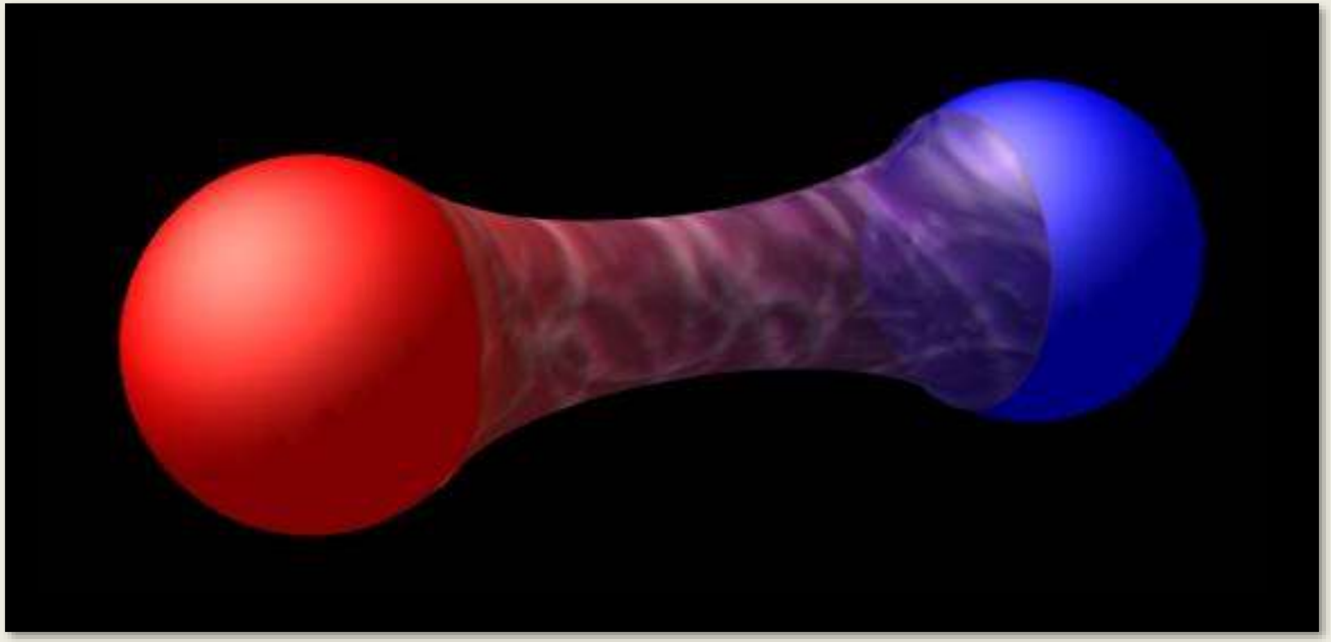
Quantum Logic Spectroscopy of Trapped Ions



P. O. Schmidt
QUEST Institute for Experimental Quantum Metrology
PTB Braunschweig and Leibniz Universität Hannover

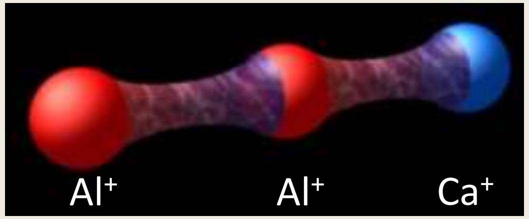
Quantum Science Seminar, 17.09.2020

Physikalisch-Technische Bundesanstalt

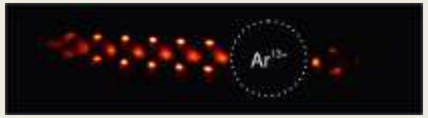
- National Metrology Institute, founded 1887
- **Tasks:** determination of fundamental constants, dissemination of SI units, development of measurement techniques,…
- ca. **1800 employees**, of which are **>200 PhD candidates**
- 60% research: >600 publications per year

www.quantummetrology.de/eqm

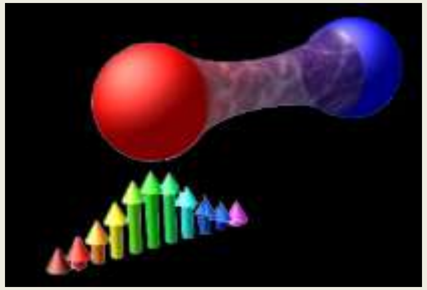
Quantum Logic Spectroscopy Group



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



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



[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

- Highly Charged Ions
- Atomic Clocks
- Complex Ions
- Quantum Engineer-ing
- Molecular Ions

[Wolf *et al.*, Nat. Commun. **10**, 2929 (2019)
Aharon *et al.*, NJP. **21**, 083040 (2019)]

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

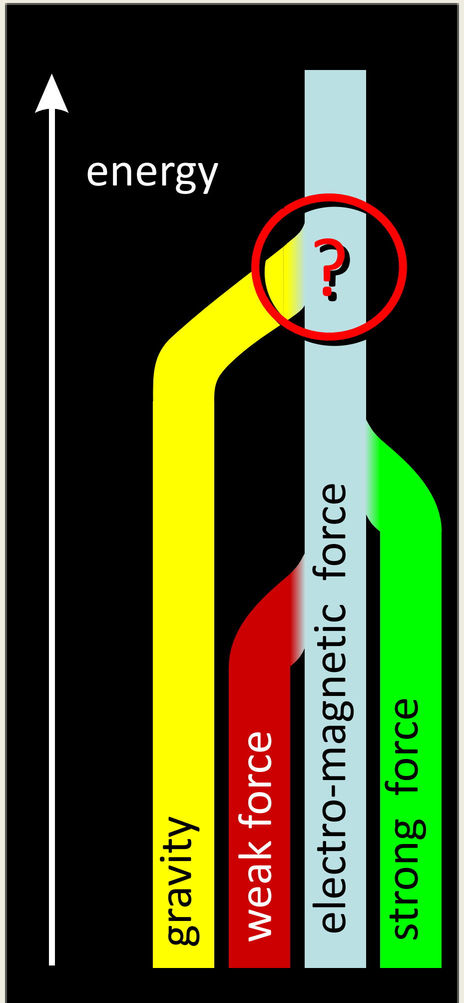
previously inaccessible systems

high resolution & accuracy

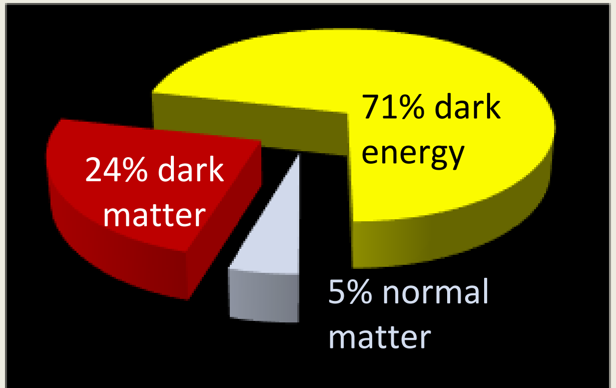
- Relativistic Geodesy
- Fundamental Physics
- Astronomy

www.quantummetrology.de/eqm

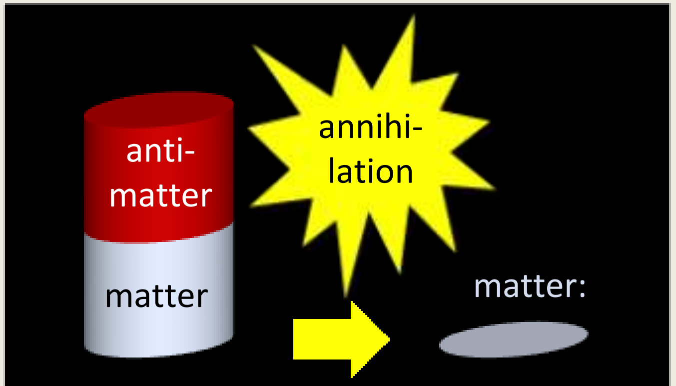
Open questions in physics



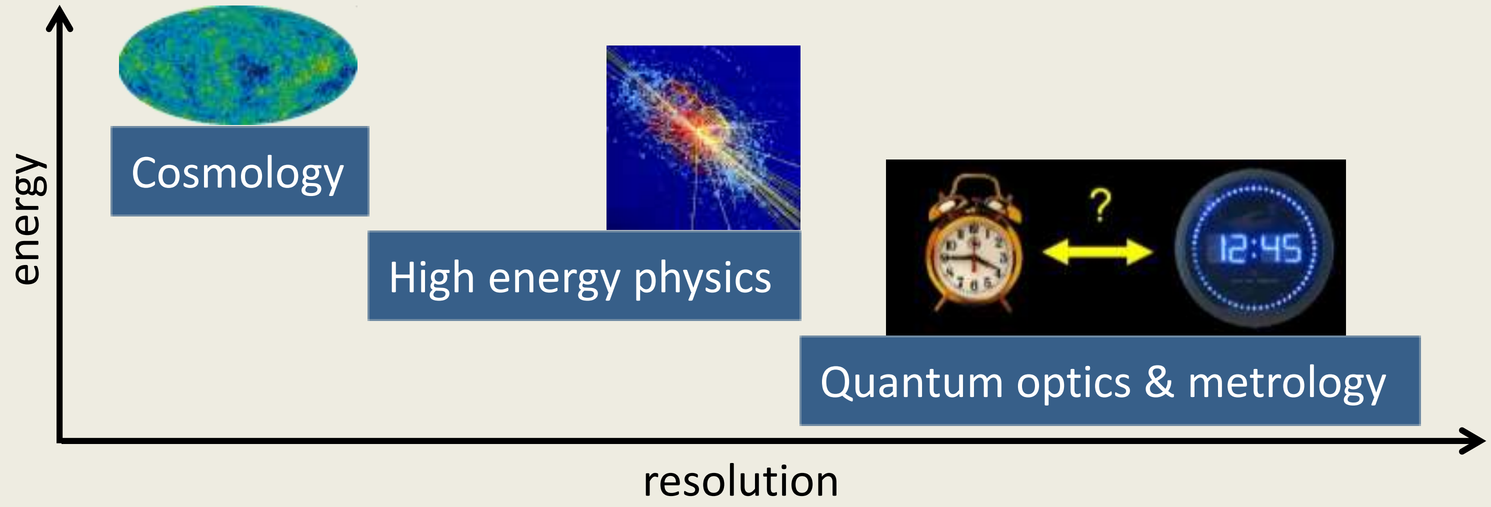
Can all forces be united?



Dark matter & dark energy?



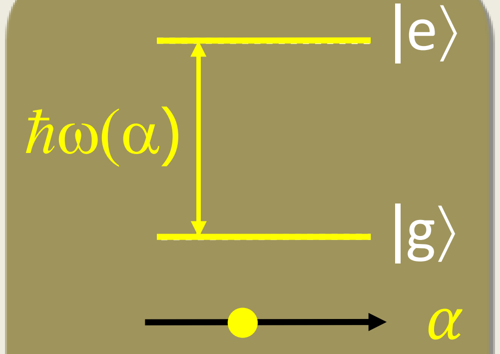
Matter/antimatter asymmetry?



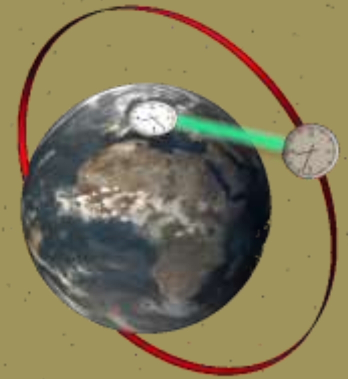
➔ low energy, high resolution

atomic & molecular systems are sensitive probes

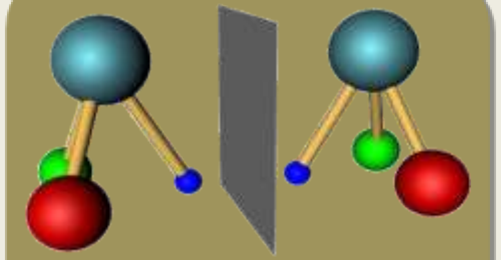
Spectroscopy probes fundamental physics



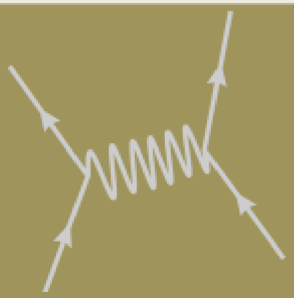
Variation of constants



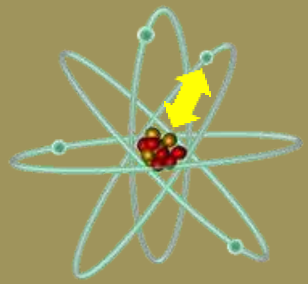
Relativity



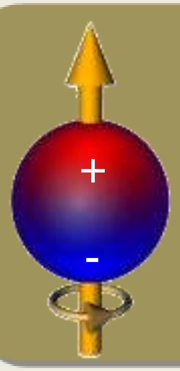
Parity Violation



test of QED



5th forces

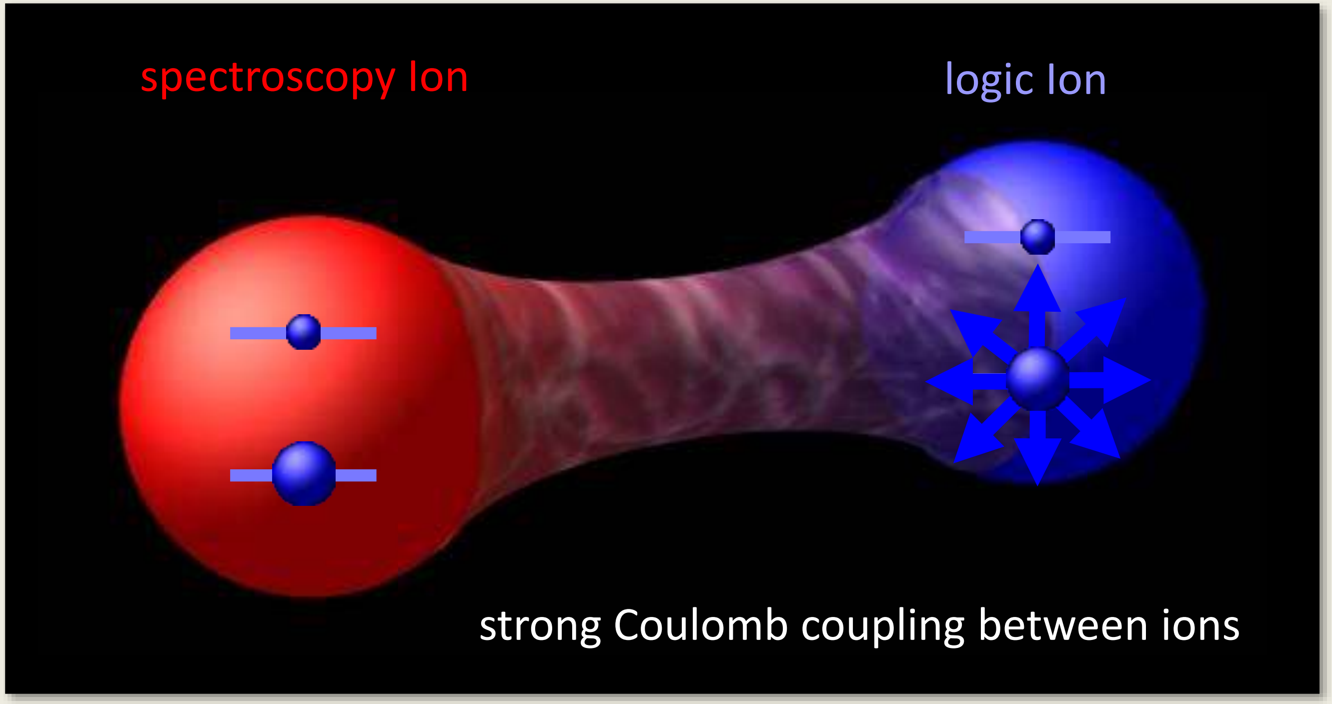


eEDM

Need transition for laser cooling and detection!

[Safronova *et al.* Rev. Mod. Phys. **90**, 025008 (2018)]

Quantum Logic Spectroscopy



Many applications demonstrated, e.g.

- Most accurate clock: Al^+
  [Brewer *et al.*, PRL **123**, 033201 (2019)]

→ Talk by D. Leibrandt
https://indico.cern.ch/event/942276

- 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

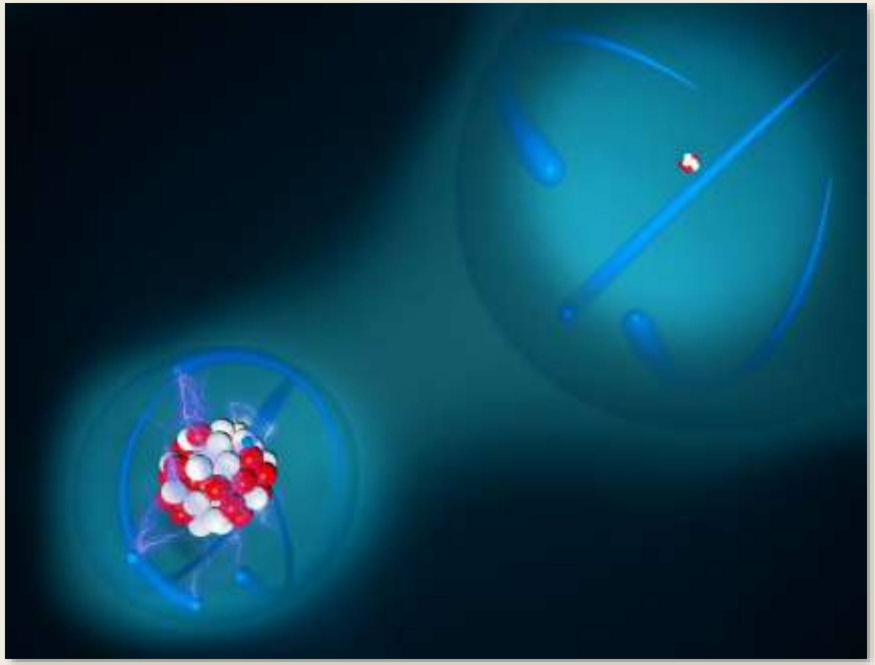
→ investigation of previously inaccessible species

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

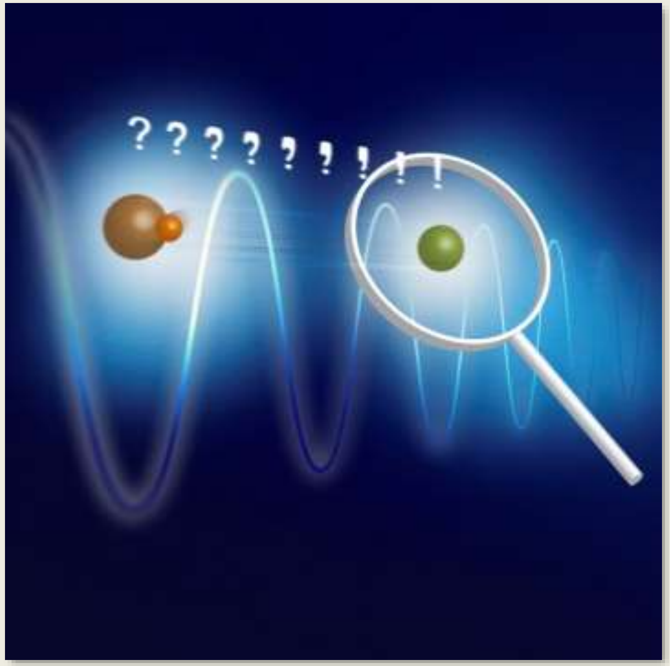
Overview

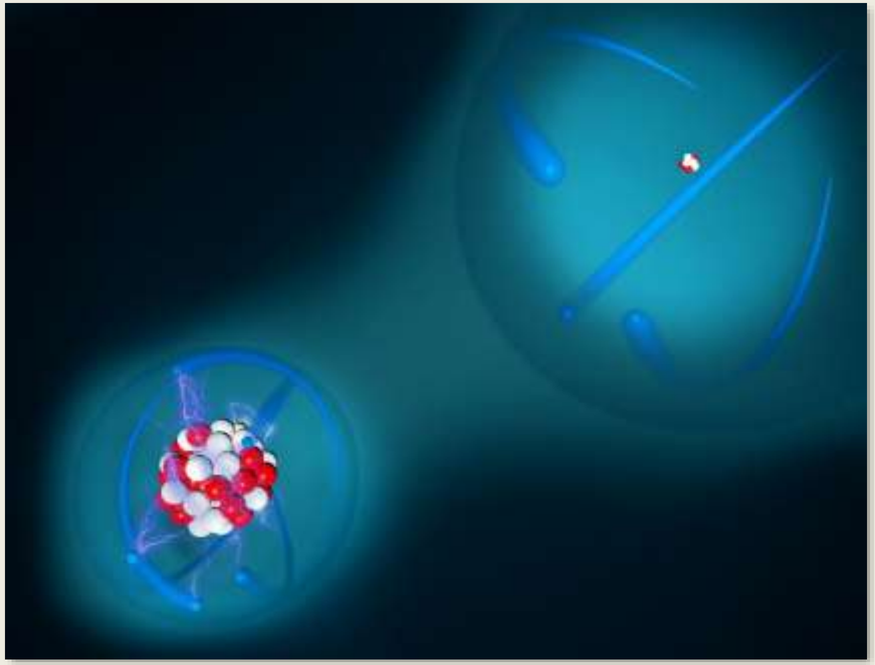
- Introduction & motivation for quantum logic spectroscopy (QLS)

QLS of highly charged ions



QLS of molecular ions

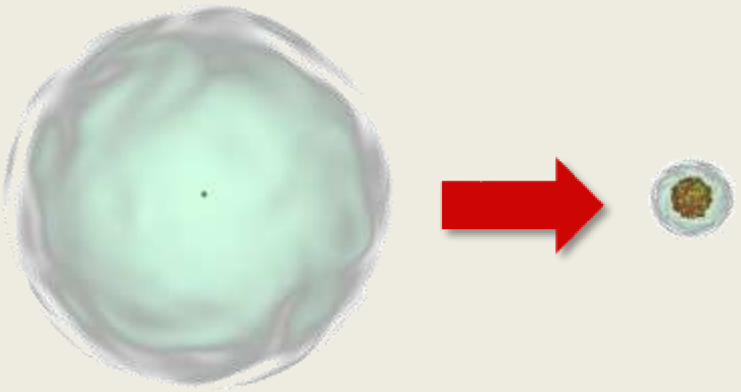


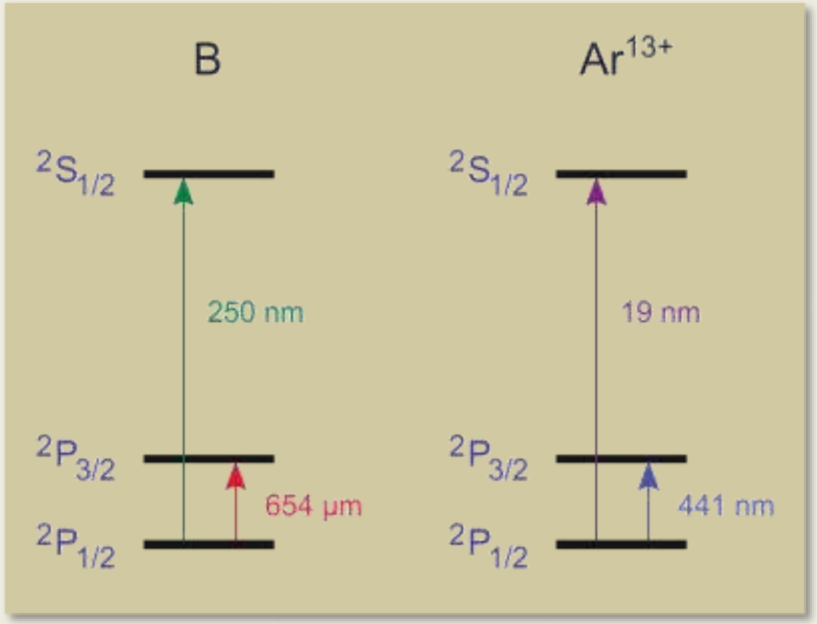


QUANTUM LOGIC SPECTROSCOPY OF HIGHLY CHARGED IONS

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}			



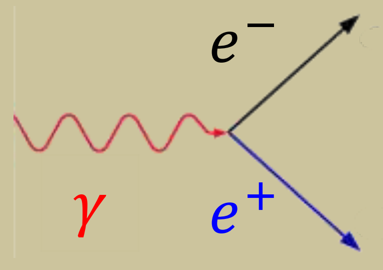


- optical transitions: fs, hfs, level crossings

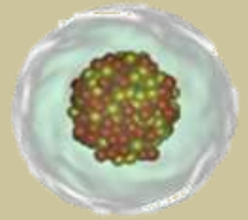
  [Kozlov *et al.* Rev. Mod. Phys **90**, 045005 (2018)]

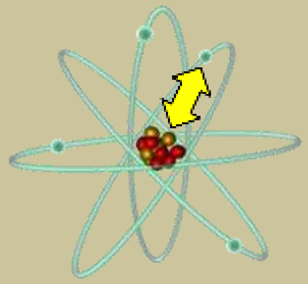
Testing fundamental physics with HCI

- simple electronic structure ➔ testbed for atomic structure theory
- QED test: g-factor ➔ QED in strong fields
- sensitive to
  - $\dot{\alpha}$ ➔ highest sensitivity of all atomic species
  - violation of local Lorentz invariance
  - isotope shifts (5th forces)
  - parity violation in XUV transitions
  - nuclear physics
  - …

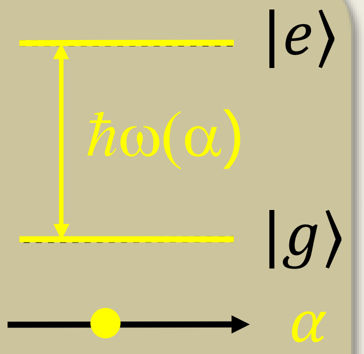


test of QED


Nuclear physics


5th forces

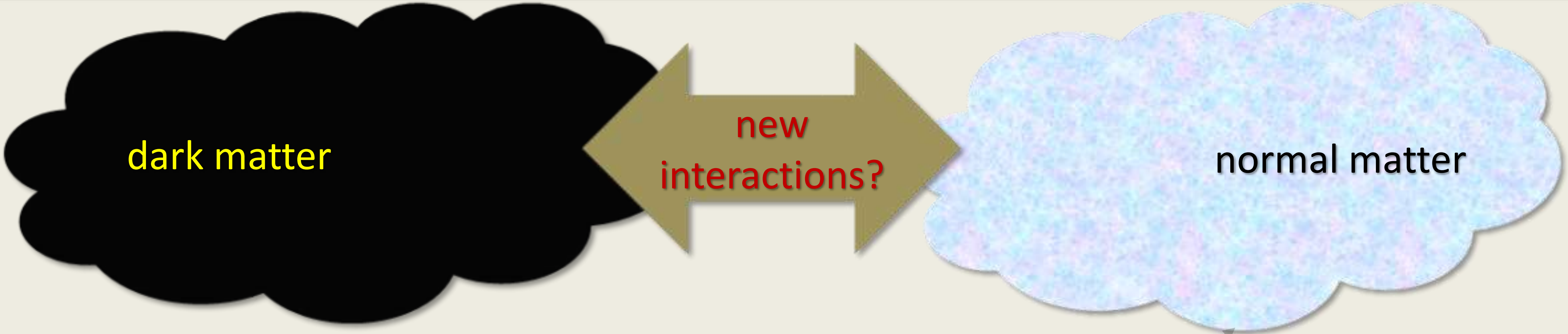

Lorentz invariance



Changing constants

[Reviews: Safronova *et al.*, RMP **90**, 025008 (2018), Kozlov *et al.* RMP **90**, 045005 (2018)]

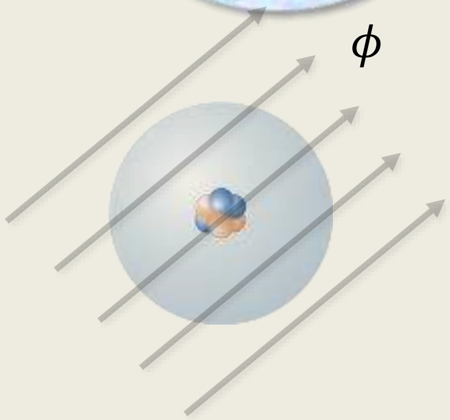
Effects of dark matter on normal matter

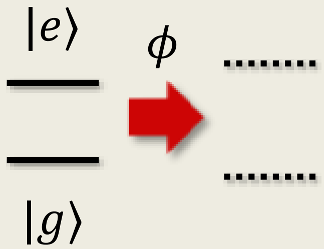


- dark matter candidate: scalar field ϕ
  - oscillating field
  - topological field (forming „clumps“)
  - …
- weak (non-gravitational) coupling to matter changes energy levels in atoms/molecules

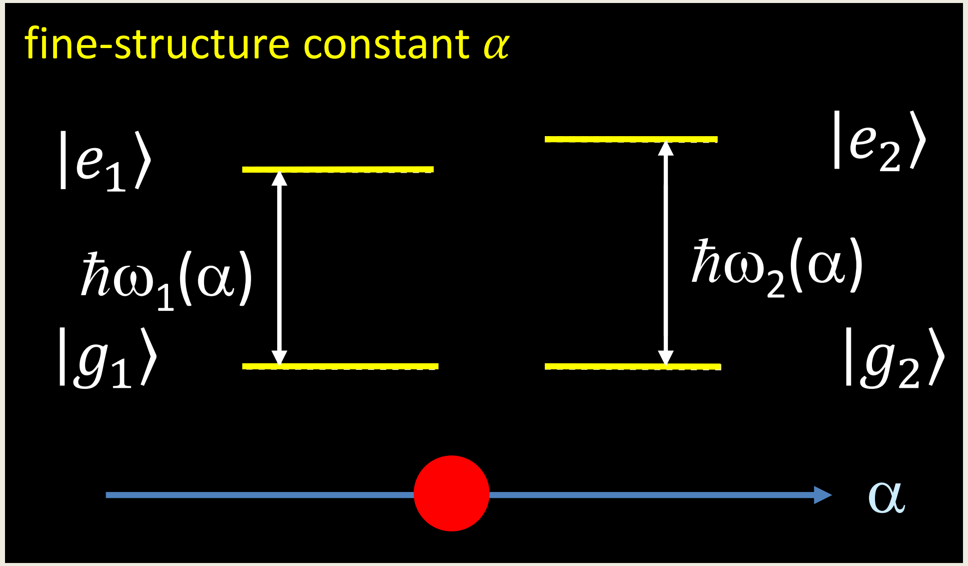
➔ apparent variation of fundamental constants

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

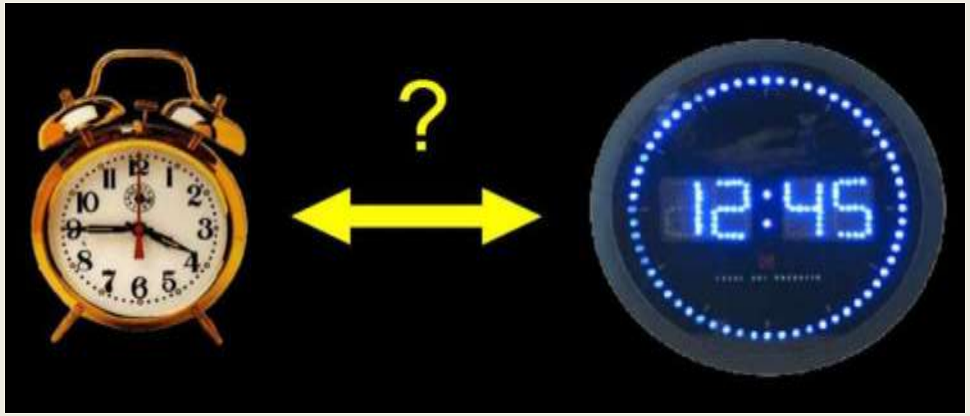




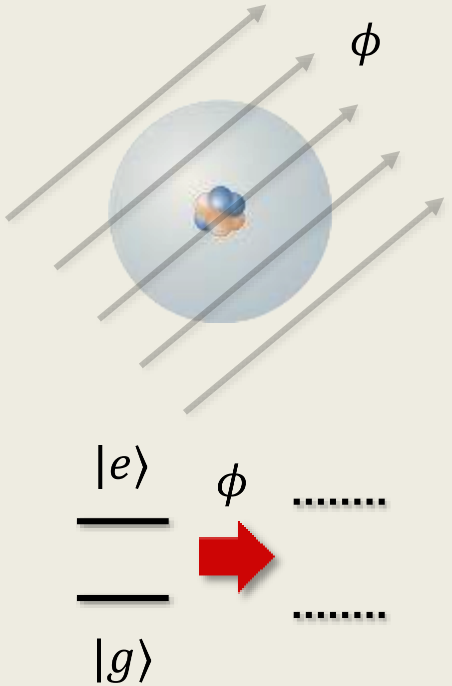
Variation of Fundamental Constants



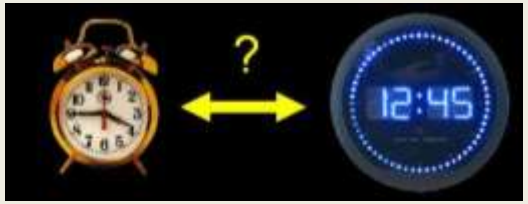
$$\frac{\Delta\omega}{\omega} = \boldsymbol{K}\frac{\Delta\alpha}{\alpha}$$

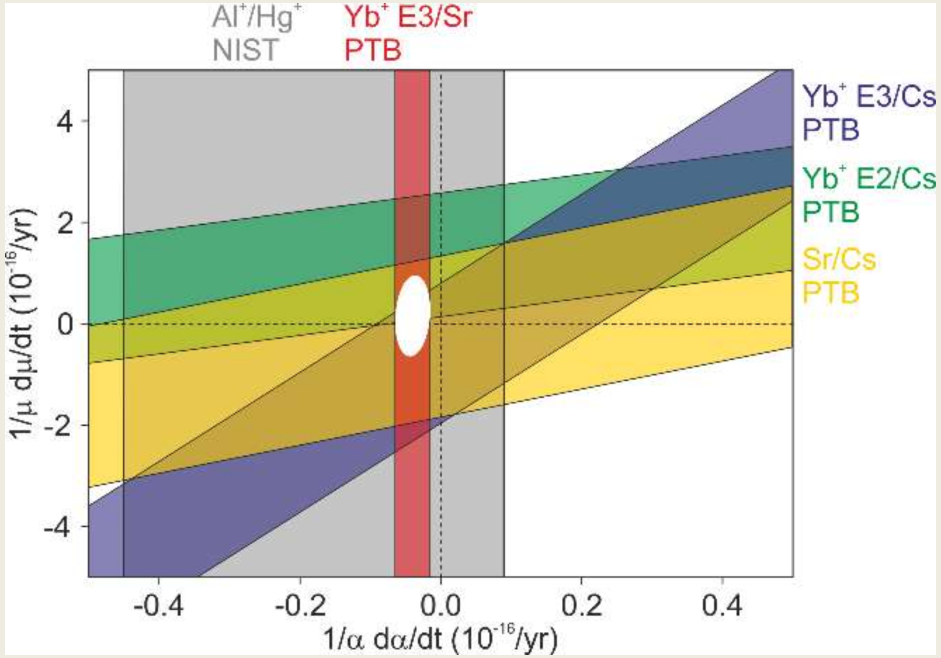


Changes in α may be induced by scalar fields ϕ, e.g. dark matter



Combined data from clocks





$$\dot{\alpha}/\alpha = -4.1(2.5) \times 10^{-18}/\text{year}$$
$$\dot{\mu}/\mu = -1.3(8) \times 10^{-17}/\text{year}$$

[Peik/Lisdat (PTB), preliminary]

highest sensitivity of all known atomic systems

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

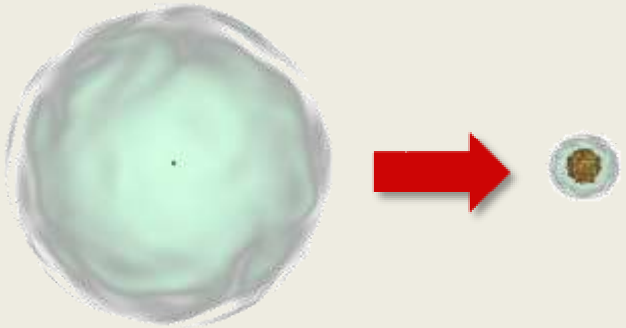
System	K	λ (nm)
Sr	0.06	699
Yb^+ E2	0.91	436
Yb^+ E3	-6	467
Hg^+	-2.9	281.5
Al^+	0.01	267
Ir^{17+} T1	-109	ca. 1416
Ir^{17+} T2	145	ca. 2000
Cf^{15+}*	57	ca. 618
Cf^{17+}*	-44	ca. 485
Th* nuclear	8000	ca. 150

Highly charged ions as optical clocks?

- **High accuracy**

  ➔ low sensitivity to resonance shifts

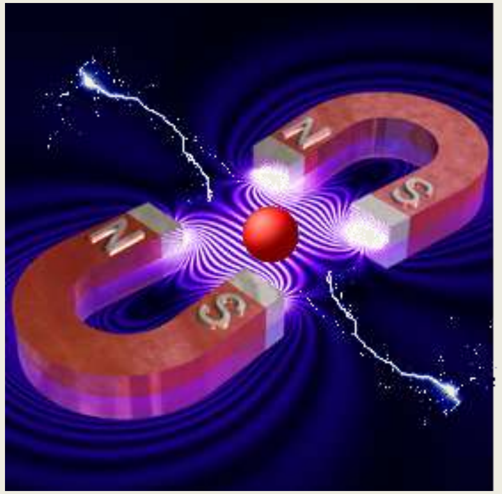
- **HCI advantage: suppressed shifts**



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.*, EPJ Web of Conferences **57**, 02001 (2013)]

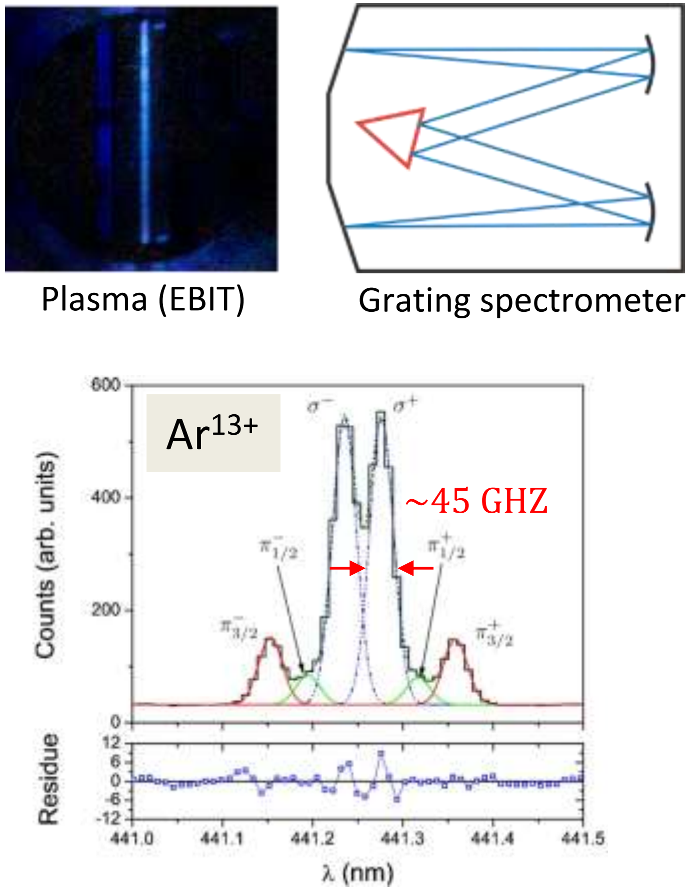


electric & magnetic fields

Other clock species requirements can be fulfilled

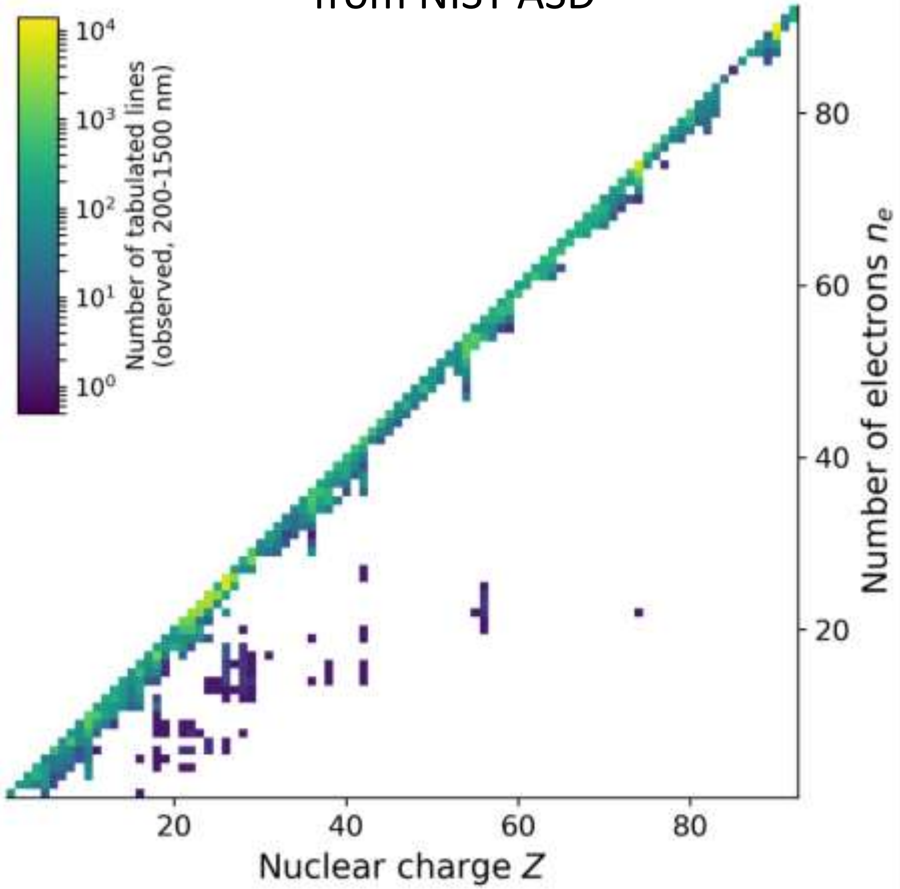
[Kozlov *et al.*, Rev. Mod. Phy. **90**, 045005 (2018)]

State-of-the-art HCI spectroscopy



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

measured optical transitions
from NIST ASD

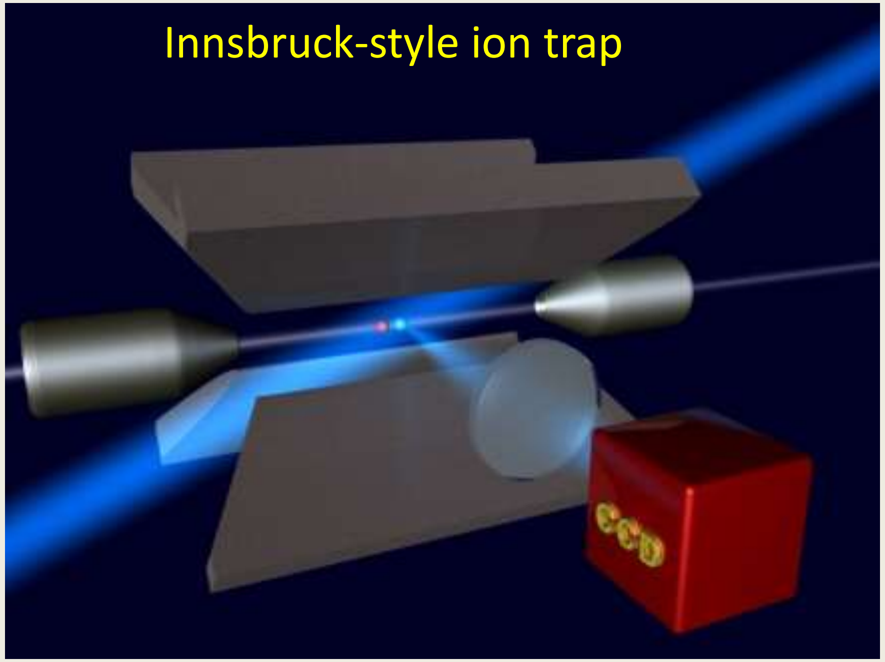


Doppler-limited resolution of ~ 150 MHz

Laser spectroscopy of single trapped ions

Features of Trapped Ions

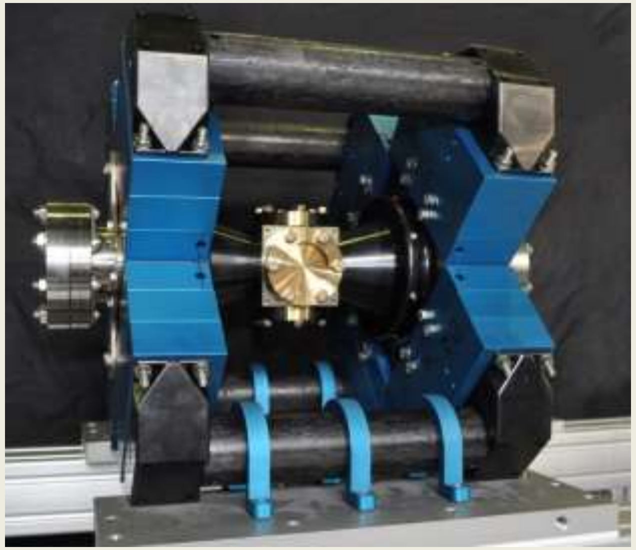
- large trap frequencies
  ➔ recoil-free absorption
- long interrogation times
- trap ion in zero field
  ➔ small trap induced shifts
- isolated from environment
  + laser cooling
  + no interactions
  ➔ high accuracy



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

Yb^+ single-ion clock: 3.2×10^{-18}
[Huntemann *et al.*, PRL **116**, 063001 (2016)]

High resolution spectroscopy of HCI?

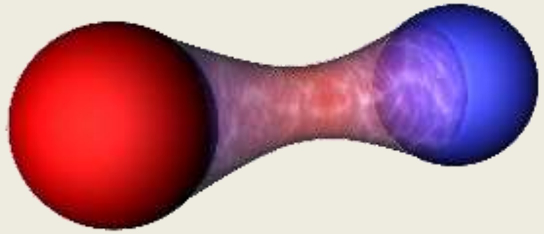


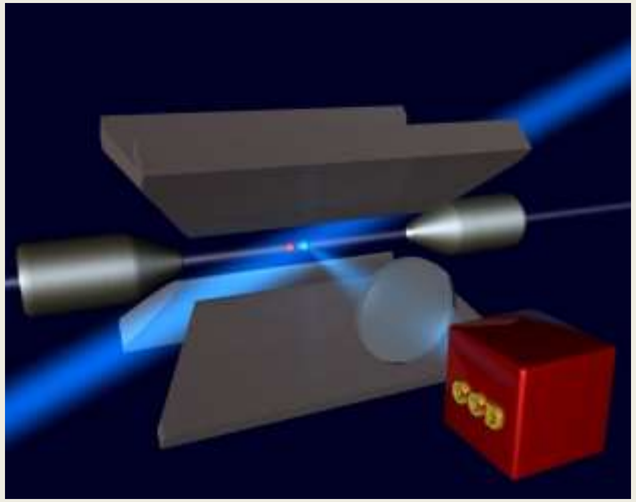
Problem:

- Electron beam ion trap (EBIT) is a noisy environment
- No cycling transition for cooling & state detection

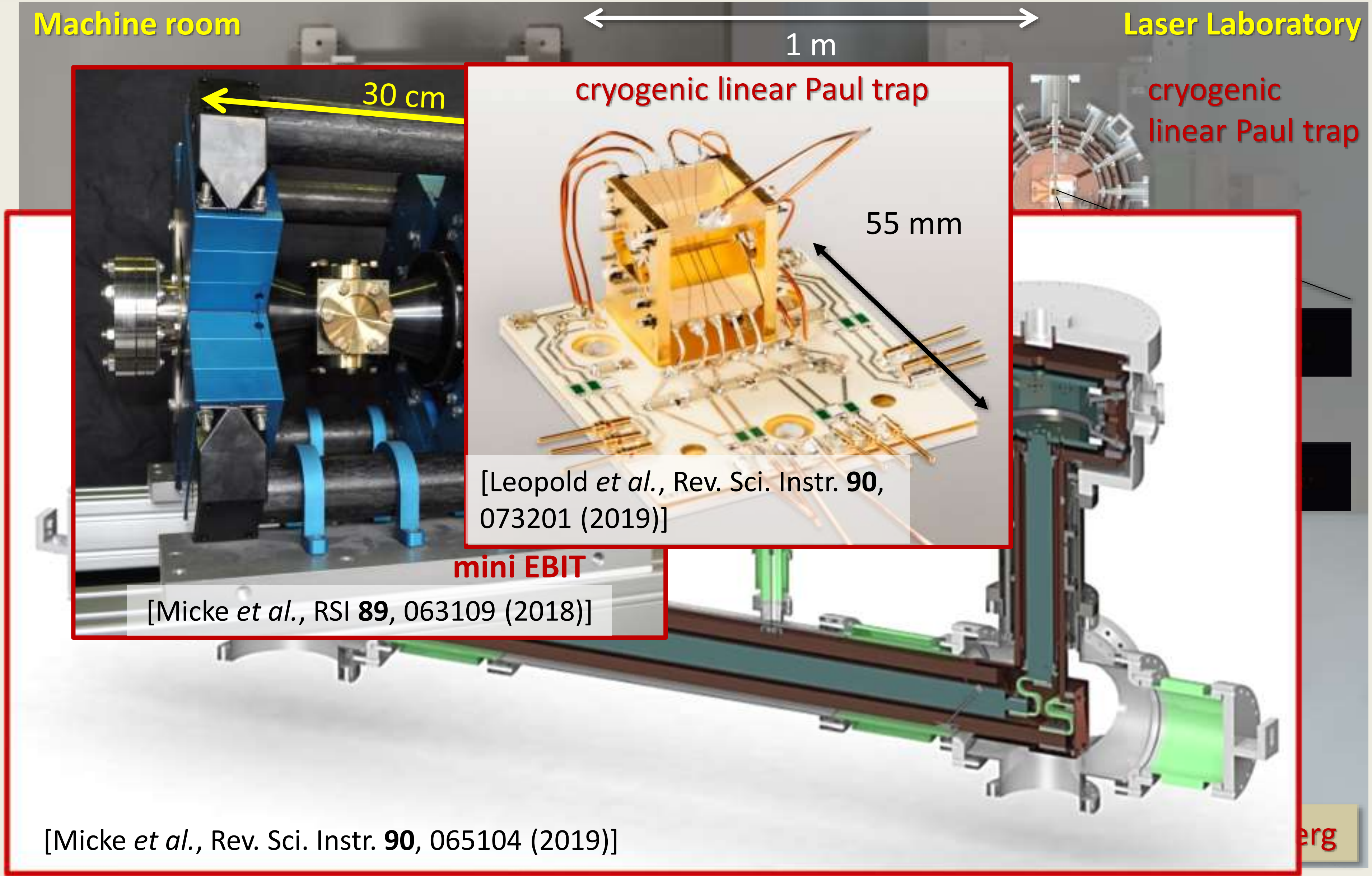
Solution:

- Paul trap environment
- cooling & detection
  ➔ Quantum Logic Spectroscopy





PTB approach to precision HCI spectroscopy



Specs vacuum system:

- Vacuum: $\sim 10^{-14}$ mbar
- Temperature: < 5 K
- Vibrations: < 20 nm
- Magnetic field: < 0.5 nT

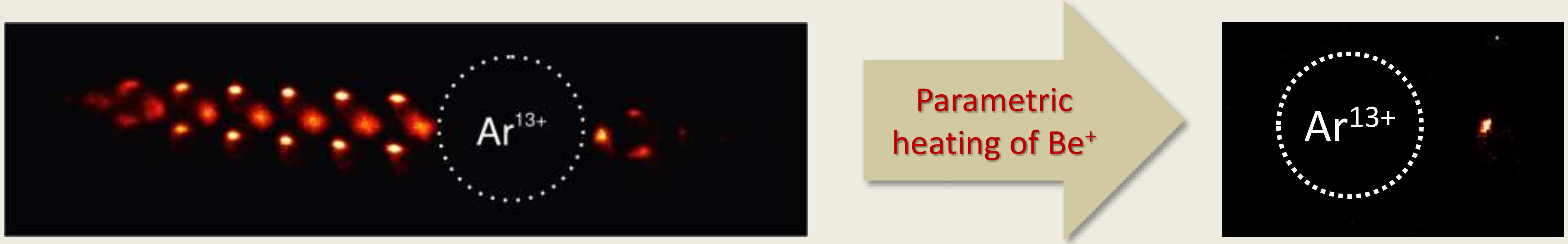
Specs EBIT:

- 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

Preparation & Lifetime of a 2-Ion Crystal



- total preparation time of Be^+/Ar^{13+} crystal: ~ few min
- Ar^{13+} lifetime: $\tau = (38.4 \pm 3.8)$ min
  ➔ residual pressure: $< 1.5 \times 10^{-14}$ mbar
  (assuming Langevin collisions)
- Sideband cooling to the motional ground state ($T < 3\ \mu\mathrm{K}$)

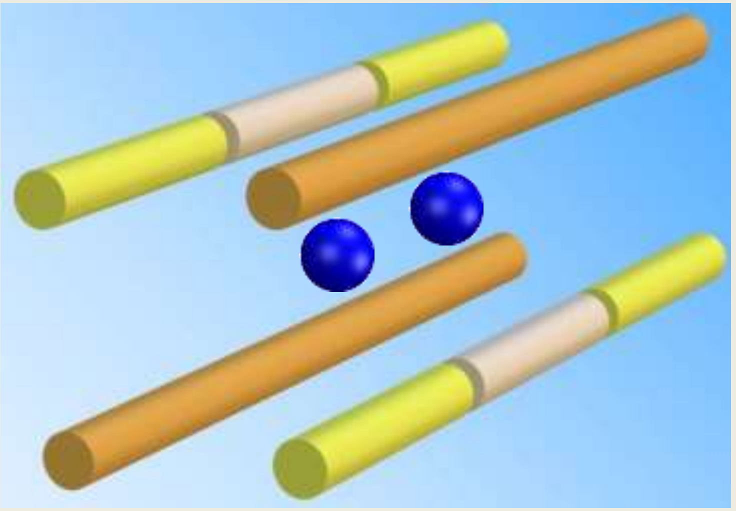
Quantum Logic with Trapped Ions

- Idea by:

J. I. Cirac

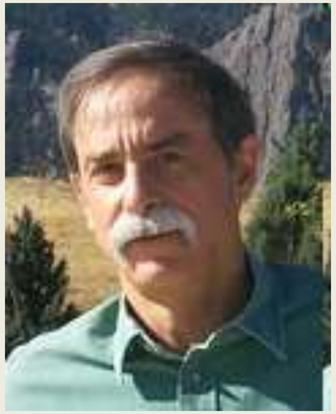
P. Zoller

PRL **74**, 4091 (1995)



Collective motion of ions described by normal modes

D. Wineland



NP 2012

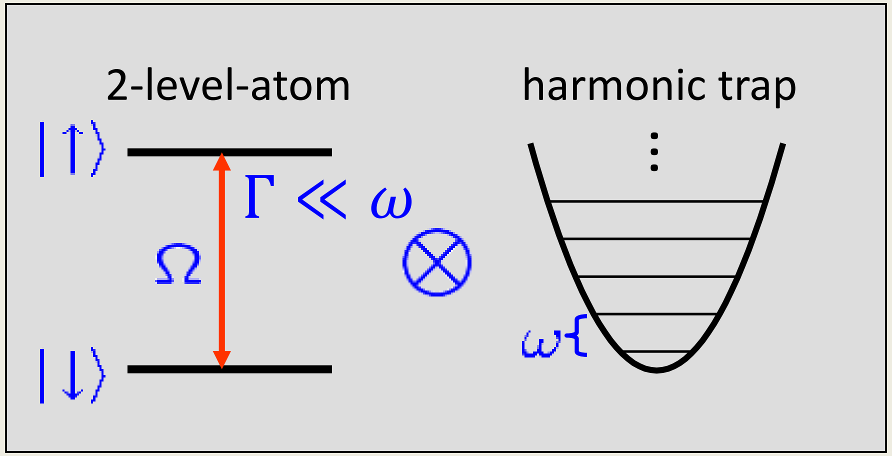
VOLUME 74, NUMBER 20 PHYSICAL REVIEW LETTERS 15 MAY 1995

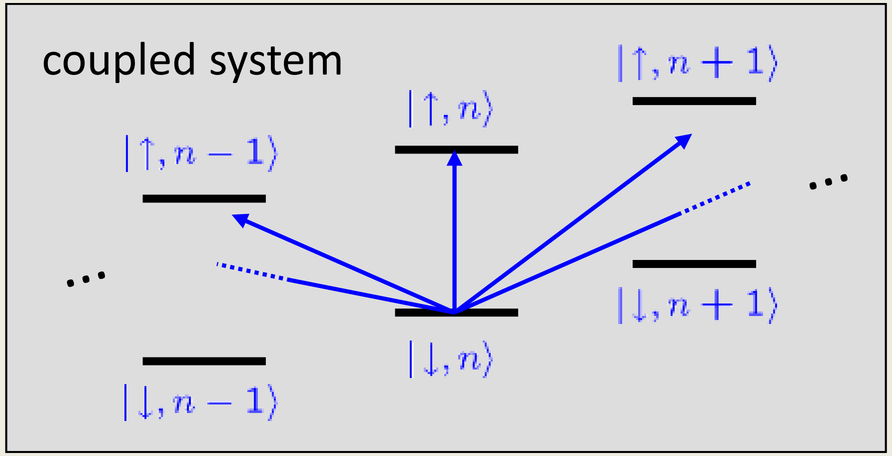
Quantum Computations with Cold Trapped Ions

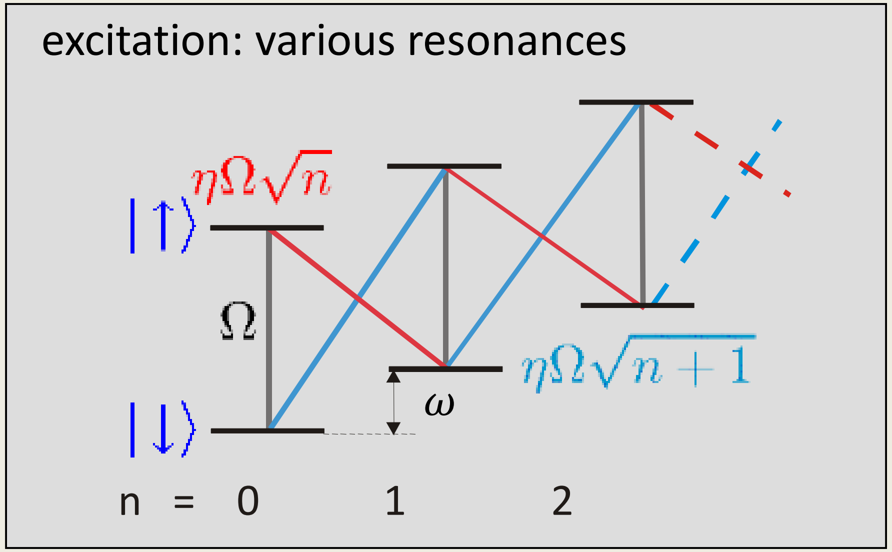
J. I. Cirac and P. Zoller*
Institut für Theoretische Physik, Universiät Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria
(Received 30 November 1994)

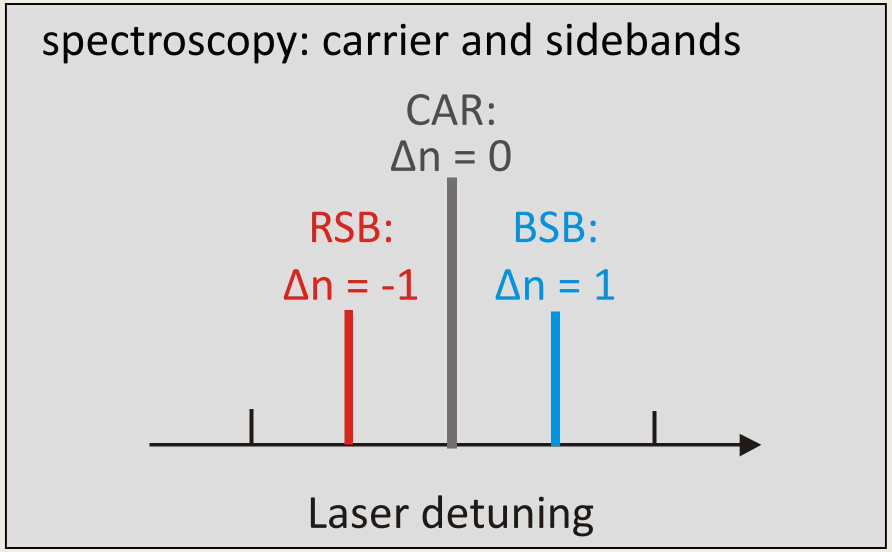
A quantum computer can be implemented with cold ions confined in a linear trap and interacting with laser beams. Quantum gates involving any pair, triplet, or subset of ions can be realized by coupling the ions through the collective quantized motion. In this system decoherence is negligible, and the measurement (readout of the quantum register) can be carried out with a high efficiency.

Quantum Logic with Trapped Ions



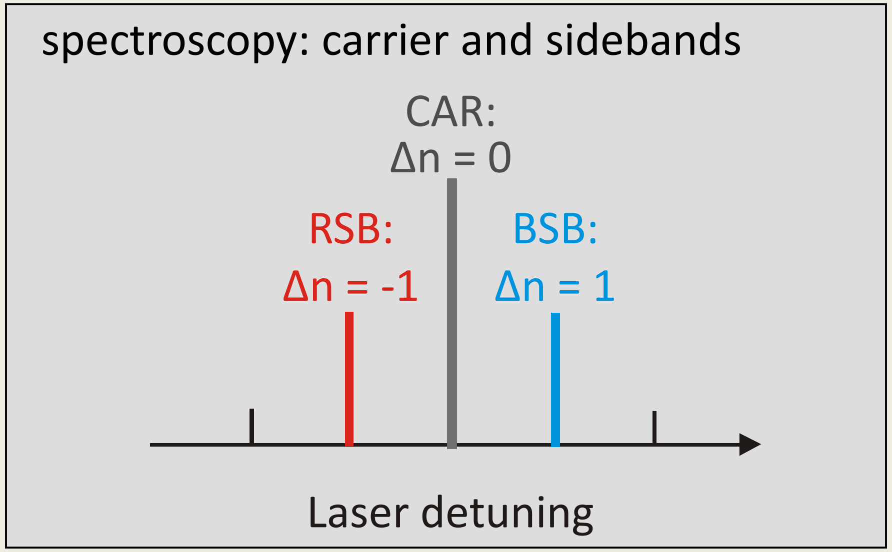




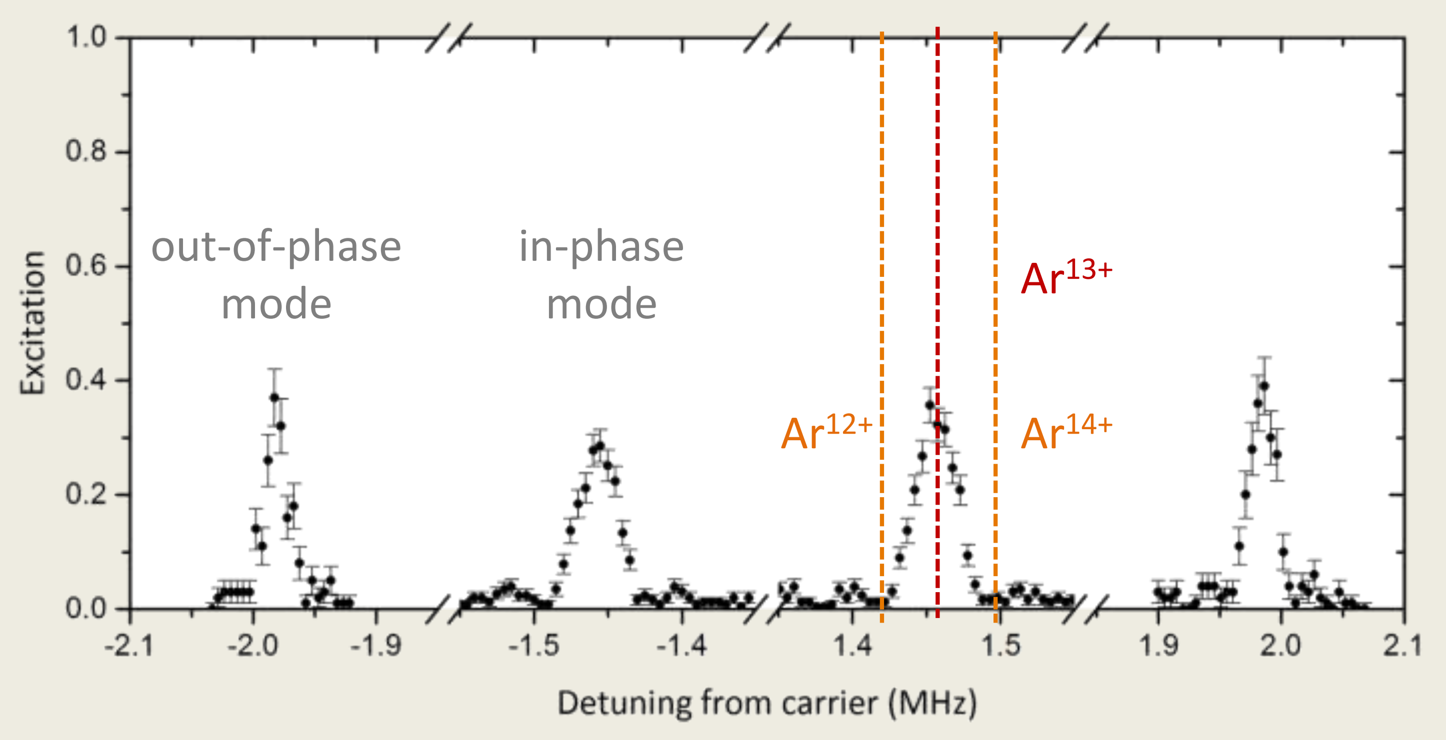


Ω: Carrier Rabi frequency; $\eta = kz_0$: Lamb-Dicke factor

Doppler cooling & charge state identification



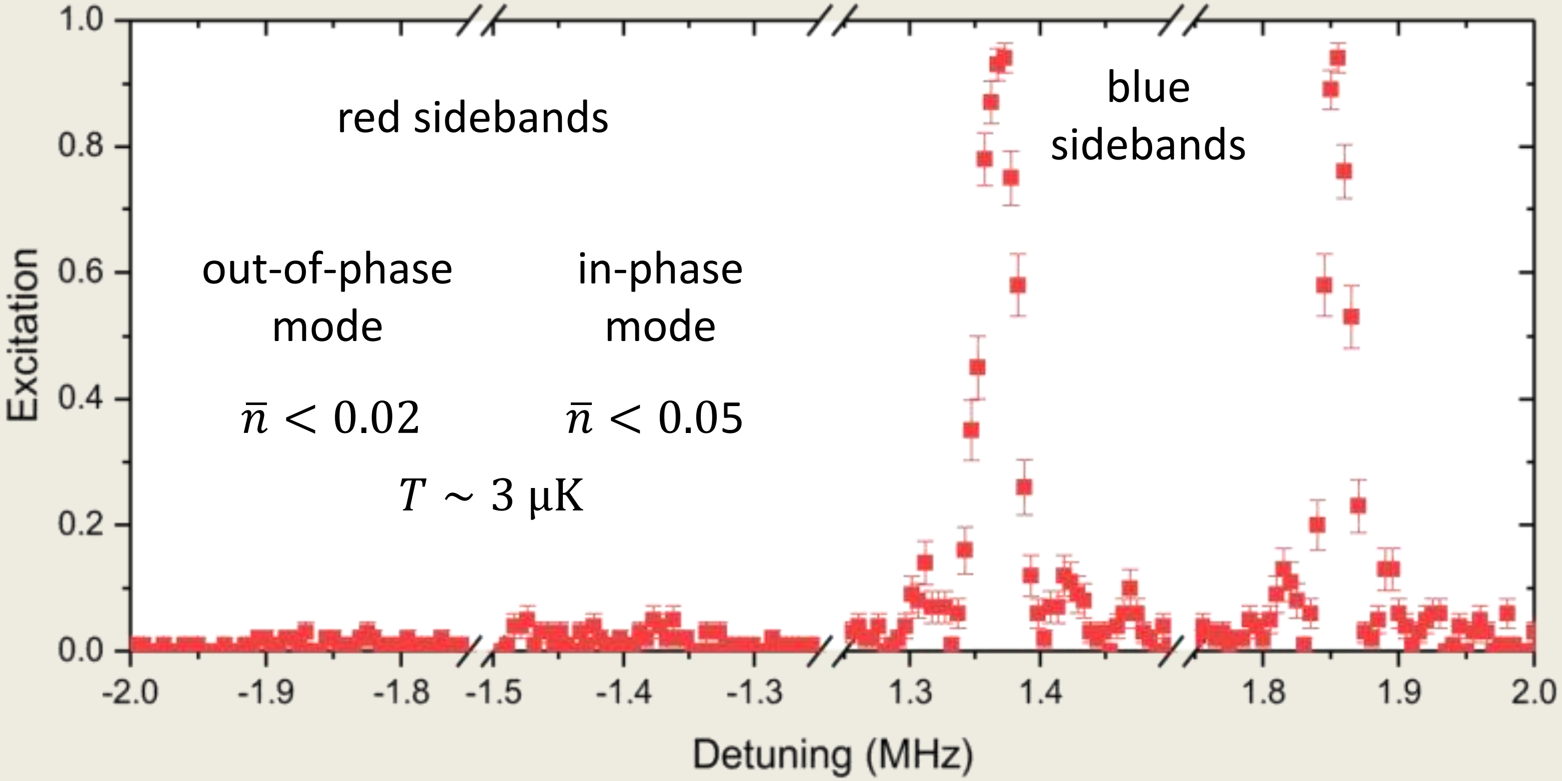
axial motional spectrum on Be^+

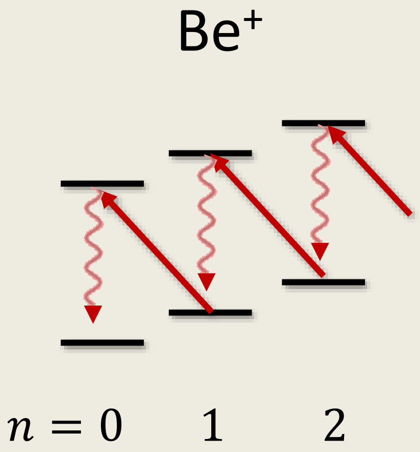


- single Be^+ axial frequency: 0.995 MHz
  ➔ Be^+/Ar^{13+} axial frequencies:
  1.47 MHz and 1.99 MHz

Sympatetic ground state cooling of Ar^{13+}

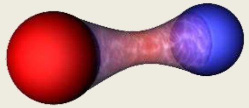
axial motional spectrum on Be^{+}



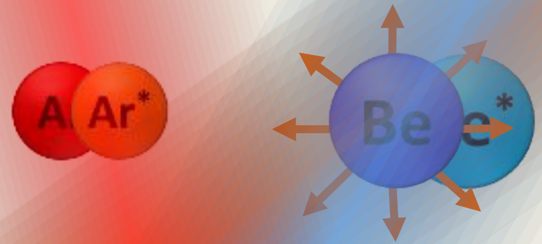


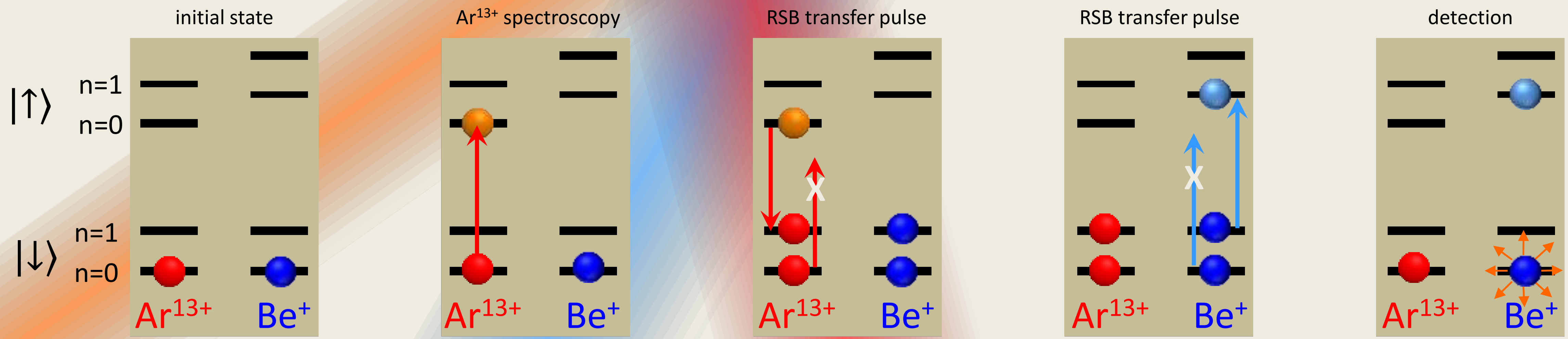
- resolved Raman sideband cooling on Be^{+}
- Lamb-Dicke parameter: $\eta_z = 0.82\sqrt{\mathrm{MHz}/\nu_z}$

[King *et al.*, in preparation]



Quantum Logic State Transfer

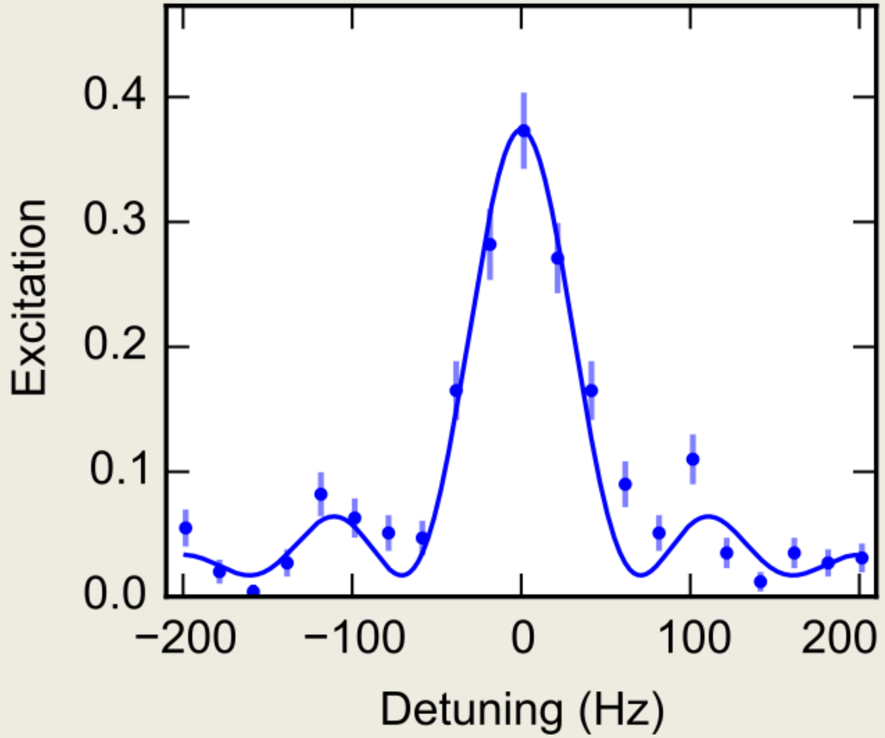




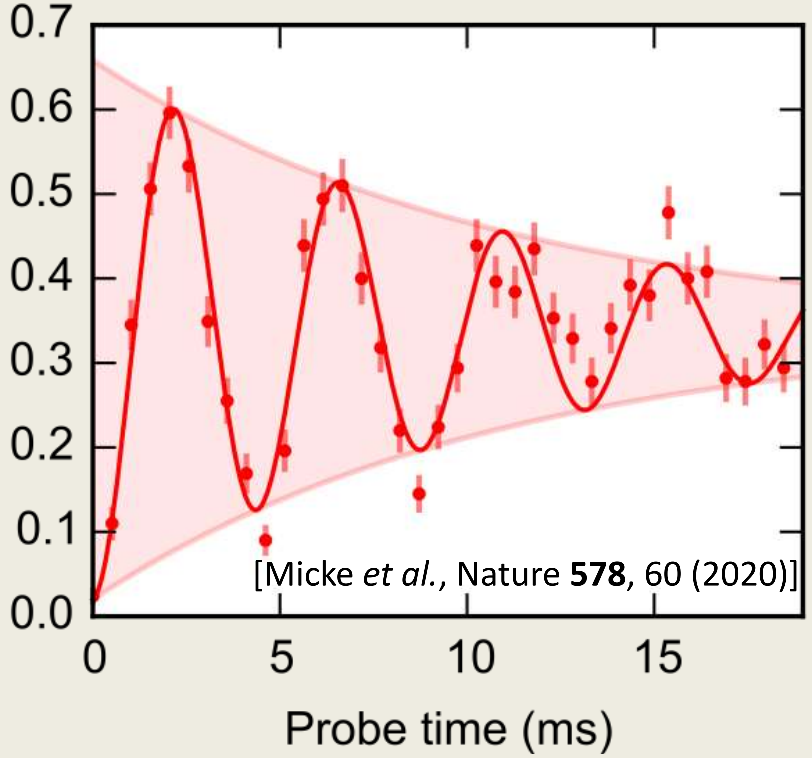
[D.J. Wineland *et. al.*, Proc. 6th Symposium on Frequency Standards and Metrology, 361 (2001); P.O. Schmidt *et al.*, *Science*, **309**, 749 (2005)]

Quantum Logic Spectroscopy of Ar^{13+}

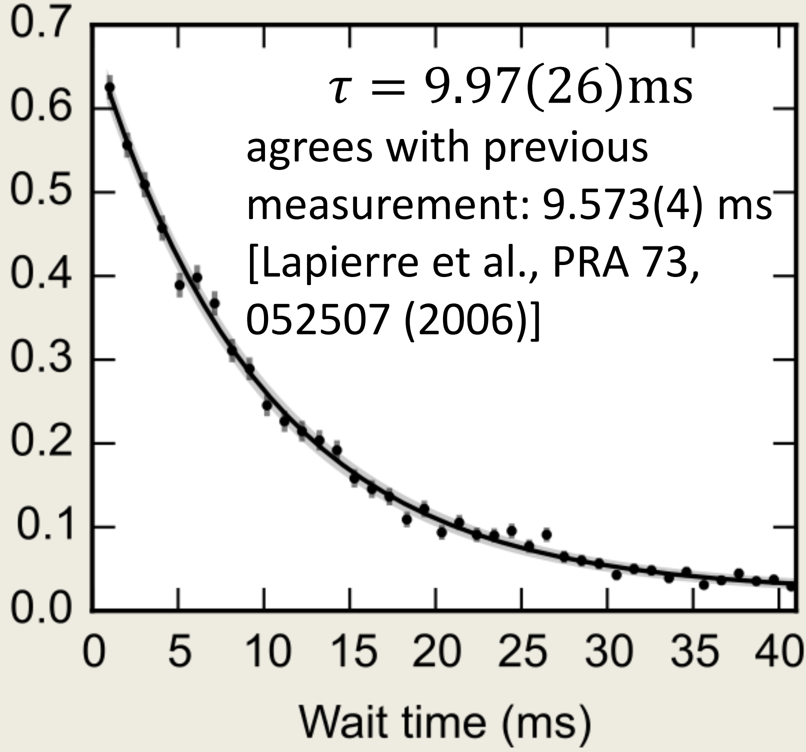
Fourier-limited linewidth: 65 Hz
(12 ms probe time) resolution: ~ 5 Hz



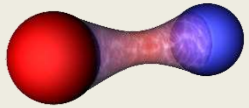
dephasing dominated by
excited state lifetime of 9.97(26)ms



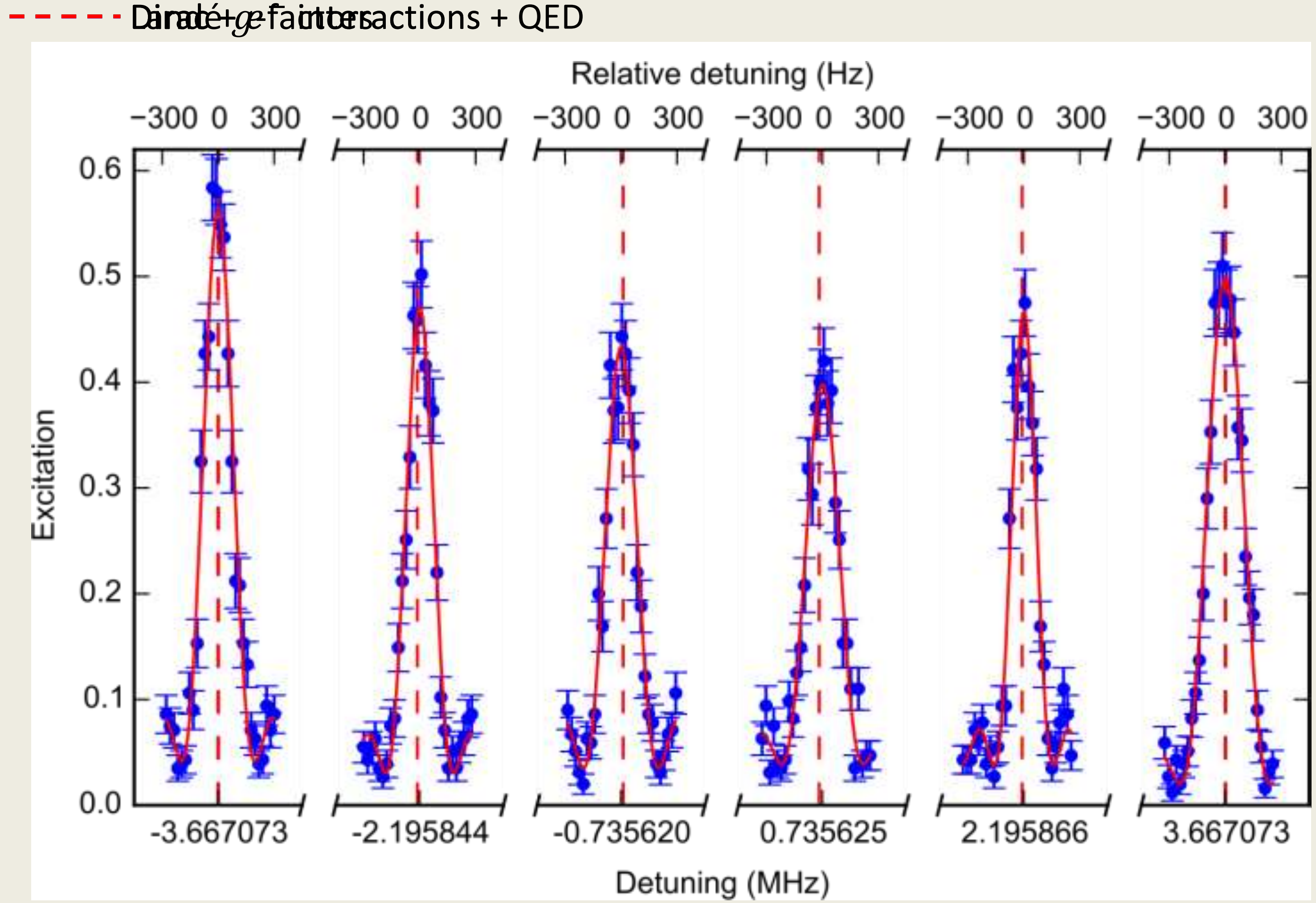
dedicated lifetime measurement

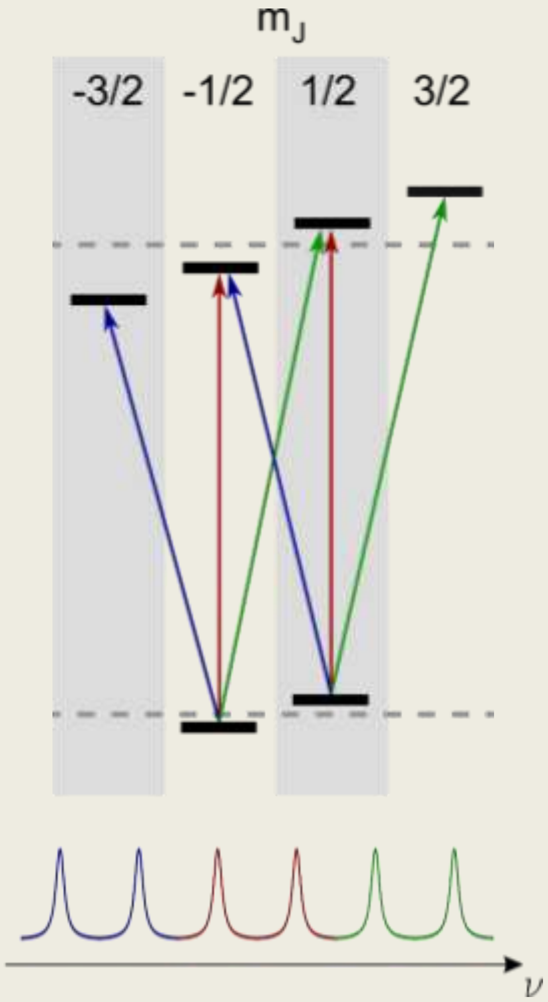


- spectroscopy laser transfer locked of Ar^{13+} to Si cavity-stabilized laser
  [Sterr & Benkler @ PTB: D. G. Matei *et al.*, Phys. Rev. Lett. **118**, 263202 (2017)]



Ar^{13+} Zeeman structure



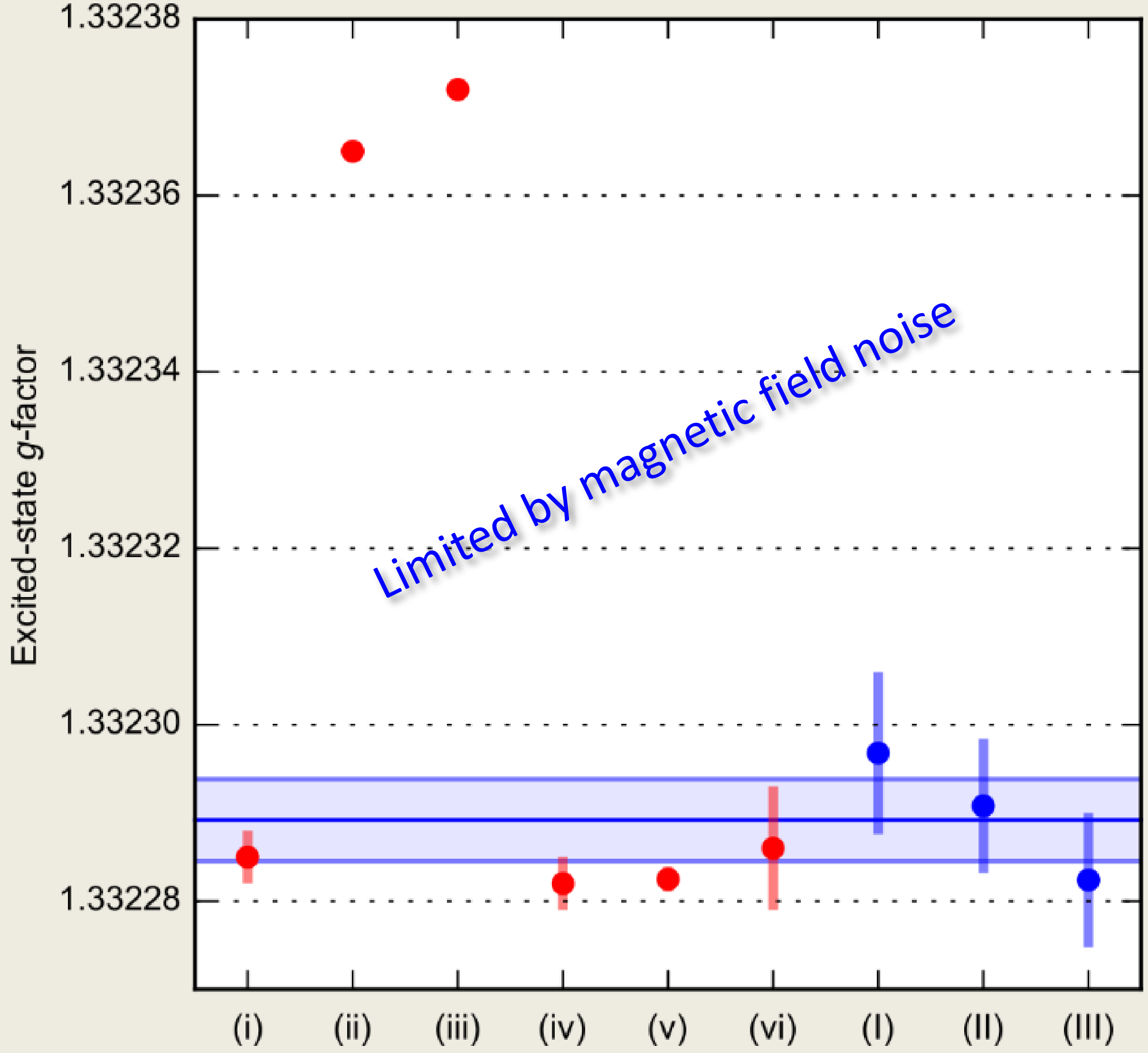


[Micke *et al.*, Nature **578**, 60 (2020)]

g-factors: [Agababaev *et al.* X-Ray Spectrom. 1-6 (2019)]

➔ measurement of ground- and **excited** state g-factors with <10 ppm

Excited state g-factor



Theory:

(i) Glazov *et al.*, Phys. Scr. **T156**, 014014 (2013)

(ii) Verdebout *et al.*, At. Data Nucl. Data Tables **100**, 1111 (2014)

(iii) Marques *et al.*, Phys. Rev. A **94**, 042504 (2016)

(iv) Shchepetnov *et al.*, J. Phys. Conf. Ser. **583**, 012001 (2015)

(v) Agababaev et al., arXiv:1812.06431 (2018)

(vi) Maison *et al.*, Phys. Rev. A **99**, 042506 (2019)

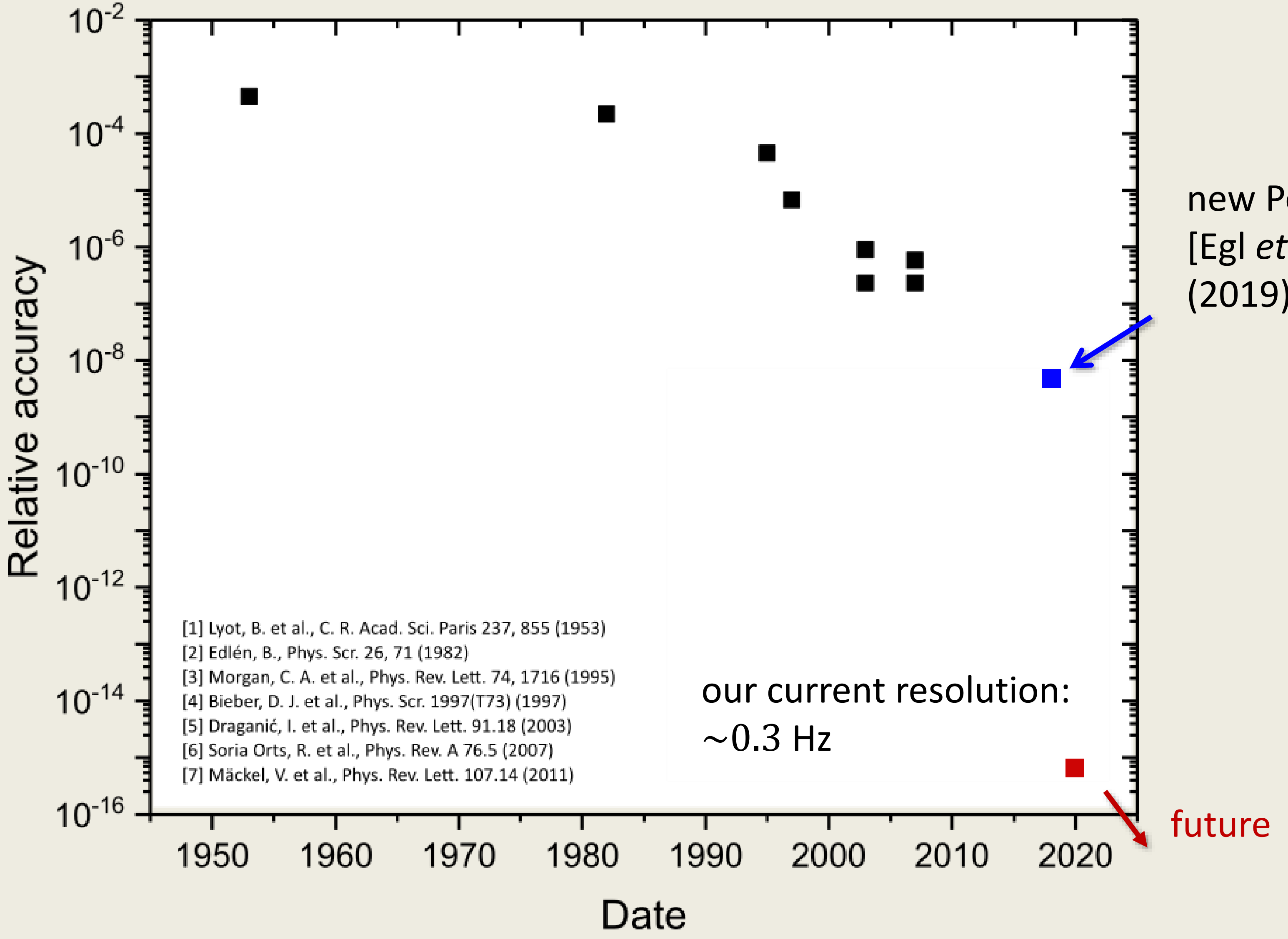
Experiment:

(I)-(III) This work

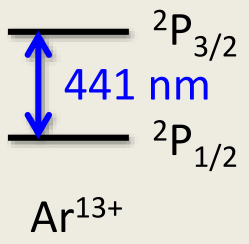
QED test of excited state g-factor

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

History of Ar^{13+} frequency measurements



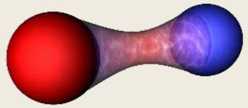
new Penning trap measurement [Egl *et al.* PRL **123**, 123001 (2019)]

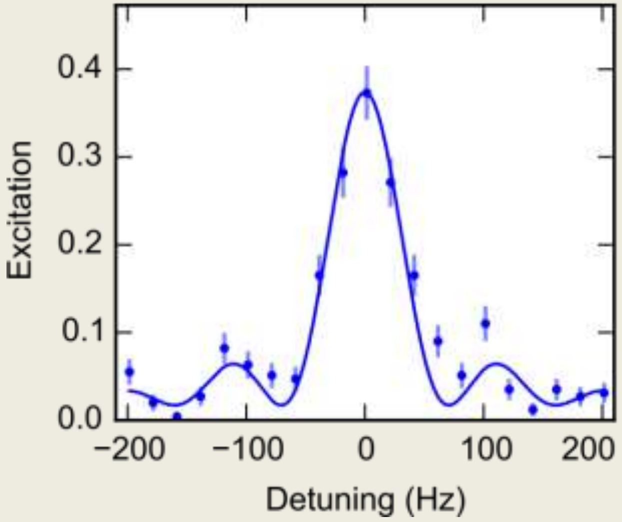


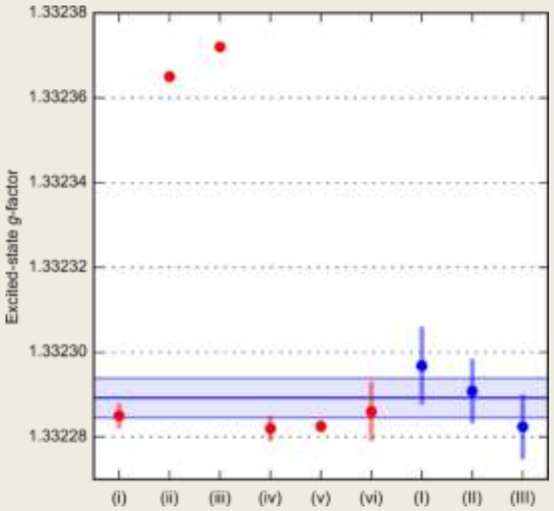
HCI Summary

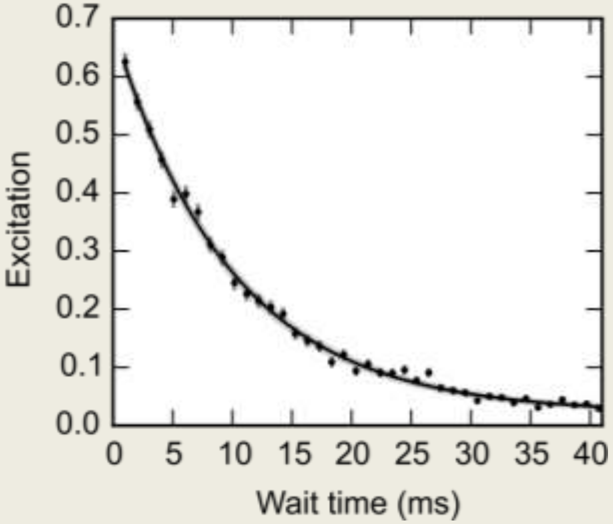
Summary

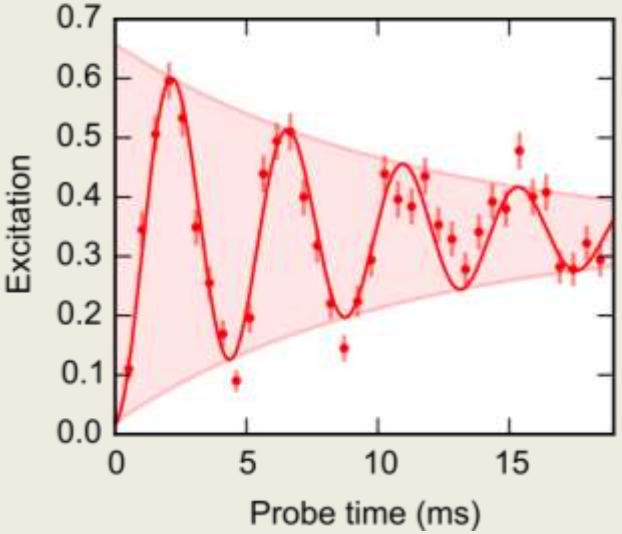
- precision spectroscopy of HCI addresses fundamental physics
- full quantum optical control over HCI achieved
- first coherent spectroscopy of HCI
- measured excited state g-factor & lifetime
- “universal“ spectroscopy scheme









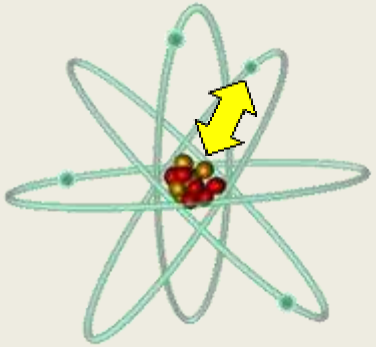


For more details see: https://indico.cern.ch/event/901588/

What‘s next?

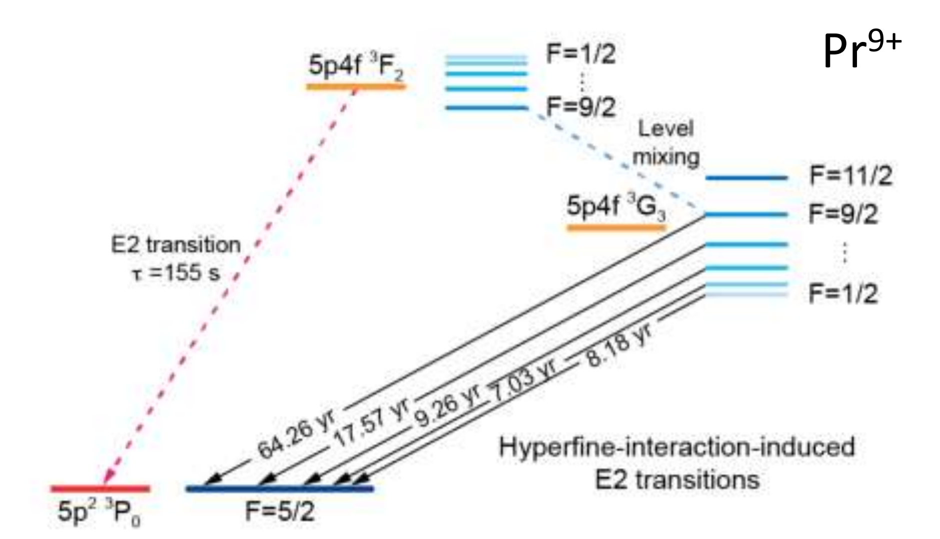
First optical HCI „clock“

- $^{36,40}Ar^{13+}$ $P_{1/2}$-$P_{3/2}$ lines: full evaluation of systematic uncertainties
- verify isotope shift atomic structure calculations
  [Yerokhin *et al.*, Phys. Rev. A **101**, 012502 (2020)]
- Isotope shift spectroscopy of $Ca^{14+/15+}$ to search for 5th forces
  [Berengut *et al.*, PRL **120**, 091801 (2018)]

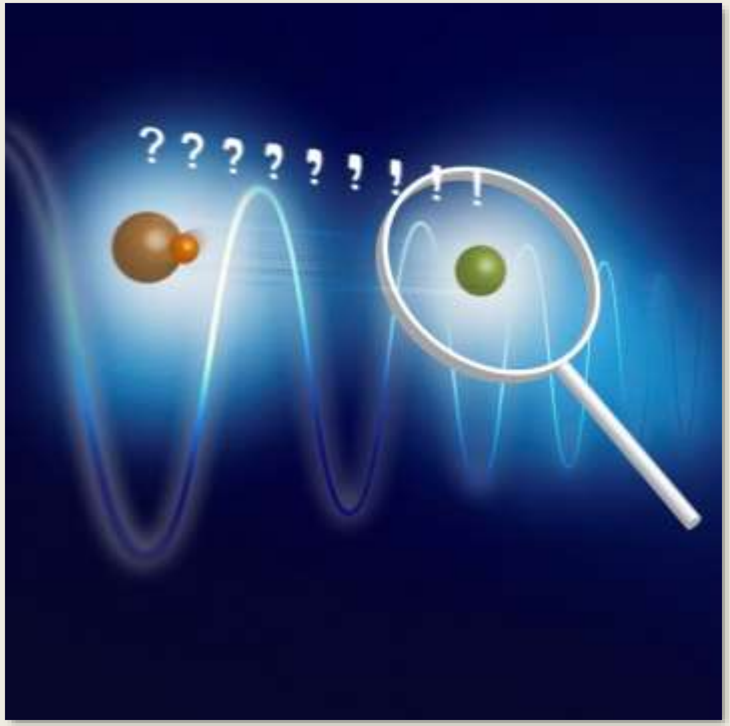


Future

- Clock candidate: $^{58}Ni^{12+}$
  [Yu & Sahoo, Phys. Rev. A **97**, 041403 (2018)]
- α-sensitive level-crossings: Pr^{9+}, Ir^{17+}, $Cf^{15+/17+}$
  [Bekker *et al.*, Nat. Commun. **10**, 5651 (2019)]
  [Windberger *et al.*, PRL **114**, 150801 (2015)]
  [Porsev *et al.*, PRA, **102**, 012802 (2020)]

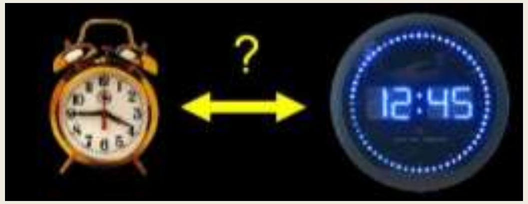


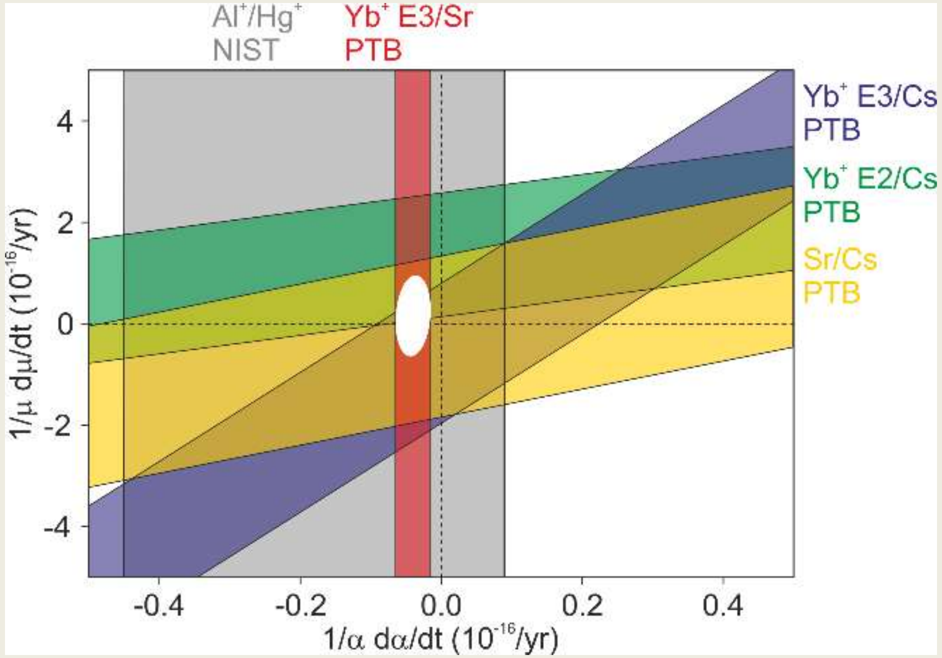
goal: optical clock-like spectroscopy of HCI to test fundamental physics



QUANTUM LOGIC WITH MOLECULAR IONS

Electron-to-proton mass ratio





$\dot{\alpha}/\alpha = -4.1(2.5) \times 10^{-18}$/year
$\dot{\mu}/\mu = -1.3(8) \times 10^{-17}$/year

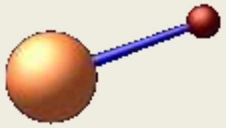
[Peik/Lisdat (PTB), preliminary]

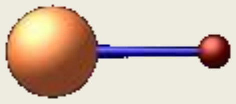
$$\frac{\dot{\mu}}{\mu} \sim 40\,\frac{\dot{\alpha}}{\alpha}$$

[Calmet & Fritzsch, Phys. Lett. B **540**, 173 (2002)]

- change in μ from clocks is model dependent
- limited uncertainty from microwave transiton

ro-vibrational optical transition in molecules provides high sensitivity for $\dot{\mu}/\mu$

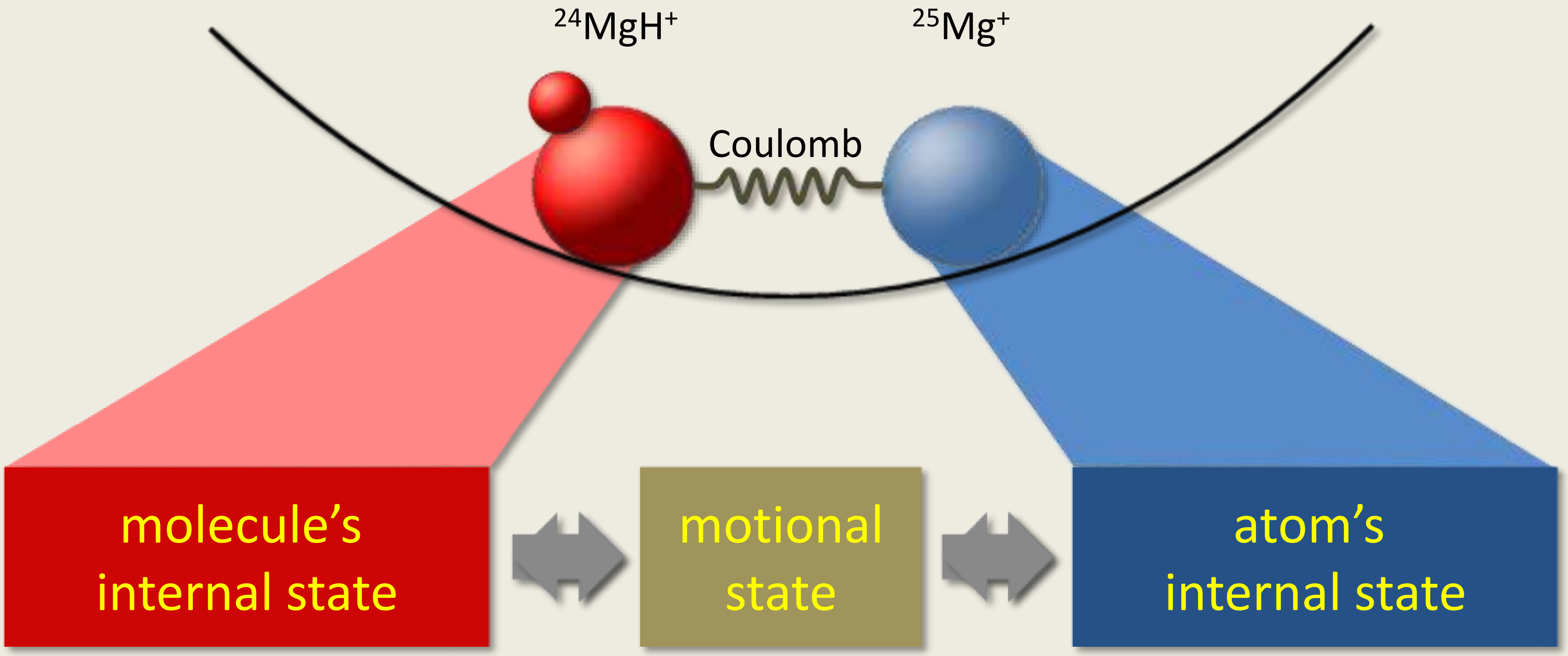




$E_{vib} \sim \sqrt{\mu}$ $E_{rot} \sim \mu$

[Schiller & Korobov, Phys. Rev. A **71**, 032505 (2005)]

State detection of a molecular ion

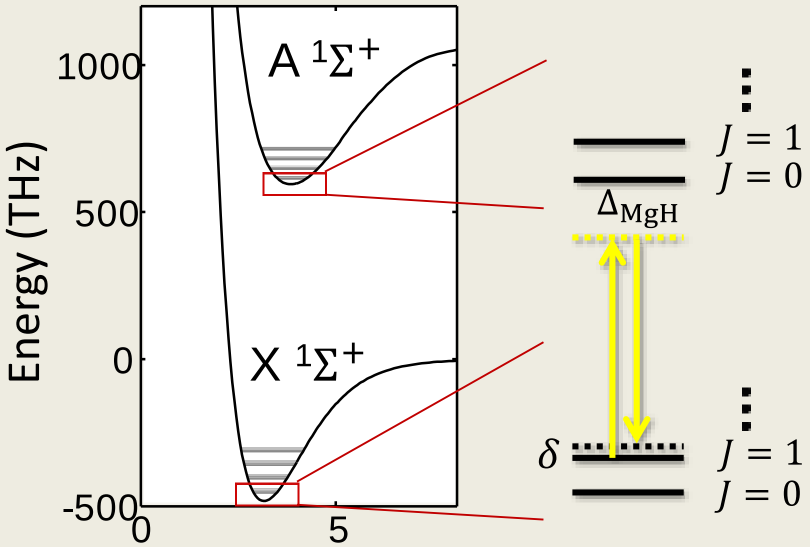


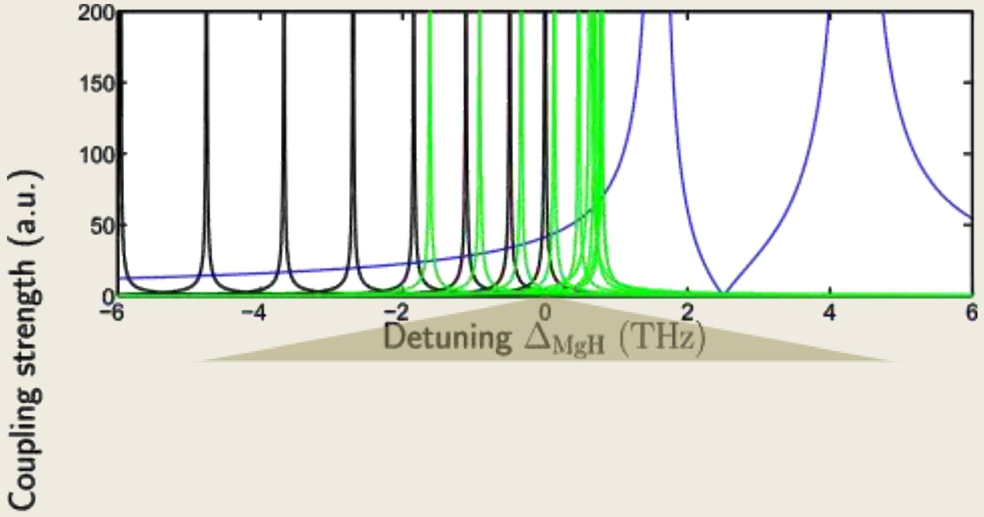
- atomic ion is a sensor for molecular ion
- molecular ion can be controlled through atomic ion
- composite system: combine advantages of both species

➔ make single molecular ions accessible for spectroscopy

[similar proposals by: Drewsen, Keller, Koelemeji; demonstrated with atoms: Hume @ NIST]

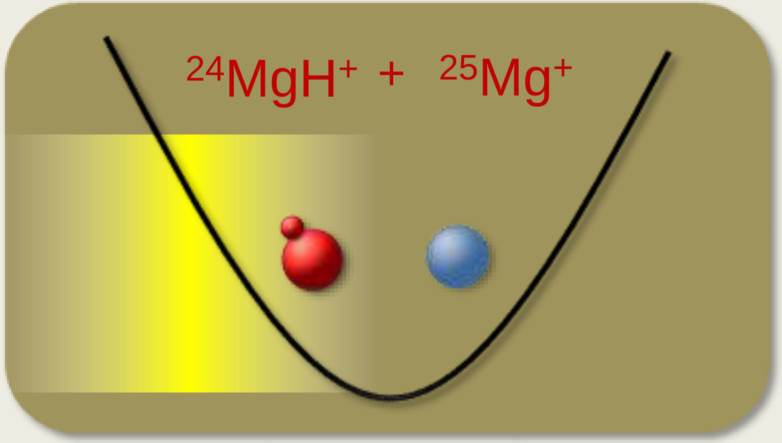
Dipole force on MgH^+/Mg^+ system





- $J \rightarrow J - 1$
- $J \rightarrow J + 1$
- $^{25}Mg^+$ D1 & D2 lines
  ➔ excitation offset

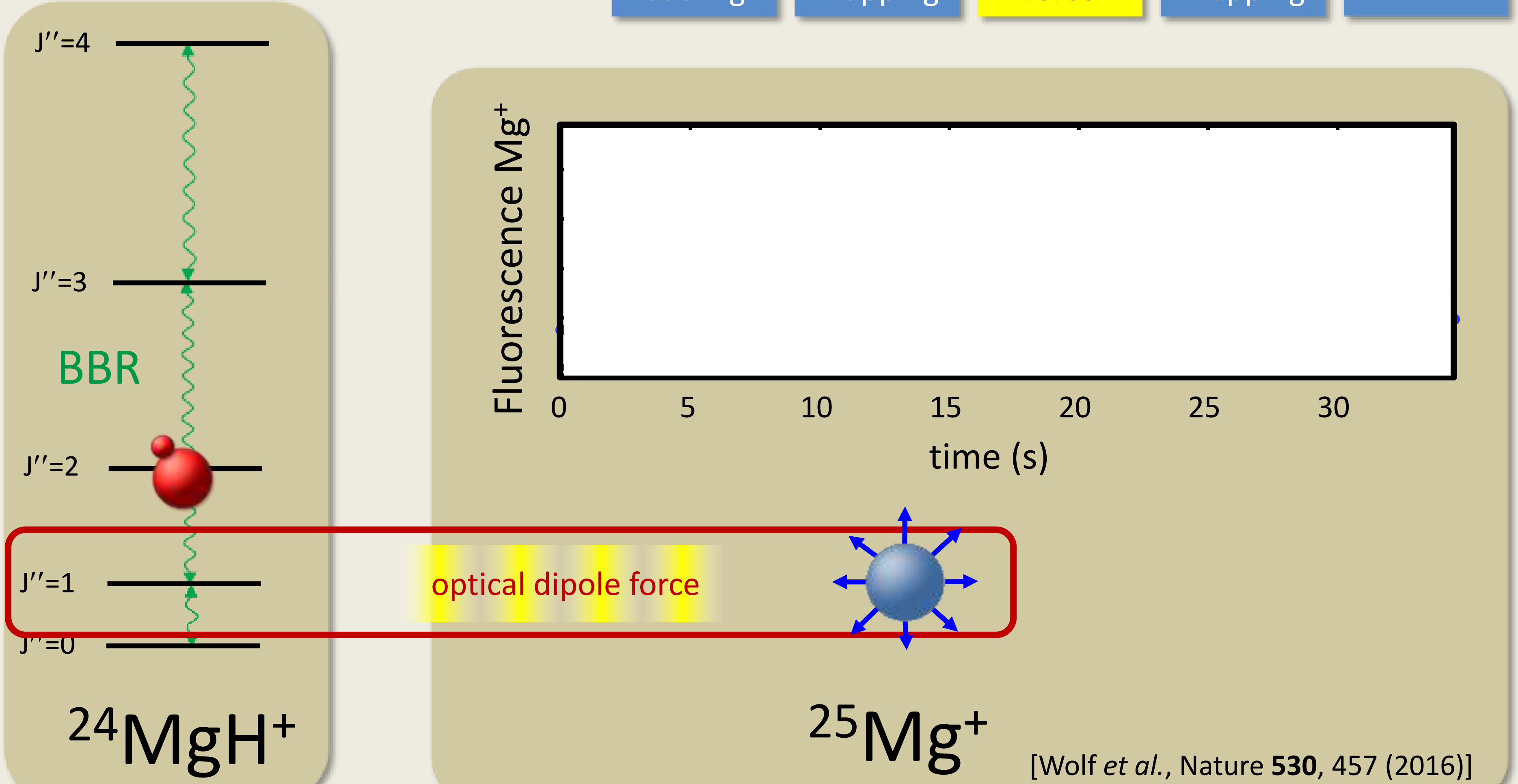
rotational state selectivity
through laser detuning

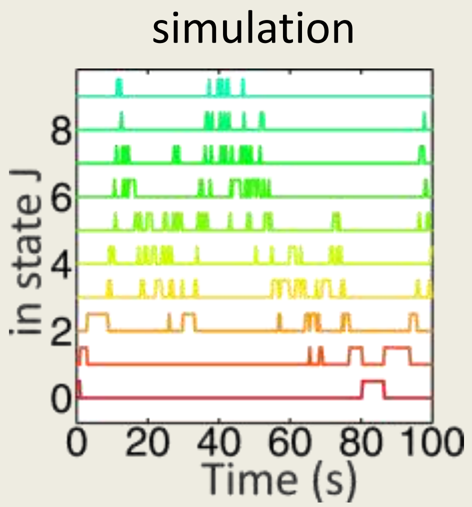


BBR-induced quantum jumps

Detection sequence:
(30x per data point)

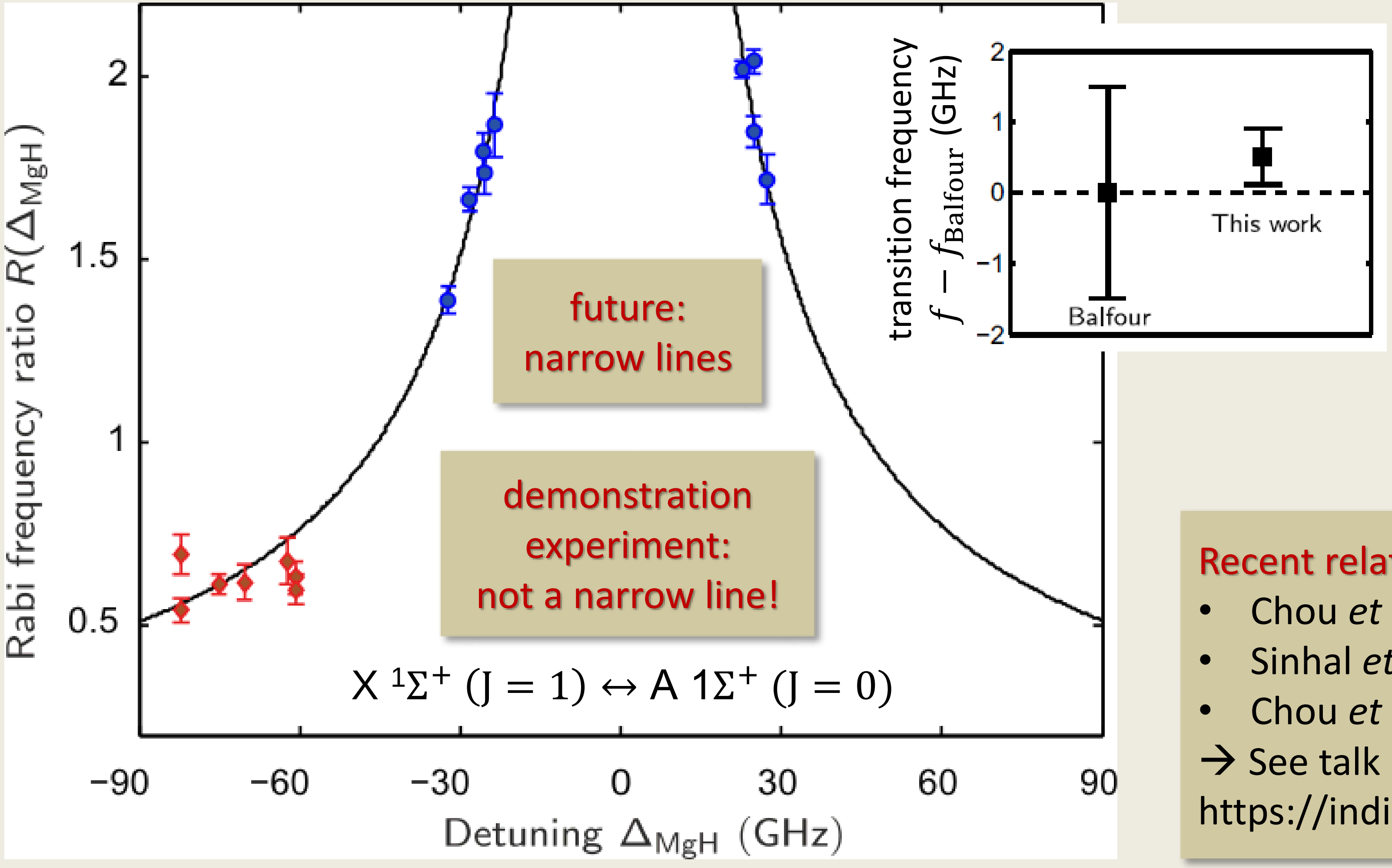
ground state cooling	spin-motion mapping	optical dipole force	motion-spin mapping	detect





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

Quantum Logic Spectroscopy of MgH^+



$f_0 = 1067.74789(40)$ THz

[in agreement with $f_0 = 1067.74730(150)$ THz
from Balfour *et al.*, Can. J. Phys. **50**, 1082 (1972)]

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

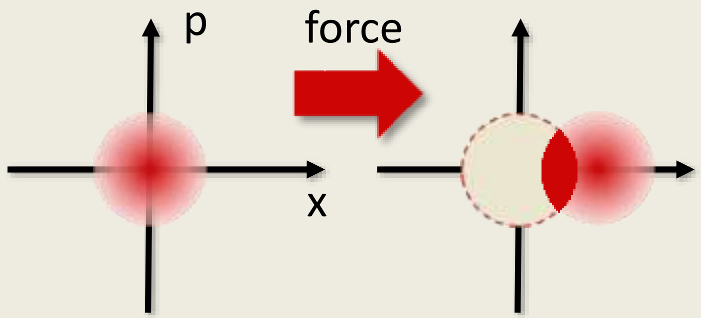
Recent related work:

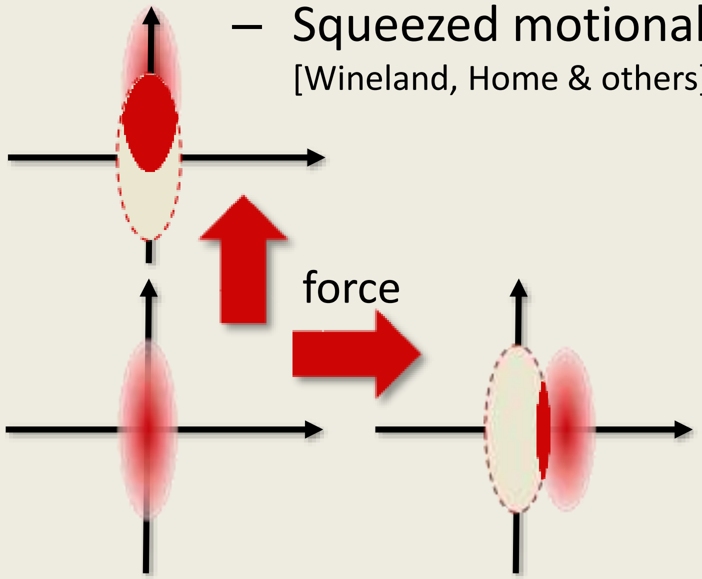
- Chou *et al.*, Nature **545**, 203 (2017)
- Sinhal *et al.*, Science **367**, 1213 (2020)
- Chou *et al.*, Science **367**, 1458 (2020)

→ See talk by. J. Chou
https://indico.cern.ch/event/930162/

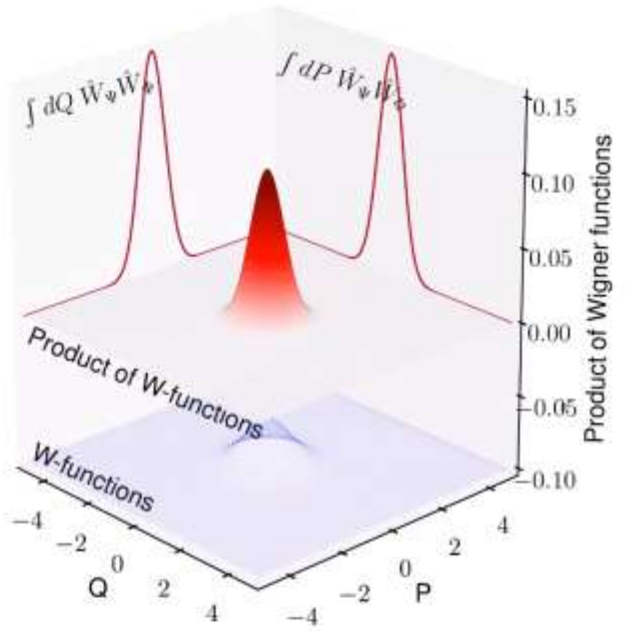
Classical detection scheme

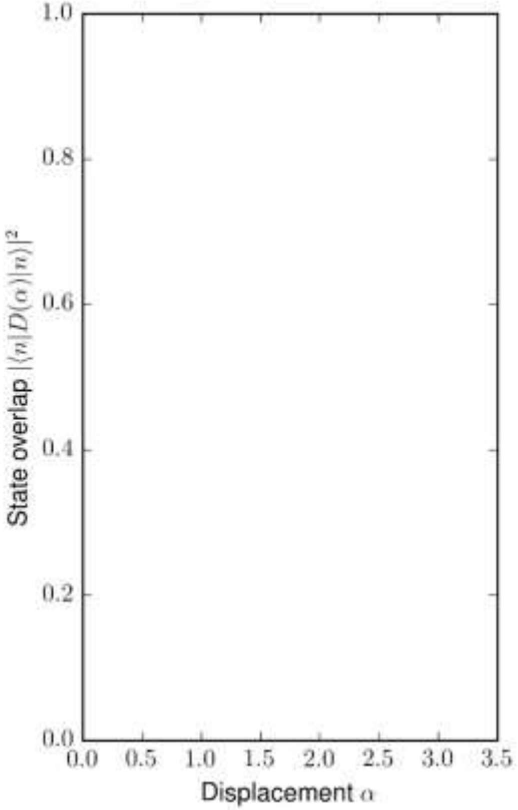
- classical scheme:
  - prepare $|0\rangle$
  - apply displacement $D(\alpha)|0\rangle$
  - overlap with $|0\rangle$: $|\langle 0|D(\alpha)|0\rangle|^2 = e^{-|\alpha|^2}$
- nonclassical schemes:
  - Schrödinger cat states
    [Hempel *et al.*, Nat Photon **7**, 630 (2013)]
  - Squeezed motional states
    [Wineland, Home & others]



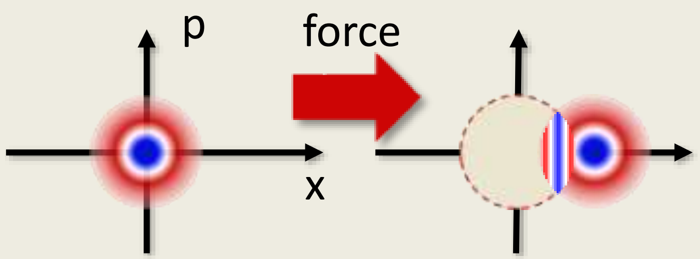


$$|\langle \Phi|\Psi\rangle|^2 = \int d\beta W_\Phi(\beta) W_\Psi(\beta)$$

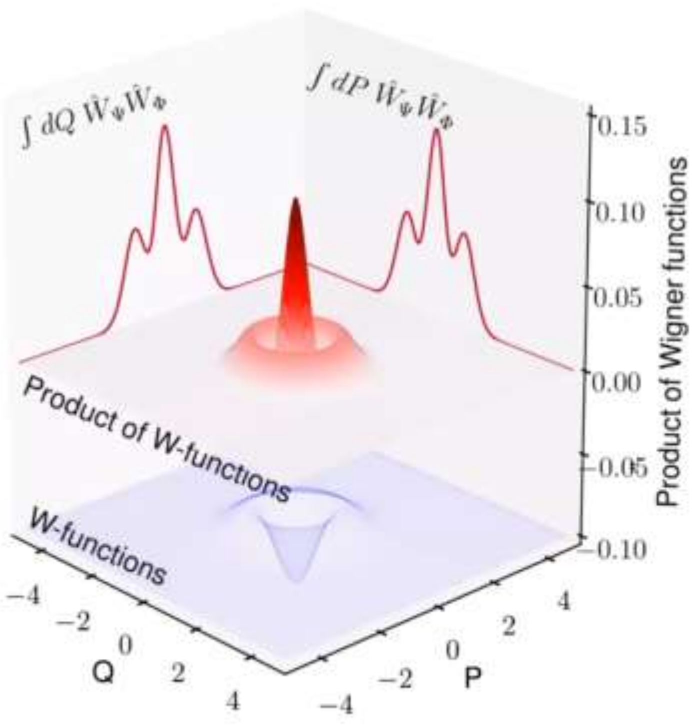


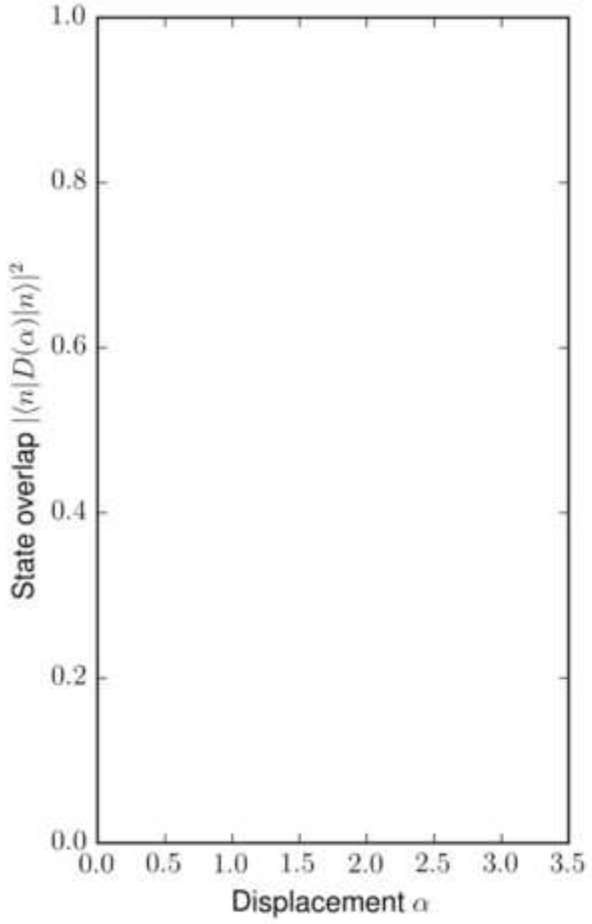


Fock state interferometry



$$|\langle\Phi|\Psi\rangle|^2 = \int d\beta W_\Phi(\beta) W_\Psi(\beta)$$



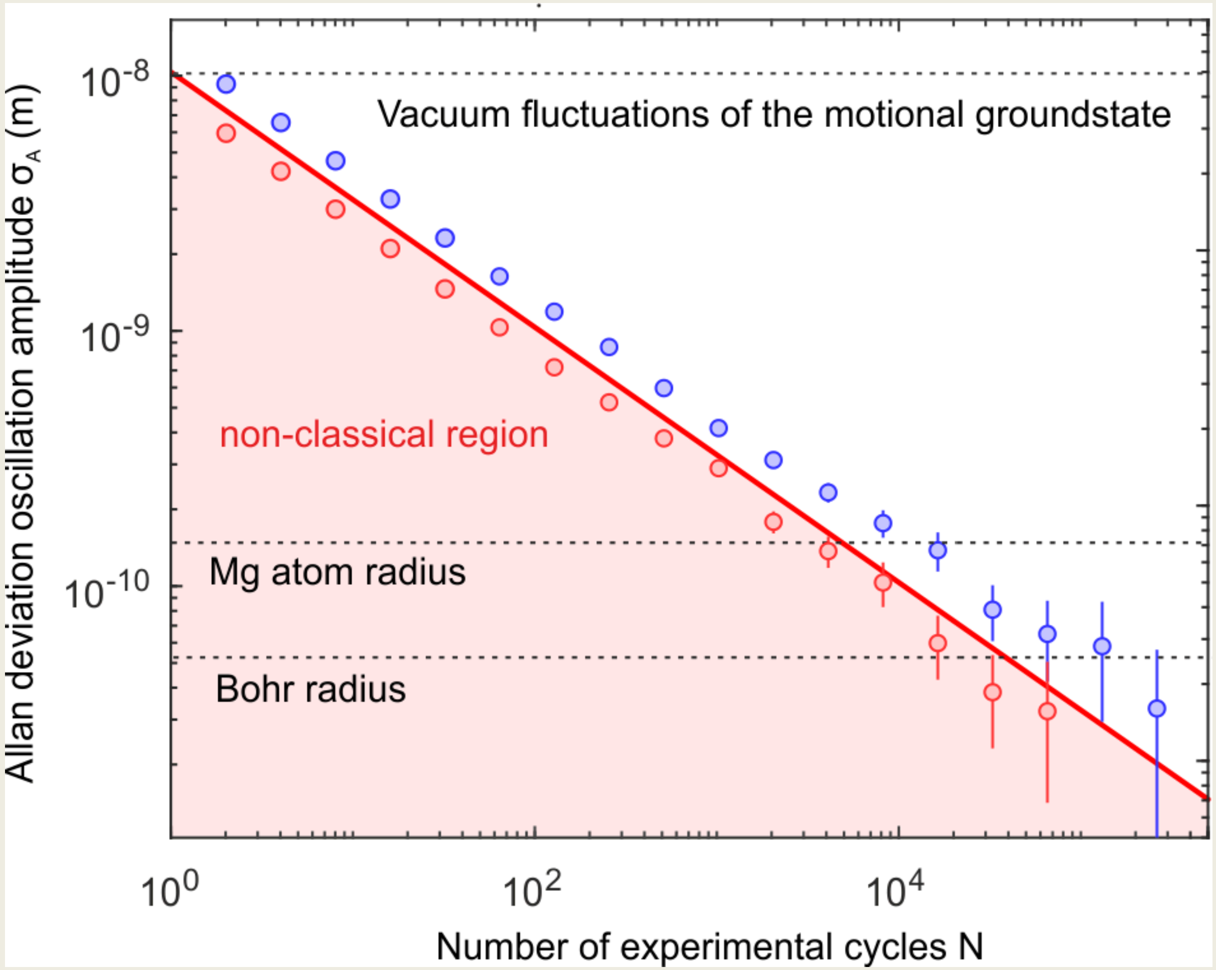


Displacement/amplitude measurement

- resolution limited by measurement time (QPN)
- $n = 1$ Fock state
  - 1.3 dB sensitivity below theoretical SQL
  - 3.6 dB sensitivity below experimental SQL

➔ reduce averaging time by x2

- sensitivity of force measurement: $\sim 112\ \mathrm{yN}/\sqrt{\mathrm{Hz}}$

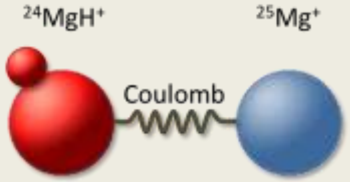


related work using classical states of motion: [Gilmore et al. PRL **118**, 263602 (2017), Shaniv et al., Nat. Commun. **8**, 14157 (2017), Biercuk *et al.*, Nat Nano **5**, 646 (2010)]]

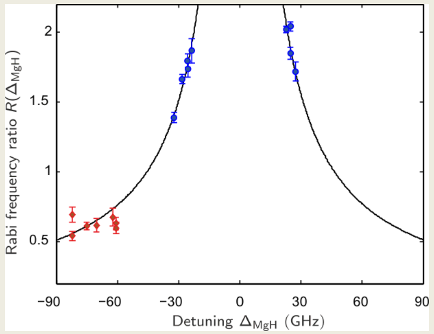
[F. Wolf *et al.*, Nature Communications **10**, 2929 (2019)]

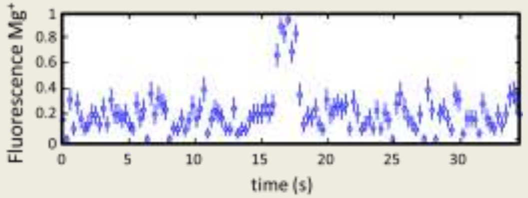
Summary & Future Molecules

- first step towards extending quantum optics control to a molecular ion

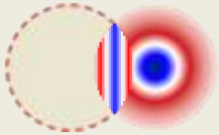


- demonstrated non-destructive state detection & simple spectroscopy



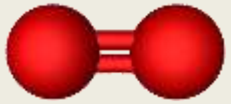


- Demonstrated sub-SQL Fock state metrology



Future:

- O_2^+ spectroscopy
  [F. Wolf et al., arXiv:2002.05584]

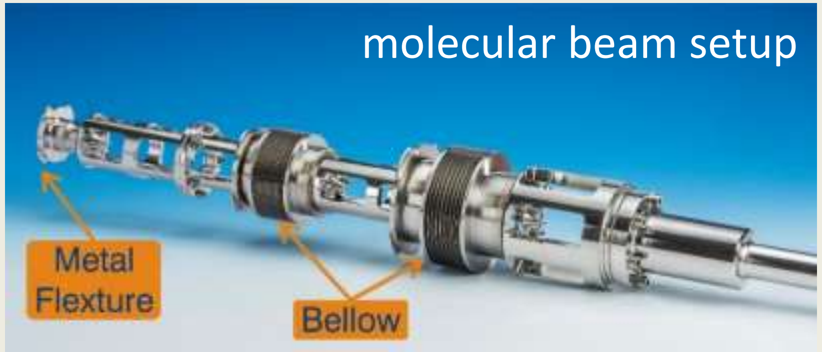


- deterministic state preparation

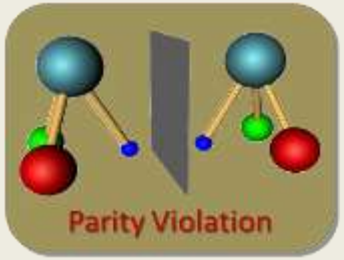
➔ full control over molecular state

➔ high-precision spectroscopy

➔ towards applications in chemistry, molecular & fundamental physics



Dream: probe for parity violation in chiral molecules



Quantum Logic Spectroscopy Group

QUEST · PTB · Leibniz Universität Hannover

M. Schwarz, L. Schmöger & J. Crespo

PhD/PostDoc openings

€

HCI: P. Micke, L. Spieß, S. King, T. Leopold

Molecules: J.C. Heip, F. Wolf, M. Zawierucha

Collaborators:

- J. Crespo López-Urrutia (MPIK, Heidelberg)
- J. Berengut (U. of New South Wales)
- K. Hammerer (LUH, Hannover)
- A. Smerzi (LENS, Florence)
- A. Retzker (U. of Jerusalem)
- A. Surzhykov (PTB & TU Braunschweig)
- M. Safronova (U. of Delaware)

EMRP European Metrology Research Programme

Niedersächsisches Ministerium für Wissenschaft und Kultur

Unterstützt von / Supported by Alexander von Humboldt Stiftung/Foundation

DFG

EXC 2123

CRC 1225

CRC 1128

CRC 1227

www.quantummetrology.de

THE END