Review of Fieldable Optical Clocks for Precision Timekeeping Applications

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WSTS

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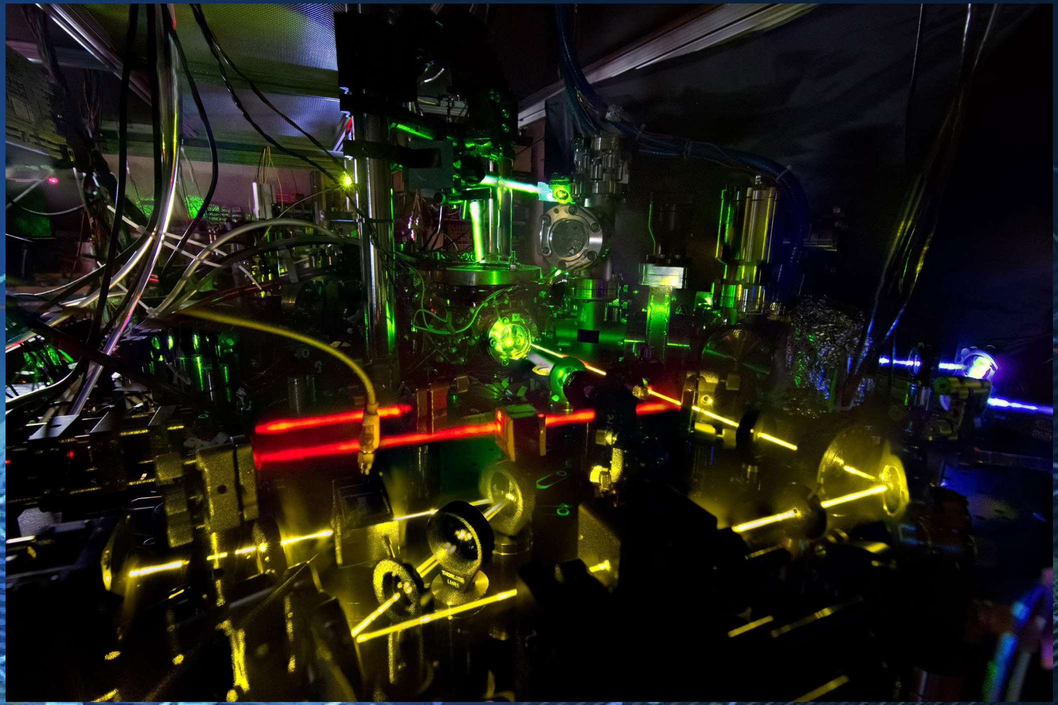
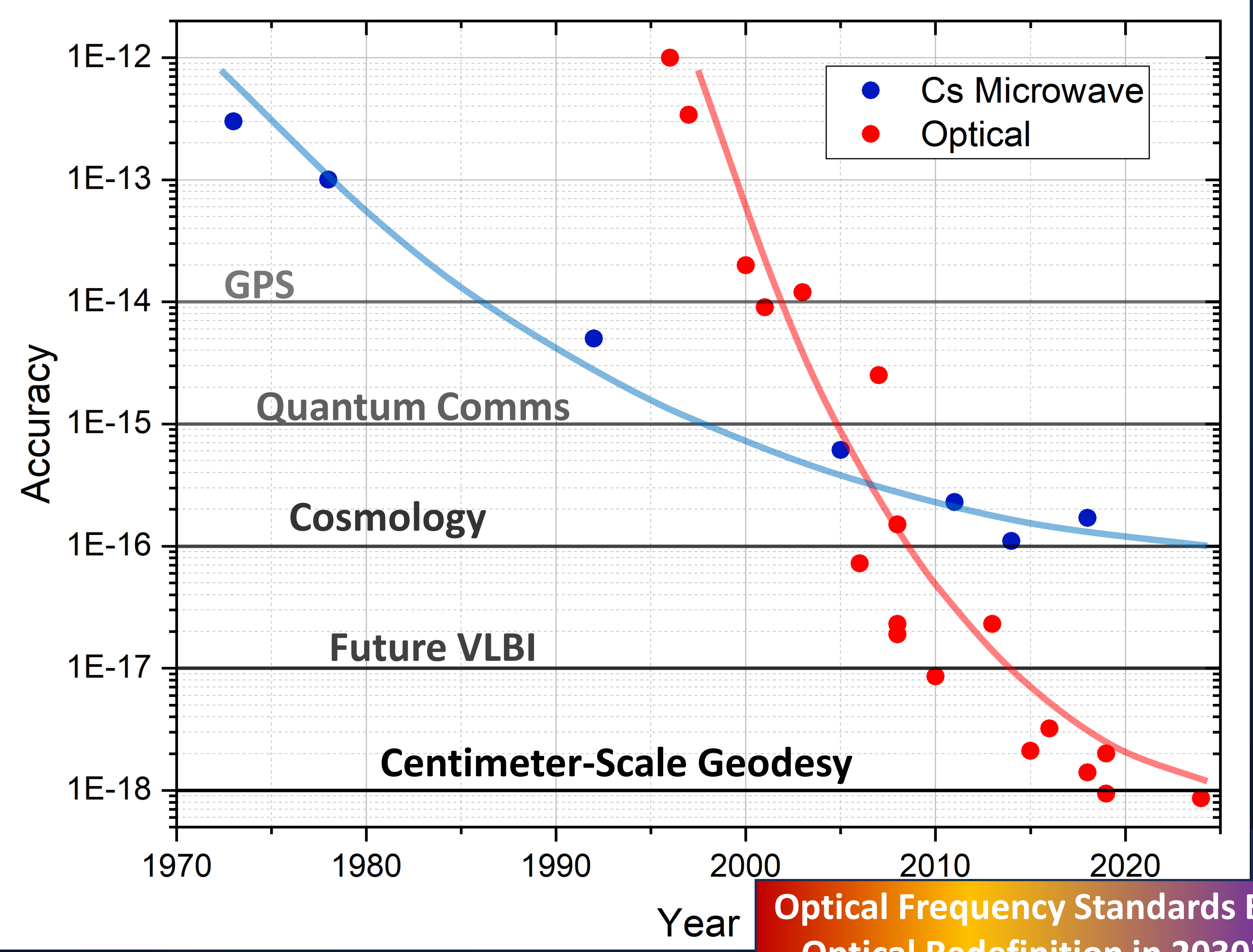
MEASURED Atomics

This Talk:

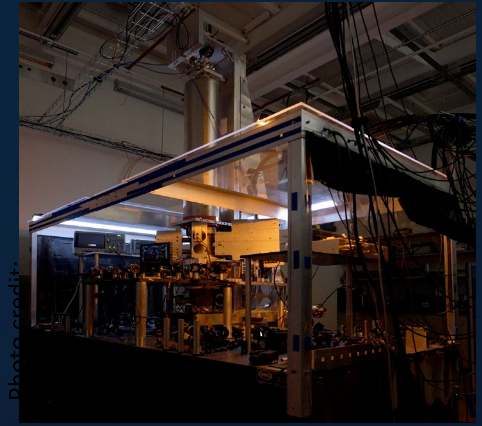
- Frequency Standards Background
- Systems and Tradeoffs
- Applications and Impact



Accuracy of atomic frequency standards

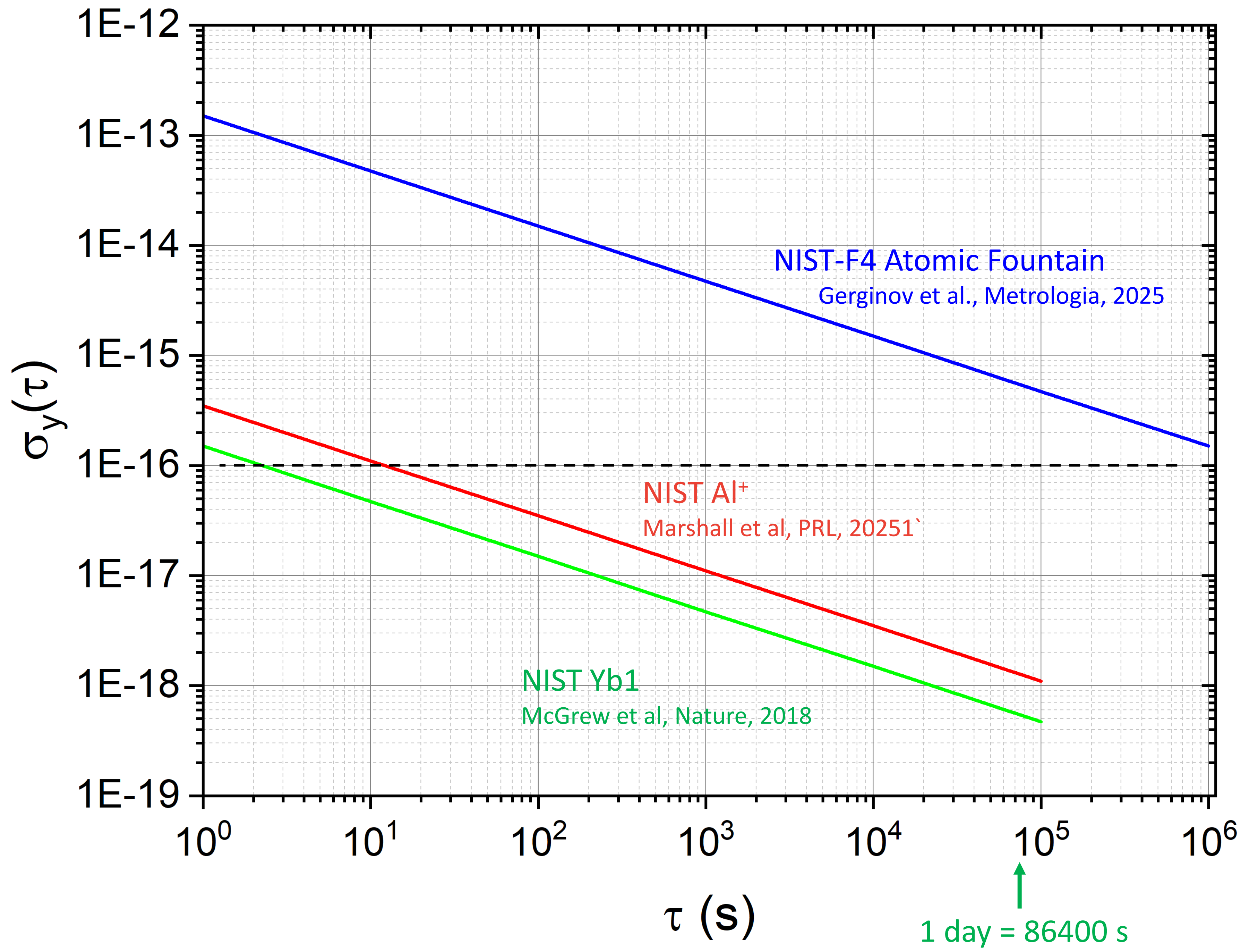


Gerginov, Metrologia, 2025.



Limit to the SI "Hz" as defined in terms of Cesium-133

Optical Frequency Standards Era
Optical Redefinition in 2030?



$$\sigma_y(\tau) \cong \frac{1}{\left({\nu_0}/{\Delta\nu}\right)(SNR)\sqrt{\tau}}$$

Center frequency

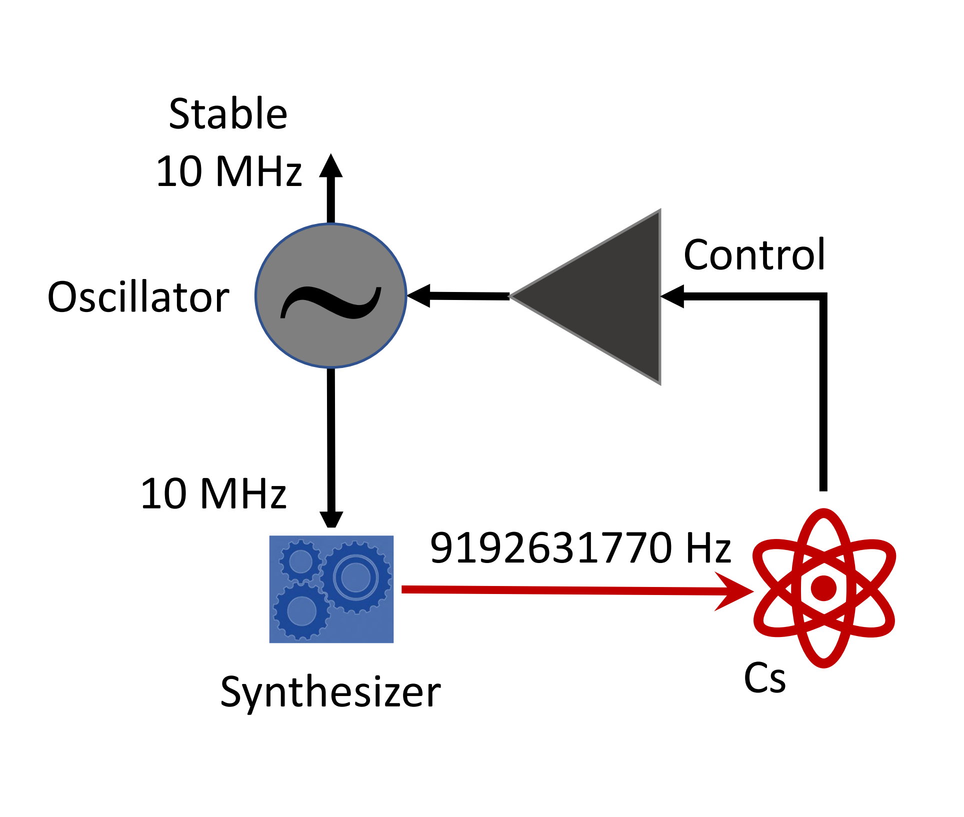
Resonance Width

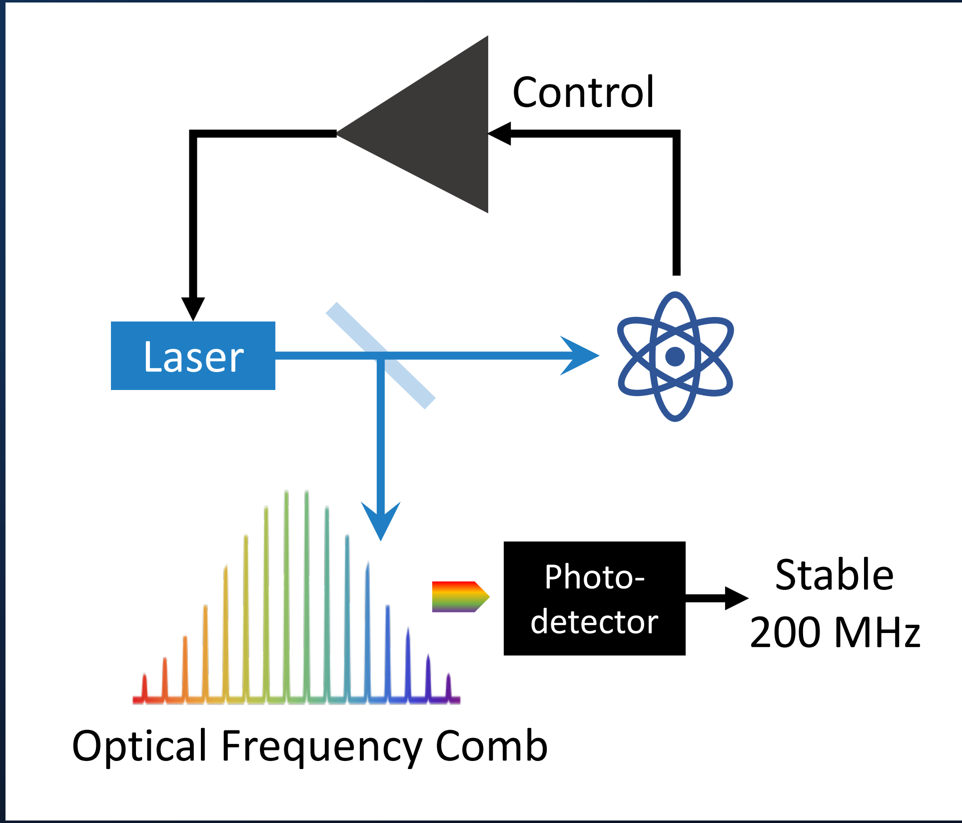
Signal-to-Noise Ratio

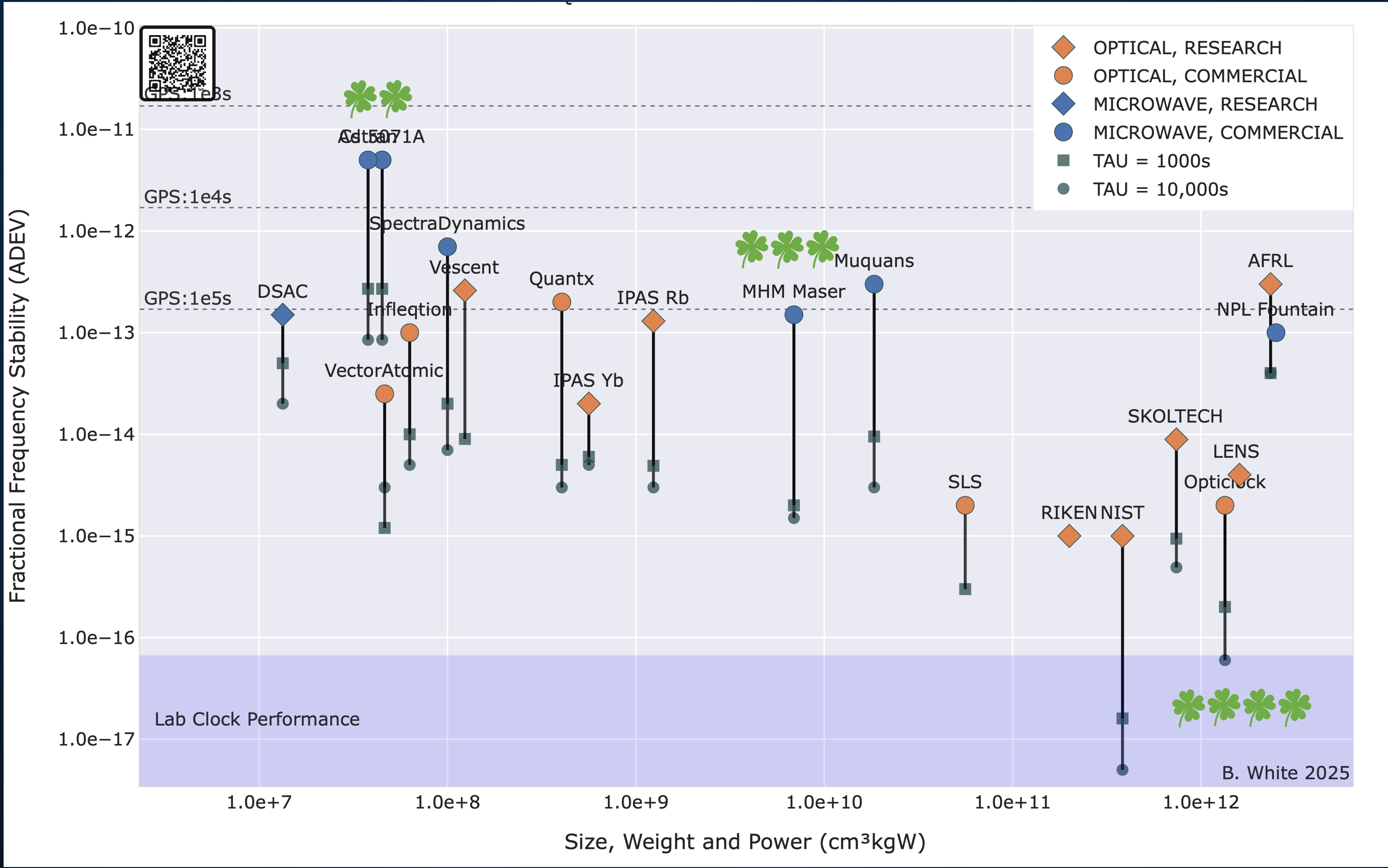
Ion clocks can reach the lowest statistical uncertainty of cesium fountains in < 10 s of averaging!

Lattice clocks reach it in 1 s!

Microwave vs Optical Atomic Clocks



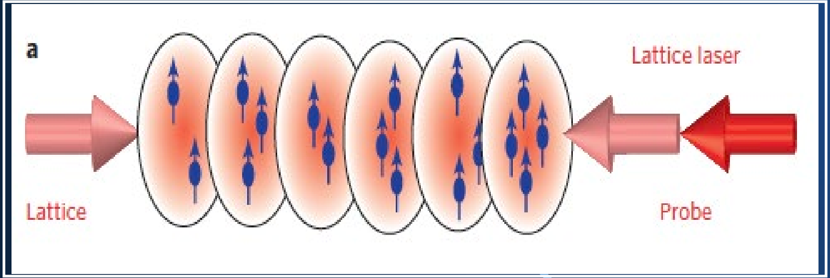




1 SWaP-C Unit:

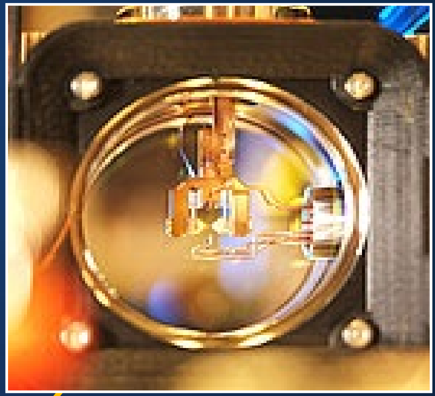
White et al., The SWaP plot: Visualising the performance of portable atomic clocks as a function of their size, weight and power," arXiv:2409.08484

Lattice Clocks



H. Katori, Nature Photonics, 2011

Ion Clocks



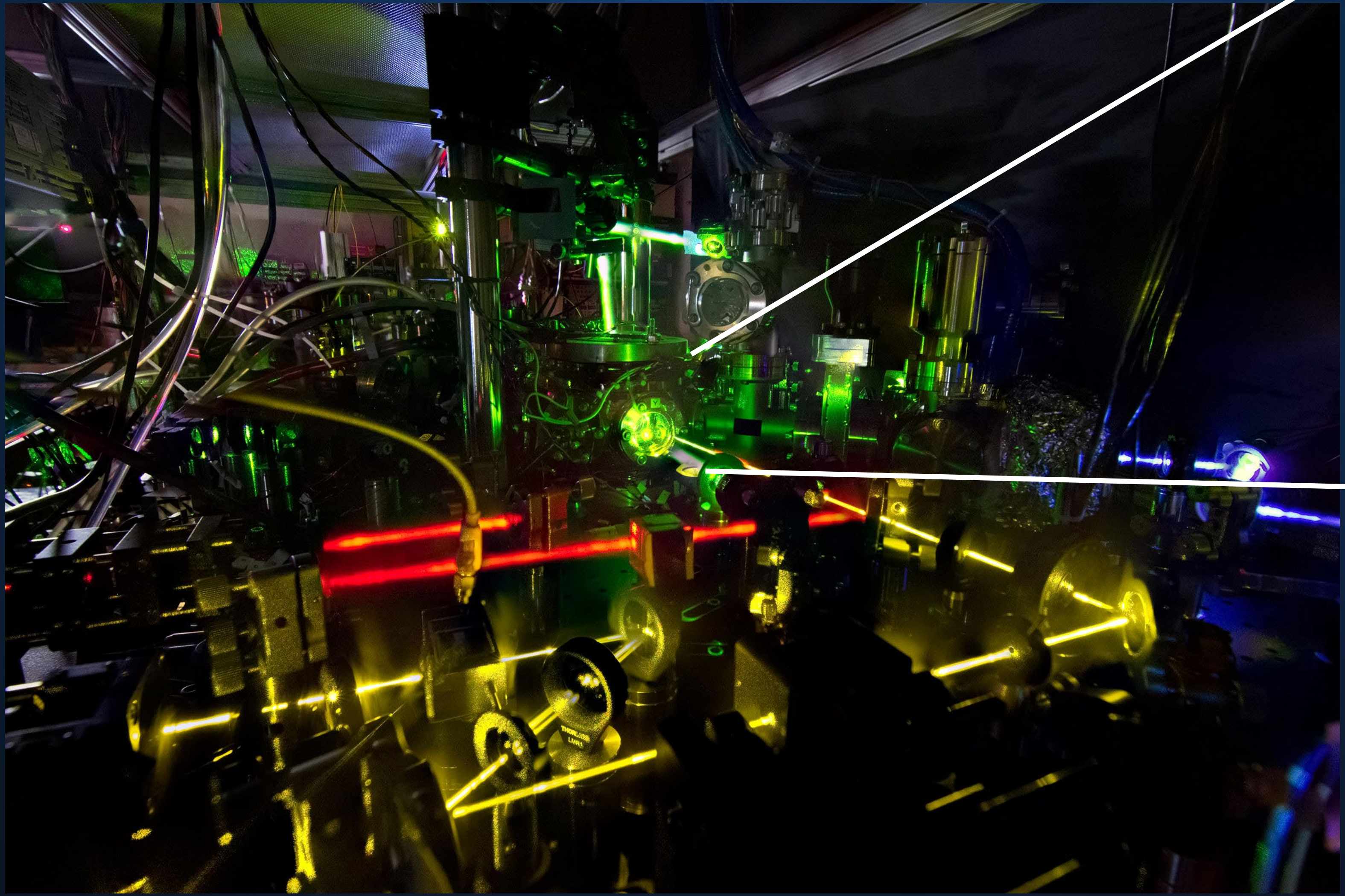
ptb.de

Vapor-Cell Clocks

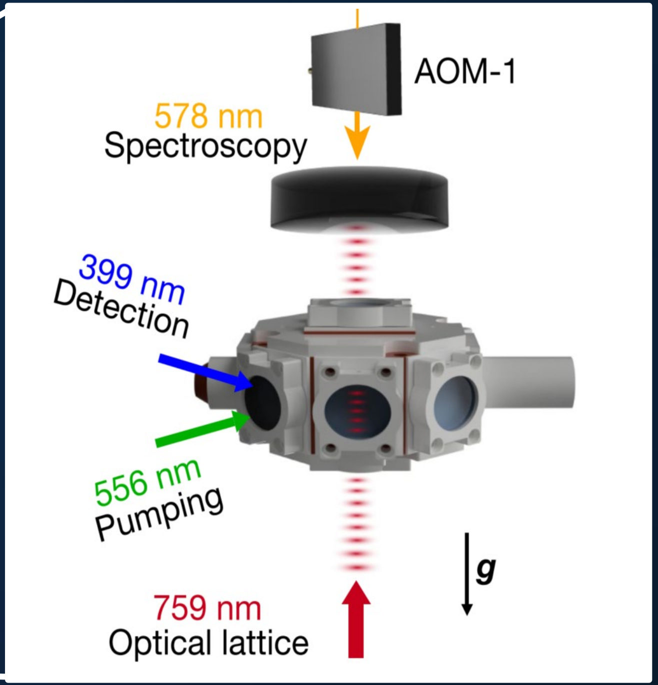
Matt Hummon/NIST

Fieldable Optical Clocks

Optical Lattice Clocks



McGrew, Nature (2018)

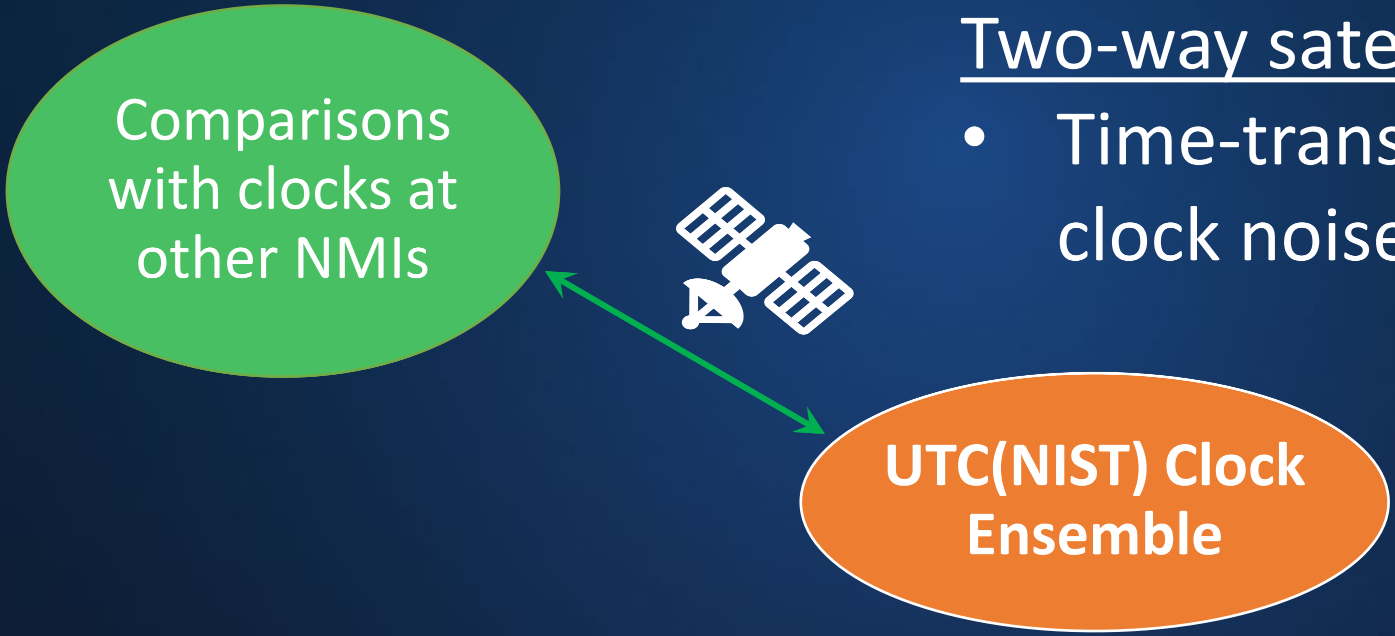


Atoms trapped in optical potentials formed from counter-propagating laser beams

~1000 trapped atoms

Systematic Uncertainty: $\sim 1\times10^{-18}$

Useful for International Time & Frequency Coordination



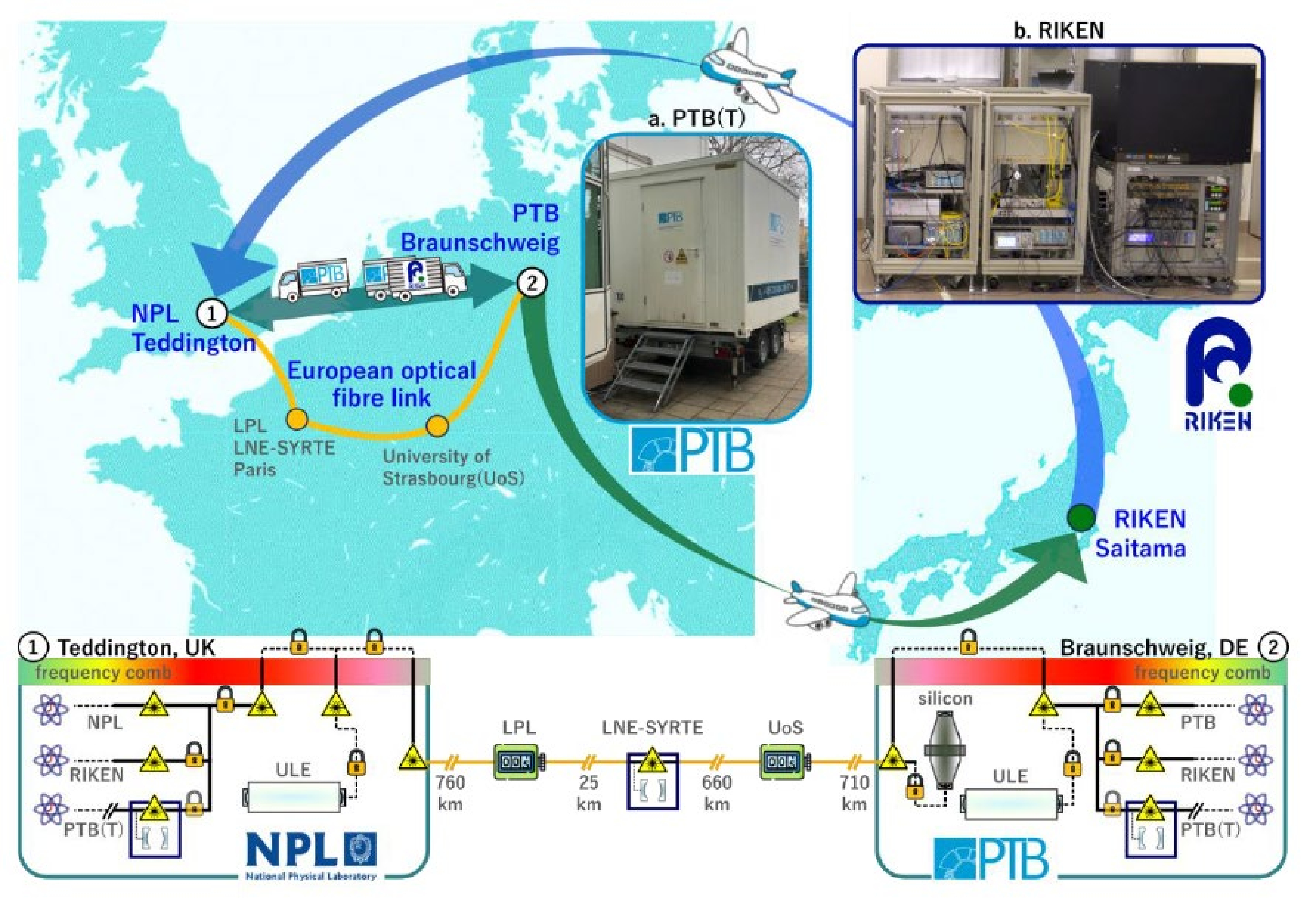
Two-way satellite links (11 - 14 GHz)

- Time-transfer noise is similar to microwave clock noise

Optical performance level comparisons can be made via:

- Optical fiber links (sparse for time transfer in the U.S.)
- Free-space optical links (don’t exist over long distances)
- Transportable optical frequency standards

ICON Collaboration, "International comparison of optical frequencies with transportable optical lattice clocks," arXiv:2410.22973



PTB: Koller et al, "Transportable Optical Lattice Clock with 7×10^{-17} Uncertainty," PRL **118**, 073601 (2017)

RIKEN: Takamoto, M. et al., "Test of general relativity by a pair of transportable optical lattice clocks," Nat. Photon. **14**, 411-415 (2020)

Commercial Transportable Strontium Lattice Clock

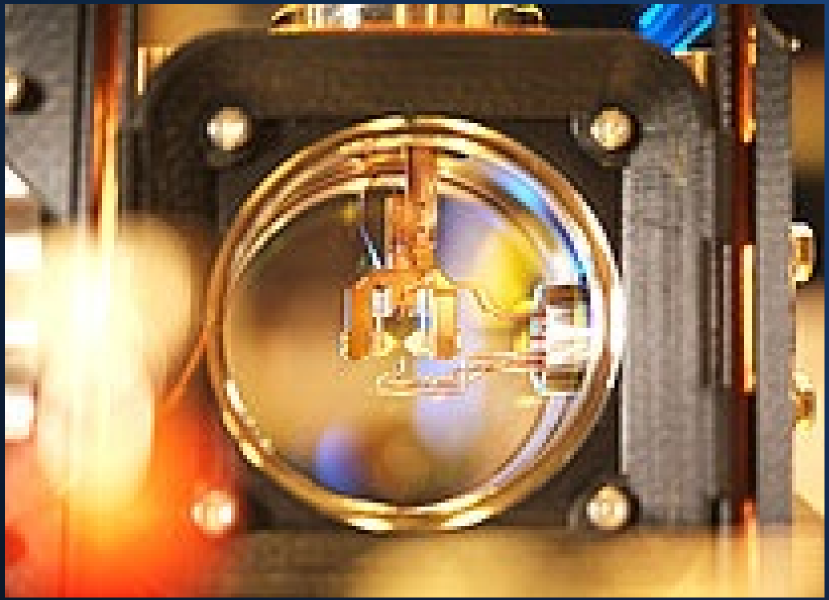
Spun off to Shimadzu from RIKEN (Japan)

Takamoto et al, Nature Photonics, 2020

- Predict $\sim 10^{-18}$ systematic uncertainty
- Taking Orders
    - 1- or 2-year lead time

SWaP-C:

Single-Ion Optical Clocks



http://ptb.de

Popular platform: single trapped Yb^+ ion

- Has two clock transitions: E2 and E3
  - E2 natural lifetime 50 ms
  - E3 natural lifetime several years

PTB:

- E3 systematic uncertainty: 2.7×10^{-18}
  Sanner et al. Nature 567 204-208 (2019)
- E2 systematic uncertainty: 26×10^{-18}
  Lange et al. PRL 126 011102 (2021)

NPL:

- E3 systematic uncertainty: 2.2×10^{-18}
  Tofful et al. Metrolopgia 61, 045001 (2024)
- Contributing to International Atomic Time

Multiple comparisons between NPL & PTB Yb^+ E3 have been made

Commercial Single-ion Yb^+ Clock

Developed under German Opticlock collaboration

Targeted Specs:

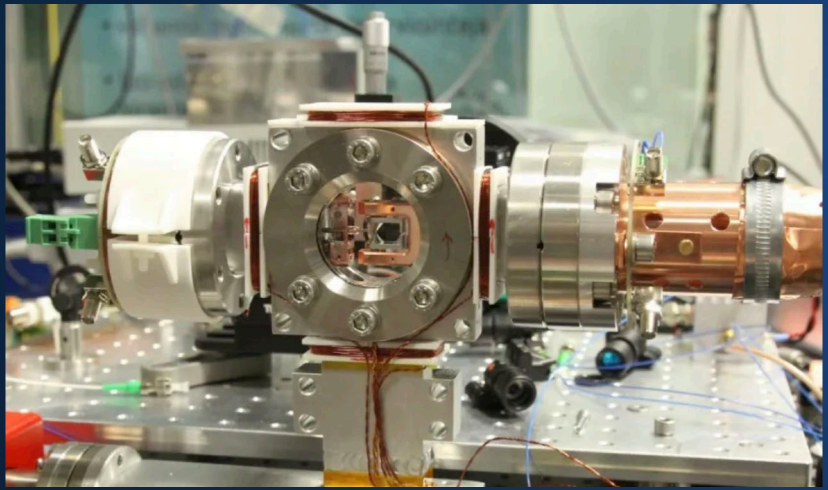
- <1000 kg, <3.5 kW, 2 transportable 19” racks
- Based on E2 transition – low laser power
- 10× better frequency stability than a H-maser

TOPTICA leading commercialization

- $\sim 2\times 10^{-18}$ systematic uncertainty
- $5\times 10^{-15} / \sqrt{\tau}$ statistical uncertainty
- J. Stuhler et al., Proc. SPIE 13920, Quantum Sensing, Imaging, and Precision Metrology IV (2026)
- 1- to 2-year lead time

SWaP-C: ☘☘☘☘

Single-Ion Sr^+ Clock



VTT-MIKES:

- Systematic uncertainty: 0.79×10^{-18}
  Lindvall et al. Phys. Rev. Applied 24, 044082 (2025)
- Relatively simple laser system
- High uptimes – as high as 99%
- Compared to transportable Yb^+ Opticlock
- To begin contributing to International Atomic Time

Being commercialized by Stable Laser Systems:

- ~ 6 ft of rack height, includes a comb
- 200 kg, ~ 235 W.

https://stablelasers.com/clocks/

SWaP-C: 

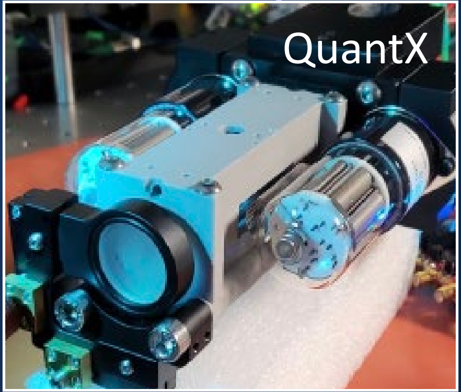
Commercial Vapor-Cell Optical Clocks

Iodine

Vapor-Cell Optical Clocks

Acetylene

2-Photon Rubidium

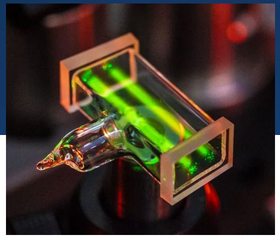


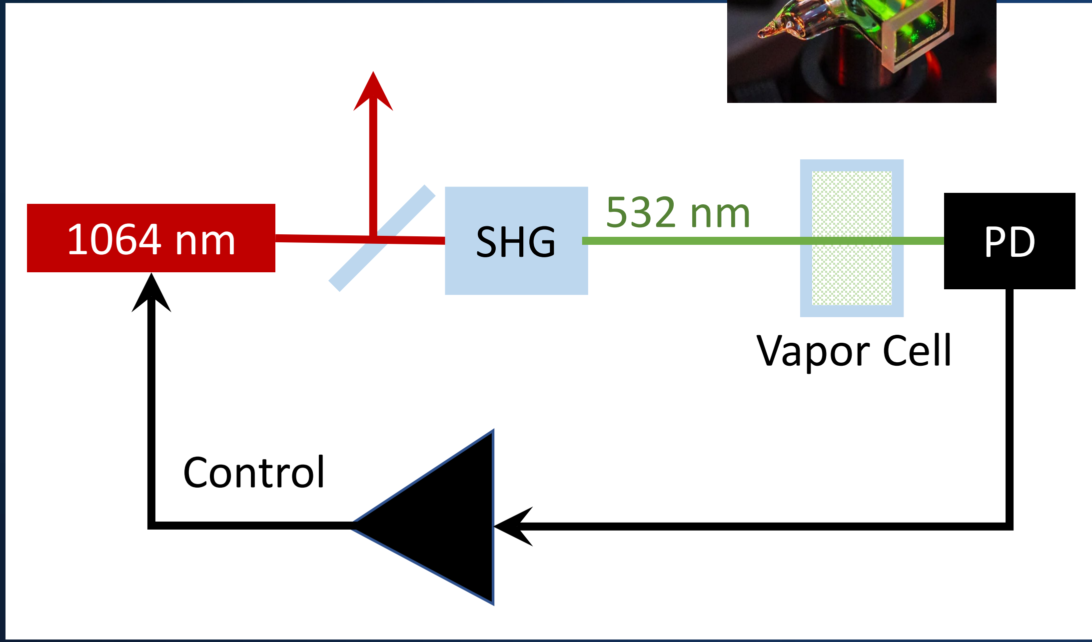
<u>Much simpler</u> than lattice and single-ion optical clocks:

- No laser cooling
- Only need the clock laser plus a frequency comb
- Significantly lower SWaP-C than other types of optical clocks

SWaP-C: 🍀🍀 – 🍀🍀🍀+

Iodine





Designed for small size and low environmental insensitivity for mobile operation

- 2.5×10^{-14} at 1 s, < 5×10^{-15} at 1 d
- Deployed at sea without dramatic loss in stability
  Roslund et al., "Optical clocks at sea," Nature **628**, 2024
- Used in the NIST time scale
- Developing a 5-liter prototype

SWaP-C: ☘☘☘

2-photon Rubidium – a Well Studied System

Review Article: Obaze-Adeleke et al., Photonics 2025, 12, 513.

Infleqtion Tiqker:

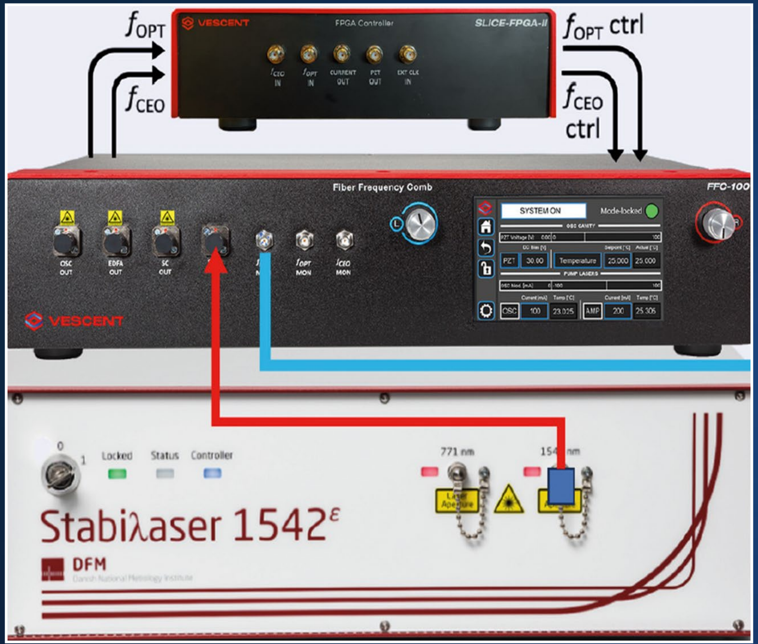
https://infleqtion.com/tiqker/

- 1556 nm laser frequency doubled to 778 nm
- Stability: 3×10^{-13} at 1 s, < 1×10^{-13} at 1 d
- 30 L, 30 kg, 3U rack mount

QuantX TEMPO PILOT:

- Two-color interrogation: 776 and 780 nm for reduced light shifts
  Parrella et al., Phys. Rev. Applied 12, 2019
- Goal Stability: 1×10^{-13} at 1 s, < 8×10^{-15} at 1 d
- 30 L, <30 kg,< 100 W

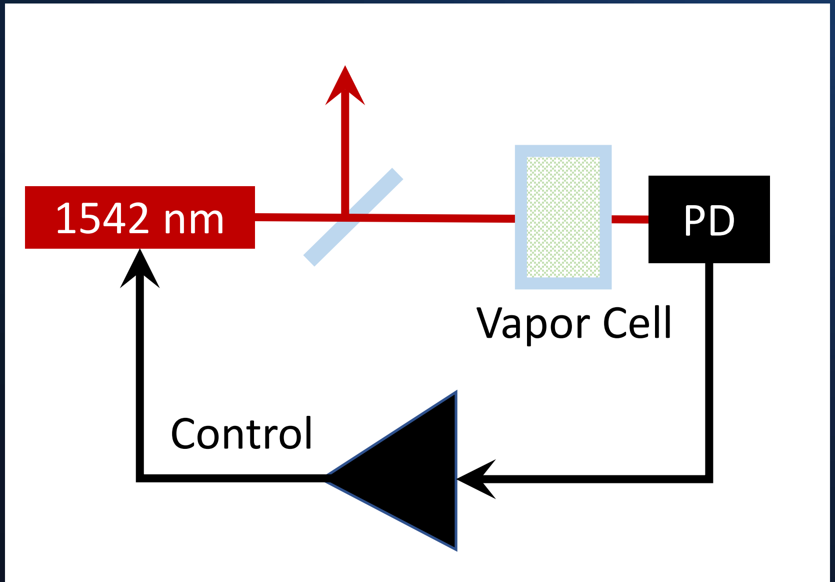
Acetylene



Plug and Play demo with Vescent Frequency Comb and DFM Stabiλaser 1542ε

- $< 3\times10^{-13}$ at 1 s, $< 2\times10^{-14}$ at 1 d

  Droste et. al., CLEO, 2024



Convenient output laser wavelength – 1542 nm in the telecom C-Band

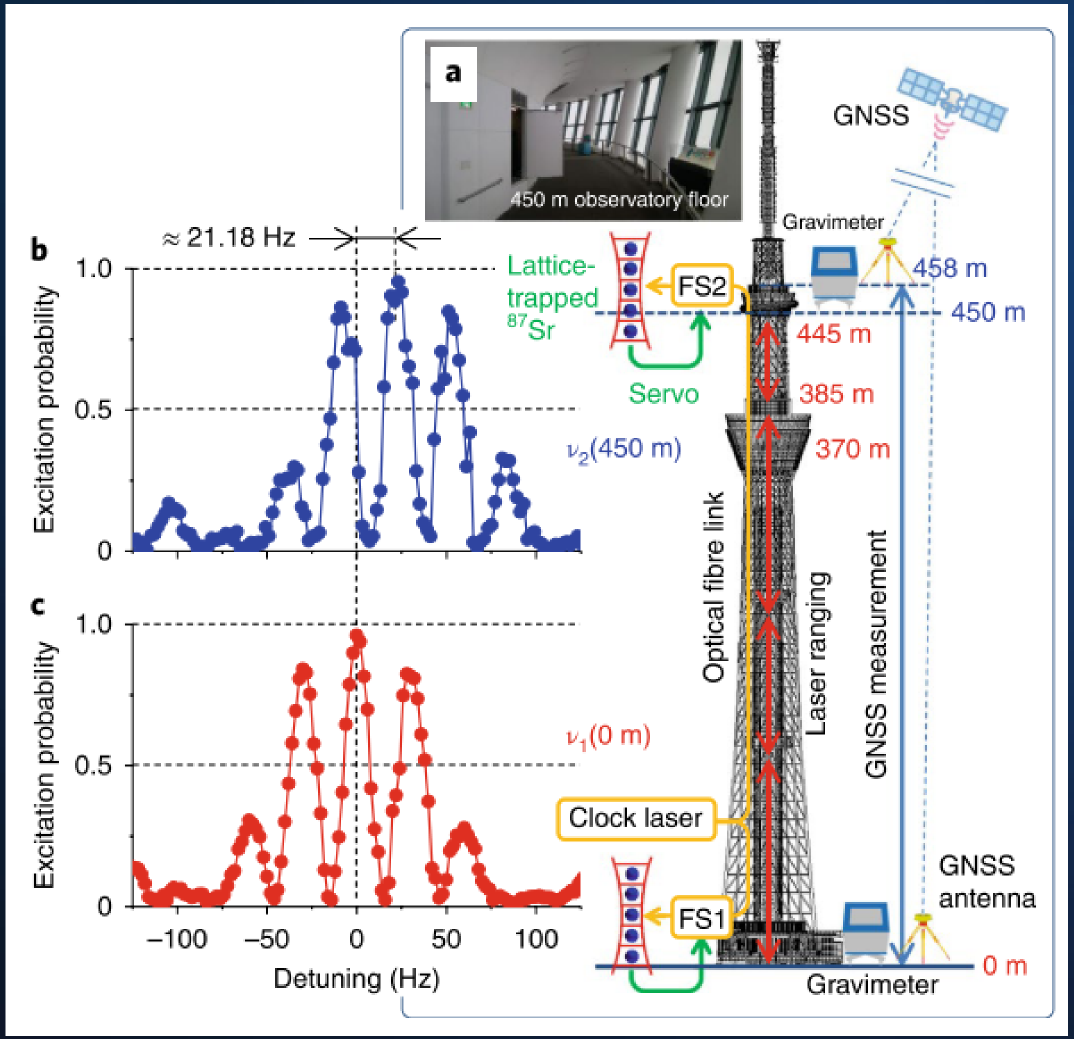
- Good for long-distance fiber transport with low loss
- No laser frequency doubling required

Working on integrating everything into one 4U package

SWaP-C: 

Applications and Impact

Chronometric Leveling



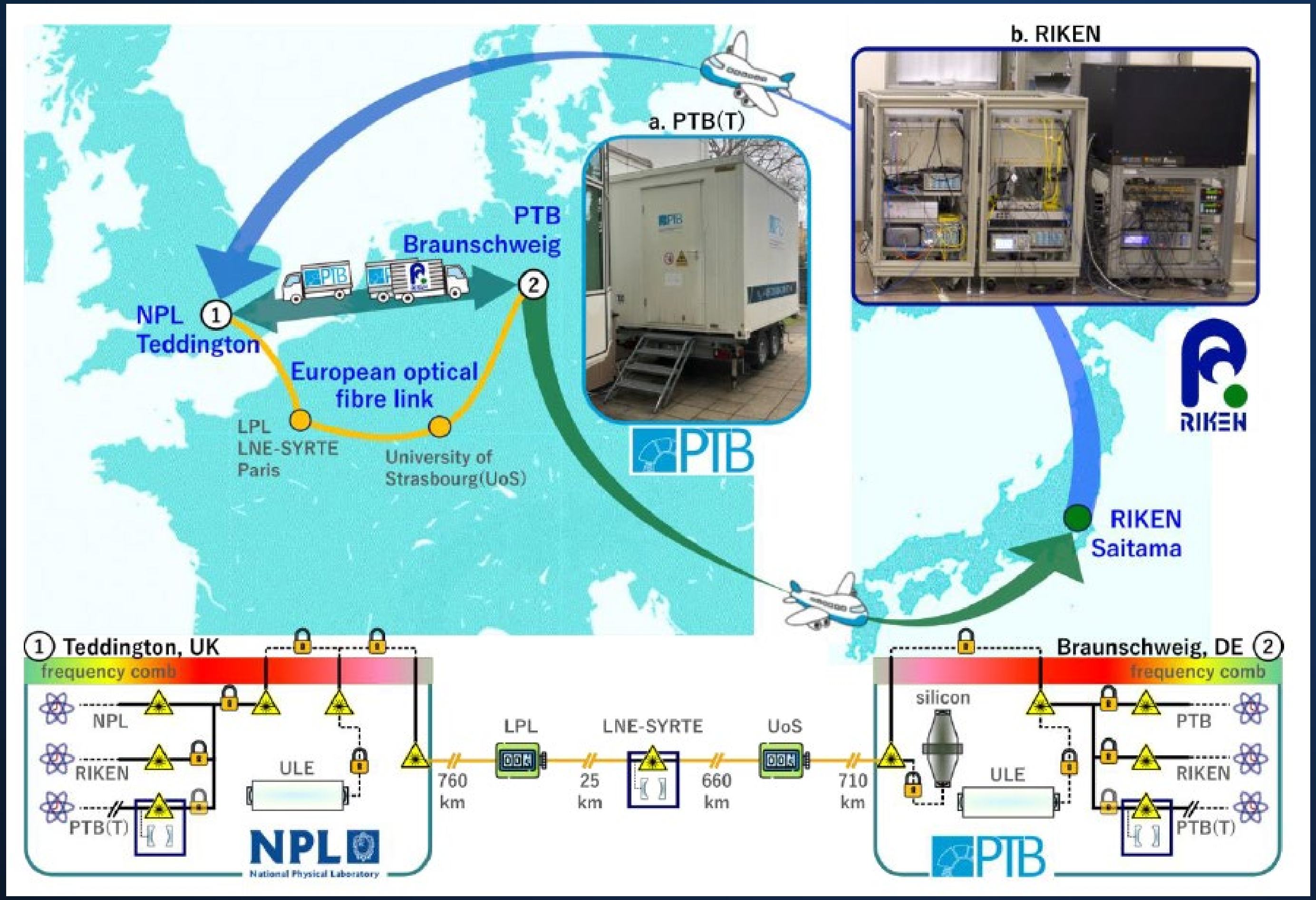
$$\frac{\Delta\nu}{\nu} = (1+\alpha)\frac{\Delta U}{c^2}$$

RIKEN (Japan)

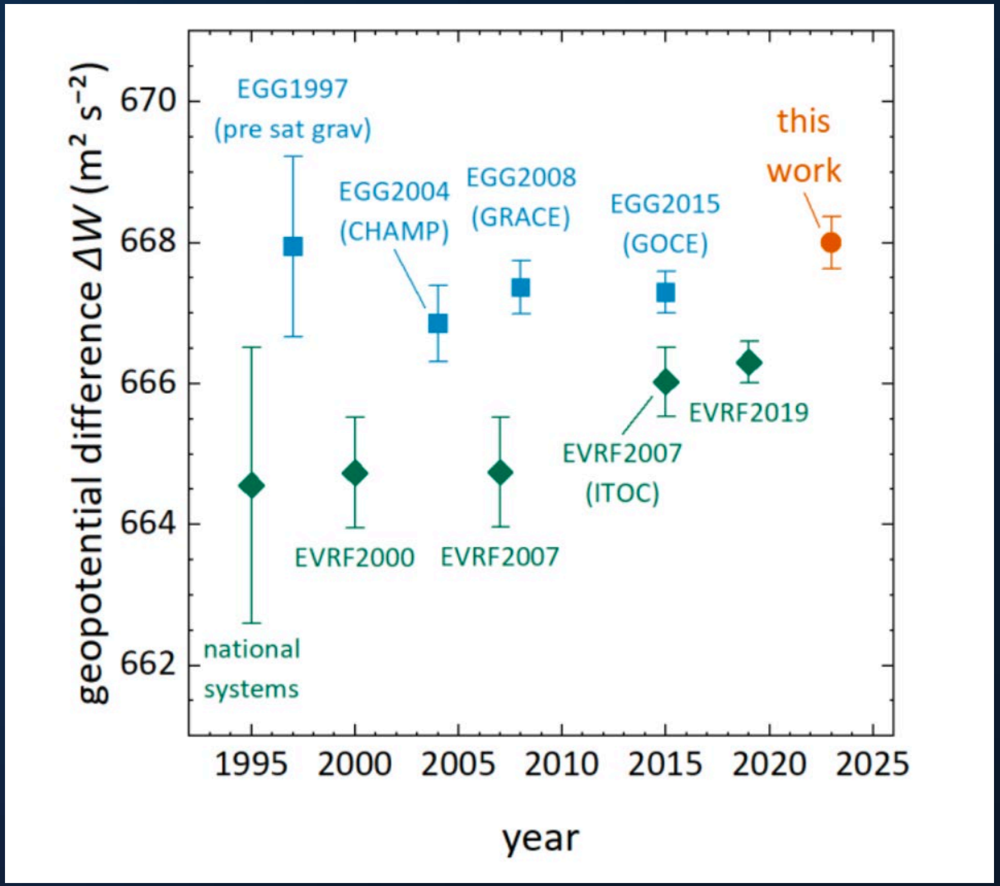
Takamoto et al, Nature Photonics, 2020

- Compared two transportable Sr lattice clocks at Skytree tower in Tokyo
- Constrained α to $\approx 10^{-4}$

Geopotential difference between PTB and NPL

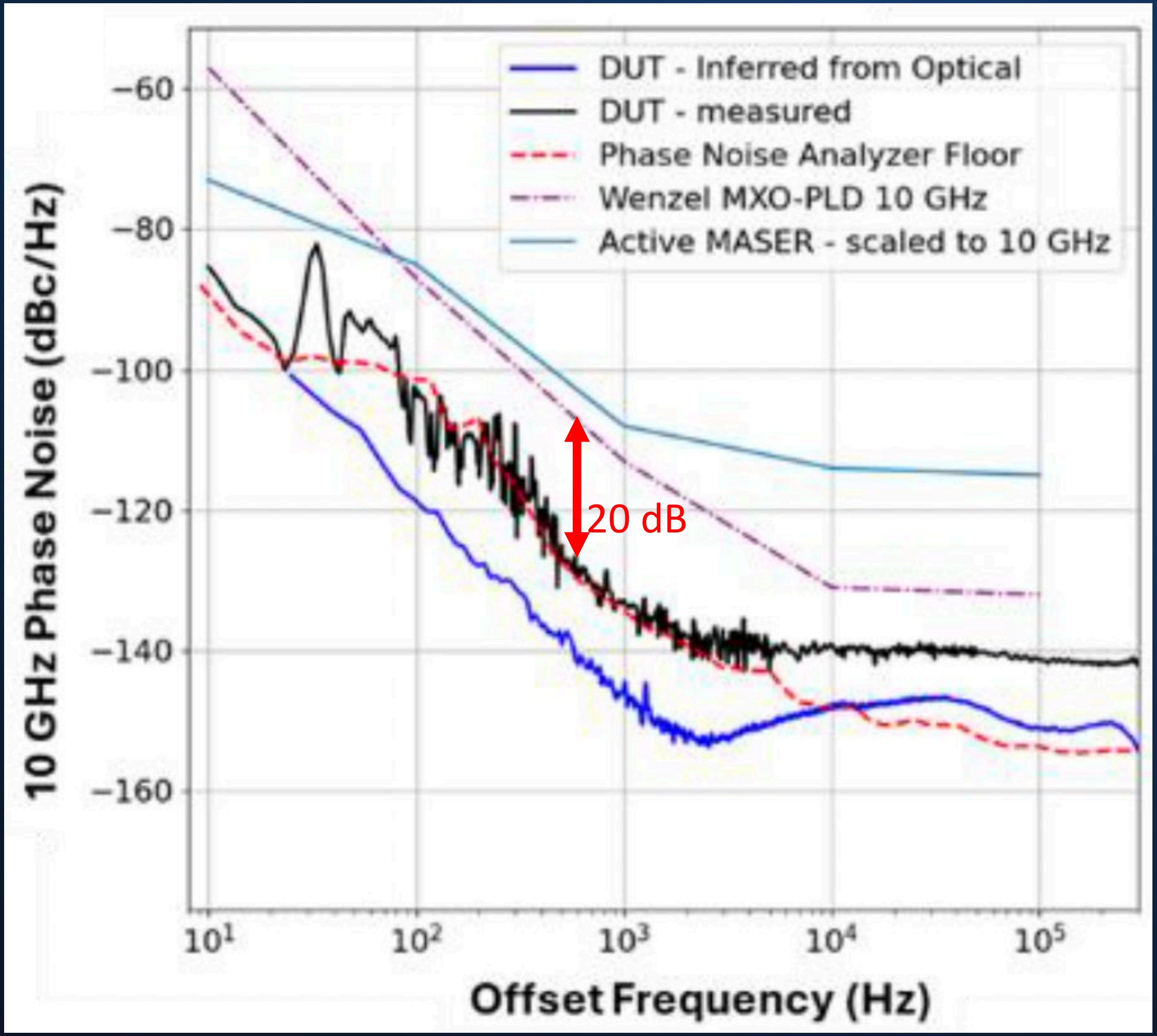


ICON Collaboration, “International comparison of optical frequencies with transportable optical lattice clocks,” arXiv:2410.22973



Clock geopotential measurements consistent with satellite data, inconsistent with classical surveys.

Ultralow phase noise



Optical Frequency Division of a narrow-linewidth laser with a frequency comb

Attar et al., Ultralow-Phase Noise Microwave Generation using Photonics for Enhanced Radar Applications, Proc. SPIE, 2024

- Close-to-carrier phase noise: 10 - 20 dB lower than for a hydrogen maser

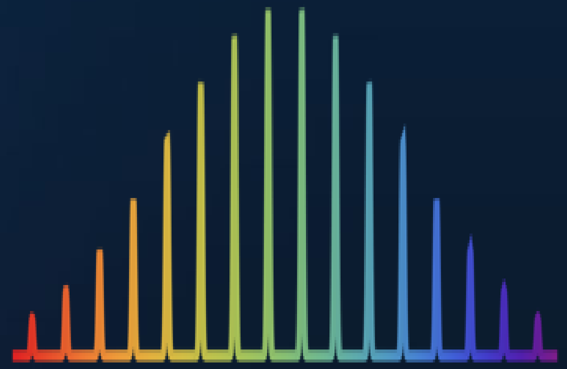
Application: RADAR

- The Doppler shift for a 10 GHz carrier reflected from a drone with v = 10 m/s: 670 Hz.
- **An optically derived radar carrier could detect objects up to 100 × smaller**

Impact of Fieldable Optical Clocks

Vapor Cell optical clocks are already having an impact

- Phase noise lower than hydrogen masers – Useful for time scales, radar, and anywhere you would normally use a hydrogen maser.
- Can have long-term stabilities like Cs beam clocks – Good for holdover needs.
- Multiple companies selling products.



It will take a few years for the highest performance commercial systems to be available in large numbers

- These can be used for interesting geopotential applications
- Can ultimately be used in international time scales as primary frequency standards.

It will take years to know what all of the applications will be!

Thank you!

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