Recent Advances in Quantum Based Timing

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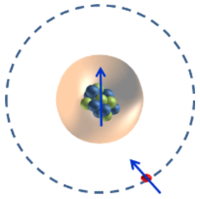
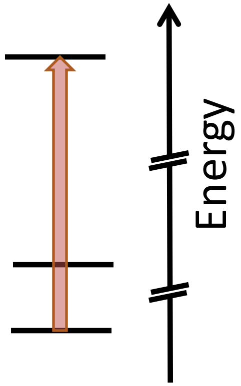
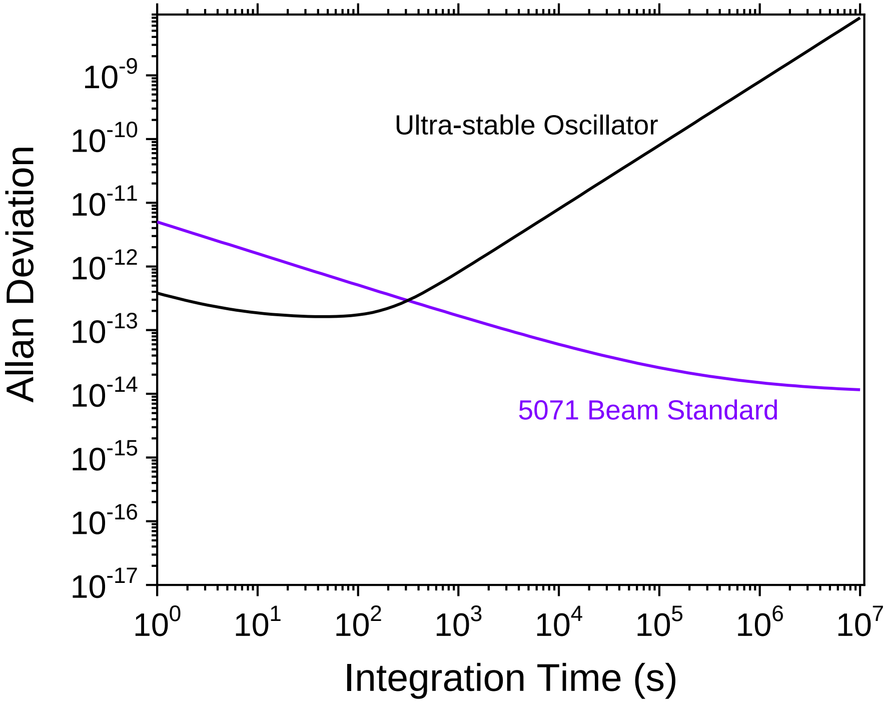
U.S. Department of Commerce

Why Atomic Clocks?

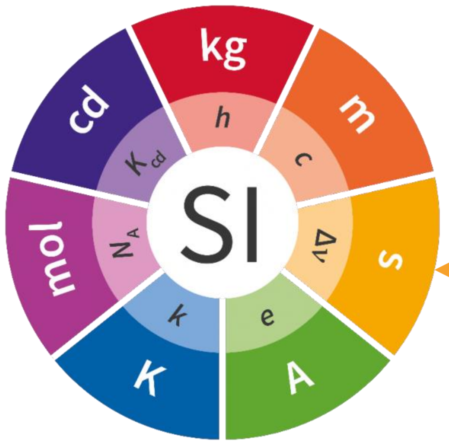


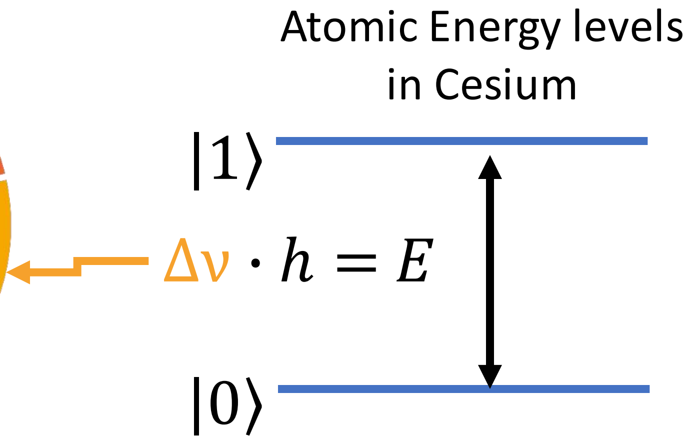
$$\omega_{hf} = \frac{\Delta E}{\hbar} = \frac{4}{3}\frac{m_e c^2 \alpha^2 g_I}{\hbar n^3}\left(1 + \frac{m_e}{m_p}\right)^{-3} \vec{I}\cdot\vec{J}$$



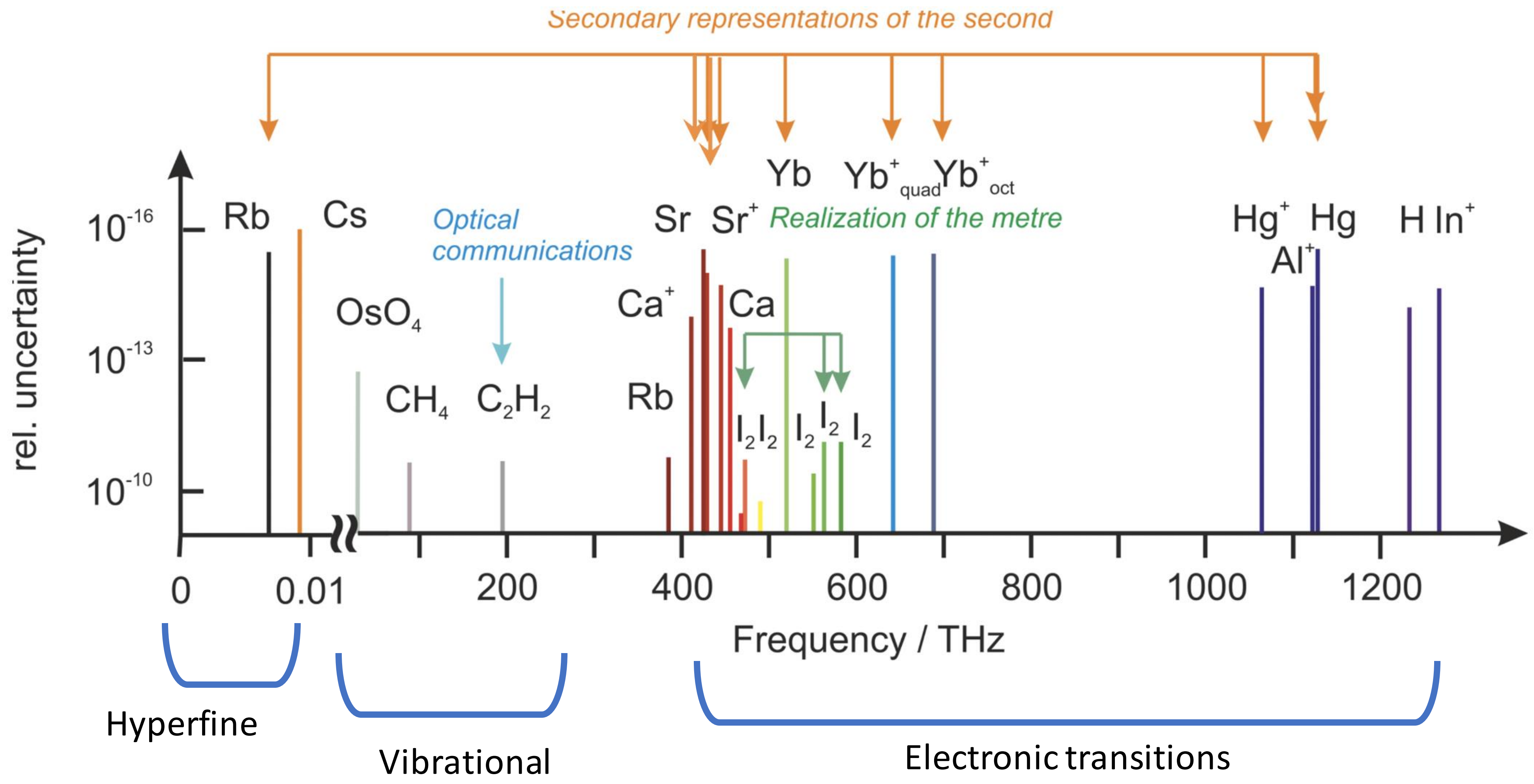


- **Isolated quantum system with energy spectrum defined by fundamental constants**
  - Long-term stability, accuracy
- **SI $\leftrightarrow$ quantum mechanics**



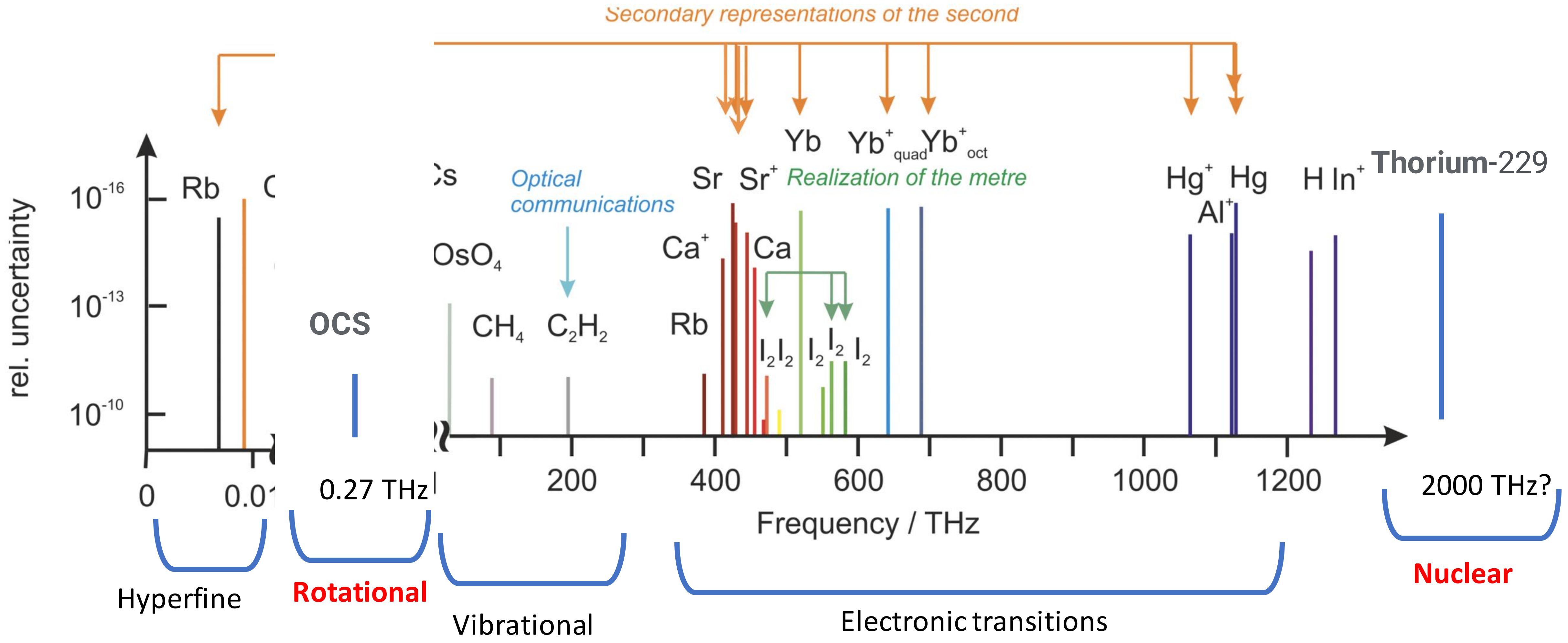


BIPM Representations of the Second



https://www.bipm.org/en/publications/mises-en-pratique/standard-frequencies-info

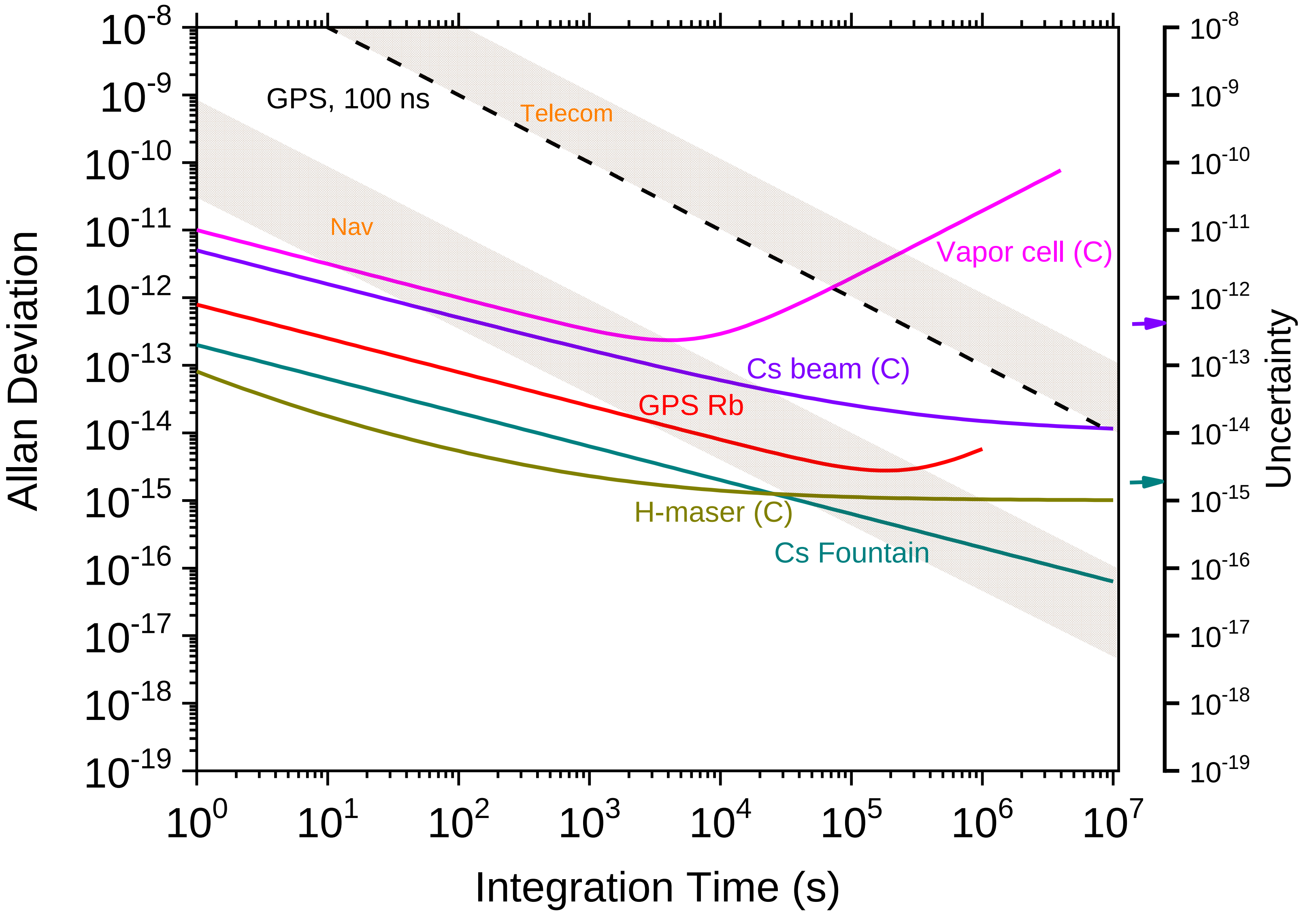
New Transitions



An on-chip fully electronic molecular clock based on sub-terahertz rotational spectroscopy, Nat. Elec. (2018). https://doi.org/10.1038/s41928-018-0102-4. (MIT)

Energy of the ^{229}Th nuclear clock transition, Nature 2019, https://doi.org/10.1038/s41586-019-1533-4)(LMU + collaboration)

Atomic Clocks 1999

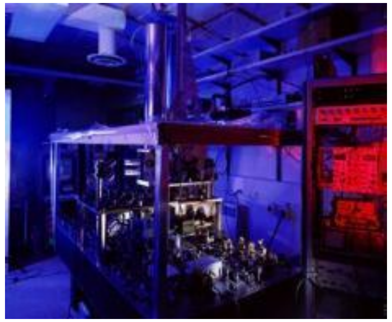


FEI Web Site

Microchip Web Site

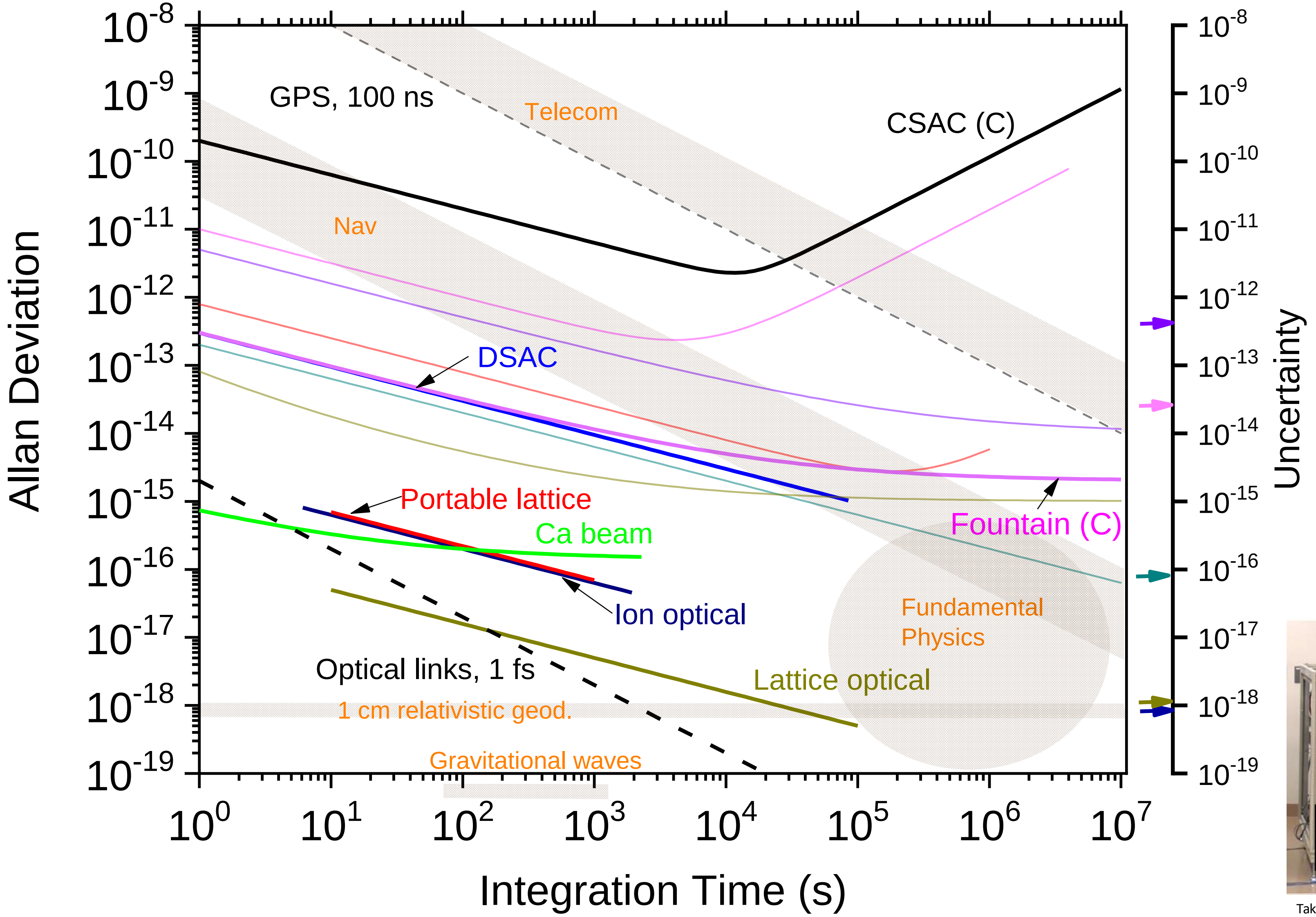
EG&G

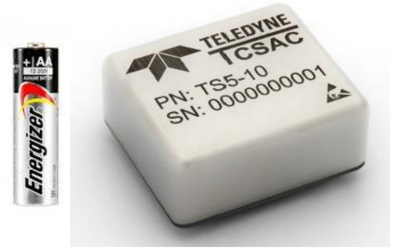
Microchip Website



NIST

Atomic Clocks 2021

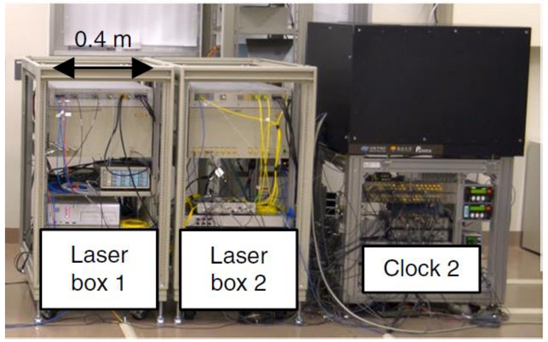




Teledyne Data Sheet

Burt, et al., Nature (2021)

AOSense Web Site



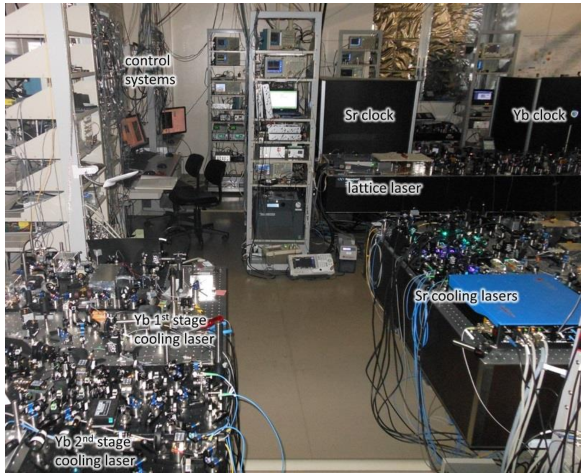
Takamoto, et al., Nat. Phot. (2020)

High Performance Clocks

Beam clocks: 1960s-90s
No lasers

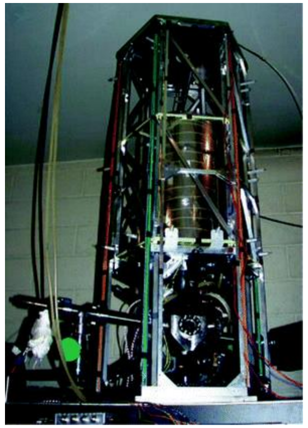
NIST

Lattice clocks: Sr, Yb, Mg, Ca...
λ: 185 nm – 700 nm



RIKEN

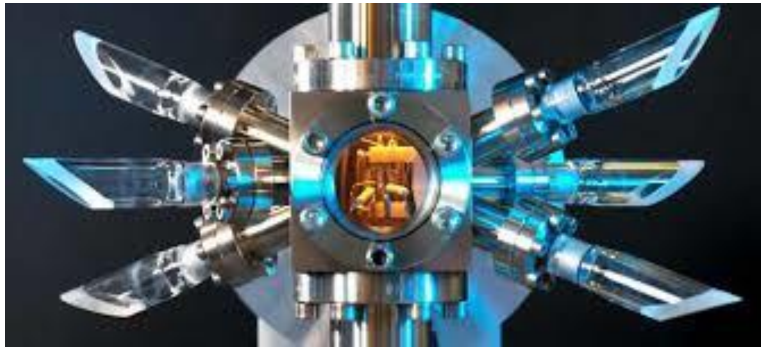
Fountain Clocks: 1990s-2000s
λ: 852 nm 895 nm



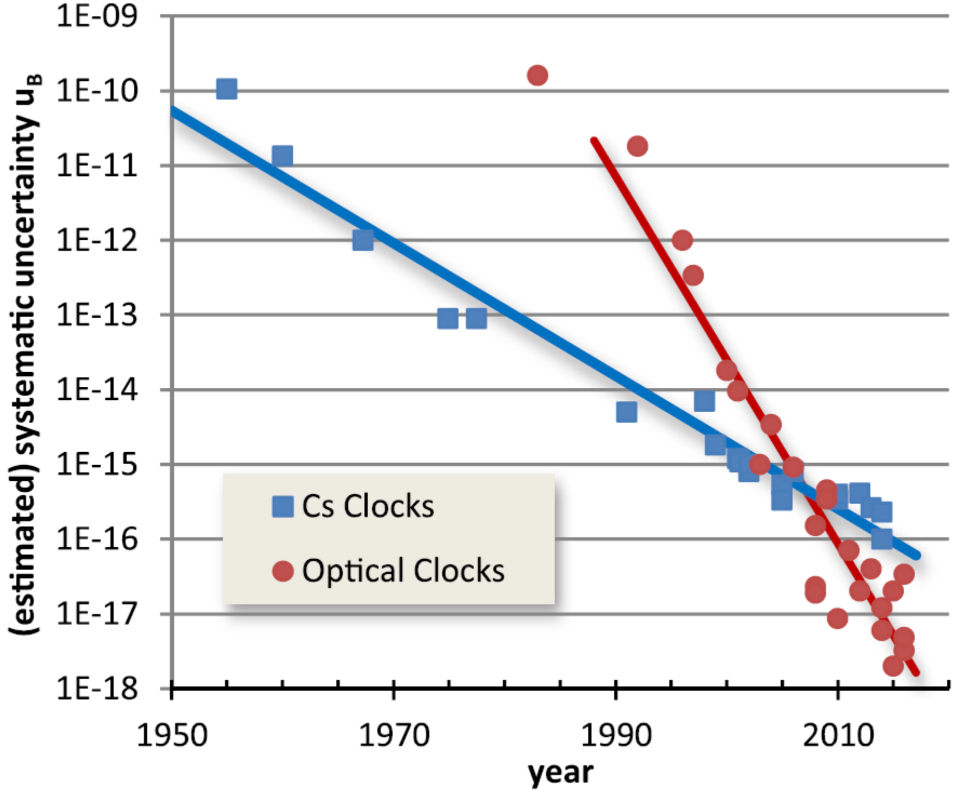
SYRTE

1-2 IR wavelengths
Some high power

Ion clocks: Al^+, Sr^+, Yb^+, Ba^+, Ca^+ ...
λ: 150 nm – 1000 nm



NPL



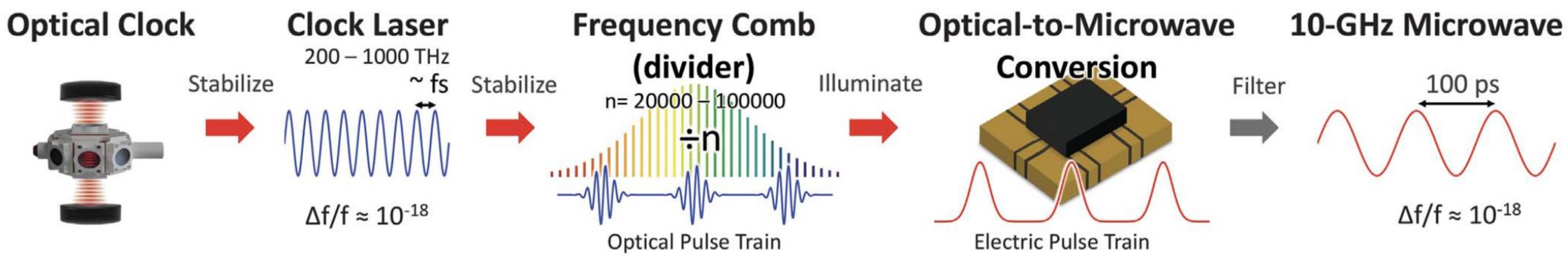
T. E. Mehlstaubler, et al., Rep. Prog. Phys. 2018

Many visible and IR wavelengths
Some high power
Some high coherence

J. Vanier and C. Tomescu, "The Quantum Physics of Atomic Frequency Standards: Recent Developments" CRC Press, 2016

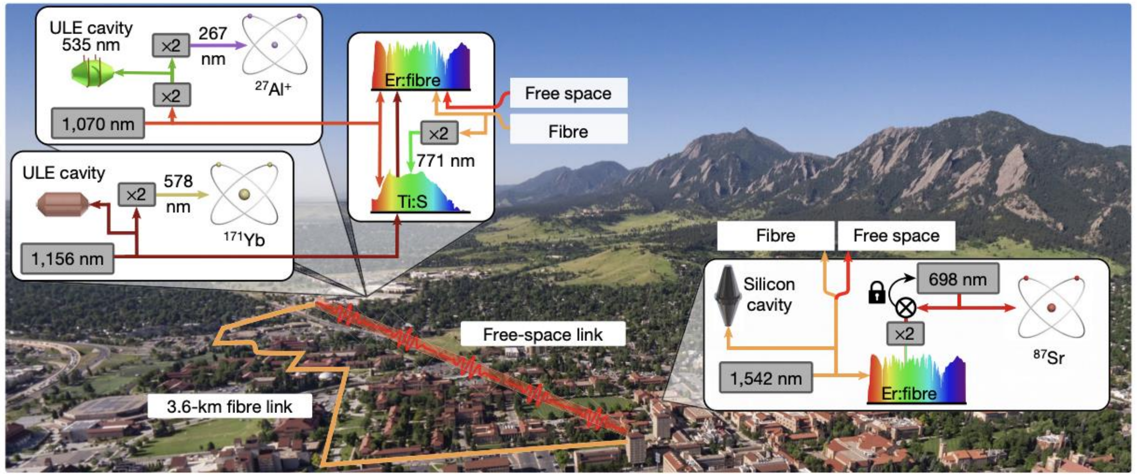
State of the Art Optical Clock Development

- Optical to Microwave conversion



Coherent optical clock down-conversion for microwave frequencies with 10^{-18} instability, Science 2020 [DOI: 10.1126/science.abb2473](https://doi.org/10.1126/science.abb2473)

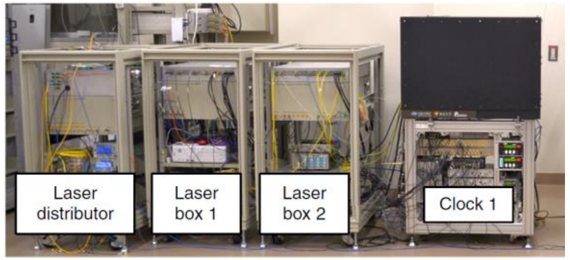
- Clock comparisons, redefinition of SI second, fundamental physics



Frequency ratio measurements at 18-digit accuracy using an optical clock network, Nature (2021). https://doi.org/10.1038/s41586-021-03253-4

Deployable Systems

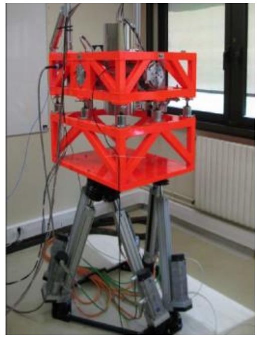
Lattice clocks
- Wavelengths (Sr): 461 nm, 496 nm, 679 nm, 689 nm, 698 nm, 813 nm
- 100's mW, some narrow-linewidth



RIKEN

M. Takamoto, et al., Nat. Phot. 2020

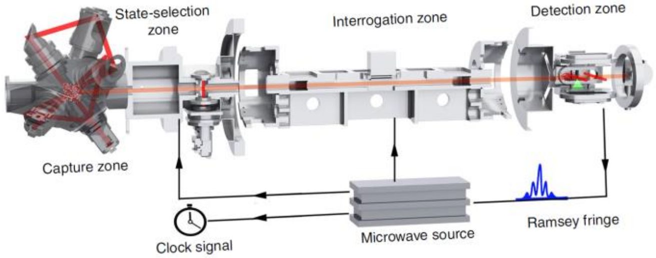
Atom interferometer inertial
- Wavelengths (Rb): 780 nm, 795 nm
- 100s mW



ONERA

Y. Bidel, et al., J. Geodesy, 2020

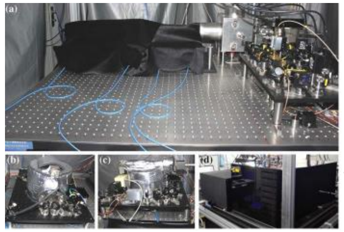
Atomic Clocks in Space
- Wavelengths (Rb): 780 nm, 795 nm
- 100s mW



L. Liu, et al., Nat. Comm., 2018

Ph. Laurent, et al., Comp. Rend. Phys., 2015

Single ion optical clocks
- Wavelengths (Ca+): 423 nm, 397 nm, 854 nm, 866 nm, 729 nm
- 100s mW, some narrow-linewidth



Wuhan

J. Cau, et al., Appl. Phys. B, 2017

Compact fountain
- Wavelength (Rb): 780 nm
- 100s mW

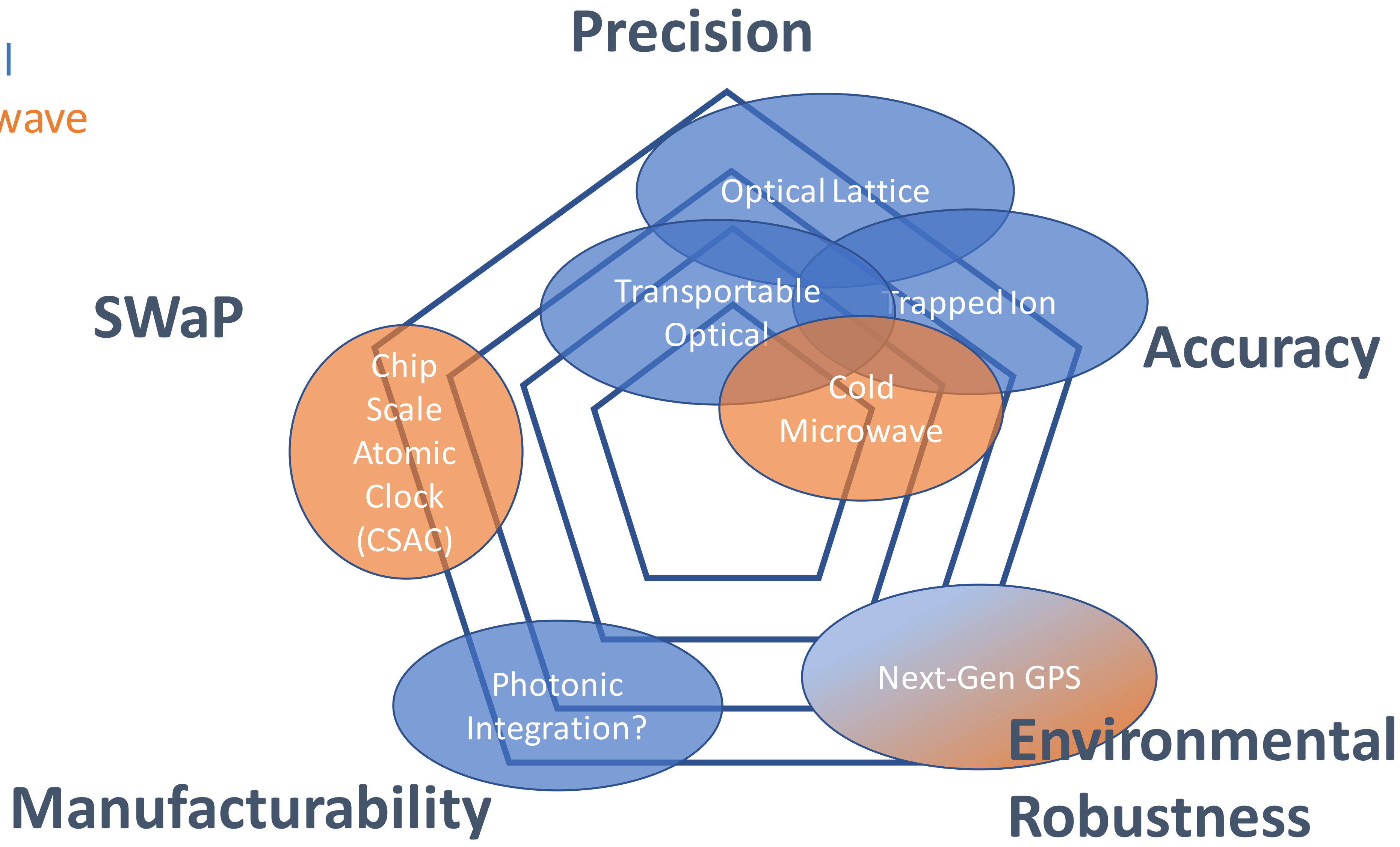
1-2 wavelengths
Some high power

Muquans

B. Pelle, et al., IFCS Proc., 2018

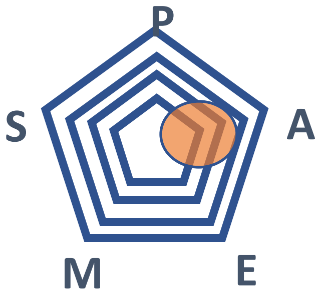
Trade space of Atomic Clocks

Optical
Microwave

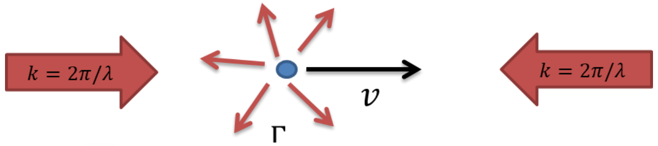


Next-Generation Compact Atomic Clocks

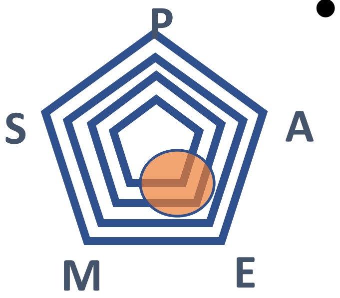
NIST



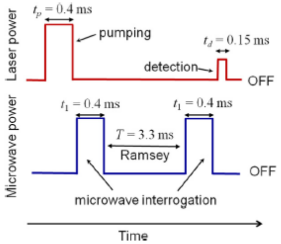
- **Laser cooling**
  - Enables current generation of primary standards
  - Potential accuracy ~ 10^{-15} range
  - Challenges: system complexity, Doppler shifts due to acceleration

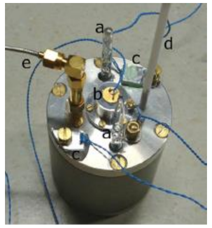


http://aosense.com https://www.muquans.com

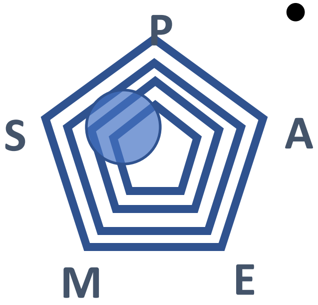


- **Pulsed vapor cell clocks (Europe)**
  - Stability ~ $10^{-13}/\sqrt{\tau} \rightarrow 10^{-15}$
  - For next-gen GPS
  - Challenges: long-term drifts, not accurate

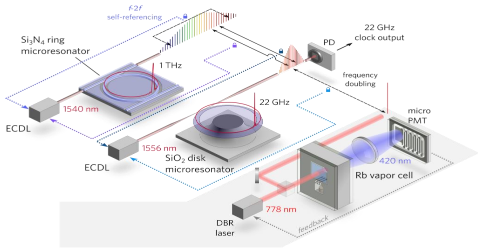




S. Micalizio, et al., Metrologia **49** (4), 425 (2012).



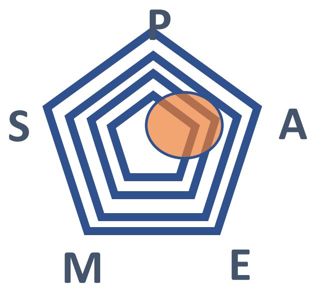
- **Compact optical clocks**
  - 10^5 higher Q-factor
  - Optical reference + microresonator frequency comb
  - Challenges: power consumption for combs, integration/manufacturability

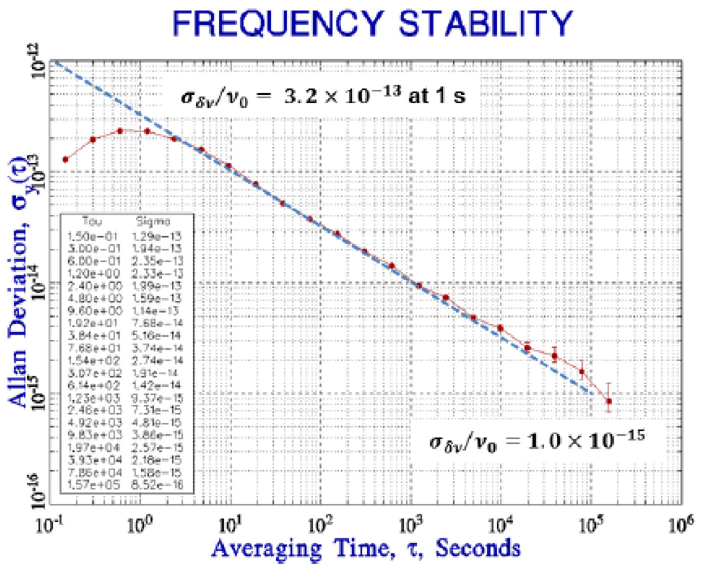


J. Grotti, et al., Nat. Phys. **14** (5), 437 (2018). NIST/Draper/Caltech/Yale (2018)

Commercial Cold Atom Clocks

- Released over last ~3 years
- Stability in 10^{-15} range
- Limited accuracy evaluations
- Applications
  - H-maser replacement
  - Metrology labs





B. Patton, et al., IFCS 2018

AOSense

MuQuans

SpectraDynamics

Space Atomic Clocks

ACES (Europe)

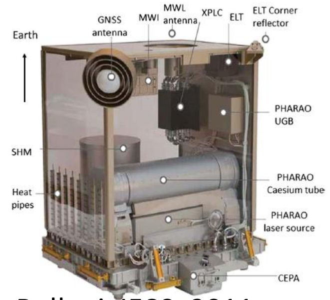
- Expected launch in 2021?
- Cold atom beam + H-maser + precise timing links
- Ground tests
  - $3\times10^{-13}/\sqrt{\tau}$; Accuracy 1.4×10^{-15}
- Technology demonstration
- Basic science
  - Gravitational redshift
  - Lorentz Invariance
  - Time variation of fund. const.

DSAC (US)

- Launched June 2019
- ACES (Europe)
- Technology demonstration
- 17 L, 16 kg, 50 W
- Ground tests:
  - $3\times10^{-13}/\sqrt{\tau}$
  - 10^{-16}/day drift

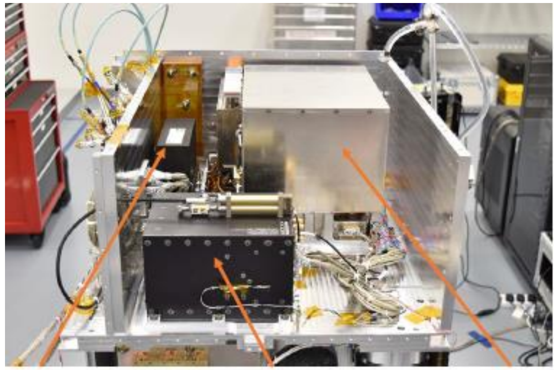
CACES (China)

- Launched Sept. 2016
- Operated in space for > 15 months
- Performance only measured on ground (no timing link)
- No obvious scientific goals
  - No way to measure stability



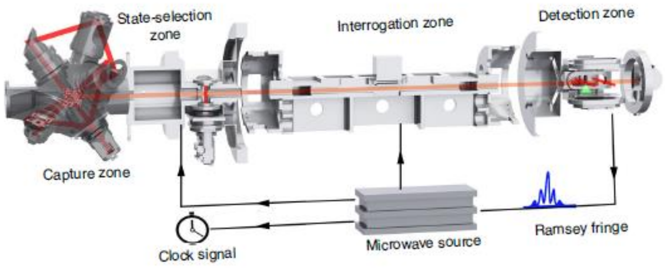
Belloni, IFCS, 2011
Laurent, C. R. Phys., 2018

Space H-maser for Galilleo



USO GPSR DSAC

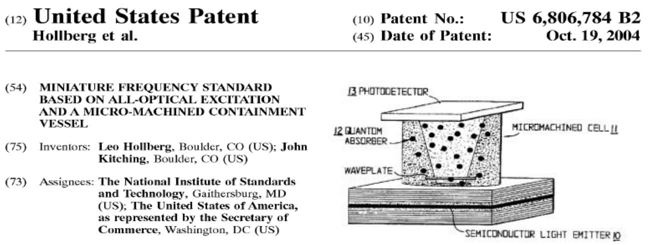
Ely, et al., Trans-UFFC, 2018



Liu, Nat. Comm. ,2018

Chip-Scale Atomic Clocks

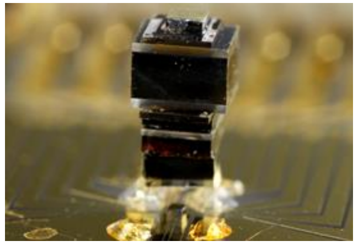
- NIST work began late 2000
  Westinghouse/DARPA late 1990s
- DARPA funded: 2002 – 2008
- Holds 100 μs over 1 day on 120 mW
- Commercial product – 2011
  120,000 sold as of 2020, > $100M in economic impact

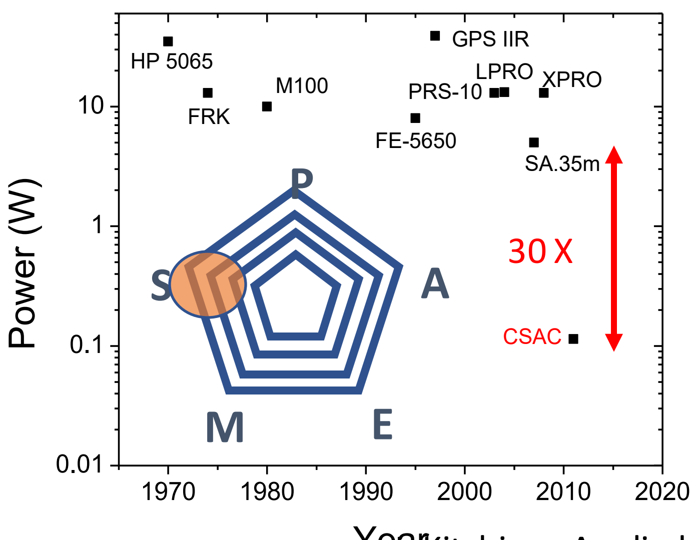

(12) United States Patent (10) Patent No.: US 6,806,784 B2
Hollberg et al. (45) Date of Patent: Oct. 19, 2004

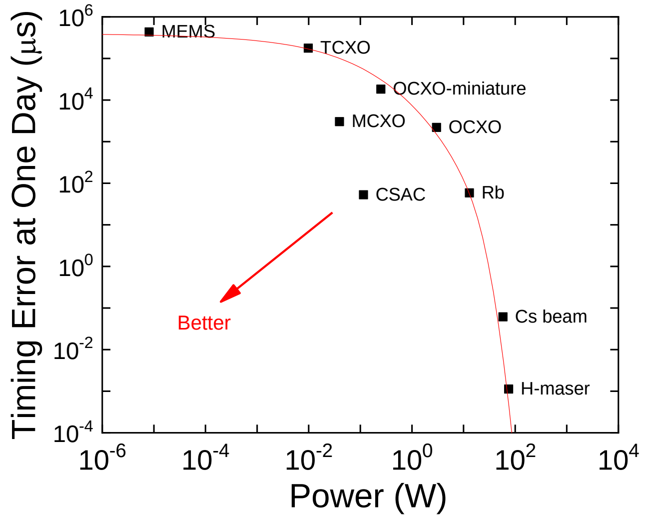
(54) MINIATURE FREQUENCY STANDARD BASED ON ALL-OPTICAL EXCITATION AND A MICRO-MACHINED CONTAINMENT VESSEL

(75) Inventors: Leo Hollberg, Boulder, CO (US); John Kitching, Boulder, CO (US)

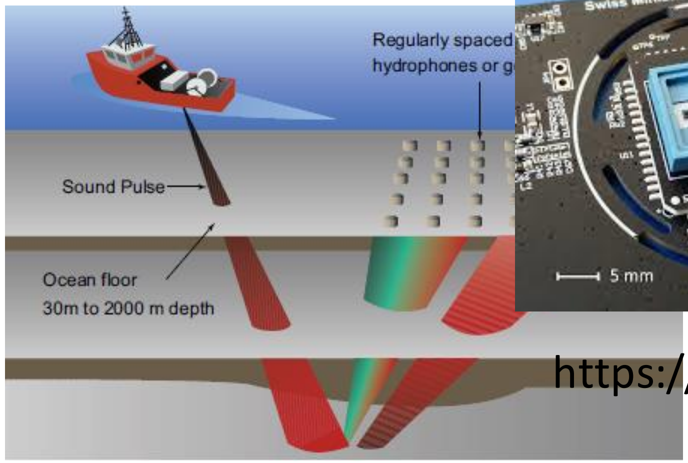
(73) Assignees: The National Institute of Standards and Technology, Gaithersburg, MD (US); The United States of America, as represented by the Secretary of Commerce, Washington, DC (US)


T. Gray, "The Elements"

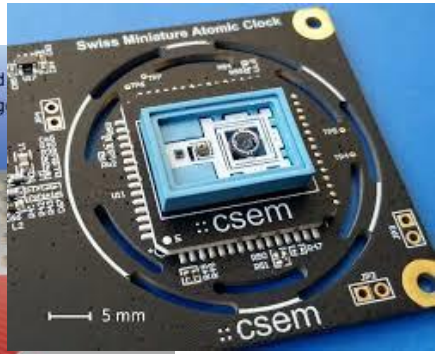




J. Kitching, Applied Physics Reviews **5**, 031302 (2018).



From Microsemi CSAC Datasheet



https://www.csem.ch/

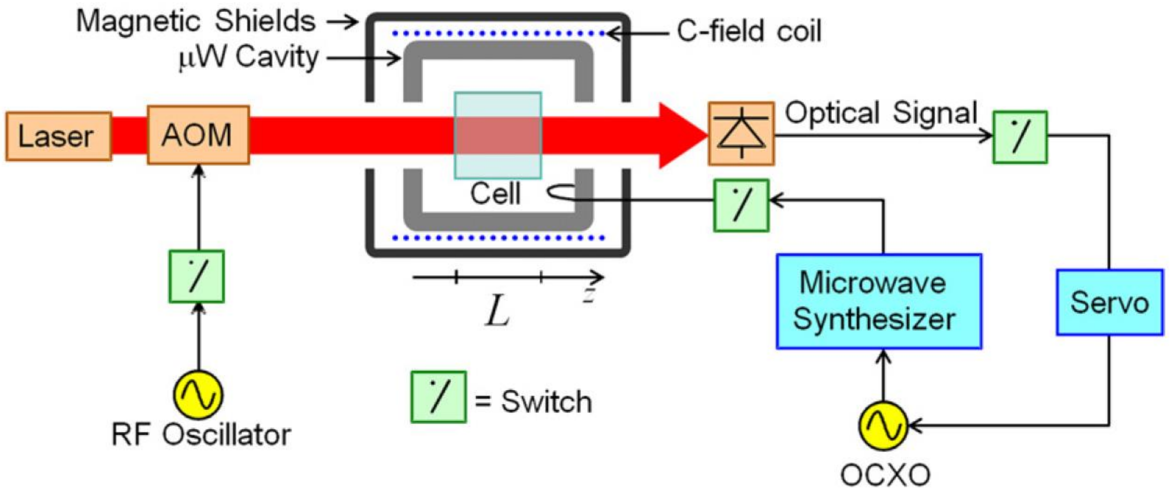
Next-Generation GPS Clocks

NIST

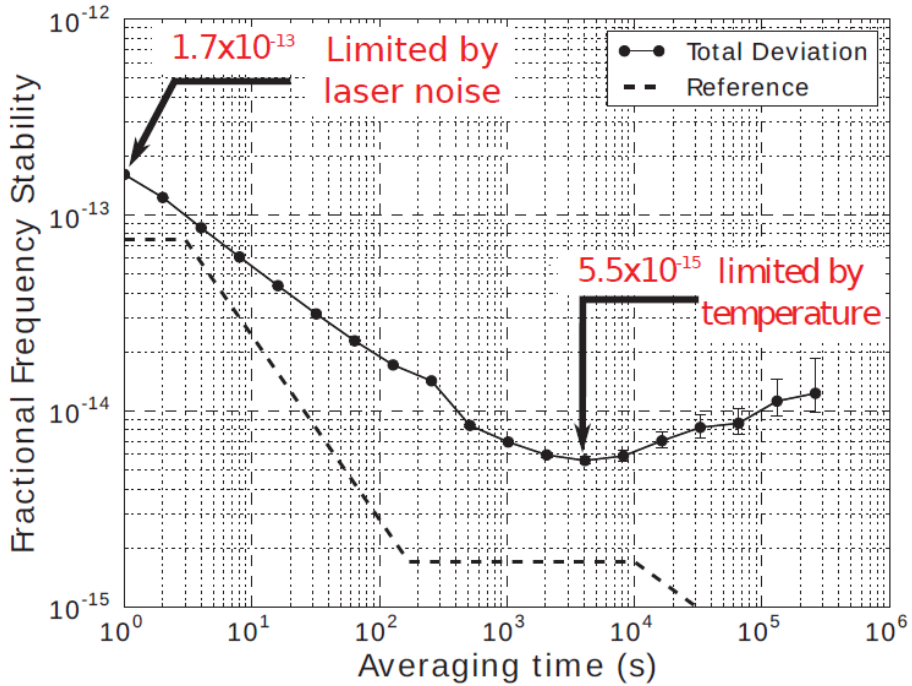
- Pulsed optical pumping (POP) clock

  Short-term stability better than GPS II-R, long-term stability similar

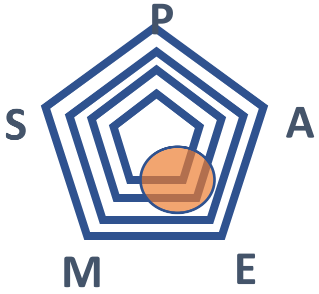
  Additional complexity of switching laser power



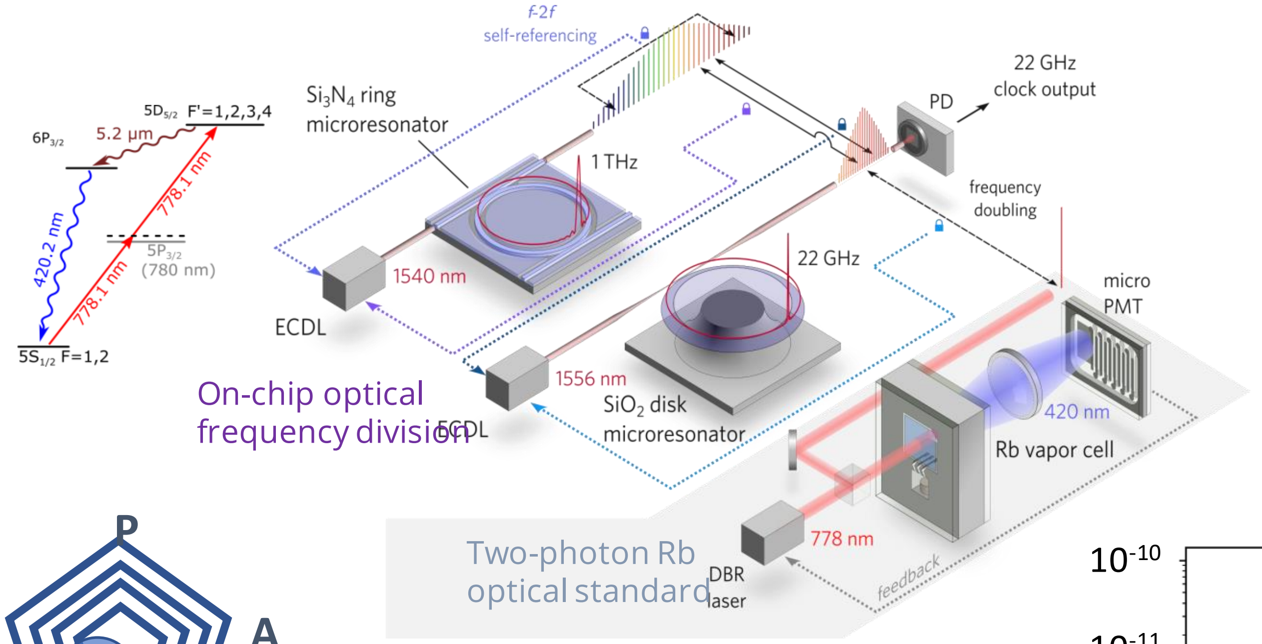
S Micalizio *et al.,* Metrologia **49,** 425, 2012

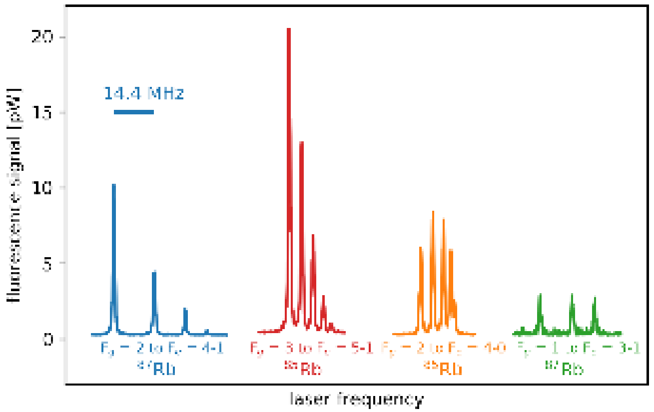


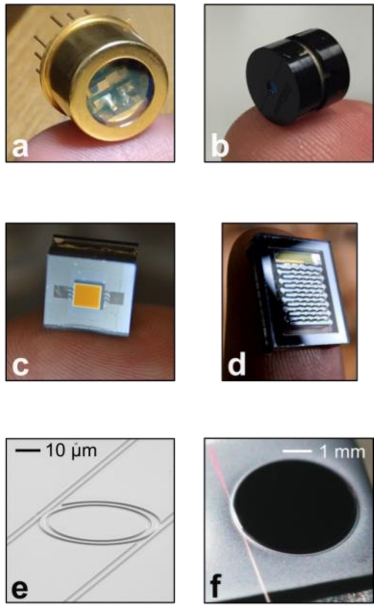
S Micalizio *et al., J. Phys.: Conf. Ser.* **723,** 012015, 2016

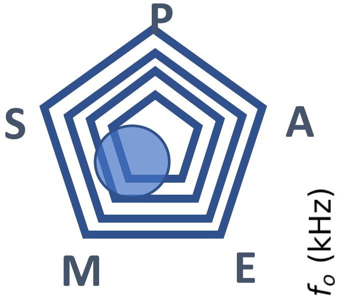


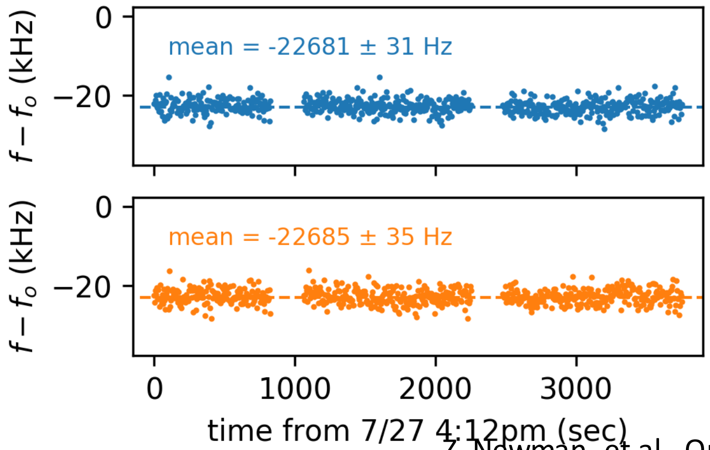
Two-Photon Chip-Scale Optical Standard



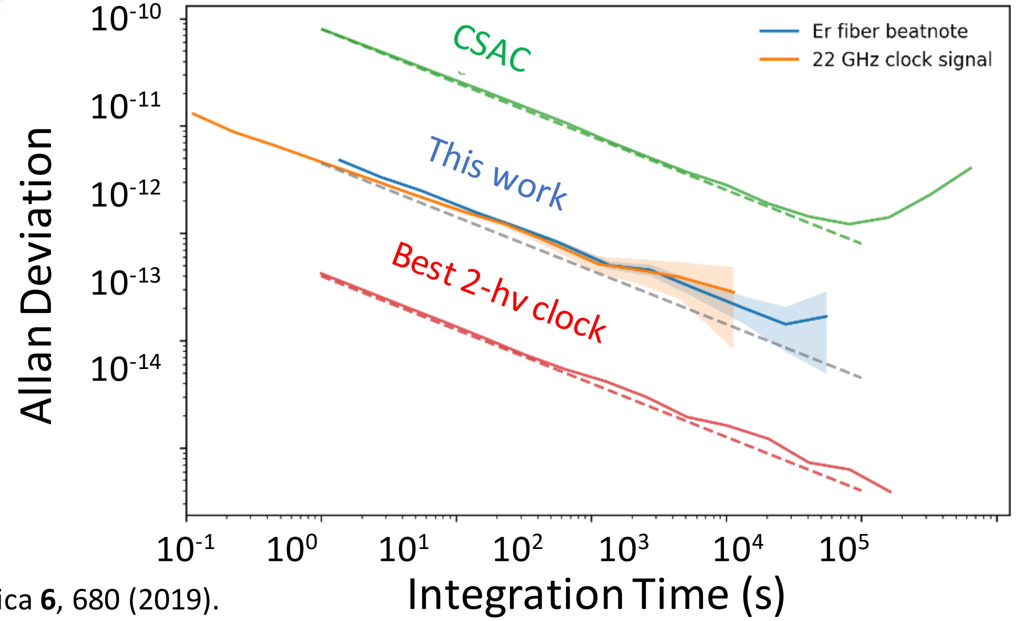






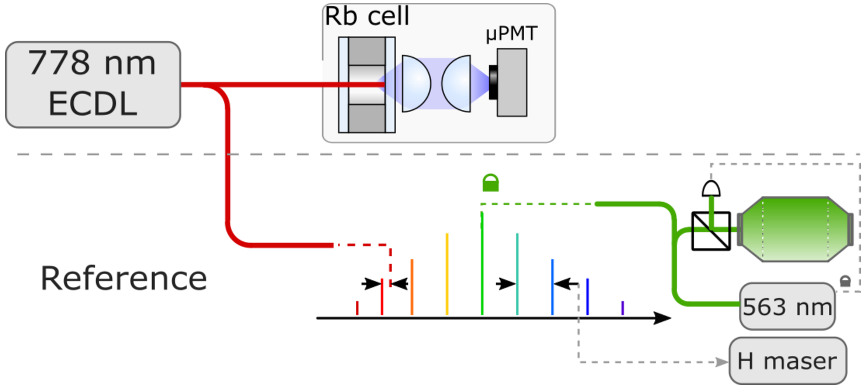


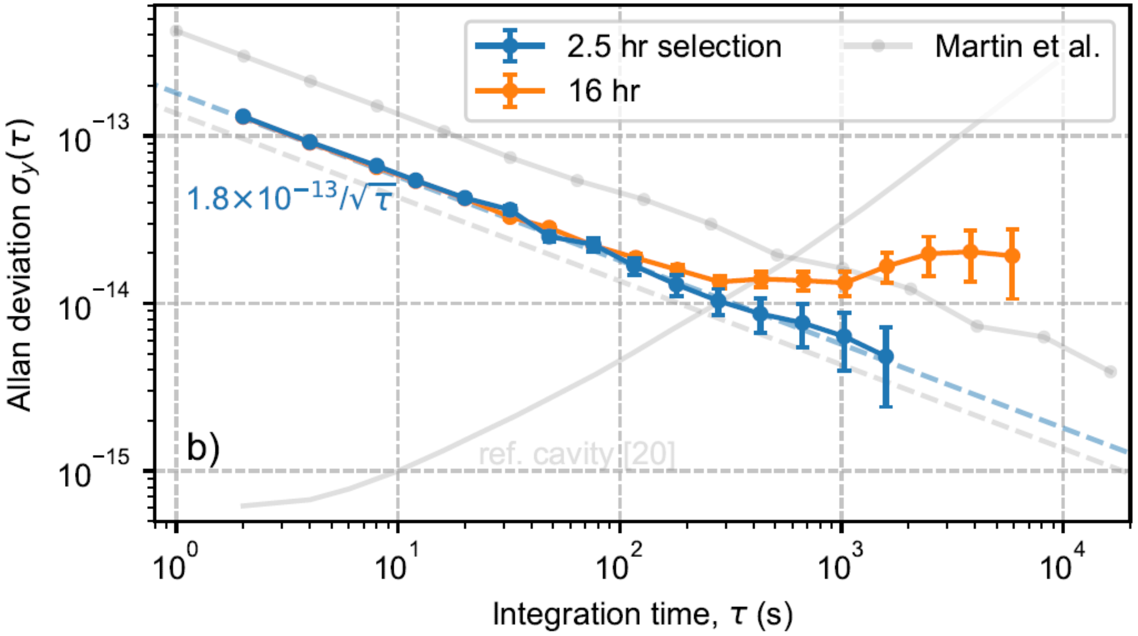
Z. Newman, et al., Optica **6**, 680 (2019).



Matt Hummon
Zach Newman
Vincent Maurice
....
NIST OFM
NIST CNST
Draper
Yale
Stanford
Caltech

Performance with a low-noise ECDL

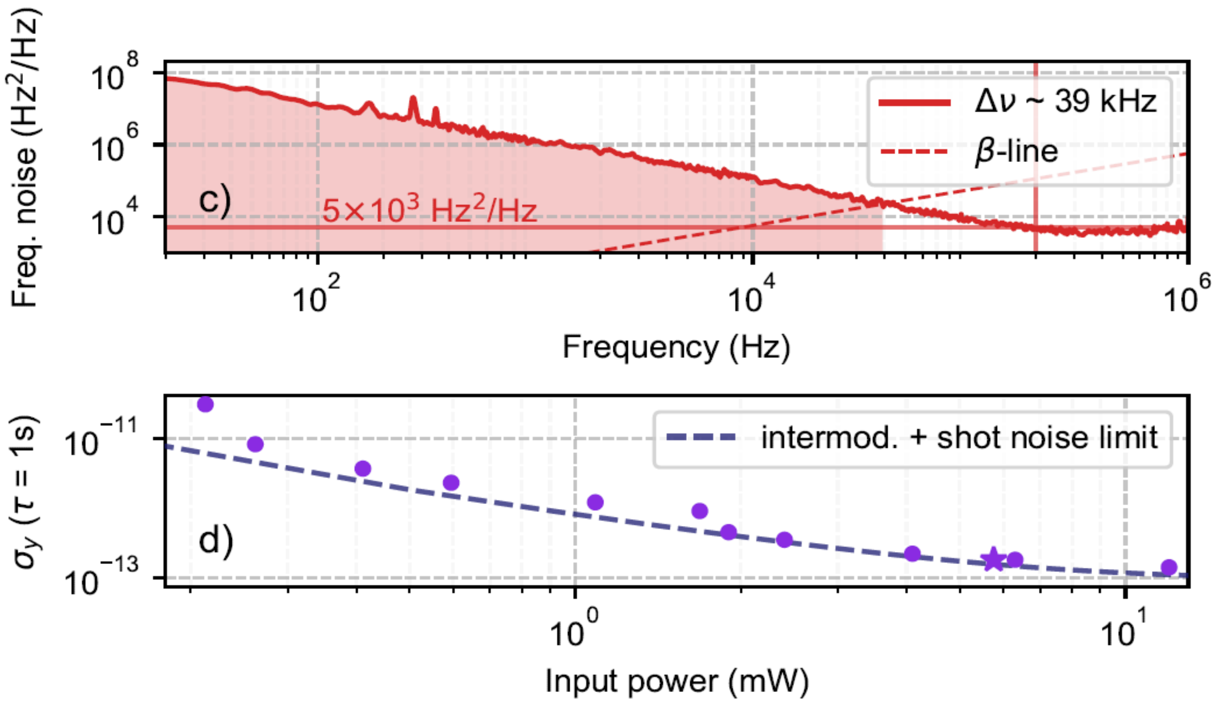




Lower frequency noise

→ reduced intermodulation effect

- Short-term: 1.9 x $10^{-13}\,\tau^{-1/2}$
- Frequency flicker floor at 2 x 10^{-14}
- Typical drift around 5 x 10^{-14}/day



Z. Newman, et al., *Opt. Lett.* 2021

Conclusions

Many new clock technologies may come on-line in coming years

- Optical clocks: filing cabinet size, 10^{-15} stability @ 1 second, 10^{-18} long-term stability and accuracy
- Next-generation GPS clocks: few 10^{-15} @ 1 day few L, 50 W

  Pulsed microwave vapor cell, ion microwave, optical vapor cell
- Next-generation CSACs

  Goal: Lower cost, $100/unit?