Gravity Probe B and other Fundamental Physics Experiments In Space

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8 Ways Space Leads to New Physics

Above the Atmosphere Transparency	*Optical reference, γ-rays, particle physics (AMS)*
Remote Benchmarks	*Lunar ranging, radar transponder on Mars*
Large Distances	*LISA, ASTROD, LATOR*
Reduced Gravity [including drag-free]	*GP-B, LISA, laser cooling, condensed matter*
Small vibration and disturbances	*especially LISA & STEP*
Varying φ	*GP-A, SUMO*
Varying g	*STEP, MICROSCOPE*
Separation of effects	*as in GP-B choice of orbit*

Curved Space vs. Scaling: 2 Views of Einstein's Achievement

- **Newton's success -- annoying.**

  GR effects are small

- **The scaling length GM/c^2**
- **Einstein's 2 ½ tests**
  - *perihelion precession* → *Leverrier's puzzle (1857)*
  - *light deflection* → *the eclipse expeditions (1919)*
  - *redshift (the ½ test)* → *Pound, Rebka (1959), Gravity Probe A (1976)*

- **Weak-field vs strong-field tests**
  - *No strong field tests of GR*
  - *The binary pulsar –4 [illegible] per year is still small!*

A conundrum: *why is it important that the Moon is much farther from the Earth than Mercury is from the Sun?*

– and how much farther away is it?

Technologies & Einstein

1919 ***The long desert after light deflection (but don't forget Hubble)***

1957-62 ***Hints of new paths***

- *Pound-Rebka*
- *Roll-Krotkov-Dicke*
- *the Weber bar*

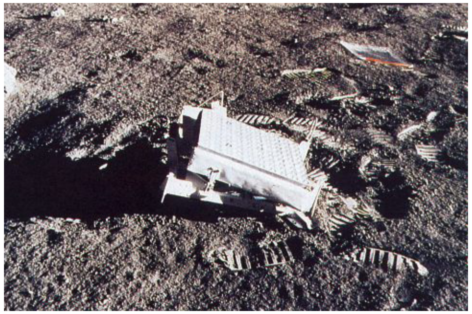
1960 on ***New technologies in earnest***

- *radar, radioastronomy*
- *Mossbauer effect*
- *cryogenics*
- *space*

1960 on ***New discoveries vs new quantitative tests***

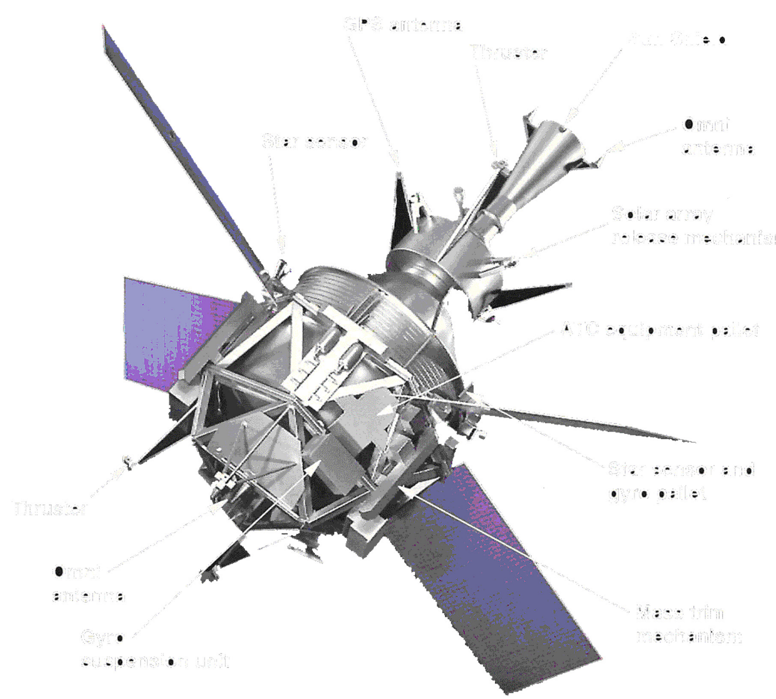
- *discoveries: pulsars, black hole in Cygnus X1, dark matter & energy*
- *tests: radar time delay, PPN null tests, Taylor-Hulse, GP-A & GP-B*

Some NASA Achievements

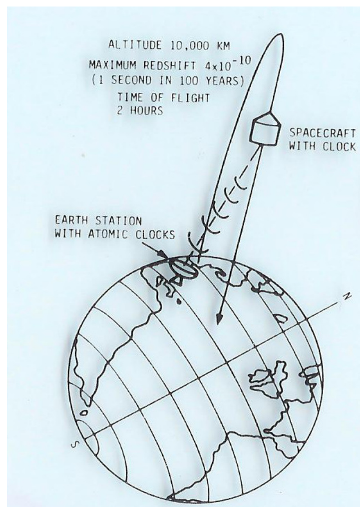


Laser Ranging
to reflectors on Moon (1968+)

Gravity Probe B
gyroscope experiment (2004+)



Gravity Probe A
clock experiment (1976)



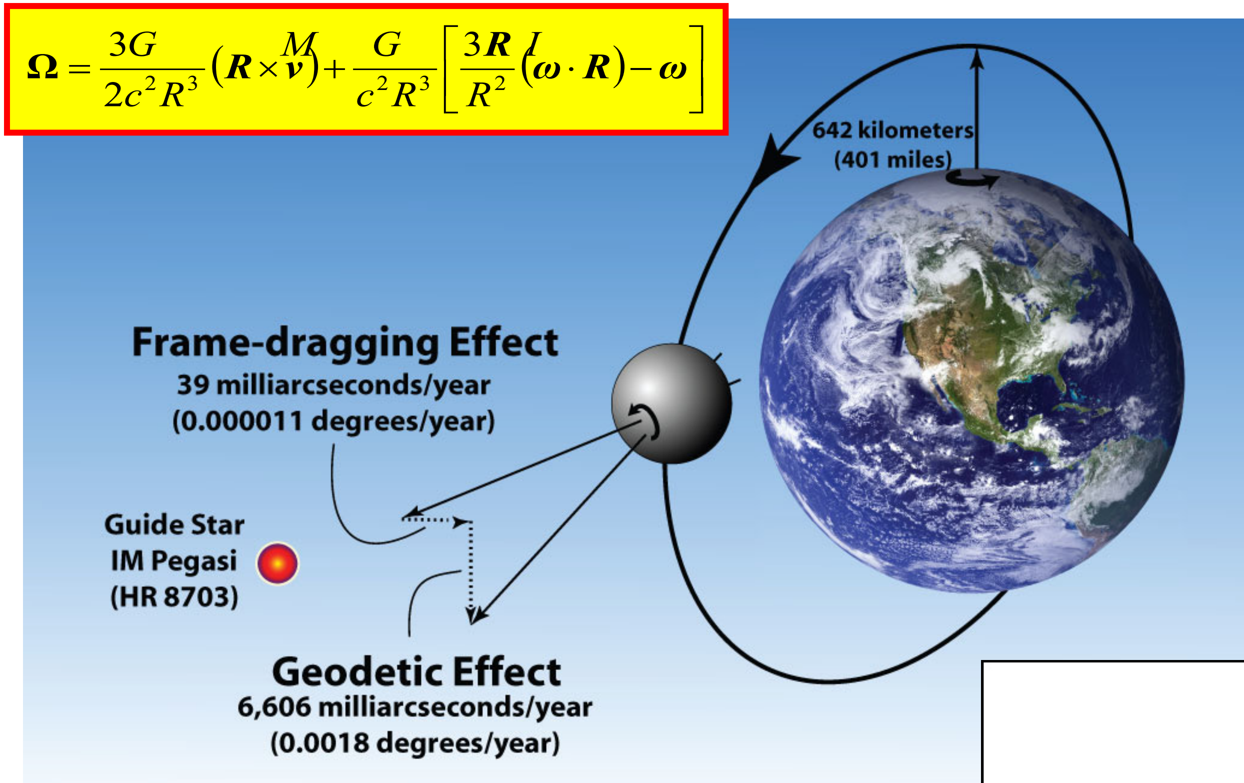
Radar Time Delay
to Viking Lander on Mars (1976)
to Cassini spacecraft around Saturn (1999+)

Observations vs Controlled Experiments

- **Cavendish (1798) vs Maskelyne (1774) on G & Earth's density**
  - *Maskelyne: the Schiehallion mountain in Scotland*
  - *Cavendish/Michell: the torsion balance test*
- **Observational tests of GR**
  - *radar ranging, LLR, Taylor-Hulse binary pulsar, LAGEOS frame-dragging*
- **Controlled physics experiments**
  - *Gravity Probe A, Gravity Probe B, ground-based EP, STEP/MICROSCOPE*
- **3 kinds of knowledge required, all quantitative & exact**
  - *theory*
  - *source & range parameters*
  - *detector characteristics*
- **Judging models & understanding systematics**
  - *ranging to Viking lander on Mars, a 2000 parameter fit*
  - *Cavendish's genius: making an unknown systematic larger in known increments*

Gravity Probe B: Testing Einstein

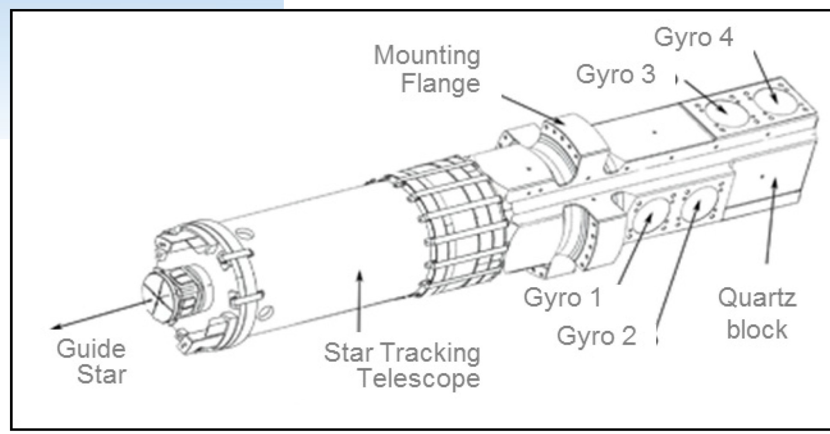
$$\boldsymbol{\Omega} = \frac{3GM}{2c^2R^3}(\mathbf{R}\times\mathbf{v}) + \frac{GI}{c^2R^3}\left[\frac{3\mathbf{R}}{R^2}(\boldsymbol{\omega}\cdot\mathbf{R})-\boldsymbol{\omega}\right]$$



Mach

Thirring

Schiff



Geodetic Effect

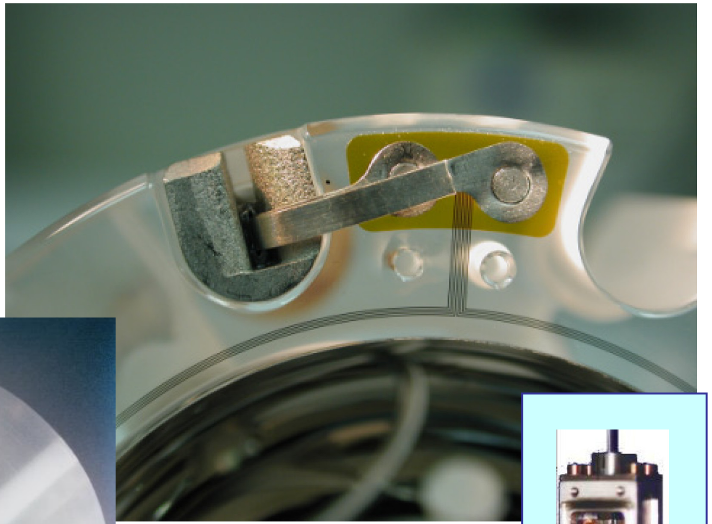
- Space-time curvature *("the missing inch")*

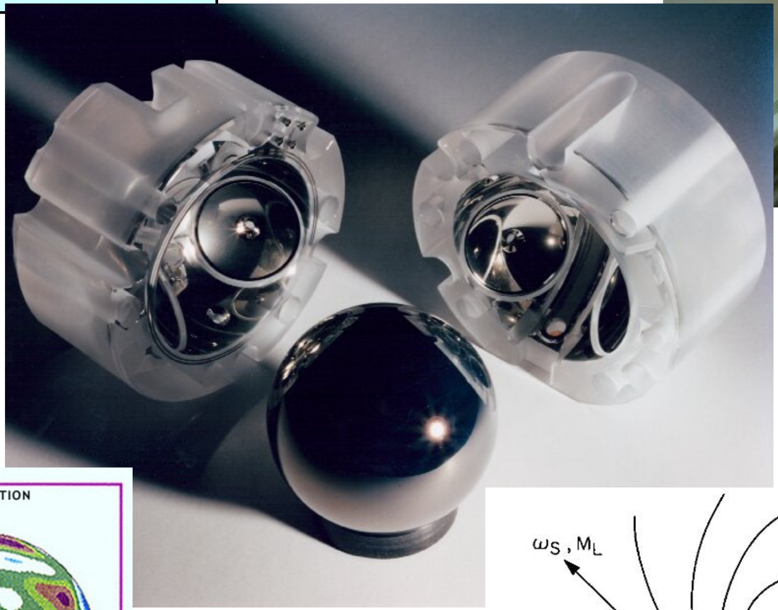
Frame-dragging Effect

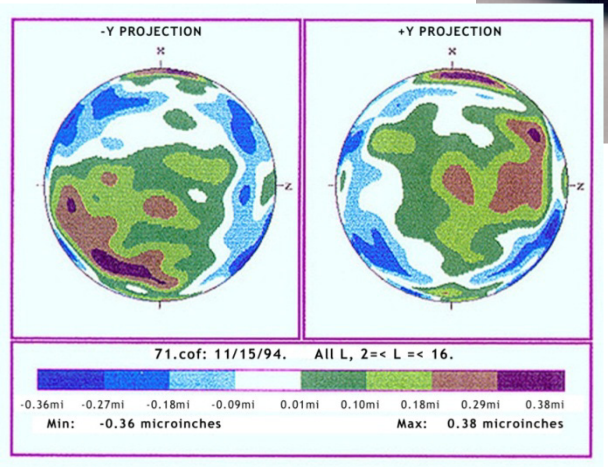
- Rotating matter drags space-time *("space-time as a viscous fluid")*

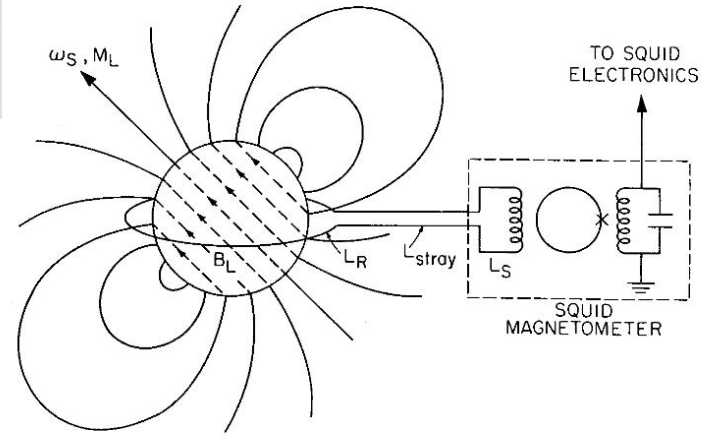
Gyroscope & LM Readout

- ***Electrical Suspension***
- ***Gas Spin-up***
- ***Magnetic Readout***
- ***Cryogenic Operation***









Space & Cryogenics

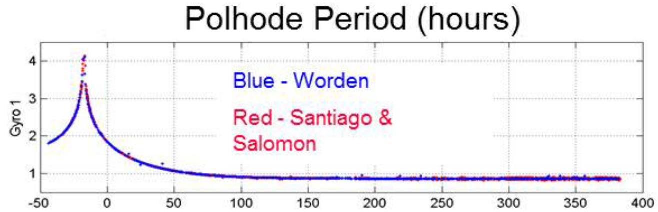
Space

- *reduced support force, "drag-free"*
- *separation of effects*
- *S/C roll about line of sight to star*

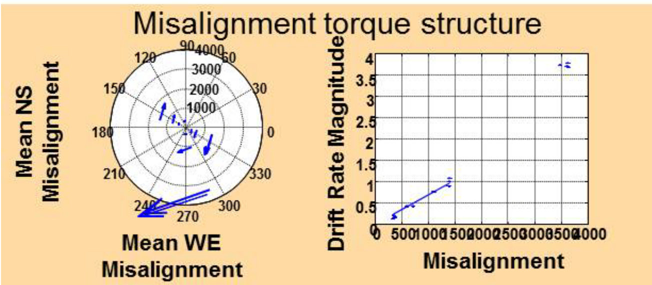
Cryogenics

- *magnetic readout & shielding*
- *thermal & mechanical stability*
- *ultra-high vacuum technology*

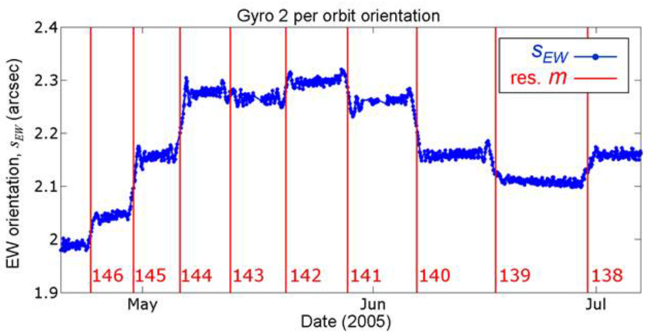
On-Orbit Gremlins



Polhode-rate variation & C_g calibration



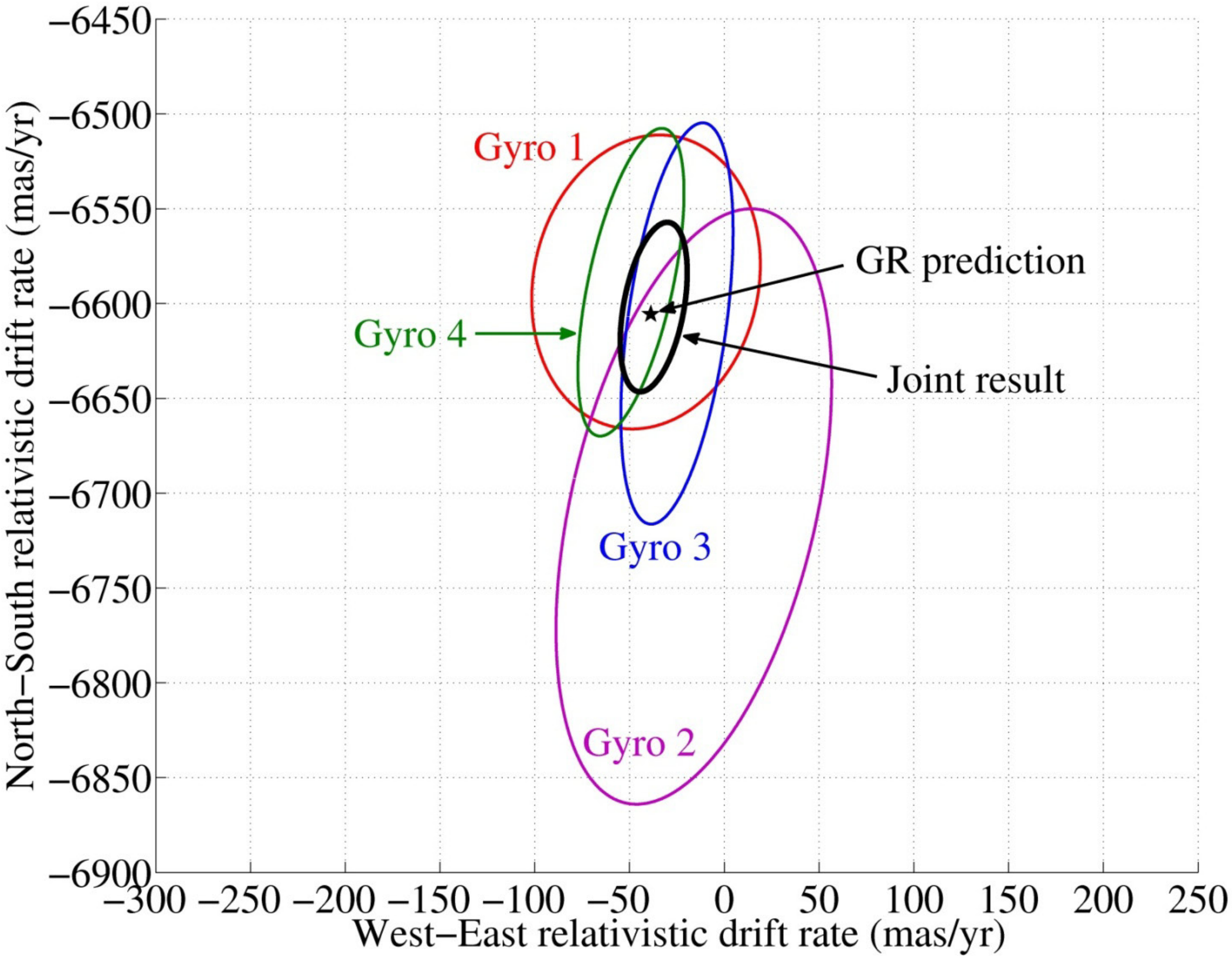
100× larger-than-expected misalignment torques



Roll-polhode resonance displacements

- ***All due to electrical out-of-roundness of housings & rotors***
- ***Calibrated by the magnetic out-of-roundness from trapped flux***
- ***3 stages of correction & cross-checks***

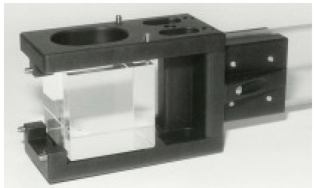
Gravity Probe B Result

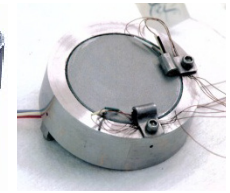


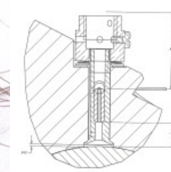
	GR Predictions	GP-B Results
r_{NS} (geodetic)	– 6,606.1	– 6,601.8 ± 18.3
r_{WE} (frame-dragging)	– 39.2	– 37.2 ± 7.2

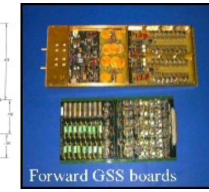
Heritage of Gravity Probe B

Technology



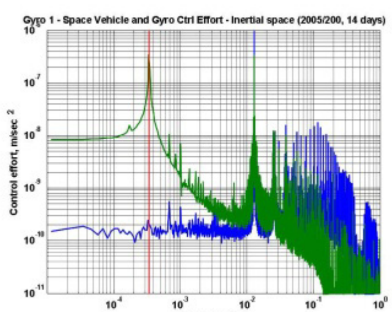


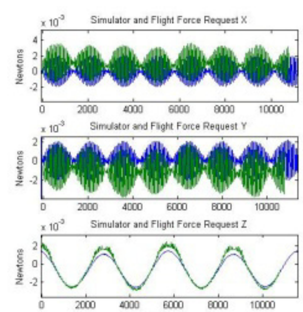




Onsite Mission Ops Center

Precision ATC





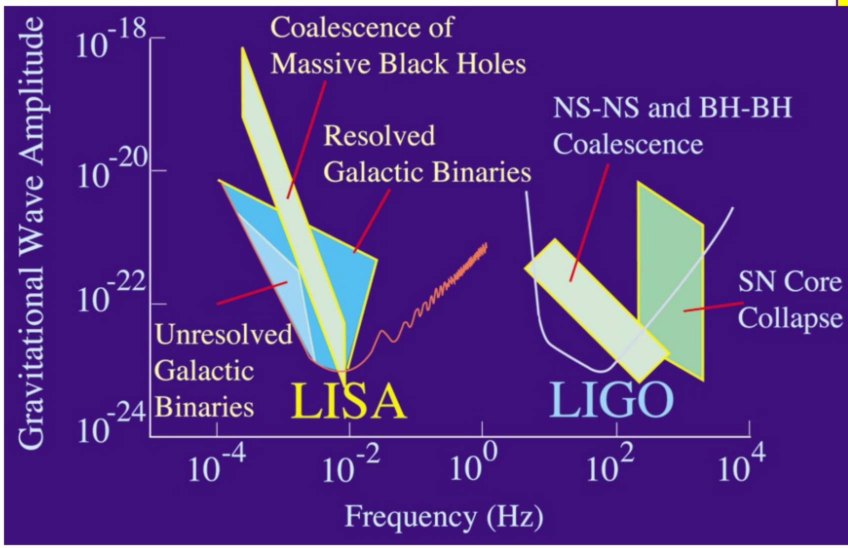
GP-B: 7 Interfolded Stories

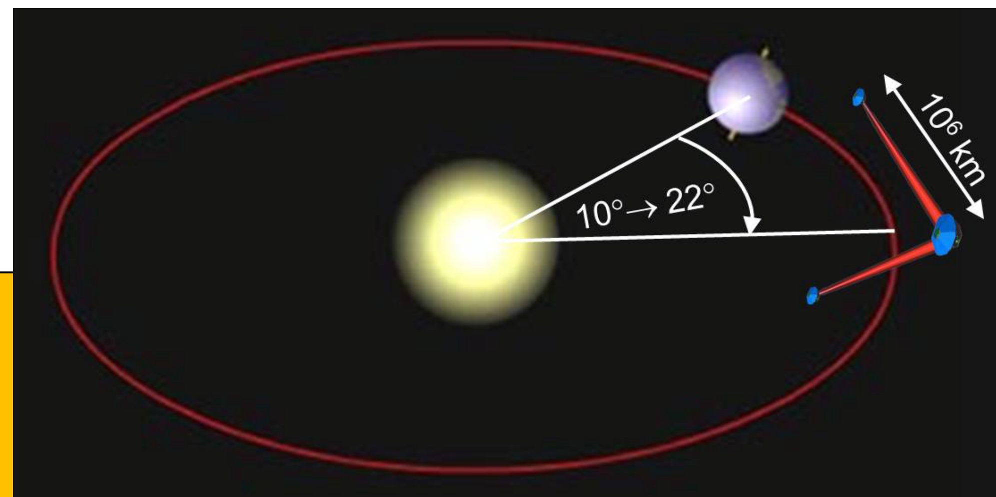
- ✓ **Testing Einstein**
- ✓ **Unexpected Technologies**
- ✓ **Two SU Departments: *Physics & Aero-Astro***
- ✓ **Students: *100 PhDs, 353 U/G, 56 high school***
- ✓ **Spin-Offs: *drag-free, porous plug, autofarm, + + + +***
- ✓ **NASA-Stanford-Industry Symbiosis**
- ✓ ***"A very interesting management experiment"* – J. Beggs, 1984**

"What we are doing here is a cross between an academic program and a Silicon Valley start-up"
– Bradford Parkinson, 1985

LISA: Laser Interferometer Space Antenna

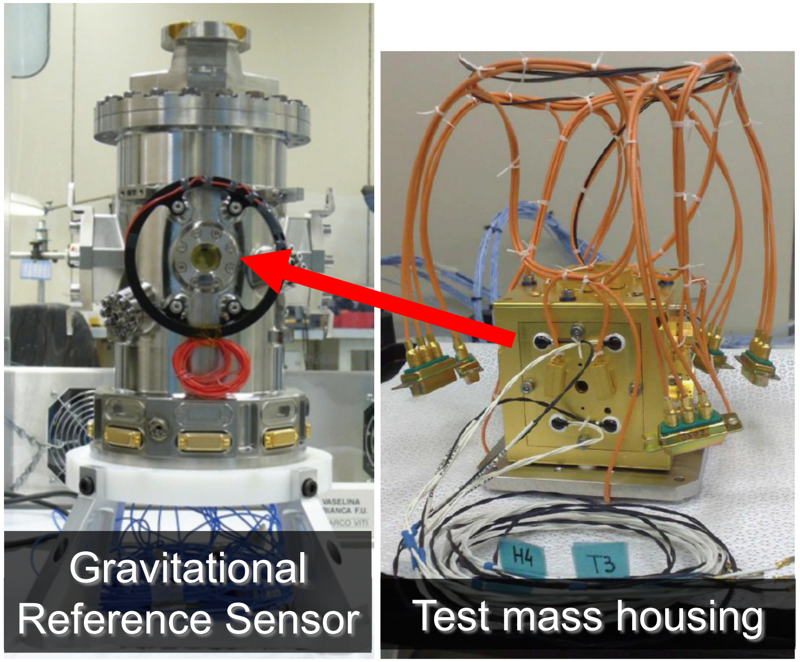
GW detection in space opens richest band: mHz
Space greatly reduces low frequency seismic noise





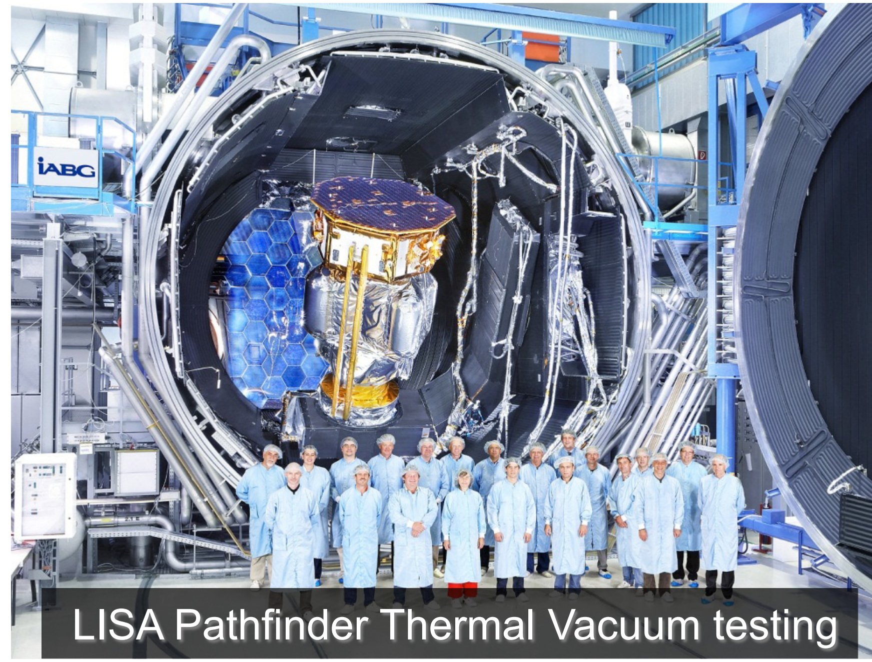
3 spacecraft in heliocentric drift-away orbit
2-arm laser interferometer: 12 pm/Hz$^{1/2}$
Drag-free: 3×10^{-15} m/sec^{2}Hz$^{1/2}$
Science band: 0.1 mHz – 1 Hz

LISA Technology

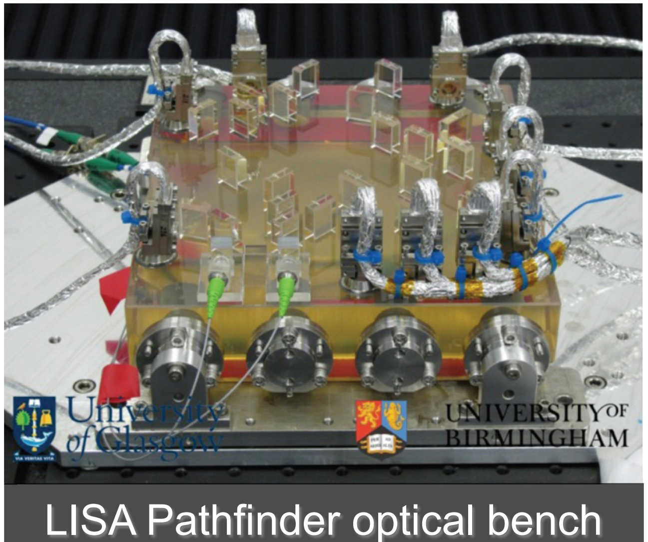


Gravitational Reference Sensor

Test mass housing



LISA Pathfinder Thermal Vacuum testing



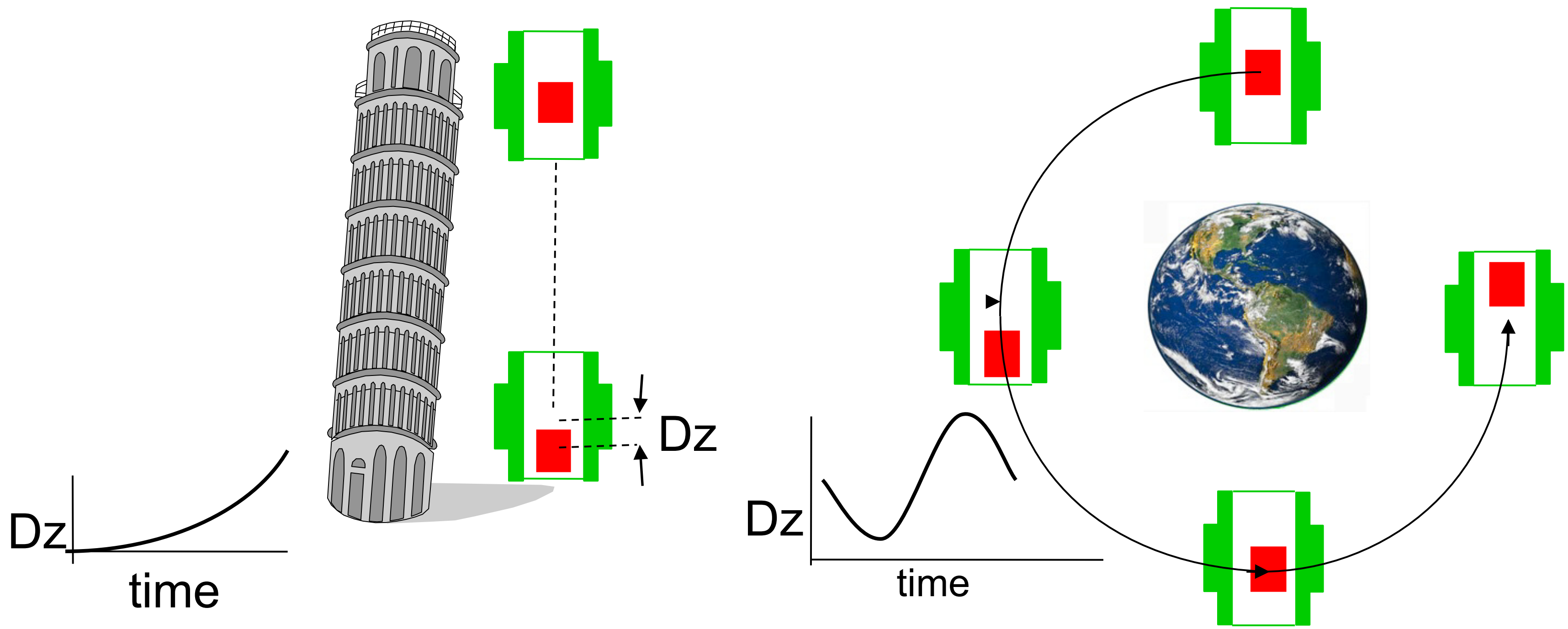
LISA Pathfinder optical bench

LISA Pathfinder will test

- *GRS*
- *μN thrusters*
- *Local laser interferometry*
- *Drag-free control*

Satellite Test of the Equivalence Principle

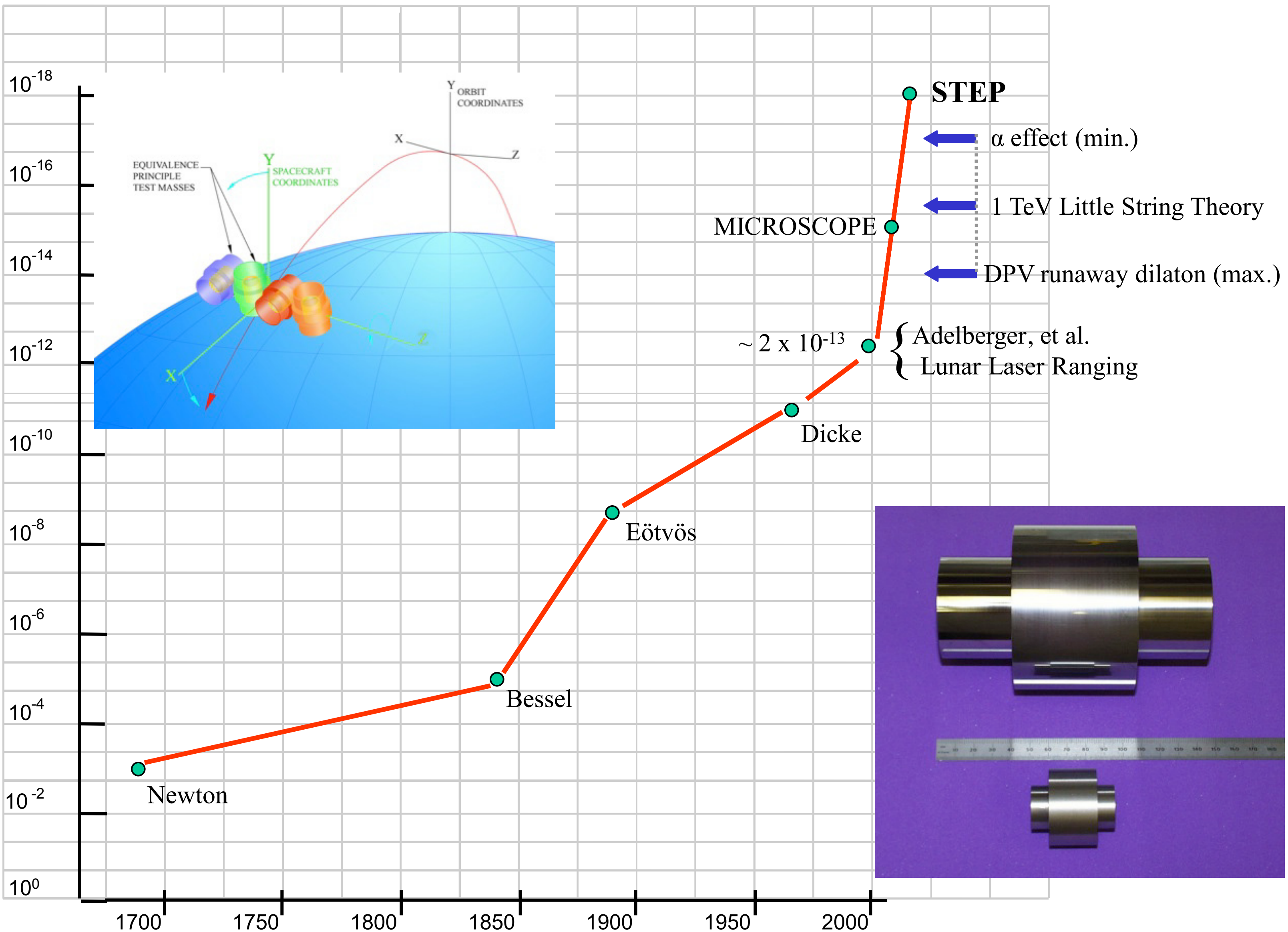
Newton's Mystery { *F = ma* — *mass - the receptacle of inertia*
F = GMm/r² — *mass - the source of gravitation*



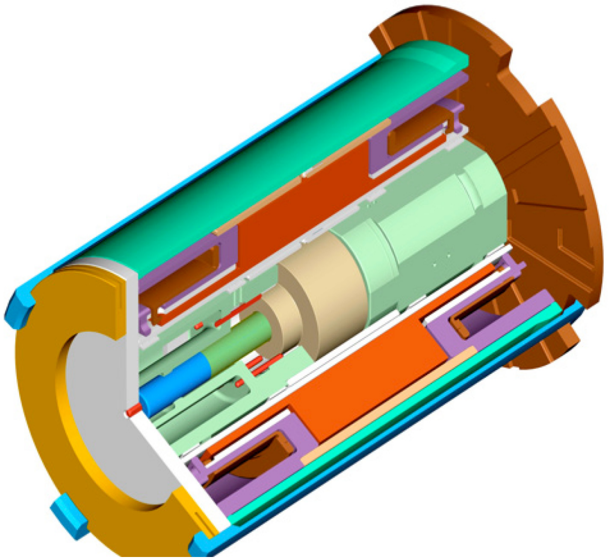
Orbiting drop tower experiment {
* More time for separation to build
* Periodic signal

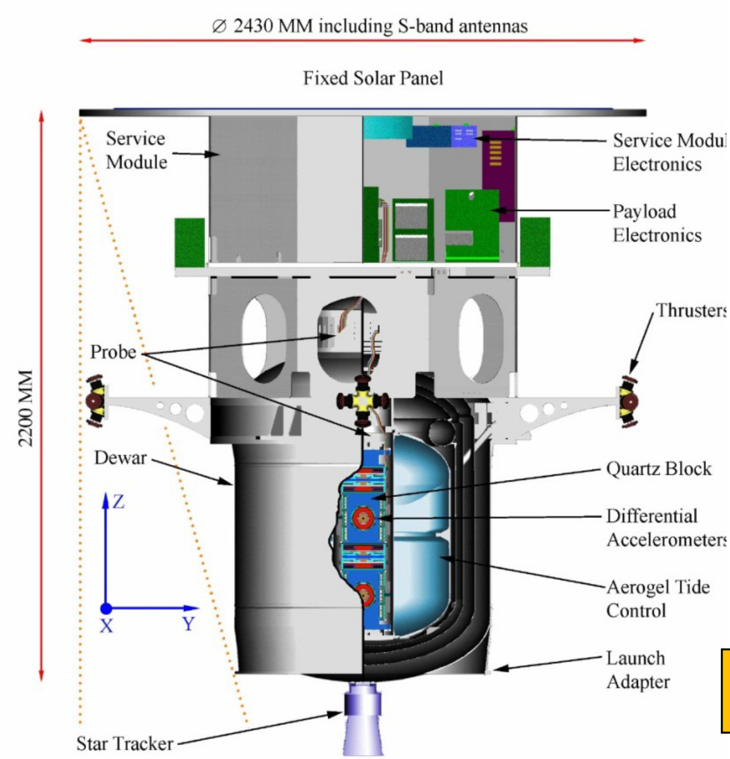
Newton in Principia: Gravity vs Magnetism

Space > 5 Orders of Magnitude Leap



STEP Mission





8 Month Lifetime

- *Sun synchronous orbit, I=97^o*
- *550 km altitude*
- *Drag-free control w/ He thrusters*

Cryogenic Experiment

- *Superfluid He flight dewar*
- *Aerogel He confinement*
- *Superconducting magnetic shielding*

4 Differential Accelerometers

- *Test mass pairs of different materials*
- *μm tolerances*
- *Superconducting bearings*
- *DC SQUID acceleration sensors*
- *Electrostatic positioning system*
- *UV fiber-optic charge control*

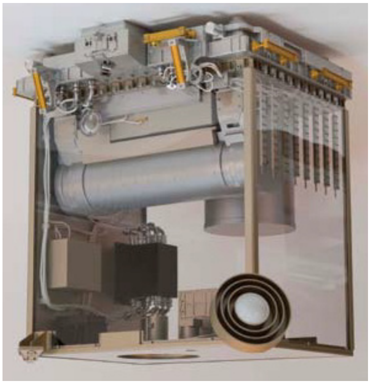
Goal: EP Measurement to 1 part in 10^{18}

Four Different Drag-Free Worlds: Challenges for Fundamental Physics

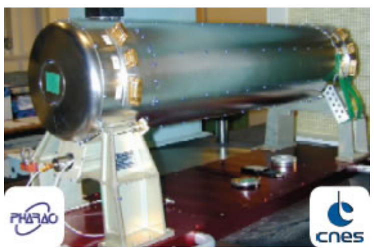
Note:
gravitational attraction between two human bodies 0.25 m apart ~ 10^{-8} g

	purpose	**contributing techniques**	**achieved**
DISCOS (1973)	gravitational orbit @ sub-m level	• bang-bang thrusters w/ derived-rate control • shaped compensating mass balances s/c attraction to high order	5×10^{-12} g continuous
GP-B (2004)	< 10^{-11} g narrow-band (~ 10^{-8} Hz) cross-track acceleration noise	• proportional thrusters • rolling spacecraft	4×10^{-12} g long-term
LISA	10^{-16} g broadband (10^{-4} Hz – 1 Hz) differential acceleration noise	• FEEP μN thrusters • rigorous thermal, magnetic, charge control	TBD from Pathfinder
STEP	10^{-14} g narrow-band (~ 10^{-6} Hz) acceleration noise w/ 10pm co-centered mass-pairs	• mass-moments balanced to 6^{th} order • Aerogel He tide control	TBD

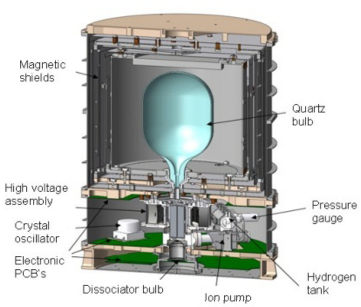
Atomic Clock Ensemble in Space (ACES)



ACES payload



PHARAO Cesium Tube

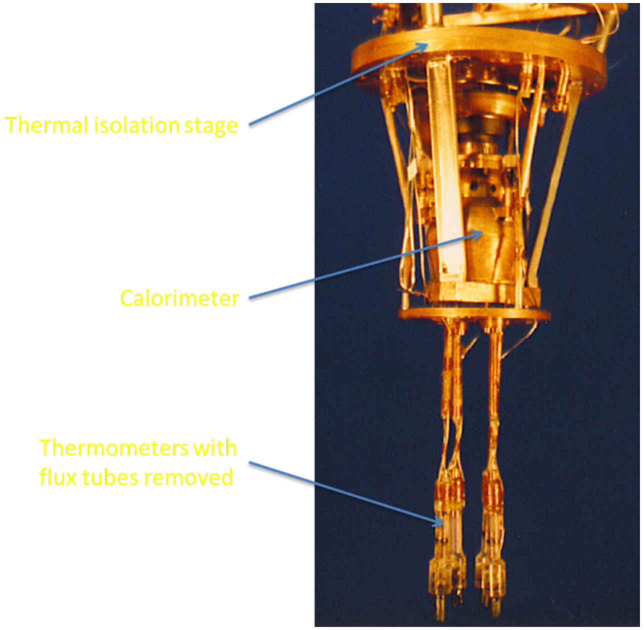


Space Hydrogen Maser

- CNES mission w/ NASA & ESA/OSS support
  - *Two clocks: PHARAO & SHM*
  - *ISS w/ Columbus launch 2014*
- PHARAO laser-cooled Cs clock
  - *Long term stable ~ 10^3 < ground-based Cs clocks*
- SHM Space Hydrogen Maser clock
  - *Outstanding short term stability in space*
- Physics goals
  - *Einstein redshift to 2 parts in 10^{-6}*
  - *α time variation to 3×10^{-17}*
  - *Lorentz invariance to ~ 10^{-10}*
- Other goals
  - *25 ps time transfer to ground-based clocks at 10 days*

Condensed Matter Physics

Lambda Point Experiment (LPE)



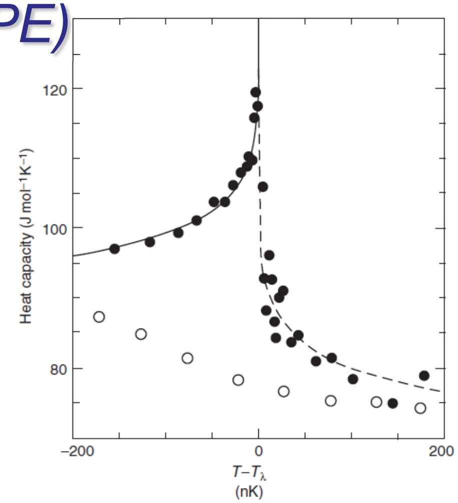
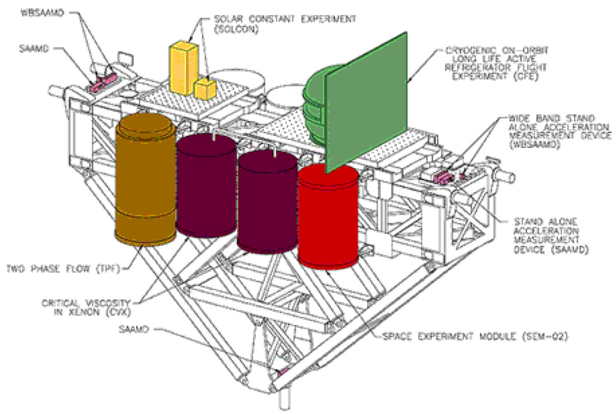


Figure 10. Measuring the Lambda point of ^4He to within 10^{-9} K. • = on-orbit LPE data, ○ = ground-based data.

Critical Viscoscity Xenon (CVX)



Confined He Experiment (CHeX)

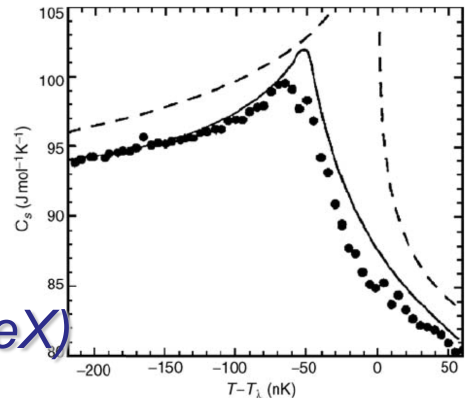


Figure 11. Heat Capacity Data from CHeX near the ^4He Lambda Point. Dots, CHeX data; Solid line, predicted; Dashed line, on-orbit results from the LPE.

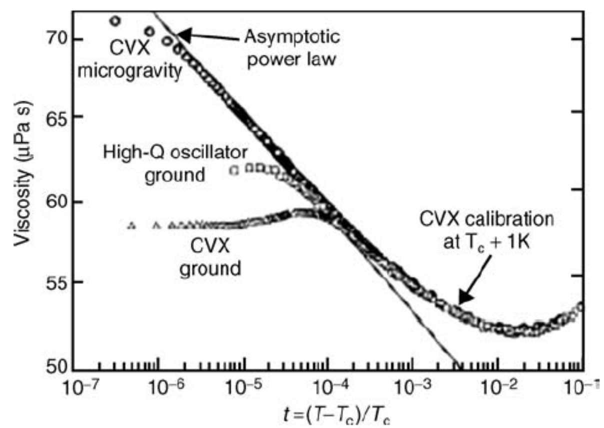
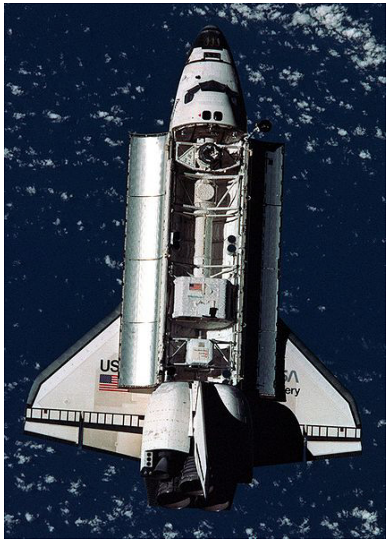
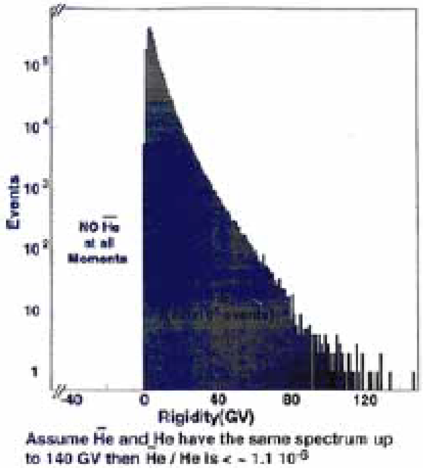


Figure 12. The Critical Velocity Xenon viscosity measurements.

Elementary Particle Physics

AMS-01 (1998)



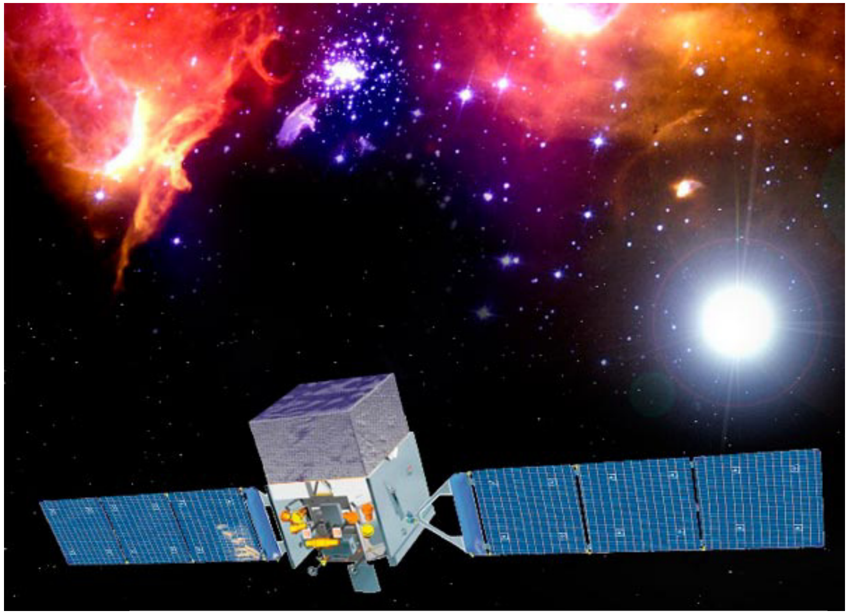


The Alpha Magnetic Spectrometer Search for Anti-helium

AMS-02 (2011)

Search for primordial antimatter

Fermi (2008)



Search for annihilation/decay of dark matter particles

Einstein's Misbelief

"…these effects, which are to be expected in accordance with Mach's ideas, are actually present according to our theory, although their magnitude is so small that confirmation of them by laboratory experiments is not to be thought of."

-- Einstein The Meaning of Relativity (1953, pp. 100-107)