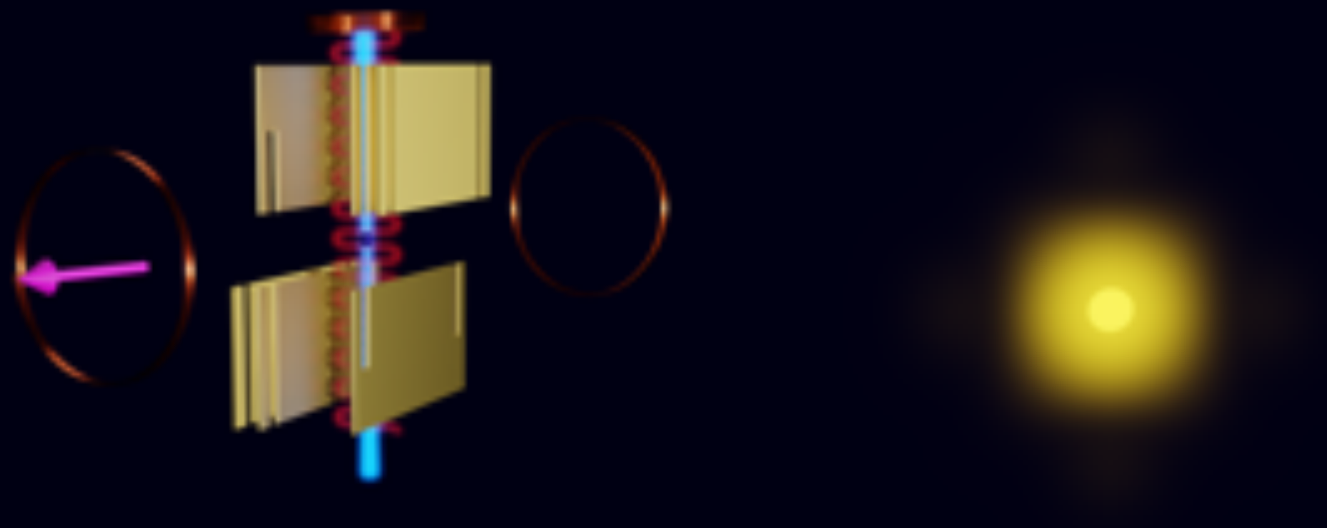


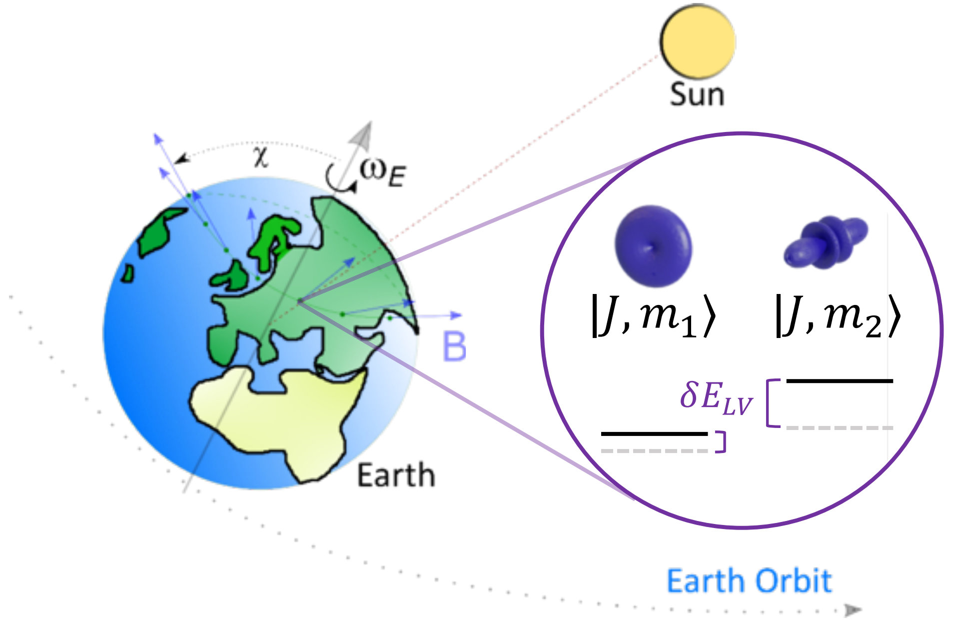
Testing local Lorentz invariance with a single $^{172}Yb^{+}$ ion

Laura S. Dreissen, Chih-Han Yeh, Henning A. Fürst, Kai C. Grensemann and Tanja E. Mehlstäubler

Content

Testing Lorentz invariance with a single trapped Yb^+ ion

- Motivation
- Measurement principle
- Experiment
- Results
- Conclusion and Outlook



Content

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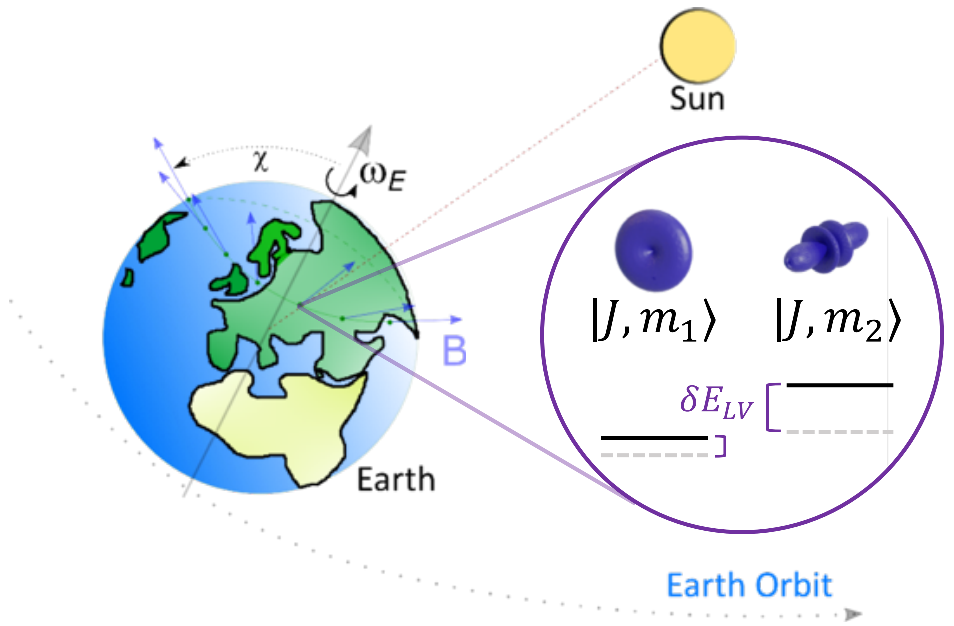
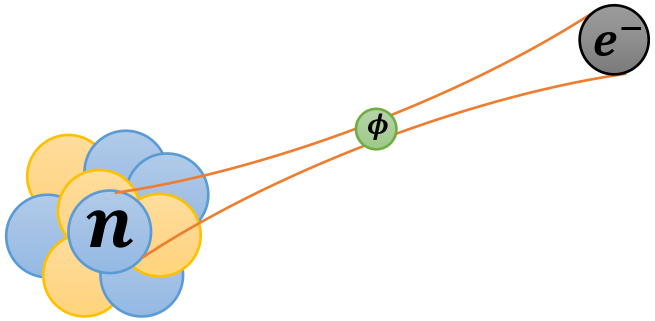


Isotope shift measurements in Yb⁺

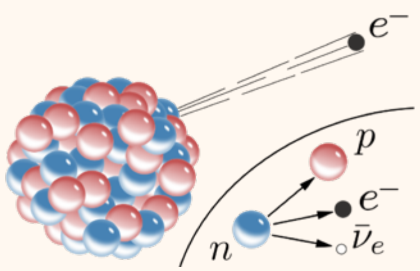
- Motivation
- Measurement principle
- Prelimanry results



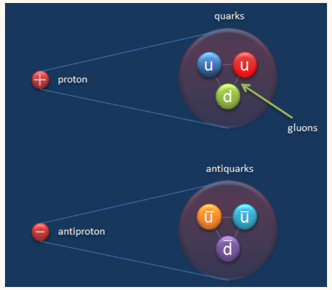
Lorentz symmetry violation

Unification of the four fundamental forces

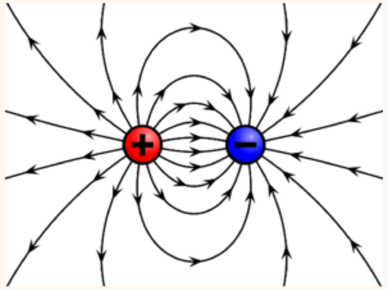
Weak force



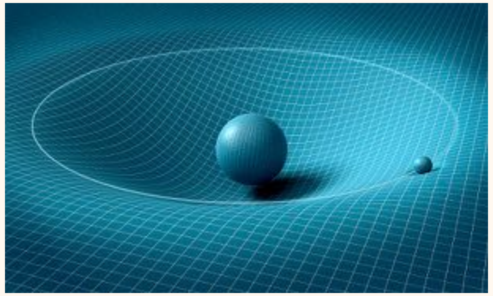
Strong Force



Electromagnetic Force



Gravitational Force



Picture citation: en.wikipedia.org; nuclear-power.net; emedicalprep.com; istockphoto.com.

Lorentz symmetry violation

Unification of the four fundamental forces

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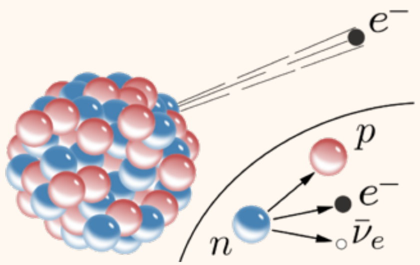

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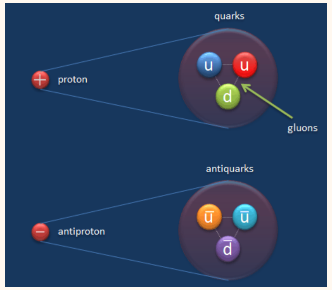

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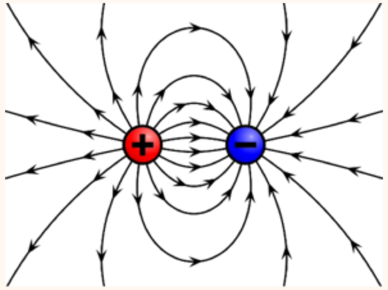

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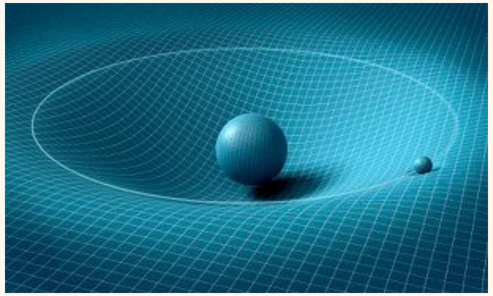
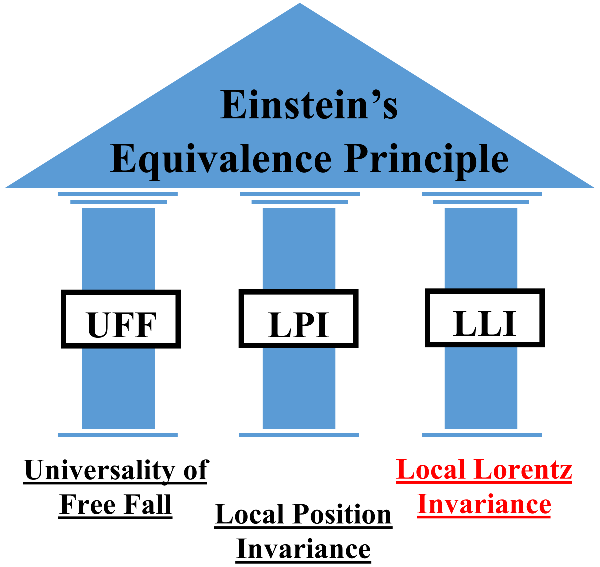
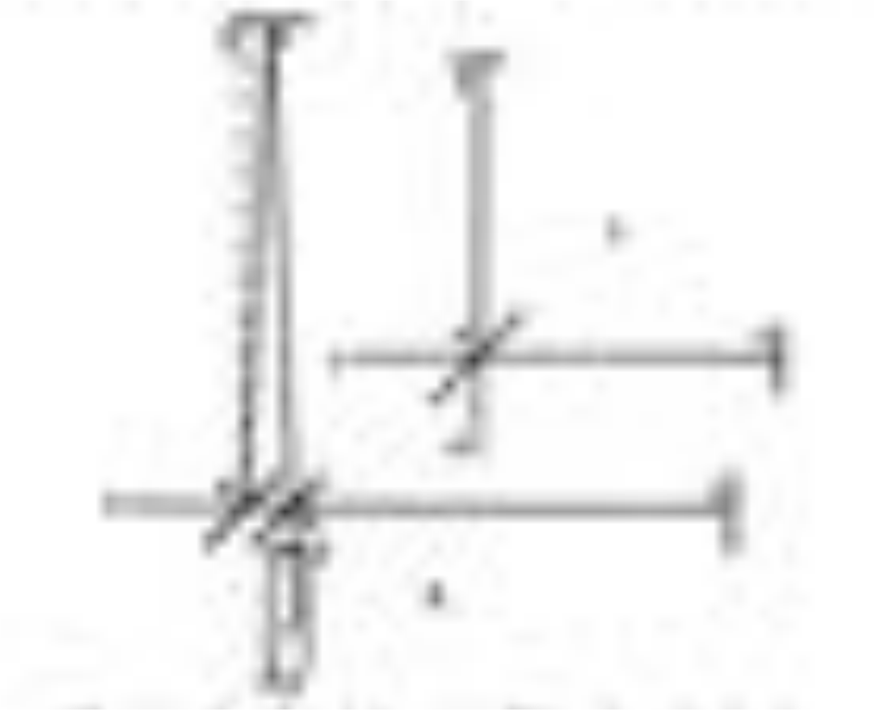




- A single quantum consistent theory of all four (known) fundamental forces: violation of Lorentz Symmetry
- Lorentz symmetry: The laws of physics are invariant under a Lorentz transformation (Rotation, Boost)
- Search for Lorentz violation with accurate low-energy measurements

Michelson-Morley experiment

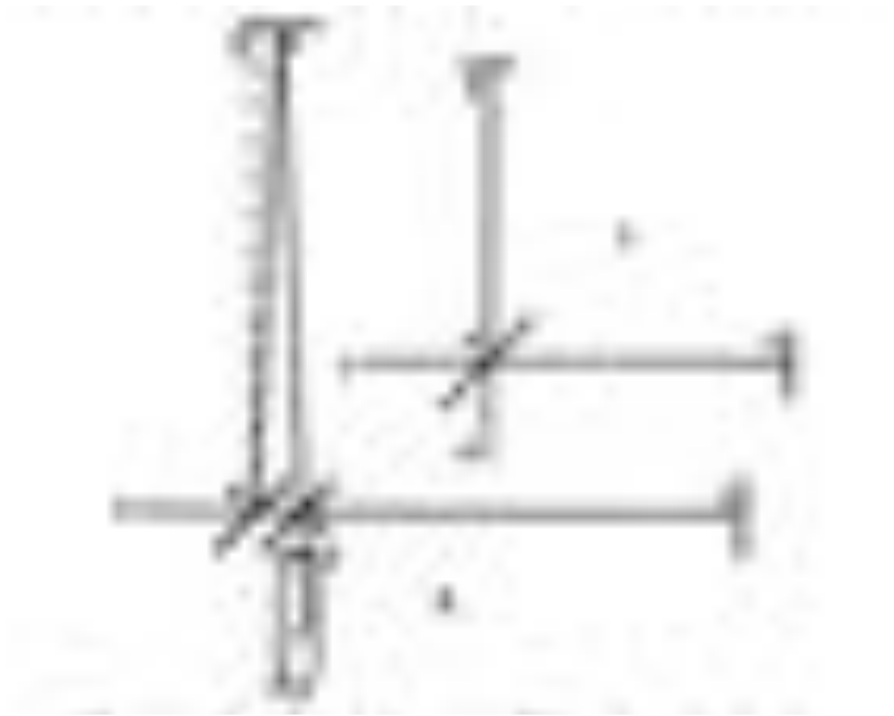


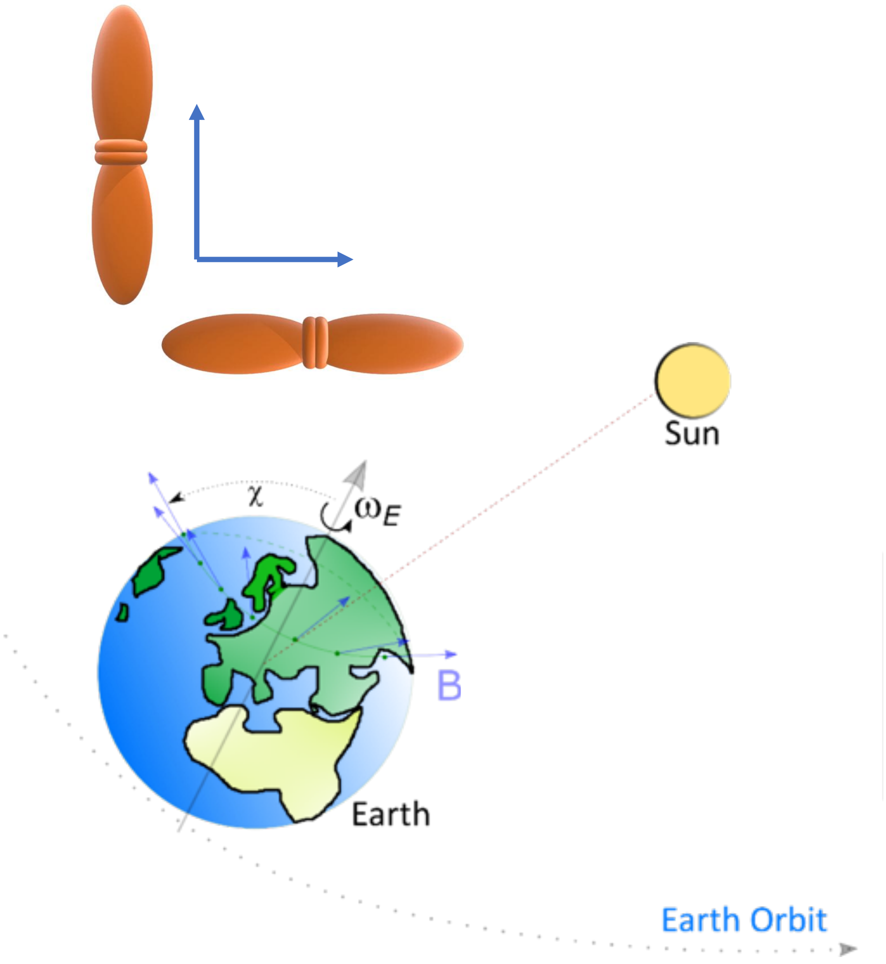
AMERICAN

JOURNAL OF SCIENCE

A. A. Michelson and E.W. Morley, *Philos. Mag. S.5*, 24(151), 449-463 (1887)

Analog of the Michelson-Morley experiment





A. A. Michelson and E.W. Morley, *Philos. Mag. S.5*, 24(151), 449-463 (1887)

Standard Model extension

- Lorentz violation (LV): quantified by adding a symmetry-breaking $c_{\mu\nu}$ tensor to the kinetic term of the SM Lagrangian

- The LV in the bound electronic states leads to a small shift of energy level according to:

$$\delta H = \frac{-C_0^{(2)} T_0^{(2)}}{6m}$$

$C_0^{(2)}$ contains components of $c_{\mu\nu}$

$T_0^{(2)} = \boldsymbol{p}^2 - 3p_z^2$ depents on the electronic momentum distribution

- For a state $|J, m\rangle$:

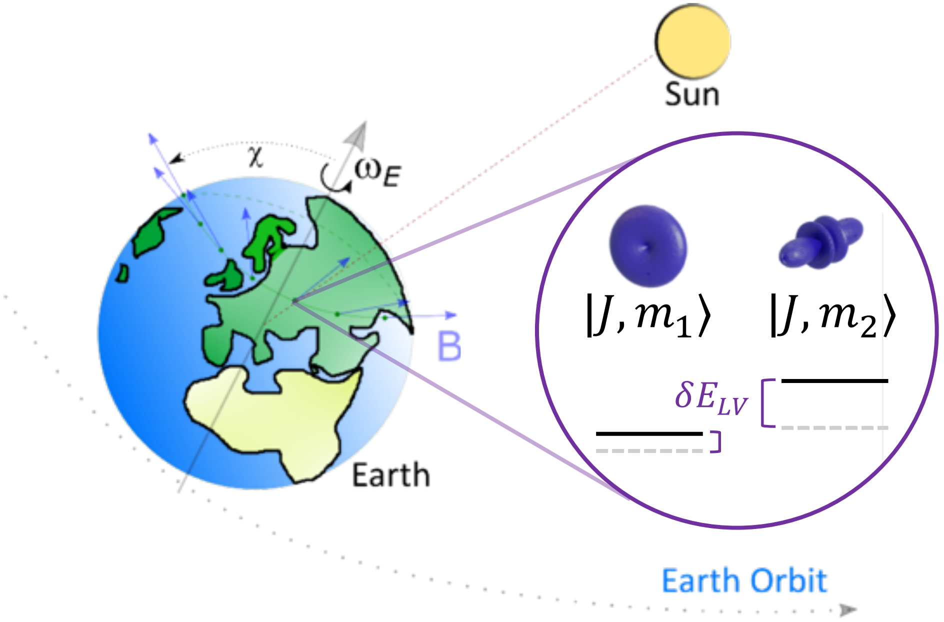
$$\left\langle J, m \left| T_0^{(2)} \right| J, m \right\rangle = \frac{-J(J+1) + 3m^2}{\sqrt{(2J+3)(J+1)(2J+1)J(2J-1)}} \times \left\langle J \left\| T_0^{(2)} \right\| J \right\rangle$$

M. A. Hohensee et al., *Phys. Rev. Lett.*, **111**: 050401 (2013)

Michelson-Morley type experiment with atomic orbitals

- Large effect of Lorentz violation (LV) in states with large electron-momentum
- Measure the energy shift between Zeeman substates, while the Earth rotates

Challenge: mitigate influence from the 1st-order Zeeman shift due to magnetic field noise



LV energy shift

$$\delta H_{LV} = \frac{-C_0^{(2)} T_0^{(2)}}{6m}$$

Elements of the $c_{\mu\nu}$ tensor

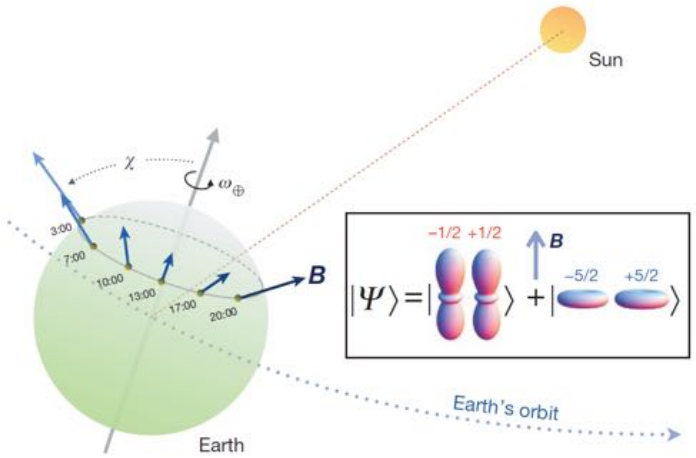
$T_0^{(2)} = \boldsymbol{p}^2 - 3p_z^2$

$$\delta E_{LV} \propto \left\langle J, m \left\| T_0^{(2)} \right\| J, m \right\rangle \times m^2$$

A. A. Michelson and E.W. Morley, *Philos. Mag. S.5*, 24(151), 449-463 (1887)
V. A. Dzuba et al., *Nature Phys.* **12**, 465-468 (2016)

Testing LLI using a decoherence free sub-state

A: engineer $m_{\text{eff}} = 0$ states → entangled state



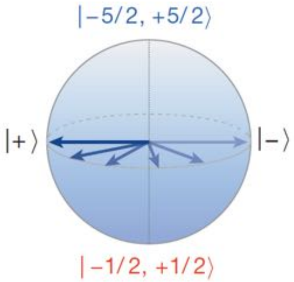
LETTER

doi:10.1038/nature14091

Michelson–Morley analogue for electrons using trapped ions to test Lorentz symmetry

T. Pruttivarasin[1,2], M. Ramm[1], S. G. Porsev[3,4], I. I. Tupitsyn[5], M. S. Safronova[3,6], M. A. Hohensee[1,7] & H. Häffner[1]

$$\frac{\Delta E}{h} = \left[\left(2.16\times 10^{15}\right) - \left(7.42\times 10^{14}\right) m_J^2\right] C_0^{(2)}$$



Constrains on components of $c_{\mu\nu}$ at the level of $10^{-18} - 10^{-19}$

Disadvantages: technically challenging and limited by decoherence (natural lifetime = 1.1 s)

T. Pruttivarasin et al. *Nature* **517**, 592-595 (2015)

Best test of LLI in the electron-photon sector

B: use $m = 0$ states in uneven isotope → 2 experiments/clocks with different quantization axis

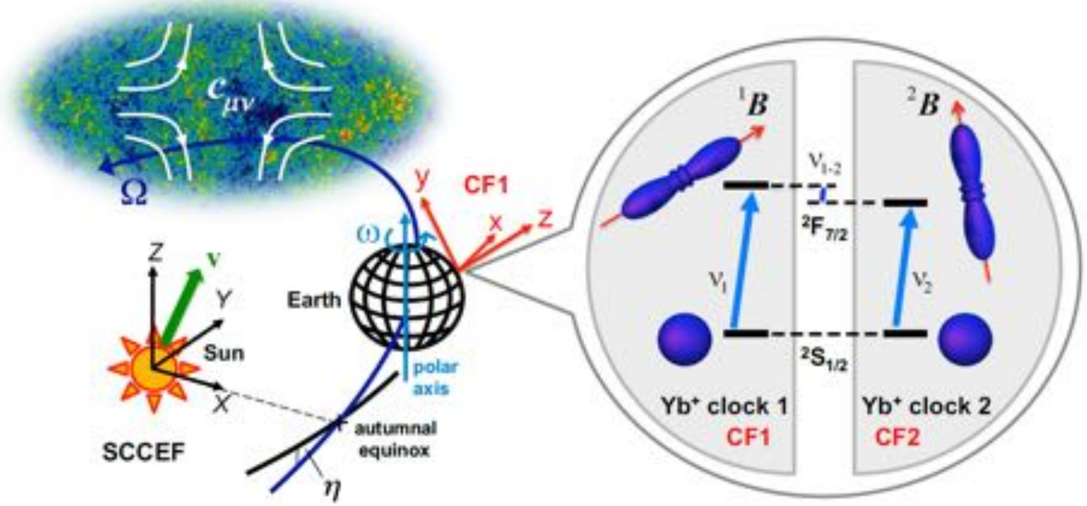

nature
International journal of science

Letter | Published: 13 March 2019

Optical clock comparison for Lorentz symmetry testing

Christian Sanner, Nils Huntemann, Richard Lange, Christian Tamm, Ekkehard Peik, Marianna S. Safronova & Sergey G. Porsev

Nature 567, 204–208 (2019) | Download Citation



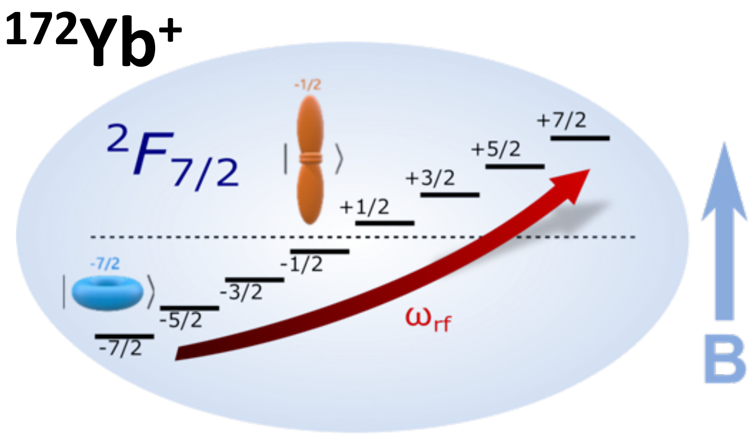
World record: constraint of one component of $c_{\mu\nu}$ at the level of $8.1{\times}10^{-21}$

Disadvantages: Requires **two** state-of-the-art optical clocks at the level of 10^{-18}

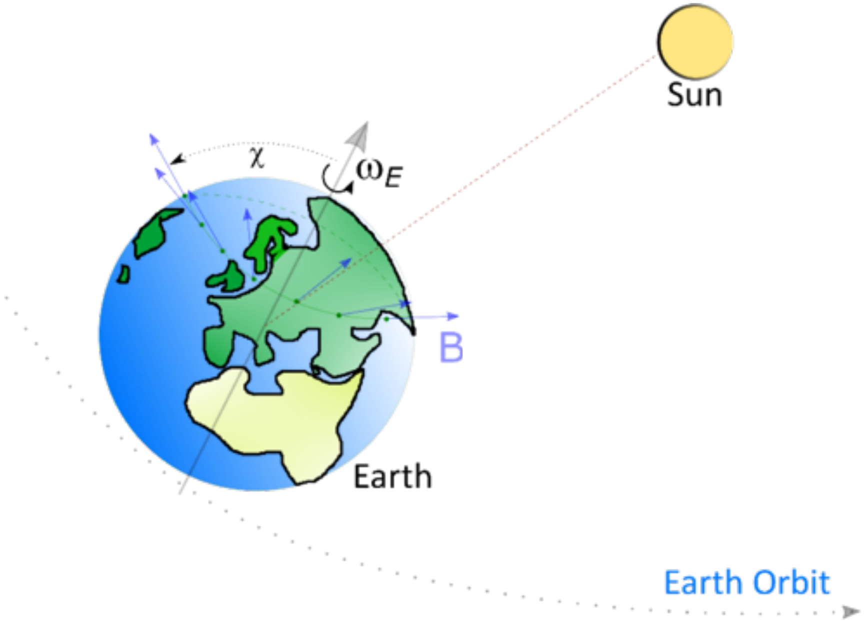
Sanner et al., *Nature* **567**, 204-208 (2019)

Rephasing with spin-echo

C: use an elaborate spin-echo rf sequence to achieve rephasing



$\mathbf{B} = B_z\hat{\mathbf{z}}$



Advantages

- A single experimental system
- Long coherence time in the rf regime→long Ramsey dark time ***T***
- Scalable to multiple ions ***N***

R. Shaniv et al., *Phys. Rev. Lett*. **120**, 103202 (2018)

Enhanced sensitivity of Yb^+

Table 1 | Reduced matrix elements of the $T^{(2)}$ operator in Ca^+, Ba^+, Yb^+ ions in atomic units.

Ion	State	$\langle J \| T^{(2)} \| J \rangle$
Ca^+	$3d\ ^2D_{3/2}$	7.09(12)
	$3d\ ^2D_{5/2}$	9.25(15)
Ba^+	$5d\ ^2D_{3/2}$	6.83
	$5d\ ^2D_{5/2}$	8.65
Yb^+	$4f^{14}5d\ ^2D_{3/2}$	9.96
	$4f^{14}5d\ ^2D_{5/2}$	12.08
	$4f^{13}6s^2\ ^2F_{7/2}$	−135.2

Ca^+ values are from ref. 6.

$$\delta H \propto \left\langle J, m \left| T_0^{(2)} \right| J, m \right\rangle = \frac{-J(J+1) + 3m^2}{\sqrt{(2J+3)(J+1)(2J+1)J(2J-1)}} \times \langle J || T || J \rangle$$

14.5 times higher sensitivity then Ca^+

F-state lifetime 1.6 years!

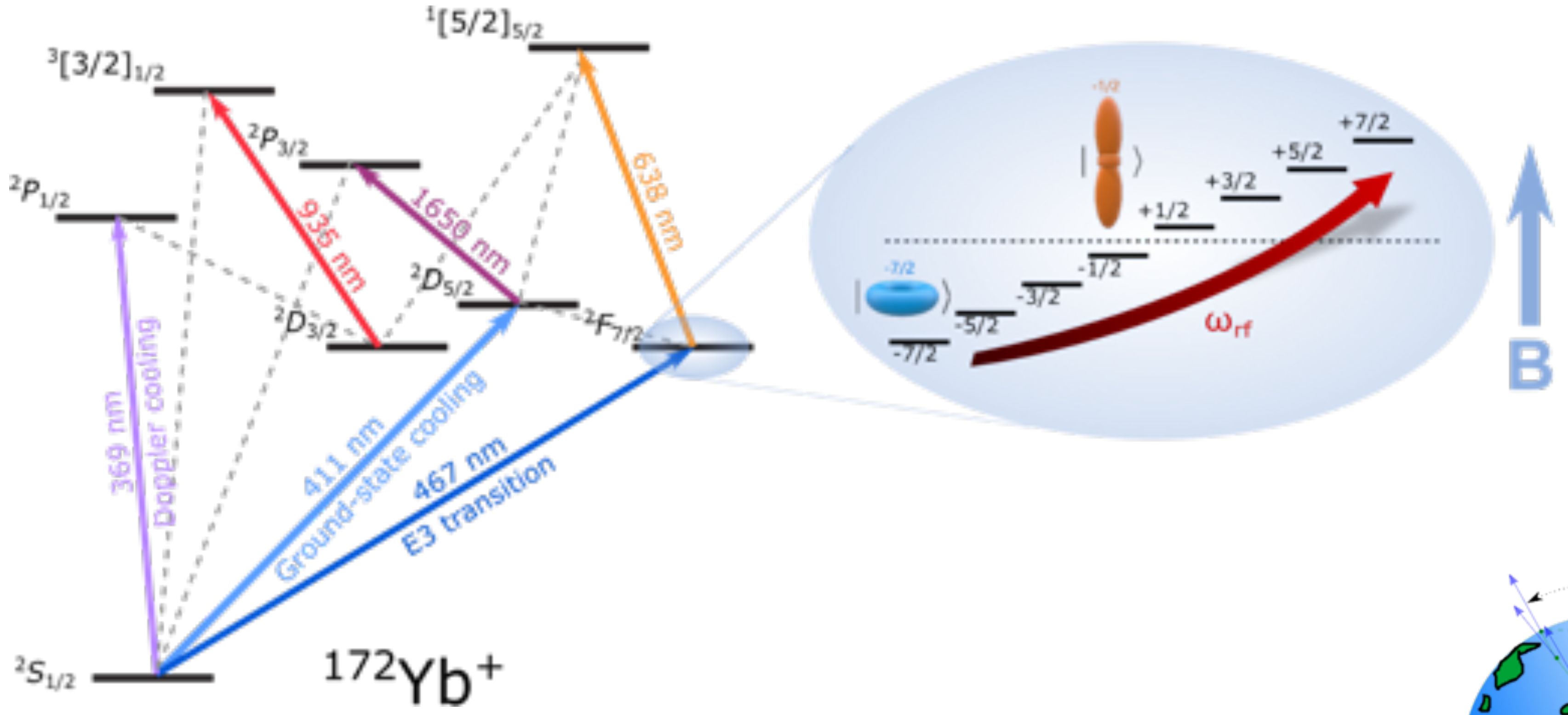
Projected LV sensitivity $\Delta C_0^{(2)} = \frac{3.1\times 10^{-18}}{\sqrt{NT\tau}}$

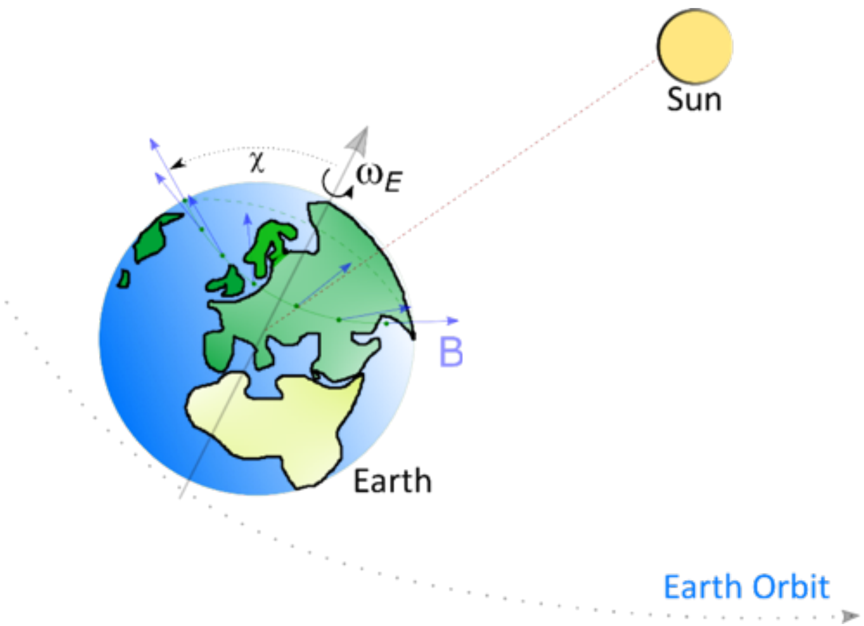
V. A. Dzuba et al., *Nature Phys.* **12**, 465-468 (2016)

R. Shaniv et al., *Phys. Rev. Lett.* **120**, 103202 (2018)

R. Lange et al., *Phy. Rev. Lett.* **127**, 213001 (2021)

Experimental requirements





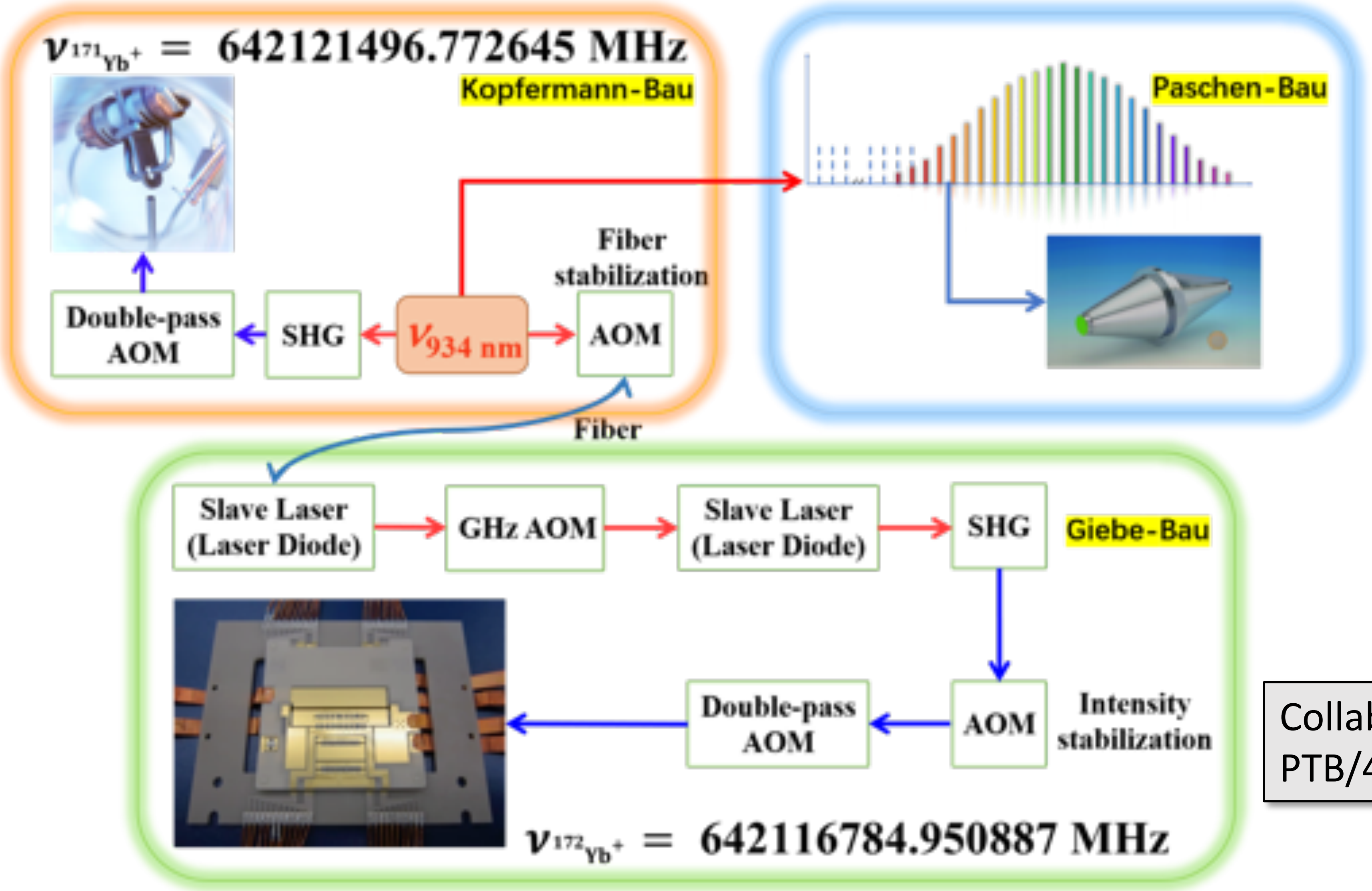
Long-term stable :

I. excite and de-excite on the highly forbidden E3 transition

II. composite rf pulse sequence in the F state with a dark time of ~1s

R. Shaniv et al., *Phys. Rev. Lett.* **120**, 103202 (2018)

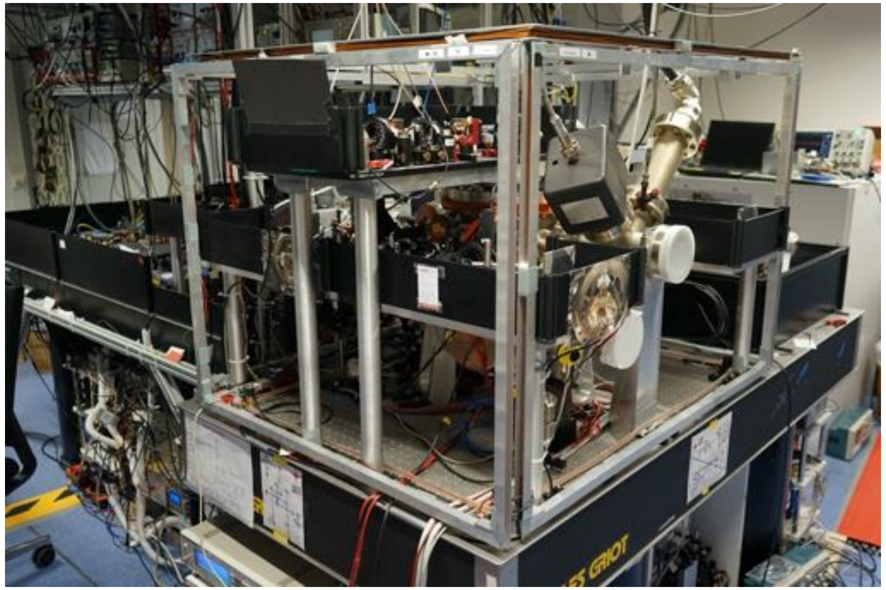
Excitation laser for the electric octupole (E3) transition



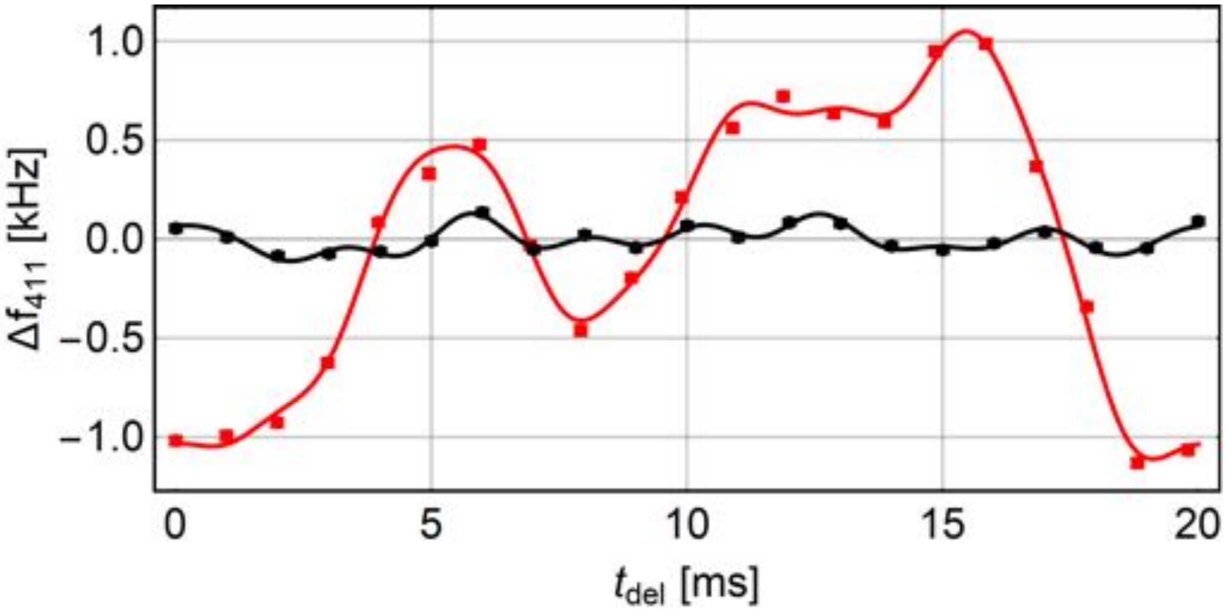
Collaboration
PTB/4.4 & PTB/QUEST

Magnetic field stabilization

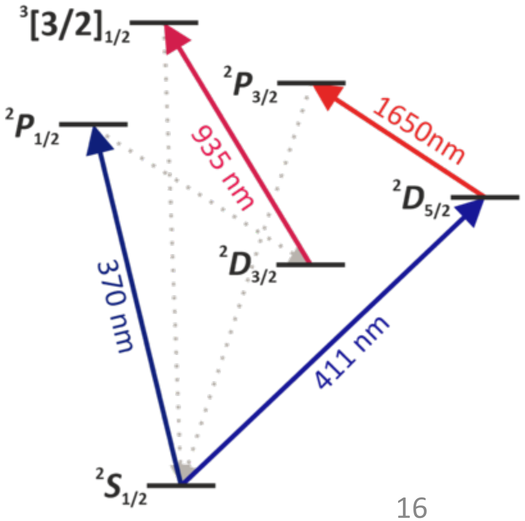
a) Feedback stabilization: noise at up to 10Hz



b) Feedforward stabilization: main power line 50Hz & harmonics



- Feedback stabilization: reduced incoherent noise to below 5nT
- Feedforward stabilization: reduced coherent noise from 70nT to about 7nT



B. Merkel et al., *Rev. Sci. Inst*. **90**, 044702 (2019)

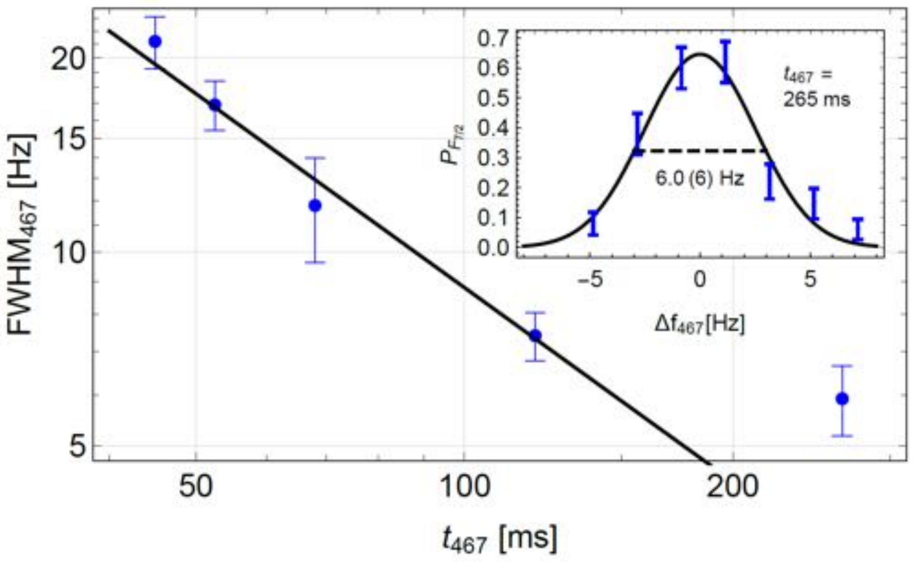
Coherent excitation of the E3 transition

PHYSICAL REVIEW LETTERS **125**, 163001 (2020)

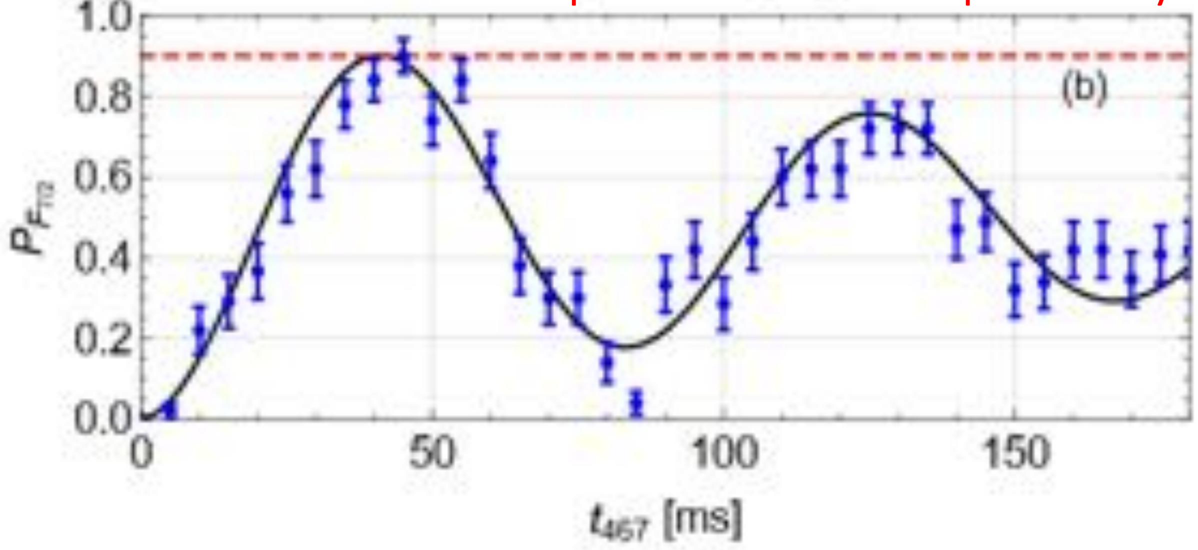
Coherent Excitation of the Highly Forbidden Electric Octupole Transition in $^{172}Yb^+$

H. A. Fürst,[1,2] C.-H. Yeh,[1] D. Kalincev,[1] A. P. Kulosa,[1] L. S. Dreissen,[1] R. Lange,[1] E. Benkler,[1] N. Huntemann,[1] E. Peik,[1] and T. E. Mehlstäubler[1,2,*]
[1]*Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany*
[2]*Institut für Quantenoptik, Leibniz Universität Hanover, Welfengarten 1, 30167 Hanover, Germany*

Coherent atomic state manipulation in 1st-order Zeeman sensitive state

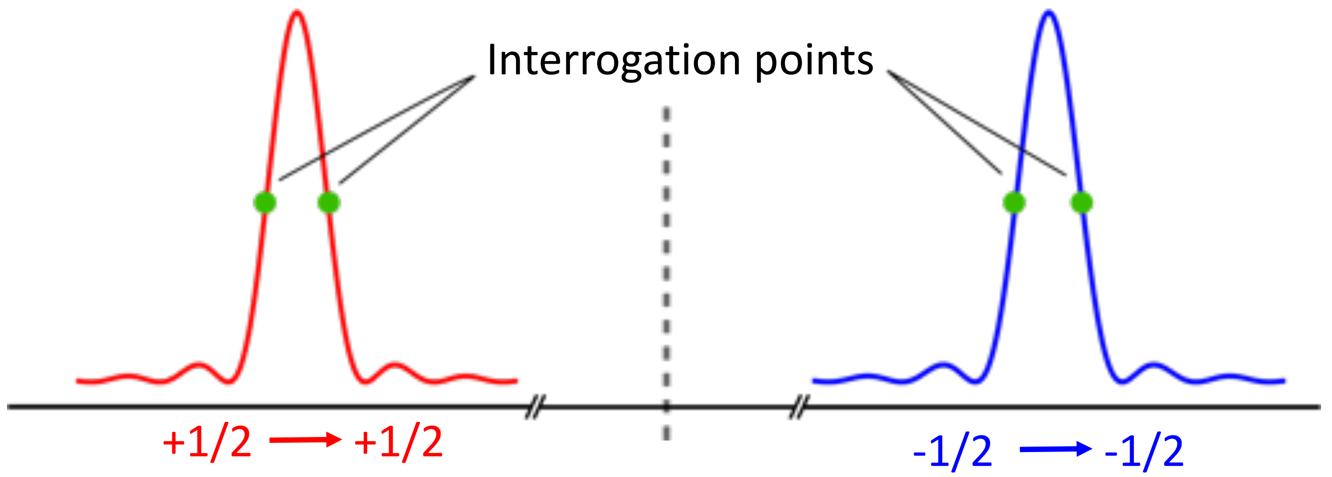


Up to 90 % excitation probability!

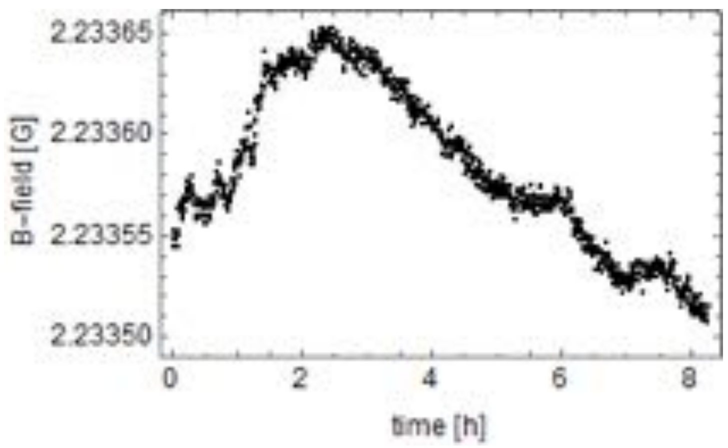


Stable excitation over long timescales

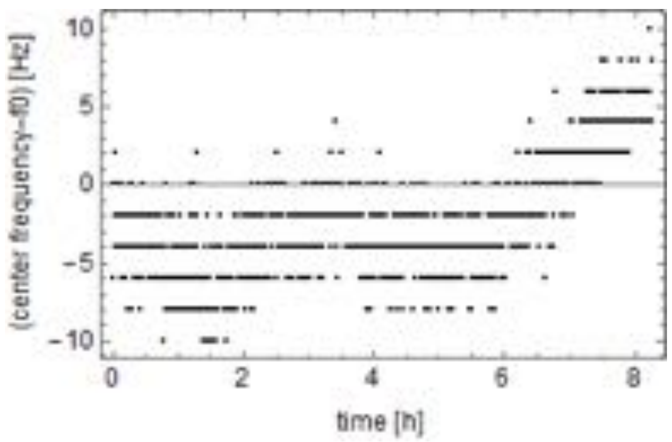
Implemented a 4-point 'clock' servo on two Zeeman transitions



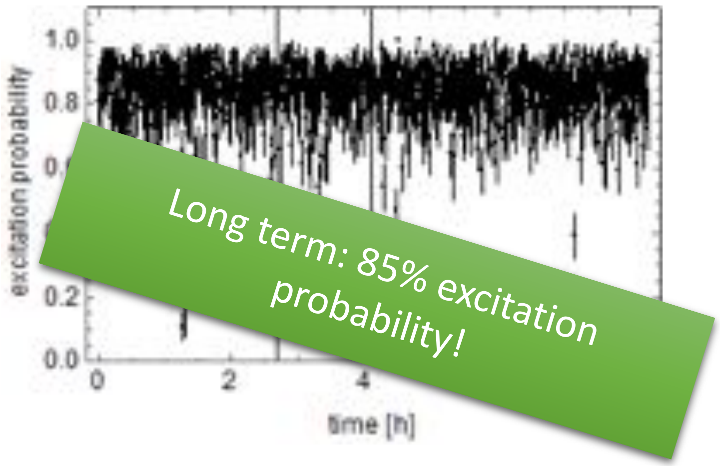
Extracted magnetic field



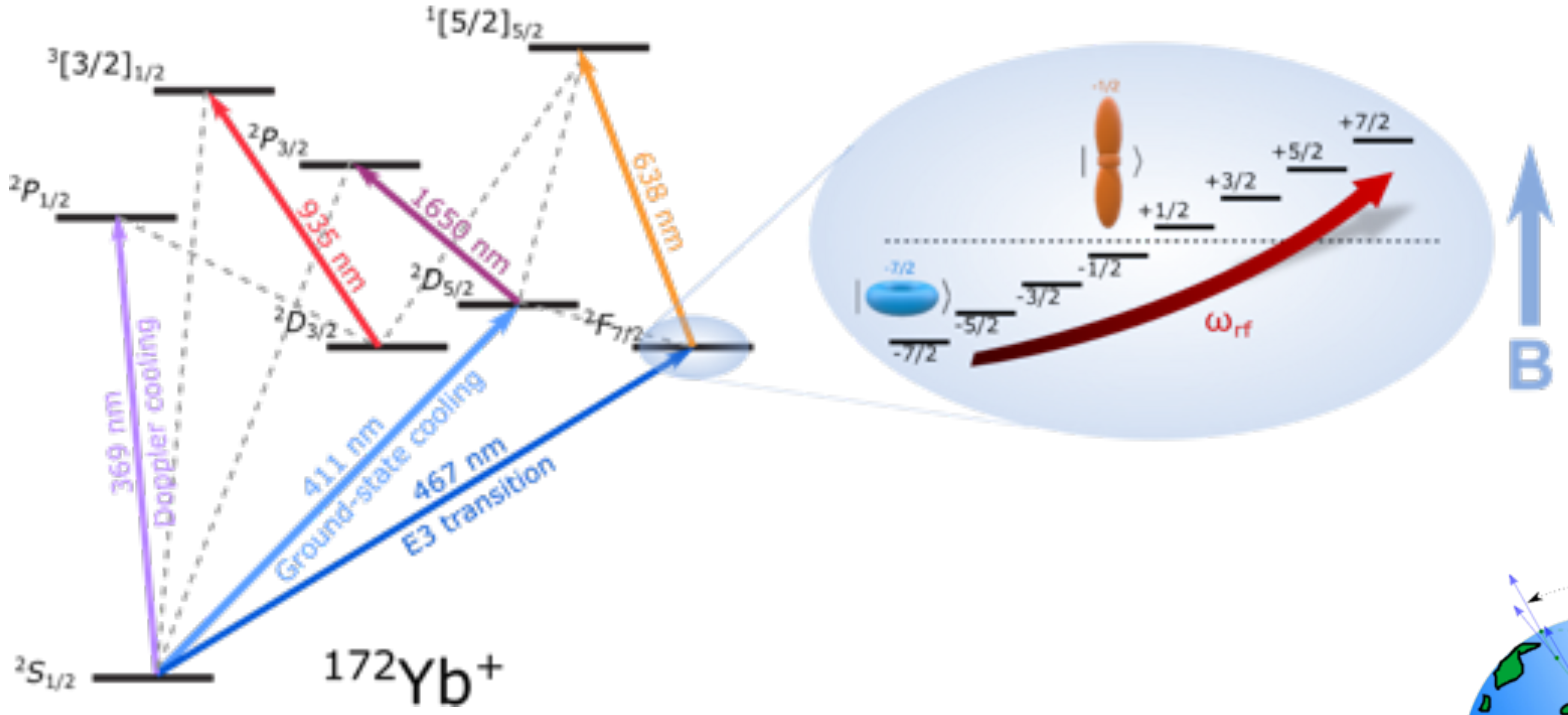
Extracted center frequency

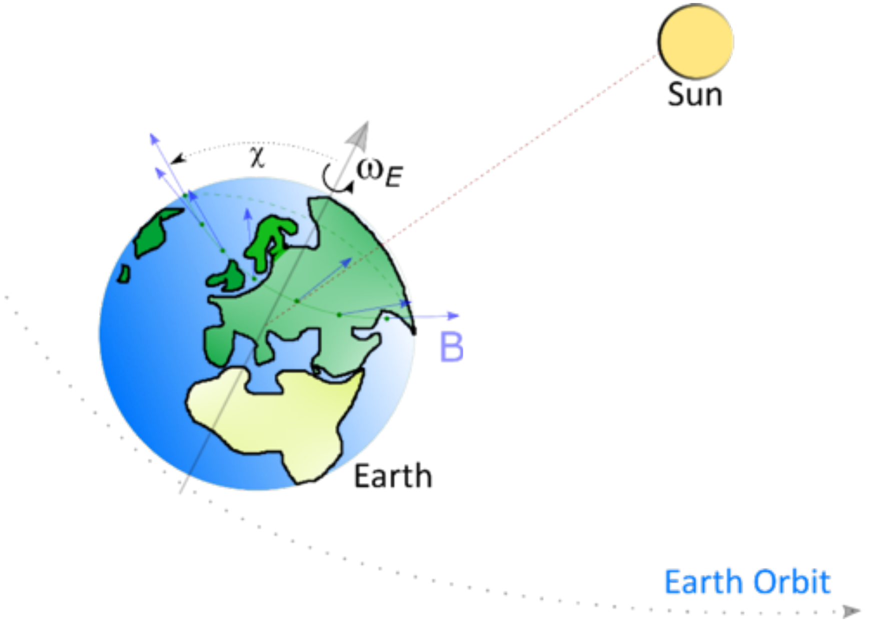


Excitation probability



Experimental requirements





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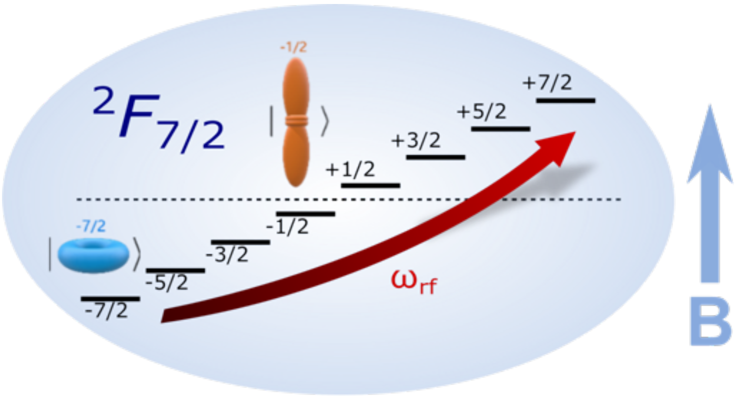
8-level system



$\mathbf{B} = B_z\hat{\mathbf{z}}$

$H_{\text{free}} = H_{\text{lin}} + H_{\text{quad}}$

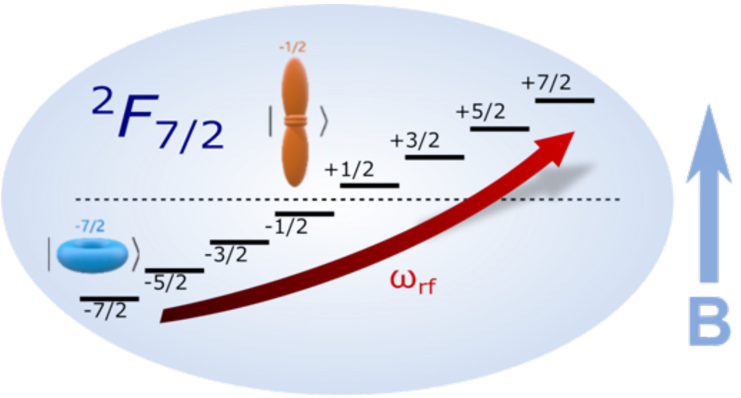
$H_{\text{lin}} = \mu_z B_z J_z$ proportional to m

$H_{\text{quad}} = \kappa J_z^2$ proportional to m^2

Contains the quadrupole shift and a **potential LLI violation**

R. Shaniv et al., *Phys. Rev. Lett.* **120**, 103202 (2018)

8-level system



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Contains the quadrupole shift and a **potential LLI violation**

Coupling: $H_{\text{coup}} = \Omega(t)\cos(\omega_{\text{rf}}\, t + \phi)J_x$ with $\omega_{rf} \approx \omega_{\text{res}} = \frac{\mu_z B_z}{\hbar} + \delta(t)$

Multi-level Rabi frequency

Drifts in the ambient magnetic field

Interaction picture + RWA: $H = \delta(t)J_z + \kappa J_z^2 + \Omega(t)[J_x\cos(\phi) - J_y\sin(\phi)]$

Assumption: $\Omega(t) \gg \dot{\kappa}, \dot{\delta}(t)$

Goal: measure κ, while mitigating the influence from $\delta(t)$

R. Shaniv et al., *Phys. Rev. Lett.* **120**, 103202 (2018)

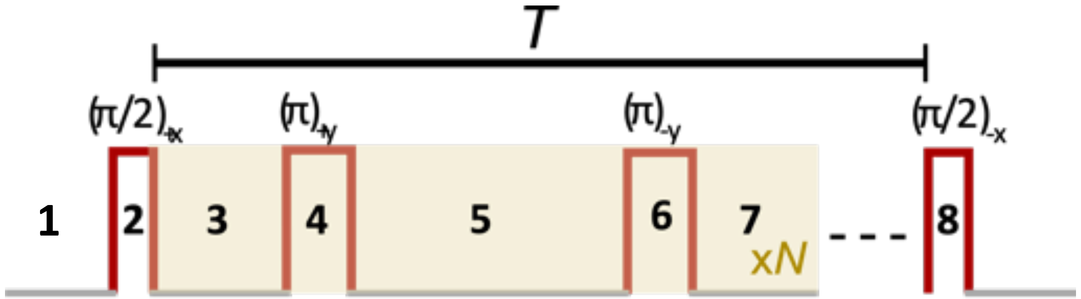
Composite rf sequence on the Bloch sphere

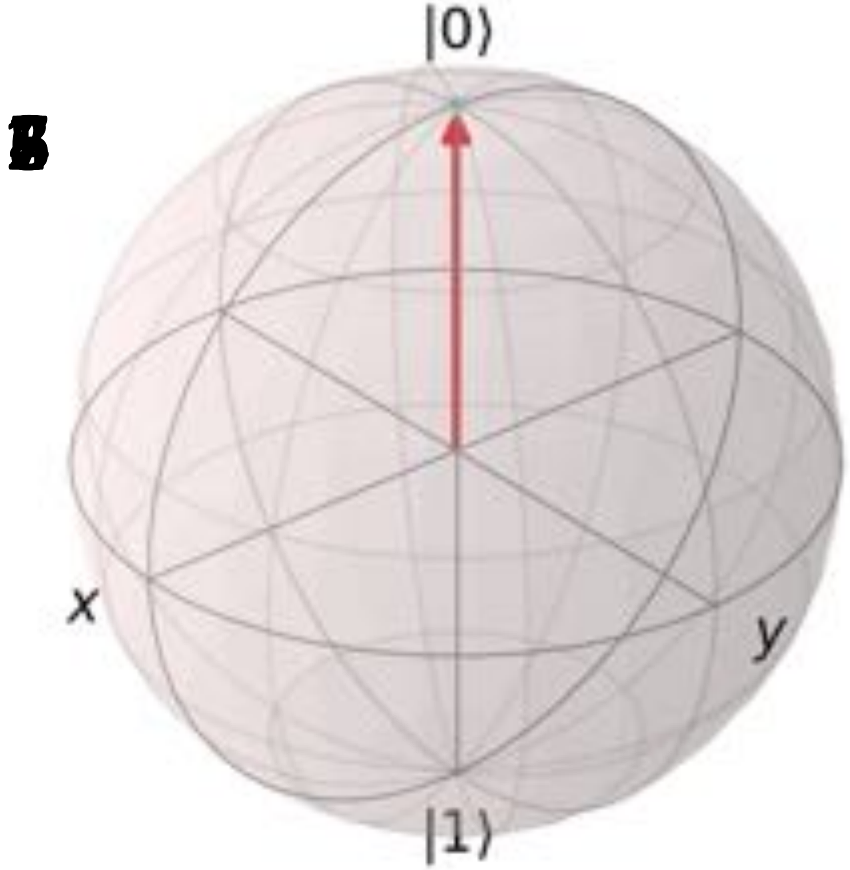
$|0\rangle = |F, m = \pm 1/2\rangle$

$|1\rangle = |F, m = \mp 1/2\rangle$

Goal: measure κ, while mitigating the influence from $\delta(t)$

Proposed pulse scheme by Shaniv et al.:





R. Shaniv et al., *Phys. Rev. Lett.* **120**, 103202 (2018)

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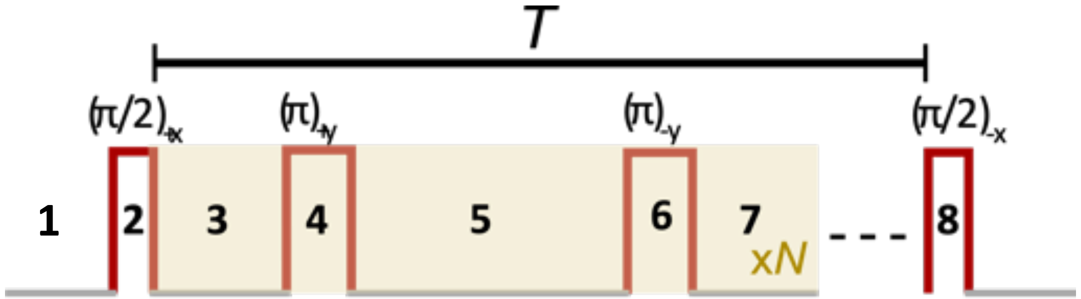
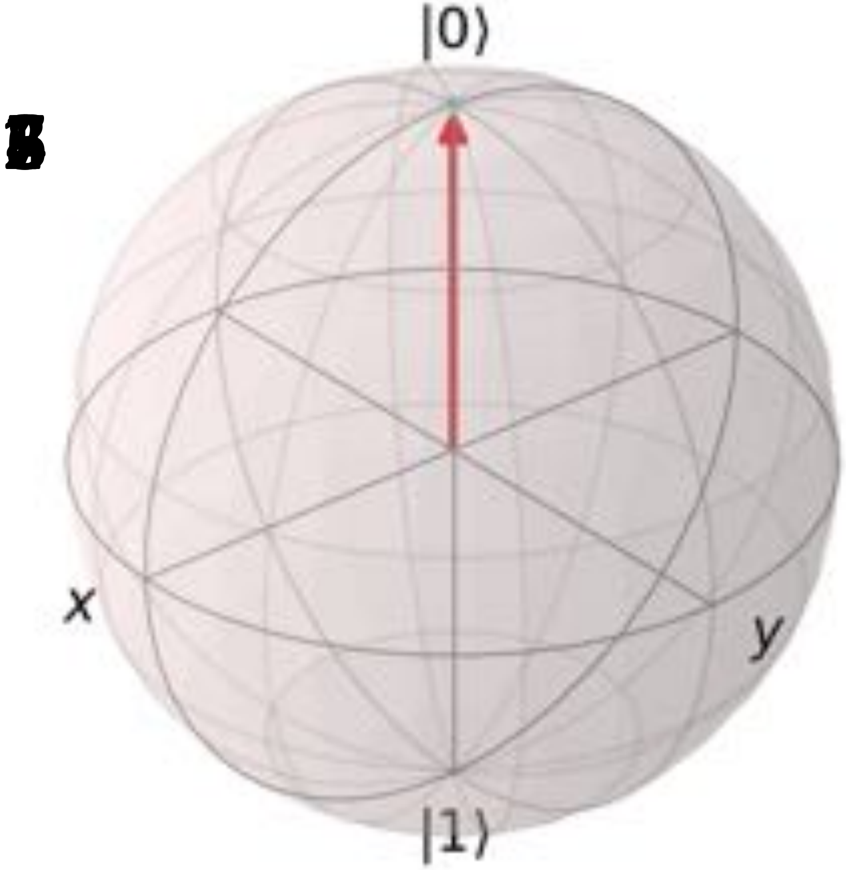


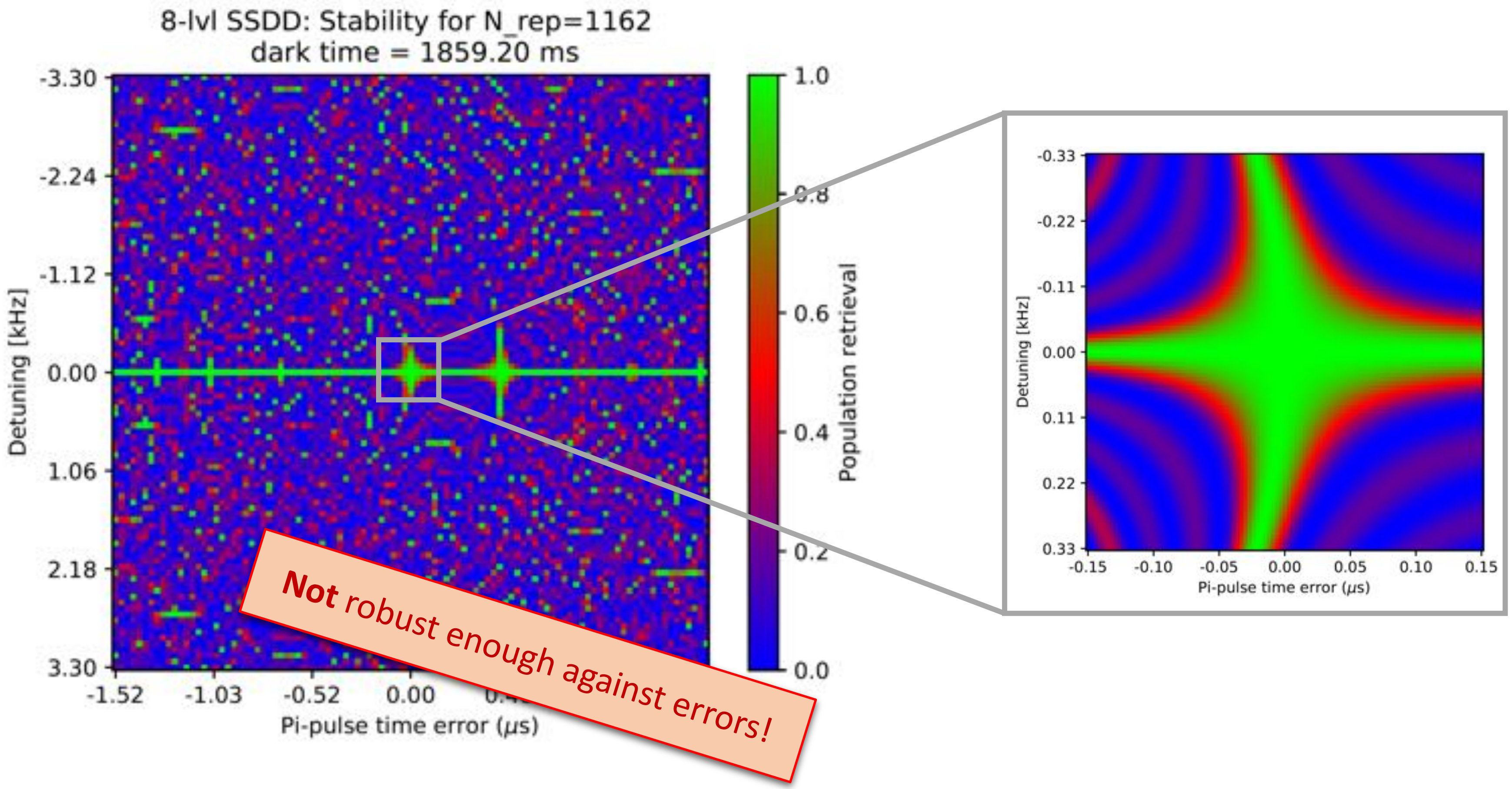
Problem: pulse errors accumulate when using many pulses (~10.000)



R. Shaniv et al., *Phys. Rev. Lett.* **120**, 103202 (2018)

Simulated stability diagram simple rf sequence

Simple spin-echo scheme



Scanning:

- Pulse time $\pm 0.1 \times t_{pi}$
- Detuning $\pm 0.1 \times \Omega_{rabi}$

Robust dynamical decoupling sequences

PRL **118,** 133202 (2017) PHYSICAL REVIEW LETTERS week ending 31 MARCH 2017

Arbitrarily Accurate Pulse Sequences for Robust Dynamical Decoupling

Genko T. Genov,[1,*] Daniel Schraft,[1] Nikolay V. Vitanov,[2] and Thomas Halfmann[1,†]

[1]*Institut für Angewandte Physik, Technische Universität Darmstadt, Hochschulstr. 6, 64289 Darmstadt, Germany*

[2]*Department of Physics, St. Kliment Ohridski University of Sofia, 5 James Bourchier blvd, 1164 Sofia, Bulgaria*

(Received 29 September 2016; published 28 March 2017)

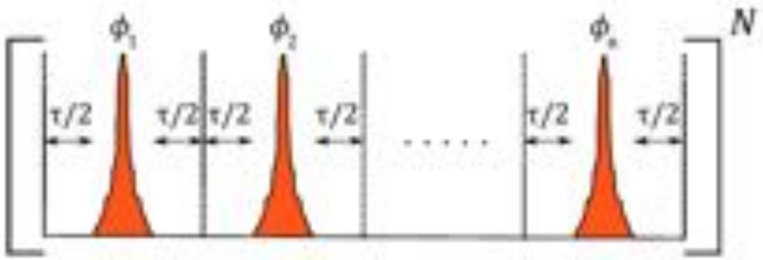


FIG. 1. Schematic description of a DD sequence with n equally separated phased pulses. A single cycle free evolution-pulse-free evolution lies within the dashed lines. The proper choice of the relative phases of the pulses compensates both pulse errors and dephasing due to the environment. The DD sequence is repeated N times during the storage time; the pulse shape can be arbitrary.

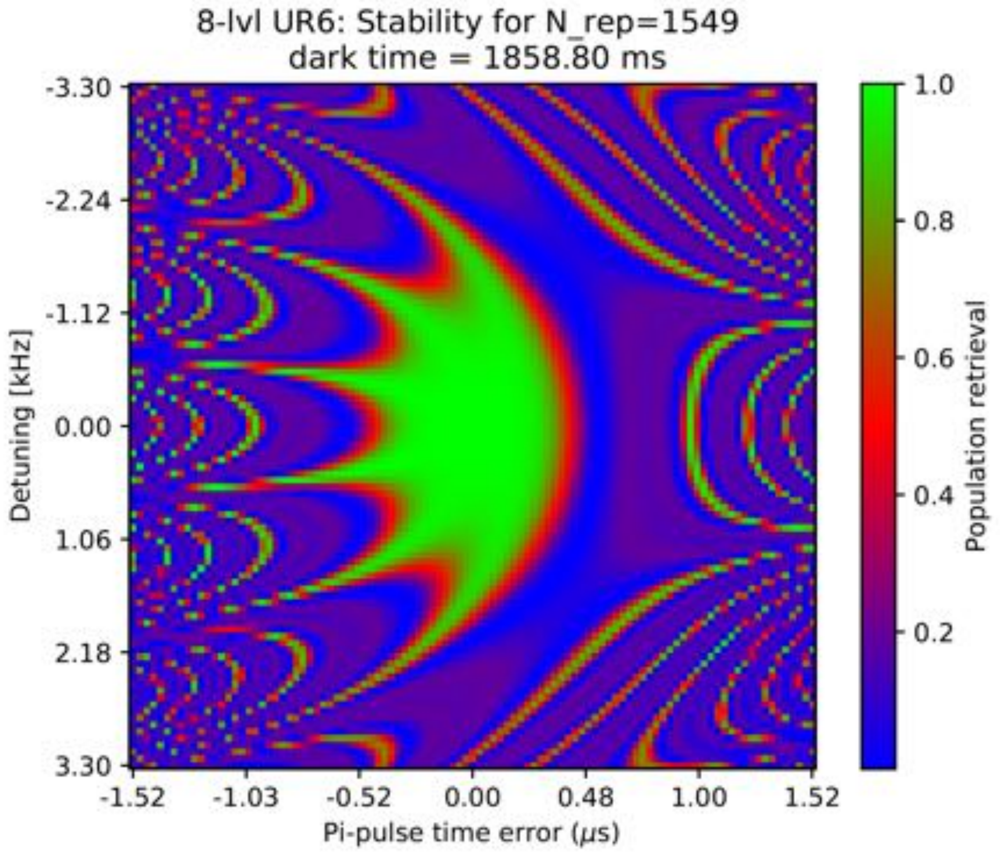
TABLE I. Phases of the symmetric universal rephasing (UR) DD sequences with n cycles (indicated by the number in the label), based on Eq. (3). Each phase is defined modulo 2π.

Sequence	Phases	$\Phi^{(n)}$
UR4	$(0, 1, 1, 0)\pi$	π
UR6	$\pm(0, 2, 0, 0, 2, 0)\pi/3$	$\pm 2\pi/3$
UR8	$\pm(0, 1, 3, 2, 2, 3, 1, 0)\pi/2$	$\pm\pi/2$
UR10	$\pm(0, 4, 2, 4, 0, 0, 4, 2, 4, 0)\pi/5$	$\pm 4\pi/5$
UR12	$\pm(0, 1, 3, 0, 4, 3, 3, 4, 0, 3, 1, 0)\pi/3$	$\pm\pi/3$
UR14	$\pm(0,6,4,8,4,6,0,0,6,4,8,4,6,0)\pi/7$	$\pm 6\pi/7$
UR16	$\pm(0,1,3,6,2,7,5,4,4,5,7,2,6,3,1,0)\pi/4$	$\pm\pi/4$

G. T. Genov et al., Phys. Rev. Lett. 118, 133202 (2017)

Simulated stability diagrams

UR 6 as given by G.T. Genov et al.:
$(0,2,0,0,2,0)\pi/3$



Scanning:

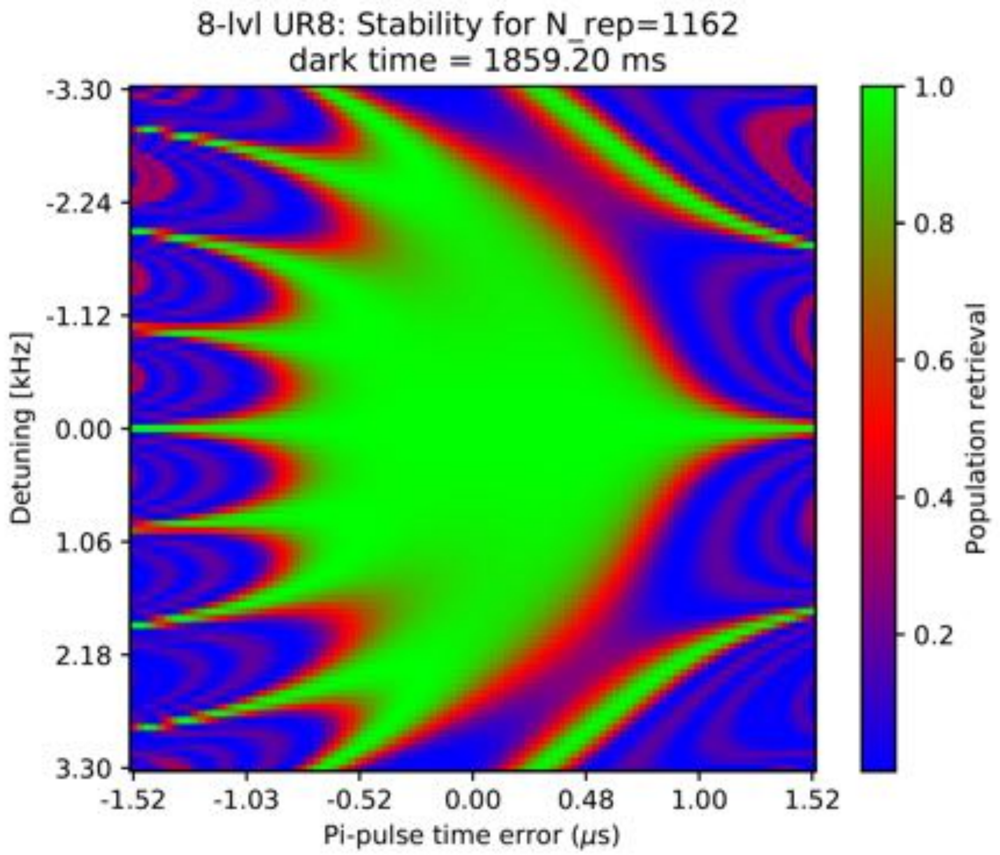
- Pulse time $\pm 0.1 \times t_{pi}$
- Detuning $\pm 0.1 \times \Omega_{rabi}$

G. T. Genov et al., Phys. Rev. Lett. 118, 133202 (2017)

Simulated stability diagrams

UR 8 as given by G.T. Genov et al.:

$$(0,1,3,2,2,3,1,0)\pi/2$$



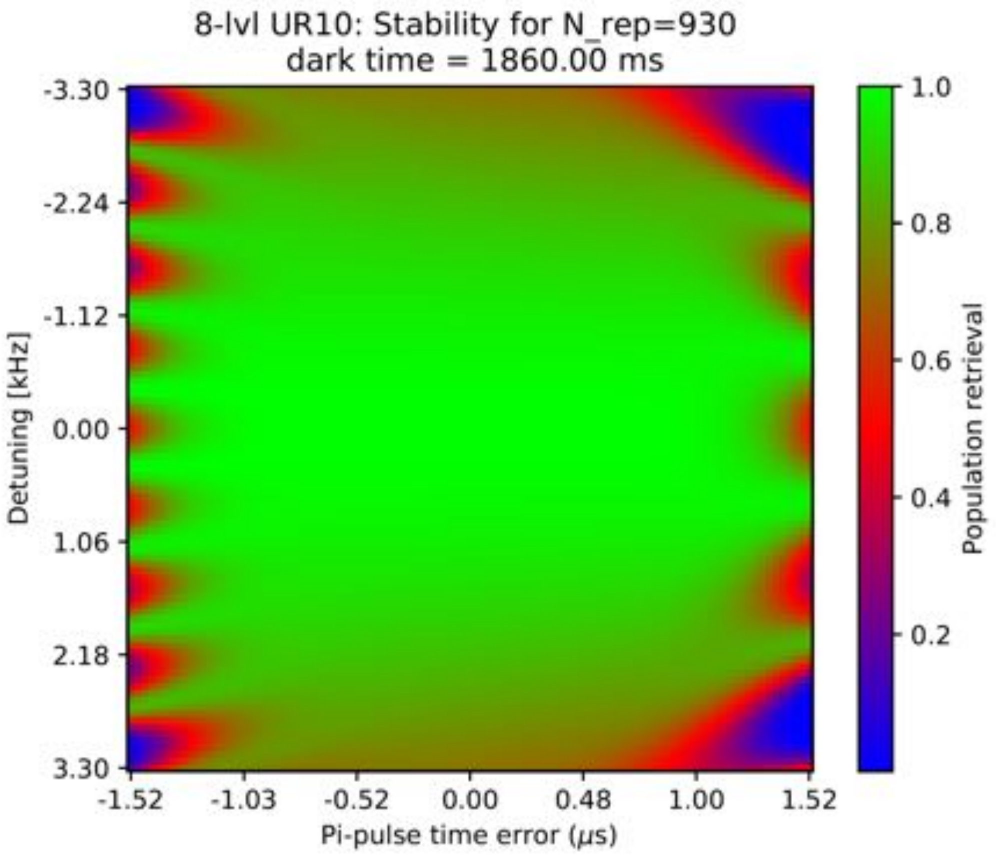
Scanning:

- Pulse time $\pm 0.1 \times t_{pi}$
- Detuning $\pm 0.1 \times \Omega_{rabi}$

G. T. Genov et al., Phys. Rev. Lett. 118, 133202 (2017)

Simulated stability diagrams

UR 10 as given by G.T. Genov et al.:
$(0,4,2,4,0,0,4,2,4,0)4\pi/5$



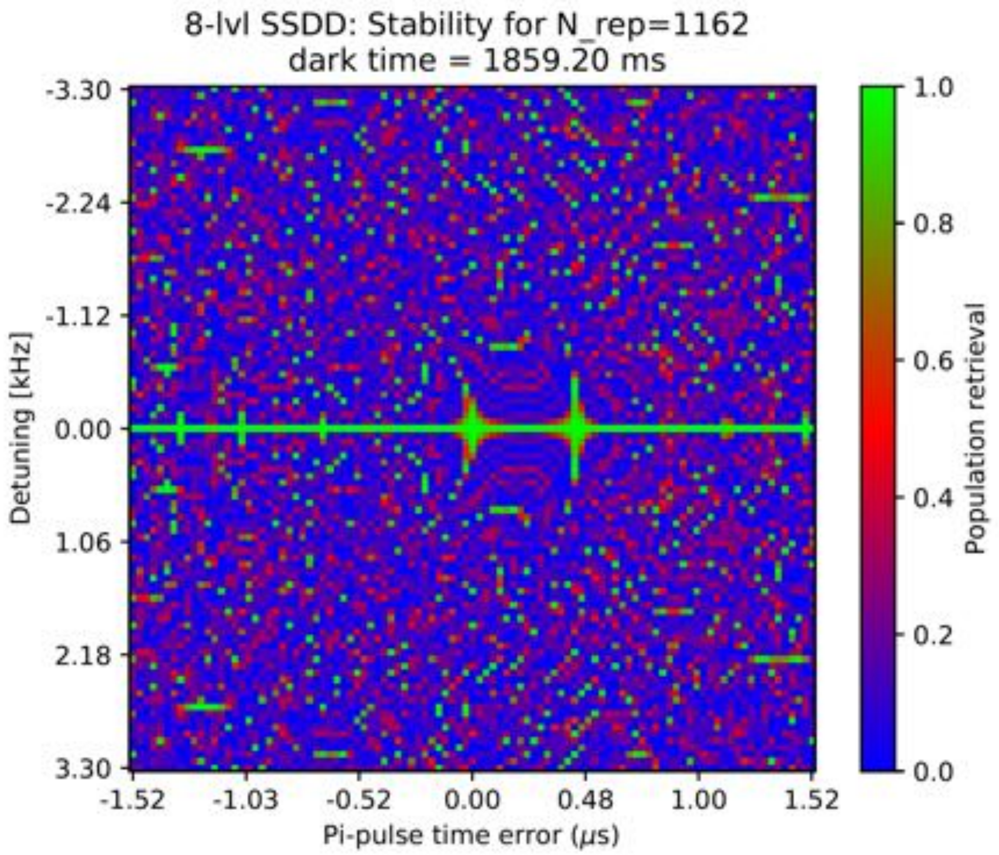
Scanning:

- Pulse time $\pm 0.1\times t_{pi}$
- Detuning $\pm 0.1\times \Omega_{rabi}$

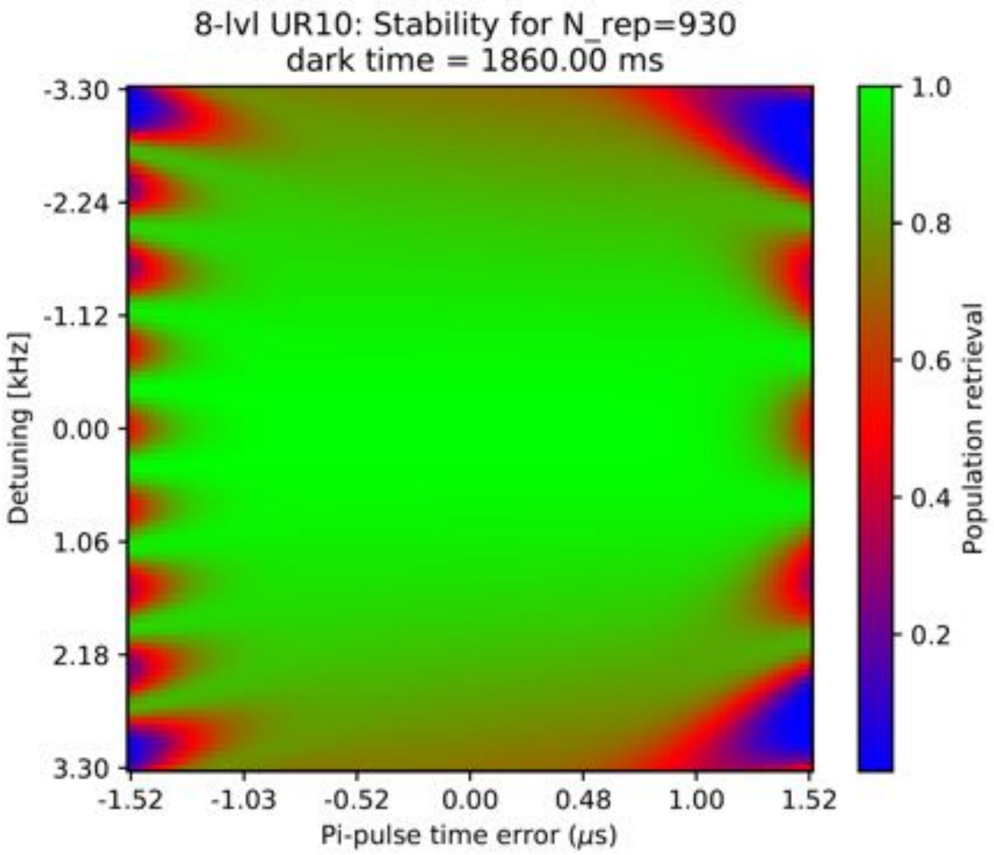
G. T. Genov et al., Phys. Rev. Lett. 118, 133202 (2017)

Simulated stability diagram UR10

Simple spin-echo scheme

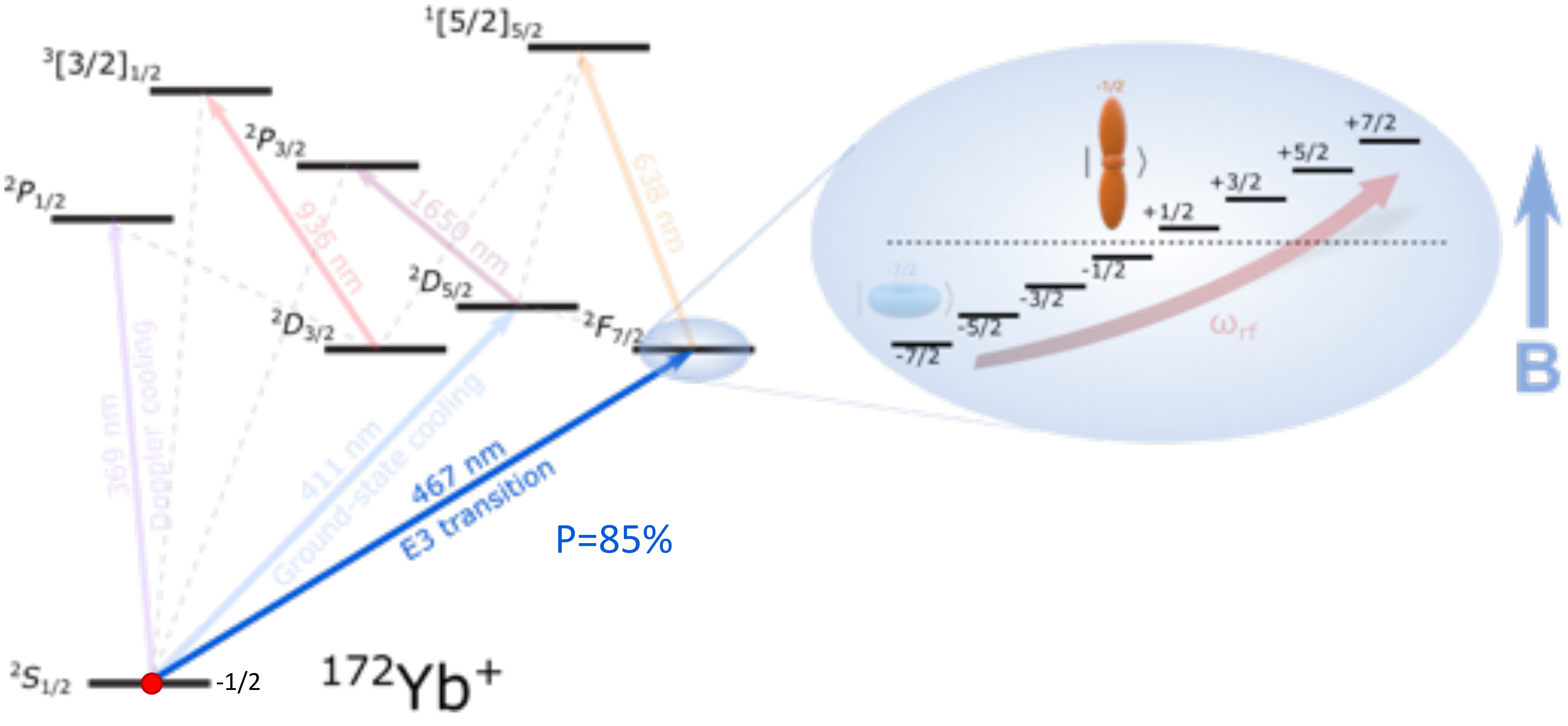


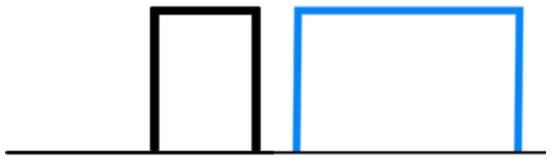
UR 10 as given by G.T. Genov et al.:
$(0,4,2,4,0,0,4,2,4,0)4\pi/5$



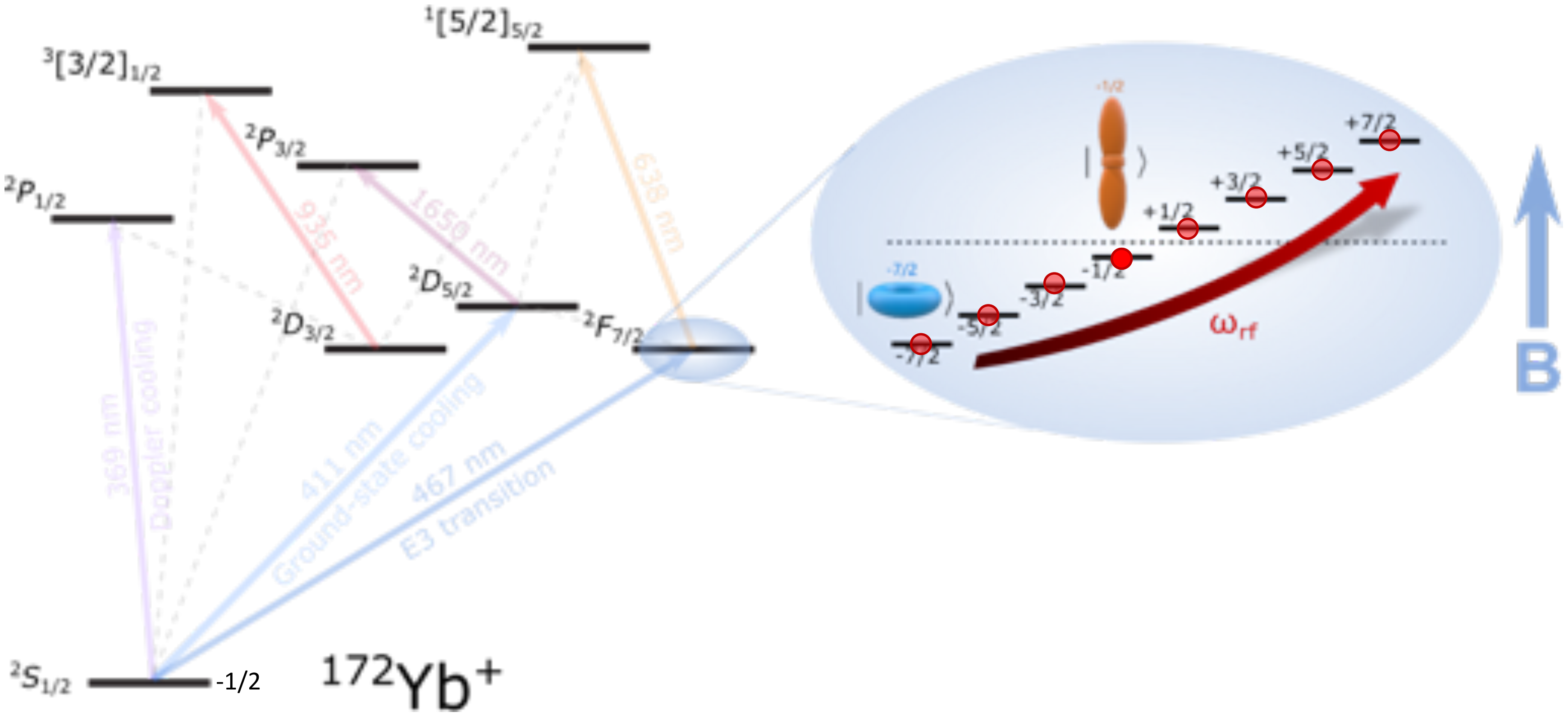
G. T. Genov et al., Phys. Rev. Lett. 118, 133202 (2017)

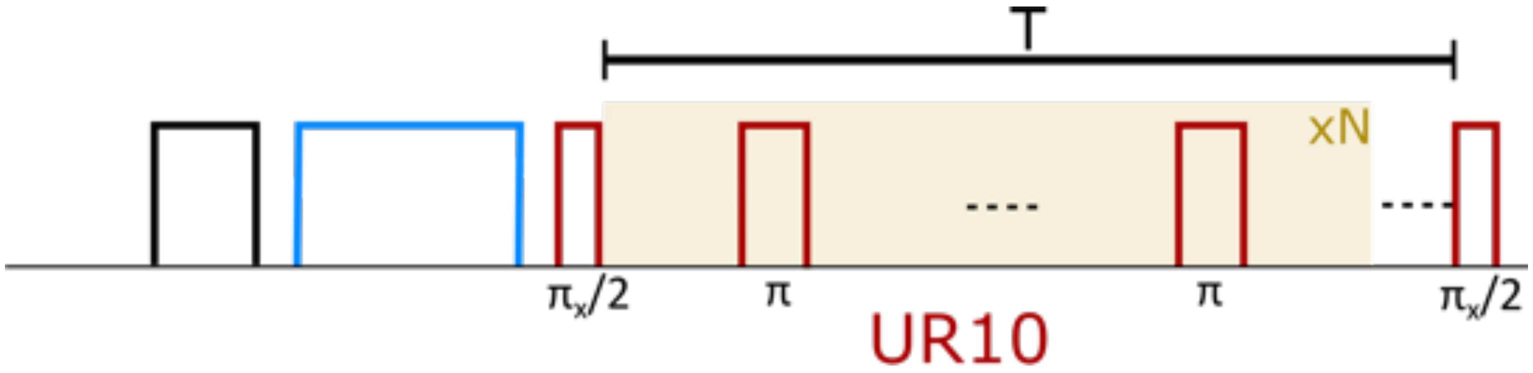
The full experimental sequence





The full experimental sequence





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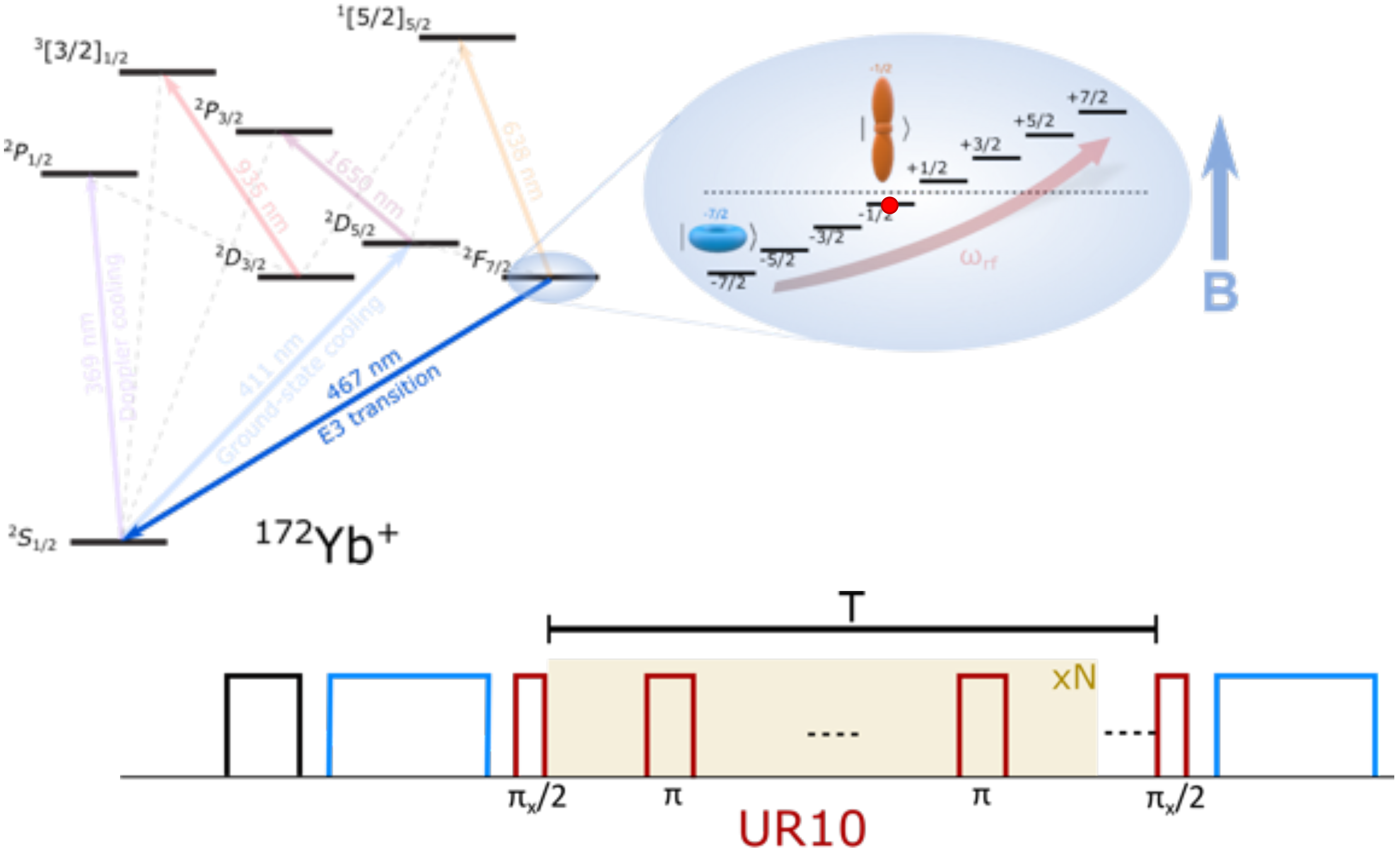

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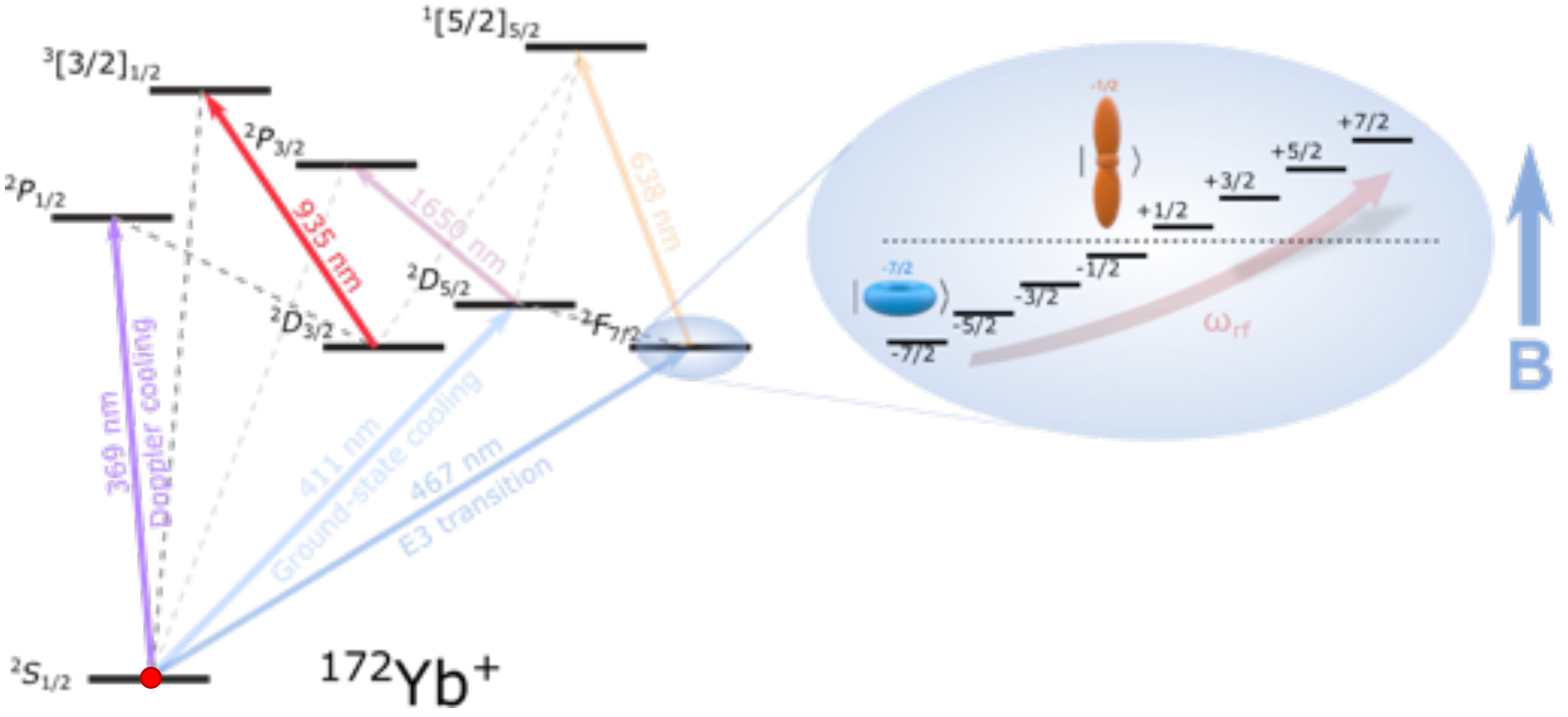
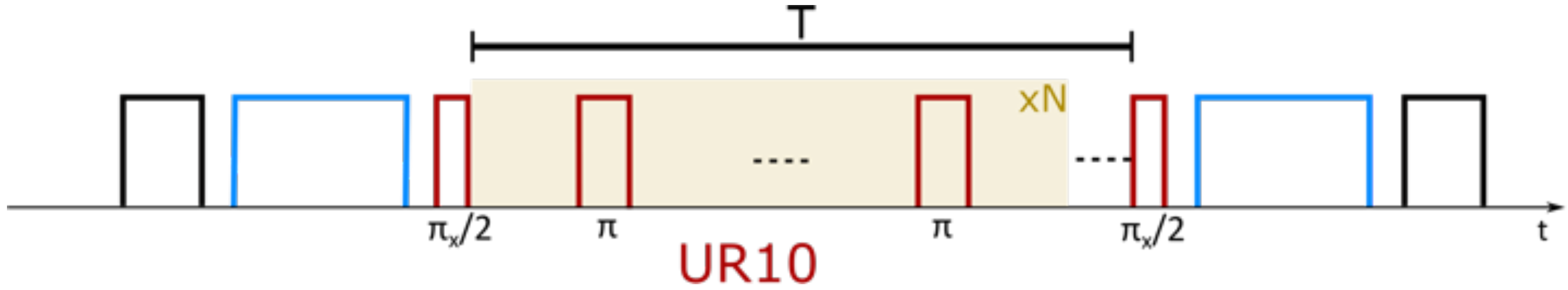
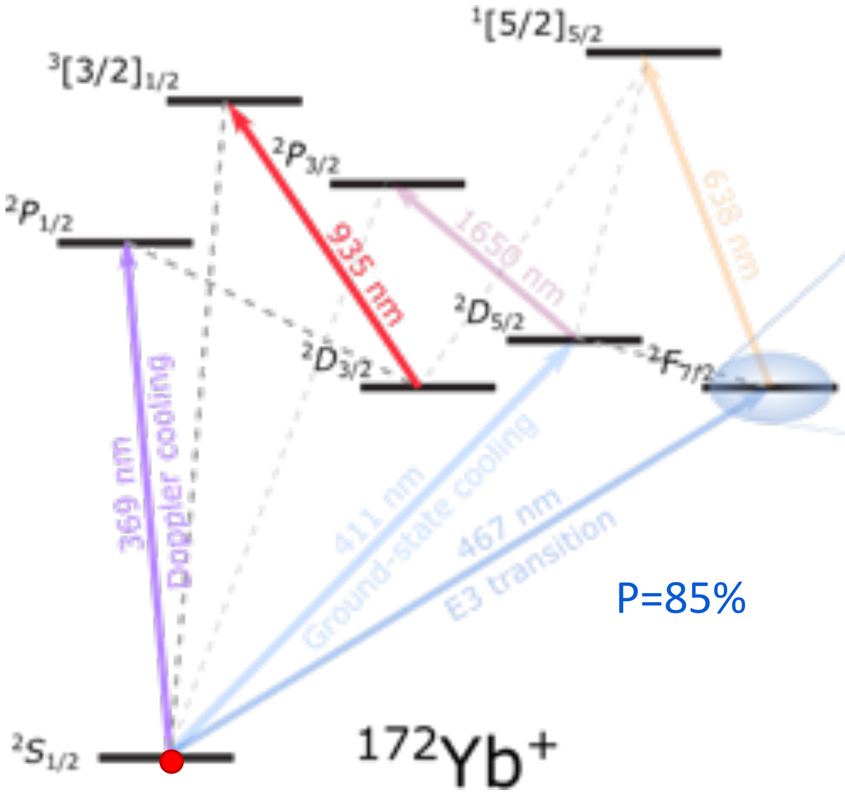
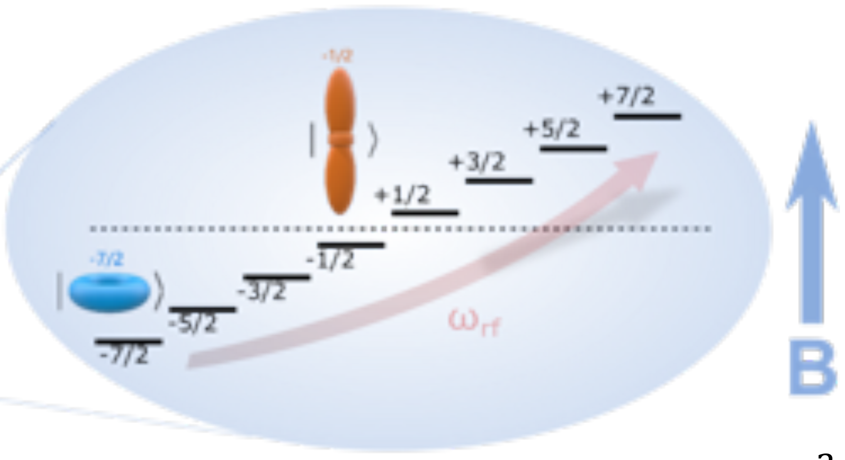




A Ramsey dark-time scan of the rf pulse sequence

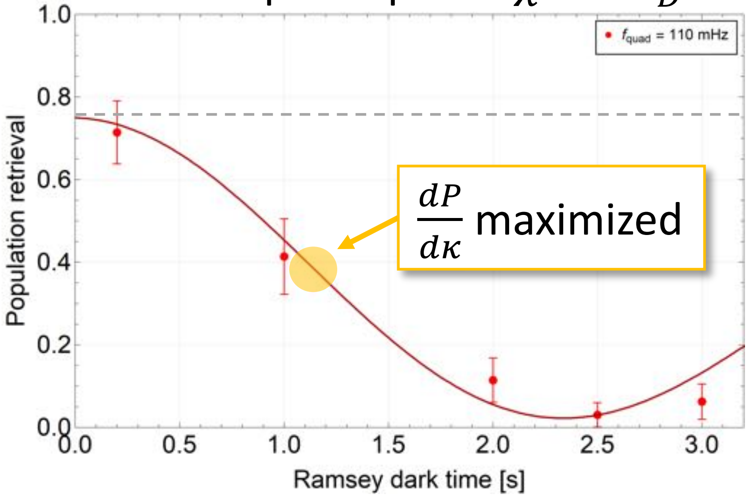




$H_{\text{quad}} = \kappa J_z^2$ proportional to m^2

Contains the quadrupole shift and a **potential LLI violation**

Retrieved population as a function of the acquired phase $\chi = \kappa T_D$



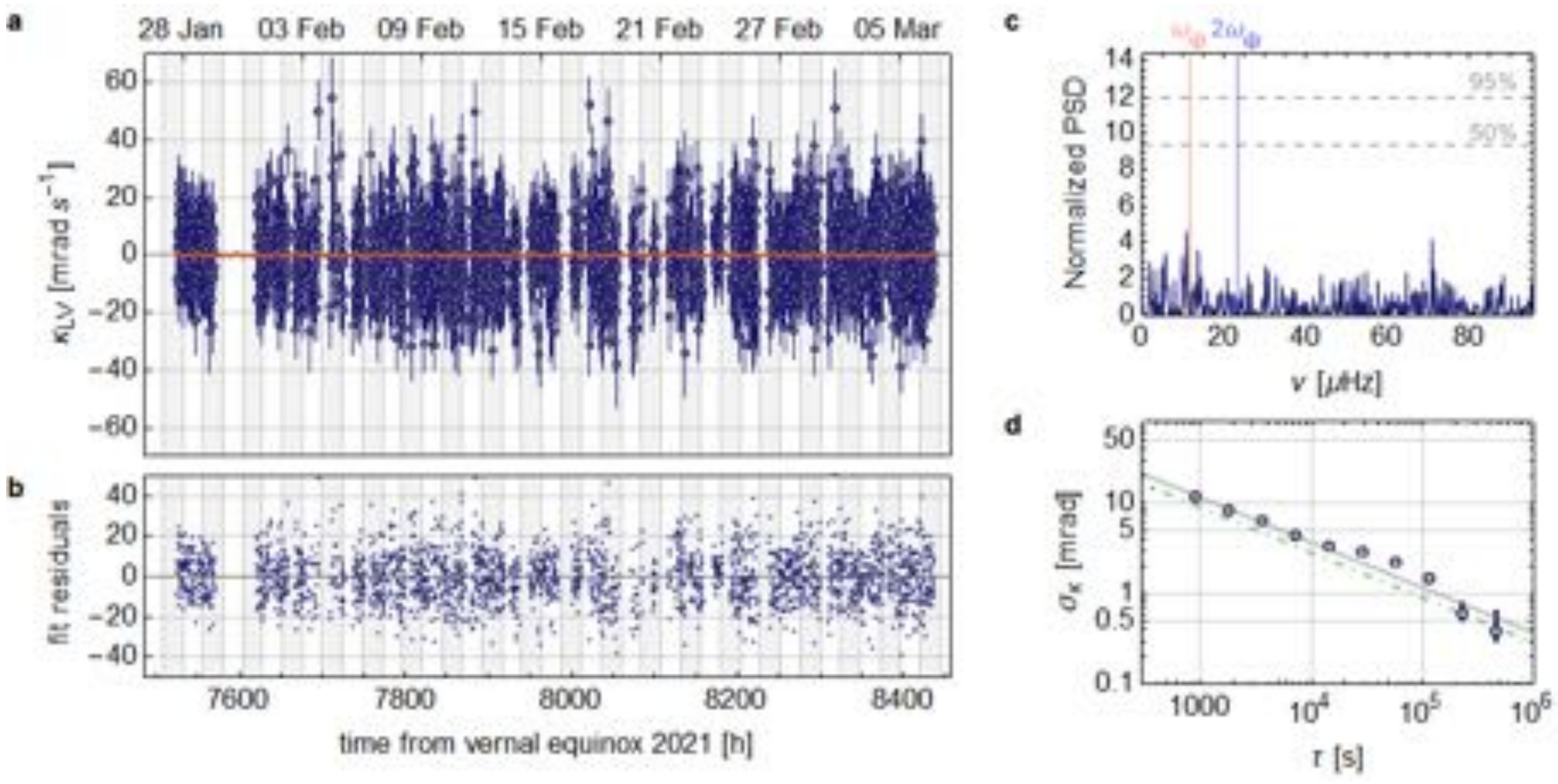
Contrast of 75%

$\kappa_{quad} = 0.13$ rad/s

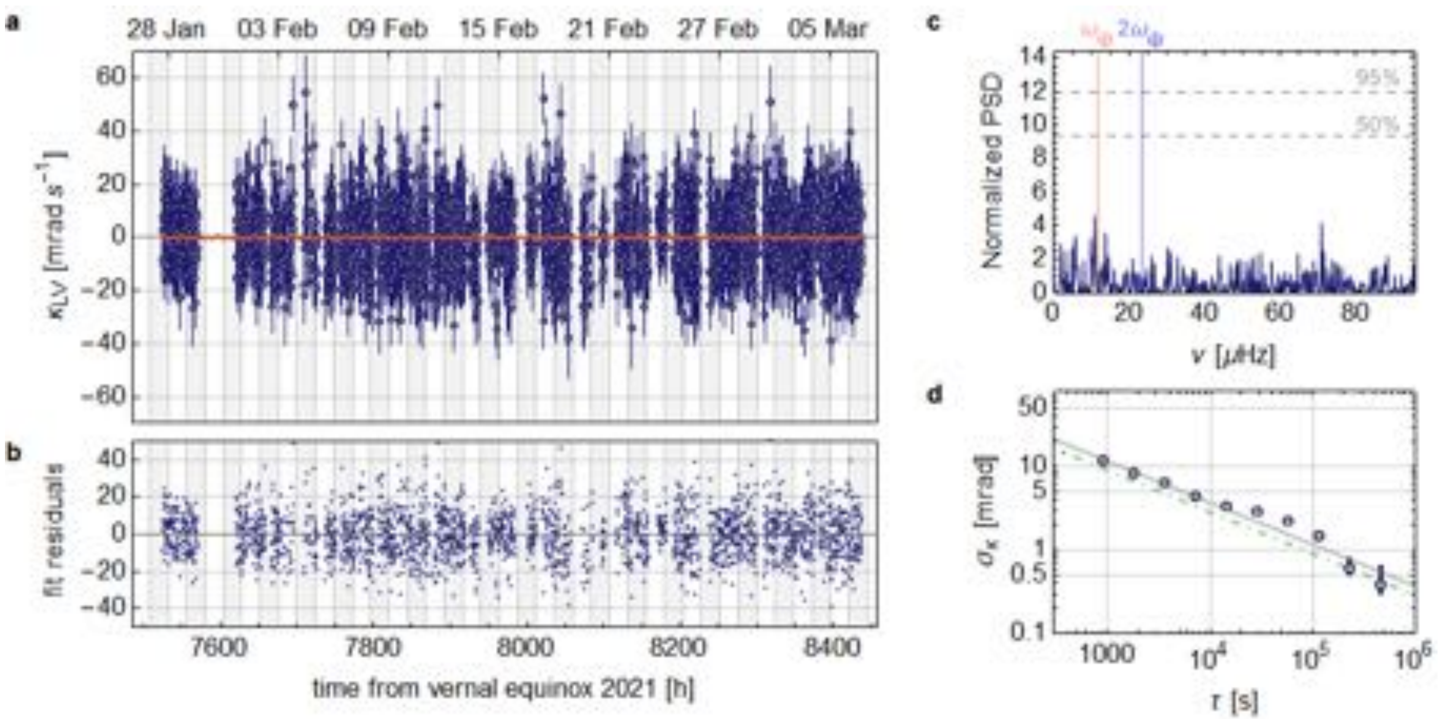
- LV: modulation of the phase $\chi = \kappa T_D$
- Sensitivity $\frac{dP}{d\kappa} = -4.4(4)$ at $T_D = 1.15$ s

Single ion test of LLI

Fit function: $\kappa_{LV} = A[B\cos(\omega_{\oplus}T) + C\sin(\omega_{\oplus}T) + D\cos(2\omega_{\oplus}T) + E\sin(2\omega_{\oplus}T)]$



Single ion test of LLI



Fit function: $\kappa_{LV} = A[B\cos(\omega_\oplus T) + C\sin(\omega_\oplus T) + D\cos(2\omega_\oplus T) + E\sin(2\omega_\oplus T)]$

Components of the symmetry-breaking $c'_{\mu\nu}$ tensor

Correlated LV parameters	Previous value [1] Measurement time: 3.9×10^6 s	Our value [2] Measurement time: 2.2×10^6 s
c_{X-Y}	$(-0.5 \pm 1.7)\times10^{-20}$	$(-5.2 \pm 7.8)\times10^{-21}$
c_{XY}	$(-7.0 \pm 8.1)\times10^{-21}$	$(4.4 \pm 3.9)\times10^{-21}$
c_{XZ}	$(0.8 \pm 1.3)\times10^{-20}$	$(-5.0 \pm 9.3)\times10^{-21}$
c_{YZ}	$(1.0 \pm 1.3)\times10^{-20}$	$(6.3 \pm 8.9)\times10^{-21}$

[1] C. Sanner et al., *Nature* **567**, 204-208 (2019)

[2] L. S. Dreissen et al., arXiv:2206.00570 [physics.atom-ph]

Single ion test of LLI

Already with a single ion we demonstrate that:

- We match the previous result obtained by the best optical [1] clocks 9 times faster [2]!
- We have improved the bounds on LV by up to a factor 2.2 and set the new world record in the electron-photon sector!

Components of the symmetry-breaking $c'_{\mu\nu}$ tensor

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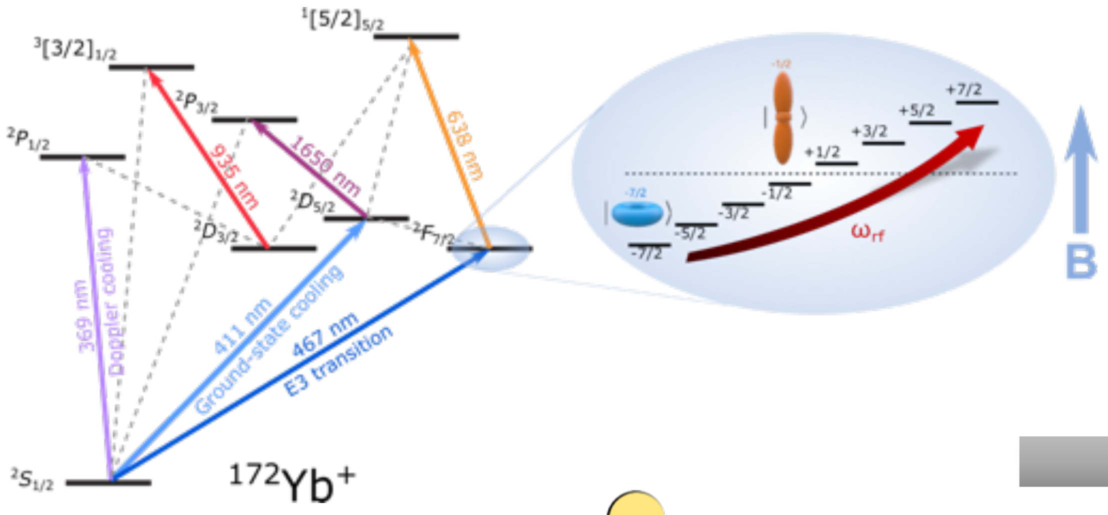
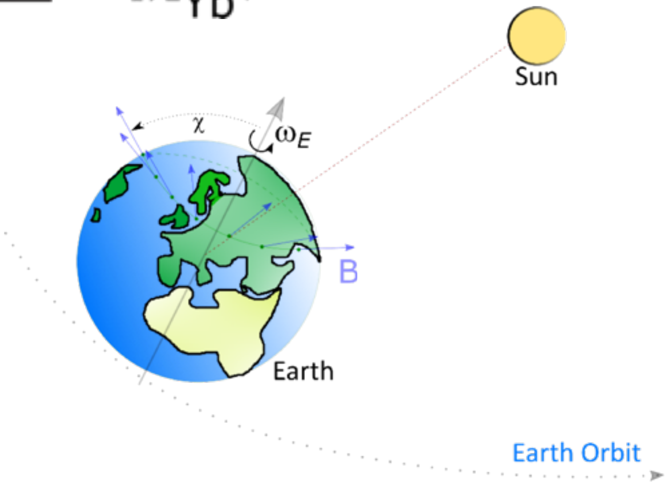
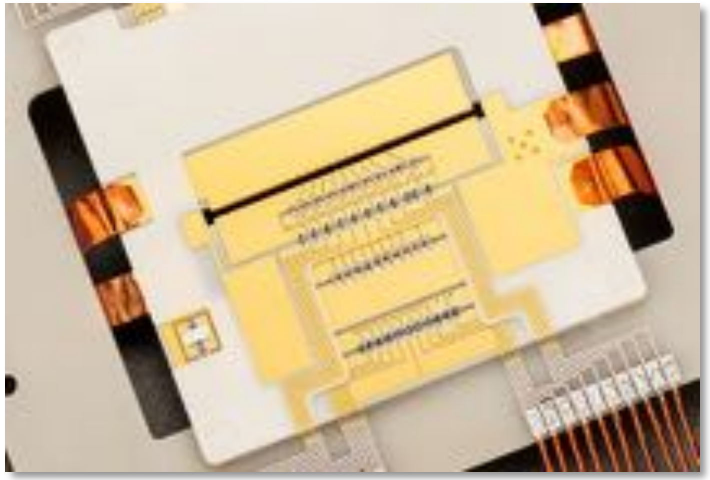
Outlook

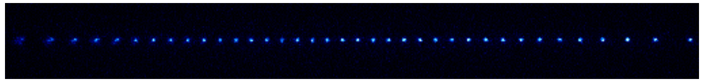
Towards multiple ions!





$$\Delta C_0^{(2)} = 3.11\times10^{-18}/\sqrt{N T \tau}$$



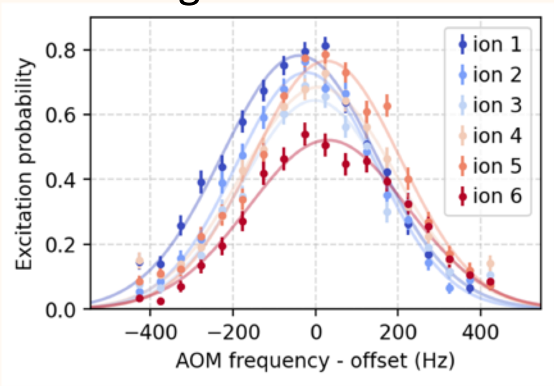


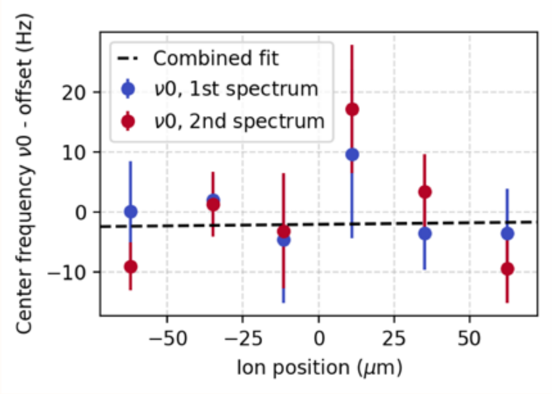
Outlook

Scaling to multiple ions for further improvement $\Delta\sigma_\kappa \propto 1/\sqrt{NT\tau}$

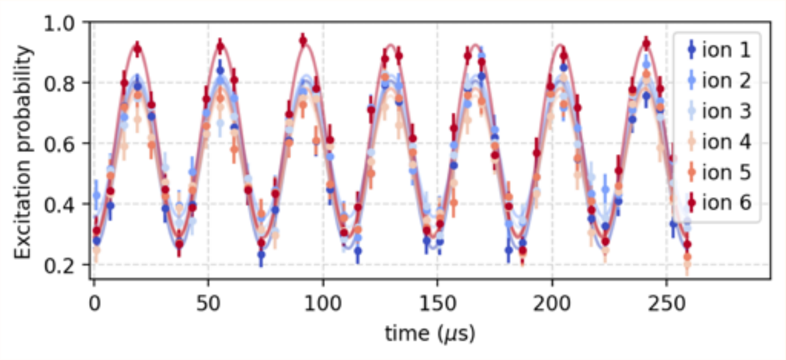
Magnetic field homogeneities

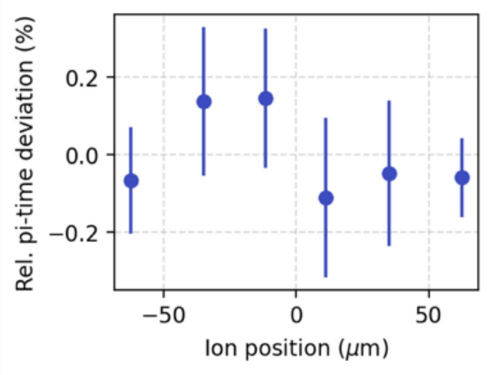
B field gradient





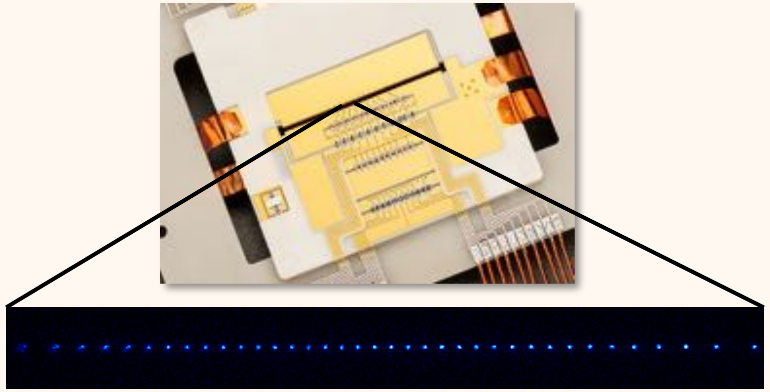
Rf excitation field gradient



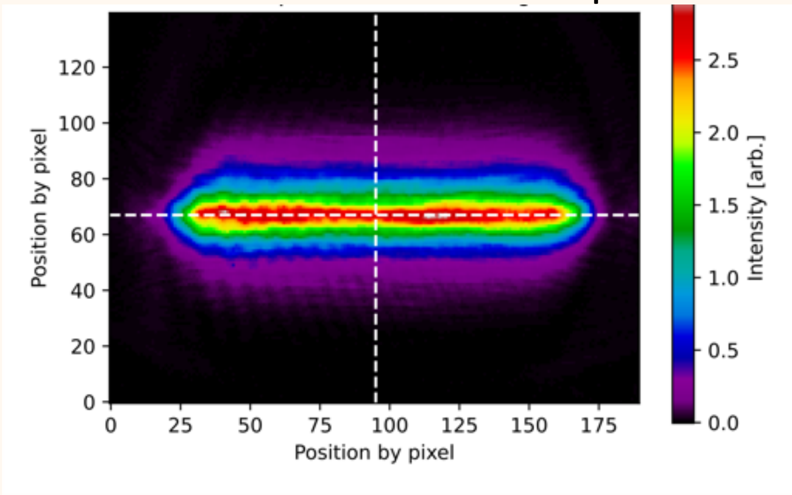


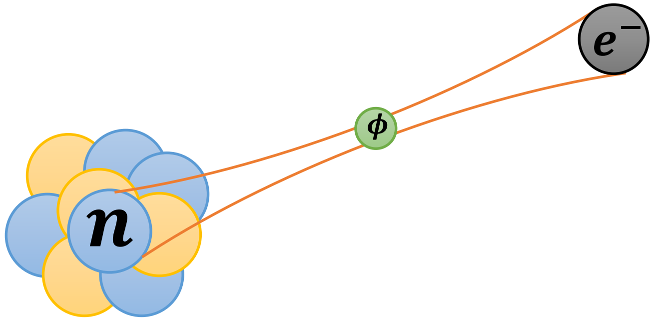
Field homogeneities are well below the required limit for the highly robust UR10 sequence!

Laser field homogeneity



Radial excitation with a Flat-top beam



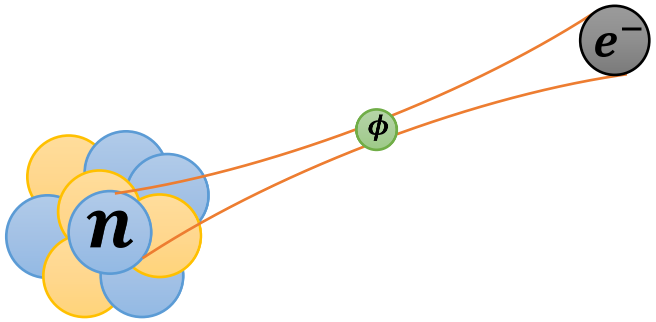


Isotope shift measurement in search for new boson

Introduction

Indirect evidence points to physics beyond the Standard Model:

- origin and composition of dark matter
- rotation curves of galaxies [1]
- gravitational lensing [2]
- etc.



[1] V. C. Rubin, et al., *Astrophys. J.* **238**, 471 (1980). [2] R. Massey, et al., *Rep. Prog. Phys*. **73**, 086901 (2006). [3] C. Delaunay, et al., *Phys. Rev. D* **96**, 093001 (2017).
[4] J. C. Berengut, et al., *Phys. Rev. Lett*. **120**, 091801 (2018).

Introduction

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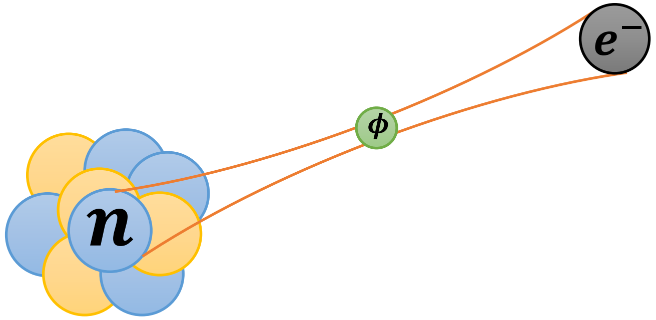

- dark-matter boson ϕ: couples to quarks and leptons

- virtual exchange of ϕ between neutrons and electrons would lead to an additional Yukawa-like potential

→energy level shifts

→the effect would drown in the less accurate calculated atomic structures

[1] V. C. Rubin, et al., *Astrophys. J.* **238**, 471 (1980). [2] R. Massey, et al., *Rep. Prog. Phys*. **73**, 086901 (2006). [3] C. Delaunay, et al., *Phys. Rev. D* **96**, 093001 (2017).
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King plot analysis

Isotope shift (IS) frequency dominated by:

- the Field shift (~4 GHz)
- The mass shift (~0.2 GHz)

$$\nu_\gamma^{AA'} = F_\gamma \delta\langle r^2\rangle^{AA'} + K_\gamma \mu^{AA'} + G_\gamma^{(4)} \delta\langle r^4\rangle^{AA'} + G_\gamma^{(2)} [\delta\langle r^2\rangle^2]^{AA'} + v_{ne} D_\gamma a^{AA'} + \cdots \qquad (1)$$

Transition dependent quantities

- F → field shift
- K → mass shift
- $G^{(4)}$ → fourth-moment shift
- $G^{(2)}$ → quadratic field shift
- D → the sensitivity to new boson

$\delta\langle r^n\rangle^{AA\prime}$ → difference in *n*th nuclear charge moment

[5] I. Counts, et al., *Phys. Rev. Lett.* **125**, 123002 (2020). [6] J. Hur, et al., *Phys. Rev. Lett.* **128**, 163201 (2022)

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King plot analysis:

- Normalize to a second transition to eliminate the dominant terms
- Observe nonlinearities in King plot of two different transitions in at least 3 isotopes

Linear in μ — Possible nonlinear contributions

$$\bar{\nu}_\gamma^{AA'} = f_{\gamma\tau} + K_{\gamma\tau} \bar{\mu}^{AA'} + G_{\gamma\tau}^{(4)} \overline{\delta\langle r^4\rangle}^{AA'} + G_{\gamma\tau}^{(2)} \overline{[\delta\langle r^2\rangle^2]}^{AA'} + v_{ne} D_{\gamma\tau} \bar{a}^{AA'}, \quad (2)$$

$$\bar{x} \rightarrow \frac{x}{\text{second transition isotope frequency difference}}$$

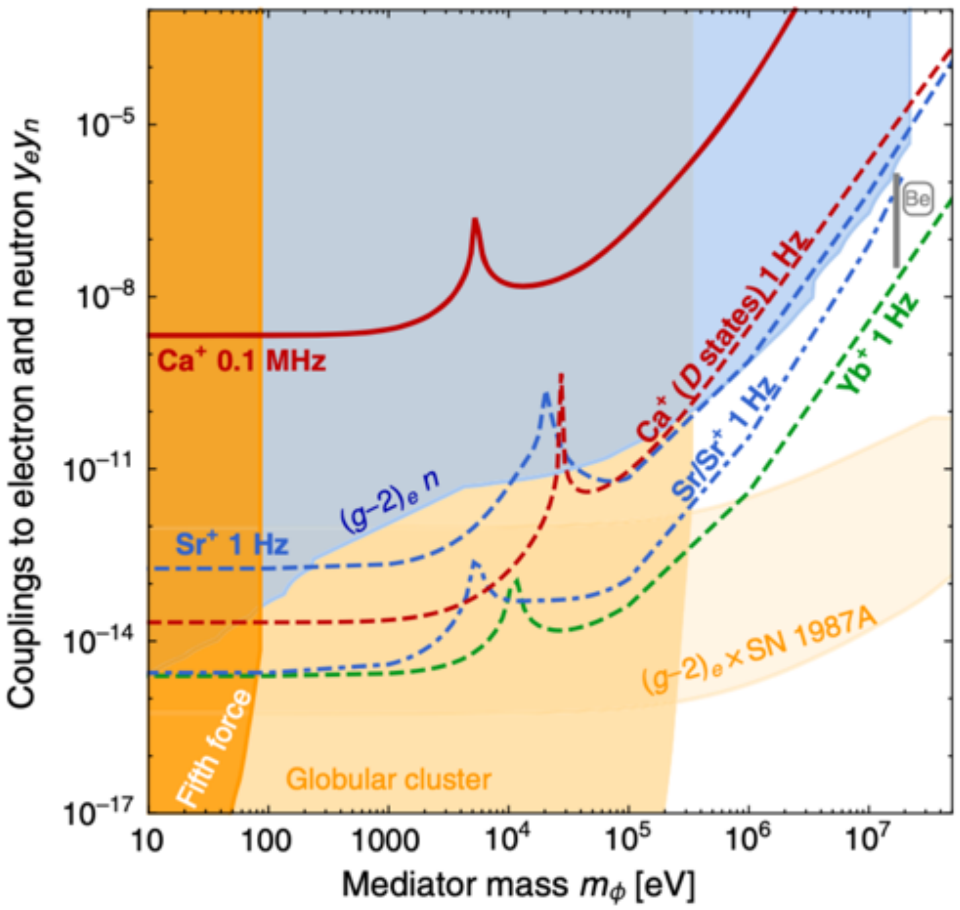
Normalize to the IS of a second transitions:

- Less sensitive to nuclear charge moment
- Common mode effects drop out

[5] I. Counts, et al., *Phy. Rev. Lett.* **125**, 123002 (2020). [6] J. Hur, et al., *Phy. Rev. Lett*. **128**, 163201 (2022)

King plot analysis

Possible bounds on a new boson



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King nonlinearity in Yb^+

PHYSICAL REVIEW LETTERS 125, 123002 (2020)

Editors' Suggestion   Featured in Physics

Evidence for Nonlinear Isotope Shift in Yb^+ Search for New Boson

Ian Counts,[1,*] Joonseok Hur,[1,*] Diana P. L. Aude Craik,[1] Honggi Jeon,[2] Calvin Leung,[1] Julian C. Berengut,[3] Amy Geddes,[3] Akio Kawasaki,[4] Wonho Jhe,[2] and Vladan Vuletić[1,†]
[1]Department of Physics and Research Laboratory of Electro… Massachusetts Institute of Technology, Cambridge, Massachusetts …
[2]Department of Physics and Astronomy, Seoul Natio…
[3]School of Physics, University of New South Wales, S…
[4]W. W. Hansen Experimental Physics Laboratory and …
Stanford, California 9430…

(Received 23 April 2020; accepted 27 July 2020; published 15 Septem…)

We measure isotope shifts for five Yb^+ isotopes with zero nuclear spin on two narrow optical quadrupole transitions $^2S_{1/2} \rightarrow {}^2D_{3/2}$, $^2S_{1/2} \rightarrow {}^2D_{5/2}$ with an accuracy of ~300 Hz. The corresponding King plot shows a 3×10^{-7} deviation from linearity at the 3σ uncertainty level. Such a nonlinearity can indicate physics beyond the Standard Model (SM) in the form of a new bosonic force carrier, or arise from higher-order nuclear effects within the SM. We identify the quadratic field shift as a possible nuclear contributor to the nonlinearity at the observed scale, and show how the nonlinearity pattern can be used in future, more accurate measurements to separate a new-boson signal from nuclear effects.

DOI: 10.1103/PhysRevLett.125.123002

PHYSICAL REVIEW LETTERS 128, 163201 (2022)

Evidence of Two-Source King Plot Nonlinearity in Spectroscopic Search for New Boson

Joonseok Hur,[1,*] Diana P. L. Aude Craik,[1,*] Ian Counts,[1,*] Eugene Knyazev,[1] Luke Caldwell,[2] Calvin Leung,[1] Swadha Pandey,[1] Julian C. Berengut,[3] Amy Geddes,[3] Witold Nazarewicz,[4] Paul-Gerhard Reinhard,[5] Akio Kawasaki,[6] Honggi Jeon,[7] Wonho Jhe,[7] and Vladan Vuletić[1,†]
[1]Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
[2]JILA, NIST and University of Colorado, Boulder, Colorado 80309, USA
[3]School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia
[4]Facility for Rare Isotope Beams and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA
[5]Institut für Theoretische Physik, Universität Erlangen, Erlangen D-91054, Germany
…ology Institute of Japan (NMIJ), National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Umezono, Tsukuba, Ibaraki 305-8563, Japan
…Astronomy, Seoul National University, Seoul 151-747, Korea

…022; accepted 2 March 2022; published 22 April 2022)

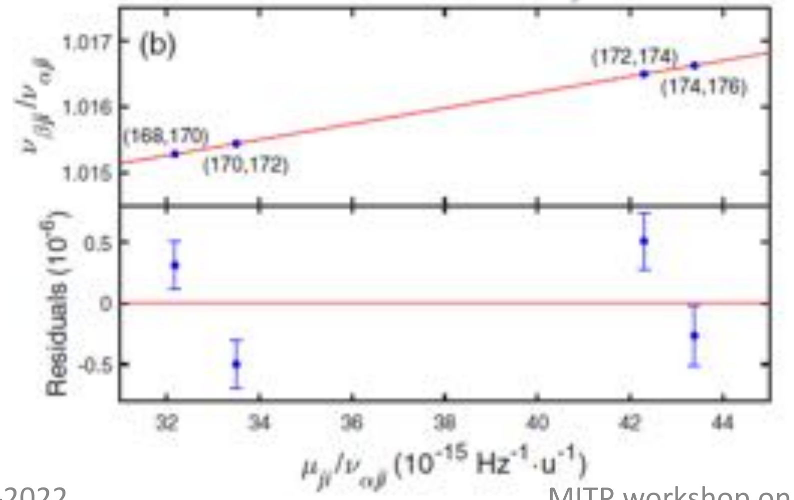
…can be used to test for new forces beyond the standard model, and to … nic nuclei. We measure isotope shifts on the highly forbidden $^2S_{1/2} \rightarrow {}^2F_{7/2}$ octupo… …rapped $^{168,170,172,174,176}Yb$ ions. When combined with previous measurements in Yb^+ and very recent measurements in Yb, the data reveal a King plot nonlinearity of up to 240σ. The trends exhibited by experimental data are explained by nuclear density functional theory calculations with the Fayans functional. We also find, with 4.3σ confidence, that there is a second distinct source of nonlinearity, and discuss its possible origin.

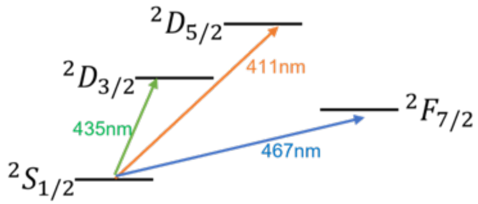
DOI: 10.1103/PhysRevLett.128.163201

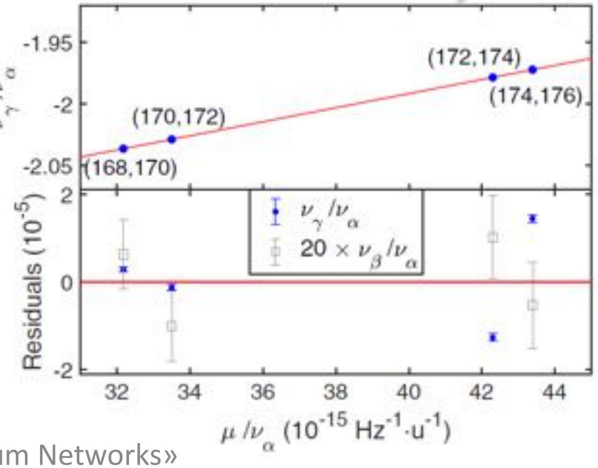
300-500 Hz accuracy

435nm, 411nm

467nm, 411nm



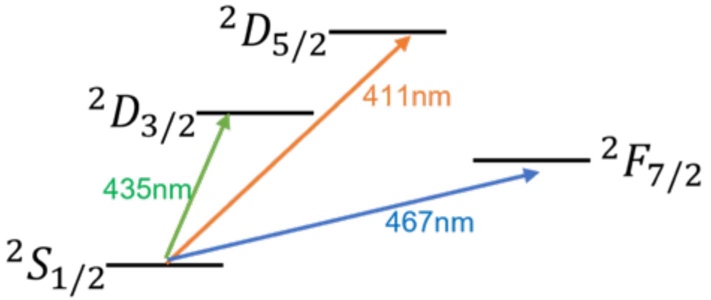




Our results

- Both the 411 nm E2 transition and the 467 nm E3 transition were measured
- We utilize the PTB infrastructure to measure with respect to the single ion $^{171}Yb^{+}$ clock

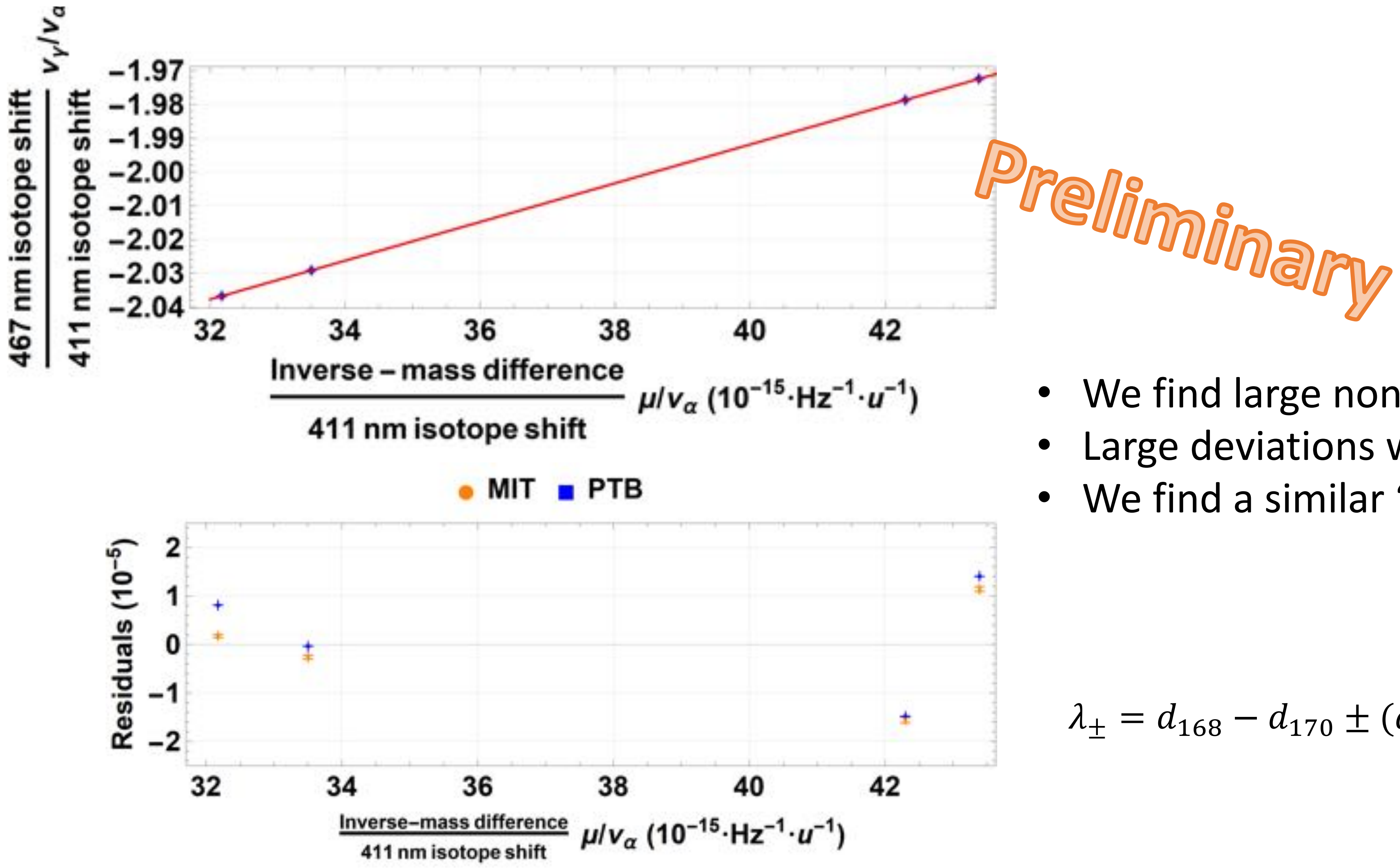
- We reach <10 Hz accuracy on the IS measurements



Isotope difference	411nm freq. diff. [Hz]	467nm freq. diff. [Hz]
168-170	2 179 098 868.0(1.8)	−4 438 159 670.8(7.0)
170-172	2 044 851 281.0(2.0)	−4 149 190 501.0(4.2)
172-174	1 583 064 149.3(2.5)	−3 132 320 458.4(5.9)
174-176	1 509 053 195.8(2.3)	−2 976 392 045.5(5.8)

Preliminary

King plot

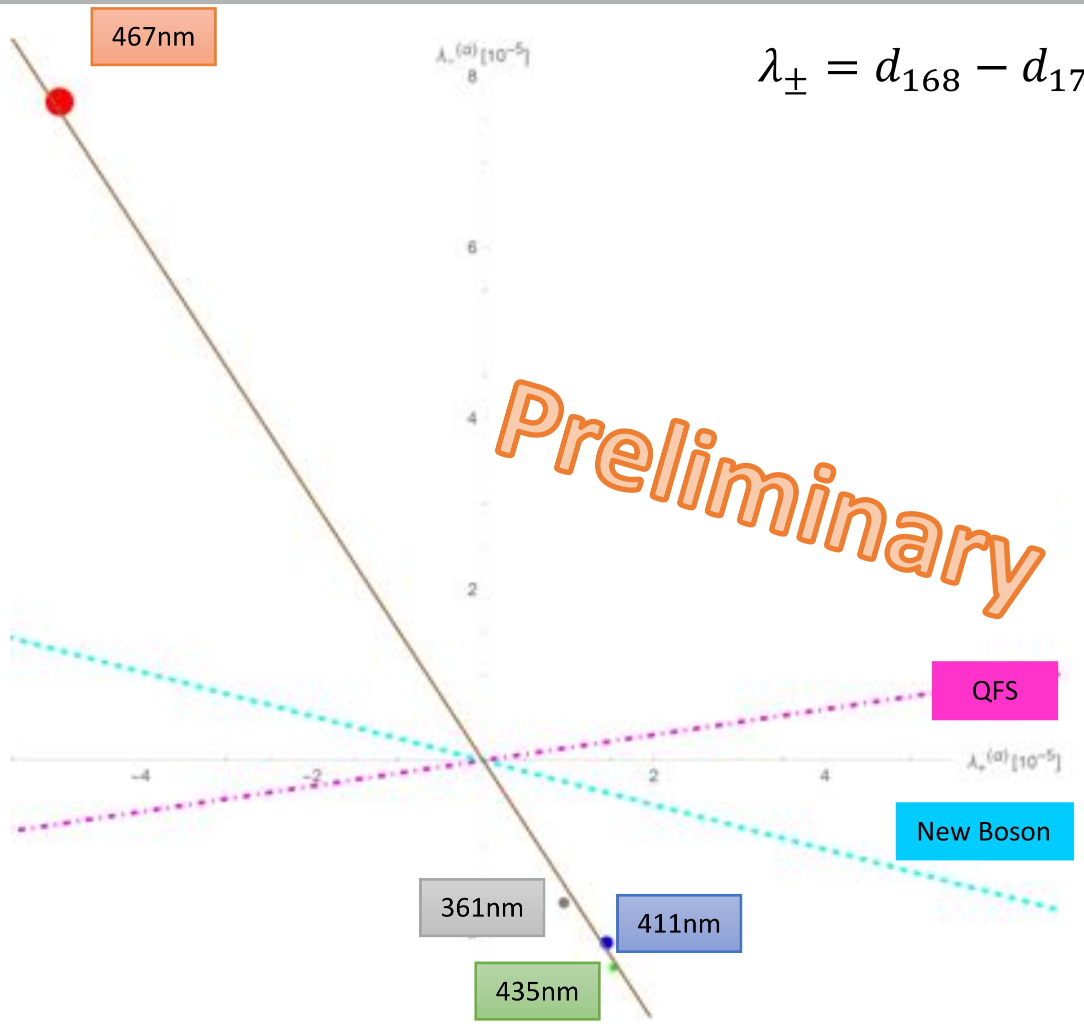


- We find large non-linearities
- Large deviations with previous results [6]
- We find a similar “shape” of the residuals

$$\lambda_\pm = d_{168} - d_{170} \pm (d_{172} - d_{174})$$

[5] I. Counts, et al., *Phys. Rev. Lett.* **125**, 123002 (2020). [6] J. Hur, et al., *Phys. Rev. Lett*. **128**, 163201 (2022)

Generalized King plot



$$\lambda_{\pm} = d_{168} - d_{170} \pm (d_{172} - d_{174})$$

To point towards a source of the non-linearity we place our data in the generalized King plot of [6]

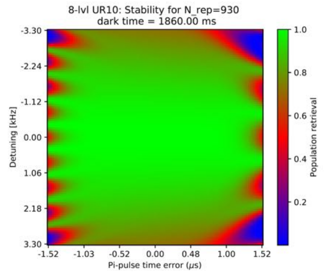
- For visibility we show our data points with enlarged uncertainty interval
- Brown line is a single source fit
- We find a 134.6σ for a second source
- Strong nuclear deformation effects in Yb have been suggested as a possible first source [8]
- In collaboration with J. Berengut, we will put constraints on a new boson assuming it's the second source

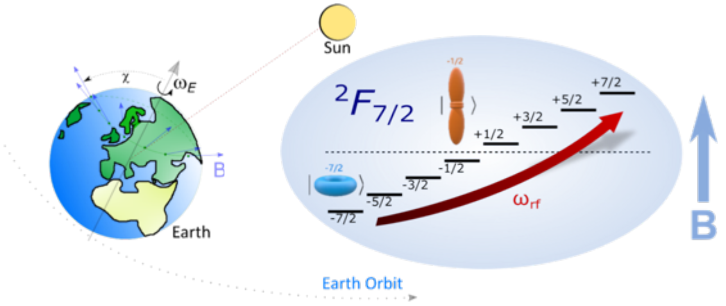
[5] I. Counts, et al., *Phy. Rev. Lett.* **125**, 123002 (2020). [6] J. Hur, et al., *Phy. Rev. Lett.* **128**, 163201 (2022)
[7] N. L. Figueroa, et al., *Phy. Rev. Lett.* **128**, 073001 (2022) [8] O. Saleh, et al., *Phy. Rev. A* **103**, L030801 (2021)

Conclusion

Testing Lorentz invariance

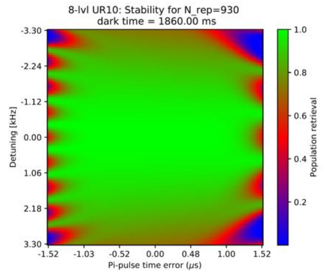
- We have achieved stable long-term clock operation on the E3 transition
- We implemented a robust composite rf sequence enables Ramsey dark time of >1 s
- The applied method has matched best atomic clock almost an order of magnitude faster
- The first test of LLI with a single ion improved on the World record by a factor of 2!





Conclusion

Testing Lorentz invariance



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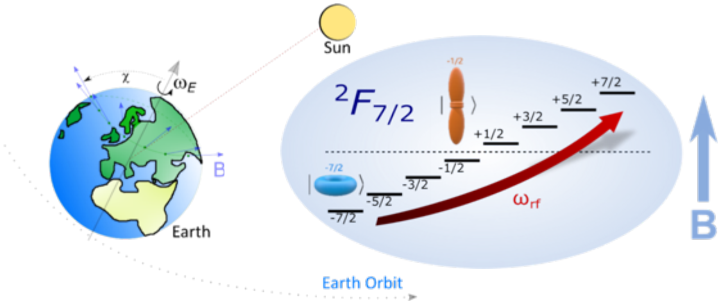
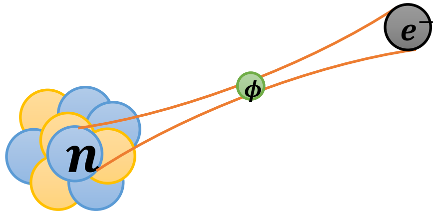


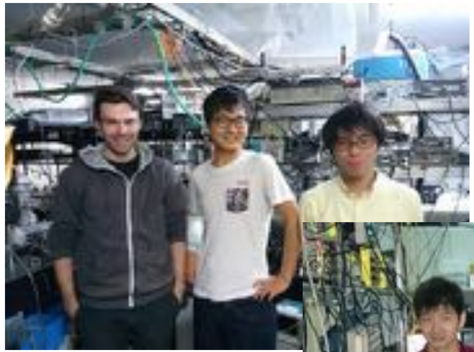
Accurate isotope shift measurements in search for a new boson

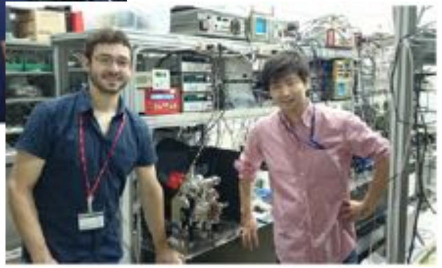


- We have use the same clock sequences for accurate IS measurements of the E2 and E3 transition
- We have reached <10 Hz accuracy on the isotope shifts
- We find significant non-linearities in the King plot and strong evidence for 2 two sources

Quantum Clocks and Complex Systems Group

Thank you for your attention!





TRIAC

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Industry Partners:


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Naneo (Lindau)
D&G (Stuttgart)
Toptica (München)
Vacom (Jena)
QUARTIQ (Berlin)
…

International Joint Laboratory for
Trapped-Ion Integrated Atomic-Photonic Circuits

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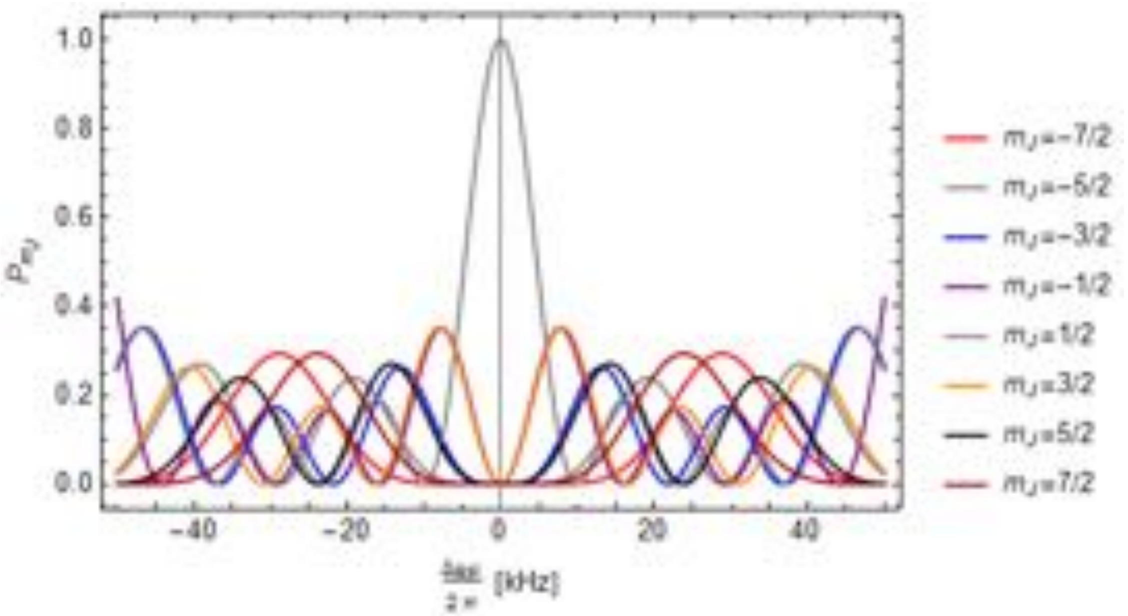
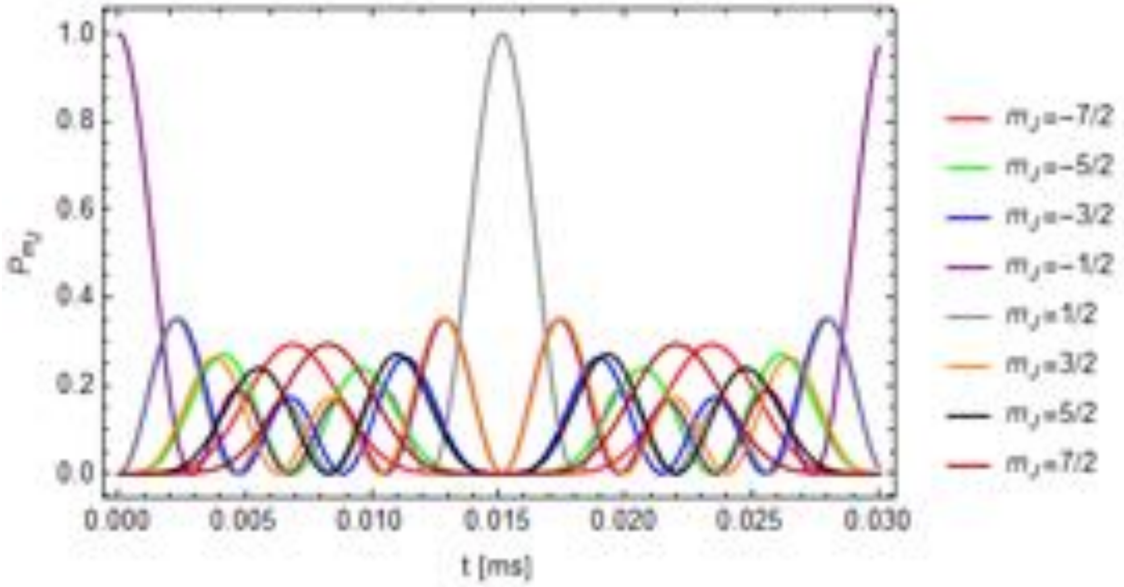
EURAMET European Association of National Metrology Institutes
TC FS
Bundesministerium für Bildung und Forschung
mat DQ
DLR
Alexander von Humboldt Stiftung/Foundation

8-level rf frequency scan and pulse time scan

frequency scan

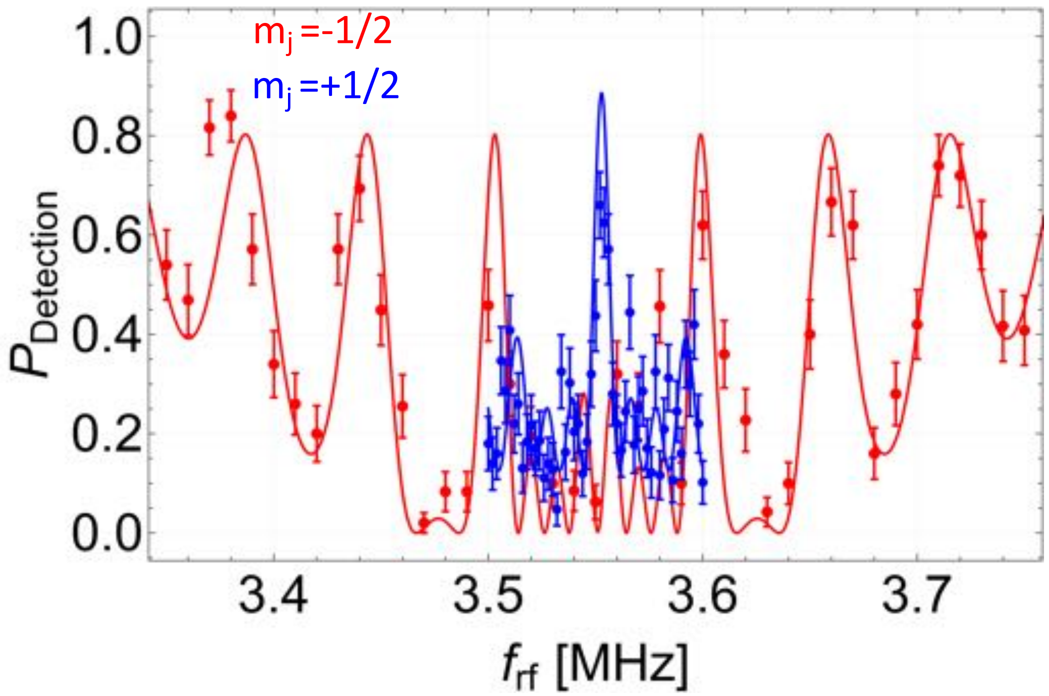


pulse-time scan



8-level rf frequency scan and pulse time scan

rf frequency scan



rf pulse time scan