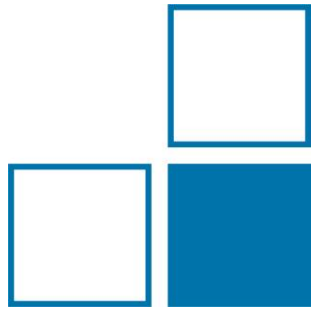
Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

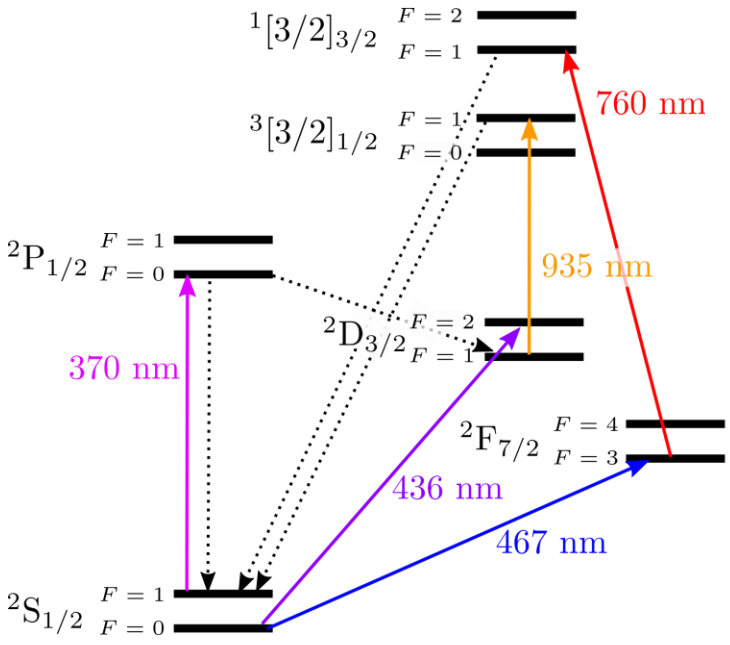
# Improved Limits for Violations of Local Position and Local Lorentz Invariance from Atomic Clock Comparisons

E. Peik, N. Huntemann, R. Lange, J. M. Rahm, C. Sanner, H. Shao, B. Lipphardt, Chr. Tamm, S. Weyers



16th Marcel Grossmann Meeting, 5.-8.7.2021

# Setting up a frequency standard




**$^{171}Yb^+$ level scheme**

**$Yb^+$ advantages**

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

**clock transitions**

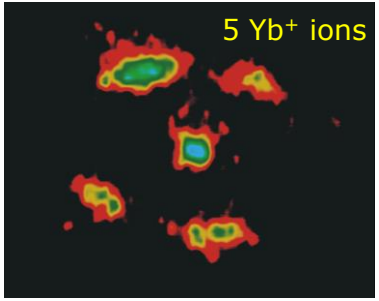
- ➢ electric quadrupole (E2) transition with 53 ms lifetime
- ➢ electric octupole (E3) transition with yearlong lifetime
- ➢ very different electronic structure
- ➢ E3 transition strongly relativistic and with large α sensitivity
  - ➢ **well suited for tests of fundamental physics**


E2: Chr. Tamm *et al.*, Phys. Rev. A **89**, 023820 (2014)
E3: N. Huntemann *et al.*, Phys. Rev. Lett. **116**, 063001 (2016)

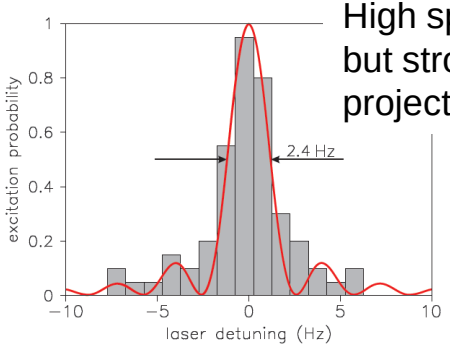
# Optical clock with a single laser-cooled ion in a Paul trap

Long interaction times

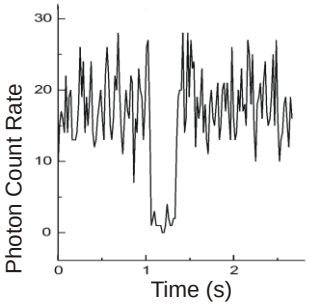
Lamb-Dicke confinement , mK temperature

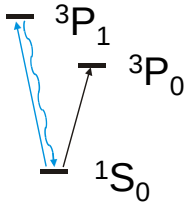



High spectral resolution, but strong quantum projection noise




individual quantum jumps




→ Suitable for narrow lines with small E-field induced shifts

# Einstein equivalence principle

1. The property of a body called “mass” is proportional to the “weight”.
   (Weak Equivalence Principle, WEP)

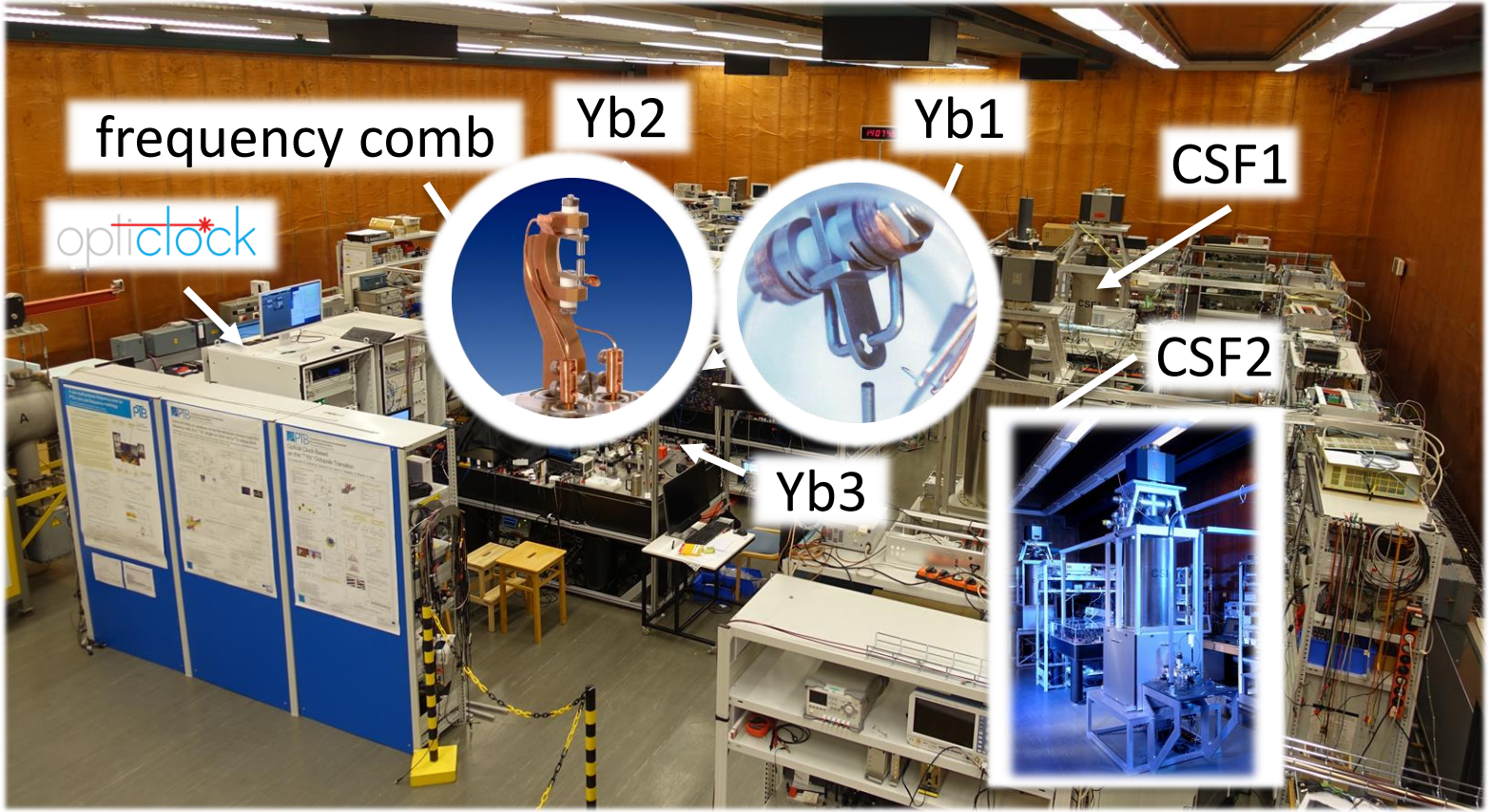
2. The outcome of any local non-gravitational experiment is independent of the velocity and orientation of the freely-falling reference frame in which it is performed.
   (Local Lorentz Invariance, LLI)

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)

# Infrastructure for clock comparisons




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

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Infrastructure

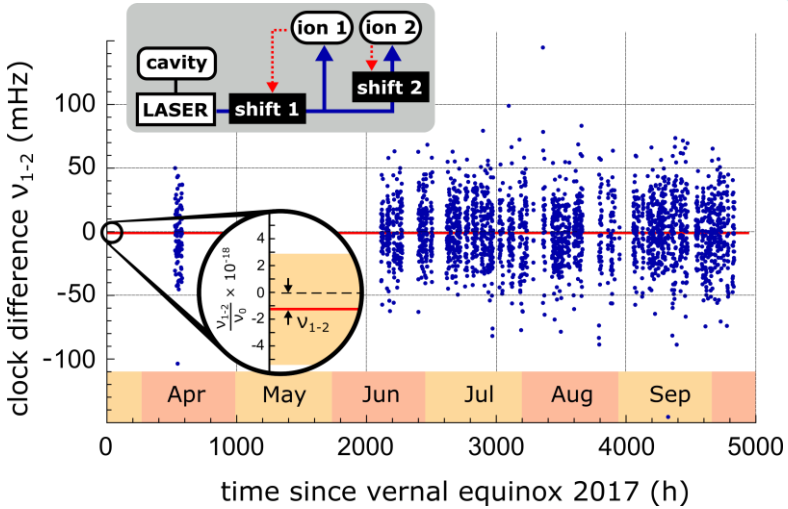
E3 clock comparison and LLI

E3/E2 clock comparison and LPI

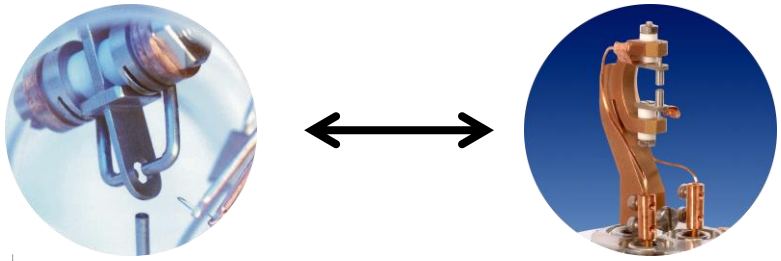
$Yb^{+}$(E3)/CsF clock comparison and LPI

# E3 clock comparison

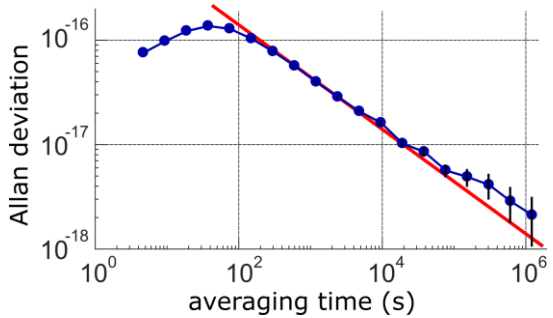
- six-month-long comparison
- two clocks on the E3 transition
- different experimental setups
- statistical uncertainty of $2.1 \times 10^{-18}$




Yb1 Yb2



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




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

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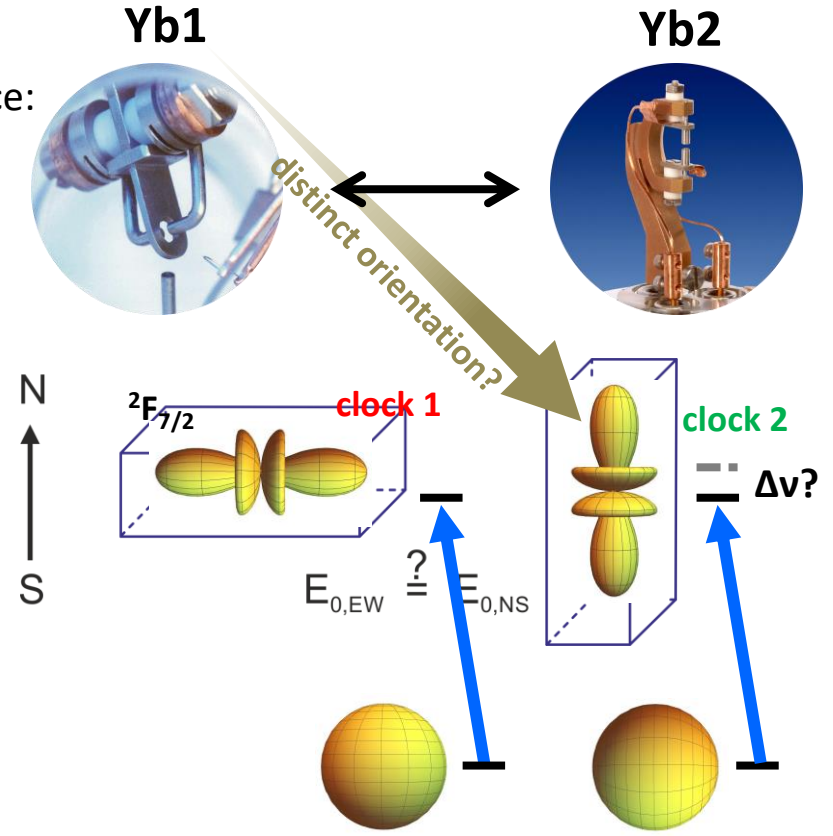
# E3 clock comparison + LLI

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)

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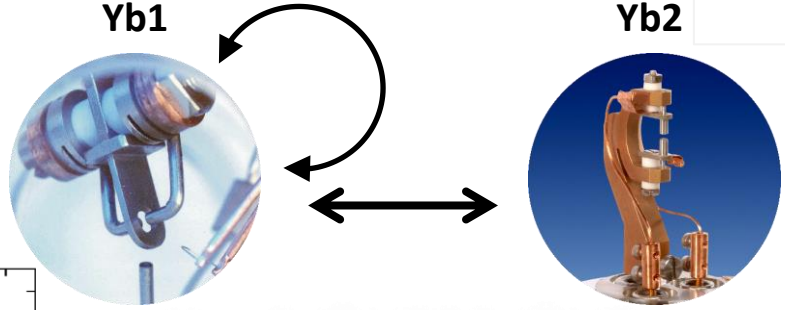
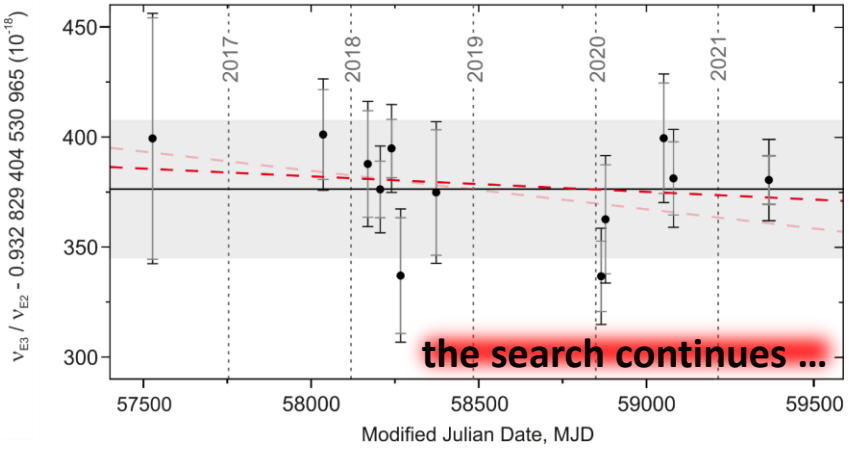
# E3/E2 clock comparison + LPI

Presenter Video

- Search for local position invariance:

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




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

dependence on fundamental constant α

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

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

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

preliminary

$$\frac{1}{\alpha}\frac{\mathrm{d}\alpha}{\mathrm{d}t} = 4.6(8.3) \times 10^{-19}/\mathrm{yr}$$

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

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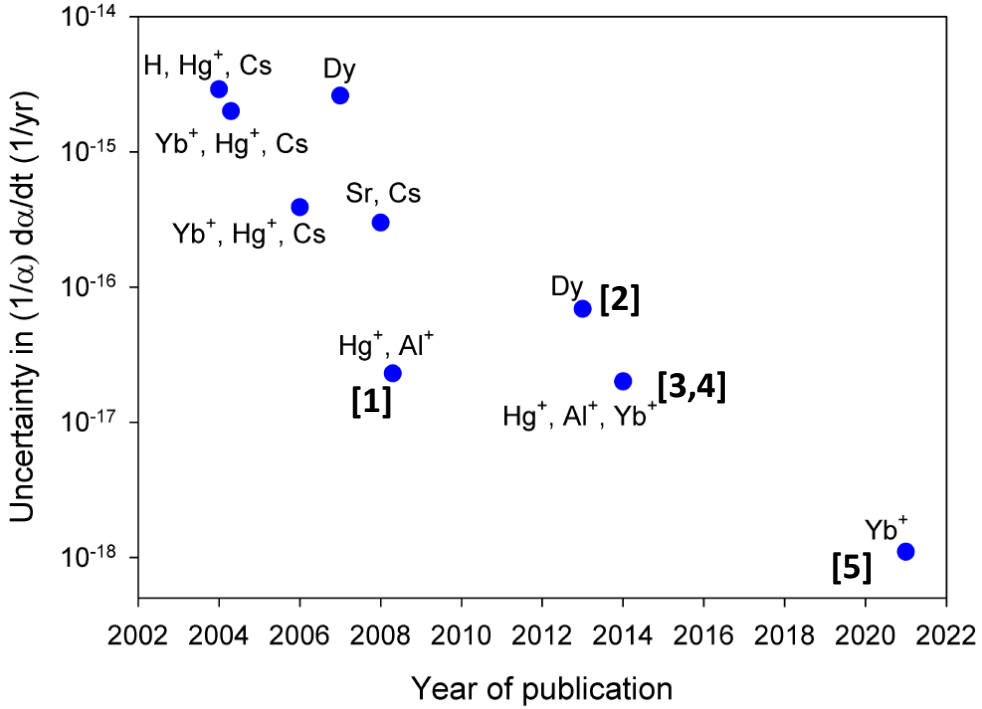
# E3/E2 clock comparison + LPI



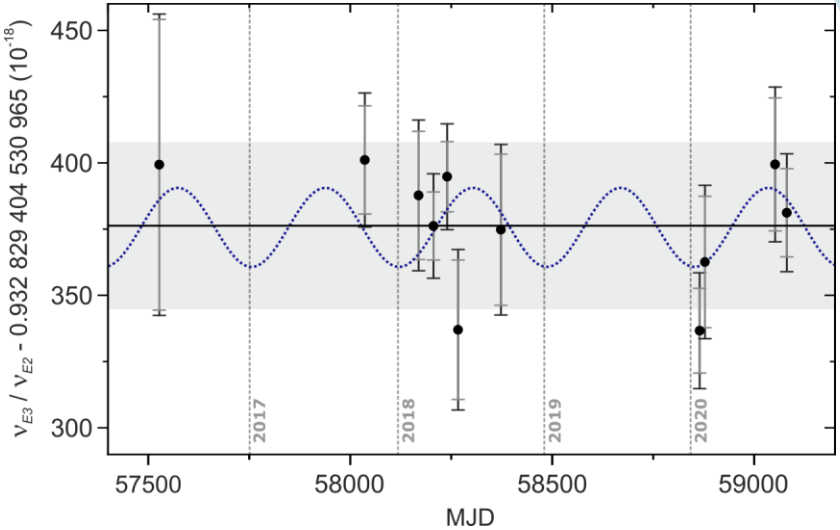


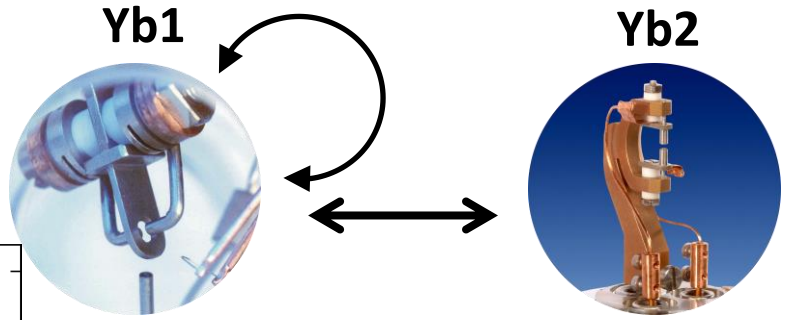
[1] T. Rosenband *et al.*, Science **319**, 1808 (2008)
[2] N. Leefer et al., PRL 111, 060801 (2013)
[3] R. Godun *et al.*, PRL **113**, 210801 (2014)
[4] N. Huntemann *et al.*, PRL **113**, 210802 (2014)
[5] R. Lange *et al.*, PRL **126**, 011102 (2021)

# E3/E2 clock comparison + 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 $\Phi$?

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

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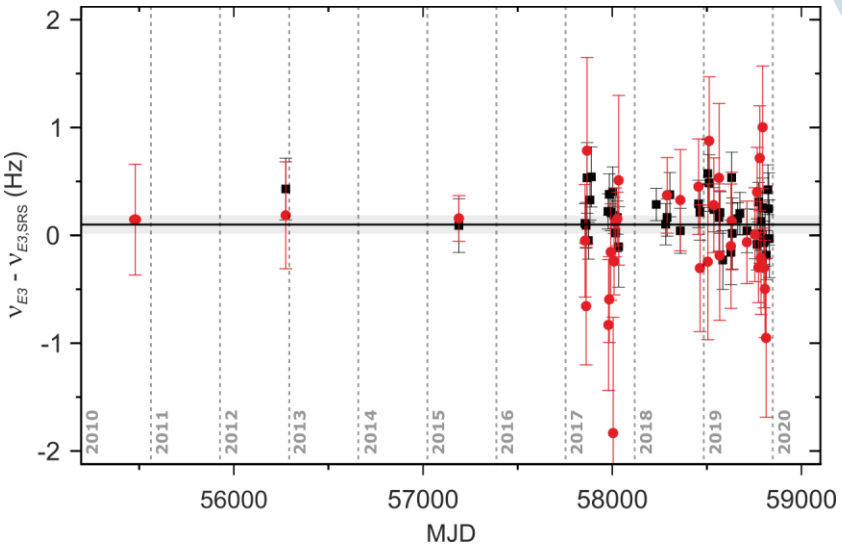
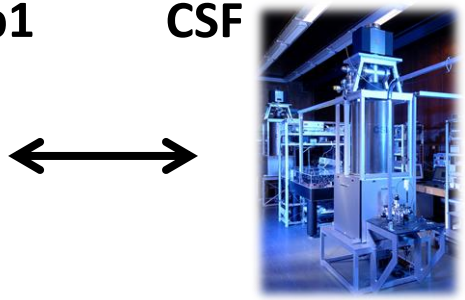
# $Yb^+$(E3) vs Cs clock comparison

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




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


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

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

- most accurate determination of an optical transition frequency

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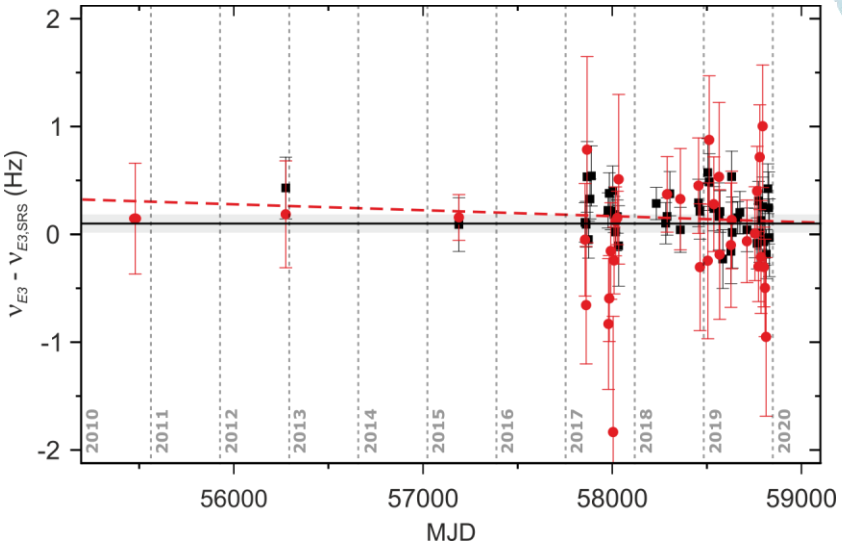
# $Yb^+$(E3) vs Cs clock comparison

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






- 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

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

- ~ 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)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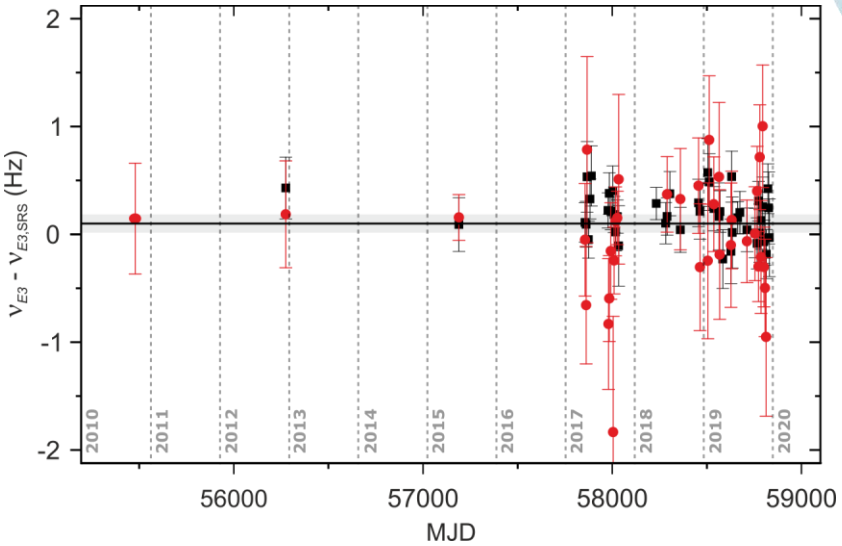




- oscillations of the ratio due to the annual variation of the Sun's gravitational potential on Earth Φ?
- limit on $X_q$ derived with [2]

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

- 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)


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# Further research topics & outlook

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

- linear trap
- multi-species clock
- $Yb^+/Sr^+$ for evaluation of BBR shift

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

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# Summary

- Frequency comparisons of

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

- agreement of two E3 clock within $4.2 \times 10^{-18}$
- 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

Yb1

Yb2

CSF

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Yb⁺ clocks
N. Huntemann
C. Sanner
R. Lange
B. Lipphardt
Chr. Tamm
M. Abdel Hafiz
Hu Shao

Cs clocks
S. Weyers
J. Rahm
M. Kazda
V. Gerginov

Theory
M. Safronova
M. Kozlov
S. Porsev


R. Lange, N. Huntemann, C. Sanner: Winners of the Helmholtz Prize 2020


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