Quantum Opportunities and Challenges for Fundamental Sciences in Space

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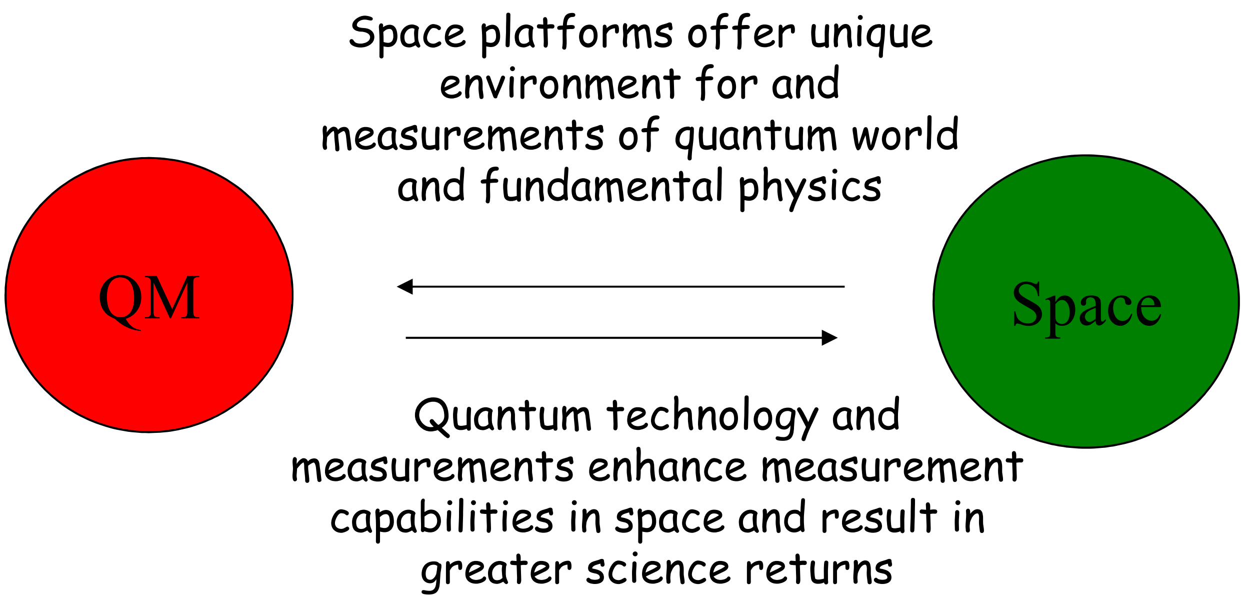
Government Sponsorship Acknowledged

Quantum Mechanics and Space

Space exploration has a dual role:

- As a challenging endeavor, unique and sensitive instrumentation is required with a combination of performance, low power, low mass, and low cost (relatively speaking).
- As a benign environment (micro gravity, low vibration, high isolation, space and time spans, etc.) it can offer unique opportunity to perform exacting tests of fundamental physics and science in general.



Quantum Properties for Technology

The fundamentally quantum phenomena of quantum coherence and interferences, wave-particle duality, entanglement, quantum photon statistics allow the realization of sensors and detectors with unprecedented capabilities

- Entanglement – quantum computing and communications….
- Quantum interference – SQUID devices (widely used); Ramsey fringes in atomic clocks; For sensors and detectors…
- Wave-particle duality - cold atom interferometers, quantum gas sensors….
- Quantum photon statistics – squeezed light and below quantum shot noise, quantum key distribution (QKD), quantum (ghost) imaging….

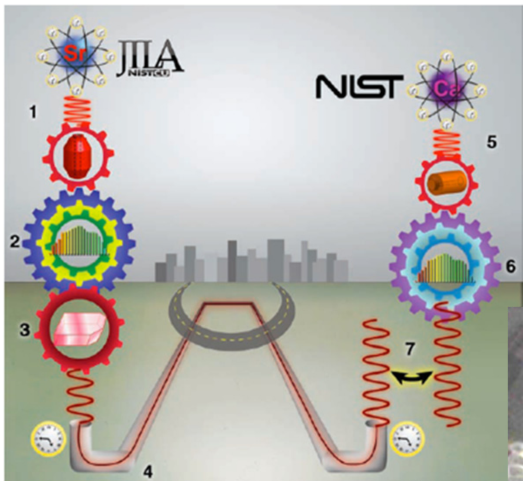
We at JPL QSTG have been exploring

- Ultra-stable clocks – timekeeping, navigation, fundamental physics tests
- Atom interferometer inertial sensors – gravity mapping for Earth science, gravity survey for planetary science, autonomous inertial navigation, tests of fundamental physics, drag-free control, pointing and guidance control
- BEC and quantum degenerate gas – enhancement for cold atom interferometers, tests for fundamental physics, quantum system modeling
- Entangled and single photon sources – for quantum communication, secure communication, imaging and computation

Optical Clocks – Next Generation High Accuracy Clocks of Cold Atoms

Science AAAS

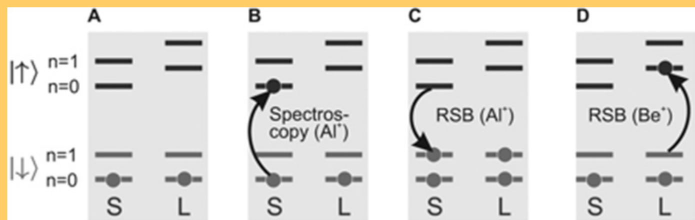
Sr Lattice Clock at 1 x 10 16 Fractional Uncertainty by Remote Optical Evaluation with a Ca Clock
A. D. Ludlow, *et al.*
Science **319**, 1805 (2008);
DOI: 10.1126/science.1153341

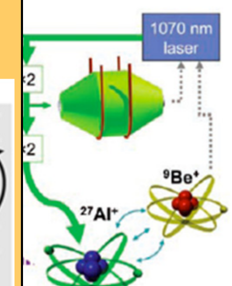


Frequency Ratio of Al^+ and Hg^+ Single-Ion Optica... Clocks; Metrology at the 17th D...mal Place

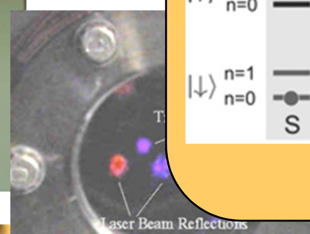
T. Rosenband,* D. ... hmidt,† C. W. Chou, A. Brusch, L. Lorini,‡ W. H. Oskay,§ R. E. Drulling... Stalnaker,‖ S. A. Diddams, W. C. Swann, ... J. C. Bergquist

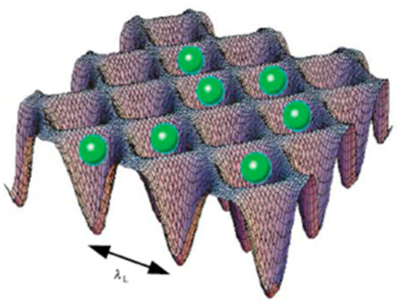
The most precise clock to date is enabled by quantum logic gates

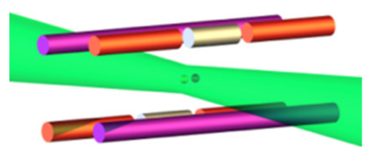


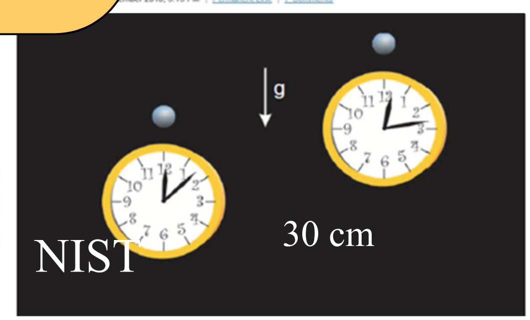


...te Clocks Confirm Your Hair Is Aging Faster ...oenails

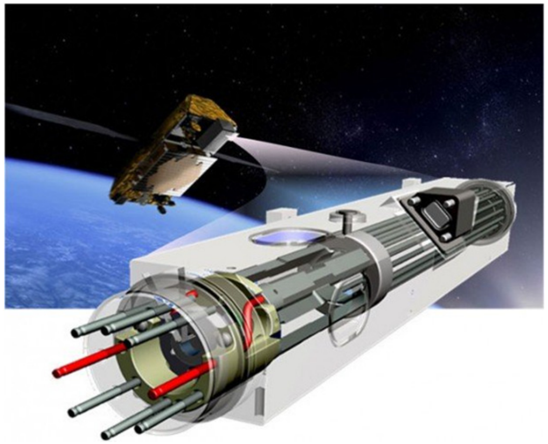




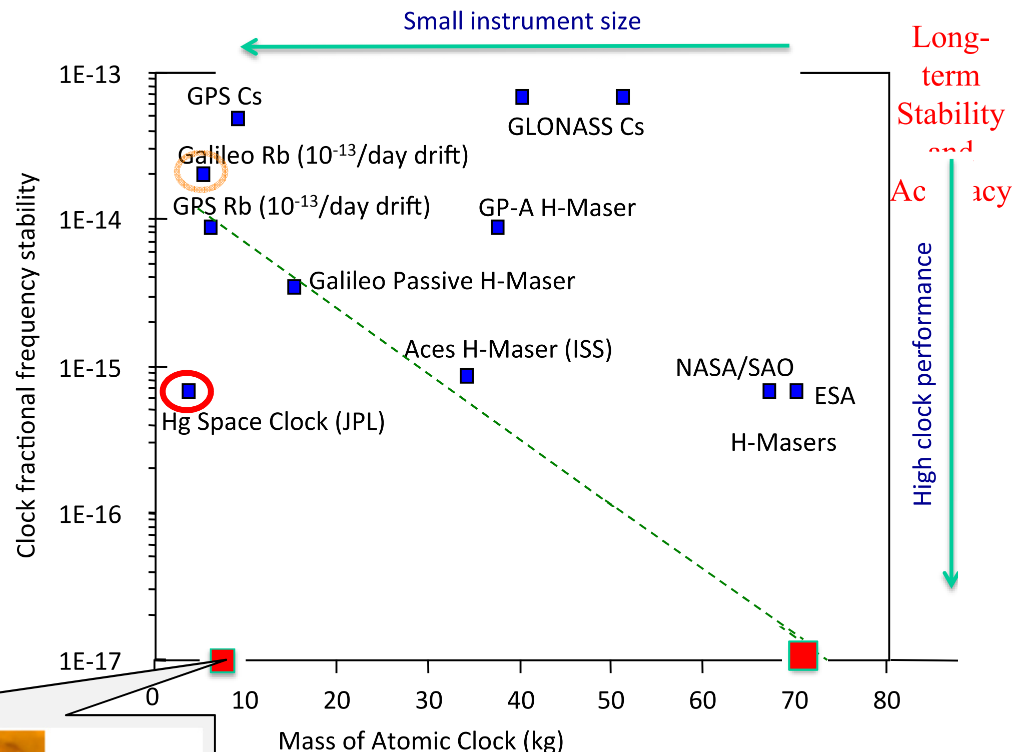




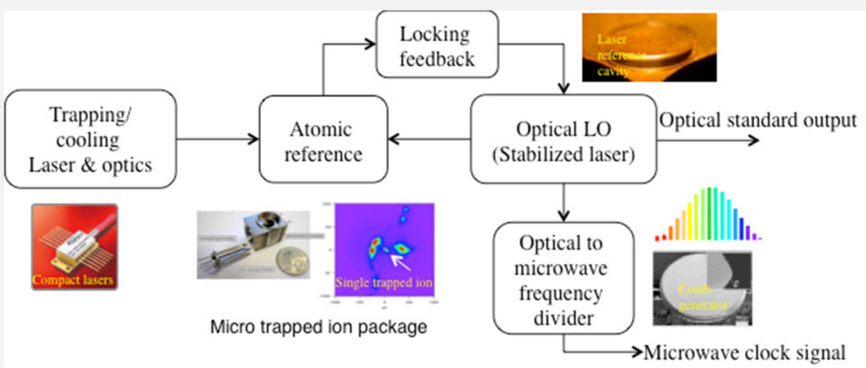
“Up in space” vs. “down to earth” clocks



Artist's rendering of a vacuum tube, one of the main components of an atomic clock that will undergo a technology flight demonstration. Image Credit: NASA



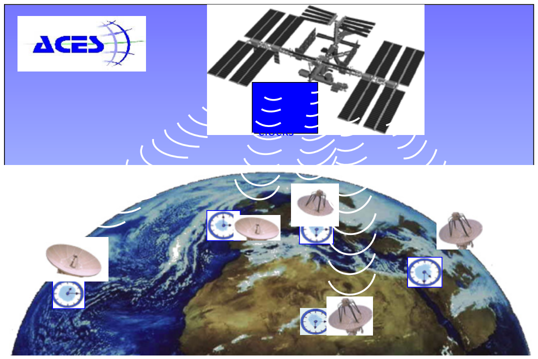
(Based on chart from J. Prestage)

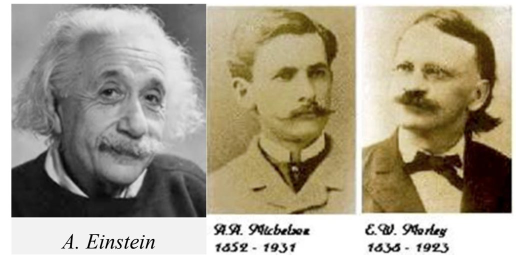


Concept of liter-sized optical atomic clock for space

Applications of high-performance atomic clocks

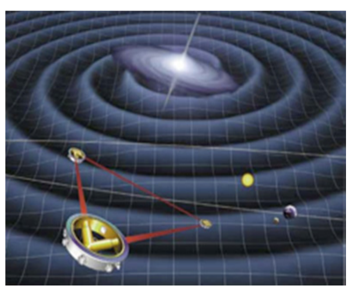
Primary frequency standards, timekeeping, and global time scale and access.



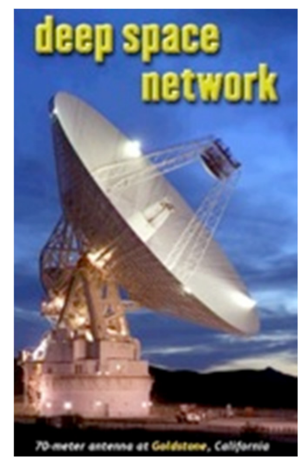


Clock-based fundamental physics tests in space: Gravitational redshift, Shapiro time delay, Lorentz Invariances, Equivalence Principle, variations of fundamental constants, gravity coupling, decoherence, …..

High-performance frequency standards are universal tools for precision measurements in space, including laser interferometers, VLBI, relativistic geodesy,



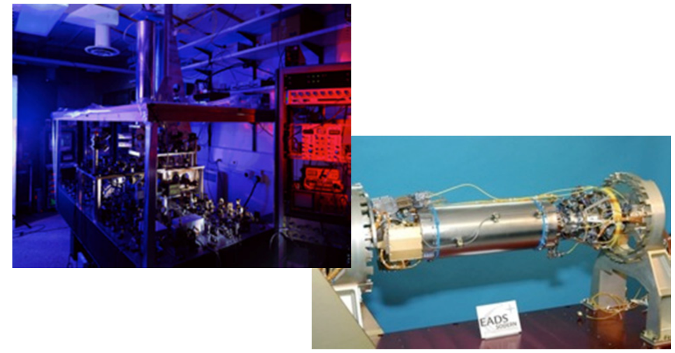
Stable reference sources for global and Deep Space Network (DSN) tracking, positioning, timing, and communication needs. Also enable tracking based science measurements – planetary gravity science, occultation, ….



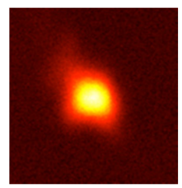
Clocks and Sensors

Digital watches

clocks

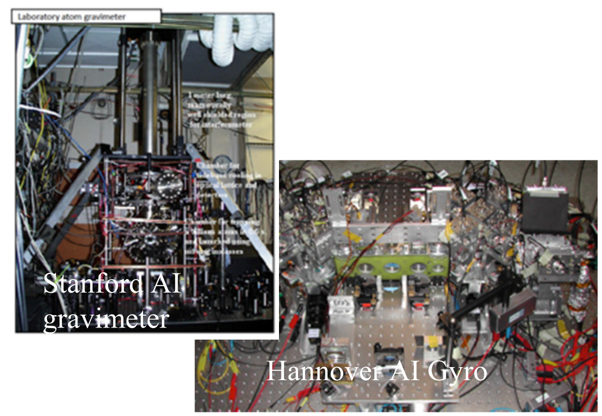


Cold atom clocks



Quartz microbalances

sensors



Atomic inertial sensors

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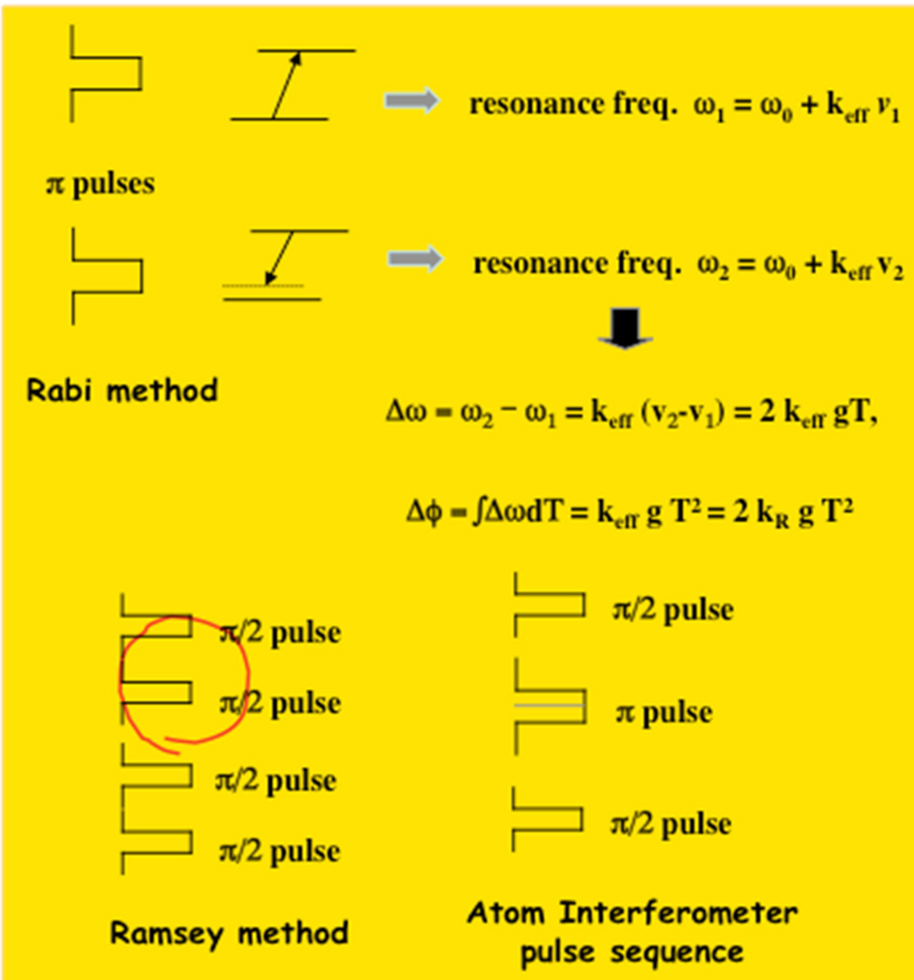
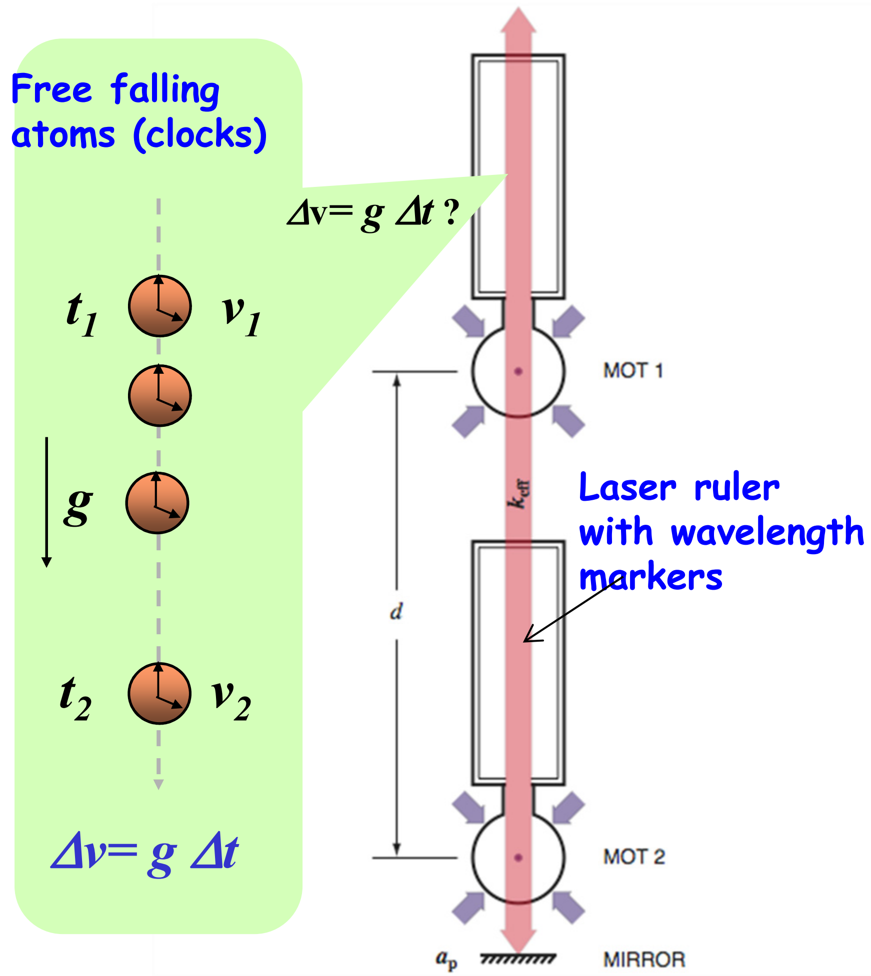
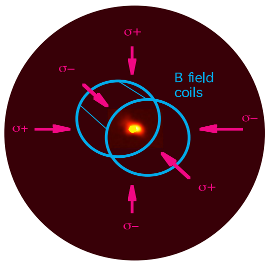
Atoms as free fall clocks



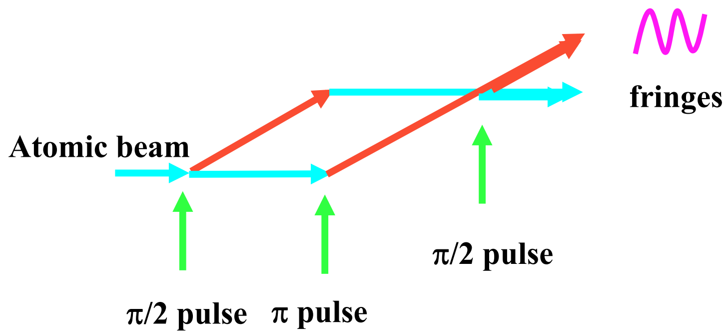


Atomic Freefall Test Mass in Space

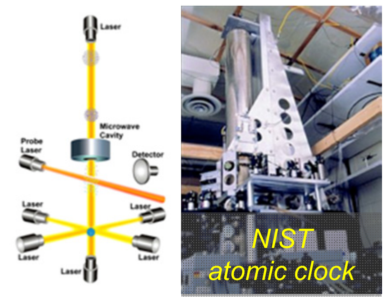
Freefall test mass + **Displacement Detection** + **Atomic system stability**



Laser-cooled Cs atom cloud at μK



atom-wave interferometer (laser-based atom optics)



Atoms are stable clocks

- Use totally freefall atomic particles as ideal test masses
  identical atomic particles are collected, cooled, and set in free fall in vacuum with no external perturbation other than gravity/inertial forces; laser-cooling and trapping are used to produce the atomic test masses at μK and nK; no cryogenics and no mechanical moving parts.
- Matter-wave interference for displacement measurements
  displacement measurements trough interaction of lasers and atoms, pm/Hz$^{1/2}$ when in space; laser control and manipulation of atoms with opto-atomic optics.
- Intrinsic high stability of atomic system
  use the very same atoms and measurement schemes as those for the most precise atomic clocks, allowing high measurement stabilities.
- Enable orders of magnitude sensitivity gain when in space
  microgravity environment in space offers long interrogation times with atoms, resulting orders of magnitude higher sensitivity compared terrestrial operations.

Proposed Fundamental Physics Experiments in Space

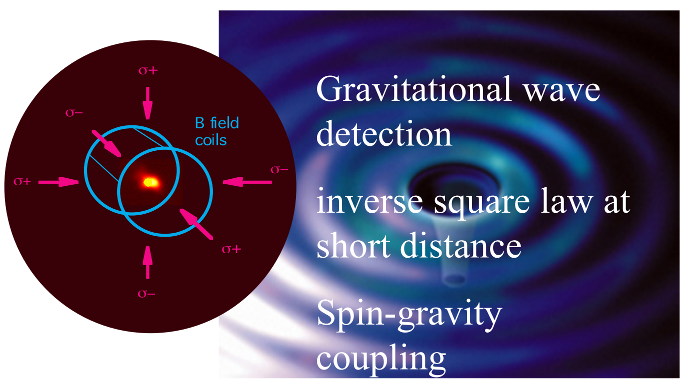
<u>Precision inertial measurement</u>
for advancement of science

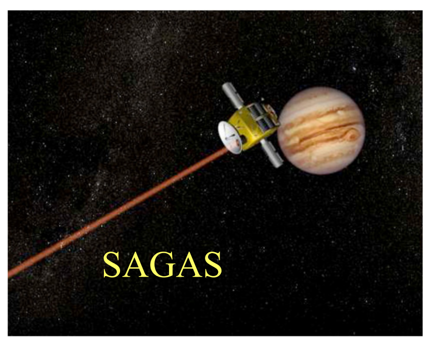
- Test of Einstein's Equivalence Principle with differential acceleration measurement of two atomic species
- Frame-dragging test of the General Relativity Theory with two pairs of atom gyroscopes and a precision star tracker
- Large scale gravity investigation
- Tests of inverse square law
- Gravitational wave detection

Quantum Interferometer Test of equivalence principle

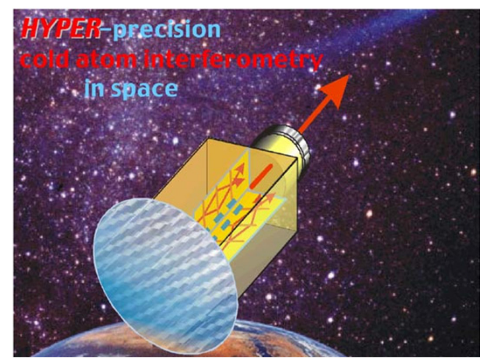
The MWXG spacecraft overall configuration

Matter Wave Explorer of Gravity





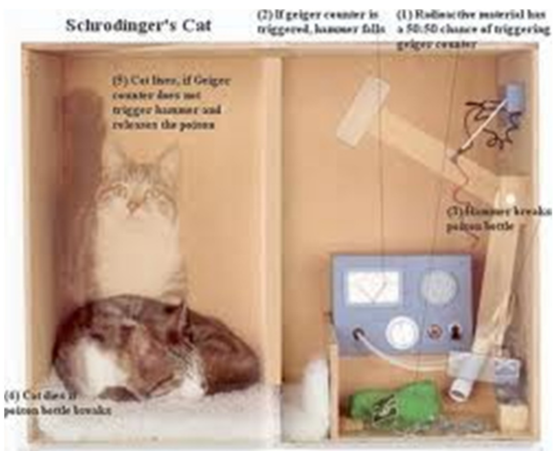
Quantum physics exploring gravity in the outer solar system



Precision measurements of Lense-Thirring effort

Big Challenges

Quantum Mechanics in Space, Why Not?



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✓ Science (operation) significance and priority
- must have over nice to have, making science priority
- observations over local measurements, science community involvement
- breakthrough over incremental improvement

✓ Technology benefit and gain
- enabling over improvement, could not done before by existing means
- simplicity over complexity, complexity brings higher risk and cost
- robustness over cleverness, competitiveness in practice: resource, risk, and cost

✓ Technology maturity

Quantum-enabled precision measurements and applications in space

Precision Measurement Technology

- Laser cooling and atom trapping
- Atom optics
- Ultra-stable lasers and frequency comb
- Atomic clocks
- Atomic sensors
- Ultra-cold atoms and quantum gases

Unique space environment

- Global access
- Free from atmospheric interference
- Microgravity
- Low vibration
- Large spatial extent
- Large gravitational field variation
- Inertial frame

Fundamental Physics and Applications

-Relativity theories
-Standard Model
-Equivalence Principle
-Gravity physics
-Cosmology and quantum decoherence
-Gravitational wave detection
-Earth and planetary gravity measurements
-Astrophysics observations
-Communication
-Navigation
-Geodesy
-Global timekeeping