Title: Atomic Clocks and Tests of Fundamental Physics

Date: Jun 16, 2014 11:30 AM

URL: http://pirsa.org/14060008

Abstract: The precision of atomic clocks continues to improve at a rapid pace: While caesium clocks now reach relative systematic uncertainties of a few 10-16, several optical clocks based on different atomic systems are now reported with uncertainties in the 10-18 range. This variety of precise clocks will allow for improved tests of fundamental physics, especially quantitative tests of relativity and searches for variations of constants. Laser-cooled and trapped ions permit the study of strongly forbidden transitions with extremely small natural linewidths and long coherence times. The frequency of the electric octupole transition S1/2 - F7/2 at 467 nm in 171Yb+ with a natural linewidth in the nHz range is remarkably insensitive against external electric and magnetic fields. We evaluate the systematic uncertainty of a frequency standard that is based on this transition as 4*10-18 at present. An even better isolation from external perturbations can be expected for the nuclear transition in 229Th3+ at about 160 nm with an expected linewidth in the mHz range. In order to excite the so far only indirectly observed nuclear transition using electronic bridge processes, we investigate the dense electronic level structure of Th+. Both transitions, in Yb+ and 229Th, are predicted to be highly sensitive to changes in the fine structure constant. I will give an update on limits on variations of constants as obtained from atomic clock comparisons.

New Ideas in Low-Energy Tests of Fundamental Physics, June 16-18, 2014, Perimeter Institute, Waterloo

Atomic Clocks and Tests of Fundamental Physics

Ekkehard Peik

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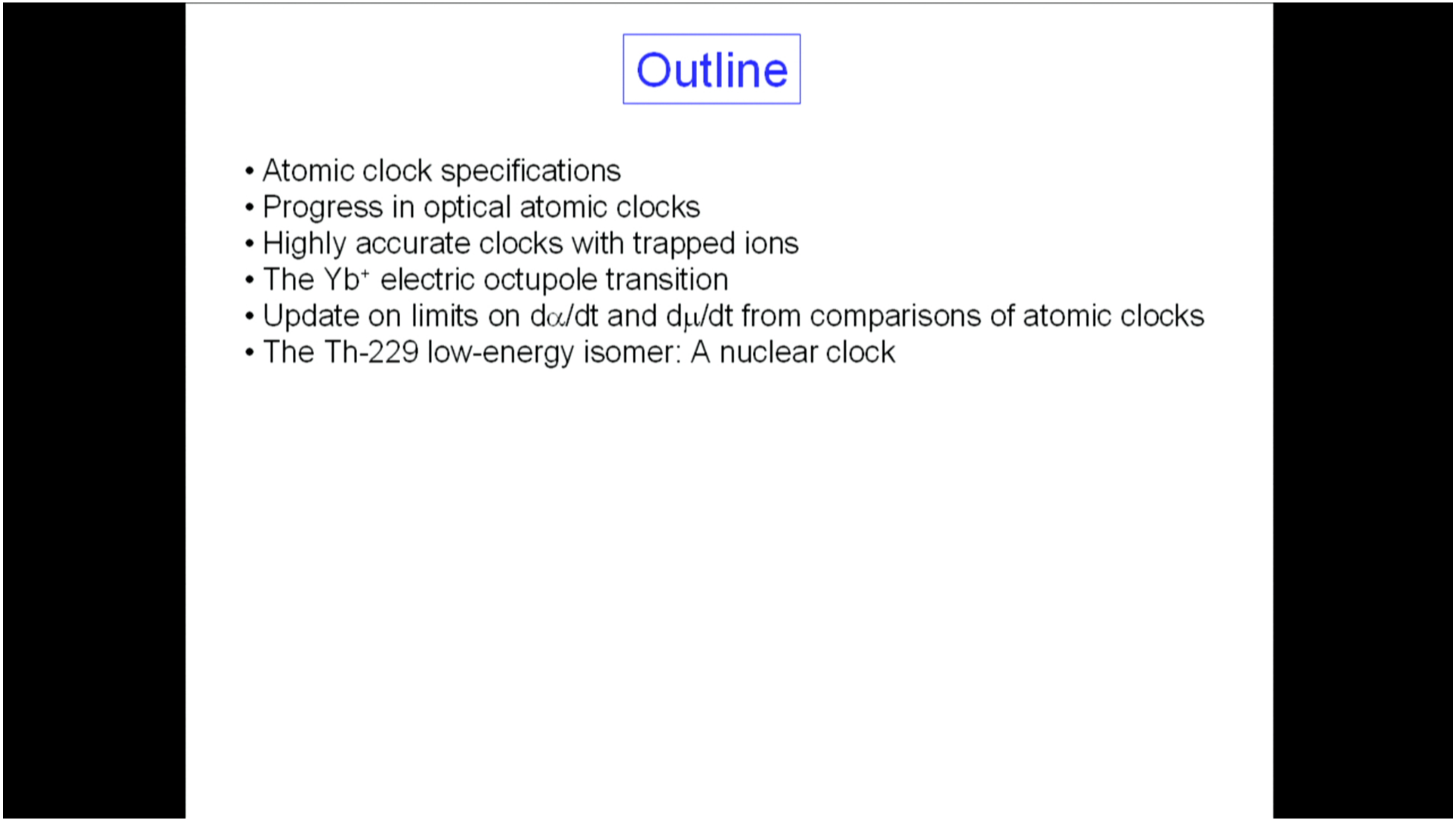
PTB
Braunschweig, Germany

PTB
Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin



Outline

- Atomic clock specifications
- Progress in optical atomic clocks
- Highly accurate clocks with trapped ions
- The Yb^+ electric octupole transition
- Update on limits on $d\alpha/dt$ and $d\mu/dt$ from comparisons of atomic clocks
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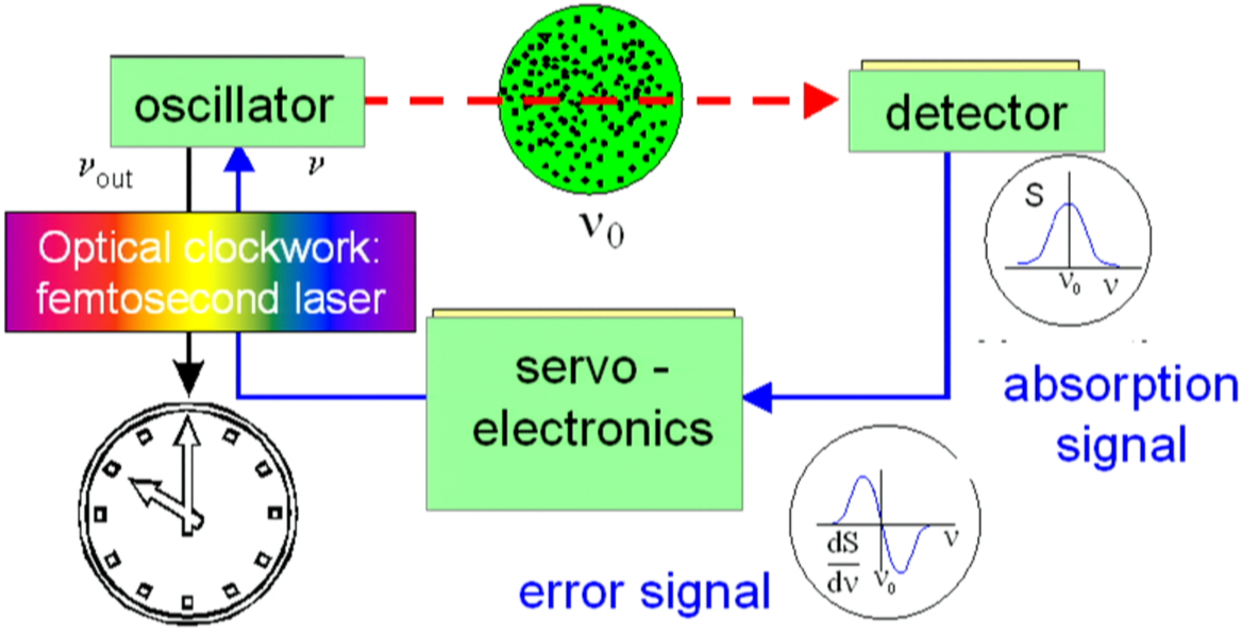
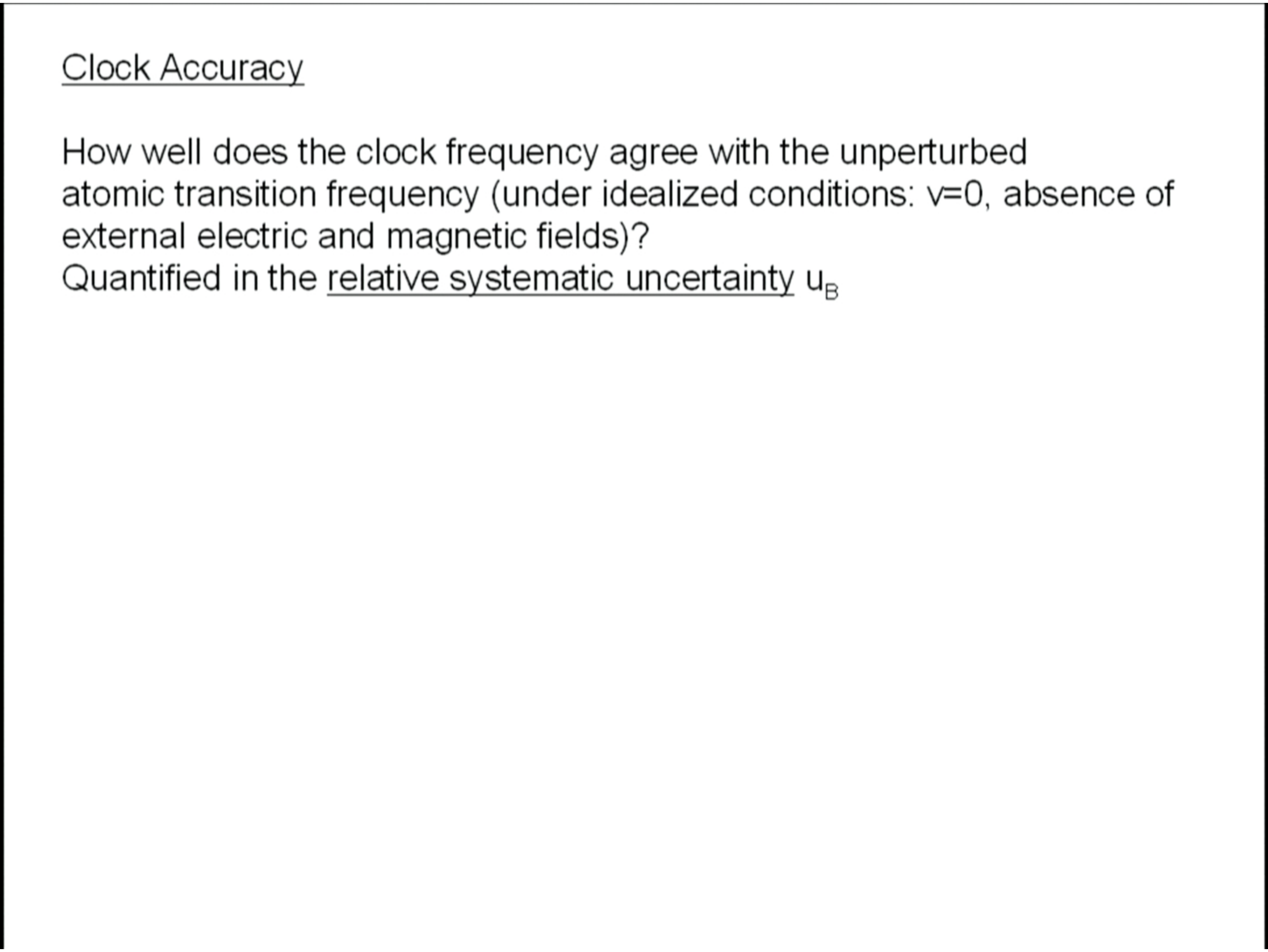
Principle of Atomic Clocks

Absorber (ions, atoms, molecules)





Clock Accuracy

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Quantified in the relative systematic uncertainty u_B

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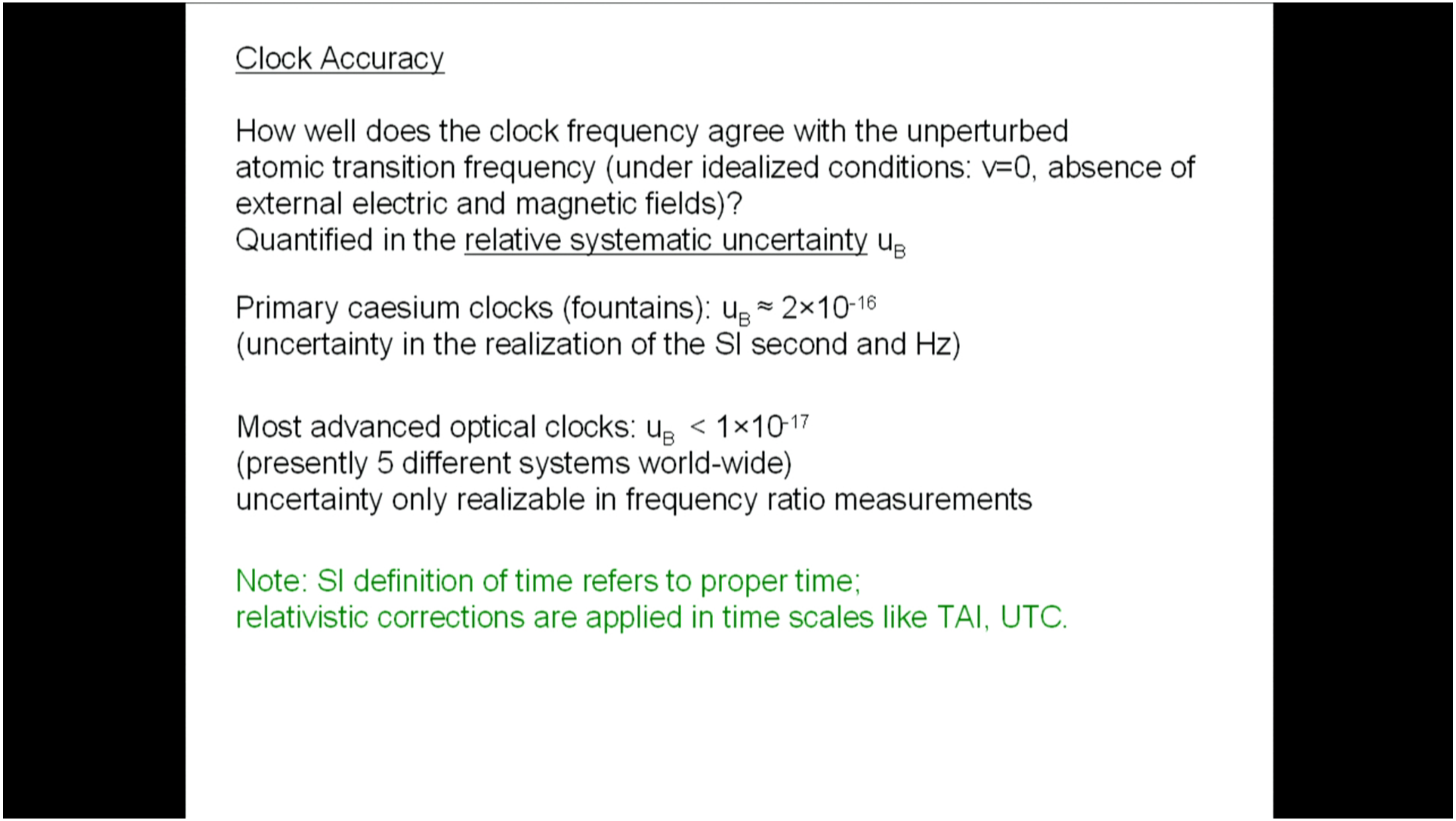
(presently 5 different systems world-wide)
uncertainty only realizable in frequency ratio measurements



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Note: SI definition of time refers to proper time;
relativistic corrections are applied in time scales like TAI, UTC.

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Quantified in the Allan deviation $\sigma_y(\tau)$

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Generic expression for an optimized, quantum projection noise-limited clock:

$$\sigma_y(\tau) \approx \frac{\Delta\nu}{\nu_0}\sqrt{\frac{T_c}{N\tau}}$$

$\Delta\nu$: observed linewidth
ν_0: reference frequency
N: atom number (projection noise limited detection)
T_c: cycle time

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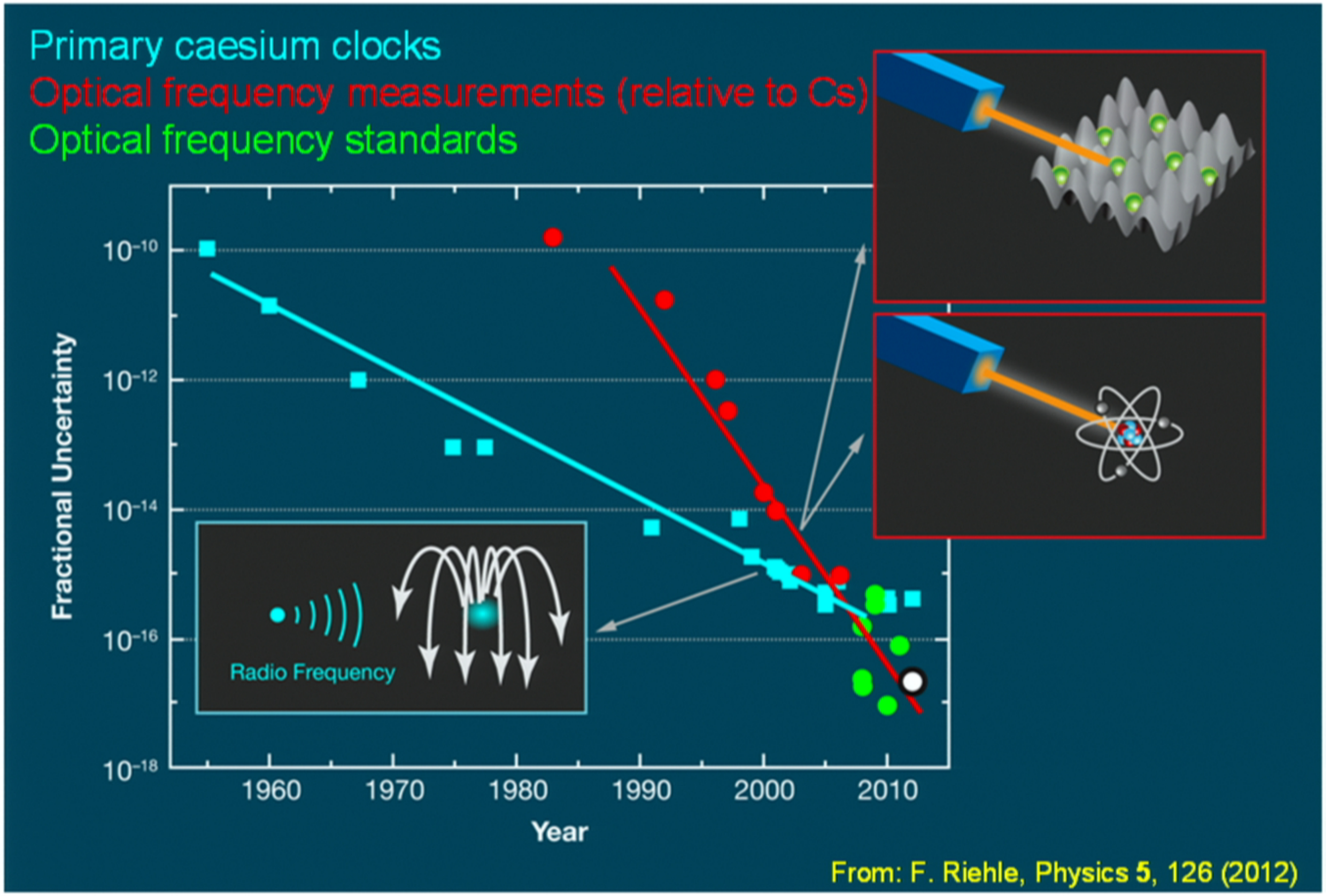
Examples:
Single-ion, optical, $\Delta\nu/\nu_0=10^{-15}$, $T_c=1$ s, $\sigma_y(\tau)=10^{-15}\,(\tau/\mathrm{s})^{-1/2}$

Cs fountain: $N=10^6$, $\Delta\nu/\nu_0=10^{-10}$, $T_c=1$ s, $\sigma_y(\tau)=10^{-13}\,(\tau/\mathrm{s})^{-1/2}$

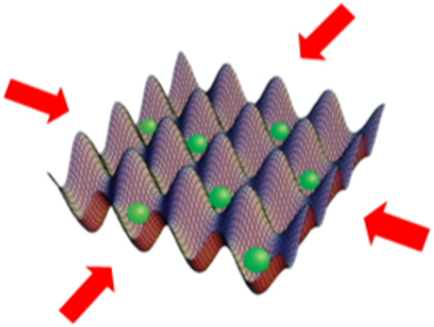
Progress in the uncertainties of atomic clocks and frequency standards



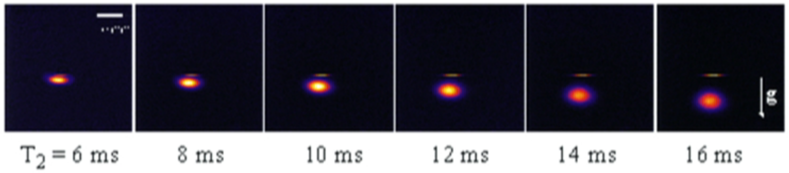
From: F. Riehle, Physics **5**, 126 (2012)

Two systems for optical clocks with atoms in traps

Optical lattice with neutral atoms



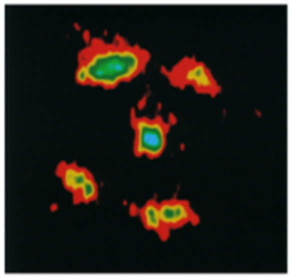
- Optical lattice: Dipole trap at the “magic” wavelength
- ~10^6 atoms interrogated simultaneously



Absorption images of trapped Sr atoms and of an expanding cloud of free atoms

Single ion in an ion trap

- Storage with minimal perturbation from the trap potential
- unlimited observation time
- one ion: no collisional shift



5 Yb^+ Ions

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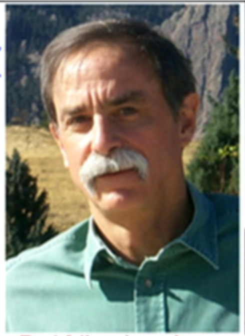
Optical Frequency Standar with a Laser-Cooled Ion in a Paul Trap



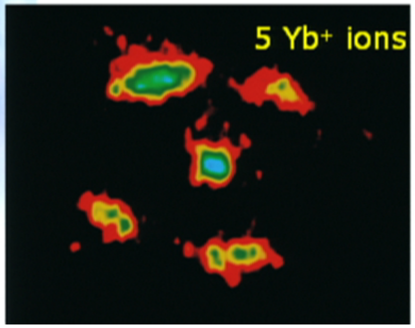
D. Wineland

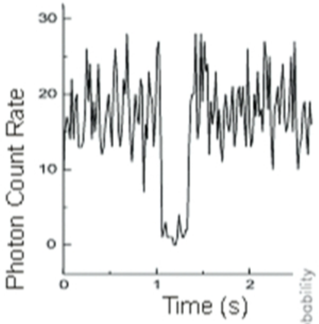
H. Dehmelt

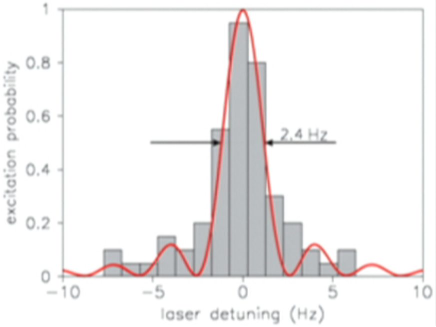
W. Paul

N. Ramsey

- Confinement in a Paul trap with minimal perturbation of the level structure
- Laser cooling to the Lamb-Dicke regime eliminates Doppler shifts
- Quantum noise limited state detection via electron shelving or quantum logic
- Long interrogation time allows to excite high-Q resonances







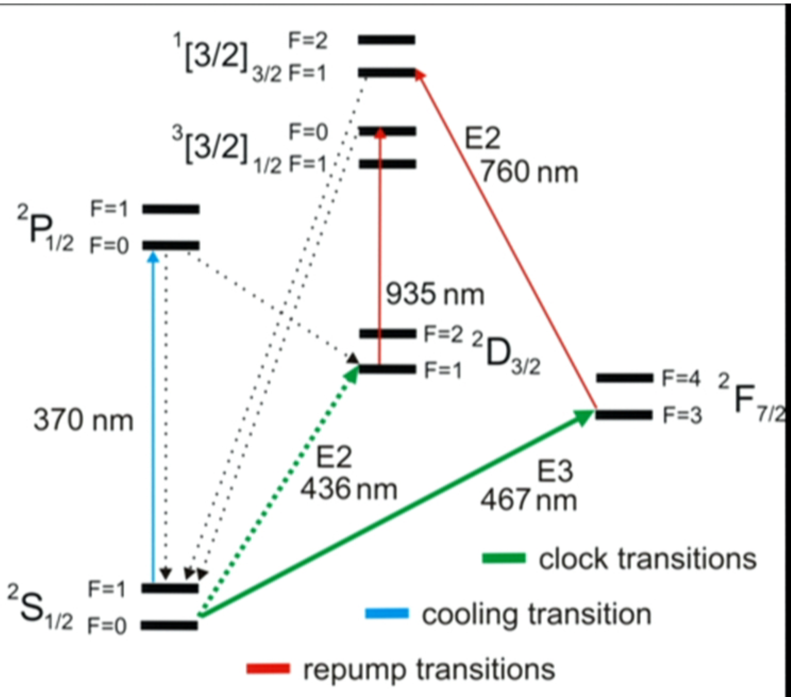
Ions and types of transition under study

J=0 -- J=0 transition, hyperfine-quenched	
$^{27}\mathrm{Al}^{+}$,$^{115}\mathrm{In}^{+}$	small field-induced shifts
S -- D electric quadrupole transition	
$^{40}\mathrm{Ca}^{+}$, $^{88}\mathrm{Sr}^{+}$, $^{171}\mathrm{Yb}^{+}$, $^{199}\mathrm{Hg}^{+}$	convenient laser systems
S -- F electric octupole transition	
$^{171}\mathrm{Yb}^{+}$	narrow linewidth, $d\alpha/dt$ test case
nuclear magnetic dipole transition	
$^{229}\mathrm{Th}^{3+}$	small field-induced shifts

Experiments at
national metrology institutes: NIST, NPL, NRC, PTB, NICT …
and universities in Innsbruck, Marseille, …

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

Advantages of Yb$^+$
- all transitions driven by diode lasers
- long storage time (months)
- ^{171}Yb$^+$: nuclear spin 1/2



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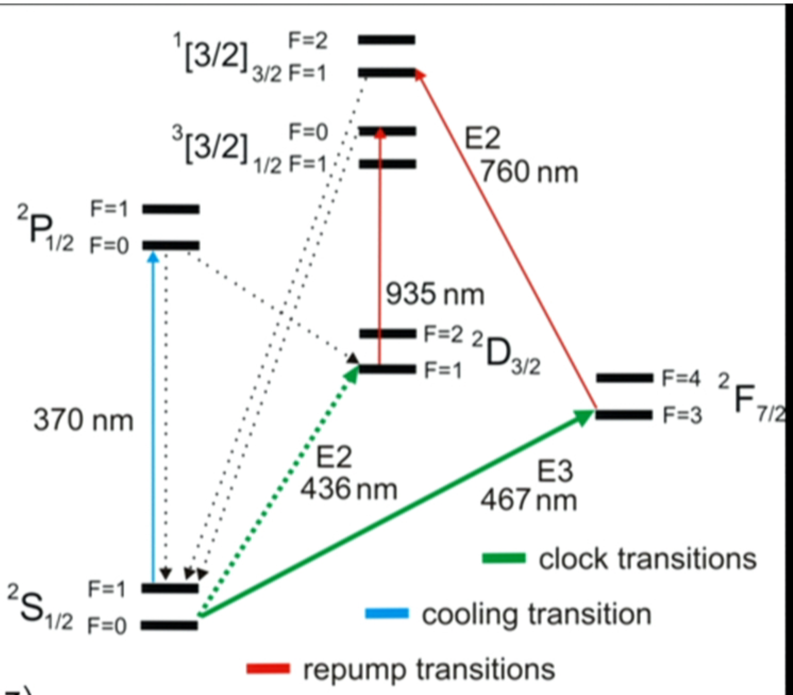

Quadrupole Transition S-D
- studied at PTB since 1990ies
- secondary representation of the second
- resolution limited by natural linewidth (3 Hz)
- syst. uncertainty ≈ 1×10^{-16} (PTB)

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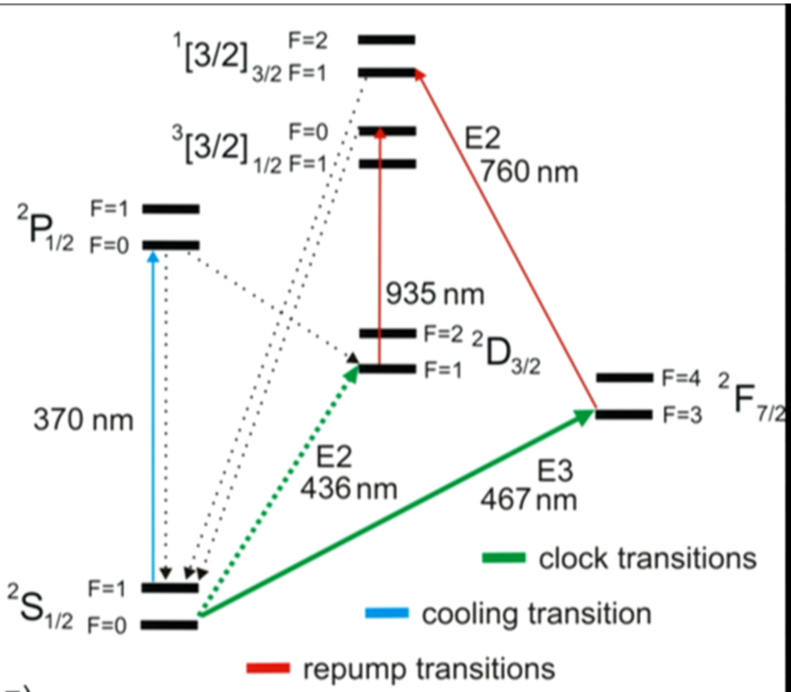

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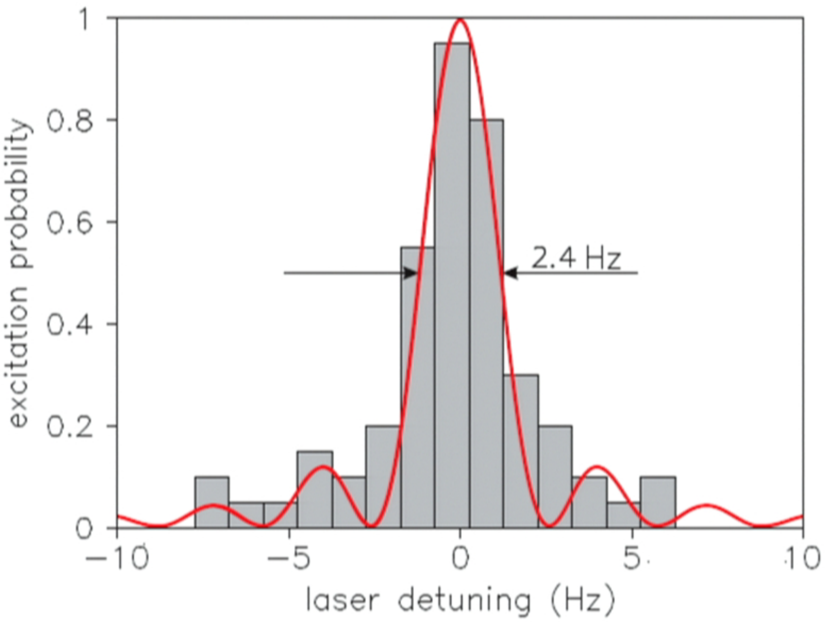
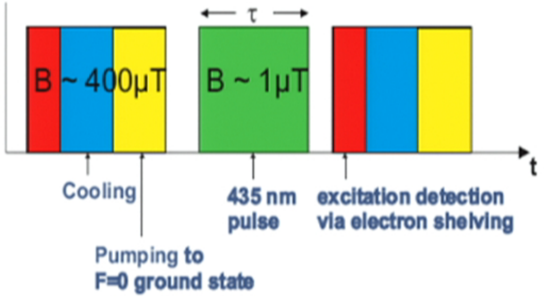
Octupole Transition S-F
- Pioneering work at NPL (M. Roberts, PRL 78, 1876 (1997)
- nHz natural linewidth
- resolution only limited by clock laser
- smaller shifts through static fields than E2 transition
- large nonresonant light shift from clock laser

High resolution excitation spectrum of the octupole transition

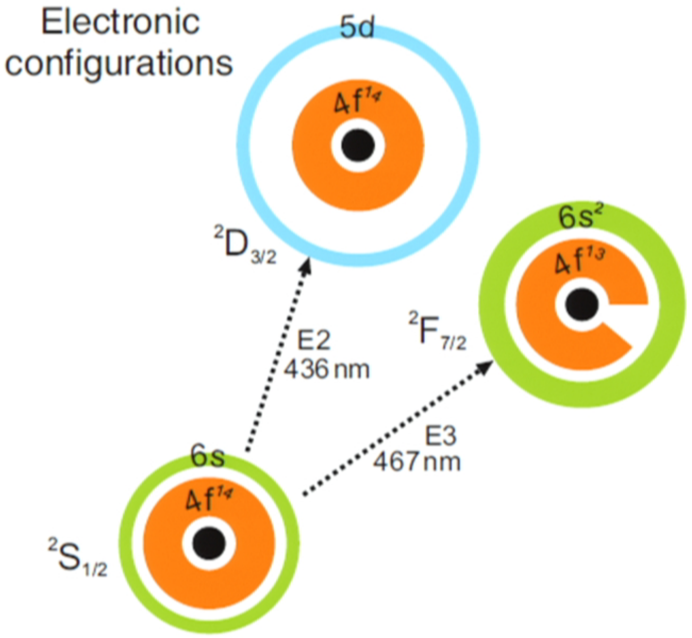


- 335 ms pulse duration
- 50 μW laser power
- Fourier-limited linewidth
- $Q = 2.7 \times 10^{14}$
- Light shift $\approx$ 4 Hz

Measurement cycle:

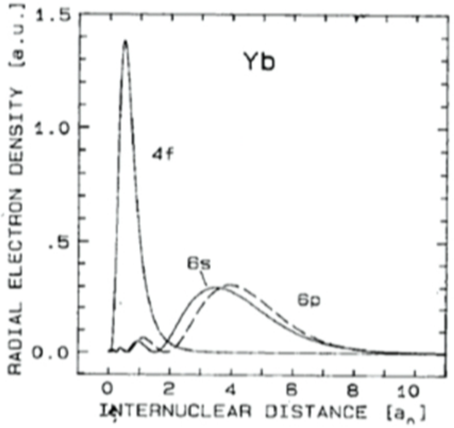


Electronic configurations for the two clock transitions in Yb⁺:



Octupole transition opens the closed 4f shell.

F state is less polarizable and has smaller quadrupole moment than D state.



H. Hotop et al., Ann. Physik 1990

Uncertainty budget (2012)

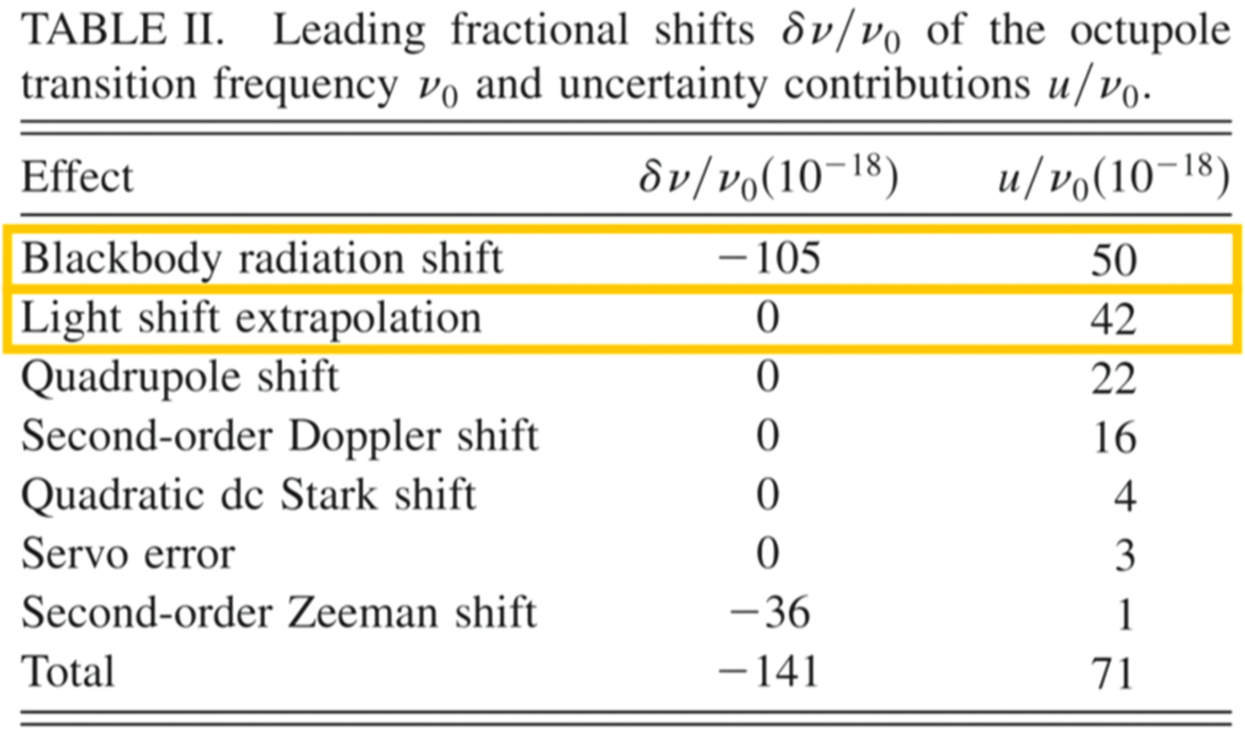


TABLE II. Leading fractional shifts $\delta\nu/\nu_0$ of the octupole transition frequency ν_0 and uncertainty contributions u/ν_0.

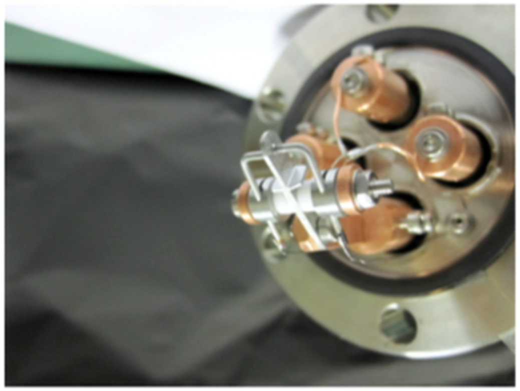
Effect	$\delta\nu/\nu_0(10^{-18})$	$u/\nu_0(10^{-18})$
Blackbody radiation shift	-105	50
Light shift extrapolation	0	42
Quadrupole shift	0	22
Second-order Doppler shift	0	16
Quadratic dc Stark shift	0	4
Servo error	0	3
Second-order Zeeman shift	-36	1
Total	-141	71

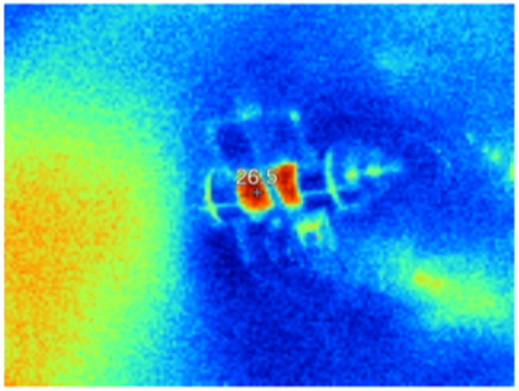
N. Huntemann *et al.*, Phys. Rev. Lett. **108**, 090801 (2012)

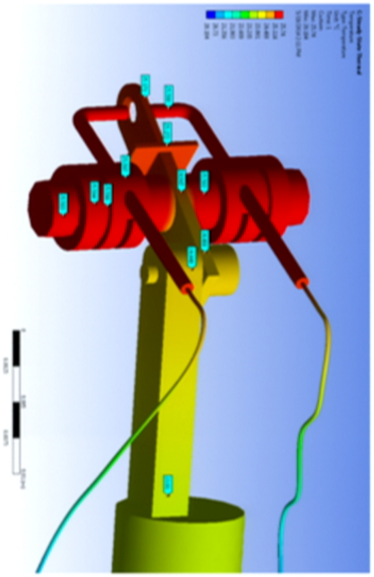
Light shift uncertainty: strongly reduced with Hyper-Ramsey excitation:
N. Huntemann, B. Lipphardt, M. Okhapkin, Chr. Tamm, E. Peik,
A.V. Taichenachev , V. I. Yudin, Phys. Rev. Lett. **109**, 213002 (2012)

Thermal environment of the ion

AC Stark shift from ambient thermal radiation leads to an important systematic shift for room temperature operation of the clock. Radiation field and polarizability have to be known precisely.



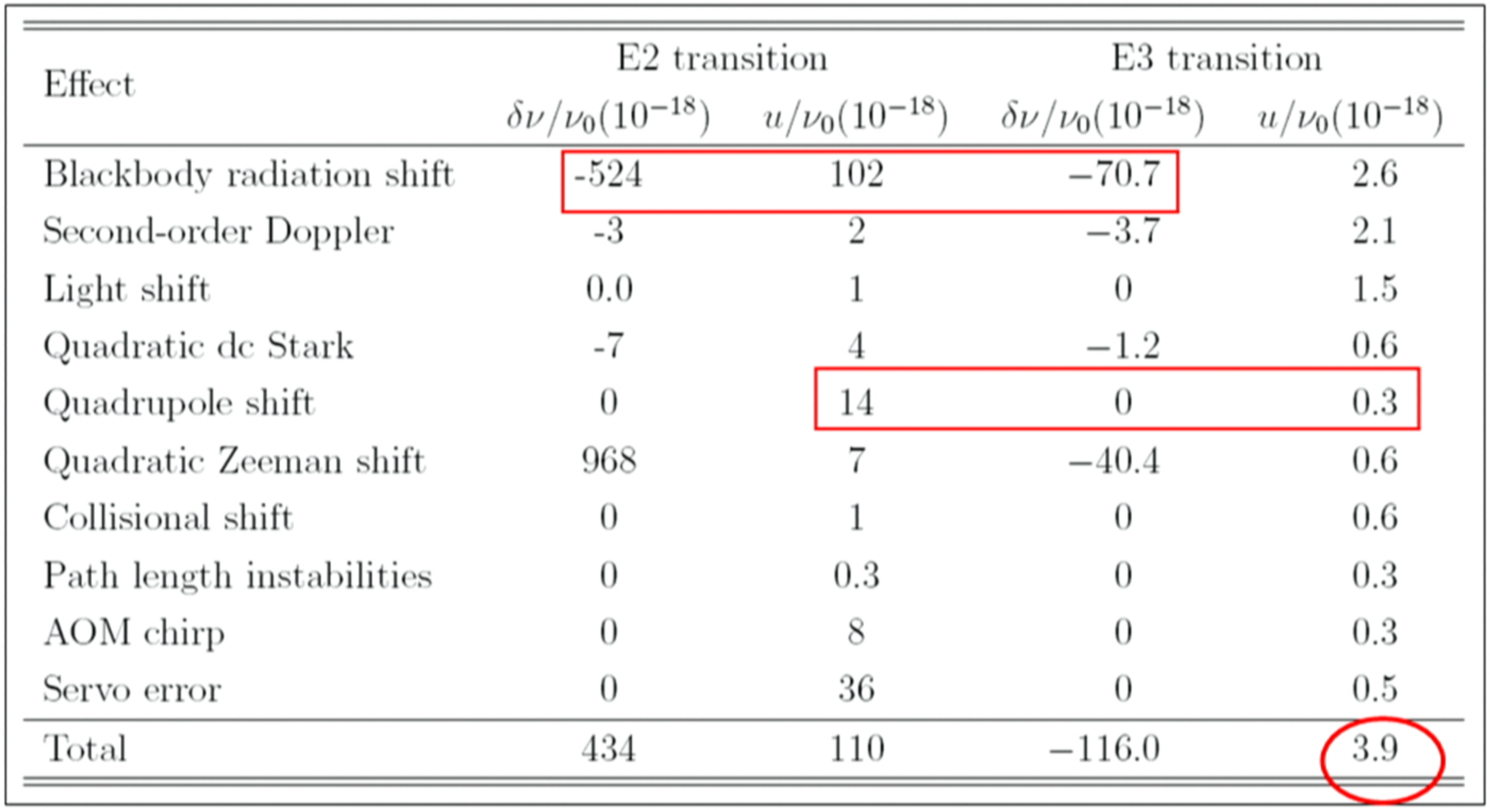




- Preliminary test with PT100 in vacuum → $\Delta T = 4.3$ K
- Temperature inside the magnetic shielding = 296(1) K
- Measurements + FEM calculations of P. Balling and M. Doležal
  → effective temperature rise $\Delta T = 2(1)$ K
- Fractional BBR shift = $-70.5(3.7) \times 10^{-18}$

EMRP
European Metrology Research Programme
Programme of EURAMET
The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

Systematic uncertainty budget (2014) for both Yb^+ transitions



Effect	E2 transition		E3 transition	
	$\delta\nu/\nu_0(10^{-18})$	$u/\nu_0(10^{-18})$	$\delta\nu/\nu_0(10^{-18})$	$u/\nu_0(10^{-18})$
Blackbody radiation shift	-524	102	−70.7	2.6
Second-order Doppler	-3	2	−3.7	2.1
Light shift	0.0	1	0	1.5
Quadratic dc Stark	-7	4	−1.2	0.6
Quadrupole shift	0	14	0	0.3
Quadratic Zeeman shift	968	7	−40.4	0.6
Collisional shift	0	1	0	0.6
Path length instabilities	0	0.3	0	0.3
AOM chirp	0	8	0	0.3
Servo error	0	36	0	0.5
Total	434	110	−116.0	3.9

N. Huntemann, PhD thesis, 2014

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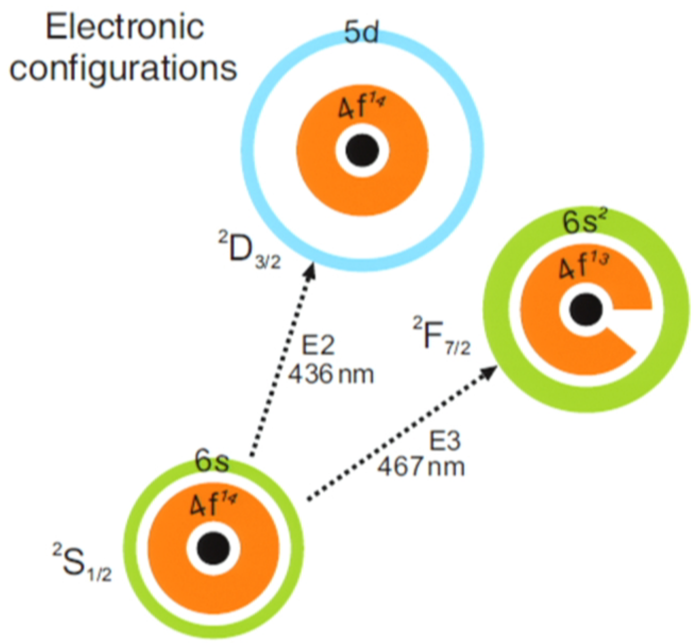
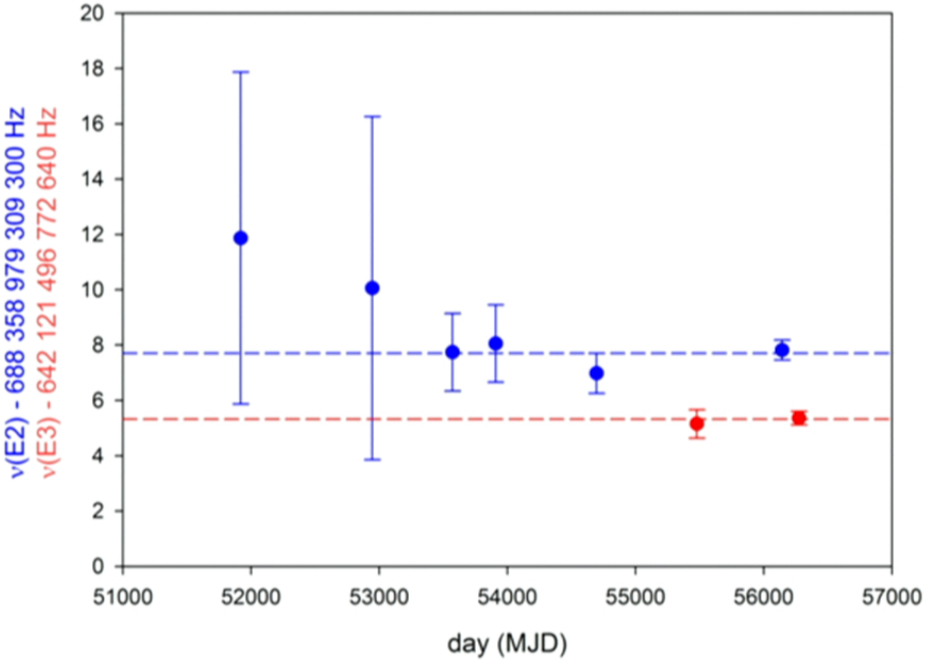


Octupole transition opens the closed 4f shell.

Relativistic contributions to level energies are big and different in D and F state.
E2/E3 frequency ratio has high sensitivity to value of α.
K(E2)= 1.0 K(E3)= - 6.0

V. V. Flambaum, V. A. Dzuba, Can. J. Phys. 87, 25 (2009)
S. N. Lea, Rep. Prog. Phys. **70**, 1473 (2007)

Results of absolute frequency measurements of Yb⁺ transitions with CSF1/CSF2 at PTB, 2000-2012



Relative uncertainty of recent measurements: ≈ 8×10^{-16} (Cs-limited)

ν(E2)=688 358 979 309 307.82(36) Hz

ν(E3)=642 121 496 772 645.34(25) Hz

Laboratory limits on variations of optical/caesium frequency ratios

Atom, transition	$d\ln f/dt$ $(10^{-16}/\mathrm{yr})$	K	
$^{87}\mathrm{Sr}$, $^1S_0 \to {}^3P_0$	-3.3 ± 3.0	0.062	**Boulder, Paris, Tokyo**
$^{171}\mathrm{Yb}^+$, $^2S_{1/2} \to {}^2D_{3/2}$	0.5 ± 1.9	1.0	**PTB, Braunschweig**
$^{171}\mathrm{Yb}^+$, $^2S_{1/2} \to {}^2F_{7/2}$	0.2 ± 4.1	-6.0	
$^{199}\mathrm{Hg}^+$, $^2S_{1/2} \to {}^2D_{5/2}$	3.7 ± 3.9	-2.9	**NIST, Boulder**

Gross structure: $$f_{GS} = C_{GS} c R_\infty F_{GS}(\alpha)$$

Hyperfine structure: $$f_{HFS} = C_{HFS} \alpha^2 c R_\infty F_{HFS}(\alpha) G_{HFS}(\mu_N/\mu_B)$$

Variation of the frequency ratio in terms of α and $\mu = m_p/m_e$

$$\frac{1}{R}\frac{dR}{dt} = (K_{GS} - K_{HFS} - 2)\frac{1}{\alpha}\frac{d\alpha}{dt} + \frac{1}{\mu}\frac{d\mu}{dt} - \kappa\frac{1}{X_q}\frac{dX_q}{dt}$$

Relativistic contributions

quark masses
(experimental limit taken from
Rb/Cs HFS, Guena et al.)

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

$$\kappa = \frac{1}{G}\frac{dG}{dX_q}$$

Laboratory limits on variations of atomic frequency ratios

Frequency ratio X	k_α	k_μ	k_q	$d\ln(X)/dt$ (yr^{-1})	Ref.
Rb/Cs	-0.49	0	-0.021	$(-1.36 \pm 0.91) \times 10^{-16}$	LNE-SYRTE, Paris
H_{hfs}/Cs	-0.83	0	-0.102	–	
H(1S – 2S)/Cs	-2.83	-1	-0.002	$(-32 \pm 63) \times 10^{-16}$	MPQ, Garching
Yb^+/Cs	-1.83	-1	-0.002	$(-4.9 \pm 4.1) \times 10^{-16}$	PTB, Braunschweig
Hg^+/Cs	-5.77	-1	-0.002	$(3.7 \pm 3.9) \times 10^{-16}$	NIST, Boulder
Sr/Cs	-2.77	-1	-0.002	$(-10 \pm 18) \times 10^{-16}$	Boulder, Paris, Tokyo
$(^{162}Dy – ^{163}Dy)$/Cs	1.72×10^7	-1	-0.002	$(-4.0 \pm 4.1) \times 10^{-8}$	UC Berkeley
Al^+/Hg^+	2.95	0	0	$(-0.53 \pm 0.79) \times 10^{-16}$	NIST, Boulder

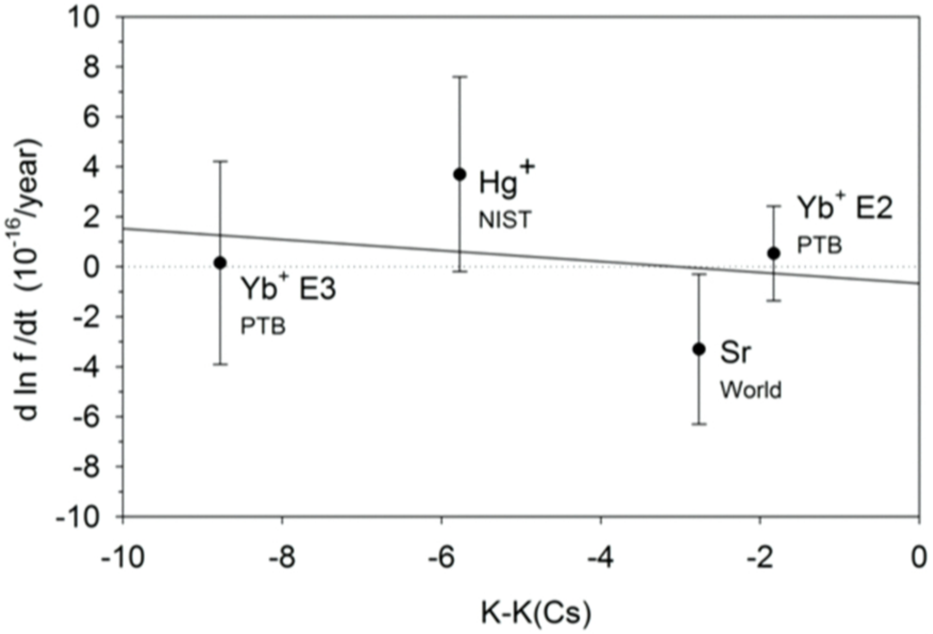
Sensitivities to α, μ and m_q/Λ_{QCD}

Flambaum, Dzuba
Dinh, Dunning

From: J. Guena et al., Phys. Rev. Lett. **109**, 080801 (2012)

Al^+/Hg^+: T. Rosenband et al., Science **319**, 1808 (2008):
$d \ln \alpha / dt = (-1.6 \pm 2.3) \times 10^{-17}$/year

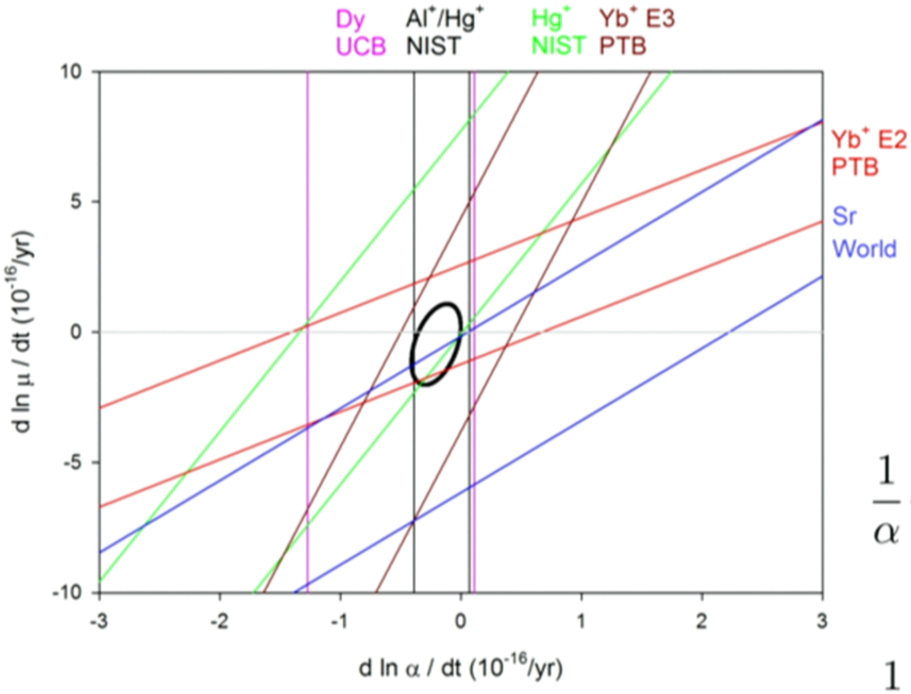
Linear regression of Cs-based frequency drift against K



$$\frac{1}{\alpha}\frac{d\alpha}{dt} = -0.22(59) \times 10^{-16}/\mathrm{y}r$$

$$\frac{1}{\mu}\frac{d\mu}{dt} = -0.5(2.4) \times 10^{-16}/\mathrm{y}r$$

Uncertainty ellipse including Al+/Hg+ and Dy data



$$\frac{1}{\alpha}\frac{d\alpha}{dt} = -0.20(21) \times 10^{-16}/\mathrm{y}r$$

$$\frac{1}{\mu}\frac{d\mu}{dt} = -0.5(1.6) \times 10^{-16}/\mathrm{y}r$$

Consistent with constancy of constants in the present epoch.
More stringent limit on dμ/dt.

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Nuclear Clock:

Contains an oscillator that is frequency-stabilized to a nuclear (γ-ray) transition

Motivation:

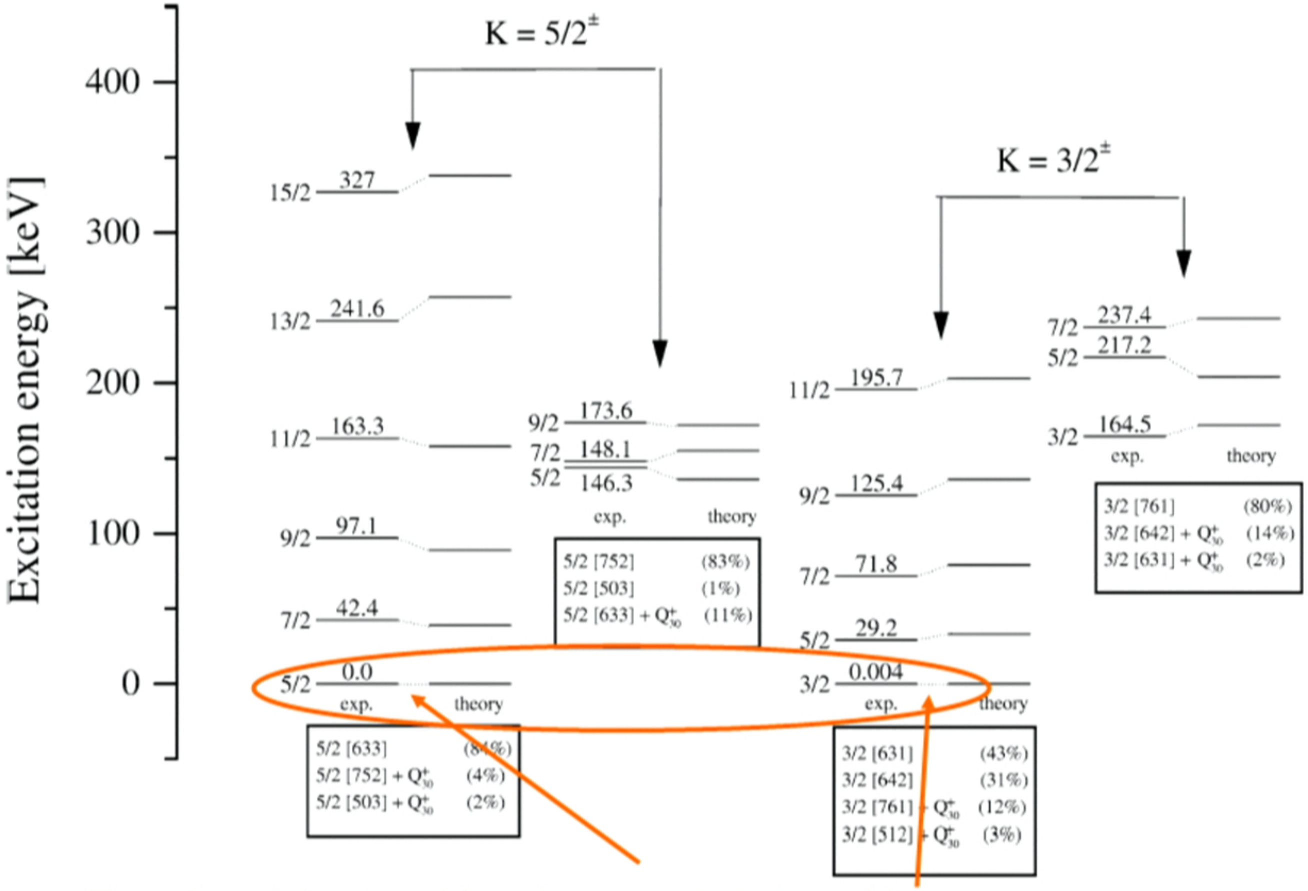
Higher precision: In most of the advanced optical clocks (trapped ion and optical lattice) field-induced shifts make a dominant contribution to the uncertainty budget (exception: Al^+ J=0-0). These can be reduced in a nuclear clock.

Higher stability: In a Mößbauer solid state nuclear clock, many absorbers may be interrogated ($>10^{10}$ instead of $\approx 10^0$ (ion) or $\approx 10^6$ (lattice)).

Higher frequency: → higher stability. VUV or even X-ray transitions may be used when suitable radiation sources become available.

K. Gulda et al. / Nuclear Physics A 703 (2002) 45–69

The nuclear structure of ^{229}Th



Two close-lying band-heads: ground state and isomer

A high-precision nuclear clock

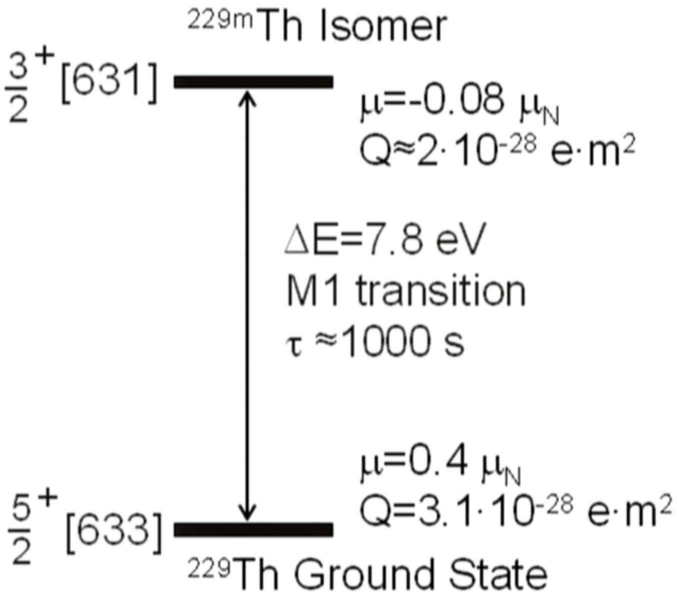
Nuclear moments are small.
Field induced systematic frequency shifts can be smaller than in an (electronic) atomic clock.

Consider hyperfine coupling, shielding and anti-shielding.
Select suitable electronic state for the nuclear excitation.

Analyzed for the Th^{3+} system in:

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

C. J. Campbell et al.,
Phys. Rev. Lett. **108**, 120802 (2012)



^{229m}Th Isomer

$\frac{3}{2}^{+}$[631]

$\mu=-0.08\ \mu_N$
$Q\approx 2\cdot 10^{-28}\ e\cdot m^2$

$\Delta E = 7.8$ eV
M1 transition
$\tau \approx 1000$ s

$\mu=0.4\ \mu_N$
$Q=3.1\cdot 10^{-28}\ e\cdot m^2$

$\frac{5}{2}^{+}$ [633]

^{229}Th Ground State

A high-precision nuclear clock

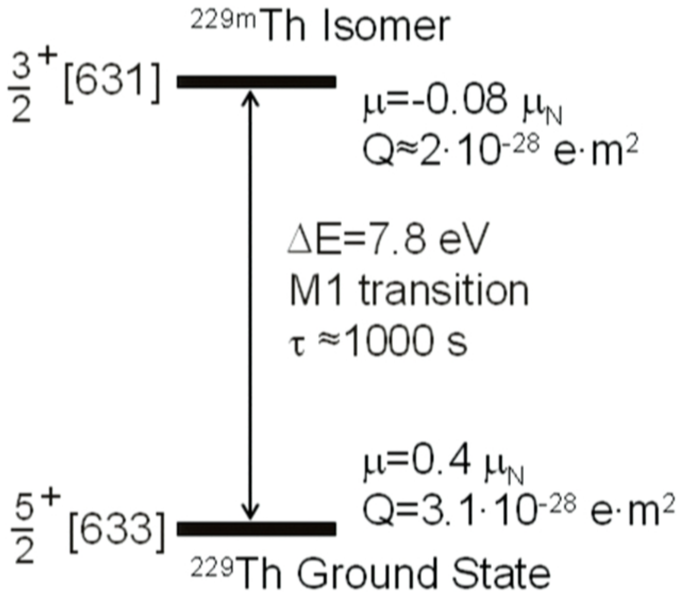
Nuclear moments are small.
Field induced systematic frequency shifts can be smaller than in an (electronic) atomic clock.

Consider hyperfine coupling, shielding and anti-shielding.
Select suitable electronic state for the nuclear excitation.

Analyzed for the Th^{3+} system in:

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

C. J. Campbell et al.,
Phys. Rev. Lett. **108**, 120802 (2012)



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$\frac{5}{2}^{+}[633]$

^{229}Th Ground State

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

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

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

But: it depends a lot on nuclear structure!

>10 theory papers
2006-2009

See for example:

A. C. Hayes, J. L. Friar, P. Möller, Phys. Rev. C **78**, 024311 (2008) ($|A|<\approx 10^3$)
E. Litvinova et al., Phys. Rev. C **79**, 064303 (2009) ($|A|<\approx 4\text{x}10^4$)

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

Possible realisations of Th-229 nuclear clocks:
- Laser-cooled Th^{3+} in an ion trap
- Th ions as dopant in a transparent crystal (like CaF_2, LiCAF etc.)

Experimental problem:
Transition energy known only to ≈ 10% uncertainty,
not a system for high resolution spectroscopy yet.

Experimental projects:

PTB:	trapped Th^{+} ions; Th in solids
Georgia Tech (A. Kuzmich):	trapped Th^{3+} ions
UCLA (E. Hudson):	Th-doped crystals
TU Vienna (T. Schumm):	Th-doped crystals

Jyväskylä/Mainz Resonance ionization spectroscopy of Th recoil nuclei
LLNL, Heidelberg γ-spectroscopy
…

Our „search“ strategy: Nuclear excitation via an „electronic bridge“

- „Electronic Bridge“ in γ-decay, theoretically discussed by V.A. Krutov and V.N. Fomenko, 1968

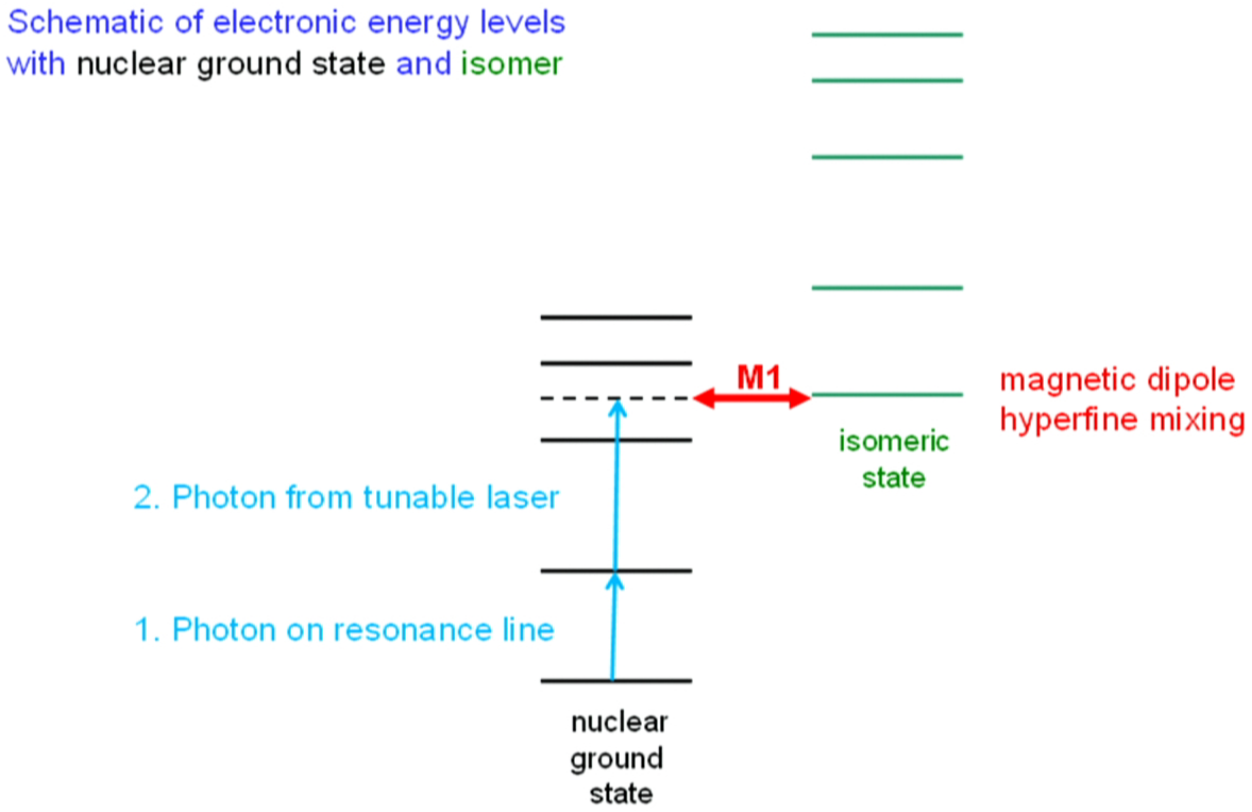
- „Inverse electronic bridge“ or NEET (Nuclear Excitation by Electron Transition): Transfer of excitation from the electron shell to the nucleus
  see reviews: S. Matinyan, Phys. Rep. **298**, 199 (1998),
  E. V. Tkalya, Phys. Uspekhi **46**, 315 (2003)

In our case:

- Excitation of the shell in a two-photon process,
  no tunable laser at ≈ 160 nm required

- Excitation rate may be strongly enhanced at resonance between electronic and nuclear transition frequency,
  This is very likely in the dense level structure of Th^+

Two-photon electronic bridge excitation (I)



Schematic of electronic energy levels with nuclear ground state and isomer

M1

magnetic dipole hyperfine mixing

isomeric state

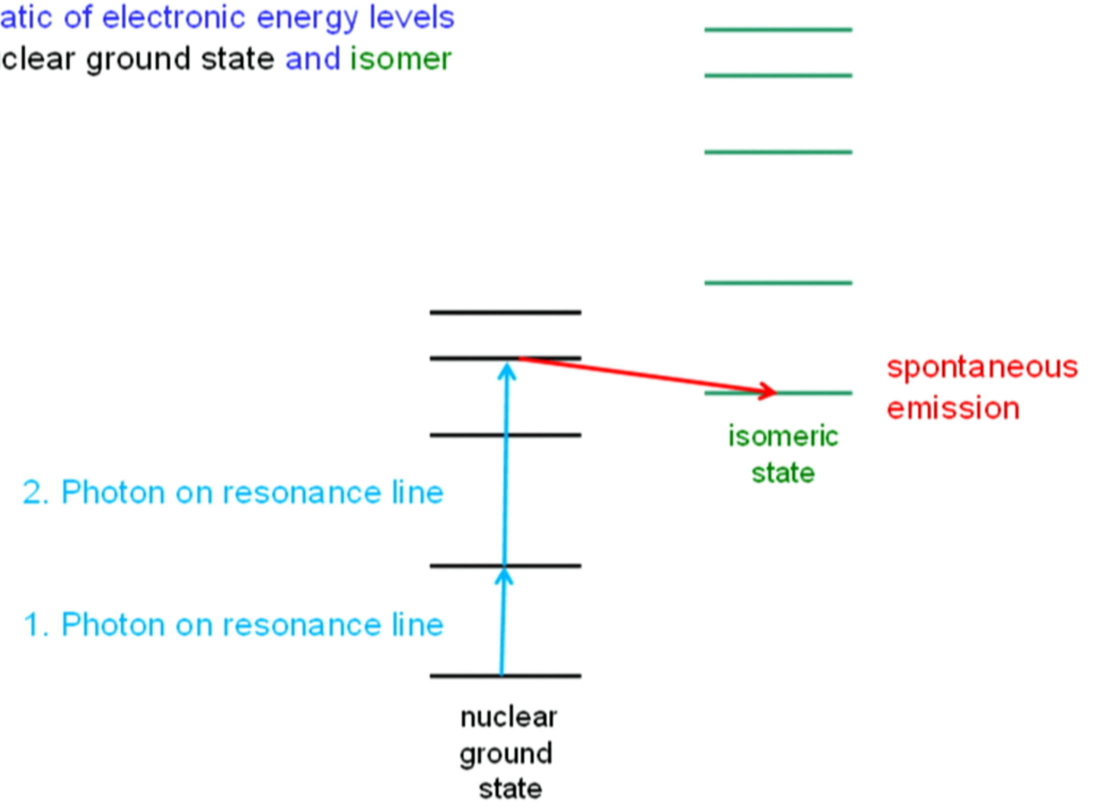
2. Photon from tunable laser

1. Photon on resonance line

nuclear ground state

Two-photon electronic bridge excitation (II)

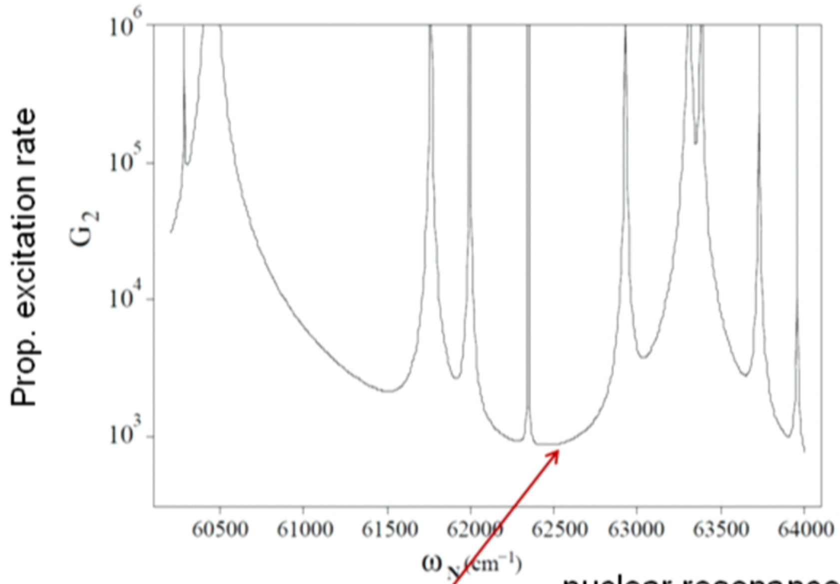
Schematic of electronic energy levels
with nuclear ground state and isomer



Two-photon electronic bridge excitation rate

S. G. Porsev, V. V. Flambaum, E. Peik, Chr. Tamm, Phys. Rev. Lett. **105**, 182501 (2010)

Based on ab-initio calculations: 10 relevant even parity states with J=3/2 or 5/2



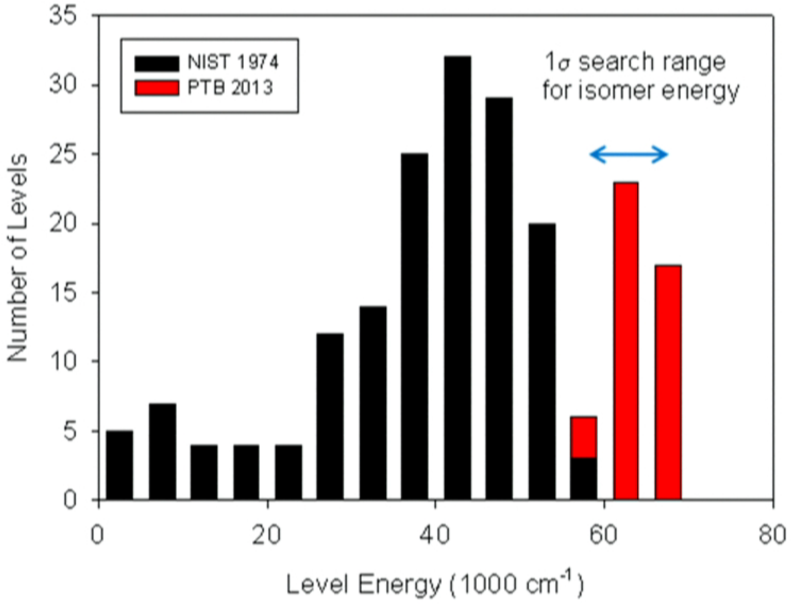
nuclear resonance frequency

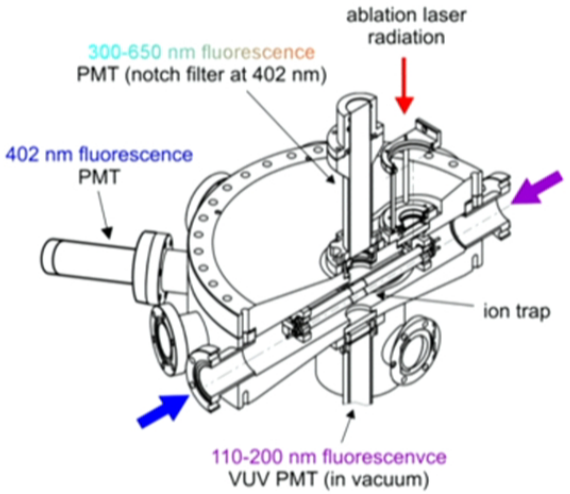
→ predicted excitation rate in the range of 10 s^{-1} with a pulsed Ti:Sa laser at GHz resolution.

Experimental data on the level structure in this range was not available.

Th$^+$- energy level density

From two-photon-excitation of ^{232}Th$^+$ in the range 7.3 – 8.3 eV: 43 new levels

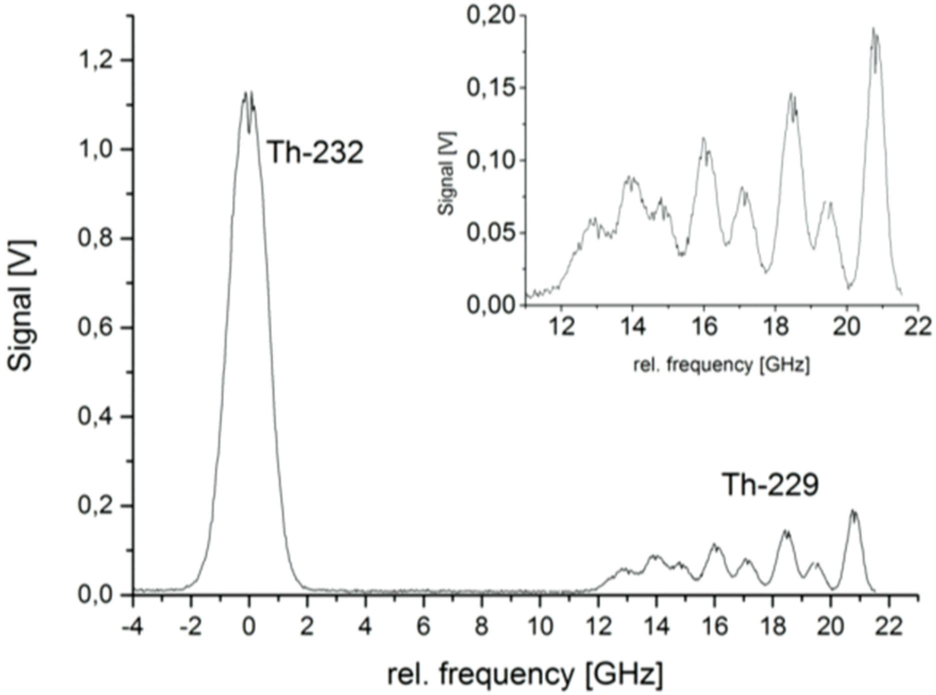




Th$^+$ levels,
P=even, J=3/2, 5/2, 7/2
(relevant for bridge processes).

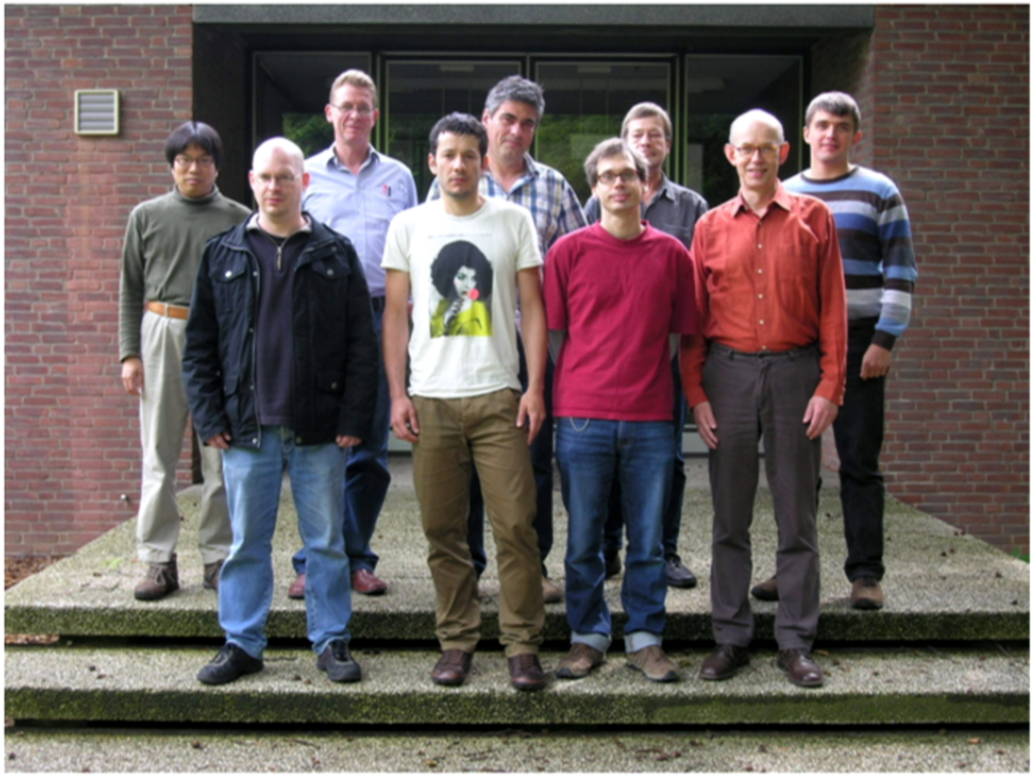
O.A. Herrera-Sancho, N. Nemitz, M. V. Okhapkin, E. Peik, Phys. Rev. A **88**, 012512 (2013)

Laser spectroscopy of trapped $^{229}Th^+$



Hyperfine structure
of the $^{229}Th^+$
resonance line
at 402 nm

Working Group: Optical Clocks with Trapped Ions at PTB



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Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

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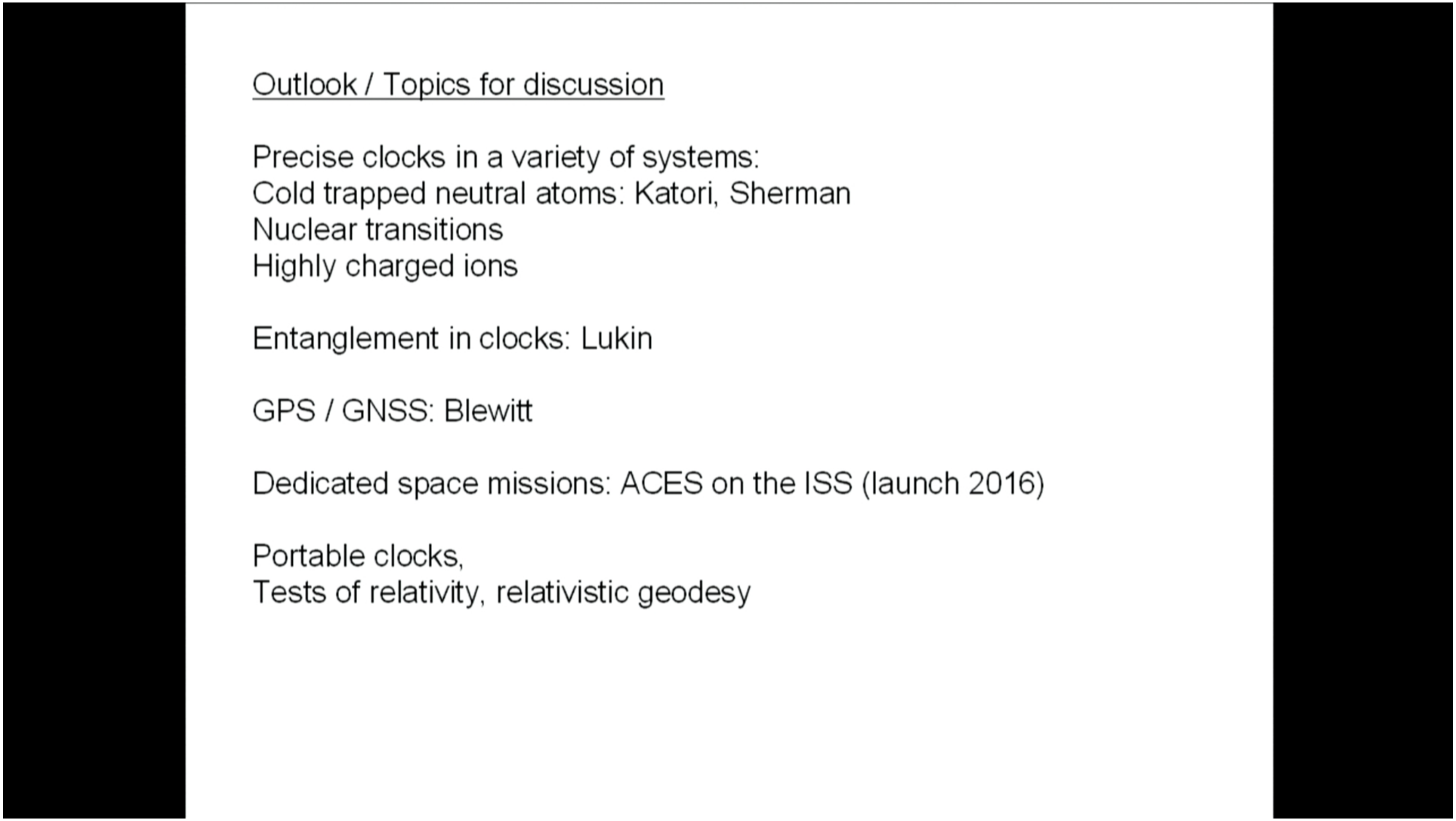
DFG, EMRP, DAAD, TEC, Humboldt-Foundation



Outlook / Topics for discussion

Precise clocks in a variety of systems:
Cold trapped neutral atoms: Katori, Sherman
Nuclear transitions
Highly charged ions

Entanglement in clocks: Lukin

GPS / GNSS: Blewitt

Dedicated space missions: ACES on the ISS (launch 2016)

Portable clocks,
Tests of relativity, relativistic geodesy