National Aeronautics and
Space Administration

NASA

EXPLORE SCIENCE

Enabling NASA Science with Quantum Sensors

Michael Seablom
Chief Technologist, Science Mission Directorate

Presentation to Office of the Undersecretary of Defense for Research & Engineering
May, 2020

Cold Atom Laboratory (CAL) Science Highlights

- The Cold Atom Out-coupler for atom laser observed, a key milestone on the way to demonstrating the first space based atom laser.
- Two PI teams continue to pursue temperatures below the achieved 100 picokelvin (in one direction).
- Continued the study of bubble-geometry traps in microgravity with new investigations into the dynamics of these quantum entities.
- Possible signs of atom interference observed for the first time in orbit. Investigating the possibility of interfering split condensates in a magnetic trap using CAL. This enables studies of coherence in microgravity.

Deep Space Atomic Clock (DSAC)

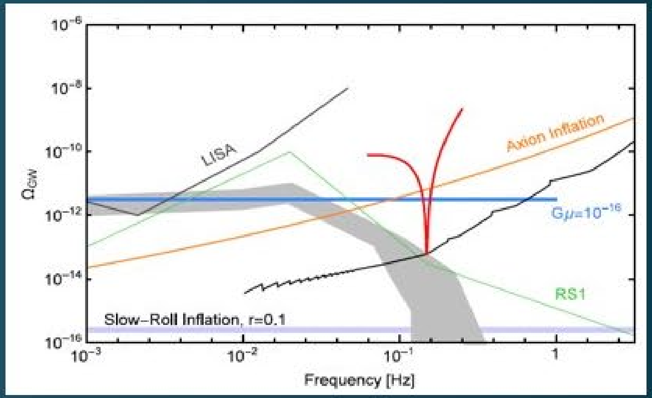
- Launched June 25, 2019 (Air Force STP-2)
- Hosted on General Atomics (GA) Orbital Testbed (OTB)
- One year experimental mission in LEO, 24 degrees, 720 km.
- Mercury trapped Ion clock
- GPS receiver for frequency stability validation against UTC
- Full suite of payload and clock telemetry


DSAC & GA Orbital Testbed


Integrated DSAC Payload

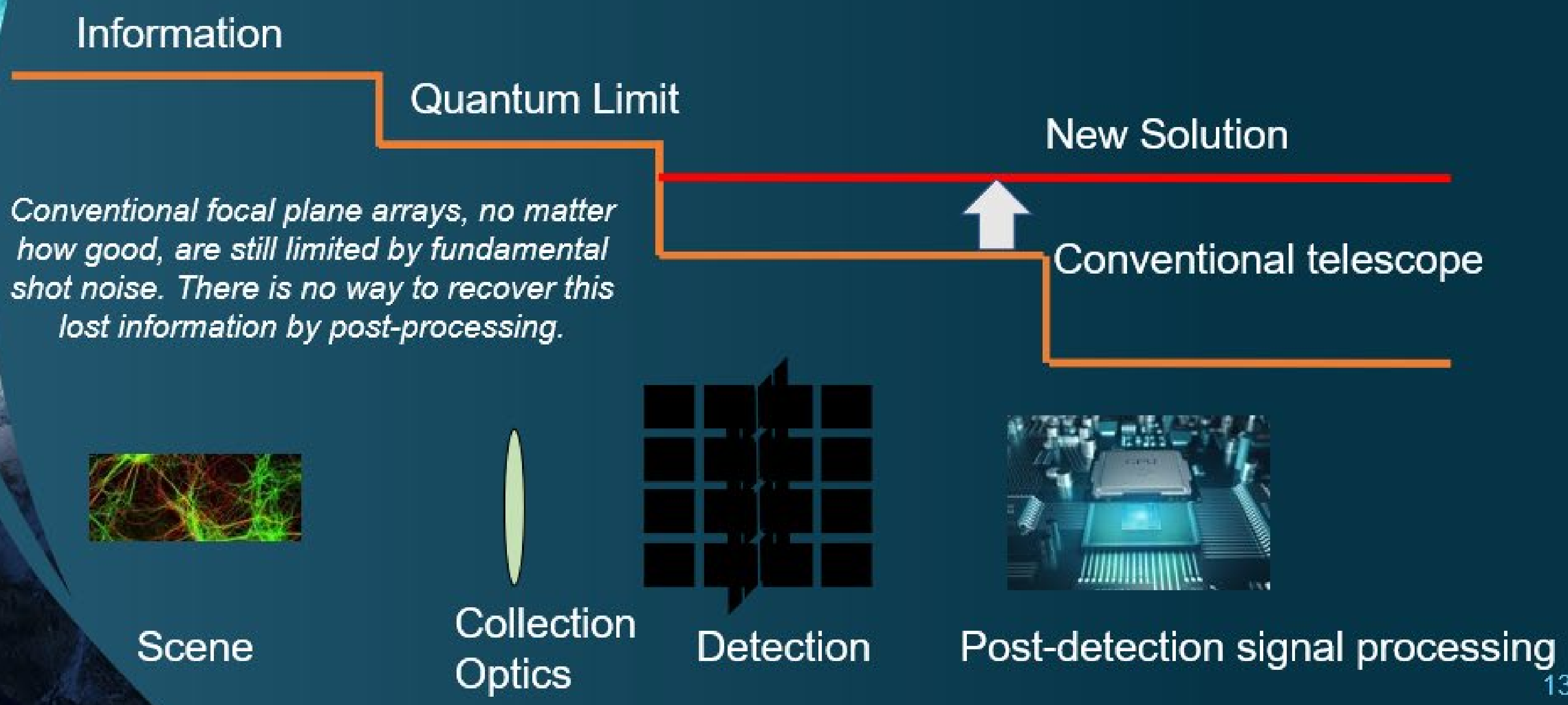
Quantum Sensing at Goddard Space Flight Center (GSFC)

- GSFC targeting Earth Science & Astrophysics applications
- Atom Interferometer Gravity Gradiometer (AIGG) for mass change measurements
  - Order of magnitude improvement over GRACE, GRACE-FO
- Optical Clock Components → Gravity Wave Detection
  - Development of technologies for positioning, navigation combined with atom interferometry will help detect gravitational waves from inflation or other cosmological sources

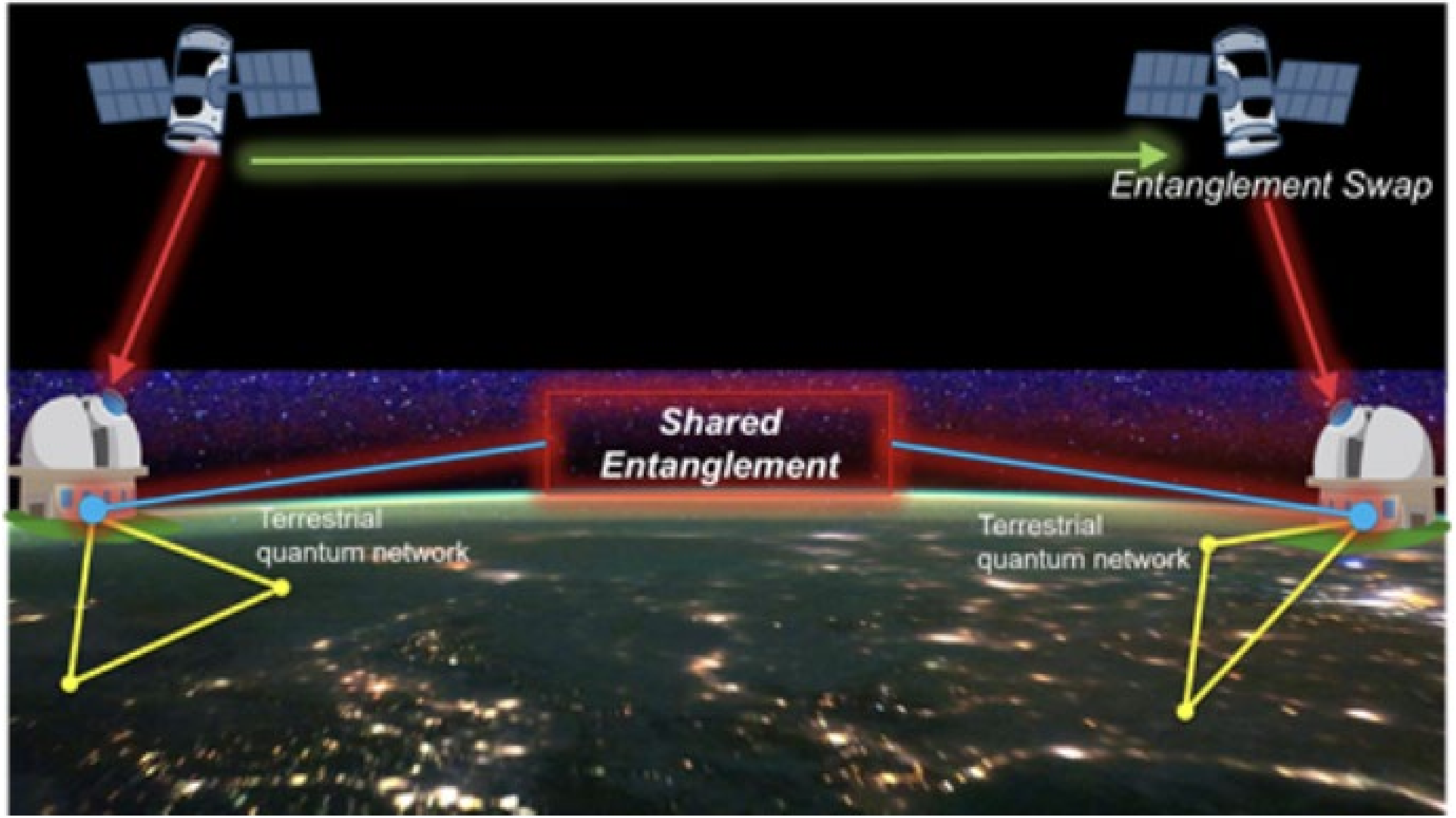


Universal Telescope

Objective: Develop a reconfigurable telescope that extracts information with efficiency close to the quantum limit in any task (esp. scene features << λ/D) with much less light collected



A Potential Scenario for the Reference Quantum Mission



QUANTUM INFORMATION SCIENCE AND NIST

DR. CARL J. WILLIAMS, DEPUTY DIRECTOR
PHYSICAL MEASUREMENT LABORATORY

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

PML's Mission

NIST

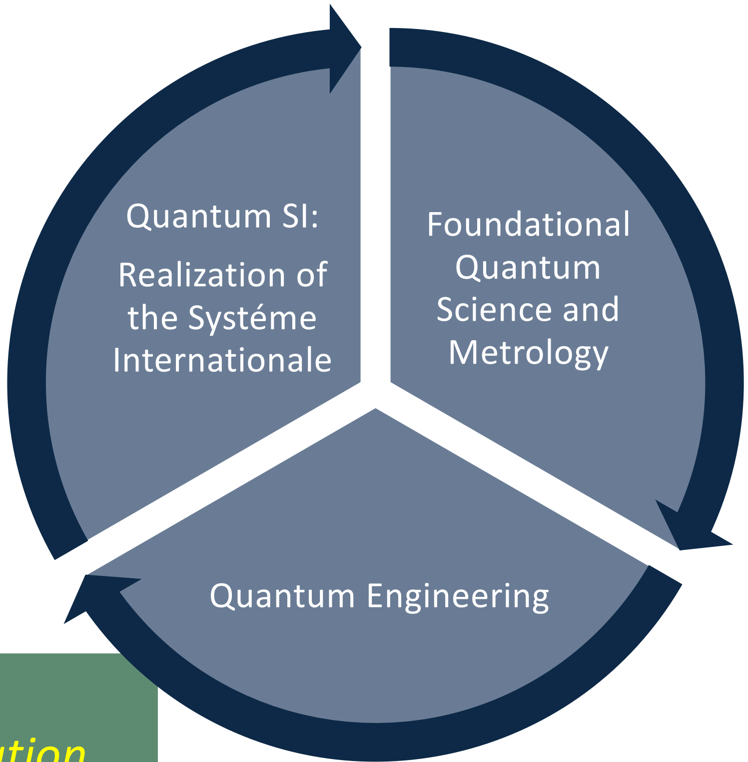
To set the definitive U.S. standards for nearly every kind of measurement employed in commerce and research.

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

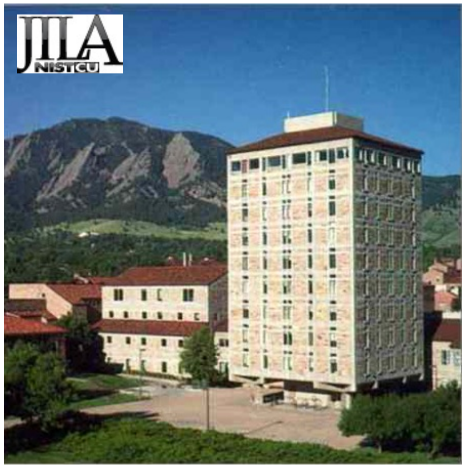
NIST will fulfill its mission in QIS through three coordinated efforts:

- 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



Three collaborative institutes at two locations provide opportunities to:

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

Quantum Economic Development Consortium

NIST

QED-C Quantum Consortium Activities

STAGE & TRL:	Basic R&D 1	Application R&D 2	Device Prototypes 3	Enabling Component Development 4	Prototype Components and Subsystems 5
ACTIVITY:	Understanding Physical Phenomena	Exploiting & Controlling Phenomena	Create First of a Kind Devices	Create Key Sub-Components & Devices/ T&E/ Performance Stds.	Develop Efficient Common Purpose-Driven Device Designs/ T&E/ Stds.

EFFICIENCIES:

- Public/Private Support: Funding & Collaboration
- Introduce New Common Enabling Devices Performance Standards

- **De-risked components**
- **Robust infrastructure**
- **Common standards**
- **Testbeds**

Create Device Production Equipment Standards

Competitive R&D And Industry Activities:

- **Production Equipment Fabrication & Sales**
- **COTS Device Manufacturing & Sales**
- **Full Quantum Systems**
- **Deploy Quantum Systems at Utility Scale**

COTS Device & Systems Performance Standards

QED-C is has been established in partnership with SRI International
Contact: joe.broz@sri.com or celia.merzbacher@sri.com

ENGAGED DISCIPLINES:

- AMO Physics / Scientific Theory / R&D / Materials
- T&E / Engineering Design & Development

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

NIST

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

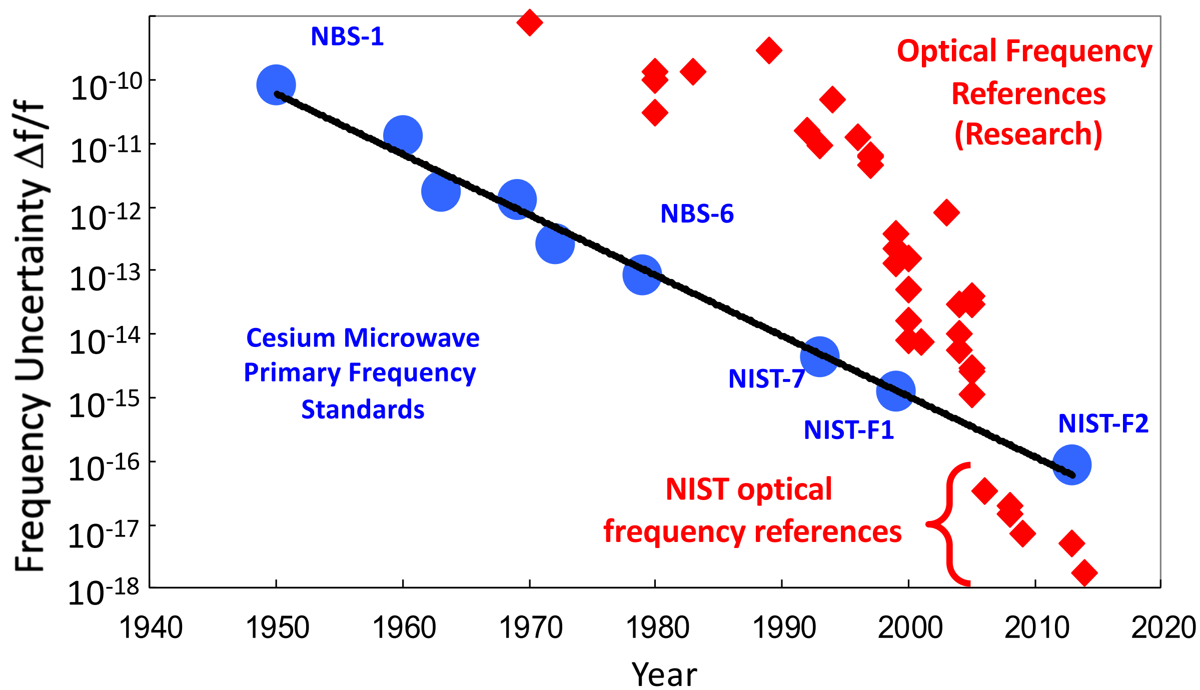
NIST

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

Science 329, 11630, 2010

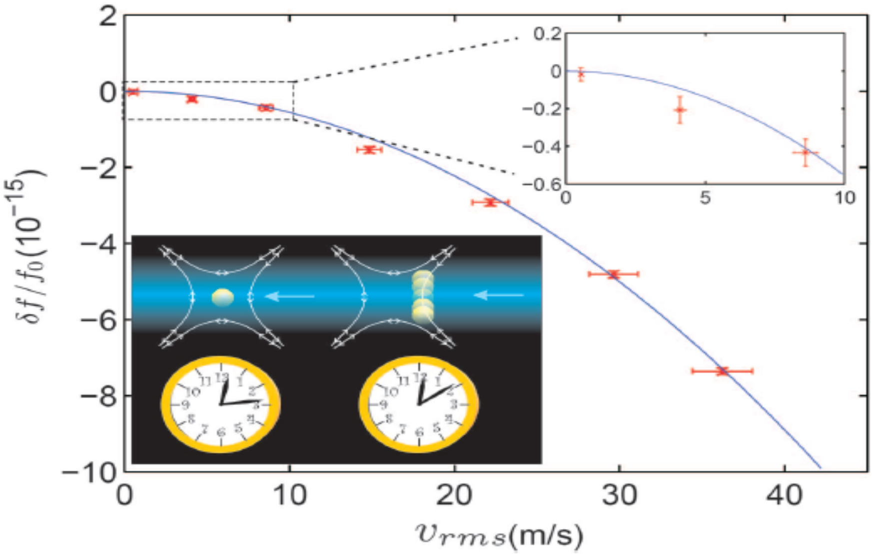


Fig. 2. Relativistic time dilation at familiar speeds (10 m/s = 36 km/hour ≈ 22.4 miles/hour). (Lower left inset) As the Al^+ ion in one of the twin clocks is displaced from the null of the confining RF quadrupole field (white field lines), it undergoes harmonic motion and experiences relativistic time 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.

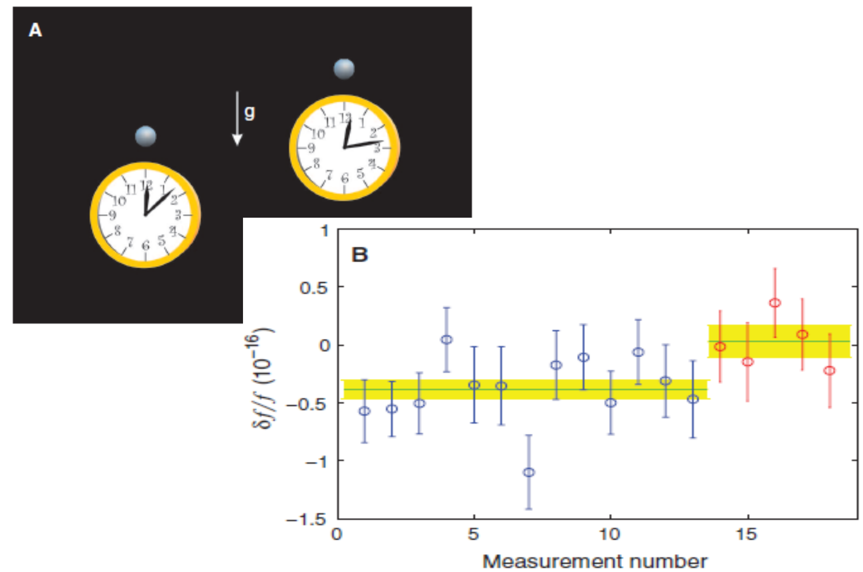
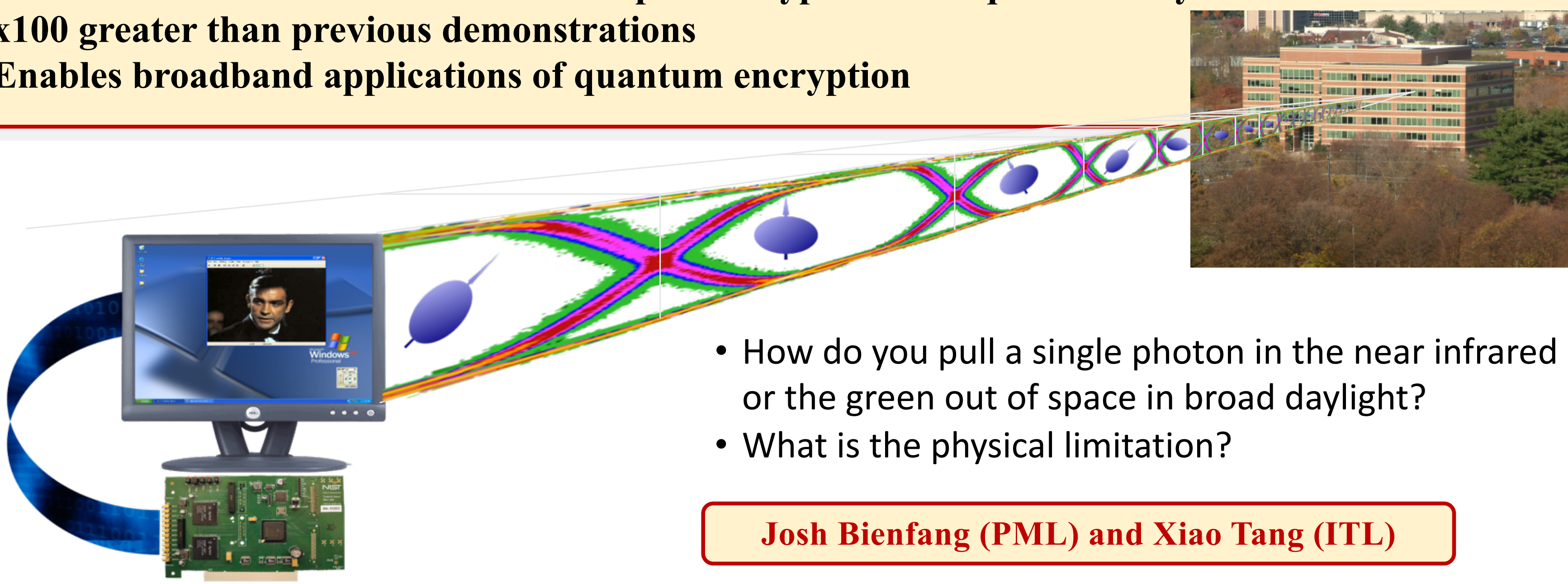


Fig. 3. Gravitational time dilation at the scale of daily life. **(A)** As one of the clocks is raised, its rate increases when compared to the clock rate at deeper gravitational potential. **(B)** The fractional difference in frequency between two Al^+ optical clocks at different heights. The Al-Mg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

Quantum Communications Effort

- **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; ~ x100 greater than previous demonstrations**
- **Enables broadband applications of quantum encryption**

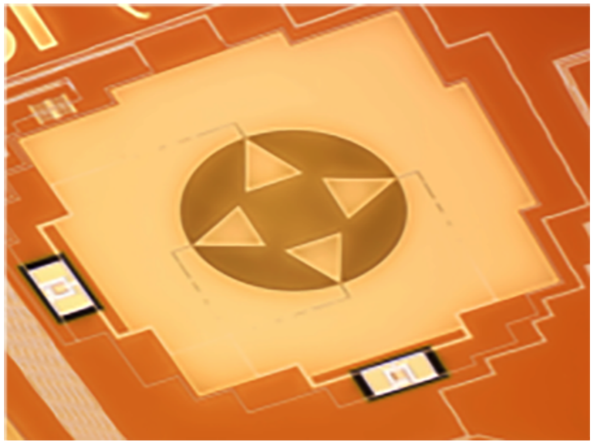


- How do you pull a single photon in the near infrared or the green out of space in broad daylight?
- What is the physical limitation?

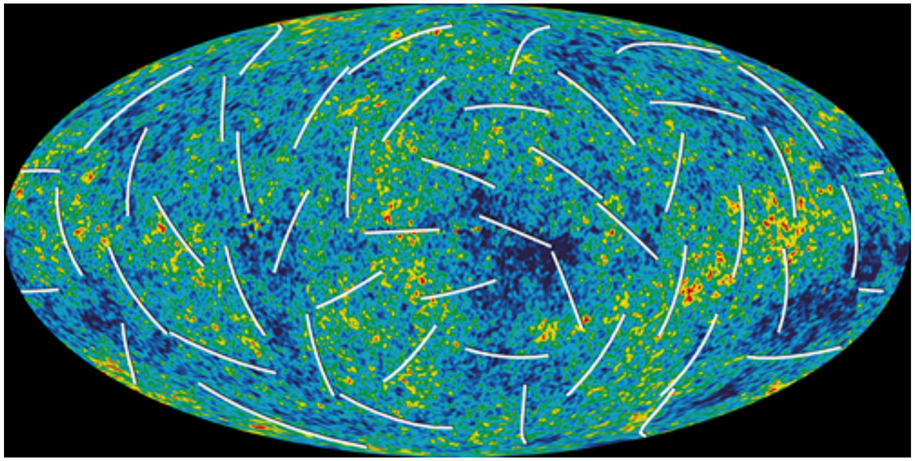
Josh Bienfang (PML) and Xiao Tang (ITL)

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

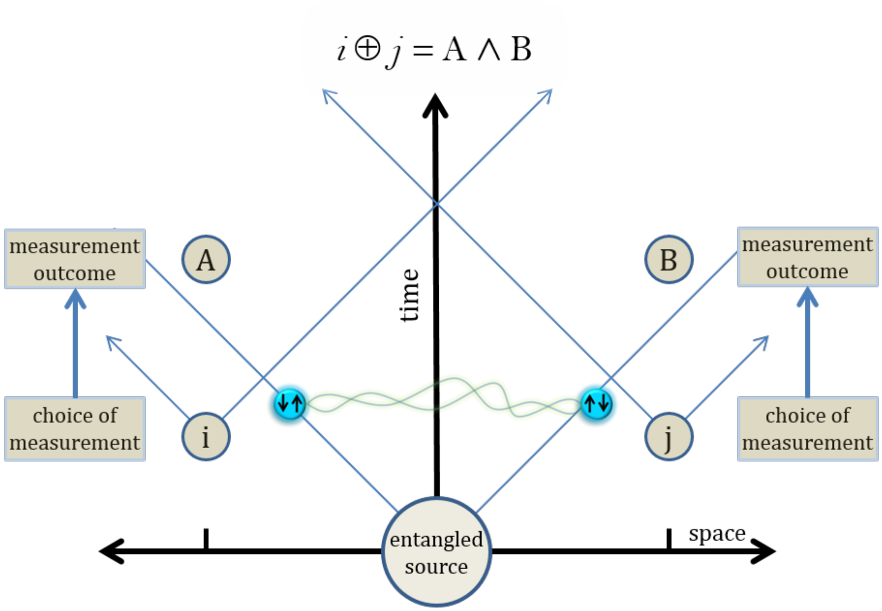


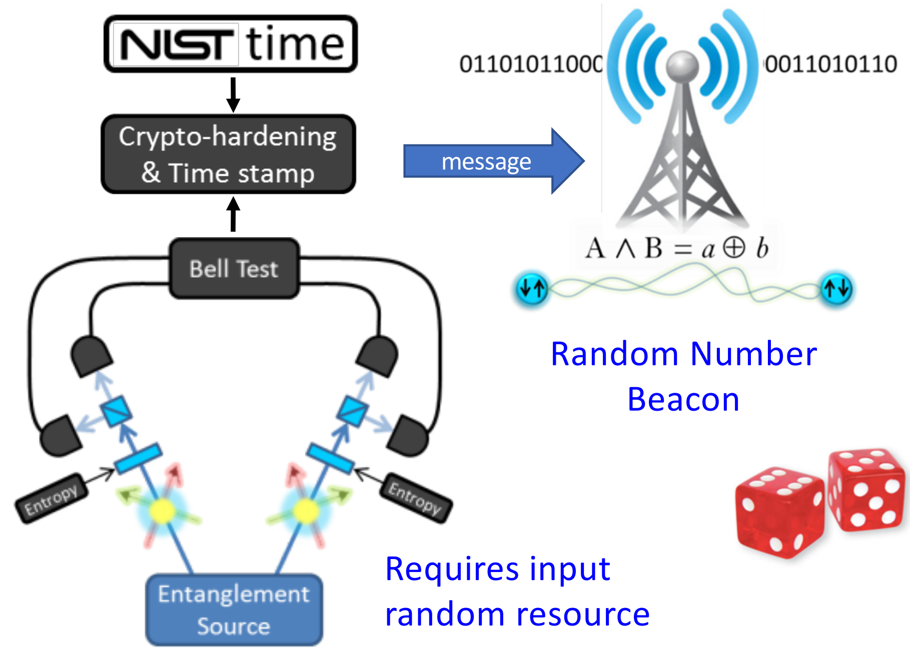
Polarization of the Cosmic Microwave Background: WMAP/NASA

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

Loophole-free Bell Test: Verifiable RNG

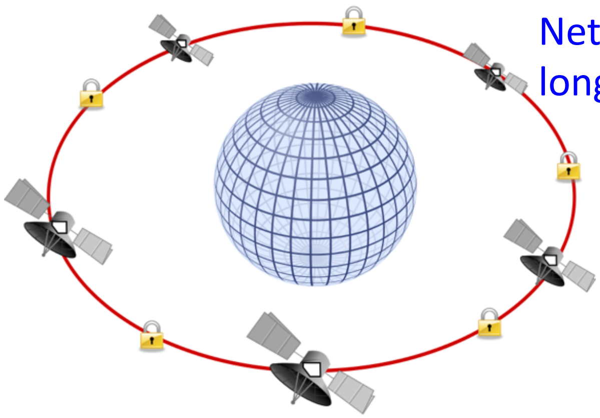
- A Bell-inequality "violation" invalidates hidden-variable pictures of reality
- Paradigm shift in RNG: the only known way to certify universal unpredictability
  - Challenges: space-like separation of measurements (prohibits secret collusion), efficient entangled-photon state collection and measurement,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



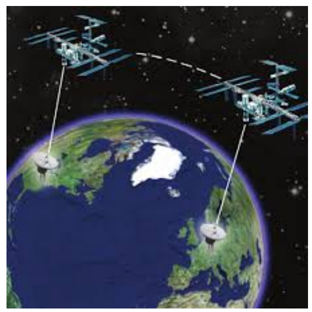


Advanced Applications Require Clocks

NIST



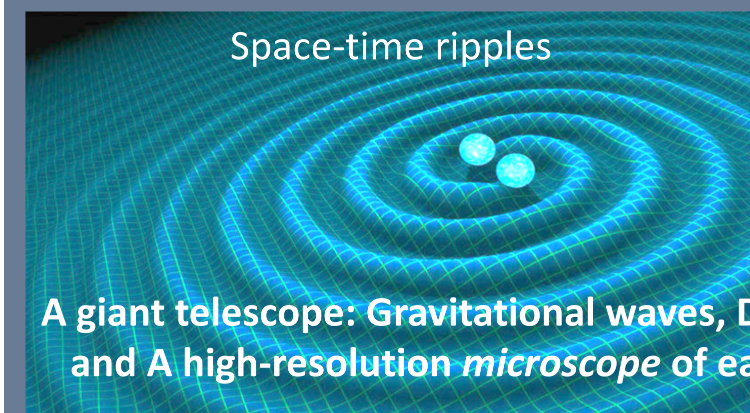
Network of clocks (10^{-21}): long baseline interferometry



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

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



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

Quantum Leap and the National Science Foundation

RIT Photonics for Quantum 2

July 20th, 2020

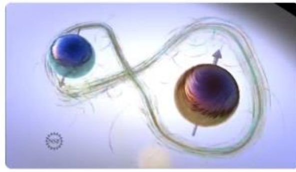
Dominique Dagenais

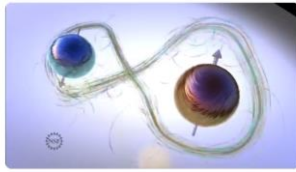
Directorate for Engineering

National Science Foundation

10 Big Ideas

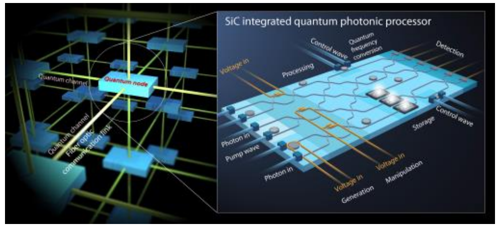
Opportunities for investment at the frontiers of science & engineering





Quantum Leap: Leading the next Quantum Revolution

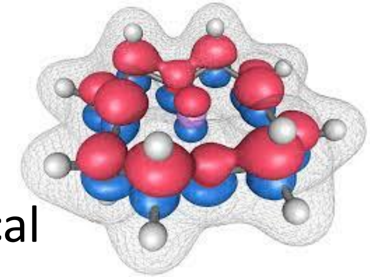
Next generation quantum devices and technologies



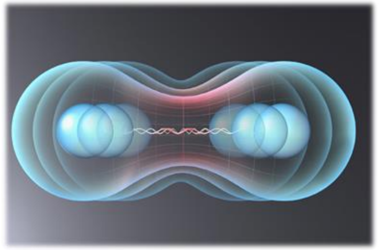
Materials, metrology, sensing, secure communications, information processing, computing

Breakthrough discoveries in natural and engineered quantum systems

Complexity, simulation, emergent behavior, theory, quantum/classical

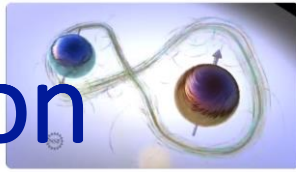


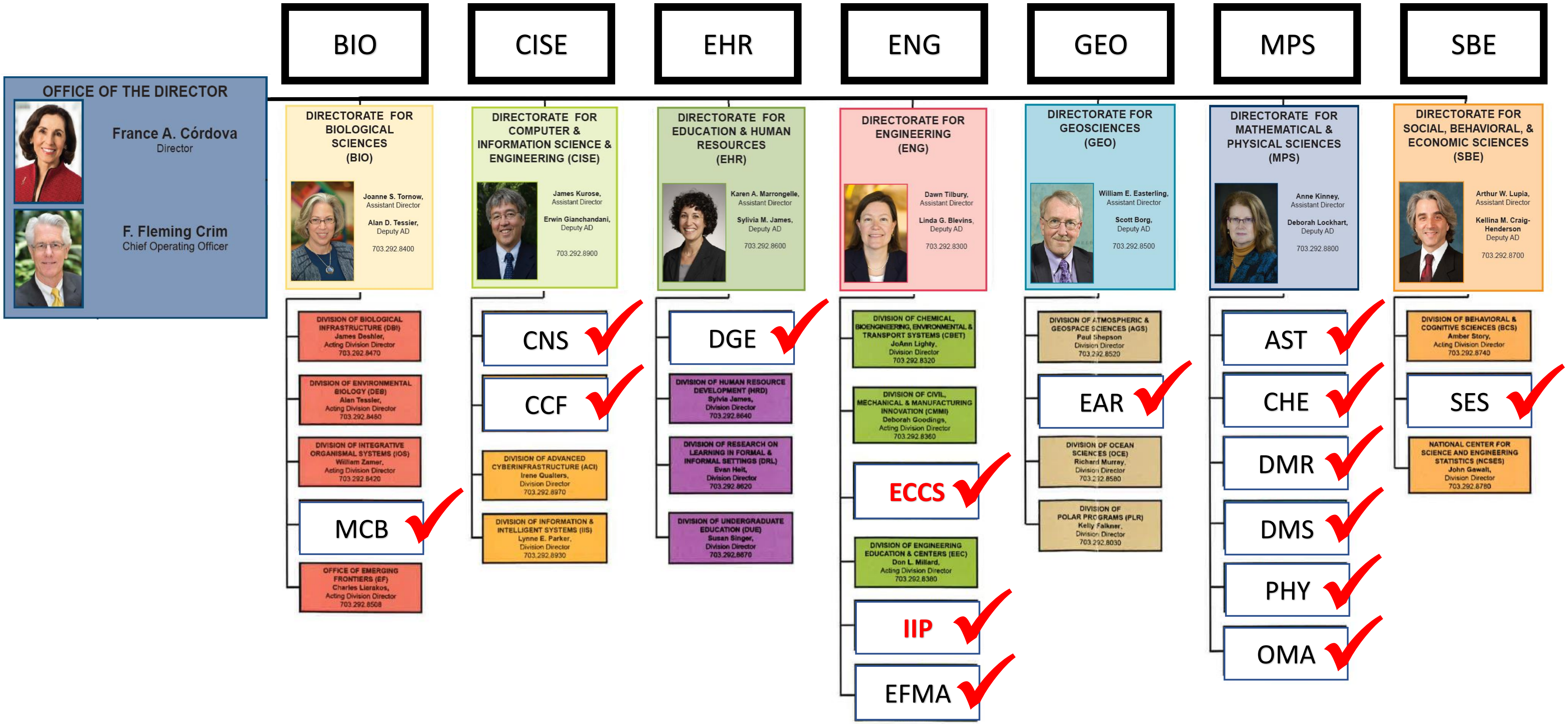
Fundamental science



Understanding basic quantum properties of entanglement, superposition, coherence, interference, and squeezing

Quantum Leap Funding Across the Foundation

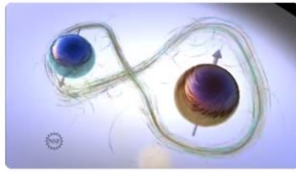


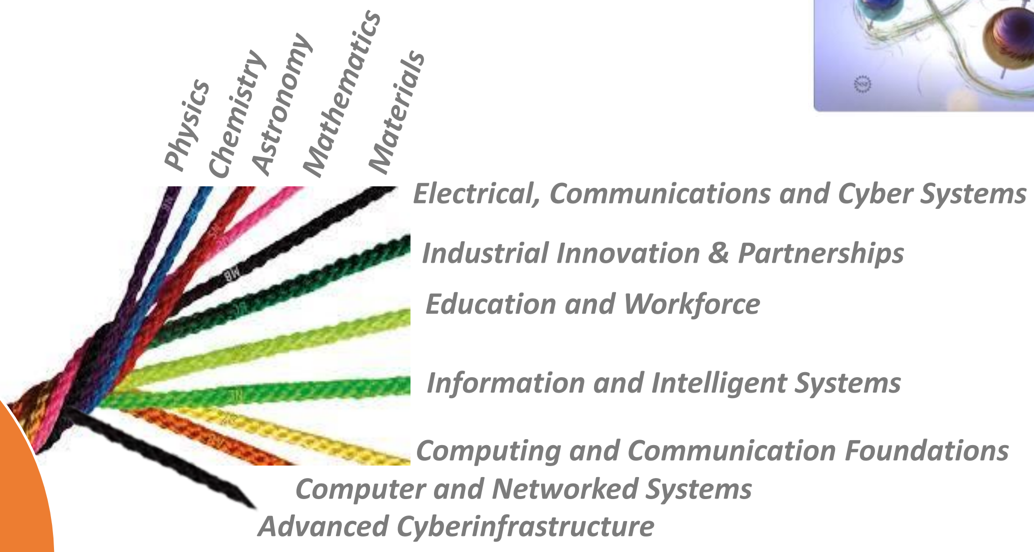


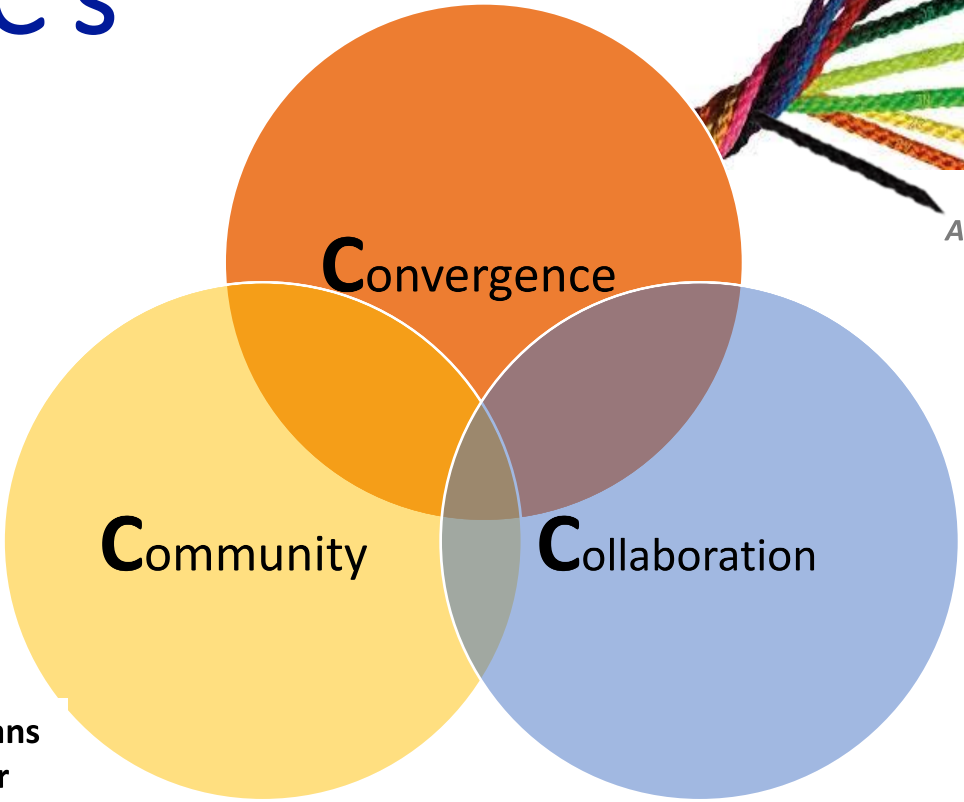
From all NSF programs combined: Over 2000 QIS-related Awards (✓)

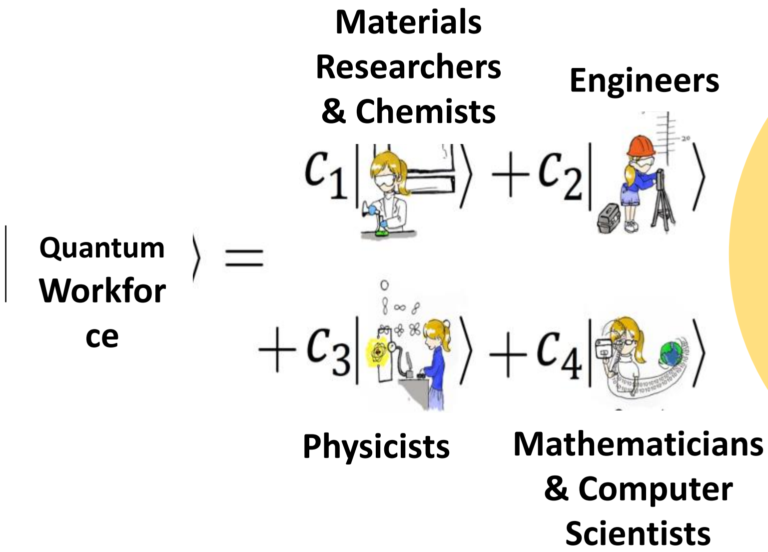
The NSF Approach

The 3 C's



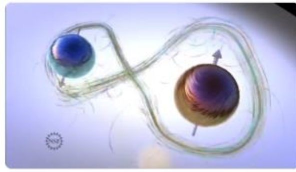






Partnerships with other government agencies and laboratories, industry, and international collaborators

NSF programs supporting Quantum Leap



Convergence Accelerator, Track C, Quantum Technologies

QL Challenge Institutes (support NQI)

TAQS Incubators: Transformational Advances in Quantum Systems

Q-AMASE-i - quantum materials and device foundry

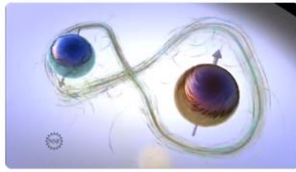
Ideas Lab: Practical Fully-Connected Quantum Computer Challenge (PFCQC)

QISE-Net – "TRIPLETS"; NSF/DOE/AFOSR: Quantum Science Summer School; 2017-2020

EFRI-ACQUIRE; Advancing Communication Quantum Information Research in Engineering

2016

2021



Thank You!

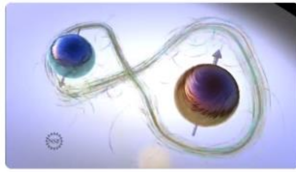
Presenter contact details:

Dominique M. Dagenais

- Directorate for Engineering - ECCS
  - Email: ddagenai@nsf.gov

Questions about the Challenge Institutes, please email directly to QLCI@nsf.gov.

NSF Quantum Leap Activities



- NSF 16-502 EFRI ACQUIRE. Quantum Communication and Networking; $18M; 9 Awds.
- NSF 17-548 Ideas Lab: Practical Fully-Connected Quantum Computer; $15M / 5yrs
- NSF 1730449 “EPiQC: Enabling Practical-scale Quantum Computing”; $10M / 5 yrs .
  Expeditions in Computing program in CISE/CCF; See NSF news release 18-011
- NSF 1743059 (NSF, DOE, & AFOSR): Quantum Science Summer School (QS^3)
- NSF 1747426 “Triplets” QISE-Net Workshop Series: Cross-Sector Connections; $2.5M
- NSF 17-053 “Braiding” DCL: EAGER Awards for Demonstrating Topological QC;
- NSF 18-035 TAQS DCL: Transformational Advances in Quantum Systems; $25M; 25 Awds.
- NSF 18-051 DCL: Enabling Quantum Leap in Chemistry; $6.4M in FY 2018
- NSF 18-046 DCL: Room-Temperature Q. Logic through Improved Low-D Materials
- NSF 18-062 EQuIP DCL: Engineering Q. Integrated Platforms for Q. Comm.; $6M; 8 Awds.
- NSF 18-578 QAMASEi: Foundries for Q. Materials Science, Engineering, and Info. $20M - $25M
- NSF 19-507 QCIS Faculty Fellows; FY’19 and FY’20; $6.7M
- NSF 19-532 QII-TAQS Transformational Advances in Quantum Systems; $26M in FY’19
- NSF 19-559 QLCI Quantum Leap Challenge Institutes; $5M/year for each of several centers