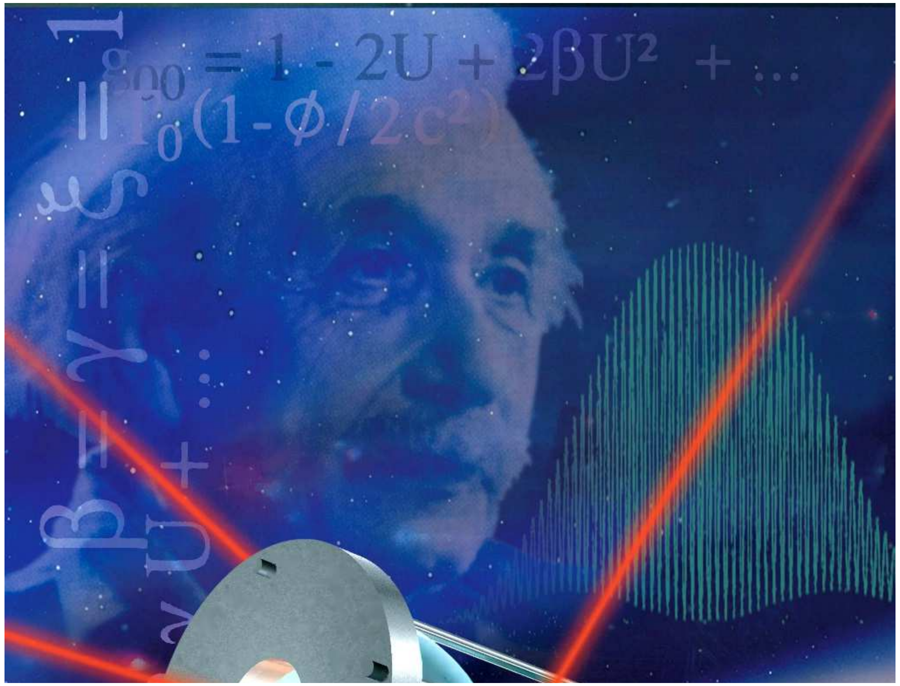
Exploring the Foundations of the Physical Universe with Space Tests of the Equivalence Principle



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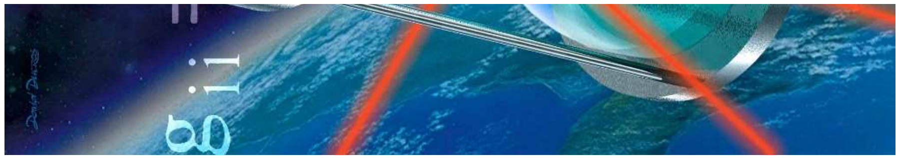

l'Observatoire de Paris — SYRTE

Systèmes de Référence Temps-Espace

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Contents

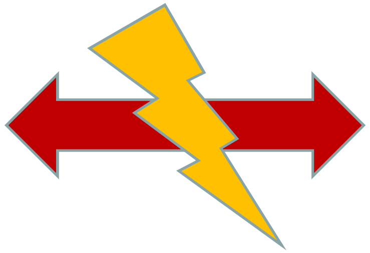
- Scientific Motivation.
- The Einstein Equivalence Principle (EEP).
- The role of EEP in the context of modern physics.
- Why would the EEP be violated ?
- Experimental tests of the universality of free fall (UFF) on ground and in space.
- Why go to space ?

- A space mission to test UFF at 10^{-17} or below:
  - An advanced MICROSCOPE mission
  - An atom interferometry mission

- Conclusion

Scientific Motivation: open questions

Quantum Field Theory (QFT)
Standard Model of Particle Physics (SM)



General Relativity (GR)
Concordance Model of Cosmology (Λ – CDM)

- Unification of GR with the other interactions of the SM ?
- Accounting for Dark energy (DE) and dark matter (DM) in the SM ?
- Why is the vacuum energy density expected from the SM 40-120 orders of magnitude larger than observed (DE)?

Most proposed answers to these questions involve new fields that have no good reason to be universally coupled to the SM-fields

$\Rightarrow$ Violation of the Einstein Equivalence Principle

The Einstein Equivalence Principle (EEP)

- It's best known manifestation is the Universality of Free Fall (UFF).
- Other aspects are Local Lorentz Invariance and Local Position Invariance – not discussed here.

Universal coupling

⇕

EEP is satisfied

⇕

Metric theory of gravitation

⇕

Gravitation = curvature of space-time

FIG. 1: *In the presence of the Grand Duke, Galileo Galilei performs the experiment of falling bodies from the Tower of Pisa.* Fresco by Luigi Catani, 1816 (Firenze, Palazzo Pitti, Quartiere Borbonico o Nuovo Palatino, sala 15). Whilst the historical veracity of this particular experiment is debatable, the fact that Galileo was one of the first scientists to carry out UFF tests is well established.

Why would the EEP be violated ?

- It is not a fundamental symmetry (like e.g. gauge invariance in the SM). Einstein himself called it at first "*the hypothesis of equivalence*".
- It makes gravitation so different from all other SM interactions (universal coupling, not a field over space-time but a curvature of space-time itself).
- Any new field (DM, DE, unification, brane scenarios, etc…) is likely to lead to EEP violation $\rightarrow$ most theories with such fields need some fine tuning to avoid existing EEP constraints. E.g. moduli fields in string theory need to be rendered massive (short range) or stabilized by cosmological considerations.
- Discovery of Higgs boson has lent credibility to fundamental scalar fields, additionally to possible new spin-1 fields.
- Quantum states of matter might not follow "classical" EEP.

So the natural question is not "why should the EEP be violated?" but rather "why haven't we seen a violation yet, and to what extent does it hold?"

Experimental tests of UFF on ground and in space

$$\eta_{AB} = 2\,\frac{a_A - a_B}{a_A + a_B}$$

Class	Elements	η	Year	Comments
Classical	Be - Ti	2×10^{-13}	2008	Torsion balance
	Pt - Ti	1×10^{-14}	2017	MICROSCOPE first results
	Pt - Ti	(10^{-15})	2019+	MICROSCOPE full data
	$M_A - M_B$	10^{-17}	2035+	Adv. MICROSCOPE, macroscopic masses M_i TBD
Hybrid	^{133}Cs - CC	7×10^{-9}	2001	AI and macroscopic corner cube (CC)
	^{87}Rb - CC	7×10^{-9}	2010	
	$At_A - M_B$	10^{-15}	2035+	Adv. MICROSCOPE, atomic species At_A TBD
Quantum	^{39}K - ^{87}Rb	5×10^{-7}	2014	different elements
	^{87}Sr - ^{88}Sr	2×10^{-7}	2014	same element, fermion vs. boson
	^{85}Rb - ^{87}Rb	$3 \times 10^{-8}(10^{-10})$	2015(19)	same element, different isotopes
	^{87}Rb - ^{87}Rb	1×10^{-9}	2017	different internal quantum superpositions
	^{85}Rb - ^{87}Rb	(10^{-13})	2020+	$\geq$ 10 m towers
	^{170}Yb - ^{87}Rb	(10^{-13})	2020+	
	^{41}K - ^{87}Rb	10^{-17}	2035+	Atom Interferometry mission
Antimatter	$\overline{\text{H}}$ - H	(10^{-2})	2020+	under construction at CERN

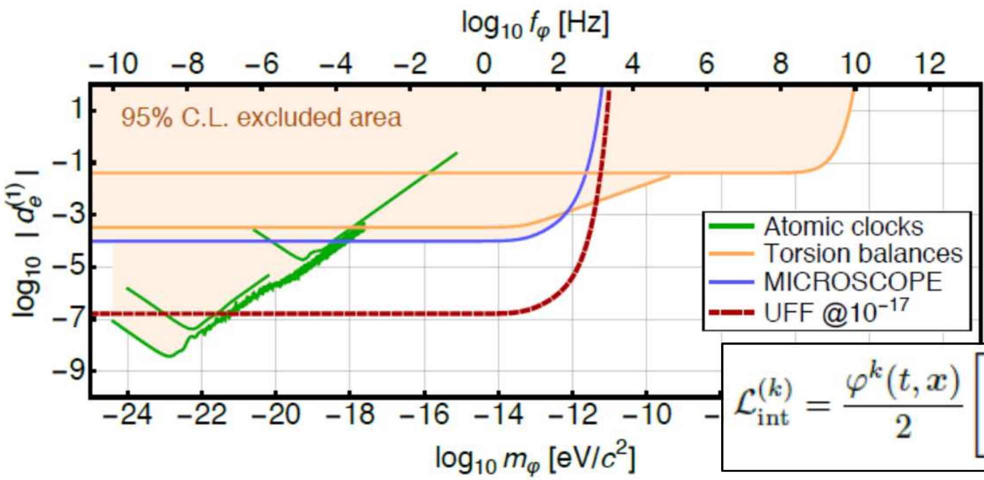
Why go to space ?

- Space offers long free fall times and a quiet, well controlled environment as convincingly demonstrated by the MICROSCOPE and LISA-Pathfinder missions.
- Ground experiments are ultimately limited by local gravity gradients and uncertainties in the positioning of the test masses. Not the case in space as demonstrated by MICROSCOPE ($\eta \sim 10^{-18}$ control).
- Europe has a clear lead in the field (MICROSCOPE, LISA-Pathfinder, ACES/PHARAO).
- Space-accelerometers (classical or cold-atoms) offer rich technological heritage for applied fields like gravity field recovery (e.g. GRACE, GOCE, GRACE-FO), navigation, planetary and lunar exploration.

Testing UFF in space at 10^{-17} or below

- Several missions for UFF tests have been proposed and studied (STEP, GG, POEM, GAUGE, STE-QUEST).
- MICROSCOPE (2016-2018), provides the best test of UFF at present (10^{-14}). Analysis of all data + systematics is expected to allow searching for a UFF violation down to 10^{-15}.
- MICROSCOPE and LISA-Pathfinder have convincingly demonstrated platform inertial control (drag-free) compatible with future UFF tests.
- Europe is world leading in this field.

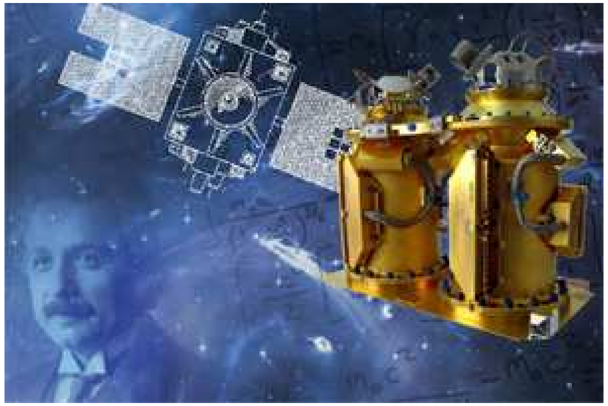
⇒ It is time for pushing the limits of knowledge further, towards our first glimpse of physics beyond the standard model and general relativity.



E.g: Scalar dark matter coupling to electromagnetism with coupling constant $d_e^{(1)}$

$$\mathcal{L}_{\text{int}}^{(k)} = \frac{\varphi^k(t,x)}{2}\left[\frac{d_e^{(k)}}{4e^2}F^2 - \frac{d_g^{(k)}\beta_3}{2g_3}\left(F^A\right)^2 - \sum_{i=e,u,d}\left(d_{m_i}^{(k)} + \gamma_{m_i} d_g^{(k)}\right) m_i \bar{\psi}_i \psi_i\right]$$

An advanced MICROSCOPE mission improving to 10^{-17} (factor 100)



- Take full advantage of the experience gathered with MICROSCOPE.
- Assume a similar orbit to Microscope (710 km, circular)

Main changes:

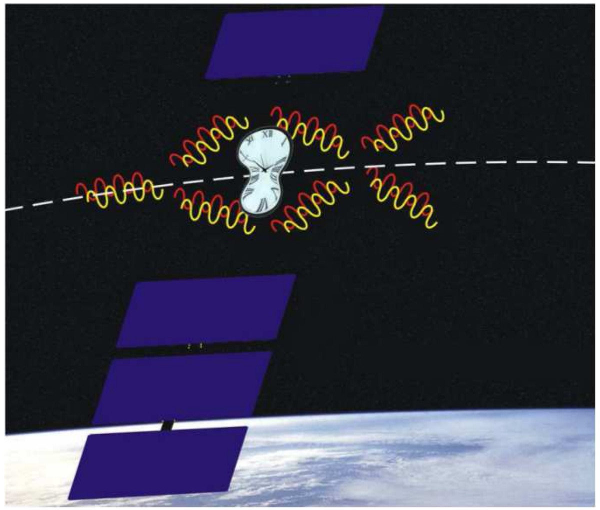
- Three concentric test masses of different composition.
- Hybridization with cold-atoms for control of low-frequency drifts.
- UV discharge lamps (LISA-PF heritage) instead of gold wire.
- Laser interferometry to reduce sensing noise (LISA-PF heritage).

Study is in early stages, but we expect this concept to fit into a M-class or smaller envelope, or a mission of opportunity.

An atom-interferometric space test of UFF at $\leq 10^{-17}$

- Based on STE-QUEST proposals (M3, M4).
- Double atom interferometer with Rb and K “test masses” in non-classical states (quantum superpositions).
- Optimized for UFF test. Assume 700 km circular orbit.
- Apply recent results on controlling gravity gradient shifts by offsetting laser frequencies, thus relaxing atom positioning requirements by factor >100.

$\Rightarrow$ Reaches 10^{-17} target after 18 months of operation.

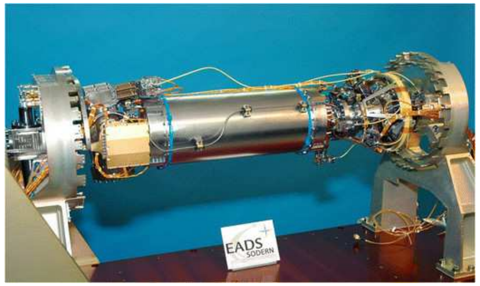


There has been tremendous technology development over the last decade to ready atom-interferometry for space.

Such a mission would also be a stepping stone for future more ambitious ones (see e.g. next presentation).

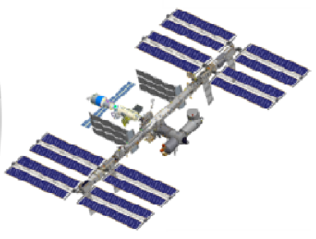
Cold-atom technology for space

ICE - CNES: Rb/K atom interferometry in 0-g plane.

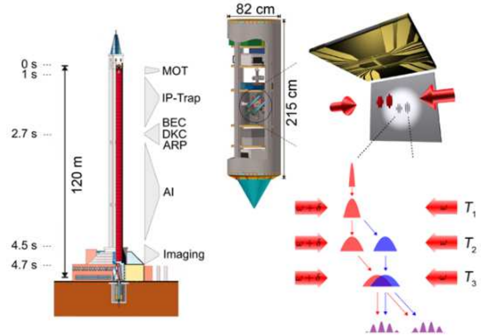


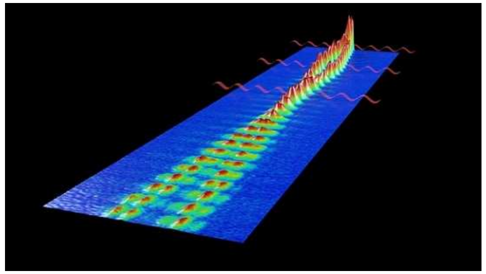
ACES – CNES/ESA: Cold-atom Cs clock on ISS planned for launch in 2021.

MAIUS - DLR: Sounding rocket mission, first BEC (^{87}Rb) in space in early 2017. Successor launches with ^{87}Rb/$^{41/39}$K planned in 2021.



CAL/BECCAL – NASA/DLR: Ultra-cold atom lab on ISS, since 2018.





QUANTUS – DLR: Bose-Einstein condensates interferometry in ZARM droptower (since 2004). Atom chip-based machine capable of operating with up to 50 g accelerations.

Conclusion

- Physics today poses serious questions at the interface of the SM and GR, even more so in the context of Λ-CDM.
- Most proposed answers include new fields that are likely to lead to a violation of the EEP.
- Tests of the EEP are our best chance of a glimpse of the new physics beyond GR and the SM, in a controlled and repeatable way.
- Ground experiments are limited by the Earth's gravitational environment, so the answer will come from space.
- Europe has clearly a leading role in the field (MICROSCOPE, LISA-Pathfinder) and should build on that.
- The involved technologies have strong synergies with other fields e.g. Earth observation, navigation, gravitational waves.

- A M-class mission to test the EEP may well lead to a revolutionary discovery, or further constrain the space of proposed solutions to what is surely one of the major challenges in our physical universe as we understand it today.