Des senseurs atomiques pour des tests de physique fondamentale en laboratoire et dans l'espace

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LNE-SYRTE , Observatoire de Paris

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CONTENTS

The People who make it possible:

- S.Bize, F.Chapelet, P.Laurent, M.Abgrall, Y.Sortais, H.Marion, S.Zhang, F.Alard, I.Maksimovic, L.Cacciapuoti, J.Grünert, C.Vian, F.Pereira dos Santos, P.Rosenbusch, N.Dimarcq, P.Lemonde, G.Santarelli, A.Clairon, A.Luiten, M.Tobar, C.Salomon

- SAGAS collaboration (> 70 scientists)

+ ….

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Institut Francilien de Recherche sur les Atomes Froids IFRAF

department of physics

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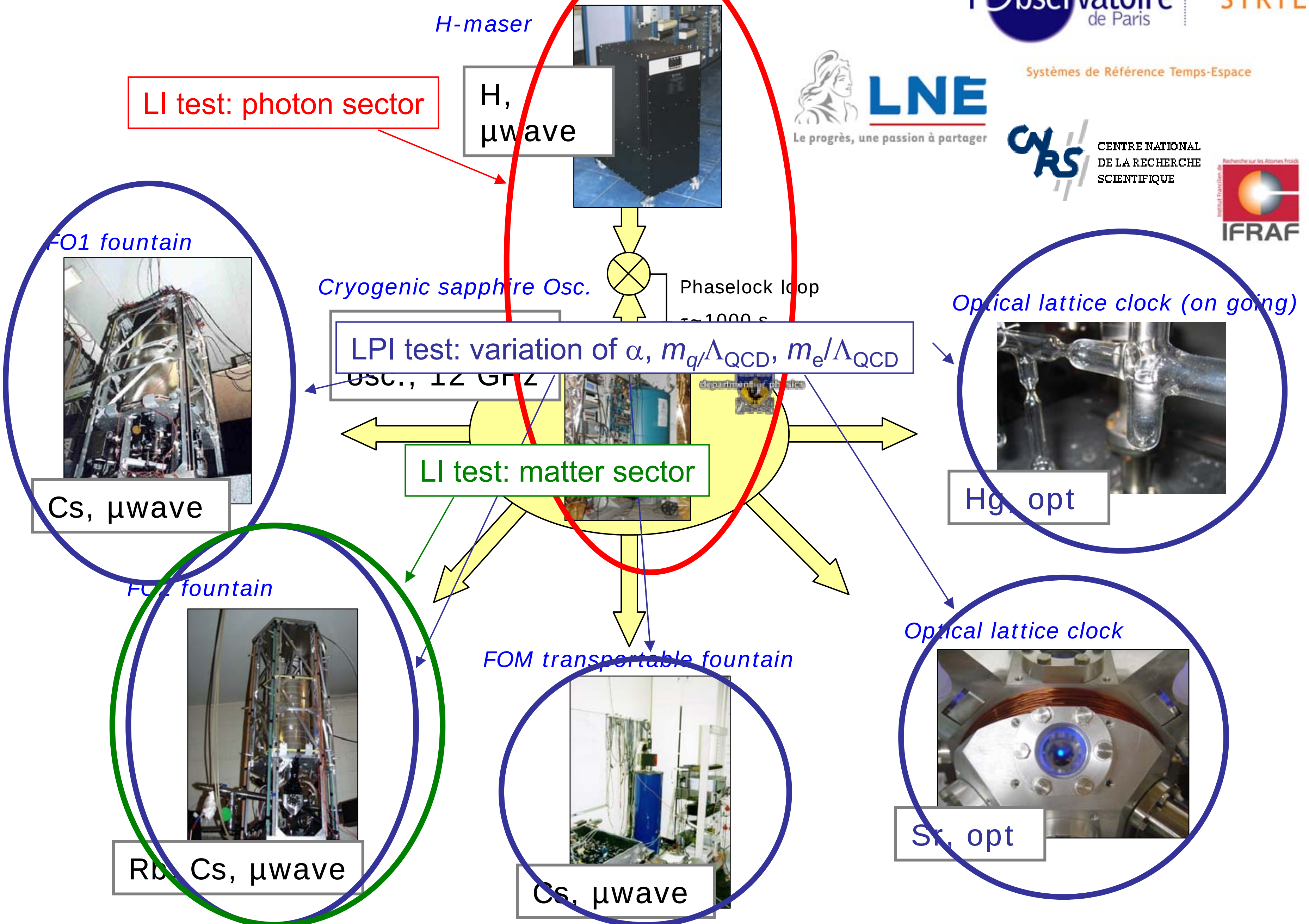
l'Observatoire de Paris — SYRTE Systèmes de Référence Temps-Espace

LNE-SYRTE CLOCK ENSEMBLE



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LNE

Le progrès, une passion à partager

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IFRAF

Invariance de Lorentz (résumé)

- Invariance de Lorentz (LI): invariance de la physique dans un repère localement inertiel) sous changements d'orientation ou de vitesse.
- Postulat fondamental de la relativité ⇒ pilier de la physique moderne.
- Théories de unification (théorie des cordes, gravitation quantique en boucles, ….) admettent une violation de LI.

  ⇒ forte motivations pour des tests de LI.
- Michelson-Morley, Kennedy-Thorndike, Ives-Stilwell, Hughes-Drever,….
- Chercher une modification de la fréquence d'une cavité en fonction de la direction de propagation de la lumière (orientation des champs E et B)
- Chercher une modification de la fréquence d'une transition atomique en fonction de l'orientation du spin.
- Un cadre théorique très large pour décrire tous les tests de LI a été développé récemment (Kostelecky et al.), l'extension du modèle standard (SME).
- Les travaux du SYRTE (en collaboration avec UWA) fournissent les meilleurs limites actuelles sur 16 paramètres du SME dans le secteur des photons et des protons. .

Variation of Fundamental Constants

Sébastien Bize, et al., J. Phys. B: At. Mol. Opt. Phys. **38** (2005) S449–S468

- Atomic transition frequencies and their dependence on fundamental constants
- Which constants vary?
- How do they vary?
- Recent results from clocks
- Two positive results from astrophysics
- Discussion and conclusion

Atomic transition frequencies and fundamental constants

Hyperfine transitions:
(microwave)

$$\nu_{hf}^{(i)} = const^{(i)} \times Ry \times \frac{\mu^{(i)}}{\mu_B} \alpha^2 F_{rel}^{(i)}(\alpha)$$

Nuclear magnetic moment

Numerical constant

Ry ~ 3.3 10^{15} Hz

Relat. Correction
Fine structure const.

Gross structure transitions:
(optical)

$$\nu^{(i)} = const^{(i)} \times Ry \times F_{rel}^{(i)}(\alpha)$$

Variation:

$$\frac{\delta(\nu_{hf}^{(i)} / Ry)}{(\nu_{hf}^{(i)} / Ry)} = (2 + K^{(i)}) \frac{\delta\alpha}{\alpha} + \frac{\delta(\mu^{(i)} / \mu_B)}{(\mu^{(i)} / \mu_B)}$$

Comparison of hf - hf or hf –opt. limits variation of combination of constants

$$\frac{\delta(\nu^{(i)} / Ry)}{(\nu^{(i)} / Ry)} = K^{(i)} \frac{\delta\alpha}{\alpha}$$

Direct comparison of two optical transitions with $K^{(1)} \neq K^{(2)}$ limits variation of α independently

Which constants vary?

V. V. Flambaum and A. F. Tedesco, PR **C73**, 055501 (2006)

- Can constrain variation of transition independent constants (α) and transition dependent ones ($\mu^{(i)}$).
- Alternatively, reduce transition dependent ones to more fundamental independent ones (quark masses, electron mass, Λ_{QCD}).
- Cosmology and unification theories in general consider variations of fundamental (transition independent) constants.
- Astrophysical observations usually given in terms of fundamental constants.

$$\boxed{\frac{\delta(\mu^{(i)}/\mu_B)}{(\mu^{(i)}/\mu_B)} = \kappa_q^{(i)} \frac{\delta(m_q/\Lambda_{QCD})}{(m_q/\Lambda_{QCD})} + \kappa_e^{(i)} \frac{\delta(m_e/\Lambda_{QCD})}{(m_e/\Lambda_{QCD})}}$$

with $m_q = (m_u+m_d)/2$ and assuming $\frac{\delta(m_s/\Lambda_{QCD})}{(m_s/\Lambda_{QCD})} = \frac{\delta(m_q/\Lambda_{QCD})}{(m_q/\Lambda_{QCD})}$

- The coefficients κ can be calculated from nuclear models.
- Schmidt model provides first approximation, but can be wrong by more than an order of magnitude.

Which constants vary?

V. V. Flambaum and A. F. Tedesco, PR **C73**, 055501 (2006)

- Recent accurate calculations of sensitivities for many commonly used transitions can be found

$$\frac{\delta(\nu^{(i)}/Ry)}{(\nu^{(i)}/Ry)} = \kappa_\alpha^{(i)}\frac{\delta\alpha}{\alpha} + \kappa_q^{(i)}\frac{\delta(m_q/\Lambda_{QCD})}{(m_q/\Lambda_{QCD})} + \kappa_e^{(i)}\frac{\delta(m_e/\Lambda_{QCD})}{(m_e/\Lambda_{QCD})}$$

	κ_α	κ_q	κ_e
Rb hf	2.34	-0.064	1
Cs hf	2.83	-0.039	1
H opt	0	0	0
Yb^+ opt	0.88	0	0
Hg^+ opt	-3.2	0	0
Dy comb.	$1.5\ 10^7$	0	0

How do fundamental constants vary?

- String theory inspired cosmological models suggest existence of additional massless (very light) scalar fields ϕ, eg. Dilaton [Damour 1994,…].
- Assuming that they couple differently to different low energy Lagrangian fields, they will lead to variation of fundamental constants in time and space.

- Assuming further that they are given by a field equation whose source is proportional to $T = T_\mu^{\ \mu}$ (the trace of the energy-momentum tensor)

$$\boxed{\phi = \phi_C + Q / r}$$

where it is reasonable to assume:

$$\boxed{Q \propto GM / c^2}$$

[Flammbaum & Shuryak physics/0701220, (2007)]

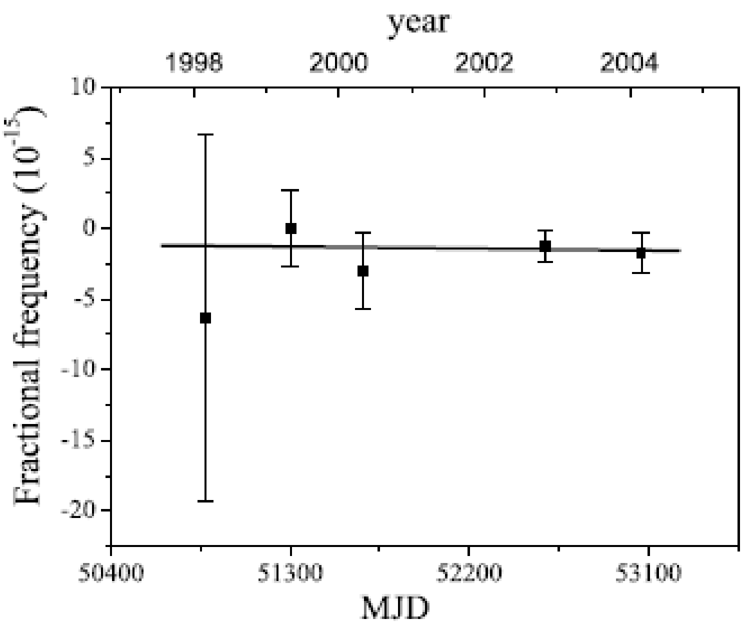
- The "local" part (Q/r) will lead to a variation of fundamental constants as a function of the Newtonian potential, and can be parameterized:

$$\boxed{\frac{\delta\alpha}{\alpha} = k_\alpha \delta\left(\frac{GM}{rc^2}\right); \ \frac{\delta(m_q/\Lambda_{QCD})}{(m_q/\Lambda_{QCD})} = k_q \delta\left(\frac{GM}{rc^2}\right); \ \frac{\delta(m_e/\Lambda_{QCD})}{(m_e/\Lambda_{QCD})} = k_e \delta\left(\frac{GM}{rc^2}\right)}$$

- This leads to two types of variation: long term drift (ϕ_C) and local (periodic) terms $\delta(GM/r)$. Can be distinguished in laboratory or space-borne experiments !!
- In the remainder of this talk we will consider only the long term drift, but laboratory measurements and constraints on the latter are starting to becoma available.

Recent measurements at LNE-SYRTE

Sébastien Bize, et al., J. Phys. B: At. Mol. Opt. Phys. **38** (2005) S449–S468



$$\frac{\frac{d}{dt}\left(\nu_{hf}^{(Rb)}/\nu_{hf}^{(Cs)}\right)}{\left(\nu_{hf}^{(Rb)}/\nu_{hf}^{(Cs)}\right)} = (-0.5 \pm 5.3)\times 10^{-16}\, yr^{-1}$$

$$\frac{\frac{d}{dt}\left(\nu_{hf}^{(Rb)}/\nu_{hf}^{(Cs)}\right)}{\left(\nu_{hf}^{(Rb)}/\nu_{hf}^{(Cs)}\right)} = -0.49\frac{\frac{d}{dt}\alpha}{\alpha} + \frac{\frac{d}{dt}\left(\mu^{(Rb)}/\mu^{(Cs)}\right)}{\left(\mu^{(Rb)}/\mu^{(Cs)}\right)} = -0.49\frac{\frac{d}{dt}\alpha}{\alpha} - 0.025\frac{\frac{d}{dt}\left(m_q/\Lambda_{QCD}\right)}{\left(m_q/\Lambda_{QCD}\right)}$$

Combined with other results:

$$\frac{\delta(\nu_{hf}^{(Rb)}/\nu_{hf}^{(Cs)})}{(\nu_{hf}^{(Rb)}/\nu_{hf}^{(Cs)})} = (-0.5 \pm 5.3)\times 10^{-16}\ yr^{-1} = -0.49\frac{\frac{d}{dt}\alpha}{\alpha} - 0.025\frac{\frac{d}{dt}(m_q/\Lambda_{QCD})}{(m_q/\Lambda_{QCD})}$$

LNE-SYRTE, JPB (2004)

$$\frac{\frac{d}{dt}(\nu_{opt}^{(Hg)}/\nu_{hf}^{(Cs)})}{(\nu_{opt}^{(Hg)}/\nu_{hf}^{(Cs)})} = (3.7 \pm 3.9)\times 10^{-16}\ yr^{-1} = -6.03\frac{\frac{d}{dt}\alpha}{\alpha} + 0.039\frac{\frac{d}{dt}(m_q/\Lambda_{QCD})}{(m_q/\Lambda_{QCD})} - \frac{\frac{d}{dt}(m_e/\Lambda_{QCD})}{(m_e/\Lambda_{QCD})}$$

NIST, PRL (2007)

$$\frac{\frac{d}{dt}(\nu_{opt}^{(Yb)}/\nu_{hf}^{(Cs)})}{(\nu_{opt}^{(Yb)}/\nu_{hf}^{(Cs)})} = (-7.8 \pm 14)\times 10^{-16}\ yr^{-1} = -1.95\frac{\frac{d}{dt}\alpha}{\alpha} + 0.039\frac{\frac{d}{dt}(m_q/\Lambda_{QCD})}{(m_q/\Lambda_{QCD})} - \frac{\frac{d}{dt}(m_e/\Lambda_{QCD})}{(m_e/\Lambda_{QCD})}$$

PTB, arXiv (2006)

$$\frac{\frac{d}{dt}(\nu_{opt}^{(H)}/\nu_{hf}^{(Cs)})}{(\nu_{opt}^{(H)}/\nu_{hf}^{(Cs)})} = (-32 \pm 63)\times 10^{-16}\ yr^{-1} = -2.83\frac{\frac{d}{dt}\alpha}{\alpha} + 0.039\frac{\frac{d}{dt}(m_q/\Lambda_{QCD})}{(m_q/\Lambda_{QCD})} - \frac{\frac{d}{dt}(m_e/\Lambda_{QCD})}{(m_e/\Lambda_{QCD})}$$

MPQ + LNE-SYRTE
PRL (2004)

$$\frac{\frac{d}{dt}(\nu_{comb}^{(Dy)}/\nu_{hf}^{(Cs)})}{(\nu_{comb}^{(Dy)}/\nu_{hf}^{(Cs)})} = (-4.0 \pm 3.9)\times 10^{-8}\ yr^{-1} = (1.5\times 10^{7})\frac{\frac{d}{dt}\alpha}{\alpha} + 0.039\frac{\frac{d}{dt}(m_q/\Lambda_{QCD})}{(m_q/\Lambda_{QCD})} - \frac{\frac{d}{dt}(m_e/\Lambda_{QCD})}{(m_e/\Lambda_{QCD})}$$

Berkley, PRL (2007)

Using a weighted least squares fit:

$$\frac{\frac{d}{dt}\alpha}{\alpha} = (-3.5 \pm 3.5)\times 10^{-16}\ yr^{-1}$$

$$\frac{\frac{d}{dt}(m_q/\Lambda_{QCD})}{(m_q/\Lambda_{QCD})} = (89 \pm 223)\times 10^{-16}\ yr^{-1}$$

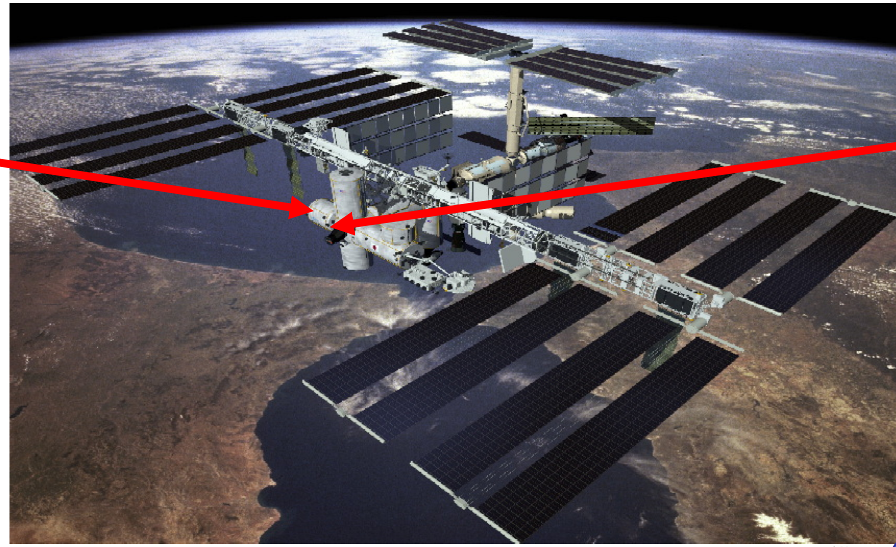
$$\frac{\frac{d}{dt}(m_e/\Lambda_{QCD})}{(m_e/\Lambda_{QCD})} = (21 \pm 24)\times 10^{-16}\ yr^{-1}$$

- limit on α var. is becoming competitive with Oklo ($\sim 10^{-17} yr^{-1}$) and Quasar limits ($\sim 10^{-16} yr^{-1}$) assuming linear change.
- however, still difficult to decorrelate variations of the different constants (correlation coefficients = -0.3, -0.9, 0.6).
- more accurate, and more diverse measurements are required!!
- analysis for annual terms allows search for variation from scalar fields with local sources ($\propto$ GM/r).

ACES: Atomic Clocks on the ISS

PHARAO

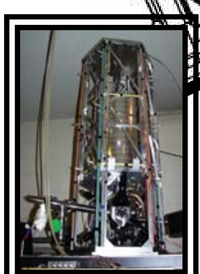
H-MASER

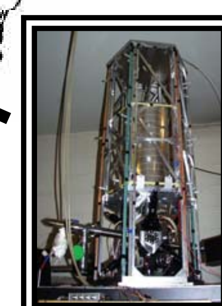


Proposal to ESA: 1997
PHARAO: CNES
Launch: 2013

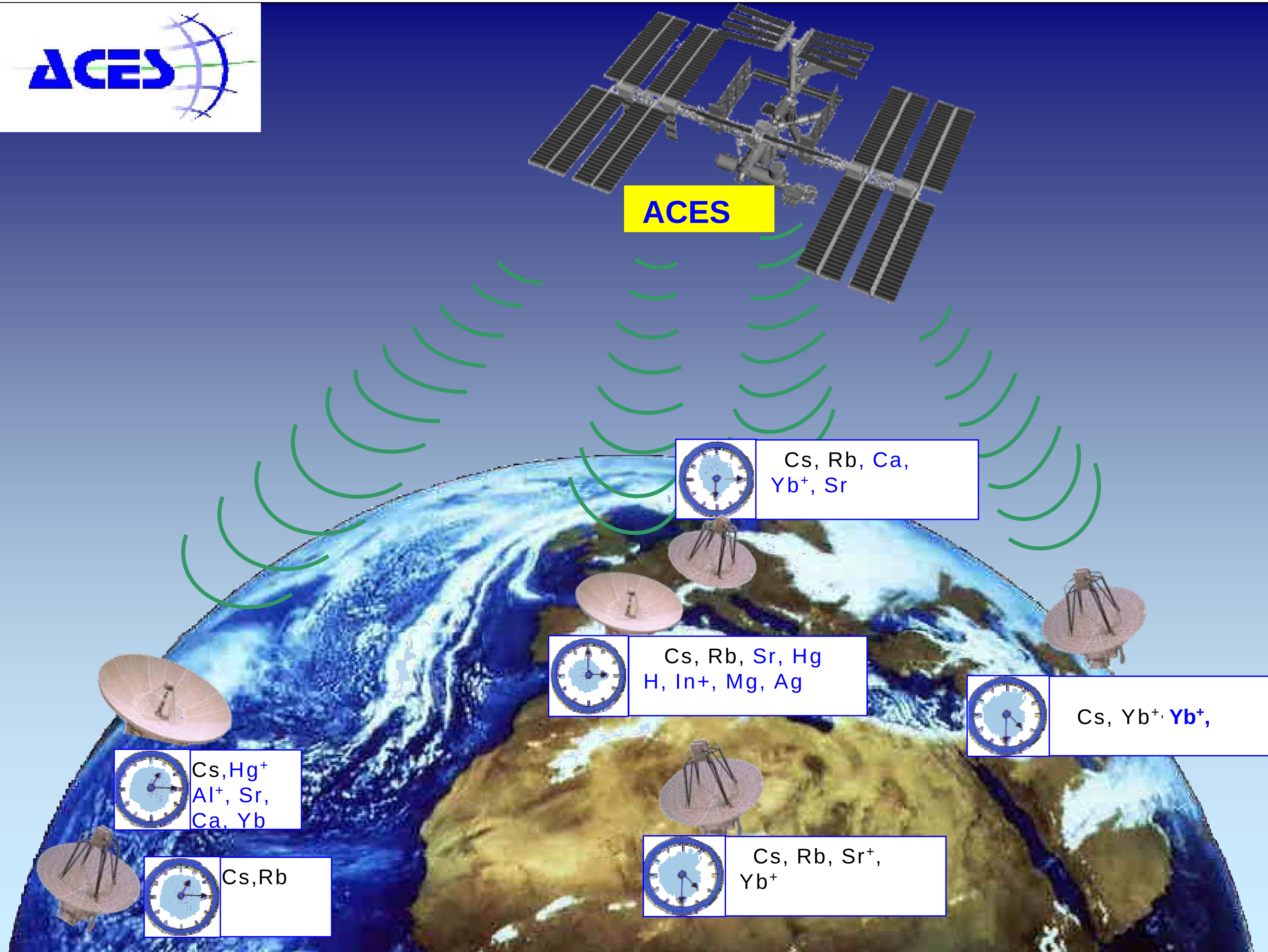
µwave-link
two-ways

µwave-link
two-ways





- Référence de temps spatiale
- Validation des horloges spatiales
- Tests de physique fondamentale


ACES
Cs, Rb, Ca, Yb^+, Sr
Cs, Rb, Sr, Hg
H, In+, Mg, Ag
Cs, Yb^+, Yb^+,
Cs, Hg^+
Al^+, Sr,
Ca, Yb
Cs,Rb
Cs, Rb, Sr^+,
Yb^+

Two positive results

Webb et al., PRL 2001, Murphy et al. Mon. Not. R. Astron. Soc. 2003:

- Absorption spectra (Keck/Hawaï) in gas clouds that intersect Quasar lines of sight
- Fine structure doublet (Alkaline) and many multiplet methods
- Total of 128 absorption systems, at 0.2 < z < 3.7
- Linear variation with time fits slightly better than constant offset
- Not confirmed by 2 other studies on southern hemisphere

$$\frac{\frac{d}{dt}\alpha}{\alpha} = (6.4 \pm 1.4) \times 10^{-16}\ yr^{-1}$$

Reinhold et al. PRL 2006:

- H_2 absorption spectra (VLT/Chile) in 2 absorption systems at (z = 2.6, 3.0)
- Obtain different value for $\eta = m_p/m_e$ than today: $\delta\eta/\eta = (2.4 \pm 0.6) \times 10^{-5}$
- Supposing a linear variation with time: $\frac{d}{dt}\eta/\eta \approx (-20 \pm 5) \times 10^{-16}\ yr^{-1}$
- Can be related to a variation of more fundamental constants:

$$0.048\frac{\frac{d}{dt}(m_q/\Lambda)}{(m_q/\Lambda)} - \frac{\frac{d}{dt}(m_e/\Lambda)}{(m_e/\Lambda)} \approx (-20 \pm 5) \times 10^{-16}\ yr^{-1}$$

Discussion and Conclusion

Clocks:
(correlation coefficients = -0.3, -0.9, 0.6)

$$\frac{\frac{d}{dt}\alpha}{\alpha} = (-3.5 \pm 3.5) \times 10^{-16}\ yr^{-1}$$

$$\frac{\frac{d}{dt}(m_q/\Lambda_{QCD})}{(m_q/\Lambda_{QCD})} = (89 \pm 223) \times 10^{-16}\ yr^{-1}$$

$$\frac{\frac{d}{dt}(m_e/\Lambda_{QCD})}{(m_e/\Lambda_{QCD})} = (21 \pm 24) \times 10^{-16}\ yr^{-1}$$

Quasar absorption spectra:

$$\frac{\frac{d}{dt}\alpha}{\alpha} = (6.4 \pm 1.4) \times 10^{-16}\ yr^{-1}$$

$$0.048\frac{\frac{d}{dt}(m_q/\Lambda)}{(m_q/\Lambda)} - \frac{\frac{d}{dt}(m_e/\Lambda)}{(m_e/\Lambda)} \approx (-20 \pm 5) \times 10^{-16}\ yr^{-1}$$

Oklo (natural nuclear reactor):

$$\frac{\frac{d}{dt}\alpha}{\alpha} \le 10^{-17}\ yr^{-1}$$

- Assuming uncorrelated results, clock limits exclude $d\alpha/dt$ from quasars, but allow $d\eta/\eta$.
- However, large correlation coefficients require more detailed statistical analysis (in progress).
- Furthermore, the above assumes constant drift. Consistency is restored when allowing for non-linear variation.
- In any case, all limits are now at similar levels of uncertainty. Clock experiments will significantly improve in the next years (Al, Hg, Sr, Dy….) and present the advantage of controlled laboratory conditions

$\Rightarrow$ significant contribution to fundamental physics and cosmology

DES SENSEURS POUR EXPLORER LA GRAVITATION DANS LE SYSTÈME SOLAIRE

(Le projet SAGAS)

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l'Observatoire de Paris — SYRTE
Systèmes de Référence Temps-Espace

UNIVERSITE PIERRE & MARIE CURIE
LA SCIENCE A PARIS

Plan

- Introduction
- Description générale de SAGAS
- Objectifs scientifiques
- Instruments et sensibilité
- Trajectoire et Satellite
- Physique fondamentale
- Exploration du Système Solaire
- Conclusion

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SAGAS

(Search for Anomalous Gravitation with Atomic Sensors)

ESA Cosmic Vision 2015-2025

Quantum Physics Exploring Gravity in the Outer Solar System

> 70 participants from:

- **France:** SYRTE, IOTA, LKB, ONERA, OCA, LESIA, IMCCE, Université Pierre at Marie Curie Paris VI, Université Paul Sabatier Toulouse III
- **Germany:** IQO Leibniz Universität Hannover, ZARM, PTB, MPQ, Astrium, Heinrich Heine Universität Düsseldorf, Humboldt Universität Berlin, Universität Hamburg, Universität Ulm, Universität Erlangen
- **Great Britain:** National Physical Laboratory
- **Italy:** LENS, University of Firenze, INFN, INRIM, Universita' di Pisa, INOA Firenze, Politecnico Milano
- **Portugal:** Instituto Superior Técnico
- **Austria:** University of Innsbruck
- **Canada:** NRC
- **USA:** JPL, NIST, JILA, Global Aerospace Corp., Stanford University, Harvard University
- **Australia:** University of Western Australia

Introduction

- Gravitation is well described by General relativity (GR).
- GR is a classical theory, which shows inconsistencies with quantum field theory.
- All unification models predict (small) deviations of gravitation laws from GR.
- Gravity is well explored at small (laboratory) to medium (Moon, inner planets) distance scales.
- At very large distances (galxies, cosmology) some puzzles remain (galactic rotation curves, SNR redshifts, dark matter and energy, ….).
- The largest distances explored by man-made artefacts are of the size of the outer solar system $\Rightarrow$ carry out precision gravitational measurements in outer solar system.

- Kuiper Belt ($\approx$ 40 AU, $\approx$ 1000 KBOs since 1992), the disk from which giant planets formed is largely unexplored.
- Known mass ($M_{KB} \approx 10^{-1}\, M_E$) about 100 times too small for in situ formation of KBOs.
- KBO masses only inferred from albedo and density hypothesis ($\Rightarrow$ uncertainty).
- "In situ" gravitational measurements yields exceptional information on M_{KB}, overall mass distribution, and individual KBO masses (+ discover new KBOs ?)
- Measurements during planetary fly by (Jupiter) can yield highly accurate determination of planetary gravity.

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SAGAS: Overview

Payload:

1. Cold atom absolute accelerometer, 3 axis measurement of local non-gravitational acceleration.
2. Optical atomic clock, absolute frequency measurement (local proper time).
3. Laser link (frequency comparison + Doppler for navigation).

Trajectory:

- Jupiter flyby and gravity assist ($\approx$ 3 years after launch).
- Reach distance of $\approx$39 AU (15 yrs nominal) to $\approx$53 AU (20 yrs, extended).

Measurements:

- *Gravitational trajectory of test body (S/C):* using Doppler ranging and correcting for non-gravitational forces using accelerometer measurements.
- *Gravitational frequency shift of local proper time:* using clock and laser link to ground clocks for frequency comparison.

$\Rightarrow$ ***Measure all aspects of gravity !***

Science Objectives: Overview

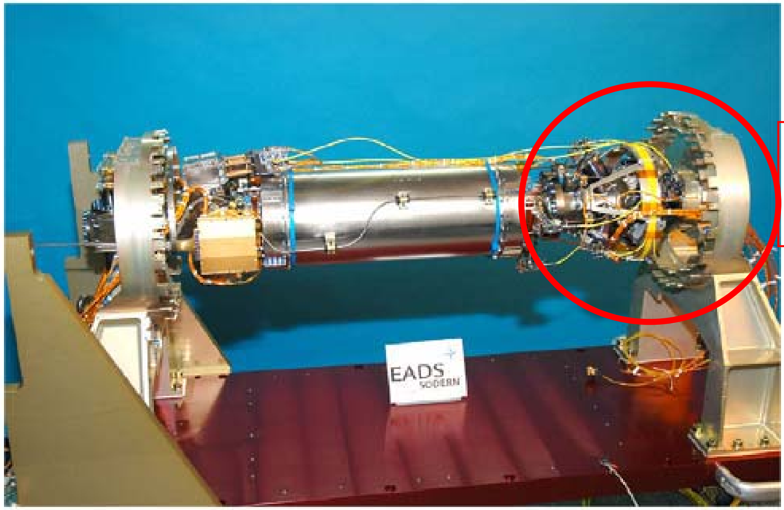
Science Objective	"Should"	"Could"	Comments
Test of Universal Redshift	**1 10^{-9}** of GR prediction	**1 10^{-9}** of GR prediction	**10^5** gain on present
Null Redshift Test	**1 10^{-9}** of GR prediction	**1 10^{-9}** of GR prediction	**10^3** gain
Test of Lorentz Invariance	**3 10^{-9}** IS test ("time dilation test")	**5 10^{-11}** IS test	**10^2** to **10^4** gain, fct. of trajectory
PPN test	$\delta(\gamma) \leq$ **1 10^{-7}**	$\delta(\gamma) \leq$ **10^{-8}**	**10^2** to **10^4** gain, dep. on δa_{NG} when using accel. + model
Large Scale Gravity	- Fill exp. data gap for scale dependent modif. of GR - Identify and measure PA to < 1% per year of data	- Provide evidence for violation of GR at large scale	Different observation types and large range of distances will allow detailed "map" of large scale gravity
Kuiper Belt (KB) Total Mass	$\delta M_{KB} \leq$ **0.03 M_E**	$\delta M_{KB} \approx$ **10^{-3} M_E**	Dep. on mass distribution and correlation of clock meas.
KB Mass Distribution	Discriminate between different common candidates	Provide major insight into solar system formation processes	Will contribute significantly to solution of the "KB mass deficit" problem
Individual KB Objects (KBOs)	Measure M_{KBO} at ≈ **10%**	- Measure M_{KBO} at ≈ **1%** - Discover new KBOs	Depending on distance of closest approach
Planetary Gravity	-Jupiter Gravity at $\leq 10^{-10}$ -Study Jupiter and its moons	Precise gravity of Uranus or Neptune	-10^2 gain on present for Jupiter -dep. on options for 2nd fly-by
Variation of Fund. Const.	$\delta\alpha/\alpha \leq$ (**2 10^{-4}**) $\delta(GM/rc^2)$	$\delta\alpha/\alpha \leq$ (**2 10^{-4}**) $\delta(GM/rc^2)$	**250**-fold gain on present
Upper limit on Grav. Waves	$h \leq$ **10^{-18}** @ 10^{-5} to 10^{-3} Hz	- Extend to 10^{-6} - 10^{-7} Hz -obs. unexpectedly large GW	Depends on ability to model low frequency motion of S/C
Technology Developement	Develops S/C and ground segment technologies for wide use in future missions (interplanetary timing, navigation, broadband communication,…)		

Payload: Accelerometer

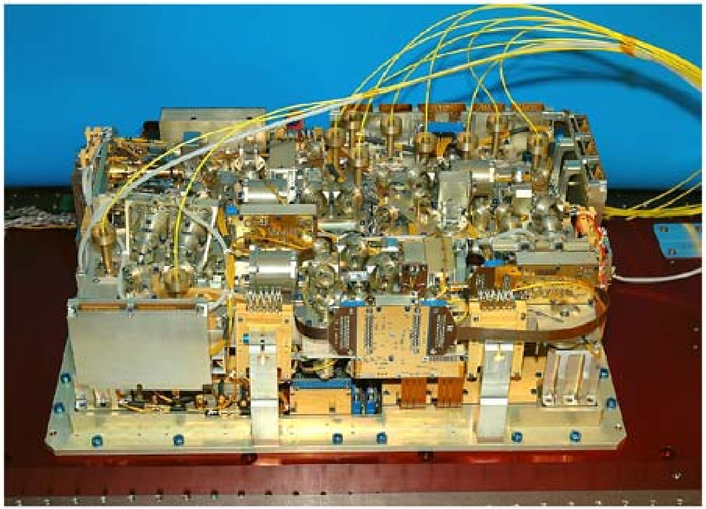
- Atom interferometer, using laser cooled Cs atoms as “test masses”.
- Interrogation of atoms using Raman laser pulses in 3D (sequentially).
- Ground atom interferometers have uncertainties comparable to best “classical” methods, $\approx 10^{-8}$ m/s^2, limited by vibrations, Earth rotation, atmosphere, tides….

- In a quiet space environment, with possibility of long interrogation times (2 s) expect:
$\sqrt{S_a(f)} = 1.3\ 10^{-9}$ m/s^2 Hz $^{-1/2}$ (limited by RF stability, PHARAO quartz USO)
Absolute accuracy 5 10^{-12} m/s^2.
- “Classical” space accelerometers have $\sqrt{S_a(f)} = 10^{-10}$ m/s^2 Hz $^{-1/2}$ (GRACE), or better (10^{-12} GOCE, μSCOPE; 10^{-15} LISA) with bias calibration at 4 10^{-11} m/s^2 (ODYSSEY).

- Based to a large extent on PHARAO technology and HYPER study.



“Accelerometer“
part



Payload: Optical Clock

- Single trapped ion optical clock, using Sr^+ with 674 nm clock transition.
- Other options kept open (Yb^+, Ca^+,…) subject to development of laser sources.
- Provides narrow and accurate laser:

Stability: $\sigma_y(\tau) = 1\ 10^{-14} / \sqrt{\tau}$ (τ = integration time in s)

Accuracy: $\delta y \leq 1\ 10^{-17}$ in relative frequency ($y = \delta f/f$)

- Best ground trapped ion optical clocks show $\sigma_y(\tau) = 7\ 10^{-15} / \sqrt{\tau}$ and $\delta y \leq 3\ 10^{-17}$.
- Challenge for SAGAS is not performance but space qualification and reliability.

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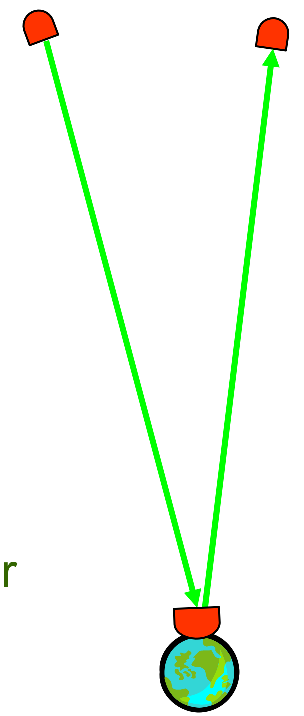
Payload: Optical Link



- Independent up and down link.
- Heterodyne frequency measurement with respect to local laser.
- Combine on board and ground measurements (asynchronous) for clock comparison (= difference) or Doppler (= sum).
- 1 W emission, 40 cm telescope on S/C (LISA), 1.5 m on ground (LLR).
- 22000 detected photons/s @ 30 AU. (LLR < 1 photon/s).
- Takes full advantage of available highly stable and accurate clock laser and RF reference.

Observable	**Performance**		**Remarks**
	Noise	**Bias**	
Doppler (D_ν)	$S(f)=(1\ 10^{-28} + 1.5\ 10^{-23}\ f^2)$ Hz^{-1}	$< 10^{-17}$	Clock and Troposphere limited
Frequency diff. (y)	$S(f) << 10^{-28}$ Hz^{-1}	$<< 10^{-17}$	Well below clock performance
Ranging (r)	4 km^2 Hz^{-1}	< 3 m	FSK or PSK modulation at 1 kHz Satellite at 30 AU
Data transfer	≈ 3000 bps		

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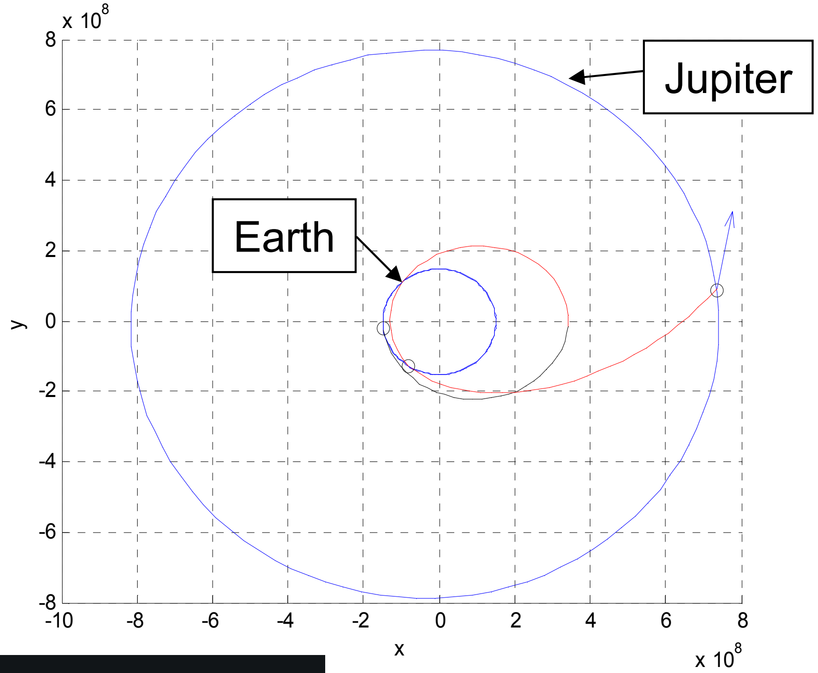
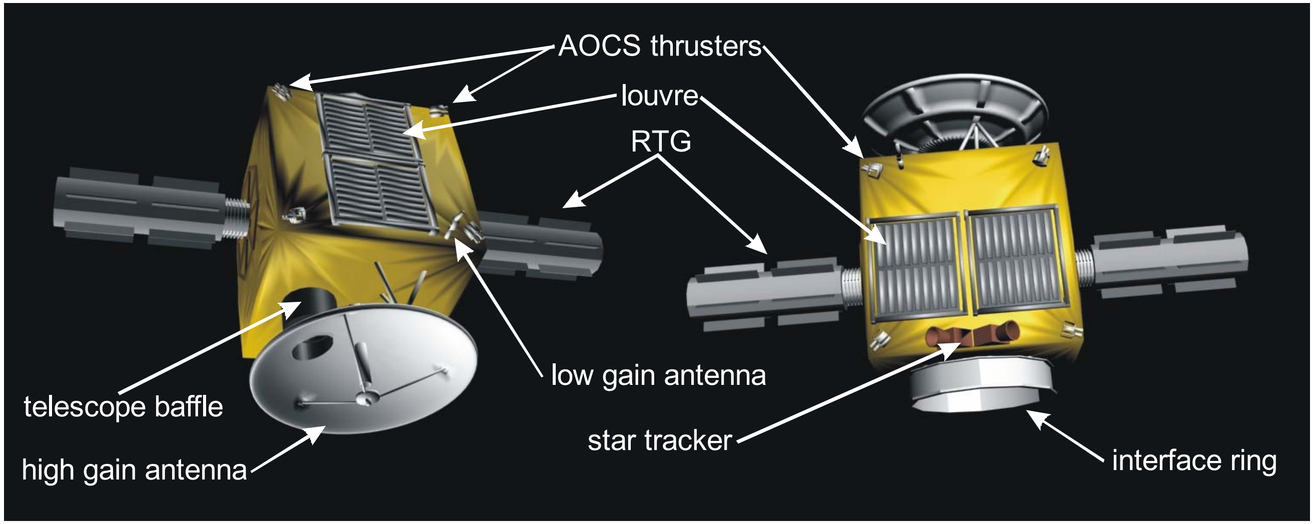
Trajectory and Spacecraft

• Present baseline: Ariane 5 ECA + propulsion module; ΔV-EGA + Jupiter GA @ 22.6 km/s 3 years after launch.
• 38 AU after 15 yrs (nominal), 53 AU after 20 yrs (extended).
• Can be shortened (- 2 yrs) by using larger launcher (Ariane 5 ECB, Atlas 5, Delta IV).
• Total: 950 kg, 390 W (incl. 20% margin).





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Fundamental Physics: Non-metric gravity

In GR: $$\frac{d\tau_S}{dt} - \frac{d\tau_G}{dt} \approx \frac{w_G - w_S}{c^2} + \frac{v_G^2 - v_S^2}{2c^2} + O(c^{-4})$$

- Gravitational frequency shift
- *w* = Newtonian potential (determined from ephemerides)
- Test of LPI (part of equivqlence principle)
- 10^{-9} measurement
- 10^5 improvement on present knowledge (GP-A)

- Also tests for coupling between gravity and e-m interaction (variation of α with grav. field).
- 250 fold improvement on present.

- 2nd order Doppler (Special Relativity)
- Ives-Stilwell test
- 10^2 to 10^4 improvement on present (TPA in particle accelerator)
- Depends on signal propagation direction with respect to CMB anisotropy.

Violation implies non - metric description of Gravitation

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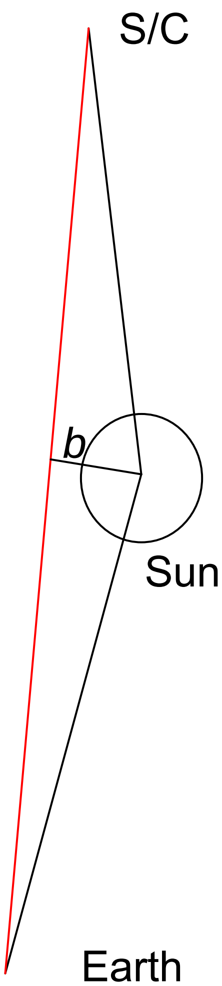
Fundamental Physics: Metric gravity

$$\delta D_v(t) \approx \frac{d}{dt}\left[2(1+\gamma)\frac{GM}{c^3}\ln\left(\frac{4r_S r_G}{b^2}\right)\right] \approx -4(1+\gamma)\frac{GM}{c^3 b}\frac{db}{dt}$$

PPN parameter, in GR $\gamma=1$



- Gravitational time delay (Shapiro delay)
- Large variation during occultation $\Rightarrow$ effect on Doppler observable
- Test of metric theories (Parametrised Post-Newtonian framework)
- 10^{-7} to 10^{-9} uncertainty on γ
- 10^{2} to 10^{4} improvement on present knowledge (Cassini)
- Well within region where some unification models predict deviations (10^{-5} to 10^{-7}).

- Takes advantage of laser and X-band (solar corona effect), and accelerometer (precise knowledge of S/C motion).
- Jupiter occultation allows for independent “test“ (100 times less precise).

Violation allows metric description of Gravitation but not GR

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Fundamental Physics: Scale dependent gravity

Search for a deviation

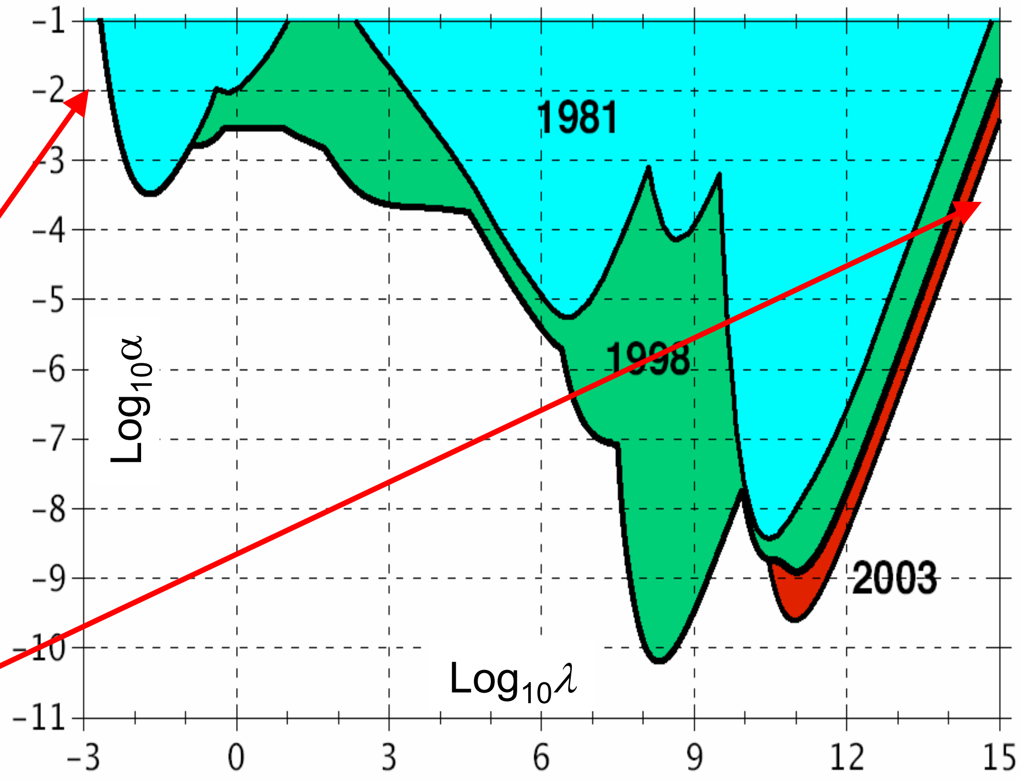
$$g_{00} = [g_{00}]_{\rm GR} + \delta g_{00}$$

For example 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

or long ranges



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)

Fundamental Physics: Large scale gravity test (Pioneer example)

- Pioneer 10 and 11 data show unexplained almost constant Doppler rate ($a_P \sim 8.7\ 10^{-10}$ m/s^2) between 20 AU and 70 AU.

Some conventional and “new physics” hypotheses (non exhaustive):

C1: Non-gravitational acceleration (drag, thermal, etc…)
C2: Additional Newtonian potential (Kuiper belt, etc…)
C3: Effect on Pioneer Doppler (DSN, ionosphere, troposphere, etc…) that also effects SAGAS ranging (sum of up and down link) but not the time transfer (difference of up and down link).
C4: Effect on Pioneer Doppler that has no effect on SAGAS ranging or time transfer (eg. ionosphere $\propto 1/f^{\,2}$)

P1: Modification of the metric component g_{00} ("first sector" in Jaekel & Reynaud, Moffat...)
P2: Modification of the metric component $g_{00}g_{rr}$ ("second sector" in Jaekel & Reynaud)

Large scale gravity sensitivity (Pioneer example)

Orders of magnitude of measurable effect with 1 year of data, satellite on radial trajectory, $v \sim 13$ km/s, $r \sim 30$ AU, $a_p \sim 8.7\ 10^{-10}$ m/s^2 :

Observable uncertainty	**Acc. / ms^{-2}** ($5\ 10^{-12}$)	**Clock** ($1\ 10^{-17}$)	**Doppler** ($\leq 10^{-13}$)
C1	$8.7\ 10^{-10}$	$4\ 10^{-15}$	$2\ 10^{-10}$
C2	-	$5\ 10^{-14}$	$2\ 10^{-10}$
C3	-	-	$2\ 10^{-10}$
C4	-	-	-
P1	-	$5\ 10^{-14}$	$2\ 10^{-10}$
P2	-	$-9\ 10^{-14}$	$2\ 10^{-10}$

Accelerometer limitation

"-" = no anomaly effect

- All instruments show sensitivity of 10^{-3} or better $\Rightarrow$ measurement of "fine structure" and evolution with **r** and *t*, ie. rich testing ground for theories.
- Complementary instruments allow good discrimination between hypotheses
- C2 and P1 are phenomenologically identical (identical modification of Newtonian part of metric in g_{00}) but precise measurement will allow "fine tuning"
- Longer data acquisition will improve most numbers

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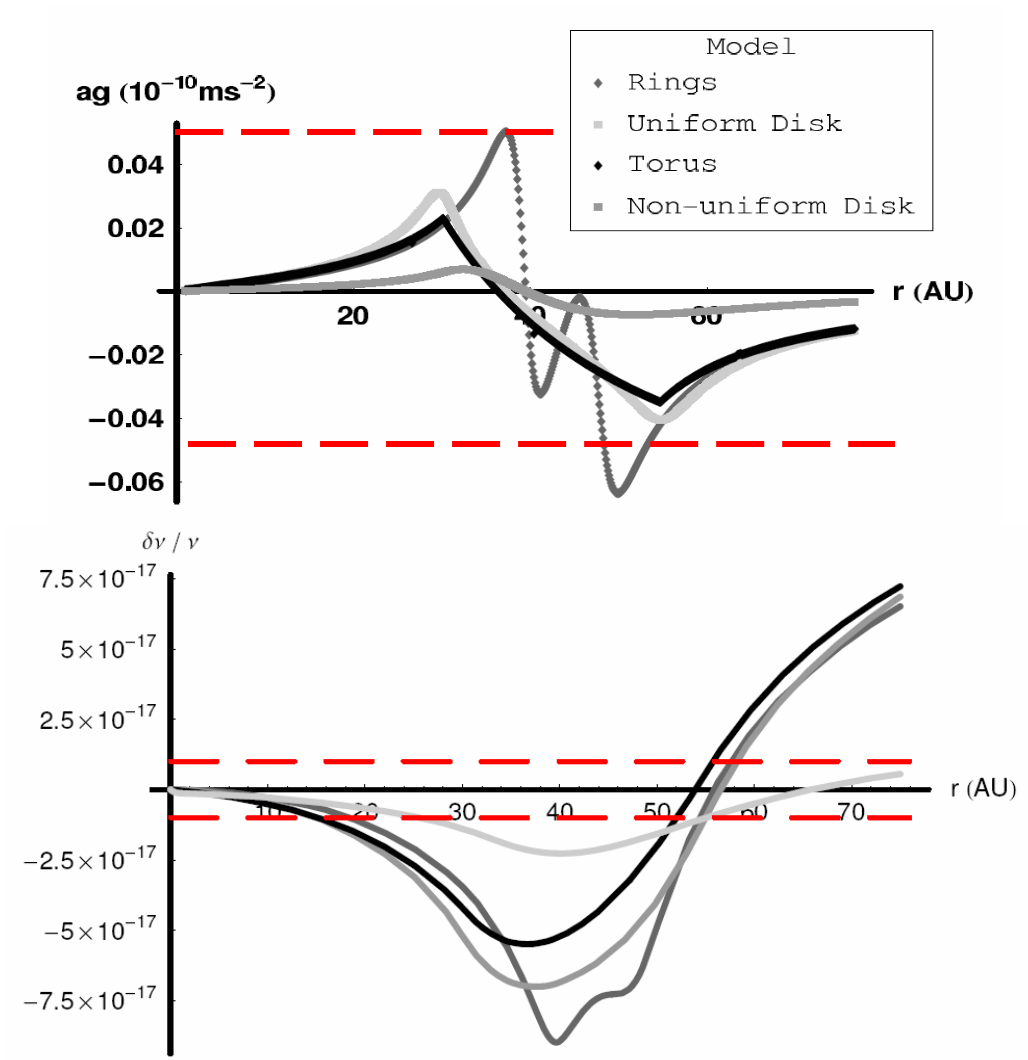
Solar System Exploration: Kuiper Belt



Kuiper belt mass distribution models, with M_{KP} = 0.3 M_E

- Remnant of disc from which giant planets formed.
- Mass deficit problem (100 times less than expected from in situ formation of KB objects.
- Acceleration sensitivity insufficient to distinguish between models ($\propto 1/r^2$).
- But clock well adapted for measurement of diffuse, large mass distributions ($\propto 1/r$).
- Depending on distribution SAGAS can determine M_{KB} with $\delta M_{KB} \approx 10^{-2} M_E$ to $10^{-3} M_E$

Provided by O. Bertolami et al.

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Solar System Exploration: KBOs and Planets

Object	Semi major axis / AU	Estimated Mass/10^{21} kg	$\delta M/M$ @ 0.5 AU	$\delta M/M$ @ 0.2 AU
Pluto	39.5	13.05	0.03	0.005
(136108) 2003 EL_{61}	43.3	4	0.1	0.02
(136472) 2005 FY_9	45.8	4	0.1	0.02
Quaoar	43.4	2	0.2	0.03
Ixion	39.7	0.6	0.7	0.1

- Trajectory (accelerometer) more sensitive at distances < 1.2 AU.
- Use trajectory to measure characteristics of individual objects, clock to subtract “background“.
- Possibility to discover new objects

Planet	$\delta GM/GM$ (present)	r_C / AU
Jupiter	$2\ 10^{-8}$	0.15
Saturn	$3\ 10^{-8}$	0.1
Uranus	$2\ 10^{-6}$	0.3
Neptune	$2\ 10^{-6}$	0.4

- Below r_C uncertainty from planet larger than measurement accuracy.
- Improve on present knowledge when sufficiently approaching planet.
- @ 0.01 AU achieve 10^2 to 10^3 improvement.
- Closest approach to Jupiter will be 0.004 AU

$\Rightarrow$ Improve knowledge on Jupiter, maybe others.

Astronomy and Cosmology: Upper limits on low frequency grav. Waves (GW)

• Doppler observable can be used to search for GW of frequency ≈ c/L.
• Strain sensitivity ≈ $10^{-14}/\sqrt{\mathrm{Hz}}$ at 10^{-5} to 10^{-3} Hz.

• Insufficient to constrain cosmic stochastic GW background below present limits (Pulsar timing).
• Would need to extend to 10^{-7} to 10^{-6} Hz (model for non-grav. accelerations?).

• For particular sources in the 10^{-5} to 10^{-3} Hz region can use template and optimal filtering. With one year data achieve $h \leq 10^{-18}$.
• Insufficient for expected sources (eg. for BHB expect $h \leq 10^{-19}$).
• But may be usefull for constraints on astrophysical models, and leaves door open for surprises.

Conclusion

SAGAS offers a unique possibility for a mission combining equally attractive objectives in fundamental physics and solar system exploration.

• Allows testing gravity at distance scales and with a sensitivity unattainable in ground or terrestrial orbit experiments.
• Theory (unification models) expects to see modifications of known physics, in particular of GR, in sensitivity regions probed by SAGAS.
• Observation at very large scales (galaxies, cosmology) also gives rise to some interrogation $\Rightarrow$ design controlled experiments at largest possible distances.
• **Potential for a major discovery in physics and major contribution to constraining theoretical models.**
• Kuiper Belt (KB) potentially holds clues for planetary formation processes, and gives rise to fundamental questions (mass deficit?).
• KB objects (KBOs) very distant, small, and difficult to observe
$\Rightarrow$ in situ gravitational measurements provide valuable information on KB total mass, KB mass distribution, and individual KBOs.
• Planetary fly by (Jupiter in particular) will allow significant improvement on knowledge of its gravity and thus the planetary system as a whole.
• **Major contribution to the understanding of planetary formation in the solar system, with potential for new discoveries (KB mass, new KBOs).**