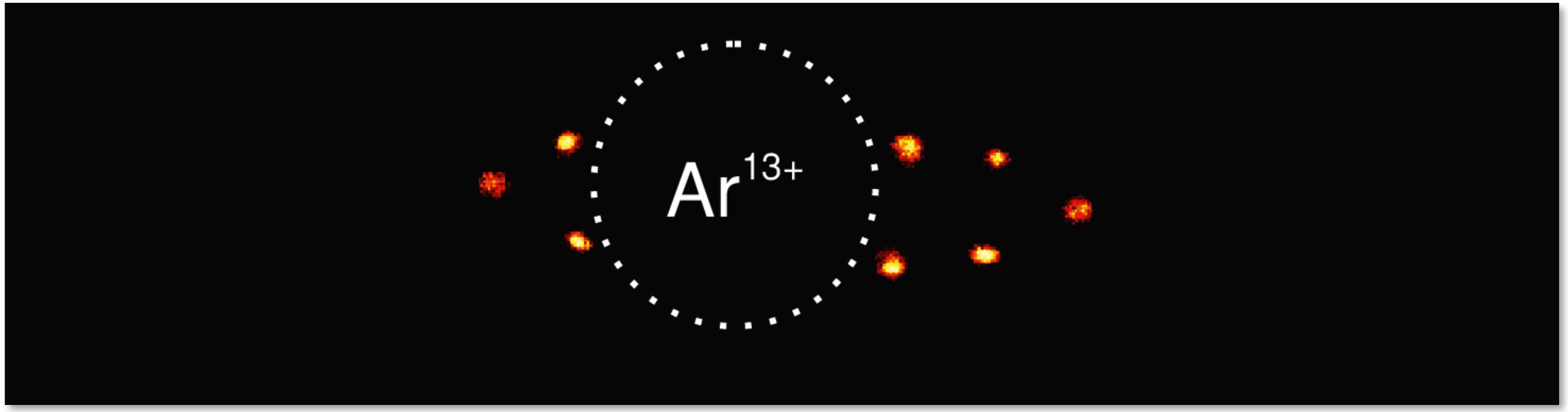
An optical clock based on a highly charged ion



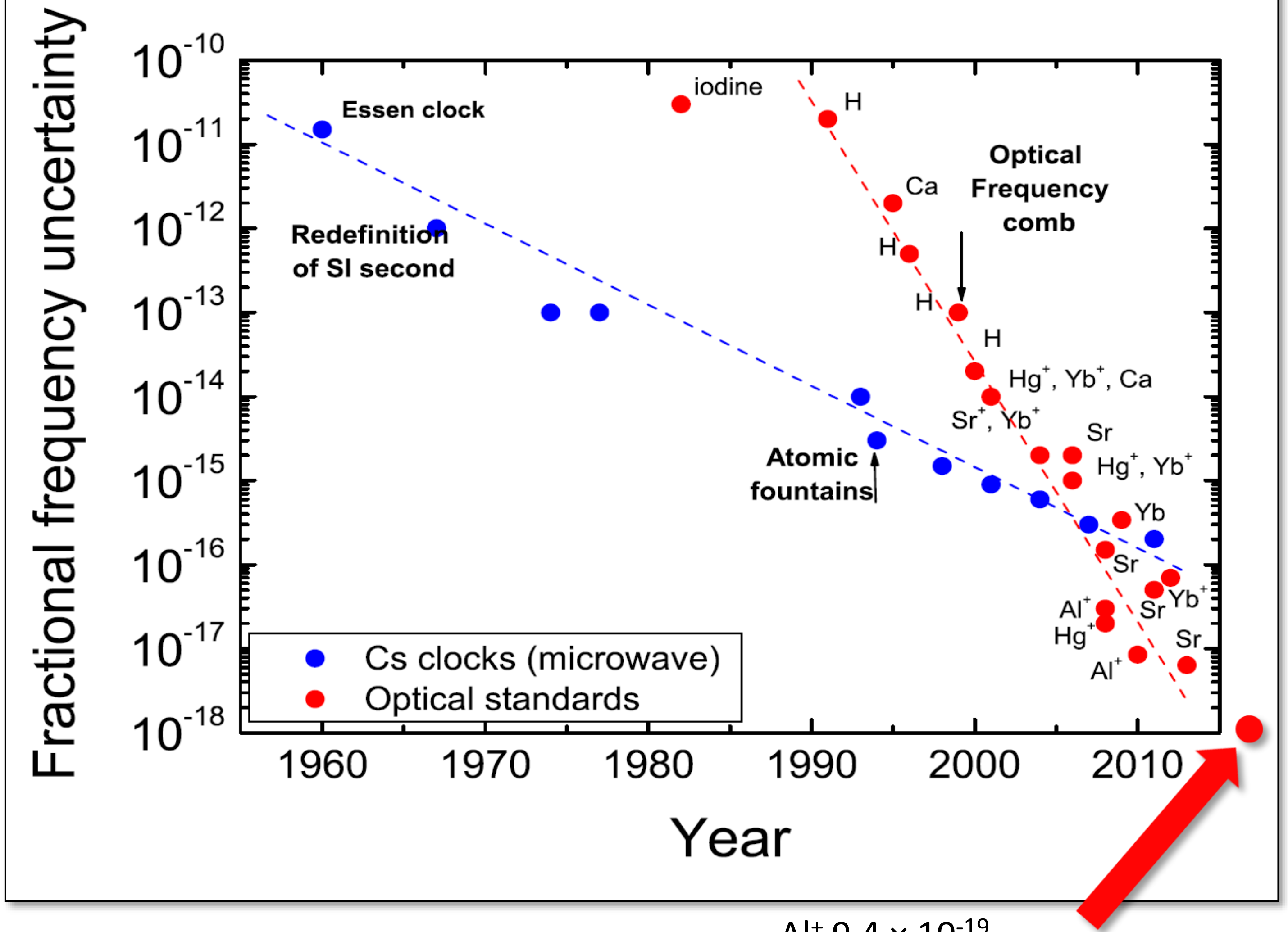
Lukas J. Spieß

Group of Piet O. Schmidt
QUEST Institute for Experimental Quantum Metrology
PTB Braunschweig, Germany

International Symposium on Stored Ions for Precision Measurements, Shanghai, 24. Nov. 2023

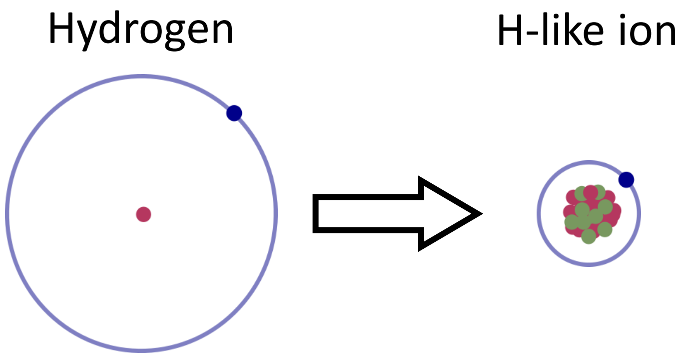
Optical clocks

Poli *et al.*, Riv. Nuovo Cimento **36** (2013)



Al^+ 9.4×10^{-19}
Brewer *et al.*, Phys. Rev. Lett. **123**, 033201 (2019)

Highly charged ions



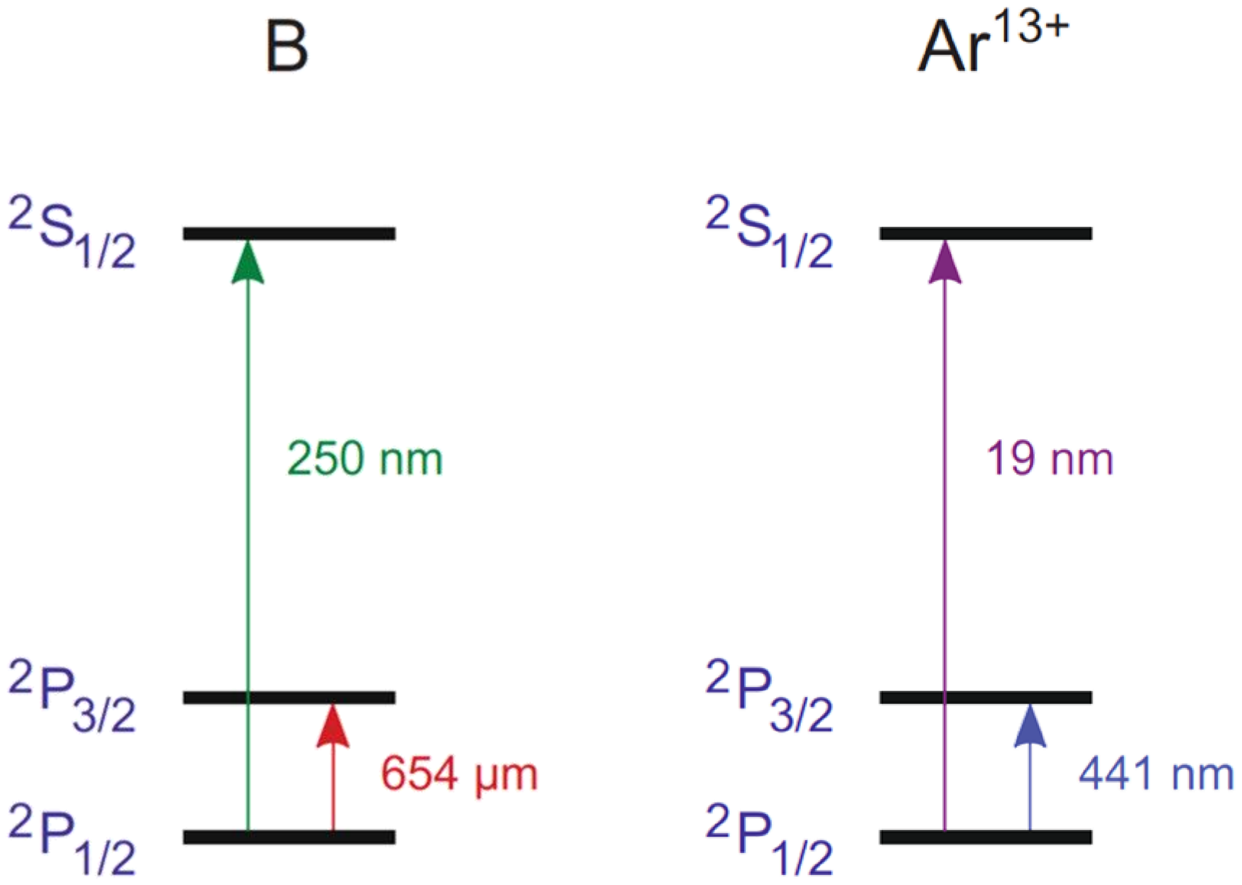
Linear Stark shift	Z^{-1}
Second order Stark shift	Z^{-4}
Linear Zeeman shift	Z^{0}
Second order Zeeman shift	$Z^{-3\ldots-4}$
Electric quadrupole shift	Z^{-2}

Intrinsically less sensitive to external perturbations

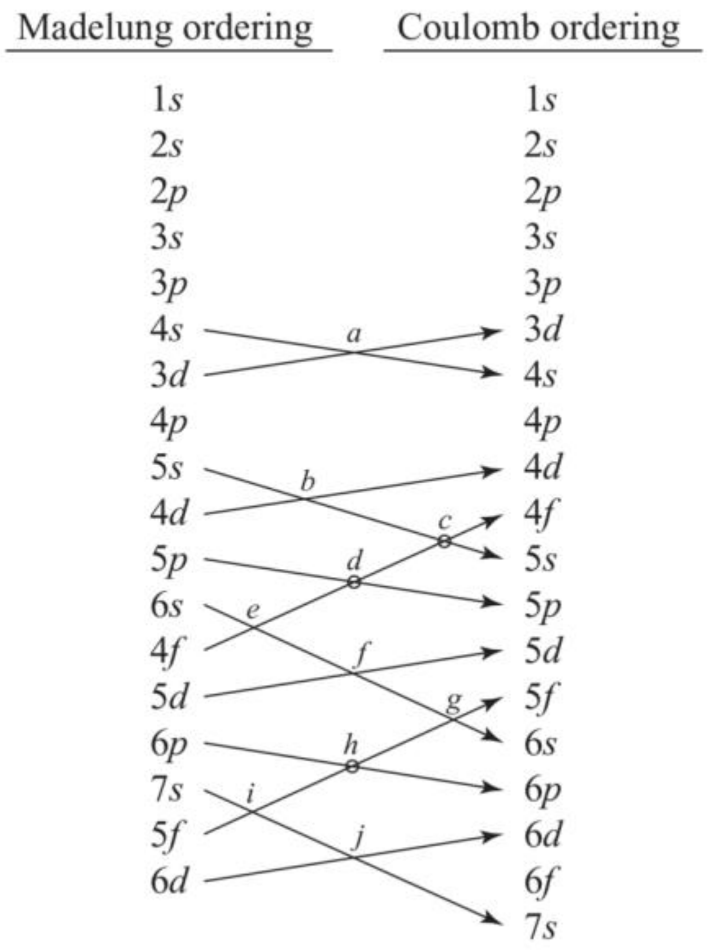
Kozlov *et al.*, Rev. Mod. Phys **90**, 045005 (2018)

Optical transitions in HCI

Fine and hyperfine structure transition



Optical transitions in HCI



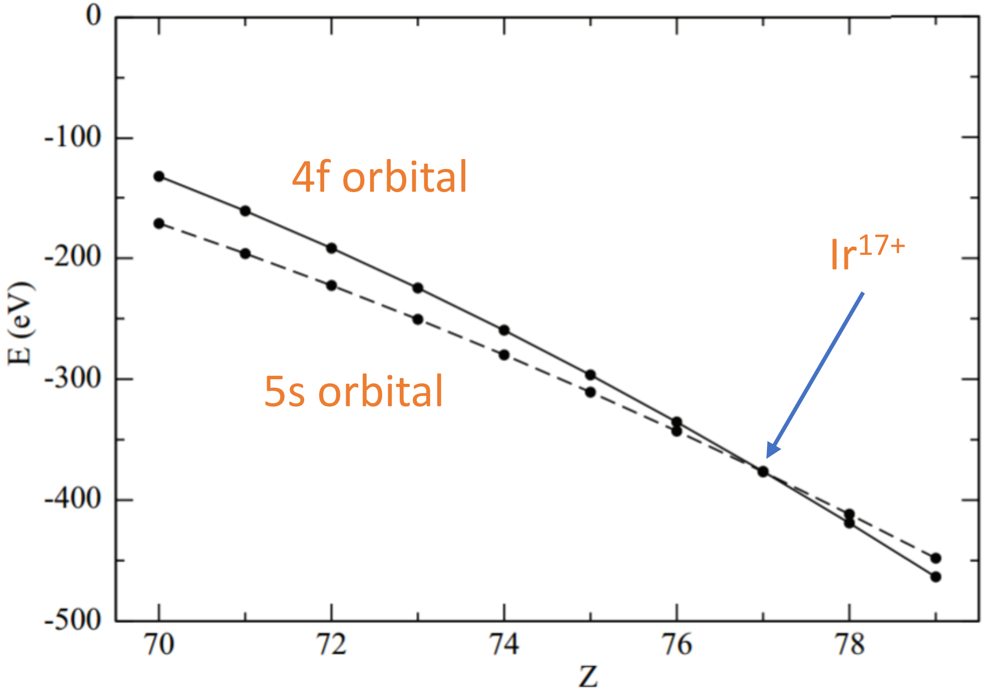
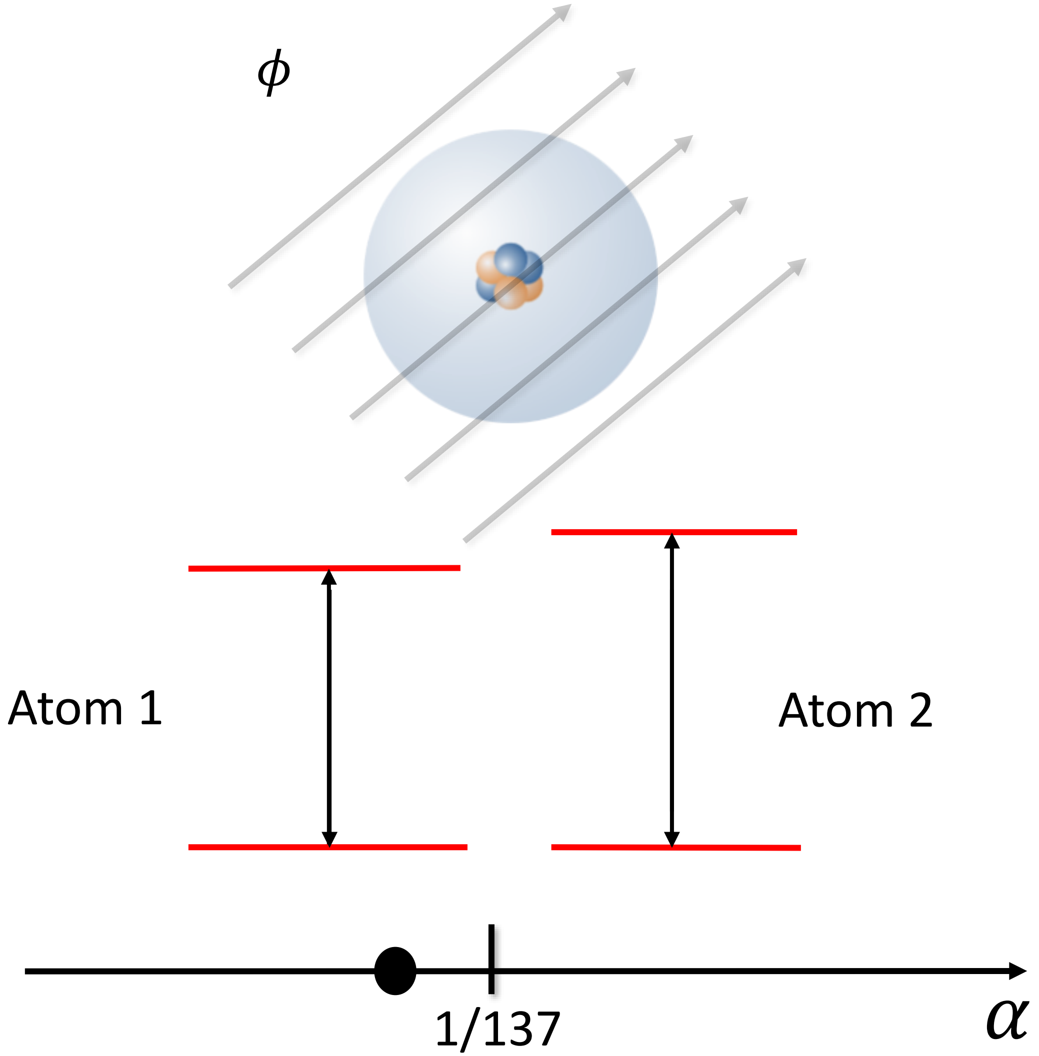


FIG. 2. Dirac-Fock energies of $4f_{7/2}$ (solid) and $5s$ (dashed) orbitals in the Sm isoelectronic sequence, $N = 62$, with closed external shells $5s^2 4f^{14}$.

J. Berengut *et al.*, Phys. Rev. Lett. **106**, 210802 (2011)

Fundamental physics with HCI



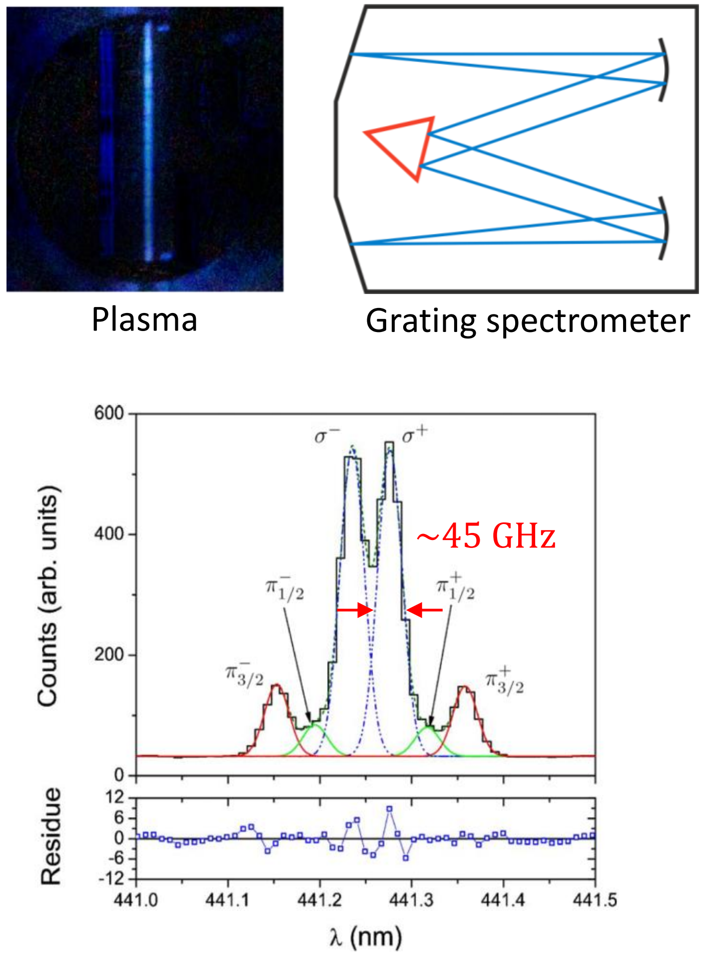
$$\frac{\Delta f}{f} = K \frac{\Delta \alpha}{\alpha}$$

System	K	λ (nm)
Sr	0.06	699
Yb^+ E2	0.91	436
Yb^+ E3	-6	467
Hg^+	-2.9	281.5
Ir^{17+} T1	-22	ca. 280
Ir^{17+} T2	145	ca. 1980
Cf^{16+*} T1	59	ca. 775
Cf^{17+*}	-48	ca. 535

$\dot{\alpha}/\alpha = 1.8(2.5) \times 10^{-19}$/year

Filzinger *et al.*, Phys. Rev. Lett. 130, 253001(2023)

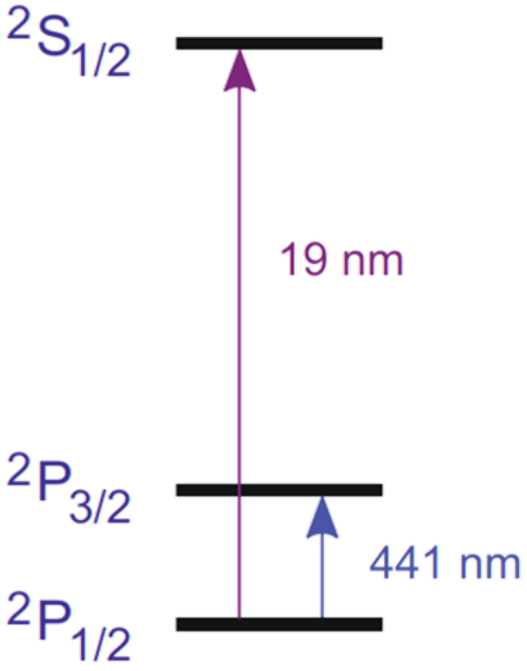
State-of-the-art HCI spectroscopy

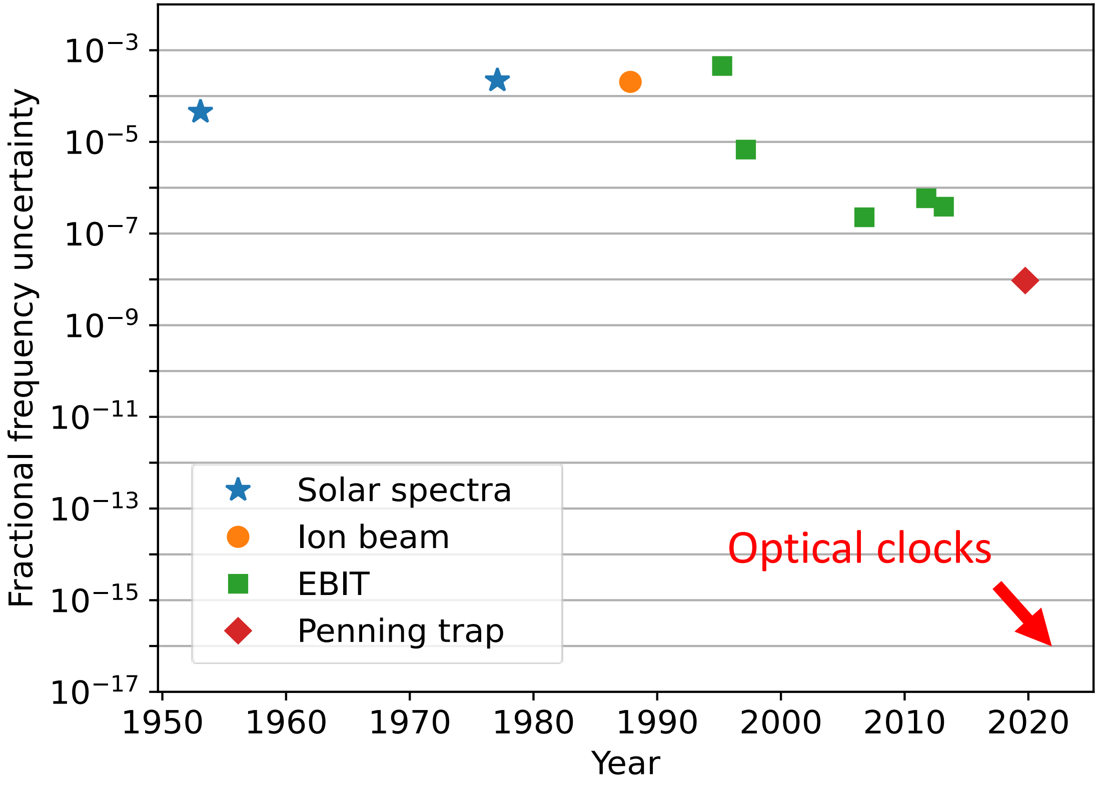


Soria Orts et al., PRA 76, 052501 (2007)

Uncertainty ~150 MHz

Ar^{13+}



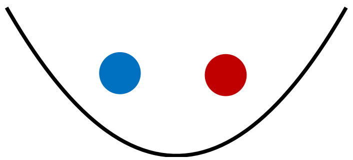


Quantum logic spectroscopy

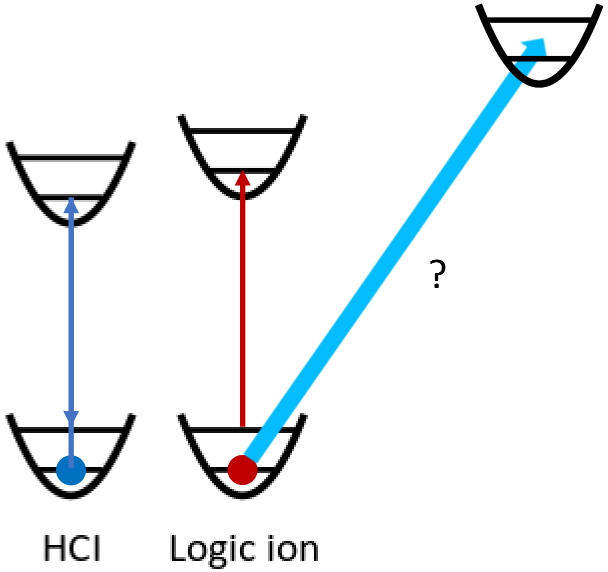
Dipole-allowed optical transitions for laser cooling / electron shelving

→ Sympathetic cooling and quantum logic spectroscopy

Coupled motion:

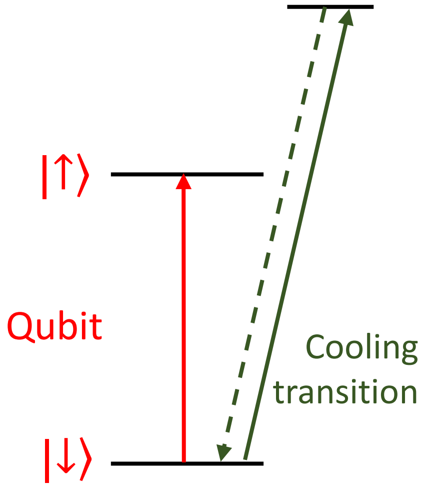


Spectroscopy ion
Ar^{13+}

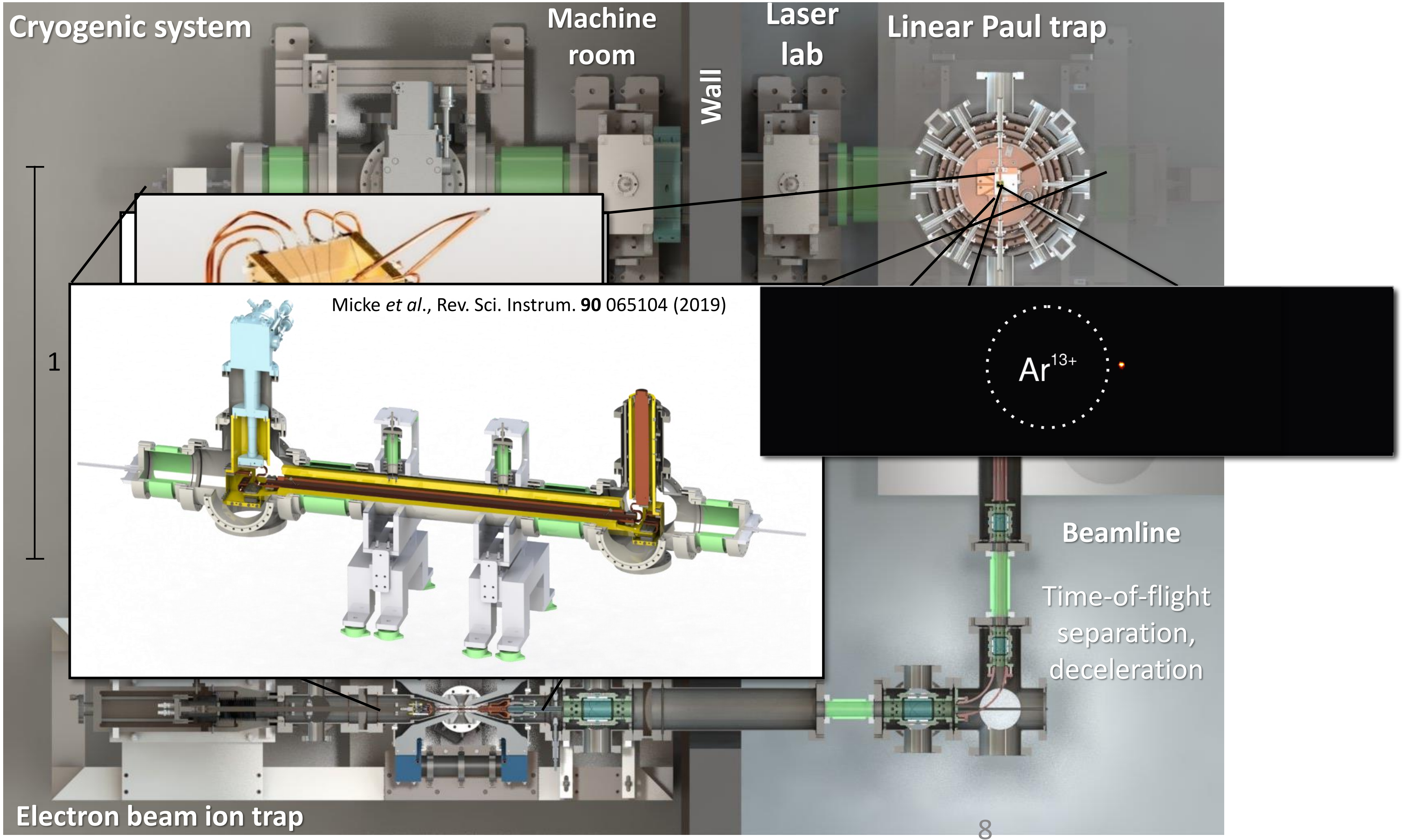


Schmidt et al., Science **309** (2005)

Logic ion
Be^+



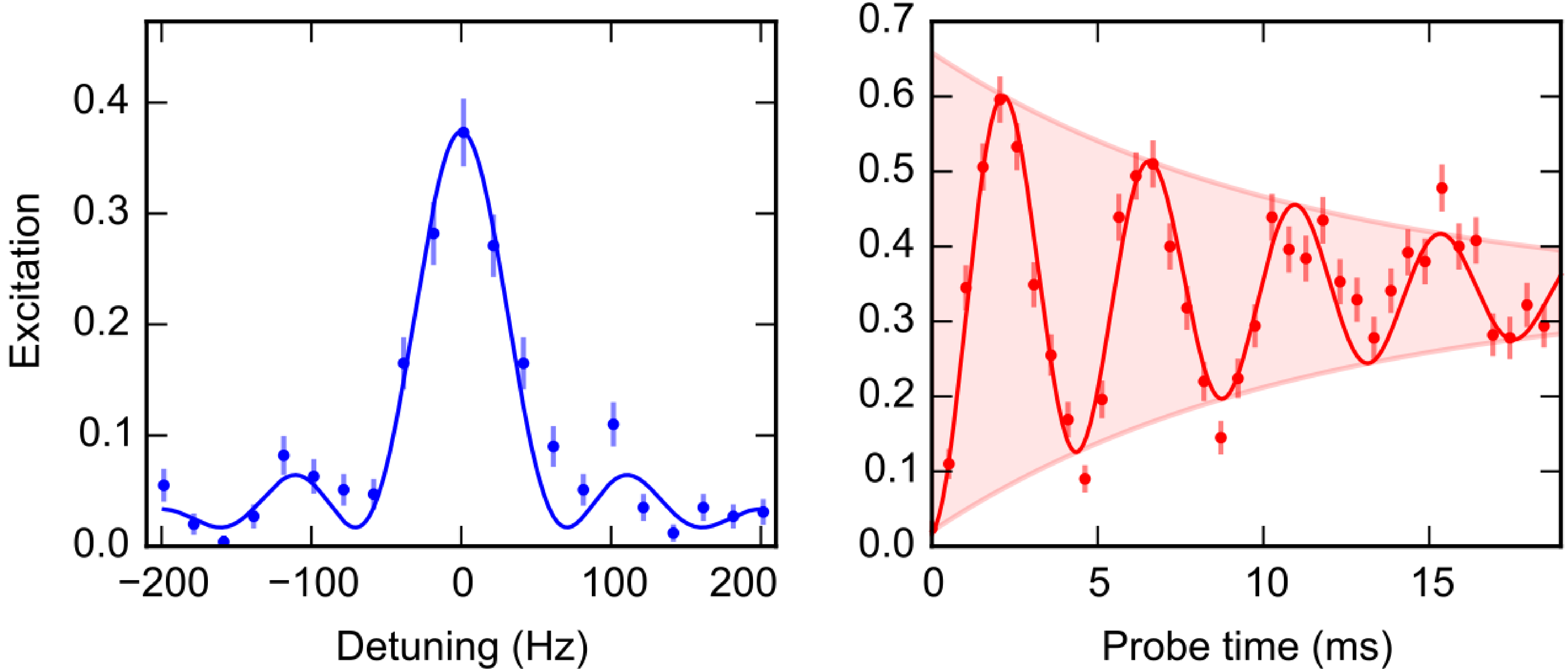
HCI lab at PTB



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)

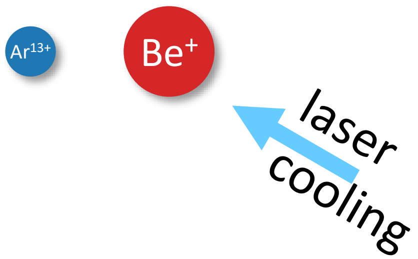
Cooling is challenging

Large q/m mismatch between ions

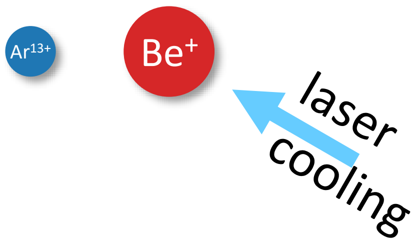
→large difference in amplitudes

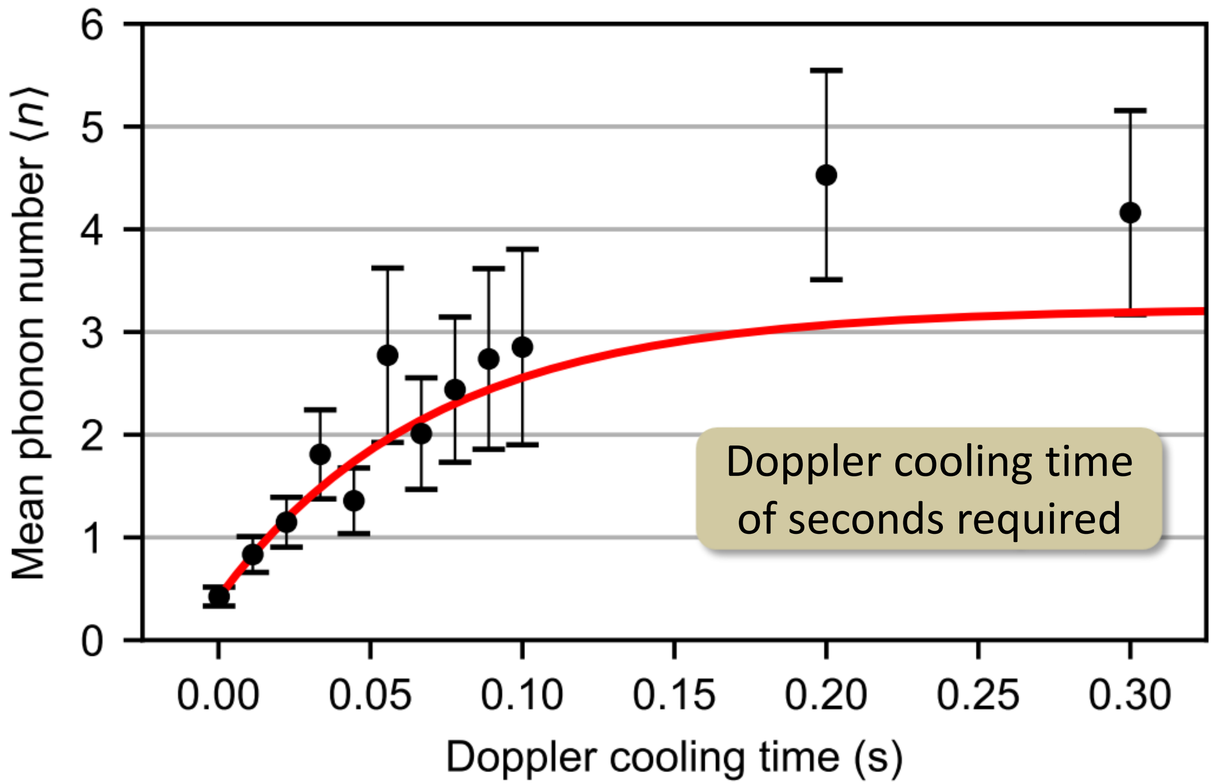
→inefficient cooling of radial modes

- radial mode #1:
  → strong cooling



- radial mode #2:
  → weak cooling



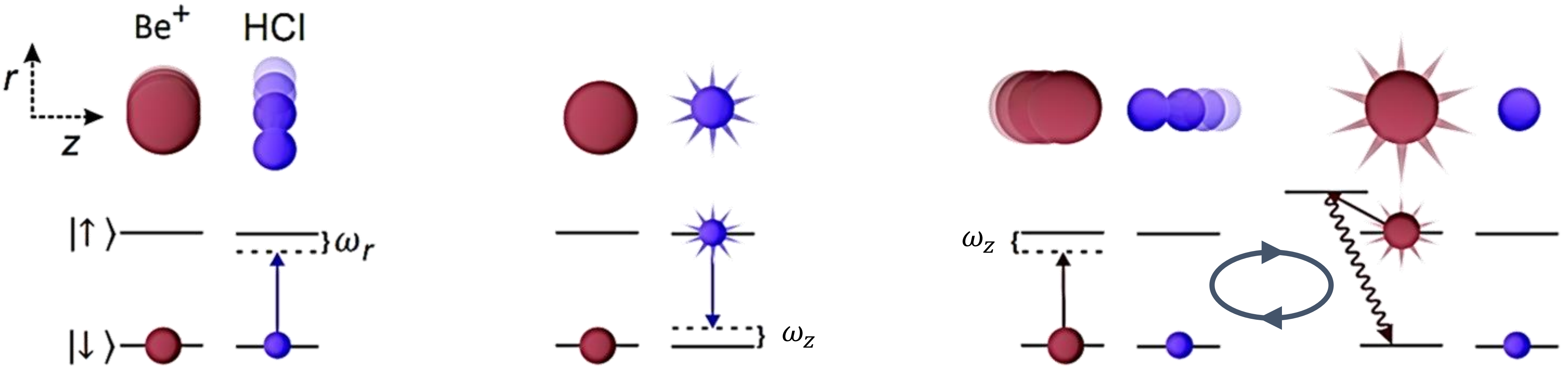


King *et al.*, Phys. Rev. X **11**, 041049 (2021)

Cooling with quantum logic

Coherently transfer radial mode phonons to efficiently-cooled axial modes

Algorithmic cooling



radial motion→ HCl spin

HCl spin → axial motion

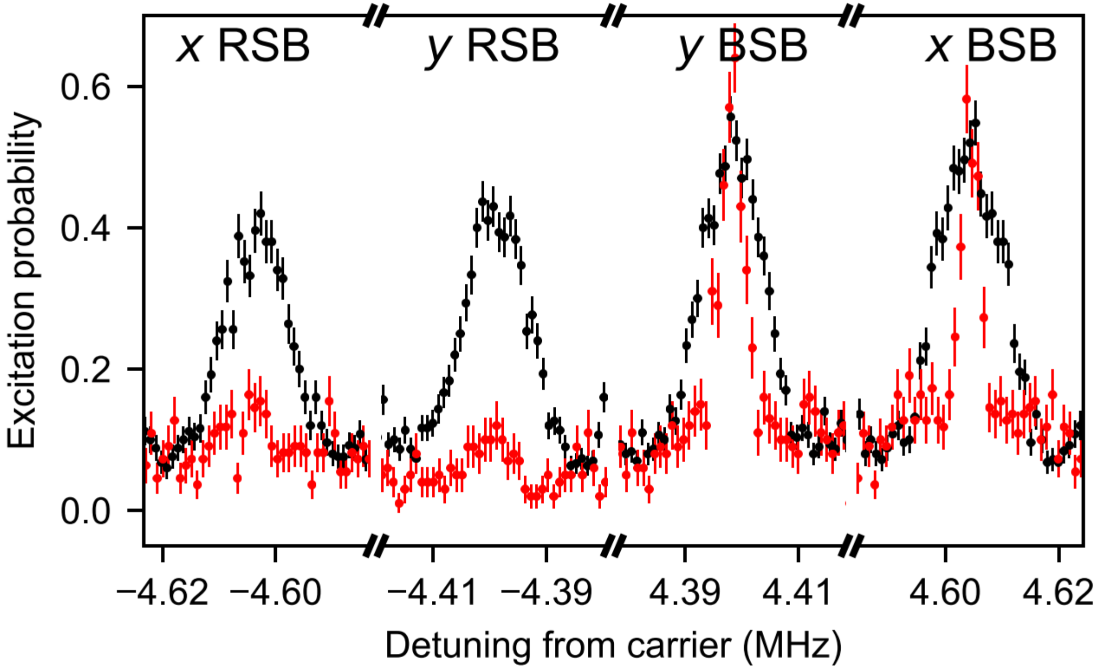
axial ground state cooling

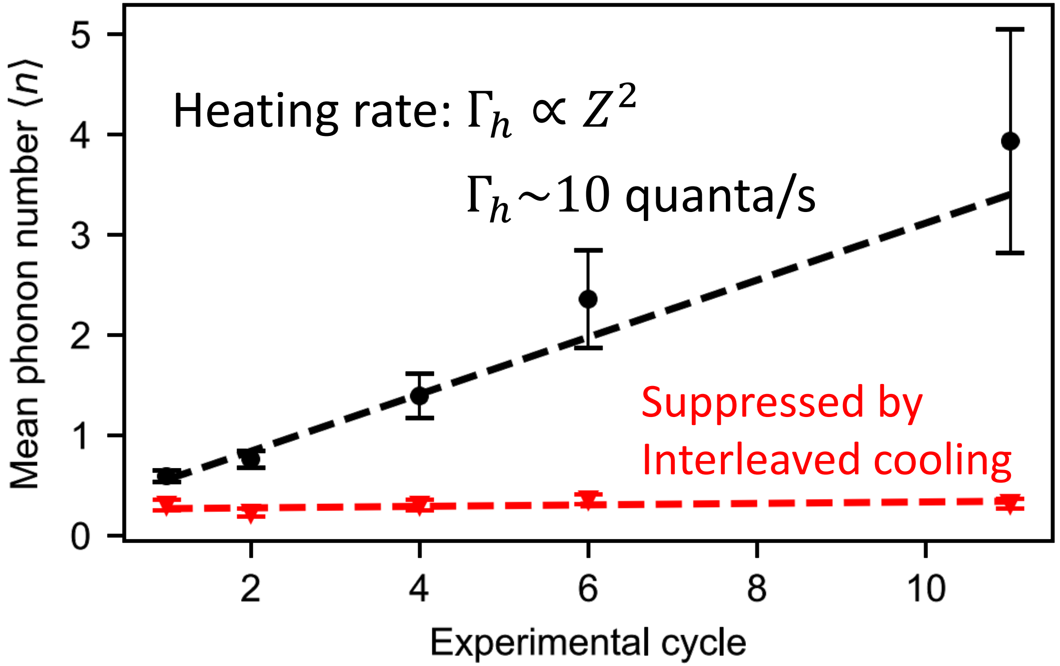
Universal applicable

Does not depend on q/m

King *et al.*, Phys. Rev. X **11**, 041049 (2021)

Cooling during clock operation





Coldest HCI of all time!
T < 200 μK in all modes

Enables <10^{-18} levels of inaccuracy for
HCI-based optical clocks

King *et al.*, Phys. Rev. X **11**, 041049 (2021)

Summary of systematic shifts ($^{40}Ar^{13+}$)

Shift source	Mitigation	Shift (10^{-18})	Uncertainty (10^{-18})
Micromotion	Real-time measurement	-443	22
Probe-laser-induced shift	Calibration at much higher powers and extrapolation	0	2
First-order Doppler	Counter-propagating beams	< 1	< 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

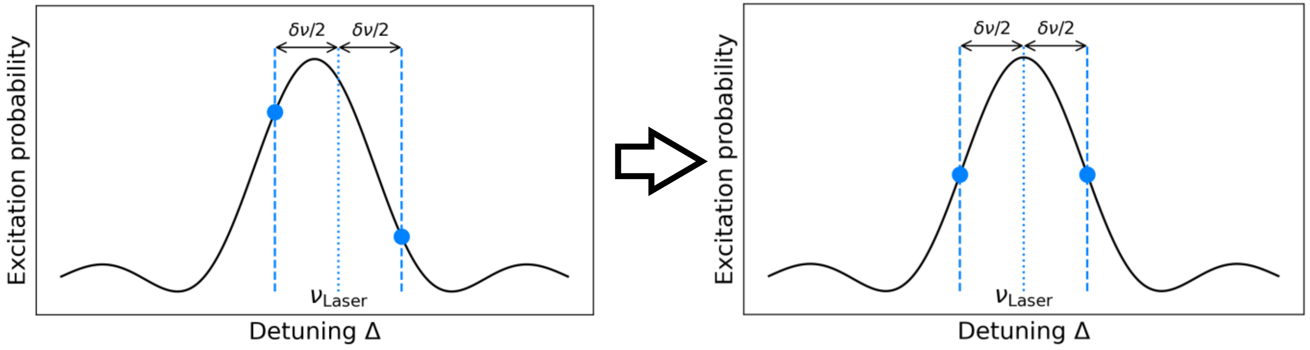
Systematic uncertainty $\sim 2 \times 10^{-17}$

atomic data from Y-M. Yu and B.K. Sahoo, PRA **99**, 022513 (2019)

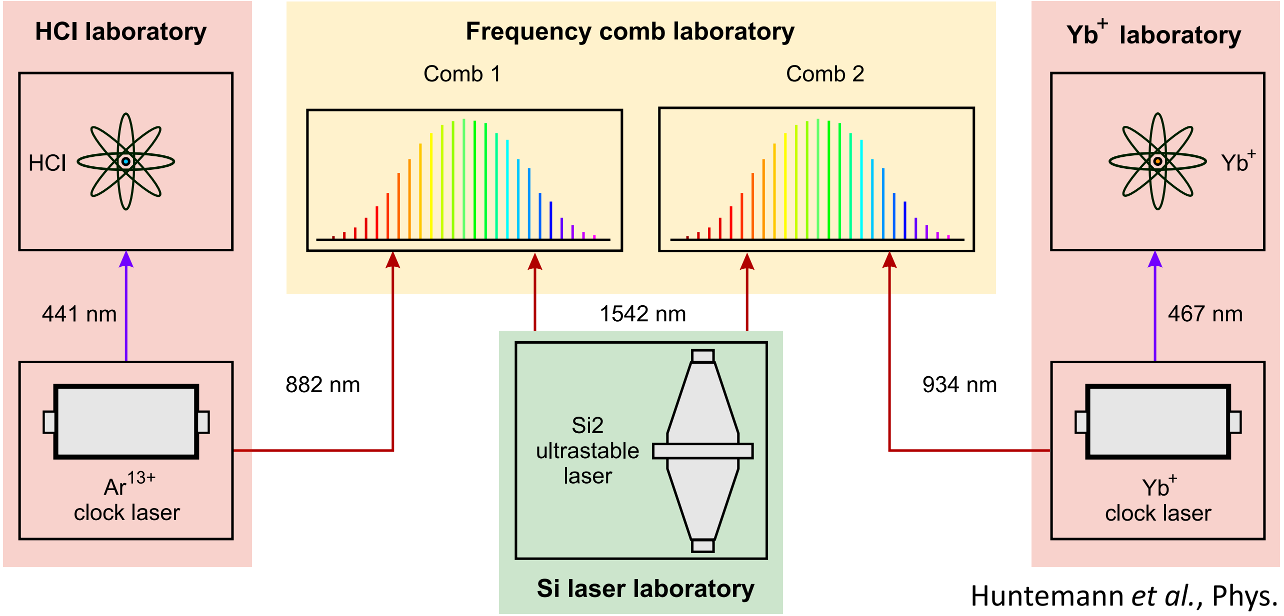
King, Spieß *et al.*, Nature **611**, 43–47 (2022)

Clock comparison

Two-point sampling

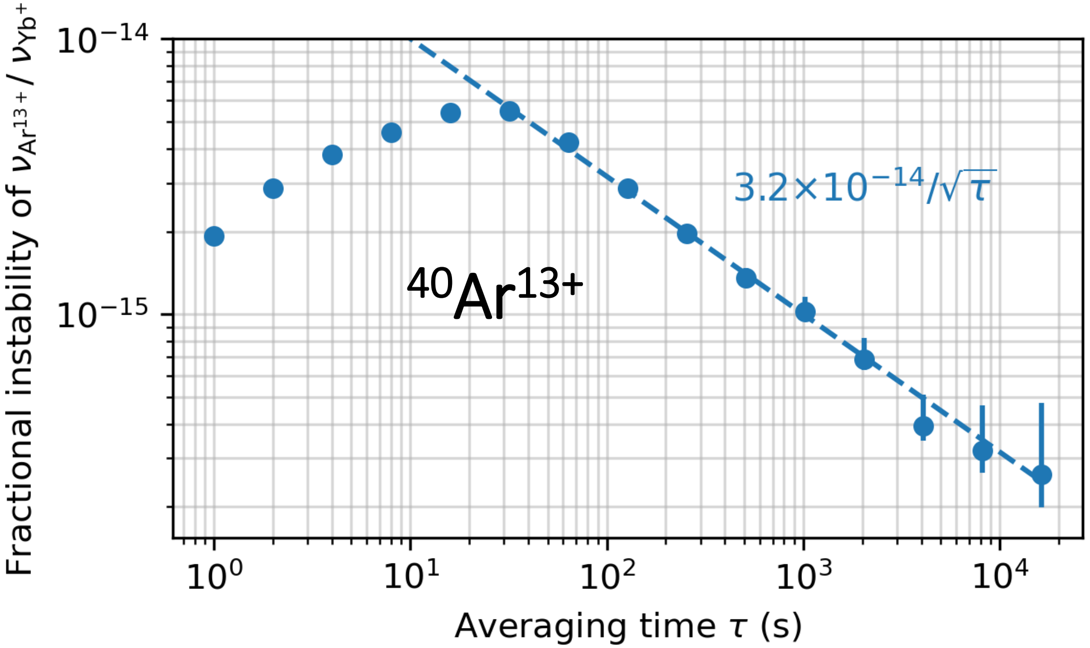


Peik *et al.*, J. Phys. B: At. Mol. Opt. Phys. **39** 145 (2006)



Matei *et al.*, Phys. Rev. Lett. **118**, 263202 (2017)

Huntemann *et al.*, Phys. Rev. Lett. **116**, 063001 (2016)



Statistical uncertainty
1×10^{-16}

Limitation: Excited-state lifetime ≈ 10 ms

King, Spieß *et al.*, Nature **611**, 43–47 (2022)

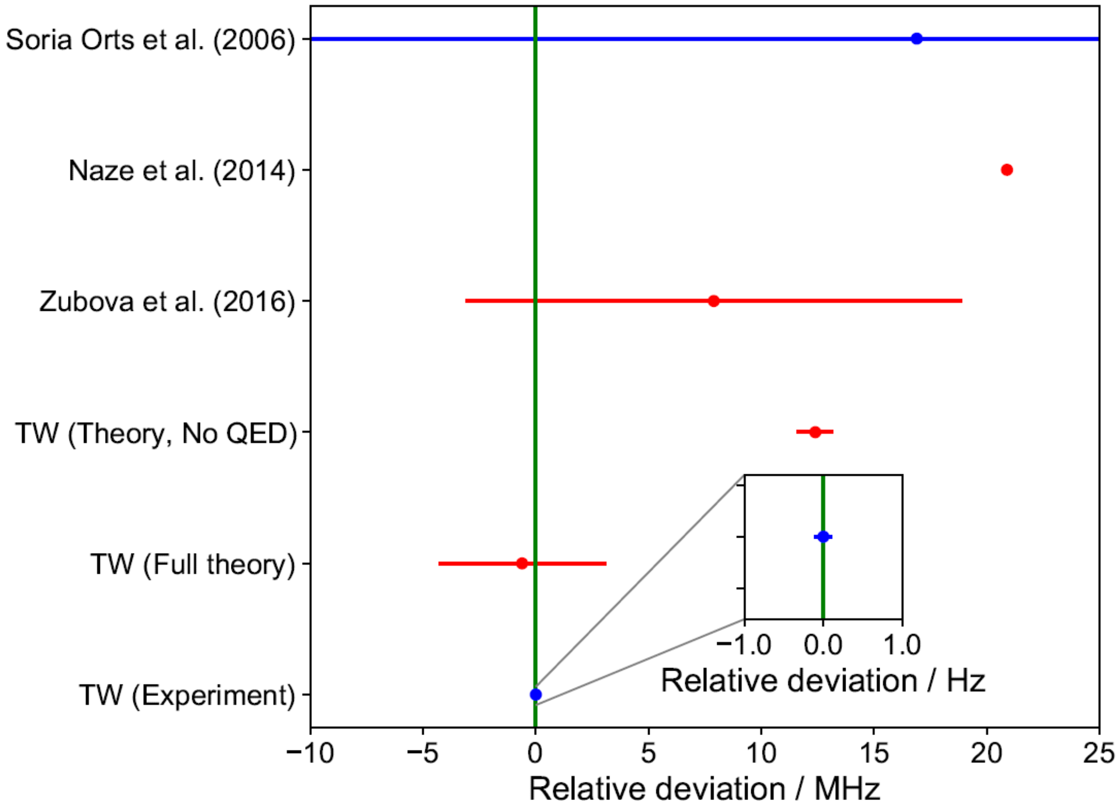
Absolute frequency

	Absolute frequency (GHz)	Relative uncertainty	Method
$^{40}Ar^{13+}$ [1]	679 216.464 (6)	8.8×10^{-9}	Penning trap
IS [2] $^{40}Ar^{13+}$ - $^{36}Ar^{13+}$	1.89 (9)	4.8×10^{-2}	EBIT
$^{40}Ar^{13+}$	679 216.462 397 957 42 (11)	1.5×10^{-16}	QLS
IS $^{40}Ar^{13+}$ - $^{36}Ar^{13+}$	1.878 110 532 52 (11)	5.7×10^{-11}	QLS

Best previously published values

[1] Egl *et al.*, Phys. Rev. Lett. **123**, 123001 (2019)
[2] Soria Orts *et al.*, Phys. Rev. Lett. **97**, 103002 (2006)

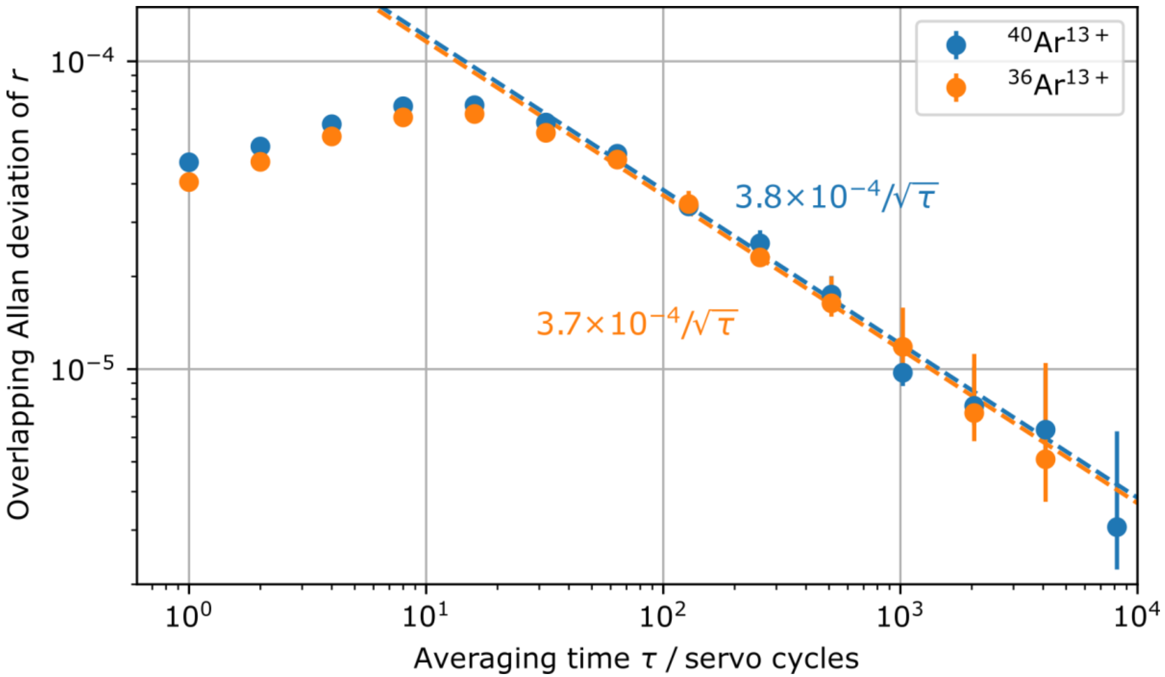
Improvement by almost eight and nine orders of magnitude respectively



King, Spieß *et al.*, Nature **611**, 43–47 (2022)

Atomic parameters

g-factor



$^{40}Ar^{13+}$: $g_{3/2} / g_{1/2} = 2.0075142(25)$

$^{36}Ar^{13+}$: $g_{3/2} / g_{1/2} = 2.0075154(32)$

	$^{40}Ar^{13+}$ $^2P_{3/2}$ g-factor
Experiment	1.332 283 7 (17)
Theory	1.332 282 5 (14)

Agababaev *et al.*, *X-Ray Spectrometry* **49**: 143– 148 (2019)

Quadrupole moment Θ

	Θ $(e\,a_0^2)$
Ca^+	1.83
Sr^+	2.6
Yb^+ E2	1.95
Yb^+ E3	-0.0297
Hg^+	-0.510
Ar^{13+} (Theory)	0.0235 [1]
$^{40}Ar^{13+}$ (Exp.)	-0.02 (9)
$^{36}Ar^{13+}$ (Exp.)	-0.03 (14)

$$\Delta\nu_{QS} \propto \Theta \frac{\partial E_z}{\partial z}$$

Ludlow *et al.*, Reviews of Modern Physics **87(2)**, 637–701 (2015)
Lange *et al.*, Phys. Rev. Lett. **125**, 143201 (2020)

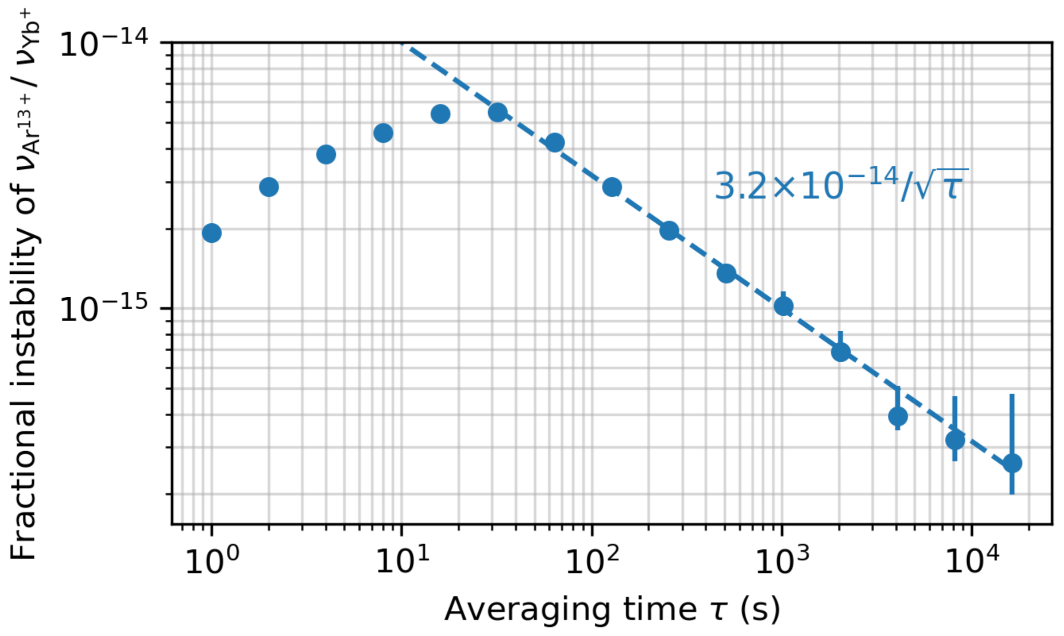
[1] Yu and Sahoo, PRA **99**, 022513 (2019)
Note: units for quadrupole moment in Tab. VI. should read $\times10^{-7}$ Hz/(V/m^2) (Y-m. Yu, priv. comm.)

King, Spieß *et al.*, Nature **611**, 43–47 (2022)

Summary and outlook

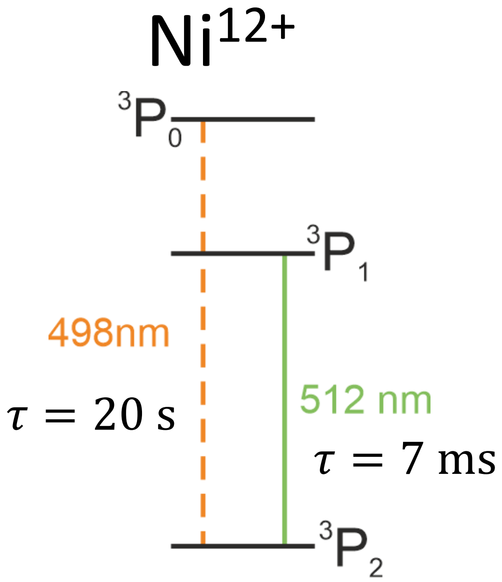
Summary

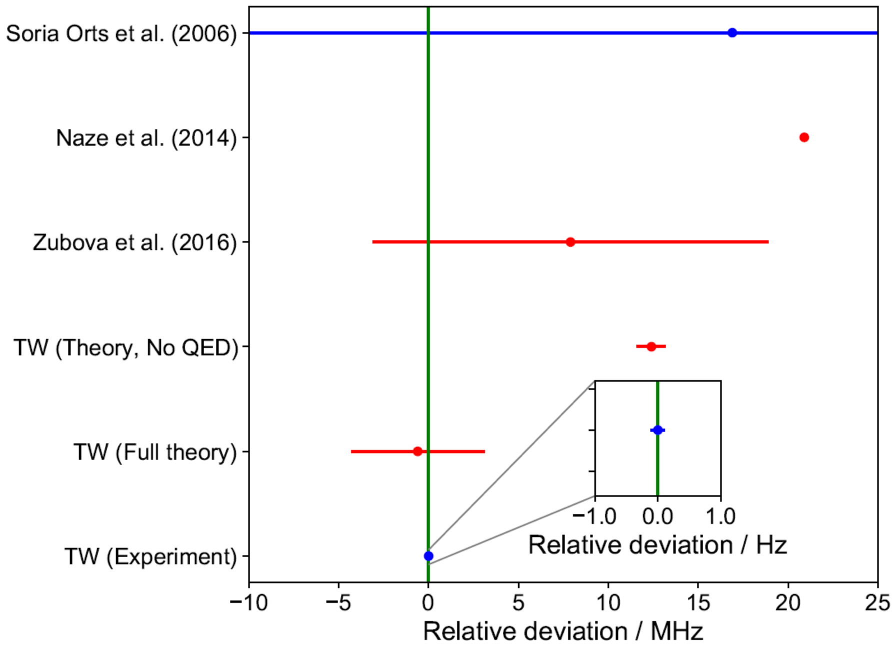
- Optical clock based on HCI with statistical uncertainty of 1×10^{-16}
- Systematic uncertainty of $\sim 2 \times 10^{-17}$
- Demonstrated optical clock comparison and improved the absolute frequency by eight orders of magnitude
- Isotope shifts for fundamental physics tests
- Atomic parameters test ab-initio calculations



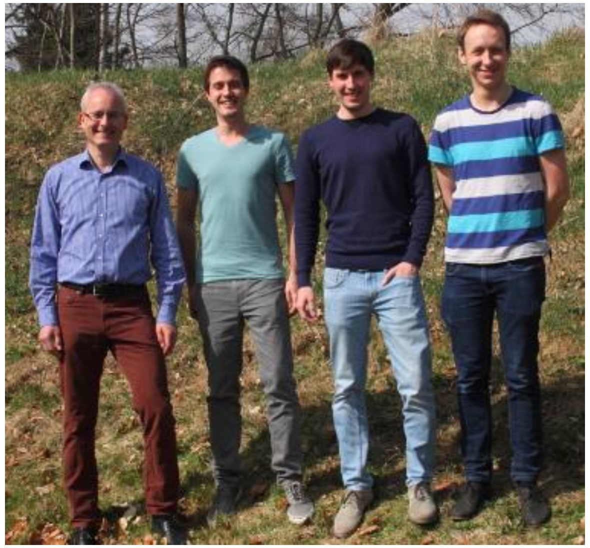
Outlook

- Further reduce systematic uncertainties
- Investigating finding narrow transitions in HCIs
- HCI optical clock based on Ni^{12+}





Acknowledgments



Yb$^+$ Experiment
- Richard Lange (PTB)
- Melina Filzinger (PTB)
- Nils Huntemann (PTB)

Frequency comb
- Erik Benkler (PTB)

Theory
- Robert Müller (PTB)
- Vladimir Yerokhin (MPIK)
- Andrey Surzhykov (PTB & TU Braunschweig)

HCI Experiment
- PTB: Piet O. Schmidt, Steven A. King, Tobias Leopold, Peter Micke, LJS, Alexander Wilzewski, Malte Wehrheim, Shuying Chen

- MPIK: José R. Crespo López-Urrutia, Lisa Schmöger, Maria Schwarz

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Max-Planck-Institut für Kernphysik Heidelberg

Unterstützt von / Supported by Alexander von Humboldt Stiftung / Foundation

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