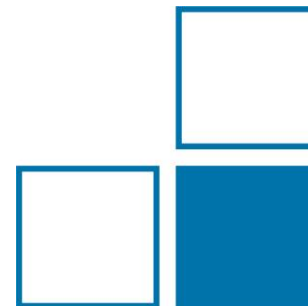
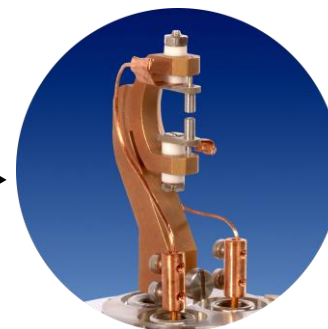
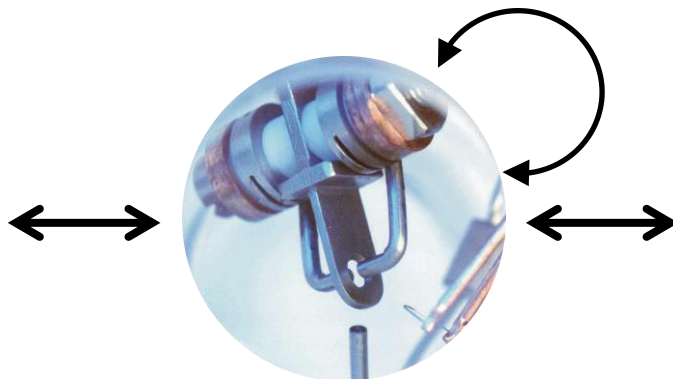
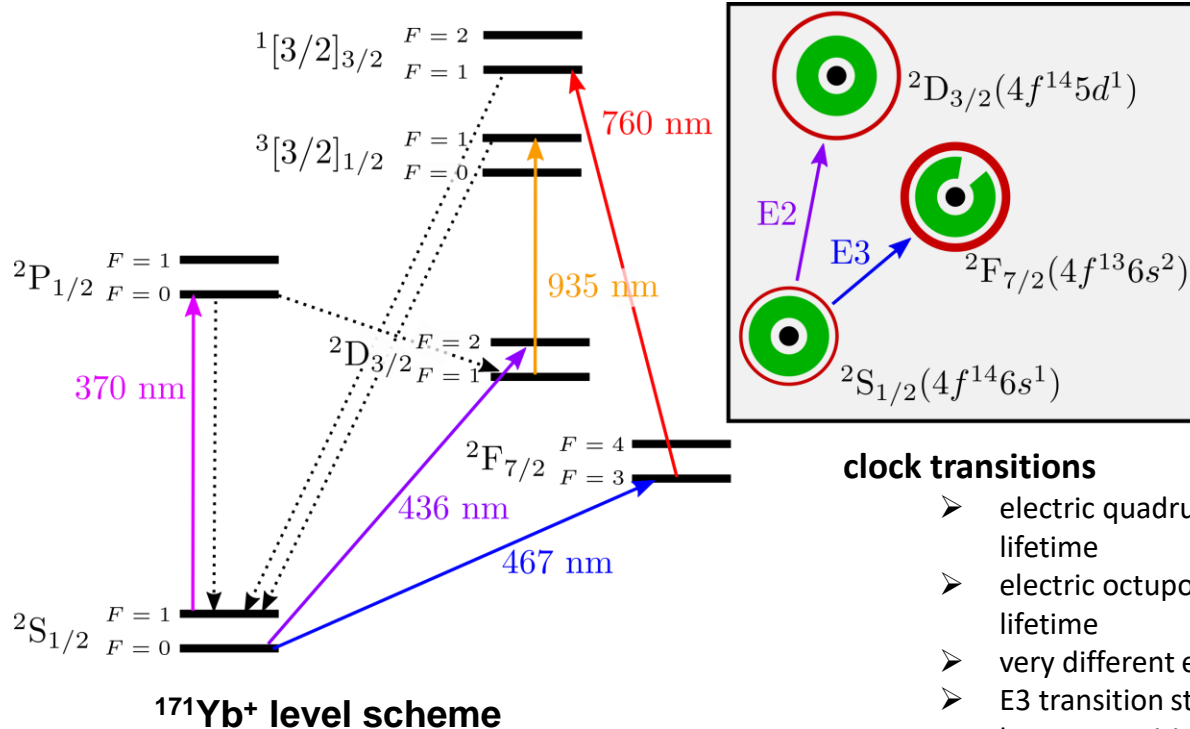


Improved Limits for Violations of Local Position Invariance and Local Lorentz Invariance from Atomic Clock Comparisons

Richard Lange, Nils Huntemann, Johannes M. Rahm, Christian Sanner, Hu Shao, Burghard Lipphardt, Christian Tamm, Stefan Weyers, Ekkehard Peik



Setting up a frequency standard



E2: Chr. Tamm *et al.*, Phys. Rev. A **89**, 023820 (2014)

E3: N. Huntemann *et al.*, Phys. Rev. Lett. **116**, 063001 (2016)

Yb⁺ advantages

- ✓ all transitions diode laser driven
- ✓ ion with large mass
- ✓ long storage times
- ✓ two clock transitions available

clock transitions

- electric quadrupole (E2) transition with 53 ms lifetime
- electric octupole (E3) transition with yearlong lifetime
- very different electronic structure
- E3 transition strongly relativistic and with large α sensitivity
 - **well suited for tests of fundamental physics**

$^{171}\text{Yb}^+$ clock

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Infrastructure

E3 clock comparison and LLI

E3/E2 clock comparison and LPI

Yb⁺(E3)/CsF clock comparison and LPI

1. The property of a body called “mass” is proportional to the “weight”.
(Weak Equivalence Principle, WEP)
2. The outcome of any **local non-gravitational experiment** is independent of the velocity and orientation of the freely-falling reference frame in which it is performed.
(Local Lorentz Invariance, LLI)
3. The outcome of any **local non-gravitational experiment** is independent of where and when in the universe it is performed.
(Local Position Invariance, LPI)

Experiments we perform: Frequency comparisons

C. M. Will, Living Rev. Relativity **9**, 3 (2006),
M.S. Safronova *et al.*, Rev. Mod. Phys. **90**, 025008 (2019)

$^{171}\text{Yb}^+$ clock

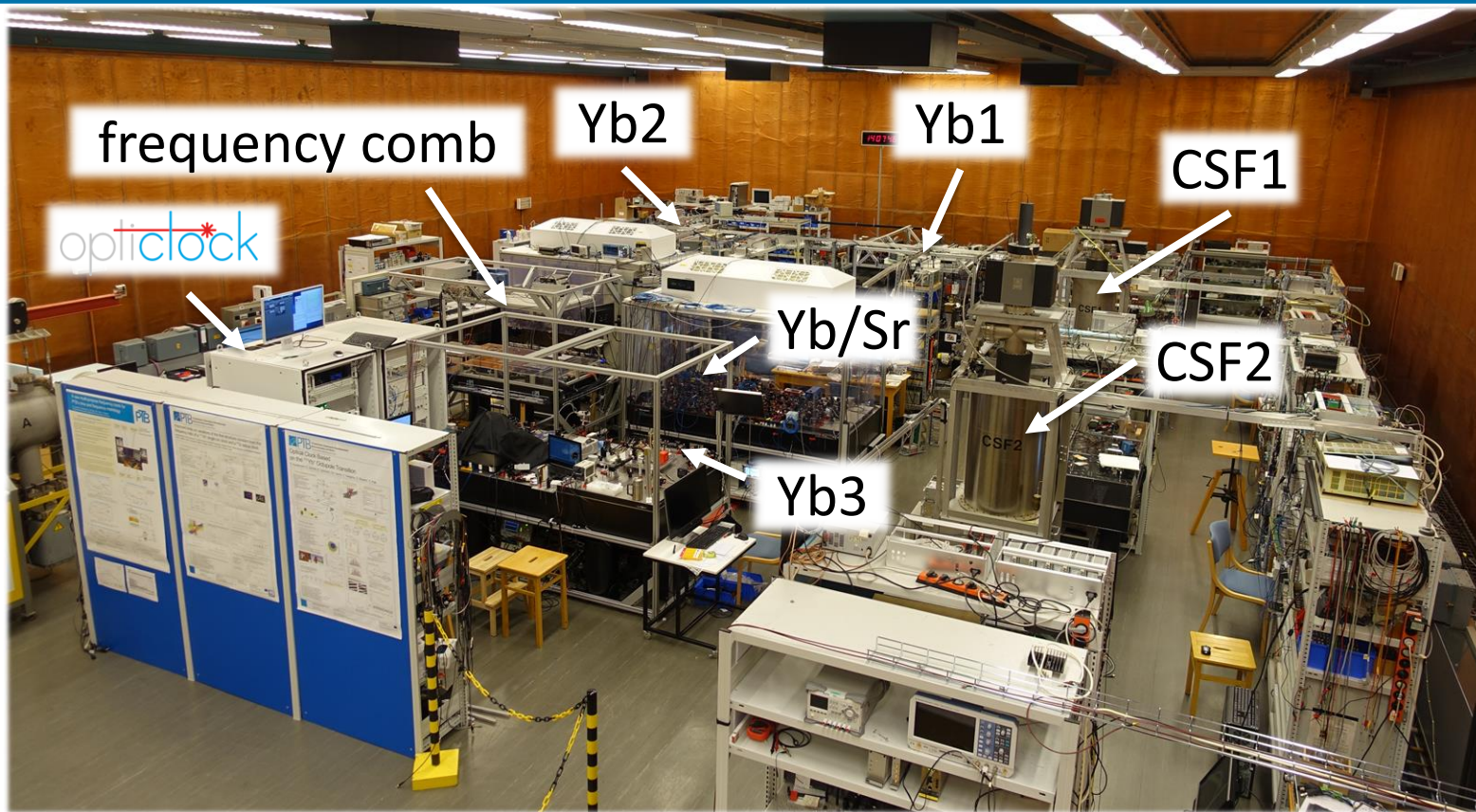
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Infrastructure

E3 clock
comparison
and LLI

E3/E2 clock
comparison
and LPI

$\text{Yb}^+(\text{E3})/\text{CsF}$
clock
comparison
and LPI



$^{171}\text{Yb}^+$ clock

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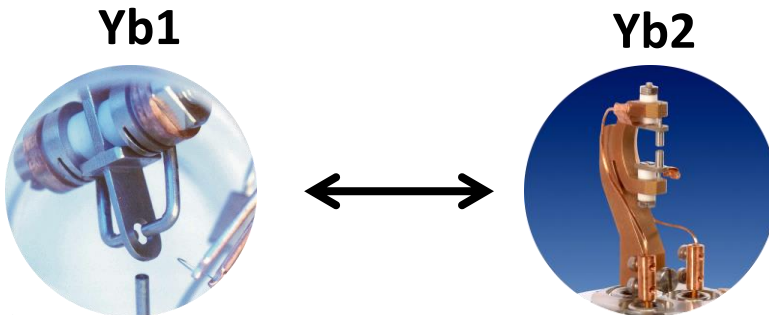
E3 clock comparison and LLI

E3/E2 clock comparison and LPI

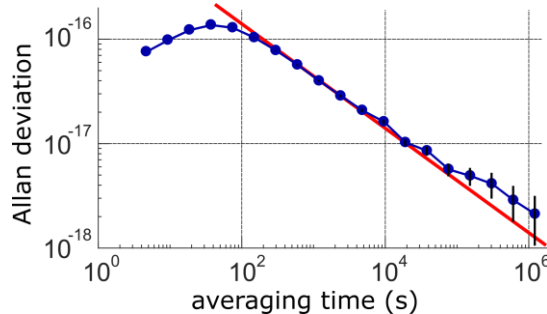
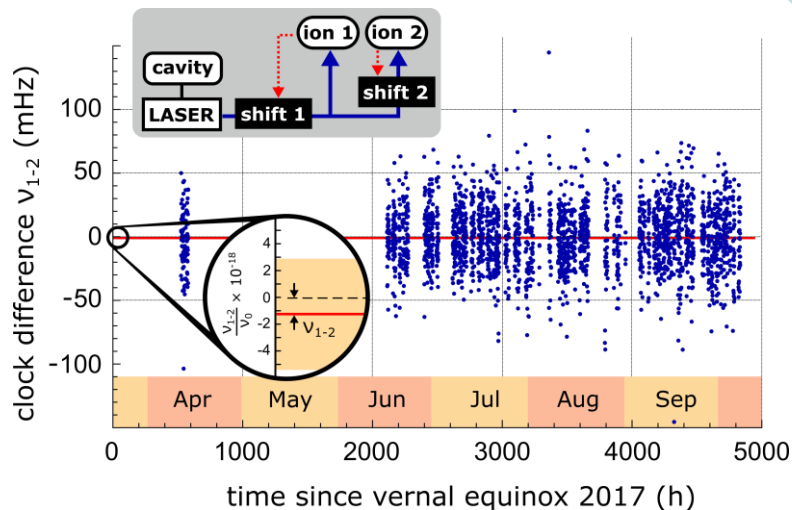
$\text{Yb}^+(\text{E3})/\text{CsF}$ clock comparison and LPI

E3 clock comparison

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



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



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

$^{171}\text{Yb}^+$ clock

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Infrastructure

E3 clock comparison and LLI

E3/E2 clock comparison and LPI

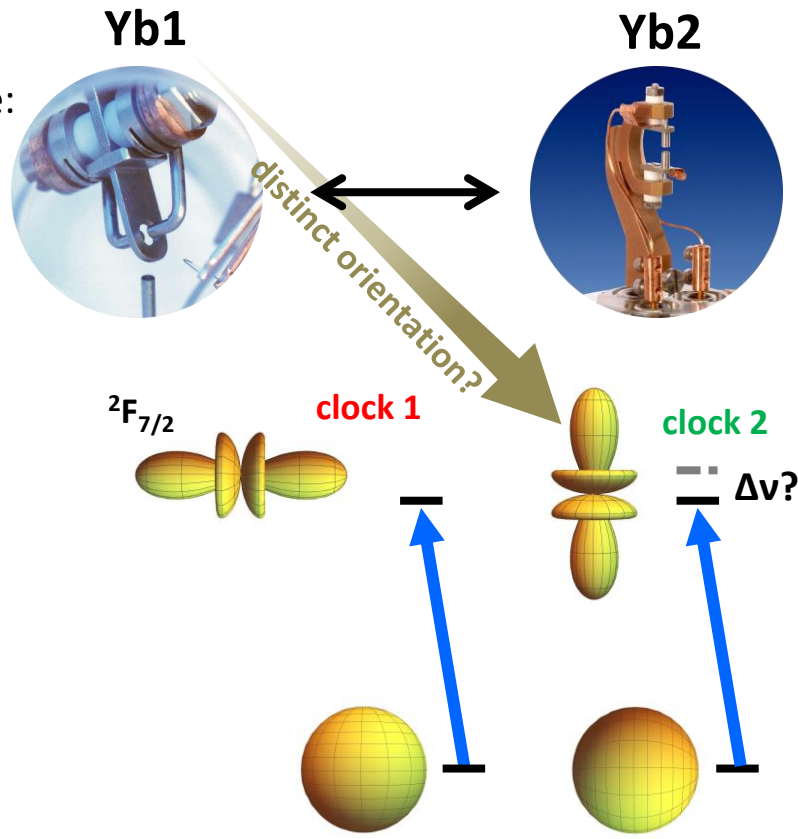
$\text{Yb}^+(\text{E3})/\text{CsF}$ clock comparison and LPI

A. Kostelecky, Standard-Model Extension:
Search for violation of Local Lorentz Invariance:

Non-gravitational experiment independent of velocity and orientation of reference frame.

- Is the electron's dispersion relation isotropic in space?
- suitable electron container: clock state
- search for modulation of frequency difference with earth rotation rate
- improvement of existing limits by two orders of magnitude

T. Pruttivarasin et al., Nature **517**, 592 (2015)
C. Sanner *et al.*, Nature **567**, 204 (2019)



$^{171}\text{Yb}^+$ clock

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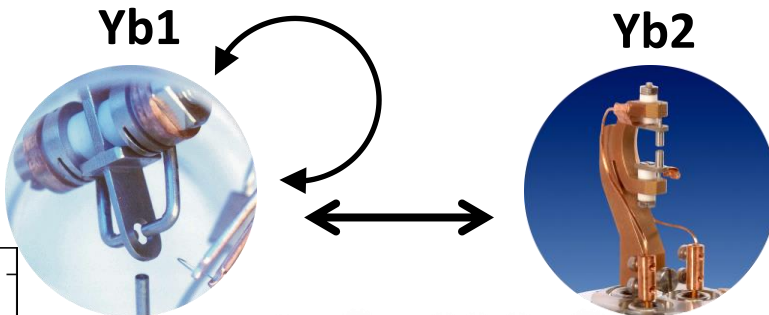
E3 clock comparison and LLI

E3/E2 clock comparison and LPI

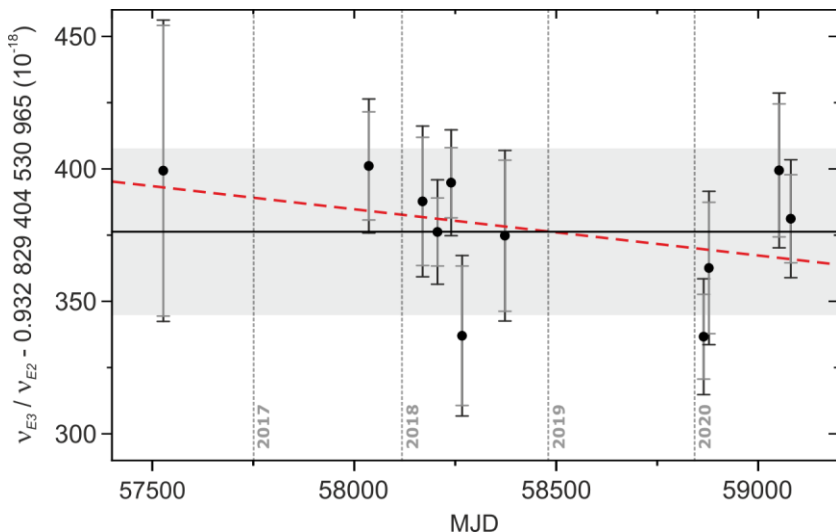
$\text{Yb}^+(\text{E3})/\text{CsF}$ clock comparison and LPI

E3/E2 clock comparison

- repeated measurements since 2016
- one clock E3, one clock E2 transition
- one trap can employ both clocks
- total fractional uncertainty: 34×10^{-18}



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



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

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

¹⁷¹Yb⁺ clock

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E3 clock comparison and LLI

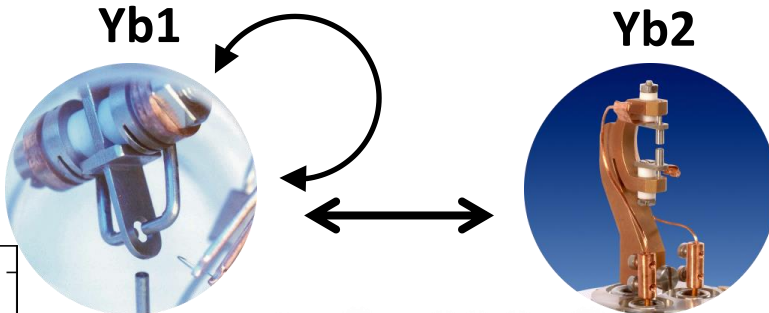
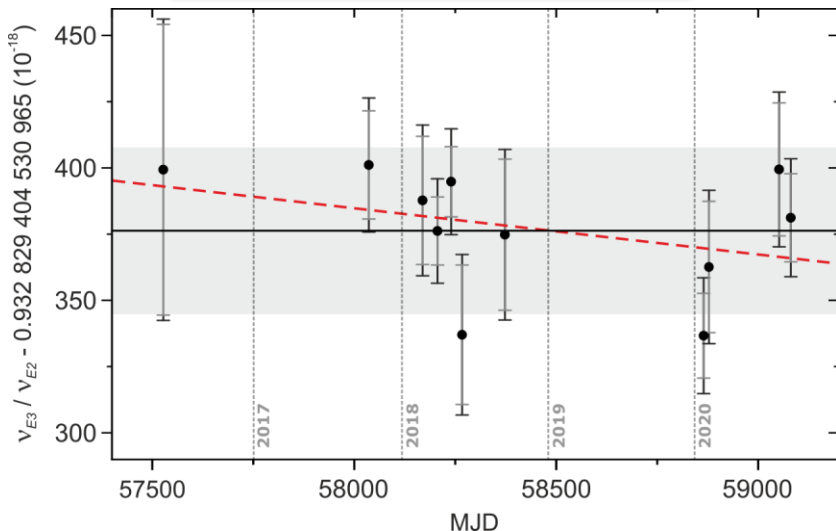
E3/E2 clock comparison and LPI

Yb⁺(E3)/CsF clock comparison and LPI

E3/E2 clock comparison + LPI

- Search for local position invariance:

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



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

dependence on fundamental constant α

$$K = -6$$

$$K = 1$$

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

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

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

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

$^{171}\text{Yb}^+$ clock

EEP

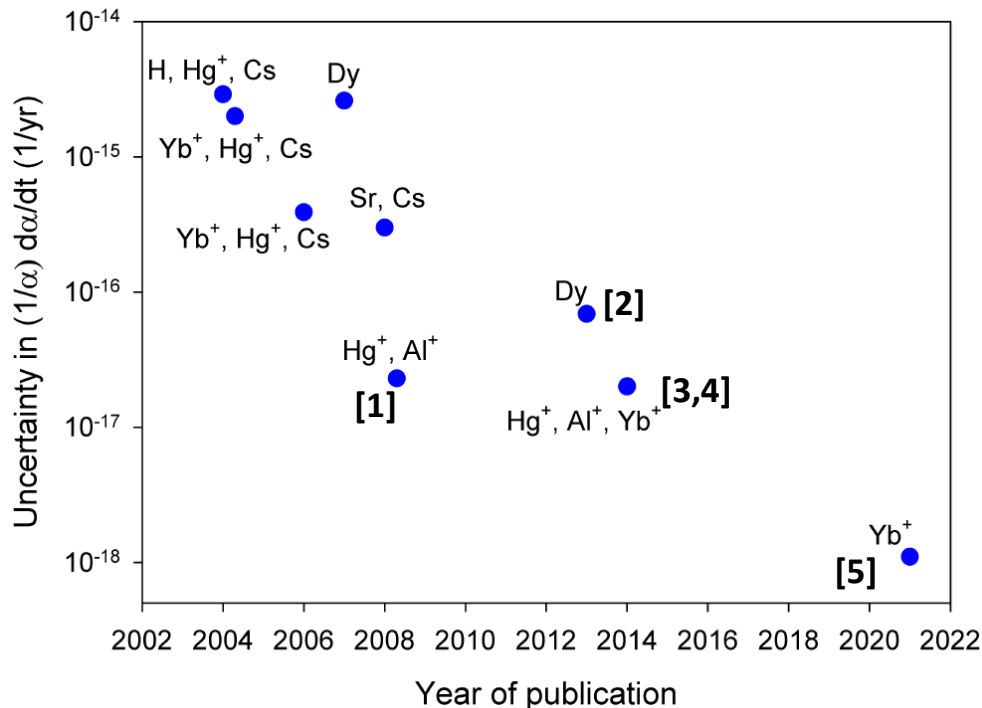
Infrastructure

E3 clock comparison and LLI

E3/E2 clock comparison and LPI

$\text{Yb}^+(\text{E3})/\text{CsF}$ clock comparison and LPI

E3/E2 clock comparison + LPI



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

[2] N. Leifer *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)

¹⁷¹Yb⁺ clock

EEP

Infrastructure

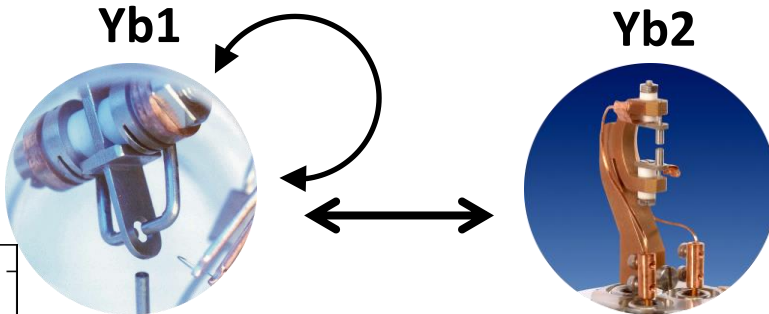
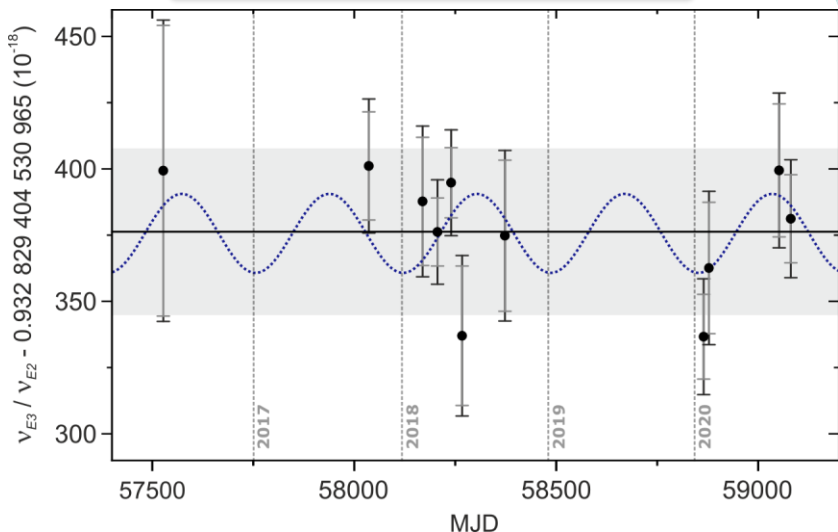
E3 clock comparison and LLI

E3/E2 clock comparison and LPI

Yb⁺(E3)/CsF clock comparison and LPI

- Search for local position invariance:

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



- oscillations of the ratio due to the annual variation of the Sun's gravitational potential on Earth Φ ?

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

- 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)

$^{171}\text{Yb}^+$ clock

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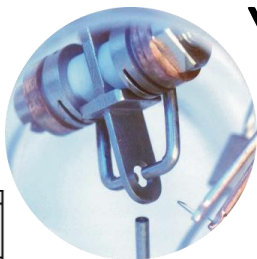
E3 clock comparison and LLI

E3/E2 clock comparison and LPI

$\text{Yb}^+(\text{E3})/\text{CsF}$ clock comparison and LPI

Yb⁺(E3) vs Cs clock comparison

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



Yb1

CsF



¹⁷¹Yb⁺ clock

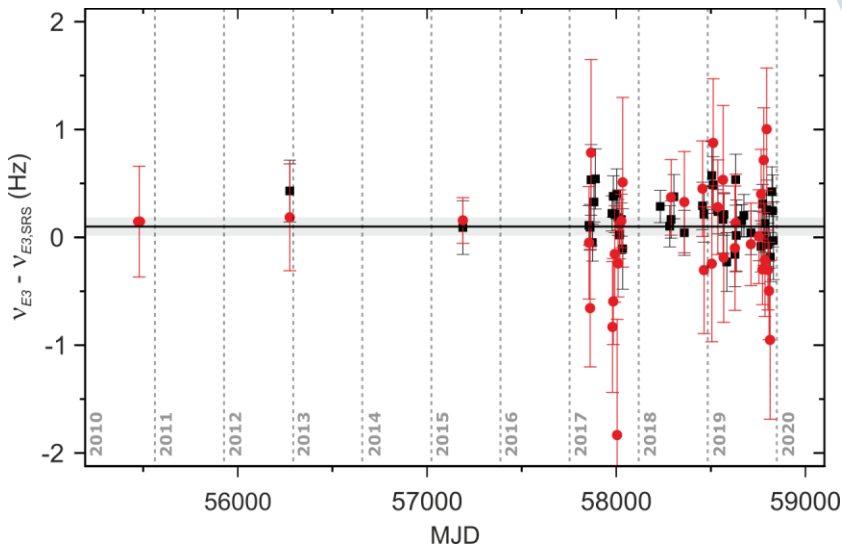
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Infrastructure

E3 clock comparison and LLI

E3/E2 clock comparison and LPI

Yb⁺(E3)/CsF clock comparison and LPI



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

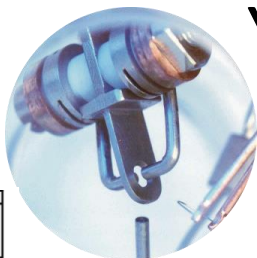
$$u_{E3}/\nu_{E3} = 1.3 \times 10^{-16}$$

- most accurate determination of optical frequency

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

Yb⁺(E3) vs Cs clock comparison

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



Yb1

CsF



¹⁷¹Yb⁺ clock

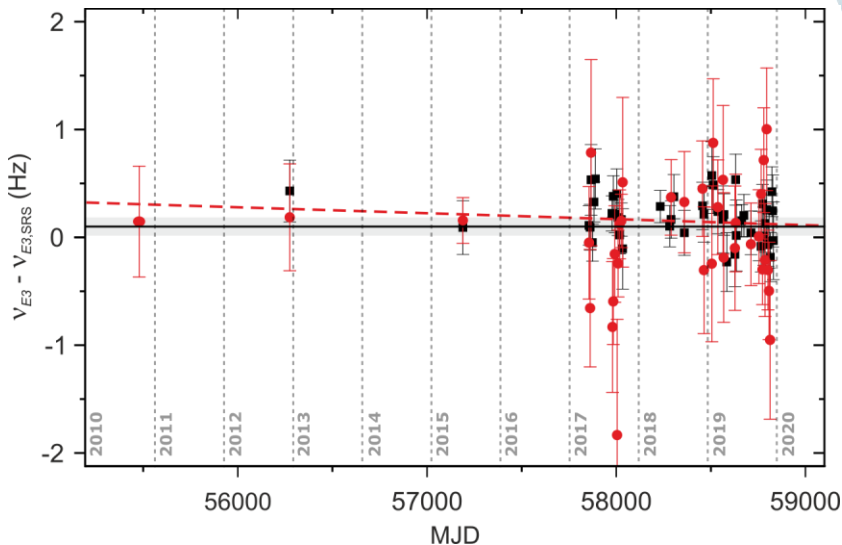
EEP

Infrastructure

E3 clock comparison and LLI

E3/E2 clock comparison and LPI

Yb⁺(E3)/CsF clock comparison and LPI



- Cs hyperfine transition sensitive to changes in

α → from E3/E2 ratio

$$\mu = m_p/m_e$$

X_q (strong interact. param.)

→ from [2], small contribution

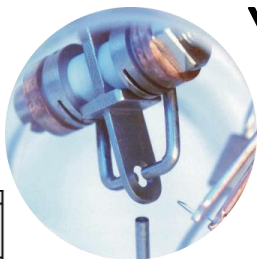
$$\frac{1}{\mu} \frac{d\mu}{dt} = -8(36) \times 10^{-18} / \text{yr}$$

- ~ factor of 2 improvement [3]

- [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)

Yb⁺(E3) vs Cs clock comparison

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



Yb1

CsF



¹⁷¹Yb⁺ clock

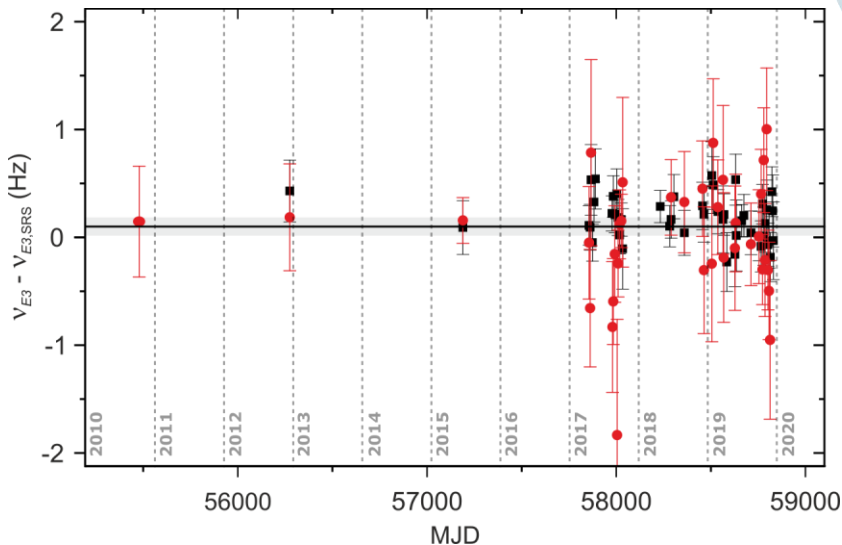
EEP

Infrastructure

E3 clock comparison and LLI

E3/E2 clock comparison and LPI

Yb⁺(E3)/CsF clock comparison and LPI



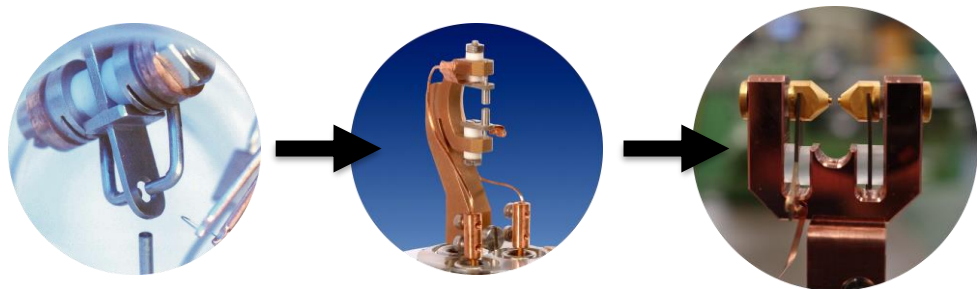
- oscillations of the ratio due to the annual variation of the Sun's gravitational potential on Earth Φ ?
- limit on X_q derived with [2]

$$\frac{1}{\mu} \frac{d\mu}{d\phi} = 7(45) \times 10^{-8} / c^2$$

- slight improvement of [3]

- [1] R. Lange *et al.*, PRL **126**, 011102 (2021)
- [2] N. Ashby *et al.*, Nature Physics **14**, 822 (2018)
- [3] R. Schwarz *et al.*, Phys. Rev. Research **2**, 033242 (2020)

Further research topics & outlook



- third-generation single-ion trap
- clock operation demonstrated
- towards 10^{-19} rel. uncertainty

collaboration with RG QUEST 2



- linear trap
- multi-species clock
- Yb^+/Sr^+ crystal

collaboration with dep. 4.3



- ^{87}Sr lattice clock
- improving the stability of the single-ion clock

$^{171}\text{Yb}^+$ clock

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Infrastructure

E3 clock comparison and LLI

E3/E2 clock comparison and LPI

$\text{Yb}^+(\text{E3})/\text{CsF}$ clock comparison and LPI

- Frequency comparisons of

$^{171}\text{Yb}^+$ E3 and E2 clocks and Cs fountains

- agreement of two E3 clock within 4.2×10^{-18}
- E3/Cs: most accurate measurement of optical transition frequency

- Search for new physics

- test of **LLI** with two Yb^+ (E3) clocks, improvement in the electron sector by factor of 100
- test of **LPI** with Yb^+ (E3) and Yb^+ (E2) clock, improvement of temporal **variations of α** by a factor of 20
- test of **LPI** with Yb^+ (E3) and Cs fountains, improvement of temporal **variations of μ** by a factor of 2



CsF

$^{171}\text{Yb}^+$ clock

EEP

Infrastructure

E3 clock comparison and LLI

E3/E2 clock comparison and LPI

Yb^+ (E3)/CsF clock comparison and LPI

Thank you for your attention!