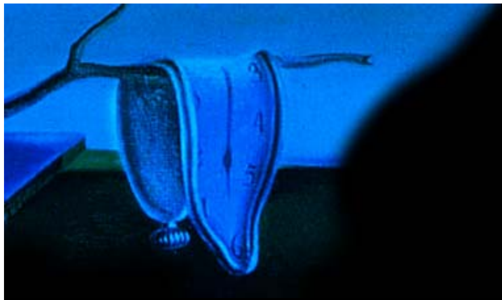


Testing Gravity in the Solar System:
Empirical Foundations of General Relativity

Slava G. Turyshev

Jet Propulsion Laboratory, California Institute of Technology

4800 Oak Grove Drive, Pasadena, CA 91009 USA

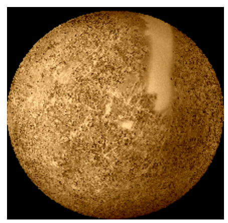
Alternative Gravities & Dark Matter Workshop

Royal Observatory, Edinburgh, Scotland, 20-22 April 2006

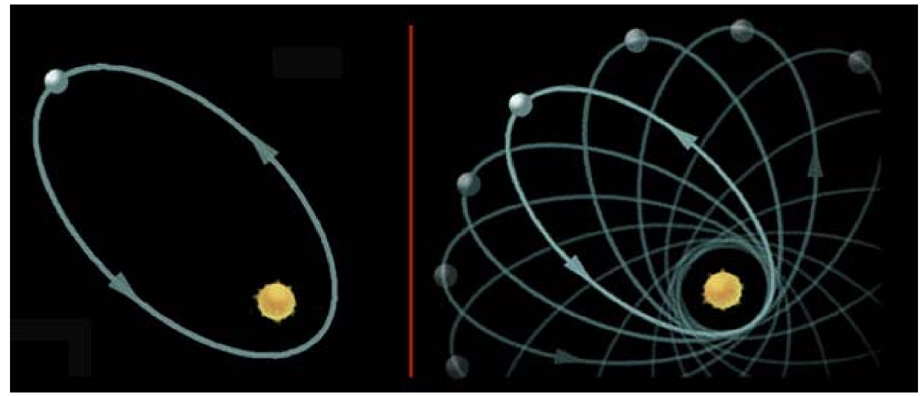
Triumph of Mathematical Astronomy in 19th Century

Discovery of Neptune: 1845

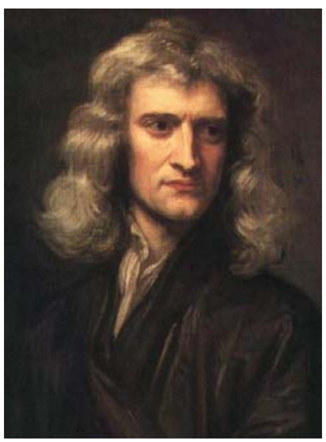
Urbain LeVerrier
(1811-1877)



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



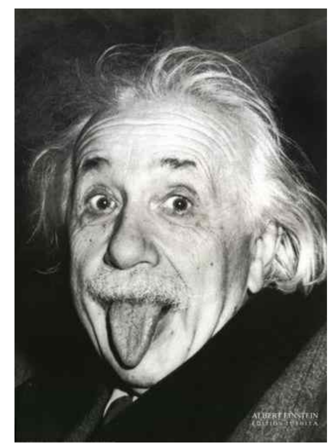
Newtonian Gravity General Relativity



Sir Isaac Newton
(1643-1727)

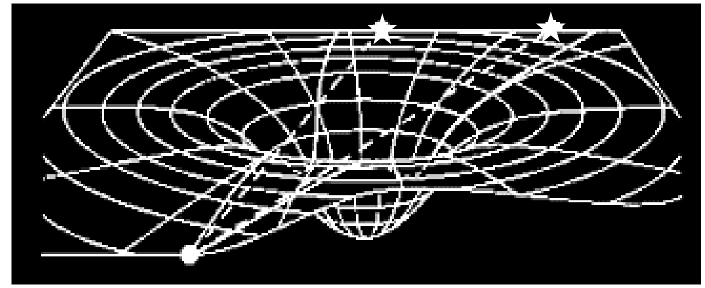
- Anomalous precession of Mercury's perihelion :
  - 43 arcsec/cy can not be explained by Newton's gravity
- Before publishing GR, in 1915, Einstein computed the expected perihelion precession of Mercury
  - When he got out 43 arcsec/cy – a new era just began!!

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

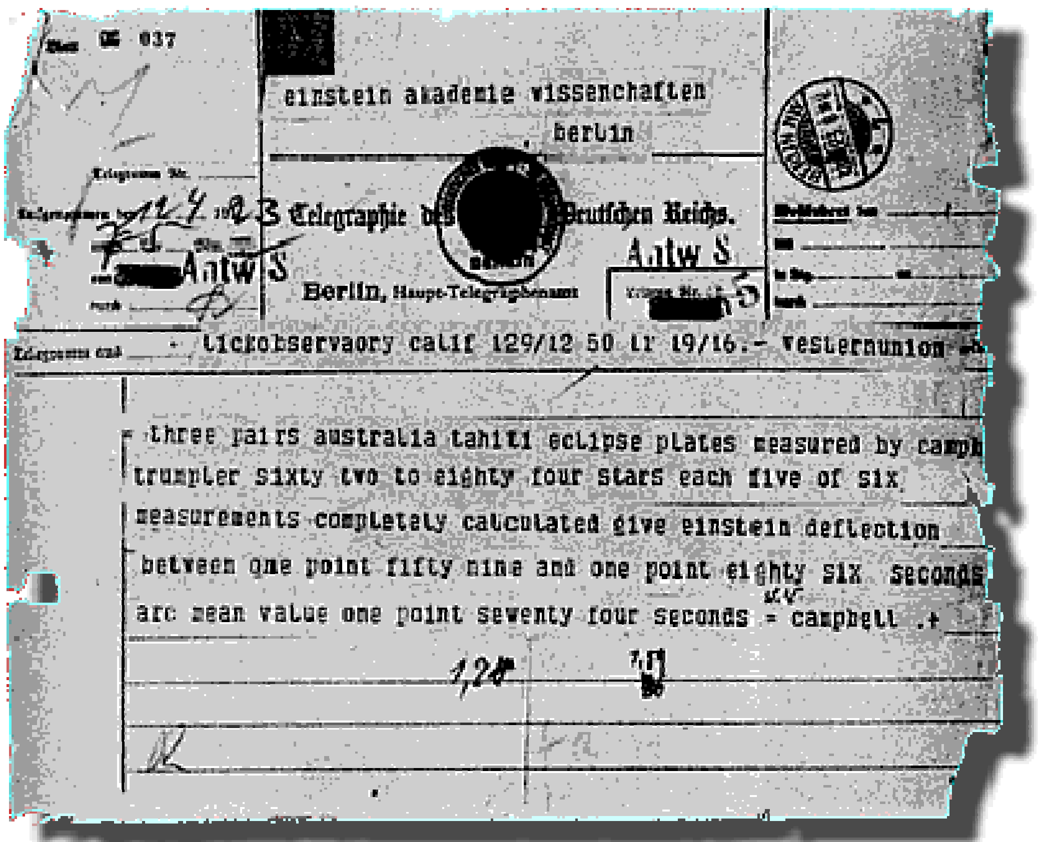


Albert Einstein
(1879-1955)

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

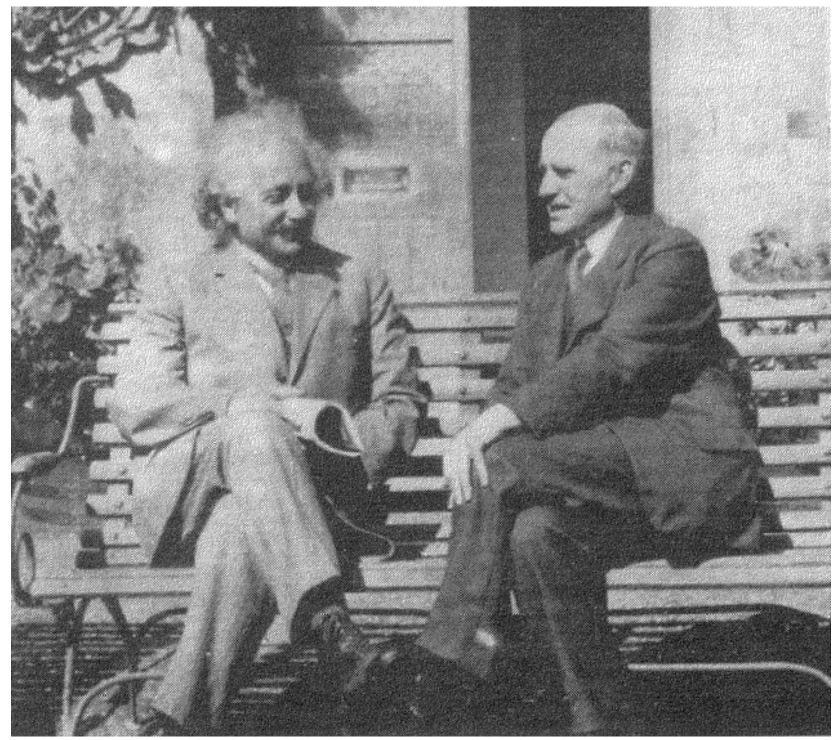
lickobservaory calif 129/12 50 lr 19/16.- westernunion

three pairs australia tahiti eclipse plates measured by camph 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

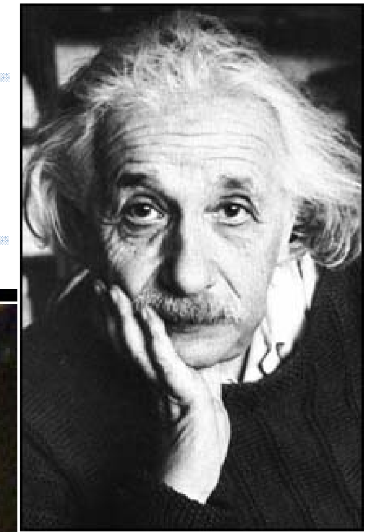
Possible outcomes in 1919:

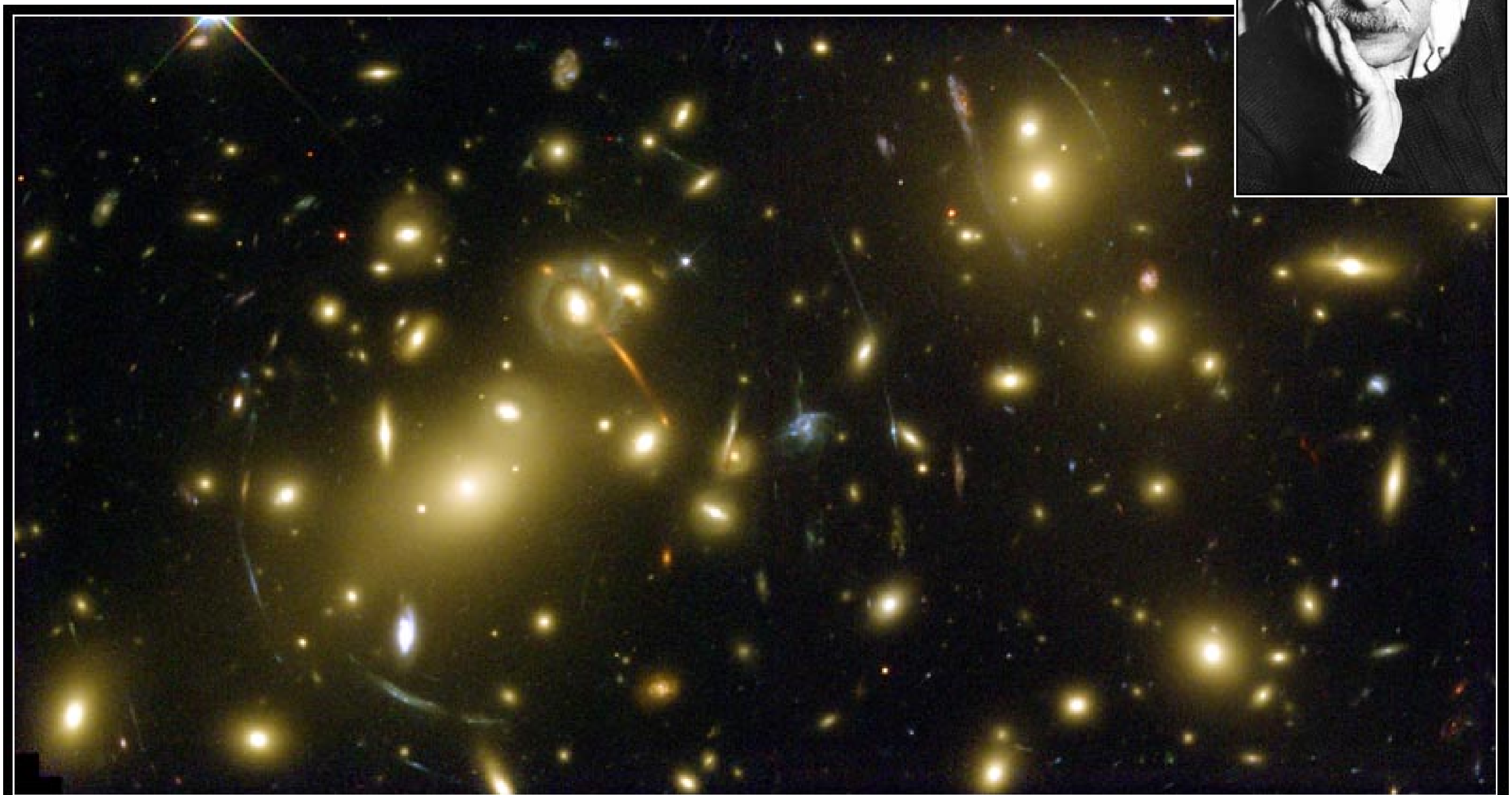
Deflection = 0;
Newton = 0.87 arcsec;
Einstein = 2 x Newton = 1.75 arcsec



Einstein and Eddington, Cambridge, 1930

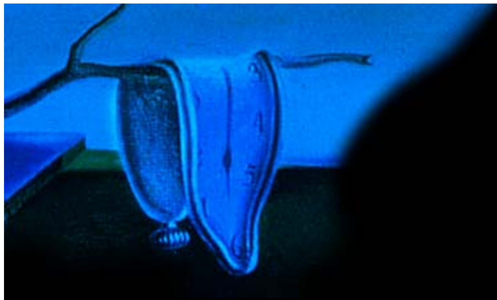
Gravitational Deflection of Light is a Well-Known Effect Today





Galaxy Cluster Abell 2218 **HST** • WFPC2

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



Theoretical landscape of early 1970s:
Competing Theories of Gravity

Newton 1686
Poincaré 1890
Einstein 1912
Nordstrøm 1912
Nordstrøm 1913
Einstein and Fokker 1914
Einstein 1916
Whitehead 1922
Cartan 1923
Fierz and Pauli 1939
Birkhoff 1943
Milne 1948
Thiry 1948
Papapetrou 1954
Papapetrou 1954
Jordan 1955
Littlewood and Bergmann 1956
Brans and Dicke 1961
Yilmaz 1962
Whitrow and Morduch 1965
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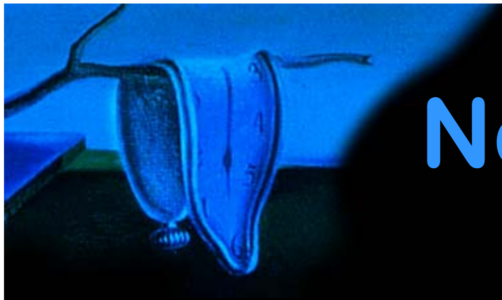
Will and Nordtvedt 1972
Ni 1973
Yilmaz 1973
Lightman and Lee 1973
Lee, Lightman and Ni 1974
Rosen 1975
Belinfante and Swihart 1975
Lee et al. 1976
Bekenstein 1977
Barker 1978
Rastall 1979
Coleman 1983
Kaluza-Klein 1932
Overlooked (20th century)

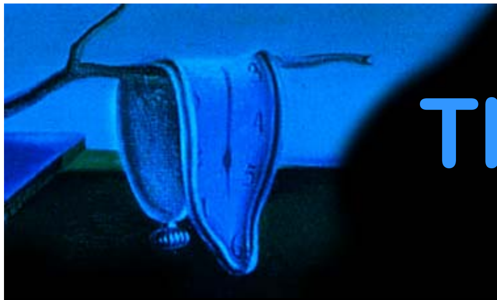


Need Criteria for Viability

Basic conditions for a successful theory of gravity:

A theory must be

- Complete
- Self-consistent
- Relativistic
- Newtonian



Theories that fail already

Newton 1686	Poincaré 1890	Einstein 1912	Nordstrøm 1912	Nordstrøm 1913
Einstein and Fokker 1914	Einstein 1916	Whitehead 1922	Cartan 1923	
Fierz and Pauli 1939	Birkhoff 1943	Milne 1948	Thiry 1948	Papapetrou 1954
Papapetrou 1954	Jordan 1955	Littlewood and Bergmann 1956	Brans and Dicke 1961	
Yilmaz 1962	Whitrow and Morduch 1965	Whitrow and Morduch 1965		
Kustaanheimo and Nuotio 1967	Deser and Laurent 1968	Page and Tupper 1968		
Bergmann 1968	Nordtvedt 1970	Bollini, Giambiagi and Tiomno 1970	Wagoner 1970	
Rosen 1971	Ni 1972	Ni 1972	Hellings and Nordtvedt 1972	Will and Nordtvedt 1972
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Belinfante and Swihart 1975	Lee et al. 1976	Bekenstein 1977	Barker 1978	Rastall 1979
Coleman 1983	Kaluza-Klein 1932	Overlooked (20^{th}century)		

Universality of Free Fall

Test the Uniqueness of Free Fall
(a.k.a. the Weak Equivalence Principle):

$$\vec{F} = m_i \, \vec{a} \quad = \quad m_g \, \vec{g}$$

$$\boxed{\Longrightarrow m_i \quad = \quad m_g}$$

All bodies fall with the same acceleration

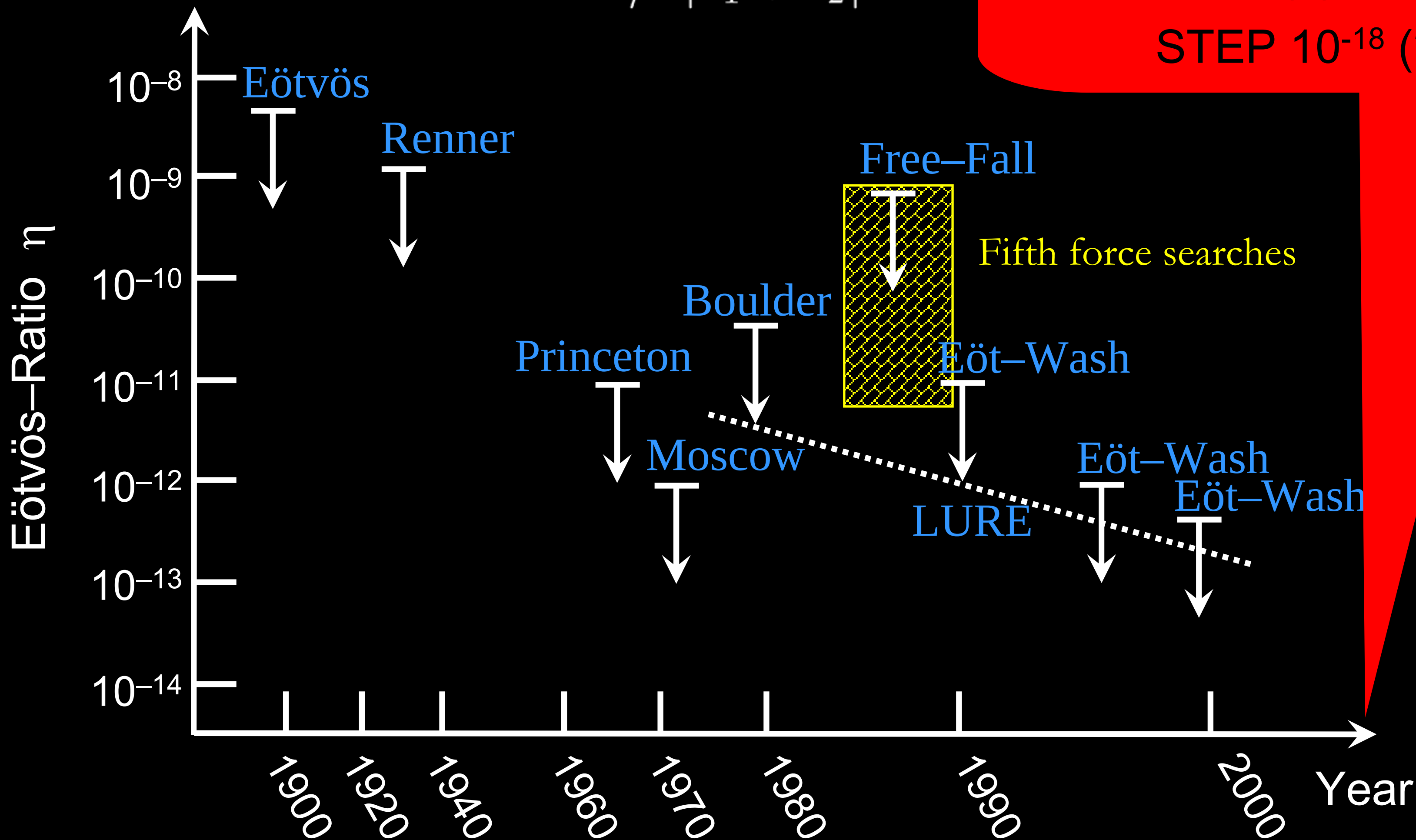
Define test parameter that signifying violation of WEP

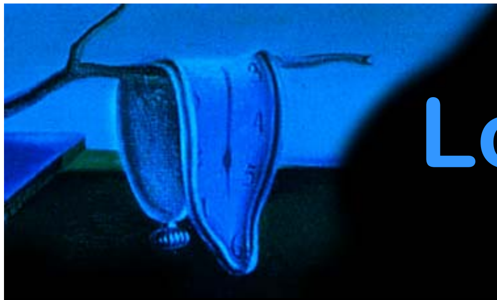
$$\eta \equiv \frac{|a_1 - a_2|}{1/2 \, |a_1 + a_2|}$$

20th Century Progress on testing WEP

$$\eta \equiv \frac{|a_1 - a_2|}{1/2\,|a_1 + a_2|}$$

Microscope 10^{-15} (2008)
TEPEE 10^{-15} (?), GG 10^{-16} (?)
STEP 10^{-18} (?)





Local Lorentz Invariance

The outcome of any local non-gravitational experiment is independent of the velocity of the freely-falling reference frame in which it is performed

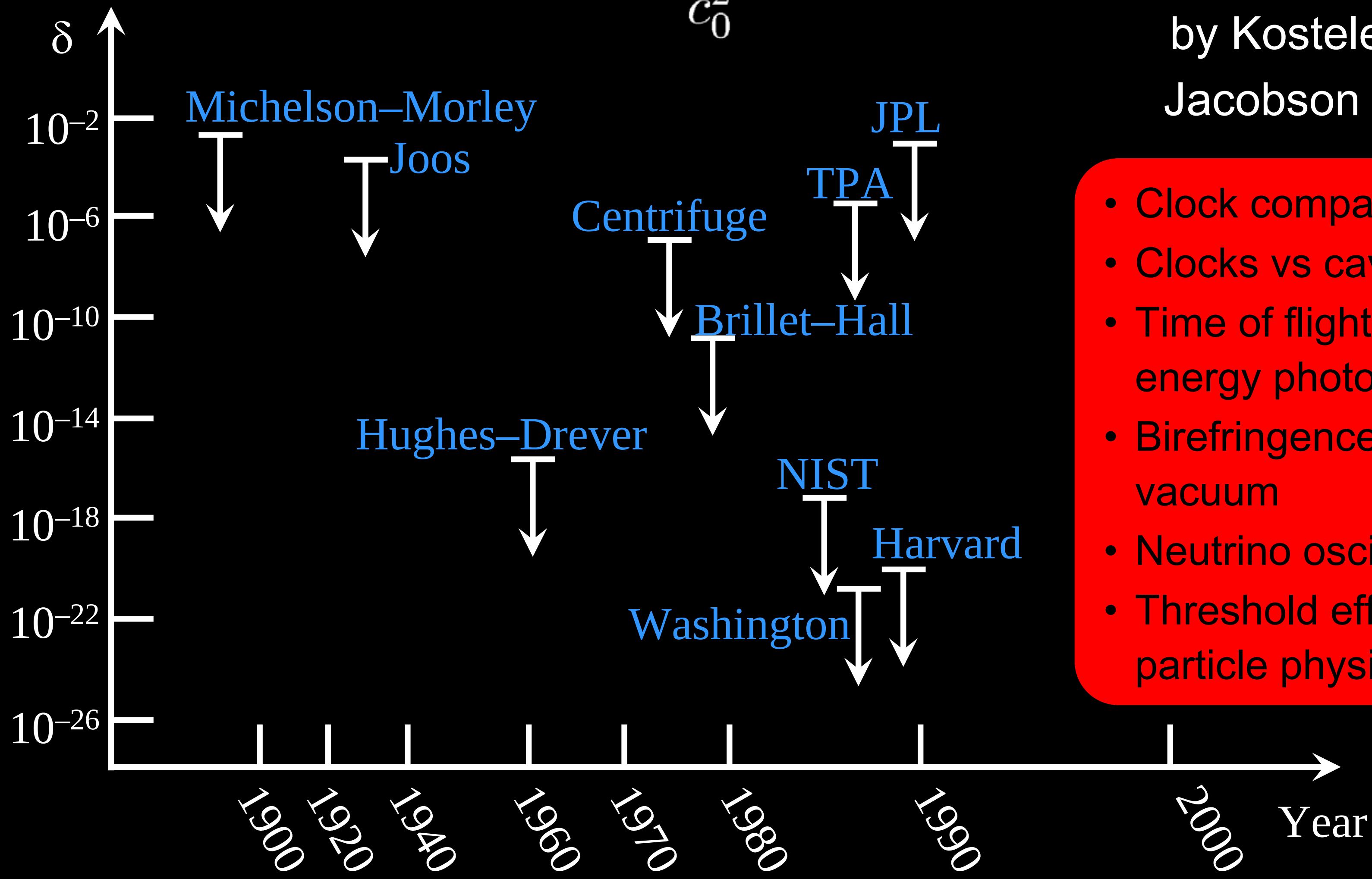
Well known from Special Relativity:

- Violations would mean
- Test parameter $c \neq c_0$

The objective is to test $\delta \equiv \frac{c^2}{c_0^2} - 1$

Upper limits on δ

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



Extended frameworks by Kostelecky, Jacobson et al.

- Clock comparisons
- Clocks vs cavities
- Time of flight of high energy photons
- Birefringence in vacuum
- Neutrino oscillations
- Threshold effects in particle physics

Local Position Invariance

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

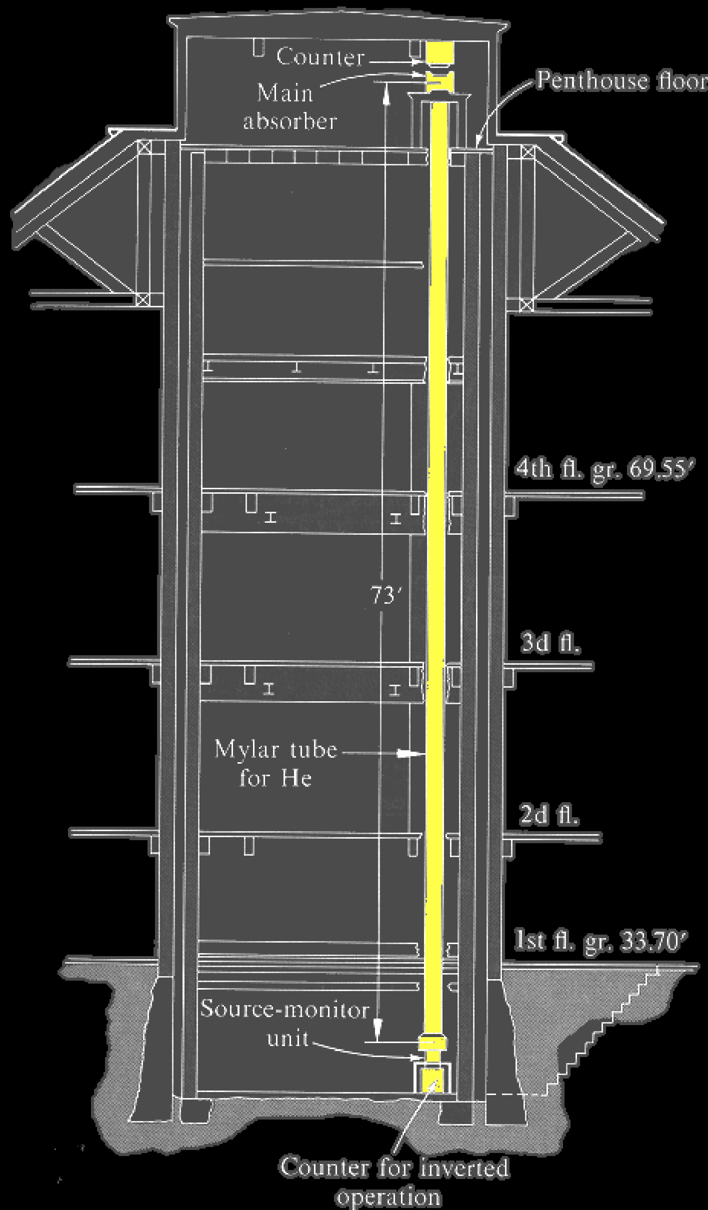
Splits into

- spatial invariance
- temporal invariance

Pound–Rebka Experiments

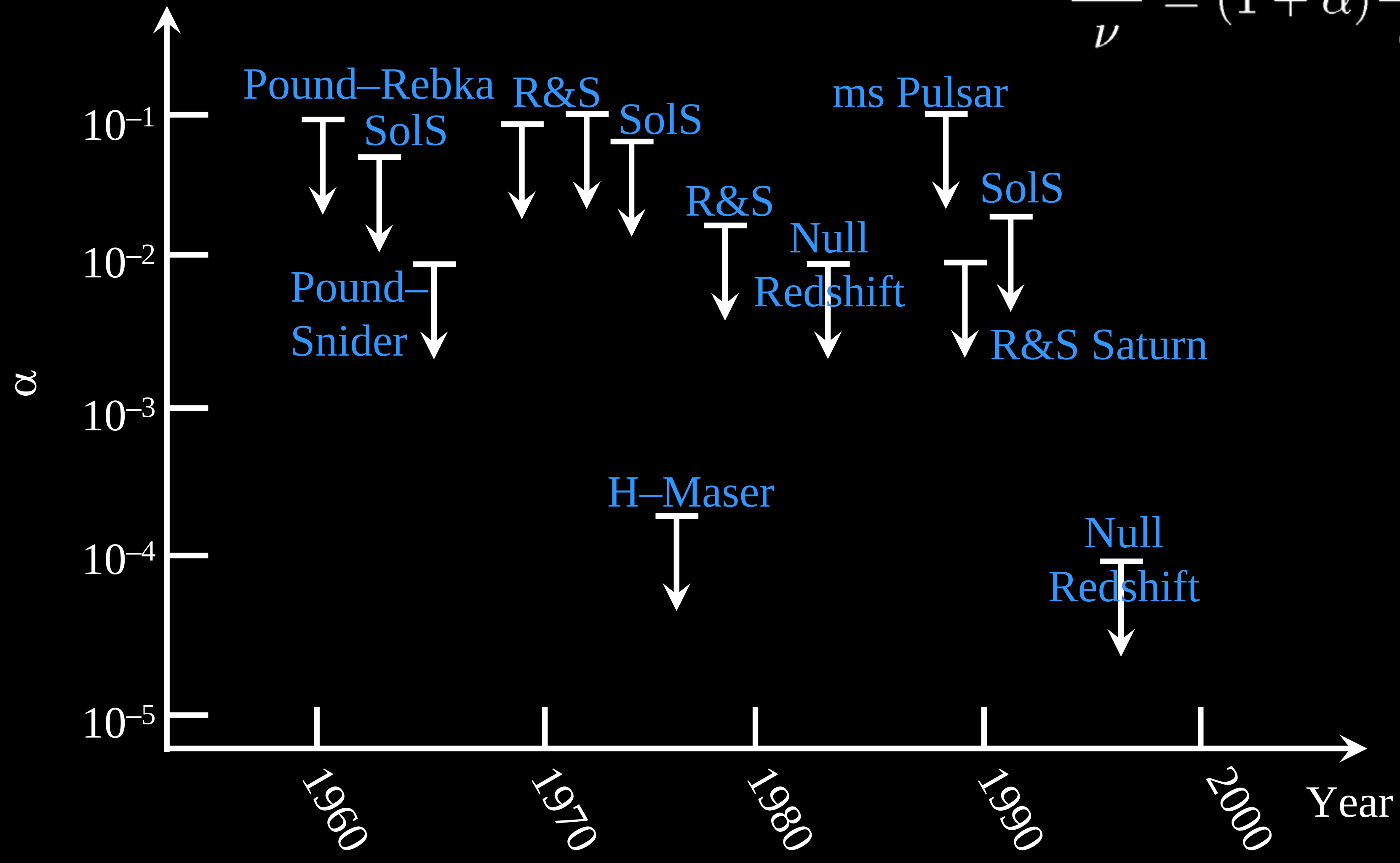
Examine
- the Gravitational Redshift to test the Spatial Local Position Invariance

Compare
- acceleration of local Lorentz frames with acceleration of test particles



Upper limits on α

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



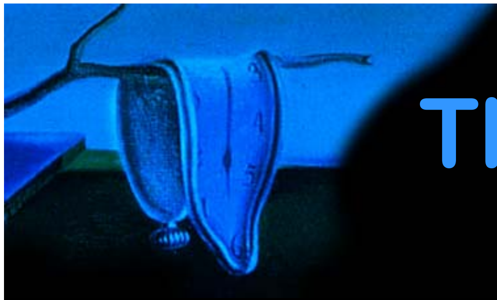
Einstein Equivalence Principle

- Einstein Equivalence Principle
  - Uniqueness of Free Fall
  - Local Lorentz Invariance
  - Local Position Invariance
- Metric Theory: Definition
  - Space-time is endowed with a symmetric metric
  - Trajectories of freely falling bodies are geodesics of that metric

Einstein Equivalence Principle

⇩

Only Metric Theories viable



Theories that violate EEP

Newton 1686 Poincaré 1890 | Einstein 1912 | Nordstrøm 1912 | Nordstrøm 1913

Einstein and Fokker 1914 | Einstein 1916 | Whitehead 1922 | Cartan 1923

Fierz and Pauli 1939 Birkhoff 1943 Milne 1948 | Thiry 1948 | Papapetrou 1954

Papapetrou 1954 | Jordan 1955 | Littlewood and Bergmann 1956 | Brans and Dicke 1961

Yilmaz 1962 | Whitrow and Morduch 1965 | Whitrow and Morduch 1965

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Bergmann 1968 | Nordtvedt 1970 | Bollini, Giambiagi and Tiomno 1970 | Wagoner 1970

Rosen 1971 | Ni 1972 | Ni 1972 | Hellings and Nordtvedt 1972 | Will and Nordtvedt 1972

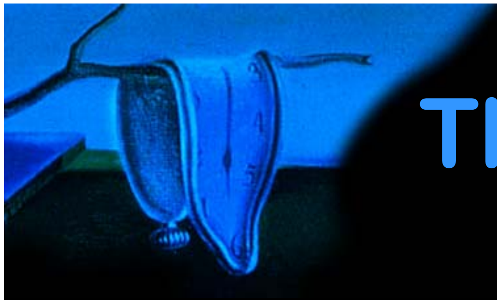
Ni 1973 | Yilmaz 1973 | Lightman and Lee 1973 | Lee, Lightman and Ni 1974 | Rosen 1975

Belinfante and Swihart 1975 | Lee et al. 1976 | Bekenstein 1977 | Barker 1978 | Rastall 1979

Coleman 1983 | Kaluza-Klein 1932 | Overlooked (20^{th} century)

Strong Equivalence Principle

- Generalized Uniqueness of Free Fall:
  All bodies fall with the same acceleration
- Generalized Local Lorentz Invariance:
  All experiments are independent of the velocity of the local Lorentz frame
- Generalized Local Position Invariance
  All experiments are independent of where and when they are performed



Theories that violate GLLI

Newton 1686
Poincaré 1890
Einstein 1912
Nordstrøm 1912
Nordstrøm 1913
Einstein and Fokker 1914
Einstein 1916
Whitehead 1922
Cartan 1923
Fierz and Pauli 1939
Birkhoff 1943
Milne 1948
Thiry 1948
Papapetrou 1954
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Wagoner 1970
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Ni 1972
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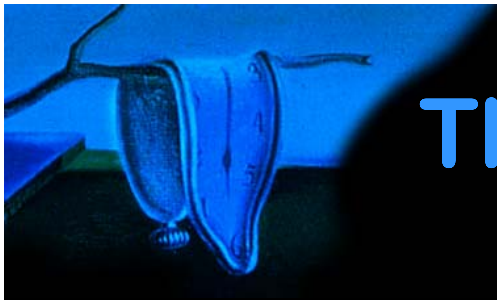

Theories that violate GLPI

Newton 1686 Poincaré 1890 Einstein 1912 Nordstrøm 1912 Nordstrøm 1913

Einstein and Fokker 1914 Einstein 1916 Whitehead 1922 Cartan 1923

Fierz and Pauli 1939 Birkhoff 1943 Milne 1948 Thiry 1948 Papapetrou 1954

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Coleman 1983 Kaluza-Klein 1932 Overlooked (20thcentury)

Parameterized Post-Newtonian Formalism (PPN) (Will & Nordtvedt, 1972)

- Solar system is the main arena to test weak gravity:
  - Expand the metrics
  - Identify various potentials
  - They have 10 PPN parameters in front

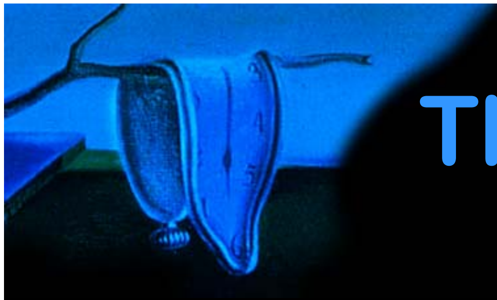
$$\gamma, \beta, \xi, \alpha_1, \alpha_2, \alpha_3, \zeta_1, \zeta_2, \zeta_3, \zeta_4$$

  - Calculate those parameters
  - Compare with experiments

- [2006: A need for Cosmological PPN?]

PPN Parameters: Their Meaning

Parameter	What it measures, relative to general relativity	Value in GR	Value in scalar tensor theory	Value in semi-conservative theories
γ	How much space curvature produced by unit mass?	1	$(1+\omega)/(2+\omega)$	γ
β	How "non-linear" is gravity?	1	$1 + \Lambda$	β
ξ	Preferred-location effects?	0	0	ξ
α_1	Preferred-frame effects?	0	0	α_1
α_2		0	0	α_2
α_3		0	0	0
ζ_1	Is momentum conserved?	0	0	0
ζ_2		0	0	0
ζ_3		0	0	0
ζ_4		0	0	0



Theories that predict $\gamma = 0$ fail

Newton 1686 Poincaré 1890 Einstein 1912 Nordstrøm 1912 Nordstrøm 1913

Einstein and Fokker 1914 Einstein 1916 Whitehead 1922 Cartan 1923

Fierz and Pauli 1939 Birkhoff 1943 Milne 1948 Thiry 1948 Papapetrou 1954

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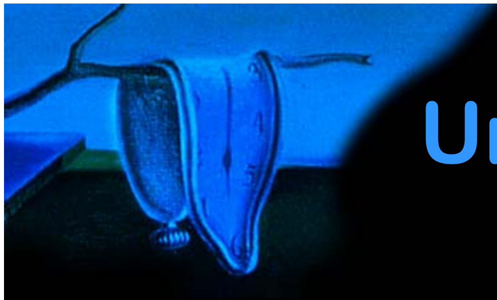

Unlikely Scalar-Tensor Theories

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Einstein and Fokker 1914 Einstein 1916 Whitehead 1922 Cartan 1923

Fierz and Pauli 1939 Birkhoff 1943 Milne 1948 Thiry 1948 Papapetrou 1954

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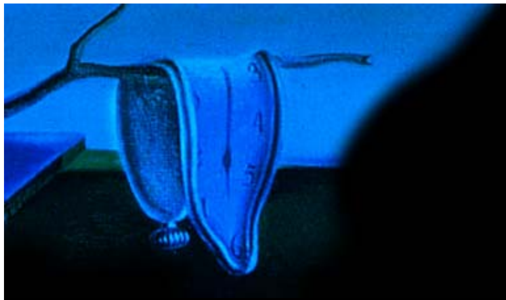

Theories that fail to explain planetary perihelion advance

Newton 1686 Poincaré 1890 Einstein 1912 Nordstrøm 1912 Nordstrøm 1913

Einstein and Fokker 1914 Einstein 1916 Whitehead 1922 Cartan 1923

Fierz and Pauli 1939 Birkhoff 1943 Milne 1948 Thiry 1948 Papapetrou 1954

Papapetrou 1954 Jordan 1955 Littlewood and Bergmann 1956 Brans and Dicke 1961

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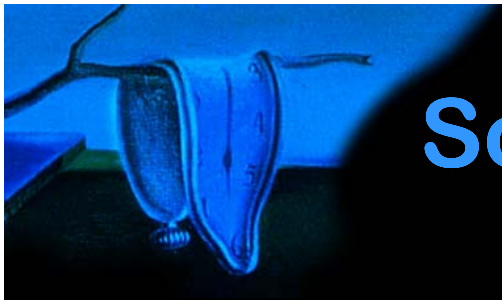

Some theories resist to fail

Newton 1686 Poincaré 1890 Einstein 1912 Nordstrøm 1912 Nordstrøm 1913

Einstein and Fokker 1914 **Einstein 1916** Whitehead 1922 Cartan 1923

Fierz and Pauli 1939 Birkhoff 1943 Milne 1948 Thiry 1948 Papapetrou 1954

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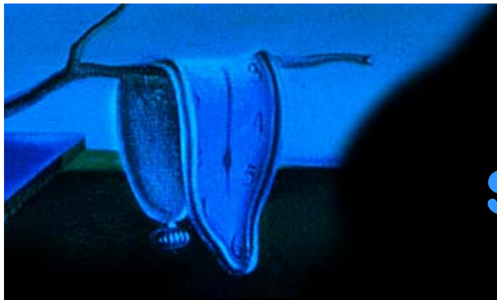

Theories that fail strong field tests – GW & pulsars

Newton 1686 Poincaré 1890 Einstein 1912 Nordstrøm 1912 Nordstrøm 1913

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Fierz and Pauli 1939 Birkhoff 1943 Milne 1948 Thiry 1948 Papapetrou 1954

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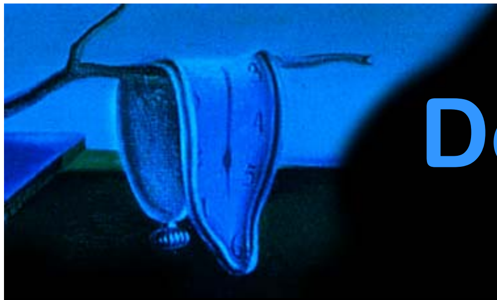


Do we really need Aesthetics?

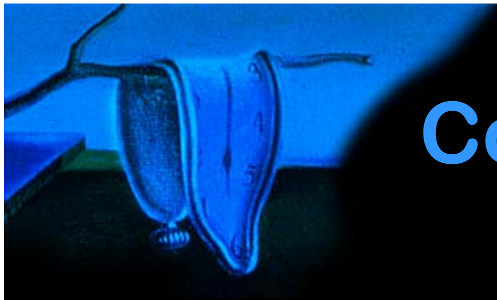
“[...] Unfortunately, any finite number of effects can be fitted by a sufficiently complicated theory. [...] Aesthetic or philosophical motives will therefore continue to play a part in the widespread faith in Einstein's theory, even if all tests verify its predictions.”

– Malcolm MacCallum, 1976

Philosophical Aspect

"Among all bodies of physical law none has ever been found that is simpler and more beautiful than Einstein's geometric theory of gravity"

– Misner, Thorne and Wheeler, 1973



Conclusion for 20th Century Tests

Newton 1686 Poincaré 1890 Einstein 1912 Nordstrøm 1912 Nordstrøm 1913

Einstein and Fokker 1914 **Einstein 1916** Whitehead 1922 Cartan 1923

Fierz and Pauli 1939 Birkhoff 1943 Milne 1948 Thiry 1948 Papapetrou 1954

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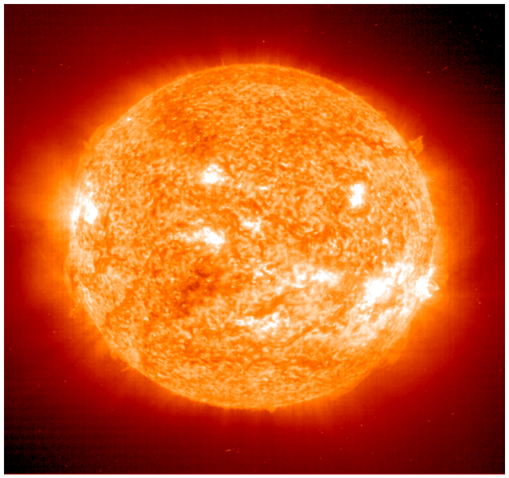
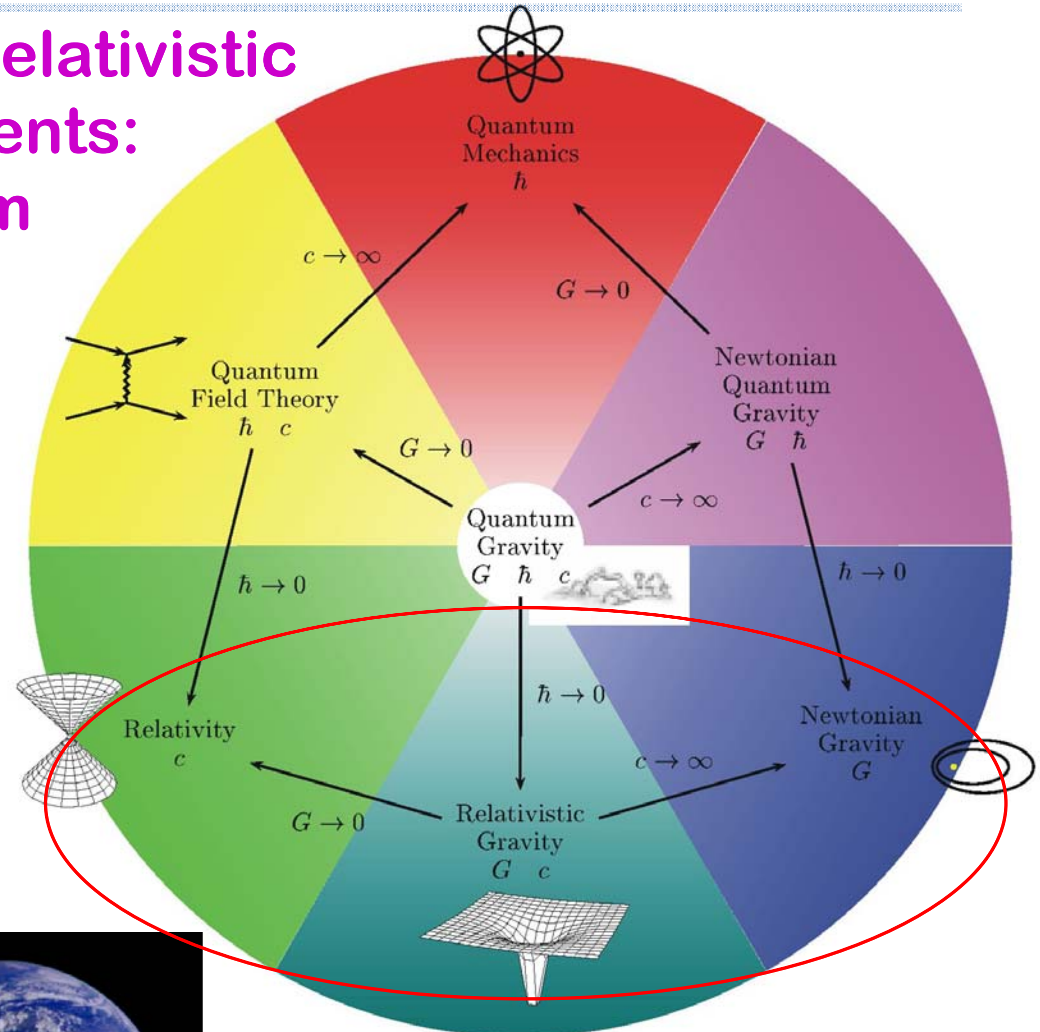
Coleman 1983 Kaluza-Klein 1932 Overlooked (20th century)

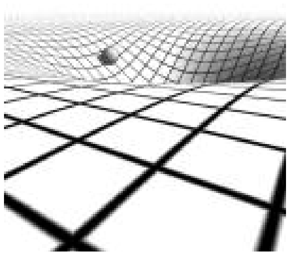
Laboratory for Relativistic Gravity Experiments: Our Solar System





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 immediate solar proximity

35 Years of Solar System Gravity Tests

Techniques for Gravity Tests:

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

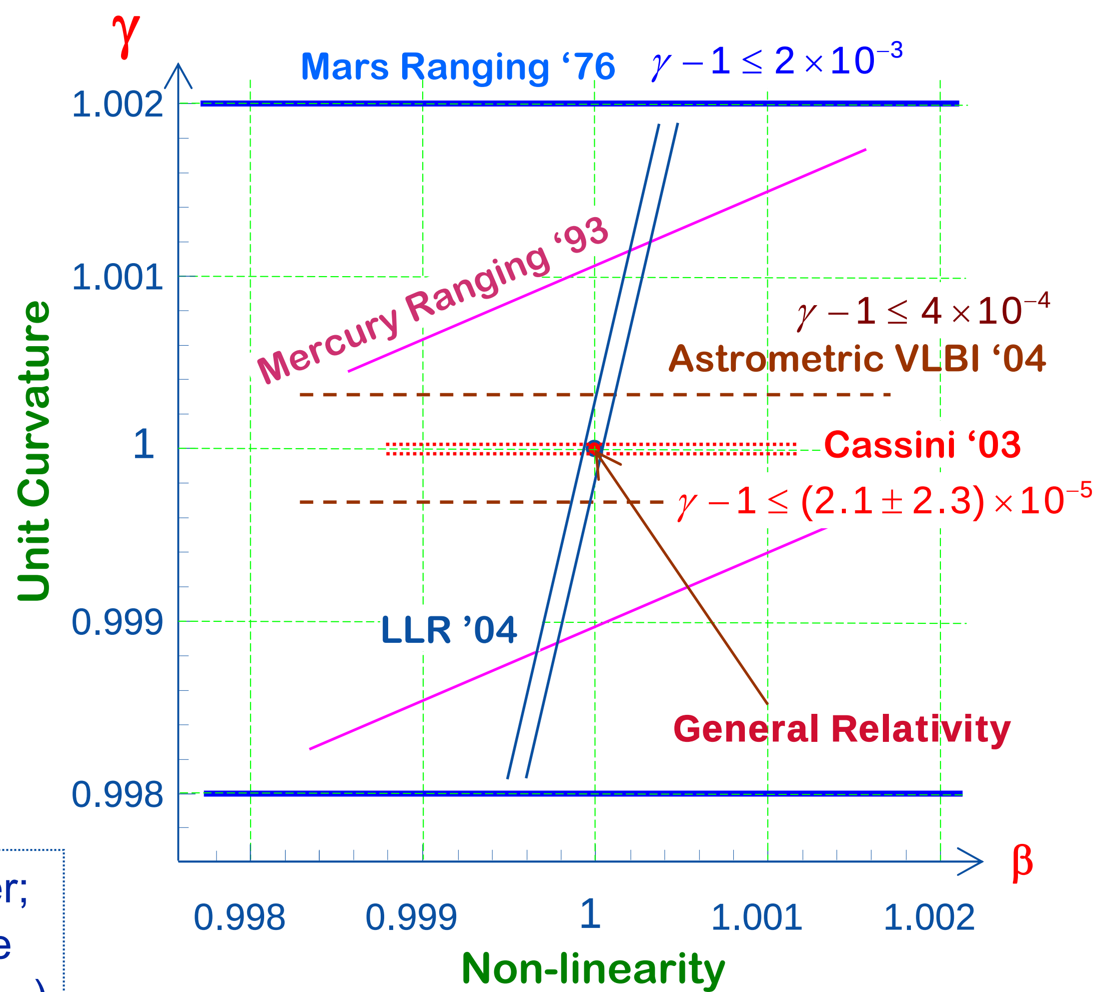
Laser:
- SLR, LLR, interplanetary, etc.

Dedicated Gravity Missions:

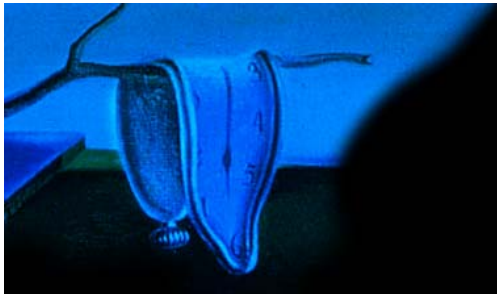
- **LLR (1969 - on-going!!)**
- GP-A, '76; LAGEOS, '76,'92; GP-B, '07; LISA, 2015

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 35 years is impressive, but is not enough for the near future!



Current (2006) Bounds on the PPN Parameters

Parameter	Effect or Experiment	Bound	Remarks
$\gamma - 1$	Time delay	2.3×10^{-5}	Cassini tracking
	Light deflection	4×10^{-4}	VLBI
β -	Perihelion shift	3×10^{-3}	$J_2 = 2 \times 10^{-7}$ from helioseismology
	Nordtvedt effect	5×10^{-4}	LLR, $\eta < 3 \times 10^{-4}$ assumed η^*
	des	10^{-3}	gravimeters
α_1	Orbit polarization	10^{-4}	LLR
		2×10^{-4}	J2317-
α_2	Spin precessi		Sun axis' alignment with ecliptic
α_3	Self-accelerati		Pulsar spindown statistics
ζ_1	--	2×10^{-2}	Combined PPN bounds
ζ_2	Binary acceleration	4×10^{-5}	PSR 1913+16
ζ_3	Newton's 3rd law	10^{-8}	Lunar acceleration
ζ_4	--		Not independent

GAIA (2011) 10^{-6}
LATOR 10^{-9}

APOLLO 3×10^{-5}

BepiColombo (2012)
$J_2 \sim 10^{-8}$

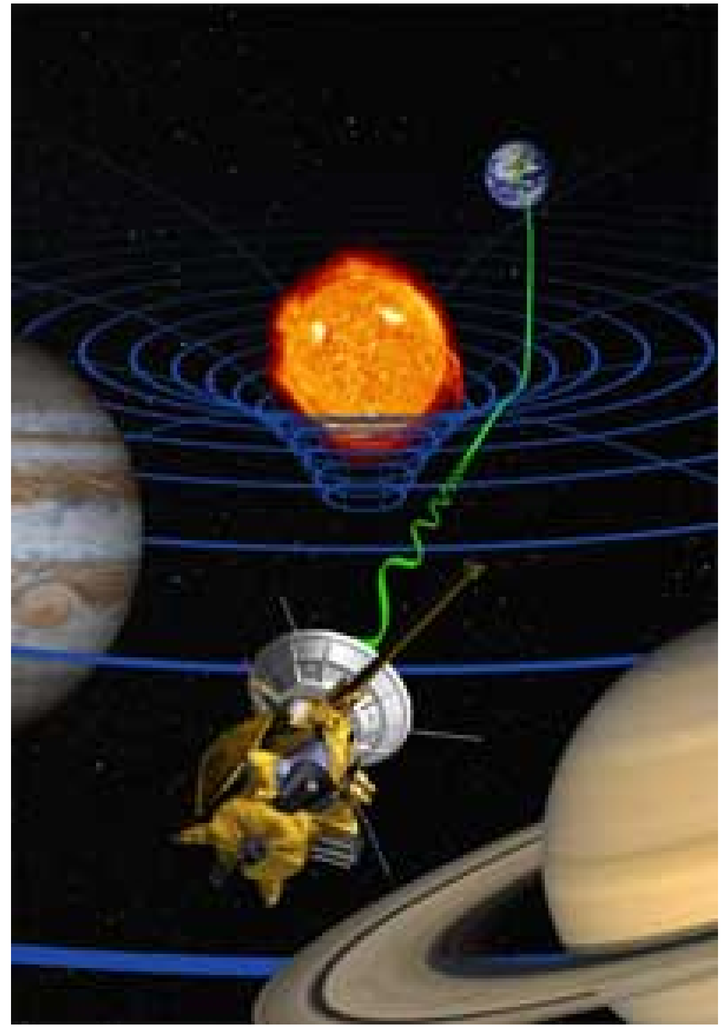
$\eta = 4\beta - \gamma - 3 - 10\xi/3 - \alpha_1 + 2\alpha_2/3 - 2\zeta_1/3 - \zeta_2/3$

Bound on scalar-tensor gravity: $\omega > 40{,}000$

Cassini 2003: Where Do We Go From Here?

Cassini Conjunction Experiment 2002:

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

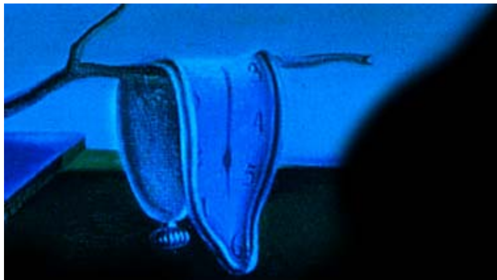


Possible with Existing Technologies?!

- VLBI [current $\gamma = 4 \times 10^{-4}$]: in 5 years $\sim 5 \times 10^{-5}$:
  - # of observations (1.6M to 16M → factor of 3)
- μ-wave ranging to a Lander on Mars $\sim 6 \times 10^{-6}$
- Optical astrometry [current $\gamma = 3 \times 10^{-3}$]:

  SIM & GAIA $\sim 1 \times 10^{-6}$ (2015/16?)
- LLR [current $\eta = 4 \times 10^{-4}$]: in 5 years $\sim 3 \times 10^{-5}$:
  - mm accuracies [APOLLO] & modeling efforts
- Tests of WEP [$< 2 \times 10^{-13}$]:
  - Microscope [2009, France, ESA] $\sim 10^{-15}$

To explore accuracies better than 10^{-6}, a dedicated mission is needed



5 years later …. – they are back!

Newton 1686 Poincaré 1890 Einstein 1912 Nordstrøm 1912 Nordstrøm 1913

Einstein and Fokker 1914 **Einstein 1916** Whitehead 1922 Cartan 1923

Fierz and Pauli 1939 Birkhoff 1943 Milne 1948 Thiry 1948 Papapetrou 1954

Papapetrou 1954 Jordan 1955 Littlewood and Bergmann 1956 **Brans and Dicke 1961**

Yilmaz 1962 Whitrow and Morduch 1965 Whitrow and Morduch 1965

Kustaanheimo and Nuotio 1967 Deser and Laurent 1968 Page and Tupper 1968

Bergmann 1968 Nordtvedt 1970 Bollini, Giambiagi and Tiomno 1970 Wagoner 1970

Rosen 1971 Ni 1972 Ni 1972 Hellings and Nordtvedt 1972 Will and Nordtvedt 1972

Ni 1973 Yilmaz 1973 Lightman and Lee 1973 Lee, Lightman and Ni 1974 Rosen 1975

Belinfante and Swihart 1975 Lee et al. 1976 Bekenstein 1977 Barker 1978 Rastall 1979

Coleman 1983 **Kaluza-Klein 1932** Overlooked (20th century)

Bekenstein 2004 | **Moffat 2005** | **DGP 2003** | **Multiple GR modifications (21st century)**

Generic Scalar-Tensor Theories | **Strings theory?** | **Multiple anomalies…**

…There are Three Dark Clouds over General Relativity….:

Dark Energy, Dark Matter, and
The Pioneer Anomaly

Prof. Dr. Jürgen Ehlers
MPI für Gravitationsphysik (Albert-Einstein- Inst.), Golm bei Potsdam,
Physics Colloquium at the University of Bremen
February 10, 2005

…There are Three Dark Clouds over General Relativity….:

Dark Energy, Dark Matter, and other Anomalies…

Dr. Slava G. Turyshev

JPL, Pasadena, CA

Alternative Gravities & Dark Matter Workshop

Royal Observatory, Edinburgh, Scotland, 20-22 April 2006

Gravity? A provocative list

cosmic acceleration

dark energy $\frac{\ddot{a}}{a}/H \approx 3.3 \times 10^{-10}\,\mathrm{m/s^2}$

galaxy rotation curves

dark matter $a_0 \sim 10^{-10}\,\mathrm{m/s^2}$

Pioneer anomaly

$$\vec{a} = -(8.74 \pm 1.33) \times 10^{-10}\,\hat{r}\,\mathrm{m/s^2}$$

Anderson et al, PRL 81 (1998) 2858

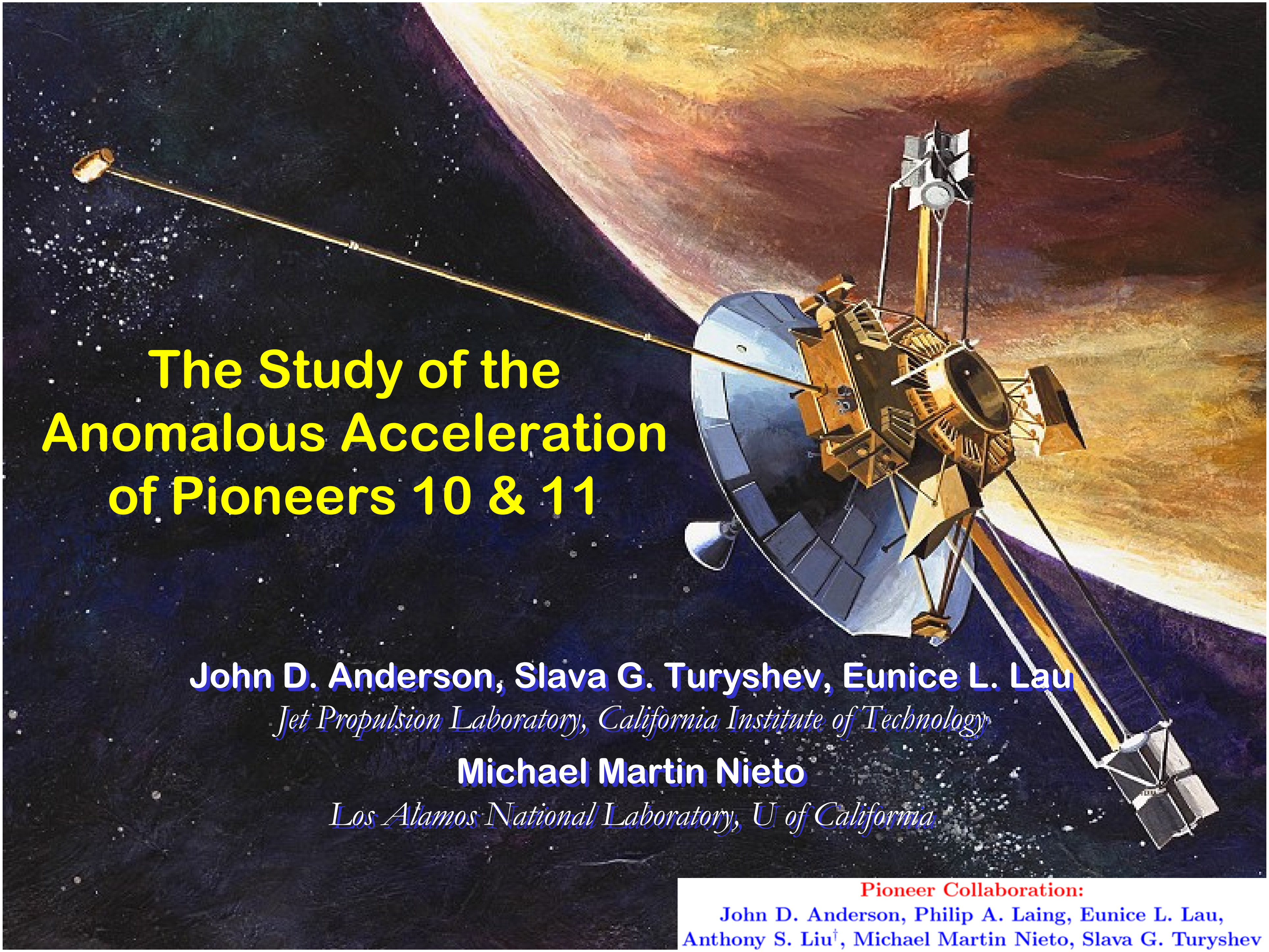
drift of Astronomical Unit

$$\frac{d}{dt}\mathrm{AU} = 15 \pm 4\,\mathrm{m/cy}$$

Krasinsky & Brumberg, Cel. Mech. & Dyn. Astro. 90 (2004) 267

$$c\dot{AU}/AU \approx 10^{-11}\,\mathrm{m/s^2}$$

drift of Moon from Earth $\frac{d}{dt}\mathrm{R} \approx 3.8\,\mathrm{m/cy}$



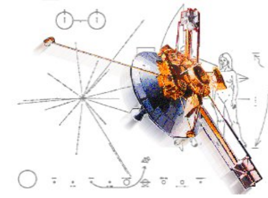
The Study of the Anomalous Acceleration of Pioneers 10 & 11

John D. Anderson, Slava G. Turyshev, Eunice L. Lau
Jet Propulsion Laboratory, California Institute of Technology

Michael Martin Nieto
Los Alamos National Laboratory, U of California

Pioneer Collaboration:
John D. Anderson, Philip A. Laing, Eunice L. Lau,
Anthony S. Liu†, Michael Martin Nieto, Slava G. Turyshev

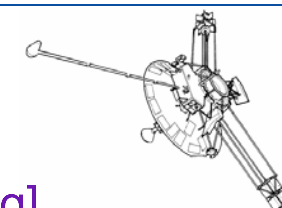
Conclusions & Outline:



- Anomalous acceleration of the Pioneers 10 and 11:
- $$a_P = (8.74 \pm 1.33) \times 10^{-10}\ \mathrm{m/s^2}$$
- A line-of-sight constant acceleration *toward* the Sun:
  - We find no mechanism or theory that explains the anomaly
  - Most plausible cause is systematics, yet to be demonstrated

Phys. Rev. D 65 (2002) 082004, gr-qc/0104064

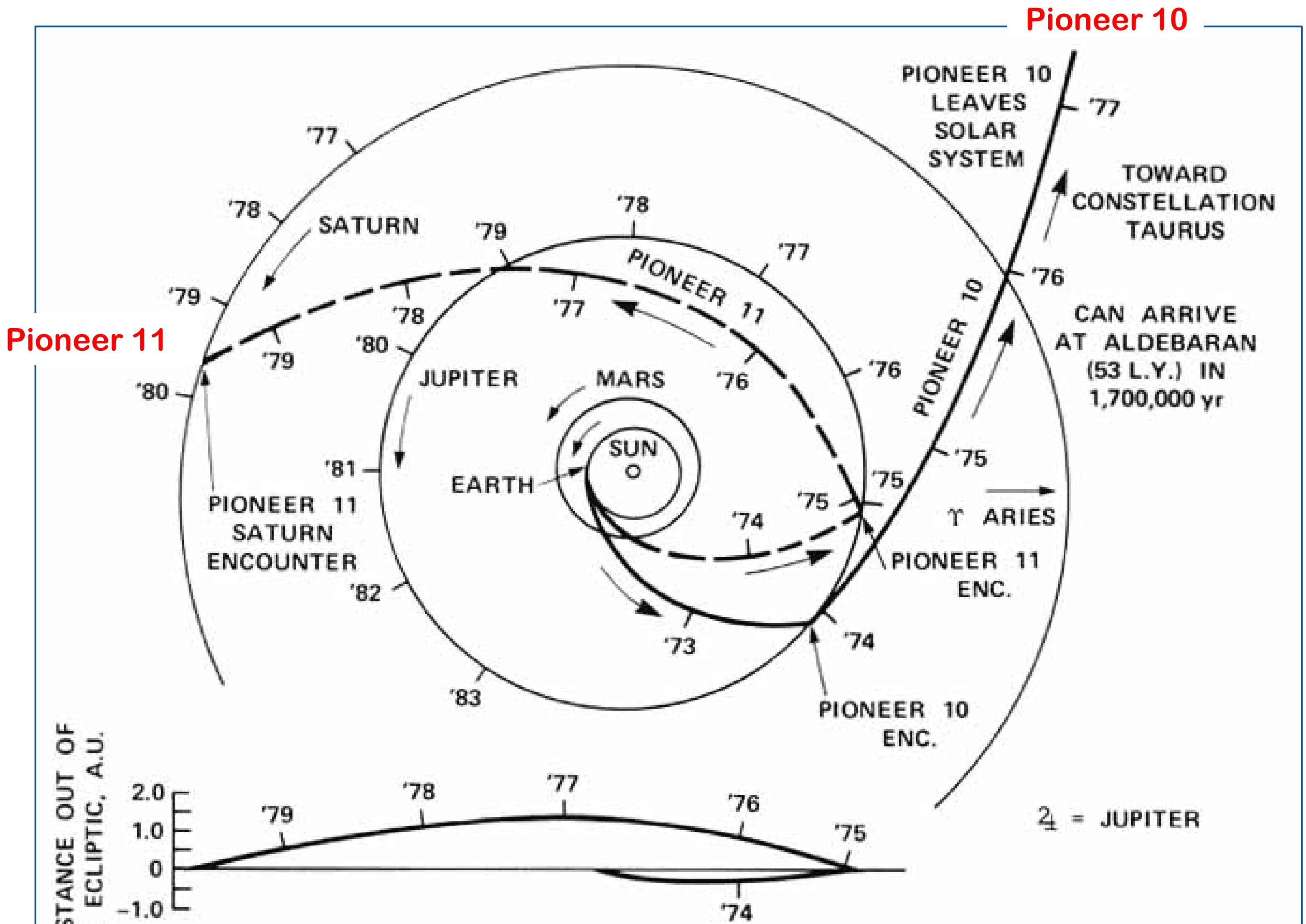
Possible Origin?



- Conventional Physics [not yet understood]:
  - Gas leaks, thermal mechanism, drag force, etc…
- New Physics [many proposals exist, some interesting]

- A “win-win” situation – both possibilities are important:
  - CONVENTIONAL explanation: i) confirmation of the Newton’s $1/r^2$ gravity law in the outer solar system, ii) improvement of spacecraft engineering for precise navigation & attitude control, or
  - NEW physics: would be truly remarkable…

Pioneers 10 and 11: Main Missions

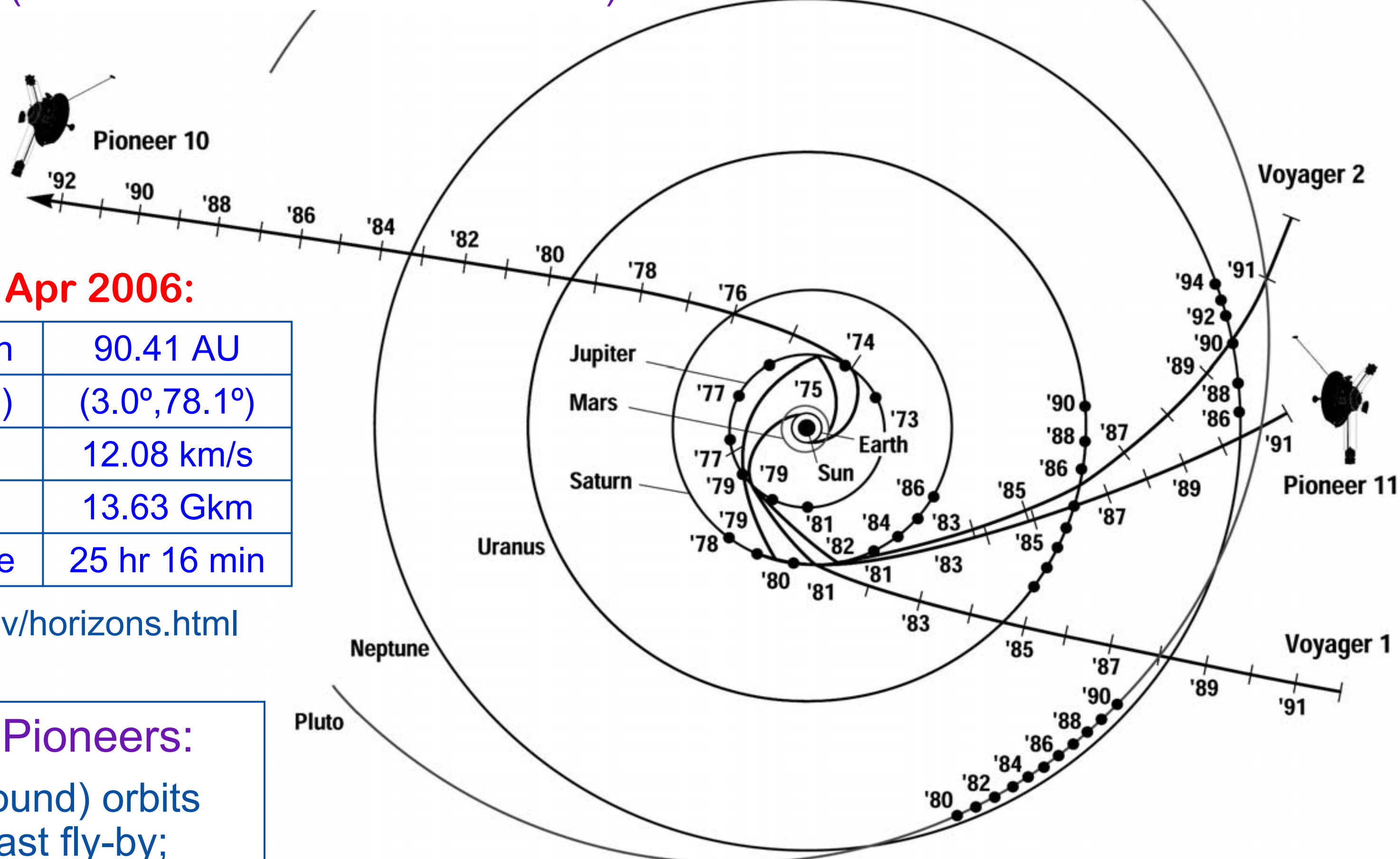


Trajectories of Pioneer 10 & 11 during the main mission phase

Trajectories of Pioneers and Voyagers

Pioneer's last, very weak signal was received on 23 January 2003 (distance from the Sun – 82.1 AU)

Pioneer 10 was contacted in March 2006: no signal received



Pioneer 10 on 20 Apr 2006:

Distance from the Sun	90.41 AU
Position, SE (lat., lon.)	(3.0º,78.1º)
Heliocentric velocity	12.08 km/s
Distance from Earth	13.63 Gkm
Round-Trip Light Time	25 hr 16 min

http://ssd.jpl.nasa.gov/horizons.html

Trajectories of Pioneers:

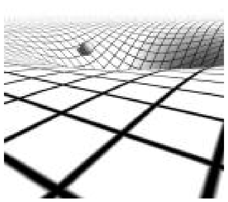
- Elliptical (bound) orbits before the last fly-by;
- Hyperbolic (escape) orbits after the last fly-by

Trajectories of Pioneer and Voyager spacecraft, as seen from north ecliptic pole.

Detection of the Effect and Earlier Studies







- 1979: search for unmodeled accelerations w/ Pioneers began:
  - Motivation: Planet X; initiated when Pioneer 10 was at 20 AU;
  - Solar-radiation pressure away from the Sun became $< 5 \times 10^{-10}$ m/s^2
- 1980: navigational anomaly first detected at JPL:
  - The biggest systematic error in the acceleration residuals – a constant bias of **$(8 \pm 3) \times 10^{-10}$ m/s^2** directed towards the Sun

PRL 81(1998) 2858-2861, gr-qc/9808081

- Initial JPL-ODP analysis in 1990-95:
  - **$(8.09 \pm 0.20) \times 10^{-10}$ m/s^2** for Pioneer 10
  - **$(8.56 \pm 0.15) \times 10^{-10}$ m/s^2** for Pioneer 11
  - NO magnitude variation with distance over a range of 40 to 70 AU
  - The error is from a batch-sequential & filter-smoothing algorithm

- **An Error in JPL's ODP?** – Numerous internal checks at JPL
- NASA Grant to The Aerospace Corporation: 1996-1998

Data used for the Analysis (1996-1998):

- **Pioneer 10**: 11.5 years; distance = 40–70.5 AU $\Rightarrow$ 20,055 data points
- **Pioneer 11**: 3.75 years; distance = 22.4–31.7 AU $\Rightarrow$ 19,198 data points

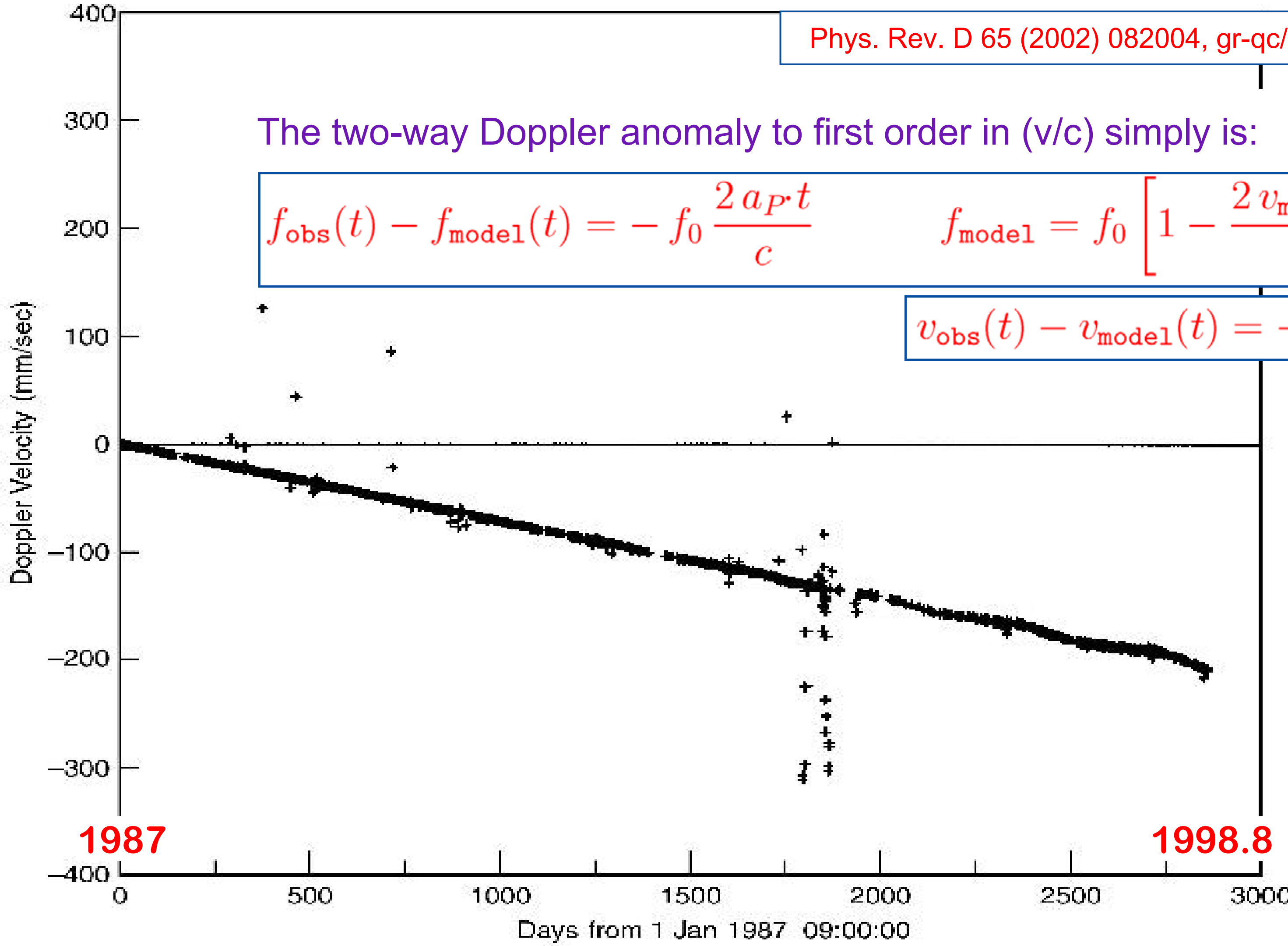
The Observed Anomalous Doppler Drift

Phys. Rev. D 65 (2002) 082004, gr-qc/0104064

The two-way Doppler anomaly to first order in (v/c) simply is:

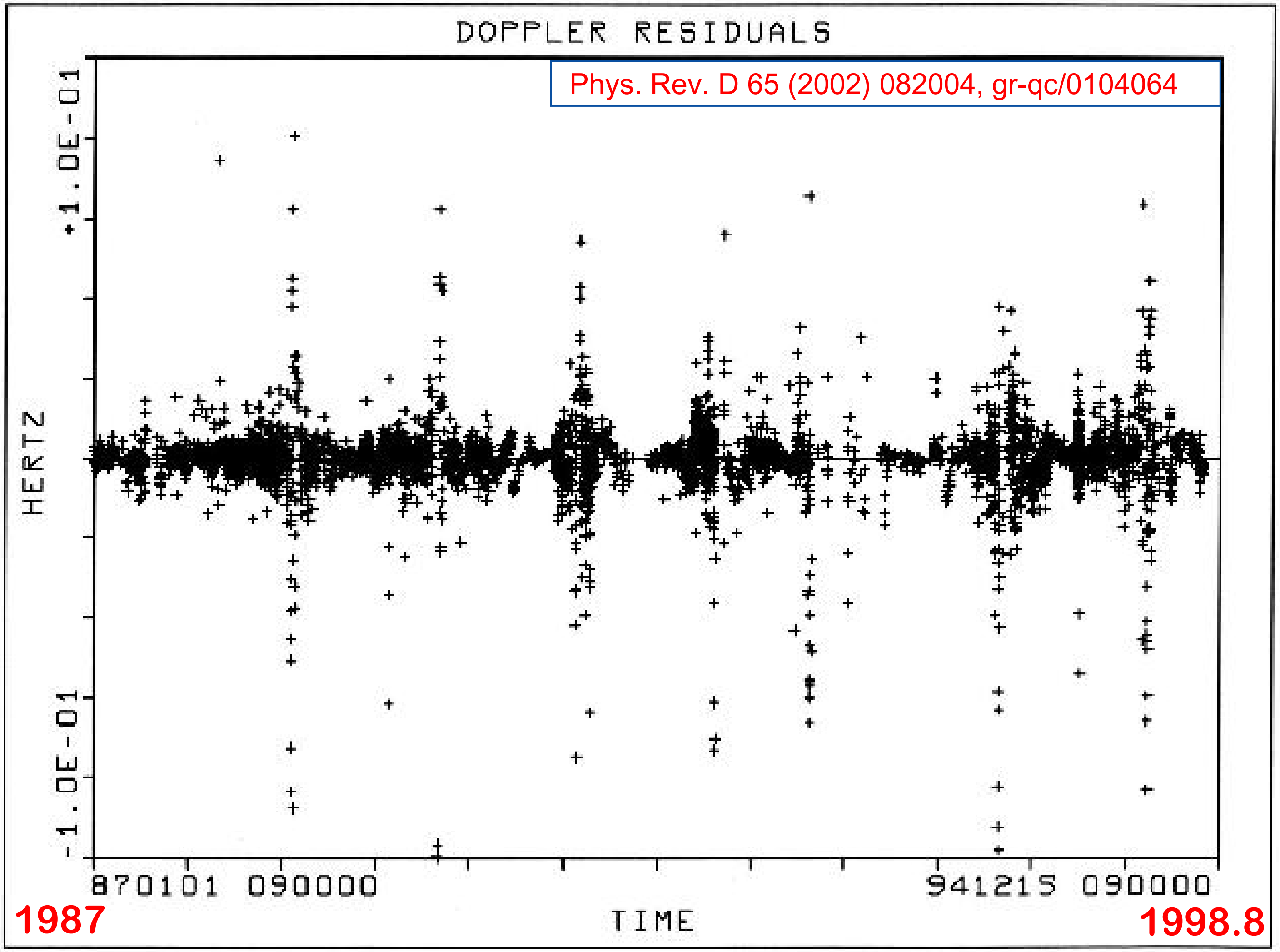
$$f_{\mathrm{obs}}(t) - f_{\mathrm{model}}(t) = -\, f_0 \frac{2\, a_P \cdot t}{c} \qquad f_{\mathrm{model}} = f_0 \left[1 - \frac{2\, v_{\mathrm{model}}(t)}{c} \right]$$

$$v_{\mathrm{obs}}(t) - v_{\mathrm{model}}(t) = -\, 2\, a_P \cdot t$$



The two-way Doppler residuals (observed Doppler velocity minus modeled Doppler velocity) for Pioneer 10 vs time [1 Hz is equivalent to 65 mm/s velocity].

The Pioneer Anomaly: Quality of Data Fit

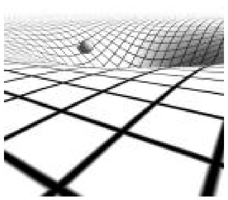


Adding only one more parameter to the model – a constant radial acceleration – led to residuals distribution ~zero Doppler velocity with a systematic variation ~3.0 mm/s. Quality of the fit is determined by ratio of residuals to the downlink carrier frequency, $f_0 \approx$ 2.29 GHz.

Modeling of Spacecraft Motion







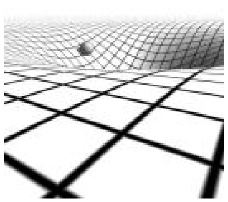
- Relativistic eq.m. for celestial bodies are correct to $(v/c)^4$:
  - Relativistic gravitational accelerations (EIH model) include: Sun, Moon, 9 planets are point masses in isotropic, PPN, N-body metric;
  - Newtonian gravity from large asteroids; terrestrial, lunar figure effects; Earth tides; lunar physical librations.
- Relativistic models for light propagation are correct to $(v/c)^2$

- Model accounts for many sources of non-grav. forces, including:
  - Solar radiation and wind pressure; the interplanetary media;
  - Attitude-control propulsive maneuvers and propellant (gas) leakage from the propulsion system;
  - Torques produced by above mentioned forces;
  - DSN antennae contributions to the spacecraft radio tracking data.
- Orbit determination procedure, includes:
  - Models of precession, nutation, sidereal rotation, polar motion, tidal effects, and tectonic plates drift;
  - Model values of the tidal deceleration, non-uniformity of rotation, polar motion, Love numbers, and Chandler wobble are obtained observationally via LLR, SLR and VLBI (from ICRF).

Focus of the 1995-2002 Analysis







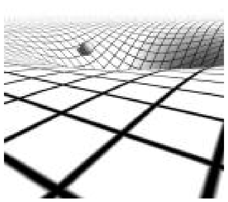
- On-board systematic & other hardware-related mechanisms:
  - Precessional attitude control maneuvers and associated “gas leaks”
  - Nominal thermal radiation due to ^{238}Pu decay [half life 87.75 years]
  - Heat rejection mechanisms from within the spacecraft
  - Hardware problems at the DSN tracking stations
- Examples of the external effects (used GLL, ULY, and Cassini):
  - Solar radiation pressure, solar wind, interplanetary medium, dust
  - Viscous drag force due to mass distribution 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’s Orientation, precession, polar motion, and nutation parameters
- 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

Most of the systematics are time or/and space dependent!

Recent Pioneer Doppler Data Recovery Effort







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- Pioneer 10: 11.5 years; distance = 40–70.5 AU ⇒ 20,055 data points
- Pioneer 11: 3.75 years; distance = 22.4–31.7 AU ⇒ 19,198 data points

Pioneer 10/11 Doppler Data available (April 2006):

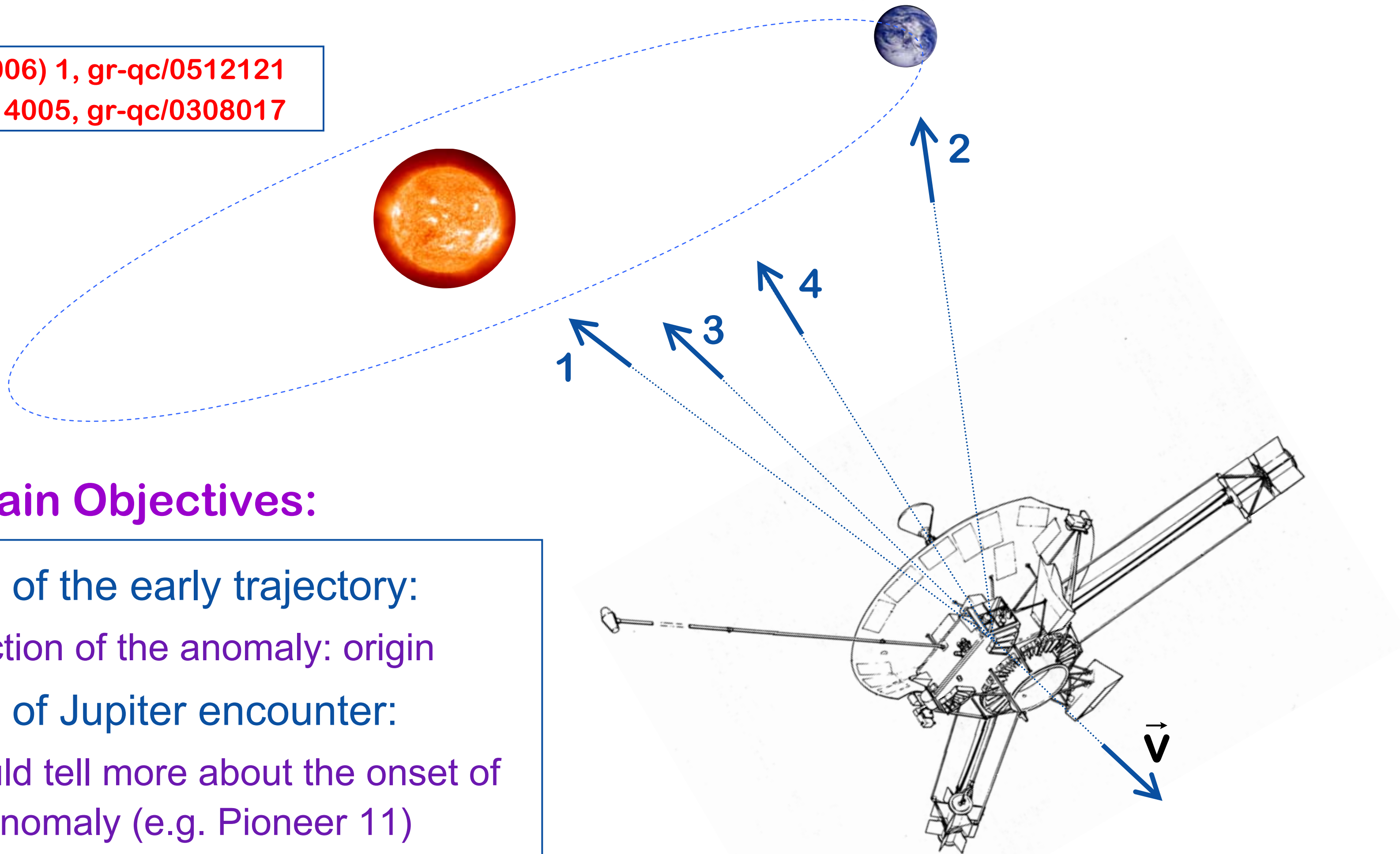
- **Pioneer 10**:
  - 1973-2002: ~30 years
  - Distance range: 4–87 AU
  - Jupiter encounter
  - ~95,000 data points, ~20GB
  - Maneuvers, spin, initial cond.
  - All telemetry is available
- **Pioneer 11**:
  - 1974-1994: ~ 20 years
  - Distance range: 1–33 AU
  - Jupiter & Saturn encounters
  - ~65,000 data points, ~15GB
  - Maneuvers, spin, initial cond.
  - All telemetry is available

- **Planning for the upcoming data analysis**:
  - After initial certification at JPL, both datasets will be made available
  - NASA funding is expected in a month – critical for the effort;
  - The Planetary Society – good but insufficient for serious work
  - ZARM, Germany: received funding, started analysis of old data
  - French group funded by CNES is also planning for analysis

Upcoming Pioneer data analysis is planned as an international effort

Critical Phases of the Proposed Experiment

IJMPD 16 (2006) 1, gr-qc/0512121
CQG 21 (2004) 4005, gr-qc/0308017



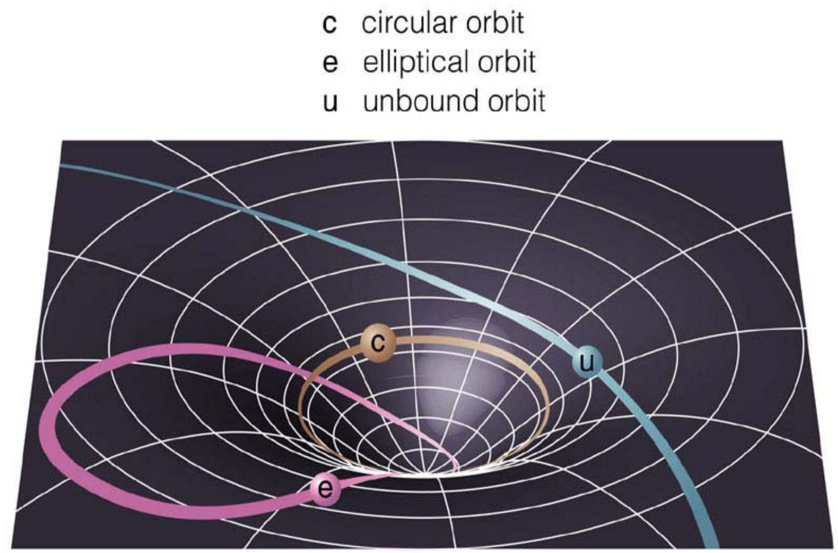
Four Main Objectives:

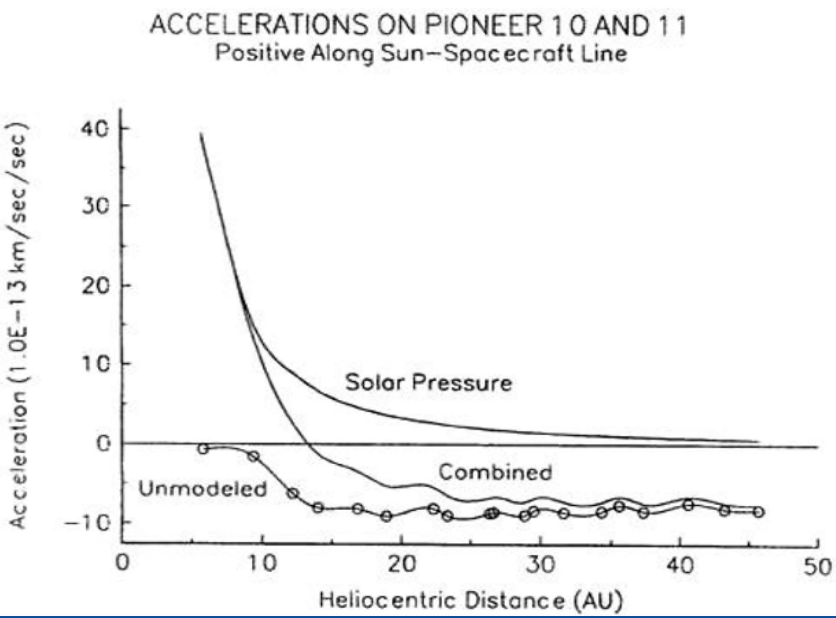
- Analysis of the early trajectory:
  - Direction of the anomaly: origin
- Analysis of Jupiter encounter:
  - Should tell more about the onset of the anomaly (e.g. Pioneer 11)
- Analysis of the entire dataset:
  - Temporal evolution of the anomaly
- Focus on on-board systematics:
  - Thermal modeling using telemetry

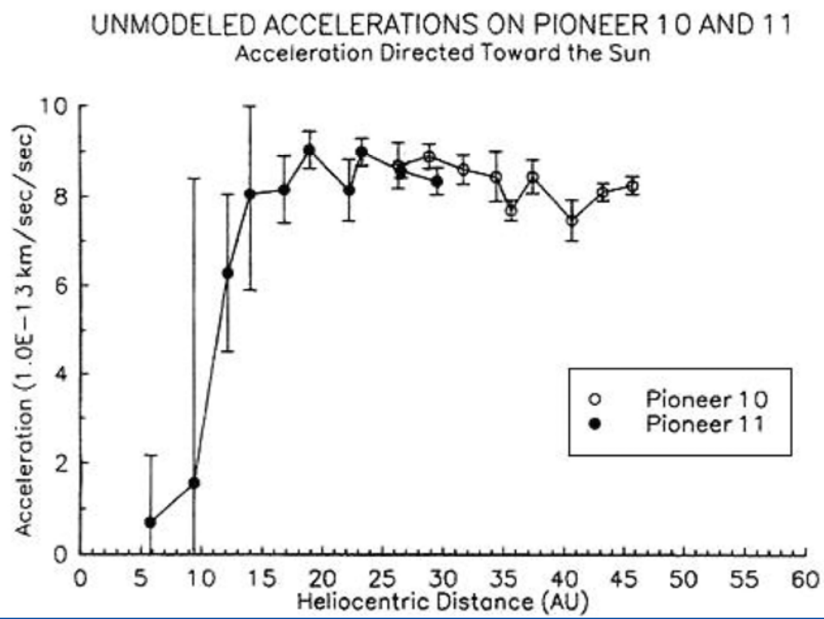
- Towards the Sun: gravitational models?
- Towards the Earth: frequency standards?
- Along the velocity vector: drag or inertia?
- Along the spin axis: internal systematics?

Difference Between Bound & Un-Bound Orbits?

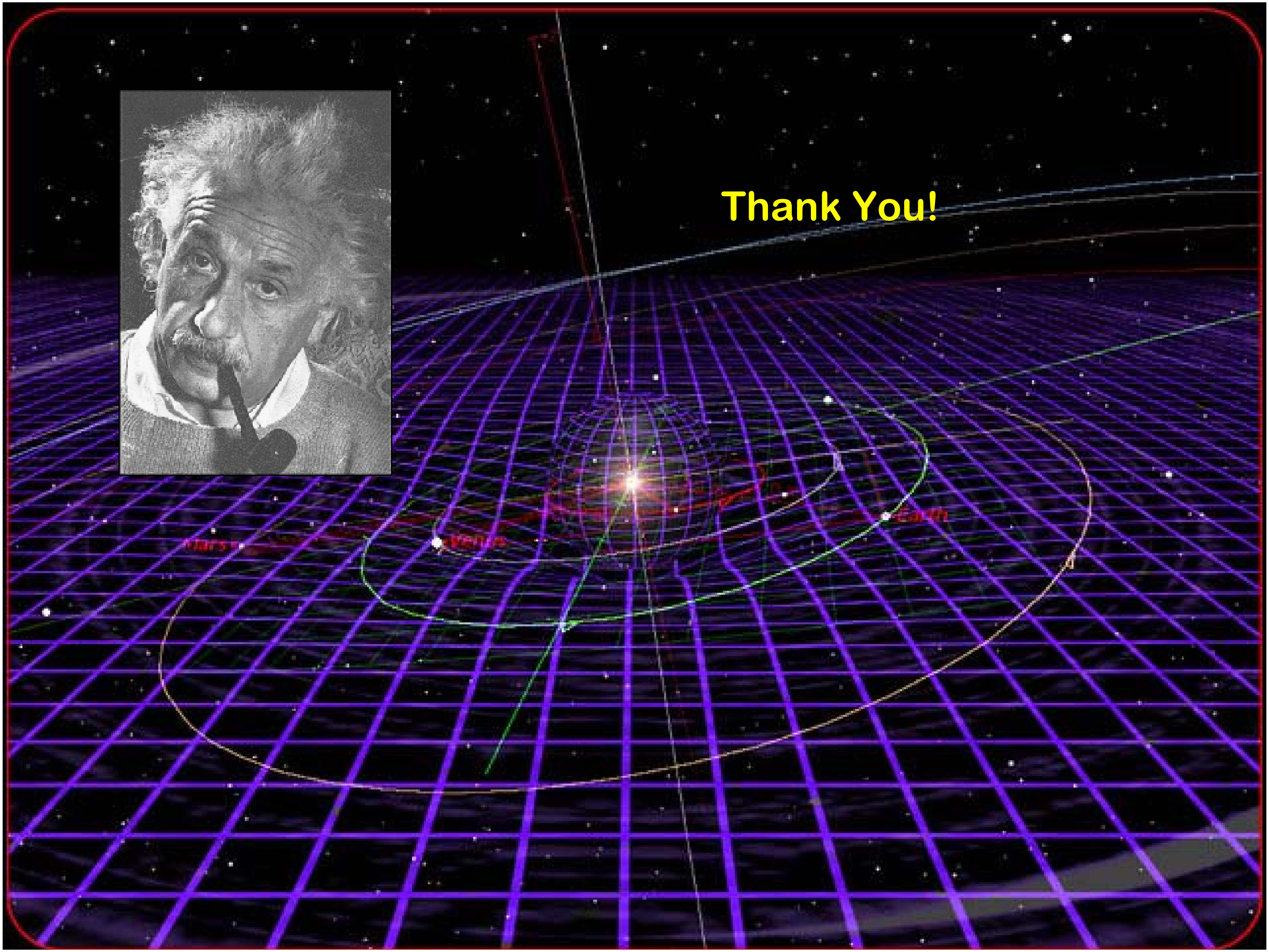
- Navigational Anomalies during Earth fly-byes were observed with multiple spacecraft:
  - Galileo: #1 on 10/8/1990 @ altitude of ~960 km;
    #2 on 12/8/1992 @ altitude of ~305 km;
  - NEAR: 01/22/1998 @ altitude of ~550 km;
  - Cassini: 08/19/1999 @ altitude of ~1,171 km;
  - Stardust: 01/15/2001 @ altitude of ~6,000 km;
  - Rosetta: 03/04/2005 @ altitude of ~1,900 km.
- Are they relevant to the Pioneer anomaly?







A plot of early unmodeled accelerations of Pioneer 10 (1981–1989), Pioneer 11 (1977–1989)


Thank You!
Mars
Venus
Earth