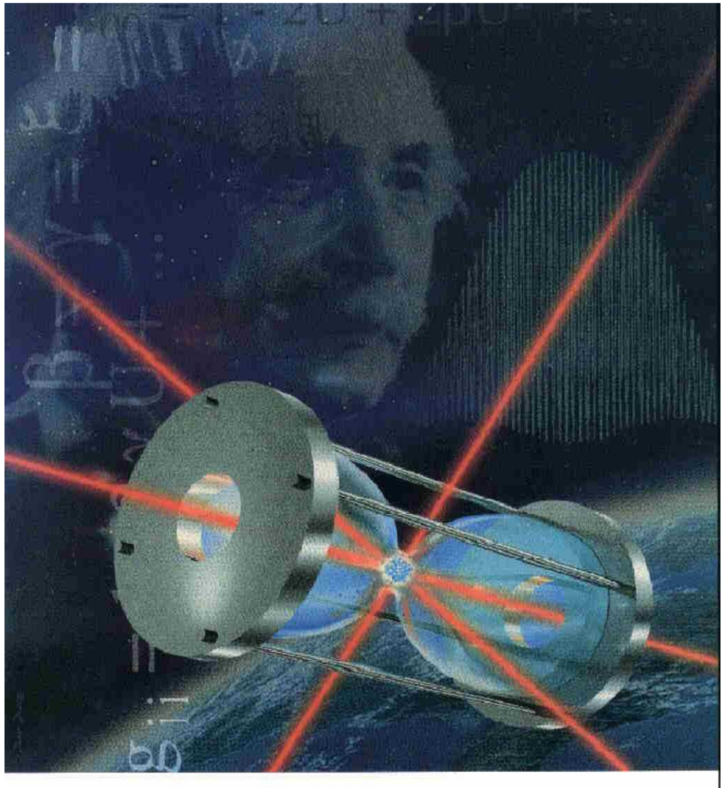
Experimental tests of gravitation at small and large scale (in the solar system)

Peter Wolf



Beyond the Standard Models, Cape Town, South Africa
February 1 – 6, 2010

Introduction

• Gravitation is well described by General Relativity (GR).
• GR is a classical theory, which is difficult to reconcile 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, planets) distance scales.
• At very short range some theoretical models predict modifications (Brane models, compactified dimensions, short range couplings, ….)
• Mechanical measurements become difficult $\Rightarrow$ atomic physics
• At very large distances (galxies, cosmology) some puzzles remain (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

Scale dependent gravity

Search for a deviation

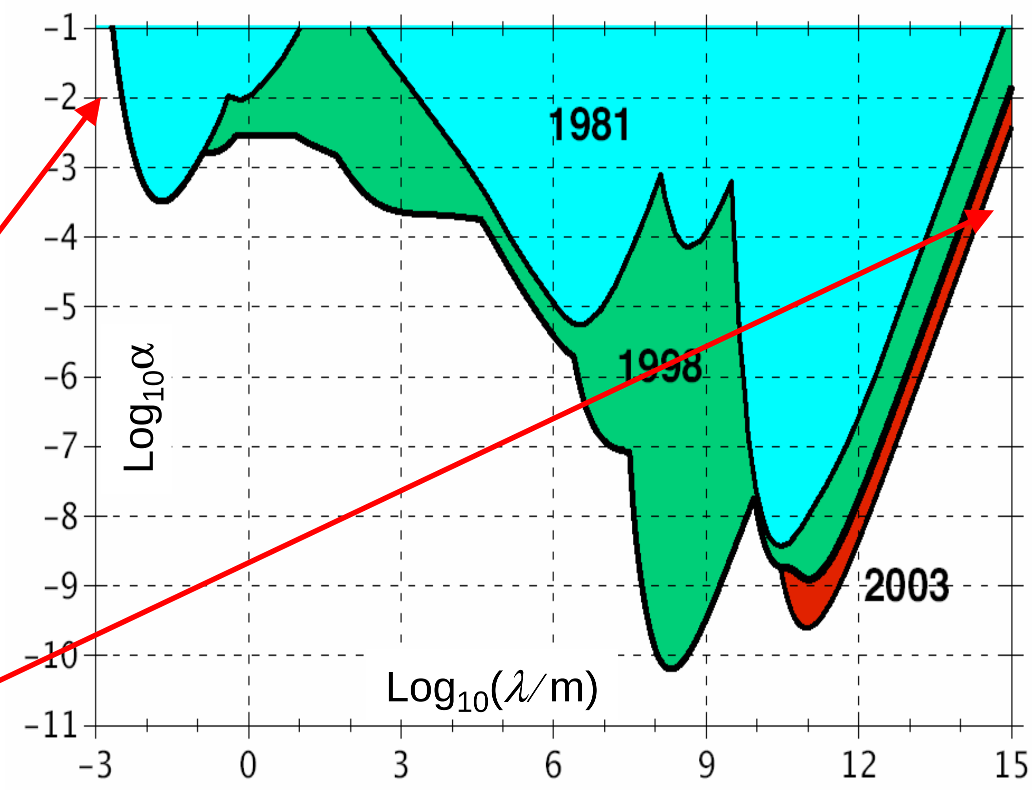
$$g_{00} \quad = \quad [g_{00}]_{\rm GR} + \delta g_{00}$$

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)

FORCA-G

CAsimir FORce and Gravitation at short range

F. Pereira Dos Santos, P. Wolf, A. Landragin, M.-C. Angonin,

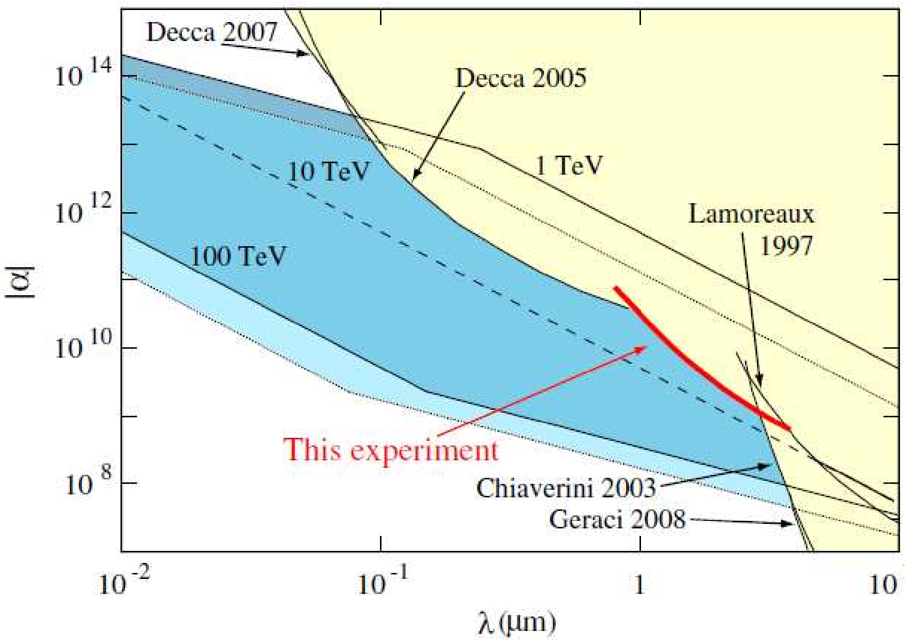
P. Lemonde, S. Bize, A. Clairon

SYRTE (Observatoire de Paris, CNRS, UPMC)

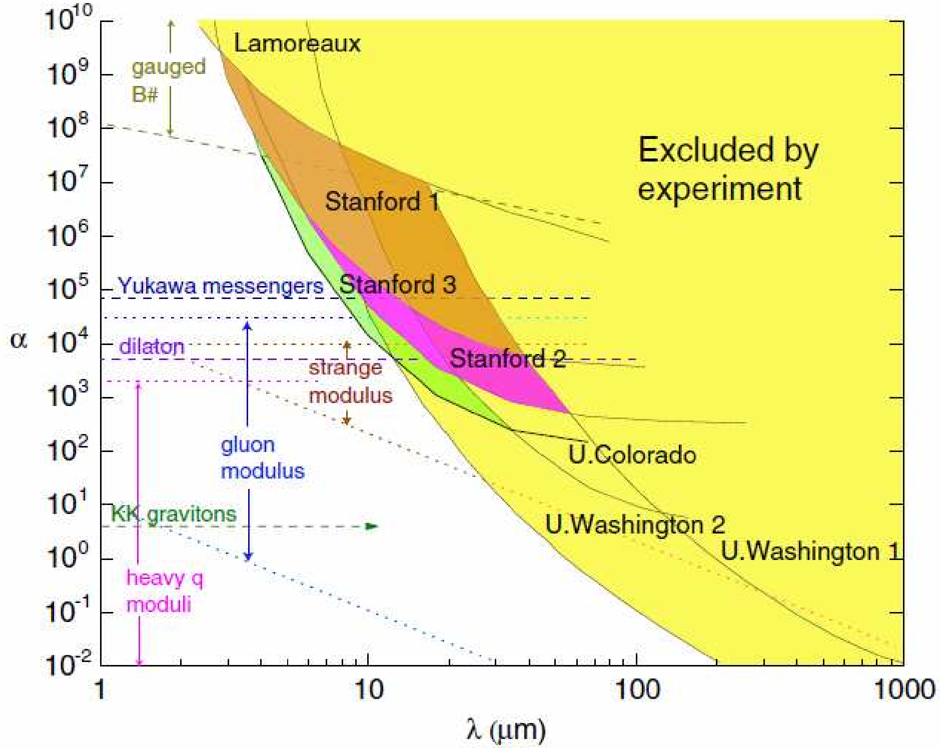
A. Lambrecht, S. Reynaud

LKB (ENS, UPMC, CNRS)

Gravitation at short range



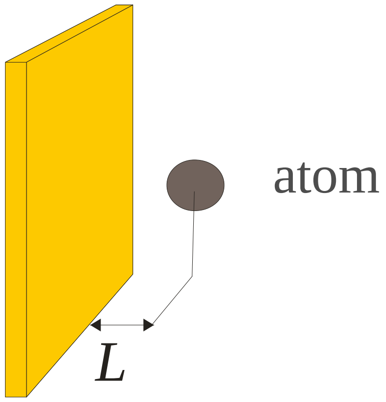
M. Masuda and M. Sasaki
PRL, 2009



A.A. Geraci, et al, PRD, 2008

Limitations: Uncertainties in macroscopic force and distance measurement
Seismic perturbations
Statistics (Duty cycle)

Casimir-Polder 1948



$$F_{CP} = \frac{3\hbar c \alpha_0}{2\pi L^5}$$

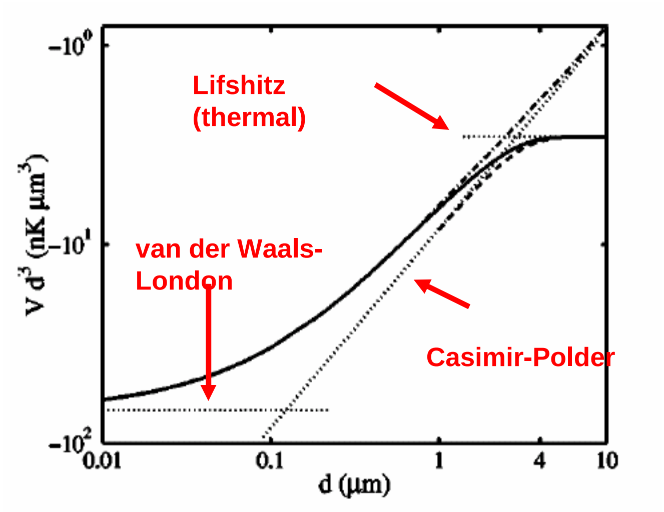
Rb

$$L = 1\mu\text{m} \rightarrow F_{CP} \approx 10^{-23}\,\text{N}$$

Rich phenomenology:

- 2 crossovers :
$1/L^4$ (VdW) to $1/L^5$ (CP) and back to $1/L^4$ (thermal)

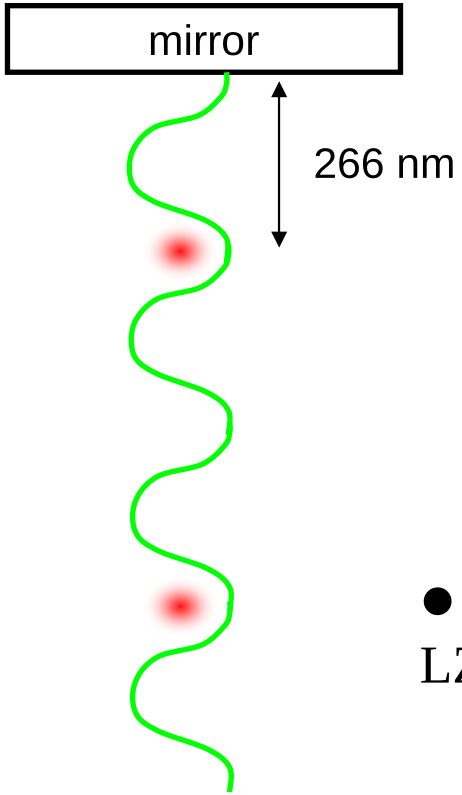
- Out of thermal equilibrium :
Additional $1/L^3$ dependence
Theory and experiment (2007)



M. Antezza et al., PRA70, 053619 (2004)

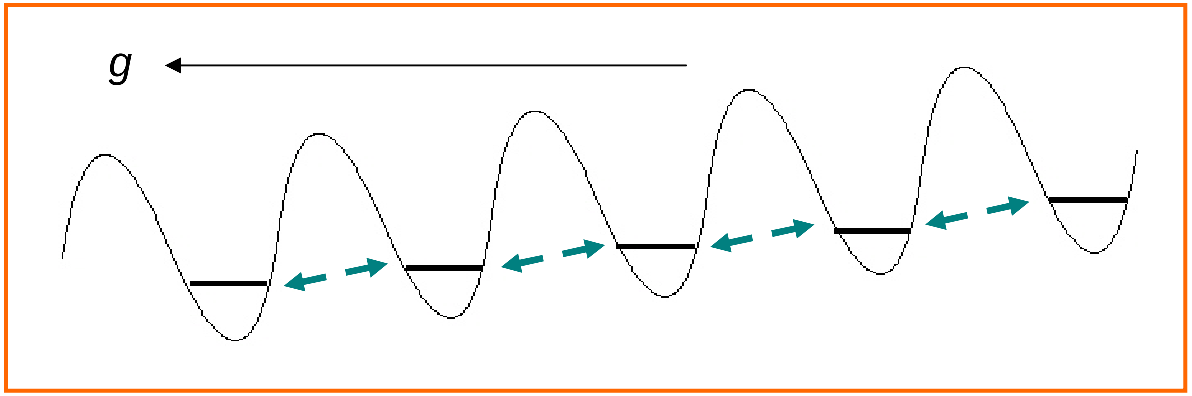
- Dependence on atomic state, surface properties, surface/environment temperature, etc….
- Experiments confirm theory at the **≥10% level**, for various atoms, distances, temperatures …

Principle of FORCA-G



- ^{87}Rb atoms
  Trapped in a blue detuned standing wave (532 nm)

- Gravity ⇒ non-resonant tunneling ⇒ Localization

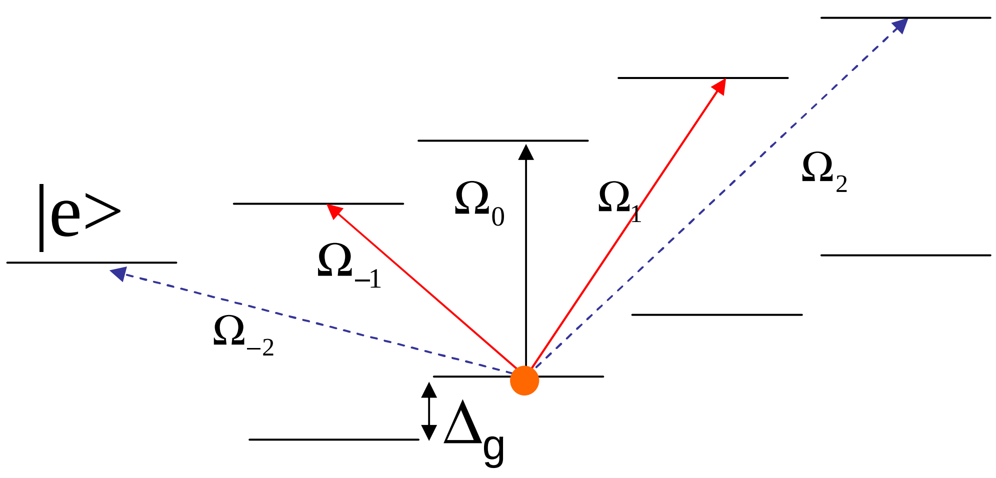


- Wannier-Stark ladder of localised metastable states
  LZ-tunneling : 10^{14} s lifetime @ U=3Er

- For Rb: $\Delta_g = m\, g\, \lambda_L/2 \sim 500$ Hz

P. Wolf *et al*, PRA 75, 063608 (2007), F. Sorrentino *et al*., PRA 79, 013409 (2009)

Climbing up or down the W-S ladder



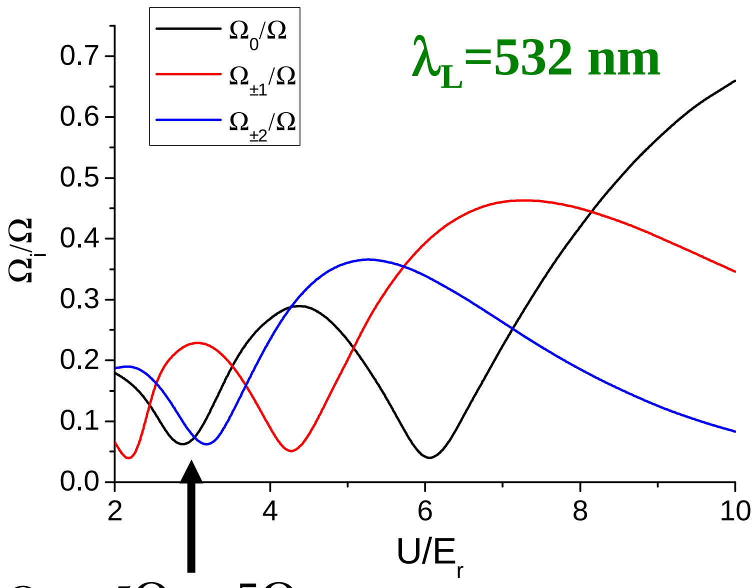
$$\Omega_i = \Omega \langle W_m | e^{ik\hat{x}} | W_{m+i} \rangle$$

Transitions induced by Raman lasers

Raman lasers couples |g> to |e> in the same well,

but also to neighbouring wells when detuned by $\pm\Delta_g$

Good efficiency for $k_{eff} \sim k_L$



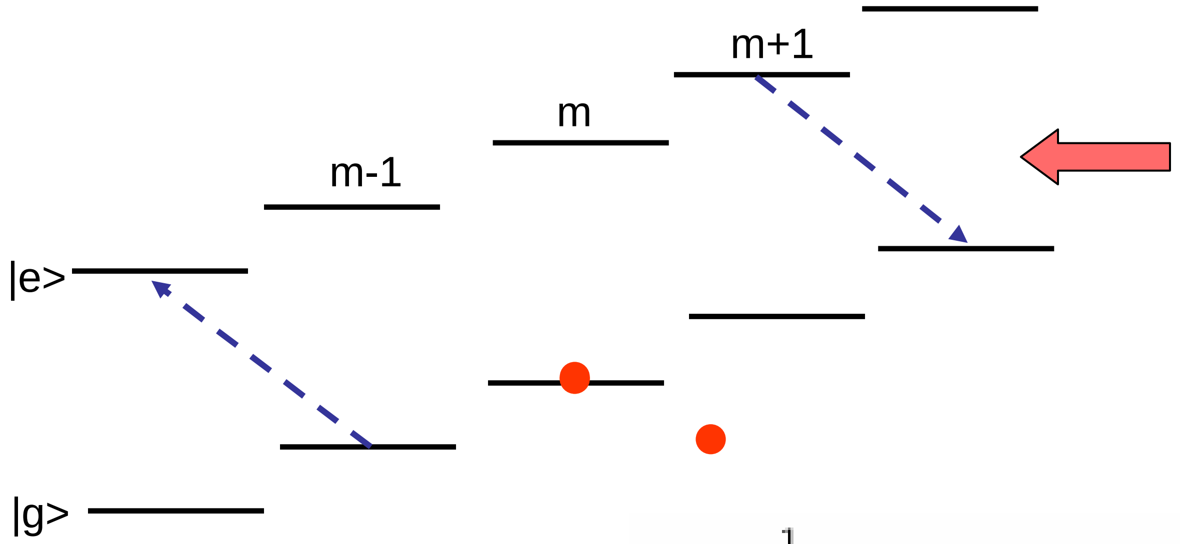
$\Omega_{\pm 1} \approx 5\Omega_0 \approx 5\Omega_{\pm 2}$

At a few E_r the coupling strengths $\Omega_0 \approx \Omega_{\pm 1}$.

$\Delta_g \approx$ **500 Hz** is resolved by Raman lasers

$\Rightarrow$ **Efficient control** of the external states using the frequency difference between the Raman lasers

Climbing up and down : the interferometer



$$\Delta\phi = \frac{1}{\hbar}\left(m_a g \lambda_l + U_{m+1} - U_{m-1}\right)(T_1 + T_2) + \left(\omega_{eg}^{(m+1)} T_1 - \omega_{eg}^{(m-1)} T_2\right) - \phi_s^{(1)} + 2(\phi_s^{(2)} - \phi_s^{(3)} + \phi_s^{(4)}) - \phi_s^{(5)}.$$

- Coherent superposition of internal states with π/2 pulse
- Separate/recombine with π pulses detuned by 0, $\pm\Delta_g$.

- Sensitivity: **$\Delta\phi$ = 10^{-4} rad** (after integration), T_1+T_2 = 0.1 s, ⇒ **$\Delta E / h \approx 10^{-4}$ Hz**
- Measurement of *g* and *m/h* at the 10^{-8} – 10^{-9} level (separating by 10 – 100 wells)

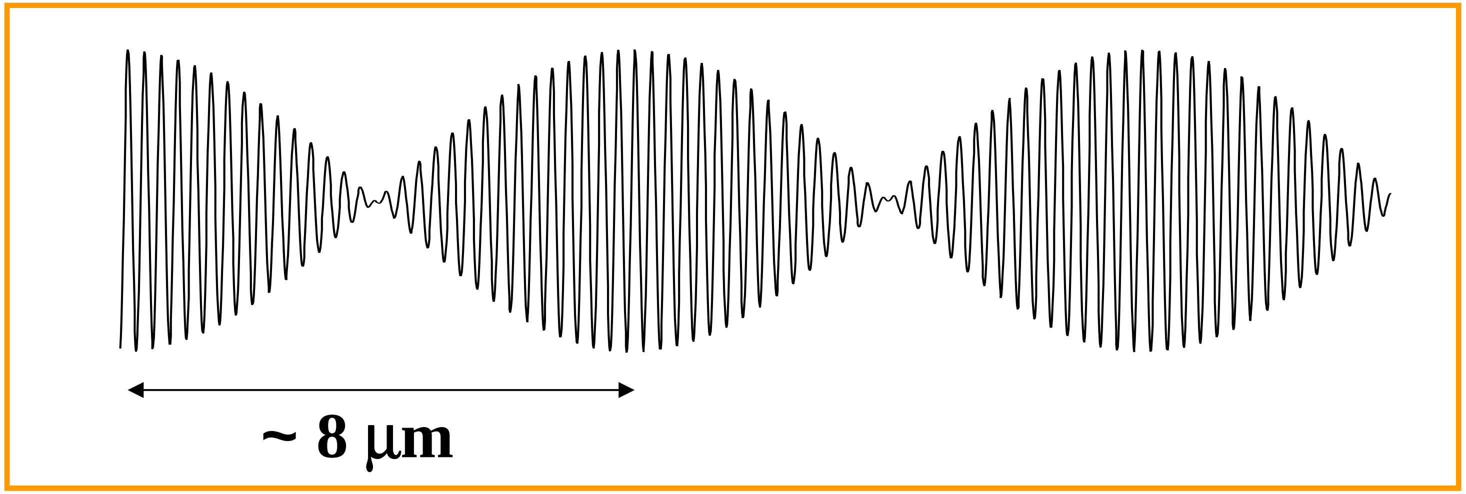
- Superposition close to the mirror : measurement of ΔU_{QED}, ΔU_{YUK}
- Accurate knowledge of the distance (determined by λ_{trap})

Site selection

Select atoms in one well

Idea : superimpose a second lattice beam @515 nm

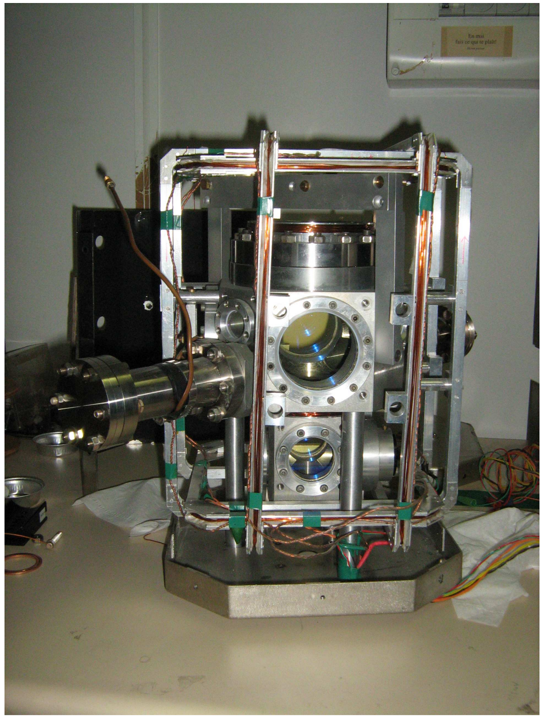
⇒ Create a **SUPERLATTICE**

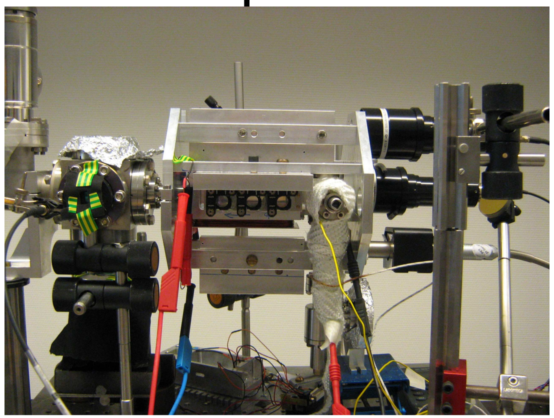


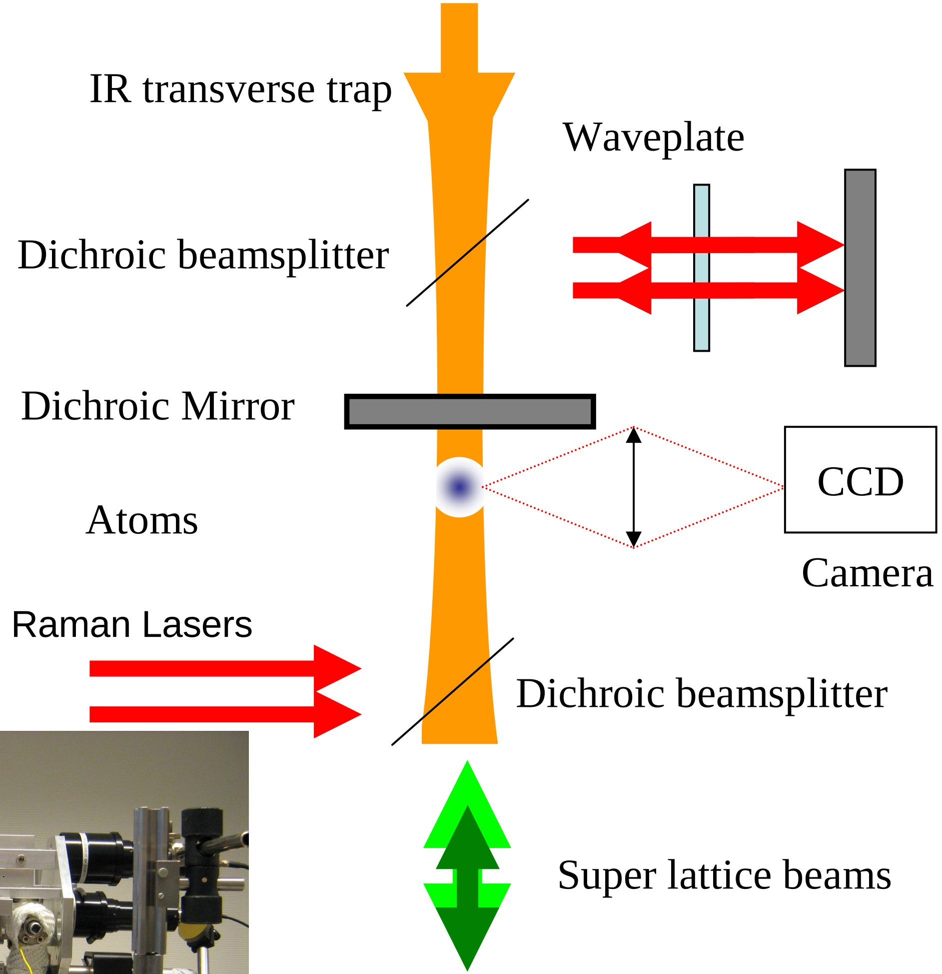
- Lifts the degeneracy between m → m+1 transitions
- Better with (moderate) increase of the lattice depth
- Provides one populated site every 8 μm → **Differential measurements**
- Need for a high resolution imaging system

Experimental setup

- **2D + 3D MOT**
- **Lattice/superlattice**
  (532 nm + 515 nm)
- **Transverse confinement (IR)**
- **Raman lasers**
  Counter/co- propagating
- **CCD Imaging**







Systematic Effects

- Phase Coherence of Raman Beams: require < 0.01 rad @ 6.8 GHz
- Vibrations: use passive isolation: $\delta a/a \approx 10^{-8}$
- Knowledge of mg/h : require $\approx 10^{-8}$
- Stray electric and magnetic fields: use $m_F \neq 0$ states, bias fields
- Collisions: require $\delta\rho \approx 10^{-3} \Rightarrow$ adiabatic passage
- Light shifts: require temporal intensity stability $< 10^{-3}$,
  spatial intensity stability $< 10^{-8}$ over a few μm
- Knowledge of atom-surface separation: $\delta r \geq 1$ nm (surface roughness, wave front distortion)

Noise and Systematics I

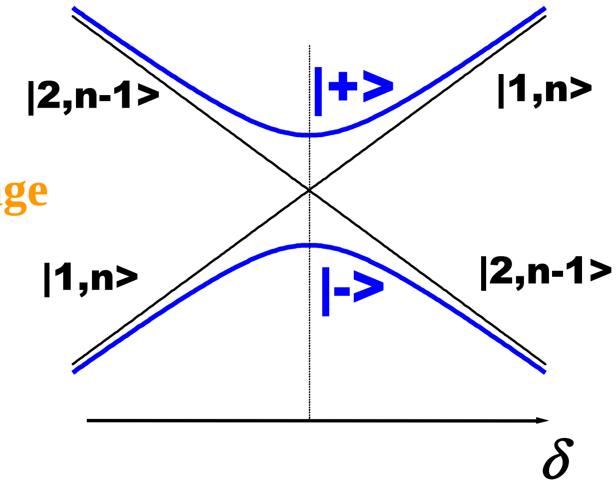
- **Phase coherence of the Raman lasers:**
  Multiplication of ultra stable quartz
  BVA $\sigma_y = 10^{-13} \Rightarrow \sigma_\phi \sim 1$ mrad @ T = 0.1 s $\Rightarrow$ O.K.

- **Vibrations:**
  Passive Isolation (MINUS K) $\rightarrow$ d$g/g \sim 10^{-8}$ @ 0.1 s $\Rightarrow$ O.K.

- **Knowledge of *mg/h*:**
  $\leq 10^{-8} \Rightarrow$ O.K.

- **Light shifts (3 E_r):**
  - Contribution to ω_{eg} : differential light shift $\sim 10^{-5}$ U_L
  $\rightarrow$ Control spatial/temporal intensity variation to 10^{-3}
  - Contribution to U_m : spatial variation < 10^{-8}
  $\rightarrow$ Control of the spatial variation close to the surface ? Scattering …

Noise and Systematics II



- **Collisions:**
  - Large waist – low density 10^{10} at/cm^3
  - Collision phase shift **7 10^{-2} rad**
  - Control of the density at the 10^{-3} level $\Rightarrow$ **Adiabatic passage**

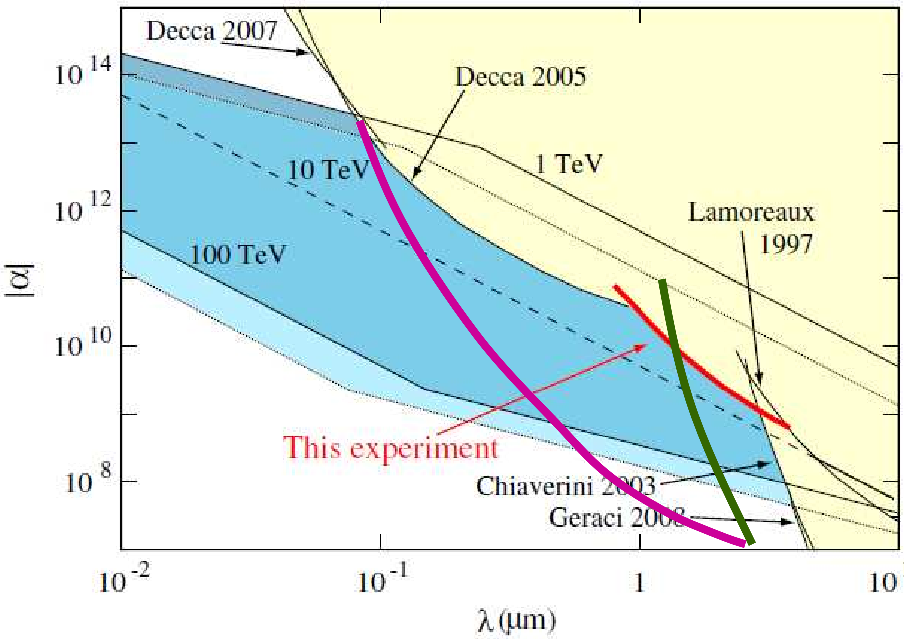
- **Electric and magnetic fields:**
  - Use m_F states for Bfield spectroscopy
  - Dielectric mirror = insulating surface $\rightarrow$ spurious charges
  - Possibility to control using additional E and B fields (cf Cornell 2007)

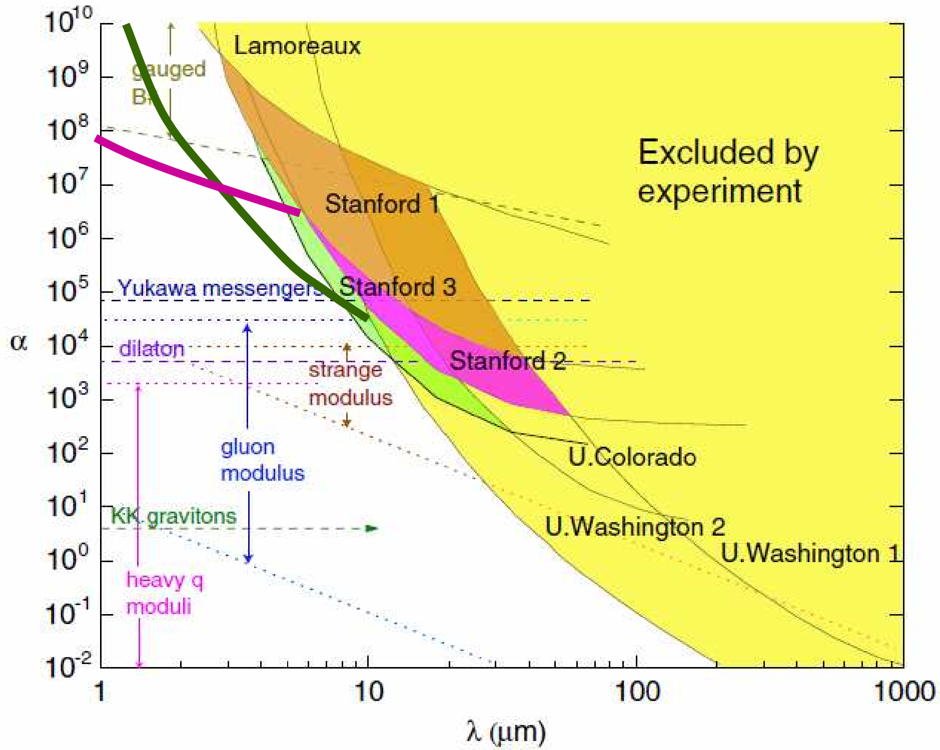
- **Knowledge of atom – surface separation:**
  - limited to ≥ 1 nm (wave-fronts, surface roughness, ….)
  - limiting factor for QED measurement, O.K. for search for new physics

Search for new interactions

- Searching for new interactions requires control of the QED potential at or below the 10^{-4} Hz level.
- Two stage experiment:

1. Calculate and correct (possible at about the % level) and place atoms sufficiently far from the surface (QED < 10^{-2} Hz) $\Rightarrow$ explore $\lambda \approx 10\ \mu m$
2. Differential measurement between ^{85}Rb and ^{87}Rb isotopes $\Rightarrow$ explore $\lambda \approx 0.2$ to $10\ \mu m$





Potential for a gain of about **3 orders of magnitude**
Qualitatively different experiment

Conclusion

● **QED measurement (Casimir–Polder, Vacuum fluctuations)**

- Limited by δL at short distances, by $\delta(\Delta\phi)$ at large distances
- 10^{-3} measurement (2 orders of magnitude improvement) seems feasible
- Many possibilities to explore phenomenology (internal states, distance, temperature…)

● **Search for new short range interactions related to gravity:**

- 3 to 4 orders of magnitude improvement seems feasible
- Explore large range of λ (two stage experiment)

● **General:**

- Complementary from previous experiments in this field
- Well supported by existing technology and know-how in atomic physics and metrology.
- Many parameters to change (P_{trap}, λ_{trap}, r, L, …)
- Choice of surface material is crucial (stray fields)
- Other atoms - fermionic isotopes

The SAGAS Project

P. Wolf on behalf of the SAGAS collaboration

peter.wolf@obspm.fr

CNRS
CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

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

UNIVERSITE PIERRE & MARIE CURIE
LA SCIENCE A PARIS

SAGAS

(Search for Anomalous Gravitation with Atomic Sensors)

arXiv: 0711.0304, (2008); Exp. Astr. **23**, 651, (2009)

Quantum Physics Exploring Gravity in the Outer Solar System

> 70 participants from:	**France, Germany, Great Britain, Italy, Portugal, Austria, Canada, USA, Australia**

Main contributors:

Science Objectives: O. Bertolami, A. Fienga, P. Gil, J. Laskar, J. Páramos, S. Reynaud, F. Roques, S. Turyshev, P. Wolf.

Accelerometer: E. Rasel, A. Landragin, G. Tino.

Clock: P. Gill, E. Peik, P. Lemonde.

Optical Link: A. Clairon, P. Wolf, E. Samain.

Laser Sources: P. Cancio, P. De Natale, M. De Rosa, G. Galzerano, G. Giusfredi, M. Inguscio, P. Laporta, A. Toncelli, M. Tonelli.

Spacecraft: A. Rathke, C. Jentsch.

Mission profile: A. Rathke, D. Izzo.

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 (≈ 3 years after launch).
- Reach distance of ≈39 AU (15 yrs nominal) to ≈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.

$\Rightarrow$ *test body trajectory + light trajectory + proper time*

= Measure all aspects of gravity !

l'Observatoire de Paris — SYRTE

Systèmes de Référence Temps-Espace

Science Objectives: Overview

Science Objective	Expected Result	Comments
Test of Universal Redshift	**1x10^{-9}** of GR prediction	**10^{5}** gain on present
Null Redshift Test	**1x10^{-9}** of GR prediction	**10^{3}** gain
Test of Lorentz Invariance	**3x10^{-9}** to **5x10^{-11}** (IS or "time dilation" test)	**10^{2}** to **10^{4}** gain fct. of trajectory
PPN test	$\delta(\gamma) \leq$ **2x10^{-7}**	**10^{2}** gain may be improved by orbit modelling
Large Scale Gravity	- Fill exp. data gap for scale dependent modif. of GR - Identify and measure PA to < 1% per year of data	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** $\boldsymbol{M_E}$	Dep. on mass distribution and correlation of clock meas.
KB Mass Distribution	Discriminate between different common candidates	Will contribute significantly to solution of the "KB mass deficit" problem
Individual KB Objects (KBOs)	Measure M_{KBO} at ≈ **10%**	Depending on distance of closest approach
Planetary Gravity	-Jupiter Gravity at $\leq 10^{-10}$ -Study Jupiter and its moons	10^{2} gain on present for Jupiter idem for other planet in case of 2nd fly-by
Variation of Fund. Const.	$\delta\alpha/\alpha \leq$ (**2x10^{-9}**) $\delta(GM/rc^2)$	**250**-fold gain on present
Upper limit on Grav. Waves	$\Omega_h \leq 10^{-5}$ @ 10^{-5} Hz $h \leq$ **10^{-18}** @ 10^{-6} to 10^{-3} Hz	**10^{3}** gain @ 10^{-6} to 10^{-3} Hz Integration over one year
Technology Developement	Develops S/C and ground segment technologies for wide use in future missions (interplanetary timing, navigation, broadband communication,…)	

Large scale gravity test example

- Pioneer 10 and 11 data show unexplained almost constant Doppler rate ($a_P \sim (8.7 \pm 1.3) \times 10^{-10}$ 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 test example

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

Observable uncertainty	**Acc. / ms^{-2}** (5 10^{-12})	**Clock** (1 10^{-17})	**Doppler** (<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}

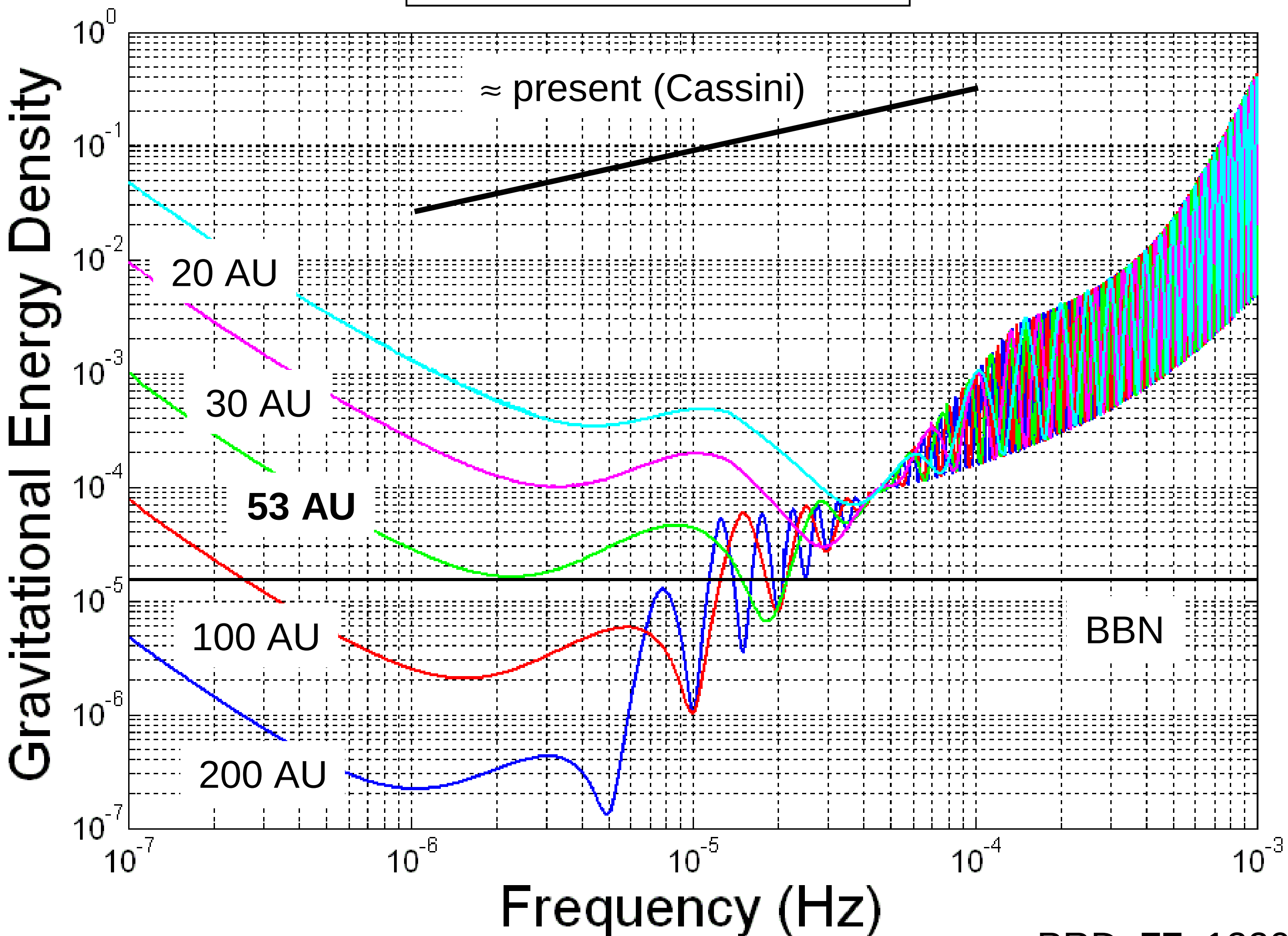
Accelerometer limitation

"-" = 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

Example: Cosmological GW background

$$\Omega_{GW}(f) = \frac{16\pi^2 f^3}{3H_0^2}\frac{S_y(f)}{b(f)}$$

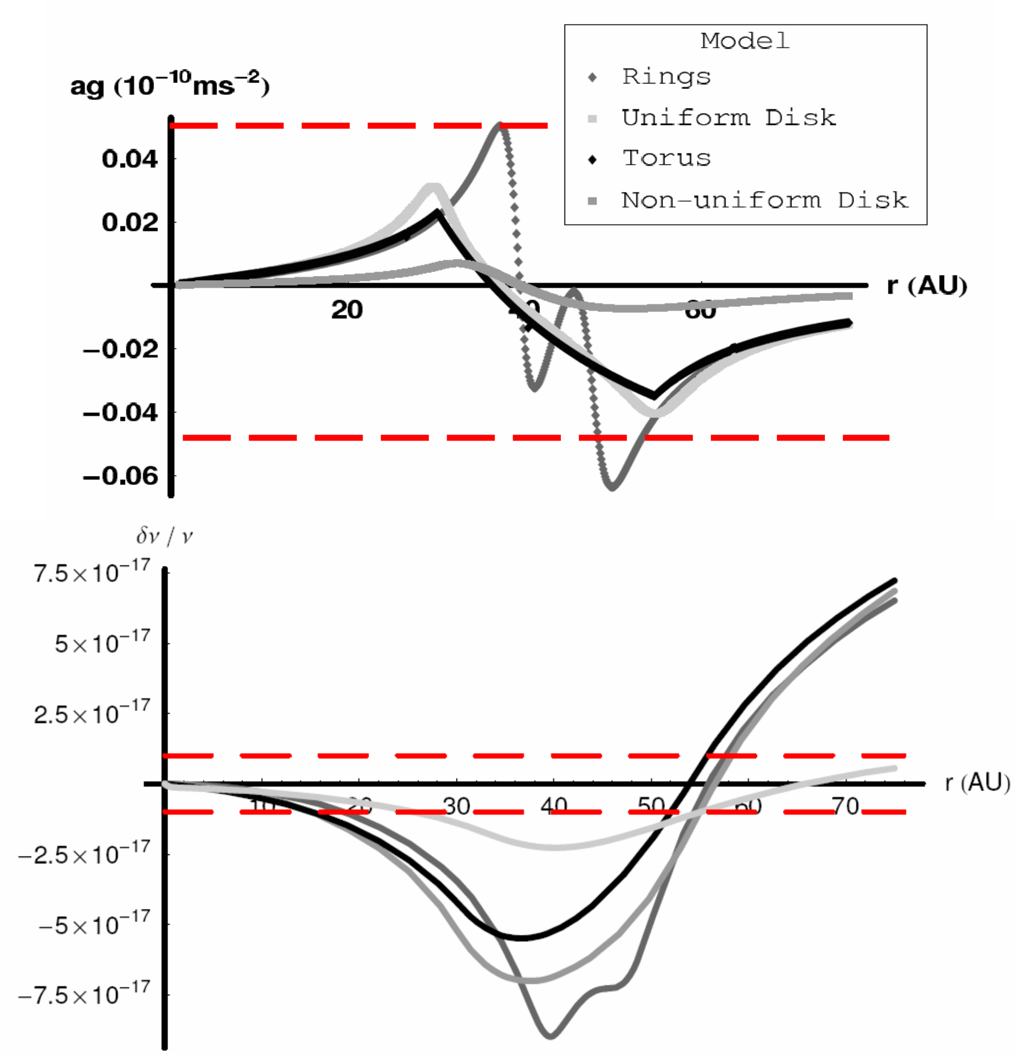


PRD, **77**, 122003, (2008)

l'Obse

Systèmes de Référence Temps-Espace

Solar System Exploration: Kuiper Belt



Provided by O. Bertolami et al.

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

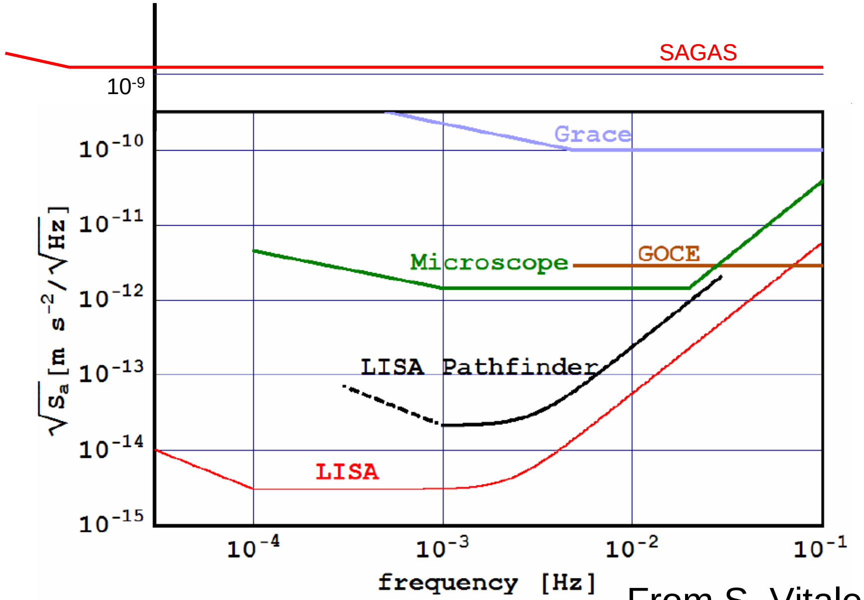
- Remnant of disc from which giant planets formed.
- Mass deficit problem (100 times less than expected from in situ formation of KB objects).
- Acceleration sensitivity insufficient to distinguish between models ($\propto 1/r^2$).
- But clock well adapted for measurement of diffuse, large mass distributions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

Payload: SAGAS requirements and state of the art

Accelerometer:

• Aim at $\sqrt{S_a}(f)$ = 1.3 10^{-9} m/s^2 Hz $^{-1/2}$ noise and absolute accuracy of 5 10^{-12} m/s^2

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



From S. Vitale

Clock:

• Single trapped ion optical clock.

• Aim at 1 10^{-14} / $\sqrt{\tau}$ stability and ≤ 1 10^{-17} accuracy

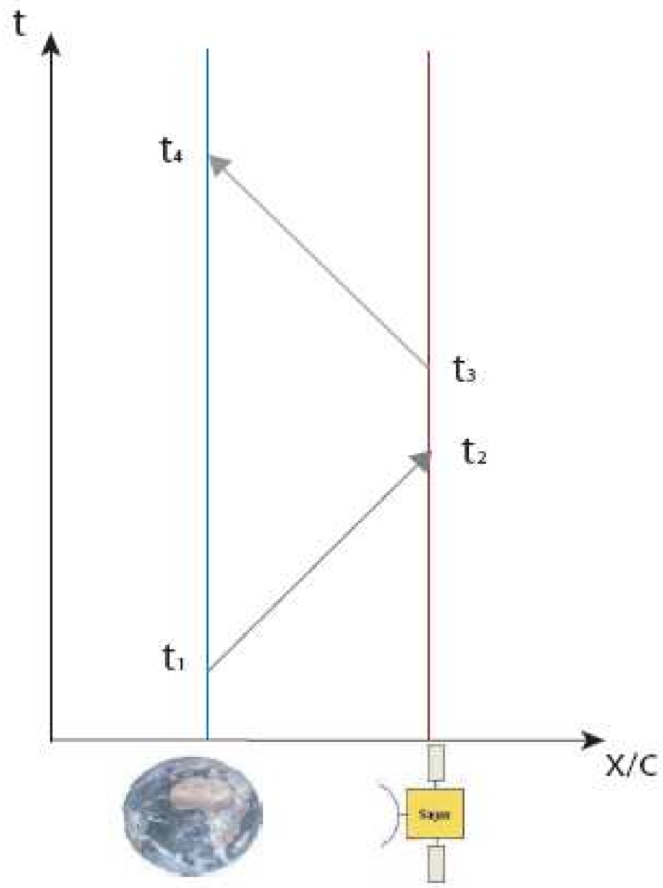
• Best ground trapped ion optical clocks show $\sigma_y(\tau)$ = 3 10^{-15} / $\sqrt{\tau}$ and δy ≤ 9 10^{-18}.


Courtesy: PTB

Challenge for SAGAS is not performance but space qualification and reliability.

Deep Space Optical Link (DOLL)

- 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.
- Technological challenges are pointing requirements (0.3”), laser availability and reliability, atmospheric turbulence, …
- Advantages: performance, data rate, reduced sensitivity to AM noise and stray light, …
- Free space version of existing fibre links



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Present Activities

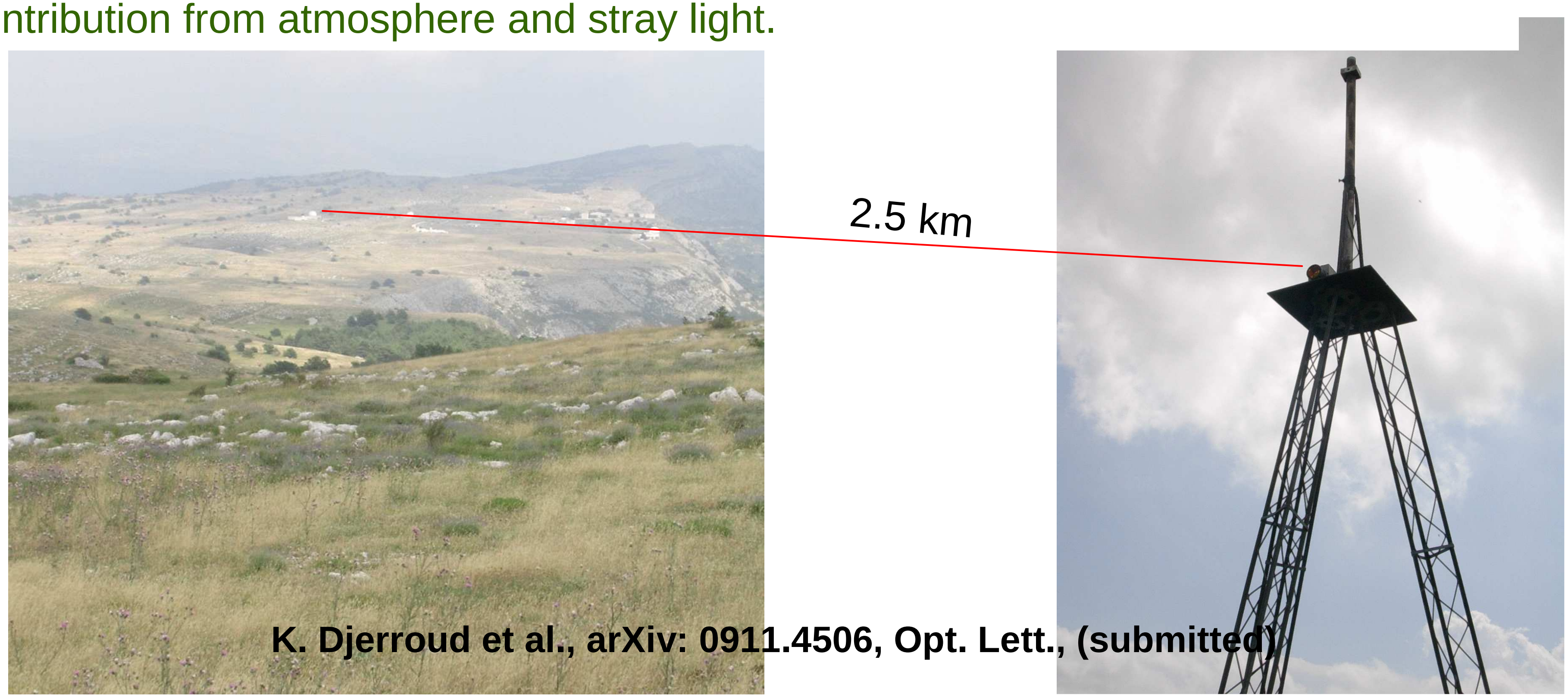
R&D (ESA, CNES, DLR, research labs, …):

• Optical clocks, laser cavities, femtosecond combs, for space applications

• Atomic accelerometers (free fall tests, PHARAO heritage, …)

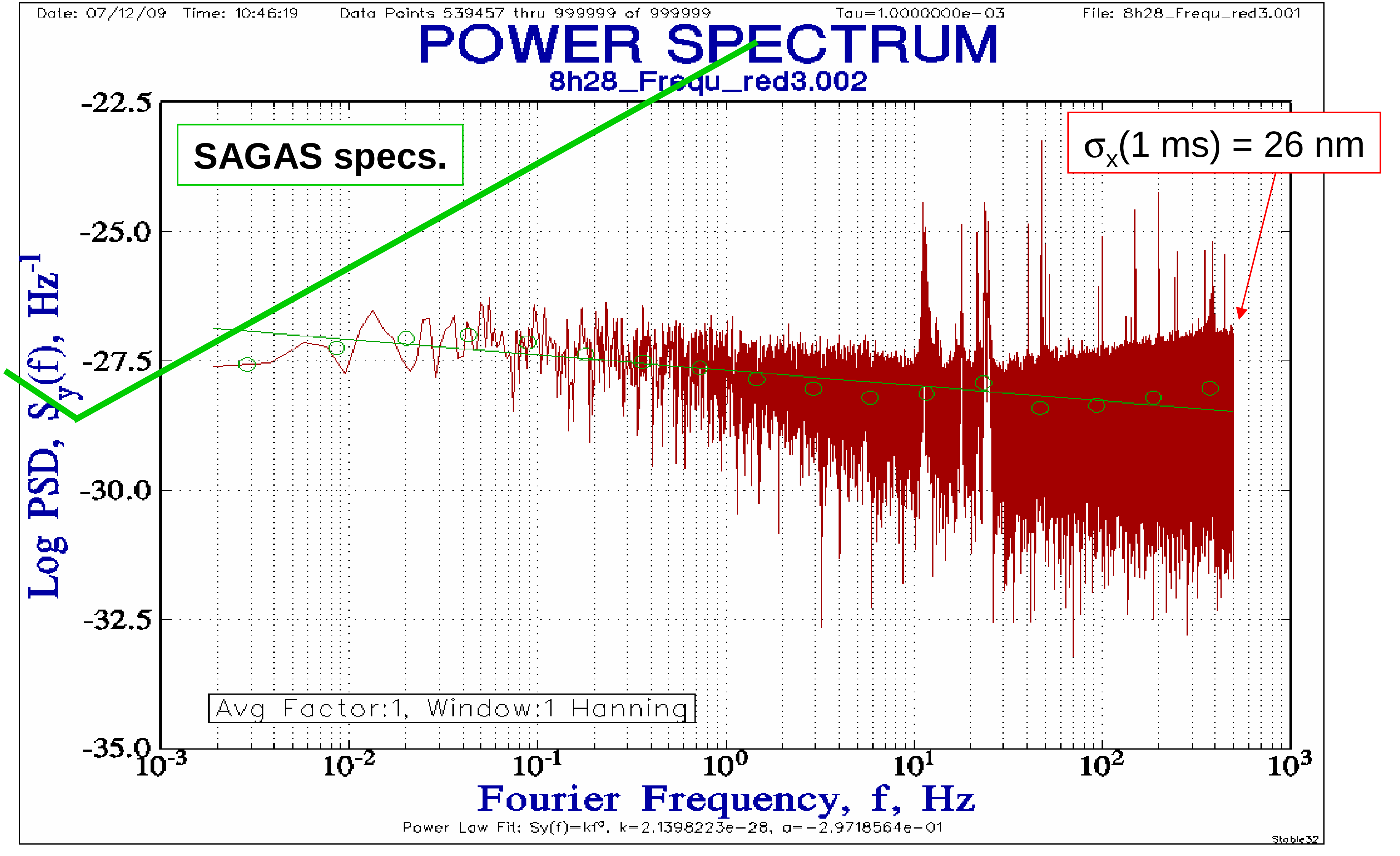
Optical Link:

• Mini-DOLL: SYRTE-OCA project, CNES support. Coherent CW optical link from ground telescope ↔ LEO satellite to demonstrate principle and to study noise contribution from atmosphere and stray light.



K. Djerroud et al., arXiv: 0911.4506, Opt. Lett., (submitted)

Results (2/07/2009)



Turbulence contribution should be OK !

CONCLUSION

- There are good theoretical and observational reasons to expect a scale dependent modification of GR
- Such modifications are least constrained at very small and very large scale
- FORCA-G allows exploring gravity at very short range with improved sensitivity and using complementary physics to existing experiments
- SAGAS offers possibility of complete characterisation of gravitation at the largest possible scale in our “laboratory”
- Both experiments hold potential for a major discovery in fundamental physics and major contribution to constraining theoretical models.