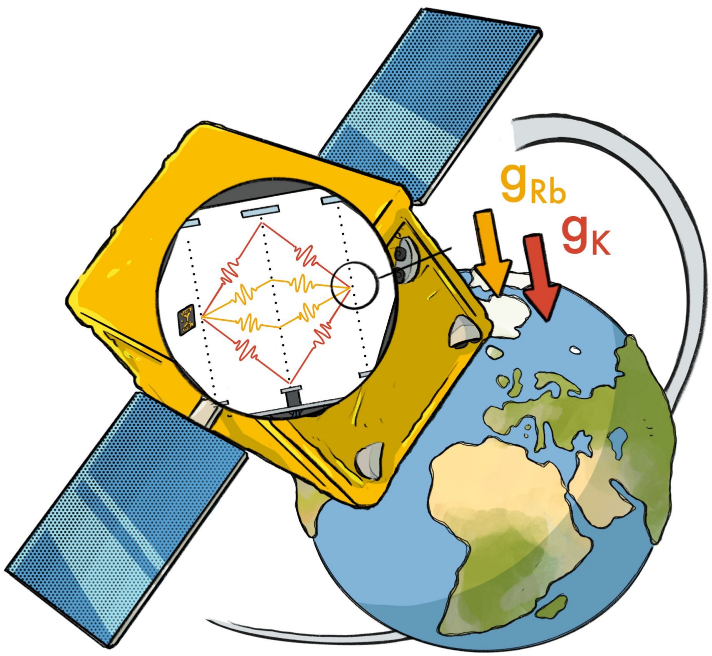
Space Time Explorer and QUantum Equivalence principle Space Test – STE-QUEST

A M-class mission proposal to test the equivalence principle at the 10^{-17} level



Credit: S. Loriani

A. Hees, SYRTE
B. Battelier, Institut d'Optique Bordeaux
R. Corgier, SYRTE
J. Gué, SYRTE
G. Métris, OCA
P. Wolf, SYRTE

TUG workshop
October 4th, 2022

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STE-QUEST is competing for the M7 ESA call

- Call for Medium Size and Fast Mission opportunity in ESA's science program (opened in December 2021)

Activity	Date
Release of the Call for an M and an F mission	13 December 2021
Registration for pre-submission briefing meeting closes	11 January 2022, 12:00 CET
Pre-submission briefing meeting	13 January 2022, 14:00 CET to 17:00 CET
Phase-1 proposal submission deadline	14 February 2022 – 12:00 (noon) CET
Phase-1 proposal assessment	February - April 2022
Phase-1 proposer notification	Mid-April 2022 (exact date TBD)
Workshops for Phase-2 proposers	End-April 2022 (exact date TBD)
Phase-2 proposal submission deadline	15 July 2022 – 12:00 (noon) CEST
Letters of Endorsement deadline	15 September 2022 – 12:00 (noon) CEST
Proposal evaluation and scientific ranking	July – October 2022
Selection of missions for study	November 2022

- STE-QUEST passed the phase 1 screening (April 2022)

- 10 proposals competing in the phase 2 selection process. 1 to 3 will be selected in November for a 3-years phase A study

- 1 selected for a launch around 2037

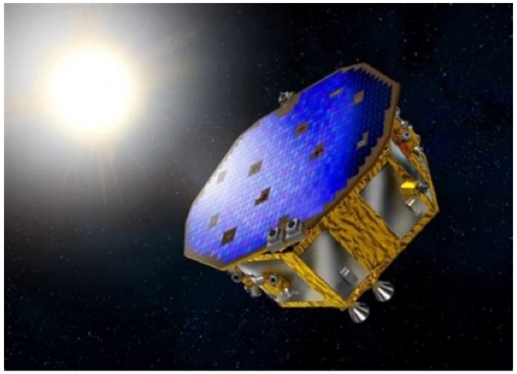
Mission concept

- Test the Equivalence Principle (Universality of Free Fall – UFF) using ^{41}Rb and ^{87}K atoms in quantum superposition
- Main goal: measure the Eötvos parameter η @10^{-17}, i.e. improve by more than 2 orders of magnitude on the recent MICROSOPE results

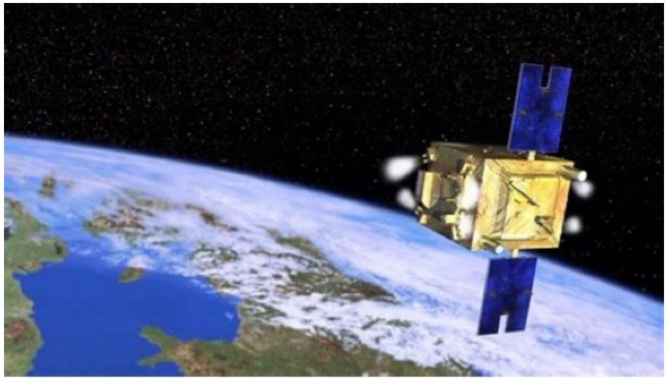
see Touboul et al, PRL 129, 121102, 2022

- Other scientific objectives: search for UltraLight Dark Matter and test of the quantum superposition principle

- Single payload S/C, Earth orbit, ~ 1400 km elevation
- Inertial attitude, drag-free, cold-gas control (GAIA, MICROSCOPE, LISA-PF)
- ^{41}Rb-^{87}K double interferometers already used on-ground and in rocket experiments (ICE, QUANTUS, MAIUS, (BEC)CAL)



LISA-PathFinder



MICROSCOPE

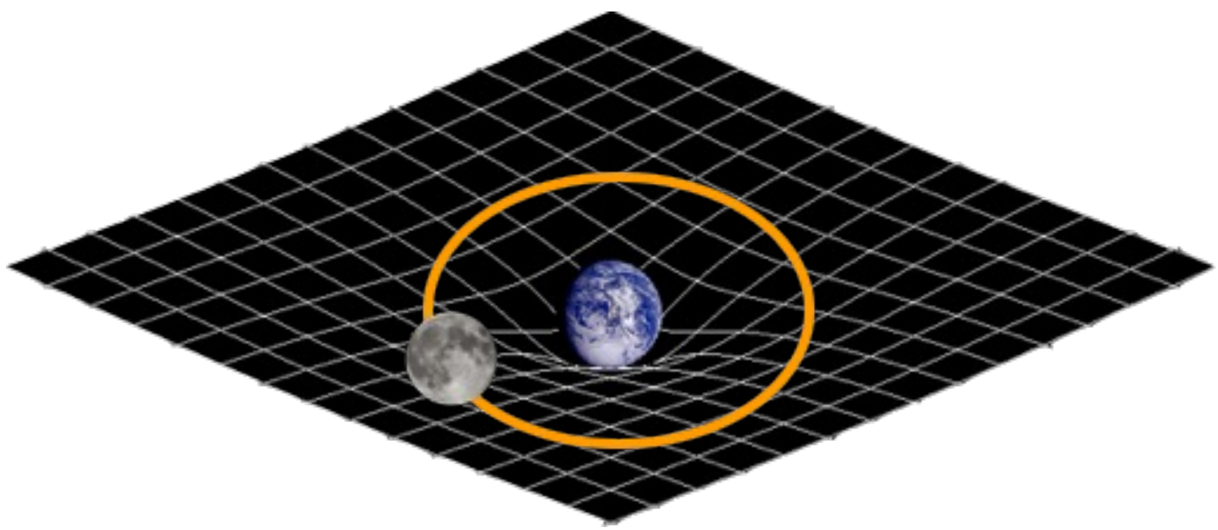
What is the Equivalence Principle?

What are the motivations to test it?

The Equivalence Principle is one of the building blocks of General Relativity

- All types of mass/energy are universally coupled to gravitation, i.e. the gravitational interaction is independent of composition, charge, flavor, etc… Very different from all other known interactions!

- It makes gravitation universal and it allows gravitation to be described as a geometrical phenomenon: space-time curvature



- But it's a heuristic hypothesis based on observations (bodies fall with the same acceleration in a gravitational potential) not based on any underlying theoretical principle (fundamental symmetry)

Why would the Equivalence Principle be violated?

1. It does not rely on any fundamental theoretical principle (like e.g. the gauge principle in the Standard Model) and the universal character of gravitation seems anomalous compared to the other interactions (does not rely on any internal charge). Why is gravitation so different?

2. Several models of Dark Matter and Dark Energy explicitly break the EP: new fields that are expected to non-universally couple to SM

3. Several unification scenarios (strings, branes, …) lead to the introduction of new fields that are expected to break the EP

4. Some attempts to develop a quantum theory of gravitation lead to a breaking of Lorentz symmetry, one facet of the EP

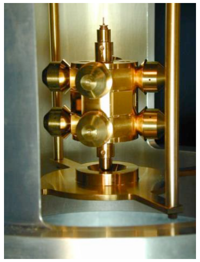
5. A breaking of the EP can provide an explanation to the values of some arbitrary constants of the SM

For a detailed discussion, see T. Damour, Class. And Quantum Grav., 2012

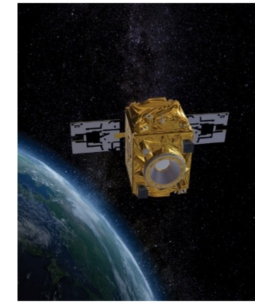
So the natural question is not “why should the EEP be violated?” but rather “why haven't we seen a violation yet, and to what extent does it hold?”

For a detailed discussion, see T. Damour, Class. And Quantum Grav., 2012

The Universality of Free Fall is currently tested at the level of 10^{-15}



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

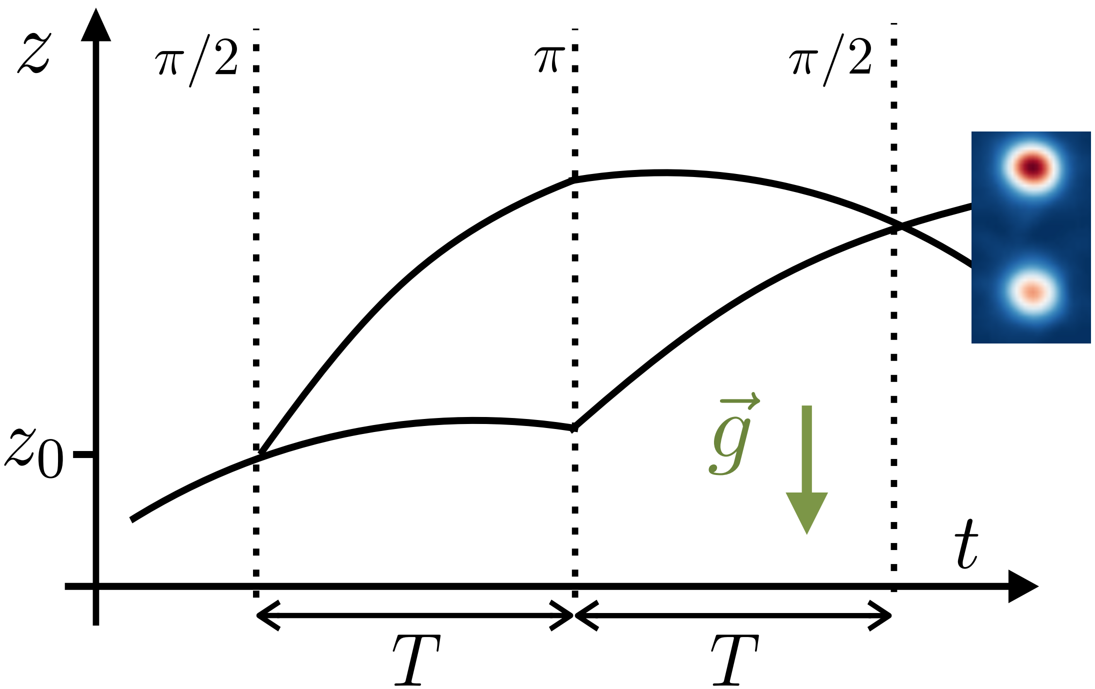


Class	Elements	η	Year [ref]	Comments
Classical	Be - Ti	2×10^{-13}	2008	Torsion balance
	Pt - Ti	1×10^{-14}	2017	MICROSCOPE first results
	Pt - Ti	2.7×10^{-15}	2022+	MICROSCOPE full data
Hybrid	^{133}Cs - CC	7×10^{-9}	2001	Atom Interferometry
	^{87}Rb - CC	7×10^{-9}	2010	and macroscopic corner cube (CC)
Quantum	^{39}K - ^{87}Rb	3×10^{-7}	2020	different elements
	^{87}Sr - ^{88}Sr	2×10^{-7}	2014	same element, fermion vs. boson
	^{85}Rb - ^{87}Rb	3×10^{-8}	2015	same element, different isotopes
	^{85}Rb - ^{87}Rb	3.8×10^{-12}	2020	10 m tower
	^{41}K - ^{87}Rb	(10^{-17})	2037	STE-QUEST
Antimatter	$\overline{\mathrm{H}}$ - H	(10^{-2})	2023+	under construction at CERN

- Space tests offer a longer interrogation time and quieter environment

2 orders of magnitude improvement with STE-QUEST

Atom interferometry provides a measurement of the gravitational acceleration



The measured output:

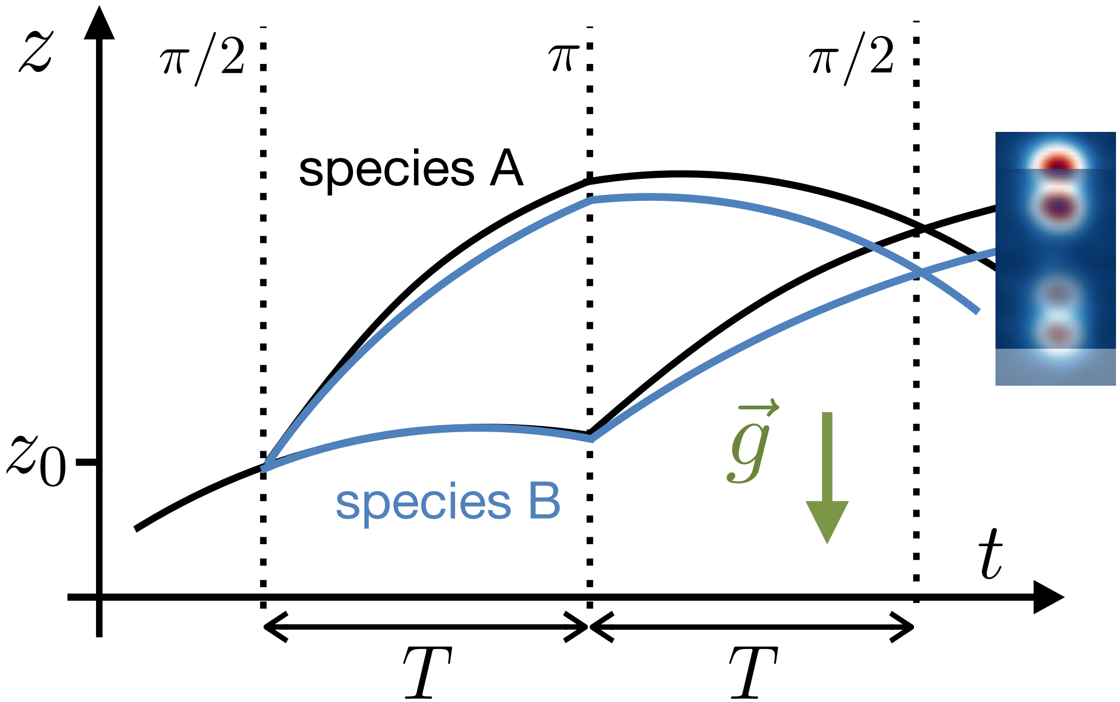
$$P \propto \cos(\Delta\phi)$$

with the phase difference

$$\Delta\phi = \overrightarrow{k_{eff}} \cdot \overrightarrow{g} T^2$$

Credit: N Gaaloul

Double Atom interferometry provides a measurement of the UFF



The measured output:

$$P \propto \cos(\Delta\phi)$$

with the phase difference

$$\Delta\phi = \overrightarrow{k_{eff}} \cdot \overrightarrow{g} T^2$$

Acceleration of each species: $a_i = \frac{\Delta\phi_i}{k_{\mathrm{eff,i}} T_i^2}$ ⟶ UFF: $\eta = 2\frac{|a_1 - a_2|}{a_1 + a_2}$

Space offers a longer interrogation time and quieter environment

Credit: N Gaaloul

M7 mission summary

PAYLOAD	
Dual Atom Interferometer	^{87}Rb vs ^{41}K differential acceleration (Δa) measurement with $\sqrt{S_a(f)} \leq 4.8 \times 10^{-13}\,\mathrm{m/s^2/\sqrt{Hz}}$. Systematics at signal frequency/phase $\leq 6.6 \times 10^{-17}\,\mathrm{m/s^2}$.
GNSS receiver	Dual-band receiver with modest performance requirements ($\approx$ 200 m).
MISSION PROFILE	
Orbit	SSO circular orbit, 1400 km altitude.
Launcher	Direct orbit injection with VEGA-C from Kourou. Launch window available all year.
Mission Duration	3 yrs with 80% science availability, including 6 months commissioning.
End of life	Solid fuel propulsion for controlled re-entry manoeuvre.
SPACECRAFT	
S/C design	Cylindrical with body mounted solar panels. STE-QUEST M3/M4 and LISA-Pathfinder (LPF) heritage.
DFACS	Drag-free and attitude control using cold-gas microthrusters/ inertial measurement unit/ star trackers. Req.: $\sqrt{S_a(f)} \leq 4.0 \times 10^{-10}\,\mathrm{m/s^2/\sqrt{Hz}}$ and $\sqrt{S_{\dot{\Omega}}(f)} \leq 3.2 \times 10^{-7}\,\mathrm{rad/s^2/\sqrt{Hz}}$ (see Tab. 3.5). MICROSCOPE and LPF heritage.
Mass	1187 kg wet mass, all margins included.
Power	1235 W average consumption, all margins included.
Communications	S/X band up/downlinks. Req.: $\leq$ 110 kbps science data in downlink.

Main Instrument: ATI

- Double species Rb-K atom interferometer.
- Standard 3-pulse atomic interferometry sequence
- Atomic shot noise limited.

Atom number N	2.5×10^6
k_{eff} for Rb	$8\pi/(780\text{ nm})$
k_{eff} for K	$8\pi/(767\text{ nm})$
Free evolution time T	25 s
Max. separation Rb	0.59 m
Max. separation K	1.27 m
Cycle time T_c	60 s
Contrast C	1
Expansion energy	10 pK
Expansion velocity $\sigma_{v,Rb}$	31 μm/s
Expansion velocity $\sigma_{v,K}$	45 μm/s
Init. pos. spread σ_r	500 μm
Init. diff. position Δr	1 μm
Init. diff. velocity Δv	0.1 μm/s
Indiv. Velocity (in S/C frame) v	1 μm/s

Table 4: *Operational parameters of the ATI.*

More relaxed requirements compared to previous STE-QUEST proposal due to the development of a new technique Gravity Gradient Cancellation which allows to significantly reduce the main noise limitation: this is why 10^{-17} is now reallistically reachable

Roura PRL2017, d'Amico PRL2017, Asenbaum PRL2018,2020, Loriani PRD2020

Preliminary study has shown that the platform requirements are realistic

- performed for Phase 2 proposal
- Evaluate impact of S/C control on the measurements (systematics) and infer platform requirement

Quantity	Constraint	Comment	μSCOPE	LPF	GRACE-FO
$\sqrt{S_a(f)}$	4.0×10^{-10} $m/s^2/\sqrt{Hz}$ in [0.01:0.5] Hz	From (15) assuming white noise	OK in (15)$^{(1)}$	OK in (15)$^{(1)}$	OK
$\langle \dot{a} \rangle_{2T}$	2.5×10^{-13} m/s^3	$\langle \dot{a} \rangle_{2T}$ = average (over 2T) of $\dot{a}$, cf. text after (15).	OK$^{(2)}$	(OK)$^{(3)}$	(OK)$^{(4)}$
Ω_{orb}	3.3×10^{-7} rad/s $^{(5)}$	Amplitude of component of Ω at orbital frequency cf. Sec. 3.4.6	OK	OK	-
$\sqrt{S_{\dot{\Omega}}(f)}$	3.2×10^{-7} rad/s$^2/\sqrt{Hz}$ in [0.01:0.5] Hz	From (17) assuming white noise	OK$^{(6)}$	OK	-
$\langle \Omega \rangle_{2T}$	5.4×10^{-7} rad/s	cf. Sec. 3.4.3	OK	OK	-
$\langle \dot{\Omega} \rangle_{2T}$	1.3×10^{-7} rad/s^2	cf. Sec. 3.4.3	OK	OK	-

Table 9: Requirements on S/C accelerations and attitude. Superscripts in brackets refer to the notes in the text. Note that the $\langle \ldots \rangle_{2T}$ constraints apply to variations at frequencies such that $2\pi f T < 1$.

The S/C requirements to reach a 10^{-17} UFF measurement are already met for existing S/C (to be refined during possible phase A study)

STE-QUEST will push the limit of fundamental physics by 2 orders of magnitude

- 2-3 orders of magnitude improvement in test of the Equivalence Principle: pushing the limit of fundamental physics into a totally unexplored region with possible groundbreaking discovery or stringent constraints for various theoretical scenarios

- There are no theoretical firm predictions at which level the EP violation is expected to arise
  but…

- several theoretical arguments make the exploration of the EP violation at this level exciting:

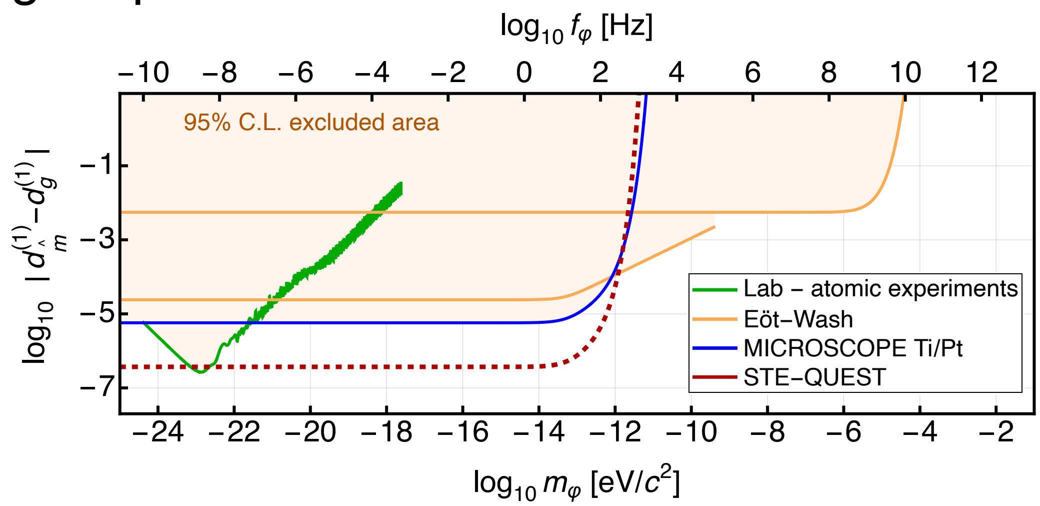
  - Dilaton least coupling principle: string inspired model, EP@10^{-12}-10^{-22}
    see e.g. Damour and Polyakov, PLB, 1994
  - Runaway dilaton (inflation): EP@ 10^{-12}-10^{-19}
    see e.g. Damour et al, PRL, 2002
    Damour and Donoghue, PRD, 2010
  - SUSY additional U(1) gauge boson EP @ 10^{-12}-10^{-16}
    see e.g. Fayet, PRD, 2018 and 2019

STE-QUEST will allow to extend then search for Ultra Light Dark Matter

- Models of light DM (m < eV), needs to be bosonic (scalar field, axion, vector field, …) motivated by the current lack of DM detection @LHC
- Observational phenomenology depends on the specific model: Yukawa 5th force, oscillatory behavior of the constants of Nature, screening/scalarization mechanism, ….

see e.g. Hees et al, PRD, 2018

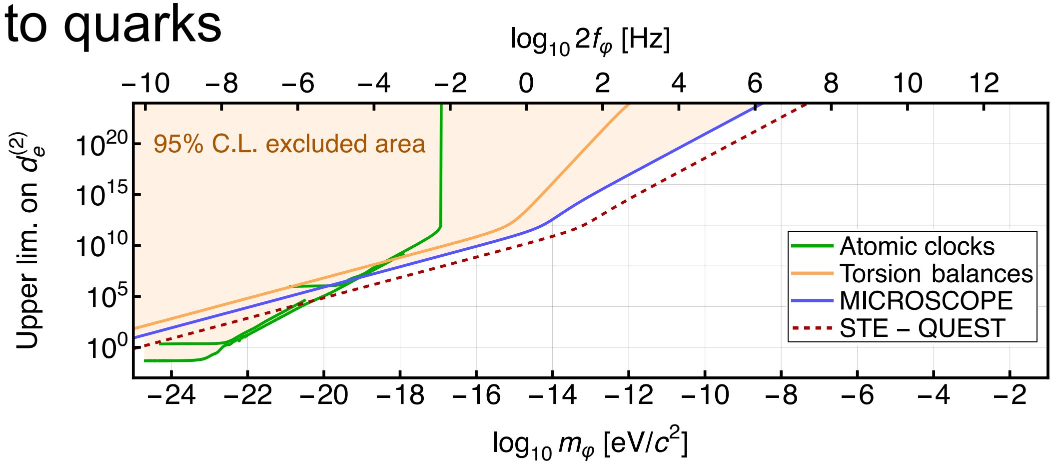
Scalar DM, linear coupling to quarks



~ 1.5 orders of mag. improvement over a 10 orders of magnitude mass range

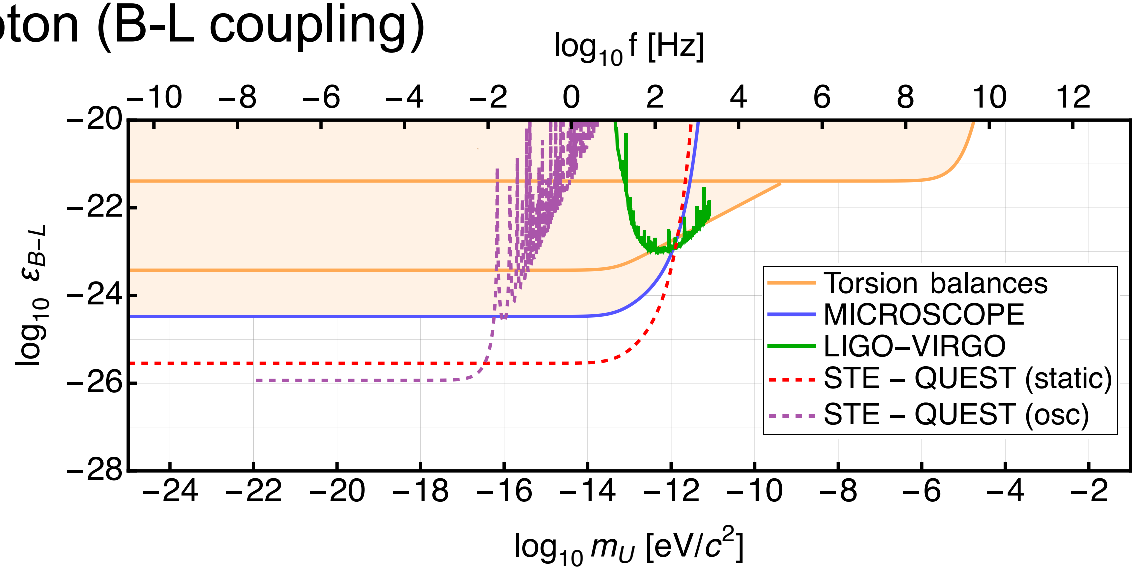
STE-QUEST and Ultra Light Dark Matter

Scalar DM, quadratic coupling to quarks



Vector DM, U boson / Dark photon (B-L coupling)

~ up to 2 orders of mag. improvement over a large mass range



Similar exploration for the axion currently on-going (J. Gué's PhD)

STE-QUEST is sensitive to a breaking of Lorentz symmetry

- Lorentz symmetry is naturally broken in models of quantum gravity, non-commutative geometry, etc, …
- The Standard Model Extension (SME) framework aims at systematically parametrizes all possible violations of Lorentz symmetry in all sectors of physics

work from Kostelecky and colleagues

- STE-QUEST is expected to be sensitive to the matter-gravity sector SME coefficients: 3 orders of magnitude improvement wrt to current constraints

Current best constraint from MICROSCOPE, see Pihan-Le-Bars et al, PRL, 2019

- This is an exciting level: if Lorentz symmetry breaking occurs at Planck scale and if it suppresses by $M_{electroweak}$ / M_{Planck} , then one can expect a violation of the EP @10^{-15}-10^{-17}.

General argument presented in Kostelecky and Potting, PRD, 1995

STE-QUEST is a mature concept

- STE-QUEST: a space test of the UFF @ 10^{-17} level using atom interferometry

- Scientific objectives: - test the UFF (Eötvos parameter)
  - search for a breaking of Lorentz symmetry
  - search for ULDM
  - test of the quantum superposition principle
  - other ideas are welcome !

- STE-QUEST science is highly rated (CNES-Séminaire de Prospective Scientifique ; ESA Space Science Advisory Committee ; ESA « Roadmap for Fundamental Physics in Space » ; …)

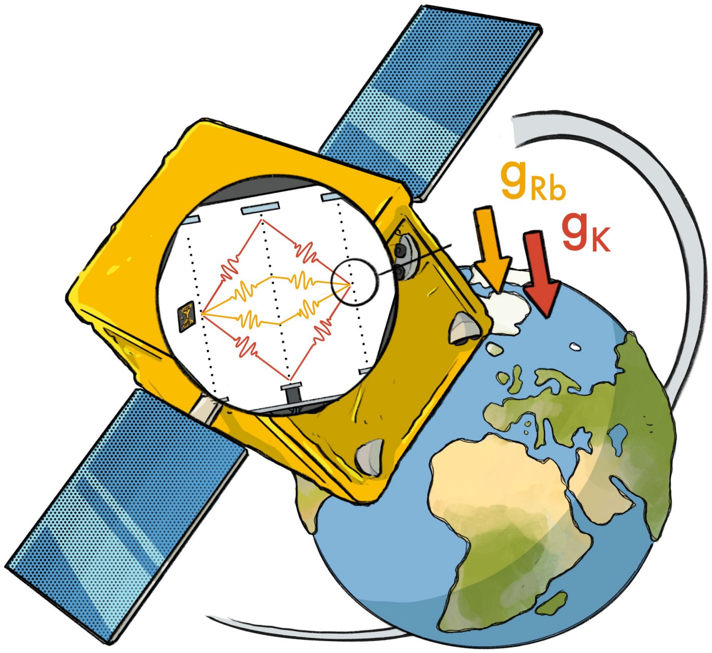
- Mature mission and payload concepts (due to M3 and M4 studies)

- Strong heritage from LISA Pathfinder, MICROSCOPE, LISA-studies

- Part of a large road-map “Cold Atoms in Space” cosigned by ~250 scientists (fundamental physics, cold atom, Earth observations, GW, …)

[arXiv: 2201.07789]

Thank you for your attention



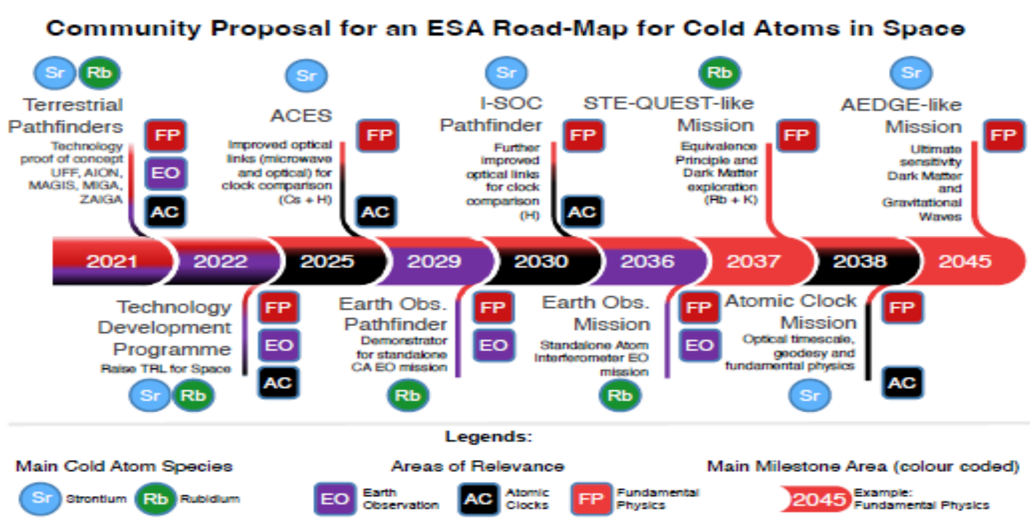
Credit: S. Loriani

STE-QUEST will provide a quantum space test of the UFF at 10^{-17}

- 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.
- Stepping stone for future more ambitious missions, and integral part of the recent community roadmap for cold atoms in space [arXiv: 2201.07789]



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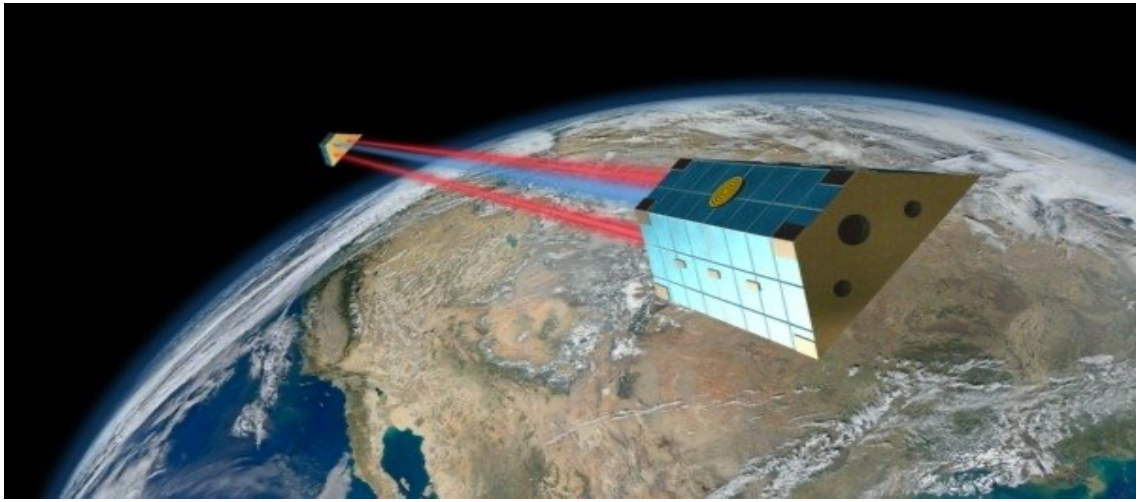
The next generation of Universality of Free Fall tests will be in space

- Space offers long free fall times and a quiet, well controlled environment. Demonstration: MICROSCOPE and LISA-Pathfinder missions
- Ground experiments: ultimately limited by local gravity gradients and uncertainties in the positioning of the test masses. Not the case in space as demonstrated by MICROSCOPE
- 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.



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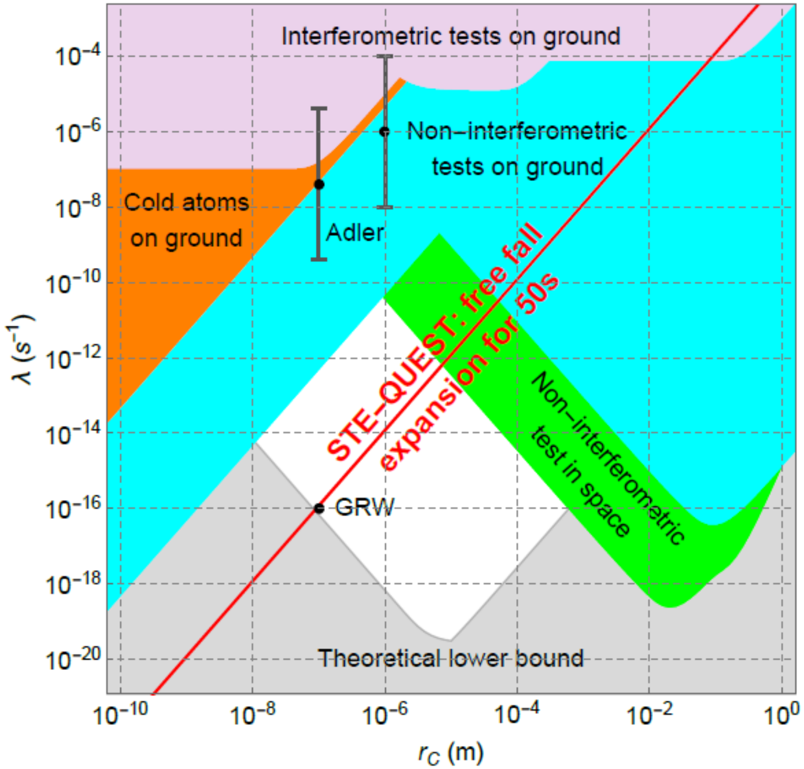
Test of Quantum Mechanics

- The collapse mechanism of quantum mechanical superpositions remains an unsolved fundamental riddle.
- Continuous collapse models modify the Schrödinger dynamics by adding (parametrized) collapse terms. E.g. CSL or DP (Diosi-Penrose).
- STE-QUEST measures the evolution of a free QM wave-packet over long evolution times (≥ 50 s), allowing a sensitive detection of any deviation from standard QM-evolution.



Improvement on present knowledge by ~2 orders of magnitude. And potential for a major discovery!

Overall management/cost

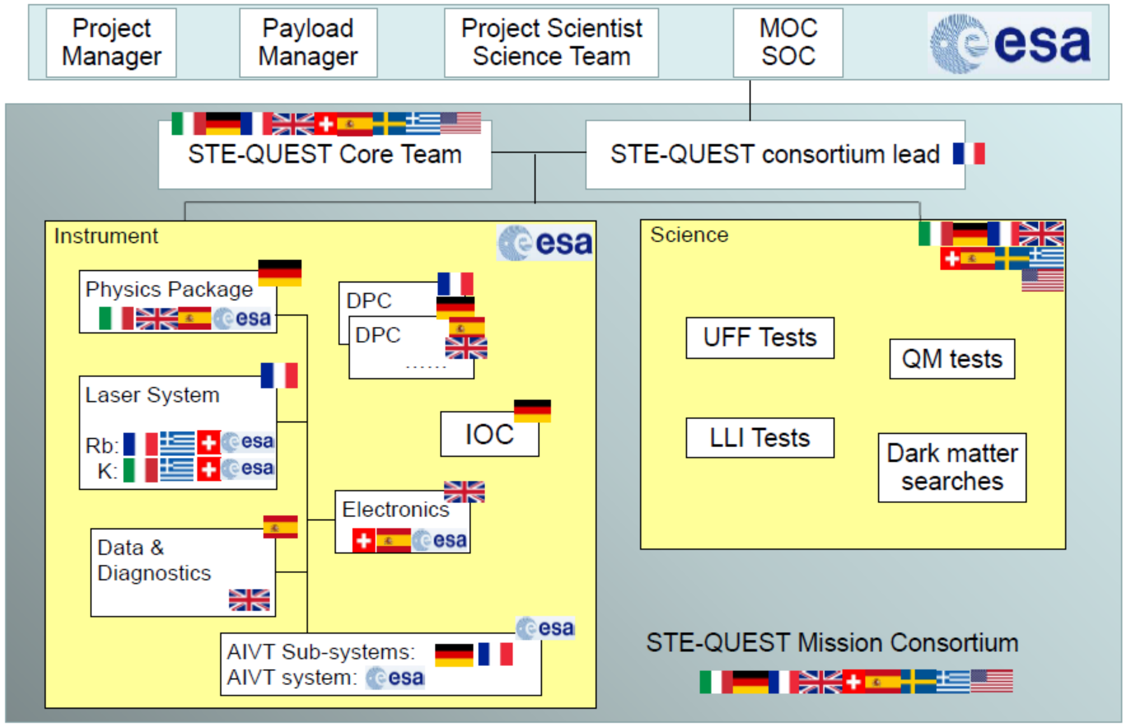
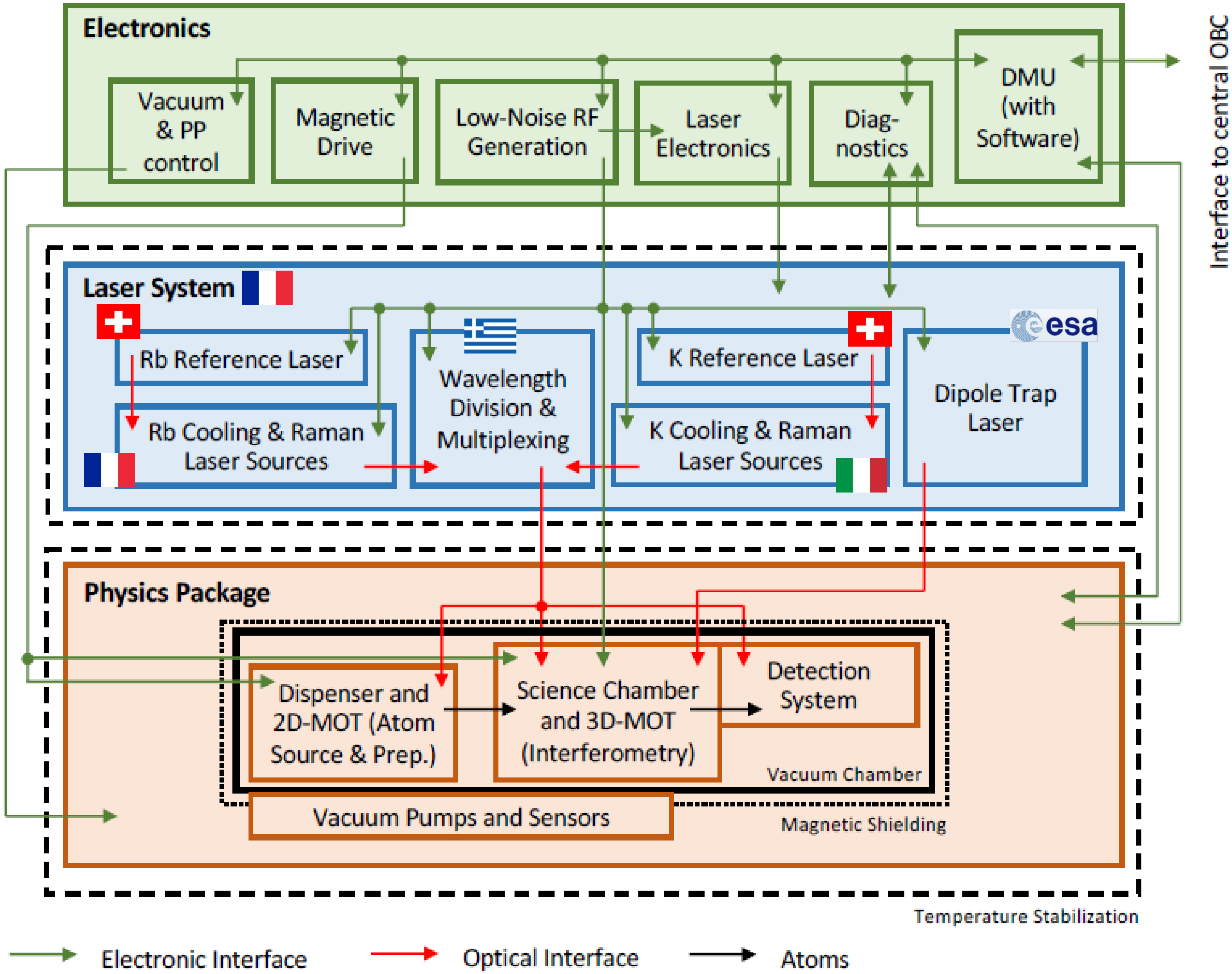


Figure 21: Proposed STE-QUEST top level management structure. MOC: Mission Operation Centre, SOC: Science Operation Center, DPC: Data Processing Center, IOC: Instrument Operation Center, AIVT: Assembly Integration Validation and Testing.

Note: All AIVT (BB, E(Q)M, FM) carried out by responsible entity for system and sub-systems (following M4-feedback).

Payload



Electronics
Vacuum & PP control
Magnetic Drive
Low-Noise RF Generation
Laser Electronics
Diag-nostics
DMU (with Software)
Interface to central OBC
Laser System
Rb Reference Laser
Rb Cooling & Raman Laser Sources
Wavelength Division & Multiplexing
K Reference Laser
K Cooling & Raman Laser Sources
esa
Dipole Trap Laser
Physics Package
Dispenser and 2D-MOT (Atom Source & Prep.)
Science Chamber and 3D-MOT (Interferometry)
Detection System
Vacuum Chamber
Vacuum Pumps and Sensors
Magnetic Shielding
Temperature Stabilization
Electronic Interface
Optical Interface
Atoms