Optical clocks with trapped ions and search for temporal variations of fundamental constants

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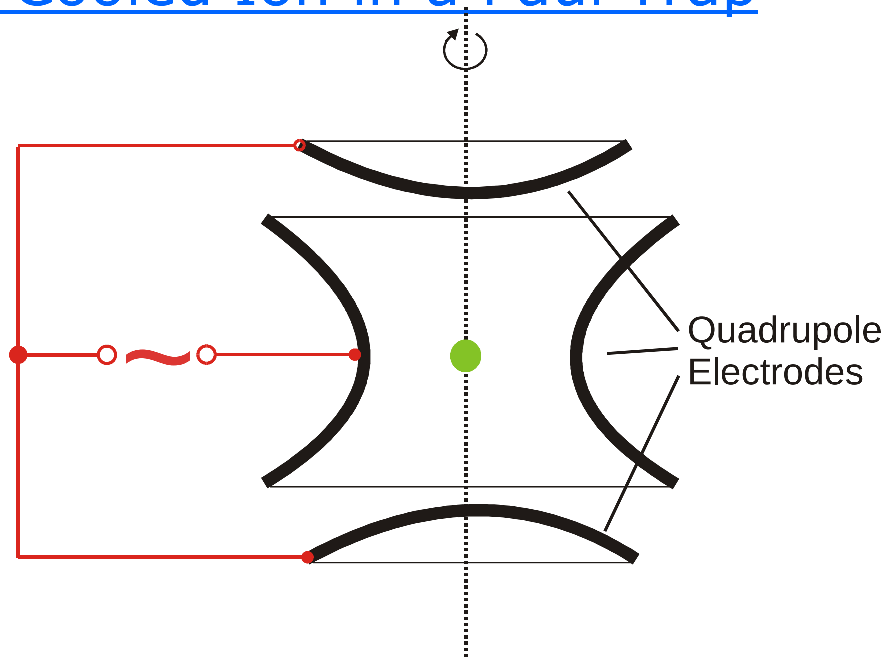
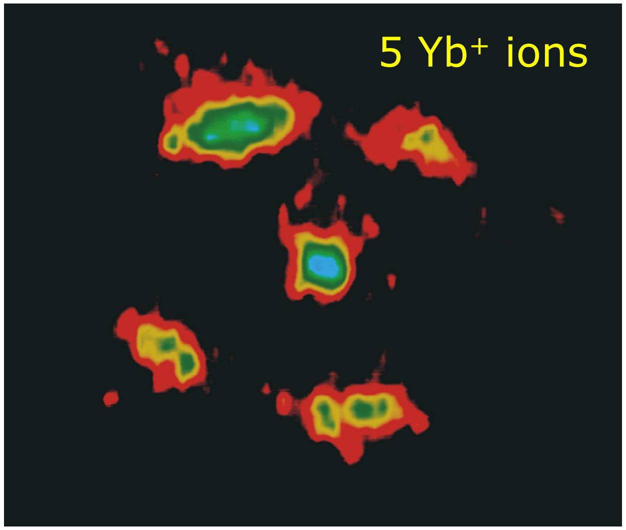
Optical Frequency Standards with a Laser-Cooled Ion in a Paul Trap





- Lamb-Dicke confinement with small trap shifts
- unlimited interaction time
- single ion: no collisions
- stability: use high-Q transition

Optical Frequency Standard with a Laser-Cooled Ion in a Paul Trap

→ Very low uncertainty is possible (to 10^{-18})
proposed by Hans Dehmelt 1975

Experiments with Hg^+ (NIST), Yb^+ (PTB, NPL), In^+ (MPG, U Wash.), Sr^+ (NRC, NPL), Ca^+(Mars., Innsb.,...), Ba^+ (U Wash.), Al^+ (NIST), ...

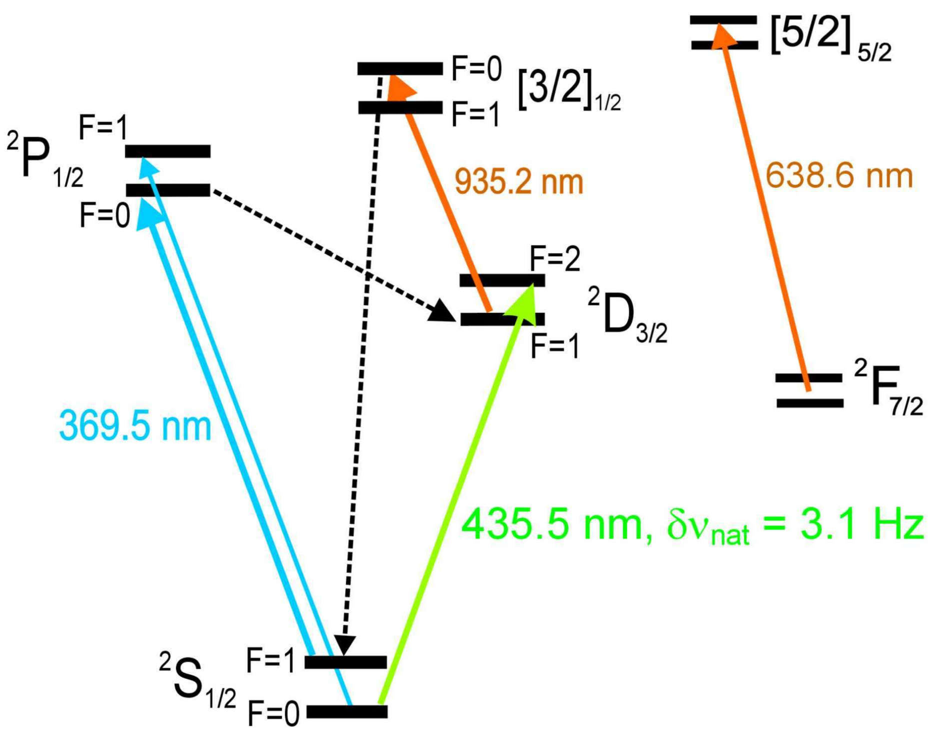
Measurements of optical transition frequencies using cesium fountains and femtosecond-laser frequency combs:

$^{199}Hg^+$ $S_{1/2}$ - $D_{5/2}$:	1 064 721 609 899 144.94(97) Hz	NIST
$^{171}Yb^+$ $S_{1/2}$ - $D_{3/2}$:	688 358 979 309 307.5(2.2) Hz	PTB
$^{88}Sr^+$ $S_{1/2}$ - $D_{5/2}$:	444 779 044 095 484.2(1.7) Hz	NPL

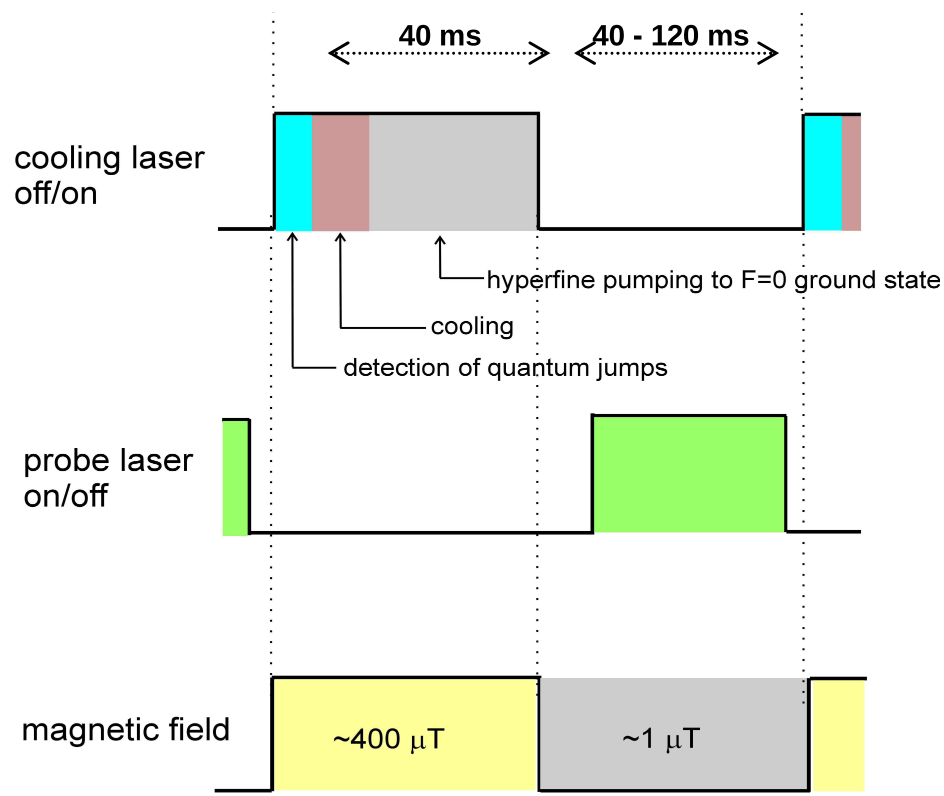
These standards are proposed as „secondary representations of the *second*“ in the optical frequency domain.

Yb+ single-ion optical frequency standard

$^{171}Yb^+$ level scheme

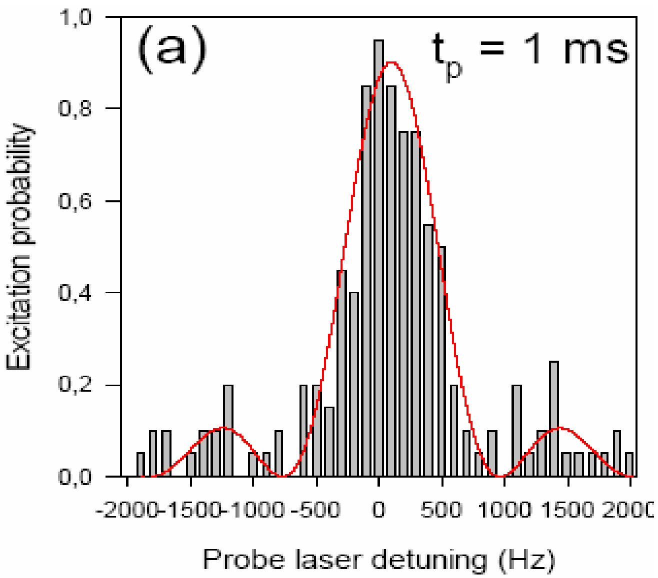


Measurement cycle

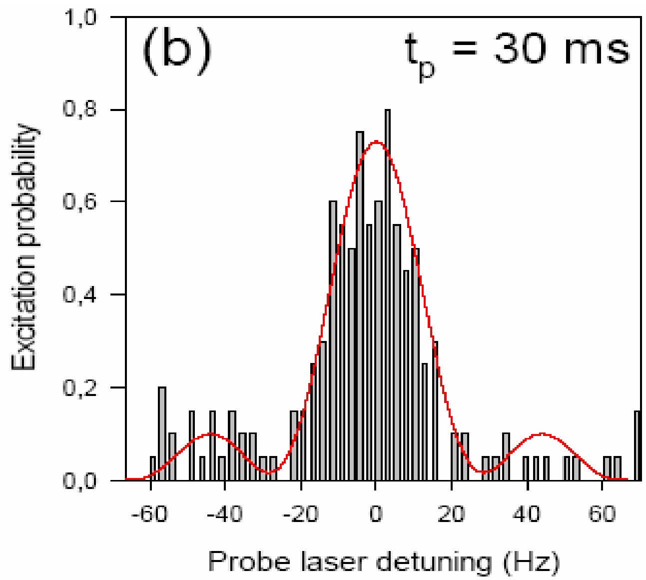


High resolution spectroscopy of the quadrupole transition at 688 THz

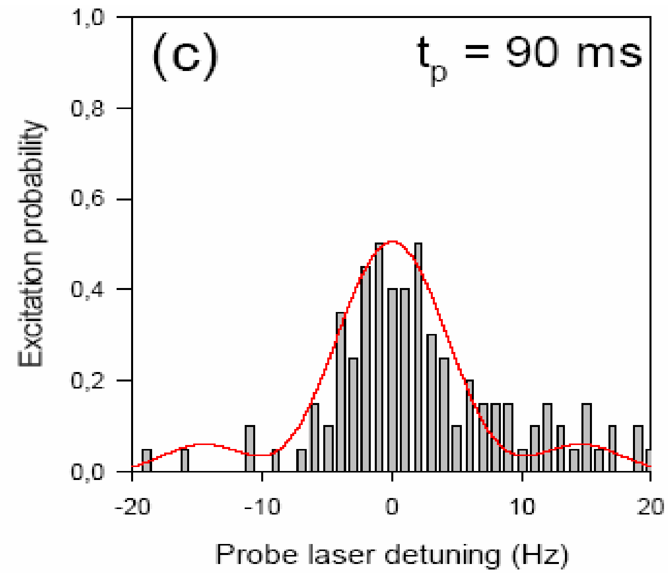
Pi-Pulse
τ(pulse)=1 ms
1 kHz linewidth



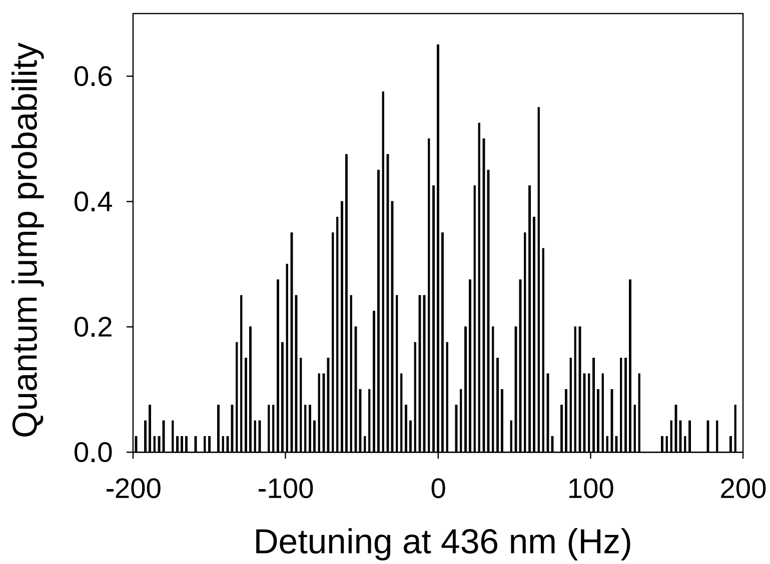
„standard operation"
τ(pulse)=30 ms
30 Hz linewidth



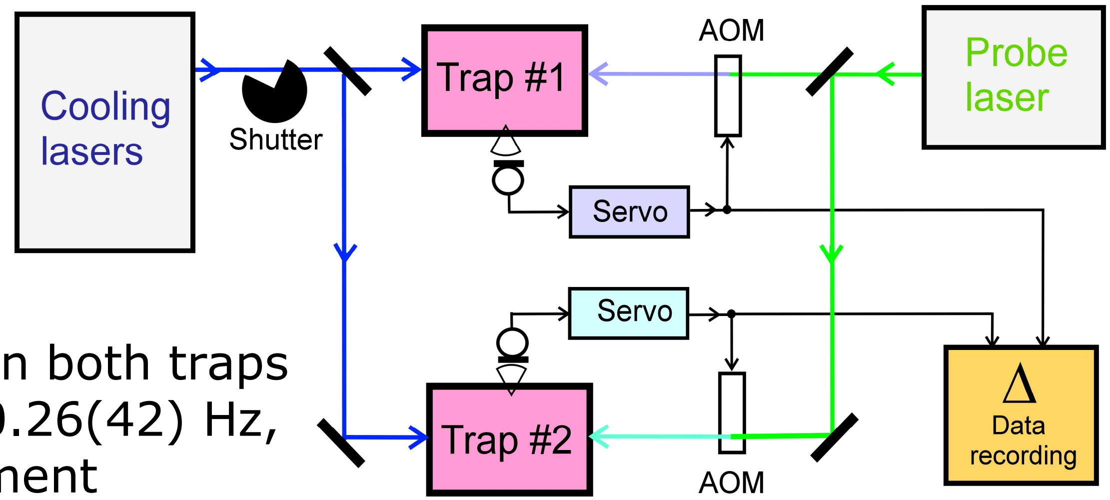
Close to the resolution limit
τ(pulse) = 90 ms ≈ 2·τ(Yb^+)
10 Hz linewidth



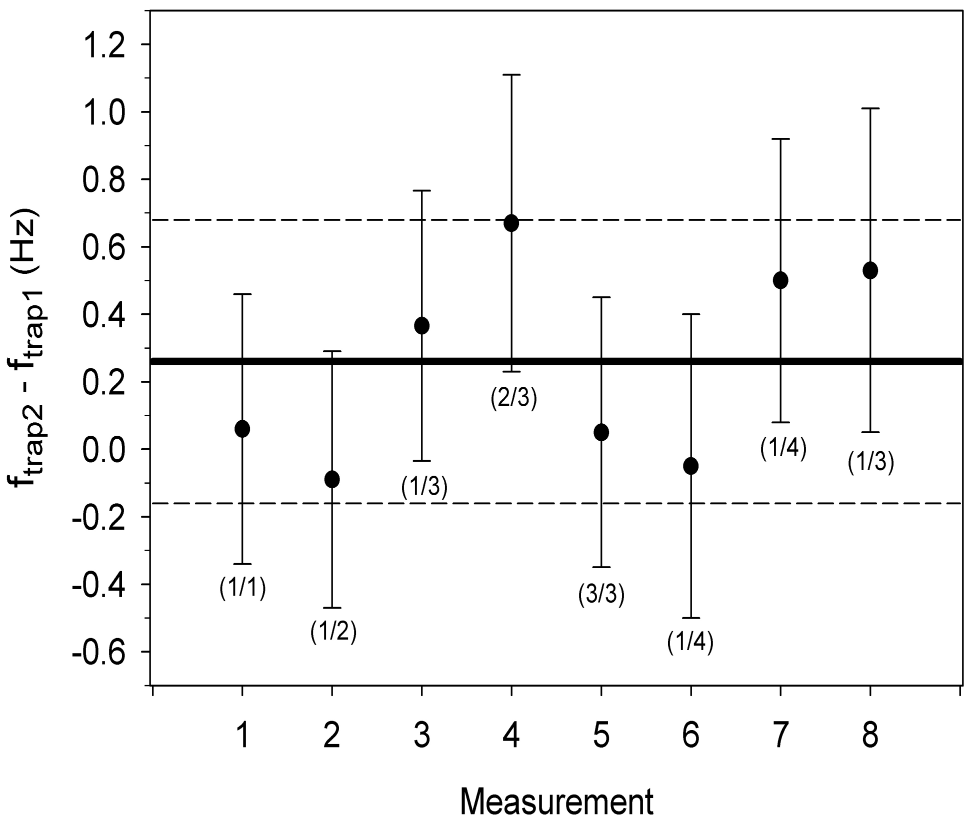
Ramsey excitation
with 30 ms pulse separation



Frequency comparison between two trapped $^{171}Yb^{+}$ ions



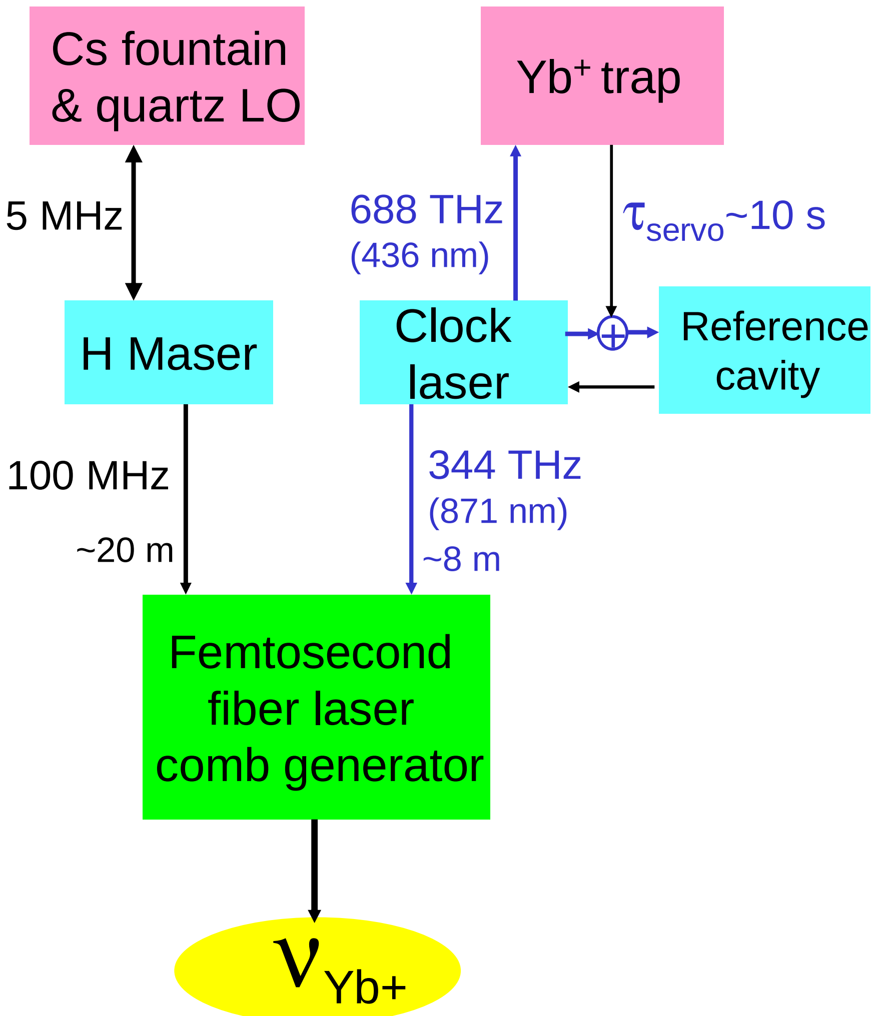
For nominally unperturbed conditions in both traps we observe a frequency difference of 0.26(42) Hz, comparable to the best relative agreement between cesium fountain clocks.



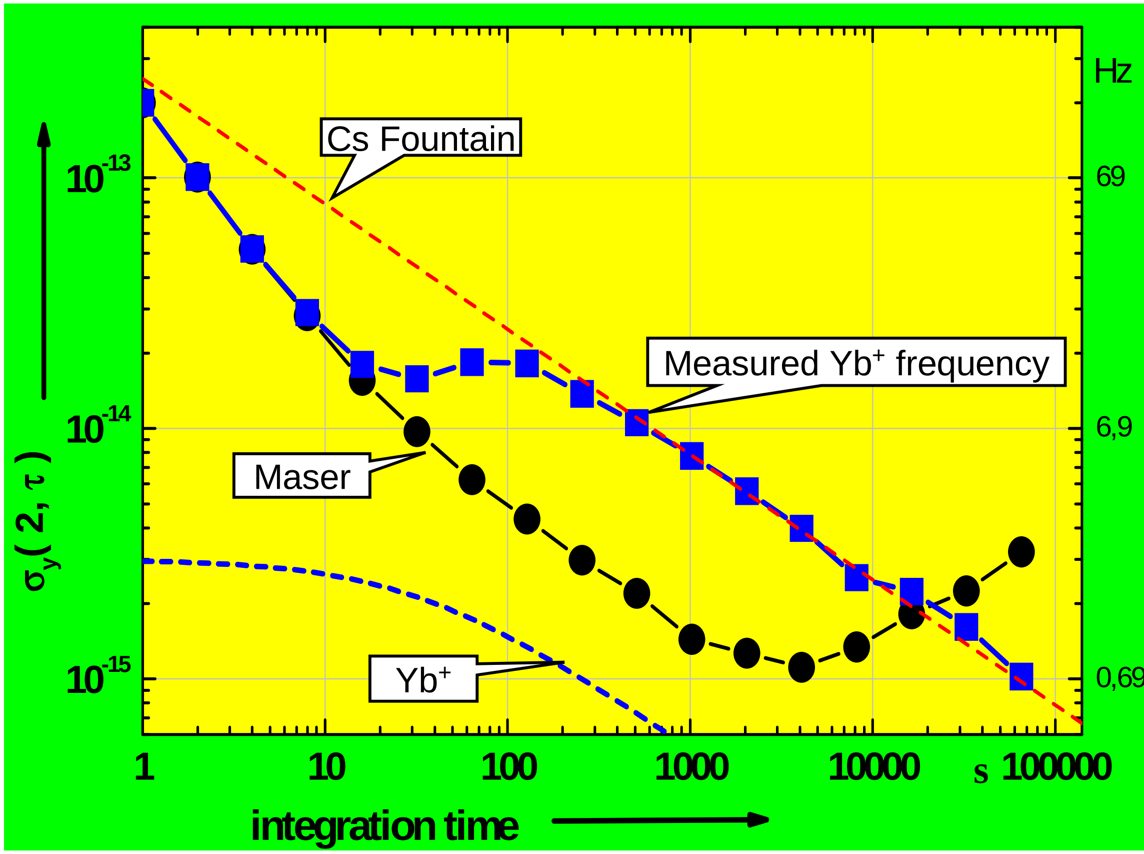
$6\text{x}10^{-16}$

T. Schneider, E. Peik, Chr. Tamm, Phys. Rev. Lett. **94**, 230801 (2005)

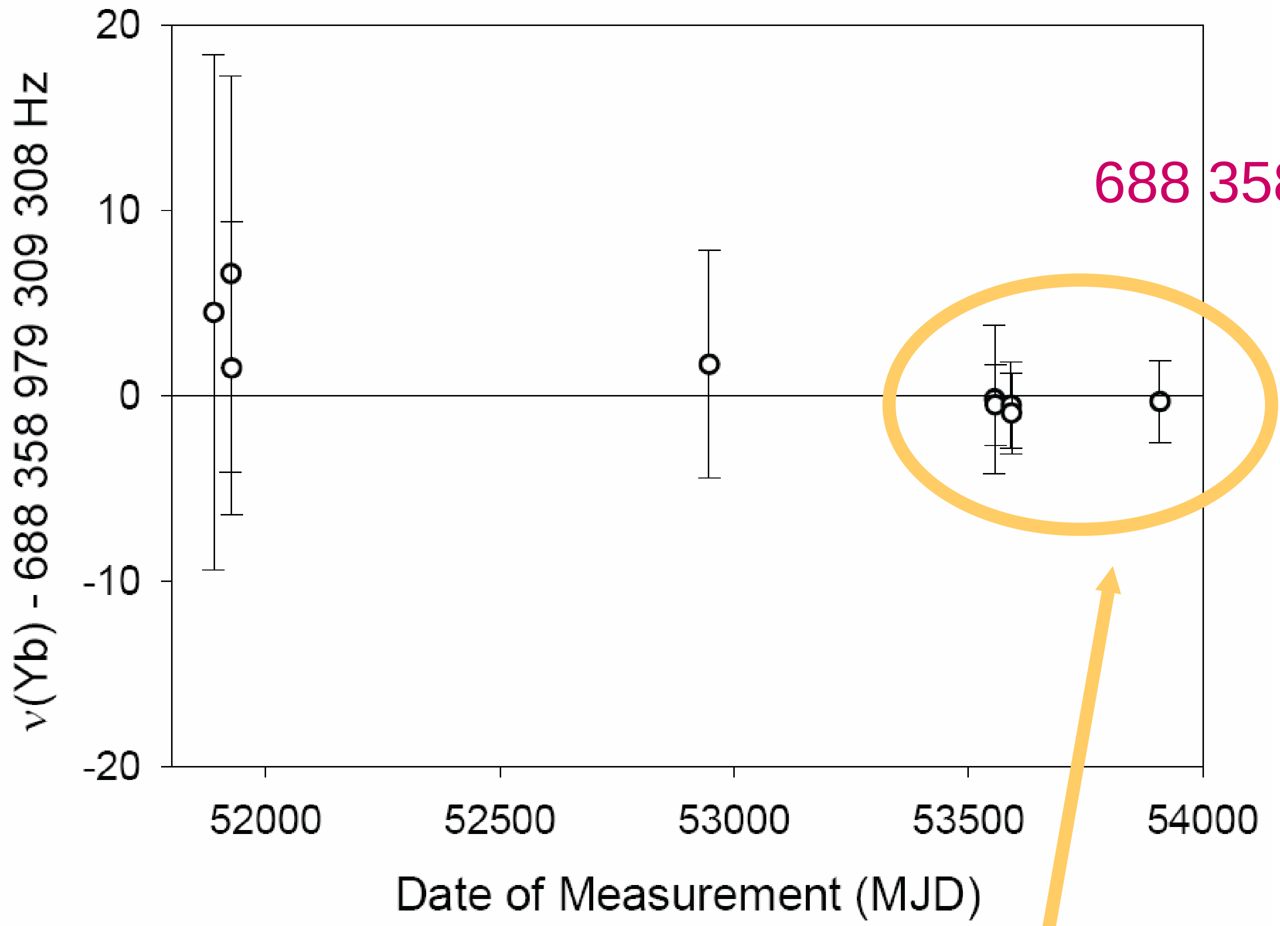
Absolute frequency measurement



Observed Allan deviations



Results of absolute frequency measurements 2000-2006



$^{171}Yb^{+}$ $S_{1/2}$ - $D_{3/2}$:
688 358 979 309 307.5(2.2) Hz

Main contributions to the uncertainty budget
of the measurements in 2005 and 2006:

u_A=0.40 Hz (continuous measurements up to 36 h)

u_B(Cs)=1.82 Hz (pulse area related shift)

$u_B(Yb^+)$=1.05 Hz (quadrupole shift, blackbody AC Stark shift)

Present uncertainty budget of Yb^+ 688 THz systematics:

1 Hz	stray-field induced quadrupole shift
0.1 Hz	line-shape asymmetry, servo error
0.3 Hz	AC Stark shift (blackbody anisotropy, deviation from 300 K)
0.03 Hz	Stark shift from trap
0.01 Hz	Relativistic Doppler shift

can be reduced significantly
via averaging schemes

improved thermal design,
cryogenic cooling,
precise polarizabilities

Search for α-variation in optical electronic transition frequencies.
Method of Analysis:
electronic transition frequency can be expressed as

$$f = Ry \cdot C \cdot F(\alpha)$$

$Ry = m_e e^4/(8\epsilon_0^2 h^3) \simeq 3.2898 \cdot 10^{15}\ \mathrm{Hz}$ Rydberg frequency in SI hertz

C numerical constant (function of quantum numbers)

$F(\alpha)$ dimensionless function of α; describes relativistic level shifts

Relative temporal derivative of the frequency:

$$\frac{\partial \ln f}{\partial t} = \frac{\partial \ln Ry}{\partial t} + A \cdot \frac{\partial \ln \alpha}{\partial t} \qquad \text{with} \quad A \equiv \frac{\partial \ln F}{\partial \ln \alpha}$$

common shift of all transition frequencies

specific for the transition under study

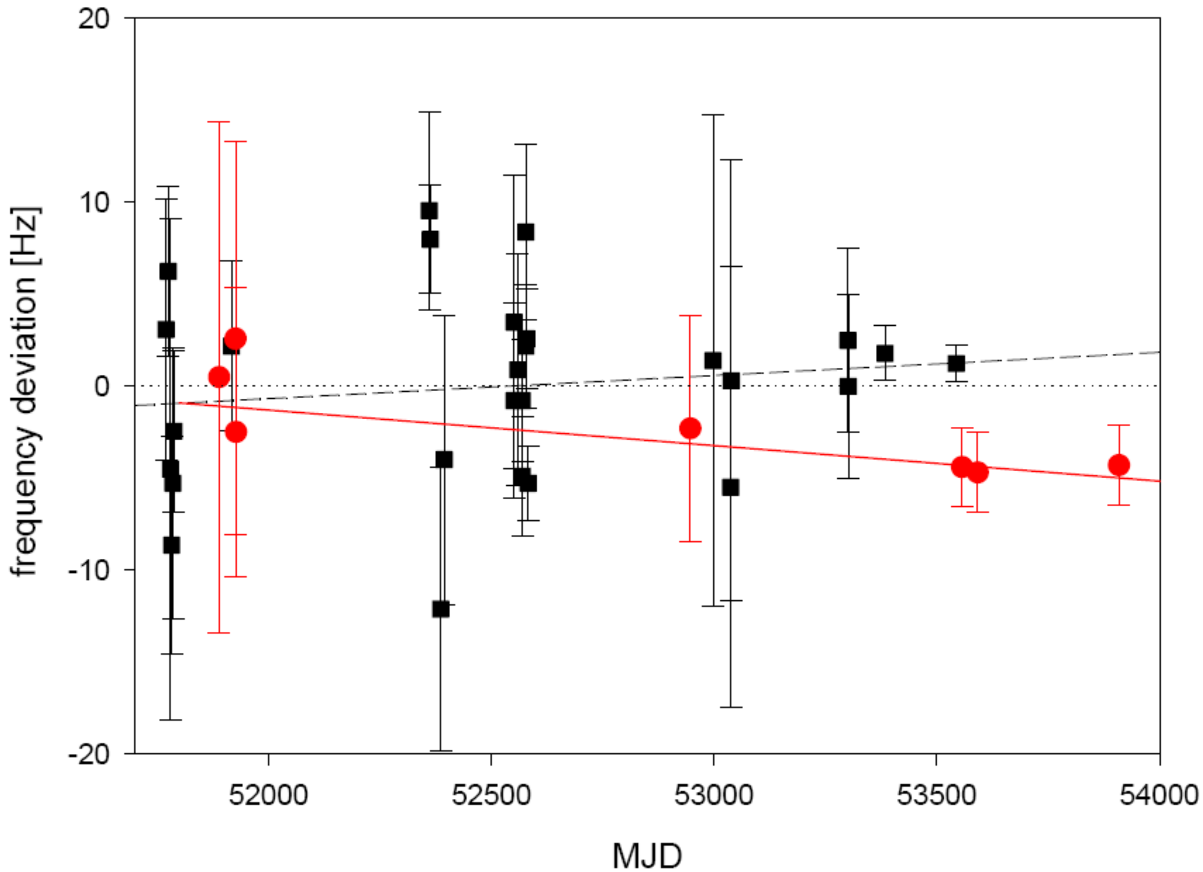
can be calculated with relativistic Hartree-Fock (Dzuba, Flambaum)

Frequency comparisons of single-ion optical clocks (via Cs fountains)

Yb$^+$, S - D at 688 THz, PTB

Hg$^+$, S - D at 1064 THz, NIST Boulder, S. Bize et al., PRL **90**, 150802 (2003)

W. Oskay et al., PRL **97**, 020801 (2006)



A(Hg)=-3.19

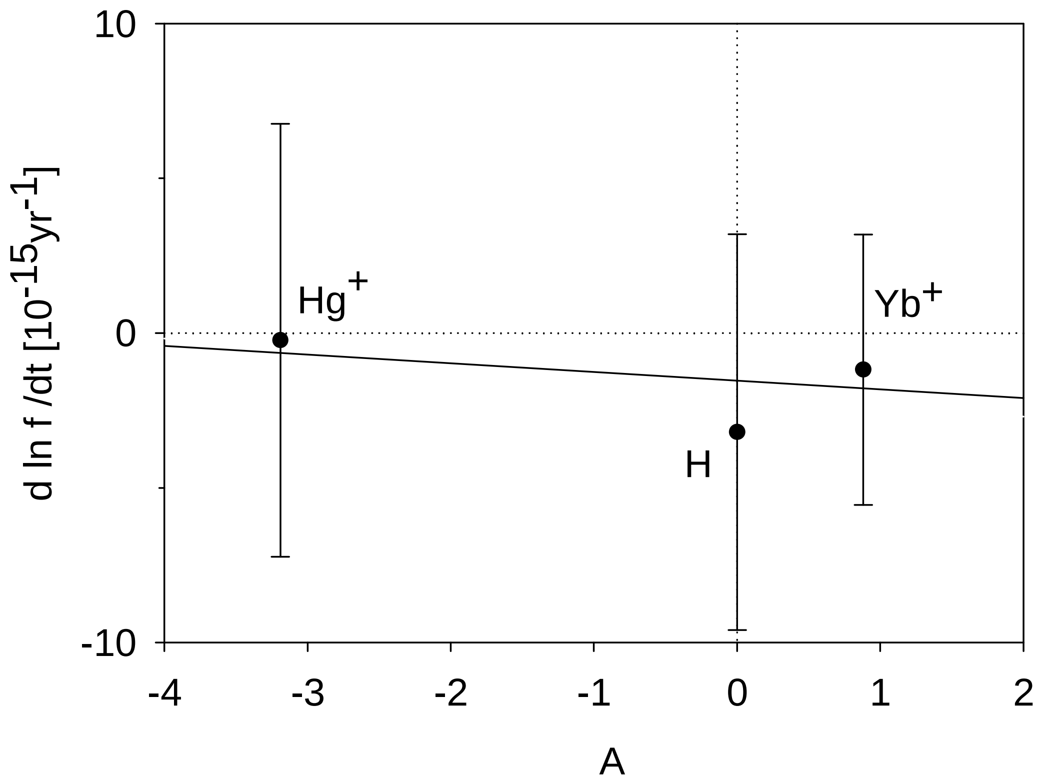
A(Yb)=0.88

New limits for the present temporal variations of fine structure constant and Rydberg frequency:

$$\frac{d\ln\alpha}{dt} = (-0.32 \pm 0.39)\cdot 10^{-15}\ \mathrm{yr}^{-1}$$

$$\frac{d\ln Ry}{dt} = (-0.74 \pm 1.22)\cdot 10^{-15}\ \mathrm{yr}^{-1}$$

Measured frequency drifts versus sensitivity factor A



$$\frac{\partial \ln f}{\partial t} = \frac{\partial \ln Ry}{\partial t} + A \cdot \frac{\partial \ln \alpha}{\partial t}$$

H-data point: 1S - 2S vs. Cs
MPQ/SYRTE group
M. Fischer et al.,
Phys. Rev. Lett. **92**, 230802 (2004)

From a weighted linear regression:

slope: $$\frac{\partial \ln \alpha}{\partial t} = (-0.3 \pm 2.0) \cdot 10^{-15}\ \mathrm{yr}^{-1}$$

intercept: $$\frac{\partial \ln Ry}{\partial t} = (-1.5 \pm 3.2) \cdot 10^{-15}\ \mathrm{yr}^{-1}$$

Consistent with „constancy of constants".

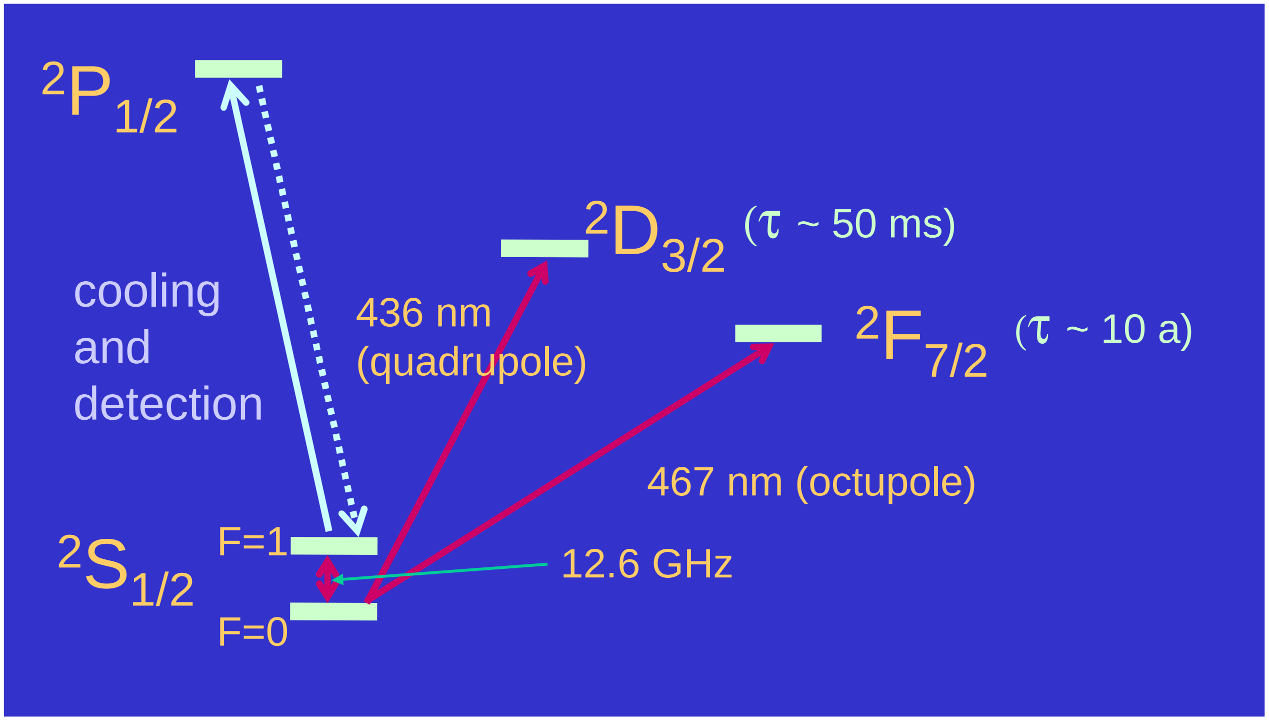
E. Peik et al., Phys. Rev. Lett. **93**, 170801 (2004)

Future Possibilities:

Direct optical frequency ratio measurements with a frequency comb: avoid uncertainty contributions from cesium clocks

- NIST: Hg^+ vs. Al^+: $|\Delta A=3.2|$
- PTB/NPL: Yb^+ octupole vs. quadrupole: $|\Delta A=6.2|$

Level scheme of $^{171}Yb^+$

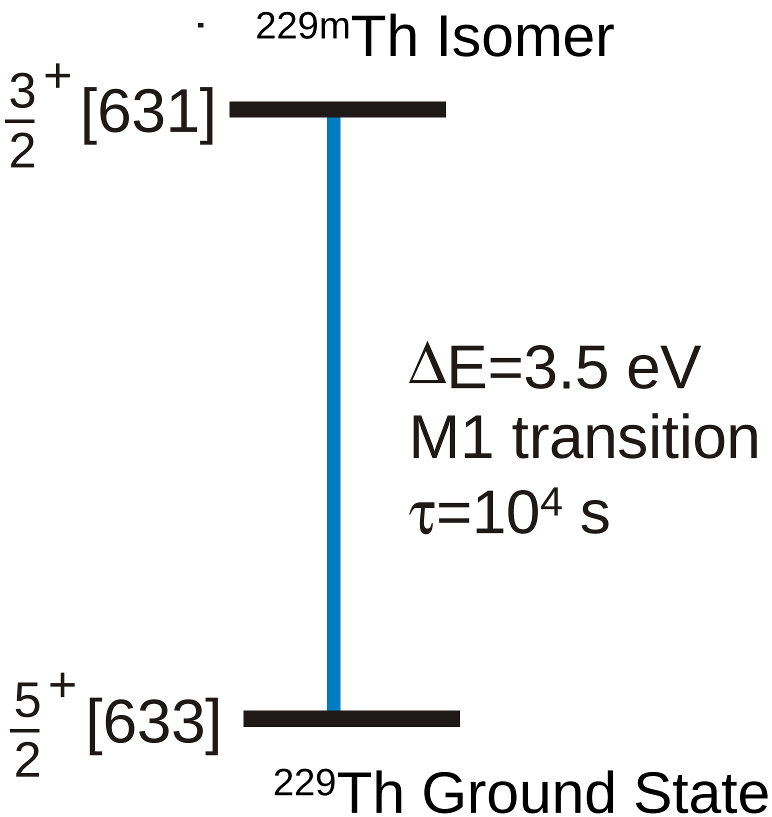


Precision data from more diverse systems:

- molecular rotational and vibrational lines → m_e/m_p
- nuclear transitions (e.g. Th-229 optical transition) → strong interaction

The Thorium Isomer at 3.5 eV: An Optical Mössbauer Transition

The lowest-lying known excited state of a nucleus is an isomer of Th-229 at about 3.5 eV. This nucleus can be excited by the absorption of ultraviolet light.



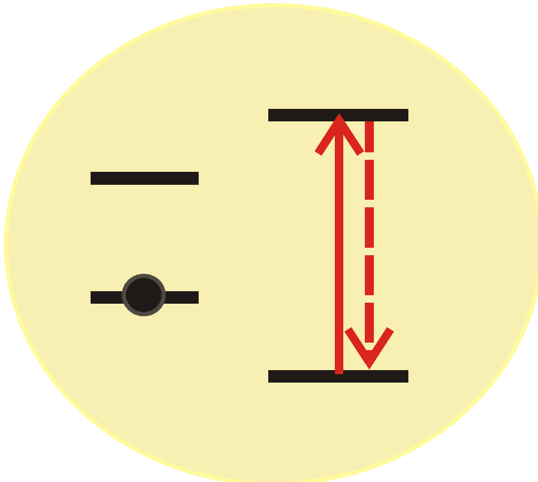
Measurements of ΔE

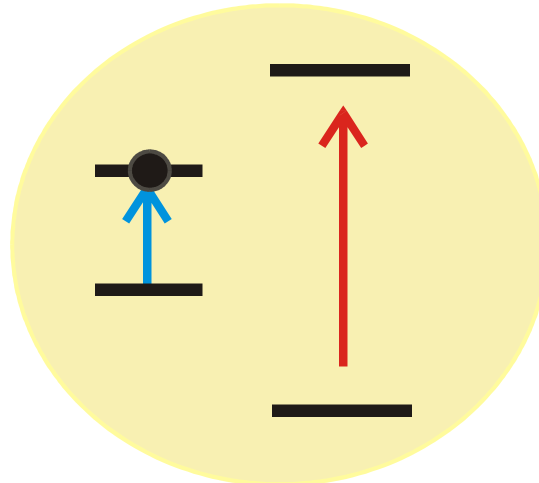
ΔE [eV]	Year	Method
<100	1976	γ-Spectr.
-1 (4)	1990	“
<5	1990	d-Scatt.
3.5 (1.0)	1994	γ-Spectr*
3.4 (1.8)	2003	“

*R. Helmer and C. Reich, Idaho

“ V. Barci et al., Nice

Detection of the Nuclear Excitation in Nuclear-Electronic Double-Resonance with a Single Ion: Observation of Quantum Jumps





Nucleus in the ground state; laser-induced fluorescence from the shell.

Laser excitation of the nucleus; change of hyperfine structure detected in intensity or polarisation of fluorescence.

→ Possibility for a single-ion frequency standard with a nuclear excitation as the reference transition.

- Th^{3+} has suitable level scheme for laser cooling
- promises a further reduction of systematic line shifts
- constitutes a precision oscillator of the strong interaction

E. Peik, Chr. Tamm, Europhys. Lett. **61**, 181 (2003)

Scaling of the ^{229}Th transition frequency ω in terms of α and quark masses:

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

$$\frac{\delta\omega}{\omega} \approx 10^5\left(4\frac{\delta\alpha}{\alpha} + \frac{\delta X_q}{X_q} - 10\frac{\delta X_s}{X_s}\right)$$

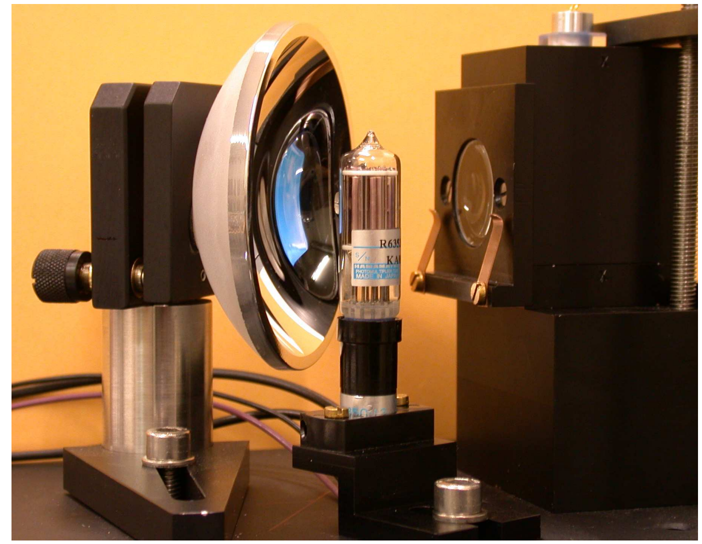
where $X_q = m_q/\Lambda_{\mathrm{QCD}}$ and $X_s = m_s/\Lambda_{\mathrm{QCD}}$

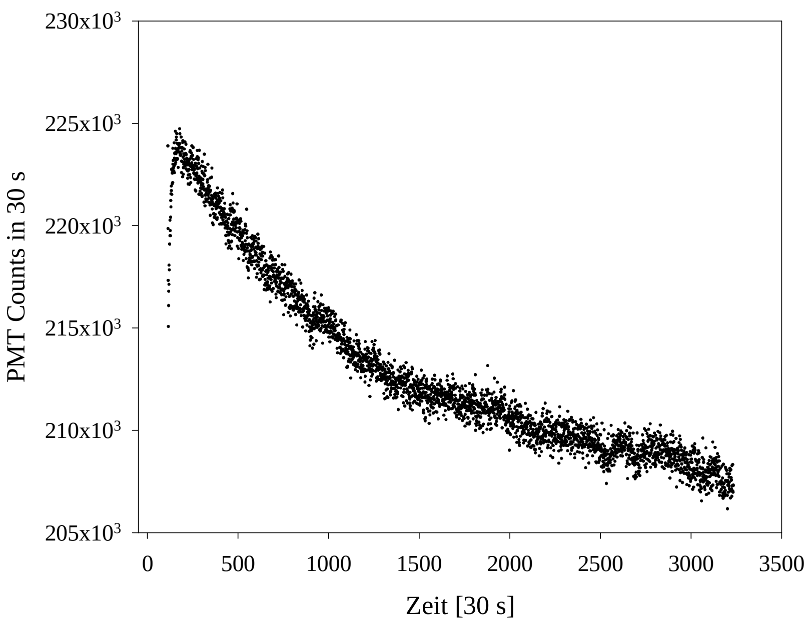
10^5 enhancement in sensitivity to variations results from the near perfect cancellation of two O(MeV) contributions to the nuclear level energies.

Comparing the Th nuclear frequency to present atomic clocks will allow to look for temporal variations at the level 10^{-20} per year.

The experimental challenge:
direct observation of the optical nuclear transition,
precise measurement of the wavelength

Fluorescence experiments with
Th solutions remained inconclusive,
improved experiments are in preparation





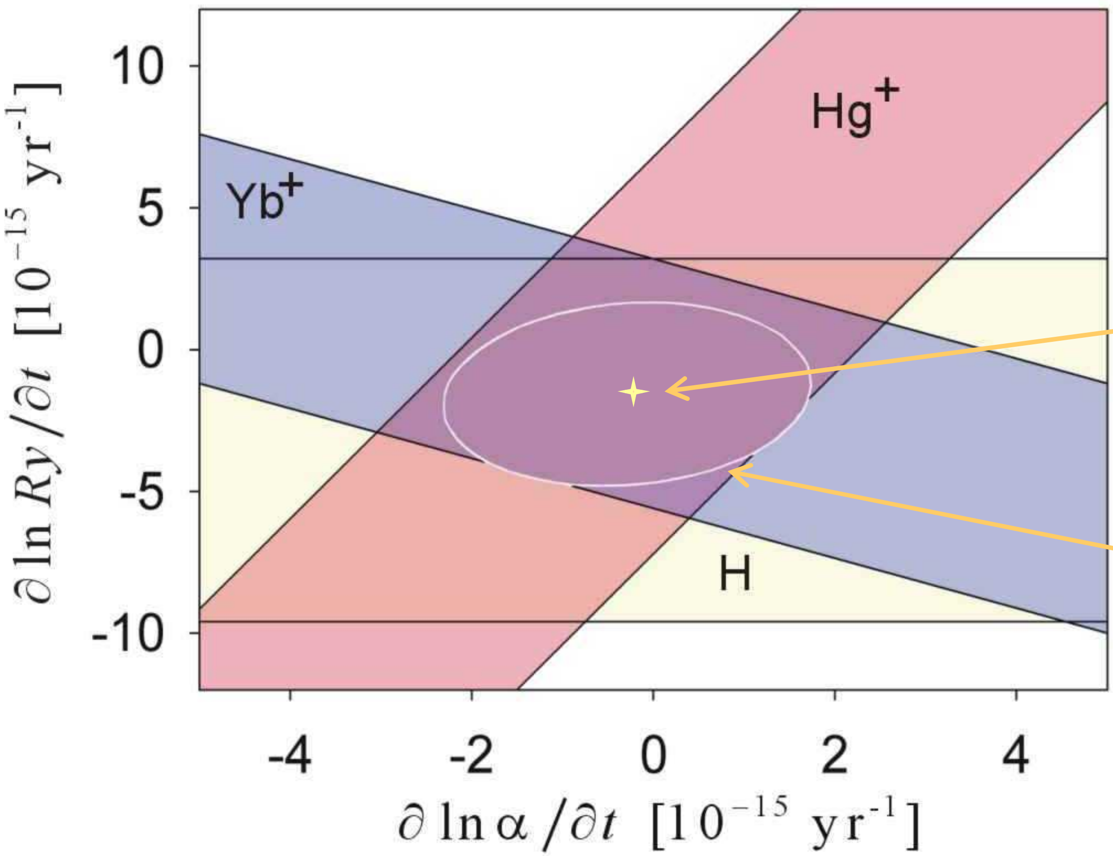
Emission from a Th solution after excitation with a HgXe lamp,
showing Cerenkov radiation, photoluminescence …..

Summary / Outlook

- optical frequency standards with < 10^{-15} uncertainty
- diversity of standards to address question of variations of constants
- nuclear clock with Th-229 or other Mößbauer lines
  ⇒ solid-state atomic clock for space applications??

Support: DFG through SFB 407, RFBR (S.G.K.)

Contributions of Yb^+, Hg^+, and H measurements to the limits on $\partial\alpha/\partial t$ and $\partial Ry/\partial t$



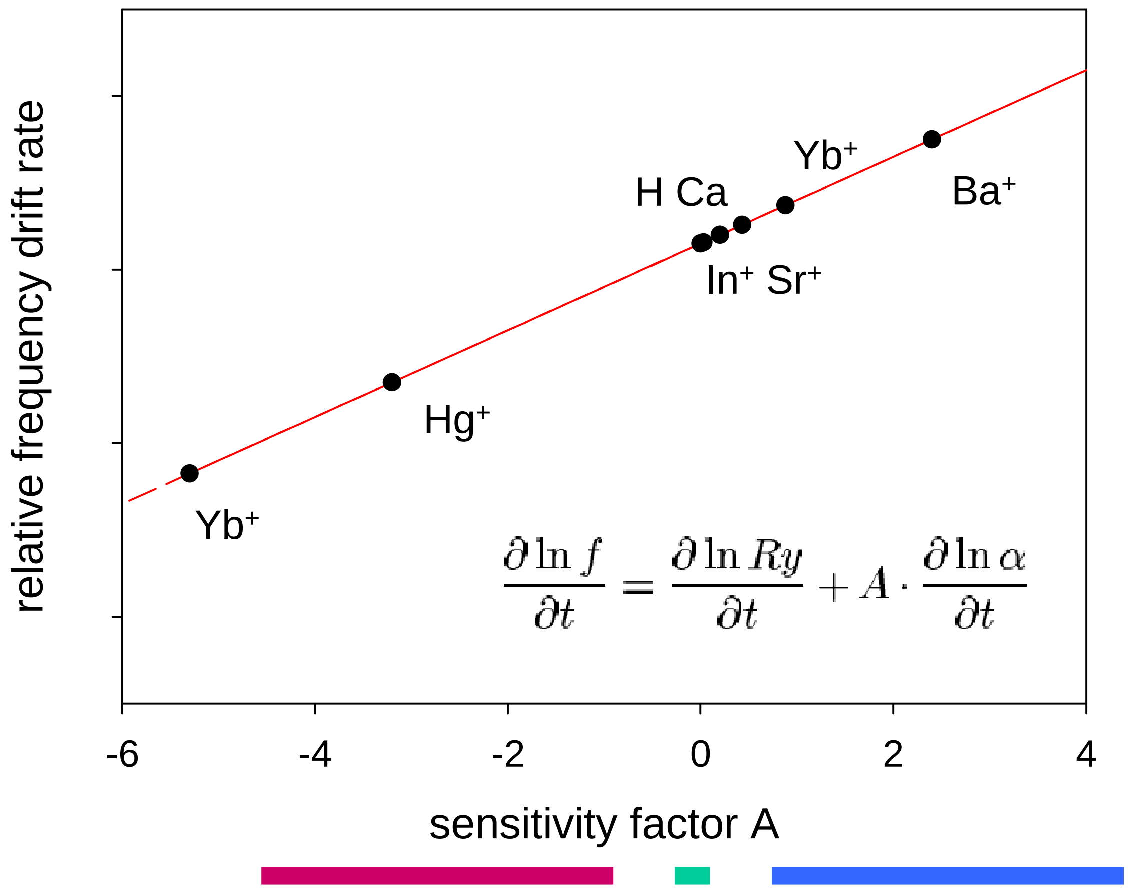
$$\frac{\partial \ln f}{\partial t} = \frac{\partial \ln Ry}{\partial t} + A \cdot \frac{\partial \ln \alpha}{\partial t}$$

$\partial\alpha/\partial t$ and $\partial Ry/\partial t$ estimate (weighted mean of Yb^+, Hg^+, H data)

standard uncertainty ellipse

Signature of a varying fine structure constant

S. G. Karshenboim
physics/0311080



relativistic level shift:

$$\sim \frac{(Z\alpha)^2}{n_*} \frac{1}{j+1/2}$$

calculations by
V. Dzuba and V. Flambaum

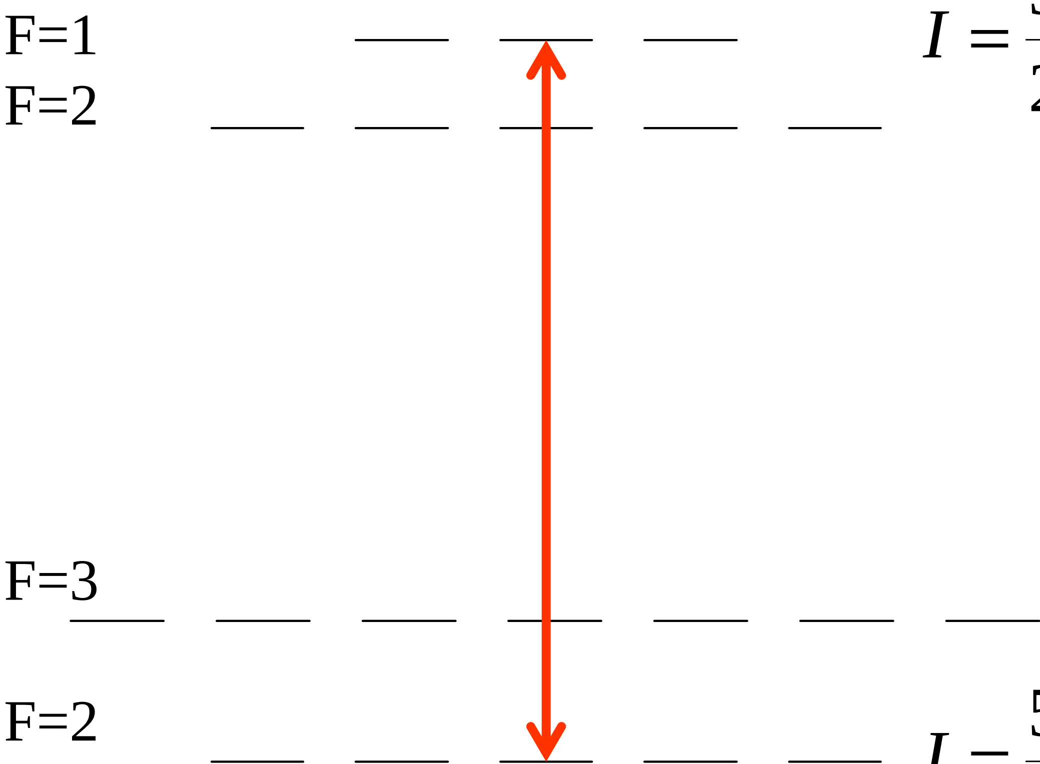
heavy atoms, $j_g > j_e$

light atoms

heavy atoms, $j_g < j_e$

Hyperfine and Zeeman Structure of the Nuclear Resonance:

electronic state: $^2S_{1/2}$



$$I = \frac{3}{2},\ {}^2S_{1/2}\ , F = 1, m_F = 0$$

Isomeric state with hyperfine coupl.

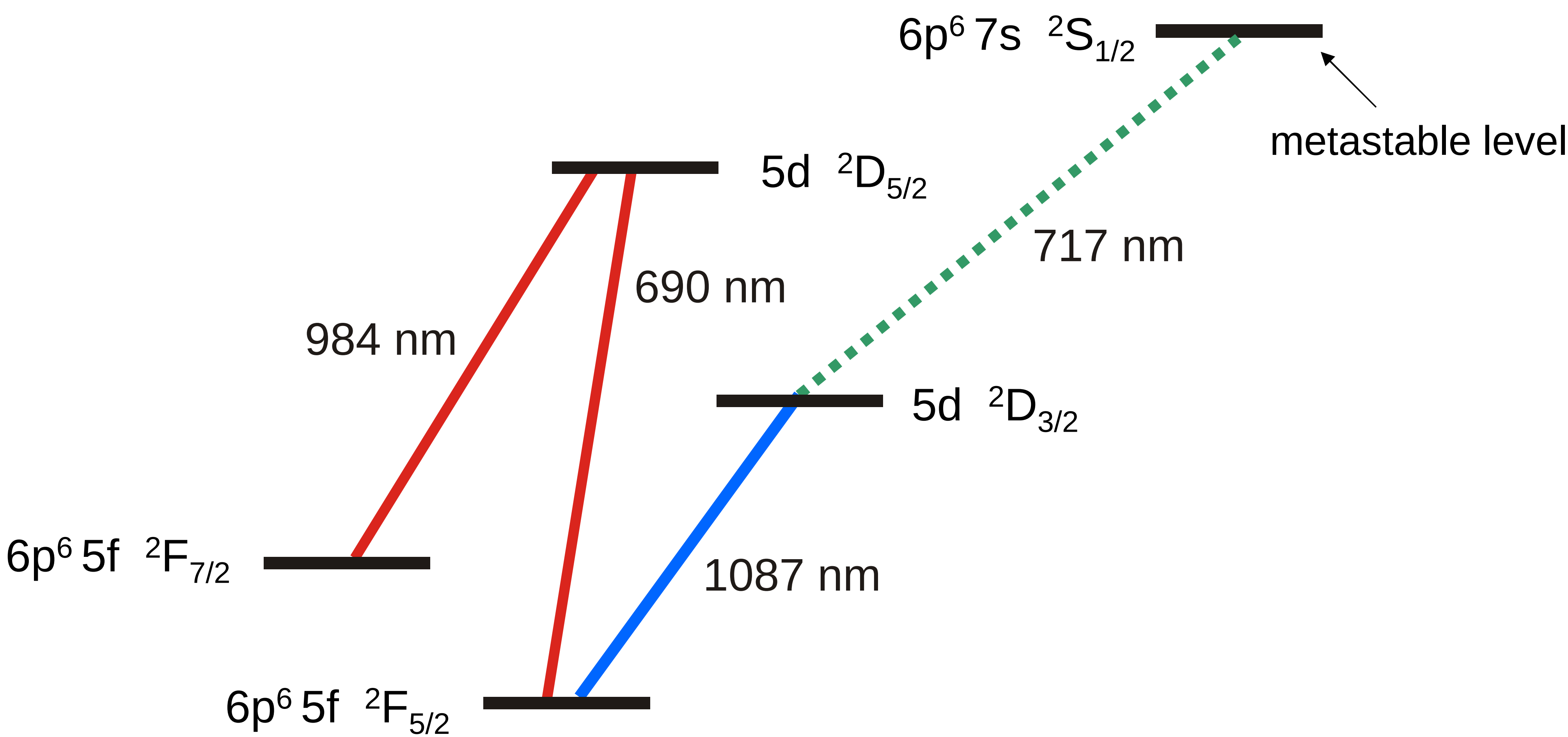
Ground state with hyperfine coupl.

$$I = \frac{5}{2},\ {}^2S_{1/2}\ , F = 2, m_F = 0$$

Absolute shifts of the transition frequency due to electromagnetic fields, collisions, etc., should be comparable to those in the Cs ground state HFS, but for a 10^5 times higher reference frequency !

Electronic Level Scheme of $^{229}Th^{3+}$

$^{229}Th^{3+}$ possesses a simple level scheme that is determined by a single valence electron. It can be stored, laser-cooled using diode lasers and detected via resonance fluorescence at red or NIR wavelengths.



Laboratory constraints on time variations of natural constants

from available data until fall of 2004 on:

- hyperfine frequencies in Rb, Cs, Yb,
- optical frequencies in H, Ca, Yb^+, Hg^+

X	$\partial \ln X/\partial t$	
α	$(-0.3 \pm 2.0) \cdot 10^{-15}\,\mathrm{yr}^{-1}$	
$\{cR_\infty\}$	$(-2.1 \pm 3.1) \cdot 10^{-15}\,\mathrm{yr}^{-1}$	
μ_{Cs}/μ_B	$(3.0 \pm 6.8) \cdot 10^{-15}\,\mathrm{yr}^{-1}$	
$\mu_{\mathrm{Rb}}/\mu_{\mathrm{Cs}}$	$(-0.2 \pm 1.2) \cdot 10^{-15}\,\mathrm{yr}^{-1}$	
$\mu_{\mathrm{Yb}}/\mu_{\mathrm{Cs}}$	$(3 \pm 3) \cdot 10^{-14}\,\mathrm{yr}^{-1}$	
m_e/m_p	$(2.9 \pm 6.2) \cdot 10^{-15}\,\mathrm{yr}^{-1}$	*
μ_p/μ_e	$(2.9 \pm 5.8) \cdot 10^{-15}\,\mathrm{yr}^{-1}$	*
g_p	$(-0.1 \pm 0.5) \cdot 10^{-15}\,\mathrm{yr}^{-1}$	*
g_n	$(3 \pm 3) \cdot 10^{-14}\,\mathrm{yr}^{-1}$	*

* uses the Schmidt model for nuclear moments.

S. G. Karshenboim, V. Flambaum, E. Peik, in:
Handbook of Atomic, Molecular and Optical Physics, Ed.: G. Drake, Springer, 2005
physics/0410074