NIST, Quantum Communications, and Clocks

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Physical Measurement Laboratory

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

NIST, the Physical Measurement Laboratory (PML), and Quantum Information Science (QIS)

NIST: Bird's Eye View

The United States' national measurement laboratory, NIST is where Nobel Prize-winning science meets real-world engineering.

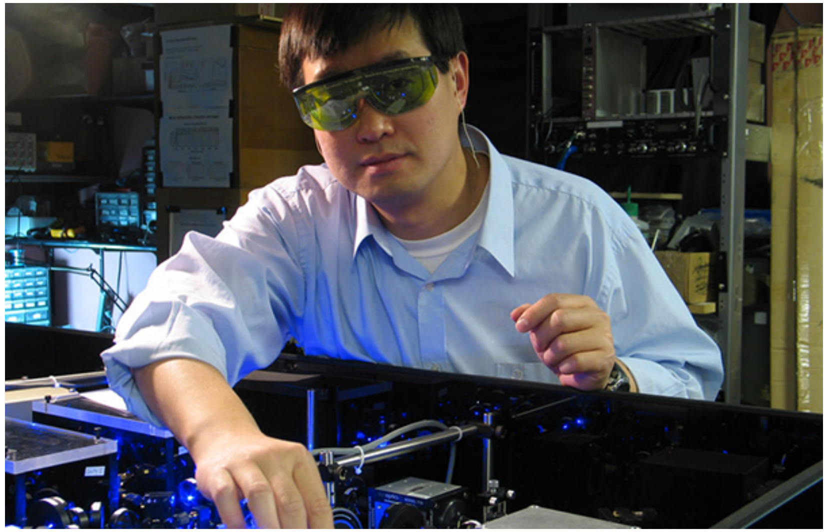
Courtesy HDR Architecture, Inc./Steve Hall © Hedrich Blessing

G. Wheeler

With an extremely broad research portfolio, world-class facilities, national networks, and an international reach, NIST works to support innovation. Sometimes we are referred to as "Industry's National Lab".

NIST Mission

To promote U.S. innovation and industrial competitiveness by advancing **measurement science, standards, and technology** in ways that enhance economic security and improve our quality of life



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.

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.

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

ENGAGED DISCIPLINES:

AMO Physics / Scientific Theory / R&D / Materials

T&E / Engineering Design & Development

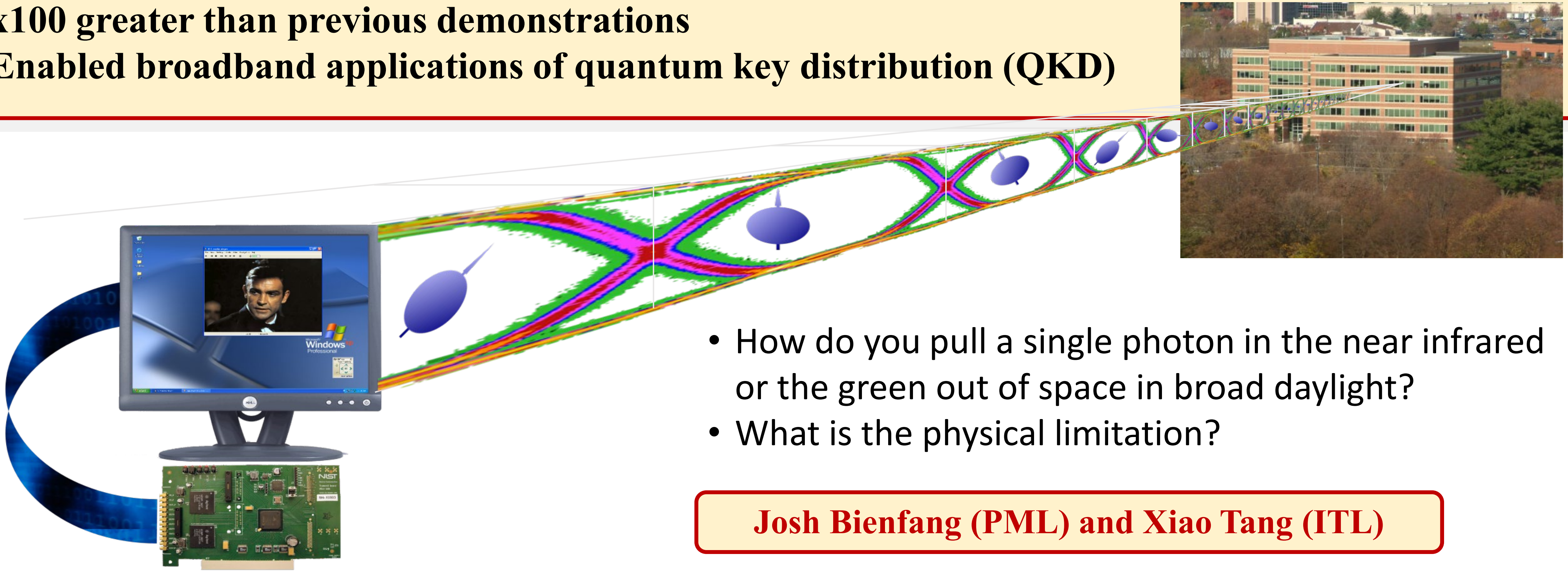
QED-C is being established in partnership with SRI International under the leadership of Joe Broz, Vice President of SRI's Advanced Technology and Systems Division (ATSD)

Contact: joe.broz@sri.com

Quantum Communications

Quantum Communications Effort: 2003-08

- 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
- Enabled broadband applications of quantum key distribution (QKD)



- 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)

NIST’s Quantum Communication Mission

NIST

Determine the physical limits of QKD – these were:

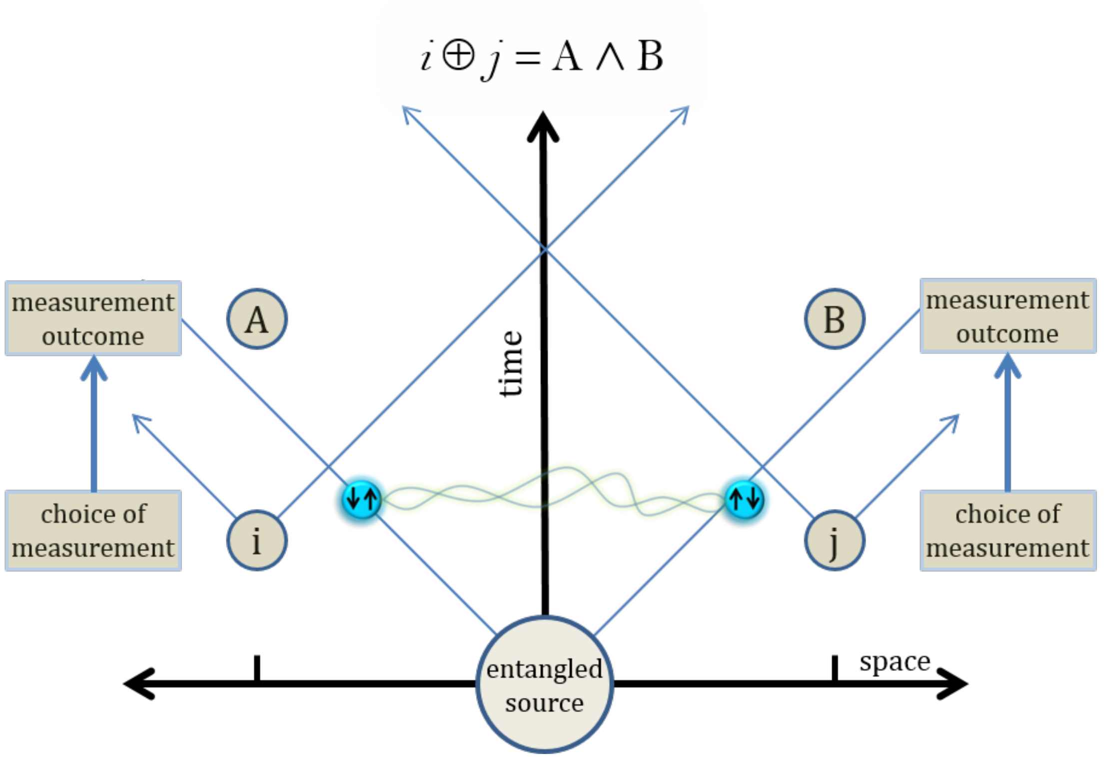
- Network timing limits total key
- Detector efficiency limits total key
- Slow detector gating increases background counts/errors
- Slow detector recovery limits total keys
- FPGA memory and distance of QKD link limits speed and total key

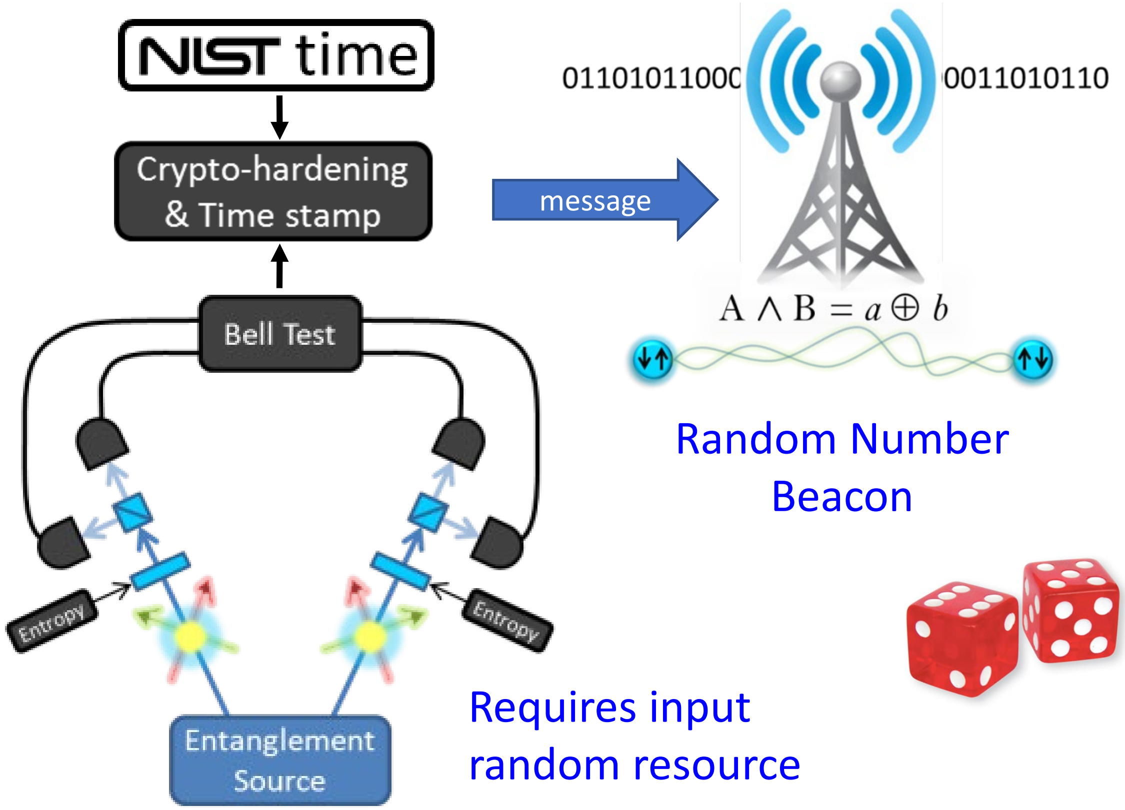
Result: NIST created a large program on improved detector efficiency, gating, and recovery

Ultimately, NIST also developed a program for characterizing single photon sources

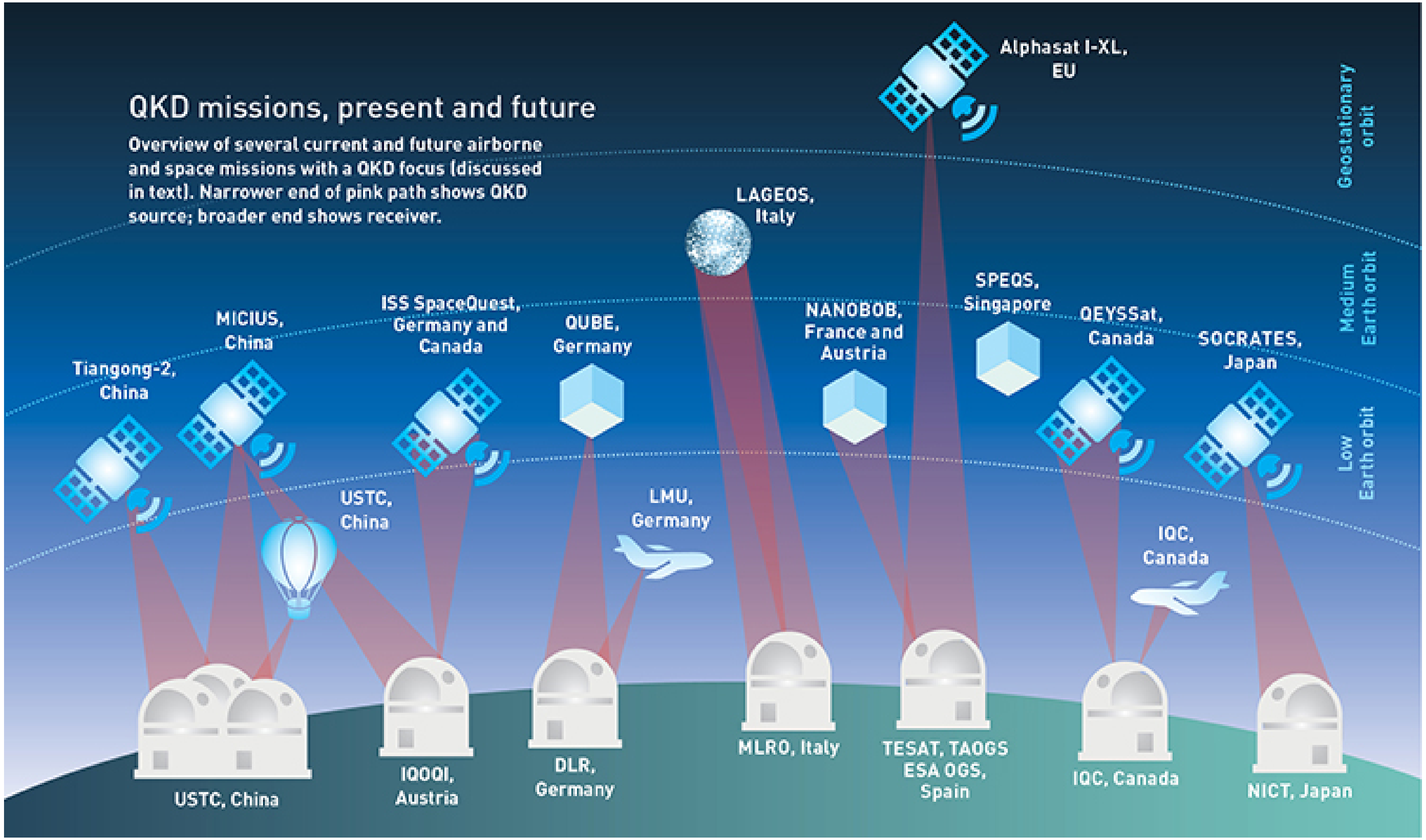
Loophole-free Bell Test: Verifiable RNG

- 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



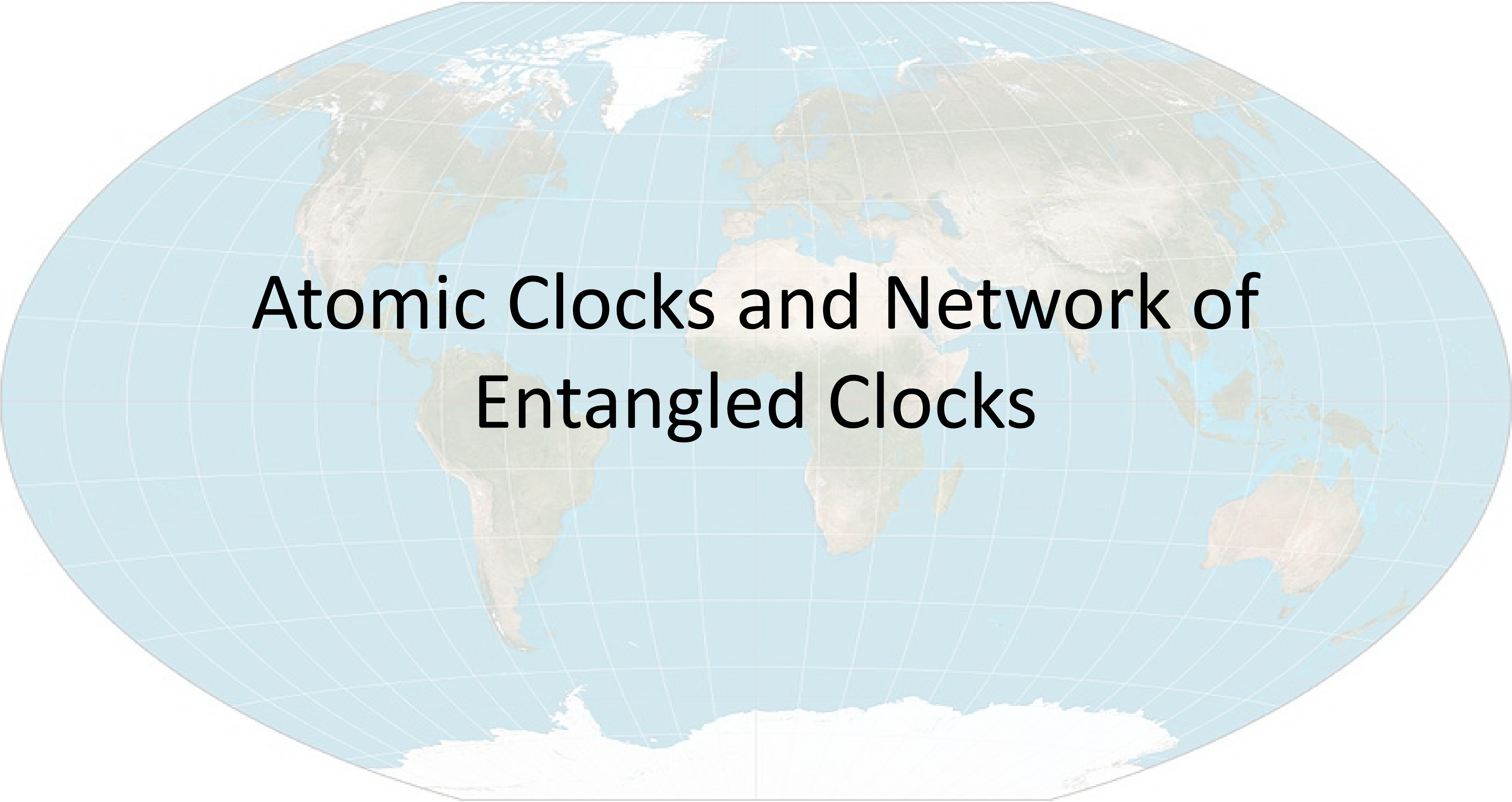


Satellite Based QKD



The US does not currently have a satellite based QKD effort.

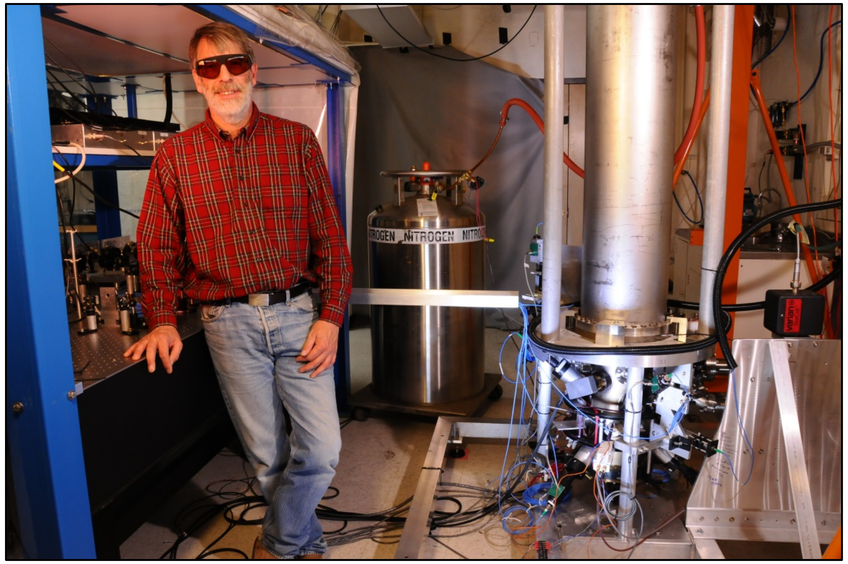
From *Optics and Photonics News*, Feb 2018 https://www.osa-opn.org/home/articles/volume_29/february_2018/features/satellite-based_qkd/



Atomic Clocks and Network of Entangled Clocks

The Power of One Quantum Bit

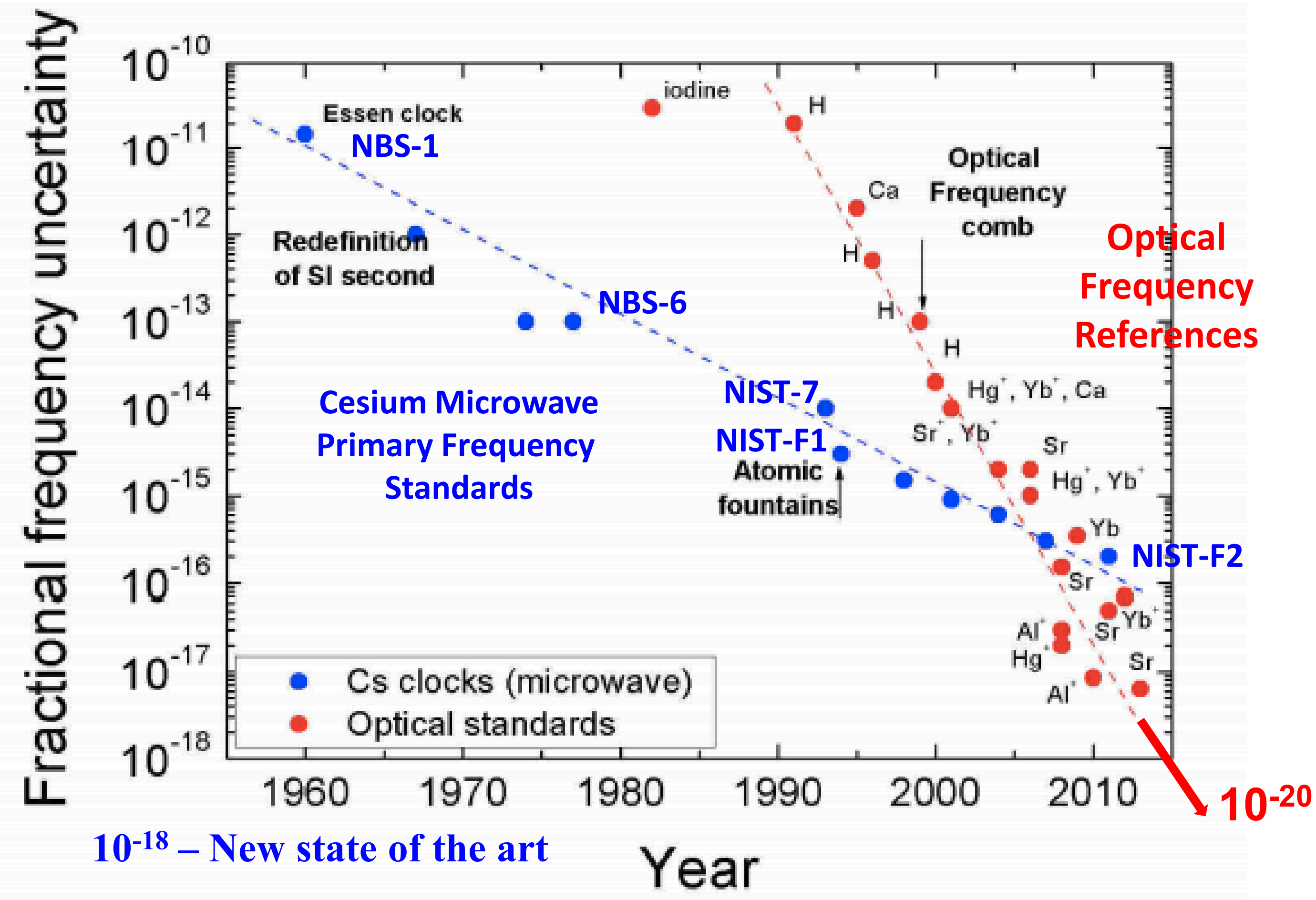
1 second is defined as the duration of 9,192,631,770 cycles of the cesium hyperfine transition.



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

Science 329, 11630, 2010

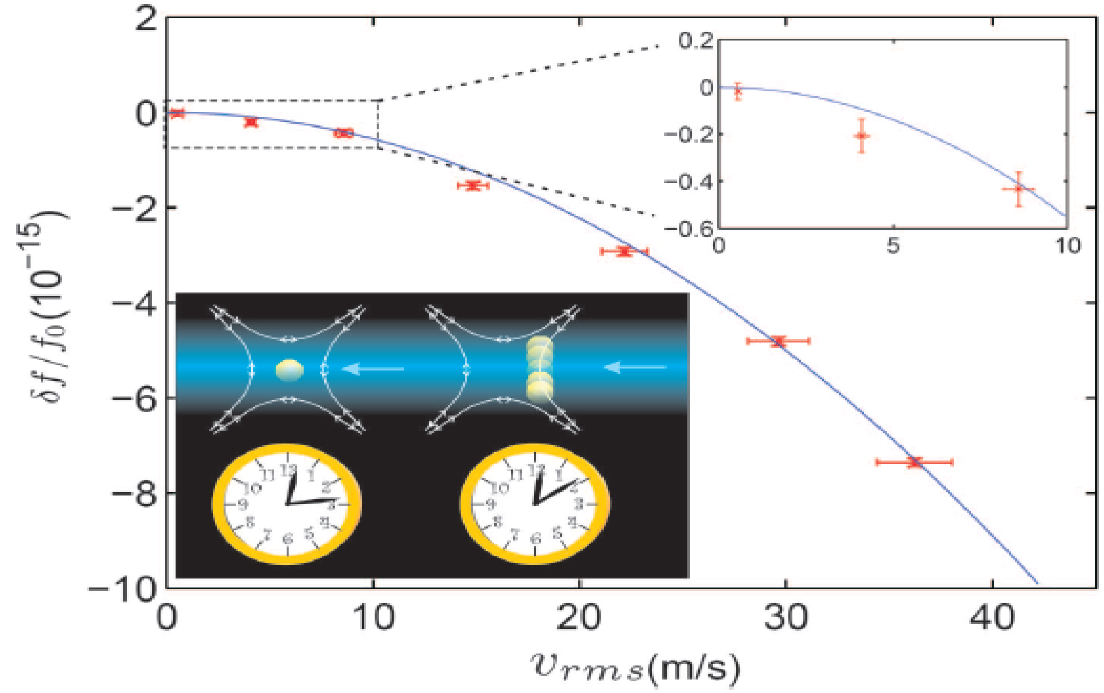


Fig. 2. Relativistic time dilation at familiar speeds (10 m/s = 36 km/hour ≈ 22.4 miles/hour). (Lower left inset) As the Al^+ ion in one of the twin clocks is displaced from the null of the confining RF quadrupole field (white field lines), it undergoes harmonic motion and experiences relativistic time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

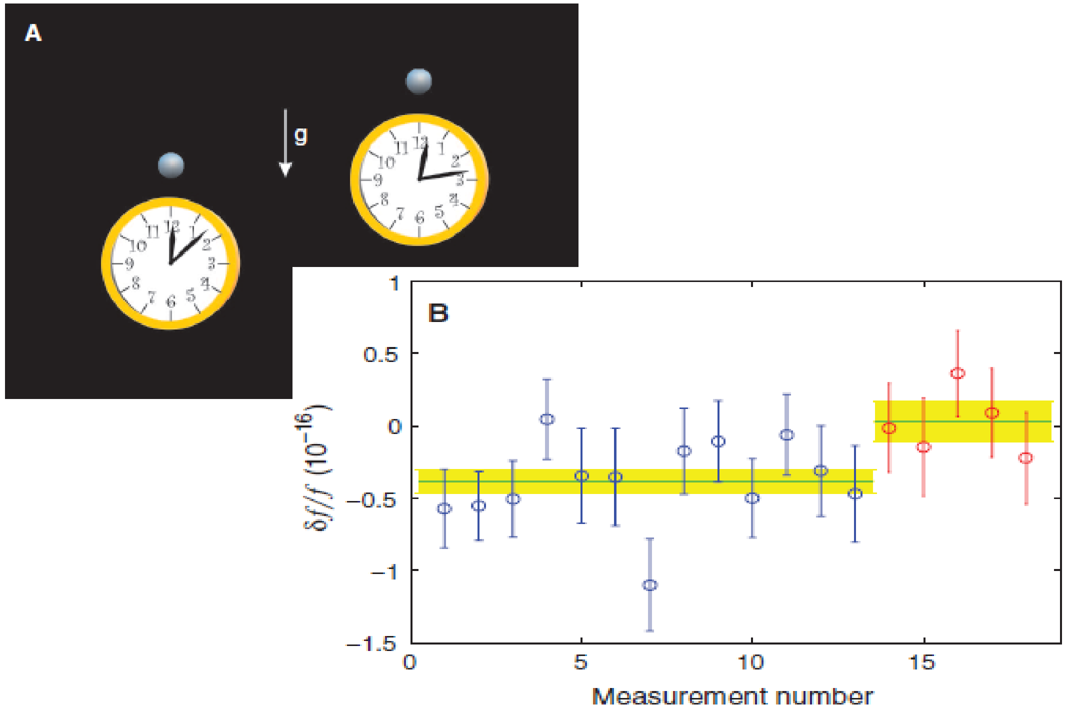
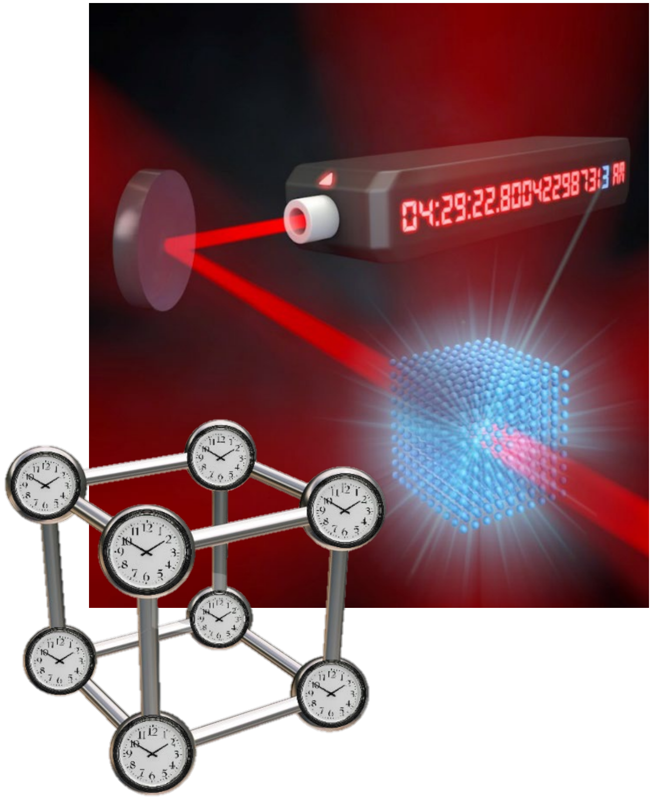
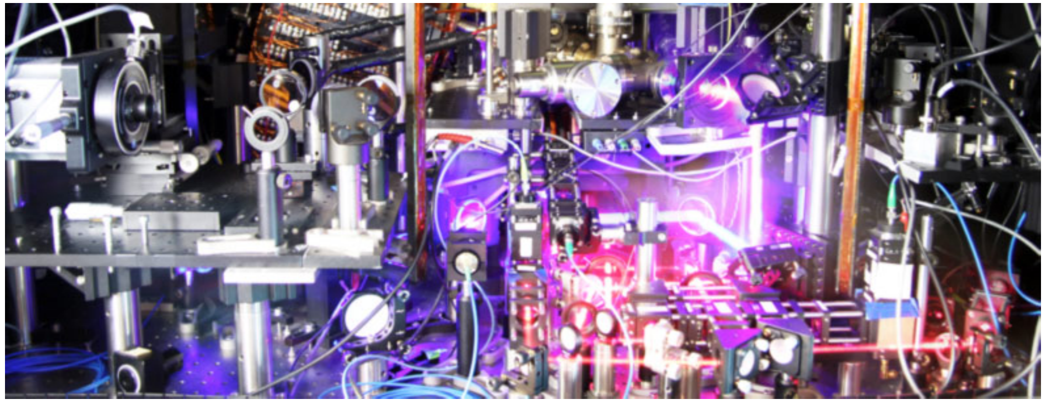


Fig. 3. Gravitational time dilation at the scale of daily life. (**A**) As one of the clocks is raised, its rate increases when compared to the clock rate at deeper gravitational potential. (**B**) The fractional difference in frequency between two Al^+ optical clocks at different heights. The Al-Mg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

3D Fermi gas strontium (Sr) optical lattice clock

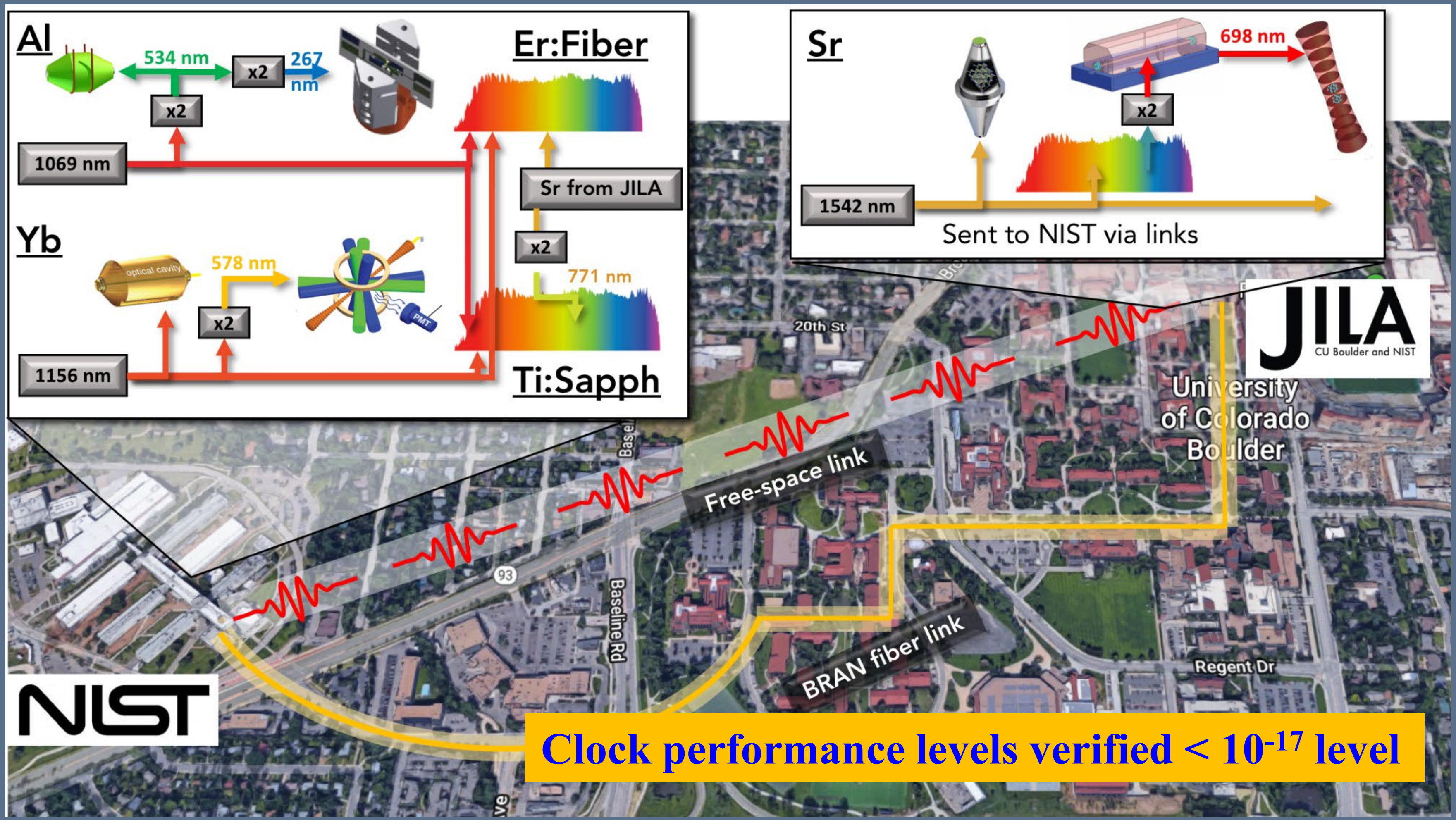




S.L. Campbell *et al.*, *Science* **358**, 90 (2017); G.E. Marti *et al.*, *Phys. Rev. Lett.* ***120***, 103201 (2018); Norcia *et al.*, *Science* **366**, 93 (2019).

- First application of a quantum degenerate gas to a “practical” measurement: *A quantum-enhanced precision measurement*
  - ✓ ~1 million atoms: 100 x 100 x 100 in a 3D-optical lattice
  - ✓ Pauli exclusion: Only one atom per lattice site
  - ✓ Precision 3 x 10^{-20} $Hz^{-1/2}$, on path to 10^{-22} in a few years
  - ✓ Coherence time 160 seconds and improving
- Potential laboratory *for fundamental physics, including quantum gravity, dark matter detection, and long-baseline astronomical observation*

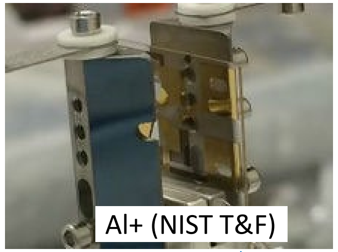
Remote Optical Clock Comparisons in Boulder

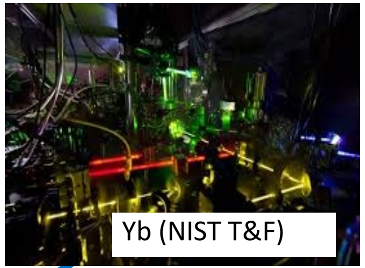


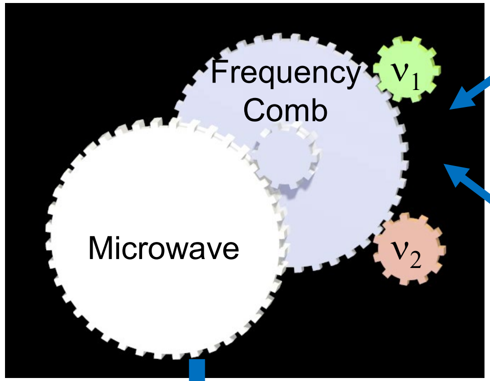
Optical clock comparisons between NIST Boulder and JILA

Quantum Metrology in an Optical Clock Network

Clocks: $\sim 10^{-18}$
Clockwork: $\sim 10^{-20}$







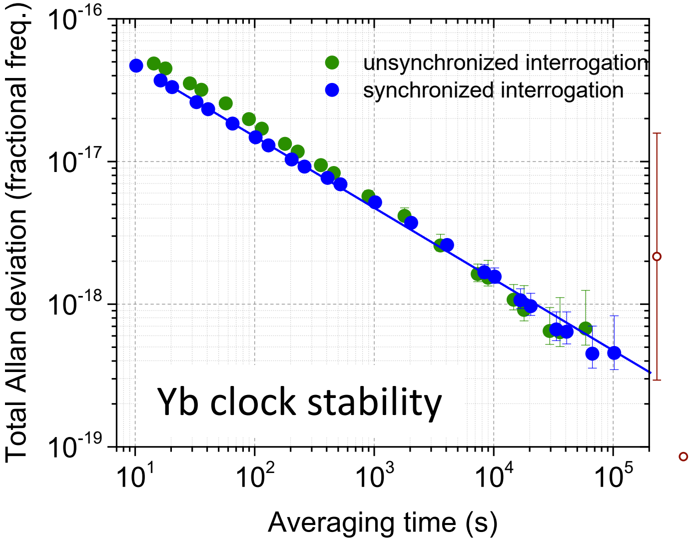
Clocks: $\sim 10^{-18}$
Clockwork: $\sim 10^{-20}$

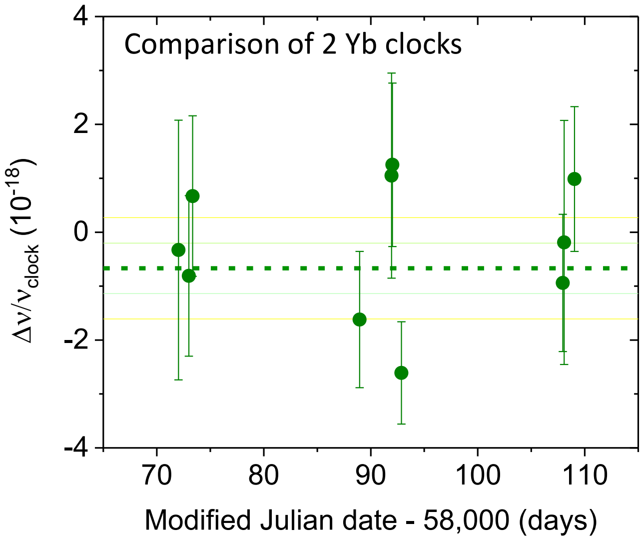
H-masers, NIST Timescale, UTC and the SI second

Boulder Optical Clock Network

- Re-definition of the SI second & optical atomic timescales
- Relativistic geodesy, VLBI telescopy, navigation
- Fundamental science (tests of relativity, search for dark matter and gravitational waves, time variation of fundamental constants, …)
- Correlation and entanglement to reduce classical & quantum noise

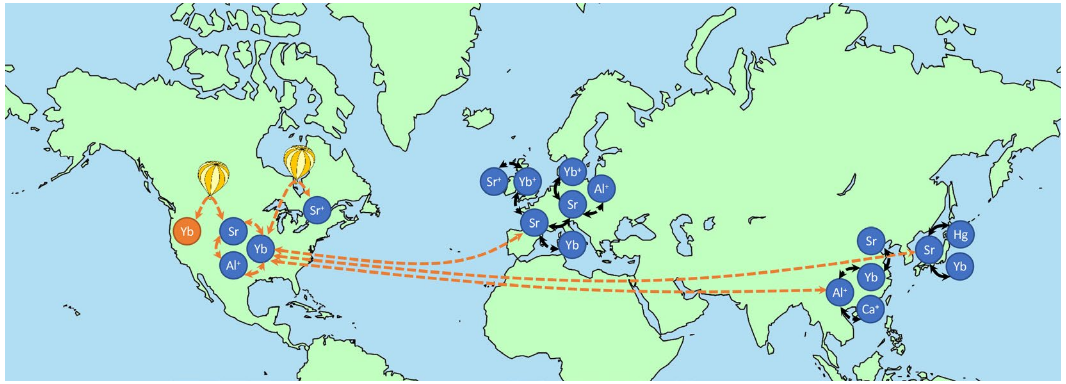
Stability and Accuracy at 1x10^{-18} level





Optical Clock Networks

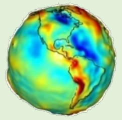
- Developing new frequency comb, clock, and phase measurement technologies
- Tech to measure clock frequency ratios
  - Expectation: 50× lower uncertainties
- Exploiting correlations to reach Heisenberg limit
  - Expectation: 1000× faster measurements
- Long range, free space laser time transfer
- Prerequisite for international redefinition of the SI second to use optical frequency



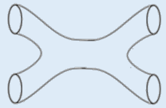
Goal: The quantum science and technology to synchronize widely separated optical atomic clocks at the level of a part in 10^{18}, or better

Potential Impacts:

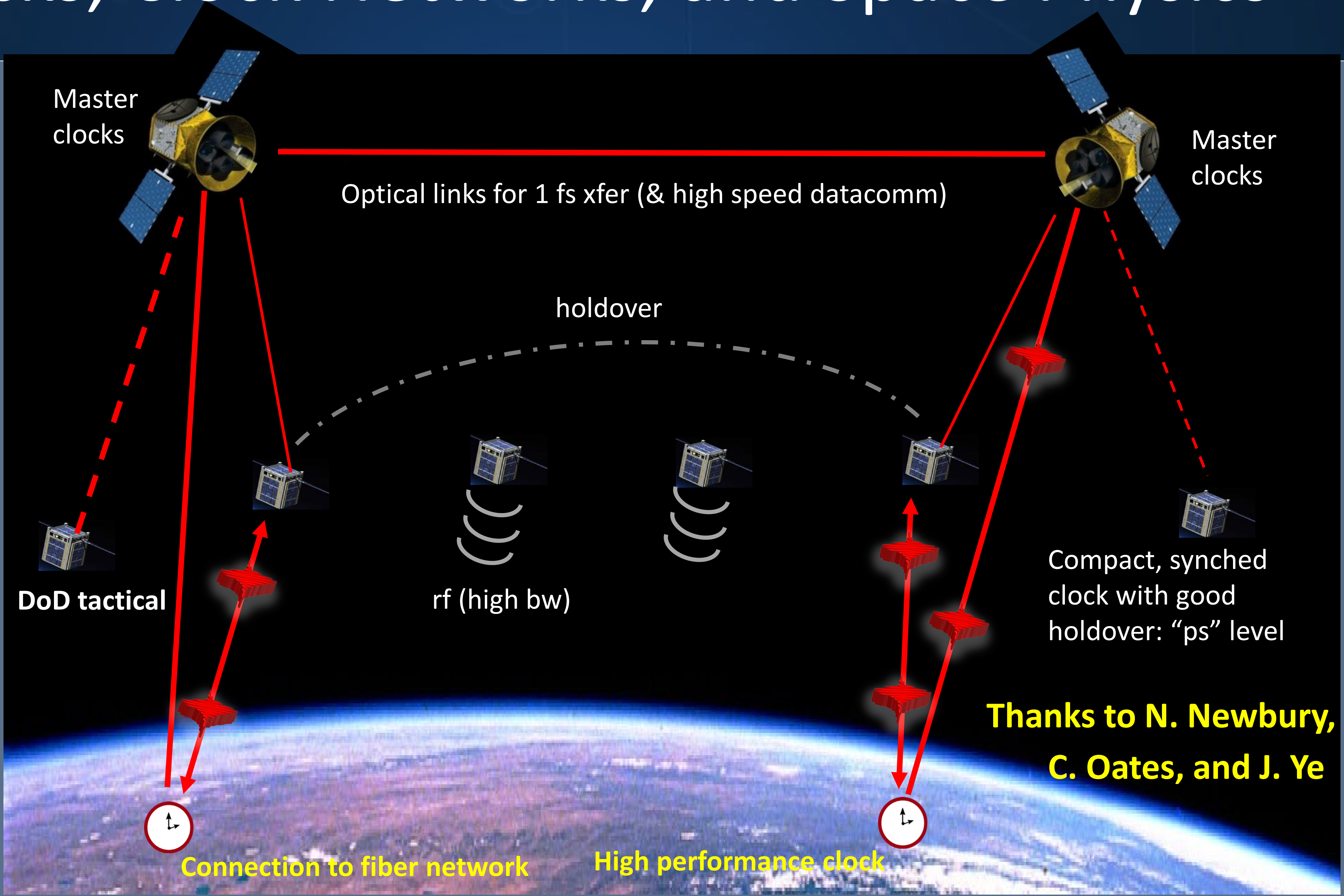
Map Gravitational Potentials



Physics Beyond the Standard Model



Clocks, Clock Networks, and Space Physics



Thanks to N. Newbury, C. Oates, and J. Ye

Advanced Applications Require Clocks

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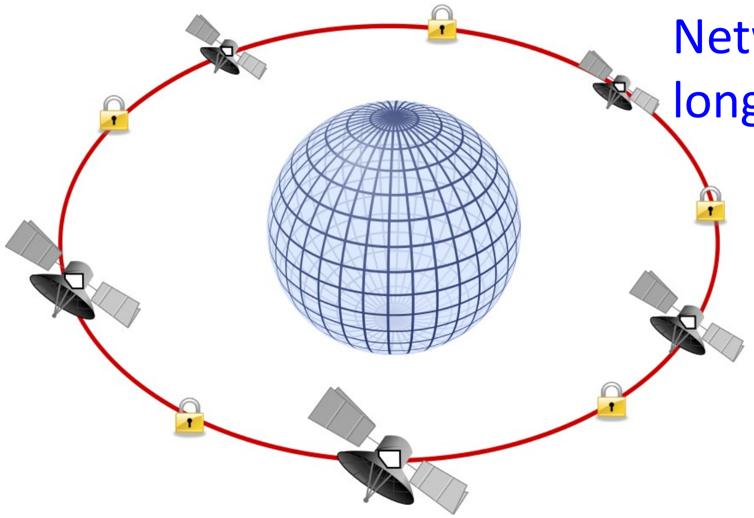
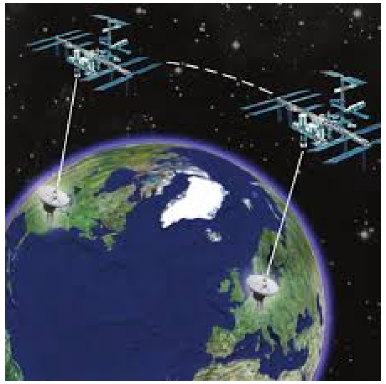
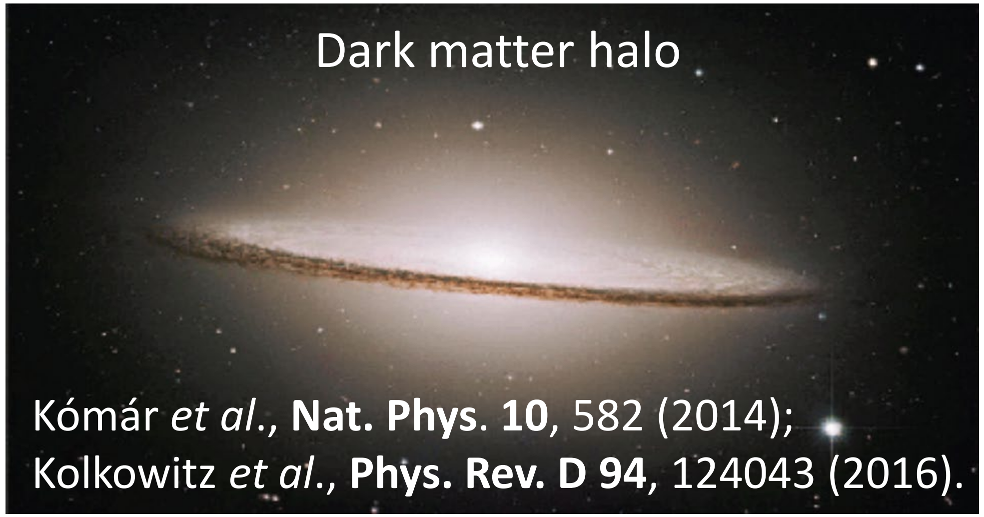


Network of clocks (10^{-21}): long baseline interferometry

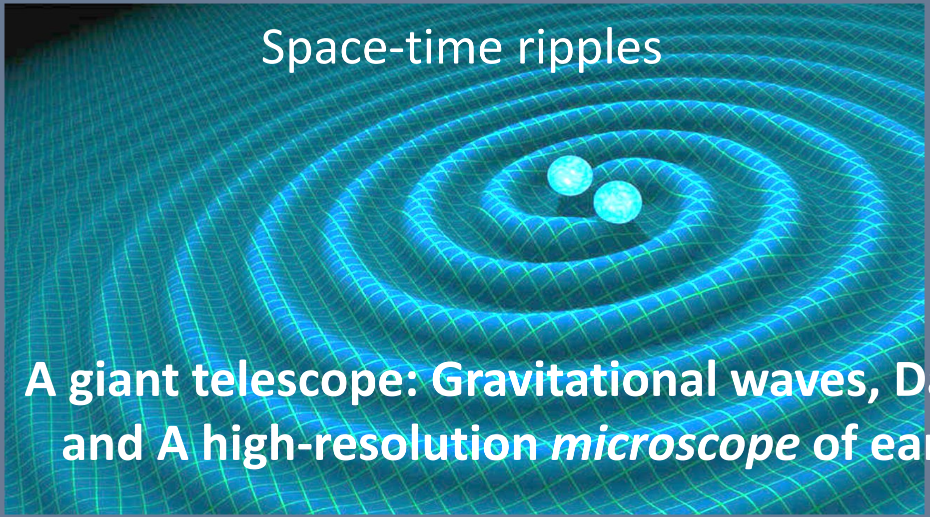


Long distance 10^{-18} Time Transfer

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



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

Trade-off Space for Space Optical Clocks

NIST

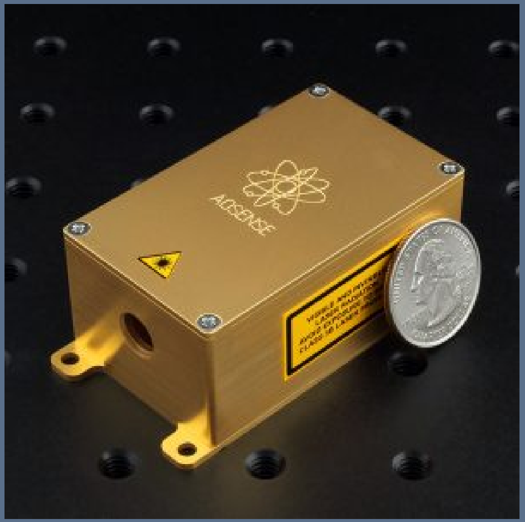
* Order of magnitude estimates	Optical FP cavity	Simple single ion (e.g., $^{88}Sr^+$)	High performance ion or lattice (e.g., ^{171}Yb, ^{87}Sr, $^{27}Al^+$, $^{171}Yb^+$ E3)
Complexity	1 direct diode laser, 1 mW 10^{-15} FP cavity, μK thermal control	3 direct diode lasers, 1 mW each 10^{-14} FP cavity No modulators	5-6 lasers, Not all direct diode, Up to 1 W each 10^{-15} FP cavity
SWAP* (physics package, omitting temp stab)	10^3 cm^3 10 kg 10 W	10^3 cm^3 10 kg 10 W	10^4 cm^3 100 kg 100 W
Statistical uncertainty*	10^{-15} from 1 to 10^3 s	$5\times10^{-15}/\tau^{1/2}$	$1\times10^{-15}/\tau^{1/2}$
Systematic uncertainty*	N/A	10^{-17}	10^{-18}
Capabilities*	Time transfer: 10^{-15} @ 90 min 2×10^{-17} @ 1 year Geodesy: 20 cm @ 1 year Equiv principle: N/A Dark matter: 5×10^8 TeV	Time transfer: 10^{-17} @ 3 days 10^{-18} @ 1 year Geodesy: 1 cm @ 1 year Equiv principle: 3×10^{-7} Dark matter: 10^8 TeV	Time transfer: 10^{-18} @ 6 days 10^{-19} @ 1 year Geodesy: 0.1 cm @ 1 year Equiv principle: 3×10^{-8} Dark matter: 5×10^8 TeV

Thanks to D. Hume & D. Leibrandt

Hardware for Compact Ion Clock

Demonstrated subsystem technology already meets SWAP & performance requirements but needs to be integrated and space qualified; Note: also require a frequency comb

Qty 3 direct diode lasers



Picture: AOSense ECDL
(Alternatives: OEWaves, Vescent, Vector Atomic, …)

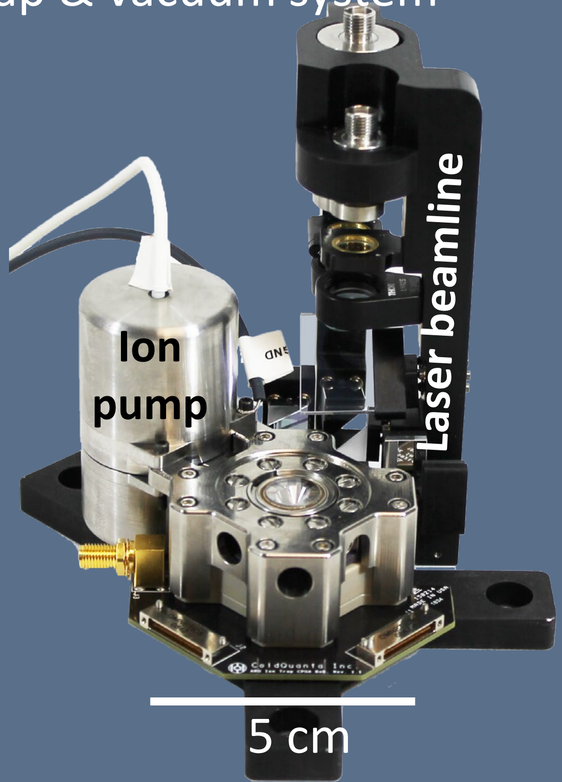
+

Low performance FP cavity

Picture: Stable Laser Systems cavity
(Alternatives: NIST, Caltech, OEWaves, …)

+

Ion trap & vacuum system



Picture: Sandia ion trap in Cold Quanta packaging
(Alternatives: NIST, Duke, …)

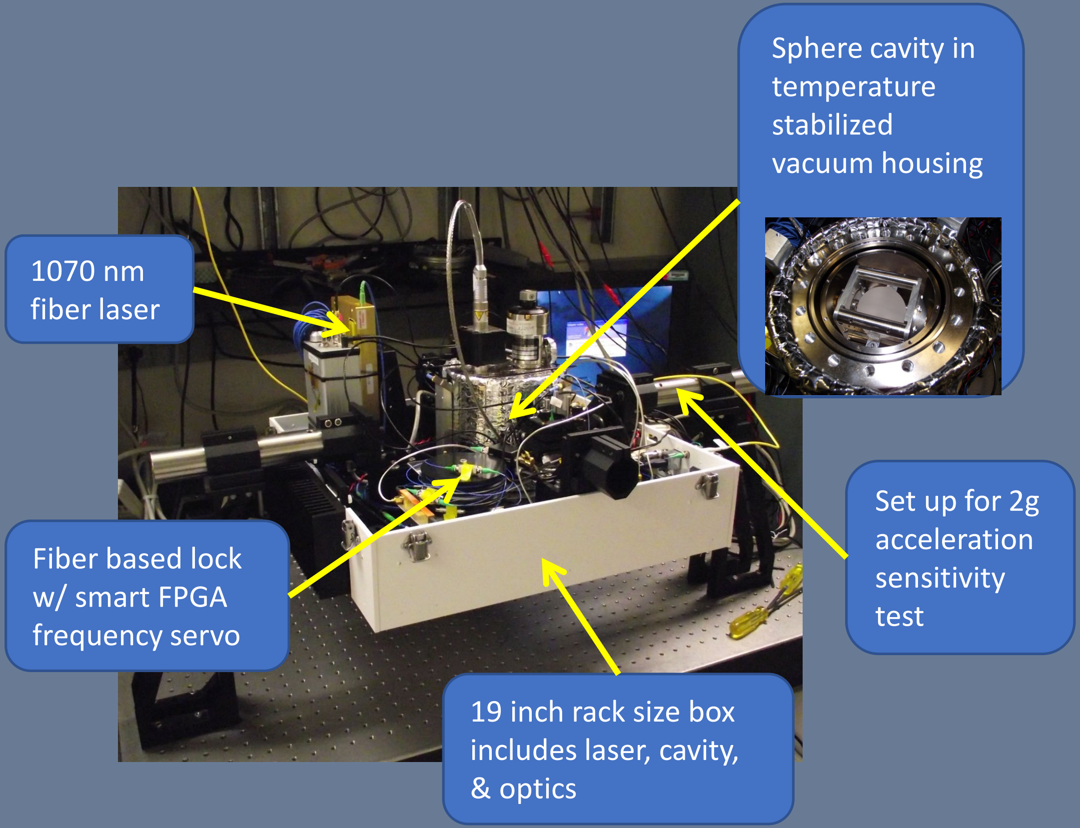
Thanks to D. Hume & D. Leibrandt

However

Big effort to transition from research projects to devices

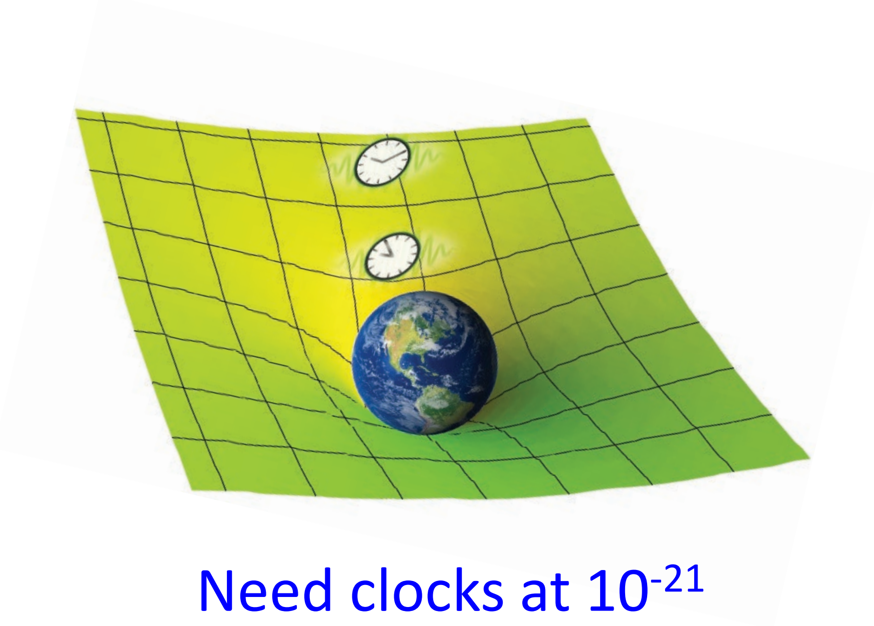
- Challenges: robustness, SWAP, cavities, lasers
- Need:
  - ➢ Higher Q optical transitions
  - ➢ New laser stabilization methods with optical coherence ~ 1 minute
  - ➢ Ultracold atoms in optical lattice: high N, long t, small perturbations
  - ➢ Optical frequency comb
- Current State-of-the-Art Clocks:
  - ➢ Accuracy ~10-^{18} = gravitational redshift @ 1 cm!
  - ➢ Precision ~3 x 10-19

Best Clocks test local position invariance and relativistic geodesy and can easily see gravitational potential difference of 1 cm



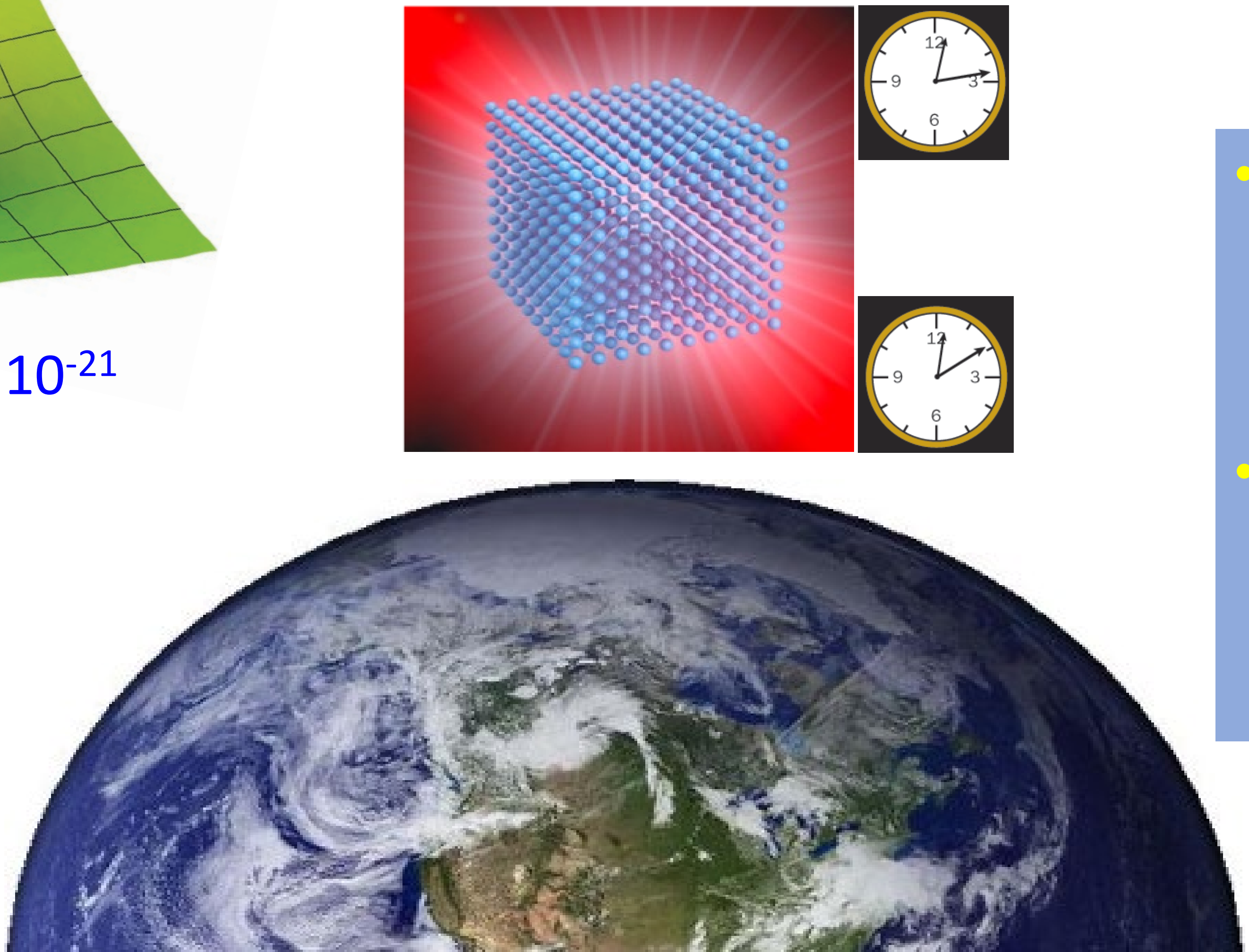
Cavity in a Rack

Unexplored Regime: Entanglement under GR



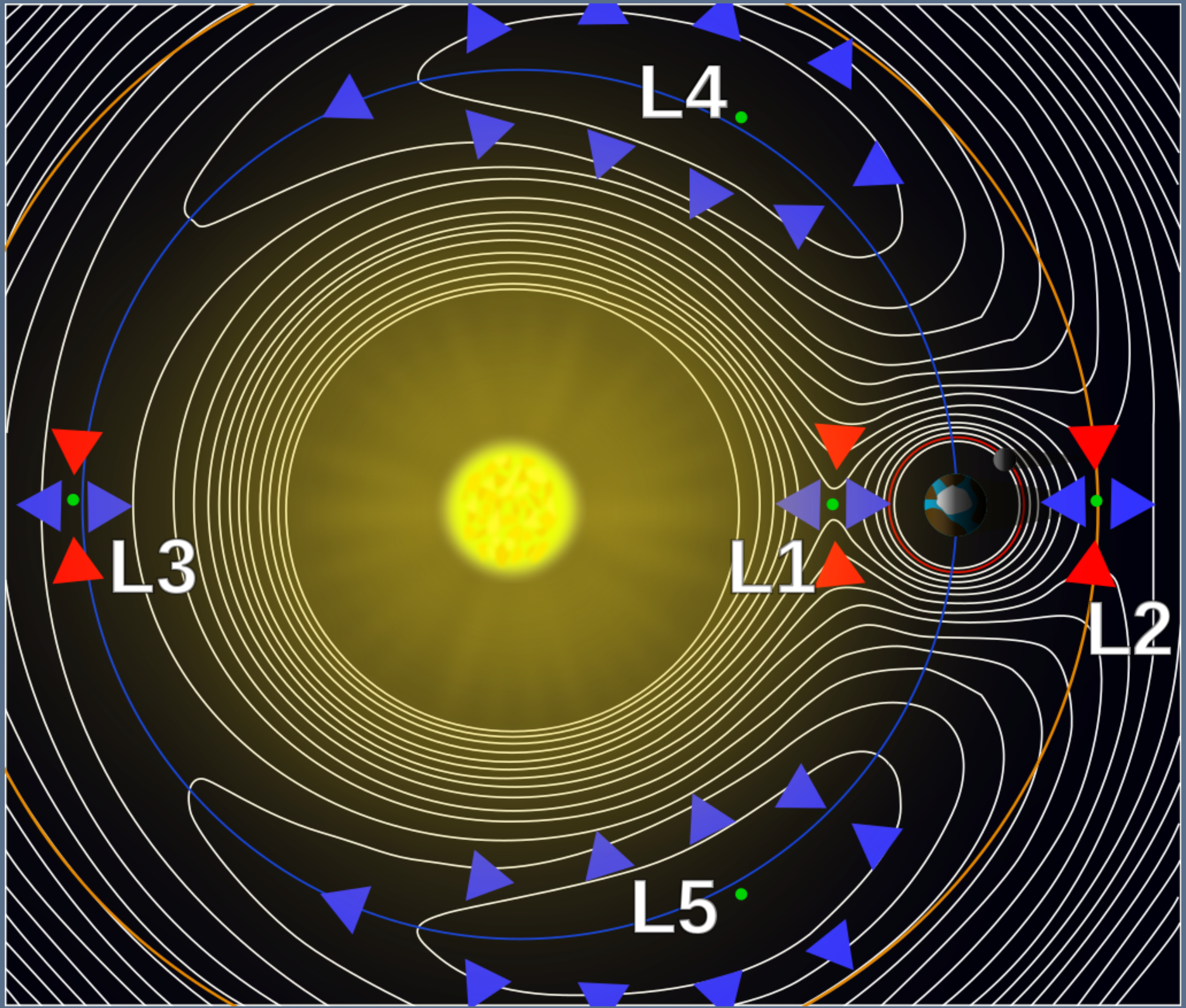
Need clocks at 10^{-21}

Extreme spatial resolution & precision



- GR entangles a clock with its spatial degrees of freedom via time dilation
- Spatial coherence modulated due to which-way information

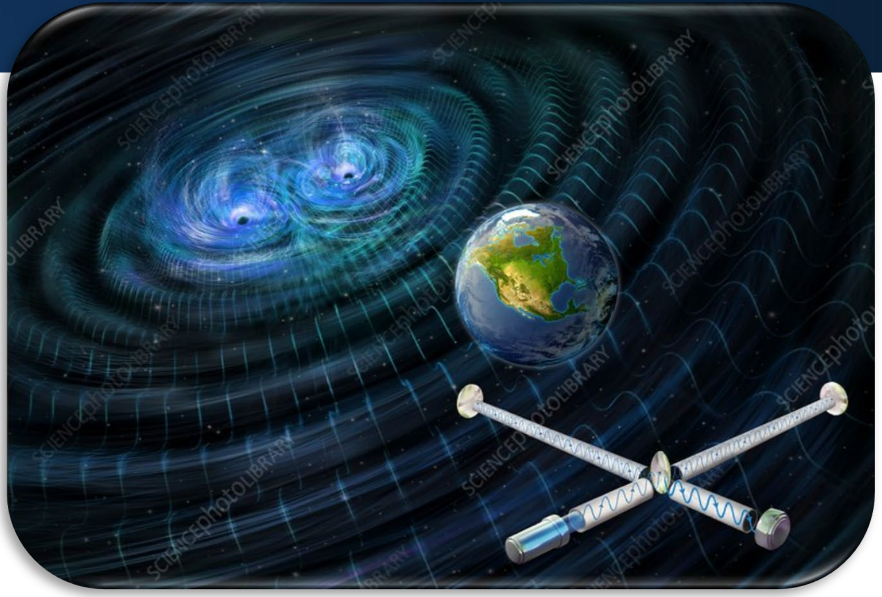
The Ultimate Deep-Space Clock Network

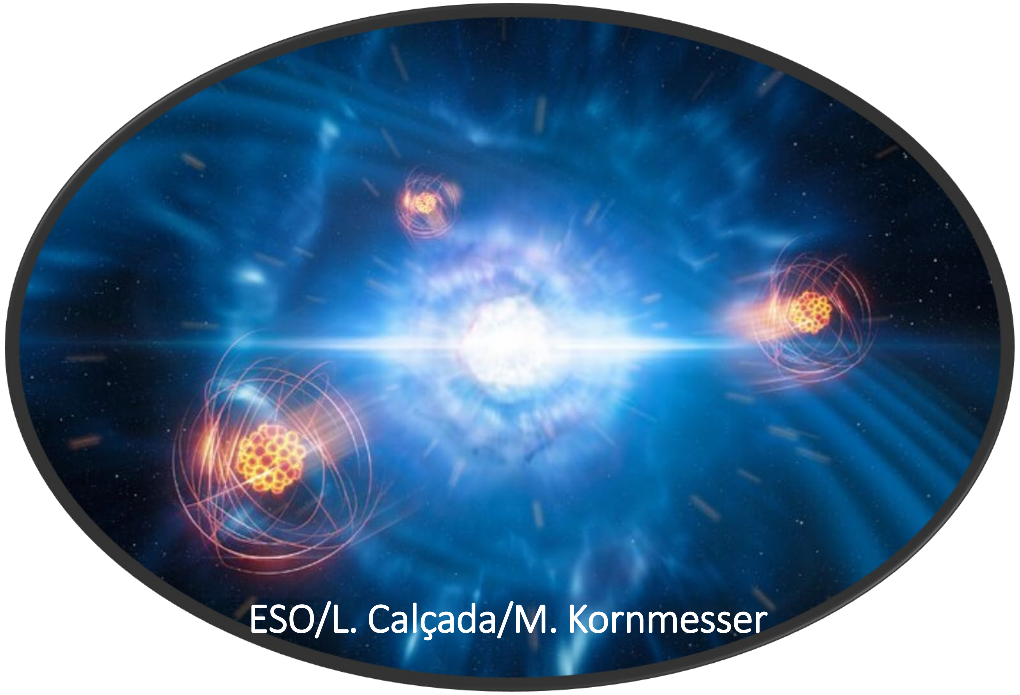


- Primary clock at the Lagrangian point (L1)
- Secondary clocks at low earth orbits

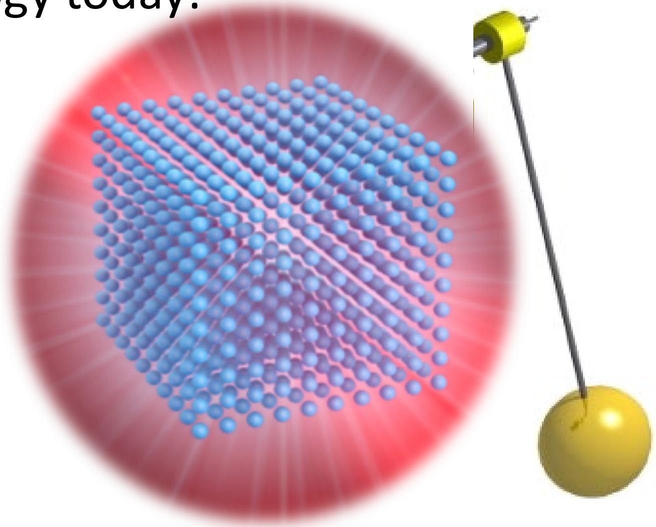
A Poetic Circle of Life

Aug. 17, 2017 LIGO-VERGO:
neutron merger GW170817





Quantum technology today:
Sr clocks on earth



Oct. 23, 2019 ESO telescope VLT:
Creation of Sr detected after GW170817

Some *Personal* Summary Thoughts

- Deep space quantum communication requires:
  - ➢ Very accurate timing
  - ➢ High efficiency detectors
  - ➢ Very accurate detector gating
  - ➢ Fast detector recovery
  - ➢ Large amounts of memory and two_way classical communication channels
- Quantum receivers can be very helpful in a signal deprived situation
- Networks of entangled clocks have many benefits from:
  - ➢ Tests of GR to exploring GR under entanglement
  - ➢ Space-based navigation
  - ➢ Clock-based geodesy
  - ➢ Space-based dark-matter searches
  - ➢ Gravity wave detection of more massive objects

QUESTIONS?