MR-ToF Devices: New Applications and Developments

Invited Talk at EMISXX, 23rd October 2025

Franziska Maria Maier

Research Associate FRIB

maierf@frib.msu.edu

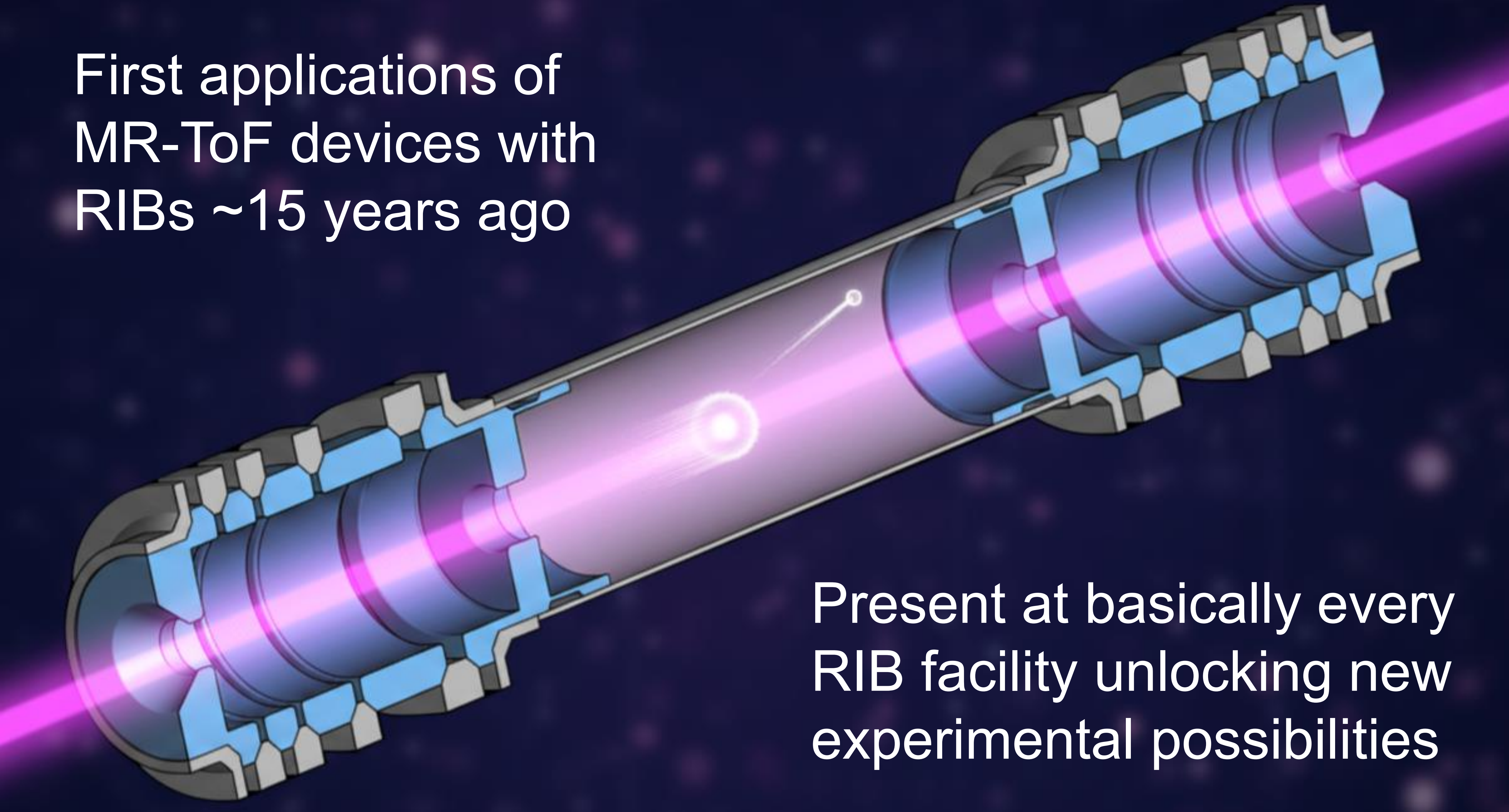
ISOLDE

CERN MIRACLS + FRIB

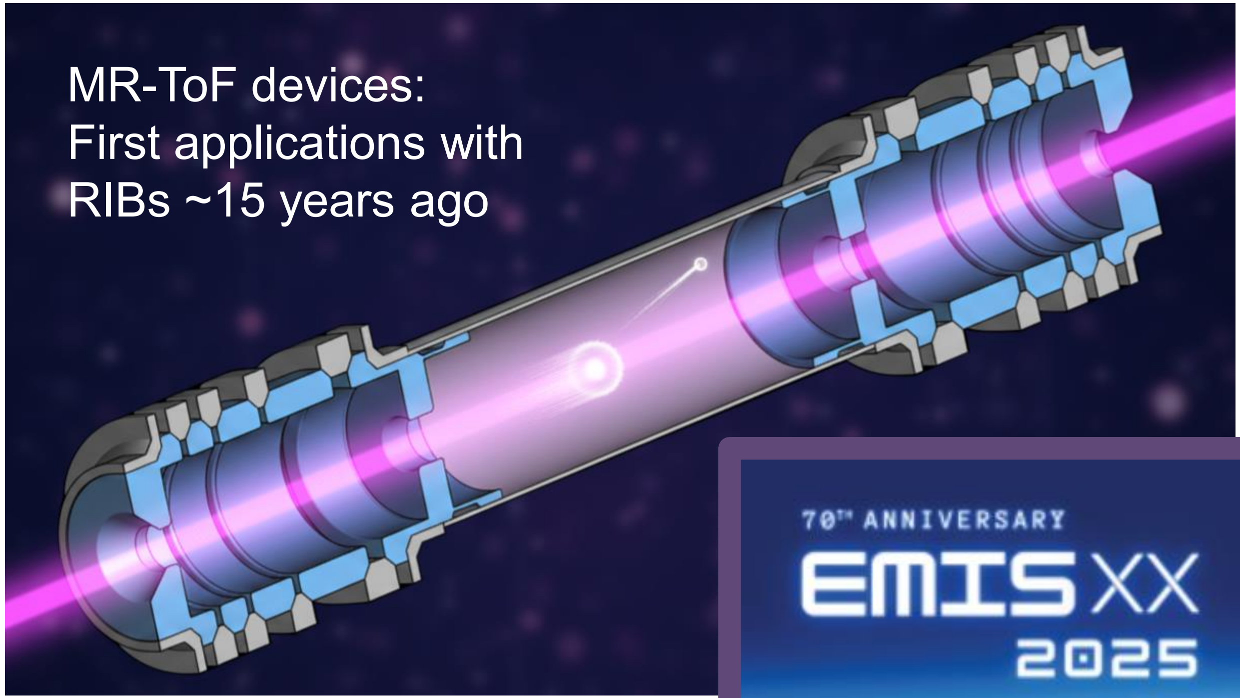
U.S. DEPARTMENT OF ENERGY Office of Science

MICHIGAN STATE UNIVERSITY

First applications of MR-ToF devices with RIBs ~15 years ago



Present at basically every RIB facility unlocking new experimental possibilities



High-precision mass measurements

- Presence and future of the MR-ToF systems at RIBF and new projects in East Asia
- Recent Advances of the S3-Low Energy Branch
- A Small Size High Resolution Multi-turn ToF Mass Analyzer
- An FPGA-based timing system for MR-ToF
- NEXT - A new setup to study Neutron-rich Exotic, heavy, nuclei produced in multinucleon Transfer reactions
- High-Precision Mass Spectrometry Near the Driplines with TITAN MR-ToF-MS
- Simultaneous mass spectrometry and in-source laser spectroscopy of exotic nuclides from ISOLDE

Mass separation

- Isobaric ion separation at CRIS
- Development of a high-flux MR-ToF isobar separator at SCRIT facility

Electron affinity measurements

- Precision spectroscopy of heavy and superheavy elements with AETHER

Fluorescence-based laser spectroscopy

Outline

- MR-ToF devices enhance sensitivity for collinear laser spectroscopy (CLS)
  - Measurement of electron affinities
  - Measurement of nuclear ground state properties
- The development of a high-voltage MR-ToF device was required to maintain the resolution of conventional fluorescence-based CLS
- A high-voltage MR-ToF device will also increase the mass separation capabilities

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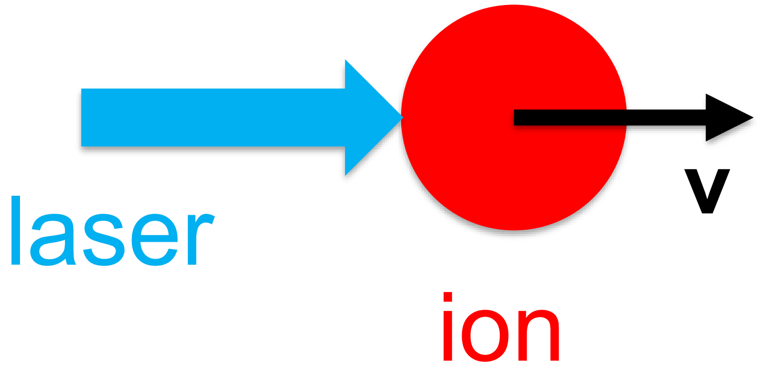
MR-ToF devices enhance sensitivity for collinear laser spectroscopy (CLS)

- CLS known for high resolution
- Limited to short observation times
- Scarcely produced ions are not accessible



MR-ToF devices enhance sensitivity for collinear laser spectroscopy (CLS)

- CLS known for high resolution
- Limited to short observation times
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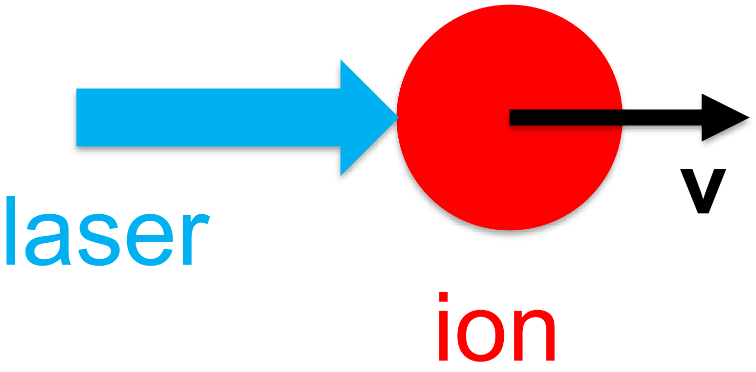
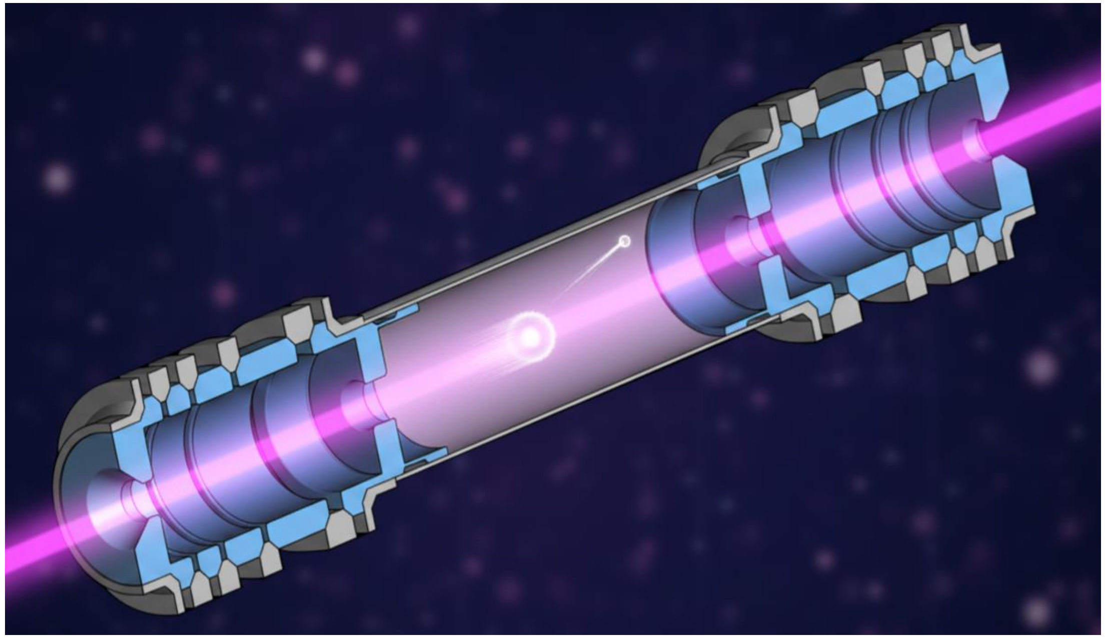
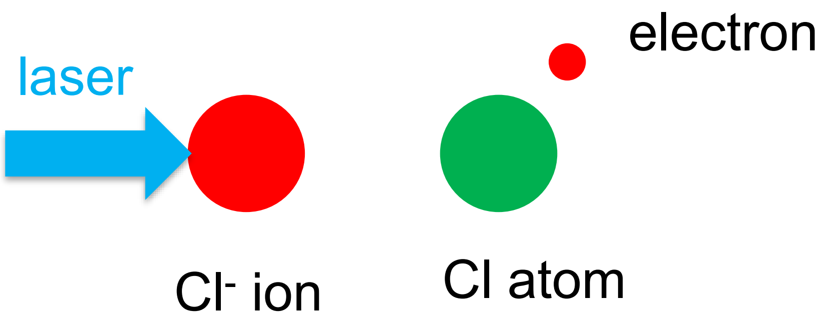
- Perform CLS within an MR-ToF device
- Ions pass laser-ion interaction region > 1000 times
- increased observation time
- more exotic nuclei accessible





Development of MR-ToF devices for CLS:

Enhanced Sensitivity for Electron Affinity Measurements



See also talk: Precision spectroscopy of heavy and superheavy elements with AETHER

F.M. Maier, E. Leistenschneider et al., Accepted in Nature Communications.

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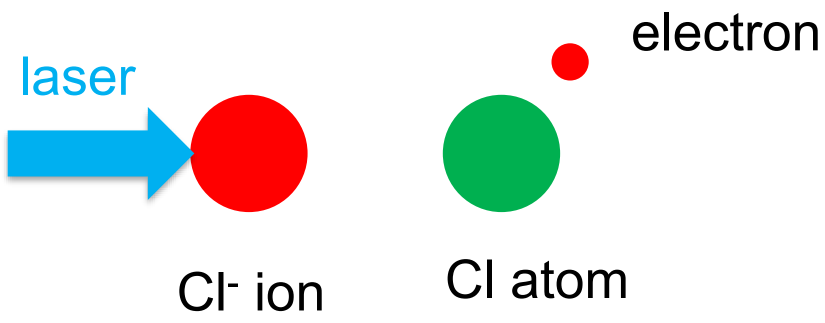

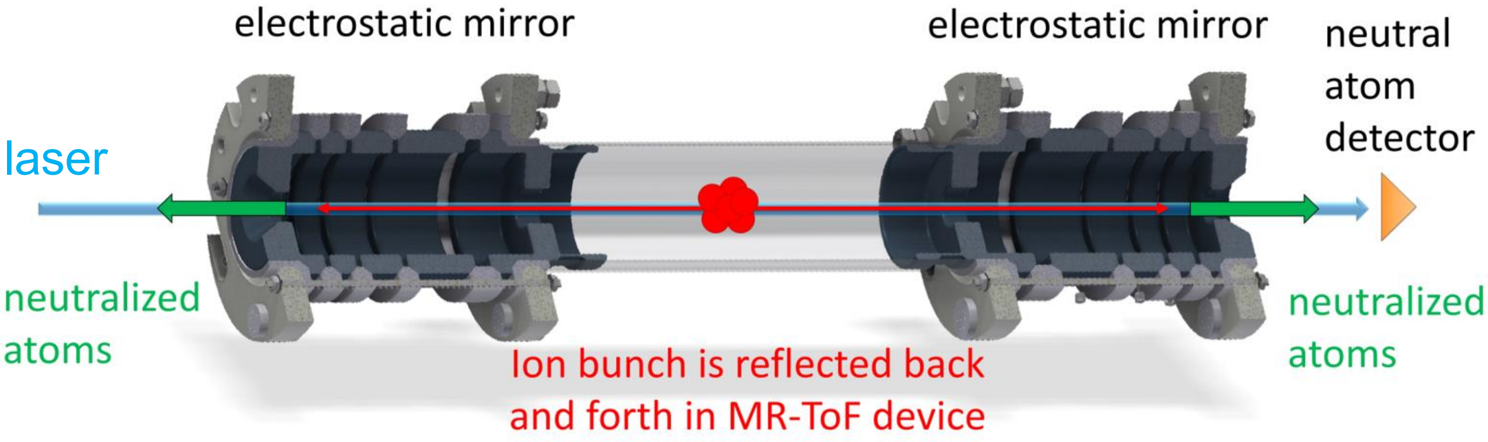

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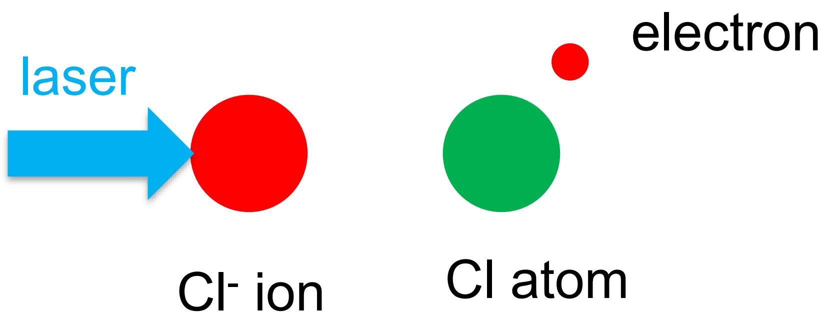

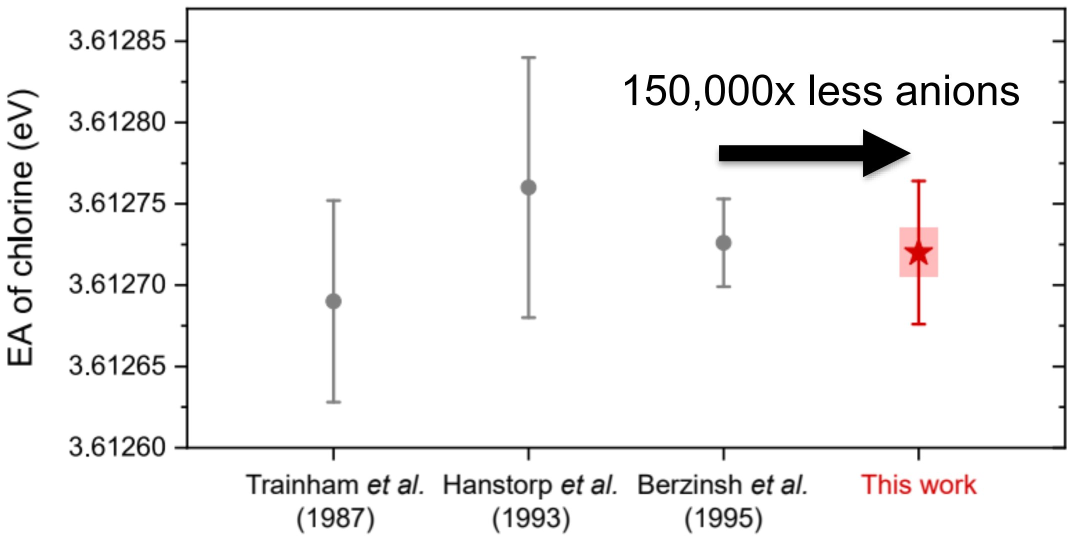

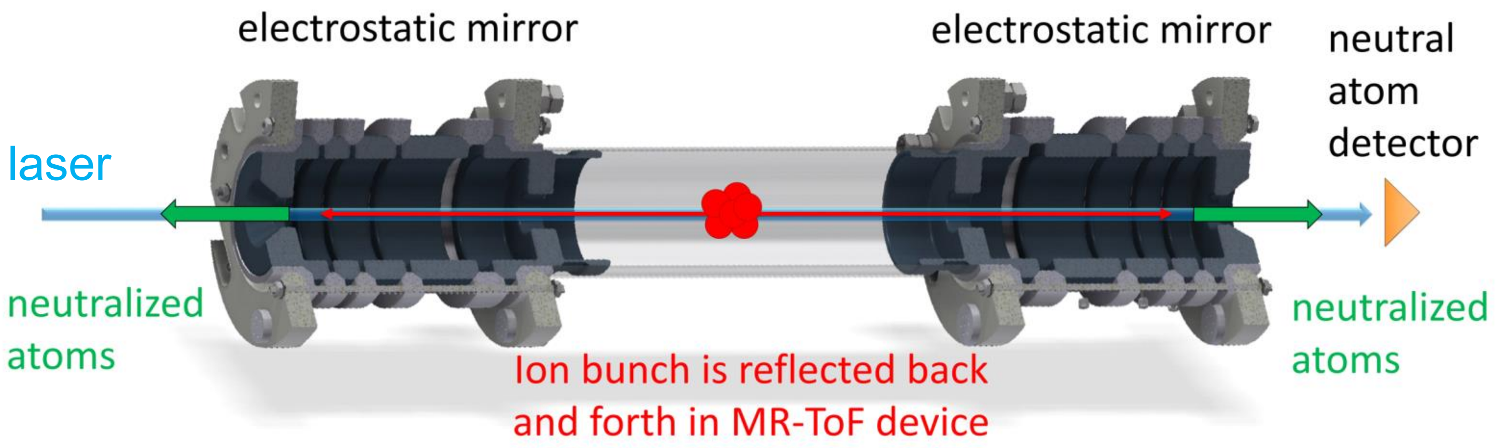

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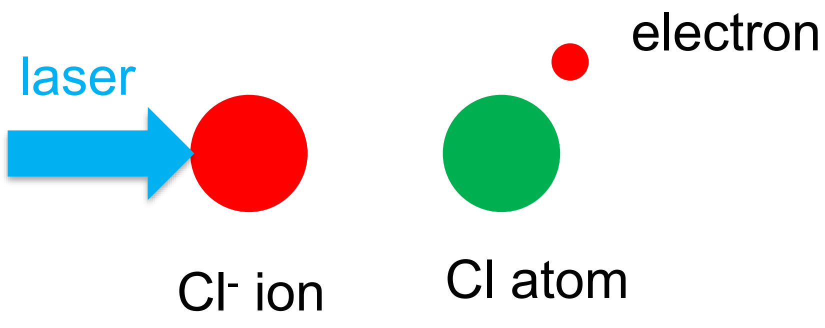

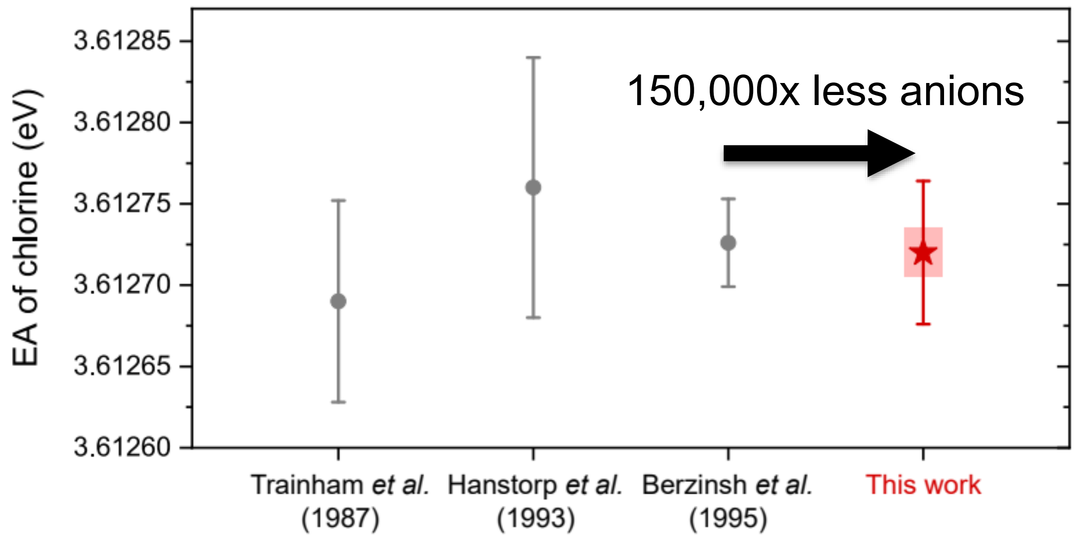

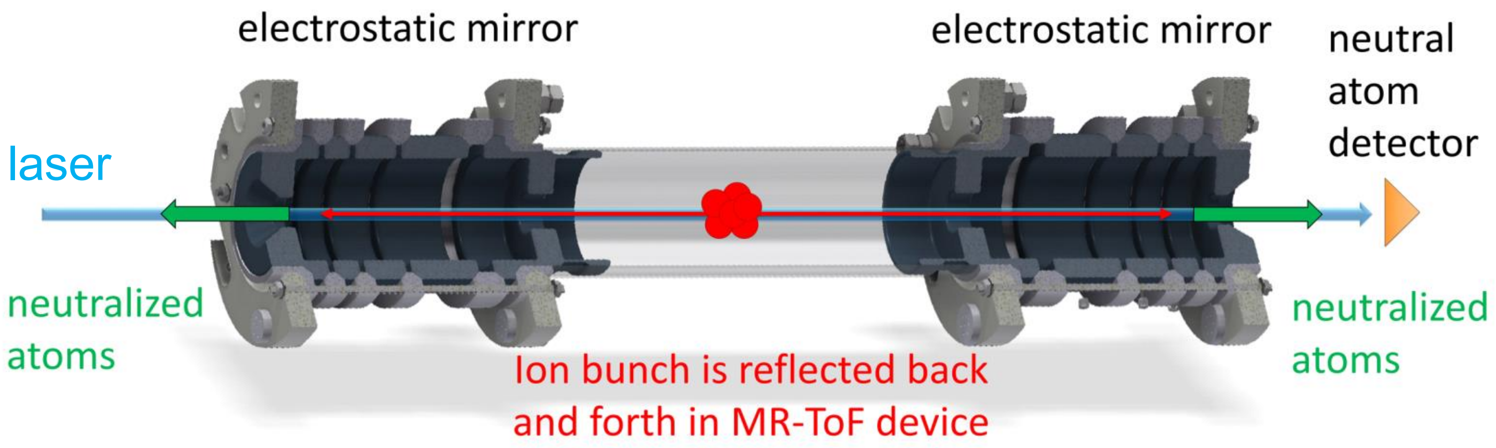

"This breakthrough is poised to have a significant impact on atomic physics, nuclear physics, and the chemistry of super-heavy elements." (Reviewer Nature Communications)

See also talk: Precision spectroscopy of heavy and superheavy elements with AETHER

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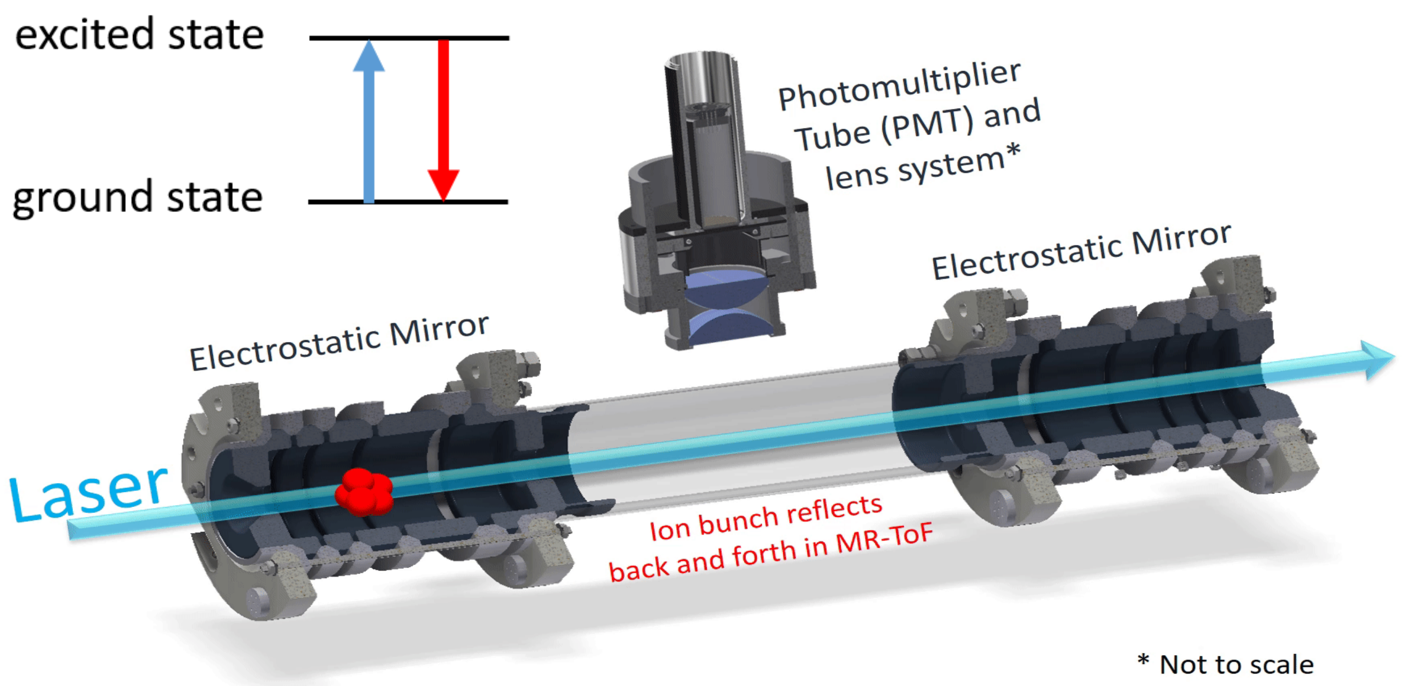
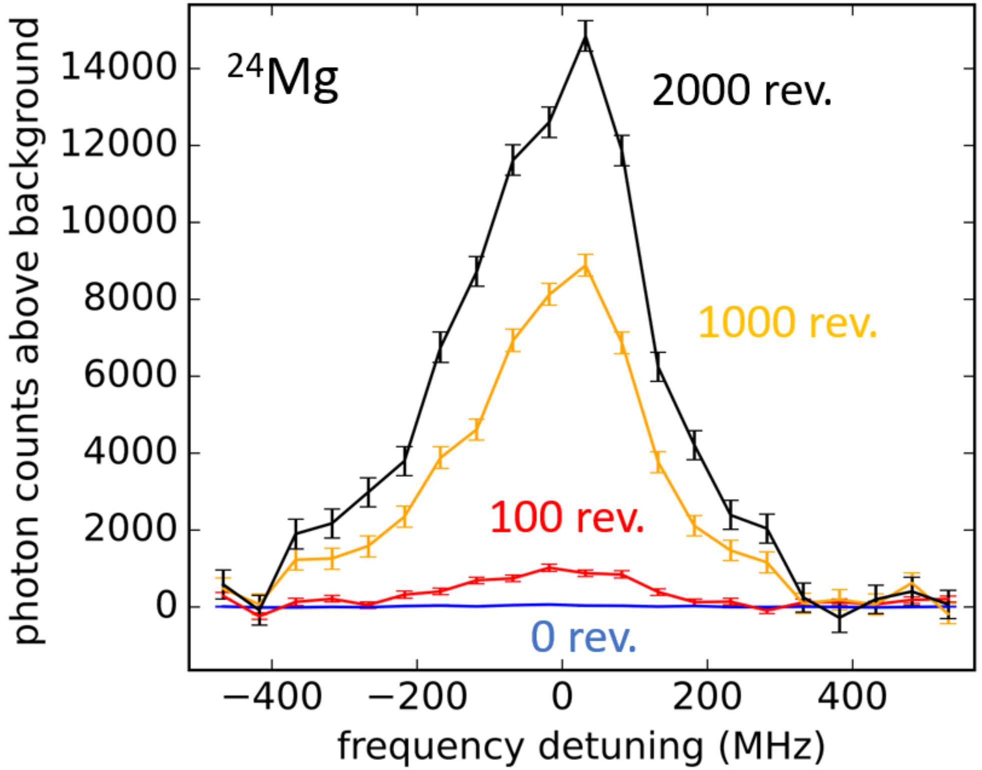
Development of MR-ToF devices for CLS:
Enhanced Sensitivity for Fluorescence-Based CLS





Increased observation time
→ gain in sensitivity by 1-2 orders of magnitude
→More exotic nuclides accessible

F.M. Maier et al., Hyperfine Interact. 240, 54 (2019).
S. Sels et al., NIMB 463, 310 (2020).
V. Lagaki, H. Heylen et al., NIMA, 1014, 165663 (2021).

Development of MR-ToF devices for CLS:

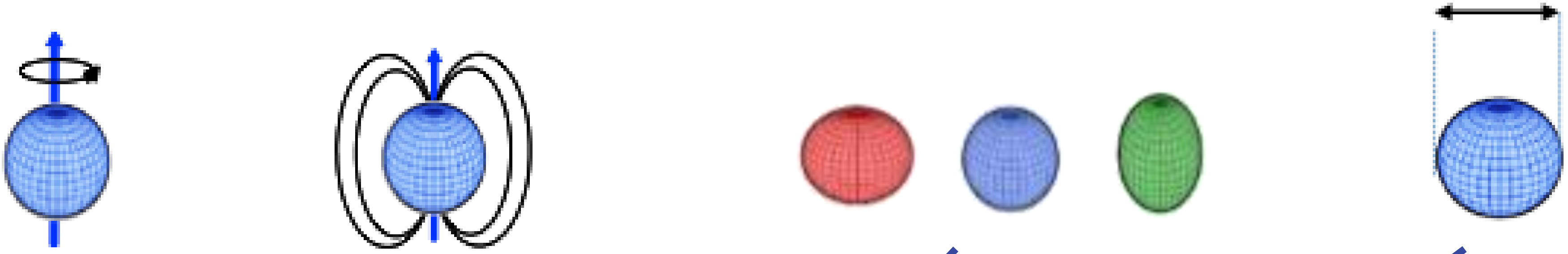
Enhanced Sensitivity for Fluorescence-Based CLS

spin I

magnetic dipol moment μ

Electric quadrupole moment Q_s

rms charge radius

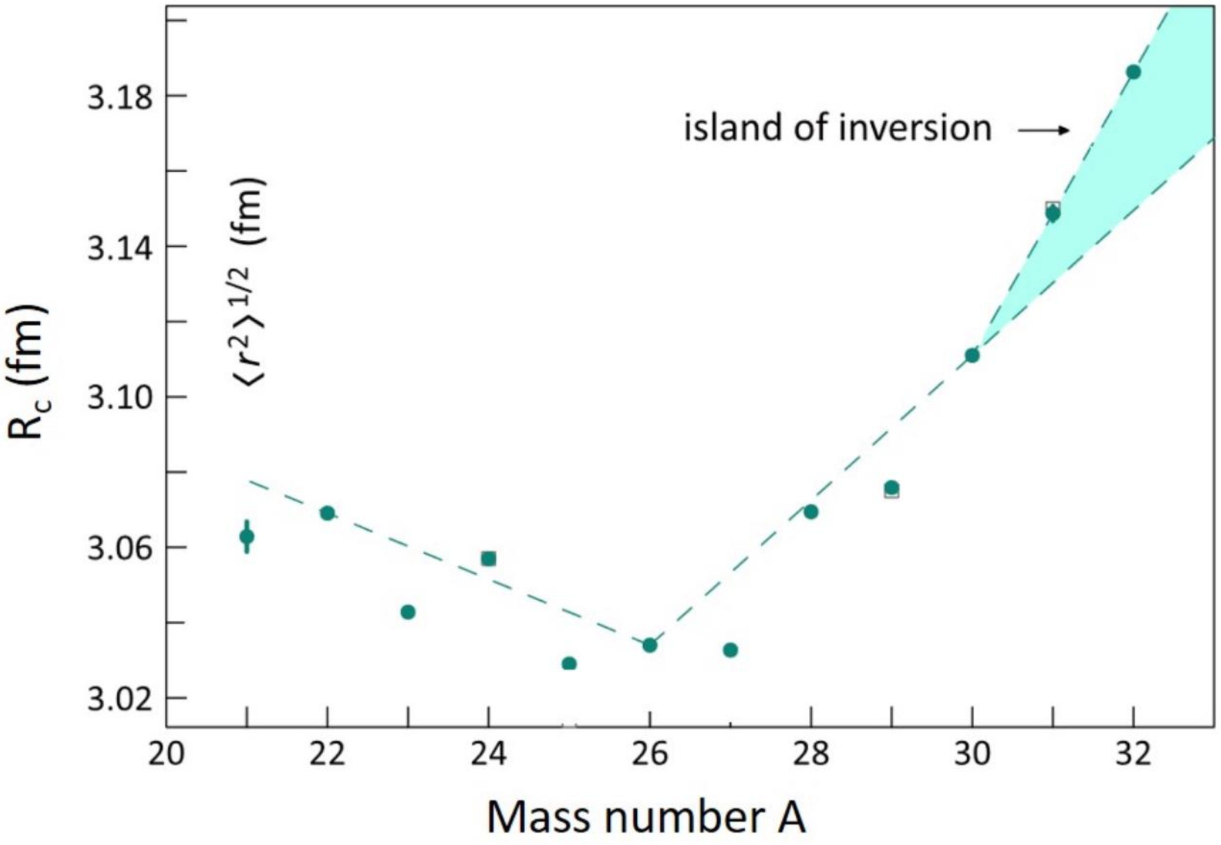


- **study nuclear structure phenomena**
- **benchmark for modern nuclear theory**

70th ANNIVERSARY EMIS XX 2025

- Online commissioning and current status of CLaSsy at RAON
- Nuclear structure studies by collinear laser spectroscopy
- Probing the silver isotopic chain with mass- and laser spectroscopy
- High-resolution collinear laser spectroscopy in a combined collinear and anti-collinear geometry

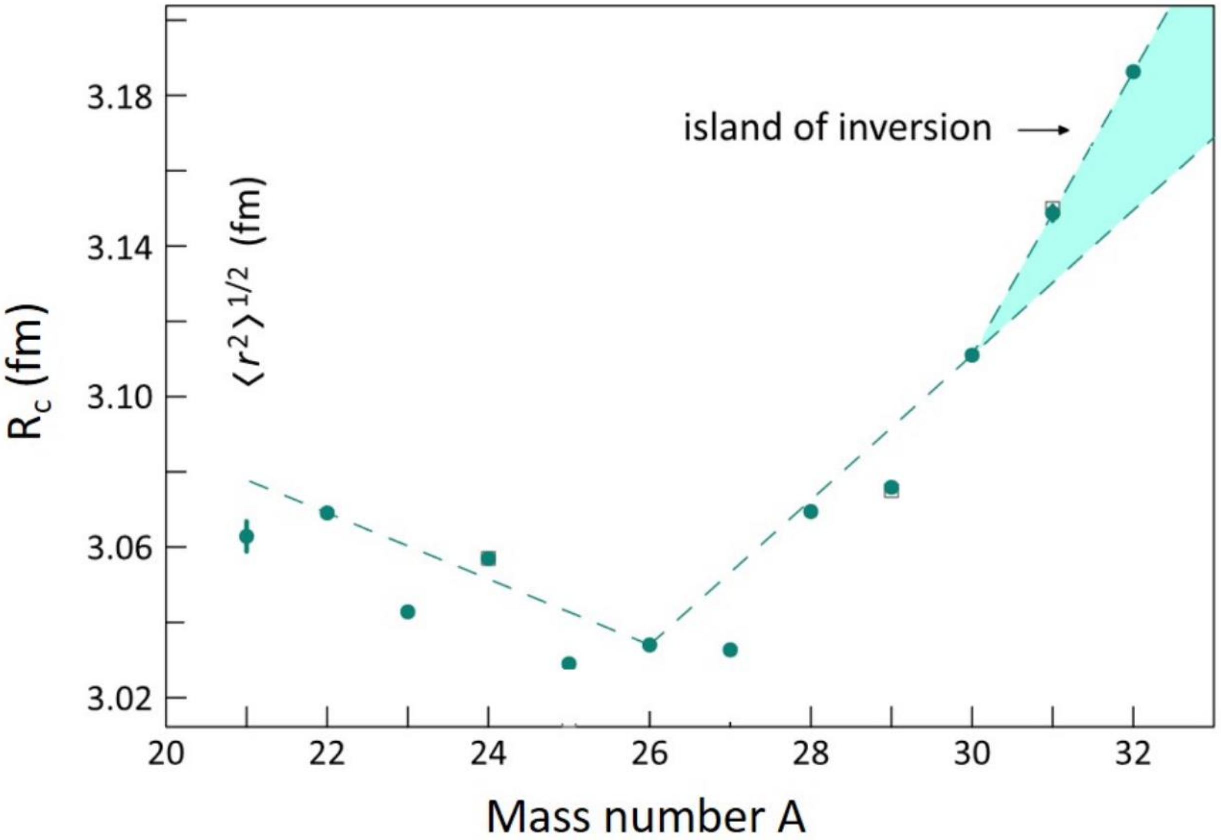
Charge radii measurements along the Mg isotopic chain provide insights into island of inversion



- Linear trends between A=21-26 & 26-30 & 31-32 in addition to odd-even staggering
- Filling of respective neutron orbits
- Island of inversion: Increasing slope → deformation, cross-shell excitation of two neutrons

D. T. Yordanov et al., Phys. Rev. Lett., 108:042504 (2012)

Charge radii measurements along the Mg isotopic chain provide insights into island of inversion



Charge Radii Measurements of ^{33,34}Mg would enable

- further insights into island of inversion
- stringent benchmark for ab initio theory

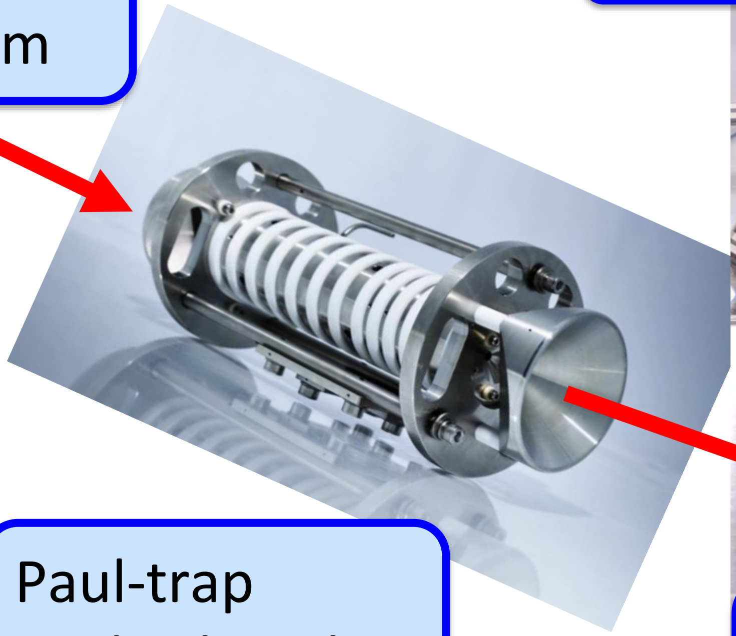
But: Very low production yields

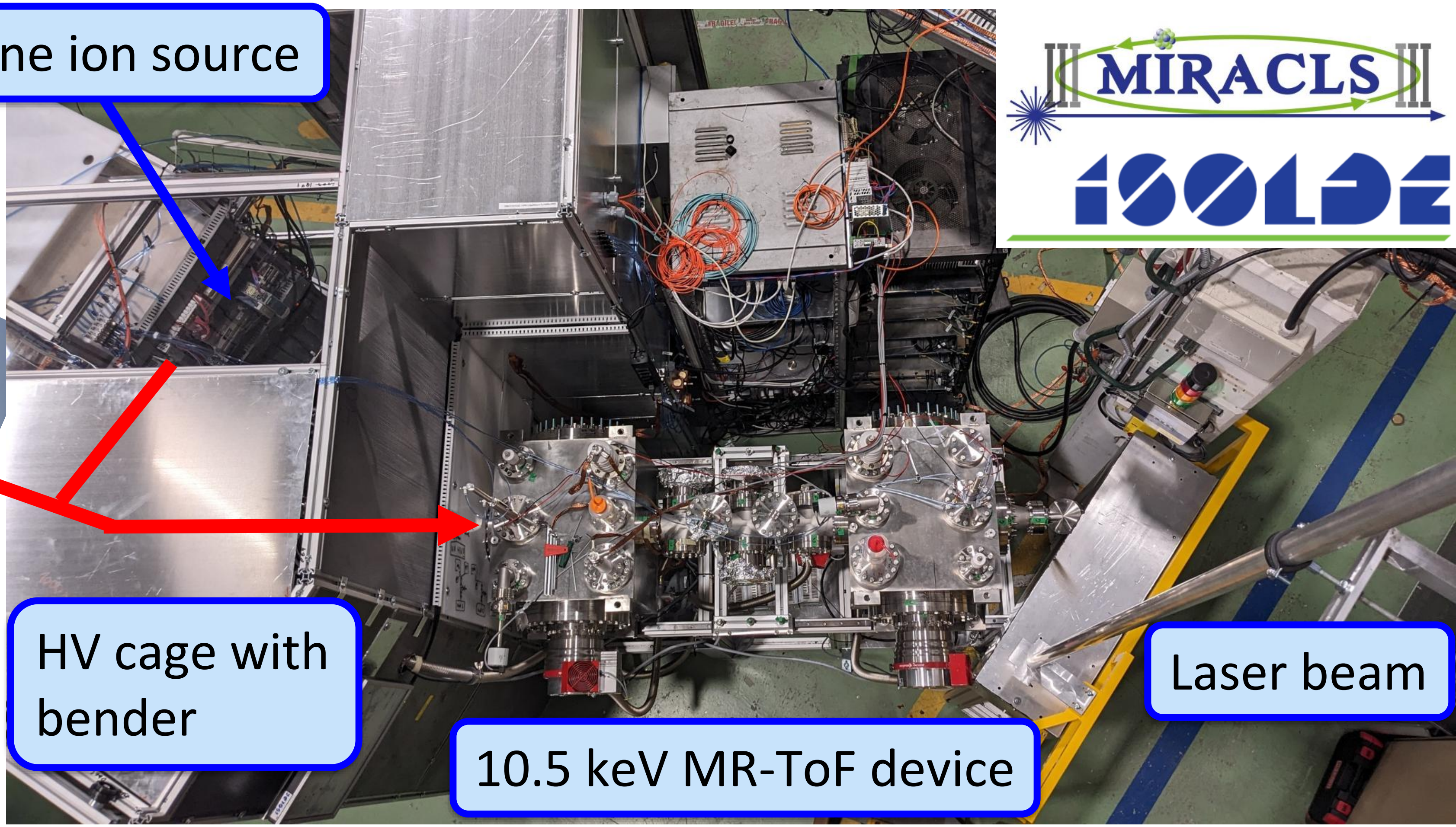
D. T. Yordanov et al., Phys. Rev. Lett., 108:042504 (2012)

The MIRACLS technique enables an increased sensitivity

- Perform CLS in an MR-ToF device
  → increase observation time → ^{33,34}Mg become accessible
  → high-voltage MR-ToF device → maintain high resolution

The MIRACLS technique enables an increased sensitivity





copies of our Paul trap also operational at Greifswald, MIT, Beijing, Darmstadt & ISOLTRAP

S. Lechner, S. Sels et al., NIMA 1065, 169471 (2024).

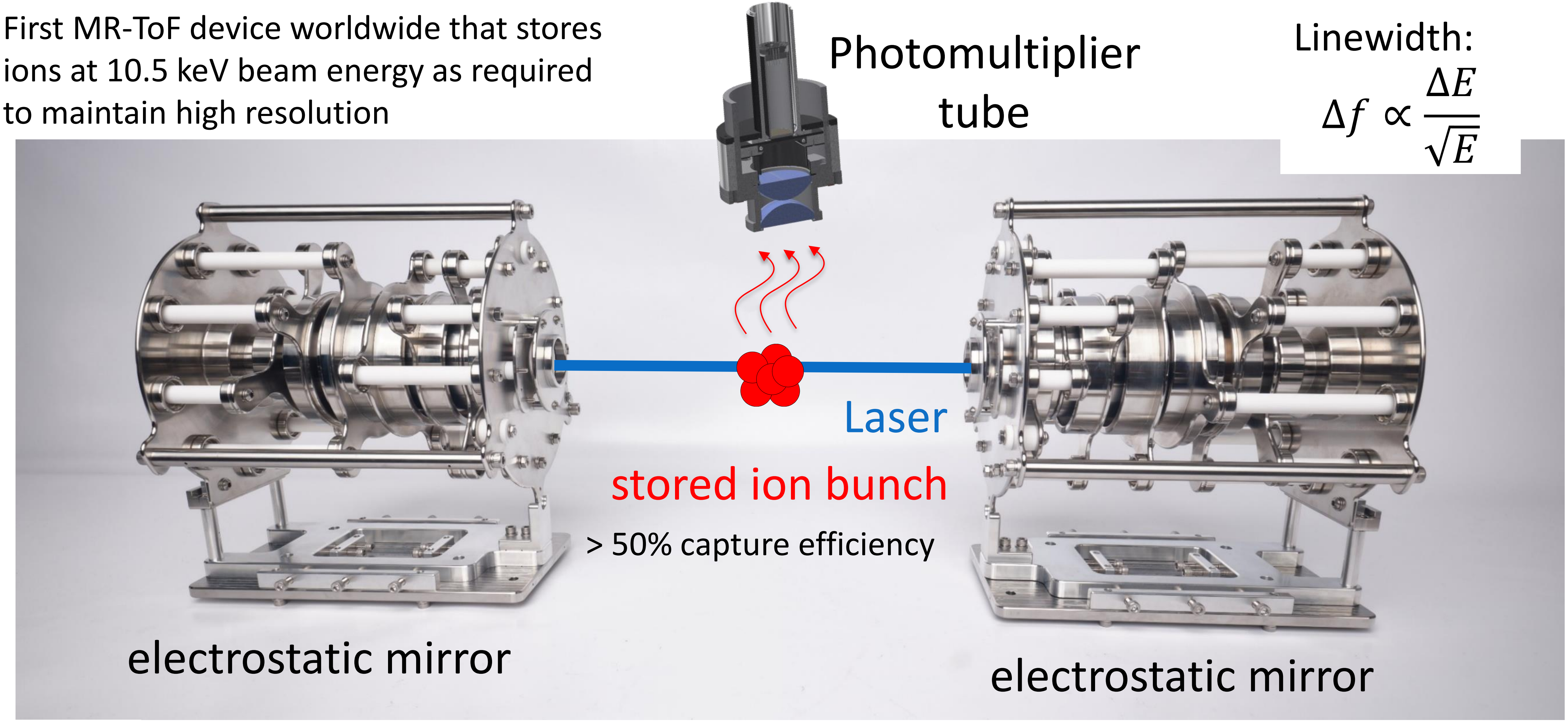
F.M. Maier, M. Vilen et al., NIMA 1048, 167927 (2023).
F.M. Maier et al., NIMA 1057, 170365 (2025).

The MIRACLS technique enables an increased sensitivity

First MR-ToF device worldwide that stores ions at 10.5 keV beam energy as required to maintain high resolution

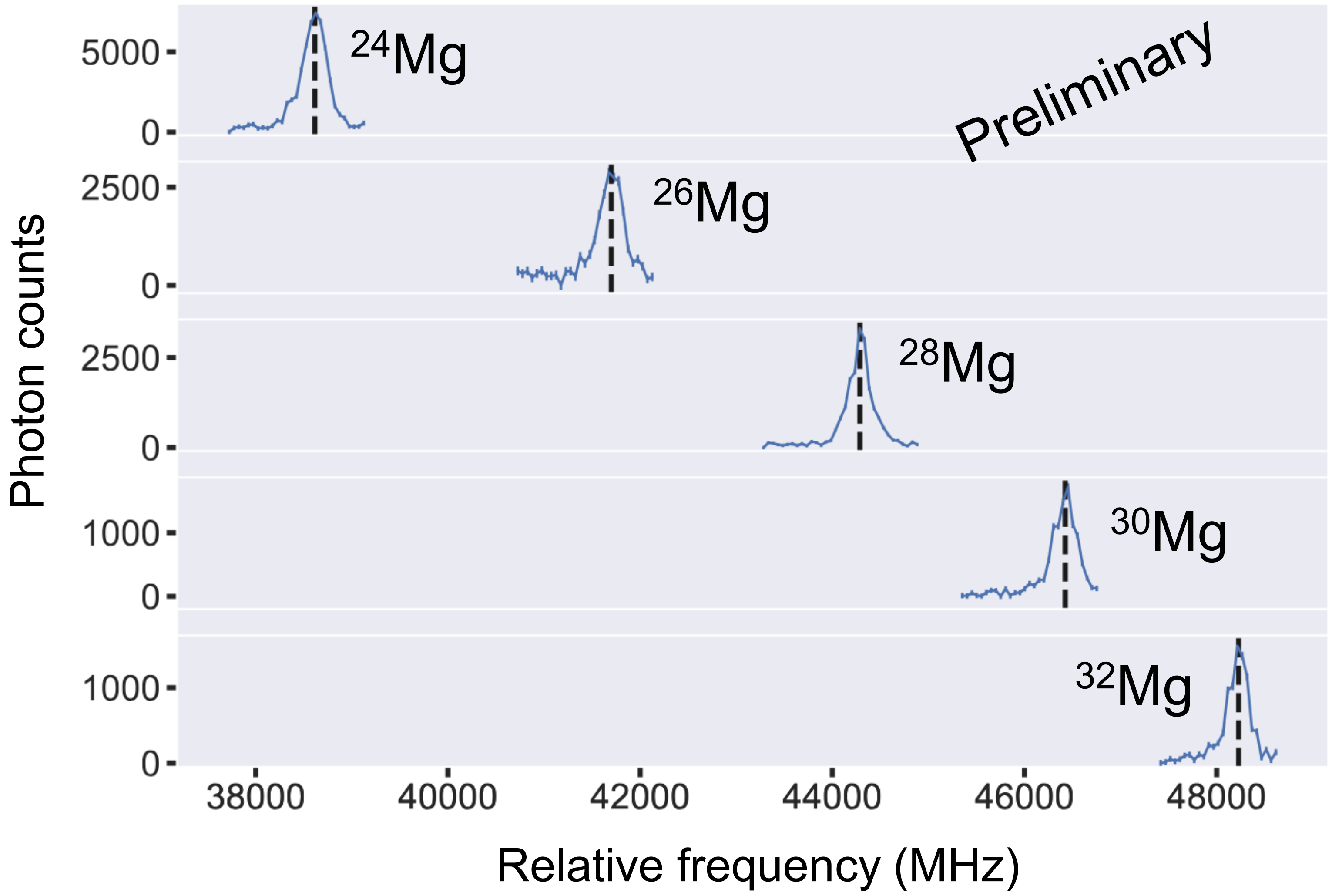
Linewidth:

$$\Delta f \propto \frac{\Delta E}{\sqrt{E}}$$

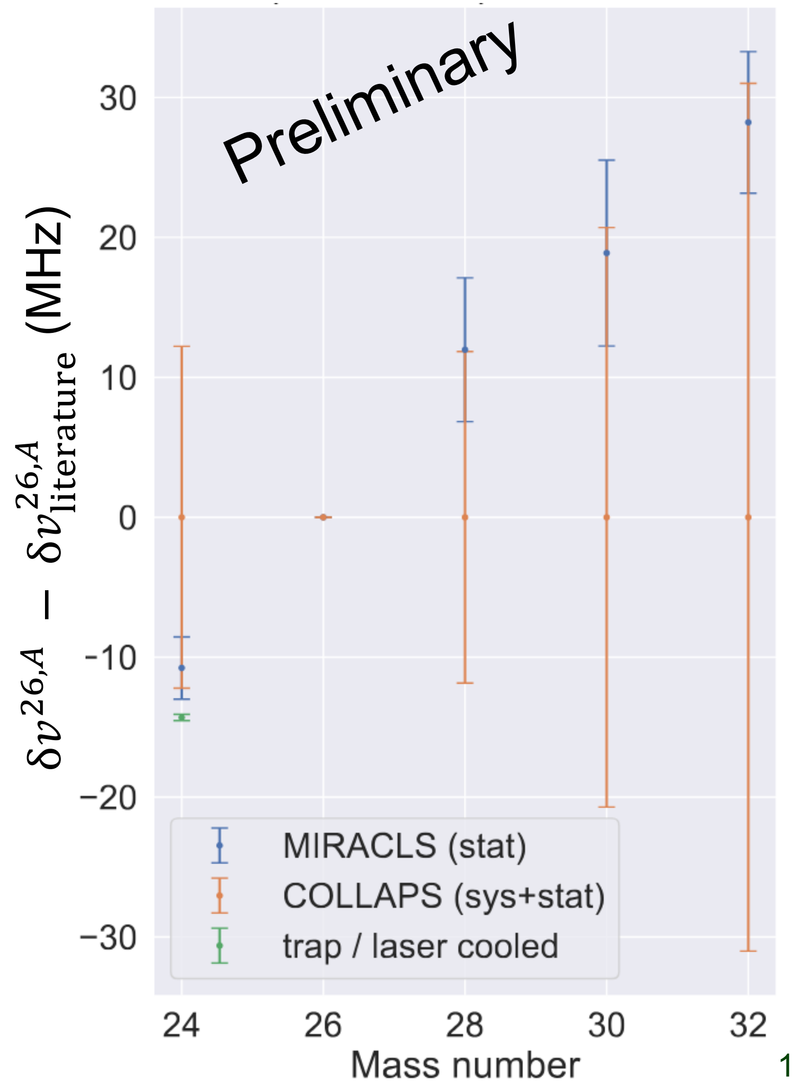


F.M. Maier, M. Vilen et al., NIMA 1048, 167927 (2023). F.M. Maier et al., NIMA 1057, 170365 (2025).

MIRACLS CLS measurement of $^{24,26,28,30,32}Mg$ is in good agreement with existing data



Comparison to literature [1,2]

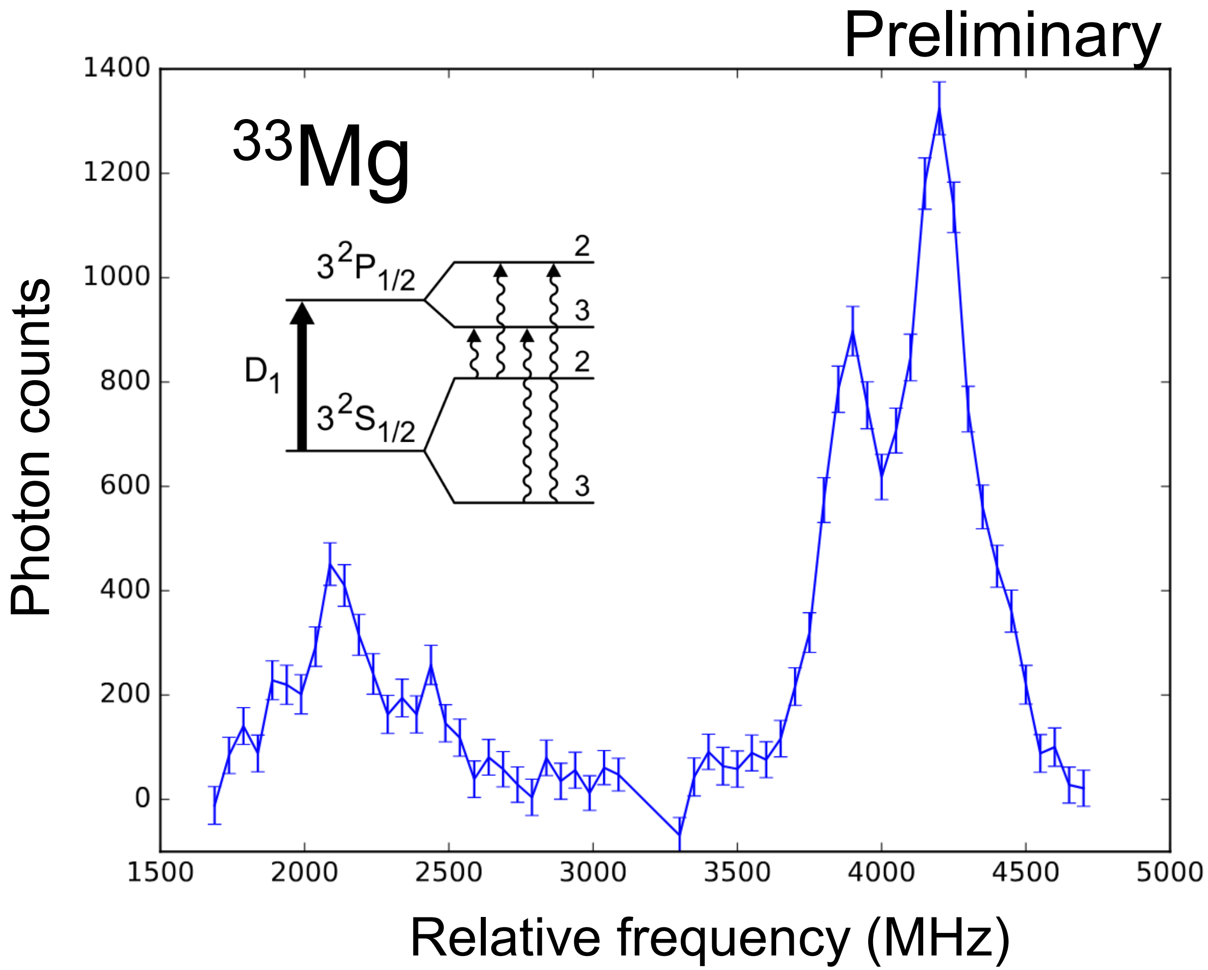


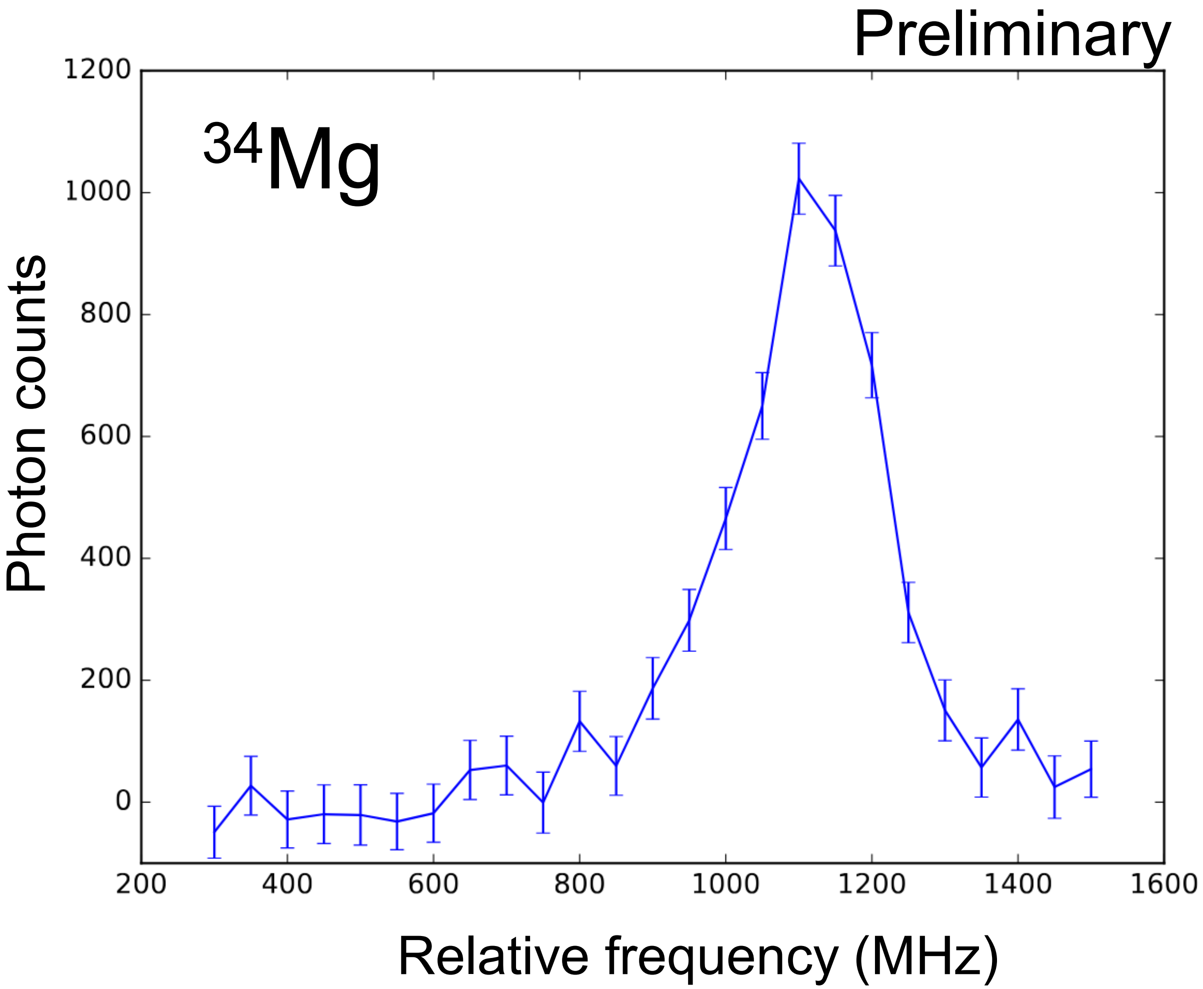
MIRACLS

[1] D. T. Yordanov *et al.*, PRL 108, 042504 (2012)
[2] V. Batteiger *et al.*, PRA 80, 022503 (2009).

MIRACLS CLS measurement of $^{33,34}Mg$ will provide insights into island of inversion

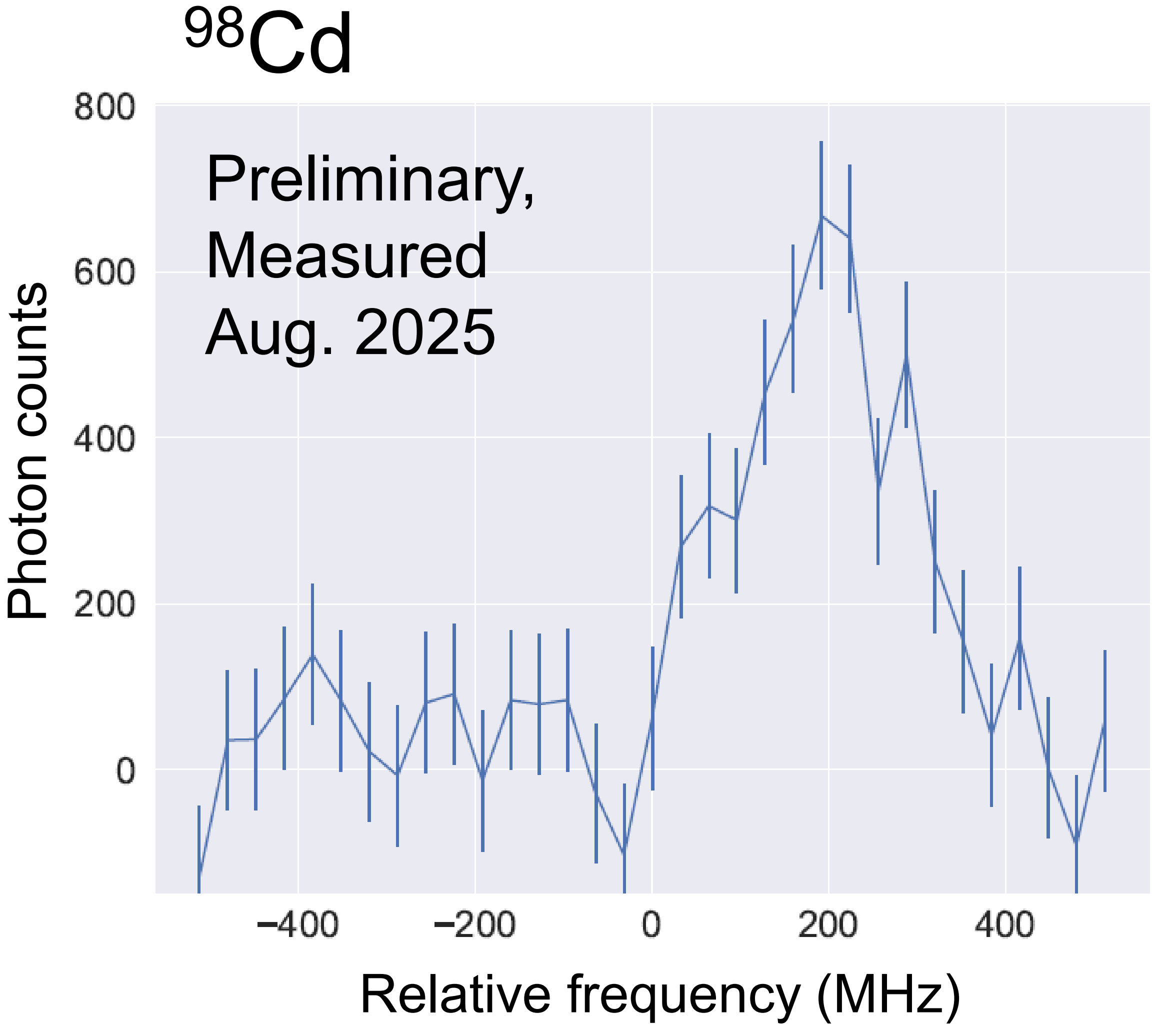
Data analysis and physics interpretation in progress

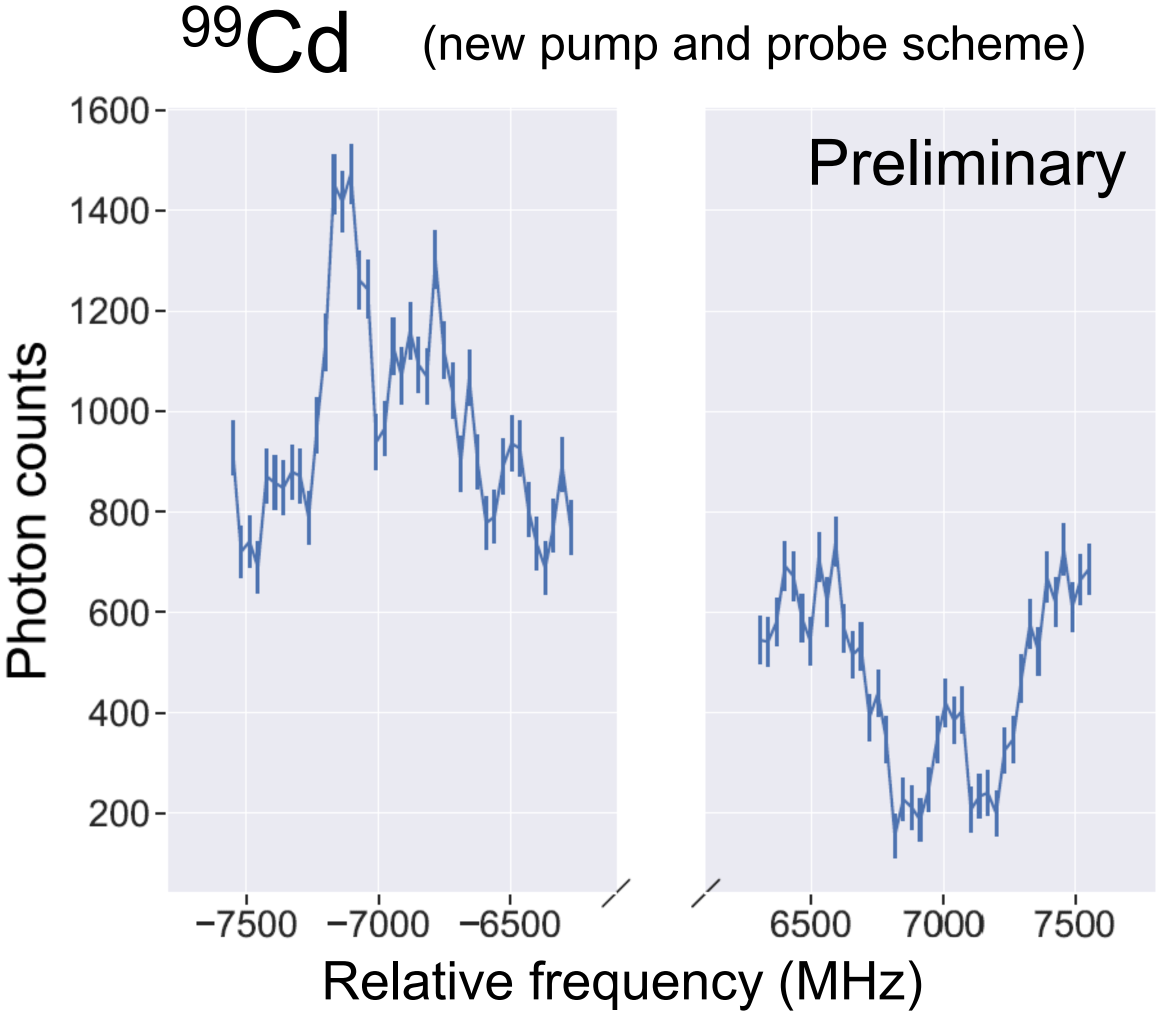




MIRACLS

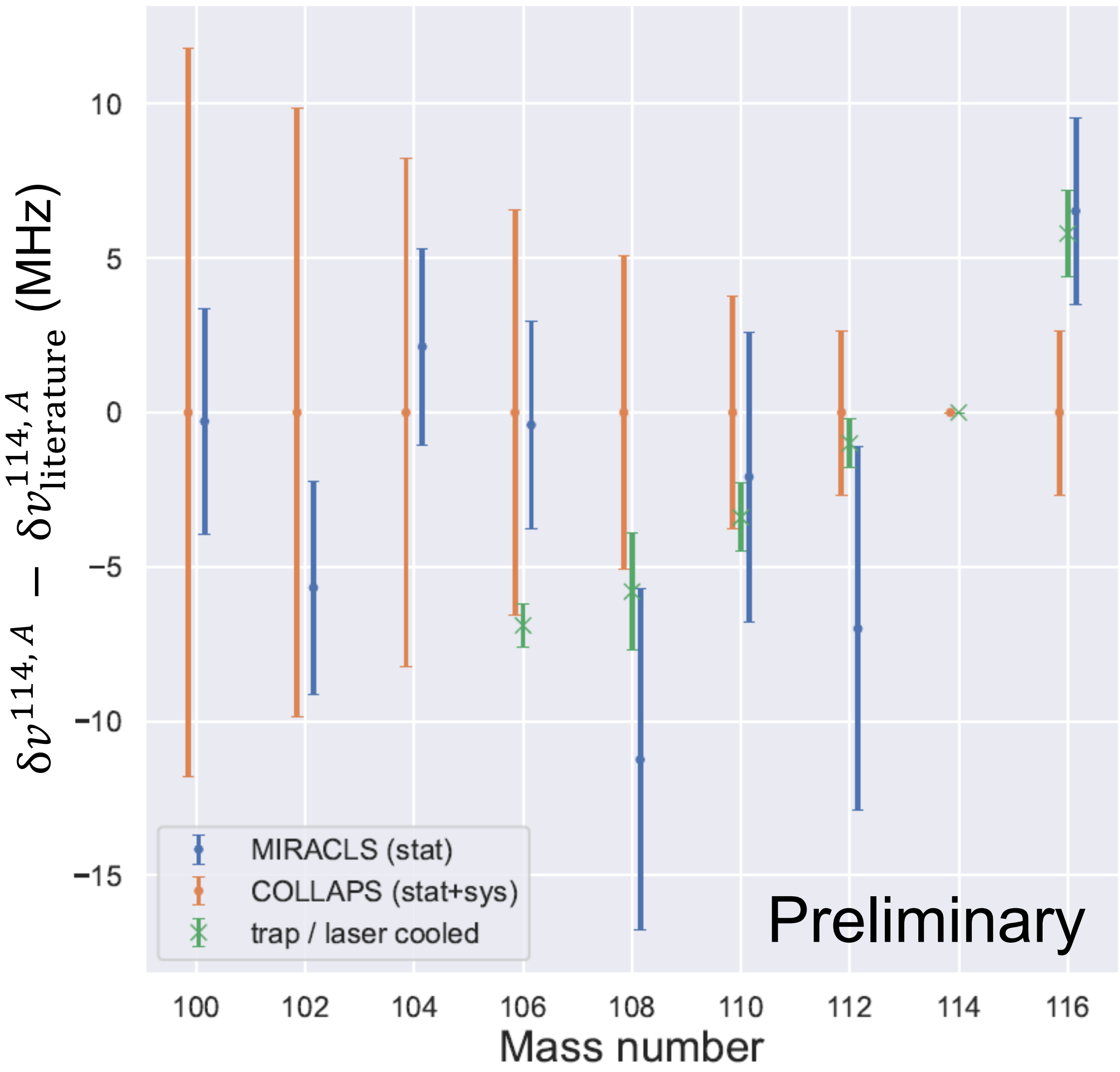
MIRACLS measurement of ^{98,99}Cd will provide insights into N=50 shell closure





MIRACLS CLS measurement of even $^{100-116}$Cd is in good agreement with existing data

Comparison to literature [1,2]



[1] M. Hammen *et al.*, PRL, 121:102501 (2018).
[2] J.Z. Han *et al.*, PRR 4, 033049 (2022).

MIRACLS

Outline

- MR-ToF devices enhance sensitivity for collinear laser spectroscopy (CLS)
  - Measurement of electron affinities
  - Measurement of nuclear ground state properties
- The development of a high-voltage MR-ToF device was required to match the resolution of conventional fluorescence-based CLS
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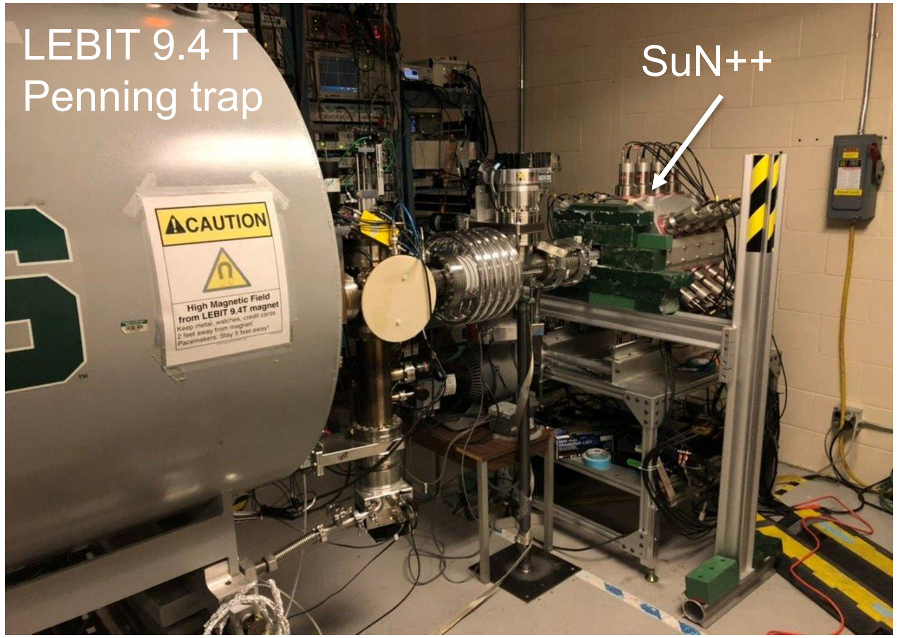
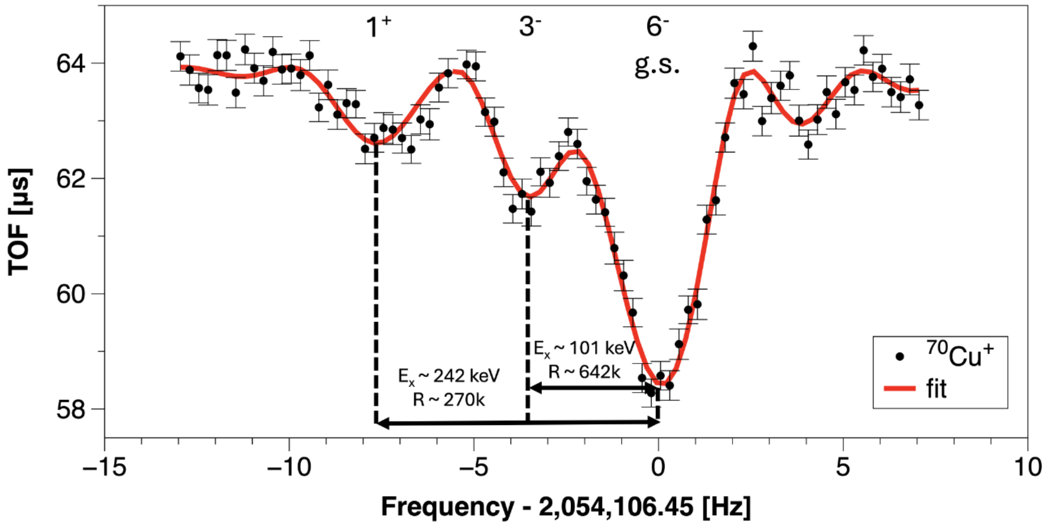
Many experiments at RIB facilities require isobarically and isomerically purified beams at high ion intensity

Example at FRIB:

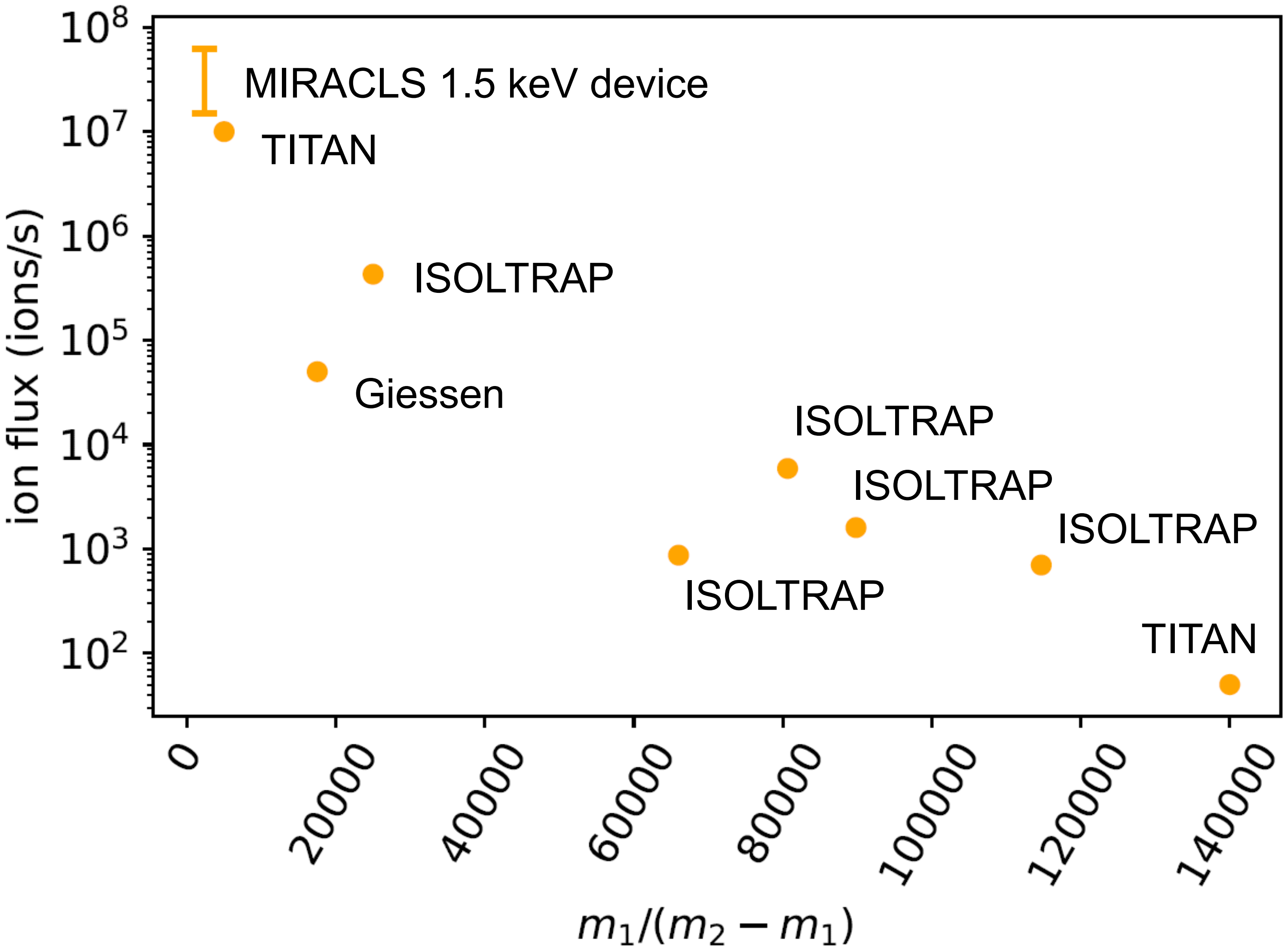
- SuN++ total absorption spectrometer required isomerically purified beams of ^{70}Cu for nuclear structure and nuclear astrophysics investigations
- LEBIT Penning trap can provided isomerically purified beams
- However, with the LEBIT Penning trap only 10 ions/s could be purified whereas 10,000 ions/s would have been available → A new technique is needed.





E.K. Ronning *et al.*, NIMA 1082, 170930 (2026).
E.K. Ronning *et al.*, submitted to PLB.

Current state-of-the-art MR-ToF mass separators: high mass resolving power but limited ion flux



ISOLTRAP:
Personal communication with F. Wienholtz, 2020.
N.M. Bouwman, Summer student report, 2023.

Giessen:
T. Dickel *et al,* NIMA 777 172-188 (2015).

TITAN:
Personal communication with A.A. Kwiatkowski, 2023.
M.P. Reiter *et al.,* NIMA 1018 165823 (2021).
C. Izzo *et al.,* PRC 103 025811 (2021).
S.F. Paul *et al.,* PRC 104 065803 (2021).

Greifswald, later MIRACLS 1.5 keV:
M. Rosenbusch *et al.,* AIP Conf. Proc. 1668 050001 (2015).
M. Rosenbusch *et al.,* AIP Conf. Proc. 1521 53-62 (2013).

Development of a high-voltage MR-ToF mass separator:
Combine high mass separation power & high ion intensity

Path forward to increase ion flux:

- Raise the kinetic energy of the stored ions – goal is 30 keV [1, 2]
- Optimize the geometry [2]
- Optimize the ion-optical tune of MR-ToF device and injection optics [2]

[1] F.M. Maier *et al.*, NIMA 1056, 168545 (2023).

[2] F.M. Maier, C.M. Ireland *et al.*, https://arxiv.org/abs/2509.16428.

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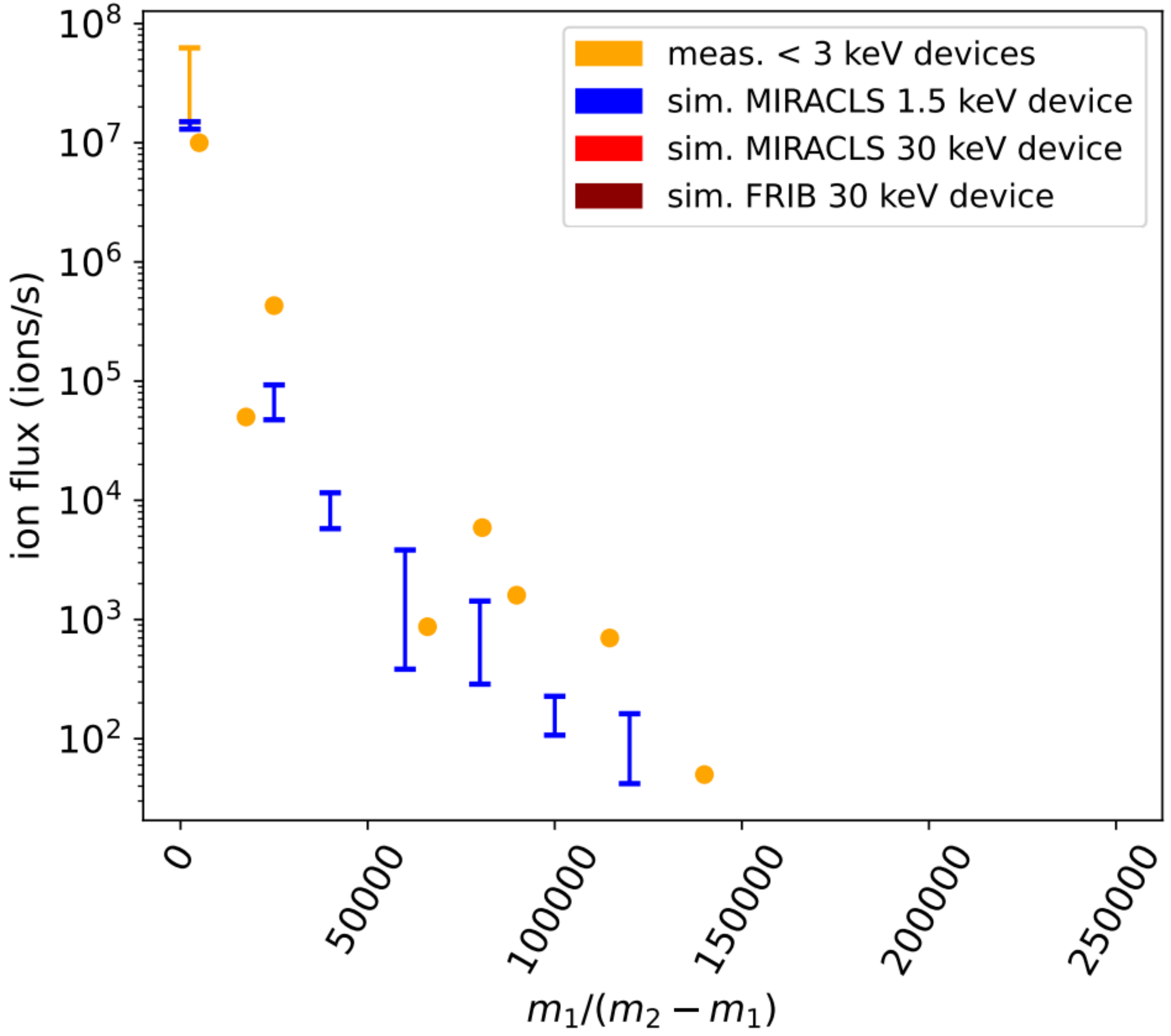

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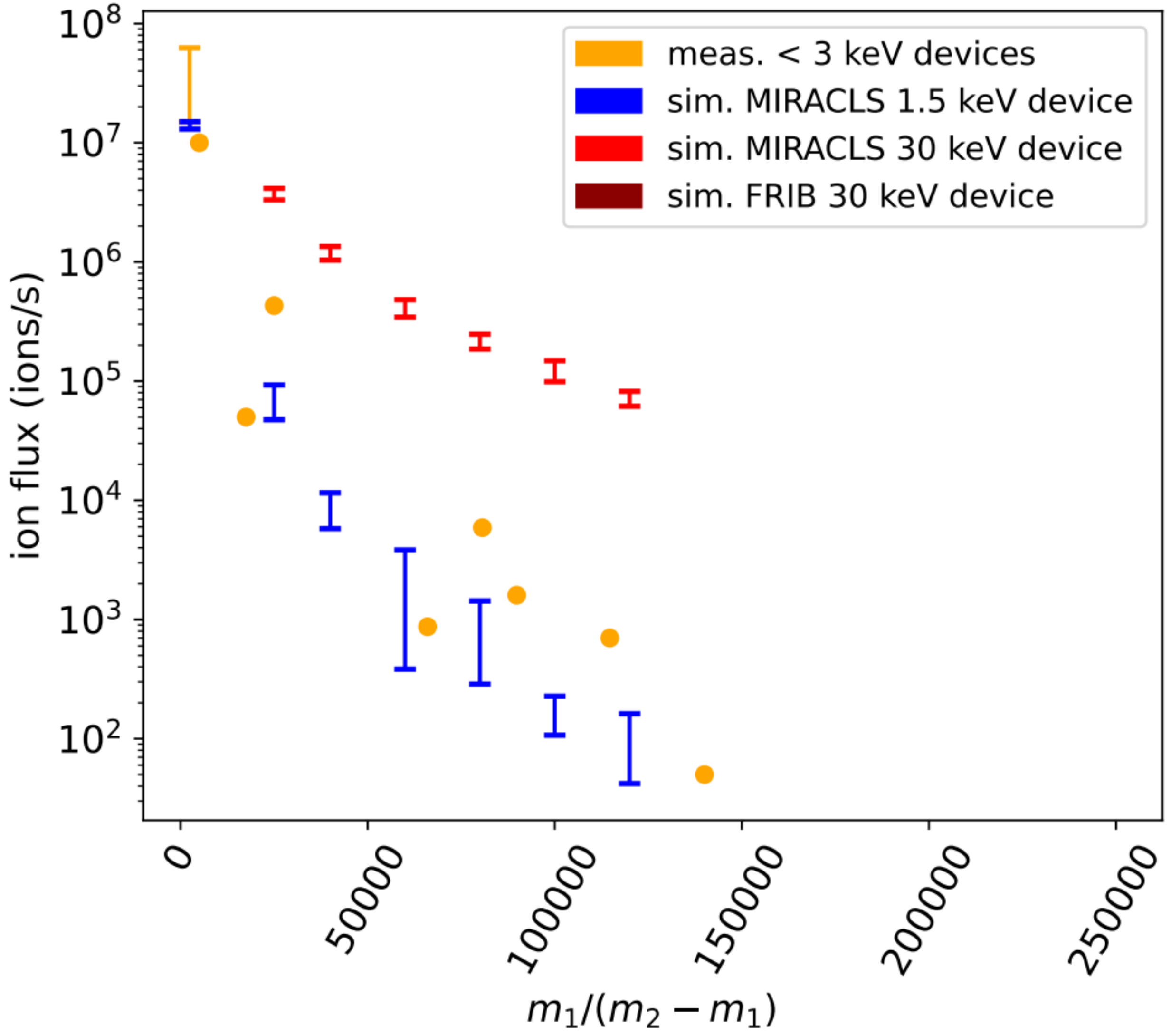

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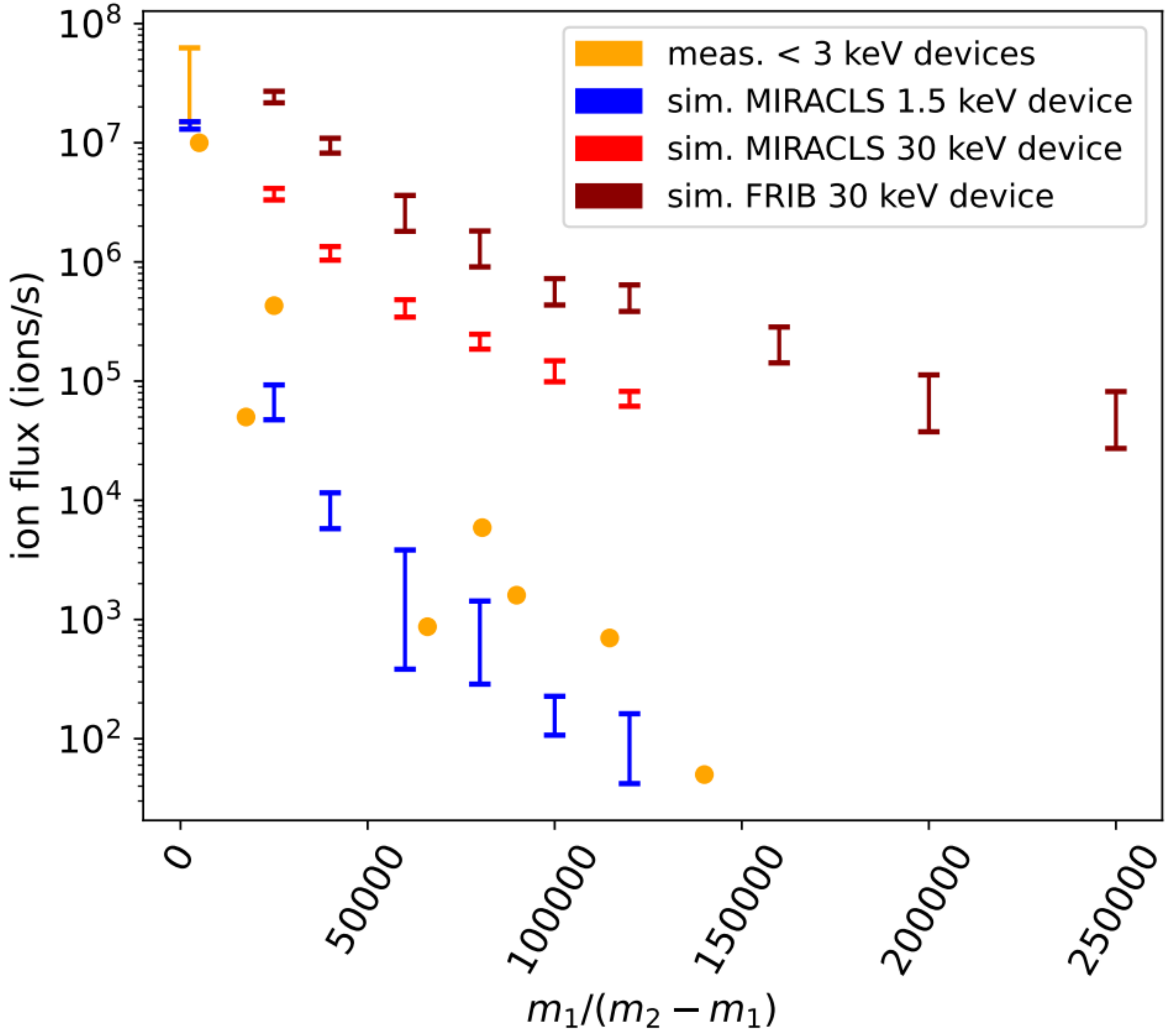

Simulated ion flux is > 2 orders of magnitude higher compared to state-of-the-art MR-ToF devices

F.M. Maier, C.M. Ireland *et al.*, https://arxiv.org/abs/2509.16428

Development of a high-voltage MR-ToF mass separator:
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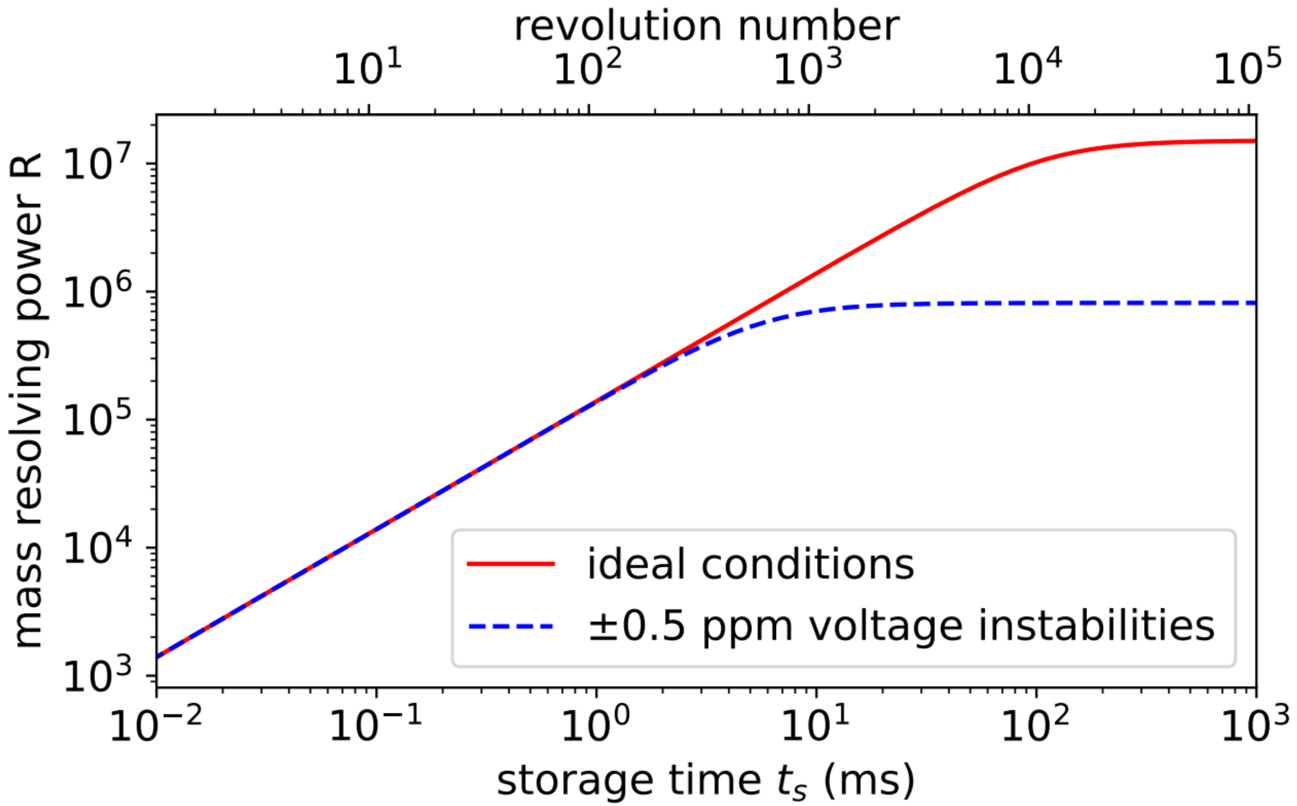
Simulated mass resolving power is high enough to resolve almost all isobars and 70% of all known isomers with half-lives above 10 ms



F.M. Maier, C.M. Ireland *et al.*, https://arxiv.org/abs/2509.16428
C.M. Ireland, F.M. Maier *et al.*, http://arxiv.org/abs/2510.11741

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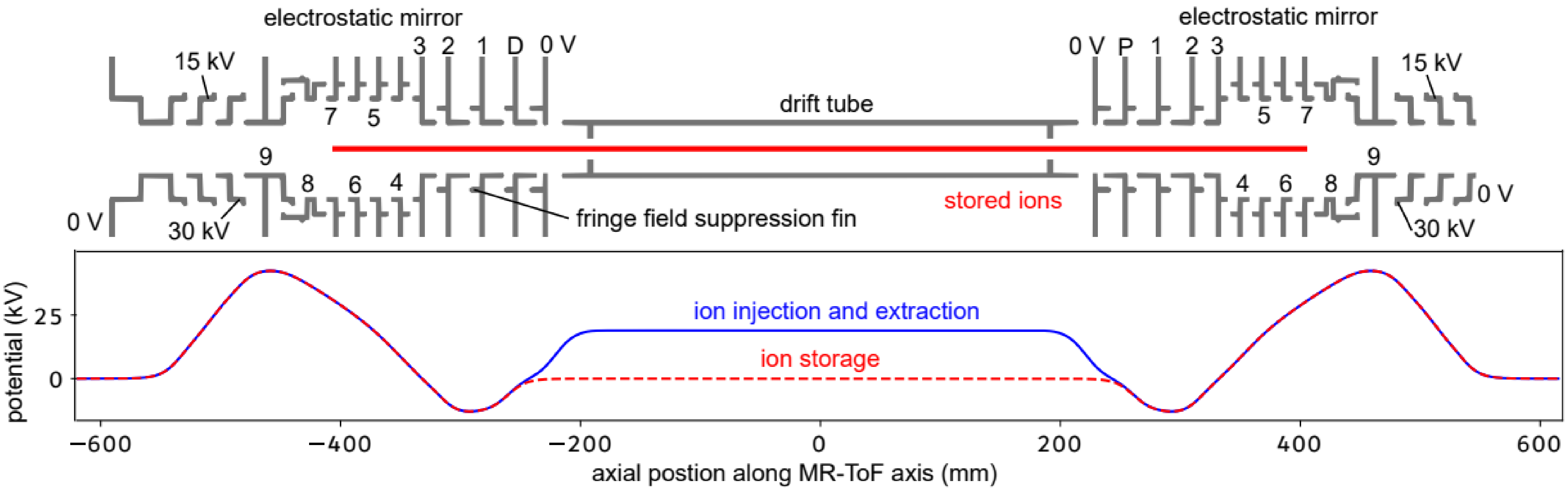

- Advances the design of MIRACLS high-voltage MR-ToF device at ISOLDE/CERN [1-3]
- High ion flux, high mass resolving power, short processing time

F.M. Maier, C.M. Ireland *et al.*, https://arxiv.org/abs/2509.16428
C.M. Ireland, F.M. Maier *et al.*, http://arxiv.org/abs/2510.11741

[1] F.M. Maier, M. Vilen *et al*, NIMA 1048, 168545 (2023).
[2] F.M. Maier *et al*, NIMA 1056, 168545 (2023).
[3] F.M. Maier *et al*, NIMA 1075, 170365 (2025).

FRIB

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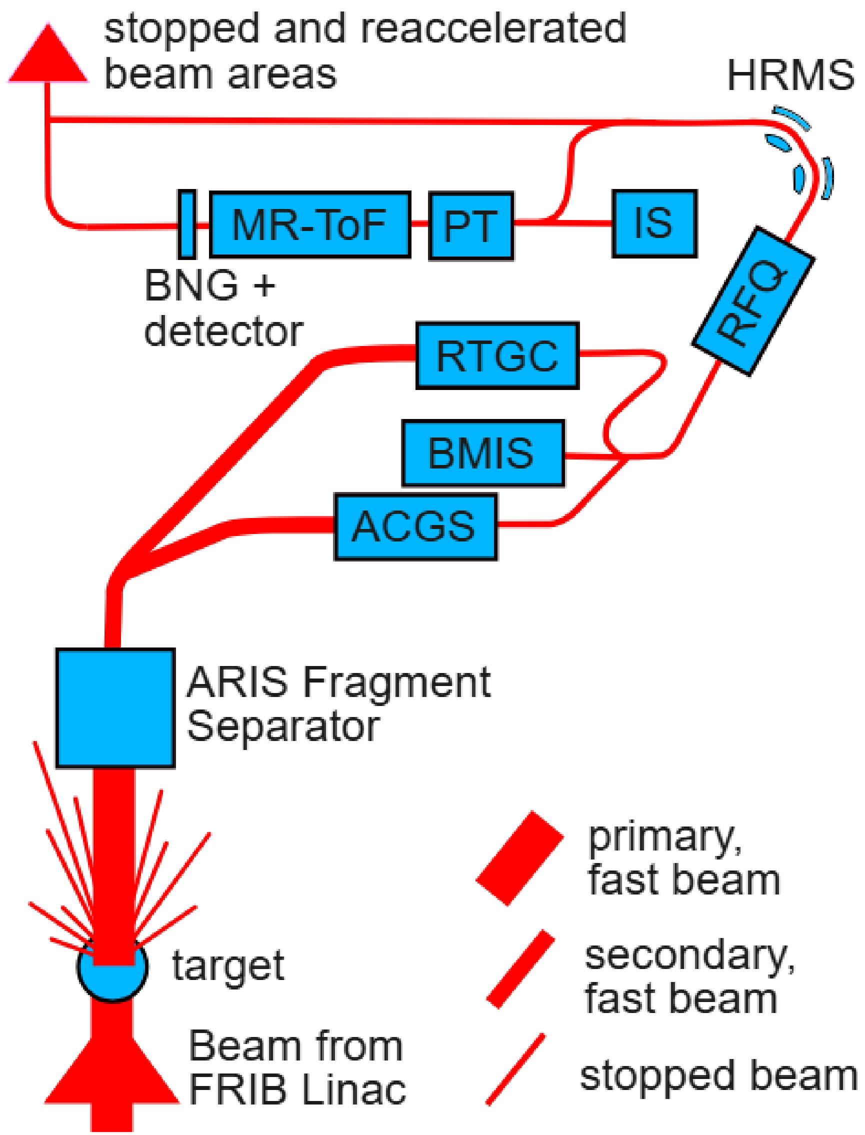
Combine high mass separation power & high ion intensity



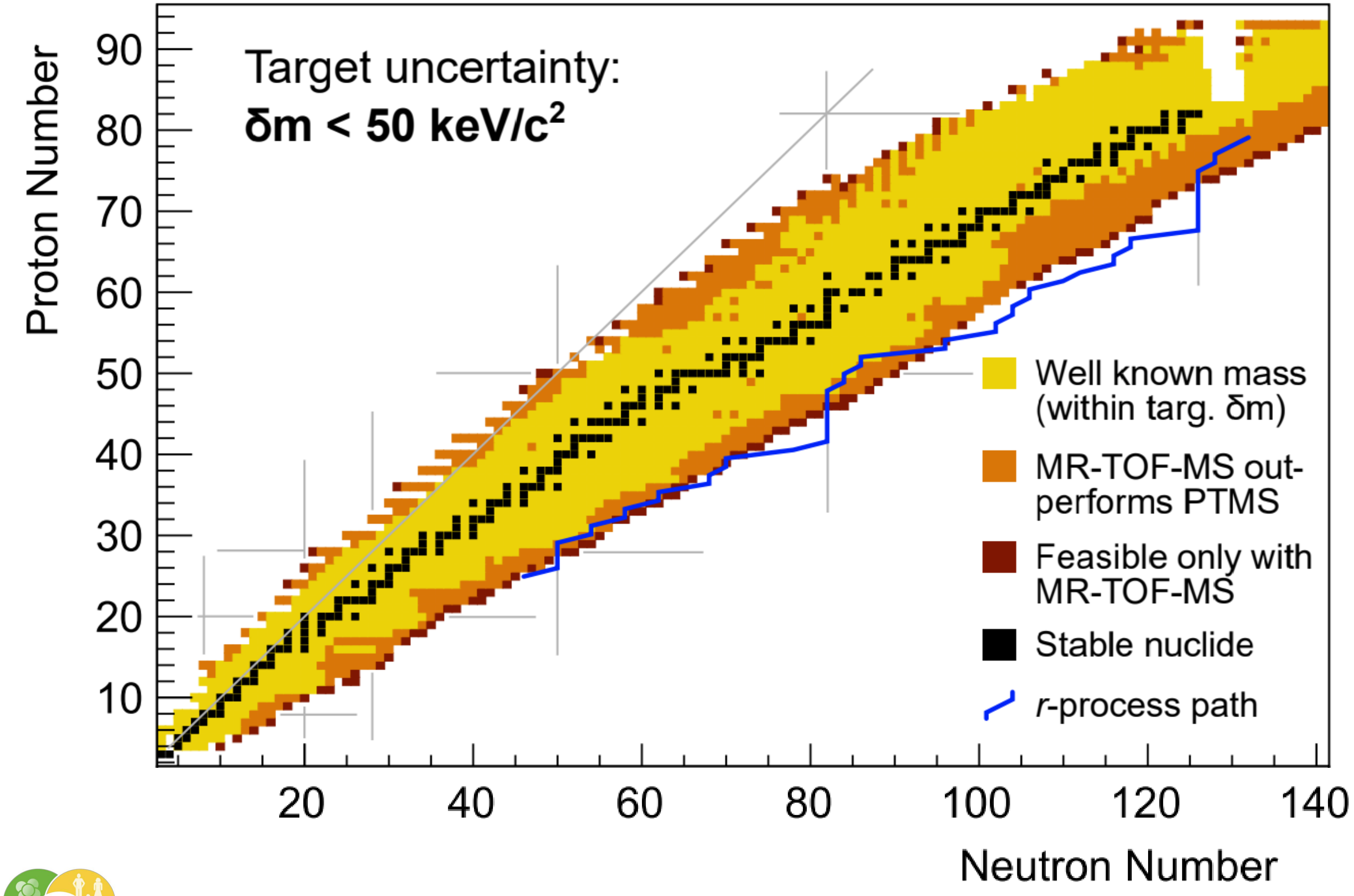
<u>Suggested expansion of FRIB's stopped beam area:</u>

- Replace current dipole magnet with a High Resolution Magnetic Mass Separator (HRMS)
  - Expected to achieve mass separation power of 10,000
- If HRMS mass separation power is sufficient transfer beam to stopped and reaccelerated beam areas
- If higher mass separation power is required inject beam into MR-ToF beamline
- MR-ToF beamline can also be used for mass measurements and beam diagnostics
- Dedicated Paul trap (PT) and offline ion source (IS) required

F.M. Maier, C.M. Ireland *et al.*, https://arxiv.org/abs/2509.16428
C.M. Ireland, F.M. Maier *et al.*, http://arxiv.org/abs/2510.11741

FRIB

A (High-Voltage) MR-ToF Device Can Also Extend Reach of Mass Measurement Program at FRIB



High-precision mass measurements of 890 nuclei can be performed which have not been known in AME2020 with less than 50 keV uncertainty in mass excess.

Out of these, 131 nuclei will only be accessible with an MR-ToF MS.

F.M. Maier, C.M. Ireland *et al.*, https://arxiv.org/abs/2509.16428
C.M. Ireland, F.M. Maier *et al.*, http://arxiv.org/abs/2510.11741

FRIB

Summary

- MR-ToF devices enhance sensitivity for collinear laser spectroscopy (CLS)
  - Measurement of electron affinities
  - Measurement of nuclear ground state properties
- The development of a high-voltage MR-ToF device was required to maintain the resolution of conventional fluorescence-based CLS
- A high-voltage MR-ToF device will also increase the mass separation capabilities
  - More than two orders of magnitude higher ion flux in simulations
  - Higher energy spread tolerance: higher mass resolving power in shorter processing time
  - Deliver isobaric and isomeric purified beams → unlock new experimental possibilities

+

Thanks to the FRIB MR-ToF Team!

Franziska Maria Maier
(maierf@frib.msu.edu)

FRIB MR-ToF collaboration:
G. Bollen, E. Dhayal, C. Ireland, E. Leistenschneider, F.M. Maier, M.P. Reiter, R. Ringle, S. Schwarz, A. Sjaarda

LEBIT core team:
G. Bollen, S. Campbell, H. Erington, C. Ireland, F. M. Maier, R. Ringle
+ all supporters

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Thanks to the MIRACLS team and collaborators!

MIRACLS PoP collaboration:
L. Bartels, I. Belosevic, P. Fischer, H. Heylen, F. Hummer, V. Lagaki, S. Lechner, F.M. Maier, W. Nörtershäuser, P. Plattner, L. V. Rodriguez, M. Rosenbusch, S. Sels, L. Schweikhard, M. Vilen, F. Wienholtz, R.N. Wolf, S. Malbrunot-Ettenauer

MIRACLS photodetachment collaboration:
M. Au, U. Berzinsh, Y.N. Vila Gracia, D. Hanstorp, C. Kanitz, V. Lagaki, S. Lechner, D. Leimbach, E. Leistenschneider, F.M. Maier, P. Plattner, M.Reponen, L.V. Rodriguez, S. Rothe, L. Schweikhard, M. Vilen, S. Malbrunot-Ettenauer

MIRACLS core high-voltage team:
F. Buchinger, L. Croquette, C. Kanitz, S. Lechner, E. Leistenschneider F.M. Maier, L. Nies, W. Nörtershäuser, P. Plattner, A. Roitman, M. Vilen, L. Schweikhard, S. Malbrunot-Ettenauer

MIRACLS Mg and Cd beam time participants and supporters (in addition to core high-voltage team):
O. Ahmad, T. Fabritz, P. Giesel, R. Hernandez, J. Hughes, C. Klink, F. Koehler, K. Koenig, D. Lange, L. Lalanne, T. Lellinger, E. Matthews, A. Mcglone, K. Mohr, J. Palmes, V. Repo, L. V. Rodriguez, C. Schweiger, J. Spahn, J. Warbinek, J. Wilson, Z. Yue, C. Farjado Zambrano

CERN | UNIVERSITÄT GREIFSWALD Wissen lockt. Seit 1456 | TECHNISCHE UNIVERSITÄT DARMSTADT | McGill | TRIUMF | UNIVERSITY OF TORONTO

erc European Research Council | ATTRACT | CERN Medical Applications Funds | NSERC CRSNG

Franziska Maria Maier
(maierf@frib.msu.edu)

Summary

- MR-ToF devices enhance sensitivity for collinear laser spectroscopy (CLS)
  - Measurement of electron affinities
  - Measurement of nuclear ground state properties
- The development of a high-voltage MR-ToF device was required to maintain the resolution of conventional fluorescence-based CLS
- A high-voltage MR-ToF device will also increase the mass separation capabilities
  - More than two orders of magnitude higher ion flux in simulations
  - Higher energy spread tolerance: higher mass resolving power in shorter processing time
  - Deliver isobaric and isomeric purified beams → unlock new experimental possibilities

Check out our latest manuscripts with content related to this presentation:

- F. M. Maier, E. Leistenschneider *et al.,* Accepted in Nat. Com.
- F. M. Maier, C. M. Ireland *et al.*, https://arxiv.org/abs/2509.16428
- C. M. Ireland, F. M. Maier *et al.,* http://arxiv.org/abs/2510.11741
- E. K. Ronning *et al*., NIMA 1082, 170930 (2026) https://doi.org/10.1016/j.nima.2025.170930
- F. M. Maier *et al*., NIMA 1075, 170365 (2025) https://doi.org/10.1016/j.nima.2025.170365

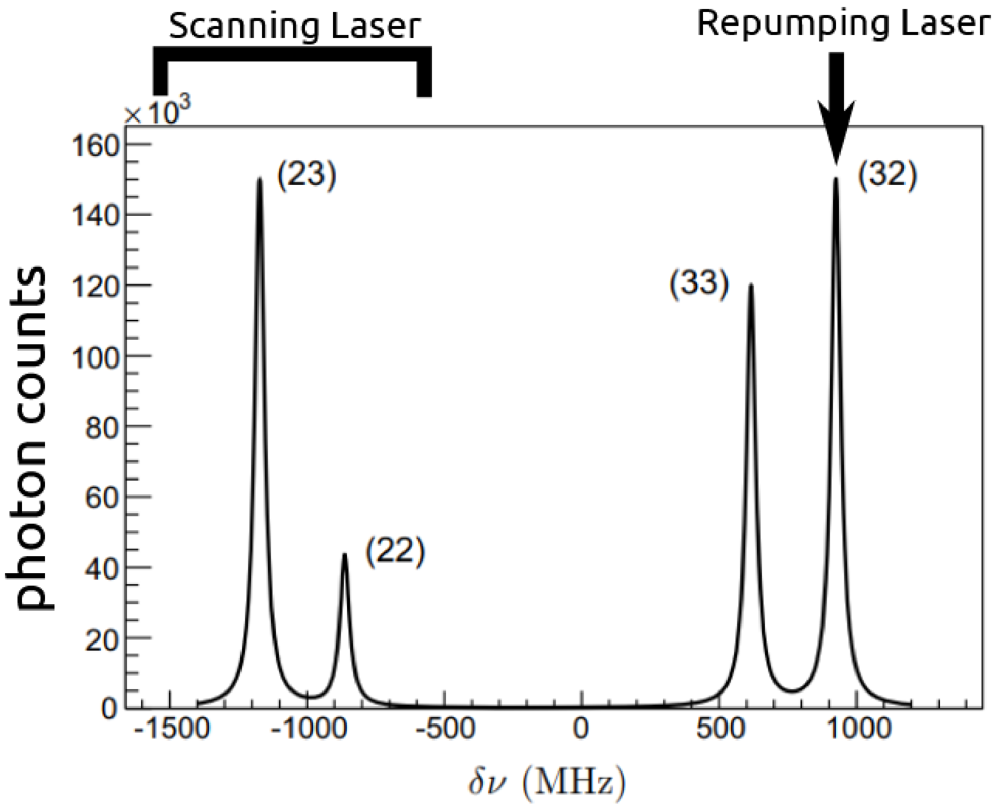
Also check out our latest LEBIT Penning trap mass measurement manuscripts:

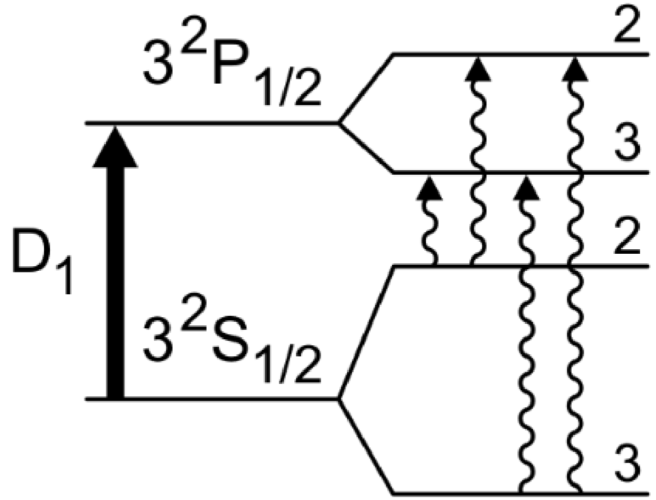
- **^{23}Si:** F.M. Maier *et al.*, PRC 112, 014329 (2025). https://doi.org/10.1103/14s5-17gj
- **$^{43\text{-}45}$Cl**: H. Erington *et al.,* PRC 112, 044313 (2025). https://arxiv.org/abs/2505.18354
- **^{103}Sn:** C.M. Ireland, F.M. Maier *et al.,* PRC 111, 014314 (2025). https://doi.org/10.1103/PhysRevC.111.014314
- **^{101}Sn:** C.M. Ireland *et al.,* https://www.arxiv.org/abs/2510.11815

MIRACLS Also Applicable Beyond Closed Two-Level Schemes

Odd-even scheme

- Repurposing Lasers: One for repumping, one for scanning





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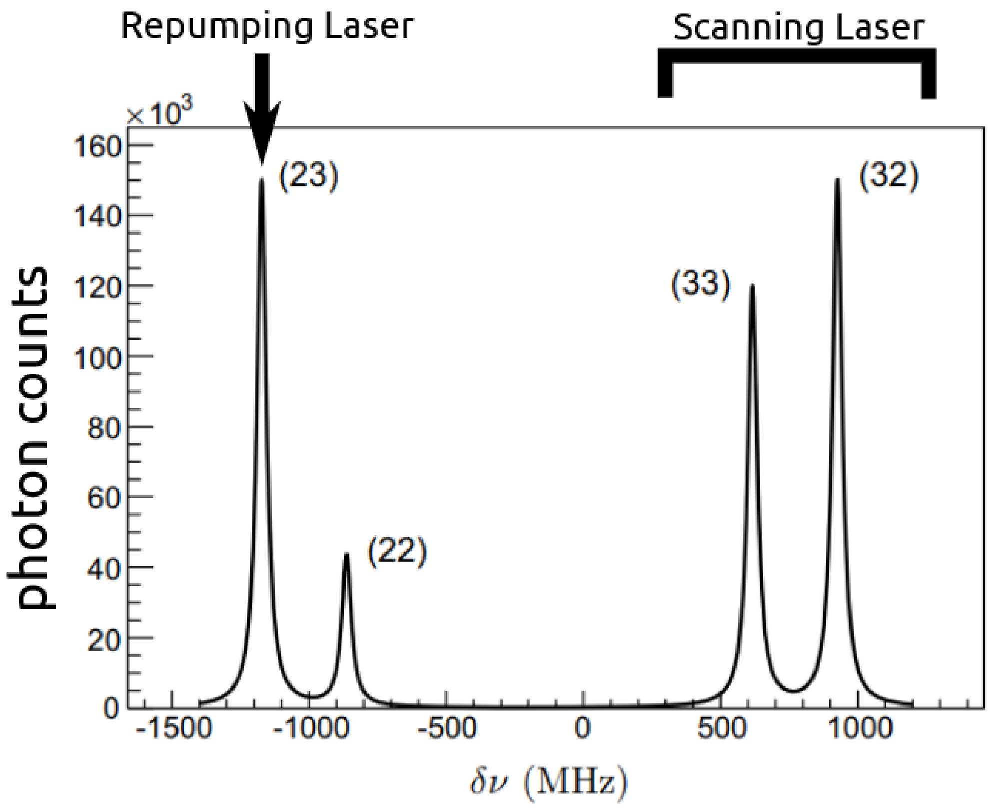
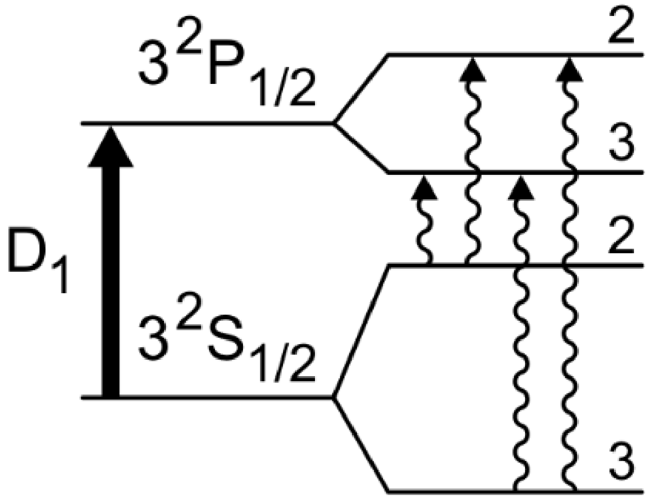
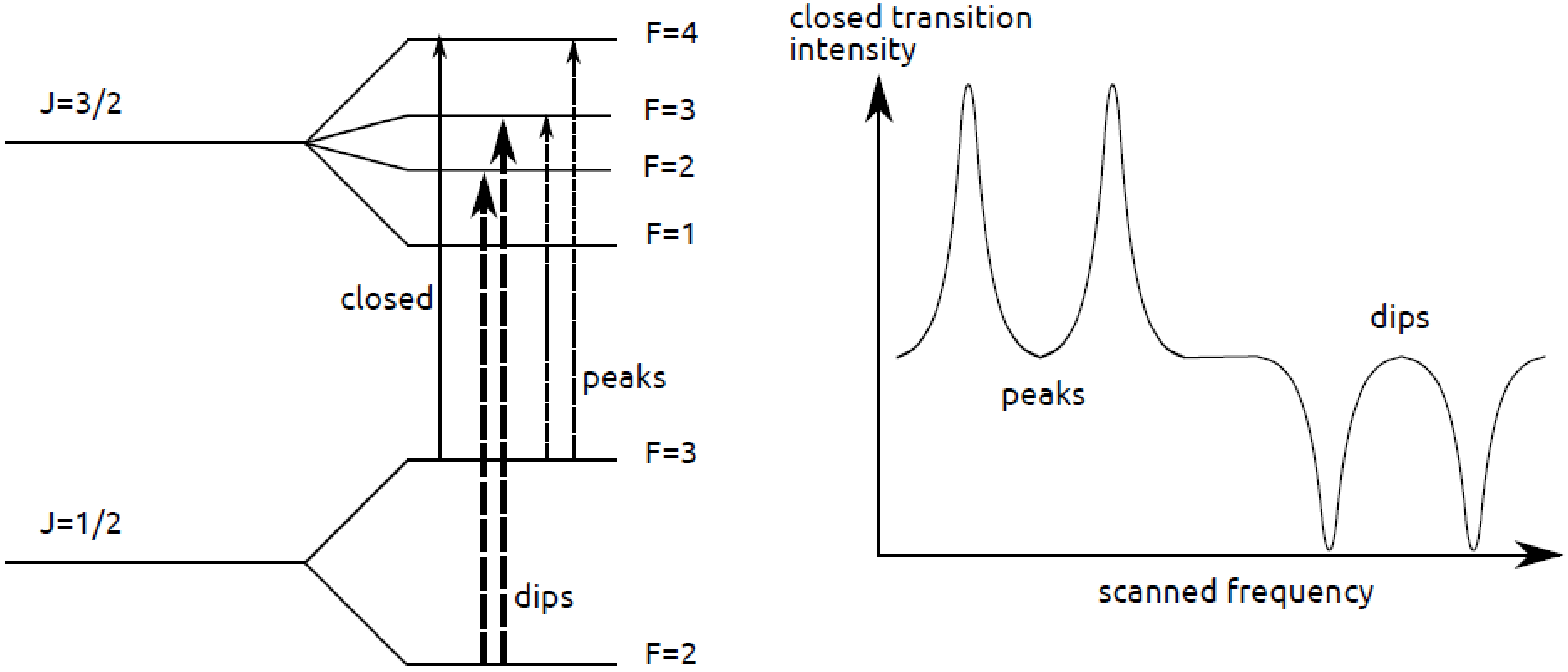


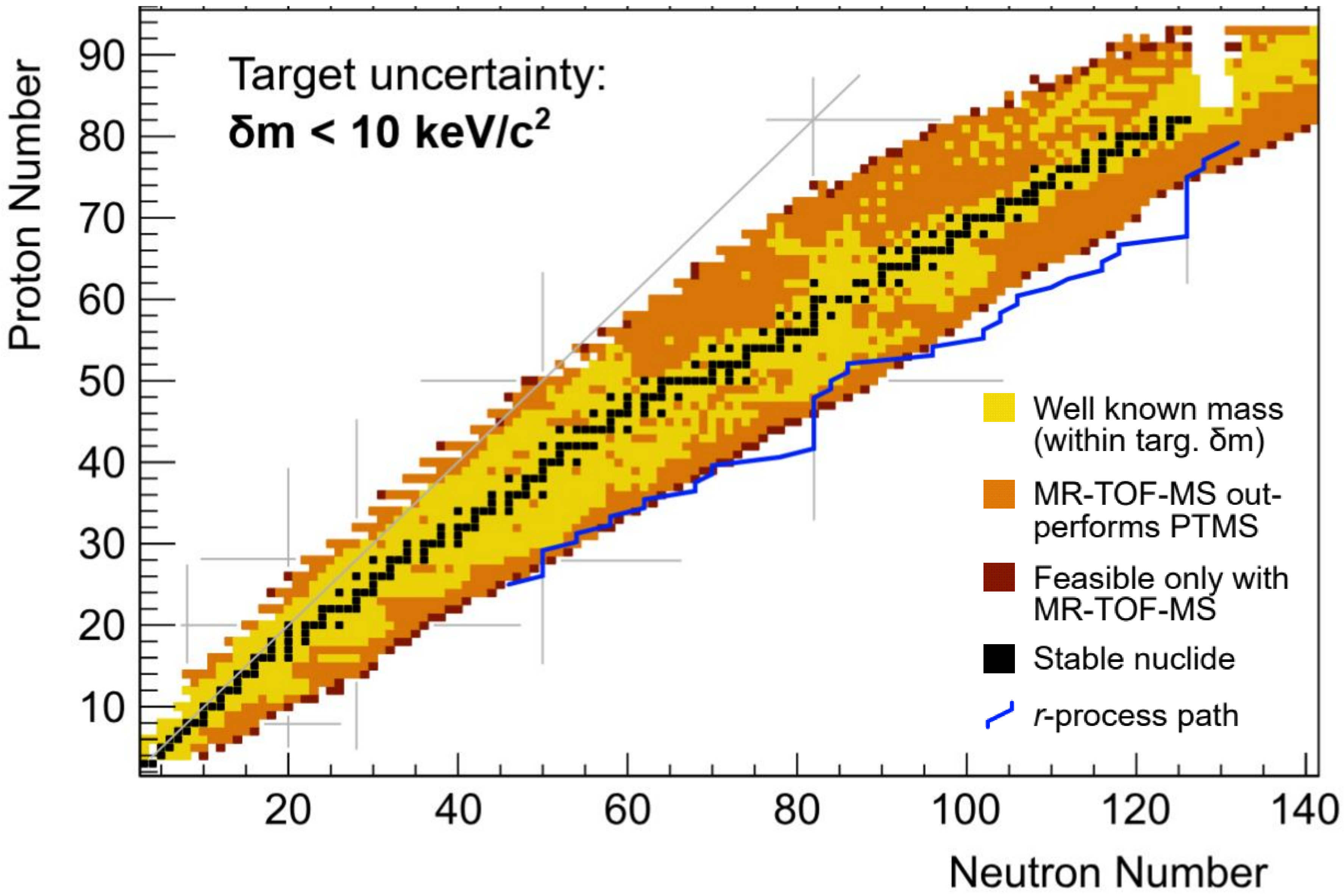


MIRACLS Also Applicable Beyond Closed Two-Level Schemes

Odd-even scheme for cadmium



A (High-Voltage) MR-ToF Device Can Also Extend Reach of Mass Measurement Program at FRIB



High-precision mass measurements of 1317 nuclei can be performed which have not been known in AME2020 with less than 10 keV uncertainty in mass excess.

Out of these, 119 nuclei will only be accessible with an MR-ToF MS.