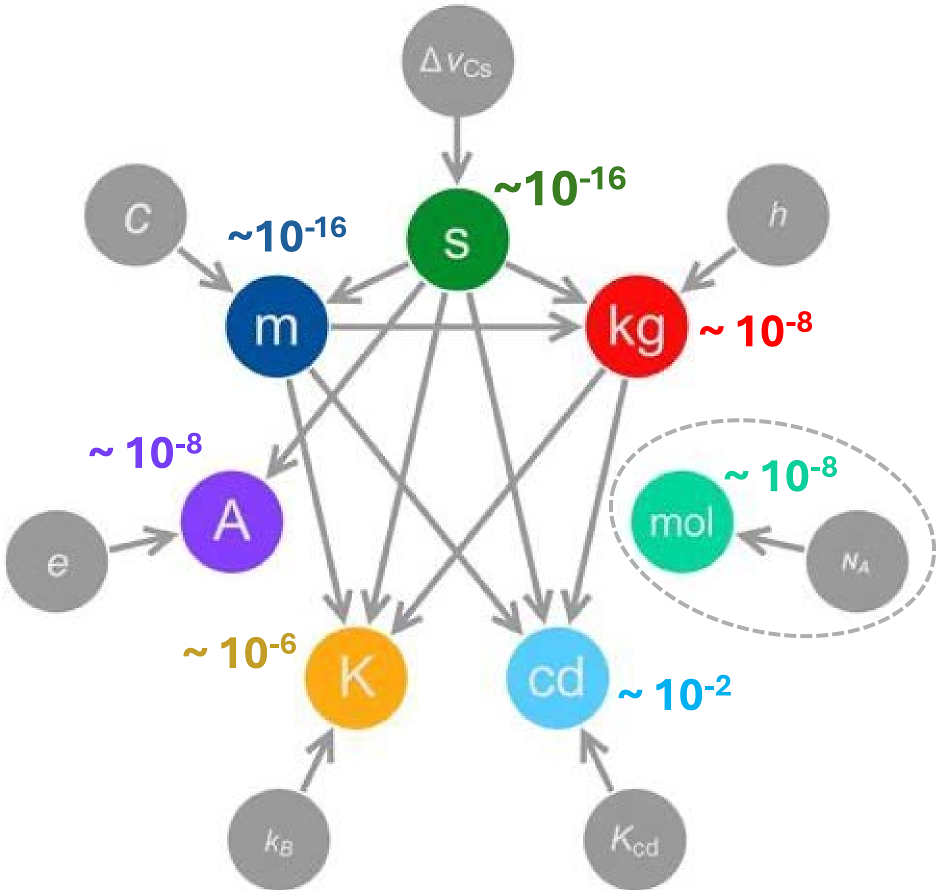
Outlook: Optical clocks and supporting technology

Tara Fortier
NIST, Time and Frequency Division
Sept 11, 2025

Why is time important?

2018 International Standard Units



1. The SI second underpins every unit in the SI except the mole.
2. Frequency = 1/time is central to precision measurement and sources using lasers:
3. Why do we use high-performance atomic clocks for timing?.... Because they are frequency references.

https://www.nist.gov/si-redefinition
https://www.bipm.org/en/measurement-units/si-defining-constants

Outline

1. **How do atomic clocks work?**

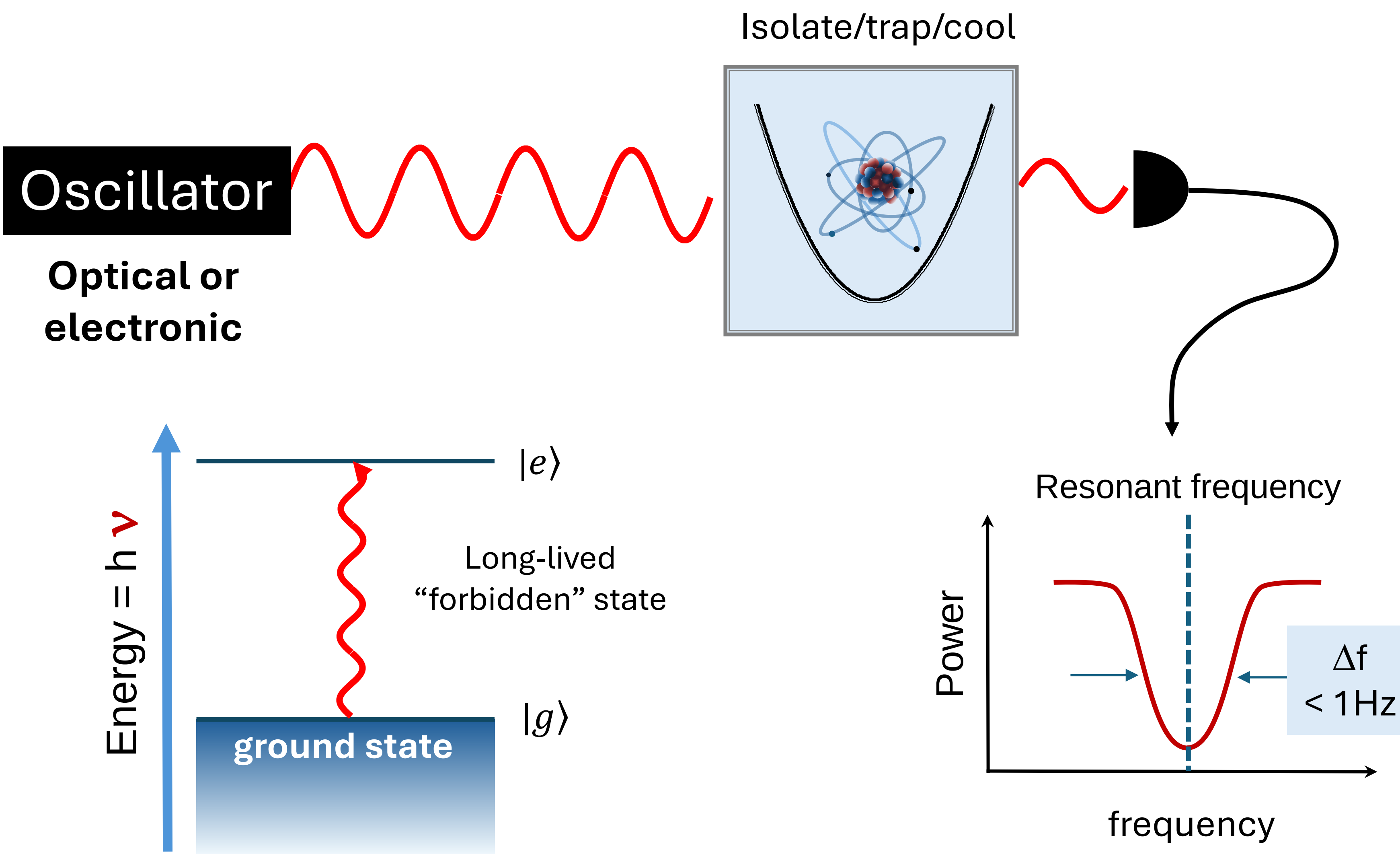
    - Where are we regarding the state of the art of optical clocks?

2. **How do frequency combs expand the versatility of optical clocks?**

3. **Applications of optical technology in time and frequency.**

How do atomic clocks work?

Review: *A. Ludlow "Atomic Clocks" Rev. Mod. Phys.* ***87*** *(2015)*



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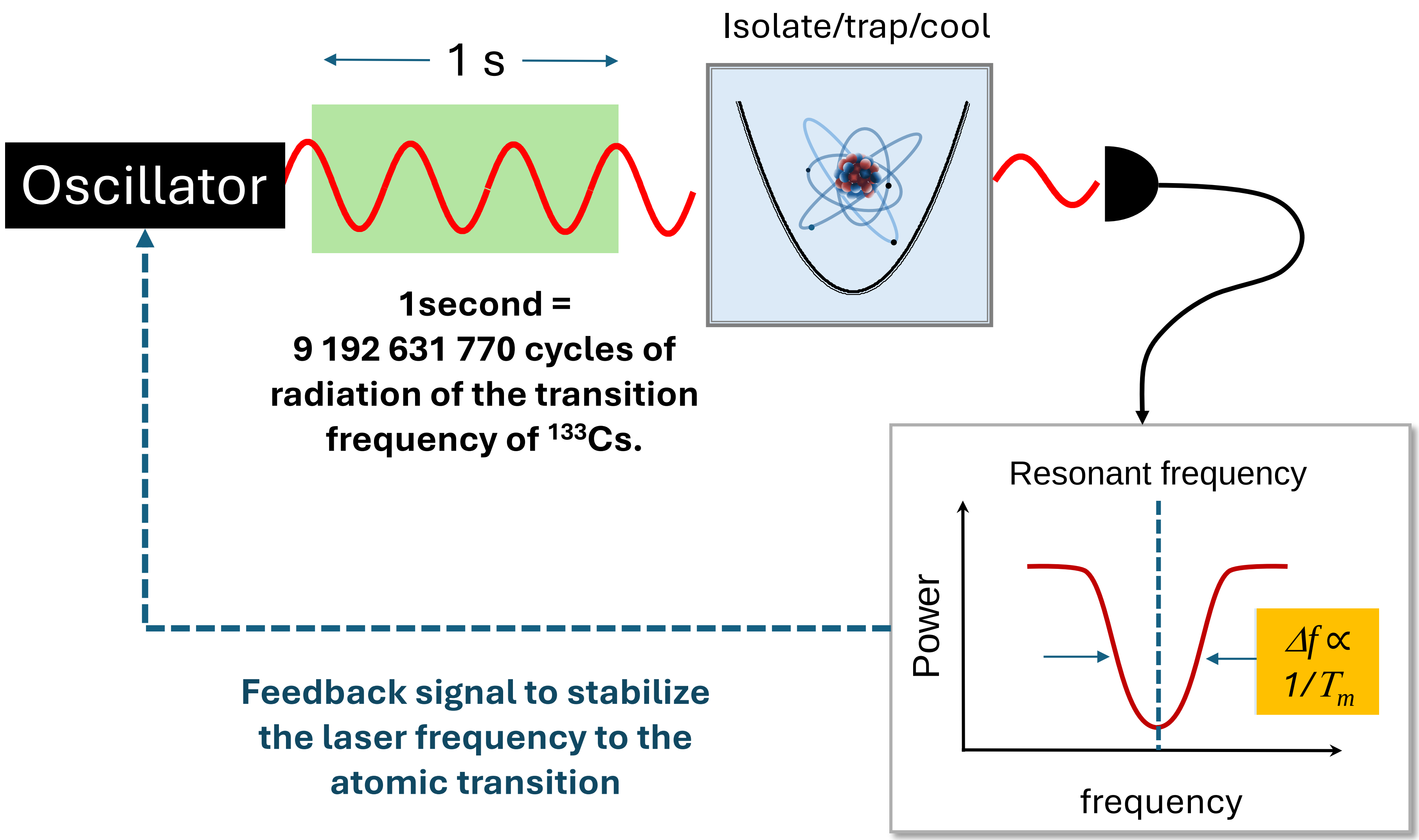
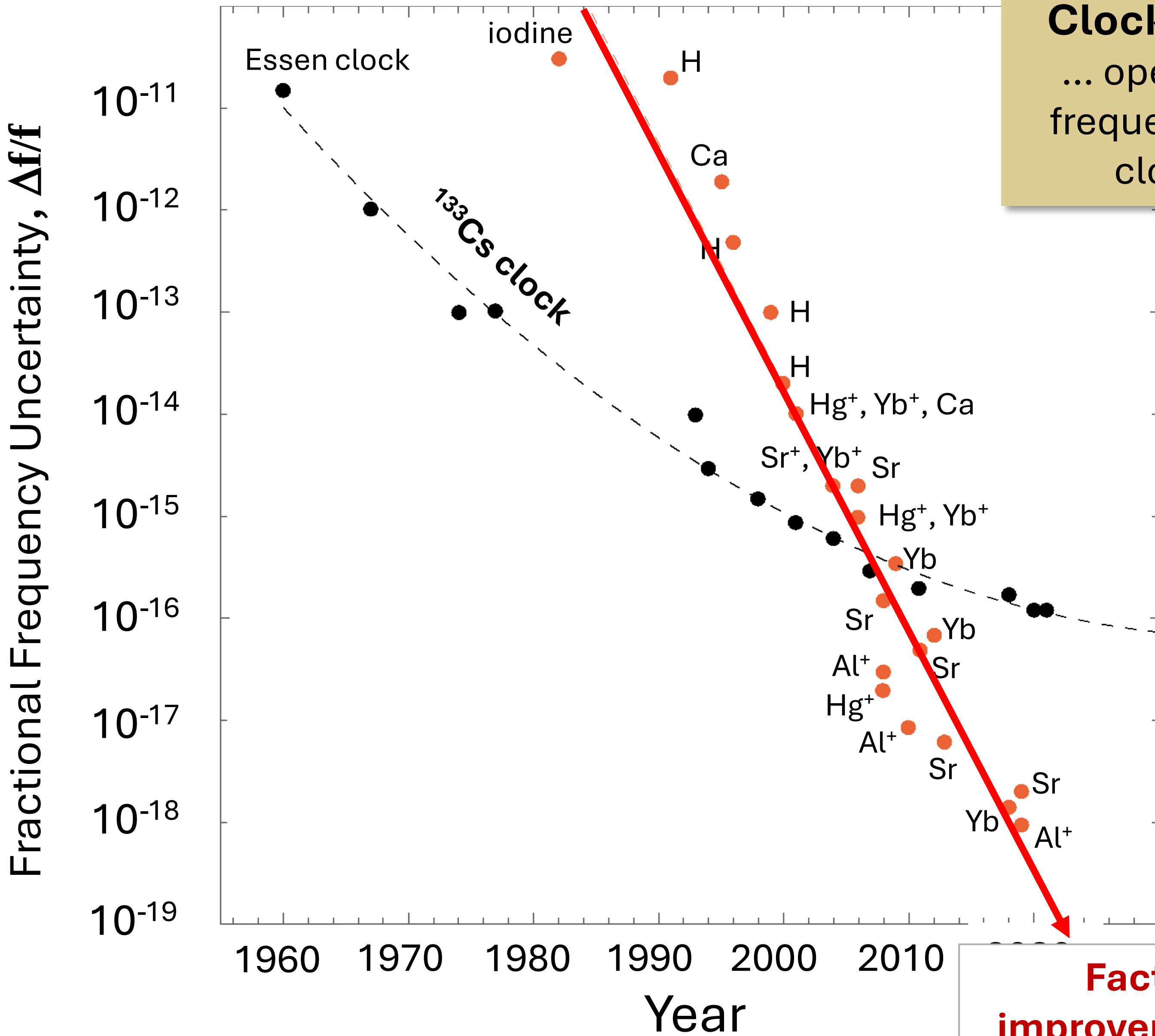


Historical performance of atomic clocks



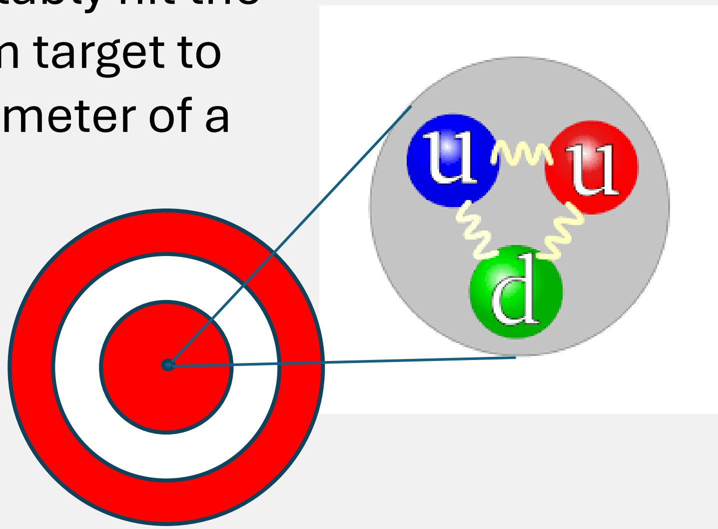
Clocks accuracy Δf/f

... operating at a higher frequency increases the clock resolution.

Factor of 100 improvement/decade!

What can you do with 10^{-18} accuracy

10^{-18} is equivalent to being able to repeatably hit the center of a 1m target to within the diameter of a quark!



Clocks accuracy $\Delta f/f$

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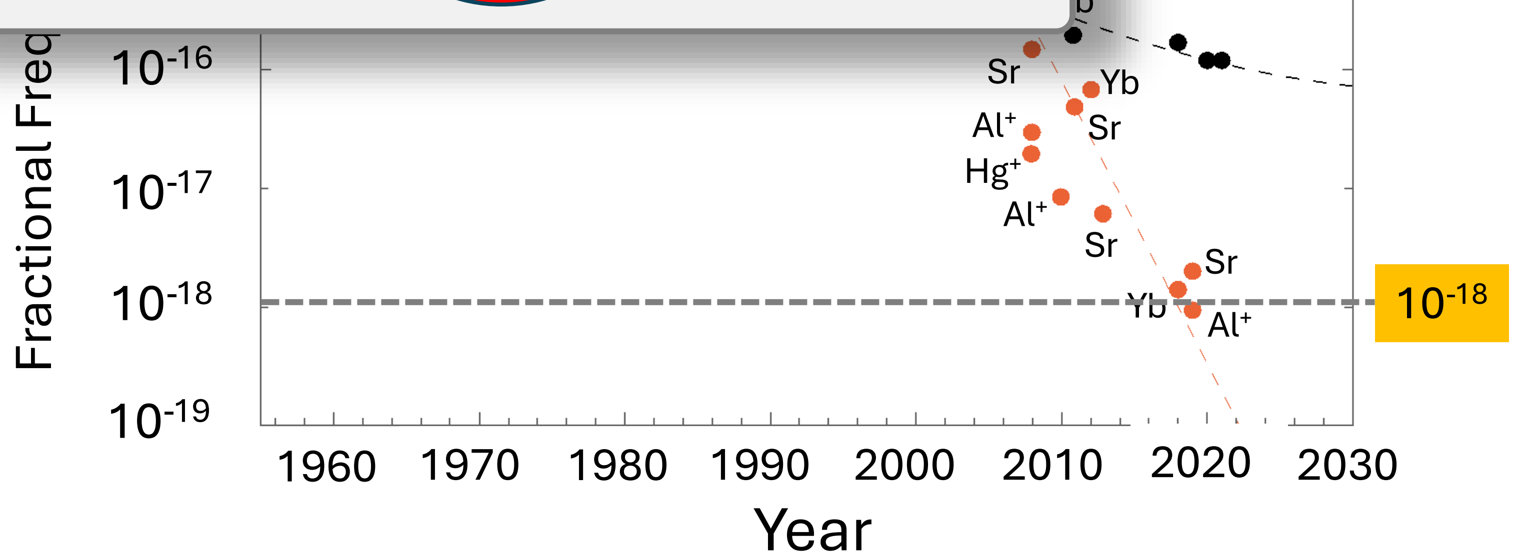
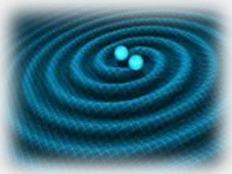
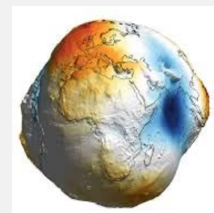


What can you do with 10^{-18} accuracy

Next generation applications:



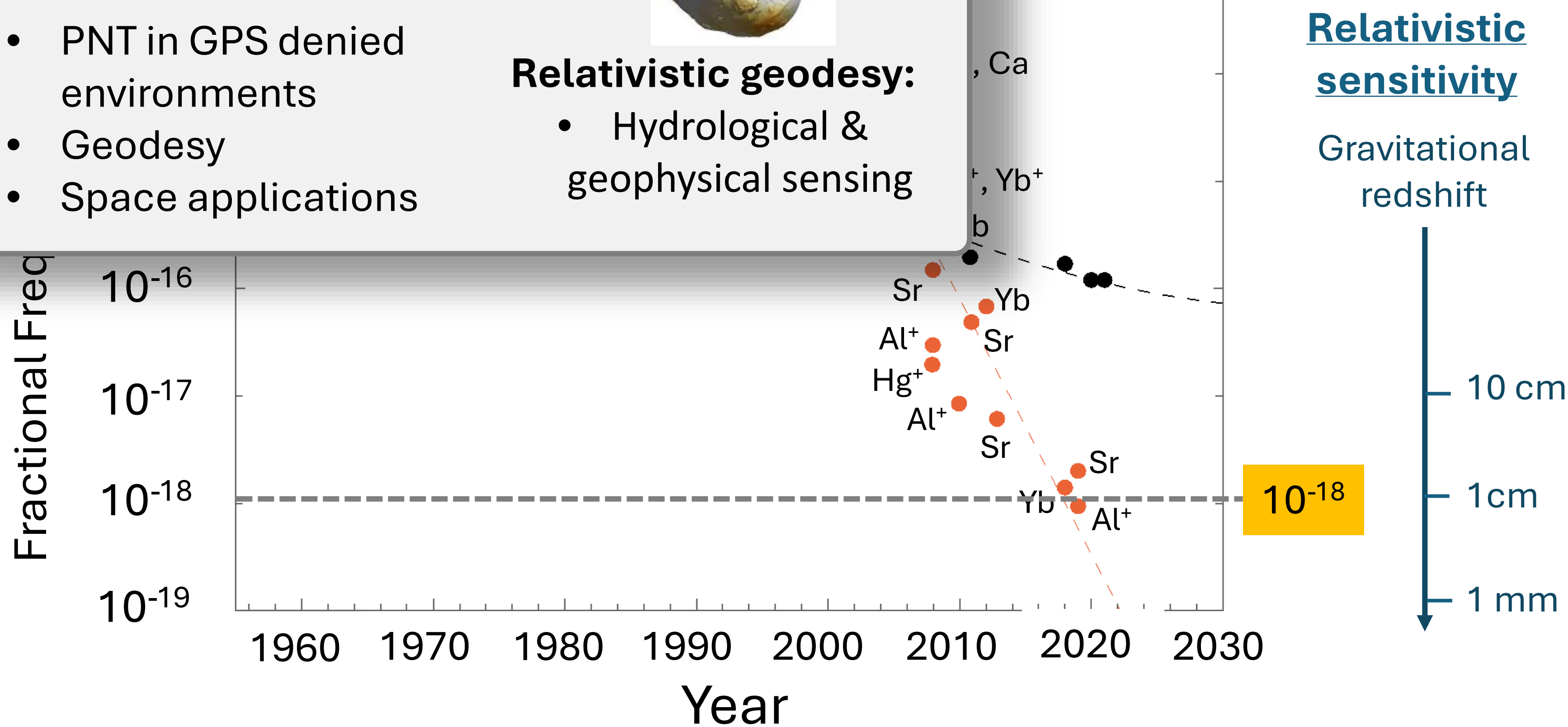
Fundamental physics:
- general relativity
- Gravitational wave detection



Portable clocks:
- PNT in GPS denied environments
- Geodesy
- Space applications

Relativistic geodesy:
- Hydrological & geophysical sensing

Clocks accuracy Δf/f
… operating at a higher frequency increases the clock resolution.



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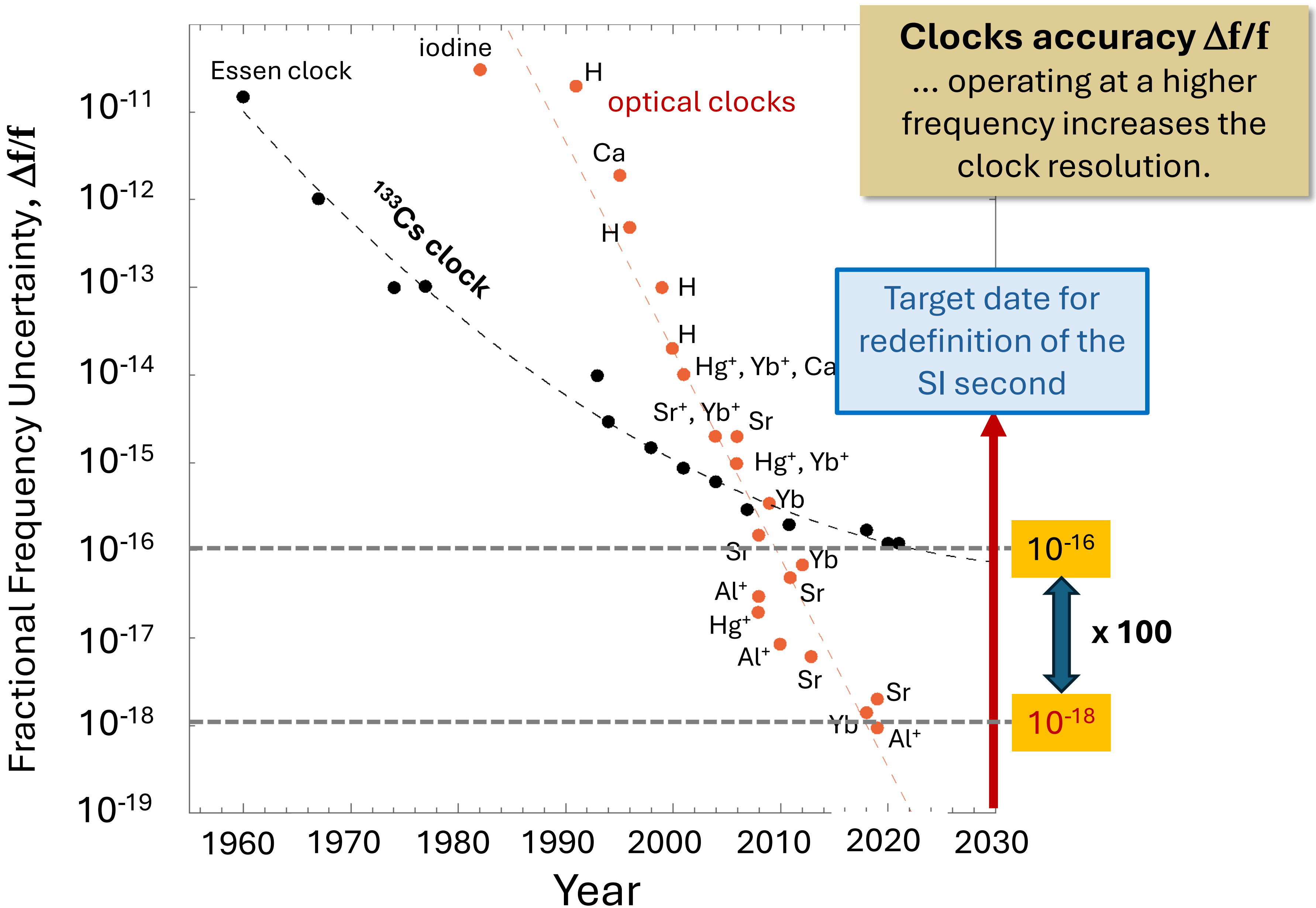

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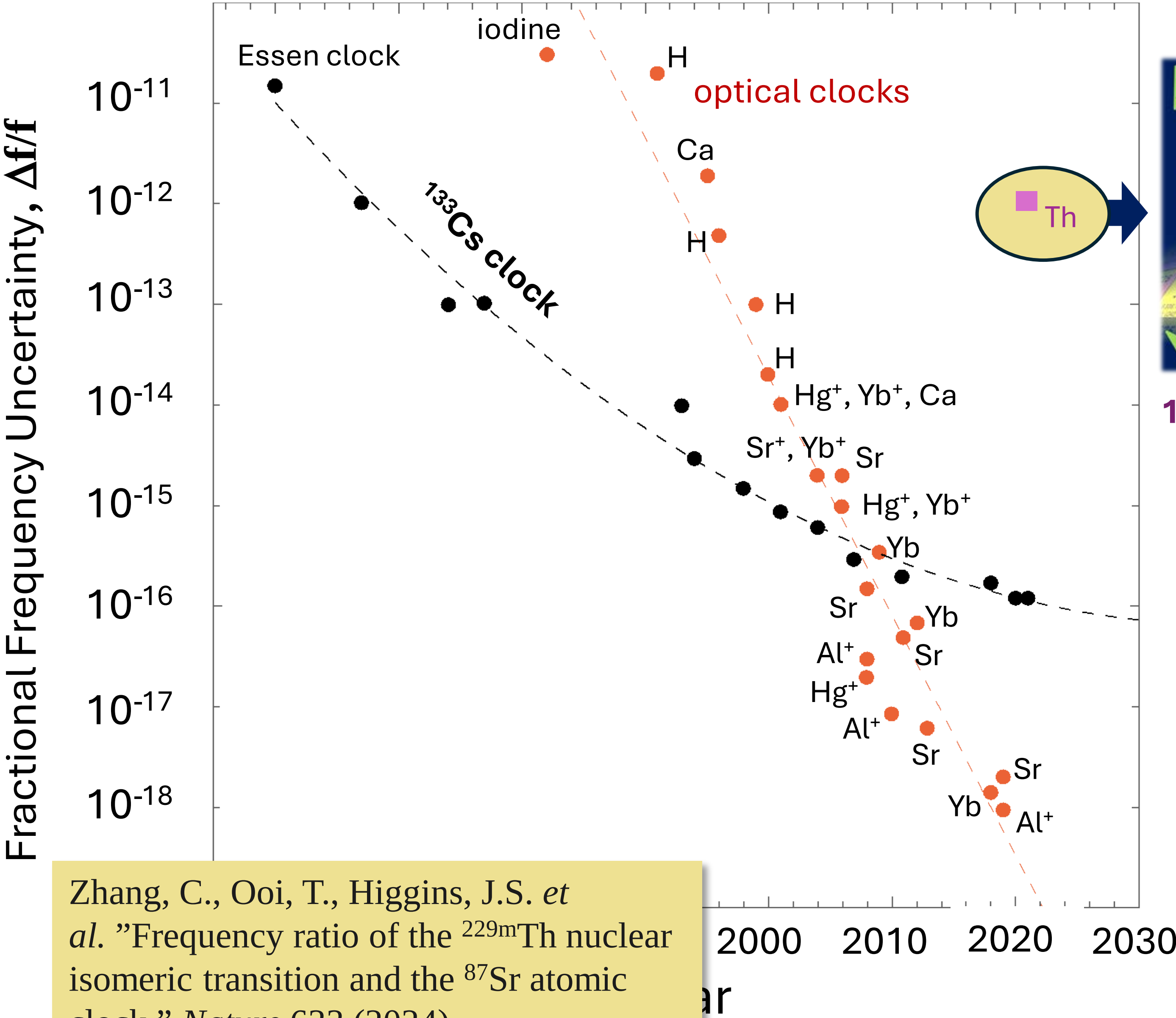
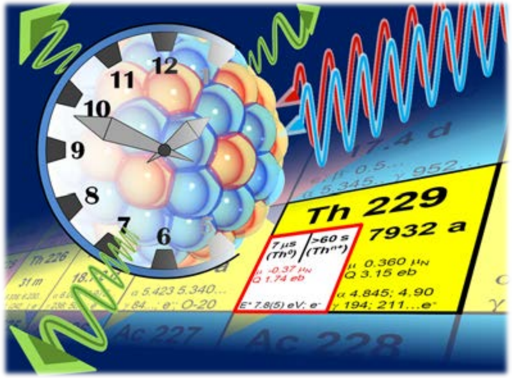


Zhang, C., Ooi, T., Higgins, J.S. *et al.* "Frequency ratio of the ^{229m}Th nuclear isomeric transition and the ^{87}Sr atomic clock." *Nature* 633 (2024).

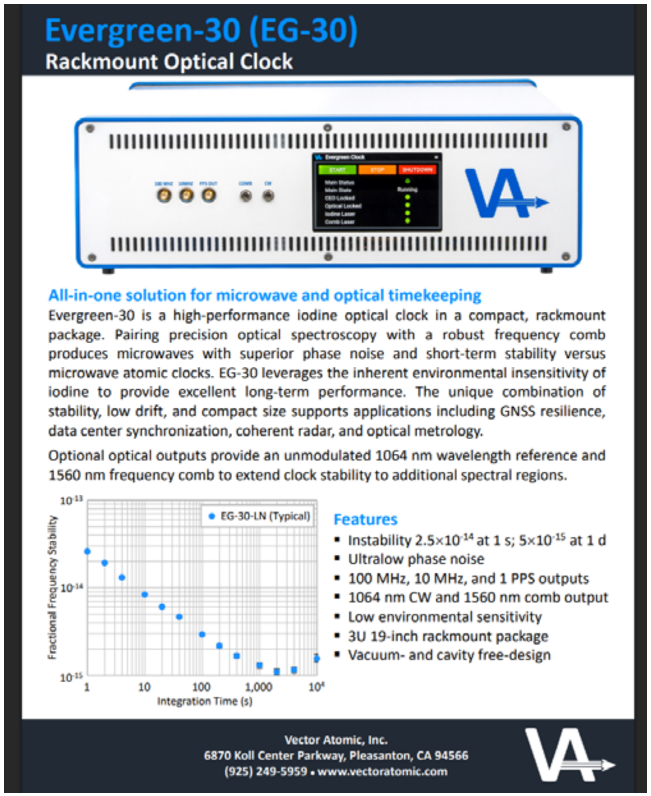


1st precision measurement of ^{229}Th nuclear clock!

- Nuclear transitions made by protons.
- Transition frequency near, $\upsilon_0 = 2$ PHz
- Insensitive to field effects.
- Exploration of nuclear physics.

Commercial push to develop optical clocks

Vector Atomic



Evergreen-30 (EG-30)
Rackmount Optical Clock

All-in-one solution for microwave and optical timekeeping

Evergreen-30 is a high-performance iodine optical clock in a compact, rackmount package. Pairing precision optical spectroscopy with a robust frequency comb produces microwaves with superior phase noise and short-term stability versus microwave atomic clocks. EG-30 leverages the inherent environmental insensitivity of iodine to provide excellent long-term performance. The unique combination of stability, low drift, and compact size supports applications including GNSS resilience, data center synchronization, coherent radar, and optical metrology.

Optional optical outputs provide an unmodulated 1064 nm wavelength reference and 1560 nm frequency comb to extend clock stability to additional spectral regions.

Features

- Instability 2.5×10^{-14} at 1 s; 5×10^{-15} at 1 d
- Ultralow phase noise
- 100 MHz, 10 MHz, and 1 PPS outputs
- 1064 nm CW and 1560 nm comb output
- Low environmental sensitivity
- 3U 19-inch rackmount package
- Vacuum- and cavity free-design

Vector Atomic, Inc.
6870 Koll Center Parkway, Pleasanton, CA 94566
(925) 249-5959 • www.vectoratomic.com

Portable system 3U 19” rack

- 3×10^{-14} @ 1s
- 5×10^{-15} @ 1day

Shimadzu Corp.

Japan Puts World's Most Accurate Clock On Sale For $3.3 Million

Known as a "strontium optical lattice clock", it is 100 times more accurate than caesium atomic clocks, the current standard for defining seconds, the precision-equipment producer said in a statement.

Agence France-Presse | World News | Mar 05, 2025 16:28 pm IST

Read Time: 2 mins

Share

The "Aether clock OC 020" is so precise that it would take 10 billion years for it to deviate by 1 second

Sr lattice optical clock

- Accuracy ~ 10^{-17}

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How fast is a light?

The big obstacle to optical clock development: light waves are too fast to count!

Up to 20 GHz

200 Tera-oscillations/s

~10,000 to 100,000 x faster than a state-of the-art counter!

A brief history of optical frequency measurement

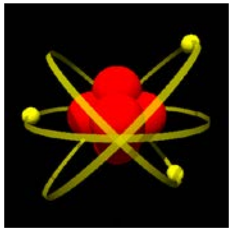
To measure the frequency of the optical transition we need to measure it against the definition of the Hz.

Atomic transition
~ 300 THz

Cs clock
9.192 GHz

Problem!

5 orders of magnitude different in frequency!



~~Counter~~

Conversely, to define the second to Optical atomic time we need to count the cycles of the clock transition.

Optical frequency measurement before OFCs

Frequency multiplication chains

Cs clock
9.192 GHz

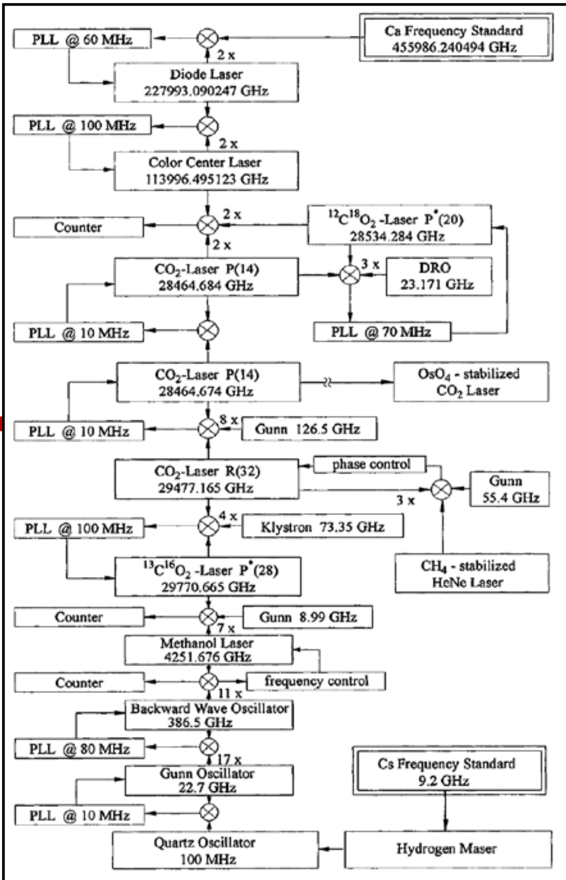


FIG. 1. PTB's frequency chain to the Ca intercombination line (PLL = phase locked loop, details are given in the text).

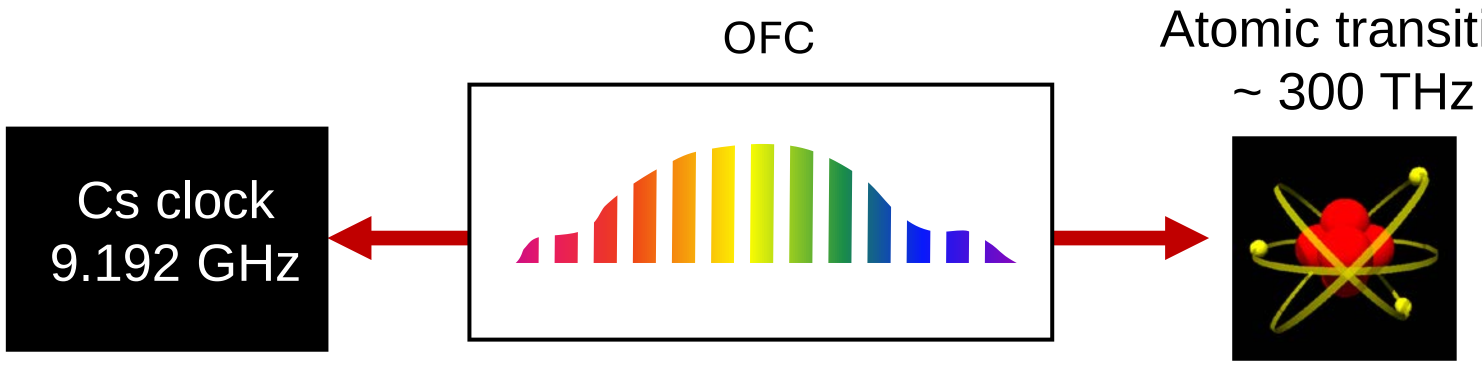
Atomic transition
~ 300 THz

Frequency chain enables multiplication of the 133Cs microwave reference to the optical domain via a series of 20 intermediate and 50 phase locked oscillators.

Schnatz, et al., Phys. Rev. Lett. 76, 19 (1996)

One-step optical-to-microwave conversion

2005 Nobel Prize: Jan Hall and Ted Haensch



In 2000, the first optical frequency comb was demonstrated:

- direct optical-to-microwave conversion with a single oscillator!

OCFs as a multi-use synthesizer

Ultra-broadband frequency synthesis

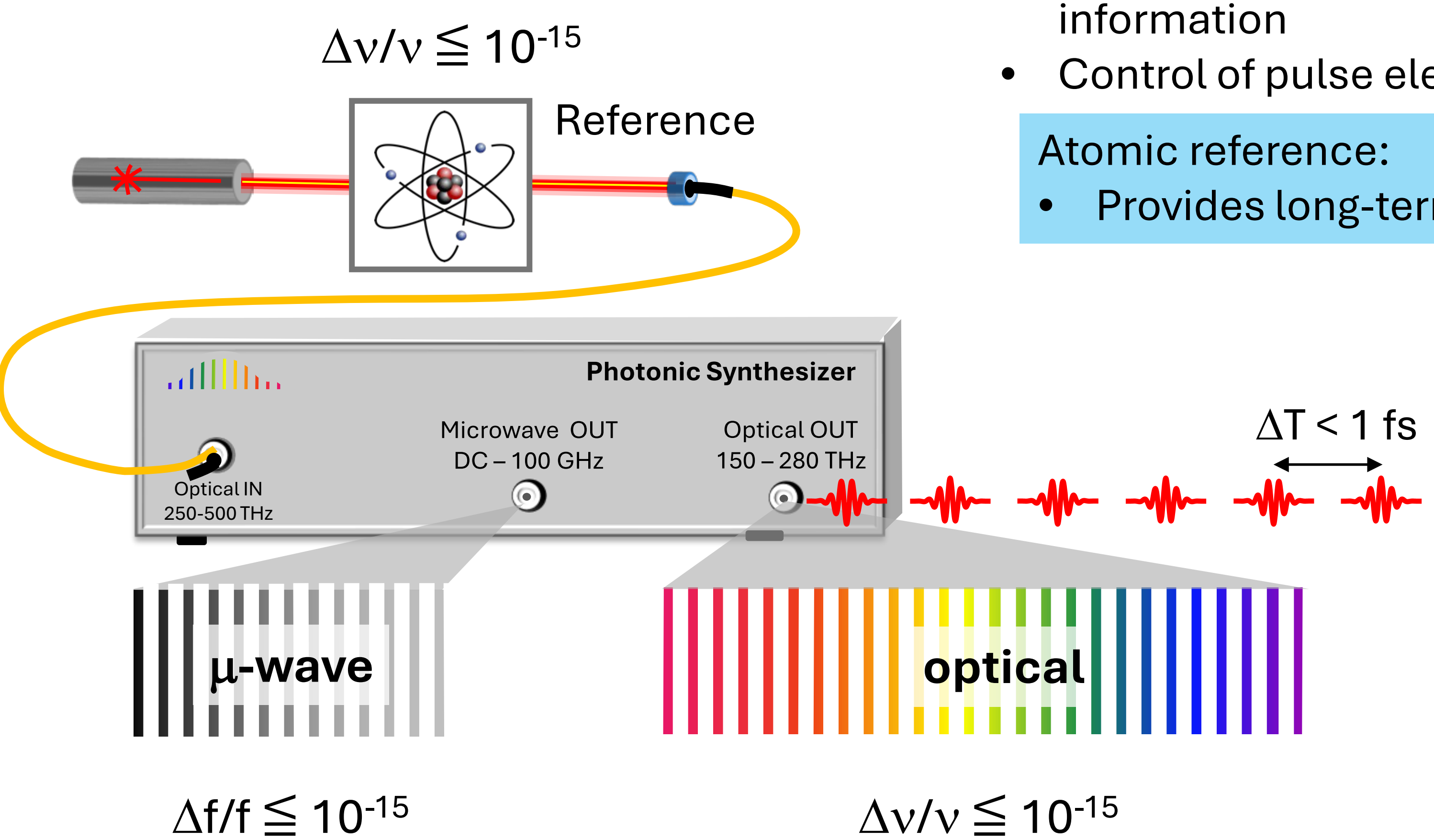
- Wideband optical synthesis/coverage
- Direct optical-to-microwave conversion
- Perfect multiplier/divider
    - High precision frequency counter

Ultra-short optical pulse synthesis

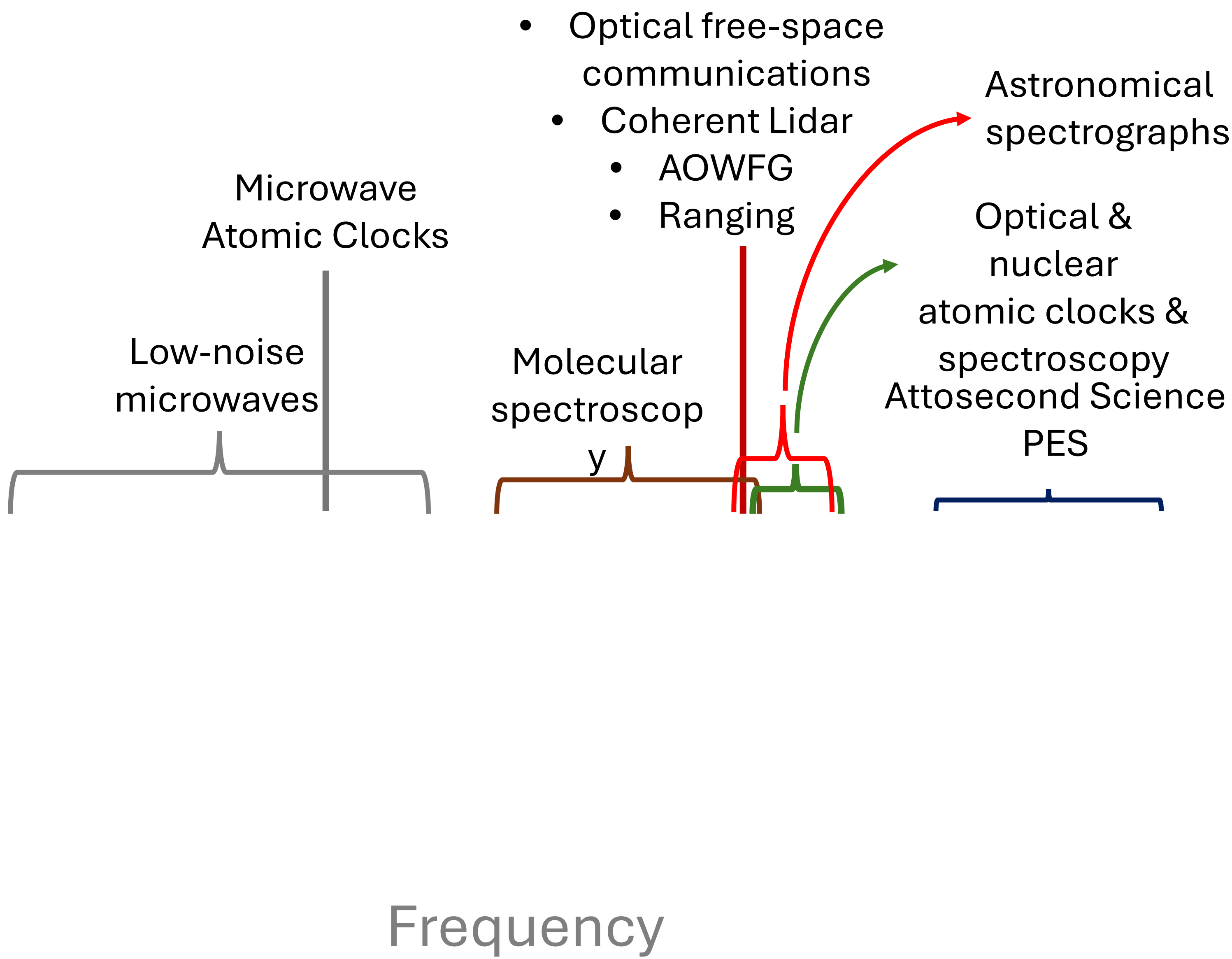
- Ultra-low pulse-to-pulse timing jitter for time/frequency dissemination
- Waveform measurement to retrieve amplitude/spectral/phase information
- Control of pulse electric field

Atomic reference:

- Provides long-term (> 1s) stability



Application of OFCs across the E-M spectrum



Commercial frequency comb systems

Home built system (50k$ + 3 months of labor).... or you can buy one

Nardelli et al. Laser & Photon. Rev. (2023)

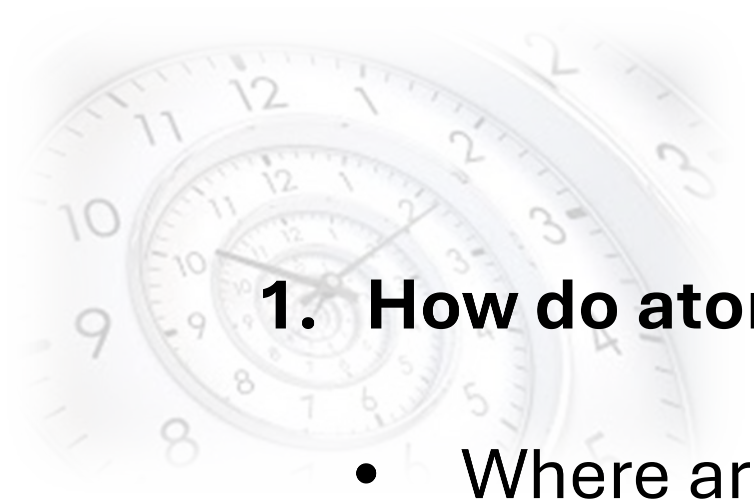
- **Telecom fiber-laser system**
- **19” rackmount systems**
- **no optical reference provided**
- **Cost ~ $200k**
- **Customization $500k – $1M**

Vescent

Menlosystems

Toptica

Electro-optic frequency comb



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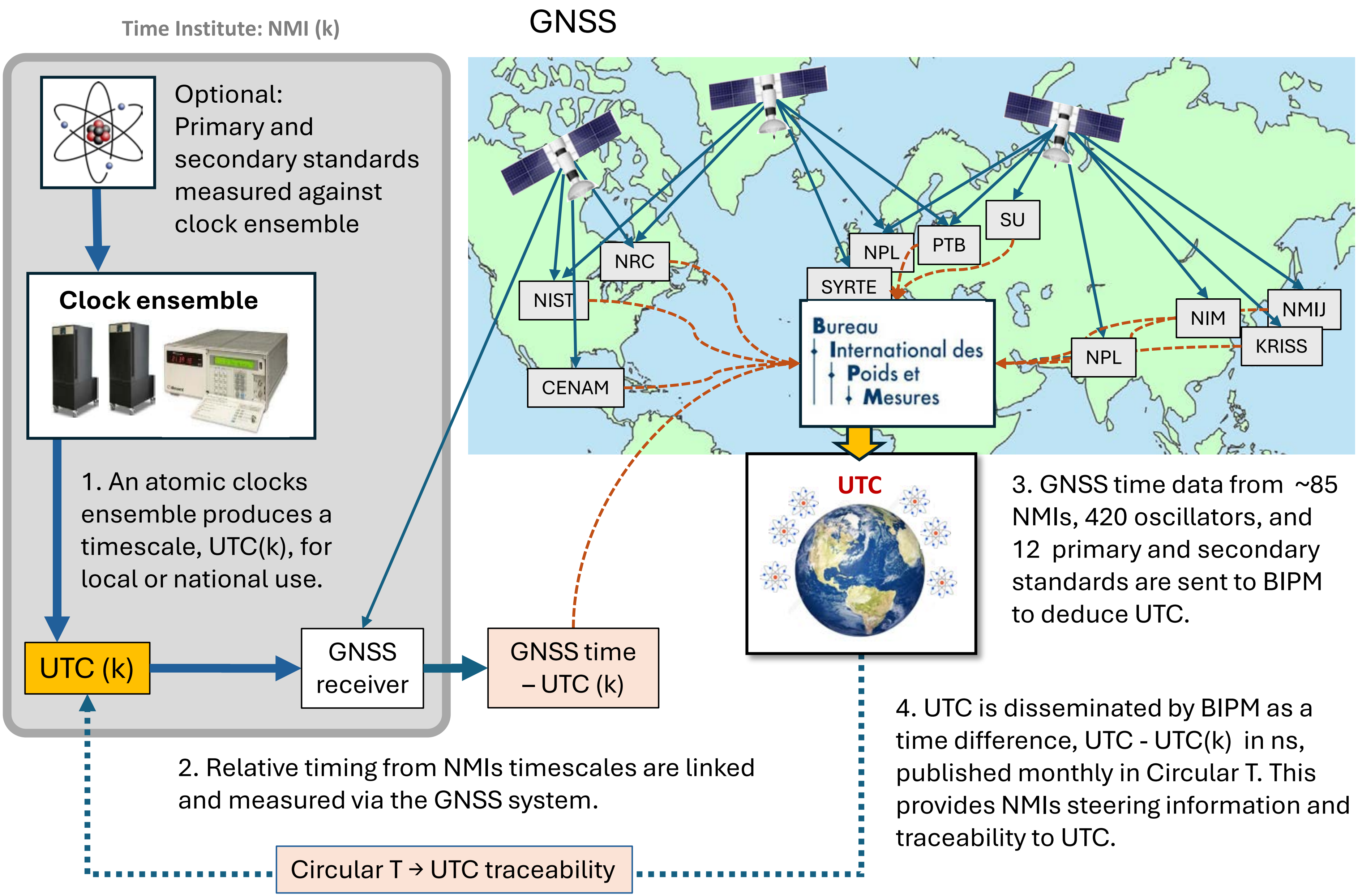
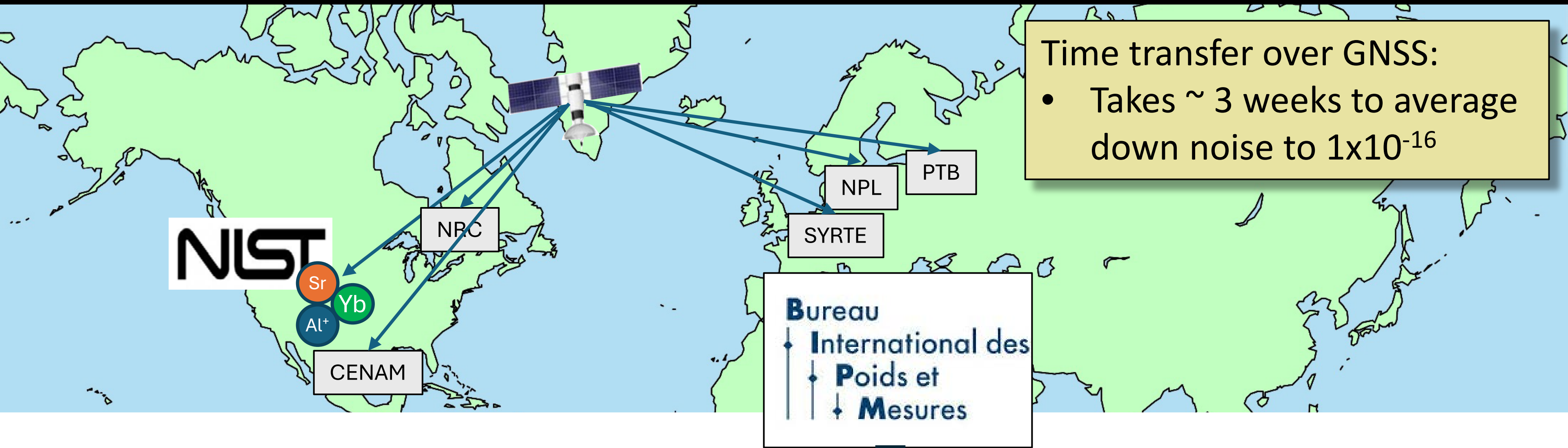
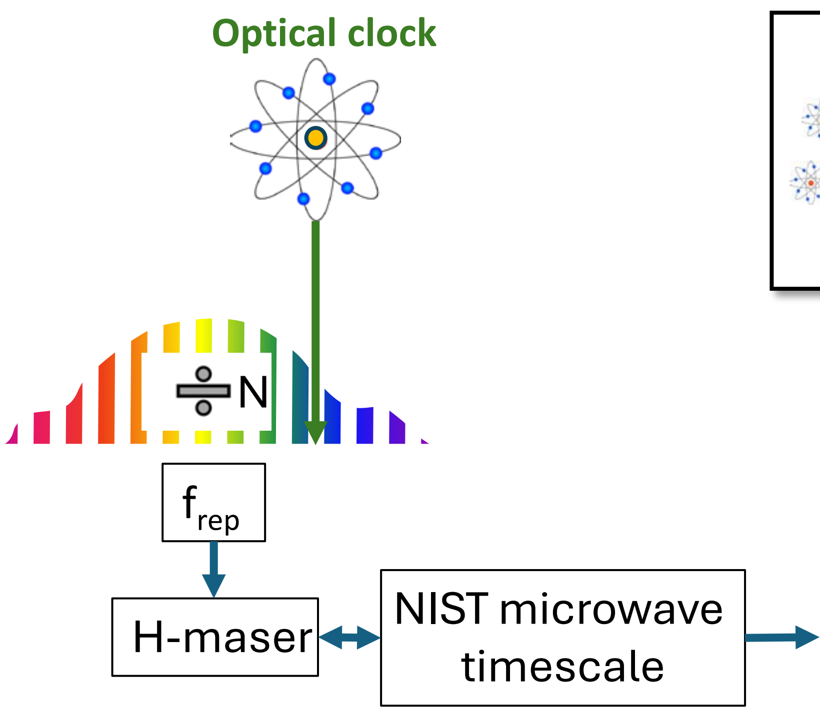
How atomic clocks contribute to UTC



How *optical* atomic clocks contribute to UTC



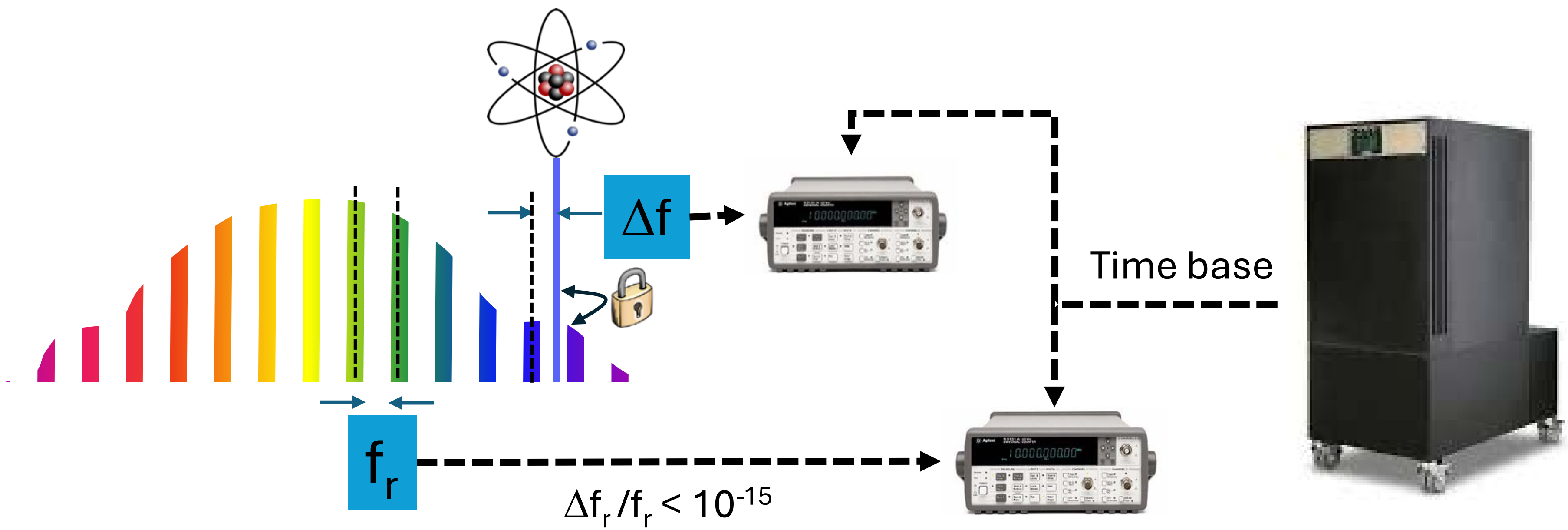
GNSS time data from ~85 NMIs, 420 oscillators, and 12 primary and secondary standards are sent to BIPM to deduce UTC.



Broadcast to BIPM via 2-way microwave satellite time transfer

Timescale calibration to an optical clock

ν_{Yb}(BIPM) = 518,295,836,590,863.6 Hz ← A constant of nature



H-maser (**local time**), tells the counter what it thinks 1-s is for gating the counters.

From the counters, we calculate:

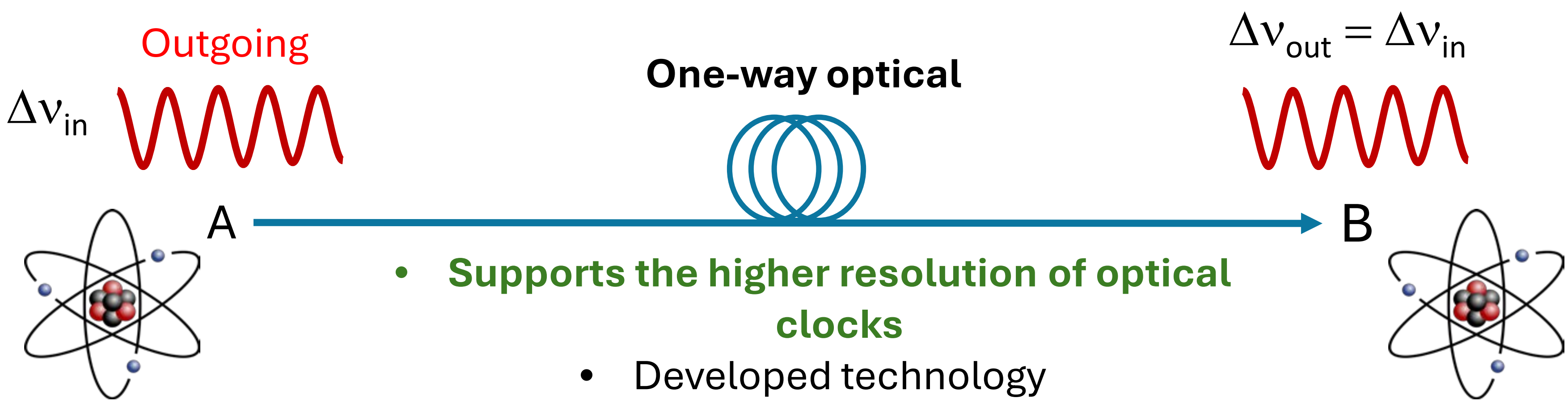
$$\nu_{Yb}\ (\text{local time}) = N \times f_r + \Delta f$$

“Local time” is calibrated to Yb atomic time by assessing the difference:

$$\nu_{Yb}\ (\text{local time}) - \nu_{Yb}(\text{SI})$$

Atomic clock comparison/dissemination

> 100 times better stability than satellite or GPS microwave dissemination



- **Supports the higher resolution of optical clocks**
- Developed technology
- Used extensively in Europe
- Lowest loss/highest reliability/highest stability

K. Predehl et al, *"A 920-kilometer optical fiber link for frequency metrology at the 19th decimal place,"* Science 336 (2012)

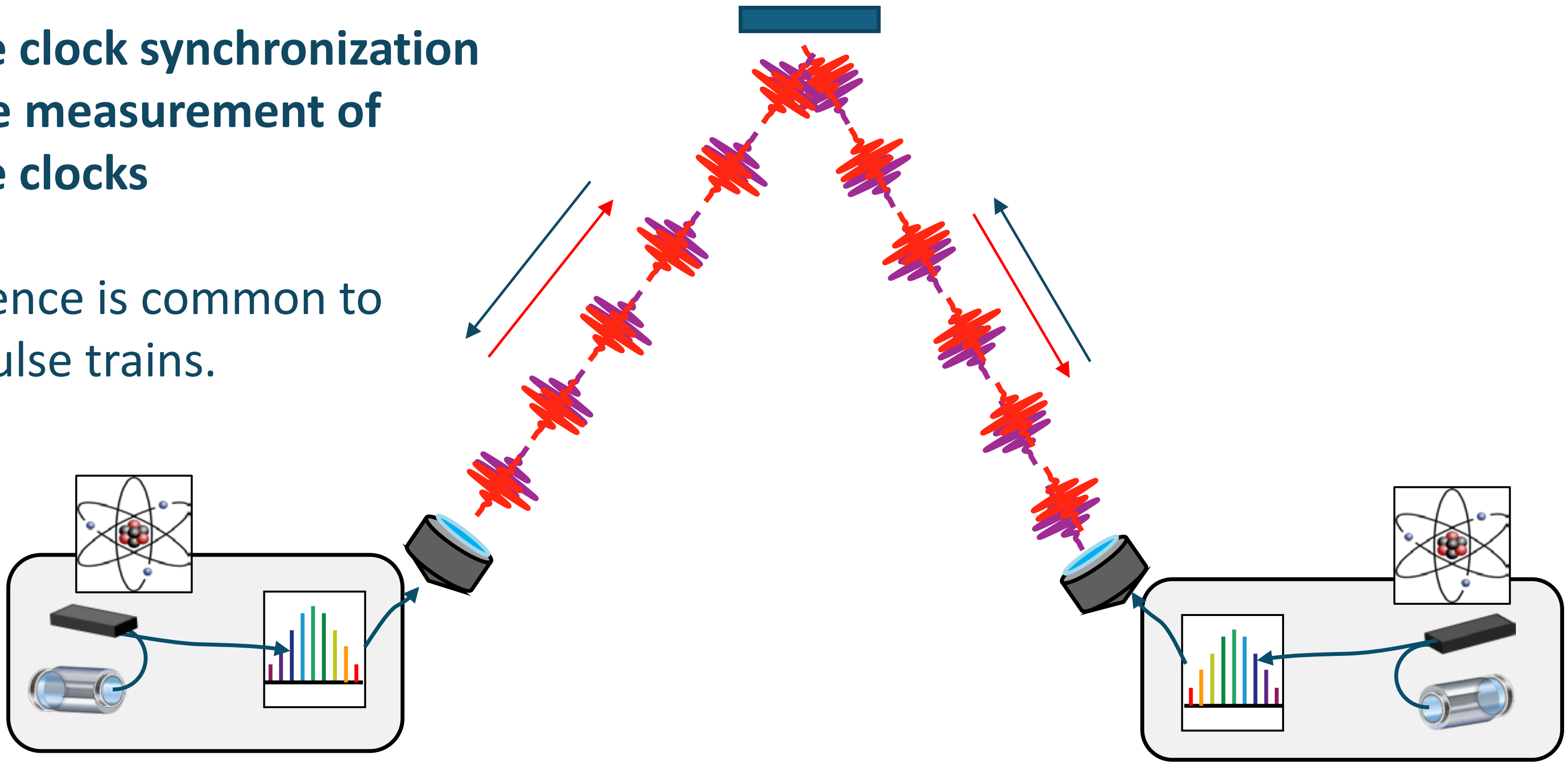
- Continuous wave laser
- $\Delta f/f = 10^{-18}$ at 10,000 s
- **920 km fiber optic link (0.025 dB loss/km @ 1550 nm)**

2-way time transfer: Clock synchronization/comparison

Clock timing difference = interference between the red and blue pulse trains.

- **remote clock synchronization**
- **relative measurement of remote clocks**

- Turbulence is common to both pulse trains.



- Enables free-space comparison of clocks in the absence of fiber networks.
- Requires line of sight and good weather

F. Giorgetta et al., Nature Photonics (2013)

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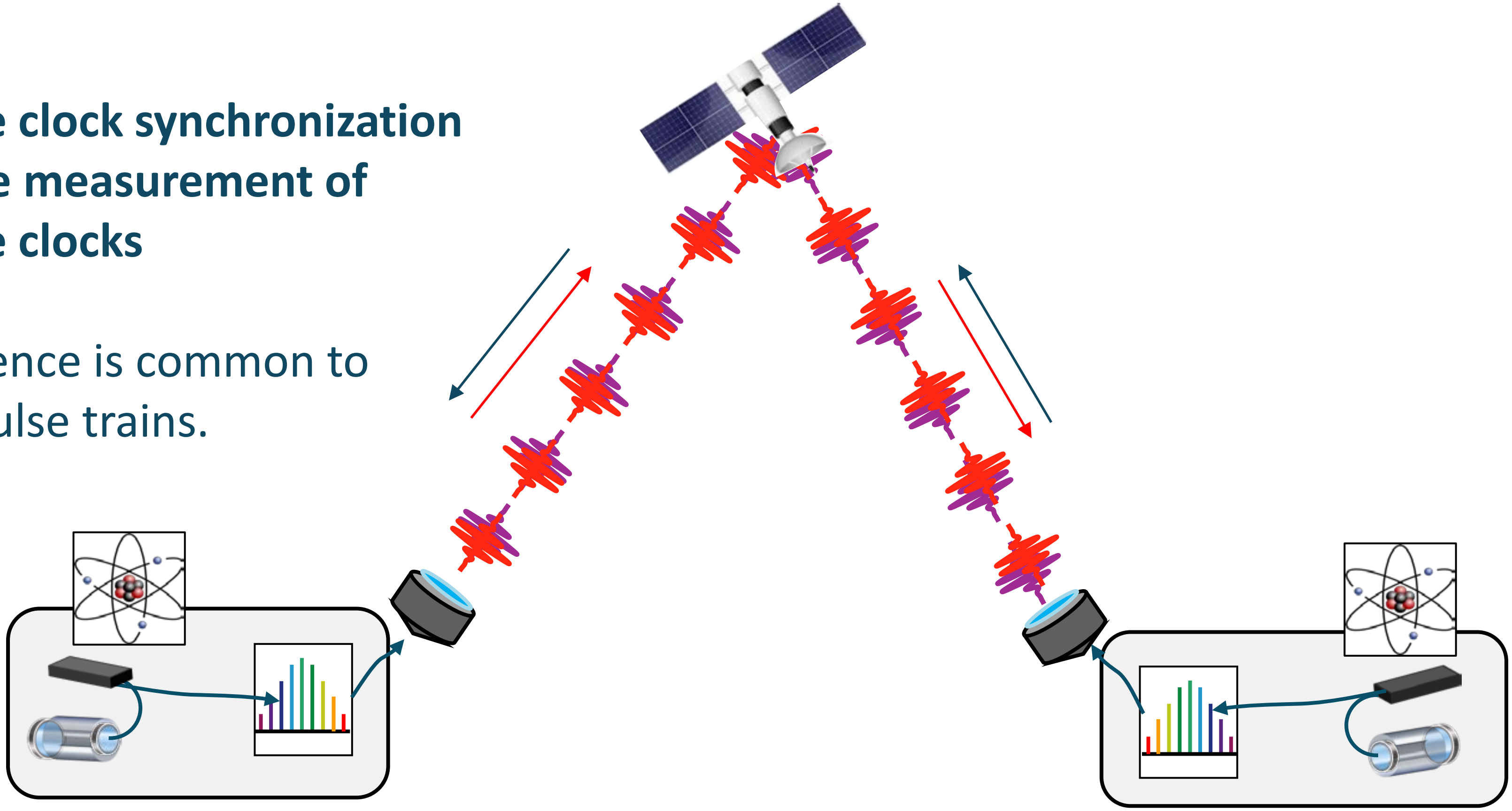

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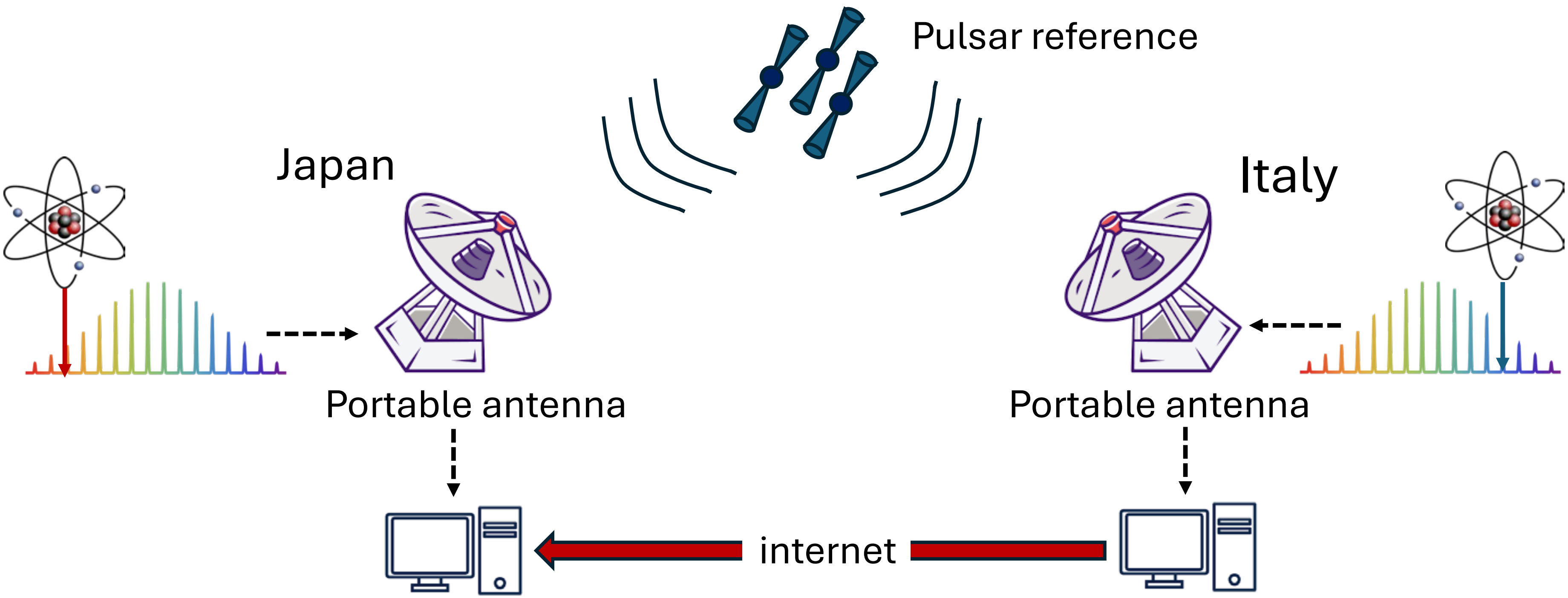
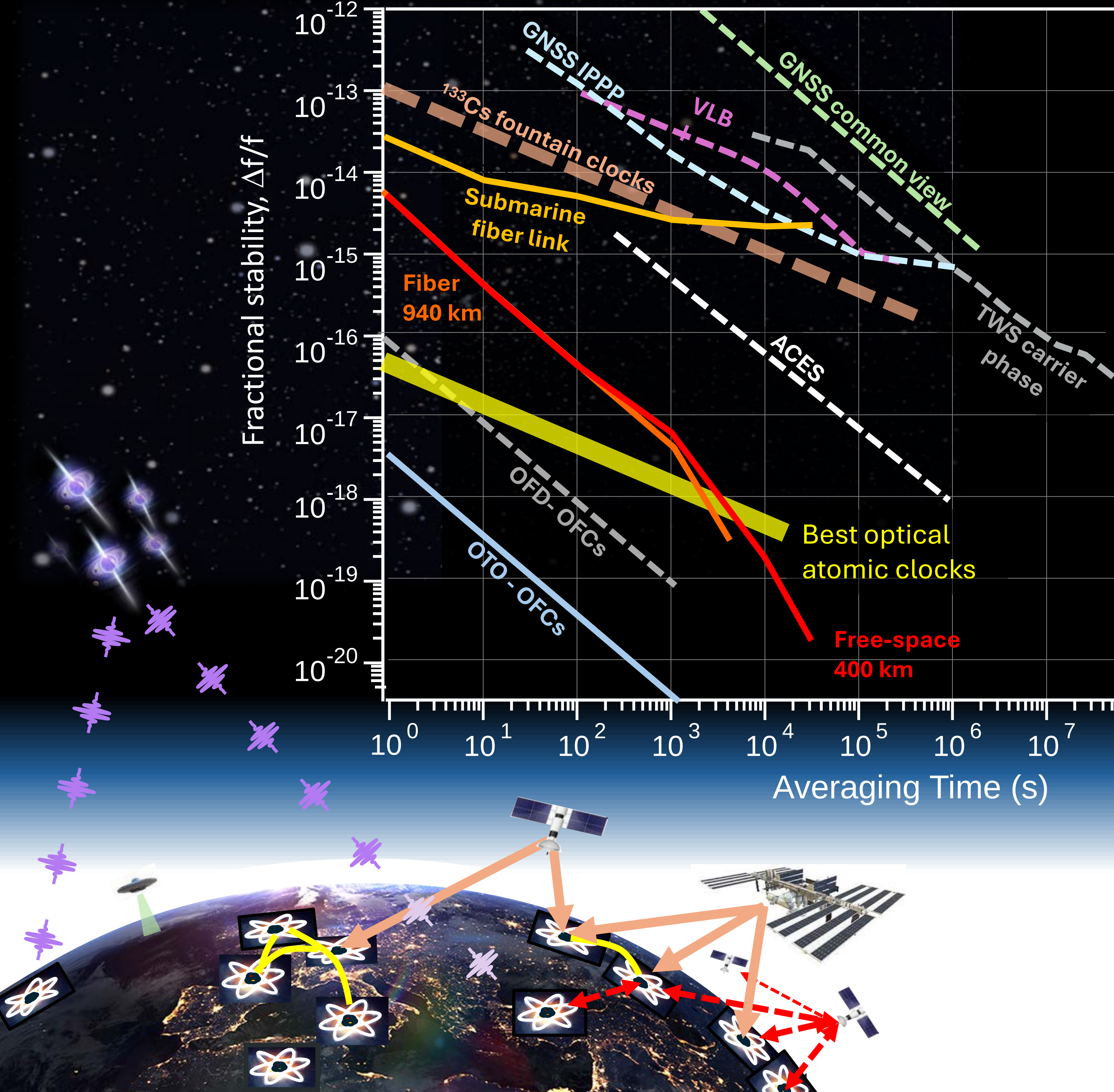
F. Giorgetta et al., Nature Photonics (2013)

Atomic clock comparisons via VLBI

M. Pizzocaro et al, "**Intercontinental comparison of optical atomic clocks through very long baseline interferometry,**" Nature **17** (2020)

- 9000 km baseline
- Measurement resolution: 5×10^{-16} (300 hours of measurement)
- Measurement uncertainty: $<1 \times 10^{-16}$ (300 hours of measurement)





Outlook: global network of optical clocks

How different technologies currently compare.

How can you participate in the "optical" revolution?

Begin developing, or working with, optical links:

Links that use "radio-over-fiber" to send RF frequency or timing information within your institute or to other end-users (as a service).

- White Rabbit (commercial solution)
  - https://white-rabbit.web.cern.ch/
- Home build "radio-over-fiber" systems ("easy" to develop for short links, becomes more complex for links > 1 km)
  - Relatively cheap to develop:

Optical links to send optical signals to end users:

- Ingredients:
  - 1 cavity stabilized laser (Stable Laser systems 60k USD)
  - Optical fiber
  - RF electronics: Voltage controlled oscillator, filters, amplifiers, mixers, splitters
  - Measurement: frequency counter, RF spectrum analyzer

Thank you for your attention!

Have additional questions, please feel free to email me:
tara.fortier@nist.gov

- **T.M. Fortier & E. Baumann, "20 years of developments in optical frequency comb technology and applications," Communications Physics 2 (2019)**
- N. Newbury, "Searching for applications with a fine-tooth comb," Science **5** (2011)
- **A. Ludlow "Optical atomic clocks,"** Reviews of Modern Physics (2015)

FIN