Testing Invariance of the Fine Structure Constant with Atomic Clocks

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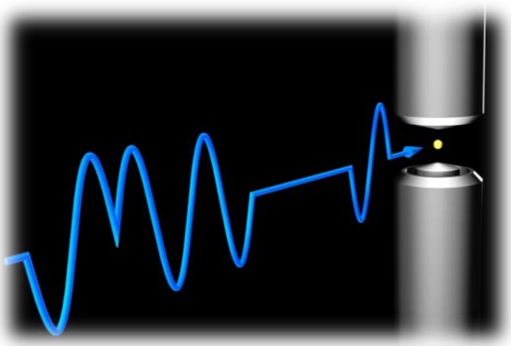
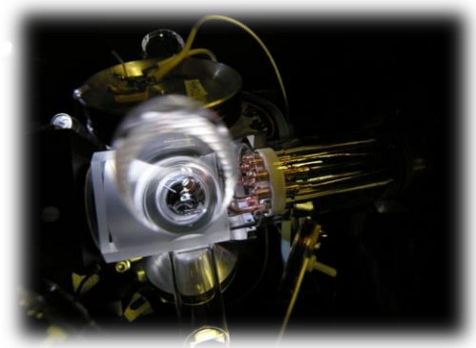




Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

Search for new physics with clocks:
Search for deviations from present theories, or experimental hints for new theories

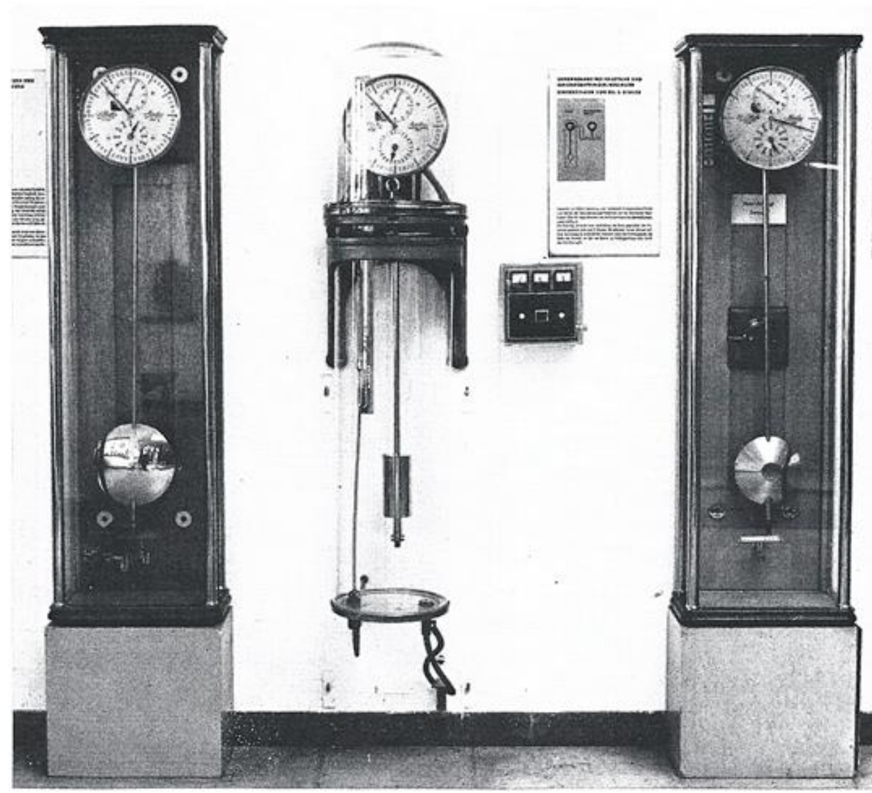
Quantum Theory	General Relativity

Clock-based precision experiments:

Transition frequencies (H, He, He^+ …)	Ephemerides of planets, spacecraft
Lamb shift (QED)	Millisecond pulsars
Magnetic moments (QED)	Red shift, Shapiro delay

A. Einstein (1916: Relativity, The Special and the General Theory)

„… we understand by the „time“ of an event the reading (position of the hands) of that one of these clocks which is in the immediate vicinity (in space) of the event.“



www.deutsches-museum.de

Search for new physics with clocks:
Search for violations of present theories, or experimental hints for new theories

Quantum Theory

General Relativity

Einstein Equivalence Principle

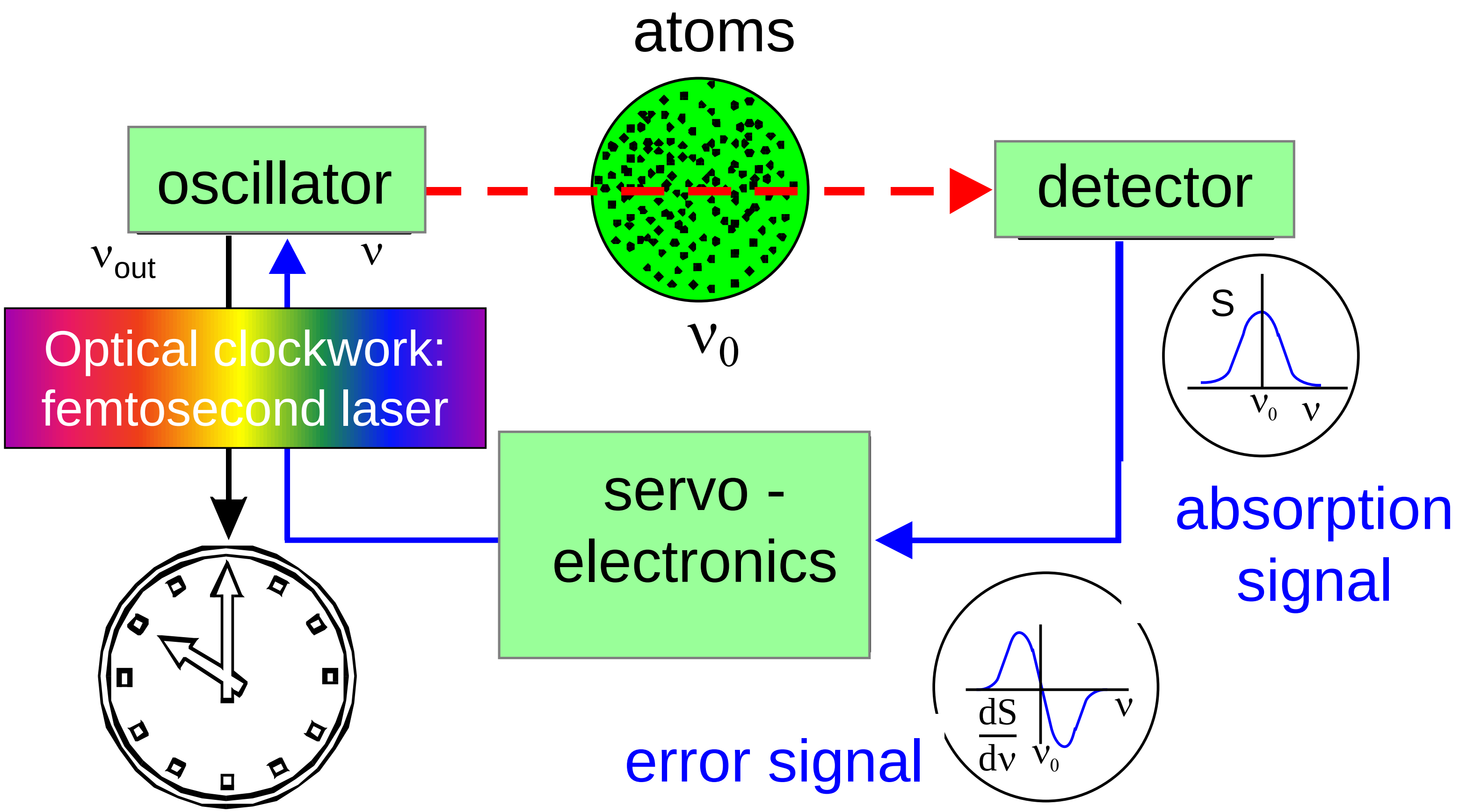
Local Position Invariance: *The outcome of any local non-gravitational test experiment is independent of where and when in the universe it is performed.*

This makes gravitation “universal” and allows it to be described as a geometrical phenomenon, but it also separates gravitation from the other fundamental interactions.

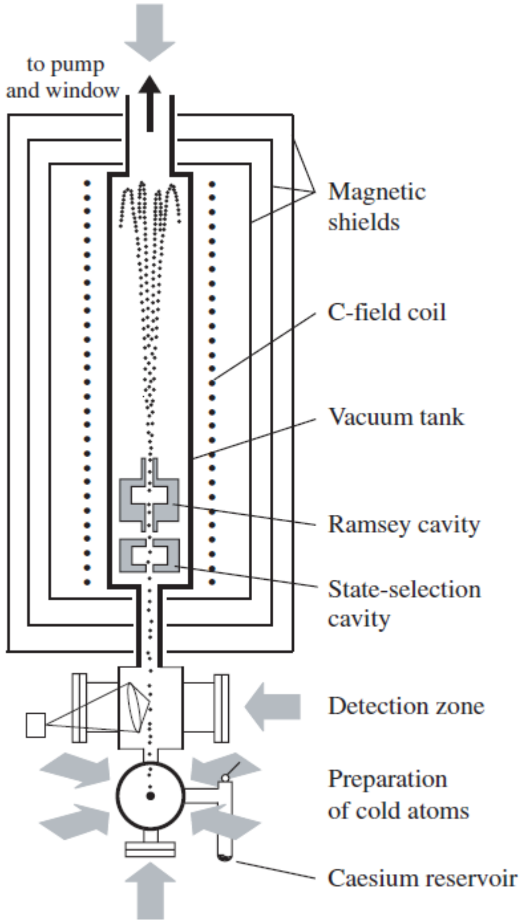
We search for violations of the Equivalence Principle with different atomic clocks:

- Search for a time dependence of fundamental constants
- Test of the universality of the gravitational red shift
- Clock comparison test of Lorentz invariance

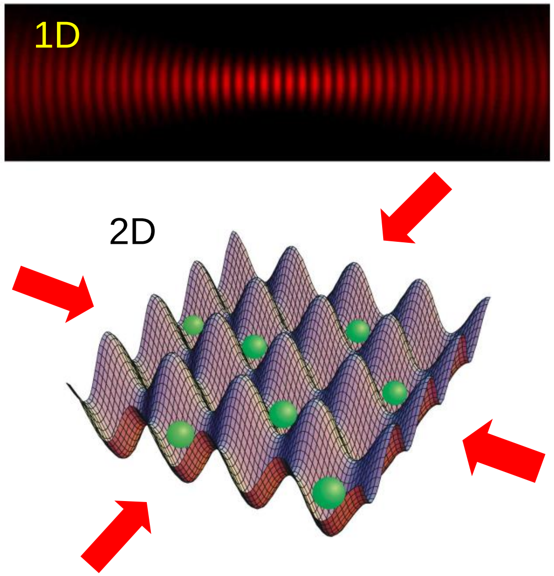
Principle of Atomic Clocks



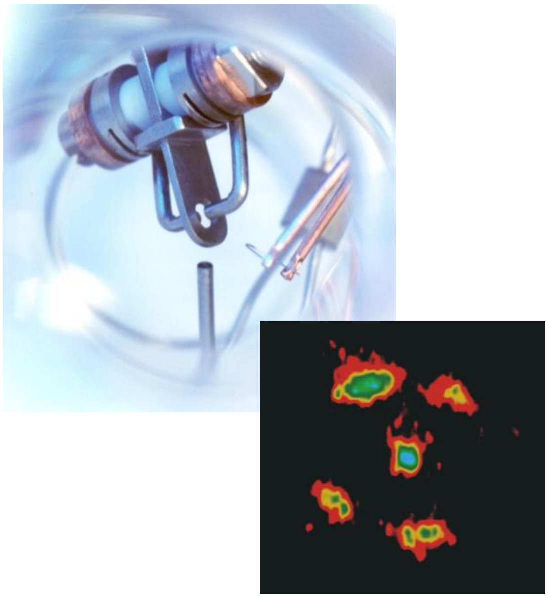
Atomic Clocks with laser-cooled atoms and ions



Caesium Fountain Clock:
Realization of the SI second,
Instability: $\sigma_y(1000\ \mathrm{s}) \approx 1\times10^{-15}$
Systematic uncertainty: 2×10^{-16}



Optical lattice clocks:
Neutral atoms in an optical trap at the „magic“ wavelength,
Instability: $\sigma_y(1000\ \mathrm{s}) \approx 1\times10^{-17}$
Systematic uncertainty: 2×10^{-18}



Single trapped ion:
Quantum limited control and very small perturbations,
Instability: $\sigma_y(1000\ \mathrm{s}) \approx 1\times10^{-16}$
Systematic uncertainty: 3×10^{-18}

Systematic uncertainty: on agreement with unperturbed transition frequency
Instability: statistical; depends on the measurement time: $\sigma_y(\tau) \propto 1/\sqrt{\tau}$

Highly accurate and stable optical clocks

atom	transition	lab.	syst. unc. (10^{-18})	$\sigma_y(1\,\mathrm{s})$ (10^{-15})	Δ(2 systems) (10^{-18})	Ref.
Cs	GS HFS		≈ 200	≈ 20	≈ 200	several
Al^+	0–0	NIST	8.6	2.8	18	PRL 104, 070802 (2010)
Yb	0–0	NIST		0.32		Science 341, 1215 (2013)
Sr	0–0	JILA	6.4	0.34	28	Nature 506, 71 (2014)
Sr	0–0	RIKEN	7.2	0.18	1.1	Nat. Phot. 9, 185 (2015)
Sr	0–0	JILA	2.1	0.22		Nat. Comm. 6, 6896 (2015)
Yb^+	E3	PTB	3.2	5		PRL 116, 063001 (2016)

Review on Optical Clocks:
A. D. Ludlow, M. M. Boyd, J. Ye, E. Peik, P. O. Schmidt
Rev. Mod. Phys. **87**, 637 (2015)

Variety of different atoms and transitions allows tests of fundamental physics.

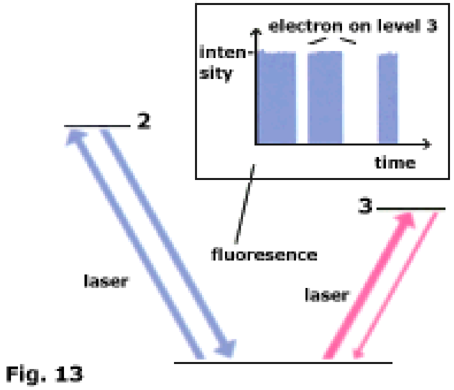
Work of the Physics Nobel Laureates of 1989 was fundamental for the single-ion clock

Wolfgang Paul

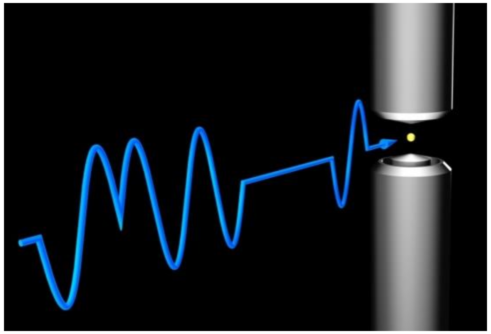
Hans Dehmelt

Norman Ramsey

Radiofrequency
Paul trap



Laser cooling, quantum jumps
„mono-ion oscillator“

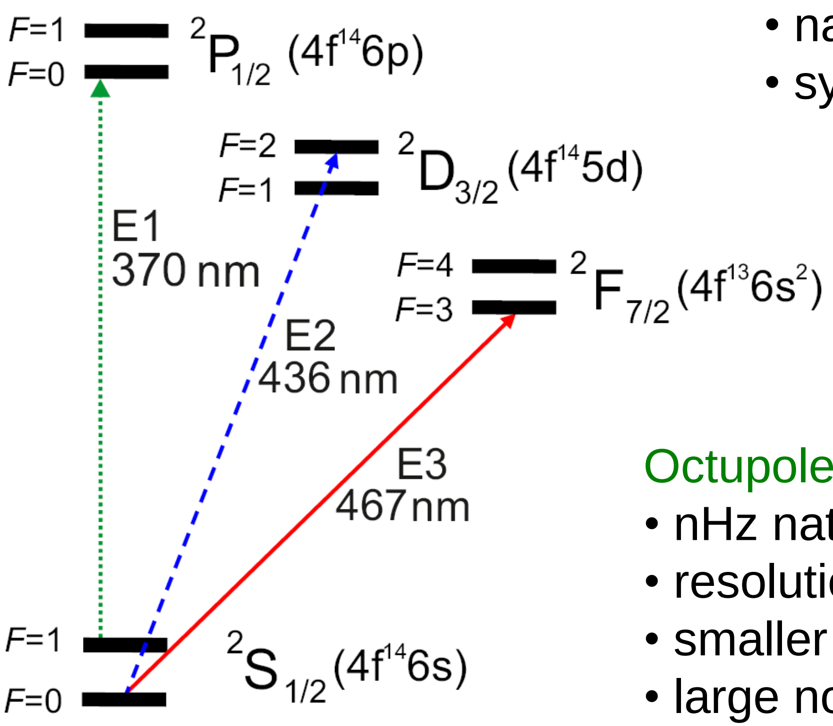


Method of separated oscillatory fields; Here: Generalized Hyper-Ramsey excitation

Two Clock Transitions in $^{171}Yb^+$

Advantages of Yb^+
- long storage time (months; photodissociation of YbH^+)
- $^{171}Yb^+$: nuclear spin ½: non-degenerate m=0 ground state

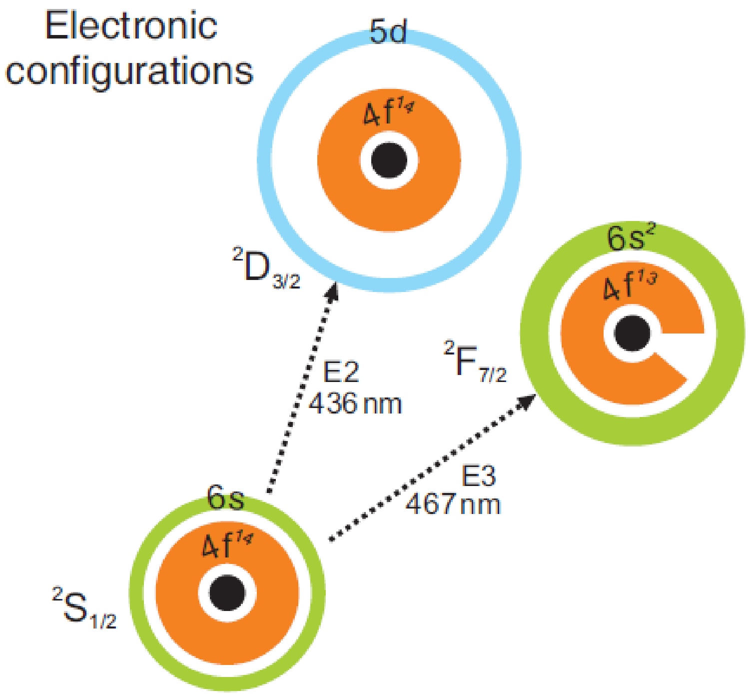
Investigated at: NPL, JPL, ILP, PTB … for clocks;
U. Maryland, Siegen, Ulm, ... for quantum logic.



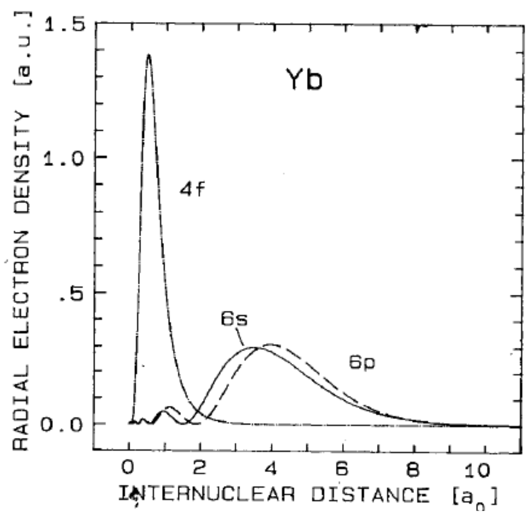
Quadrupole Transition (E2): S-D
- natural linewidth: 3 Hz
- syst. uncertainty ≈ 1×10^{-16} (BBR shift)

Octupole Transition (E3): S-F
- nHz natural linewidth
- resolution only limited by clock laser
- smaller shifts through static fields than E2 transition
- large nonresonant light shift from clock laser
- syst. uncertainty ≈ 3×10^{-18}

Special properties of the Yb^{+} $^{2}F_{7/2}$ level



Hole in the 4f shell,
surrounded by the filled 6s shell
→ strongly relativistic,
somewhat „shielded“ from external perturbations



H. Hotop et al., Ann. Physik 1990

Uncertainty budget of the PTB $^{171}Yb^+$ E3 single-ion clock

TABLE I. Fractional frequency shifts $\delta\nu/\nu_0(10^{-18})$ and related relative uncertainties $u/\nu_0(10^{-18})$ in the realization of the unperturbed $^2S_{1/2}(F=0) \to {}^2F_{7/2}(F=3)$ transition frequency ν_0 of a single trapped $^{171}Yb^+$ ion.

Effect	$\delta\nu/\nu_0$ (10^{-18})	u/ν_0 (10^{-18})
Second-order Doppler shift	−3.7	2.1
Blackbody radiation shift	−70.5	1.8
Probe light related shift	0	1.1
Second-order Zeeman shift	−40.4	0.6
Quadratic dc Stark shift	−1.2	0.6
Background gas collisions	0	0.5
Servo error	0	0.5
Quadrupole shift	0	0.3
Total	−115.8	3.2

Better control of localisation, lower heating

Better materials and design of trap

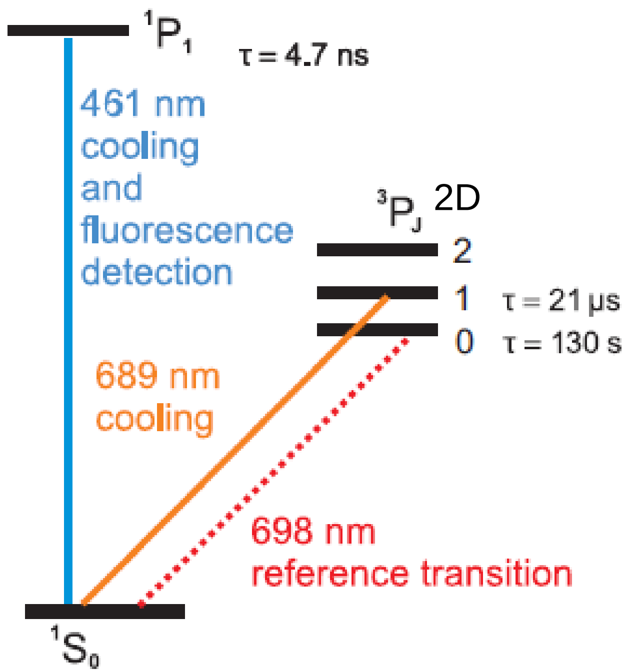
Hyper-Ramsey interrogation

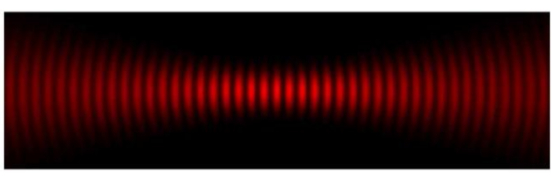
Nearly 100 times lower than for the most precise Cs-clocks

N. Huntemann, C. Sanner, B. Lipphardt, Chr. Tamm, E. Peik, Phys. Rev. Lett. **116,** 063001 (2016)

Reference System: Strontium lattice clock

The ^{87}Sr $^1S_0 \rightarrow {}^3P_0$ transition frequency (J=0 → J=0) serves as a stable „anchor“; it is only weakly relativistic, and rotationally symmetric.

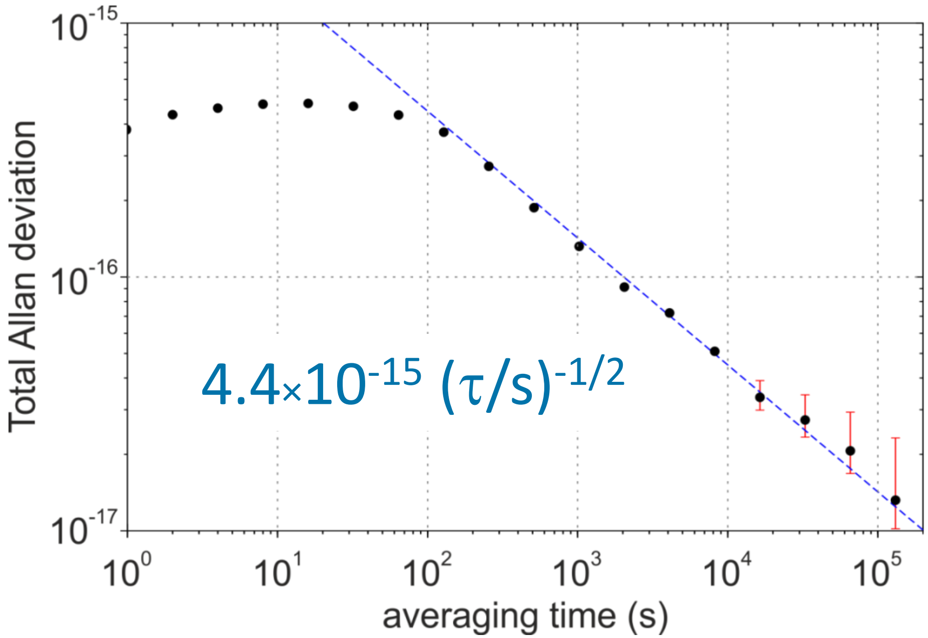




1D optical lattice clock

PTB Sr clock uncertainty: 1.9×10^{-17}
C. Grebing et al., Optica **3**, 563 (2016)

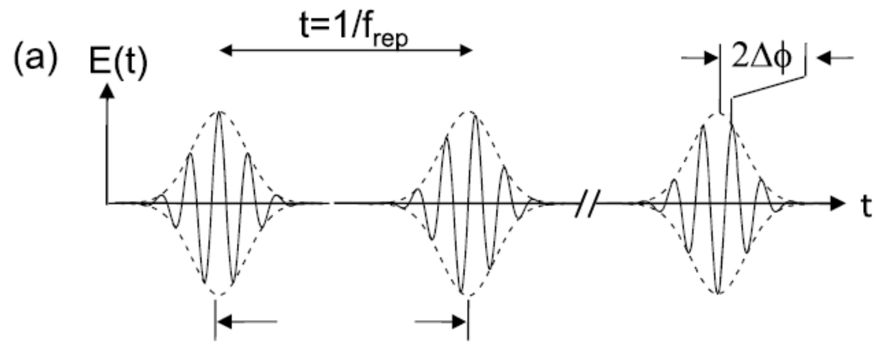
Statistical uncertainty of Yb$^+$/Sr comparison reaches 1×10^{-17} in ≈ 2 days



Measuring optical frequencies and frequency ratios with a femtosecond laser as a frequency comb

Time Domain

A femtosecond laser emits a regular sequence of short pulses, from the locking of many modes of the laser resonator.



Frequency Domain

$$f_{opt} = n f_{rep} + f_{beat} + f_{ceo}$$

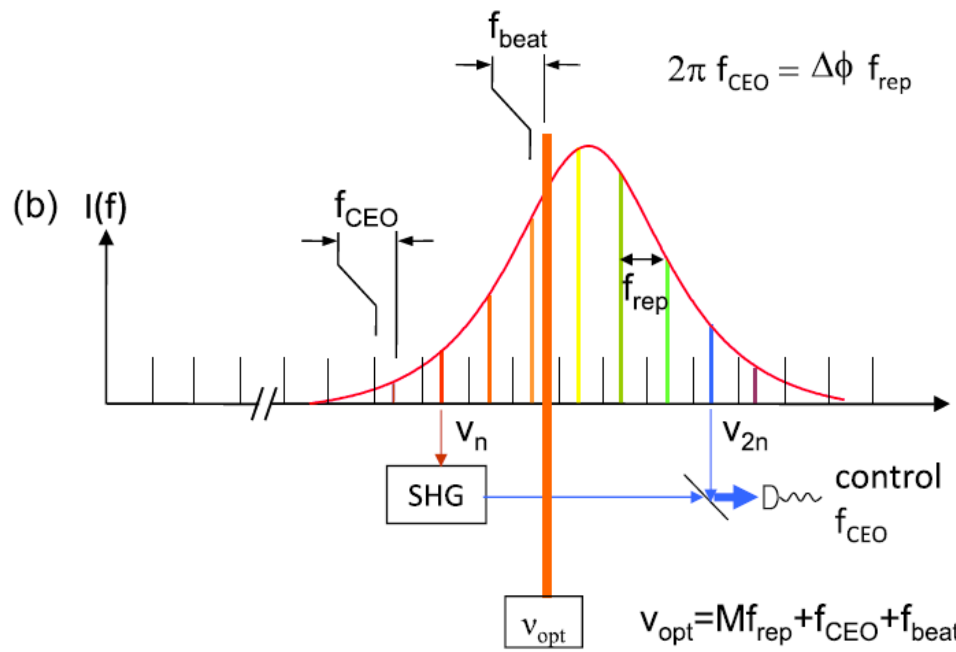


Photo: Sears.P.Studio

John L. Hall

Photo: F.M. Schmidt

Theodor W. Hänsch

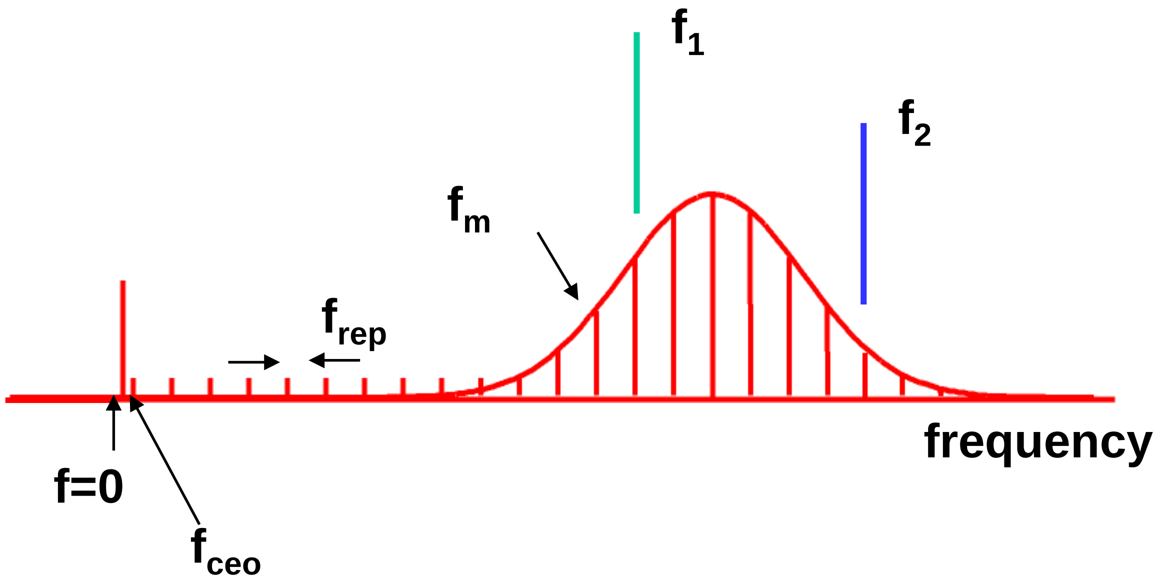
Coupling two frequencies to the comb,
and using f_{rep} as the common counter-reference signal,
allows to measure the optical frequency ratio to arbitrary precision.

$$f_1 = n_1 f_{rep} + f_{b1} + f_{ceo}$$

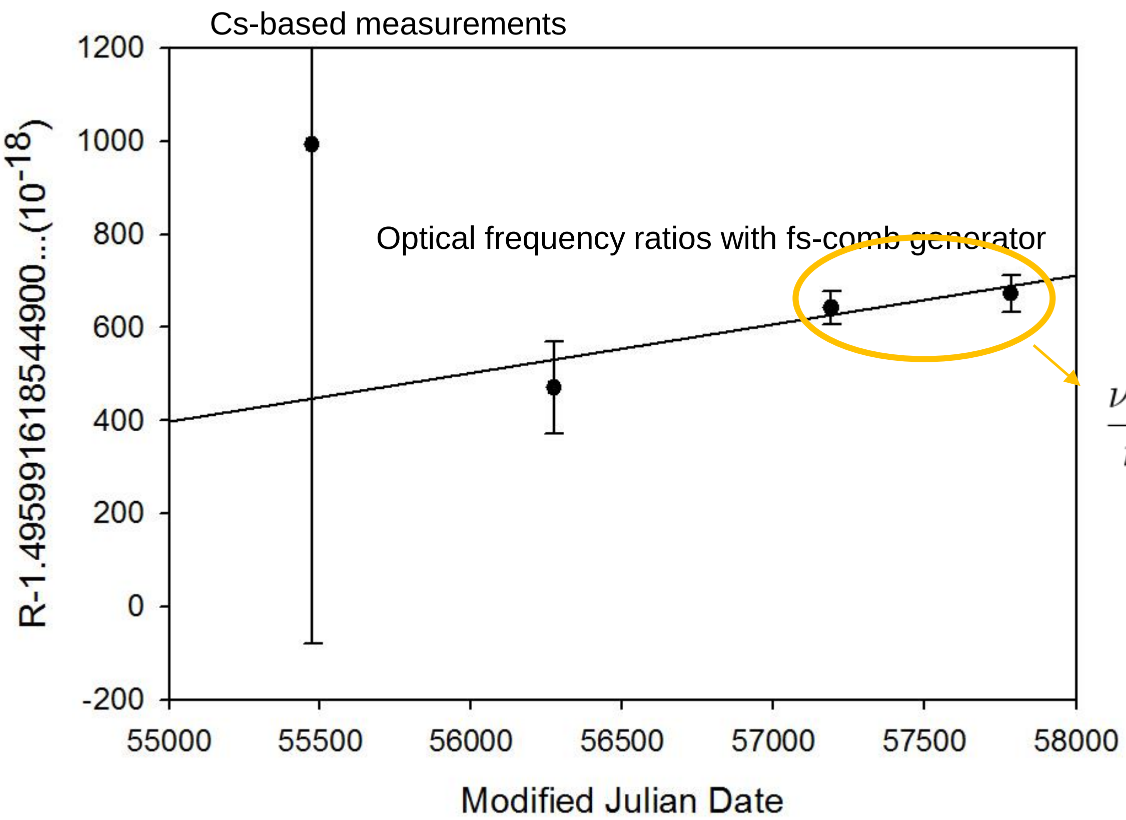
$$f_2 = n_2 f_{rep} + f_{b2} + f_{ceo}$$

$$\frac{f_1}{f_2} = \frac{n_1 + f_{b1}/f_{rep} + f_{ceo}/f_{rep}}{n_2 + f_{b2}/f_{rep} + f_{ceo}/f_{rep}}$$

ratios can be measured with standard electronic counter



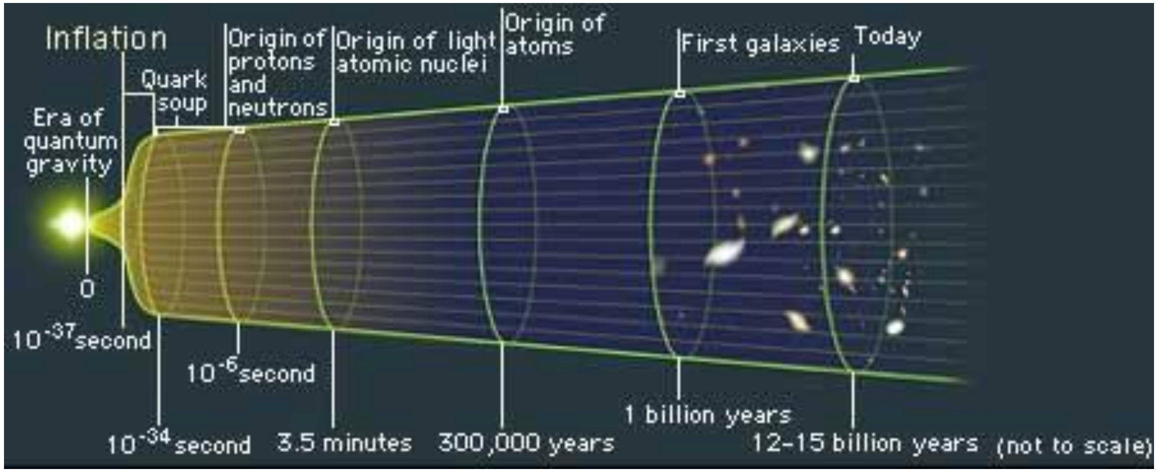
Results of frequency ratio measurements: Yb^+ E3 single–ion / Sr lattice clock



$$\frac{\nu(Yb^+)}{\nu(Sr)} = 1.495991618544900655(35)$$

Relative uncertainty: 2.3×10^{-17}

Search for temporal variations of fundamental constants



Discover Mag., A. Guth

Scaling of transition frequencies with fundamental constants

Transition		Energy scaling
Atomic	Gross structure	Ry
	Fine structure	α^2Ry
	Hyperfine structure	$\alpha^2(\mu/\mu_B)$Ry
Molecular	Electronic structure	Ry
	Vibrational structure	$(m_e/m_p)^{1/2}$Ry
	Rotational structure	(m_e/m_p)Ry
Relativistic corrections		Function of α^2

H spectroscopy

M. Savedoff, 1956

Cs + Rb fountain clocks

R. Thompson, 1975

J. Prestage, 1995
V. Flambaum et al.

Optical clocks with
heavy ions or atoms

From: S. G. Karshenboim, E. Peik (eds.)
Astrophysics, Clocks and Fundamental Constants,
Lect. Notes in Physics **648** (2004)

Sensitivity factors for different atomic clocks to the value of α

Optical transition frequency of electronic „gross“ structure with relativistic contribution

$$f = cR_\infty CF(\alpha)$$

Sensitivity factor: $K = \frac{1}{F}\frac{dF}{d\alpha}$

Obtained from ab initio calculations:
V. V. Flambaum, V. A. Dzuba
Can. J. Phys. **87**, 25 (2009)

Atom, transition	K	
$^{87}\mathrm{Sr},\ ^1S_0 \to {}^3P_0$	0.062	← anchor
$^{171}\mathrm{Yb}^+,\ ^2S_{1/2} \to {}^2D_{3/2}$	1.0	
$^{171}\mathrm{Yb}^+,\ ^2S_{1/2} \to {}^2F_{7/2}$	−6.0	← most sensitive clock
$^{199}\mathrm{Hg}^+,\ ^2S_{1/2} \to {}^2D_{5/2}$	−2.9	

$$\mathcal{R} = \nu(\mathrm{Yb}^+, E3)/\nu(\mathrm{Sr})$$

$$\frac{\Delta\mathcal{R}}{\mathcal{R}} = -6\frac{\Delta\alpha}{\alpha}$$

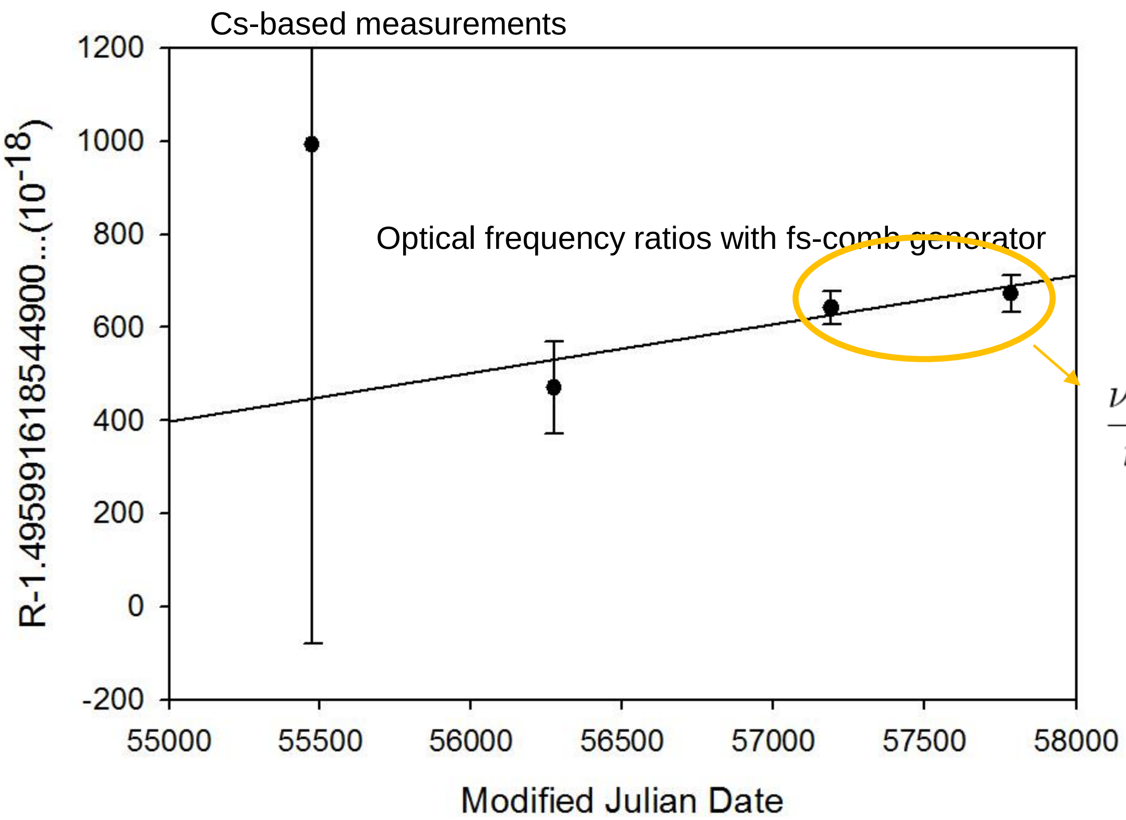
Yb^+/Sr frequency ratio would change 6x faster than α

Hyperfine transition:
(e.g.: caesium clock)

$$f_{hfs} = \alpha^2 cR_\infty CF(\alpha)G(\mu_N/\mu_B)$$

Also sensitive to nuclear magnetic moments and nuclear structure

Results of frequency ratio measurements: Yb^+ E3 single–ion / Sr lattice clock

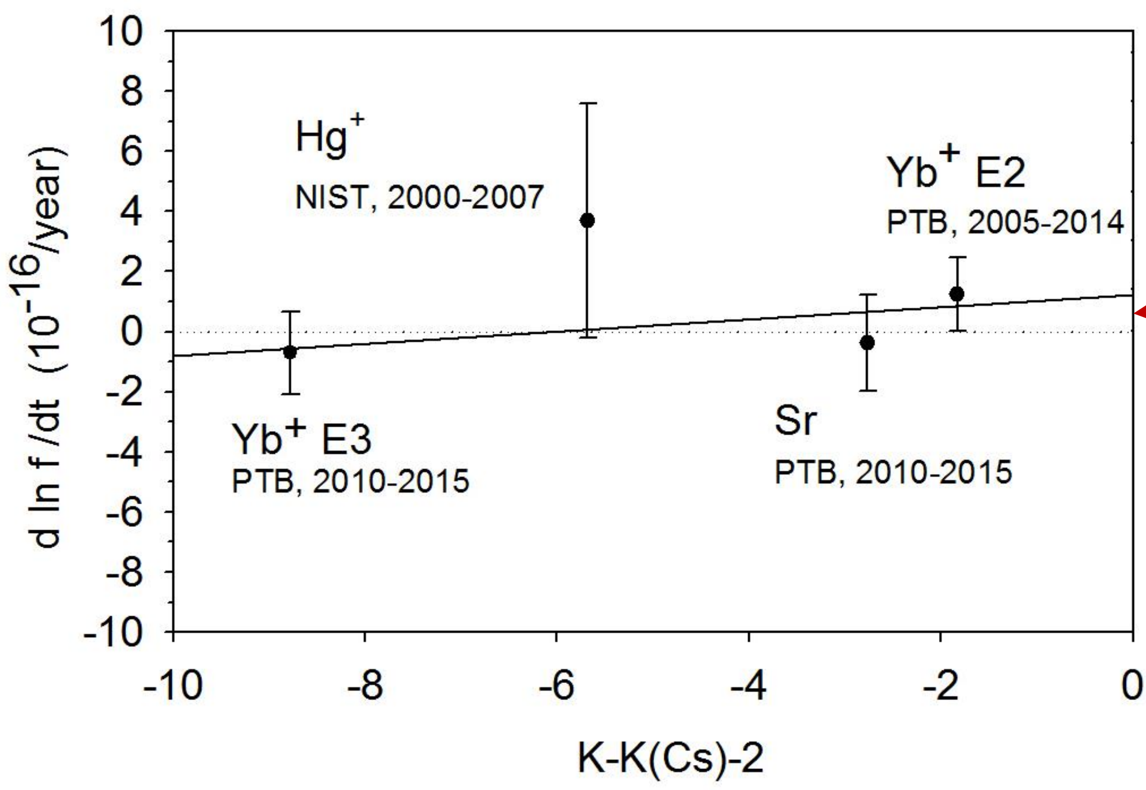


$$\frac{\nu(Yb^+)}{\nu(Sr)} = 1.495991618544900655(35)$$

Relative uncertainty: 2.3×10^{-17}

From a linear regression: $$\frac{d\ln\alpha}{dt} = (-4.3 \pm 2.5)\cdot 10^{-18}\ \mathrm{yr}^{-1}$$

Results of optical frequency measurements with Cs clocks

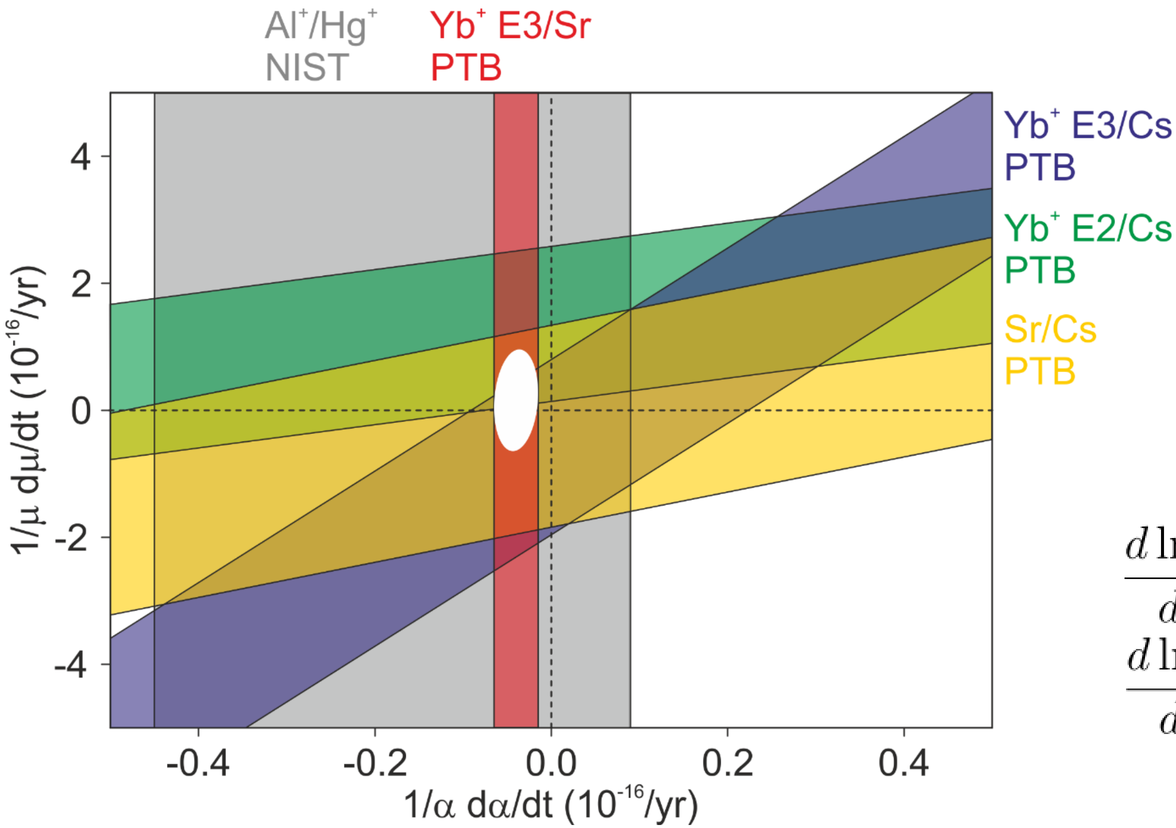


Slope:
change of α

Intercept:
change of ^{133}Cs
nuclear properties

From a linear regression: $$\frac{d\ln\alpha}{dt} = (2.0 \pm 2.5)\cdot 10^{-17}\ \mathrm{yr}^{-1}$$

Improved limits on temporal variations of fundamental constants: α and $\mu=m_p/m_e$



Al^+/Hg^+:
T. Rosenband et al.
Science **319**, 1808 (2008)

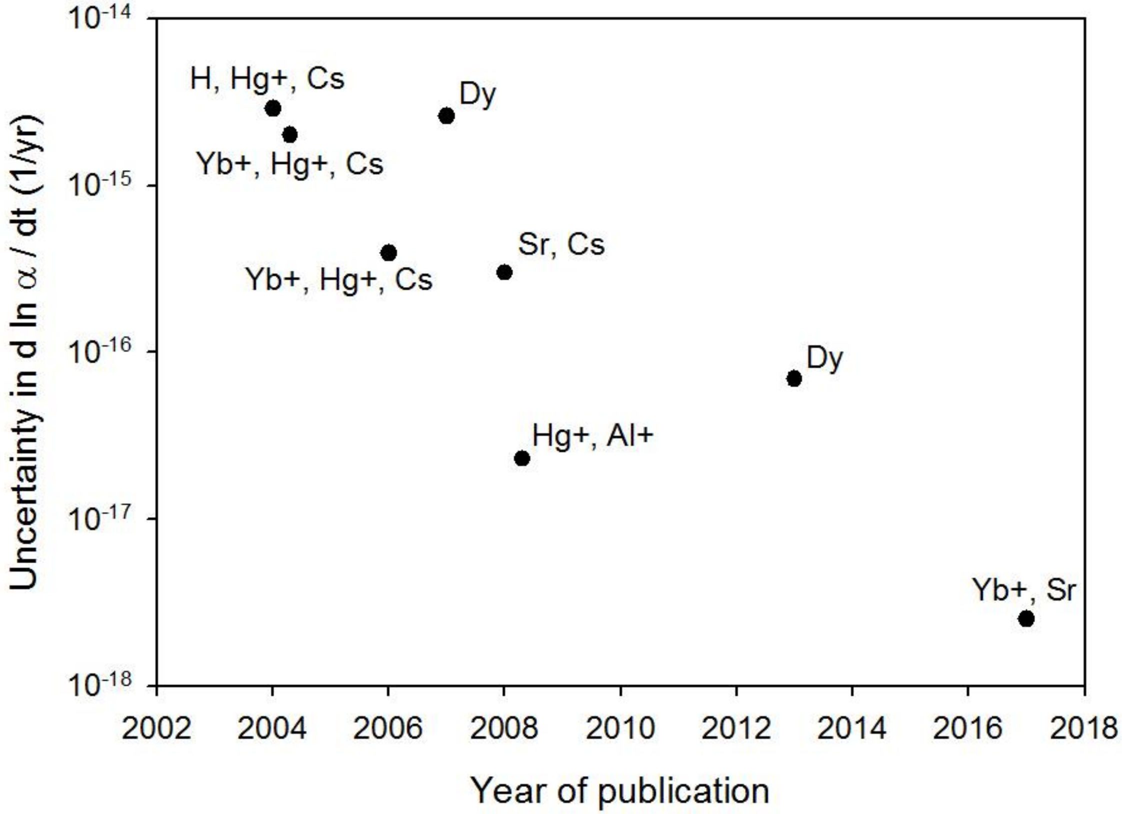
$$\frac{d\ln\alpha}{dt} = (-4.1 \pm 2.5)\cdot 10^{-18}\ \mathrm{yr}^{-1}$$

$$\frac{d\ln\mu}{dt} = (1.4 \pm 8.0)\cdot 10^{-17}\ \mathrm{yr}^{-1}$$

Improves uncertainties in:
d lnα/dt by factor ≈ 8 (model-independent)
d lnμ/dt by factor ≈ 2 (using relation of Cs-HFS to μ)

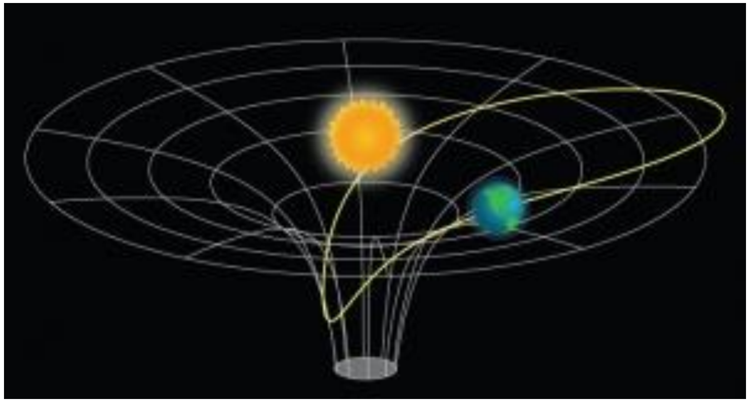
Earlier analyses of Cs-based measurements for m_p/m_e, :
R.M. Godun et al. (NPL), PRL **113**, 210801 (2014)
N. Huntemann et al. (PTB), PRL **113**, 210802 (2014)

Improvement in uncertainty on the time variation of α from atomic clocks



For comparison:	$d \ln \alpha / dt$ (1/yr)
Dirac's large number hypothesis:	$H_0 \approx 7 \times 10^{-11}$
Uncertainties in quasar absorption spectra:	$10^{-15} \dots 10^{-16}$
Movement of earth in „Australian dipole“ (J. Webb)	$\approx 1 \times 10^{-19}$

Testing the universality of gravitational red shift



JILA

Search for annual frequency variations as a test of Local Position Invariance

Solar gravitational potential on the geoid shows annual variation
(in $\Delta U/c^2$ by 3.3×10^{-10}) because of the ellipticity of the earth orbit.

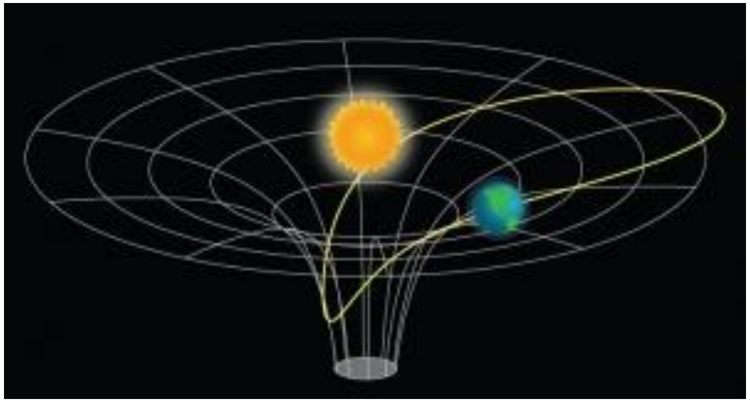
Search for a frequency difference in gravitational red-shift between two dissimilar clocks

$$\frac{\Delta f}{f} = (\beta_2 - \beta_1)\frac{\Delta U}{c^2}$$

„Null gravitational red-shift experiment“: J. P. Turneaure et al., 1983

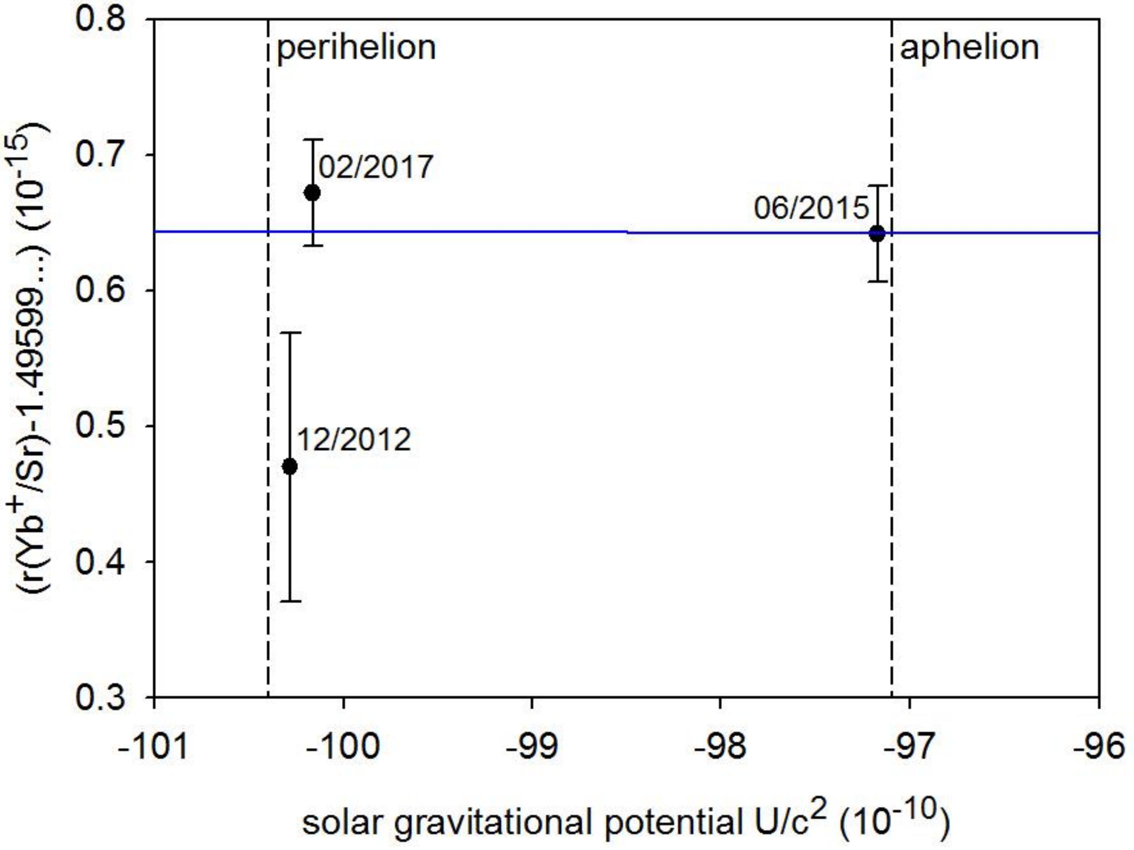
Here: Search for a change of α in the Yb^+/Sr frequency ratio

$$\frac{\Delta\alpha}{\alpha} = \beta_\alpha \frac{\Delta U}{c^2}$$



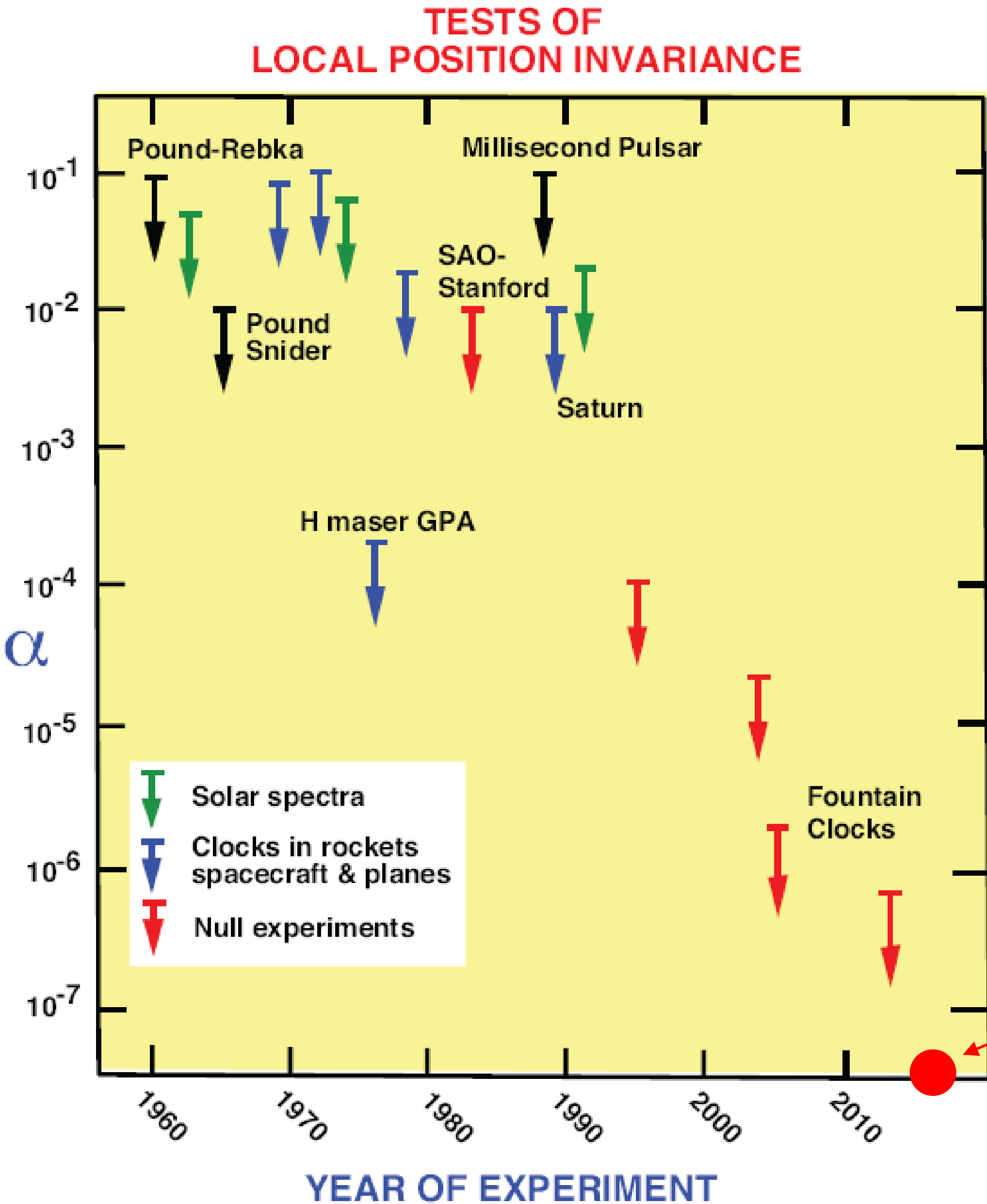
JILA

Dependence of the Yb^+/Sr frequency ratio on the gravitational potential



Coupling of α to gravity $$\frac{c^2}{\alpha}\frac{d\alpha}{dU} = (0.0 \pm 1.9) \cdot 10^{-8}$$

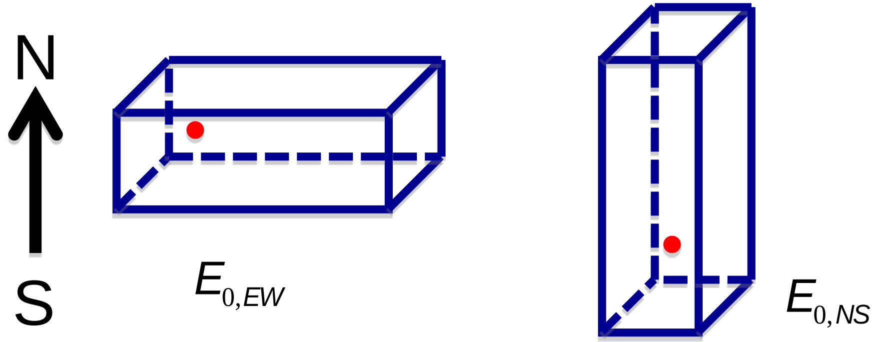
≈24x more stringent than previous limits from Rb/H, Rb/Cs, Dy/Cs
see: M. Abgrall *et al., Comptes Rendus Physique* **16,** 461 (2015)



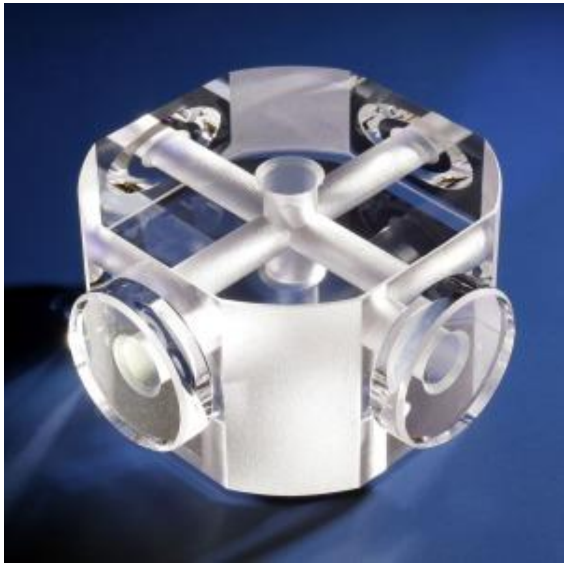
C. Will
Living Review Relativity
17 (2014) 4

this experiment

Clock comparison test of Lorentz invariance



Optical tests of Lorentz invariance:
Michelson-Morley experiment

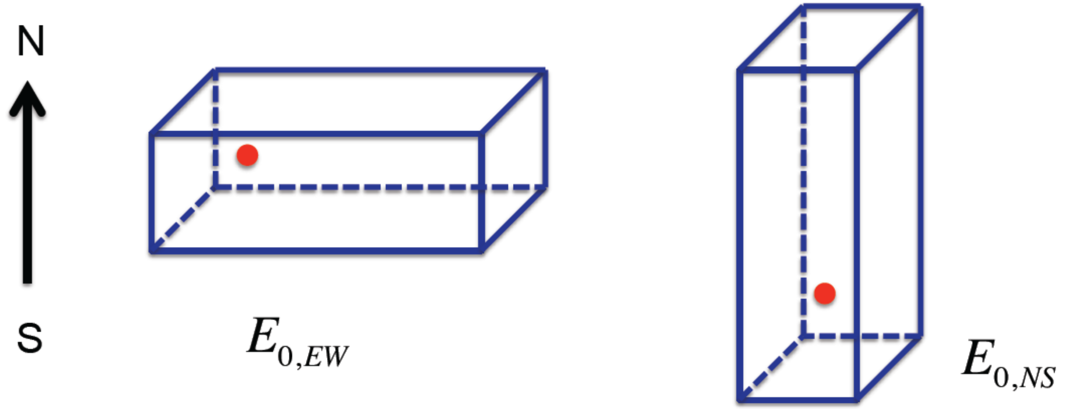


E. Fesseler,
A. Peters, HU Berlin

A. Kostelecky, Standard-Model Expansion:
Search for Lorentz and CPT violation in all interactions of the standard model

Is the electron‘s dispersion relation isotropic in space?

Michelson-Morley experiment
for electrons



Ca$^+$ experiment:
T. Pruttivarasin et al.,
Nature **517**, 592 (2015)

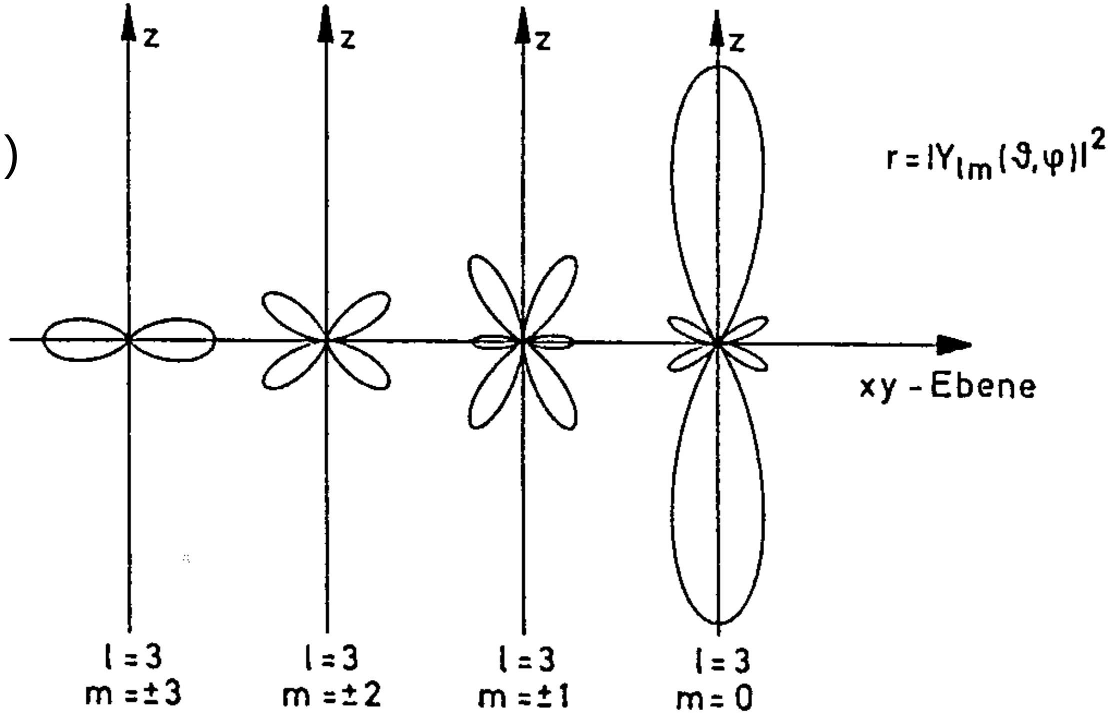
There is a large variety of electron containers...

Parametrizing the energy shift

SME framework (Kostelecky et al.)

$$\delta H = -\frac{1}{6m_e} C_0^{(2)} (\mathbf{p}^2 - 3p_z^2)$$

Look for states with significant momentum quadrupole moments



$$\langle Jm_J | \mathbf{p}^2 - 3p_z^2 | Jm_J \rangle = \langle J \| T^{(2)} \| J \rangle \times \frac{-J(J+1) + 3m_J^2}{\sqrt{(2J+3)(J+1)(2J+1)J(2J-1)}}$$

for Yb^+ $F_{7/2}$ enhanced by a factor 15 compared to Ca^+ $D_{5/2}$

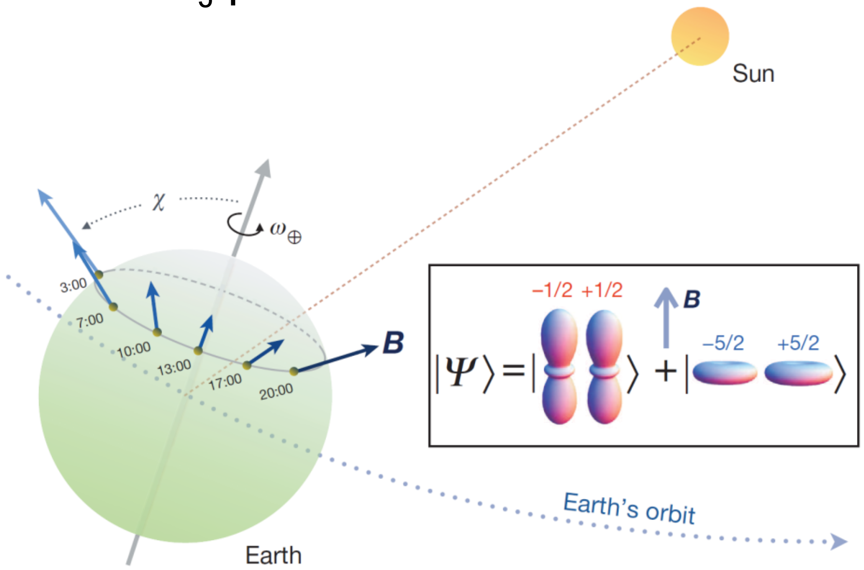
V. A. Dzuba et al., Nature Physics 12, 465 (2016)

Measuring the energy shift of pairs of Zeeman-sublevels

Diagnose <…|δH|…> by looking for a shift of ± m_J level pairs with earth's rotation.

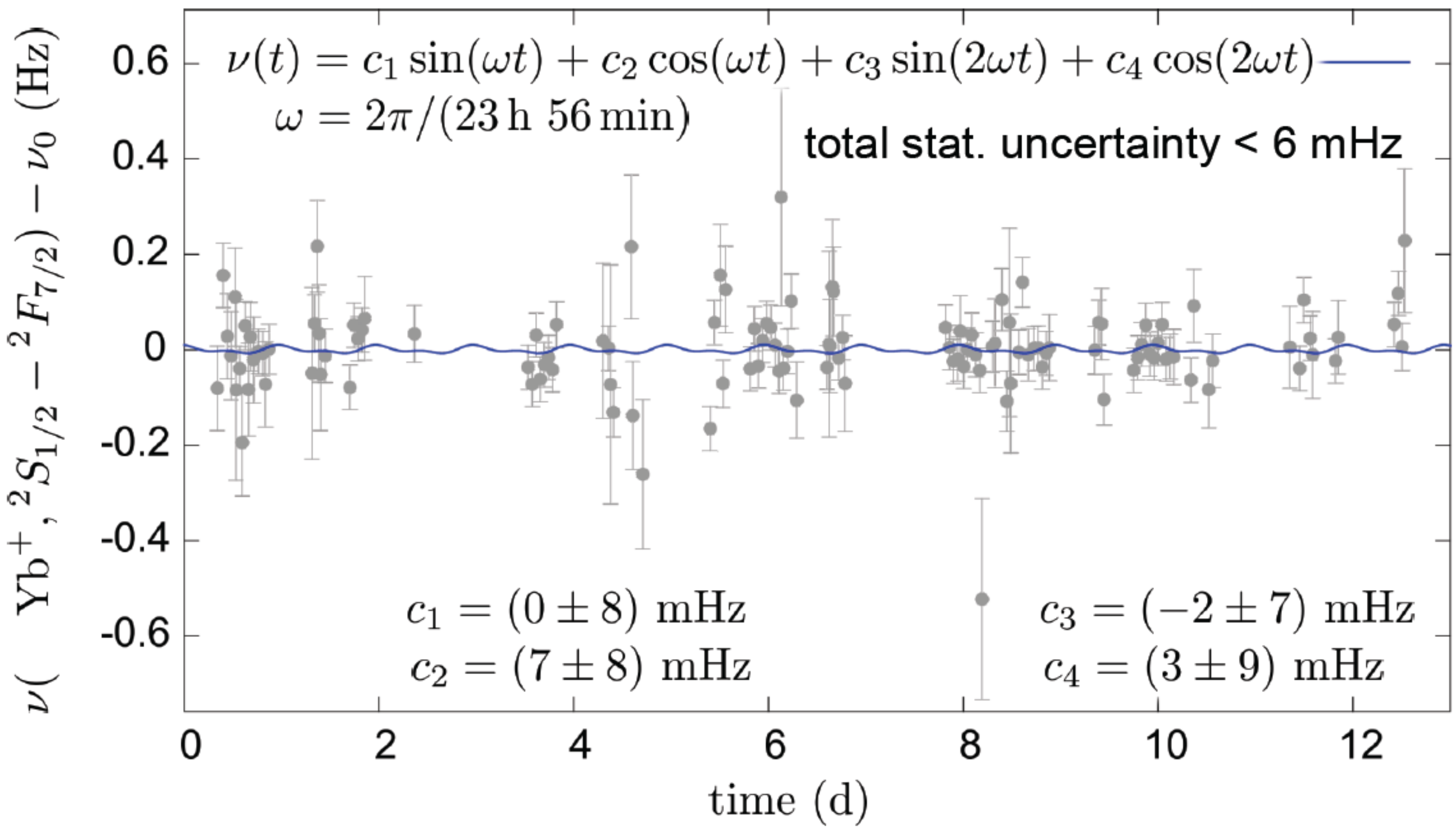
Prepare a two ion state, e.g., $|m_{J1}=-1/2, m_{J2}=1/2>$ and monitor its energy with respect to a second m_J pair

For I=1/2 the $|m_F=0>$ state is a superposition of $m_J=\pm 1/2$. Measure the shift of (F=3, m_F=0) with respect to the ground state, i.e. the frequency of the $^{171}Yb^+$ E3 optical clock



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

Comparing $^{171}Yb^{+}$ $^{2}F_{7/2}$ to ^{87}Sr $^{3}P_{0}$



Preliminary analysis (more data upcoming):

About ×3 improvement in limit of $C_0^{(2)}$ over Ca^{+} experiment.

Summary and Conclusion

Progress in the accuracy of atomic optical clocks leads to sensitive opportunities in searches for New Physics.

The Yb^+ $S \rightarrow F$ octupole transition has been used in improved tests of:

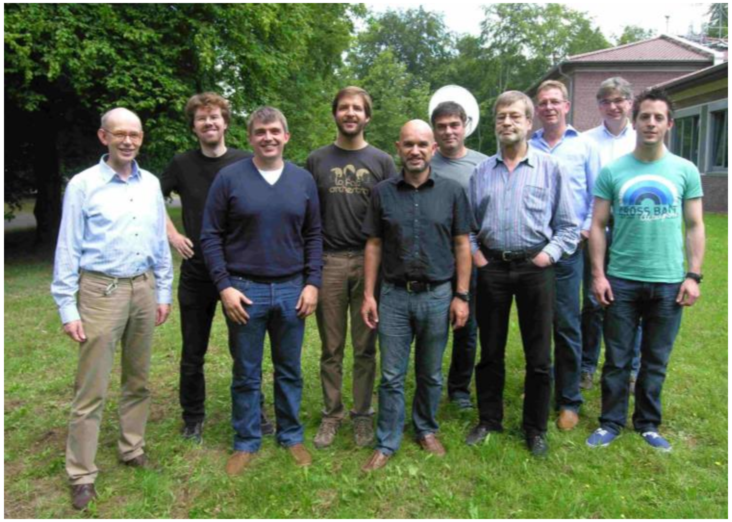
- Temporal variations of α and m_p/m_e
- Coupling of α to gravity
- Lorentz invariance for electrons

The equivalence principle has passed all tests with clocks so far.

Even these Null results are useful, as the experiments help to improve the clocks and thus may open new fields of applications.

More sensitive experiments will be possible with new systems, like the Th-229 nuclear clock.

PTB Working Groups: Optical Clocks with Trapped Ions, Caesium Fountain Clocks, Optical Lattice Clocks



Yb^+ clocks
N. Huntemann
C. Sanner
R. Lange
B. Lipphardt
Chr. Tamm

Th-229
M. Okhapkin
D.-M. Meier
J. Thielking
P. Glowacki

Cs clocks
S. Weyers
M. Kazda
V. Gerginov

Sr lattice clock
S. Dörscher, A. Al-Masoudi, S. Häfner,
C. Lisdat, C. Grebing, U. Sterr
N. Lemke, S. Falke

Postdoc Position Available

PTB
Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

EMRP
European Metrology Research Programme
Programme of EURAMET

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nuClock

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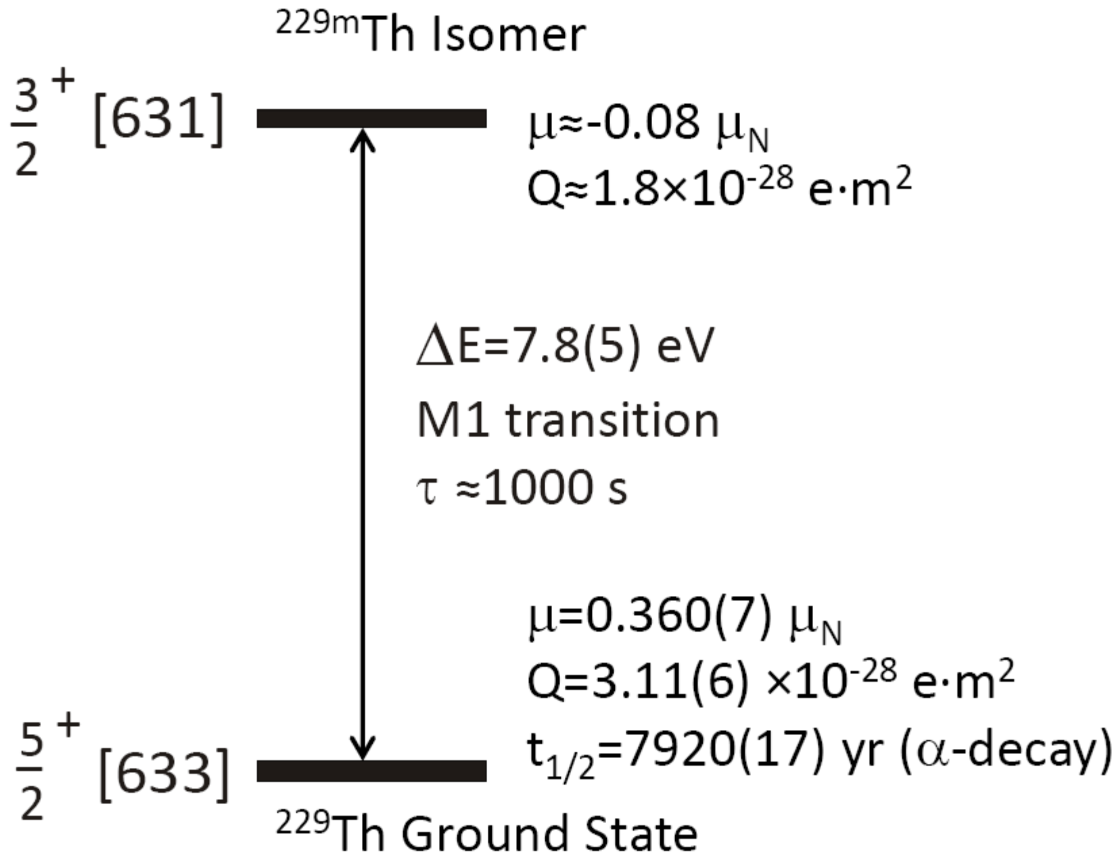
DQmat

Horizon 2020
European Union funding
for Research & Innovation

Thorium-229: the nucleus with the lowest-lying excited state

The only known isomer with an excitation energy in the optical range and in the range of outer shell electronic transitions.



Review article:

E. Peik, M. Okhapkin, Comptes Rendus Physique **16**, 536 (2015)
also available at: arXiv:1502.07322

Th-229: the most sensitive probe in a search for variations of the fundamental coupling constants?

V. Flambaum: Phys. Rev. Lett. **97**, 092502 (2006):

α-sensitivity of nuclear transition frequency ω is due to the Coulomb contribution to the nuclear energy difference.

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

$$K = \frac{E_{C,m} - E_{C,g}}{\hbar\omega}$$

$$|K| = 0\ldots 10^5$$

Predictions vary widely, depending on model of nuclear structure

Solution: Use measurements of isomer shifts, HFS and atomic structure calculations
J. C. Berengut, V. A. Dzuba, V. V. Flambaum, S. G. Porsev, PRL **102**, 210808 (2009)

Measure: $\Delta\langle r^2\rangle$ from isomer shift (field shift)

Similar sensitivity of ω to QCD contributions expected.

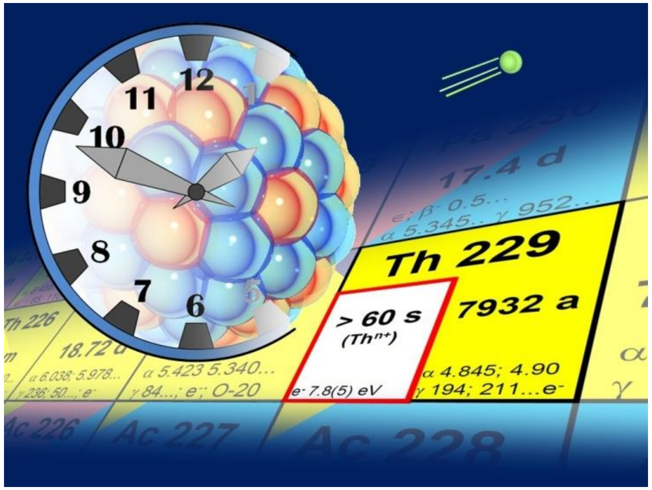
Low-energy nuclear physics with ^{229}Th

• modified decay rates in different electronic environments, electronic bridge processes. Tkalya, Karpeshin, et al.

• highly precise and highly stable optical nuclear clock, trapped ions and doped solids. Peik and Tamm, Hudson, Kuzmich, Schumm

• test system for „new physics": variations of fundamental constants, violation of Lorentz invariance. Flambaum et al.

- γ-ray laser. Tkalya
- …



GSI

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