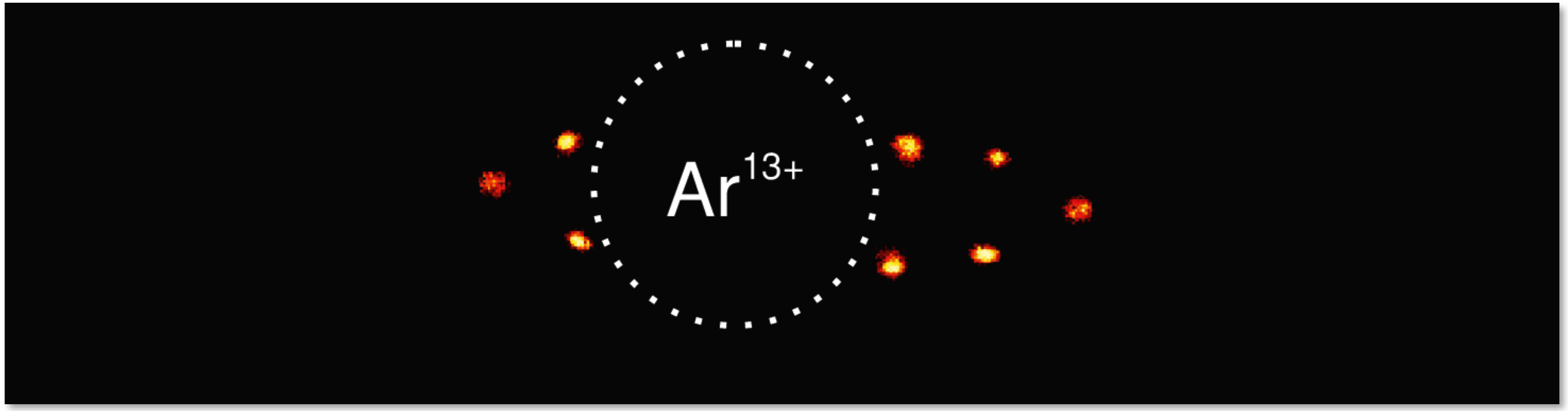
Sub-hertz spectroscopy of highly charged ions



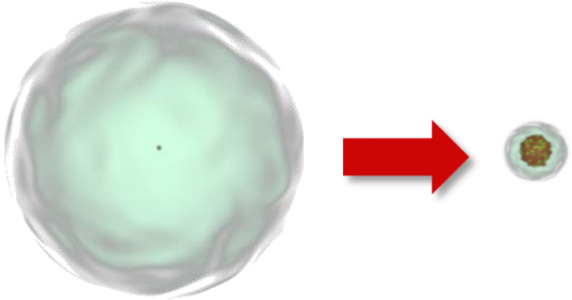
Steven King

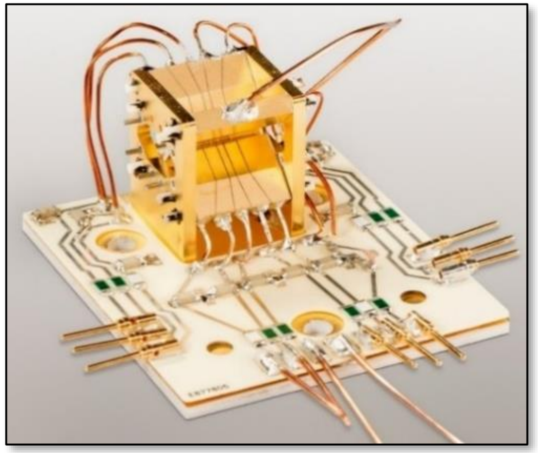
QUEST Institute for Experimental Quantum Metrology
PTB Braunschweig

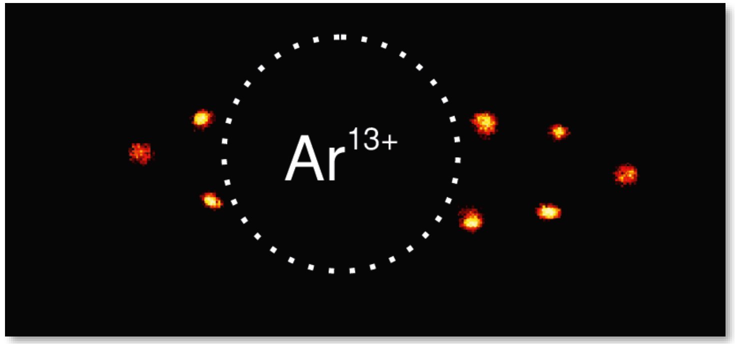
Quantum Frontiers Topical Group Meeting, 26.10.2021

Overview

- Motivation
- Experimental overview
- Algorithmic cooling
- Optical frequency ratio measurements
- Preliminary results
- Preliminary analysis of systematic shifts
- Summary and outlook

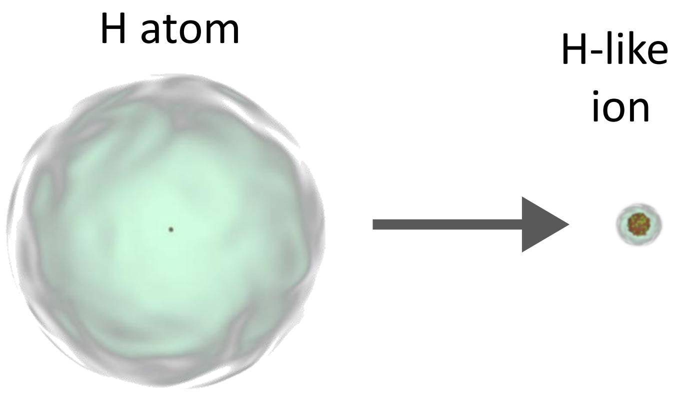






Motivation for HCI-based clocks

Better clocks

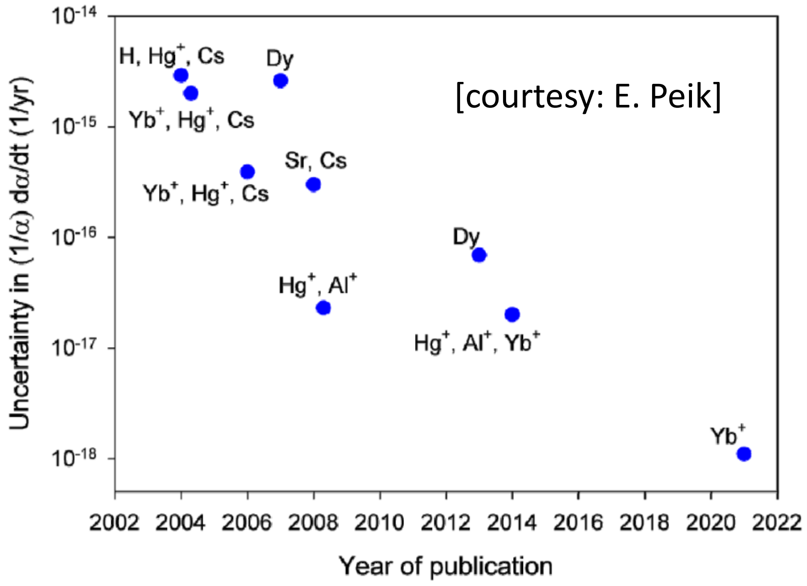


Linear Stark shift	Z^{-1}
Second order Stark shift	Z^{-4}
Linear Zeeman shift	Z^{0}
Second order Zeeman shift	$Z^{-3...-4}$
Electric quadrupole shift	Z^{-2}

Intrinsically less sensitive to external perturbations

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

Variation of constants



$\dot{\alpha}/\alpha = 1.0(1.1) \times 10^{-18}$/year

Lange *et al.* PRL **126**, 011102 (2021)

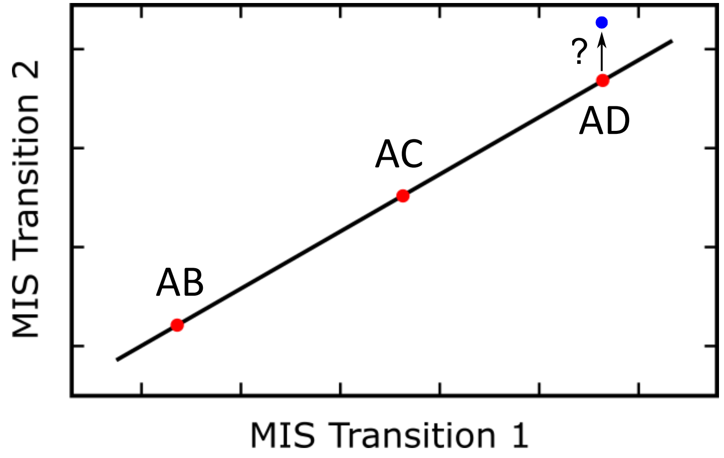
also e.g.

Rosenband *et al.*, Science **319**, 1808 (2008)

Godun *et al*., Phys. Rev. Lett. **113**, 210801 (2014)

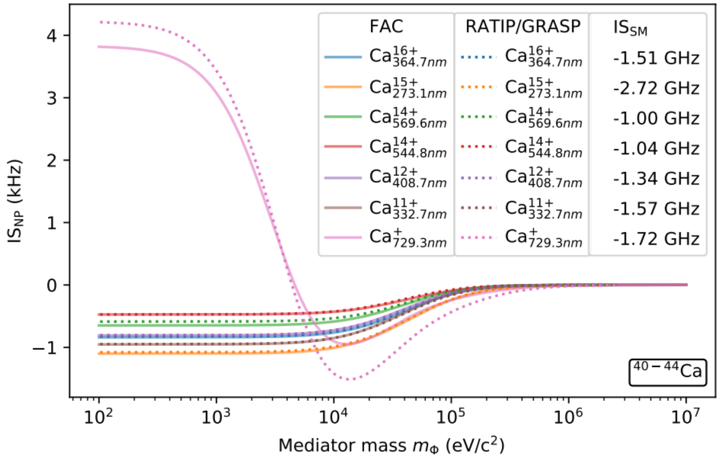
Huntemann *et al*., Phys. Rev. Lett. **113**, 210802 (2014)

King plots



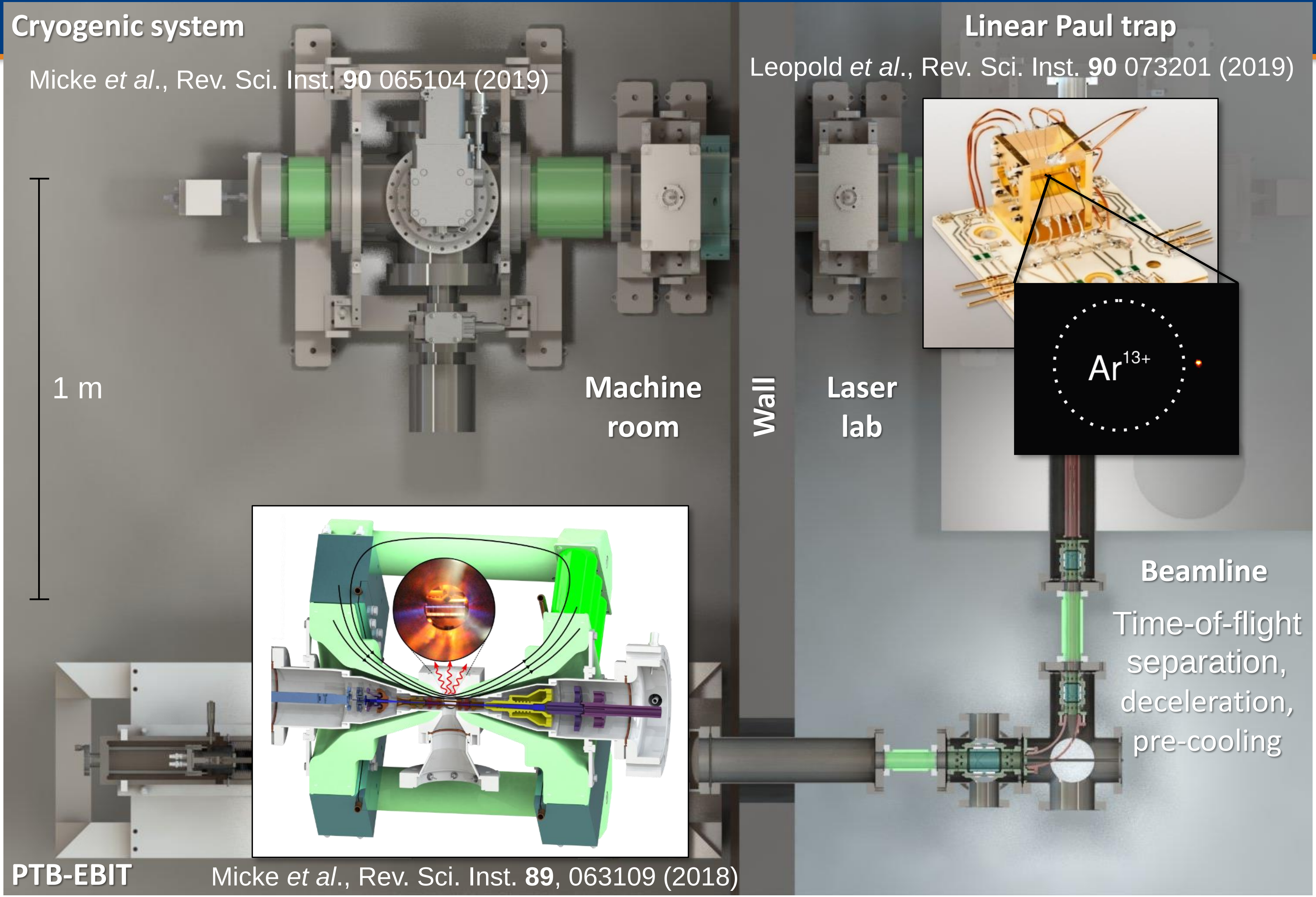
e.g. Yerokhin *et al*., PRA **101**, 012502 (2020)

Berengut *et al*., Phys. Rev. Research **2**, 043444 (2020)



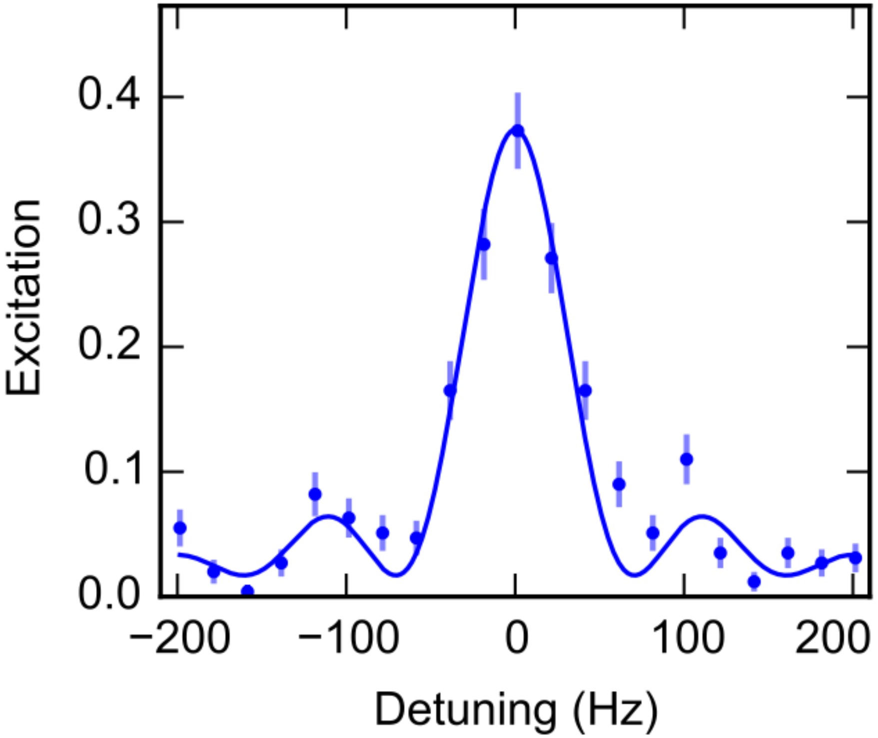
Rehbehn *et al*., PRA **103** L040801 (2021)

HCI lab at PTB

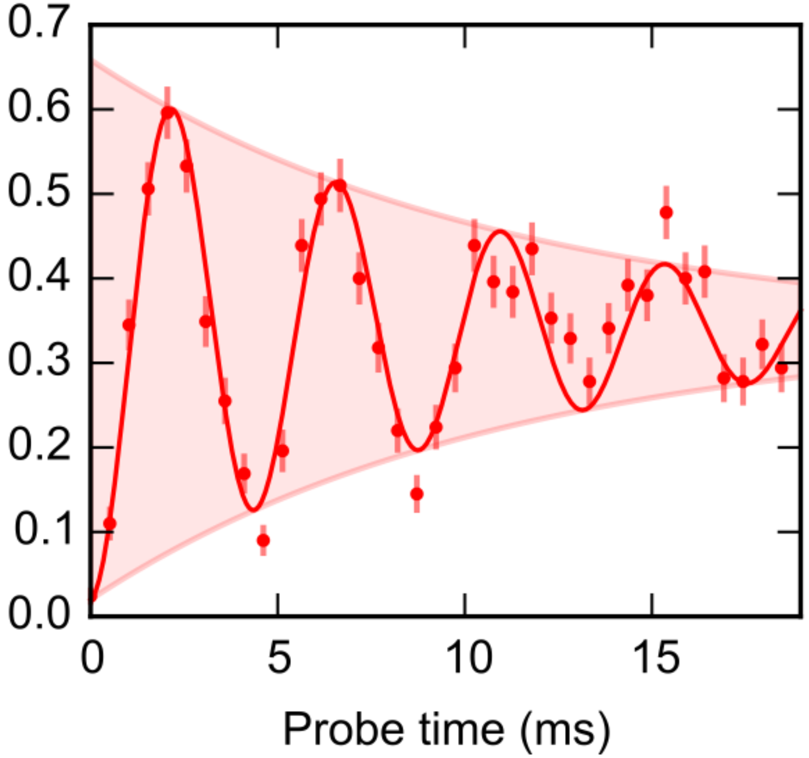


Quantum logic spectroscopy of Ar^{13+}

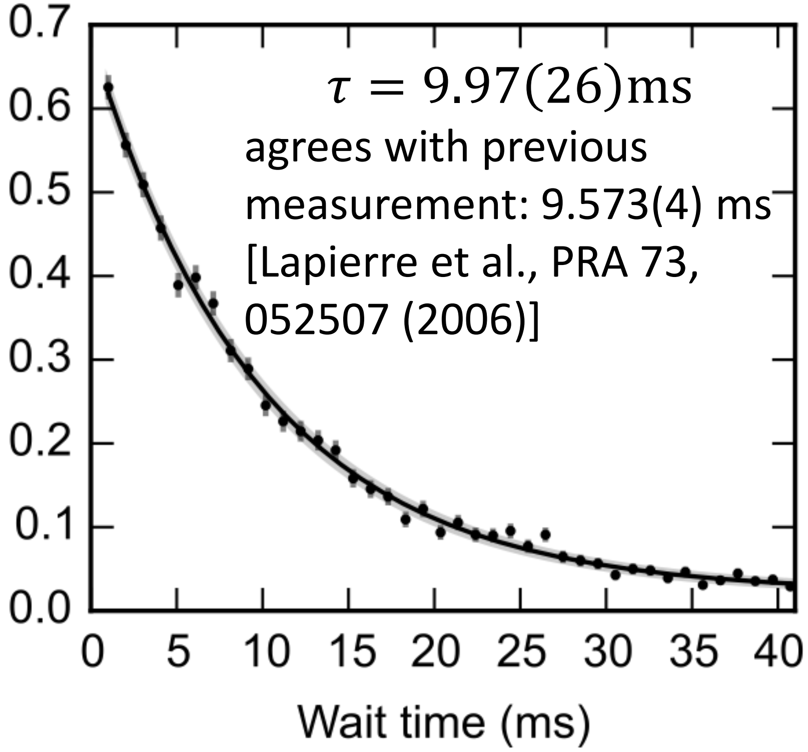
Fourier-limited linewidth: 65 Hz
(12 ms probe time) resolution: ~ 5 Hz



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



dedicated lifetime measurement



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

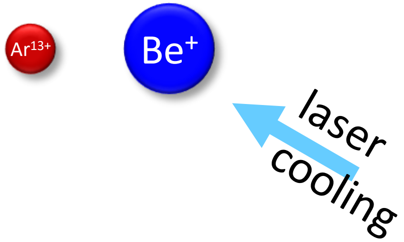
Cooling challenges....

Large q/m mismatch between ions

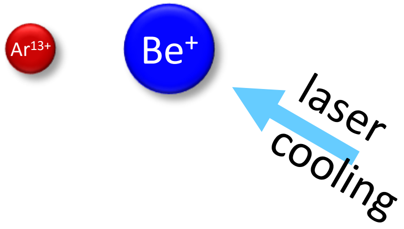
→ large difference in amplitudes

→ inefficient cooling of radial modes

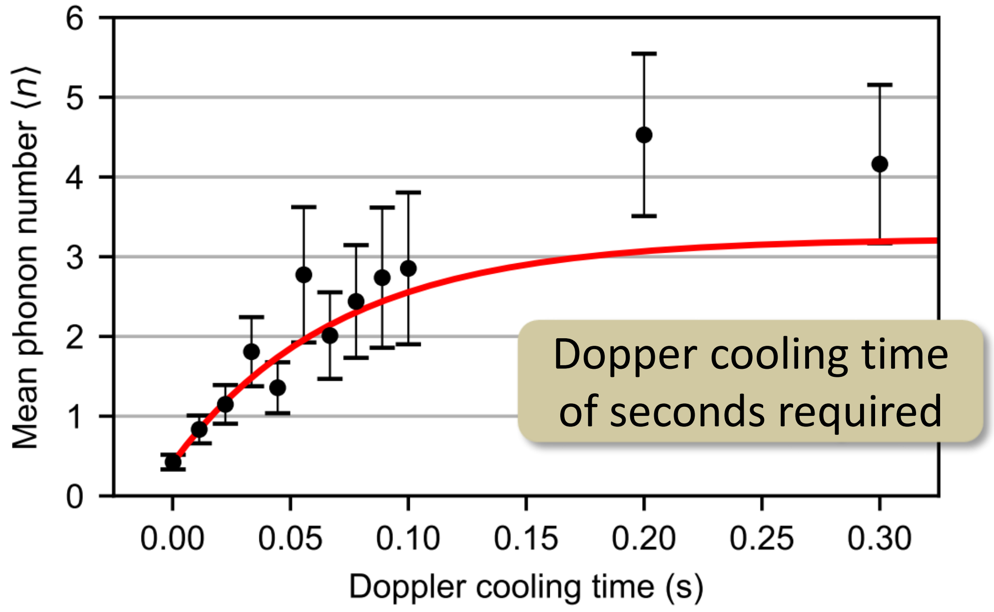
- radial mode #1:
  → strong cooling



- radial mode #2:
  → weak cooling



[Kozlov *et al*., Rev. Mod. Phy. **90**, 045005 (2018)]

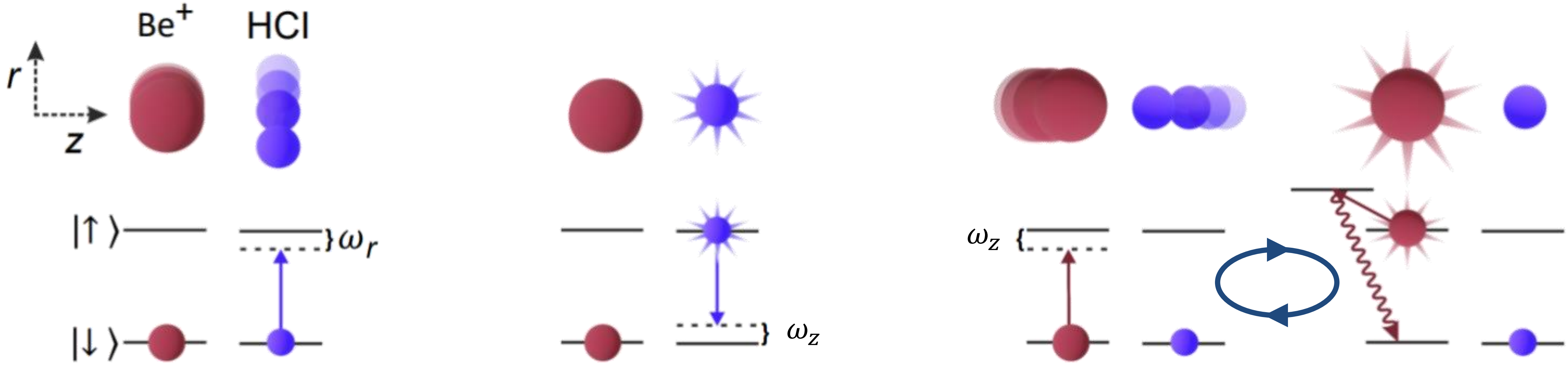


King *et al.*, arxiv 2102.12427v2 (2021), accepted by Phys. Rev. X

Ground-state cooling using quantum logic

Coherently transfer radial mode phonons to efficiently-cooled axial modes

„Algorithmic cooling“



radial motion→ HCI spin

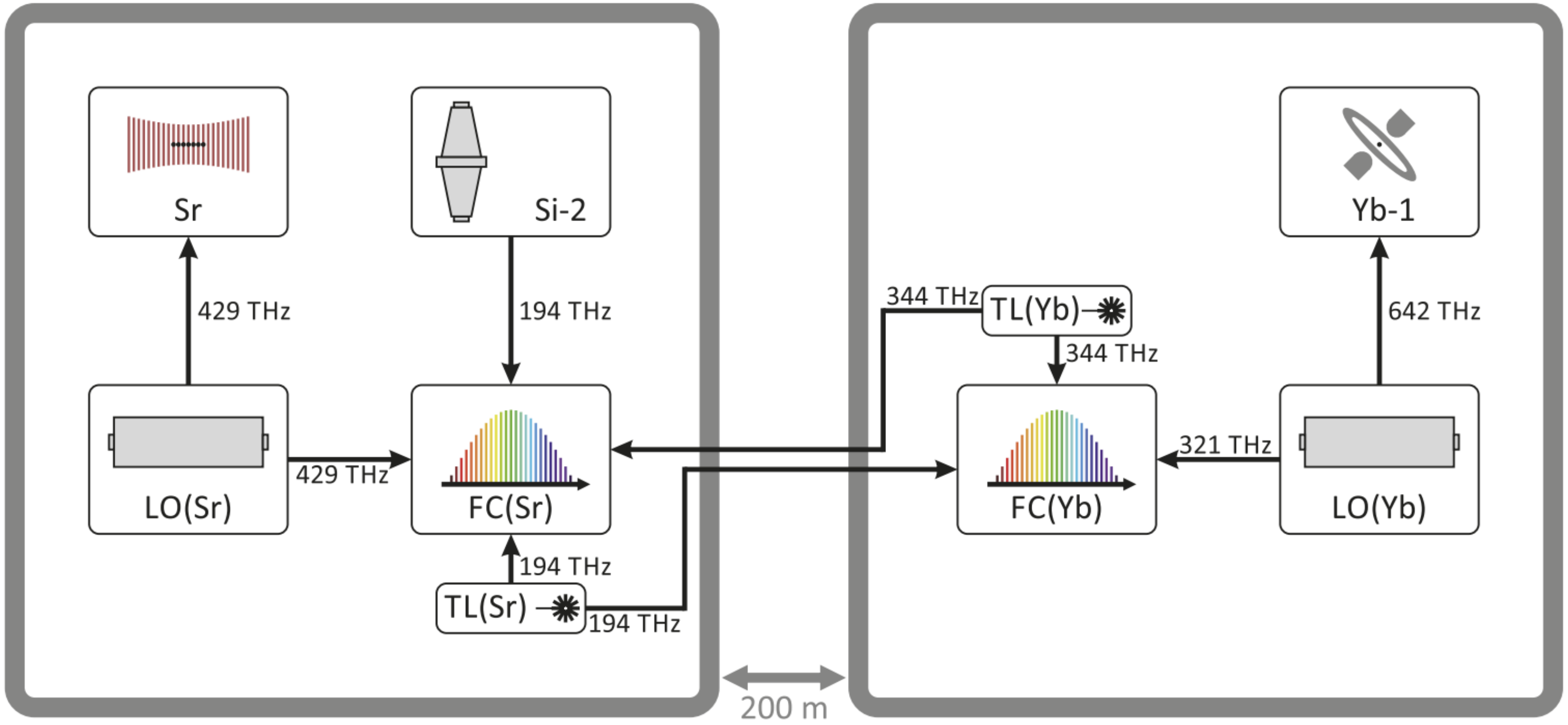
HCI spin → axial motion

axial ground state cooling

King *et al.*, arxiv 2102.12427v2 (2021), accepted by Phys. Rev. X

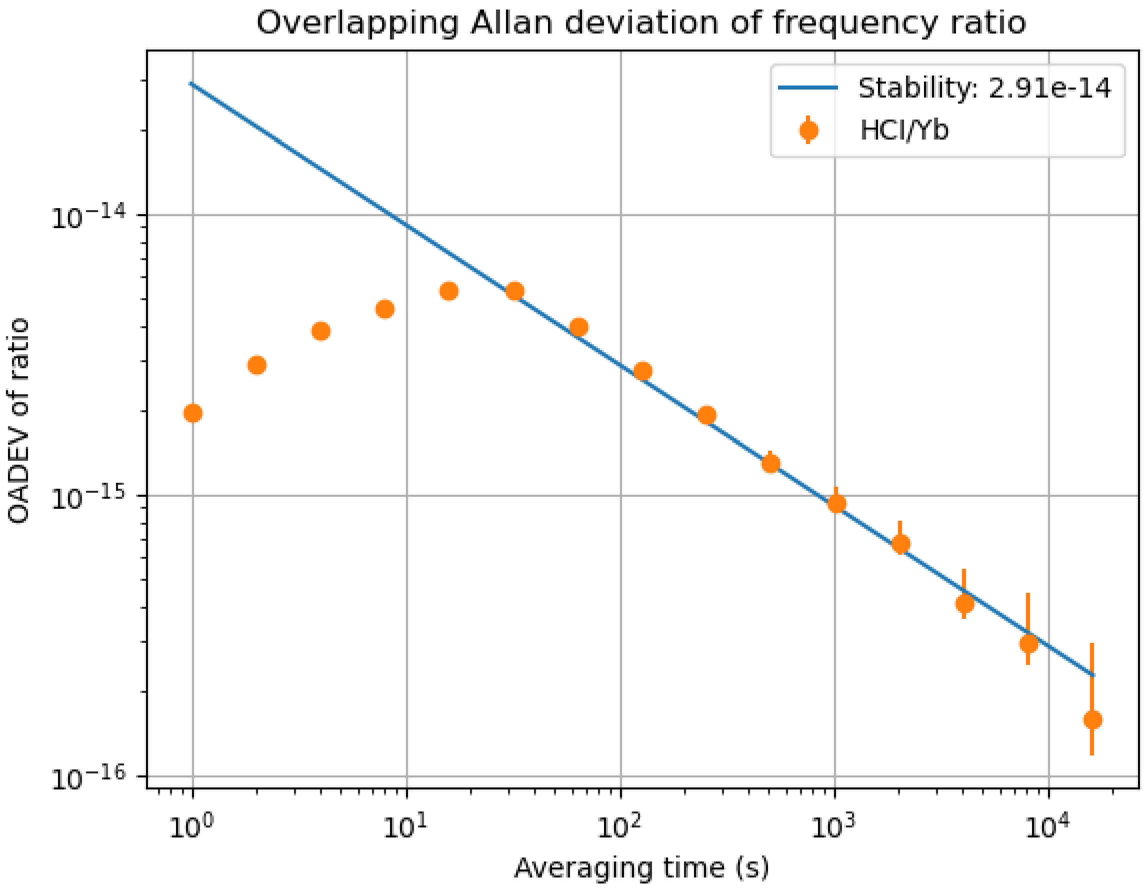
Measurement procedure

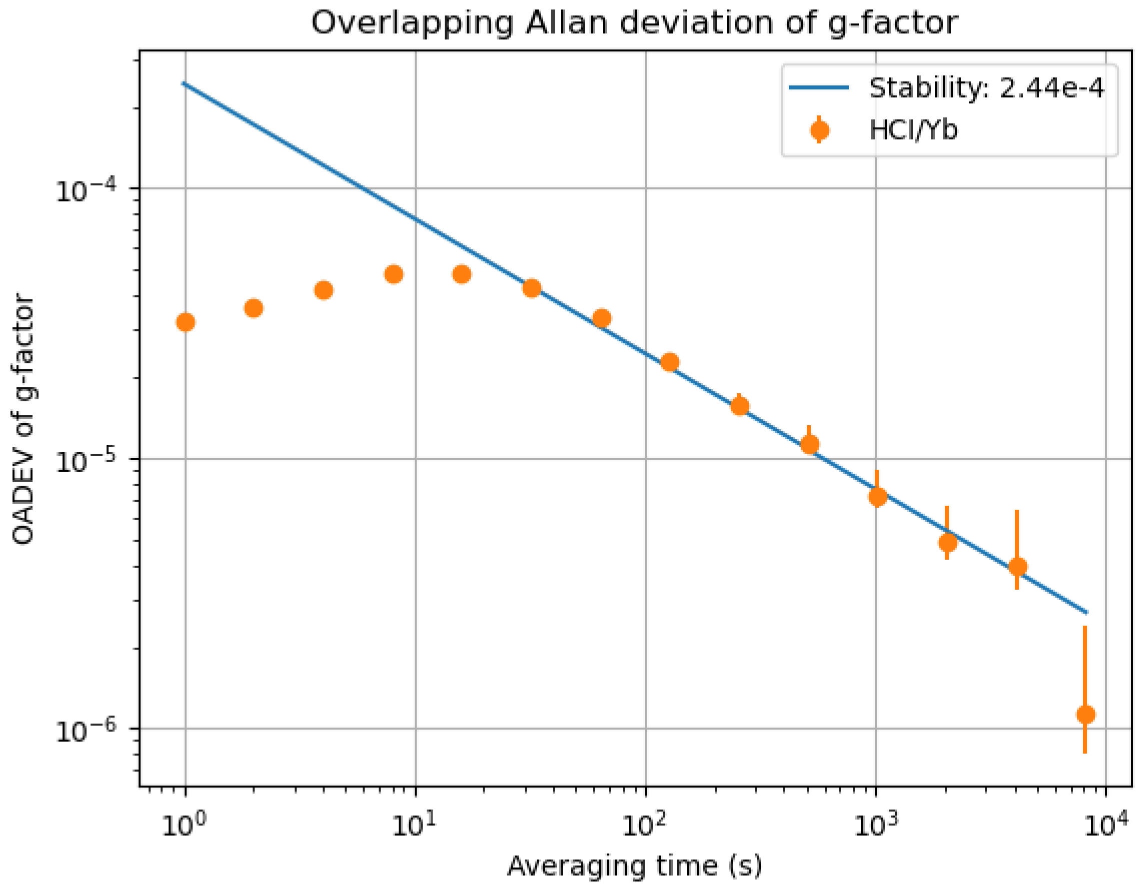
- Determine absolute frequency by reference to the SI second
- But Cs fountain averages much slower than optical clocks when operated in high-accuracy mode ($\sim 1 \times 10^{-13}/\sqrt{\tau/s}$) [Weyers *et al.*, Metrologia 55 789 (2018)]
- Compare to another optical standard to take advantage of better stability ($\sim 10^{-14}/\sqrt{\tau/s}$)
- Yb^{+} clock transition is a secondary representation of the SI second, therefore we obtain the absolute frequency!



S Dörscher *et al.*, Metrologia 58 015005 (2021)

Preminimary(!) results





- Total statistical uncertainty ~1e-16 (70 mHz)
- Systematic uncertainty hopefully below 5e-17
- cf. Systematic uncertainty of Cs fountain = 1.3e-16

- Statistical uncertainty <2e-6
- Previous total uncertainty ~6e-6
  [Micke *et al.*, Nature 578, pp60–65 (2020)]

Systematic shifts

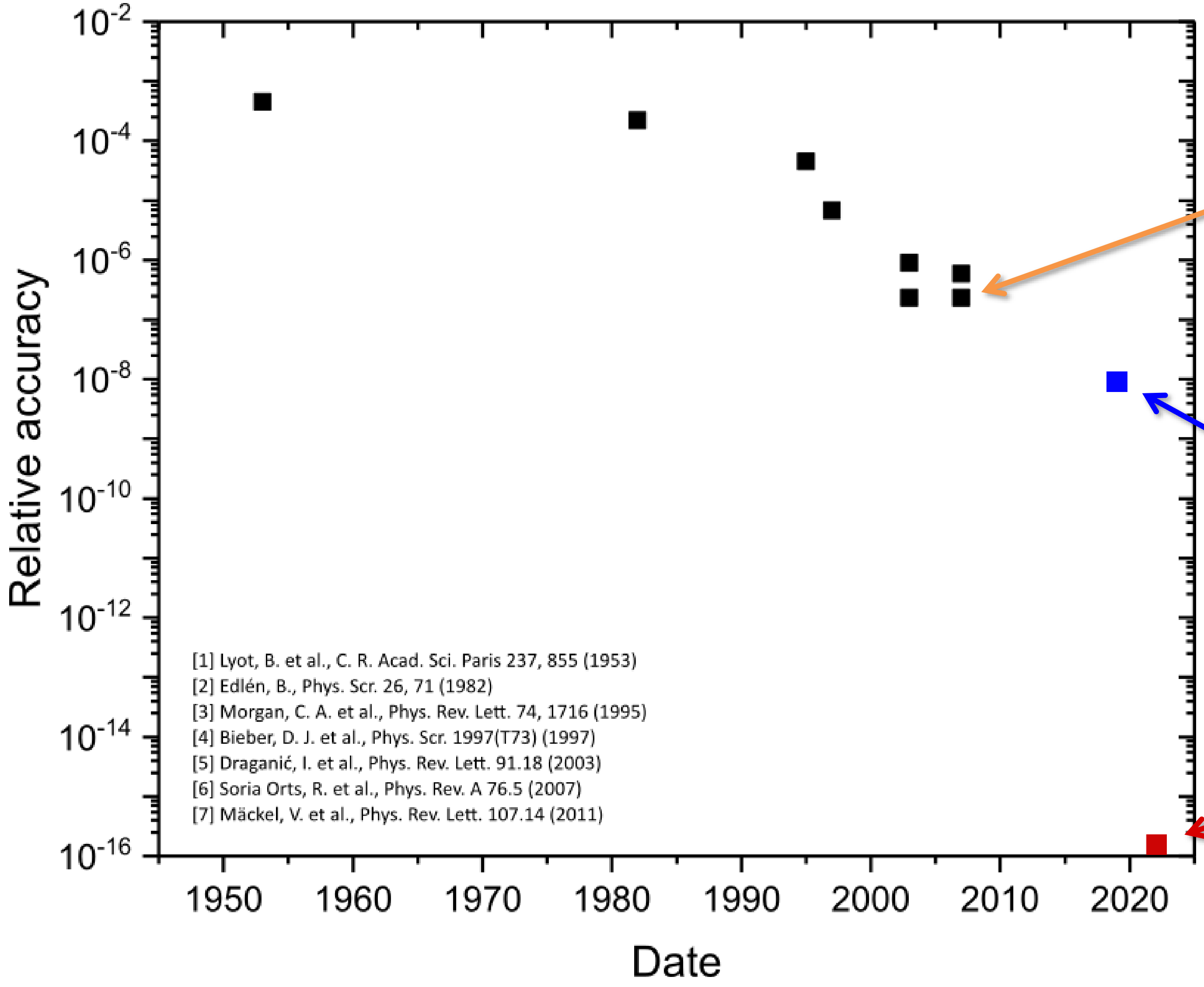
Shift source	Mitigation	Expected residual uncertainty
Micromotion	Real-time measurement	~10^{-17}
AC Zeeman shift	Calibration at much higher powers and extrapolation	~10^{-18}
First-order Doppler	Counter-propagating beams	<10^{-18}
Quadrupole and linear Zeeman	Averaging over multiple Zeeman components	<10^{-18}
Quadratic Zeeman	Small coefficient, small field	<10^{-18}
Secular temperature	Algorithmic cooling	<10^{-18}

} no fundamental limitation to a HCI-based clock

Yu and Sahoo, PRA **99**, 022513 (2019)

King *et al.*, arXiv:2102.12427 (2021), accepted for Phys. Rev. X

History of Ar^{13+} frequency measurements



In-EBIT measurements
3×10^{-7}

Penning trap measurement
9×10^{-9}
Egl *et* al., PRL **123**, 123001 (2019)

This measurement (preliminary!)
1.6×10^{-16}

Summary and outlook

- Highly charged ions have significant potential for use as optical clocks or tests of fundamental physics
- We have built and brought online the first HCI optical clock
- Frequency measurement with $^{40}Ar^{13+}$ has statistical uncertainty of ca. 1×10^{-16} (70 mHz)
- Systematic error should be below 5×10^{-17}
- Measurement will now be repeated with $^{36}Ar^{13+}$ in order to determine the isotope shift with uncertainty $\sqrt{2} \times 70$ mHz

Acknowledgements

EMPIR EURAMET

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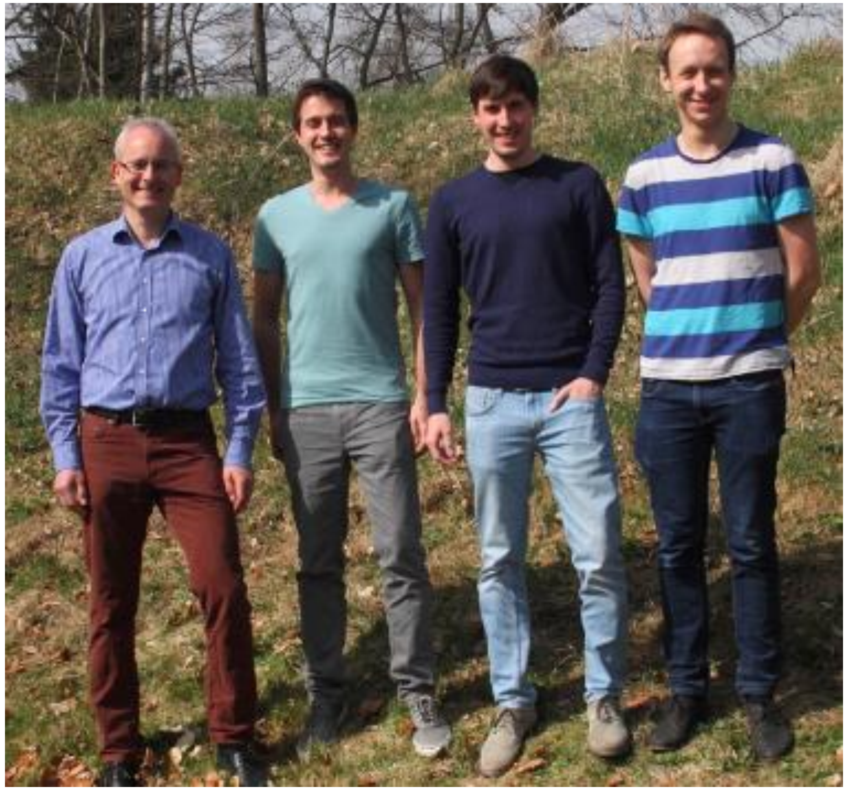
European Research Council

Established by the European Commission



PTB: Piet O. Schmidt, Tobias Leopold (DLR), Peter Micke (BASE), S.A.K., Lukas J. Spieß, Alexander Wilzewski, Erik Benkler

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

Postdocs, PhD and masters positions available!

Learn more about our experiment with these publications:

Micke *et al.*, Rev. Sci. Inst. 90 065104 (2019)

Leopold *et al.*, Rev. Sci. Inst. 90 073201 (2019)

Micke *et al.*, Nature 578, pp60–65 (2020)

Micke *et al.*, Rev. Sci. Inst. 89, 063109 (2018)

King *et al.*, arXiv:2102.12427 (2021), accepted for Phys. Rev. X

Applications of HCI

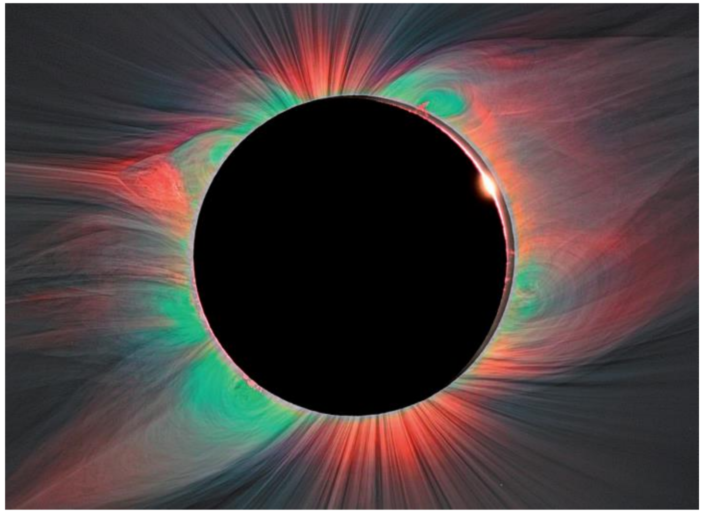
- abundant in the universe
  ➔ probes for cosmic & stellar processes

- diagnostic tools for plasma physics

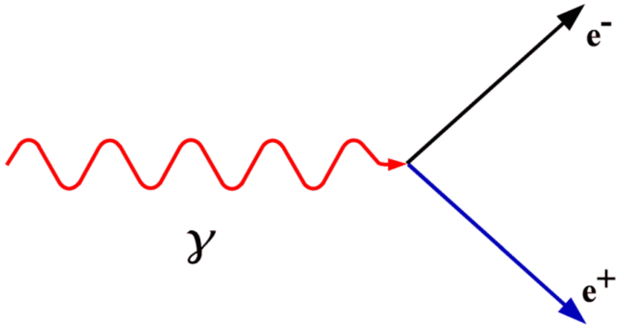
- XUV light generation for semiconductor fabs

- simple electronic structure
  ➔ testbed for atomic structure theory

- exhibit extreme properties
  ➔ tests of fundamental physics
  - g-factor
  - breakdown of QED
    (spontaneous pair production)
  - sensitive to $\dot{\alpha}$, $\dot{\mu}$, violation of local Lorentz invariance, isotope shifts,…
    [Safronova *et al.*, RMP **90**, 025008 (2018), Kozlov *et al.* Rev. Mod. Phys. **90**, 045005 (2008)]

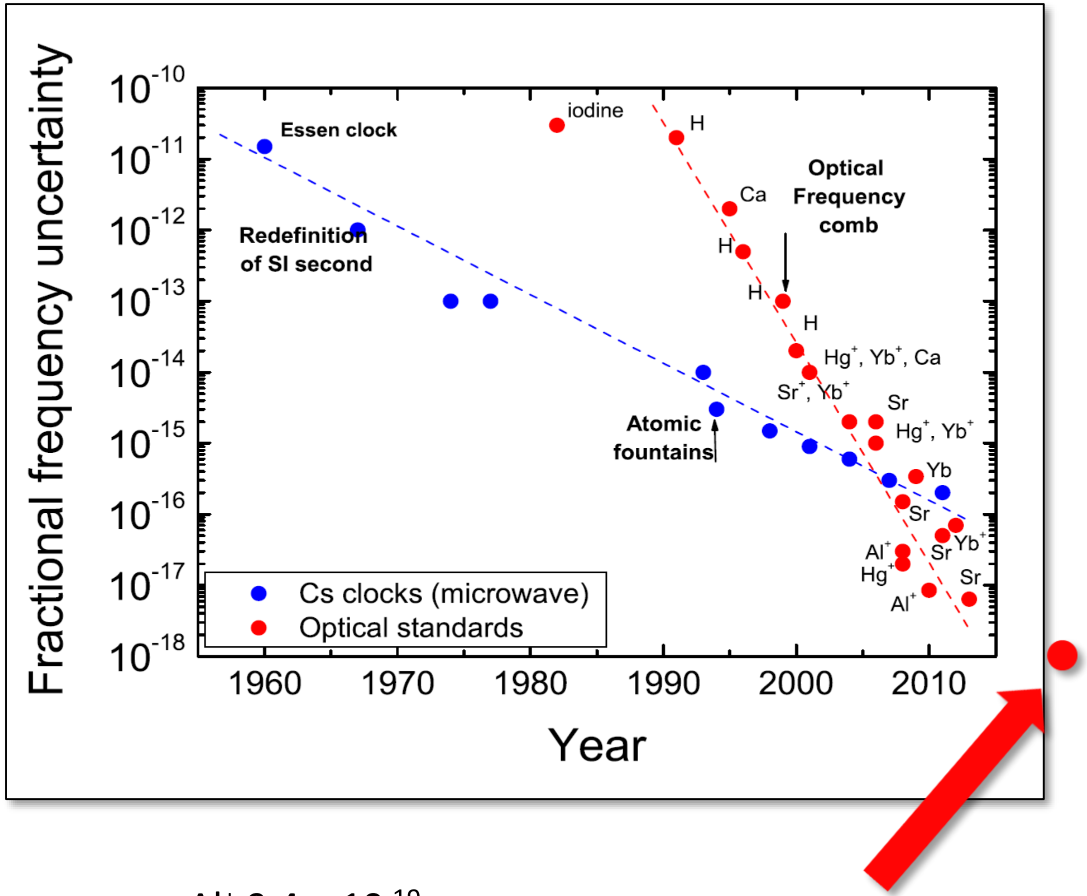


[S. Rifai Habbal, M. Druckmuller *et al.*, The Astrophysical Journal **719**, 1362 (2010)]



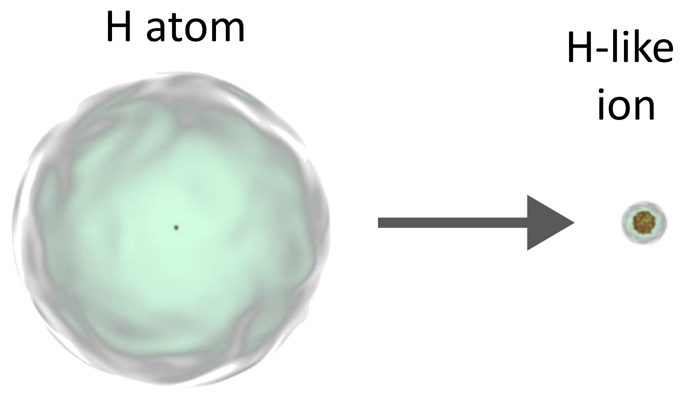
HCIs for optical atomic clocks

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



Al^+ 9.4×10^{-19}

Brewer *et al.*, Phys. Rev. Lett. **123**, 033201 (2019)



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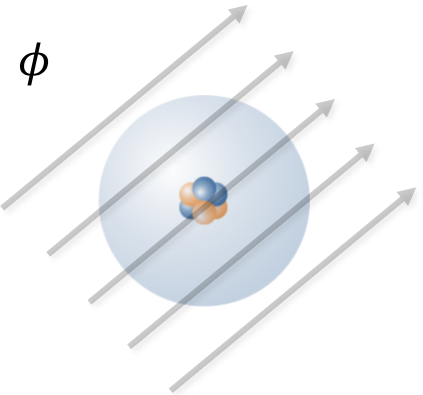
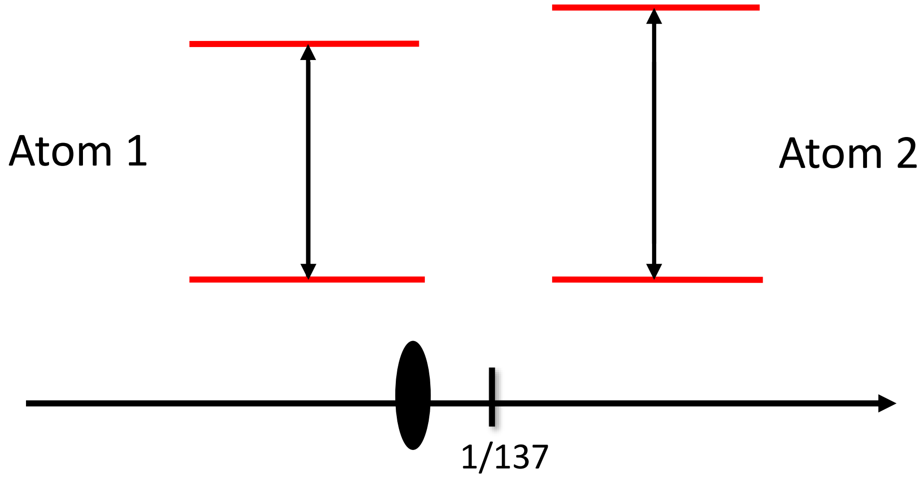
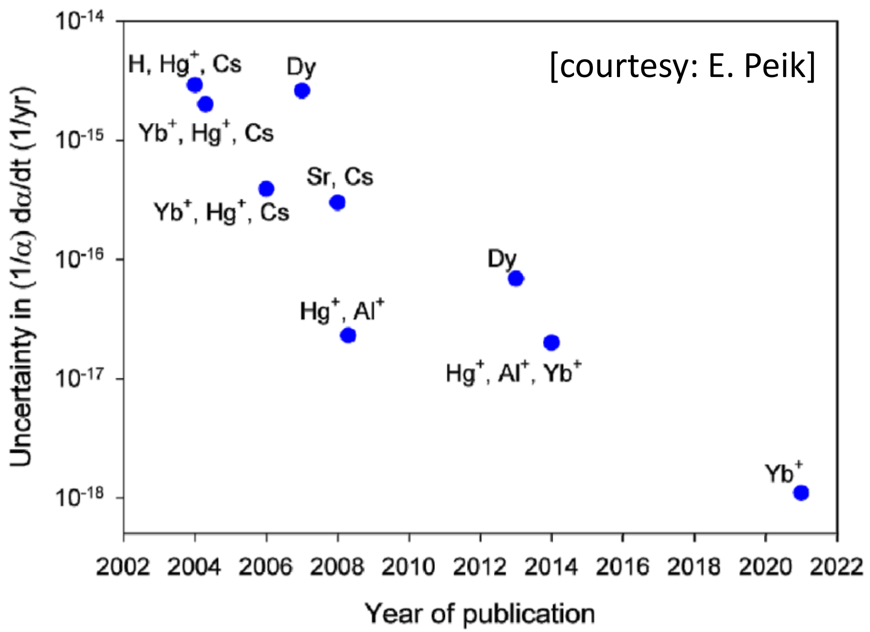
Kozlov *et al.*, Rev. Mod. Phy. **90**, 045005 (2018)

HCIs for fundamental physics





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



$$\dot{\alpha}/\alpha = 1.0(1.1) \times 10^{-18}/\text{year}$$

[Lange *et al.* PRL **126**, 011102 (2021)]

also e.g.

Rosenband *et al.*, Science **319**, 1808 (2008)

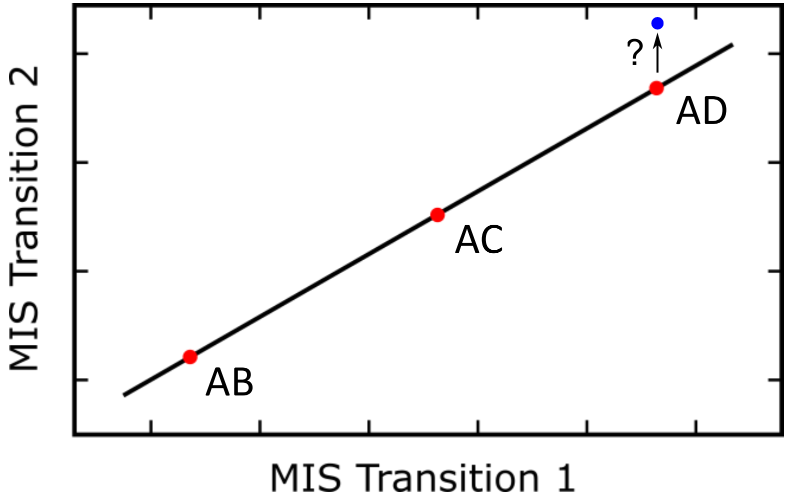
Godun *et al.*, Phys. Rev. Lett. **113**, 210801 (2014)

Huntemann *et al.*, Phys. Rev. Lett. **113**, 210802 (2014)

System	K	λ (nm)
Sr	0.06	699
Yb^+ E2	0.91	436
Yb^+ E3	-6	467
Hg^+	-2.9	281.5
Al^+	0.01	267
Ir^{17+} T1	-22	ca. 280
Ir^{17+} T2	145	ca. 1980
Cf^{16+*} T1	59	ca. 775
Cf^{17+*}	-48	ca. 535

King plots to search for new physics

- Nonlinearities in King plot could point to new physics
- But SM already introduces nonlinearities.....
- Can suppress using generalised King plot (except isotope mass?)
- HCI offer more E1-forbidden transitions!



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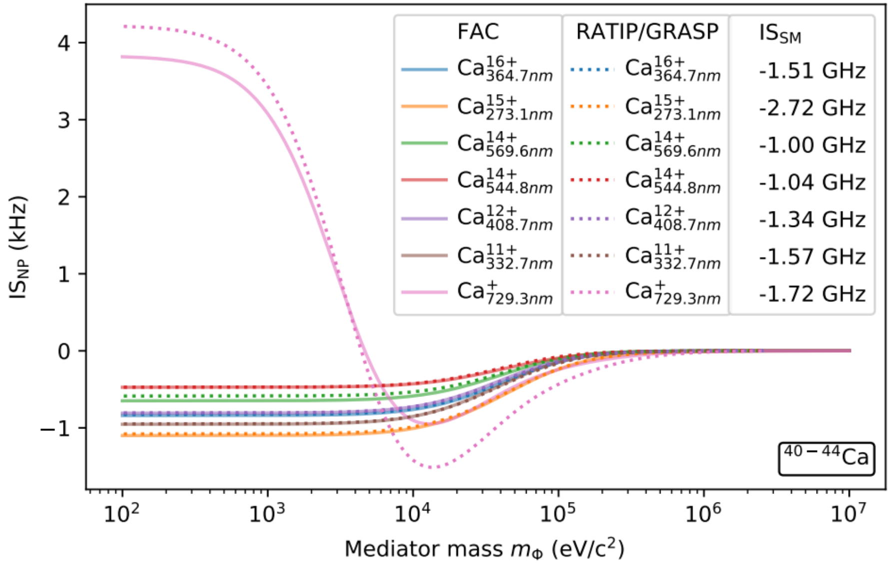
Berengut *et al*., Phys. Rev. Research **2**, 043444 (2020)



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