

QUANTUM INFORMATION SCIENCE AND NIST

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PHYSICAL MEASUREMENT LABORATORY

PML's Mission

NIST

To set the definitive U.S. standards for nearly every kind of measurement employed in commerce and research.

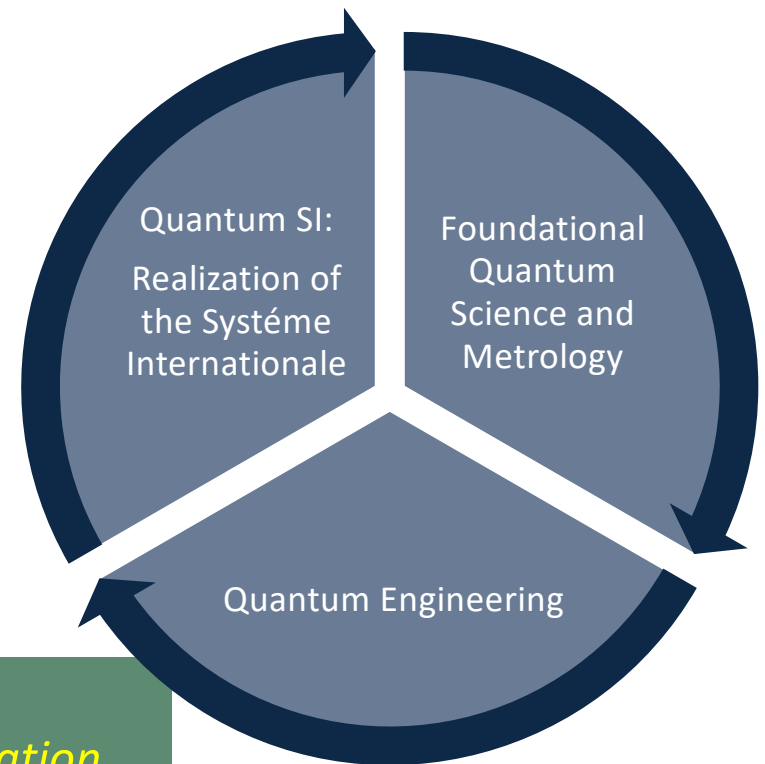
To be a world leader in the science of measurement, devising procedures and tools to revolutionize how measurements are made in every application.

NIST QIS Strategic Vision

NIST will fulfill its mission in QIS through three coordinated efforts:

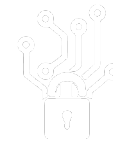
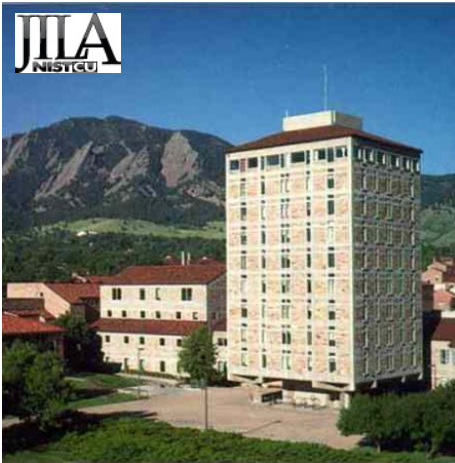
- Foundational research emphasizing QIS and Metrology
- Applied research to engineer and improve the robustness of prototypes: Quantum Engineering
- Realization and Dissemination of the units of measure: The Quantum SI

These three activities form an interrelated and self-reinforcing system in which, for example, next-generation atomic clocks are engineered to be smaller and more robust and thereby enable tomorrow's measurement services.



NIST Existing Joint Institutes

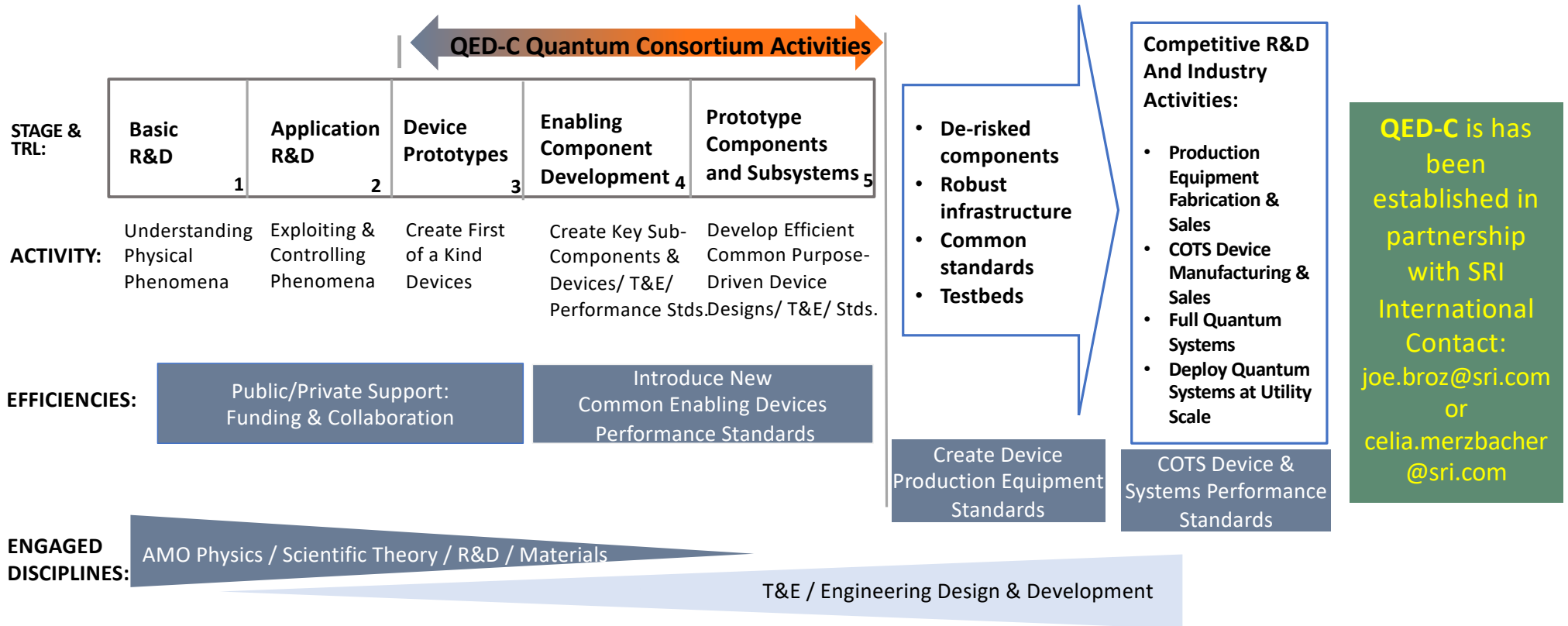
NIST



Three collaborative institutes at two locations provide opportunities to:

- Attract world class scientists
- Train students and postdocs
- Transfer technology

Quantum Economic Development Consortium



NIST was tasked in the NQI to establish a consortium whose goal is to build the supply chain for the future quantum economy

Quantum Information Science in a Nutshell



Quantum information science (QIS) exploits unique quantum properties such as *coherence*, *superposition*, *entanglement*, and *squeezing* to *acquire*, *transmit*, and *process* information in ways that greatly exceed existing capabilities.

QIS is a field of scientific inquiry in its own right, with applications in:

- *sensing and metrology*: precision navigation, timekeeping, magnetic fields, ...
- *communication*: secure data transmission and storage, random number generation, ...
- *simulation*: complex materials, molecular dynamics, QCD, ...
- *computing*: cryptanalysis, quantum chemistry, optimization, quantum field theory, ...

**NIST's
QIS
Program
covers all
of this**

and robust intellectual connections to numerous areas of basic research.

NIST's formal QIS program is now 20 years old and first paper dates to 1992

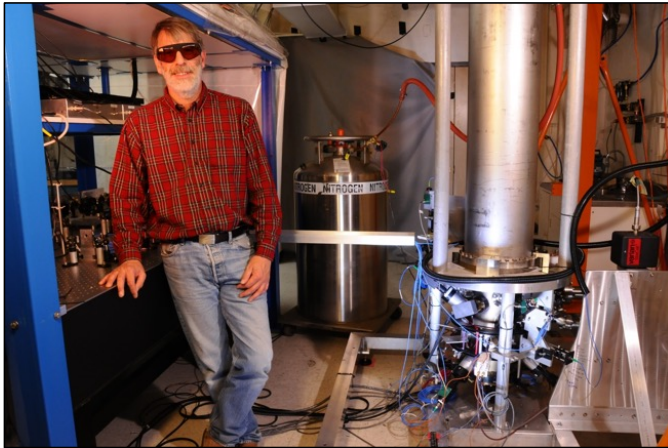
Why NIST was Positioned in QIS



- Extensive background in
 - Coherent manipulation of atoms and ions for clocks ([power of a single qubit](#))
 - Superconducting electronics for Josephson Voltage Systems
 - Only National Measurement Institute (NMI) to ever close the electrical metrology triangle ($V=IR$ or Ohm's Law) at a few parts part in 10^7 – Single electron transistors (SETs)
 - Achieved more than 20 years ago and abandoned *15 year ago* because it was *too hard and not competitive* with direct approaches (for a recent review see H. Scherer *et al.*, Meas. Sci. Technol. **23**, 124010 (2012))
 - In the next few years several other NMIs may duplicate and improve – on this *20 year old result*
 - NIST is reinvesting in SETs in Si that should not have the charge offset noise problem in the Al SETs used 20 years ago
- A long history of manipulating quanta and quantum objects

The Power of One Quantum Bit

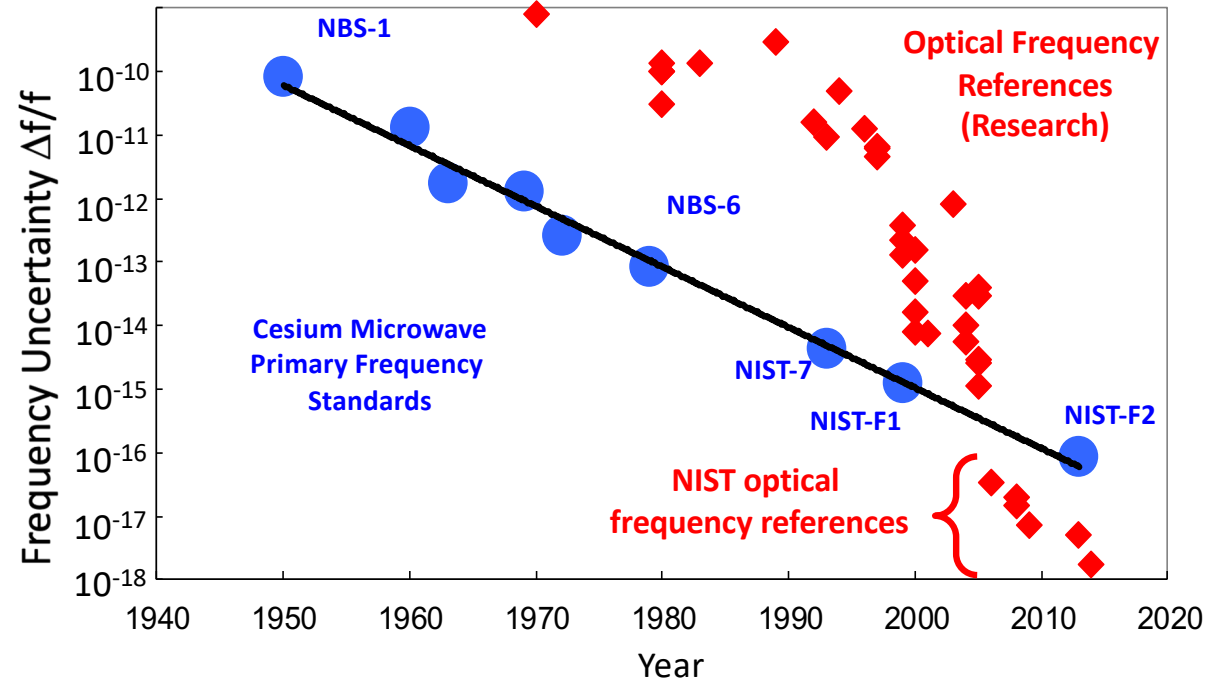
1 second is defined as the duration of 9,192,631,770 cycles of the cesium hyperfine transition.



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



Quantum Logic Clock and Metrology

NIST

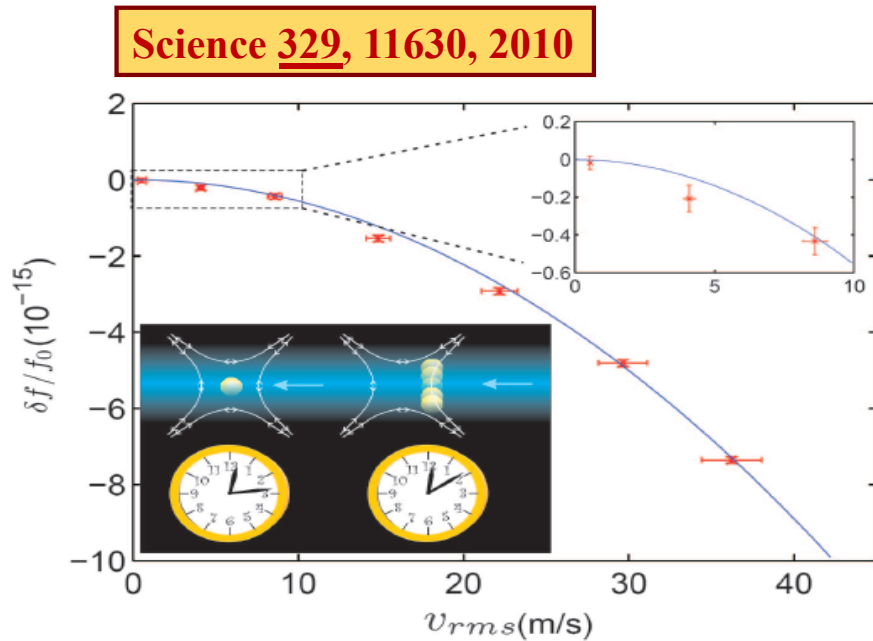


Fig. 2. Relativistic time dilation at familiar speeds (10 m/s = 36 km/hour \approx 22.4 miles/hour). (Lower left inset) As the Al^+ ion in one of the twin clocks is displaced from the null of the confining RF quadrupole field (white field lines), it undergoes harmonic motion and experiences relativistic 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 ($v_{\text{rms}} = \sqrt{\langle v^2 \rangle}$) (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 $v_{\text{rms}} < 10$ 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.

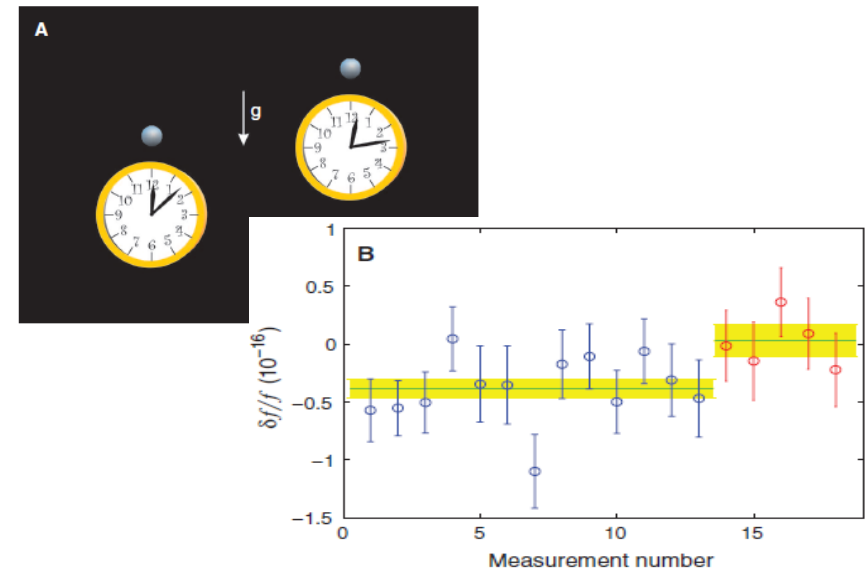
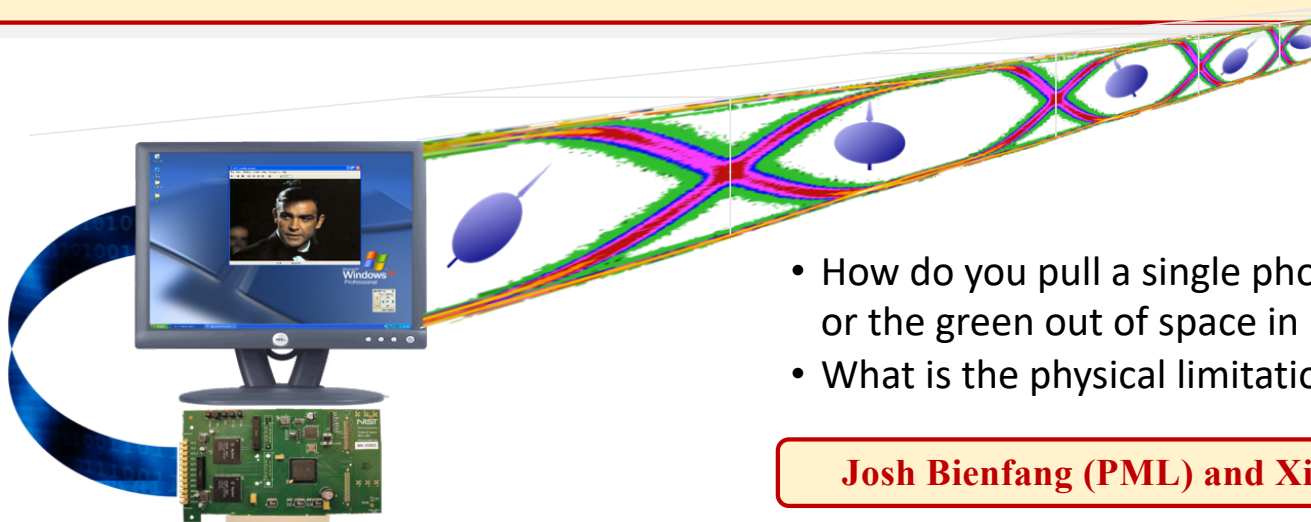


Fig. 3. Gravitational time dilation at the scale of daily life. (A) As one of the clocks is raised, its rate increases when compared to the clock rate at deeper gravitational potential. (B) The fractional difference in frequency between two Al^+ optical clocks at different heights. The Al-Mg clock was 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.

Quantum Communications Effort

NIST

- Transmission of “*single photons*” using clock-synchronization enables up to 6 GHz rate – both free space and in fiber
- Key processing uses multi-threaded Forward Error Correction algorithm
- Demonstration of continuous one-time-pad encryption with quantum key at a data rate > 4 MB/s; \sim x100 greater than previous demonstrations
- Enables broadband applications of quantum encryption

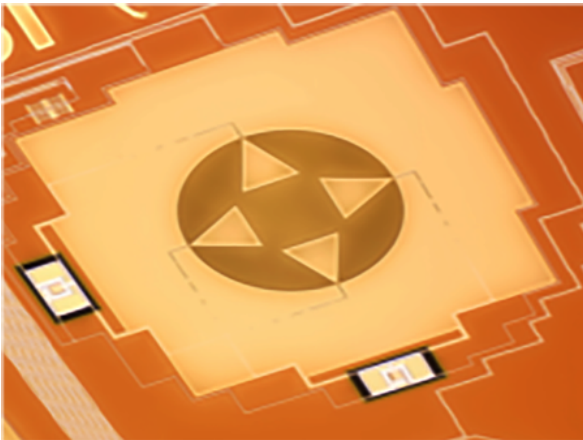


- How do you pull a single photon in the near infrared or the green out of space in broad daylight?
- What is the physical limitation?

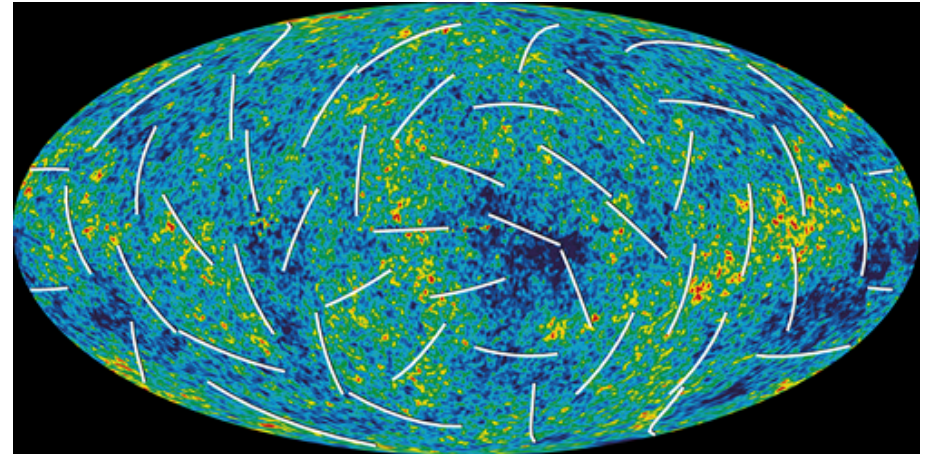
Josh Bienfang (PML) and Xiao Tang (ITL)

Superconducting Photon Detectors: Bolometers

- Related technology used for NIST Transition Edge Sensors (single photon detectors) and the Atacama Cosmology Telescope



Part of a NIST detector array for the ACT



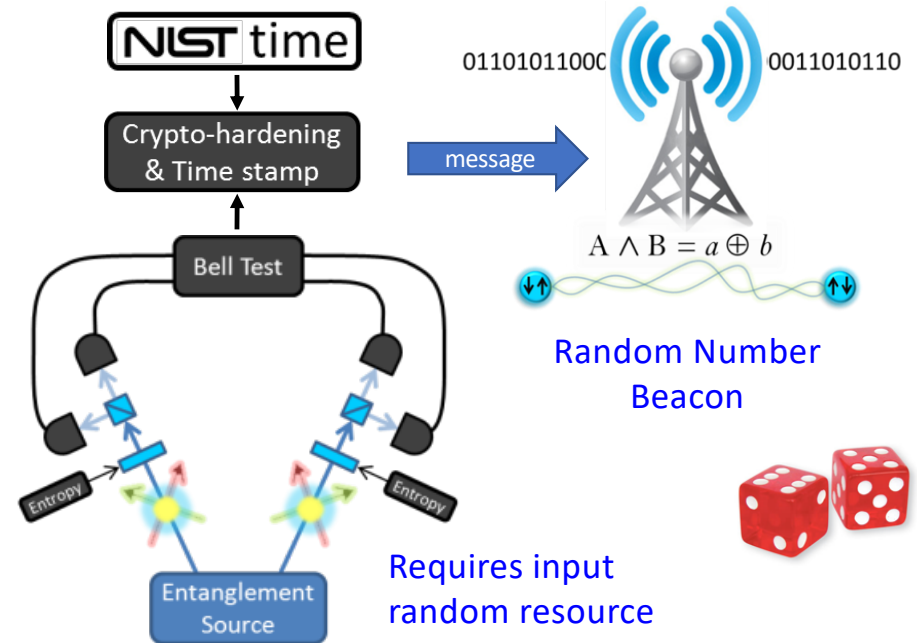
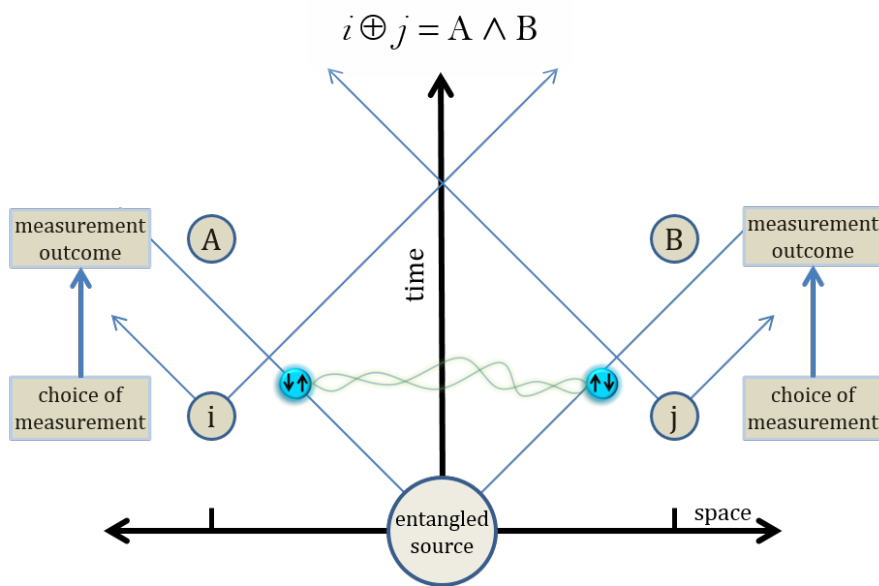
Polarization of the Cosmic Microwave Background:
WMAP/NASA

See: <http://www.nist.gov/pml/div686/devices/cmb-polarization-detector.cfm>

Loophole-free Bell Test: Verifiable RNG

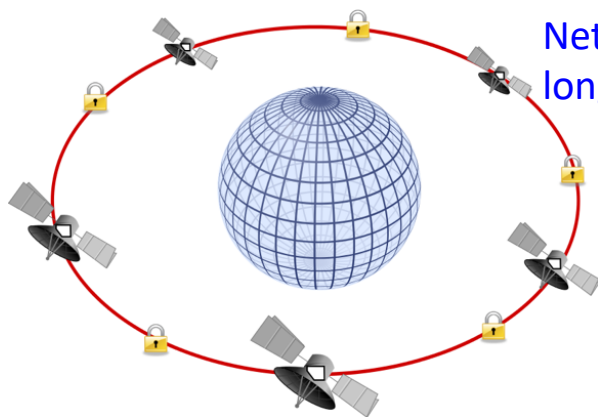


- A Bell-inequality “violation” invalidates hidden-variable pictures of reality
- Paradigm shift in RNG: the only known way to certify universal unpredictability
- Challenges: space-like separation of measurements (prohibits secret collusion), efficient entangled-photon state collection and measurement,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

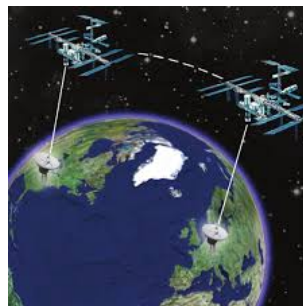


Advanced Applications Require Clocks

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Network of clocks (10^{-21}):
long baseline interferometry



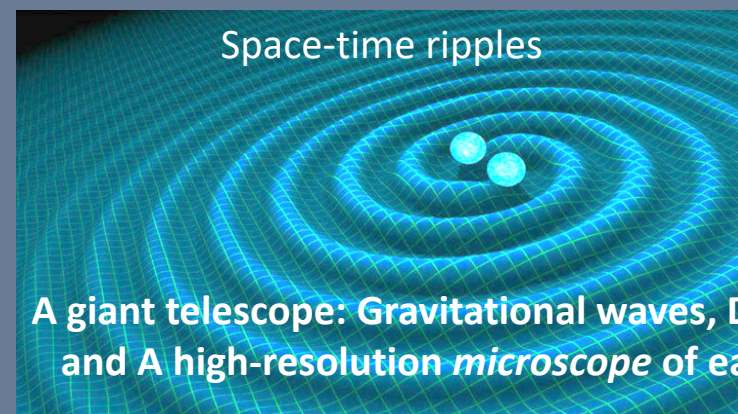
Long distance 10^{-18} Time Transfer

- Tests of fundamental physics (different species)
- Space-based navigation
- Clock-based geodesy
- Precision timing applications (microwaves, VLBI)
- Space-based dark-matter searches



Dark matter halo

Kómár *et al.*, *Nat. Phys.* **10**, 582 (2014);
Kolkowitz *et al.*, *Phys. Rev. D* **94**, 124043 (2016).



Space-time ripples

A giant telescope: Gravitational waves, Dark Matter
and A high-resolution *microscope* of earth