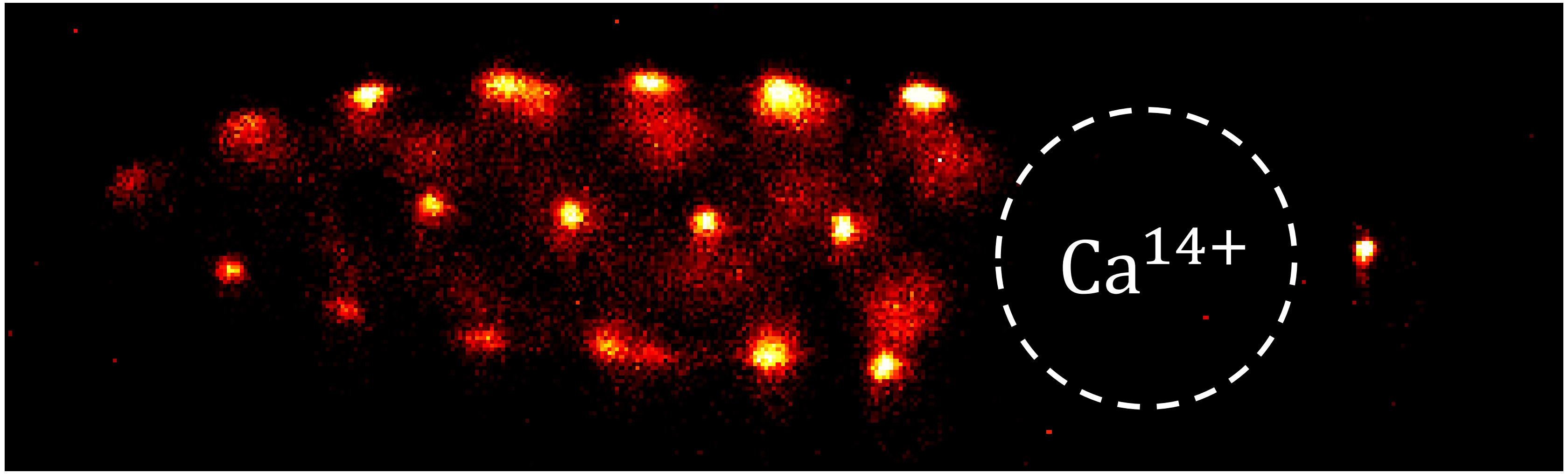
New Physics Searches with Highly Charged Ions

Precision isotope shift measurements of Ca^{14+}



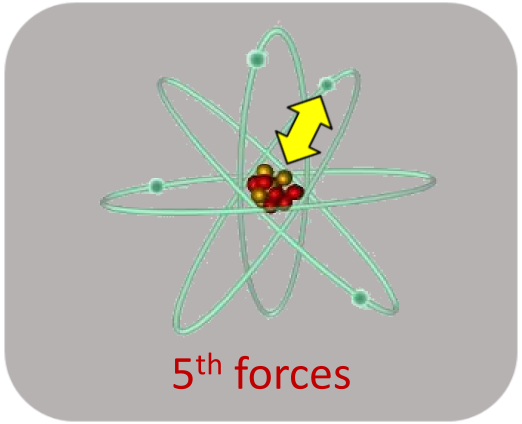
Alexander Wilzewski

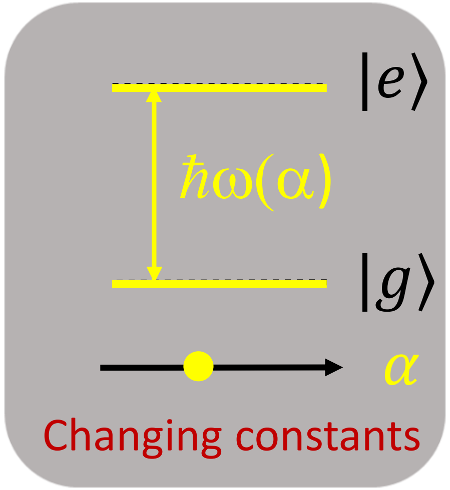
QUEST Institute for Experimental Quantum Metrology
German Metrology Institute - PTB, Germany

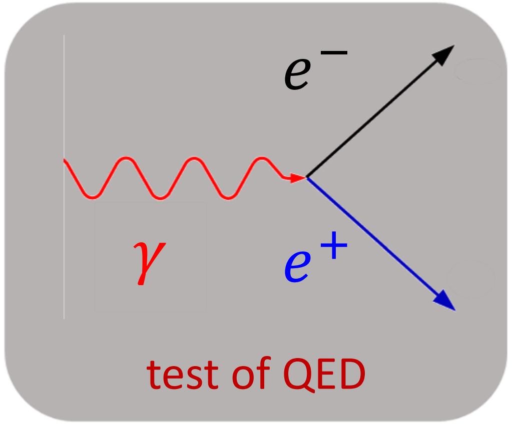
ECCTI, Innsbruck, 11.07.2024

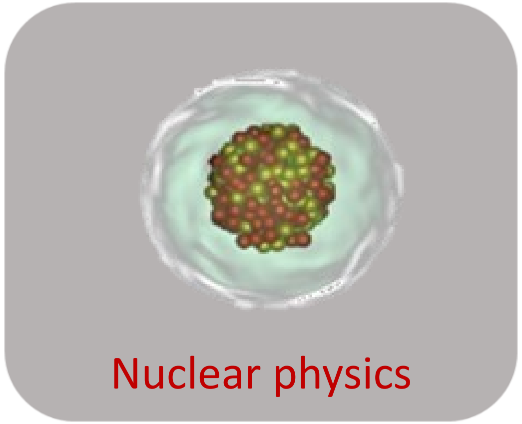
Why HCI?

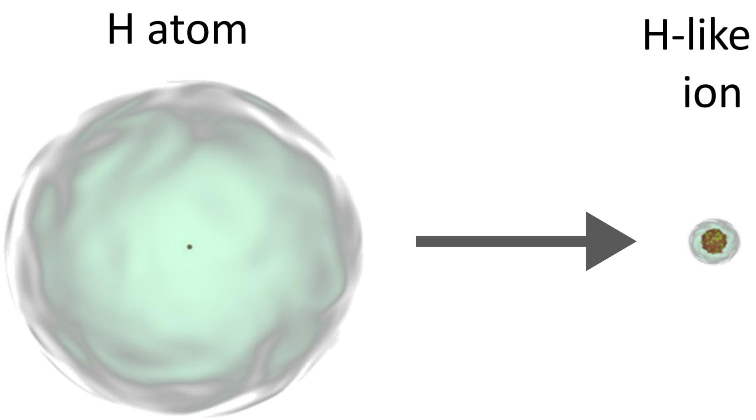
- Highly charged ions (HCI) promising optical clock candidates
- Properties useful for fundamental physics:
  - strongly relativistic (QED tests)
  - sensitive to variation in α
  - electrons close to nucleus
  - probes for 5^{th} forces
  - …











Linear Stark shift	Z^{-1}
Second order Stark shift	Z^{-4}
Linear Zeeman shift	Z^{0}
Second order Zeeman shift	$Z^{-3\ldots-4}$
Electric quadrupole shift	Z^{-2}

Intrinsically less sensitive to external perturbations

Kozlov *et al.*, Rev. Mod. Phys **90**, 045005 (2018)

Optical transitions in HCI

Level crossing transitions

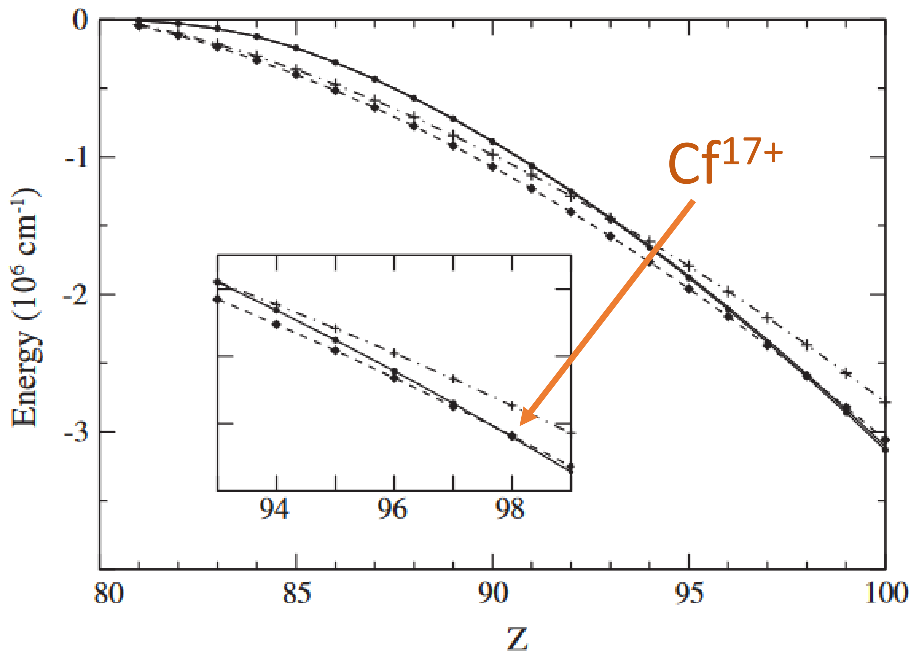
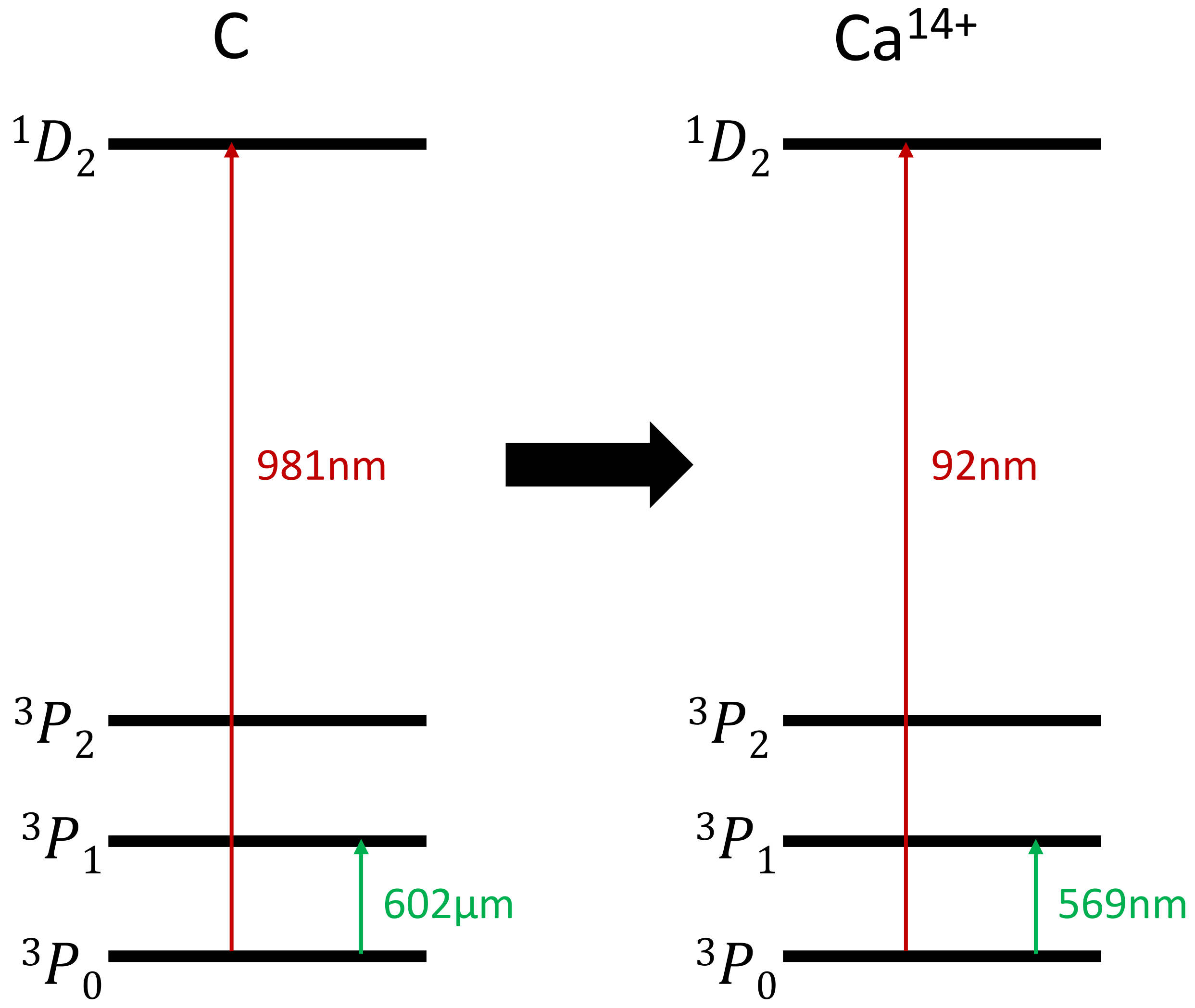


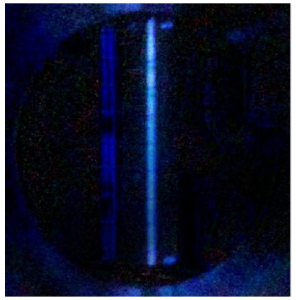
FIG. 1. Dirac-Fock energies of the $6p_{1/2}$ (diamonds, dashed line), $6p_{3/2}$ (crosses, dot-dashed line), and $5f$ (circles, solid line) levels in the thallium isoelectronic sequence with increasing nuclear charge. The inset shows an enlarged view of the crossing region.

J. Berengut *et al.*, Phys. Rev. Lett. **109**, 070802 (2012)

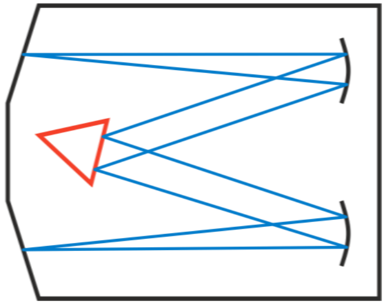
(Hyper-)Fine structure transitions



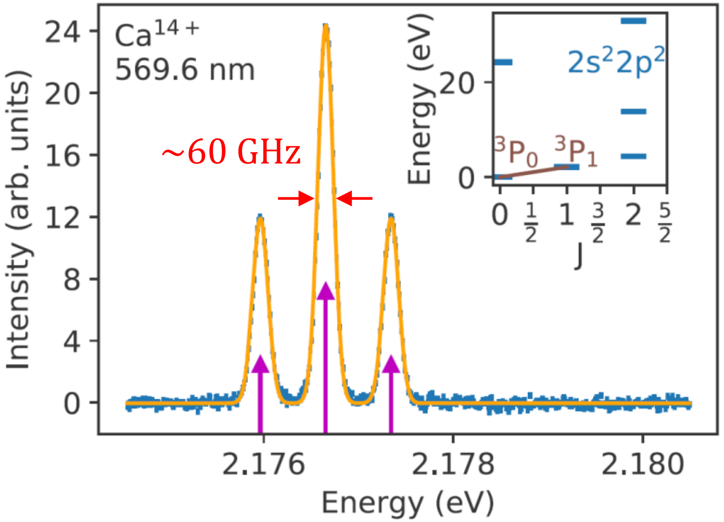
HCI spectroscopy



Plasma

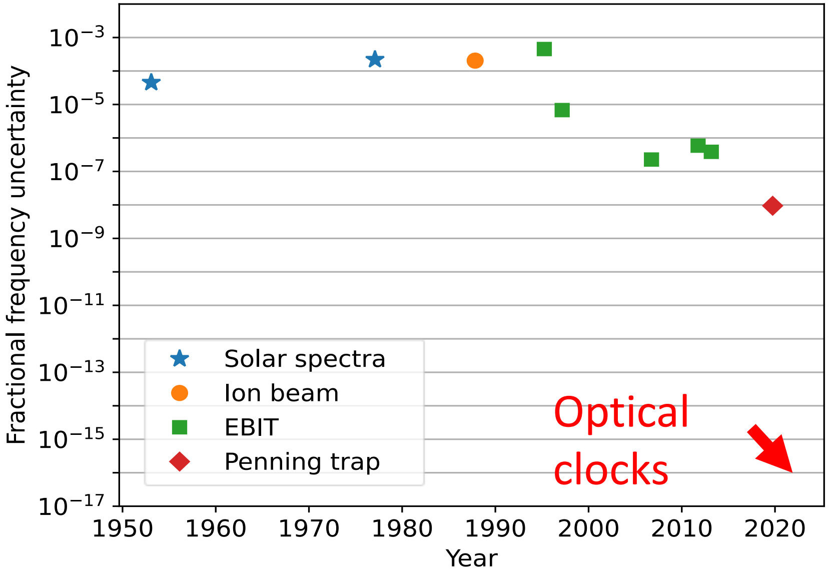


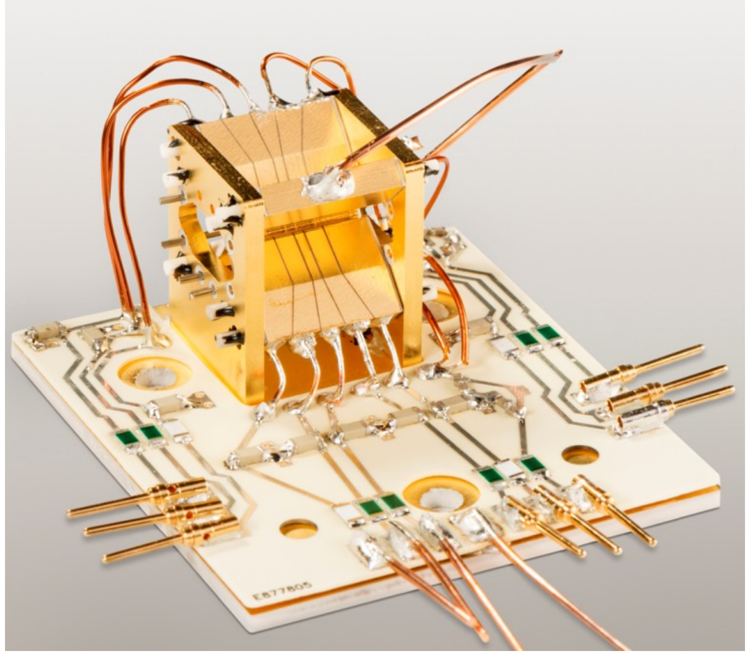
Grating spectrometer



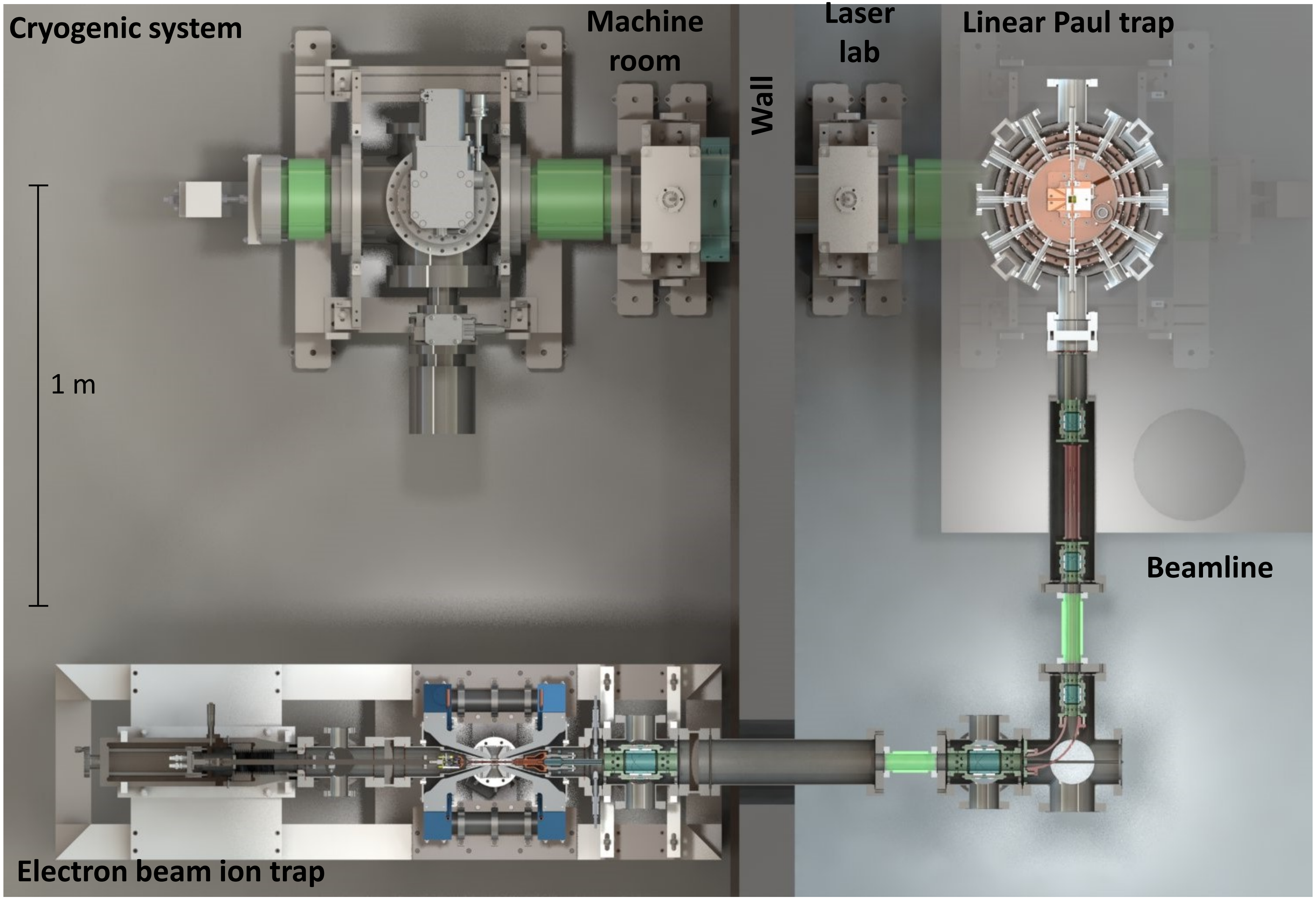
[Rehbehn et al., PRA **103**, L040801 (2021)]

Uncertainty ~250 MHz

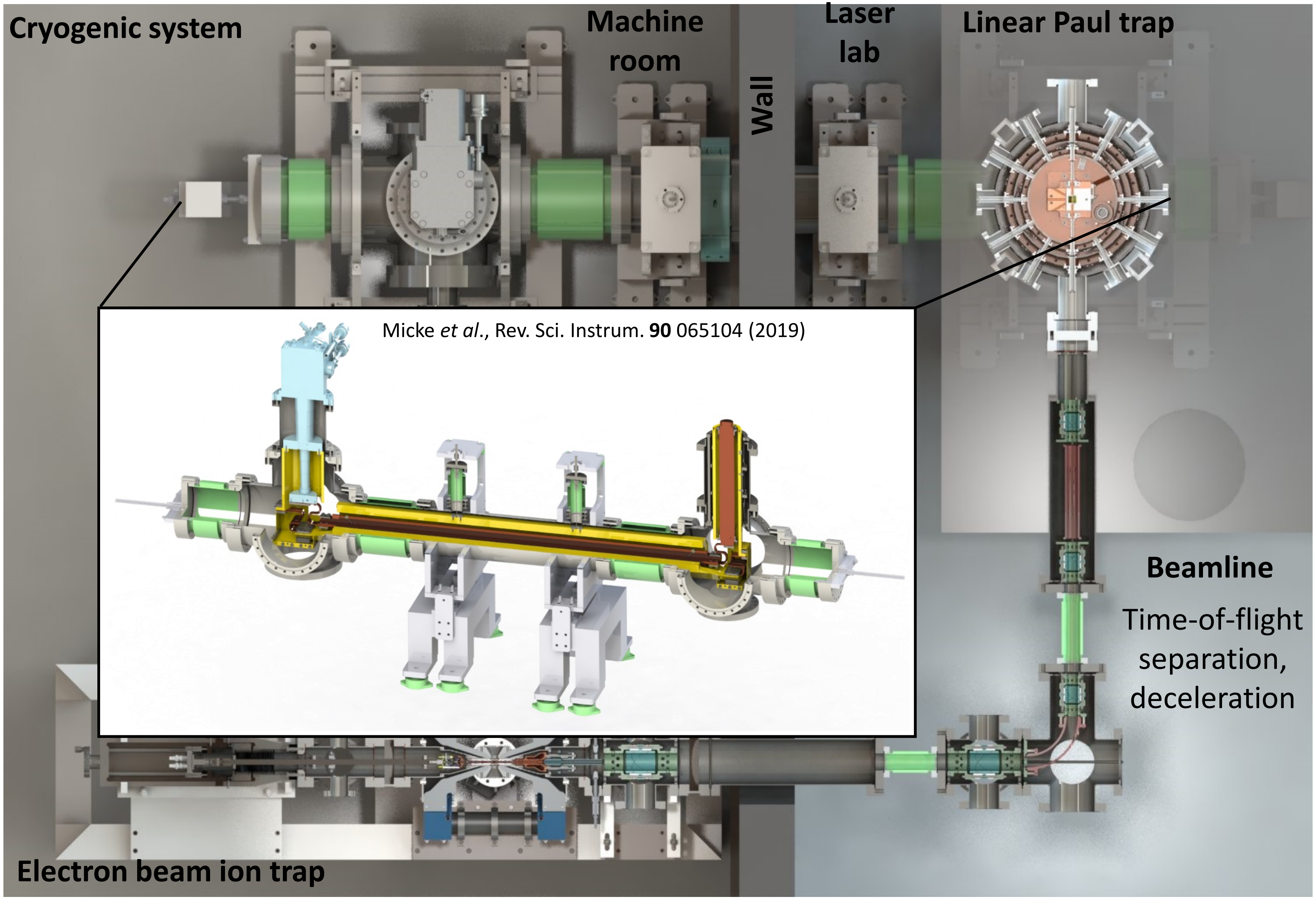




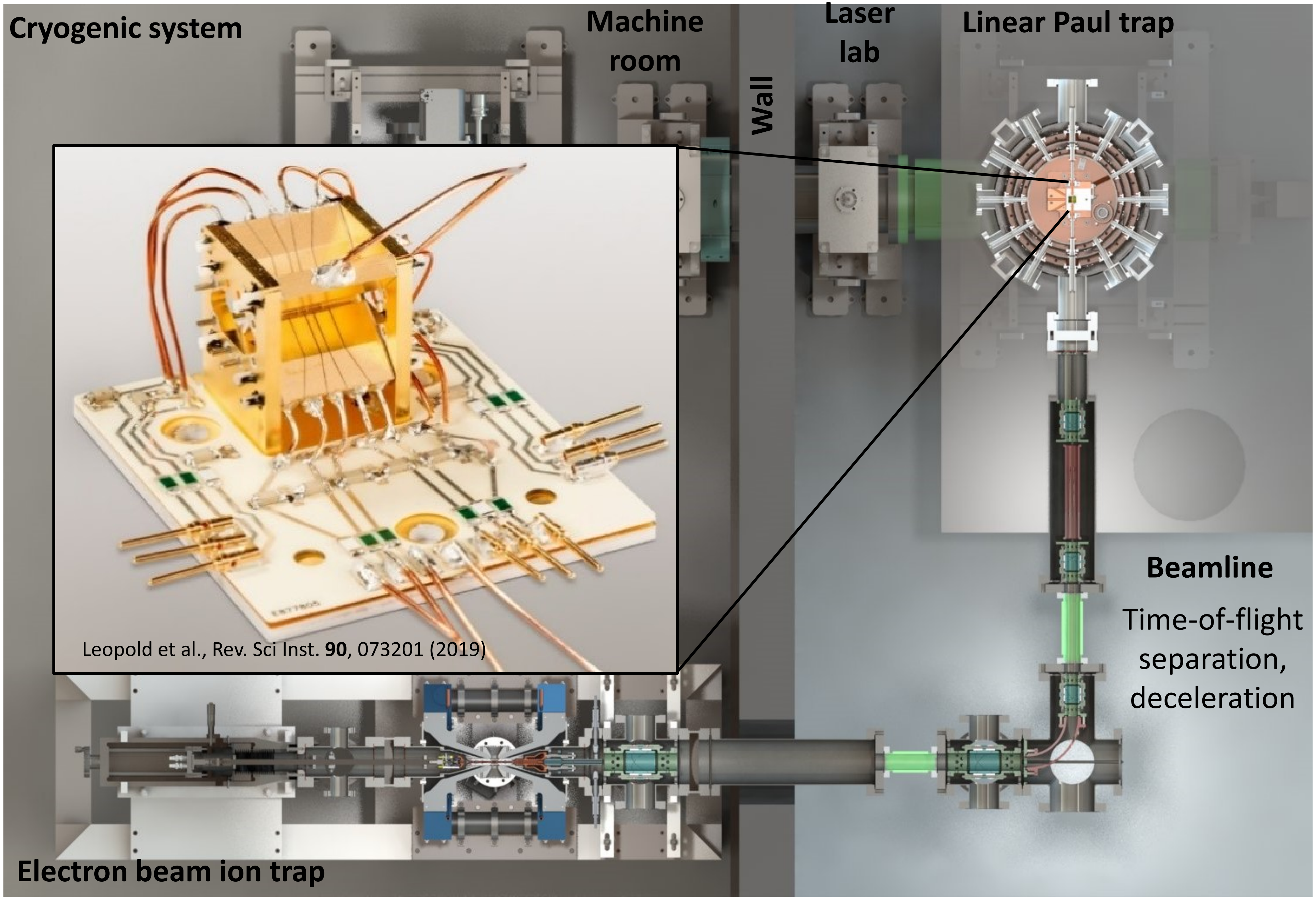
HCI lab at PTB



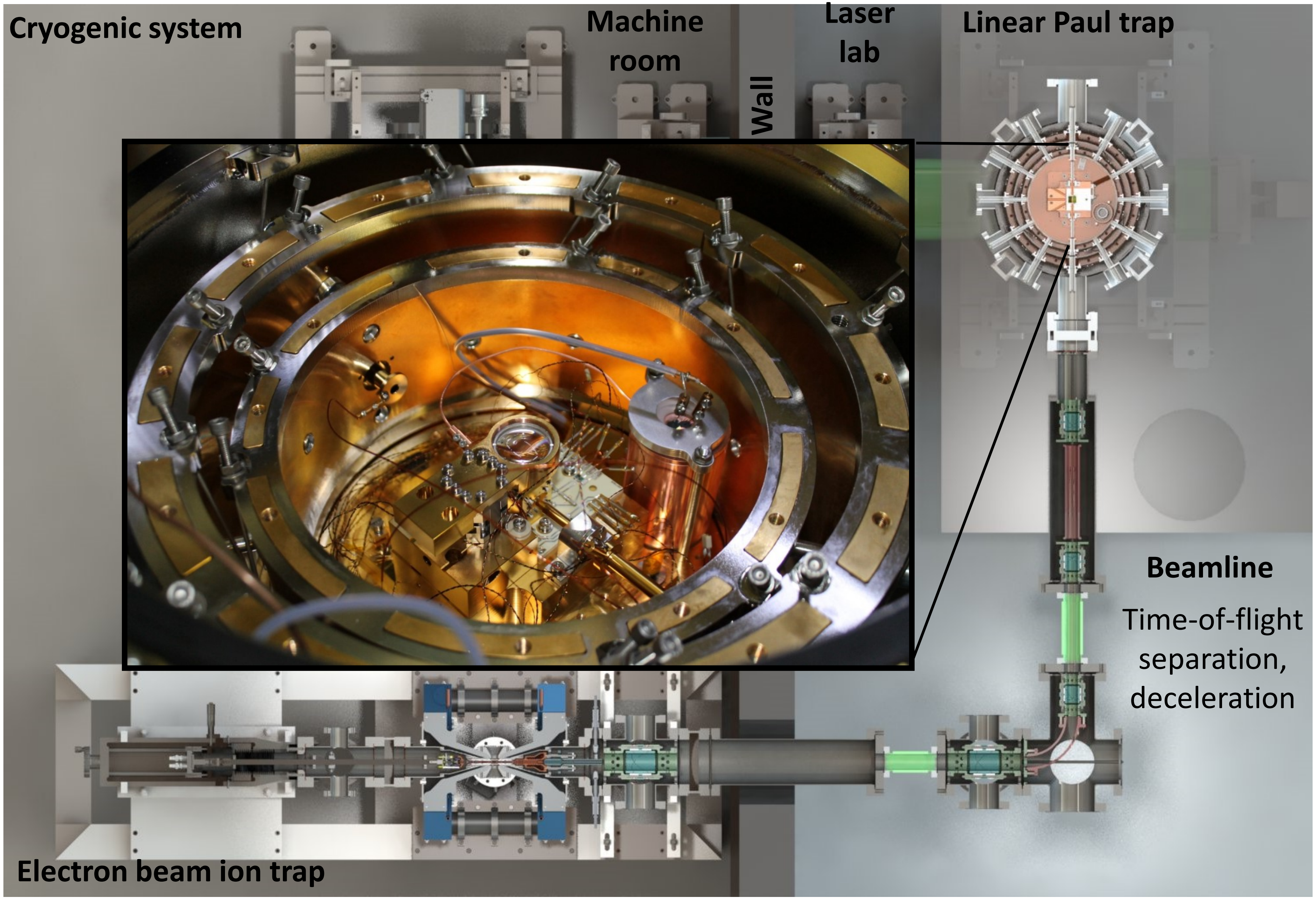
Cryo cooler


Cryogenic system
Machine room
Wall
Laser lab
Linear Paul trap
Micke *et al.*, Rev. Sci. Instrum. **90** 065104 (2019)
Beamline
Time-of-flight separation, deceleration
Electron beam ion trap

Paul trap


Cryogenic system
Machine room
Wall
Laser lab
Linear Paul trap
Leopold et al., Rev. Sci Inst. **90**, 073201 (2019)
Beamline
Time-of-flight separation, deceleration
Electron beam ion trap

Paul trap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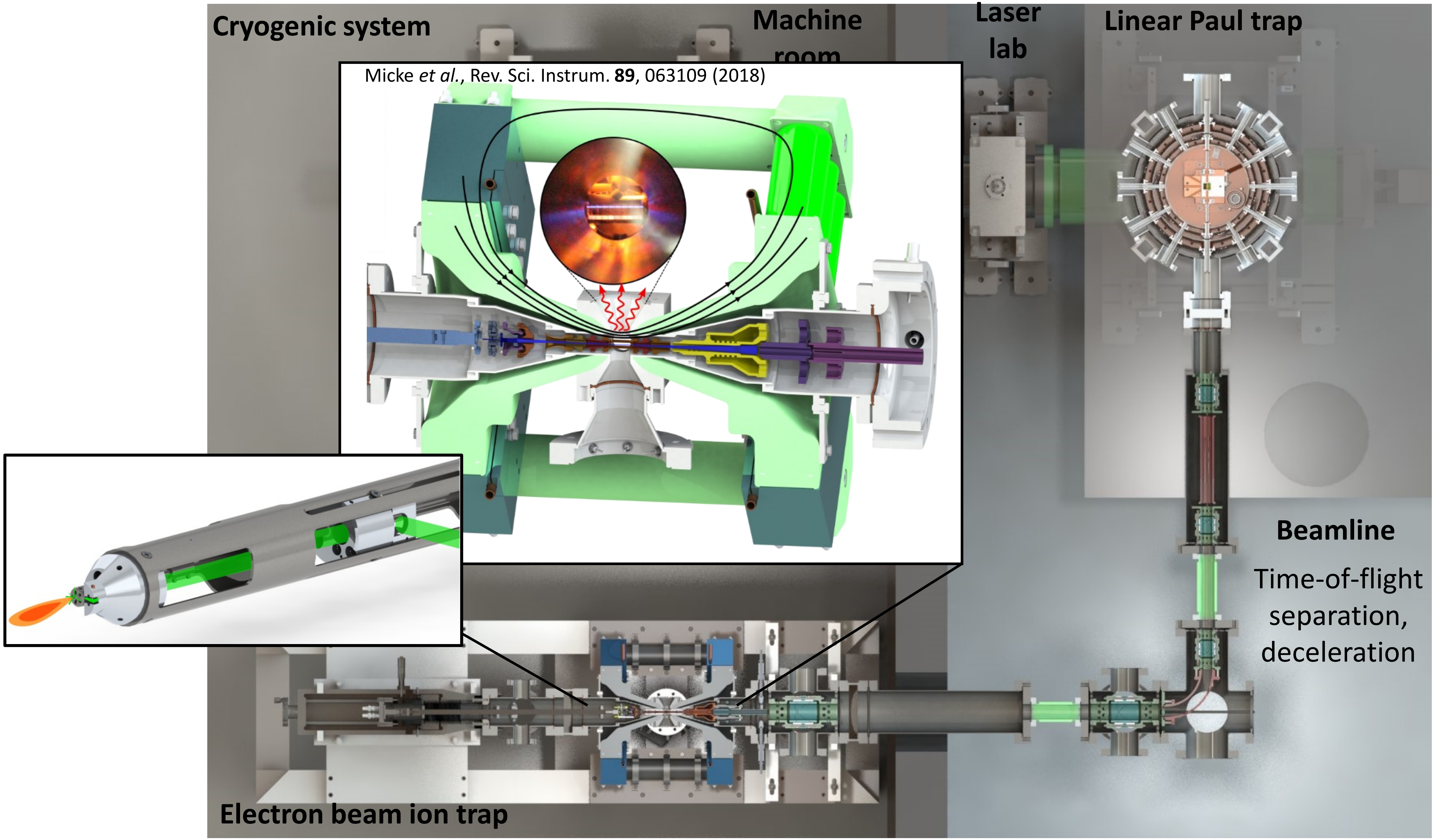
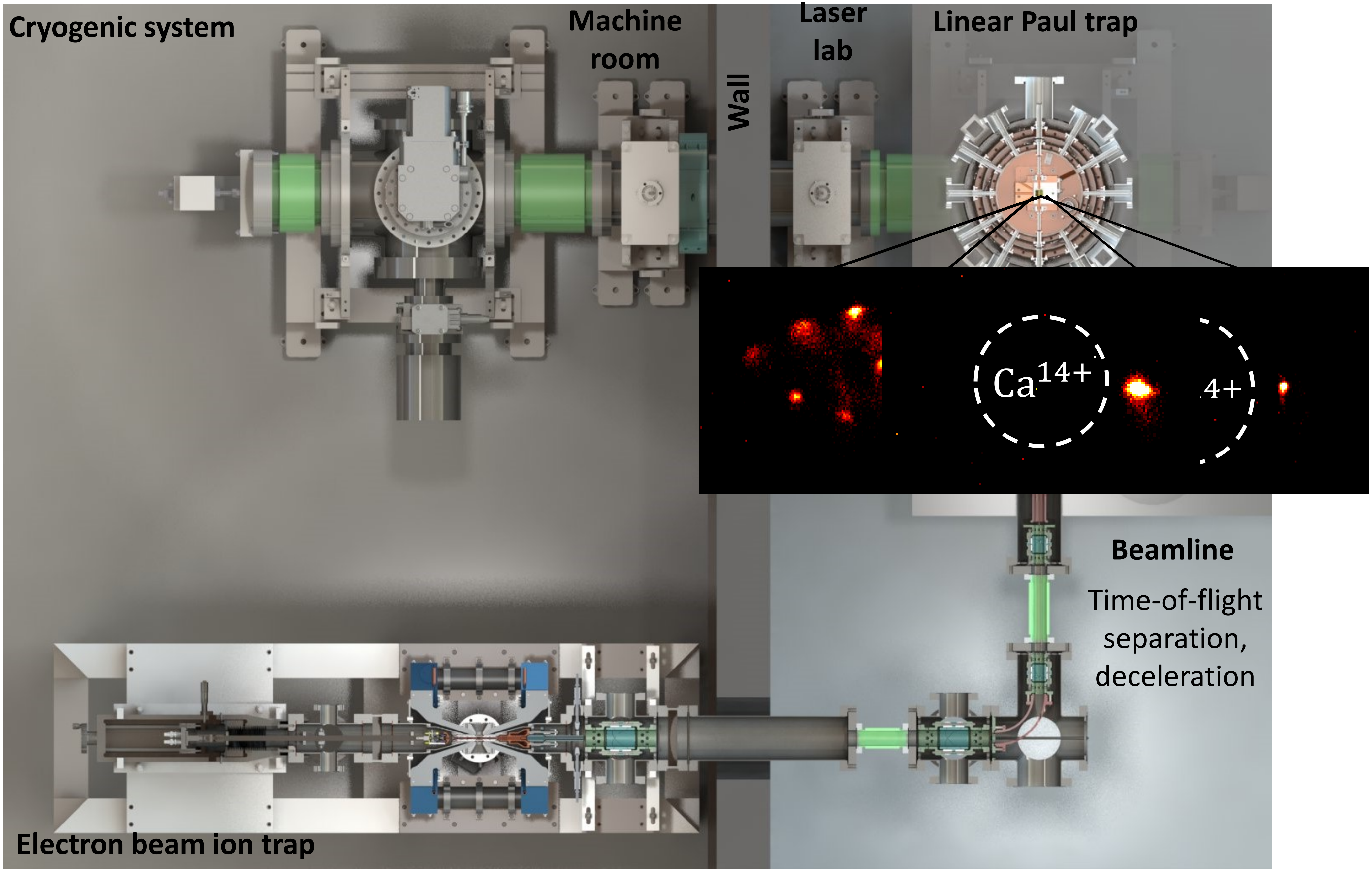
Electron beam ion trap



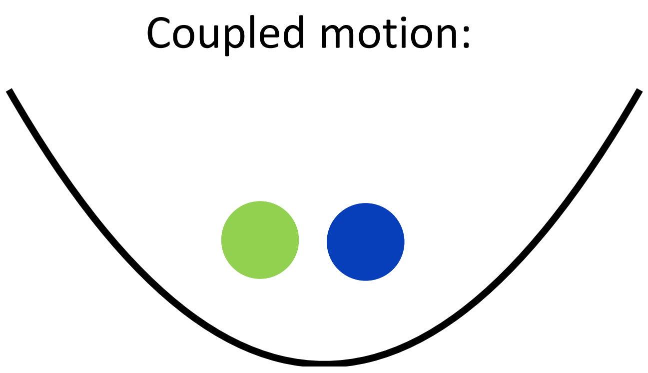
HCI lab at PTB

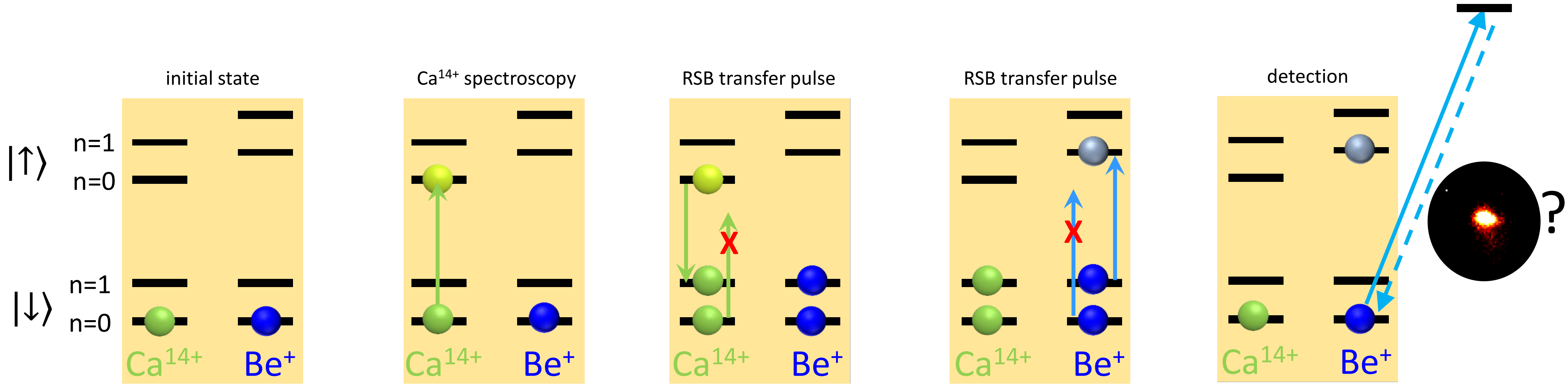


Quantum logic spectroscopy

Dipole-allowed optical transitions for laser cooling / electron shelving

→ Sympathetic cooling and quantum logic spectroscopy

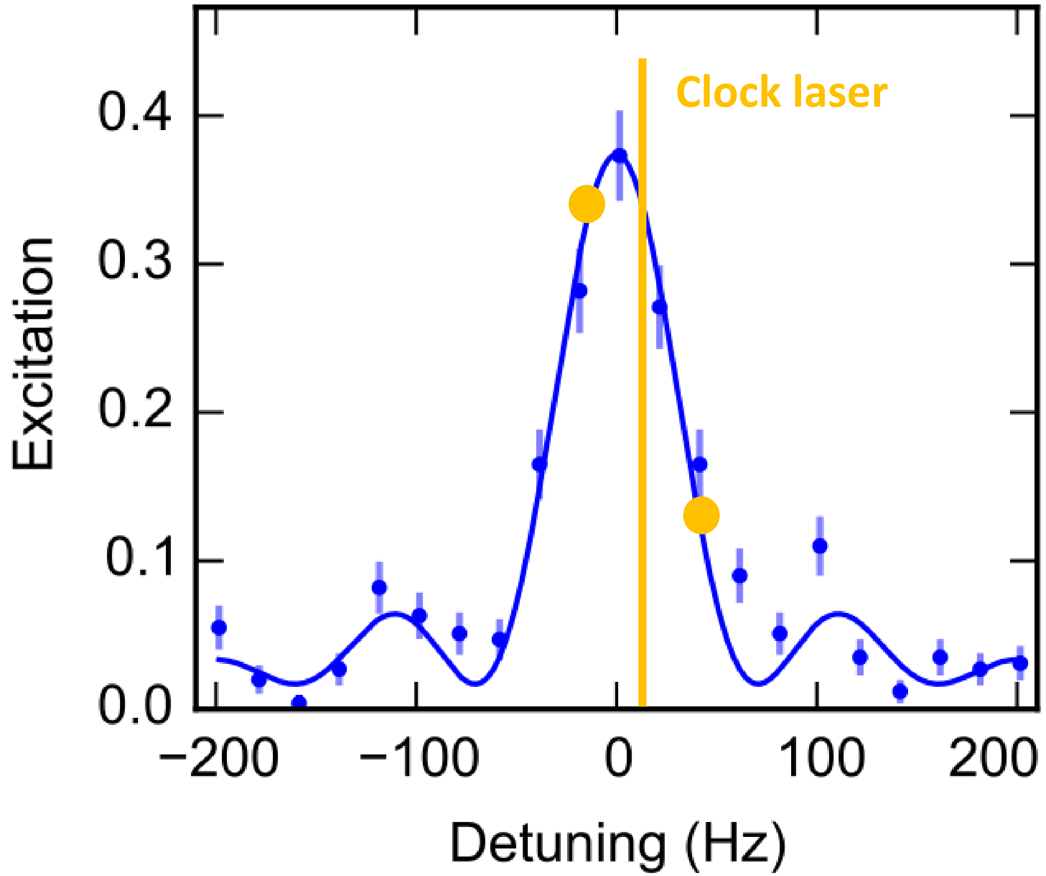




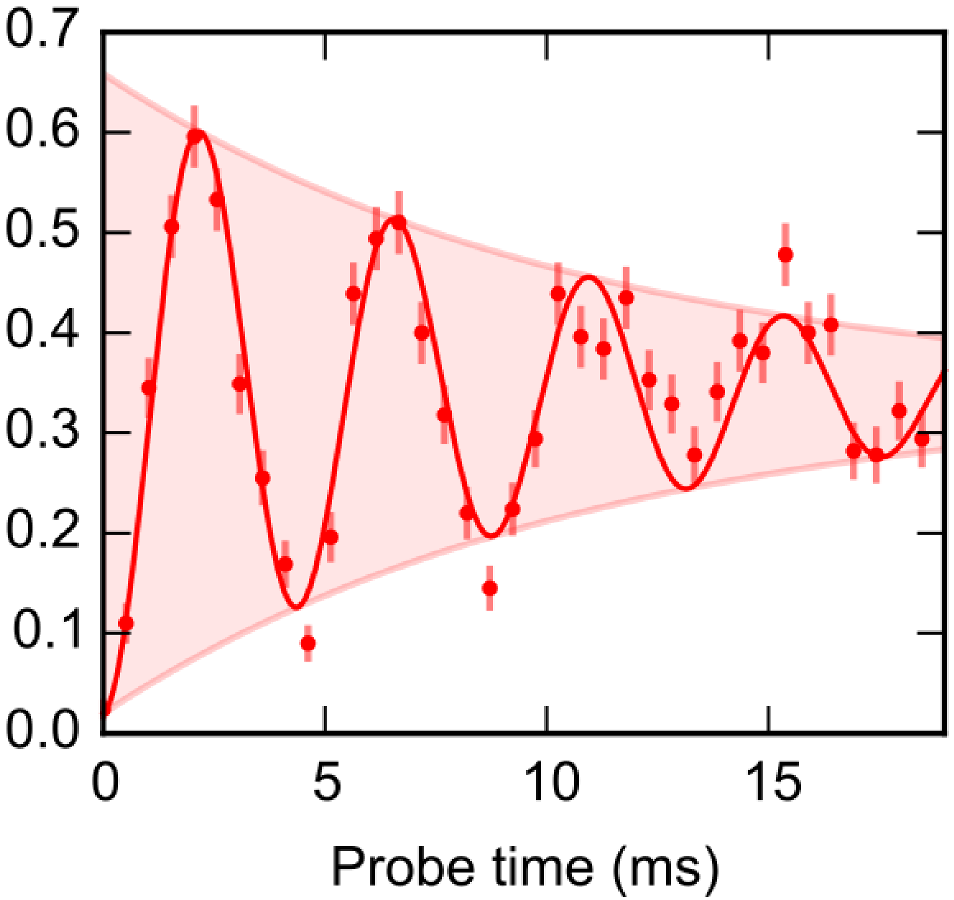
[Schmidt *et al.*, Science **309** (2005)]

Quantum logic spectroscopy

Fourier-limited linewidth: 65 Hz
(12 ms probe time) resolution: ~ 5 Hz



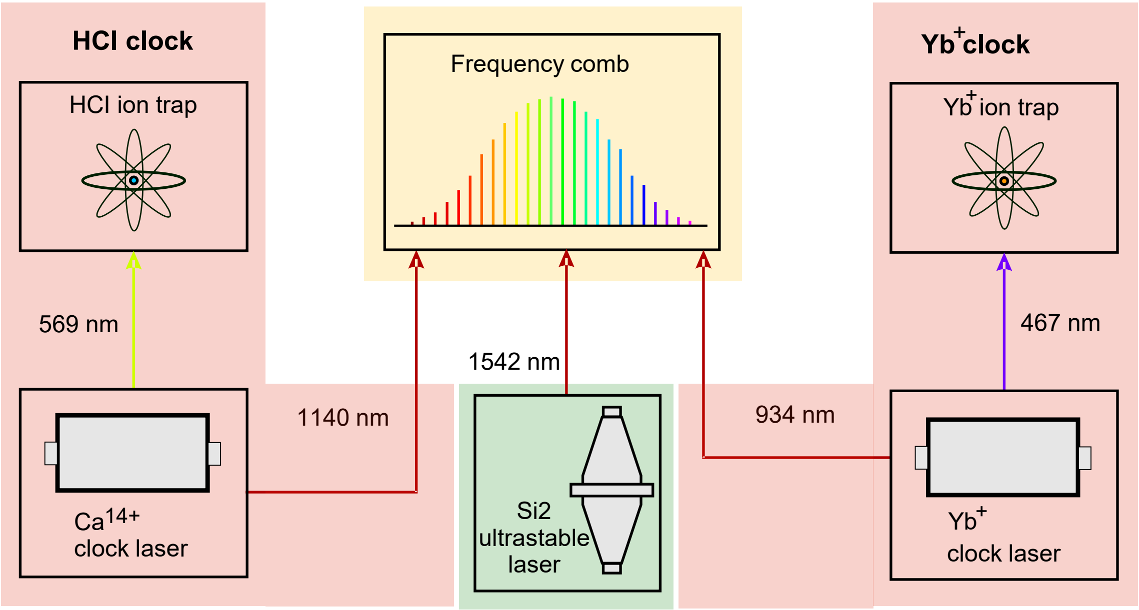
decoherence dominated by
excited state lifetime of 9.97(26)ms



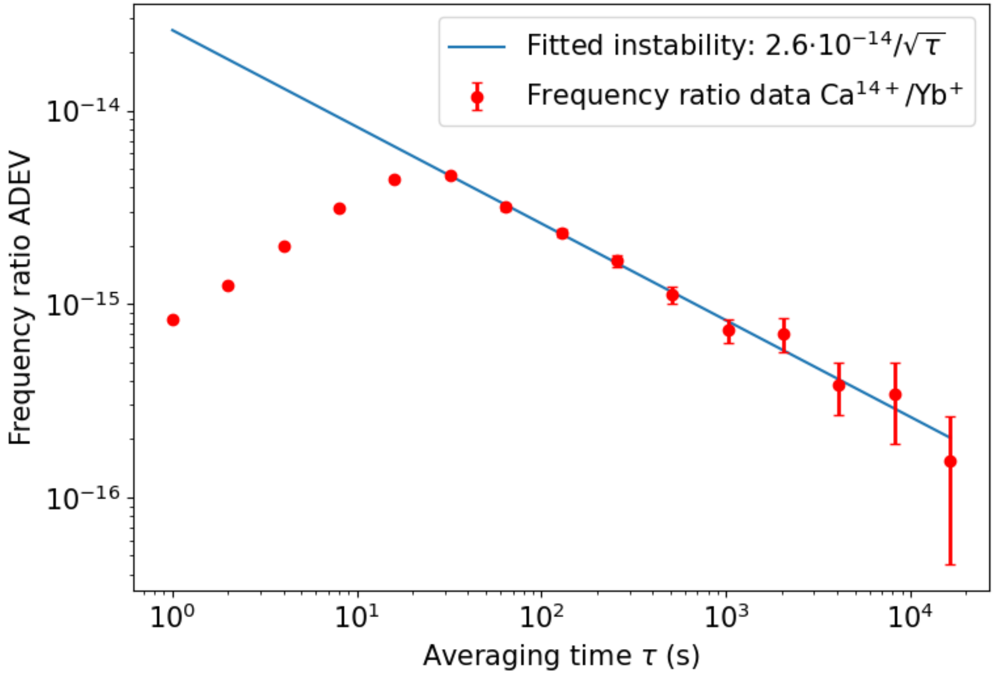
[Micke *et al.*, Nature **578**, 60 (2020)]

Ar^{13+}

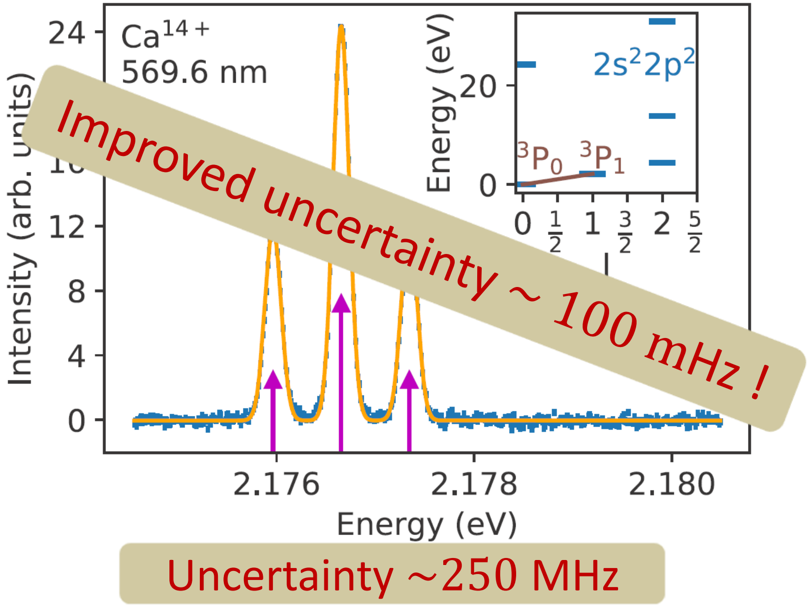
Clock comparison



[Matei *et al.*, Phys. Rev. Lett. **118**, 263202 (2017)]
[Filzinger *et al.*, Phys. Rev. Lett. **130**, 253001 (2023)]



- Yb^+ absolute frequency is known with a fractional uncertainty of 1.3×10^{-16}
- Measurements to $\sim 1 \times 10^{-16}$ statistical uncertainty
- Systematic uncertainty at $\sim 5 \times 10^{-17}$



[S.A. King & L.J. Spieß *et al.*, Nature **611**, 43-47 (2022)]

Summary of systematic shifts

Shift source	Mitigation	Shift (10^{-18})	Uncertainty (10^{-18})
Micromotion	Real-time measurement	-605	< 50
Probe-laser-induced shift	Calibration at much higher powers and extrapolation	0	2
First-order Doppler	Counter-propagating beams	0	< 1
Linear Zeeman	Averaging over multiple Zeeman components	0	< 1
Quadratic Zeeman	Small coefficient, small field	< 1	$\ll 1$
Electric quadrupole	Small coefficient, Averaging over multiple Zeeman components	0	< 1
2nd order Doppler	Algorithmic cooling	-1	< 1

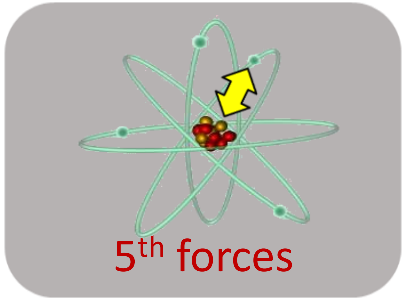
no fundamental limitations

Systematic uncertainty $\sim 5 \times 10^{-17}$

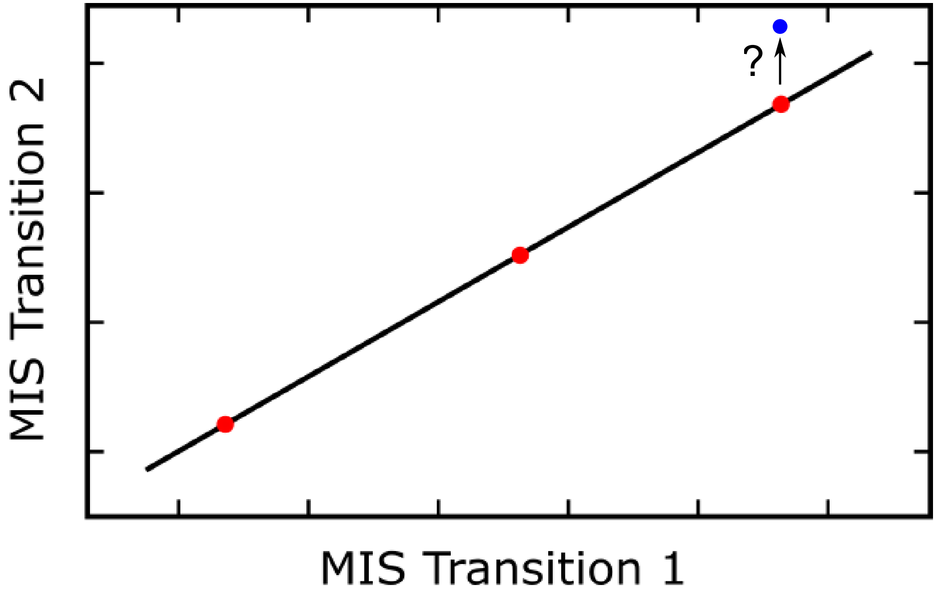
Isotope shifts in calcium

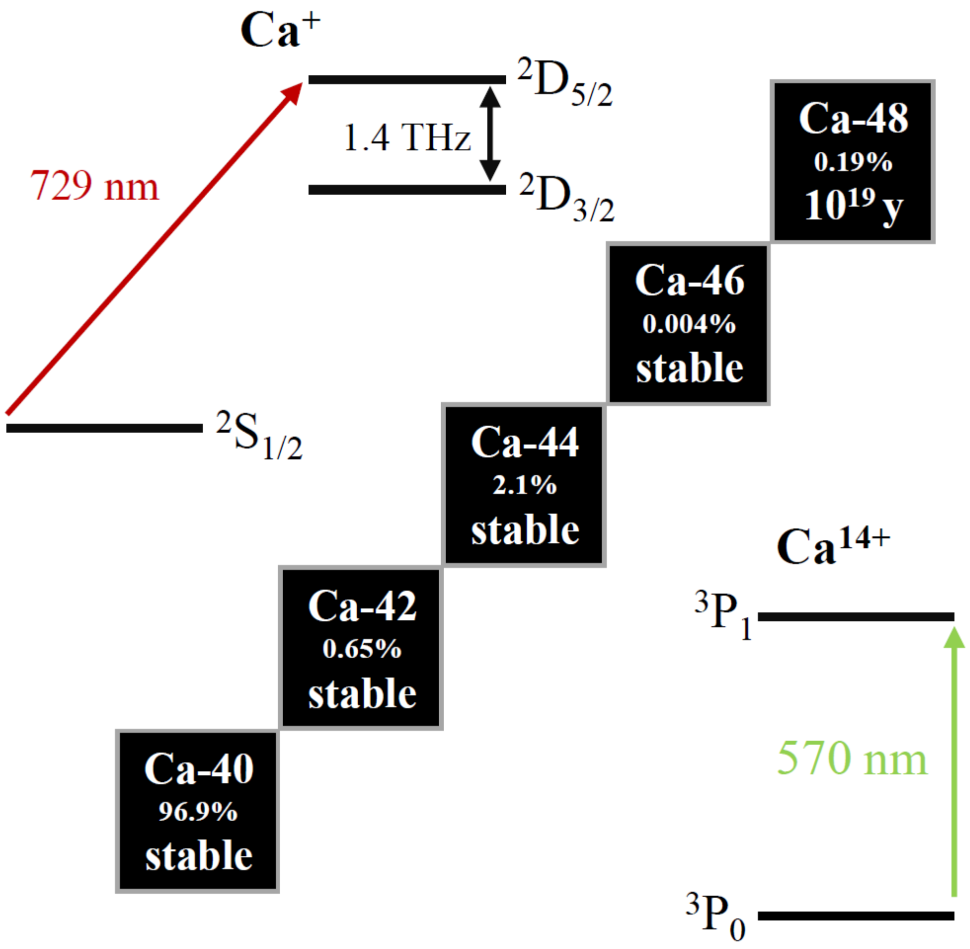
$$\delta\nu_{570}^{A,A'} = \frac{K_{570}}{\mu_{A,A'}} + F_{570}\delta\langle r_c^2\rangle^{A,A'} \quad \mu_{A,A'} = \frac{m_A m_{A'}}{m_A - m_{A'}}$$

$$\delta\nu_{729}^{A,A'} = \frac{K_{729}}{\mu_{A,A'}} + F_{729}\delta\langle r_c^2\rangle^{A,A'} + X\gamma^{A,A'}$$



$$\mu\delta\nu_{570}^{A,A'} \not\propto \mu\delta\nu_{729}^{A,A'}$$

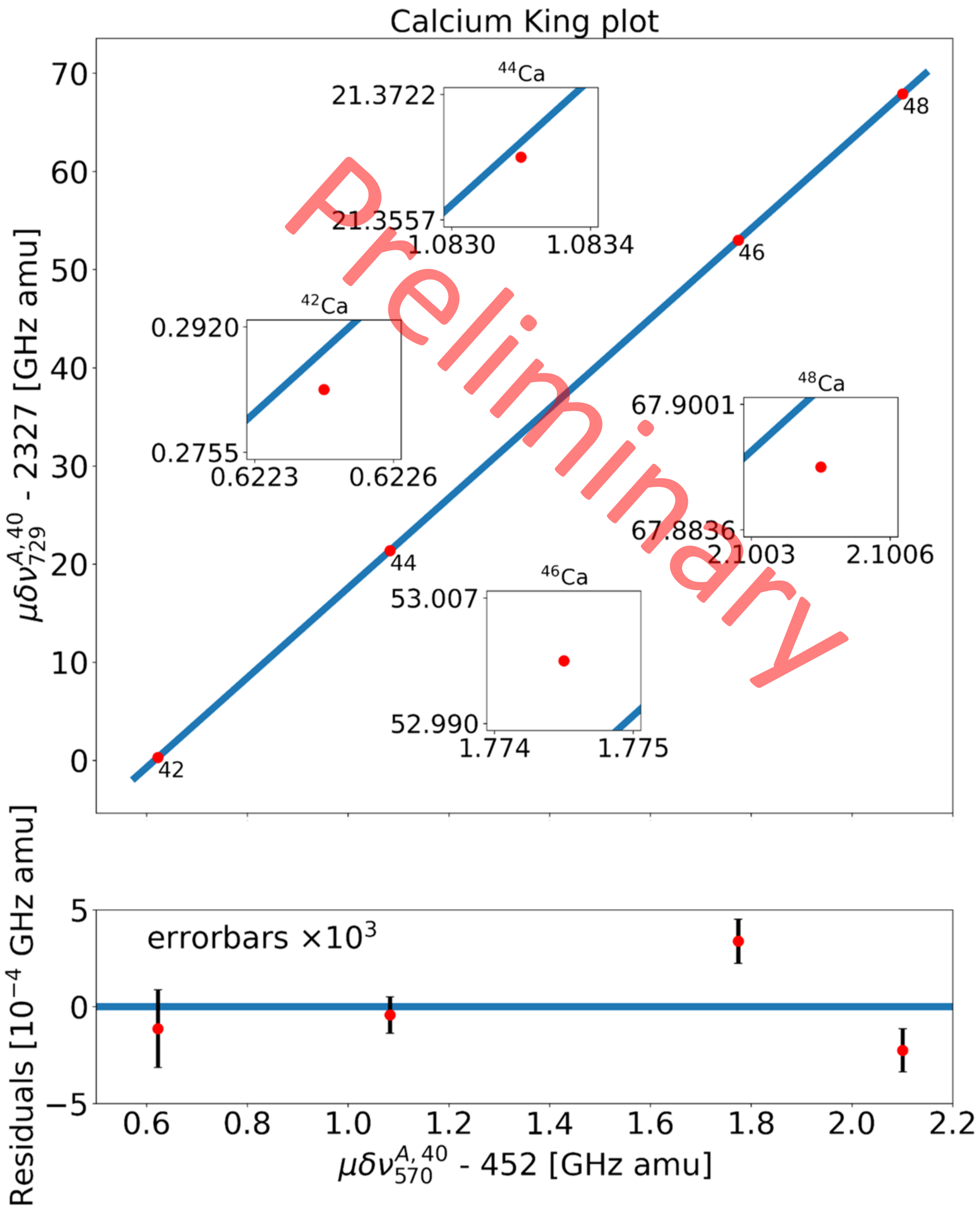




King plot including Ca^{14+} transition

For King plot analysis we combine our data with:

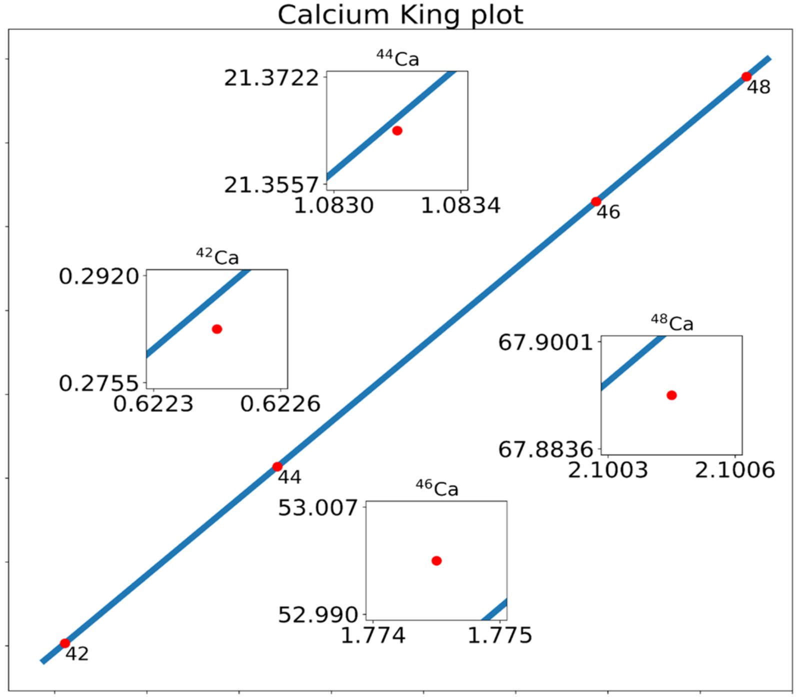
- Nuclear masses by group of Klaus Blaum at MPIK
- Isotope shift of $^2S_{1/2} \rightarrow {}^2D_{5/2}$ in Ca^+ by group of Jonathan Home at ETH Zürich
- **Find large nonlinearity of King plot**
- Can still improve new physics constraints, **analysis ongoing**

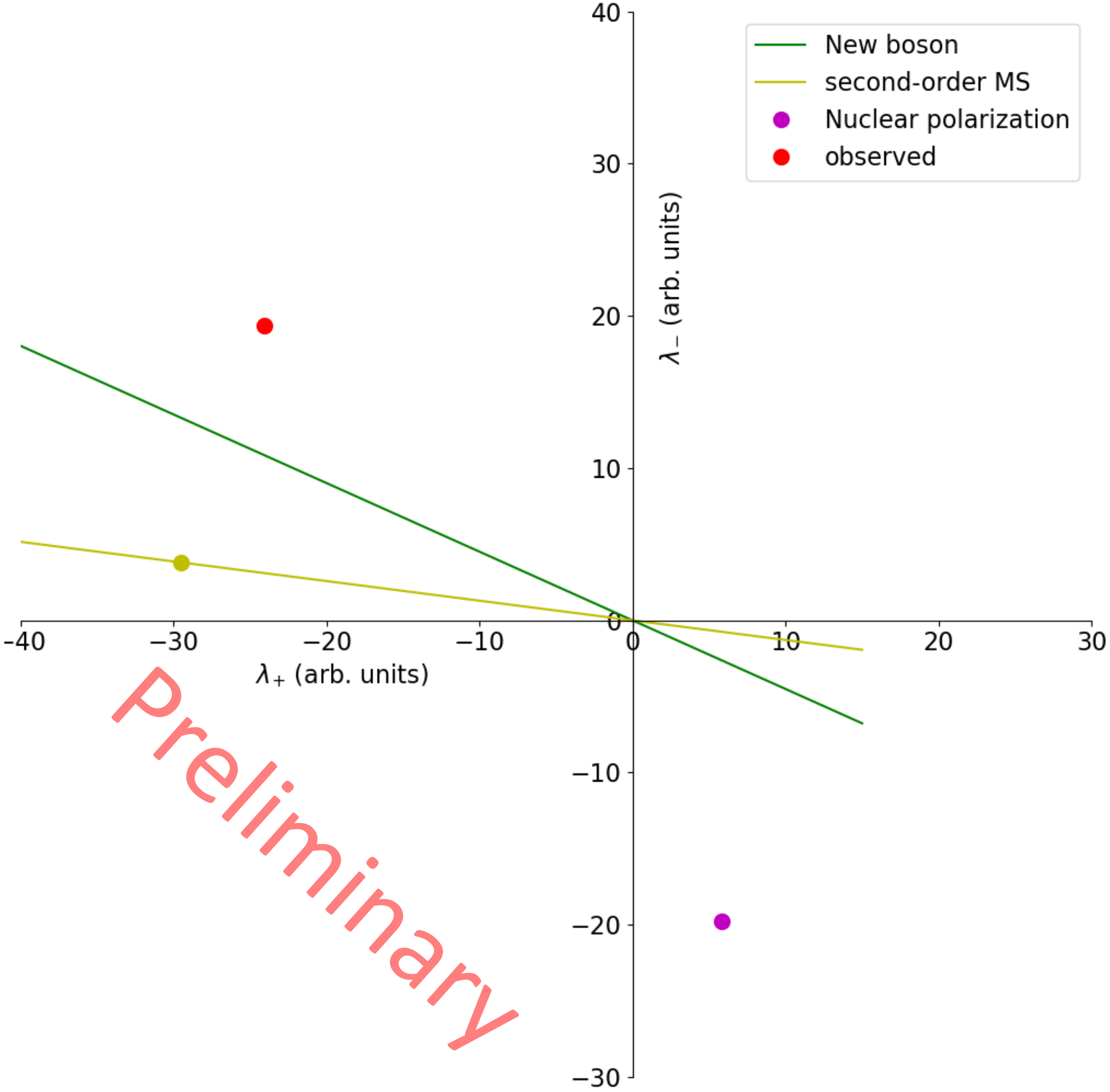


Nonlinearity decomposition

Relate pattern of residuals to source of nonlinearity

- Relate patter of NL to its source **if factorizable**:
  - $\lambda_+ \propto$ zig-zag pattern
  - $\lambda_- \propto$ U-shape pattern
- Known SM nonlinearities in Ca:
  - Second-order recoil shift
  - Nuclear polarization – Calculations for Ca^{14+} missing! [A. Viatkina *et al.*, PRL **108**, 022802 (2023)]

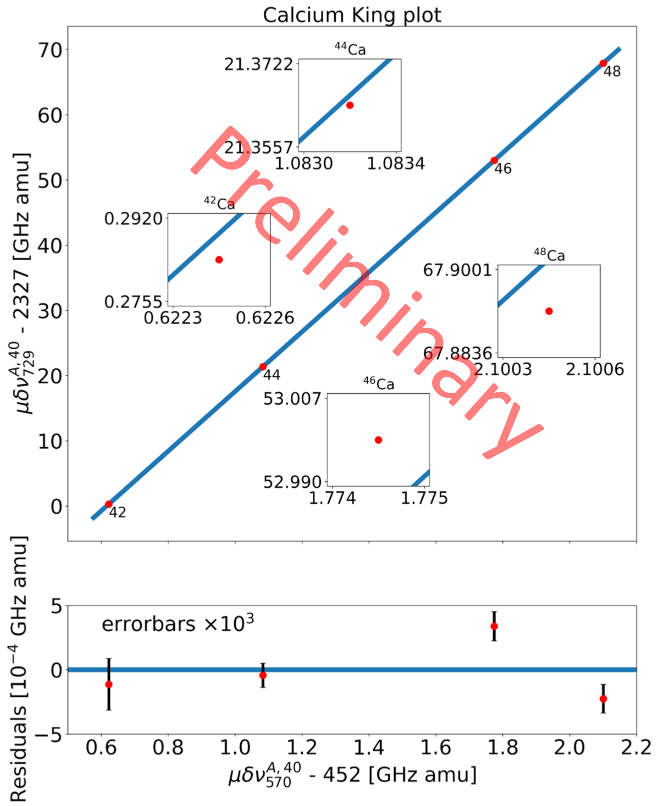




Summary and outlook

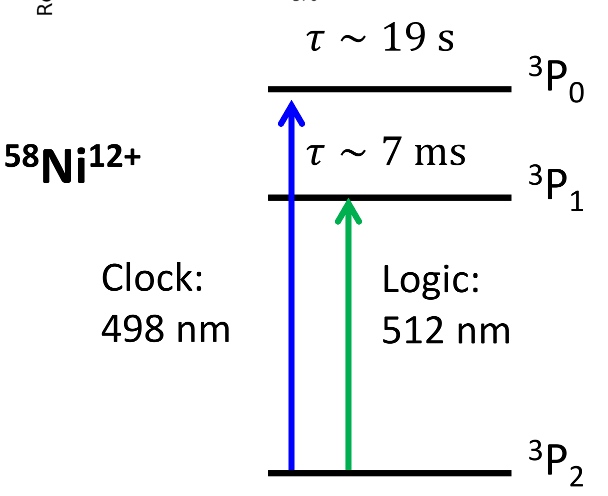
Summary

- **Optical clock comparison** between Ca^{14+} and Yb^{+} with statistical uncertainty of $\sim\mathbf{1\times10^{-16}}$ and systematic uncertainty of $\sim\mathbf{5\times10^{-17}}$
- Combination of Ca^{14+} IS data with new Ca^{+} IS data and nuclear masses reveal large nonlinearity



Outlook

- Decompose nonlinearity and see whether it can be fully explained by higher-order Standard Model terms
- Reduce systematic uncertainties, new Paul trap
- HCI optical clock based on Ni^{12+} which has a long-lived clock state
- HCI with high sensitivity to variations in fine-structure constant like Cf^{17+}



[S. Chen *et al.*, arXiv:2406.04015 (2024)]

Acknowledgements

HCI Experiment
PTB: Piet O. Schmidt, Tobias Leopold, Peter Micke, Steven A. King, Lukas J. Spieß, AW, Malte Wehrheim, Shuying Chen
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Yb⁺ Experiment
- Richard Lange
- Nils Huntemann
- Melina Filzinger
- Martin Steinel

Frequency comb
- Erik Benkler

Nuclear masses
- Menno Door
- Klaus Blaum

Ca⁺ isotop shift
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- Diana Craik
- Jeremy Flannery
- Roland Matt
- Jonathan Home

Theory
- Elina Fuchs
- Agnese Mariotti
- Jan Richter
- Julian Berengut
- Andrey Surzhykov
- Anna Viatkina
- Vladimir Yerokhin

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European Research Council
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