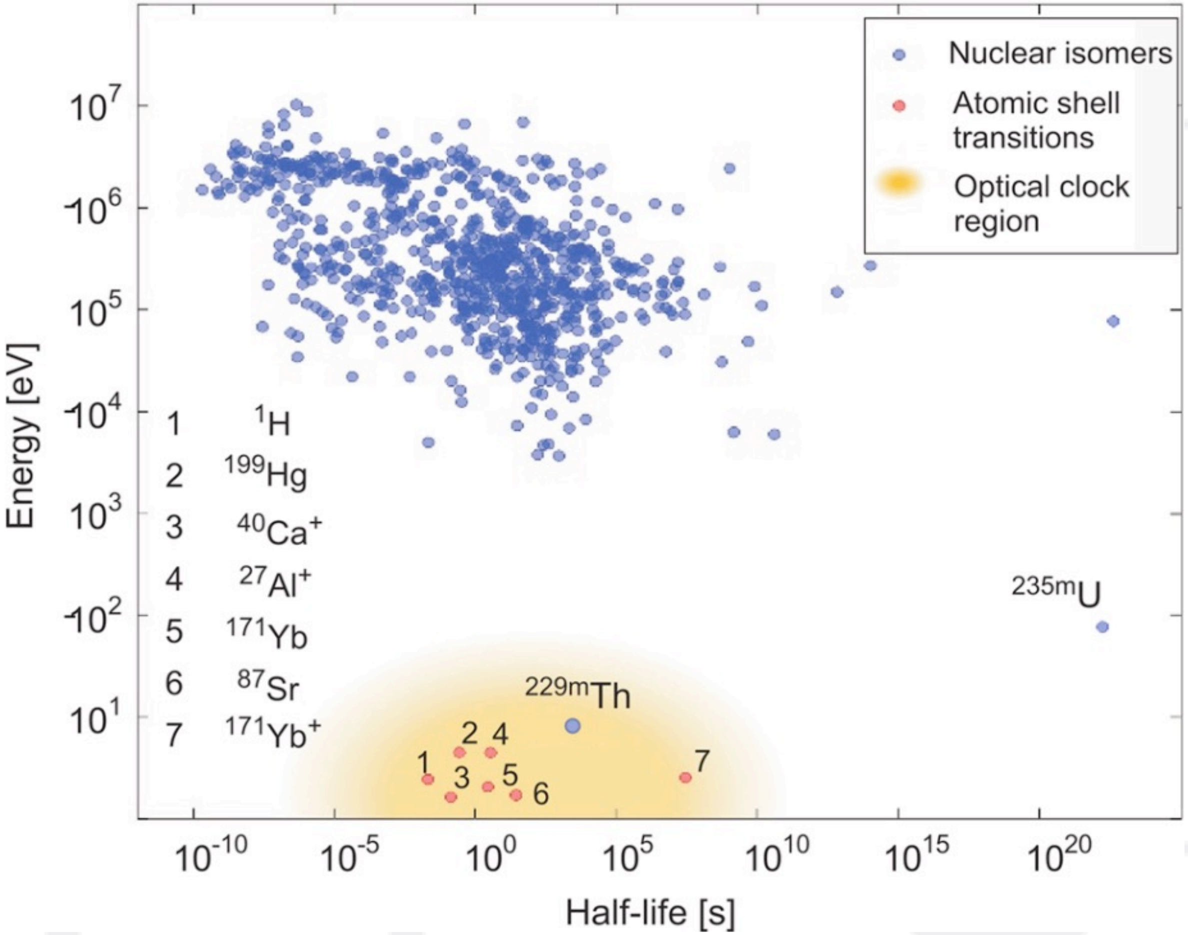
Progress of the LMU $^{229m}Th^{3+}$ Trapped-Ion Nuclear Clock Project

Georg Holthoff & Markus Wiesinger on behalf of
Kevin Scharl, Tamila Teschler, Irtiza Hussain, Daniel Moritz, Lilli Löbell, Sandro Kraemer,
Tim Theuner, Stephan Wissenberg, and Peter G. Thirolf

LMU Munich

European Research Council
Established by the European Commission

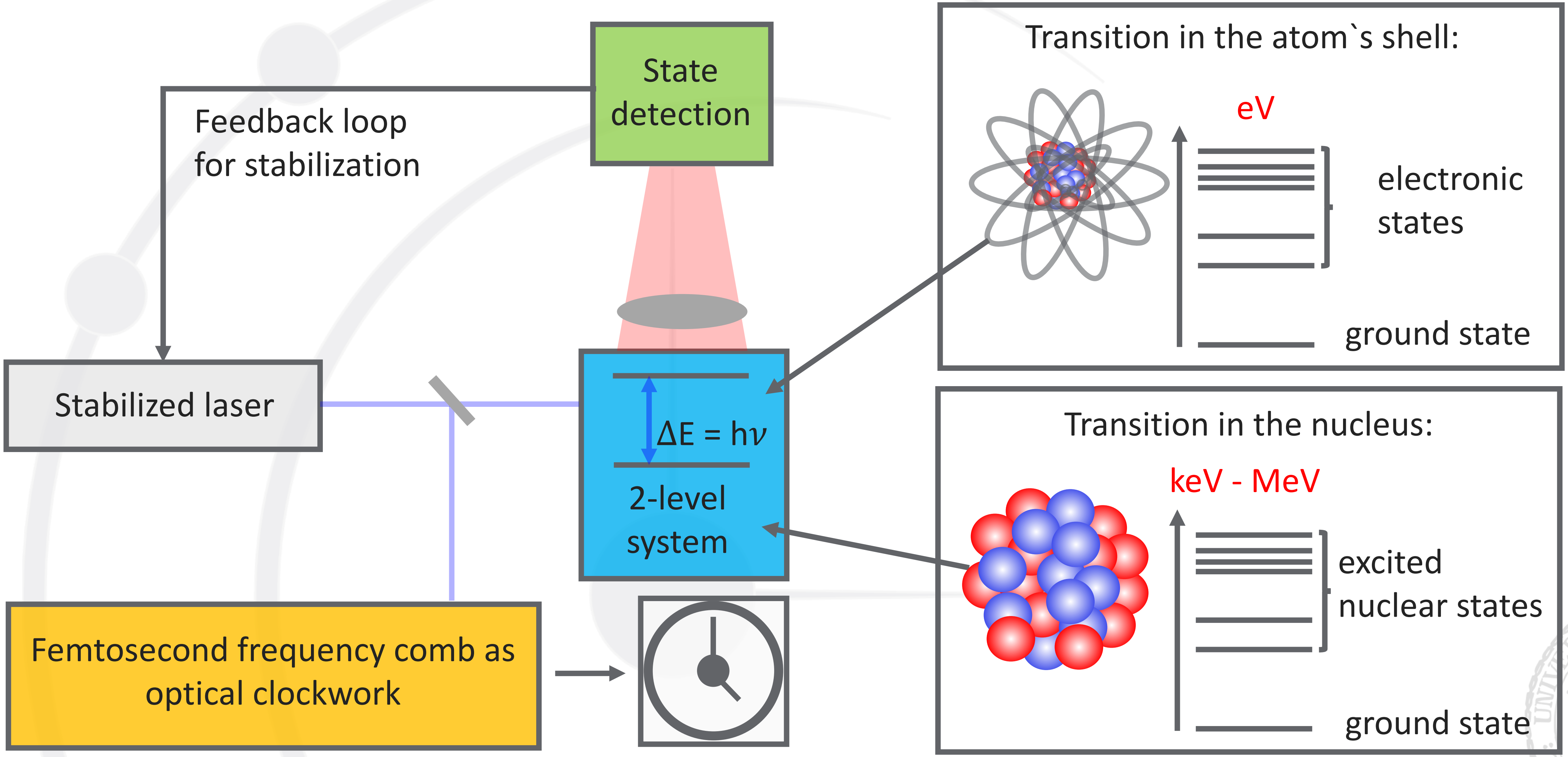
^{229m}Th – a Unique Nucleus



Original version in L. von der Wense *et al.*, Nature **533**, 47–51 (2016), updated in P. G. Thirolf *et al.*, Eur. Phys. J. Spec. Top. (2024).

- Existence of the isomer: identified via conversion electrons
  L. von der Wense *et al.*, Nature **533**, 47–51 (2016)
- Lifetime of the neutral isomer: τ_{IC} = 7 $\pm$ 1 μs
  B. Seiferle *et al.*,Phys. Rev. Lett. **118**, 042501 (2017)
- Hyperfine structure of $^{229(m)}Th^{2+}$ measured via collinear laser spectroscopy
  J. Thielking *et al.*, Nature **556**, 321-325 (2018)
- Excitation energy measurement:
  via conversion electrons → E_{ex} = 8.28 $\pm$ 0.17 eV
  B. Seiferle *et al.*, Nature **573**, 243–246 (2019)
  via magnetic microcalorimetry → E_{ex} = 8.10 $\pm$ 0.17 eV
  T. Sikorsky *et al.*, Phys. Rev. Lett. **125**, 142503 (2020)
  via radiative decay → E_{ex} = 8.338 $\pm$ 0.024 eV
  S. Kraemer *et al.*, Nature **617**, 706–710 (2023)
- Expected systematic frequency uncertainty
  $\frac{\Delta\nu}{\nu}$ =1.5 x 10^{-19}
  C. Campbell *et al.*, Phys. Rev. Lett. **108**, 120802 (2012)

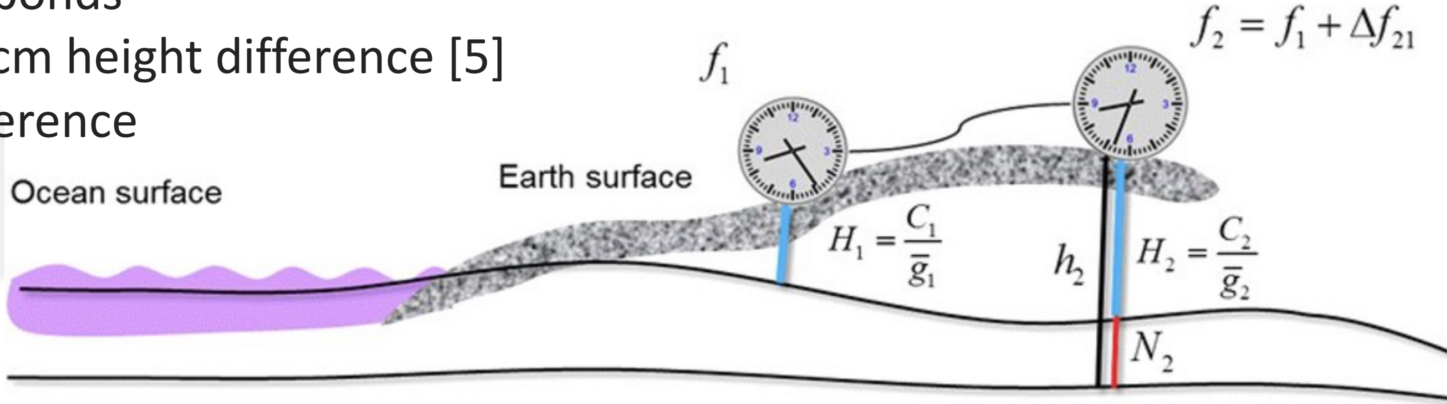
The Concept of a ^{229}Th Nuclear Clock



E. Peik & C. Tamm, Europhys. Lett. **61**(2), 181-186 (2003)

Possible Applications of a Nuclear Clock

- Same operation principle as atomic clocks – but strong interaction contributes to transition frequency
  → **complementary to atomic clocks where the transition frequency is determined by the Coulomb force [1,2]**
- Search for time variation of fundamental constants ($\dot{\alpha}$, Λ)
  → ^{229}Th provides a largely enhanced sensitivity to changes in α [1, 3, 4]
- Search for ultralight Dark Matter candidates [1, 5]
- Improved precision of satellite-based navigation [5]
- Gravity sensor: 10^{-18} relative precision corresponds
  to gravitational frequency shifts caused by 1 cm height difference [5]
  → systematic uncertainty ≈ 1 mm height difference



[1] E. Peik *et al.*, Quantum Science and Technology **6,** 034002 (2021)
[2] K. Beeks *et al.*, Nat. Rev. Phys. **3**, 238–248 (2021)
[3] J. P. Uzan, Living Rev. Relativ. **14**, 2 (2011)
[4] V. V. Flambaum, Phys. Rev. Lett. **97**, 092502 (2006)
[5] P. G. Thirolf et al., Annalen der Physik **531**, 1800381 (2019)

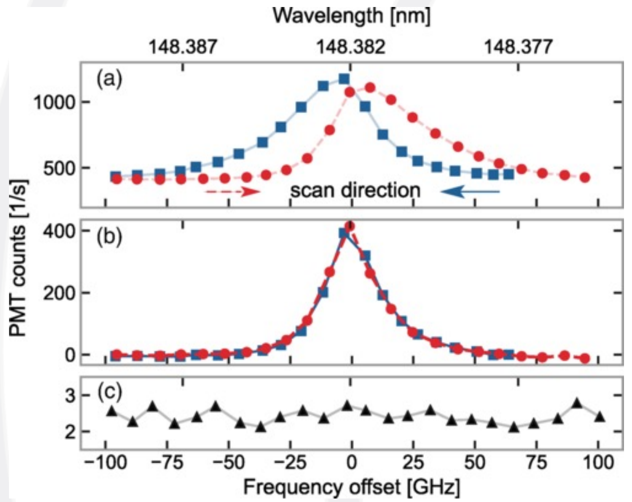
Recent Breakthroughs

PTB / TU Wien Team:
Laser excitation of Th-229 in a CaF_2 crystal

ν = 2020.409(7) THz

E = 8.355 74(3) eV

λ = 148.3821(5) nm



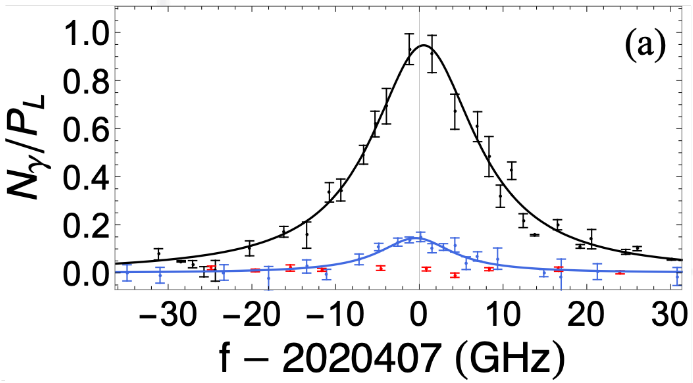
J. Tiedau *et al.*, Phys. Rev. Lett. **132** 182501 (2024)

UCLA Team:
Laser excitation of Th-229 in a $LiSrAlF_6$ crystal

ν = 2020 407.3(5)$_{stat}$(30)$_{sys}$ GHz

E = 8.355 733(2)$_{stat}$(10)$_{sys}$ eV

λ = 148.382 19(4)$_{stat}$(20)$_{sys}$ nm

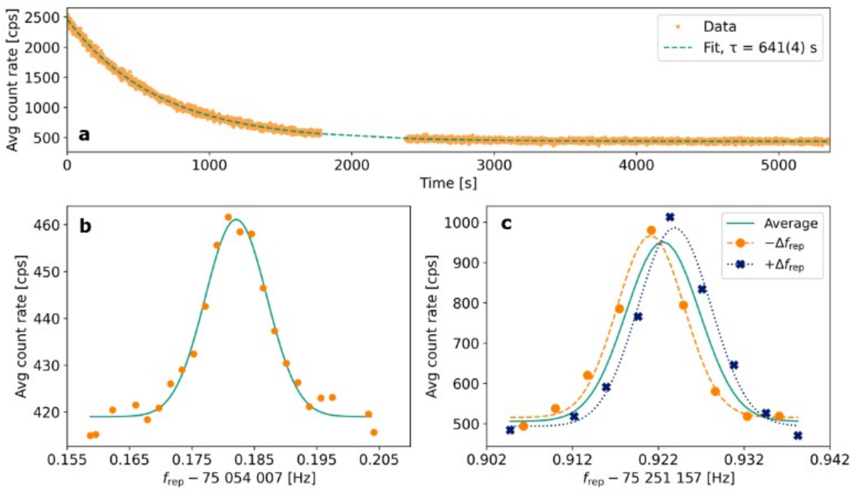


R. Elwell *et al.*, Phys. Rev. Lett. **133,** 013201 (2024)

JILA Boulder / TU Wien Team:
Frequency comb spectroscopy of Th-229 in a CaF_2 crystal

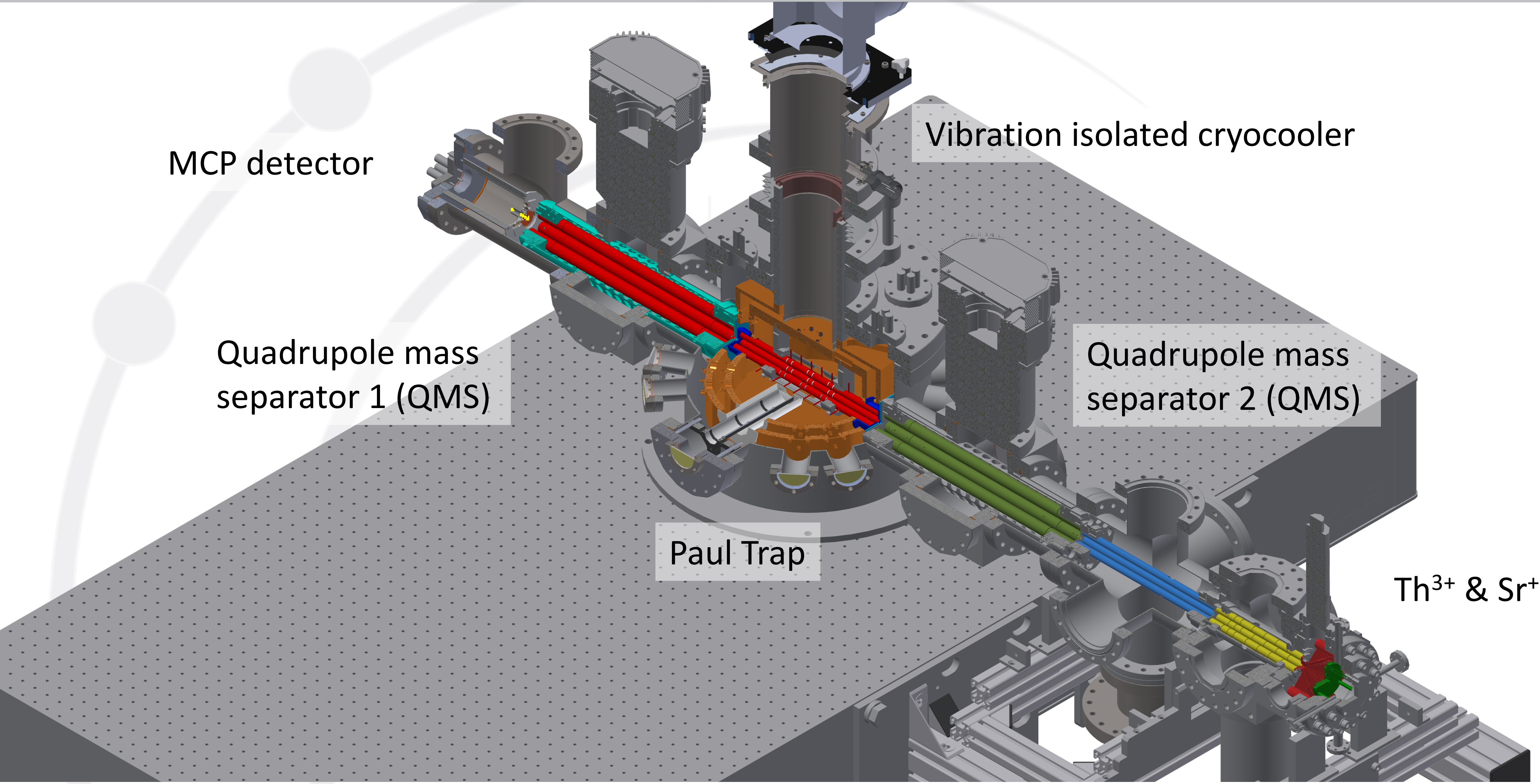
ν_{Th} = 2 020 407 384 335(2) kHz

ν_{Th}/ν_{Sr} = 4.707 072 615 078(5)



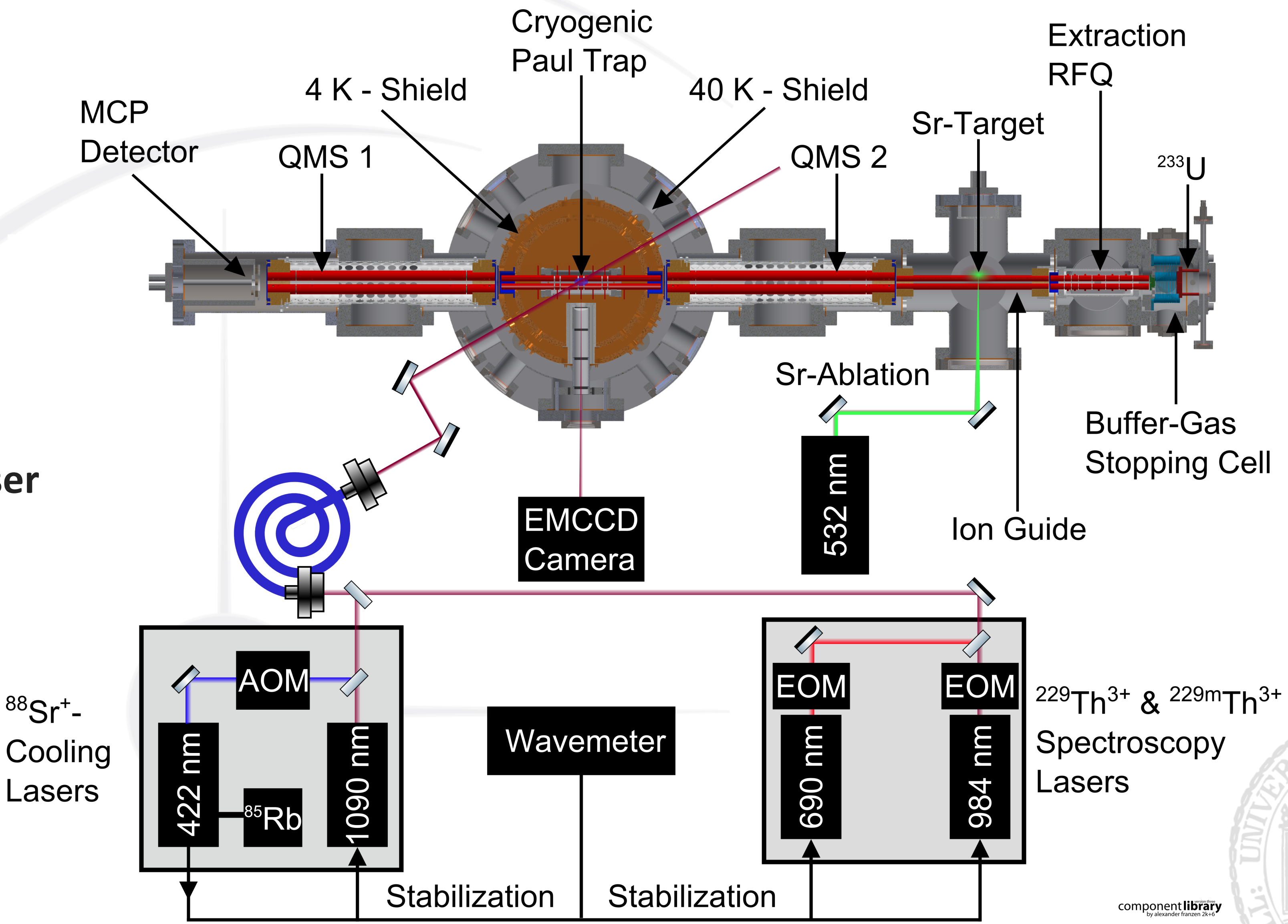
Zhang et al., arXiv:2406.18719 (2024)

Cryogenic Paul-Trap Experiment at LMU

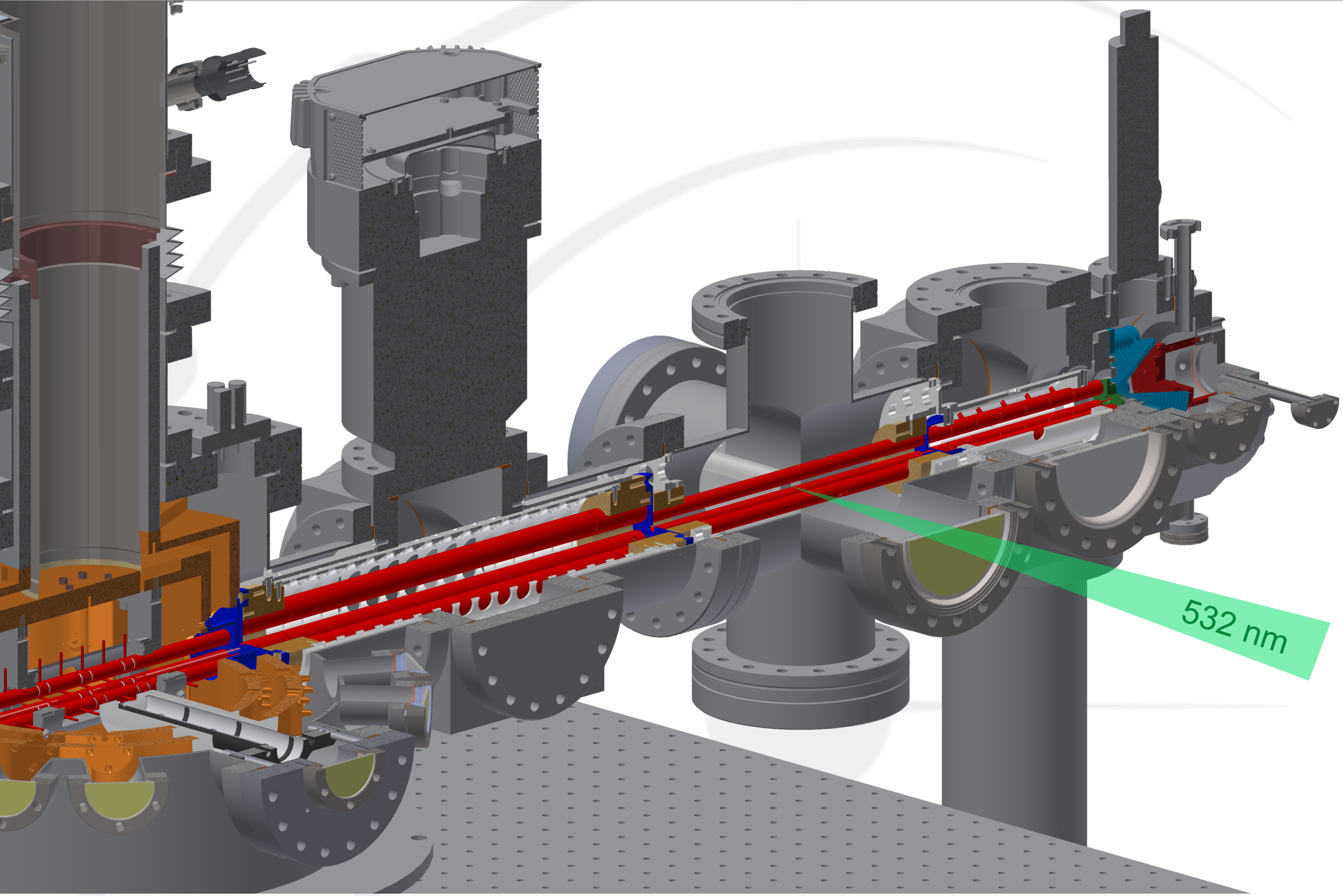


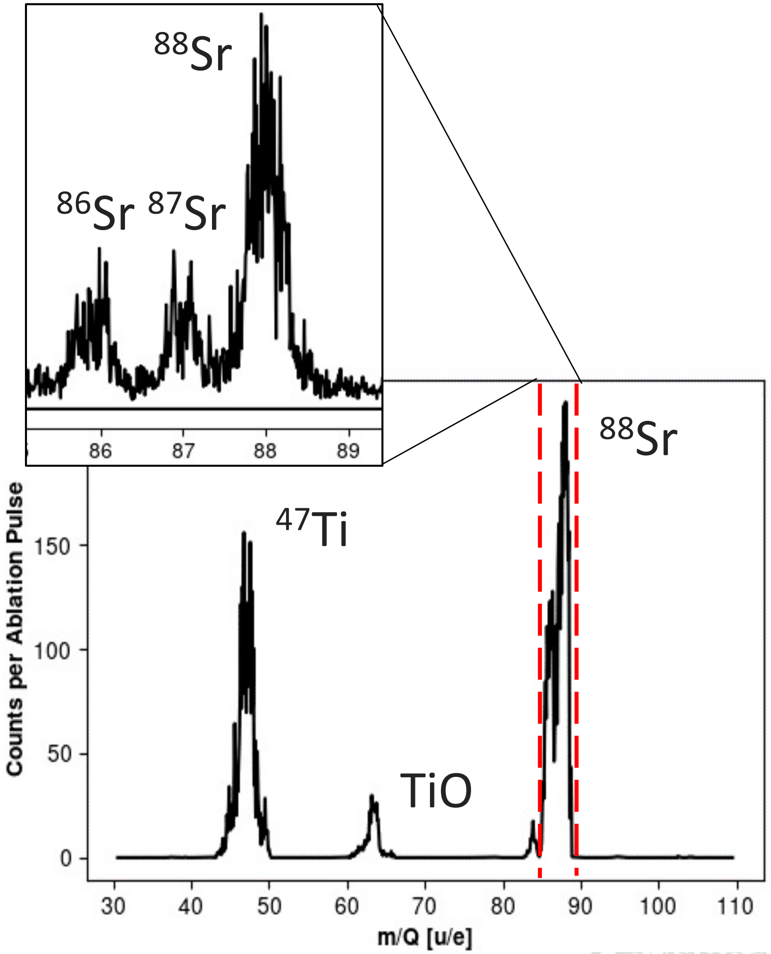
Laser System

- **422 nm diode laser**
  for Sr^+ cooling
  stabilized to Rb cell
- **1092 nm diode laser**
  for Sr^+ repumping
  stabilized to wavemeter
- **690 nm & 984 nm diode laser**
  for Th^{3+} spectroscopy
  stabilized to wavemeter
- **Pulsed 532 nm Nd:YAG laser**
  for Sr^+ ablation



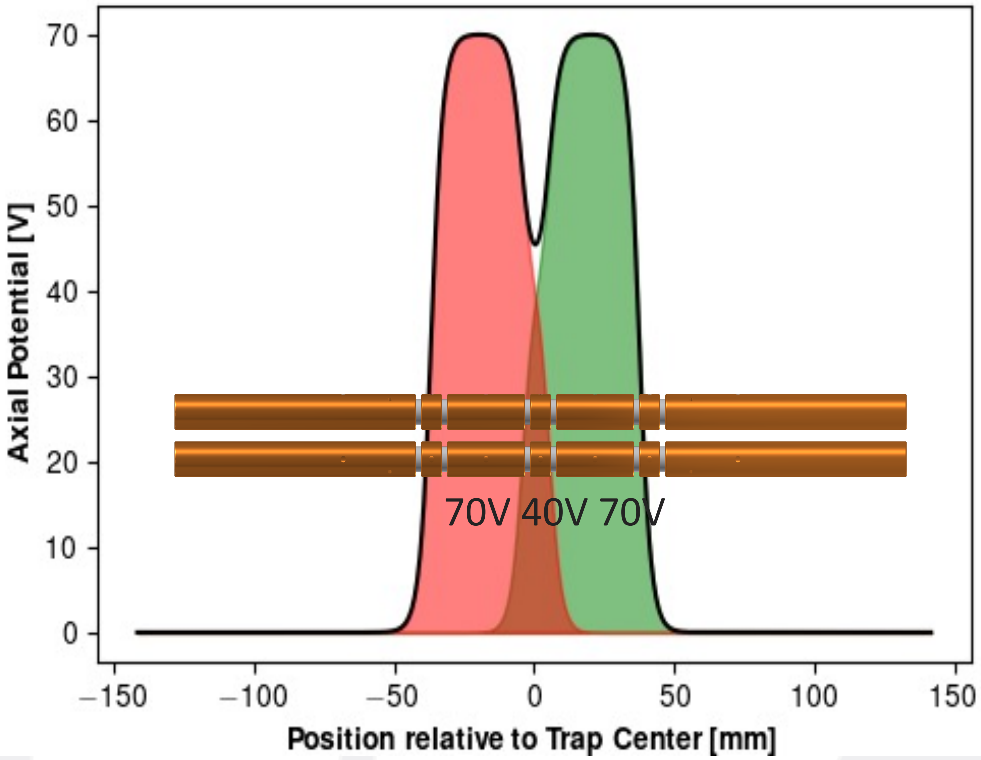
$^{88}Sr^+$ Ablation

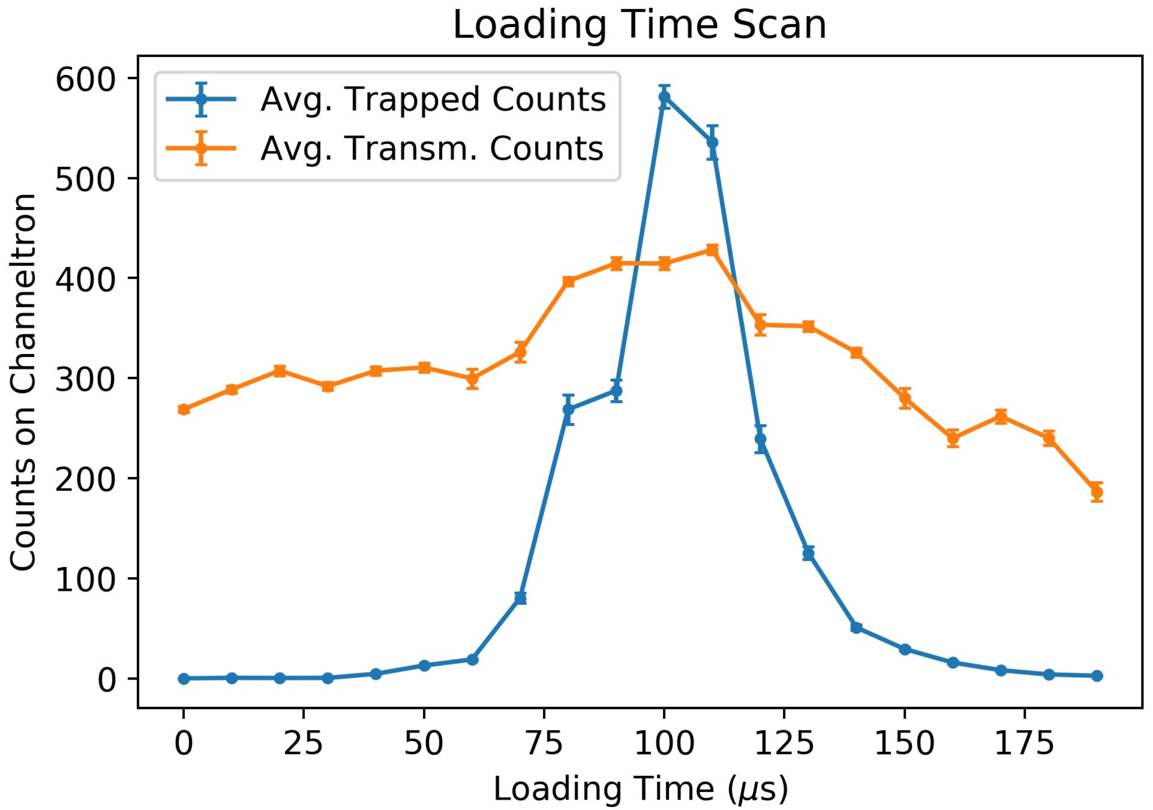




Ablation on $SrTiO_3$-crystal with 2 mJ laser pulses of 5 ns at 532 nm
→ up to 60 eV particle energy

$^{88}Sr^{+}$ Trapping





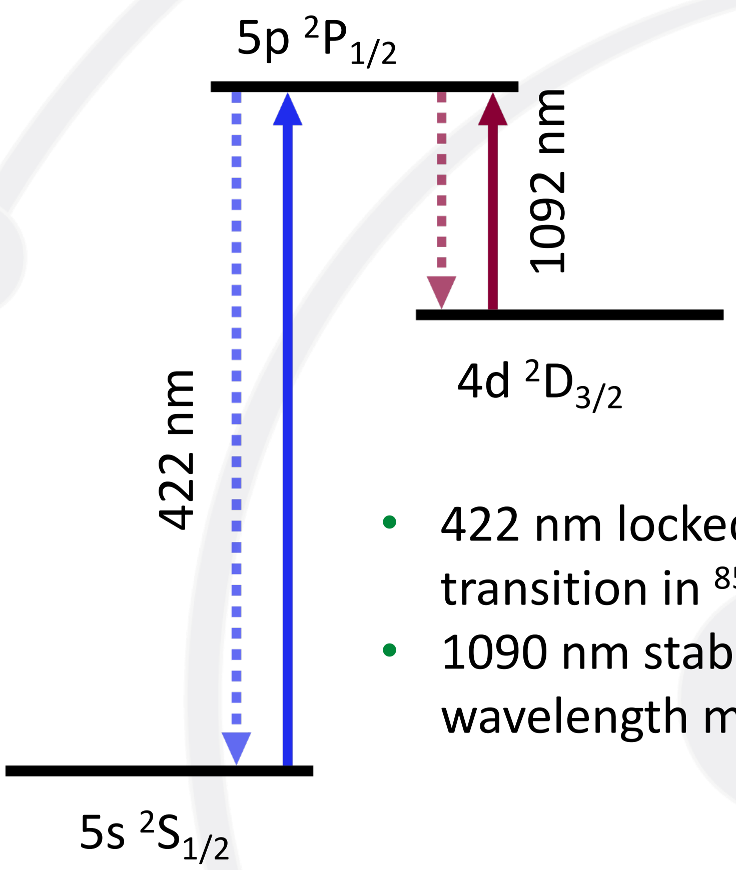
- Loading potential
- Trapping potential
- Release potential

RF-Frequency: 1.96 MHz
RF-Amplitude: 720 Vpp
$\Rightarrow q = 0.27$

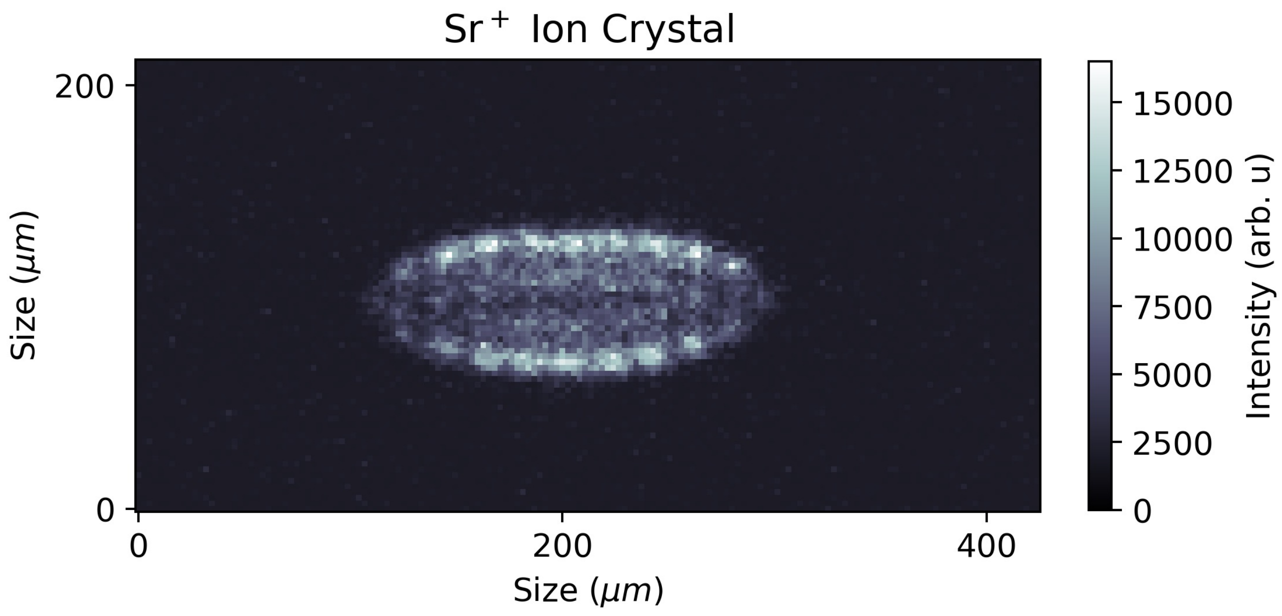
Channeltron saturation on transmission, but not for trap counts

$^{88}Sr^{+}$ Laser Cooling

$^{88}Sr^{+}$ laser cooling scheme:

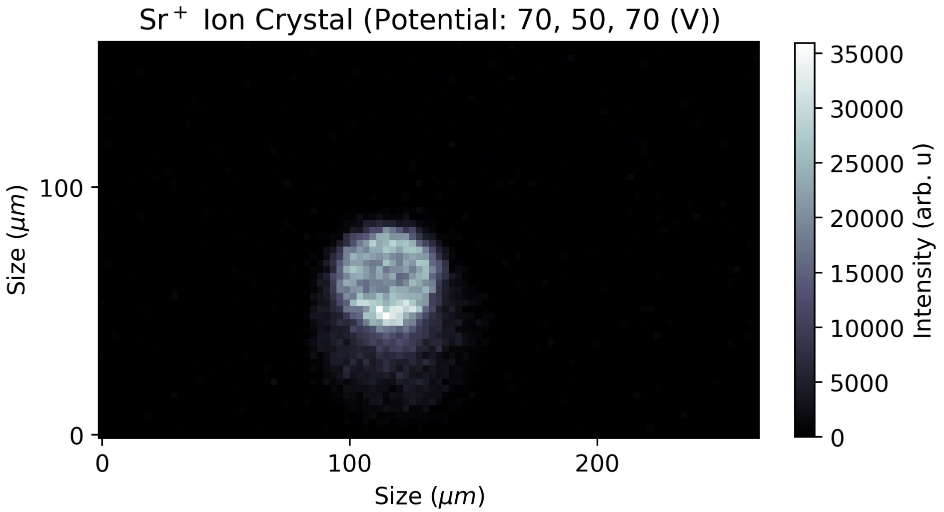


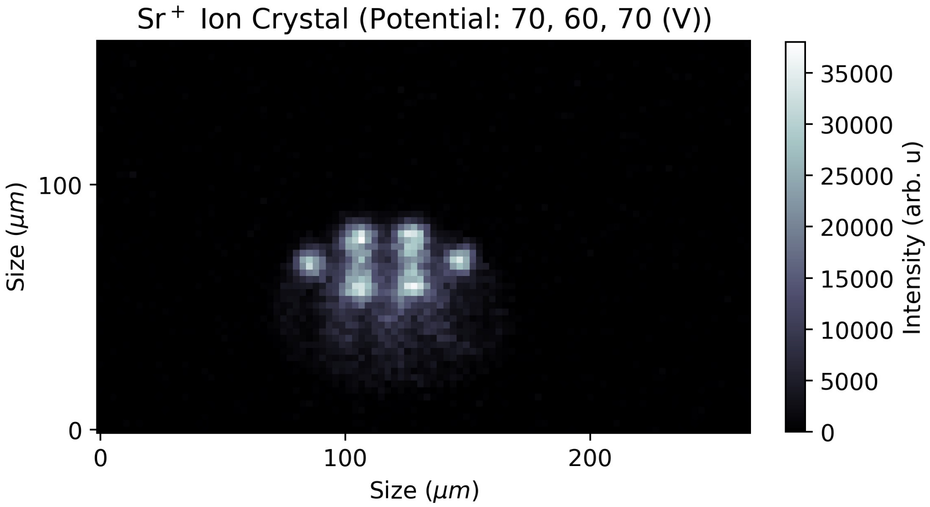
- 422 nm locked to HFS transition in ^{85}Rb
- 1090 nm stabilized with wavelength meter

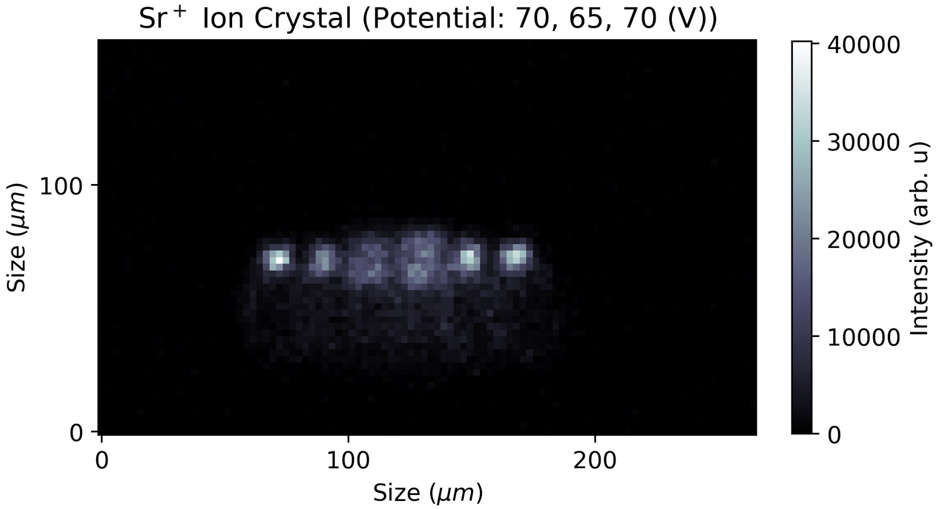


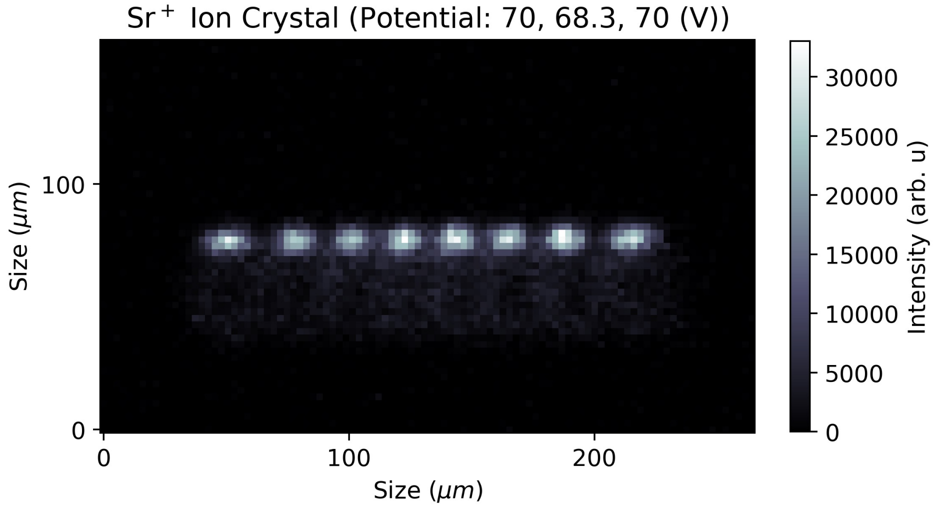
Crystal with several hundred ions
10 V well depth

$^{88}Sr^{+}$ Ion Crystals





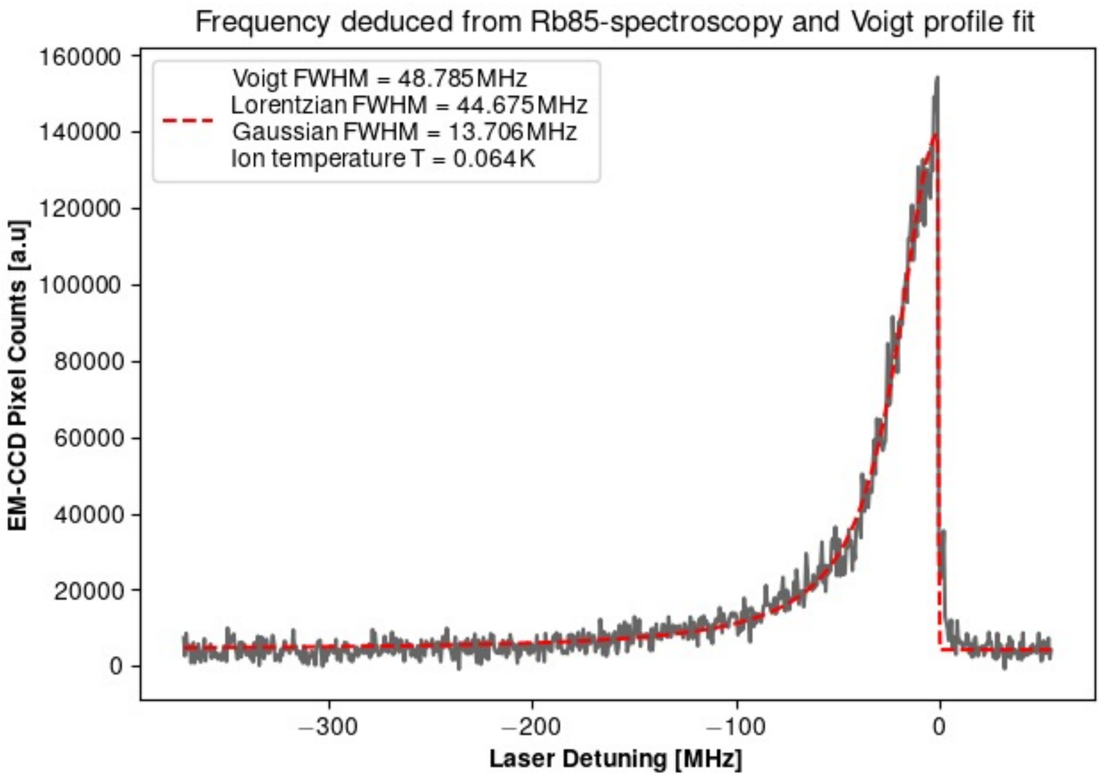




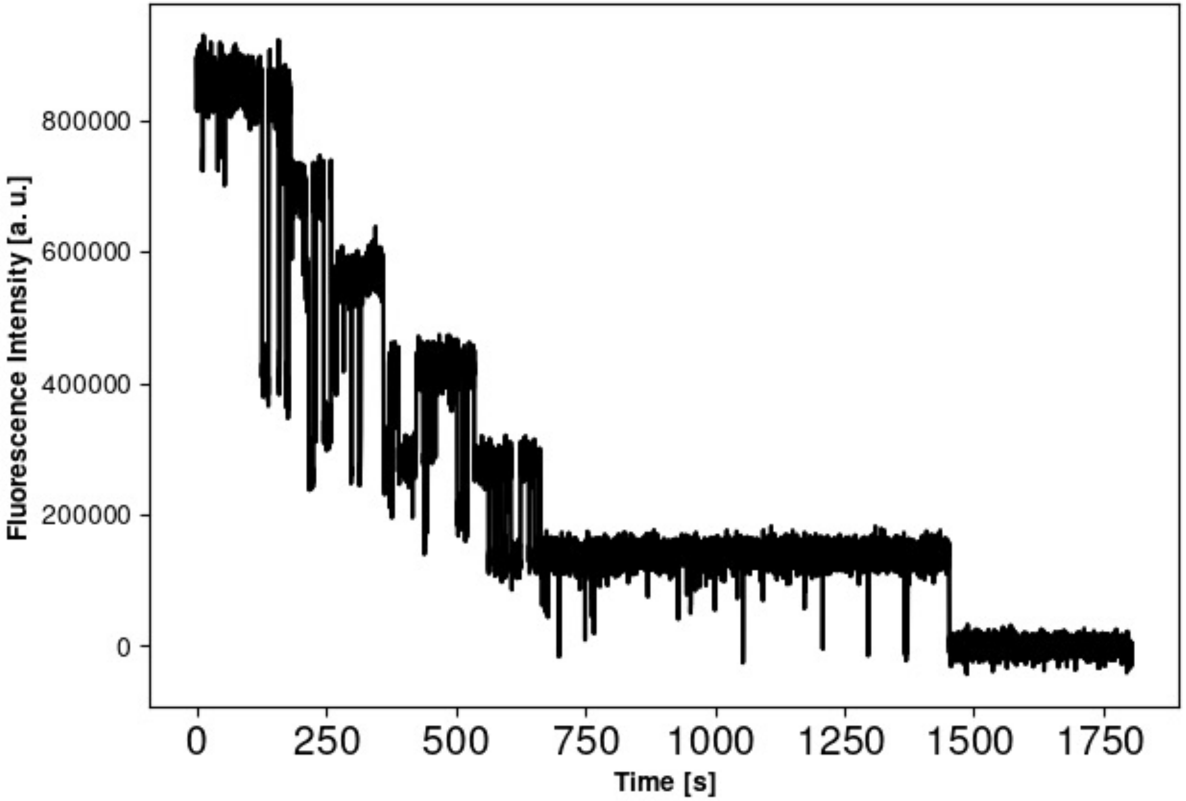
8 ions at 20K, p < 5 E-10 mbar

$^{88}Sr^{+}$ Temperature Estimate

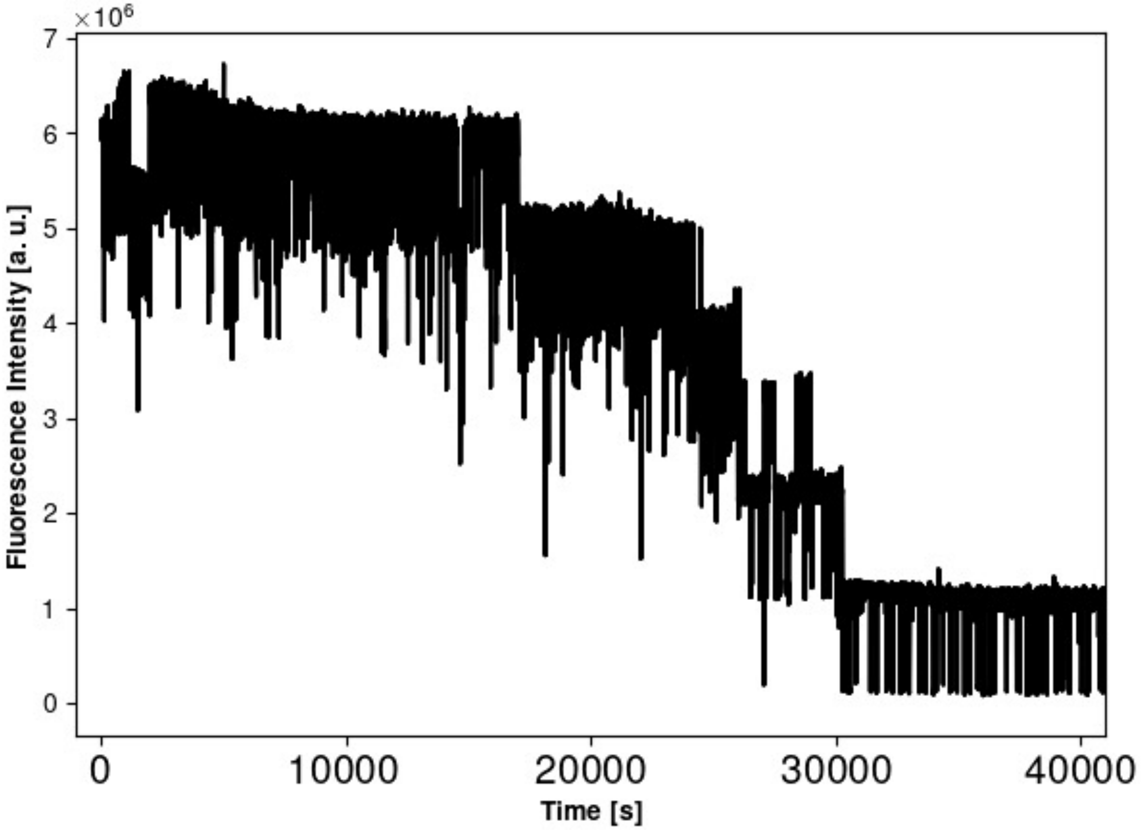
- Scan of 422 nm resonance (6 ions)
- Fit a truncated Voigt profile
- Gaussian width gives estimate of ion temperature ⇒ 64 mK



$^{88}Sr^{+}$ Storage Time

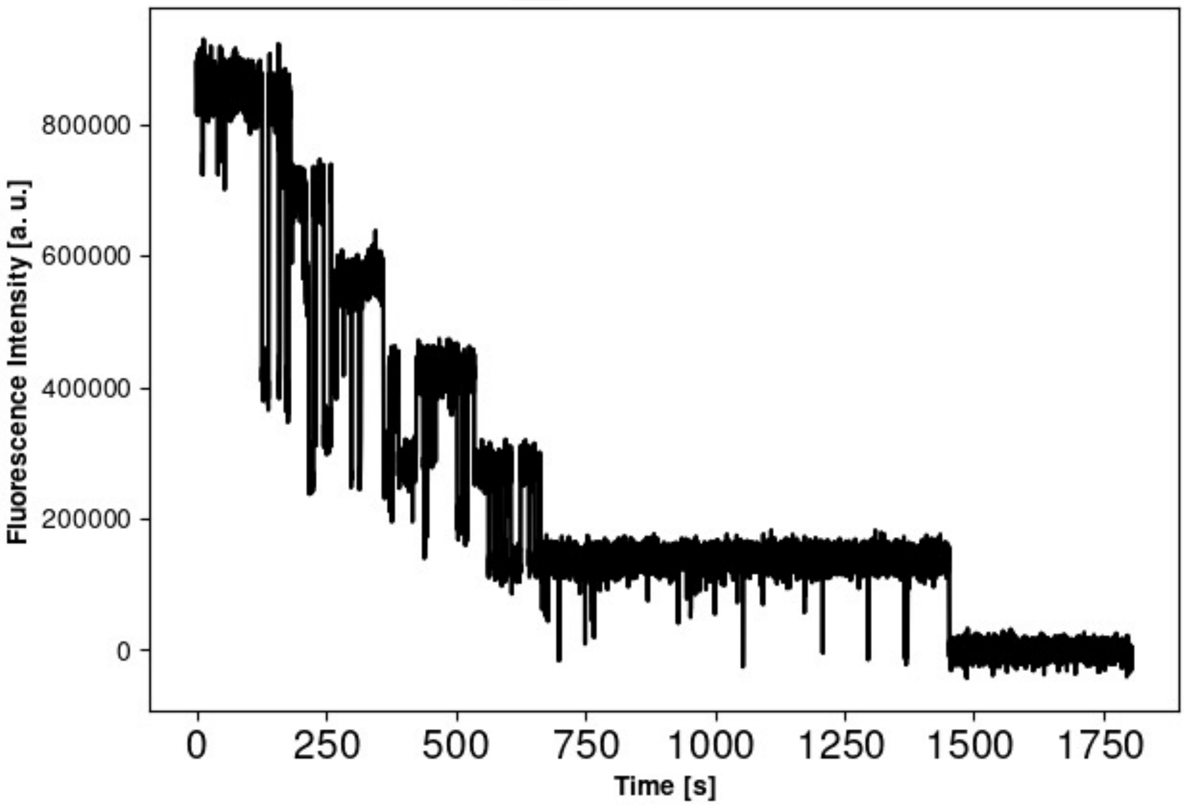


Room temperature measurement starting with 6 ions

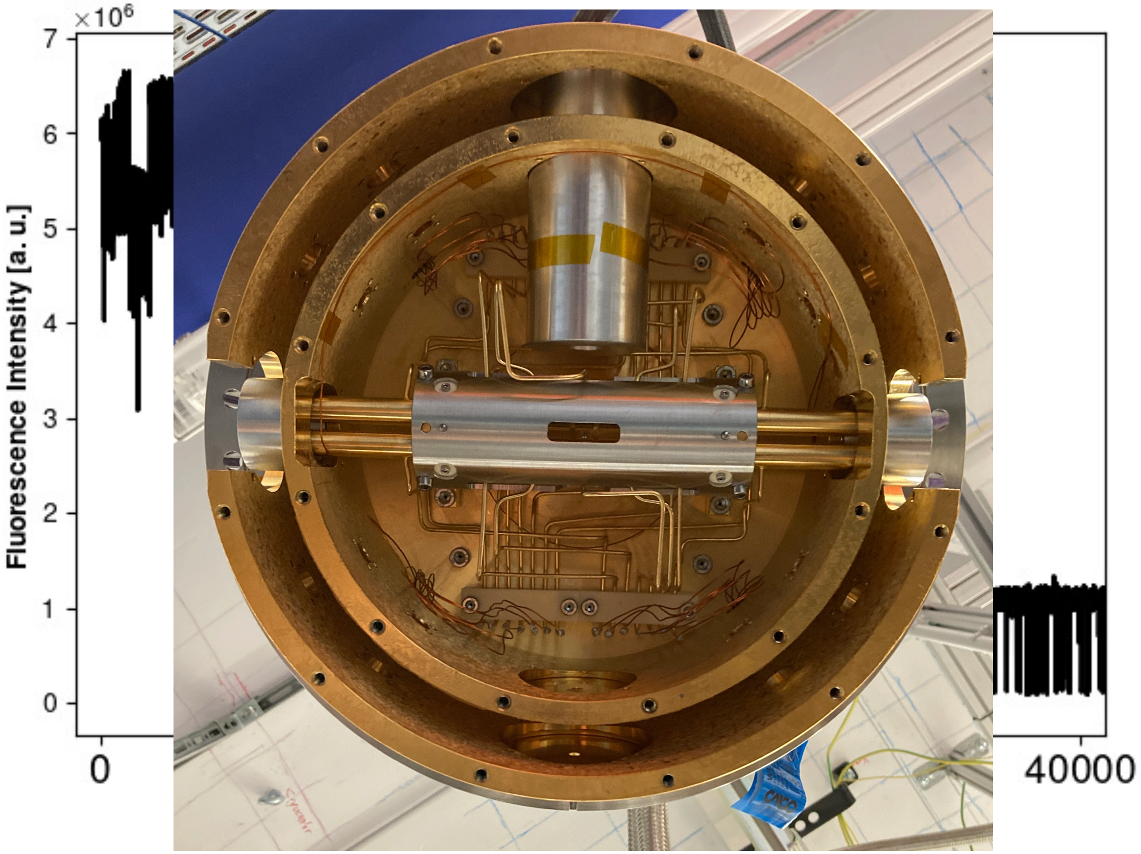


Cryogenic measurement starting with 6 ions (with parts of the thermal shielding not yet installed ⇒ 20 K)

$^{88}Sr^{+}$ Storage Time



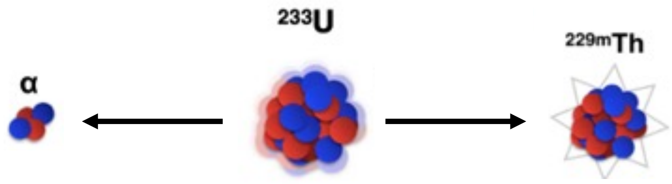
Room temperature measurement
starting with 6 ions

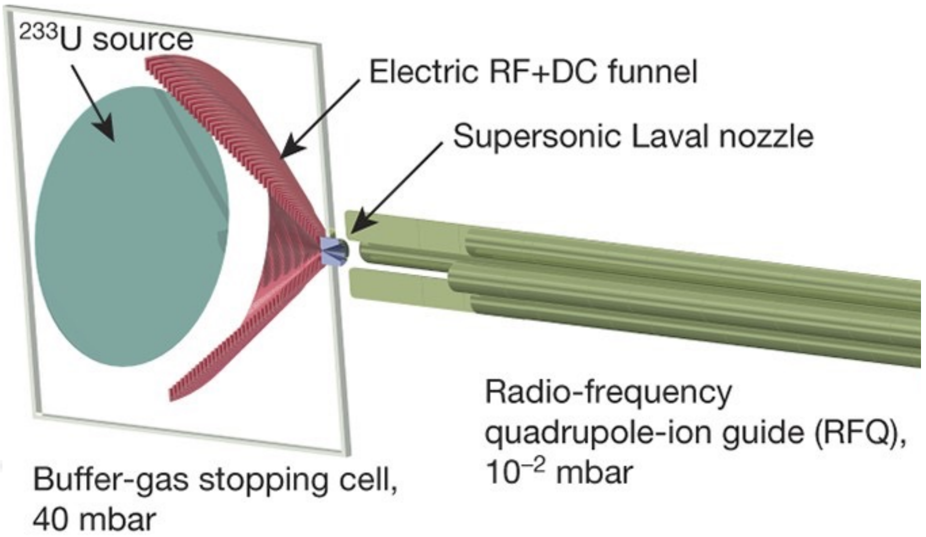


Cryogenic measurement
starting with 6 ions
(with parts of the thermal
shielding not yet installed ⇒ 20 K)

Principle of Th^{3+} Ion Source

- Alpha decay of ^{233}U (10 kBc)
- Recoil daughters ^{229}Th (98%) and ^{229m}Th (2%) with 84 keV kinetic energy
- Stopped in 30 mbar He buffer gas
- Collected with RF funnel
- Re-accelerated by supersonic gas jet through de Laval nozzle (d = 400 µm)

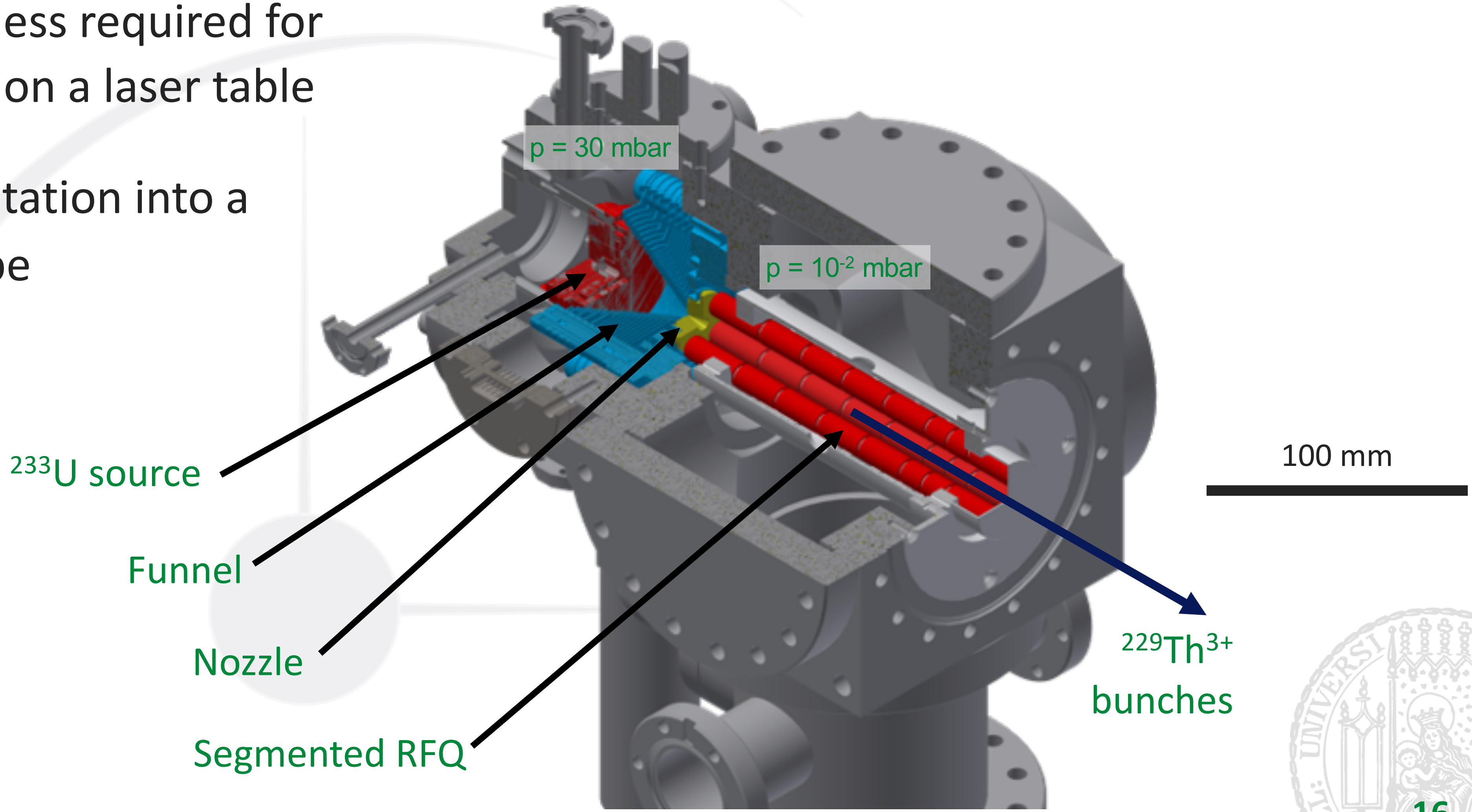




von der Wense, L. *et al.* *Nature* **533**, 47–51 (2016)

A Compact Th^{3+} Ion Source

- Compactness required for mounting on a laser table
- Implementation into a CF100 cube



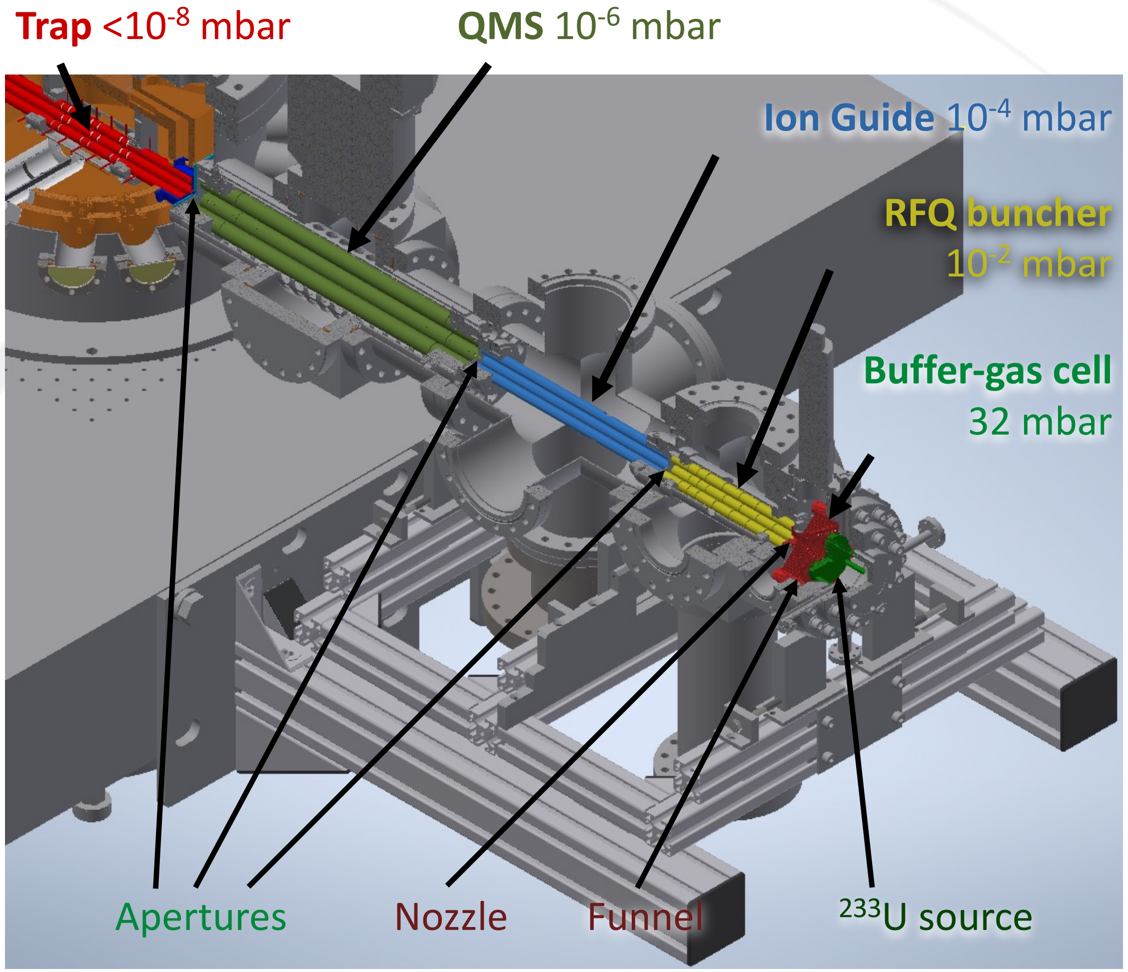
Differential Pumping

- **Vacuum requirement:**

  32 mbar He in buffer-gas cell

  $<10^{-8}$ mbar in ion trap

- **Differential Pumping!**



- **Vacuum achieved:**

  32 mbar He in buffer-gas cell

  5×10^{-3} mbar in RFQ

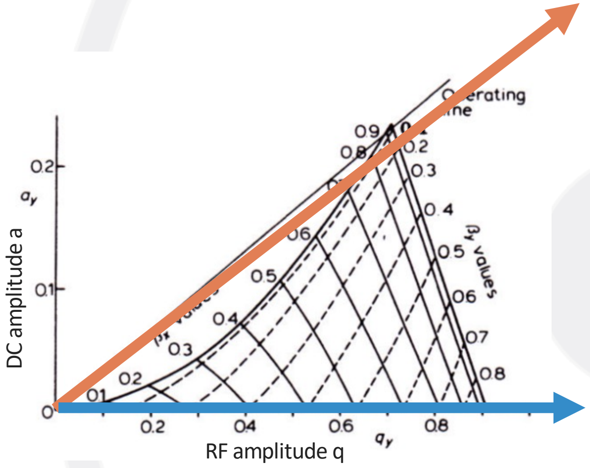
  7×10^{-6} mbar in Ion Guide

  6×10^{-7} mbar in QMS

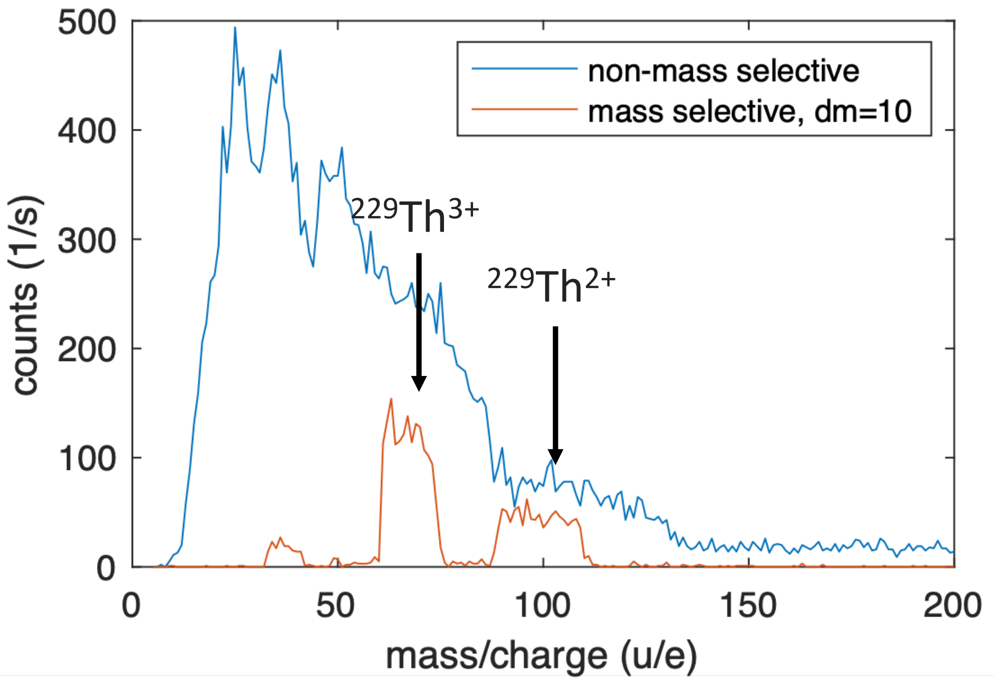
  6×10^{-9} mbar in ion trap

Mass Spectra of Th^{3+}

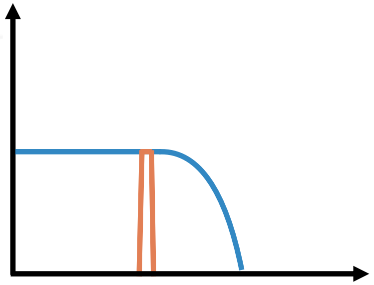
- RFQ section:
  non-mass selective
- IG section:
  mass selective or
  non-mass selective



Dawson, Quadrupole Mass Spectrometry and Its Applications (1976)

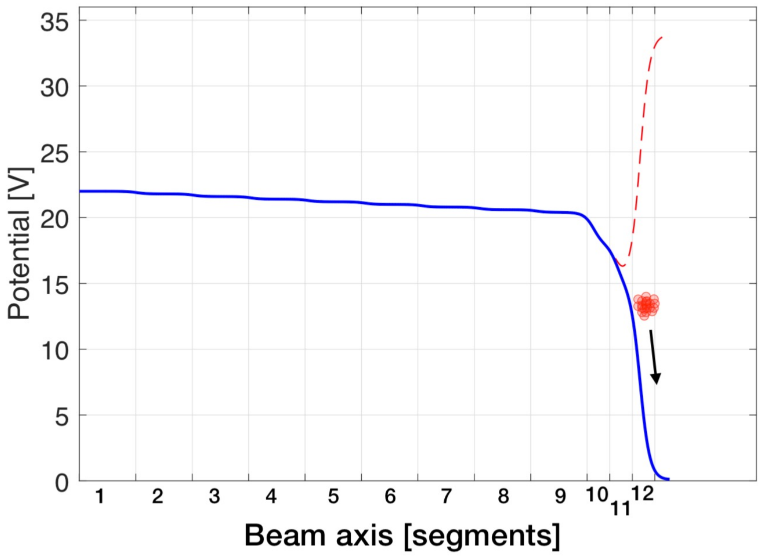


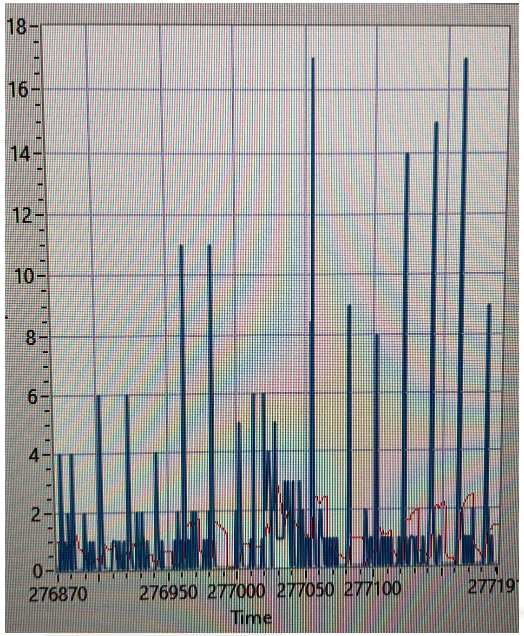
ideal spectra:



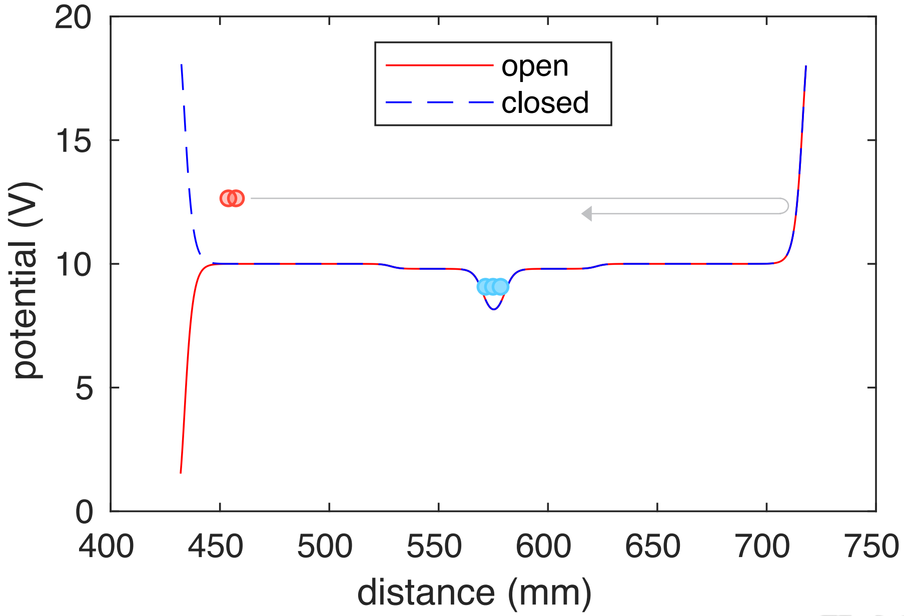
Pulsed Extraction and Re-Trapping of Th^{3+}

Pulsing the RFQ voltage from trapping to extraction:



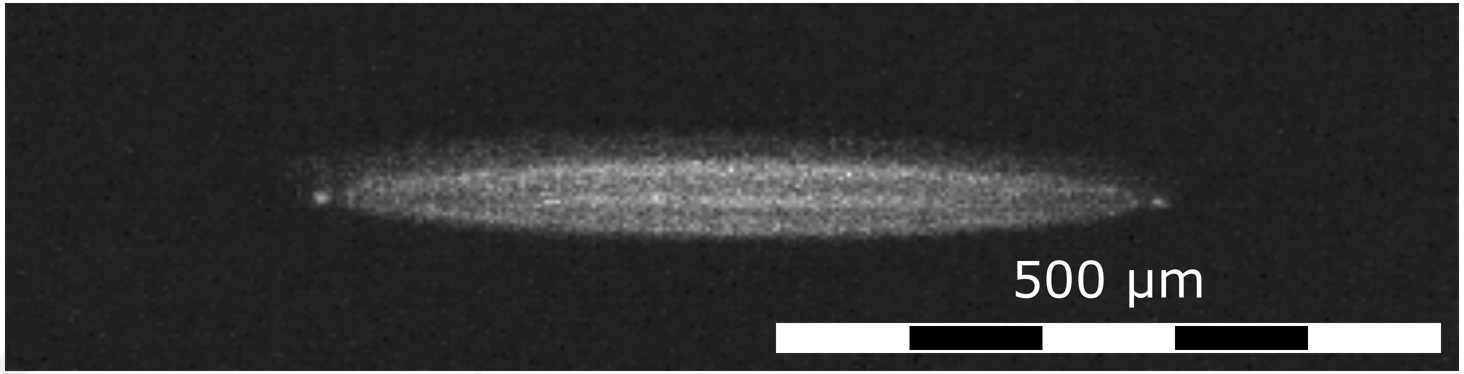


Catching the Th^{3+} ions in the Paul trap:



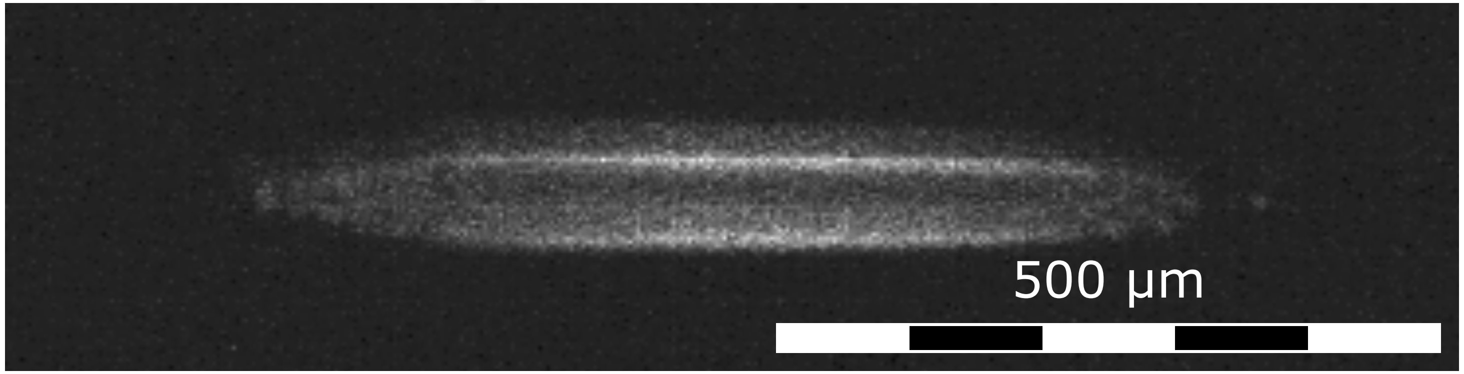
Mixed Th^{3+} Sr^{+} Ion Crystals

A cloud of Sr^{+} ions before loading Th^{3+}



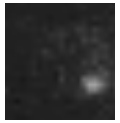
Sr^{+}

A mixed cloud of Sr^{+} and Th^{3+} ions after loading Th^{3+}

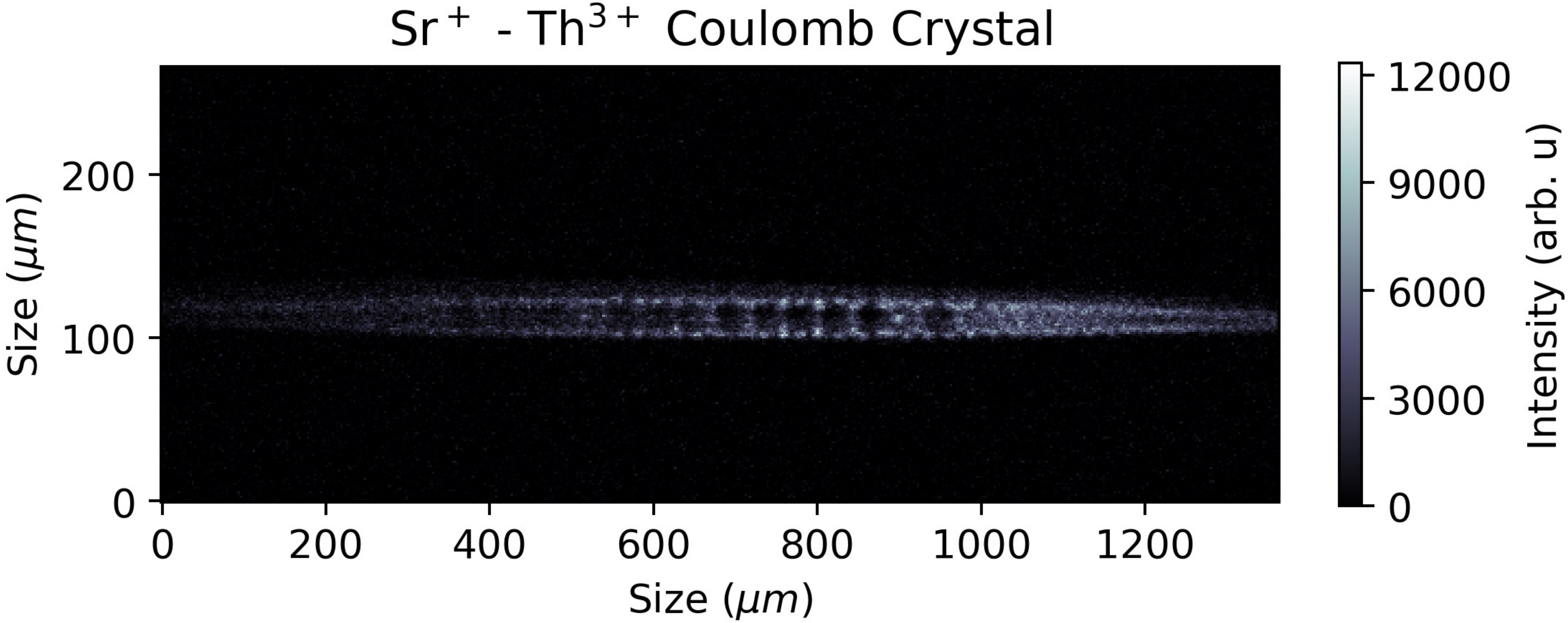


$Sr^{+} + Th^{3+}$

Note: point spread function contains aberrations



Mixed Th^{3+} Sr^{+} Ion Crystals



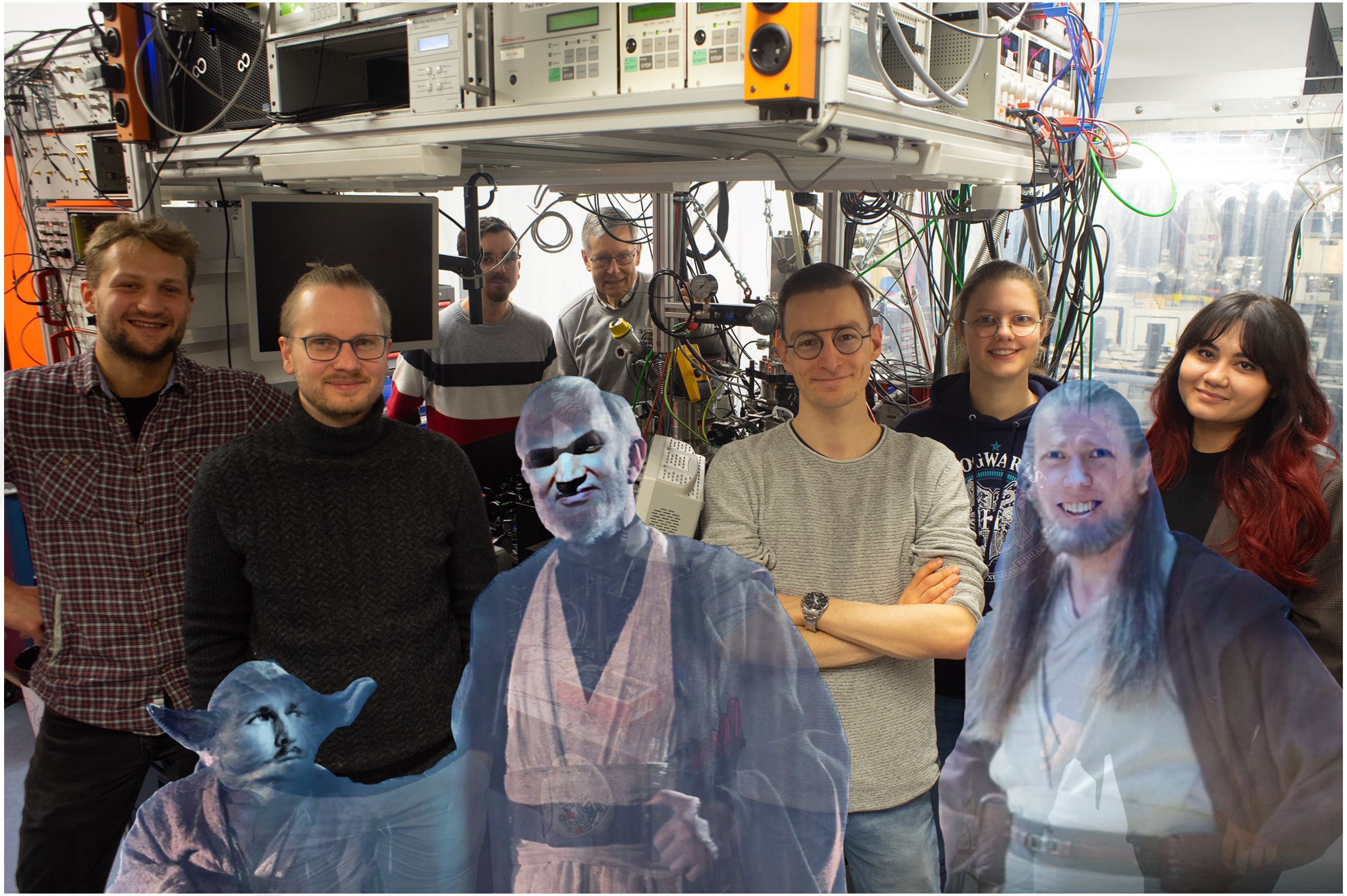
Next Steps / Outlook

Spectroscopy of the electronic transitions of $^{229(m)}Th^{3+}$ and resolving the HFS

Lifetime measurement of the isomer in $^{229m}Th^{3+}$ in vacuum

VUV frequency comb spectroscopy of the nuclear transition

Many Thanks to the LMU-Team …



From left to right:
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Markus Wiesinger
Daniel Moritz
Mahmood I. Hussain (Obi-Wan)
Peter G. Thirolf
Georg Holthoff
Lilli Löbell
Tim Theuner (Qui-Gon Jinn)
Tamila Rozibakieva

… and our International Colleagues

ERC Synergy:

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Johannes Tiedau
Ke Zhang
Maksim Okhapkin
Piet O. Schmidt
Adriana Pálffy (University of Würzburg)
Tobias Kirschbaum
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Thomas Sikorsky
Ira Morawitz

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Sandro Kraemer, Janni Moens
Eric Hudson (UCLA)
Ricky Elwell, James Terhune
Peter Micke (MPI Heidelberg)
José Crespo López-Urrutia (MPI Heidelberg)
Timo Dickel (GSI)
Wolfgang Plaß (GSI)

thorium nuclear clock

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