STE-QUEST M7

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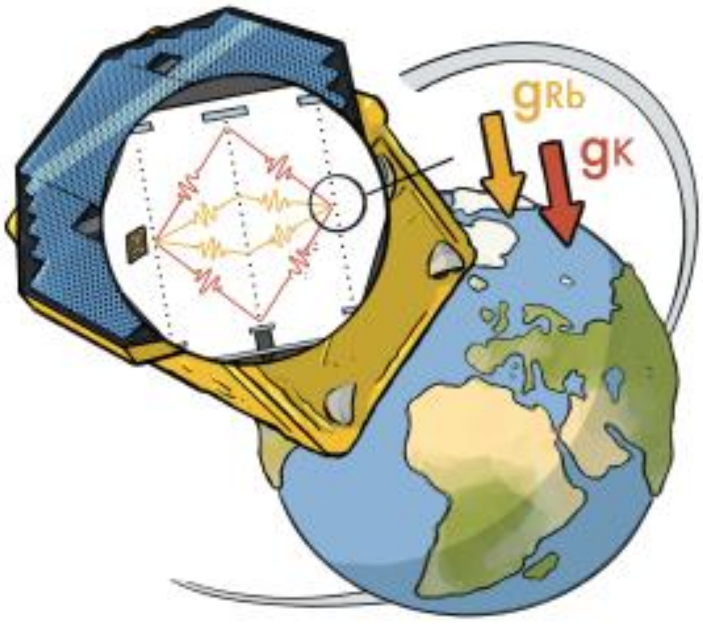
ACES-Workshop
Paris, 20/10/2022

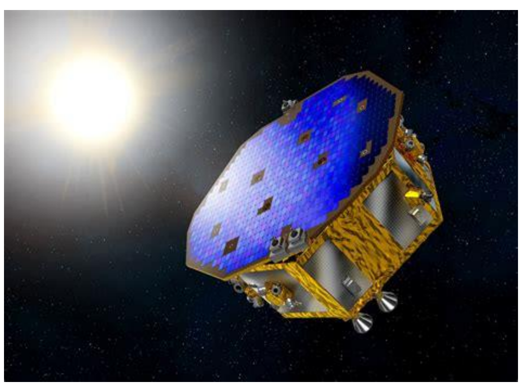


Mission Concept

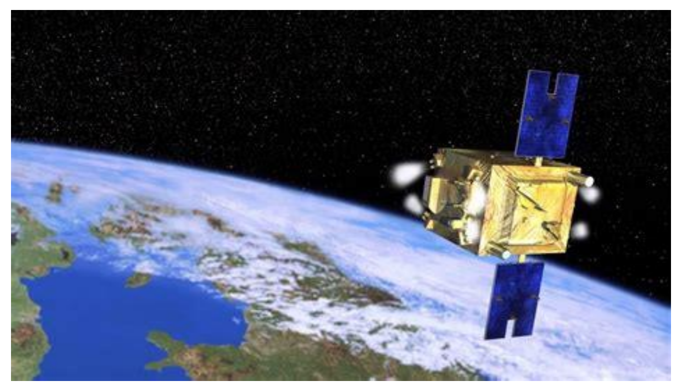
Space-Time Explorer and Quantum Equivalence Space Test

- Test the equivalence principle (universality of free fall and Lorentz invariance) using ^{41}Rb and ^{87}K atoms in quantum superpositions.
- Improve by >2 orders of magnitude on final (14/09/2022) Microscope results
- Other science objectives are searches for dark matter and tests of Quantum mechanics.

- ➢ SSO at 1400 km (1000-1400 km pending phase A optimization)
- ➢ Inertial attitude, drag free, cold-gas control (GAIA, Microscope, and LISA-PF heritage)
- ➢ ^{41}K-^{87}Rb double atom interferometer using BECs (ICE, QUANTUS, MAIUS, (BEC)CAL)

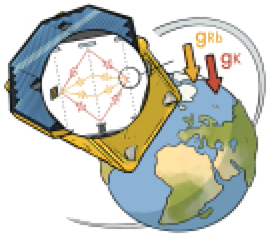


LPF: 2015-2017



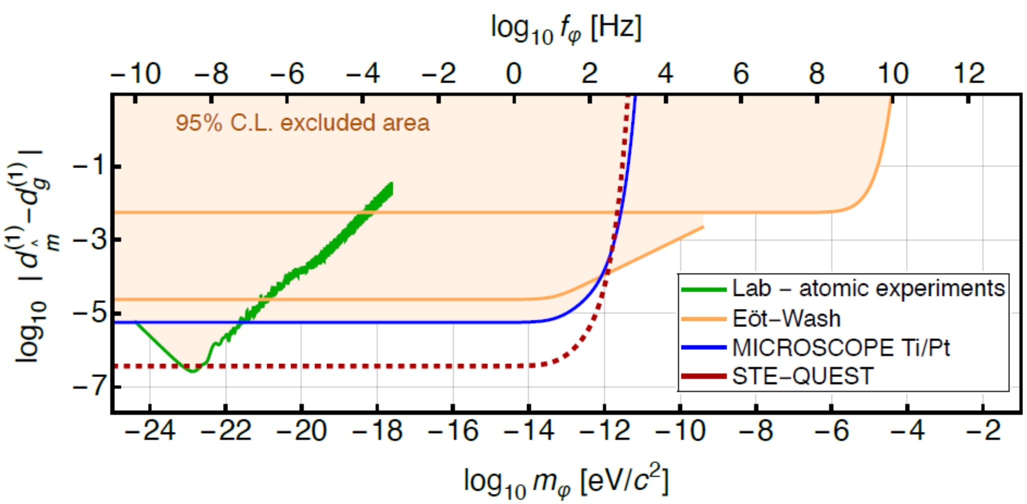
MICROSCOPE : 2016-2018

Expected scientific outcome from STE-QUEST



- Over 2 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 theoretical scenarios

- Extend the parameters search for various Dark Matter candidates by 1-2 orders of magnitude: scalar Ultra Light Dark matter, new U(1) gauge boson, …



- Extend the parameter search for a violation of Lorentz or CPT symmetry by 3 orders of magnitude (Standard Model Extension formalism)

- Test the foundation of Quantum Mechanics: the validity and the breakdown of the superposition principle. Expected improvement by up to 4 orders of magnitude.

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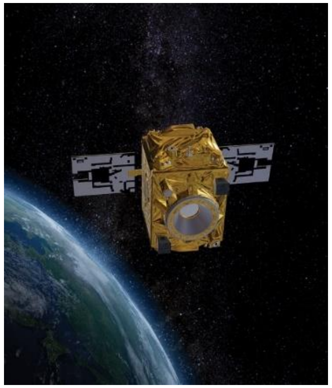
SYstèmes de Référence Temps-Espace

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

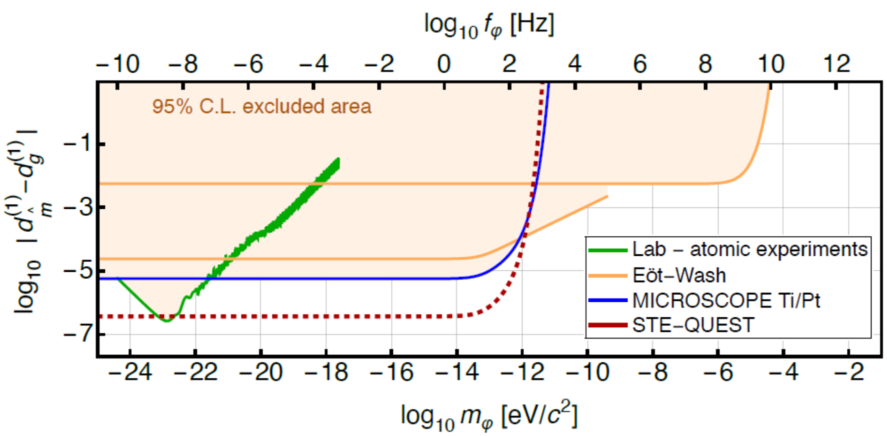
$$\eta_{AB} = 2\,\frac{a_A - a_B}{a_A + a_B}$$



Class	Elements	η	Year	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 drop tower
	^{41}K - ^{87}Rb	(10^{-17})	2037	STE-QUEST
Antimatter	$\overline{\text{H}}$ - H	(10^{-2})	2023+	under construction at CERN

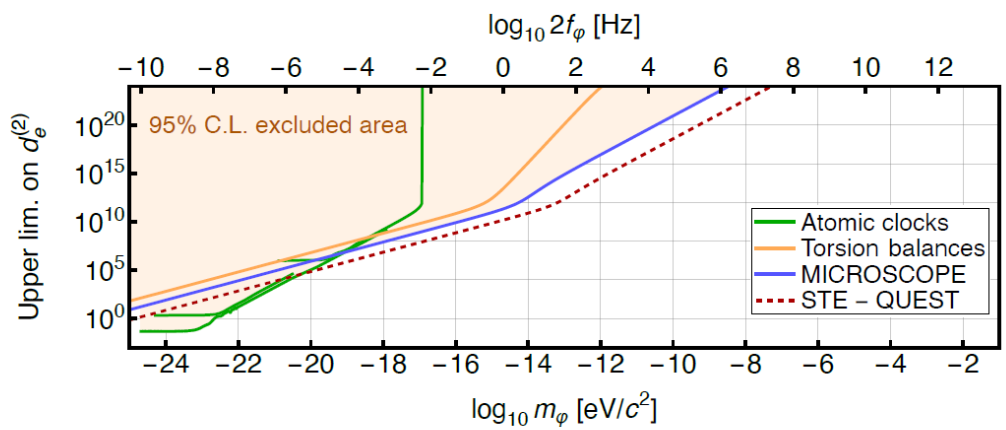
Over 2 orders of magnitude improvement with STE-QUEST

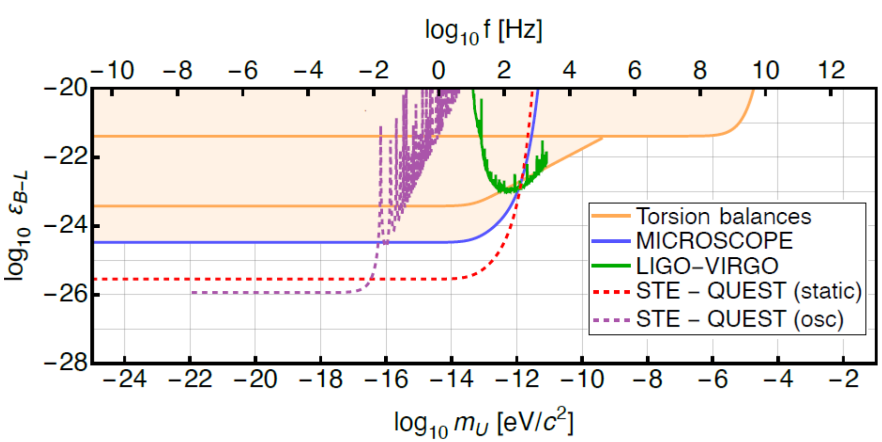
Search for Dark Matter



Scalar DM, linear coupling to quarks

Scalar DM, quadratic coupling to photons





Spin 1 DM, (B-L) coupling

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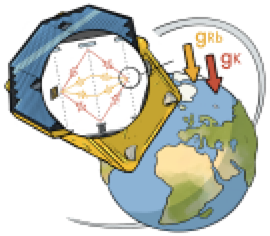
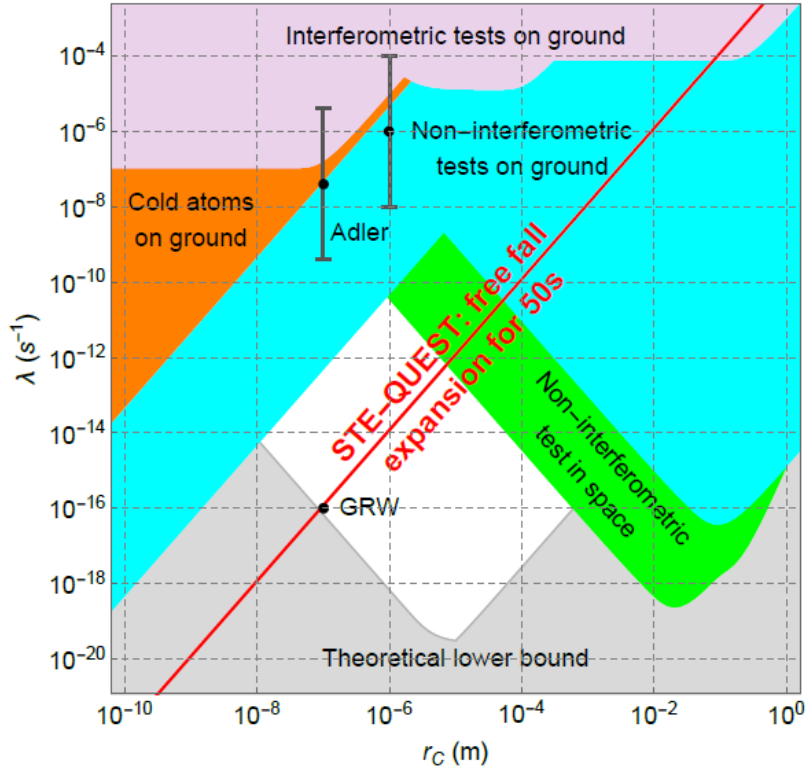
Test of Quantum Mechanics

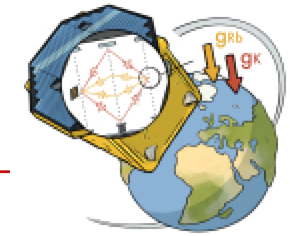


- The collapse mechanism of quantum mechanical superpositions remains an unsolved fundamental riddle.
- Continuous collapse models modify the Schrödinger dynamics by adding (parametrized) collapse terms. E.g. CSL or DP (Diosi-Penrose).
- STE-QUEST measures the evolution of a free QM wave-packet over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

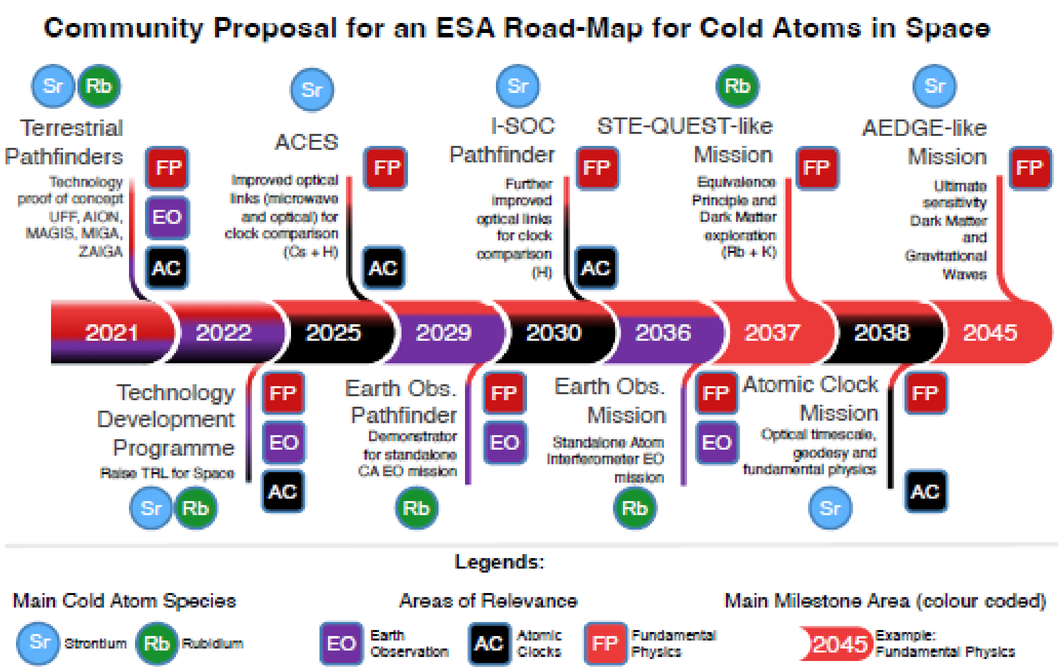


Improvement on present knowledge by ~2 orders of magnitude.
And potential for a major discovery!

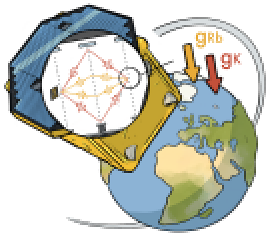
Scientific and technological context



- Scientific priority in numerous evaluations (ESA-FPRAT, PSWG, CNES, EU, ..)
- Heritage from M3 (phase A) and M4 STE-QUEST proposals
- Integral part of the recent community roadmap for cold atoms in space authored by 250 scientists world wide [arXiv:2201.07789].
- Space-quantum heritage from PHARAO, QUANTUS, MAIUS, ICE, (BEC)CAL, CARIOQA-PMP
- Mission heritage from Microscope and LISA-Pathfinder
- Europe, and France in particular, are leaders in fundamental physics in space (Microscope, LISA-PF, ACES/PHARAO, LISA) => consolidate that position

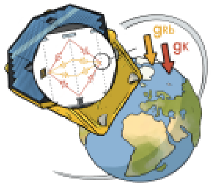


M7 mission summary



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 Power Communications	1187 kg wet mass, all margins included. 1235 W average consumption, all margins included. 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 sequence in double-Raman or double-Bragg configuration.
- Atomic shot noise limited.
- Gravity Gradient Cancellation (GGC) implemented [1]

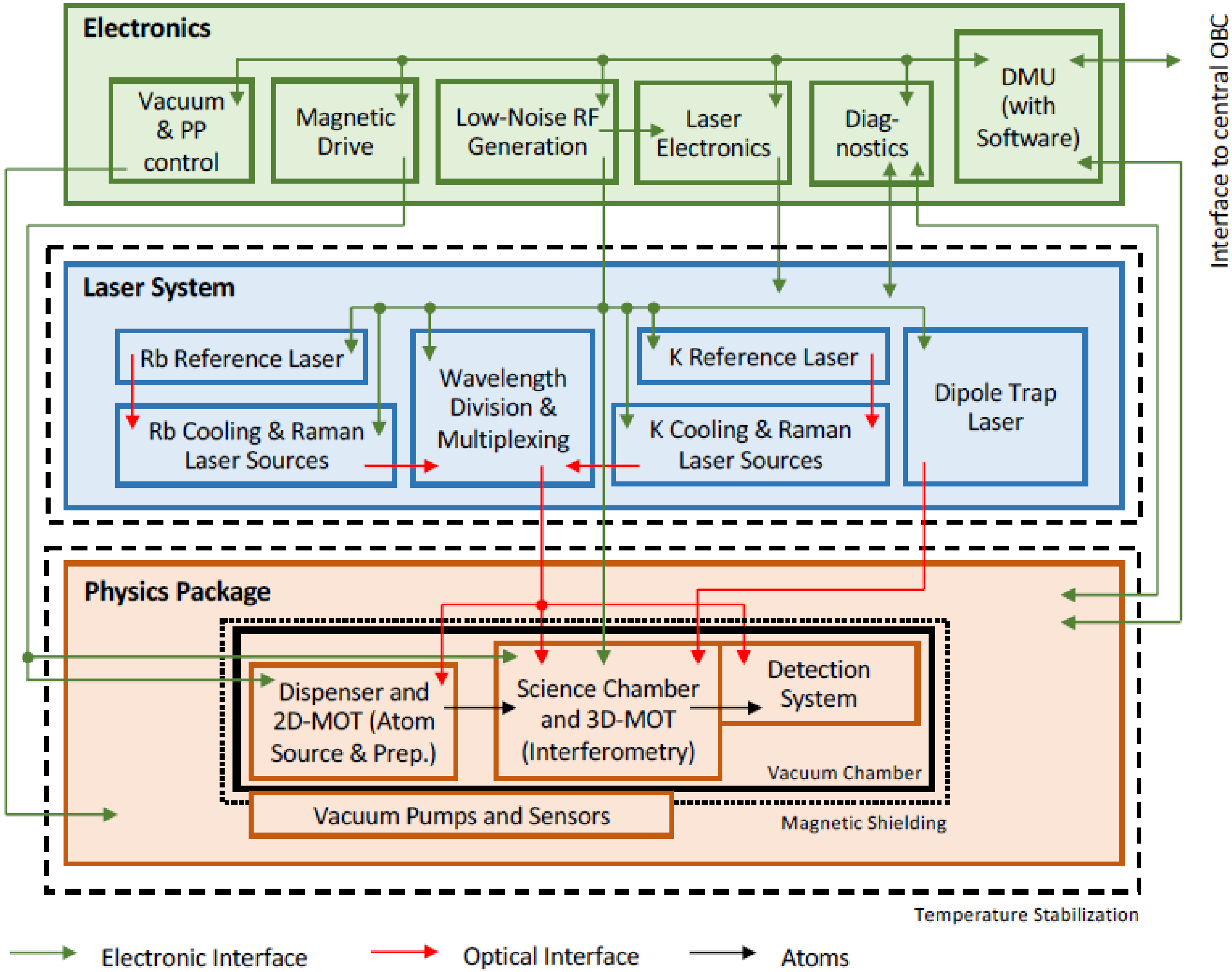
Atom number N	2.5×10^6
k_{eff} for Rb	$8\pi/(780 \text{ nm})$
k_{eff} for K	$8\pi/(767 \text{ nm})$
Free evolution time T	25 s
Max. separation Rb	0.59 m
Max. separation K	1.27 m
Cycle time T_c	60 s
Contrast C	1
Expansion energy	10 pK
Expansion velocity $\sigma_{v,Rb}$	31 μm/s
Expansion velocity $\sigma_{v,K}$	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.*

Improved performance also requires re-evaluation of other systematics, eg. residual satellite rotations and accelerations.

[1] Roura, PRL, 2017; Loriani et al., PRD, 2020.

Payload



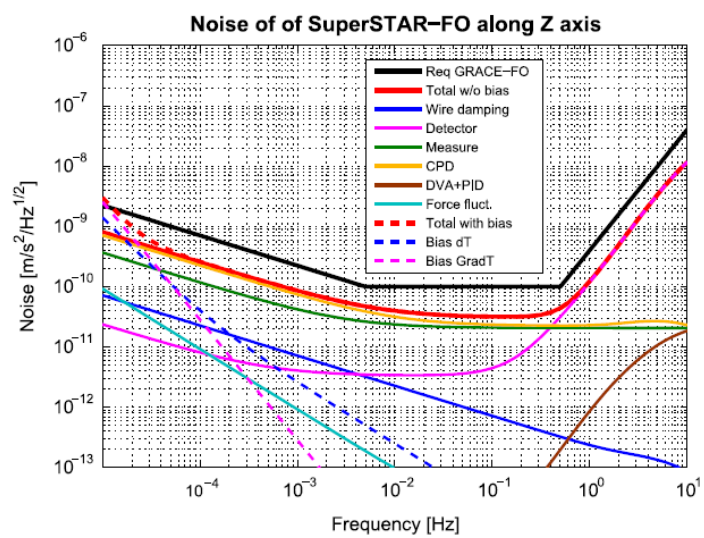
Electronics
Vacuum & PP control
Magnetic Drive
Low-Noise RF Generation
Laser Electronics
Diag-nostics
DMU (with Software)
Interface to central OBC
Laser System
Rb Reference Laser
Rb Cooling & Raman Laser Sources
Wavelength Division & Multiplexing
K Reference Laser
K Cooling & Raman Laser Sources
Dipole 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

Platform requirements

Quantity	Constraint	Comment	μSCOPE	LPF	GRACE-FO
$\sqrt{S_a(f)}$	4.0×10^{-10} m/s$^2/\sqrt{\text{Hz}}$ 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$^2/\sqrt{\text{Hz}}$ 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 $\langle \dots \rangle_{2T}$ constraints apply to variations at frequencies such that $2\pi f T < 1$.

- Heritage from previous missions is OK, but with little margin in some cases.
- But, room for improvement e.g. high freq. servo acting on laser frequency, optimized feed forward strategies, ….



Management

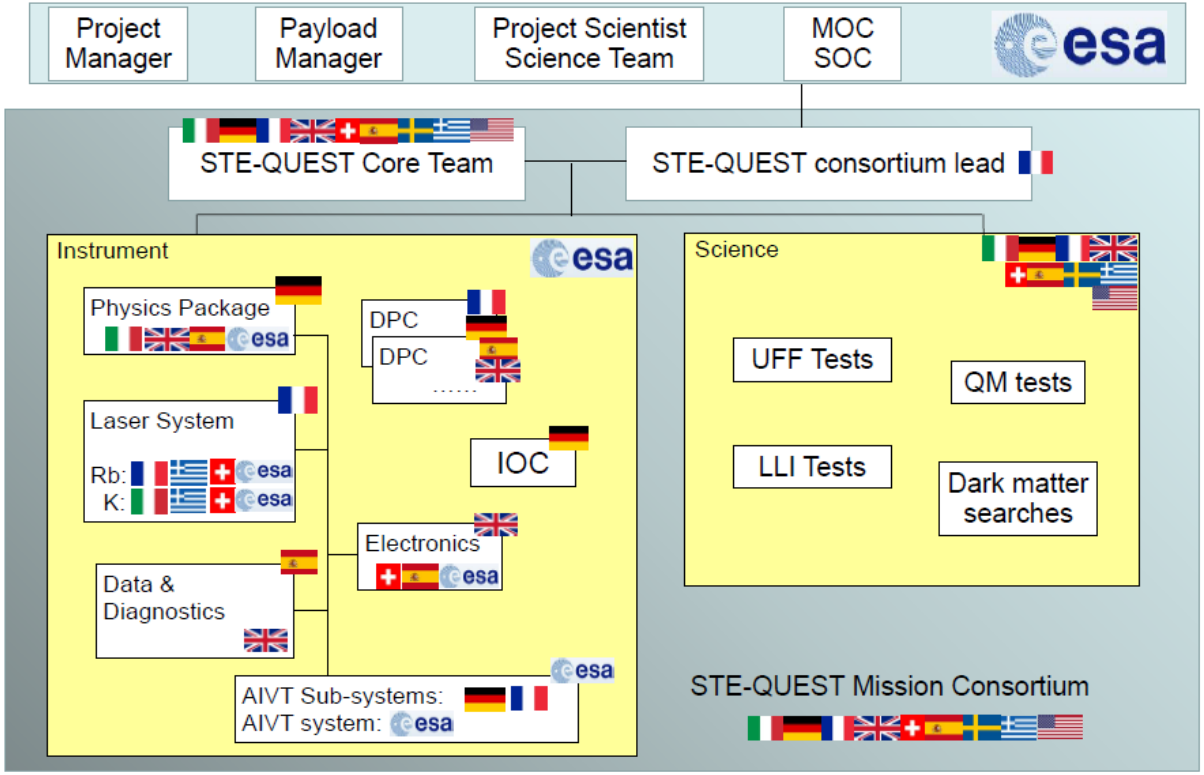


Figure 21: Proposed STE-QUEST top level management structure. MOC: Mission Operation Centre, SOC: Science Operation Center, DPC: Data Processing Center, IOC: Instrument Operation Center, AIVT: Assembly Integration Validation and Testing.

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

Past and Future

- Initially proposed in M3 (2010) in very different form. Passed first selection => phase A study (2011-2013) with two other candidates. Not selected in final round (mainly TRL problems).
- Re-proposed in M4 (2014). Not selected (mainly financial problem as cost-cap @ 450 M€).
- Re-proposed in M7 (02/2022):
  - Passed phase-1, 04/2022 (with 9 other M candidates, out of 26).
  - Phase 2 proposal, 07/2022.
  - ESA Q&A audition, 09/2022.

- Selection of 1-3 missions for 3-year phase-A study, 11/2022
- Down selection to 1 mission in 2025/26
- Phase B1/B2/C/D 2026 – 2036
- Launch around 2037

Cost cap: ESA 550 M€
Payload contributions from member states: ~150 M€