Search for New Physics with Atomic Clocks

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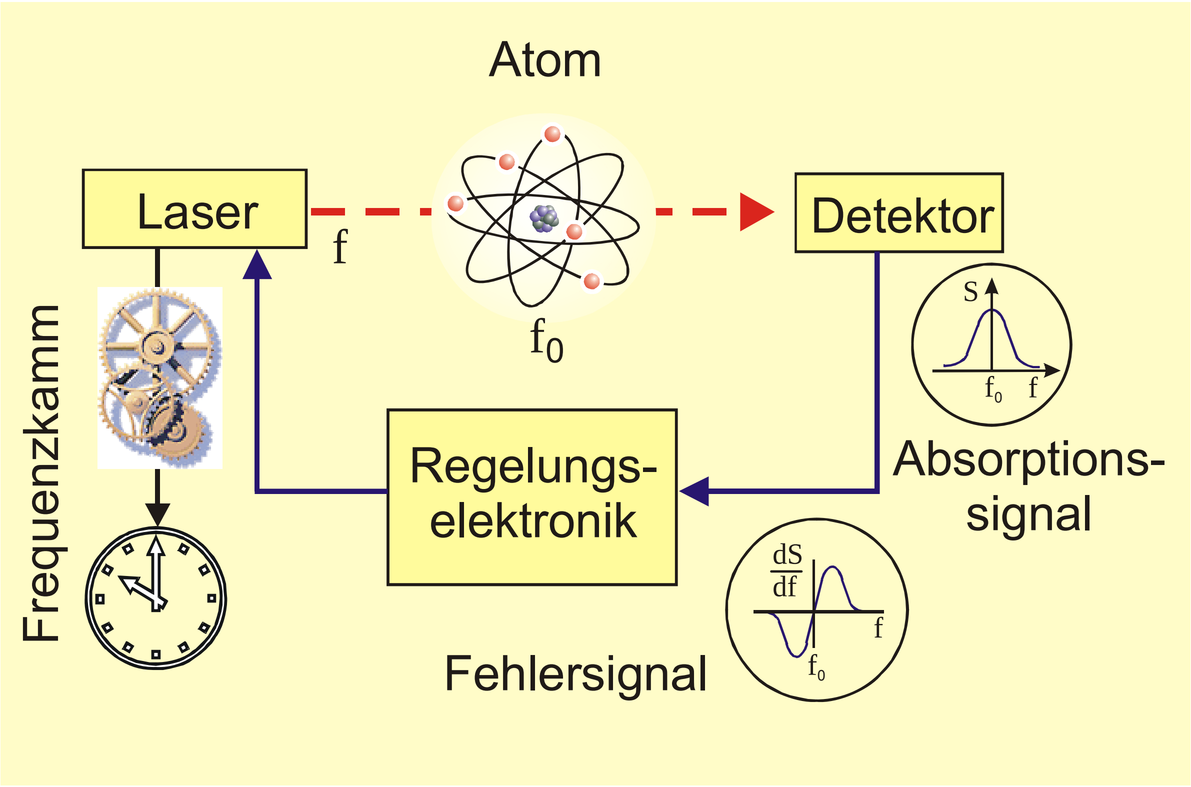
PTB

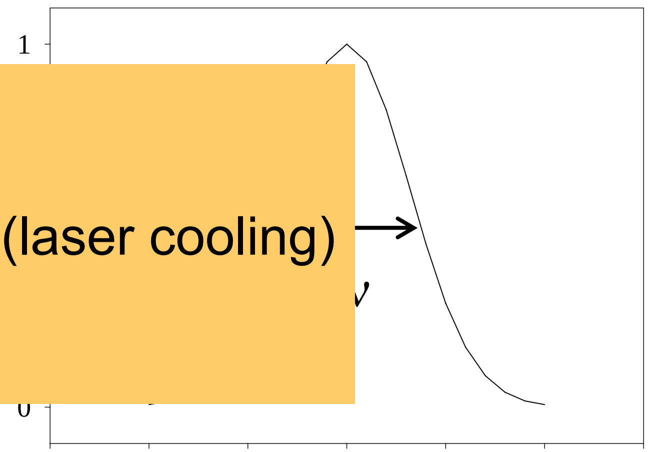
Outline

- Measuring Time with Atomic Clocks
- Optical Clock with a Single Trapped Ion
- Test of Local Position Invariance
- Search for Variations of Fundamental Constants

Schematic of an (optical) Atomic Clock



Stability and Accuracy of Atomic Frequency Standards



Strategies for improved clocks:
- reduce $\Delta\nu$ with slow or trapped atoms (laser cooling)
- increase ν_o (microwave $\rightarrow$ optical)

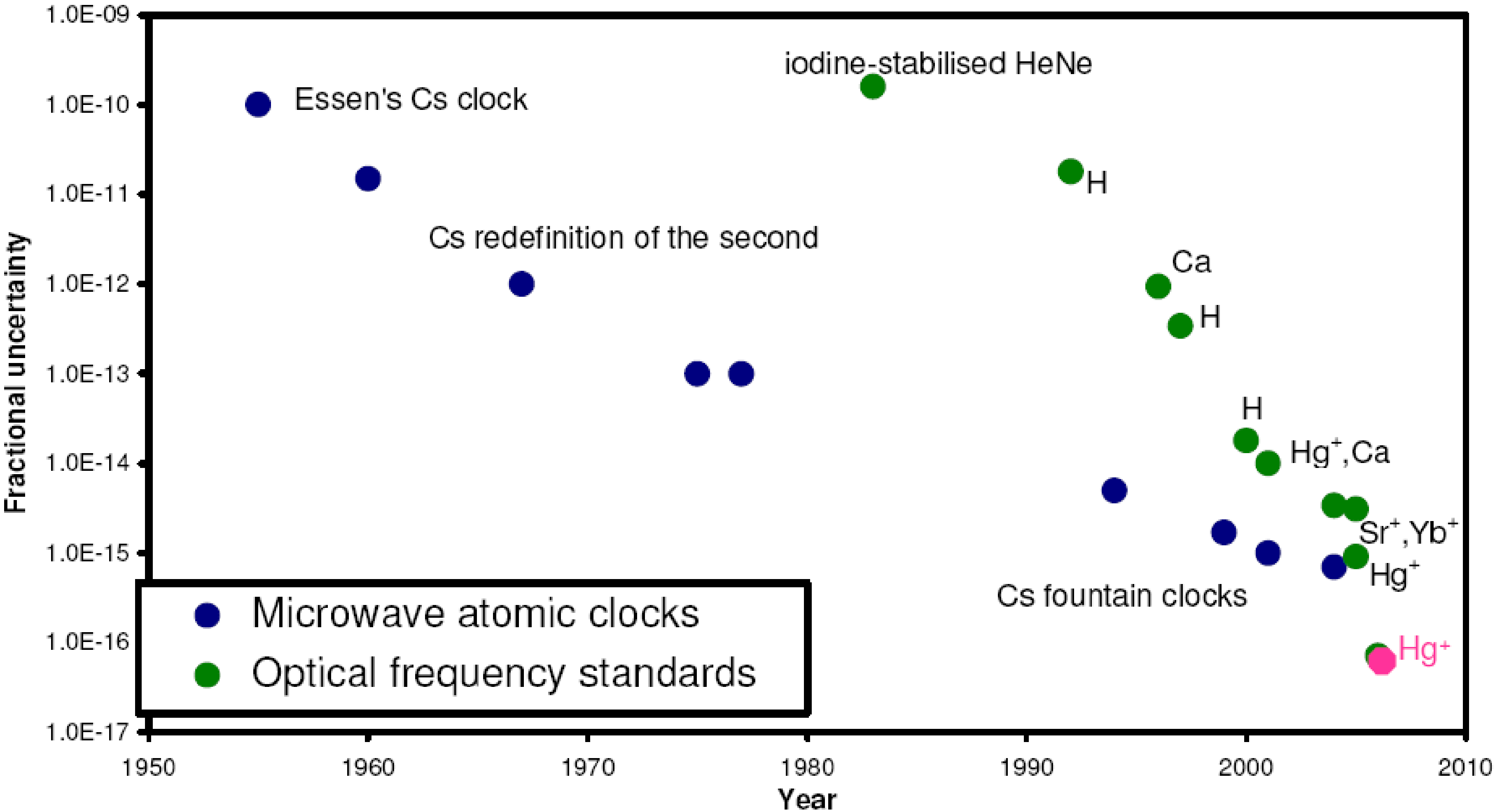
$\Delta\nu$: linewidth, ideally Fourier limited ~$1/T_c$, requires stable atomic levels, long interaction time, narrow oscillator for interrogation

Δp: measurement noise, ideally projection noise limited ~$1/\sqrt{N}$
N: atom number, white spectrum

Stability: normalized two-sample Allan variance $$\sigma_y(\tau) \approx \frac{\Delta\nu}{\nu_0}\sqrt{\frac{T_c}{N\tau}}$$

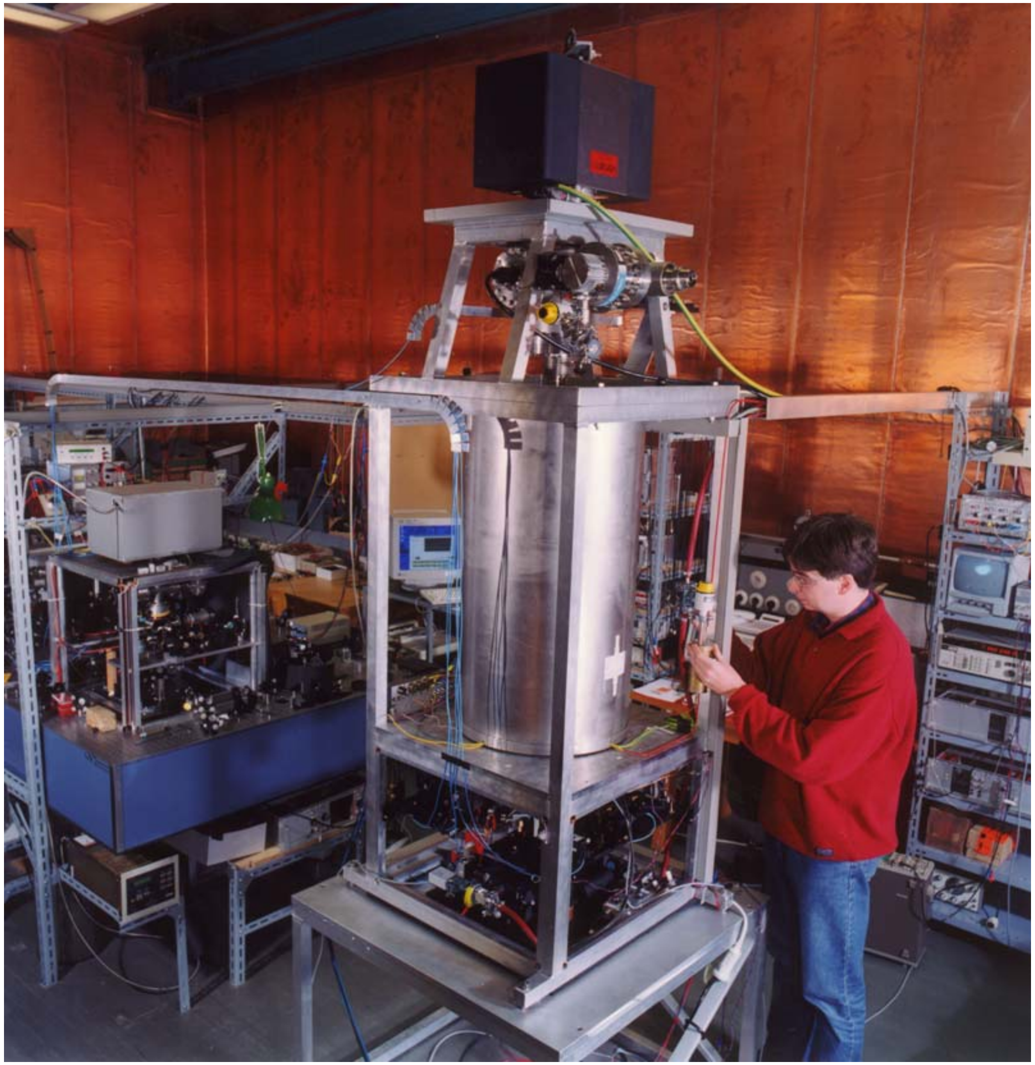
Accuracy: $|\nu_{out} - \nu_o| / \nu_o$
for a primary clock: based on evaluation of the uncertainty

Accuracy of primary cesium clocks and of optical frequency standards



prepared by P. Gill, NPL

The Caesium Fountain

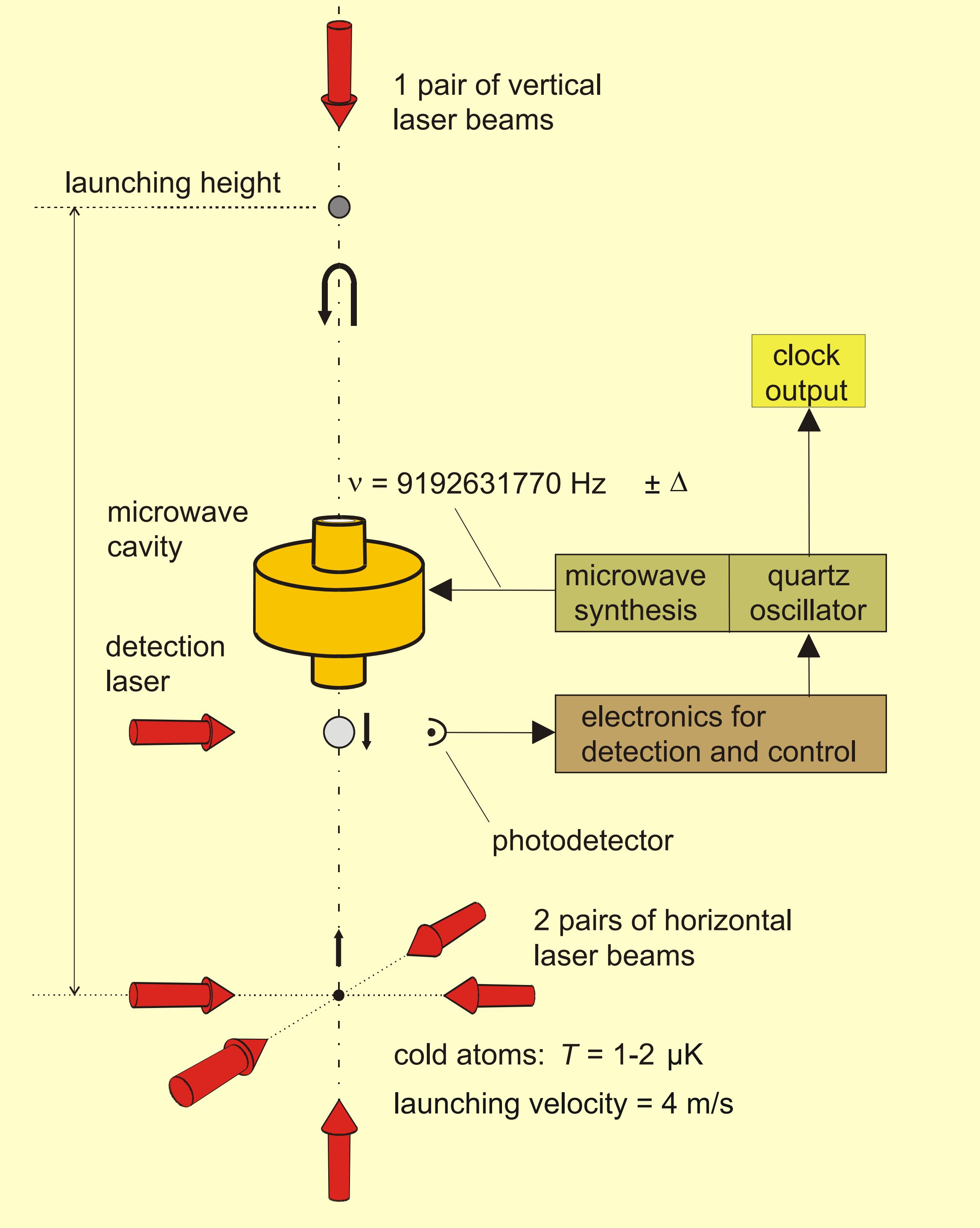


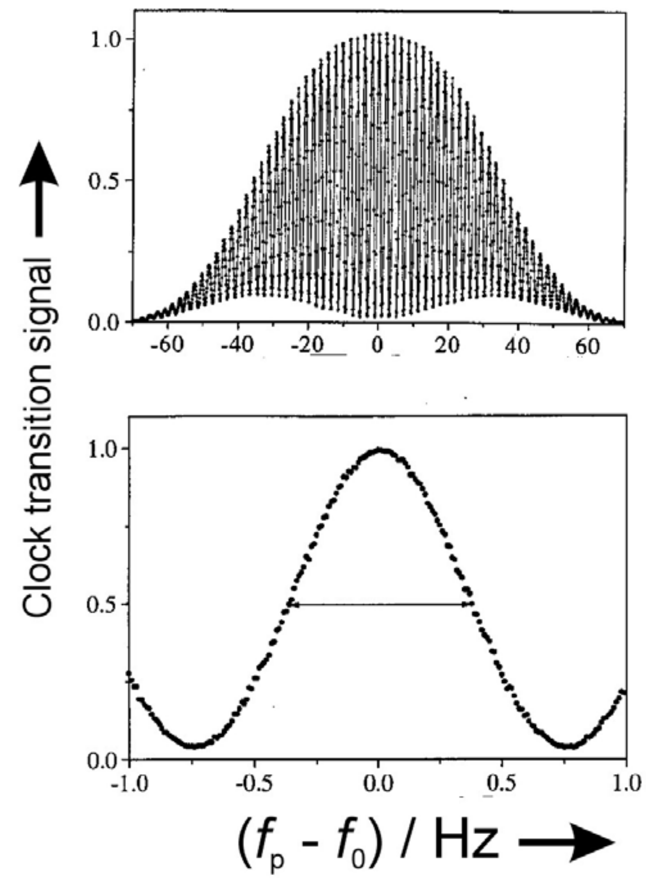
Early fountain experiments:

1953 Zacharias, MIT (hot Cs, failed)
1989 Chu, Stanford (cold Na)
1991 ENS/LPTF (cold Cs)

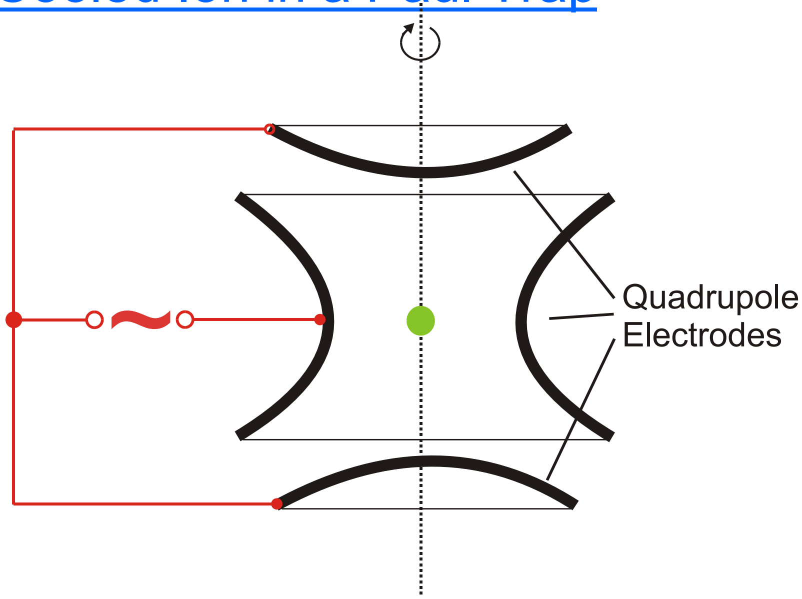
PTB‘s fountain clock CSF1

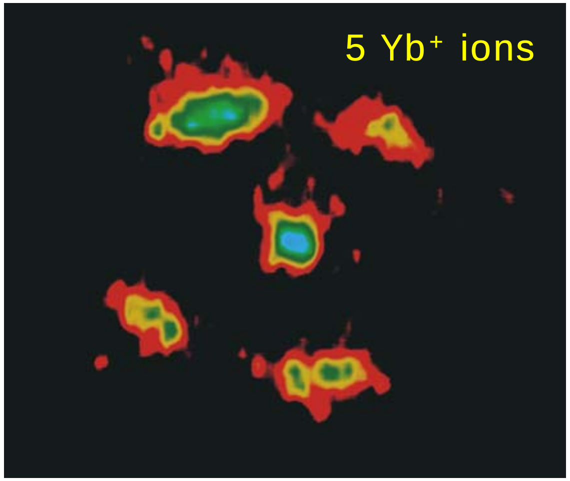
S. Weyers
R. Wynands
A. Bauch
U. Hübner
R. Schröder
Chr. Tamm
D. Griebsch


1 pair of vertical laser beams
launching height
clock output
ν = 9192631770 Hz ± Δ
microwave cavity
microwave synthesis
quartz oscillator
detection laser
electronics for detection and control
photodetector
2 pairs of horizontal laser beams
cold atoms: T = 1-2 μK
launching velocity = 4 m/s


1.0
0.5
0.0
-60
-40
-20
0
20
40
60
Clock transition signal
1.0
0.5
0.0
-1.0
-0.5
0.0
0.5
1.0
(f_p - f_0) / Hz

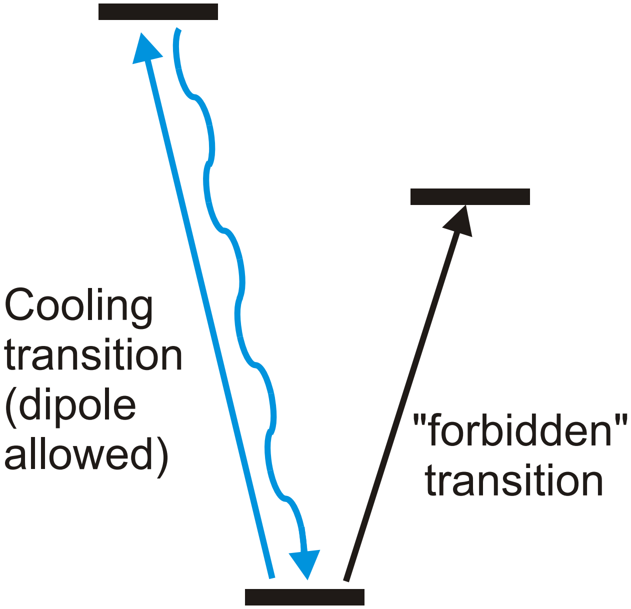
Optical Frequency Standards with a Laser-Cooled Ion in a Paul Trap

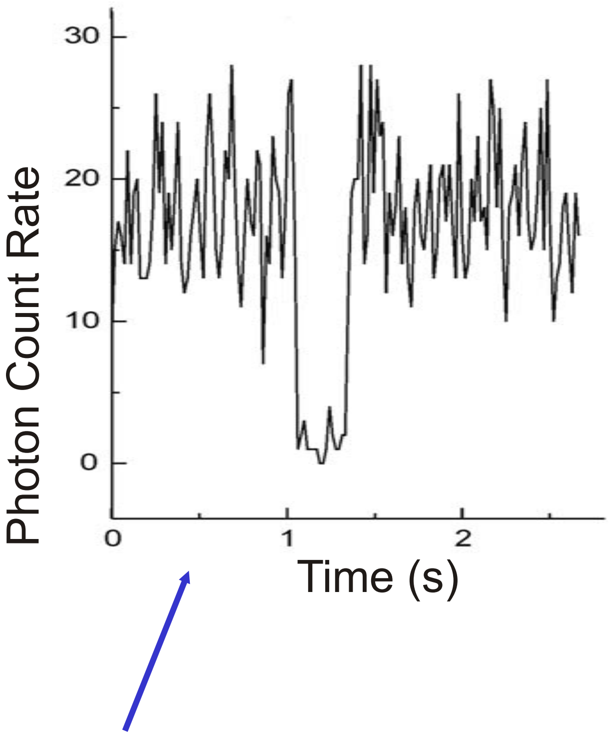




- Lamb-Dicke confinement with small trap shifts
- unlimited interaction time
- single ion: no collisions
- stability: use high-Q transition

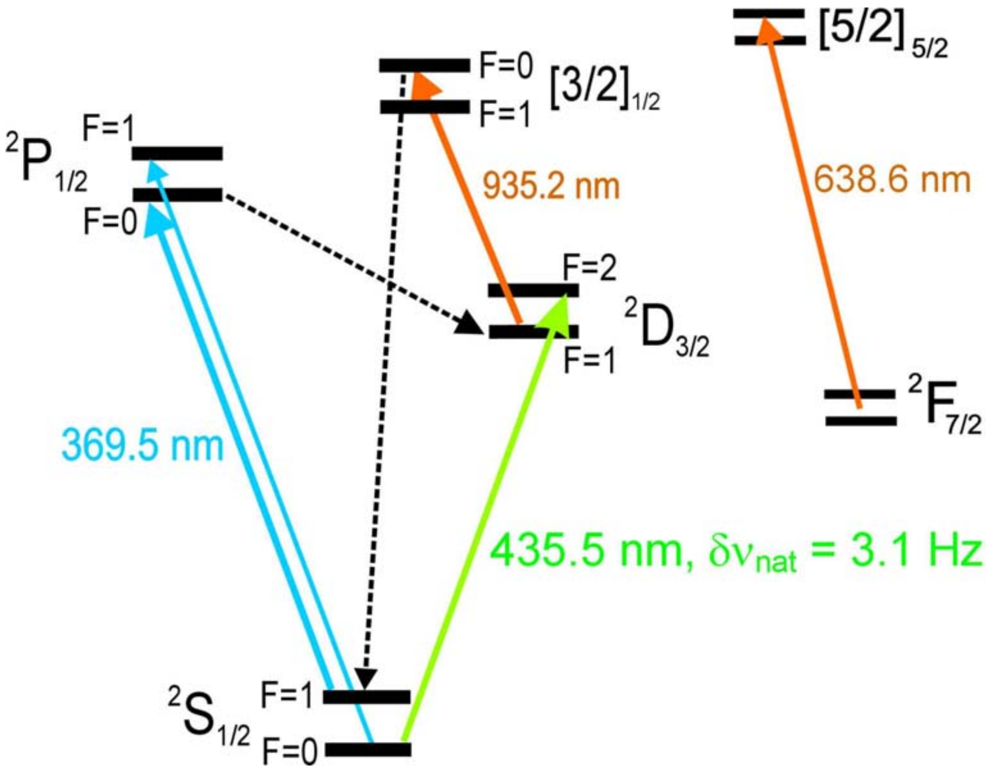
Projection Noise Limited State Detection via Electron Shelving





Single ion data (In^+):
Observation of a „Quantum Jump“

Yb⁺ Single Ion Optical Frequency Standard

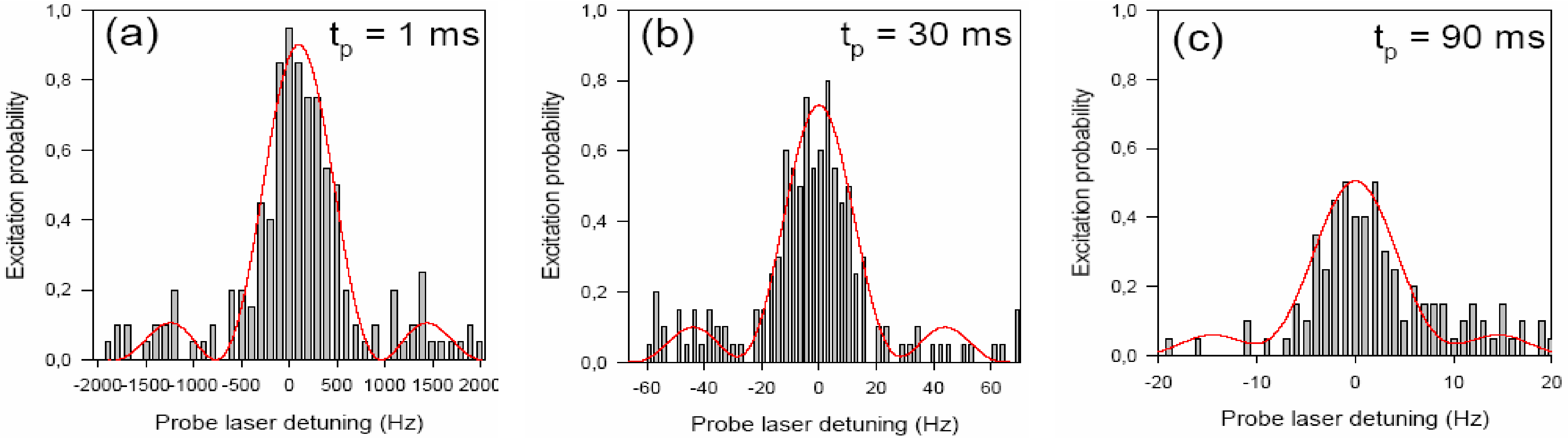


High resolution spectroscopy of the quadrupole transition at 688 THz

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

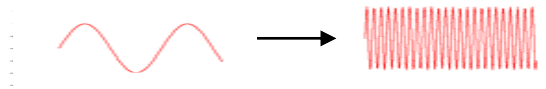
„standard operation"
τ(pulse)=30 ms
30 Hz linewidth

Close to the resolution limit
$\tau(\text{pulse}) = 90\ \text{ms} \approx 2 \cdot \tau(Yb^+)$
10 Hz linewidth



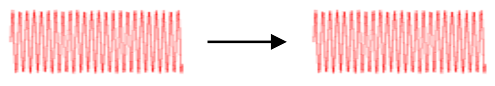
Three tasks in optical frequency metrology

absolute measurement



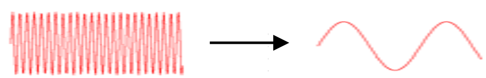
→ **comparison of an optical frequency and a Cs frequency standard**

relative measurement



→ **comparison of two optical frequencies as difference or ratio**

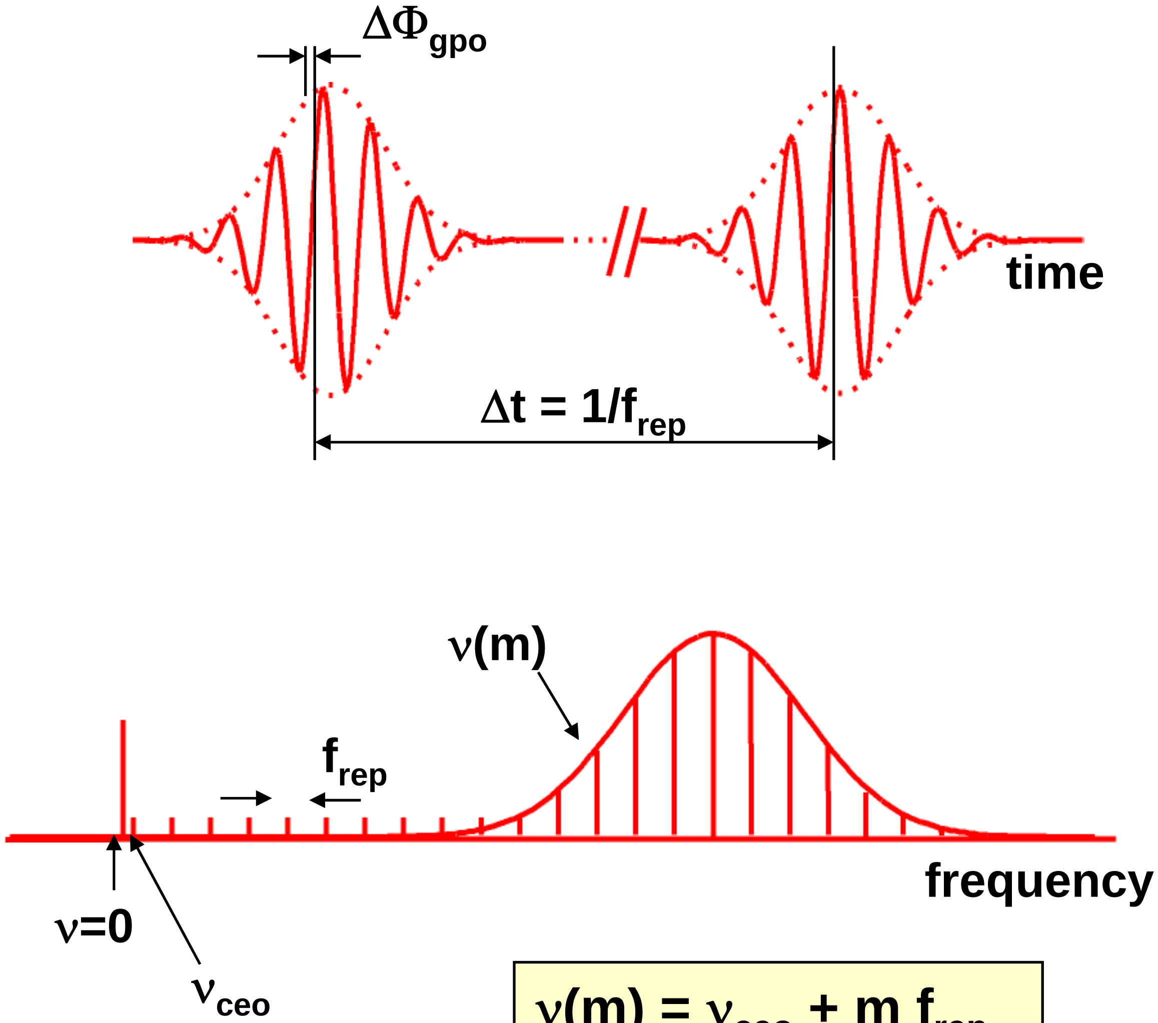
frequency division



→ **generation of a microwave frequency from an optical reference, „optical clockwork“**

Femtosecond laser as optical frequency comb generator

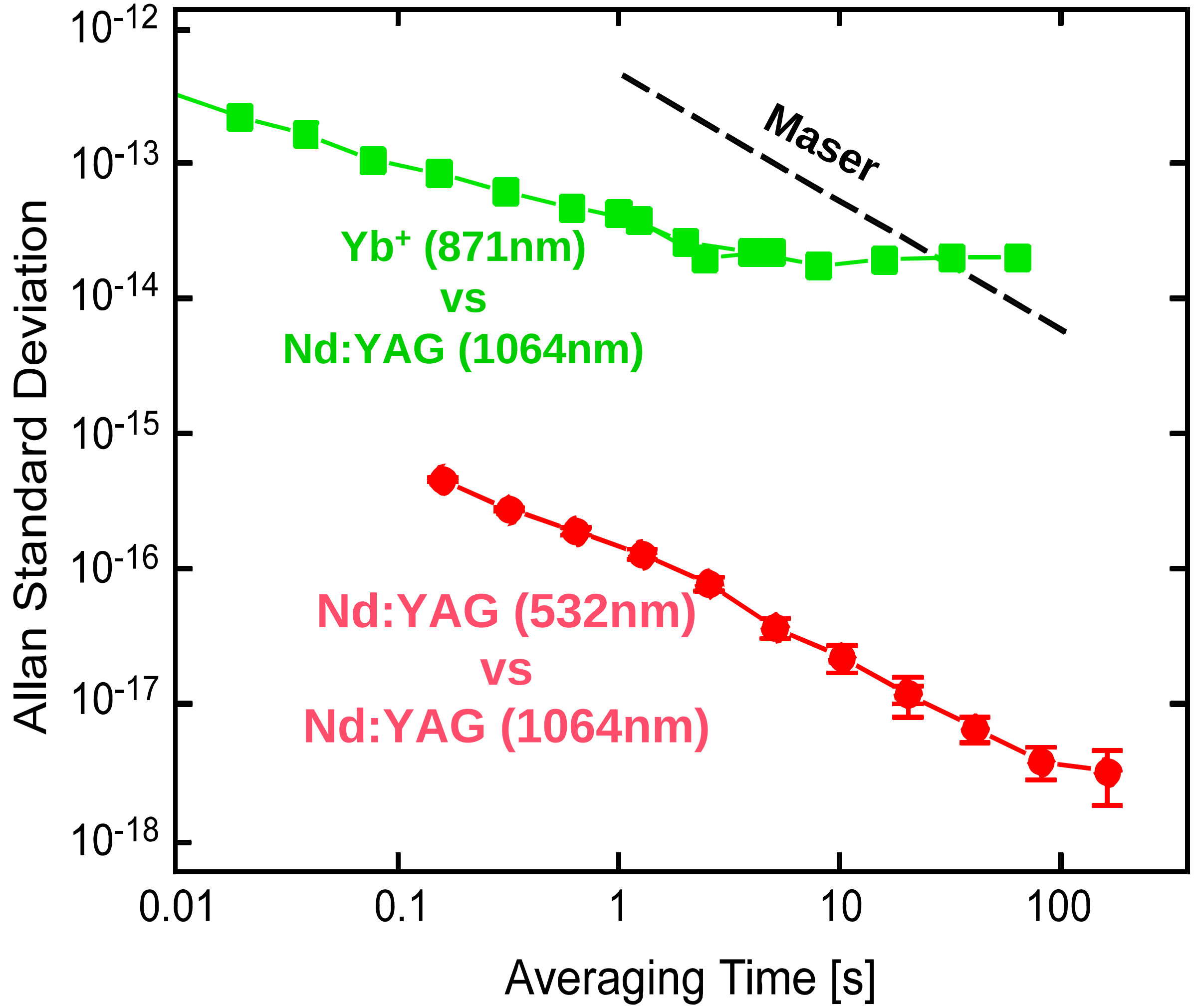
T. Hänsch, MPQ, J. Hall, JILA …NIST PTB ILP...



$$\nu(m) = \nu_{ceo} + m\, f_{rep}$$

Measurement of ν_{ceo} and f_{rep} fixes the frequencies of all modes

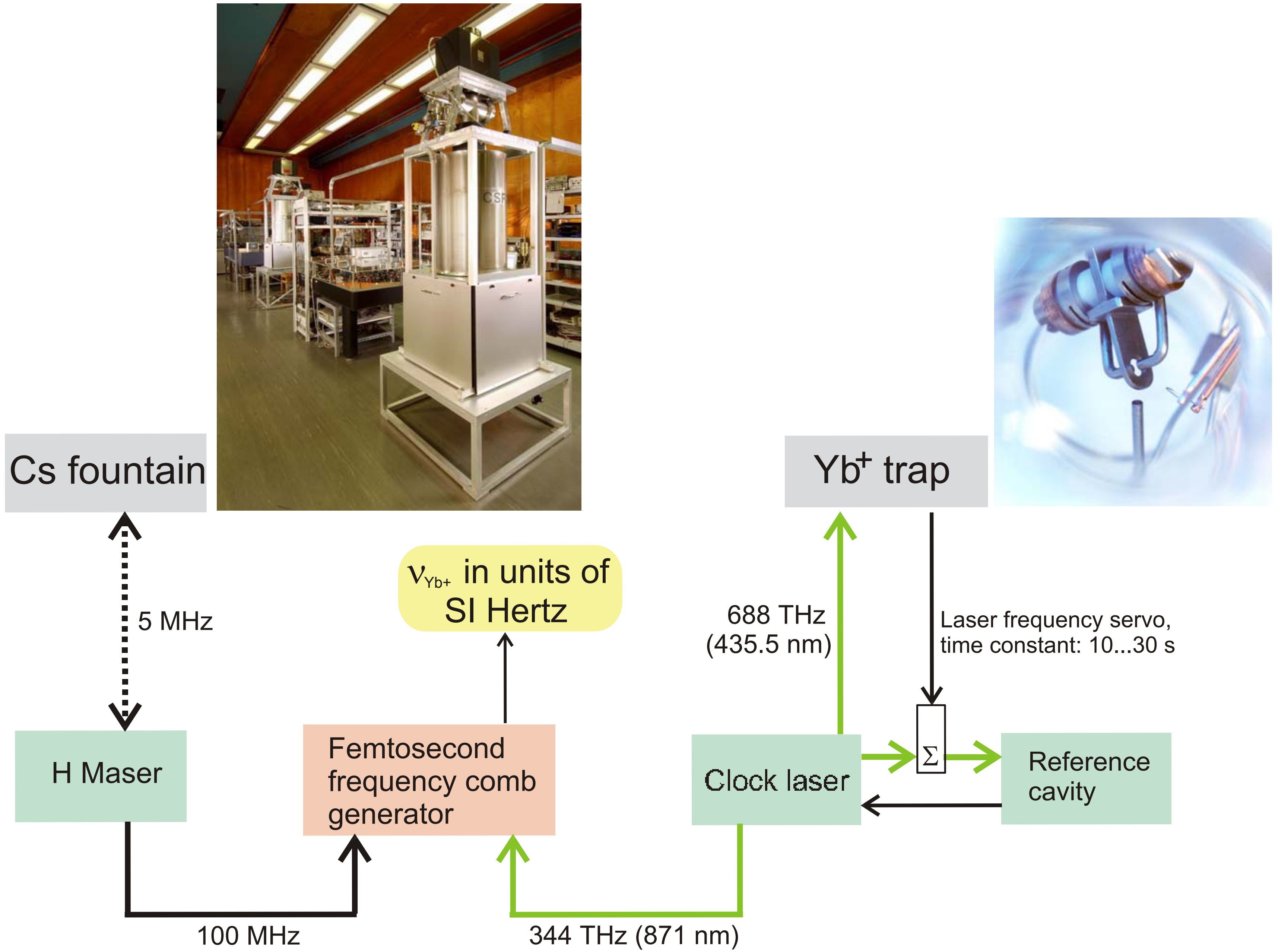
Measurement of optical frequency ratios



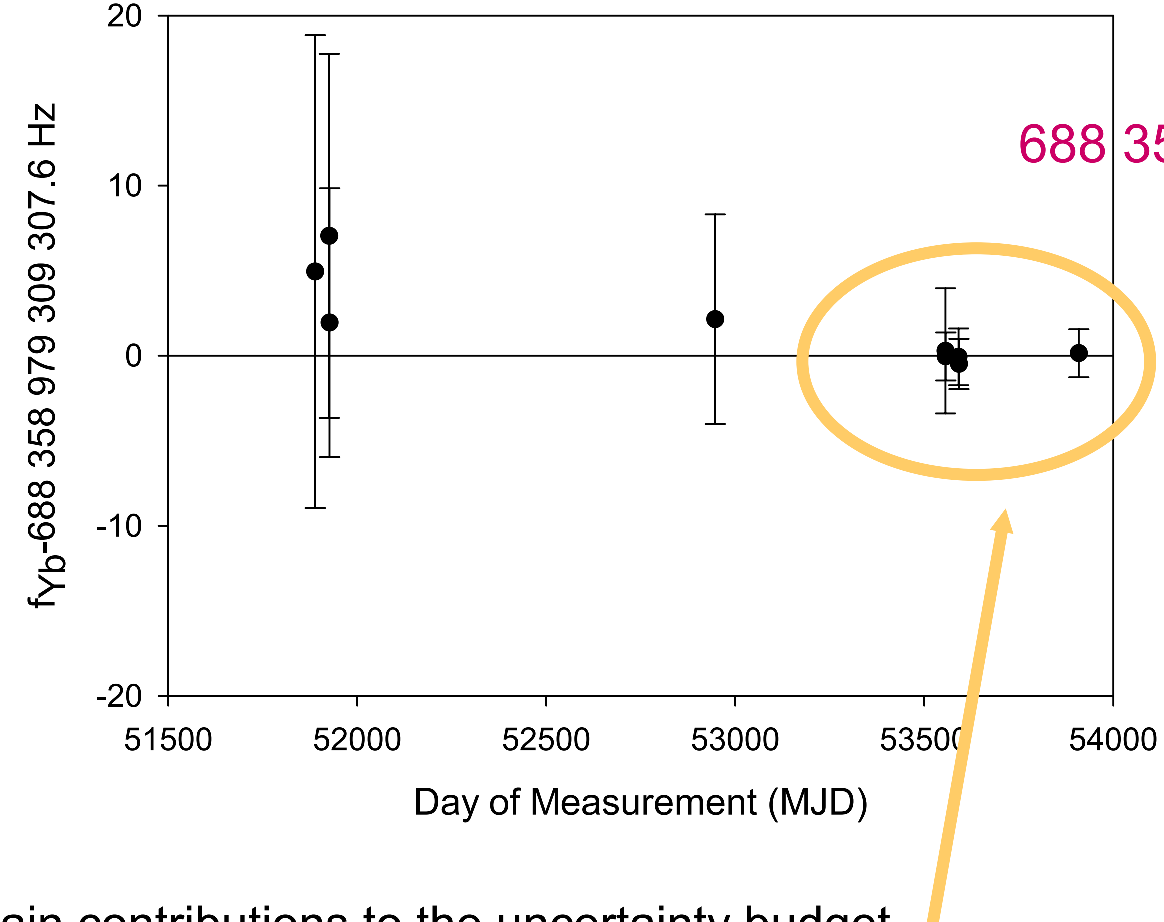
$$\nu_{SH} / \nu_0 = 2.\,000\,000\,000\,000\,000\,001 \cdot (1 \pm 7 \cdot 10^{-19})$$

J. Stenger et al. Phys. Rev. Lett. **88**, 073601 (2002)

Setup for absolute optical frequency measurements



Results of absolute frequency measurements 2000-2006



$^{171}Yb^{+}$ $S_{1/2}$ - $D_{3/2}$:
688 358 979 309 307.5(1.4) 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)
$u_B(Cs)$=0.83 Hz
$u_B(Yb^+)$=1.05 Hz (quadrupole shift, blackbody AC Stark shift)

Test of Relativity:
Universality of the gravitational red-shift

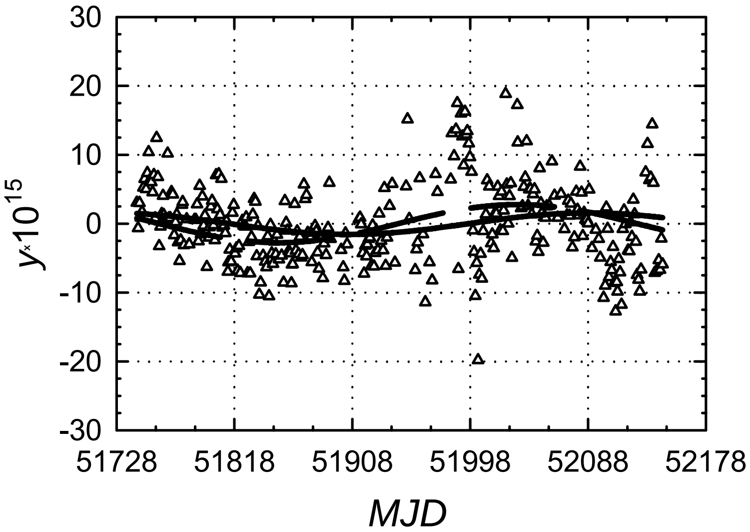
Search for annual frequency variations as a test of Local Position Invariance

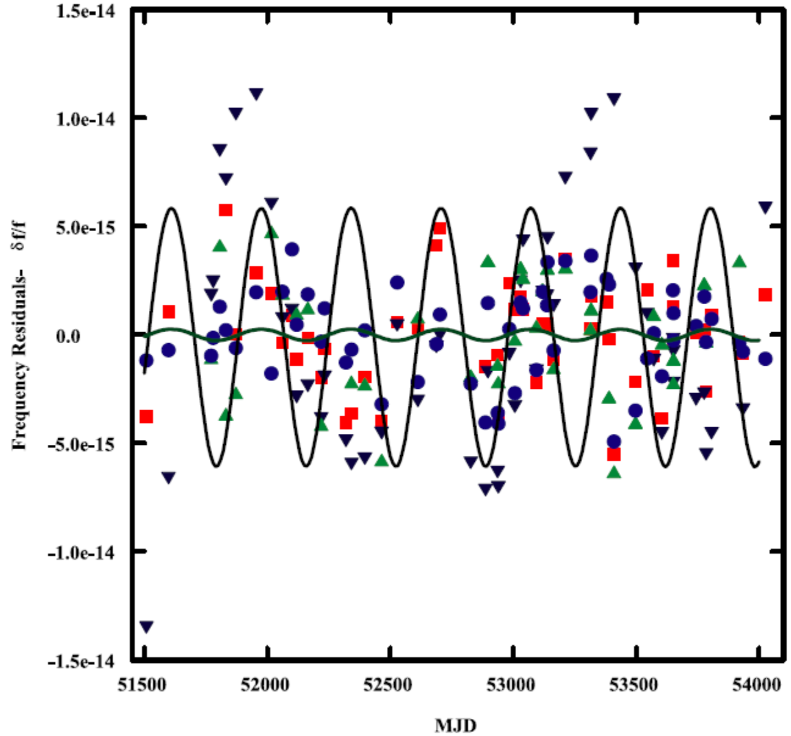
Search for a frequency difference in gravitational red-shift between dissimilar clocks

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

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

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





Cs fountain vs. H masers
$|\Delta\beta| < 2.1\times10^{-5}$

A. Bauch, S. Weyers
Phys. Rev. D **65**, 081101 (2002)

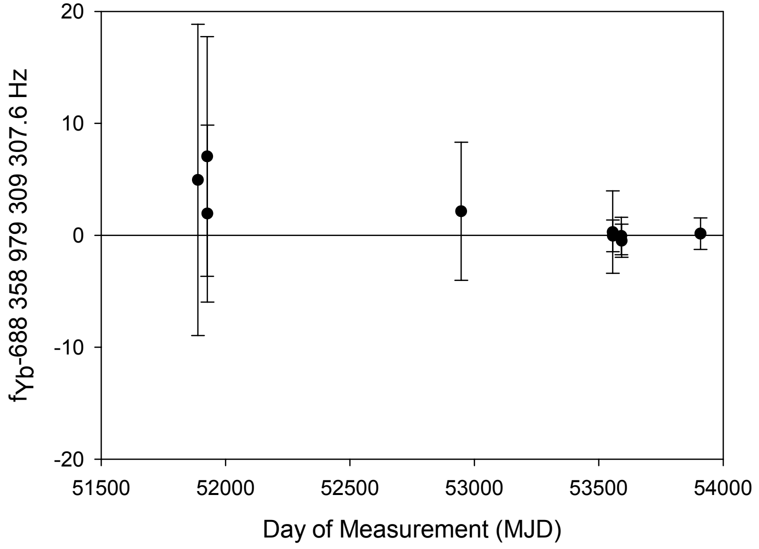
Cs fountains vs. H masers
$|\Delta\beta| < 1.4\times10^{-6}$

N. Ashby et al.
Phys. Rev. Lett. **98**, 070802 (2007)

Cs fountain vs. Hg^{+} optical clock
$|\Delta\beta| = 5.8\times10^{-6}$

T. Fortier et al.
Phys. Rev. Lett. **98**, 070801 (2007)

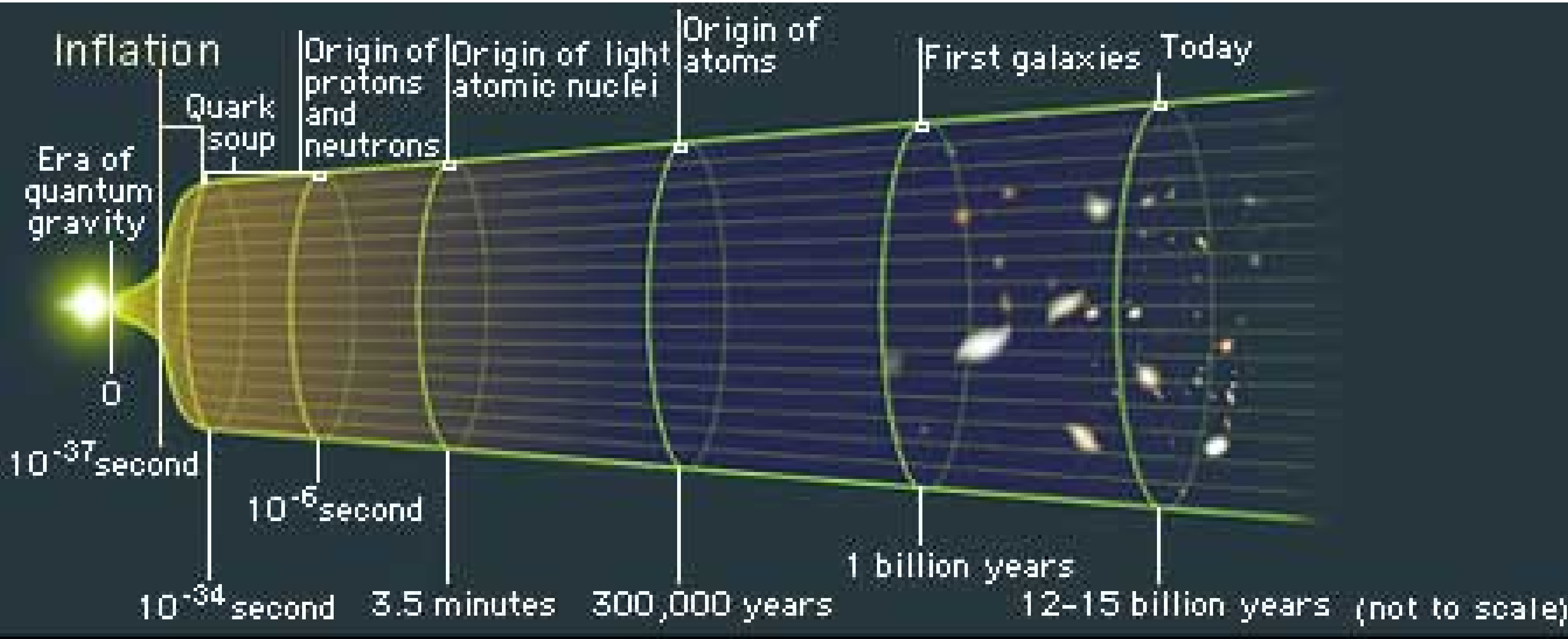
Testing the Constancy Of Fundamental Constants



Why should fundamental constants be variable?

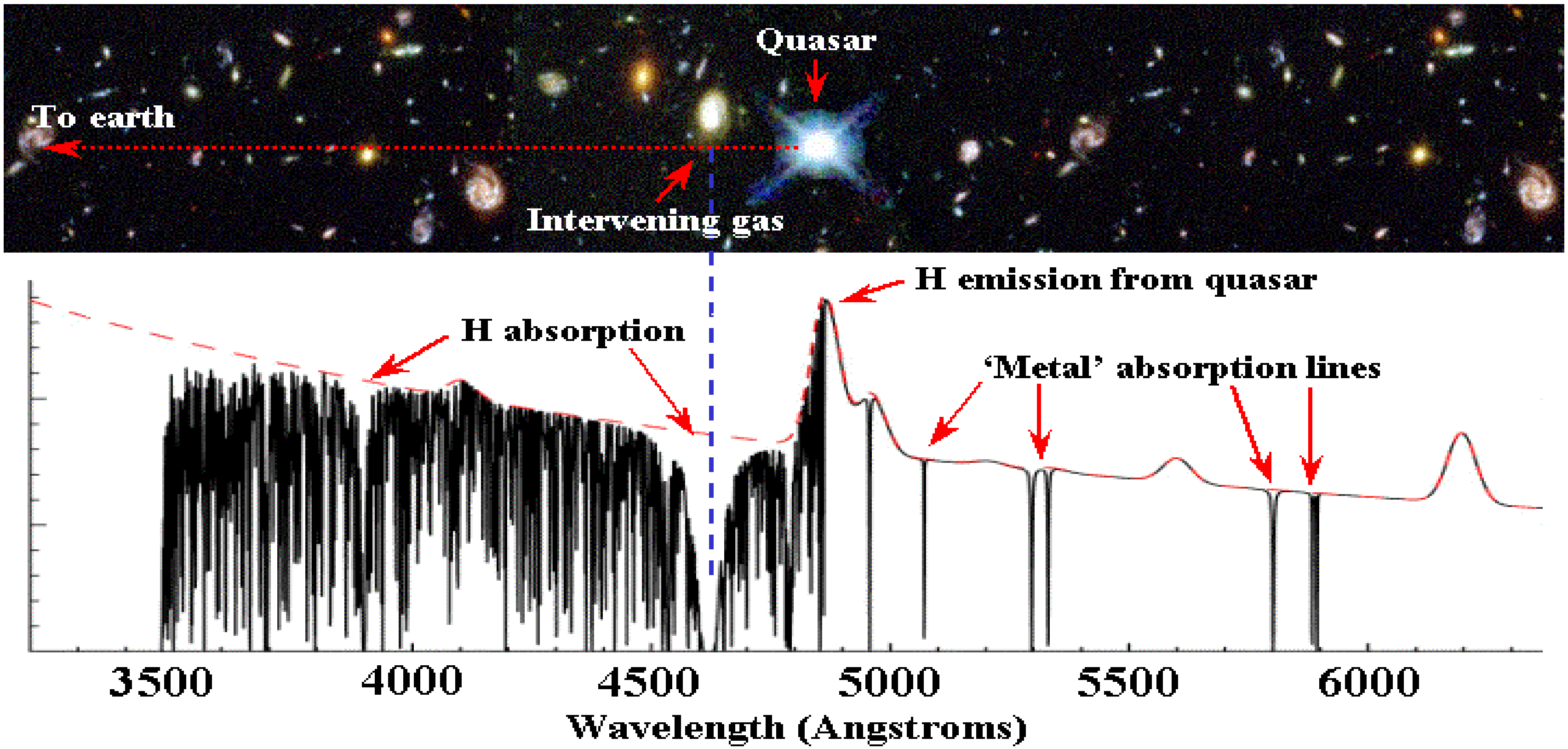
- Cosmology: The early universe went through a phase transition that determined particle properties (Inflation).
  Maybe remnants are still observable in later epochs.

Discover Mag., A. Guth

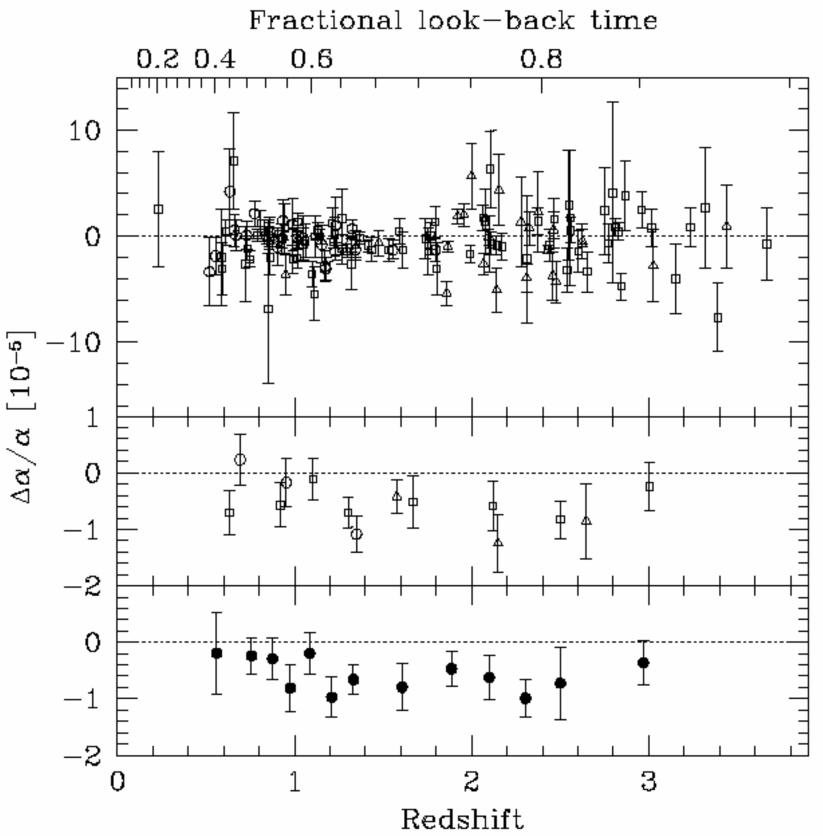


Evidence for variations of the fine structure constant on a cosmological time scale ?

Analysis of absorption spectra in the light from quasars,
J. Webb, M. Murphy, V. Flambaum et al., Univ. New South Wales, Sydney



Many Multiplet Method: transition frequencies in MgI, MgII, FeII, CrII etc. have different dependence on α because of relativistic contributions.



Result:

$$\Delta\alpha/\alpha = (-0.54 \pm 0.12) \cdot 10^{-5}$$

>4σ evidence for changing α

Linear regression:

$$\partial \ln \alpha / \partial t = (6.4 \pm 1.4) \cdot 10^{-16}\ \mathrm{yr}^{-1}$$

M. T. Murphy, J. K. Webb, V. V. Flambaum, Mon. Not. R. Astron. Soc. **345**, 609 (2003).

Value	Constraint
$\Delta\alpha/\alpha$	$(-5.4 \pm 1.2) \times 10^{-6}$
$\Delta\alpha/\alpha$	$(-0.1 \pm 1.8) \times 10^{-6}$
$\Delta\mu/\mu$	$(2.6 \pm 0.6) \times 10^{-5}$
$\lvert\Delta\mu/\mu\rvert$	$\leq 4.9 \times 10^{-5}$ (CL = 95%)

Observations and analyses of different groups are not consistent.

Search for α-variation in optical electronic transition frequencies. Method of Analysis:

electronic transition frequency can be expressed as

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

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

C numerical constant (function of quantum numbers)

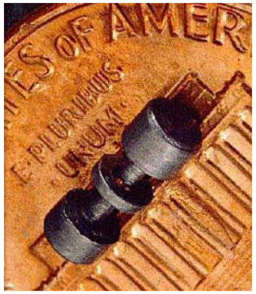
$F(\alpha)$ dimensionless function of α; describes relativistic level shifts

Relative temporal derivative of the frequency:

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

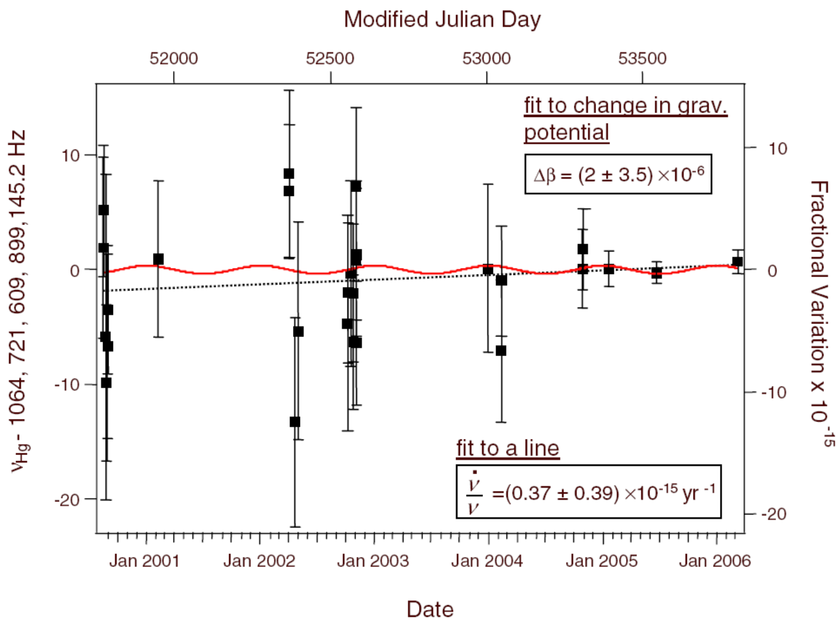
- $\frac{\partial \ln Ry}{\partial t}$: common shift of all transition frequencies
- $\frac{\partial \ln \alpha}{\partial t}$: specific for the transition under study
- A: can be calculated with relativistic Hartree-Fock (Dzuba, Flambaum)

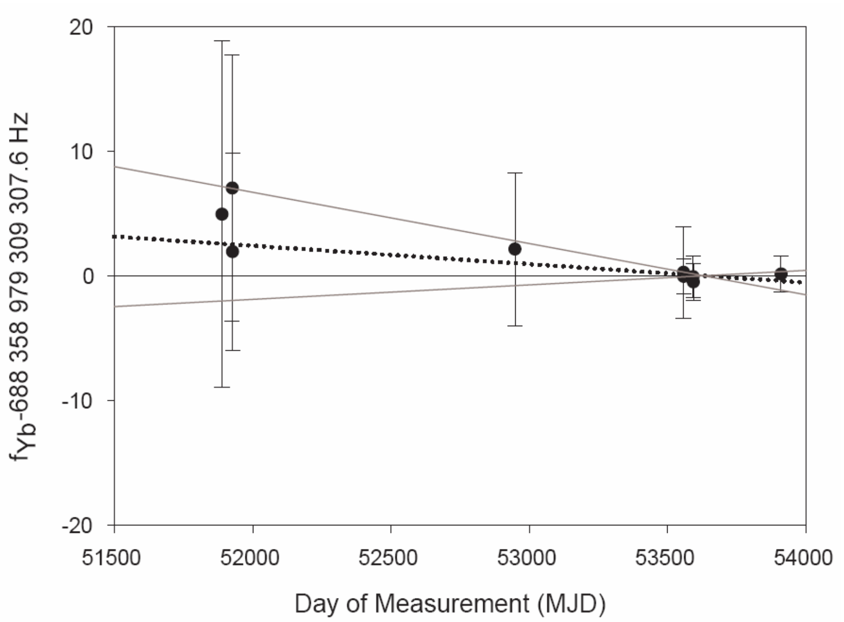
Remote comparison of single-ion clocks NIST-PTB, 2000-2006



$^{199}Hg^{+}$, S - D at 1064 THz (NIST Boulder)

$^{171}Yb^{+}$, S - D at 688 THz (PTB)



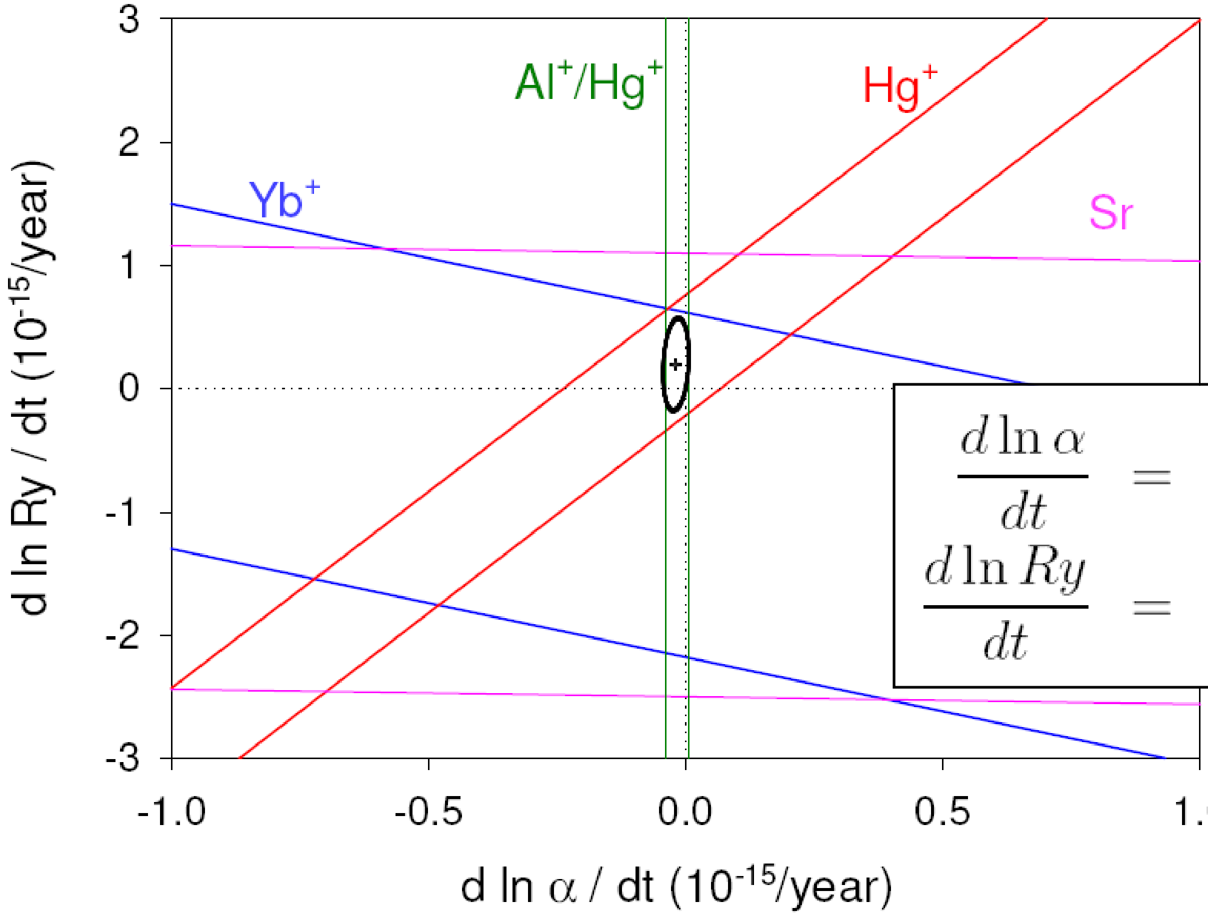


T. Fortier et al., Phys. Rev. Lett. **98**, 070801 (2007)

A(Yb)= 0.88
A(Hg)=−3.19

E. Peik et al., physics/0611088
Proc. 11th Marcel Grossmann Meeting, Berlin 2006

Limits for Temporal Variations of Fundamental Constants: Combination of available data from optical clocks (spring 2008)

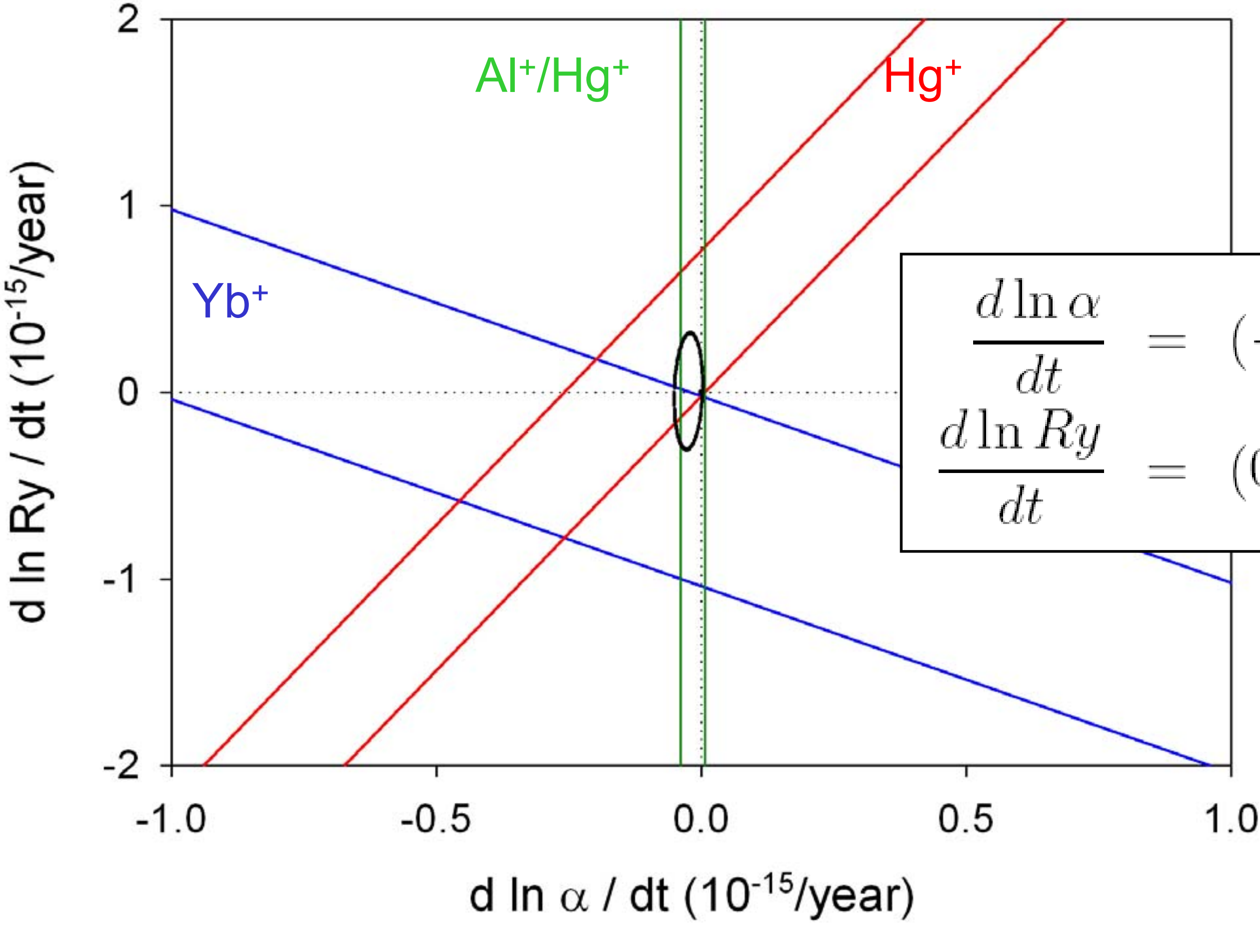


$$\frac{d \ln \alpha}{dt} = (-1.6 \pm 2.3) \cdot 10^{-17}\ \mathrm{yr}^{-1}$$

$$\frac{d \ln Ry}{dt} = (1.9 \pm 3.8) \cdot 10^{-16}\ \mathrm{yr}^{-1}$$

Al^+/Hg^+: T. Rosenband et al., Science **319**, 1808 (2008)
Sr: S. Blatt et al., Phys. Rev. Lett. **100**, 140801 (2008)

Limits for Temporal Variations of Fundamental Constants: Combination of available data from optical clocks

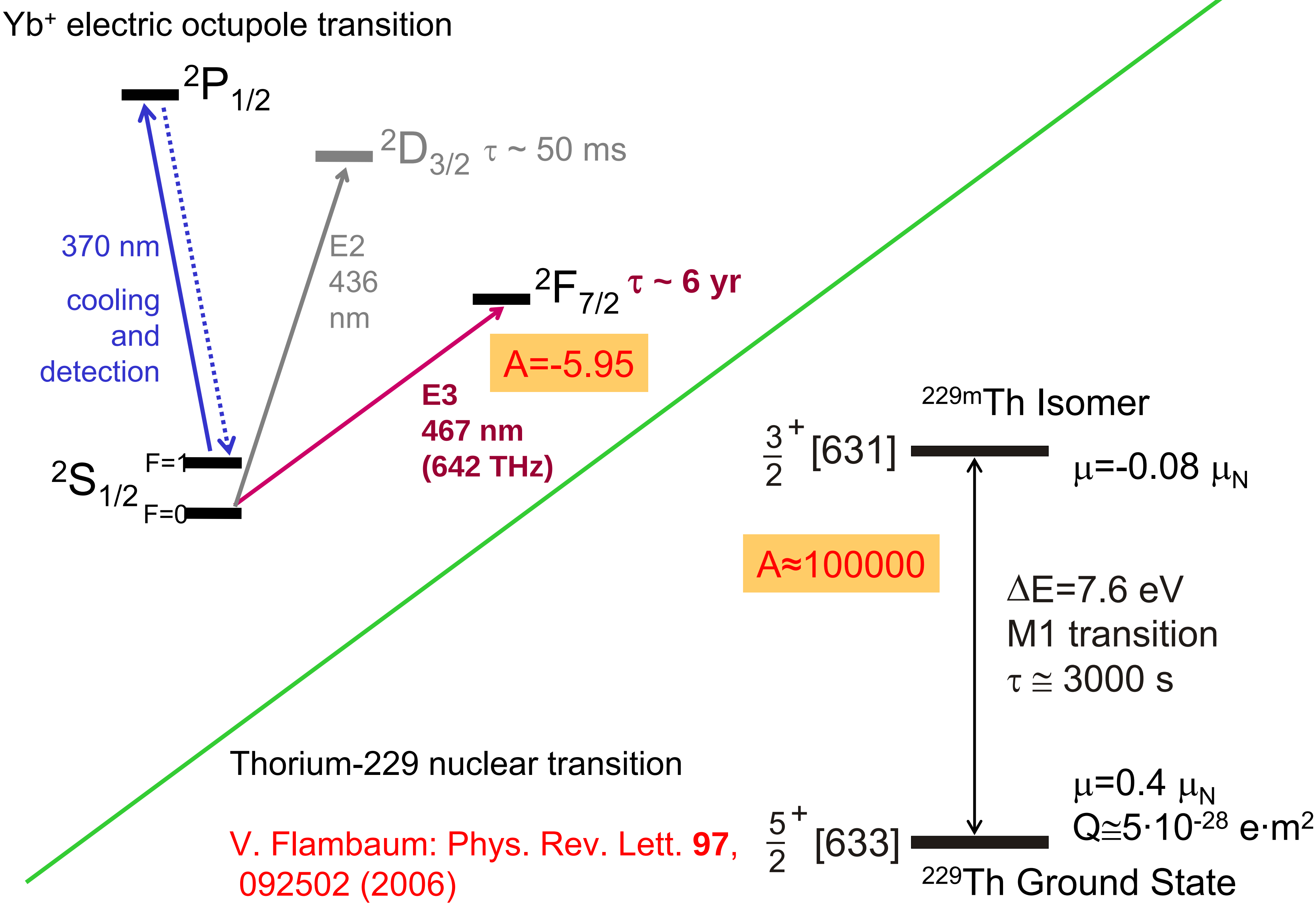


$$\frac{d\ln\alpha}{dt} = (-2.4 \pm 2.7)\cdot 10^{-17}\ \mathrm{yr}^{-1}$$

$$\frac{d\ln Ry}{dt} = (0.0 \pm 3.2)\cdot 10^{-16}\ \mathrm{yr}^{-1}$$

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

Prospects for dα/dt measurements



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

- Measuring Time with Atomic Clocks
- Optical Clock with a Single Trapped Ion
- Test of Local Position Invariance
- Search for Variations of Fundamental Constants

New Physics with better clocks?

Acknowledgements

A. Bauch
B. Lipphardt
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R. Wynands
K. Zimmermann

S. Karshenboim, VNIIM and MPQ

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DFG
FQXi
QUEST

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

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

Ions under study:
Hg^+ (NIST), Yb^+ (PTB, NPL), Sr^+ (NRC, NPL),
In^+ (MPG, U Wash.), Ca^+ (Mars., Innsb.,...), Al^+ (NIST), Ba^+ (U Wash.) ...

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

$^{199}Hg^+$ $S_{1/2}$ - $D_{5/2}$:	1 064 721 609 899 144.94(97) Hz	NIST
$^{171}Yb^+$ $S_{1/2}$ - $D_{3/2}$:	688 358 979 309 307.7(1.4) Hz	PTB
$^{88}Sr^+$ $S_{1/2}$ - $D_{5/2}$:	444 779 044 095 484.6(1.5) Hz	NPL

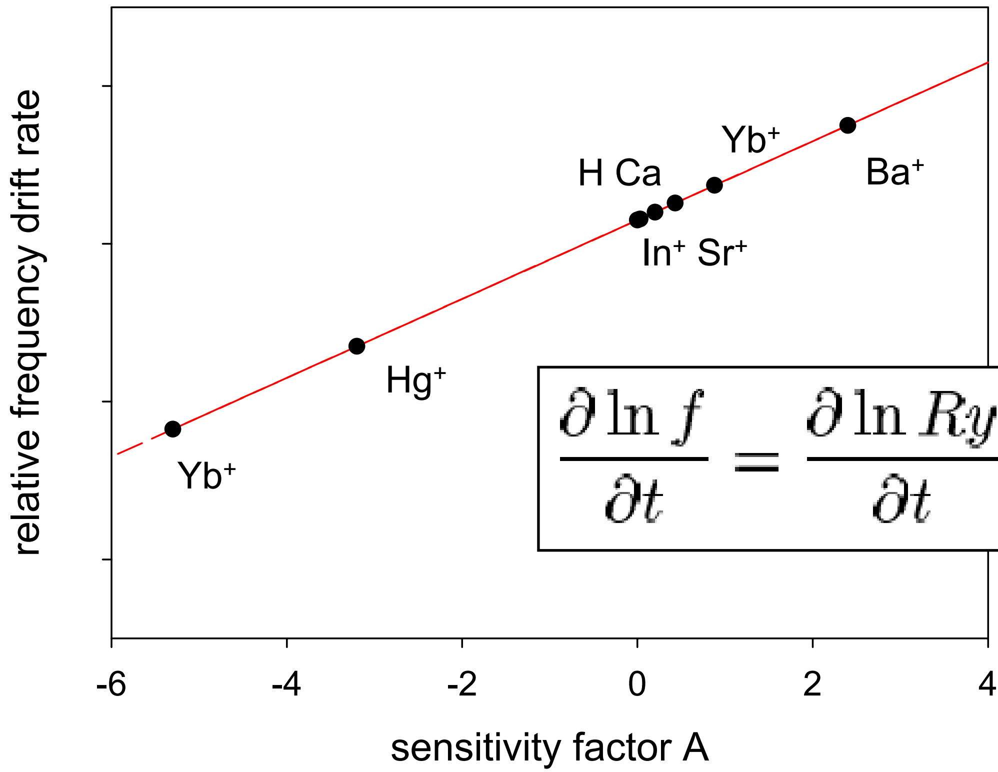
CIPM proposed these standards as “secondary representations of the *second*“ in the optical frequency domain.

Measurement of an optical frequency ratio:

f(Al^+)/f(Hg^+): 1.052871833148990438(55) NIST

Search for variations of the fine structure constant in atomic clock comparisons

S. G. Karshenboim
physics/0311080



relativistic level shift:

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

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

calculations by
V. Dzuba and V. Flambaum

heavy atoms, $j_g > j_e$

light atoms

heavy atoms, $j_g < j_e$

Limits for Temporal Variations of Fundamental Constants

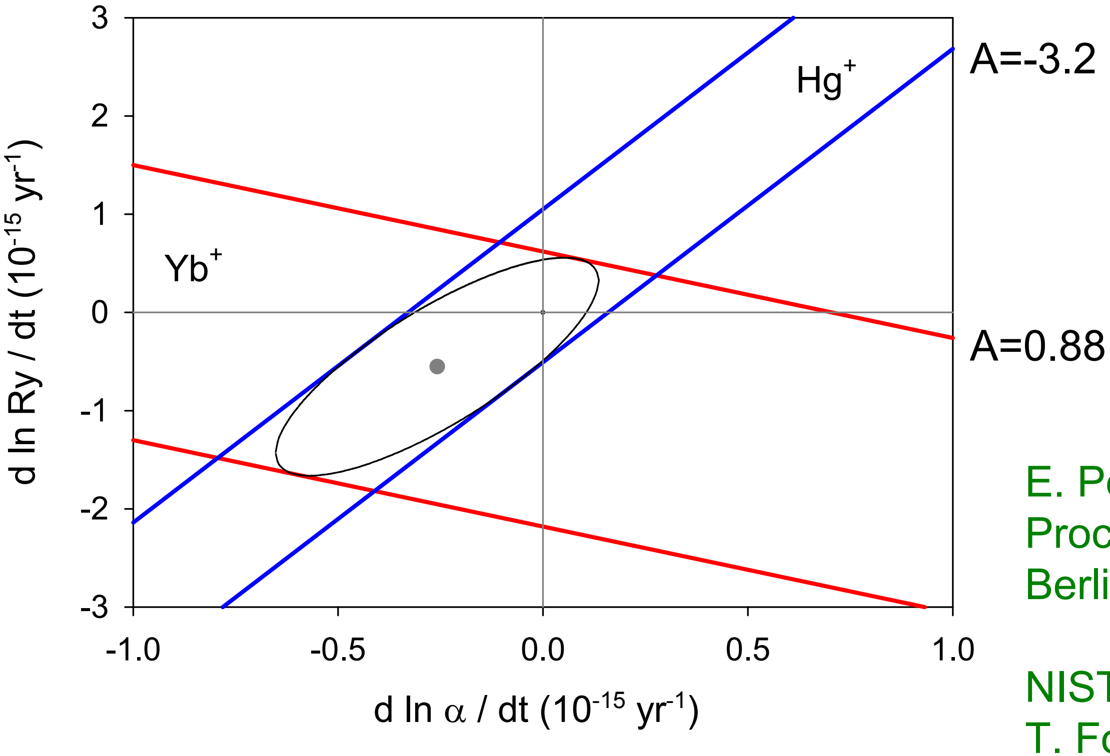
Combining the data from Yb^+ with those from the Hg^+ frequency standard at NIST, W. H. Oskay et al., Phys. Rev. Lett. **97**, 020801 (2006), yields model-independent limits

For the fine structure constant:

$$\frac{d\ln\alpha}{dt} = (-0.26 \pm 0.39)\cdot 10^{-15}\ \mathrm{yr}^{-1}$$

For the Rydberg frequency:

$$\frac{d\ln Ry}{dt} = (-0.55 \pm 1.11)\cdot 10^{-15}\ \mathrm{yr}^{-1}$$



E. Peik et al., physics/0611088
Proc. 11th Marcel Grossmann Meeting, Berlin 2006

NIST group:
T. Fortier et al., PRL 98, 070801 (2007)

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

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

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

See also:

V. V. Flambaum, N. Auerbach, V. F. Dmitriev, arXiv:0807.3218 [nucl-th] (α)

V. V. Flambaum, R. B. Wiringa, arXiv:0807.4943 [nucl-th] (quark masses)