MR-ToF Devices: New Applications and Developments

Invited Talk, NUSTAR meeting
26th Feb. 2026

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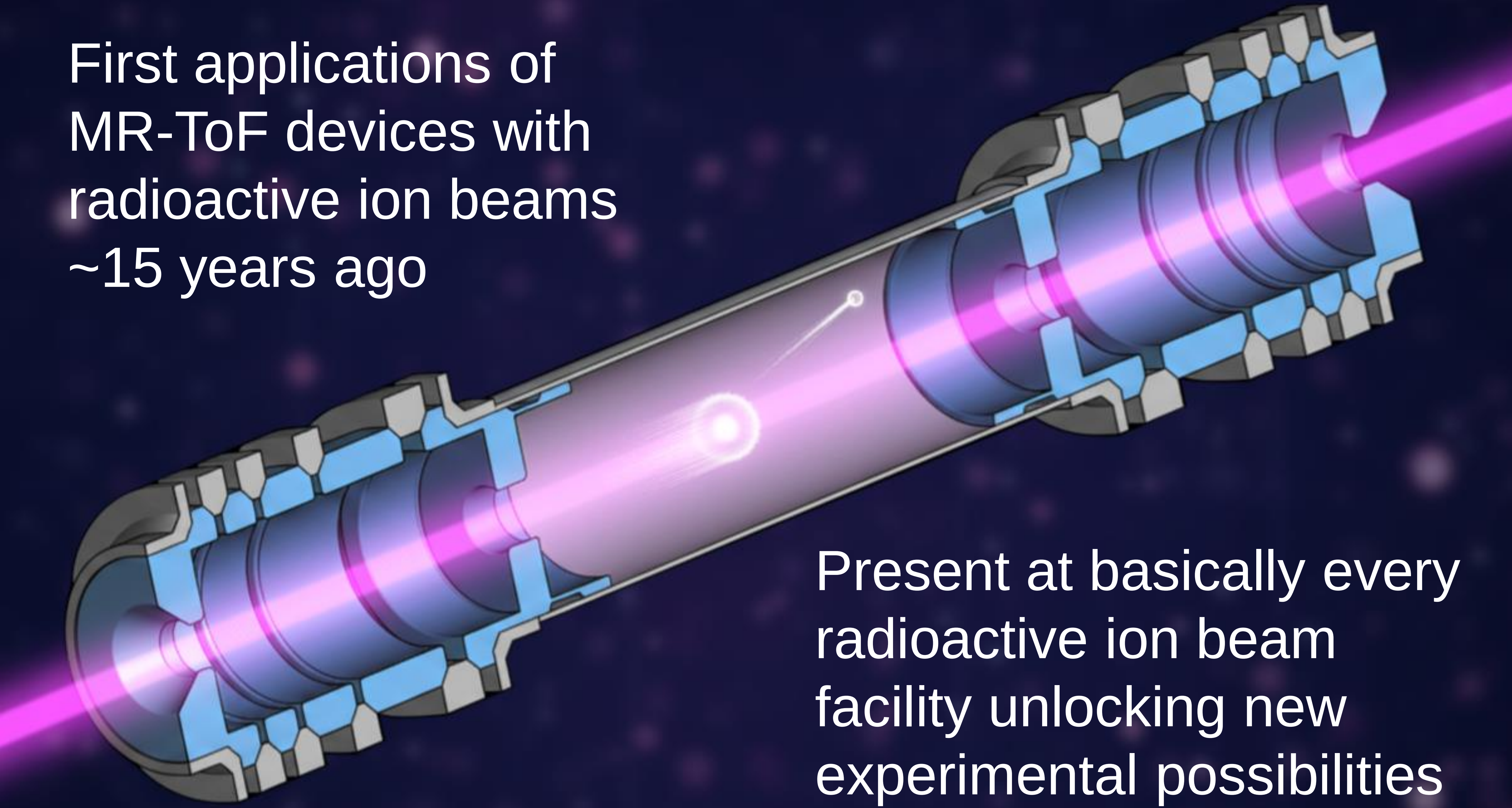
First applications of MR-ToF devices with radioactive ion beams ~15 years ago



Present at basically every radioactive ion beam facility unlocking new experimental possibilities

Outline

- MR-ToF devices enhance sensitivity for collinear laser spectroscopy (CLS)
  - Access electron affinities of rarely produced ions e.g. superheavies
  - Access nuclear ground state properties of scarcely produced radionuclides
- 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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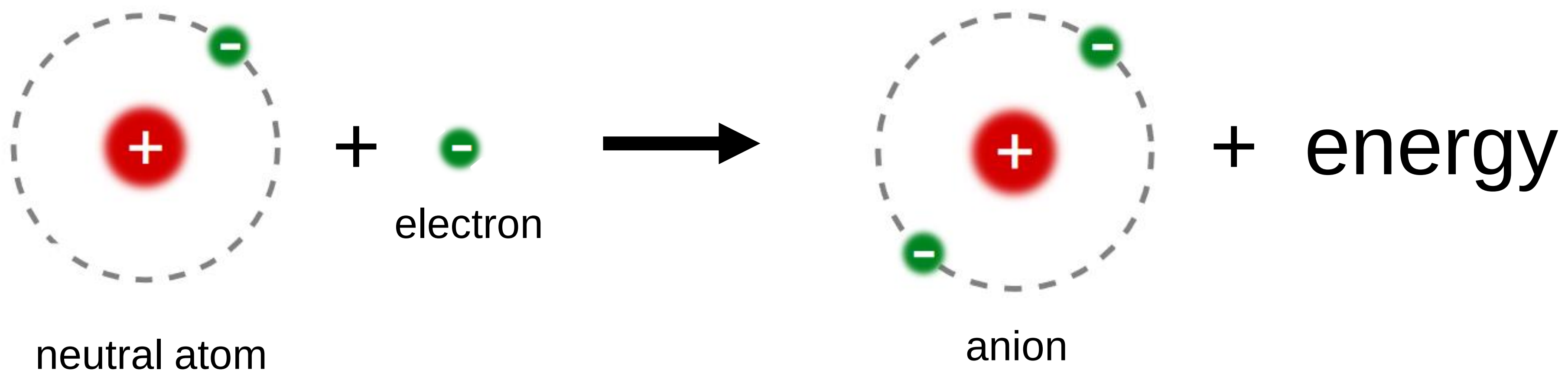
Development of MR-ToF devices for CLS:
Enhanced Sensitivity for Electron Affinity Measurements

Electron Affinity EA:

- Energy released when an electron is attached to a neutral atom forming an anion
- Encodes key information about atomic structure, electron correlation effects and chemical reactivity



Development of MR-ToF devices for CLS:
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Atomic Physics

Medical applications (tumor-targeting biomolecules)

Chemistry

Electron Affinities

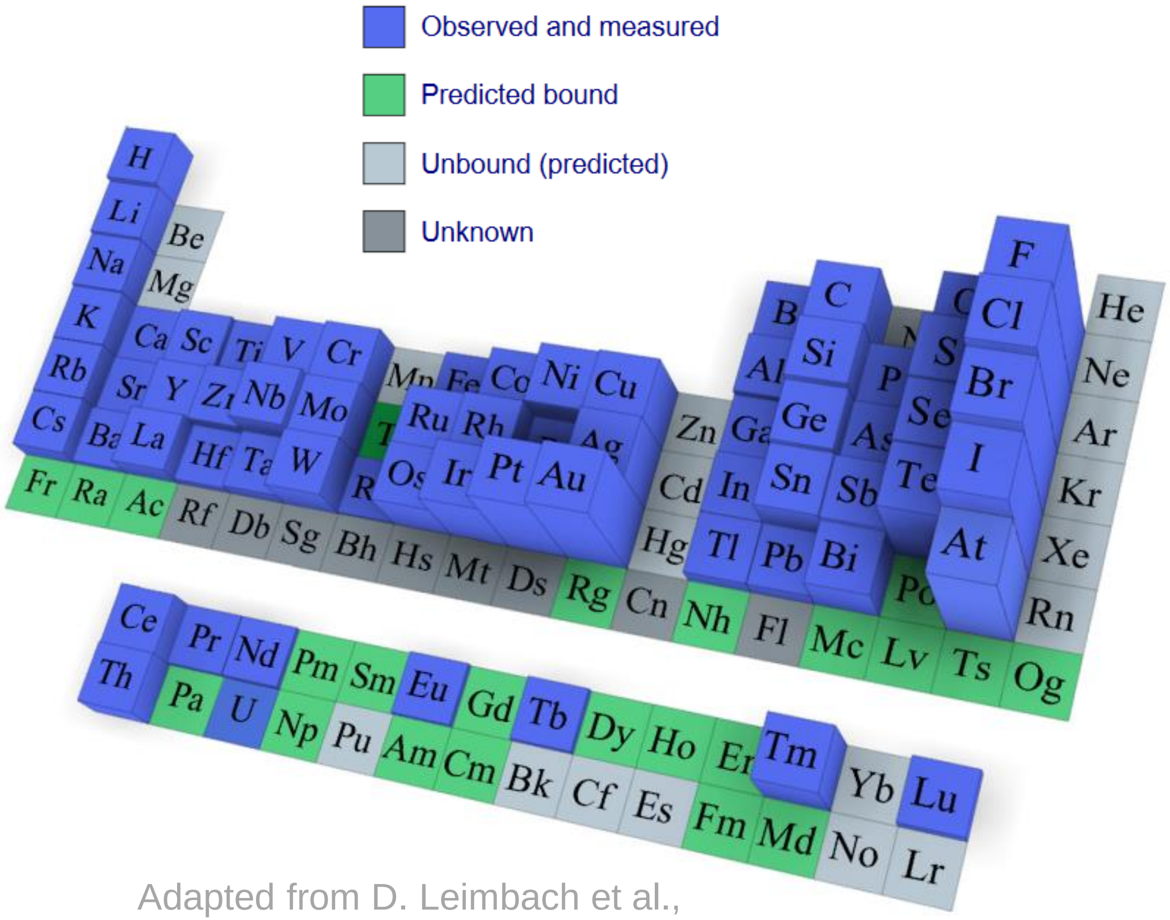
Astrophysics

Nuclear Structure Studies

Fundamental Symmetries

Development of MR-ToF devices for CLS:
Enhanced Sensitivity for Electron Affinity Measurements

Electron affinities are unknown for about 1/3 of the elements



Adapted from D. Leimbach et al.,
Nat Commun 11, 3824 (2020)

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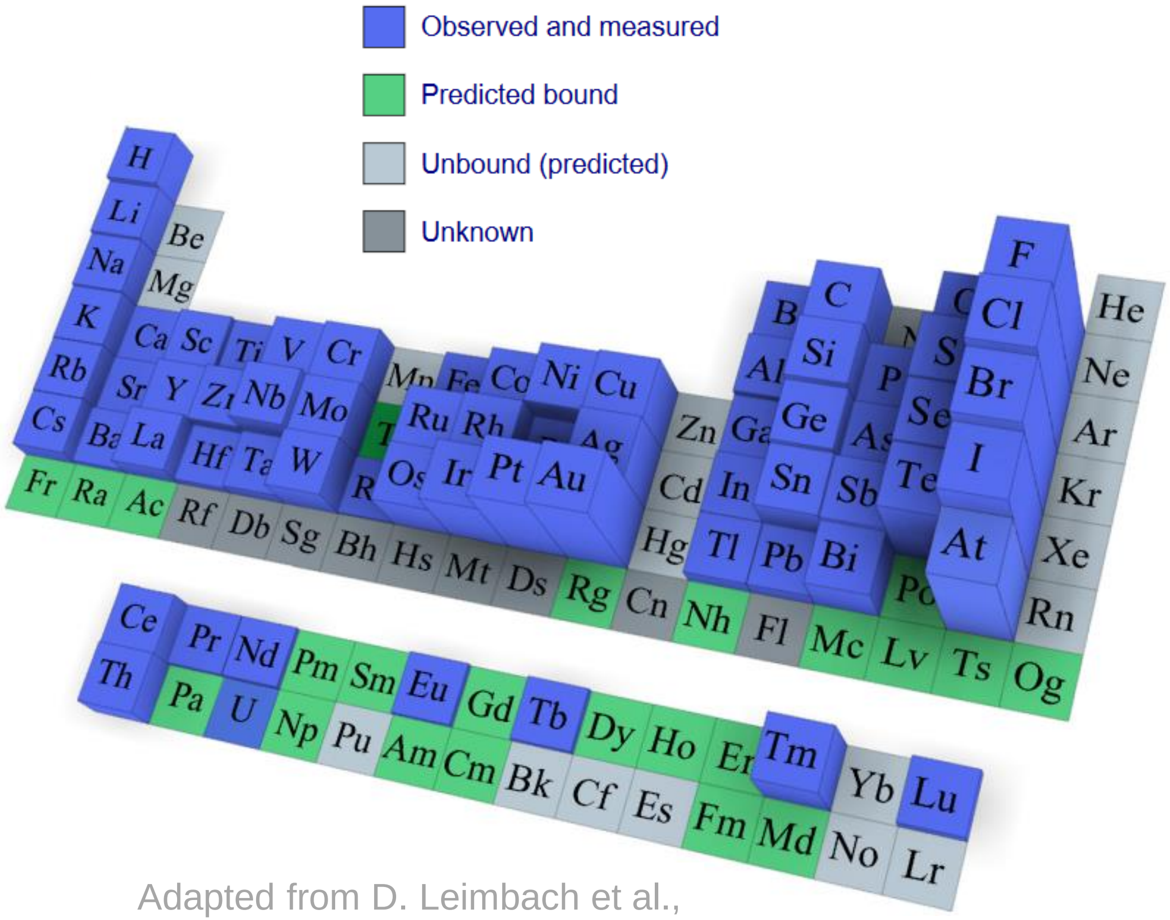

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(Super)heavy atoms only exist in trace amounts or must be produced artificially

ISOLDE succeeded in two electron affinity measurements of radioactive isotopes

→ ^{128}I: 35,000 ions/s [1]

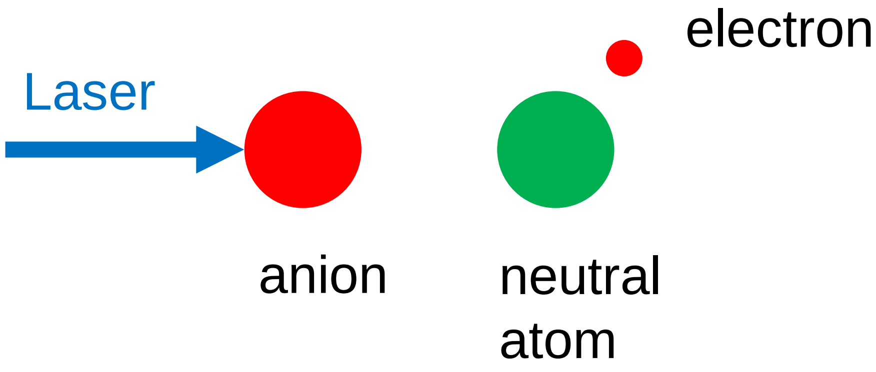
→ ^{211}At: 3,750,000 ions/s [2]

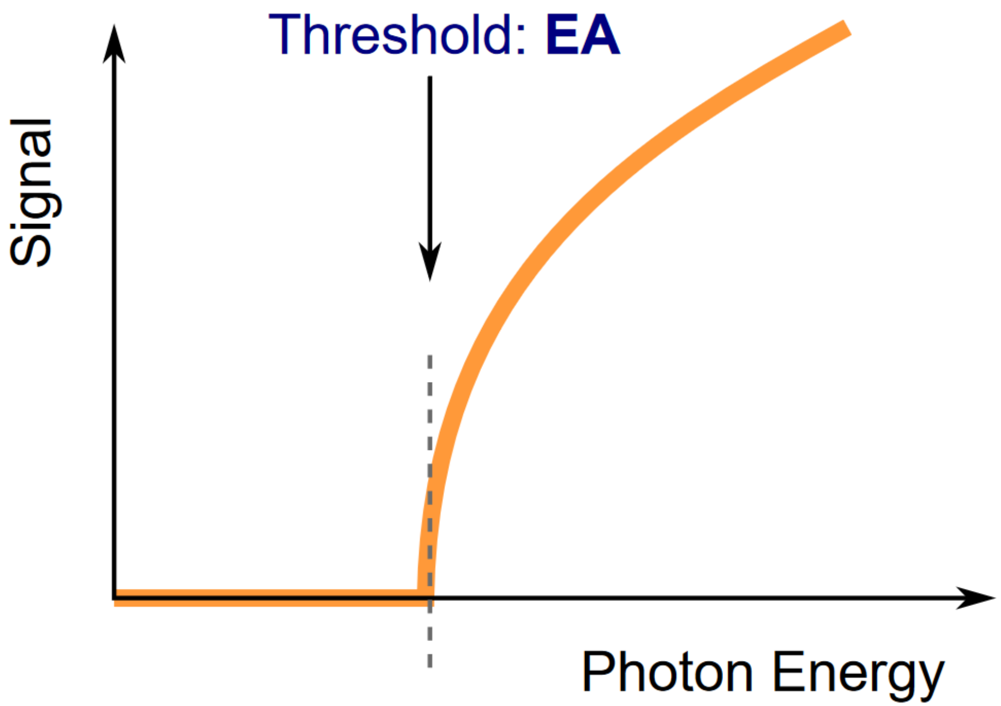
→ **Limited measurement opportunities**

[1] D. Leimbach et al. Nat Commun 11, 3824 (2020).
[2] S. Rothe et al., Journal of Physics G 44(10): 104003 (2017).

Enhanced Sensitivity for Electron Affinity Measurements

Electron Affinities obtained via Laser Photodetachment Threshold Spectroscopy:





- Cross section σ follows Wigner threshold law
- Threshold corresponds to EA

Enhanced Sensitivity for Electron Affinity Measurements

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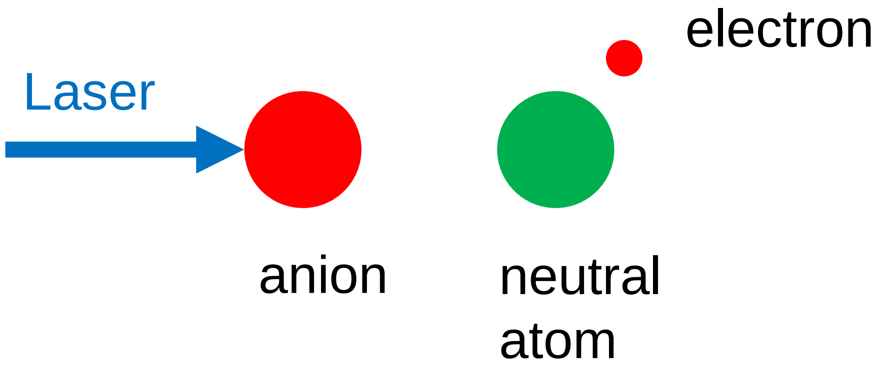

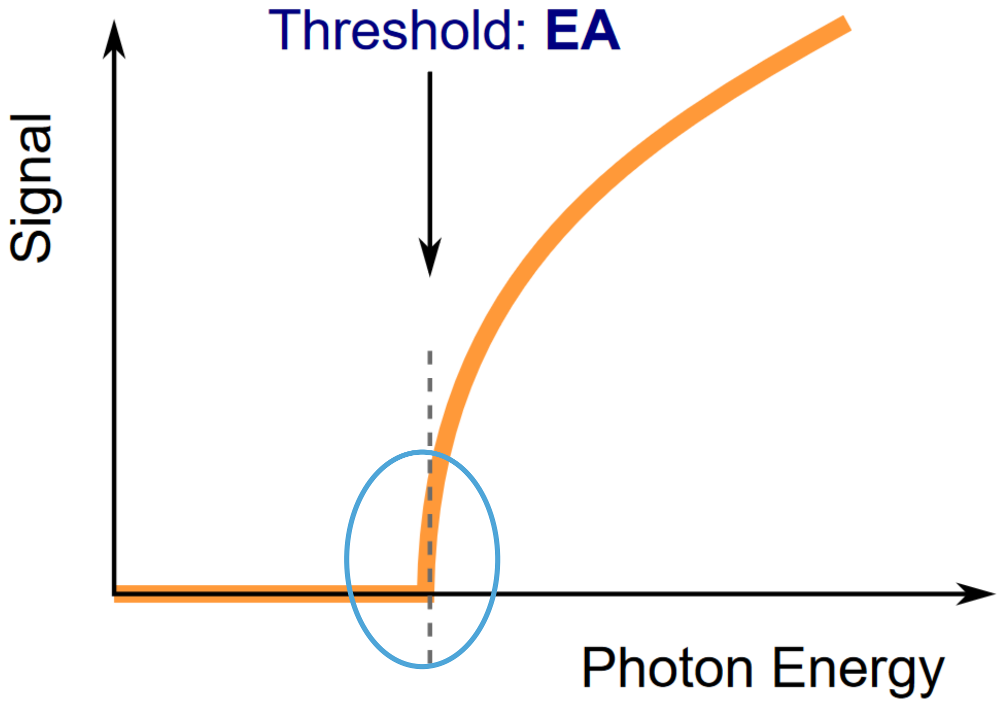

- Cross section σ follows Wigner threshold law
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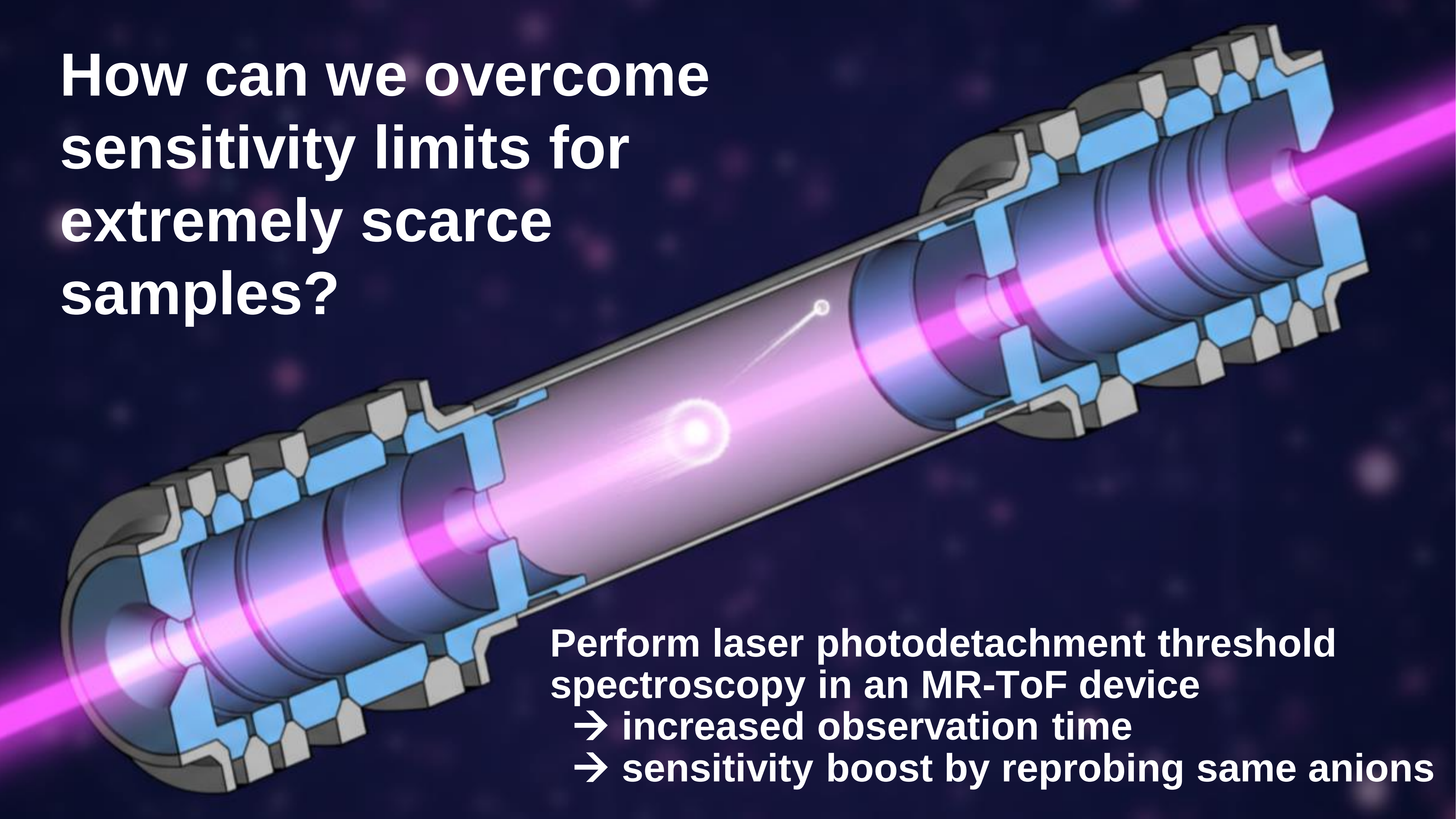
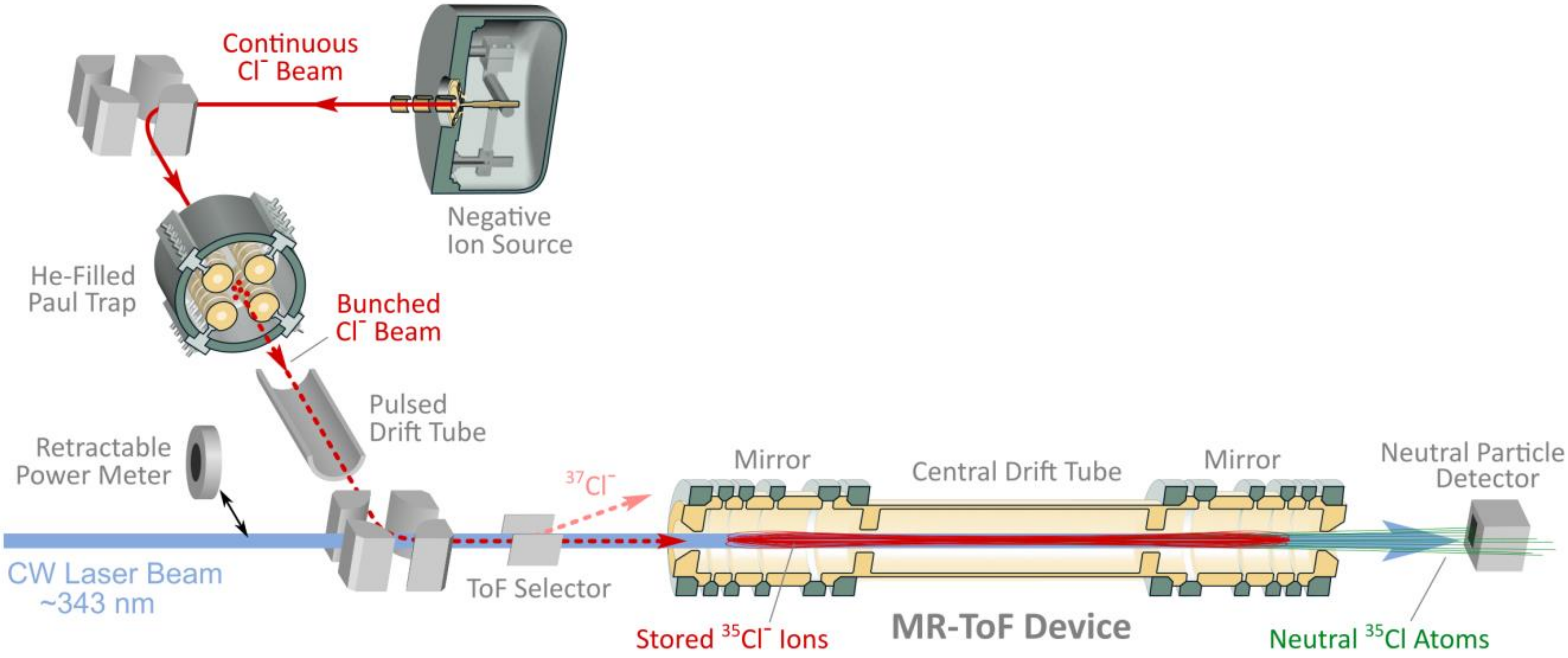
Challenge: very low photodetachment probability around threshold


How can we overcome sensitivity limits for extremely scarce samples?
Perform laser photodetachment threshold spectroscopy in an MR-ToF device
→ increased observation time
→ sensitivity boost by reprobing same anions

Development of MR-ToF devices for CLS:
Enhanced Sensitivity for Electron Affinity Measurements



F.M. Maier, E. Leistenschneider et al., Nat. Commun. 16, 9576 (2025).

low-voltage
MR-ToF device

Development of MR-ToF devices for CLS:
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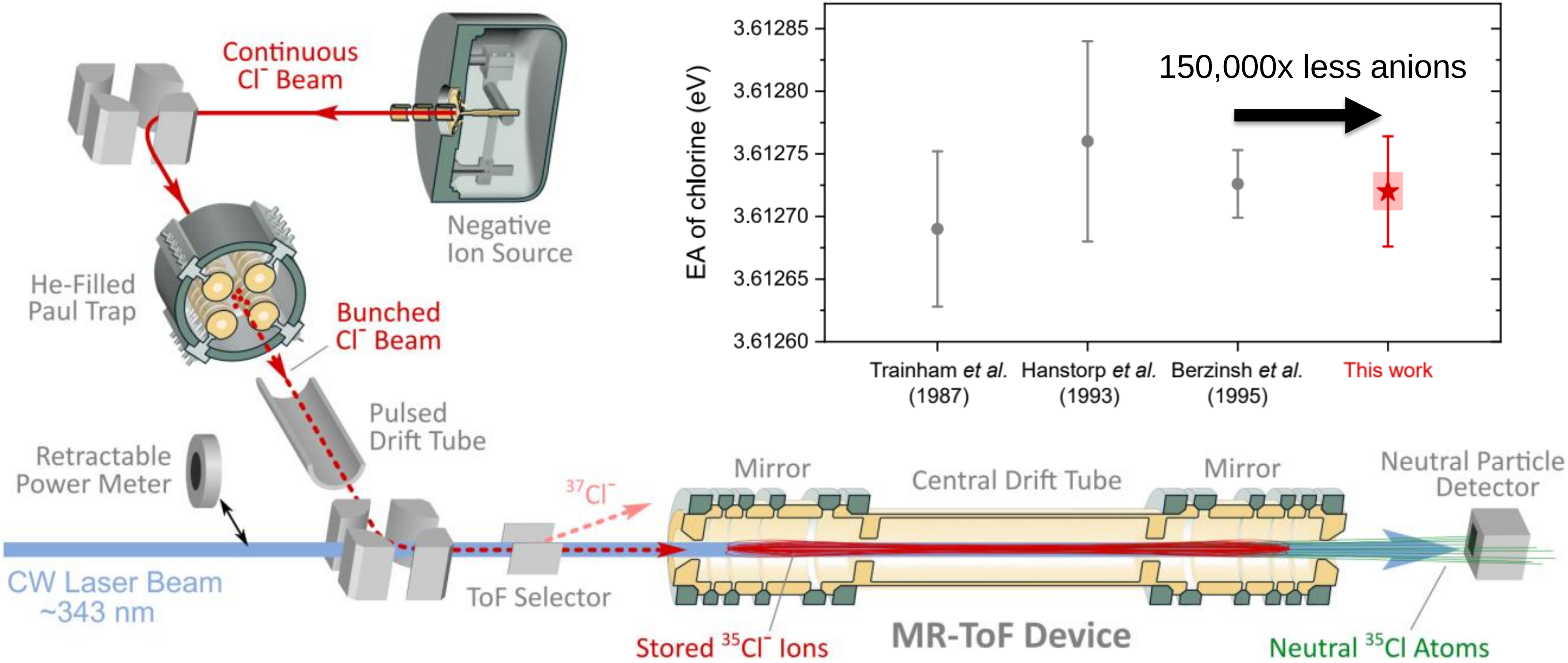

“This breakthrough is poised to have a significant impact on atomic physics, nuclear physics, and the chemistry of super-heavy elements.” (Reviewer Nature Communications)

F.M. Maier, E. Leistenschneider et al., Nat. Commun. 16, 9576 (2025).

low-voltage
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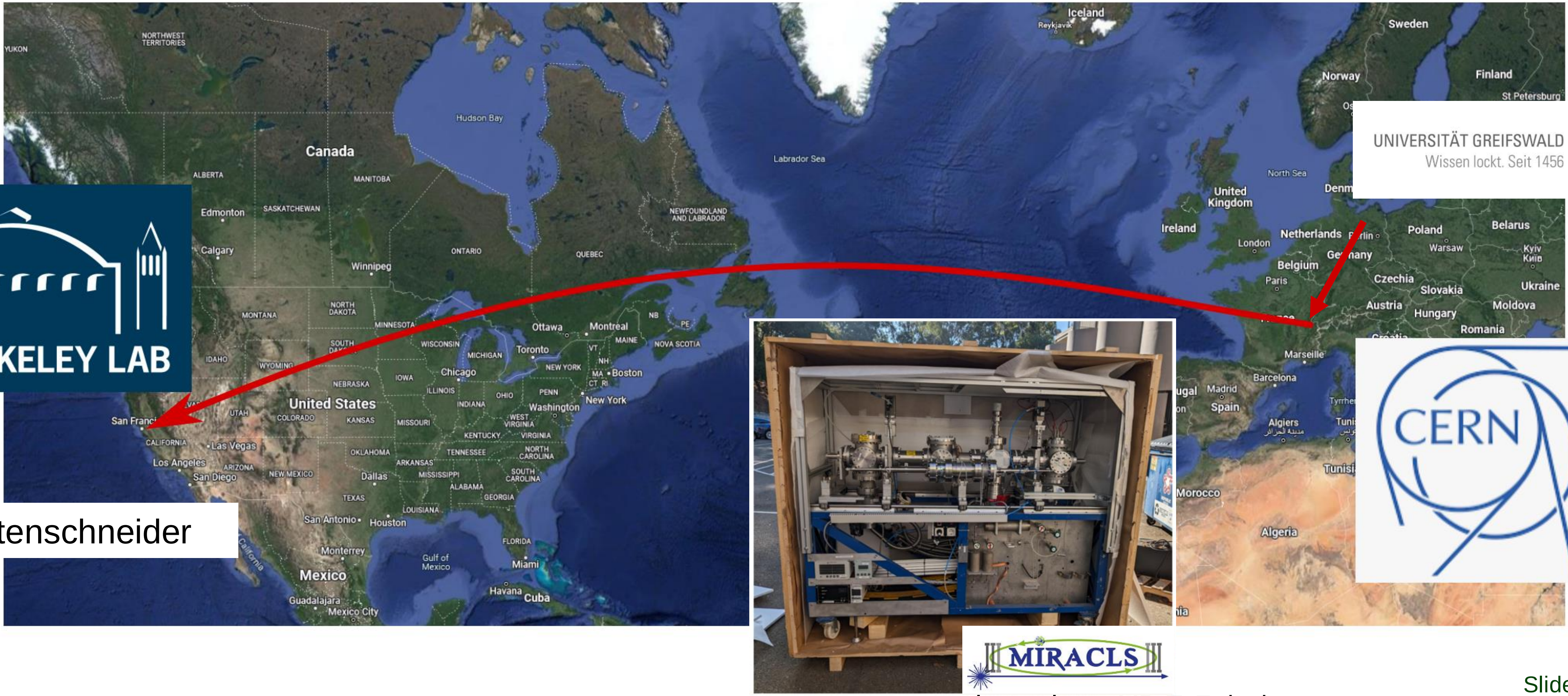
Development of MR-ToF devices for CLS:
Enhanced Sensitivity for Electron Affinity Measurements

Shipped our MR-ToF setup to Lawrence Berkeley National Laboratory to measure electron affinities of (super)heavy elements



E. Leistenschneider

low-voltage MR-ToF device

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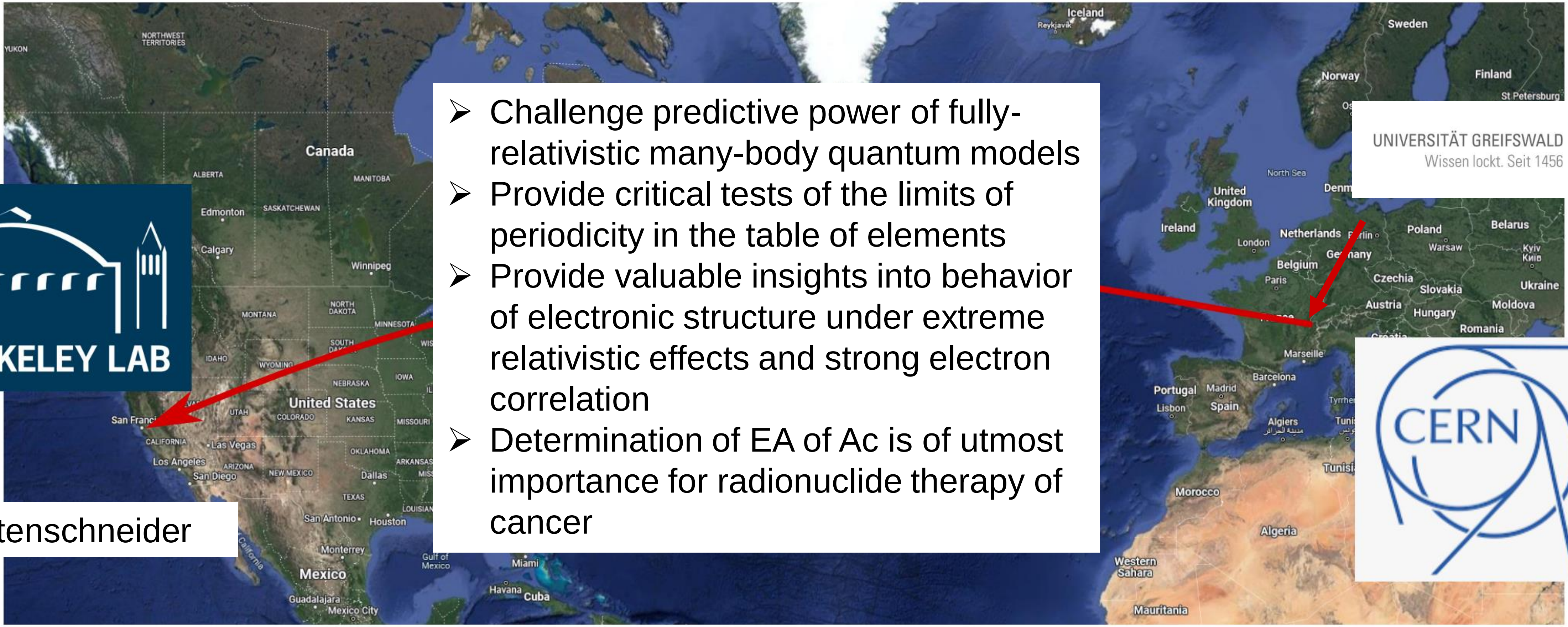

BERKELEY LAB

UNIVERSITÄT GREIFSWALD
Wissen lockt. Seit 1456

CERN

- Challenge predictive power of fully-relativistic many-body quantum models
- Provide critical tests of the limits of periodicity in the table of elements
- Provide valuable insights into behavior of electronic structure under extreme relativistic effects and strong electron correlation
- Determination of EA of Ac is of utmost importance for radionuclide therapy of cancer

E. Leistenschneider

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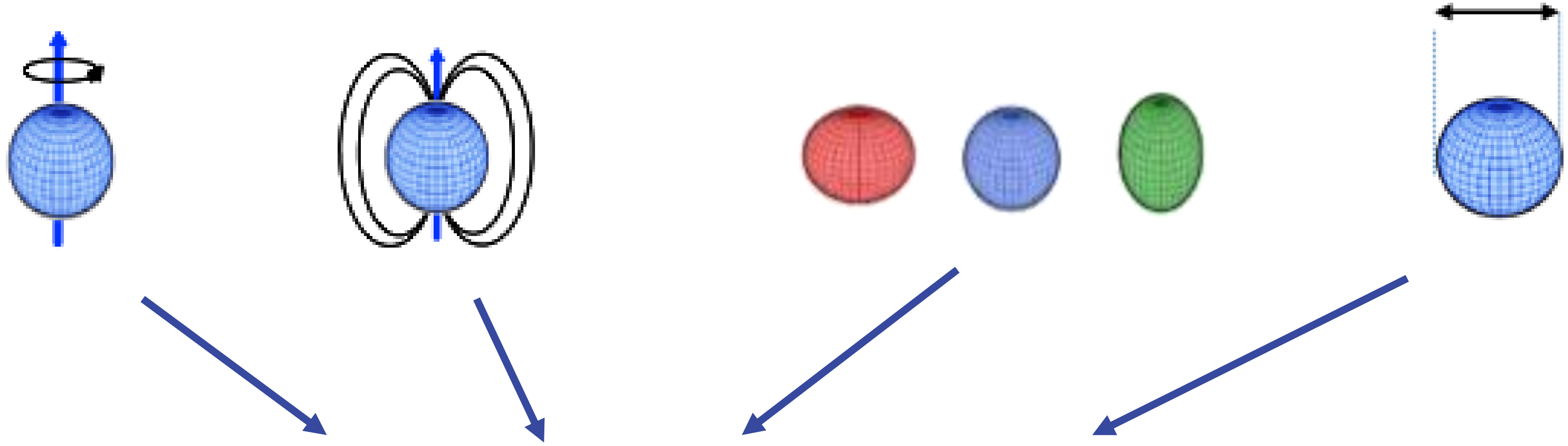
Enhanced Sensitivity for Fluorescence-Based CLS

spin I

magnetic dipol moment μ

Electric quadrupole moment Q_s

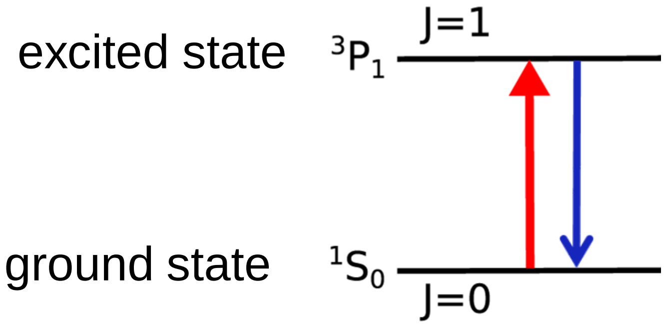
rms charge radius

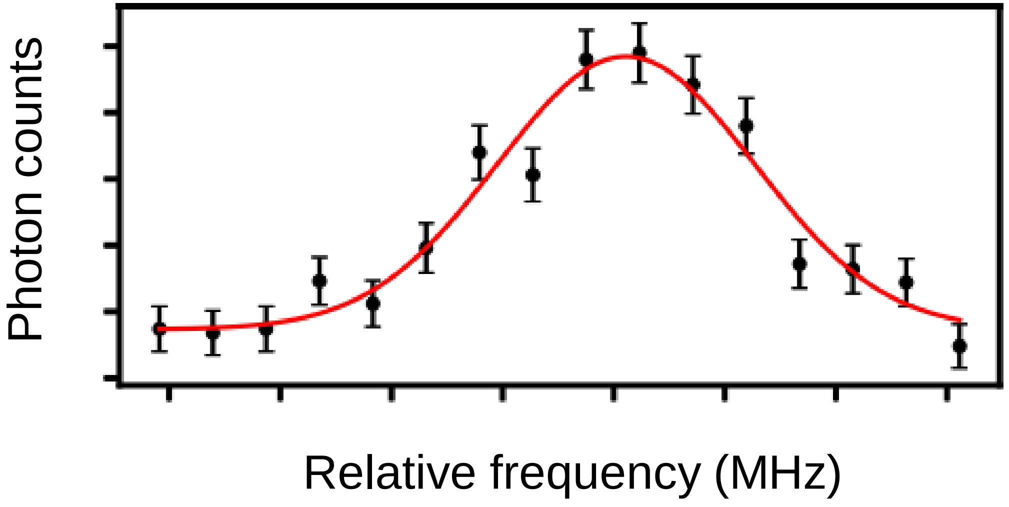


- study nuclear structure phenomena
- benchmark for modern nuclear theory

Enhanced Sensitivity for Fluorescence-Based CLS

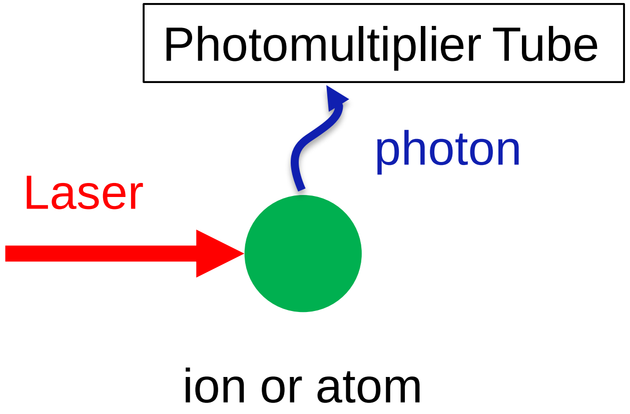
- Fluorescence-based laser spectroscopy:





Excitation using laser photons

De-excitation:
detect fluorescence photons

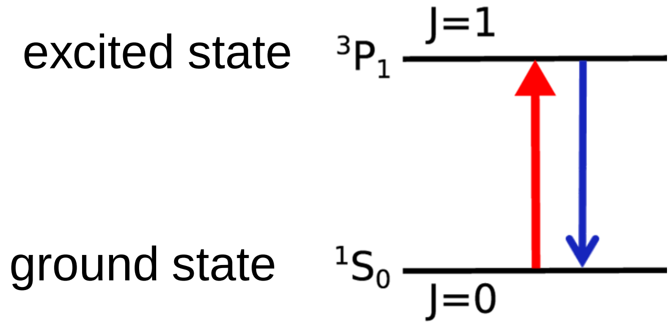


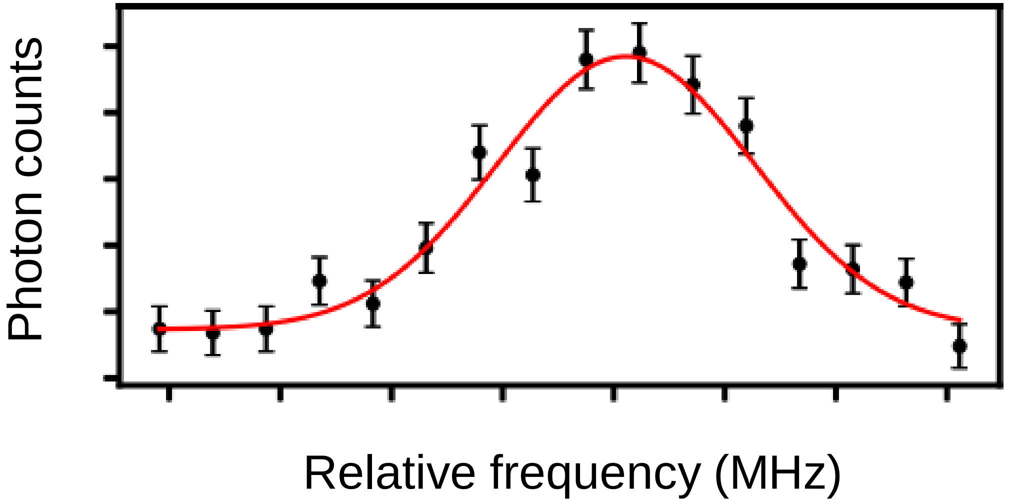
K. Blaum et al., Phys. Scr. T152, 014017 (2013)
P. Campbell et al., Prog. Part. and Nucl. Phys. 86, 127-180 (2016)
R. Neugart et al., J. Phys. G: Nucl. Part. Phys. 44, 064002 (2017)

Development of MR-ToF devices for CLS:

Enhanced Sensitivity for Fluorescence-Based CLS

- Fluorescence-based laser spectroscopy:





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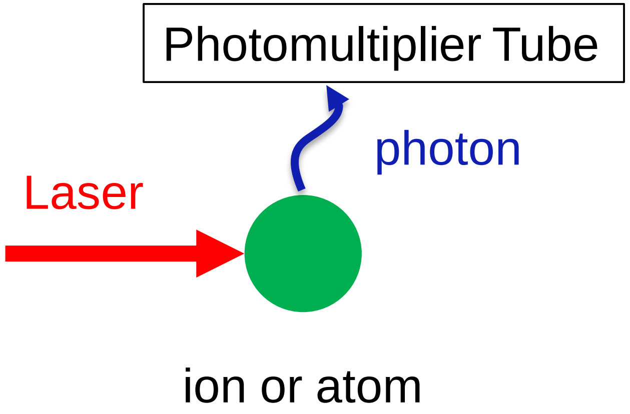

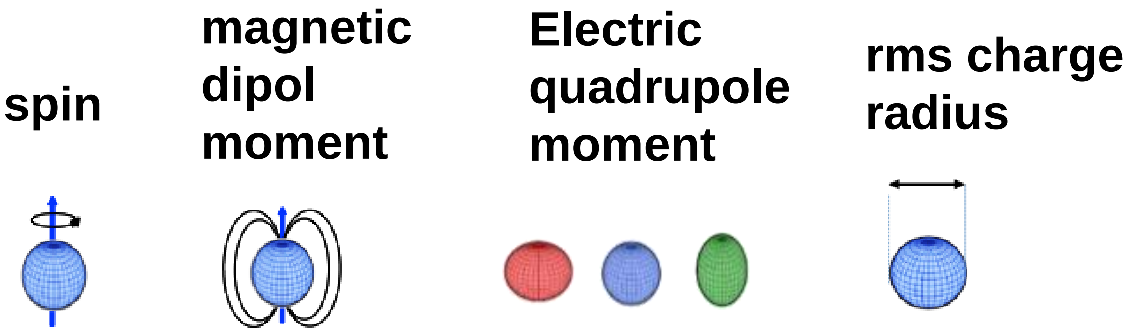

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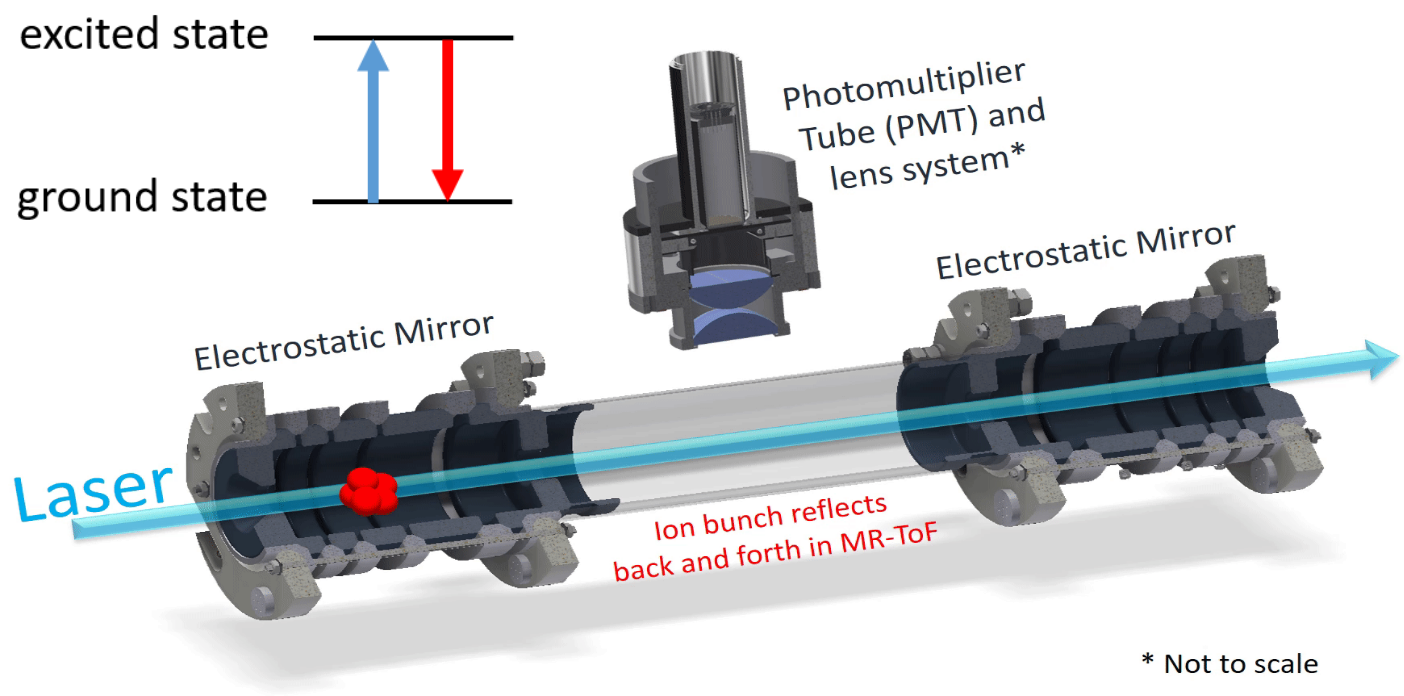

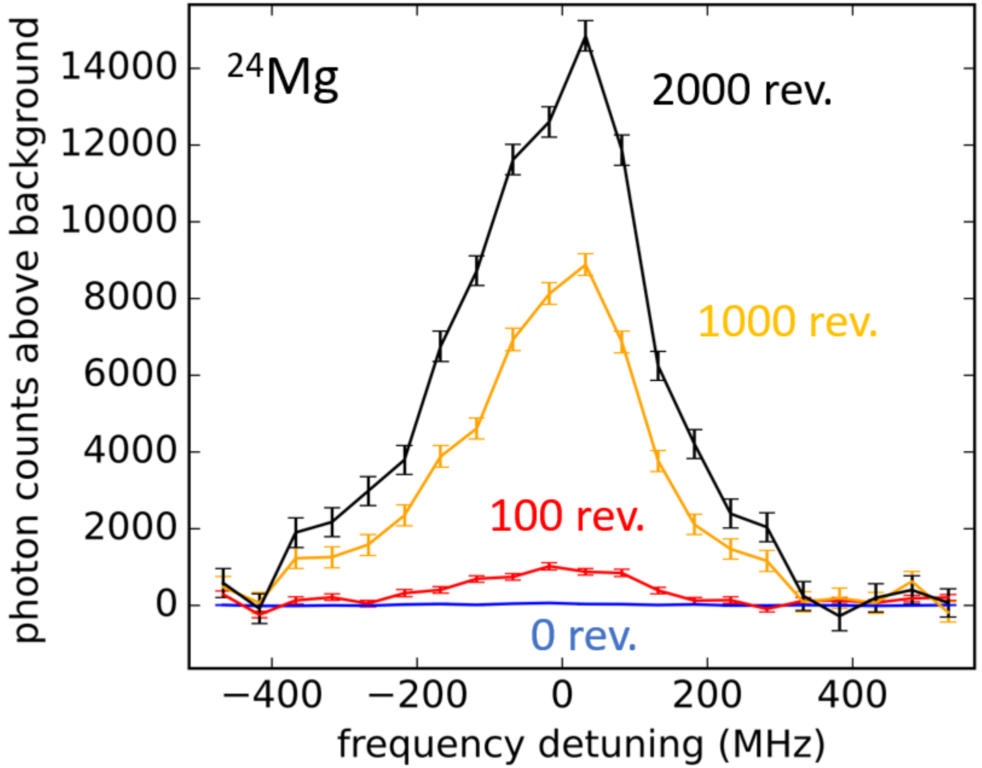

Increased observation time
→ Gain in sensitivity by 1-2 orders of magnitude
→ More exotic nuclides accessible

low-voltage MR-ToF device

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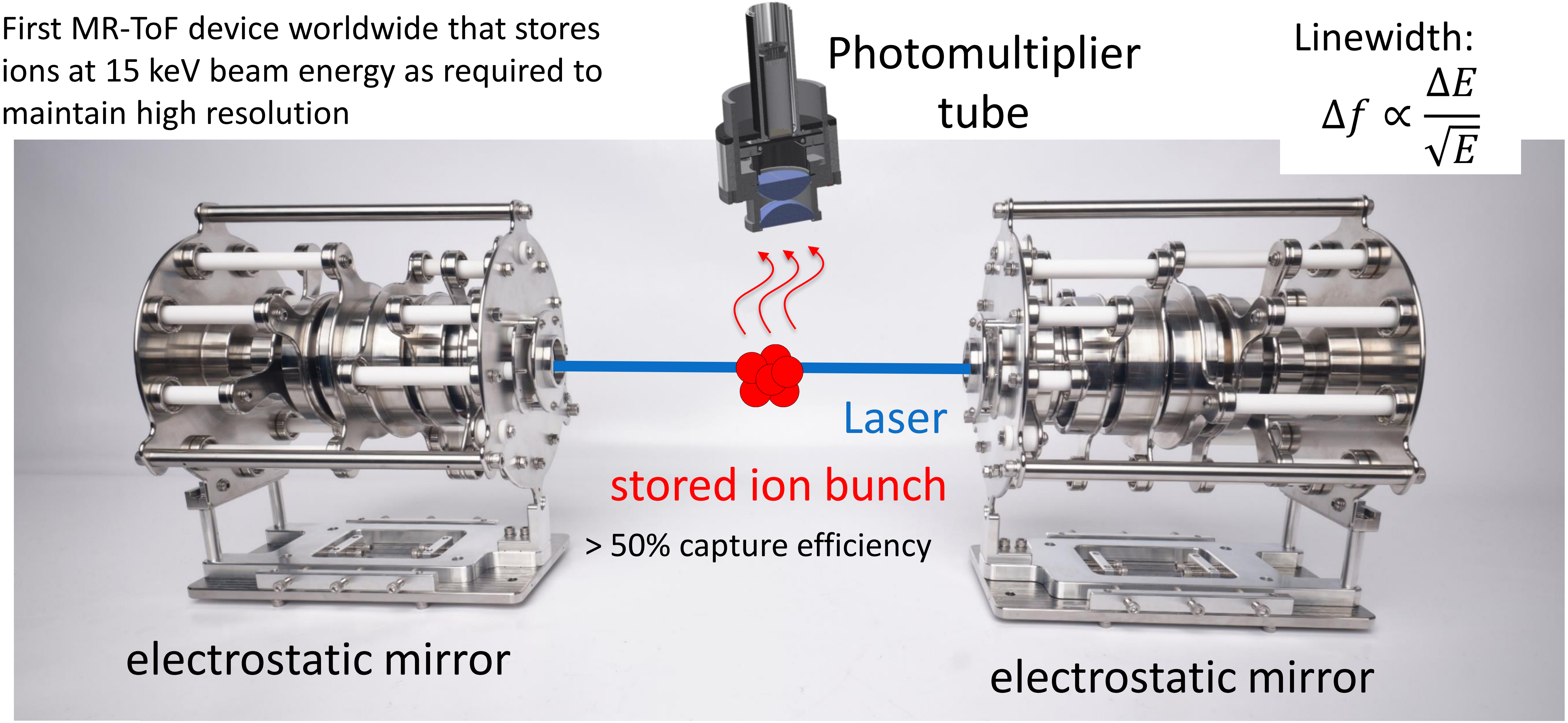
+

Development of MIRACLS High-Voltage MR-ToF Setup
Enhanced Sensitivity for Fluorescence-Based CLS

First MR-ToF device worldwide that stores ions at 15 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).

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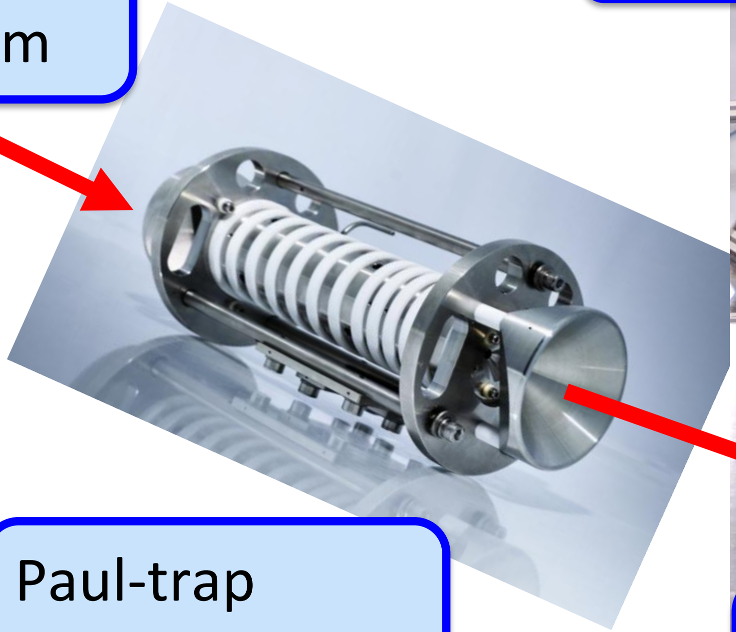
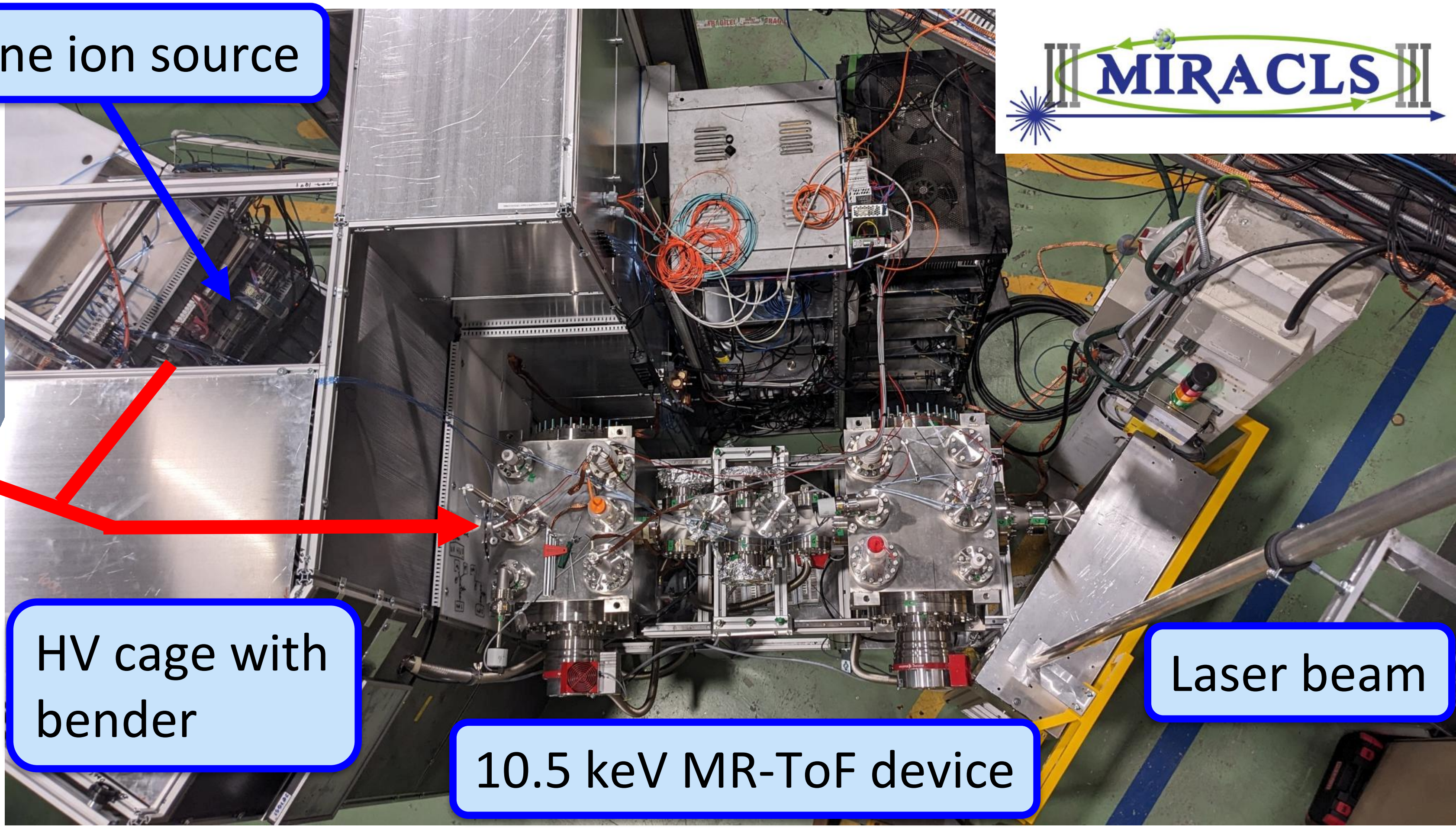




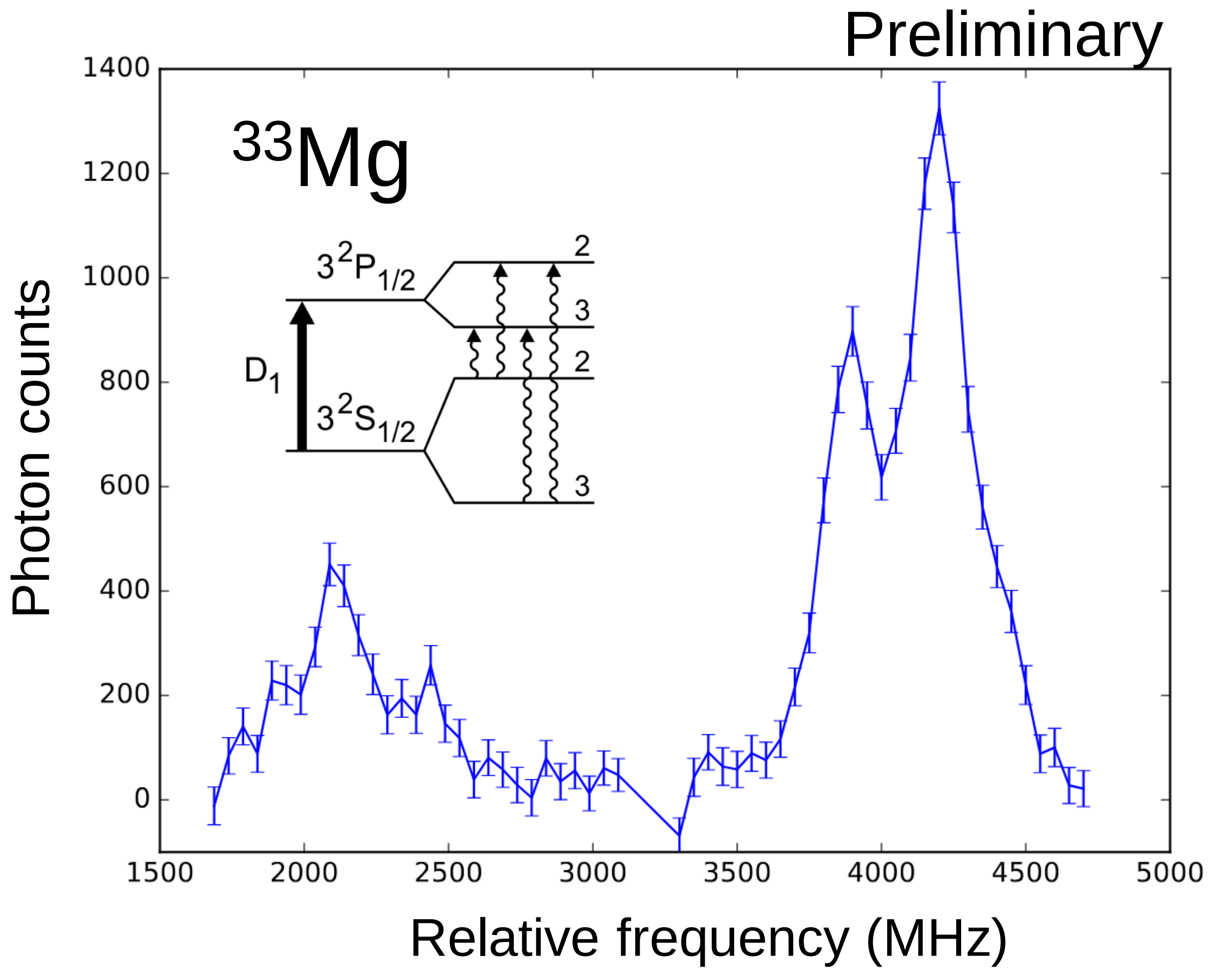
copies of our Paul trap also operational at Greifswald, MIT, Beijing, Darmstadt & ISOLTRAP

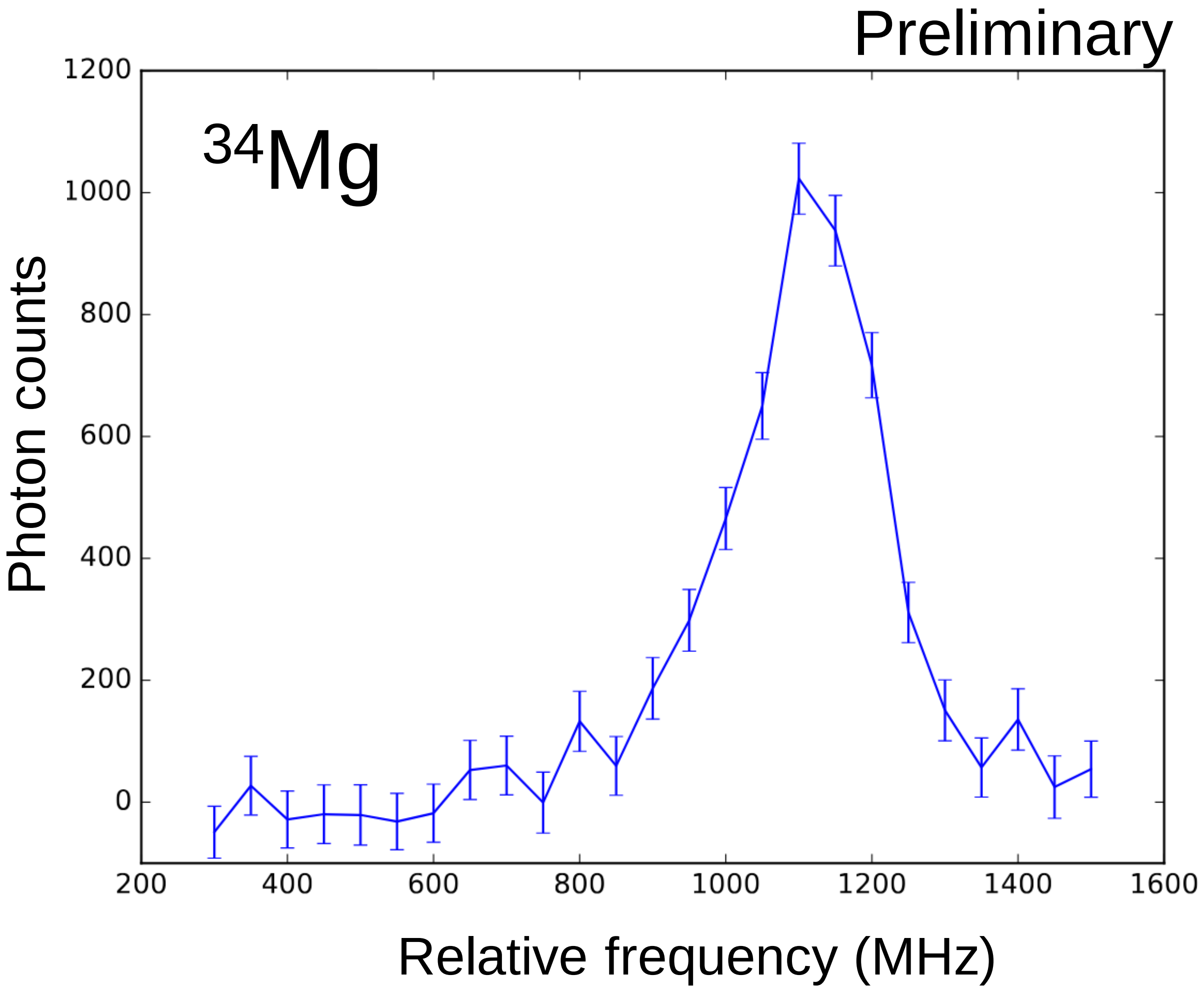
S. Lechner, S. Sels et al., NIMA 1065, 169471 (2024).

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

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

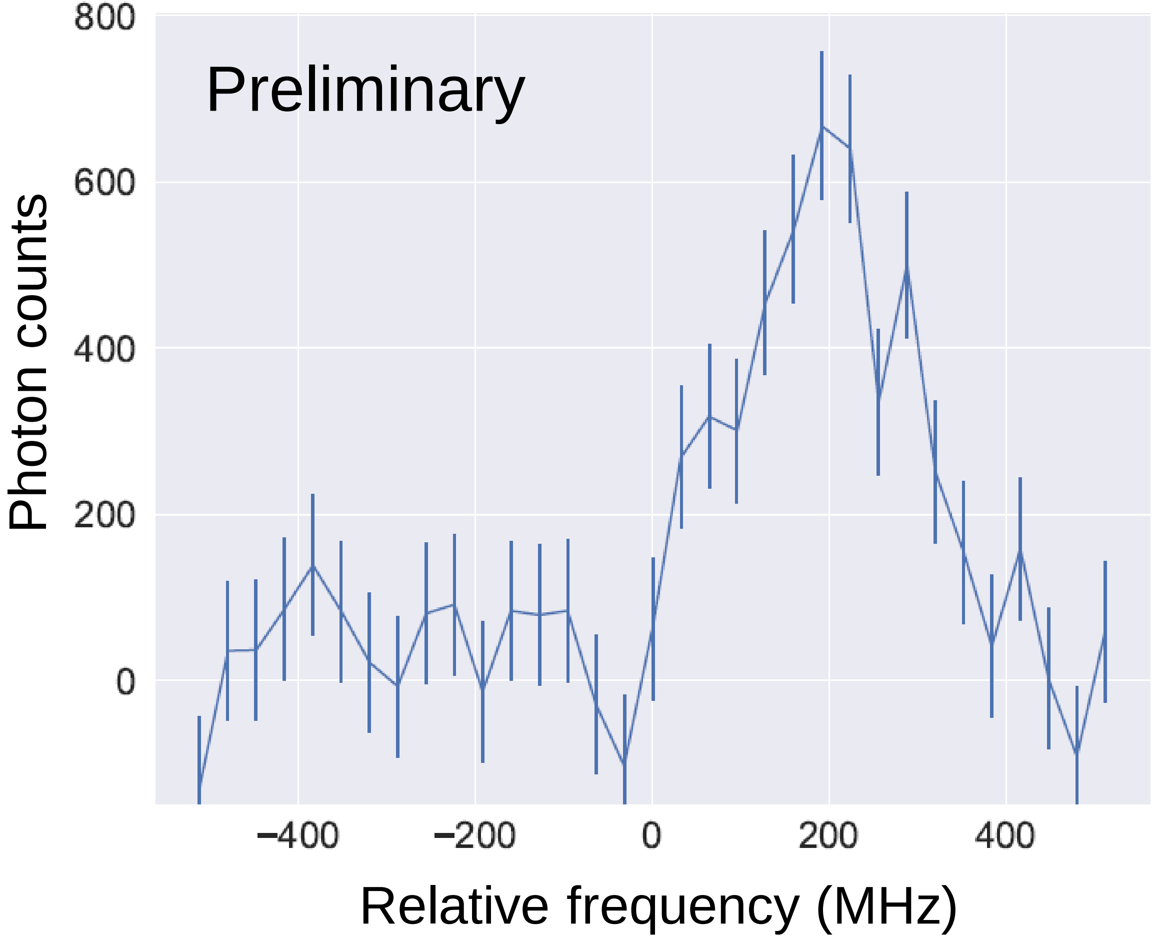
Data analysis and physics interpretation in progress



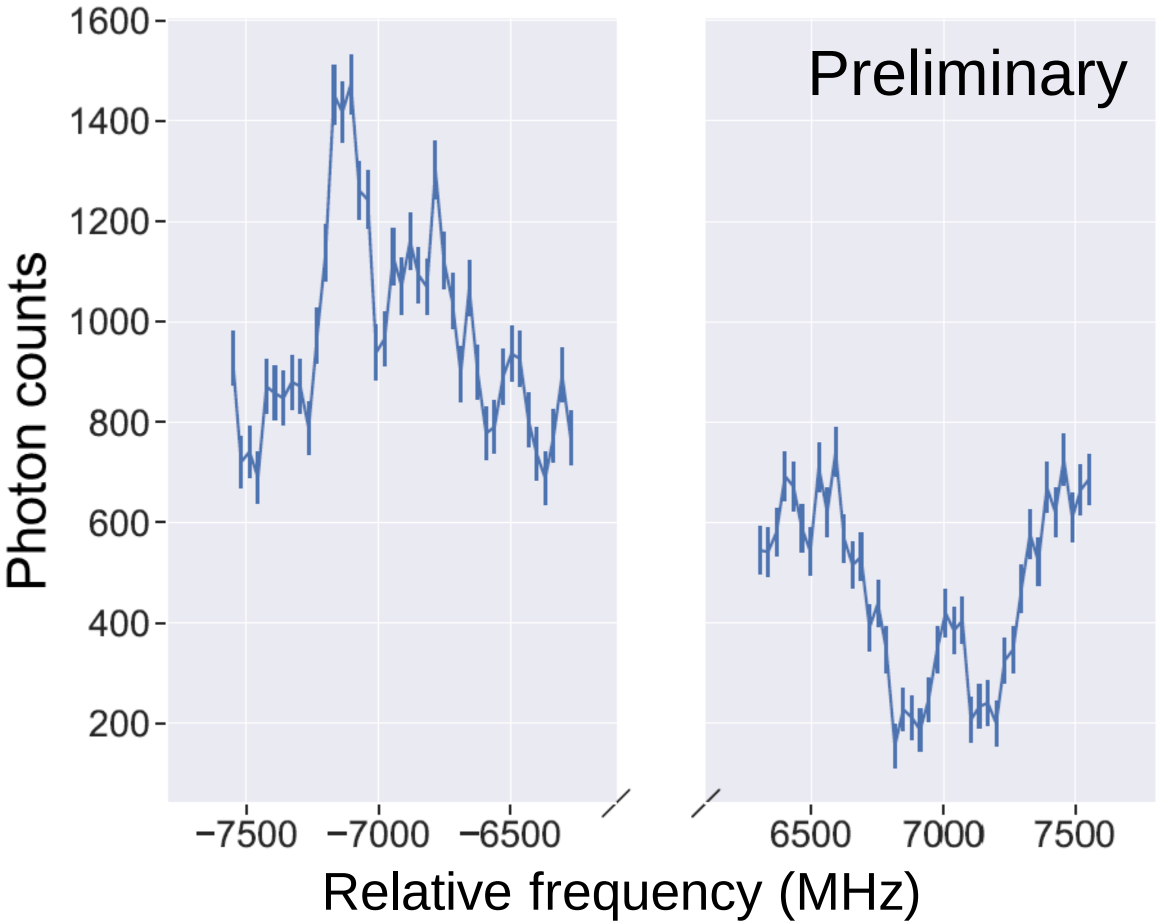


MIRACLS measurement of $^{98,99}Cd$ will provide insights into N=50 shell closure

^{98}Cd



^{99}Cd (new pump and probe scheme)



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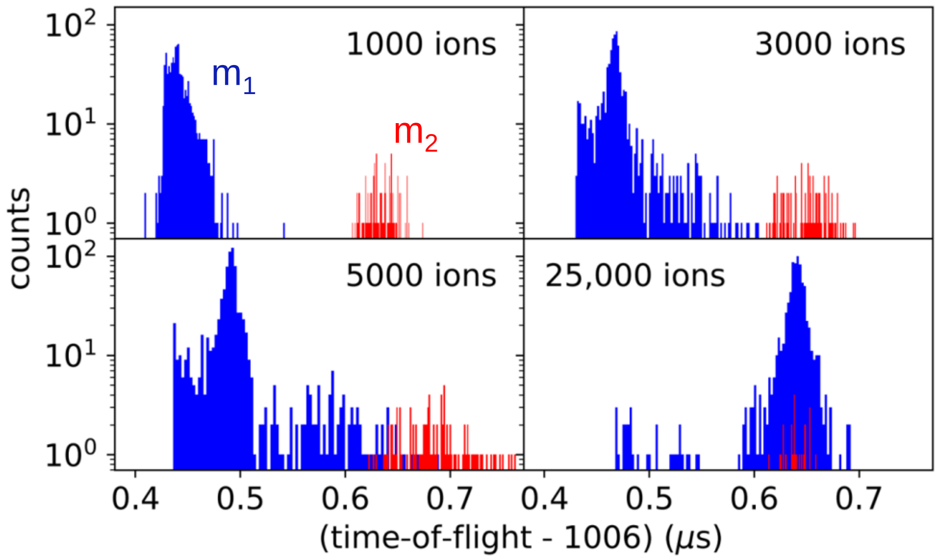
Many experiments at RIB facilities require isobarically and isomerically purified beams at high ion intensity

- Up to today: Either high mass separation power or high ion intensity

	Magnetic mass separators	Penning traps	current MR-ToF mass separators
Mass separation power	<10,000	$>10^6$	$>10^5$
Processing time	continuous	~ 100 ms	(tens of) ms
Ion flux (= ions/s injected)	10^{13} ions/s	~ 10 ions/s	$\sim 10^2$-10^7 ions/s depending on m/Δm



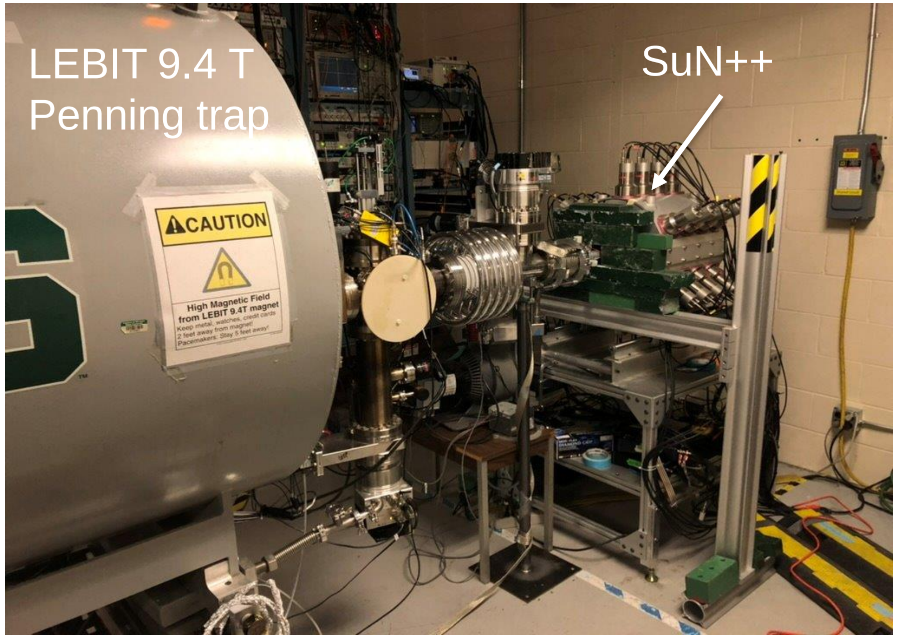
Simulations of ions extracted from the MR-ToF mass separator

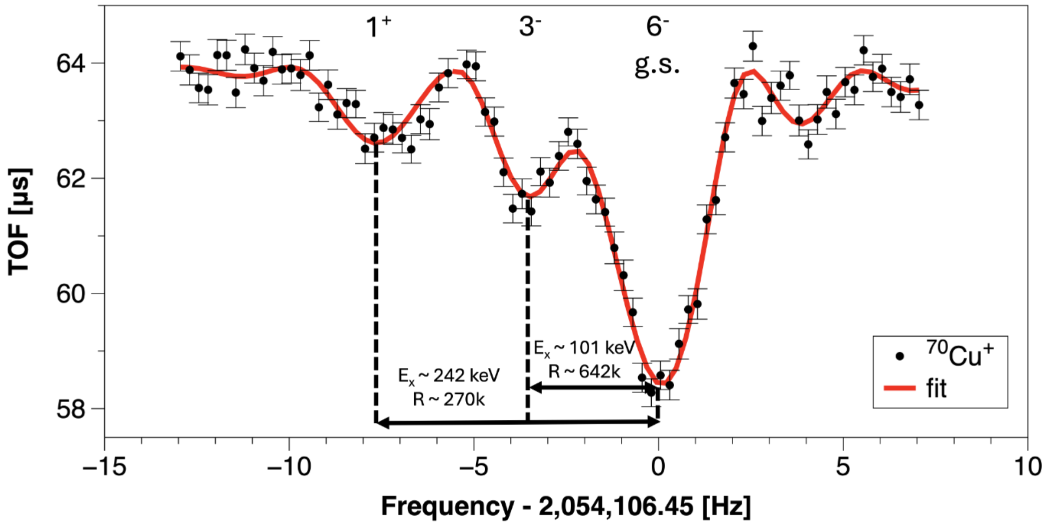
F.M.Maier et al, NIMA 1056, 168545 (2023)

Many experiments at RIB facilities require isobarically and isomerically purified beams at high ion intensity

Example at FRIB:

- SuN++ total absorption spectrometer often requires isomerically purified beams
- Using LEBIT's Penning trap, we provided isomerically pure beam of ^{70}Cu
- Determined electromagnetic nature of the low energy enhancement of the γ-ray strength function of ^{70}Zn + constrained astrophysical neutron capture reaction rates
- However, with the LEBIT Penning trap only 10 ions/s could be purified whereas 10,000 ions/s would have been available → An MR-ToF device can overcome this shortcoming

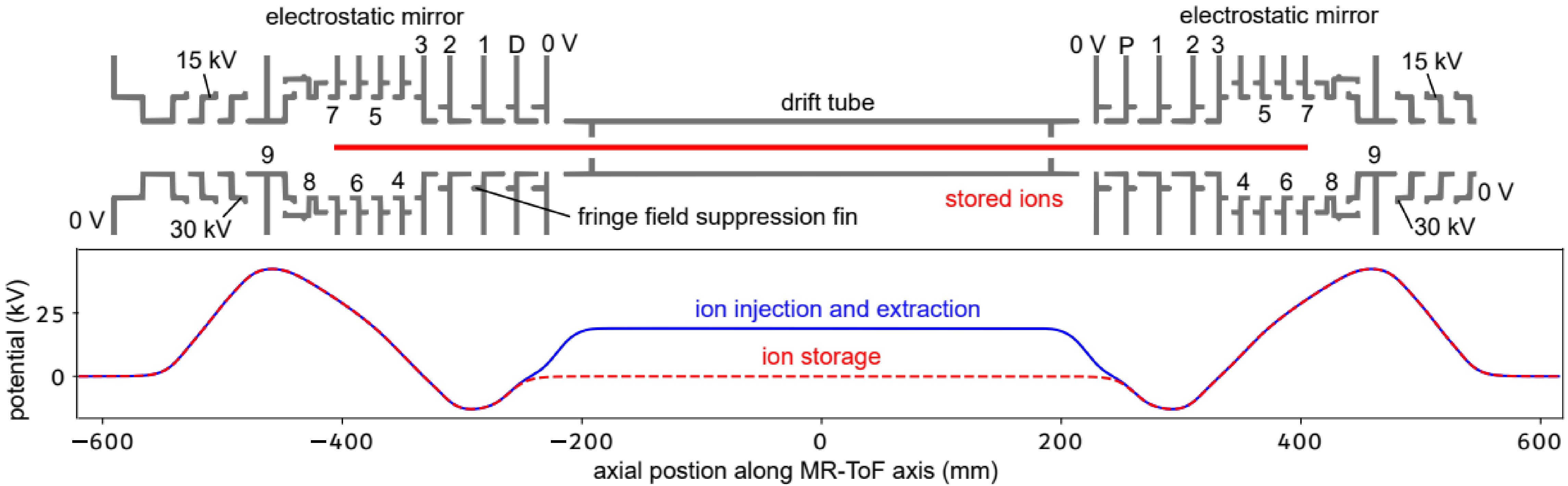




E.K. Ronning *et al.*, NIMA 1082, 170930 (2026).
E.K. Ronning *et al.*, submitted.

FRIB

Development of a High-Voltage MR-ToF Device Extend FRIB's Mass Measurement and Separation Capabilities



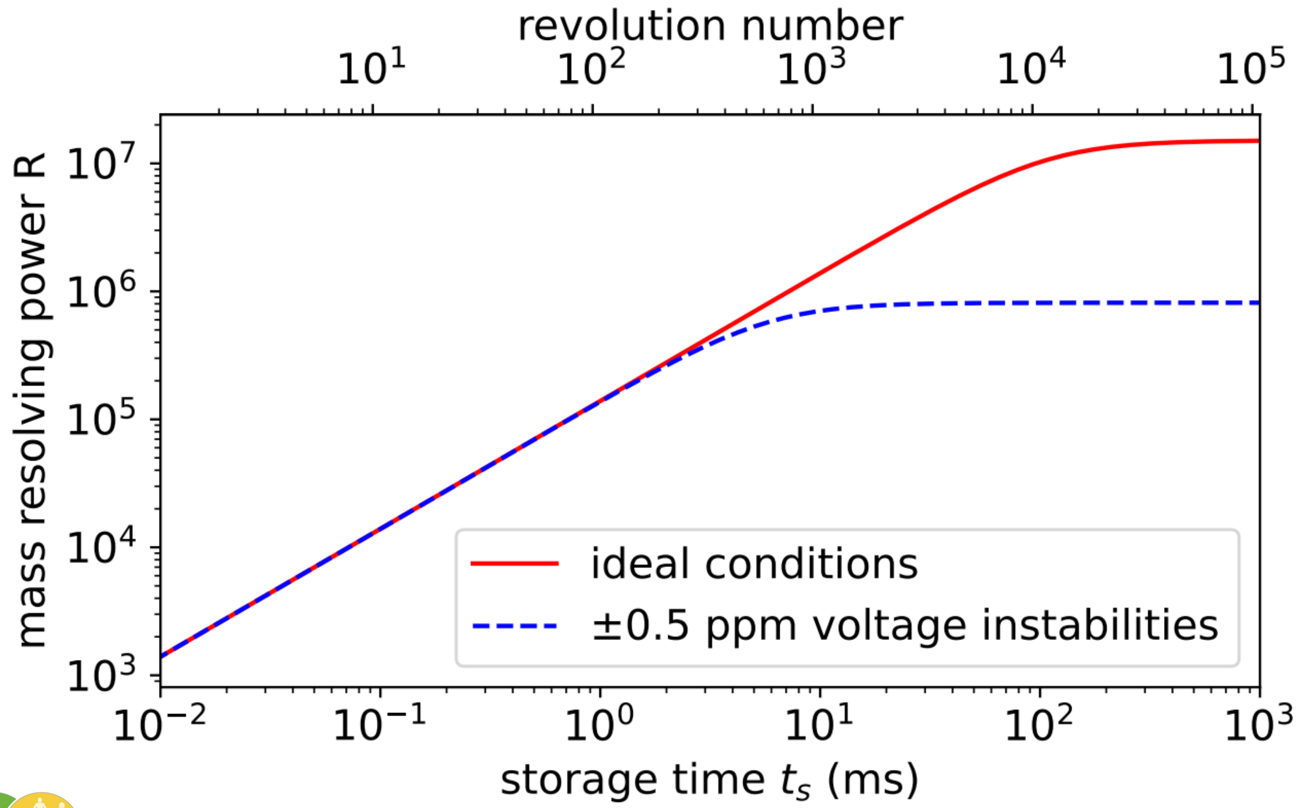
- Advances the design of MIRACLS high-voltage MR-ToF device at ISOLDE/CERN [1-3]
- High ion flux, high mass resolving power, short processing time

F.M. Maier, C.M. Ireland *et al.*, NIMA 1084, 171220, 2026.
C.M. Ireland, F.M. Maier *et al.*, https://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).

Development of a High-Voltage MR-ToF Device
Extend FRIB's Mass Measurement and Separation Capabilities

- Simulated mass resolving power is high enough to resolve almost all isobars and 70% of all known isomers with half-lives above 10 ms



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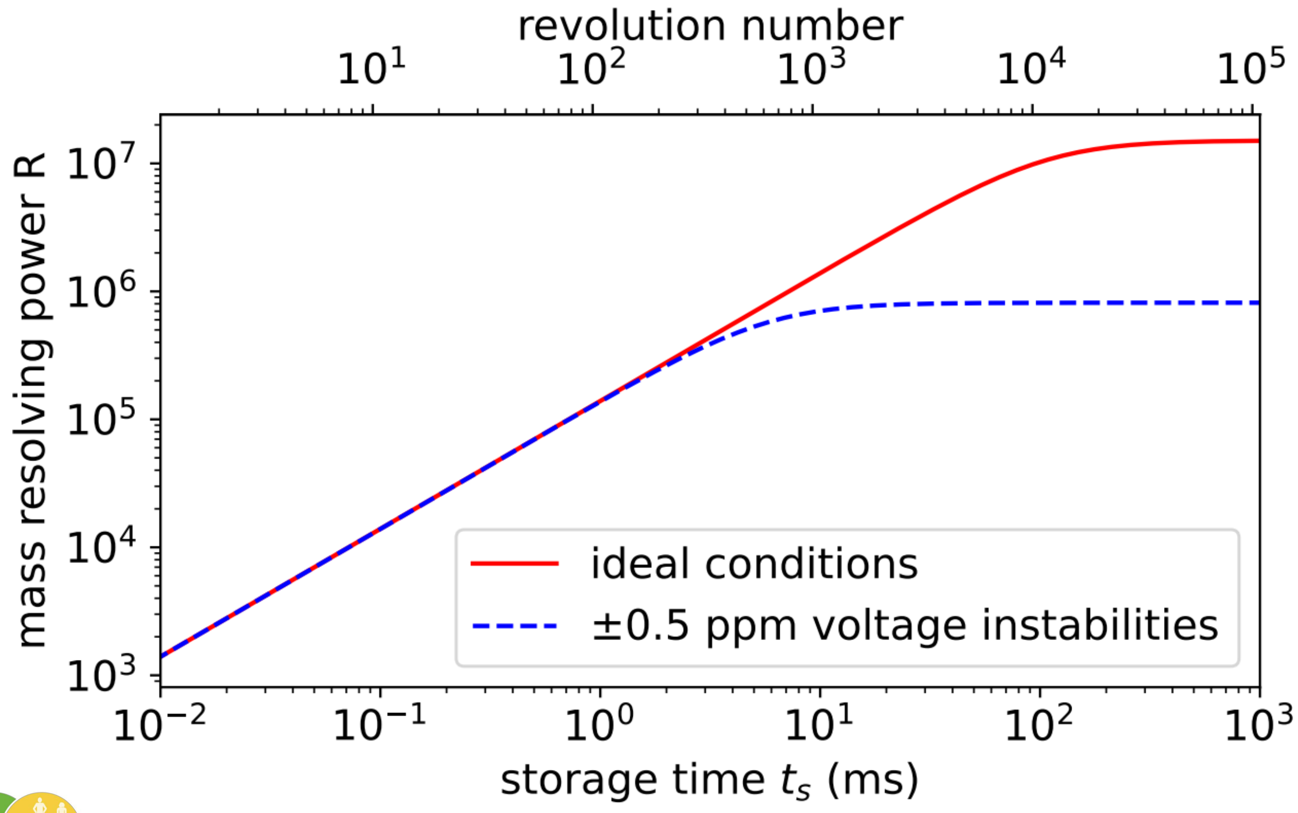
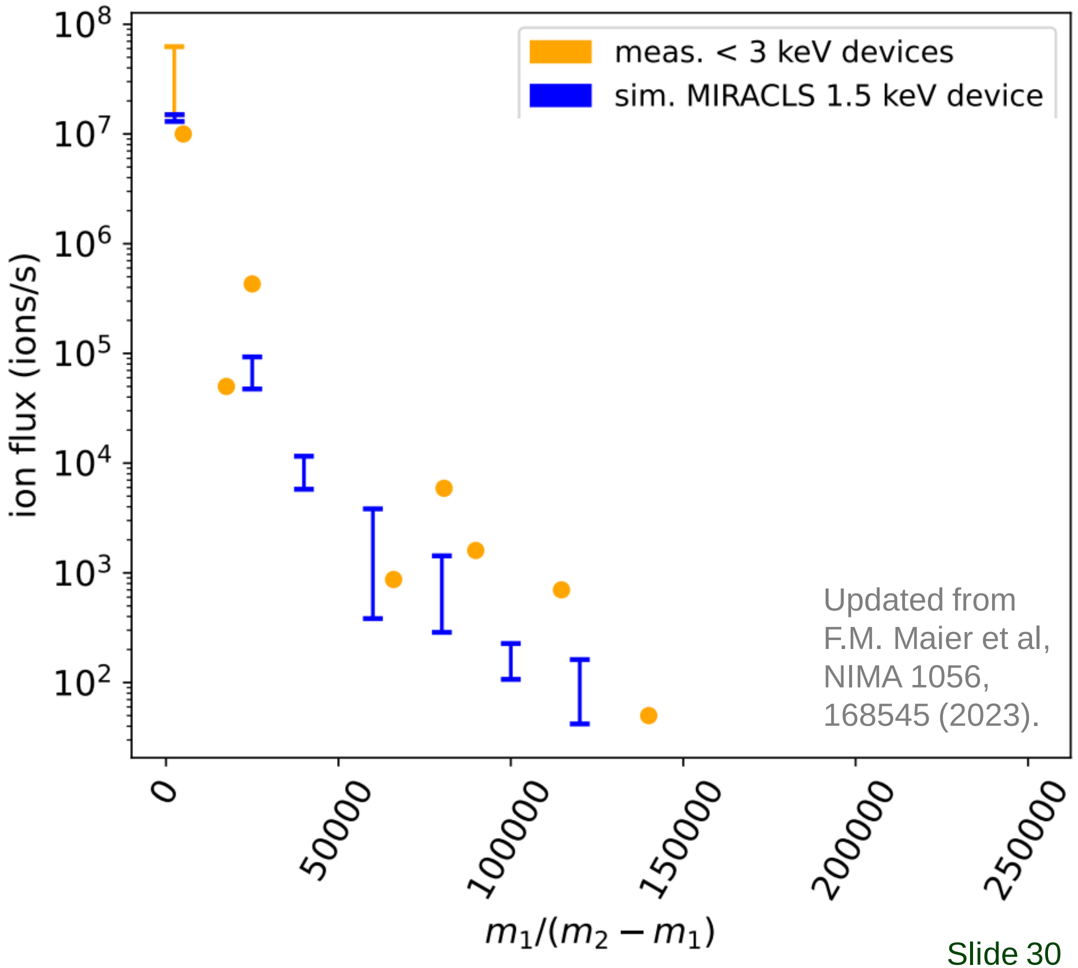


- Simulated ion flux is > 2 orders of magnitude higher compared to state-of-the-art MR-ToF devices



Updated from F.M. Maier et al, NIMA 1056, 168545 (2023).

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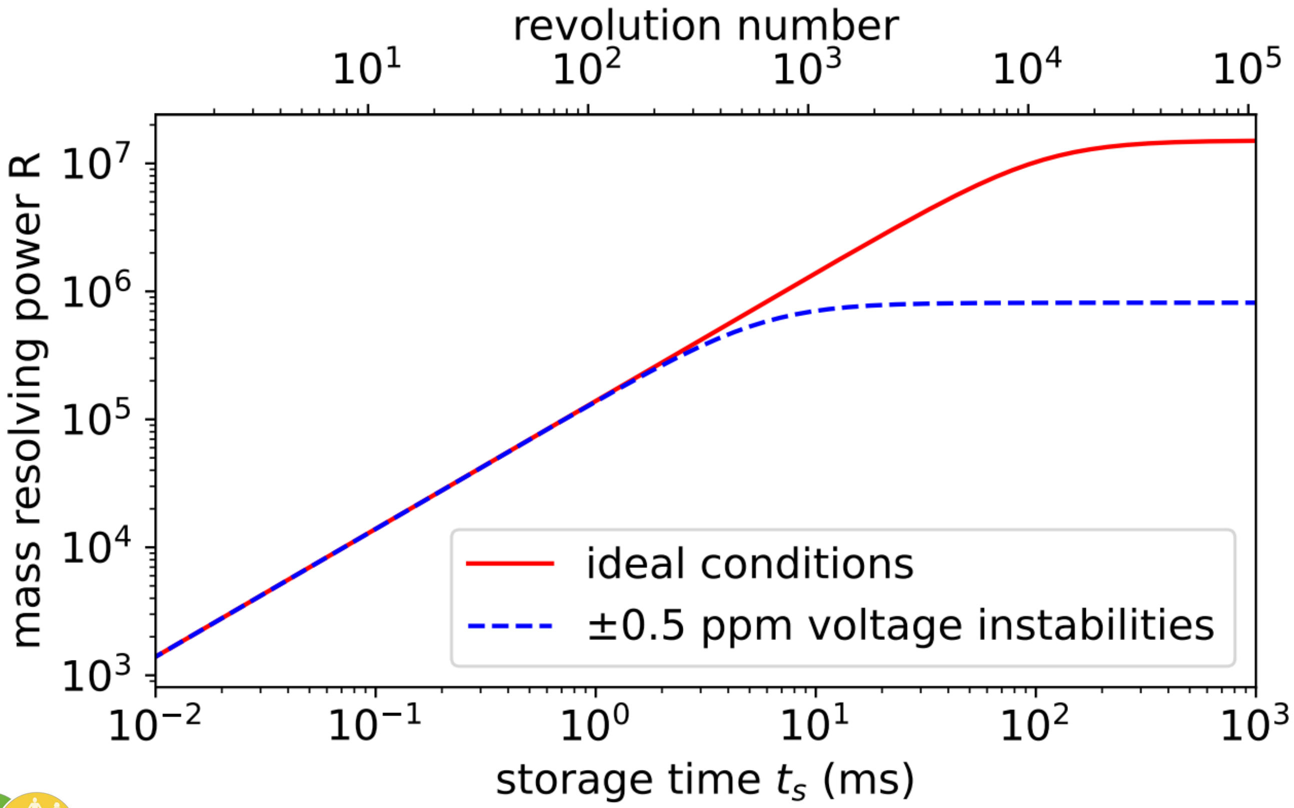

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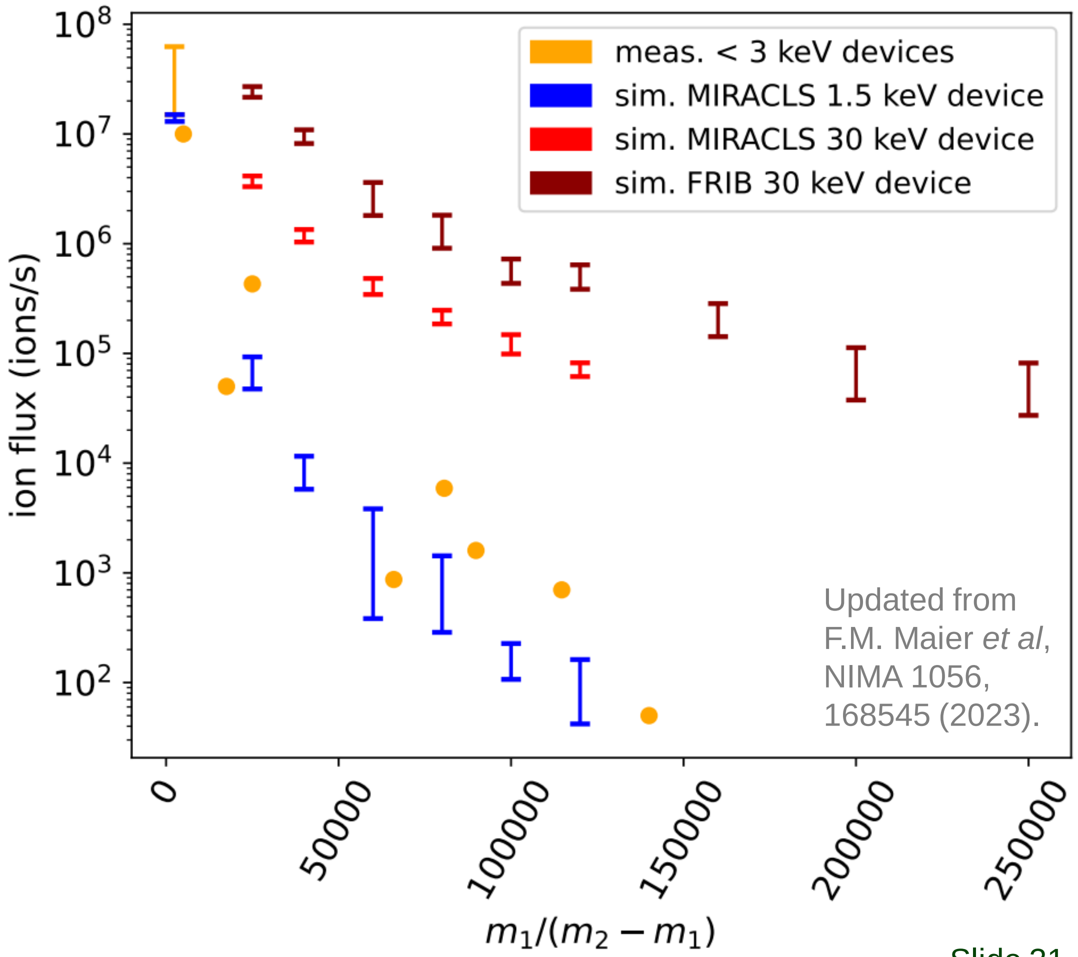

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FRIB

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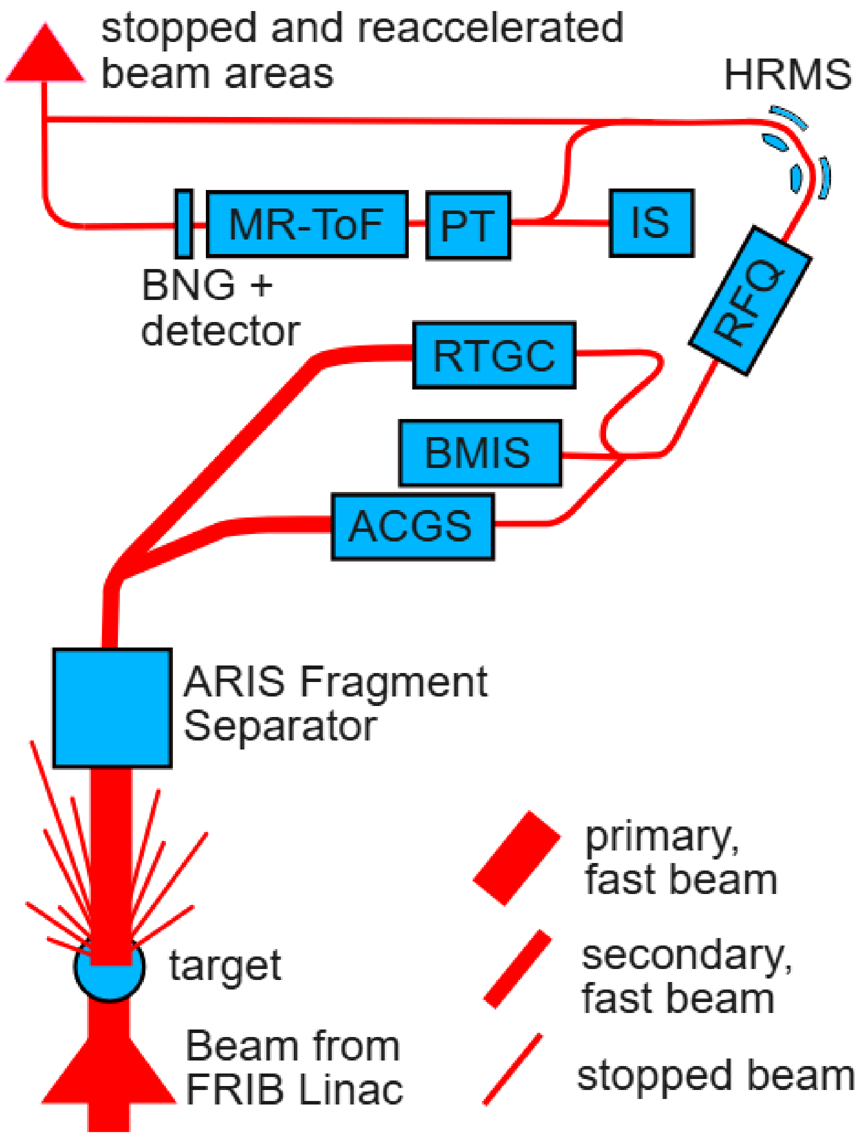
Extend FRIB's Mass Measurement and Separation Capabilities



<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

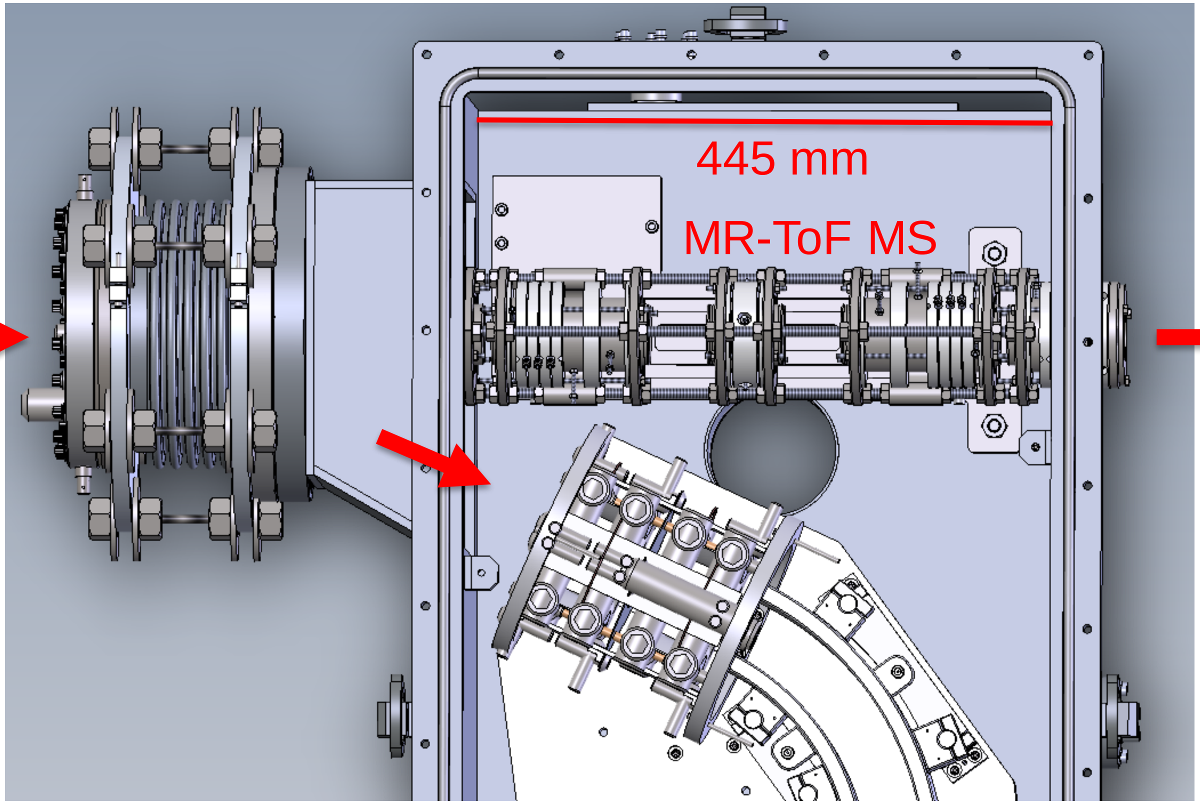
F.M. Maier, C.M. Ireland *et al.*, NIMA 1084, 171220, 2026.
C.M. Ireland, F.M. Maier *et al.*, https://arxiv.org/abs/2510.11741

FRIB

A ‘Quick and Cheap’ Mini-MR-ToF MS
Bridge the Time Until the Main MR-ToF Device Becomes Available

- Bridge the time until the high-flux MR-ToF device becomes available
  - Fast beam diagnostics, low-intensity mass separation for LEBIT and SuN++, mass measurements
- Developed Mini-MR-ToF device matching space constraints and performance characteristics of existing Paul trap - Funding received in Feb. 2026

LEBIT’s
Paul-trap
cooler-buncher

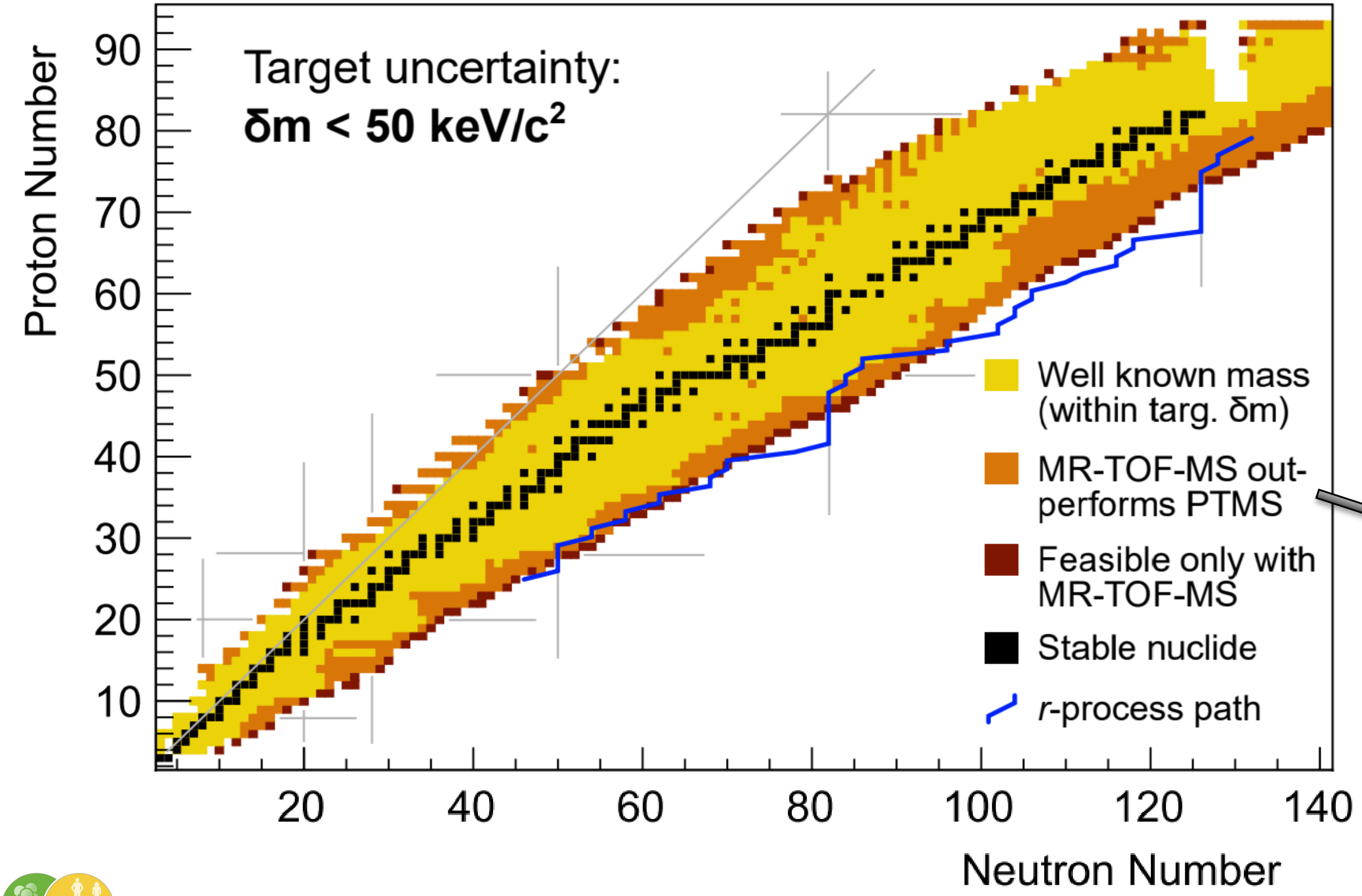


LEBIT’s
Penning trap

Bender
towards SIPT

FRIB

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



Based on FRIB yield estimates for 400 kW primary beam & < 60 hours beam-on-target time

If target δm > 10 keV/c^2

F.M. Maier, C.M. Ireland *et al.*, NIMA 1084, 171220, 2026.
C.M. Ireland, F.M. Maier *et al.*, https://arxiv.org/abs/2510.11741

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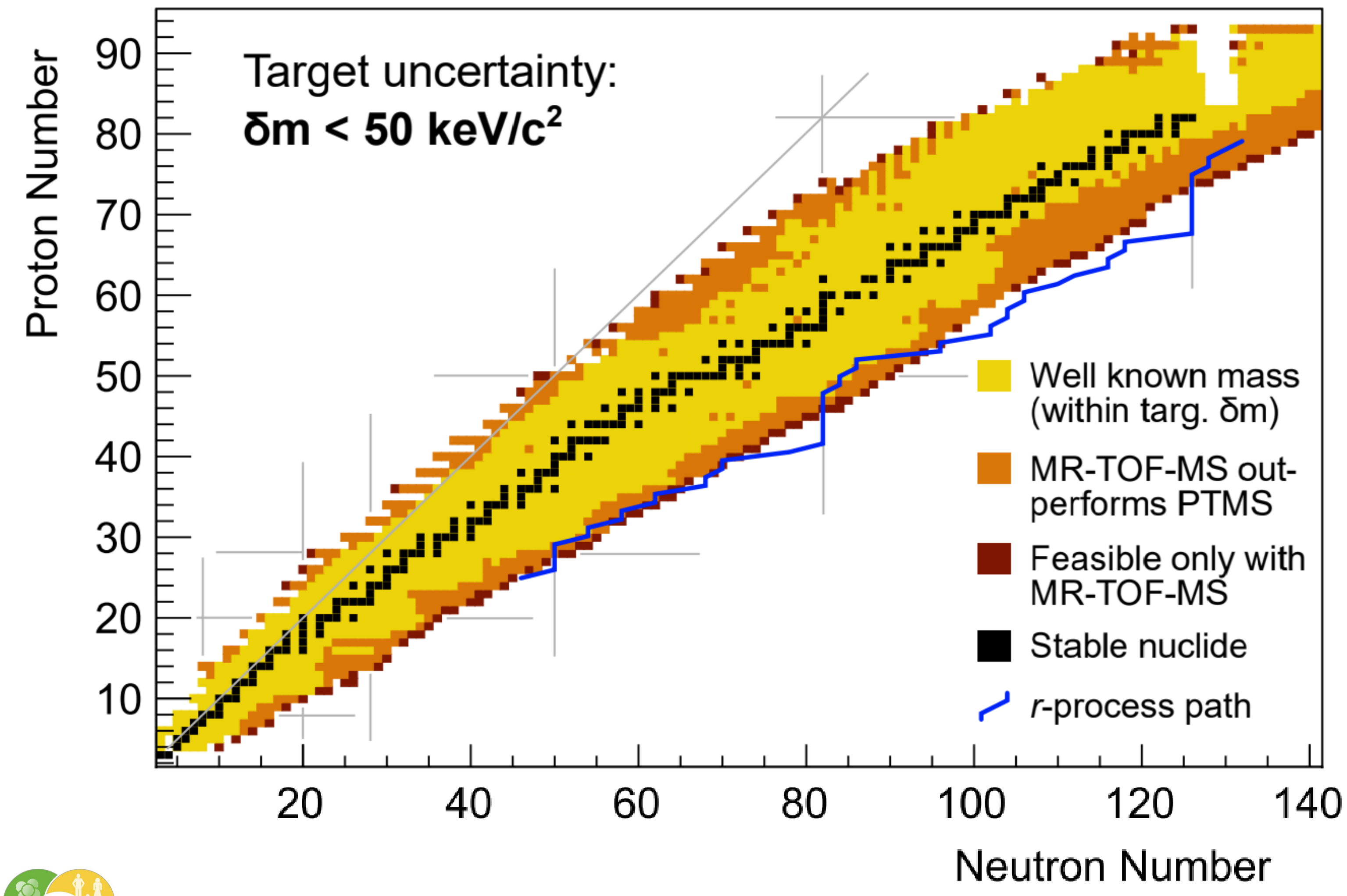

Recent mass measurements at LEBIT:

- ^{22}Al
  S.E. Campbell et al., PRL 132, 152501 (2024).
- ^{103}Sn
  C.M. Ireland, F.M. Maier et al., PRC 111, 014314 (2025).
- ^{101}Sn
  C.M. Ireland et al., PRC 113, L021302 (2026).
- ^{23}Si
  F.M. Maier et al, PRC 112, 014329 (2025).
- ^{51}Co + ^{52}Ni
  Measured a month ago
- $^{77\text{-}80}$Y + ^{79,80}Zr + ^{82,83}Nb
  Measured 1 week ago

Talk at SAMOP:
Mo, 2nd March, 17:00 – 17:30,
MS 2.1, N6

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FRIB

Summary

- MR-ToF devices enhance sensitivity for collinear laser spectroscopy (CLS)
  - Access electron affinities of rarely produced ions e.g. superheavies
  - Access nuclear ground state properties of scarcely produced radionuclides
- 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
  - Higher energy spread tolerance: higher mass resolving power in shorter processing time
  - Deliver isobaric and isomeric purified beams → unlock new experimental possibilities

ISOLDE CERN MIRACLS + FRIB U.S. DEPARTMENT OF ENERGY Office of Science MICHIGAN STATE UNIVERSITY

Thanks to the LEBIT and FRIB MR-ToF Team!

F.M. Maier, E. Dhayal, C. Ireland, E. Leistenschneider, A. Sjaarda, R. Ringle
for the FRIB MR-ToF collaboration

F.M. Maier, G. Bollen, S. Campbell, H. Erington, C. Ireland, R. Ringle
for the LEBIT collaboration

Thanks to all our experimental and theory collaboration partners!

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PostDoc

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Thanks to the MIRACLS team and collaborators!

MIRACLS proof-of-principle CLS 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 electron affinity collaboration:
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MIRACLS core high-voltage CLS collaboration:
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 CLS collaboration):
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

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

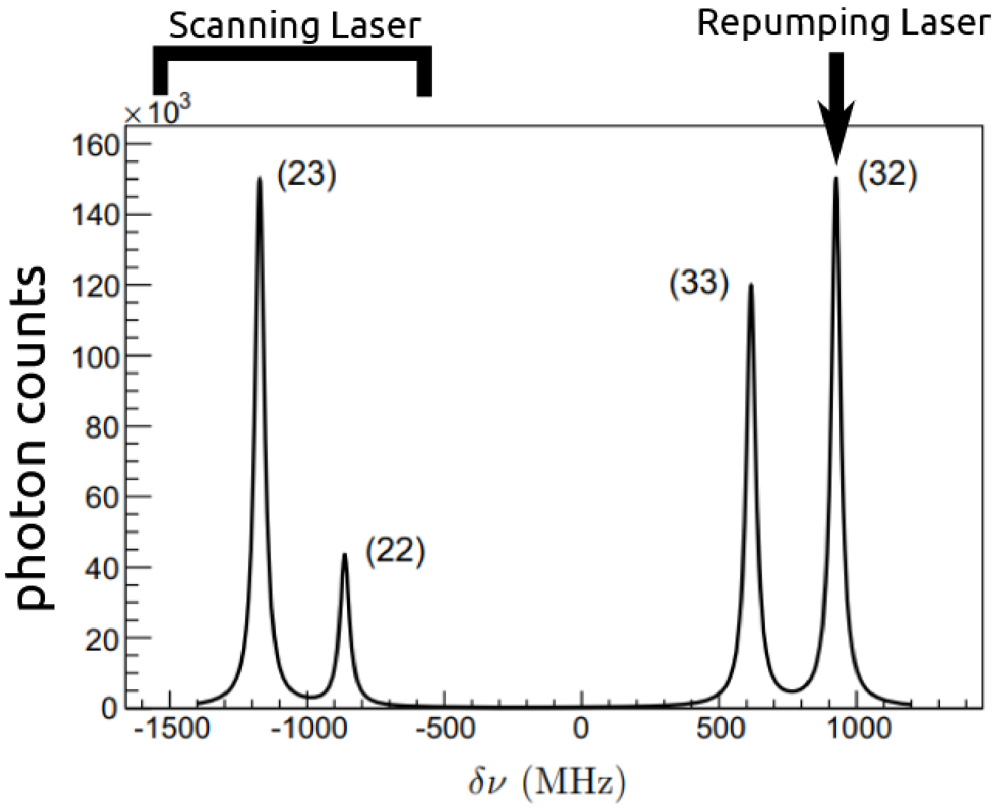
- F. M. Maier, E. Leistenschneider et al., Nat. Commun. 16, 9576 (2025) https://www.nature.com/articles/s41467-025-64581-x
- F.M. Maier, C.M. Ireland et al., NIMA 1084, 171220 (2026) https://doi.org/10.1016/j.nima.2025.171220
- C.M. Ireland, F.M. Maier et al., https://arxiv.org/abs/2510.11741
- E. K. 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

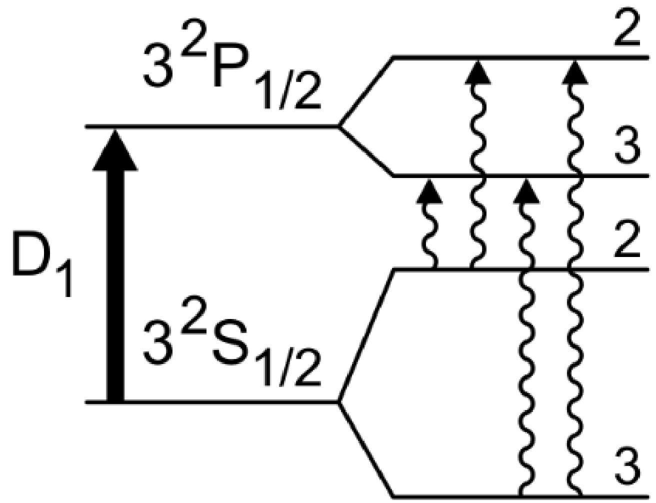
Our latest mass measurements at LEBIT I will present at SAMOP, Mo, 2nd March, 17:00-17:30, MS 2.1, N6.

MIRACLS Also Applicable Beyond Closed Two-Level Schemes

Odd-even scheme

- Repurposing Lasers: One for repumping, one for scanning

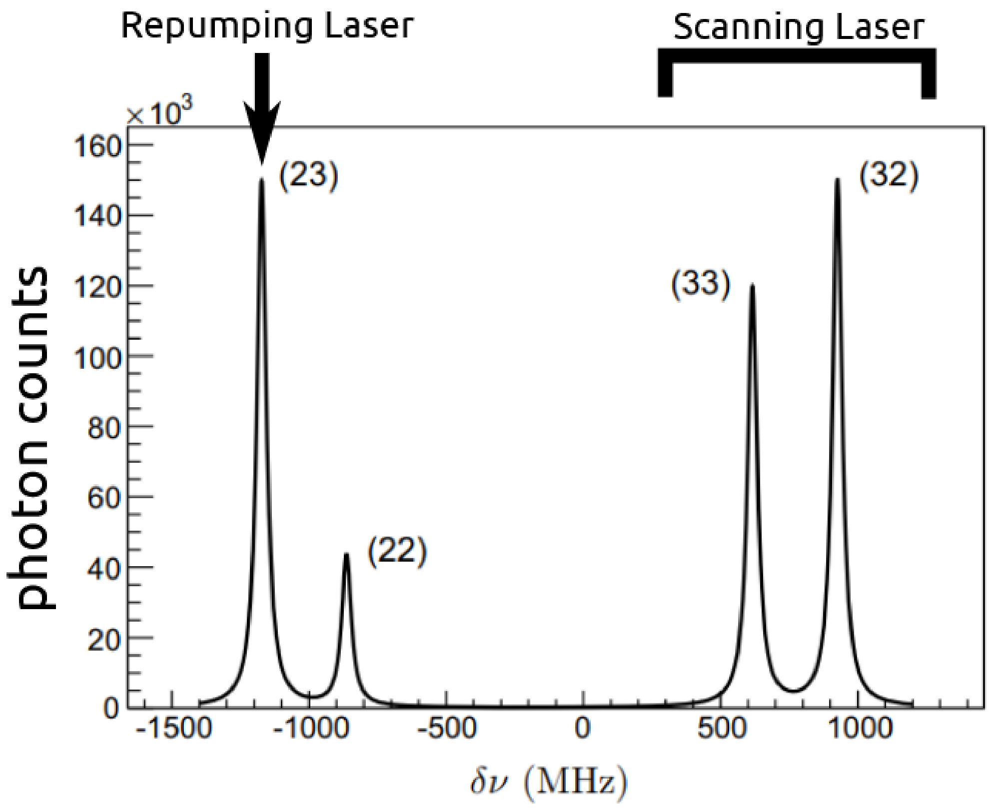


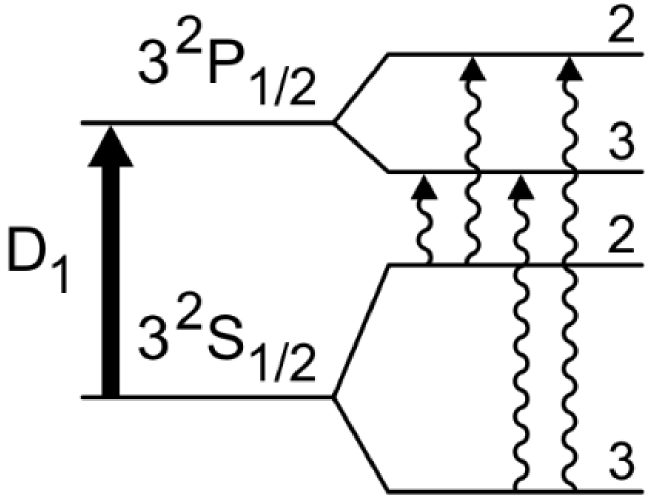


MIRACLS Also Applicable Beyond Closed Two-Level Schemes

Odd-even scheme

- Repurposing Lasers: One for repumping, one for scanning





MIRACLS Also Applicable Beyond Closed Two-Level Schemes

Odd-even scheme for cadmium