Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

Atomic and nuclear clocks for testing fundamental physics

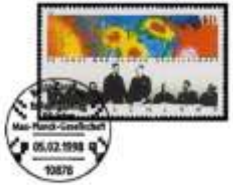
Ekkehard Peik

Time and Frequency Department

PTB, Braunschweig, Germany

PRISMA Kolloquium, Uni Mainz, 15.06.2022

Ekkehard Peik: short scientific CV



1987: Diploma at LMU München,
Max-Planck-Institut für Quantenoptik, supervisor: H. Walther
First observation of Coulomb crystals of laser-cooled ions in a Paul trap

1993: PhD at LMU, MPQ, supervisor: H. Walther

Trapping and cooling of In^+, first laser excitation of a $J=0 \rightarrow 0$ transition in a single trapped In^+ ion

1994-1996: Postdoc at Laboratoire Kastler Brossel, ENS, Paris,
Group of C. Salomon and C. Cohen-Tannoudji

Sub-recoil laser cooling, Bloch oscillations of atoms in an optical lattice

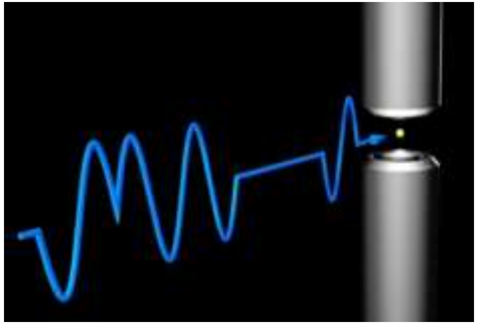
1996-2001: Ludwig-Maximilians-Universität München (Habilitation 1999)
and Max-Planck-Institut für Quantenoptik

Optical frequency measurement in a single trapped In^+ ion with a femtosecond frequency comb (Groups of H. Walther and T. Hänsch)

Ekkehard Peik: short scientific CV

PTB Braunschweig: Time and Frequency Department
2001: Scientific Staff
2003: Group Leader Optical clocks with trapped Ions
Since 2007: Department Head

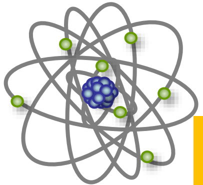
Research:
Yb^{+} optical clock,
Th-229 nuclear clock,
Fundamental tests with clocks



PTB Braunschweig and Berlin:

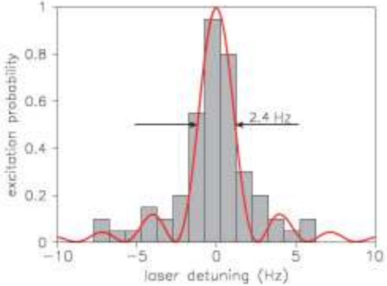
- National Metrology Institute (NMI)
- Federal Ministry of Economics (BMWK)
- 250 Mio. € annual budget, plus third party funding
- Approx. 2100 staff including 110 PhD students and 140 apprentices
- 600 scientific papers per year

Atomic clocks and fundamental physics



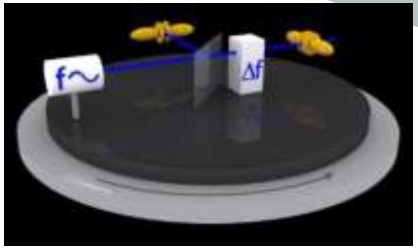
Atomic and nuclear structure, Quantum theory

Spectroscopy



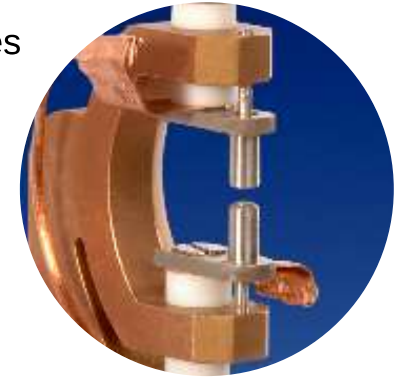
Tests of quantum theory and relativity

Clocks and Frequency Standards

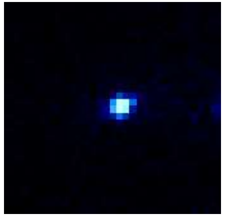


Optical clock with a single laser-cooled ion in a Paul trap

The ion trap provides long interaction and coherence times

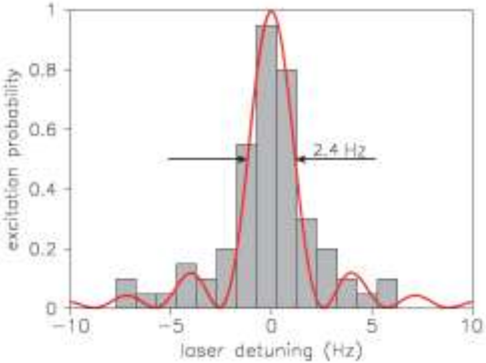


Combined with laser cooling: Lamb-Dicke confinement of a single ion

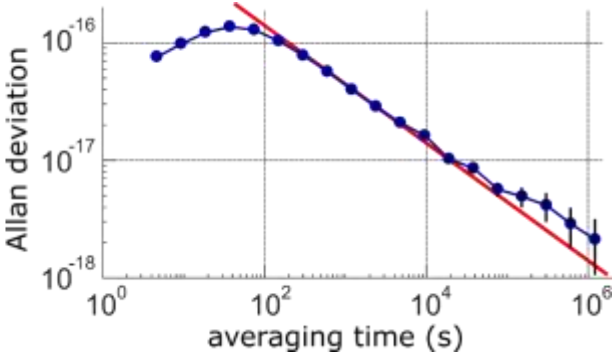


Hans Dehmelt

high spectral resolution, excellent control of systematic shifts

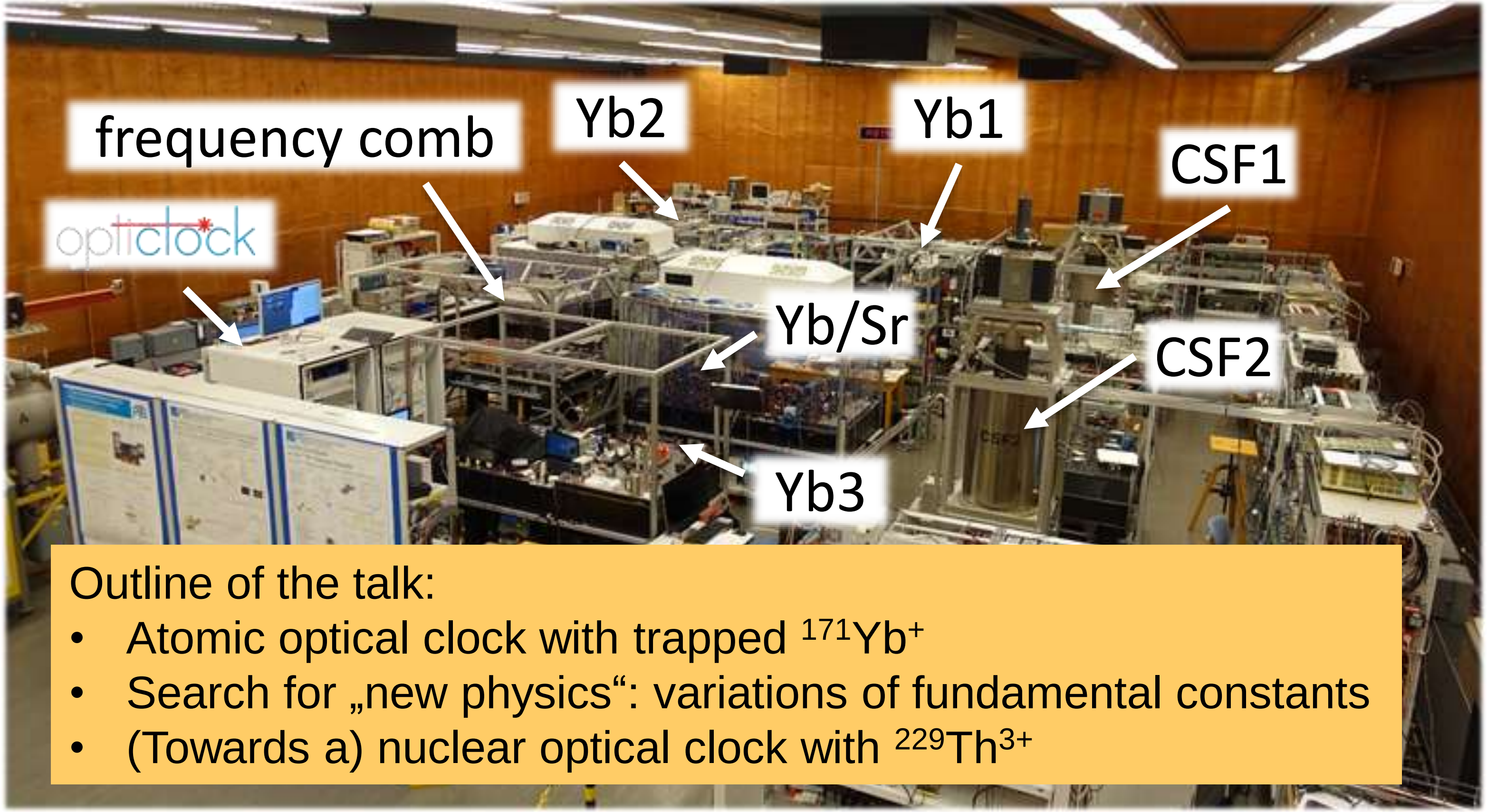


quantum noise limited stability



Motivation:
Primary atomic clocks: Redefinition of the SI second in ≈2030
Clock-based searches for „new physics“

Clock ensemble in PTB‘s clock hall



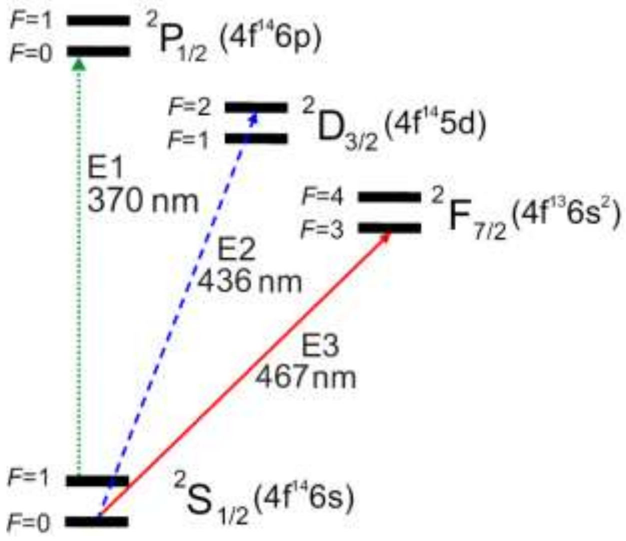
Outline of the talk:

- Atomic optical clock with trapped $^{171}Yb^{+}$
- Search for „new physics“: variations of fundamental constants
- (Towards a) nuclear optical clock with $^{229}Th^{3+}$

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

Advantages of $^{171}Yb^+$: - nuclear spin ½: non-degenerate (F=0,m=0) ground state
- two different optical clock transitions, two microwave transitions

Investigated at: NPL, PTB, JPL, ILP, … for clocks;
U. Maryland, IonQ, Honeywell, Siegen, Mainz, Erlangen, Ulm, Sussex ... for QIP etc.



Quadrupole Transition (E2): S-D
- natural linewidth: 3 Hz
- syst. uncertainty ≈ 3×10^{-17}

Octupole Transition (E3): S-F
- nHz natural linewidth
- resolution limited by clock laser / interaction time
- smaller shifts through external fields than E2
- light shift from clock laser: controlled in generalized Ramsey schemes
- syst. uncertainty ≈ 2×10^{-18}

Radiative lifetime of the Yb^+ $F_{7/2}$ state

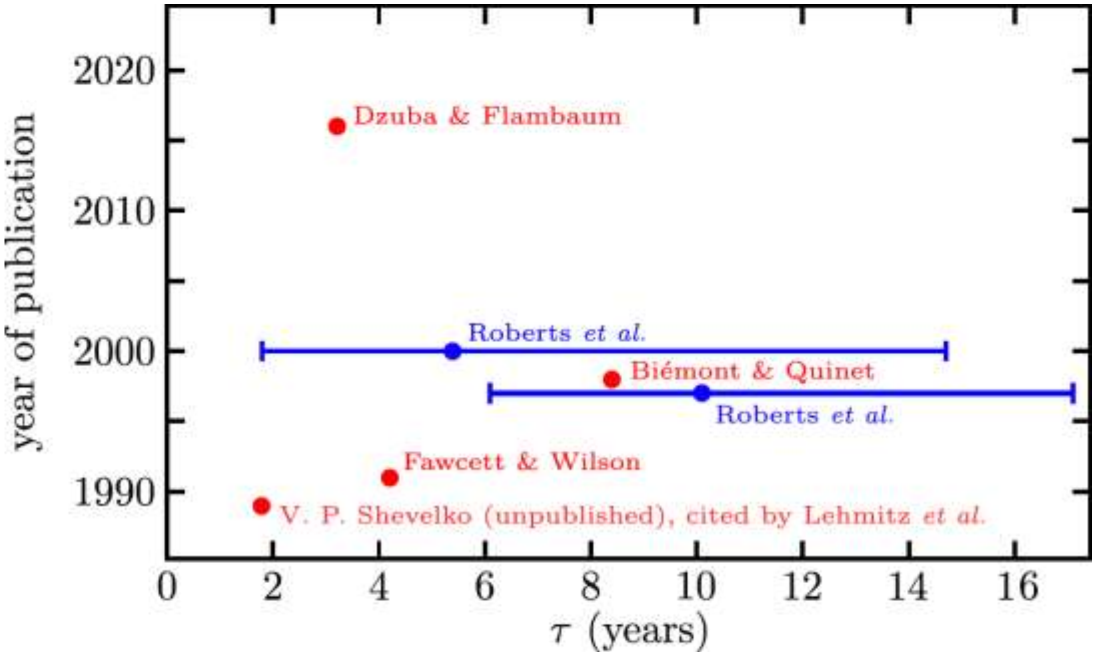
Linked to the strength and natural linewidth of the S-F electric octupole transition.

Difficult to **calculate**:

open 4f shell

Difficult to **measure**:

F-state population
is quenched on the
<1 h timescale



Radiative lifetime of the Yb^+ $F_{7/2}$ state

Measurement based on coherent excitation of the E3 transition.

Radiative lifetime and transition matrix element: $\tau \propto 1/|V_{eg}|^2$

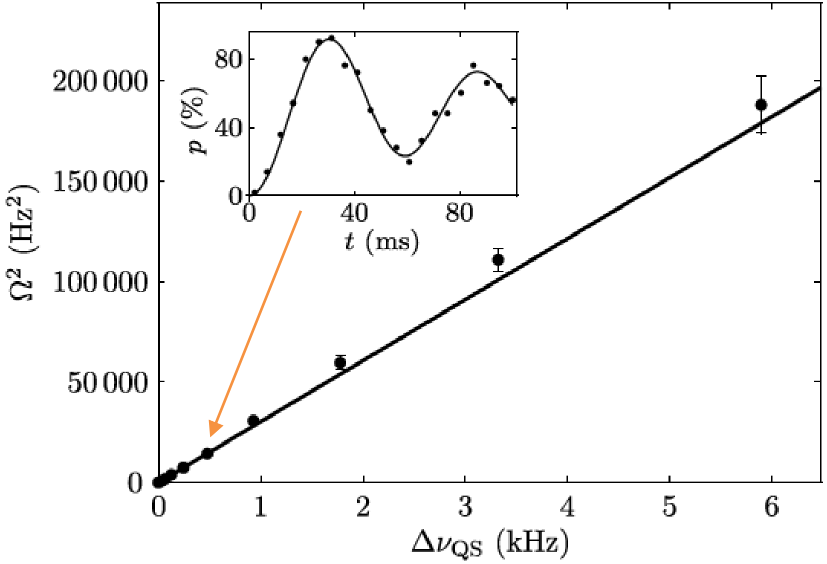
Resonant Rabi frequency: $\Omega = 2\pi E_0 |V_{eg}|/h$

The laser field also induces a quadratic Stark shift: $\Delta\nu_{QS} = E_0^2 \Delta\alpha_{eg}(\nu_0)/(2h)$

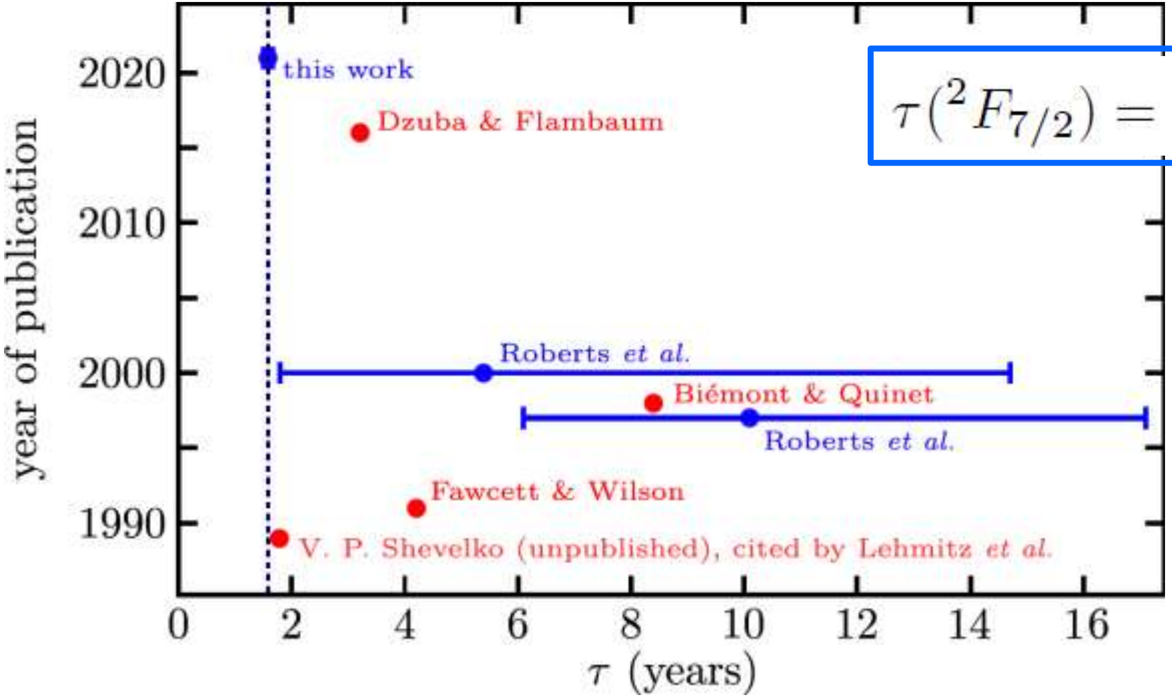
The ratio $\xi = \Omega^2/\Delta\nu_{QS}$ is independent from E_0, contains the matrix element and differential polarizability.

Experimental result: ξ=30.3(9) Hz

$\Delta\alpha$ from light shift measurements in multiple positions in the laser beam.



Radiative lifetime of the Yb^+ $F_{7/2}$ state



$$\boxed{\tau(^2F_{7/2}) = 4.98(25) \times 10^7 \text{ s}}$$

1.58(8) years

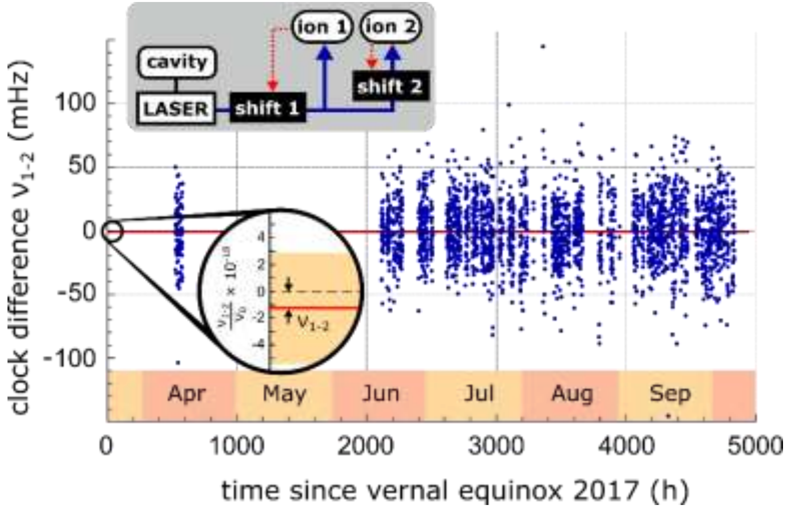
R. Lange, A. A. Peshkov, N. Huntemann, Chr. Tamm, A. Surzhykov, E. Peik,
Phys. Rev. Lett. **127**, 213001 (2021)

E3 clock comparison

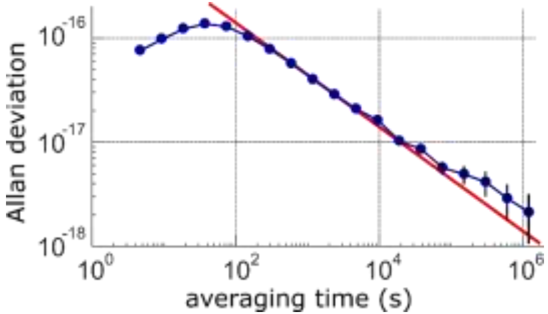
- six-month-long comparison
- two clocks on the E3 transition
- different experimental setups
- statistical uncertainty of 2.1 × 10^{-18}

Yb1

Yb2



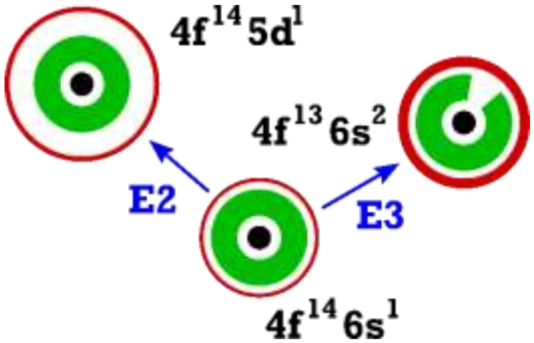
$$\nu_{1\text{-}2}/\nu_0 = 2.8\ (4.2) \times 10^{-18}$$



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

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

- ✓ E2 transition frequency is much more sensitive than E3 to field-induced systematic shifts and can be used as an in-situ sensor for perturbations of the E3 clock frequency
- ✓ E3 transition frequency has much larger relativistic contributions than E2. This can be used in fundamental tests: Constancy of the fine structure α (Local Position Invariance)



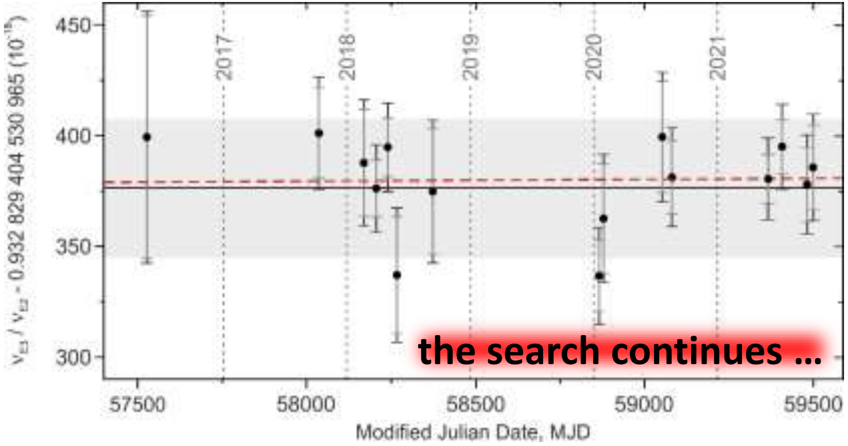
clock transitions	E2	E3
transition	electric quadrupole	electric octupole
natural linewidth	3 Hz	nHz
external perturbations quadrupole shift (in ea_0^2) 2nd order Zeeman shift (in mHz/μT^2)	sensitive 1.95(1) 52.14(3)	insensitive -0.0297(5) (÷ 68) -2.082(2) (÷ 25)
α sensitivity coefficient	0.88	-5.95

E2: Chr. Tamm *et al.*, Phys. Rev. A **89**, 023820 (2014)
E3: N. Huntemann *et al.*, Phys. Rev. Lett. **116**, 063001 (2016)
α(E2): V. A. Dzuba et al., Phys. Rev. A 68, 022506 (2003)
α(E3): V. A. Dzuba and V. V. Flambaum, Phys. Rev. A 77, 012515 (2008)

E3/E2 clock comparison + LPI

- Search for local position invariance:

> Non-gravitational experiment independent of where and <u>when</u> it is performed.



Yb1

Yb2

$$\mathcal{R} = \nu(\mathrm{Yb}^+, \mathrm{E3})/\nu(\mathrm{Yb}^+, \mathrm{E2})$$

dependence on fundamental constant α

$K = -6$ $\quad$ $K = 1$

$^2P_{1/2}$

cooling

$$\frac{\Delta\mathcal{R}}{\mathcal{R}} = -7\frac{\Delta\alpha}{\alpha}$$

$^2D_{3/2}$

$$\frac{1}{\alpha}\frac{\mathrm{d}\alpha}{\mathrm{d}t} = 1.0(1.1)\times 10^{-18}/\mathrm{yr}$$

E2

$^2F_{7/2}$

preliminary

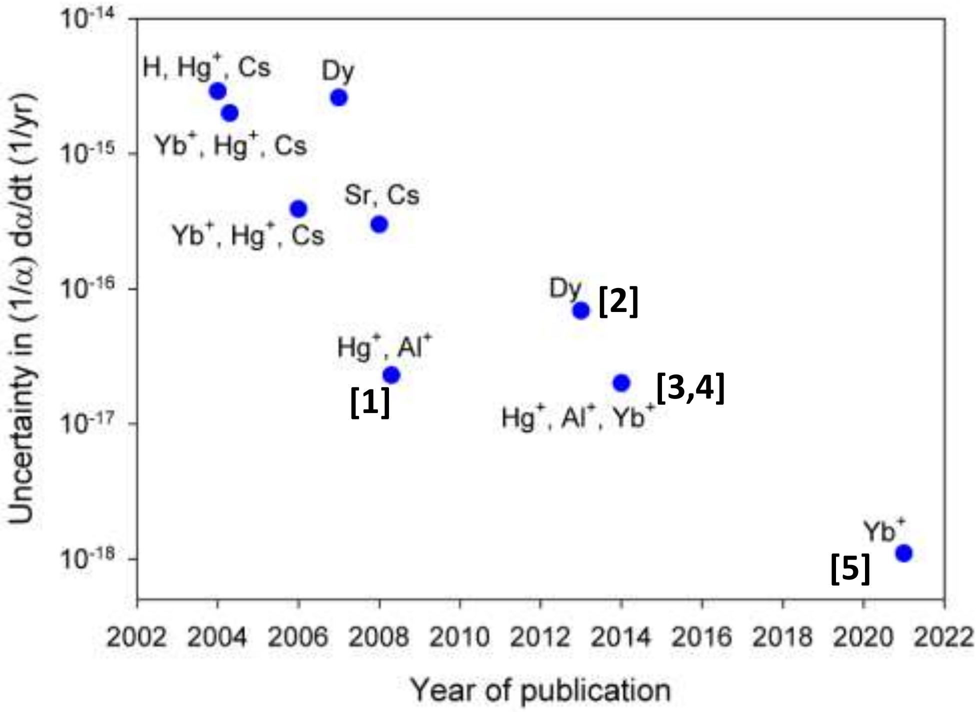
$$\frac{1}{\alpha}\frac{\mathrm{d}\alpha}{\mathrm{d}t} = 0.5(4.5)\times 10^{-19}/\mathrm{yr}$$

$^2S_{1/2}$

E3

R. Lange *et al.*, PRL **126**, 011102 (2021)
V. V. Flambaum *et al.*, Can. J. Phys. **87**, 25 (2009)

E3/E2 clock comparison + LPI



[1] T. Rosenband *et al.*, Science **319**, 1808 (2008)

[2] N. Leefer et al., PRL 111, 060801 (2013)

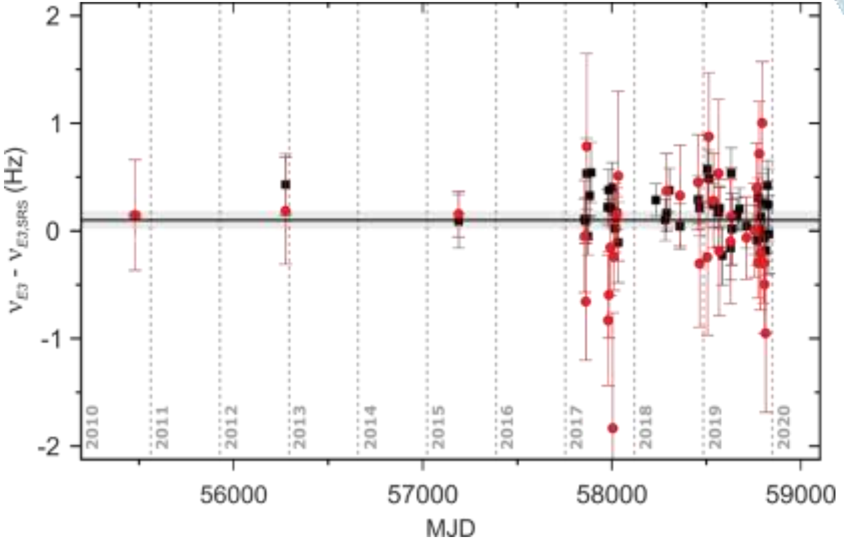
[3] R. Godun *et al.*, PRL **113**, 210801 (2014)

[4] N. Huntemann *et al.*, PRL **113**, 210802 (2014)

[5] R. Lange *et al.*, PRL **126**, 011102 (2021)

Yb$^+$(E3) vs Cs clock comparison

- repeated measurements since 2017
- Yb1(E3) and two caesium fountains



[1] R. Lange *et al.*, PRL **126**, 011102 (2021)

Yb1

CSF

$$\nu_{\mathrm{E3}} = 642\,121\,496\,772\,645.10(8)\ \mathrm{Hz}$$

$$u_{\mathrm{E3}}/\nu_{\mathrm{E3}} = 1.3 \times 10^{-16}$$

- most accurate determination of an optical transition frequency

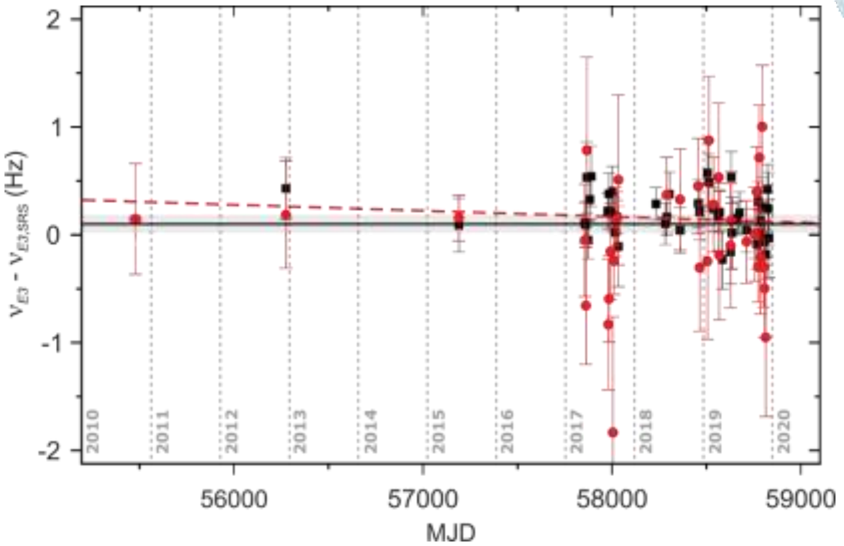
Yb$^+$(E3) vs Cs clock comparison

- repeated measurements since 2010
- Yb1(E3) and two caesium fountains
- test of LPI

Yb1

$\longleftrightarrow$

CSF



- Cs hyperfine transition sensitive to changes in
  - α $\rightarrow$ from E3/E2 ratio
  - $\boxed{\mu = m_p/m_e}$
  - X_q (strong interact. param.) $\rightarrow$ from [2], small contribution

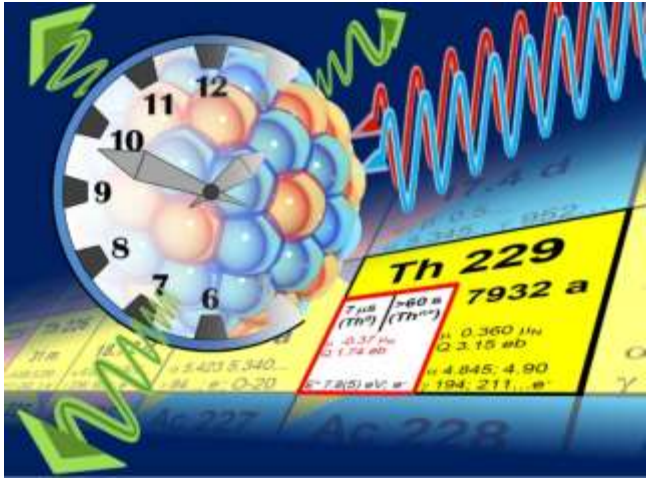
$$\boxed{\frac{1}{\mu}\frac{\mathrm{d}\mu}{\mathrm{d}t} = -8(36) \times 10^{-18}/\mathrm{yr}}$$

- ~ factor of 2 improvement [3]

[1] R. Lange *et al.*, PRL **126**, 011102 (2021)
[2] J. Guéna *et al.*, PRL **109**, 080801 (2012)
[3] R. Schwarz *et al.*, Phys. Rev. Research **2**, 033242 (2020)

Nuclear Clock:

Oscillator that is frequency-stabilized
to a nuclear (γ-ray) transition



Motivation:

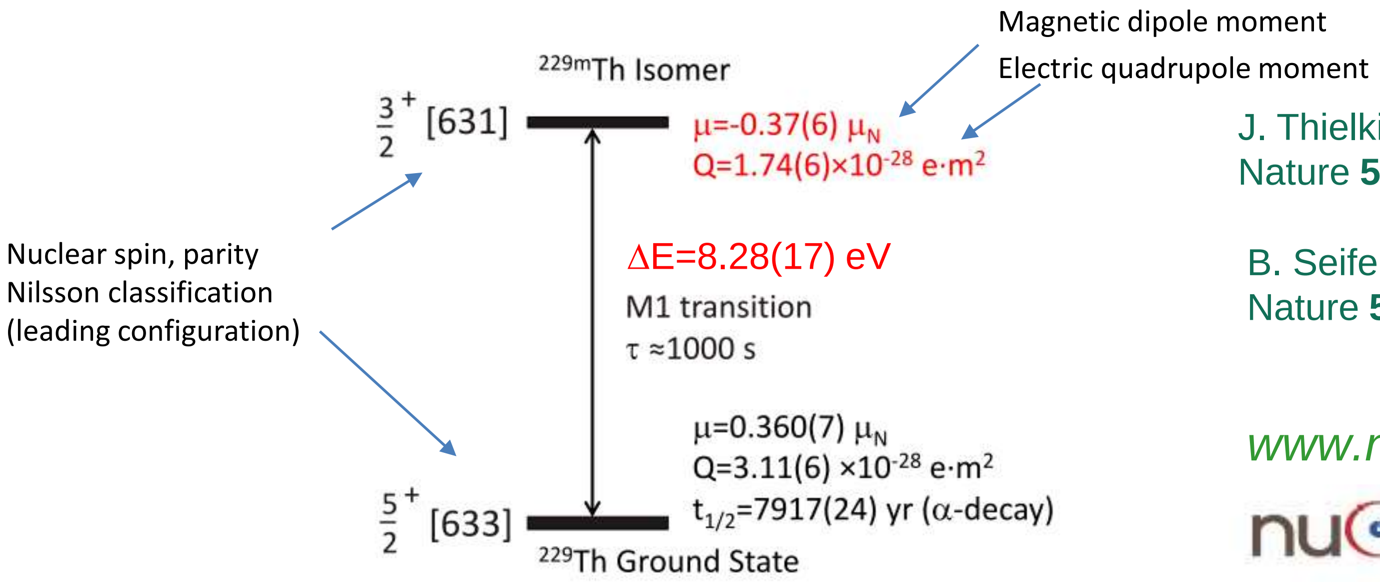
Higher precision: In many of the advanced optical clocks (trapped ion and optical lattice) field-induced shifts make a dominant contribution to the uncertainty budget. These can be reduced in a nuclear clock.

Higher stability: In a Mößbauer solid state nuclear clock, many absorbers may be interrogated ($>10^{10}$ instead of $\approx 10^0$ (ion) or $\approx 10^4$ (lattice)).

Higher frequency: $\rightarrow$ higher stability. EUV or even X-ray transitions may be used when suitable radiation sources become available.

Low-energy transition in Th-229 as a reference for a nuclear clock

accessible for laser excitation at ≈ 150 nm



J. Thielking et al. (PTB, LMU)
Nature **556**, 321 (2018)

B. Seiferle et al. (LMU)
Nature **573**, 243 (2019)

www.nuclock.eu

Advantage of the nuclear over the atomic clock: (nearly) free choice of a suitable electronic state for the interrogation of the nuclear resonance.

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

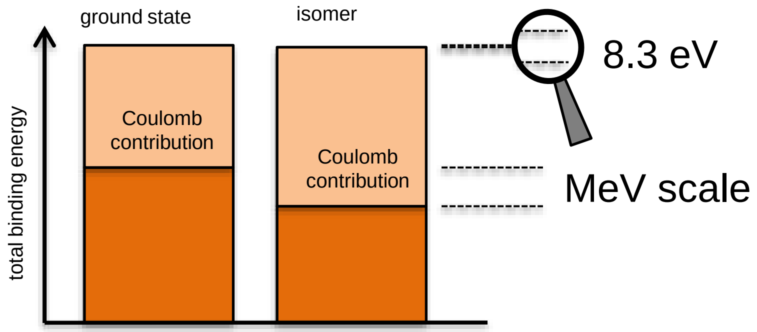
K. Beeks et al., Nat. Rev. Phys. **3**, 238 (2021)

High sensitivity of a Th-229 nuclear clock for violations of the equivalence principle

- Transition frequency is sensitive to the strong interaction (in addition to electromagnetism)

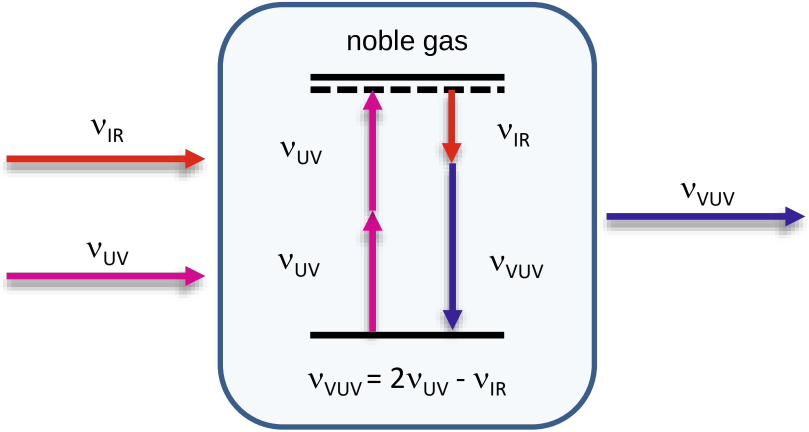
- Coulomb- and strong- contributions (MeV scale) cancel in the transition energy
  Enhanced sensitivity to variations of fundamental constants:
  V. Flambaum, Phys. Rev. Lett. 97, 092502 (2006)

- Bound system of massive particles (n, p) at high energies
  Enhanced effect of LLI violation:
  V. Flambaum, Phys. Rev. Lett. 117, 072501 (2016)



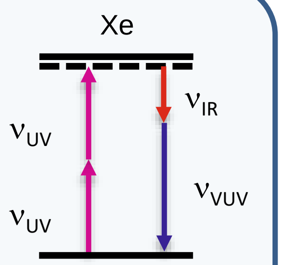
8-eV VUV generation: Four wave (difference) mixing principle

- Near-resonantly driving of 2-photon transition in noble gas.
- Inversion symmetry of free atom requires decay with two photons.
- Supplying one decay photon with ν_{IR} yields fourth photon with $\nu_{VUV} = 2\nu_{UV} - \nu_{IR}$.
- Several gases can be employed in FWM systems, e.g., Xe, Kr, Hg, …
- Two-photon transition in Xe at 2 x 250 nm is suitable for VUV tunability from 167 nm to 148 nm, i.e. 7.42 eV to 8.38 eV.

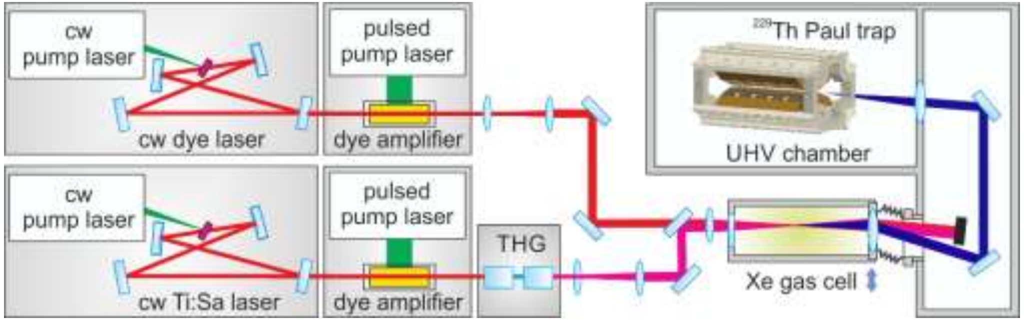


8-eV VUV generation: Four wave (difference) mixing principle

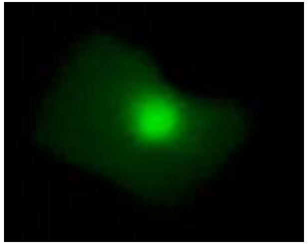
- Tuning over the range 7.9 eV to 8.3 eV requires laser beams at 250 nm and 610-759 nm.
- Third order process needs high intensity to achieve suitable efficiency.
- Pulsed lasers (~10 ns, 30 Hz repetition rate) best compromise between VUV pulse energy ($>10^{13}$ photons/pulse) and Fourier transform limited bandwidth (<1 GHz).
- Our setup:
  - Two cw ring lasers as seed: 750 nm Ti:Sa laser, 610-759 nm tunable dye laser.
  - Pulsed dye amplifiers (~60 mJ/pulse, 30 Hz repetition rate).
  - Third harmonic generation to achieve 250 nm for two-photon transition.



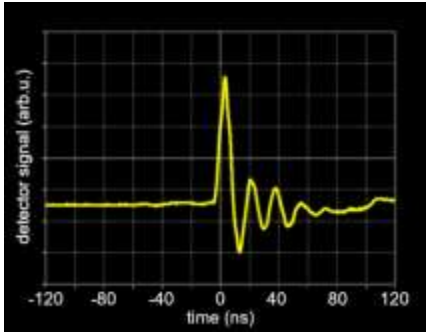
$\nu_{VUV} = 2\nu_{UV} - \nu_{IR}$



FWM laser system at PTB

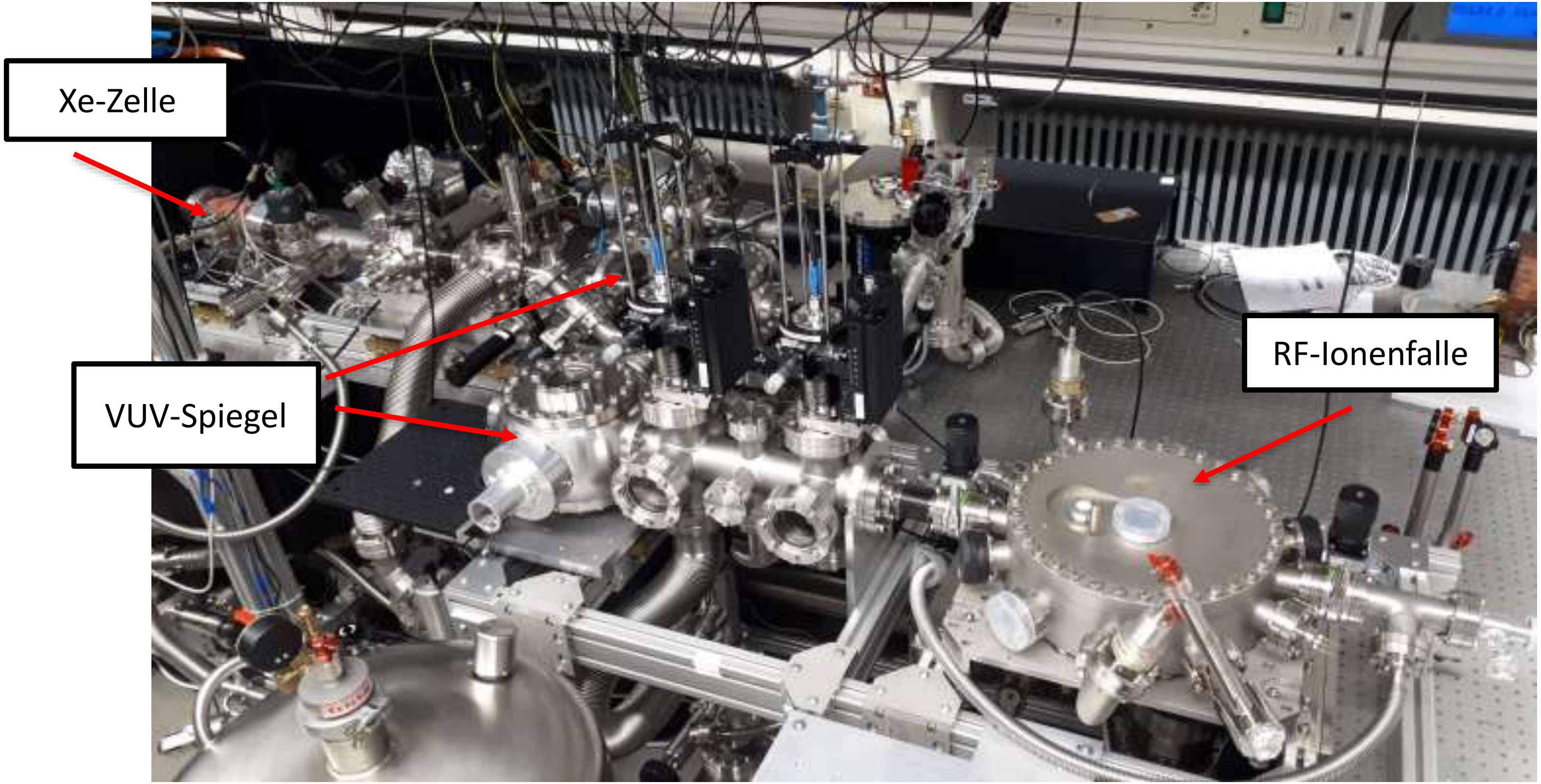


VUV beam visualization on Ce:YAG phosphor



- Relative power measurements with Cu-based photo-electron detector.
- Absolute measurements with pyro-electric power meter show $E_{pulse} > 5\ \mu J$.

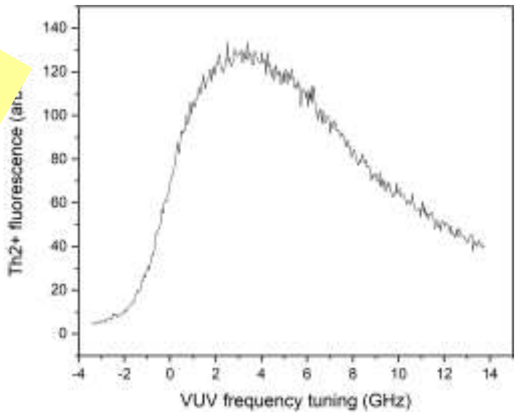
VUV Beam Line

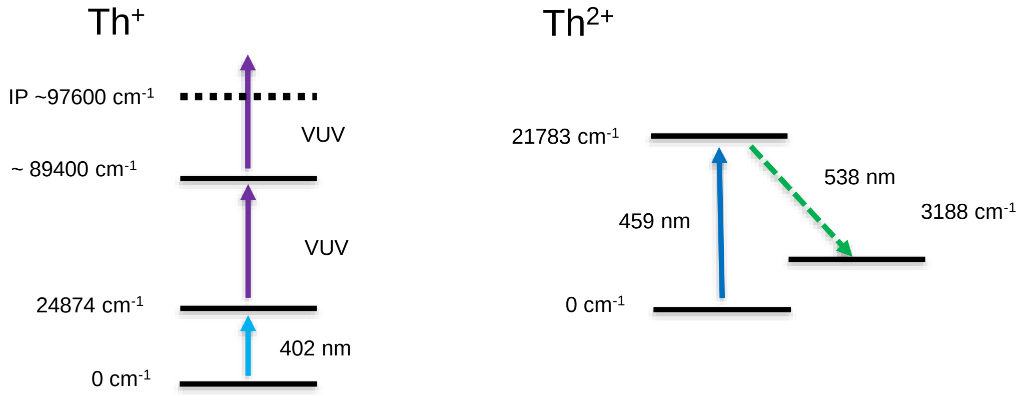


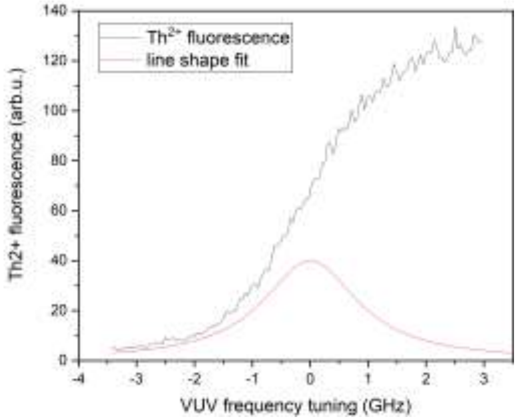
VUV laser excitation of Th^+

preliminary

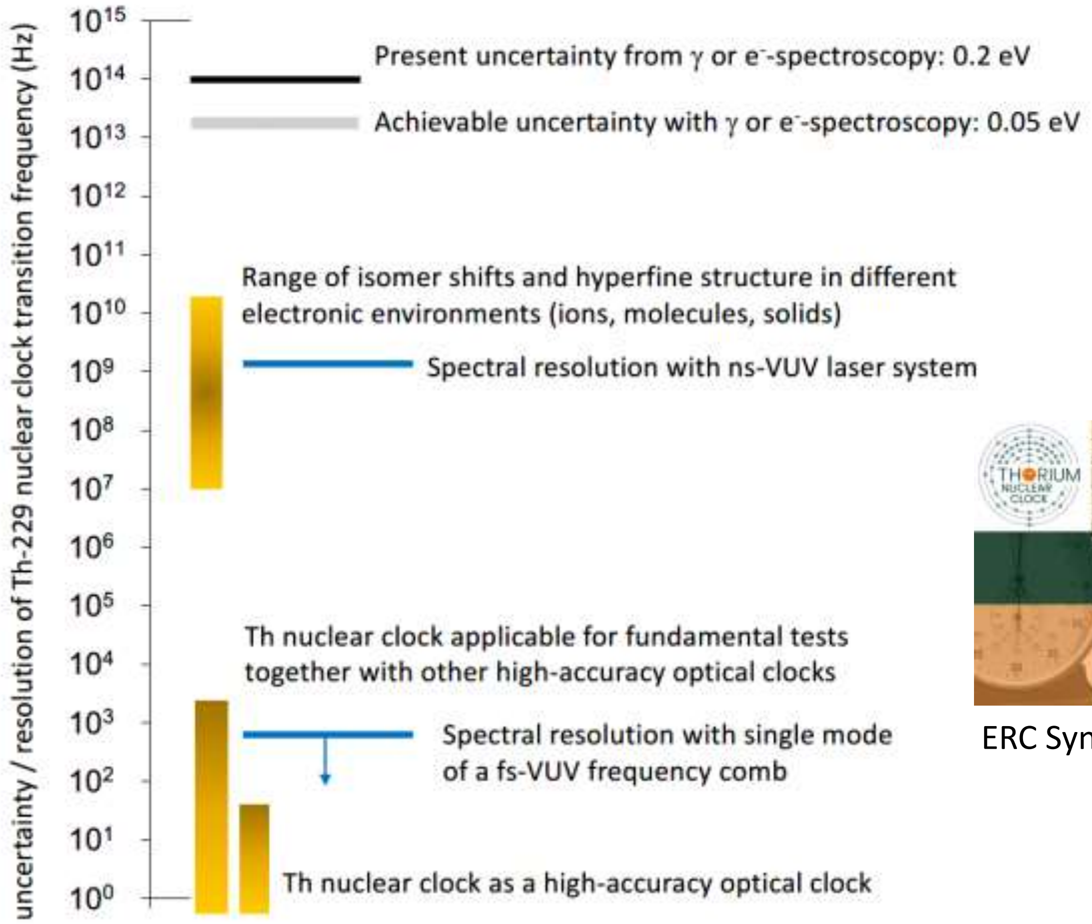
- Estimation of upper limit for the VUV linewidth based on resonance enhanced ionization of Th^+.
- First excitation step using ECDL at 402 nm, second and third step VUV to continuum.
- Background free fluorescence detection of Th^{2+} ions.
- Linewidth can be estimated from front edge of the ionization feature to be < 2 GHz.







„Roadmap“ in frequency uncertainty for the Th-229 nuclear transition



ERC Synergy Project 2020

European Research Council

PTB Working Groups: Optical Clocks with Trapped Ions / Nuclear Laser Spectroscopy

Yb^+ clocks

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M. Steinel
M. Filzinger
C. Sanner now: JILA
M. Abdel Hafiz now: U. Franche Comté
Hu Shao now: CAS
J. Zhang now: NYU

Th-229

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J. Thielking
G. Zitzer
J. Tiedau
K. Zhang
P. Glowacki now: U. Poznan
D.-M. Meier now: VW

Theory

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S. Porsev

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for Research & Innovation

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Established by the European Commission

PTB
Physikalisch-Technische Bundesanstalt
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