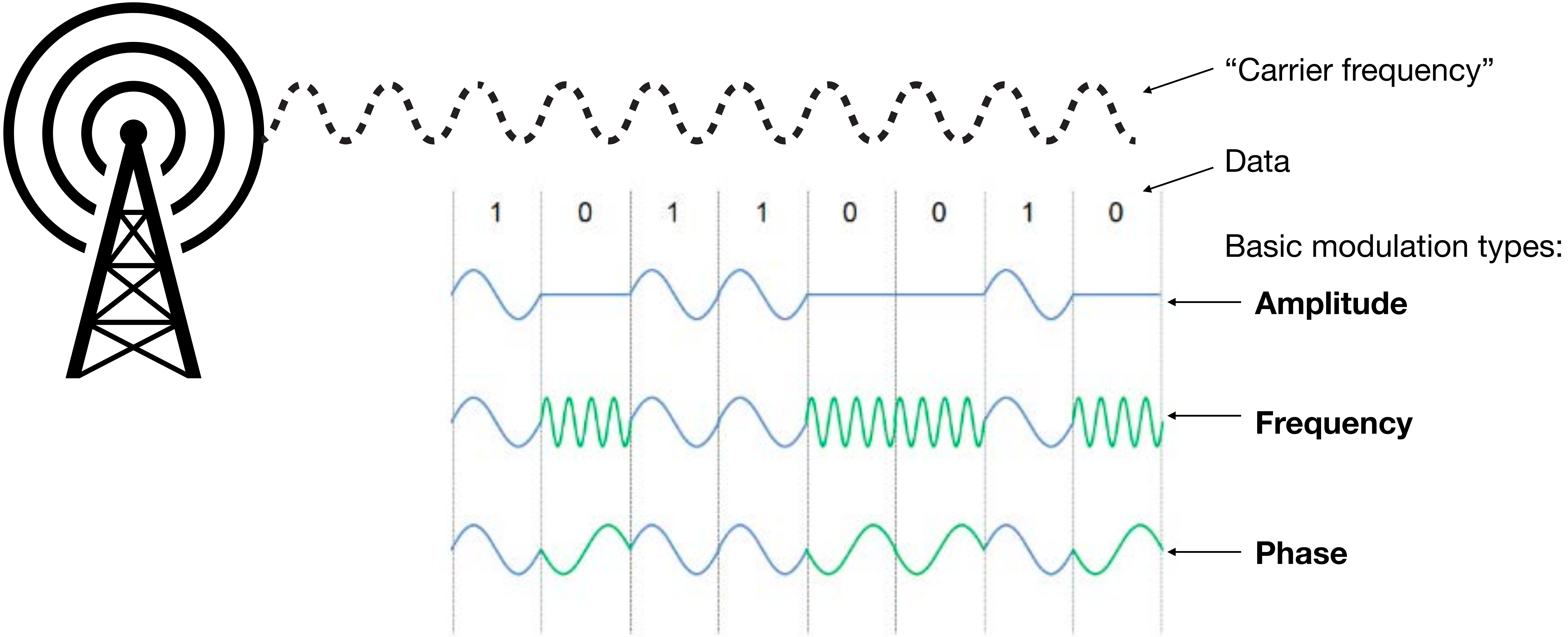
“Beyond 5G” and precision timekeeping are allies

Prepared for: NICT Beyond 5G open discussion (11 March 2022 JST)

Dr. Jeff A. Sherman (jeff.sherman@nist.gov)
NIST // Time and Frequency Division
Boulder, CO, USA

(image attribution: unknown, https://i.imgur.com/v4xbEz7.jpg)

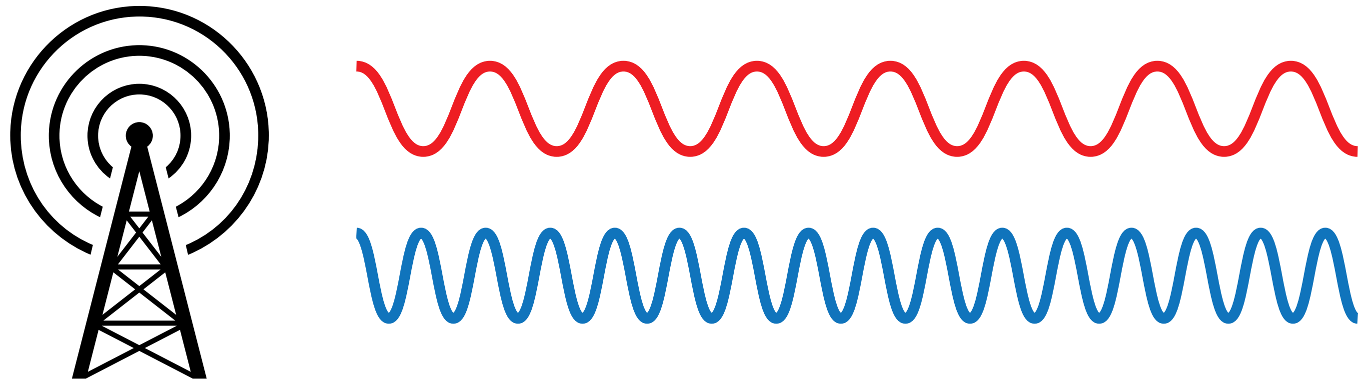
All radio communication requires transmission and modulation of pure tones



Adapted from Huawei, “WDM Basics” (https://info.support.huawei.com/ta/wdmwiki/index.html#/en/basic)

Beyond 5G will likely mean:

1. Higher carrier frequencies, more bandwidth



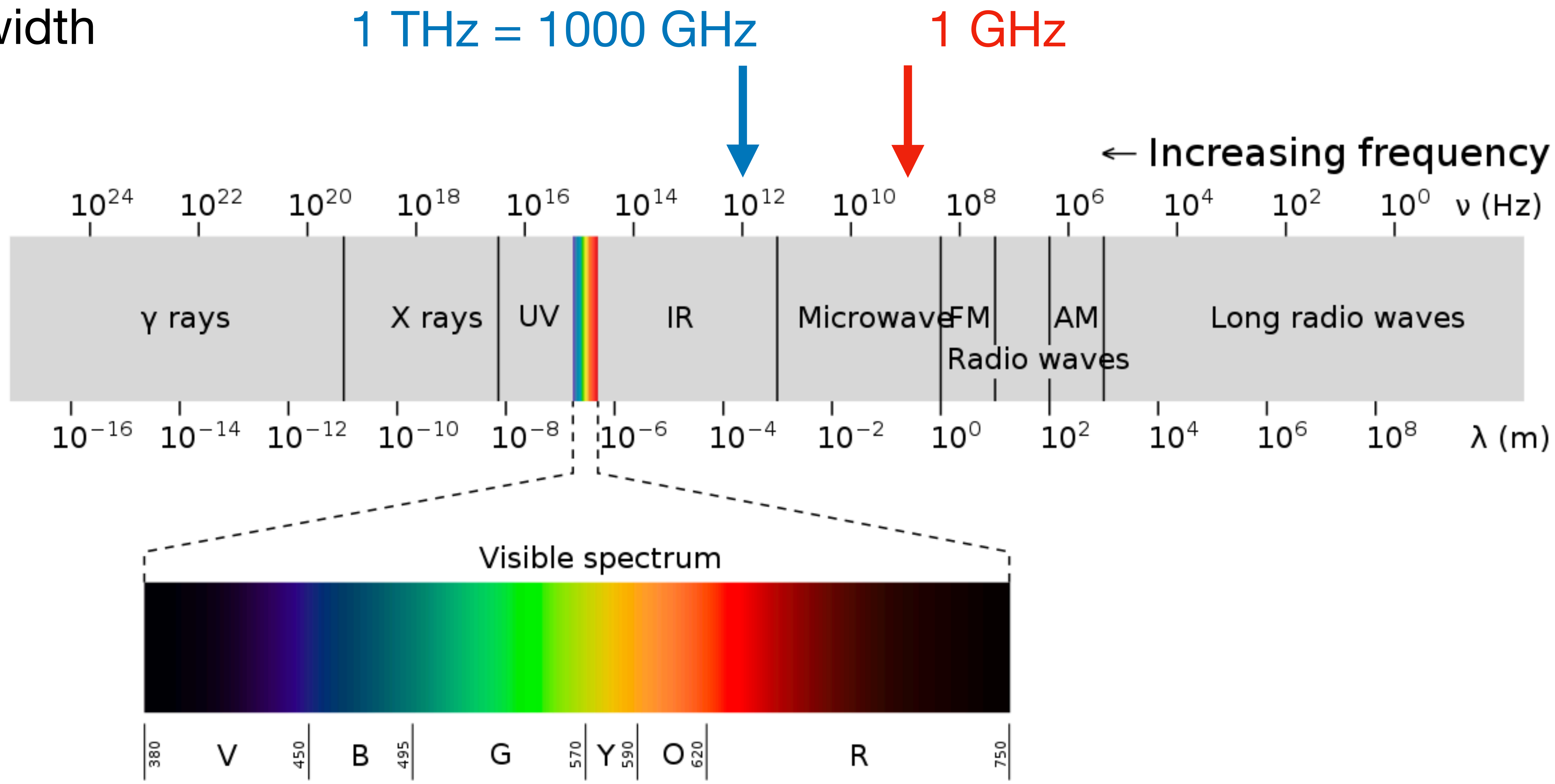


Figure: Wikimedia Commons, EM spectrum (https://commons.wikimedia.org/wiki/File:EM_spectrum.svg)

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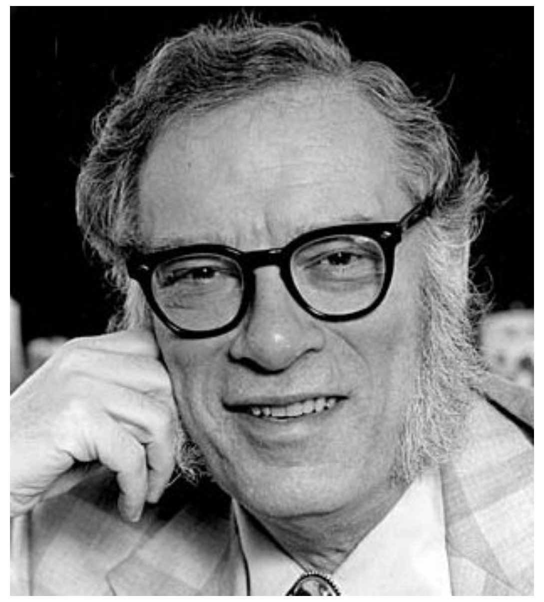
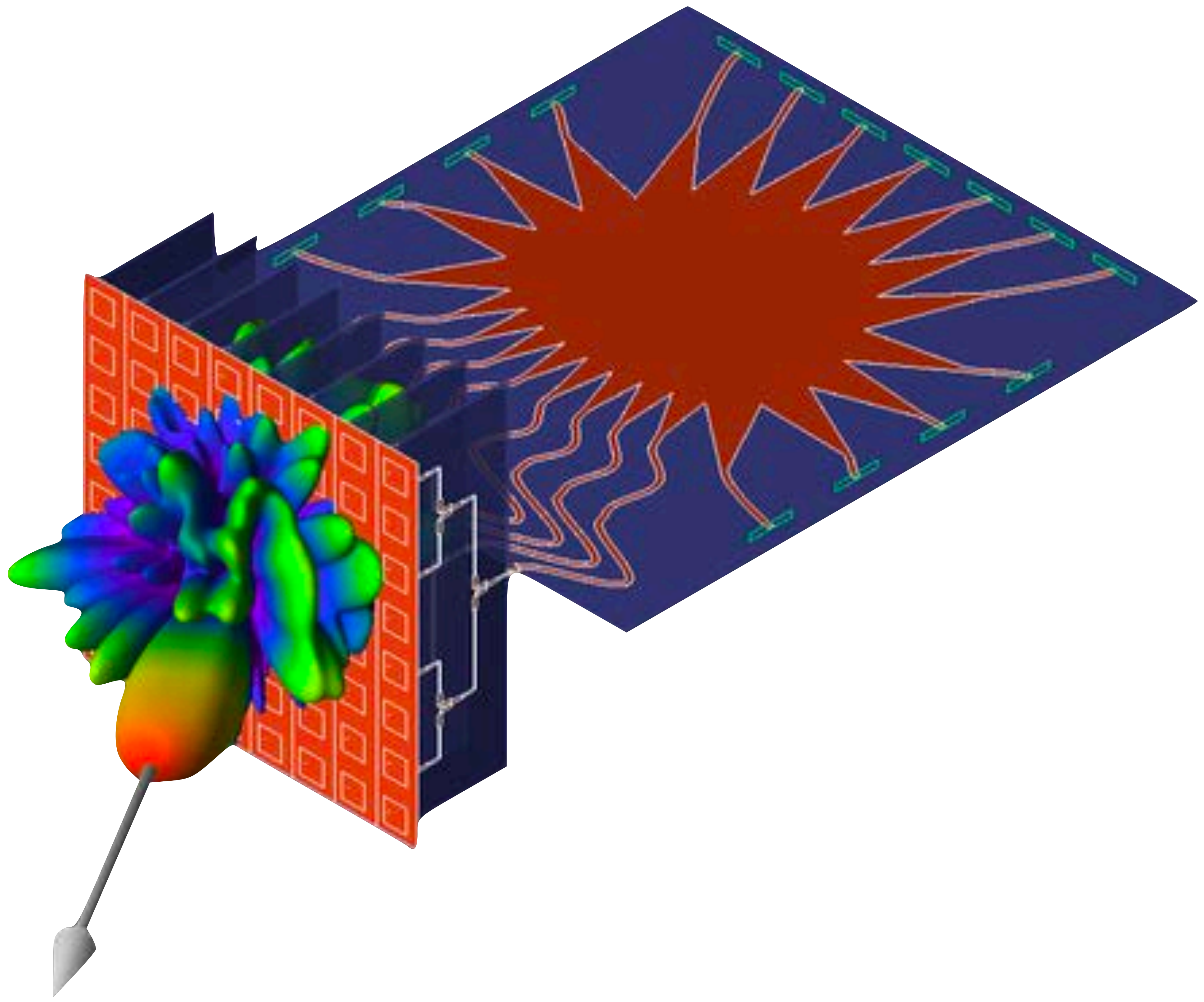


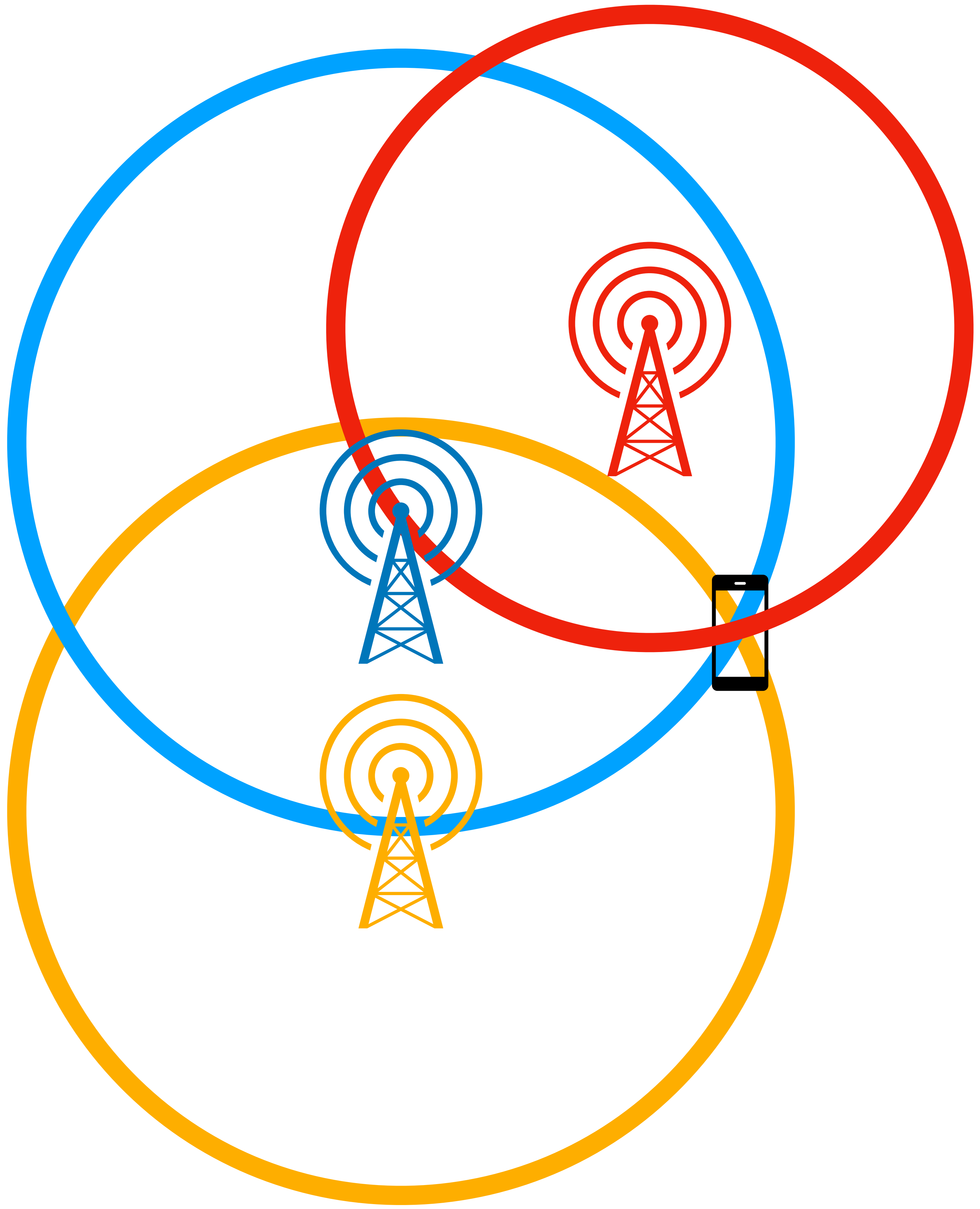
"… there are more high frequencies than low frequencies …"

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

Beyond 5G will likely mean:

2. Coherent techniques to make better use of spectrum (e.g. beamforming, massive MIMO)





Left: REMCOM “Design and simulation of 28 GHz beamforming system and antenna array for 5G network base stations”
https://www.remcom.com/examples/2019/3/19/design-and-simulation-of-28-ghz-beamforming-system-and-antenna-array-for-5g-network-base-stations

Problem: few stable, practical oscillators 100 GHz - 1 THz

Idea 1: multiply 1 GHz (microwave) sources by $n \approx 100$

Idea 2: divide 100 THz (optical or infrared) sources by $n \approx 100$

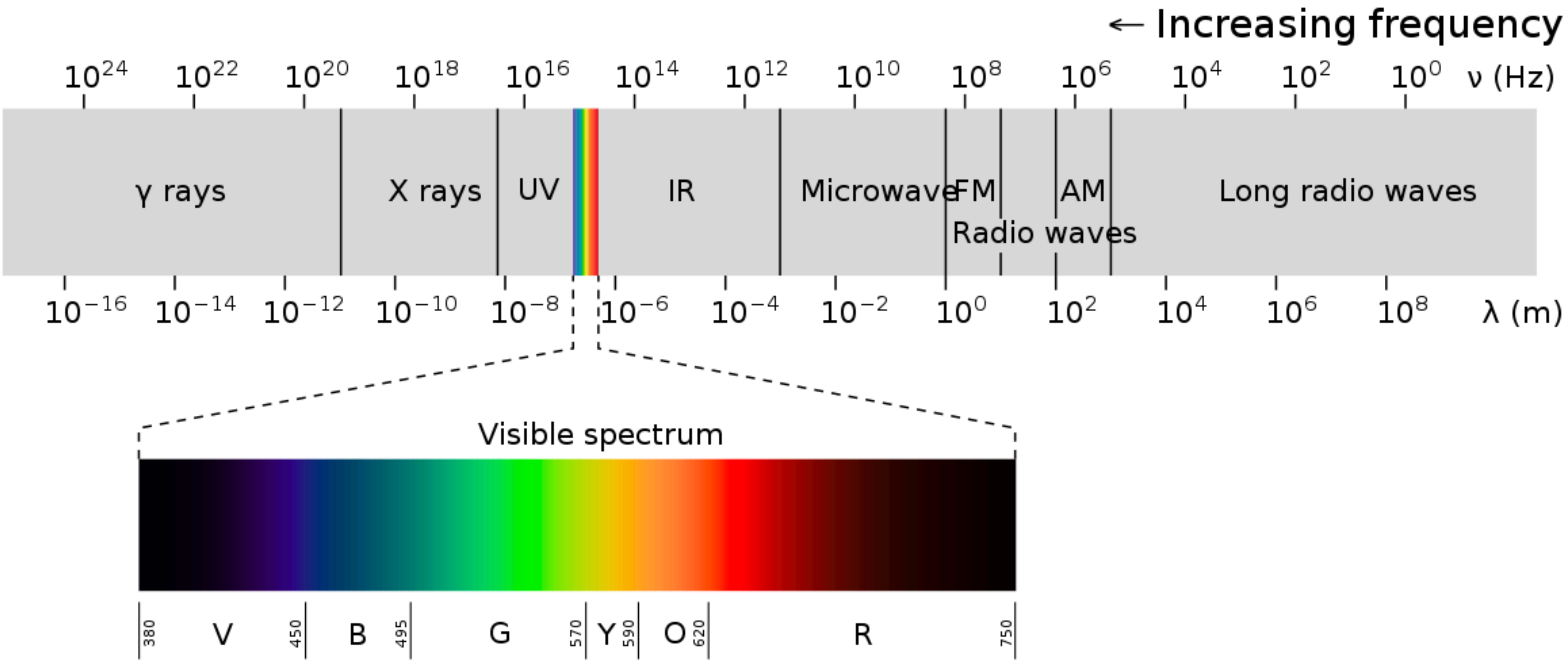


Figure: Wikimedia Commons, EM spectrum (https://commons.wikimedia.org/wiki/File:EM_spectrum.svg)

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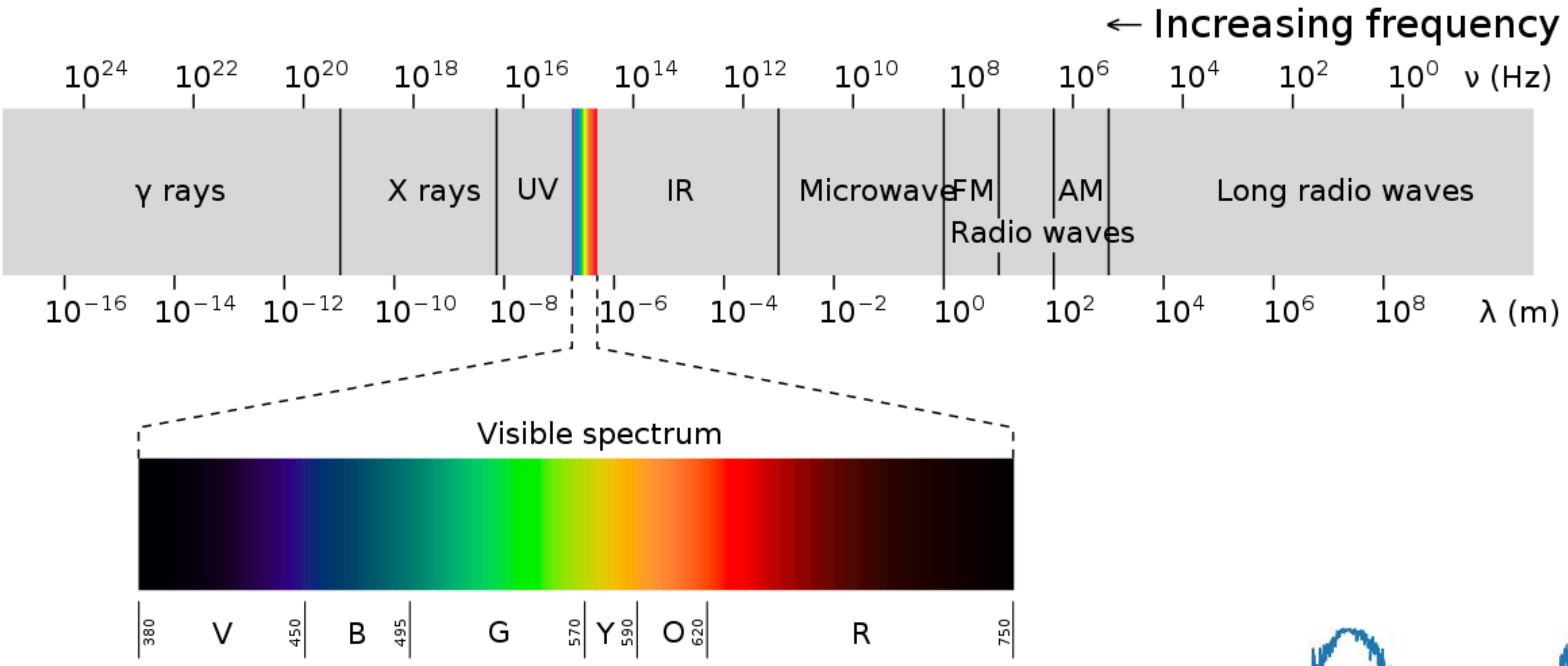
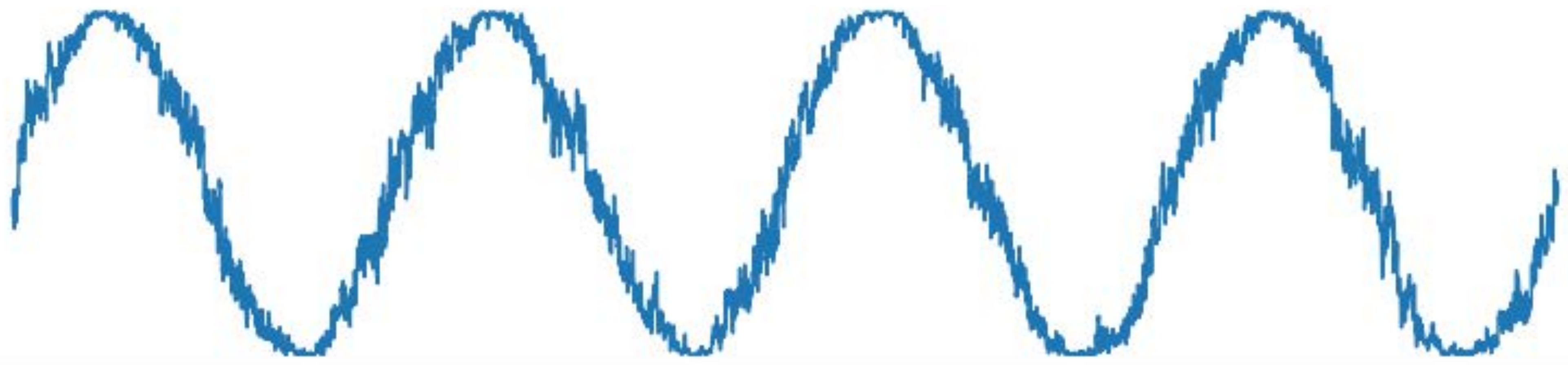




Frequency **division** improves *phase noise* power spectral density by $n^2 \approx 10{,}000$!

Figure: Wikimedia Commons, EM spectrum (https://commons.wikimedia.org/wiki/File:EM_spectrum.svg)

Beyond 5G may benefit from coherent division of stable infrared/optical oscillators

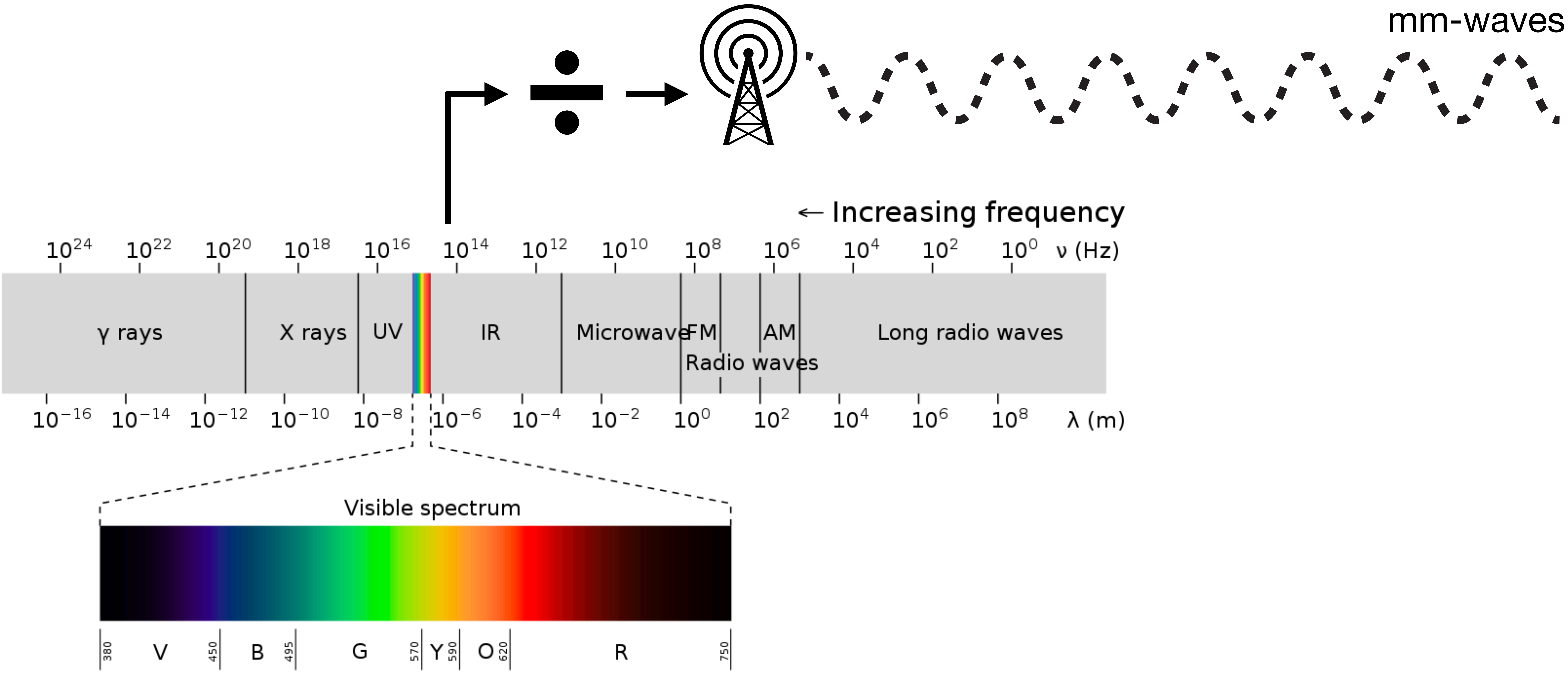
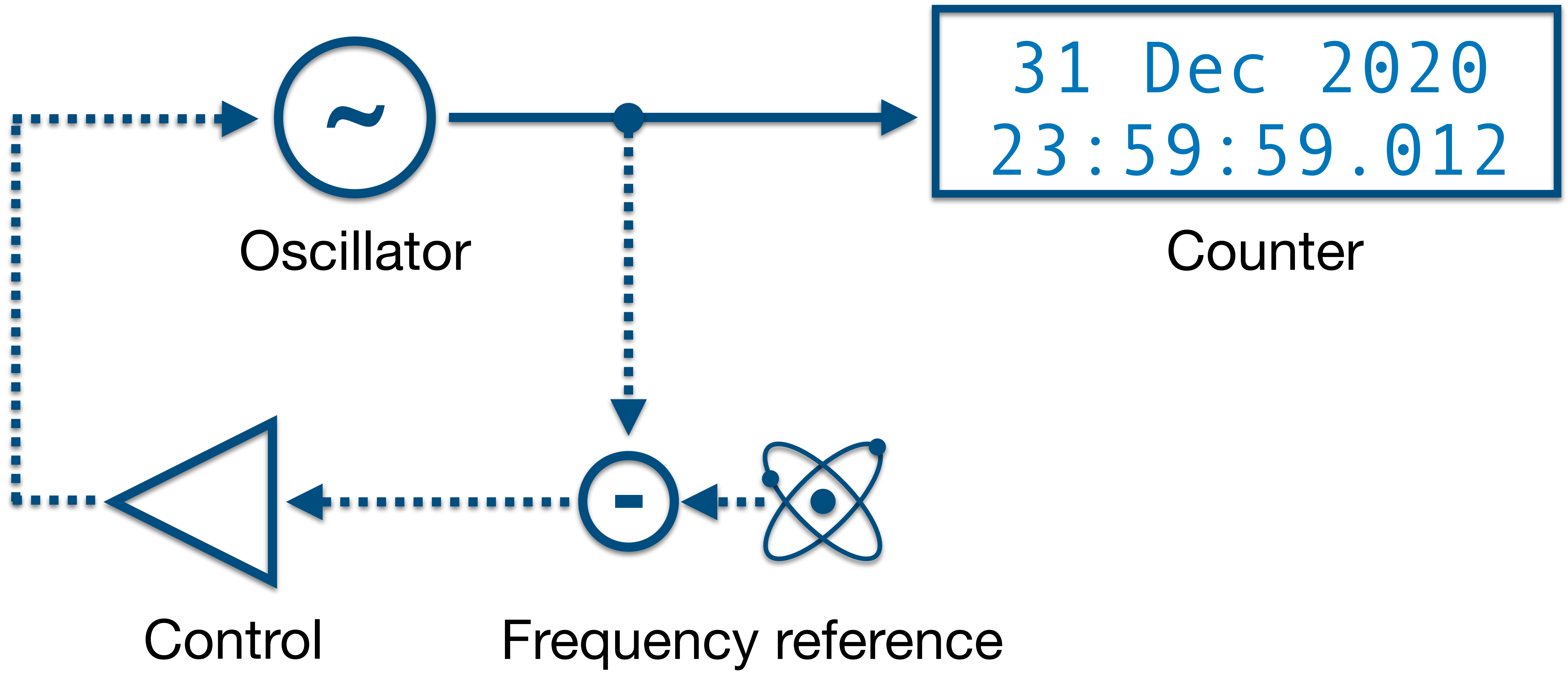
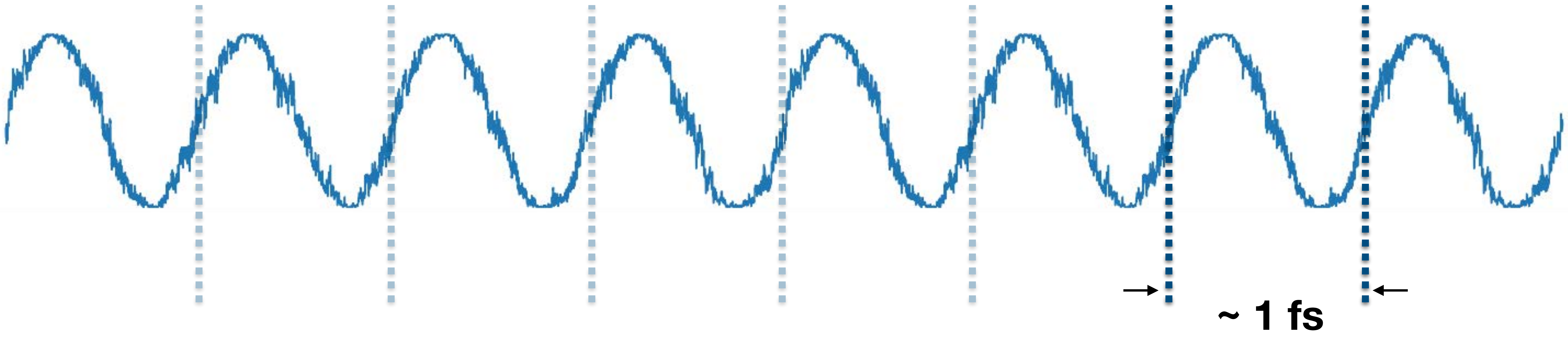


Figure: Wikimedia Commons, EM spectrum (https://commons.wikimedia.org/wiki/File:EM_spectrum.svg)

***Stable oscillator*? That's a clock!**



Timekeeping also benefits from higher frequencies, reduced effects of phase noise.



Optical clocks forecast last century

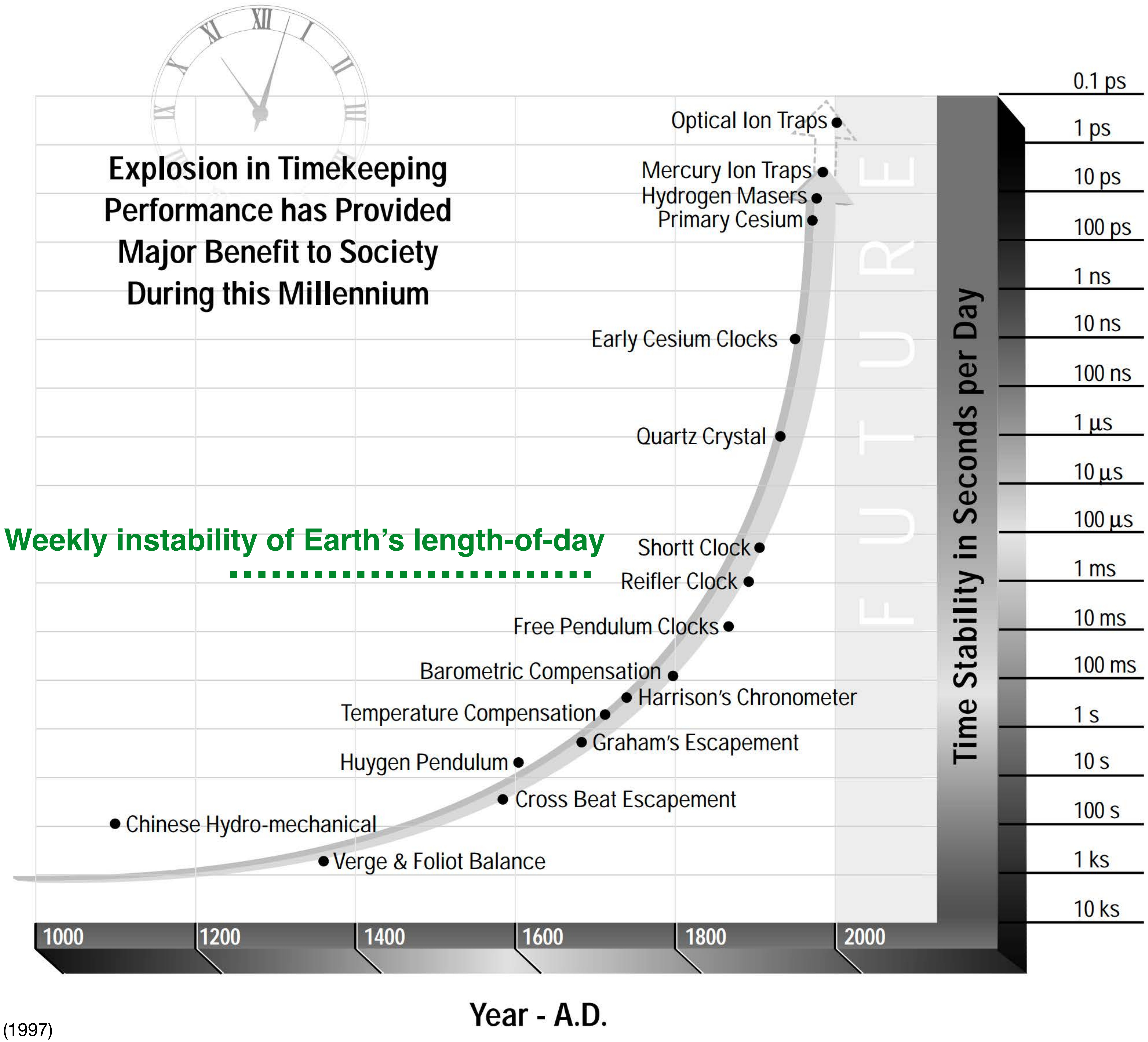


Figure: DW Allan, N Ashby, C Hodge, HP application note 1289: *Science of Timekeeping* (1997)

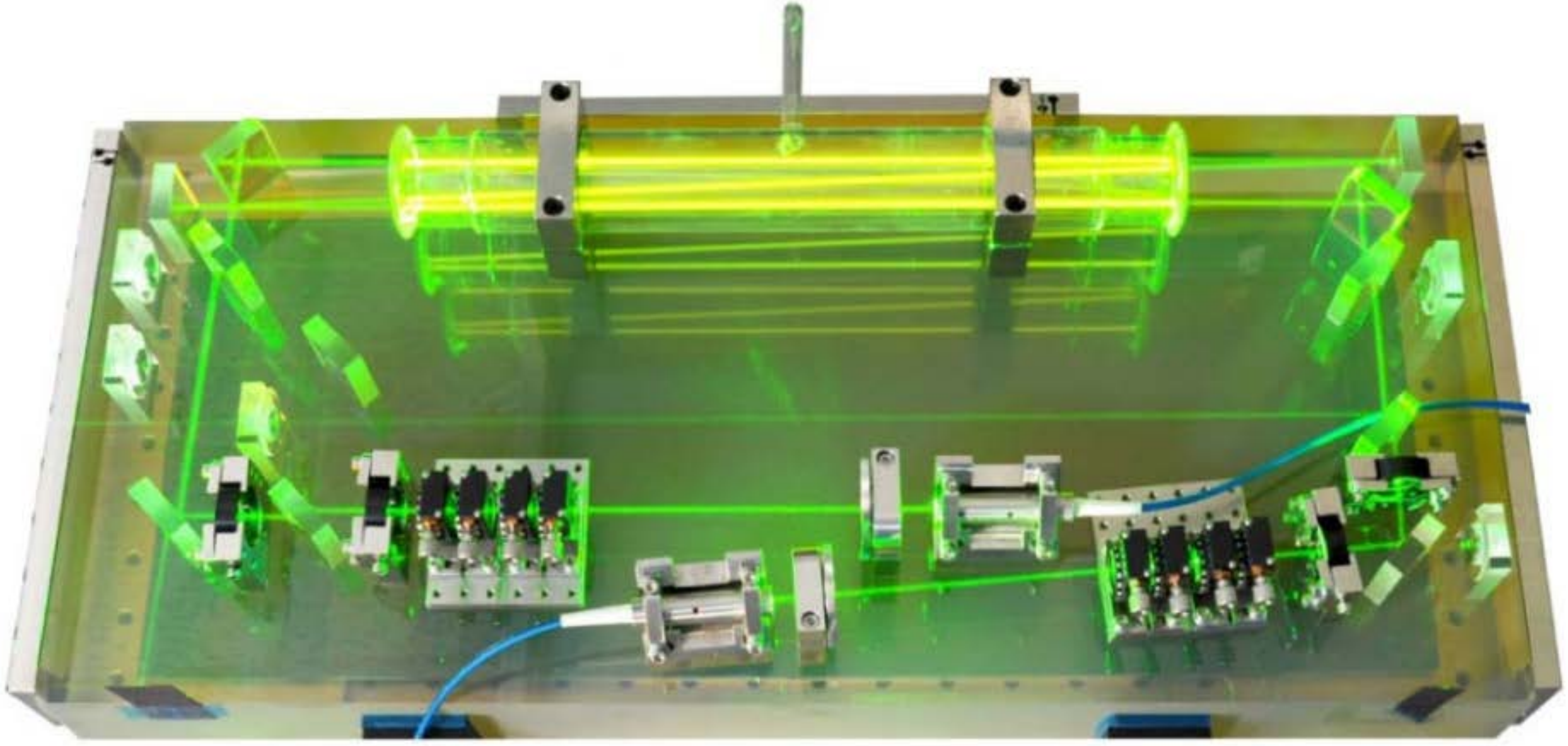
Rough comparison of oscillator technologies

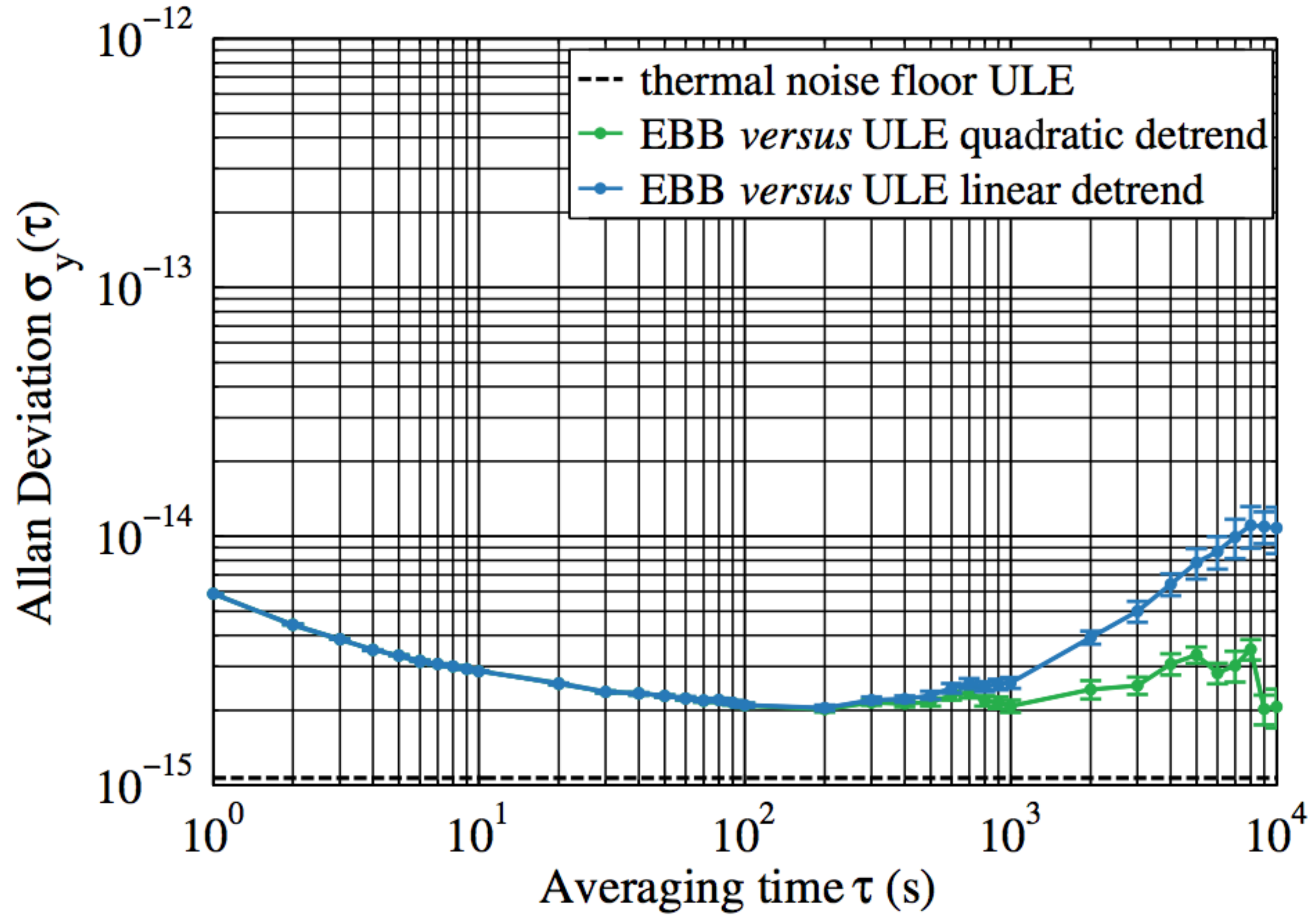
	Microwave	Optical
Frequency range:	10 kHz — 10 GHz	100 THz — 500 THz
Materials:	Quartz, ceramic resonators, MEMS	Si, fused silica (low-expansion), sapphire
Mode:	Active; electro-mechanical	Passive; laser stabilized to length
Stability @ 1 s average	10^{-11}	10^{-16}
Cost (best available)	~ $1k USD	~ $1M USD
Complications	Likely fully developed	Early in development; cryogenics, vibration sensitivity, large physical size, cost, “unique” components, etc.

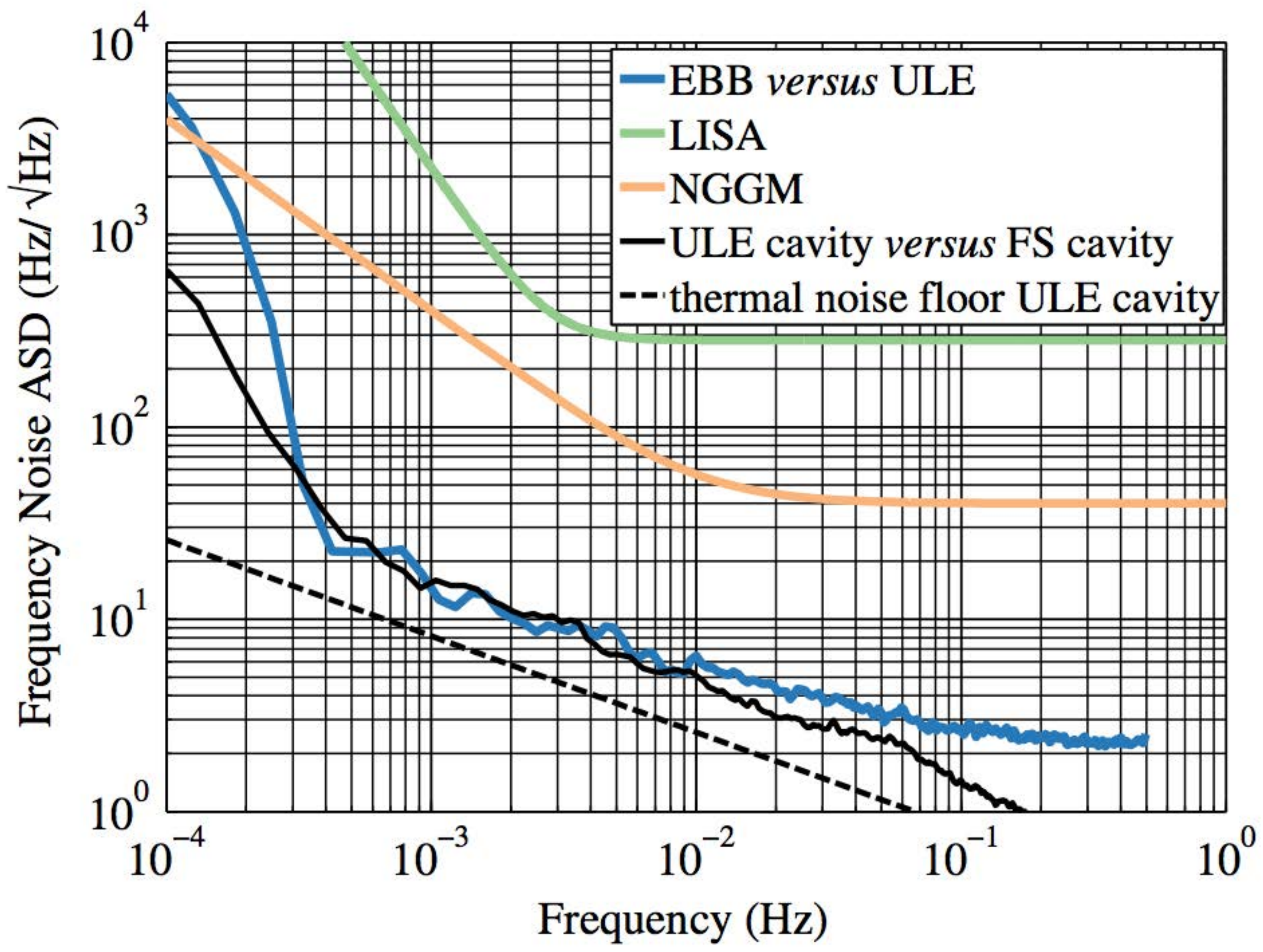
Left: http://lowpowerradio.blogspot.com/2017/02/Instant-AM-radio-station-hacking-1-mhz-crystal-oscillator.html

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

Other optical oscillator schemes directly use atoms/molecules

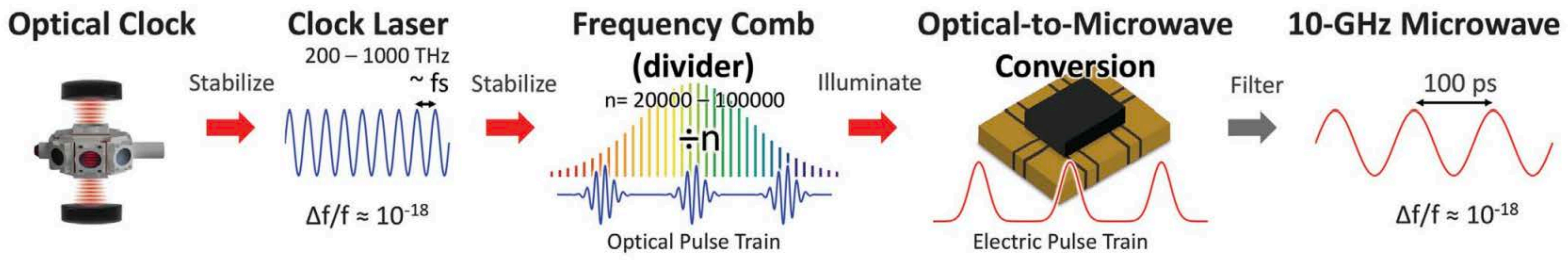


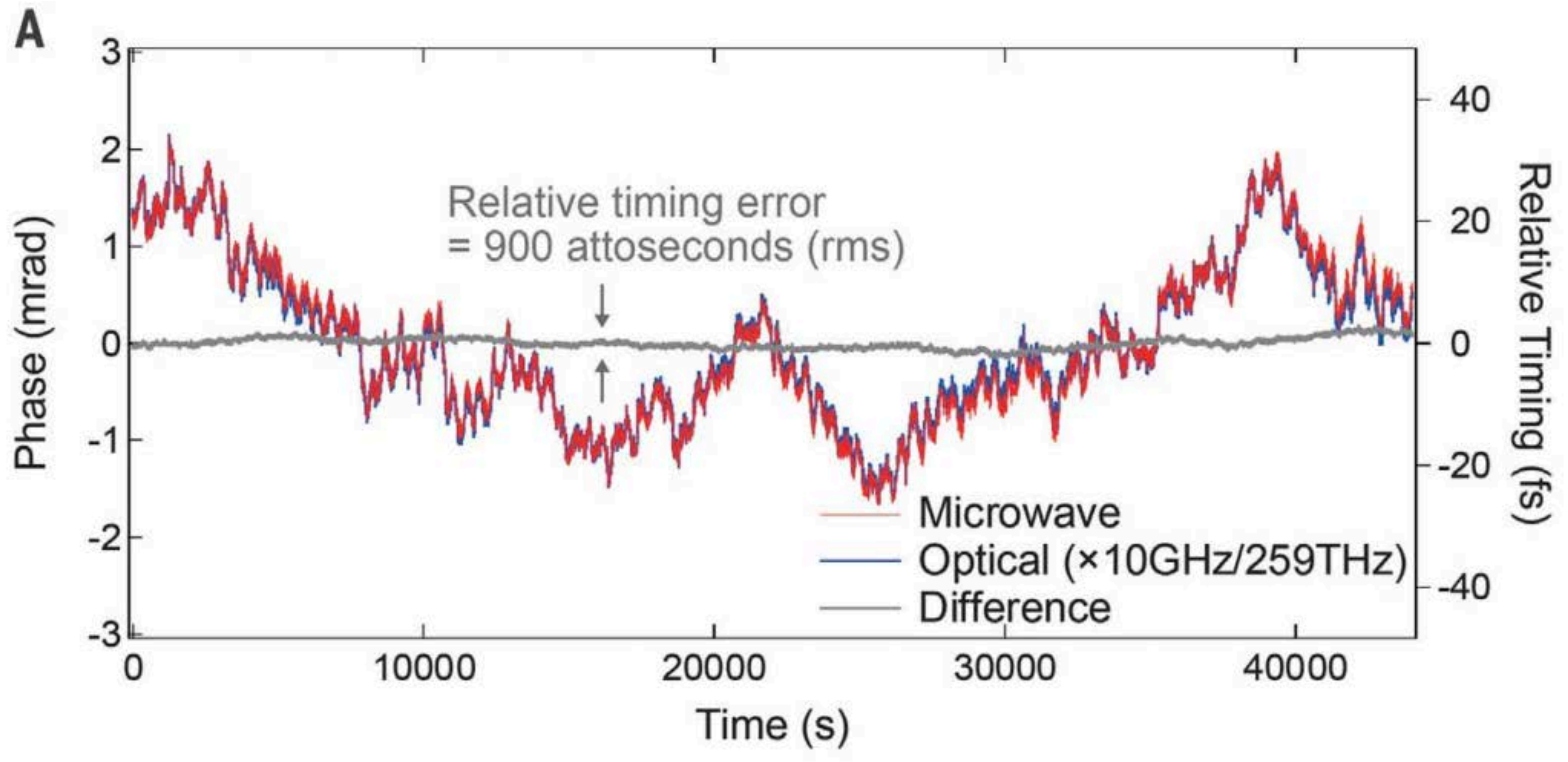


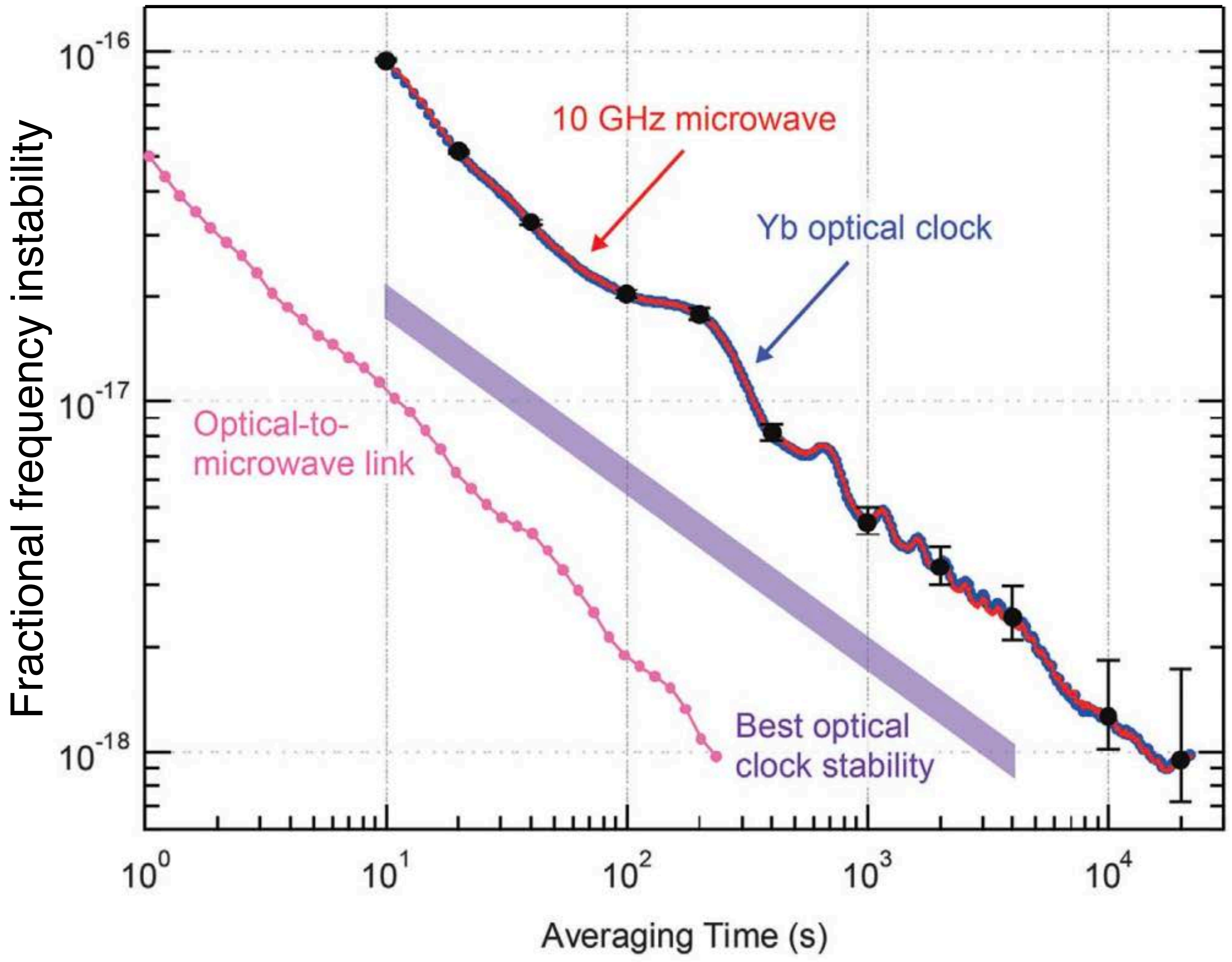


Th Schuldt, K Döringshoff, E Kovalchuk, et al., Appl. Optics 56(4), 1101 (2017)

Accurate, bias-free, optical-to-microwave conversion (errors at 10^{-18})

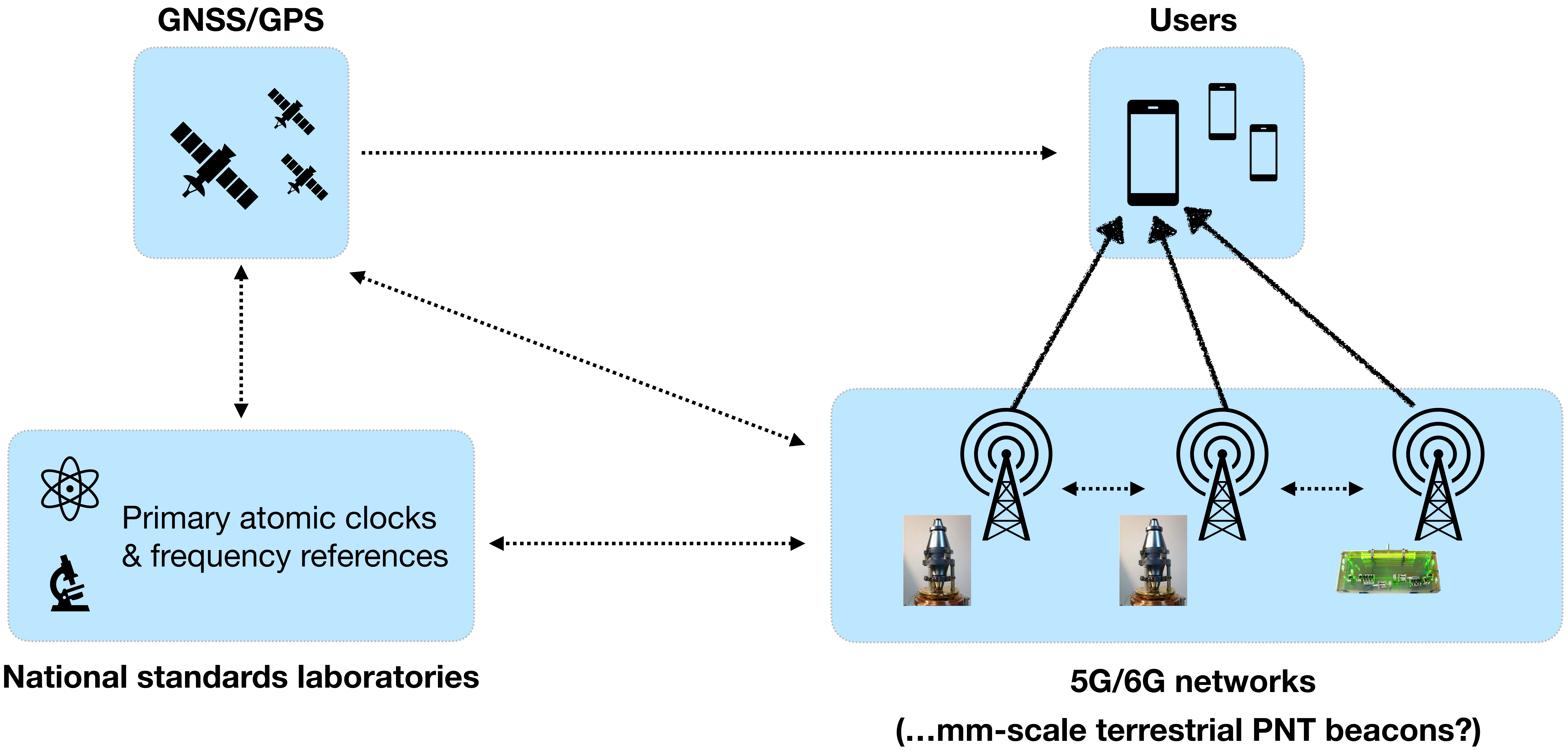






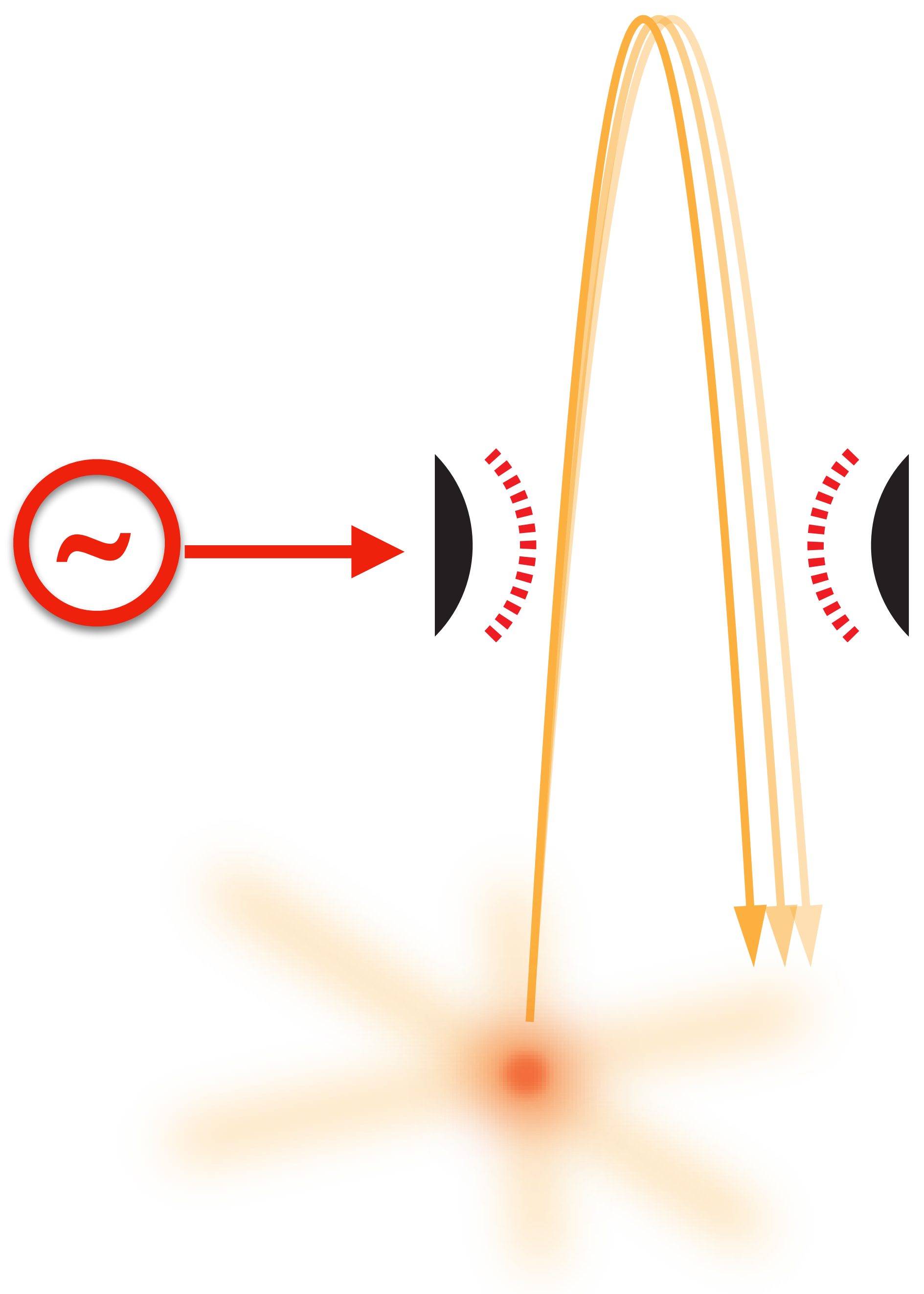
[1]: T Nakamura, JD Rodriguez, H Leopardi, et al., "Coherent optical clock down-conversion for microwave frequencies with 10^{-18} stability", Science **368**, 889-892 (2020).

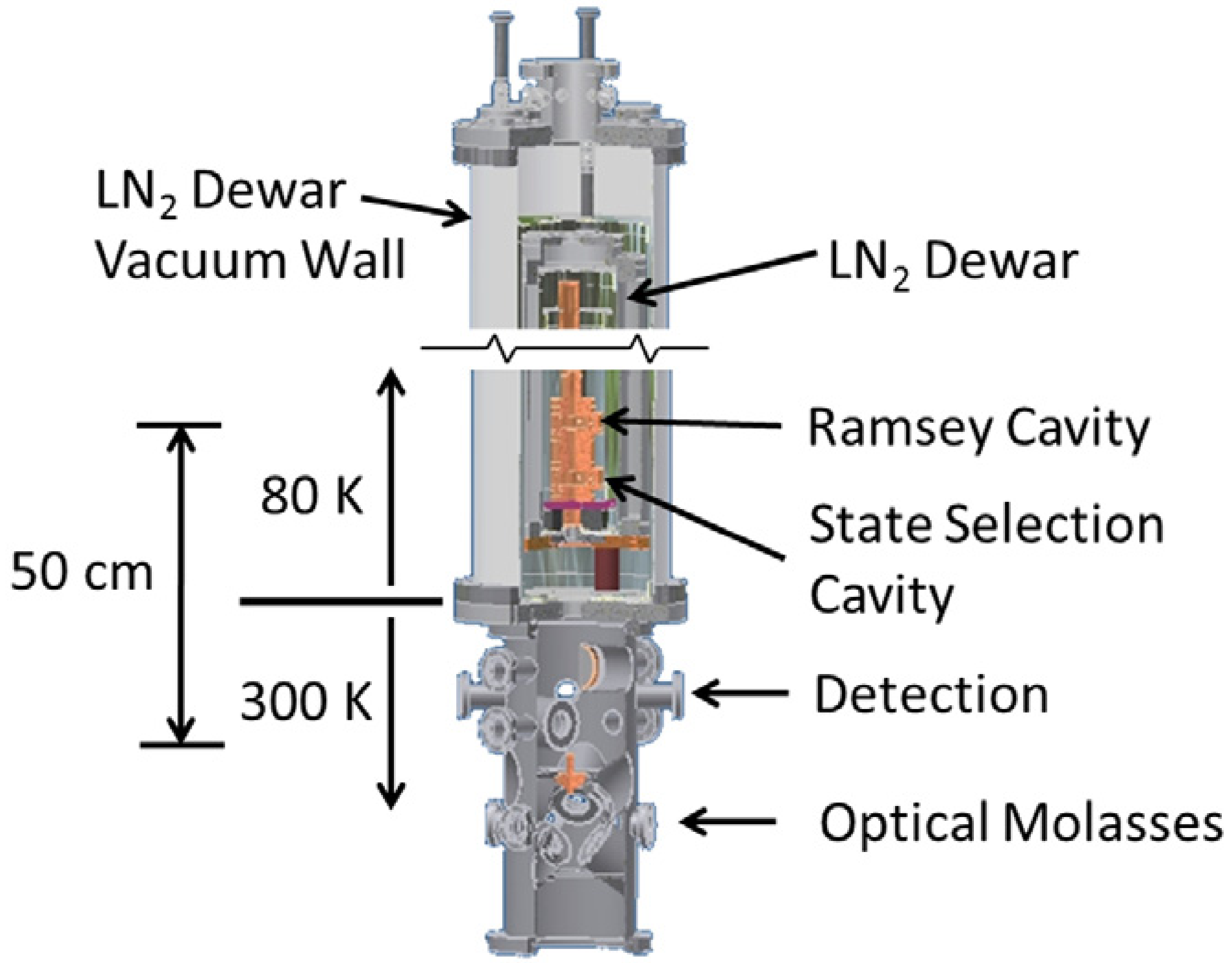
Wide distribution model for stable/accurate frequency

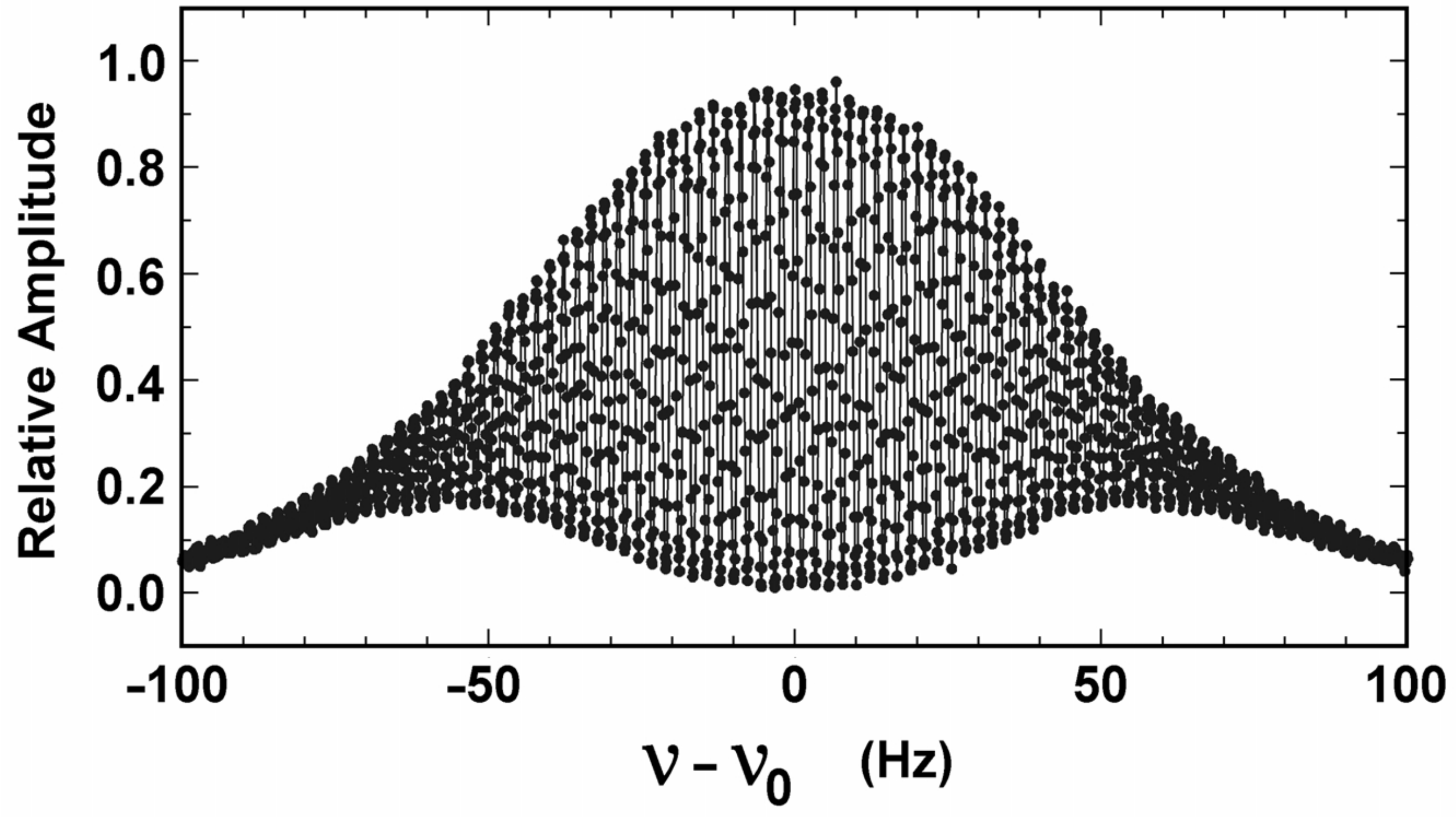


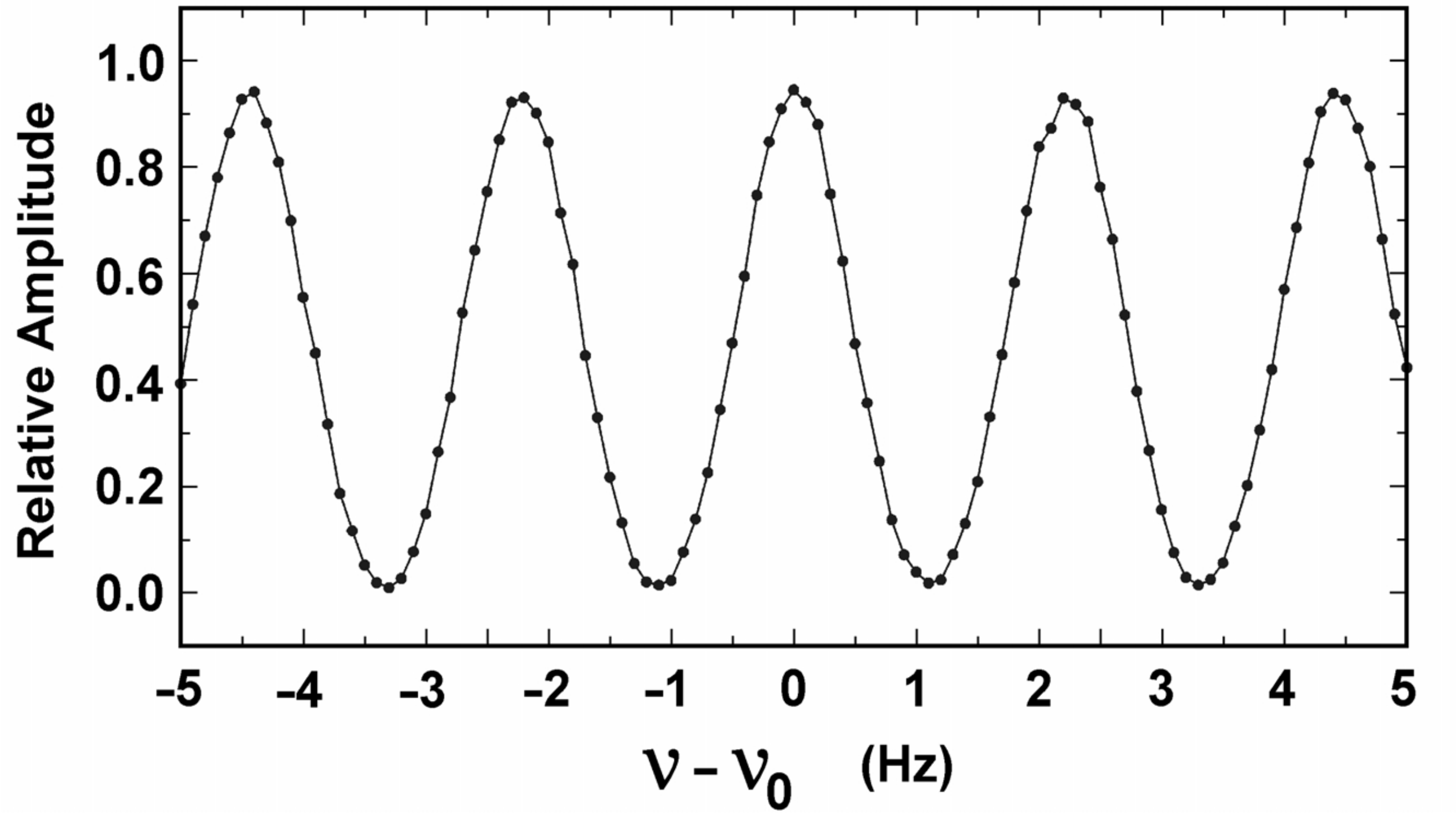
Evolution of the definition of frequency?

"The **second** is … **9 192 631 770 periods** of the radiation corresponding to the transition between two **hyperfine levels of the ground state of the cesium-133 atom**... at rest and at a temperature of 0 K."





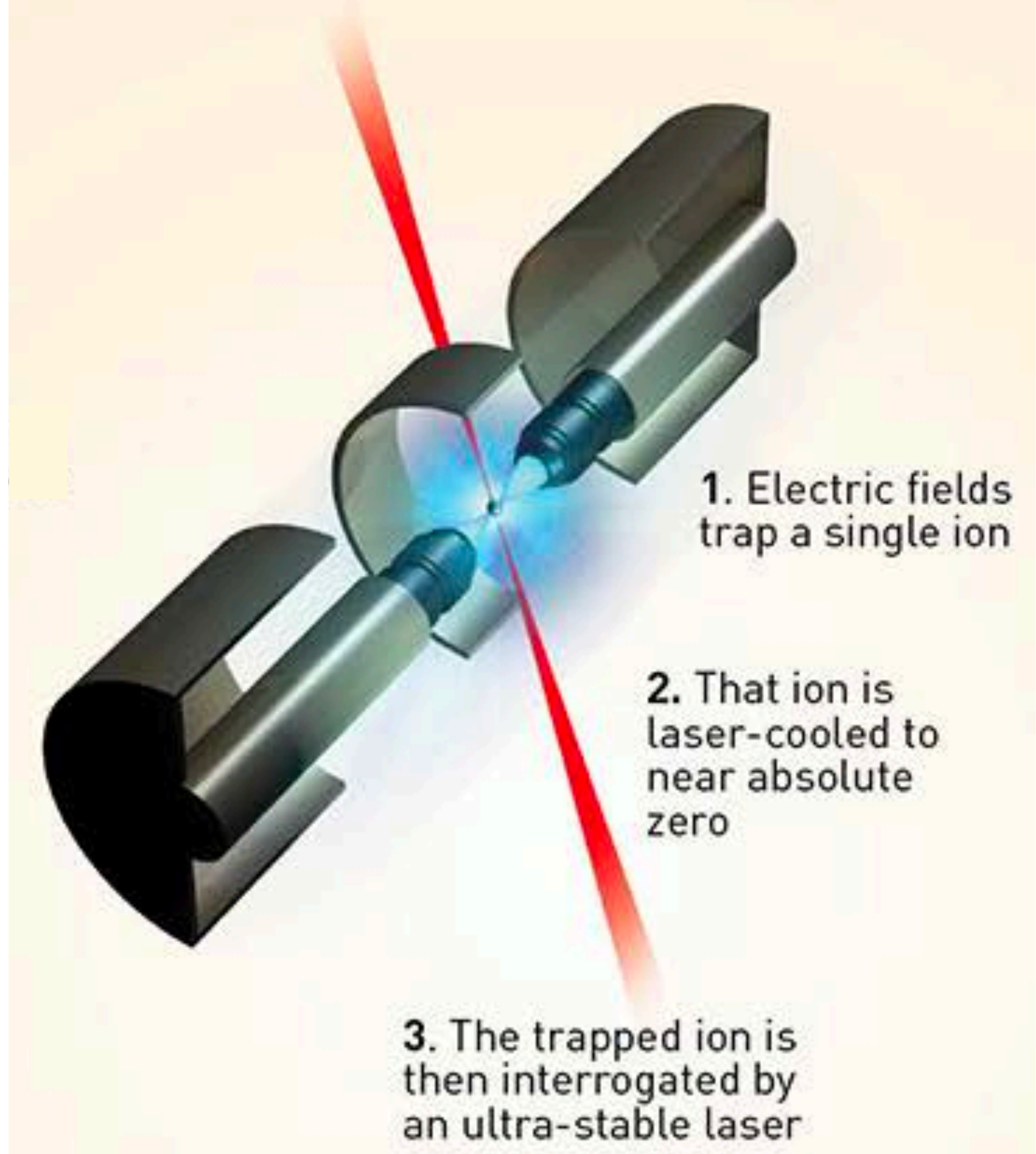




DB Sullivan, JC Bergquist, JJ Bollinger, et al., J. Res. NIST **106**, 47–63 (2011)
TP Heavner, EA Donley, Filippo Levi, et al., *Metrologia* **51**, 174–182 (2014)

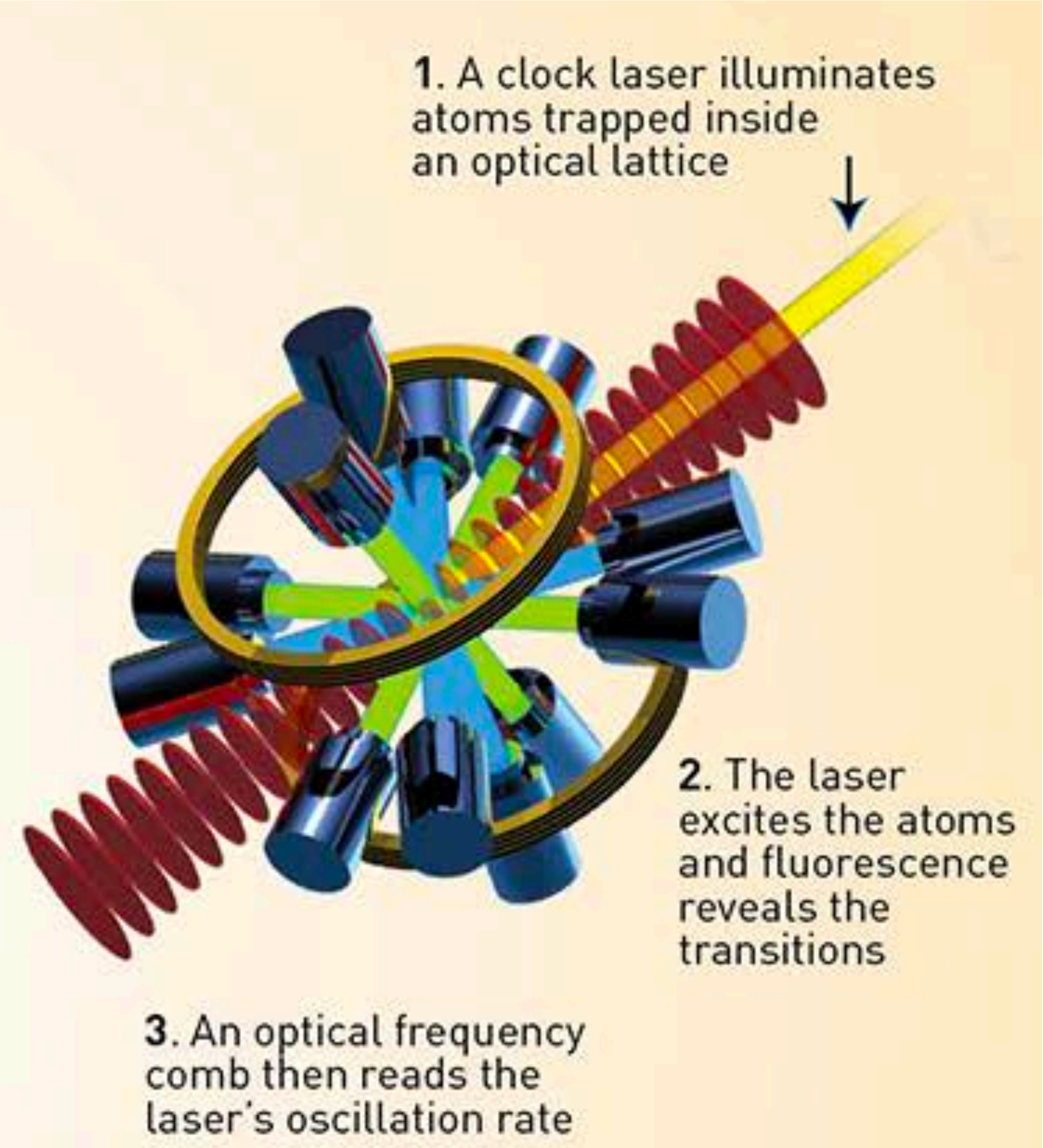
Two leading technologies for absolute optical frequency references (errors at 10^{-18})

Single (rf-) trapped ion



- ✅ possibly lower systematics
- ✅ path to low BBR uncertainty
- ❌ residual motional effects

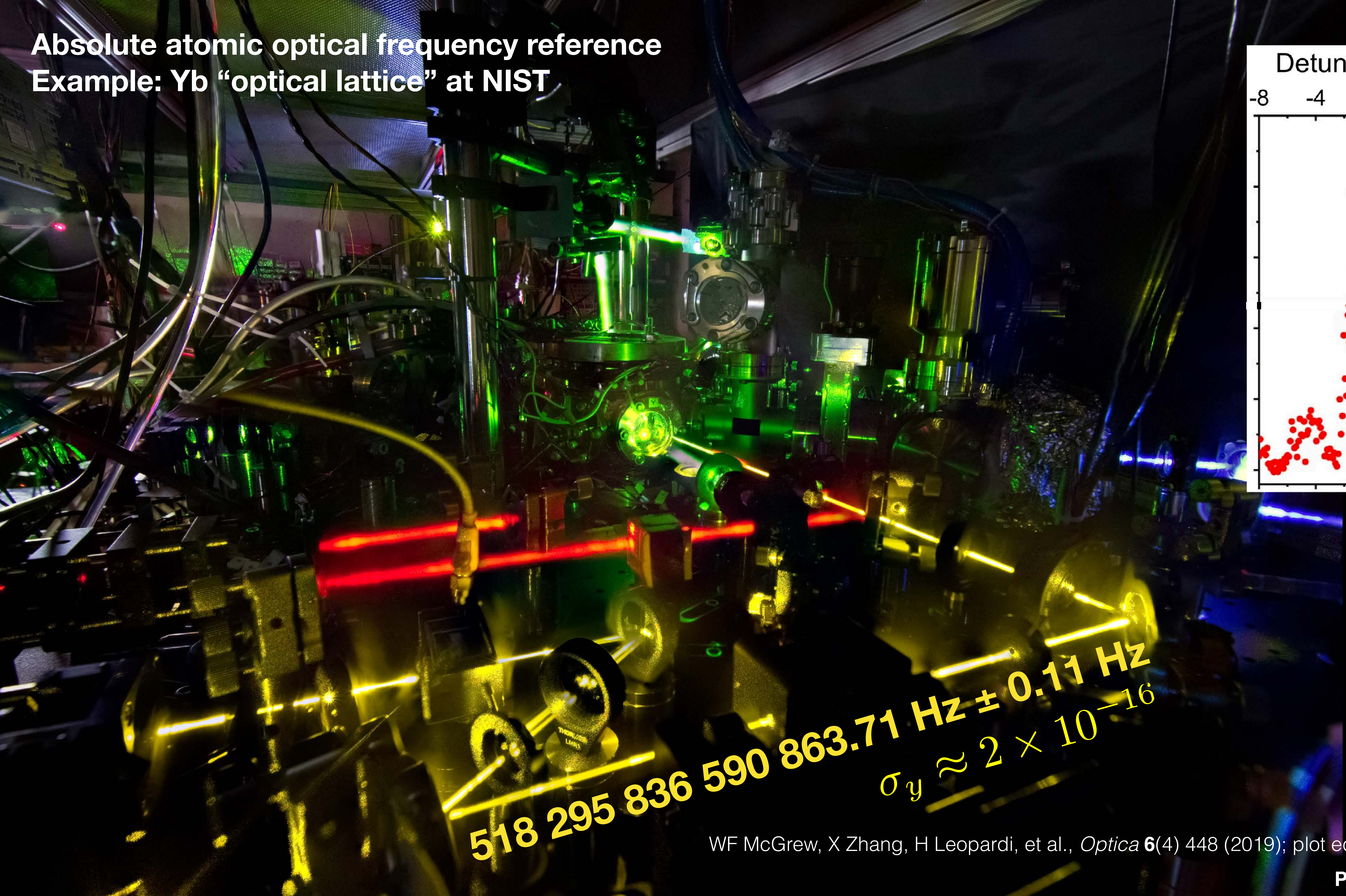
Optical-lattice trapped atoms

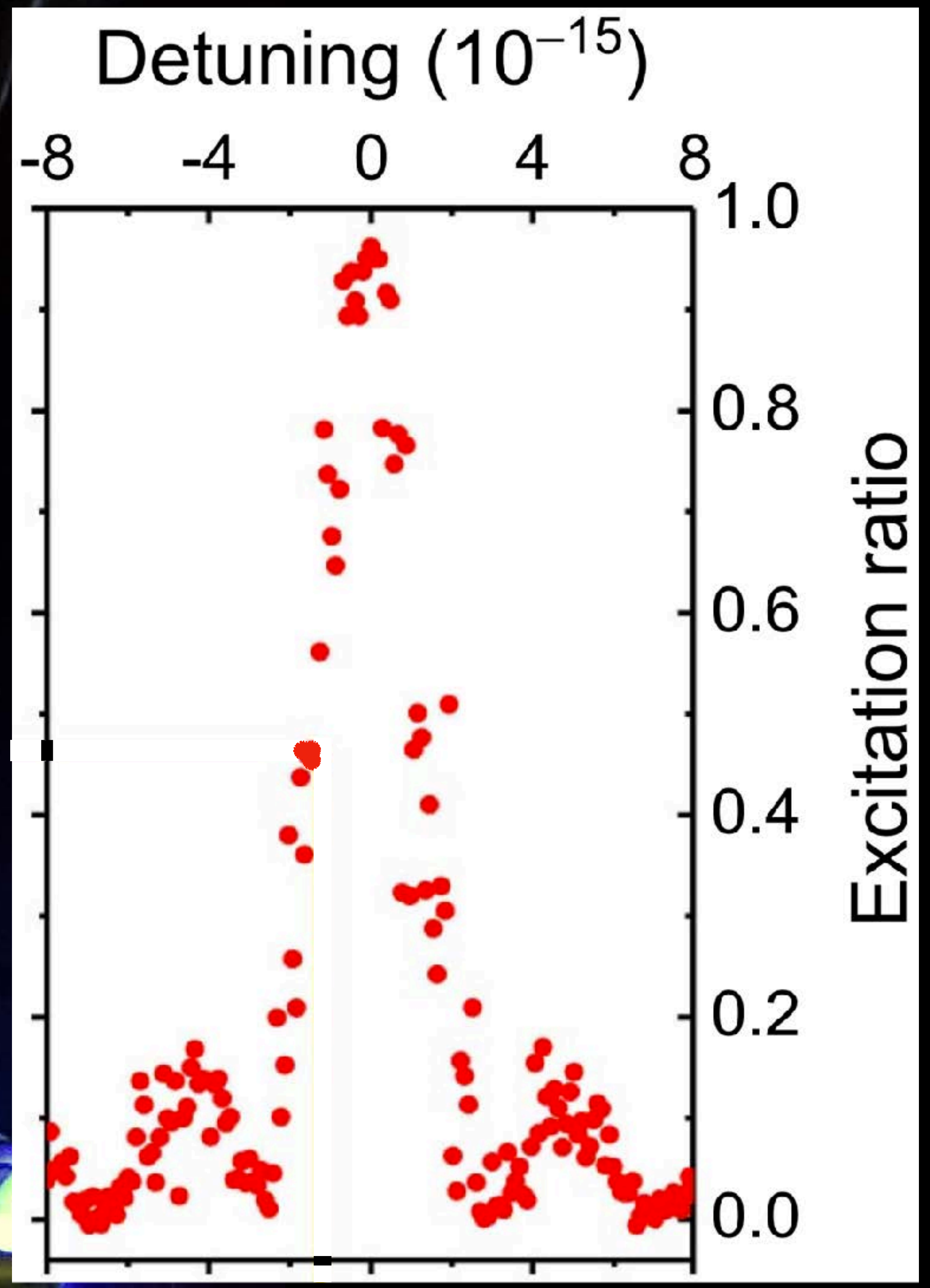


- ✅ higher S/N
- ✅ path to low BBR uncertainty
- ❌ uncanceled Stark shifts

Illustration: Phil Saunders. From E Cartlidge, "Toward the optical second", Opt. & Phot. (OSA) 2019 (https://www.osa-opn.org/home/articles/volume_30/february_2019/features/toward_the_optical_second/)

Absolute atomic optical frequency reference
Example: Yb “optical lattice” at NIST





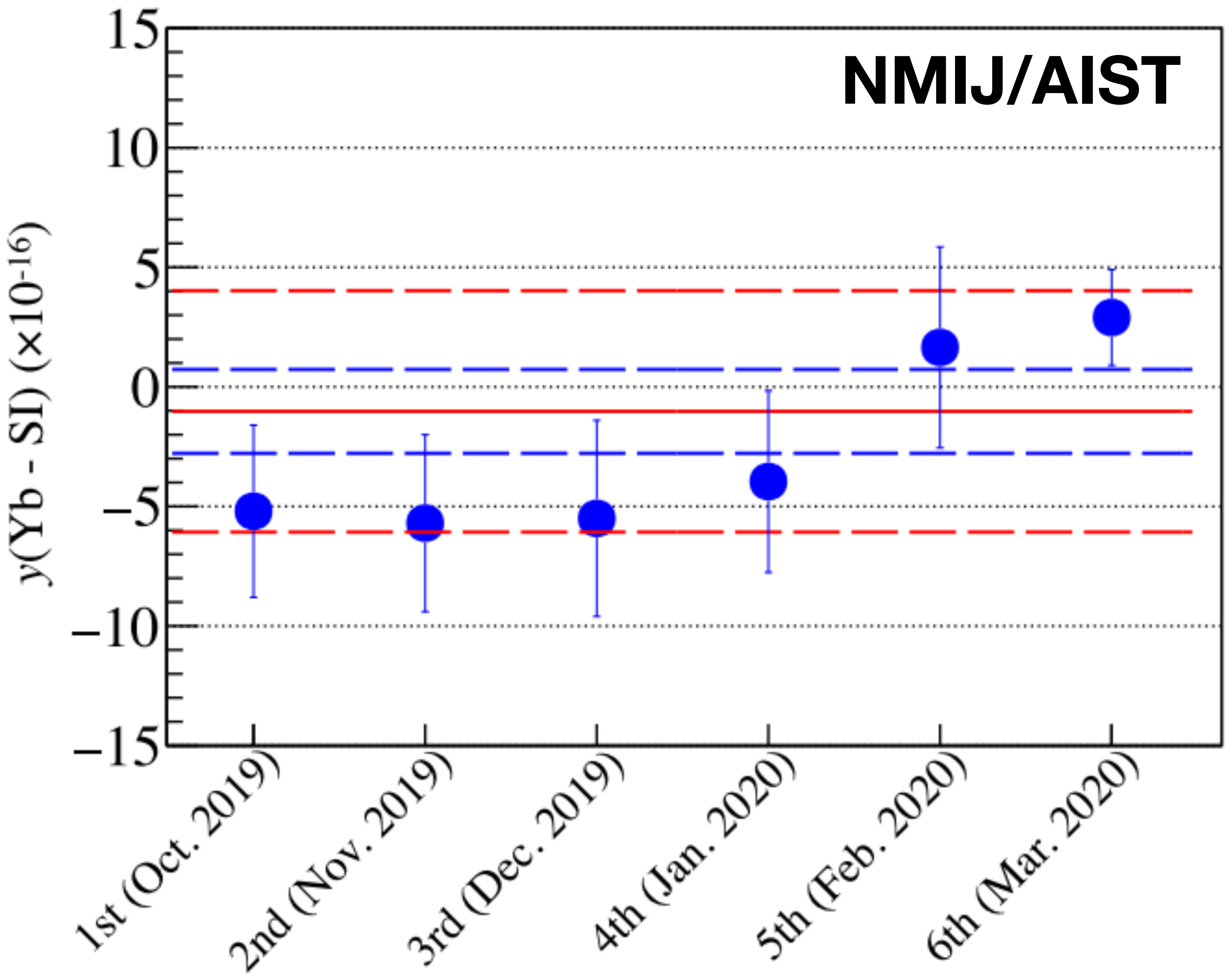
518 295 836 590 863.71 Hz ± 0.11 Hz

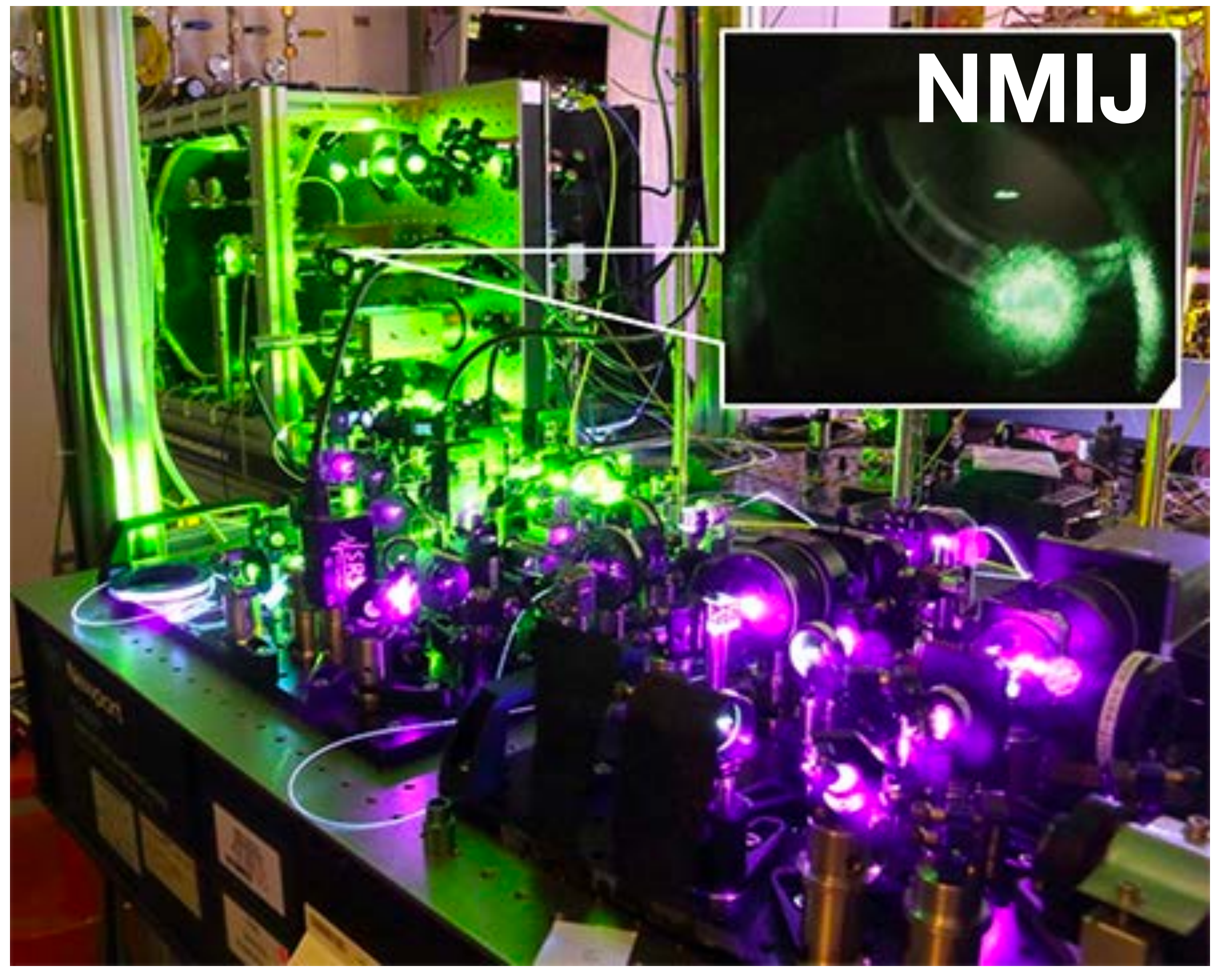
$$\sigma_y \approx 2 \times 10^{-16}$$

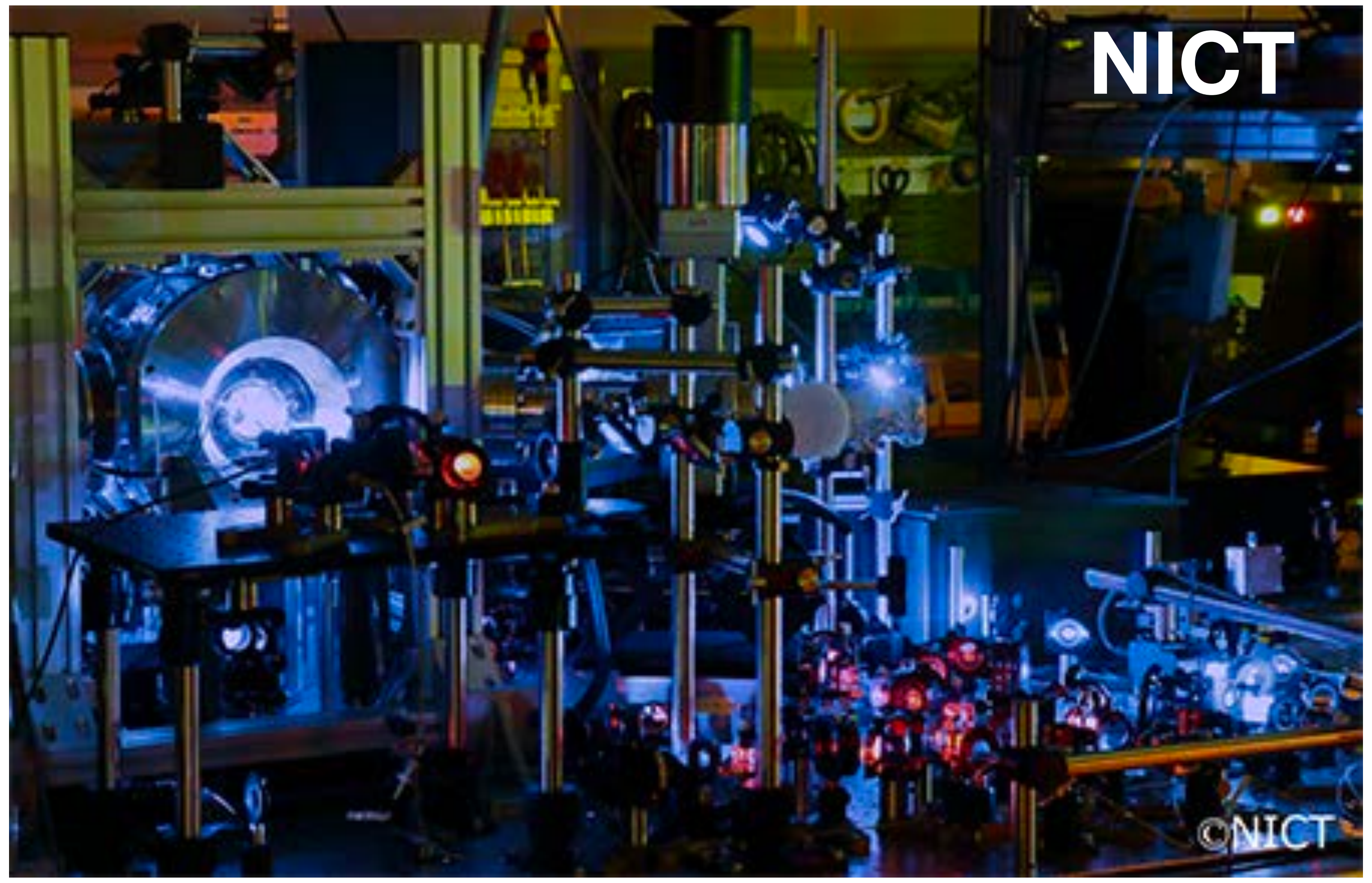
WF McGrew, X Zhang, H Leopardi, et al., *Optica* **6**(4) 448 (2019); plot edited to remove annotation

Photo: Nate Phillips, NIST

Recent examples from Japan (1)



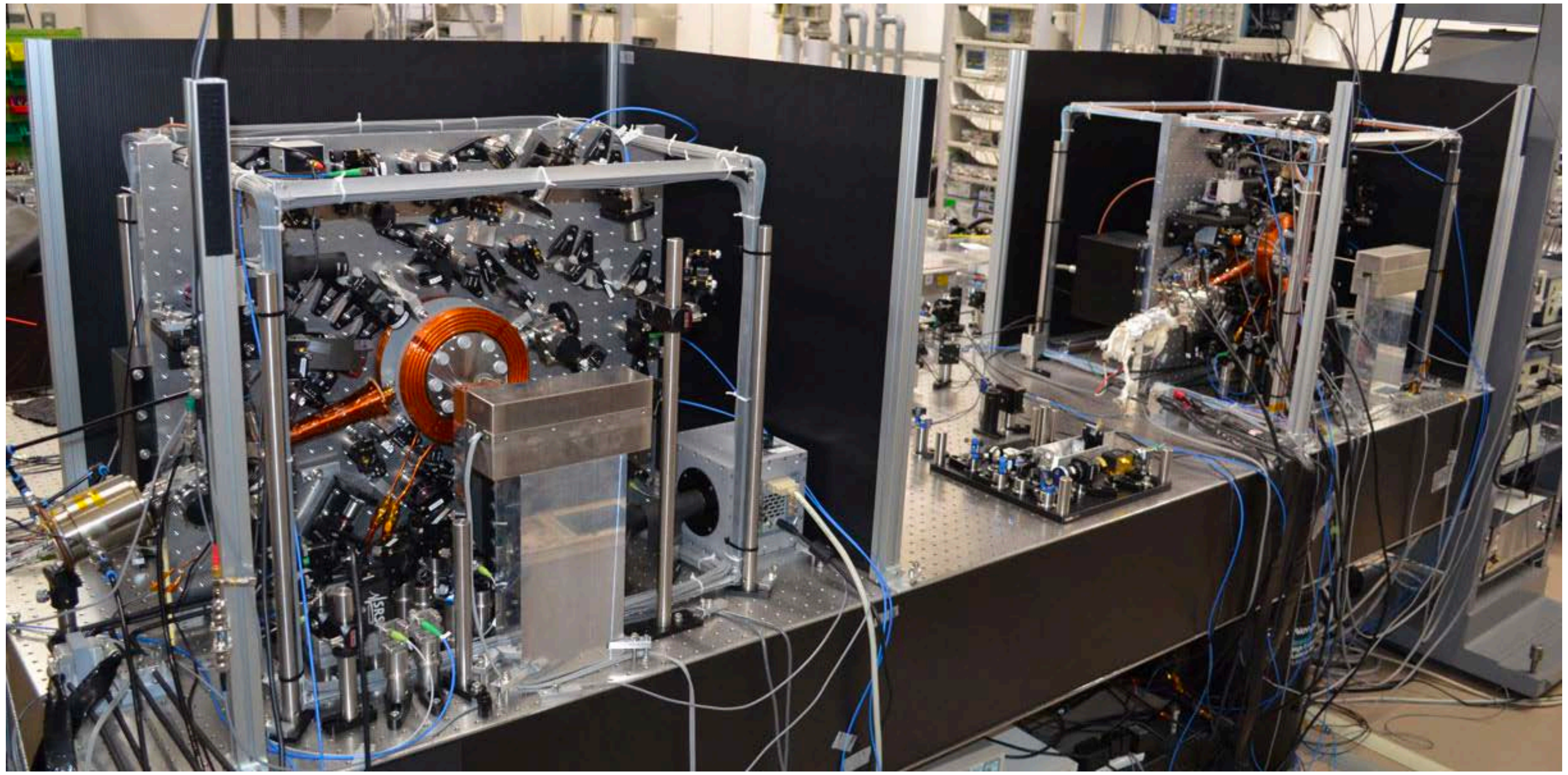


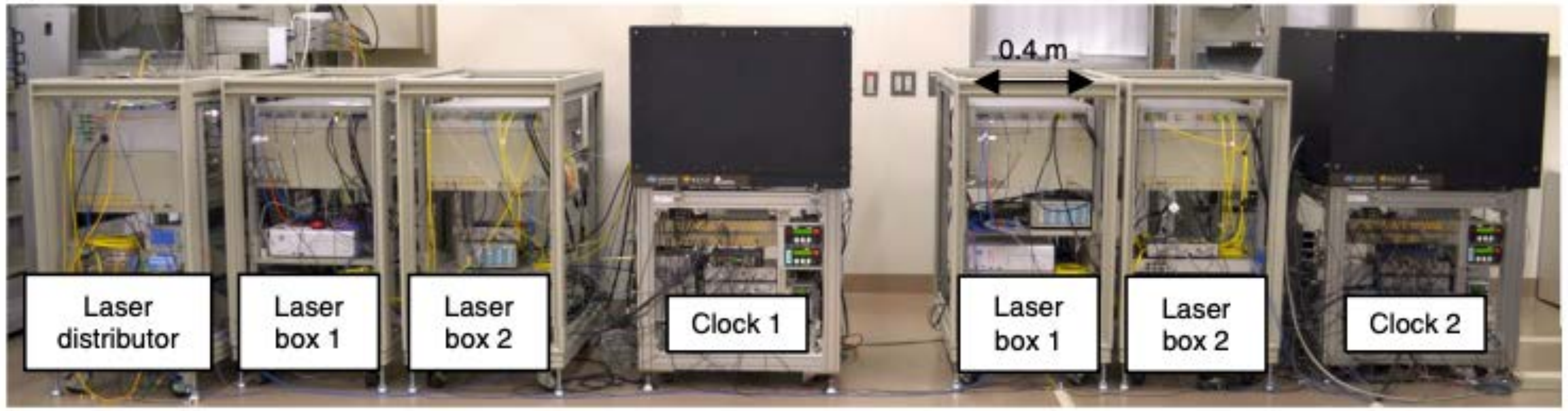


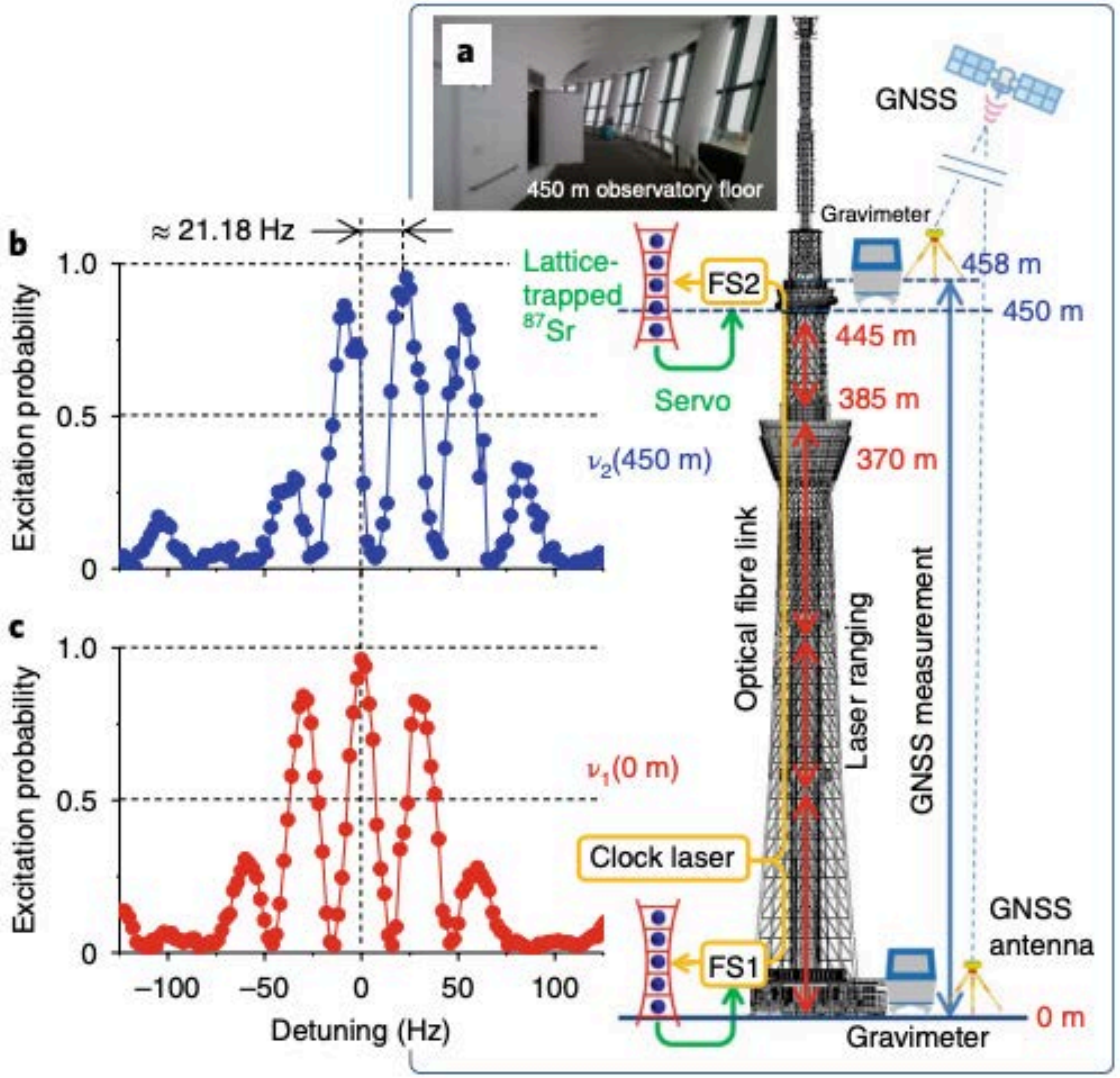
NICT: link between optical clocks (Japan/Italy)

[1] T Kobayashi, D Akamatsu, K Hosaka, Y Hisai, M Wada, H Inaba, T Suzuyama, F-L Hong, M Tasuda, "Demonstration of the nearly continuous operation of an ^{171}Yb optical lattice clock for half a year", Metrologia 57, 065021 (2020)
[2] M Pizzocaro, M Sekido, K Takefuji, et al., "Intercontinental comparison of optical atomic clocks through VLBI", Nature Physics 17, p. 223–227 (2021)

Recent examples from Japan (2)

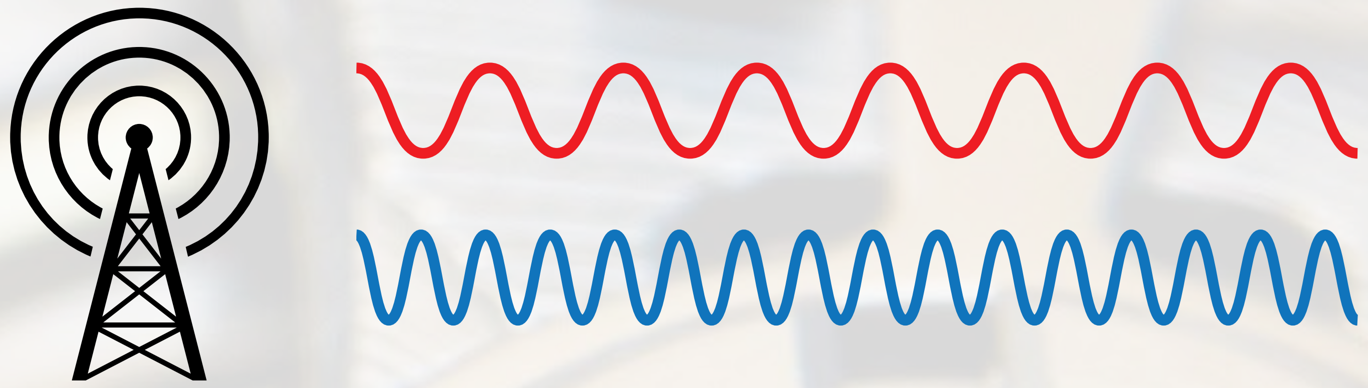






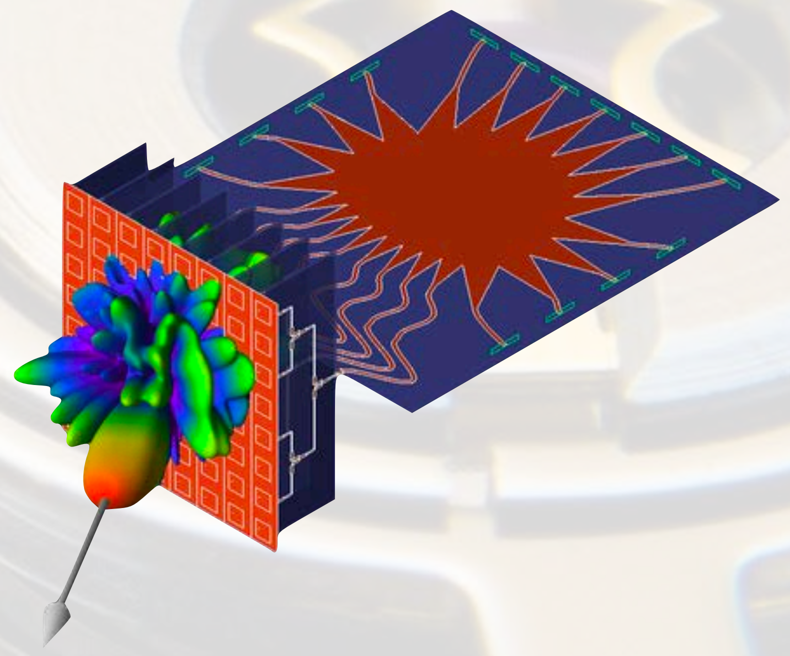
M Takamoto, I Ushijima, N Ohmae, T Yahagi, K Kokado, H Shinkai, H Katori, “Test of general relativity by a pair of transportable optical lattice clocks,” Nat. Photonics 14, pp. 411–415 (2020).

Summary



Beyond 5G likely requires:

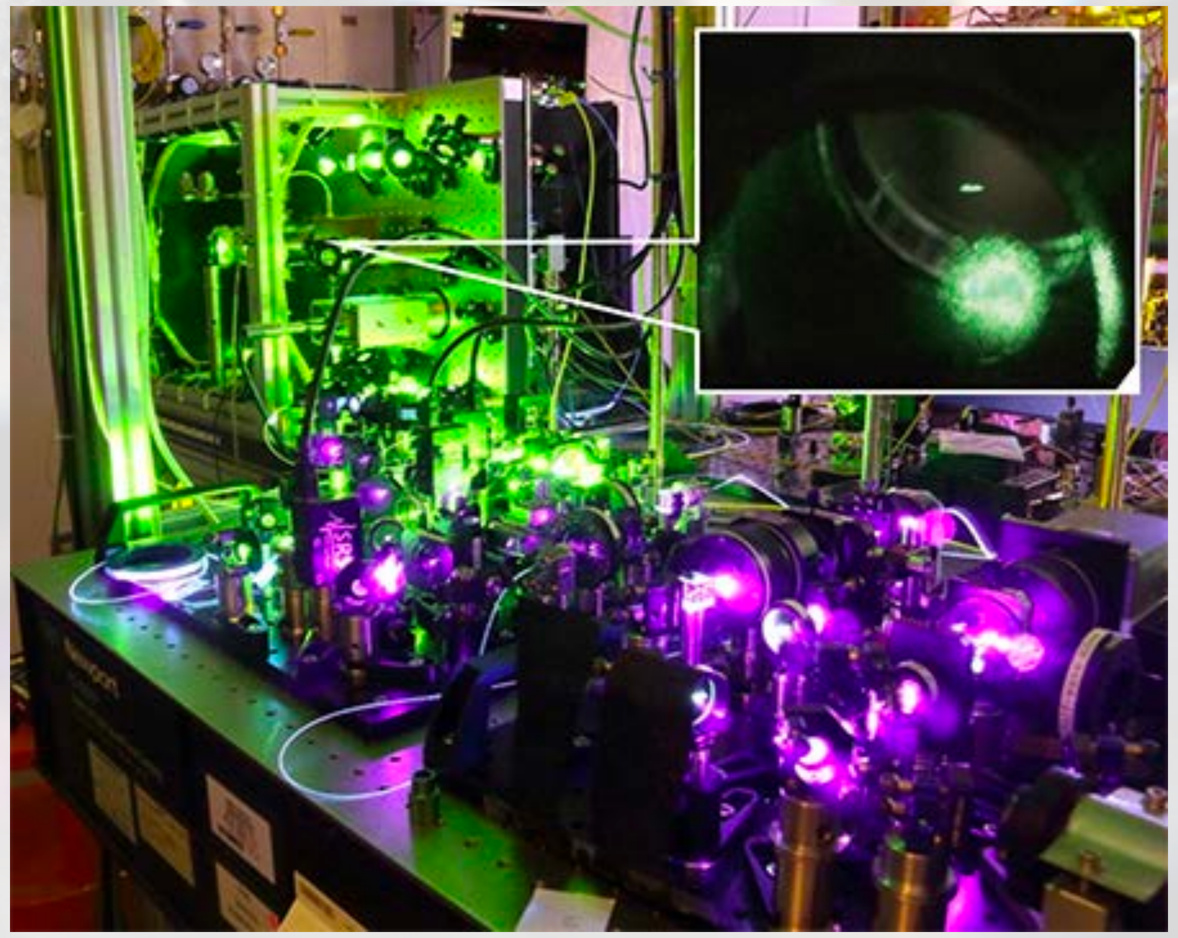
- Higher carrier frequencies
- Higher bandwidths
- Highly coherent transmitters (e.g. beamforming)



All these needs served by coherent-division of optical oscillators

A parallel, fascinating technology track in precision optical timekeeping exists:

- Highly stable optical oscillators
- Coherent optical-to-microwave division
- Highly accurate optical frequency references
- Motivation for redefinition of the SI unit of time
- Supports fundamental science and novel sensing



(image attribution: unknown, https://i.imgur.com/v4xbEz7.jpg)