



Physikalisch-Technische Bundesanstalt  
Braunschweig and Berlin  
National Metrology Institute

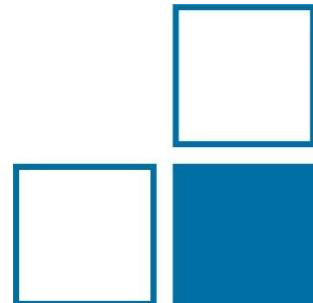
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## Symmetry Tests with Atomic Clocks

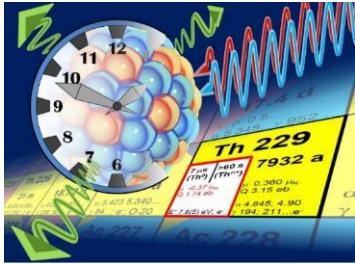
**Ekkehard Peik**

Time and Frequency Department

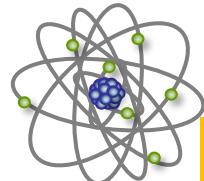
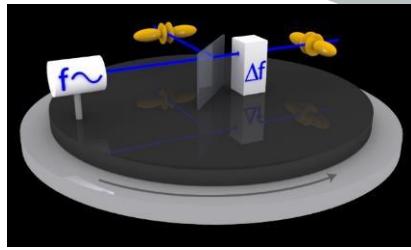
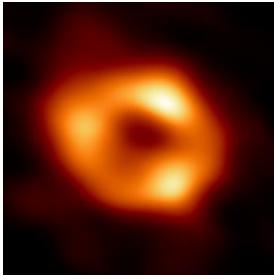
PTB, Braunschweig, Germany



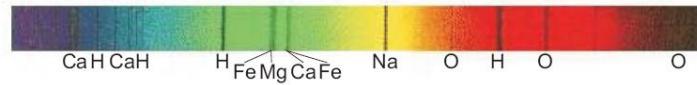
# Atomic clocks and fundamental physics



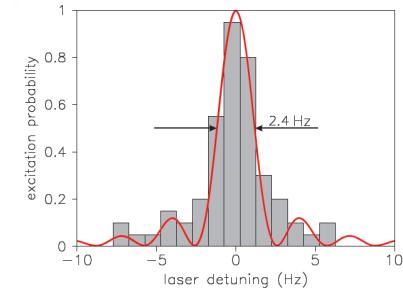
Tests of quantum theory and relativity



Atomic and nuclear structure,  
Quantum theory



Spectroscopy

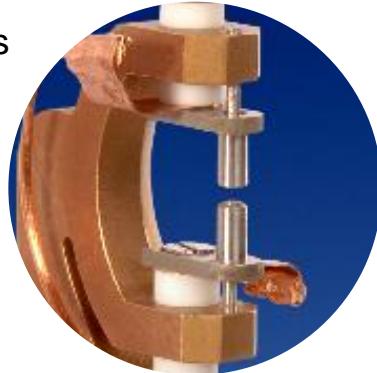


Clocks and Frequency Standards

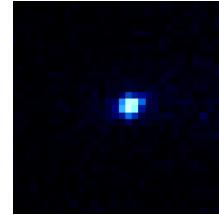


## Optical clock with a single laser-cooled ion in a Paul trap

The ion trap provides long interaction and coherence times

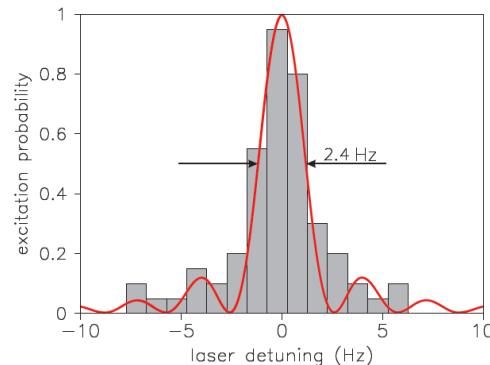


Combined with laser cooling:  
Lamb-Dicke confinement of a single ion

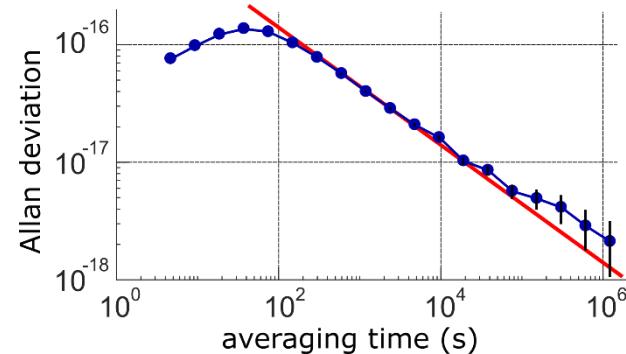


Hans Dehmelt

high spectral resolution,  
excellent control of systematic shifts



quantum noise limited stability



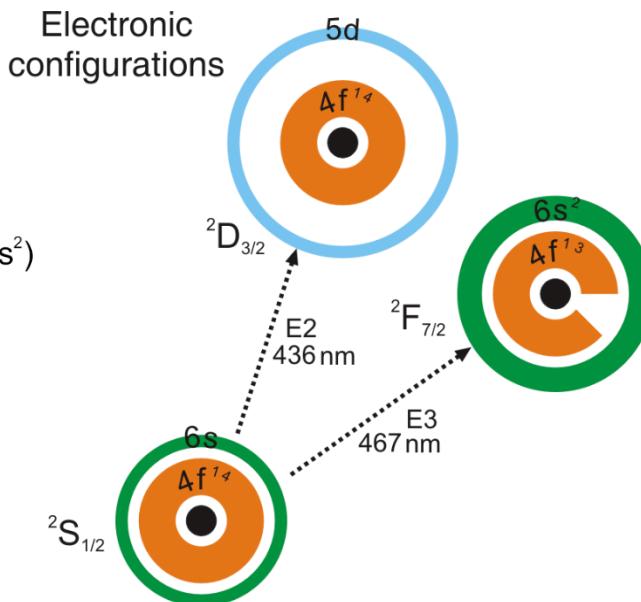
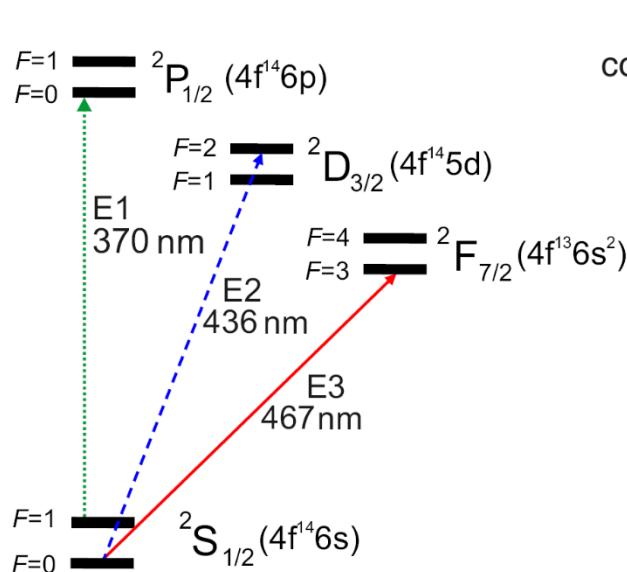
Motivation:

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

# $^{171}\text{Yb}^+$ : for clocks, fundamental tests and QIP

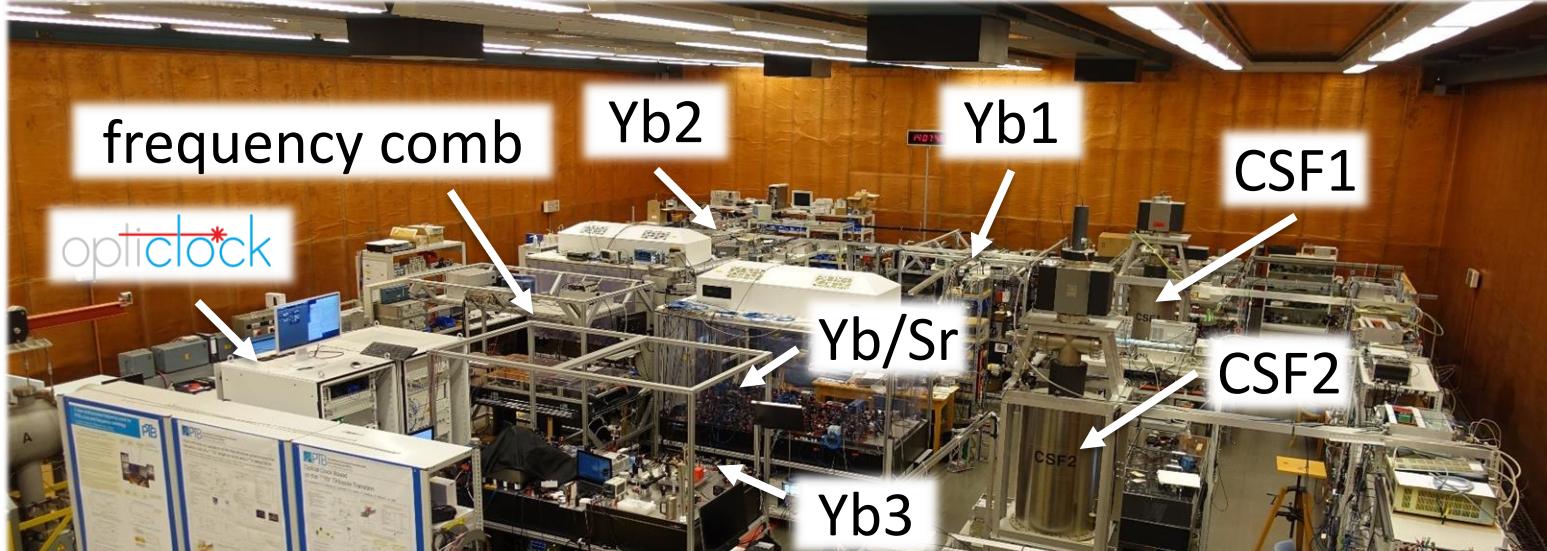
Advantages of  $^{171}\text{Yb}^+$ :

- nuclear spin  $\frac{1}{2}$ : non-degenerate ( $F=0, m=0$ ) ground state
- two different optical clock transitions, two microwave transitions



- Quadrupole Transition (E2): S-D
- natural linewidth: 3 Hz
  - syst. uncertainty  $\approx 3 \times 10^{-17}$  (PTB)
  - Sensitivity to the value of the fine structure constant  
 $K = (\alpha/f) df/d\alpha \approx 1$

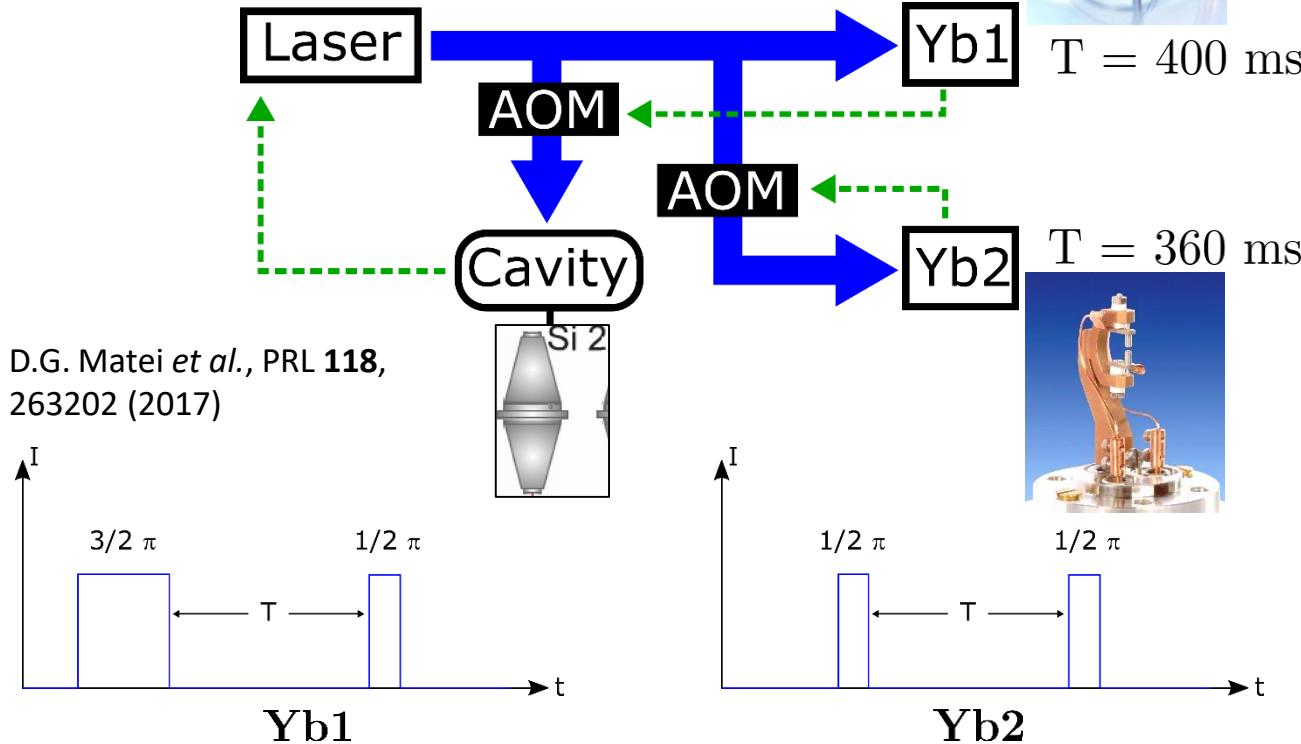
- Octupole Transition (E3): S-F
- natural linewidth: 3 nHz
  - syst. uncertainty  $\approx 2 \times 10^{-18}$  (PTB)
  - $K = (\alpha/f) df/d\alpha \approx -6$



### Outline of the talk:

- Atomic optical clock with trapped  $^{171}\text{Yb}^+$
- Search for „new physics“: Violations of Local Lorentz invariance, variations of fundamental constants, ultralight bosonic dark matter
- Options with a nuclear optical clock with  $^{229}\text{Th}^{3+}$

## Comparison of two Yb<sup>+</sup> E3 clocks

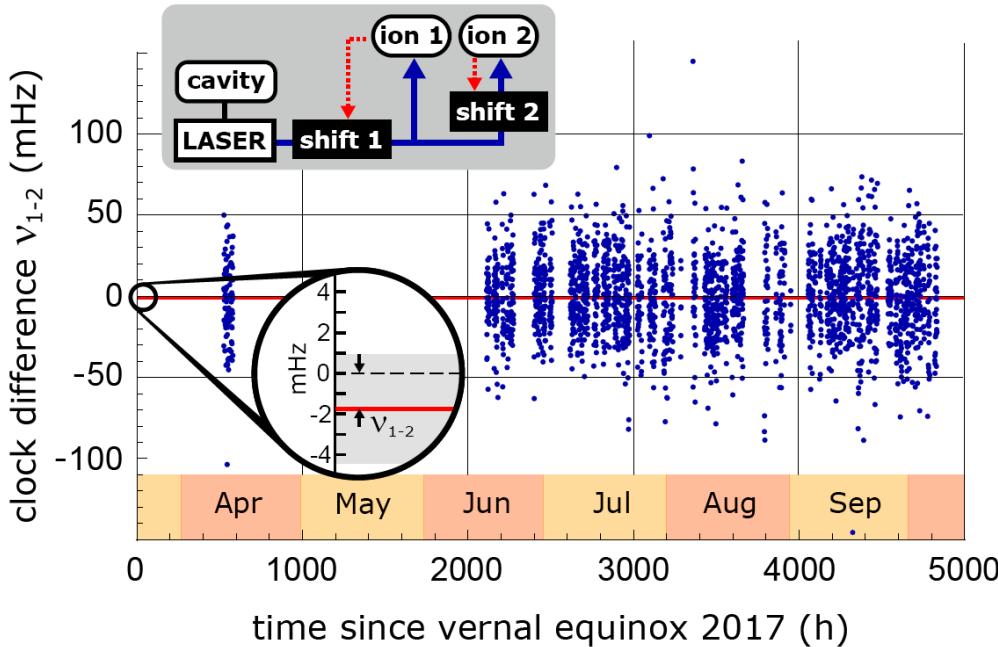


Controlled Hyper-Ramsey spectroscopy  
N. Huntemann *et al.*, PRL **116**, 063001 (2016)

Frequency-shifted Ramsey spectroscopy  
A. V. Taichenachev *et al.*, JETP Lett. **90**, 713 (2010)

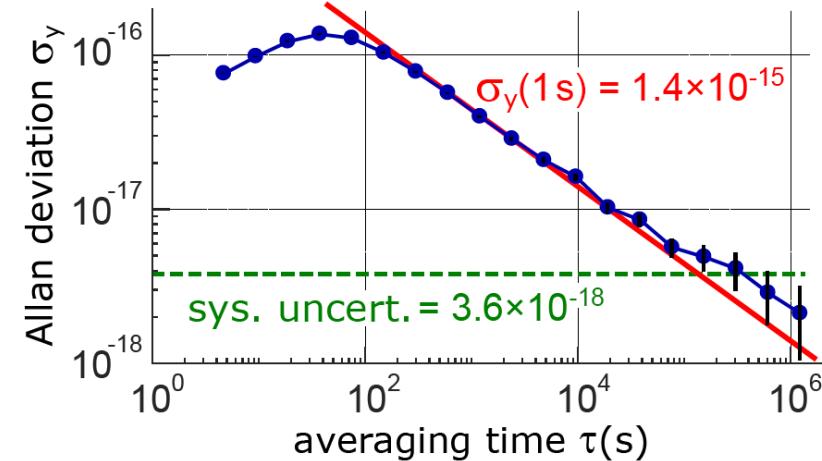
## Comparison of two Yb<sup>+</sup> E3 clocks

A



Total measurement time =  $3.9 \times 10^6$  s during 6 months

Relative frequency difference:  $(f(\text{Yb1})/f(\text{Yb2}) - 1)$ :  $2.8 \times 10^{-18}$   
Uncertainty  $u_a$ :  $2.1 \times 10^{-18}$  (statistical)  
 $u_b$ :  $3.6 \times 10^{-18}$  (systematic)

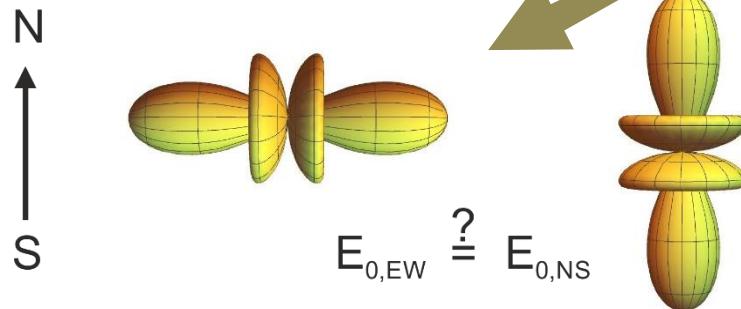


Instability:  
Dominated by single-ion  
quantum projection noise

## Test of local Lorentz invariance

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

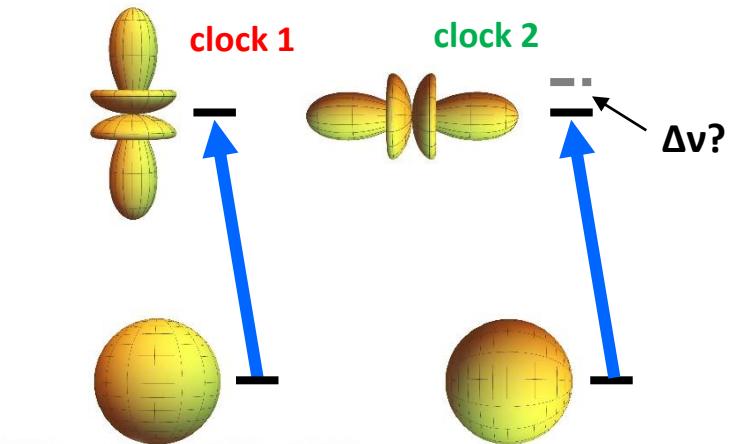
Is the electron's dispersion  
relation isotropic in space?



There is a large variety of electron containers...

$^{171}\text{Yb}^+, 4f^{13}6s^2, ^2\text{F}_{7/2}, F = 3, m_F = 0$

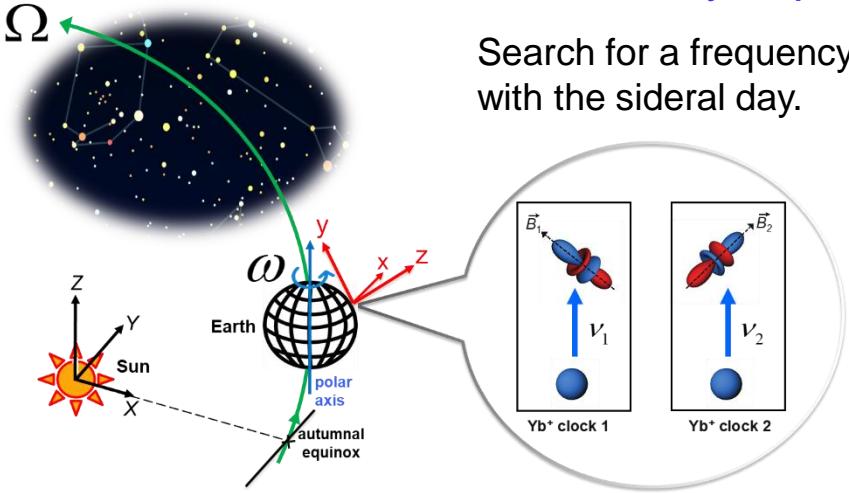
Measure the energy relative  
to an isotropic state.



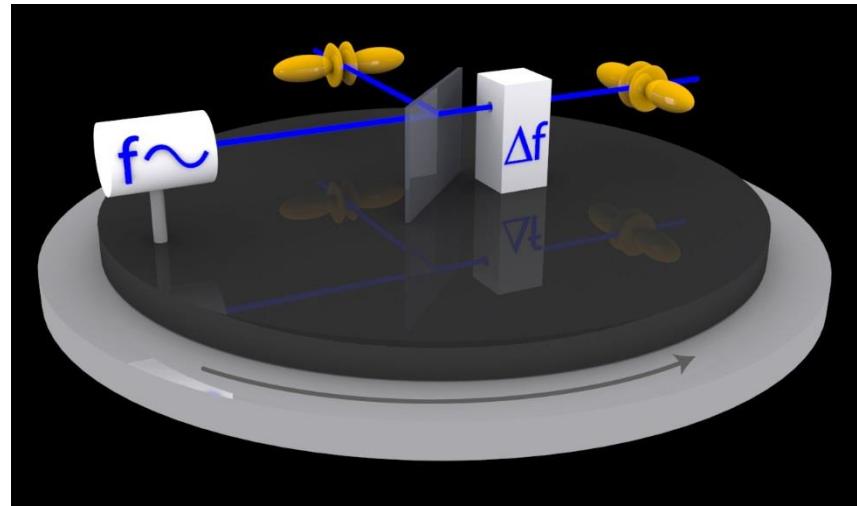
$^{171}\text{Yb}^+, 4f^{14}6s^1, ^2\text{S}_{1/2}, F = 3, m_F = 0$

Lorentz violation → frequency offset

## Michelson Morley experiment with electrons



Search for a frequency dependence  
with the sideral day.

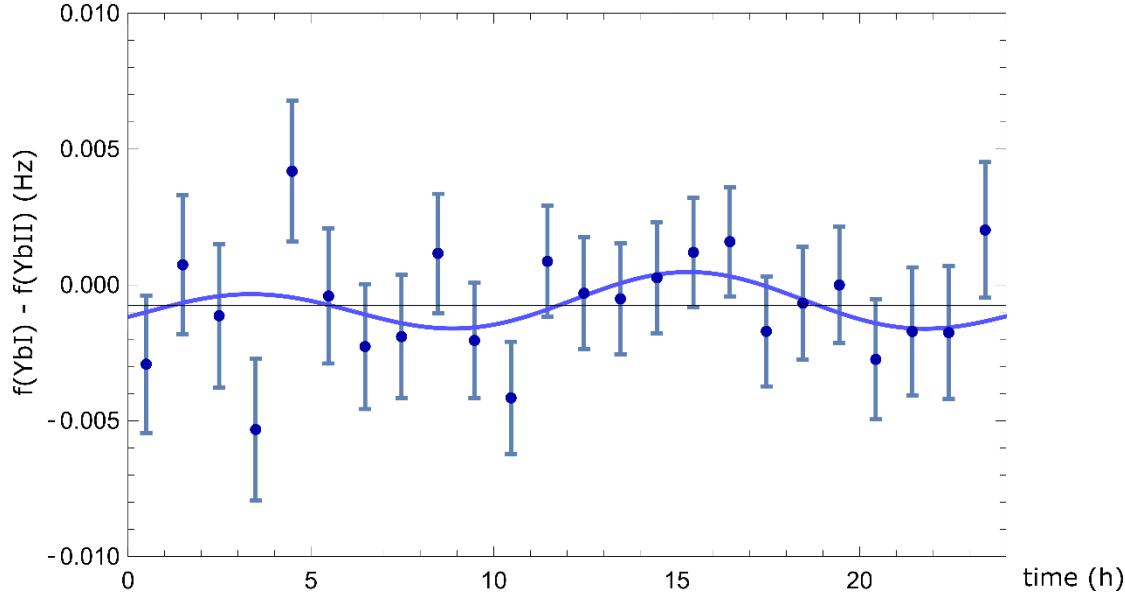


Berkeley: entangled Ca<sup>+</sup> ions, D<sub>5/2</sub> state

T. Pruttivarasin et al., Nature **517**, 592 (2015), E. Megidish et al., Phys. Rev. Lett. **122**, 123605 (2019)

Proposal for Yb<sup>+</sup> F-state: V. A. Dzuba et al., Nature Phys. **12**, 465 (2016)

## Comparison of two Yb<sup>+</sup> clocks as a test of Lorentz symmetry



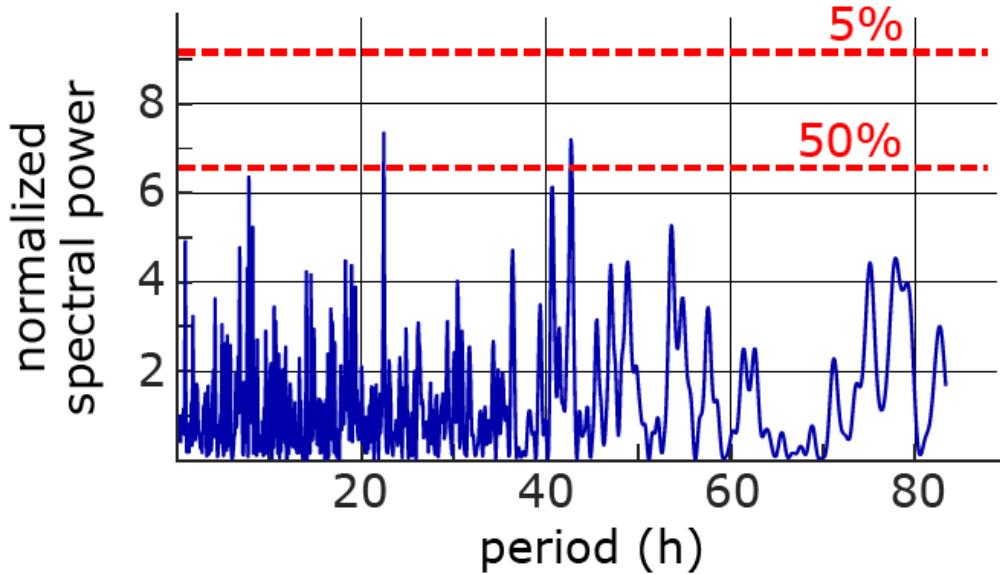
$$\nu_{\text{clock1}} - \nu_{\text{clock2}} = c_1 \sin(\omega t) + c_2 \cos(\omega t) + c_3 \sin(2\omega t) + c_4 \cos(2\omega t) + \Delta\nu_{c-c}$$

$$\omega = 2\pi/23.94 \text{ h}$$

$$c_1 = (-0.4 \pm 0.5) \text{ mHz} \quad c_3 = (-0.1 \pm 0.4) \text{ mHz}$$

$$c_2 = (-0.3 \pm 0.3) \text{ mHz} \quad c_4 = (0.8 \pm 0.4) \text{ mHz}$$

## 100-fold improved limits on violations of Local Lorentz Invariance for electrons



Lomb periodogram

Probability of finding  $\geq 1$  peak  
in a white-noise data set

→ No significant periodic signal

## Comparison of two Yb<sup>+</sup> clocks as a test of Lorentz symmetry

Absence of sidereal modulation allows us to improve limits on LV within the Standard Model Extension by 2 orders of magnitude

Correlated LV parameters	New limits	Ca <sup>+</sup> limits <sup>10</sup>	Dy limits <sup>9</sup>	Astrophysical limits <sup>8</sup>
$c_{X-Y}$	$(-0.5 \pm 1.7) \times 10^{-20}$	$(-0.2 \pm 2.3) \times 10^{-18}$	$(2.9 \pm 5.7) \times 10^{-17}$	$(3.3 \pm 6.2) \times 10^{-15}$
$c_{XY}$	$(-7.0 \pm 8.1) \times 10^{-21}$	$(-0.8 \pm 1.2) \times 10^{-18}$	$(0.7 \pm 3.6) \times 10^{-17}$	$(0.0 \pm 3.0) \times 10^{-15}$
$c_{XZ}$	$(0.8 \pm 1.3) \times 10^{-20}$	$(-3.4 \pm 7.9) \times 10^{-19}$	$(0.9 \pm 1.1) \times 10^{-16}$	$(0.0 \pm 3.0) \times 10^{-15}$
$c_{YZ}$	$(1.0 \pm 1.3) \times 10^{-20}$	$(-1.7 \pm 7.1) \times 10^{-19}$	$(3.1 \pm 6.6) \times 10^{-17}$	$(-0.4 \pm 2.2) \times 10^{-15}$
$c_{TX}$	$(-0.4 \pm 8.5) \times 10^{-17}$		$(5.7 \pm 8.3) \times 10^{-15}$	$(-1.5 \pm 5.5) \times 10^{-15}$
$c_{TY}$	$(4.4 \pm 8.7) \times 10^{-17}$		$(-8.3 \pm 7.5) \times 10^{-13}$	$(0.5 \pm 1.0) \times 10^{-15}$
$c_{TZ}$	$(-1.2 \pm 1.6) \times 10^{-16}$		$(1.9 \pm 1.7) \times 10^{-12}$	$(-1.0 \pm 3.0) \times 10^{-17}$

Previous experiments:

Ca<sup>+</sup>: T. Pruttivarasin et al., Nature 517, 592 (2015)

Dy: M. A. Hohensee et al., Phys. Rev. Lett. 111, 050401 (2013)

This work:

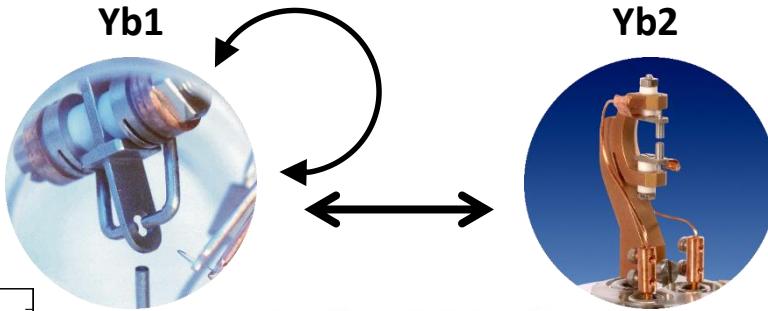
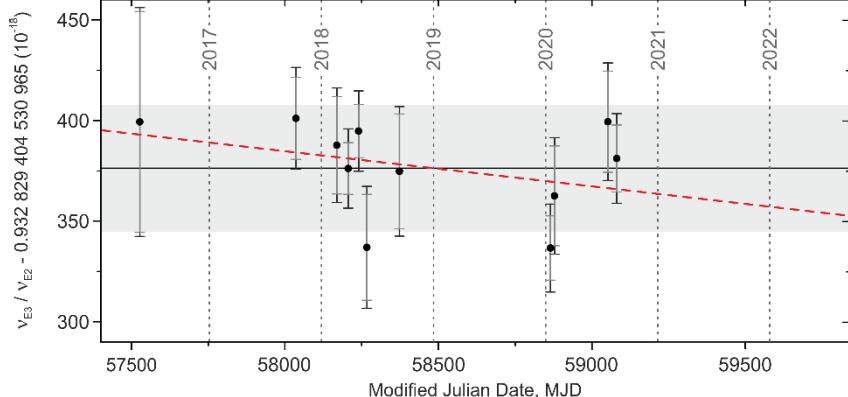
C. Sanner et al., Nature 567, 204 (2019)

Recent experiment with a single Yb<sup>+</sup> (improvement factor 1.4 to 2.2 on the four xy parameters):  
L. Dreissen et al. (PTB-QUEST), arXiv 2206.00570

# E3/E2 clock comparison

- Search for a violation of LPI:

Non-gravitational experiment  
independent of where and when  
it is performed.



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

dependence on fundamental constant  $\alpha$

$$K = -6$$

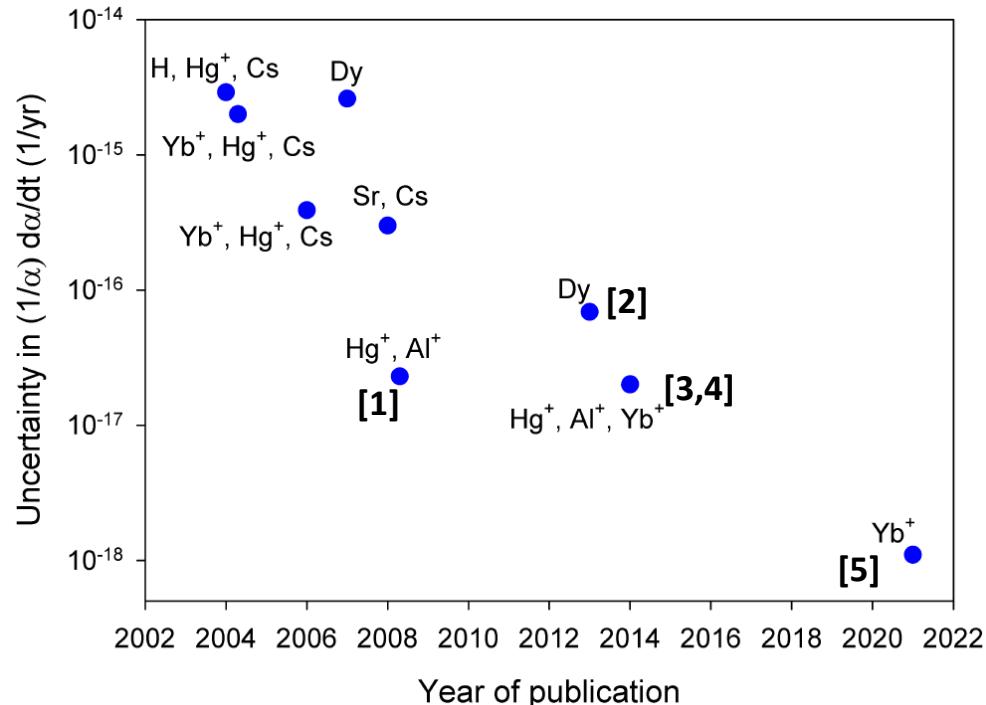
$$K = 1$$

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

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

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

V. V. Flambaum *et al.*, Can. J. Phys. **87**, 25 (2009)



[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)

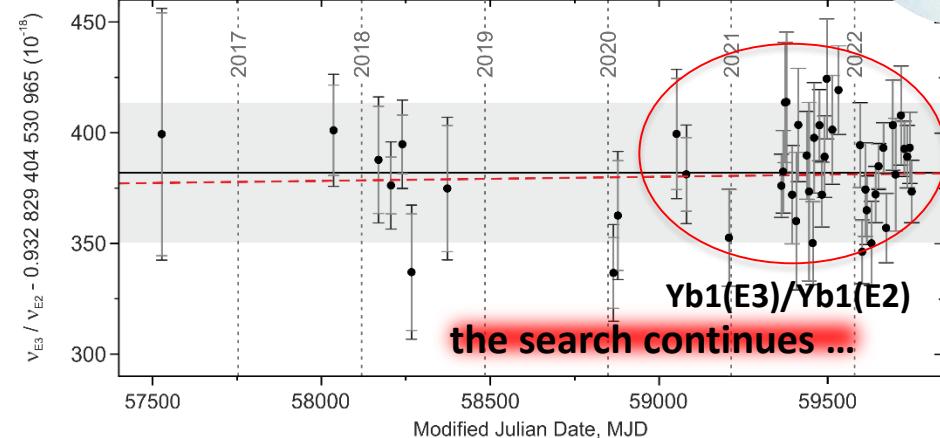
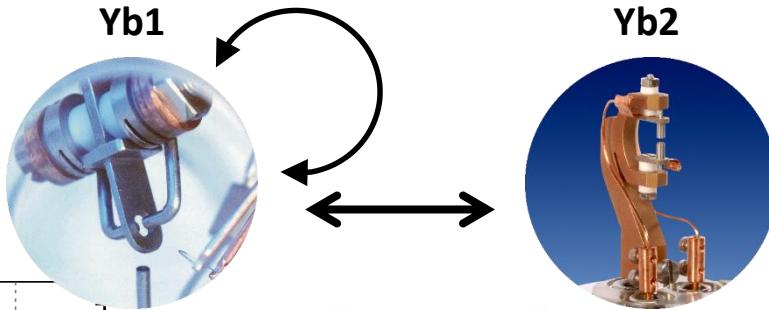
[4] N. Huntemann *et al.*, PRL **113**, 210802 (2014)

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

# E3/E2 clock comparison

- Search for a violation of LPI:

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

dependence on fundamental constant  $\alpha$

$$K = -6$$

$$K = 1$$

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

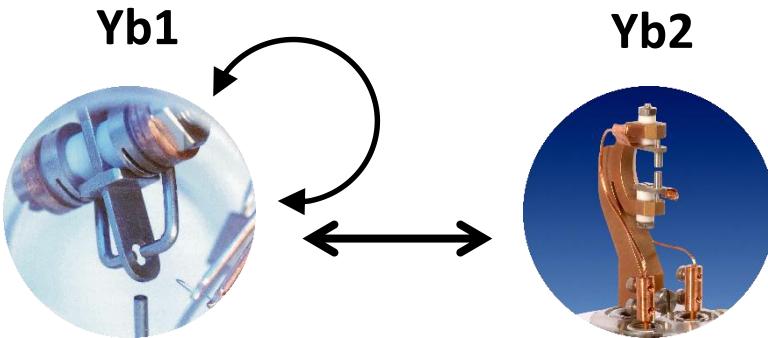
$$\frac{1}{\alpha} \frac{d\alpha}{dt} = 1.0(1.1) \times 10^{-18} / \text{yr}$$

*preliminary*

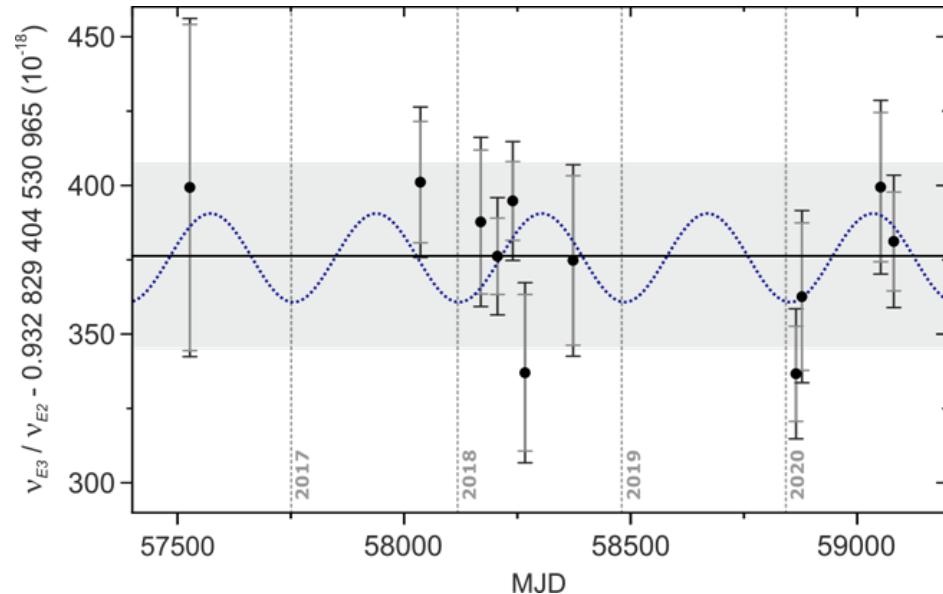
$$\frac{1}{\alpha} \frac{d\alpha}{dt} = 1.1(3.0) \times 10^{-19} / \text{yr}$$

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

V. V. Flambaum *et al.*, Can. J. Phys. **87**, 25 (2009)



- oscillations of the ratio due to the annual variation of the Sun's gravitational potential on Earth?
- improves previous limits by one order of magnitude [2]



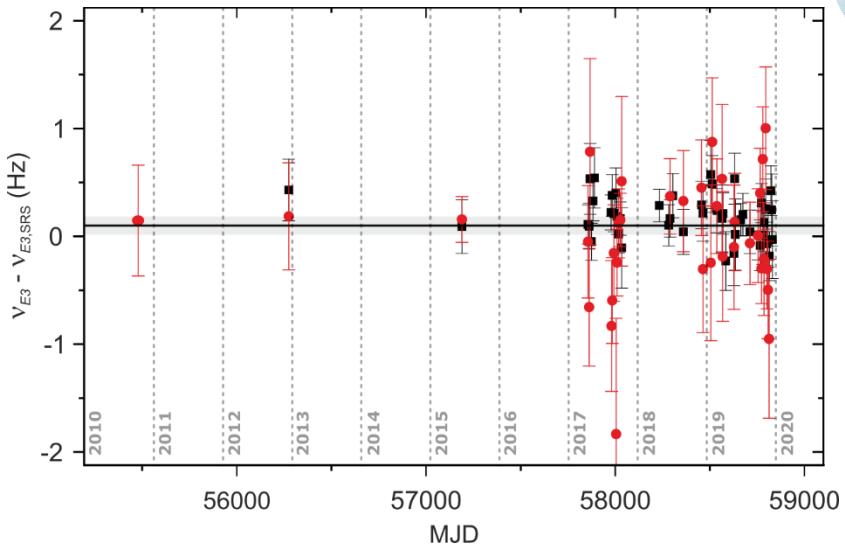
[1] R. Lange *et al.*, PRL **126**, 011102 (2021)

[2] V. A. Dzuba *et al.*, Phys. Rev. D **95**, 015019 (2017)

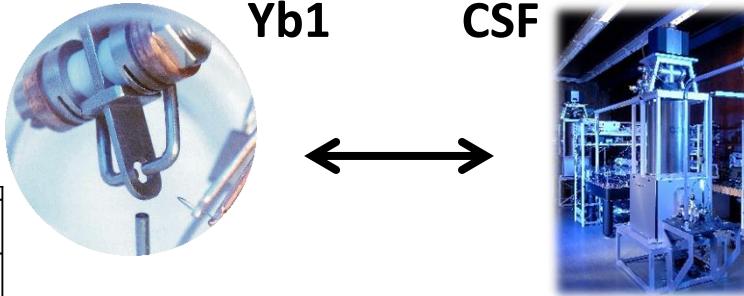
$$\frac{1}{\alpha} \frac{d\alpha}{d\Phi} = 14(11) \times 10^{-9} / c^2$$

# $\text{Yb}^+(\text{E3})$ vs Cs clock comparison

- repeated measurements since 2017
- $\text{Yb1(E3)}$  and two caesium fountains



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



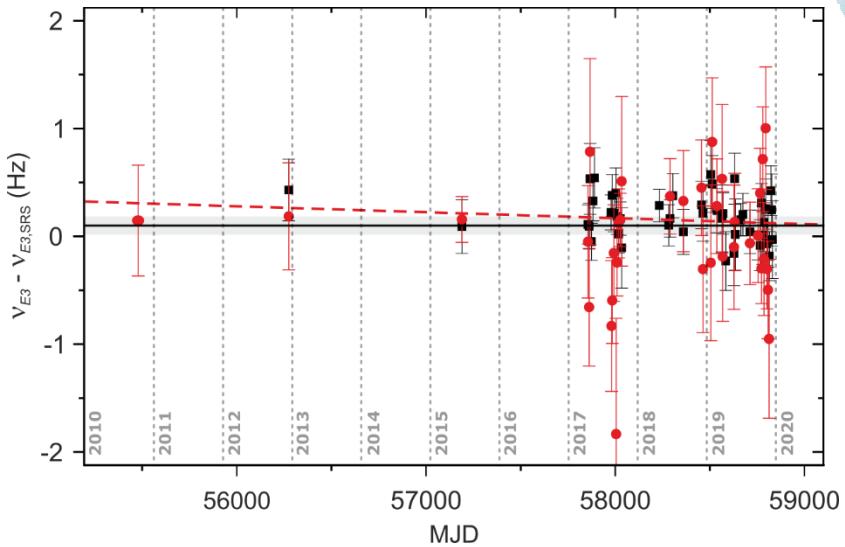
$$\nu_{\text{E3}} = 642\,121\,496\,772\,645.10(8) \text{ Hz}$$

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

- most accurate determination of an optical transition frequency

# Yb<sup>+</sup>(E3) vs Cs clock comparison

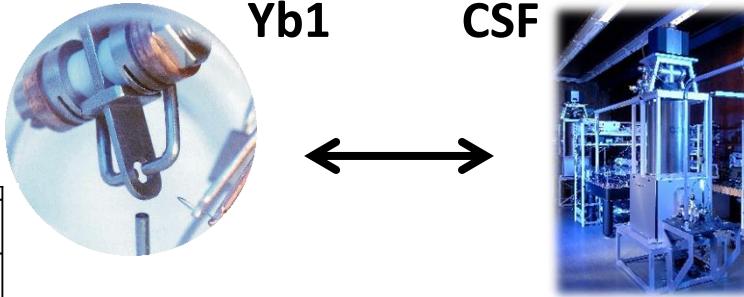
- repeated measurements since 2010
- Yb1(E3) and two caesium fountains
- test of LPI: Variations of  $m_p/m_e$



[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)



- Cs hyperfine transition sensitive to changes in

$\alpha$  → from E3/E2 ratio

$$\mu = m_p/m_e$$

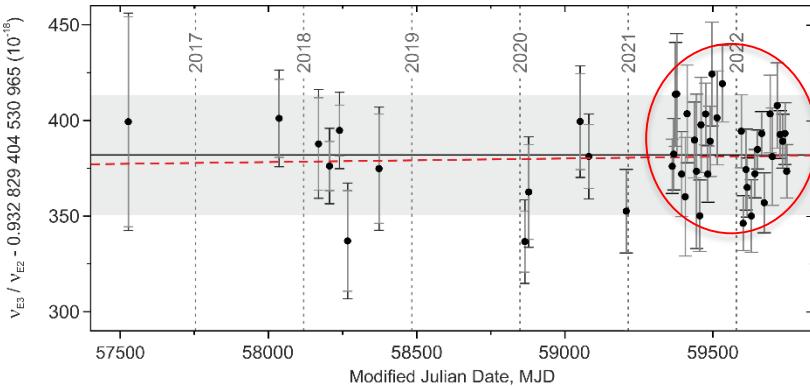
$X_q$  (strong interact. param.)

→ from [2], small contribution

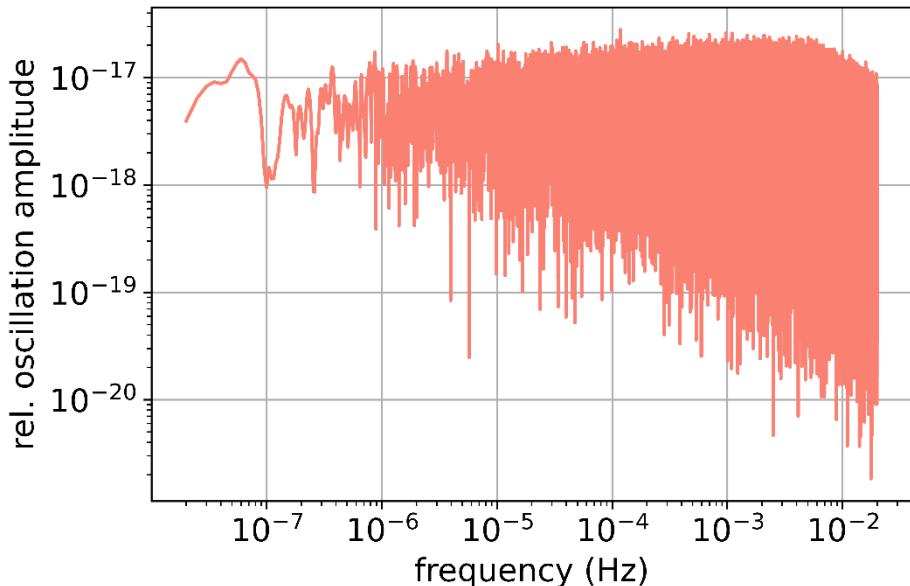
$$\frac{1}{\mu} \frac{d\mu}{dt} = -8(36) \times 10^{-18} / \text{yr}$$

- ~ factor of 2 improvement [3]

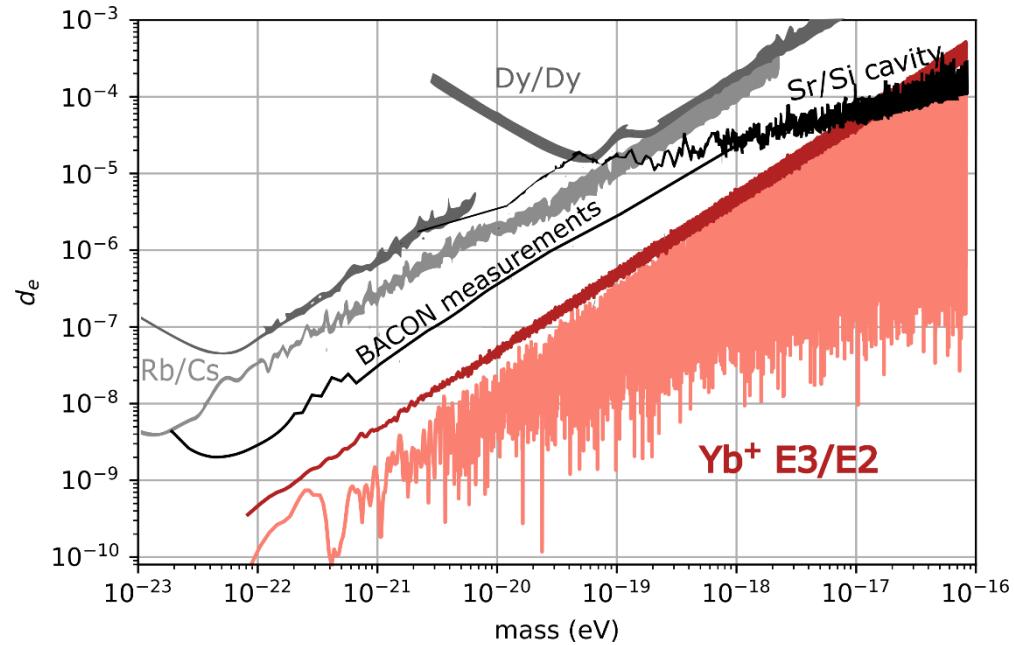
- Investigation using data from the last 1.3 years
- No indications for significant deviations from white frequency noise
- Motivates a search for ultra-light bosonic dark matter [1]



Lomb-Scargle periodogram

[1] A. Arvanitaki *et al.*, PRD 91, 015015 (2015)

- Ultralight bosonic dark matter expected to locally behave like a classical field with a frequency given by the Compton frequency [1]
- A coupling  $d_e$  of such a dark matter field to  $\alpha$  would lead to coherent oscillations  $\alpha$



[Dy/Dy] K. Van Tilburg et al., PRL 115, 011802 (2015)

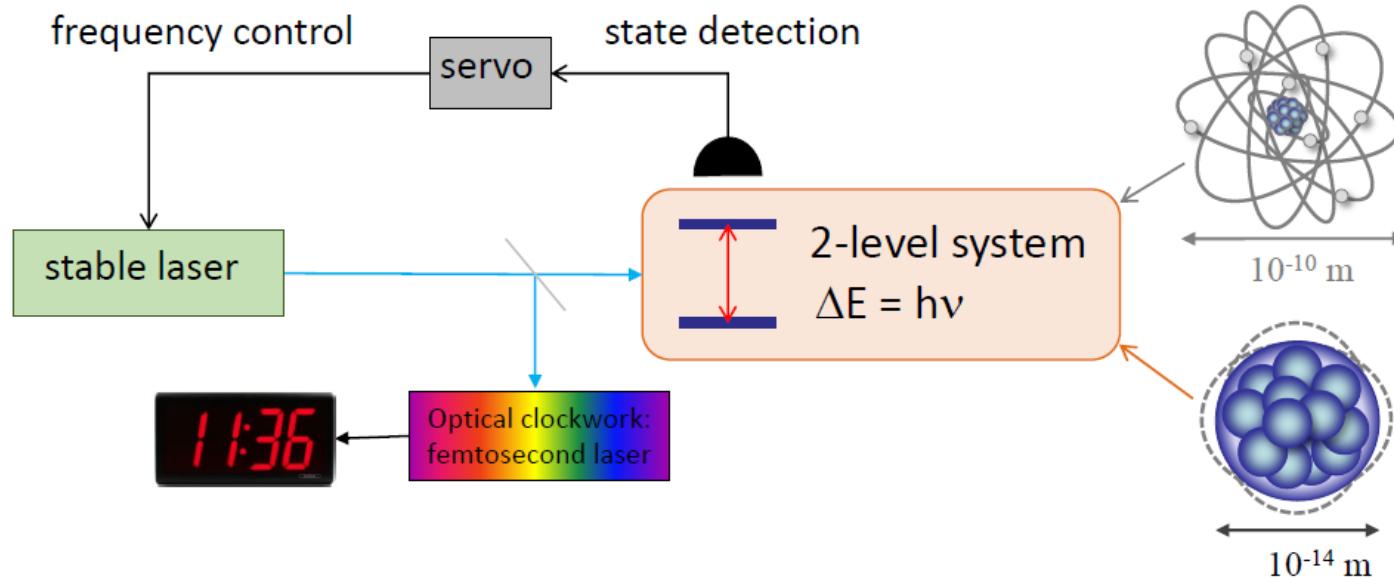
[Rb/Cs] A. Hees et al., PRL 117, 061301 (2016)

[Sr/Si cav] C. J. Kennedy et al., PRL 125, 201302 (2020)

BACON collab., Nature 564, 564 (2021)

[1] A. Arvanitaki et al., PRD 91, 015015 (2015)

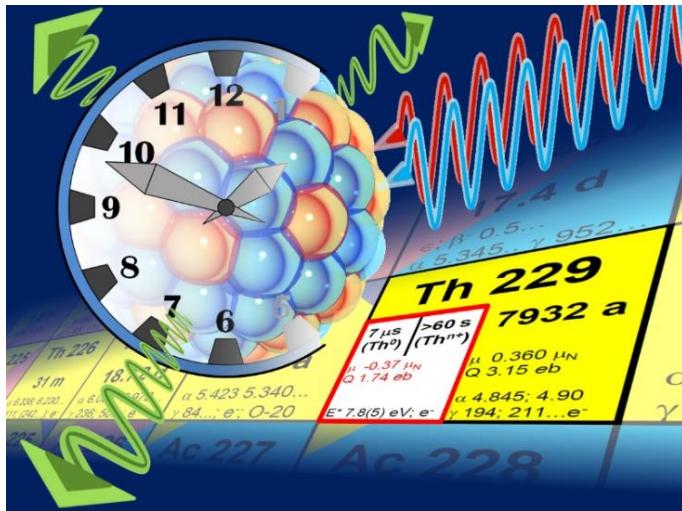
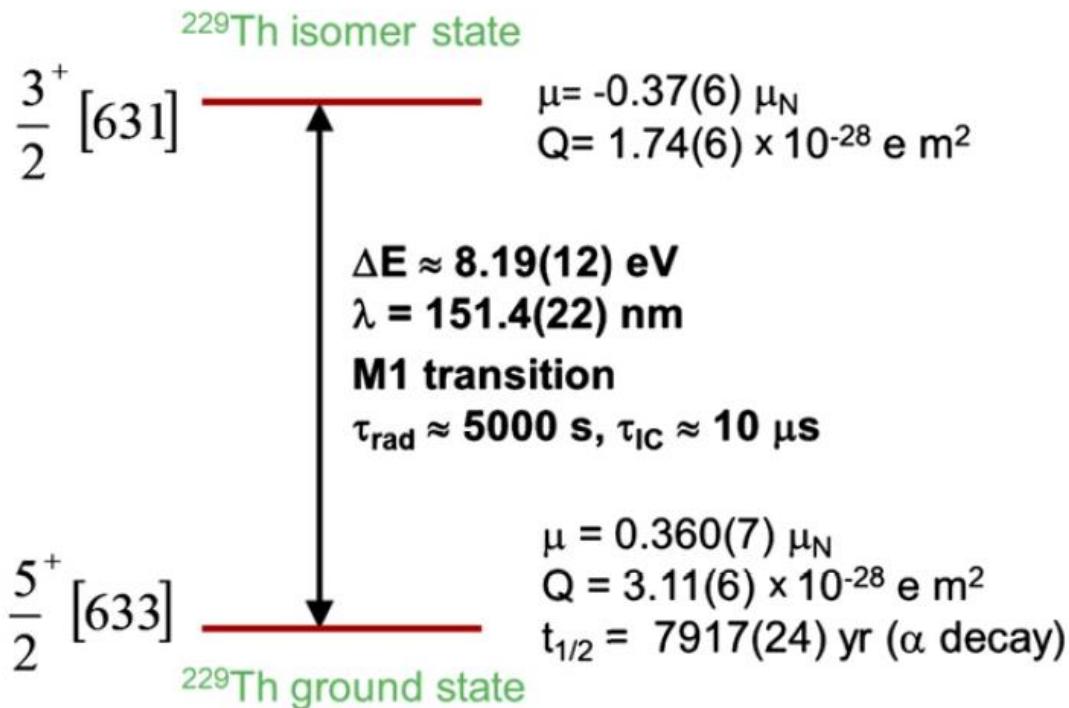
# From the atomic to the nuclear clock



The nuclear clock promises:

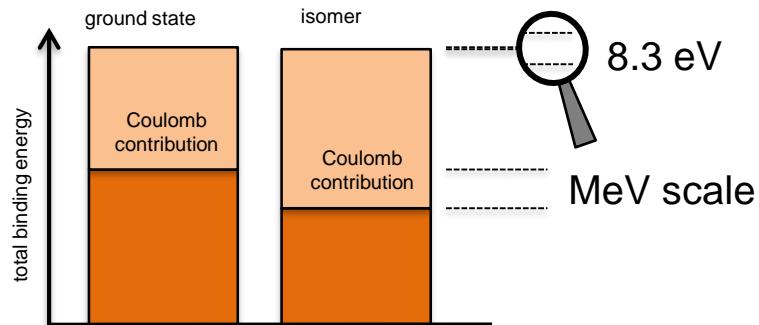
- High accuracy (with laser cooled trapped ions)
- High stability (solid state reference like Th:CaF<sub>2</sub>)
- High sensitivity to new physics

# The Th-229 low-energy isomer



## 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)



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

## Yb<sup>+</sup> clocks

N. Huntemann  
R. Lange  
B. Lipphardt  
Chr. Tamm  
M. Steinel  
M. Filzinger  
C. Sanner  
M. Abdel Hafiz  
Hu Shao  
J. Zhang

now: JILA  
now: U. Franche Comté  
now: CAS  
now: NYU

## Th-229

M. Okhapkin  
J. Thielking  
G. Zitzer  
J. Tiedau  
Ke Zhang  
P. Glowacki  
D.-M. Meier

now: U. Poznan  
now: VW

## Theory

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M. Kozlov  
S. Porsev  
  
A. Surzhykov (PTB, TUBS)  
R.A. Müller  
S.A.-L. Schulz  
A.A. Peshkov  
Y.M. Bidasyuk

Postdoc position available  
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Horizon 2020  
European Union funding  
for Research & Innovation



European Research Council  
Established by the European Commission