Use of geodetic measurements to probe fundamental physics

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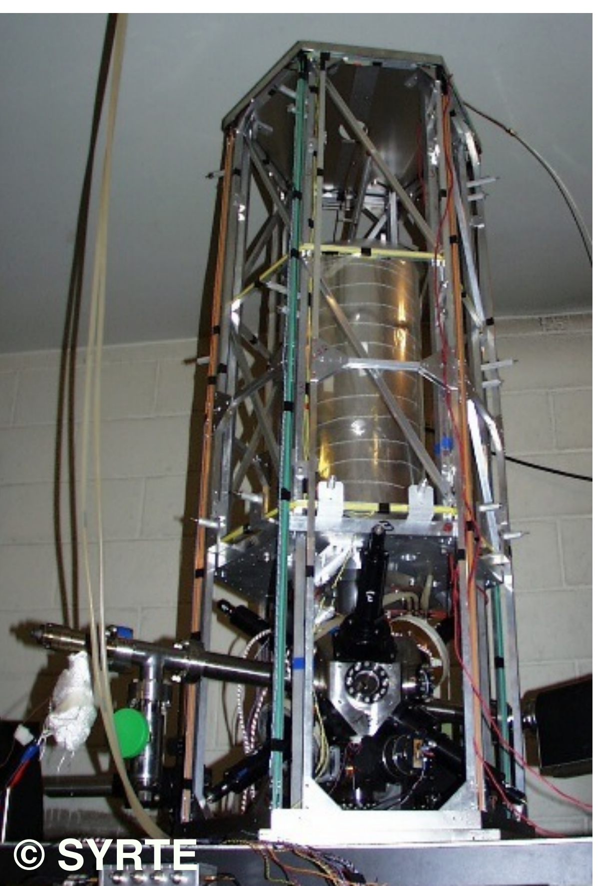
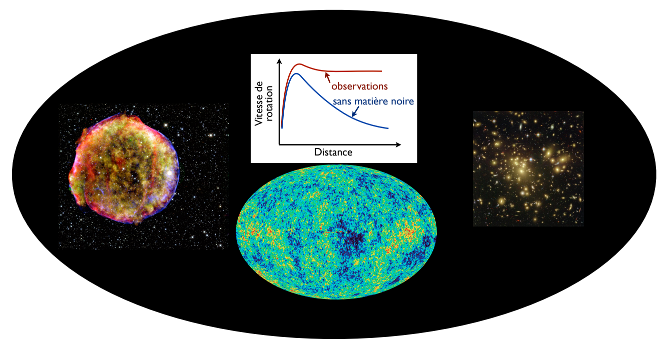


Colloque du G2, Observatoire de Paris
November 23rd 2021

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

Global picture & motivations

- Some of the "greatest challenges" in theoretical physics:
  - what are Dark Matter and Dark Energy ?
  - how can we develop a quantum theory of gravity and/or unify it with the Standard Model of particles ?
- local physics measurements can give some clue about these



Astronomy & cosmology

(SNIa, CMB, structure formation, galactic dynamics, …)

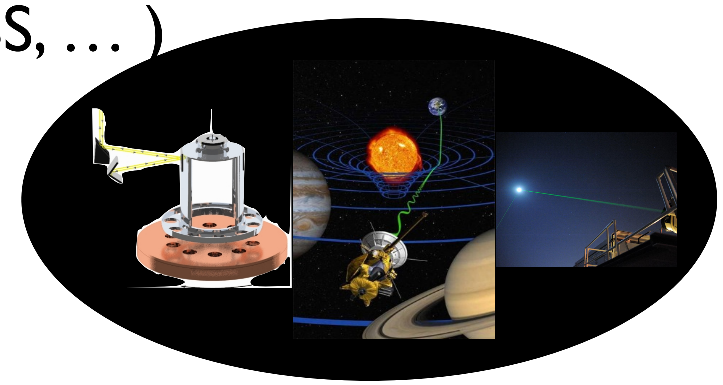
Quantum Gravity

Unification

DM and DE

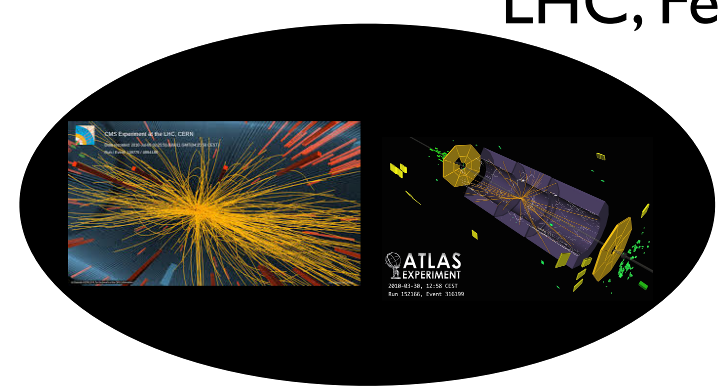
Local physics

(Solar System, lab tests, GNSS, …)



High energy

(particle physics: CERN-LHC, Fermilab, DESY, …)



Picture inspired by Altschul et al, Adv, in Space Res. 55, 501, 2015

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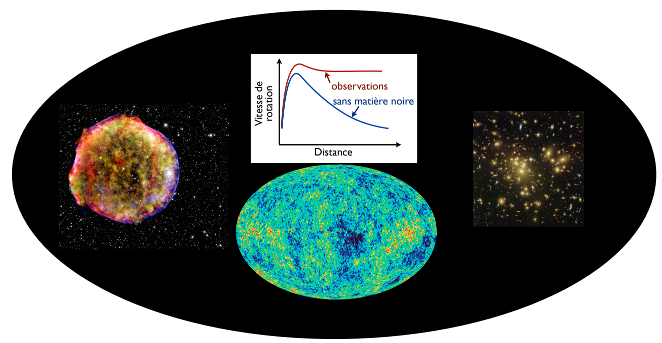

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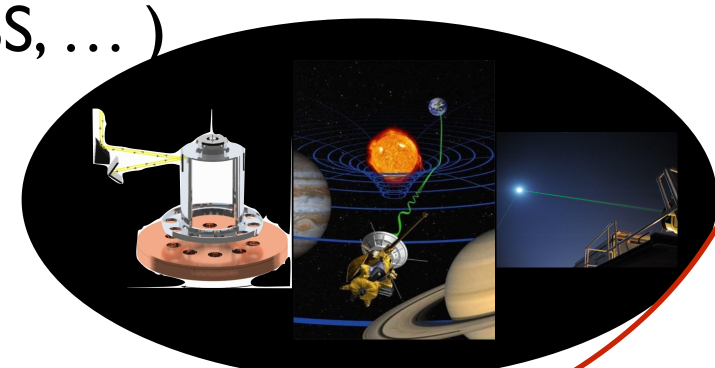

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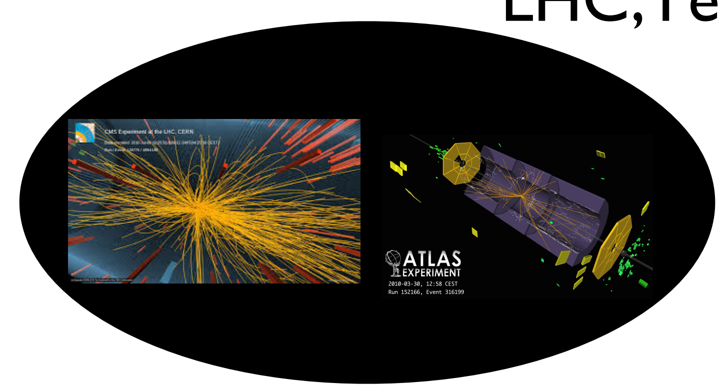

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A lot of "alternative theories" of gravitation and a lot of Dark Matter candidates

- See for example the review: (189 pages - and it is not exhaustive)

Physics Reports 513 (2012) 1–189

Contents lists available at SciVerse ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

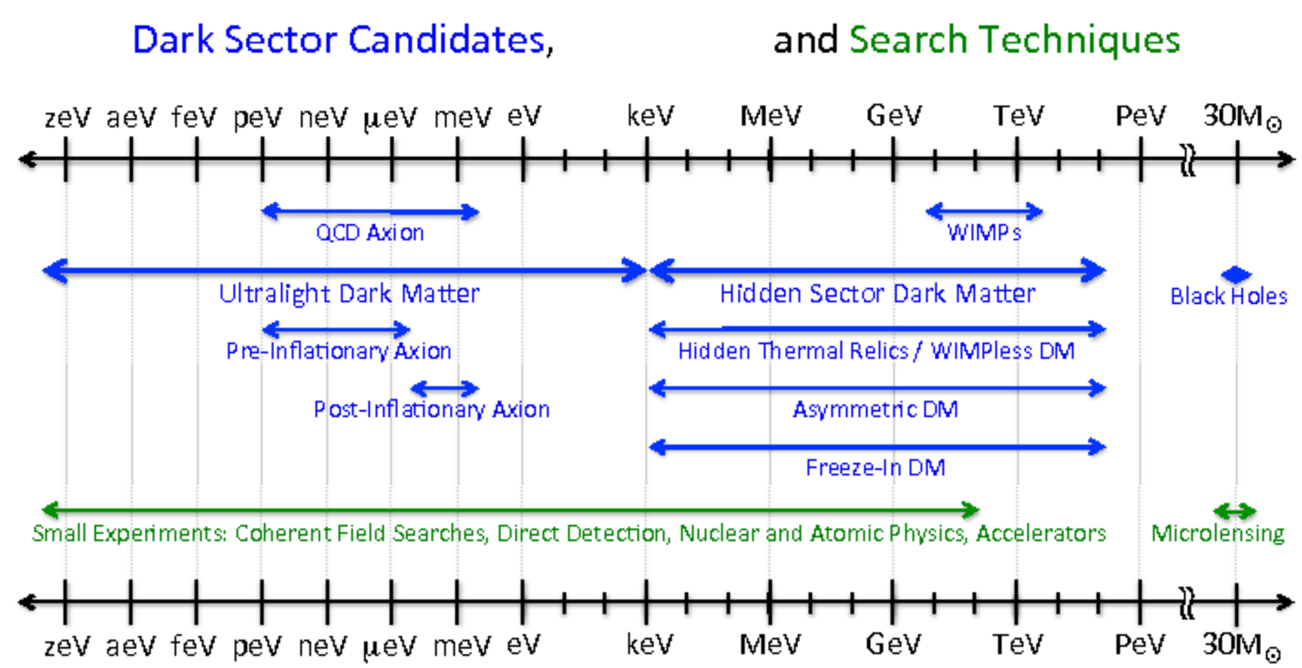
Modified gravity and cosmology

Timothy Clifton[a], Pedro G. Ferreira[a,*], Antonio Padilla[b], Constantinos Skordis[b]

[a] *Department of Astrophysics, University of Oxford, UK*
[b] *School of Physics and Astronomy, University of Nottingham, UK*

- Dark Matter can be searched for in a huge region of mass

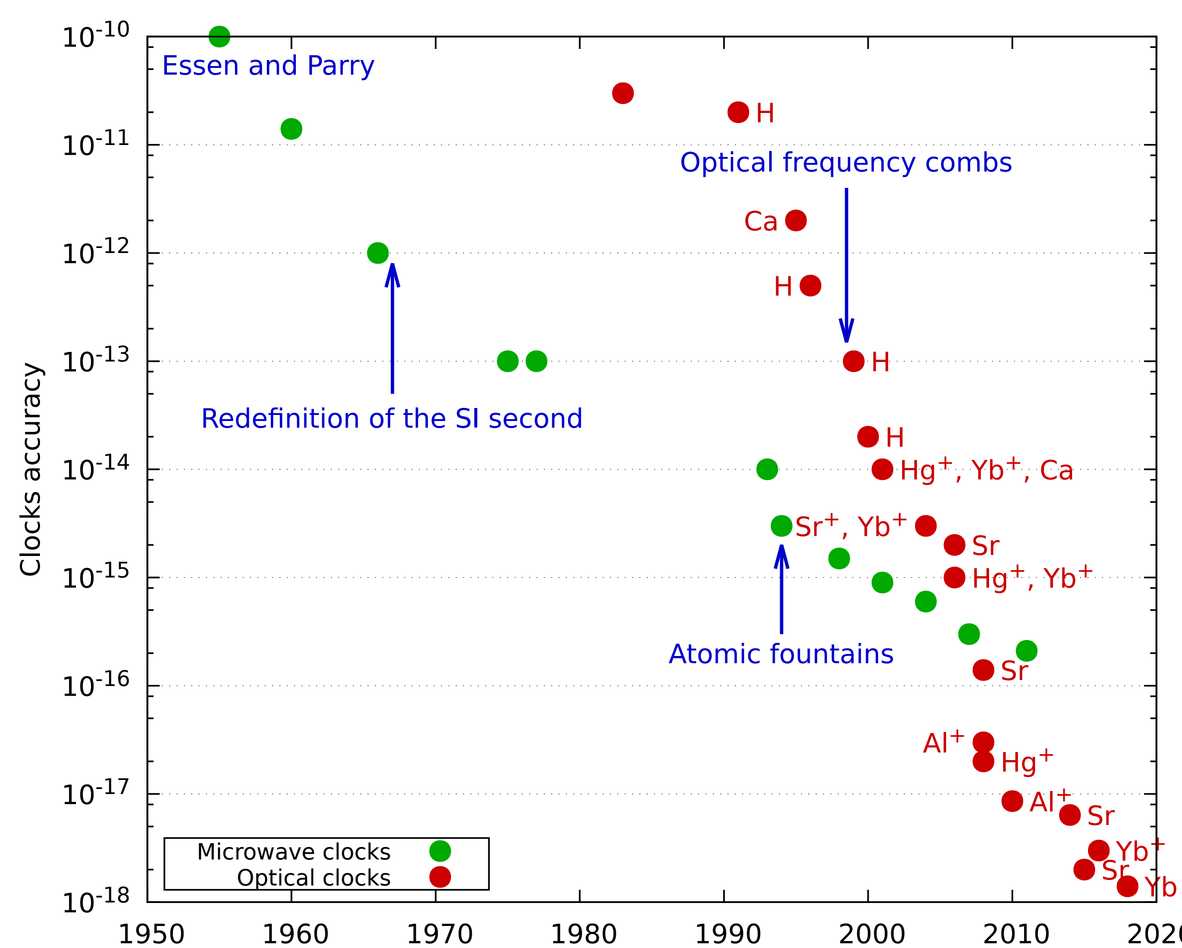
Fig. from *US cosmic vision*, 2017



We need observations to detect, constrain or rule out these propositions

Geodetic measurements are becoming more and more accurate and are now commonly used to probe fundamental physics

- Very high accuracy/stability
- Extremely good control over the systematics
- Reproducibility (even by different labs)
- Can easily be optimized to search for specific signatures
- Built for other scientific goals: "Affordable"



In this talk: I will review recent results obtained by the SYRTE theory and metrology group

- Use of atomic clocks: variations of fundamental constants and search for Dark Matter
- GNSS measurements: test of the gravitational redshift
- Lunar Laser Ranging: search for a breaking of Lorentz symmetry
- MICROSCOPE: search for a breaking of Lorentz symmetry
- Very Long Baseline Interferometry: search for a breaking of Lorentz symmetry

Space/time variations of the constants of Nature are a signature of a breaking of the Equivalence Principle

- The Einstein Equivalence Principle is a building block of General Relativity
- Identification of gravitation with a unique space-time curvature (geometry) which governs the motion of bodies, light, the evolution of proper time, …

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- Standard tests of the Equivalence Principle:

Universality of Free Fall

Two test masses fall with the same acceleration in a gravitational field

Tested at 10^{-14} with MICROSCOPE

See Touboul et al, PRL, 2018

SM constants are constant

Fine structure constant, masses of fermions independent of space/time

Tested with atomic clocks, e.g.

$$\frac{\dot{\alpha}}{\alpha} < 10^{-17}\mathrm{yr}^{-1}$$

$$\frac{d\ln\alpha}{dU/c^2} < 10^{-7}$$

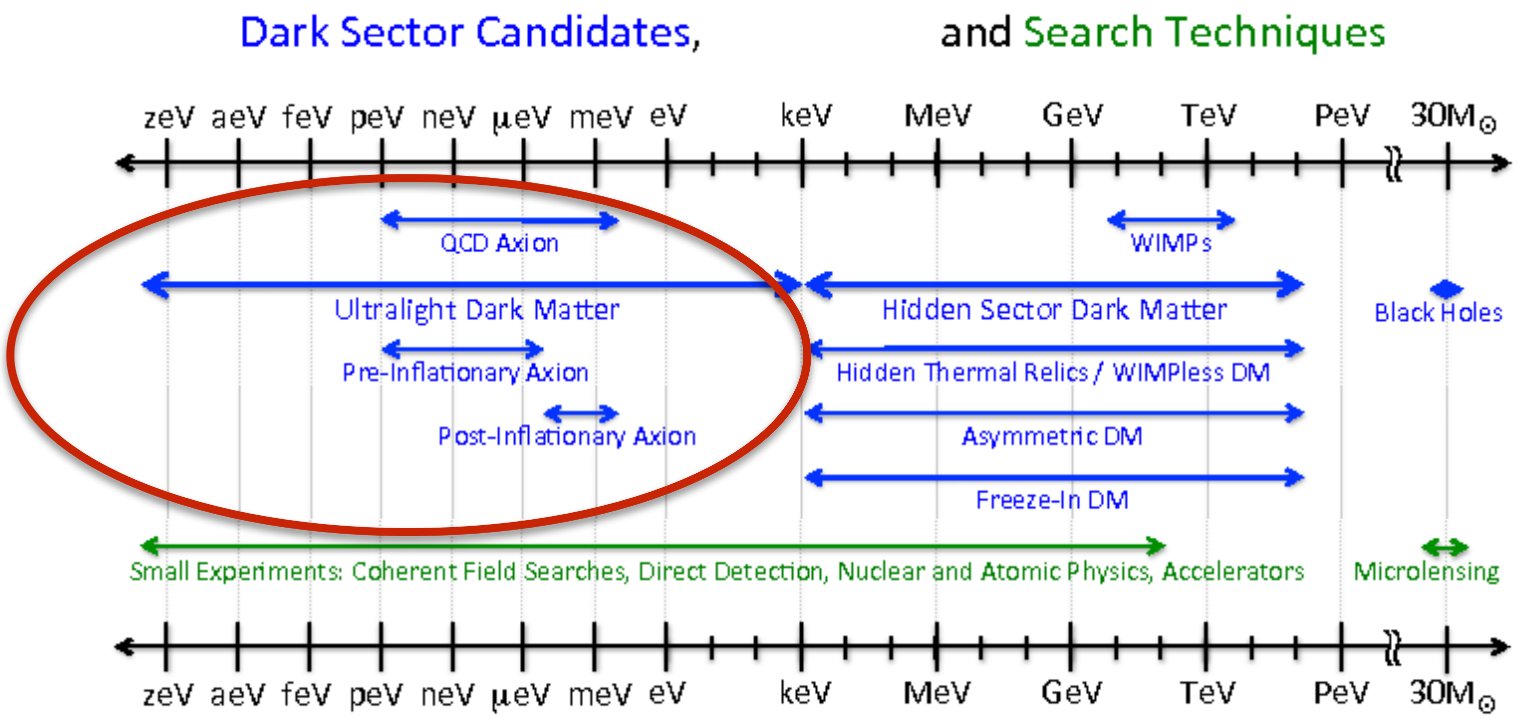
For a review, see Uzan, LRR, 2011

Gravitational Redshift

The comparison between two clocks depend on the difference of their gravitational potential

Tested with Galileo data (see later)

A massive scalar field is a good Dark Matter candidate



- DM below ~ 10 eV: only bosons (exclusion principles): axion, scalar field, vector field, …
- Mass << eV: huge occupation number: the boson field can be treated classically (no quantization)
- At cosmological scales, the boson field oscillates at its Compton frequency and behaves like CDM

$$\varphi \sim \cos mt$$

see e.g. Arvanitaki et al PRD, 2015 or Stadnik and Flambaum, PRL 2015

The scalar field is coupled to SM and induces oscillations of the "constants of Nature"

- An effective Lagrangian for the scalar-matter coupling

$$\mathcal{L}_{\rm mat}\left[g_{\mu\nu},\Psi,\varphi\right]=\mathcal{L}_{SM}\left[g_{\mu\nu},\Psi\right]+\varphi^i\left[\frac{d_e^{(i)}}{4e^2}F_{\mu\nu}F^{\mu\nu}-\frac{d_g^{(i)}\beta_3}{2g_3}F^A_{\mu\nu}F^{\mu\nu}_A-\sum_{j=e,u,d}\left(d_{m_j}^{(i)}+\gamma_{m_j}d_g^{(i)}\right)m_j\bar\psi_j\psi_j\right]$$

see Damour and Donoghue, PRD, 2010

- Couplings usually considered:
  - linear in φ: lowest order expansion (cfr Damour-Donoghue)
  - quadratic in φ: lowest order if there is a Z_2 symmetry (cfr Stadnik et al)
- This leads to a space-time dependance of some constants of Nature to the scalar field

$$\alpha(\varphi)=\alpha\left(1+d_e^{(i)}\varphi^i\right)$$

$$m_j(\varphi)=m_j\left(1+d_{m_j}^{(i)}\varphi^i\right)\qquad\text{for } j=e,u,d$$

$$\Lambda_3(\varphi)=\Lambda_3\left(1+d_g^{(i)}\varphi^i\right)$$

Can be interpreted as a signature of a violation of the Einstein Equivalence Principle and searched for using atomic sensors!

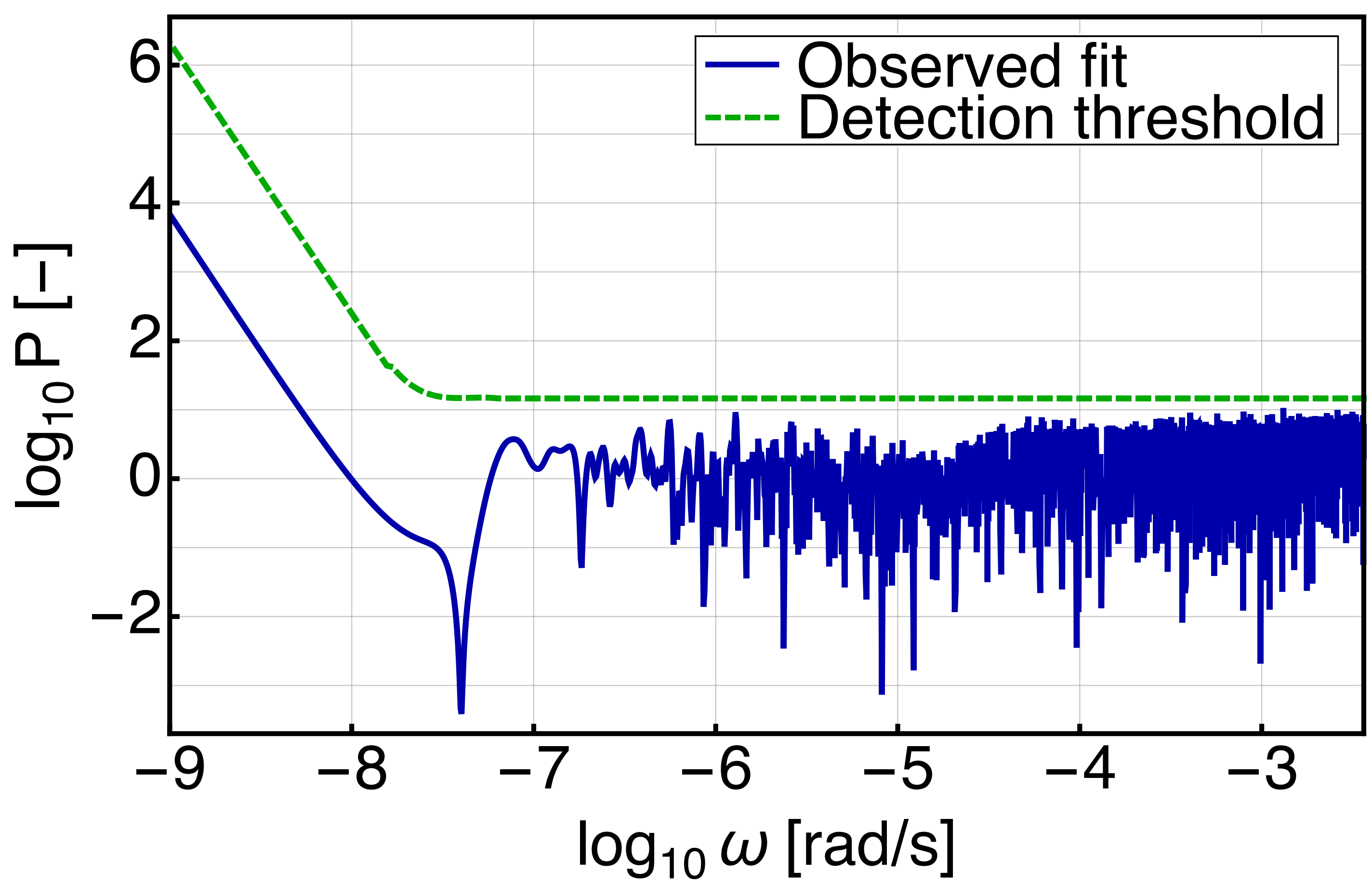
see also Arvanitaki et al, PRD 2015, Hees et al, PRD, 2018

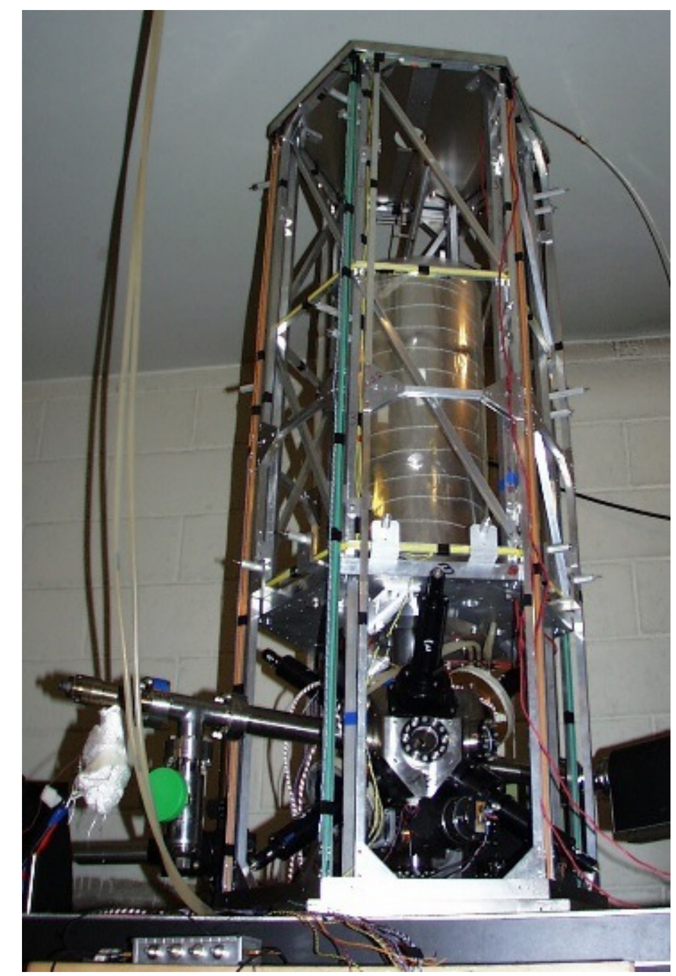
Search for a periodic signal in Cs/Rb comparison

- Cs/Rb FO2 atomic fountain data from SYRTE: high accuracy and high stability, data used from 2008

see J. Guéna et al, Metrologia, 2012 and J. Guéna et al., IEEE UFFC, 2012

- Search for a periodic signal in the data using Scargle's method, see Scargle ApJ, 1982





l'Observatoire de Paris SYRTE

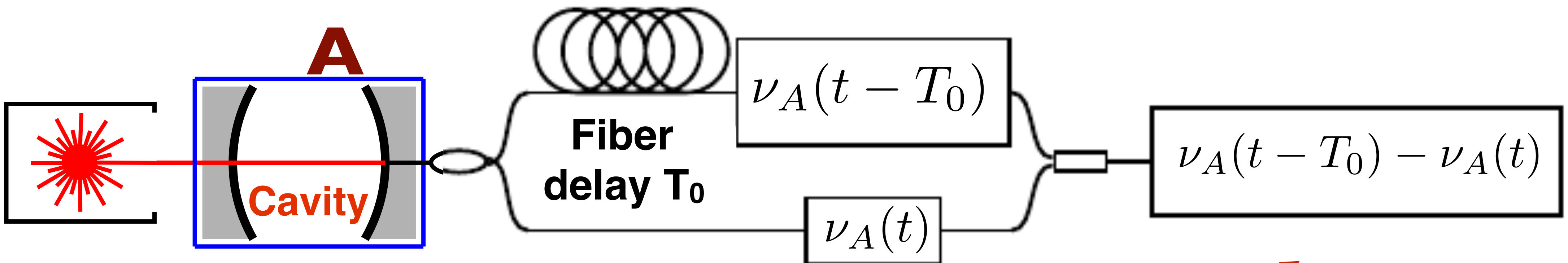
Systèmes de Référence Temps-Espace

No positive detection

A. Hees, J. Guéna, M. Abgrall, S. Bize, P. Wolf, PRL, 2016

Search for a periodic signal in a Mach-Zender interferometer

- New type of experiment (E. Savalle's PhD)



$$\frac{\Delta\nu_A}{\nu_A} = \kappa_A^{(i)}\varphi^i$$

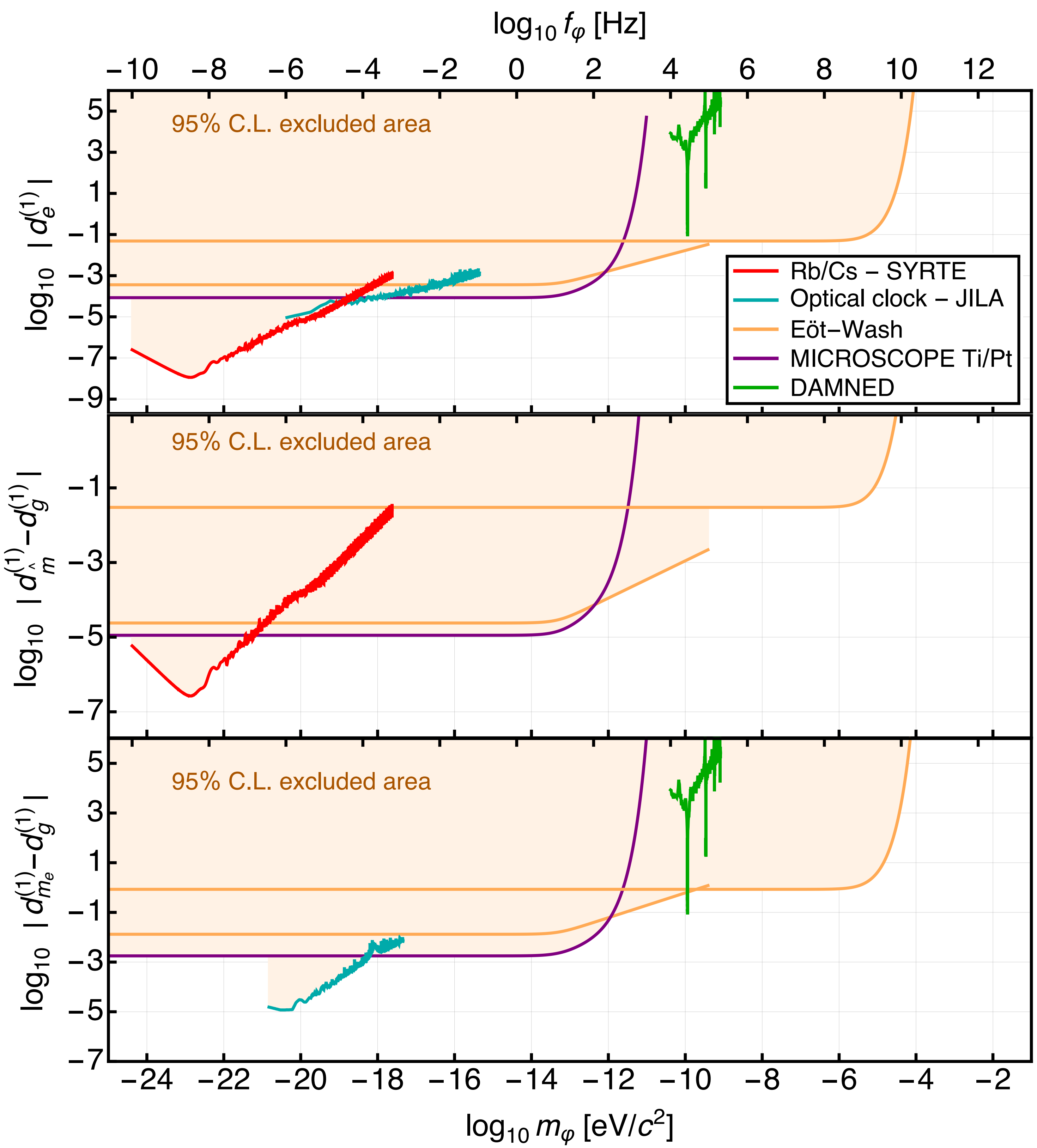
Oscillations of the scalar field

- Main advantage: explored frequency range ~ kHz-MHz while standard clocks are limited to 100 mHz
- Oscillations of: (i) the output cavity frequency, (ii) the refractive index of the fibre and (iii) the length of the finer
- First experiment built @SYRTE: no significant periodic signal is detected (Lomb Scargle analysis)

see Savalle et al, PRL 2021

Constraints on the linear couplings

Assuming the DM density to be constant over the whole Solar System (0.4 GeV/cm³)



Update from Hees et al, PRD, 2018

Results from:

- Rb/Cs: Hees et al, PRL, 2016
- JILA: Kennedy et al, PRL, 2020
- Eöt-Wash: Wagner et al, CQG, 2012
- MICROSCOPE: Bergé et al, PRL, 2018
- DAMNED: Savalle et al, PRL 2021

Quadratic coupling exhibits a richer (more complex) phenomenology.
More info in Hees et al, PRD, 2018

Quantum sensors have recently provided some of the best constraints on some DM candidates although they have been developed for other purposes (TAI, chronometric geodesy, …)

- Fiber comparison of clocks located around UK, Germany, France has also provided constraints on some DM models

see Roberts et al, N. J. Of Physics, 2020 and also the talk from B. Bertrand for a description of those DM models

- Current on-going project: how to use such devices to search for axions? PhD thesis of J. Gué

The gravitational redshift is a consequence of the Equivalence Principle

- compare the frequency of 2 clocks located in different gravitational potentials

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

see C. Will, LRR, 2014

- In 2014, two Galileo S/C have been launched on wrong eccentric orbits
- Useful to measure the gravitational redshift signal

see P. Delva et al, CQG 2015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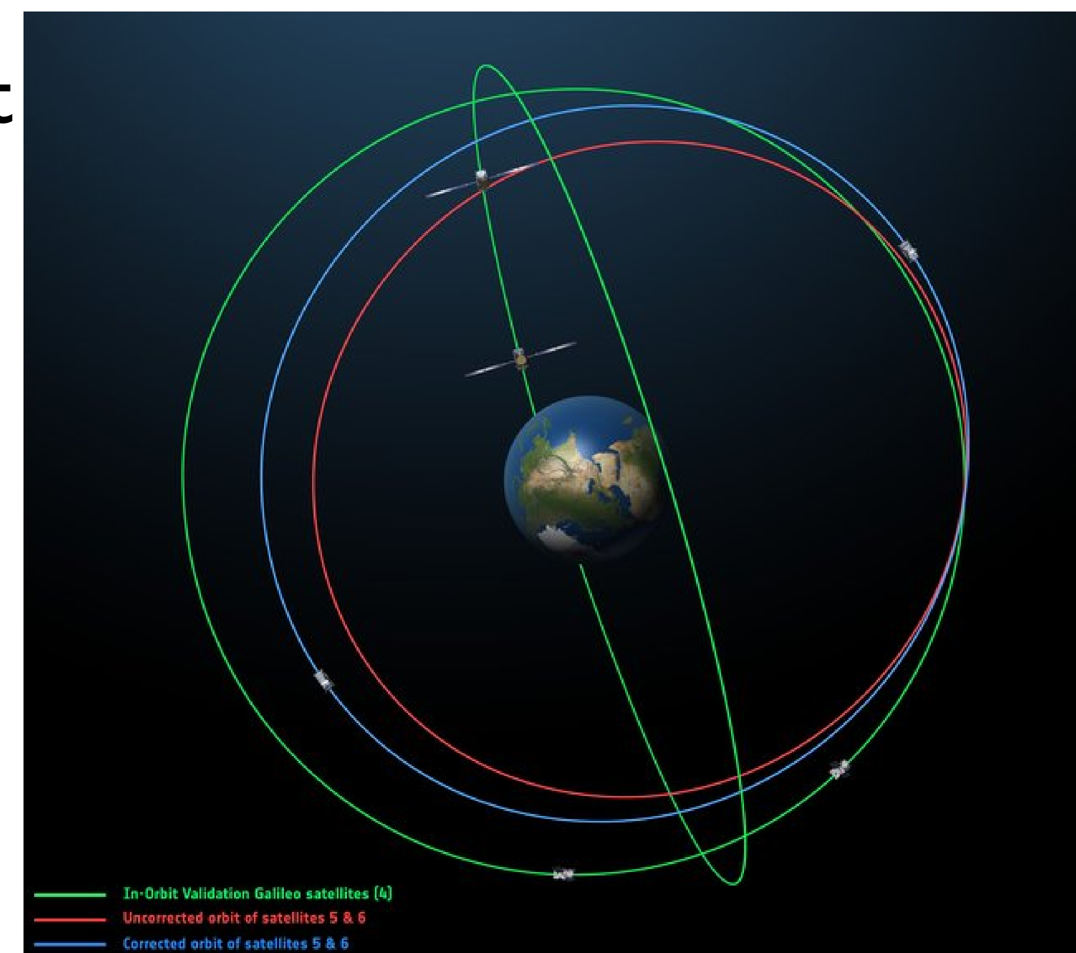
NATURE | NEWS

Wayward satellites repurposed to test general relativity

Scientists will use wonky orbit to test Einstein's theories.

Elizabeth Gibney

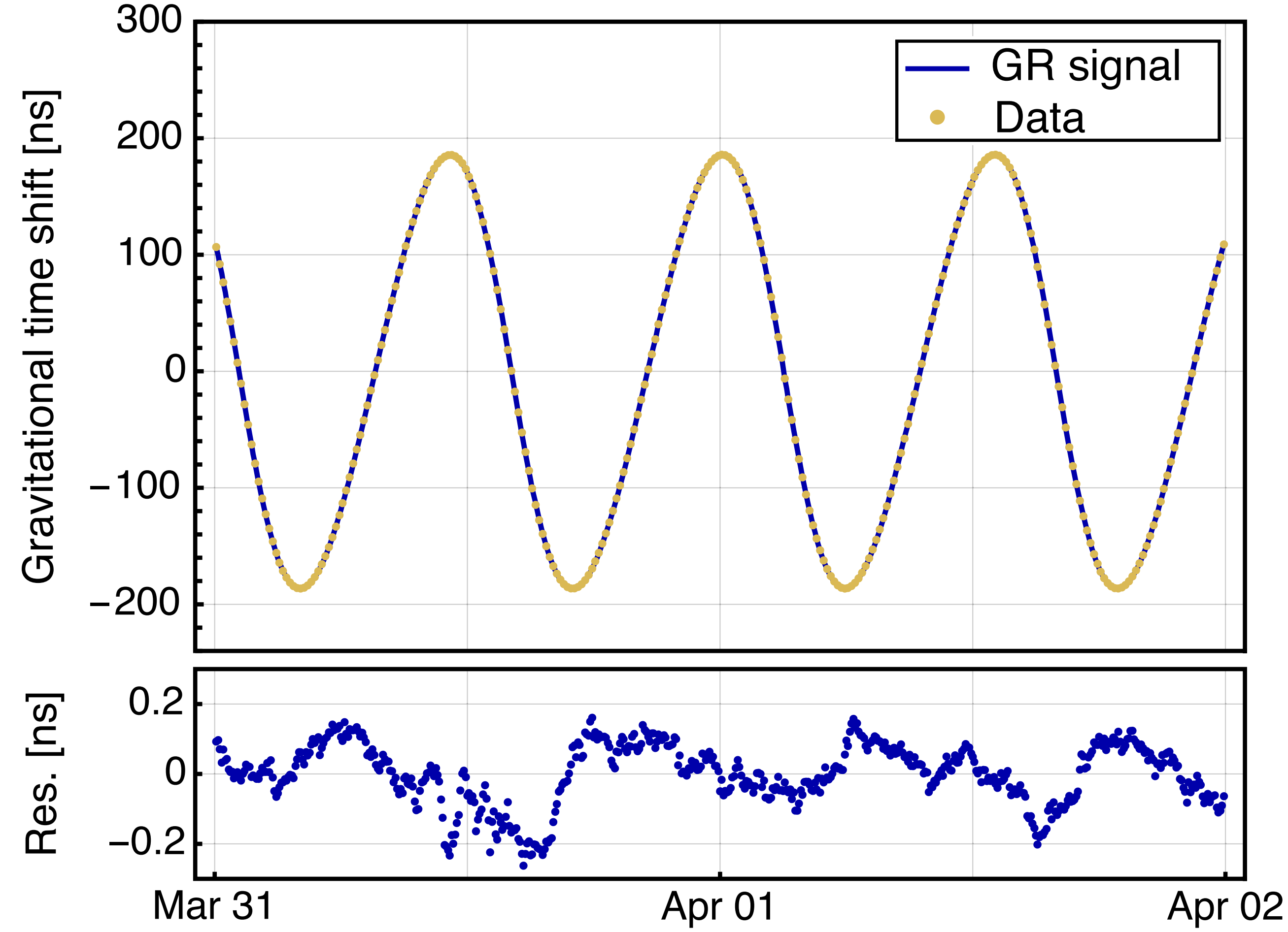
12 November 2015



Galileo satellites provide the best current measurement of the gravitational redshift

- The orbit eccentricity induces a periodic modulation of the signal
- Use of 3 years of clock bias data (2015-2018) to search for this modulation
- Systematics have been estimated using a dedicated campaign of SLR measurements
- The best measurement of the gravitational redshift

$$\alpha_{\mathrm{redshift}} = (0.19 \pm 2.48) \times 10^{-5}$$



See Delva et al, PRL, 2018 and Herrman et al, PRL 2018

GNSS measurements provide the best measurements of the gravitational redshift

- GNSS measurements are also used to search for some Dark Matter candidates

see the talk from B. Bertrand

Tests of the gravitational dynamics

- The Einstein Equivalence Principle stipulates that space-time geometry governs motion of bodies, etc…
- Second building block of General Relativity: the Einstein field equations describe how space-time curvature is generated by Matter/Energy

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Standard tests: orbital dynamics (advance of periastron), light propagation (deflection, time delay), dynamics of spinning bodies (Gravity Probe B)

see Will, LRR, 2014

- Two phenomenological frameworks widely used so far to test the Einstein field equations: the parametrized post-Newtonian (PPN) and the fifth force formalisms

see Will, LRR, 2014

A breaking of Lorentz symmetry from a fundamental unified theory can lead to a modification of the Einstein field equations

- like e.g.: strings, noncommutative space-time, loop quan. theory
- General framework to study Lorentz violation:
  Standard-Model Extension (SME)

developed by Kostelecky and collaborators in the 90s

- SME is an effective field theory developed from a Lagrangian

$$\mathcal{L} = \underbrace{\mathcal{L}_{\rm SM}}_{\text{standard model}} + \underbrace{\mathcal{L}_{\rm GR}}_{\text{General Relativity}} + \underbrace{\mathcal{L}_{\rm LV}}_{\text{All possible Lorentz violating terms constructed from SM \& GR fields and background coefficients}}$$

The Standard Model Extension predicts deviations in the gravitational sector

- lowest order (minimal SME):
  - 9 Lorentz-violating coefficients: $\bar{s}_{\mu\nu}$ impacts orbital dynamics, GW propagation, light propagation
    See Bailey, PRD, 2006
  - coefficients that break the EEP/UFF: $\bar{a}_\mu$
    See Kostelecky and Tasson, PRD, 2011
- Next-to-leading order: K_{ijkl} coefficients. Violation of CPT symmetry. Velocity-dependent signature on orbital dynamics (unusual)
  See Bailey and Havert, PRD, 2017
- searches for signatures from a breaking of Lorentz symmetry have been done using pulsars, VLBI, LLR, atomic gravimeters, GW, …

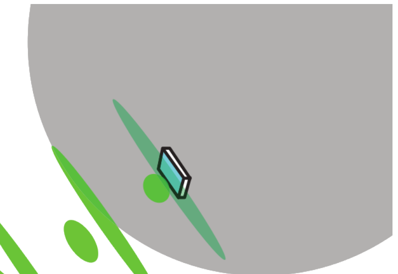
For a review, see Hees et al, Universe, 2015

Lunar Laser Ranging in a nutshell

A. Bourgoin, et al, PRL, 2016, PRL 2017 and PRD 2021

5 LLR stations :

- McDonald 2.7*m*, MLRS1, MLRS2 (Texas)
- Grasse Yag, Rubis, MeO (France)
- Haleakala (Hawaii)
- Matera (Italie)
- Apache-point (Texas)



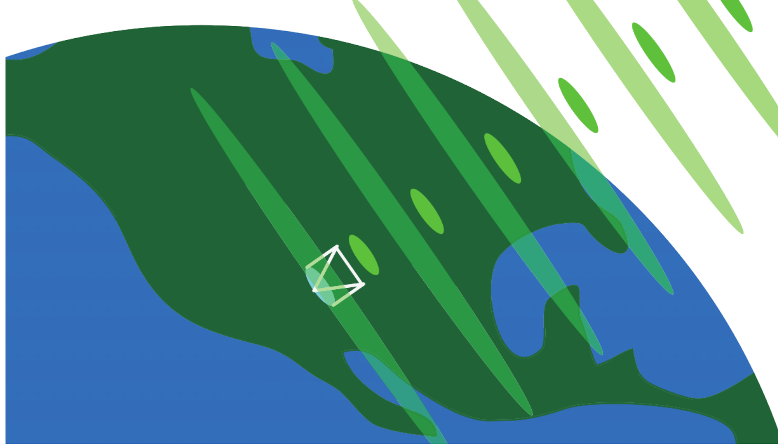
Only 1 photon
over 10^9 is reflected

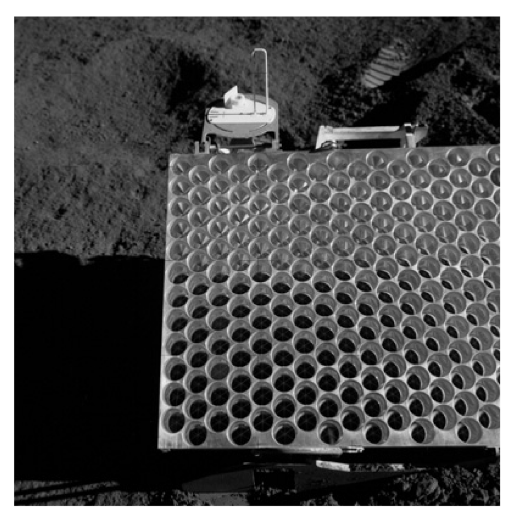
5 retroreflectors :

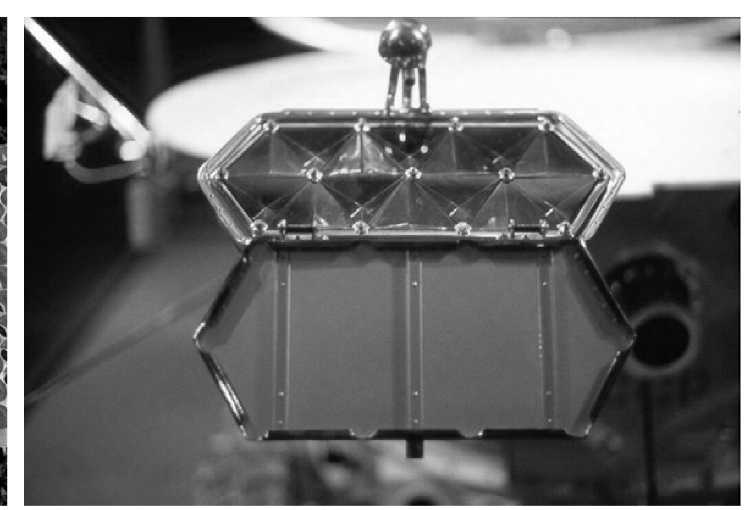
- Apollo XI
- Apollo XIV
- Apollo XV
- Lunokhod 1
- Lunokhod 2

1 pulse $\simeq 0.2ns$
pulse separation $\simeq 2.9ns$

1 pulse contains
10^{18} photons







LLR residuals ~ 5cm

Courtesy to Adrien Bourgoin for this slide

LLR provides one of the best test of LV

A. Bourgoin, et al, PRL, 2016, PRL 2017 and PRD 2021

- Full numerical integration of the SME eq. of motion (and partials) for the first time + time delay
- ~ 21 000 normal points, covering 45 years
- Two analyses: one for $\bar{s}_{\mu\nu}$ and $\bar{a}_{\mu}$ and one for K_{ijkl}
- First result: 6 independent combinations of $\bar{s}_{\mu\nu}$ and $\bar{a}_{\mu}$ are constrained

$$
\begin{aligned}
\bar{s}^1 &= \bar{s}^{XY},\\
\bar{s}^2 &= \bar{s}^{XZ},\\
\bar{s}^3 &= \bar{s}^{XX} - \bar{s}^{YY},\\
\bar{s}^4 &= 0.35\bar{s}^{XX} + 0.35\bar{s}^{YY} - 0.70\bar{s}^{ZZ} - 0.94\bar{s}^{YZ},\\
\bar{s}^5 &= -0.62\bar{s}^{TX} + 0.78\alpha(\bar{a}^{e+p}_{\mathrm{eff}})^X + 0.79\alpha(\bar{a}^{n}_{\mathrm{eff}})^X,\\
\bar{s}^6 &= 0.93\bar{s}^{TY} + 0.34\bar{s}^{TZ} - 0.10\alpha(\bar{a}^{e+p}_{\mathrm{eff}})^Y - 0.10\alpha(\bar{a}^{n}_{\mathrm{eff}})\\
&\quad - 0.044\alpha(\bar{a}^{e+p}_{\mathrm{eff}})^Z - 0.044\alpha(\bar{a}^{n}_{\mathrm{eff}})^Z.
\end{aligned}
$$

SME	Constraints
$\bar{s}^1$	$(-0.5 \pm 3.6) \times 10^{-12}$
$\bar{s}^2$	$(+2.1 \pm 3.0) \times 10^{-12}$
$\bar{s}^3$	$(+0.2 \pm 1.1) \times 10^{-11}$
$\bar{s}^4$	$(+3.0 \pm 3.1) \times 10^{-12}$
$\bar{s}^5$	$(-1.4 \pm 1.7) \times 10^{-8}$
$\bar{s}^6$	$(-6.6 \pm 9.4) \times 10^{-9}$

No signature from a Lorentz symmetry breaking

Best constraint for several of these SME coefficients

LLR provides one of the best test of LV

- Second result: 15 independent K_{ijkl} which parametrises the lowest order of a breaking of both Lorentz and CPT symmetries

Canonical	Value and uncertainties (m)
K_{XXXY}	$(+0.7 \pm 0.4 \pm 2.9) \times 10^3$
K_{XXXZ}	$(+0.8 \pm 0.9 \pm 5.9) \times 10^3$
K_{XXYY}	$(-0.4 \pm 1.3 \pm 8.4) \times 10^3$
K_{XXYZ}	$(+0.5 \pm 0.2 \pm 1.6) \times 10^4$
K_{XXZZ}	$(-1.9 \pm 0.6 \pm 4.1) \times 10^4$
K_{XYYY}	$(-0.7 \pm 0.3 \pm 1.2) \times 10^4$
K_{XYYZ}	$(+4.6 \pm 1.6 \pm 6.9) \times 10^3$
K_{XYZZ}	$(-0.2 \pm 0.8 \pm 4.1) \times 10^3$
K_{XZZZ}	$(+1.2 \pm 0.3 \pm 1.3) \times 10^4$
K_{YXXZ}	$(+0.1 \pm 0.3 \pm 2.3) \times 10^4$
K_{YXYZ}	$(-4.7 \pm 0.8 \pm 4.0) \times 10^3$
K_{YXZZ}	$(-1.6 \pm 0.5 \pm 2.4) \times 10^3$
K_{YYYZ}	$(+0.9 \pm 0.3 \pm 1.8) \times 10^4$
K_{YYZZ}	$(-1.5 \pm 0.5 \pm 3.4) \times 10^4$
K_{YZZZ}	$(-1.2 \pm 0.8 \pm 5.1) \times 10^4$

- 3 orders of magnitude improvement wrt pulsars: large number of data that helps to decorrelate the 15 coefficients

- Combined analysis with other probes (pulsars, Lageos, planetary ephemerides) can help to reduce correlations

No signature from a CPT symmetry breaking

A. Bourgoin, et al, PRD 2021

MICROSCOPE provides also constraints on Lorentz violation

- MICROSCOPE: dedicated mission to test the UFF between Pt/Ti in space @10^{-15} (first published result @10^{-14})

Touboul et al, PRL, 2018


© CNES - Juin 2003/Illust. D. Ducros

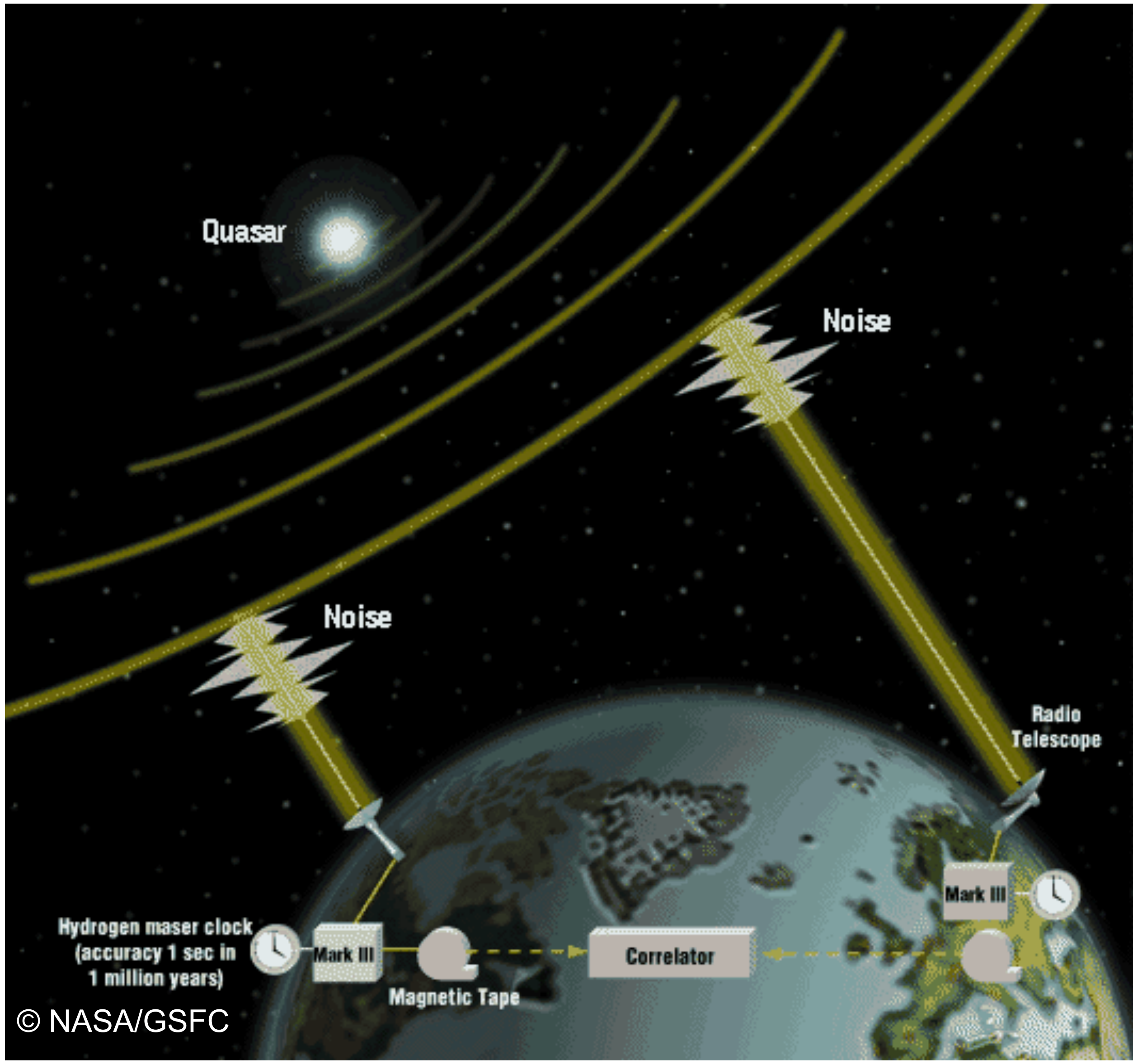
- Dedicated talk on MICROSCOPE on Thursday
- Alternative data analysis pipeline developed @SYRTE (H. Pihan Le-Bars thesis): confirmation of the consortium results with independent method + search for Lorentz violations $\bar{a}_\mu$
- The LV signature: annual modulation of the UFF violation
- Best constraints on some of the SME violating parameters + combinations complementary to LLR results

Coefficient	Value and uncertainties [GeV]
$\alpha(\bar{a}^{(\text{n-e-p})}_{\text{eff}})_T$	$(6.3 \pm 12)\,(10)(6.0) \times 10^{-14}$
$\alpha(\bar{a}^{(\text{n-e-p})}_{\text{eff}})_X$	$(0.81 \pm 1.7)\,(1.4)(0.98) \times 10^{-9}$
$\alpha(\bar{a}^{(\text{n-e-p})}_{\text{eff}})_Y$	$(0.67 \pm 3.1)\,(1.4)(2.7) \times 10^{-7}$
$\alpha(\bar{a}^{(\text{n-e-p})}_{\text{eff}})_Z$	$(-1.55 \pm 7.1)\,(3.2)(6.3) \times 10^{-7}$

Pihan Le-Bars et al, PRL, 2019

SME and VLBI

- Observations of distant quasar from 2 stations (measure of a time delay determined through a correlator)



- Uses:

  - Earth rotation

  - light deflection (already used in PPN formalism)

    see S. Lambert and C. Le Poncin-Lafitte, A&A, 2009 and 2011

- Roughly 10^7 observations available between ~ 1980 and today

- Current accuracy of VLBI catalogues ~ 0.04 mas (limitation from tropo)

SME and VLBI

- Lorentz symmetry violations impact light propagation

see Q. Bailey, PRD 2009 and R. Tso and Q. Bailey, PRD, 2011

- VLBI time delay in SME (leading term here)

$$\Delta\tau_{(\mathrm{grav})} = 2\frac{\widetilde{GM}}{c^3}(1 - \frac{2}{3}\bar{s}^{TT})\ln\frac{r_1 + \boldsymbol{k}.\boldsymbol{x}_1}{r_2 + \boldsymbol{k}.\boldsymbol{x}_2} + \frac{2}{3}\frac{\widetilde{GM}}{c^3}\bar{s}^{TT}(\boldsymbol{n}_2.\boldsymbol{k} - \boldsymbol{n}_1.\boldsymbol{k})$$

implemented in geodetic VLBI data reduction software (Calc/Eph)

- Full data reduction (no postfit analysis)

$$\bar{s}^{TT} = (-5 \pm 8) \times 10^{-5}$$

see Le Poncin-Lafitte et al, PRD, 2016

- Improvement by 1 order of magnitude wrt previous constraint

Rq.: in SME, this parameter controls the speed of gravitation and is now better constrained with GW (sensitive to different systematics)

see Abbott et al, ApJ Letters, 2017

Lunar Laser Ranging, the MICROSCOPE space-mission and Very Long Baseline Interferometry provide some of the best constraints on Lorentz and CPT symmetry violation

Conclusion

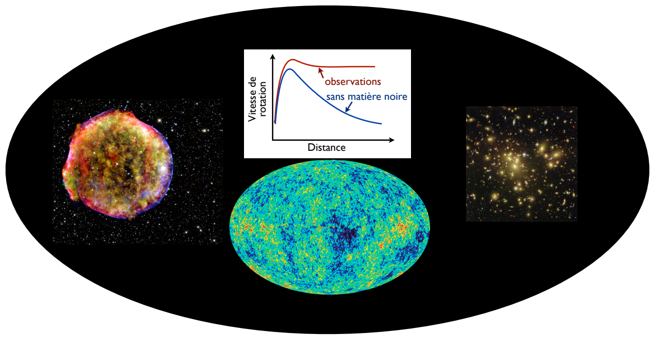
- GR is likely not the ultimate theory of gravitation
- Challenge

  - theory: construct alternative theories
    1) not suffering from theoretical pathology
    2) able to explain a wide set of observations at different scales
    3) that would solve some of the theoretical problems (quantum gravity, DM/DE…)

  - observations:
    1) constraint a wider and wider class of alternative theories of gravitation and DM candidates
    2) searching for "tiny" deviations (in Solar System) or searching for signatures not considered so far

Geodetic measurements are very helpful in this context

Thank you for your attention



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(SNIa, CMB, structure formation, galactic dynamics, …)

Quantum Gravity

Unification

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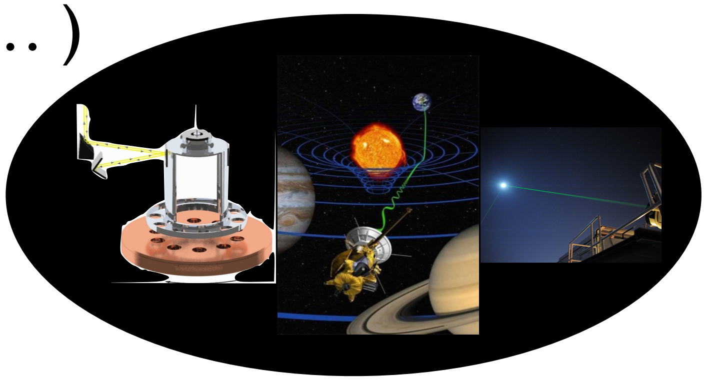
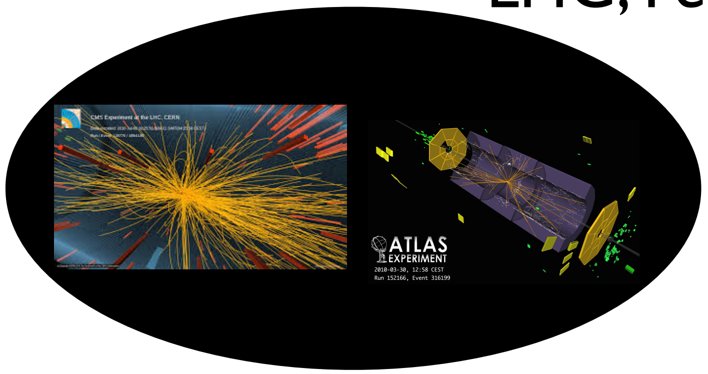
Local physics

(Solar System, lab tests, GNSS, …)



High energy

(particle physics: CERN-LHC, Fermilab, DESY, …)



Picture inspired by Altschul et al, Adv, in Space Res. 55, 501, 2015