



Fundamental Physics and Precision Measurements in Space

John L. Callas

Fundamental Physics

Jet Propulsion Laboratory, California Institute of Technology

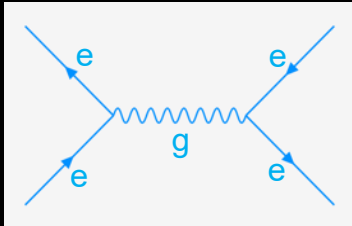
John.L.Callas@jpl.nasa.gov

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).

Predicted the
Higgs Boson
discovered in 2012

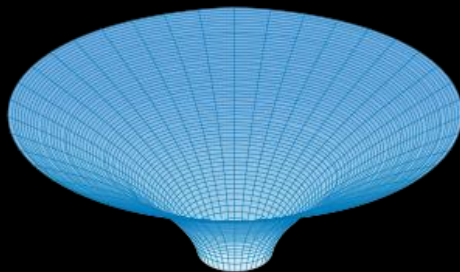
Standard Model of Elementary Particles



General Relativity

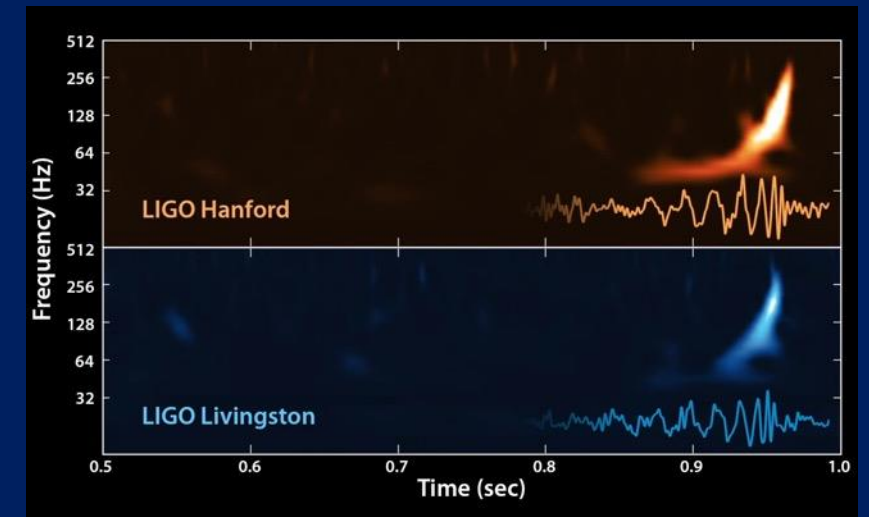
(Gravity)

Metric Theory

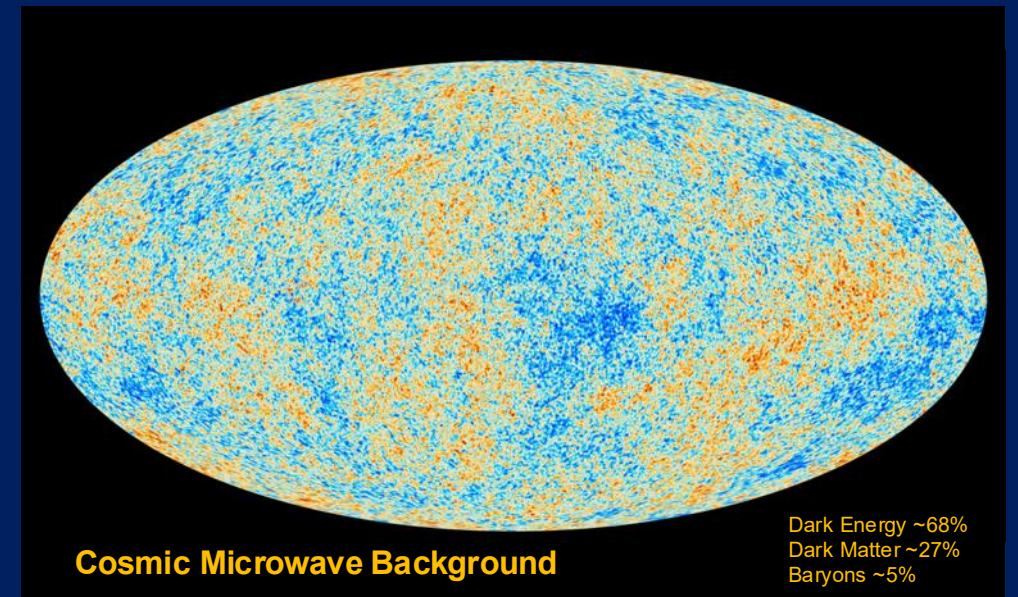
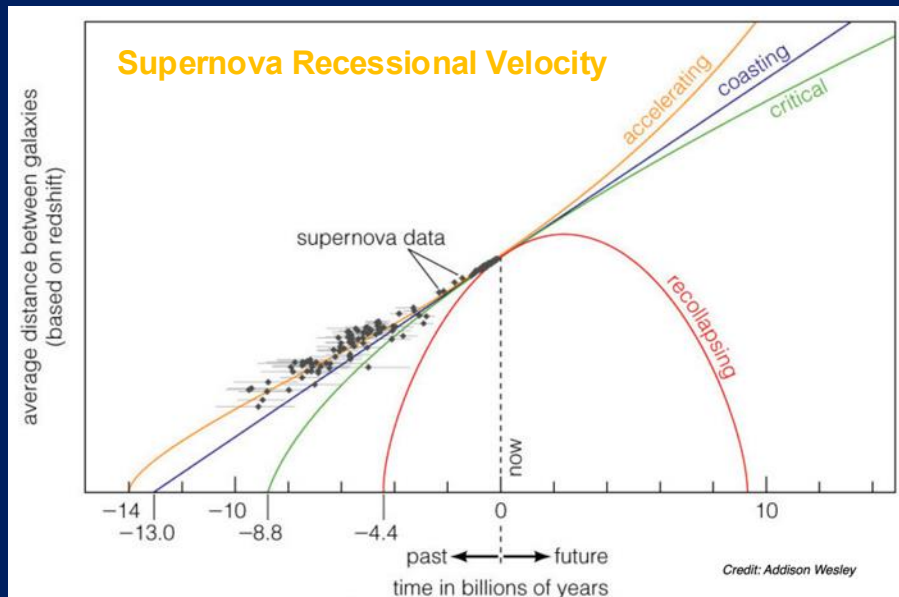
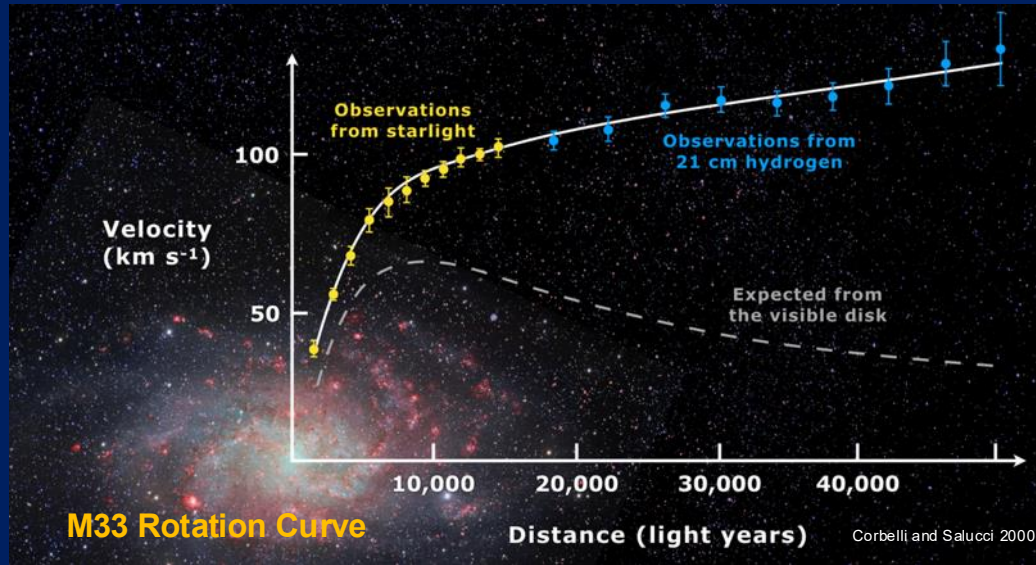


Force manifested by Curved Space (geometry), but requires the Equivalence Principle.

Predicted
Gravitational Waves
first observed in 2015.



But Problems



New Questions

- **Why is 95% of the Universe dark to us?**
 - What is Dark Matter? What is Dark Energy?
 - Why does the Standard Model describe less than 5% of the Universe?
- **Why is the Universe made up of only (baryonic) matter and no antimatter?**
 - The Standard Model predicts equal amounts.
- **Is General Relativity the last word on Gravity?**
 - Why can't gravity be unified with the other (quantum) forces?
 - Does gravity have a quantum aspect?

Our great laboratories have found no new physics.

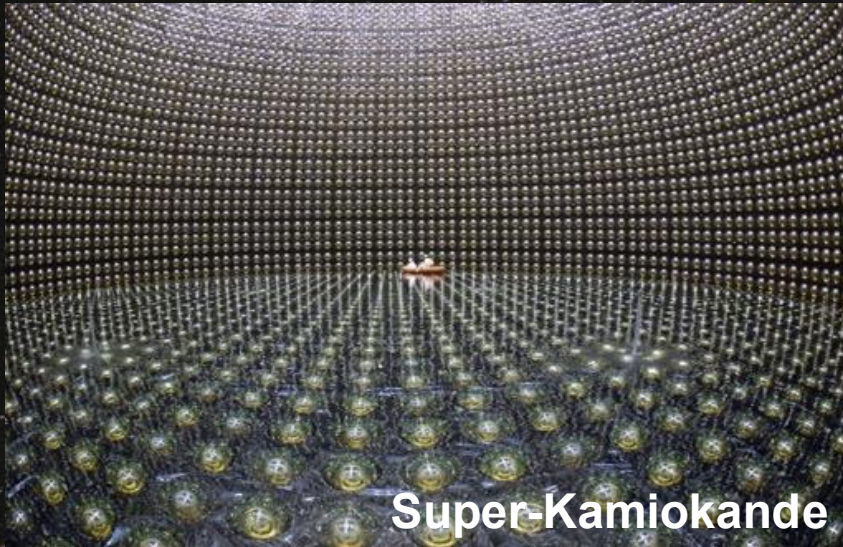


CERN

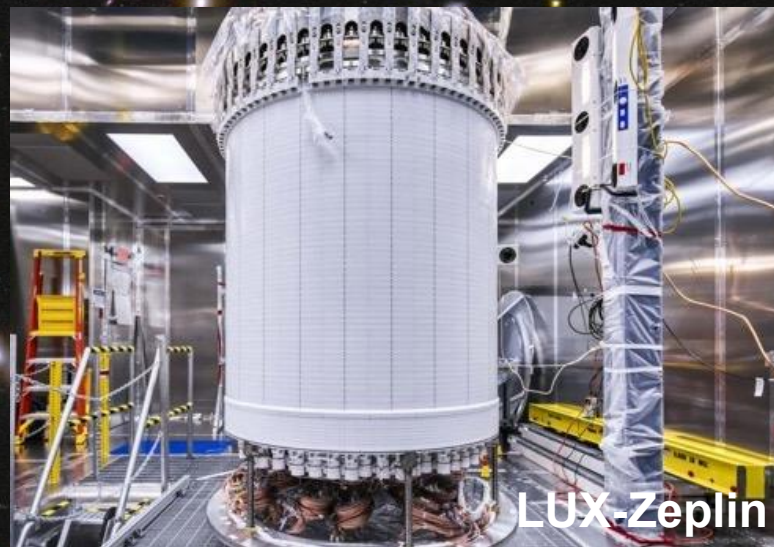


DES

**No Super-Symmetry
No Proton Decay
No Axions
No WIMPs
No New Forces
No New Fields**



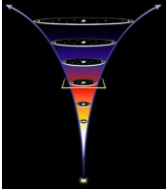
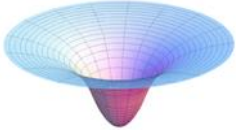
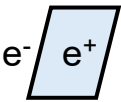
Super-Kamiokande



LUX-Zeplin

*Maybe we are
looking in the
wrong way.*

A New Search Space – Precision Measurements

Scientific Question	Hypothesis	Observable	Measurement
Ultra-Light Dark Matter 	Coupling to the Standard Model $L_{DM}^{(n)} = (-\Gamma_f \bar{\psi}\psi + \Gamma_\alpha \frac{1}{4} F_{\mu\nu} F^{\mu\nu}) \phi^n$	Variation of atomic constants $\alpha \simeq \alpha_0(1 + \Gamma_\alpha \phi^n)$ with frequency oscillation $f = m_\phi c^2 / h$	Atomic clock frequency comparisons (LPI); Atom interferometer tests of UFF for composition dependence
Dark Energy 	Vainshtein, Galileon theory, Chameleon, symmetron scalar field, Yukawa field $U_{mod} = \frac{\mu_0}{r} (1 + \alpha e^{-r/\lambda})$	Non-zero gravity gradient $\nabla^2 U = tr(T) = \tau(r, t)$	Laser interferometric, atom interferometric measurement of gravity gradient
Modified Gravity 	New dynamical fields, Fifth force, Extra dimensions, Quantum gravity	Equivalence Principle violation; Inverse Square Law violation; Variation of gravitational constant; Gravitation redshift of quantum states	Atomic clock tests of LPI and LLI; Atom interferometer tests of UFF; Lunar laser ranging of SEP, PPN; Redshift tests of entangled states
Baryon Asymmetry 	CPT/Lorentz symmetry tests related to matter–antimatter asymmetry	Local Lorentz Invariance violation	Atomic clock tests of LPI and atom interferometric tests of UFF vs orientation and velocity

Why Space?

- **Greatly reduced gravitational and non-gravitational sources of noise.**
 - Enabling ultra-precise measurements
- **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
- **Access to vacuum and cold conditions of space.**



Atomic Clocks in Space



Atomic Clocks

(multi-species/self-referenced)

$$\frac{\Delta v}{v} = K_{\alpha_0} \frac{\delta \alpha_0}{\alpha_0}$$



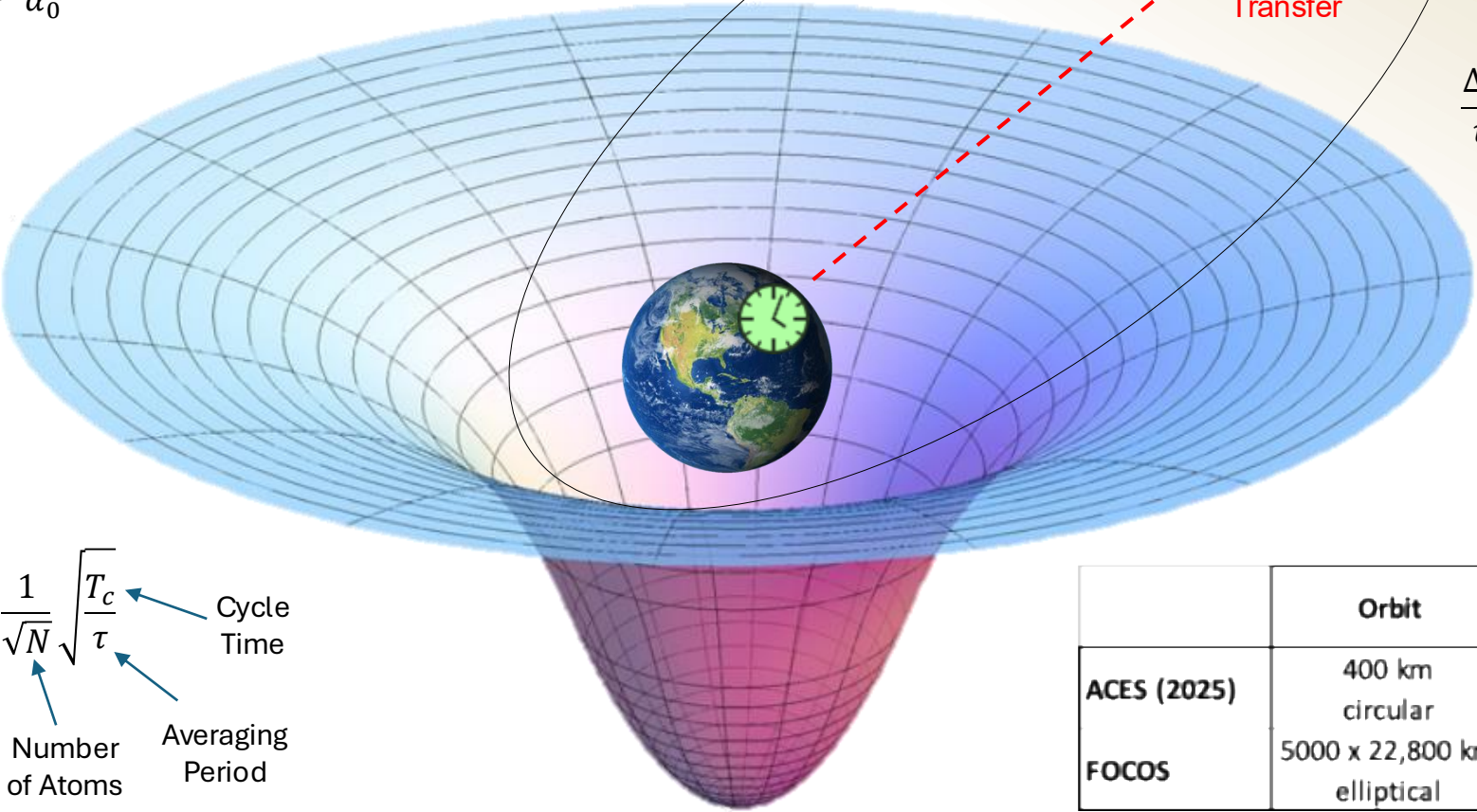
Atomic Clocks

(ground referenced)

$$\frac{\Delta v}{v} = \underbrace{-(1 + \alpha) \frac{\Delta U}{c^2}}_{\text{LPI}} - \underbrace{\frac{1}{2} (1 + \epsilon) \frac{\Delta v^2}{c^2}}_{\text{LLI}}$$

LPI

LLI



Linewidth

Clock Stability

Transition Frequency

Number of Atoms

Averaging Period

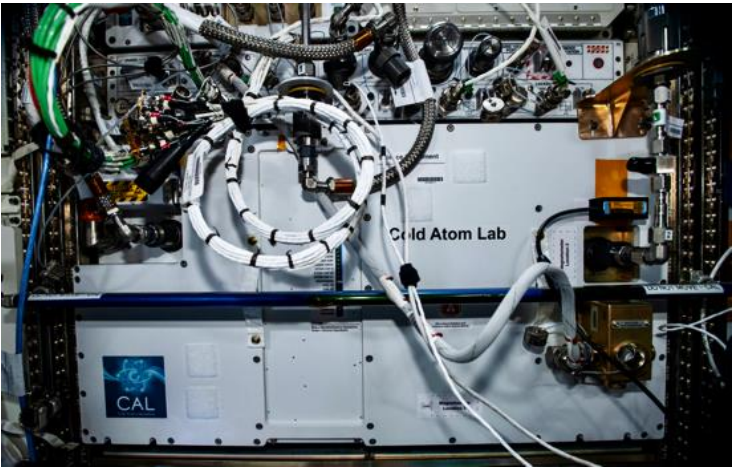
Cycle Time

$$\sigma_y(\tau) \sim \frac{\Delta v}{v_0} \frac{1}{\sqrt{N}} \sqrt{\frac{T_c}{\tau}}$$

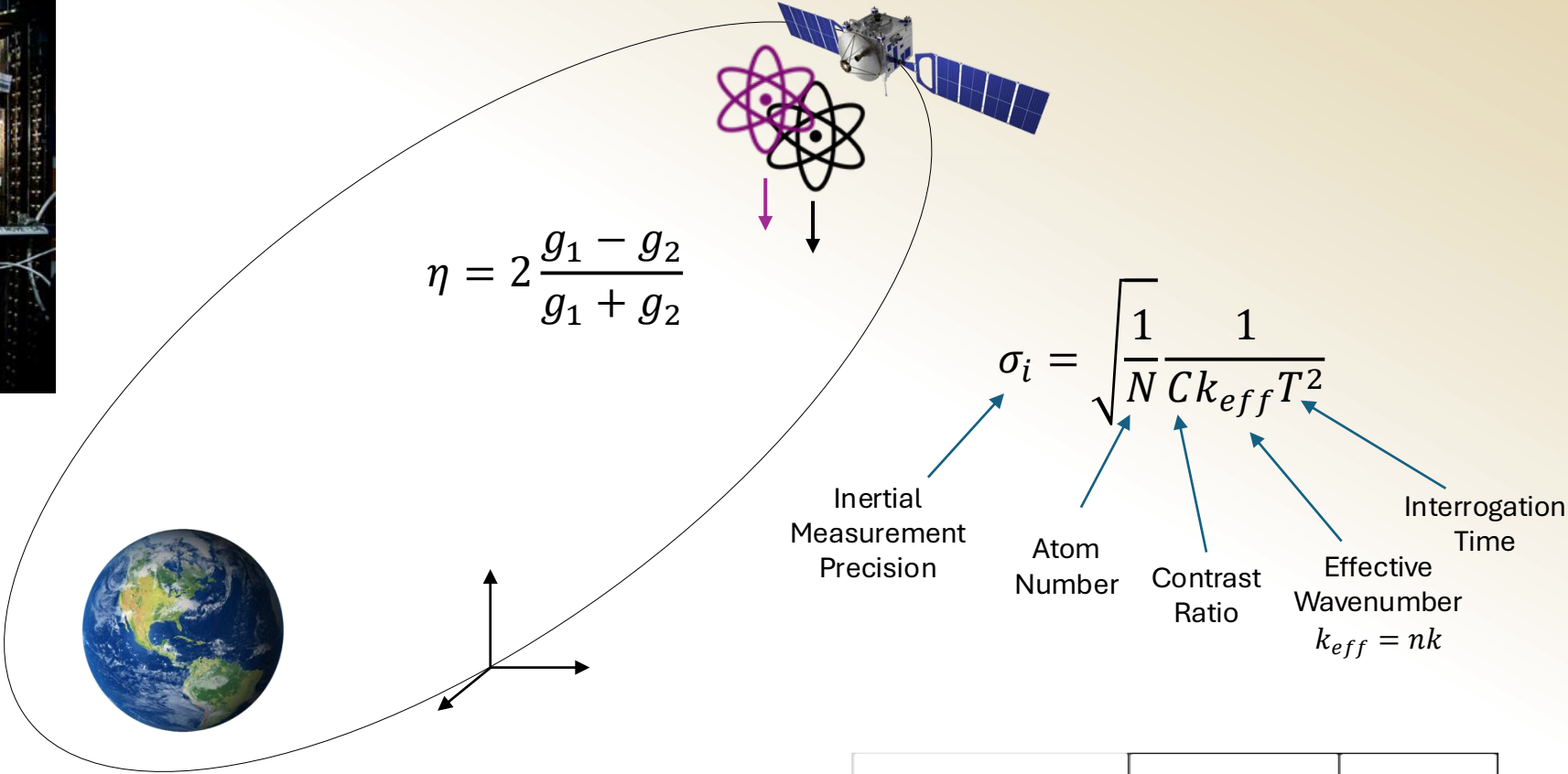
	Orbit	Clock Stability	LPI	LLI
ACES (2025)	400 km circular	1×10^{-16}	2×10^{-6}	1×10^{-10}
FOCOS	5000 x 22,800 km elliptical	1×10^{-18}	2×10^{-9}	1×10^{-12}

LPI – Local Positional Invariance, LLI – Local Lorentz Invariance

Atom Interferometry in Space

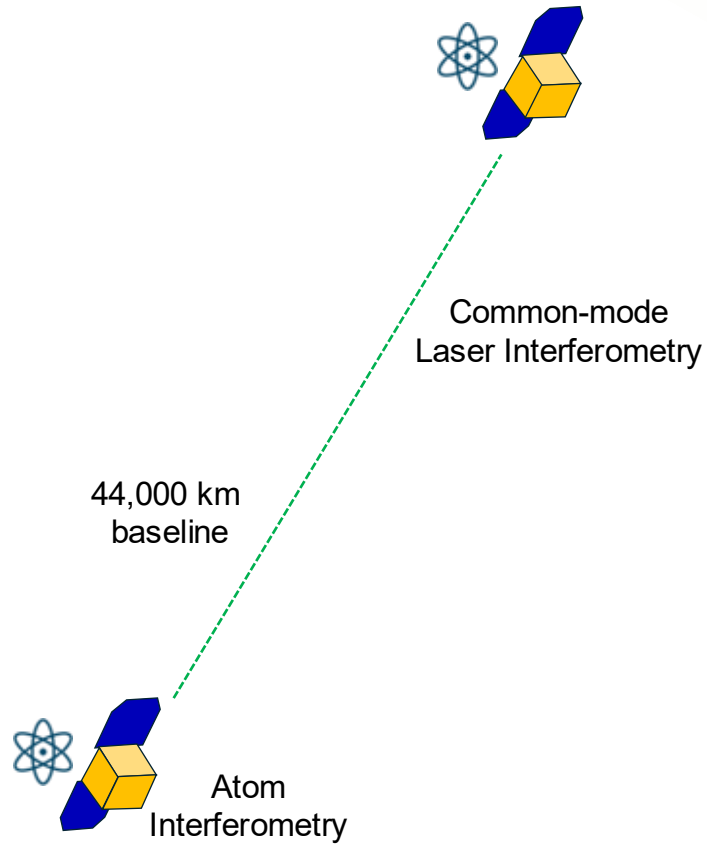


Cold Atom Lab (ISS, 2018), JPL

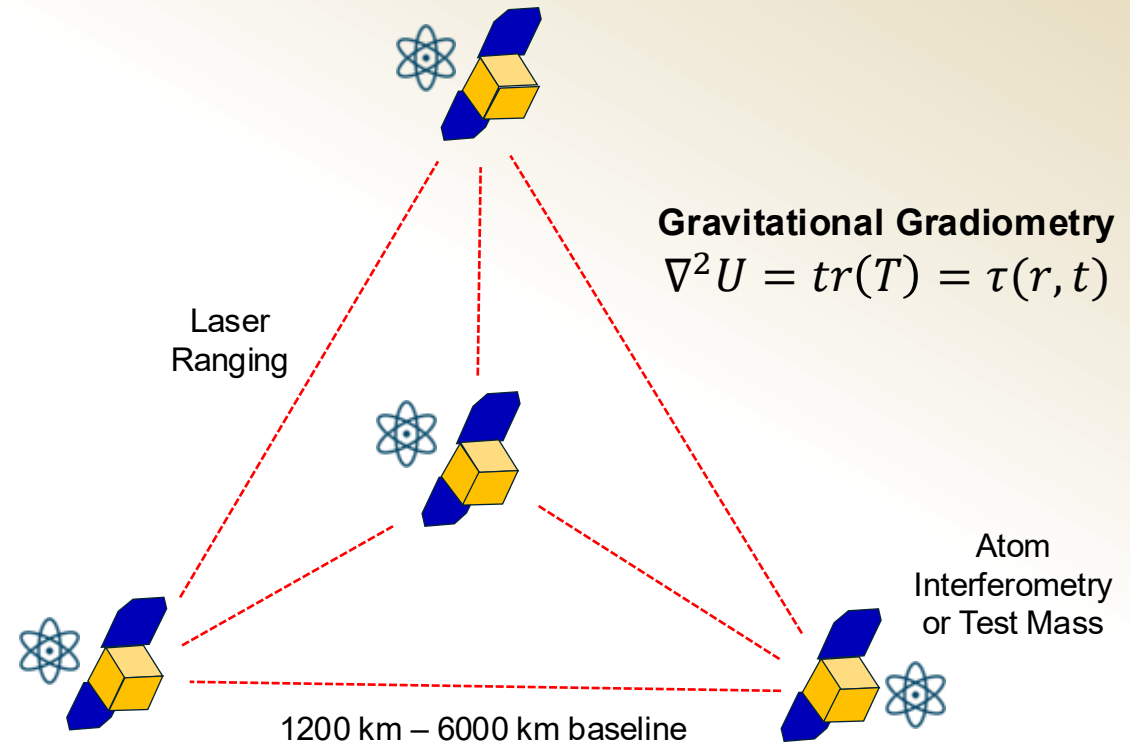


	Orbit	η (UFF)
MICROSCOPE (2016)	710 km SSO polar	1.5×10^{-15}
STE-QUEST	700 x 51,000 km elliptical	1×10^{-17}

Gravitational Gradiometry in Space



AEDGE
GW 0.01 – 3 Hz
DM 10^{-17} – 10^{-15} eV

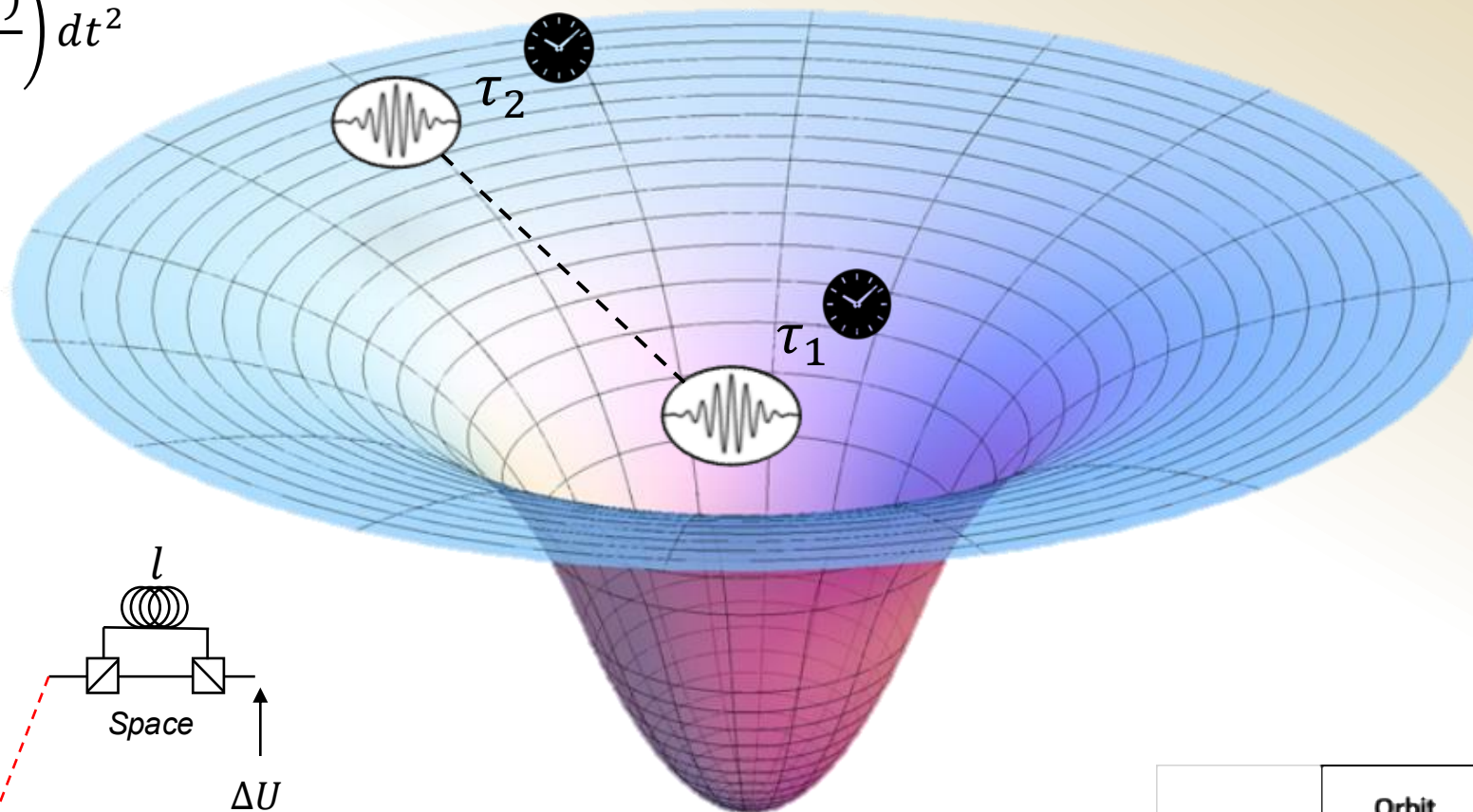


TETRA-GGT
 $\tau \sim 10^{-24} \text{ s}^{-2}$
(GW, DM)

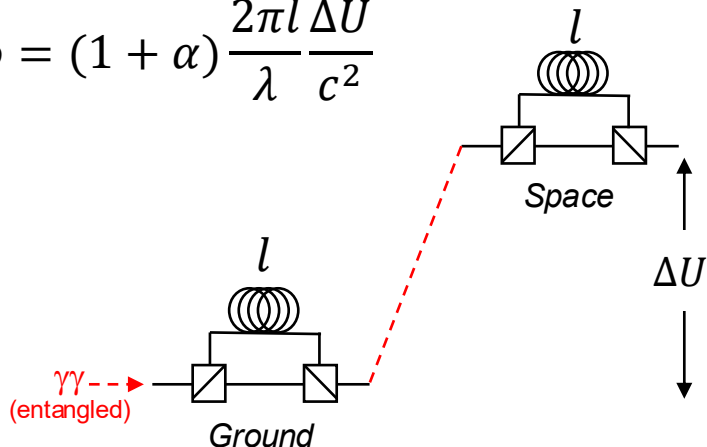
Gravitational Gradiometry
 $\nabla^2 U = \text{tr}(T) = \tau(r, t)$

Entangled Photons in Curved Space-Time

$$d\tau_r^2 = \left(1 + \frac{2U(r)}{c^2}\right) dt^2$$



$$\Delta\phi = (1 + \alpha) \frac{2\pi l}{\lambda} \frac{\Delta U}{c^2}$$



	Orbit	LPI
DSQL	5000 km elliptical	1×10^{-6}

DSQL – Deep Space Quantum Link

Lunar Laser Ranging

Testing Einstein's Equivalence Principle with Lunar Laser Ranging.

- Laser range to the moon from JPL Table Mountain Observatory (TMO) 1-m telescope with a high-power (2 kW) CW laser. Expect to achieve $\sim 30 \mu\text{m}$ 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	$ \Delta a/a < 2.4 \times 10^{-14}$	$< 10^{-14}$	10^{-15}
Strong EP	$ \eta < 3.4 \times 10^{-4}$	3×10^{-5}	3×10^{-6}
PPN parameter β	$ \beta - 1 < 7.2 \times 10^{-5}$	$< 10^{-5}$	10^{-6}
Time variation of G	$9.5 \times 10^{-15} \text{ yr}^{-1}$	5×10^{-15}	$< 1 \times 10^{-15}$
Inverse Square Law	$ \alpha < 3 \times 10^{-12}$	10^{-12}	10^{-13}



JPL Table Mountain Observatory
Optical Communication Test Laboratory (OCTL)

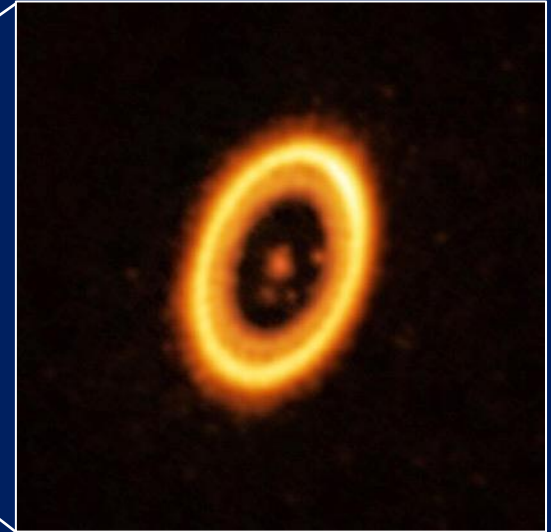
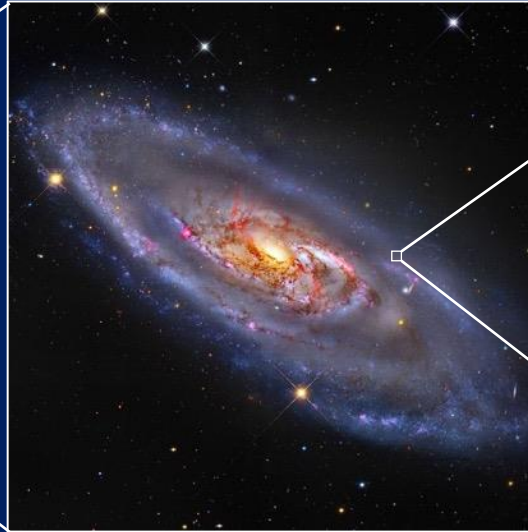


Apollo
Retroreflector

JPL High-power Lunar Laser



Precision



Classical Physics

$$F = q(E + v \times B)$$

$$F = -\frac{GMm}{r^2}$$



Modern Physics

$$H\psi = -i\hbar \frac{\partial}{\partial t} \psi$$

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



Physics Beyond the
Standard Model

$$\mathcal{L}(\hbar, c, G) +$$





Jet Propulsion Laboratory
California Institute of Technology