

Helmholtz Investigator Group: Quantum Logic Spectroscopy

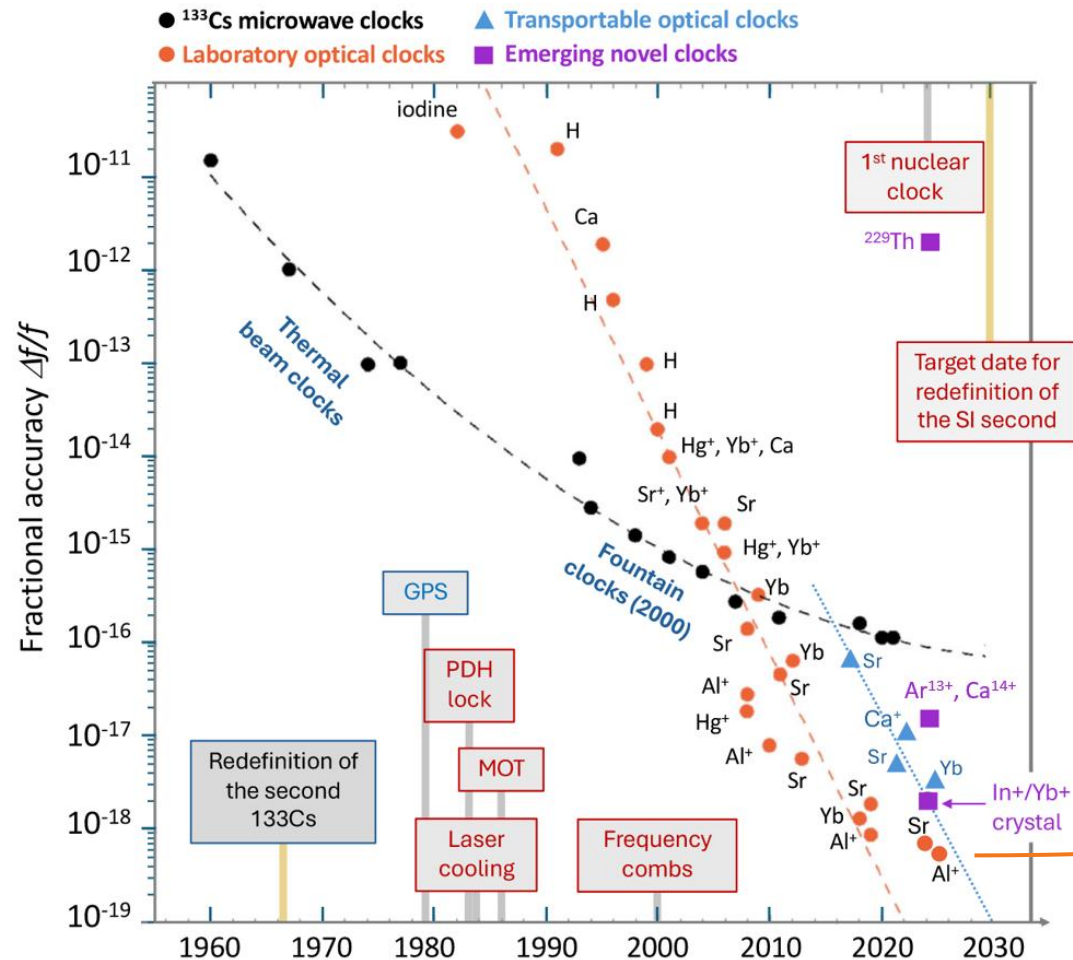
Peter Micke

Helmholtz Institute Jena

GSI Helmholtz Center for Heavy Ion Research, Darmstadt

Friedrich Schiller University Jena

Quantum logic spectroscopy and novel optical clocks



T. M. Fortier, A. N. Luiten, and H. S. Margolis, *Optica* **13**, 143–163 (2026)

Highly charged ions

PHYSICAL REVIEW LETTERS **135**, 033201 (2025)

Editors' Suggestion

High-Stability Single-Ion Clock with 5.5×10^{-19} Systematic Uncertainty

Mason C. Marshall^{1,*} Daniel A. Rodriguez Castillo^{1,2} Willa J. Arthur-Dworschack^{1,2} Alexander Aeppli^{2,3}
Kyungtae Kim^{2,3} Dahyeon Lee^{2,3} William Warfield^{2,3} Joost Hinrichs^{1,4} Nicholas V. Nardelli¹
Tara M. Fortier¹ Jun Ye^{2,3} David R. Leibbrandt^{1,2,5} and David B. Hume^{1,2,†}

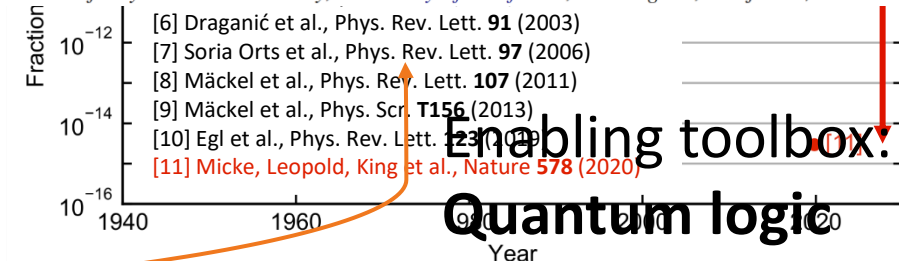
¹*Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado, USA*

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³*JILA, National Institute of Standards and Technology and the University of Colorado, Boulder, Colorado, USA*

⁴*Institute of Quantum Optics, Leibniz University Hannover, Hannover, Germany*

⁵Department of Physics and Astronomy, *University of California*, Los Angeles, California, USA



nature

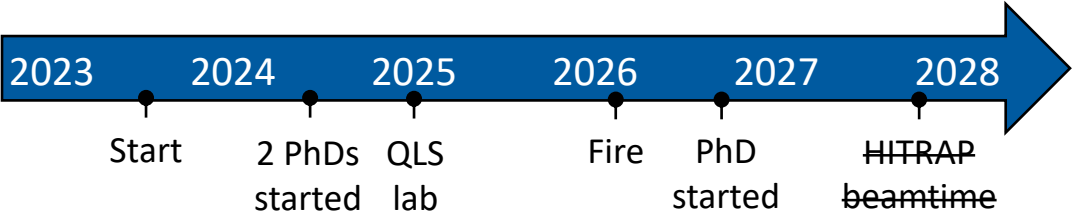
P. Micke et al., Nature **578**, 60–65 (2020)

Helmholtz Investigator Group

Host institute: **Helmholtz Institute Jena**
University partner: **Friedrich Schiller University Jena**

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

SUPPORTED BY THE HELMHOLTZ
INITIATIVE AND NETWORKING FUND
HELMHOLTZ



Universal quantum logic spectroscopy experiment for highly charged heavy ions

- **Atomic transitions**
($^{207}\text{Pb}^{81+}$, $^{XXX}\text{Tl}^{80+}$, $^{111}\text{Sn}^{49+}$, ...)
- **Nuclear transitions**
($^{229}\text{Th}^{89+}$, $^{229}\text{Th}^{90+}$, ...)

Network-Related Funding Helmholtz

FROM MATTER TO MATERIALS AND LIFE

Rima Schüssler
Frank Herturth
Manuel Vogel
Wolfgang Quint ...

Matter

Tanja Meh
Christian O
Fabian Wo

IP

DTS



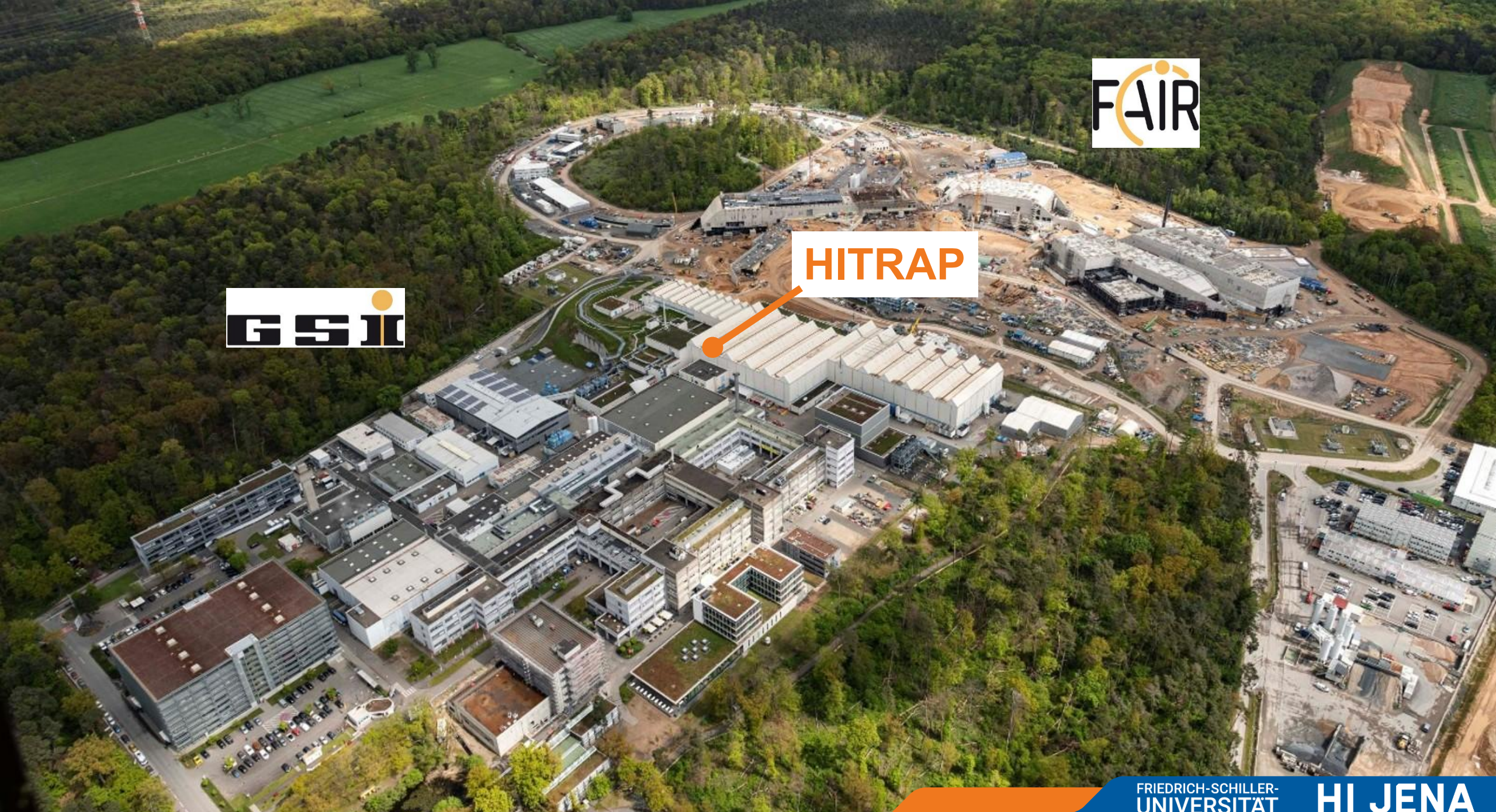
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG
Innovation Pool Project



Quantum Sensors for Physics (QS4Physics)

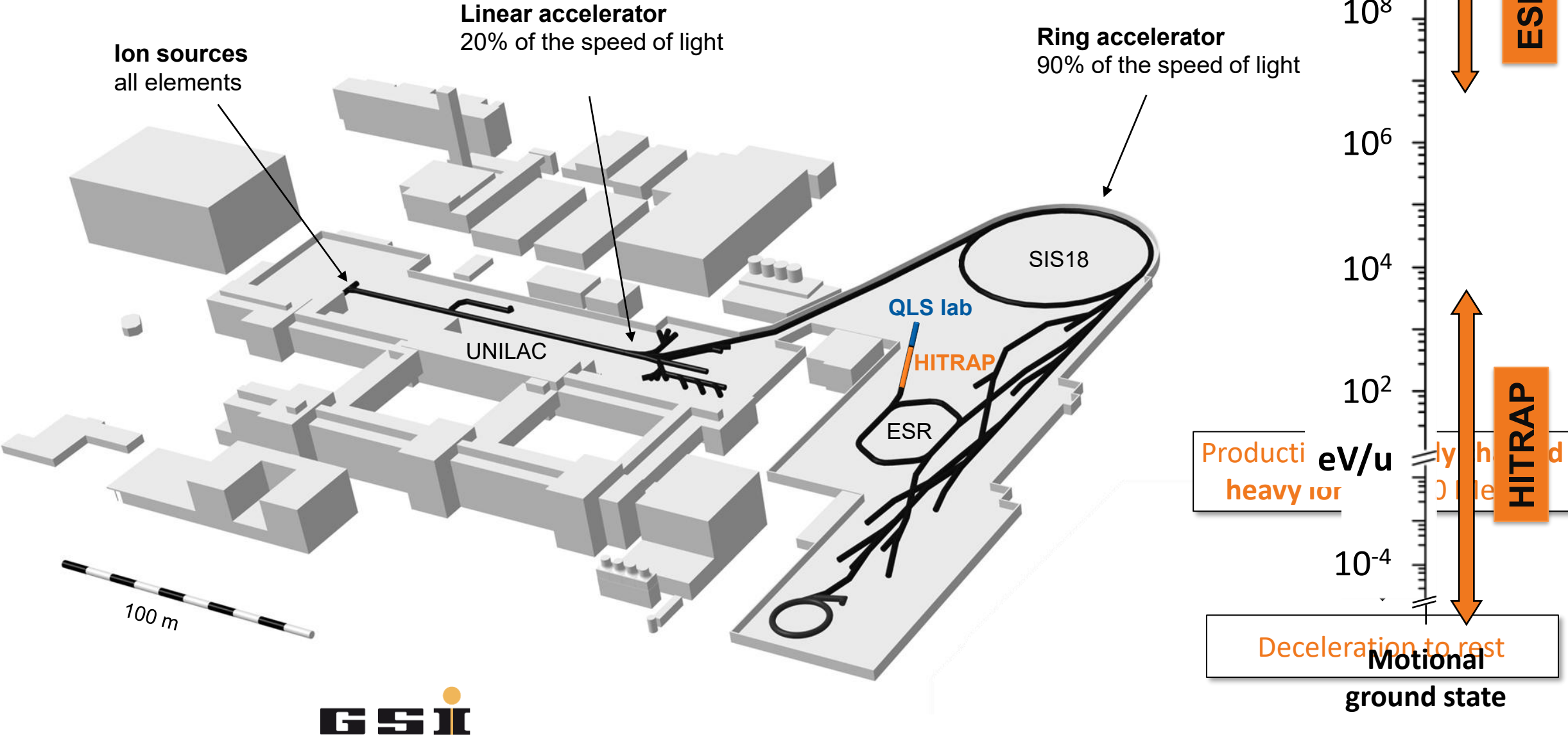
us Blaum
omas Pfeifer
é R. Crespo Lopez-Urte
ra M. Schäfer ...

Stefan Umer
Christian Smorra
Jochen Walz ...



HITRAP

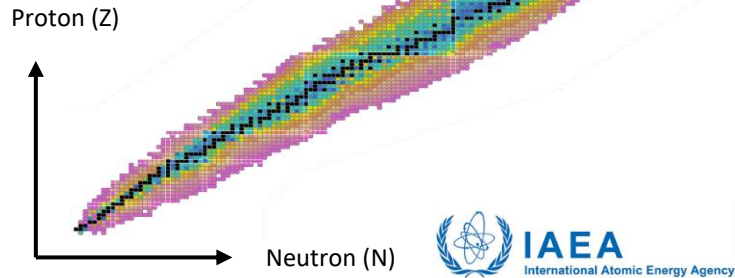
GSI Helmholtz Center for Heavy Ion Research



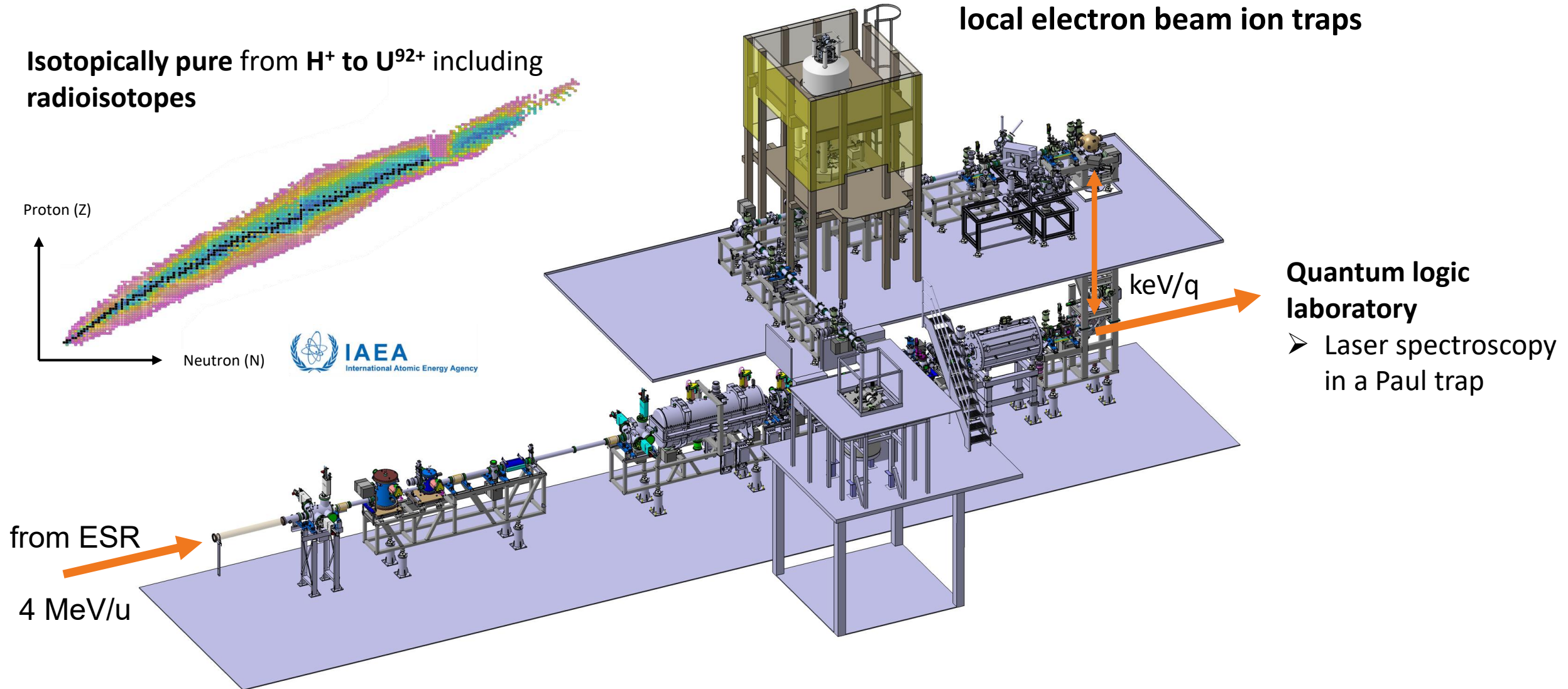
HITRAP facility

Accelerator-produced ions

Isotopically pure from H^+ to U^{92+} including radioisotopes



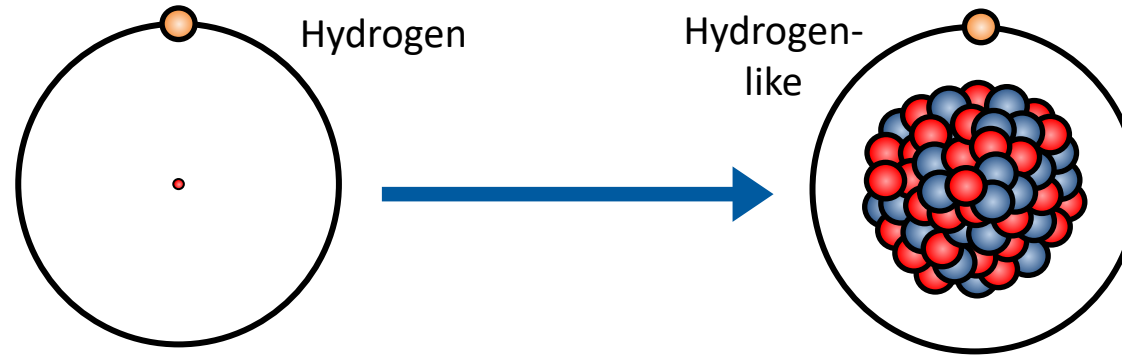
Ions produced in
local electron beam ion traps



Quantum logic
laboratory

➤ Laser spectroscopy
in a Paul trap

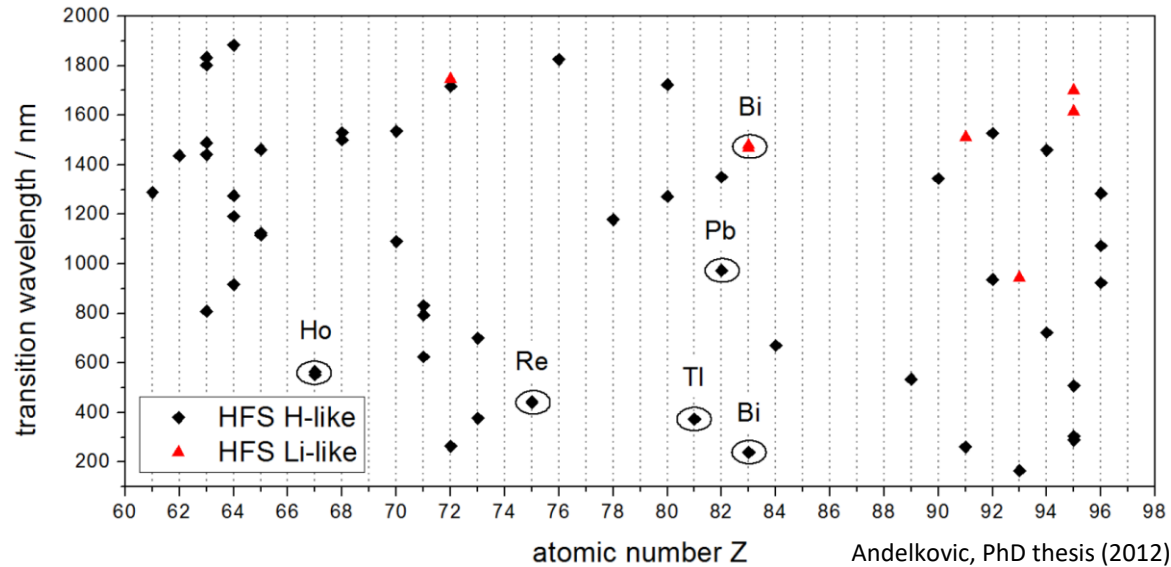
Highly charged heavy ions



2 nd -order Stark shift	Z^{-4}
Black-body radiation shift	negligible
Electric-quadrupole shift	Z^{-2}
1 st -order Zeeman shift	Z^0
2 nd -order Zeeman shift	suppressed
Motional shifts	Z^0
Collisional shift	negligible

- **Simple** structure for accurate predictions
- **Extreme** electromagnetic fields
 - **Highly sensitive** to fundamental physics
 - **Robust** against external perturbations

Optical hyperfine structure in extreme systems



Tests of **QED in strongest fields**:
 Comparison of H-like and Li-like
 ions to cancel nuclear contribution

Shabaev et al., PRL **86**, 3959–3962 (2001)
 Horst et al., Nat. Phys. **21**, 1057–1063 (2025)
 Morgner et al., PRL **134**, 123201 (2025)
 Morgner et al., Science **388**, 945–949 (2025)

$$\Delta E_{\text{HFS}}^{1s} = \frac{4}{3} \alpha (\alpha Z)^3 \cdot \frac{\mu}{\mu_N} \cdot \frac{m_e}{m_p} \cdot \frac{2I+1}{2I} \cdot [A \cdot (1-\delta) \cdot (1-\varepsilon) + \chi]$$

Annotations for the equation:

- Nuclear magnetic moment (points to $\frac{\mu}{\mu_N}$)
- Relativistic factor (1 ... 2) (points to $\alpha (\alpha Z)^3$)
- Nuclear magnetization distribution correction (points to $(1-\varepsilon)$)
- Nuclear charge Distribution correction (points to $(1-\delta)$)
- QED (points to χ)

Nuclear metrology

Studies of **nuclear properties and structure** by assuming QED to be correct

Example: Hydrogen-like $^{207}\text{Pb}^{81+}$

PRL **98**, 180801 (2007) week ending
4 MAY 2007
PHYSICAL REVIEW LETTERS

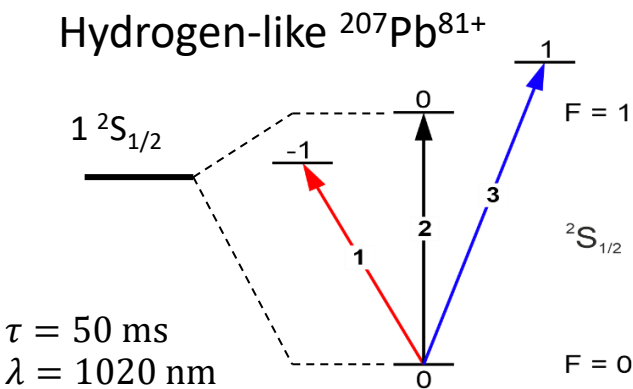
Hydrogenlike Highly Charged Ions for Tests of the Time Independence of Fundamental Constants

S. Schiller

Institut für Experimentalphysik, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany
(Received 18 October 2006; published 30 April 2007)

Hyperfine transitions in the electronic ground state of cold, trapped hydrogenlike highly charged ions have attractive features for use as frequency standards because the majority of systematic frequency shifts are smaller by orders of magnitude compared to many microwave and optical frequency standards. Frequency measurements of these transitions hold promise for significantly improved laboratory tests of local position invariance of the electron and quark masses.

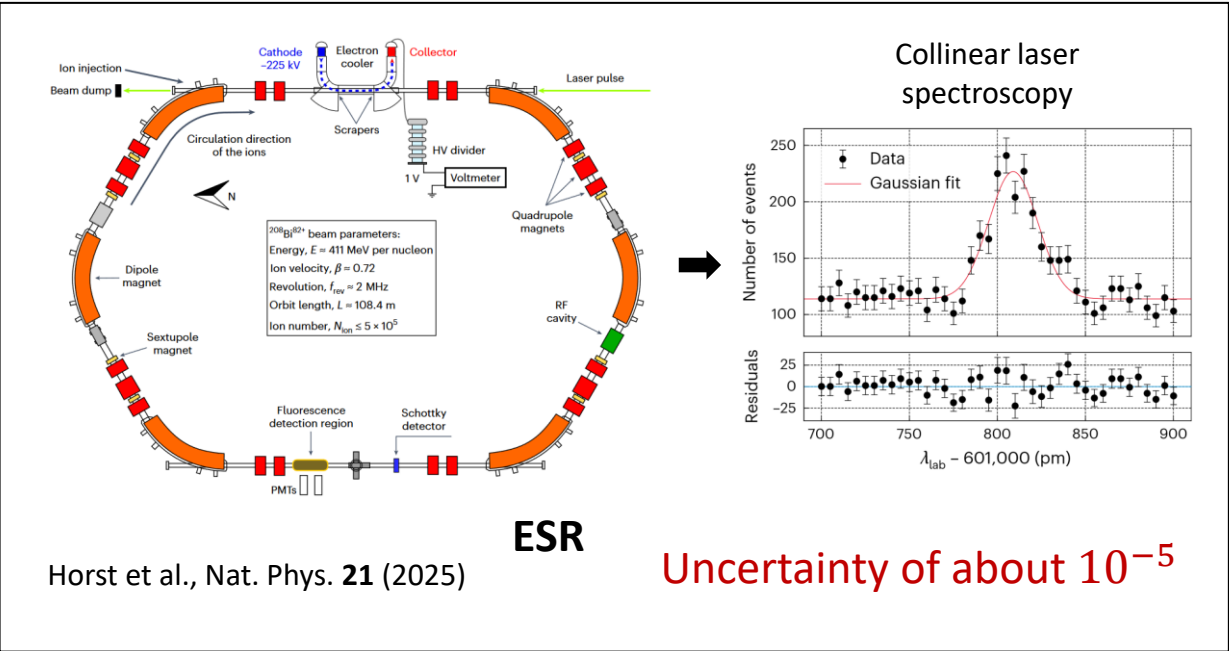
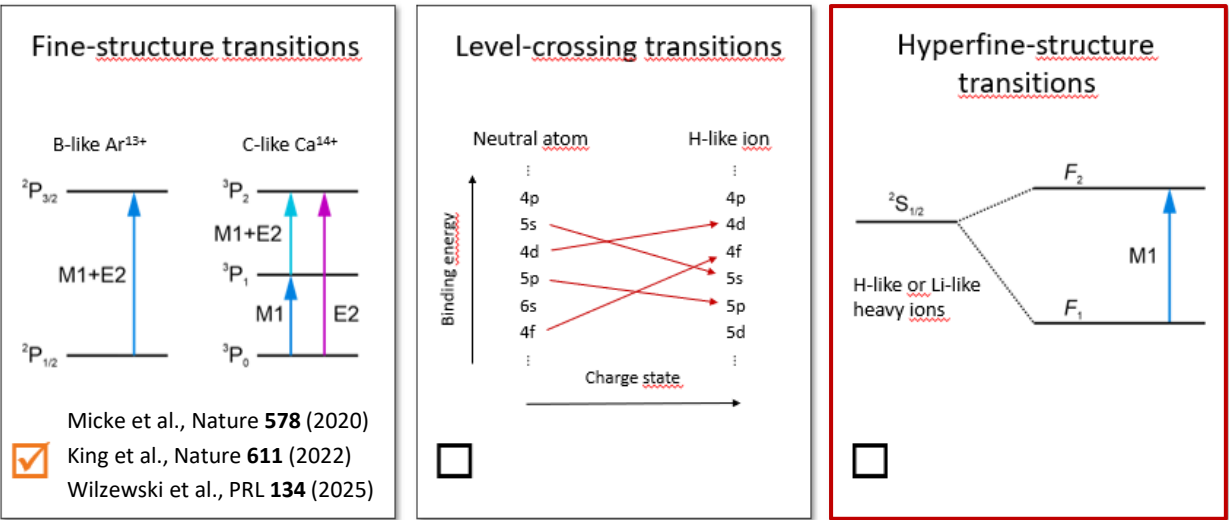
DOI: [10.1103/PhysRevLett.98.180801](https://doi.org/10.1103/PhysRevLett.98.180801) PACS numbers: 06.20.Jr, 06.30.Ft, 31.30.Gs, 32.30.Dx



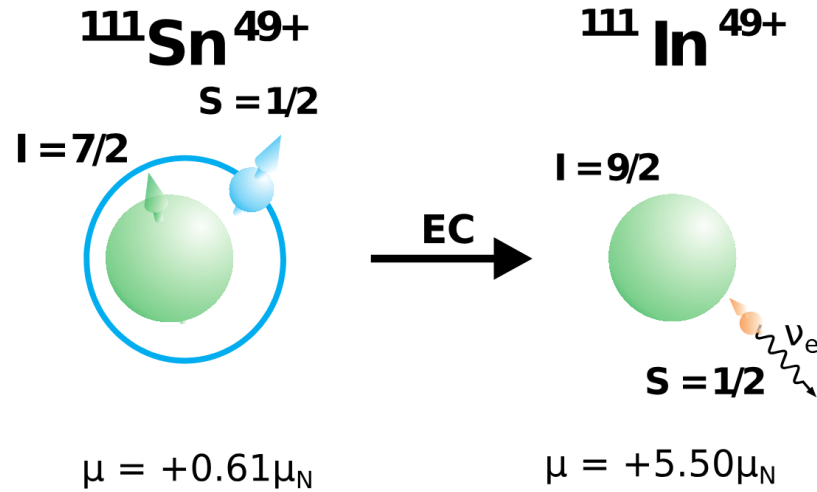
Tests of Lorentz symmetry

Improve limits on SME coefficients by orders of magnitude

A. J. Vargas, arXiv:2609.20953 (2026)



Alternatives during InterLAC periode after fire?



$$F = I + S \left\{ \begin{array}{l} 4 \\ 3 \end{array} \right. \begin{array}{l} \nearrow \\ \searrow \end{array} \begin{array}{l} 5 \\ 4 \end{array} \left. \vphantom{\begin{array}{l} 4 \\ 3 \end{array}} \right\} F = I + S$$

Eur. Phys. J. A (2023) 59:102
<https://doi.org/10.1140/epja/s10050-023-00978-w>

THE EUROPEAN
 PHYSICAL JOURNAL A



Regular Article - Experimental Physics

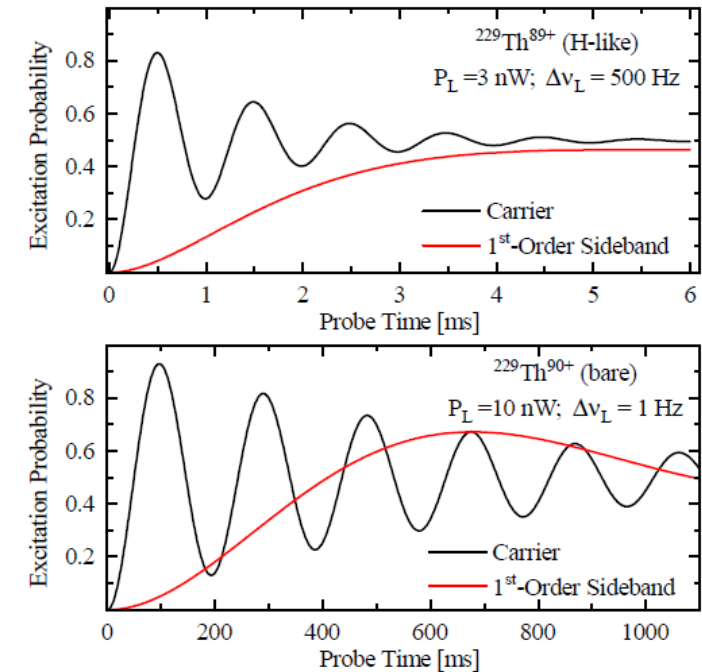
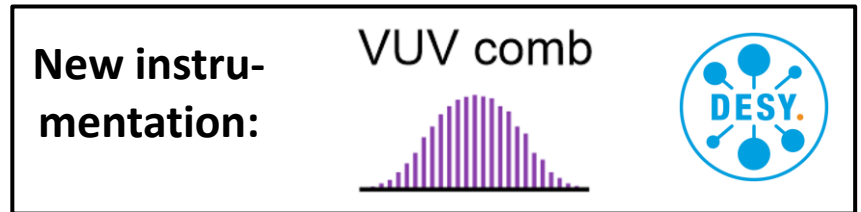
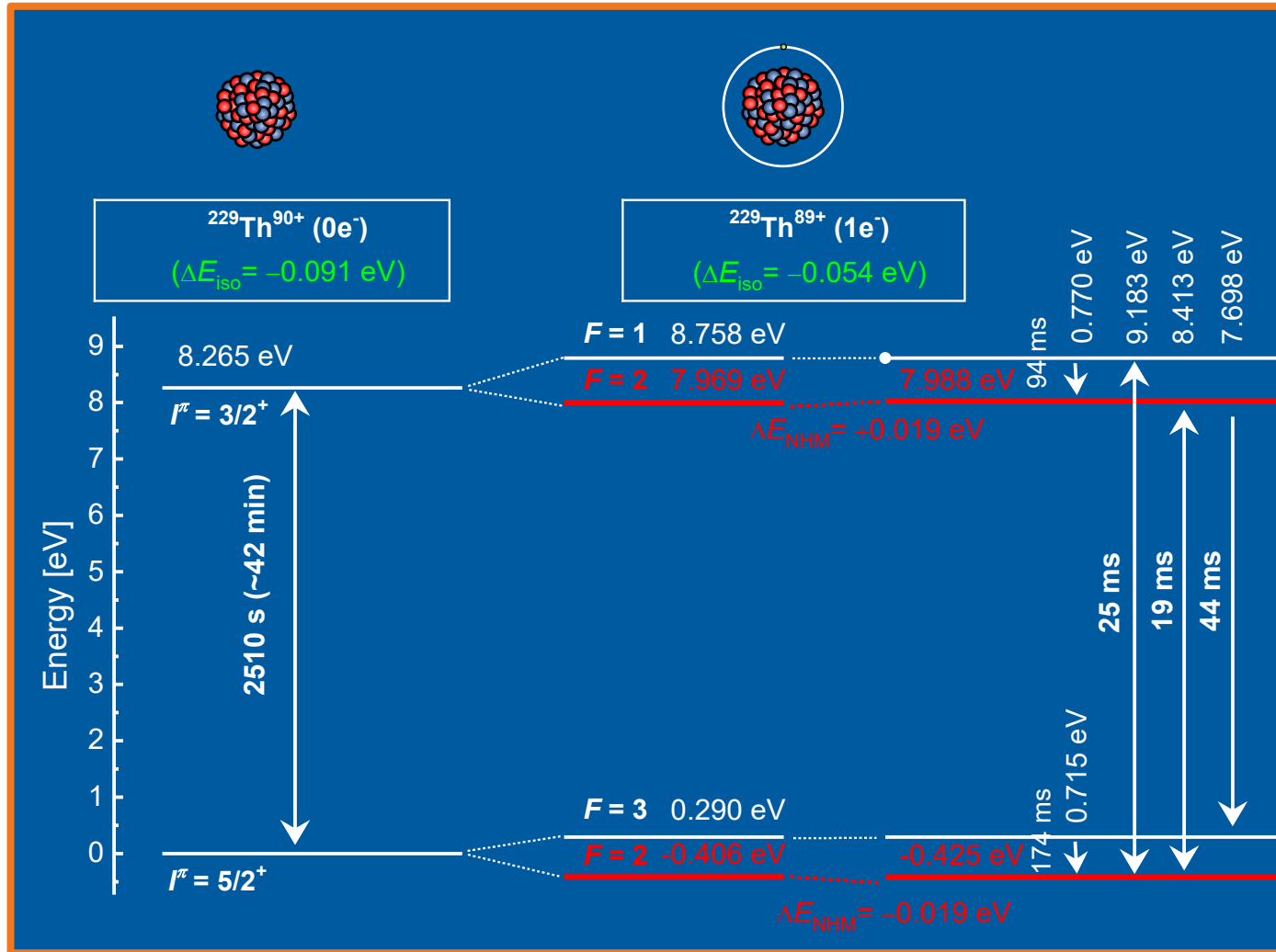
Radioactive decays of stored highly charged ions

Yury A. Litvinov^a, Rui Jiu Chen^b

Atomic, Quantum & Fundamental Physics Division, GSI Helmholtz Center for Heavy Ion Research GmbH, Planckstraße 1, Darmstadt 64291, Hesse, Germany

Can we **manipulate or even control the radioactive decay** of single ions with laser pulses that deterministically switch the hyperfine state?

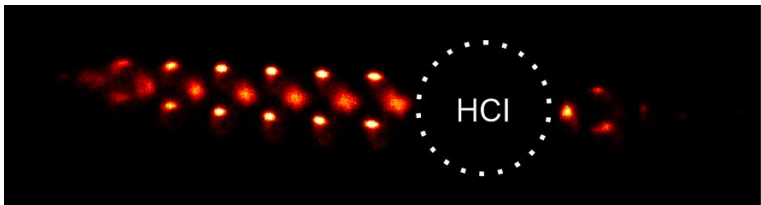
The nuclear transition in Th-229



C. Brandau, P. Micke et al., arXiv:2608.08133 (2026)

Enabling toolbox

Capture of highly charged ion in a Paul trap



HCl: Highly charged ion

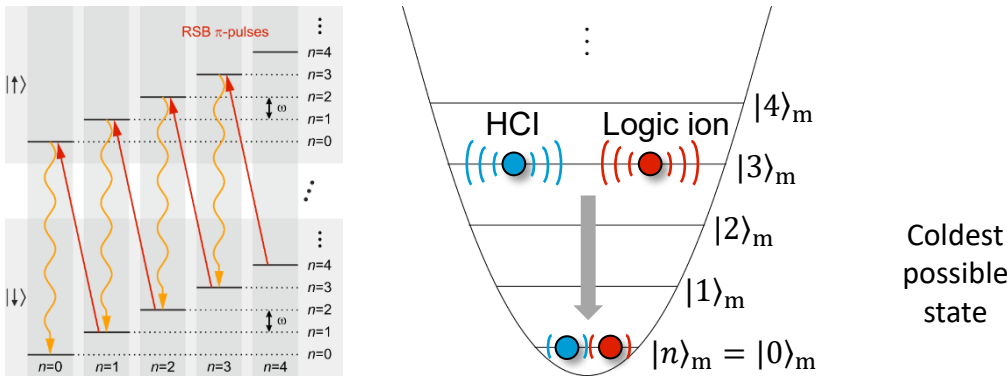
Two-ion crystal preparation



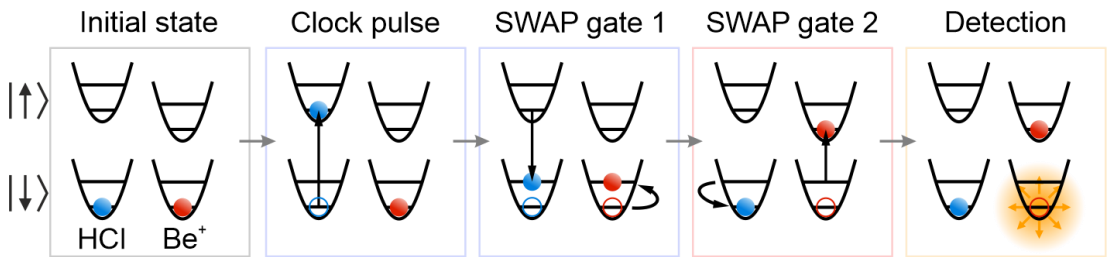
Be⁺: Logic ion

P. Micke et al., Nature **578**, 60–65 (2020)

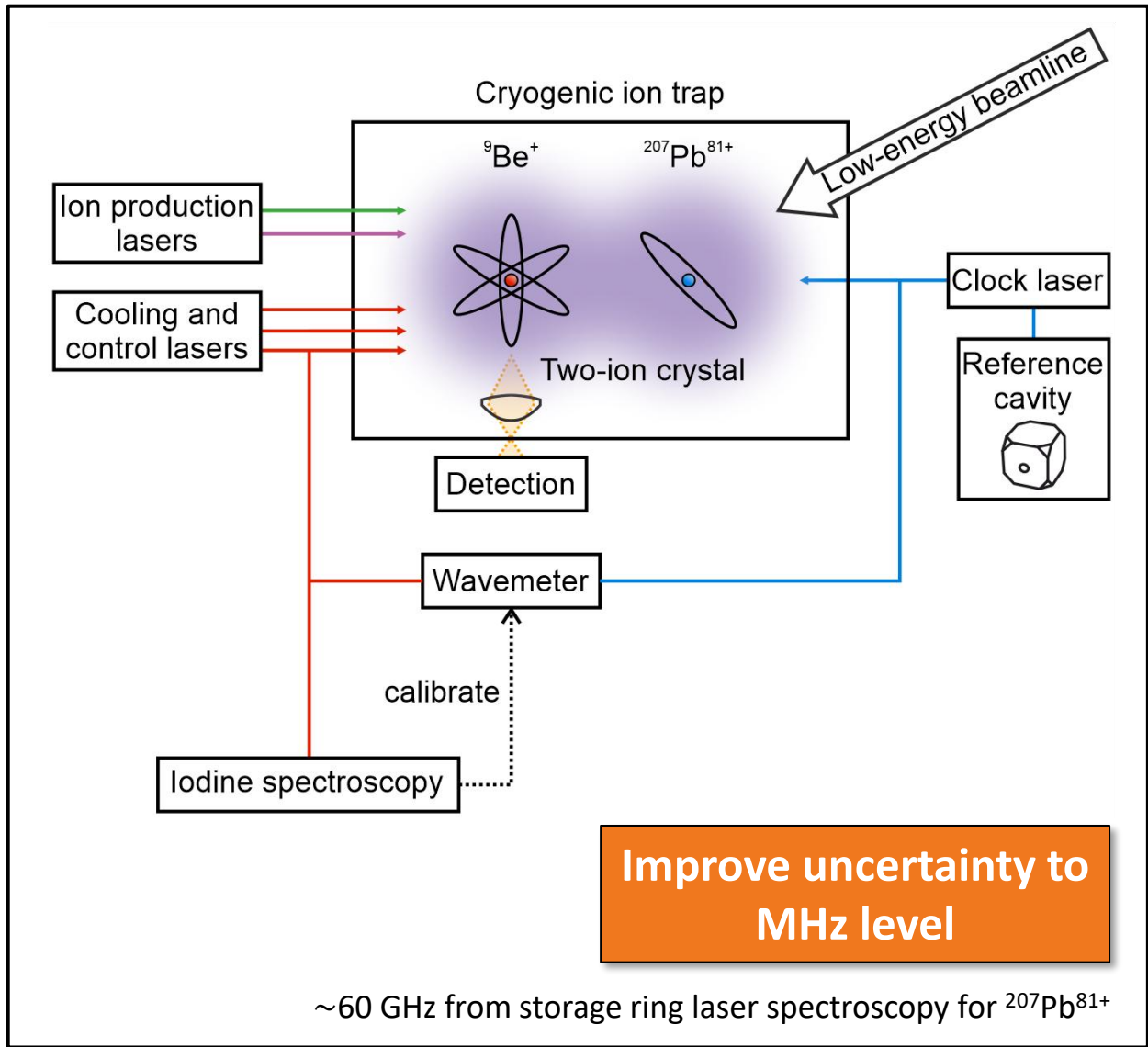
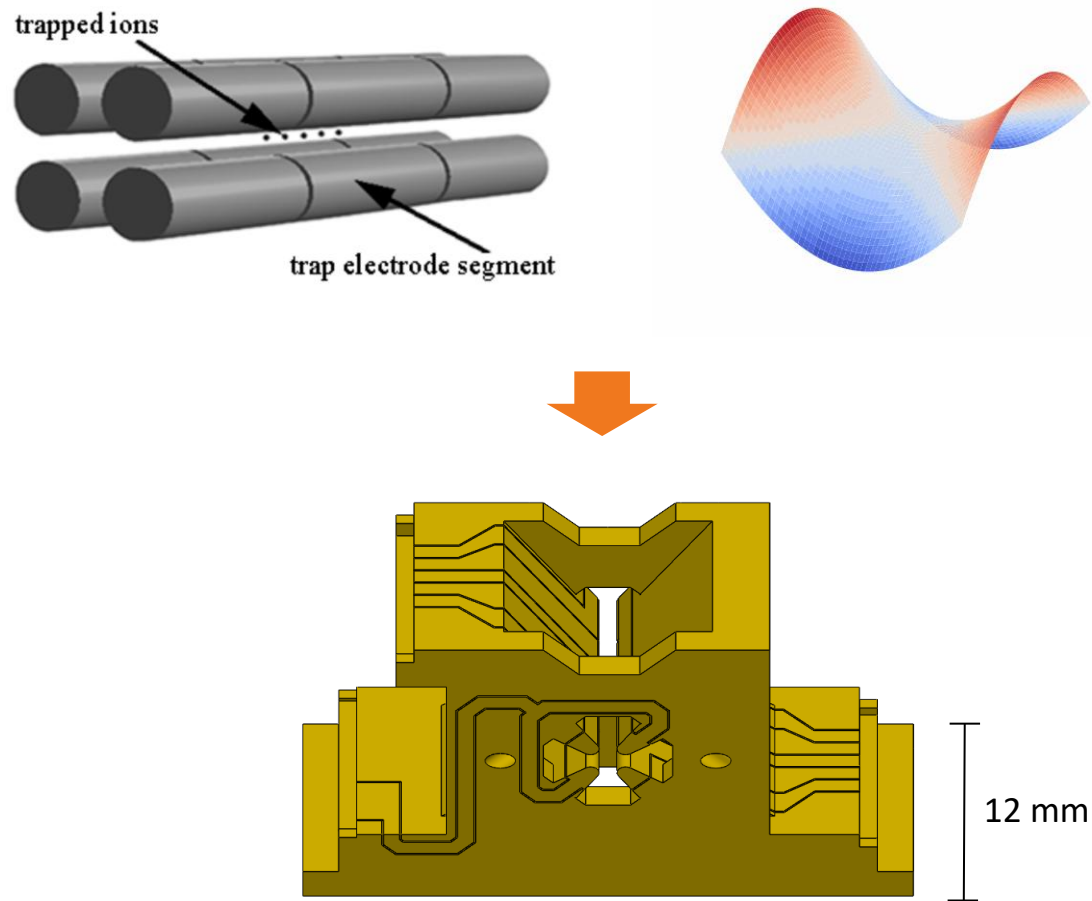
Cooling to quantum-mechanical ground state of motion



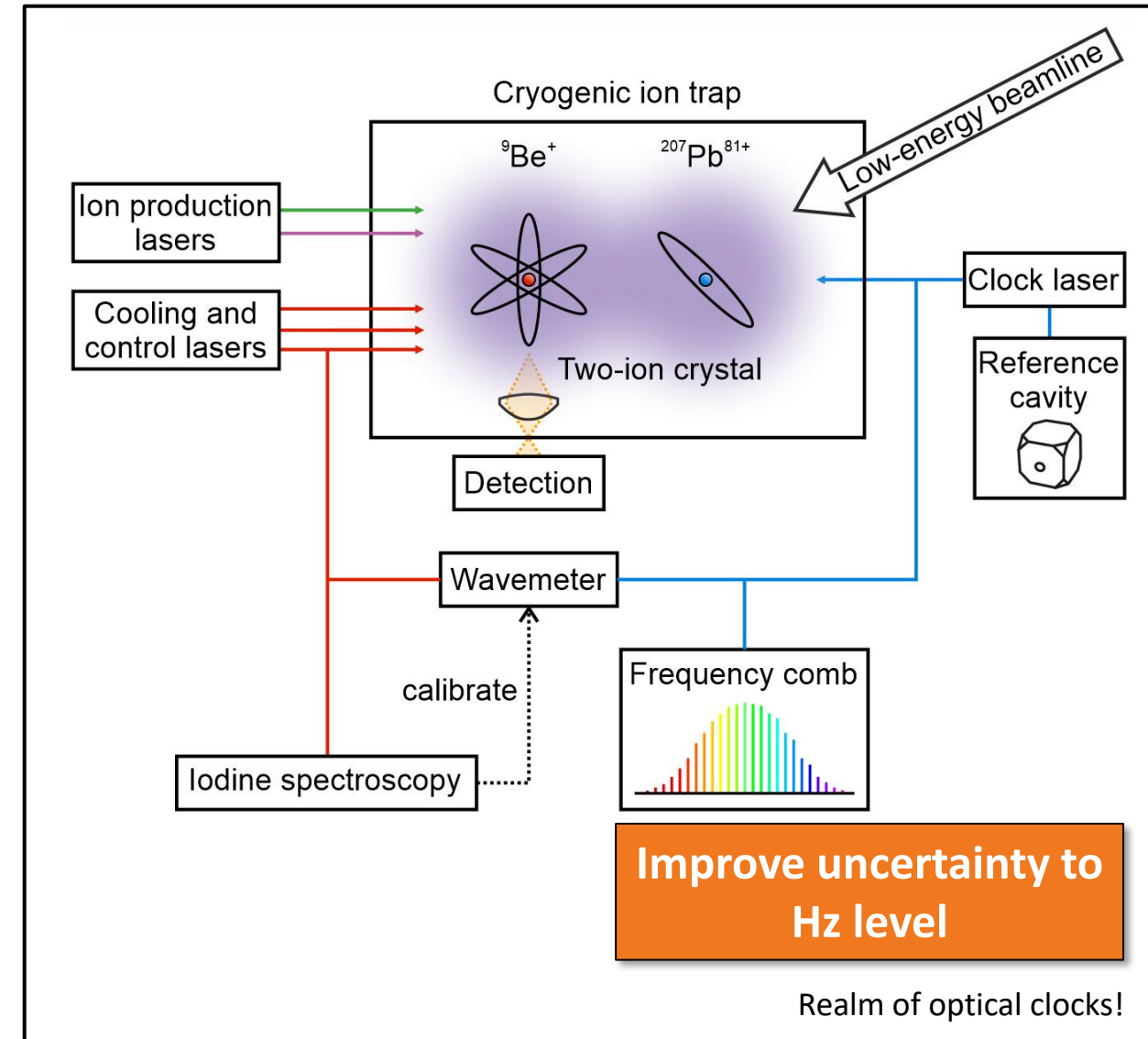
Quantum logic spectroscopy



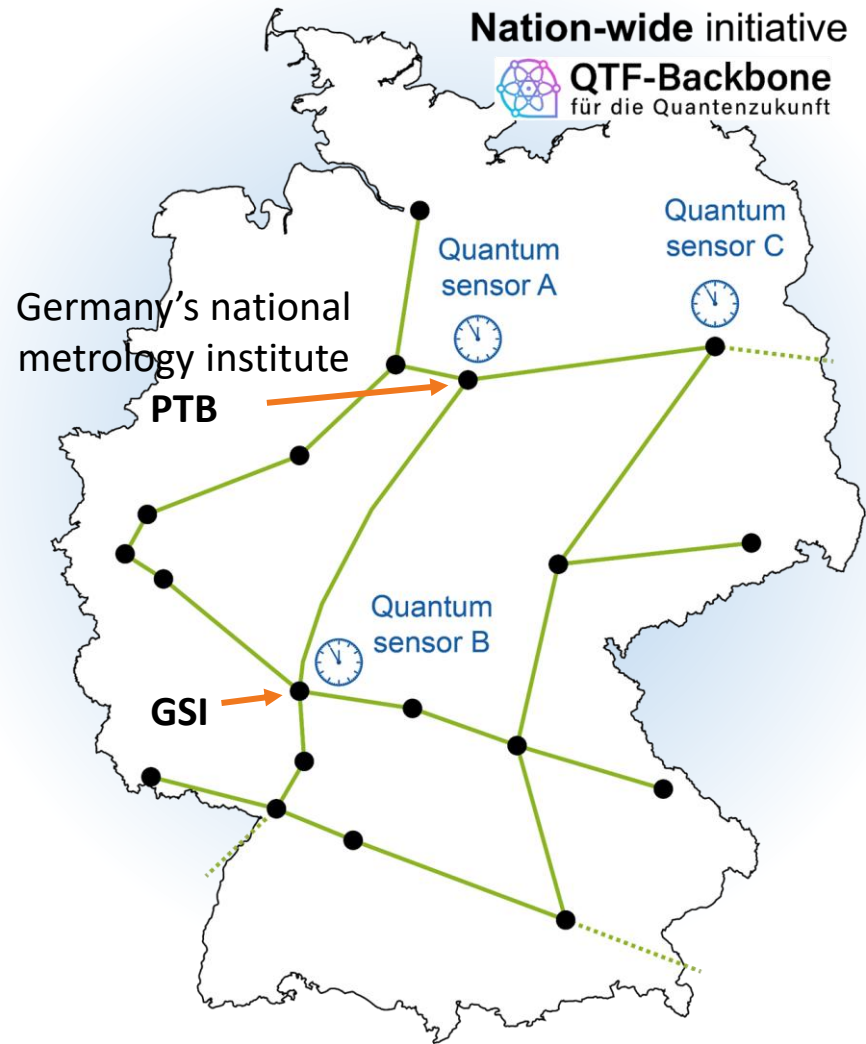
Implementation



Frequency comb upgrade



Fiber link, clock comparisons, and a quantum sensor network



Eur. Phys. J. Spec. Top.
<https://doi.org/10.1140/epjs/s11734-026-02451-3>

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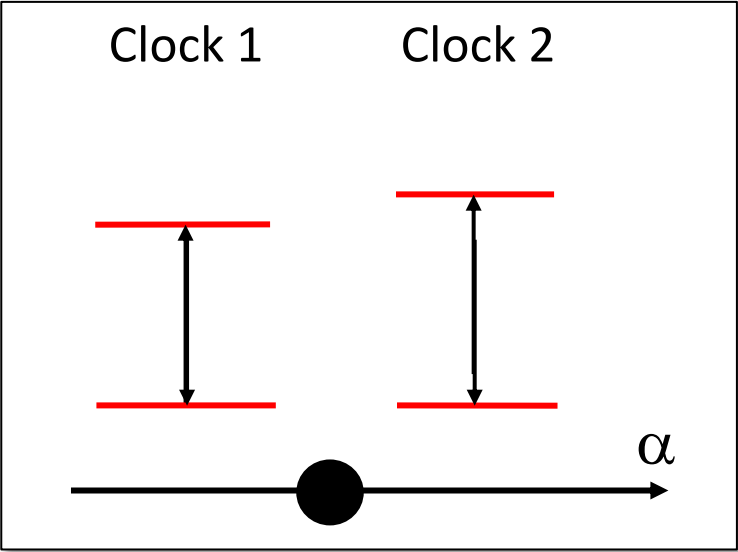
Regular Article

The QTF Backbone: proposal for a nationwide optical fibre backbone in germany for quantum technology and time and frequency metrology

Tara Cubel Liebisch^{1,a}, Peter Kaufmann², Harald Schnatz¹, Susanne Naegele-Jackson³, Jochen Kronjäger¹, Klaus Blaum⁴, Stefan Kück¹, Dieter Meschede⁵, Stephan Schiller⁶, Laura Agazzi⁷, Soroosh Alighanbari⁶, Joachim Ankerhold⁸, Georgy V. Astakhov⁹, Stefanie Barz^{10,11}, Ingo Baumann¹², Rainer Baumgart¹³, Christoph Becher¹⁴, Hendrik Bekker¹⁵, Oliver Benson¹⁶, Paolo Bianco¹⁷, Ronald Bieber¹⁸, Immanuel Bloch^{19,20}, Ulrike Blumröder²¹, Rainer Bockholt⁵, Johannes Bouman²², Claus Braxmaier^{8,23}, Enrico Brehm²⁴, Dagmar Bruss⁶, Dmitry Budker^{15,25,26}, Hans-Joachim Bungartz^{27,28}, Erik Busley²⁹, José R. Crespo López-Urrutia⁴, Cornelia Denz¹, Christian Deppe³⁰, Guido Dietl³¹, Fei Ding³², Thomas Eickermann¹⁷, Florian Elsen³³, Wolfgang Ertmer³², Stefan Filipp^{27,34}, Marc Fischer³⁵, Jakob Flury³², Thomas Fröhlich²¹, Johann Furthner⁷, Ilia Gerhardt³², Kay Uwe Giering³⁶, Christoph Glingener³⁷, Helmut Grießer³⁸, Rüdiger Grimm³⁹, Christian Grimm², Andreas Gritsch²⁷, Fritz Hack⁴⁰, Theodor Hänsch^{19,20}, Thomas Halfmann⁴¹, Andreas Hanemann⁴², Daniel Harlacher⁴³, Niklas Hegemann⁴⁴, Tobias Heindel⁴⁵, Robert Heinkelmann⁴⁶, Luis Hellmich^{16,24}, Thomas Hildmann⁷⁴, David Hock⁴⁷, Sven Höfling^{31,48}, Bruno Höft⁴⁹, Harald Hofmann⁷, Peter Hollecek³, Ronald Holzwarth^{19,50}, Wolfgang Hommel⁵¹, Thomas Hühn⁵², Urs Hugentobler²⁷, David Hunger⁴⁹, Nils Huntemann¹, Cigdem Issever¹⁶, Fedor Jelezko^{8,11}, Klaus Jöns⁵³, Tim Johann⁵⁴, Philippe Jousset⁴⁶, Bernd Jungbluth⁵⁵, Franz Kärtner^{56,57,58}, Jonas Kankel^{16,24}, Heike Kaufmann², Dmitry Khabib¹⁰, Thomas Kissinger²¹, Carsten Klempt⁵⁹, Thomas Klügel²², Ann-Kathrin Kniggendorf¹, Jan Kodet^{27,60}, Uwe Konrad⁹, Joachim Kopp¹⁵, Michael Kramer⁶¹, Stefan Kremling⁴⁷, Michael Krist²⁹, Markus Krutzik^{16,62}, Sascha Kwasniok⁶³, Yvonne Leifels²⁵, Gerd Leuchs⁶⁴, Christian Lisdat¹, Yuri Litvinov²⁵, Manfred Lochter⁶⁵, Peter van Loock¹⁵, Paul Lüsse⁶⁶, Eberhard Manske²¹, Tanja Mehlstäubler^{1,32}, Peter Michler¹⁰, Peter Micke^{25,67,68}, Martin Migura¹⁵, Jürgen Müller³², Wilfried Nörtershäuser^{25,41}, Stephan Pachnicke⁵⁴, Ralf Paffrath², Ekkehard Peik¹, Wolfgang Pompe², Achim Peters¹⁶, Thomas Pfeifer⁴, Dirk Piester¹, Randolph Pohl¹⁵, Ernst Maria Rase³², Helmut Reiser⁶⁹, Andreas Reiserer²⁷, Manfred Rieck¹⁸, Fritz Riehle¹, Stephan Ritter⁷⁰, Norbert Rogge²¹, Esther Ruiz Ben², Lakshmi Priya Kozhiparambil Sajith^{16,24}, Laura Sanchez²⁷, Vera Schäfer⁴, Wolfgang Schaefer⁷¹, Nick Schieferdecker⁷², Piet Schmidt^{1,32}, Roman Schnabel⁵⁸, Steffen Schön³², Ulli Schreiber^{27,60}, Carsten Schuck⁴⁵, Harald Schulz⁴⁶, Henrik Schulz⁹, Julius Schulz-Zander⁷³, Ullrich Schwanke¹⁶, Jean-Pierre Seifert⁷⁴, Klaus Sengstock⁵⁸, Kemal Shafak⁵⁶, Christine Silberhorn⁵³, Christian Smorra⁶, Nicolas Spethmann¹, Jonathan Steiert⁶⁶, Simon Stellmer⁵, Uwe Sterr¹, Thomas Stöhlker^{25,67,68}, Jürgen Stuhler⁷⁰, Sven Sturm⁴, Peter G. Thirol²⁰, Christian Töbeck⁷⁵, Thomas Udem⁷⁶, Stefan Ulmer⁶, Suren Vasilyan²¹, Asha Vincent³², Tobias Vogl^{27,77}, Raimund Vogl⁴⁵, Thomas Walther⁴¹, Harald Weinfurter²⁰, Christian Weinheimer⁴⁵, Lars von der Wense¹⁵, Arne Wickenbrock^{15,25}, Lisa Wörner⁵⁹, Fabian Wolf¹, Steven Worm^{16,24}, Yang Yang⁵⁷, Matthias Zimmermann²³, and Michael Zopf³²

T. C. Liebisch et al., Eur. Phys. J. Spec. Top. **235**, 3353–3387 (2026)

Search for variations of fundamental constants



$$\frac{\Delta f}{f} = K \frac{\Delta \alpha}{\alpha}$$

$$\frac{\Delta(f_1/f_2)}{(f_1/f_2)} = (K_1 - K_2) \frac{\Delta \alpha}{\alpha}$$

$$\dot{\alpha}/\alpha = 1.8(2.5) \times 10^{-19}/\text{year} \quad \text{M. Filzinger et al., Phys. Rev. Lett. \textbf{130} (2023)}$$

$$\dot{\alpha}/\alpha = 2.4(2.7) \times 10^{-19}/\text{year} \quad \text{M. Lide et al., arxiv:2609.26775 (2026)}$$

System	<i>K</i>	λ (nm)
Sr	0.06	699
Yb ⁺ E3	-6	467
Yb ⁺ E2	0.91	436
Al ⁺	0.01	267
Ir ¹⁷⁺	145	ca. 1978
Ir ¹⁷⁺	-22	ca. 283
Pr ⁹⁺	6.3	ca. 452
Pb ⁸¹⁺	5.6	1020

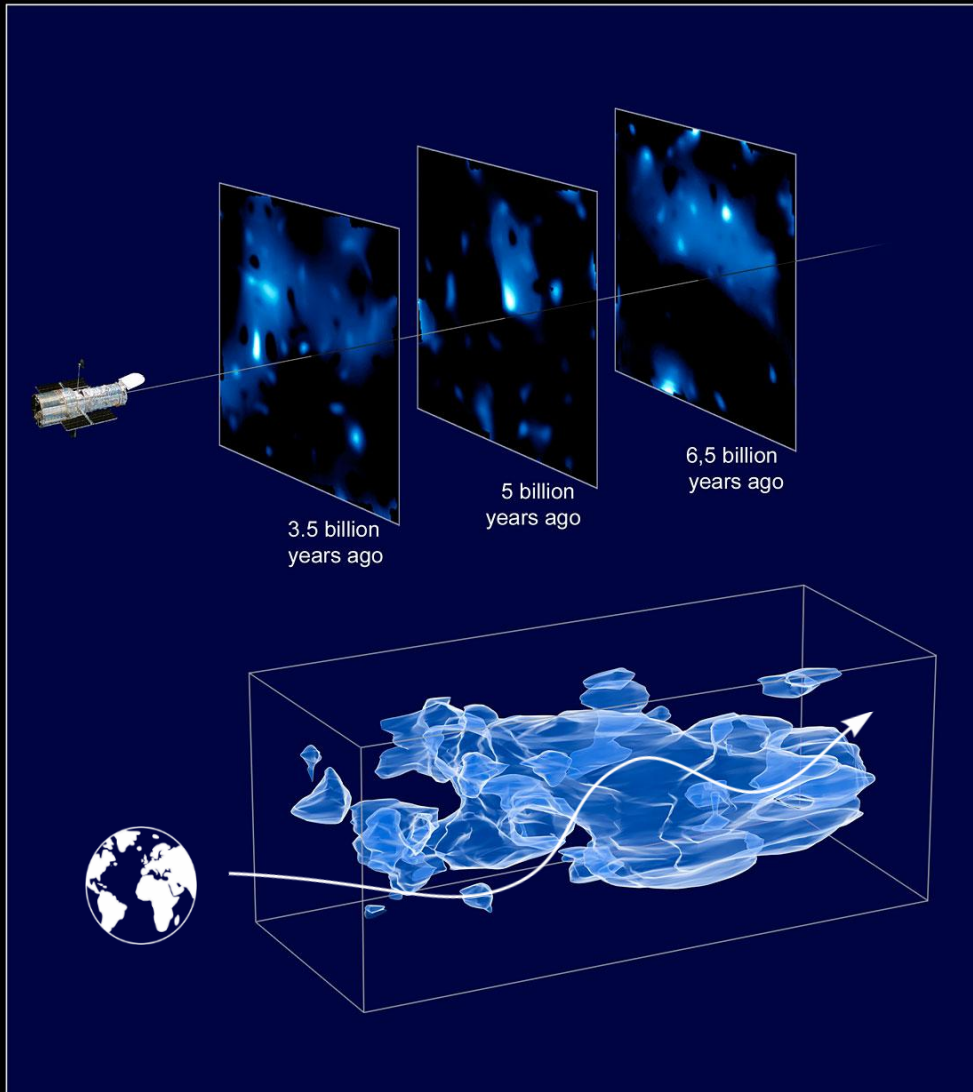
J. C. Berengut et al., PRL **106** (2011)

H. Bekker et al., Nat. Com. **10** (2019)

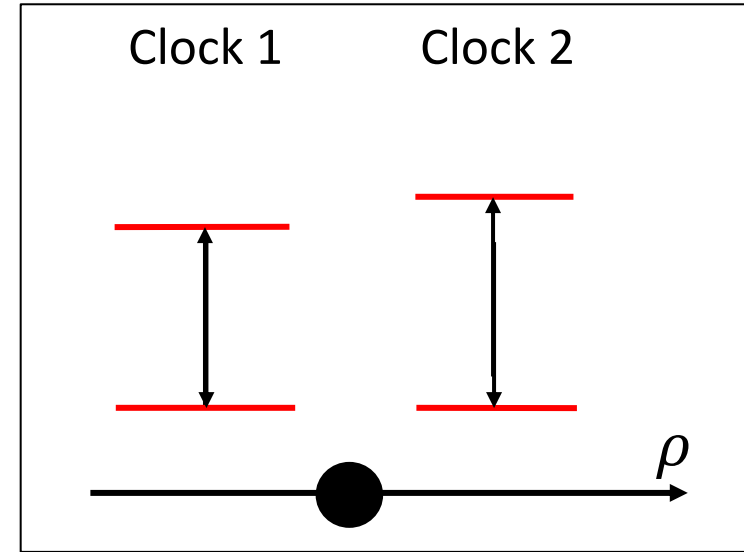
N. S. Oreshkina et al., PRA **96** (2017)

and others ...

Search for ultralight dark matter

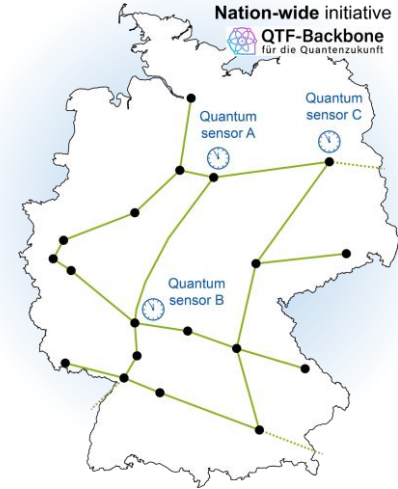
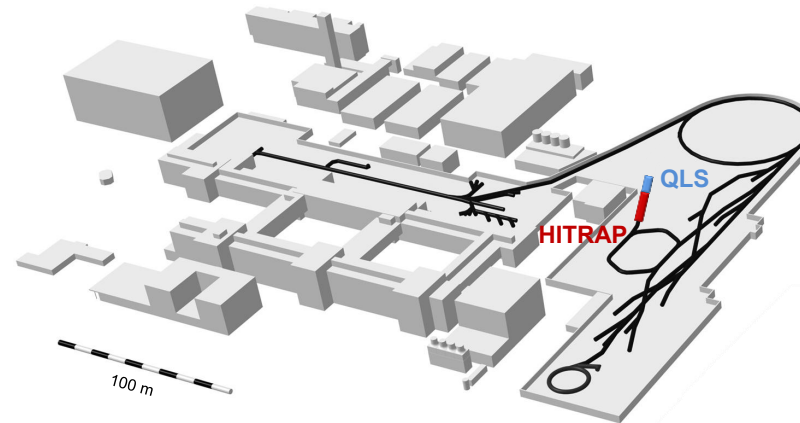


NASA, ESA, and R. Massey (Caltech), modified



- A. Derevianko and M. Pospelov, Nat. Phys. **10** (2014)
Y. V. Stadnik and V. V. Flambaum, Phys. Rev. Lett. **115** (2015)
Y. V. Stadnik and V. V. Flambaum, Phys. Rev. A **94** (2016)
M. S. Safronova et al., Rev. Mod. Phys. **90** (2018)
M.G. Kozlov et al., Rev. Mod. Phys. **90** (2018)

- **Universal platform for optical frequency metrology** to study **fundamental, atomic, and nuclear** physics
 - Universal ion production
 - Universal spectroscopy method
 - Clock comparisons and sensor network through optical fiber link



Unique setup!

Thank you very much!

