The SI second as a count of oscillations and ~~much more~~ or not!

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NIST Time and Frequency Division

March 30, 2023

NIST NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
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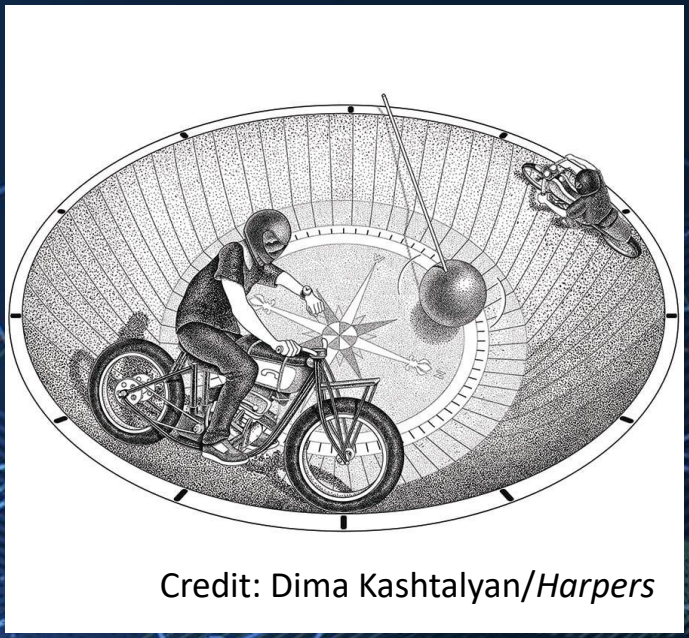
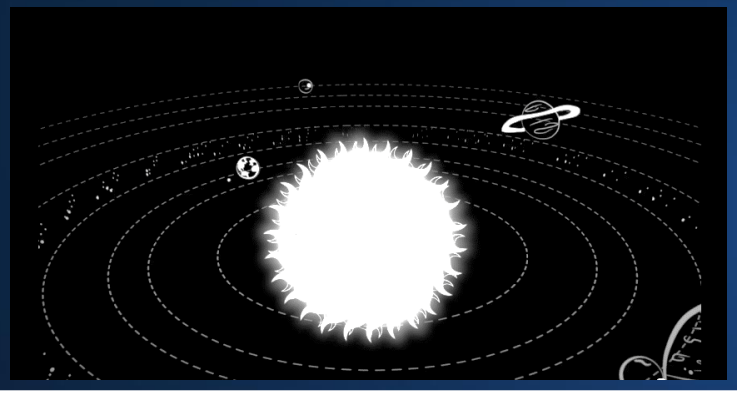
This Talk:

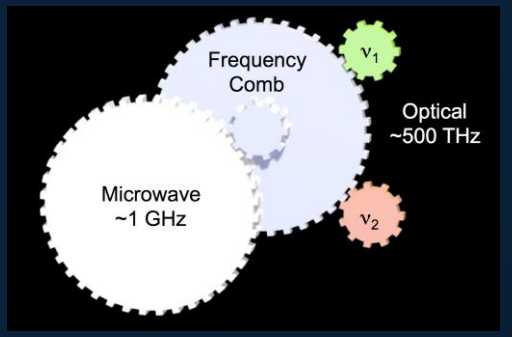
- The SI Second
- How we realize it (usually not by counting!)
- The state of the art of frequency measurement



Credit: Dima Kashtalyan/*Harpers*

The Quantum SI Second



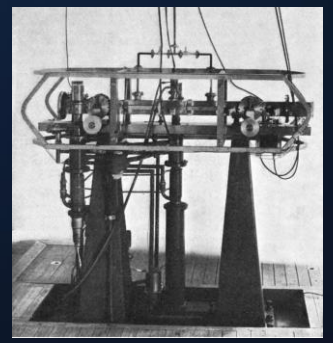


11th CGPM (1960): The second is the fraction 1/31 556 925.9747 of the tropical year for 1900 ….

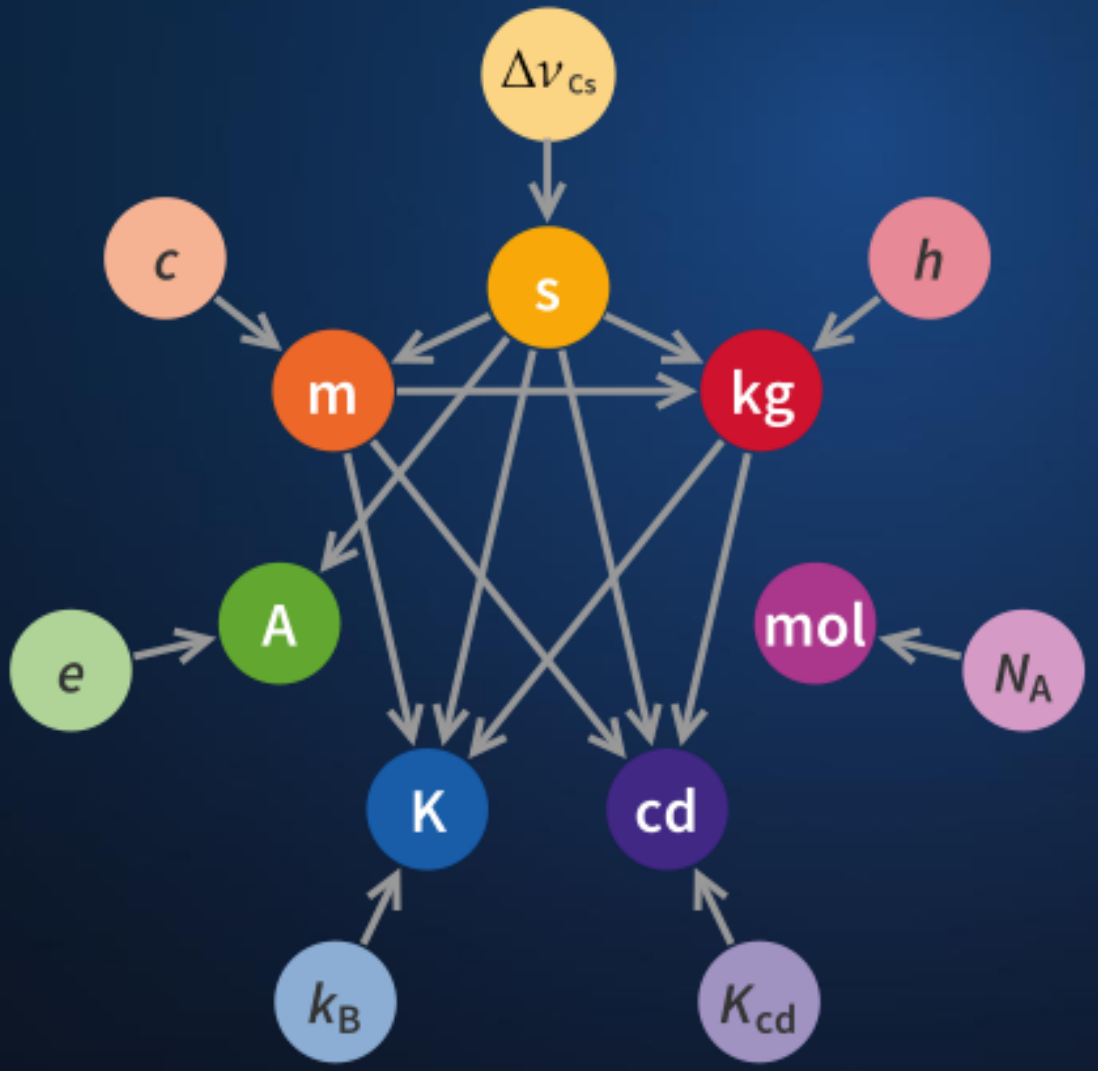
26th CGPM (2019): Defined by taking the fixed numerical value of $\Delta\nu_{Cs}$, the unperturbed ground-state hyperfine transition frequency of the ^{133}Cs atom, to be 9 192 631 770 when expressed in the unit Hz, which is equal to s^{-1}.

1960 1970 1980 1990 2000 2010 2020

13th CGPM (1967): The duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the ^{133}Cs atom



The Second in the SI



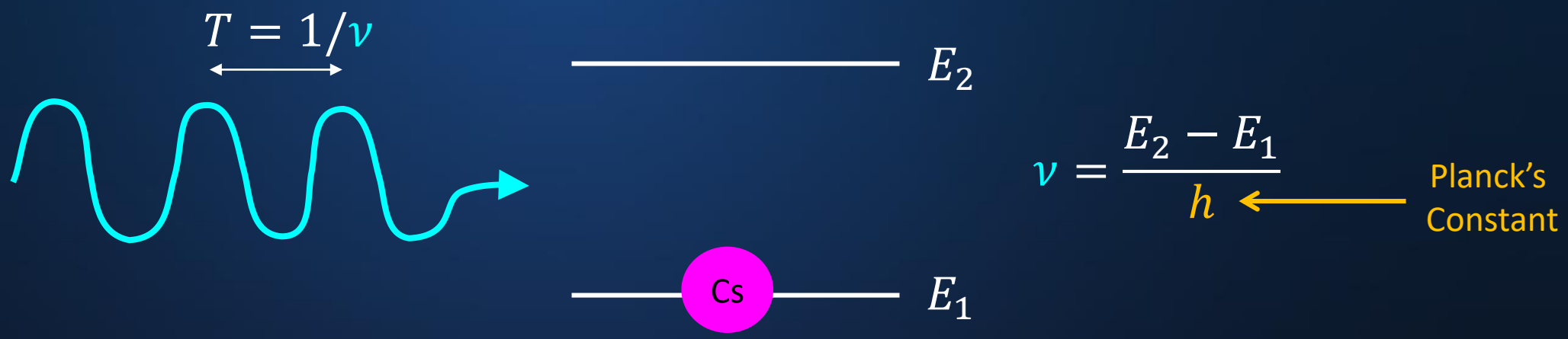
SI Seconds are needed to realize the definitions of all but one of the other units!

We can realize frequency measurements very well:

- At the 1×10^{-16} level with the current definition
- At the 6×10^{-18} level for optical frequency ratios!!!

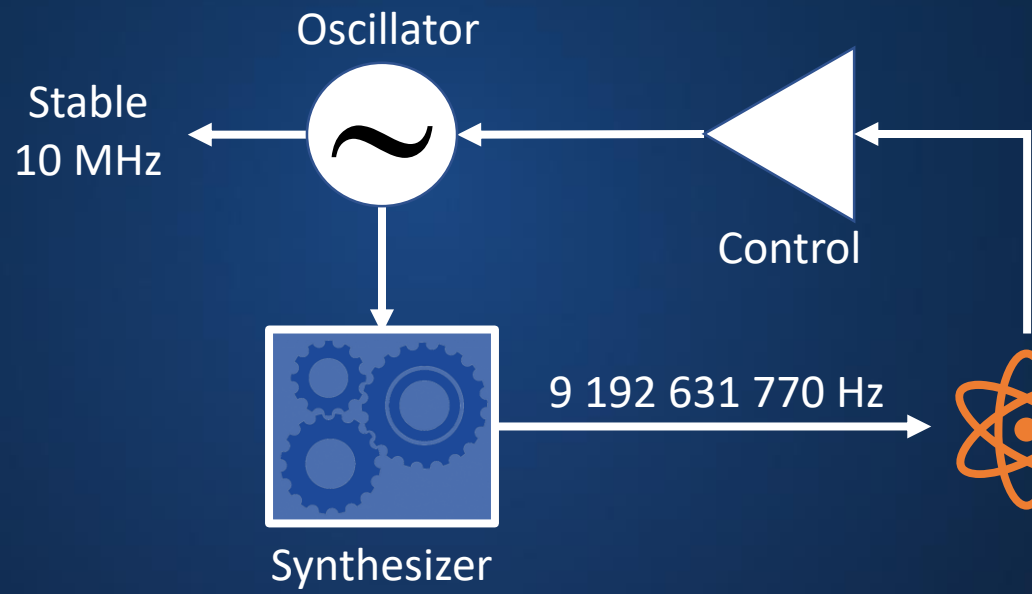
An Atomic Frequency Standard :

Uses resonant electromagnetic fields that cause transitions between atomic energy levels as the frequency standard's oscillator



The standard's oscillator frequency ν: the <u>field frequency</u> that causes transitions between "clock" states

Realizing a Primary Frequency Standard

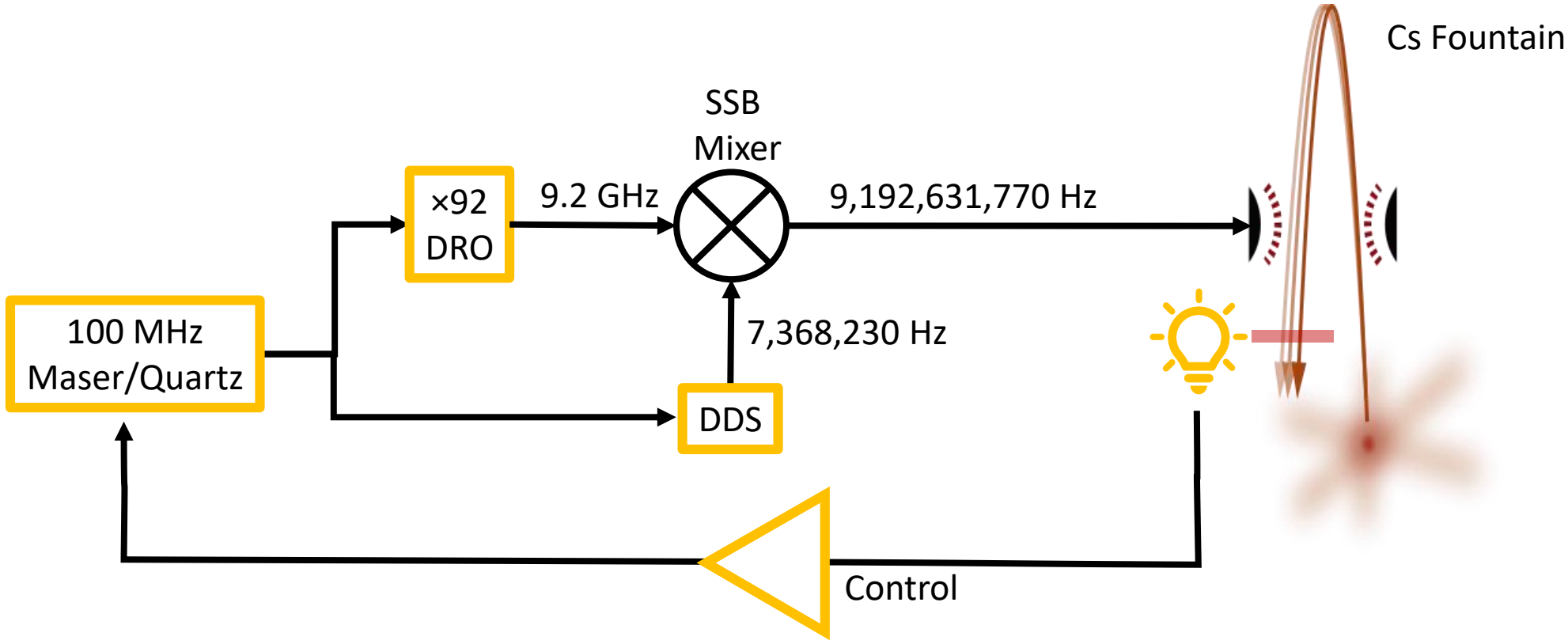


- Synthesize EM signal resonant with atoms using a quartz oscillator reference with Electronic “gears”
- Lock the quartz oscillator to the atomic response using feedback to stabilize the oscillator output

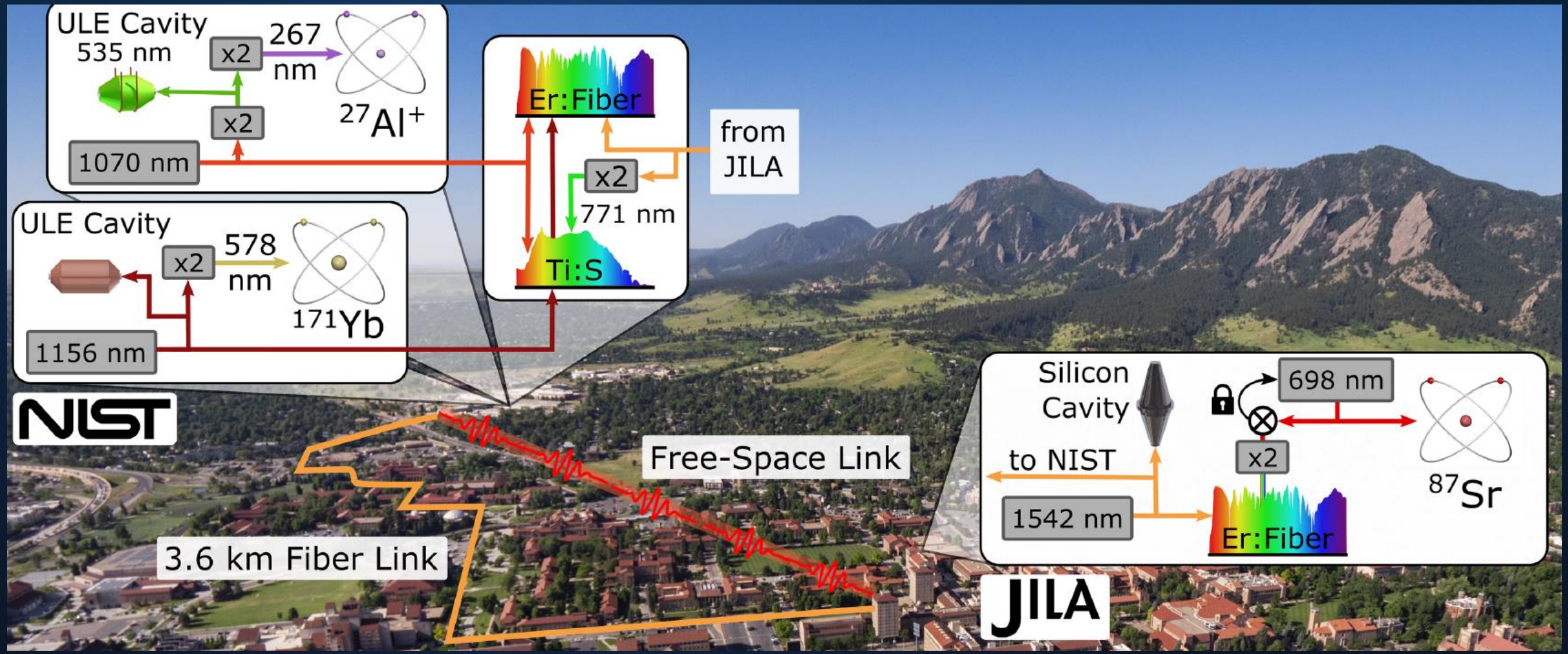
It’s useful to think of the synthesizer as a gear box – with the frequency ratio of the atomic transition to the quartz sets the gear ratio of the synthesizer.

Example: A Cesium Synthesizer

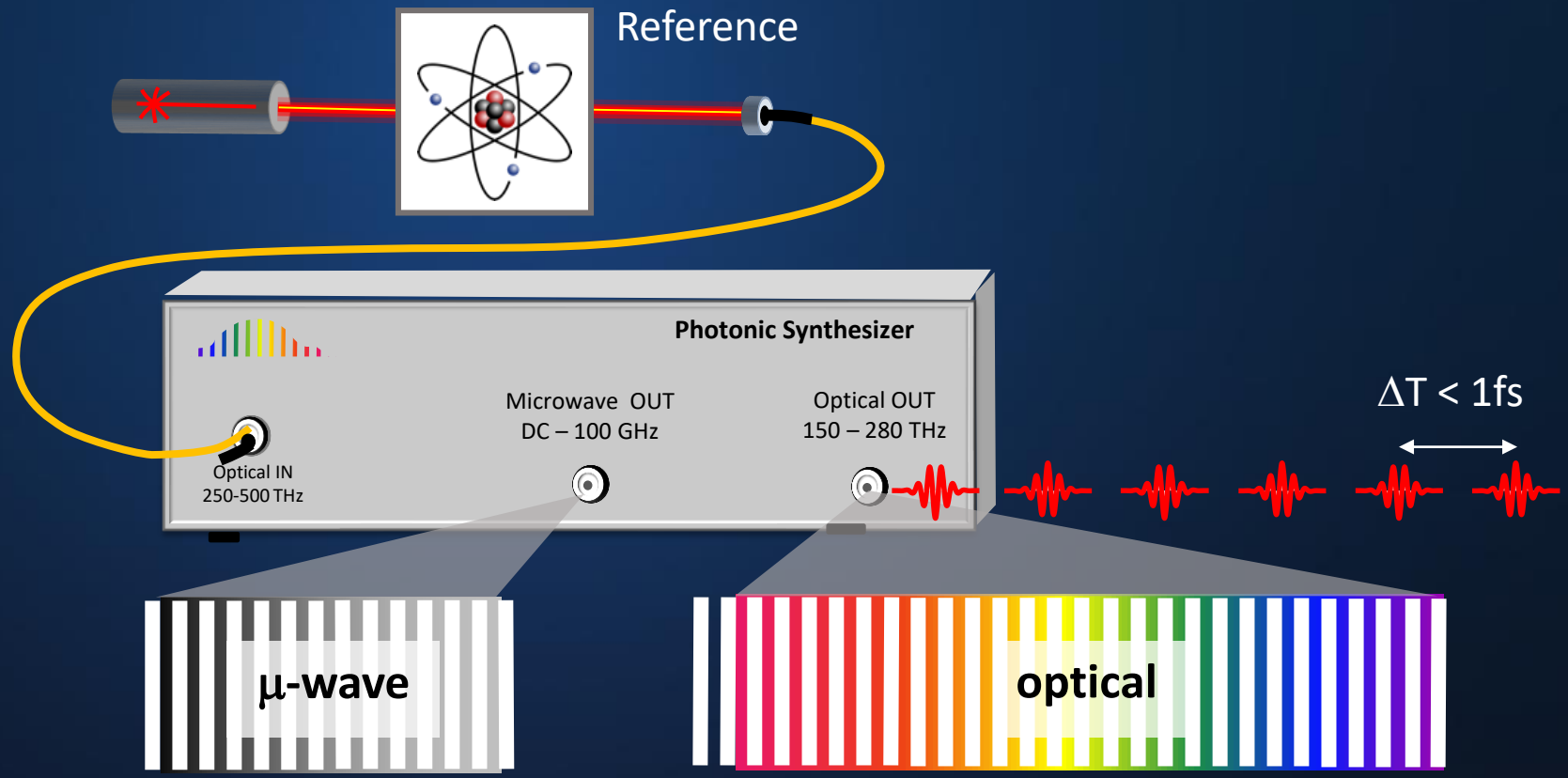
- Synthesize 9,192,631,770 Hz with an electronic “gear box” from a Maser-derived 100 MHz input
- Stabilize the 100 MHz reference with feedback



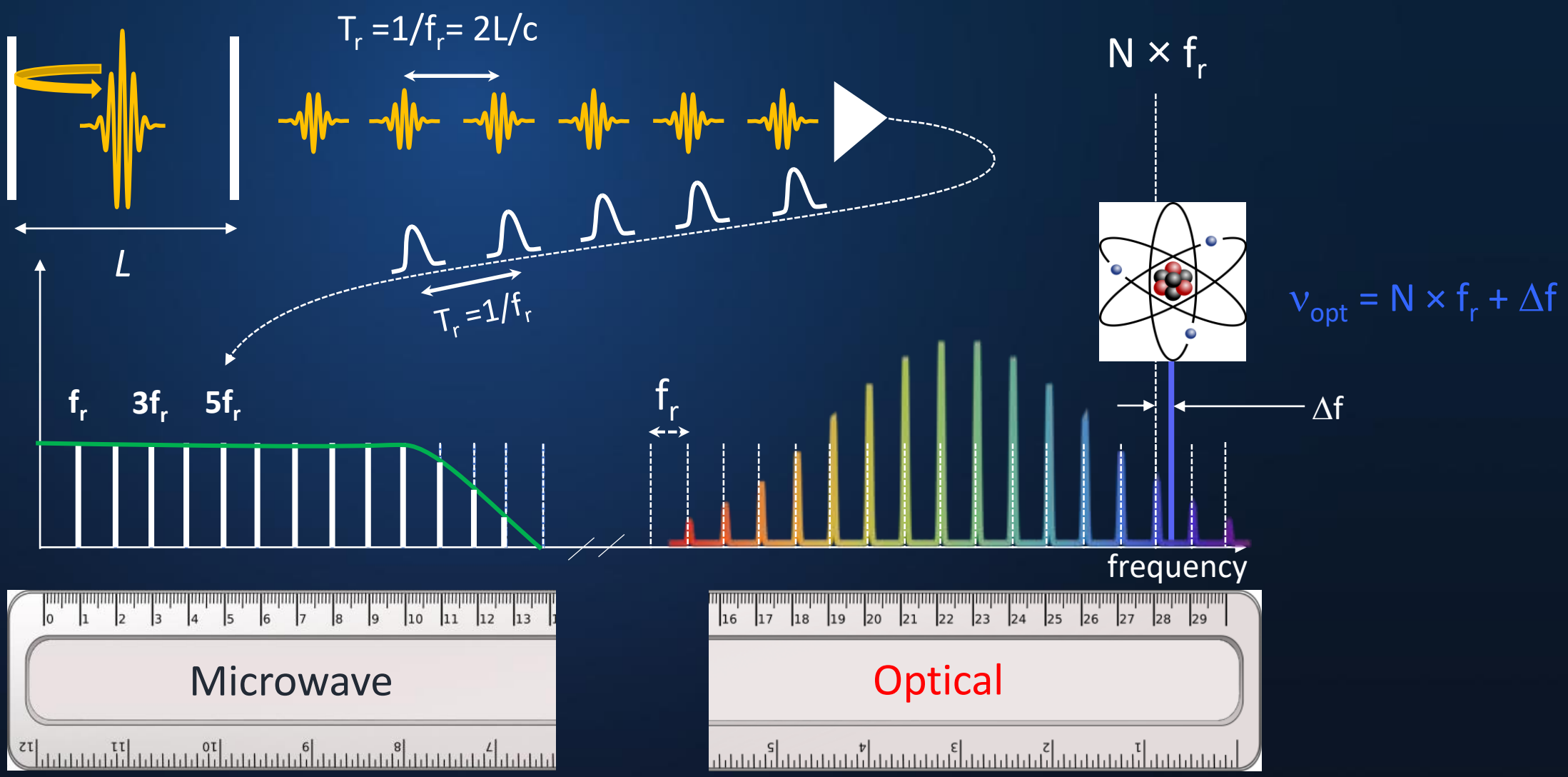
Boulder Optical Clock Network



Optical Frequency Combs: The Ultimate Gear Box!



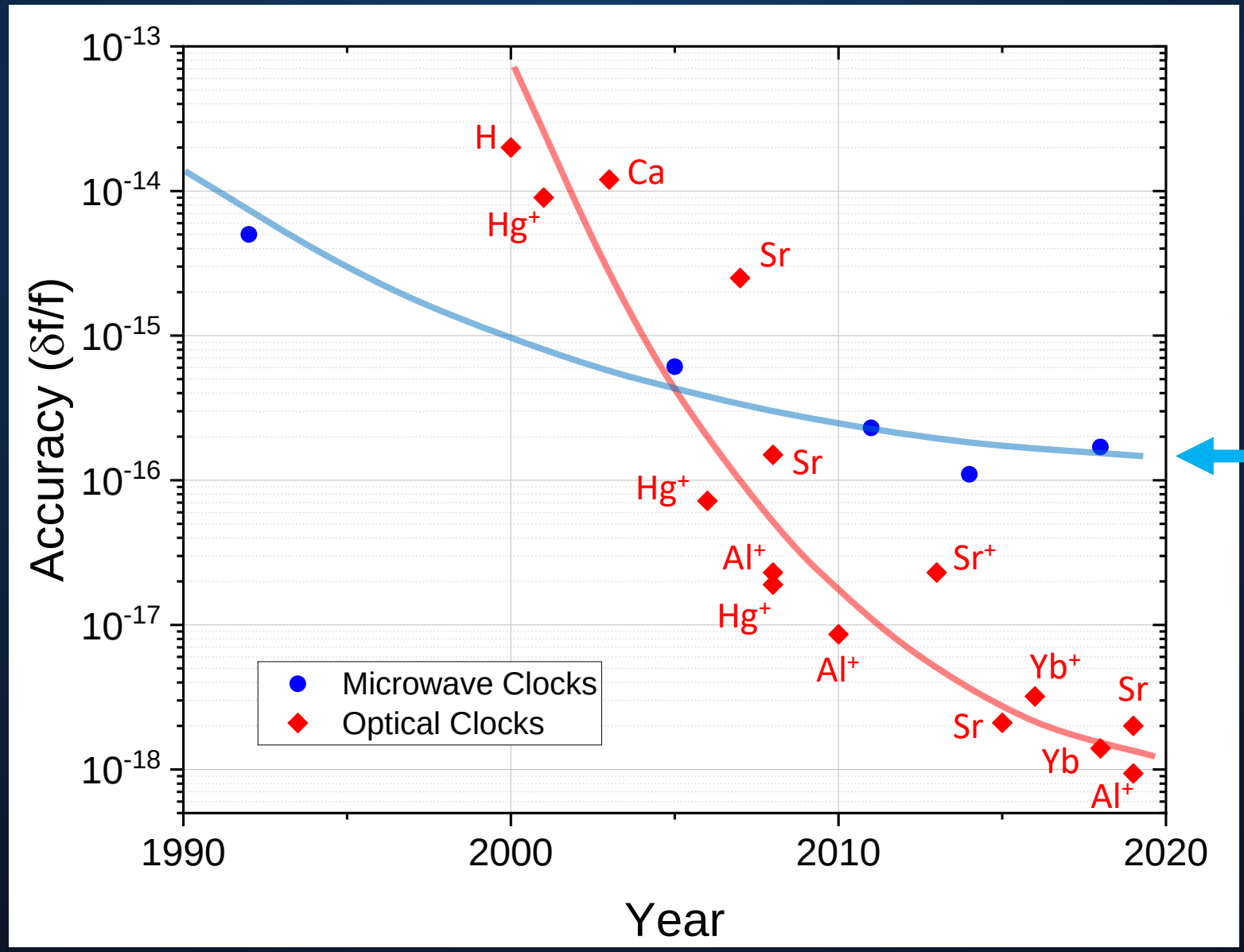
Femtosecond Frequency Combs



Combs for Frequency Measurement

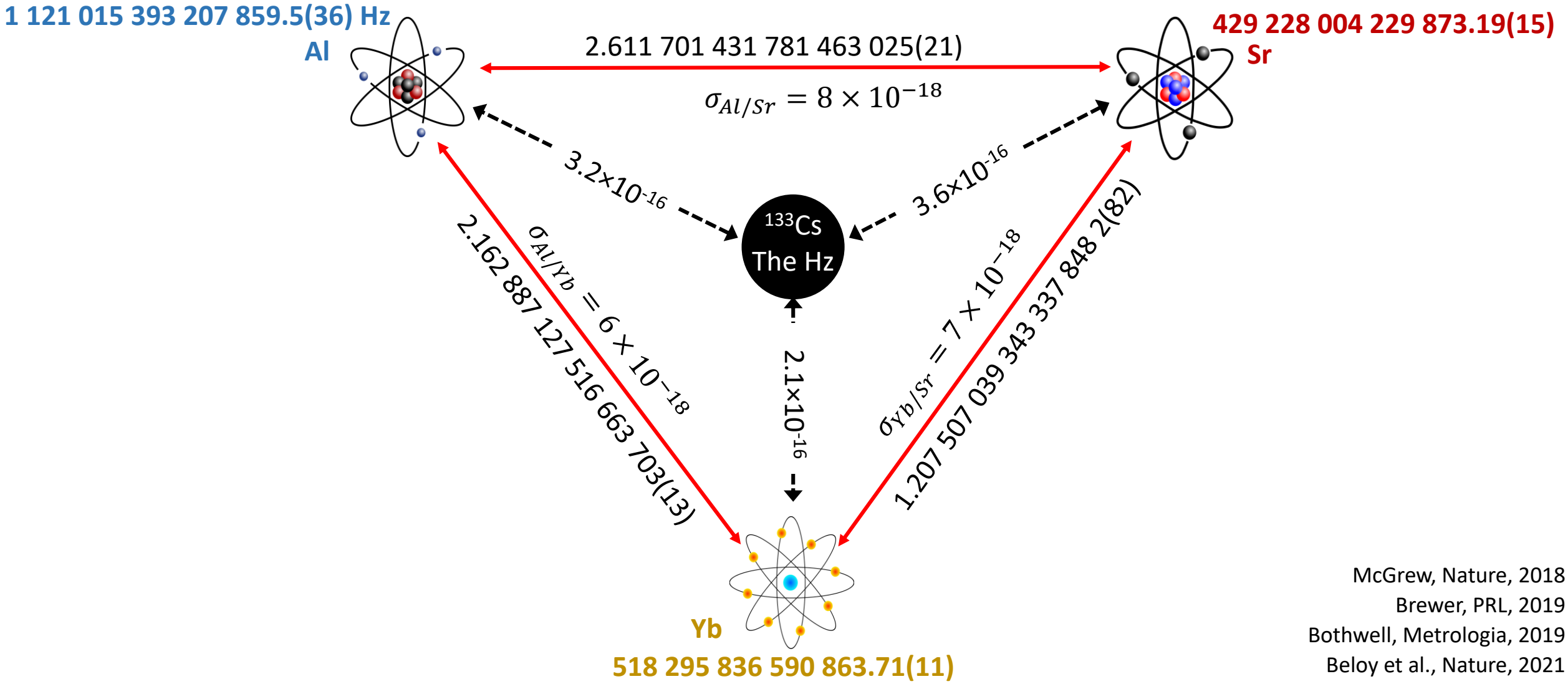
Credit: NIST

Accuracy of atomic frequency standards



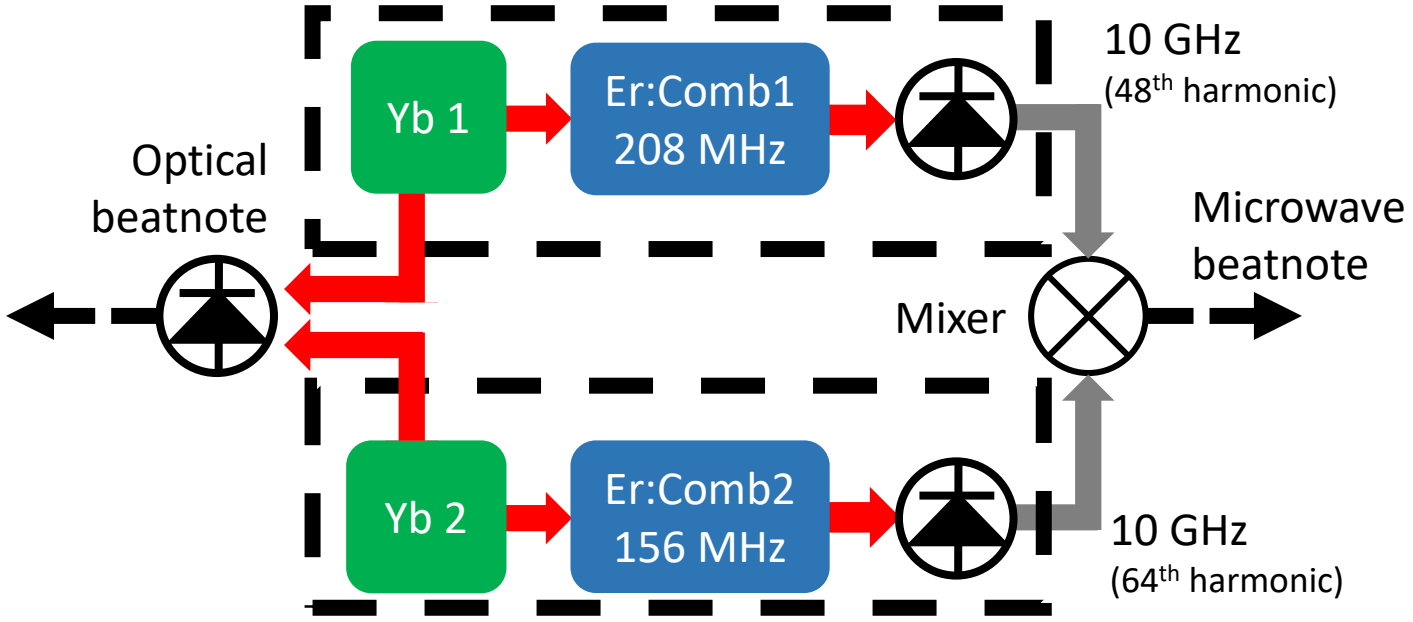
Limit to the SI "Hz" as defined by ^{133}Cs

Frequency and Frequency Ratio Measurements

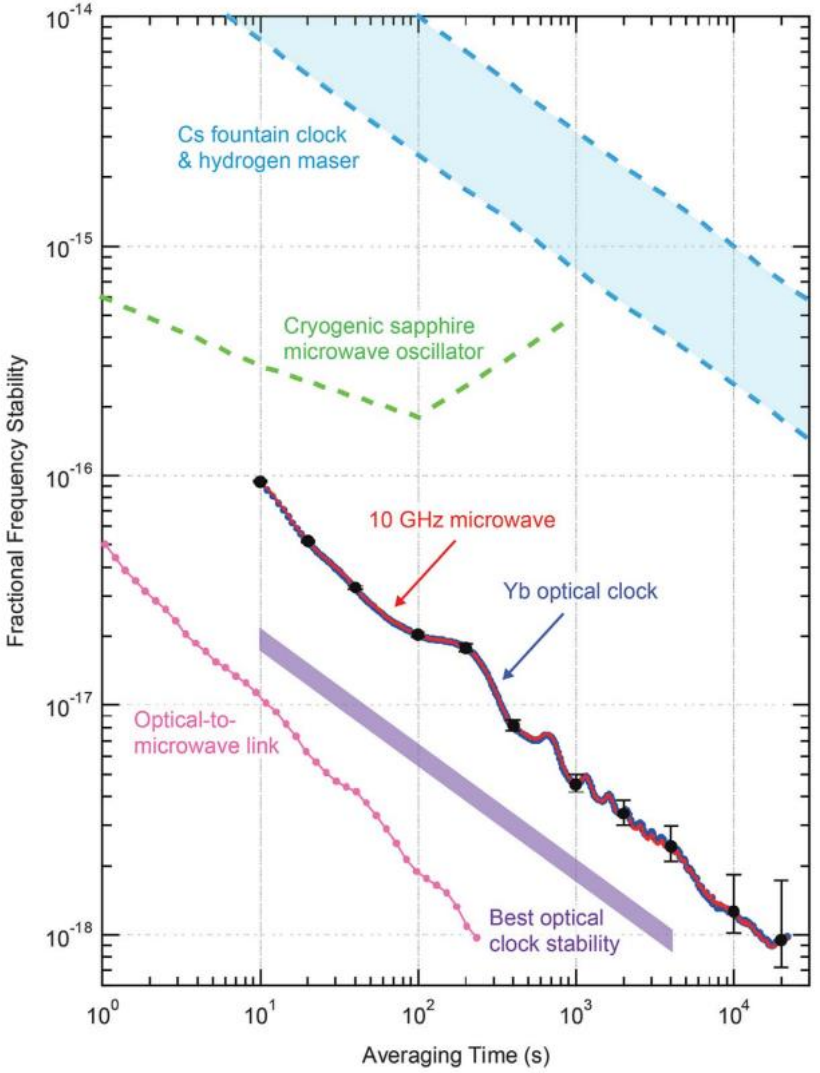


McGrew, Nature, 2018
Brewer, PRL, 2019
Bothwell, Metrologia, 2019
Beloy et al., Nature, 2021
Leopardi, Metrologia, 2021

Coherent Frequency Division



Nakamura, Science (2020)



Two independent optical-to-electronic frequency dividers

Each produces 10-GHz microwaves with phase exactly tracking its Yb clock, yielding an absolute fractional frequency instability of 1×10^{-18} in the electronic domain.

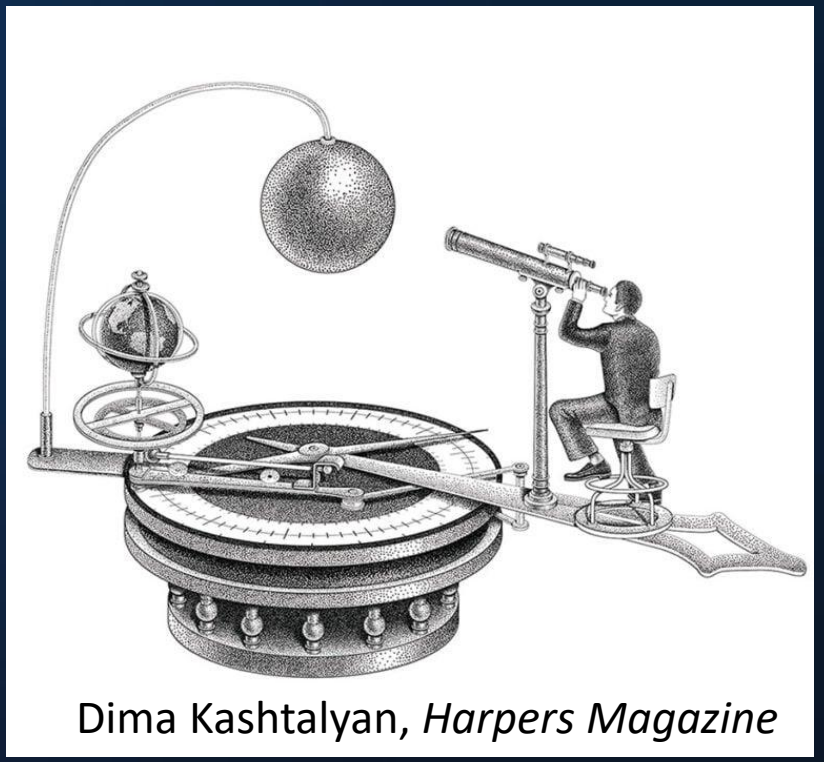
The microwave frequency is only 10^{10} and we can measure it to 10^{18} !!

We're tracking phase not counting cycles.

Take Home Message

For frequency metrology:

- We don’t usually count periods of radiation…
- We mainly measure frequency ratios through frequency synthesis



Dima Kashtalyan, *Harpers Magazine*

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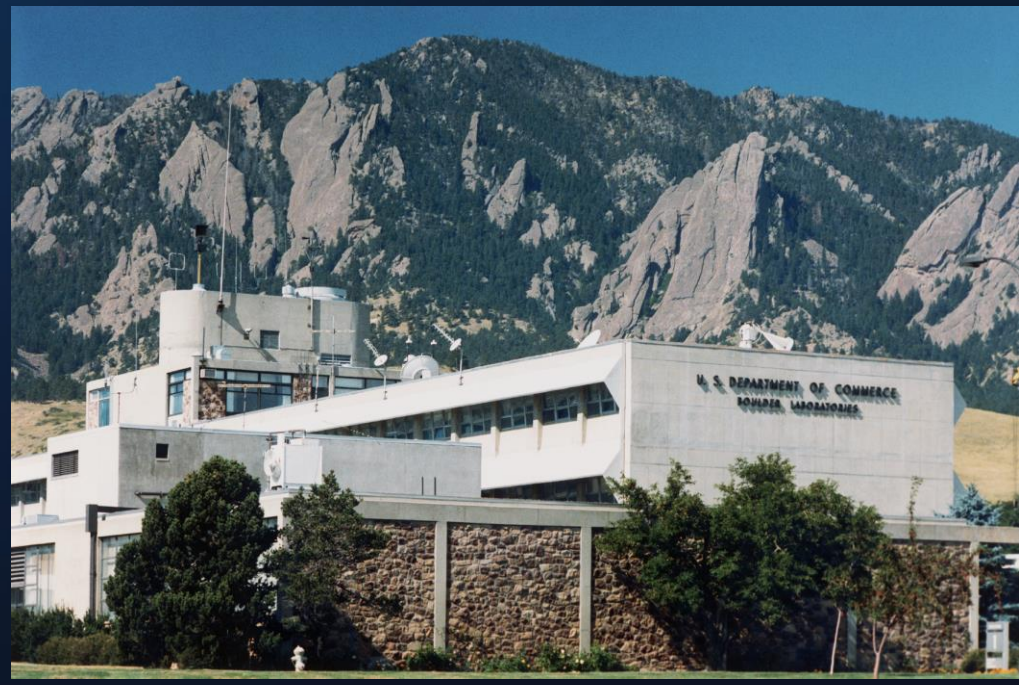

Thank you!

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