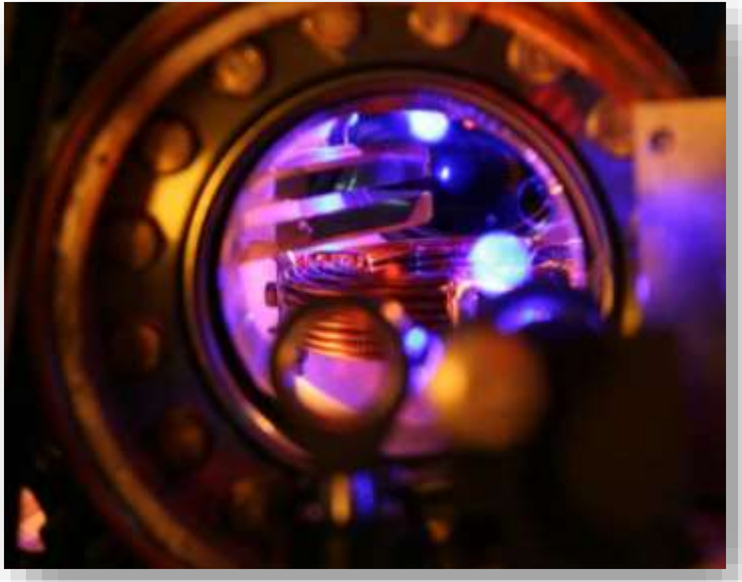


Experiments with strontium lattice clocks at PTB

Christian Lisdat

and the teams

at the PTB Sr lattice and

Yb^+ single ion clocks

EXC 2123

SFB 1464

EMPIR

EURAMET

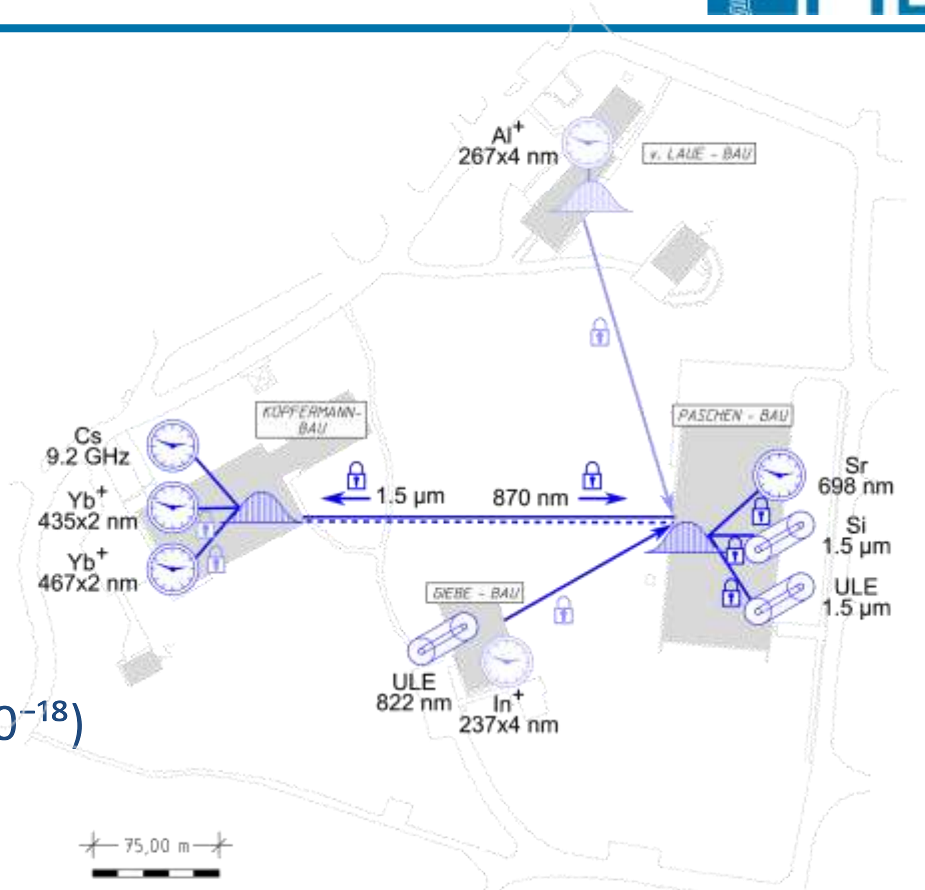
SFB 1227

DFG

20.11.2022, ACES Workshop, Paris

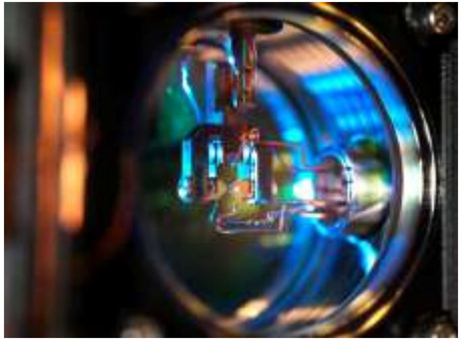
We are not alone

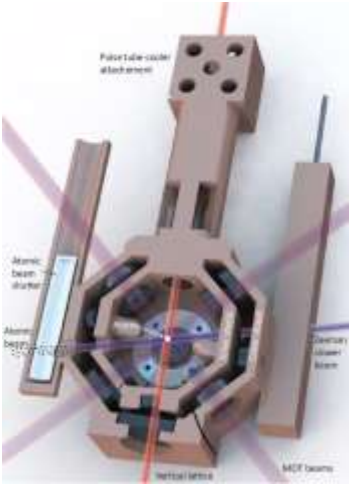
- ► 2 Cs fountain clocks
  (uncertainty 2×10^{-16})
- ► 2/3 Yb^+ E3/E2 clocks
  (uncertainty 3×10^{-18})
- ► In^+ clock
  (uncertainty $<1\times10^{-17}$)
- ► ^{87}Sr lattice clock
  + transportable, (uncertainty 3×10^{-18})
- ► Al^+ on the way

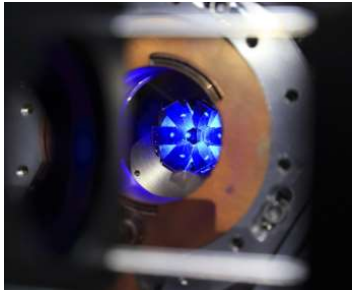


Outline

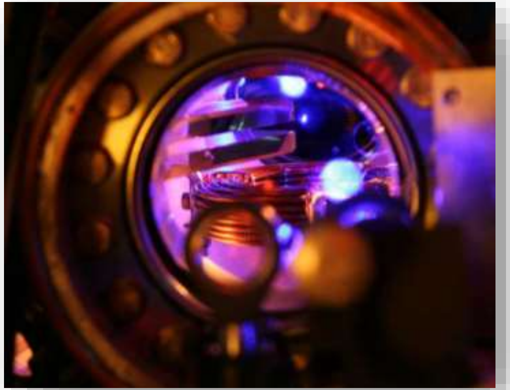
- first Sr clock (Sr1)
  comparisons with Cs & Yb^+
  LPI tests
- cryogenic lab clock (Sr3)
  cooling in homogeneous environment
  low 10^{-18} uncertainty
- transportable clock (Sr2 & Sr4)
  new insights in old data
  clock laser with 10^{-16} instability
  single-beam MOT + cryo-environment

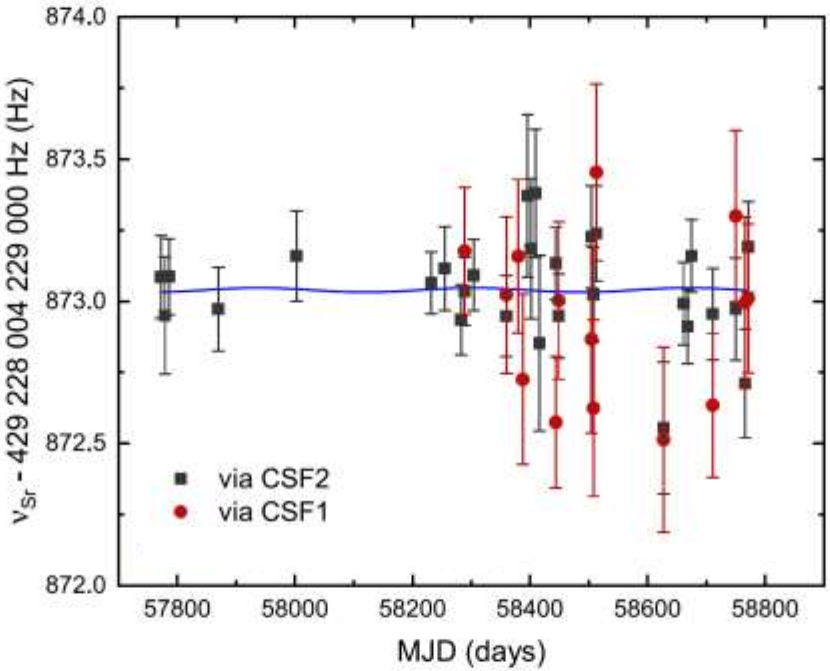






First lab clock Sr1





long-term operation, many comparisons with Cs fountain clocks

Schwarz *et al*, Phys. Rev. Res. **2**, 033242 (2020)

First lab clock Sr1

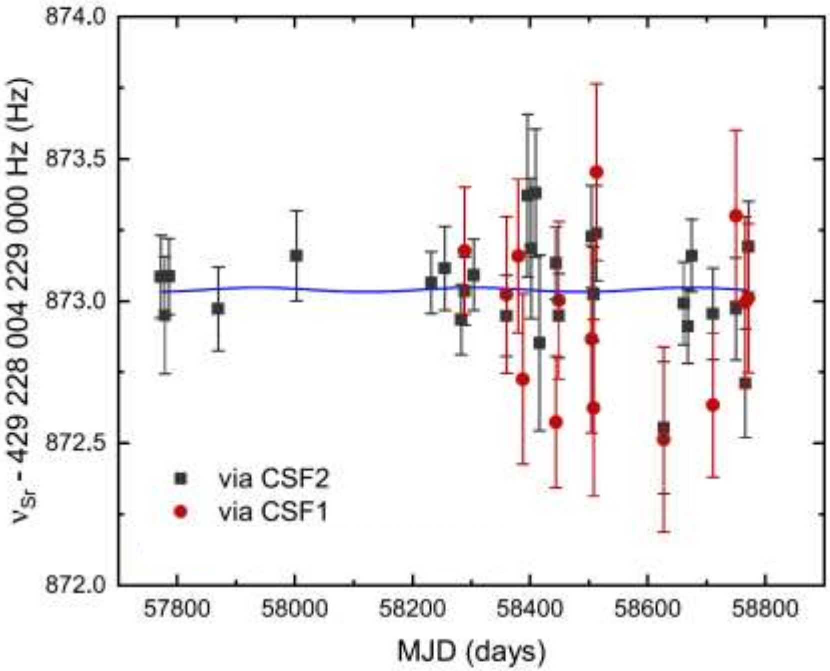
Frequency variations:

- temporal drift
- coupling to gravitational field

$$\frac{1}{F}dF = \kappa_\alpha \frac{1}{\alpha}d\alpha + \kappa_\mu \frac{1}{\mu}d\mu + \kappa_q \frac{1}{X_q}dX_q$$

$$X_q = m_q/\Lambda_{QCD}$$

Sr – Cs: mostly $\mu = m_p/m_e$



Schwarz *et al*, Phys. Rev. Res. **2**, 033242 (2020)

First lab clock Sr1

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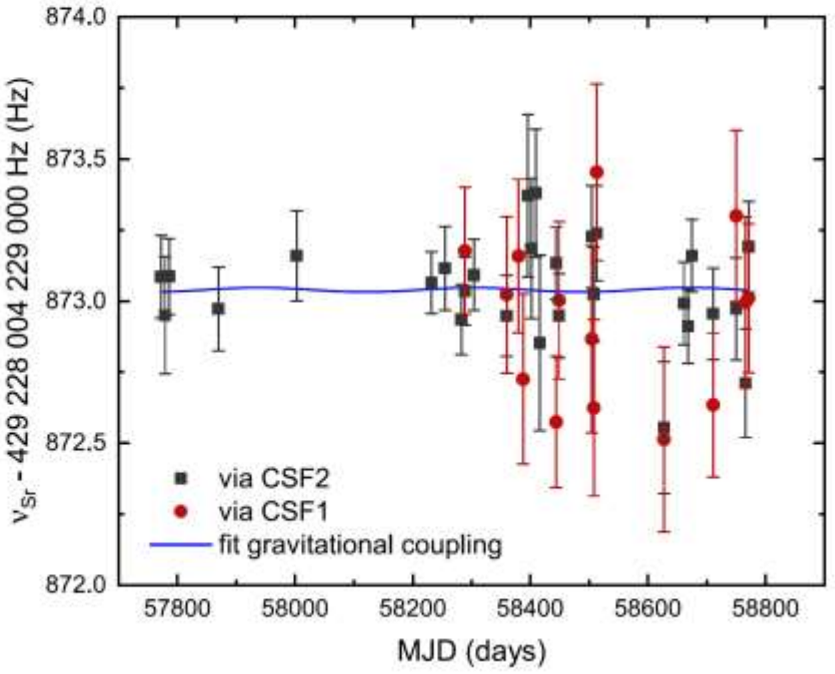
Sr – Cs: mostly $\mu = m_p/m_e$

$$\nu_{Sr}(t) = \nu_0\{1 + A\cos[2\pi(t - t_0)/T_0]\}$$

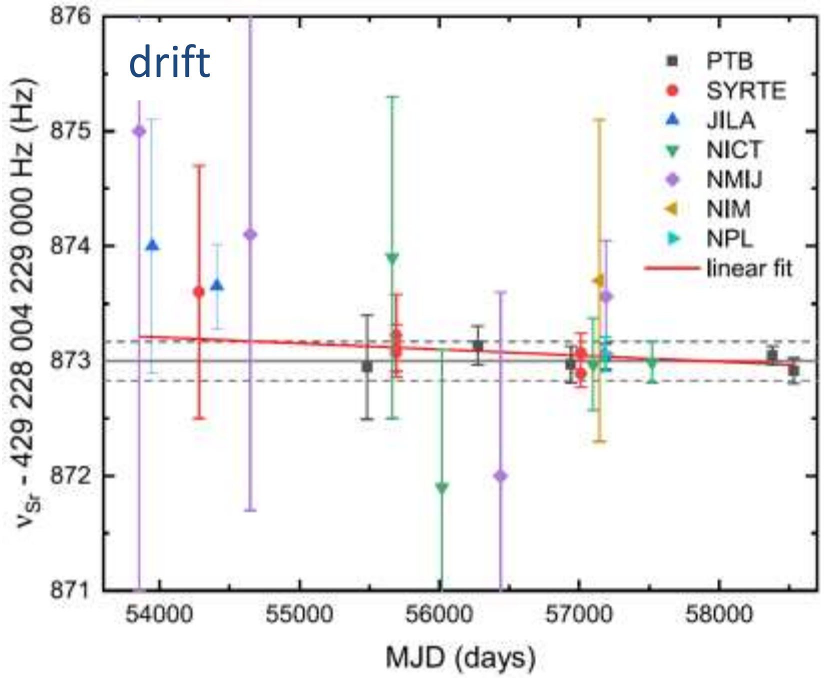
$$\beta_{Sr,Cs} = \frac{A}{\Delta\Phi/c^2} = -1.1(5.2) \times 10^{-7}$$

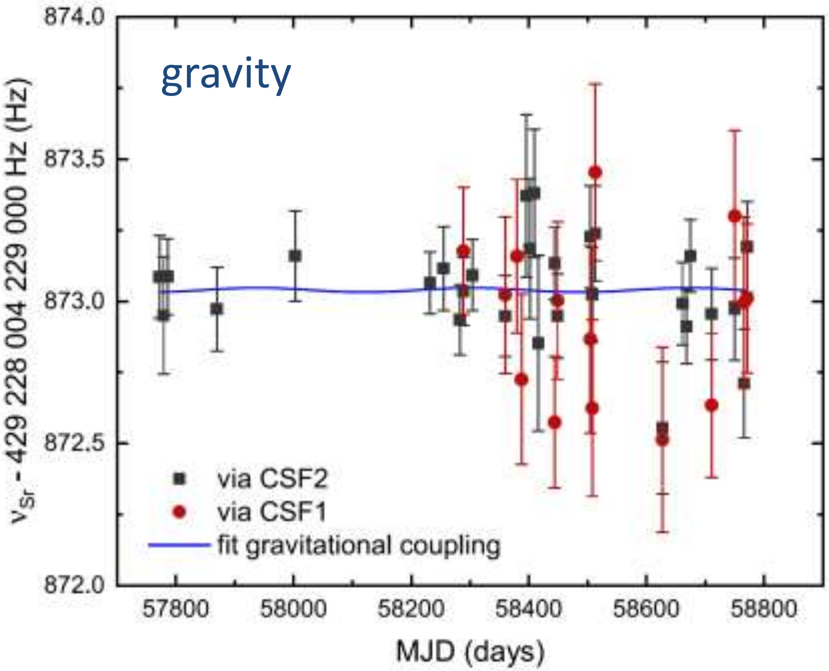
Schwarz *et al*, Phys. Rev. Res. **2**, 033242 (2020)



$$\Rightarrow \boxed{k_\mu = 3.5(5.9) \times 10^{-7}}$$

First lab clock Sr1





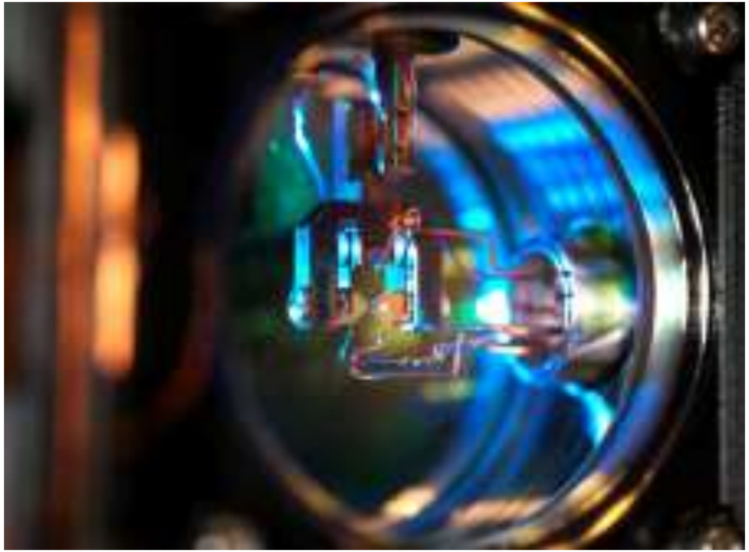
$\Rightarrow$ $\dot{\mu}/\mu = -6.9(6.5) \times 10^{-17}/\mathrm{a}$

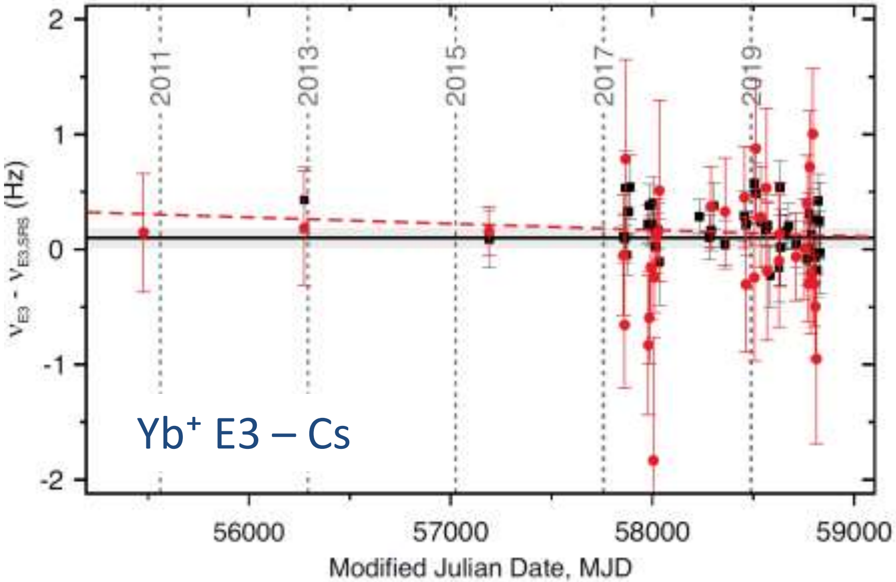
$\Rightarrow$ $k_\mu = 3.5(5.9) \times 10^{-7}$

Schwarz *et al*, Phys. Rev. Res. **2**, 033242 (2020) McGrew *et al*, Optica **6**, 448 (2019)

Other clocks are more sensitive: Yb^+

Two clock transitions in one atom (E2/E3), high sensitivity





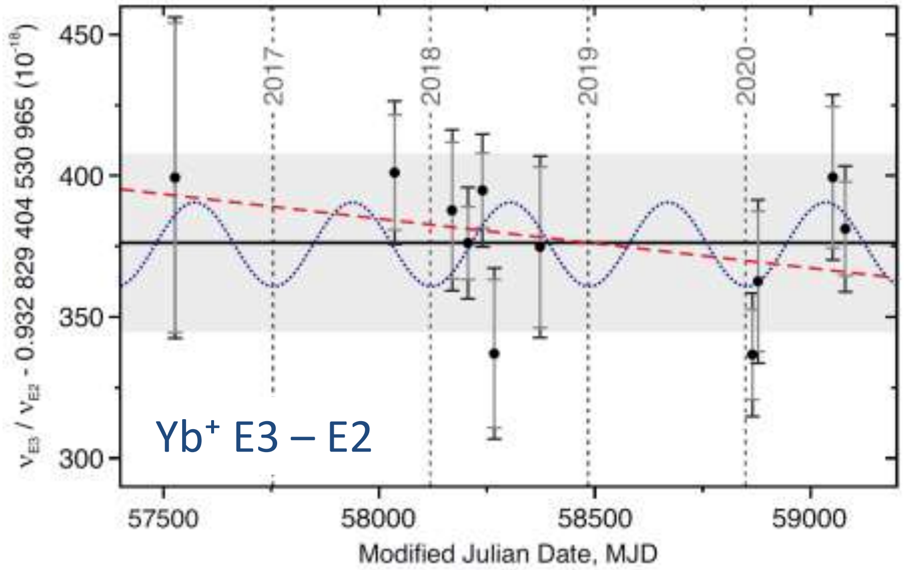
strongly lowered limits: temporal α variation 1.0(1.1)×10^{-18}

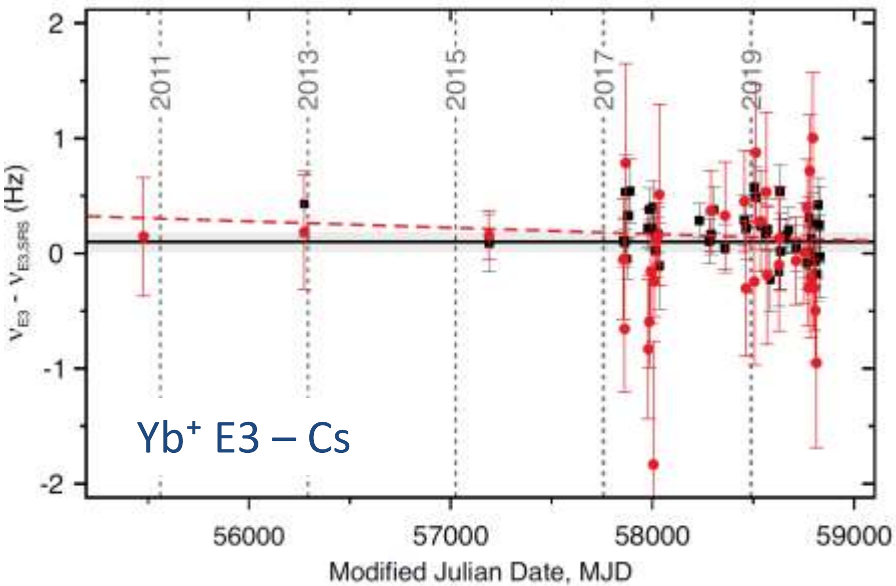
gravitational α variation 14(11)×10^{-9}

Lange *et al*, Phys. Rev. Lett. **126**, 011102 (2021)

Other clocks are more sensitive: Yb⁺

Two clock transitions in one atom (E2/E3), high sensitivity





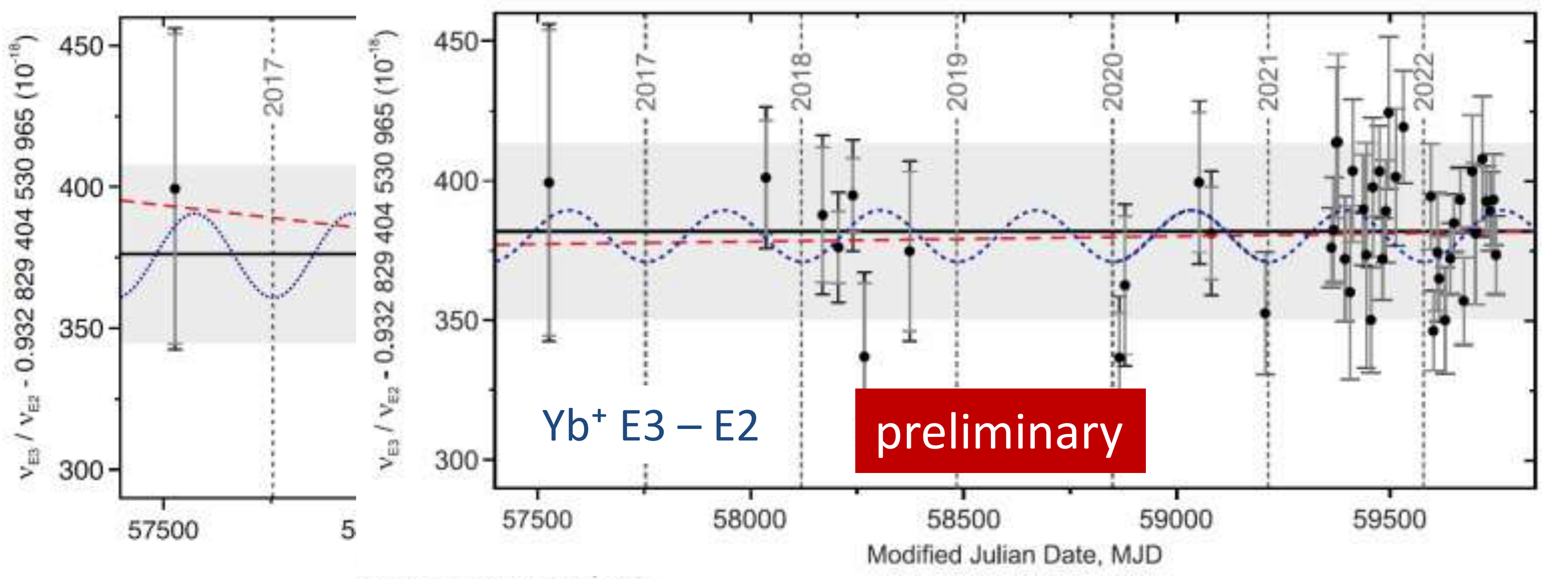
strongly lowered limits: temporal α variation 1.0(1.1)×10⁻¹⁸

gravitational α variation 14(11)×10⁻⁹

Lange *et al*, Phys. Rev. Lett. **126**, 011102 (2021)

Other clocks are more sensitive: Yb^+

Two clock transitions in one atom (E2/E3), high sensitivity

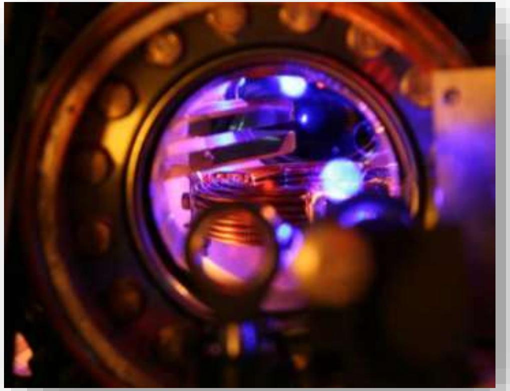


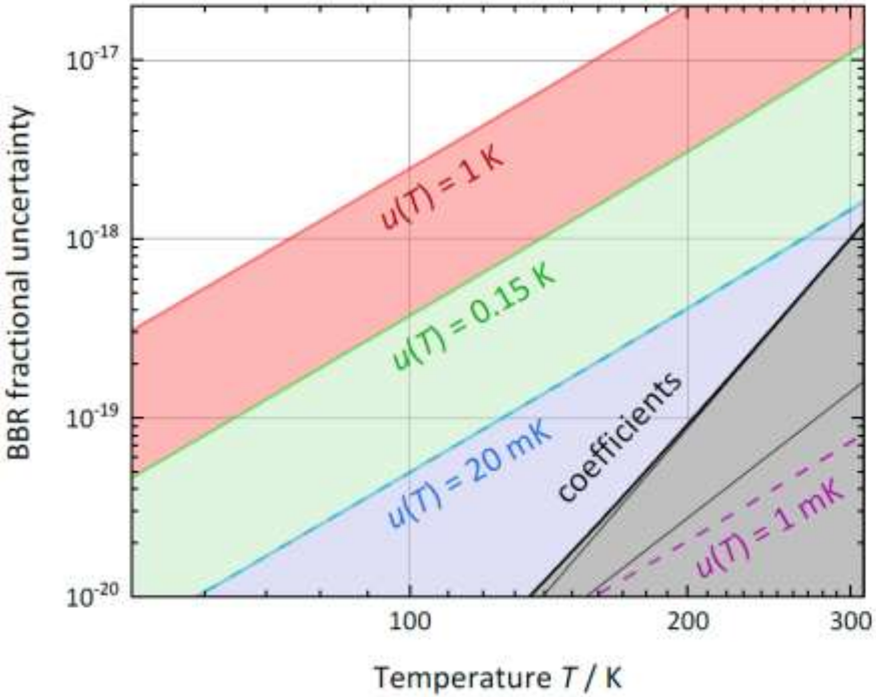
strongly lowered limits: temporal α variation ~~1.0(1.1)~~ 0.11(0.30)×10⁻¹⁸

gravitational α variation ~~14(11)~~ 8.6(3.9)×10⁻⁹

Lange *et al*, Phys. Rev. Lett. **126**, 011102 (2021)

First lab clock Sr1





So far:
probing of ^{87}Sr in large chamber,
in vacuum coils

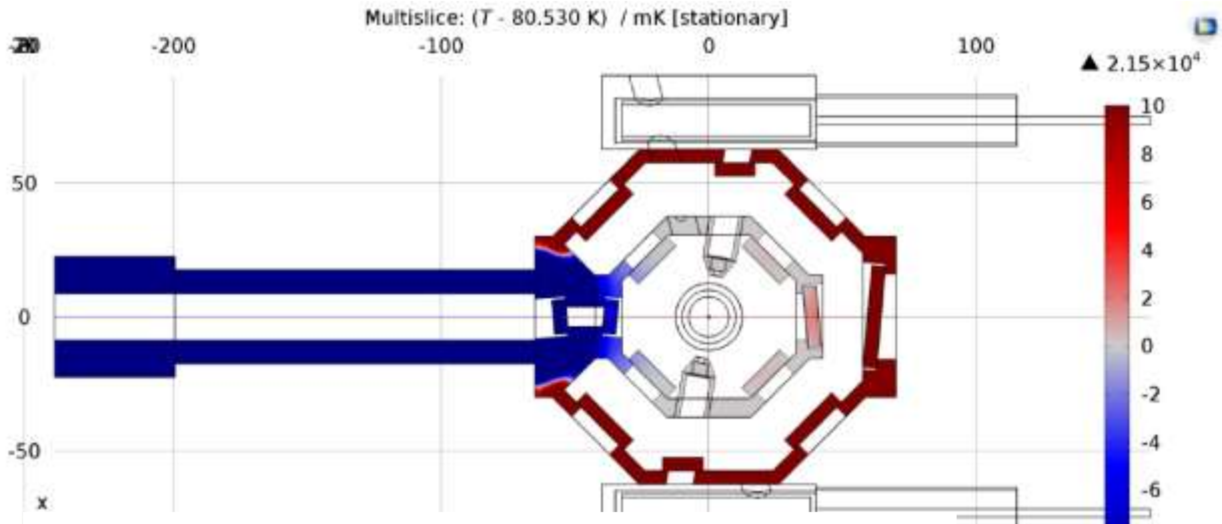
$\Rightarrow$ thermal gradients, large uncertainty (interaction with radiation)

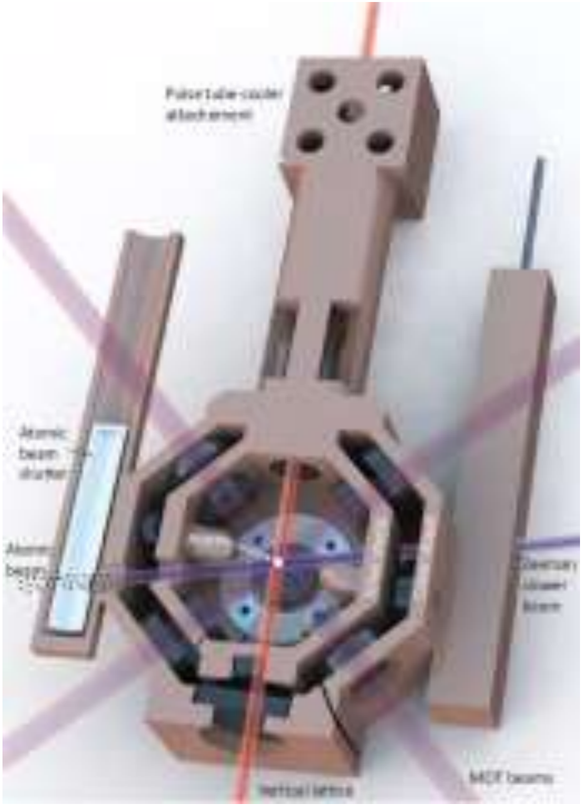
careful with atomic coefficients: Lisdat *et al*, Phys. Rev. Res. **3**, L042036 (2021)

Cryogenic lab clock Sr3

in-vacuum heat shield

operation between 300 K and 80 K



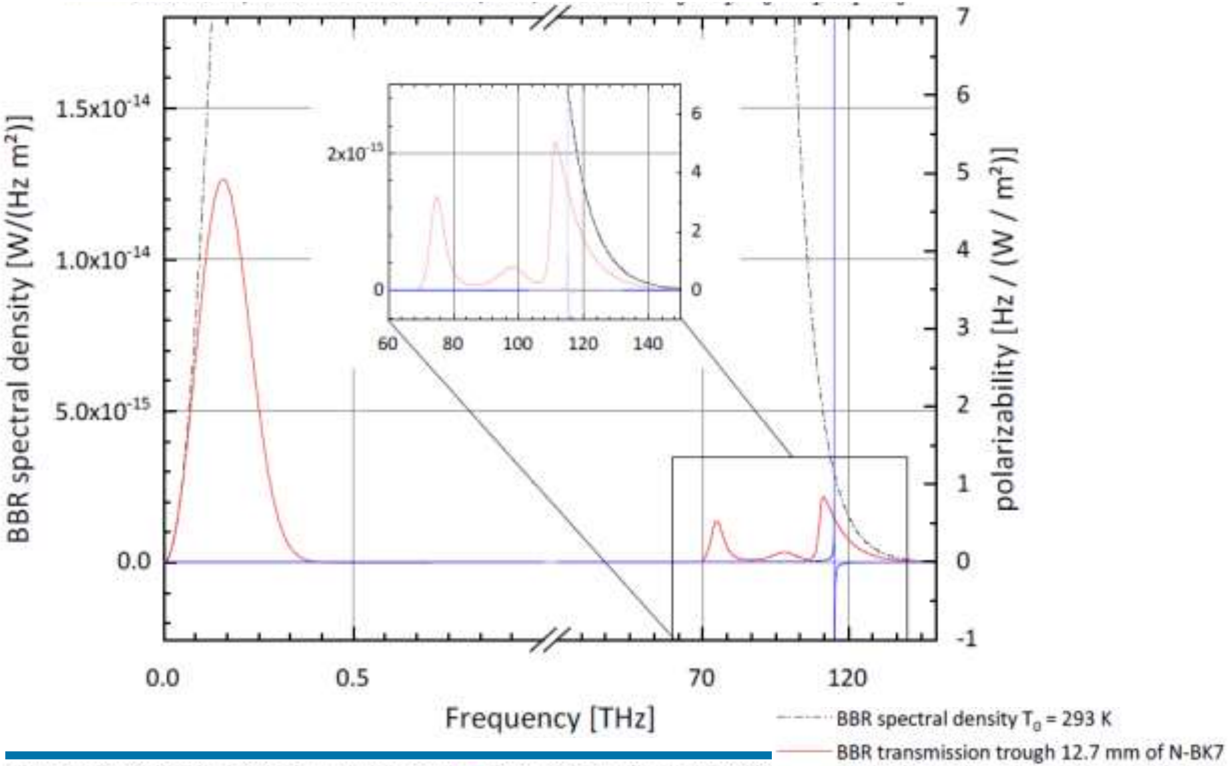


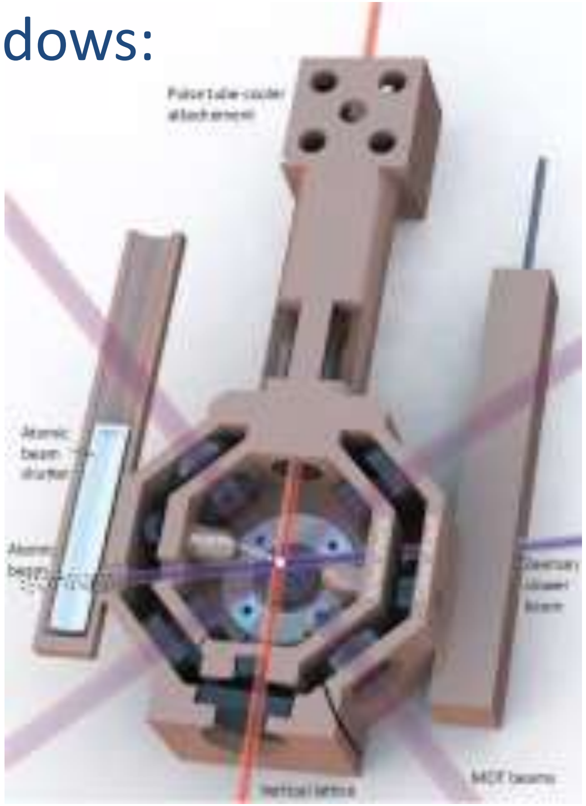
ΔT = 30 mK on inner shield

simulation and measurements are consistent

Cryogenic lab clock Sr3

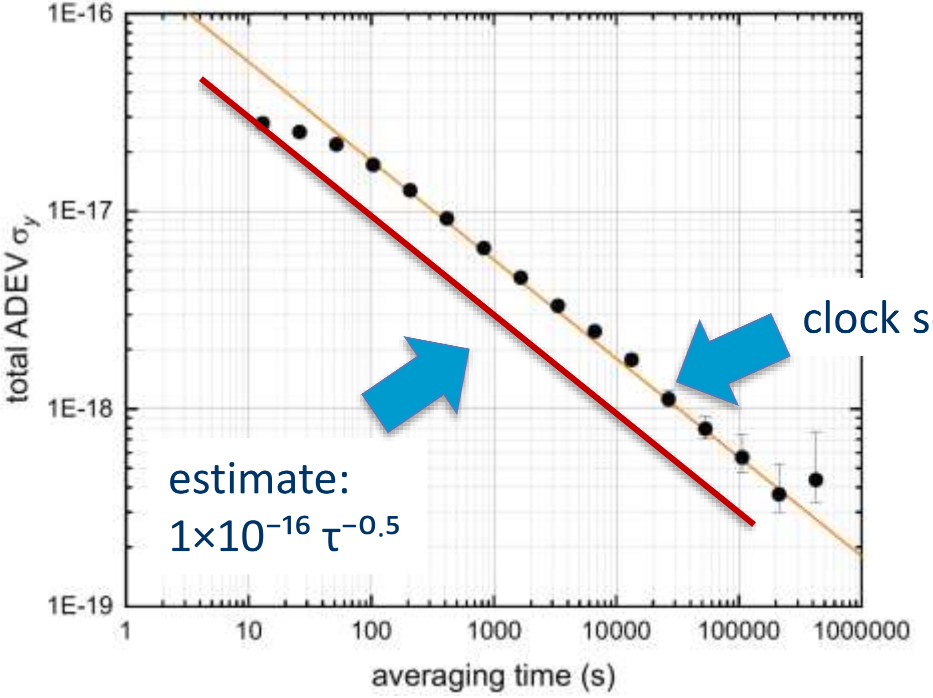
residual blackbody radiation transmission of windows:



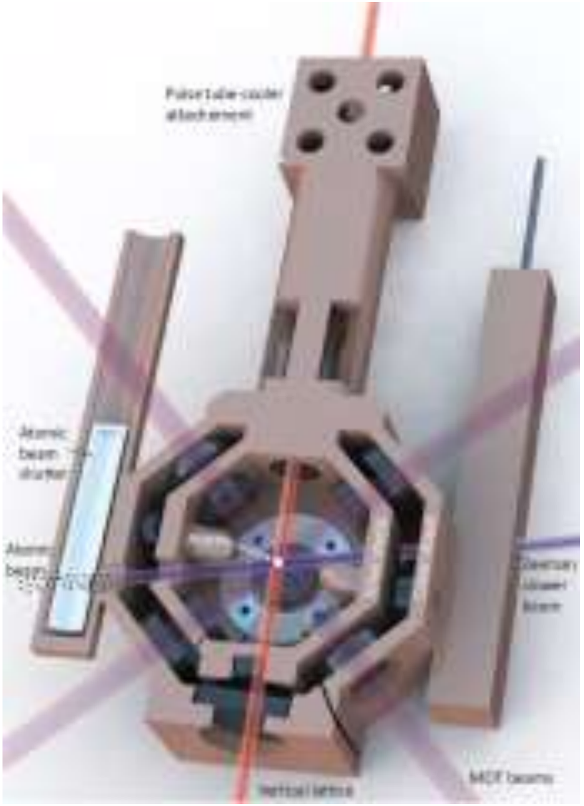


Cryogenic lab clock Sr3

high clock stability thanks to ultra-stable cavities



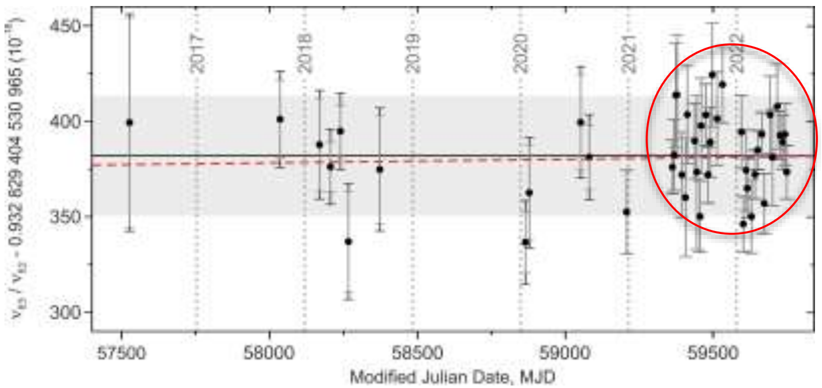
clock self-comparison



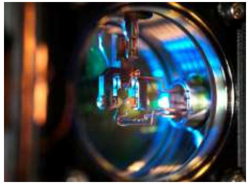
Matei *et al*, Phys. Rev. Lett. **118**, 263202 (2017)

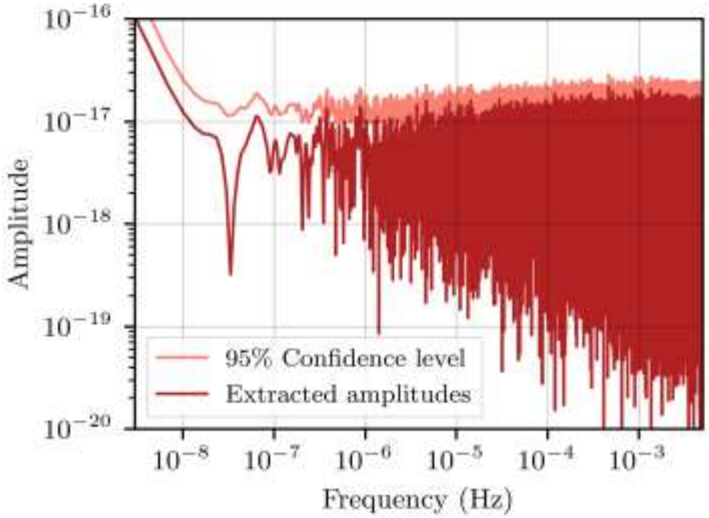
Search for a characteristic oscillation of ν(E3)/ν(E2)

- Investigation using data from the last 1.5 years
- No indications for significant deviations from white frequency noise
- Motivates a search for ultra-light bosonic dark matter [1]



Lomb-Scargle periodogram

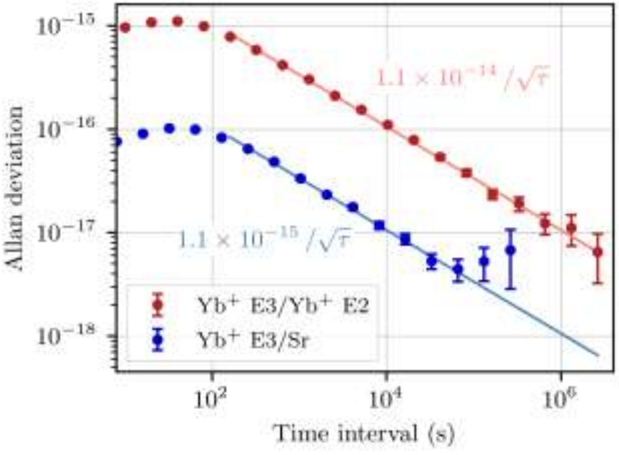




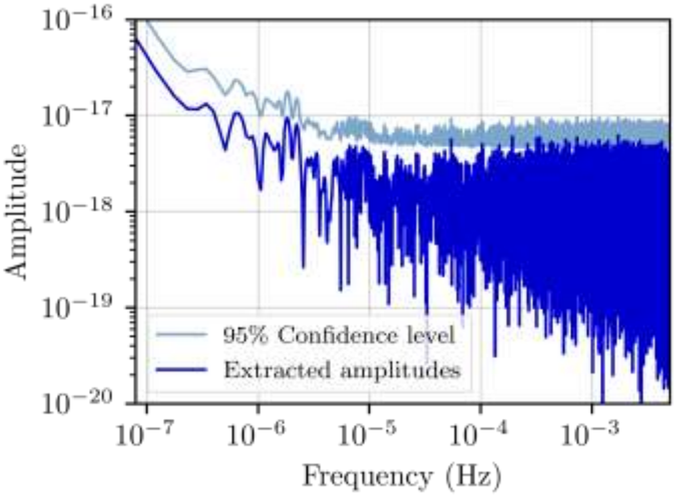
[1] A. Arvanitaki *et al.*, PRD 91, 015015 (2015)

Search for a characteristic oscillation of ν(E3)/ν(Sr)

- Data from measurement campaign in spring 2022
- High stability of lattice clock + high sensitivity of $^{171}Yb^{+}$ E3 transitions to variations of α
- Motivates a search for ultra-light bosonic dark matter [1]



PRELIMINARY:

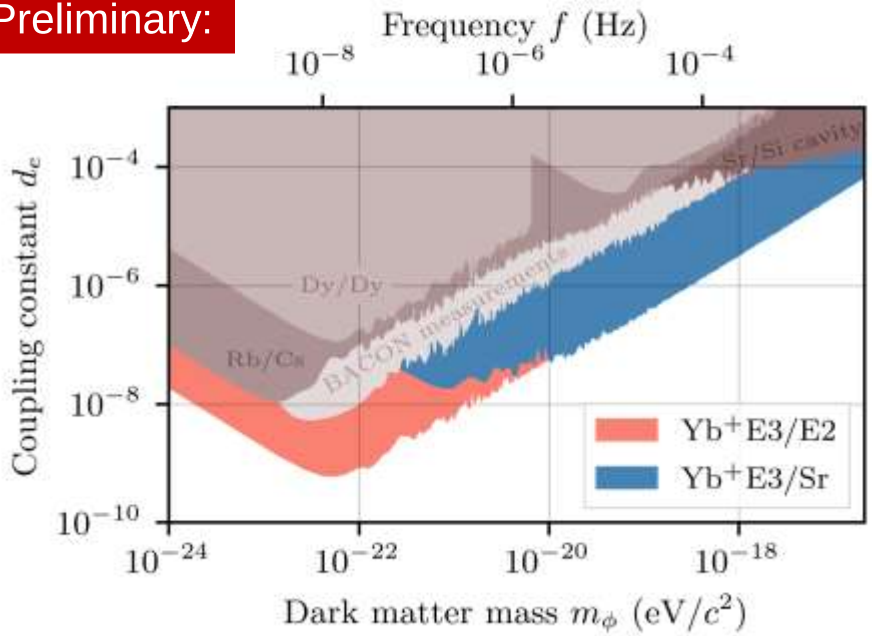


[1] A. Arvanitaki *et al.*, PRD 91, 015015 (2015)

Search for ultra-light dark matter

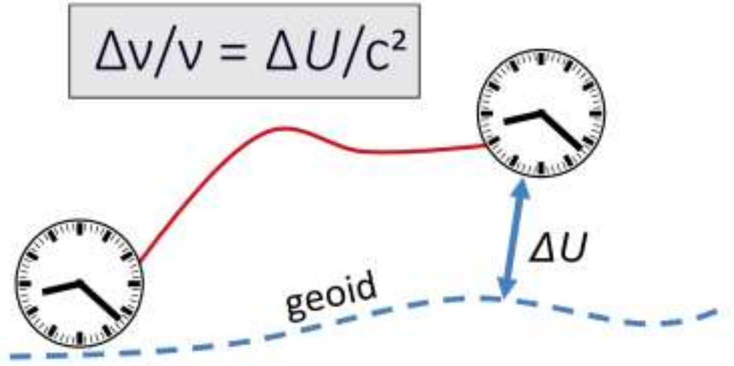
- Ultralight bosonic dark matter expected to locally behave like a classical field with a frequency given by the Compton frequency [1]
- A coupling d_e of such a dark matter field to α would lead to coherent oscillations α
- Re-scaling due to stochastic nature of dark matter [2]

Preliminary:



[1] A. Arvanitaki et al., PRD 91, 015015 (2015)
[2] G.P. Centers et al., Nat. Com. 12,7321 (2021)
[Dy/Dy] K. Van Tilburg et al., PRL 115, 011802 (2015)
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)

Transportale clocks: chronometric levelling



$$\frac{\Delta\nu}{\nu} = 1 \times 10^{-18} \iff \Delta U \cong 0.1\,\frac{\mathrm{m}^2}{\mathrm{s}^2} \iff \Delta h \cong 1\ \mathrm{cm}$$

fractional frequency difference | geopotential | height

Wish list:

- two clocks
- a link to compare their frequencies
- frequency offset/ratio must be know
- frequency resolution of 10^{-18}
- flexibility in deployment

Transportable Sr lattice clock Sr2

- so far: setup in car trailer, uncertainty 2×10^{-17} instability $2 \times 10^{-15}\, \tau^{-0.5}$

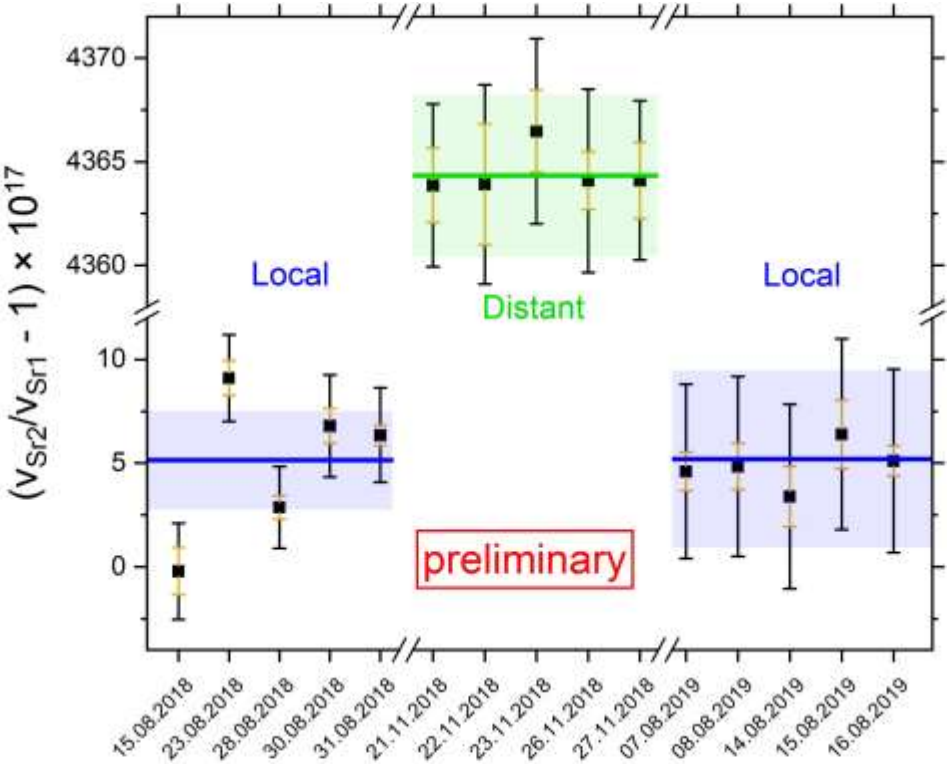
Koller *et al*, Phys. Rev. Lett. **118**, 073601 (2017)
Grotti *et al*, Nature Phys. **14**, 437 (2018)

Transportable Sr lattice clock Sr2

Munich – Braunschweig 2018

- First spectroscopy 5 days after arrival
- Some trouble with the fibre link
- Break of a few weeks
- Four days to recover clock operation
- Five days for data taking

Transportable Sr lattice clock Sr2



Munich – Braunschweig 2018

- Good: same ratio before and after transportation
- Sr–Sr comparison should have a local ratio of 1, something is not good
- We would not mind if we had different clocks (where we do not know the frequency ratio)
- Assume that the clocks keep their frequency
- Derive $\Delta U_{\text{clock}} = 3917.84(397)\ \text{m}^2/s^2$
- Compare with $\Delta U_{\text{geod}} = 3915.94(42)\ \text{m}^2/s^2$

Transportable Sr lattice clock Sr2

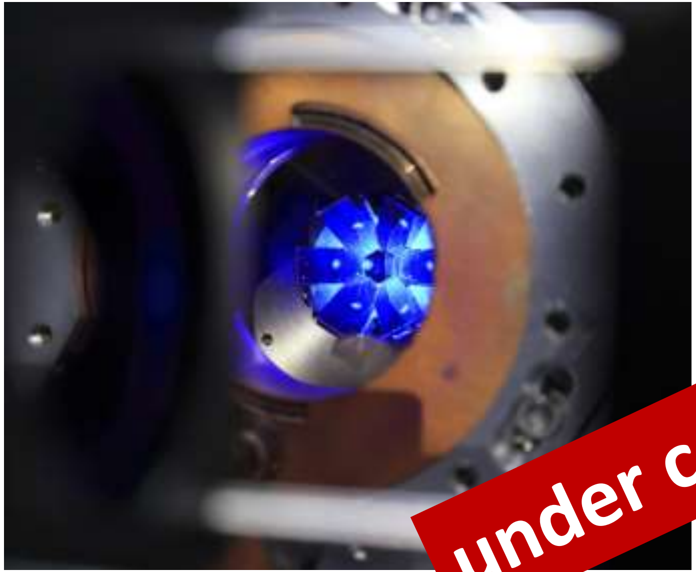
- so far: setup in car trailer,
  uncertainty 1×10^{-17}
  instability $2\times10^{-15}\,\tau^{-0.5}$

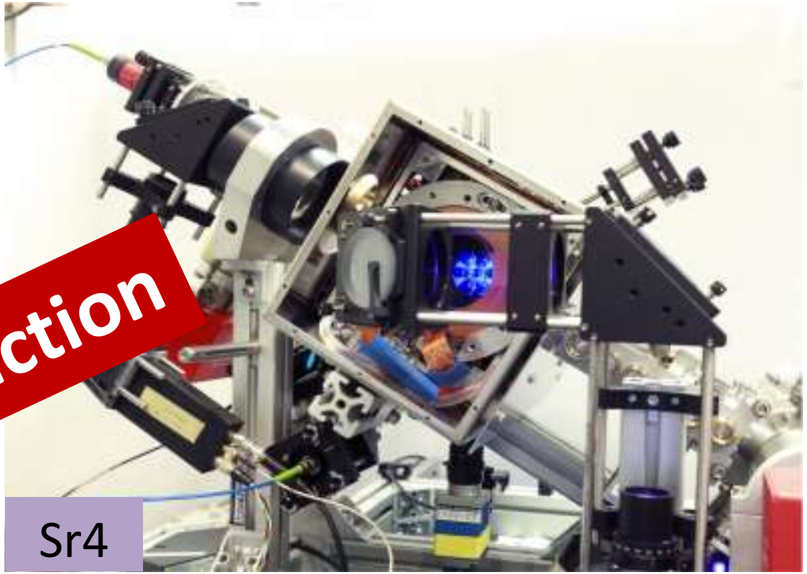
- application:
  chronometric levelling – determination of height differences by measurement of relativistic redshift

- 10 cm – 20 cm height resolution insufficient for geodesy

Koller *et al*, Phys. Rev. Lett. **118**, 073601 (2017)
Grotti *et al*, Nature Phys. **14**, 437 (2018)

Transportable Sr lattice clock Sr4





under construction

Technical solutions:

Phys. Rev. A **101**, 013420 (2020),

J. Phys. B **47**, 075006 (2014),

Nature Phot. **9**, 185-189 (2015)

Transportable clock Sr4

operation 300 K to 80 K

minimizing leading uncertainty (BBR)

Transportable Sr clock laser

- Clock stability is strongly dependent on clock laser performance
- Rigid cavity mounting is challenging (seismic perturbations)
- Short cavities (5 cm – 10 cm), relatively high thermal noise floor

New generation:

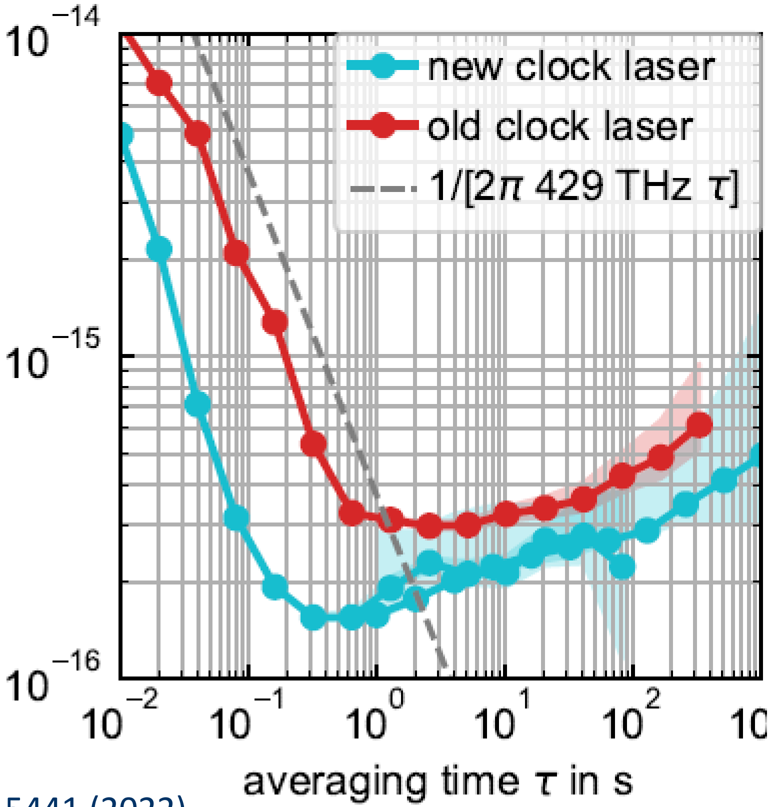
- 20 cm spacer
- single crystalline mirror coatings (operation at subharmonic of clock transition)

Häfner *et al*, Opt. Expr. **28**, 16407 (2020), Herbers *et al*, Opt. Lett. **47**, 5441 (2022)

Transportable Sr clock laser

New generation:

- significantly lower noise
- not as low as expected for single-crystalline coatings
- fibre noise cancellation to
  - frequency doubler/atoms
  - frequency comb
  - cavity
- no active stabilization of residual amplitude modulation (RAM)



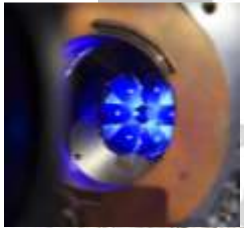
Häfner *et al*, Opt. Expr. **28**, 16407 (2020), Herbers *et al*, Opt. Lett. **47**, 5441 (2022)

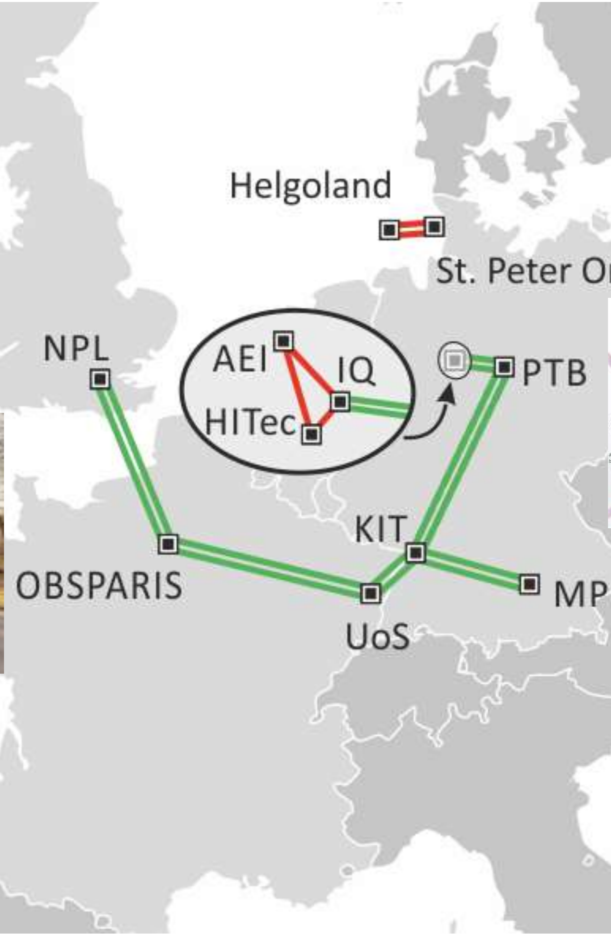
Transportable Sr lattice clock Sr4

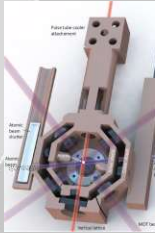
Hopefully early in 2023:

full transportable lattice clock with

- low-10^{-18} uncertainty and
- mid 10^{-16} instability (in 1 s)





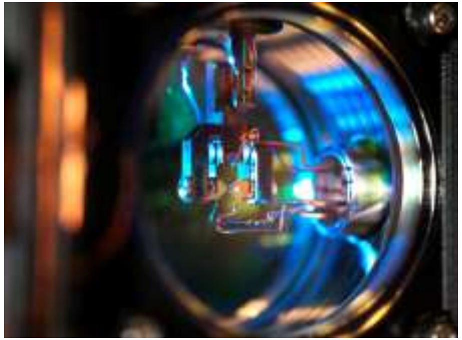


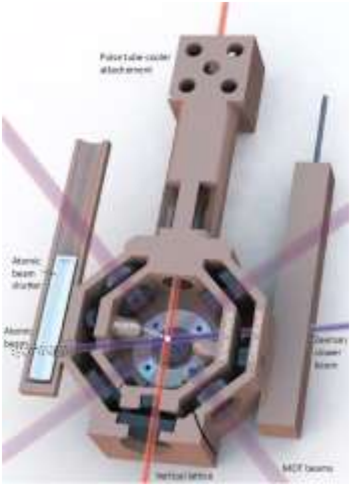
Application in chronometric levelling centimetre height resolution

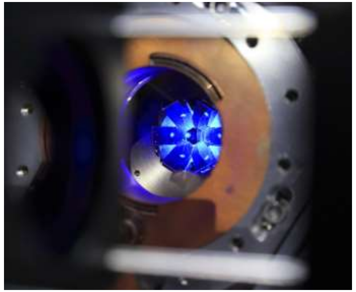
Terra SFB 1464 and ICON network

In conclusion:

- **first Sr clock (Sr1)**
  comparisons with Cs & Yb^+
  LPI tests
- **cryogenic lab clock (Sr3)**
  cooling in homogeneous environment
  low 10^{-18} uncertainty
- **transportable clock (Sr2 & Sr4)**
  new insights in old data
  clock laser with 10^{-16} instability
  single-beam MOT + cryo-environment







EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States
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EXC 2123
SFB 1227
SFB 1464