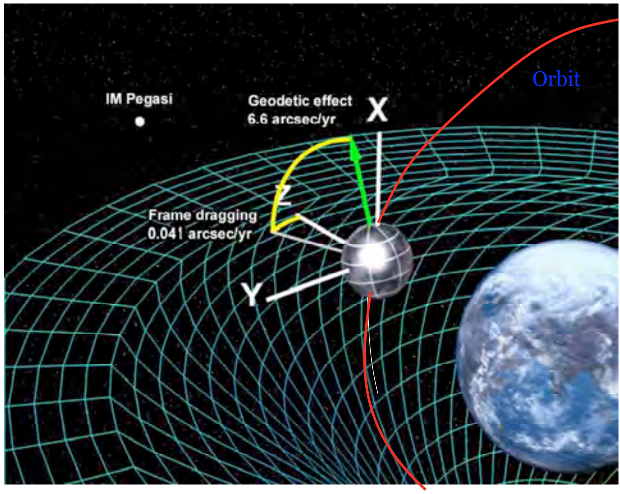
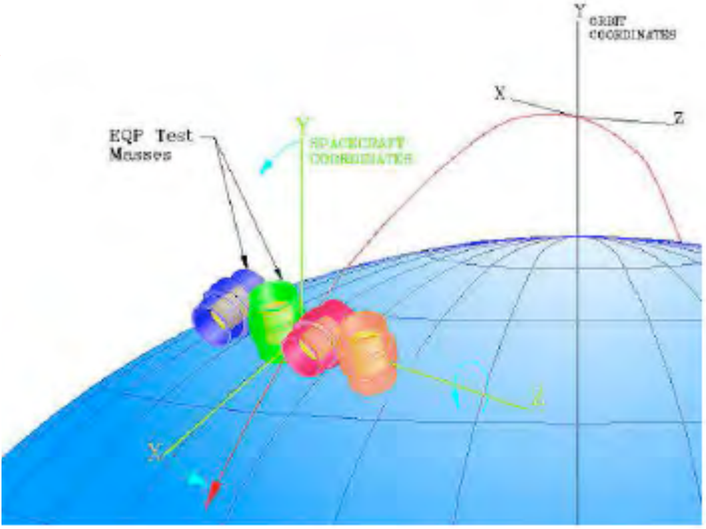
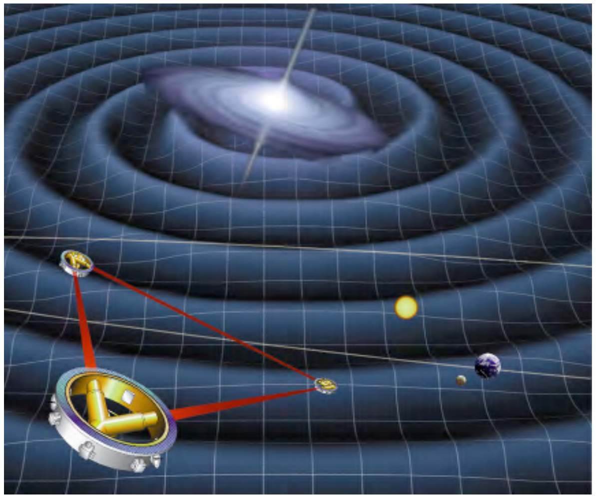
Precision Tests of General Relativity in Space

John Mester

Stanford University







Fundamental Physics in Space

Space provides unique opportunities to advance our knowledge of fundamental physics
enabling new experiments of unprecedented precision
impossible to perform on the ground.

Particularly True For Tests of General Relativity and Gravitation

Committee on Space Research - COSPAR Definition

- **Commission H established in 1996 Inclusive Definition of Fundamental Physics**

1) fundamental physical laws governing matter, space and time

- gravitational and particle physics,
- study of gravitational waves in space,
- equivalence principle tests,
- the search for new hypothetical long-range forces,
- the search for antimatter in the universe,
- unification of the fundamental interactions of Nature.

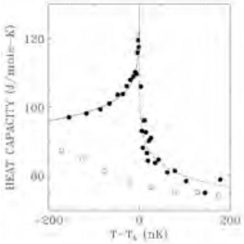
2) organizing principles from which structure and complexity emerge

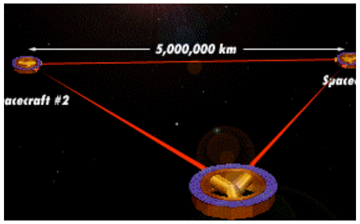
- quantum phenomena and their applications
- critical phenomena in superfluids
- Bose-Einstein condensation
- symmetry principles in macroscopic physics
- renormalization group studies
- laser cooling technologies for advanced clocks and rotation sensors

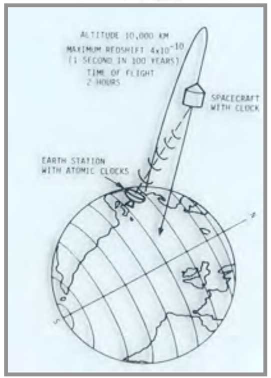
Advantages of Space for Fundamental Physics

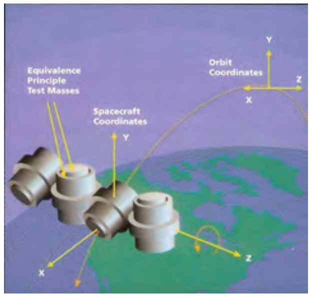
from Everitt et al. ASR

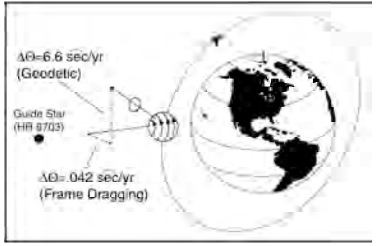
Above the Atmosphere	**Optical reference, γ-rays, particle physics (AMS)**
Remote Benchmarks	**Lunar ranging, Mars radar transponder**
Large Distances	**LISA, ASTROD, LATOR**
Reduced Gravity	**Condensed Matter, Laser Cooling, Precision Clocks, Inertial Sensing**
Seismically Quiet	**LISA , STEP, MicroSCOPE**
Varying ϕ	**GP-A, SUMO**
Varying g	**STEP, MicroSCOPE**
Separation of effects	**GP-B choice of orbit**

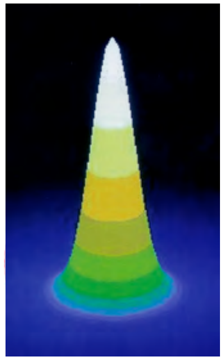












Tests of General Relativity: Background

Einstein Equivalence Principle (EEP)

- Weak EP – Universality of Free Fall
- Local Lorentz Invariance
- Local Position Invariance
- Gravitational energy Gravitates

EEP ==> metric theory of Gravity

- events in spacetime separated by invariant line element
- $ds^2 = g_{\mu\nu} dx^{\mu} dx^{\nu}$
- objects in free fall follow geodesics of the metric

Weak Field Limit $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ $\eta_{\mu\nu}$ is the Minkowski metric

Tests of General Relativity: Background 2

Einstein Field Equation $G_{\mu\nu} = R_{\mu\nu} - 1/2\, g_{\mu\nu}R = (8\pi G/C^4)T_{\mu\nu}$

“matter tells spacetime how to curve, and curved space tells matter how to move”

No adjustable parameters

- G directly measurable Newtonian gravitational constant

Schwarzschild solution: static, spherically symmetric field of a point mass

- weak field expansion to first order

$ds^2 = (1–2GM/C^2R)C^2dt^2 – (1+2GM/C^2R)dr^2$

$g_{00} = -(1–2\, \Phi/C^2)$

Tests of General Relativity: Background 3

For laboratory tests and even solar system tests spacetime distortions due to gravity are small

$\Phi/C^2 = GM/RC^2$

At surface of	a proton	$\Phi/C^2 = 10^{-39}$
	1m diam Tungsten sphere	$\Phi/C^2 = 10^{-23}$
	earth	$\Phi/C^2 = 7\text{x}10^{-10}$
	sun	$\Phi/C^2 = 2\text{x}10^{-6}$
	neutron star	$\Phi/C^2 = 0.15$
	black hole	$\Phi/C^2 =1$

The "Annoying Success of Newton"

Solar system and all accessible environments space-time distortions are small =>

both earth bound and space based experimental tests require high precision…

and often cancellation or complex "fitting out" of Newtonian and perturbing effects

Special Relativity Tests

Unlike GR, special relativity is tested to extremely high precision

Instead of Φ,   the relevant parameter for testing special relativity is γ

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}} \text{ is the Lorentz factor.}$$

⇒For speeds approaching C, the speed of light, special relativistic effects become large and are easily distinguished from pure Newtonian effects

Large range of types of experiments

Special Relativity Tests 2

Tests of Time Dilation and Transverse Doppler Effect

- * Ives and Stilwell
- * Particle Lifetimes
- * Doppler Shift Measurements

Example:

Rossi-Hall Exp: -Muons with v=.98C in cosmic ray showers
Decay lifetime ~5 times rest lifetime of 2.2¨sec

$$\Delta t' = \gamma \Delta t = \frac{\Delta t}{\sqrt{1 - v^2/c^2}}$$

Tests of Relativistic Kinematics

- * Elastic Scattering
- * Limiting Velocity c
- * Relativistic Mass Variations

Example:

Relative velocity measurements of 15 GeV electrons and gammas.
No difference observed within ~2 parts in 10^7

A comparison of neutrino and photon speeds from supernova SN1987A
1 part in 10^8 verification

Special Relativity Tests 3

Special Relativity in Combination with Quantum field theory => QED

g - gyromagnetic ratio of electron: 2 for a classical particle with charge and spin.

So g-2 measures the anomalous magnetic moment of the particle, and can be used (via QED) as a test of SR

electron's spin g-factor measurement in Penning trap:

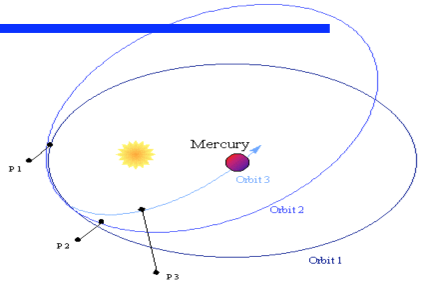
g/2 = 1.001 159 652 180 85 (76),

a precision of better than one part in a trillion!

^ B. Odom, D. Hanneke, B. D'Urso, and G. Gabrielse, Phys. Rev. Lett. 97, 030801 (2006).

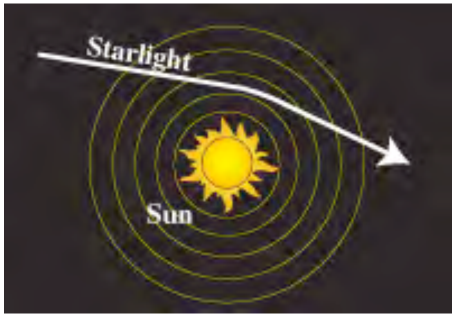
3 Classical Tests of GR

Einstein's 2 1/2 Tests



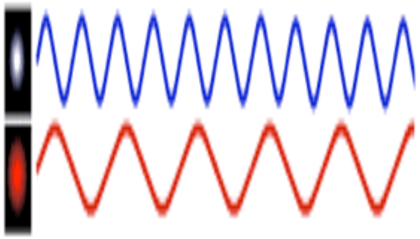
Perihelion Shift of Mercury

GR resolved 43 arcsec/century discrepancy



Deflection of light by the sun

GR correctly predicted 1919 eclipse data
1.75 arcsec deflection



Gravitational Redshift -- Test of EP

1960 Pound-Rebka experiment, $\Delta\nu/\nu=2.5\text{x}10^{-15}$
1976 Vessot-Levine GP-A

Testing GR requires high precision, even the sun is a weak source

More Recent Tests of GR

1968 – Through present

Shapiro Time Delay Viking

Recent Result - Cassini Spacecraft: 3-5 X10^{-5}

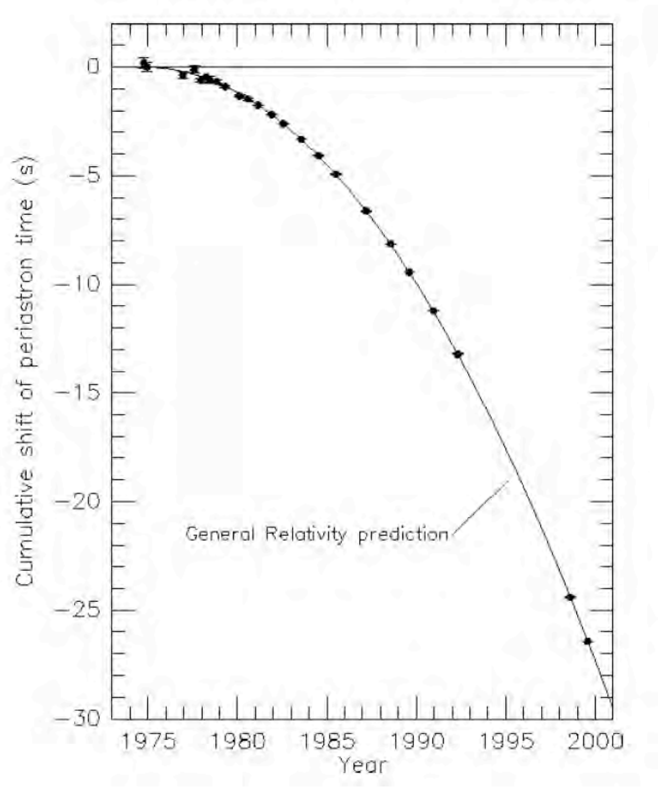
1969 – Through present

Lunar Laser Ranging

EP, Nordtvedt Effect, Geodetic Effect

1974 – Through present

Taylor Hulse Binary Pulsar- Evidence for Gravitational radiation

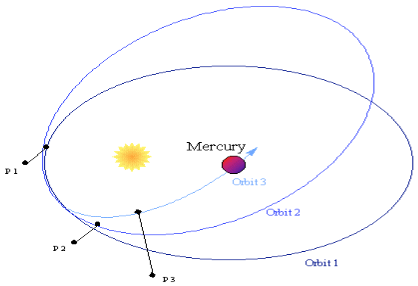


2004 – GP-B Launch

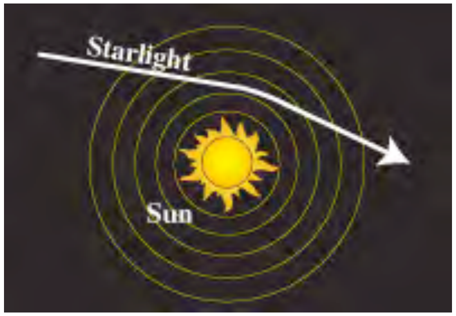
Observation and Experiment

Observations and experiments can provide complementary information

¿Can observations yield precise tests?   Absolutely



GR resolved 43 arcsec/cen discrepancy in Perihelion Shift of Mercury



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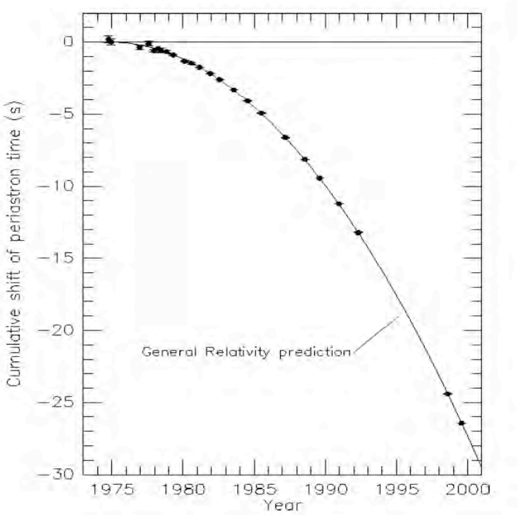


Binary pulsar, multiple tests

But sometimes controlled experiments are needed.

Gravitational Redshift: Einstein's 3rd test

$$\frac{\Delta\nu}{\nu} = \phi(x_2) - \phi(x_1)$$

At surface of the sun $\Phi = 2\text{x}10^{-6}$
So the frequency of light admitted from an atomic transition on the sun should be shifted by 2 ppm compared to same transition on earth: **2ppm is easy to detect.**

Except that: Doppler shifts can mask the effect.

In order to produce a shift of $2\ \text{x}10^{-6}$ requires a velocity of 600m/sec.

Rotation of sun and earth are known and can be accounted for

Thermal effects are an issue
At 3000K (surface temps are 6000K) typical velocities of C,N and O
(light elements but heavier than the predominant H and He)
Are ~ 2 km/sec. Now this only causes broadening so with enough signal to noise one could determine the center to higher precision than the line width.

Gravitational Redshift: Observation

More serious issue is motion due to unknown convection currents
(and these can be seen to differ in different region of the solar disk)
This can be minimized by looking at the limb of the sun since the major convection motion is vertical. Even so, quantitative results that test the theory and not solar models are difficult.

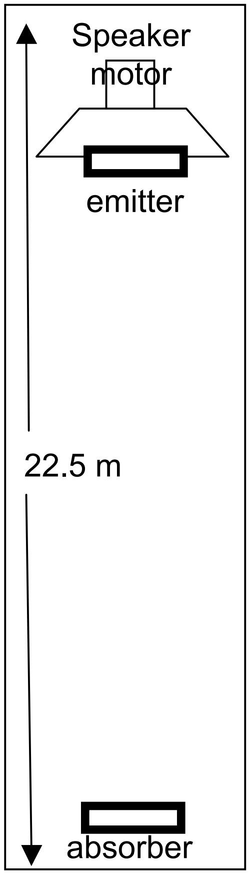
White dwarfs have about the mass of the sun and smaller radii
(1/10 to 1/100 of sun) so the larger ϕ can produce redshift 10 to 100 times higher

Here the problem is knowing ϕ or even knowing the mass of the white dwarfs to make a quantitative test. A partial way out is to find white dwarf binaries to get an independent mass determination.
Still, white dwarf models are needed to determine ϕ.

What about the earth?
The effect is much smaller but one can take advantage of a controlled experiment.

Pound-Rebka Experiment

Harvard's Jefferson Physical Laboratory – 22.5 meter tower.



Over this height the gravitational potential of the earth varies by 2.5×10^{-15} (gh/C^2)

To measure a relative frequency shift this small Pound needed to find an EM transition of narrow line width

The 14kev γ ray transition in Fe 57

Natural Lifetime $\tau = \sim 10^{-7}$ sec

Natural Linewidth $\Gamma = h/\tau = 10^{-8}$ eV

➔ a fractional FWHM $\Gamma / E = 1\times10^{-12}$

divide line by recoil free resonant absorption: Mössbauer Effect

Pound and Rebka measured $2\Delta\nu = (5.13 \pm 0.51) \times 10^{-15}$ a result good to 10%

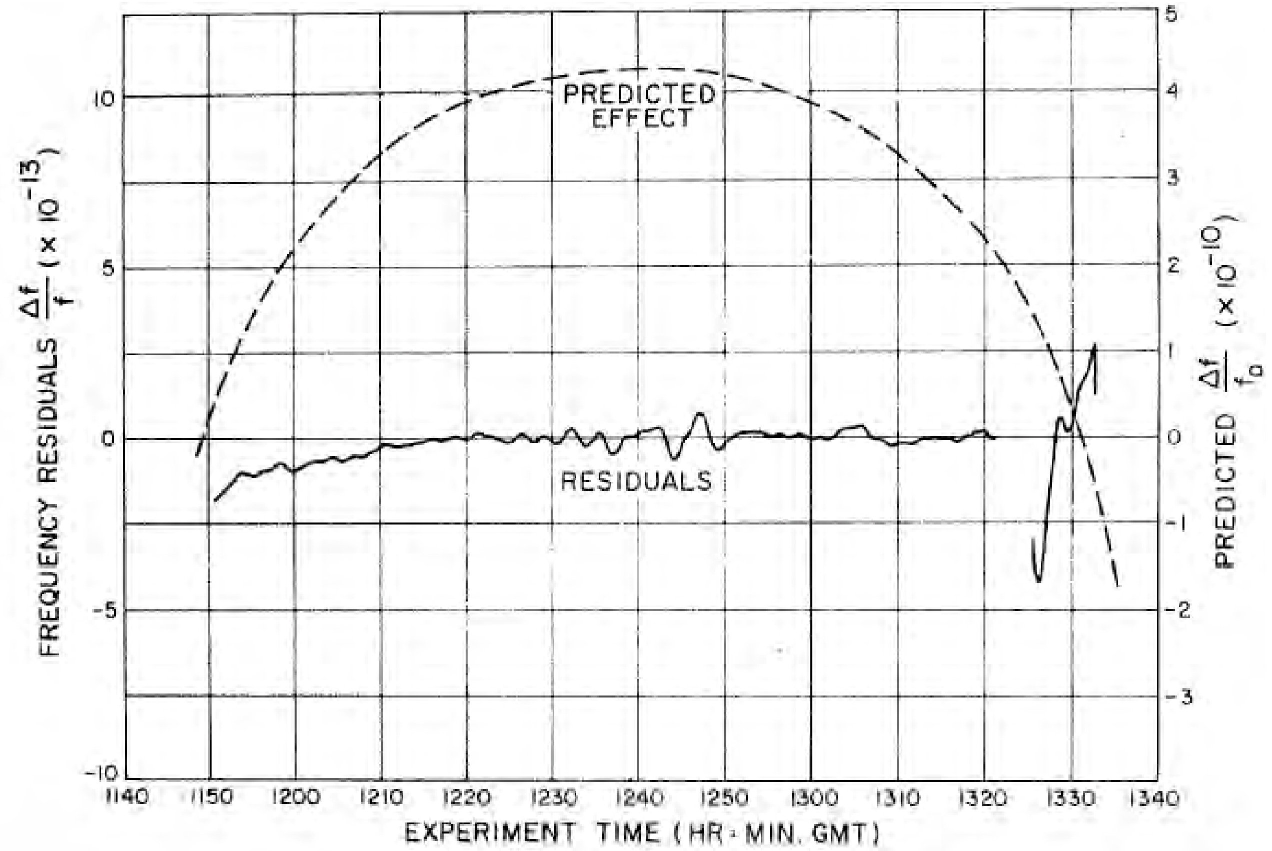
Pound and Rebka, PRL 4 7 April 1 1960 *The Apparent Weight of Photons*

Later Pound and Snider reduced the uncertainty to 1%, PRL 13 539 (1964)

Gravity Probe A

Space Experiment designed to take advantage of large change in Φ

Hydrogen Maser launched on scout rocket to 10000 km



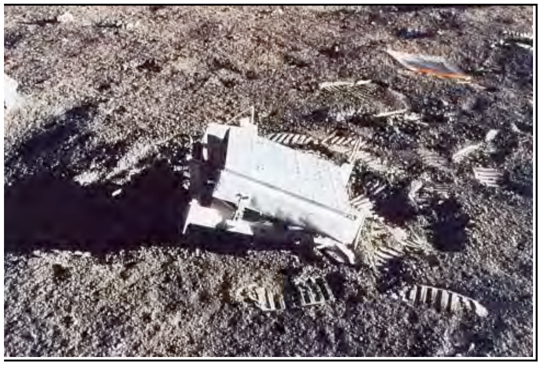
$$\frac{\Delta f}{f_0} = \frac{\varphi_s - \varphi_e}{c^2} - \frac{|\vec{v}_e - \vec{v}_s|^2}{2c^2} - \frac{\vec{r}_{se} \cdot \vec{a}_e}{c^2}$$

Vessot et al. PRL 45 26 (1980)

Overall residuals: 70 parts per million.

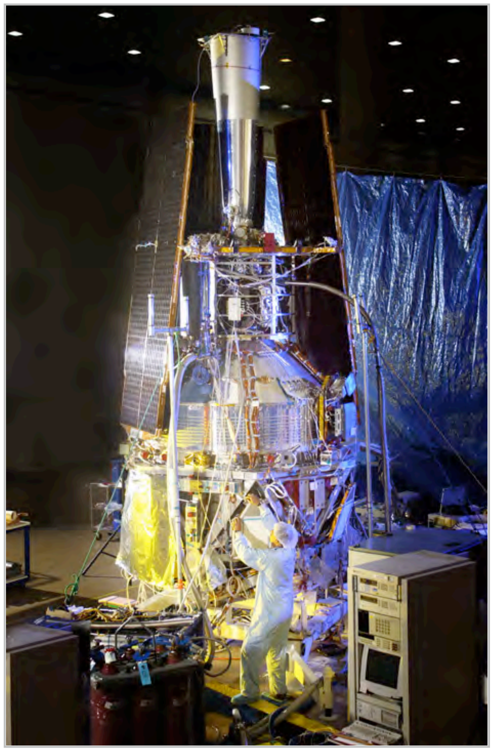
After 30 years still the best measurement of Gravitational redshift

Testing Einstein – Contributions of Space

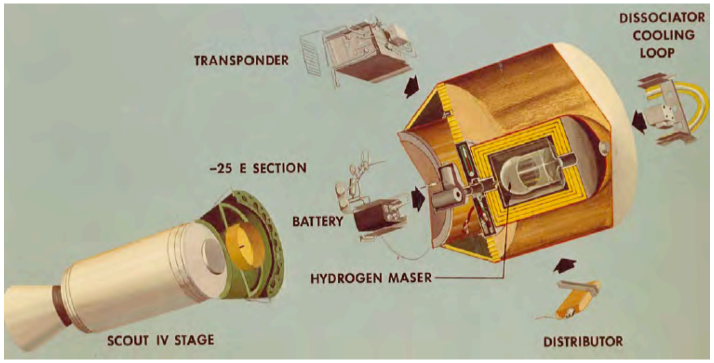


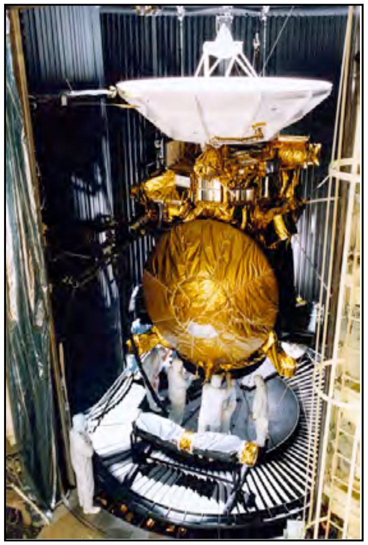
Laser Ranging:
to reflectors on Moon
(1969+)

Gravity Probe B
Two effects with
ultra-accurate gyroscopes



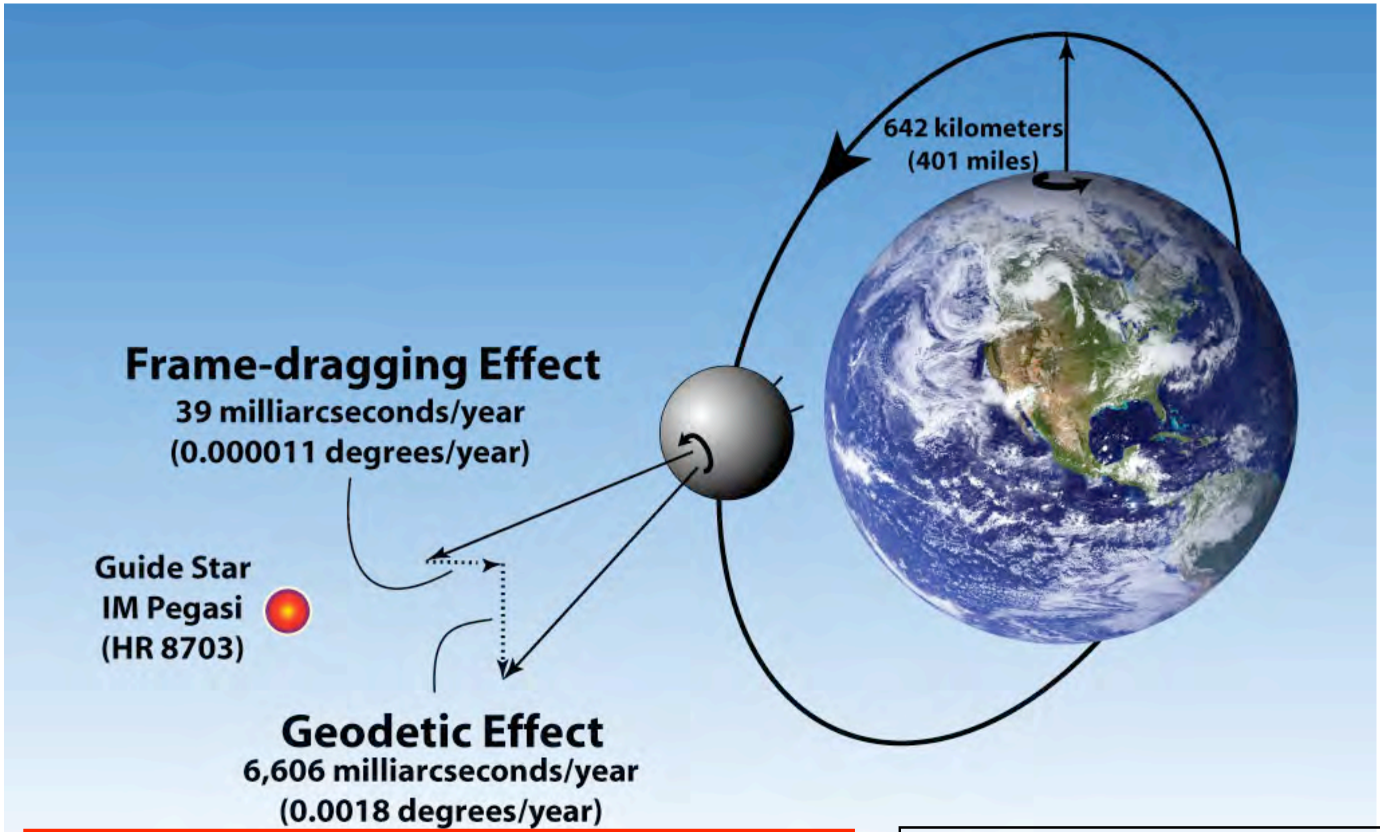
The Gravity Probe A
clock experiment (1976)





Radar Time Delay:
to Viking Lander on Mars (1976)
to Cassini spacecraft
toward Saturn (1999+)
Italian Space agency –> high gain antenna

The Gravity PROBE B Mission Concept



$$\grave{\mathrm{U}} = \frac{3GM}{2c^2R^3}\left(\boldsymbol{R}\times\boldsymbol{v}\right)+\frac{GI}{c^2R^3}\left[\frac{3\boldsymbol{R}}{R^2}\left(\grave{\boldsymbol{u}}\cdot\boldsymbol{R}\right)-\grave{\boldsymbol{u}}\right]$$

- *1 marc-sec/yr = 3.2 × 10^{-11} deg/hr*
- *1 marc-sec = width of a human hair seen from 10 miles*

- Geodetic Effect — Space-time curvature ("the missing inch")
- Frame-dragging Effect – Rotating matter drags space-time ("space-time as a viscous fluid")

Future Missions

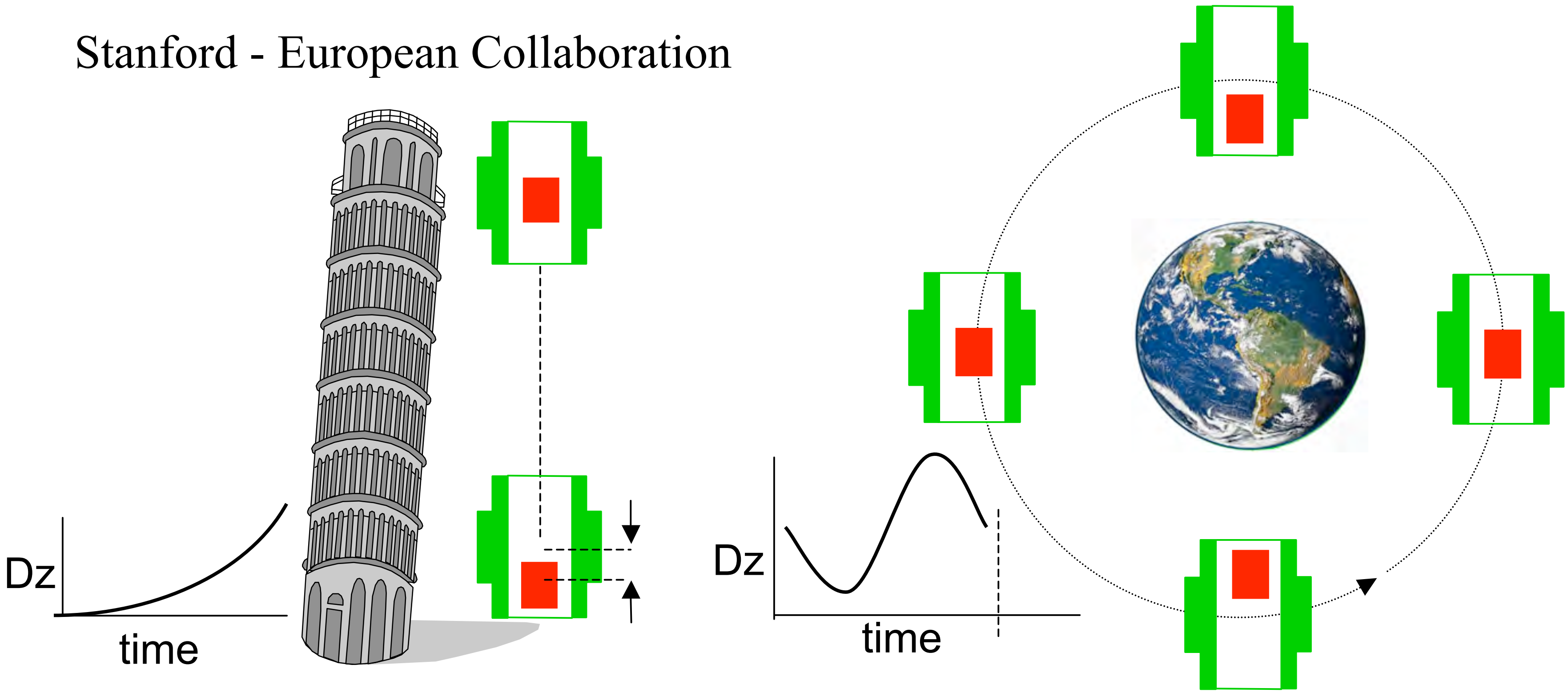
Shared Technology Requirements

Attitude Control and Translation Control
beyond the state of the art
Recent advances => these future missions are feasible

- Gravity Probe B – testing of General Relativity (in analysis)
- GAIA global space astrometry mission– goal: most precise three-dimensional map of our Galaxy
- MICROSCOPE, STEP – testing Equivalence Principle
- LISA –gravitational waves, opening a unique window to study the universe. +BBO and future concepts

STEP – Mission Overview

Stanford - European Collaboration



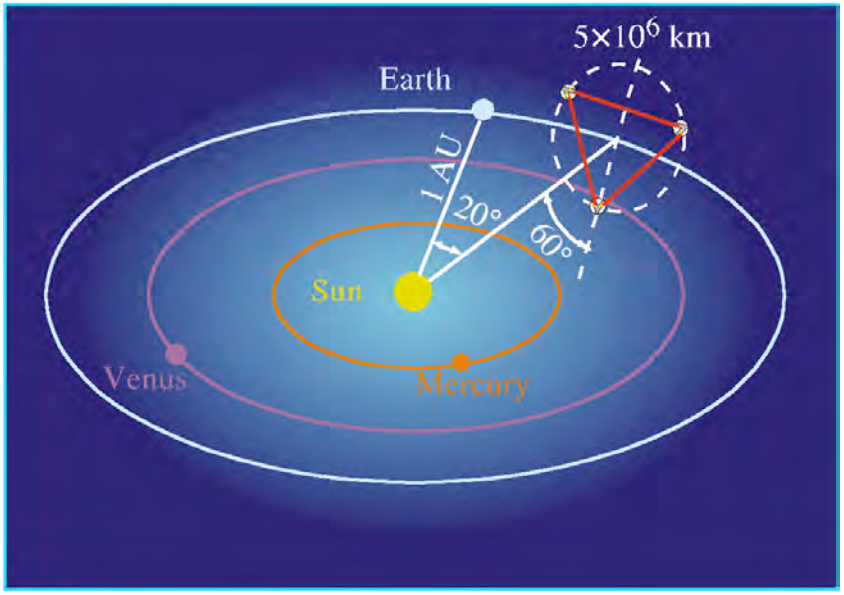
Measurement Goal: Universality of Freefall to 1 part in 10^{18}

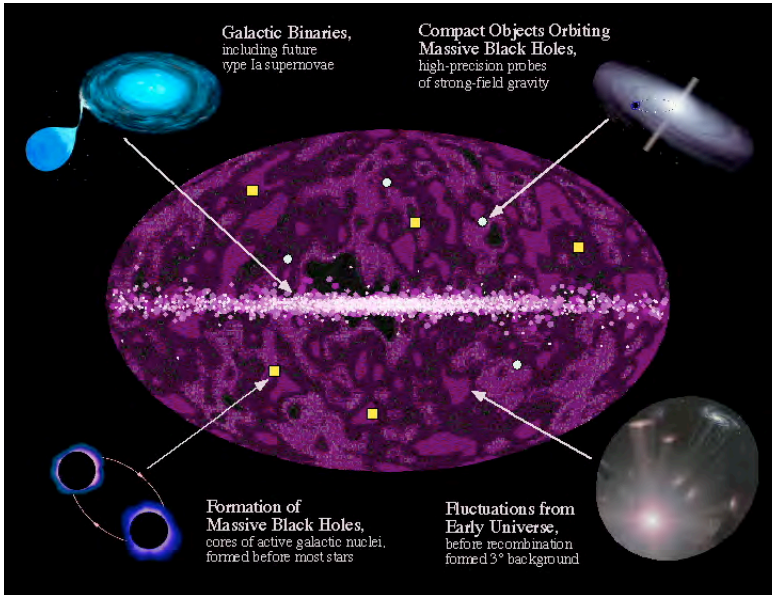
Spacecraft with 2 inertial sensors per accelerometer

Requires 10^{-14}g residual acceleration in measurement band

MicroSCOPE room temperature mission with goal 1 part in 10^{15}

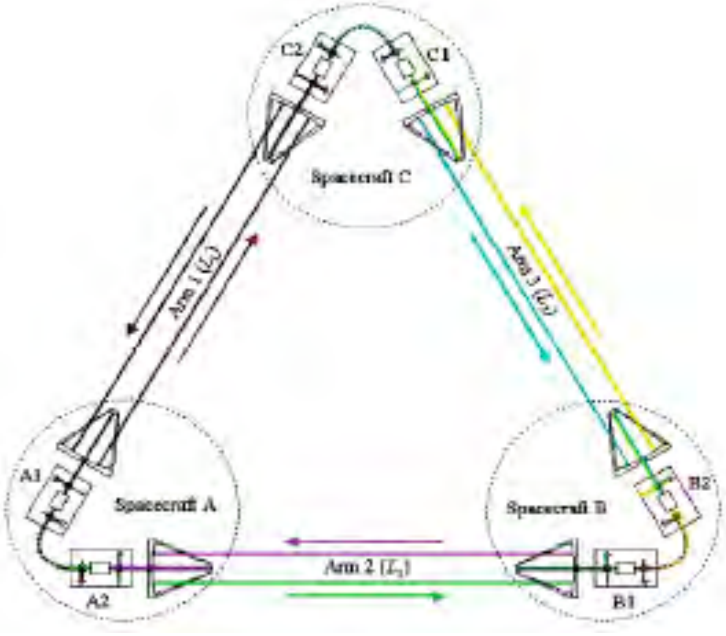
LISA – Mission Overview





3 Spacecraft, each with 1 or 2 inertial sensors

Requires 10^{-16}g residual acceleration
broad band



GP-B, STEP, LISA: Atypical Space Missions

Shared Technology requirements

What is Different?

- Sophisticated drag-free & attitude control system.
- Payload is space vehicle sensor in a single integrated unit.
- GP-B is the first operational satellite of this class of missions.

Human & Management Implications:

- Integrated engineering/physics team *for whole development phase*
- New approaches to requirement verification
- Co-located operations/science team essential for initial on-station setup.

Telescopes	GP-B	STEP	LISA
3 DOF Precision Control	9 DOF Precision Control	18 DOF Precision Control	3x19 DOF Precision Control

Limited communication links for non LEO missions present serious challenges