Optical frequency references, signal transfer, and time-keeping

WSTS 2018
San Jose, CA

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Outline

Part I:

A fundamental principle of modern timekeeping

Why optical frequencies?

Part II:

Technological overview w/
analogies to microwave components:

- Oscillators
- Frequency references
- "Counters"
- Frequency/time-transfer

Estimates of technological readiness

A fundamental principle:

Nature gives us

no

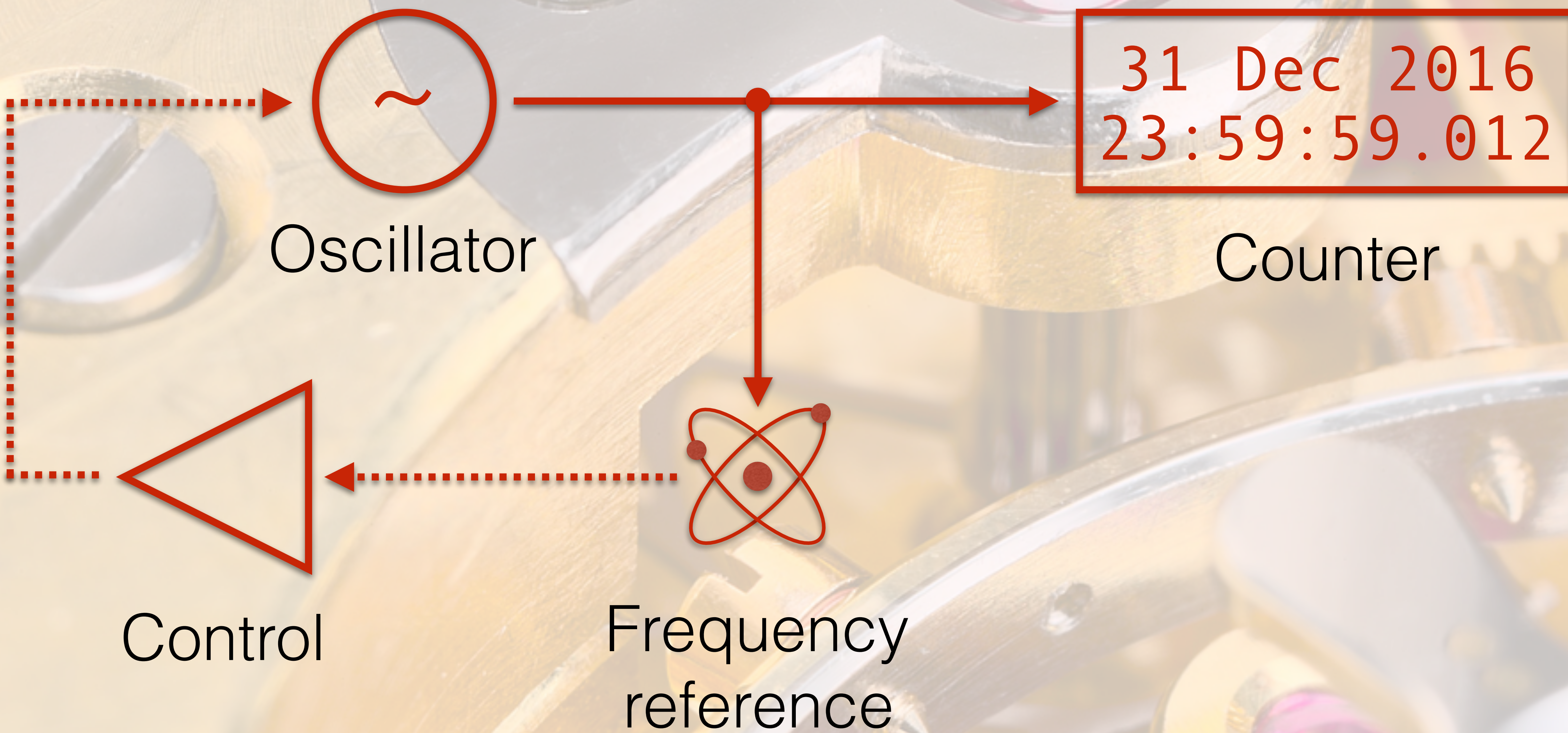
(sufficiently universal, practical, stable)

time

reference

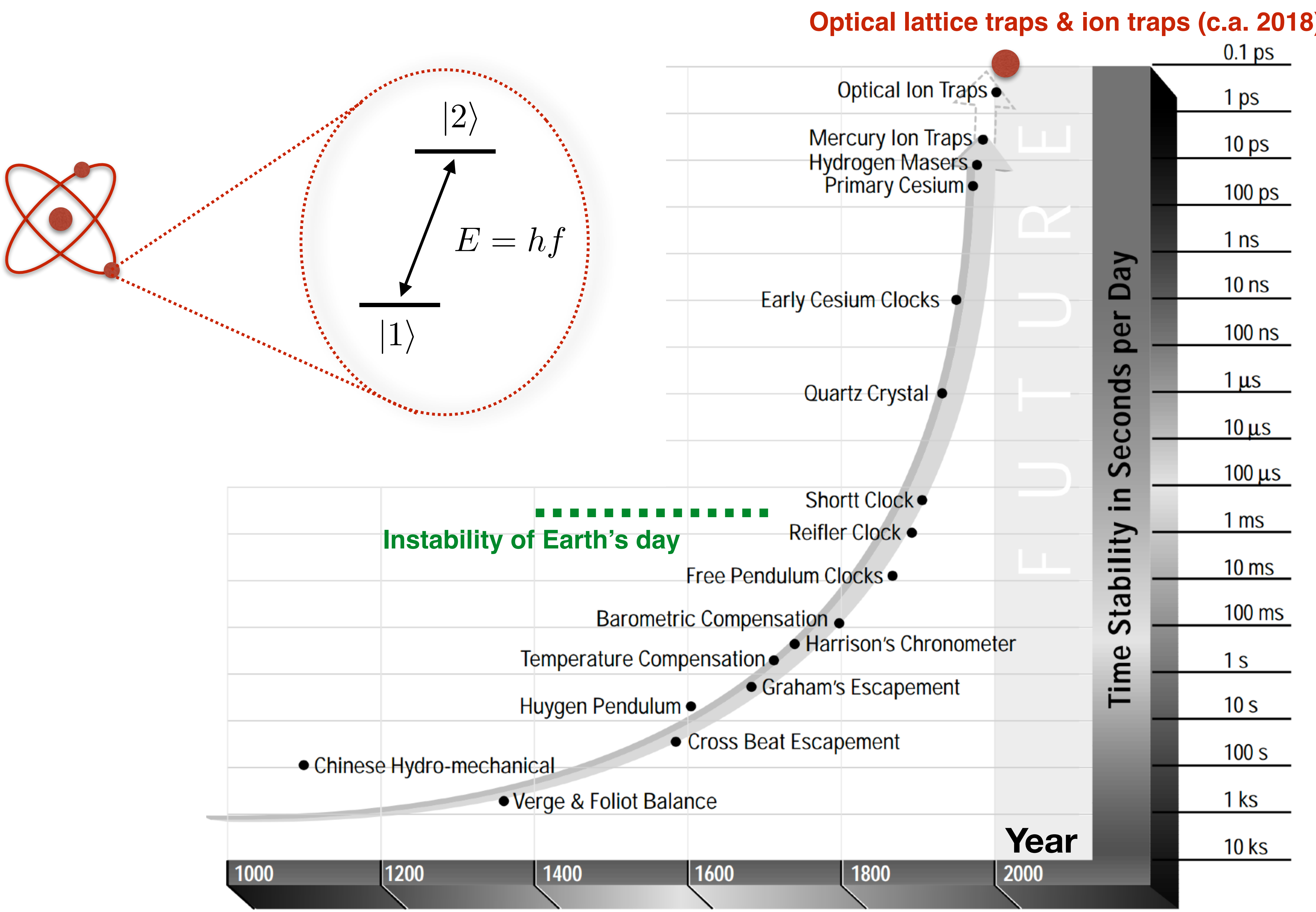
Photo: Steve Gurevitz

Our best strategy yet:



“Count cycles of an oscillator, which is itself referenced to a minimally-perturbed atomic resonance.”

Photo: Steve Gurevitz



Plot: DW Allan, N Ashby, C Hodge, HP application note 1289: *Science of Timekeeping* (1997)

Why optical frequencies?

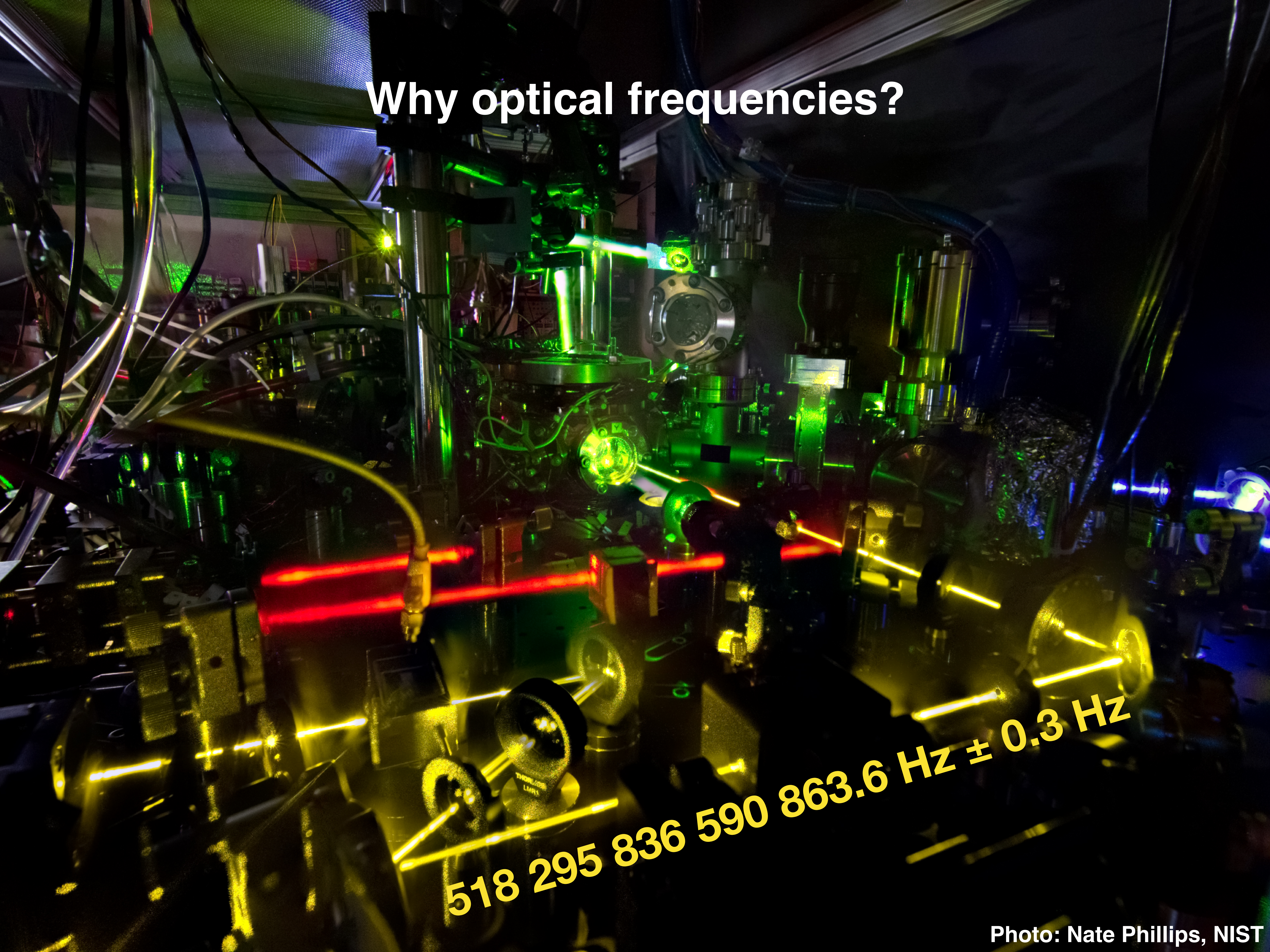
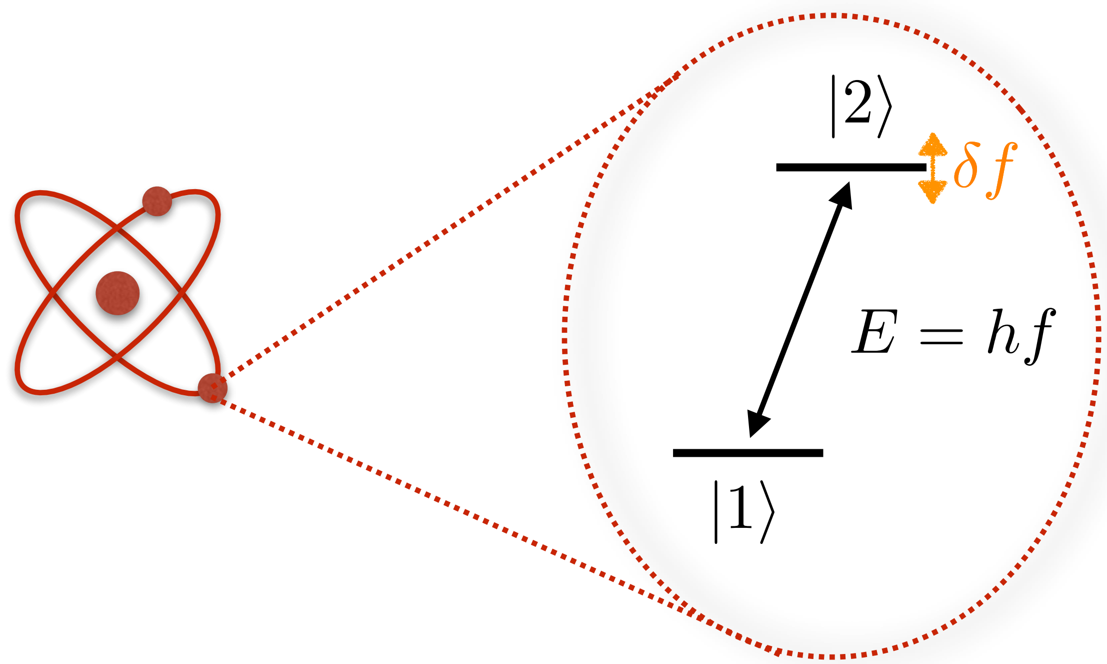


Photo: Nate Phillips, NIST

All else being equal, a faster oscillation frequency is better.



Fractional frequency instability:

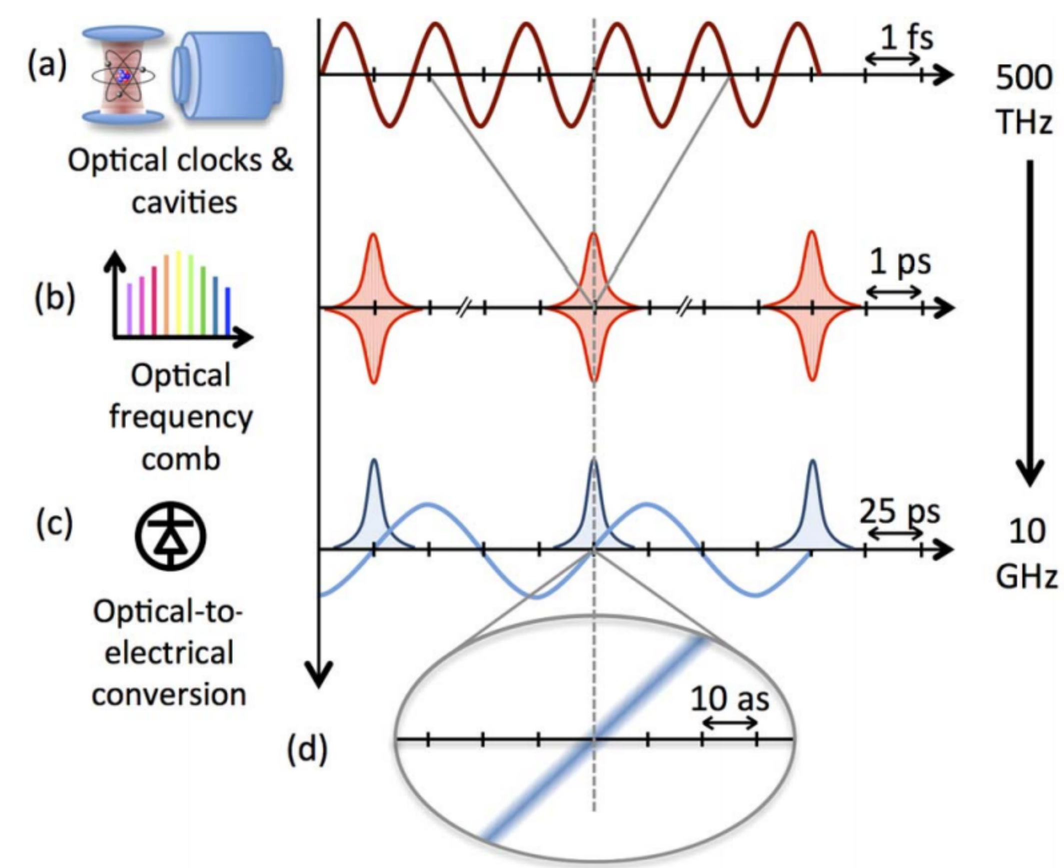
$$\sigma_y(\tau) \propto \frac{\delta f}{f}\sqrt{\frac{1}{N}}\sqrt{\frac{T_c}{\tau}}$$

make f bigger!

Imagine counting electromagnetic waves:

$$\delta t = \frac{1}{\mathrm{S/N}}\frac{\lambda}{c} \approx 3\,\mathrm{fs}\left(\frac{1}{\mathrm{S/N}}\right)\left(\frac{\lambda}{1\,\mu\mathrm{m}}\right)$$

divide time into small intervals!



Right: F Baynes, F Quinlan, T Fortier, et al., *Optica* **2**(2) 141 (2015)

Optical atomic frequencies are better inter-compared than absolutely known.

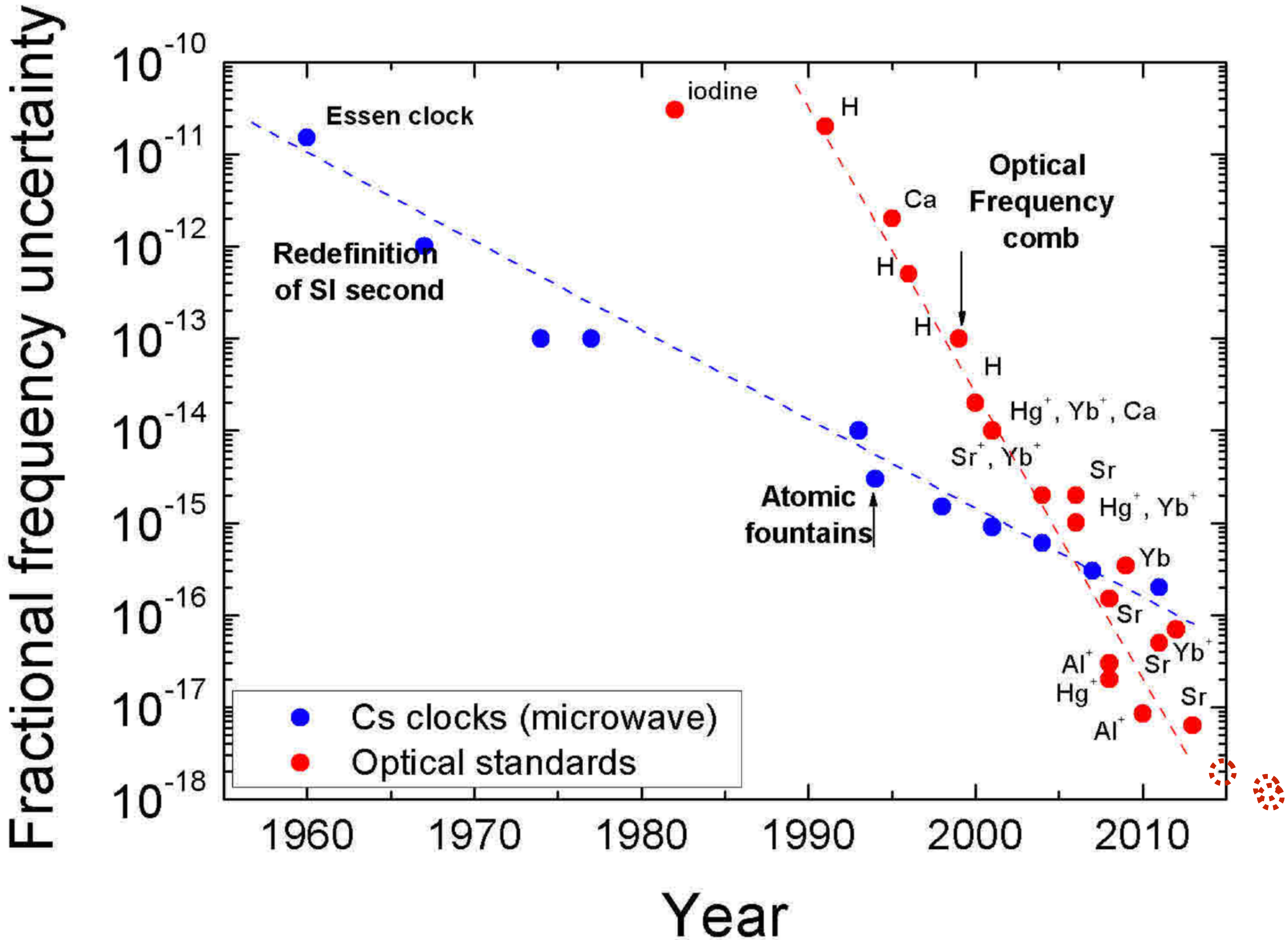
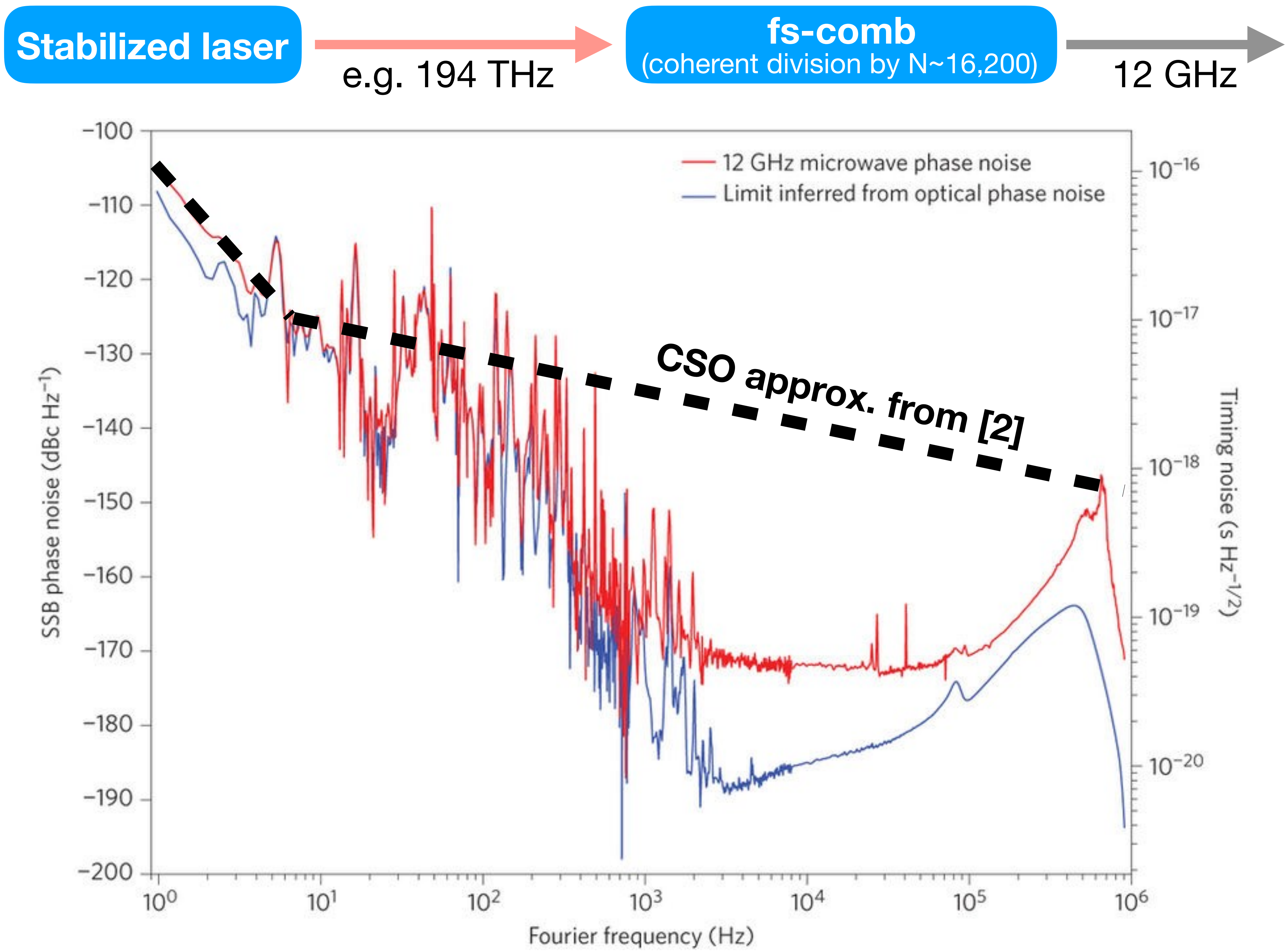


Image: N Poli, CW Oates, P Gill, GM Tino, *La Rivista del Nuovo Cimento* **36**(12), pp. 555–624 (2013)
Additional points: TL Nicholson, SL Campbell, RB Hutson, et al., *Nature Communications* **6**, 2896 (2015)
TK Beloy, W McGrew, X Zhang, et al., *Proceedings EFTF*, paper 7159 (2018)
S Brewer, J-S Chen, D Hume, et al., *Proceedings EFTF*, paper 7097 (2018)

Low phase-noise microwaves can be generated by “dividing” optical oscillators.



[1] X Xie, R Bouchand, D Nicolodi, Nature Photonics 11, 44–47 (2017)

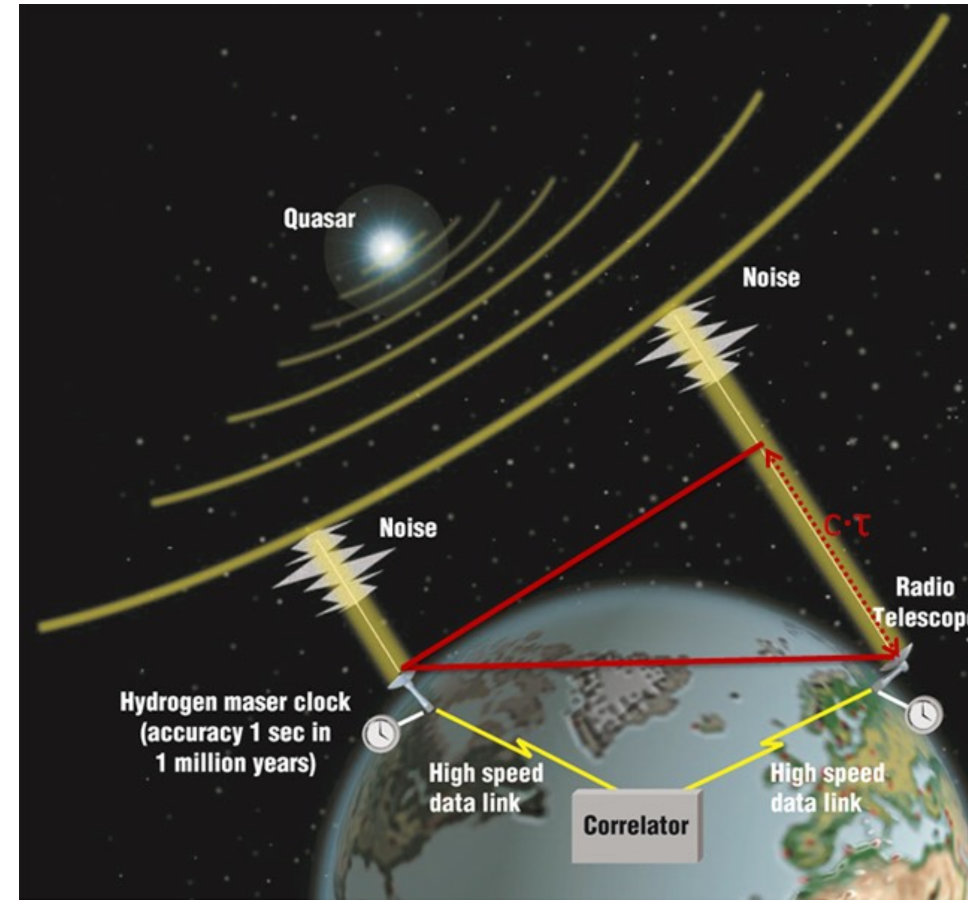
[2] J Hartnett, N Nand, C Lu, Appl. Phys. Lett. 100, 183501 (2012)

Impact on "non-clock" applications:

Very-long baseline radio-telescope interferometry

Laser-ranging / remote Doppler

Astronomical spectrograph calibration
… exoplanet detection



https://space-geodesy.nasa.gov/techniques/VLBI.html

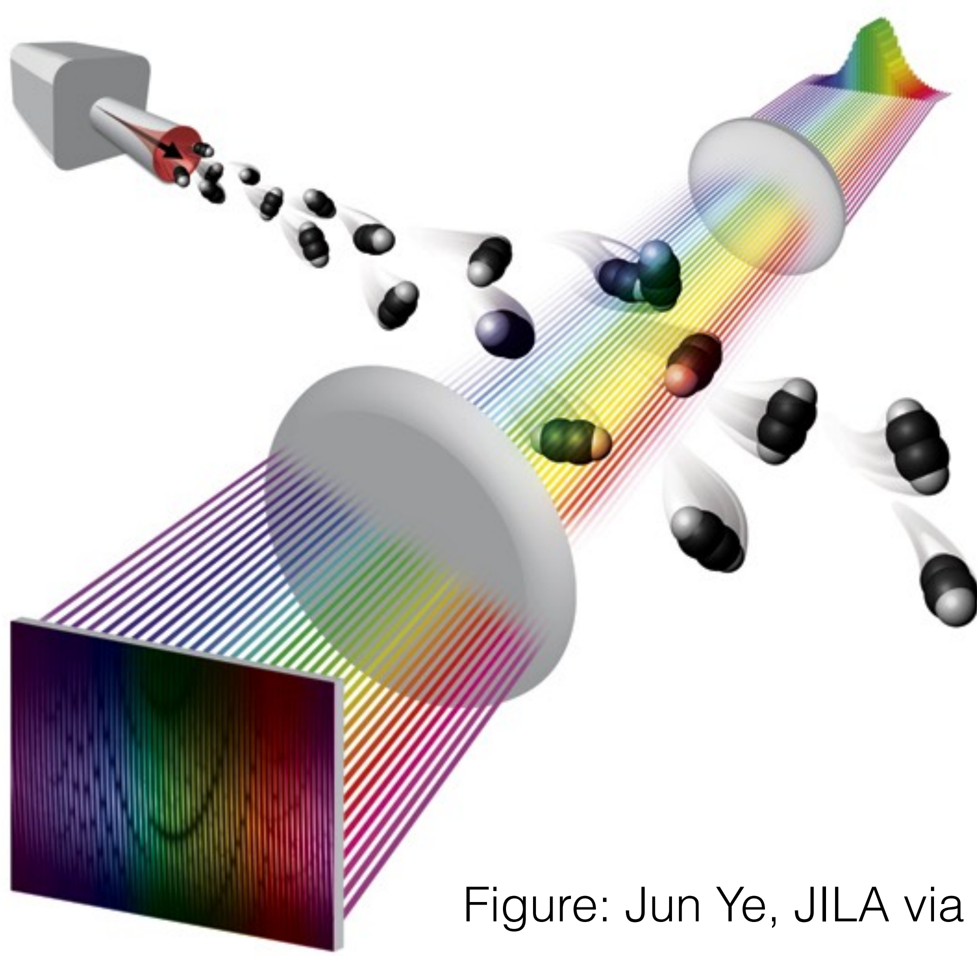


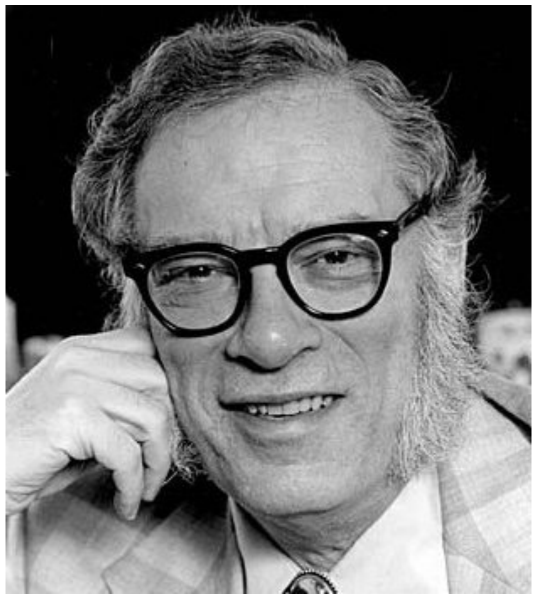
Figure: Jun Ye, JILA via aps.org

Trace-gas sensing

Ultra-high harmonic generation
… atto-second science

Impact on “non-clock” applications:

Communications

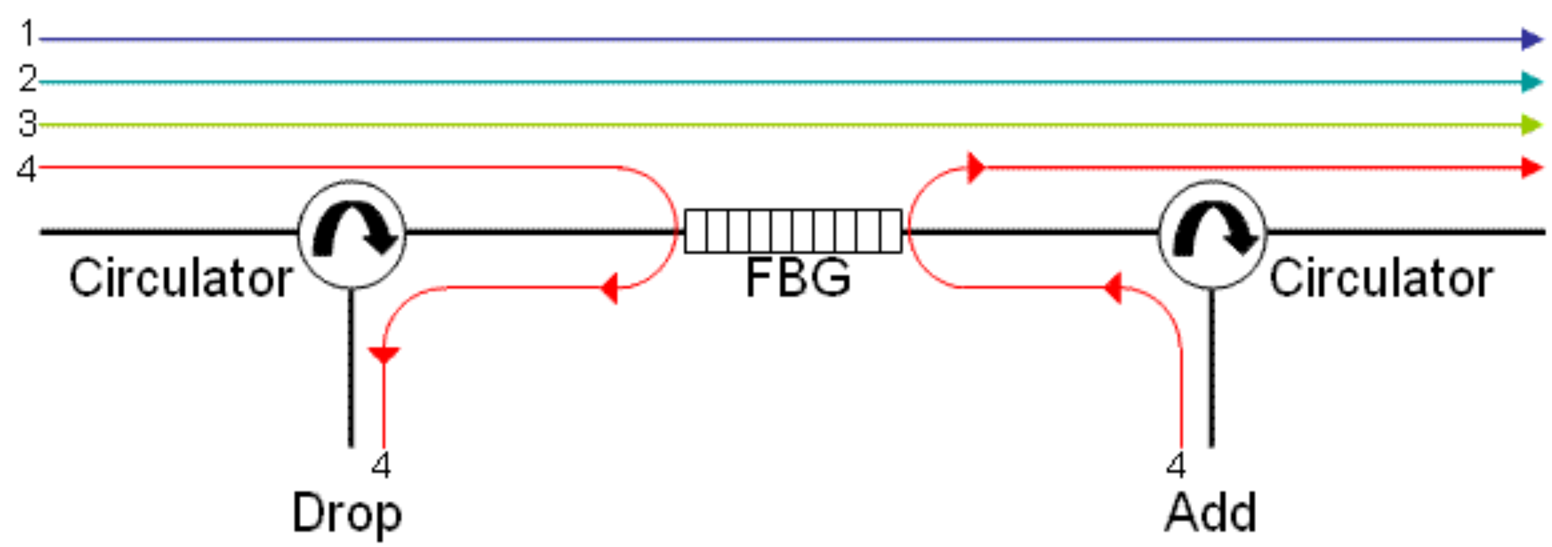


“… there are more high frequencies than low frequencies …”

Isaac Asimov
(Understanding Physics, p. 130, 1993)

Typical DWDM spacing: 50 or 100 GHz…

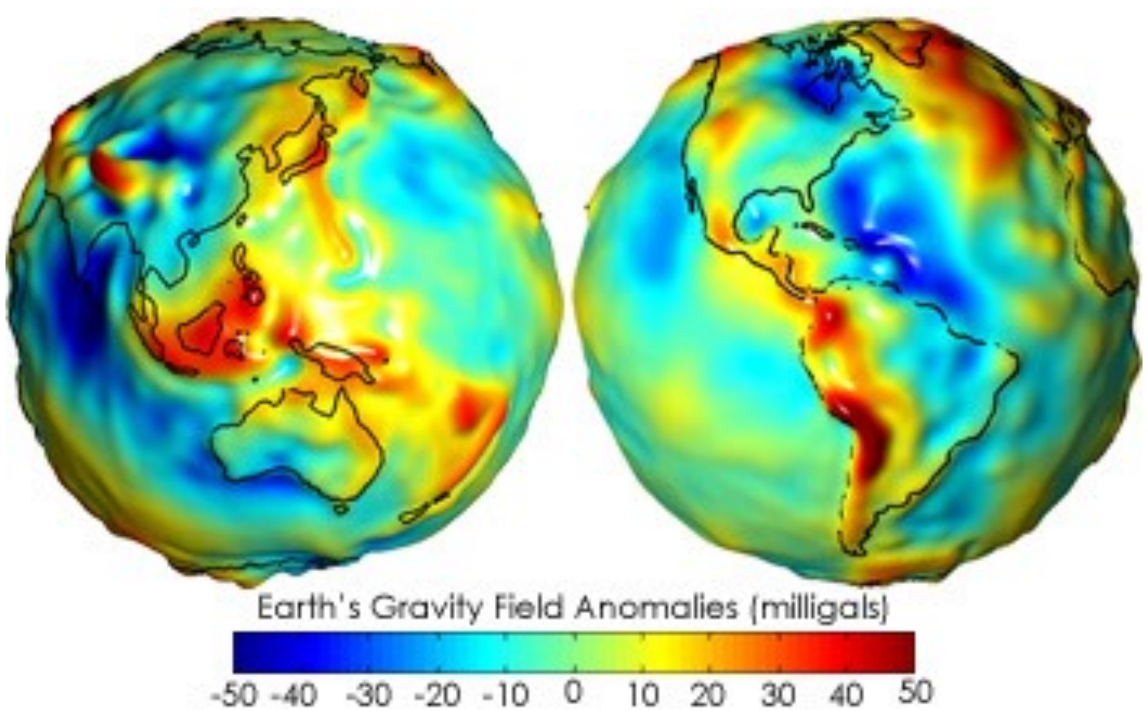
… could be **much** closer if carriers were coherent.



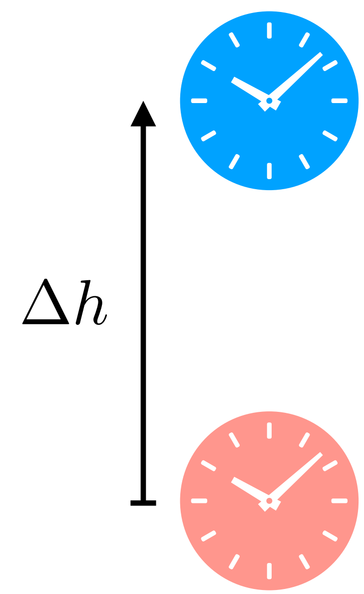
Figures: Wikimedia

“New” applications:

Relativistic geodesy

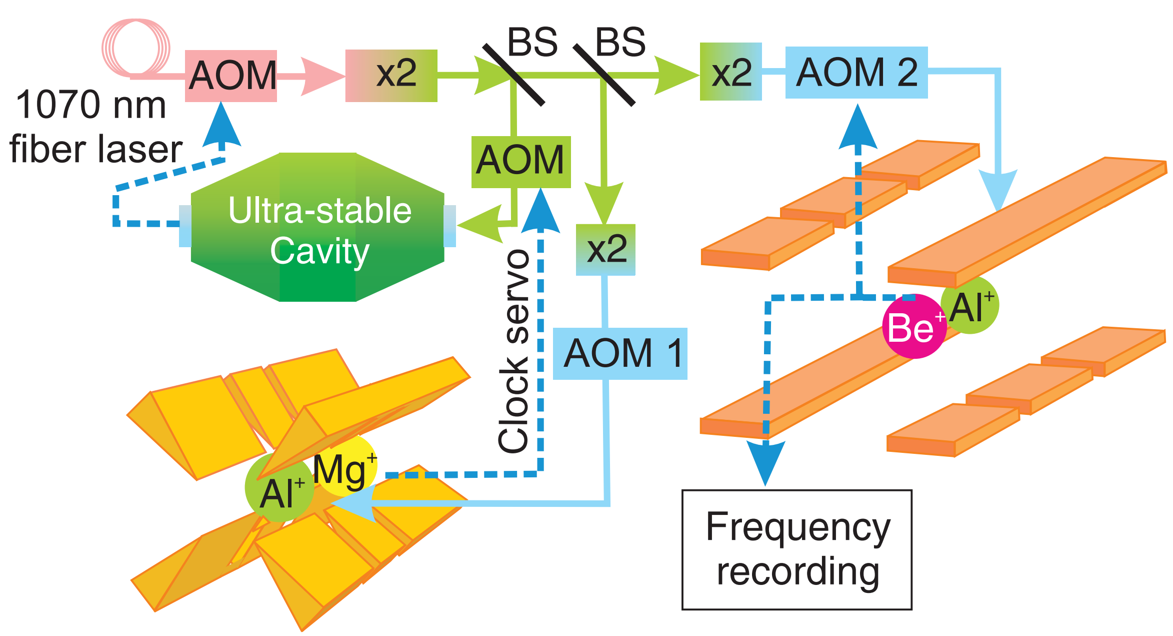


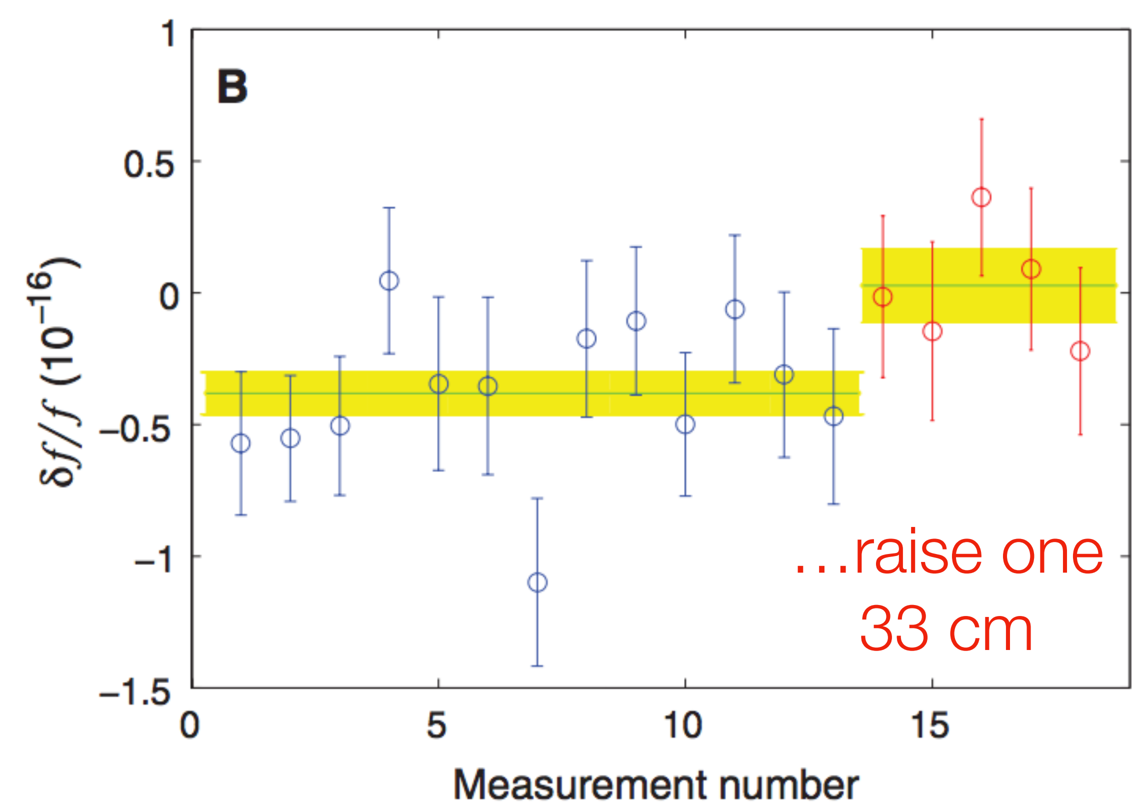
Near Earth’s surface:



$$\frac{\Delta f}{f} = \frac{g\Delta h}{c^2} \approx 10^{-18}\left(\frac{\Delta h}{1\,\mathrm{cm}}\right)$$

Comparison of two Al+ optical clocks:



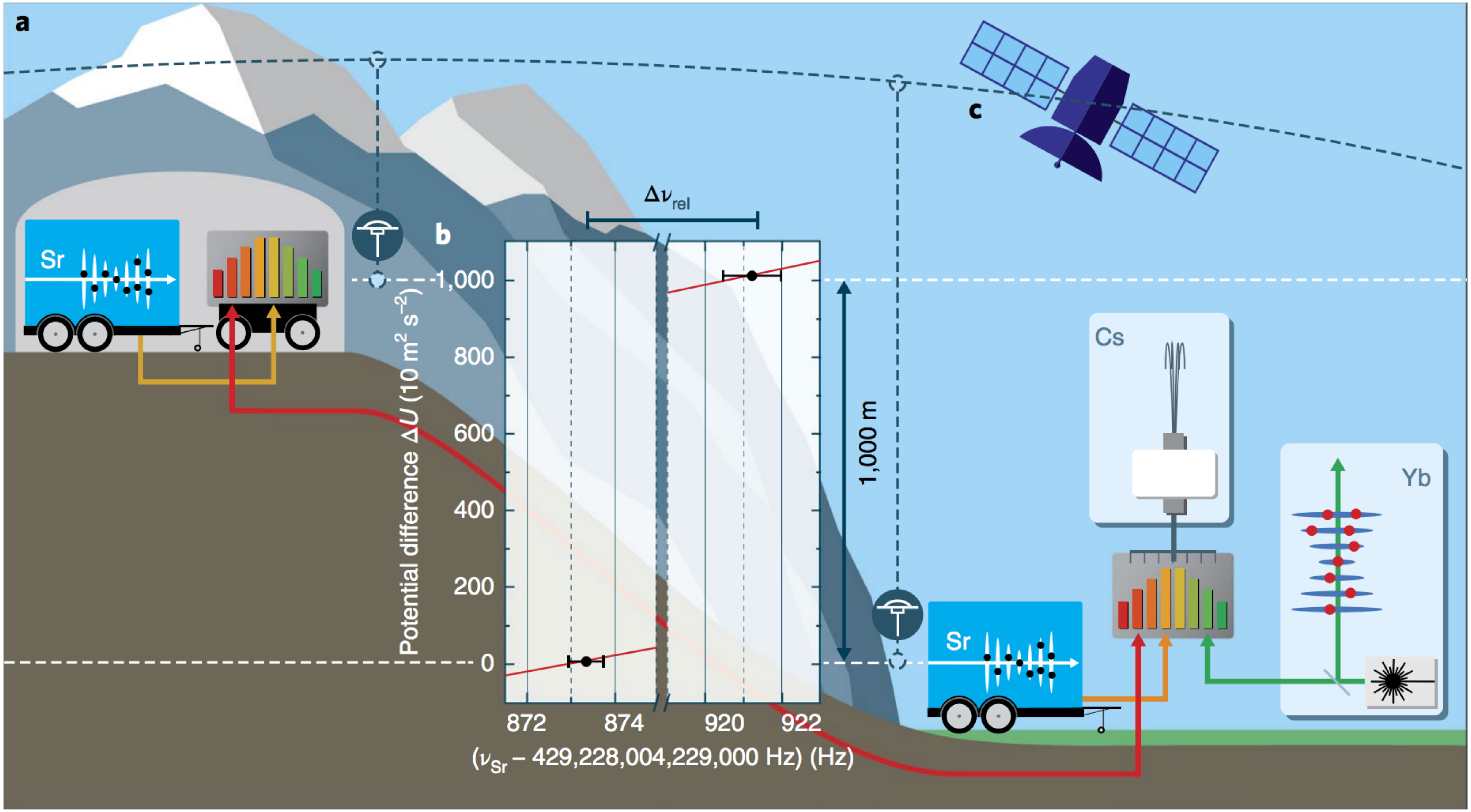


[1] Top: NASA GRACE mission

[2] Bottom: CW Chou, DB Hume, T Rosenband, D Wineland, Science 329, 1630 (2010)

“New” applications:

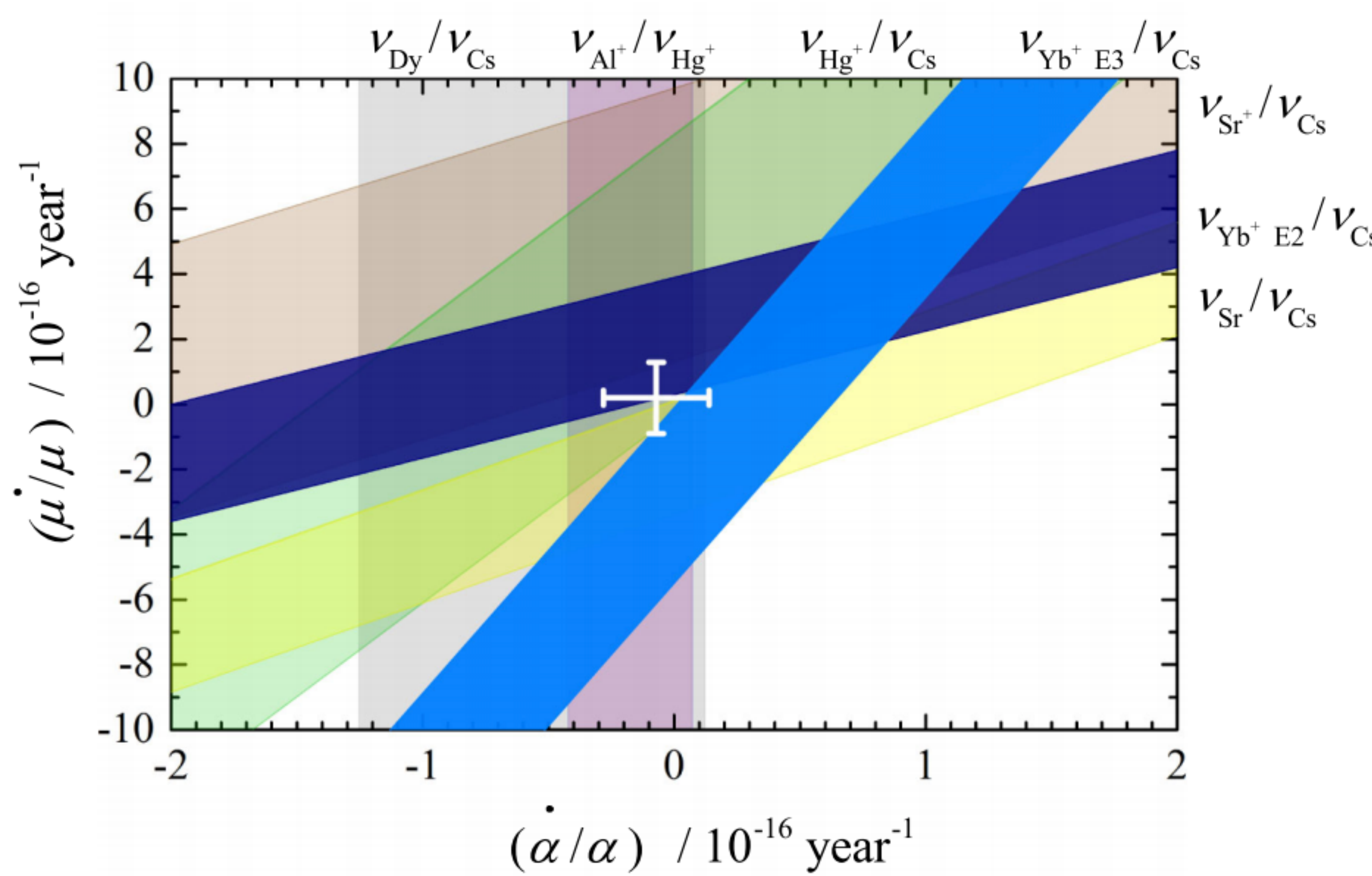
Relativistic geodesy: demonstrated with transportable optical clock



J Grotti, S Koller, S Vogt, et al., *Nature Physics* **14**, 437 (2018)

“New” applications:

Are fundamental “constants” of nature time-varying?



RM Godun, PBR Nisbet-Jones, JM Jones, et al., *PRL* **113**, 210801 (2014)

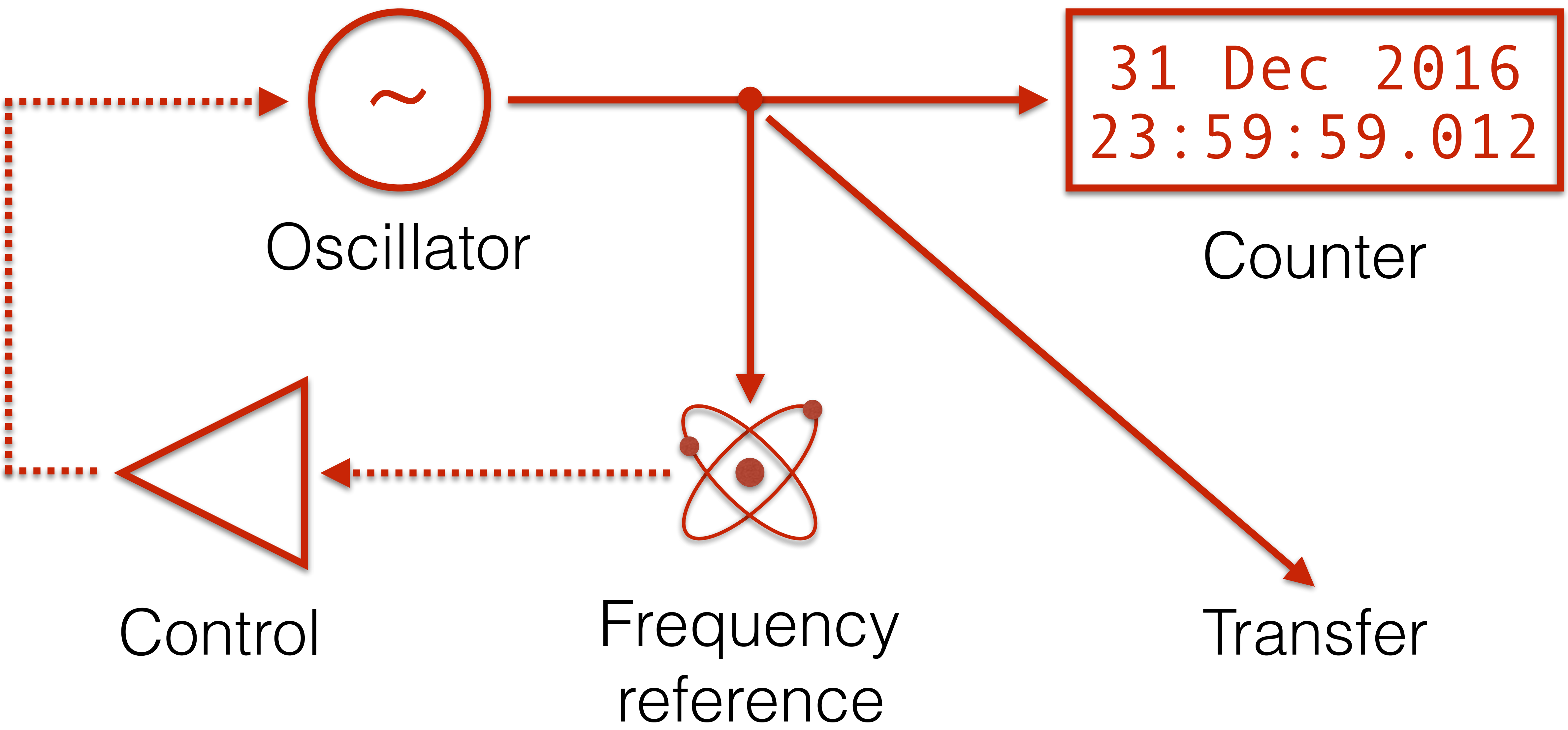
Optical clocks as low-frequency gravitational wave detectors

S Kolkowitz, I Pikovski, N Langellier, et al., PRD **94**, 124043 (2016)

Optical clocks as speculative dark matter candidate detectors

A Arvanitaki, J Huang, K Van Tilburg, PRD **91**, 015015 (2015)

Technological comparisons: microwave vs. optical



Oscillator

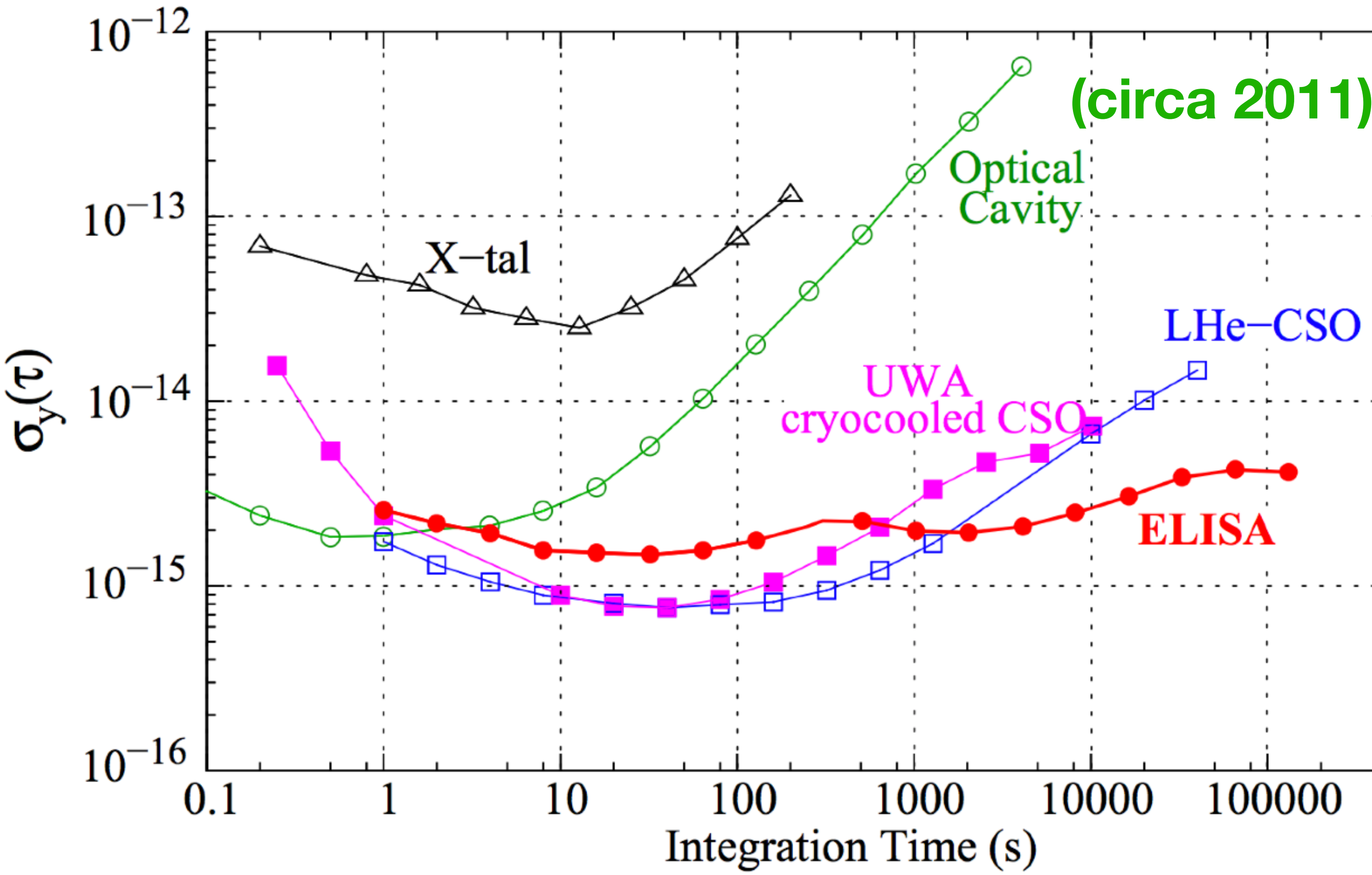
Derive a (short-term-) stable frequency from an object's physical dimensions

Microwave

Optical

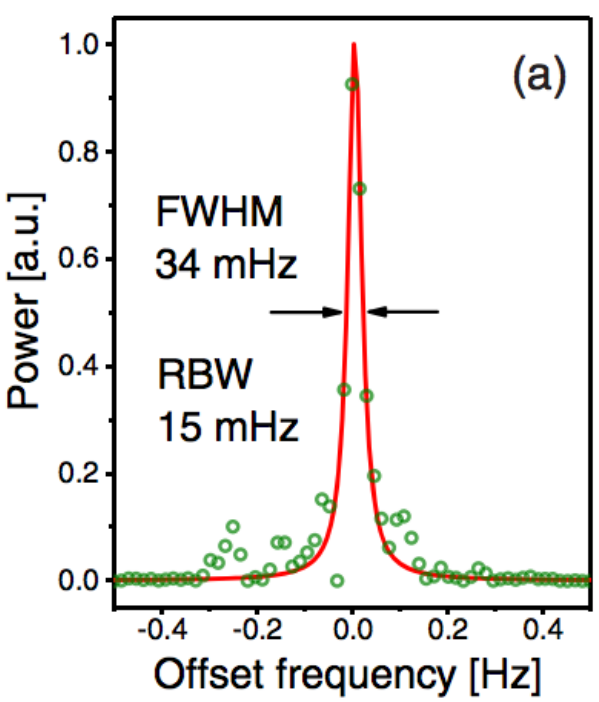
Left: http://lowpowerradio.blogspot.com/2017/02/Instant-AM-radio-station-hacking-1-mhz-crystal-oscillator.html

Right: PTB & JILA, photo reproduced at https://www.sciencedaily.com/releases/2017/06/170629101709.htm

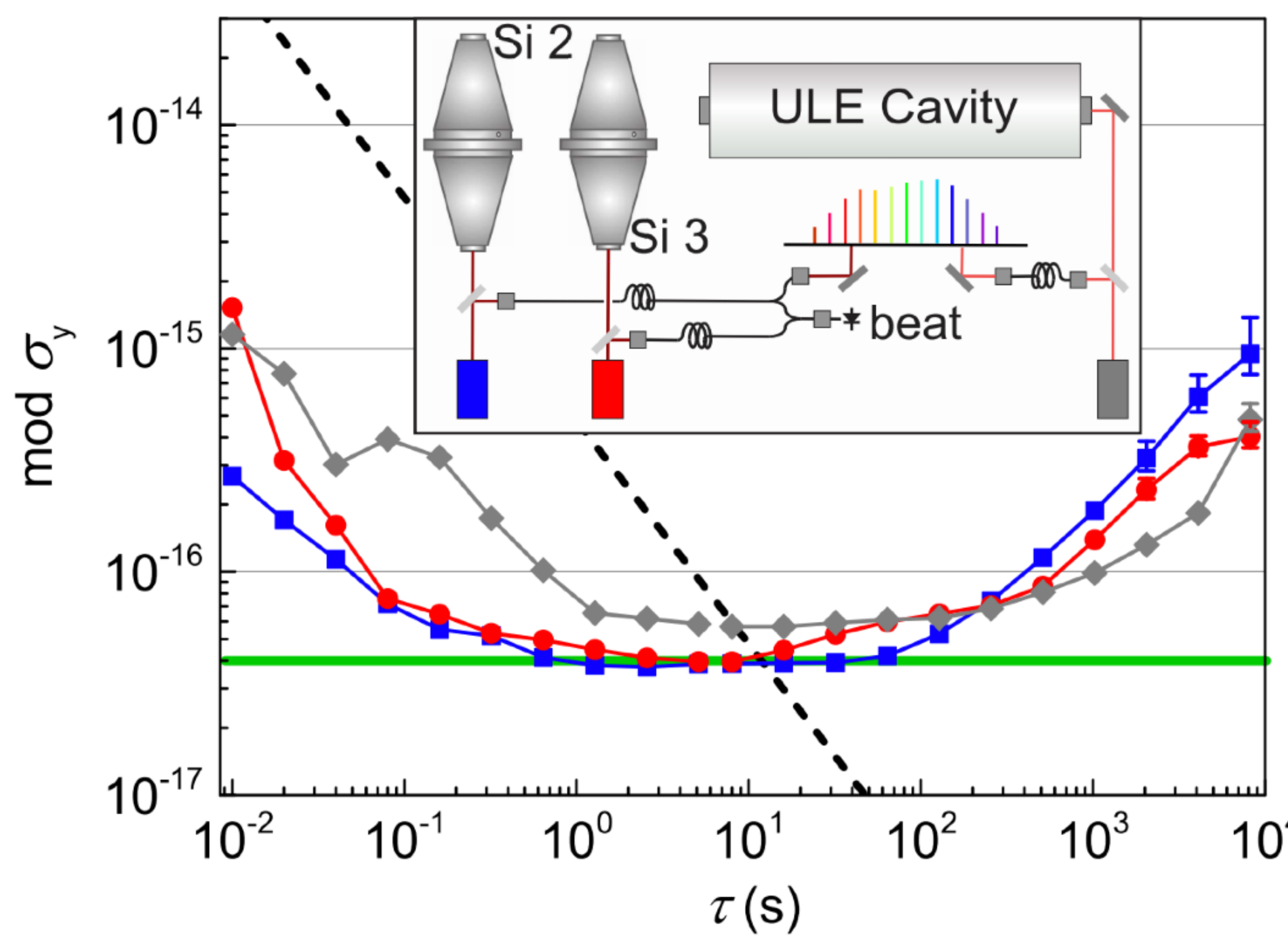


[1] S Grop, W Schafer, P Bourgeois, et al., IEEE Trans. UFFC 58(8), 1694–7 (2011)

[2] DG Matei, T Legero, S Häfner, et al., Phys. Rev. Lett. **118**, 263202 (2017)



Q ~ 1.5 x 10^{16}



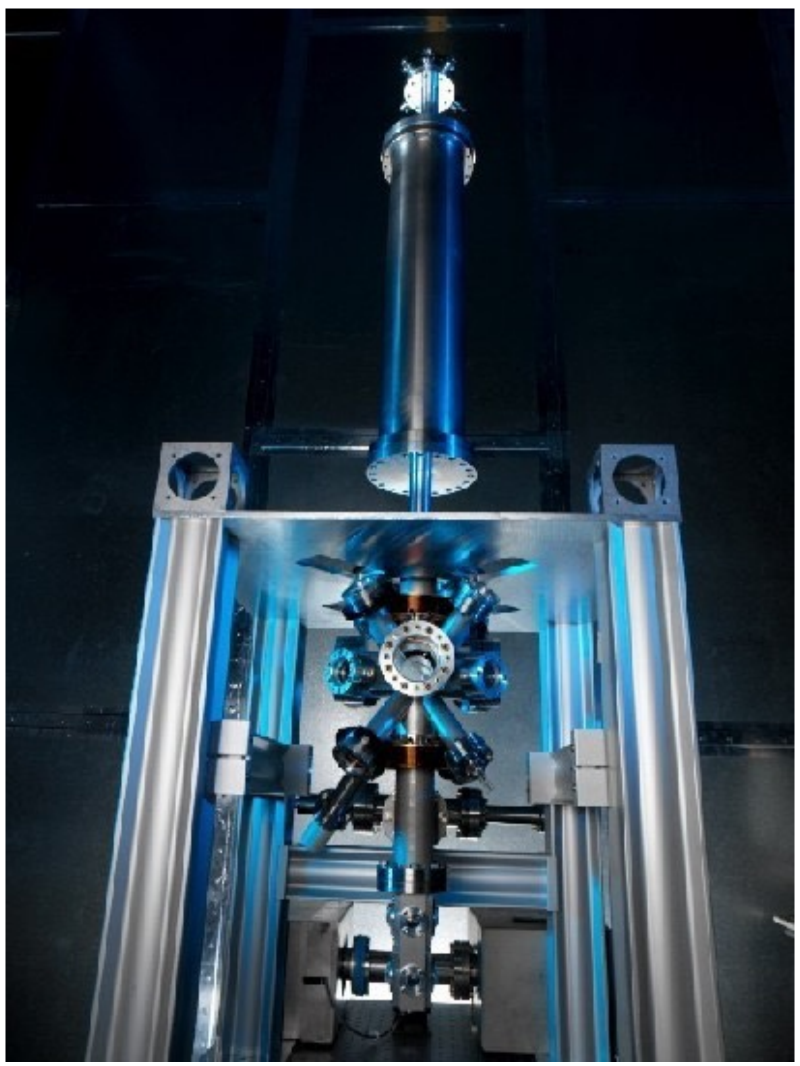
[3] W Zhang, JM Robinson, L Sonderhouse, et al., Phys. Rev. Lett 119, 243601 (2017)

Frequency reference

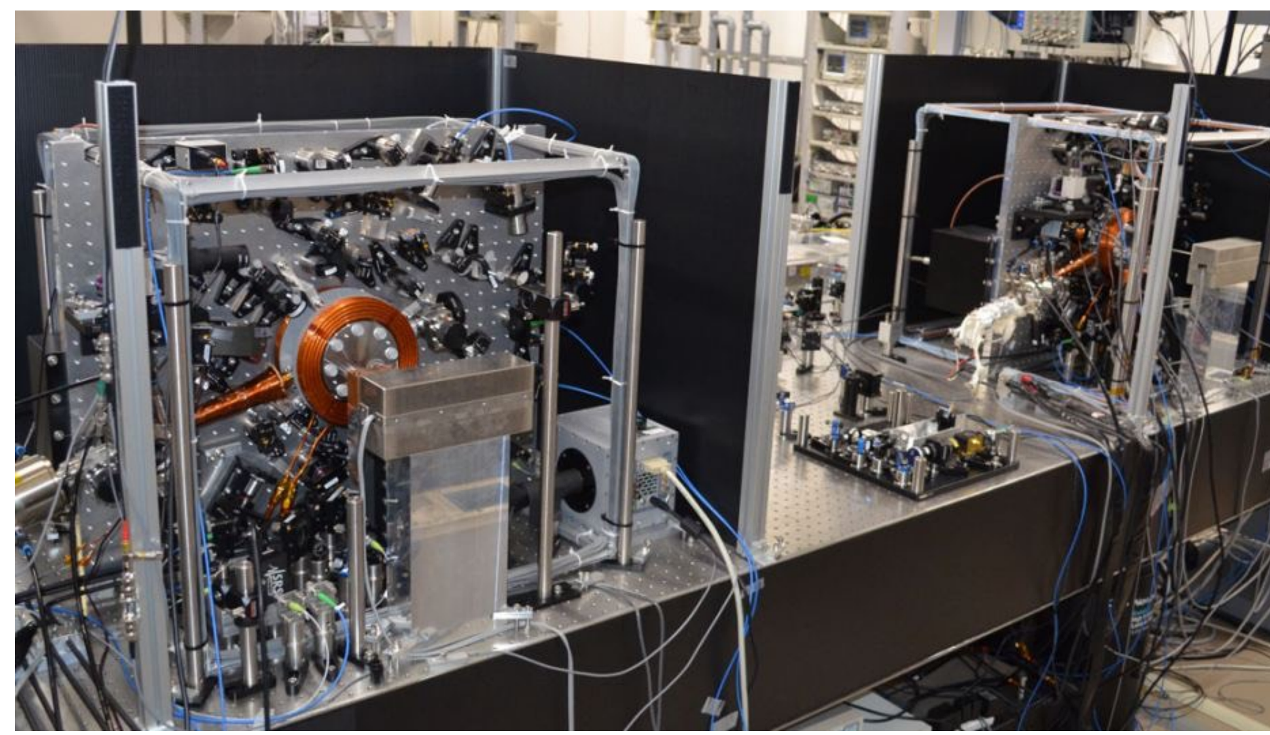
Derive an accurate frequency from a quantum-mechanical system

$\sim \$10^6$

Microwave



Optical



Left: National Physical Laboratory, UK. Right: H Katori, University of Tokyo

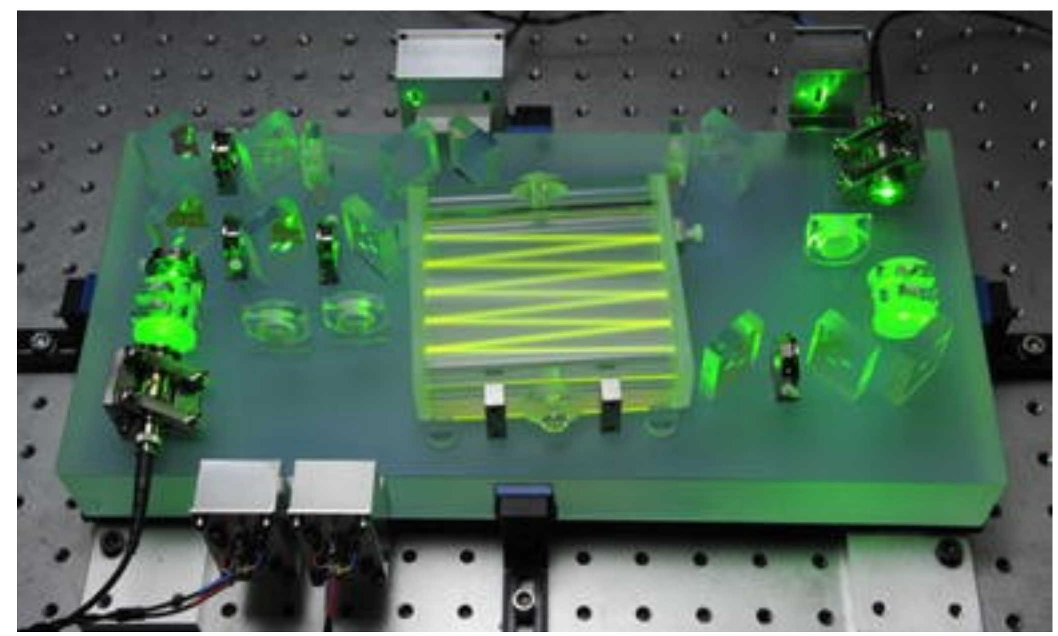
Frequency reference

Derive an accurate frequency from a quantum-mechanical system

~$ 10^5

Microwave

Optical



Left: Microsemi. Right: Institut für Physik, Humboldt-Universität zu Berlin

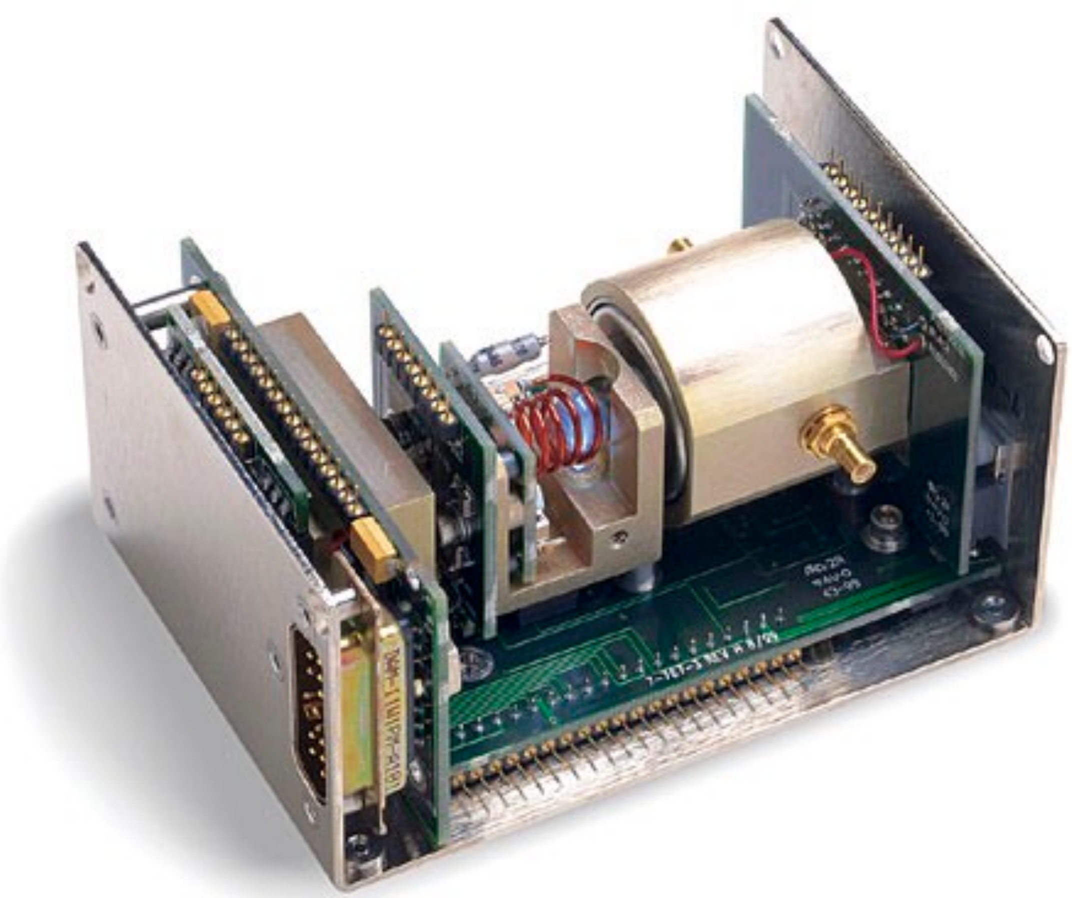
Frequency reference

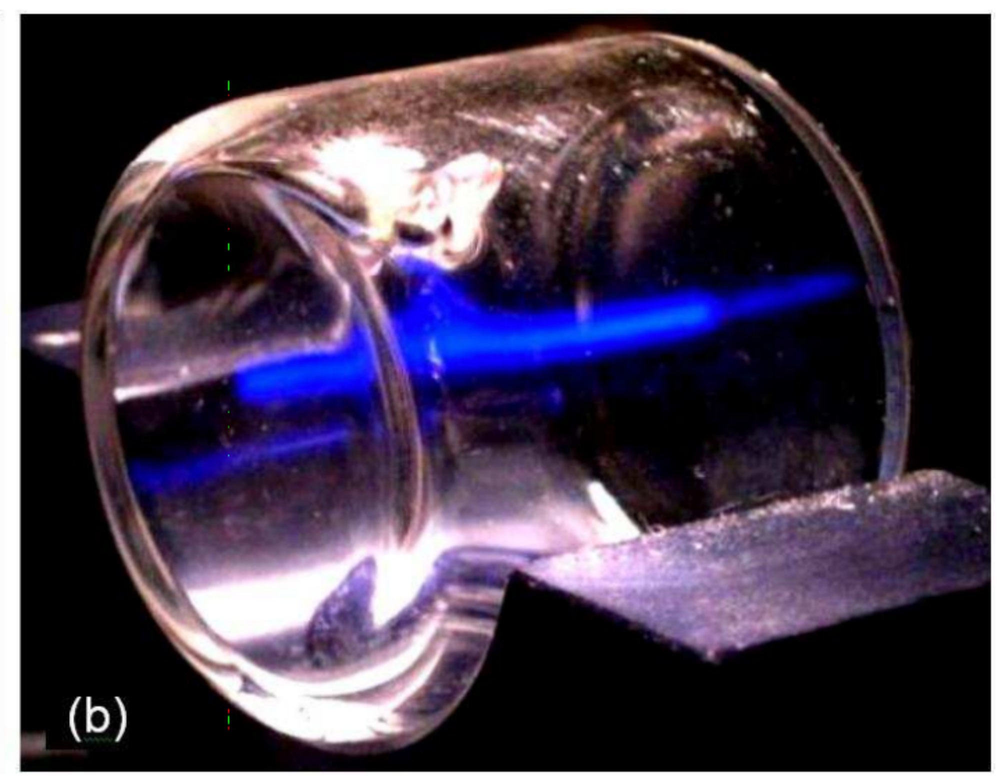
Derive an accurate frequency from a quantum-mechanical system

~$ 10^4

Microwave

Optical





Left: Stanford Research Systems. Right: Swinburne University of Technology, Melbourne

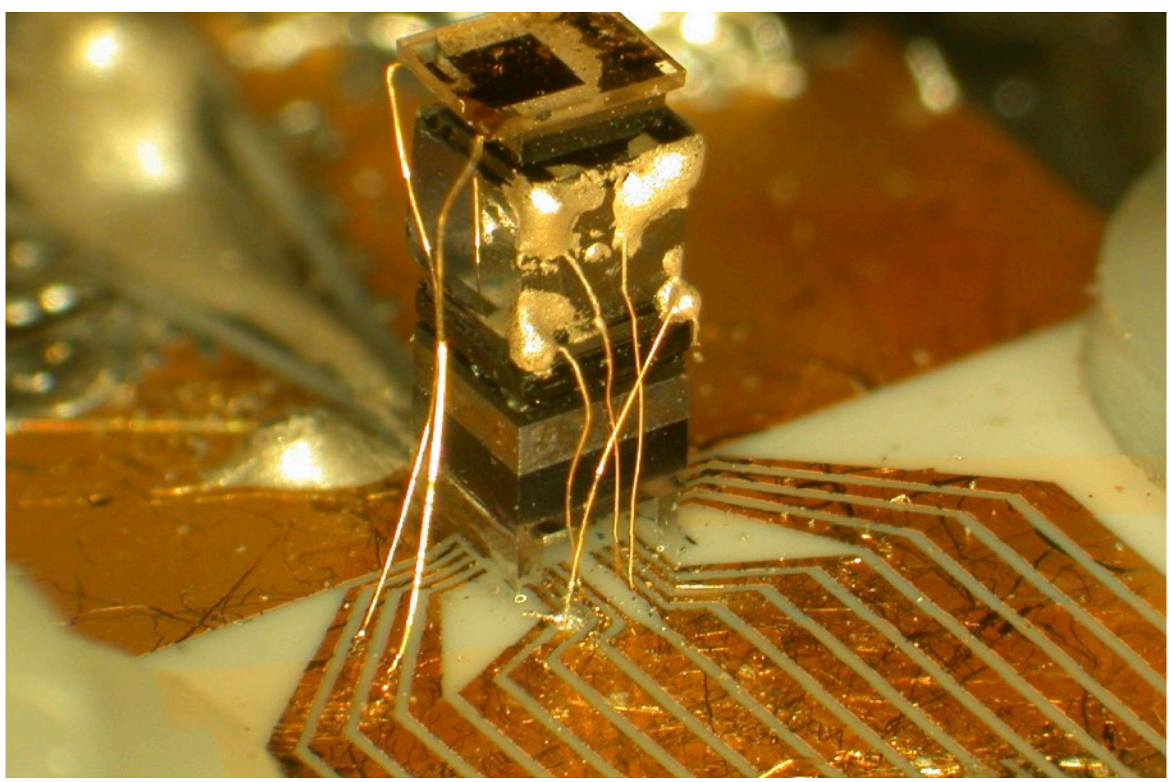
Frequency reference

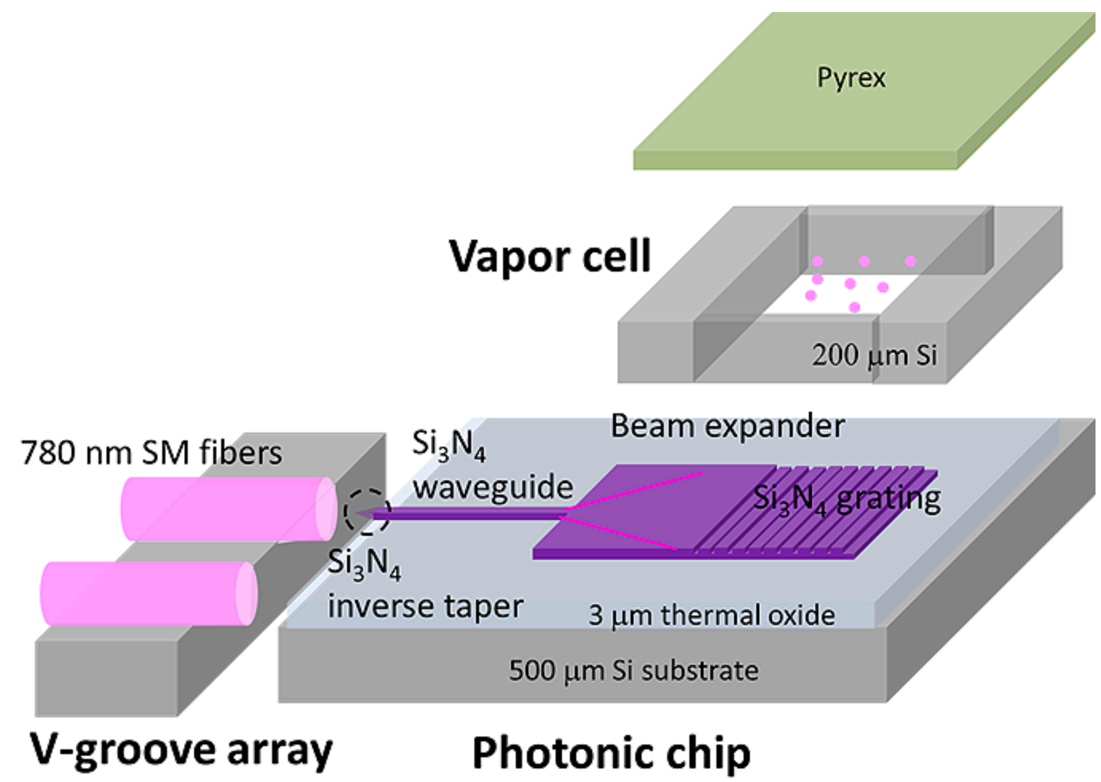
Derive an accurate frequency from a quantum-mechanical system

~$ 10^3

Microwave

Optical



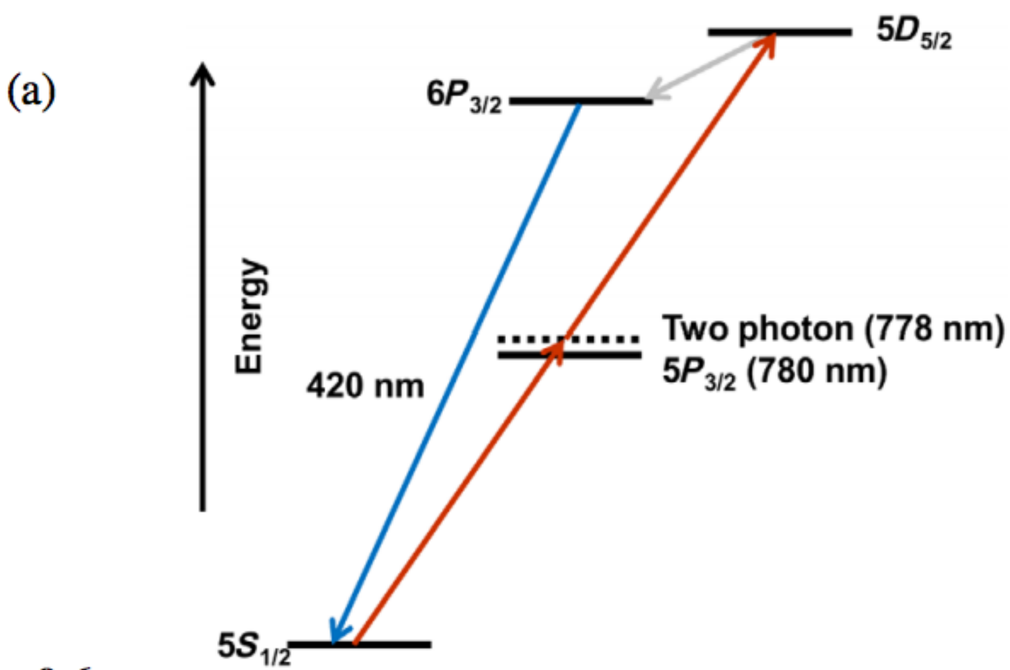


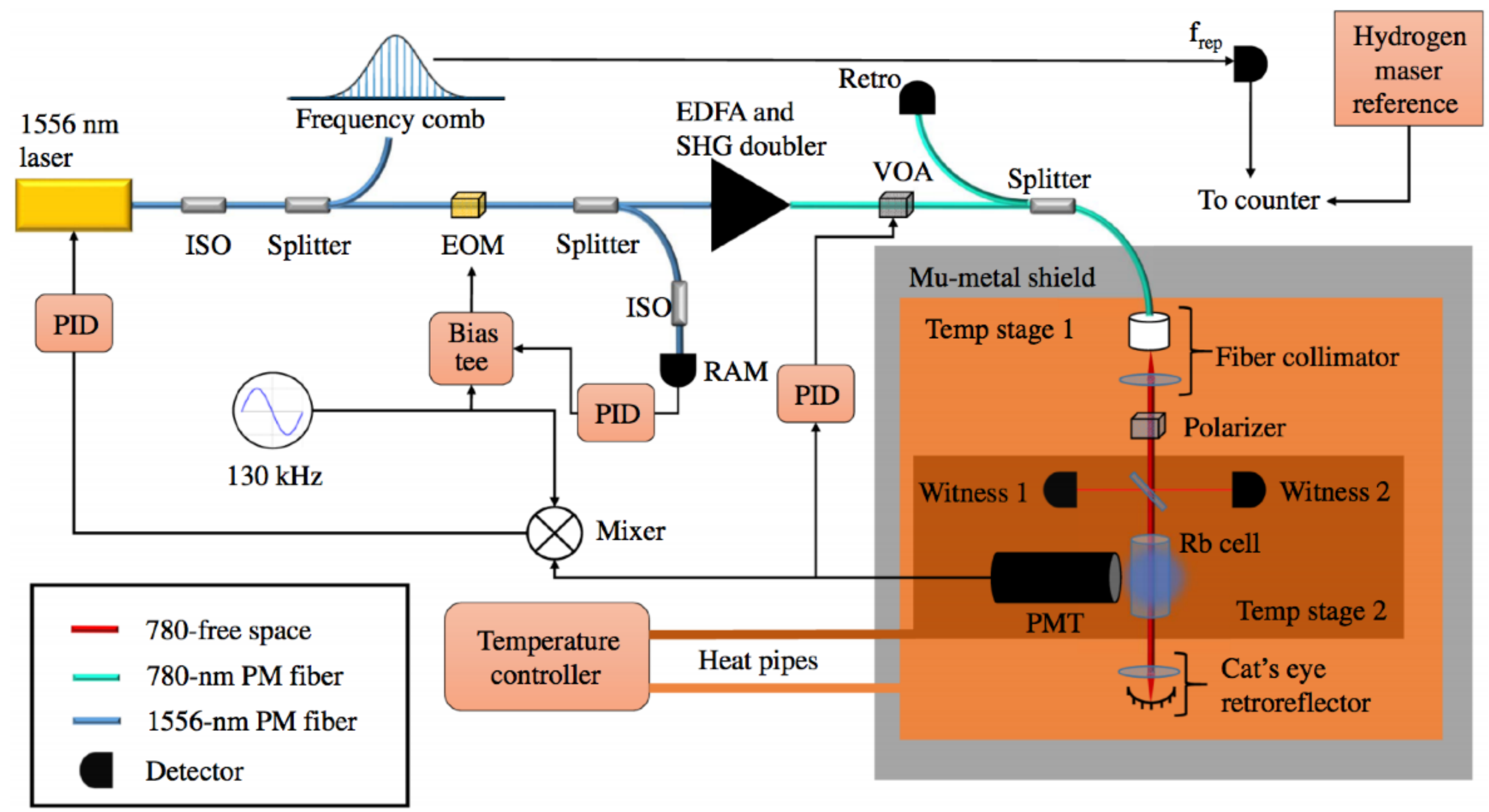
Left: NIST chip-scale atomic clock prototype. Right: “NIST-on-a-chip” wavelength-reference concept art

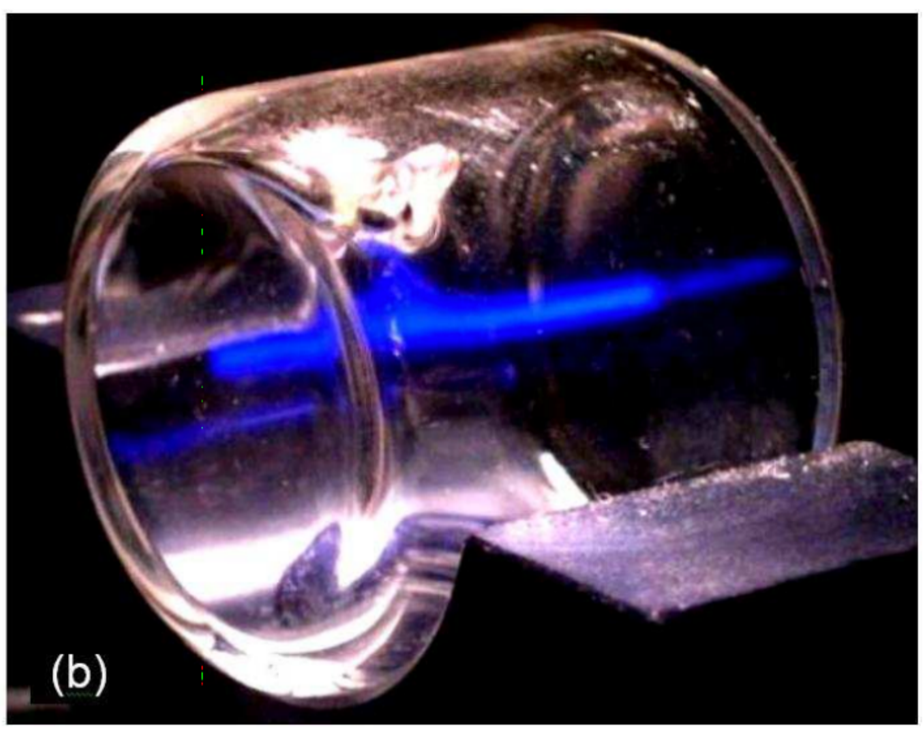
Frequency reference

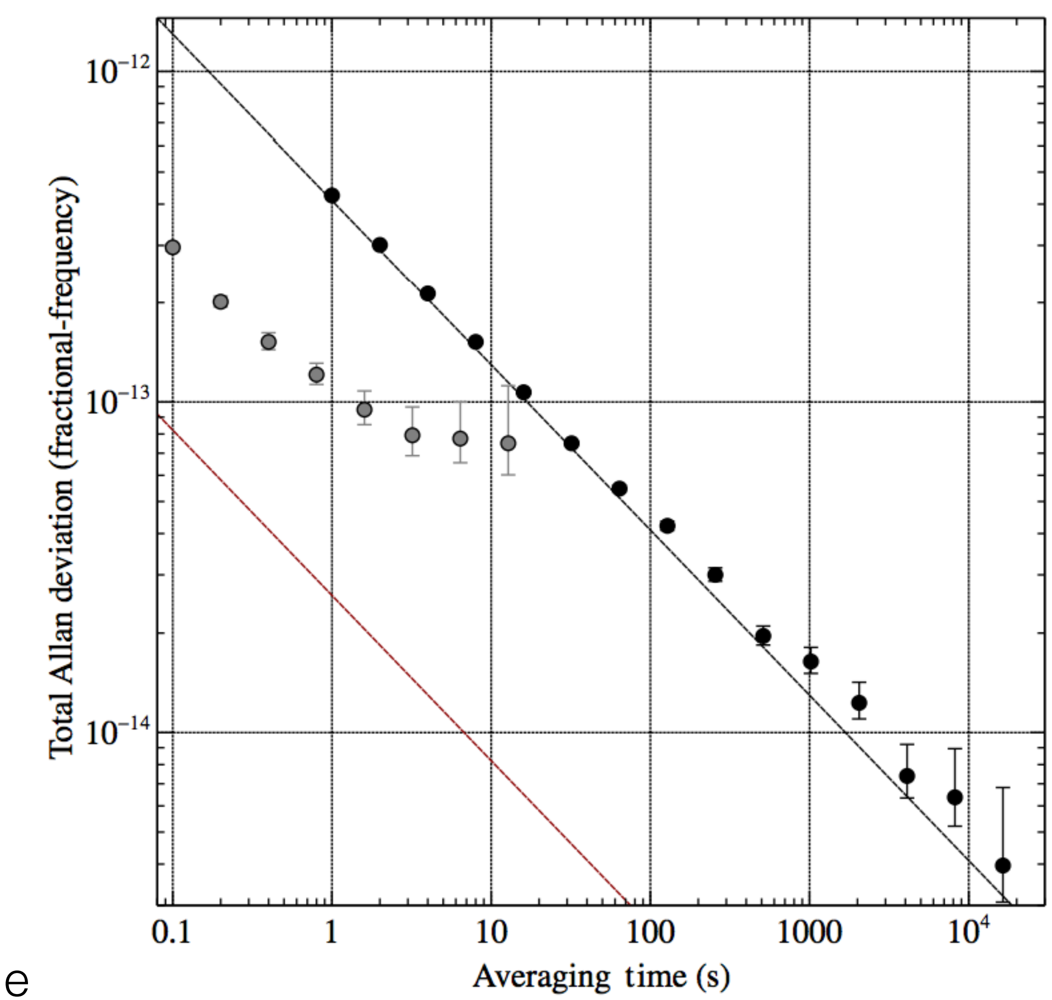
Ok, but which optical frequency references are “closest” to commercial availability?

e.g two-photon Rb









K Martin, G Phelps, ND Lemke, et al., Phys. Rev. Appl. **9**, 014019 (2018)
Photo (here for illustration): Swinburne University of Technology, Melbourne

e.g iodine molecule

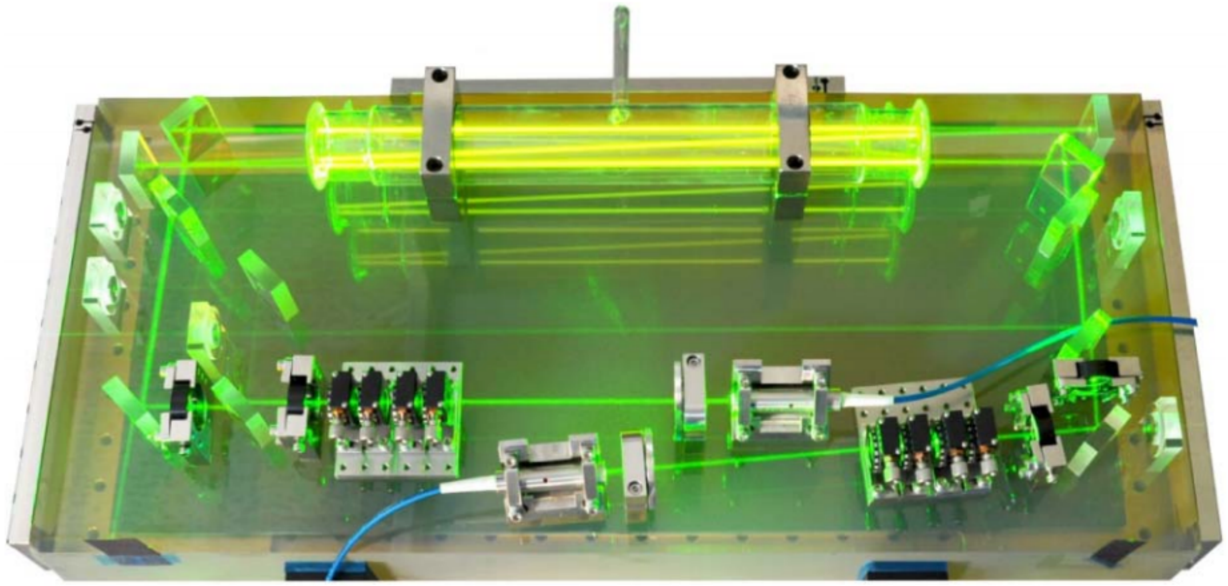
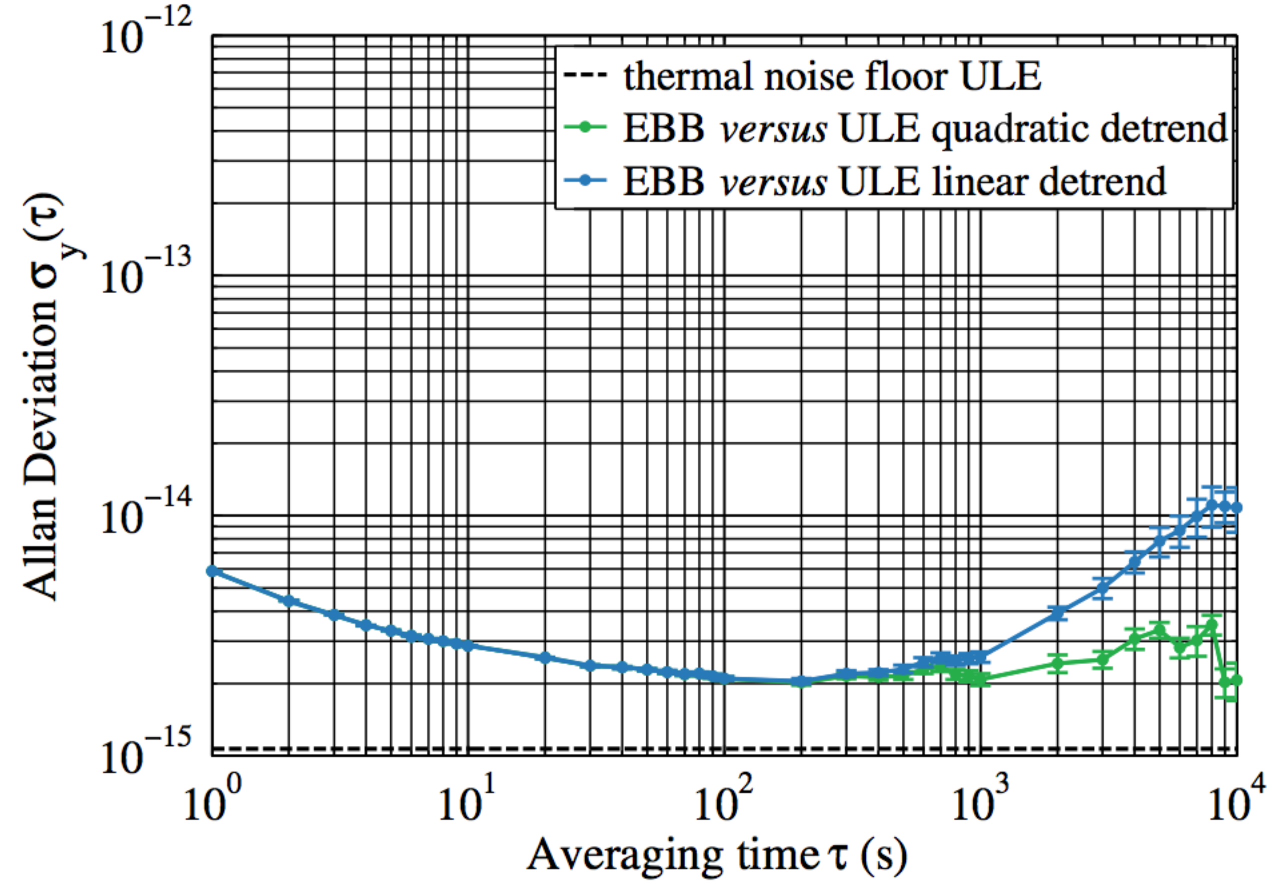
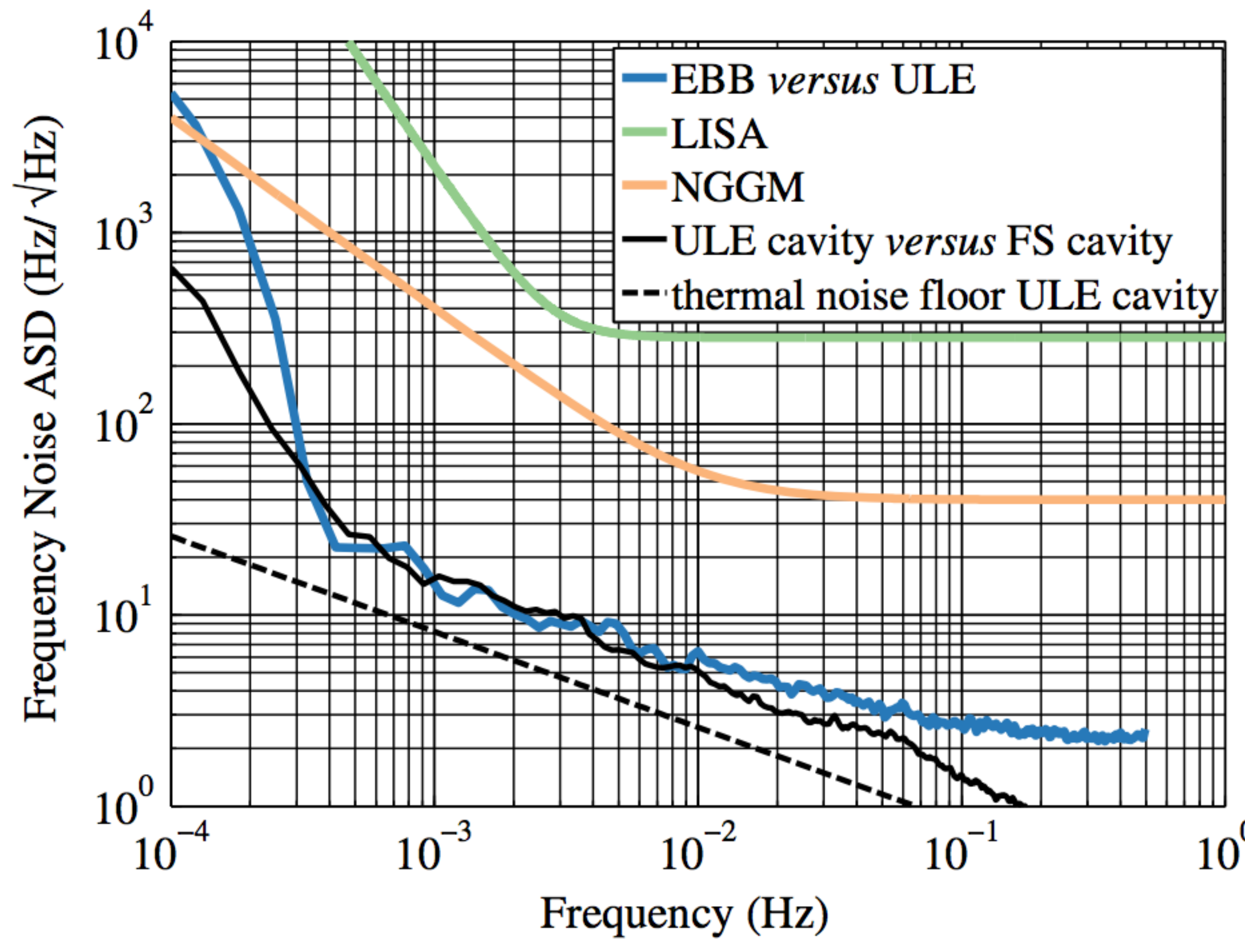


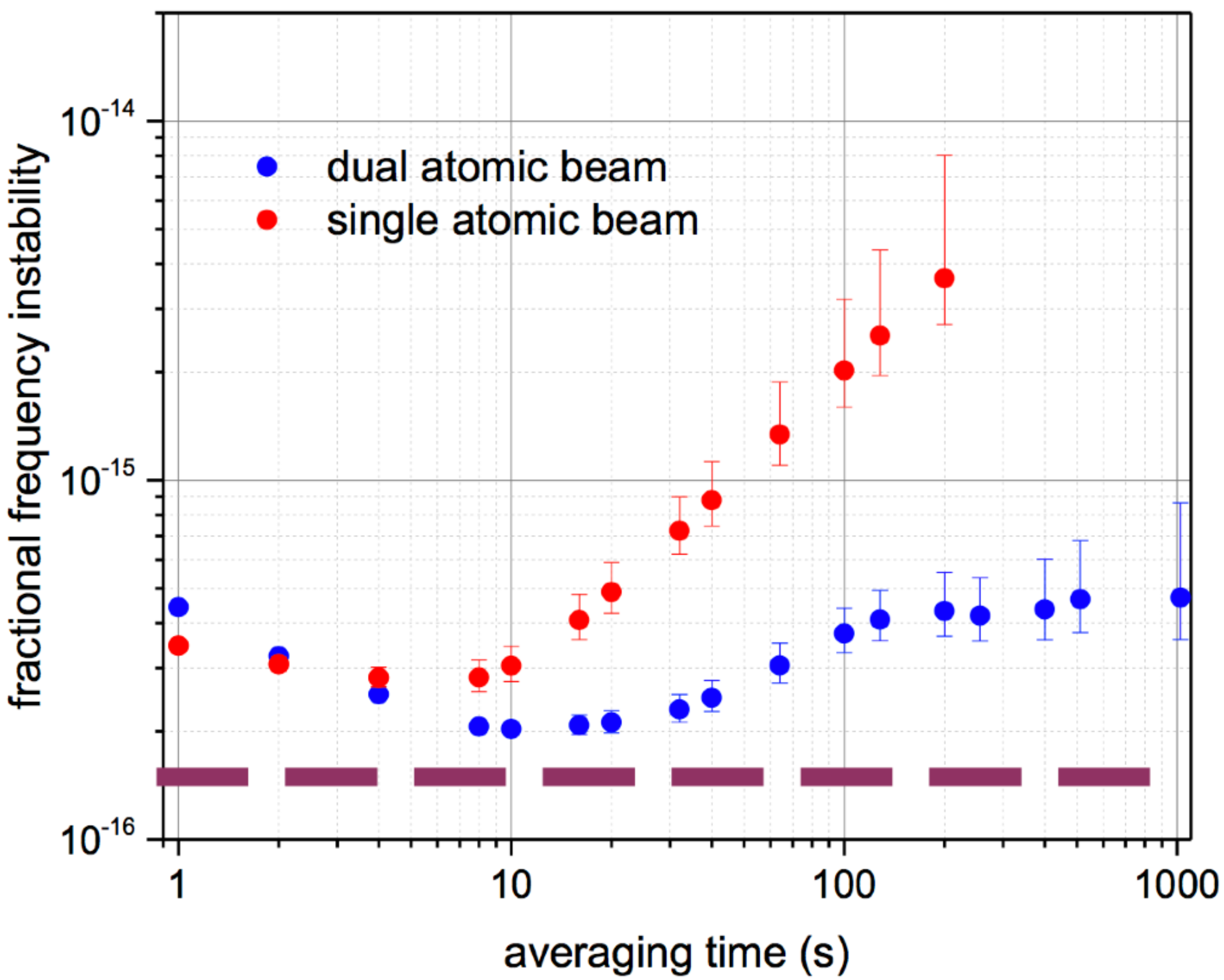
Fig. 1. Photograph of the integrated EBB setup. Optics are joined to a thermally and mechanically highly stable glass baseplate made from OHARA Clearceram-HS using adhesive bonding technology. The footprint of the EBB baseplate is 550 mm × 250 mm. The length of the iodine cell is 30 cm.

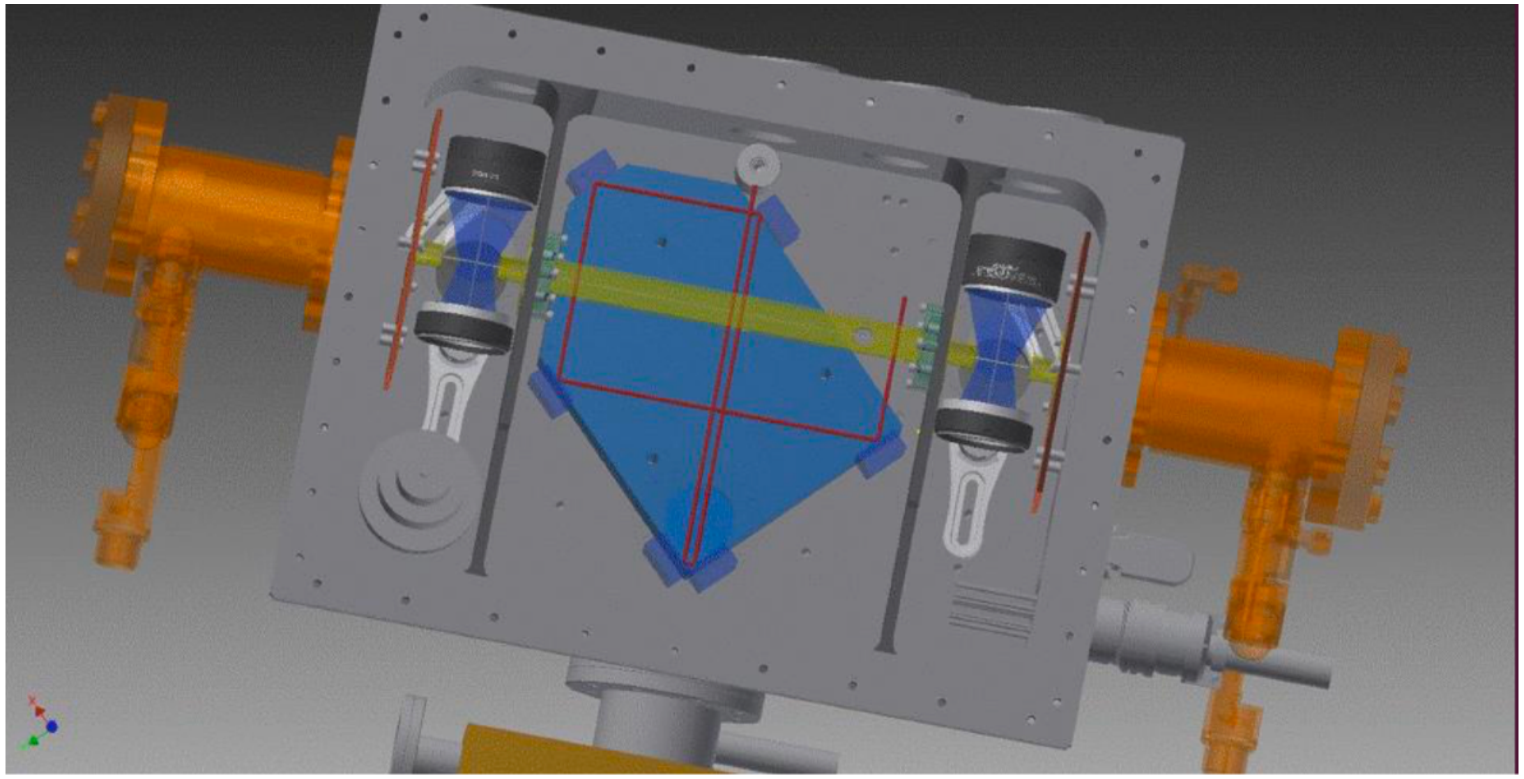




Th Schuldt, K Döringshoff, E Kovalchuk, et al., Appl. Optics 56(4), 1101 (2017)

e.g calcium thermal beam





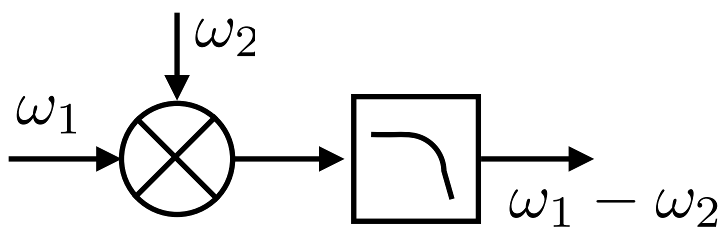
from J Olson, et al., presentation at EFTF/IFCS 2017

31 Dec 2016
23:59:59.012

Counter

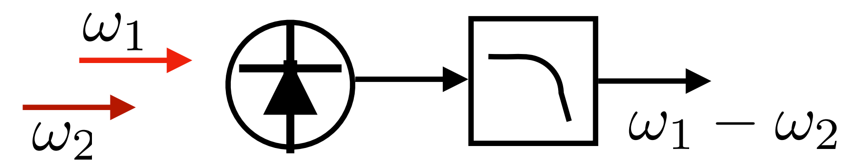
Measure oscillator
phase & frequency differences

Microwave



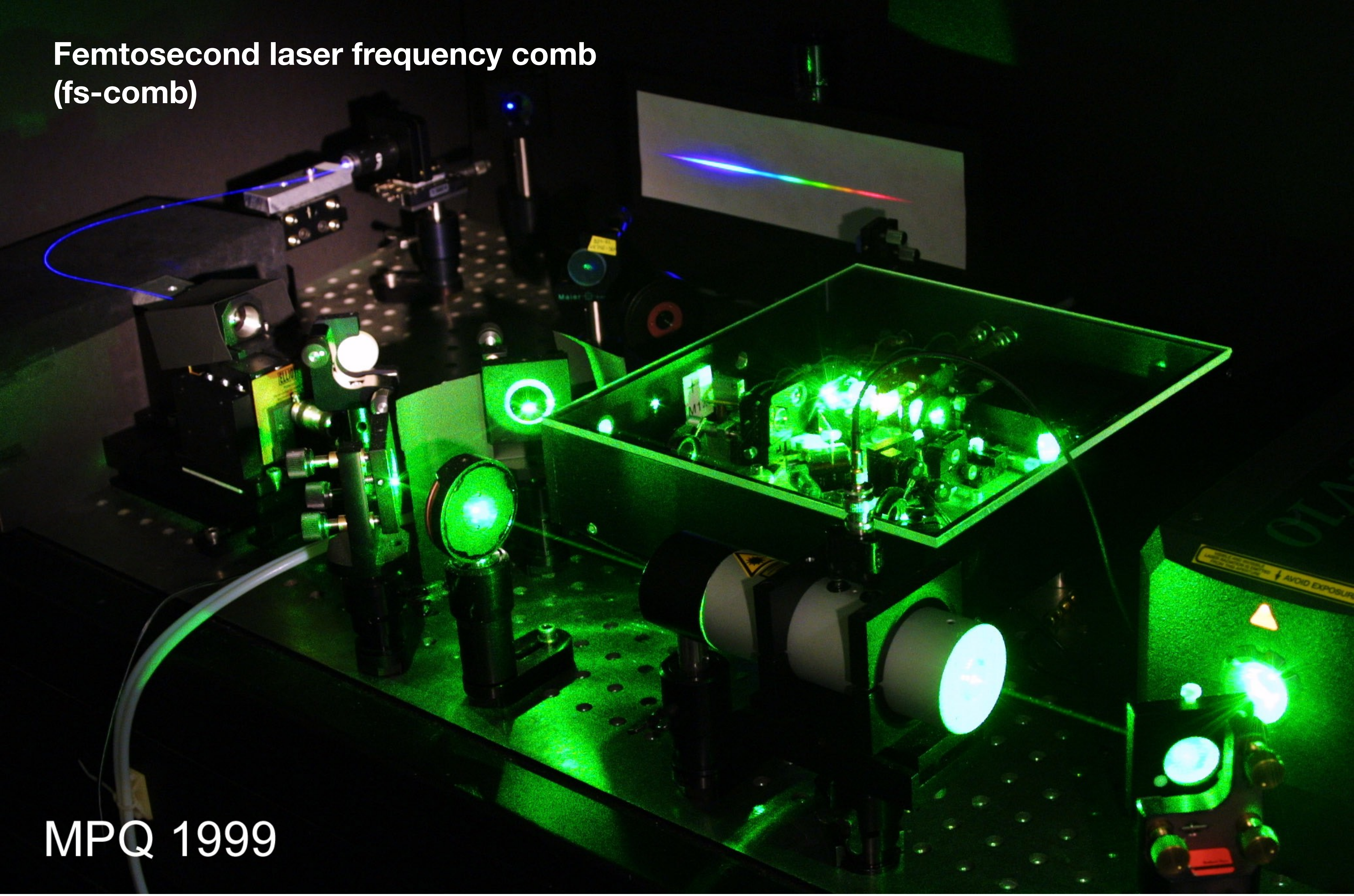
"Phase/frequency subtraction in a mixer"

Optical



"Interference on a photodiode"

Femtosecond laser frequency comb (fs-comb)



MPQ 1999

Femtosecond laser frequency comb (fs-comb)

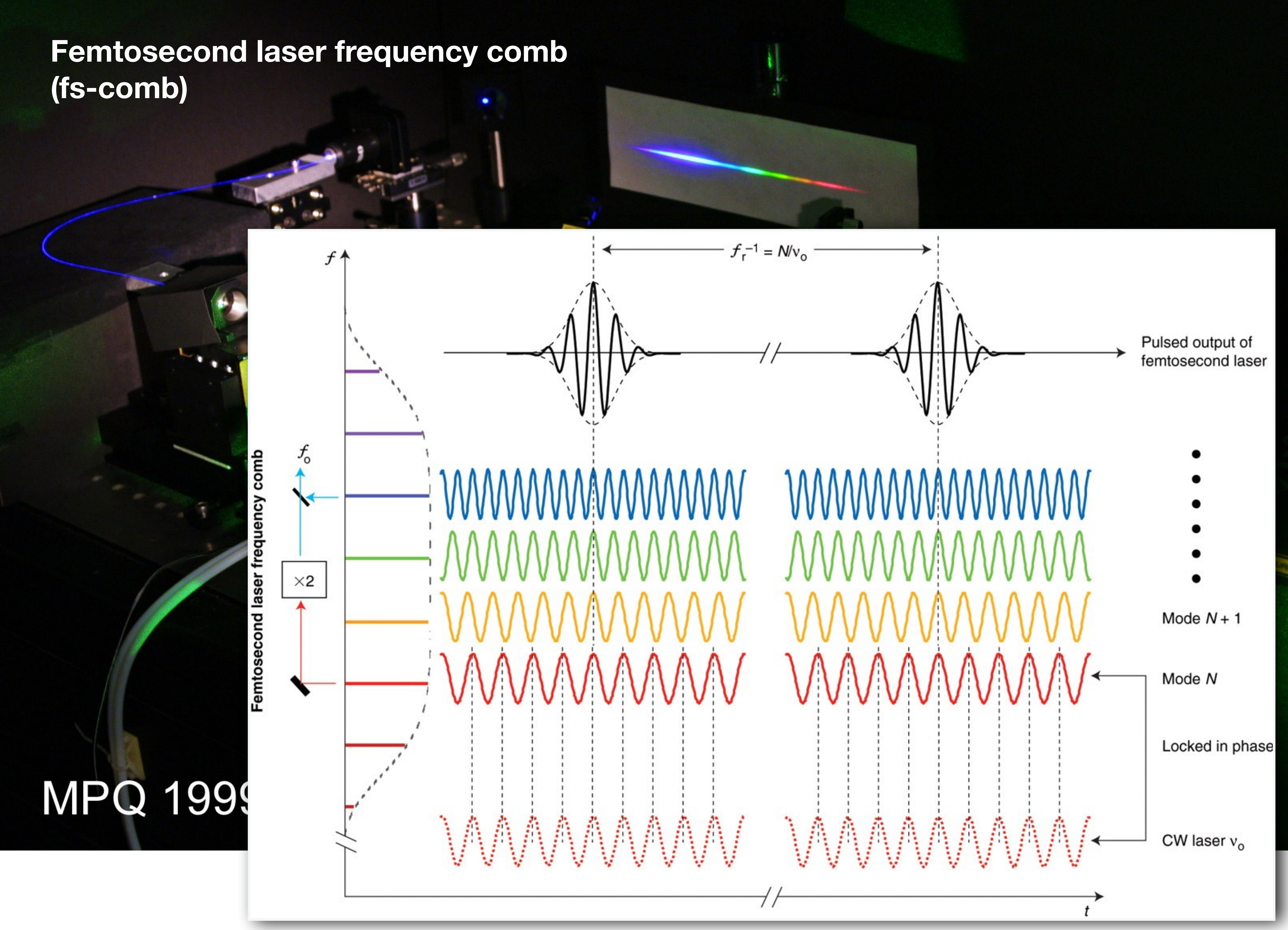
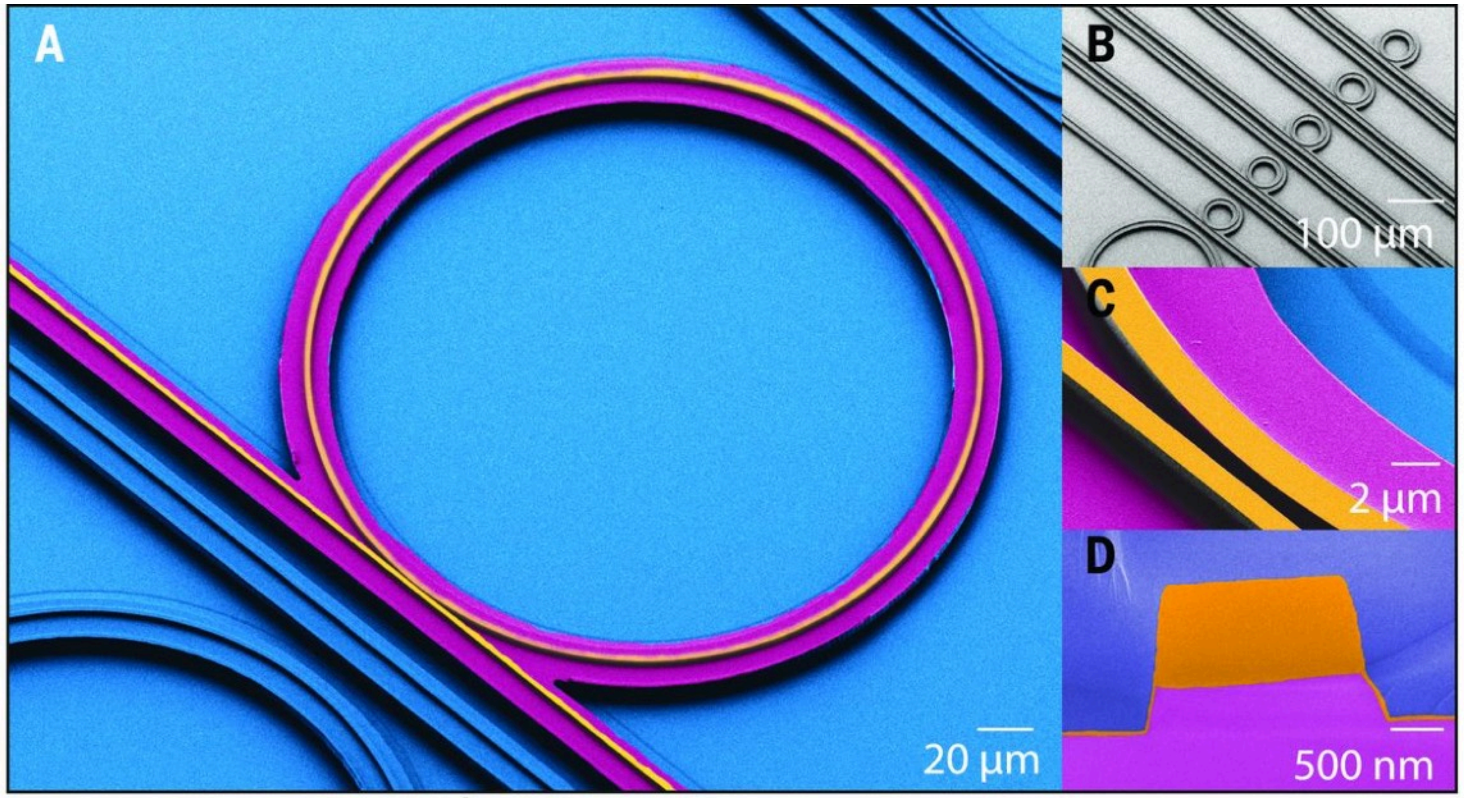
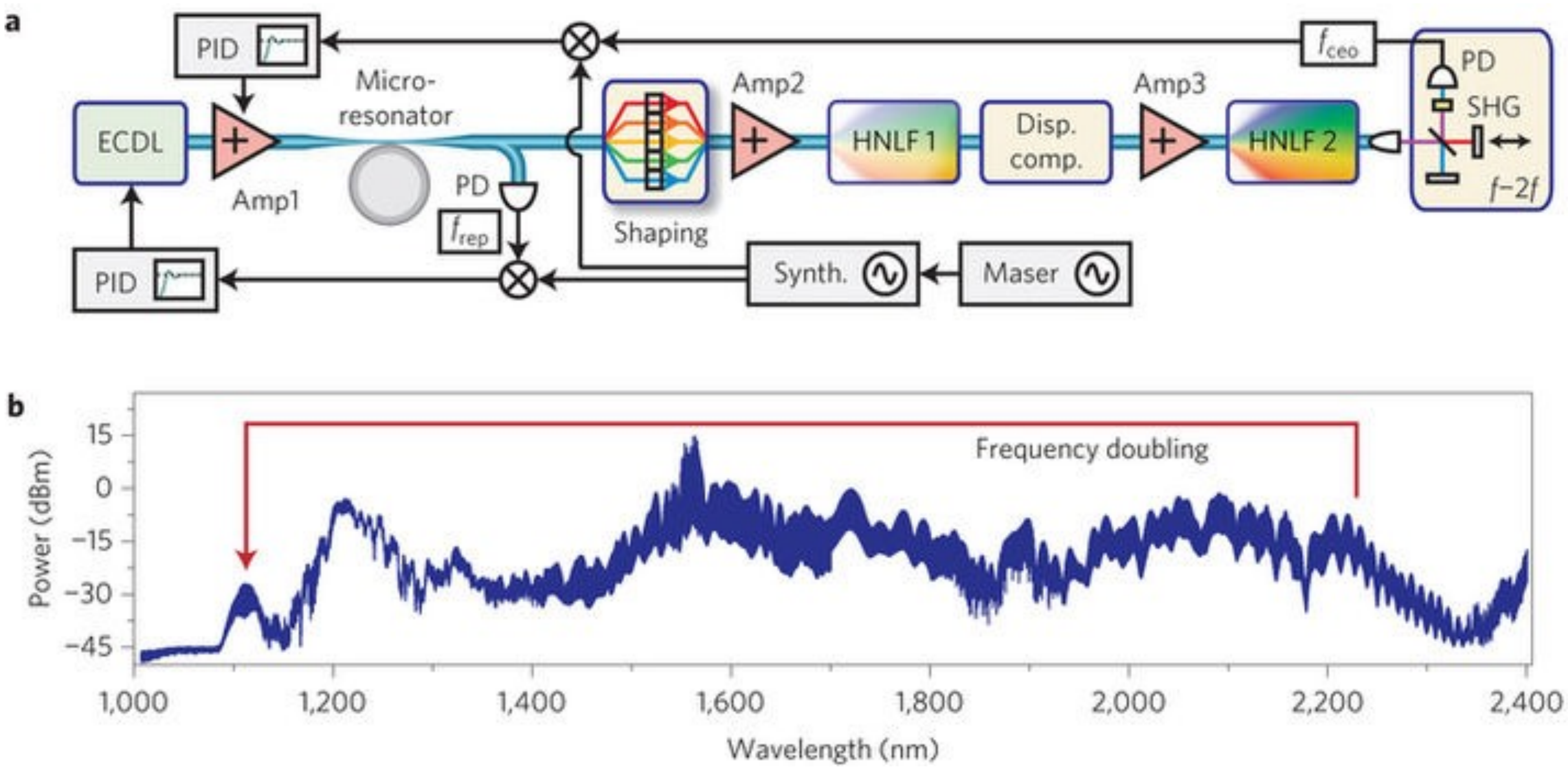


Diagram: S Diddams, J Bergquist, S Jefferts, C Oates, Science **306**(5700), 1318 (2004)

Commercialized fs-combs

Micro-resonator combs



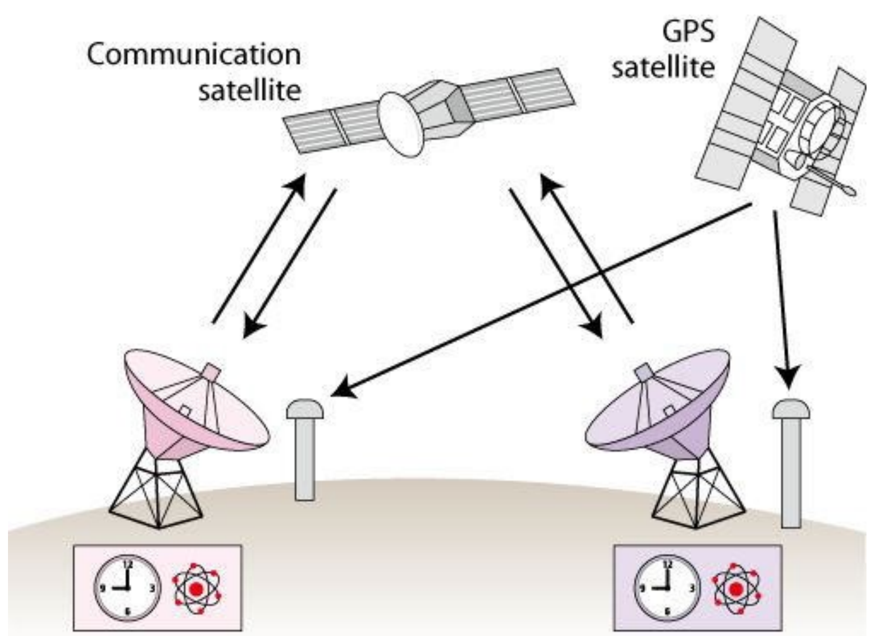


Top: V Brasch, M Geiselmann, T Herr, et. al, *Science* **351**(6271), 357 (2016)
Bottom: P Del'Haye, A Coillet, T Fortier, et al., *Nature Photonics* **10**, 516 (2016)

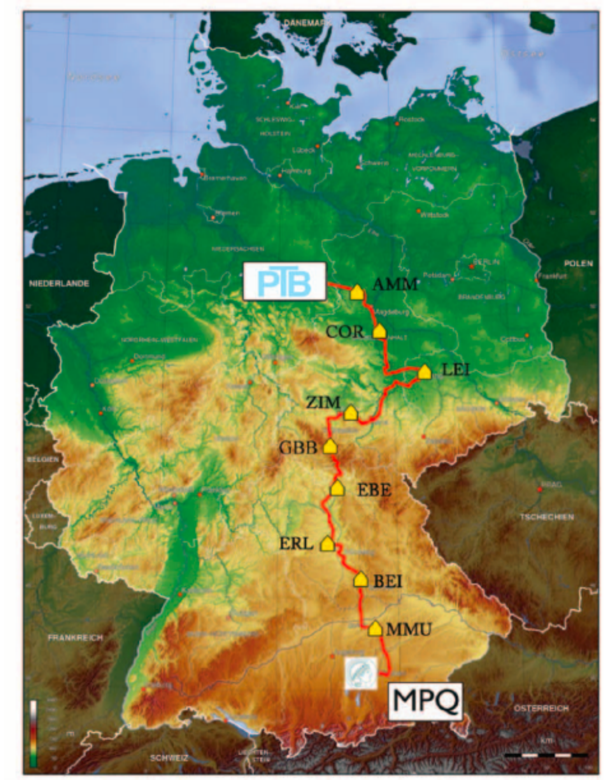
Transfer

Deliver phase/frequency over an unknown & unstable delay.

Microwave



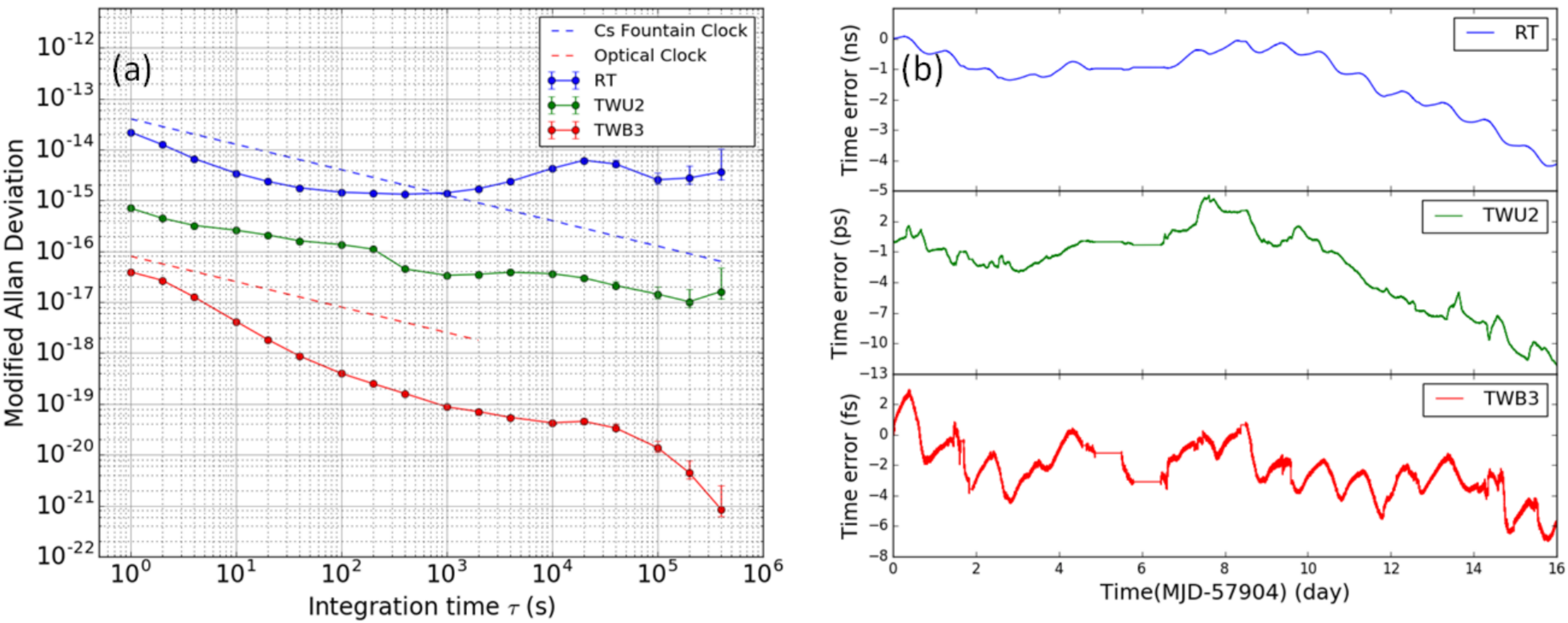
Optical



Common theme: without knowledge-of-path, transfer must be **two-way** and **symmetric**!

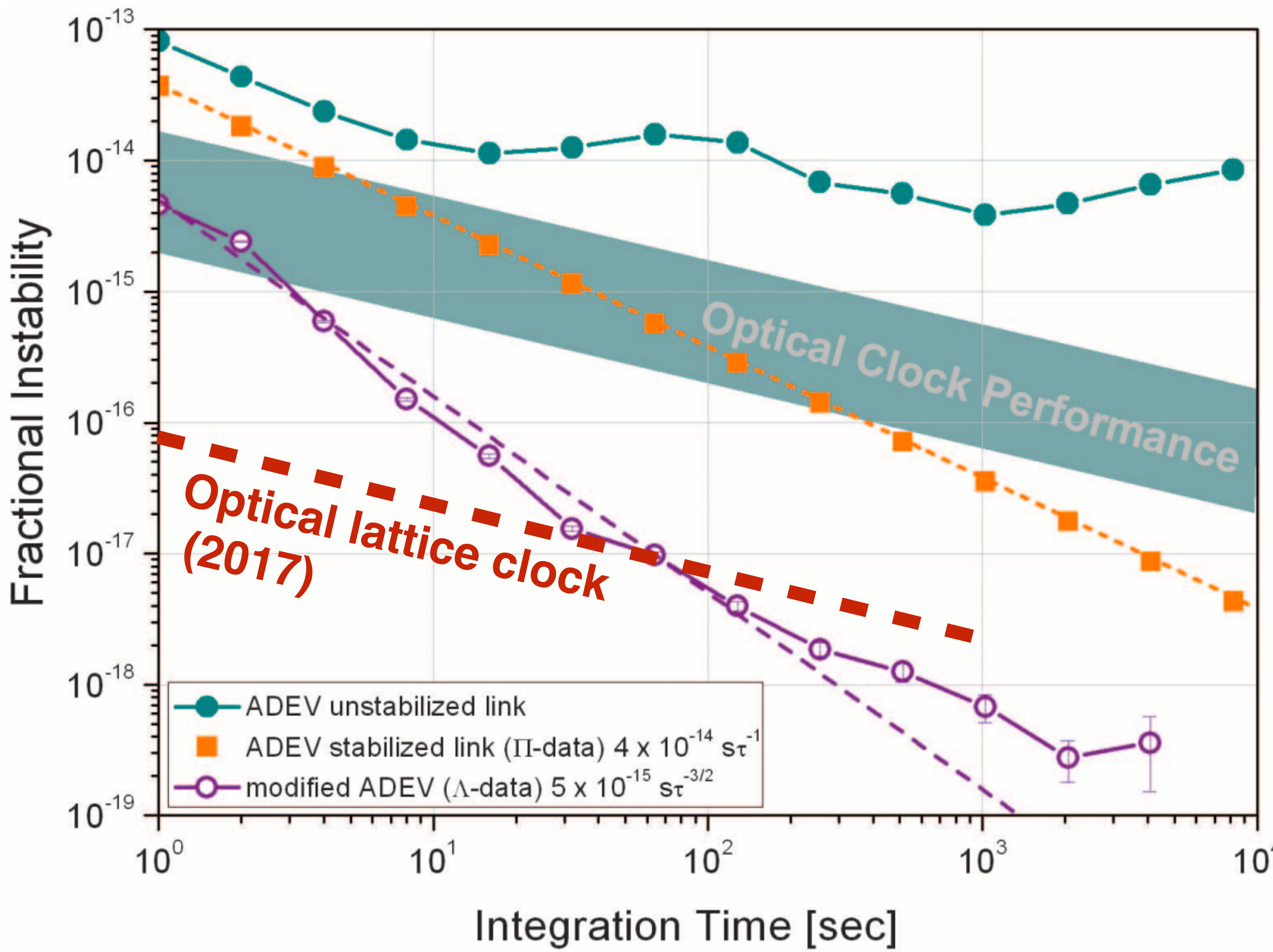
Note for optical signals: effectively building an **optical interferometer**

e.g. 43 km, urban fiber between Paris laboratories: SYRTE and LPL



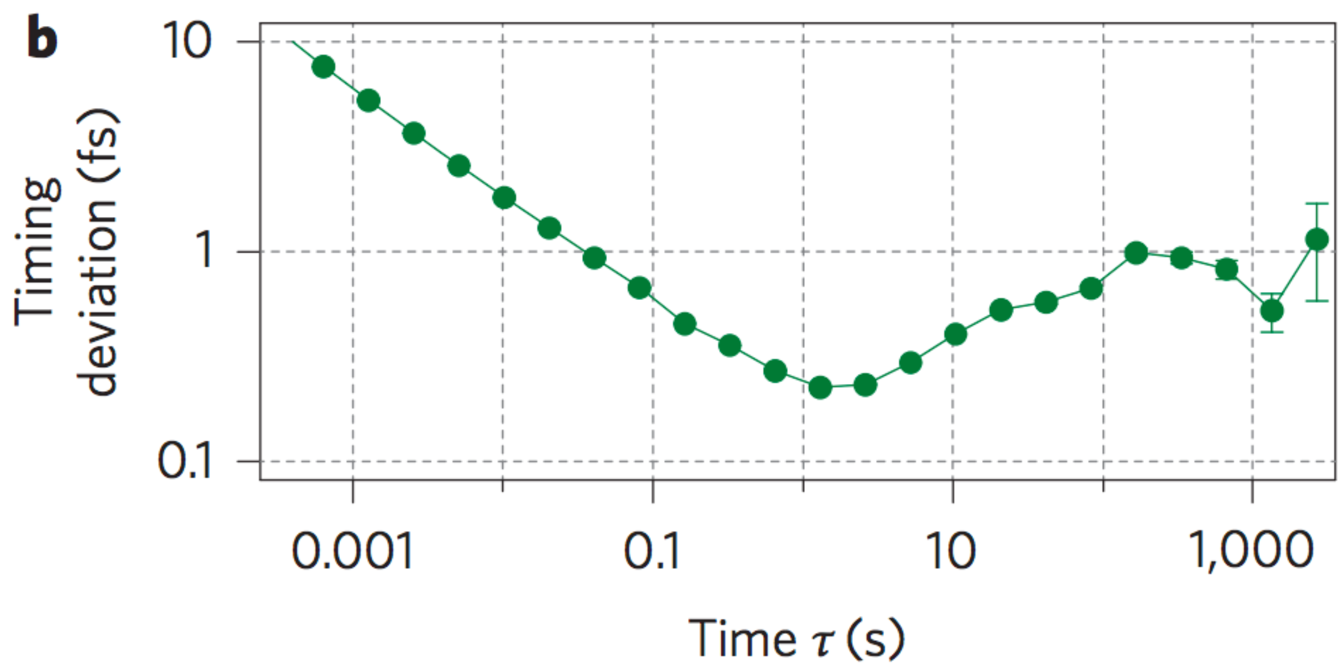
[1] D Xu, W Lee, F Stefani, *Optics Express* **26**(8), 9515 (2018)

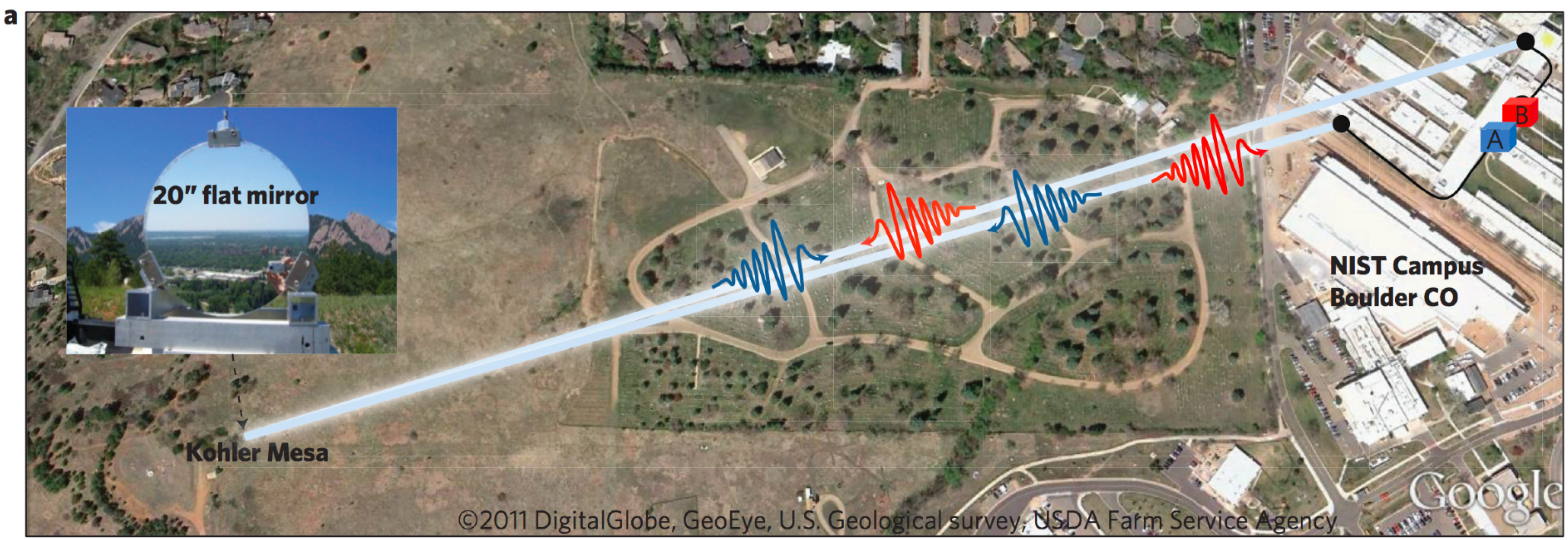
e.g. optical carrier phase transfer through several amplifiers ~ 920 km



K Predehl, G Grosche, SMF Raupach, et al., Science **336**, 441 (2012)

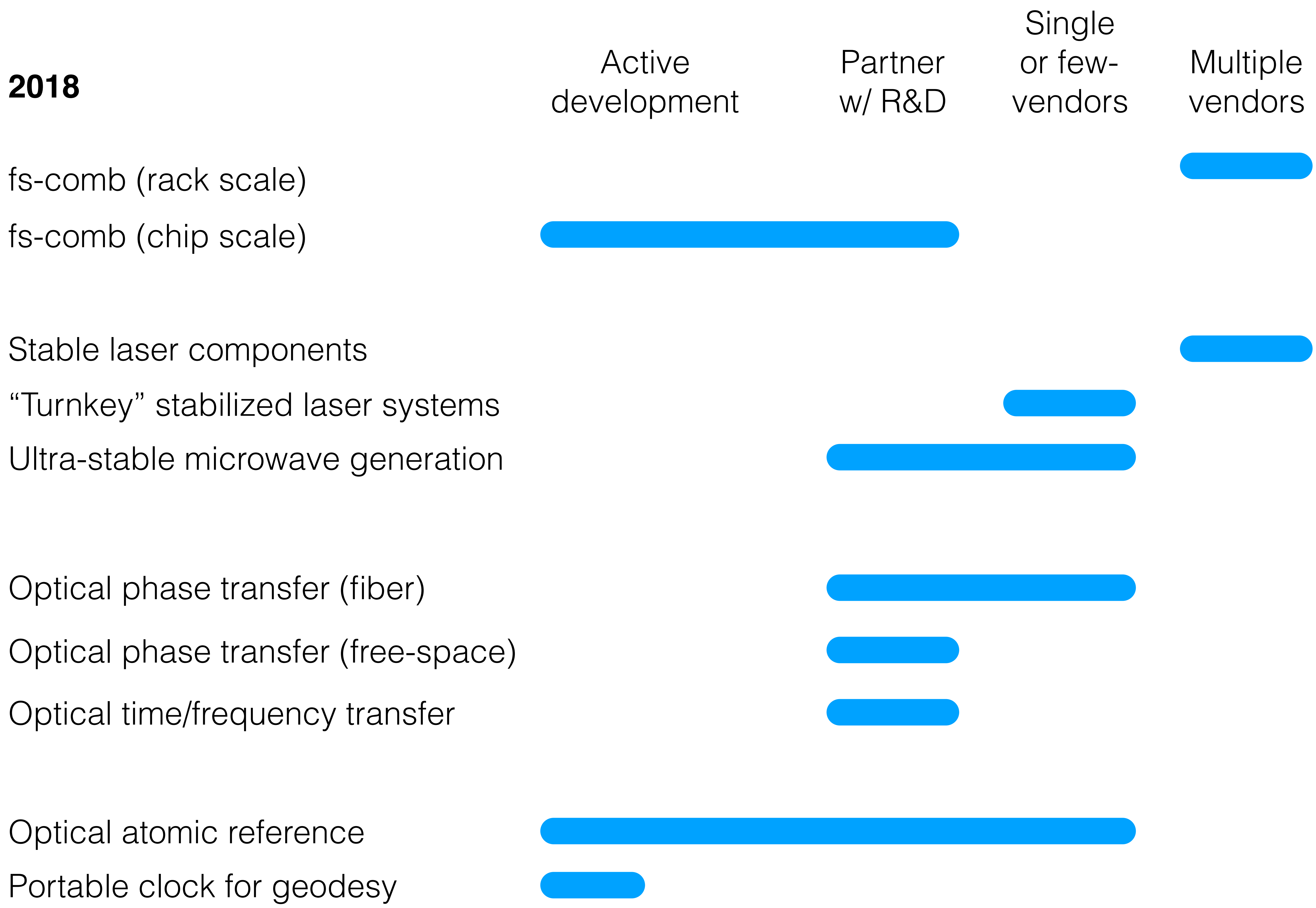
e.g. few km free-space transfer w/ fs-comb pulses



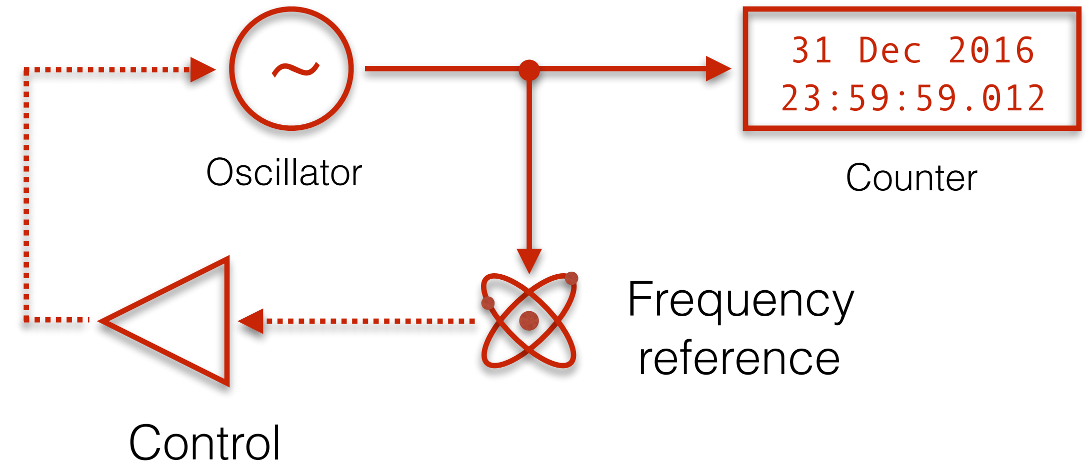


FR Giogetta, WC Swann, LC Sinclair, et al., Nat. Photonics **7**, 434–438 (2013)

Rough estimates of technological readiness


2018
Active development
Partner w/ R&D
Single or few-vendors
Multiple vendors
fs-comb (rack scale)
fs-comb (chip scale)
Stable laser components
“Turnkey” stabilized laser systems
Ultra-stable microwave generation
Optical phase transfer (fiber)
Optical phase transfer (free-space)
Optical time/frequency transfer
Optical atomic reference
Portable clock for geodesy

Review/takeaways



Part I: Principle of modern timekeeping:

Why optical frequencies?

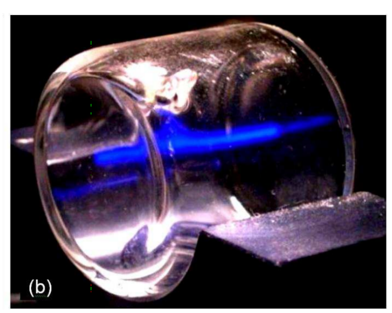
Divide time into finer intervals
Optical references inherently more stable

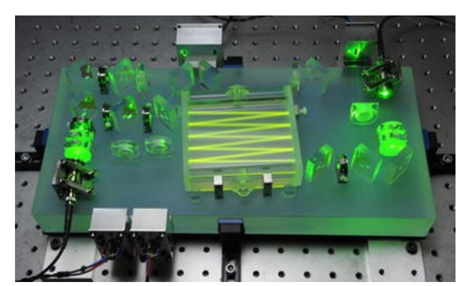
Part II:

Technological overview w/ analogies to microwave components:

- Oscillators
- Frequency references
- "Counters"
- Frequency/time-transfer

Lots of examples:





Estimates of technological readiness

stable lasers, fs-comb technology, phase transfer commercially available

compact versions, optical atomic references, microwave-generation, "turnkey" optical time-keeping/transfer solutions under active development