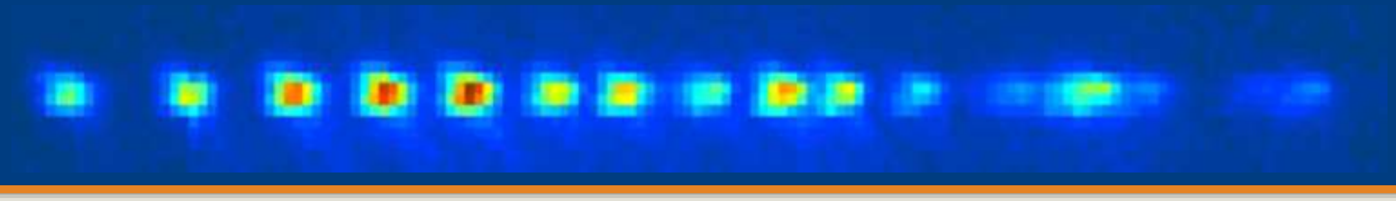
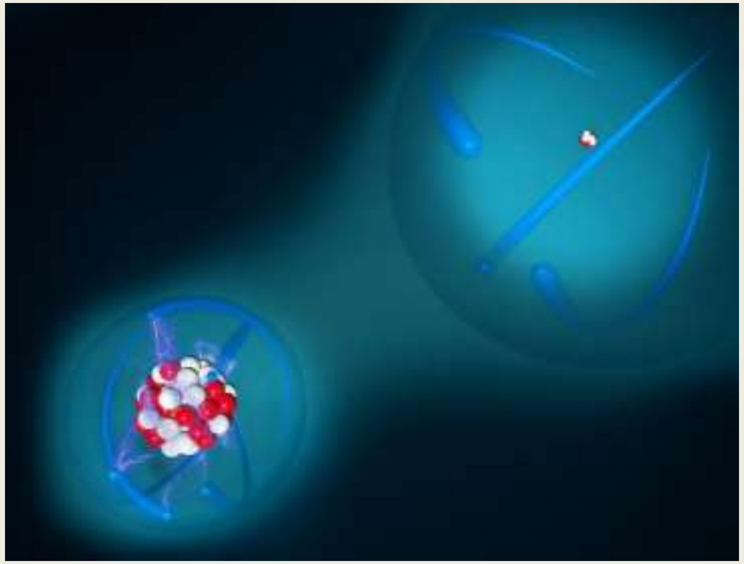


Highly Charged Ion Optical Clocks to Test Fundamental Physics



P. O. Schmidt

QUEST Institute for Experimental Quantum Metrology
PTB Braunschweig and Leibniz Universität Hannover

LTP/PSI Thursday Colloquium, PSI, 25.04.2024

Physikalisch-Technische Bundesanstalt

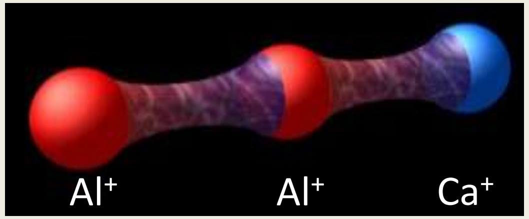

Hermann v. Helmholtz


Location Braunschweig: 1 km^2, approx. 1500 employees

- National Metrology Institute, founded 1887
- **Tasks:** determination of fundamental constants, dissemination of SI units, development of measurement techniques,…
- ca. **2100 employees**, of which are **>200 PhD candidates**
- 60% research: >600 publications per year

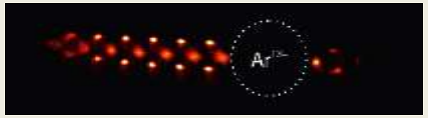
www.quantummetrology.de/eqm

Quantum Logic Spectroscopy Group



[Scharnhorst *et al.*, PRA **98**, 023424 (2018);
Hannig et al., RSI. **90**, 053204 (2019)]

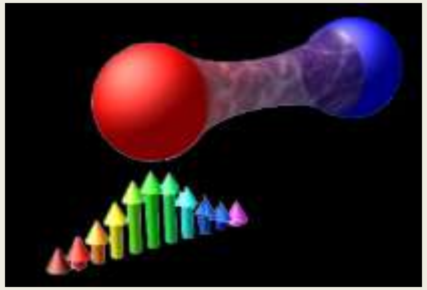
Highly Charged Ions



[Micke *et al.*, Nature **578**, 60 (2020);
King *et al.*, Nature **611**, 43 (2022)]

Atomic Clocks

Complex Ions



[Wan *et al.*, Nat. Commun. **5**, 4096 (2014);
Gebert *et al.*, PRL **115**, 053003 (2015);
Shi *et al.*, Appl. Phys. B **123**, 2 (2017)]

Quantum Logic Spectroscopy

Quantum Engineering

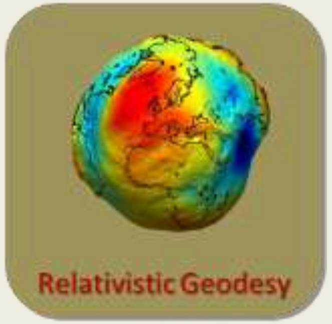
[Wolf *et al.*, Nat. Commun. **10**, 2929 (2019); King *et al.*, PRX **11**, 041049 (2021)]

Molecular Ions

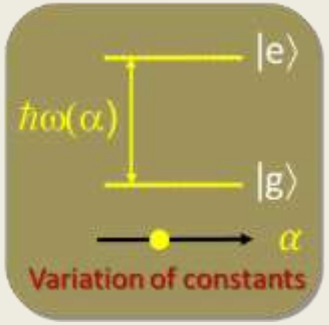
[Wolf *et al.*, Nature **530**, 457 (2016)]

previously inaccessible systems

high resolution & accuracy



Relativistic Geodesy



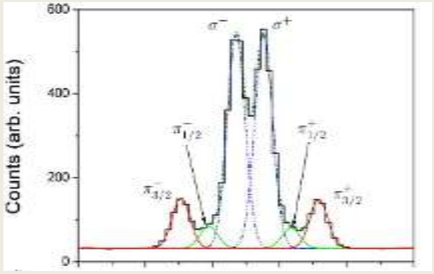
Variation of constants

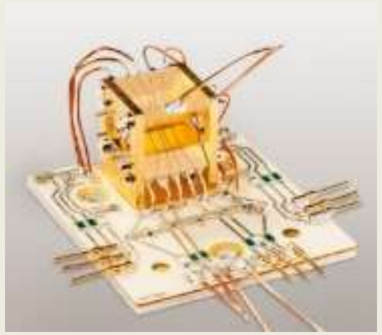
dark matter search

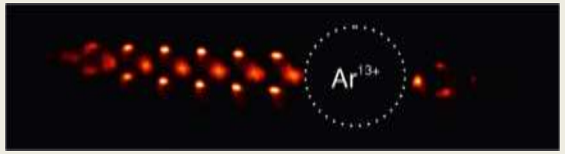
5th forces

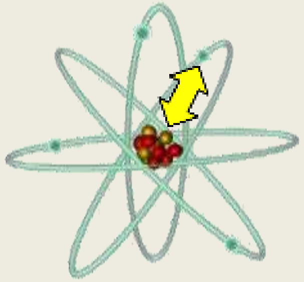
Overview

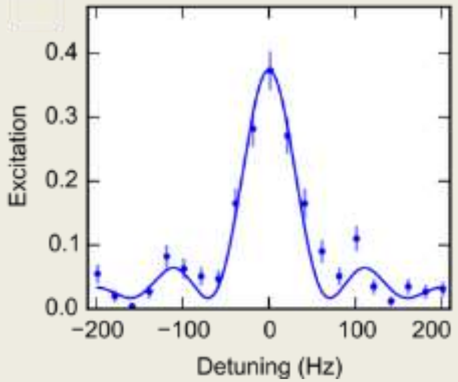
- Introduction to clocks
- Introduction to highly charged ions
- State-of-the art generation & spectroscopy of highly charged ions
- Quantum logic spectroscopy of Ar^{13+}
- Ar^{13+} optical clock
- search for 5th forces: ^{40,42,44,46,48}Ca^{14+} isotope shift
- Summary & future







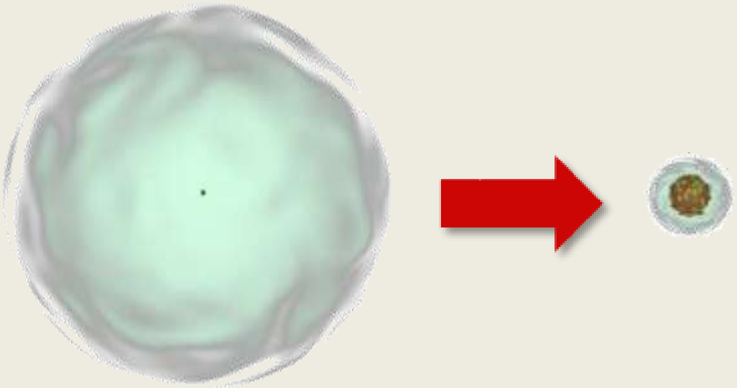


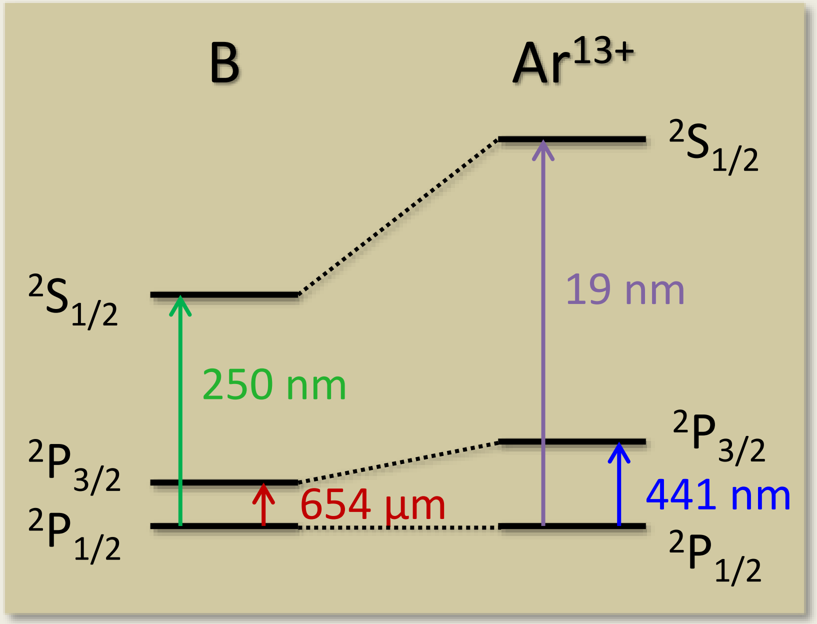


[Overview article: Schmidt & Crespo, Physik Journal **15** (2016) Nr. 10
Review: Kozlov, Safronova, Crespo, Schmidt, Rev. Mod. Phys **90**, 045005 (2018)]

Highly Charged Ions

Charge state dependence:		***H***	→	***U^{91+} (H-like)***
• Binding energy	~ Z^2	10 eV	→	140 keV
• Hyperfine splitting	~ Z^3	µeV	→	eV
• QED effects	~ Z^4	µeV	→	300 eV
• Stark shifts	~ Z^{-6}			





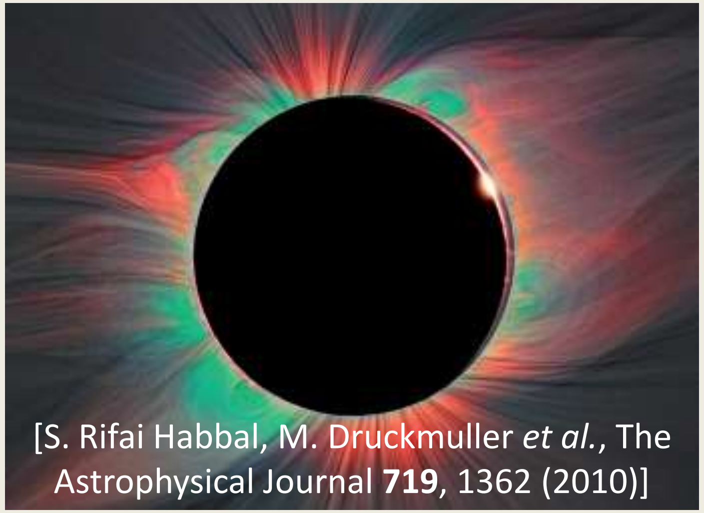
strongly relativistic systems with large QED effects

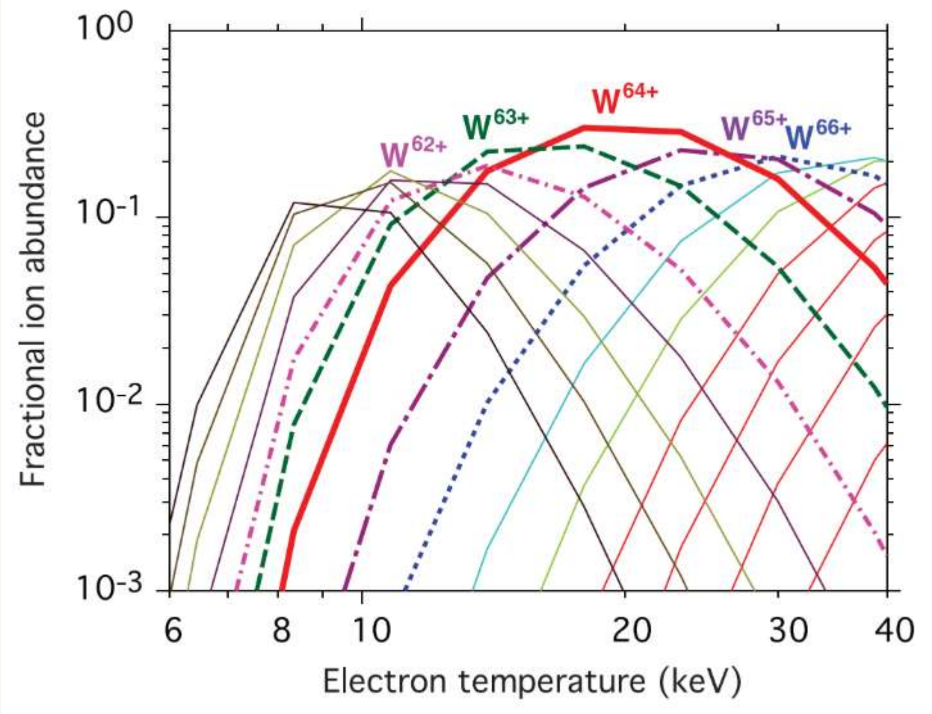
- optical transitions: fs, hfs, level crossings

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

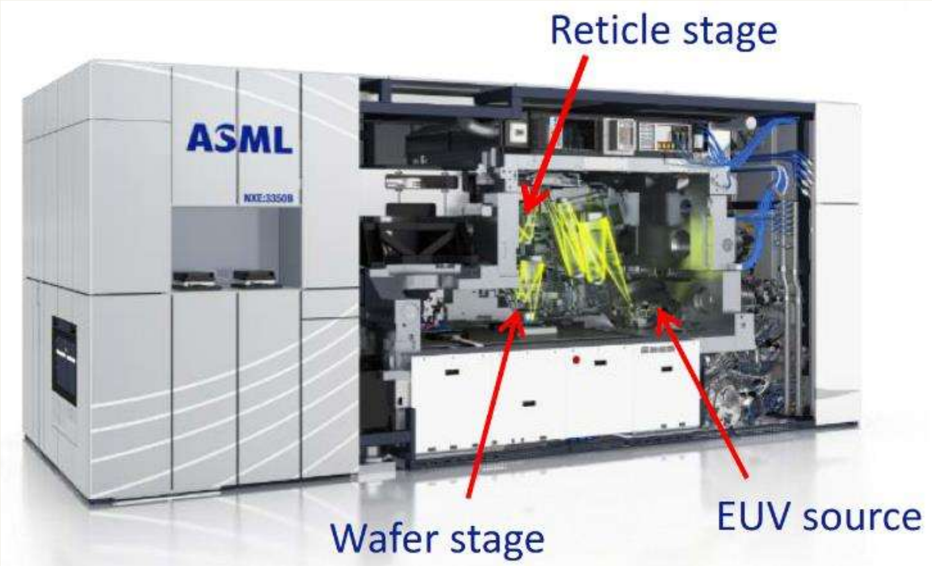
Applications of HCI

- abundant in the universe
  → probes for cosmic & stellar processes
- diagnostic tools for plasma physics


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



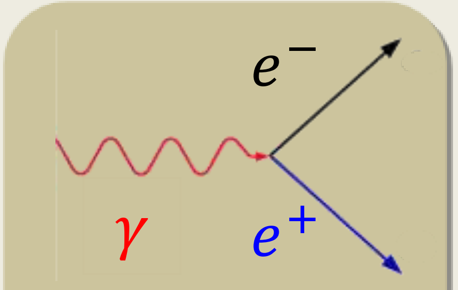
[Beiersdorfer, J. Phys. B **48**, 144017 (2015)]



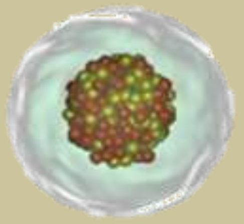
XUV light generation in Sn^{12+} @ 13.5 nm for semiconductor fabs

Testing fundamental physics with HCI

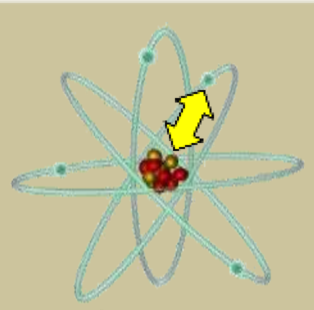
- few remaining electrons → calculable systems
- features
  - strong QED effects: g-factor measurements → QED in strong fields
  - strongly relativistic & high ionization potential:
    → highest sensitivity of all atomic species to $\dot{\alpha}$ & dark matter
  - strongly relativistic → violation of local Lorentz invariance
  - electrons close to nucleus
    → isotope shifts (5th forces), nuclear physics, parity violation, …



test of QED

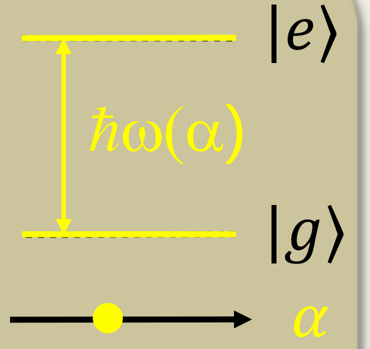


Nuclear physics



5th forces

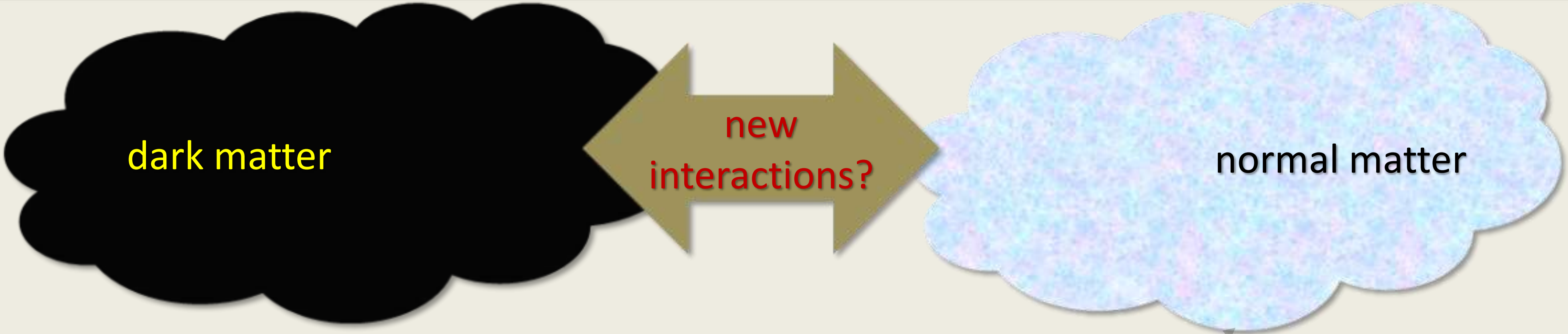
Lorentz invariance



Changing constants

[Reviews: Indelicato, J. Phys. B **52**, 232001 (2019), Safronova *et al.*, RMP **90**, 025008 (2018), Kozlov *et al.* RMP **90**, 045005 (2018)]

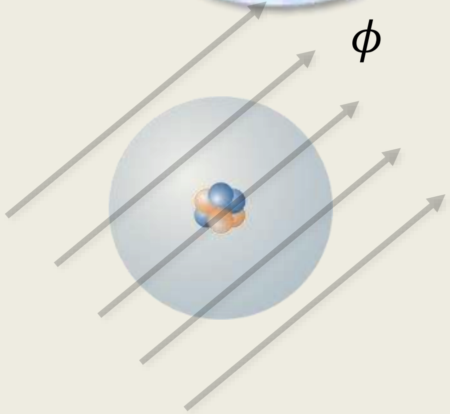
Effects of dark matter on normal matter

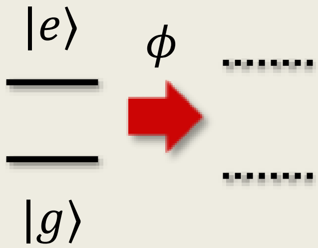


- dark matter candidate: scalar field ϕ
  - oscillating field
  - topological field (forming „clumps“)
  - …
- weak (non-gravitational) coupling to matter changes energy levels in atoms/molecules

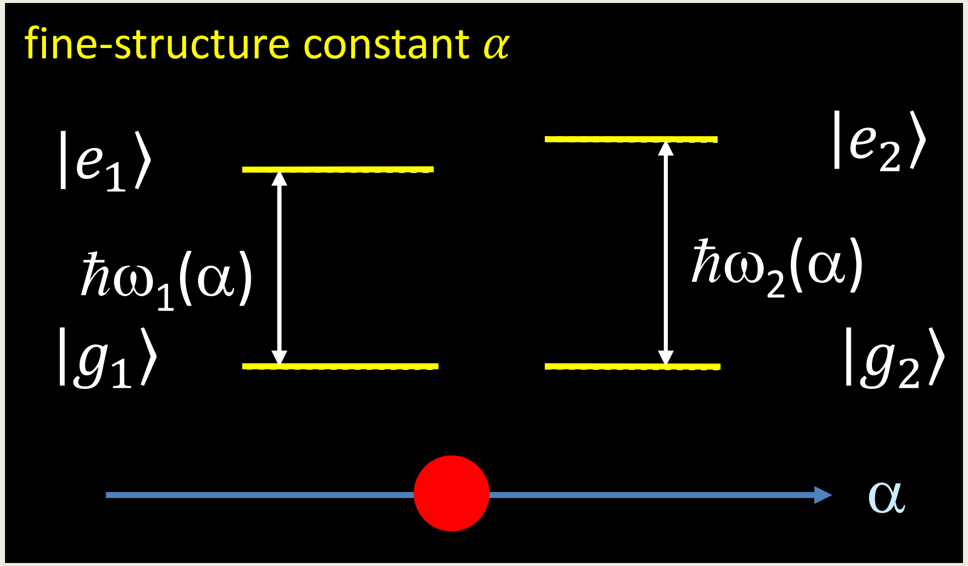
➔ apparent variation of fundamental constants

[review: Safronova *et al.*, RMP **90**, 025008 (2018)]

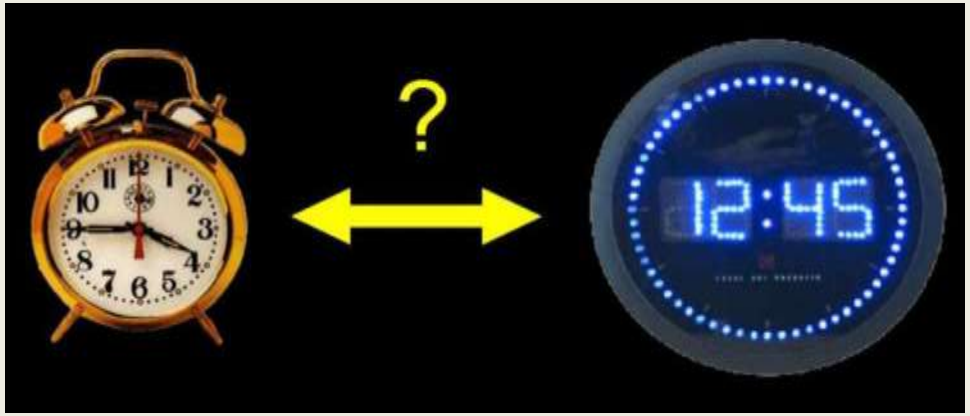


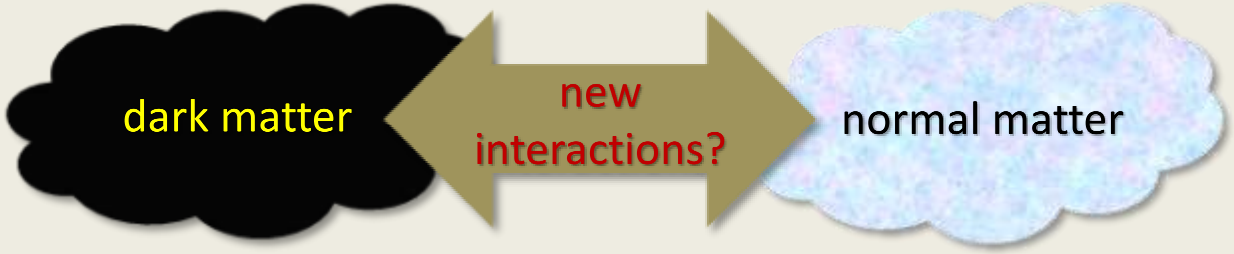


Variation of Fundamental Constants & Dark Matter

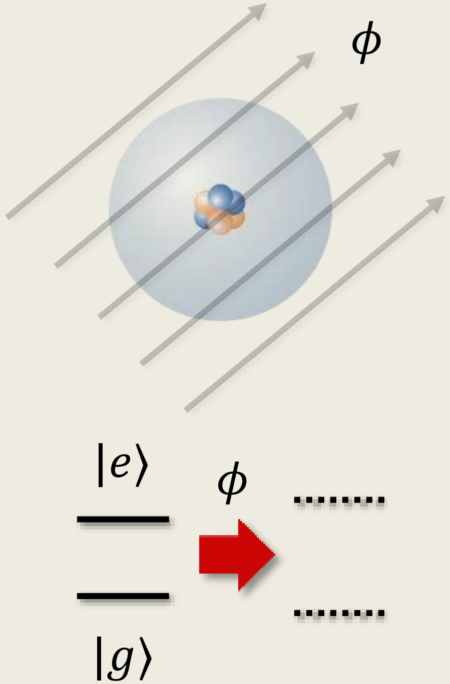


$$\frac{\Delta\omega}{\omega} = \boldsymbol{K}\frac{\Delta\alpha}{\alpha}$$

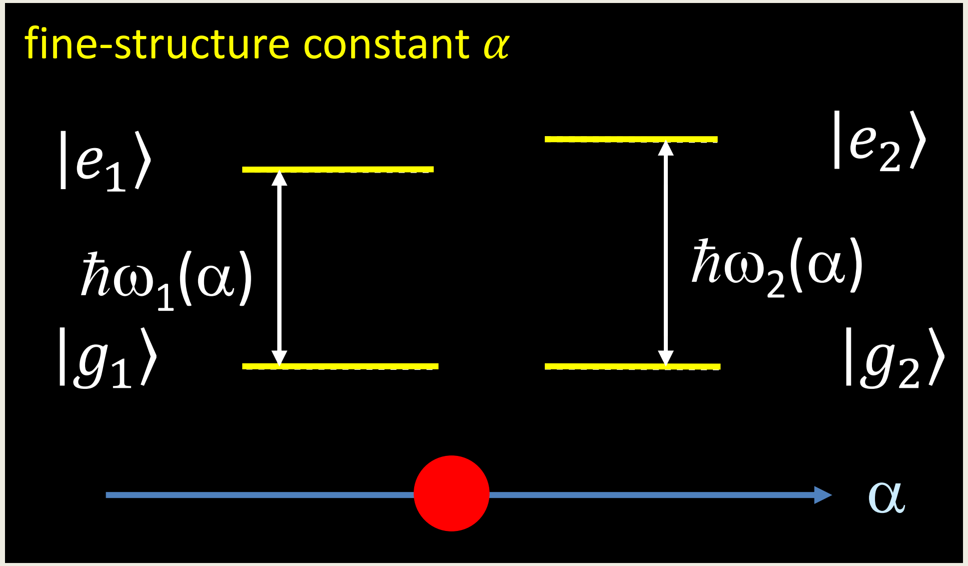




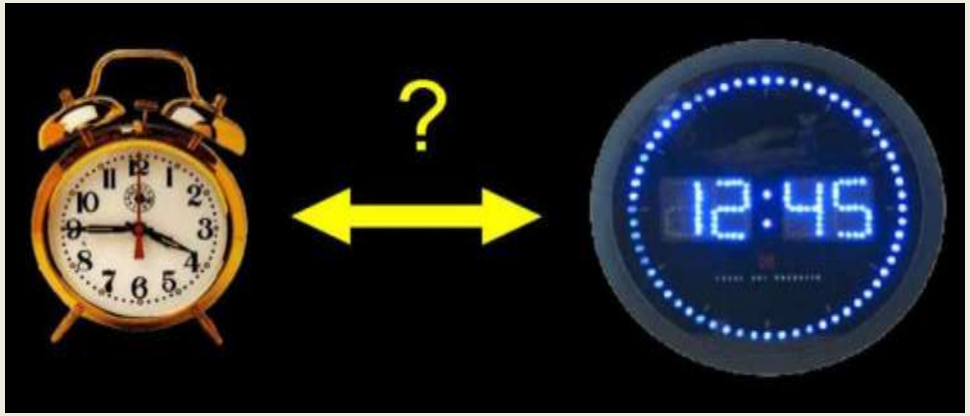
Apparent changes in α may be induced by scalar fields ϕ, e.g. dark matter



Variation of Fundamental Constants



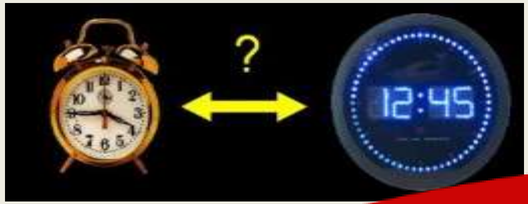
$$\frac{\Delta\omega}{\omega} = \boldsymbol{K}\frac{\Delta\alpha}{\alpha}$$

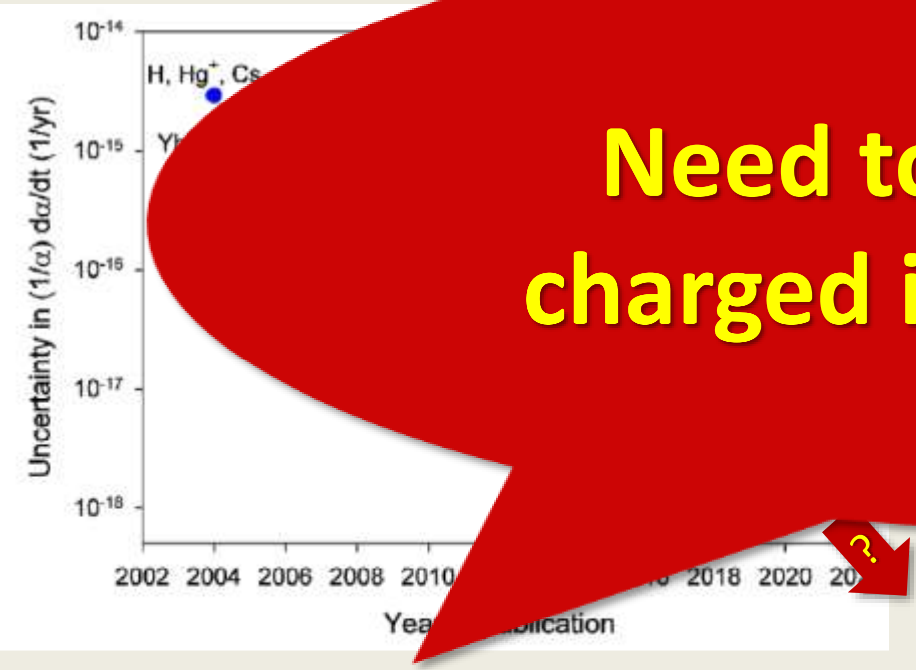


$$\frac{\Delta\omega}{\omega} = \boldsymbol{K}\frac{\Delta\alpha}{\alpha}$$

System	K	**λ (nm)**
Sr	0.06	699
Yb^+ E2	0.91	436
Yb^+ E3	-6	467
Hg^+	-2.9	281.5
Al^+	0.01	267

Combined data from clocks





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

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

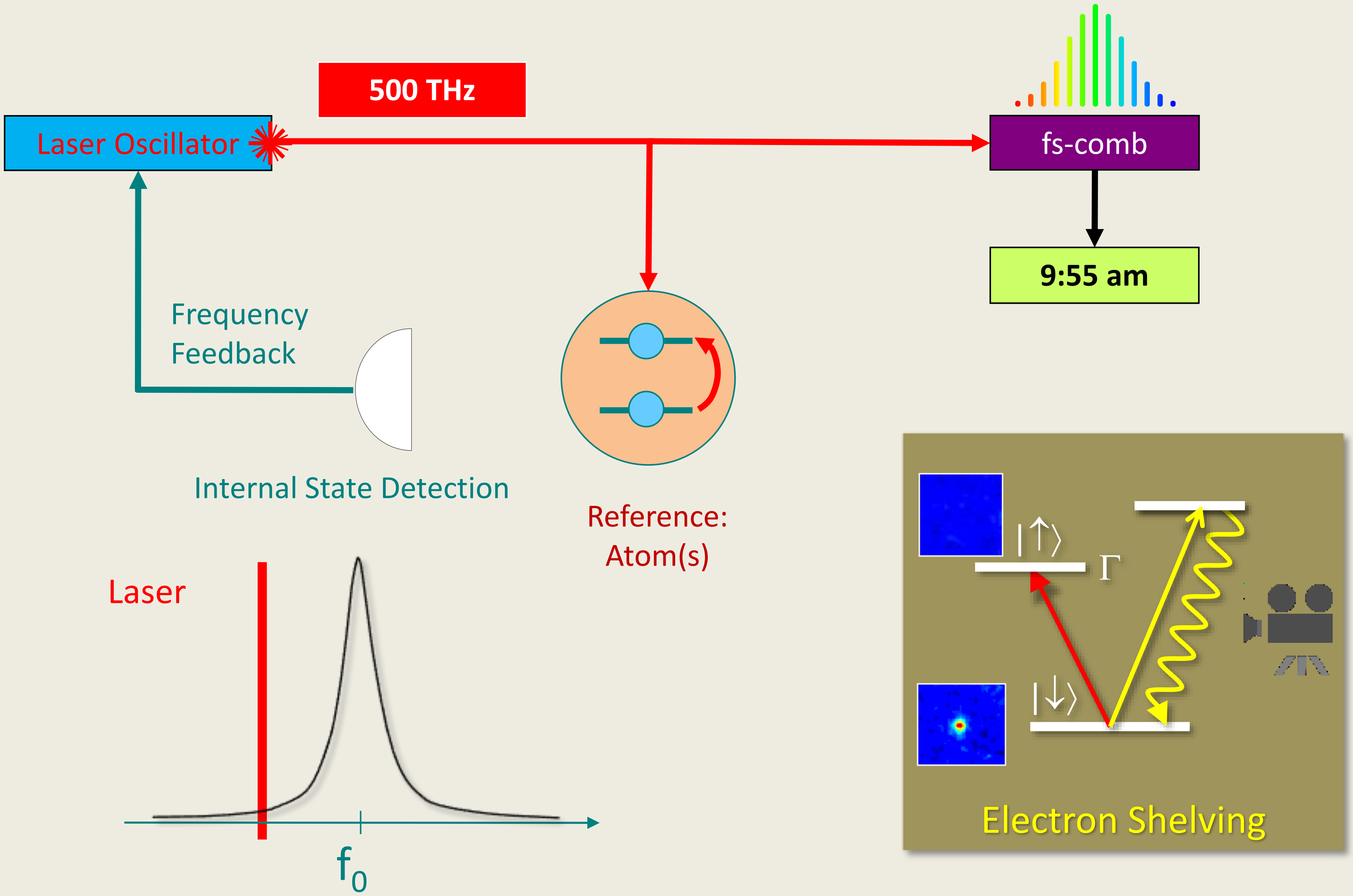
Need to build a highly charged ion optical clock!

all known atomic systems

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

System	K	λ (nm)
	0.06	699
		36
		67
	-22	ca. 280
Ir^{17+} T2	145	ca. 1980
Cf^{16+*} T1	59	ca. 775
Cf^{17+*}	-48	ca. 535
Th* nuclear	8000	ca. 150

Principle of Optical Clocks



500 THz

Laser Oscillator

fs-comb

9:55 am

Frequency Feedback

Internal State Detection

Reference: Atom(s)

Laser

f_0

$|\uparrow\rangle$

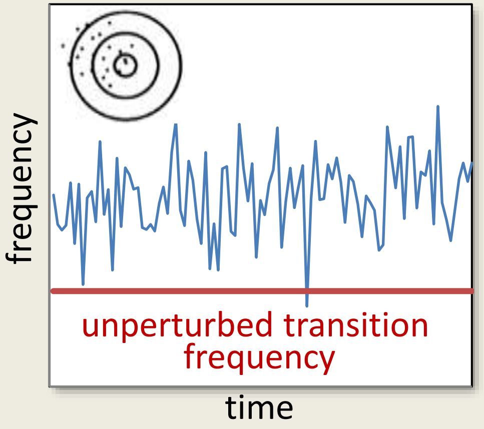
Γ

$|\downarrow\rangle$

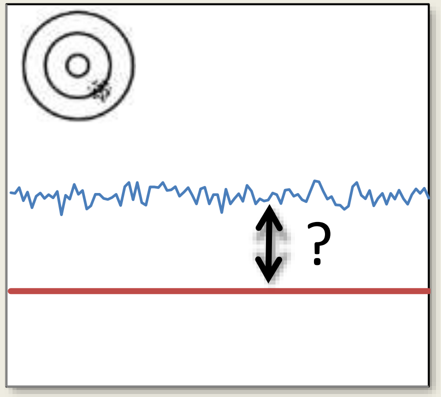
Electron Shelving

Clock characterization

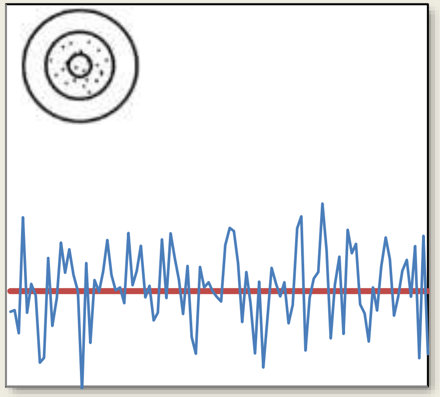
Two (main) notions: Stability & Accuracy



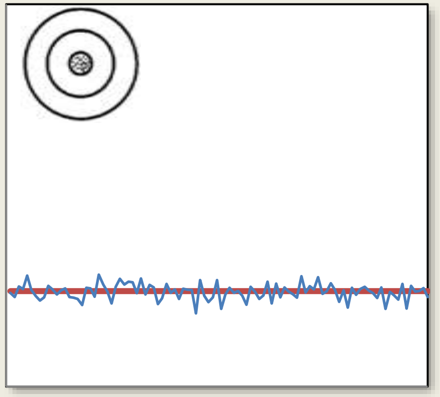
unstable,
inaccurate



stable,
inaccurate



unstable,
accurate



stable,
accurate

- (In-)Stability: How large is the scatter of data points?
  ➔ Uncertainty type A (u_A, only statistical) “statistical uncertainty”
- (In-)Accuracy: How well is the unperturbed reference reproduced?
  ➔ Uncertainty type B (u_B, outside information) “systematic uncertainty”

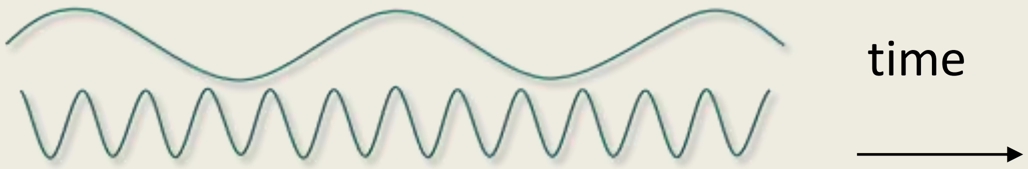
Problem: value of unperturbed reference a priori not known!

Why optical clocks?

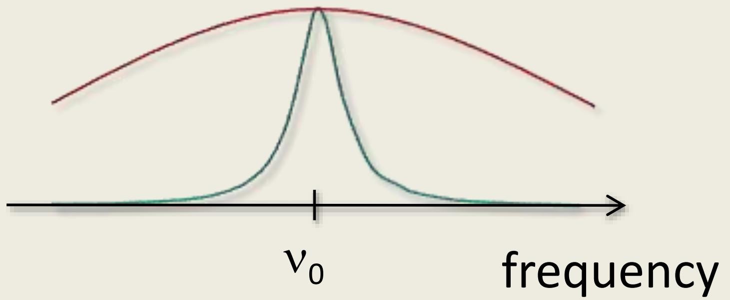
statistical uncertainty

- microwave vs. optical clocks

low frequency (mw)
↓ $\times 10^5$
high frequency (optical)



- line width $\Delta\nu$

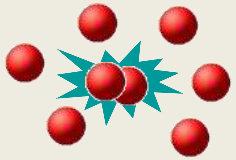


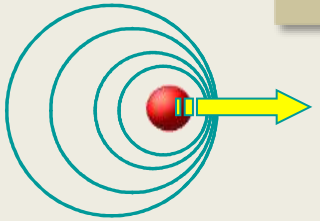
relevant quantity: $\frac{\Delta\nu}{\nu_0}$

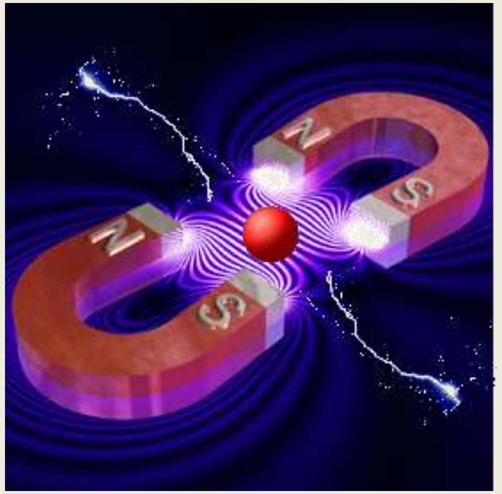
systematic uncertainty

- small frequency shift $\delta\nu$
  → even smaller relative shift $\delta\nu/\nu_0$

species dependent
→ small for HCI

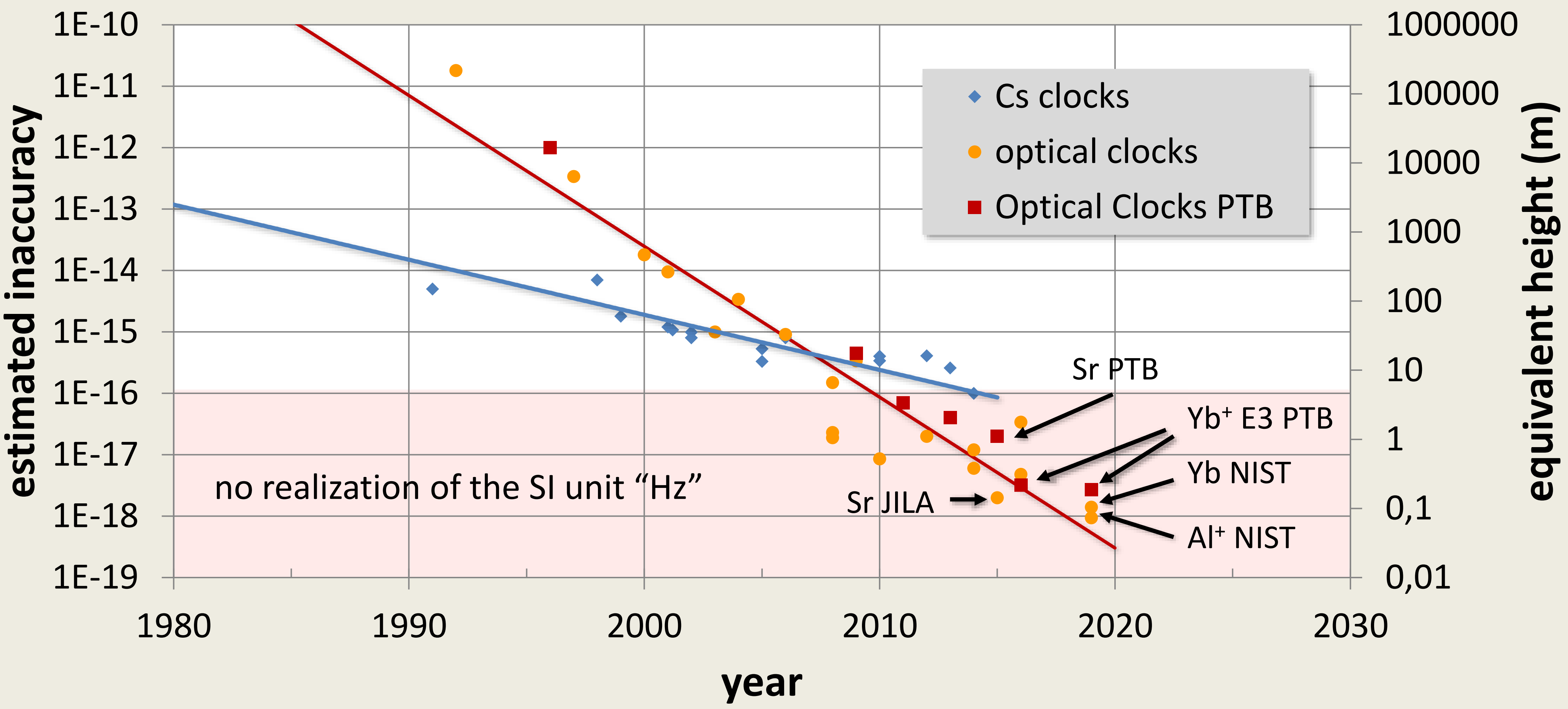

collisions


Doppler shift



electric and magnetic fields

Evolution of (estimated) clock accuracy

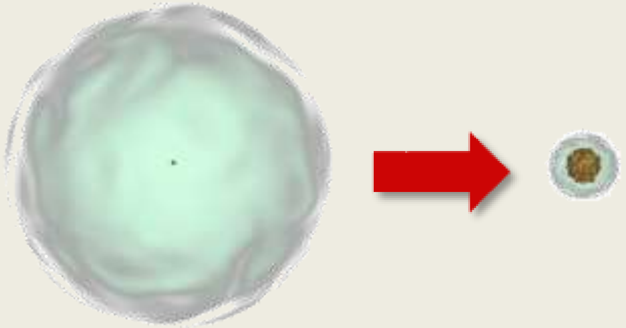


Highly charged ions as optical clocks?

- **High accuracy**

  → low sensitivity to resonance shifts

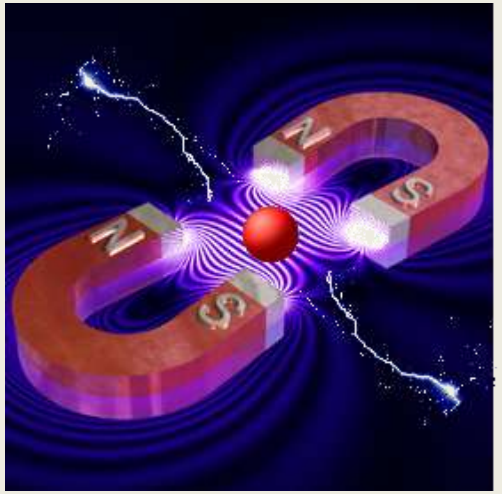
- **HCI advantage: suppressed shifts**



Hydrogen-like HCI:

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}

[Berengut *et al.*, PRA **86**, 022517 (2012)]



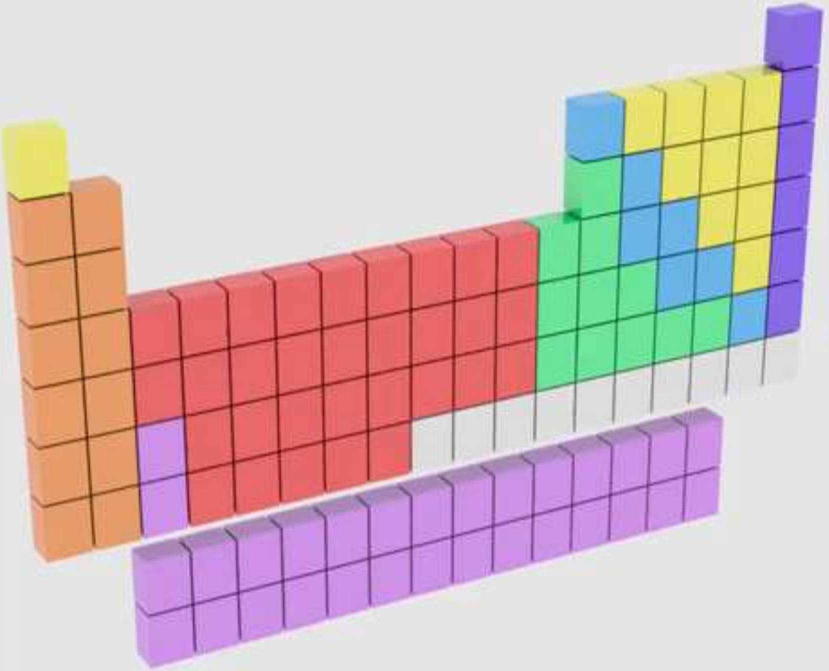
electric & magnetic fields

Other clock species requirements can be fulfilled:

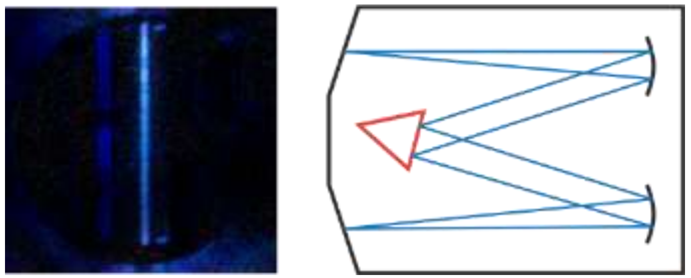
narrow, laser accessible transition, simple level structure, …

[dozens of proposals, many summarized in: Kozlov *et al.*, Rev. Mod. Phy. **90**, 045005 (2018)]

Many HCI to choose from…

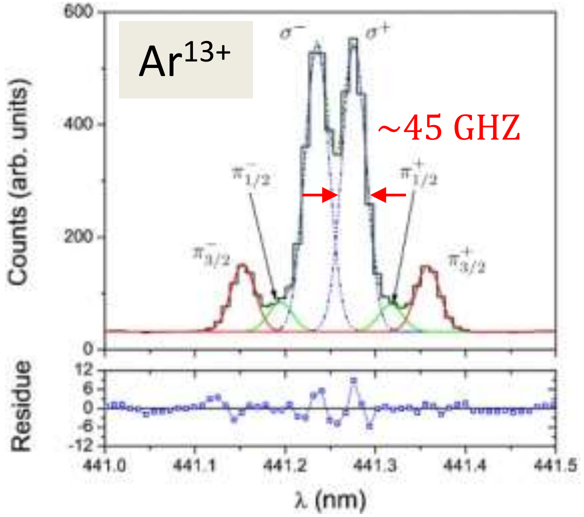


State-of-the-art HCI spectroscopy



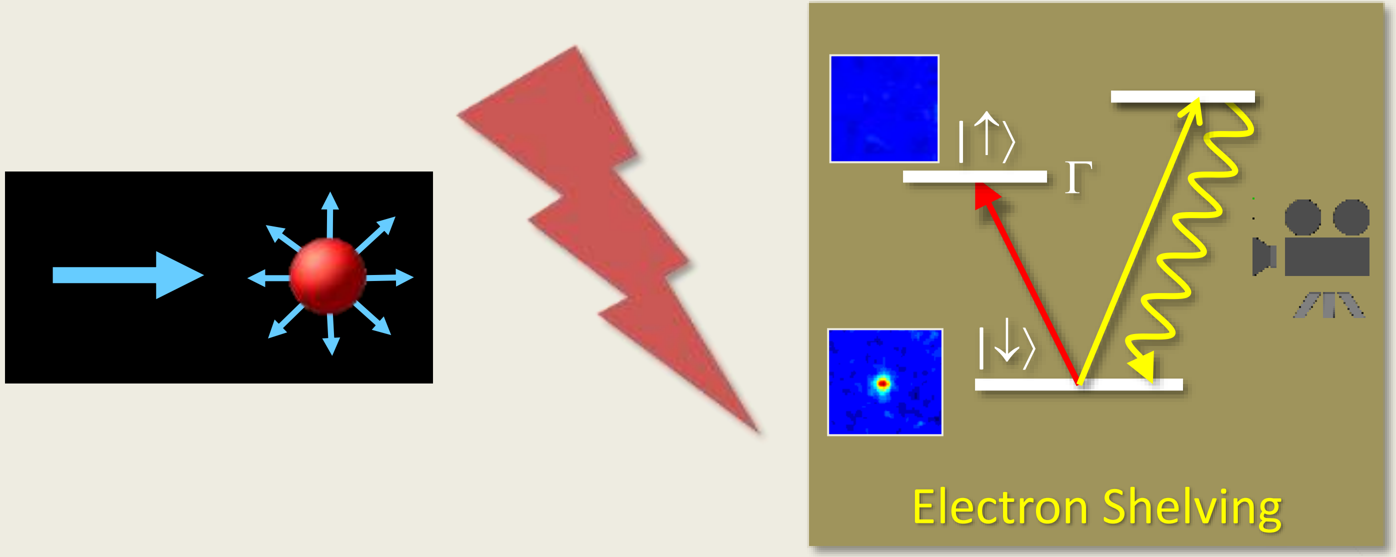
Plasma (EBIT)

Grating spectrometer



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

- Problem #1: Electron beam ion trap (EBIT) is a noisy & hot environment
- Problem#2: No cycling transition for cooling & state detection

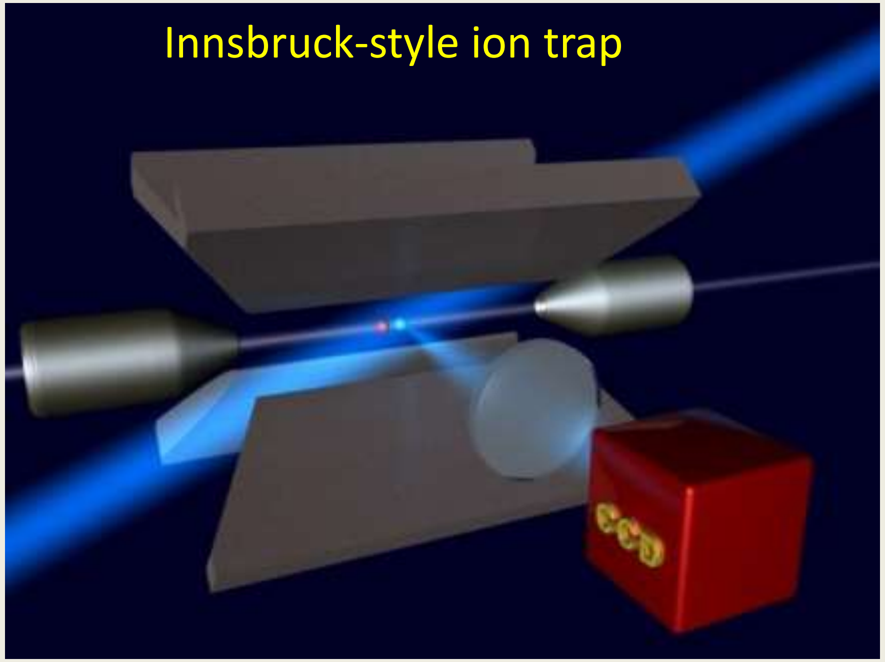


Doppler-limited resolution of ~ 150 MHz

Solution #1: Transfer HCIs into a Paul trap

Features of trapped ions

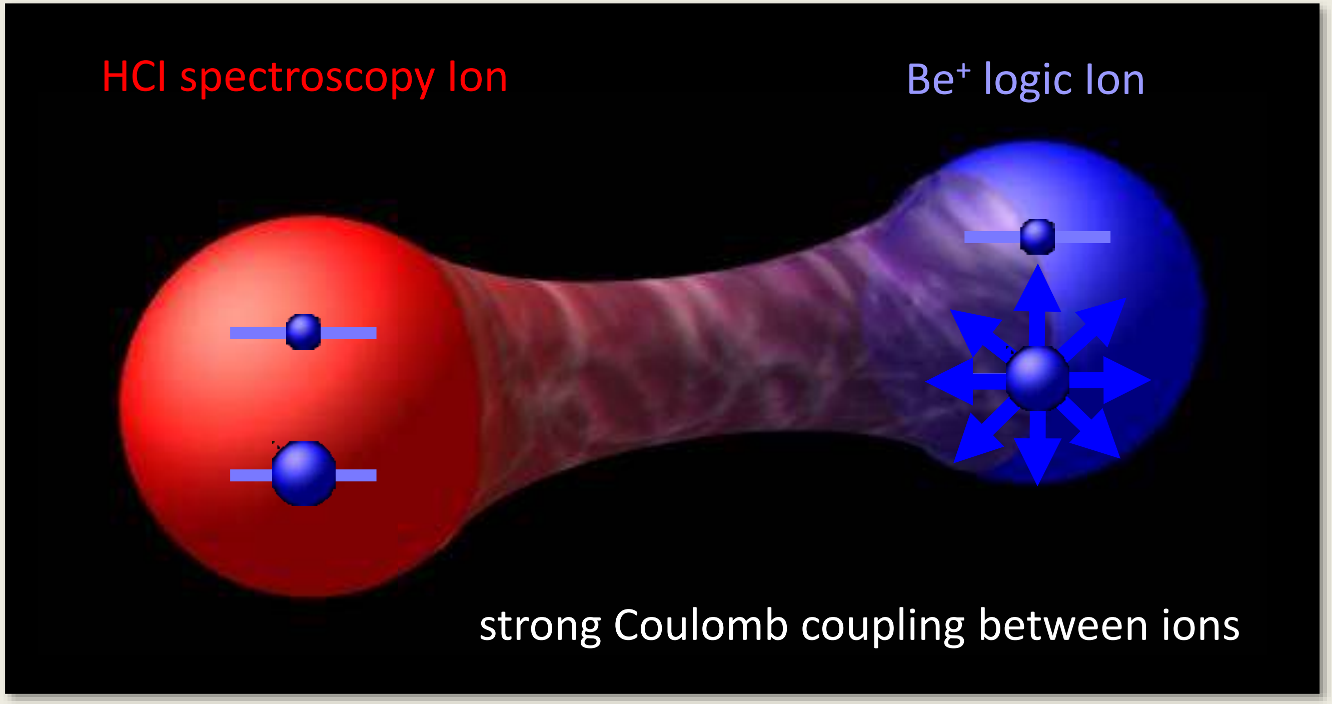
- large trap frequencies
  ➔ recoil-free absorption
- long interrogation times
- trap ion in zero field
  ➔ small trap induced shifts
- isolated from environment
  + laser cooling
  + no interactions
  ➔ high accuracy



$d_{\text{ion-electr}} \sim 0.8$ mm
$\omega_z \sim 2$ MHz, $\omega_r \sim 4$ MHz

Yb^+ single-ion clock: 3×10^{-18}
[Sanner *et al.*, Nature **567**, 204 (2019)]

Solution #2: Quantum Logic Spectroscopy



Many more applications demonstrated, e.g.

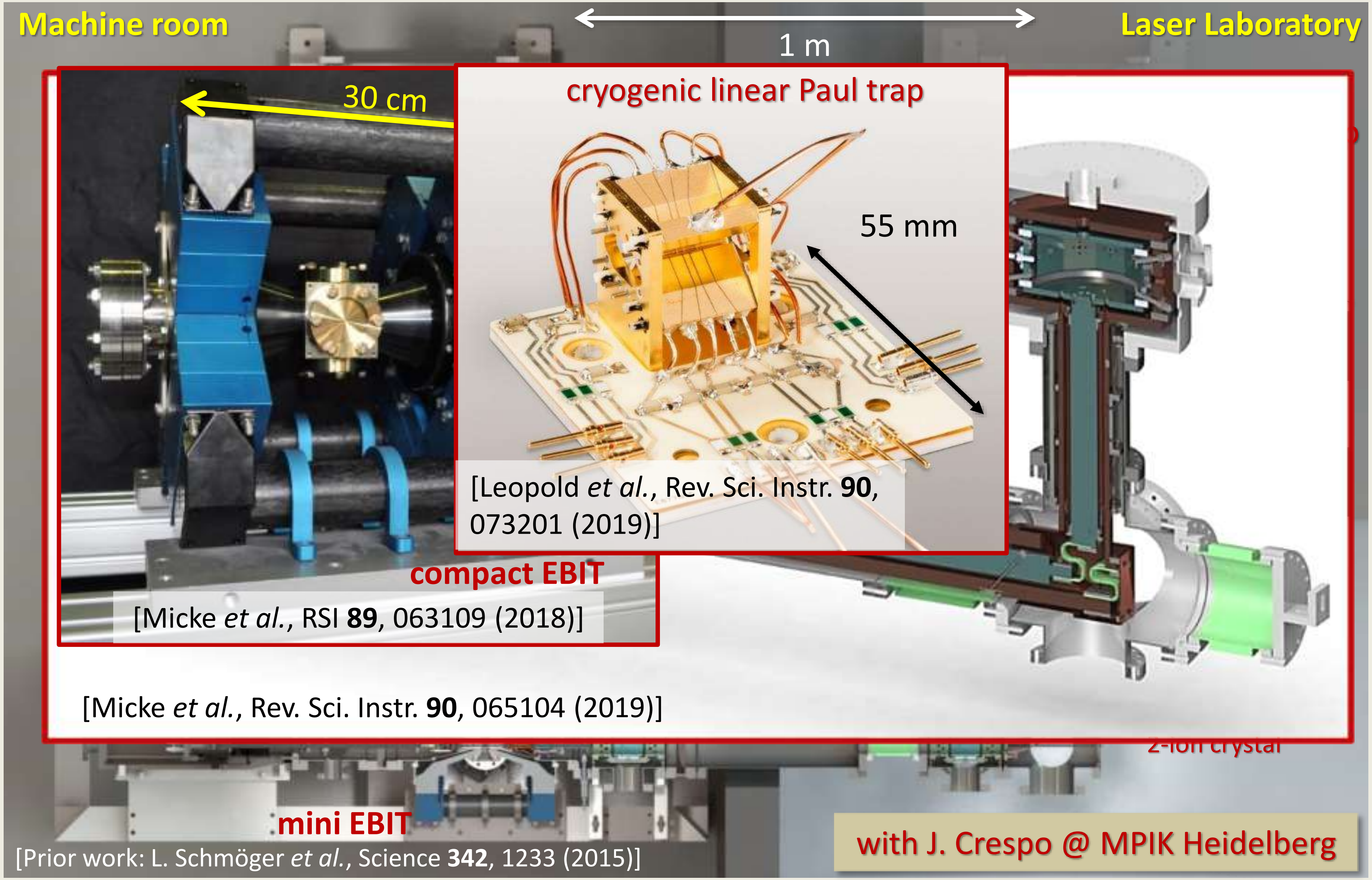
- Most accurate clock: Al^+
  [Brewer *et al.*, PRL **123**, 033201 (2019)]
- Molecular ion state detection and preparation
  [Wolf *et al.*, Nature **530**, 457 (2016); Chou *et al.*, Nature **545**, 203 (2017)]

- ions in linear Paul trap → high accuracy achievable
- logic ion provides sympathetic cooling & signal readout
- strong Coulomb interaction couples motional modes
- composite system: combine advantages of both species

→ investigation of previously inaccessible species

[D.J. Wineland *et. al.*, Proc. 6th Symposium on Frequency Standards and Metrology, 361 (2001); P.O. Schmidt *et al.*, *Science*, **309**, 749 (2005)]

Approach to precision HCI spectroscopy: CryPTEx-PTB



[Leopold *et al.*, Rev. Sci. Instr. **90**, 073201 (2019)]

[Micke *et al.*, RSI **89**, 063109 (2018)]

[Micke *et al.*, Rev. Sci. Instr. **90**, 065104 (2019)]

[Prior work: L. Schmöger *et al.*, Science **342**, 1233 (2015)]

with J. Crespo @ MPIK Heidelberg

Specs vacuum system:

- Vacuum: $< 10^{-14}$ mbar
  → HCI lifetime: ~ 100 min
- Temperature: < 5 K
- Vibrations: < 20 nm
- Magnetic field: < 200 pT

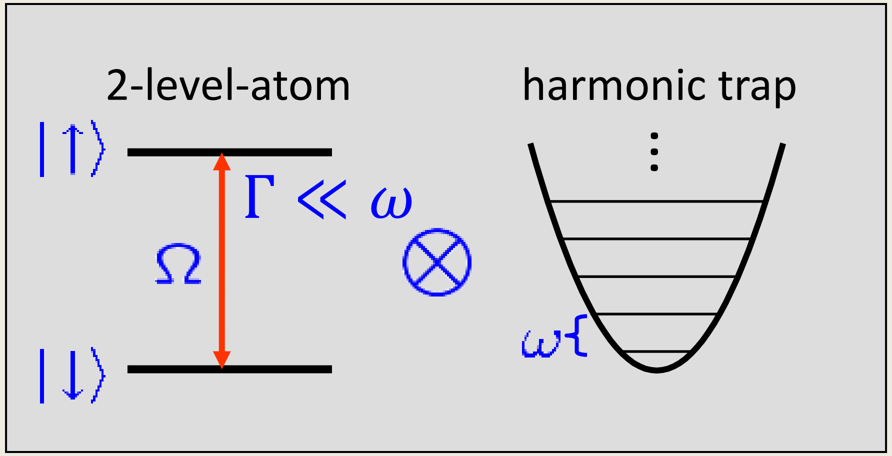
Specs EBIT:

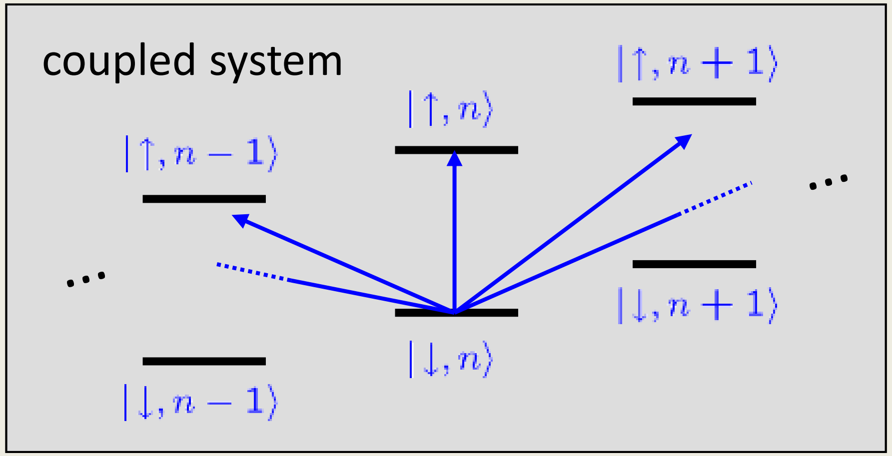
- Magnetic field: 0.86 T (72 permanent magnets)
- Acceleration voltage: 10 kV
- Current: > 80 mA

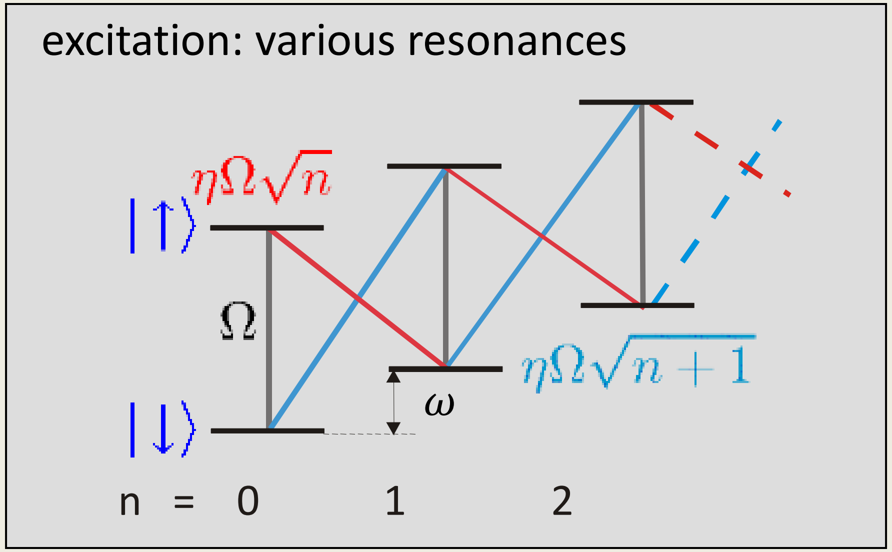
Specs ion trap:

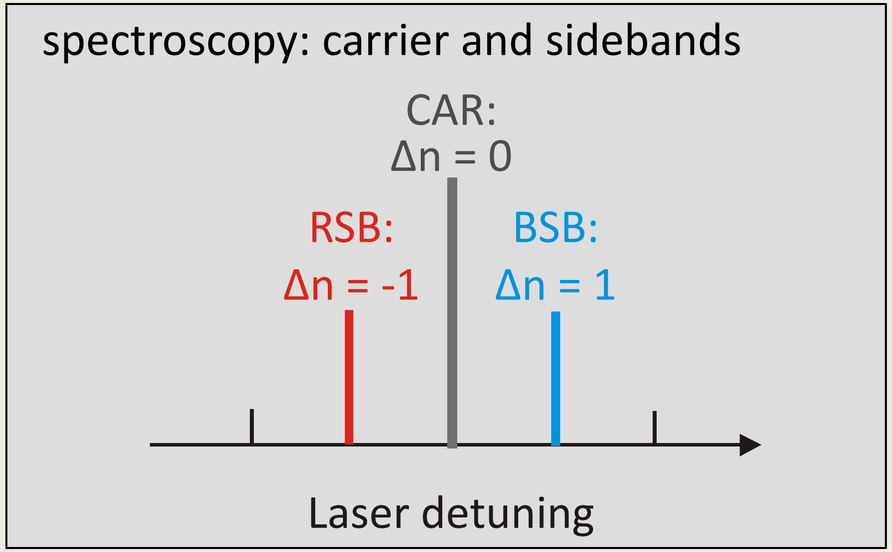
- 5 segments, Au-coated Al_2O_3, 0.7 mm ion-electrode distance
- Trapping frequencies: > 1 MHz
- Heating rates: ~ 1 1/s
- f/# ~ 1 imaging with bi-aspheric lens

Quantum Logic with Trapped Ions



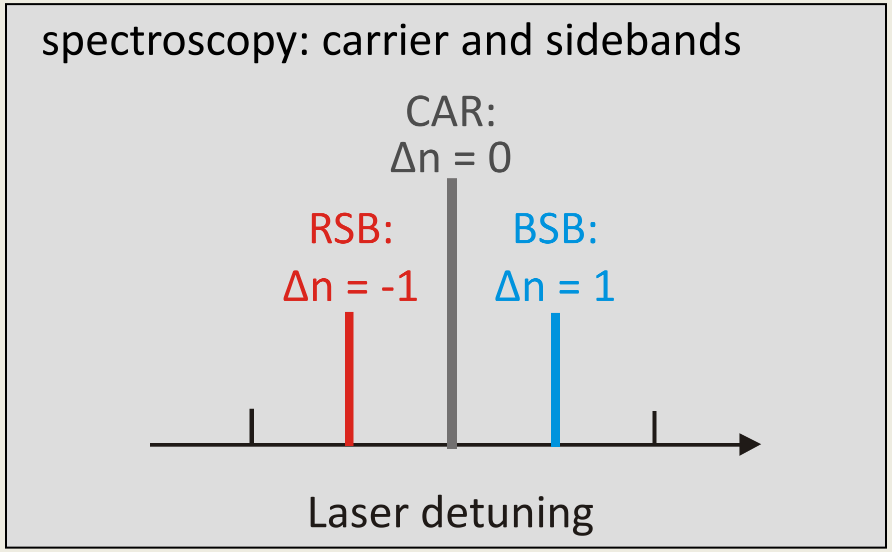




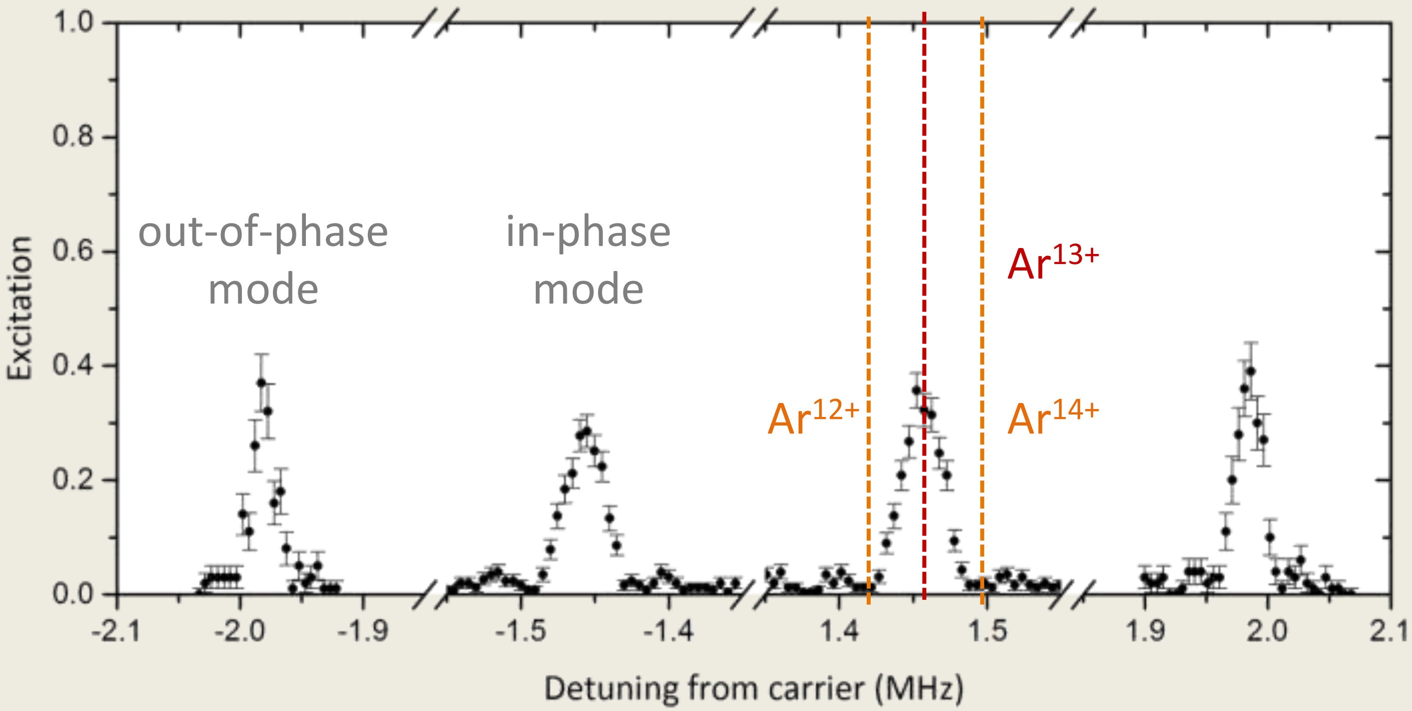


Ω: Carrier Rabi frequency; $\eta = kz_0$: Lamb-Dicke factor

Doppler cooling & charge state identification



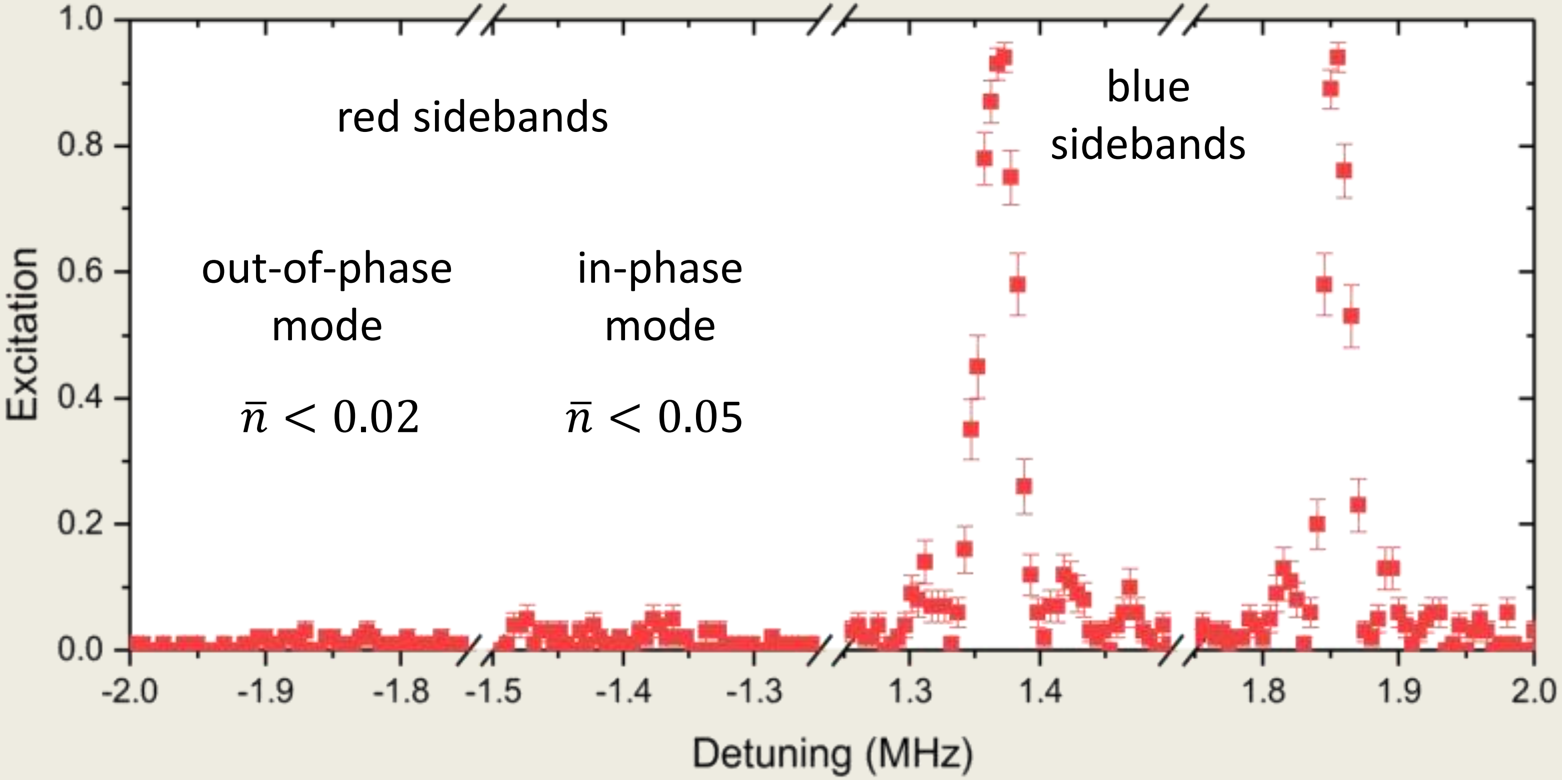
axial motional spectrum on Be^+

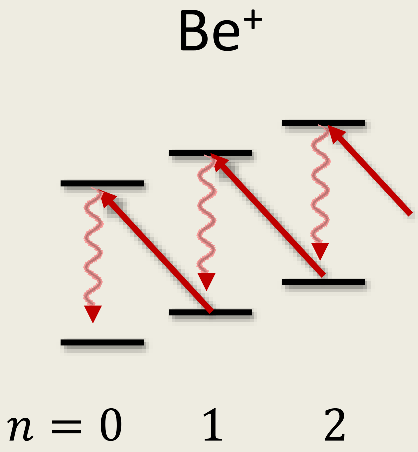


- single Be^+ axial frequency: 0.995 MHz
  ➔ Be^+/Ar^{13+} axial frequencies:
  1.47 MHz and 1.99 MHz

Sympathetic axial ground state cooling of Ar^{13+}

axial motional spectrum on Be$^+$

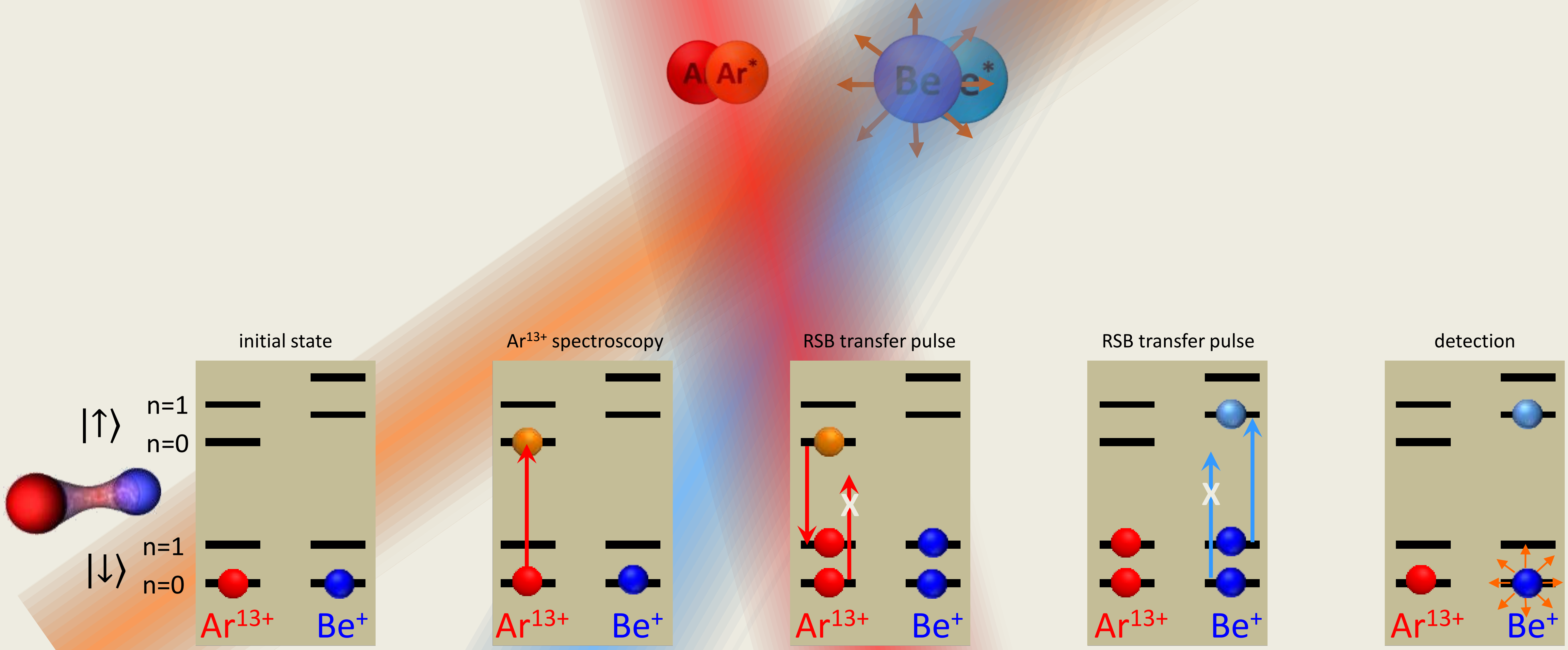




- resolved Raman sideband cooling on Be$^+$ + algorithmic cooling of radial modes
- Lamb-Dicke parameter: $\eta_z = 0.82\sqrt{\mathrm{MHz}/\nu_z}$

[Leopold et al., Rev. Sci. Instrum. **90**, 073201 (2019); King *et al.*, PRX **11**, 041049 (2021)]

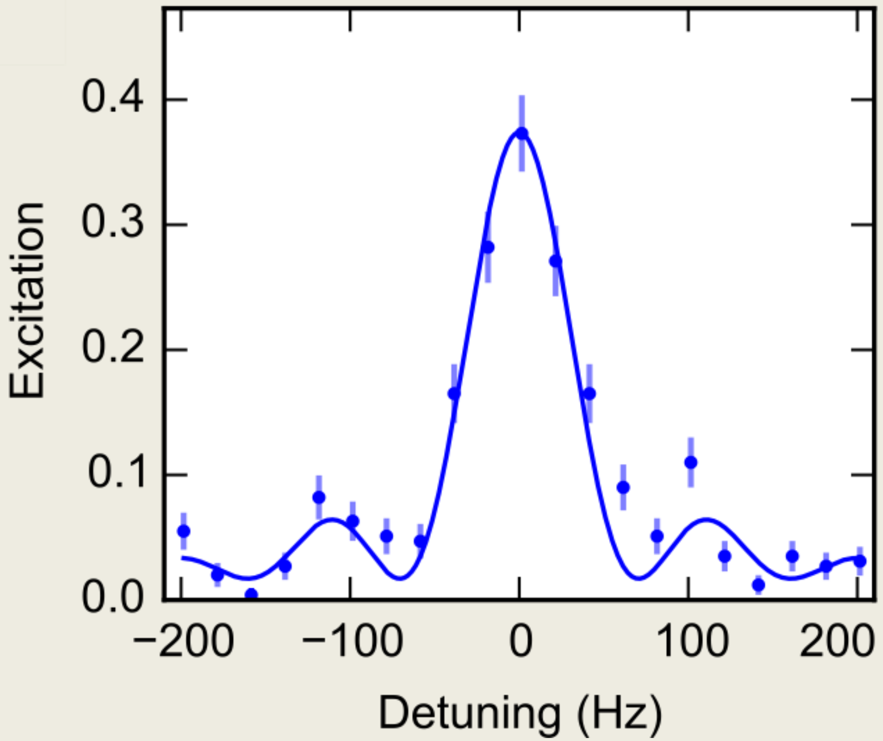
Quantum Logic State Transfer

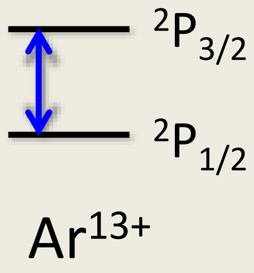


[D.J. Wineland *et. al.*, Proc. 6th Symposium on Frequency Standards and Metrology, 361 (2001); P.O. Schmidt *et al.*, *Science*, **309**, 749 (2005)]

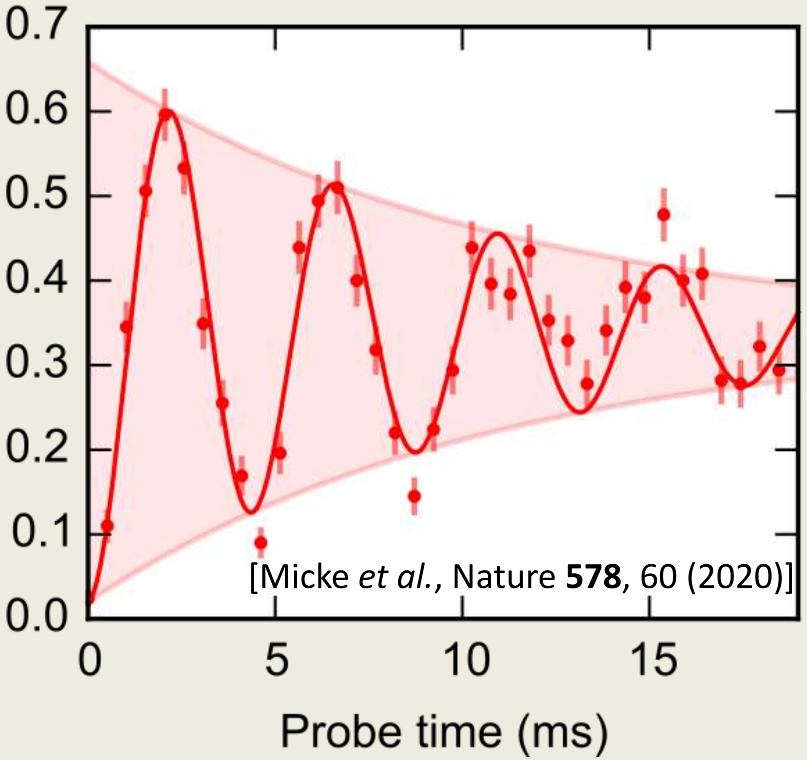
Quantum Logic Spectroscopy of Ar^{13+}

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





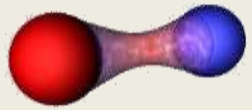
dephasing dominated by
excited state lifetime of 9.97(26)ms



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

- spectroscopy laser transfer locked of Ar^{13+} to Si cavity-stabilized laser
  [Sterr & Benkler @ PTB: D. G. Matei *et al.*, Phys. Rev. Lett. **118**, 263202 (2017)]

How to turn this into a clock? → Evaluation of systematic frequency shifts



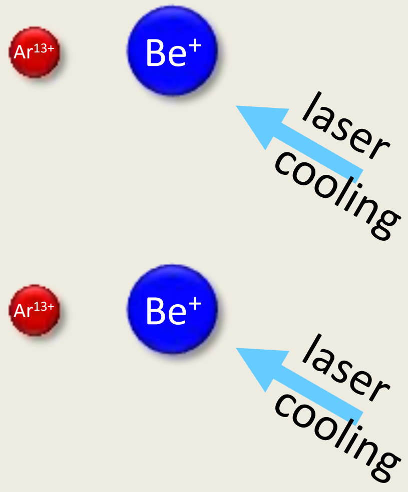
Time dilation shift: cooling challenges....

Large q/m mismatch between ions

→ large difference in radial amplitudes

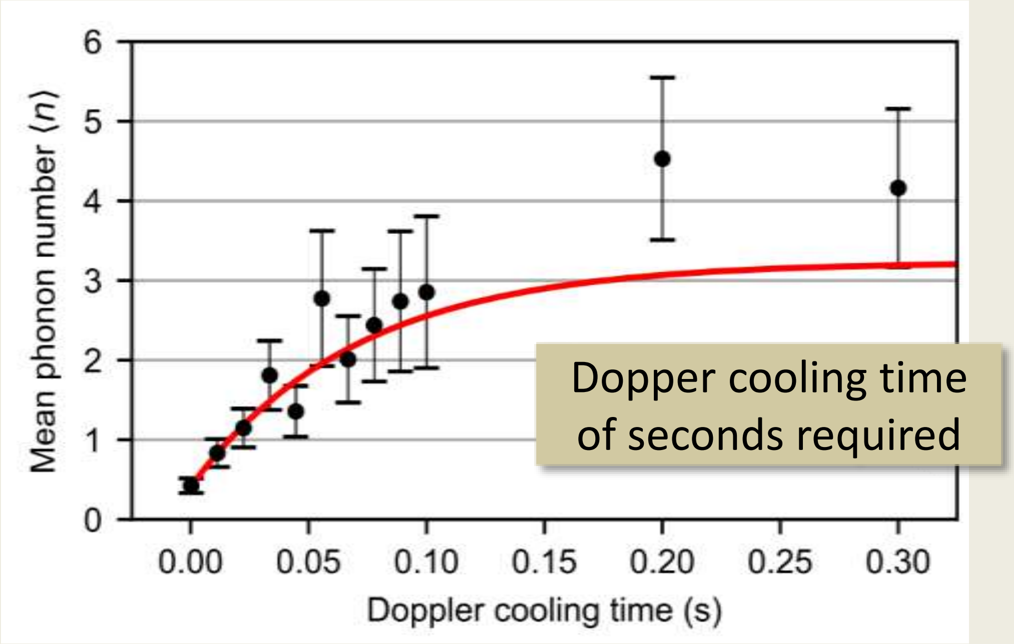
→ inefficient cooling of radial modes

- radial mode x_1:
  → strong cooling
- radial mode x_2:
  → weak cooling



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

Doppler „heating“

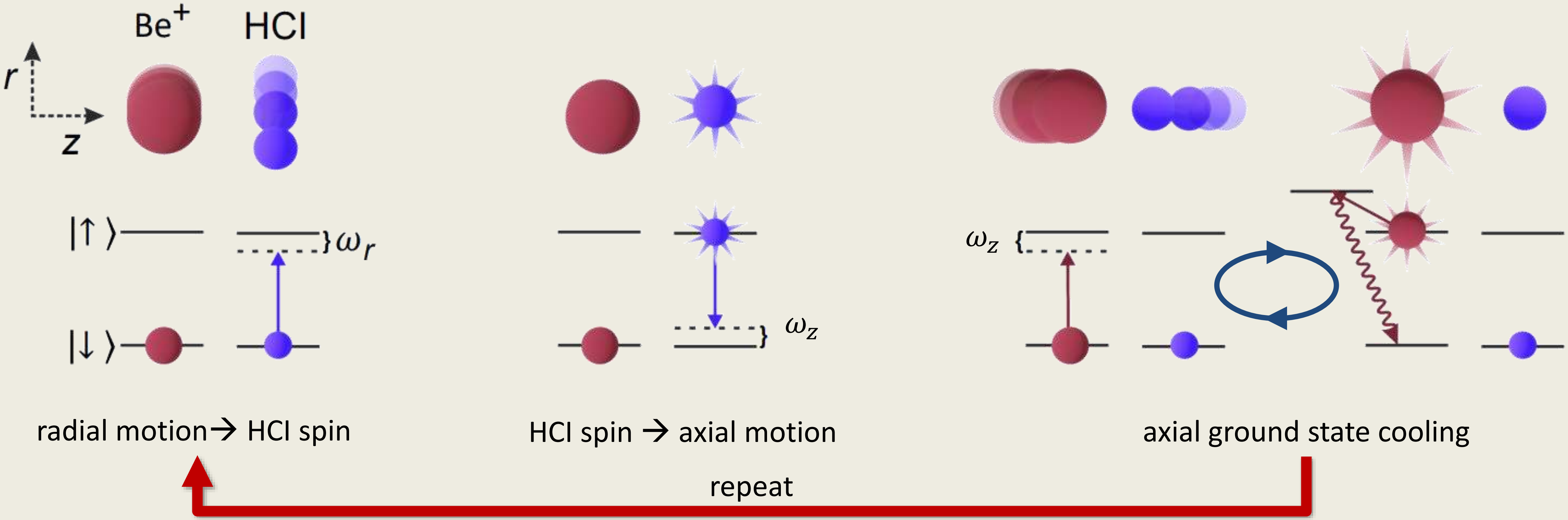


Dopper cooling time of seconds required

[King *et al***.,** PRX **11**, 041049 (2021)]

Ground-state cooling using quantum logic

Coherently transfer radial mode phonons to efficiently-cooled axial modes
„Algorithmic cooling“



radial motion→ HCl spin

HCl spin → axial motion

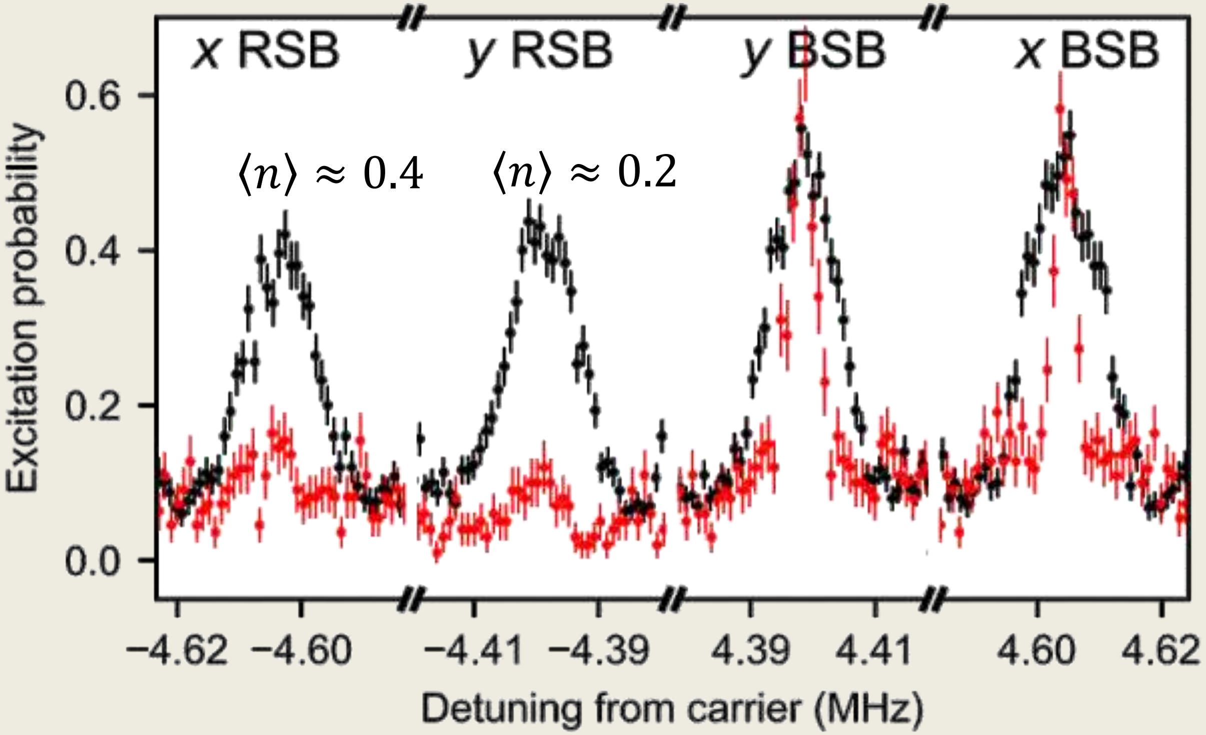
axial ground state cooling

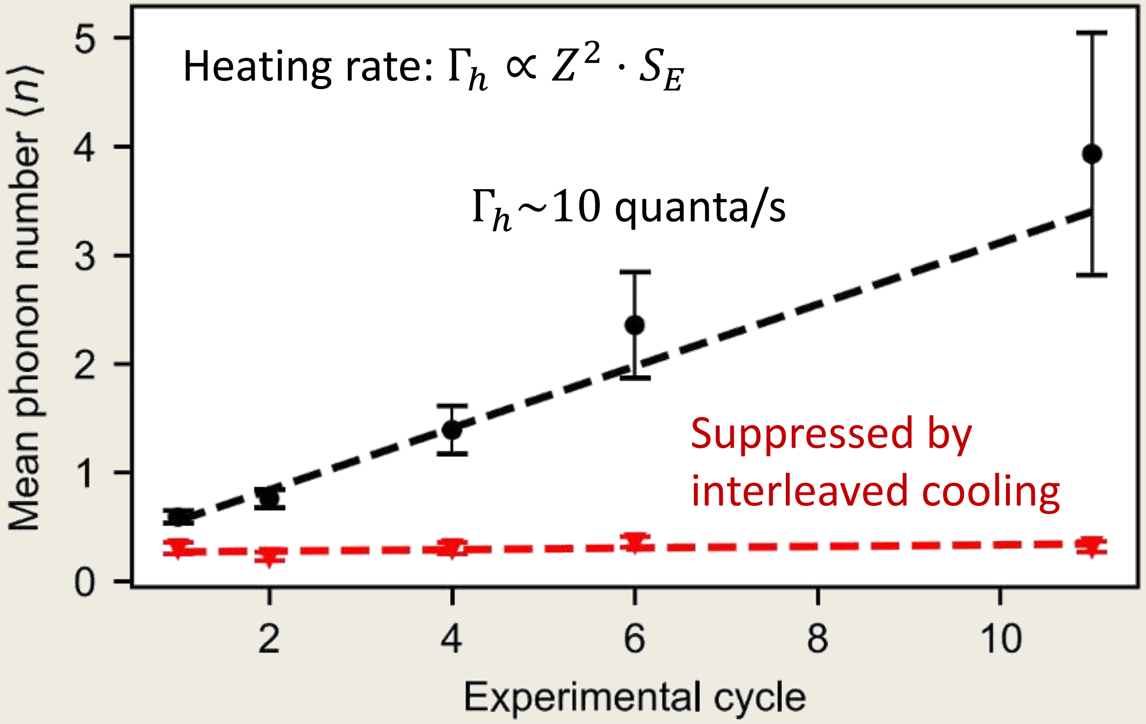
repeat

Generic scheme applicable to other systems:
large molecules, nanoparticles, …

[King *et al.*, PRX **11**, 041049 (2021)]

Algorithmic cooling: results





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.*, PRX **11**, 041049 (2021)]

Systematic shifts for Ar^{13+}

Shift source	Mitigation	Shift (10^{-18})	Uncertainty (10^{-18})
Micromotion	Real-time measurement	-443	22
AC Zeeman shift	Calibration at much higher powers and extrapolation	0	2
First-order Doppler	Counter-propagating beams	0	< 1
Electric quadrupole	Small coefficient, averaging over multiple Zeeman components	0	< 1
Linear Zeeman	Averaging over multiple Zeeman components	0	< 1
Quadratic Zeeman	Small coefficient, small field	< 1	$\ll 1$
2nd order Doppler	Algorithmic cooling	-1	< 1

$\}$ no fundamental limitations

$^{40}Ar^{13+}$ clock with 2.2×10^{-17} estimated systematic uncertainty

8 orders of magnitude improvement

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

[King, Spieß *et al.*, Nature **611**, 43-47 (2022)]

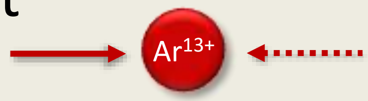
Clock operation

Stabilisation to 4 Zeeman components

- eliminate linear Zeeman shift
- eliminate quadrupole shift
- measure quadrupole moment & g-factor

Interrogation from two possible directions

- eliminate linear Doppler shift

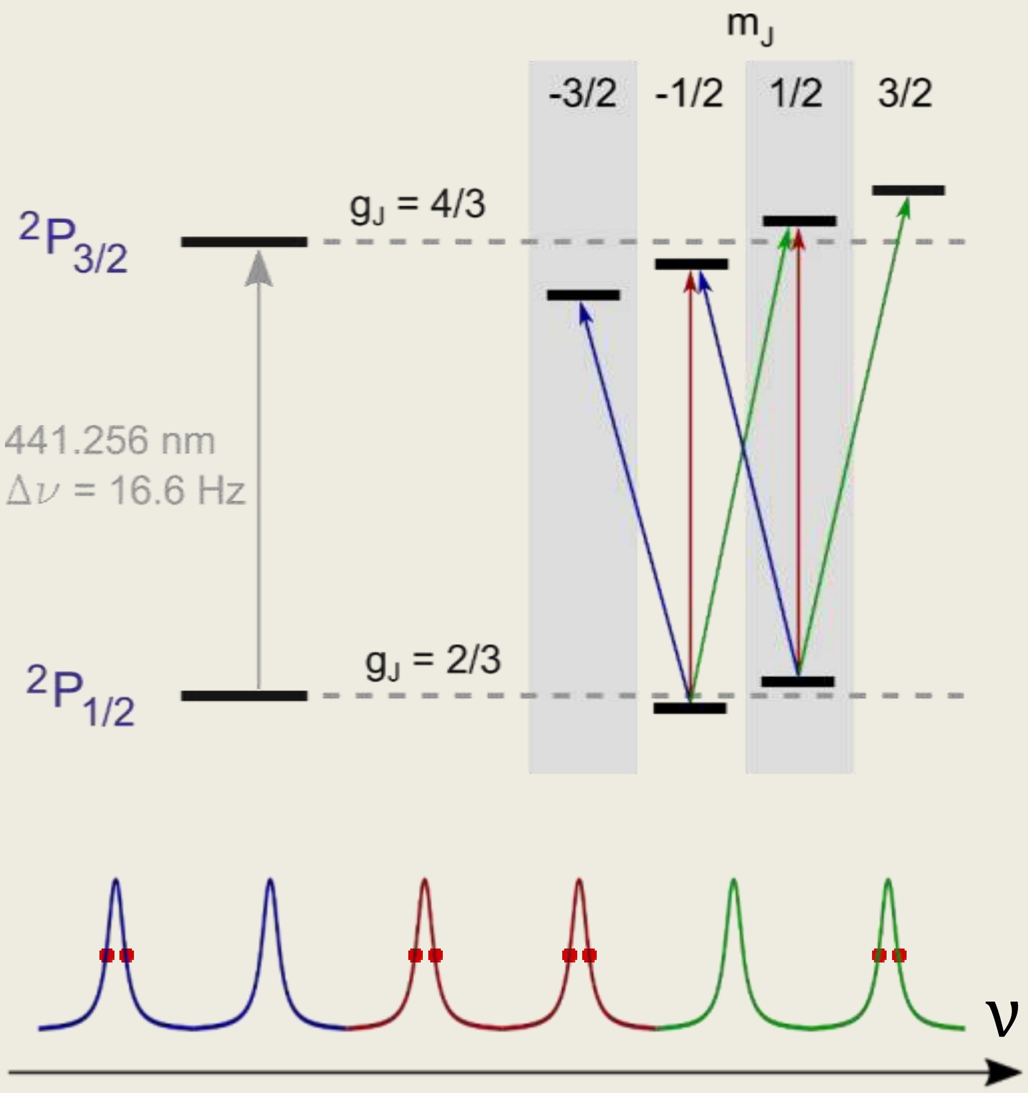


Pseudorandomisation of component & direction

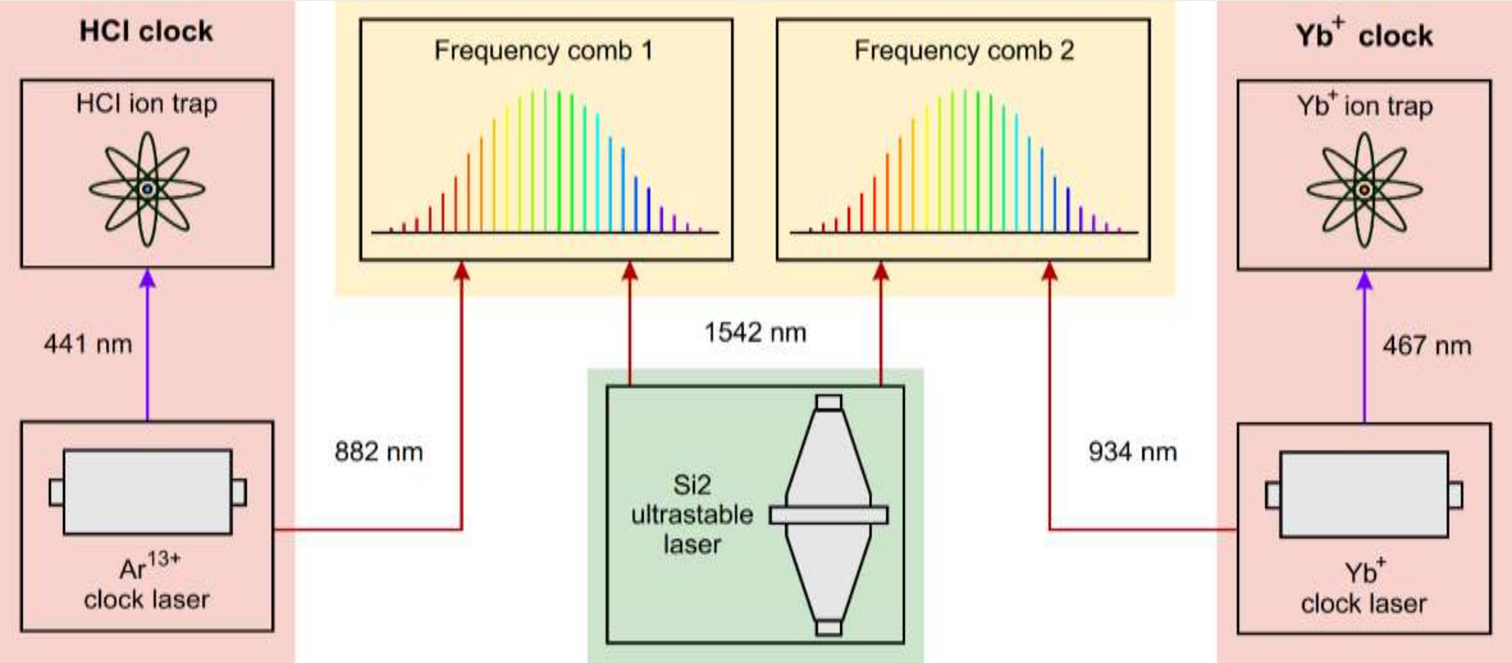
- sensitivity to drifts suppressed

Interleaved measurements:

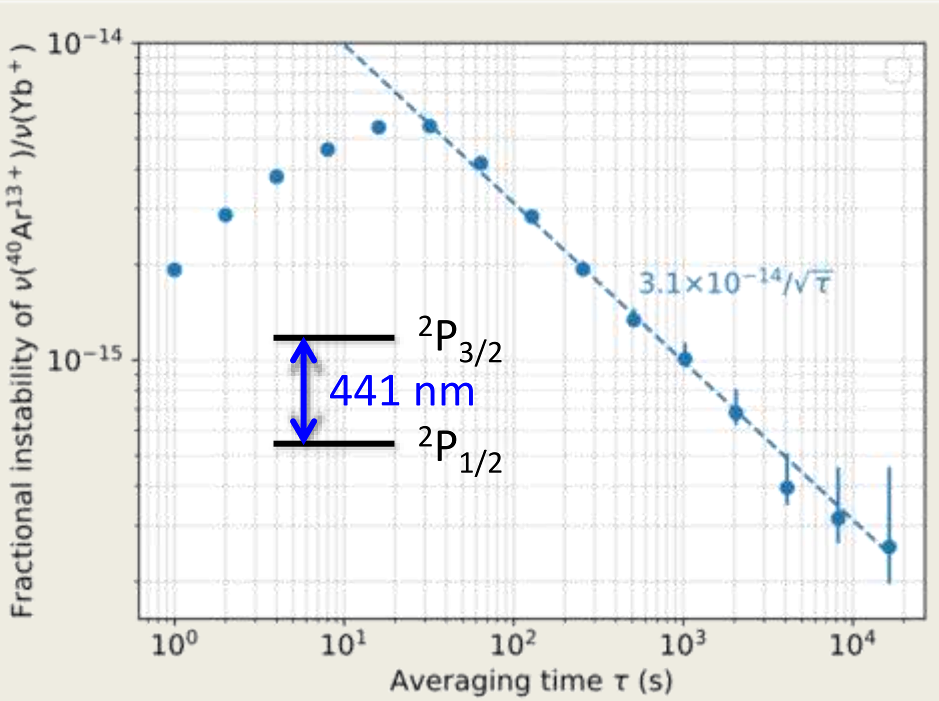
- Micromotion
- Secular temperature



Frequency ratio measurement Ar^{13+}/Yb^{+} E3



Comparison: E. Benkler, Yb^{+} E3 clock: R. Lange, N. Huntemann

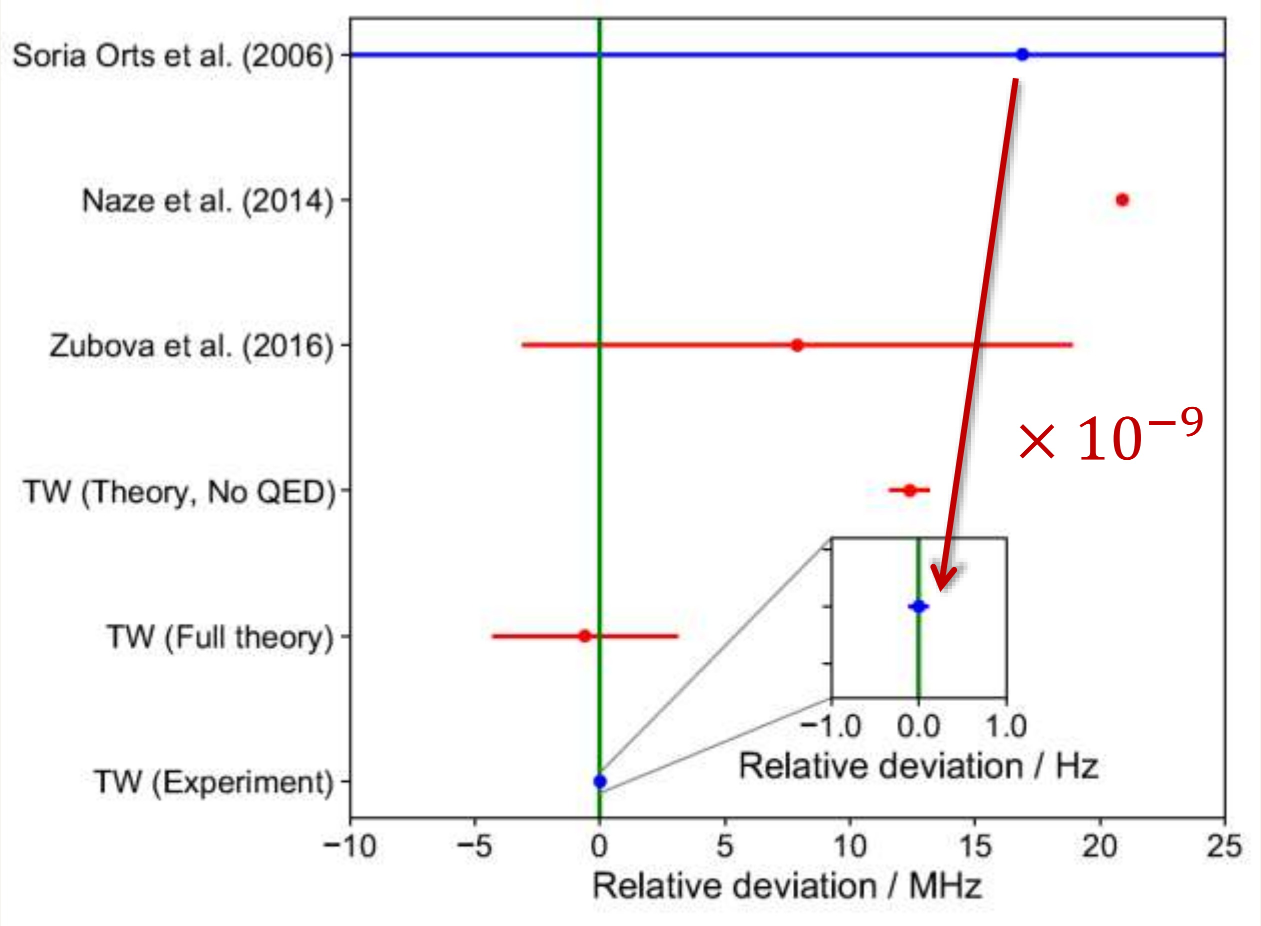


R = 1.05776938758748093(11)

- Frequency ratio uncertainty limited by Ar^{13+} excited state lifetime to $\sim 3 \times 10^{-14}/\sqrt{\tau}$
- Measurements to $\sim 1 \times 10^{-16}$ statistical uncertainty for $^{40}Ar^{13+}$ and $^{36}Ar^{13+}$
- Yb^{+} E3 absolute frequency known with 1.3×10^{-16} fractional uncertainty

[King, Spieß *et al.*, Nature **611**, 43-47 (2022)]

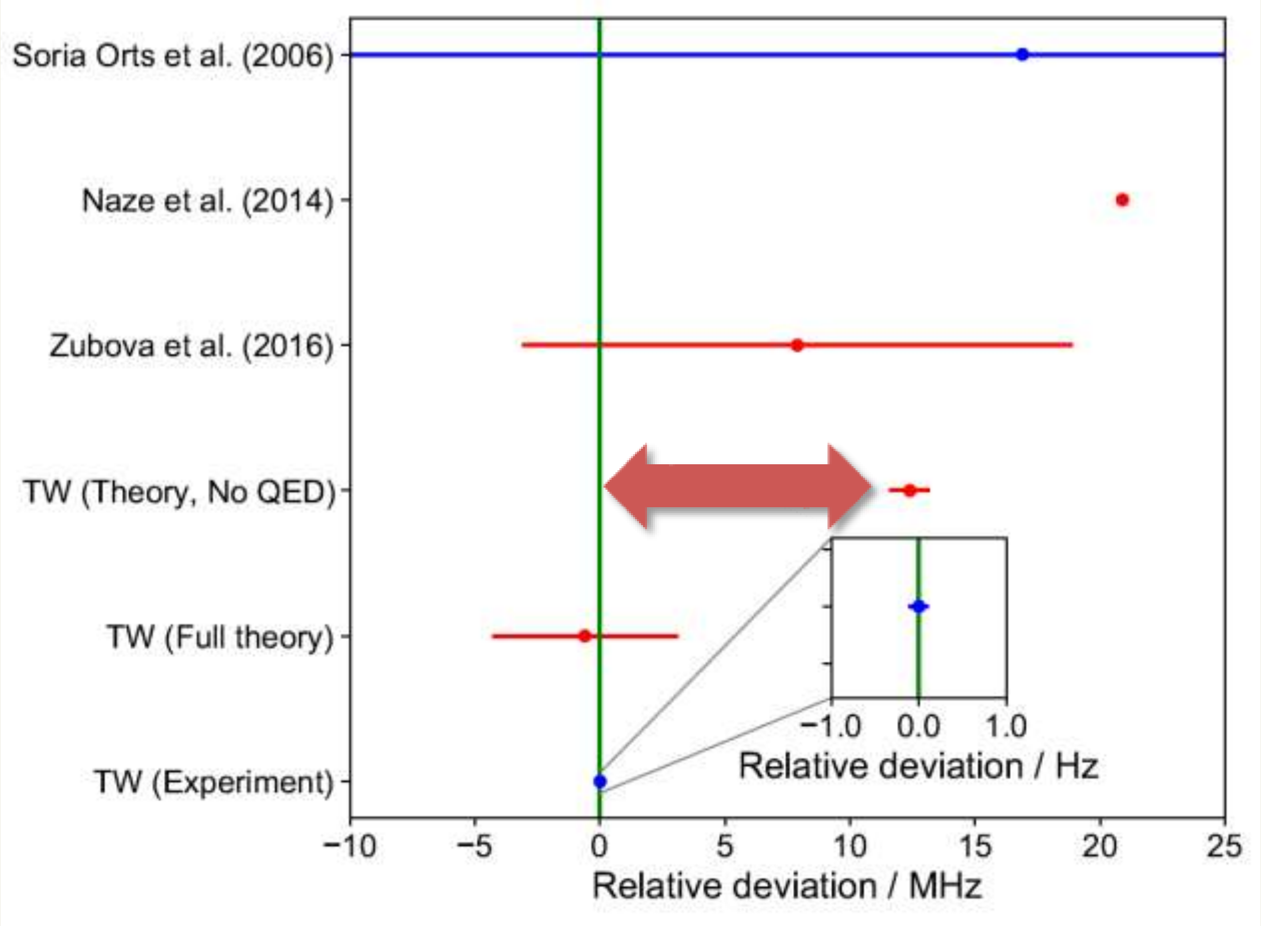
Isotope shift $^{40}\mathrm{Ar}^{13+} \leftrightarrow {}^{36}\mathrm{Ar}^{13+}$



[Soria Orts *et al.*,
PRL **97**, 103002 (2006)]

[King, Spieß *et al.*, Nature **611**, 43-47 (2022)]

Isotope shift $^{40}\mathrm{Ar}^{13+} \leftrightarrow {}^{36}\mathrm{Ar}^{13+}$



[Soria Orts *et al.*,
PRL **97**, 103002 (2006)]

First experimental verification
of QED nuclear recoil effect in a many-electron system

[see also: T. Sailer *et al.* Nature **606**, 479–483 (2022)]

[King, Spieß *et al.*, Nature **611**, 43-47 (2022)]

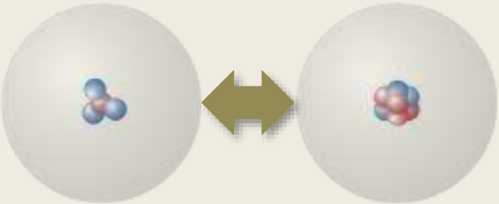
Search for 5th forces

Isotope shift spectroscopy: King plot

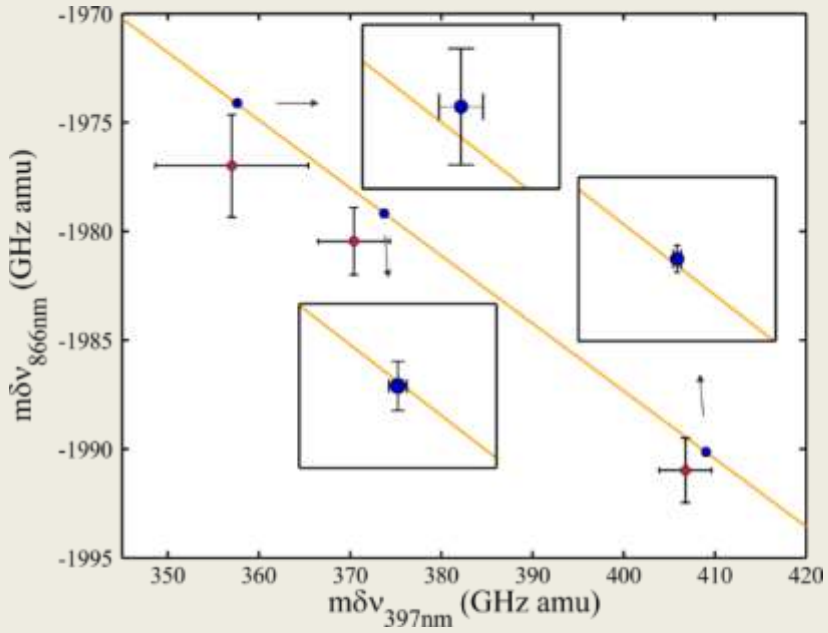
- $\delta\nu_i^{A,A'} = F_i \delta\langle r^2\rangle_{A,A'} + k_i \frac{A-A'}{AA'}$

field shift

recoil shift

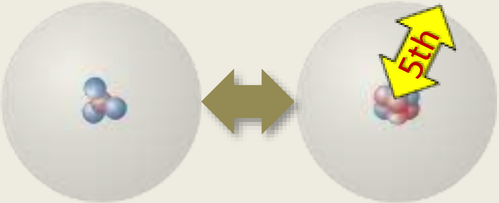


- use 2 transitions i, j → eliminate $\delta\langle r^2\rangle_{A,A'}$



Additional hypothetical 5th force (relaxion, DM, …)

- new force mediated through scalar field with mass $m_\phi \to X_i$
- coupling constant: α_{NP}



→ nonlinearity in King plot:

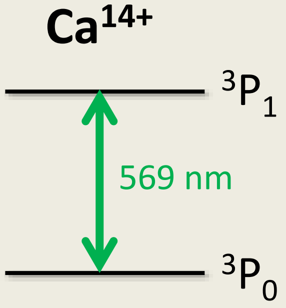
$$\delta\nu_i^{A,A'} = F_i \delta\langle r^2\rangle_{A,A'} + k_i \frac{A-A'}{AA'} + \alpha_{NP} X_i (\mathrm{A} - \mathrm{A}')$$

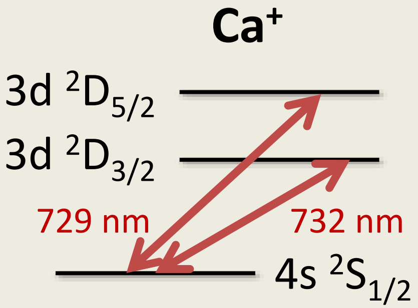
[Stadnik, PRL **120**, 223202 (2018); Berengut *et al.*, PRL **120**, 091801 (2018); Frugiuele *et al.*, Phys. Rev. D **96**, 015011 (2017); Delaunay *et al.*, Phys. Rev. D **96**, 093001 (2017); Delaunay *et al.*, Phys. Rev. D **96**, 115002 (2017)]

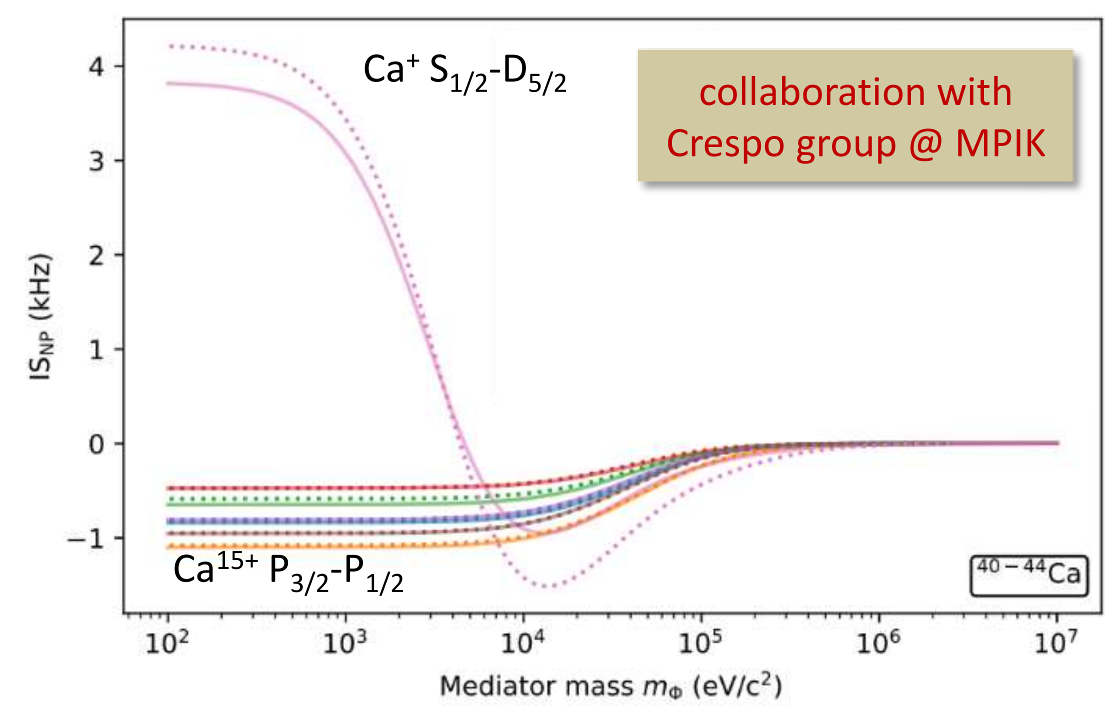
Isotope shift spectroscopy of $^{40,42,44,46,48}\mathrm{Ca}^{+/14+/15+}$

need: pair of narrow transitions with different electronic character

promising approach: isotope shifts of clock transitions in Ca^+ & **Ca^{14+}**





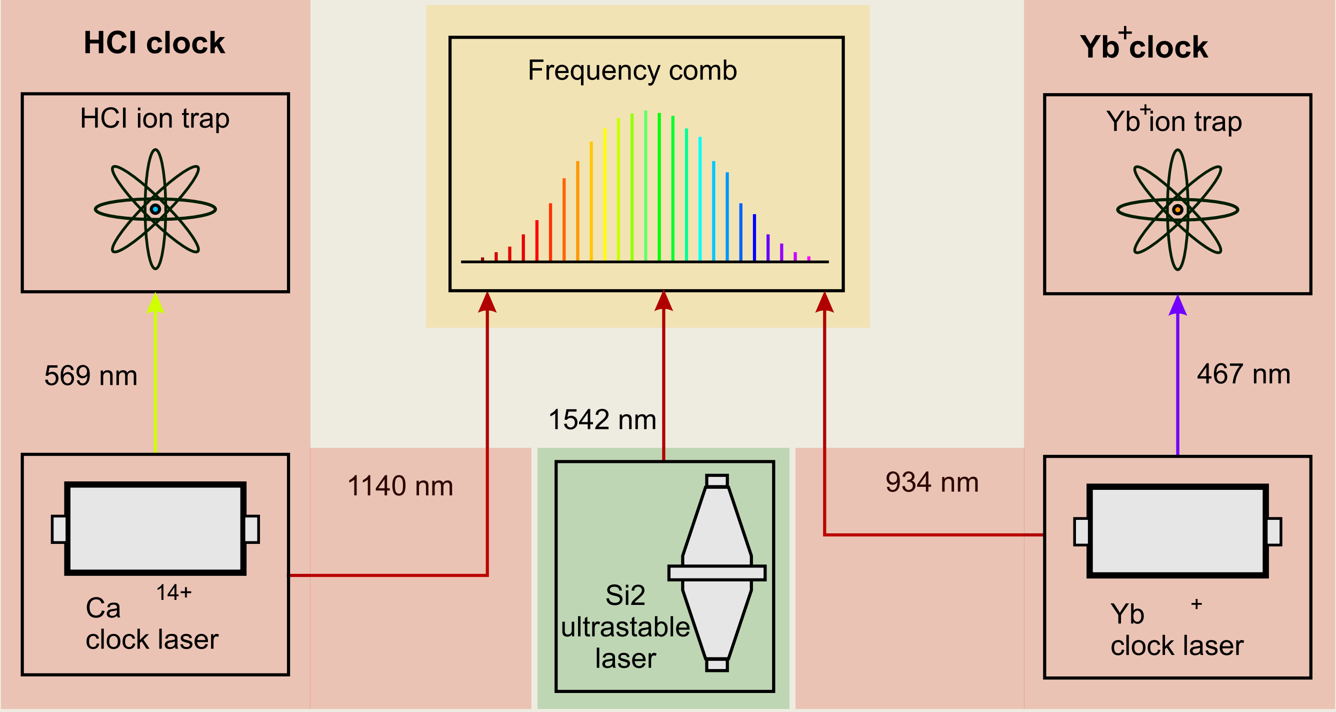


collaboration with Crespo group @ MPIK

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

related experimental work:
[Chang *et al.*, arXiv:2311.17337
Figueroa *et al.*, PRL **128**, 073001 (2022)
Ohayon *et al.*, NJP **24**, 123040 (2022)
Hur *et al.*, PRL **128**, 163201 (2022)
Ono *et al.*, PRX **12**, 021033 (2022)
König *et al.*, PRC **103**, 054305 (2021)
Neely *et al.*, PRA **103**, 032818 (2021);
Solaro *et al.*, PRL **125**, 123003 (2020);
Counts *et al.*, PRL **125**, 123002 (2020);
Bhatt *et al.*, PRA **101**, 052505 (2020);
Müller *et al.*, Phys. Rev. Research **2**, 043351 (2020);
Miyake *et al.*, Phys. Rev. Research **1**, 033113 (2019);
Manovitz *et al.*, PRL **123**, 203001 (2019);
Knollmann *et al.*, PRA **100**, 022514 (2019);
Imgram *et al.*, PRA **99**, 012511 (2019);
Gebert *et al.*, PRL **115**, 053003 (2015)]

Frequency ratio measurements $^{40,42,44,46,48}Ca^{14+}$ / Yb^{+} E3



HCl clock

HCl ion trap

569 nm

Ca^{14+} clock laser

1140 nm

Frequency comb

1542 nm

Si2 ultrastable laser

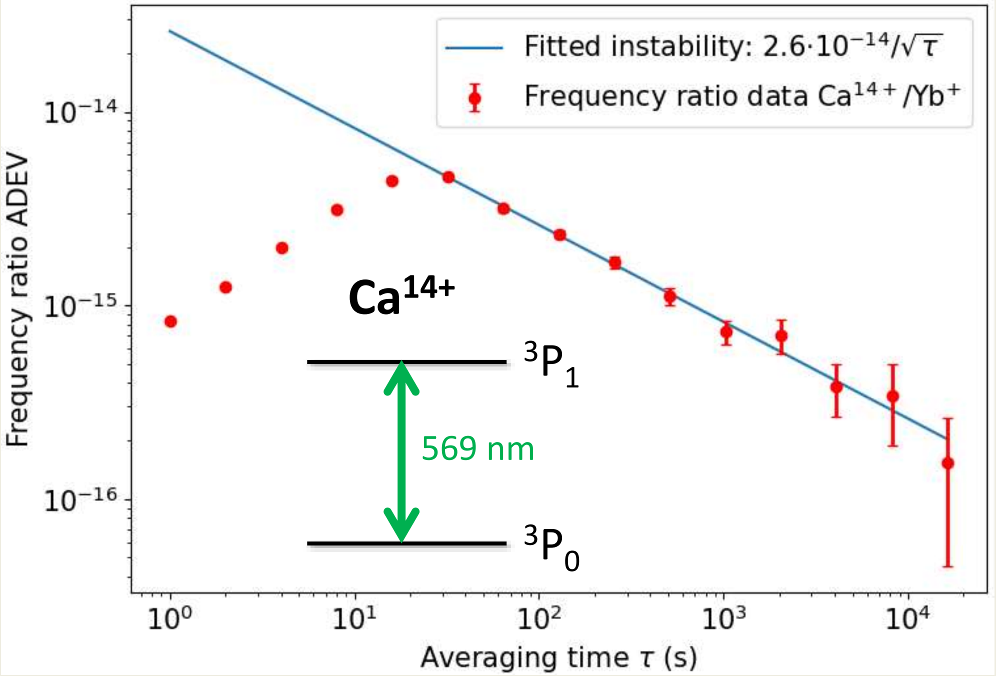
934 nm

Yb^{+} clock

Yb^{+} ion trap

467 nm

Yb^{+} clock laser



Comparison: E. Benkler, Yb^{+} E3 clock: M. Filzinger, N. Huntemann

- Yb^{+} E3 absolute frequency: 1.3×10^{-16}
- statistical uncertainty: $\sim 1 \times 10^{-16} \rightarrow$ 0.1 Hz (improvement by $\times 10^{-9}$)
- systematic uncertainty: $\sim 3 \times 10^{-17}$

[A. Wilzewski *et al.*, in preparation]

Higher order SM contributions

1st order mass shift (MS)

1st order field shift (FS)

$$\delta R^2_{ia} = \frac{1}{\lambda_C^2}\left(\langle r_i^2\rangle - \langle r_a^2\rangle\right)$$

$$\Delta E_{ij} = \boxed{K^{(1)}}\left(\frac{m}{M_i} - \frac{m}{M_j}\right) + \boxed{F^{(1)}}\delta R^2_{ij}$$

purely electronic

$$+ \boxed{K^{(2)}}\left(\frac{m^2}{M_i^2} - \frac{m^2}{M_j^2}\right) + \delta_{R_i} F^{(1)} \delta R^2_{ij} + \boxed{F^{(2)}}\left(\delta R^2_{ij}\right)^2$$

2nd order MS

1st order FS correction

2nd order FS

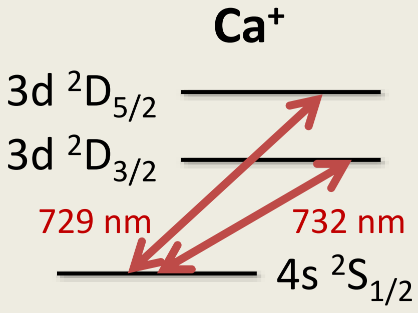
up to 99% nonlinearity contribution

$$+ \Delta_{\mathrm{np},ij} + \Delta_{\mathrm{MS-FS},ij}$$

nuclear polarization

MS-FS cross term

up to 25% nonlinearity contribution



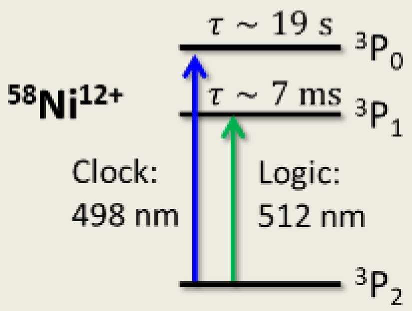
courtesy: Anna Viatkina
[PRA **108**, 022802 (2023)]

[also: Flambaum *et al.*, PRA **97**, 032510 (2018); Yerokhin *et al.*, PRA **101**, 012502 (2020); Counts *et al.*, PRL **125**, 123002 (2020)]

Outlook

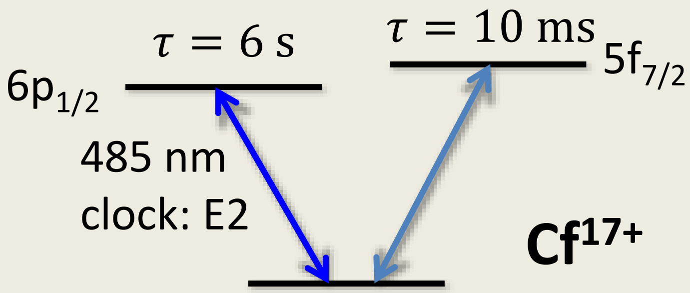
Future: competitive clocks & fundamental physics

- Clock candidate: ^{58}Ni^{12+}
  [Yu & Sahoo, Phys. Rev. A **97**, 041403 (2018);
  Chen *et al.*, Phys. Rev. Res. **6**, 013030 (2024)]
  also: Gao (Wuhan)
  Challenge: transition energy uncertainty of several THz (few nm)



better calculations:
M. Safronova +
new search strategies
for narrow transitions

- dark matter & α-sensitive level-crossings:
  - Pr^{9+} [Bekker *et al.*, Nat. Commun. **10**, 5651 (2019)]
  - Ir^{17+} [Windberger *et al.*, PRL **114**, 150801 (2015)]
  - Cf^{15+} & Cf^{17+} [Porsev *et al.*, PRA **102**, 012802 (2020)]
    also: V. Schäfer (MPIK), G. Barontini (Birmingham)



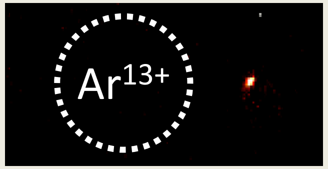
Other ideas

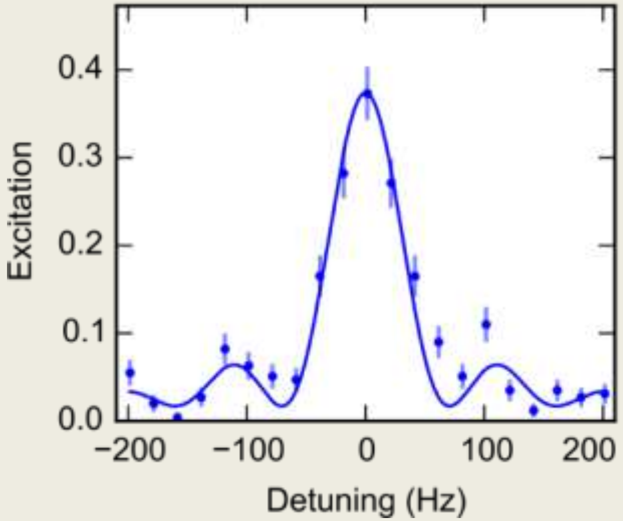
- Ba^{4+}, Pr^{10+}: S. Brewer (Colorado State)
- XUV clocks: J. Crespo (MPIK)
- few-electron HCI: P. Micke (GSI/Jena)

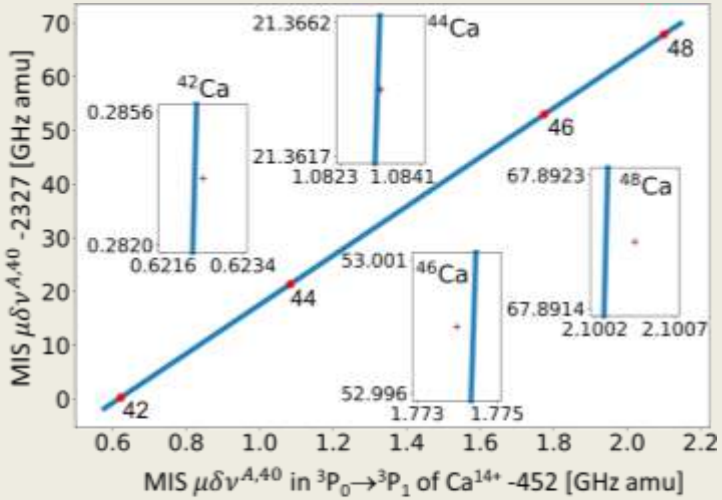
Summary

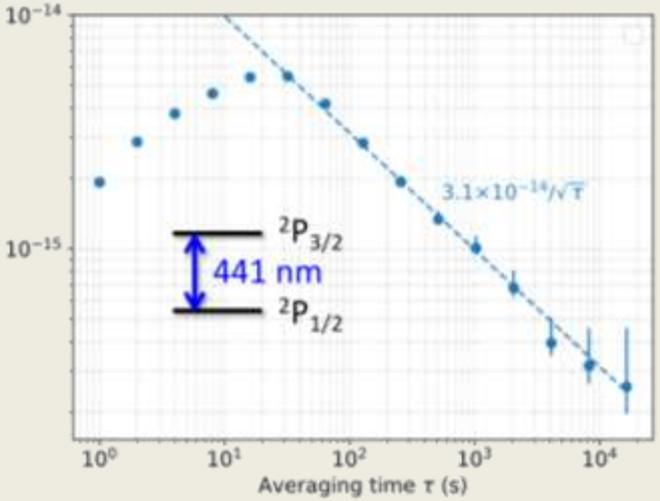
Summary

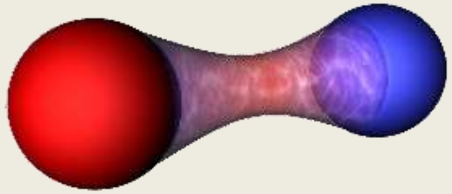
- precision spectroscopy of HCI addresses fundamental physics
- full quantum optical control over HCI achieved
- first coherent spectroscopy of HCI
- optical HCI clock with 2.2×10^{-17} syst. uncertainty
- improved absolute frequency & isotope shift by 10^8 & 10^9
- test of fundamental physics: verification of QED nuclear recoil & bounds on 5th forces
- new HCI clocks with high sensitivity to dark matter and α-variations
- “universal“ spectroscopy scheme











Heraeus Seminar Announcement

WILHELM UND ELSE
HERAEUS-STIFTUNG

Precision Atomic Physics Experiments to Probe for New Physics

817. WE-Heraeus-Seminar

23 Sep - 27 Sep 2024 at the Physikzentrum Bad Honnef

Confirmed speakers:

Maria Archidiacono,University of Milano
Julian Berengut, University of New South Wales
Liliane Biskupek, Leibniz University of Hannover
Diego Blas, CERN
Dima Budker, University of Mainz
Eric Cornell, JILA, Boulder
Sergei Eliseev, MPIK Heidelberg
Alexey Elykov, KIT
Melina Filzinger, PTB Braunschweig
Elina Fuchs, PTB & Leibniz University of Hannover
Jens Gundlach, University of Washington, Seattle
Hans Hepach, University of Vienna
Meike List, DLR-SI Hannover
Riccardo March, INFN Frascati
Christian Panda, UC Berkeley
Gilad Perez, Weizmann Institute
Marianna Safronova, University of Delaware
D. Sheng, University of Science and Technology of China
Sven Sturm, MPIK, Heidelberg
Yoshiro Takahashi, Kyoto University
Michael Tobar, University of Western Australia
Stefan Ulmer, University of Düsseldorf
Vladan Vuletic, MIT (USA)
Peter Wolf, OBSPM Paris (France)

quest PTB Leibniz Universität Hannover

Quantum Logic Spectroscopy Group

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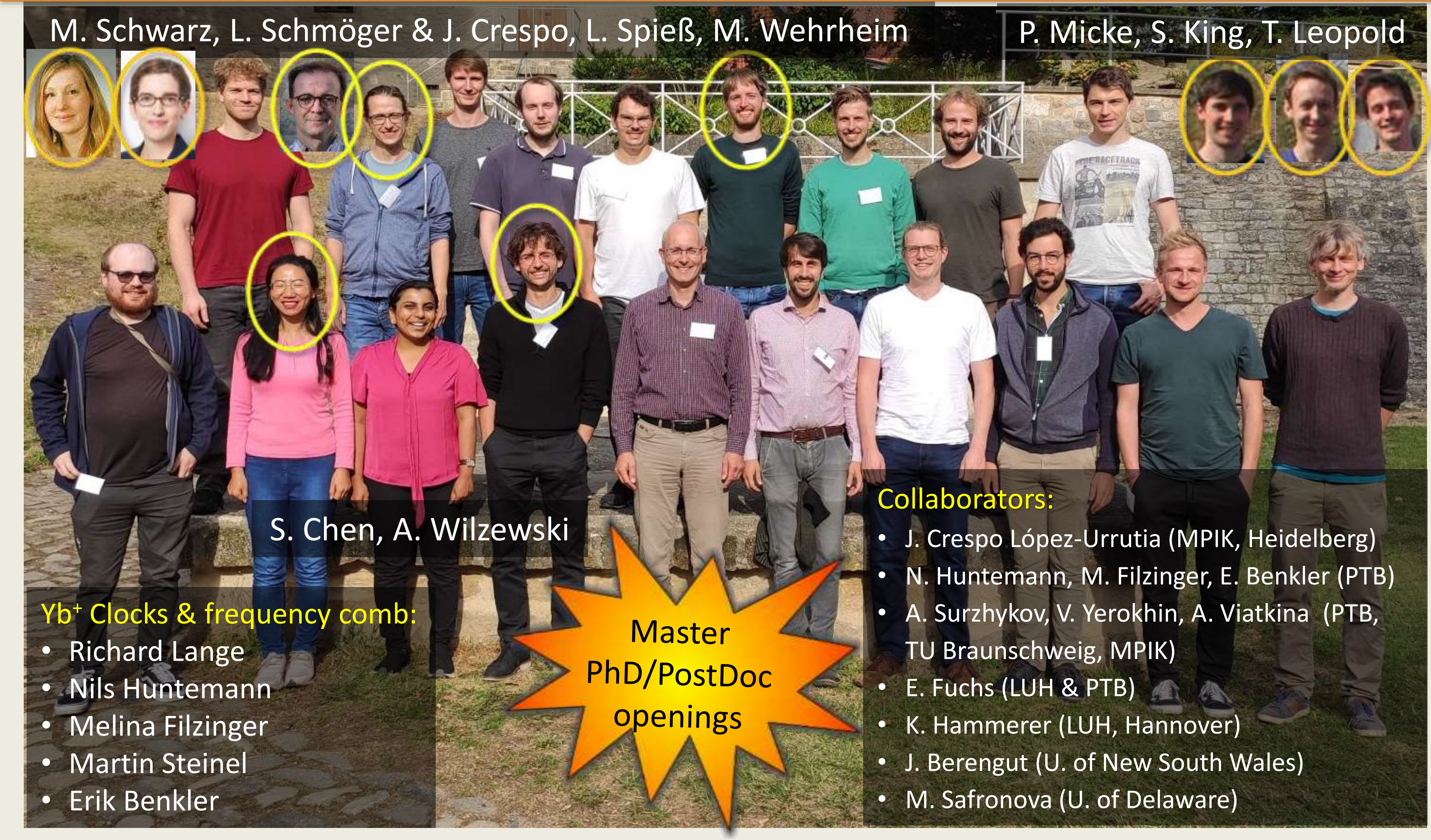

M. Schwarz, L. Schmöger & J. Crespo, L. Spieß, M. Wehrheim

P. Micke, S. King, T. Leopold

S. Chen, A. Wilzewski

Yb$^+$ Clocks & frequency comb:

- Richard Lange
- Nils Huntemann
- Melina Filzinger
- Martin Steinel
- Erik Benkler

Master PhD/PostDoc openings

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