Quantum Information Science: From a NIST Perspective

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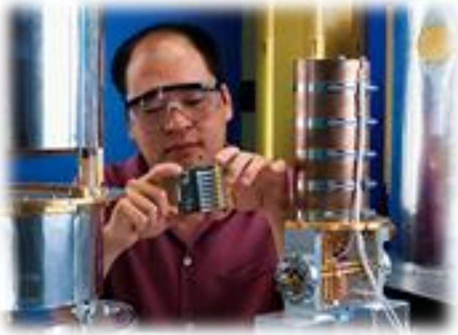
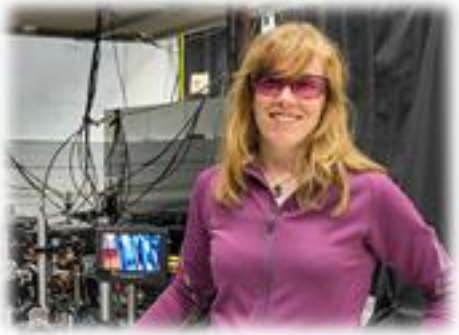
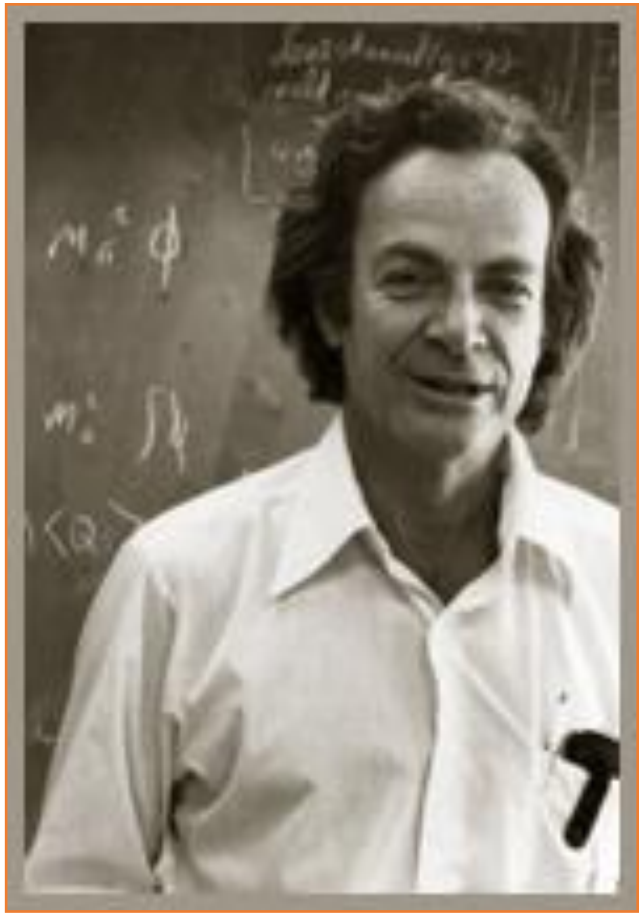


NIST
National Institute of
Standards and Technology
U.S. Department of Commerce



PML
PHYSICAL MEASUREMENT LABORATORY

A First Hint of Quantum Information?

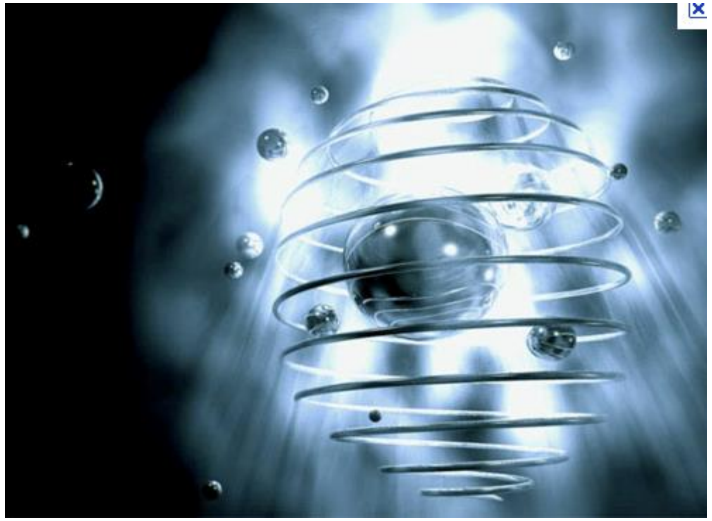


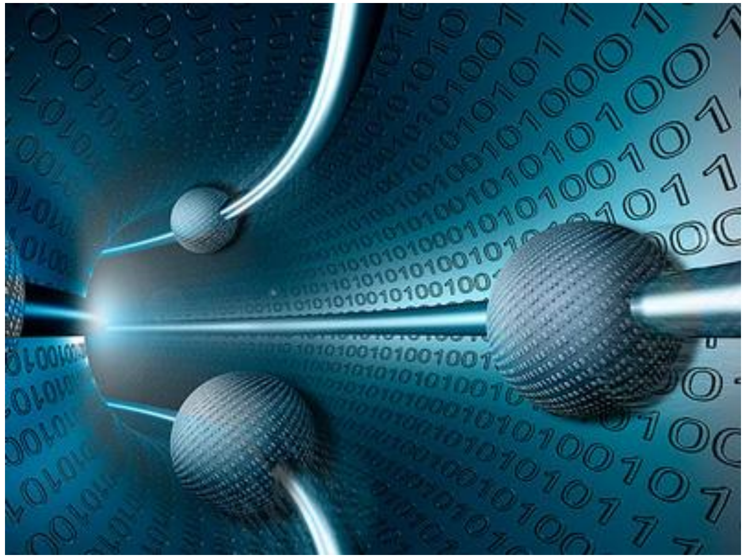
"When we get to the very, very small world---say circuits of seven atoms---we have a lot of new things that would happen that represent *completely new opportunities* for design. Atoms on a small scale behave like nothing on a large scale, for they satisfy the laws of quantum mechanics. So, as we go down and fiddle around with the atoms down there, we are working with different laws, and *we can expect to do different things*. We can manufacture in different ways. We can use, not just circuits, but some system involving the quantized energy levels, or the interactions of quantized spins, etc." -- Richard P. Feynman, "*Plenty of Room at the Bottom*", December 1959

Quantum Mechanics & Information Science

Two of the most important and revolutionary developments of the 20th century, both for **science** and **technology**:

Quantum Mechanics changed the way we think about the physical world.





Information Science changed the way we think about processing and communicating information

QIS is a convergence of these two 20th Century's revolutions

"Quantum information is a radical departure in information technology, more fundamentally different from current technology than the digital computer is from the abacus." -- W. D. Phillips, 1997 Nobel Prize in Physics

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:

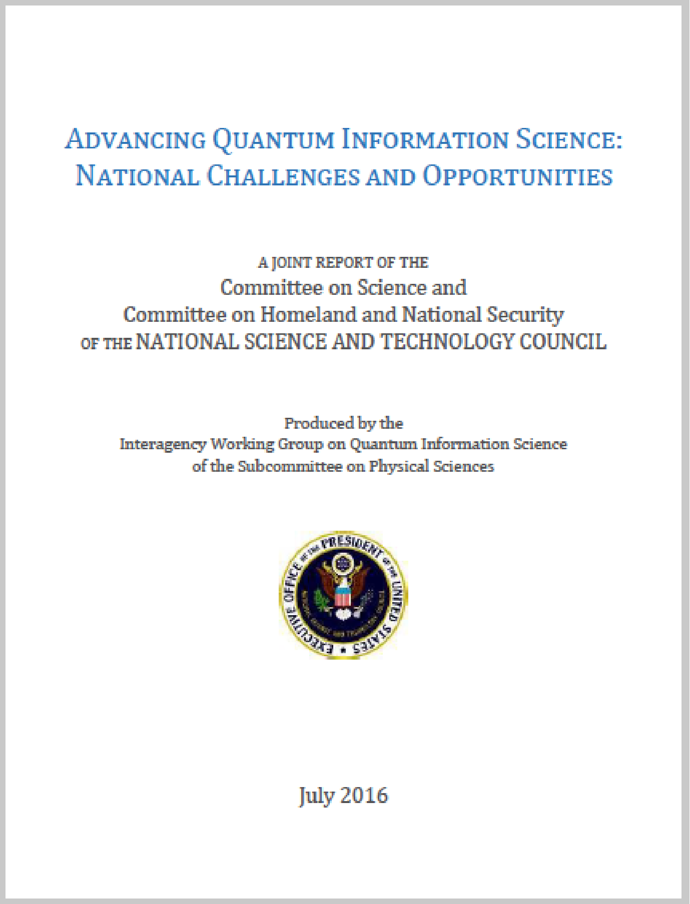
- *sensing and metrology:* precision navigation, timekeeping, …
- *communication:* secure data transmission and storage, random number generation, …
- *simulation:* complex materials, molecular dynamics, QCD, …
- *computing:* cryptanalysis, quantum chemistry, optimization, quantum field theory, …

and robust intellectual connections to numerous areas of basic research.

We focus here on QIS because it is much broader than just quantum computing!

QIS and the US Government

- QIS is of active interest to USG
  - Subject of numerous reports and focused meetings of various agencies
  - Coordinated across the agencies
  - Public report released in July 2016 → (also see: https://obamawhitehouse.archives.gov/blog/2016/07/26/realizing-potential-quantum-information-science-and-advancing-high-performance)
- White House OSTP hosted a Forum on QIS on October 18, 2016 (see: https://obamawhitehouse.archives.gov/blog/2016/10/18/identifying-strategic-options-advancing-quantum-information)



ADVANCING QUANTUM INFORMATION SCIENCE:
NATIONAL CHALLENGES AND OPPORTUNITIES

A JOINT REPORT OF THE
Committee on Science and
Committee on Homeland and National Security
OF THE NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

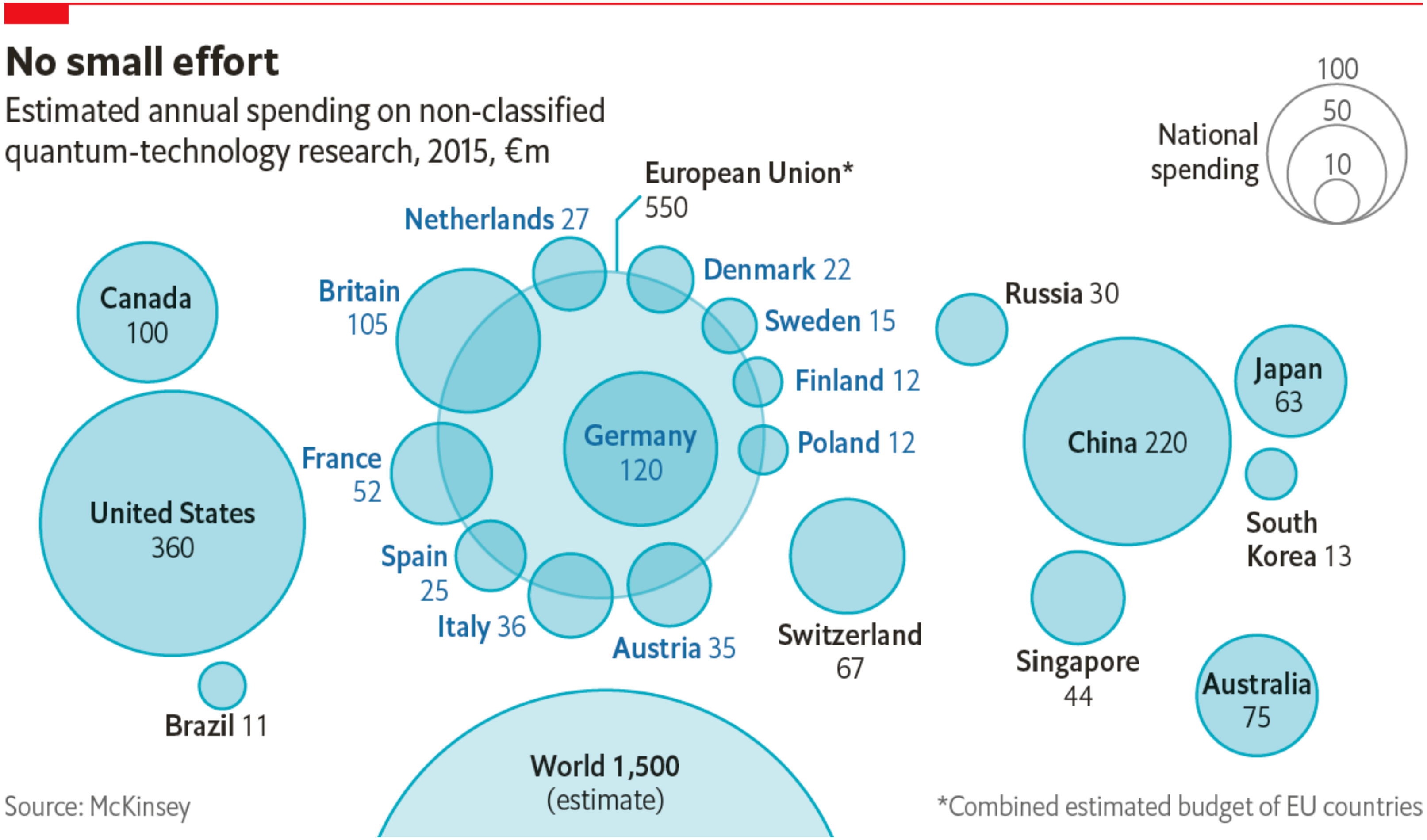
Produced by the
Interagency Working Group on Quantum Information Science
of the Subcommittee on Physical Sciences

July 2016

https://www.whitehouse.gov/sites/whitehouse.gov/files/images/Quantum_Info_Sci_Report_2016_07_22%20final.pdf

Nations and Companies are Investing

March 11, 2017



No small effort

Estimated annual spending on non-classified quantum-technology research, 2015, €m

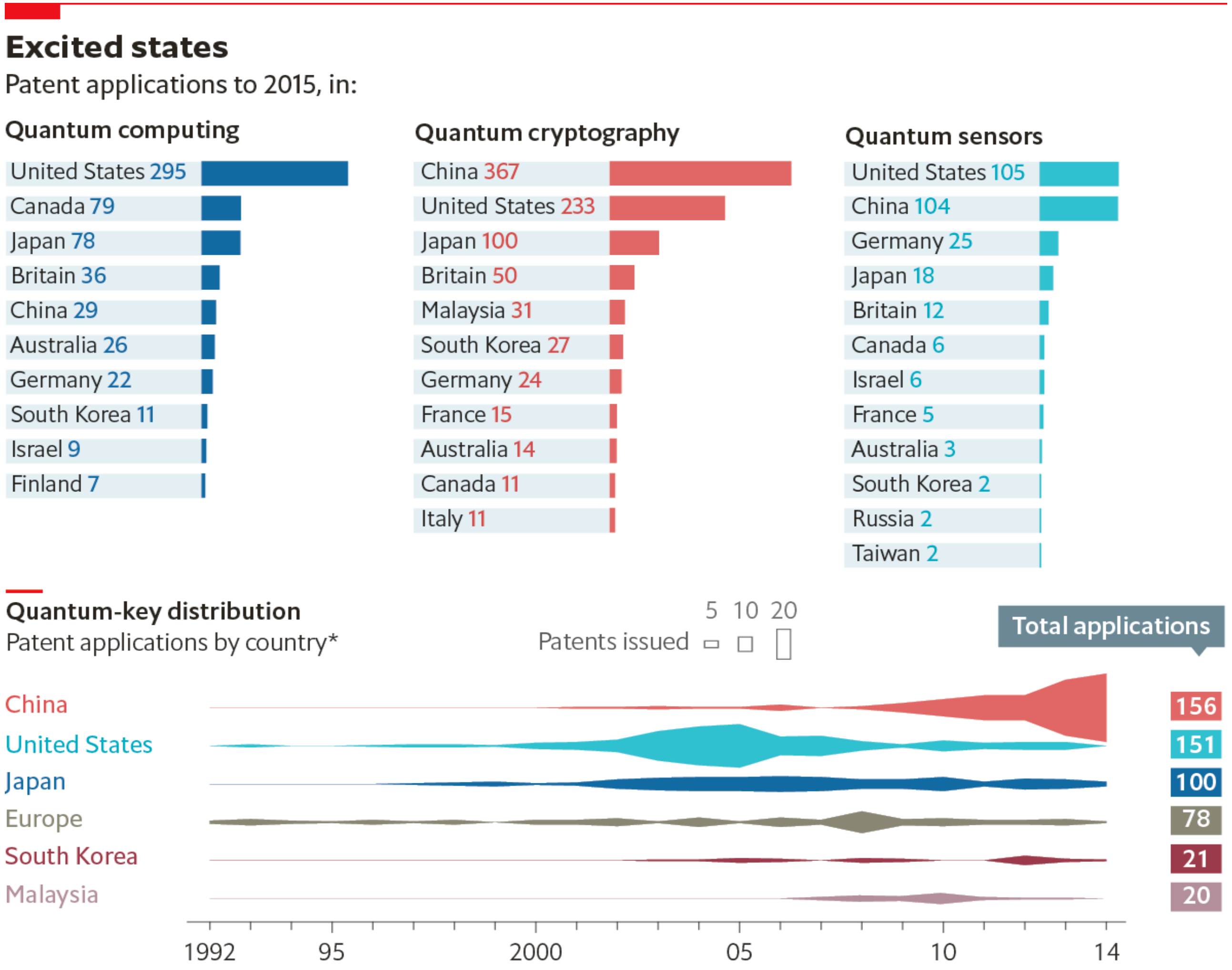
Source: McKinsey

*Combined estimated budget of EU countries

World-wide Patents

March 11, 2017

Extracted from the Economist



Excited states

Patent applications to 2015, in:

Quantum-key distribution

Patent applications by country*

Sources: UK Intellectual Property Office; European Commission

*By location of corporate headquarters

QIS and DOE/OS/BES

According to the BES website: “Basic Energy Sciences (BES) supports fundamental research to understand, predict, and ultimately control matter and energy at the electronic, atomic, and molecular levels in order to provide the foundations for new energy technologies and to support DOE missions in energy, environment, and national security.”

- The future of *understanding, predicting, and controlling matter and energy at* these levels is not just based on quantum mechanics but on QIS! Feynman *foresaw the answer more than 50 years ago*!
- Moreover, one of the largest application of a QIS will be the efficient solution (emulation, simulation, and/or computation) of one quantum problem by another quantum system!

Applications of QIS Relevant to DOE/OS

- For BES:
  - Material characterization
  - New quantum materials for computing or energy collection and harvesting
  - Understanding of fundamental interactions relevant to AMO
  - Computational Theoretical Chemistry – whether exact or new density functionals
  - Condensed Matter Physics including theoretical CMP
  - Fundamental research to predict and control matter and energy
- For the broader OS:
  - Computation
  - Search for Dark Matter
  - Gravity wave detectors
  - Sensor and detectors for HEP

Possible Applications of Q. Computers

- Solution of basics physics problems including:
  - Lattice Quantum Electro/Chromo-Dynamics (QED/QCD)
  - Simulations of Condensed Matter Hamiltonians – High Tc Superconductivity
- Optimization of commercially important problems:
  - Electronic Circuit layout
  - Airline Schedules (efficiency here – even at a fraction of a penny per mile can drive out competitors)
- Accelerated search of large databases (numerous possibilities)
- Simulation of important physical systems:
  - Biological applications: e.g. protein folding & pharmaceutical binding
  - Potential design of new commercial materials with unimagined properties
- Other undreamt of applications – remember:
  - In 1960 nobody believed the laser would be used for eye surgery, welding, …
  - In 1950 nobody guessed the transistor would lead to the information revolution, little own the integrated circuit and personal PC!!!

Why Now

- Intellectual Frontier where scientific and technical opportunities have implications for:
  - **National Security**: cryptanalysis, secure communications, inertial navigation
  - **Economic Competiveness**: new sensors and imaging tools, improved metrology
  - **Frontiers of Science**: discovery of new materials, insights into cosmology
- QIS is at a Tipping Point – U.S. and international companies are investing:
  - **Major IT industries**: *for e.g*. Google, Microsoft, IBM, Intel
  - **Technology companies**:
  - **Small and/or New companies:**
  - **Venture capital** is appearing and investing
  - **Niche products** are appearing – considered to be harbinger of a nascent field (chip-scale atomic clocks, quantum gravimeters, quantum-secure networks, …)
- Foreign competition is growing rapidly:
  - Some foreign investment levels are approaching those in the U.S.
  - Foreign governments are implementing focused QIS initiatives
    - China, UK, Germany, Canada, Japan, Australia, Netherlands, EU, …
  - Lucrative research opportunities abroad are attracting top-tier U.S. researcher's

Some NIST Quantum Definitions

- Quantum Technology:
  - Materials/systems that provide individual sensitivity to quanta – whether light, spins, charge, …
  - Enabling technologies – *e.g.* stable chip scale lasers, chip-scale frequency combs, …
  - Enabling technology that creates high-efficiency detection and transport of quanta – *e.g.* UV fiber for UV lasers, materials with less charge trapping or fewer stray electron spins, ion traps with lower decoherence, *etc.* – basically how to beat down noise and decoherence
- Quantum Metrology:
  - The exploitation of quantum technology to improve measurement science to make better detectors, sources, magnetic or electric field sensors, improved QHR devices, improved SETs,
  - Includes clocks, magnetometers, self-correcting interferometers
  - Transduction of signals – including both classical and quantum
  - Squeezing to allow measurement beyond the Standard Quantum Limit (SQL) – this together with transduction allows amplification and parametric amplification of signals beyond the SQL
- Quantum Based Measurement:
  - The exploitation of quantum technology, quantum metrology, superposition, entanglement, or squeezing to improve a physical measurement

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

Why NIST Cares about QIS

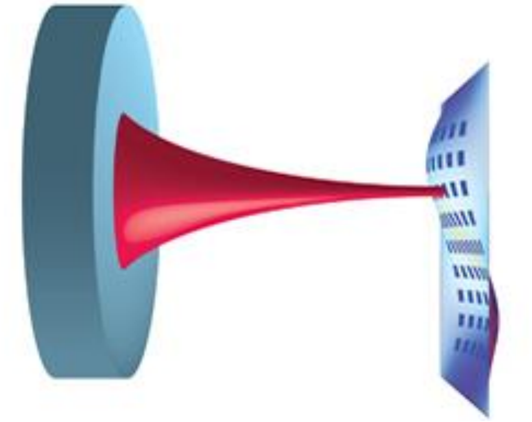
Allows better measurements

- Improved clocks
- Clocks so good they sense their environment → search for gravity waves, dark matter
- If I have technology that can integrate two legs of the electrical metrology triangle on chip then I have the ultimate self-calibrating electrical instrument
- Standards are increasingly quantum in nature – QHR, JVS, clocks, magnetometers, …
- Quantum transduction provides technology to directly convert classical rf or microwaves to optical signal
- Control and manipulation of JJs may lead to high-speed arbitrary waveform generators (100 GHz)
- Technology may enable operation in extreme environments
- Technology allows measurements beyond the shot noise or standard quantum limit

History of QI at NIST

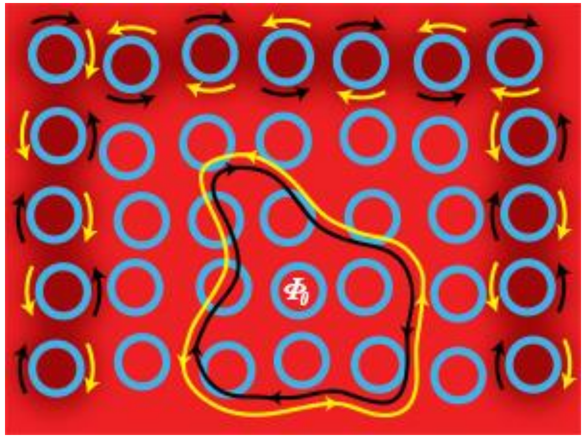
- 1992 Wineland suggests spin squeezing for improved sensitivity of clocks
- 1993 Competence project initiated to support idea
- 1994 First Workshop focused on QI held at NIST, Gaithersburg (August 94)
- 1995 Cirac and Zoller propose gate based on ion traps
- 1995 Wineland and Monroe implement concept
- 2000 NIST QI Program established
- 2000 First NIST QI Competence (like LDRD)
- 2001 DARPA supports Q. Communication effort
- 2003 NIST QI Program broadened
- 2005 First NIST Initiative for QI is funded
- 2006 Joint Quantum Institute established (FY07 Initiative)
- 2012 Wineland wins Nobel Prize for research in support of Q
- 2104 Joint Center for Quantum Information in Computer Science (QuICS) is established

Quantum Information Science at NIST



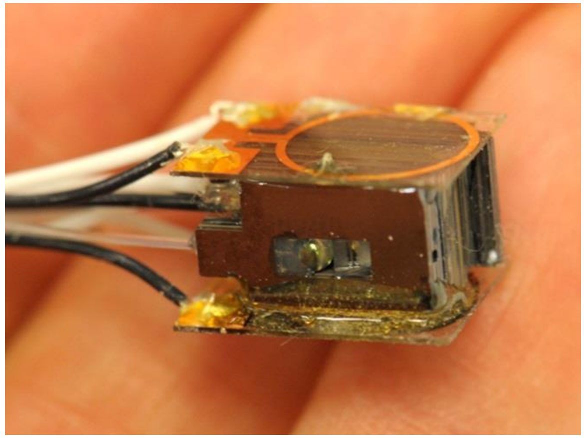
Quantum Transduction

We must realize efficient transfer of information between quanta of different types. Shown here: an optical cavity coupled to a vibrating, mechanical membrane.



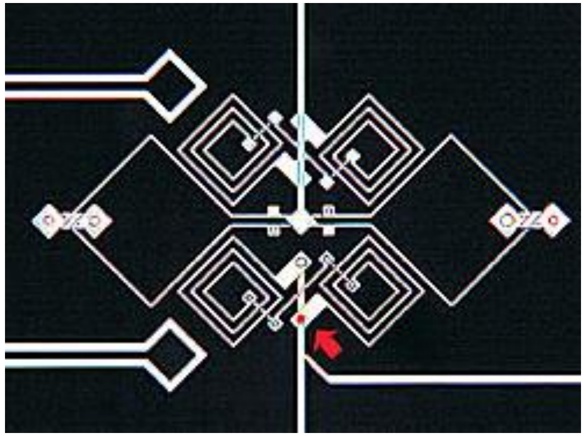
Complex Quantum Systems

We must develop tools for understanding, controlling, and measuring complex quantum systems. Shown here: a photonic chip with ring resonators provides topologically robust transport of photons.



Small Quantum Systems

Small quantum systems will be improved sensors and better standards. Shown here: a chip-scale atomic magnetometer.

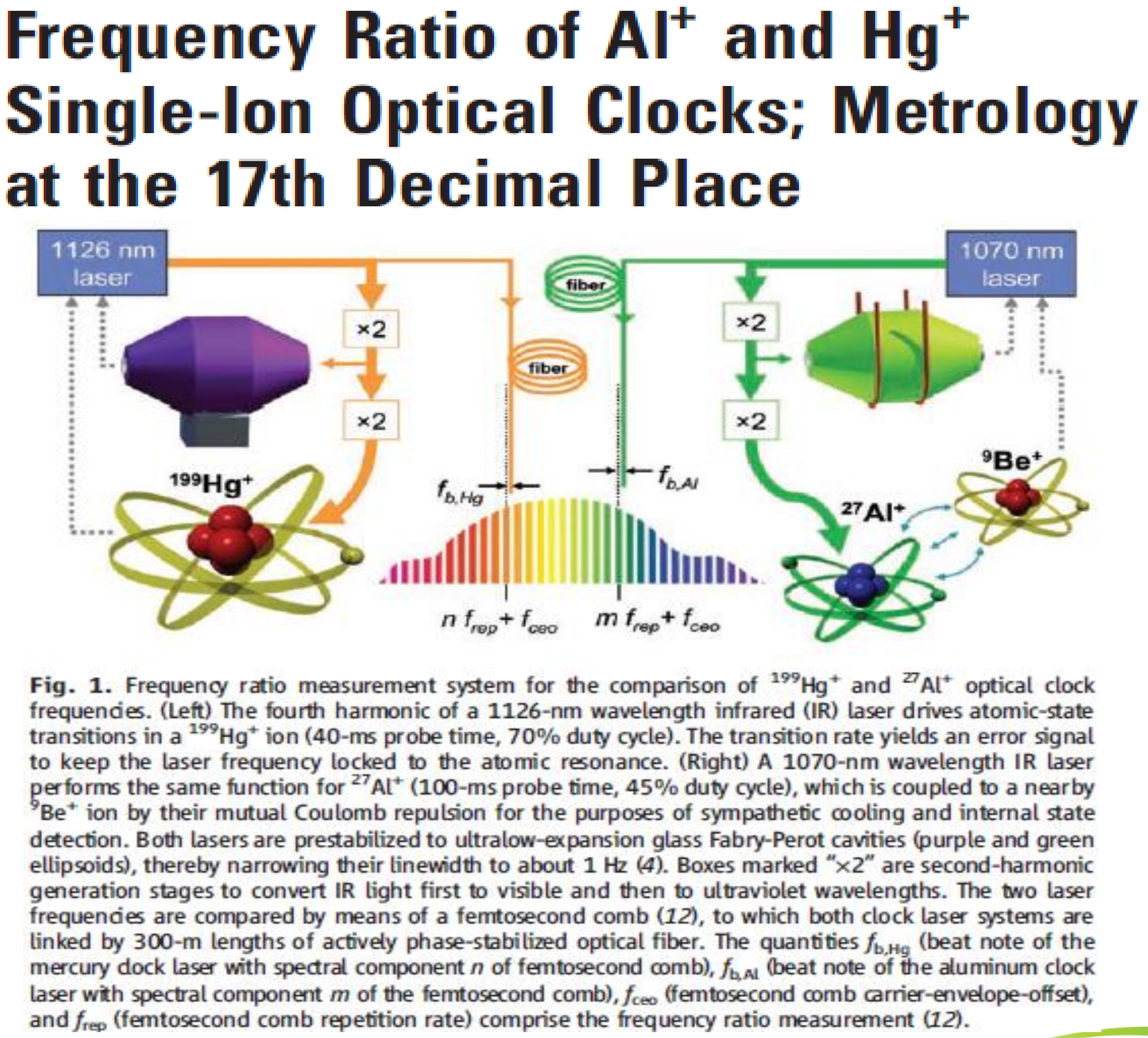


Quantum Materials and Solid State Qubits

Solid state realizations of qubits are promising for mass production, though additional research is required. Shown here: a Josephson junction qubit.

Quantum Information Prospects

- Quantum Logic Clock
- Quantum Transduction
- Single photon sources and detectors – many apps.
- Low noise, high-speed, amplifiers and parametric amplifiers beyond the SQL
- Random Number Beacons
- Quantum Based Measurements – electrical, optical, …
- Improved Sensors
- Quantum Communication & Computing



Frequency Ratio of Al$^+$ and Hg$^+$ Single-Ion Optical Clocks; Metrology at the 17th Decimal Place

Fig. 1. Frequency ratio measurement system for the comparison of ^{199}Hg$^+$ and ^{27}Al$^+$ optical clock frequencies. (Left) The fourth harmonic of a 1126-nm wavelength infrared (IR) laser drives atomic-state transitions in a ^{199}Hg$^+$ ion (40-ms probe time, 70% duty cycle). The transition rate yields an error signal to keep the laser frequency locked to the atomic resonance. (Right) A 1070-nm wavelength IR laser performs the same function for ^{27}Al$^+$ (100-ms probe time, 45% duty cycle), which is coupled to a nearby ^{9}Be$^+$ ion by their mutual Coulomb repulsion for the purposes of sympathetic cooling and internal state detection. Both lasers are prestabilized to ultralow-expansion glass Fabry-Perot cavities (purple and green ellipsoids), thereby narrowing their linewidth to about 1 Hz (*4*). Boxes marked "×2" are second-harmonic generation stages to convert IR light first to visible and then to ultraviolet wavelengths. The two laser frequencies are compared by means of a femtosecond comb (*12*), to which both clock laser systems are linked by 300-m lengths of actively phase-stabilized optical fiber. The quantities $f_{b,Hg}$ (beat note of the mercury clock laser with spectral component *n* of femtosecond comb), $f_{b,Al}$ (beat note of the aluminum clock laser with spectral component *m* of the femtosecond comb), f_{ceo} (femtosecond comb carrier-envelope-offset), and f_{rep} (femtosecond comb repetition rate) comprise the frequency ratio measurement (*12*).

Science 319, 1808, 2008

Quantum Logic Clock & Metrology

Science 329, 11630, 2010

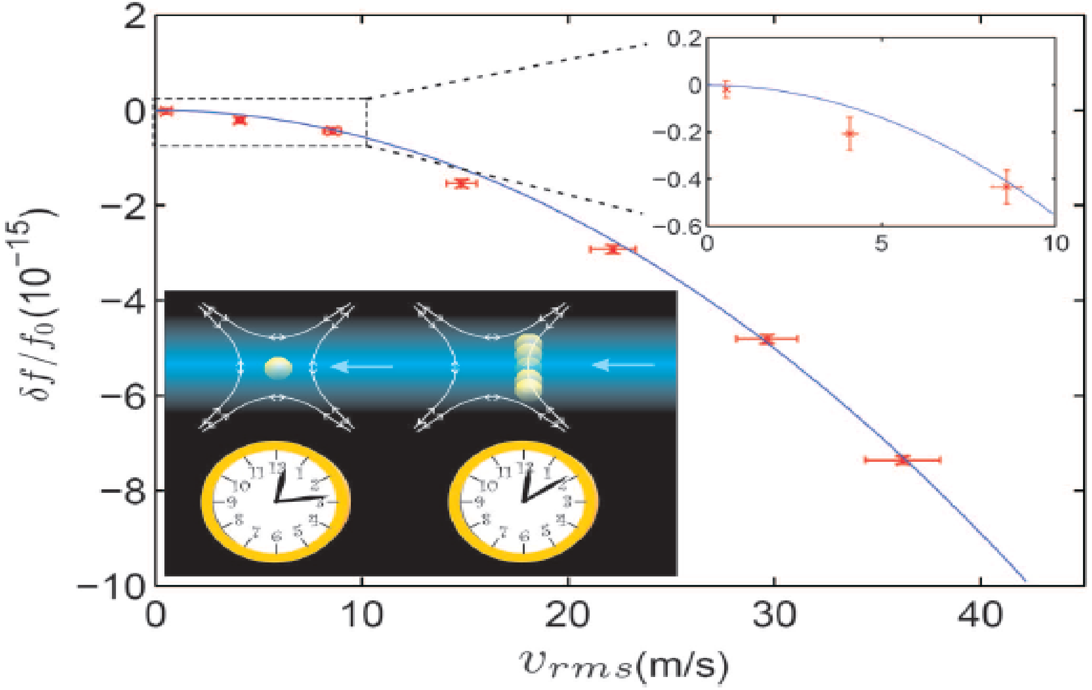


Fig. 2. Relativistic time dilation at familiar speeds (10 m/s = 36 km/hour ≈ 22.4 miles/hour). (Lower left inset) As the Al$^+$ ion in one of the twin clocks is displaced from the null of the confining RF quadrupole field (white field lines), it undergoes harmonic motion and experiences relativistic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

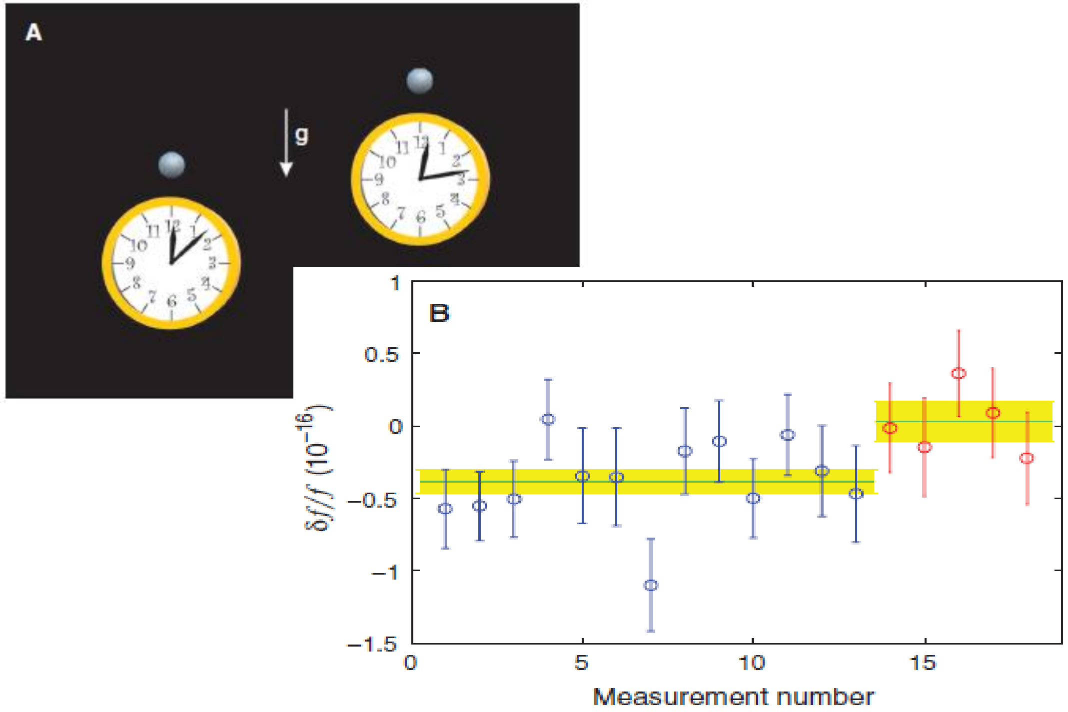


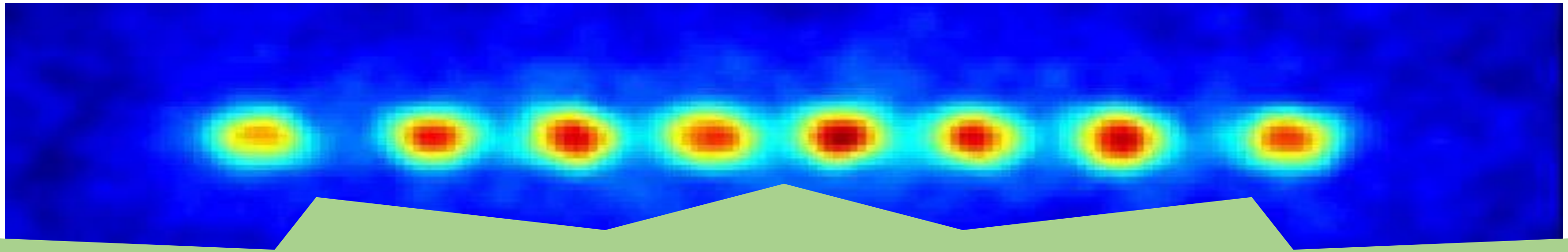
Fig. 3. Gravitational time dilation at the scale of daily life. (**A**) As one of the clocks is raised, its rate increases when compared to the clock rate at deeper gravitational potential. (**B**) The fractional difference in frequency between two Al$^+$ optical clocks at different heights. The Al-Mg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

Harness Entanglement to Reduce Quantum Noise

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

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

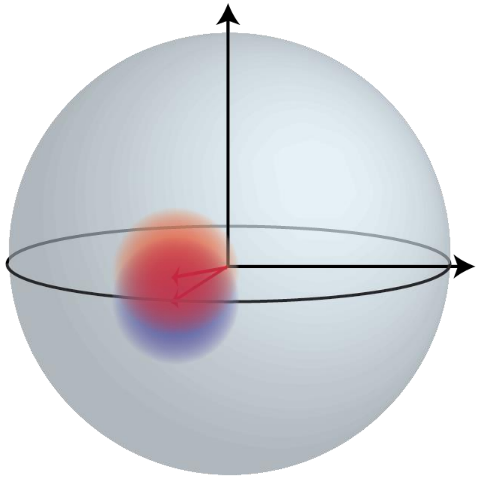
- Differential excitation overcomes atom/laser desynchronization
- **→ 1x10^{-18} measurement precision in 1 hour! (1000x improvement)**



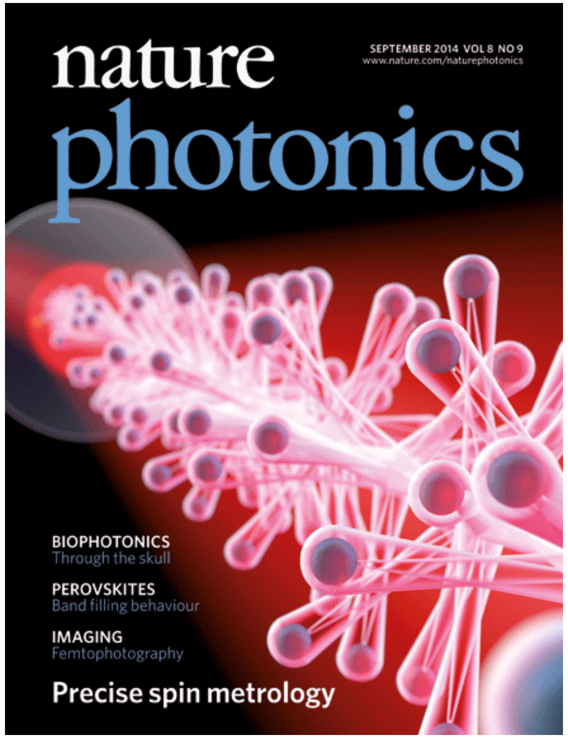
High risk: differential excitation and entanglement have never been implemented in state-of-the-art clocks!

Entanglement-Enhanced Quantum Measurements

Quantum noise smears out the orientation of quantum sensors, **limiting the precision of the information that can be extracted.**



Cavity-based **measurements forge entanglement or quantum links between a million atoms.**



nature photonics

SEPTEMBER 2014 VOL 8 NO 9
www.nature.com/naturephotonics

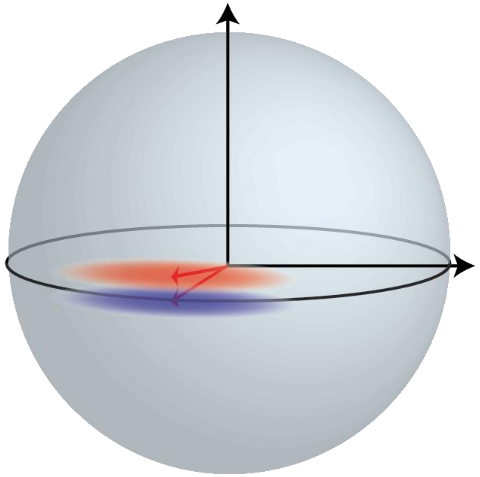
BIOPHOTONICS
Through the skull

PEROVSKITES
Band filling behaviour

IMAGING
Femtophotography

Precise spin metrology

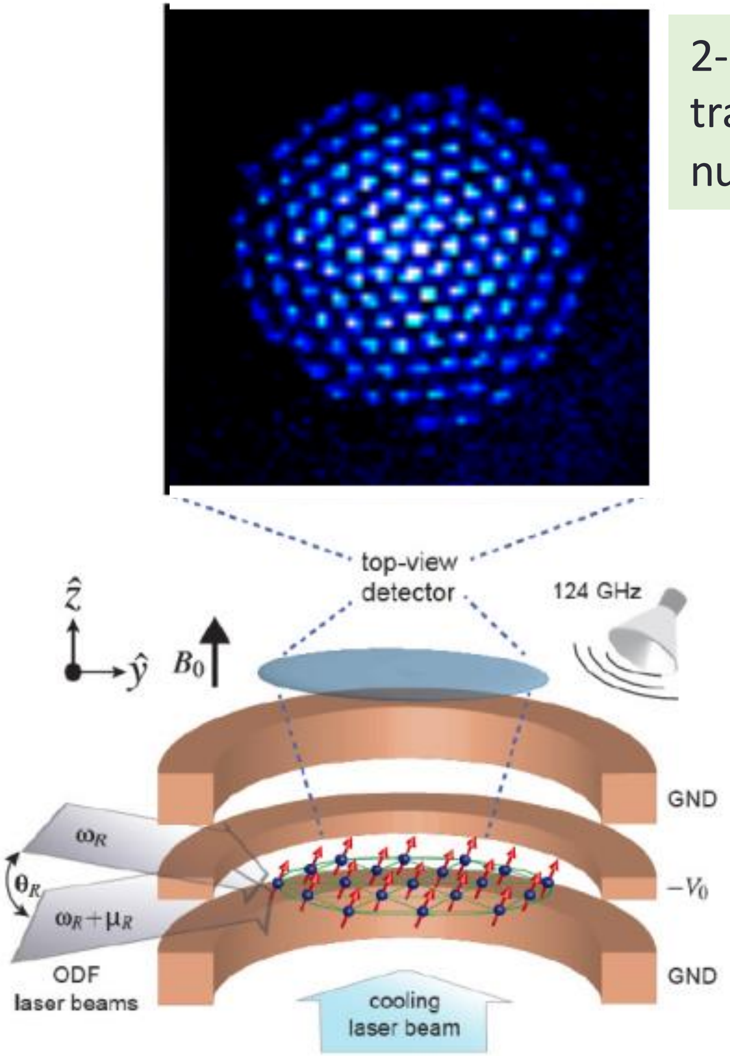
The entanglement squeezes the quantum noise, enhancing the precision of the information that can be extracted **by a factor of 10.**



Technique directly applicable to improving state-of-the art optical lattice clocks and inertial sensors.

J. G. Bohnet; et al., *Nature Photonics* **8**, 731-736 (2014)

Simulating Spin-Spin Interactions



2-d arrays of hundreds of ions formed and controlled in a Penning trap; provides platform for simulation of quantum magnetism with a number of spins that is intractable on a conventional computer

- Synthesized transverse Ising model on 100s of spins

$$H = \frac{1}{N}\sum_{i<j} J_{i,j}\sigma_i^z\sigma_j^z + B_x\sum_i \sigma_i^x$$

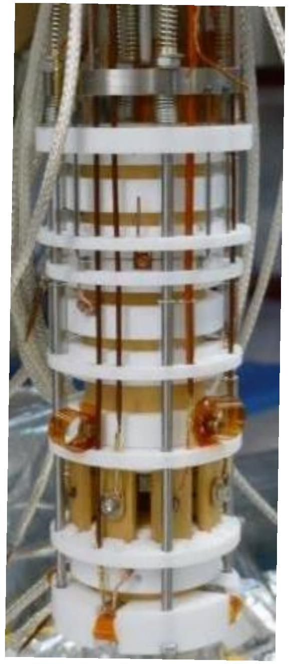
J. Britton *et al*., **Nature** 484, 489 (2012)

- Benchmarked quantum dynamics and entanglement

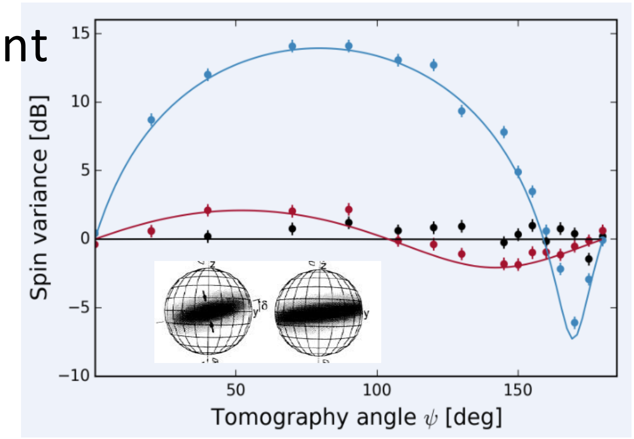
G. Bohnet *et al*., **Science** 352, 1297 (2016)

- Implement protocol for out-of-time-order correlation measurement → quantifies spread of quantum information

Gaerttner *et al*., arXiv:1608.08938



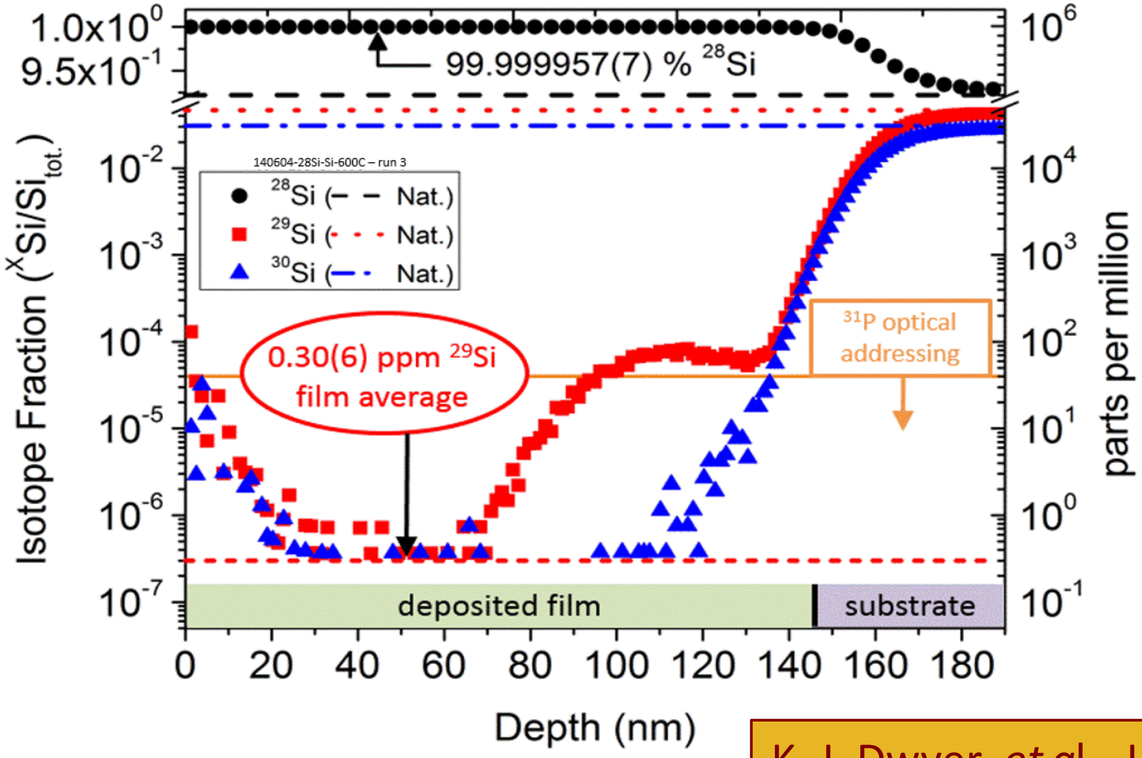
New trap: increases spin-spin coupling by 50

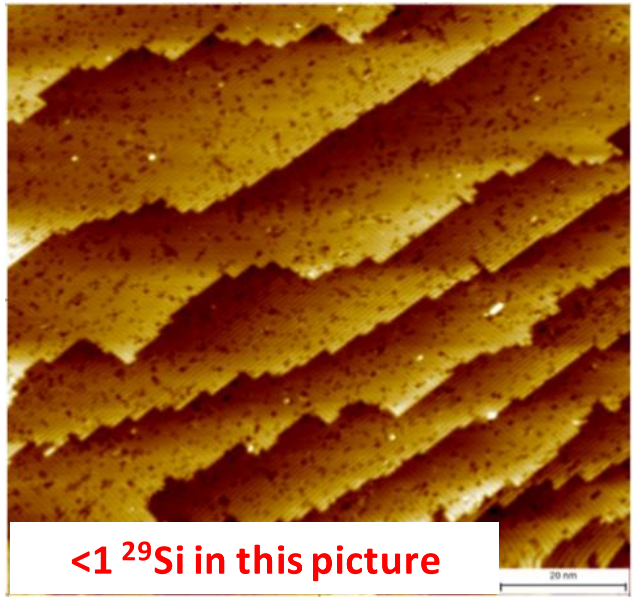


Enriched ^{28}Si for quantum devices

BBC News - Purer-than-pure silicon solves problem for quantum tech

Physicists make the purest silicon ever seen, solving a supply problem for research into quantum computers.





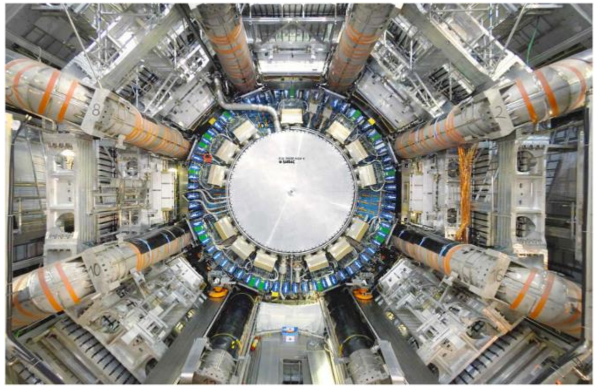
<1 ^{29}Si in this picture

Enriched silicon has been shown to dramatically extend coherence (T2) times and also reduce optical linewidths. We are producing the most highly enriched silicon known, allowing the technical limits of these benefits to be tested while providing an enabling source for ongoing Si QIS qubit efforts based on these benefits.

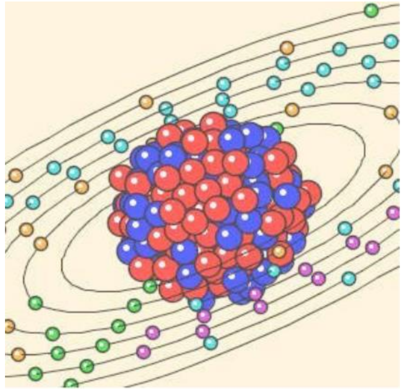
K. J. Dwyer, *et al.*, J. Phys. D: Appl. Phys. **47**, 345105 (2014)

Simulating Quantum Field Theory

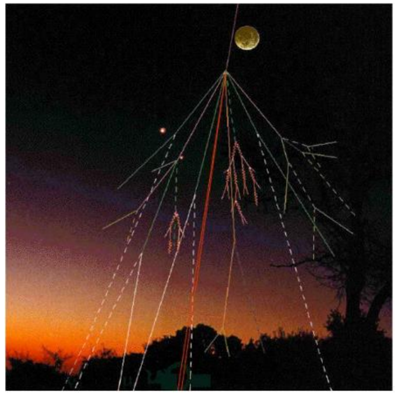
- Quantum field theory describes relativistic quantum systems:



particle physics



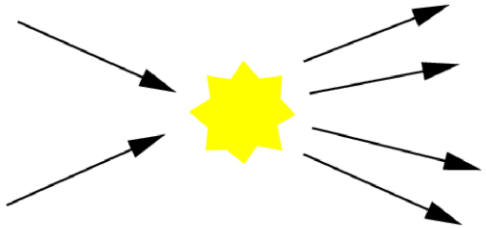
nuclear physics



cosmic rays

- Classical supercomputers cannot compute dynamics of strongly coupled quantum field theories.
- Can quantum computers succeed where classical computers fail?

Simulating Quantum Field Theory



Problem: Simulate particle scattering

Given: list of incoming particles and their momenta

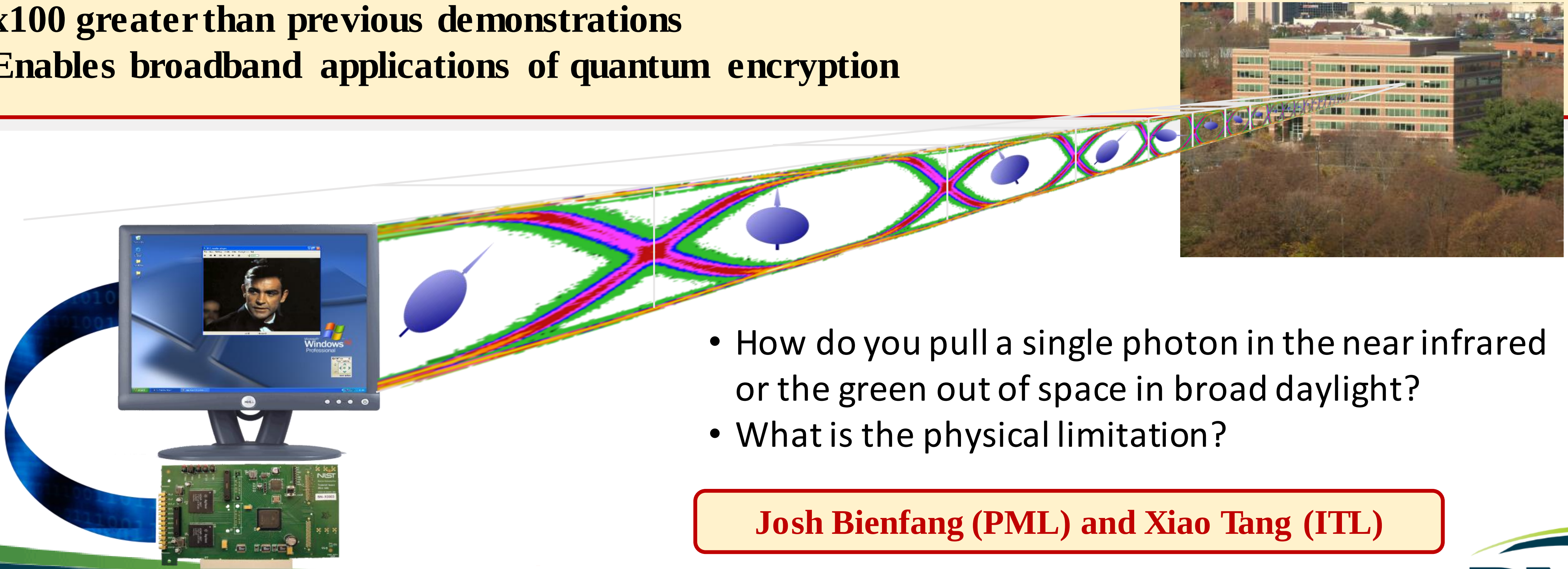
Goal: sample from probability distribution over outgoing particles that would be observed in an experiment

Results: quantum computers can do this efficiently (polynomial time) whereas classical computers in many cases cannot

[Jordan, Lee, Preskill, Science 336:1130 (2012)]
[Jordan, Lee, Preskill, arXiv:1404.7115 (2014)]

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**

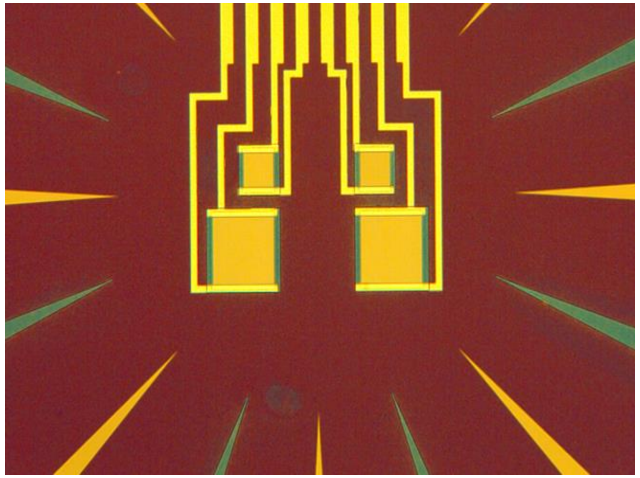


- How do you pull a single photon in the near infrared or the green out of space in broad daylight?
- What is the physical limitation?

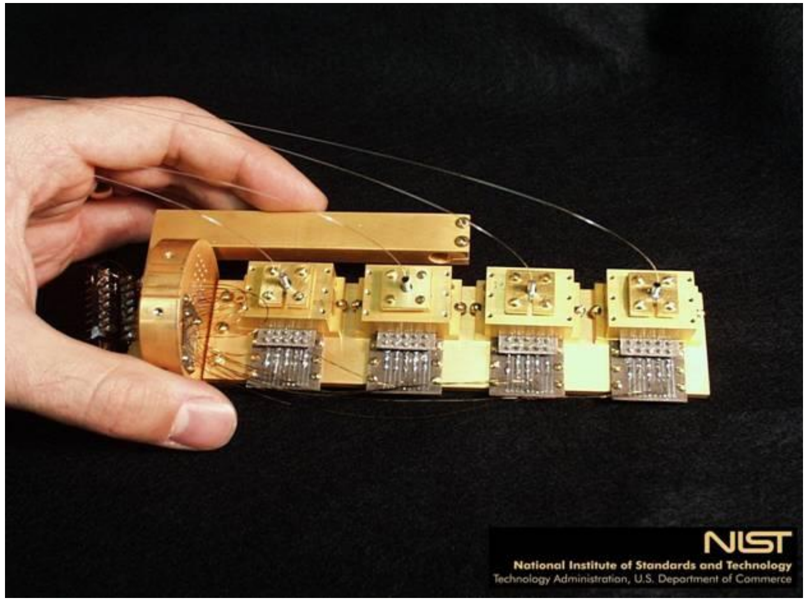
Josh Bienfang (PML) and Xiao Tang (ITL)

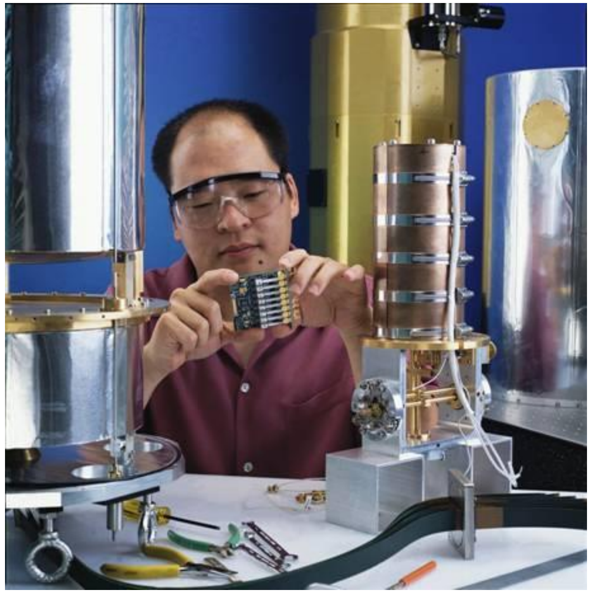
Superconducting Photon Detectors

- **Demonstrated Transition Edge Sensor with QE > 99 % – Optics Express 16, 1808, (2008); SPIE (2010)**
- **Developing improved materials for detectors**
- **High-speed single photon superconducting detectors with QE > 93% – Nature Photonics 7, 210, (2013)**



TES Detector



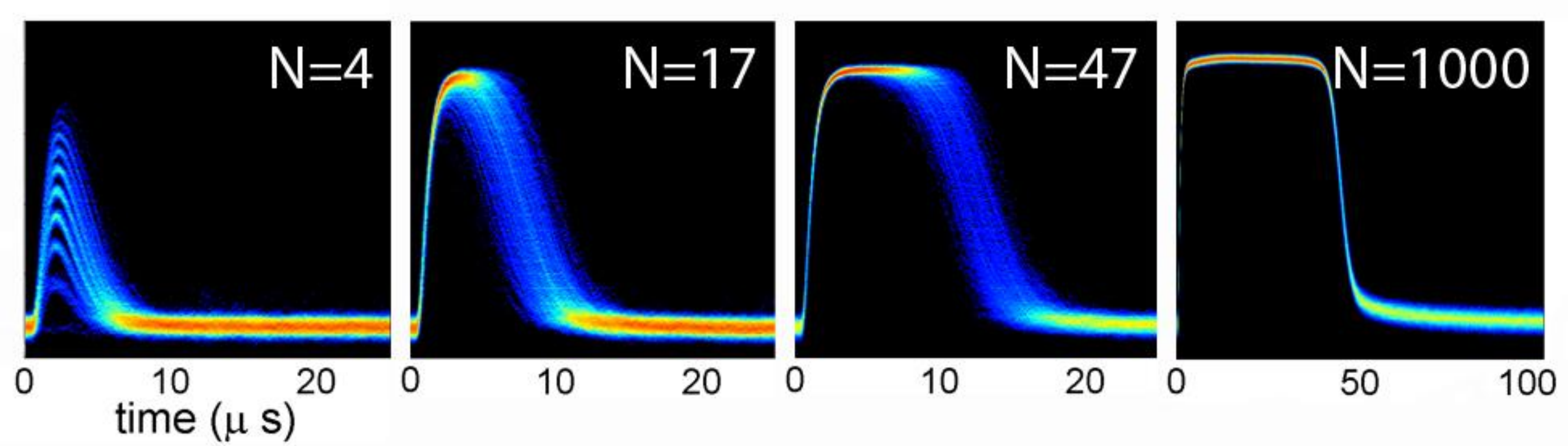


Sae Woo Nam

Used to set a QKD distance record of 200 km!

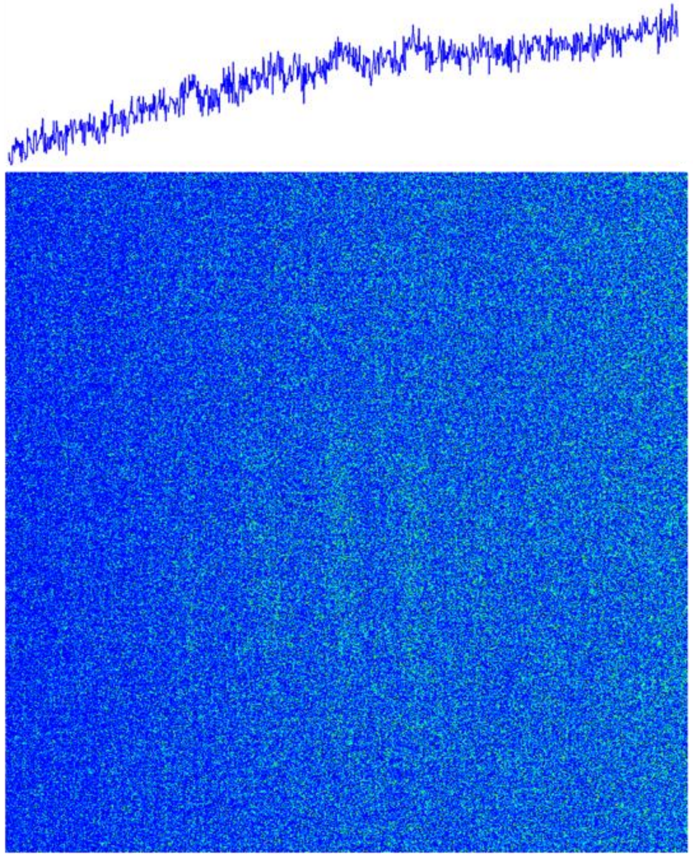
Determining Photon Number in a Weak Pulse

Transition edge sensor (TES) is capable of counting the number of as many as 1,000 photons in a single pulse of light with an accuracy limited mainly by the quantum noise of the laser source.

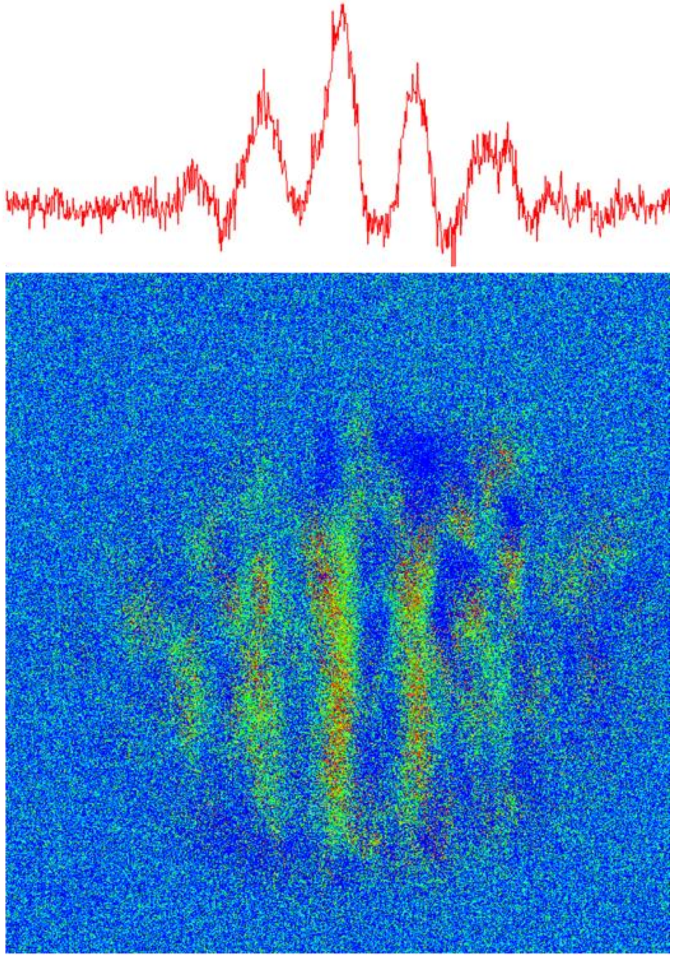


This series of data read-outs shows how the TES relaxation time increases with photon number. For N=4 photons, the TES returns from the elevated-resistance state to the edge of the transition region in less than 10 µs. At N=47 photons, it takes around 15 µs. And when the count is 1000, the relaxation time is approximately 50 µs.

Phase Sensitive Amplifier



Input (unamplified) image



PSA amplified image

Signal must be in the proper quadrature; monochromatic and low-resolution for now, but preserves SNR at maximum gain

Noiseless amplification for defense and medical imaging applications

U. Vogel, *et al.*; New J. Phys. 16, 013011 (2014); N. V. Corzo, *et al.*; Phys. Rev. Lett. 109, 043602 (2012)

Same color scale (false color), both with their respective backgrounds subtracted (single shot of each)

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

Quantum Information Science Summary

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

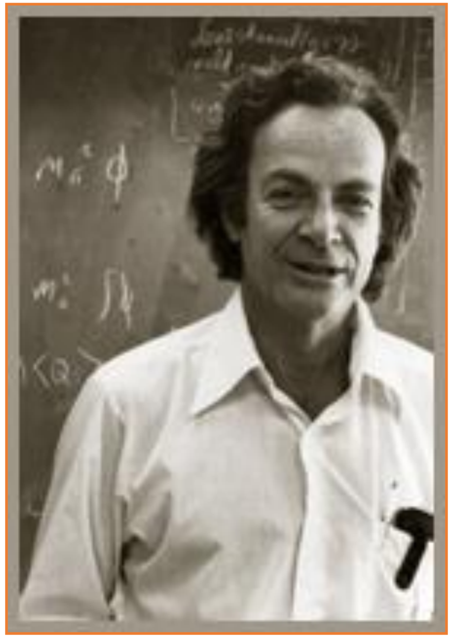
- *sensing and metrology:* precision navigation, timekeeping, …
- *communication:* secure data transmission and storage, random number generation, …
- *simulation:* complex materials, molecular dynamics, QCD, …
- *computing:* cryptanalysis, quantum chemistry, optimization, quantum field theory, …

and robust intellectual connections to numerous areas of basic research.

- Quantum communication is available today – not necessarily valuable today
- Quantum sensing and metrology is in the lab and being commercialized
- Quantum simulation is an exciting research field and within the next few years will simulate a *classically incalculable problem*
- Quantum computing, especially generalized QC, is years off but companies are investing

Why is Quantum Information Useful?

We are witnessing the second quantum revolution where technology
- Will use the weird properties of quantum mechanics
- Will exploit how nature works at the quantum level



"... and if you want to make a simulation of Nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy." -- Richard P. Feynman, "*Simulating Physics with Computers*", May 1981

- In the 20th Century only atomic clocks used the strange aspects of QM (GPS)
- Now chip scale atomic clocks are available
- Related technologies include exquisitely sensitive magnetometers, accelerometers, gravimeters
- NV centers may be lead to unimaginable magnetic imaging systems

- ➢ A quantum computer, if it existed, could break all preser encryption systems
- ➢ Quantum encryption can defeat any computational atta
- ➢ Quantum Logic Clocks, Magnetometers, Gyroscopes
- ➢ Quantum Simulations, Drug Design, other problems

Thank you!

Any questions?

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NIST

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