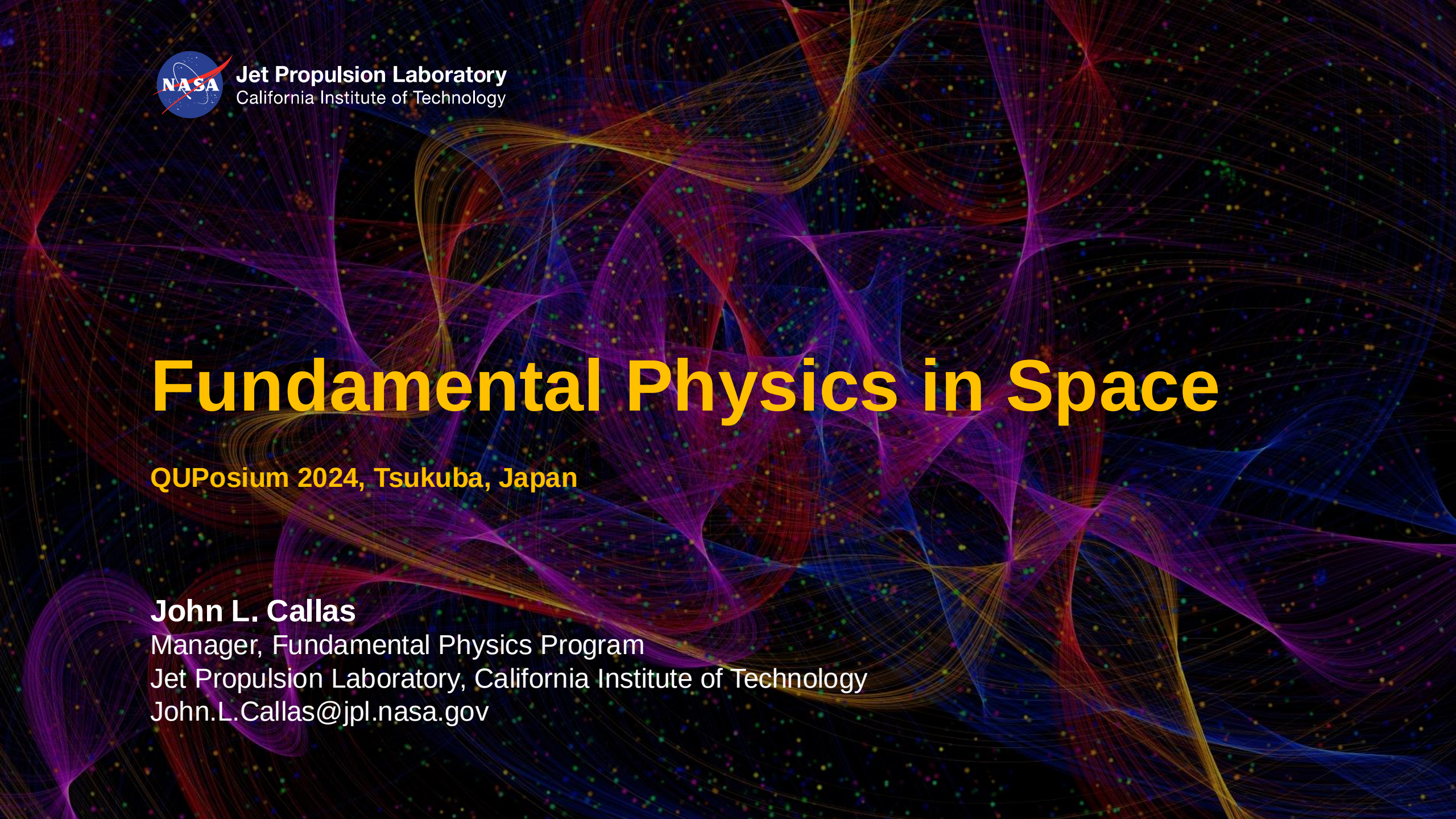


Fundamental Physics in Space

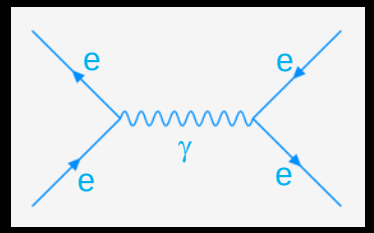
QUPosium 2024, Tsukuba, Japan

John L. Callas
Manager, Fundamental Physics Program
Jet Propulsion Laboratory, California Institute of Technology
John.L.Callas@jpl.nasa.gov

The Two Great Theories of Modern Physics

The Standard Model

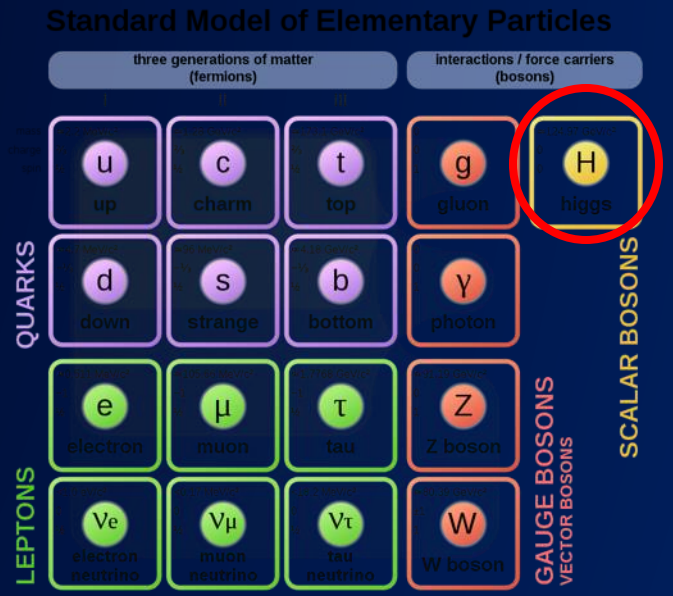
(EM, Weak Nuclear, Strong Nuclear - Quantum)
Gauge Theory



Force mediated by exchange of Bosons (integer spin particles).

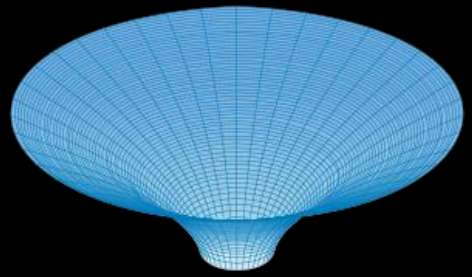
The physics of the very small.

Predicted the Higgs Boson discovered in 2012



General Relativity

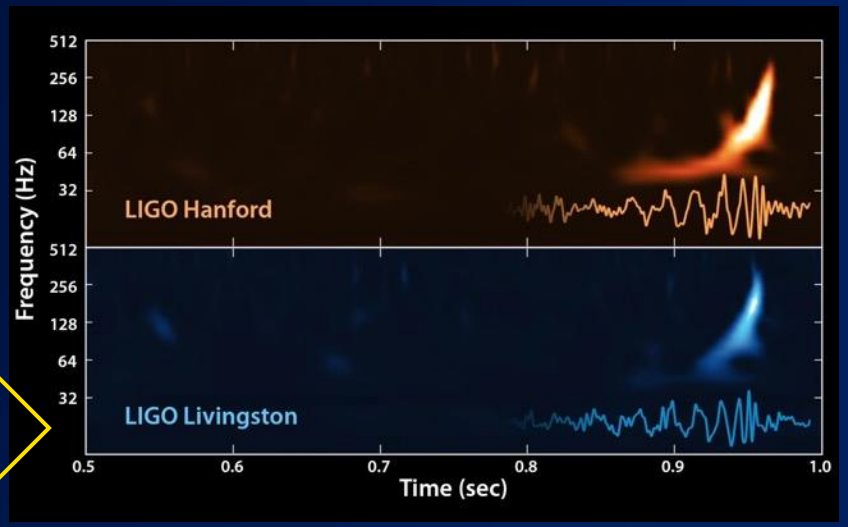
(Gravity)
Metric Theory



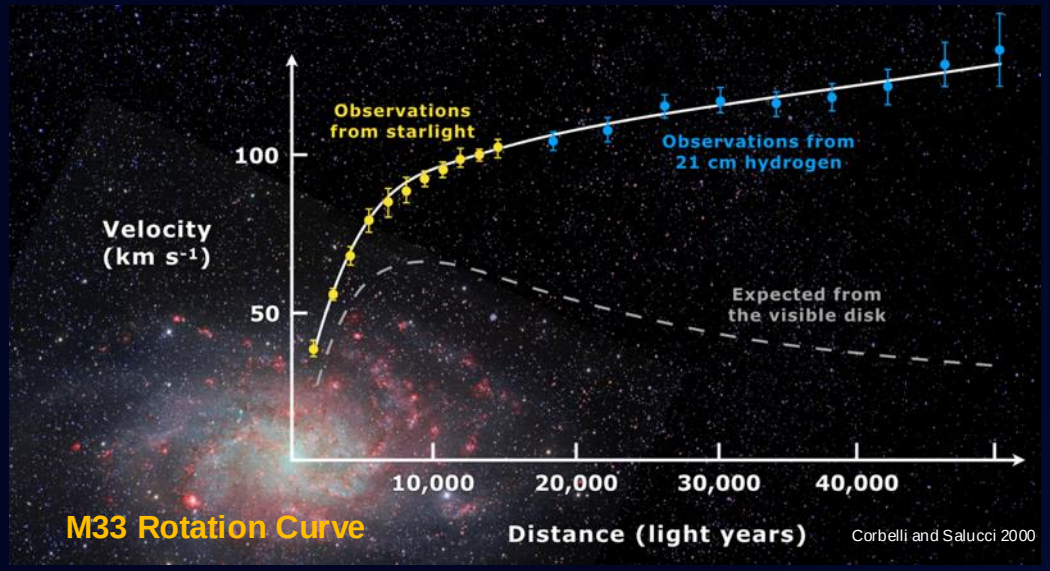
Force manifested by Curved Space (geometry), but requires the Equivalence Principle.

The physics of the very big.

Predicted Gravitational Waves first observed in 2015.

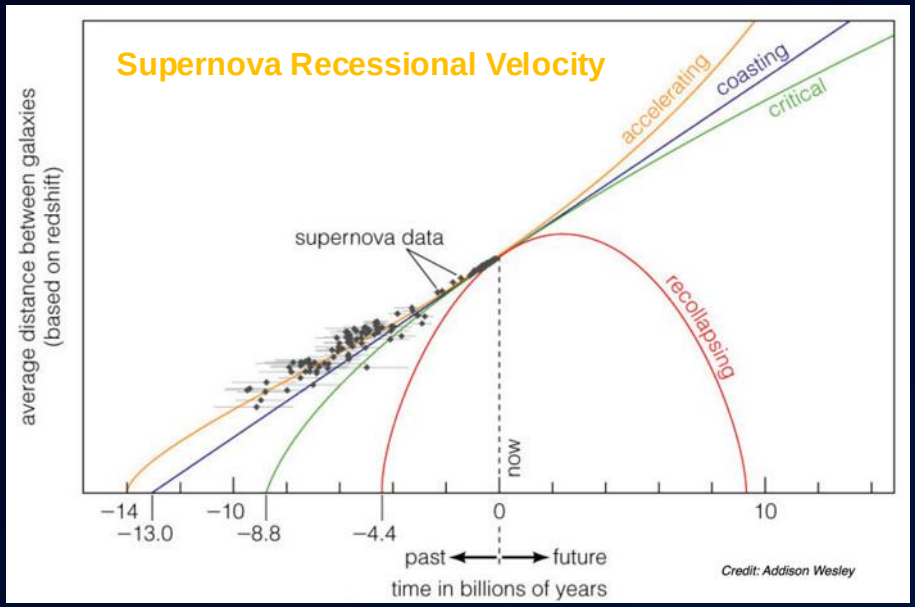


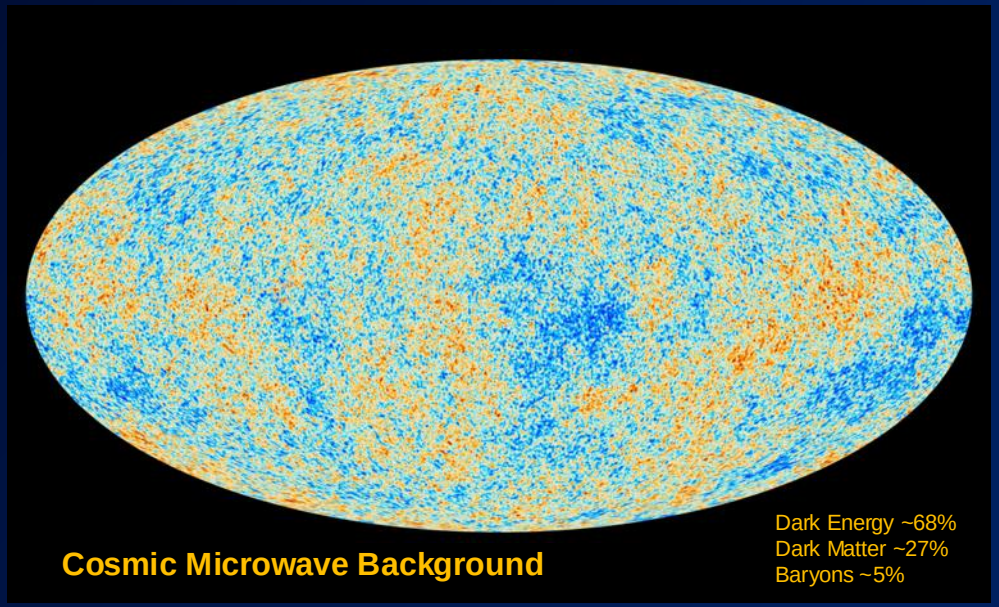
Problems



M33 Rotation Curve

Bullet Cluster Collision




Cosmic Microwave Background

Dark Energy ~68%
Dark Matter ~27%
Baryons ~5%

New Questions

Why is 95% of the Universe dark to us?

What is Dark Matter? What is Dark Energy?

The Standard Model describes less than 5% of the Universe.

Why is the Universe made up of only (baryonic) matter and no antimatter?

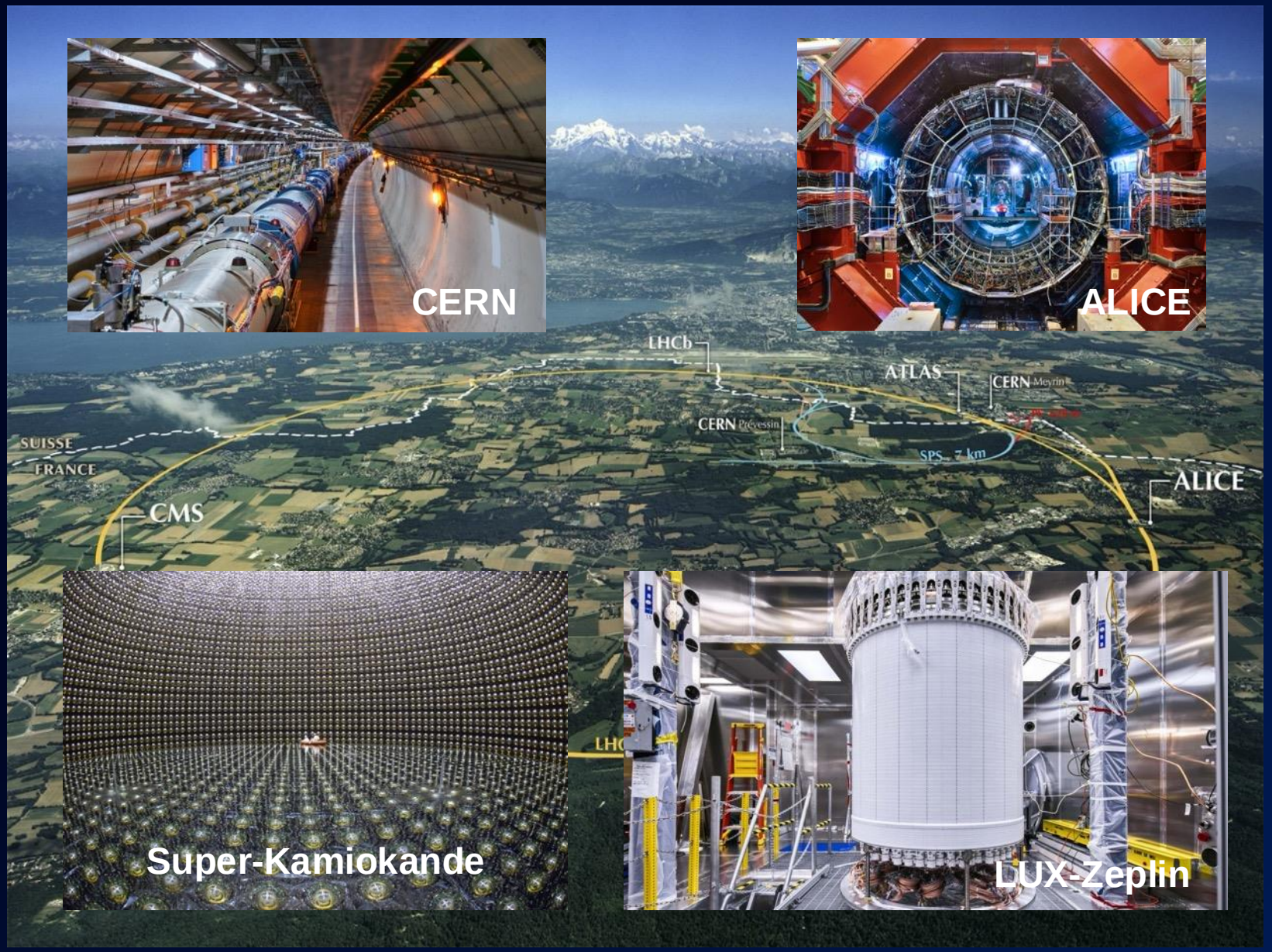
The Standard Model expects equal amounts.

Is General Relativity the last word on Gravity?

Why can't Gravity be unified with the other (quantum) forces?

Is there a quantum aspect to gravity?

Our giant laboratories have found no physics beyond the Standard Model



No Super-Symmetry
No Proton Decay
No Axions
No WIMPs
(Weakly Interacting Massive Particles)

Maybe we are looking in the wrong place.

A Different Search Space

NASA's Fundamental Physics Program

Dark Matter

- Most searches have been looking for massive particle-like, dark matter candidates ($\mathrm{m} \gg 1eV/c^2$).
  - Perhaps, the search should be for wave-like ultra-light candidates.
- Look for a dark matter field as variations to fundamental constants; violations of Local Position Invariance.

Dark Energy

- Dark energy is seen at the cosmic scale (acceleration of the universe) but not at the galactic-to-terrestrial scale.
  - Maybe dark energy has a screening effect in the presence of matter.
- Precision tests of Universal Free Fall with individual (cold) atoms might avoid a screening effect.

Baryon Asymmetry

- Baryon asymmetry might be revealed in violations of Local Lorentz Invariance that manifest as tiny shifts in atomic spectra as a function of orientation relative to some velocity vector.

Quantum Gravity

- Precise comparisons between classical and entangled photons over large changes in gravitational potential (e.g., ground to space) would test a quantum aspect of gravity.

The Observables

Equivalence Principle

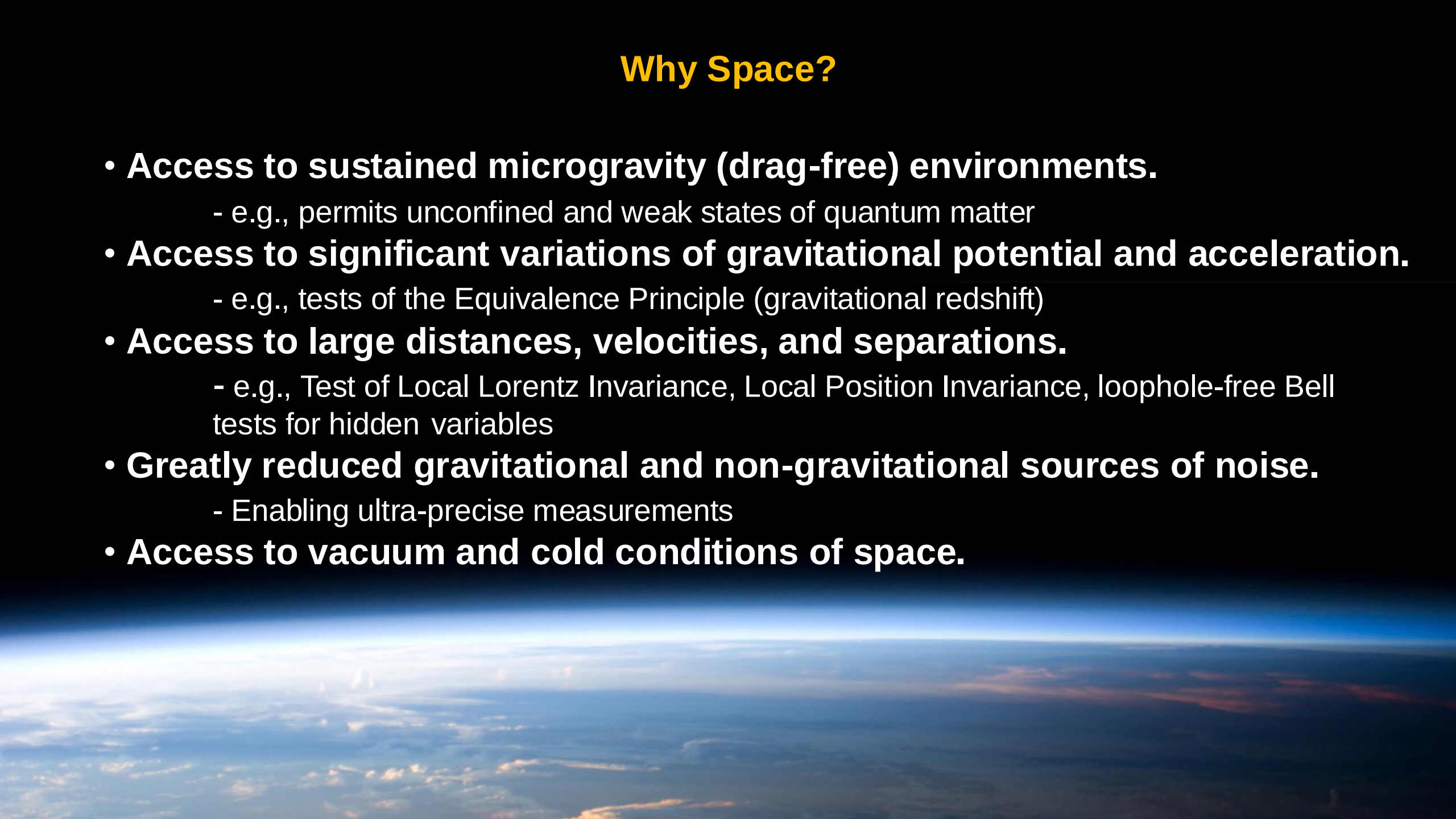
- The Einstein Equivalence Principle (EEP) has three elements:
  - **Universal Free Fall** (UFF) – Objects of different composition all fall at the same rate. (Galileo's Leaning Tower of Pisa experiment)
  - **Local Lorentz Invariance** (LLI) – experiments performed in different inertial reference frames should give the same results.
  - **Local Position Invariance** (LPI) – experiments performed in different locations and/or at different times should yield the same results.

New Theories

- Many of the (field) theories beyond the Standard Model predict violations of the Equivalence Principle to explain dark matter, dark energy, baryon asymmetry, and quantum gravity.
- These violations may be seen as tiny deviations in gravitational redshift, variations of fundamental constants, violation of invariance, or in the existence of new forces (accelerations).

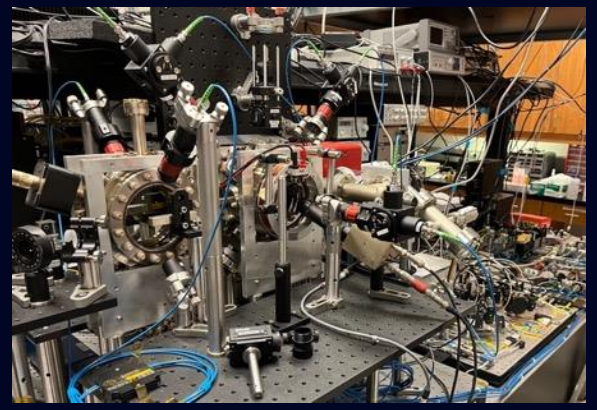
Why Space?

- **Access to sustained microgravity (drag-free) environments.**
  - e.g., permits unconfined and weak states of quantum matter
- **Access to significant variations of gravitational potential and acceleration.**
  - e.g., tests of the Equivalence Principle (gravitational redshift)
- **Access to large distances, velocities, and separations.**
  - e.g., Test of Local Lorentz Invariance, Local Position Invariance, loophole-free Bell tests for hidden variables
- **Greatly reduced gravitational and non-gravitational sources of noise.**
  - Enabling ultra-precise measurements
- **Access to vacuum and cold conditions of space.**

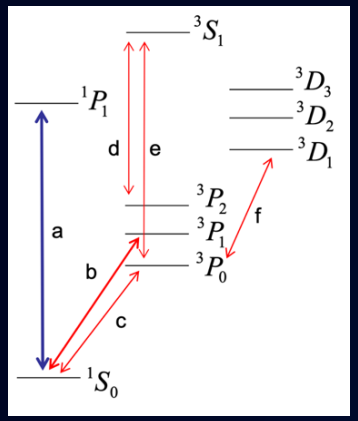


The Precision Techniques Are Quantum-based

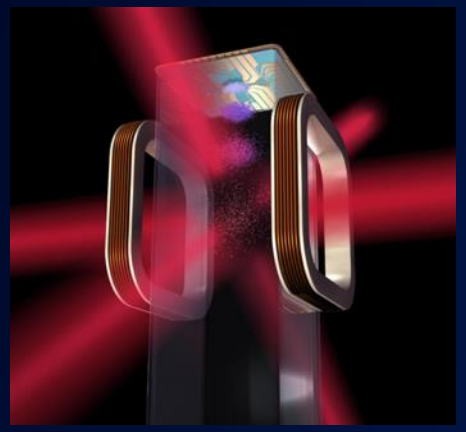
Atomic Clocks

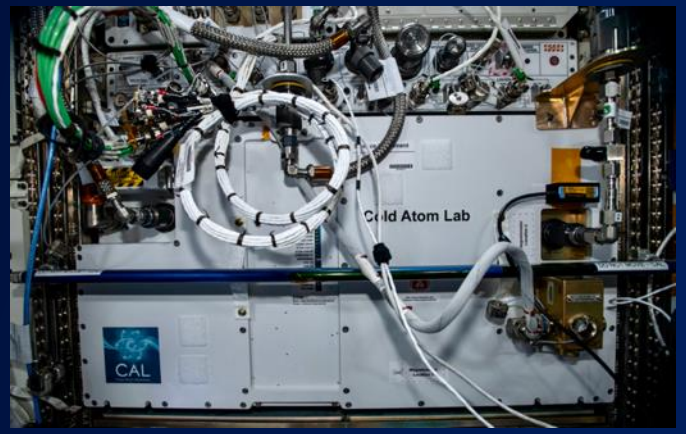


Strontium Optical Lattice Clock/JPL



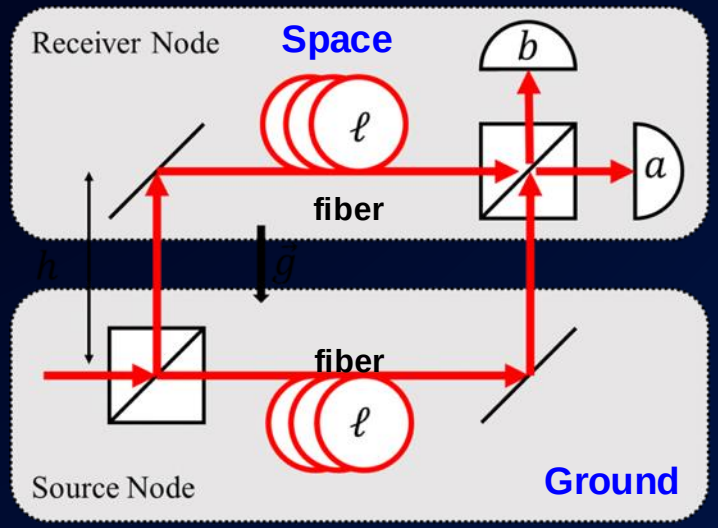
Atom Interferometry

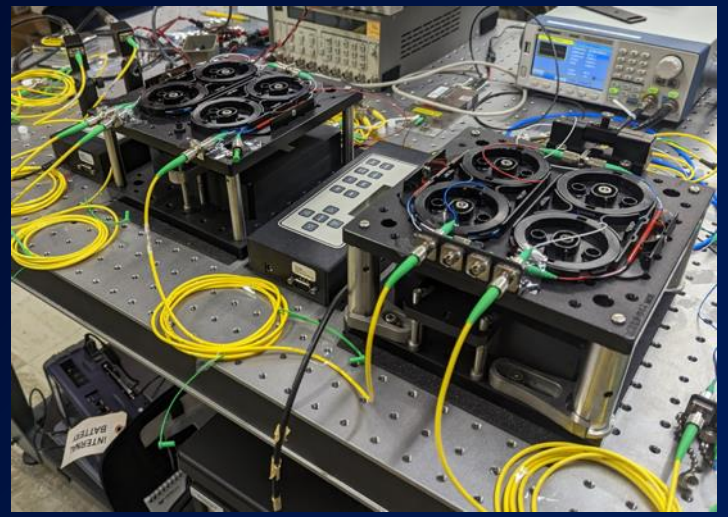




Cold Atom Lab/ISS

Quantum Entanglement



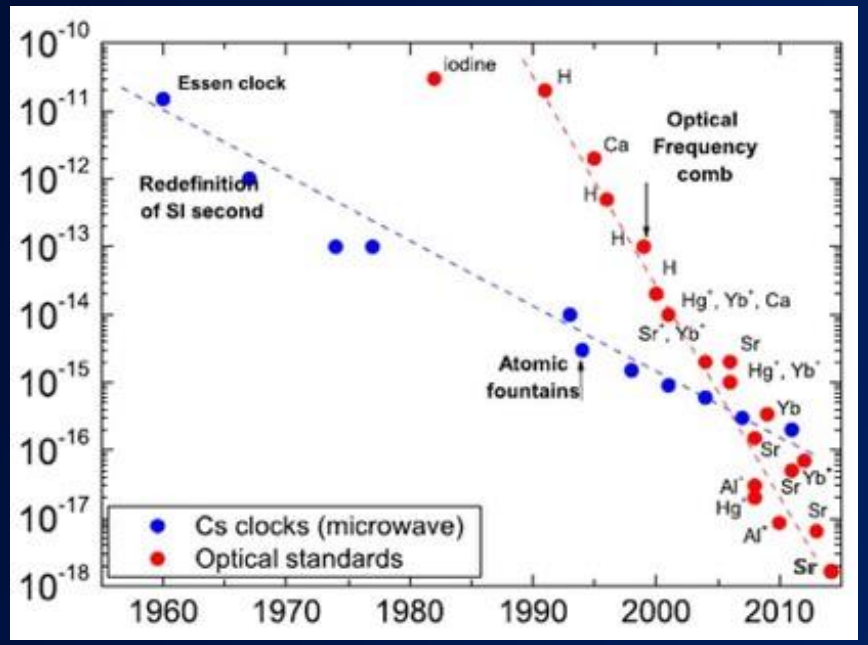


DSQL Interferometer/JPL

Why Clocks?

- Clocks are both precision timekeepers and precision quantum sensors.
  - Now, regularly achieving precision better than 10^{-18} in the lab.
- Atomic clocks exploit the indistinguishability of like atomic species to produce identical atomic spectra as a timing standard.
- Gravity, velocity, and unseen forces affect the tick rate of clocks:

$$\frac{\Delta f}{f} = \underbrace{\frac{\Delta U}{c^2}}_{\text{LPI}} + \underbrace{\frac{1}{2}\frac{v^2}{c^2}}_{\text{LLI}}$$



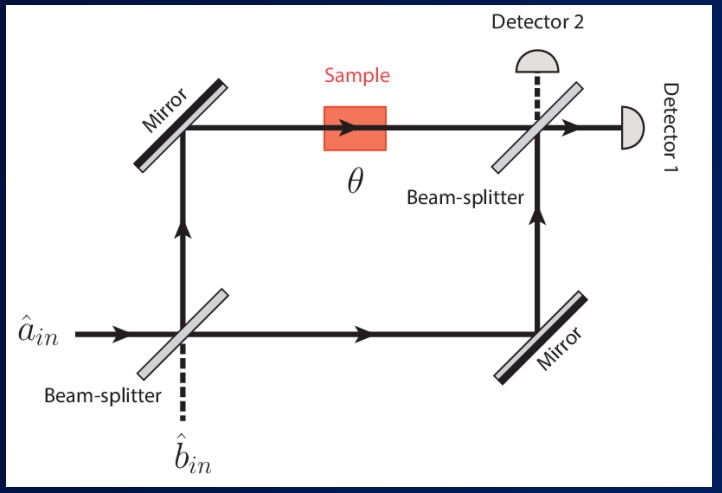
NIST

- By monitoring the tick rate (by comparing to other clocks elsewhere), ultra-precise atomic clocks can search for changes and deviations in gravity, new forces, and variations to fundamental constants.

Why Atom Interferometers?

• An atom interferometer can be used to measure accelerations (forces, g or ΔU) by observing changes in the quantum mechanic phase (ϕ) of atoms along different paths:

$$\Delta\phi = kgT^2 = \frac{\Delta U}{c^2}\frac{mc^2}{\hbar}T$$



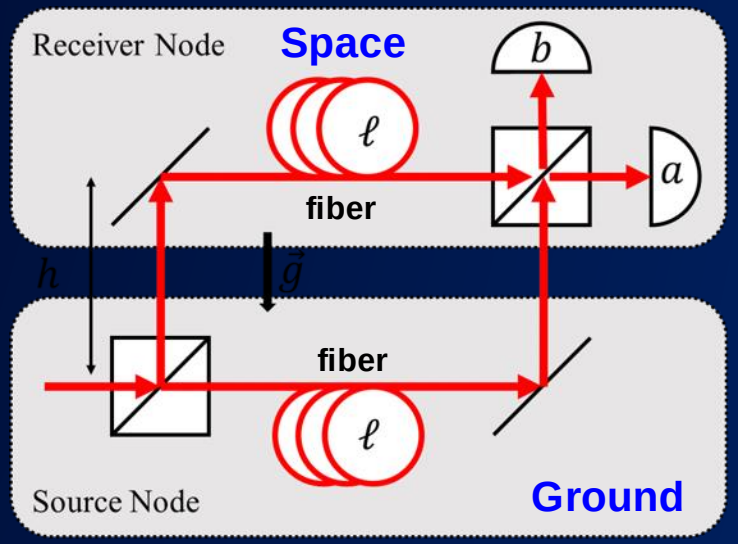
• Atom interferometers exploit the wave-particle duality of atoms to interfere (constructively, destructively) the same way that light does.

• Because the Compton wavelength for atoms are orders of magnitude shorter than for photons, the phase change to accelerations (gravity) is orders of magnitude more sensitive.

Why Entangled Photons?

• An untested prediction of general relativity is that quantum states of photons are affected by gravity.
• Quantum optical interferometers can be used to sense the effect of gravity on quantum entanglement by measuring a phase shift:

$$\Delta\phi = kg\frac{hl}{c^2} = \frac{\Delta U}{c^2}\frac{2\pi}{\lambda}l$$



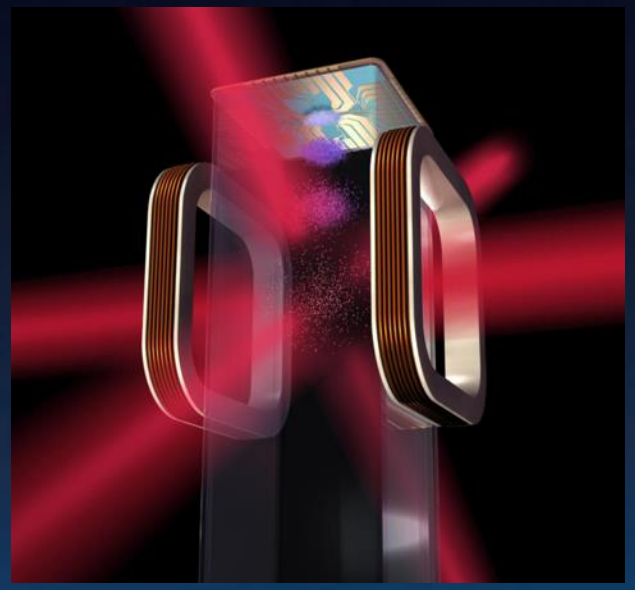
• A space-ground interferometer can be constructed for a pair of photons where one photon spends more time on the ground (in a long spool of optical fiber, l) and the other spends more time in space (in another long spool of fiber) before they are interferometrically recombined.
• Performing this test with both classical and quantum states of light will be the first direct-test of quantum field theory in curved spacetime, a foundational step forward towards tests of quantum gravity.

NASA Fundamental Physics Flight Portfolio

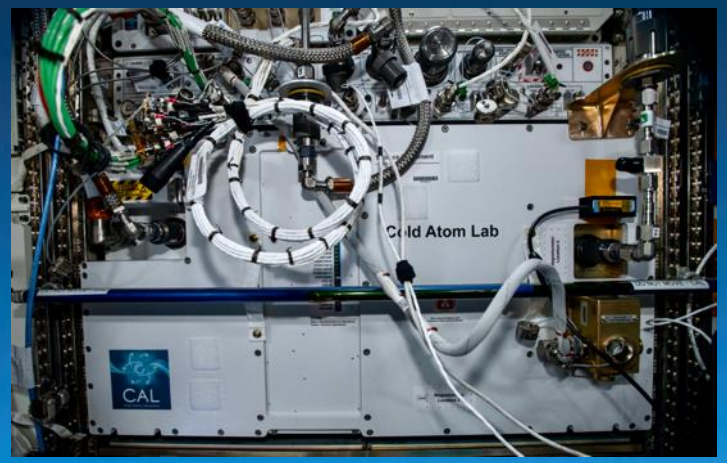
- CAL
- SEAQUE
- ACES
- BECCAL

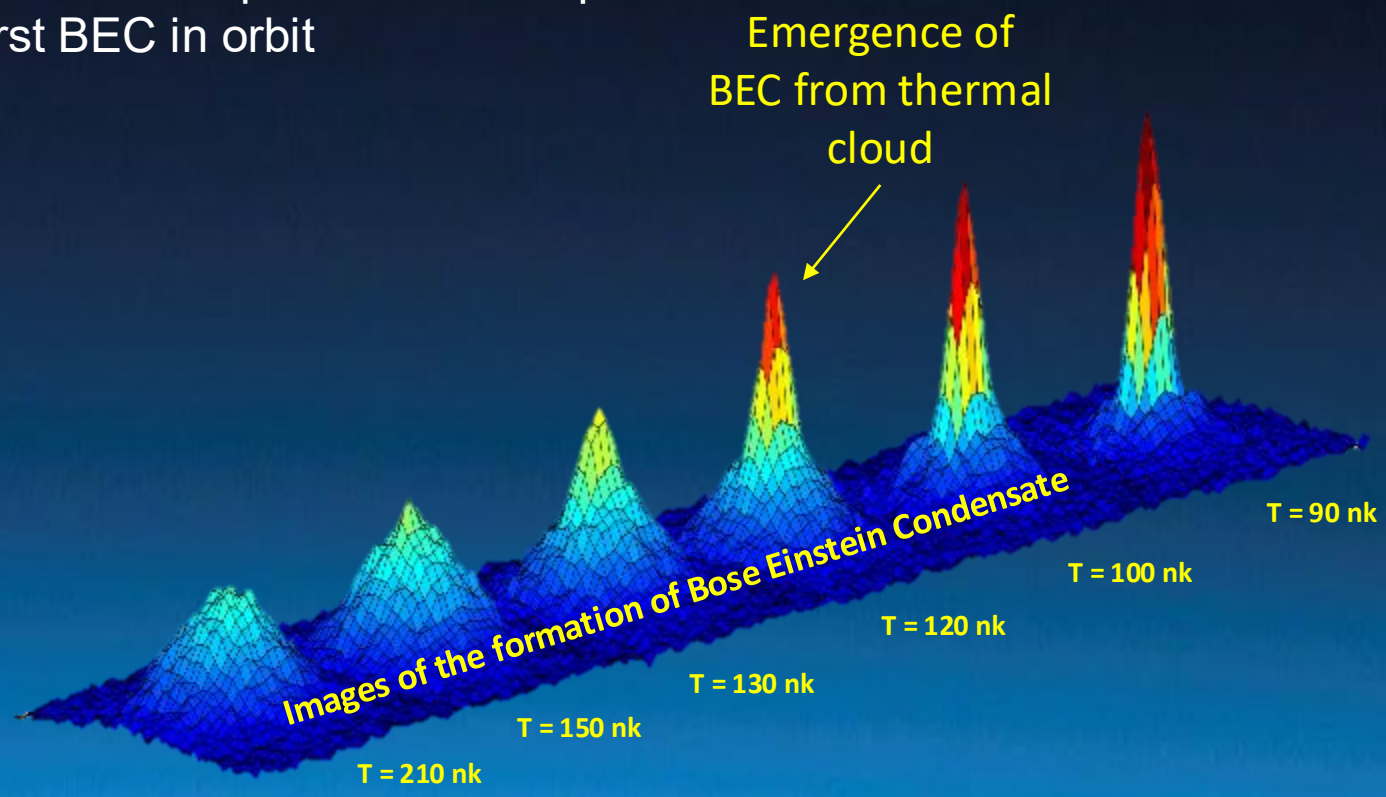
Cold Atom Lab (CAL)

- CAL operating on the ISS has created Bose-Einstein condensates (BECs), quantum bubbles, and atom interferometers and has collected data from tens of thousands of experimental runs for five principal investigation teams.



- Launched to ISS in 2018
- Dual species: ^{87}Rb, ^{41}K and ^{39}K
- Achieved temperatures <100 pK
- First BEC in orbit



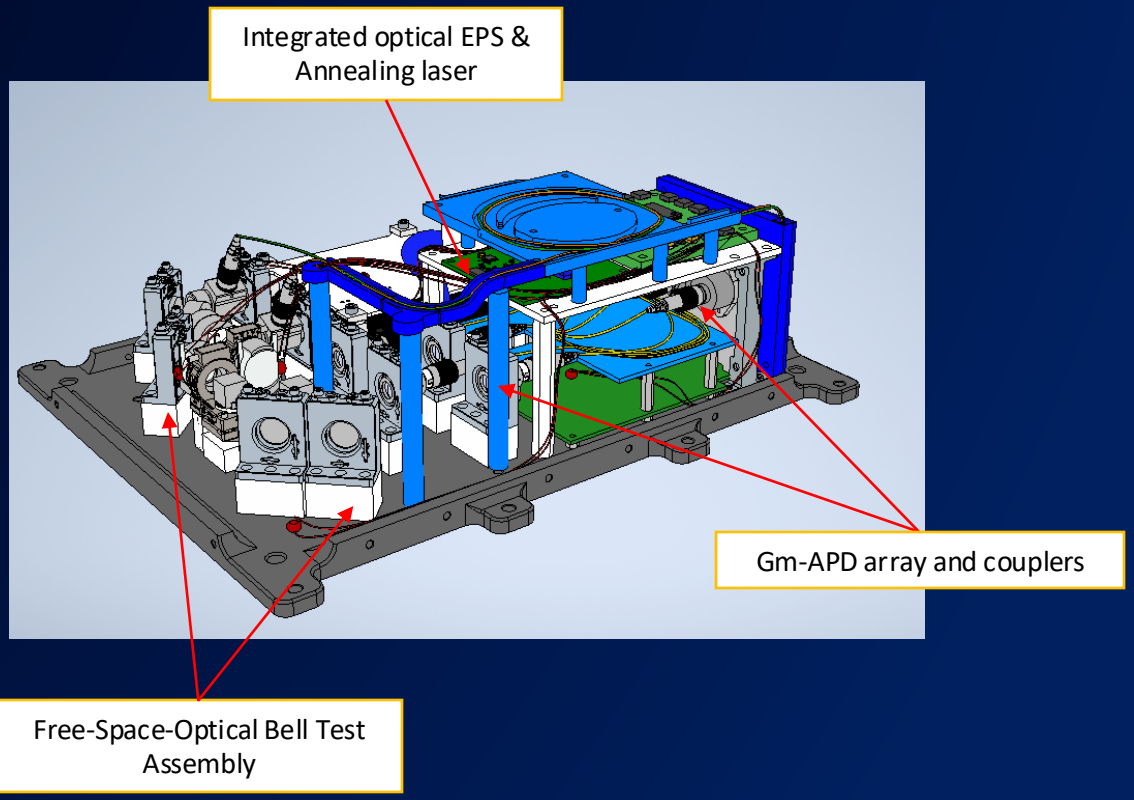


SEAQUE

(Space Entanglement and Annealing Quantum Experiment)

- The SEAQUE mission will demonstrate an integrated optical entangled photon pair source, compact Bell-test system, and in-space detector annealing to repair radiation damage on the ISS.
- SEAQUE will be the first US quantum optical flight-mission.
- SEAQUE development was funded through SMD/BPS's "Deep Space Quantum Link" and JPL's Office of Space Technology.
- Built by University of Illinois Urban-Champaign
- Launched to ISS in November 2024.

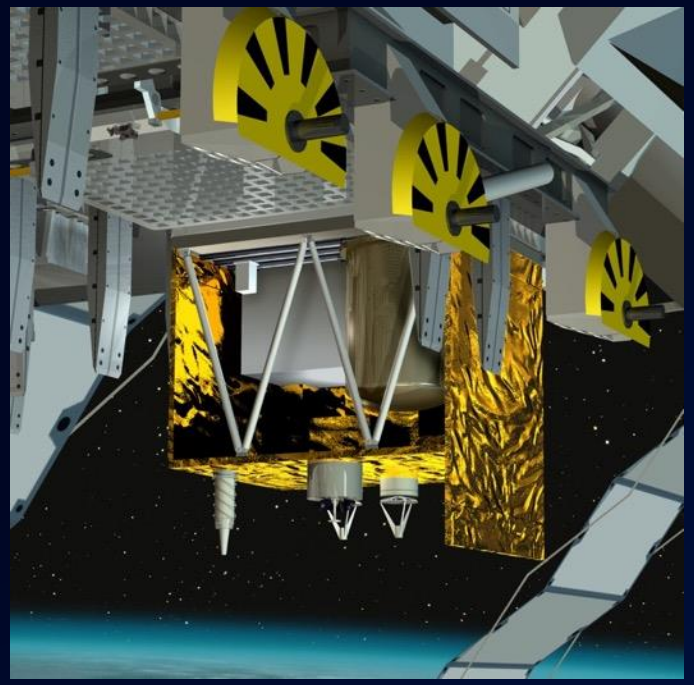
Mass: 6 kg, Power: 30 W
Size: 30 cm x 20 cm x 10 cm



ACES

Atomic Clock Ensemble in Space

- NASA/ESA cesium atomic clock (10^{-16} stability) on the ISS with microwave ground links to explore gravitational redshift for tests of Equivalence Principle and geodesy.
- Launch to ISS in April 2025.
- JPL (Pasadena, CA) and NIST (Boulder, CO) are each serving as one of several microwave ground link stations that will provide ground clock references.



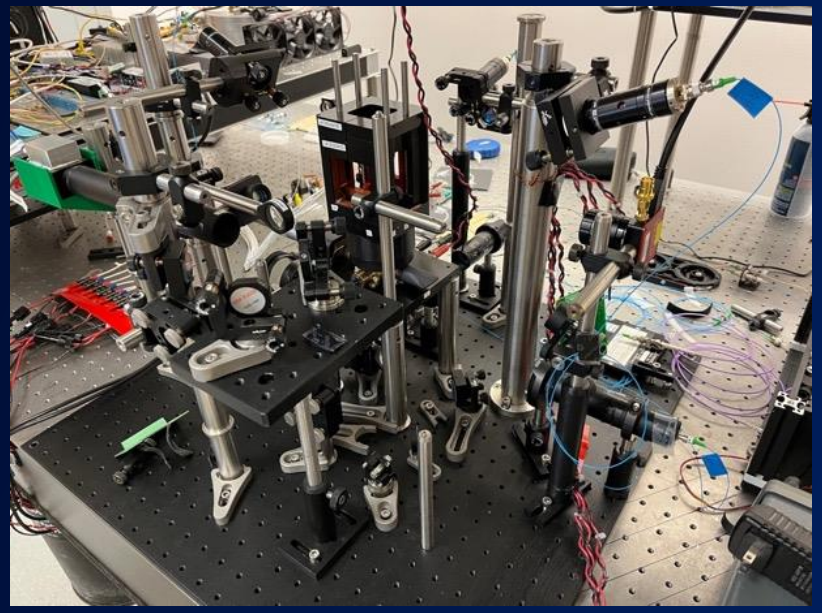
Artist rendering of ACES on ISS. Source: ESA

Mockup of ACES. Source: L. Cacciapuoti

BECCAL

Bose-Einstein Condensate Cold Atom Lab

Arbitrary shaped potential landscapes possible with the Blue Detuned Box Potential.
Source: Matteo Sbroscia



JPL BECCAL Blue Detuned Box Potential Testbed

- BECCAL is the joint DLR/NASA follow-on to CAL on ISS.
- Expected launch to ISS in 2027.
- BECCAL will have greater atom number and a blue detuned box potential capable of configuring arbitrary potentials.
- JPL is developing a narrow-scope ground testbed to provide PI support and training prior to full DLR-provided ground testbed system delivered to JPL.
- Selection of US BECCAL Researchers planned before launch.

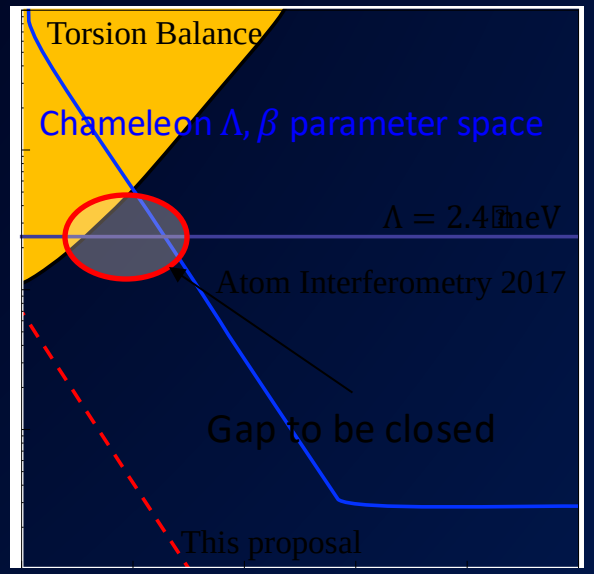
NASA Fundamental Physics Ground Research

- D3E3/Atom Interferometry
- Optical Clocks
- Deep Space Quantum Link
- Lunar Laser Ranging

D3E3/DESIRE

Direct Detection of Dark Energy with the Einstein Elevator

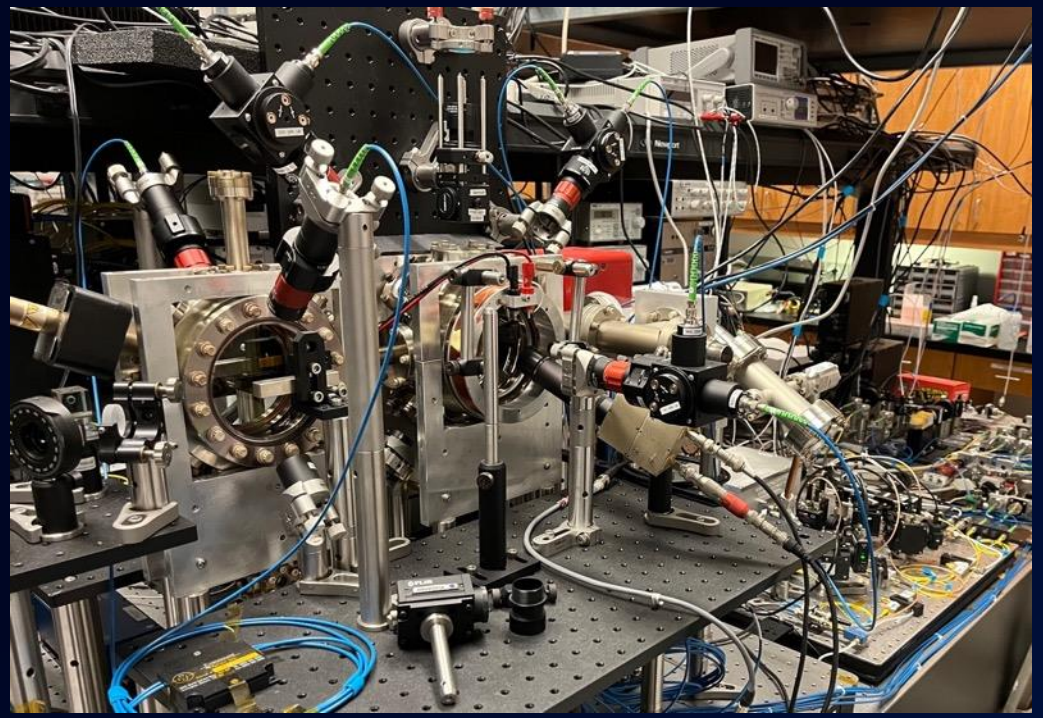
- Collaboration between JPL and Leibniz University Hannover funded by NASA and DLR.
- Direct test of chameleon dark energy scalar field theory using atom interferometers in modified MAIUS-A payload with JPL-provided test mass in the 20-m Einstein Elevator drop tower (>100 shots/day).
- Improve parameter constraints by 10^3 in 5 days of operation.
- Drop science campaign expected to begin in 2025.



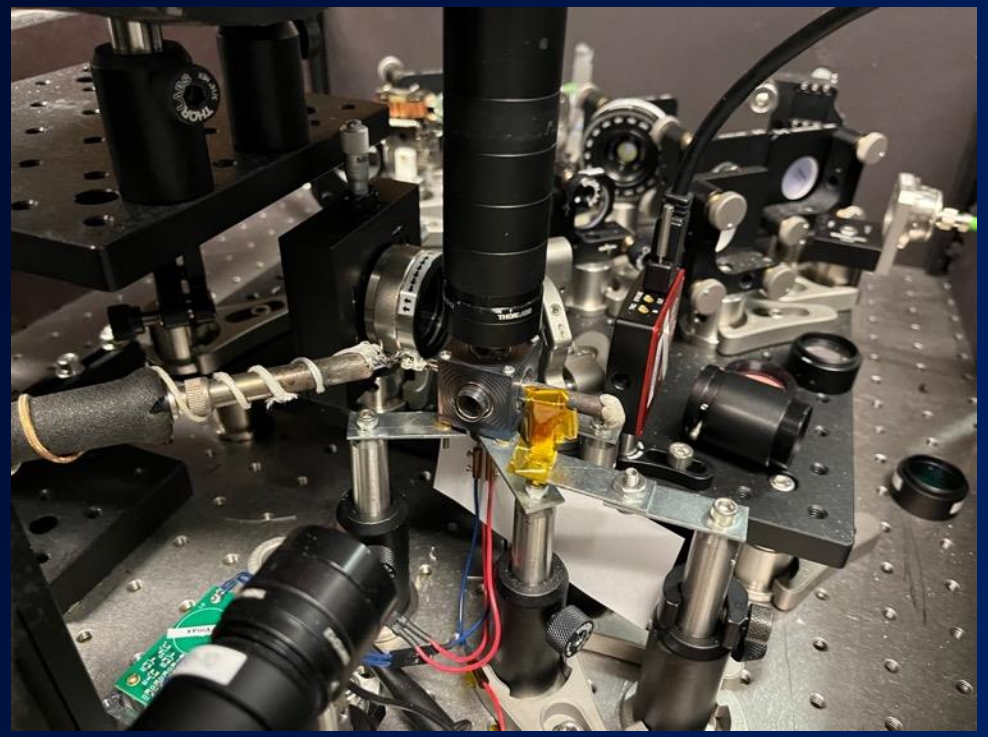
D3E3 (MAIUS) Physics Package

Optical Clock Development

- Developing a strontium (Sr) optical lattice clock in the lab that achieves stability of order 10^{-18} while advancing technologies for a future flight instrument.
- Advancing a miniature ytterbium (Yb+) trapped-ion clock.
  - Both laboratory clocks may serve as ground references for the ACES mission.



JPL Strontium Optical Lattice Clock



JPL Ytterbium Ion Miniature Space Optical Clock

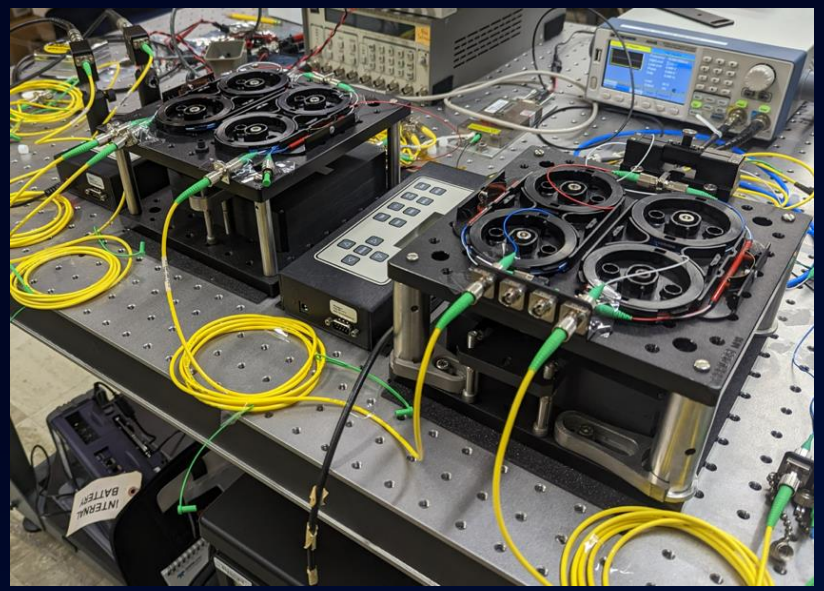
Deep Space Quantum Link (DSQL)

A series of quantum experiments in space

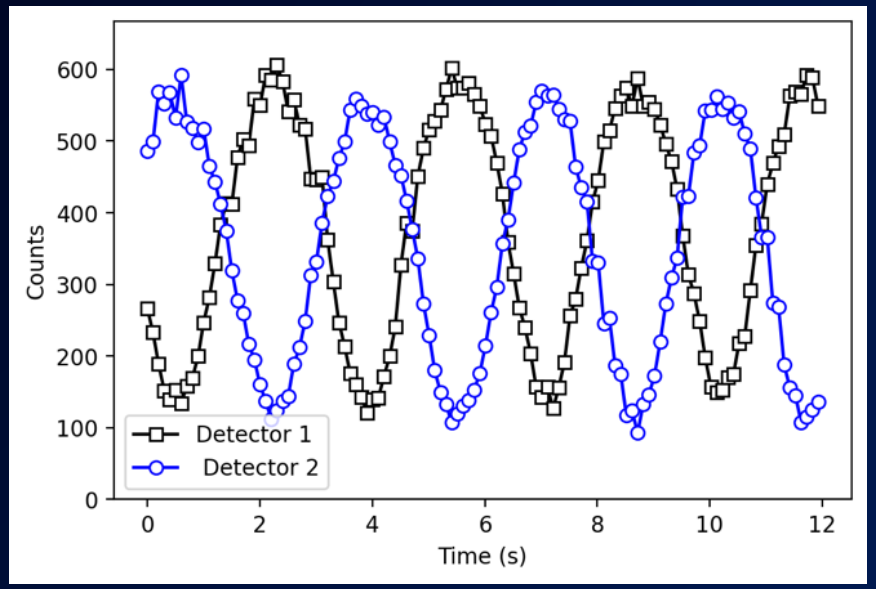
Quantum interferometry: To use interferometric quantum optical links to test quantum field theory (quantum mechanics) in curved spacetime (gravity).

Bell-tests: To show non-locality of quantum entangled states on currently inaccessible baselines.

Quantum teleportation: To teleport quantum states across long baselines and/or gravitational potentials.



JPL Quantum Interferometer Testbed



Laboratory tests of single photon long-baseline (4 km fiber) interferometry

JPL Free-Space Entangled Photon Link

Lunar Laser Ranging (LLR)

Testing for Violation of Einstein's Equivalence Principle using the Moon.

- Laser range to the moon from JPL Table Mountain Observatory (TMO) 1-m telescope with a high-power (2kW) CW laser. Expect to achieve ~30 μm range precision.

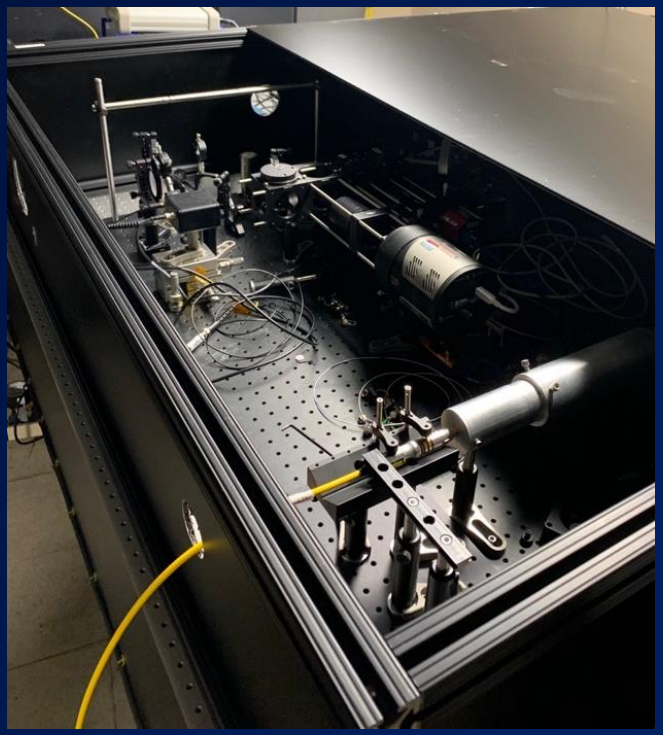
New science investigations:

- Improved tests of relativistic gravitation.
- Search for stochastic gravitational waves.
- Enhances knowledge of deep lunar interior.
  - Lunar core: shape, rotation, dissipation, free libration.

Science	Current (1 cm)	1 mm	0.1 mm
Weak EP	$\lvert\Delta a/a\rvert < 2.4\times10^{-14}$	$<10^{-14}$	10^{-15}
Strong EP	$\lvert\eta\rvert < 3.4\times10^{-4}$	3×10^{-5}	3×10^{-6}
PPN parameter β	$\lvert\beta-1\rvert < 7.2\times10^{-5}$	$<10^{-5}$	10^{-6}
Time variation of G	9.5×10^{-15} yr^{-1}	5×10^{-15}	$<1\times10^{-15}$
Inverse Square Law	$\lvert\alpha\rvert < 3\times10^{-12}$	10^{-12}	10^{-13}

JPL Table Mountain Observatory
Optical Communication Test Laboratory (OCTL)

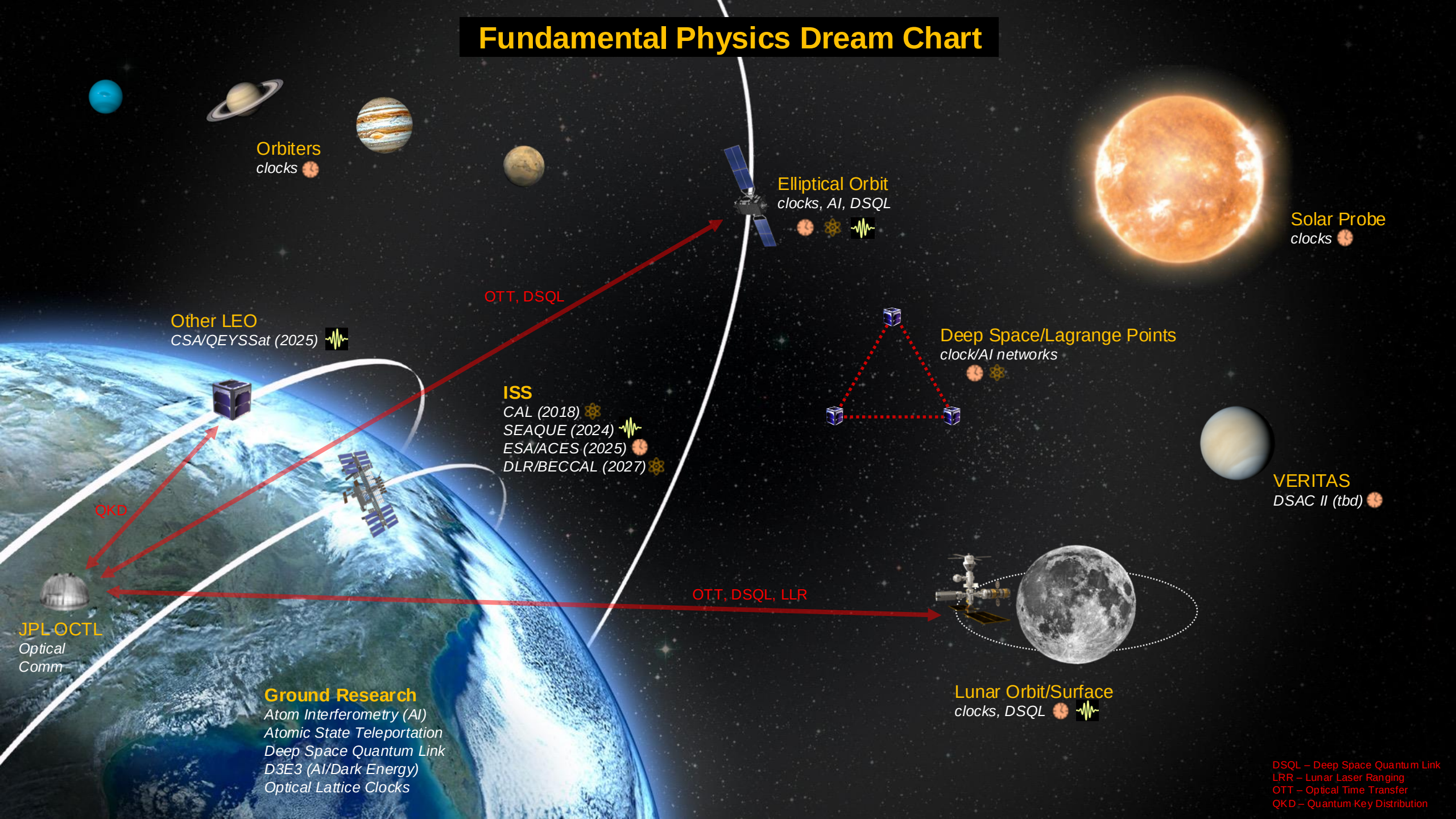
Apollo Retroreflector



JPL High-power Lunar Laser

The Forward Vision

Fundamental Physics Dream Chart



DSQL – Deep Space Quantum Link
LRR – Lunar Laser Ranging
OTT – Optical Time Transfer
QKD – Quantum Key Distribution

Jet Propulsion Laboratory
California Institute of Technology