

Tests expérimentaux de la gravitation

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Remerciements aux :

- Expérimentateurs/Théoriciens cités
- Membres du « GREX »
GDR 2062 du CNRS (SPM/PNC/STIC/SDU)
- Membres du « Groupe adhoc
Physique Fondamentale » du CNES

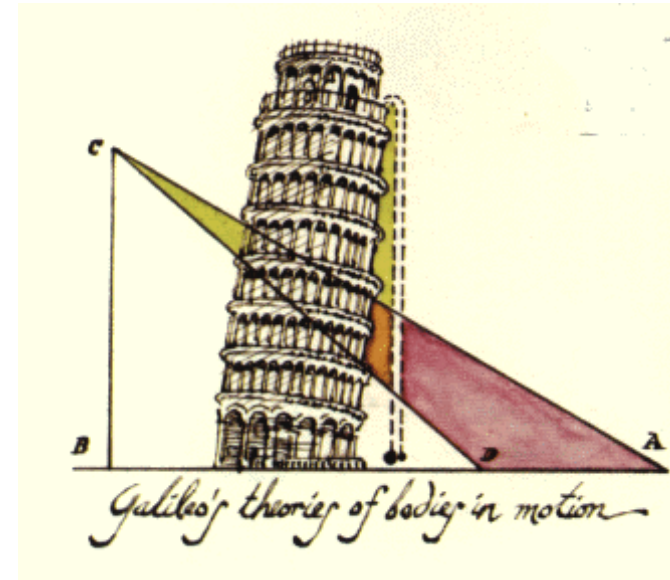
Des tests « classiques »...

Galilée ... Newton ...

- Universalité de la chute libre
- Mouvements des planètes et leurs perturbations

... Einstein ...

- Tests de la relativité restreinte
- Déflexion des rayons lumineux
- Décalage vers le rouge des horloges
- Avance du périhélie de Mercure



} Relativité
Générale

...aux problématiques actuelles

Principe d'équivalence élargi (EEP) :

- Principe d'équivalence faible (WEP)
- Invariance de Lorentz locale (LLI)
- Invariance de position locale (LPI)

Relativité générale :

- Paramètres PPN
- Terre-Lune (LLR)
- Loi de Newton
- Pulsars binaires
- Effet Lense-Thirring

Station
Laser-Lune
OCA Grasse



Autres tests (dont je ne parle pas)

Détection directe des ondes

gravitationnelles (exposé de J.-Y. Vinet)

Cosmologie, Astrophysique (exposés d'hier)

Positionnement

Galileo

Astrométrie

Mécanique céleste

Navigation ...

Géodésie ...

30 satellites including 3 in-orbit spares

altitude 23616



Status WEP

Weak Equivalence Principle

≈ Universality of free fall

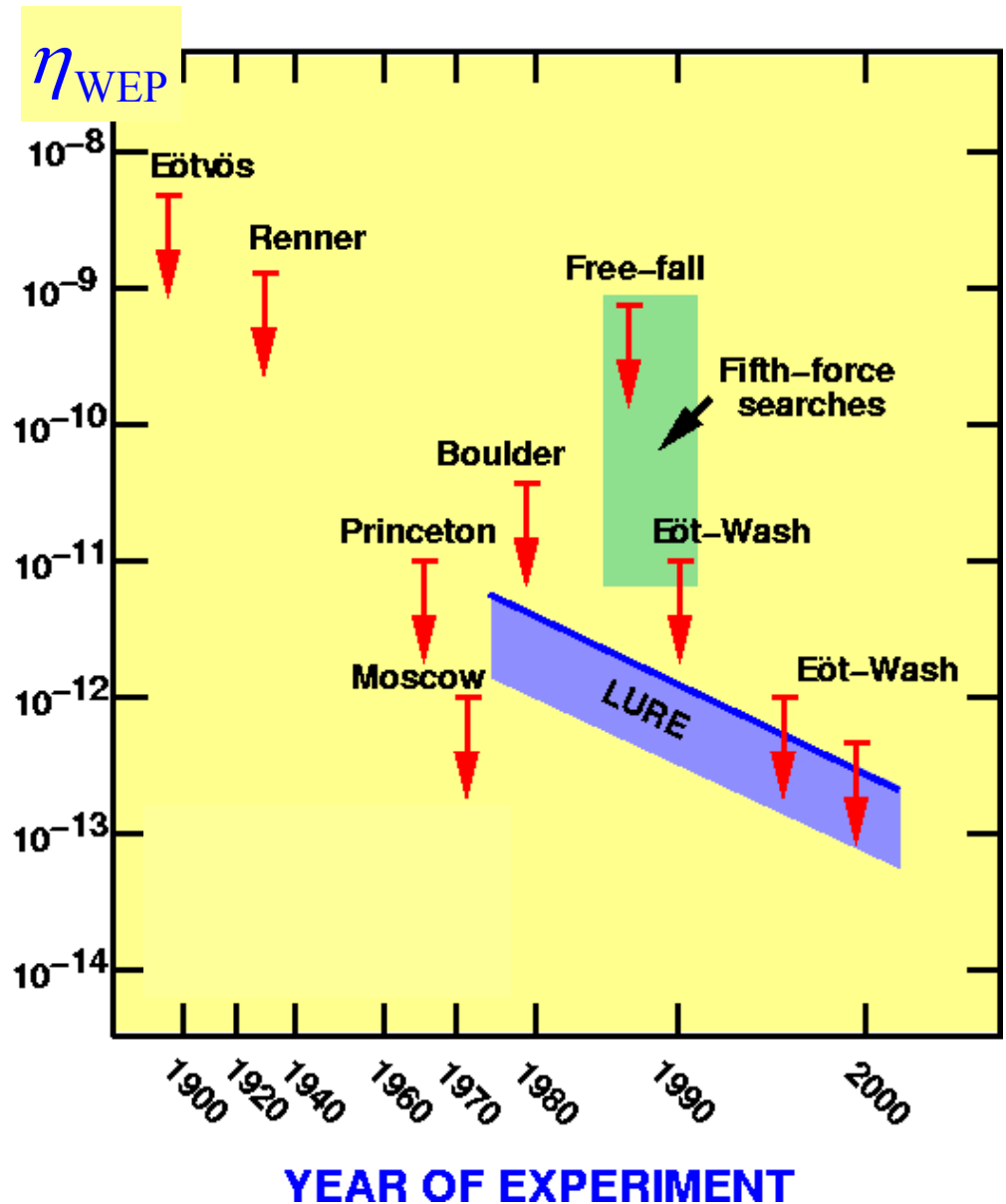
$$\eta_{\text{WEP}} = 2 \frac{a_1 - a_2}{a_1 + a_2}$$

Clifford Will

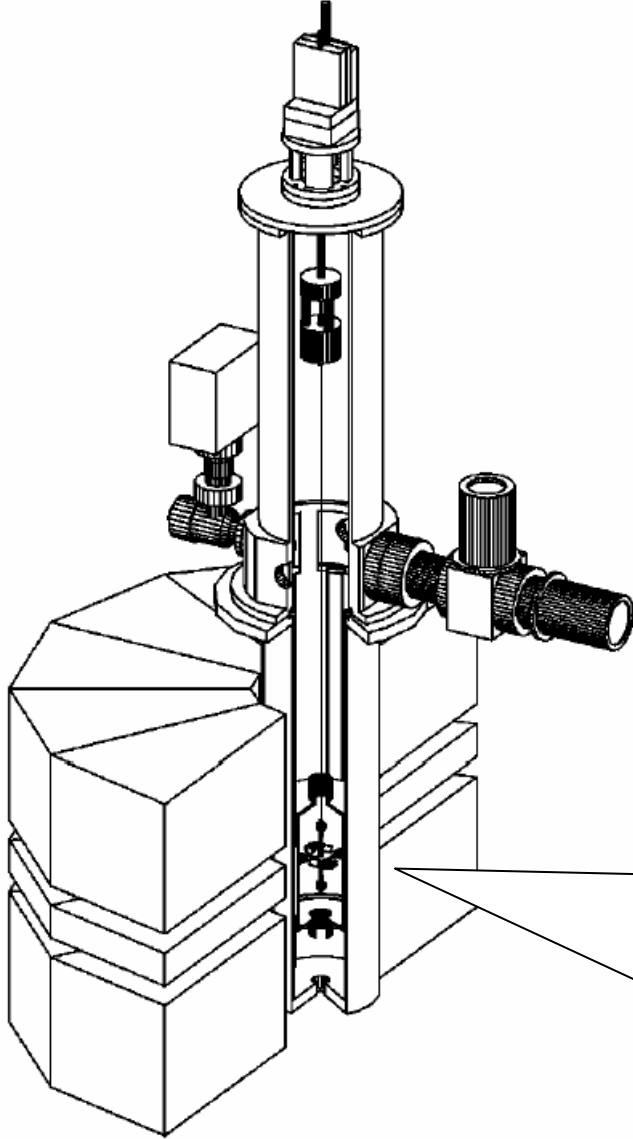
Living Reviews in
Relativity (2001)

www.livingreviews.org

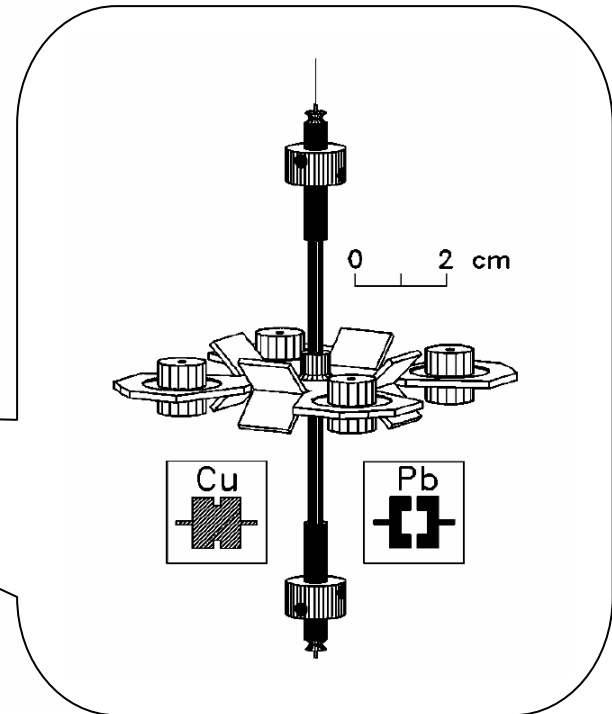
TESTS OF THE WEAK EQUIVALENCE PRINCIPLE



Eöt-Wash group (Adelberger *et al*)
PRD 61 (1999) 022001



Rotating attractor



Torsion pendulum

LLI : Local Lorentz Invariance

The Mansouri-Sexl kinematical theory generalizes the Lorentz transformation :

$$T = \left(1 - \alpha_{\text{MS}} \frac{v^2}{c^2} \right) \left(t - \frac{\mathbf{v} \cdot \mathbf{x}}{c^2} \right) + O\left(\frac{1}{c^4} \right)$$

Special relativity

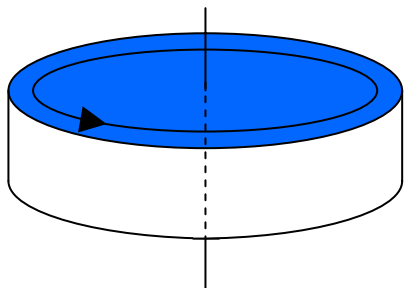
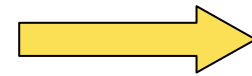
$$\alpha = -1/2, \beta = 1/2, \delta = 0$$

$$\mathbf{X} = \left(1 - \delta_{\text{MS}} \frac{v^2}{c^2} \right) \mathbf{x} - \left(1 - (\delta_{\text{MS}} - \beta_{\text{MS}}) \frac{v^2}{c^2} \right) \frac{\mathbf{v}(\mathbf{v} \cdot \mathbf{x})}{v^2} + \mathbf{v}T + O\left(\frac{1}{c^4} \right)$$

Experiments measure the deviation of the Mansouri-Sexl parameters from their SR values.

Cryogenic microwave oscillator

BNM-SYRTE-Observatoire Paris
P.Wolf *et al*, PRL 90 (2003) 060402



Whispering
gallery mode

Brought along Earth motion

Bounds on Mansouri-Sexl theory

Clock comparisons with GPS data

$$\left| \alpha_{\text{MS}} + \frac{1}{2} \right| < 8 \times 10^{-7} \quad \text{P.Wolf \& G.Petit 1997}$$

Michelson-Morley and Kennedy-Thorndike tests

$$\left. \begin{array}{l} \text{MM} \quad \left| \delta_{\text{MS}} - \beta_{\text{MS}} + \frac{1}{2} \right| < 2.5 \times 10^{-9} \\ \text{KT} \quad \left| \beta_{\text{MS}} - \alpha_{\text{MS}} - 1 \right| < 3 \times 10^{-7} \end{array} \right\} \text{P.Wolf et al 2003}$$

More sophisticated dynamical theories :

Clifford Will

Living Reviews in
Relativity (2001)

www.livingreviews.org

P. Wolf et al (2004)

arXiv:gr-qc/0401017

Parametrized Post Newtonian

PPN parameters change the effect of gravitation sources on the metric :

$$g_{ij} = \left(1 + 2\gamma_{\text{PPN}} \frac{U}{c^2} \right) \eta_{ij} + \mathcal{O}\left(\frac{1}{c^4}\right)$$
$$g_{00} = 1 - 2\frac{U}{c^2} + 2\beta_{\text{PPN}} \left(\frac{U}{c^2}\right)^2 + \dots$$

General relativity

$$\gamma_{\text{PPN}} = \beta_{\text{PPN}} = 1$$

Other parameters describing preferred location effects (ξ_{PPN}) preferred frame effects (α_{PPN})

...

General relativity

$$\xi_{\text{PPN}} = \alpha_{\text{PPN}} = 0$$

Status γ_{PPN}

Light deflection
(or time delay)

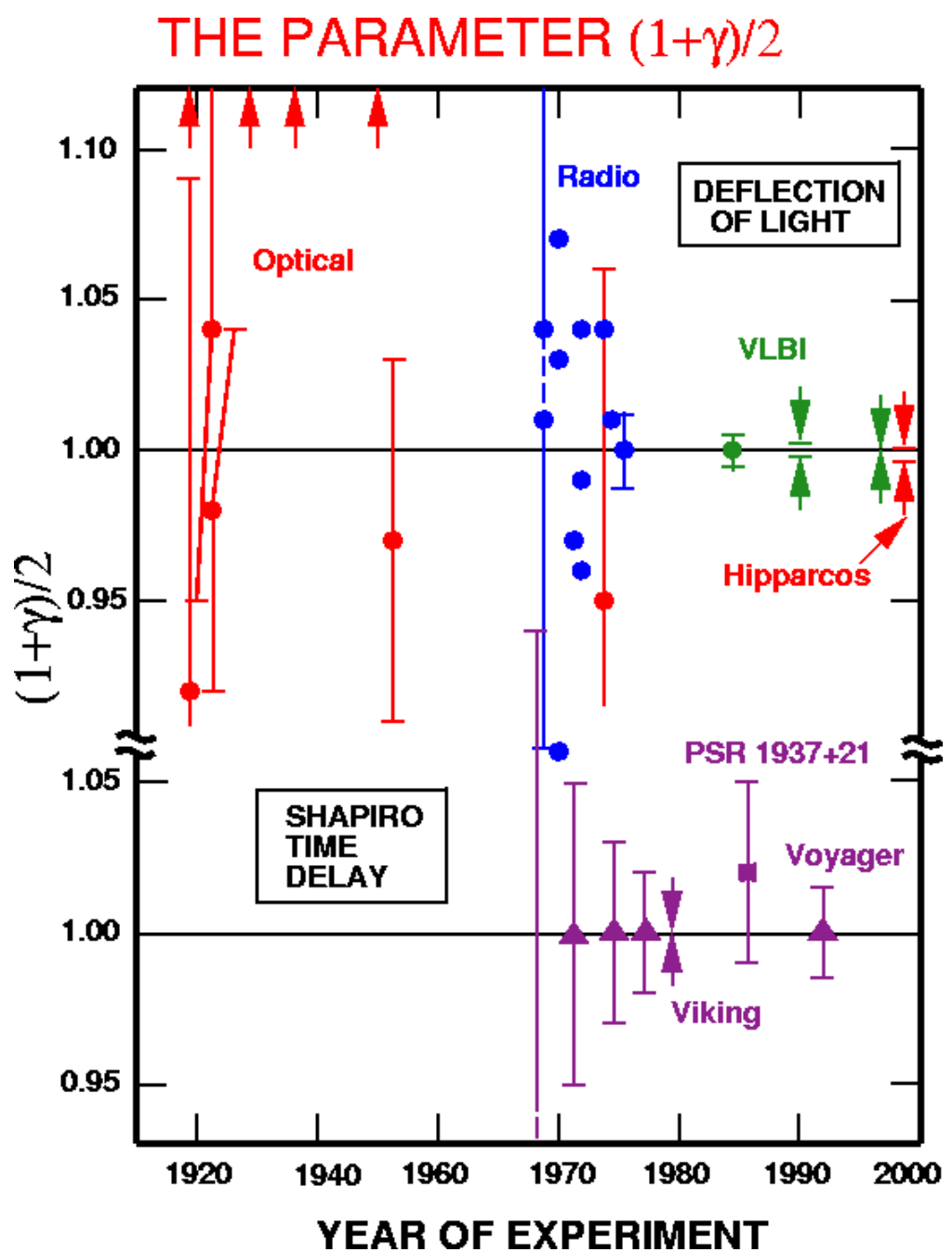
$$\Delta\theta = \frac{1 + \gamma_{PPN}}{2} \Delta\theta_{GR}$$

$$|\gamma_{PPN} - 1| \leq 3 \times 10^{-4}$$

Clifford Will

Living Reviews in
Relativity (2001)

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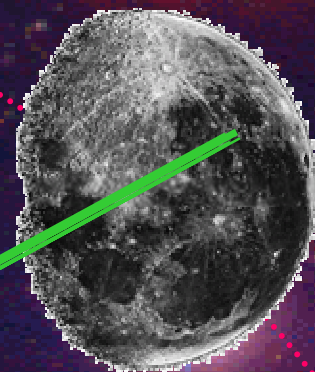


Status β_{PPN}

$$\eta_{PPN} = 4\beta_{PPN} - \gamma_{PPN} - 3$$

$$|\eta_{PPN}| \leq 9 \times 10^{-4}$$

$$|\beta_{PPN} - 1| \leq 4 \times 10^{-4}$$



$$|dG/Gdt| < 10^{-12}/yr$$

$$\text{WEP à } 2 \times 10^{-13}$$

Précision $\sim 3\text{mm}$

François Mignard
CERGA Laser-Lune

Status New Forces ...

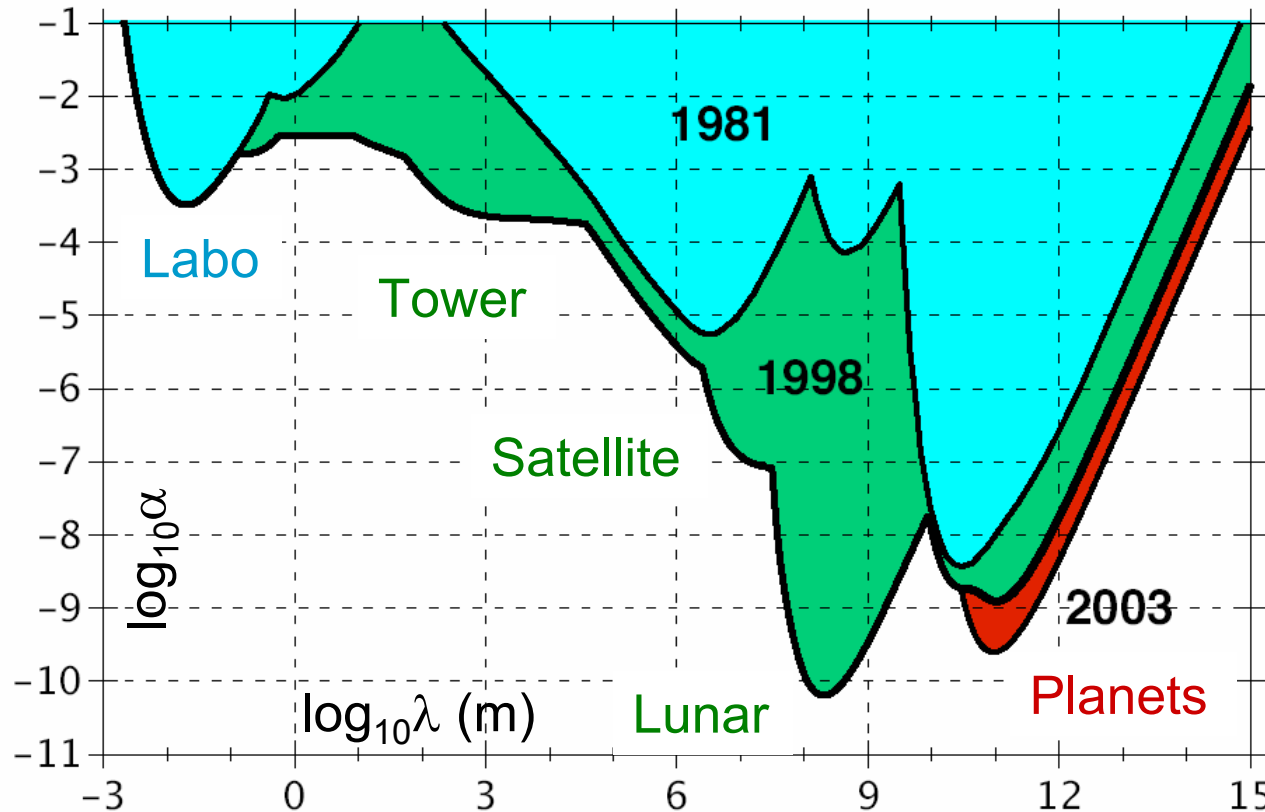
Bounds on 5th force, extra dimensions...

J. Coy, E. Fischbach, R. Hellings, C. Talmage & E.M. Standish (2003)

Yukawa potential added to Newton potential

$$\frac{GM_1M_2}{r} \left(1 + \alpha e^{-\frac{r}{\lambda}} \right)$$

Bounds shown on a plot (λ, α)



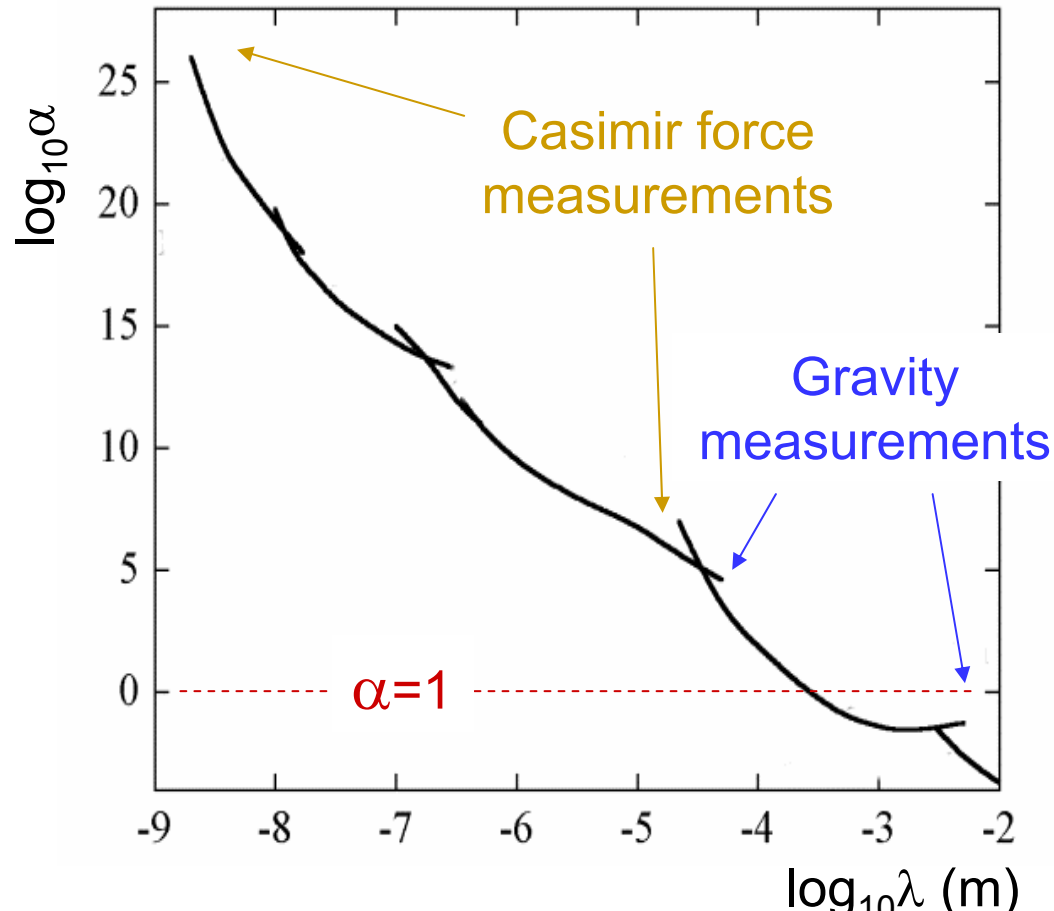
... with Short Ranges

Gravity measurements
at short distances
(~ millimetric)

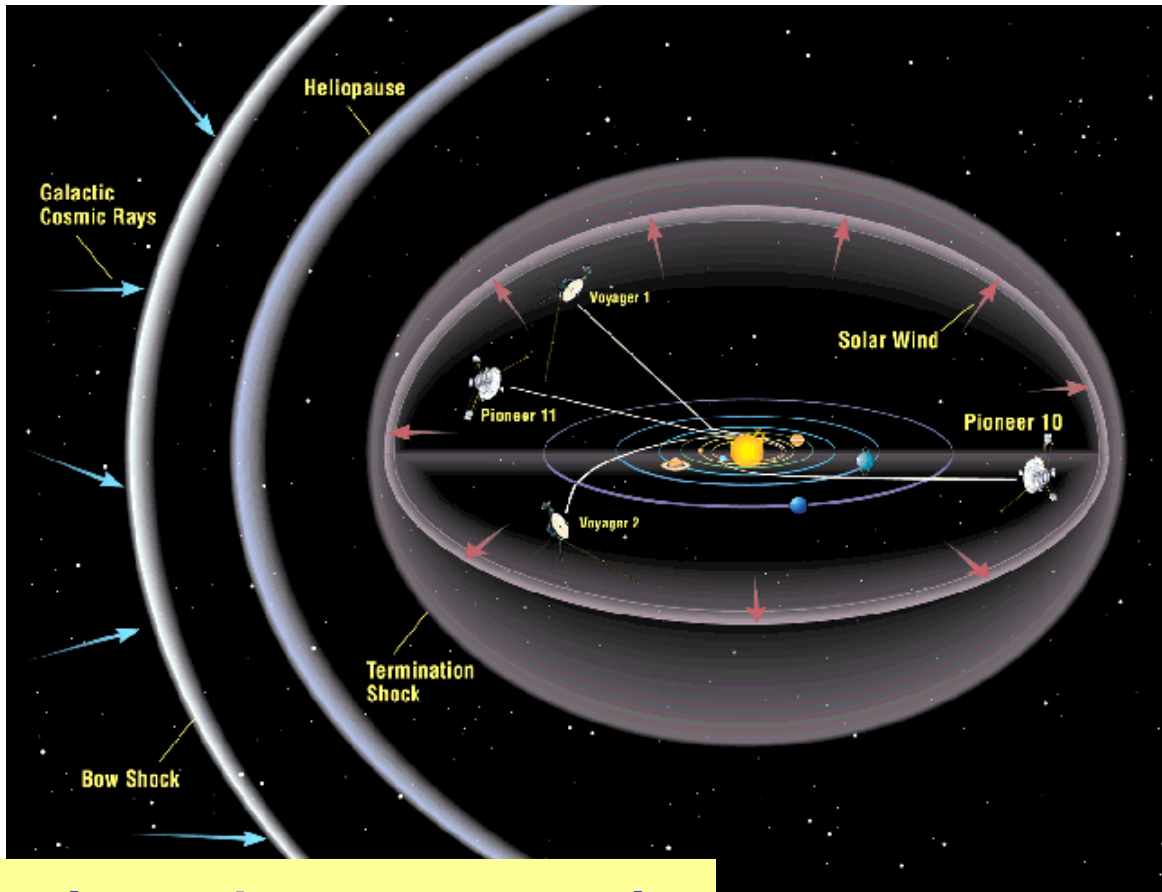
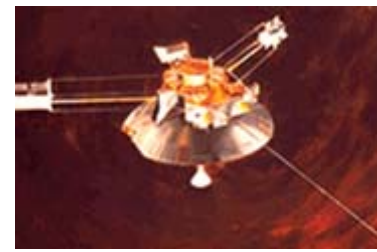
$$\frac{GM_1M_2}{r} \left(1 + \alpha e^{-\frac{r}{\lambda}} \right)$$

For $\lambda \leq 30\mu\text{m}$,
comparison between
experimental results
and theoretical
predictions of the
Casimir force

Data collected by
E. Fischbach (2003)



... with Long Ranges



up to
80 AU

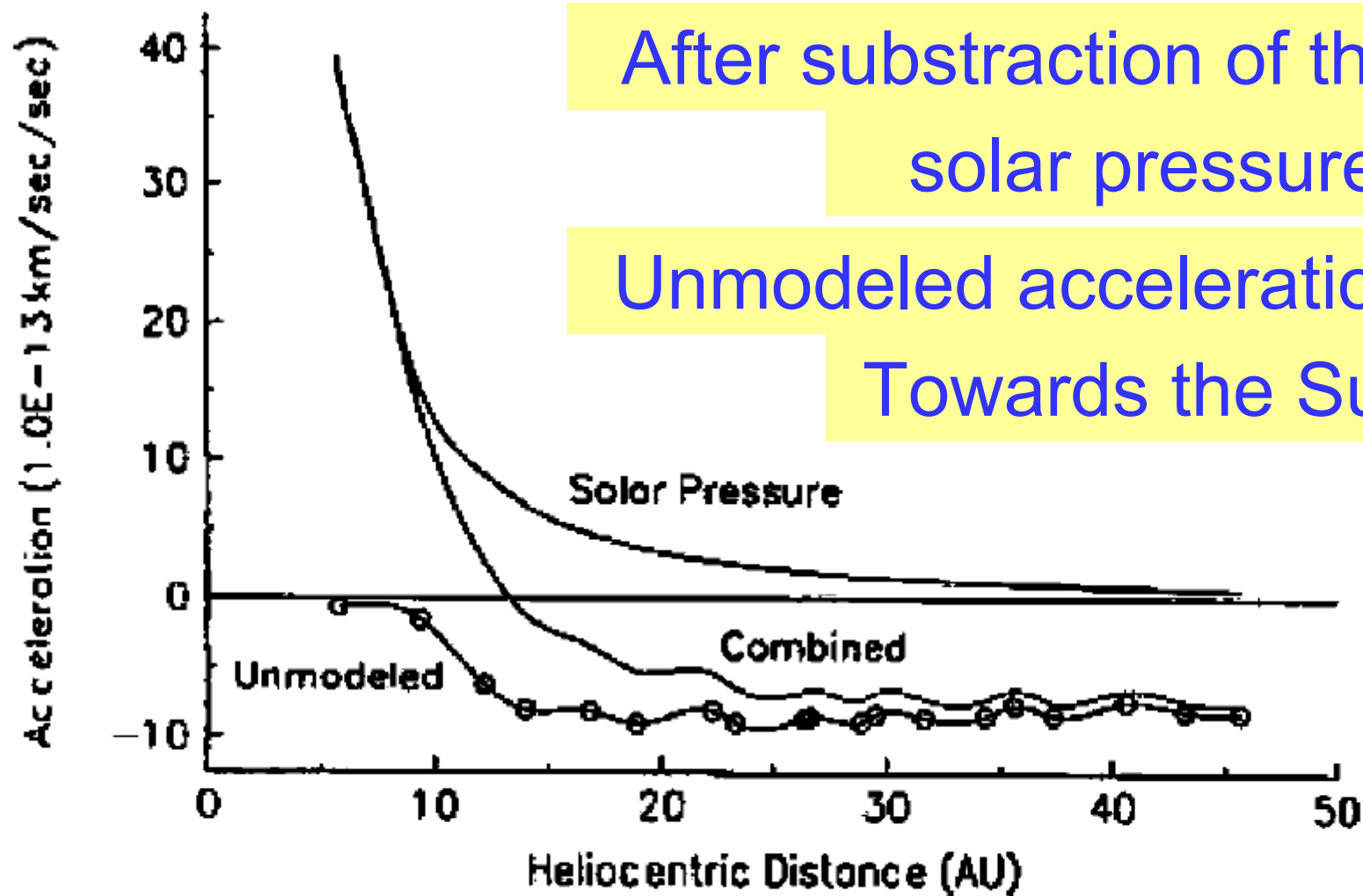
Acceleration anomaly
on Pioneer 10/11

and Galileo
and Ulysses



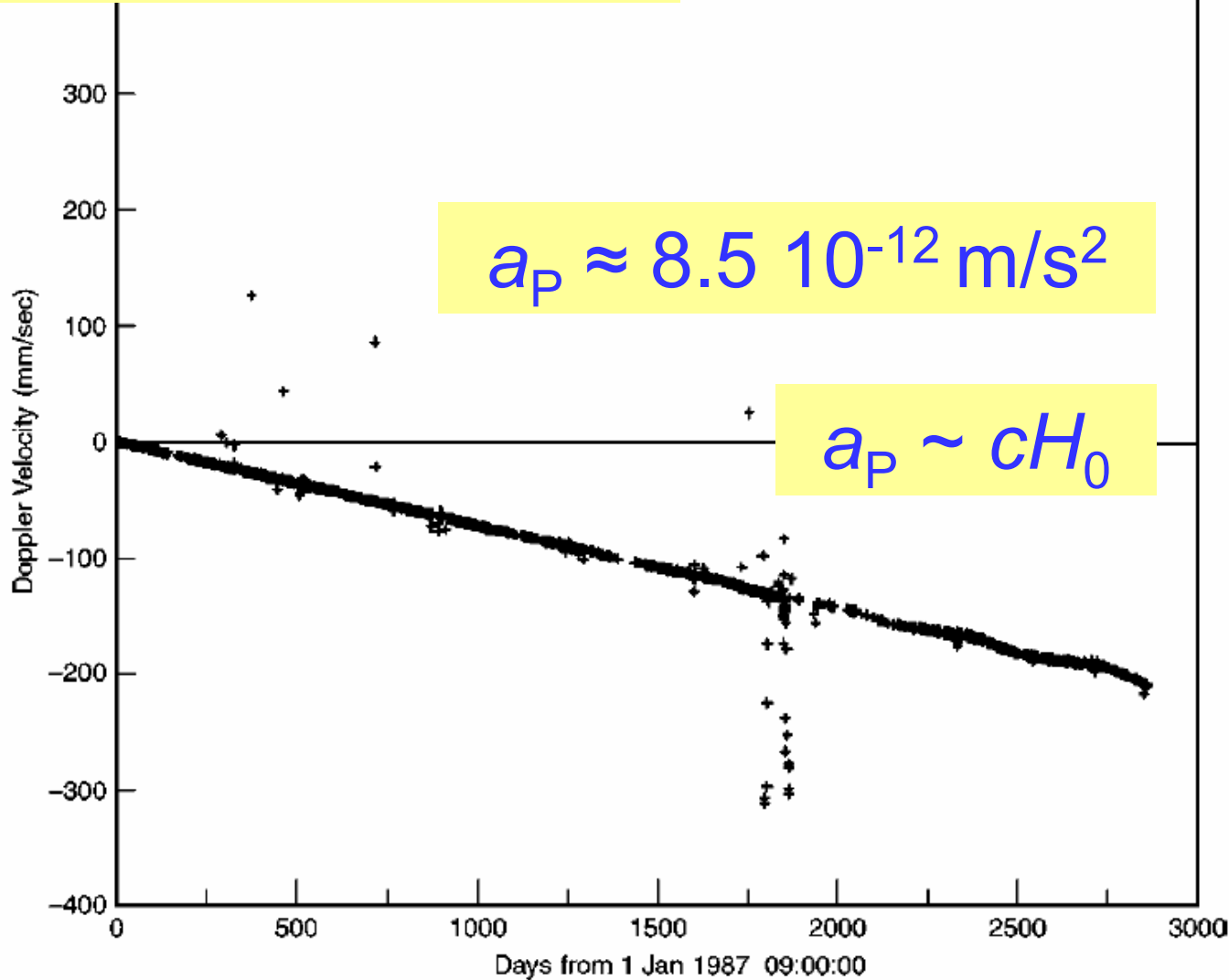


ACCELERATIONS ON PIONEER 10 AND 11 Positive Along Sun-Spacecraft Line





Doppler velocimetry



up to
80 AU



Expériences spatiales

Le principe d'équivalence est testé avec une précision meilleure que 10^{-12}

Mais il est violé (très faiblement) dans tous les modèles de grande unification des interactions fondamentales...

Pour améliorer la précision

→ Expériences spatiales !

- Bruit environnemental limité
- Quasi impesanteur
- Temps de chute très long

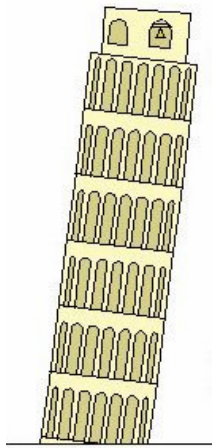
STEP

Stanford, NASA...

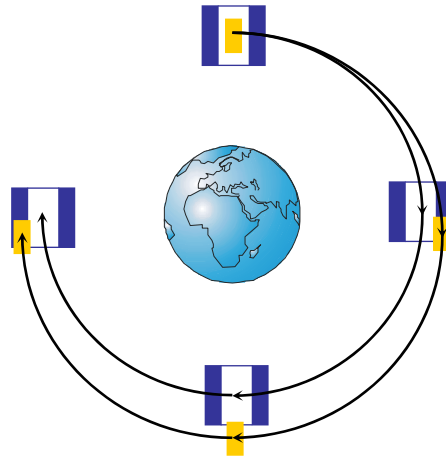
Microscope

ONERA-CNES,
+ ESA...

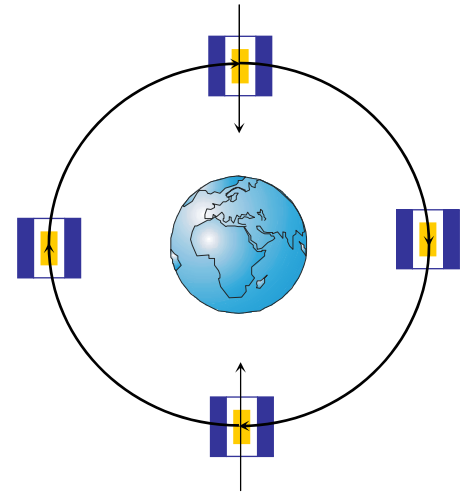
Testing EP in space



Galileo



« Free-Fall »
in space



MICROSCOPE

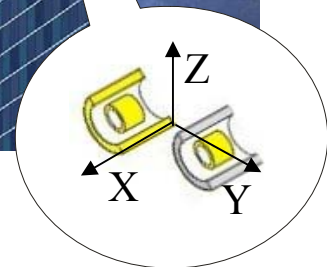
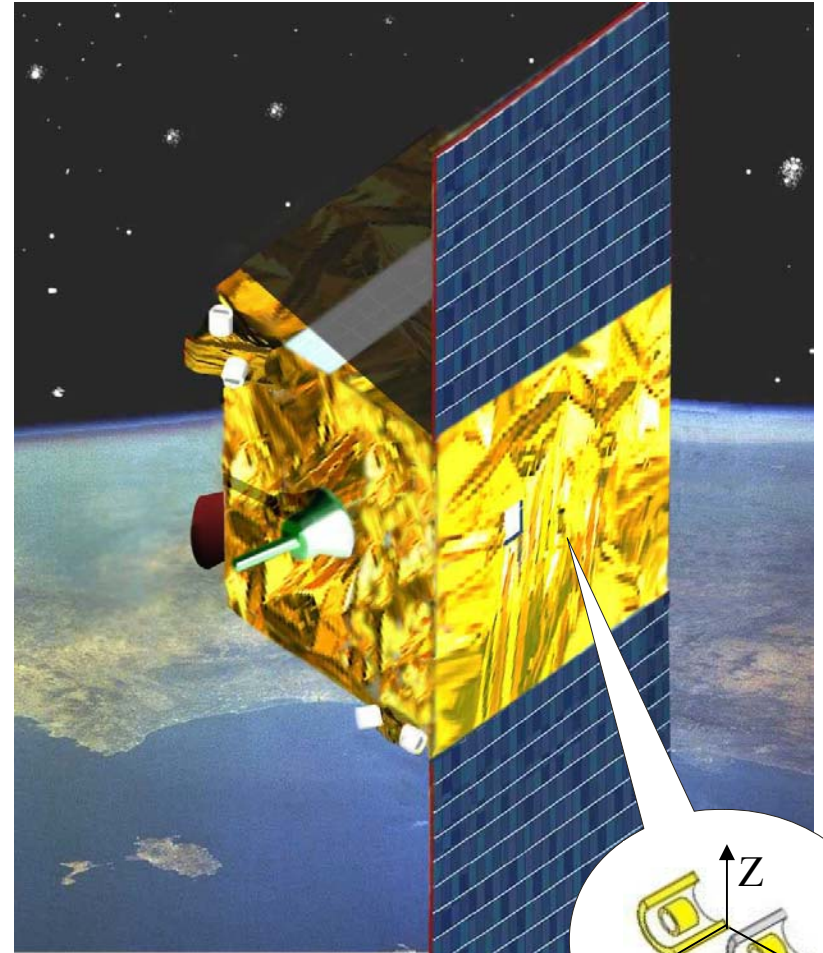
- Drag free system : the masses follow the same motion
- Potential EP violation measured on the applied forces when the masses have different compositions

Testing EP in space



- Launch in 2007
- Circular orbit 700km
- Microsat MYRIADE
- Mission duration
 $\frac{1}{2}$ to 1 year
- Accelerometer noise
 $1.5 \times 10^{-12} \text{ ms}^{-2} / \sqrt{\text{Hz}}$
- Acceleration resolution
 $5 \times 10^{-15} \text{ ms}^{-2}$

➤ EP Test 0.9×10^{-15}



Horloges à atomes froids

Atomes froids en microgravité :

- Stabilité et exactitude excellentes
~ 10^{-16} en relatif sur un jour

Synchronisation d'horloges :

- Précision excellente
- Disponible sur la planète

Pharao

BNM-SYRTE-LKB,
CNES

Aces

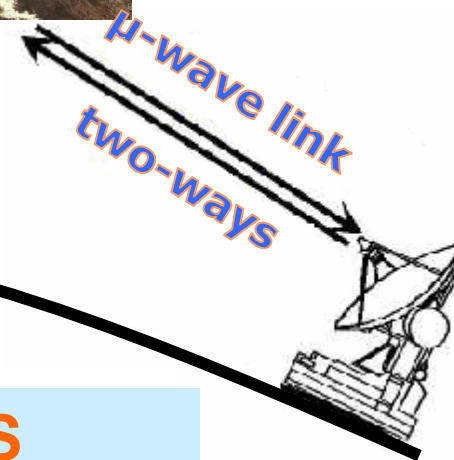
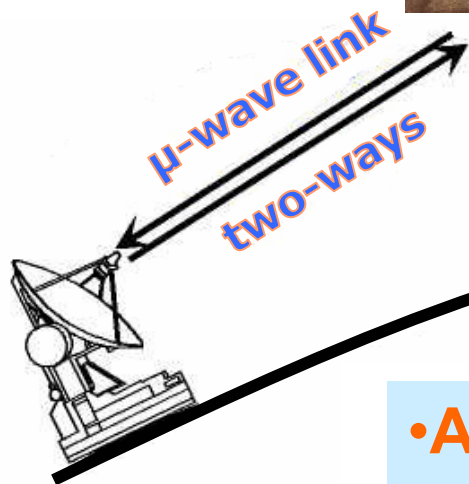
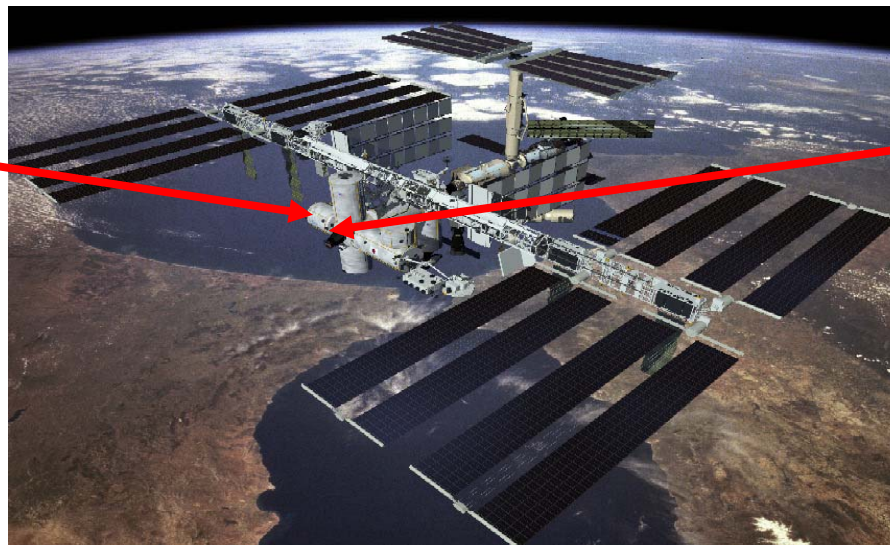
(+ ESA...)

A plus long terme :

- Contribution aux mesures géodésiques
- Réalisation du temps atomique depuis l'espace
(successeurs de GPS/Galileo)

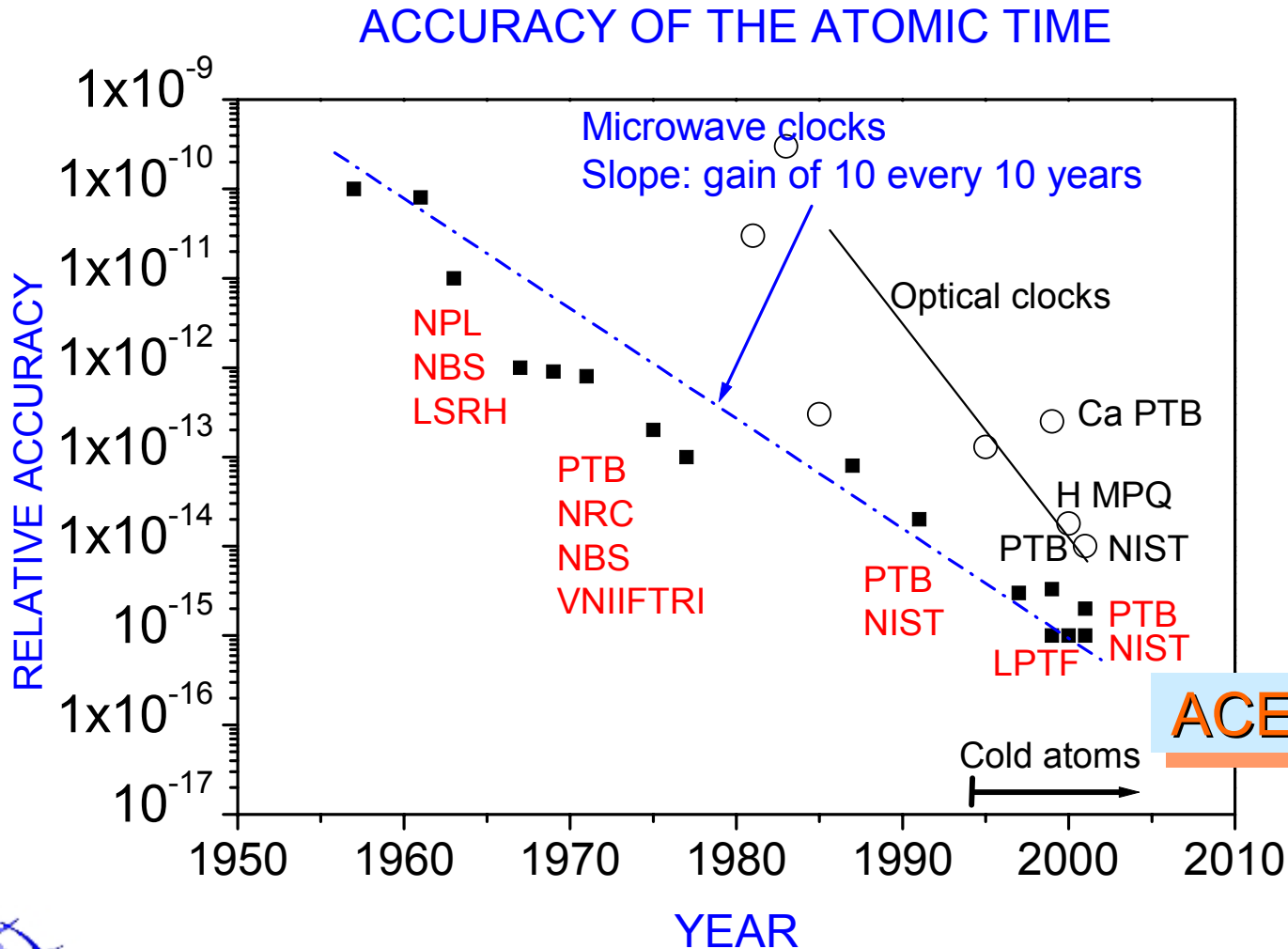
PHARAO

H-MASER



- Atomic clocks on the ISS
- Worldwide time comparisons
- Fundamental physics tests

Accuracy of the atomic time



ACES Scientific Objectives

Clock comparison

→ Einstein redshift :

$$\frac{\Delta \nu}{\nu} = \frac{\Delta U}{c^2}$$

Clock accuracy of 10^{-16}
→ test at 3×10^{-6}

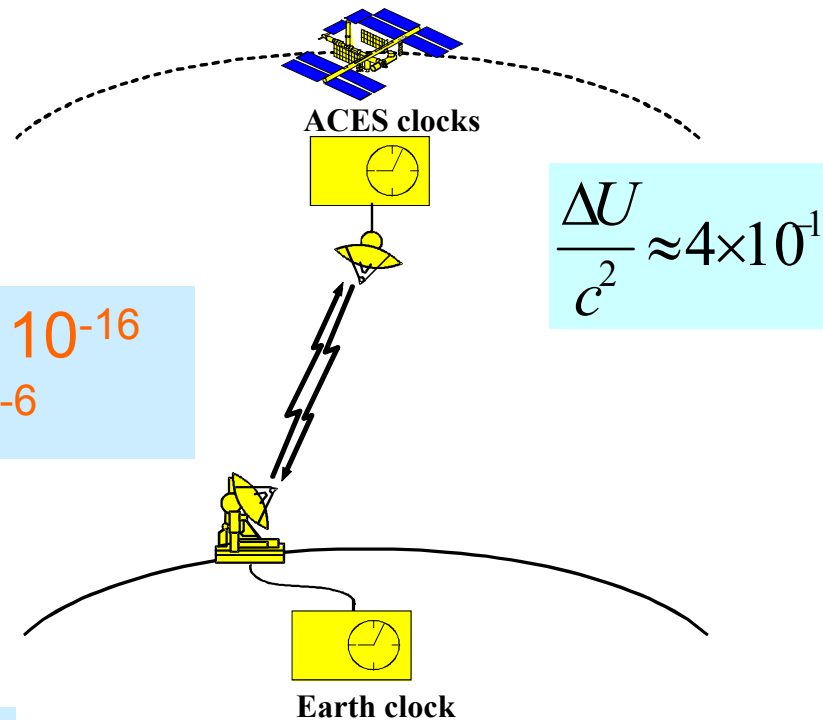
x 25 sensitivity improvement

Potential variation of α :

$$d\alpha/\alpha dt < 10^{-16}/\text{yr} \quad (\times 50)$$

Potential anisotropy of c :

x 10 sensitivity improvement



GDR 2062 du CNRS Gravitation et Expérience dans l'Espace

<http://www.spectro.jussieu/GREX>

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