SUMMARY OF THE BIPM QUANTUM METROLOGY WORKSHOP

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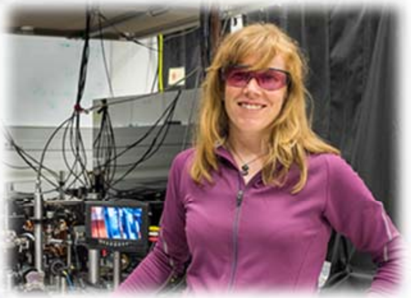
October 19, 2017

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



PML
PHYSICAL MEASUREMENT LABORATORY

Summary: Quantum Revolution in Metrology

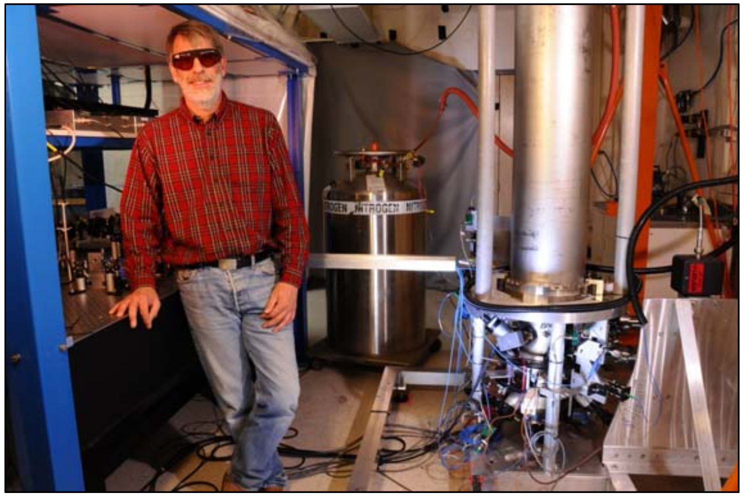
- Workshop held on September 28-29, 2017 at the BIPM in Sèvres
  - 135 participants from 40 National Metrology Institutes (NMIs), universities, and research laboratories
  - 20 countries represented, 19 oral presentations including 4 review talks, over 60 posters in 2 sessions
- Five oral sessions covering:
  - Single photon measurements, radiometry with entangled sources, superconducting particle detectors
  - Quantum standards for mass, pressure, vacuum, temperature, acoustics and vibration
  - Highly entangled systems for metrology, entangled optical clocks
  - Advances in quantum electrical standards, single electron transistors and demonstrations of the "quantum metrology triangle
  - Beyond quantum metrology

Quantum Standards from Past to Future

- Two sessions focused on *existing but evolving* quantum standards:
  - *Electrical units* which are more than 25 years old
  - *Atomic clocks* (time and frequency) which have been in existence for more than 60 years
- Two sessions focused on *new or pending* quantum standards:
  - *Photometry/radiometry*, single photon measurements, and single and entangle photon source, superconducting particle detectors
  - *Mass, pressure, vacuum, temperature, acoustics and vibration*
- One session on *future* quantum standards/technologies with concepts coming from all sessions – including:
  - Atomic scale magnetometry, chip scale clocks, entangled clocks, relativistic geodesy
  - Quantum interference to human perception
  - Improved sensitivity and resolution due to quantum entanglement

Existing Quantum Standards: Power of One Qubit

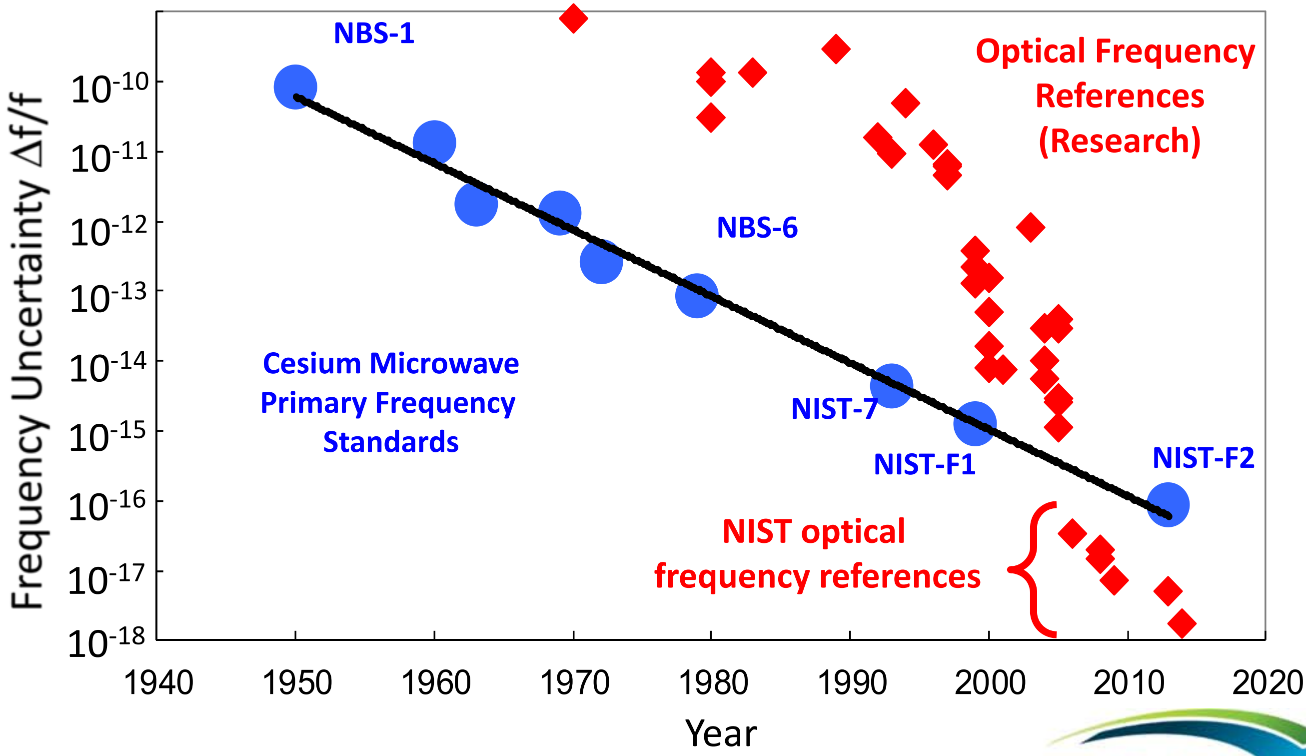
1 second is defined as the duration of 9,192,631,770 cycles of the cesium hyperfine transition.



NIST-F2 laser-cooled atomic clock

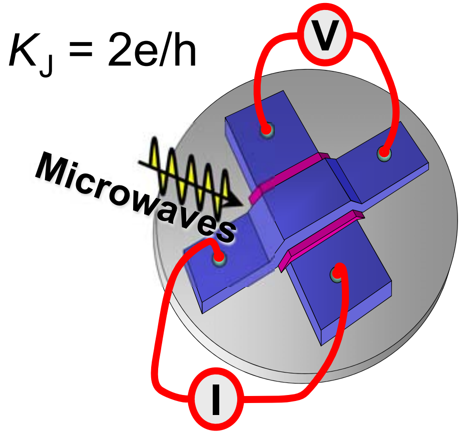
- Frequency uncertainty: $\Delta f/f = 1 \times 10^{-16}$
- 1 second in 300 million years.
- Enabled by laser cooling and trapping.

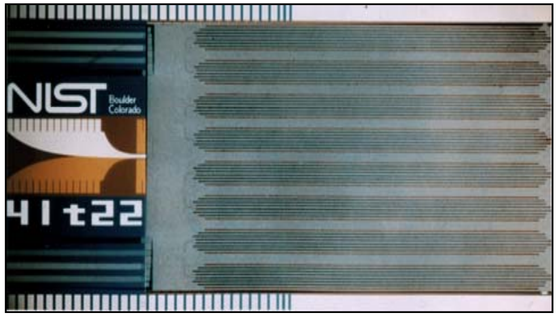
- Optical frequency standards have shown better fractional uncertainty since 2005
- Possible redefinition of time being discussed for 2026



Existing Standards for Electrical Units Since 1990

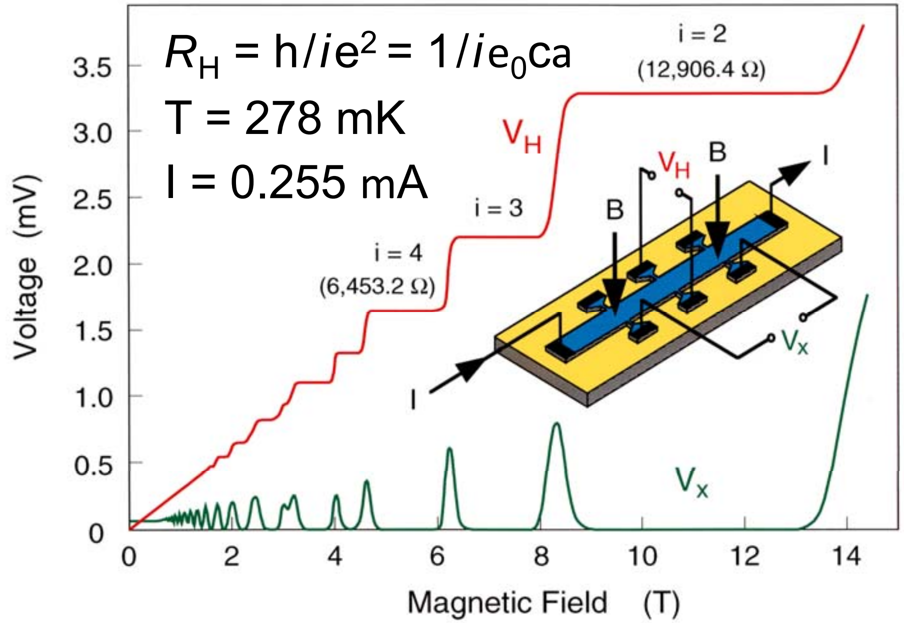
Josephson Voltage Standard





The "volt" realized by Josephson Junction devices, with K_{J-90} = 483,597.9 GHz/V

GaAs Quantum Hall Resistance



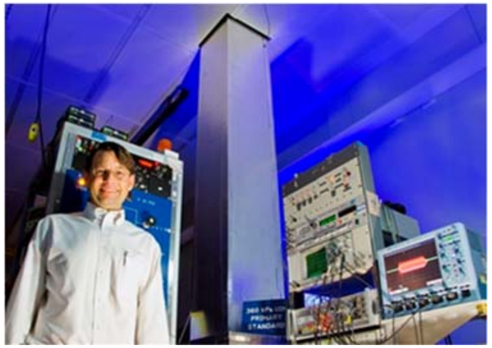
The "ohm" realized by Quantum Hall Effect devices, with R_{K-90} = 25,812.807 Ω
(Graphene QHR underway)

$R_K = h/e^2$
or $R_H = R_K/i$

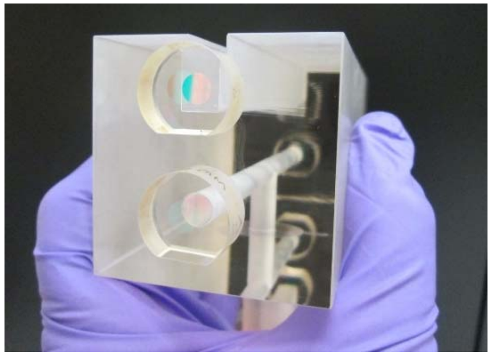
These quantum standards, the Josephson effect (1962, Nobel Prize 1973) and the quantum Hall effect (von Klitzing 1980, Nobel Prize 1985) are so robust that in 1987 the CGPM (Resolution 6) established *conventional electrical units!*

Basically, we do not realize the Ampere and we use non-SI units

New Quantum Pressure Standard and Sensor



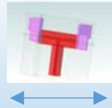
Hg manometer



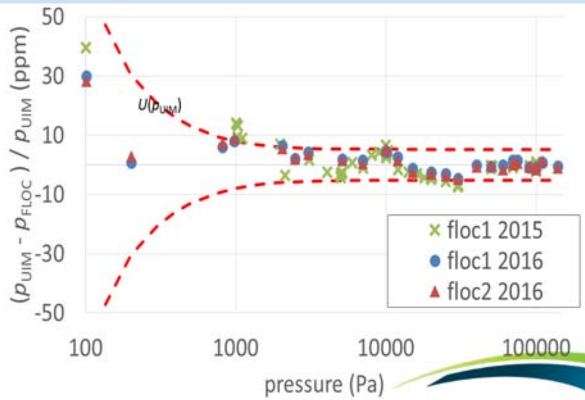
Photonic standard

- Elimination of mercury-based pressure standards
- Range of 1 mPa to 1,000 kPa (10 atm): 8-decades of pressure measurement
- 35× more sensitive
  - Resolution of 0.1 mPa
- 100× faster
  - Replaces inherently slow electrical-based measurements
- Uncertainty smaller than Hg manometer
  - Identifies unknown limitations of UIMs
  - FLOC better than planned (Primary Standard)

Brings SI to the factory floor



- Pressure and Length
- Reducible to size of cell phone
- Replaces multiple commercial gauge technologies

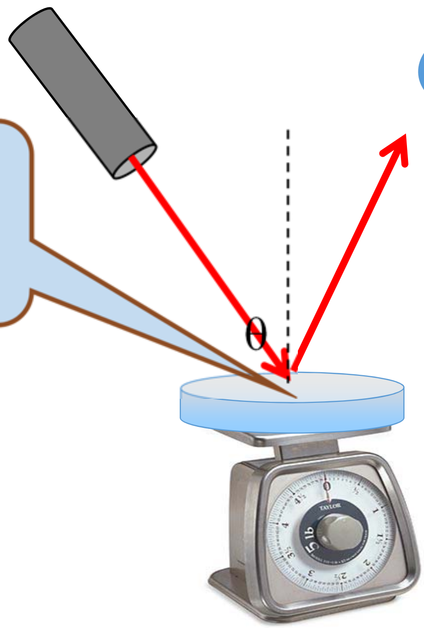


New/Pending: Measuring Radiation Force

A precision scale with a mirror can measure the radiation force of light.

Minimal absorption, power-scalable, no thermal recovery time.

laser light still available for use

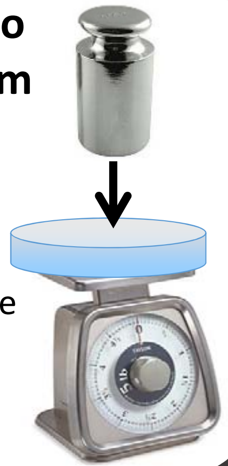


$$F = (2P / c) r \cos\theta$$

F = Force (Newtons)
P = optical power (Watts)
c = speed of light (m/s)
$r = R + (1-R)\alpha/2 \rightarrow$ reflectivity
θ = angle of incidence

$$P = F \cdot (c / 2r \cos\theta)$$

Traceable to the kilogram



Calibration done with a standard mass.

Williams, *et al.*, Optics Letters **38**, 4248-4251 (2013)

Measuring Radiation Force: Sensitivity

Laser power	Application	Equivalent mass	Comparable mass
10 W	marking	6.7 microgram	eyelash 
1 kW	welding/cutting	670 microgram	grain of sand 
100 kW	Research / Defense	67 milligrams	two staples 

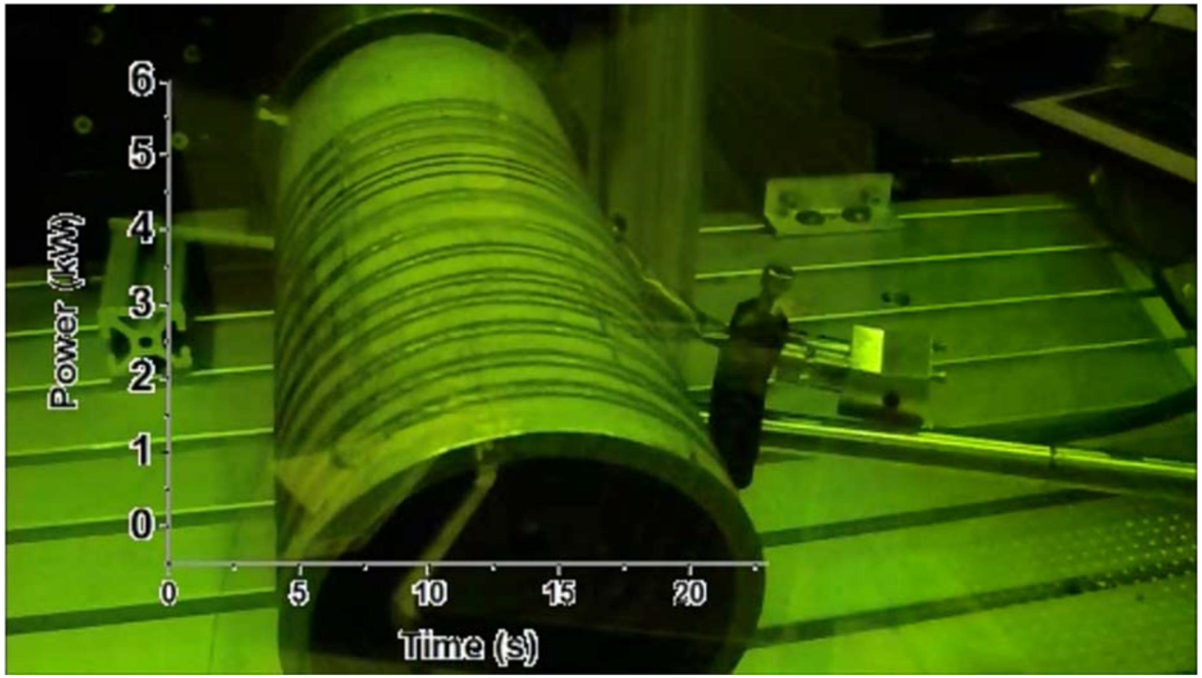
Conversion factor (for normal incidence and perfectly reflecting mirror):

$$k = 6.67 \times 10^{-9}\ \mathrm{N/W} \longrightarrow 670\ \mu\mathrm{g}\ /\ \mathrm{kW}$$

"The photonic mole:" One mole of photons at wavelength of 1 μm is approximately 120 kW

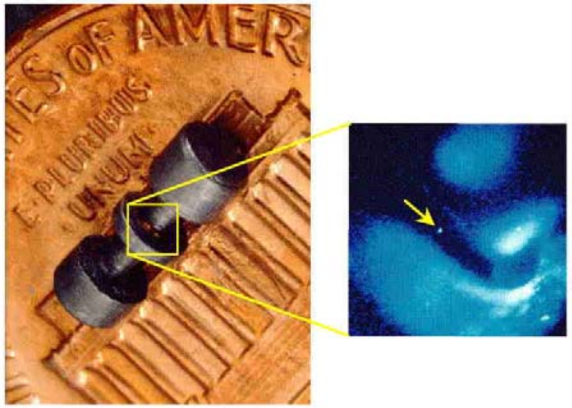
Embedded Standard: Towards a Calibrated Laser Weld

- First real-time, calibrated laser power measurement during a laser weld
- New radiation pressure technique measures the very small force of light as it reflects from a mirror
  - Force is proportional to laser power
  - Laser beam not absorbed, also used for the weld
  - Force measured with sensitive, commercial scale

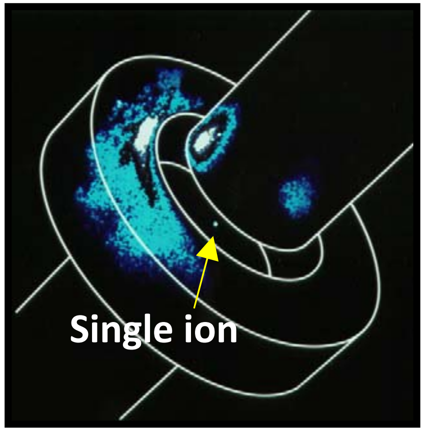


B. Simonds, P. Williams, J. Sowards, J. Hadler

Future Quantum Standards: Optical Frequency Standards

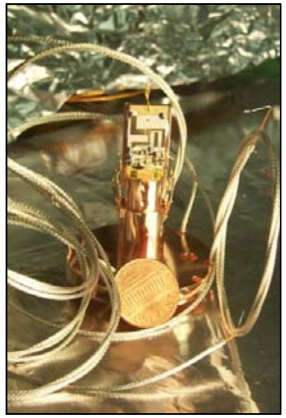


$\Delta f/f \sim 10 \times 10^{-18}$



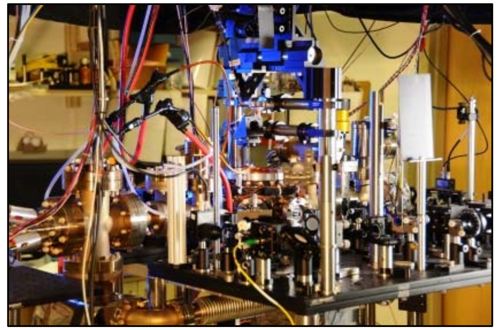
Single mercury ion trap

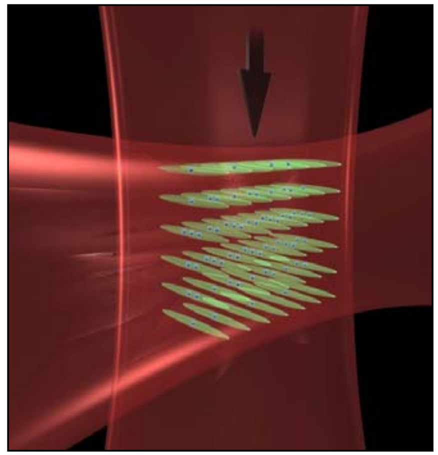
$\Delta f/f \sim 8 \times 10^{-18}$



Aluminum ion logic clock

$\Delta f/f \sim 2 \times 10^{-18}$





Strontium or Ytterbium optical lattice clocks

- High-frequency optical clocks outperform microwave (cesium) clocks.
- Potential to perform ~100 times better than best cesium clocks
- Many years before SI second redefined to optical standard(s) *(est. now 2026)*

Quantum Logic Clock & Metrology

Science <u>329</u>, 11630, 2010

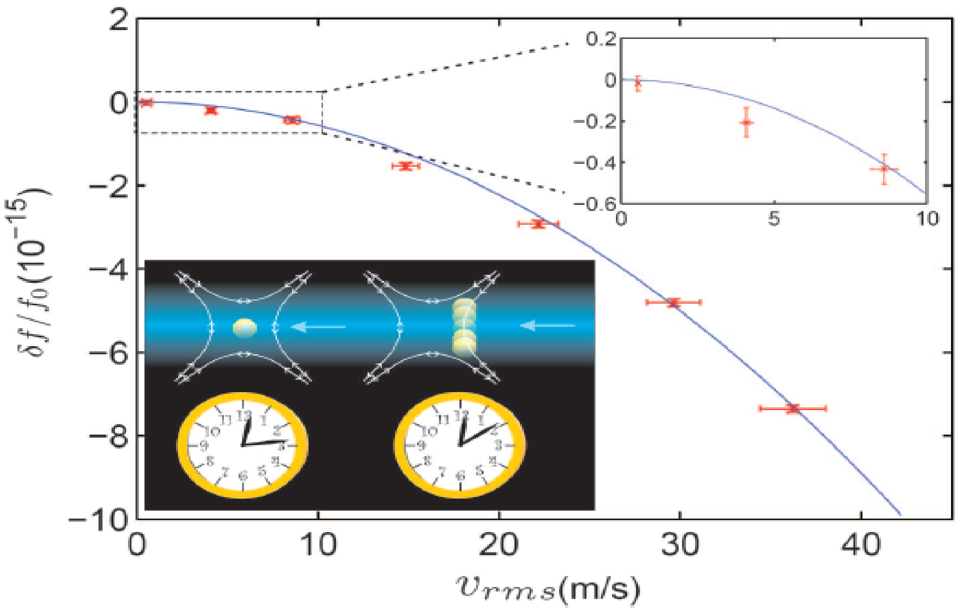


Fig. 2. Relativistic time dilation at familiar speeds (10 m/s = 36 km/hour ≈ 22.4 miles/hour). (Lower left inset) As the Al^+ ion in one of the twin clocks is displaced from the null of the confining RF quadrupole field (white field lines), it undergoes harmonic motion and experiences relativistic time dilation. In the experiments, the motion is approximately perpendicular to the probe laser beam (indicated by the blue shading). The Al^+ ion clock in motion advances at a rate that is slower than its rate at rest. In the figure, the fractional frequency difference between the moving clock and the stationary clock is plotted versus the velocity ($v_{rms} = \sqrt{\langle v^2 \rangle}$) (rms, root mean square) of the moving clock. The solid curve represents the theoretical prediction. (Upper right inset) A close-up of the results for $v_{rms} < 10$ m/s in the dashed box. The vertical error bars represent statistical uncertainties, and the horizontal ones cover the spread of measured velocities at the applied electric fields.

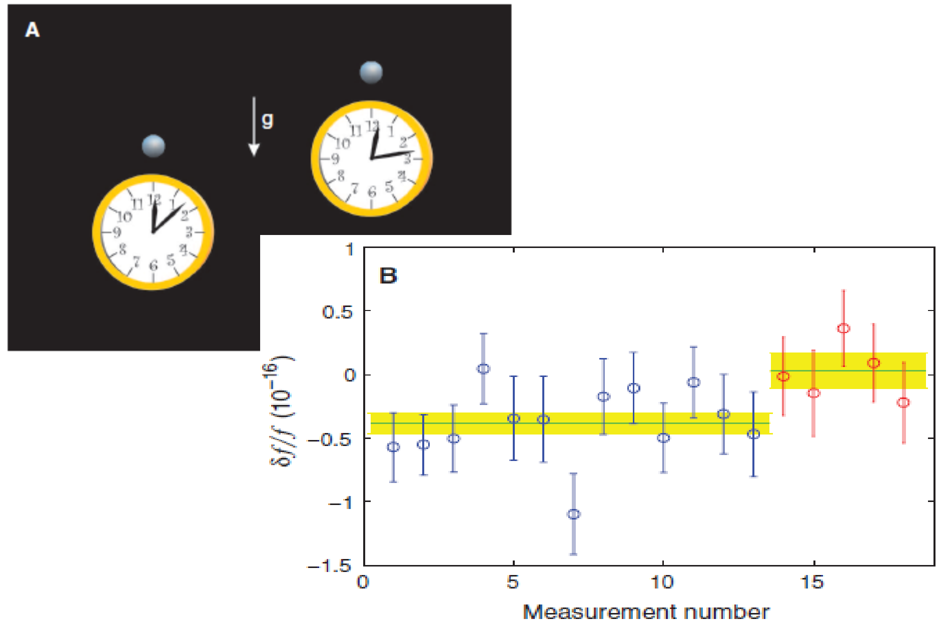


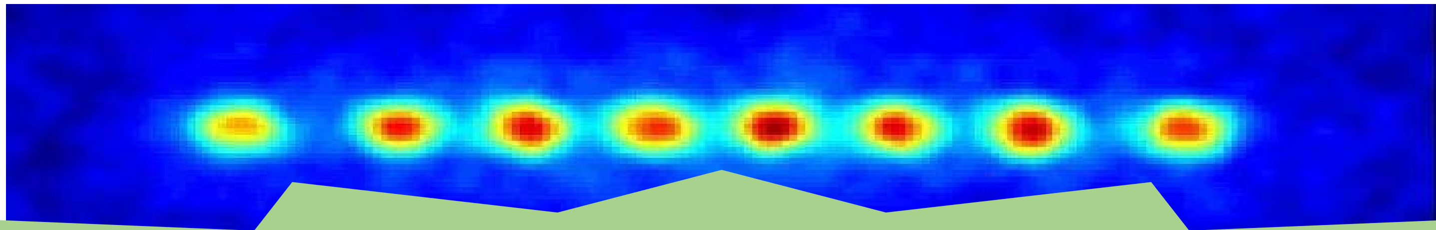
Fig. 3. Gravitational time dilation at the scale of daily life. **(A)** As one of the clocks is raised, its rate increases when compared to the clock rate at deeper gravitational potential. **(B)** The fractional difference in frequency between two Al^+ optical clocks at different heights. The Al-Mg clock was initially 17 cm lower in height than the Al-Be clock, and subsequently, starting at data point 14, elevated by 33 cm. The net relative shift due to the increase in height is measured to be $(4.1 \pm 1.6) \times 10^{-17}$. The vertical error bars represent statistical uncertainties (reduced $\chi^2 = 0.87$). Green lines and yellow shaded bands indicate, respectively, the averages and statistical uncertainties for the first 13 data points (blue symbols) and the remaining 5 data points (red symbols). Each data point represents about 8000 s of clock-comparison data.

Harness Entanglement to Reduce Quantum Noise

- Operate Al^+ clock with N = 5 ions in fully entangled state: Reduced quantum noise

$$\sigma_y(\tau) = \frac{1}{\omega\sqrt{NT\tau}} \quad \Rightarrow \quad \sigma_y(\tau) = \frac{1}{\omega N\sqrt{T\tau}}$$

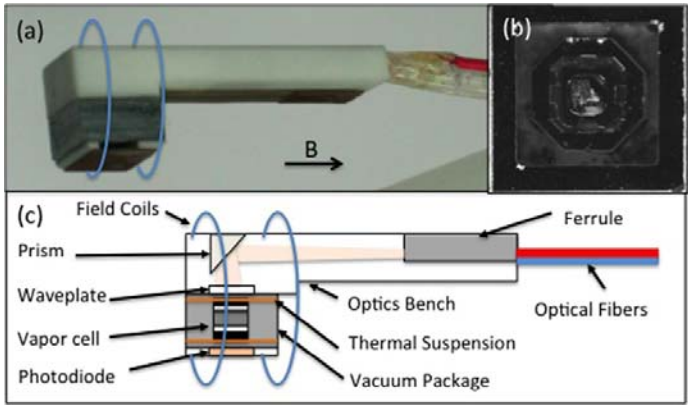
- Differential excitation overcomes atom/laser desynchronization
- **→ $1\text{x}10^{-18}$ measurement precision in 1 hour! (1000x improvement)**



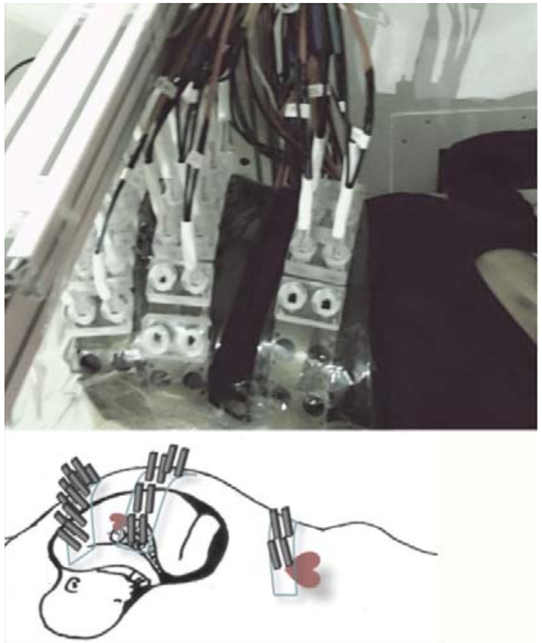
High risk: differential excitation and entanglement have never been implemented in state-of-the-art clocks!

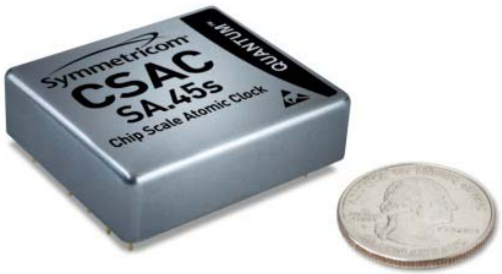
Chip-Scale Atomic Magnetometers

- Derived from Chip-Scale Atomic Clock research
  - Similar technology
  - Optimized to be sensitive to small magnetic fields
- May replace some SQUIDs
  - Femtotesla sensitivity
  - Operates at room temperature
- Application areas include:
  - Magnetoencephalography
  - Fetal magnetocardiography



Above: Microfabricated magnetic sensor head, with the optical fibers on the right and the vapor cell on the left. **Left**: Three belts of sensors attached to the abdomen and chest of a pregnant women lying on her back during the measurement.



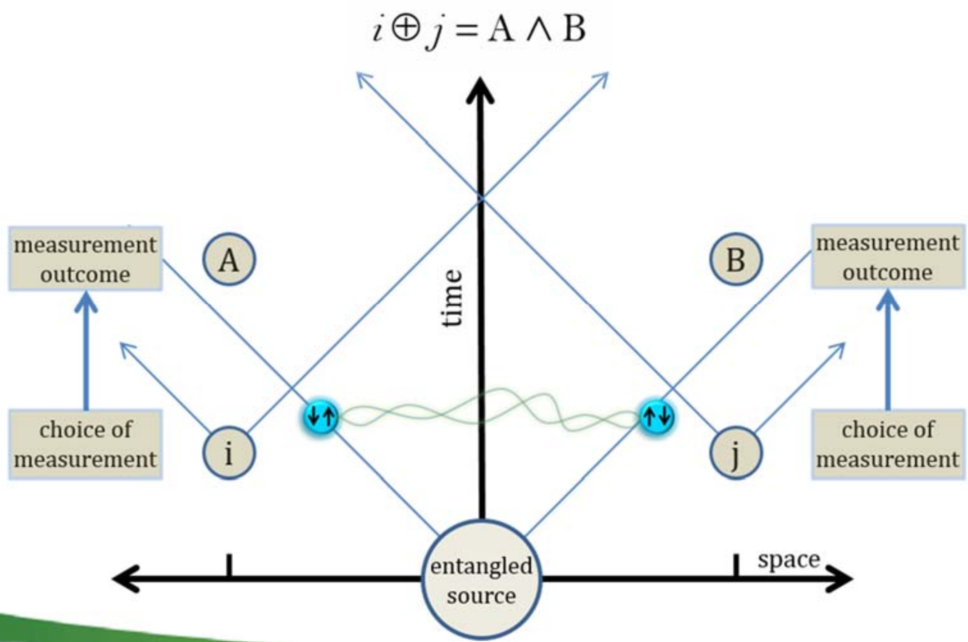


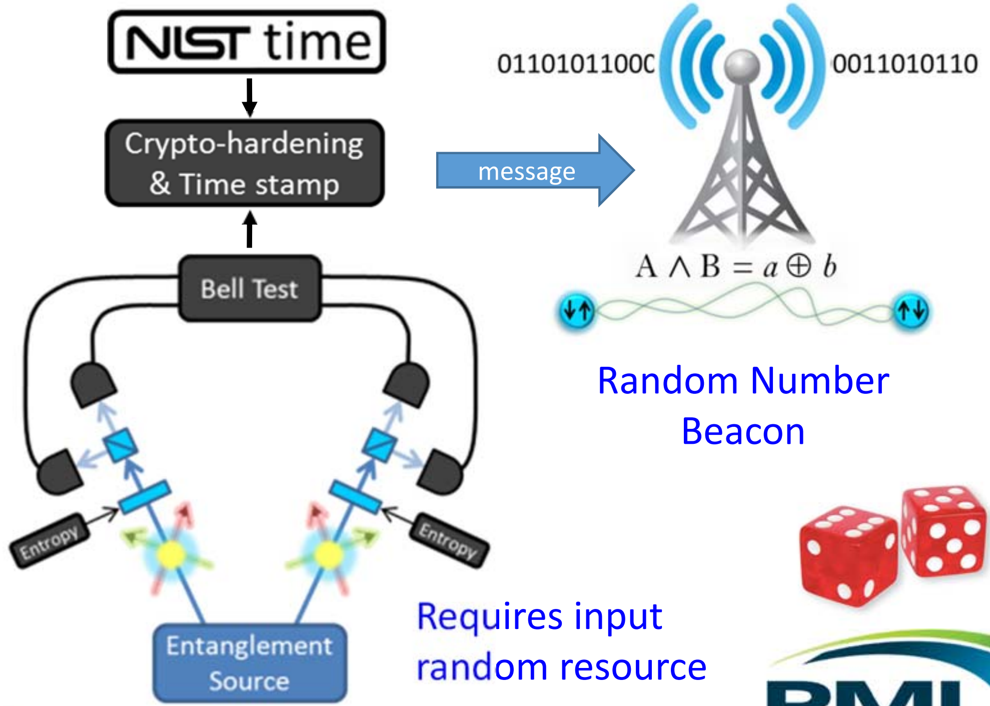
Chip-scale atomic clock
Commercialized by Symmetricom – Now MicroSemi

See:Phys. Med. Biol. **60,** 4797–4811 (2015)

Loophole-free Bell Test: Verifiable RNG

- A Bell-inequality “violation” invalidates hidden-variable pictures of reality
- Paradigm shift in RNG: the only known way to certify universal unpredictability
  - Challenges: space-like separation of measurements (prohibits secret collusion), efficient entangled-photon state collection and measurement, low-latency random-number generation, proper confidence bounds





Requires input random resource

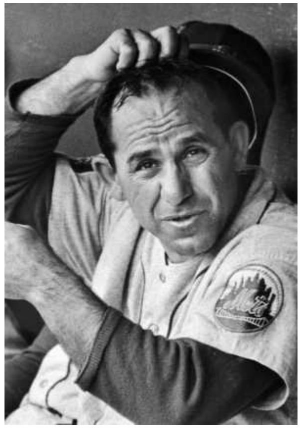
How Quantum Standards May be Used

- Intrinsic quantum standards like the existing Josephson voltage standards, quantum hall resistance standards, and atomic clocks may be in the purview of NMIs and primary labs
- Chip scale and quantum embedded standards will be utilized on the factory floor – think chip scale atomic clock, laser power radiometry for welding, dynamic force in measurements in STM
- Finally quantum technologies may result in improved security — such as quantum resistant (also referred to as post-quantum) cryptography, guaranteed secure random number generator, …

Quantum SI – Future Implications ?

- For NIST or any NMI
  - Focus shifts to best measurement one can do anywhere
  - Commercialization challenges
  - New metrology frontiers
  - Measurement expertise is still essential
  - Solving really hard problems
  - Training

- For industry
  - Zero-chain traceability
  - Embedded NIST Quantum SI instrumentation
  - Integrated standards and sensor



"It's hard to make predictions, especially about the future"

Yogi Berra

NIST Perspective on Future Quantum Technologies

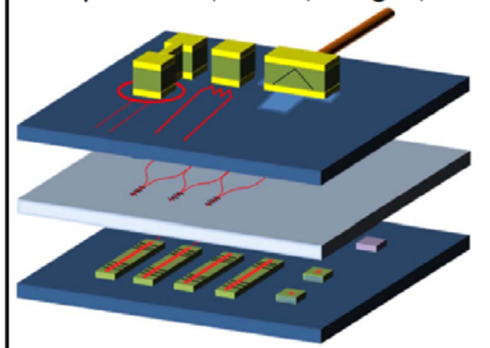
- Ability to manipulate and detect quanta provides new tools for both classical and quantum measurables
- Emerging technologies and nanofabrication are enabling disruptive change
- Embedded standards (NIST-on-a-chip) will change everything from infrastructure monitoring to drilling and mining
- Control of quantum objects will enable high speed (300 GHz) arbitrary waveform synthesis and detection beyond the standard quantum (shot-noise) limit

Embedded Standards

Develop SI-traceable measurements and physical standards that are:

- **Deployable** in a factory, lab, device, system, home, anywhere...
- **Usable:**. Small size (usually), low power consumption, rugged, easily integrated and operated
- **Flexible**: Provide a range of SI-traceable measurements and standards (often quantum-based) relevant to the customer's needs / applications
  - One, few, or many measurements from a single small form package
- **Manufacturable:**
  - Potential for production costs commensurate with the applications
  - Low cost for broad deployment; or
  - Acceptable cost for high-value applications

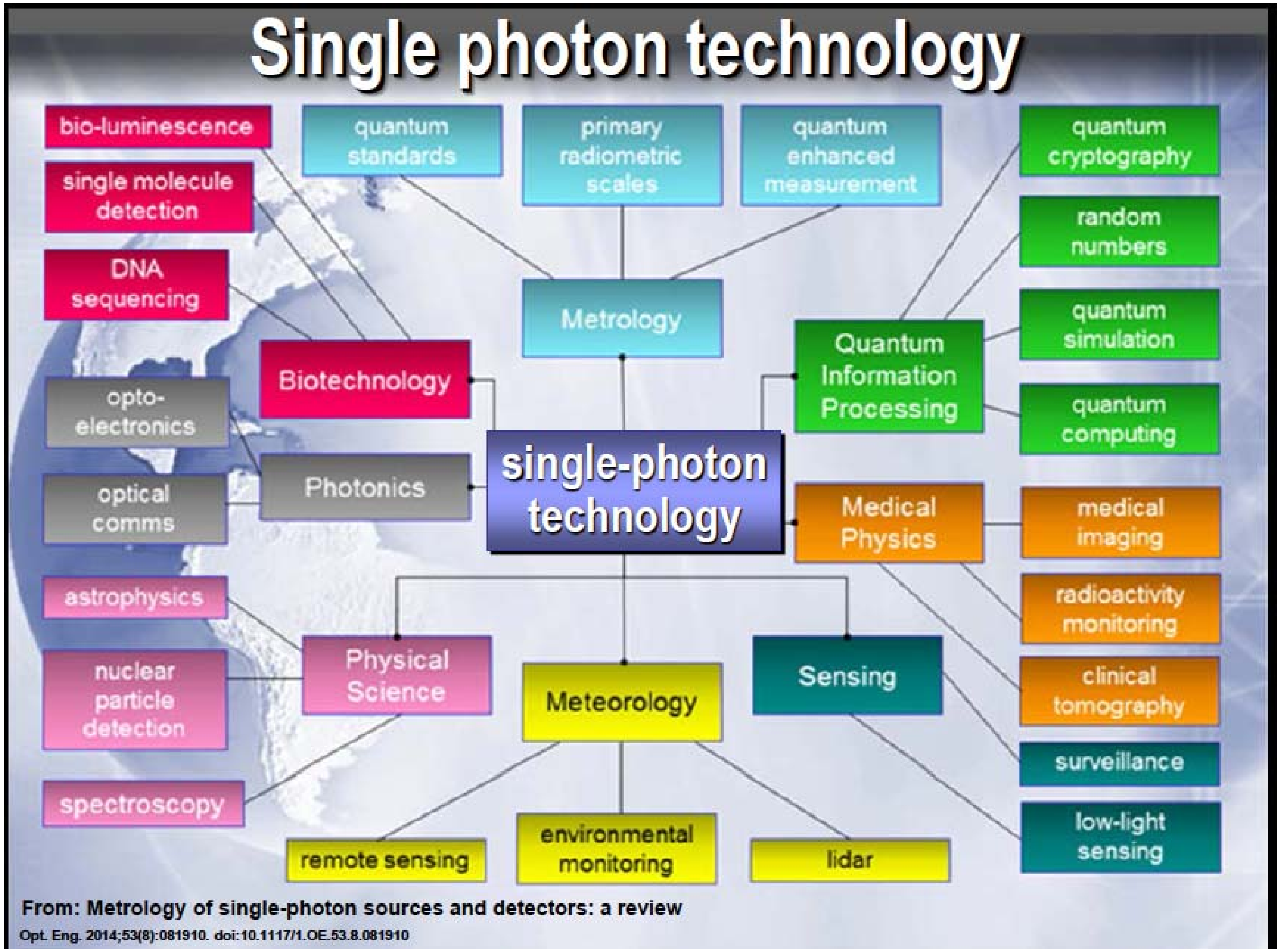
Time, electrical, magnetic, temperature, force, length, etc.



Physical, chemical, material, biological, etc.

Borrowed from:
“Quantum Optical Metrology by Photons”

BIPM Workshop
Maria Luisa Rastello



Quantum Standards: New Roles for NMIs?

Questions to frame the discussion:

- What is the evolving role of an NMI in traceability when primary standards can be directly realized outside of NMIs?
- How will/might this change the MRA?
- What is the impact on NMI's when calibration services no longer establish the chain of traceability?
- What is the role of the BIPM and NMIs in a new era of zero-chain traceability?
- How do we maintain integrity of the SI if fewer NMIs are involved?
- Others???

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