Tests of gravity at short and long distances

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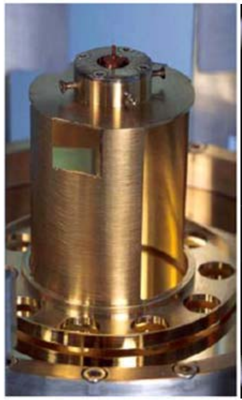
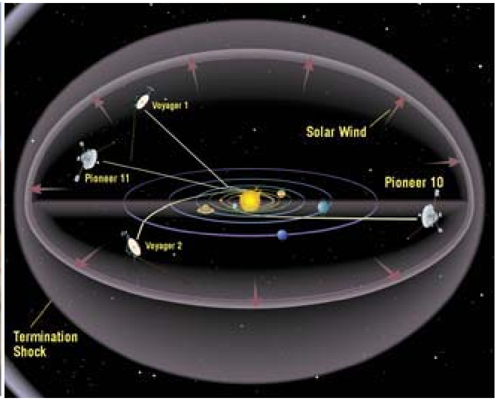




General Relativity (in two slides …)

Einstein 1907-1913 (with Grossman …)

- applies the principle of relativity to gravitation
- introduces the equivalence principle as the geometrical base of the theory of gravitation
- ideal (atomic) clocks measure the proper time along their trajectory $$\mathrm{d}s^2 \equiv g_{\mu\nu}\,\mathrm{d}x^\mu \mathrm{d}x^\nu$$
- freely falling probes (test masses and light rays) follow geodesics $$\delta\left[\int \mathrm{d}s\right] = 0$$

Gravitational field ↔ metric in Riemannian space-time

One of the most accurately ever tested principles of physics : free fall of test masses with ≠ compositions coincide within a few parts in 10^{13} ; accuracy attained in lab tests (torsion pendulums) as well as in space tests (Lunar Laser Ranging)

General Relativity (in two slides …)

Einstein 1912-1915 (with Grossman, Hilbert …)

- curvature tensors = (non linear) differential expressions built up on the metric tensor
- one curvature tensor has a null divergence (Bianchi identities) $$E_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R \qquad D^\nu E_{\mu\nu} \equiv 0$$
- the stress tensor too (conservation laws) $$D^\nu T_{\mu\nu} \equiv 0$$

Einstein-Hilbert equation

- the 2 tensors are simply proportional to each other $$E_{\mu\nu} = \frac{8\pi}{c^4} G_N T_{\mu\nu}$$
- equation to be tested by comparing its consequences with observations

General Relativity (GR) in the solar system

Solution for the metric

- with the Sun treated as a point-like motionless source
- using spatially isotropic coordinates
- with the Newton potential

$$g_{00} = (1 + 2\phi + 2\phi^2 + \ldots)$$
$$g_{jk} = -(1 - 2\phi + \ldots)\,\delta_{jk}$$
$$\phi \equiv -\frac{G_N M}{rc^2} \quad , \quad |\phi| \ll 1$$

GR usually tested through its confrontation with the larger family of PPN metrics

$$g_{00} = (1 + 2\alpha\phi + 2\beta\phi^2 + \ldots) \qquad \alpha = 1 \text{ fixes } G_N$$
$$g_{jk} = -(1 - 2\gamma\phi + \ldots)\,\delta_{jk} \qquad \beta = \gamma = 1 \text{ in GR}$$

- Motions predicted as the geodesics of this metric
- Comparisons between observations and predictions expressed in terms of anomalies of the PPN parameters $\beta - 1\,,\ \gamma - 1$

After 30 years of PPN tests of GR

Living Reviews in Relativity, C.F. Will (2001, regularly updated)

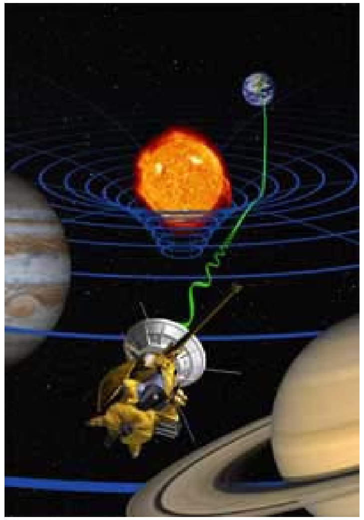
The best test to date :
Doppler velocimetry on Cassini during its cruise from Jupiter to Saturn

$$\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5}$$

Using also Lunar Laser Ranging :

$$|\beta - 1| \lesssim 3 \times 10^{-4}$$

Tests select GR out of the PPN family



Courtesy : Cassini @ *NASA*

Good reasons to going on testing GR

Theoretical reasons :

- GR is a classical theory which show inconsistencies with quantum field theory
- All unification models predict (small) deviations of gravitation laws from GR

Observational reasons :

- “Dark matter” and “dark energy” are observed as gravitational anomalies; as long as they are not also observed through independent means, they may as well be interpreted as modifications of gravity laws at galactic and cosmic scales
- A few measurements in the solar system show deviations from the predictions of GR

Scale dependent tests of GR

“Fifth-force” tests of the Newton law

Search for a deviation

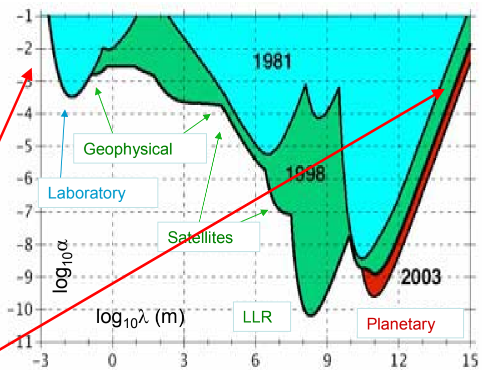
$$g_{00} = [g_{00}]_{\mathrm{GR}} + \delta g_{00}$$

in particular under the form of a Yukawa correction

$$\delta g_{00}(r) = 2\phi(r)\,\alpha \exp\left(-\frac{r}{\lambda}\right)$$

Windows remain open for deviations at short ranges $\lambda < 1\,\mathrm{mm}$

or long ranges $\lambda > 10^{16}\,\mathrm{m}$



Courtesy : J. Coy, E. Fischbach, R. Hellings, C. Talmadge, and E. M. Standish (2003)

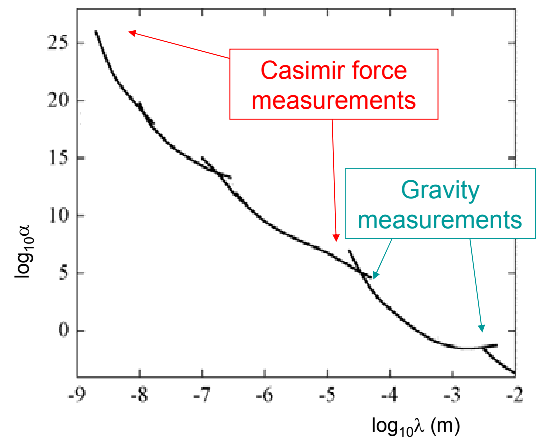
The Search for Non-Newtonian Gravity, E. Fischbach & C. Talmadge (1998)

Searches in the short-range window

Gravity measurements at short distances

λ > a few 10µm

At shorter ranges, tests consist in theory-experiment comparisons for the Casimir force



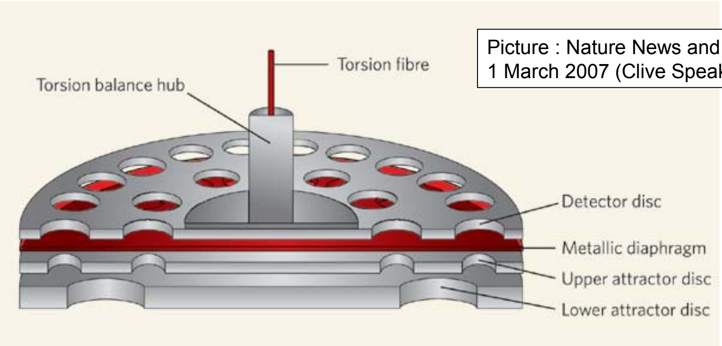
No deviation reported to date in the short-range window !

E. Adelberger et al Annu. Rev. Nucl. Part. Sci. (2003) hep-ph/0307284

Eöt-Wash experiment (Adelberger et al)

"Missing-mass" torsion balance

Two disks with holes, the attractor is rotated uniformly, the produced torque is extracted at harmonic frequencies. The systematic errors are carefully controlled



Picture : Nature News and Views, 1 March 2007 (Clive Speake)

Newtonian signals used to calibrate hypothetical new forces

Eöt-Wash experiment

The strongest constraint obtained at small distances :

At 95% confidence, a Yukawa interaction with gravitational strength (α=1) must have a range λ<56μm

More discussions of particle physics implications in E.G. Adelberger et al, arXiv:hep-ph/0611223

D.J. Kapner et al PRL **98** (2007) 021101

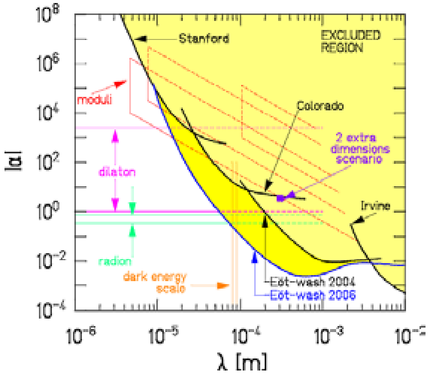
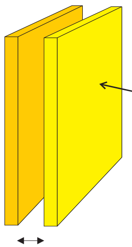


FIG. 6: Constraints on Yukawa violations of the gravitational $1/r^2$ law. The shaded region is excluded at the 95% confidence level. Heavy lines labeled Eöt-Wash 2006, Eöt-Wash 2004, Irvine, Colorado and Stanford show experimental constraints from this work, Refs. [11], [14], [15] and [16, 17], respectively. Lighter lines show various theoretical expectations summarized in Ref. [9].

The Casimir force

$$F_{\text{Cas}} = -\frac{\hbar c \pi^2}{240\, L^4} A$$

$$E_{\text{Cas}} = -\frac{\hbar c \pi^2}{720\, L^3} A$$



$A >> L^2$

L

Assumptions

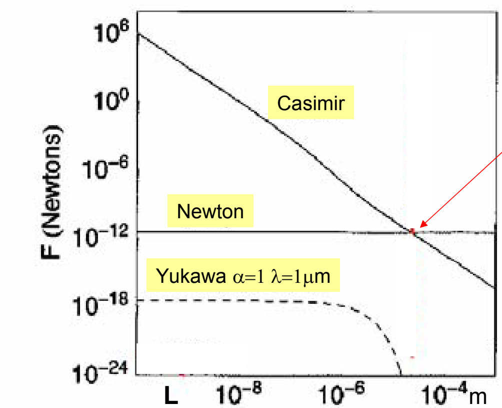
- plane parallel mirrors
- perfect reflection
- zero temperature
- perfectly flat surfaces

Order of magnitude of the (negative) pressure

$$L = 1\mu\text{m} \rightarrow \left|\frac{F_{Cas}}{A}\right| \approx 10^{-3}\,\text{Pa}$$

More realistic description needed to compare experiments to theory

Casimir vs Newton : the challenge



For two Cu plates (1cm x 1cm x 1mm), Casimir dominates Newton at L<10μm

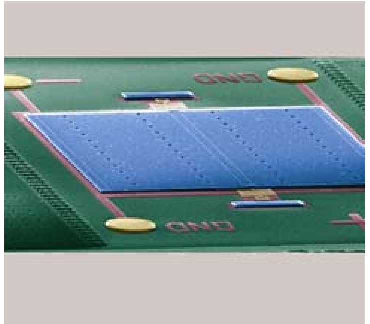
Gravity tests rely on comparisons of Casimir force measurements with QED predictions

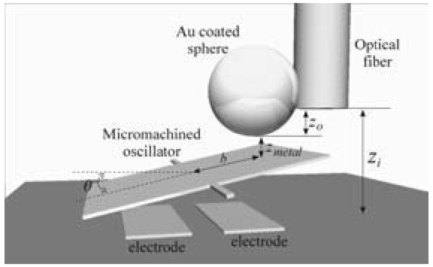
The theory has to be independent and as accurate as the experiments

Focus issue in the New Journal of Physics (Oct 2006)

- A. Lambrecht, P.A. Maia Neto, S. Reynaud,
- R. Onofrio

New Dynamic Casimir Measurement: Experimental Setup (Decca et al., IUPUI)





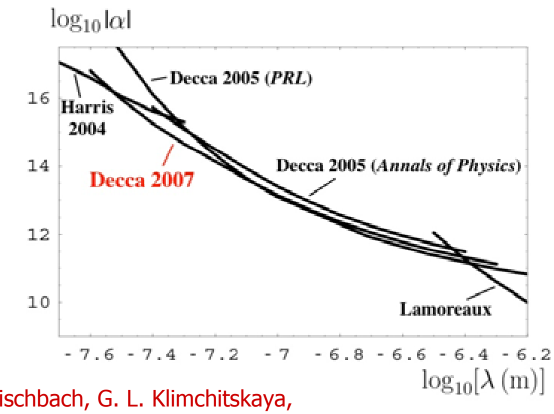
Sphere Radius: R = 150 μm
MTO Dimensions: 500 μm × 500 μm × 3.5 μm

Force Gradient Measurement:

Change in Oscillator Resonance Frequency

Proximity Force Approximation

Current Limits on Yukawa Forces: Casimir Force Experiments



R. S. Decca, D. López, E. Fischbach, G. L. Klimchitskaya, D. E. Krause, V. M. Mostepanenko (unpublished, March 2007)

Same authors : Annals of Physics (N.Y.) **318** 37 (2005)

Searches in the long-range window

Best example to date :
NASA approval to extend Pioneer 10/11 missions after their primary planetary goals have been met with the aim (among other ones) of testing Celestial Mechanics at large heliocentric distances

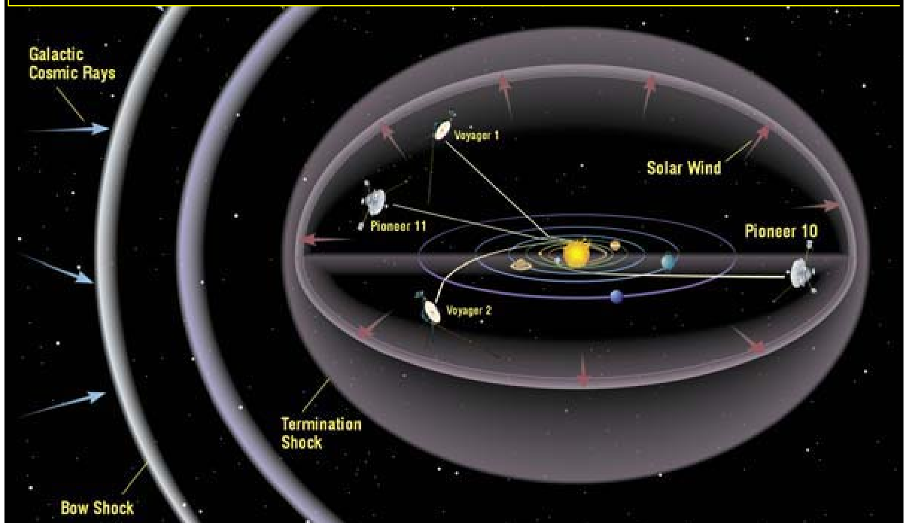
Pioneer 10: pre-launch testing

Agency: NASA	Pioneer 10	Pioneer 11
Launch	2 March 1972	5 April 1973
Planetary fly-bys	Jupiter: 4 Dec 1973	Jupiter: 2 Dec 1974 Saturn: 1 Sep 1979
Last data point received	27 Apr 2002 distance ~80.2 AU	1 Oct 1990 distance ~30 AU

Courtesy : S. Turyshev

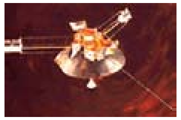
The most precisely ever navigated deep-space vehicles :
- Spin-stabilization and design permitted acceleration sensitivity ~10^{-10} m/s^2, unlike a Voyager-type 3-axis stabilization that were almost 50 times worse

The Pioneer "gravity test": the largest scaled test ever carried out…



…and it failed to confirm the known laws of gravity !

The Doppler observable



A radio signal is sent from a station on Earth to the probe, sent back (transponded) by the probe, and finally received by a station on Earth (the same=2-way ; another one=3-way)

The observable is the frequency ratio, interpreted as a relative velocity (Minkowskian formula), but it accounts for all relativistic and gravitational effects

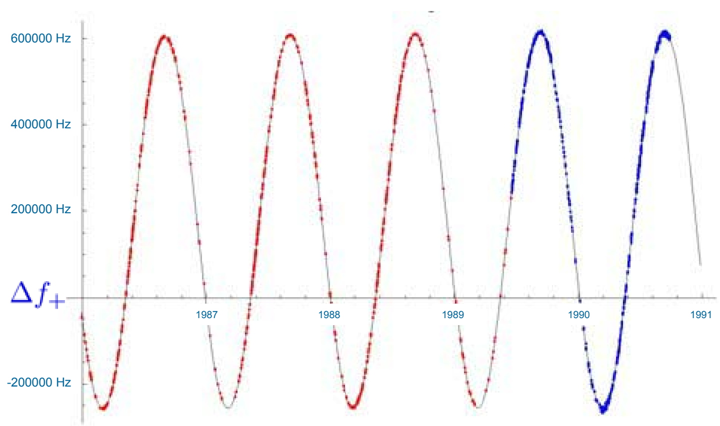
$$\frac{f_+}{f_-} = \frac{1-\frac{v}{c}}{1+\frac{v}{c}}$$

f_- (up) , f_+ (down)

It must also be corrected for propagation effects, station motions….

Annual variation

Doppler shift Pioneer 11 – 2 Way (red) and 3 Way (blue)
Compared to NASA **Horizon ephemeris (black)**

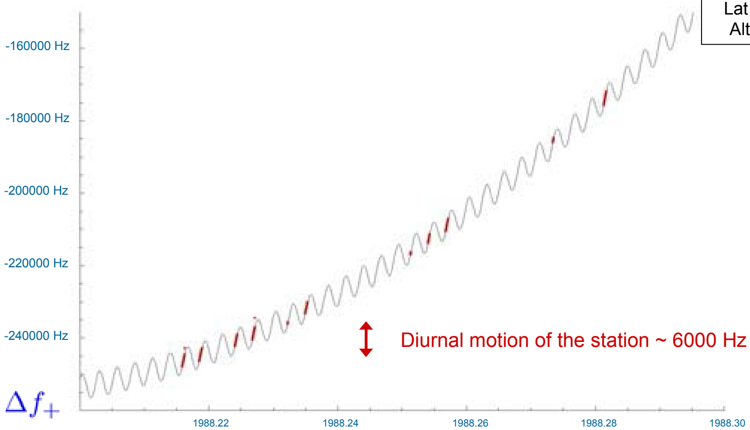


Courtesy : Agnès Lévy (ONERA) and Jean-Michel Courty (LKB)

Diurnal variation

Doppler shift Pioneer 11 – 2 way station DSN 43 Camberra
Compared to NASA **Horizon ephemeris (black)**

Long : 148.9813°
Lat : -35.4025°
Alt : 694.83m



Courtesy : Agnès Lévy (ONERA) and Jean-Michel Courty (LKB)

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THE DEEP SPACE GRAVITY PROBE SCIENCE TEAM

Anomalous acceleration

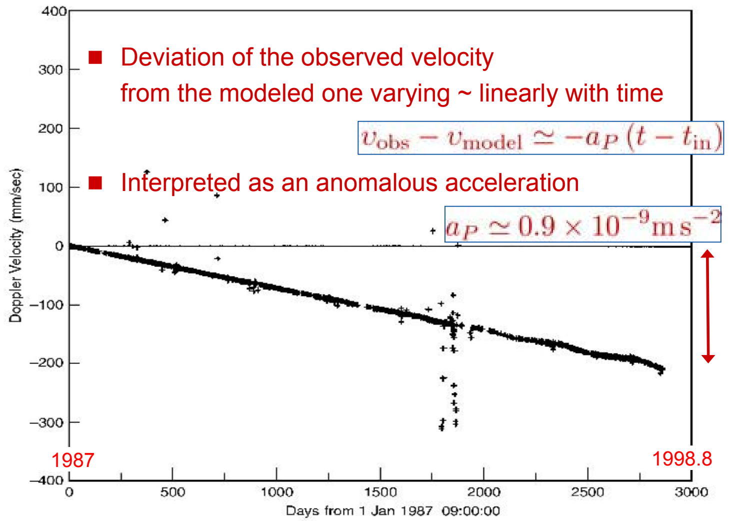
1 Hz is equivalent to 65 mm/s velocity

- Deviation of the observed velocity from the modeled one varying ~ linearly with time

$$v_{\mathrm{obs}} - v_{\mathrm{model}} \simeq -a_P\,(t - t_{\mathrm{in}})$$

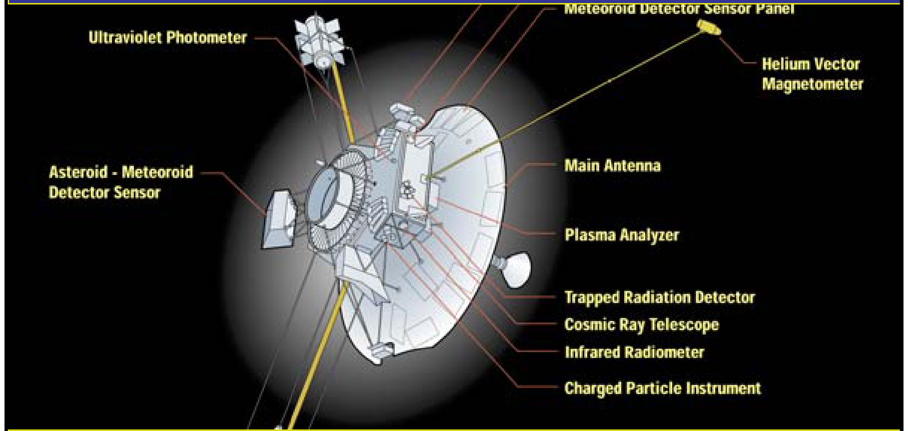
- Interpreted as an anomalous acceleration

$$a_P \simeq 0.9 \times 10^{-9}\,\mathrm{m\,s^{-2}}$$



J. Anderson et al, Phys. Rev. D 65 (2002) 082004

The anomaly has been registered on the two deep space probes with the best navigation accuracy



The two probes were identical and had similar trajectories :

↳ one experiment performed twice with the same result

Might be an artefact ?

Satisfactory explanation actively looked for, not yet found

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Detailed Analysis by NASA (1980-2002)

- On-board systematic & other hardware-related mechanisms:
  - Precessional attitude control maneuvers and associated “gas leaks”
  - Nominal thermal radiation due to ^{238}Pu decay [half life 87.75 years]
  - Heat rejection mechanisms from within the spacecraft
  - Hardware problems at the DSN tracking stations
- Examples of the external effects:
  - Solar radiation pressure, solar wind, interplanetary medium, dust
  - Drag force due to mass distributions in the outer solar system
  - Gravity from the Kuiper belt; gravity from the Galaxy
  - Gravity from Dark Matter distributed in halo around the solar system
  - Errors in the planetary ephemeris, in the Earth Orientation Parameters, precession, and nutation
- Phenomenological time models:
  - Drifting clocks, quadratic time augmentation, uniform carrier frequency drift, effect due to finite speed of gravity, and many others
- All the above were rejected as explanations

J. Anderson et al, Phys. Rev. D 65 (2002) 082004

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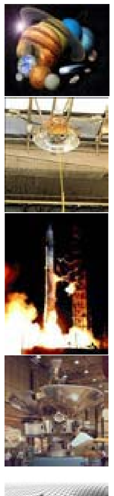
Recent Pioneer Data Recovery Effort



Data used for the analysis of 1998-2002 (1996-1998) :

- Pioneer 10: 11.5 years; distance = 40–70.5 AU
- Pioneer 11: 3.75 years; distance = 22.4–31.7 AU

Pioneer data recently recovered (Planetary Society & JPL) :

- Telemetry & Doppler data recovered from launch to the last data point

V. Toth and S. Turyshev, arXiv:gr-qc/0603016

Doppler Data now available :

- Pioneer 10:
  - 1973-2002: ~ 30 years
  - Distance range: 4–87 AU
  - Jupiter encounter
  - ~60,000 data points, ~20GB
  - Maneuvers, spin, initial cond.
- Pioneer 11:
  - 1974-1994: ~ 20 years
  - Distance range: 4–33 AU
  - Jupiter & Saturn encounters
  - ~50,000 data points, ~15GB
  - Maneuvers, spin, initial cond.

- Ongoing Pioneer data re-analysis planned as an international effort : teams at work in US, Canada, Germany, France, Italy, Norway…

More informations on the website “Investigation of the Pioneer Anomaly” Team @ ISSI
http://www.issi.unibe.ch/teams/Pioneer ; results expected within the next year

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A challenge ahead of us

Will we be able to solve the discrepancy and to show that Pioneer gravity test once more confirmed GR ?

Or to confirm the existence of a gravity anomaly ?

Any of these two conclusions would be of great value for fundamental physics, astrophysics and cosmology

Motivations and lessons for a future probe : arXiv:gr-qc/0506139

Can the PA be a metric anomaly ?

It is unlikely that the equivalence principle be violated at the level of the Pioneer anomaly

$$a_N \sim 1\mu\mathrm{m\,s}^{-2} \quad , \; a_P \sim 1\mathrm{nm\,s}^{-2} \quad , \; \frac{a_P}{a_N} \sim 10^{-3}$$

We keep the description of gravitation as a Riemannian metric theory with motions identified as geodesics

But the Einstein-Hilbert equation can be modified, leading to modifications of geodesic motions in the solar system

These metric extensions of GR define a phenomenology larger than the PPN framework

Pioneer observations as well as other gravity tests have to be re-analyzed in this new framework

M.-T. Jaekel, S. Reynaud, Classical and Quantum Gravity **23** (2006) 7561