Report from NIST

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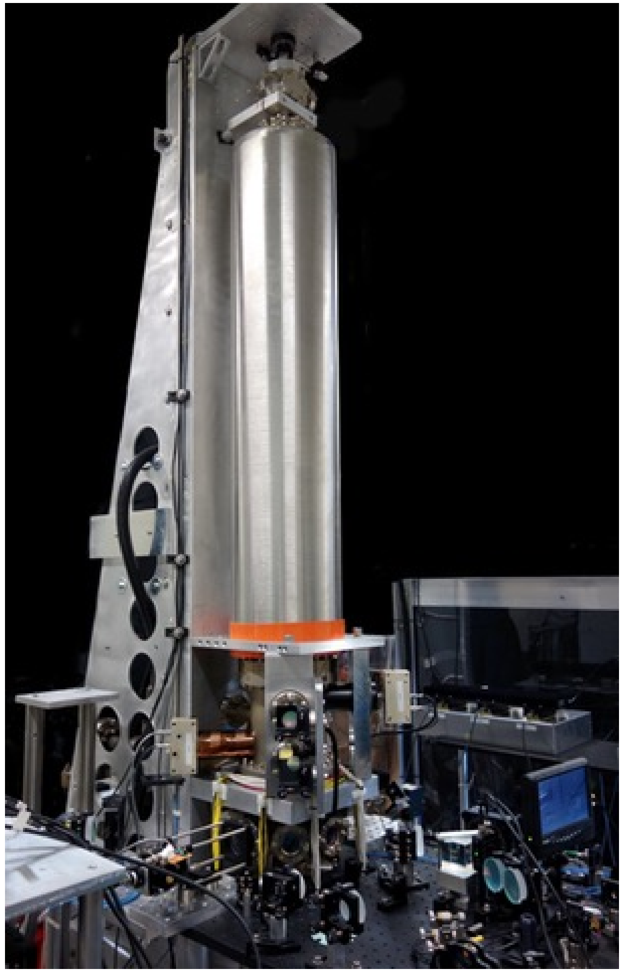
CGSIC, 2023

Report from NIST

NIST: Clocks to Quantum

- Timescale
- Update on services
- Time keeping to quantum information processing

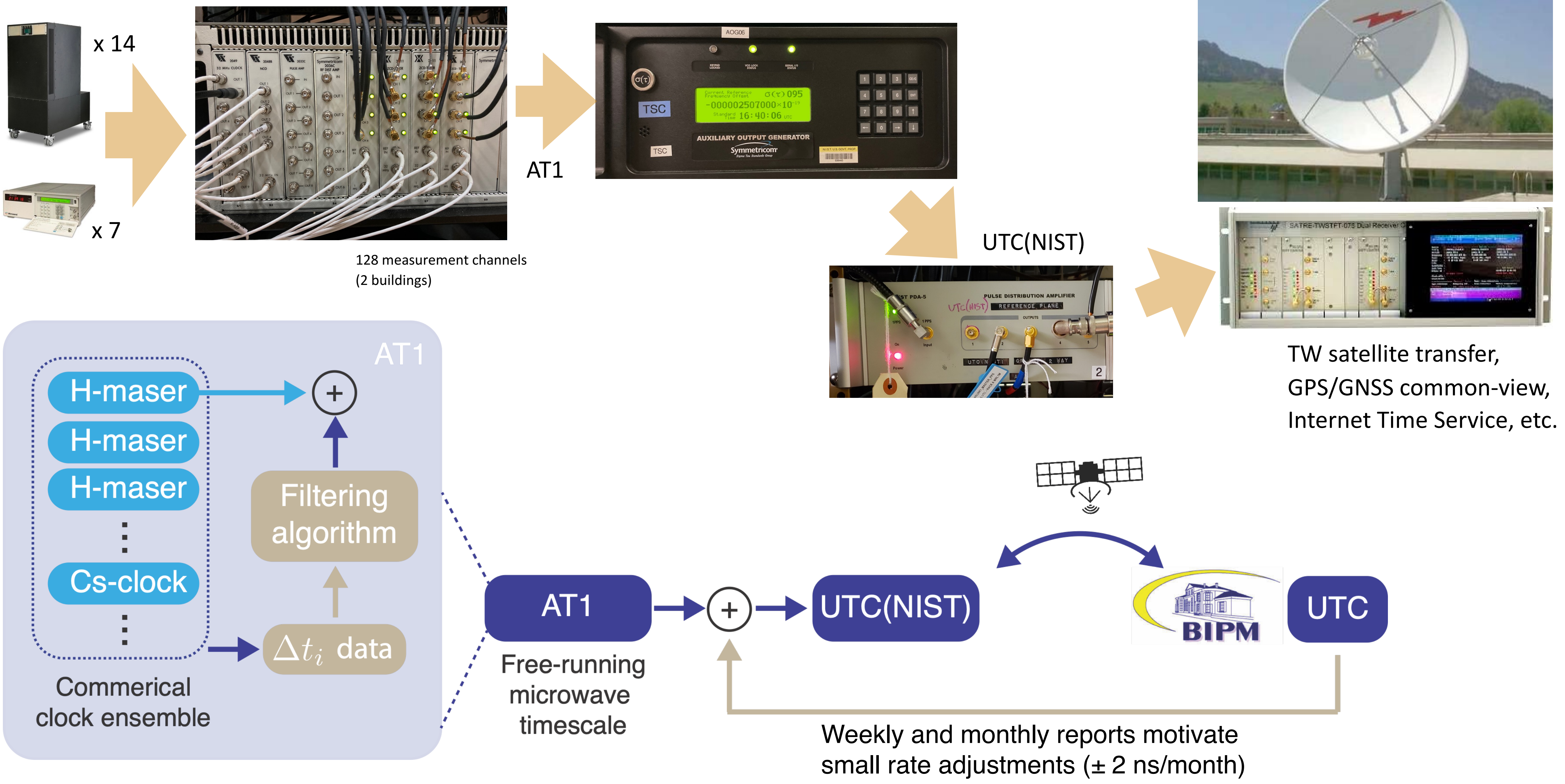


NIST-F4, Photo credit: A. Novick

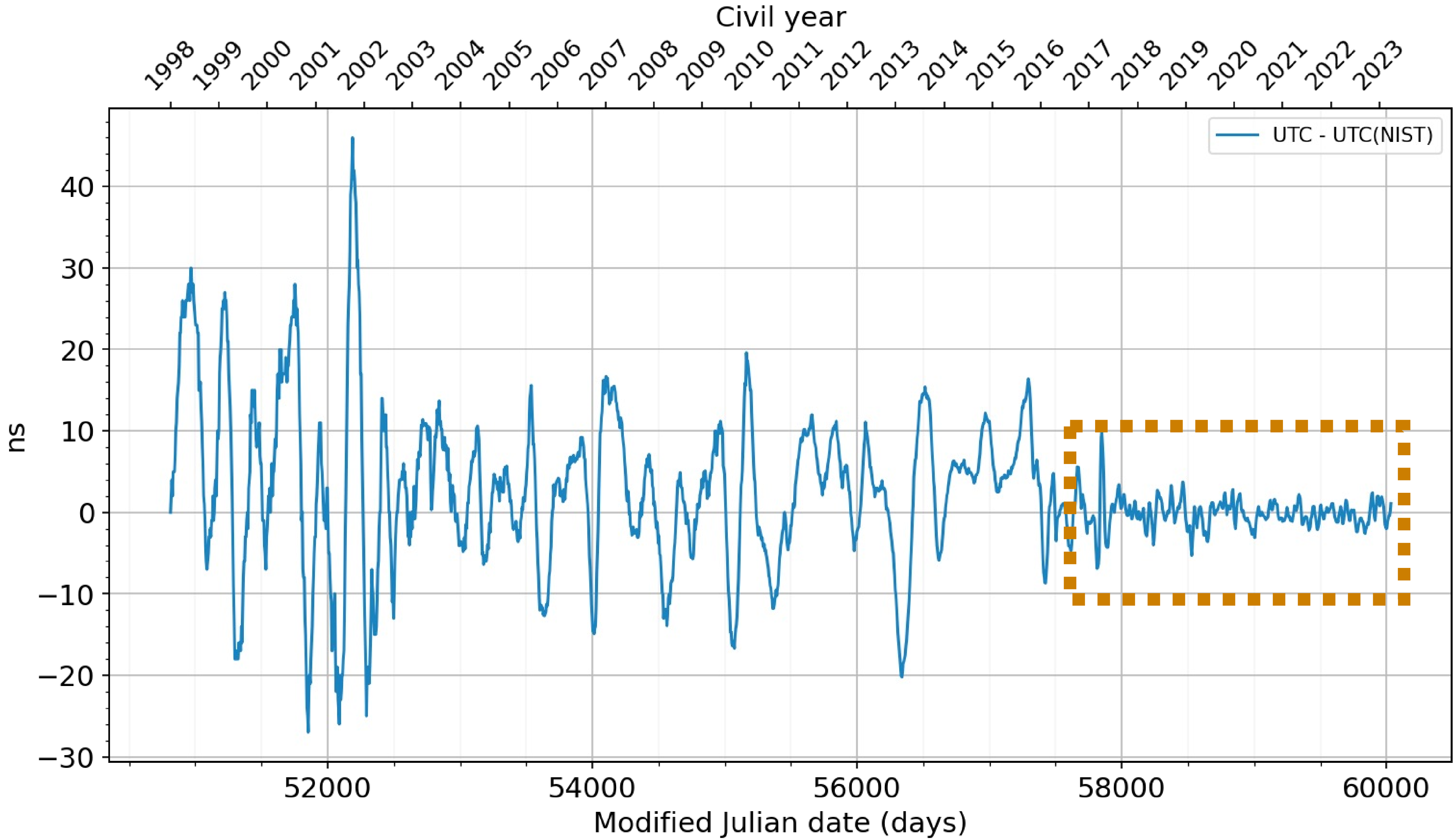
Time Realization & Distribution Group

The Time Realization and Distribution group distributes standard time and frequency signals generated by the Coordinated Universal Time scale, UTC(NIST), maintained at the NIST laboratories in Boulder, Colorado. UTC(NIST) is the U. S. national standard for time-of-day, time interval, and frequency.

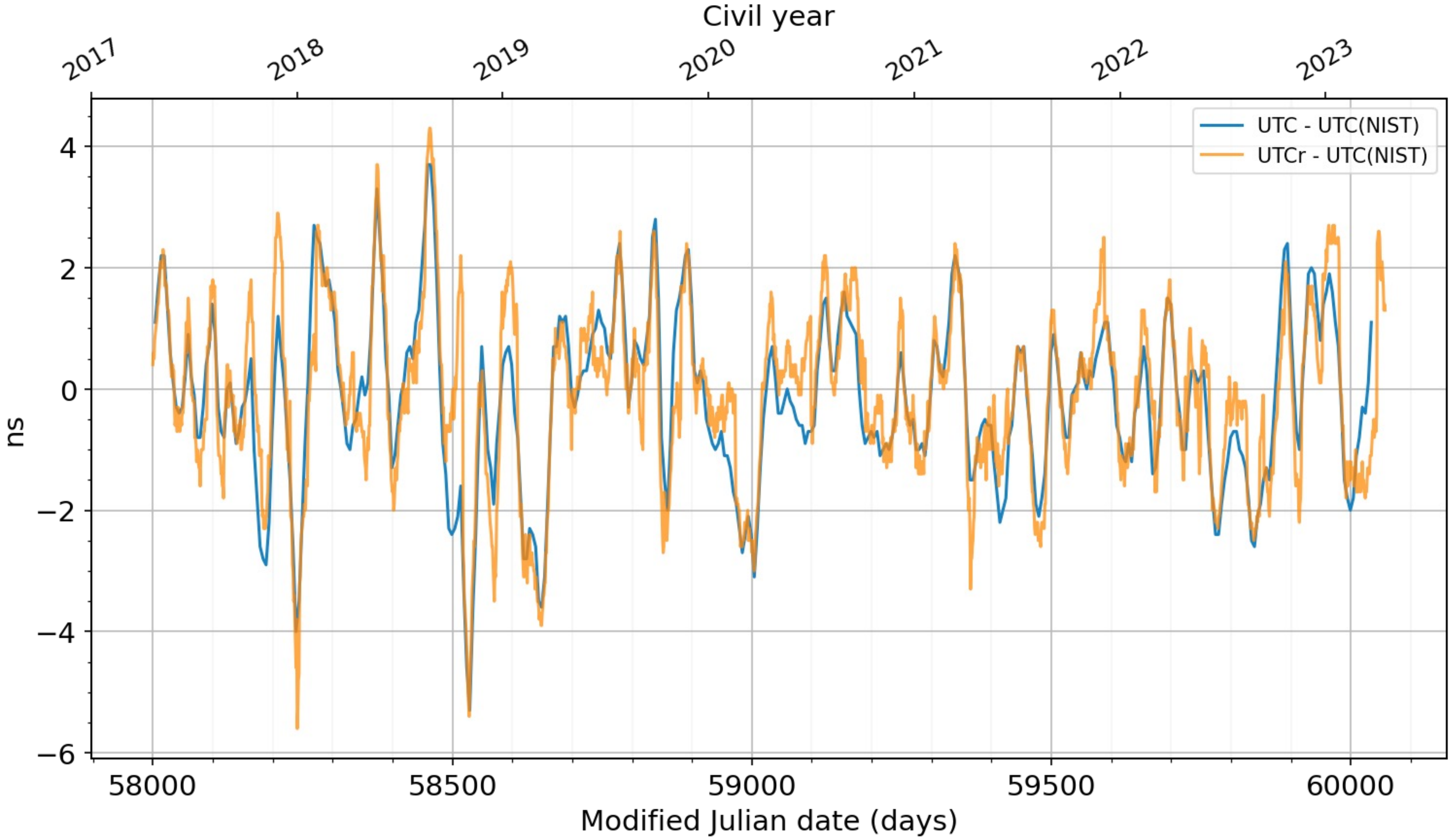
Synthesis of UTC(NIST)



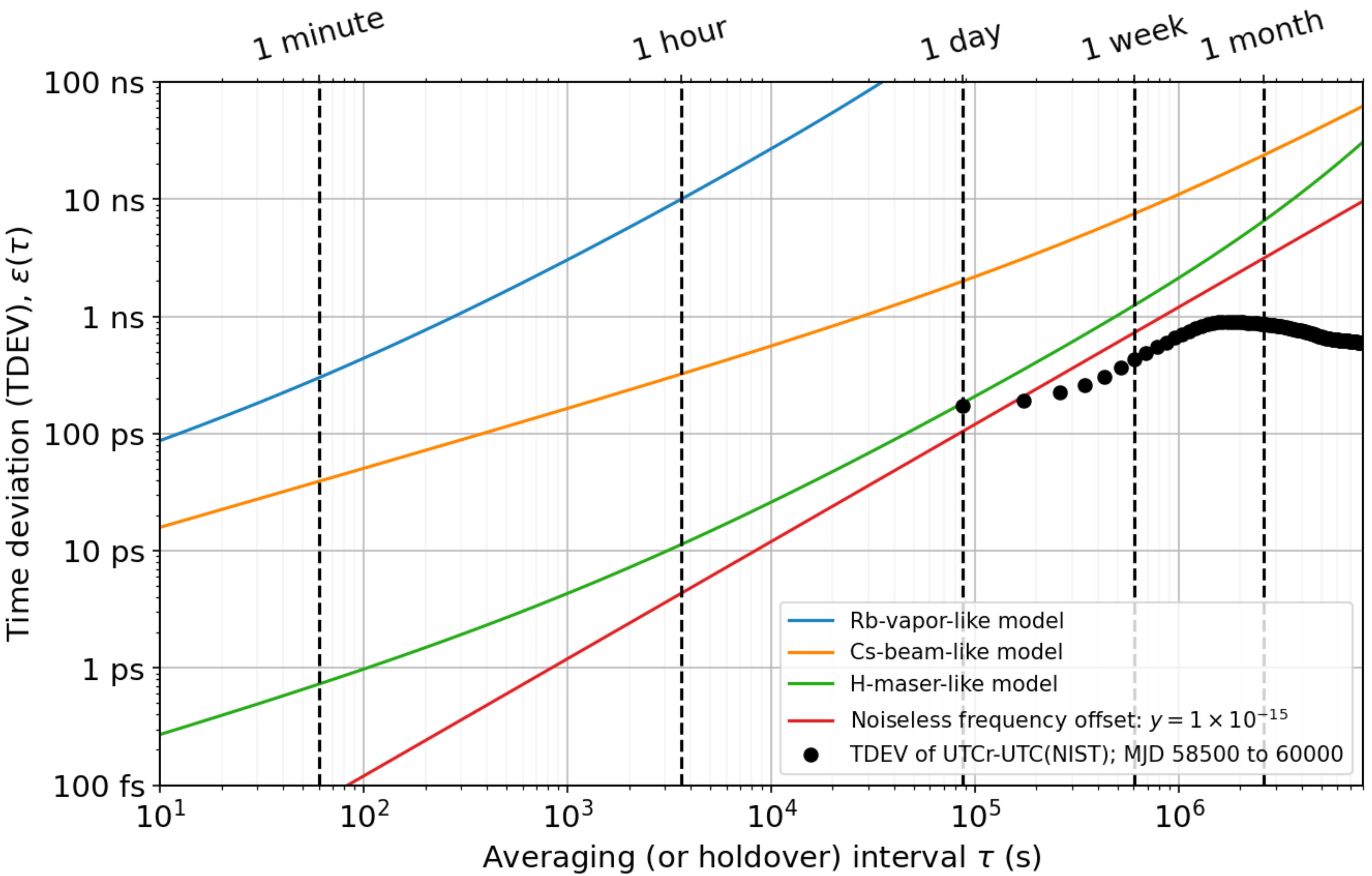
UTC(NIST): continual improvement with no discontinuities



UTC(NIST): peak offsets generally < 2 ns



UTC(NIST) performance compared to single atomic clocks

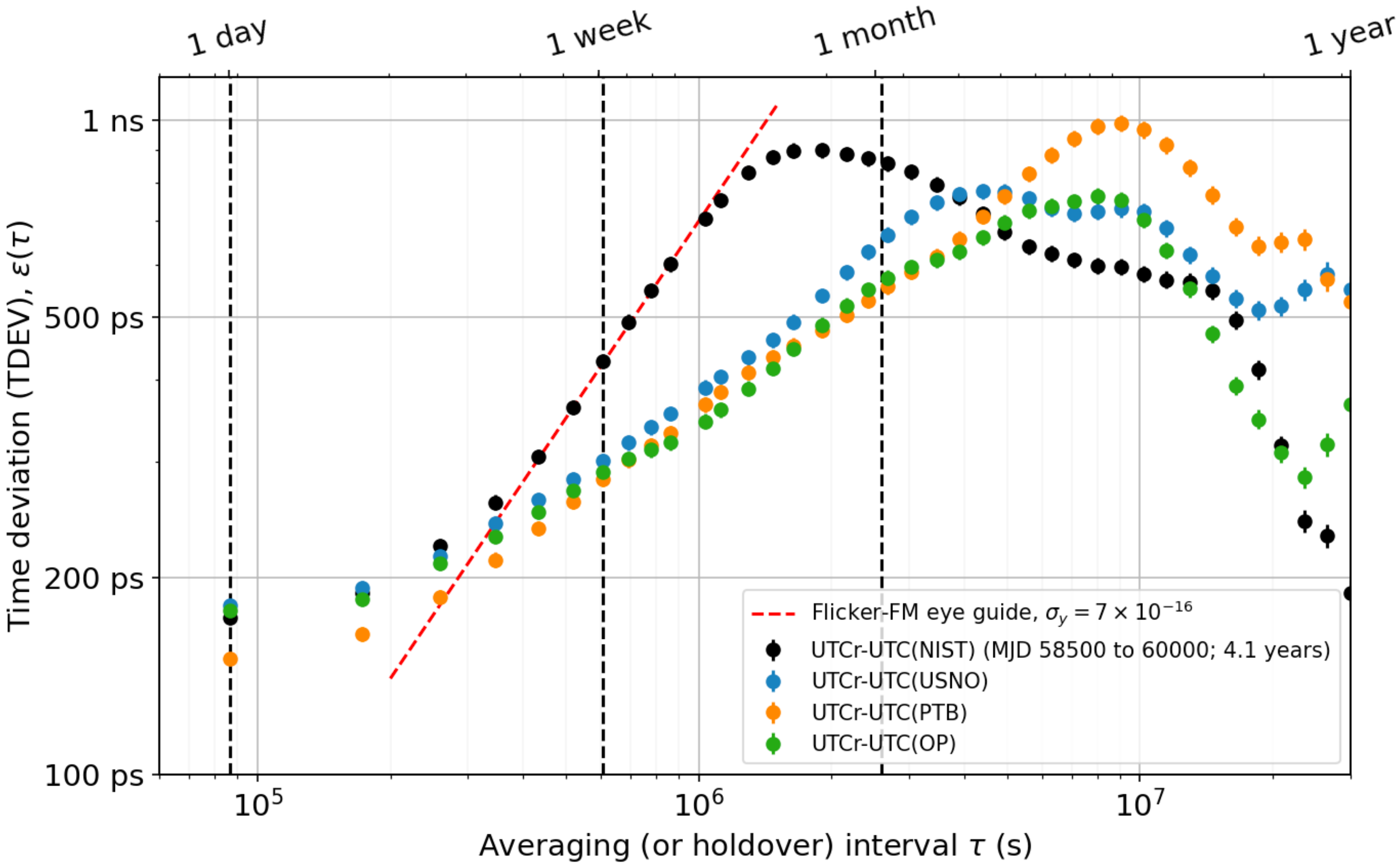


Stability, generally:

±1 ns

≤ 1 x 10^{-15}

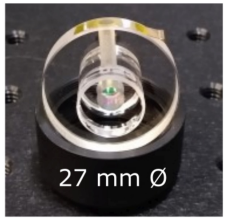
Opportunities for improvement



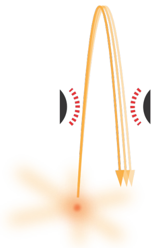
Over short intervals:
… incorporate optical clocks and oscillators

JILA Cryogenic Si-cavity

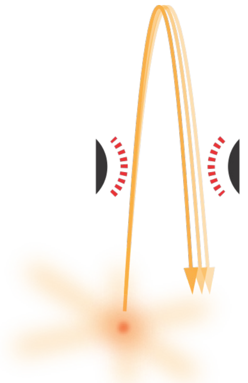
Commercial and NIST-developed cavities



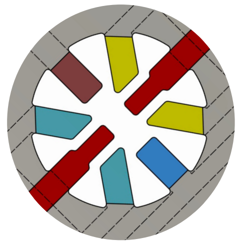
Over long intervals:
… use quasi-continuous atomic references



NIST-F3



NIST-F4



In development: NIST-Sr⁺

Status of NIST primary frequency standards

NIST-F1

Physically relocated.
Cavity re-etched.
Cavity fully replaced (aluminum).

2021: fatal biases identified.

New cavity (Cu); rebuilt.
First lock: May 3, 2023

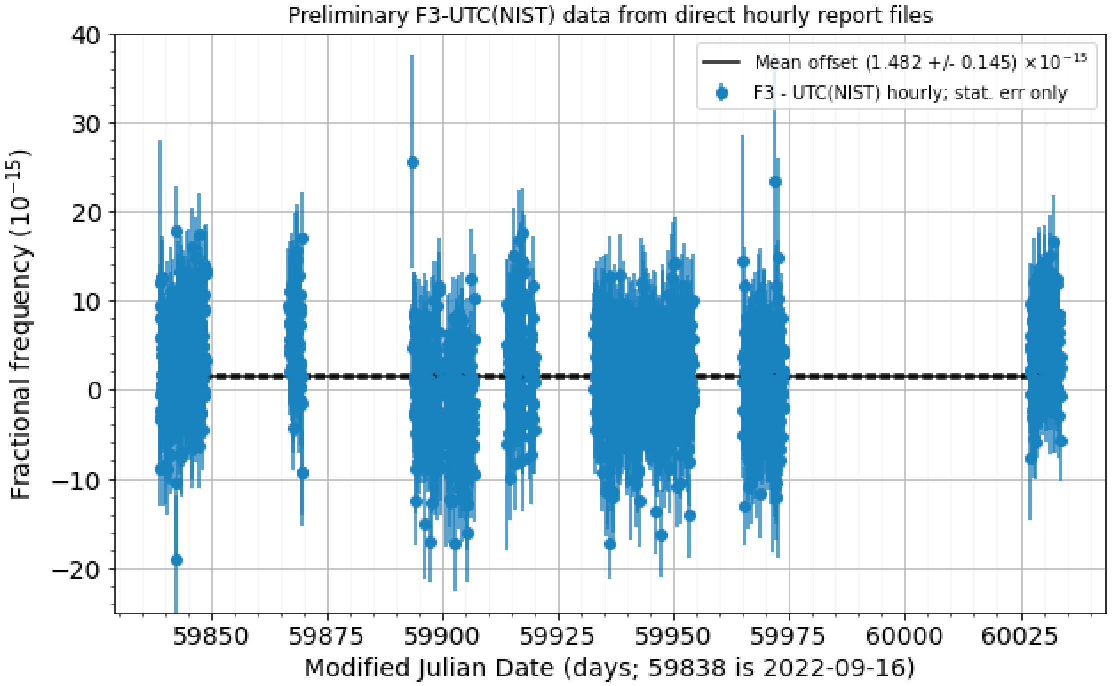
NIST-F4

NIST-F2 (Cryogenic)

Disabled

NIST-F3 (Simpler design)

Completed Sep. 2022.
Already operated at 34% duty cycle during commissioning study.



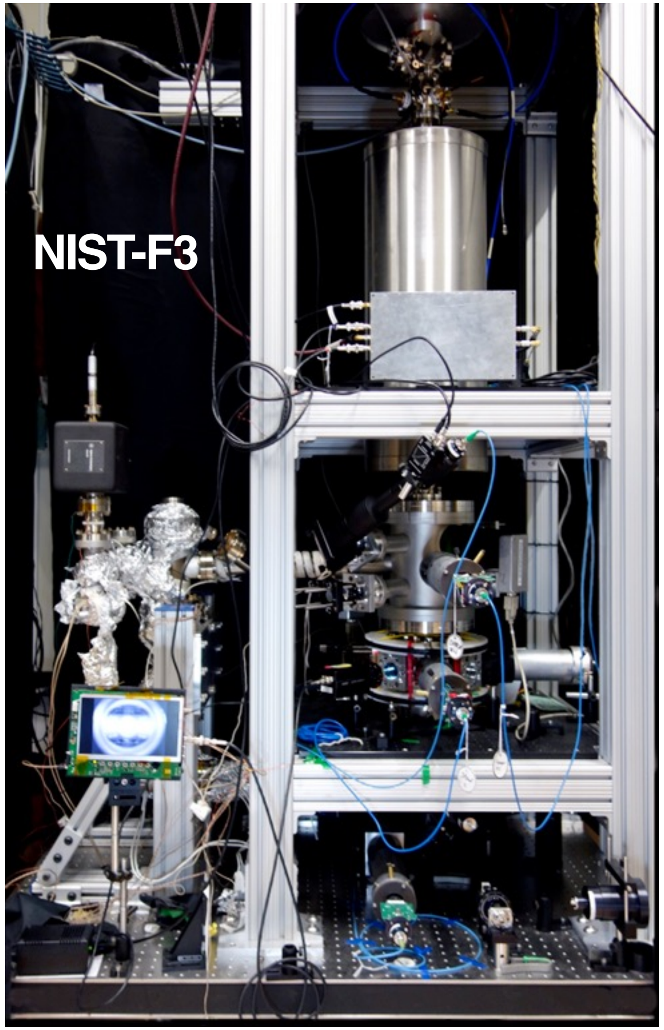
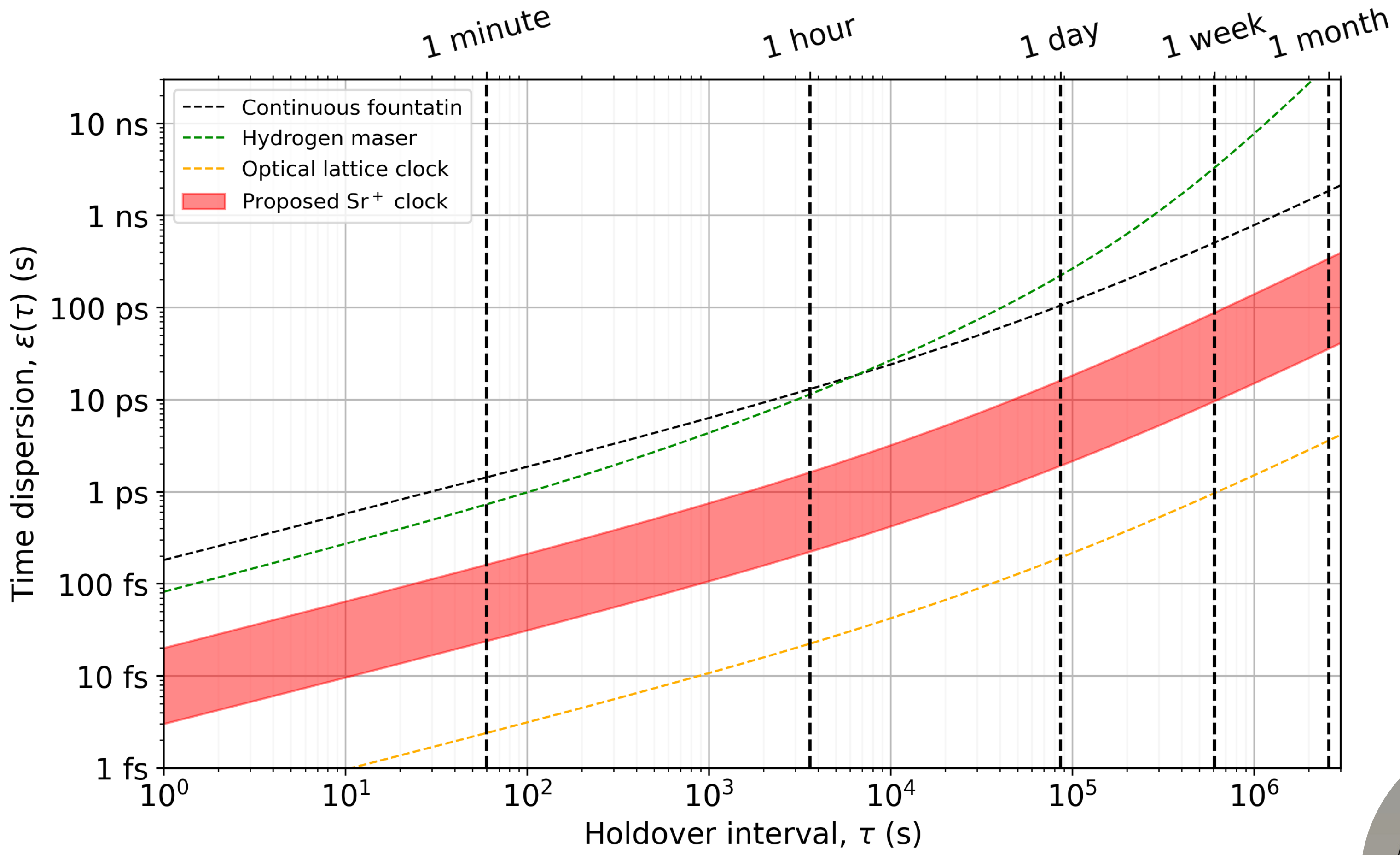
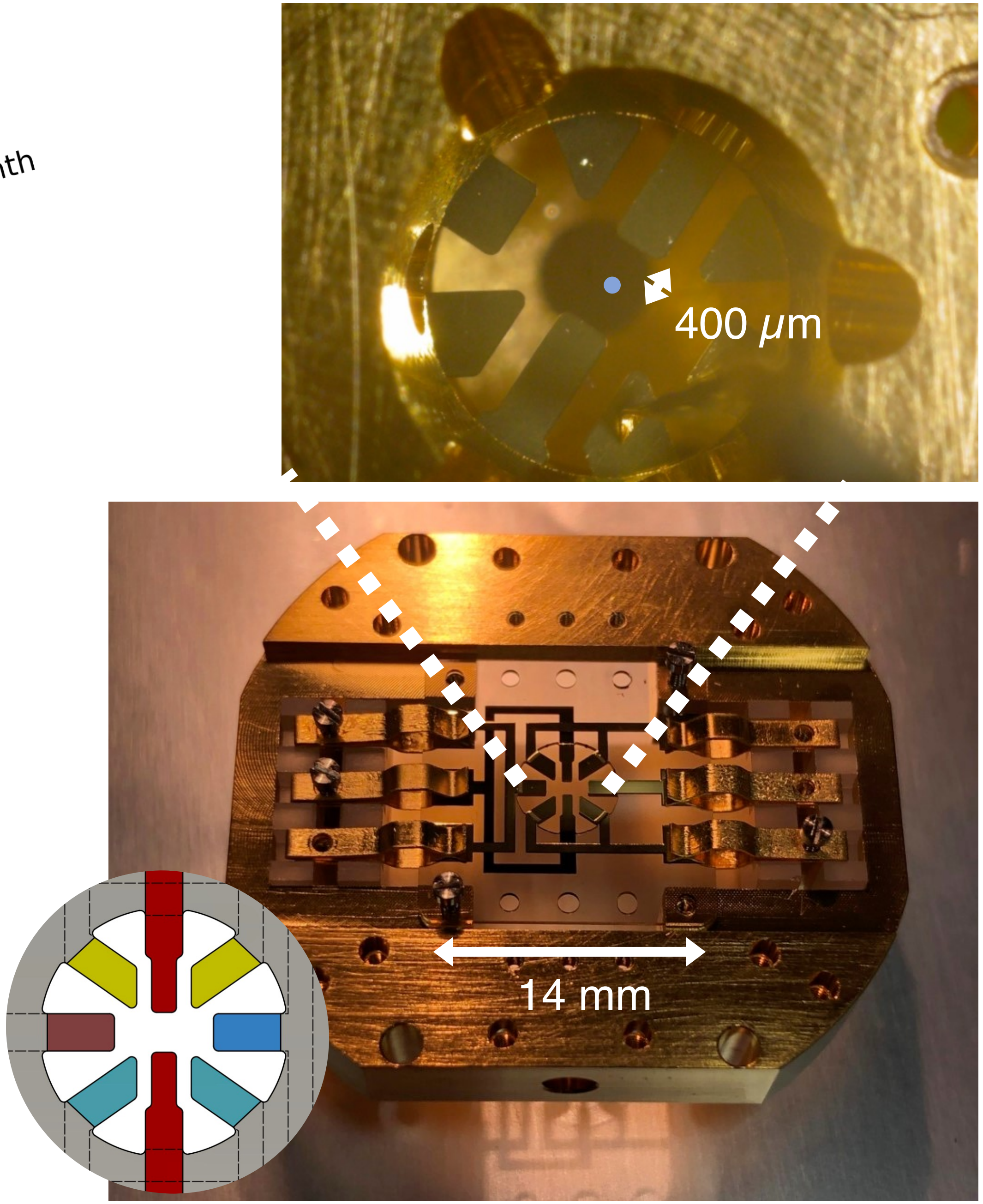


Photo (left): JILA machine shop, CU. Photo (right): Andrew Novick

A quasi-continuous < 10^{-16} "workhorse": $^{88}Sr+$





Plot: R Brown, J Sherman

NIST Network Time Services (J. Levine)

NIST National Institute of Standards and Technology U.S. Department of Commerce

NTP

Standard NTP and SNTP, open access

- 1 000 000 requests per second
  - 95% IP version 4
  - 5% IP version 6

Authenticated NTP, limited to registered users

- NTP + digital signature (details to follow)
- 1600 registered addresses, IPv4 only
  - Many international users (Americas, Europe, Asia …)

UT1 time in NTP format, open access

- UTC(NIST) + dut1 from IERS bulletin A (details to follow)
- 1000 IP addresses, IPv4 only

Services in other time formats

- 26 000 requests per second

All services provided at no cost to users

NIST Network Time Services (J. Levine)

NIST National Institute of Standards and Technology U.S. Department of Commerce

Authenticated NTP

- Standard NTP message + digital signature
- Signature computed from NTP message and key string
- Signature uses symmetric key method
  - Unique key for each organization
  - Signature formats:
    - MD5 (default, largest number of users)
    - SHA-1
    - SHA-256
    - HMAC-SHA-256 (Now being developed and tested)
- Users must register and submit IP addresses of clients
- Key linked to registered IP addresses
- Key distribution by out-of-band secure channel
- Four physical servers support this service
  - One at each site
  - All accept the same keys

Real Time GNSS

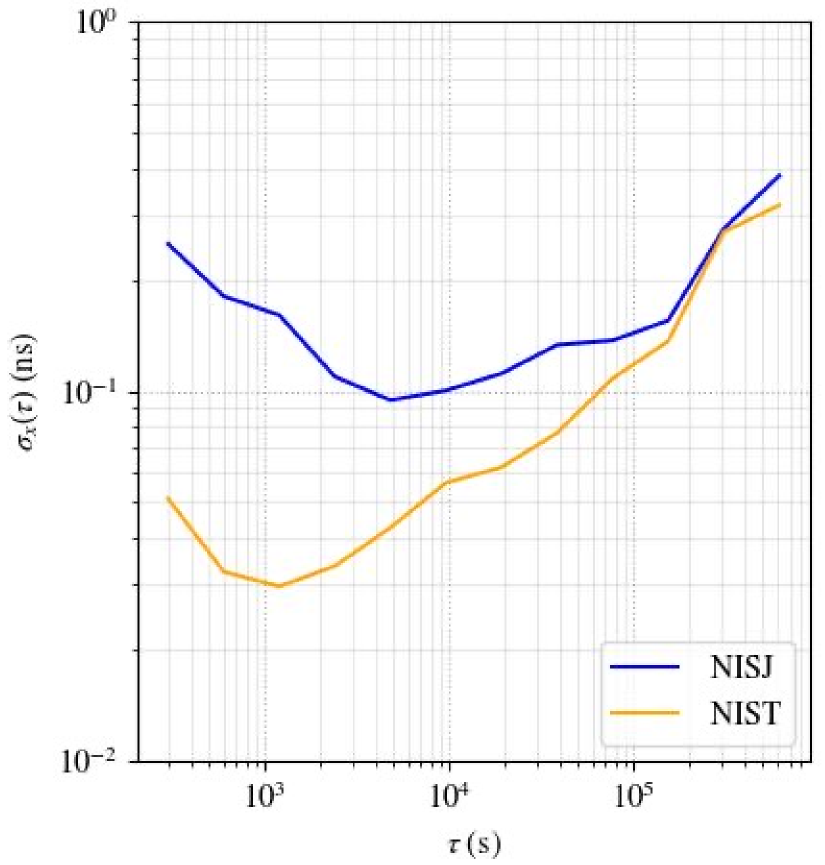
NIST National Institute of Standards and Technology U.S. Department of Commerce

CDDIS NASA's Archive of Space Geodesy Data

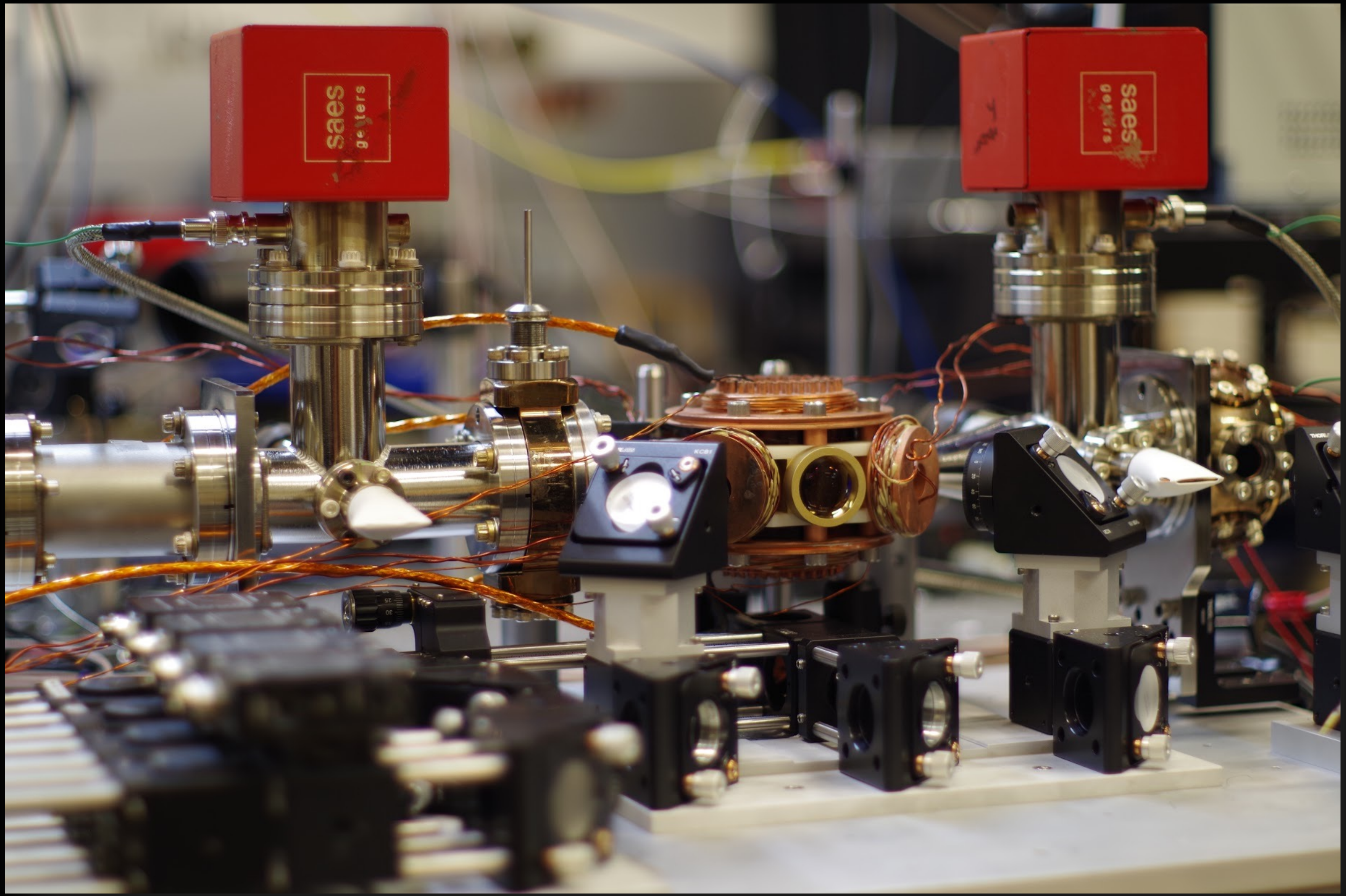
As an example, station clock performance (TDEV) over ~30 days processed every 5 min : NISJ00USA0 (NISJ) and NIST

Caster: https://cddis-caster.gsfc.nasa.gov/
Station ID: NISJ00USA0
Data rate: 1 Hz
Message: type 6 Multiple Signal Message
GPS L1,L2 observables: code, phase, CNR

Timing accuracy ~100 ps
Position accuracy < 2 cm in each direction



First Deployments of NIST's Transportable Yb Optical Lattice Clock



Wesley Brand, Tobias Bothwell, Robert Fasano, Tristan Rojo, Richard Fox, and Andrew Ludlow

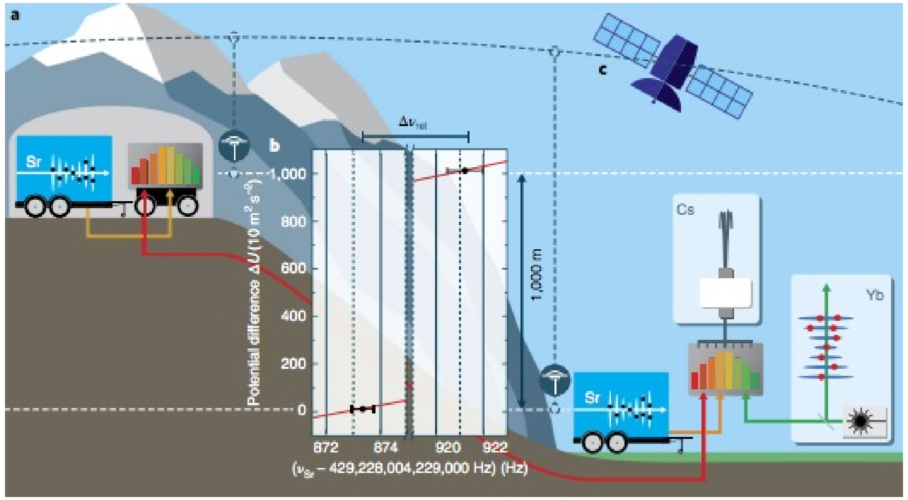
NIST, Neutral Atom Optical Clocks Group

NIST

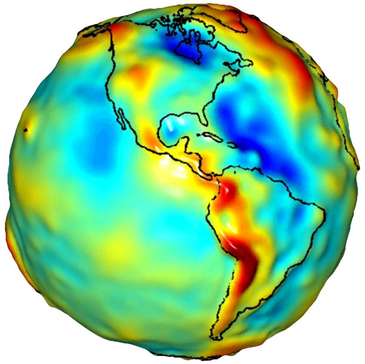
CGSIC 2023

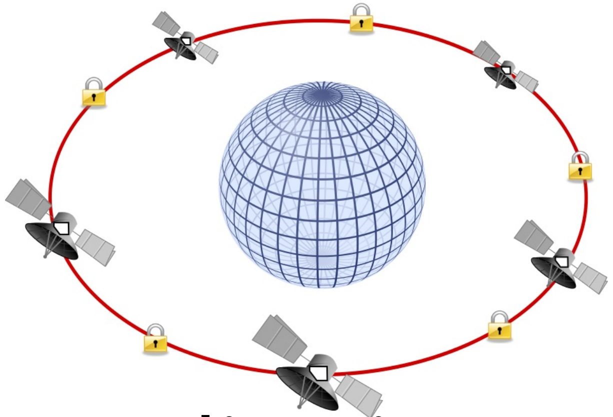
Portable Optical Lattice Clocks

Relativistic geodesy

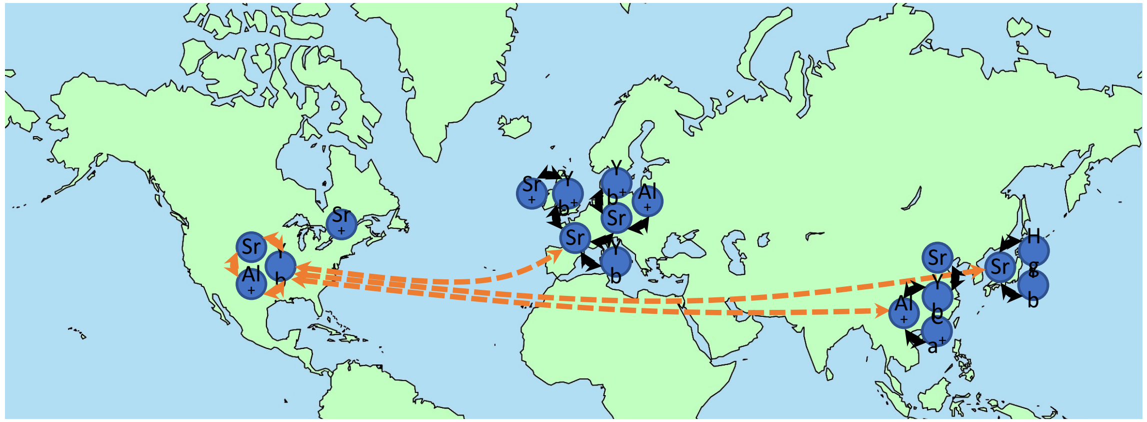


Grotti et al. "Geodesy and metrology with a transportable optical clock." *Nature Physics* (2018): 1.



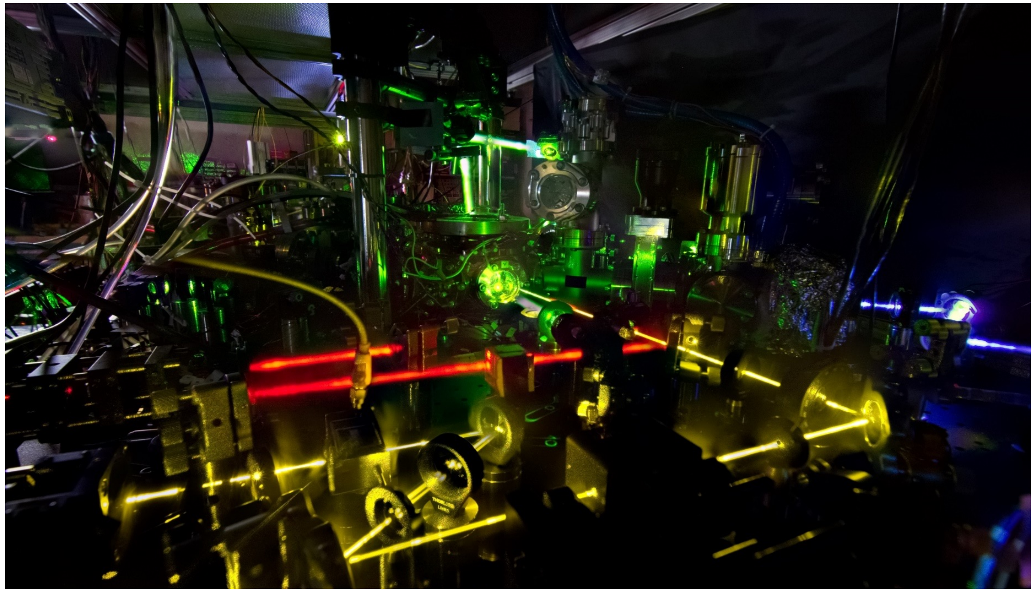


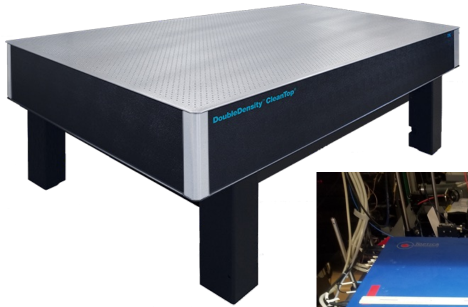
Space applications

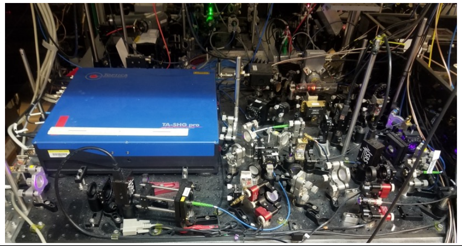


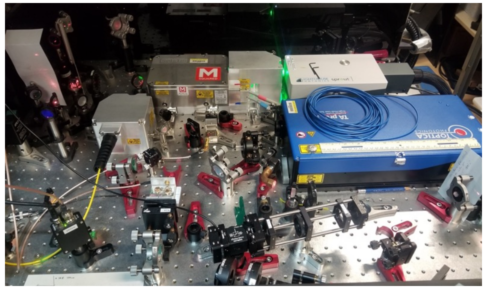
Redefinition of the second

Lab to Portable

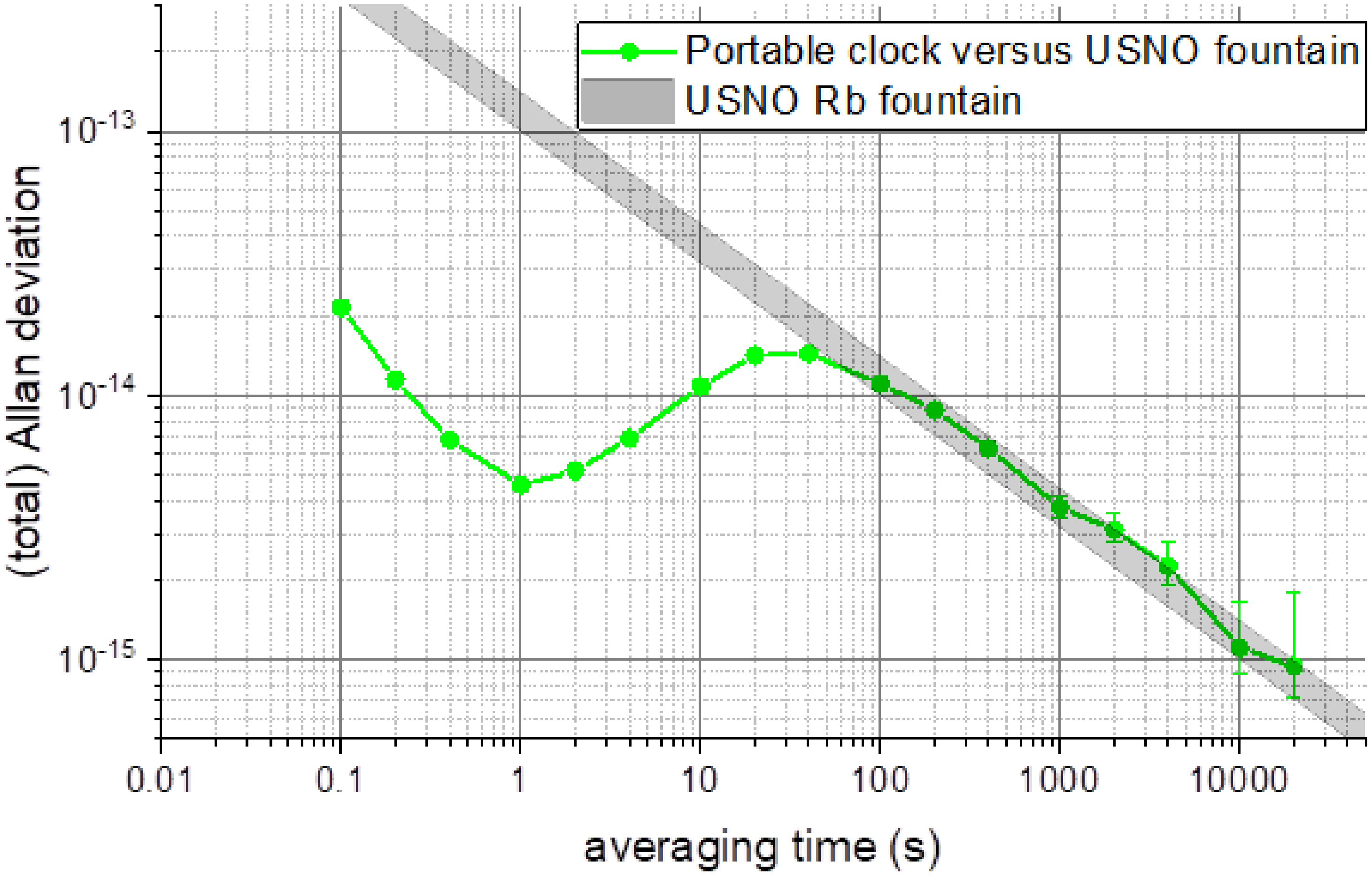








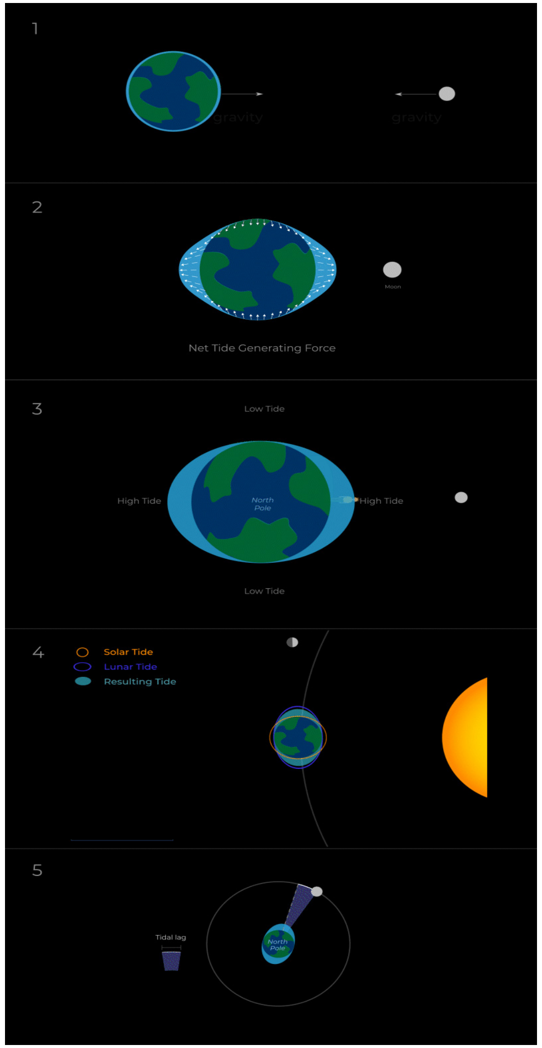
Portable Yb Versus USNO Rb @ 10 GHz



50,000 s overnight data run

Clock comparisons: Factors to consider (Ashby/Patla)

National Institute of Standards and Technology
U.S. Department of Commerce



Credit: NASA

Earth's gravitational potential	$\Delta f/f$
Monopole potential	-6.95348×10^{-10}
Quadrupole correction	-3.764×10^{-13}
Centripetal correction	-1.203×10^{-10}
Φ_0/c^2 (sum of all the above; IAU resolution)	$-6.969290134 \times 10^{-10}$
Quadrupole term induced orbit changes (non Keplerian)	$\sim 7.0 \times 10^{-15}$

Relativistic effects	$\Delta f/f$
Earth tide perturbation (affecting position and velocity)	$\sim 2.0 \times 10^{-15}$
Lunar tides	$\sim 2.5 \times 10^{-15}$
Solar tides (peak-to-peak)	$\sim 3.5 \times 10^{-15}$

Orbit determination	$\Delta f/f$
Position uncertainty , $\delta(GM/rc^2)$ for $\delta r \sim 0.1\,\mathrm{m}$	$\sim 1.0 \times 10^{-18}$
Velocity uncertainty, $\delta(v^2/2c^2)$ for $\delta v \sim 0.001\,\mathrm{m/s}$	$\sim 5.0 \times 10^{-17}$

Comparing frequency: coordinate systems (Ashby/Patla)

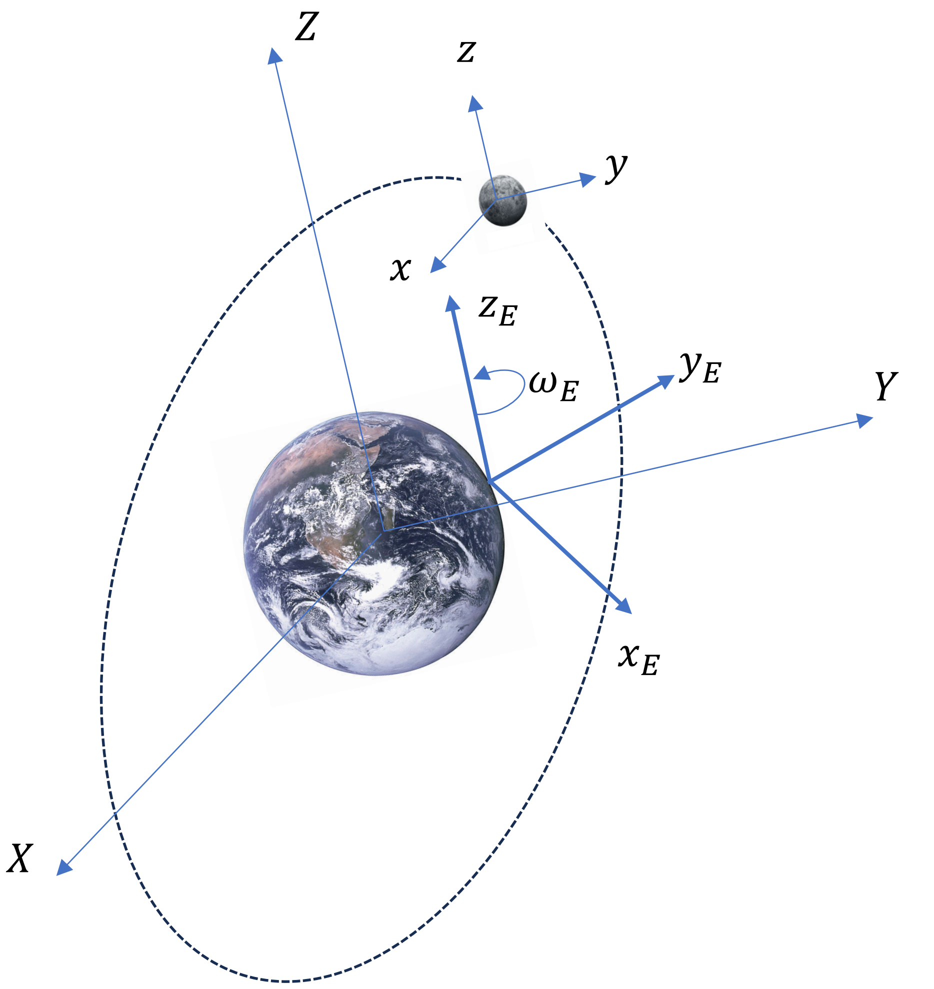
Earth-centered Inertial (ECI) :
Origin coincides with the earth's center X, Y, Z

Earth-centered Earth-fixed (ECEF) :
Rotates with earth x_E, y_E, z_E

Freely (almost) falling frame (FFF):
Parallel to ECI, origin coincides with center of mass of the satellite x, y, z

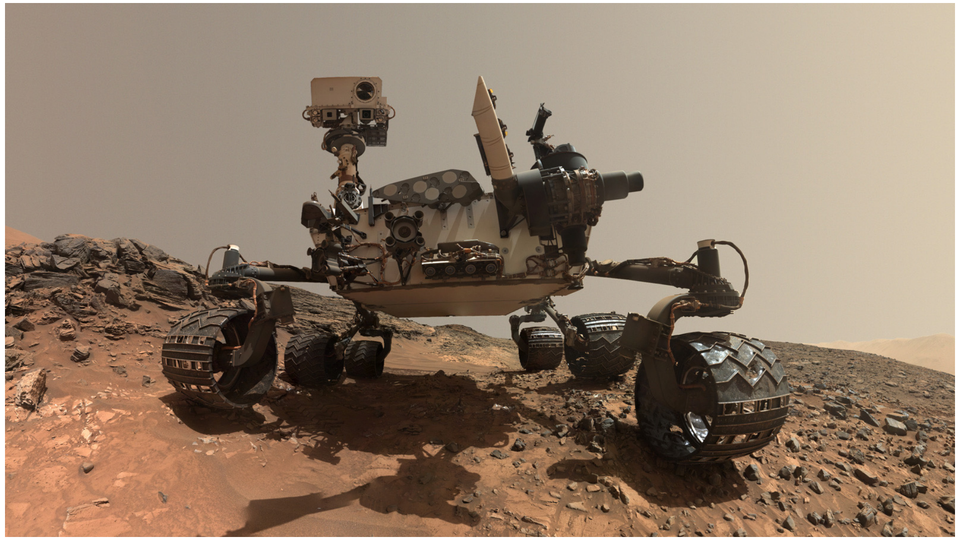
Keplerian orbit frame:
Orbital elements relate to ECI

Body-fixed frame:
Origin coinciding with CM of satellite and axes fixed to the satellite x_B, y_B, z_B



Exploration on Moon and Mars (Ashby/Patla)

Illustration of NASA astronauts on the lunar South Pole. Credit: NASA



Curiosity (rover) . Credit: NASA

$$\frac{f_B}{f_0} = 1 + \left(\frac{\phi_E - \phi_S}{c^2}\right) - \frac{V_G^2}{2c^2} - \frac{U^2}{2c^2} + \frac{Q_u^2}{c^2} - \frac{n^2(1-e^2)(x_B^2 + z_B^2)}{2c^2(1 - e\cos E)^4(1 + e\cos E)^2} - \frac{\omega_E^2(x_E^2 + y_E^2)}{2c^2}$$

$$U = \frac{n(1-e^2)^{1/2}(x_B k_z^B - z_B k_x^B)_u}{k^B(1 - e\cos E)^2(1 + e\cos E)} \qquad Q_u = \frac{\omega_E(x_E k_y^E - y_E k_x^E)_u}{k^E}$$

Ion Storage Group

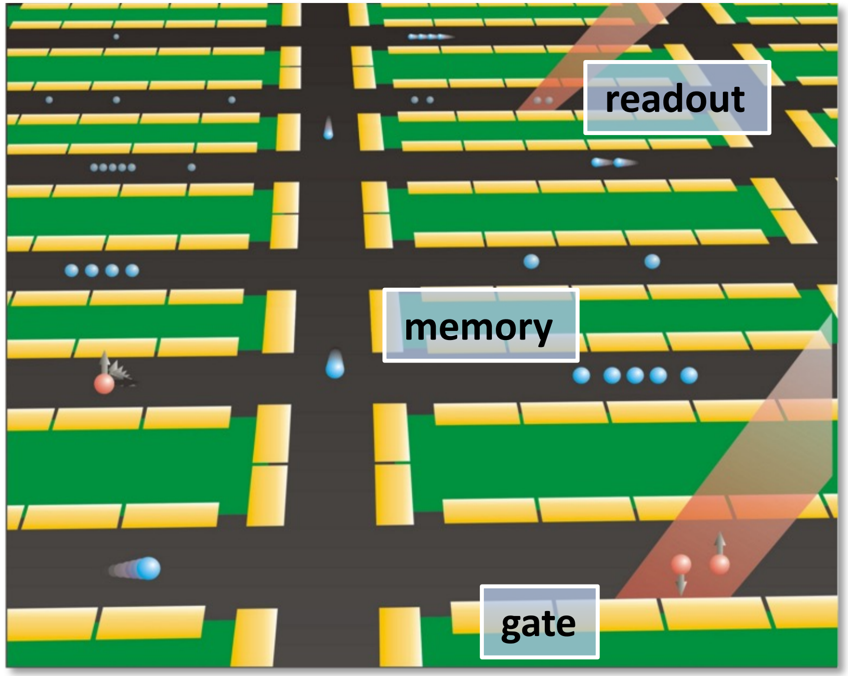
NIST National Institute of Standards and Technology U.S. Department of Commerce

The Ion Storage Group conducts experiments on atomic and molecular ions that are confined in vacuum in electromagnetic traps. We cool and manipulate the ions with lasers and electric or magnetic fields for applications in quantum information science and precision measurement.

Techniques for scalable trapped ion QIP

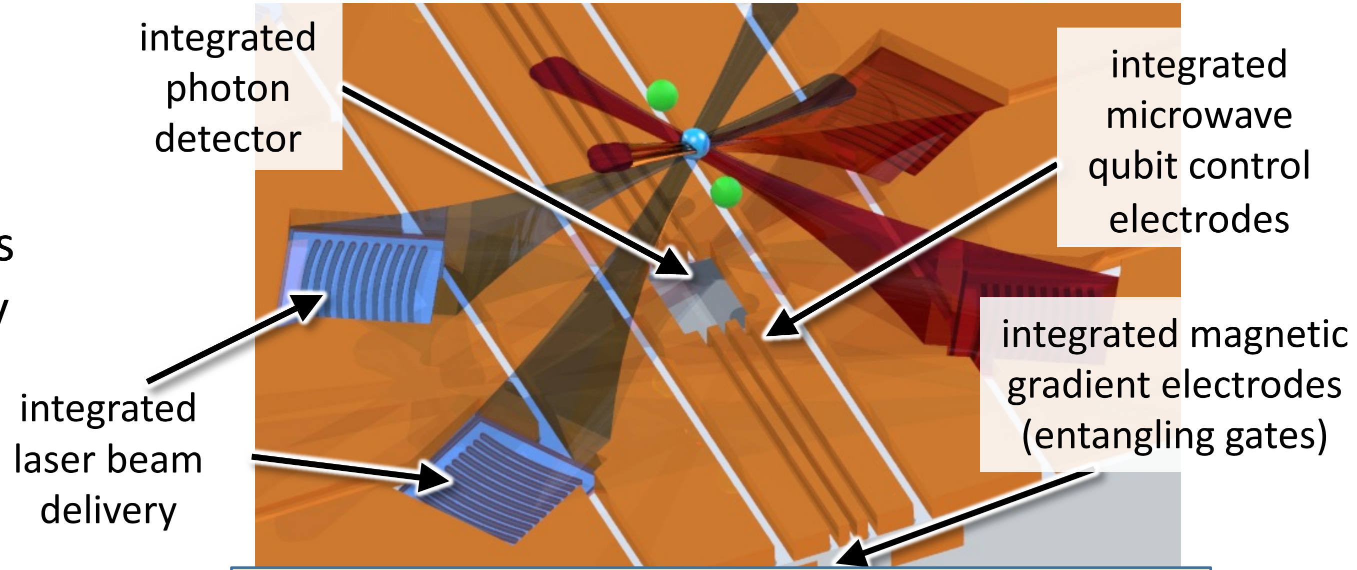
Trapped ion qubits

- Coherence times ~minutes – **good clocks too!!**
- High-fidelity qubit state control and readout
- **Scaling:** microfabricated multi-zone traps
  - Move/rearrange ions in trap for interactions
  - Pioneered at NIST, now adopted by industry

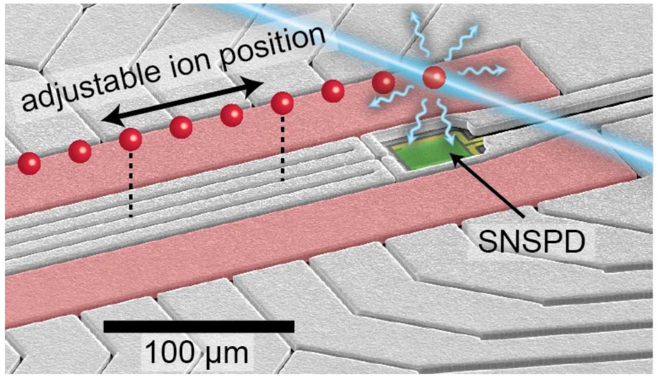


D. Wineland *et al.*, Proc. ICAP **15,** 31 (1996)
D. Wineland *et al.*, J. Res. NIST **103,** 259 (1998)
Kielpinski, Monroe, Wineland, Nature **417,** 709 (2002)

The next frontier: control/readout integration

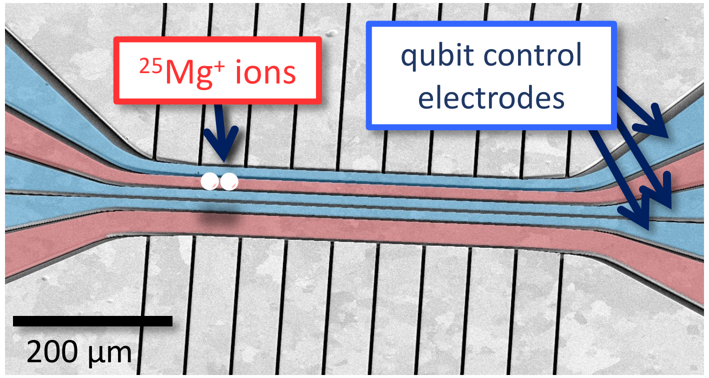


integration => scalability, stability, robustness



detector integration prototype

Todaro *et al.*, PRL **126**, 010501 (2021)

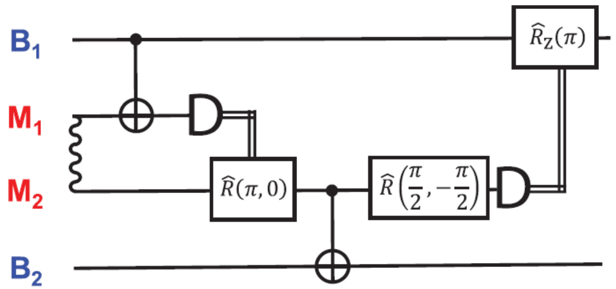


control integration prototype

Srinivas *et al.*, Nature **597**, 209 (2021)

Recent scientific highlights – trapped ion QIP

NIST

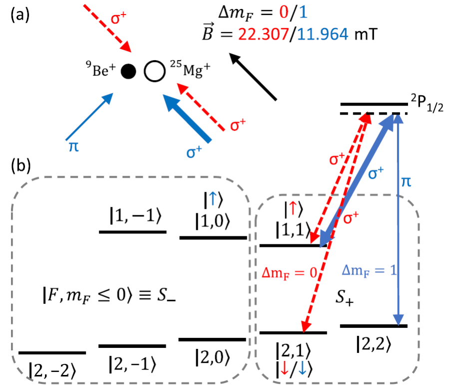


Teleportation of an entangling gate

entangle remote qubits

⇒ essential for quantum networks

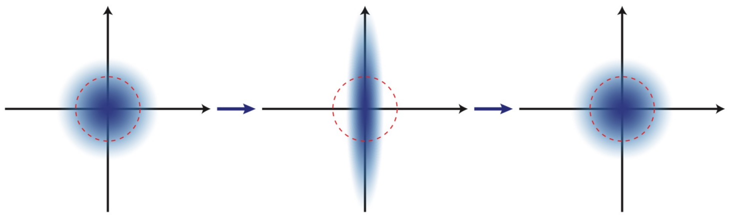
Science **364**, 875 (2019)



High-fidelity indirect qubit readout

qubit readout error ~10^{-4} or below

PRL **128**, 160503 (2022)



Quantum squeezing of ion motion

up to 21 dB of reversible squeezing

⇒ metrological gain for sensing

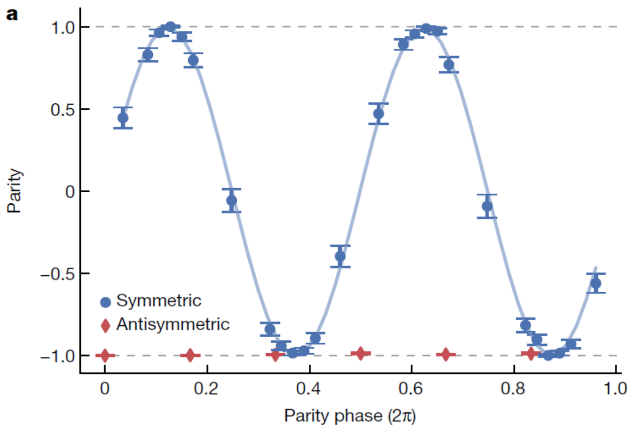
⇒ speedup of quantum dynamics

Science **364**, 6446 (2019)

Nature Phys. **17**, 898 (2021)

Science **373**, 673 (2021)

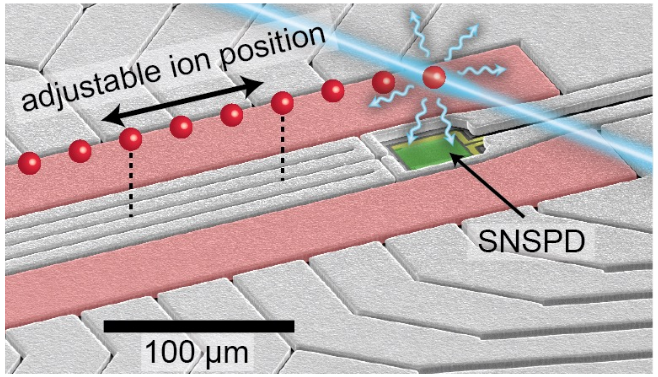
arXiv 2304.05529 (2023)



Scalable laser-free entanglement

fidelity equivalent to best laser-based schemes

Nature **597**, 209 (2021)



Trap-integrated photon detectors for readout

qubit readout error ~10^{-3}

PRL **126**, 010501 (2021)

APL **122**, 174001 (2023)

Time Realization & Distribution

https://www.nist.gov/pml/time-and-frequency-division/time-services

Neutral Atom Optical Clocks

https://www.nist.gov/pml/time-and-frequency-division/neutral-atom-optical-clocks

Ion Storage

https://www.nist.gov/pml/time-and-frequency-division/ion-storage