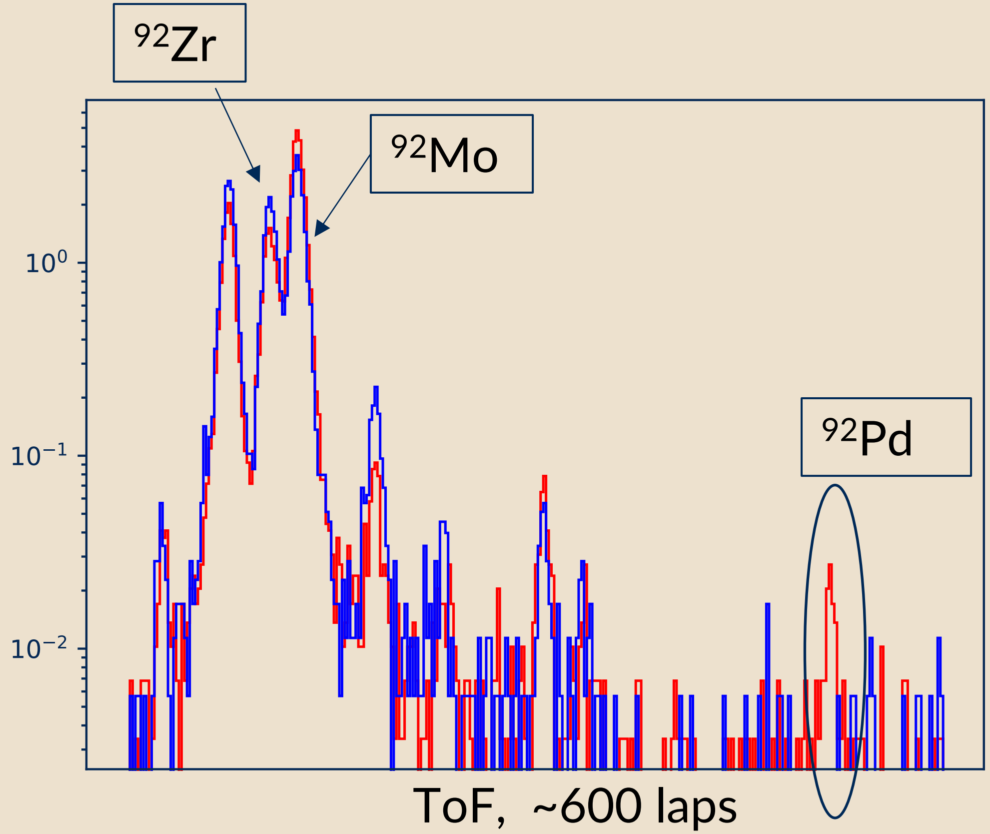
- **(At this moment, MR-TOF assisted laser-spectroscopy measurement running!)**

N=Z hot cavity + MR-TOF measurement outlook

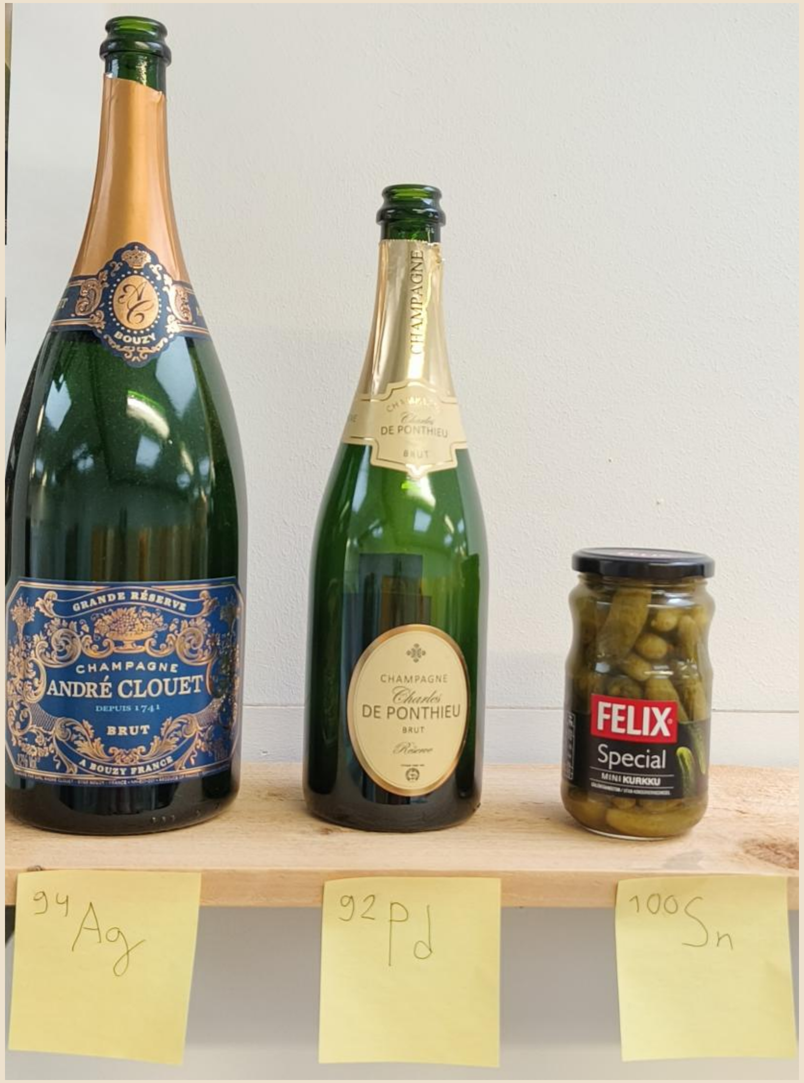
- ^{93}Pd:
  - p-decay daughter of ^{94}Ag
  - Measured also at FRS ion catcher @ GSI



- ^{92}Pd (N=Z=46)

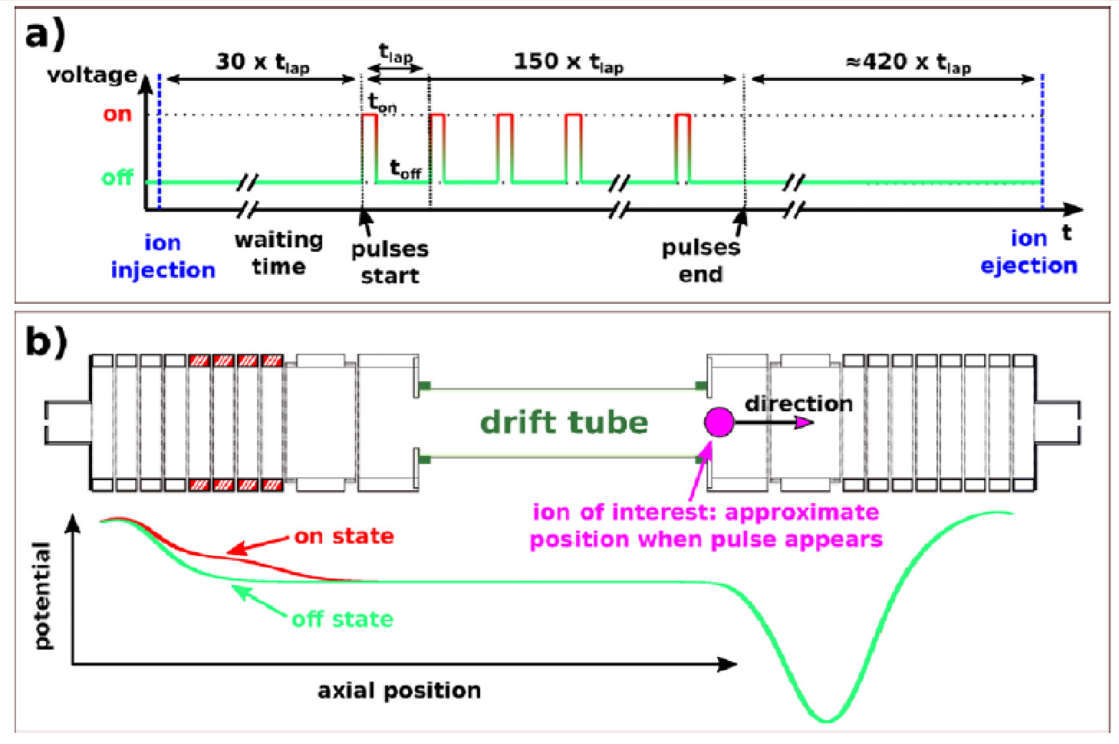


Progress so far... and possible future mass adventures

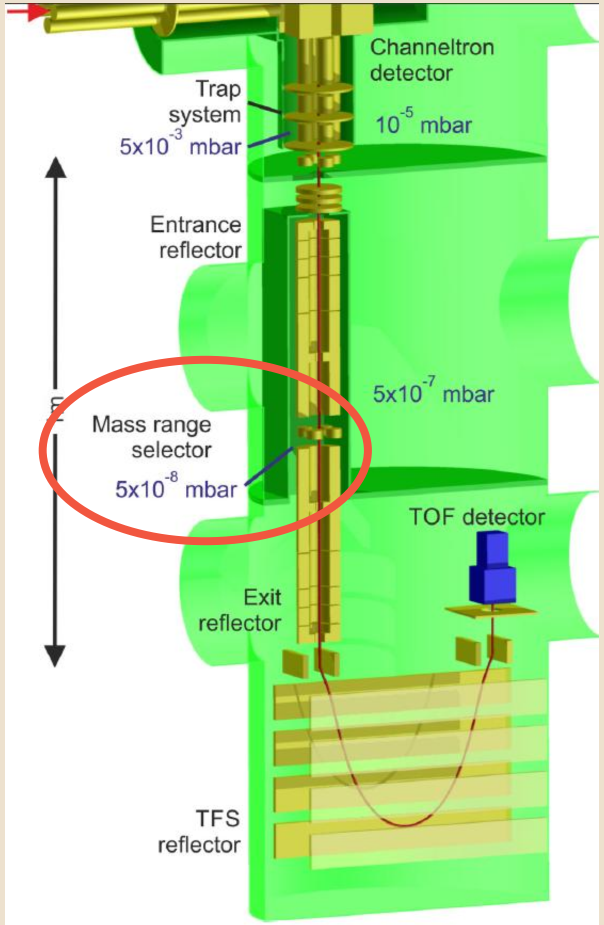


- Hot-cavity + MRTOF is a powerful combination

MRTOF in-trap contamination removal



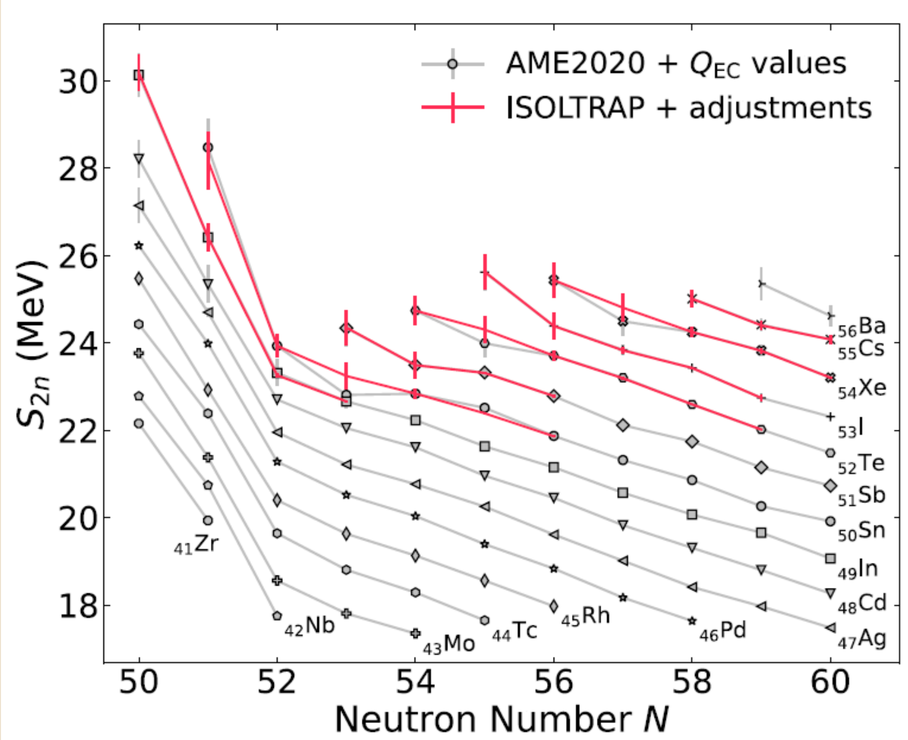
RIKEN zero-degree spectrometer
M. Rosenbusch et al. NIMA 1047, 167824 (2023)

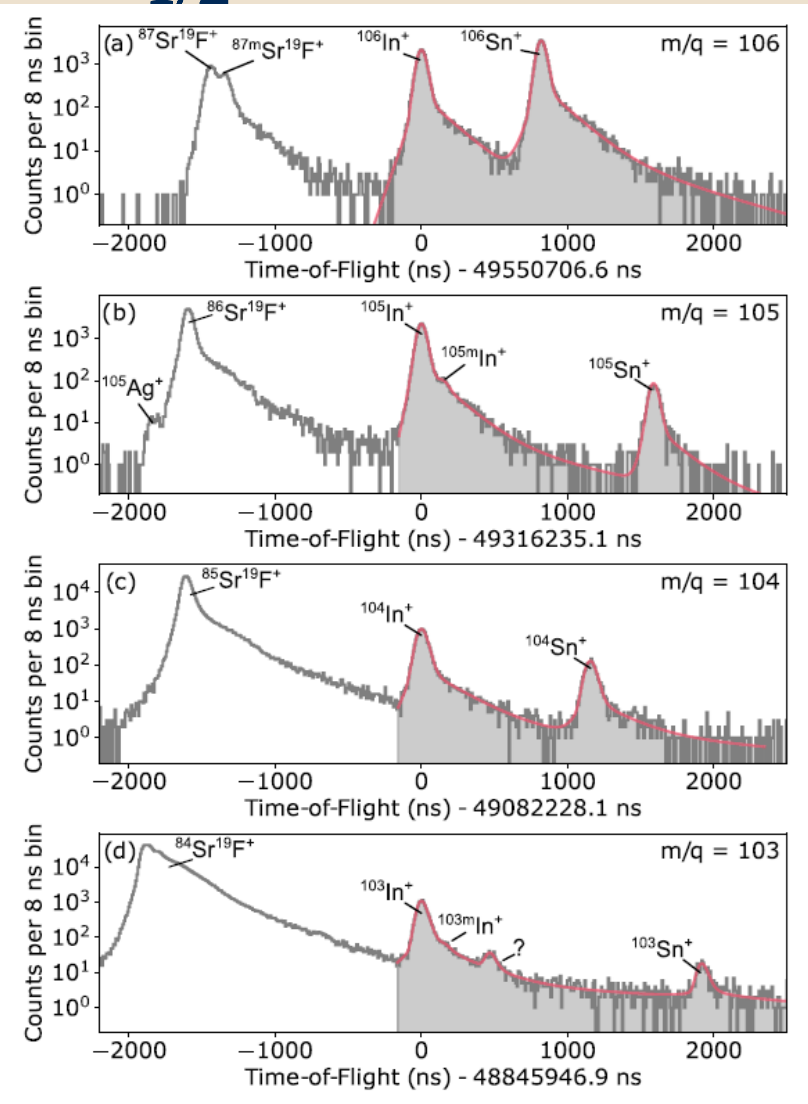


FRS ion catcher MRTOF
S. Ayet et al. PRC 99, 064313 (2019)

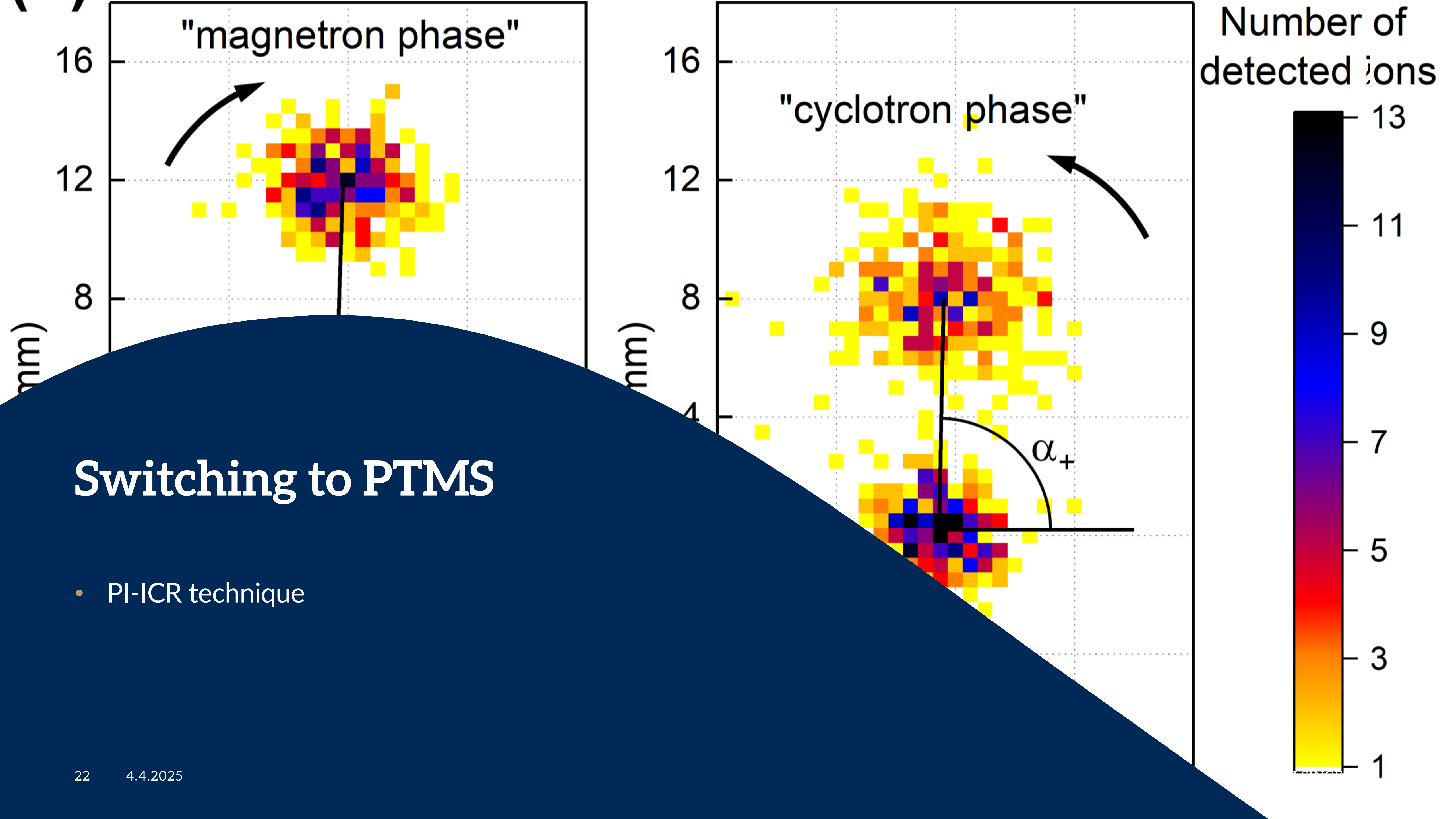
MRTOF is the method of choice for $T_{1/2}$ < 50 ms

- For N=Z nuclei below ^{100}Sn
- ISOLTRAP Sn isotopes
  - Down to ^{103}Sn
- Smoothening of the mass surface





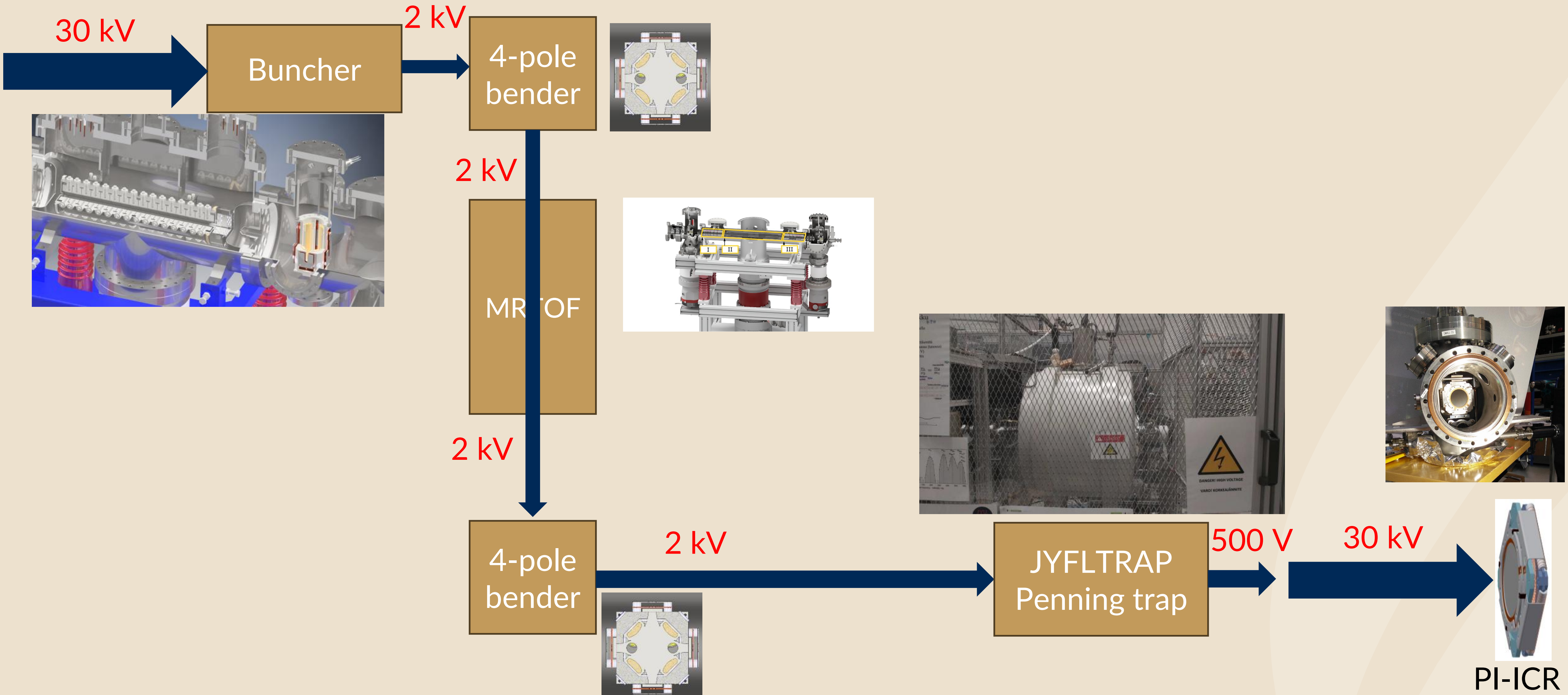
Nies et al PRC 111, 014315 (2025)



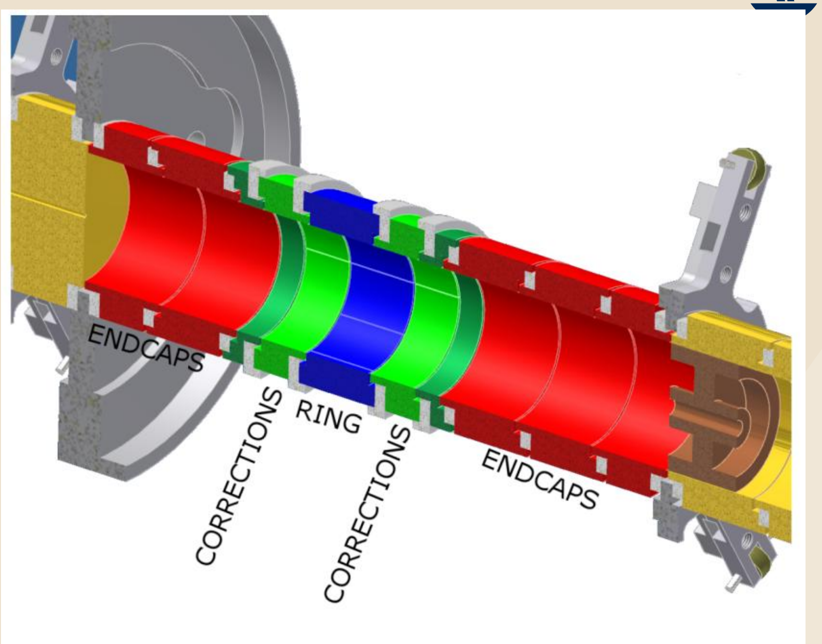
Switching to PTMS

- PI-ICR technique

Penning trap mass spectrometry at IGISOL

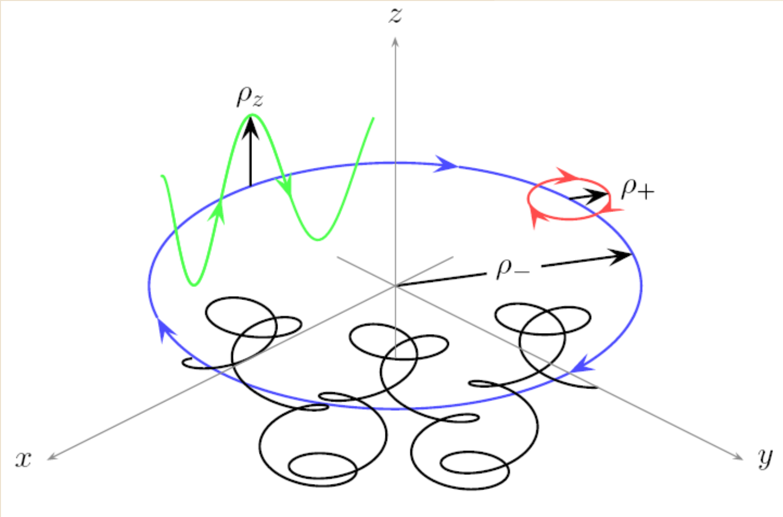


Penning trap mass spectrometry

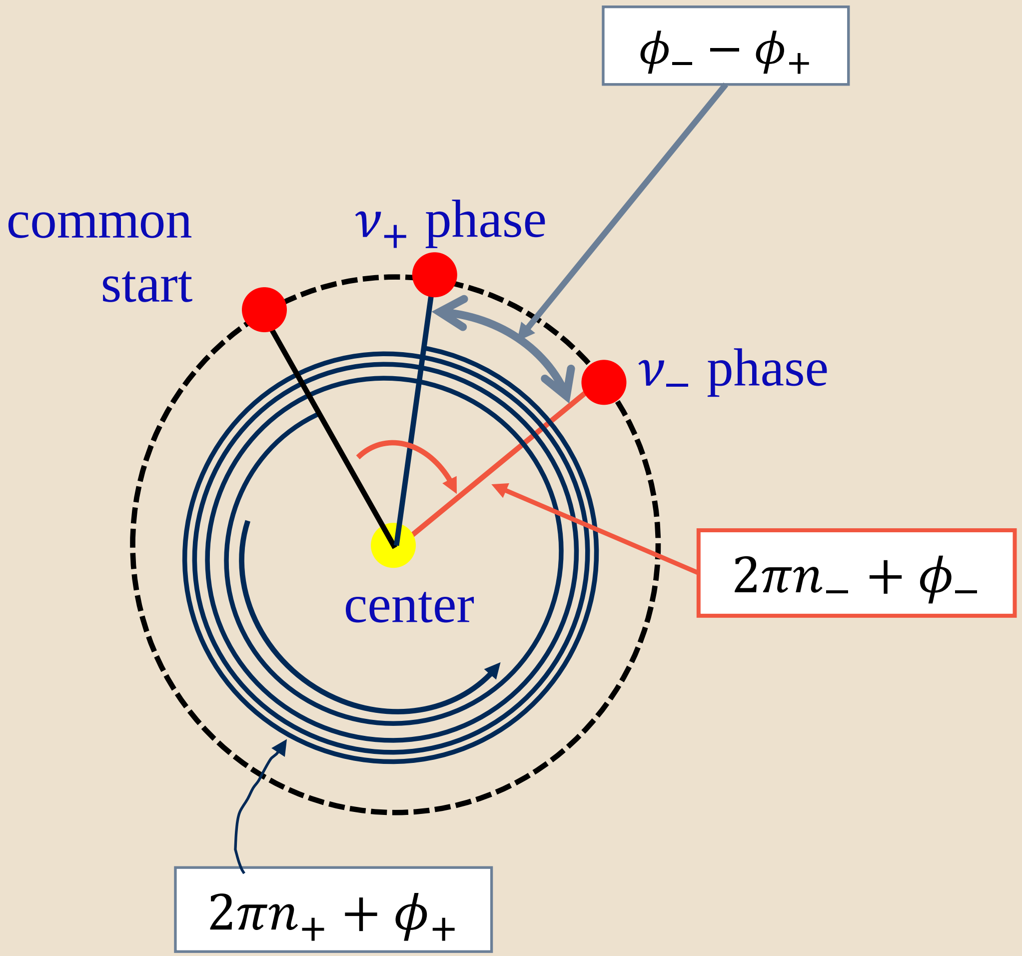


- Strong magnetic field B + electrostatic quadrupole potential
- Three in-trap motions:
  - Axial (z), frequency $\upsilon_z = \frac{1}{2\pi}\sqrt{\frac{qV_0}{md^2}}$
  - Radial (+,-) frequencies $\upsilon_\pm = \frac{1}{2}\left(\upsilon_c \pm \sqrt{\nu_c^2 - 2\nu_z^2}\right)$
- To measure: free-space cyclotron frequency $\nu_c = \frac{1}{2\pi}\omega_c = \frac{1}{2\pi}\frac{q}{m}B$
  - Through side-band coupling frequency

$$\boxed{\upsilon_- + \upsilon_+ = \upsilon_c}$$



Phase detection method with 2D ion detection

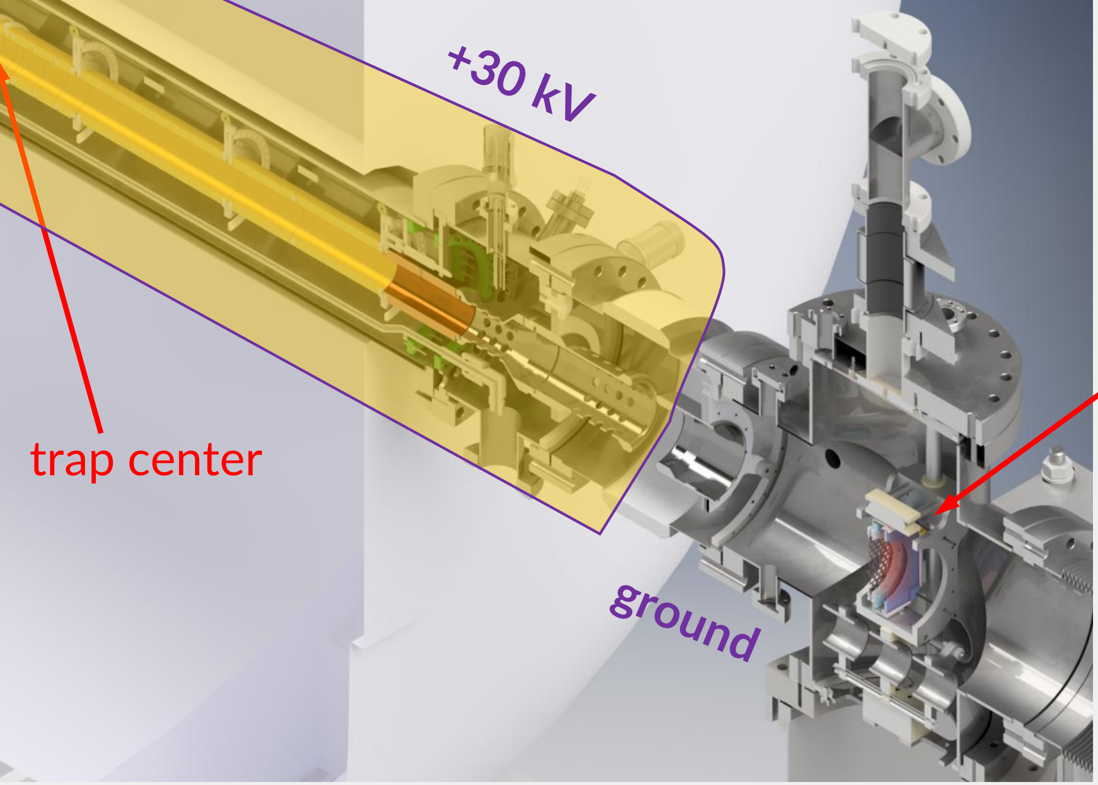


- For exact set duration of t_{acc}, let ions
- 1. revolve in ν_+ motion (mass dependent)
- 2. revolve in ν_- motion (mass independent)
- Both accumulate phase $2\pi n + \phi$
- Detect ϕ_+ and ϕ_- , figure out n_- and n_+

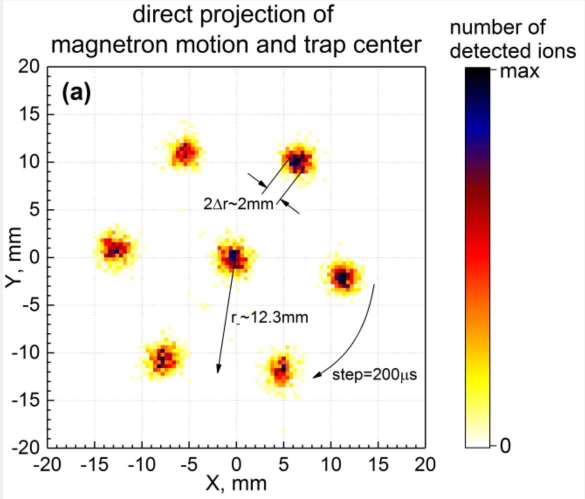
- It is best to set t_{acc} to be exact multiples of $\frac{1}{\nu_c}$,
  - $\phi_- - \phi_+$ will vanish (or becomes small)

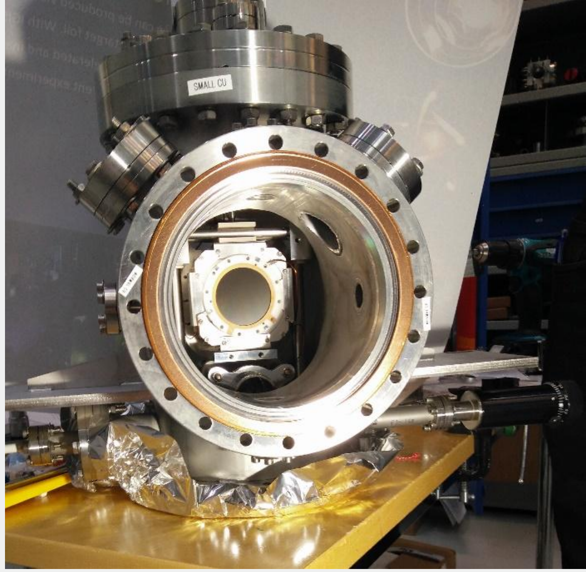
$$\boxed{\nu_c = \frac{(\phi_+ - \phi_-) + 2\pi \mathrm{n}_c}{2\pi t_{acc}}}$$

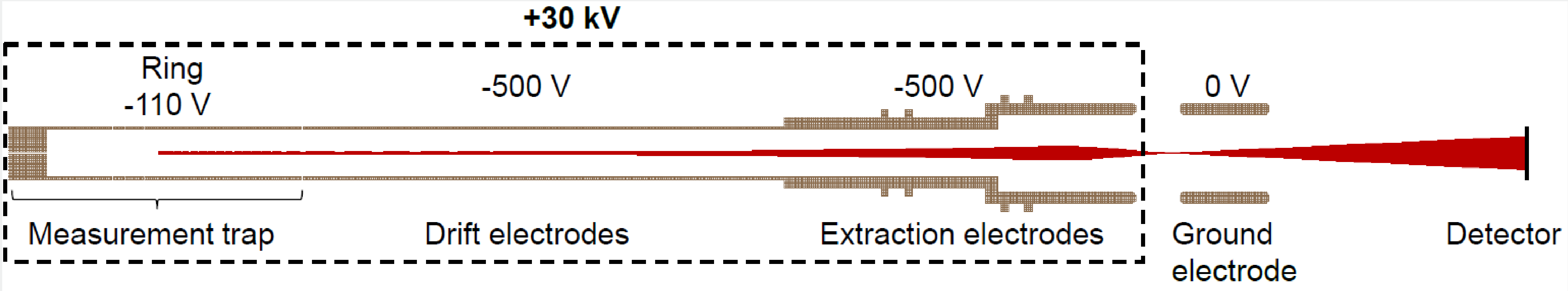
$$\boxed{R = \frac{M}{\Delta M} = \frac{\nu_+}{\Delta\nu_+} > 10^6\text{, beyond } 10^7}$$



position-sensitive detector
(MCP with delay line)



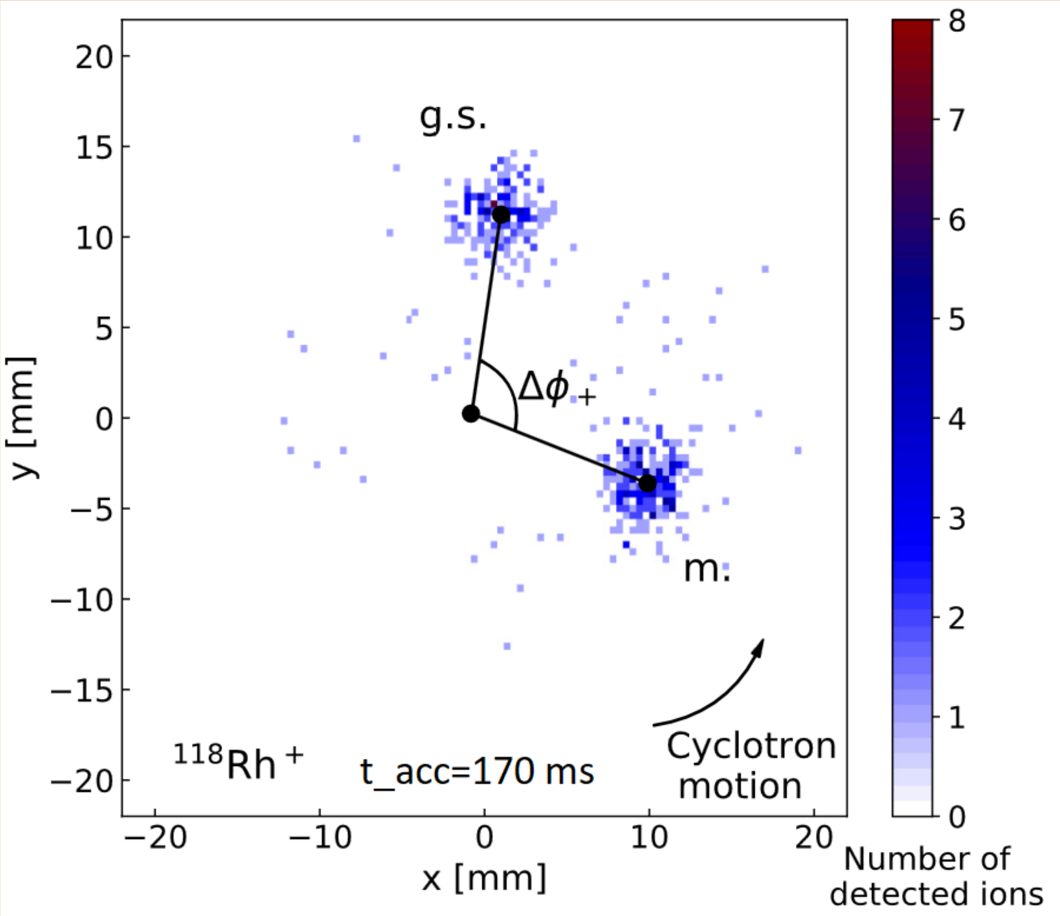




Mass measurements of isomers of n-rich nuclei

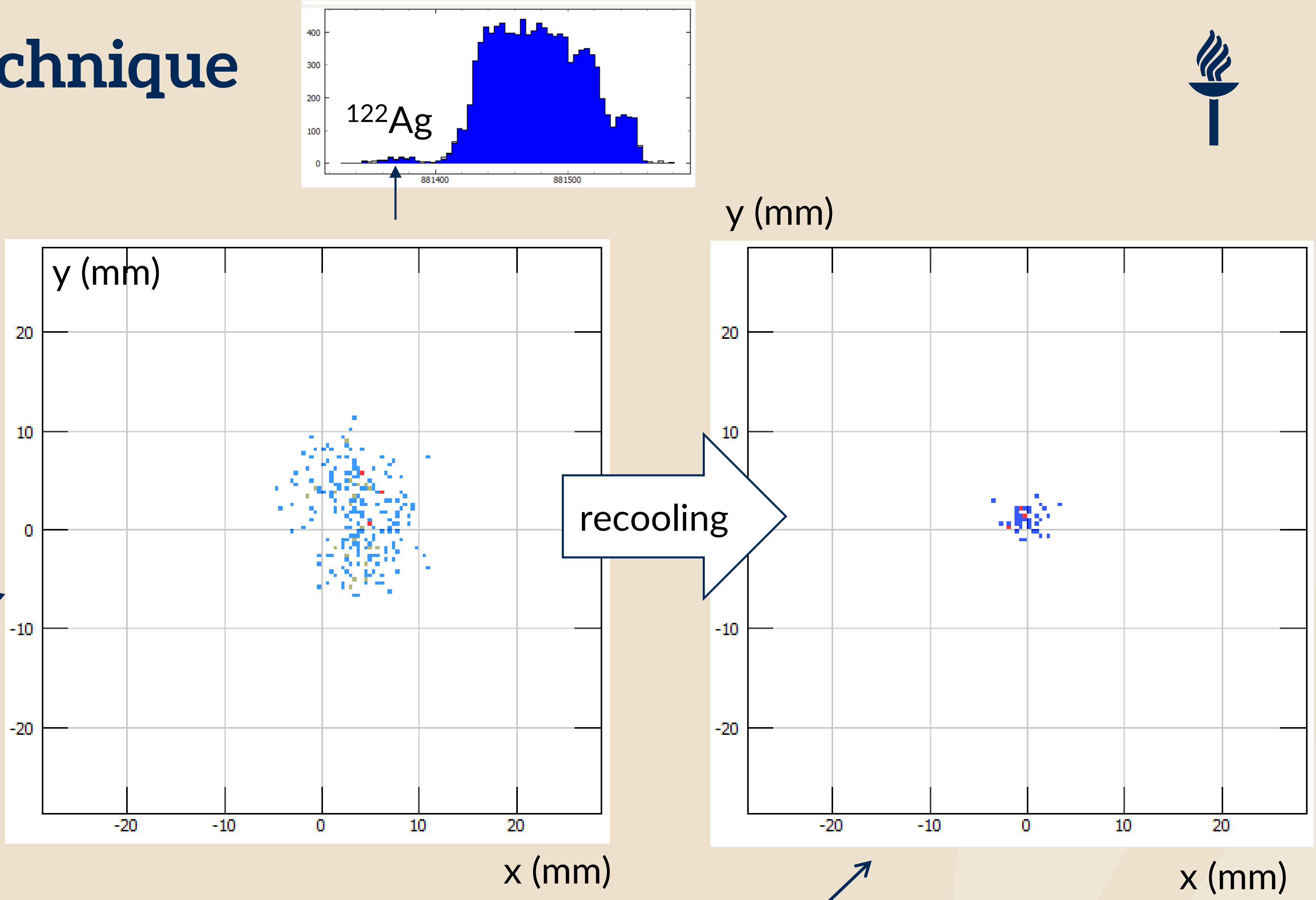
- PI-ICR technique $R = \frac{M}{\Delta M} > 10^7$
- Allows separation down to ~10 keV level

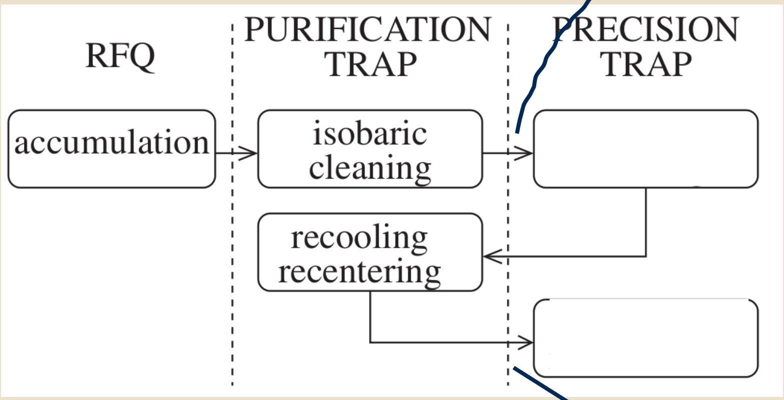
- Even A n-rich Rh isomers
  - Hukkanen et al. PRC 107, 014306 (2023).



Double-cooling technique

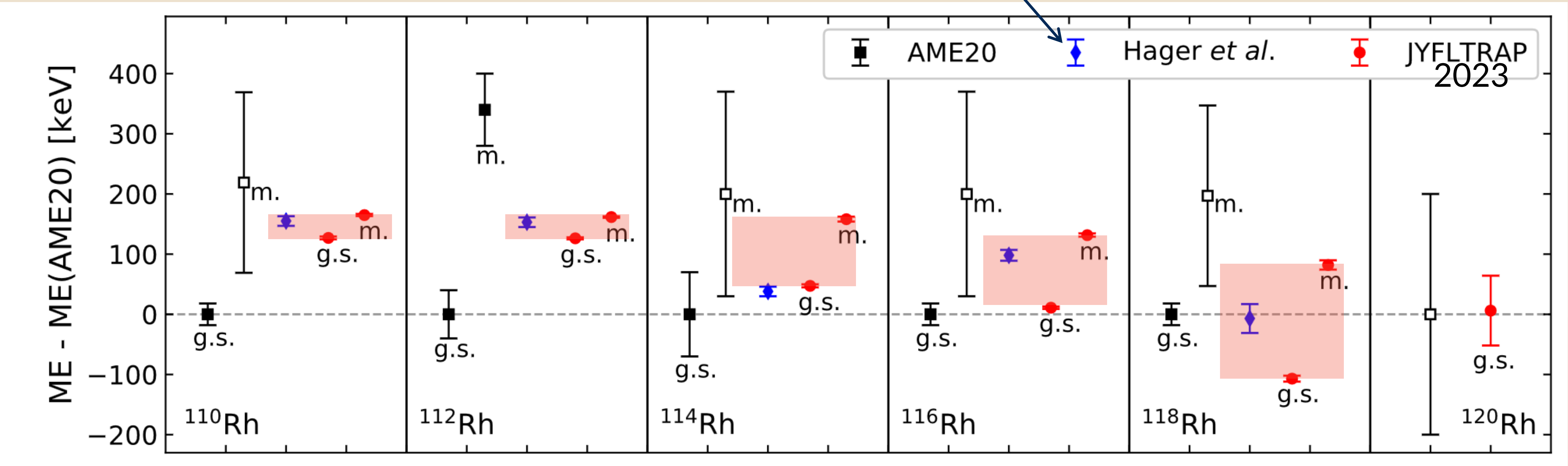
- Good to apply when
  - Lot's of ions in the trap
  - High resolution needed





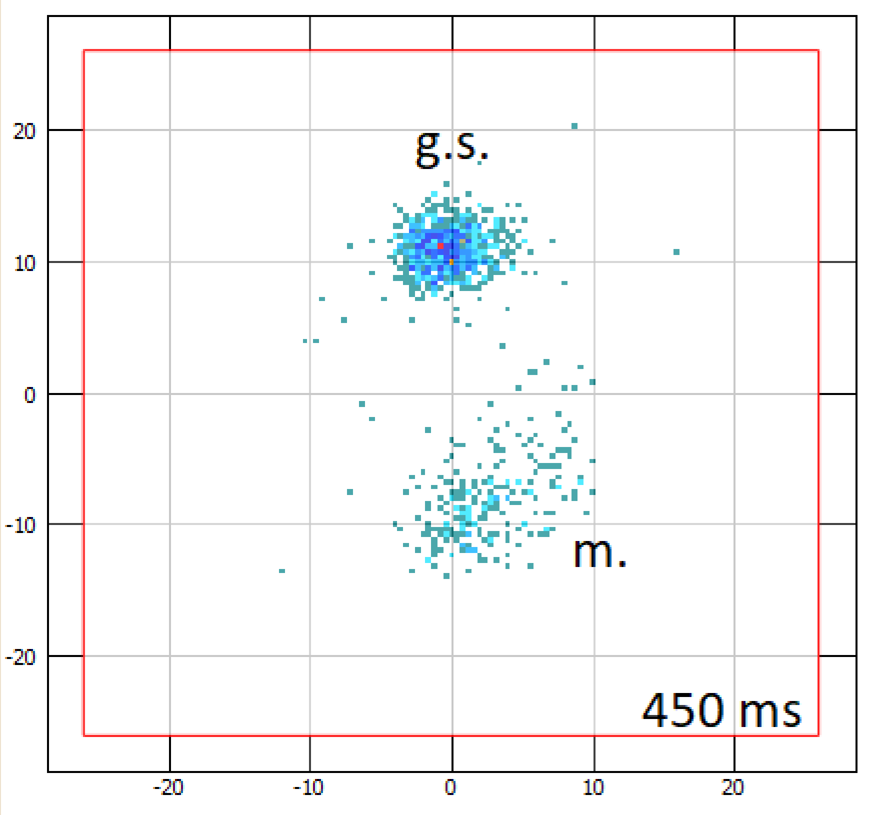
Comparison to TOF-ICR

JYFLTRAP TOF-ICR 2007

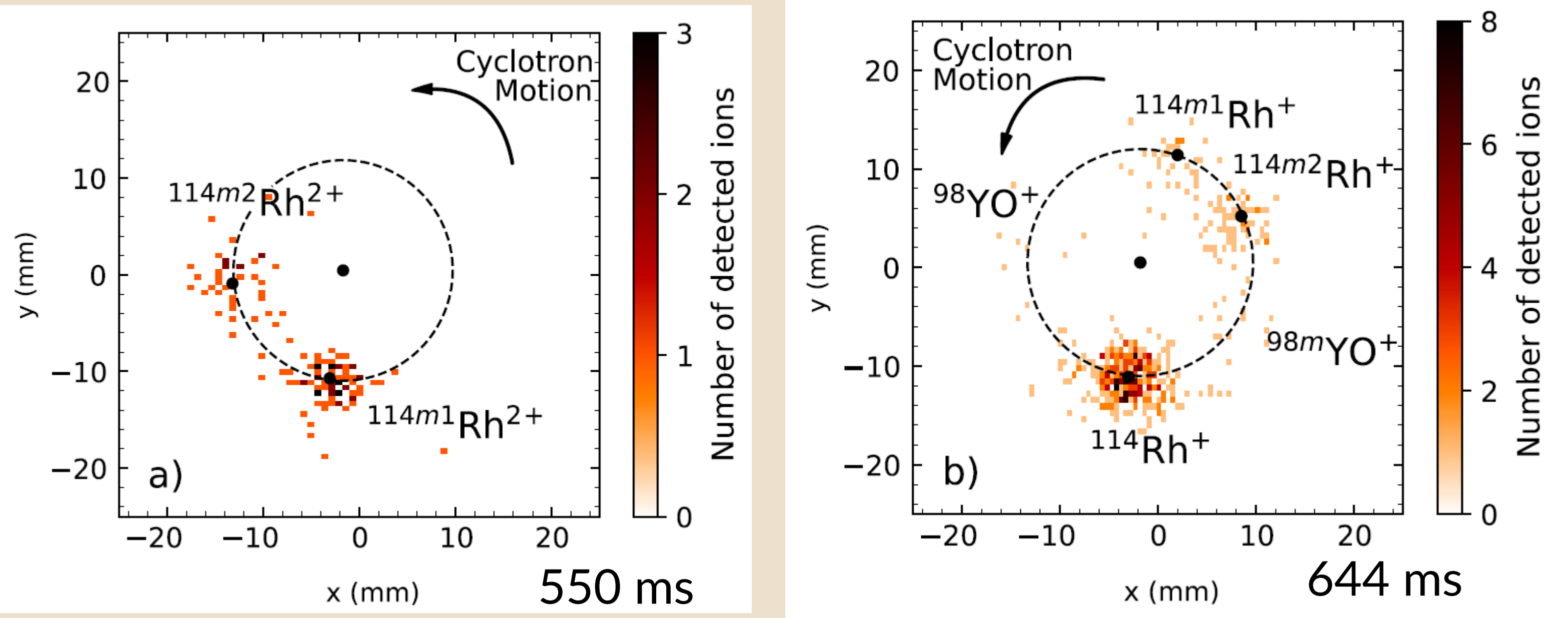


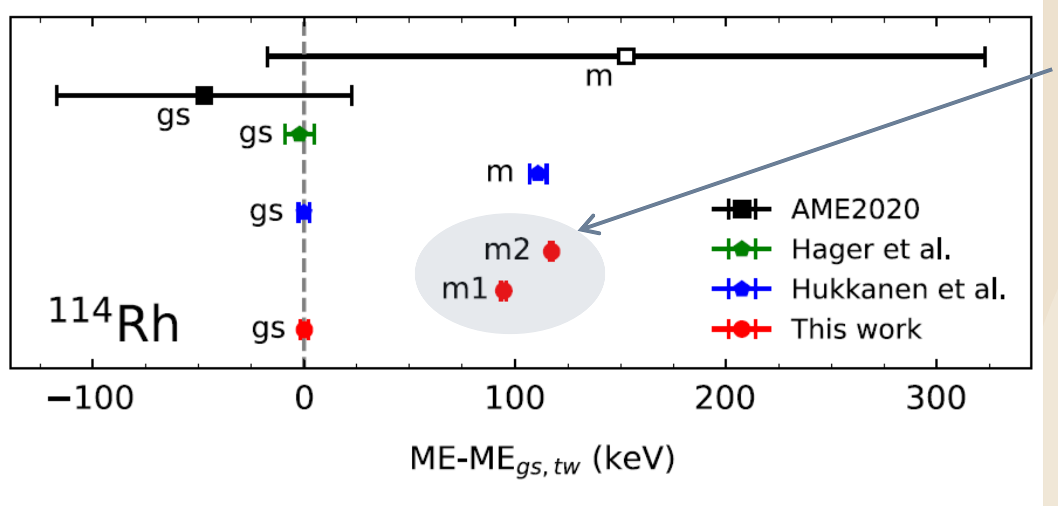
Also measured at Canadian Penning trap:
https://arxiv.org/abs/2410.00389

^{114}Rh states revisited



Hukkanen 2023





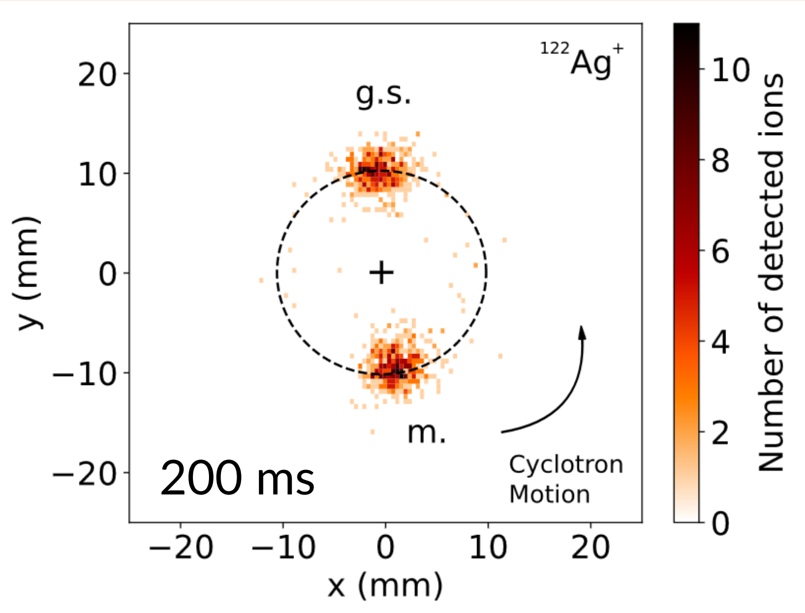
$\Delta E = 22.4(9)$ keV !

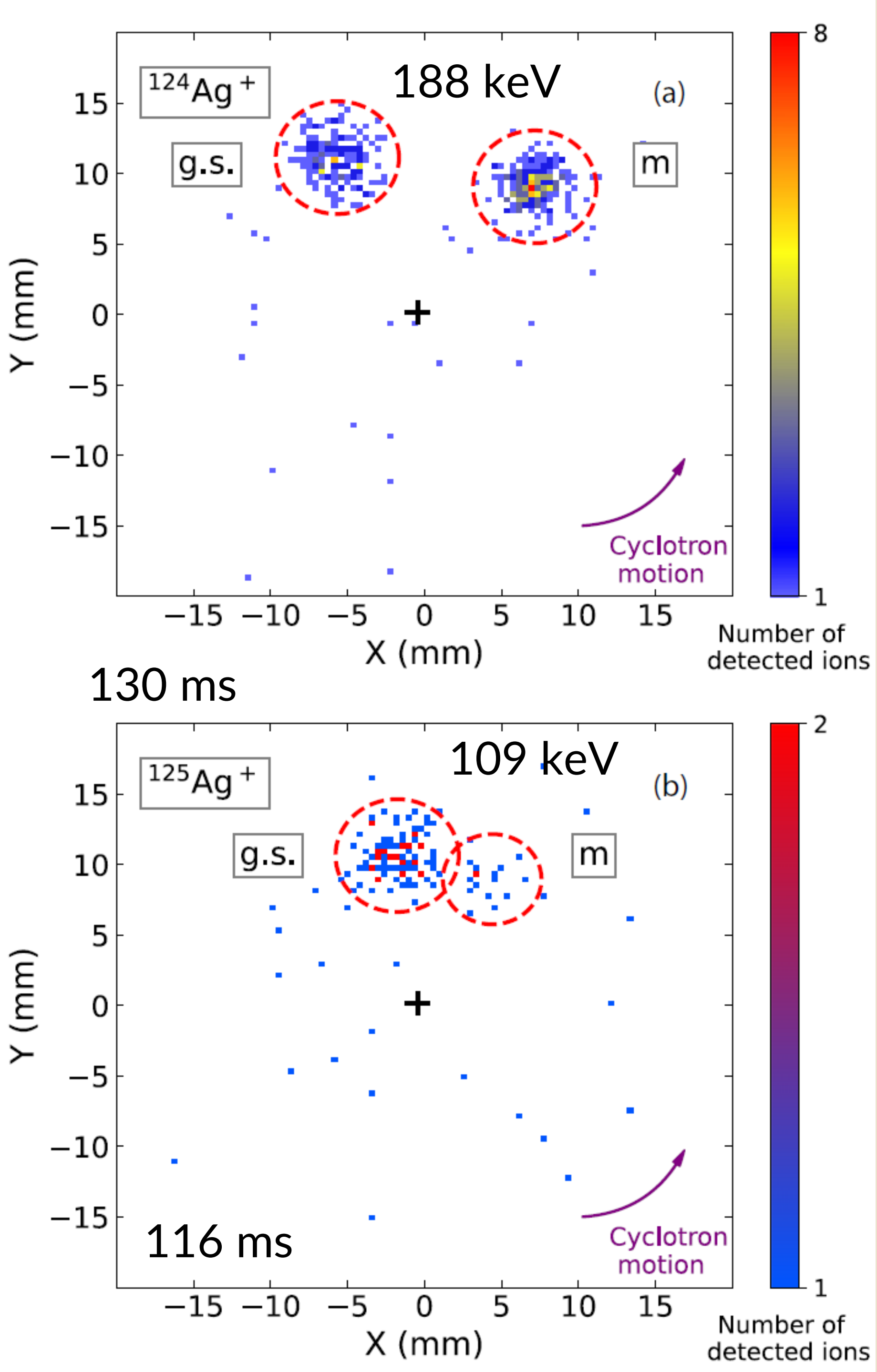
Stryjczyk PLB 862, 139359 (2025)

N-rich Ag isomers

- A. Jaries et al. PRC 110, 034326 (2024)
- J. Ruotsalainen et al. Arxiv 2408.14181 (2024)
- $T_{1/2}$~150 ms

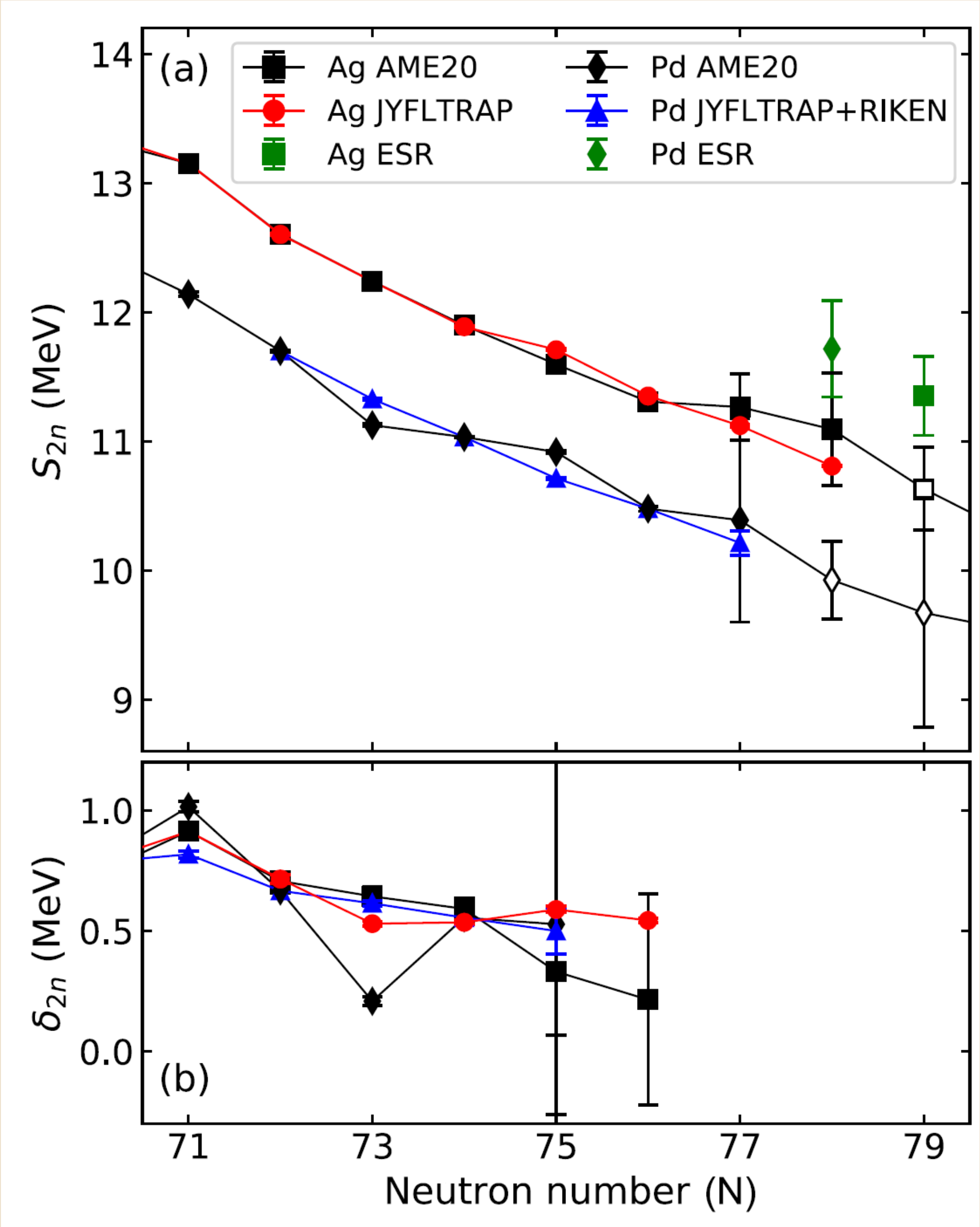
- ^{122}Ag: NUBASE20, ENSDF: 3 states
  - JYFLTRAP: only 2 seen, m1 is actually gs!





S_{2n} values of n-rich Ag

Smooth all the way



Combatting contaminants and gaps in yield

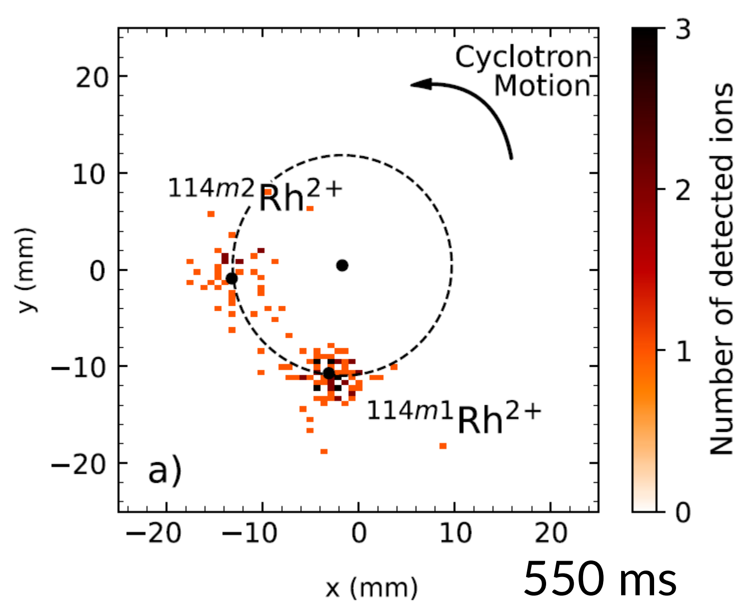
In-trap β^- decay assisted PTMS

- Let singly-charged parent ion to decay in Penning trap
- Daughter is 2+ charged, recoil remains trapped

- Simply: Capture bunch to gas-filled preparation trap
- Wait (ideally) few half-lives
- Use sideband buffer gas cooling technique to clean rest away
- Do PI-ICR
  - Also gained x2 precision due to q=2e!

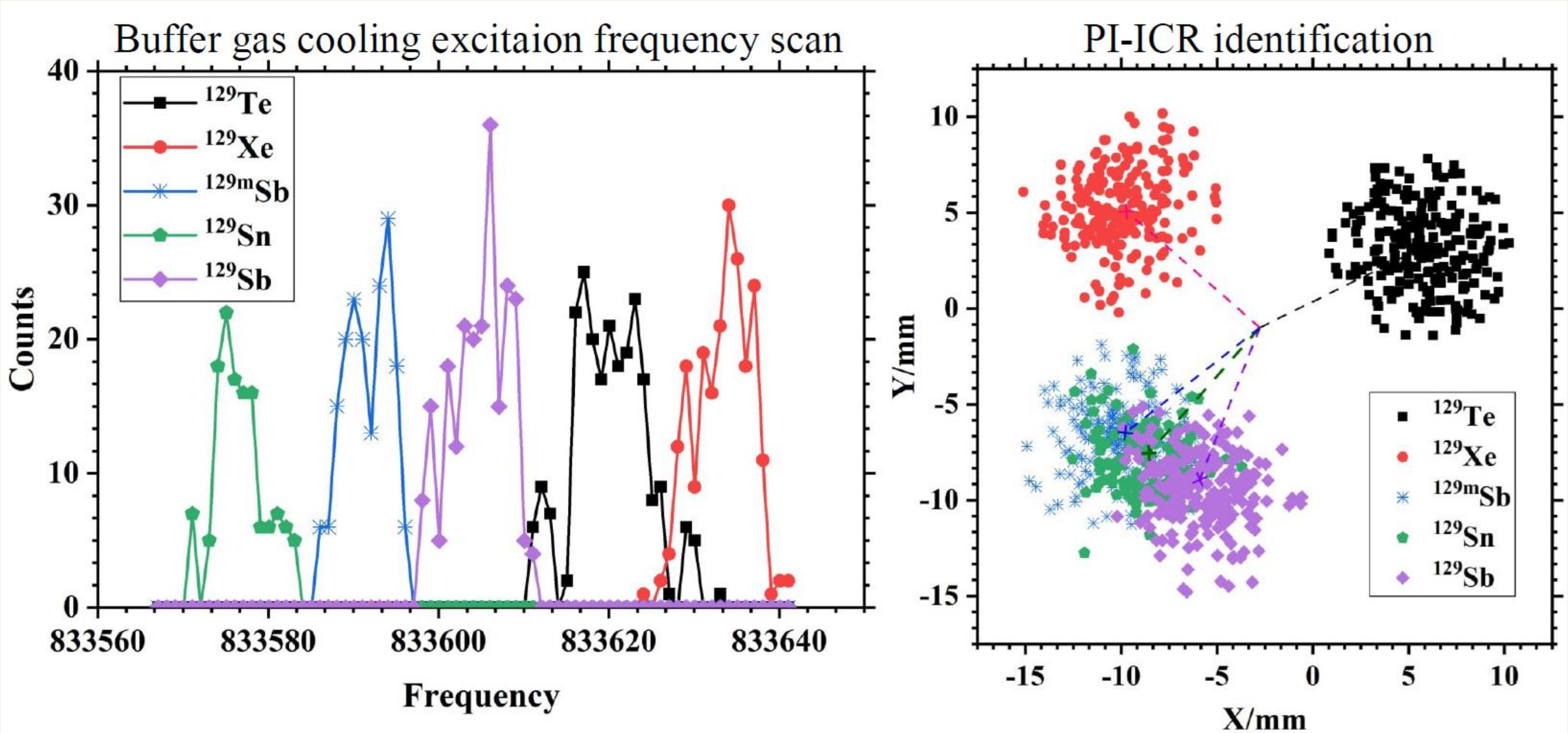
- ^{114}Rh case: Learned also that ^{114}Ru beta decay does not feed ^{114}Rh gs
- HELPS to fill gaps in primary production (here p+U)

$\Delta E = 22.4(9)$ keV !



Combination of different mass filters

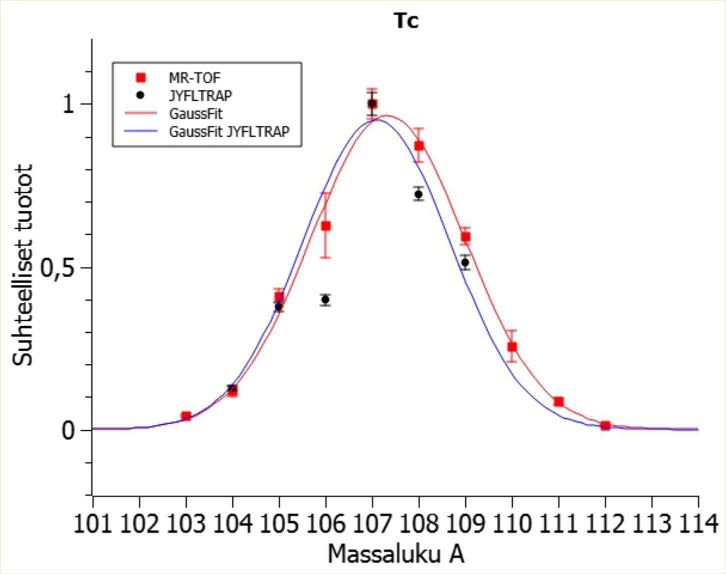
Purification Penning trap + PI-ICR

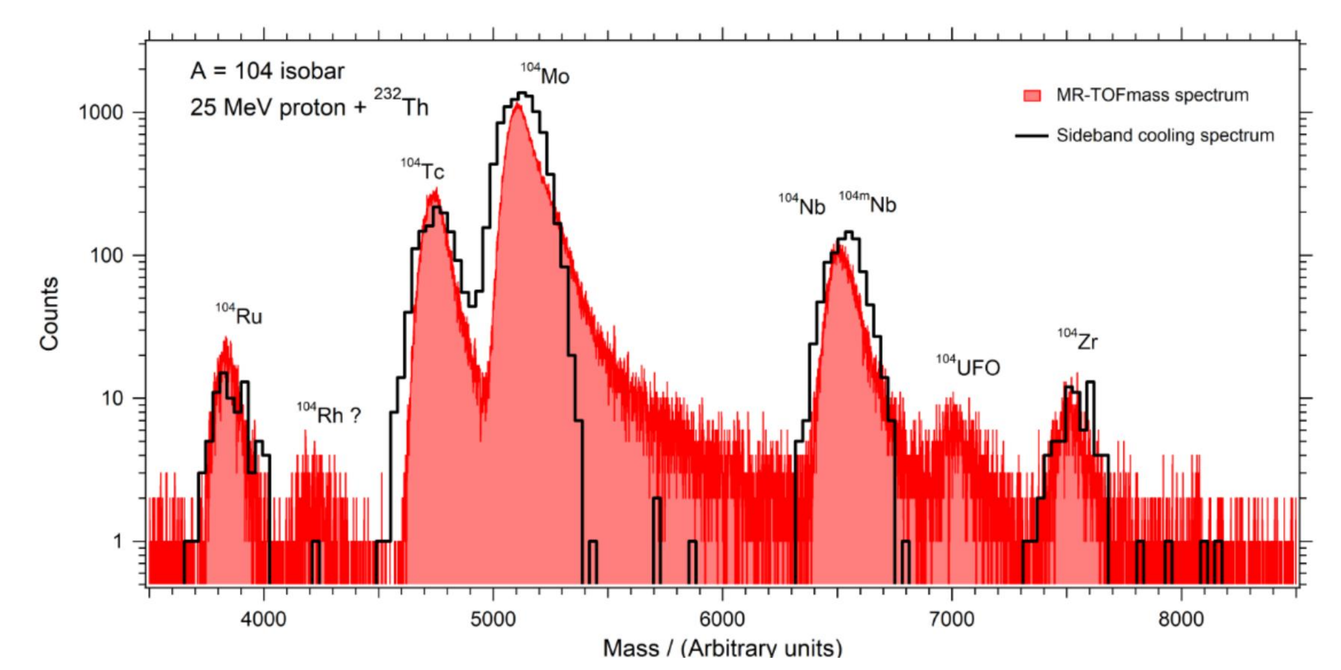


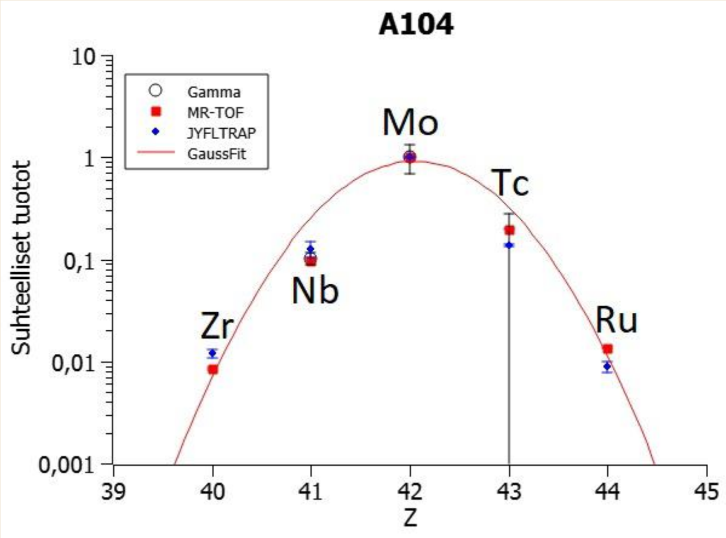
Plot by Z. Ge

Independent fission yields

- Mass spectroscopy means
  - Penning trap purification trap (scanning)
  - MR-TOF (non-scanning)



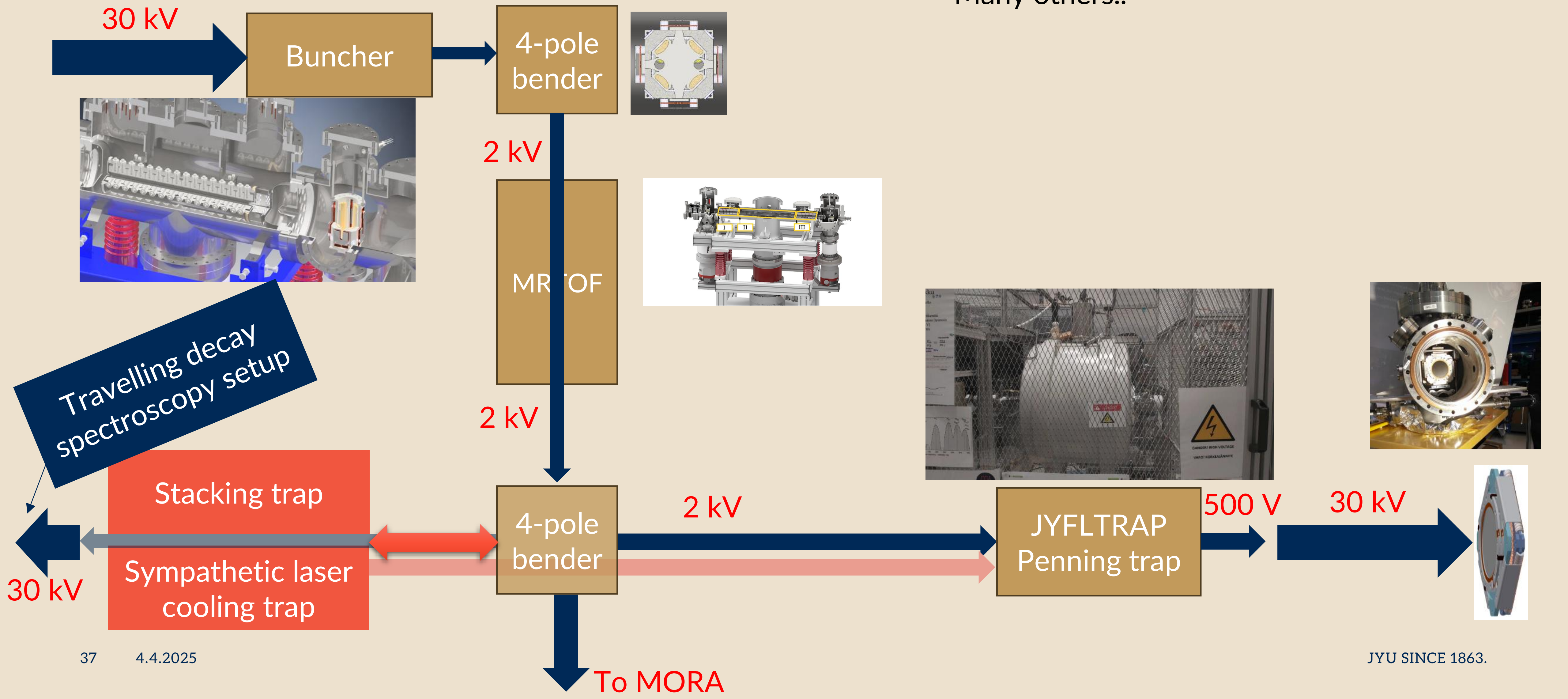




Rami Korkiamäki MSc thesis Thorium-232 proton induced fission yield distribution
http://urn.fi/URN:NBN:fi:jyu-202406124567

New developments

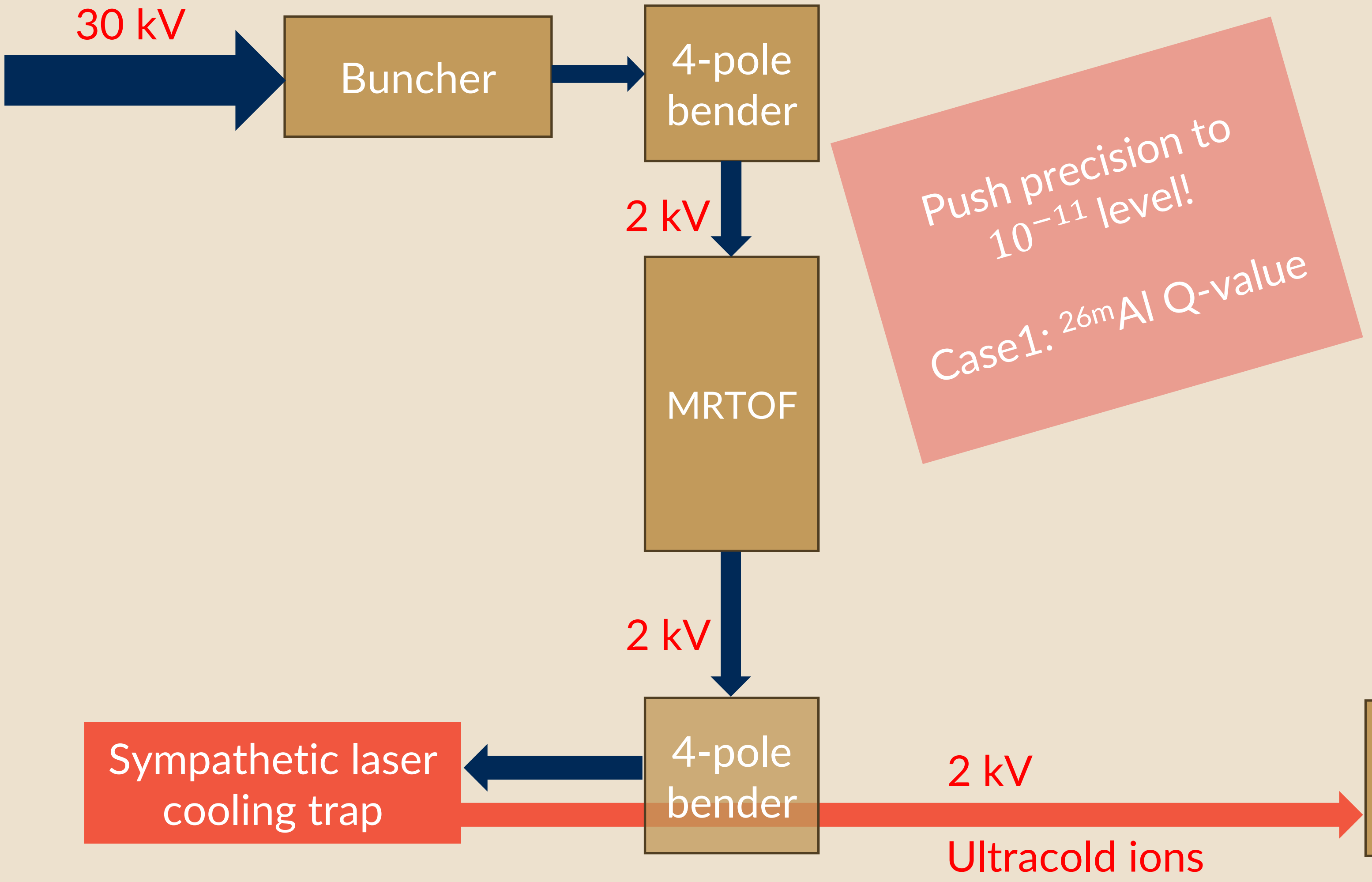
- MRTOF+JYFLTRAP coupling
  - Demonstrated but not yet efficient
- Many others..

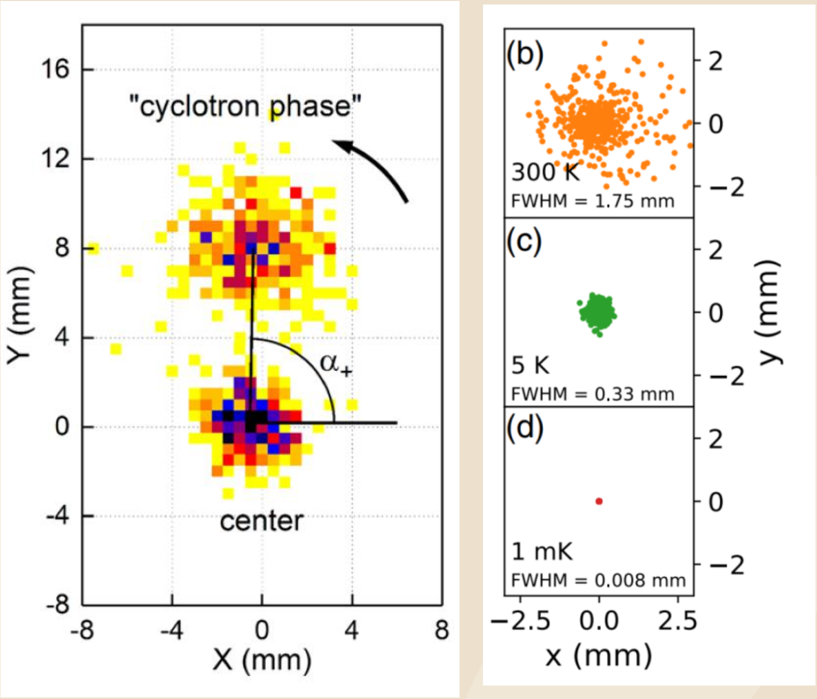


PI-ICR with ultracold ions

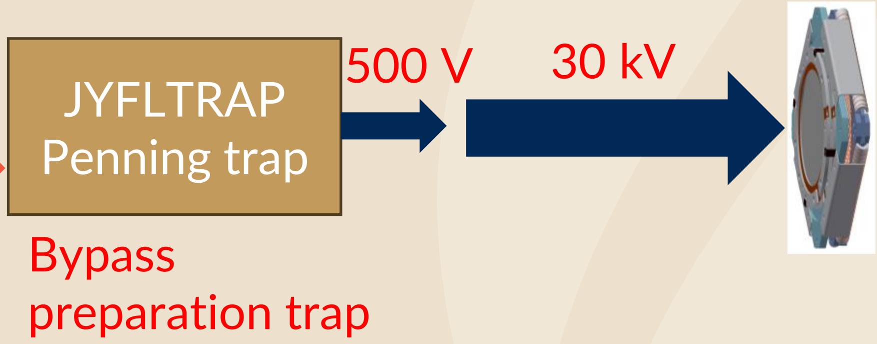
KU LEUVEN

Collaboration being formed

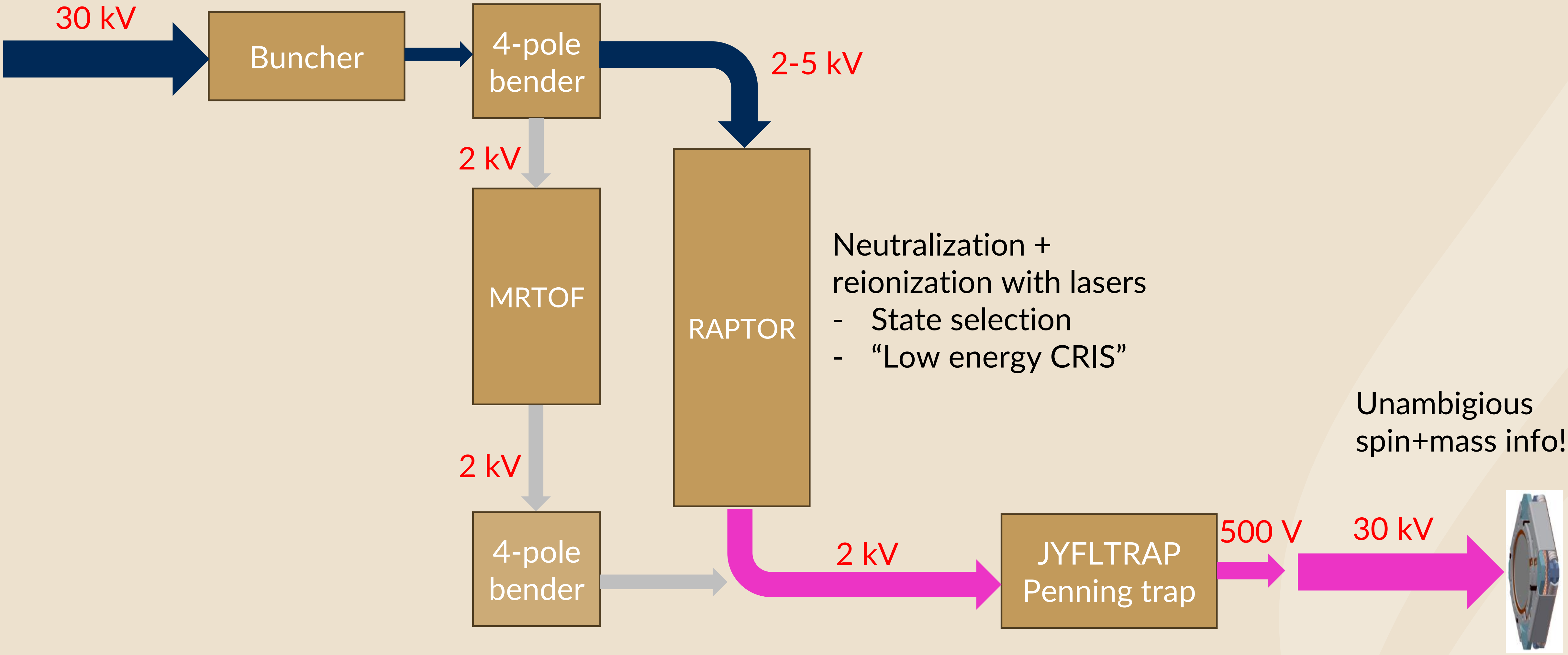




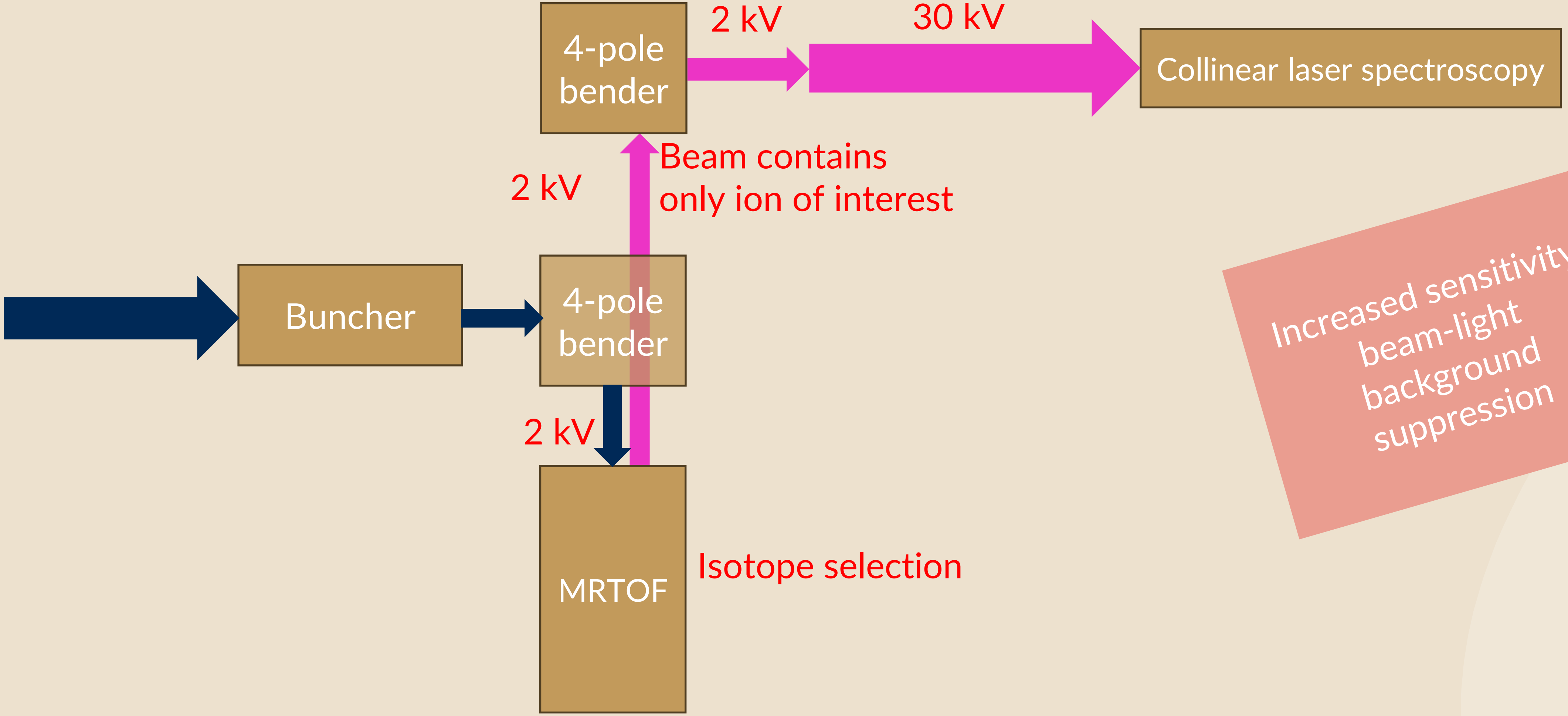
S. Sels, Phys. Rev. Res. 4, 033229 (2022)



State-selective mass spectrometry with RAPTOR

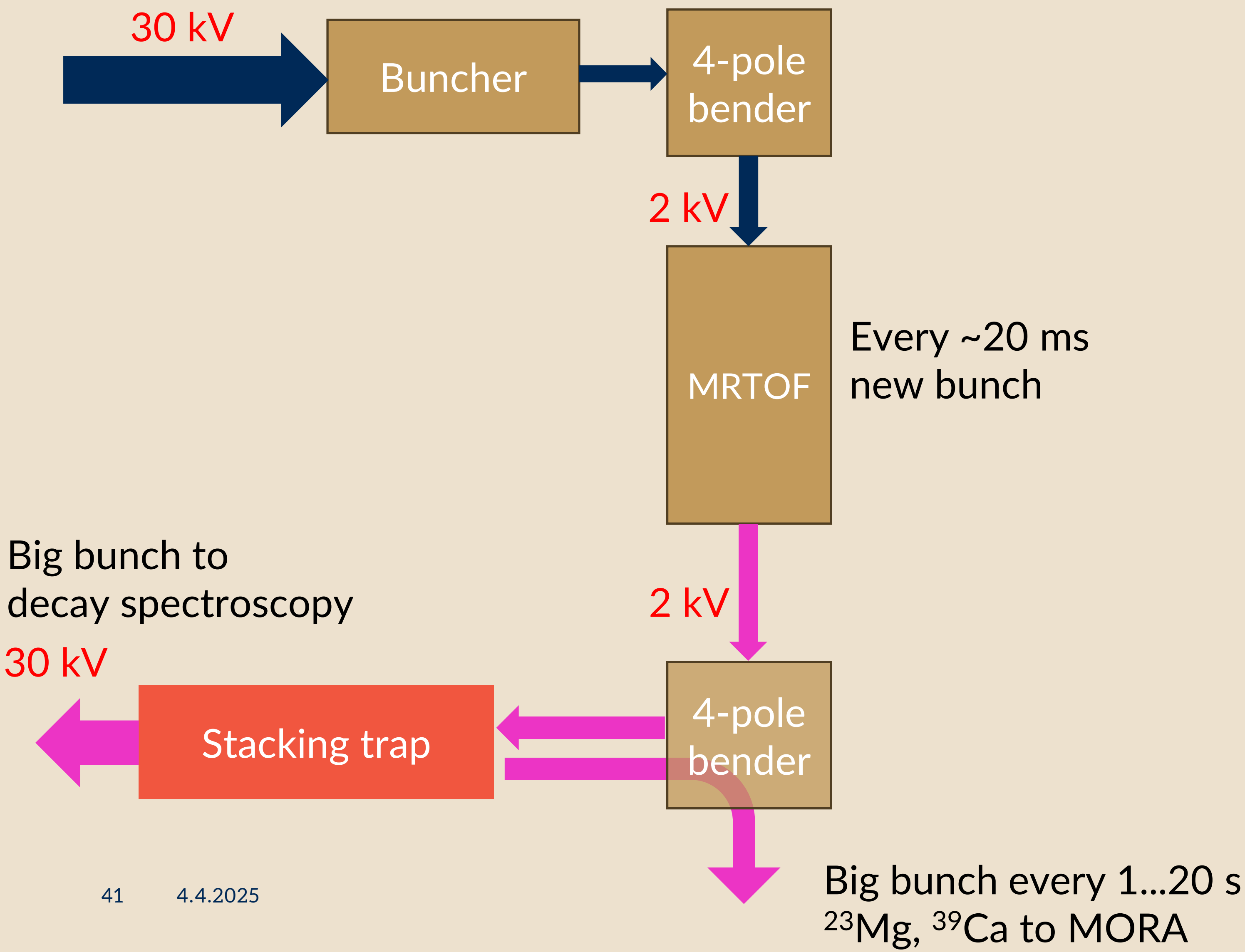


Mass-separation assisted laser spectroscopy



Increased sensitivity, beam-light background suppression

Stacking trap for accumulation of pure ion sample



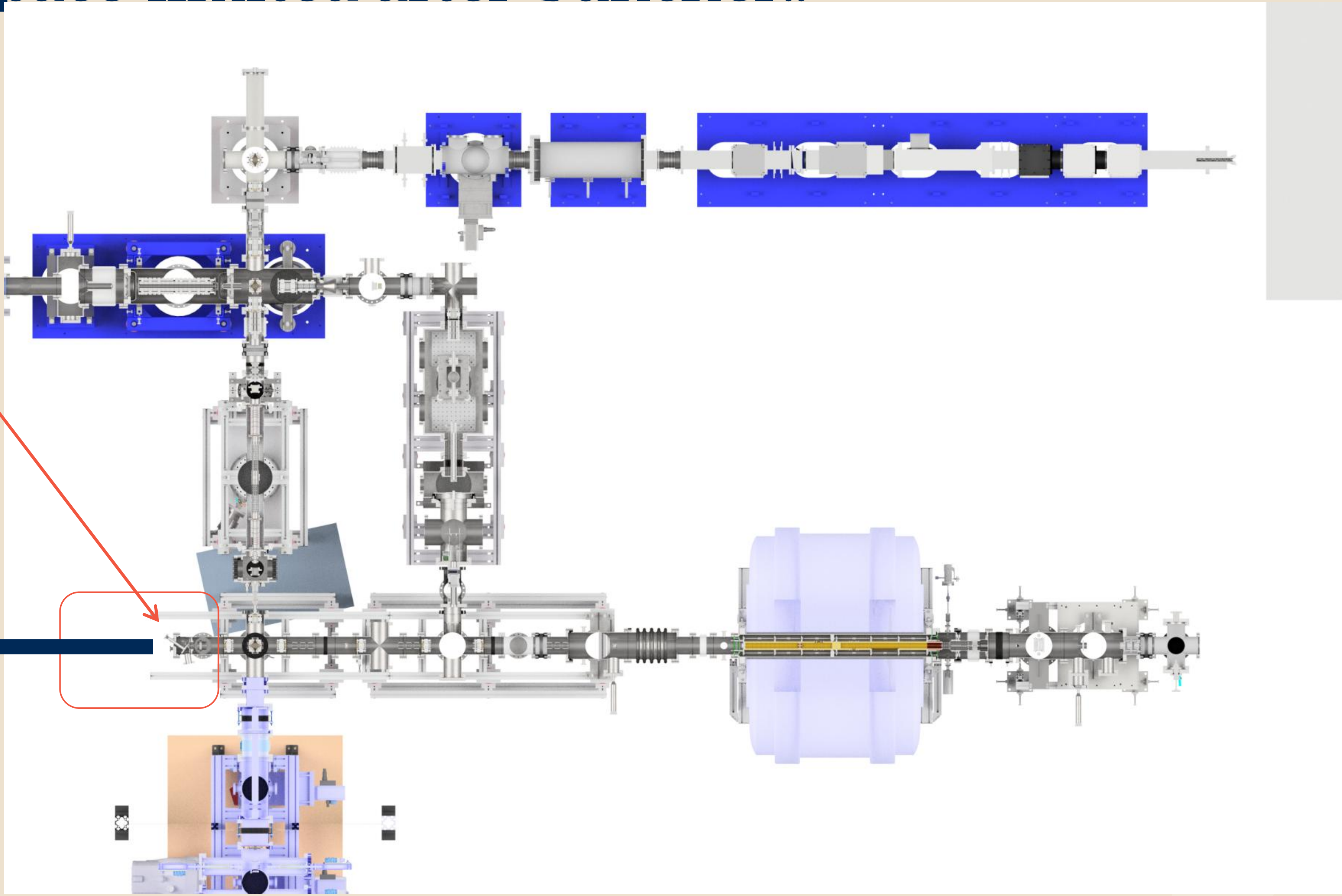
IGISOL is space-limited after buncher..

Stacking trap

Sympathetic cooling trap

Also..

Visiting setups, decay spectroscopy



MRTOF-cleaned beam
- ”Warsaw” beamline
- SEASON, MONSTER..
- Bertram?

Exotic front vs precision front

Precision measurements, “close” to stability

- Expect high yields, particular impurities

- Standard Model testing
- Neutrino physics

- PI-ICR PTMS, with ultracold ions
- Expand high-precision work from stable to radioactive nuclei
  - E.g. King plot linearity tests

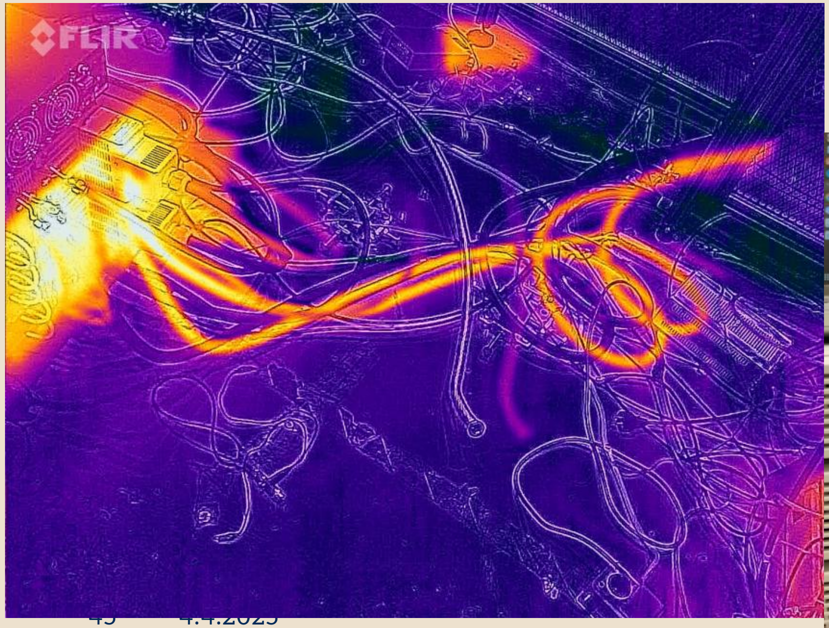
Exotic nuclei, very far from stability

- Expect low yields and lots of contamination
- High contamination ratios
  - Pre-separation essential
- Masses with MR-TOF
  - Still, e.g. ^{101}Sn was measured at FRIB with PI-ICR at LEBIT trap

Thank you for listening!

JYFLTRAP magnet quench and re-energization

- Energized ourselves (3rd time was a charm), shimmed too
- Thanks MLLtrap (Enrique) ffinallyor NMR Tesla-probe
- Thanks SHIPTRAP for shimming tools
- And we at JYFLTRAP have the main current lead stick



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