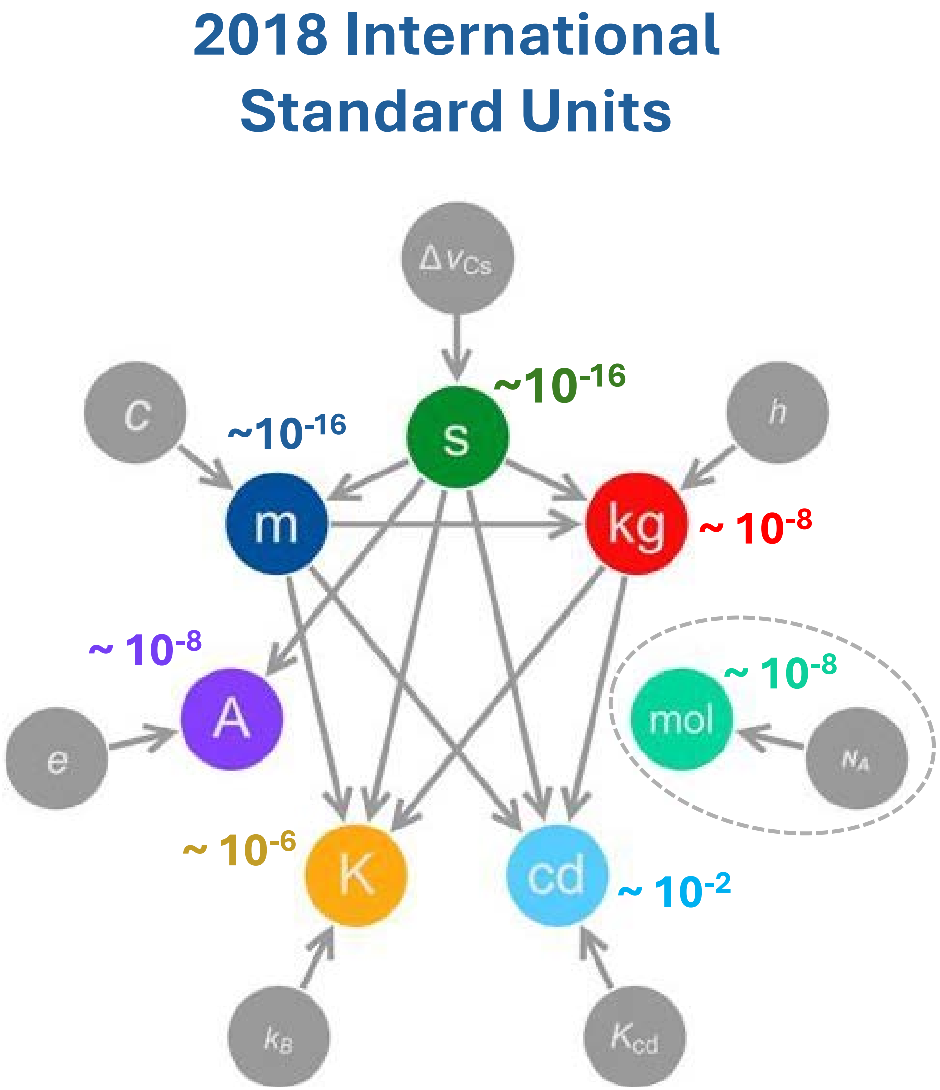
Outlook: optical clocks, frequency combs and optical timescales

Tara Fortier
NIST, Time and Frequency Division

May 9, 2025

Why is time important?



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.

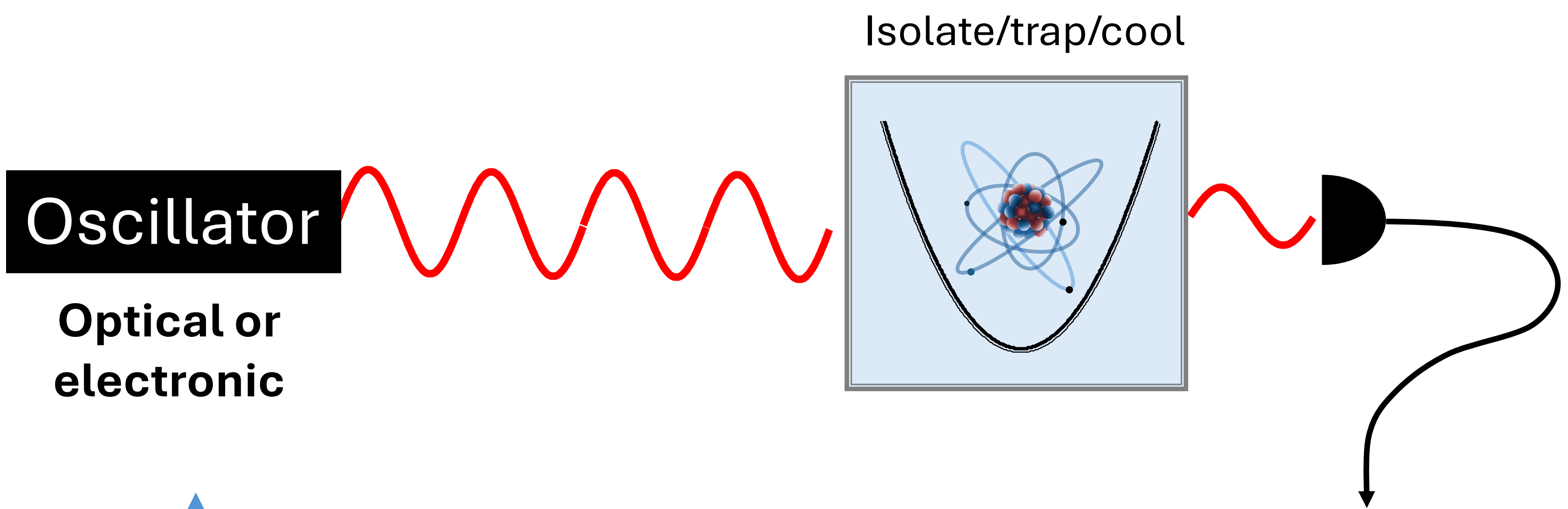
https://www.nist.gov/si-redefinition
https://www.bipm.org/en/measurement-units/si-defining-constants

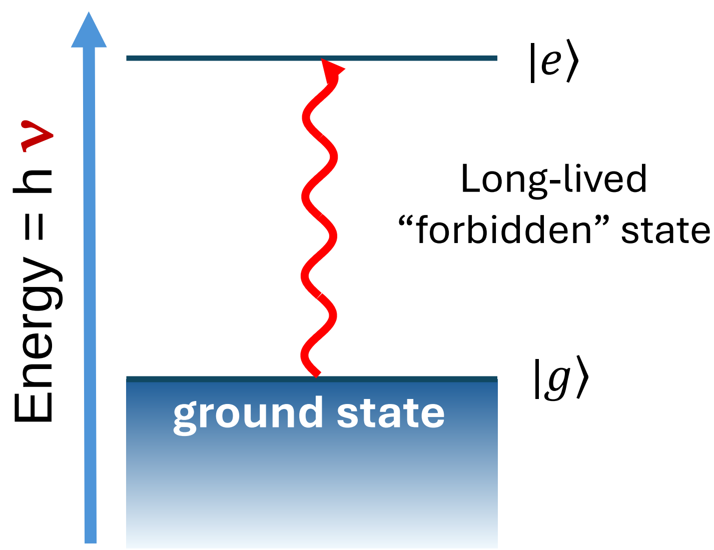
Outline

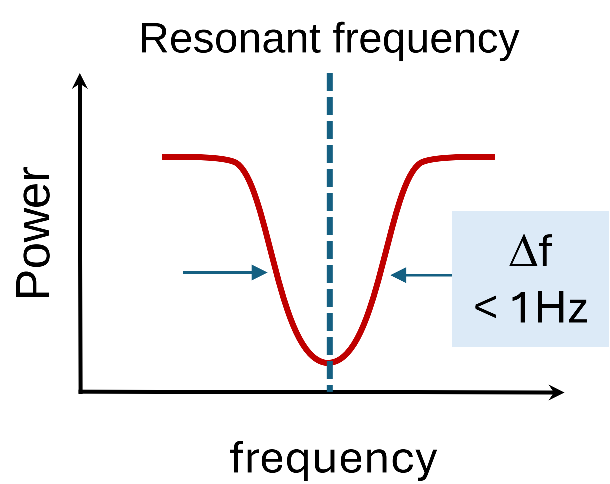
1. **How do atomic clocks work?**
   - Where are we regarding the state of the art of optical clocks?
2. **How do frequency combs expand the versatility of optical clocks?**
3. **How will optical clock and combs work together to enable future timescales?**
4. **Where is the field going next?**

How do atomic clocks work?

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







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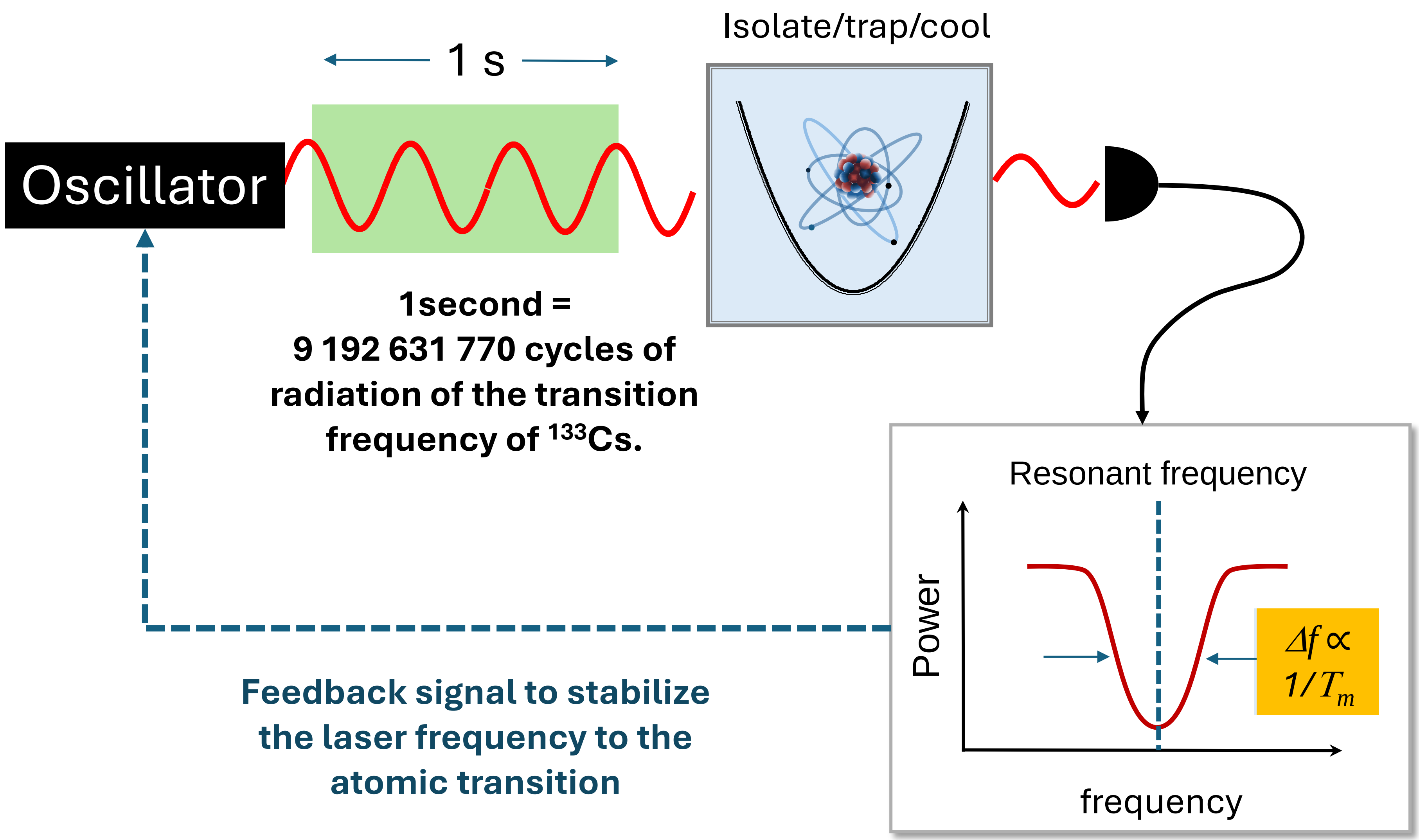
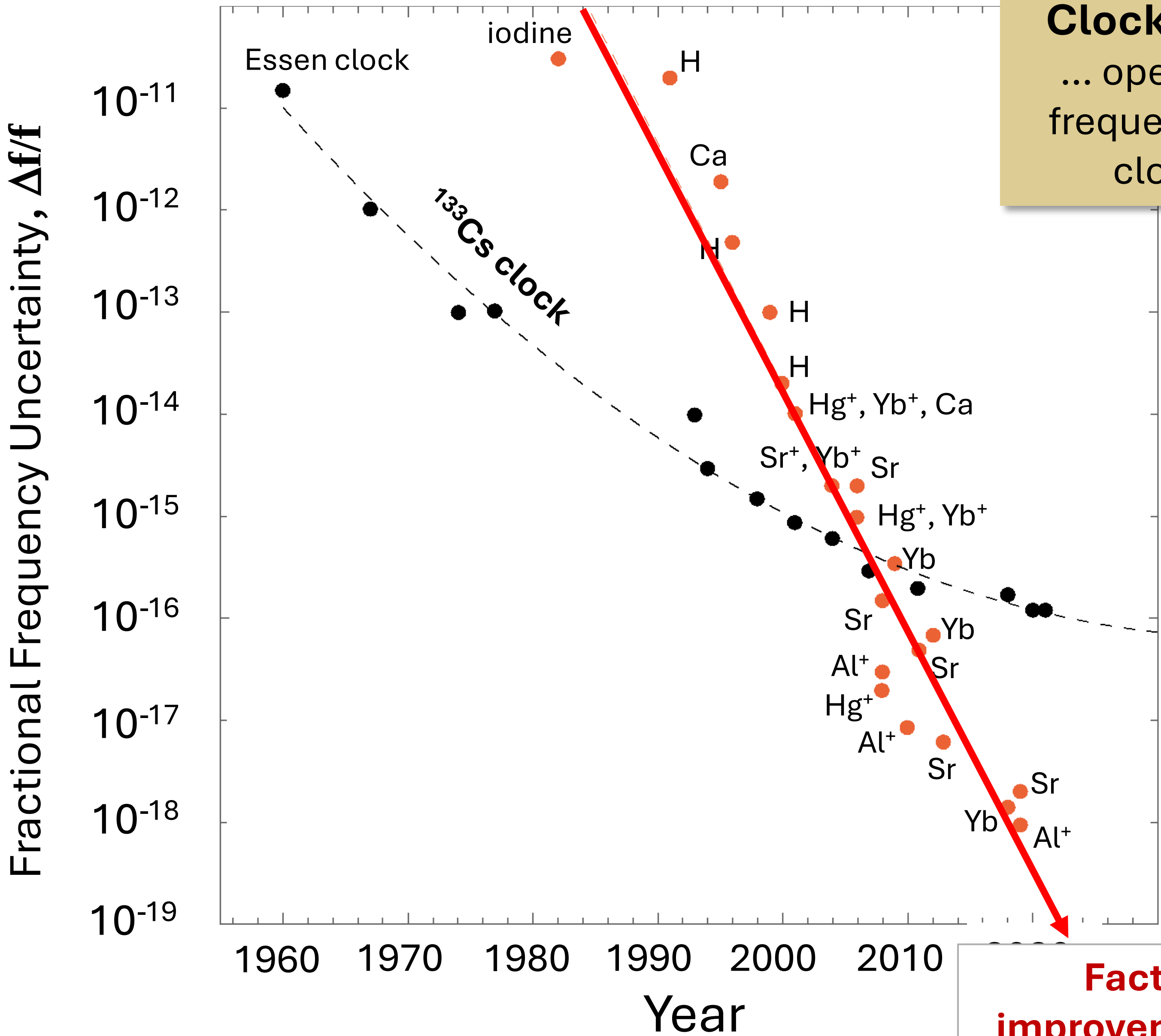


1second =
9 192 631 770 cycles of radiation of the transition frequency of ^{133}Cs.

Feedback signal to stabilize the laser frequency to the atomic transition

Historical performance of atomic clocks

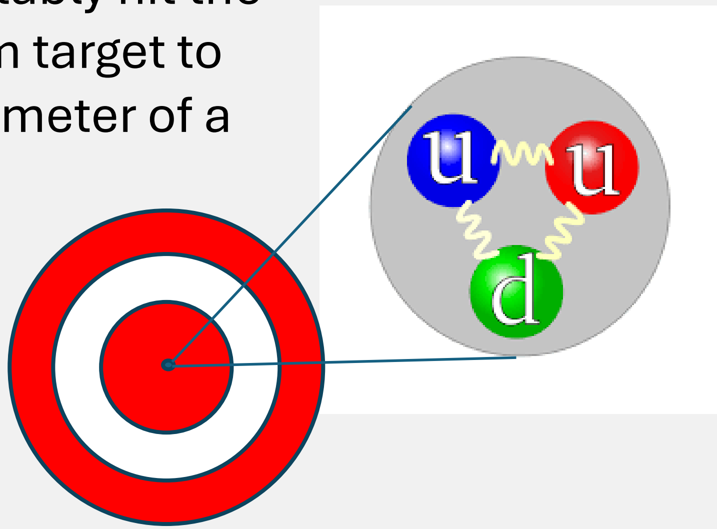


Clocks accuracy Δf/f
... operating at a higher frequency increases the clock resolution.

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!



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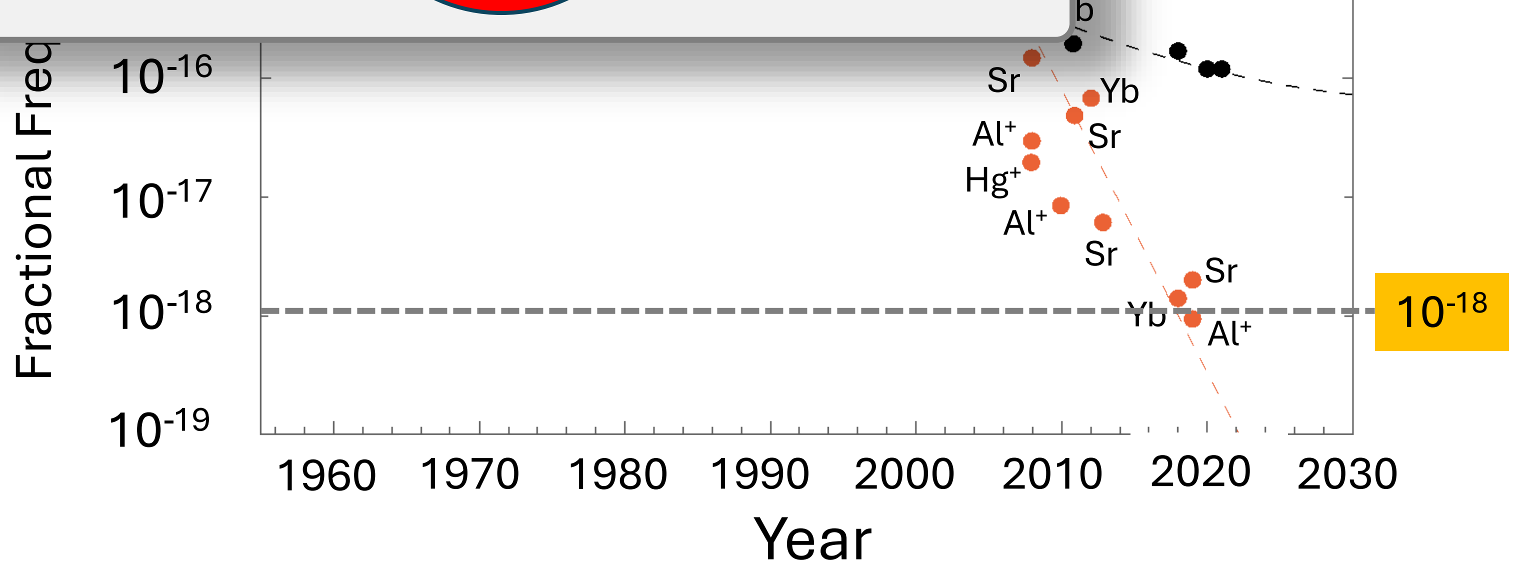
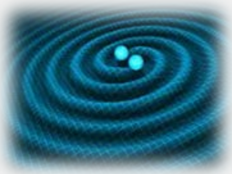
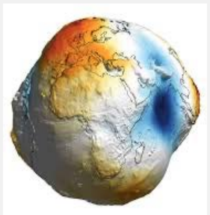


What can you do with 10^{-18} accuracy

Next generation applications:



Fundamental physics:
- general relativity
- Gravitational wave detection



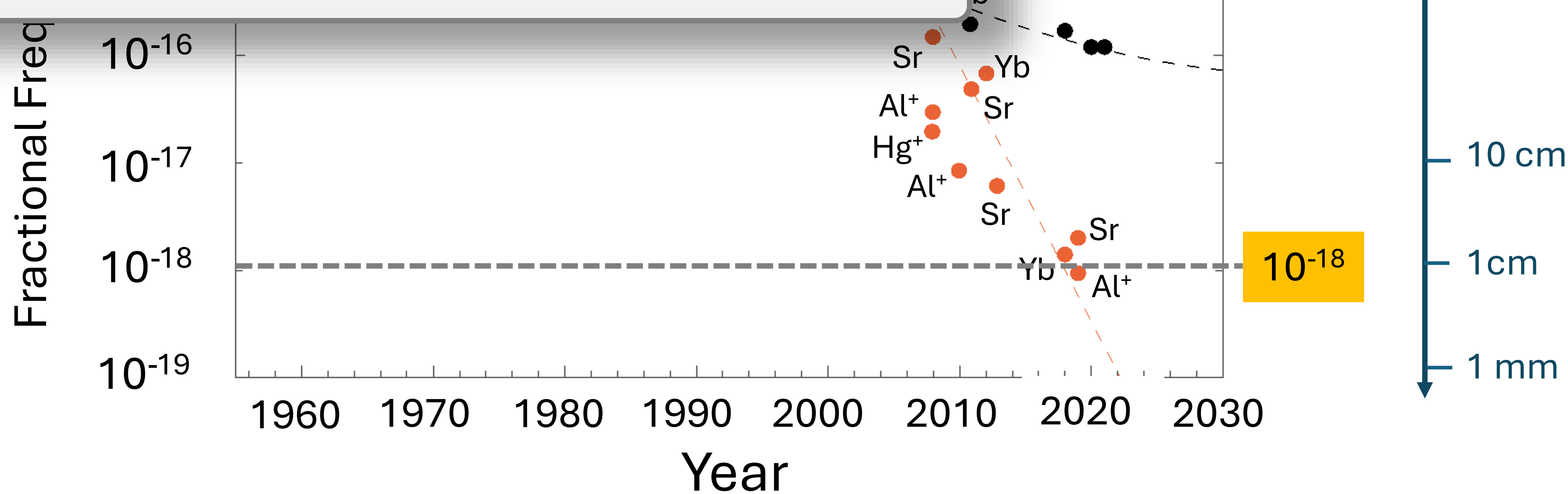
Portable clocks:
- PNT in GPS denied environments
- Geodesy
- Space applications

Relativistic geodesy:
- Hydrological & geophysical sensing

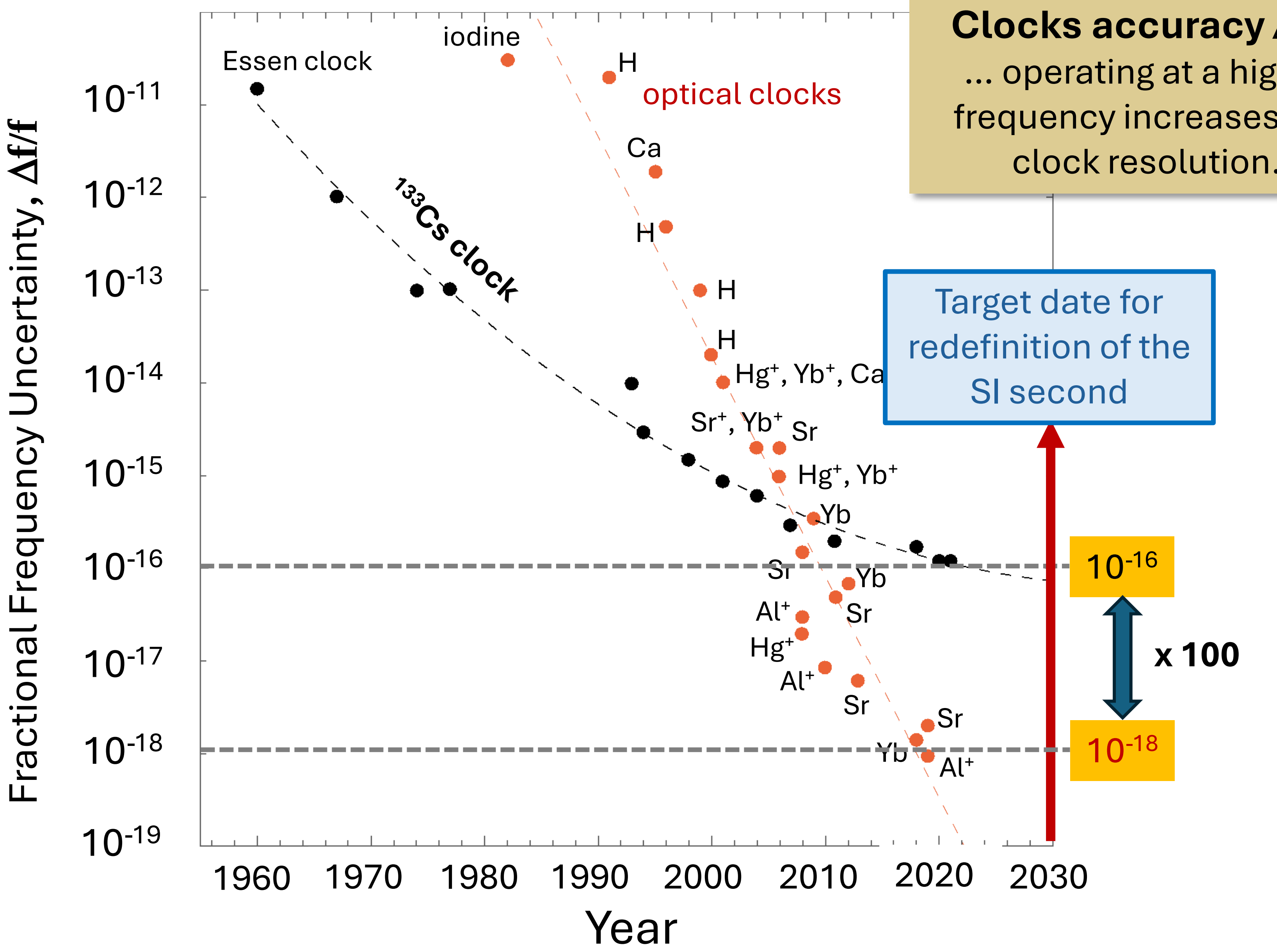
Clocks accuracy Δf/f
... operating at a higher frequency increases the clock resolution.

Relativistic sensitivity

Gravitational redshift



Historical performance of atomic clocks

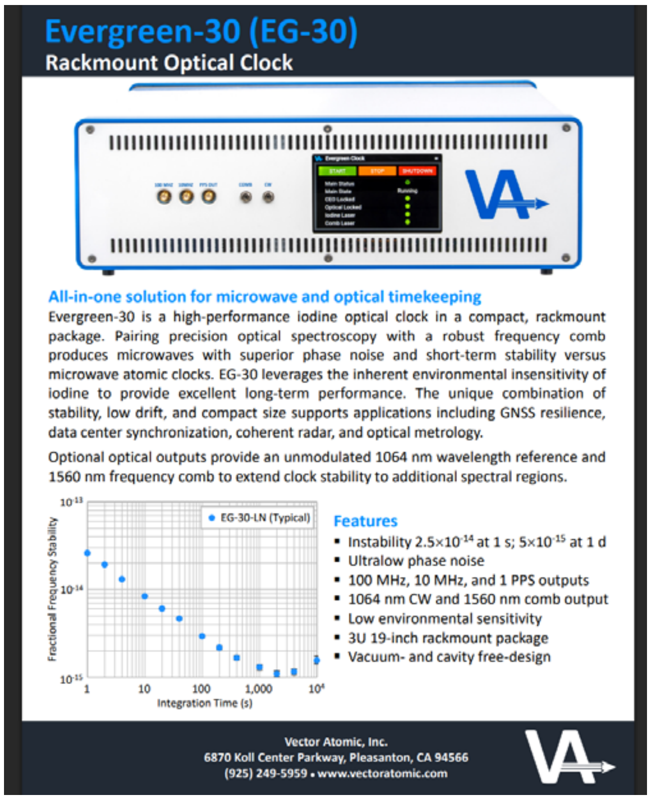


Clocks accuracy Δf/f

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

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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Challenges with optical clocks

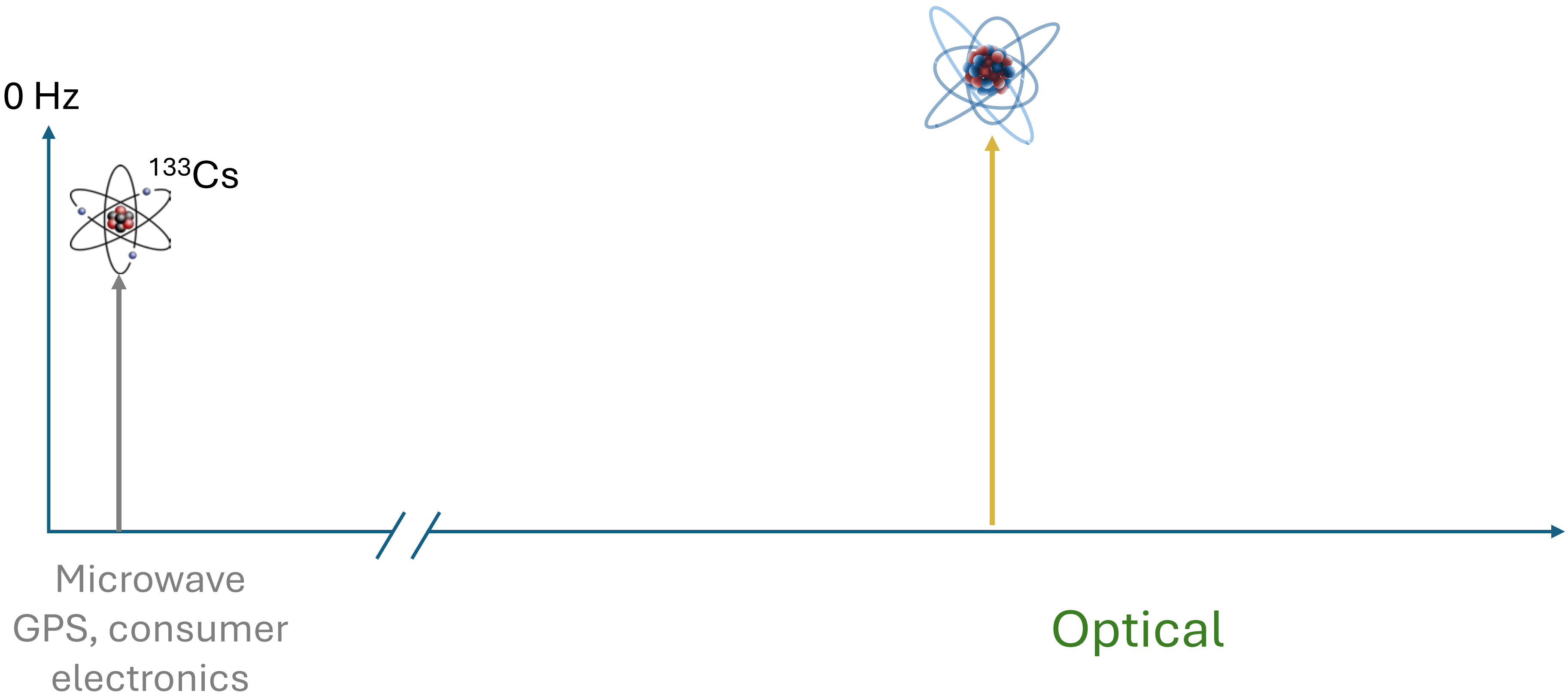
How can you count optical cycles?!

4 GHz

← x 100,000 →

400 THz

Review: *T.M. Fortier & E. Baumann, Communications Physics* ***2*** *(2019)*



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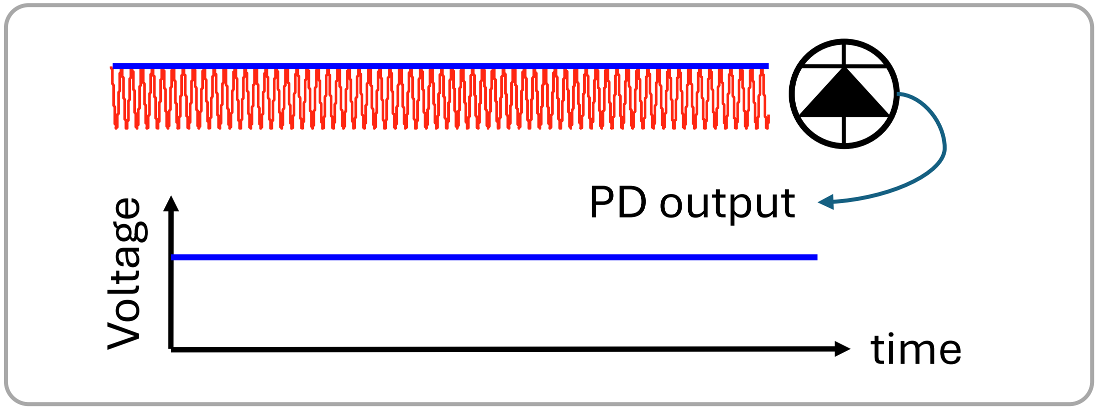
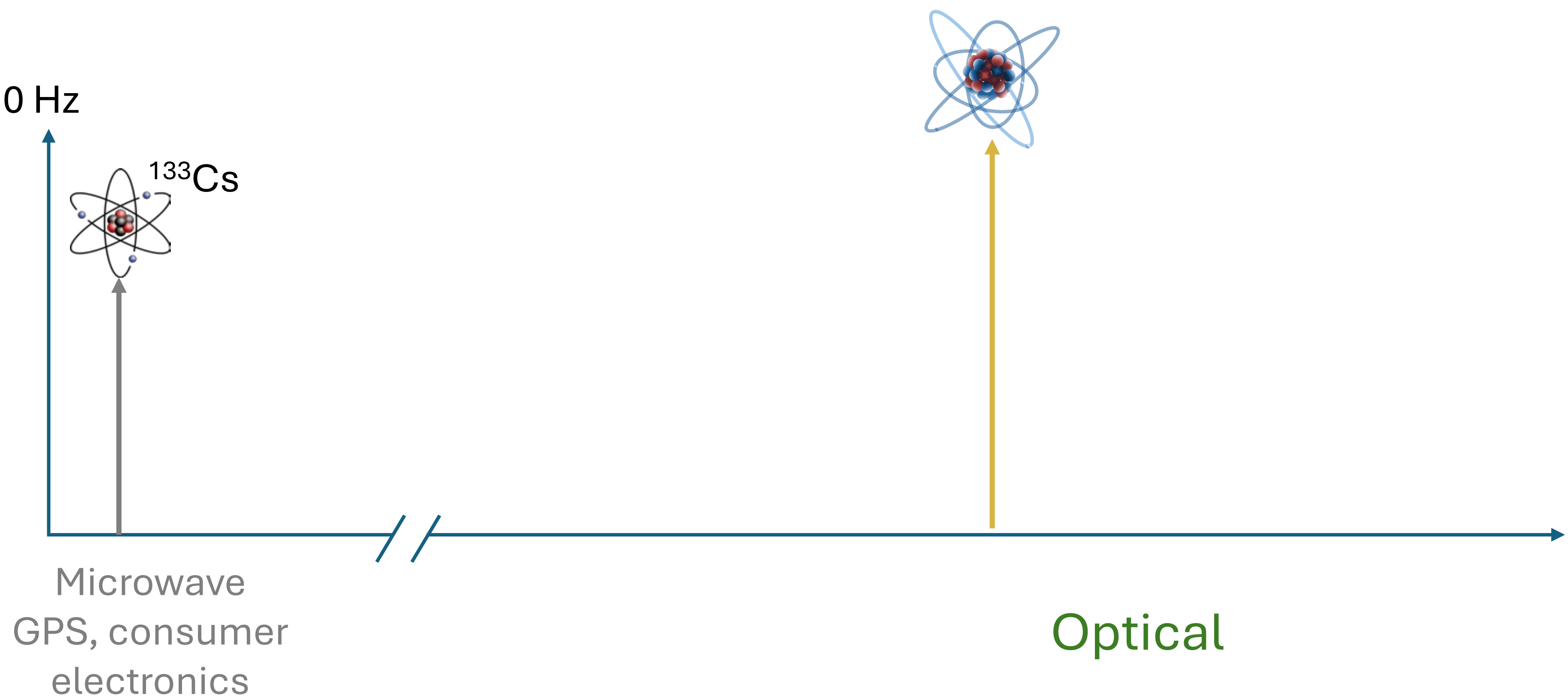




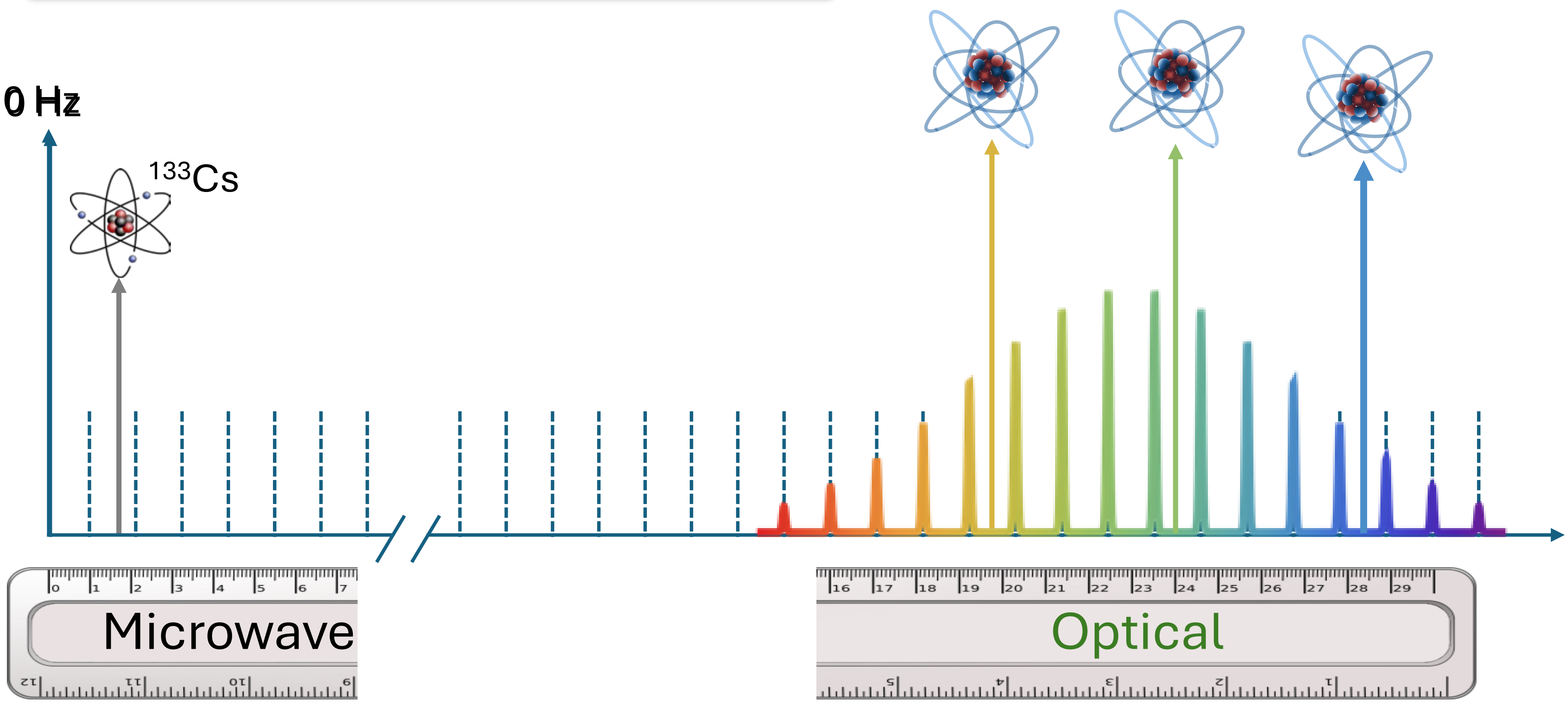
Challenges with optical clocks

Frequency combs:
Optical-to-microwave connection
- traceability to the SI second → Hz.
- measurement of unknown optical transitions.

Broad optical bandwidth:
- comparison of optical clocks.

Review: T.M. Fortier & E. Baumann, *Communications Physics* **2** (2019)

Equidistance in the optical modes measured to < 10^{-20}!



How a frequency comb works

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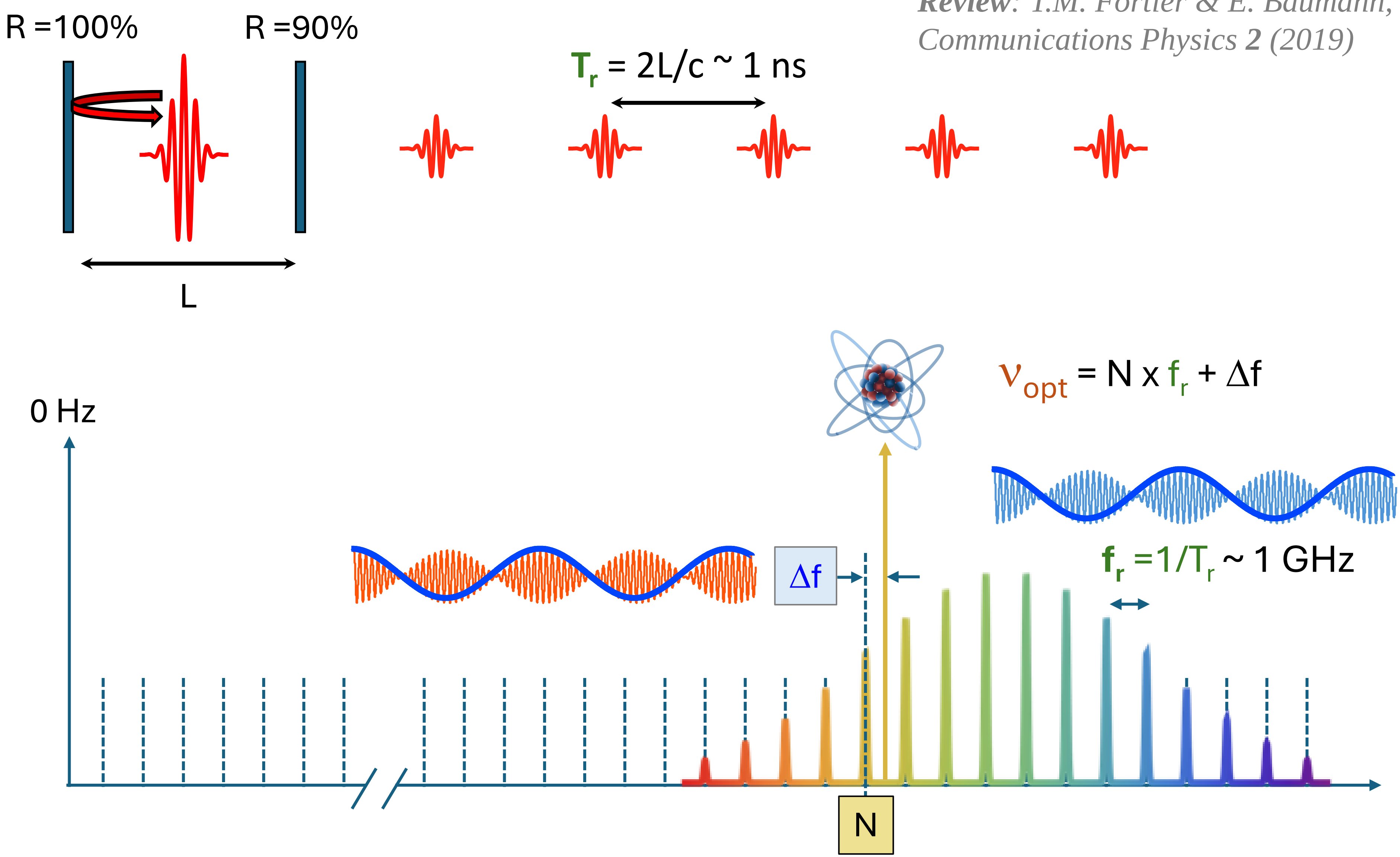

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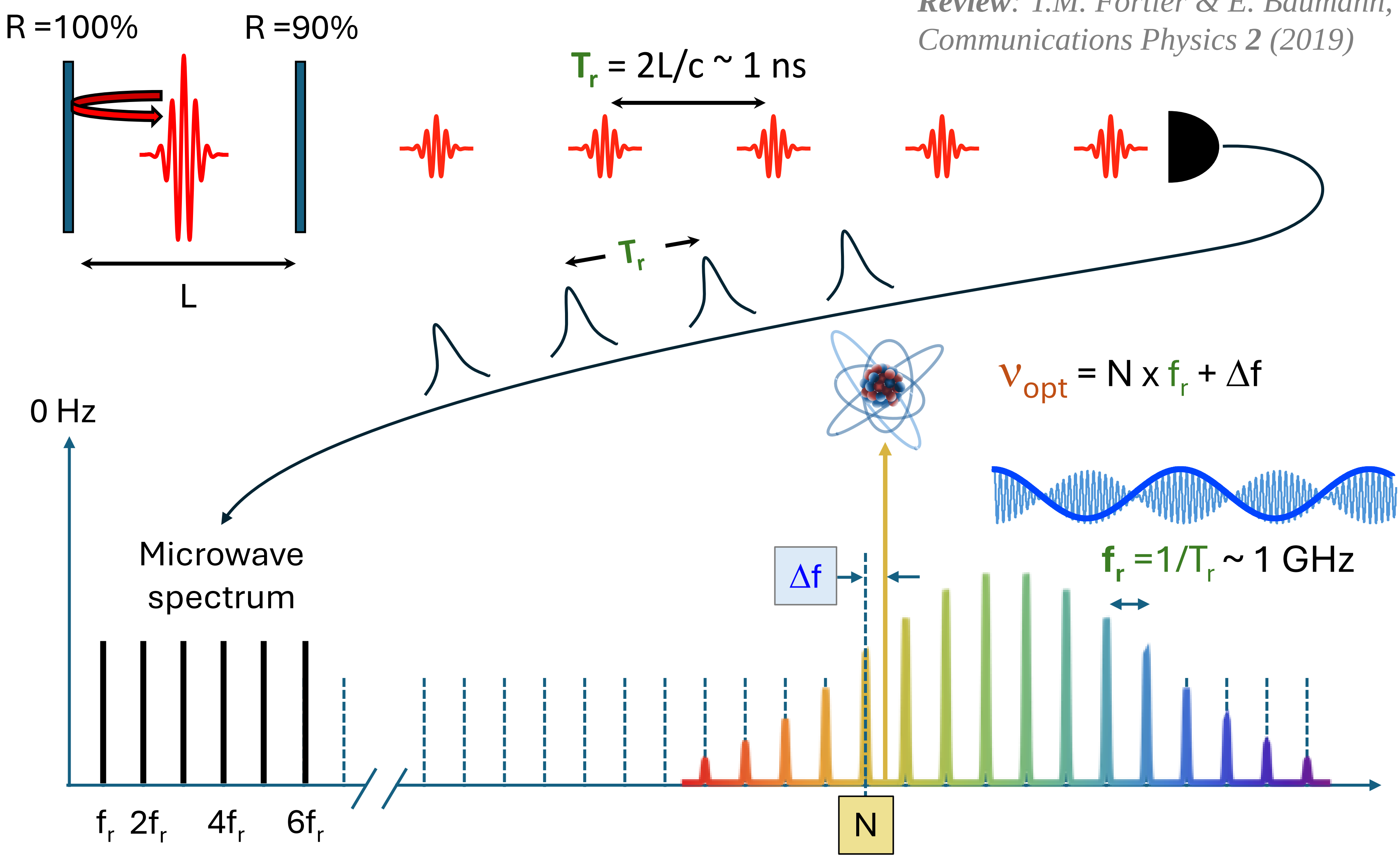

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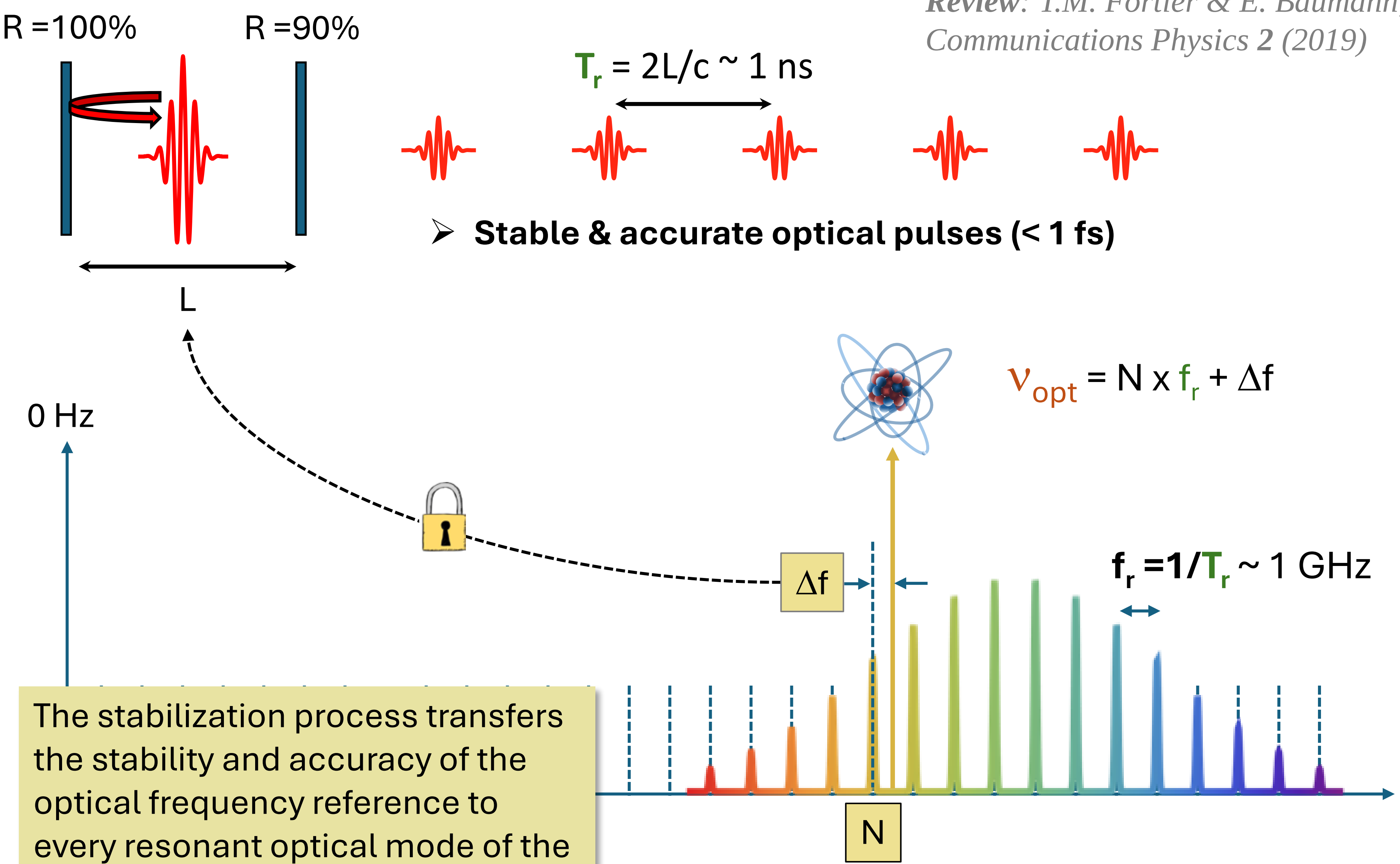

The stabilization process transfers the stability and accuracy of the optical frequency reference to every resonant optical mode of the OFC laser spectrum!

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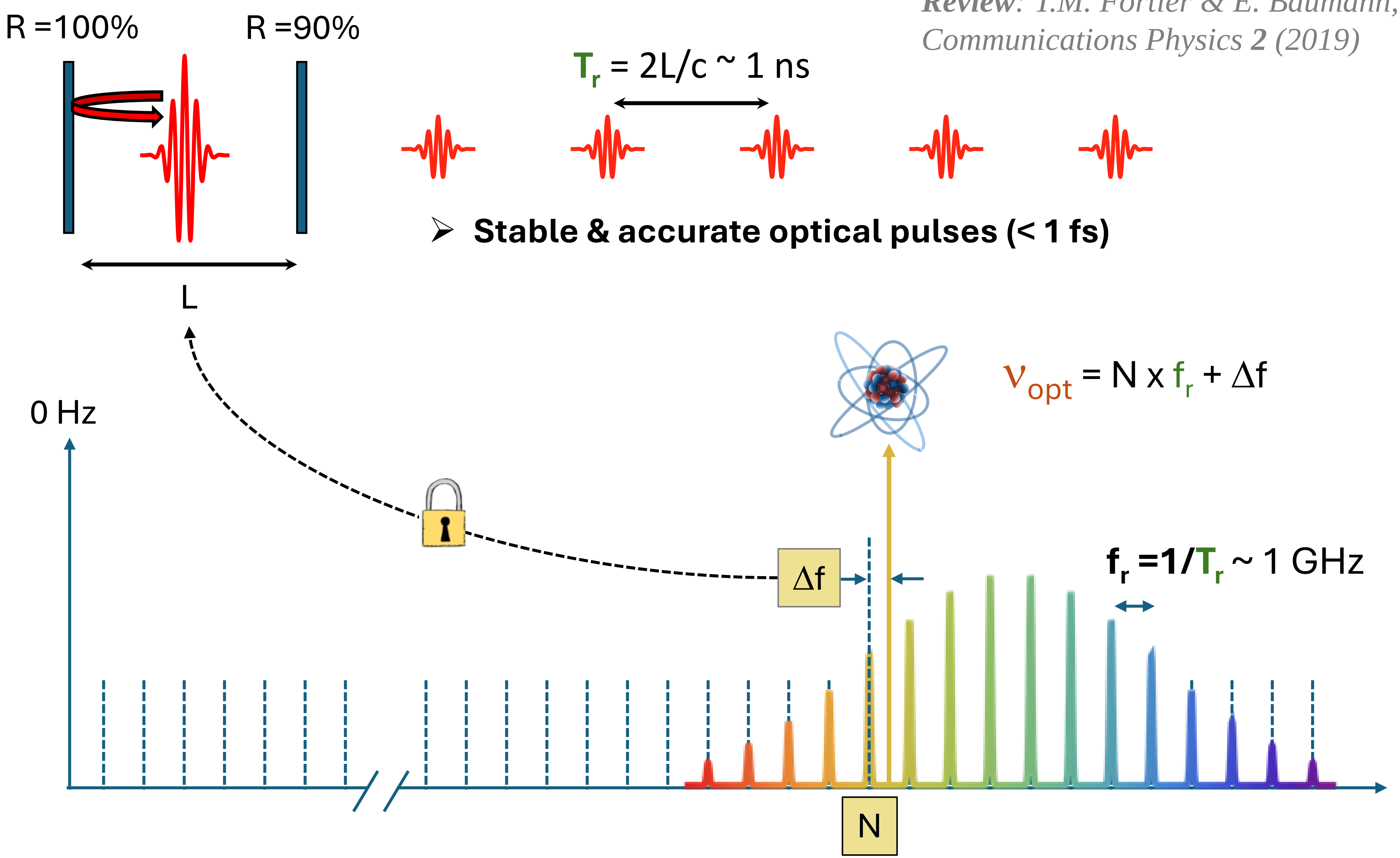
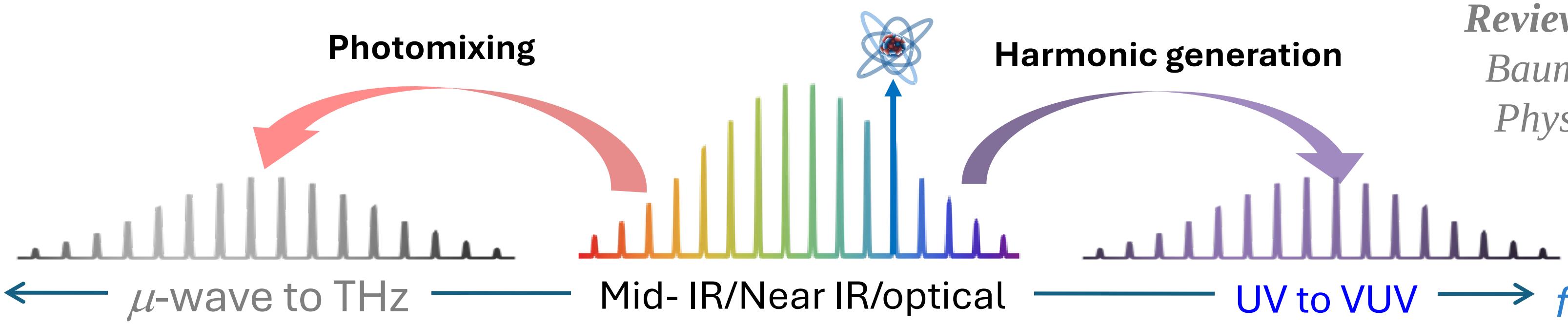
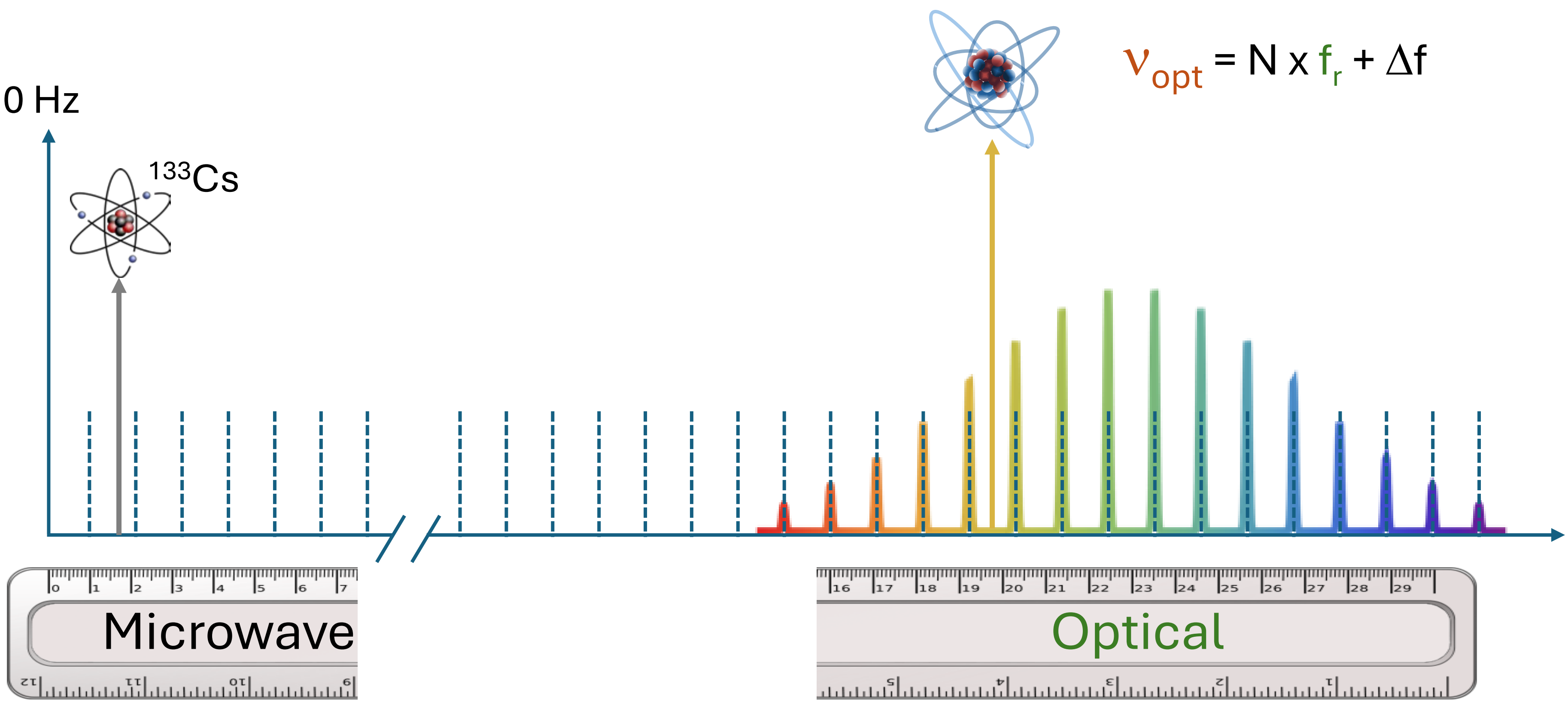


➢ **Stable & accurate optical pulses (< 1 fs)**

Frequency combs: connecting Atomic Clocks

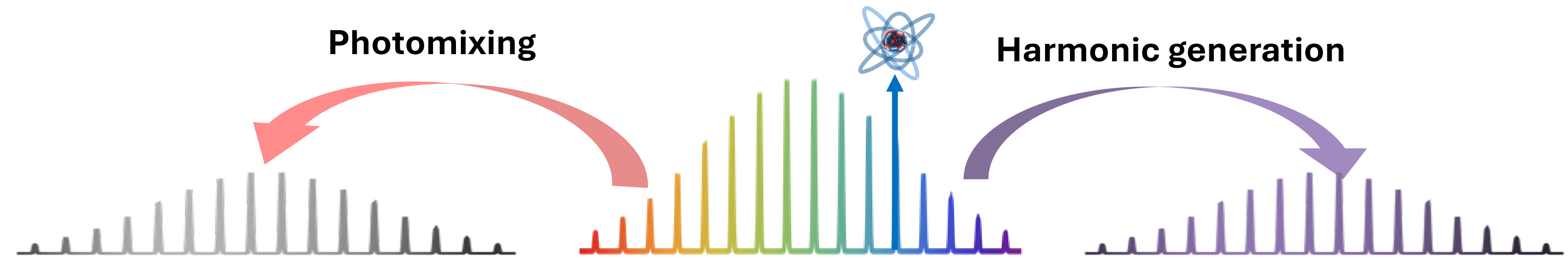
Review: *Fortier and Baumann, Comm. Physics* ***2*** *(2019)*





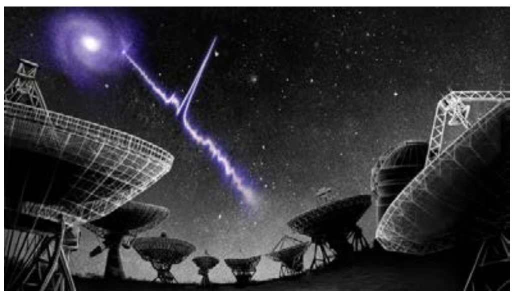
Applications across the electro-magnetic spectrum

Photomixing **Harmonic generation**



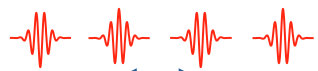
← μ-wave to THz — Mid- IR/Near IR/optical — UV to VUV → f

References for VLBI



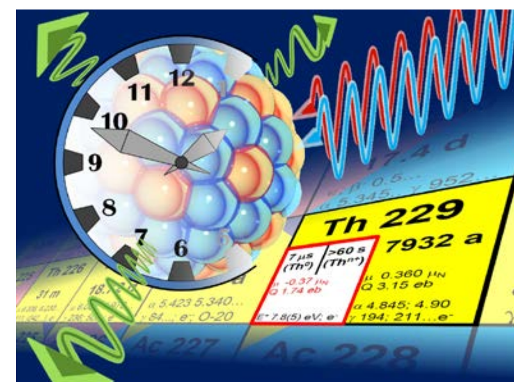
Clivati et al. Rev. Sci. Instr. ***7*** *(2017)*
Pizzocaro, M. et al. Nat. Phys. (2021)

Free-space optical time transfer



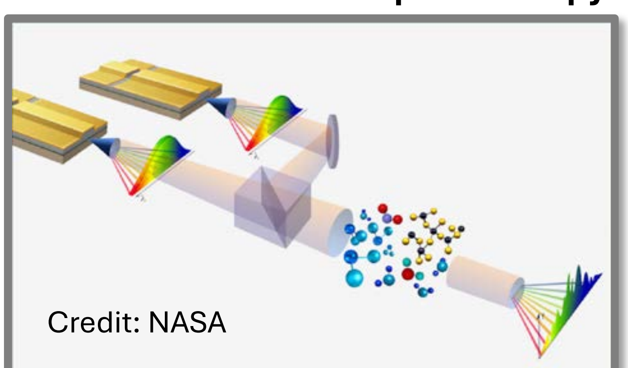
$T_r < 1$ fs

Nuclear atomic clocks



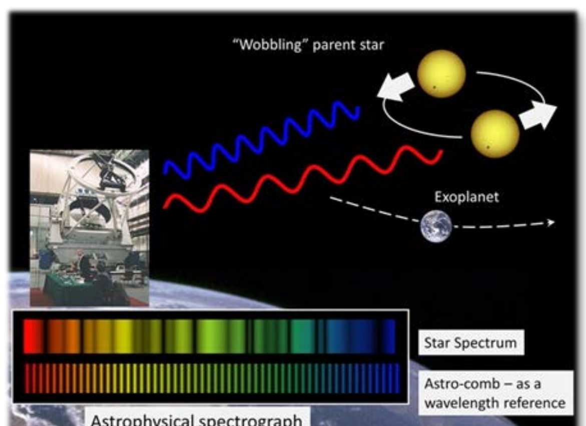
Review: *Pupeza. I. et al. Nat. Photon* ***15*** *(2022)*

Molecular spectroscopy



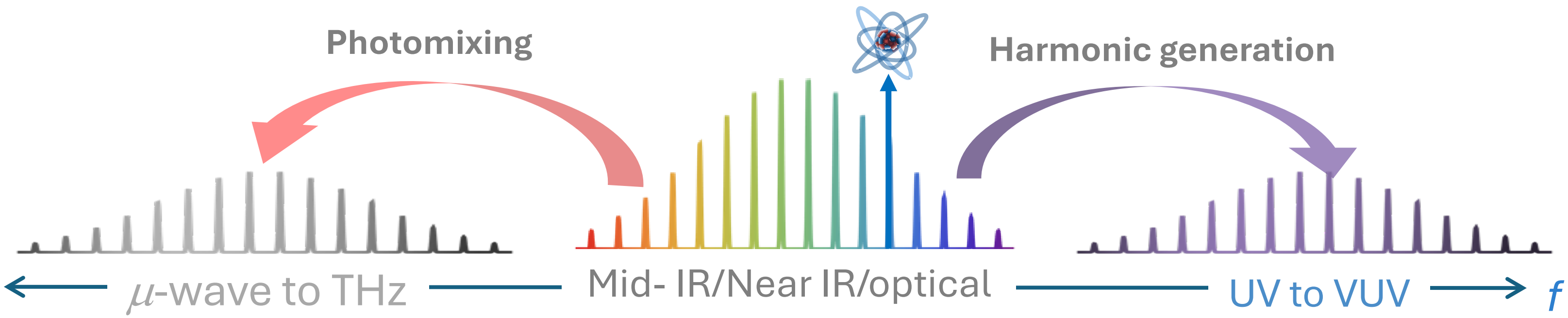
Review: *Schliesser et al. Nature* ***6*** *(2015)*

Calibration of astronomical spectrographs



Review: *McCracken et al. Opt. Exp. (2017)*

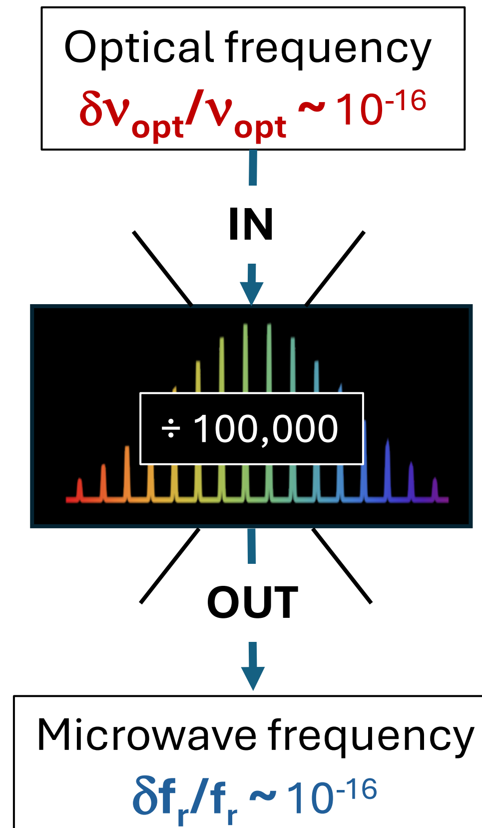
Frequency measurement across the E-M spectrum



Frequency combs: measurement and synthesis of atomic references from near 0 Hz – XUV with a fractional precision near $\Delta f/f \sim 10^{-18}$!

vs.

Mass metrology:
↑mass = ↑ precision



OCFs as a multi-use synthesizer

Ultra-broadband frequency synthesis

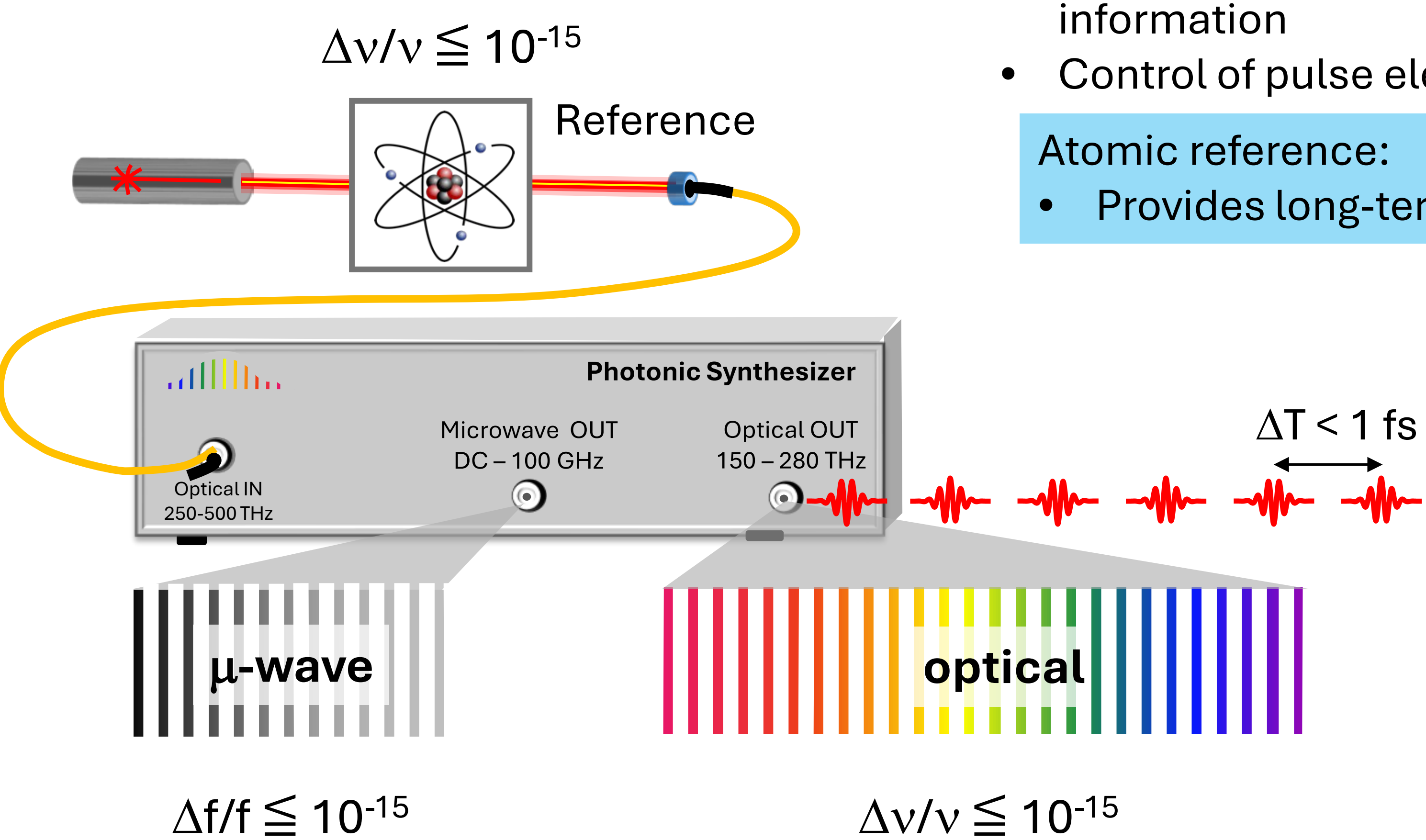
- Wideband optical synthesis/coverage
- Direct optical-to-microwave conversion
- Perfect multiplier/divider
  - High precision frequency counter

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



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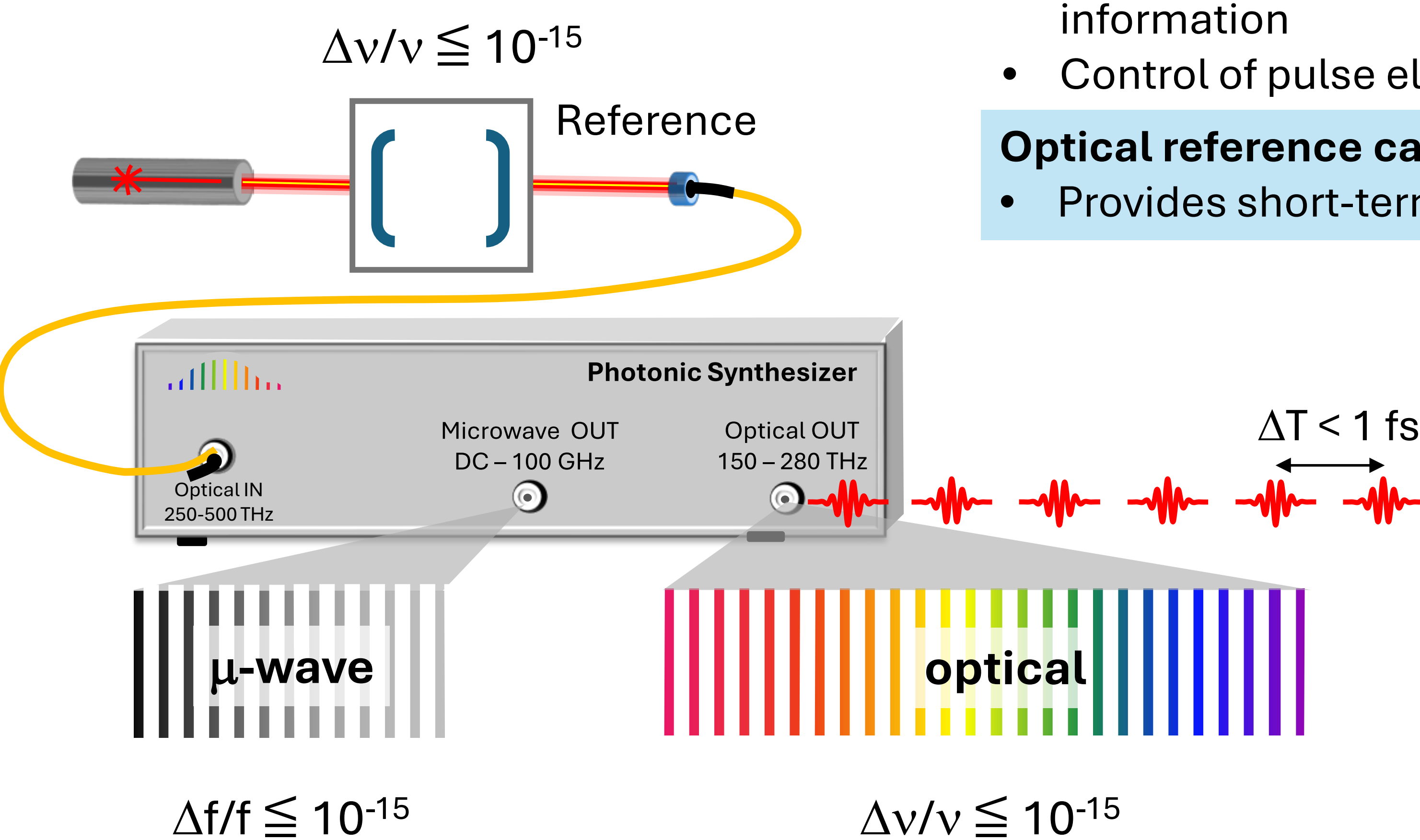
Optical reference cavity:

- Provides short-term (< 1s) stability



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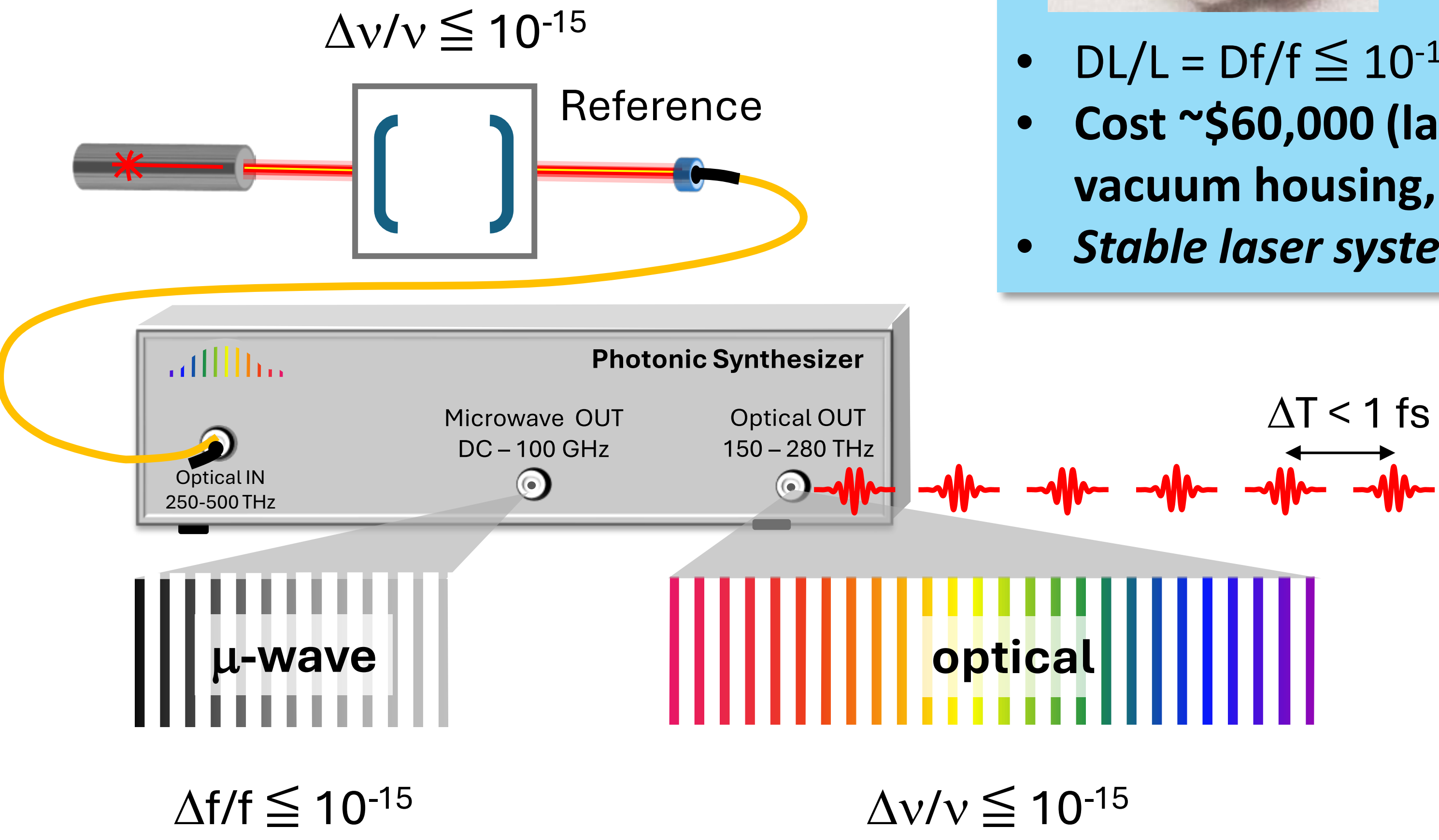

Fabry-Perot reference cavity:

- Two high-reflectivity mirrors
- Low-expansion spacer
- DL/L = Df/f $\leqq 10^{-15}$ @ 1s
- **Cost ~$60,000 (laser, cavity, vacuum housing, stabilization)**
- ***Stable laser systems***

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

Build your own comb? Cost ~ 50k USD

Paper on the performance of and how to align an ErYb:glass laser frequency comb:

- https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=935207

Components needed to build a telecom (1.5 um) frequency comb:

1. **A modelocked laser at 1.5 um**
   - Optical mounts and mirrors
   - 1 x pump laser at 980 nm + pump laser driver
   - 1 x ErYb:glass crystal
   - SESAM for auto-modelocking
2. **An optical amplifier:**
   - 3 pump lasers at 980 nm
   - Pump beam combiners
   - Er:doped fiber
   - Wavelength division multiplexer
   - SMF 28 (standard telecom optical fiber)
   - Fiber splicer
3. **Highly nonlinear fiber to broaden the optical spectrum for f-2f detection**
4. **f-2f interferometer:**
   - Mirrors, lenses, translation stage, filters, polarizer and mounts
   - Nonlinear crystal
   - Photodetector (EOT)
5. **Repetition rate detection for feedback and optical-to-microwave conversion:**
   - Optical filter
   - Photodetector (EOT)
6. **Electronic and optical feedback:**
   - PID filter
   - RF amplifiers, splitters, filters, connectors
   - Piezo-electric actuated mirror (fr stabilization)
   - Pump laser power (f0 stabilization)

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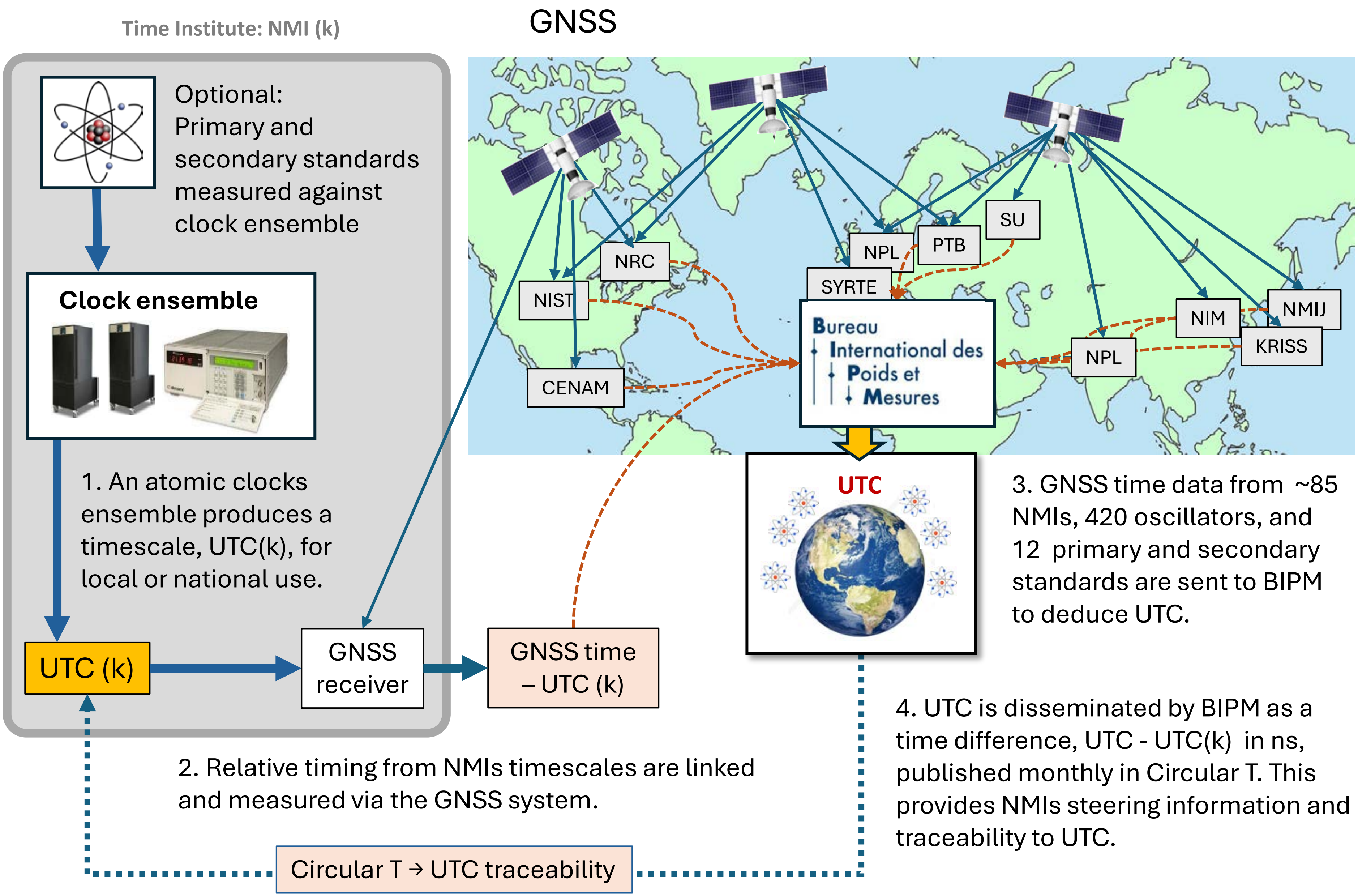
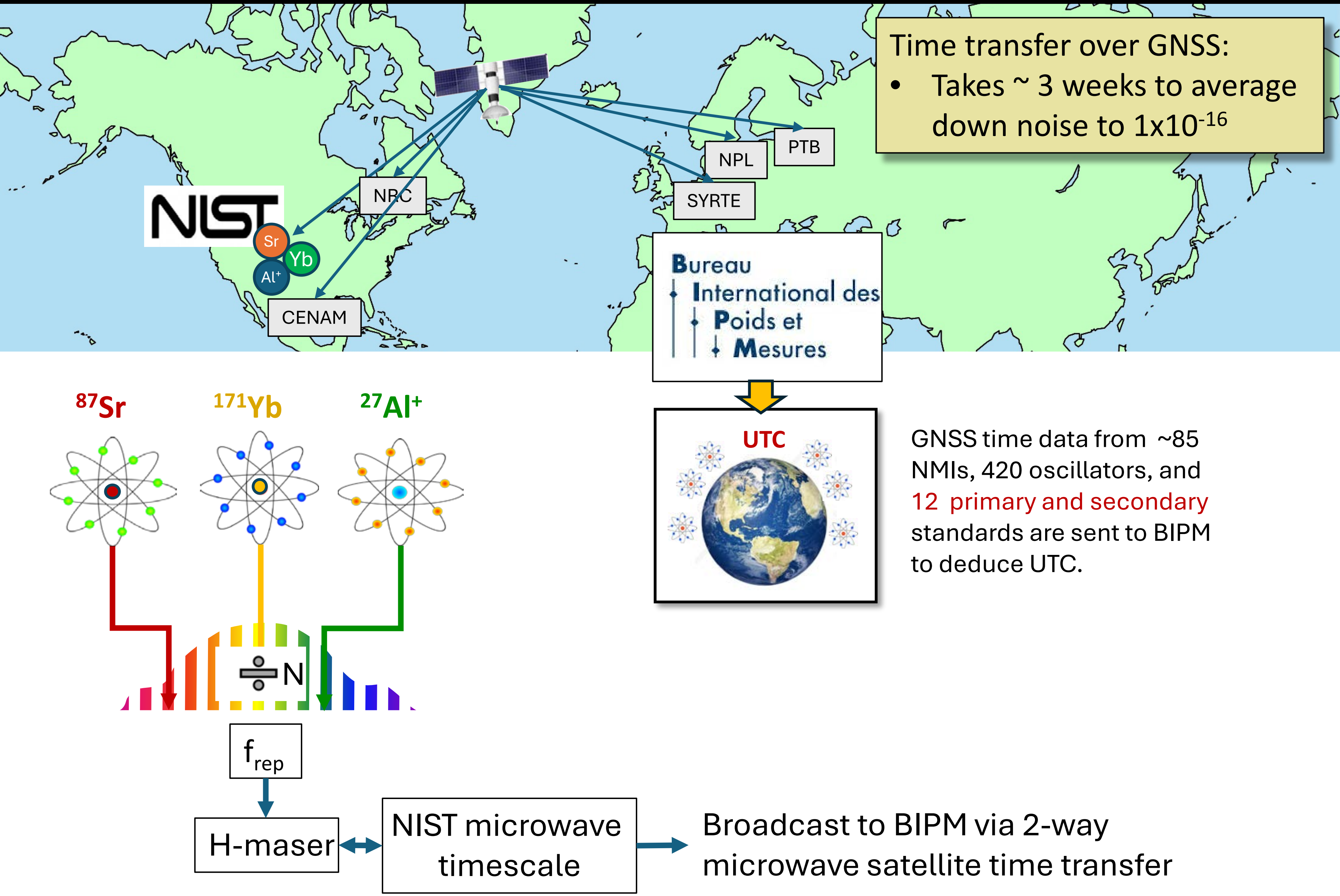
How atomic clocks contribute to UTC

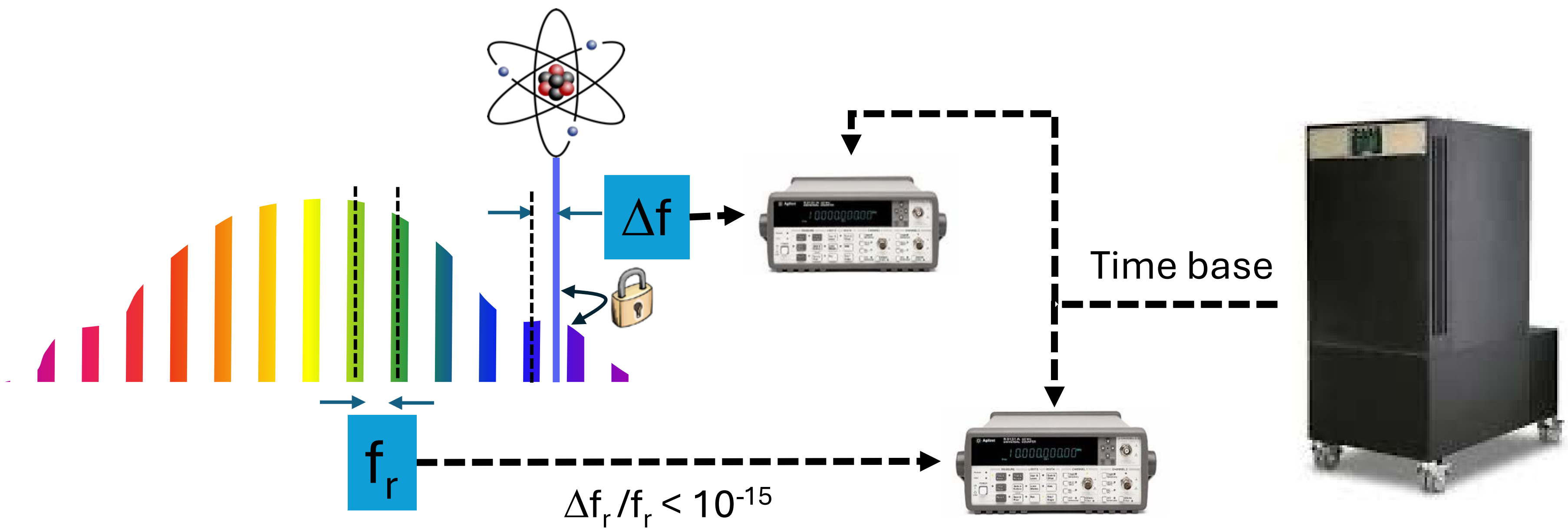


How *optical* atomic clocks contribute to UTC



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:

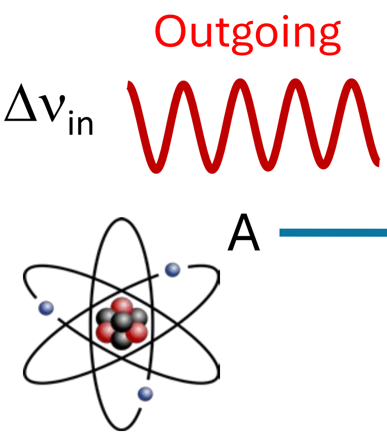
$$\nu_{Yb}\ (\text{local time}) = N \times f_r + \Delta f$$

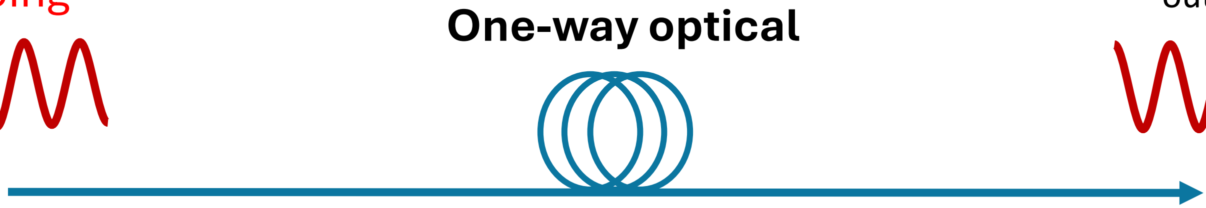
"Local time" is calibrated to Yb atomic time by assessing the difference:

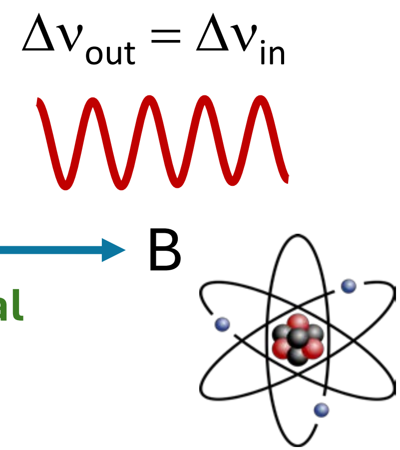
$$\nu_{Yb}\ (\text{local time}) - \nu_{Yb}(\text{SI})$$

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)

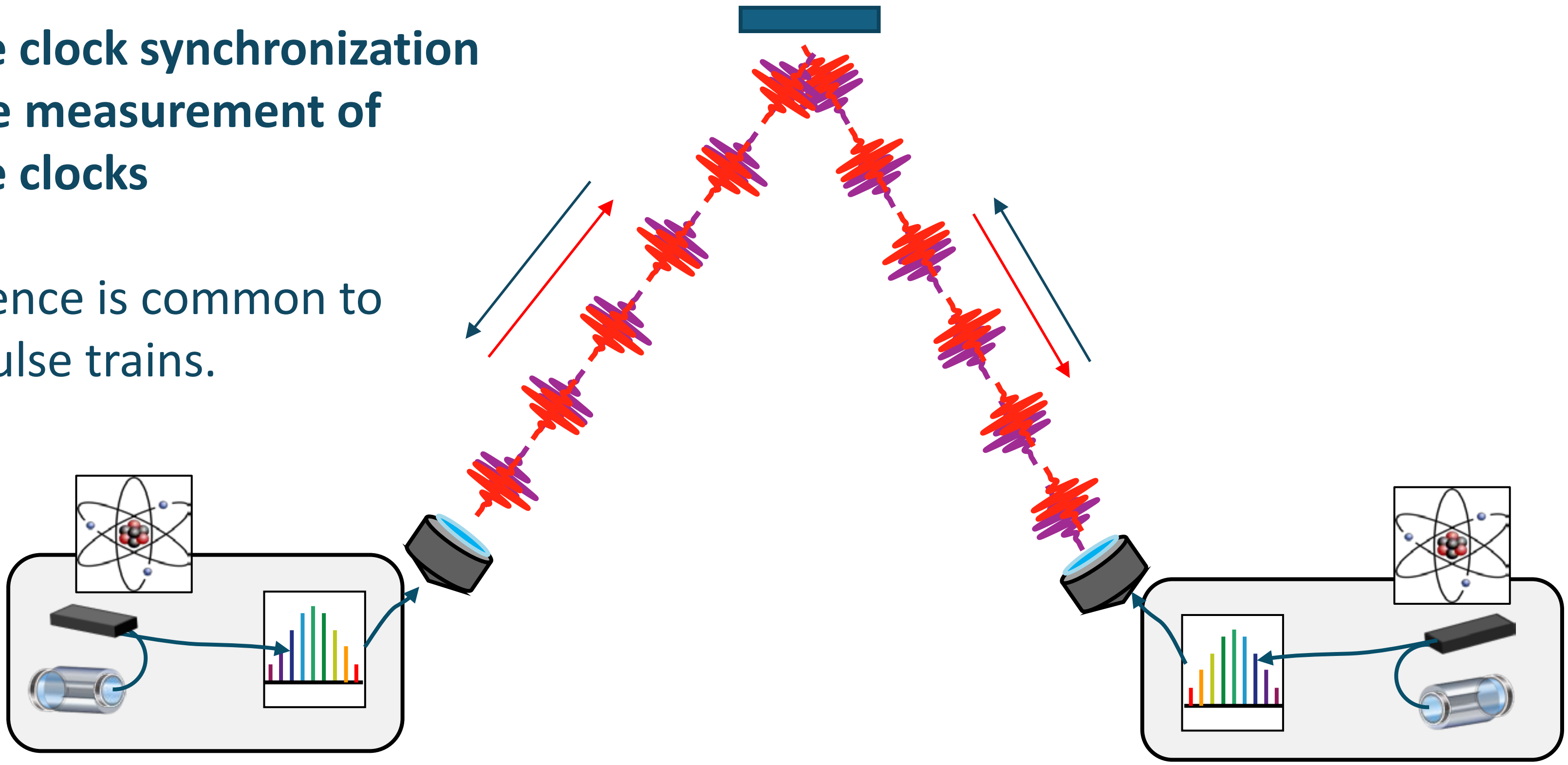
- Continuous wave laser
- $\Delta f/f = 10^{-18}$ at 10,000 s
- **920 km fiber optic link (0.025 dB loss/km @ 1550 nm)**

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.



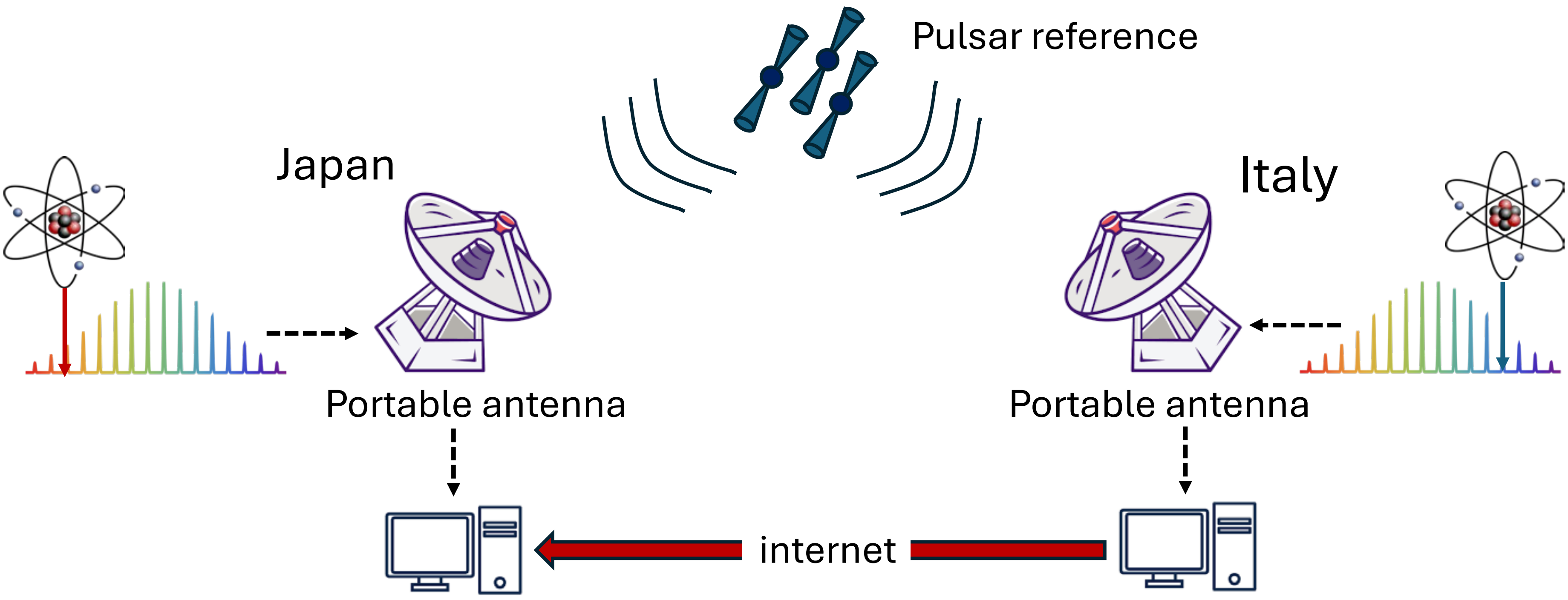
- Enables free-space comparison of clocks in the absence of fiber networks.
- Requires line of sight and good weather

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

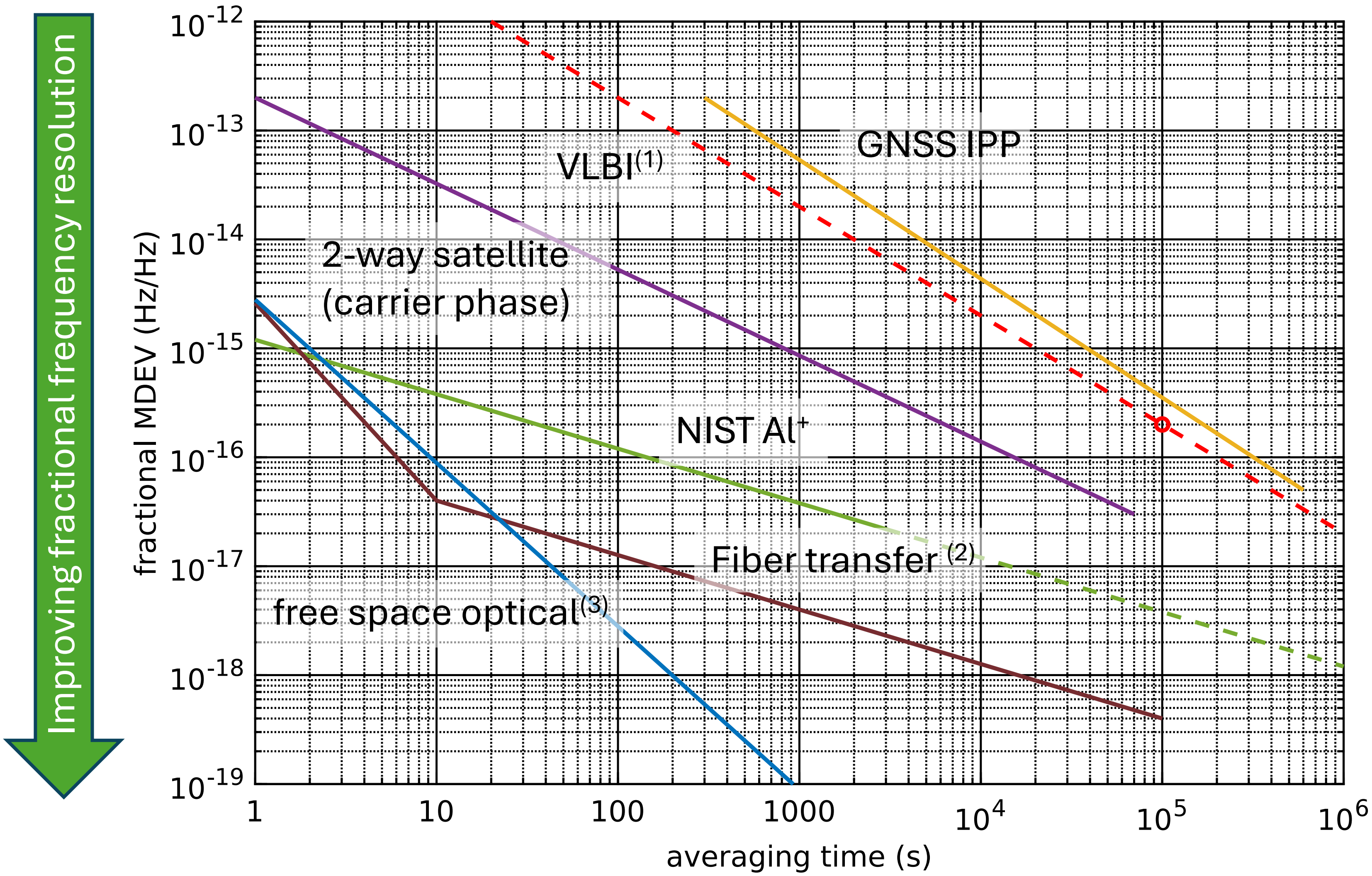
Atomic clock comparisons via VLBI

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

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



Performance vs time/frequency transfer method



(1) assuming white phase noise
(2) REFIMEVE Paris-CERN link (920 km)
(3) Caldwell et al

Credit: Michael Wouters

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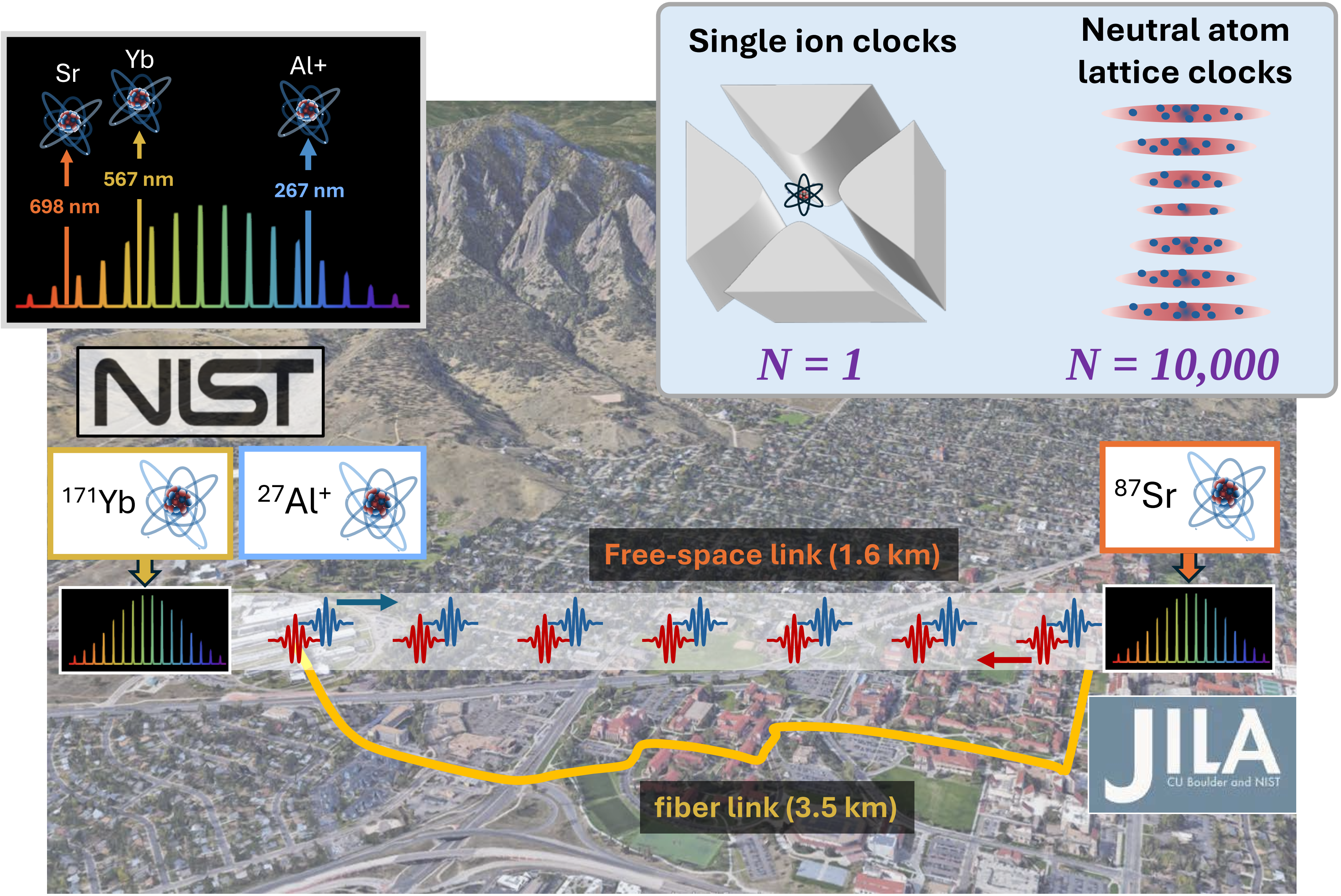
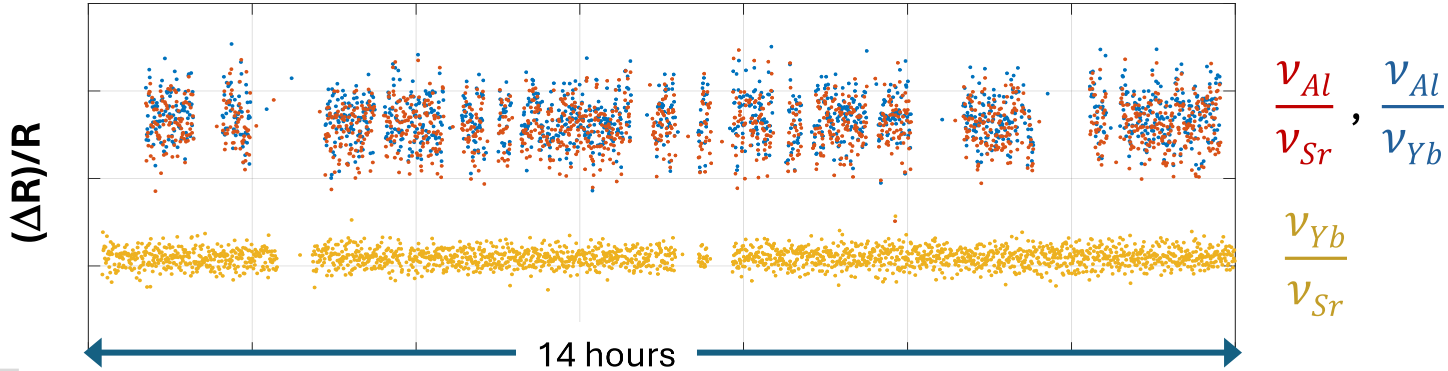
Boulder optical atomic clock network

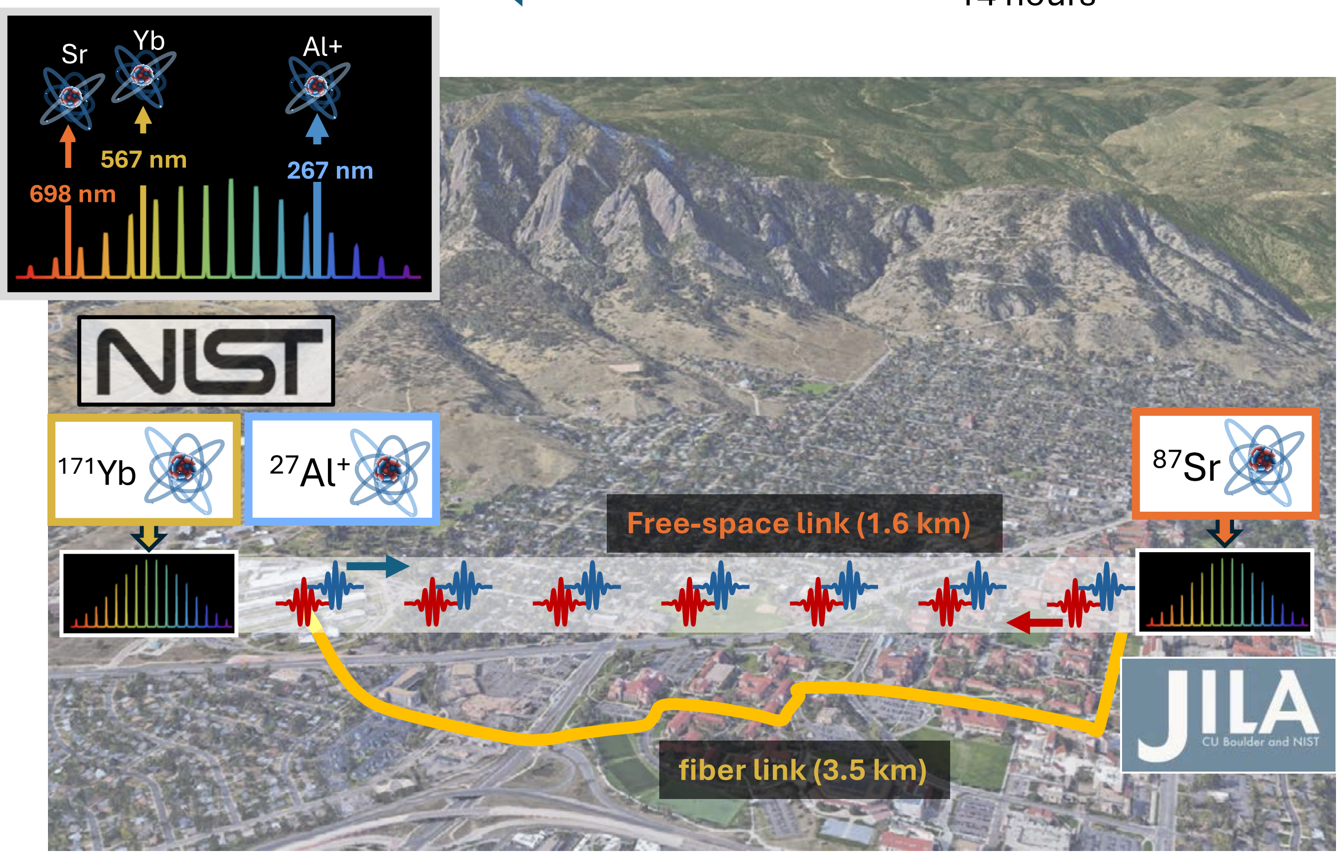


Boulder Atomic Clock Optical Network Collaboration. Nature ***591*** *(2021).*

Boulder optical atomic clock network

$$\frac{\nu_{Sr}(\text{Hz})}{\nu_{Yb}(\text{Hz})}$$



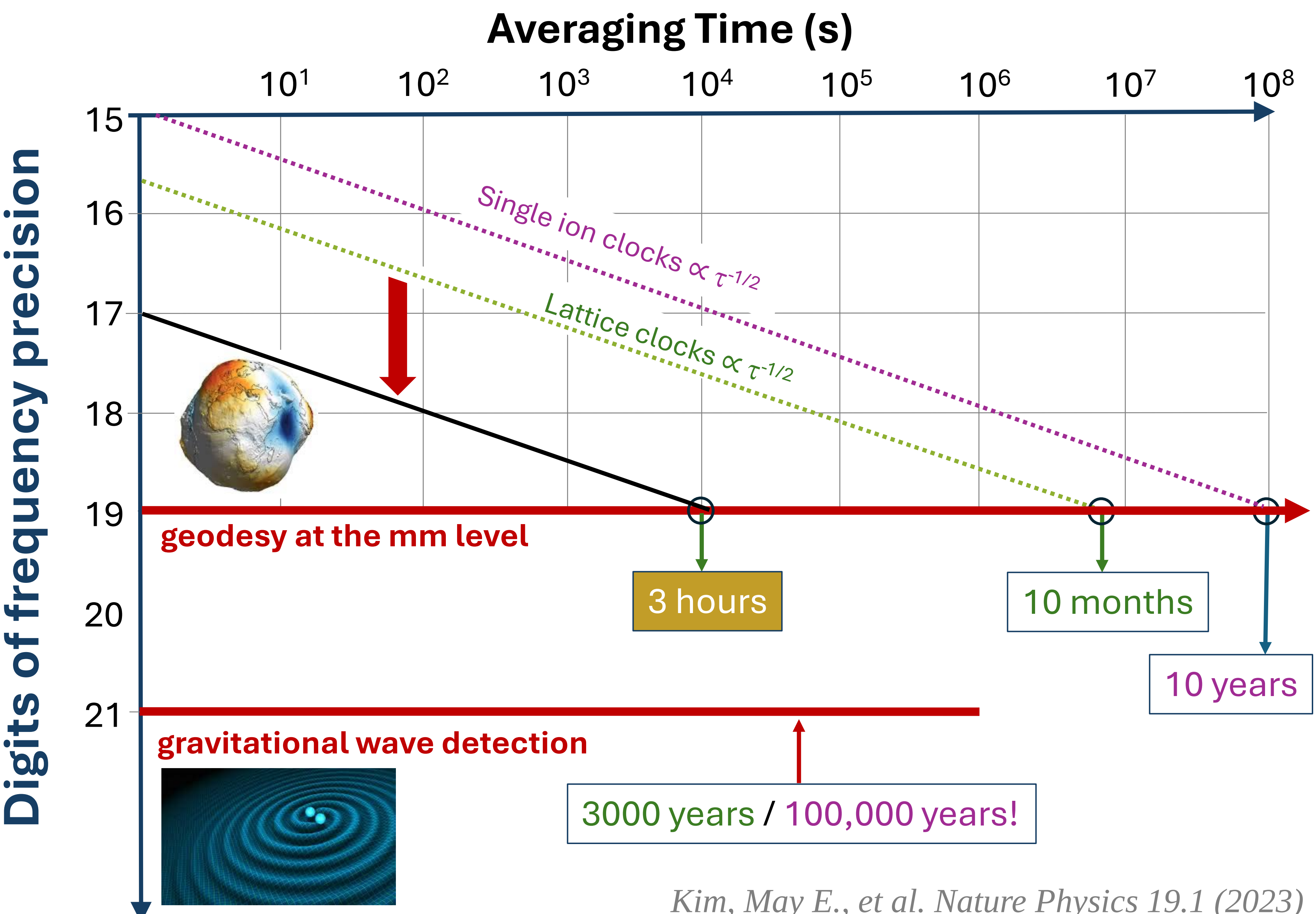


Ratio measurements:

- Assess clock consistency and performance.
- Can be used to look for variations in physical laws, including searches for dark matter.

Boulder Atomic Clock Optical Network Collaboration. Nature ***591*** *(2021).*

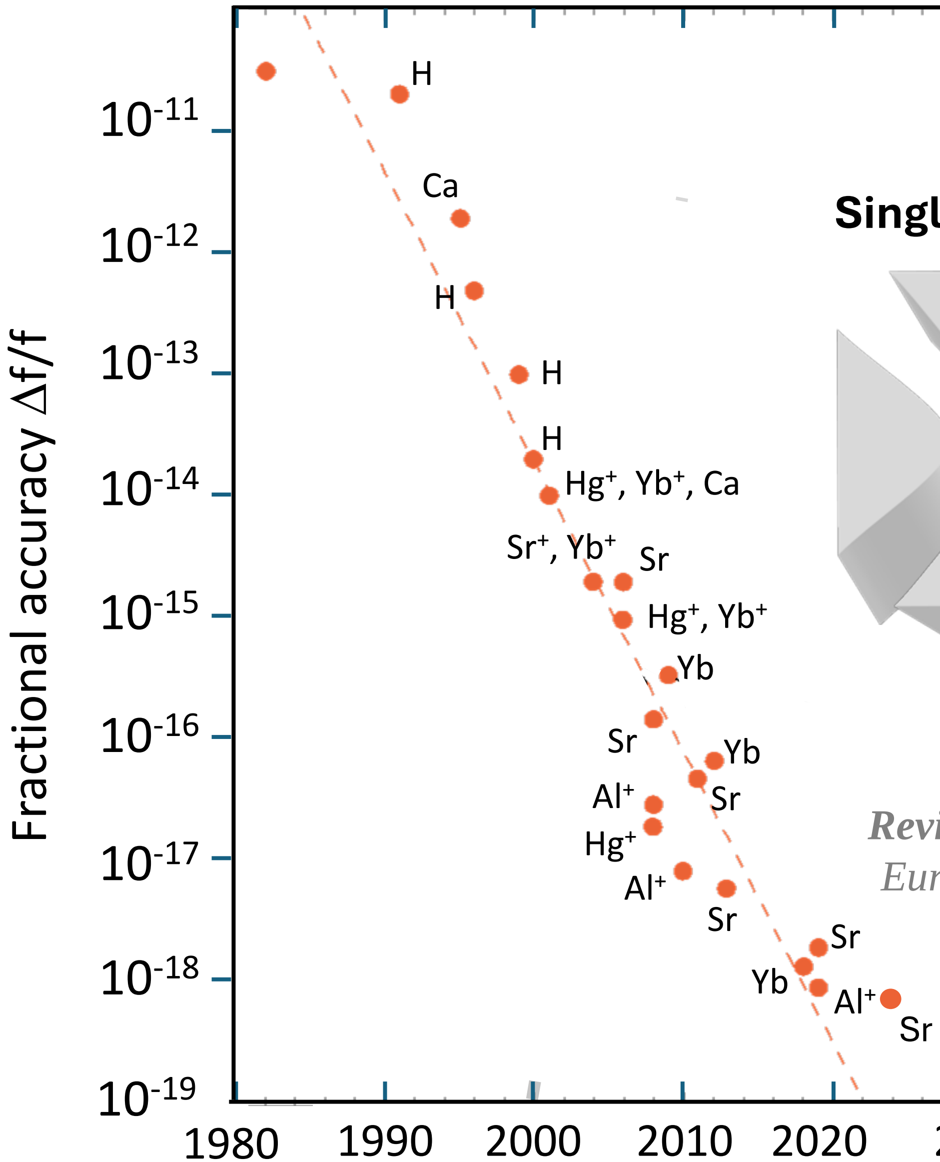
Precision and measurement time



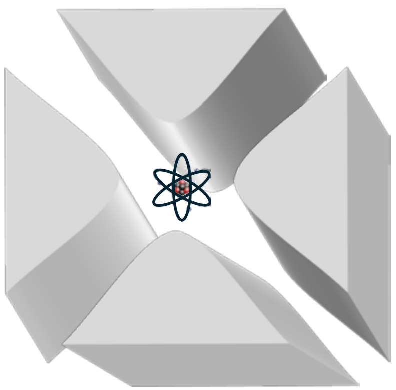
Kim, May E., et al. Nature Physics 19.1 (2023)

Clocks pushing the quantum limit

$$\mathrm{SNR} \propto \upsilon_0 \sqrt{N\tau}$$



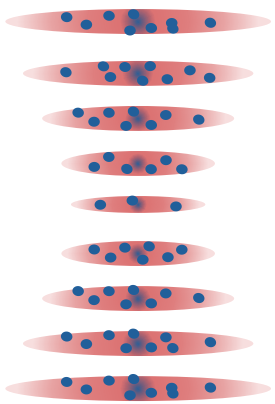
Single ion clocks



N = 1

Review: *Margolis, H. Euro. Phys. Journal 172.1 (2009)*

Neutral atom clocks

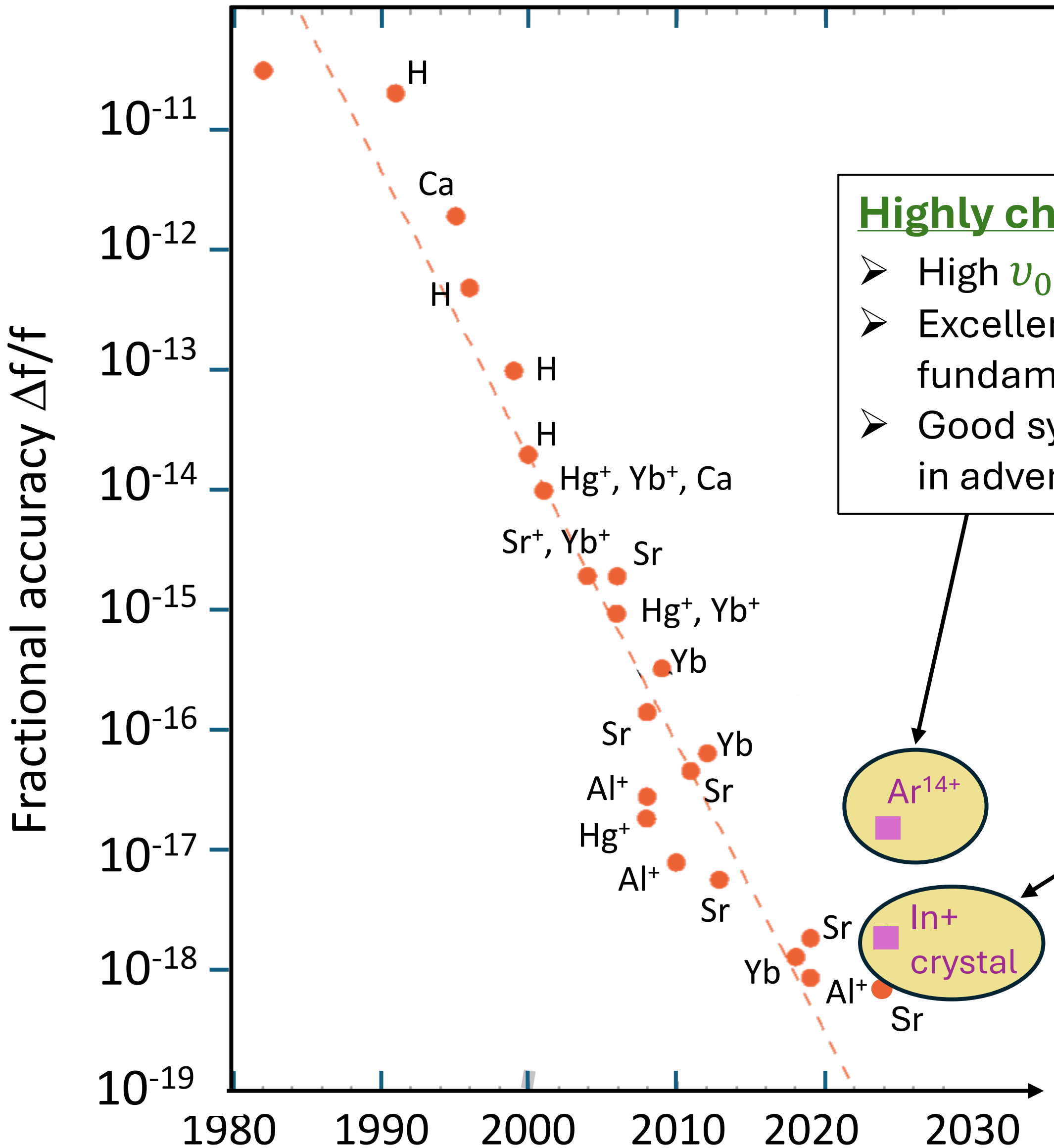


N = 10,000

Review: *Takamoto, M and Katori, H Quantum Photonics. (2024)*

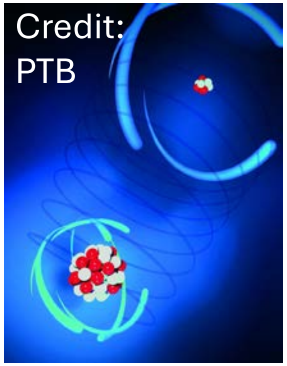
Clocks pushing the quantum limit

$$\mathrm{SNR} \propto \upsilon_0 \sqrt{N\tau}$$



Highly charged ion clocks:

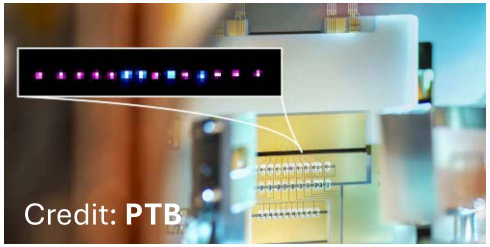
- High υ_0
- Excellent testbeds for fundamental physics
- Good systems for operation in adverse environment.



*King, S. et al, Nature **611** (2022)*

Ion crystal clocks:

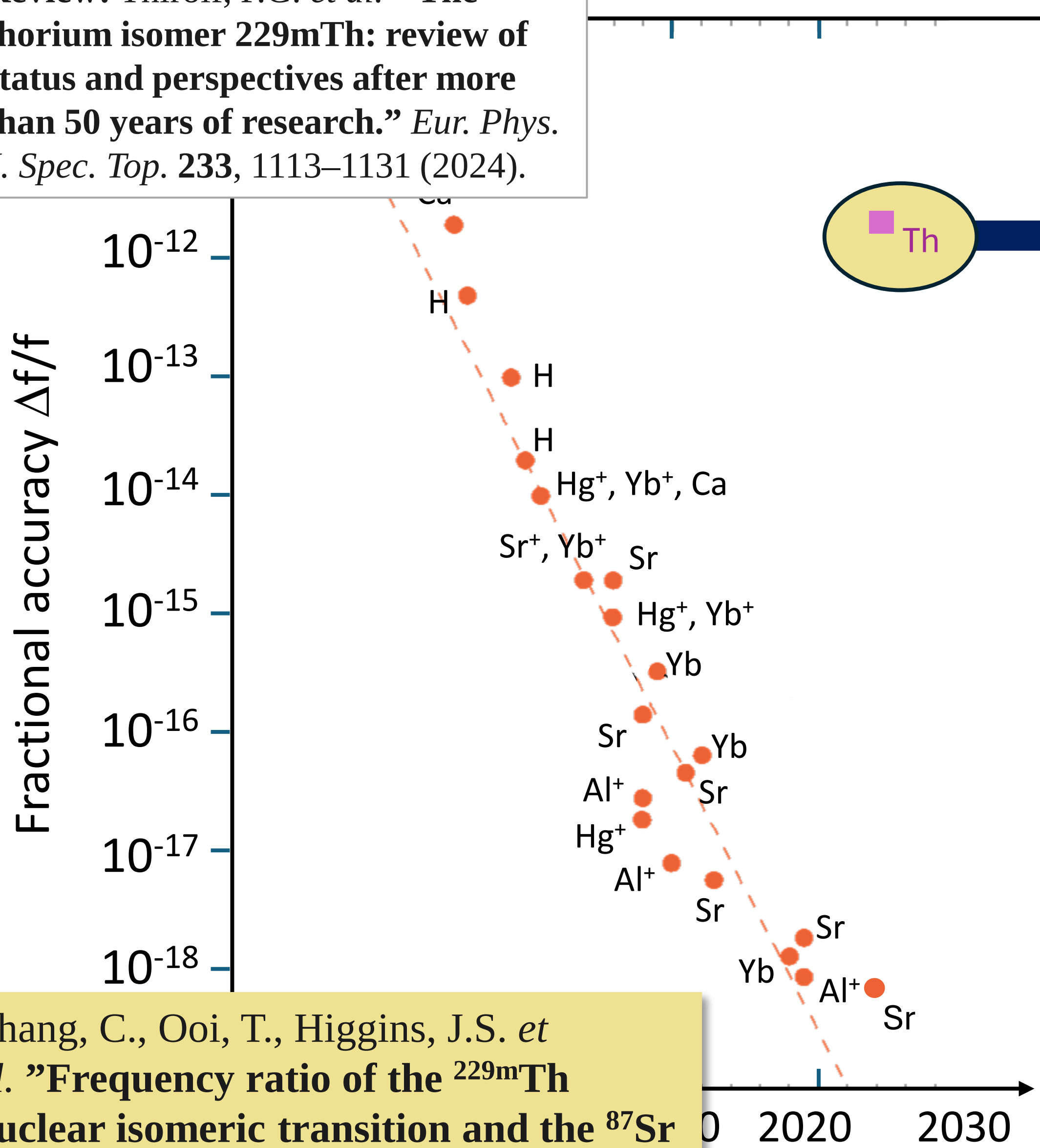
- *N = 12 (In^+ and Yb^+)*



Hausser HN. et al, PRL 134 (2025)

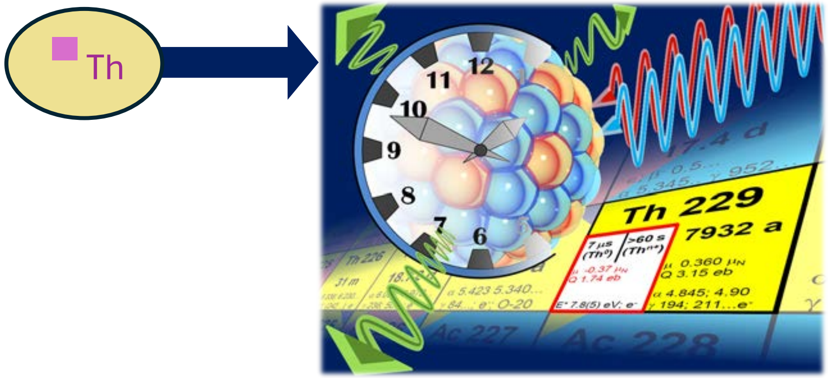
Clocks pushing the quantum limit

Review: Thirolf, P.G. *et al.* **"The thorium isomer 229mTh: review of status and perspectives after more than 50 years of research."** *Eur. Phys. J. Spec. Top.* **233**, 1113–1131 (2024).



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).

$$\text{SNR} \propto \upsilon_0 \sqrt{N\tau}$$



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.

Future: expanded global network of atomic clocks

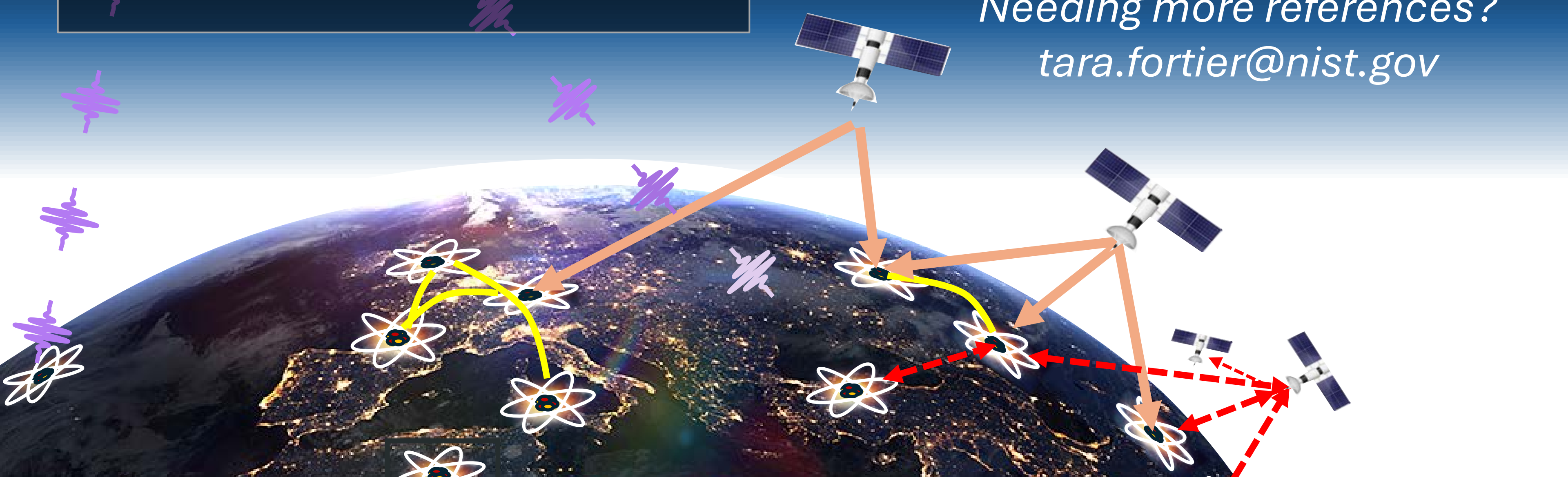
Portable optical clocks:

- **NIST Upcoming:** Portable Yb clock + free space link Mount Blue Sky in Colorado!
- GR test Tokyo Skytree Tower: Takamoto, M, et al. Nat. Photon. (2020)
- *Rugged and high-performance laser systems: combs, cavity stabilized lasers.*

Improved link infrastructure:

- 920 km fiber across UK, France, Germany and Italy.
  - *Predehl, K, et al. Science (2012)*
- Free-space optical links:
  - *Caldwell, E. et al. Nature (2023)*
  - *Shen, Q, et al. Nature (2022)*
- VLBI link from Japan to Italy:
  - *Pizzocaro, M. et al. Nature Physics (2021)*

Needing more references?
tara.fortier@nist.gov



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

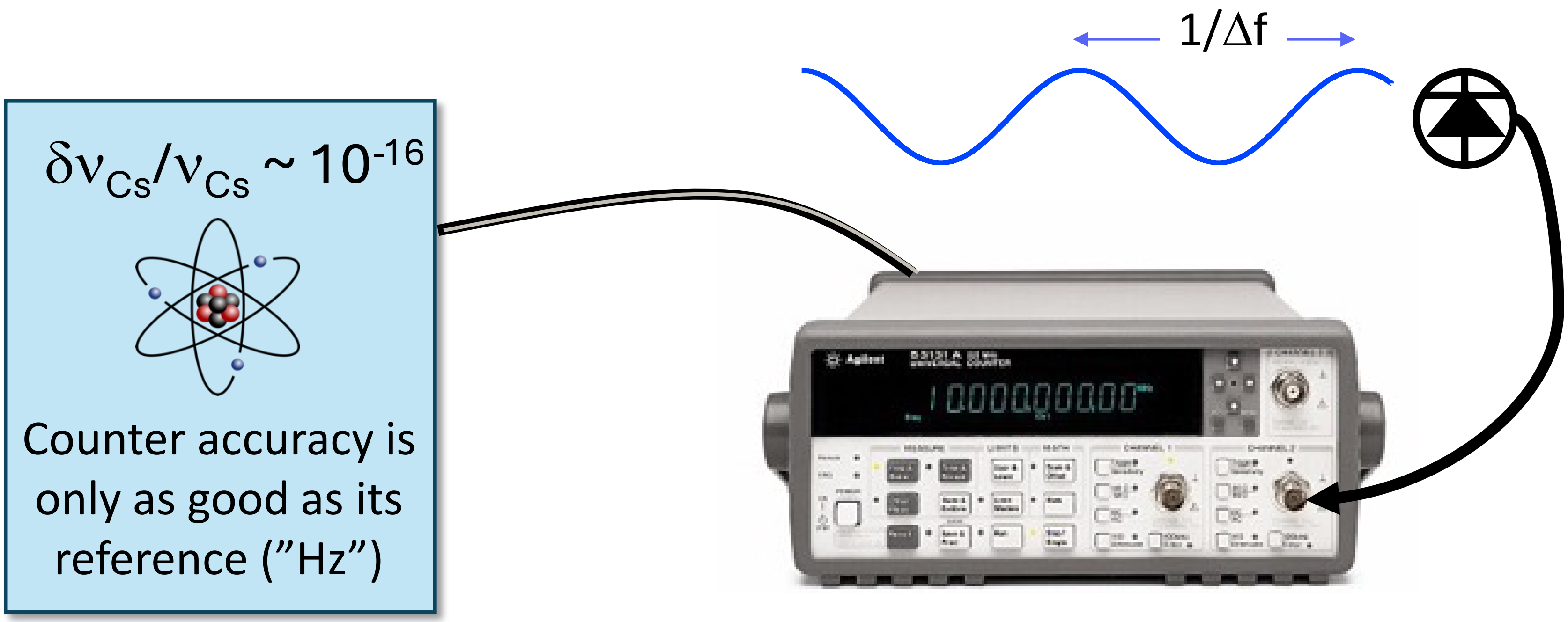
Thank you for your attention!

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

Accuracy in microwave frequency counting



Counted frequency → Δf

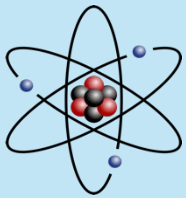
$$\frac{\Delta f * \delta\nu_{Cs}}{/\nu_{Cs}} = 1 \times 10^{-16}$$

↗ Δf

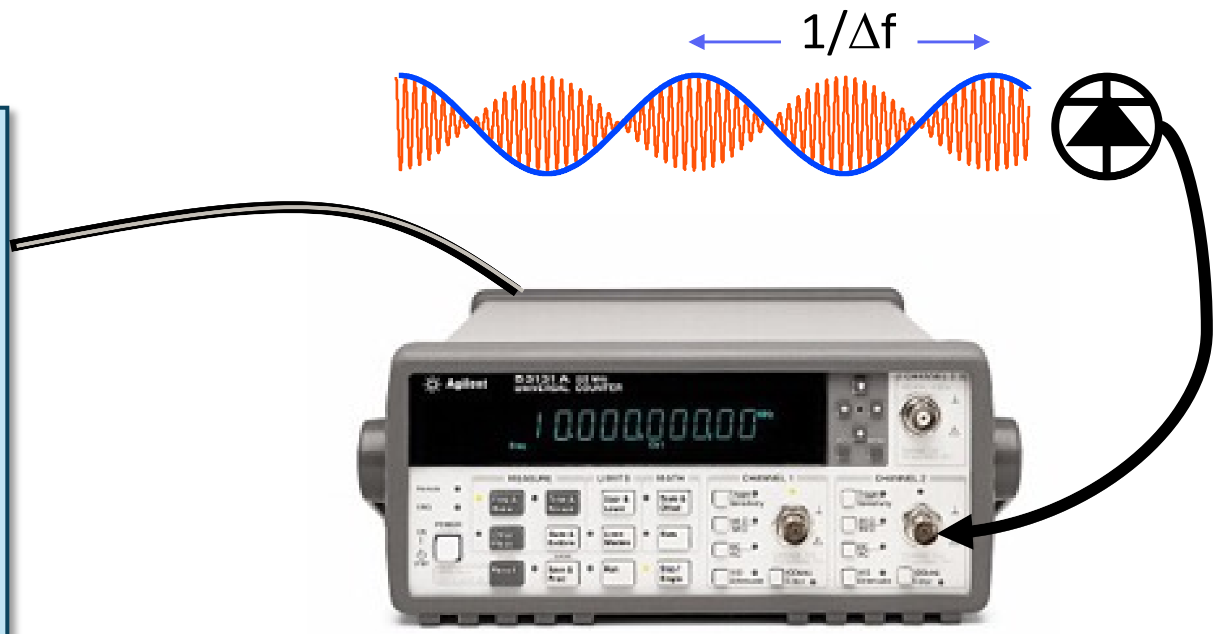
Normalization frequency

Accuracy in optical difference frequency counting

$\Delta\nu_{Cs}/\nu_{Cs} \sim 10^{-16}$



Counter accuracy is only as good as its reference ("Hz")



$$\frac{\Delta f * \delta\nu_{Cs}/\nu_{Cs}}{\nu_{opt}} = \frac{100\ \text{MHz} * 10^{-16}}{1\ \text{PHz}} = 10^{-7} \times 10^{-16} = \mathbf{1 \times 10^{-23}\,!}$$

Normalization frequency

Because of the large normalization frequency, optical difference frequencies can be counted with extremely high resolution ($10^{-19}\ t^{-1}$) and accuracy using a microwave reference and standard frequency counter.