Solar System Tests of Relativistic Gravity:

Recent Progress and Future Directions

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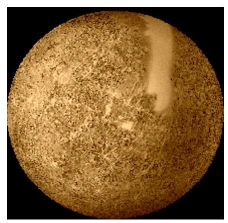
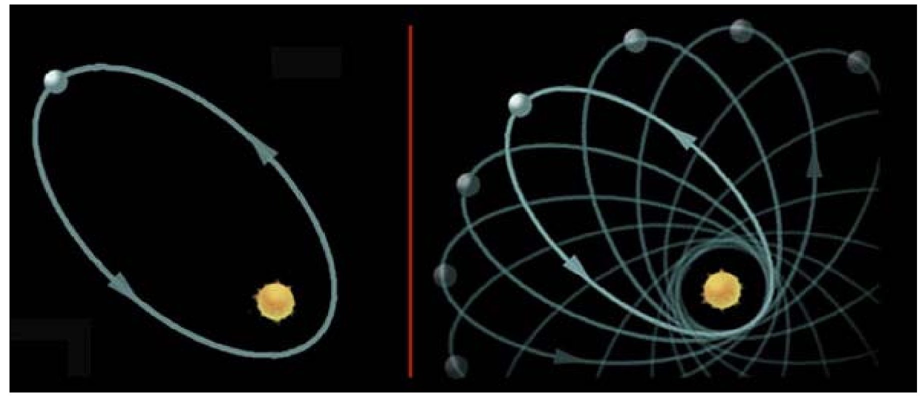
Triumph of Mathematical Astronomy in 19th Century

Discovery of Neptune: 1845

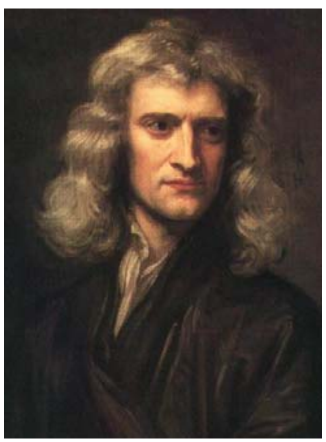
Urbain LeVerrier
(1811-1877)



- 1845: the search for Planet-X:
  - Anomaly in the Uranus' orbit → Neptune
  - Anomalous motion of Mercury → Vulcan



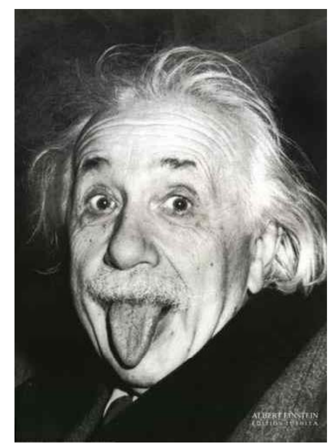
Newtonian Gravity   General Relativity



Sir Isaac Newton
(1643-1727)

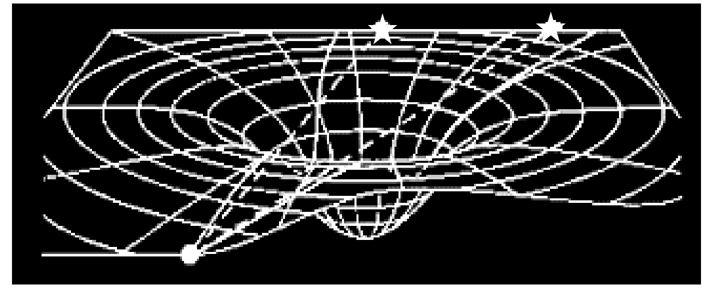
- Anomalous precession of Mercury's perihelion :
  - 43 arcsec/cy can not be explained by Newton's gravity
- Before publishing GR, in 1915, Einstein computed the expected perihelion precession of Mercury
  - When he got out 43 arcsec/cy – a new era just began!!

Almost in one year LeVerrier both confirmed the Newton's theory (Neptune) & cast doubt on it (Mercury's' anomaly).

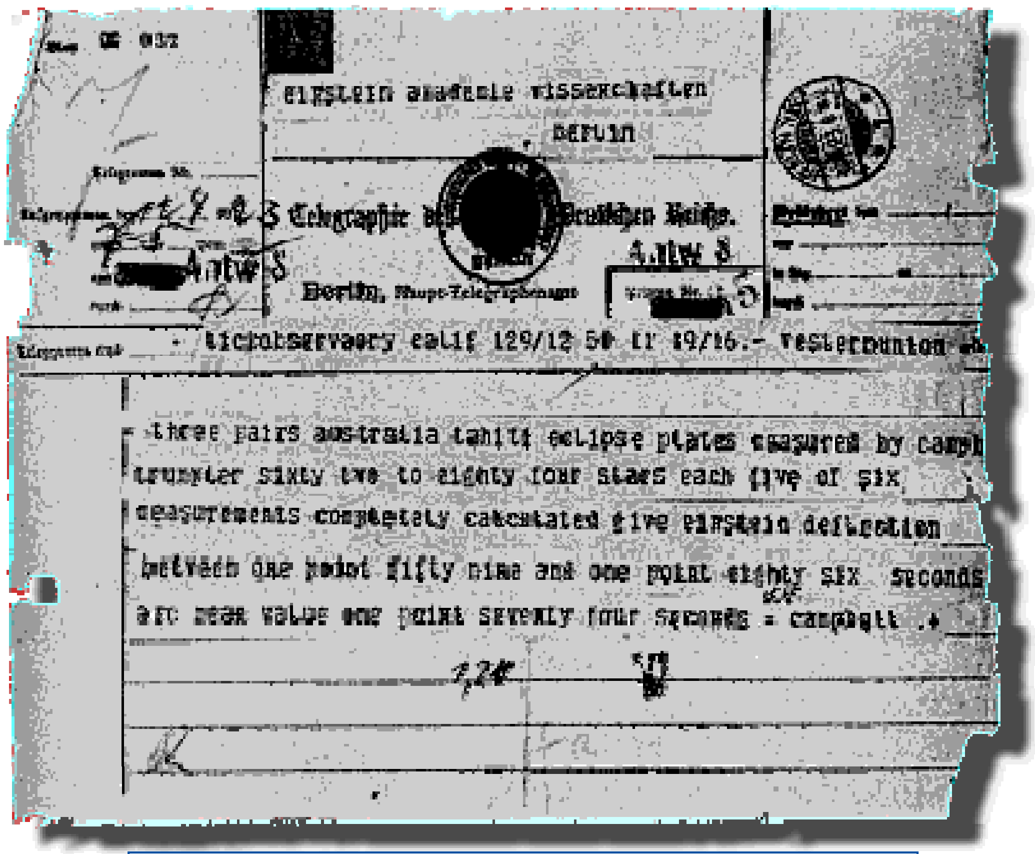


Albert Einstein
(1879-1955)

The First Test of General Theory of Relativity



Gravitational Deflection of Light:
Solar Eclipse 1919



einstein akademie wissenschaften
berlin

Telegraphie des Deutschen Reichs.

Berlin, Haupt-Telegraphenamt

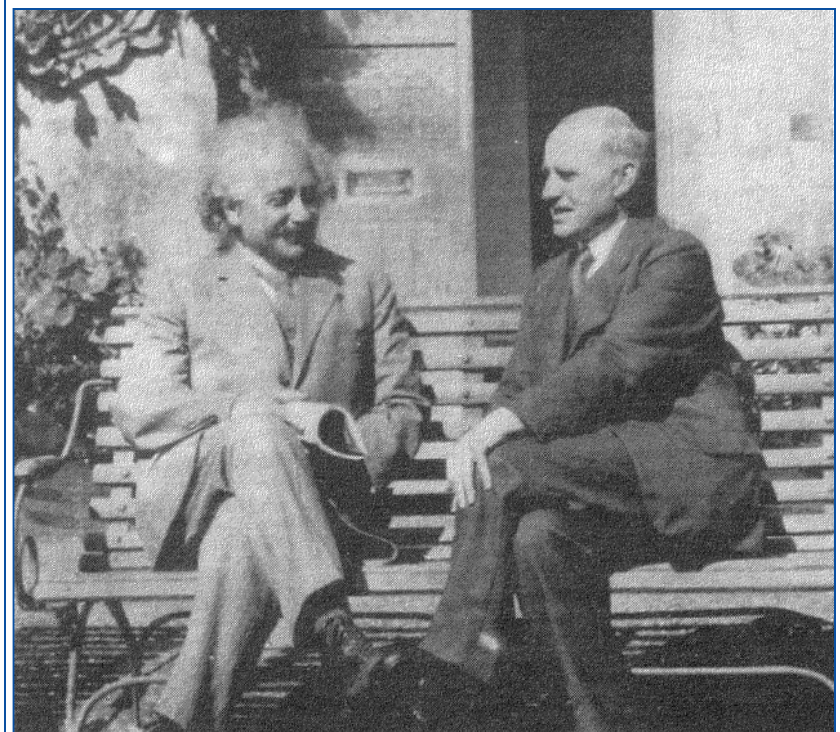
victobservatory calif 129/12 50 tr 19/16.- vestermunton

three pairs australia tahiti eclipse plates measured by campb
trumpler sixty two to eighty four stars each five of six
measurements completely calculated give einstein deflection
between one point fifty nine and one point eighty six seconds
arc mean value one point seventy four seconds = campbell

Eddington's telegram to Einstein, 1919

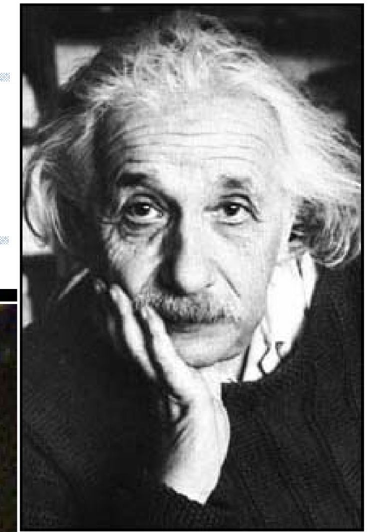
Possible outcomes in 1919:

Deflection = 0;
Newton = 0.87 arcsec;
Einstein = 2 x Newton = 1.75 arcsec



Einstein and Eddington, Cambridge, 1930

Gravitational Deflection of Light is a Well-Known Effect Today

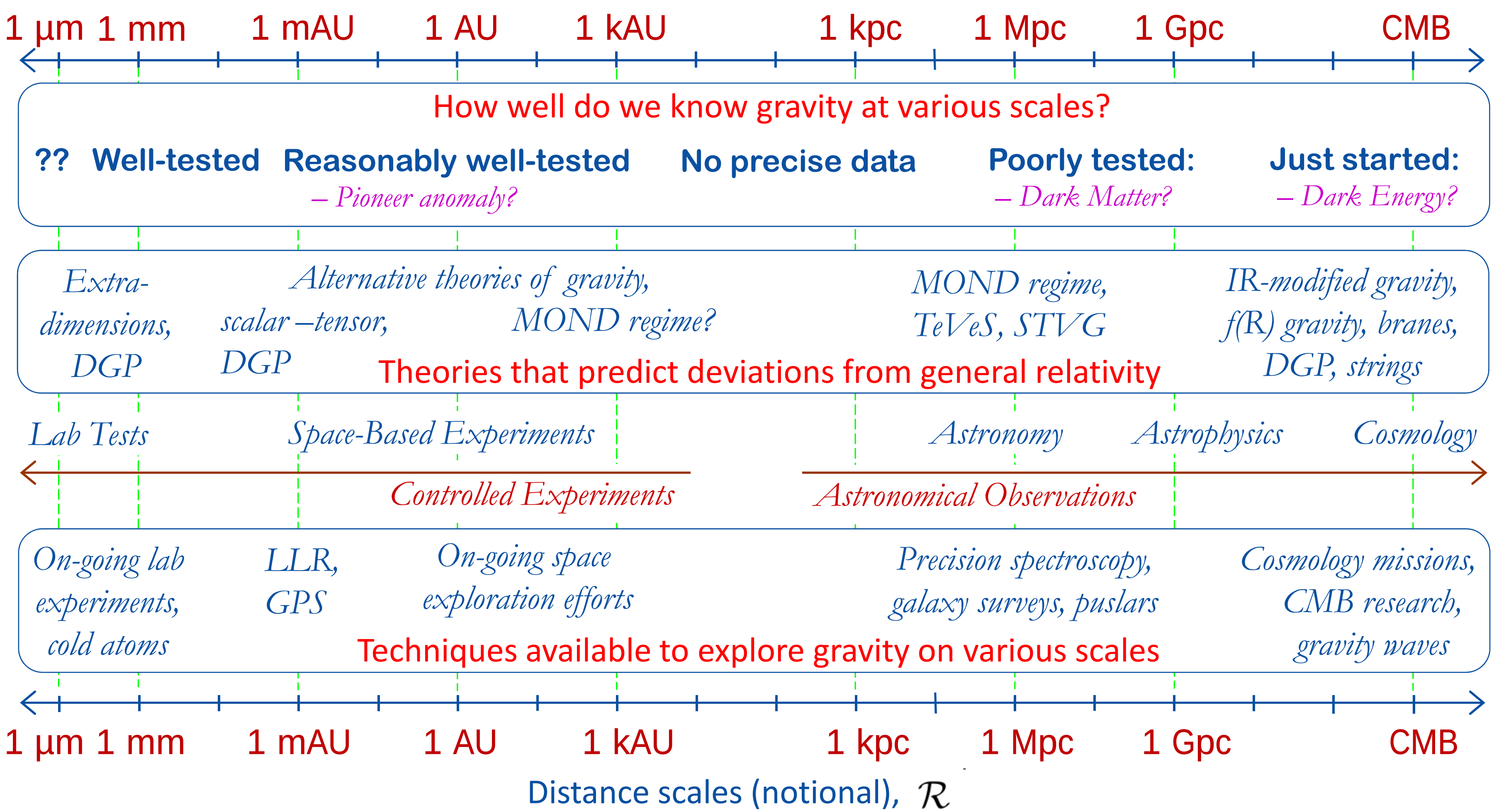


Galaxy Cluster Abell 2218 **HST • WFPC2**

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

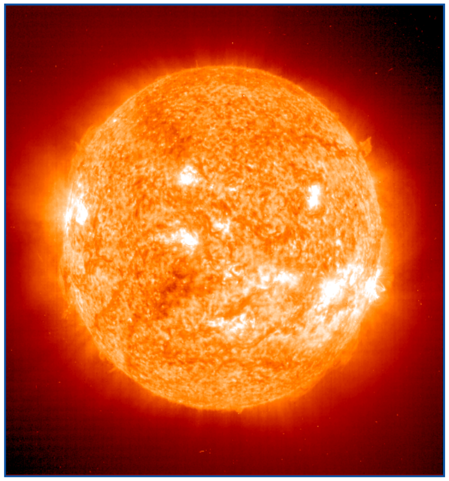
Theoretical Landscape of the 21th Century:

How well do we know gravity?



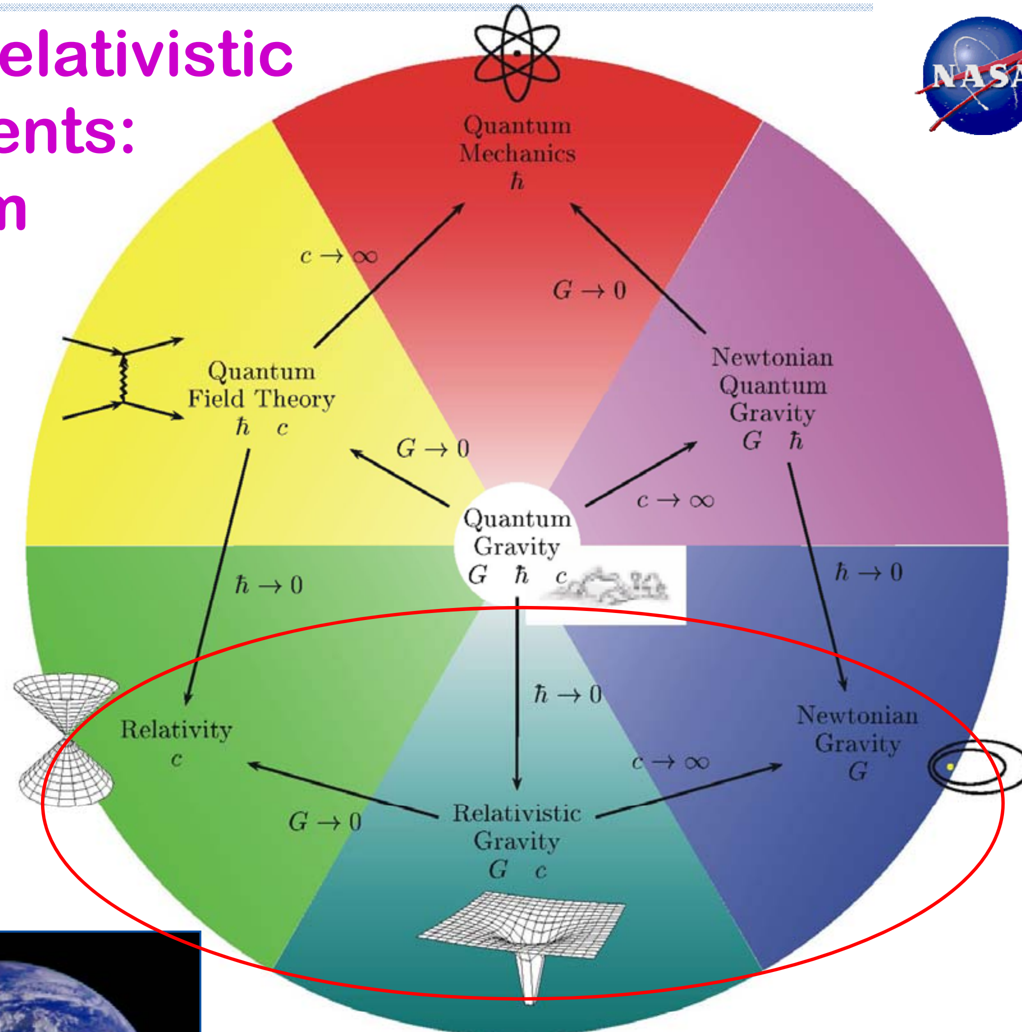
Solar system experiments allow for improvements in our knowledge of gravity

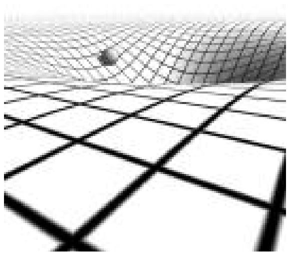
Laboratory for Relativistic Gravity Experiments: Our Solar System



Strongest gravity potential

$$\frac{GM_{Sun}}{c^2 R_{Sun}} \sim 10^{-6}$$





$$\frac{GM_{\oplus}}{c^2 R_{\oplus}} \sim 10^{-9}$$

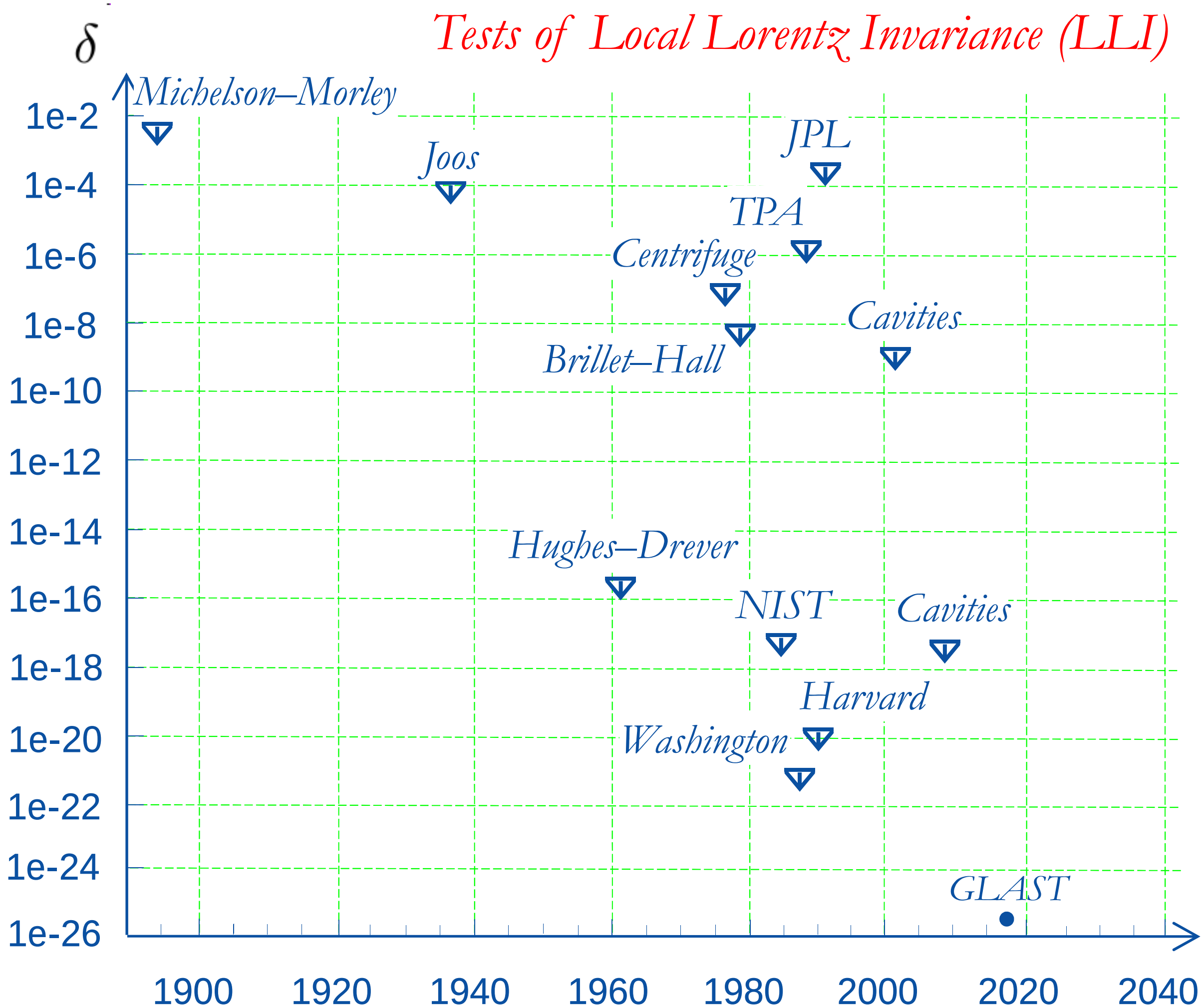
Most accessible region for gravity tests in space:

- ISS, LLR, SLR, free-fliers

Technology is available to conduct tests in the immediate solar proximity

Empirical Foundations of General Relativity:

Confrontation Between the Theory and Experiment



– Michelson-Morley, Joos, Brillet-Hall: Round-trip propagation

– Centrifuge, TPA, JPL: One-way propagation

– Rest: Hughes-Drever experiments

$$\delta \equiv \frac{c^2}{c_0^2} - 1$$

Local Lorentz Invariance:

– Extended frameworks by Kostelecky et al., Jacobson et al.

Future experiments:

– Clock comparisons

– Clocks vs cavities

– Time of flight of high energy photons

– Birefringence in vacuum

– Neutrino oscillations

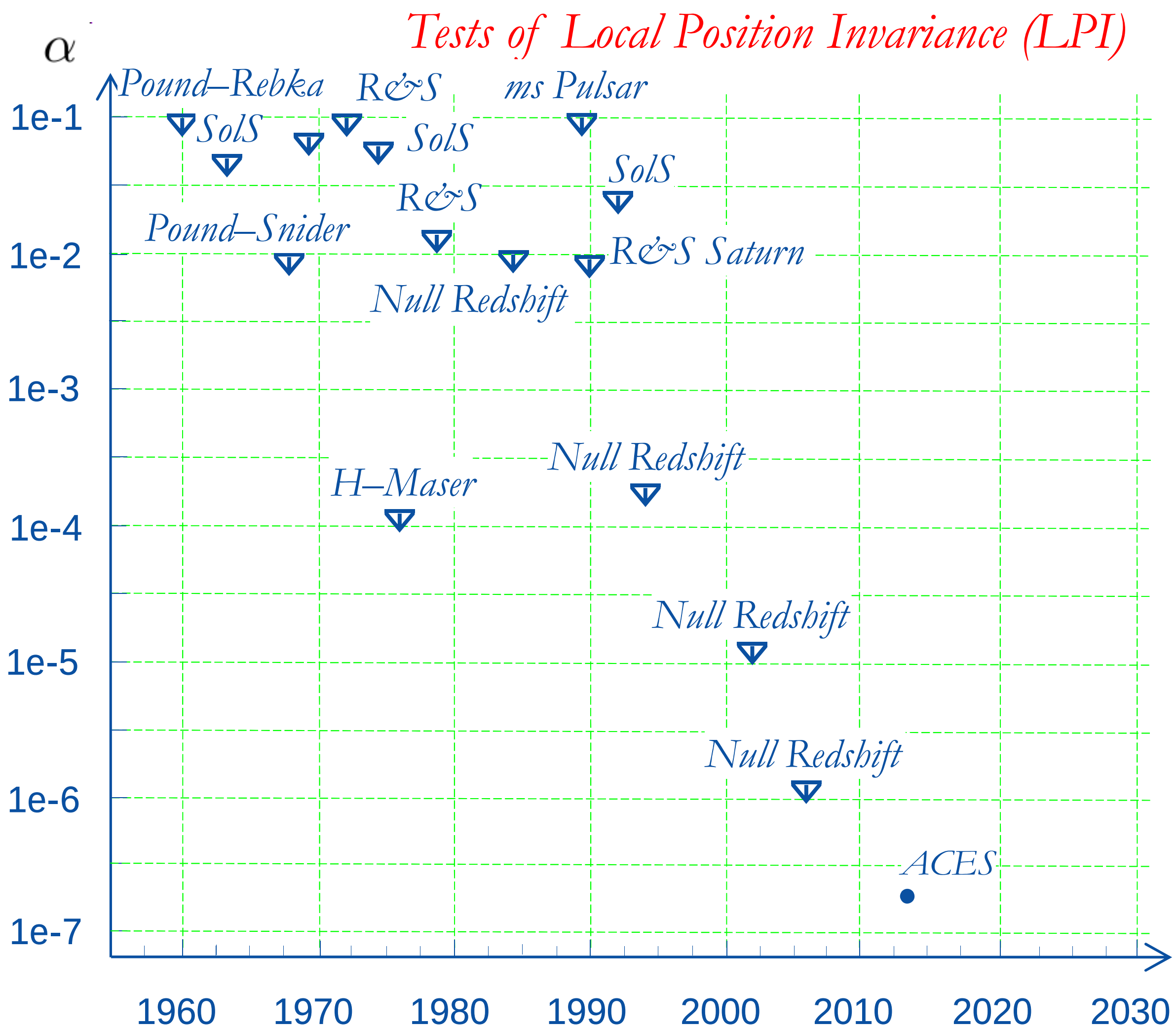
– Threshold effects in particle physics

Test of one-way speed of light:

– Important to fundamental physics, cosmology, astronomy and astrophysics

Empirical Foundations of General Relativity:

Confrontation Between the Theory and Experiment



– SolS: Solar Spectra; – R&S: Rockets and Spacecraft

– Null Redshift: comparison of different atomic clocks

$$\frac{\Delta \nu}{\nu} = (1+\alpha)\frac{\Delta U}{c^2}$$

Local Position Invariance:

– The outcome of any local non-gravitational experiment is independent of where & when in the universe it is performed

Splits into:

– spatial invariance

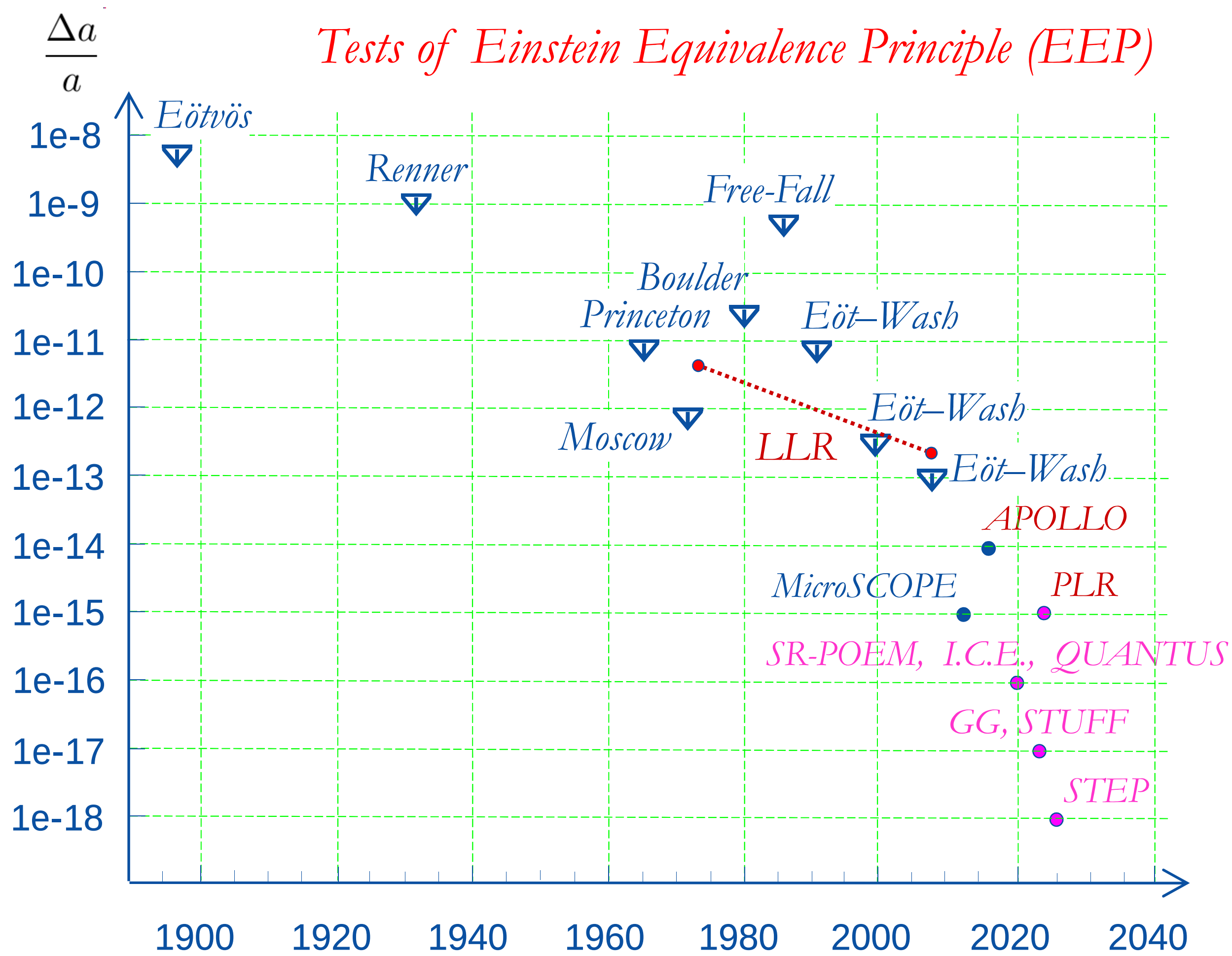
– temporal invariance

– Current best result is by Ashby et a., Phys. Rev. Lett. 98, 070802 (2007)

$$|\alpha| < 1.4 \times 10^{-6}$$

Empirical Foundations of General Relativity:

Confrontation Between the Theory and Experiment



– • funded projects

– • proposed projects

– *LLR*, *APOLLO*, and *PLR* testing the Strong Equivalence Principle (SEP)

$$\left[\frac{m_G}{m_I}\right]_{\text{SEP}} = 1 + \eta\left(\frac{\Omega}{mc^2}\right)$$

Uniqueness of Free Fall
(≡ Weak Equivalence Principle):

$$\vec{F} = m_I\vec{a} = m_G\vec{g}$$
$$\Rightarrow m_I = m_G$$

All bodies fall with the same acceleration

Define the test parameter that signifies a violation of the **WEP**

$$\frac{\Delta a}{a} = \frac{(a_1 - a_2)}{\frac{1}{2}(a_1 + a_2)} = \left[\frac{m_G}{m_I}\right]_1 - \left[\frac{m_G}{m_I}\right]_2$$

Let Ω is the gravitational binding energy of a test body, then the test parameter that signifies a violation of the **SEP** is

$$\frac{\Delta a}{a} = (4\beta - \gamma - 3)\left\{\left[\frac{\Omega}{mc^2}\right]_1 - \left[\frac{\Omega}{mc^2}\right]_2\right\}$$

40 Years of Solar System Gravity Tests

Techniques for Gravity Tests:

Radar Ranging:
- Planets: Mercury, Venus, Mars
- s/c: Mariners, Vikings, Pioneers, Cassini, Mars Global Surveyor, Mars Orbiter, etc.
- VLBI, GPS, etc.

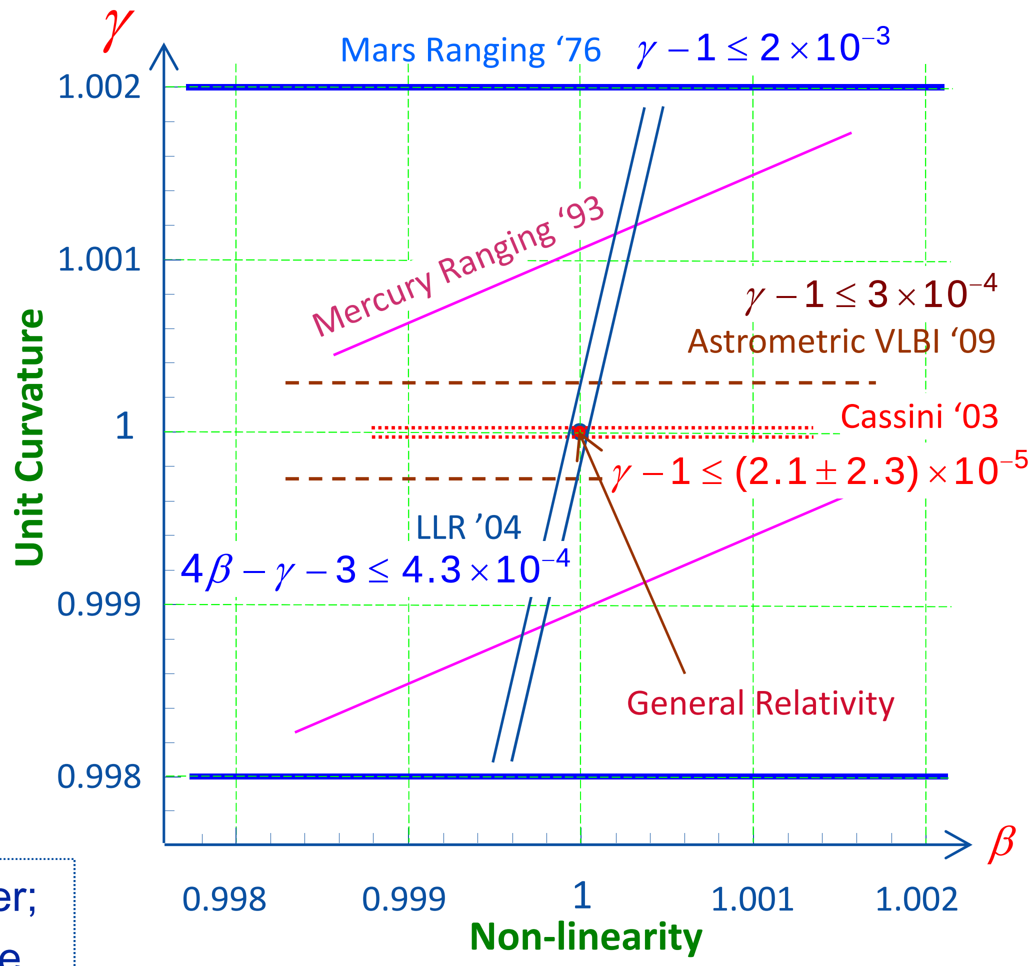
Laser:
- SLR, LLR, interplanetary, etc.

Dedicated Gravity Missions:

- **LLR (1969 - on-going!!)**
- GP-A, '76; LAGEOS, '76,'92; GP-B, '04; LARES, '10; LISA, 2018 (?)

New Engineering Discipline – Applied General Relativity:

- Daily life: GPS, geodesy, time transfer;
- Precision measurements: deep-space navigation & astrometry (SIM, Gaia,....).



A factor of 100 in 40 years is impressive, but is not enough for the near future!

Cassini 2003: Where Do We Go From Here?

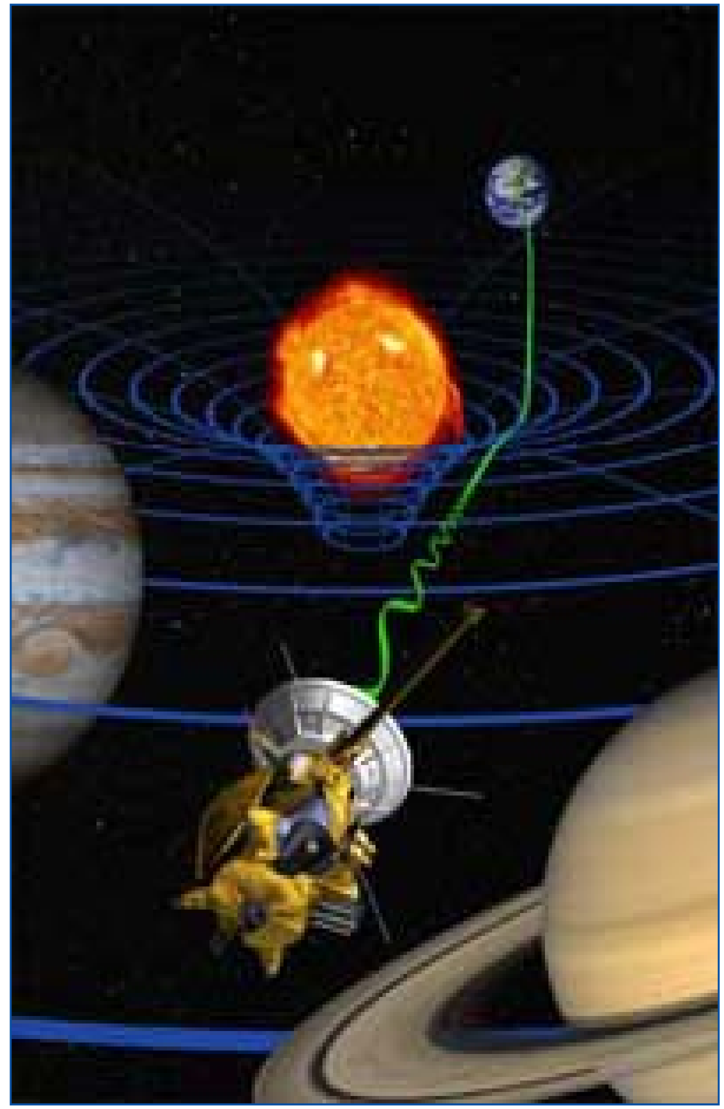
Cassini Conjunction Experiment 2003:

- Spacecraft—Earth separation > 1 billion km
- Doppler/Range: X~7.14GHz & Ka~34.1GHz
- Result: $\gamma = 1 + (2.1 \pm 2.3) \times 10^{-5}$

Possible with Existing Technologies?!

- VLBI [current $\gamma = 3 \times 10^{-4}$]: limited to $\sim 1 \times 10^{-4}$:
  - uncertainty in the radio source coordinates
- LLR [current $\eta = 4 \times 10^{-4}$]: in 6 years $\sim 3 \times 10^{-5}$:
  - mm accuracies [APOLLO] & modeling efforts
- μ-wave ranging to a lander on Mars $\sim 6 \times 10^{-6}$
- tracking of BepiColombo s/c at Mercury $\sim 2 \times 10^{-6}$
- Optical astrometry [current $\gamma = 3 \times 10^{-3}$]:

  Gaia & SIM $\sim 1\text{-}5 \times 10^{-6}$ (2016/18?)



One needs a dedicated mission to explore accuracies better than 10^{-6} for both PPN parameters γ (and β). Interplanetary laser ranging is a possibility.

LUNAR LASER RANGING SCEINCE

Lunar Laser Ranging

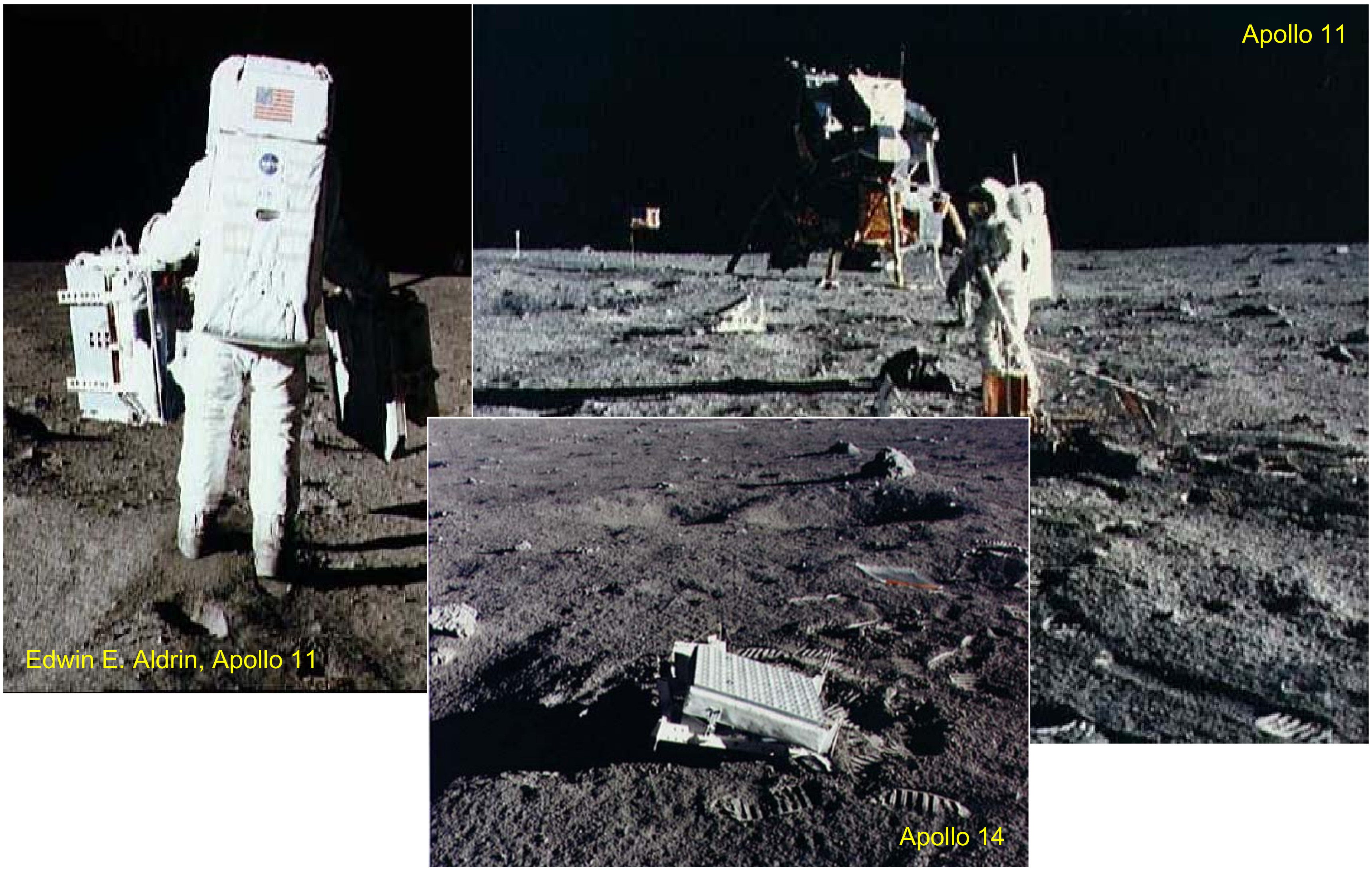
It is all begun 40 year ago…

Laser Ranges between observatories on the Earth and retroreflectors on the Moon started by Apollo in 1969 and continue to the present

- 4 reflectors are ranged:
  - Apollo 11, 14 & 15 sites
  - Lunakhod 2 Rover
- LLR conducted primarily from 3 observatories:
  - McDonald (Texas, USA)
  - OCA (Grasse, France)
  - Haleakala (Hawaii, USA)
- New LLR stations:
  - Apache Point, (NM, USA)
  - Matera (Matera, Italy)
  - South Africa, former OCA LLR equipment

Excellent Legacy of the Apollo Program

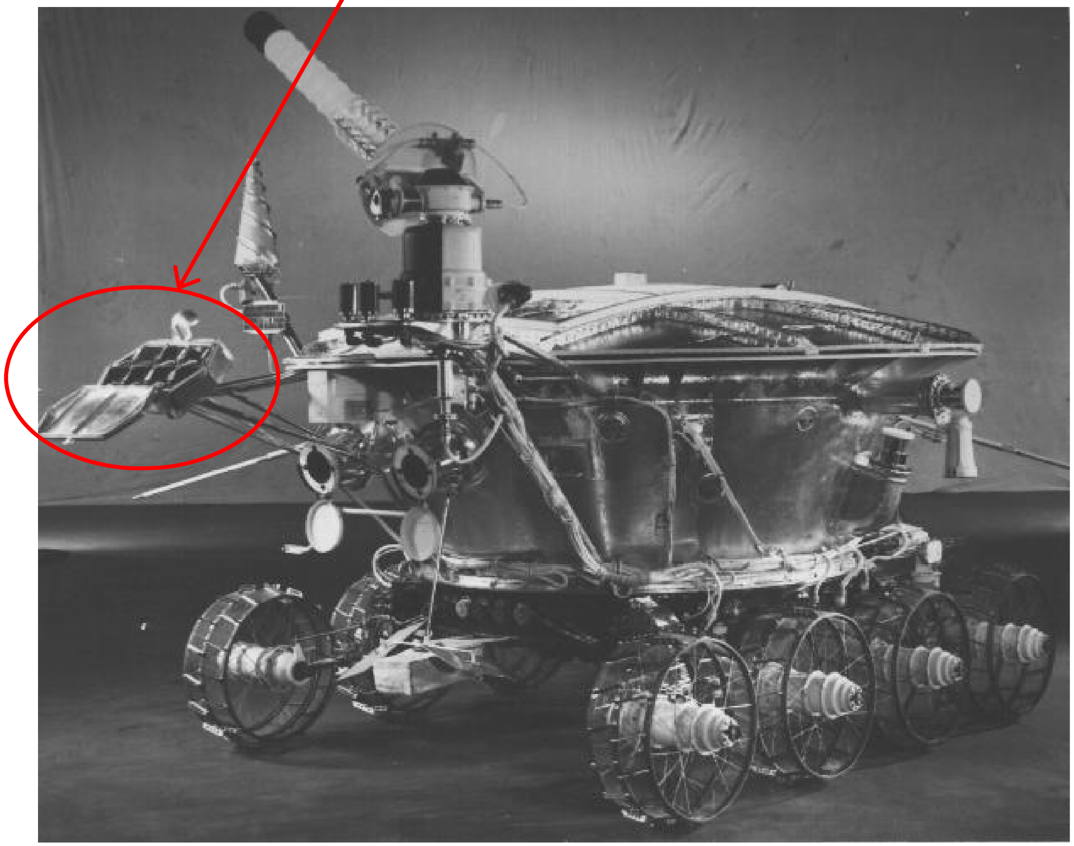
The Apollo 11 retroreflector initiated a shift from analyzing lunar position angles to ranges. Today LLR is the **only** continuing experiment since the Apollo-Era



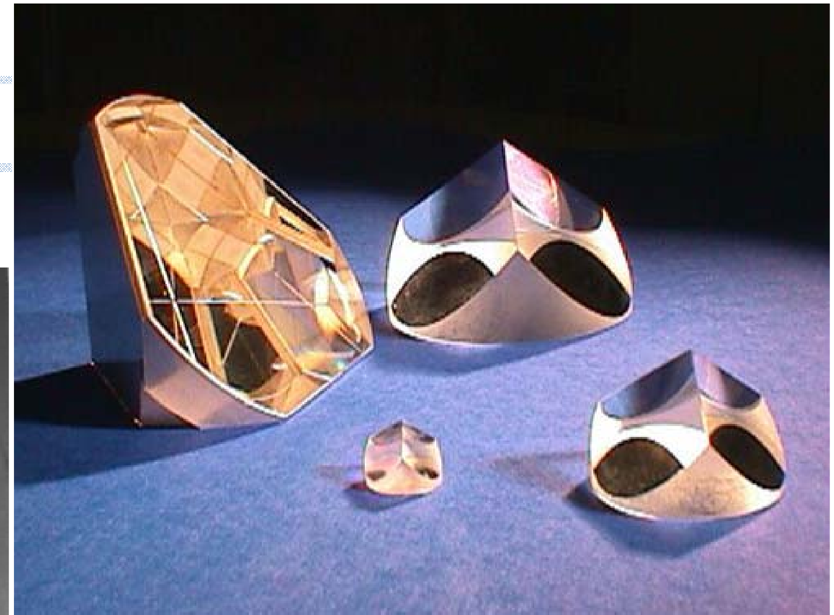
LUNAR LASER RANGING SCEINCE

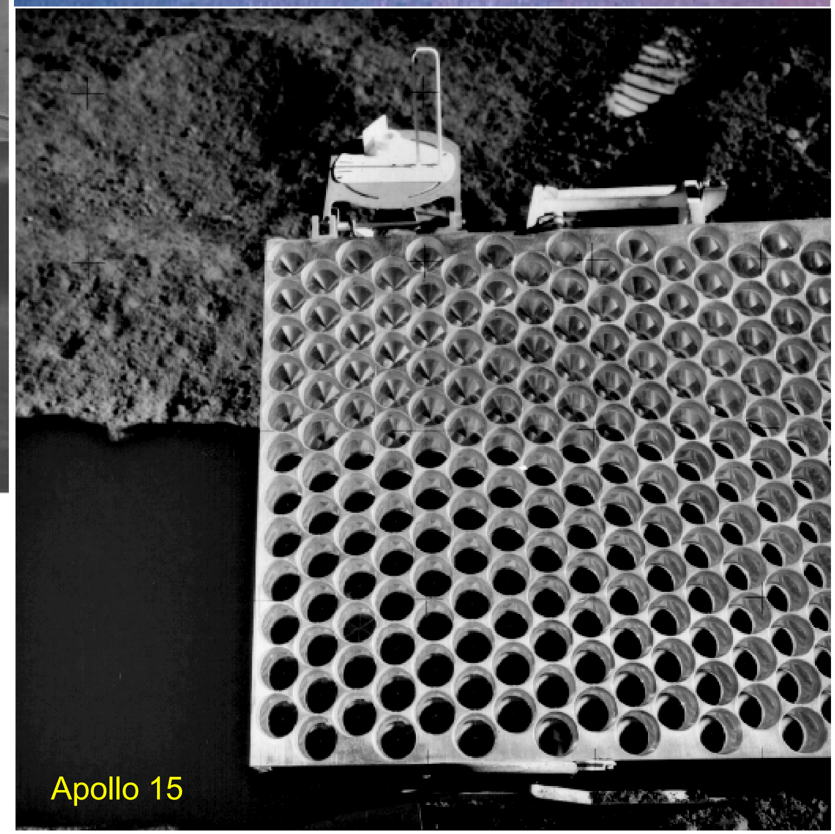
Lunar Retroreflectors

French-built retroreflector array



Lunokhod Rover (USSR, 1972)





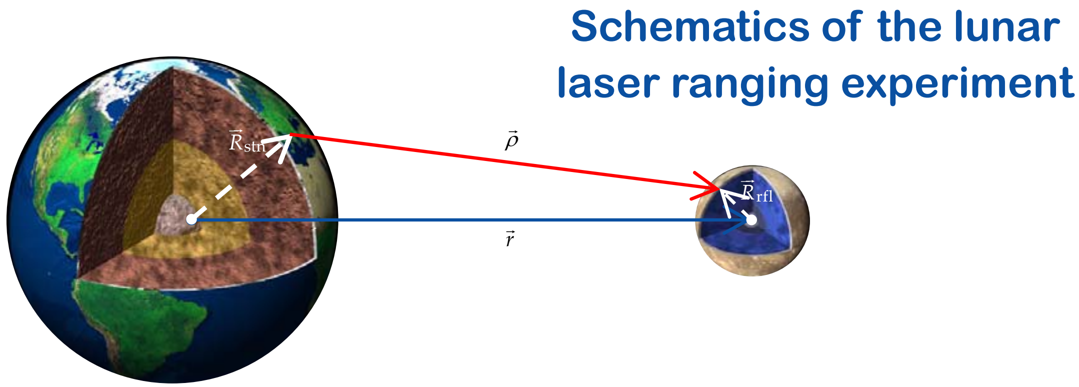
Apollo 15

Beginning of the laser ranging technology.

Today, laser ranging has many applications:

- Satellite laser ranging, communication systems, metrology, 3-D scanning, altimetry, etc.

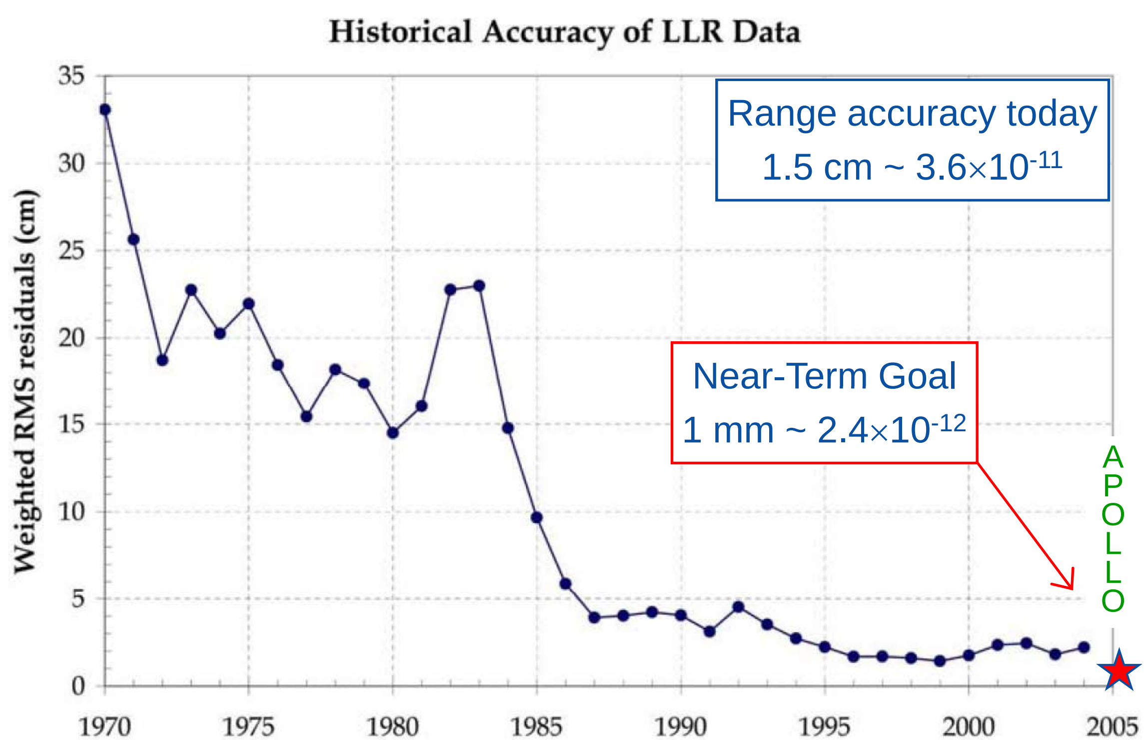
Historical Accuracy of LLR



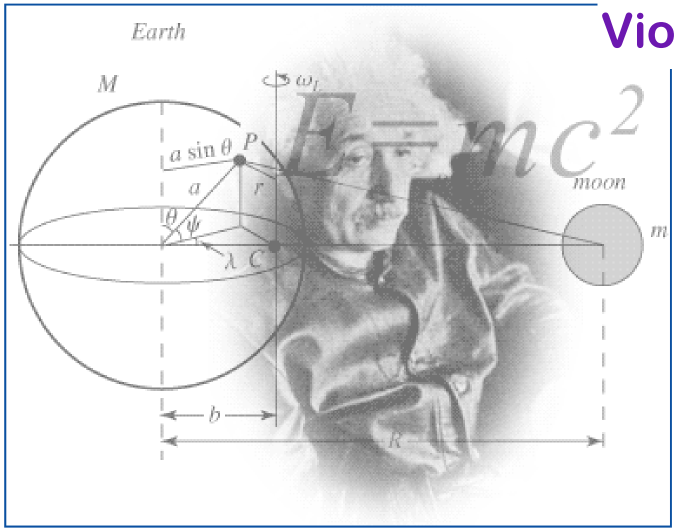
- Raw ranges vary by ~1,000s km
- Present range accuracy ~1.5cm

Solution parameters include:

- Dissipation: tidal and solid / fluid core mantle boundary (CMB);
- Dissipation related coefficients for rotation & orientation terms;
- Love numbers k_2, h_2, l_2;
- Correction to tilt of equator to the ecliptic – approximates influence of CMB flattening;
- Number of relativity parameters.



Testing General Relativity with LLR



Violation of the Equivalence Principle in PPN formalism:

$$\frac{\Delta a}{a} \equiv \frac{2(a_1 - a_2)}{(a_1 + a_2)} = \left(\frac{m_G}{m_I}\right)_1 - \left(\frac{m_G}{m_I}\right)_2, \qquad \frac{m_G}{m_I} = 1 + (4\beta - \gamma - 3)\frac{\Omega}{mc^2}$$

$$\frac{\Delta a}{a} = \eta \cdot \left(\frac{\Omega_e}{m_e c^2} - \frac{\Omega_m}{m_m c^2}\right) = -\eta \cdot 4.45 \times 10^{-10}, \qquad \eta \equiv 4\beta - \gamma - 3.$$

If η =1, this would produce a 13 m displacement of lunar orbit. By 2007, range accuracy is ~1.5 cm, the effect was not seen.

Recent LLR results (April 2008):

16,471 normal points through May 29, 2007, including 147 APOLLO points plus MLRS, OCA, and HALA

$$\Delta\left(\frac{m_G}{m_I}\right) = (-0.95 \pm 1.30) \times 10^{-13}$$ – corrected for solar radiation pressure from Vokrouhlicky (1997).

$$\frac{\Delta a}{a} = (-1.95 \pm 1.91) \times 10^{-13}$$ – test of the Strong Equivalence Principle with Adelberger (2001) results for WEP $\quad \eta = 4\beta - \gamma - 3 = (4.4 \pm 4.3) \times 10^{-4}$

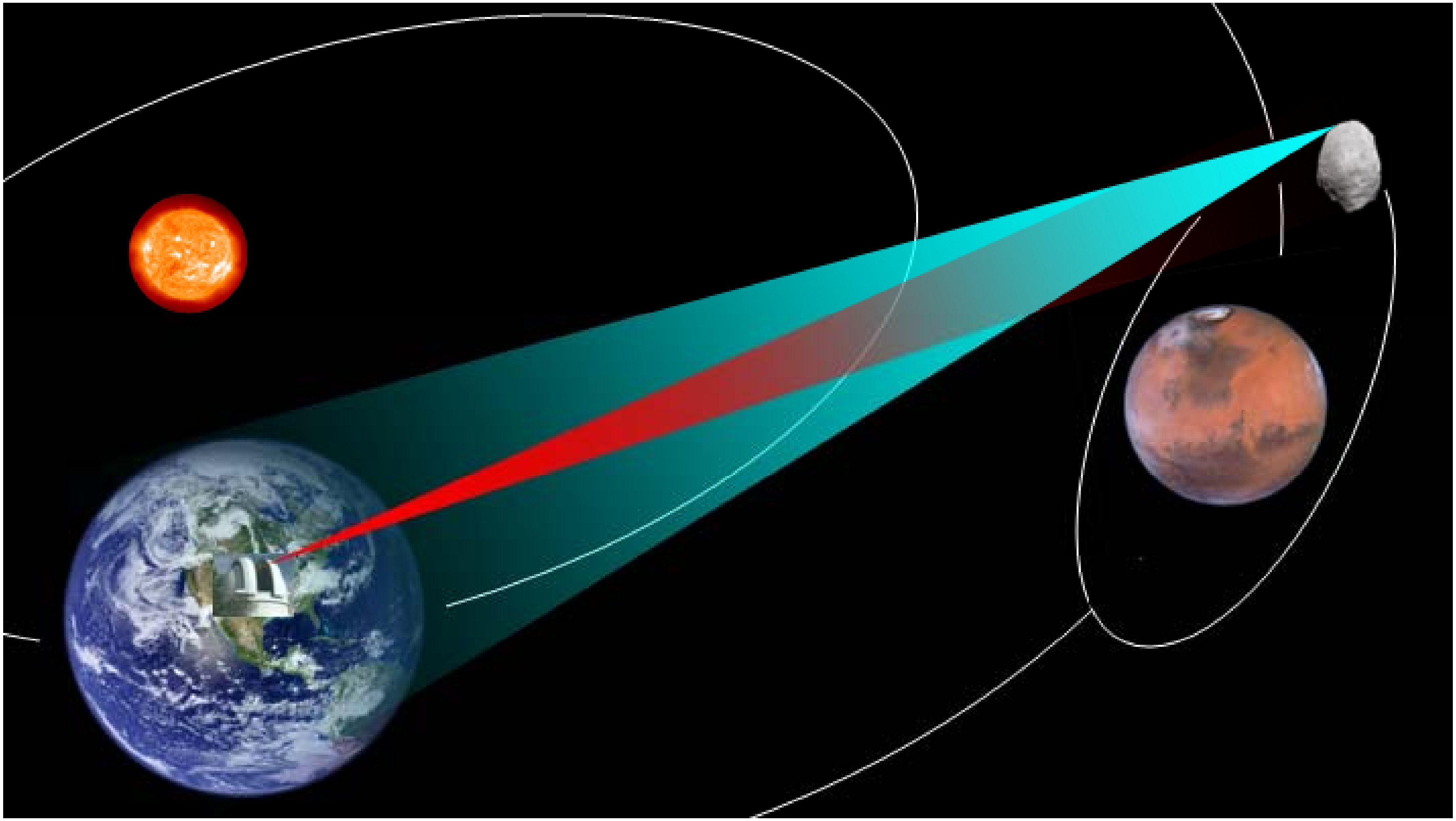
Using Cassini '03 result $\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5} \;\Rightarrow\; \beta - 1 = (1.2 \pm 1.1) \times 10^{-4}$

$$K_{\mathrm{GP}} = -0.0007 \pm 0.0047$$ – Geodetic / de Sitter-Fokker precession

$$\boxed{\dot{G}/G = (4.9 \pm 5.7) \times 10^{-13} \ \ \mathrm{yr}^{-1}}$$

Pulsars are getting competitive

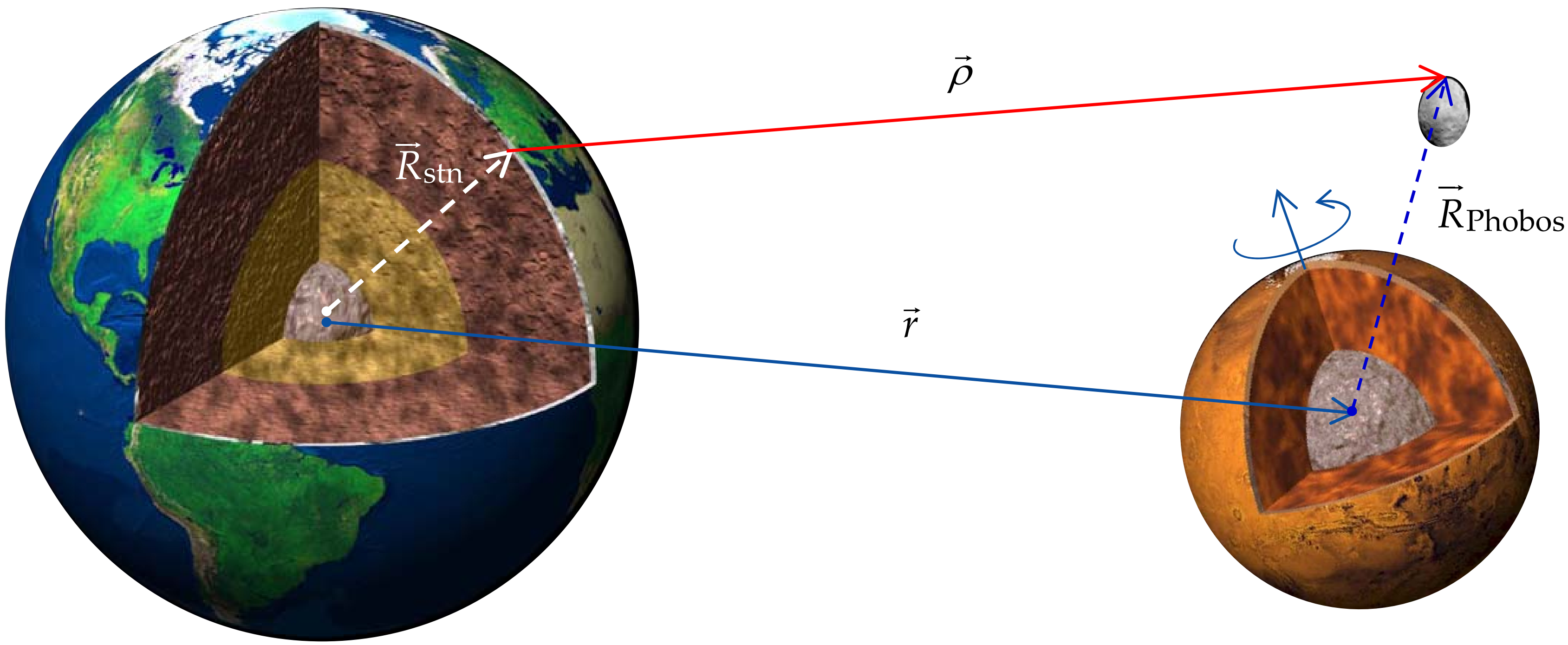
Phobos Laser Ranging Architecture



Next Step – Interplanetary Laser Ranging

Phobos Laser Ranging: Principle

1 mm range accuracy with PLR is possible



Impact on:

- Test of general relativity
- The science of Phobos, especially its interior

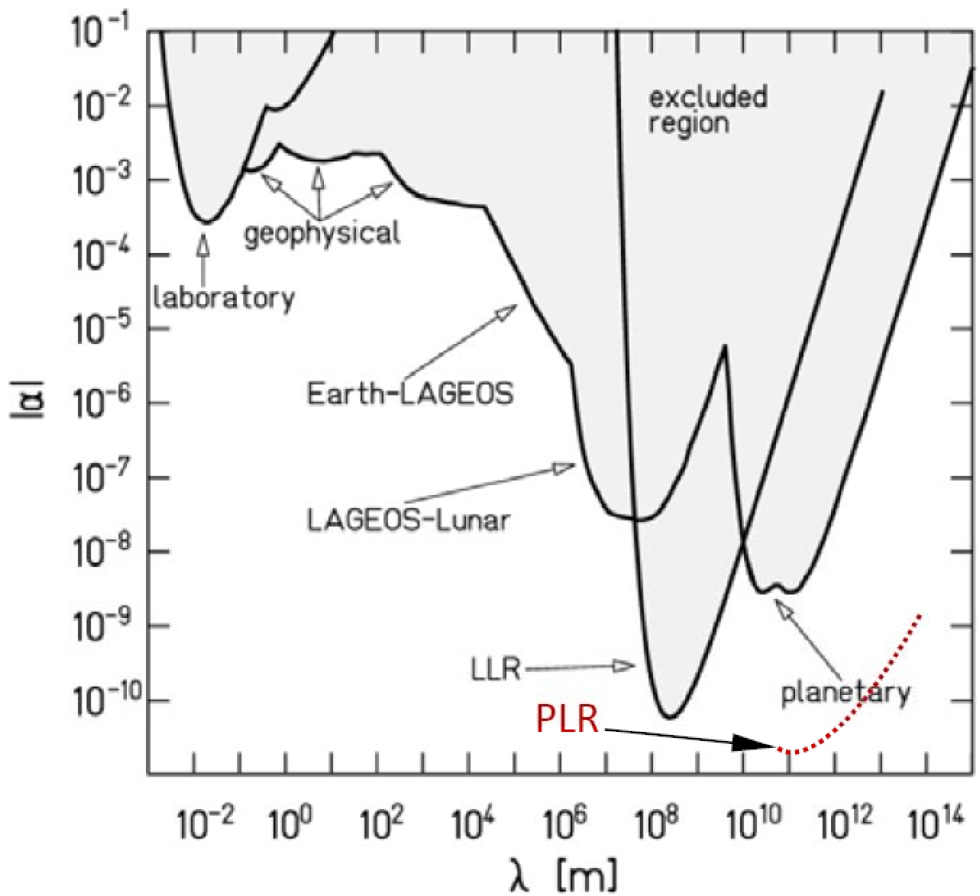
@ $550M (FY 2009 $)

Gravity Tests with PLR vs Experiment Duration

Relativistic Effect	Current best	Mission duration / N of conjunctions		
		1 yr / 1 cnj	3 yr / 2 cnj	6 yr / 3 cnj
PPN parameter γ	2.3×10^{-5}	3.1×10^{-7}	1.4×10^{-7}	7.9×10^{-8}
PPN parameter β	1.1×10^{-4}	4.3×10^{-4}	1.6×10^{-4}	9.4×10^{-5}
Test of Strong Equiv. Principle, η	4.3×10^{-4}	1.5×10^{-3}	2.8×10^{-4}	8.8×10^{-5}
Solar oblateness coeff., J_2	2.0×10^{-7}	6.9×10^{-8}	3.2×10^{-8}	2.3×10^{-8}
Search for time variation in the grav. constant G, $dG/dt/G$, yr^{-1}	7×10^{-13}	1.7×10^{-14}	2.8×10^{-15}	1.0×10^{-15}
Temporal variation of the solar mass M, $dM/dt/M$, yr^{-1}	est:7×10^{-14}	4.7×10^{-14}	1.7×10^{-14}	1.1×10^{-14}
Gravitational inverse square law	2×10^{-9} @ 1.5 AU	4×10^{-11} @ 1.5 AU	2×10^{-11} @ 1.5 AU	1×10^{-11} @ 1.5 AU

Simulations by W.M. Folkner, JPL

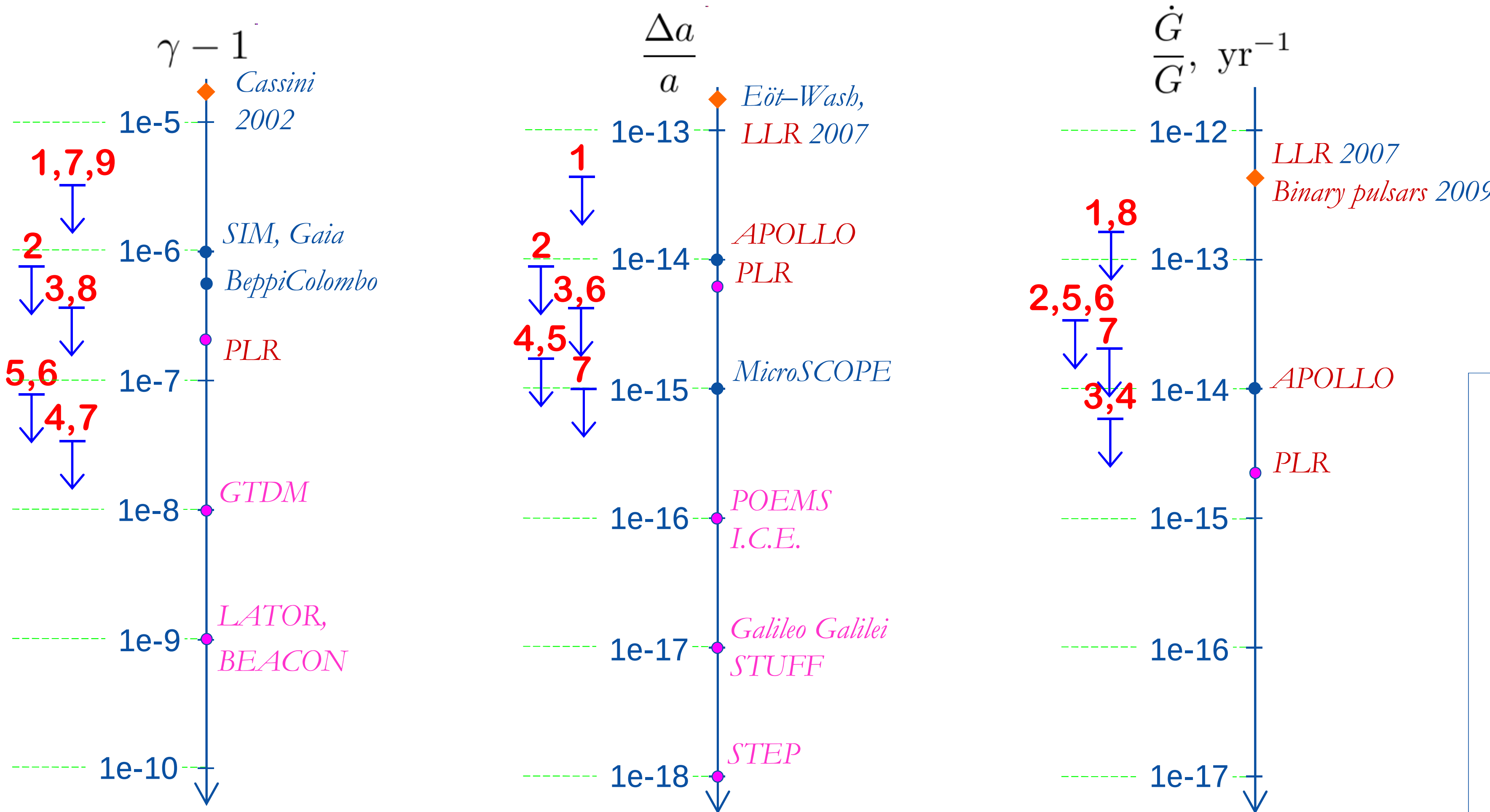
Gravity Tests with PLR: Limits on the ISL violations

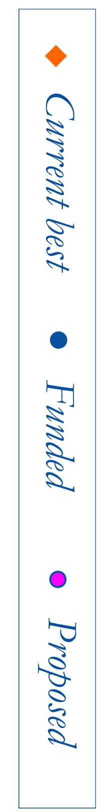


Simulations by W.M. Folkner;
background graphics from (Adelberger et al., 2003)

Theoretical Landscape of the 21th Century:

Confrontation Between Theory and Experiment





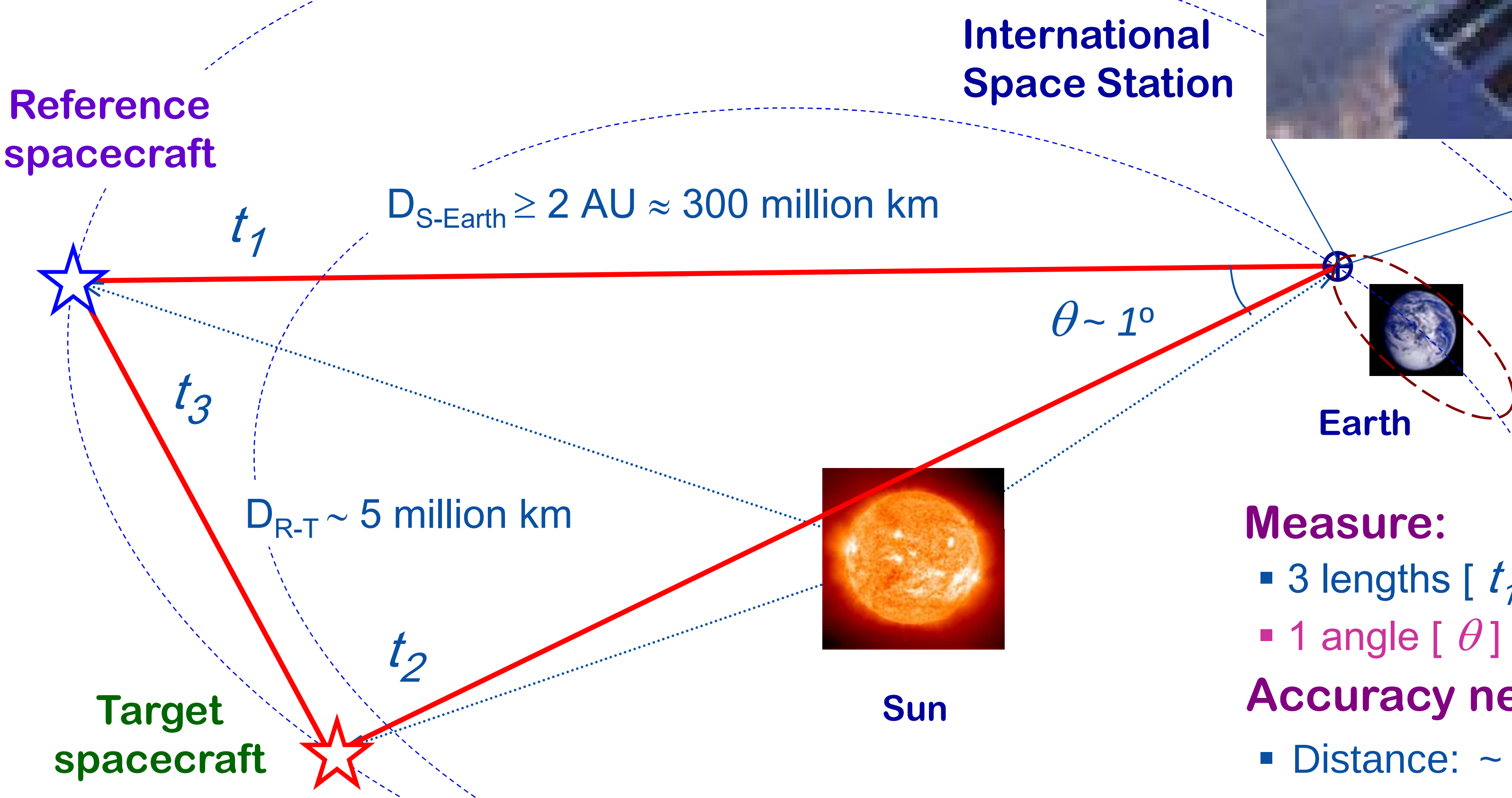
New Theories & Future Tests

1. *Damour-Polyakov-Nordtvedt 1993*
2. *Damour-Esposito-Farese 1996*
3. *Damour-Piazza-Veneziano 2002*
4. *Arkani-Dimopoulos-Dvali 2000*
5. *Dvali-Gabadadze-Poratti 2003*
6. *F(R) gravity models 2003-07*
7. *Bekenstein 2004*
8. *Moffat 2005*
9. *Jaekel-Reynaud 2006*

LASER ASTROMETRIC TEST OF RELATIVITY

LATOR Mission Concept

CQG 21 (2004) 2773-2799, gr-qc/0311020



Measure:

- 3 lengths [t_1, t_2, t_3]
- 1 angle [θ]

Accuracy needed:

- Distance: ~ 3 mm
- Angle: 0.01 picorad

Euclid is violated in gravity:

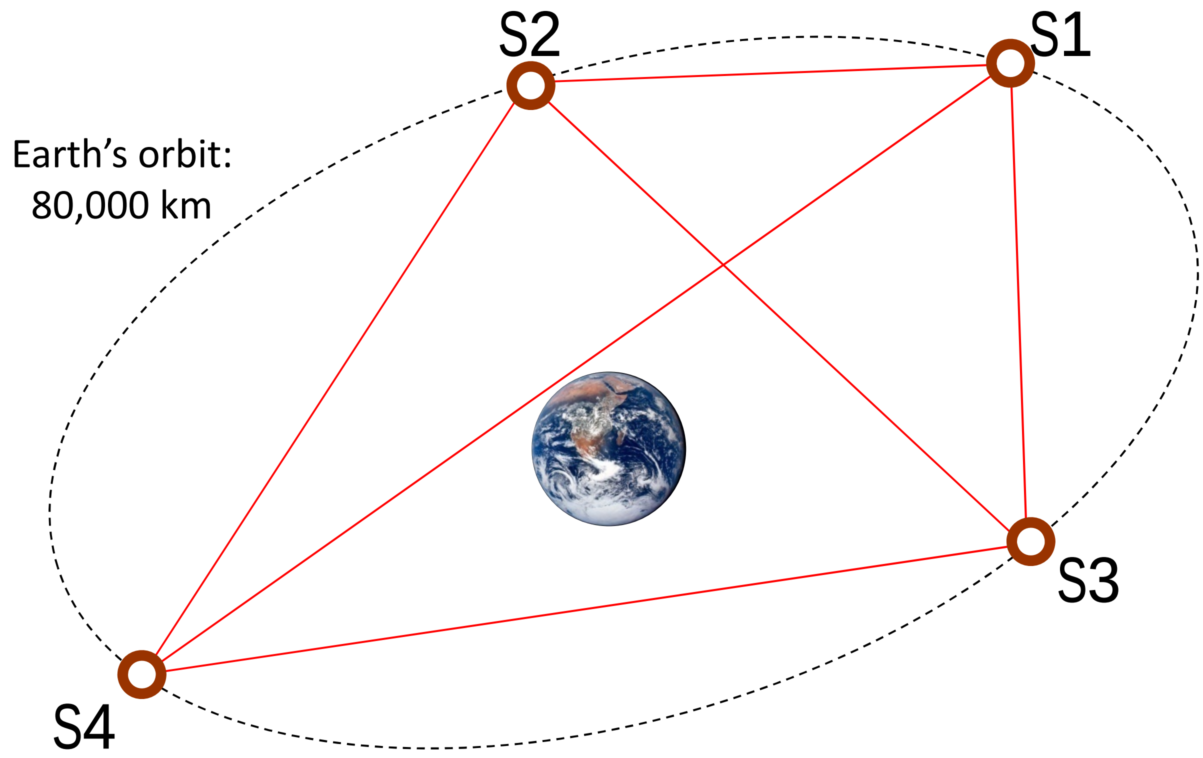
$$\cos\theta \neq (t_1^2 + t_2^2 - t_3^2)/2t_1t_2$$

Geometric redundancy enables a very accurate measurement of curvature of the solar gravity field

Accurate test of gravitational deflection of light to 1 part in 10^9

@ $630M (FY 2009 $)

Beyond Einstein Advanced Coherent Optical Network (BEACON)



Schematic of the BEACON experiment

Measure:

- 4 lengths [t_1, t_2, t_3, t_4]

Accuracy needed:

- Distance: ~ 0.1 nm

Geometric redundancy:

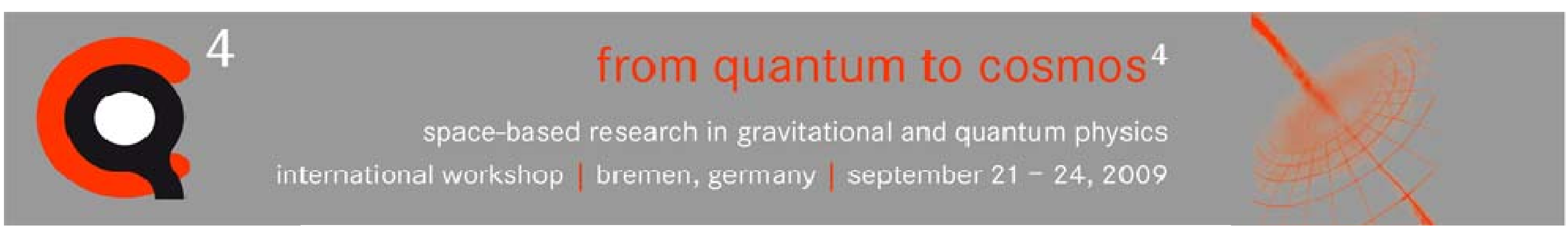
- Enables a very accurate measurement of curvature of the Earth's gravity field
- Reduces the need for drag-free spacecraft

Accurate test of gravitational delay (Shapiro effect) of light to 1 part in 10^9

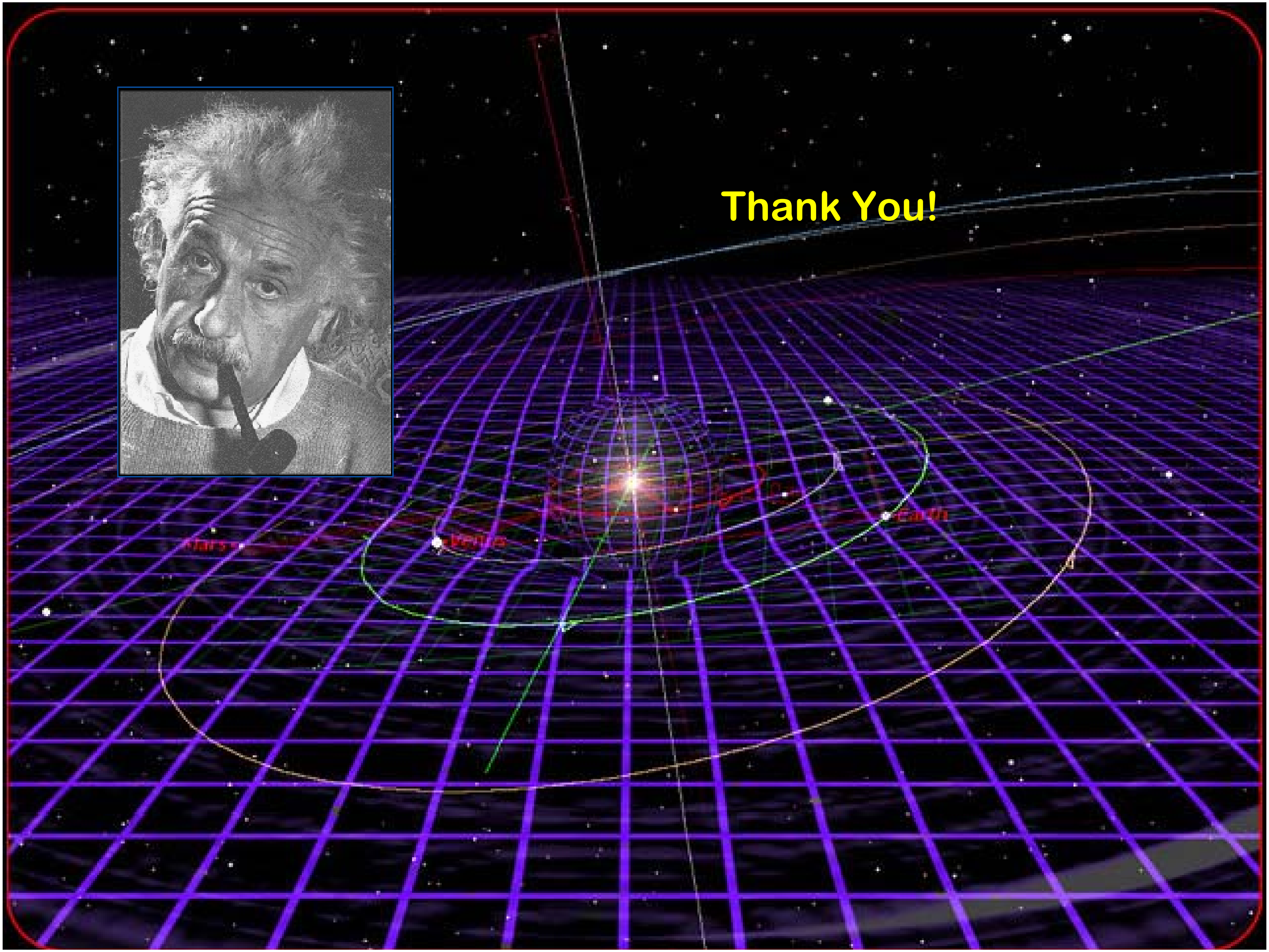
@ $680M (FY 2009 $)

Conclusions

- Recent technological progress: **arXiv:0902.3004 [gr-qc]**
  - Resulted in new instruments with unique performance
  - Could lead to major improvements in the tests of relativistic gravity
  - Already led to a number of recently proposed gravitational experiments
- Challenges remain:
  - GR is very hard to modify, embed, extend or augment (whatever is your favorite verb)…
  - Dedicated space-based experiments are very expensive – the science must worth the cost…
  - Science motivation remains the biggest challenge, as there is no strong expectation to see deviations from GR in the solar system (we are mostly looking for anomalies…)



http://www.zarm.uni-bremen.de/Q2C4/


Thank You!
Mars
Venus
Earth