Is Physics in the Solar System really understood?

Hansjörg Dittus, Claus Lämmerzahl
ZARM, University of Bremen, Germany,

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and the
Pioneer Anomaly Explorer Science Team

The Pioneer Anomaly Explorer Mission Science Team

H. Dittus, C. Lämmerzahl, S. Theil *(ZARM, U of Bremen),*
B. Dachwald, W. Seboldt *(DLR, Köln),* **W. Ertmer, E. Rasel** *(IQO Hannover),*
U. Johann, R. Förstner *(Astrium, Friedrichshafen),* **T.J. Sumner** *(Imperial College, London),*
B. Kent, R. Bingham *(RAL, Didcot),* **O. Bertolami, J. Páramos** *(IST, Lisboa),*
C. Kiefer, F. Hehl *(U of Cologne),* **J.L. Rosales** *(QIG, RSME, Madrid),*
P. Touboul, B. Foulon, B. Christophe *(ONERA, Châtillon),* **P. Bouyer** *(IOTA, Paris),*
S. Reynaud *(ENS/LKB, Paris),* **E. Samain, A. Brillet, F. Bondu** *(Observatoire de la Côte Azur, Grasse),* **H.-J. Blome** *(FH Aachen),* **D. Giulini** *(U of Freiburg/Brsg.),*
C. de Matos, A. Rathke, C. Erd, D. Izzo, J.C. Grenouilleau *(ESA/ESTEC),*
J.D. Anderson, S.W. Asmar, S.G. Turyshev, G. Giampieri, E.E. Lau *(JPL, Pasadena CA, USA),*
M.M. Nieto *(LANL, Los Alamos, NM USA),* **B. Mashhoon** *(U of Missouri, USA),* *V. Toth, C. Marquart, O. Olsen, T. Morley (ESOC)*

Background

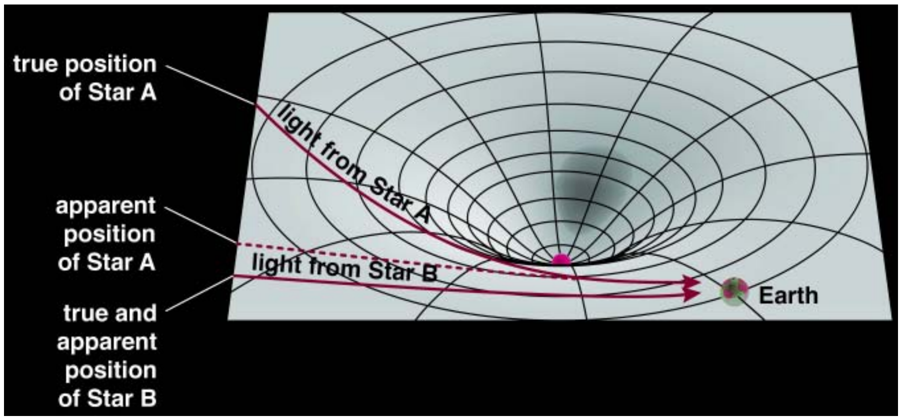
- Many aspects of General Relativity are well tested and confirmed:

Foundations:

- Universality of Free Fall
- Local Lorentz Invariance
- Universality of Gravitational Redshift

Predictions:

- Solar System Effects
  - Perihelion shift
  - Gravitational Redshift
  - Light deflection
  - Time delay
  - Gravitomagnetic effects
- Strong field observations
  - Binary systems
  - Black holes
- Gravitational waves
- Cosmology



Experimental confirmation

- Tests within PPN frame

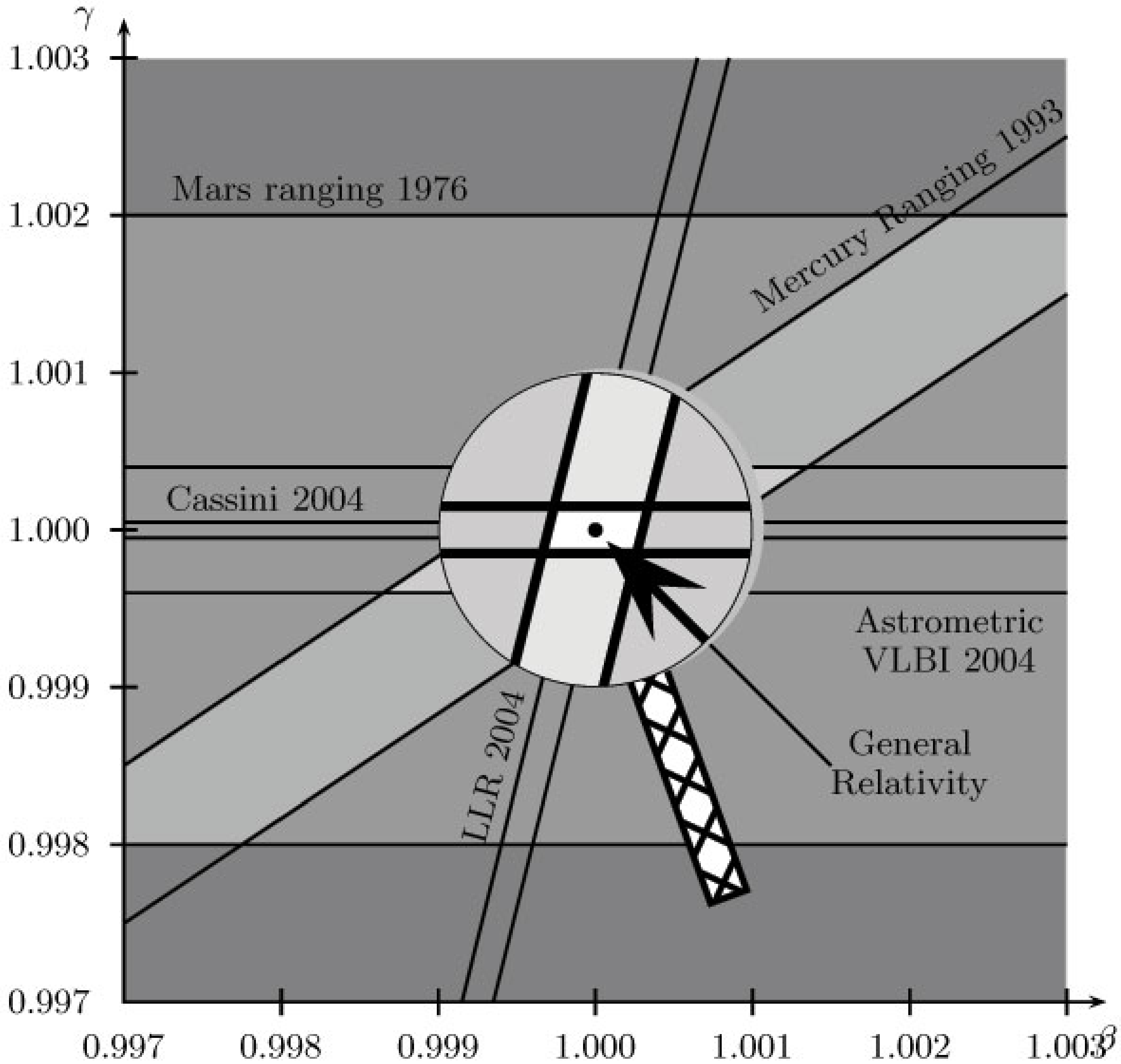
$$g_{00} = -1 + 2\alpha \frac{U}{c^2} - 2\beta \frac{U^2}{c^4}$$

$$g_{0i} = 4\mu \frac{\left(\vec{J} \times \vec{r}\right)_i}{c^3 r^3}$$

$$g_{ij} = (1 + 2\gamma)\frac{U}{c^2}$$

perihelion shift	astronomical observations	$\left\|\frac{2}{3}(\alpha+\gamma) - \frac{1}{3}\beta - 1\right\| \leq 10^{-4}$
light deflection	Very Long Baseline Interference	$\|\gamma - 1\| \leq 10^{-4}$
time delay	Cassini S/C	$\|\gamma - 1\| \leq 2 \cdot 10^{-5}$
gravitational redshift	Gravity Probe A	$\|\alpha - 1\| \leq 1.4 \cdot 10^{-4}$
Lense-Thirring effect	LAGEOS satellites	≤ 0.1
Schiff effect	Gravity Probe B	$\leq 5 \cdot 10^{-3}$ not yet confirmed)

Space experiments for Eddington parameters

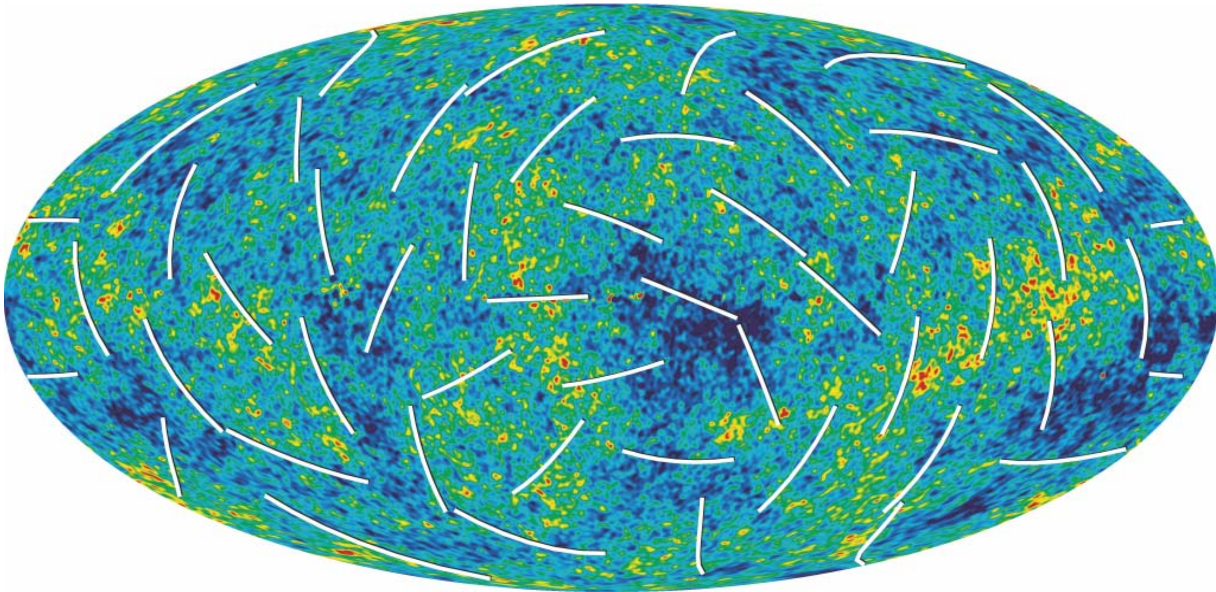


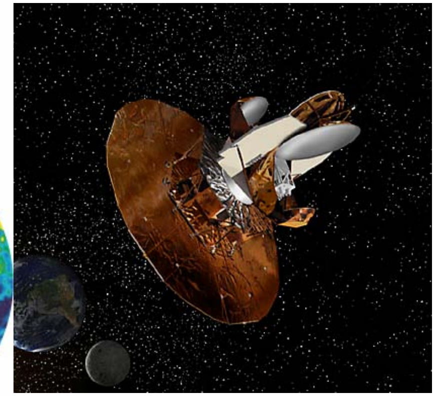
Turyshev et al., 2006

Open questions and observed phenomena

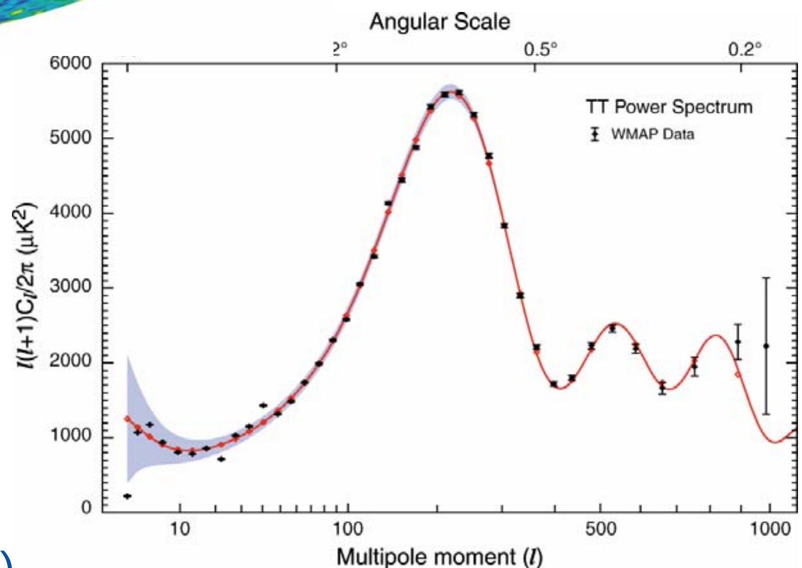
- Unexplained phenomena within GR

W-MAP and the Cosmic Questions





The anisotropy of the cosmic microwave background
measured by WMAP (3 year result 2006)
WMAP Science Team 2006



- confirms cosmological model / inflation)
- dark energy /dark matter
- only 5 % of the Universe consists of „ordinary“ matter ??

Open questions and observed phenomena

- Unexplained phenomena within GR
  - Dark Matter (*Zwicky* 1933):
    to describe galactic rotation curves, gravitational lensing effects and early structure formation in cosmological models
  - Dark Energy (*Turner* 1999):
    to describe the accelerated expansion of the universe seen from supernovae observations and CMB anisotropy measurements

Increase of the Astronomical Unit

- Observation:
  - *Krasinsky and Blumberg* (2005): 15 ± 4 m / 100 a
  - *Pitjeva* (in *Standish* (2005)): 7± 1 m / 100 a

- Remarks and questions:
  - $dG/dt \neq 0$ exluded by Lunar Laser Ranging
  - Mass loss of Sun causes only 1 m / 100 a
  - Influence by cosmic expansion many orders of magnitude too small
  - Increase of solar wind plasma on long time scales ?
  - Drift of clocks $t \to t + \alpha t^2$ with $\alpha \approx 3 \cdot 10^{-20}$ s^{-1} ?

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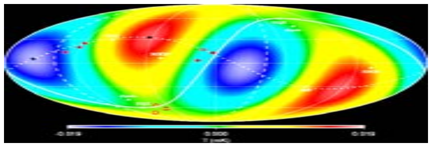
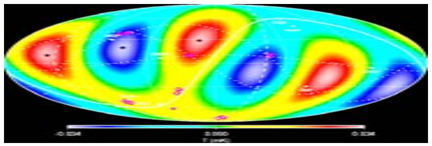
  - Increase of the Astronomical Unit (*Pitjeva* 2005, *Krasinski* 2005):
    length scale related to the earth-sun distance increases by 7 ± 1 m per 100 years (confirmed by astronomical observations); solar mass loss only explains ca. 1 m per century

Quadrupole / octopole anomaly

- Observation:
  - Anomalous behaviour of low ℓ contributions to CMB quadupole and octopole aligned to > 99.87 %
  - Quadrupole and octopole aligned to ecliptic to > 99 %
  - No correlation with the galactic plane
    (Oliveira et al (2004), *Schwarz* et al (2005)*)*

- Remarks and questions:
  - Influence of solar system on CMB observations ?
  - Systematics ?





Schwarz et al 2004, Copi et al. 2005

Open questions and motivation

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    quadrupole and octopole of CMB are correlated with solar system eclipse
    [illegible]4)

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    quadrupole and octopole of CMB are correlated with solar system eclipse
  - Pioneer Anomaly (*Anderson et al.* 1998,2002/04)

Pioneer Anomaly

- Pioneers 10/11: most precisely navigated deep space satellites (Jet Propulsion Lab., Pasadena CA)
- Observation of a small, anomalous, blue-shifted Doppler frequency drift (*Anderson* et al. 1998, 2002), uniformly changing with the rate of

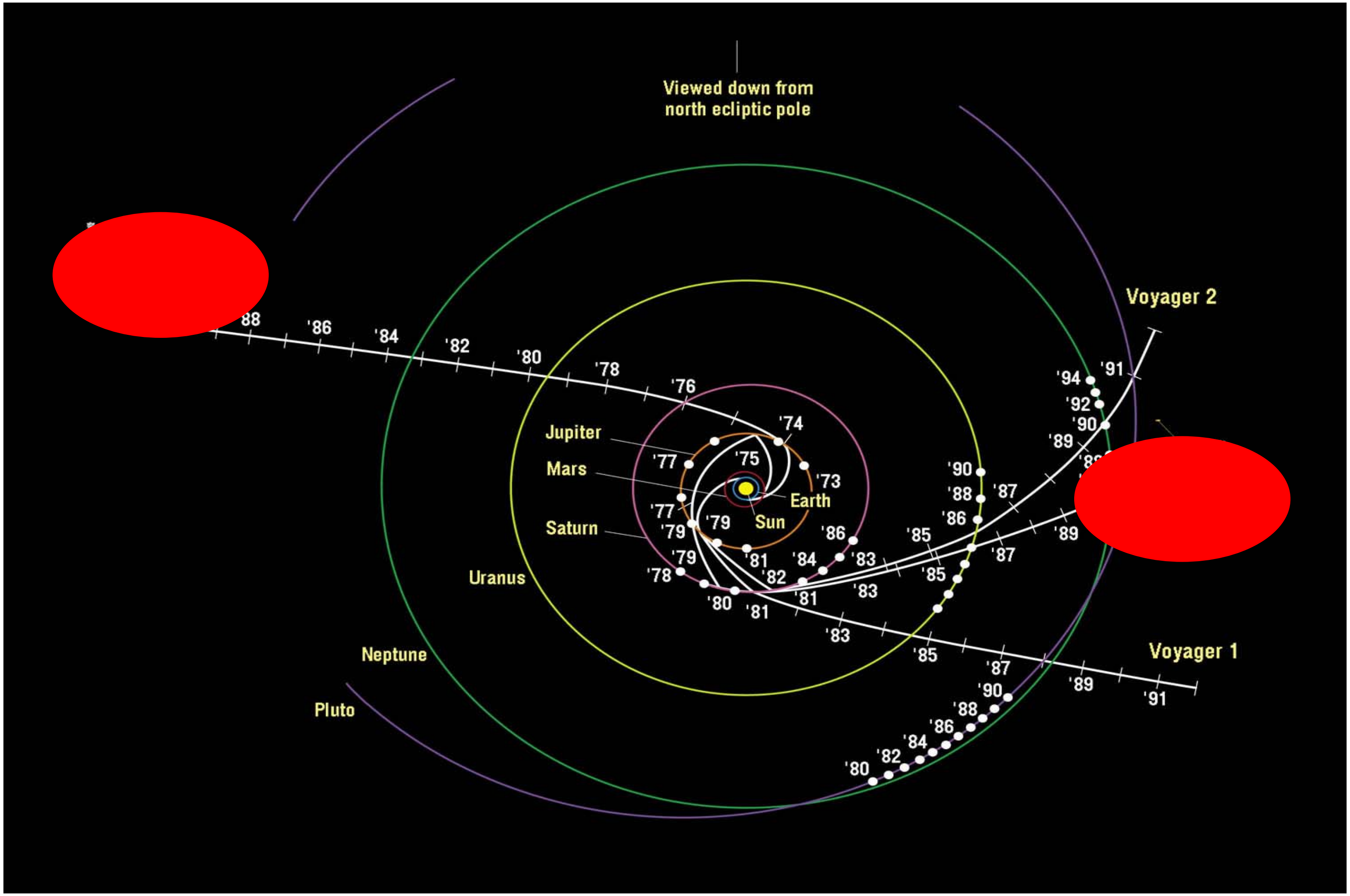
$$\dot{f}_p = (5.99 \pm 0.01) \cdot 10^{-9} \text{ Hz / s}$$

- Drift can be interpreted as a sunward constant acceleration of

$$a_p = (8.74 \pm 1.33) \cdot 10^{-10} \text{ m/s}^2$$

- This interpretation has become known as the Pioneer Anomaly:
  - Constant acceleration of the spacecraft toward the Sun
  - Analysed with data (1987–1998) for heliocentric distances 20 - 70 AU
  - Anomaly occurs when satellites have set to hyperbolic (escape) orbits
  - No real indication of how far out the anomaly goes.
  - Temporal and spatial variations are less than 3%

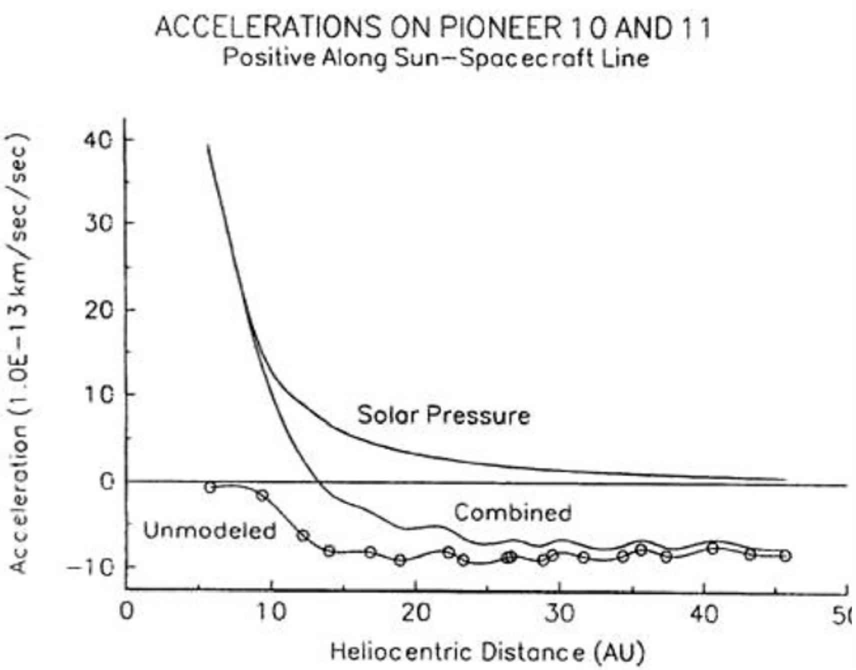
The orbits of Pioneer 10 and 11

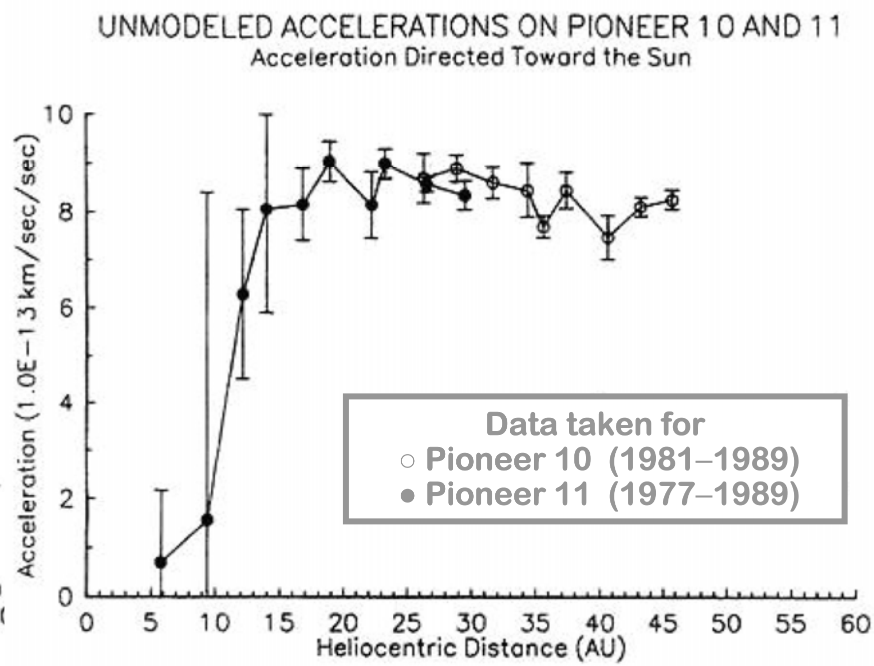


- Elliptical (bound) orbits before last fly-by
- Hyperbolic (escape) orbits after last fly-by

Detection of the Anomaly

- Search for unmodeled accelerations with Pioneers started in 1979:
  - Motivation: search for Planet X – initiated when Pioneer 10 was at 20 AU;
  - The solar-radiation pressure away from the Sun became $< 5 \times 10^{-10}$ m/s^2
- Original detection of the anomaly by JPL orbit determination in 1980:
  - The analysis found the biggest systematic error in the acceleration residuals is a constant bias $a_P \sim (8 \pm 3) \times 10^{-10}$ m/s^2 directed towards the Sun





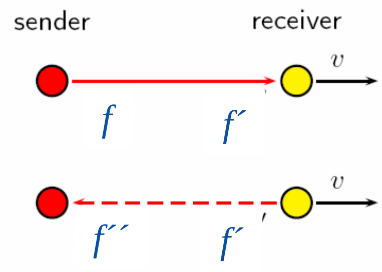
Observed Anomalous Doppler Drift

frequency received at S/C:

$$f' = \frac{1}{\sqrt{1-v^2/c^2}}\left(1-\frac{v}{c}\right)\cdot f$$

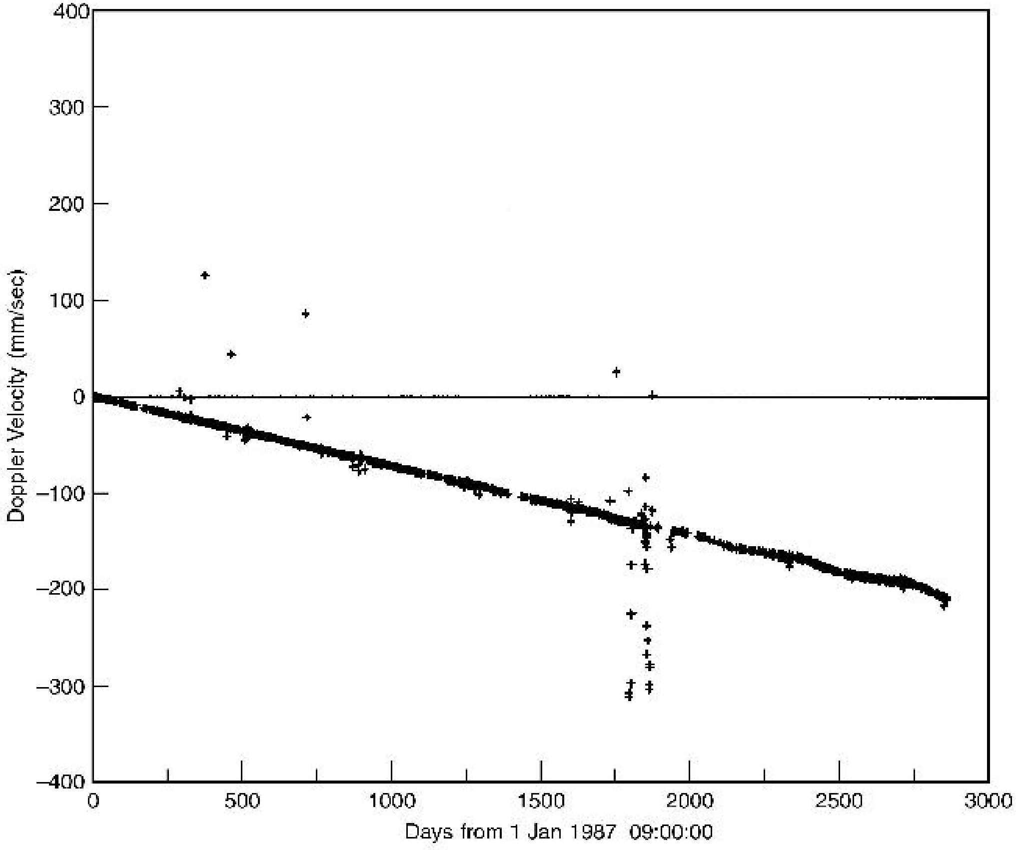
frequency sent back and received on earth:
(neglecting the transponder shift)

$$f'' = \frac{1}{\sqrt{1-v^2/c^2}}\left(1-\frac{v}{c}\right)\cdot f'$$



$$\frac{f''-f}{f} = -2\frac{v/c}{1+v/c} \approx -2\frac{v}{c}$$

$$v_{observed} - v_{modelled} = -a_p t$$



The two-way Doppler residuals for Pioneer 10 vs time
[1 Hz is equal to 65 mm/s range change per second].

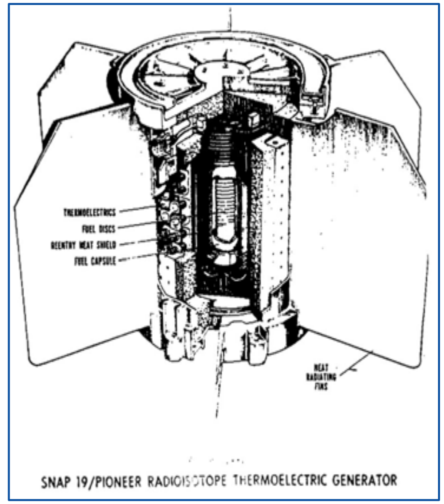
Anderson et al.

Sources of External Systematic Error

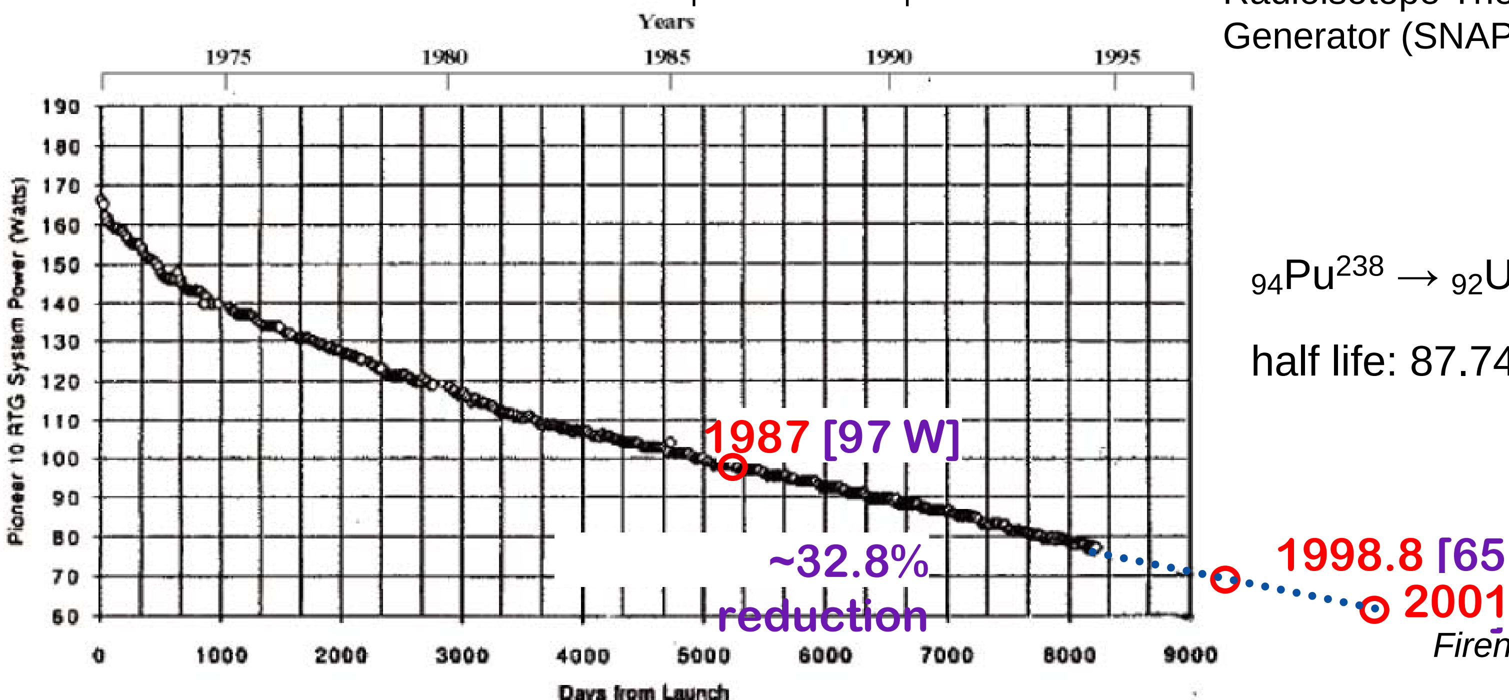
error budget constituents	bias [10^{-10}m/s^2]	uncertainty [10^{-10} m/s^2]
sources of extrenal systematics		
solar radiation pressure		± 0.001
→ sol. rad. press. from mass uncertainties	+ 0.03	± 0.01
solar wind		± 0.00001
solar corona effects		± 0.02
Lorentz force (em-effects)		± 0.0001
Kuiper belt´s gravity		± 0.03
earth rotation		± 0.001
mechanical / phase stability of DSN antenna		± 0.001
clock effects on phase stability		± 0.001
DSN station location		± 0.00001
tropospheric and ionospheric effects		± 0.001
computational systematics		
numerical stability of least-square estimations		± 0.02
accuracy of consistency / model tests		± 0.13
→ mismodelling of manoeuvers		± 0.01
→ mismodelling of solar corona		± 0.02
annual / diurnal terms		± 0.32

On-board Systematics: Power and Heat

error budget constituents	bias $[10^{-10}\ m/s^2]$	uncertainty $[10^{-10}\ m/s^2]$
radio beam reaction force	+ 1.10	± 0.11
thermal and propulsion effects from RTGs		
→ RTG heat reflected off the S/C	-0.55	± 0.55
→ differential emissivity of the RTGs		± 0.85
→ non-isotropic radiative cooling of S/C		± 0.16
→ expelled He produced within the RTGs	+0.15	± 0.16
mass expulsion / gas leakage		± 0.56
variation between S/C determinations	+0.17	± 0.17



Radioisotope Thermoelectrical Generator (SNAP-19)



$_{94}Pu^{238} \rightarrow {}_{92}U^{234} + {}_{2}He^{4}$

half life: 87.74 years

A Drag Through Dust ?

- Interplanetary Medium
  - is a thinly scattered matter (neutral Hydrogen, microscopic particles) with two main contributions, IPD and ISD:
  - Interplanetary Dust (IPD), modelled:

$$\rho_{IPD} \leq 10^{-24} \text{ g/cm}^3$$

  - Interstellar Dust (ISD), measured on Ulysses S/C:

$$\rho_{ISD} \leq 10^{-26} \text{ g/cm}^3$$

- **Drag on a spacecraft is given by:**

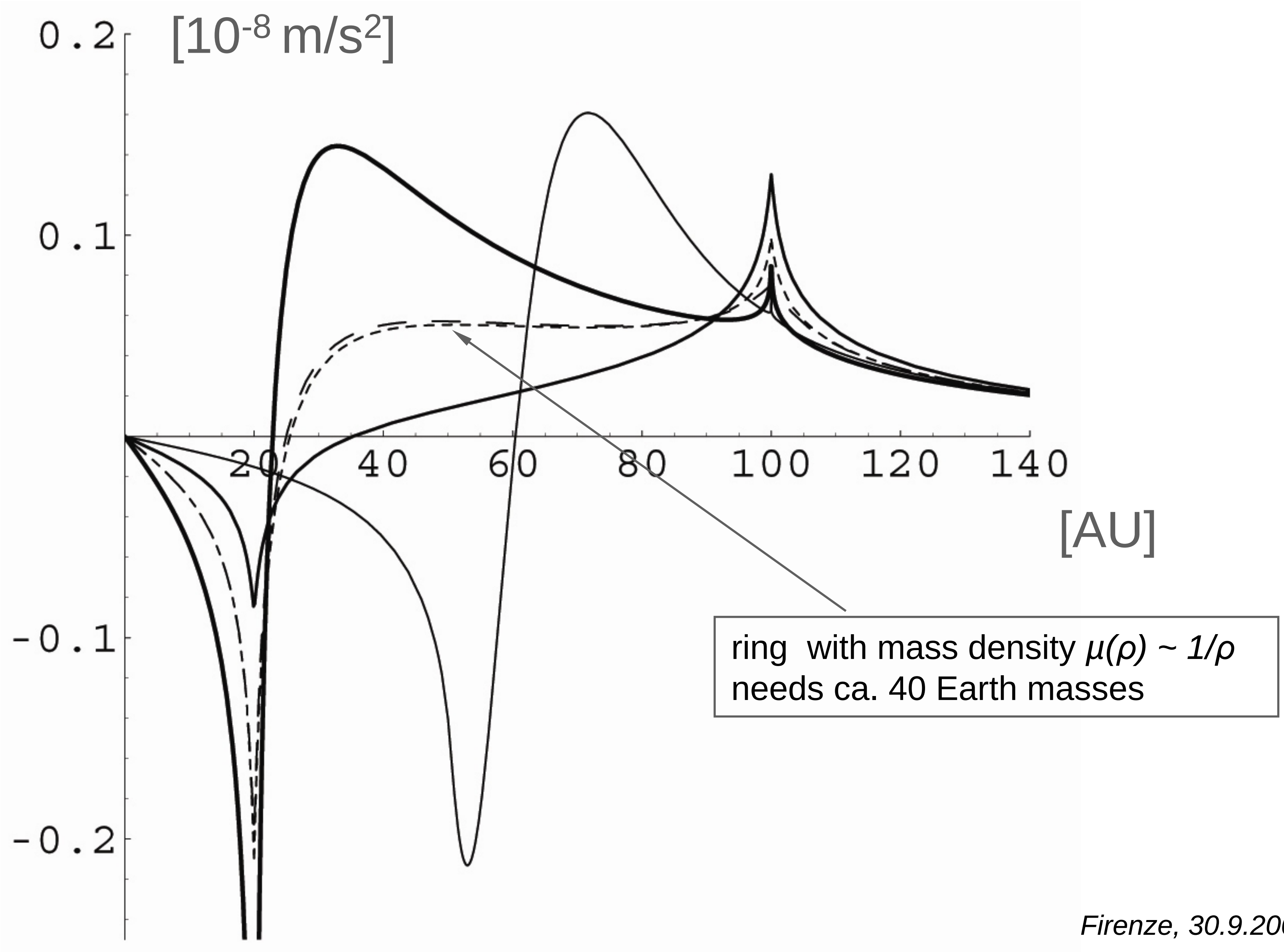
$$a_{drag} = -c_s \frac{\rho(r) v_s A_s}{m_s}$$

➡ The Pioneer Anomaly (between 20 and 70 AU) could only be explained with an axially-symmetric dust distribution with a constant uniform density of

$$\rho(r) \leq \rho_0 = 3 \cdot 10^{-19} \text{ g/cm}^3 \approx 300.000(\rho_{IPD} + \rho_{ISD})$$

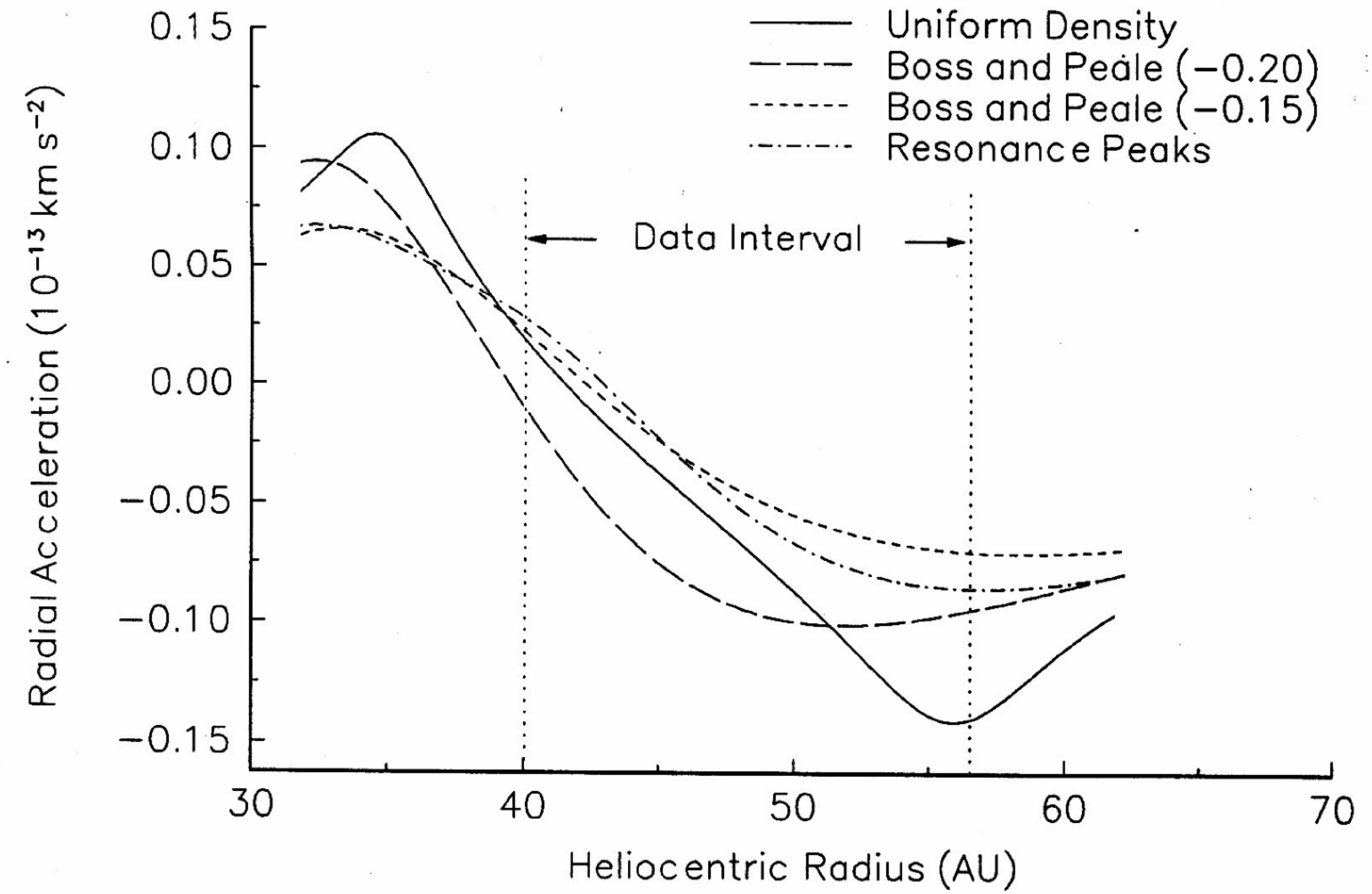
Unexpected masses in the solar system (2)

- acceleration vs. distance for different mass density distribution
  (Nieto, 2005*)*



Unexpected Masses in the Kuiper Belt

Models for 1 Earth mass in the Kuiper belt



Suggested Explanations: New Physics

- Observation [redacted] stimulated some suggestions:
  - Gravity of the solar system is not static w.r.t. the cosmic expansion
  - Cosmological models with a time-varying gravit. constant *G(t)*

- Scalar-field approaches:
  - Long-range scalar field, with oscillatory decline in a_P, $d \geq$100 AU
  - Flavor oscillations of neutrinos in the Brans-Dicke theory of gravity may produce a quantum mechanical phase shift of neutrinos
  - A theory of conformal gravity with dynamical mass generation

- Drift of clocks
  - $t \rightarrow t + \alpha t^2$ with $\alpha \approx 3 \cdot 10^{-19}$ s^{-1}?

Doppler Tracking in the expanding universe

- Cosmology
  - **Dynamics in curved space-time**

    light rays: $g(l,l)=0, \quad g(k,k)=0, \quad \mathrm{D}_l l = 0$

    point particles: $g(v,v)=1, \quad \mathrm{D}_v v = 0$

  - **Measured quantities**

    Observer 4-velocity *u* with *g(u,u)* = 1

    frequency: $\nu_u = k(u)$

    velocity: $g(u,v) = 1\big/\sqrt{1 - V^2/c^2}$

  - **Einstein-deSitter universe**

    metric: $\mathrm{d}s^2 = -\mathrm{d}t^2 + R^2(t)\left(\mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2\right)$

    Hubble constant: $H = \dot{R}\big/R$

    deceleration parameter: $q = -\frac{1}{H^2}\frac{\ddot{R}}{\dot{R}}$

Doppler Tracking in the expanding universe

- Redshifts

  - **Conserved quantities**

light $$\nu_u(t)R(t) = const.$$

$\rightarrow$ Hubble red shift $$\nu_u(t) = \frac{R(t_0)}{R(t)}\nu_u(t_0) \approx (1 - H(t - t_0))\nu(t_0)$$

massive particles $$R^2(t)\frac{\mathrm{d}r(s)}{\mathrm{d}s} = const. \quad \Leftrightarrow \quad R(t)\frac{1}{\sqrt{1 - V^2(t)}}V(t) = const.$$

$\rightarrow$ slow down at small velocities:

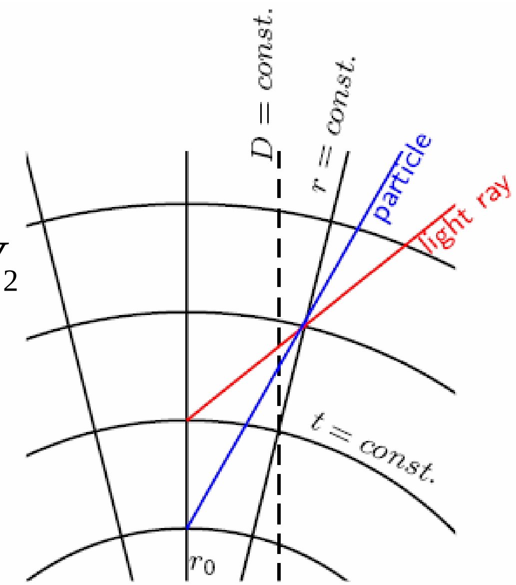
$$R(t)V(t) = const. \quad \Rightarrow \quad V(t_2) = \frac{R(t_1)}{R(t_2)}V(t_1) = (1 - H(t_2 - t_1))V(t_1)$$

Doppler Tracking in the expanding universe

- Kinematics

  – Distance measured by time-of-flight of light rays

$$D = R(r_2 - r_1) \quad \text{with} \quad \frac{\mathrm{d}D}{\mathrm{d}t} = \dot{R}(r_2 - r_1) + R\dot{r}_2 = HD + V_2$$



  – Trajectory at constant distance to observer has local velocity

$$0 = \dot{D} = HD + V_2 \quad \Rightarrow \quad V_2 = -HD$$

  – Observer at rest in cosmic substrate
  – Pioneer S/C move on geodesics and become slowed down
  – Cosmic redshift of frequency
  – Resulting Doppler effect (velocity of points of consatnt distance wrt cosmic substrate

$$\nu_2(t_2) = \left(1 - H(t_2 - t_1) - V_2^{tot}\right)\nu_0(t_1) \quad \text{and} \quad V_2^{tot}(t_2) = H(t_2 - t_1) - V_2^{tot} H(t_2 - t_1)$$

  – Red shift and Doppler effect from the velocity induced by constant ditance cancel
  – Only the satellite´s slow down ist left over.

$$a = HV = \frac{V}{c} cH << cH$$

Yukawa modification? (1)

- Ansatz

(*Lämmerzahl*, 2005)

$$V(r) = G\frac{M_{Sun}}{r}\left(1 + \alpha \cdot e^{-r/\lambda}\right)$$

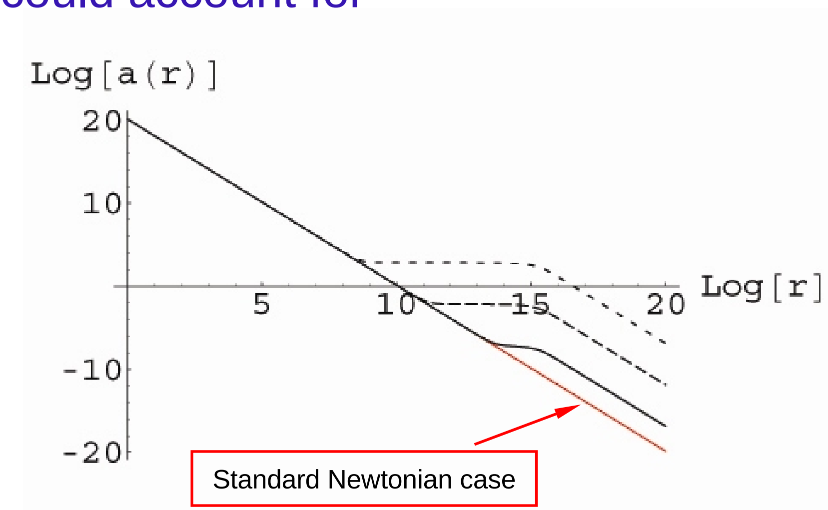
- with Taylor extension and
  $G_0 = (1+\alpha)G$ as observed grav. constant for $r \to \infty$

$$a(r) = -G_0\frac{M_{Sun}}{r^2} + \quad \cdots \quad - \frac{\alpha}{1+\alpha}G_0\frac{M_{Sun}}{3\lambda^2}\frac{r}{\lambda} + \ldots$$

= a_p(anomalous Pioneer acceleration)

- Next order term smaller by 2/3(r/λ) ≤ 0.06 (could account for small decrease observed during missions)

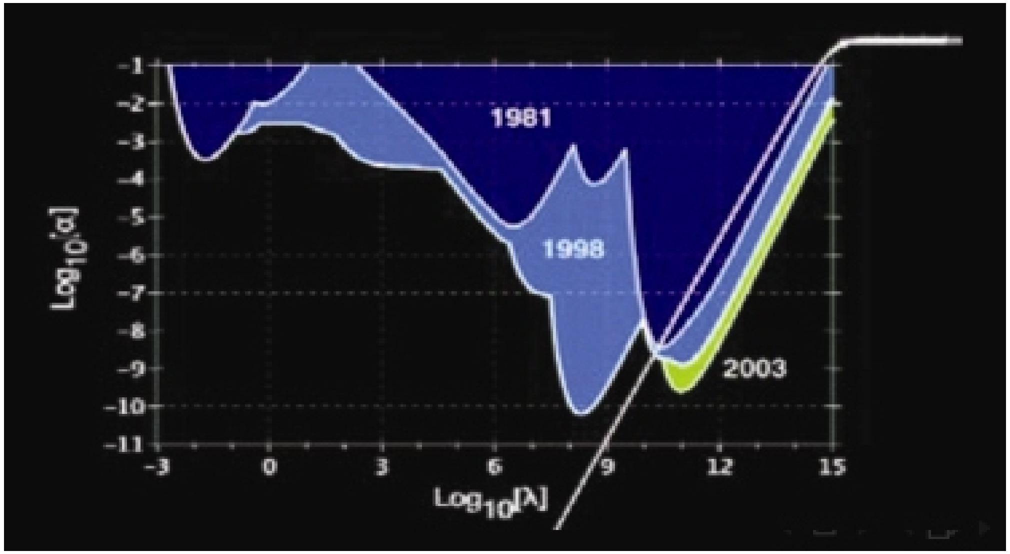
- Strong α (≈ 1)
  → long range coupling
  → acceleration plateau
  between ca. 1 – 100 AU.



Yukawa modification? (2)

$$a_p = \frac{\alpha}{1+\alpha} G_0 \frac{M_{Sun}}{2\lambda^2} \quad \Rightarrow \quad \alpha = \frac{2\lambda^2 a_p}{G_0 M_{Sun} - 2\lambda^2 a_p}$$

$$\Rightarrow \quad \lambda \geq \sqrt{\frac{G_0 M_{Sun}}{2 a_p}} = 2.8 \cdot 10^{14} \text{ m}$$



A viable model?

- Pioneer anomaly
  $\log_{10}(\lambda) > 16,\ \alpha + 1 \leq 10^{-5}$
- Galactic rotation curves
  $\log_{10}(\lambda) > 16,\ \alpha + 1 \leq 10^{-1}$
- Local strength: modification by „Yukawa in Yukawa“

$\log_{10}(\lambda) > 16$ for $\log_{10}|\alpha| = 1$ compatible with present experimental results in the solar system (including planetary orbits)

(*Lämmerzahl*, 2005)

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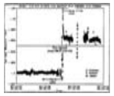
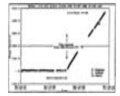
  - Quadrupole/Octopole Anomaly (*Tegmark et al*. 2005, *Schwarz et al.* 2005*):*
    quadrupole and octopole of CMB are correlated with solar system eclipse
  - Pioneer Anomaly (*Anderson et al.* 1998/2002)
  - Fly-by Anomalies (*Antresian and Guinn* 1998*, Anderson and Williams* 2001*, Morley* 2005, *Campbell* 2006
    confirmed for 3 satellites
    satellite trajectory velocities are too high by some [mm/s] after planetary fly-bys / require non-conservative gravitational potential

Fly-by Anomaly

- 2-way S-band Doppler and range residuals during fly-bys at Earth show an exit (asymptotic) velocity greater than expected reported by several authors (*Antreasian & Guinn* 1998, *Anderson & Williams* 2001, *Morley* 2005, *Preuss* 2006)

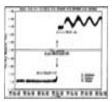


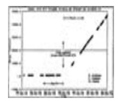


Galileo

2-way Doppler S-band residuals

range residuals





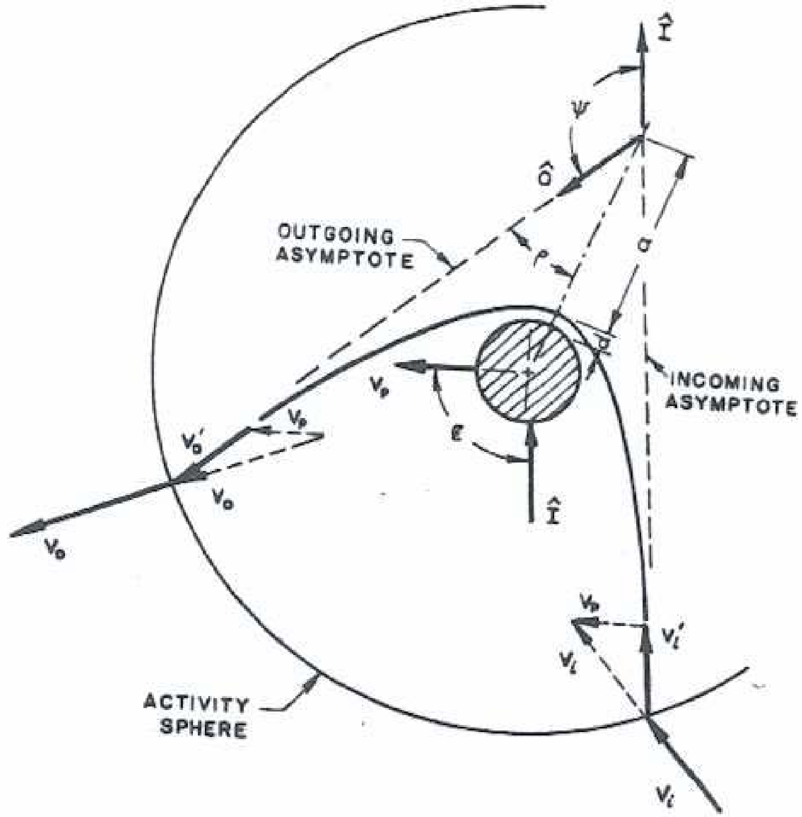
NEAR

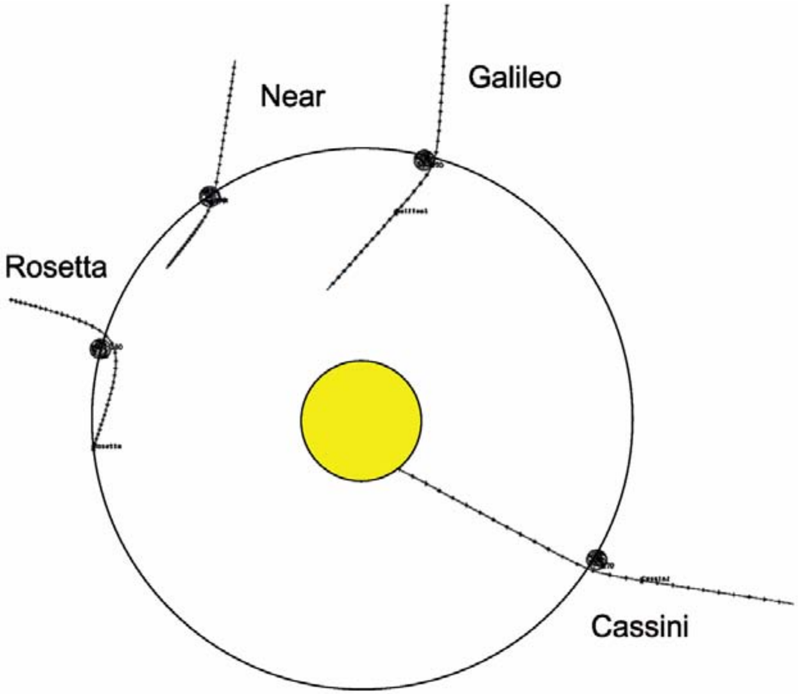
2-way Doppler S-band residuals

range residuals

Fly-by / gravity assist manoeuver

$$\Delta E_{kin} / m_{sat} = \left(v_0^2 - v_i^2\right)/2$$
$$= v_{earth}\left(v_0' - v_i'\right)$$





Anderson, Campbell, Nieto, 2006

Earth fly-by´s analyzed

	Galileo (1st fly-by)	NEAR	Cassini	Rosetta	Messenger
v_∞ [km/s]	8.949	6.851	16.01	3.863	4.056
v_F [km/s]	13.738	12.739	19.03	10.517	10.389
h [km]	956	532	1,172	1,954	2,336
ε	2.47	1.81	5.86	1.31	1.13
Θ [°]	47.67	66.92	19.66	99.396	94.7
i [°]	142.9	108.0	25.4	144.9	133.1
Fly-by	8.12.1990	23.1.1998	18.8.1999	4.3.2005	2.8.2005
Δv_∞ [mm/s]	3.92 ± 0.08	13.46 ± 0.13		1.82 ± 0.05	
Δv_F [mm/s]	2.56 ± 0.05	7.24 ±0.07	|-0.2| (?)	0.67 ± 0.02	O (0)

- to be implemented: Hayabusa fly by 05/2004 (h = 3,725 km)
- Cassini data not reliable due to perigee manoeuver
- 2nd Galileo fly by too deep / large atmospheric influence

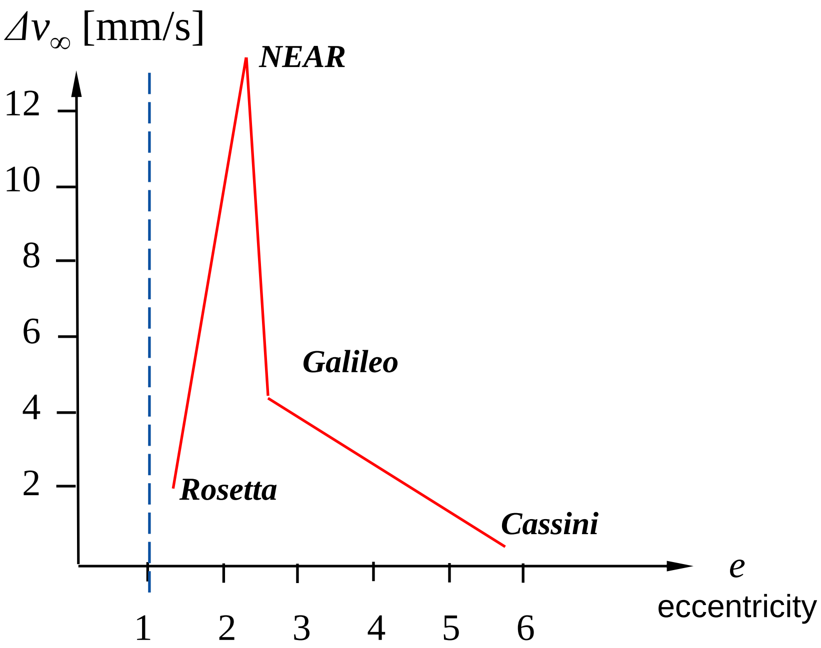
Firenze, 30.9.2006

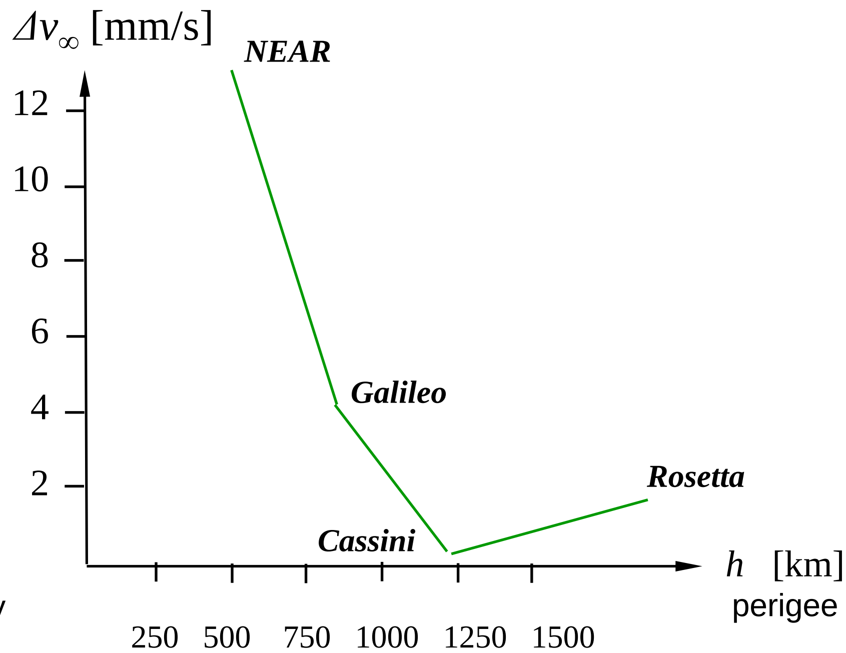
Error analysis

error budget constituents	bias $[10^{-5}\ m/s^2]$
Atmospheric drag	- 0.0001
Ocean tides	± 0.1
Solid earth tides	« |0.15|
S/C charging (modeled / analyzed for LISA; for charging $Q < 10^{-7}$ C	± 0.0001
Magnetic moments ($< 2 \cdot 10^{-7}$ G/m)	$\pm 10^{-10}$
Earth albedo (1 t S/C)	± 0.00024
Solar wind	± 0.0003
Relativistic corrections $U \cdot v^2 / c^2 \approx 10^{-20}$	not affecting
Spin rotation coupling (coupling of the helicity of radio waves with S/C spin and Earth rotation (only effective for 2-way Doppler ranging)	not affecting

Phenomenological observations

- Δv decreases with increasing eccentricity and perigee height
- Δv disappears at $e = 1$ (as expected for bound orbits)





$$a_{Fly-by} = 10^{-4}\ \text{m/s}^2 \qquad \frac{a_{Fly-by}}{a_{Newton}} \approx 10^{-5} \approx \frac{a_{PA}}{a_{Newton}}$$

General modification of particle motion

- Universality of Free Fall

$$0 = v^\nu \partial_\mu v^\nu + H^\mu(x, v) = v^\nu \partial_\mu v^\nu + \{^{\mu}_{\rho\sigma}\} v^\mu v^\sigma +$$

non-metric

- Non-relativistic approximation / expansion for small velocities

$$\frac{d^2 x^i}{dt^2} = -\left(\{^{i}_{\mu\nu}\} - \{^{0}_{\mu\nu}\} \frac{dx^i}{dt} \right) \frac{dx^\mu}{dt} \frac{dx^\nu}{dt} + \left(\frac{dt}{ds} \right)^{-2} \left(\gamma^i(v, x) - \frac{dx^i}{dt} \gamma^0(v, x) \right)$$

$$\approx \quad + \quad + \dot{x}^2 \partial_i V + \dot{x}^i \dot{V} + Y^i + Y^i_j \dot{x}^j + Y^i_{jk} x^j x^k + \ldots$$

Newton

Lense-Thirring

with:

$$Y^i = A_{11} \frac{GM}{r^2} \frac{r^i}{r}$$

$$Y^i_j = A_{21} \frac{GM}{r^2} \frac{r^i r^j}{r^2} + A_{22} \frac{GM}{r^2} \delta^i_j$$

$$Y^i_{jk} = A_{31} \frac{GM}{r^2} \frac{r^i r^j r^k}{r^3} + A_{32} \frac{GM}{r^2} \frac{r^i}{r} \delta_{jk} + A_{33} \frac{GM}{r^2} \frac{r^j}{r} \delta^i_k$$

General modification of particle motion

- Acceleration terms obtained:

$$\ddot{x}^i_{(1)} = A_{11}\frac{GM}{r^2}\frac{r^i}{r} \qquad \text{(Newton)}$$

$$\ddot{x}^i_{(2)} = \quad \frac{GM}{r^2}\frac{\dot{r}^i_{ll}}{c} + \quad \approx 10^{-4}\ \text{m/s}^2$$

chosen = 0

Maximum at perigee
applies to fly-bys

0 at perigee

0 for $r \to \infty$

$$\ddot{x}^i_{(3)} = A_{31}\frac{GM}{r^2c^2}\frac{\dot{r}^i(r\cdot\dot{r})^2}{r^3} + A_{32}\frac{GM}{r^2c^2}\frac{\dot{r}^i}{r}\dot{r}^2 + A_{33}\frac{GM}{r^2c^2}\frac{\dot{r}^i}{r}(r\cdot\dot{r}) \ll 10^{-4}\ \text{m/s}^2$$

- Remarks:
  - Energy not conserved
  - Universality of Free Fall still valid
  - Gravity cannot be transformed away (contradicts the Einstein elevator)
  - r – dependence in all terms (cannot explain Pioneer anomaly)
  - Unstable bound orbits: How can dynamical equations distinguish between bound and escape orbits?
  - Hyperbolic orbits are rare natural orbits.

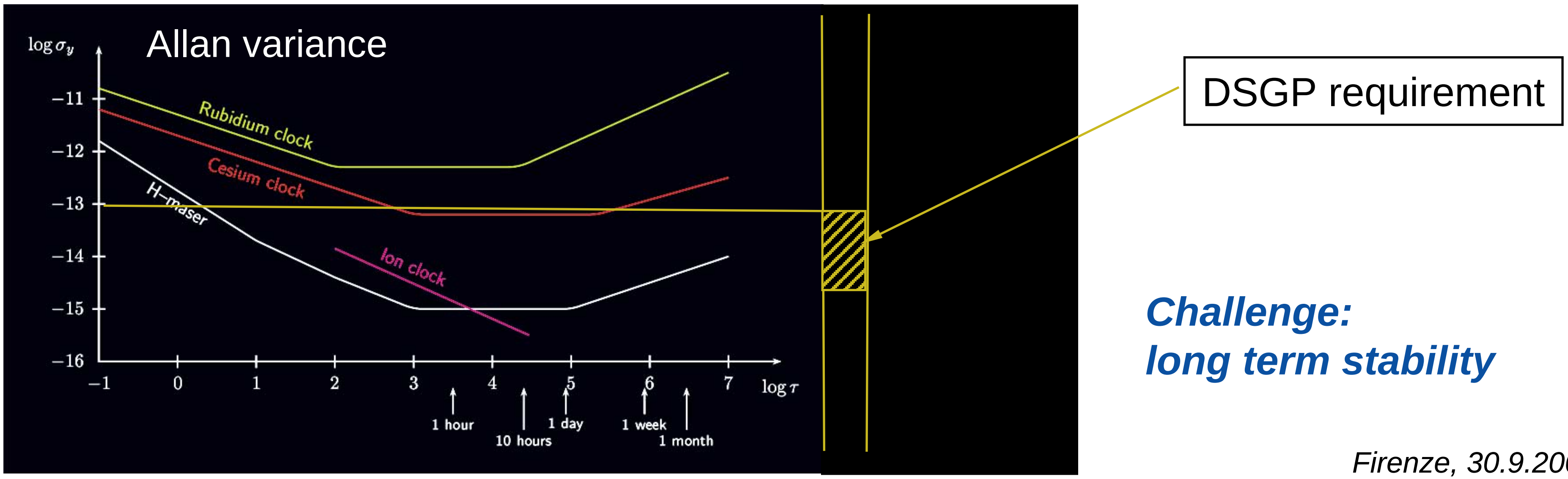
Clocks to explore the anomalies

- Redundant measurements
  - Measuring acceleration of S/C on geodesic via ranging and Doppler tracking
  - Measuring redshift of clocks on-board S/C

    for Pioneer Anomaly

$$\frac{\Delta\nu}{\nu} = \frac{1}{c^2}\int_{20\,AU}^{90\,AU} a_{PA}\,dx \approx 10^{-13}$$

  - Clock exploration does not depend on geodesic motion, independent from acceleration
  - Cock exploration is cumulative
  - Clocks automatically isolate the pure gravity sector
  - Clocks represent an absolute DC-accelerometer



Challenge:
long term stability

Conclusion and final remarks

- Unexplained phenomena
  - Dark matter (does it affect solar system physics?)
  - Dark energy
  - Increase of AU
  - Quadrupole / Octopole anomaly
  - Pioneer Anomaly
  - Fly-by anomalies
- It´s worth to discuss the anomalies
  - Try to find systematics
  - Try to find conventional explanations
  - Try to find relations between anomalies (Anomalies most probably are not isolated phenomena.)
  - Are there similar effects in other gravitating systems?
  - What´s about hyperbolic orbits?
- Observation of future fly-bys of satellites
  - Rosetta Mars fly-by 02 / 2007 (orbital height: ca. 250 km)
  - Rosetta Earth fly-by 11 / 2007 (orbital height: ca. 5,000 km)
  - Rosetta Earth fly-by 11 / 2009 (orbital height: ca. 2,500 km)
  - New Horizon Jupiter fly-by in 2008 ?
- Use clocks

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