Next generation space tests of the equivalence principle: scientific motivations

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On behalf of the STE-QUEST collaboration

Workshop on Atomic Experiments for Dark
Matter and Gravity Exploration
CERN, July 23rd, 2019

Context

- Call for white paper for VOYAGE2050: one paper is currently being written about the next generation of tests of the Einstein Equivalence Principle in space (paper led by Peter Wolf, Observatoire de Paris with many contributors)

- Topic of that paper:

  1) scientific motivation

  2) Next generation of MICROSCOPE-like mission

  3) STE-QUEST (Space-Time Explorer and QUantum Equivalence principle Space Test)

Content

- The Einstein Equivalence Principle

  - Current test

  - Ultralight Dark Matter

- STE-QUEST

  - M4 mission and payload

  - Science objectives

  - Evolution since 2014

- Conclusion

General Relativity
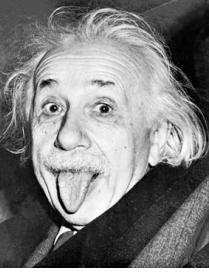
Einstein Equivalence Principle

Effects of gravitation ⟷ Space-time geometry
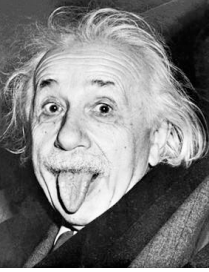
$$g_{\mu\nu}$$

see K. Thorne et al, PRD, 1972

$$S_{\mathrm{mat}} = \int d^4x \sqrt{-g} \mathcal{L}_{\mathrm{mat}}(g_{\mu\nu}, \Psi)$$

- Governs the motion of test-particles, light ray, gyroscope, etc… from a given metric

see C. Will, 1993

General Relativity

Einstein Equivalence Principle

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Einstein Field Equations

Space-time geometry ⟷ Energy/Matter content

$$S_{\mathrm{grav}} = \frac{1}{2\kappa} \int d^4x \sqrt{-g} R$$

- Contains the dynamics of the space-time metric: how is space-time curved?

- Light deflection, GW propagation, orbital dynamics, …

see C. Will, 1993

The Einstein Equivalence Principle

$$S_{\mathrm{mat}} = \int d^4x \sqrt{-g}\, \mathcal{L}_{\mathrm{mat}}(g_{\mu\nu}, \Psi)$$

- The basis of General Relativity

- All types of mass-energy are coupled universally to gravitation, i.e. the gravitational interaction is independent of composition, charge, flavor, etc…

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

- This is somehow "anomalous" as none of the other interactions are universal (they all depend on some charges)

- It does not rely on any "symmetry" or on a more fundamental theoretical argument. It is rather the expression of an experimental fact "bodies fall the same way in the same gravitational potential"

see the discussion in Damour, CQG, 2012

Why searching for a breaking of the EEP?

- Since the "universal" character of gravitation seems "anomalous" the question should rather be: why is the EEP satisfy?

see the discussion in Damour, CQG, 2012

- The SM of particle contains several arbitrary constants: this seems rather unsatisfactory $\Rightarrow$ introduction of dynamical fields that replace the constants and explain their values see the discussion in Damour, CQG, 2012

- Several models of DM break the EEP see e.g. Hees et al, PRD, 2018

- Several models of Dark Energy also break the EEP

see Damour and Polyakov, Gen. Rel. Grav., 1994

- Several unification scenarios and most attempts to develop a quantum theory of gravity breaks the EEP

see e.g. refs in Altschul et al, 2015

Searching for a breaking for the EEP seems promising and can shed light on new physics

Standard tests of EEP

WEP/UFF

$$\eta = \frac{\Delta a}{a}$$

If any uncharged test body is placed at an initial event in space-time and given an initial velocity there, then its subsequent trajectory will be independent of its internal structure and composition

LPI

The outcome of any local non-gravitational experiment is independent of where and when in the Universe it is performed

LLI

The outcome of any local non-gravitational experiment is independent of the velocity of the (free falling) apparatus

Standard tests of Equivalence Princ.

UFF

$$\eta = \frac{\Delta a}{a}$$

- with MICROSCOPE @10⁻¹⁴

    Touboul et al, PRL, 2017

- with LLR @10⁻¹⁴

    Viswanathan et al, MNRAS, 2018

- with torsion balances @10⁻¹³

    Schlamminger et al, PRL, 2008

- with atom interferometer @10⁻⁹

    See e.g. Peters et al, Nature, 1999

- Anti Matter vs Matter: test coming @CERN

LPI

- redshift test: @10⁻⁵ with Galileo

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

    see e.g. Delva et al, PRL, 2018

- Do the constants of Nature depend on space and time?

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

    for a review, see J.P. Uzan, LRR, 2011

LLI

- Standard Model Extension (SME): violation of Lorentz symmetry in all sector of physics
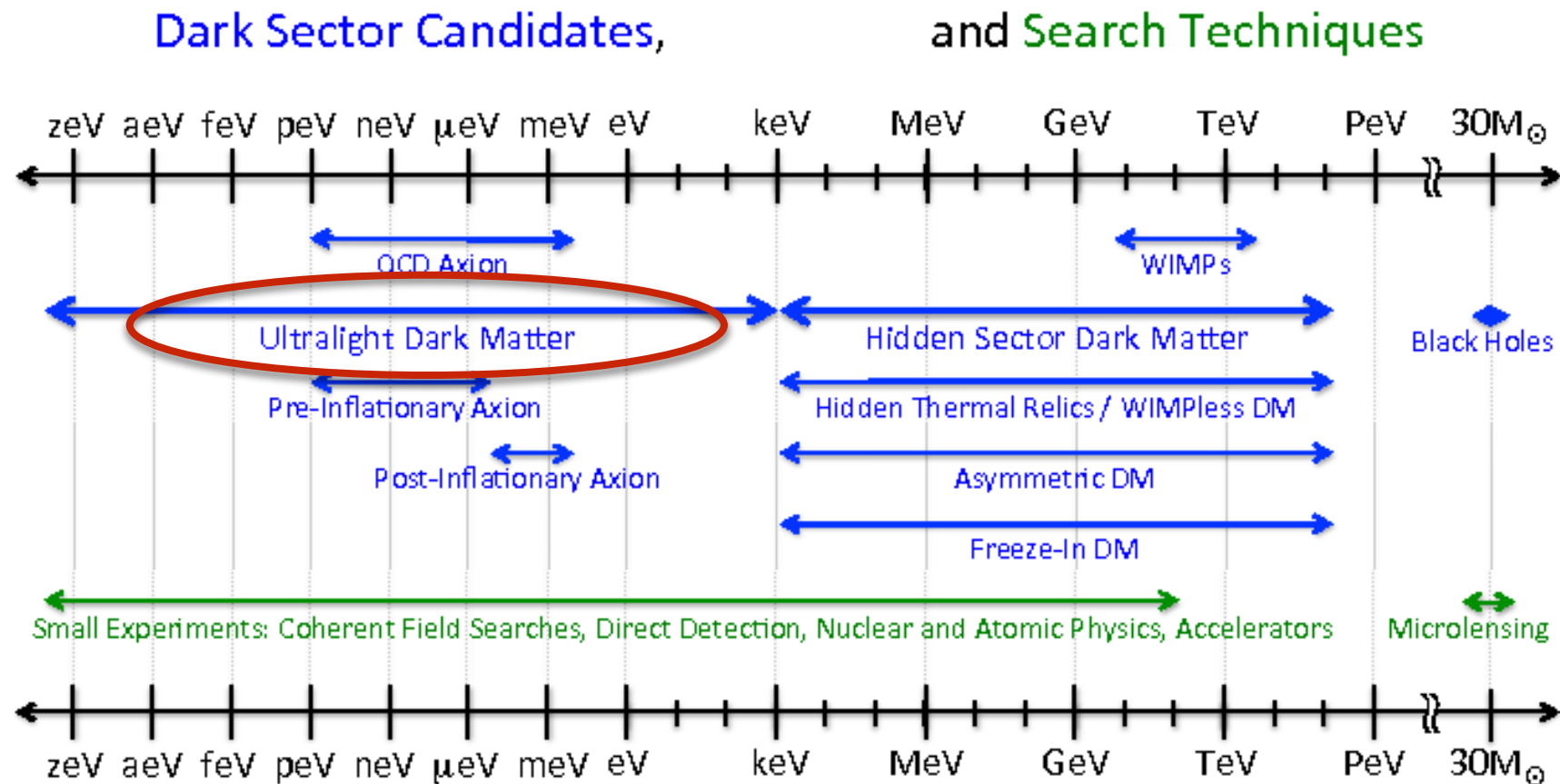
    see e.g. A. Kostelecky, N. Russel, Rev. of Mod. Phys., 83/11, 2011

e.g. constraints on the SME $\bar{a}^J$ @10⁻⁸ from MICROSCOPE

    Pihan-Le-Bars, to be submitted

Motivations: Dark Matter?

- Required to explain several astro/cosmo observations: CMB, galactic rotation curves, lensing, structures formation, …
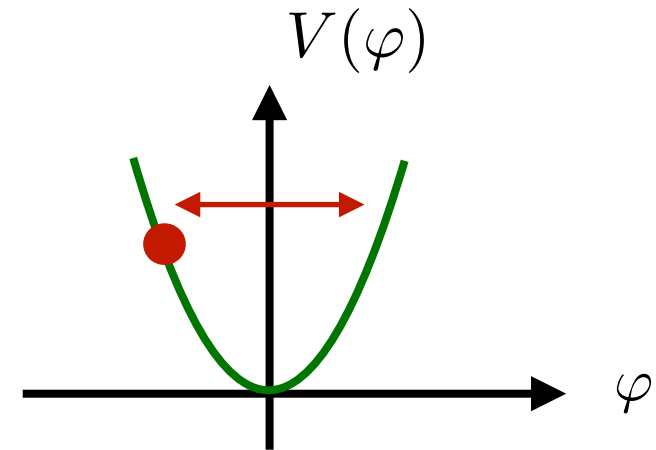
- So far: Not directly detected at high energy

Dark Matter can be made out of a bosonic scalar particles

A scalar model of DM

- ***Axions***: pseudo scalar particle

- ***Dilatons***: a scalar particle

$$V(\varphi)$$

$$\varphi$$

$$S = \frac{1}{c} \int d^4x \frac{\sqrt{-g}}{2\kappa} [R - 2g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - V(\varphi)]$$

- will oscillate at the cosmological level $\quad \varphi = \varphi_0 \cos\left[\frac{mc^2}{\hbar}t\right]$

- similar to pressure less fluid with $\quad \rho \propto m^2\varphi_0^2$

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

- can produce structure formation if $\quad m > 10^{-23}eV$

see e.g. Marsh, Phys. Reports, 2016

If couple to the SM, this DM candidate will induce a breaking of the EEP

- An effective Lagrangian for the scalar-matter coupling

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

see Damour and Donoghue, PRD, 2010

- Most usual couplings: linear (cfr Damour-Donoghue) or quadratic (cfr Stadnik et al) in φ

- This leads to a space-time dependance of some constants of Nature to the scalar field

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

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

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

A signature of a violation of the Einstein Equivalence Principle !

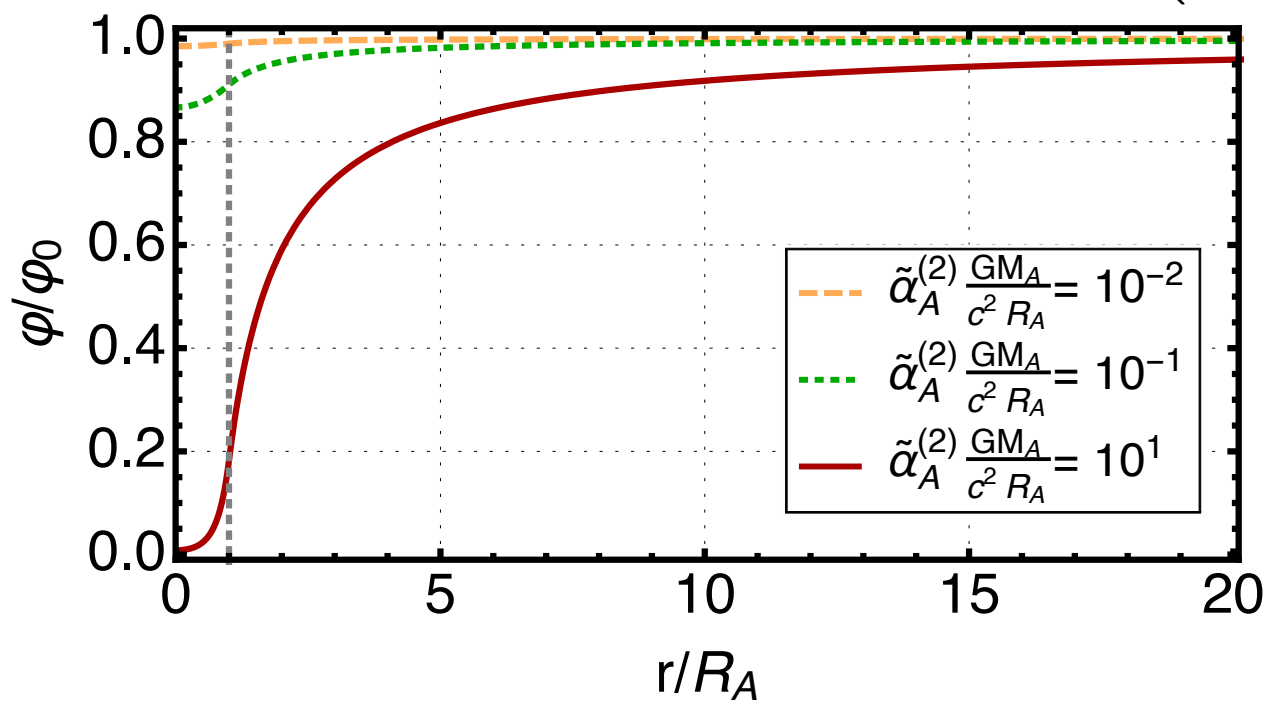# The linear and quadratic cases are slightly different

- LINEAR

$$\varphi^{(1)}(t, \boldsymbol{x}) = \varphi_0 \cos\left(\boldsymbol{k}.\boldsymbol{x} - \omega t + \delta\right) - s_A^{(1)} \frac{GM_A}{c^2 r} e^{-r/\lambda_\varphi}$$

Oscillating DM

Fifth force
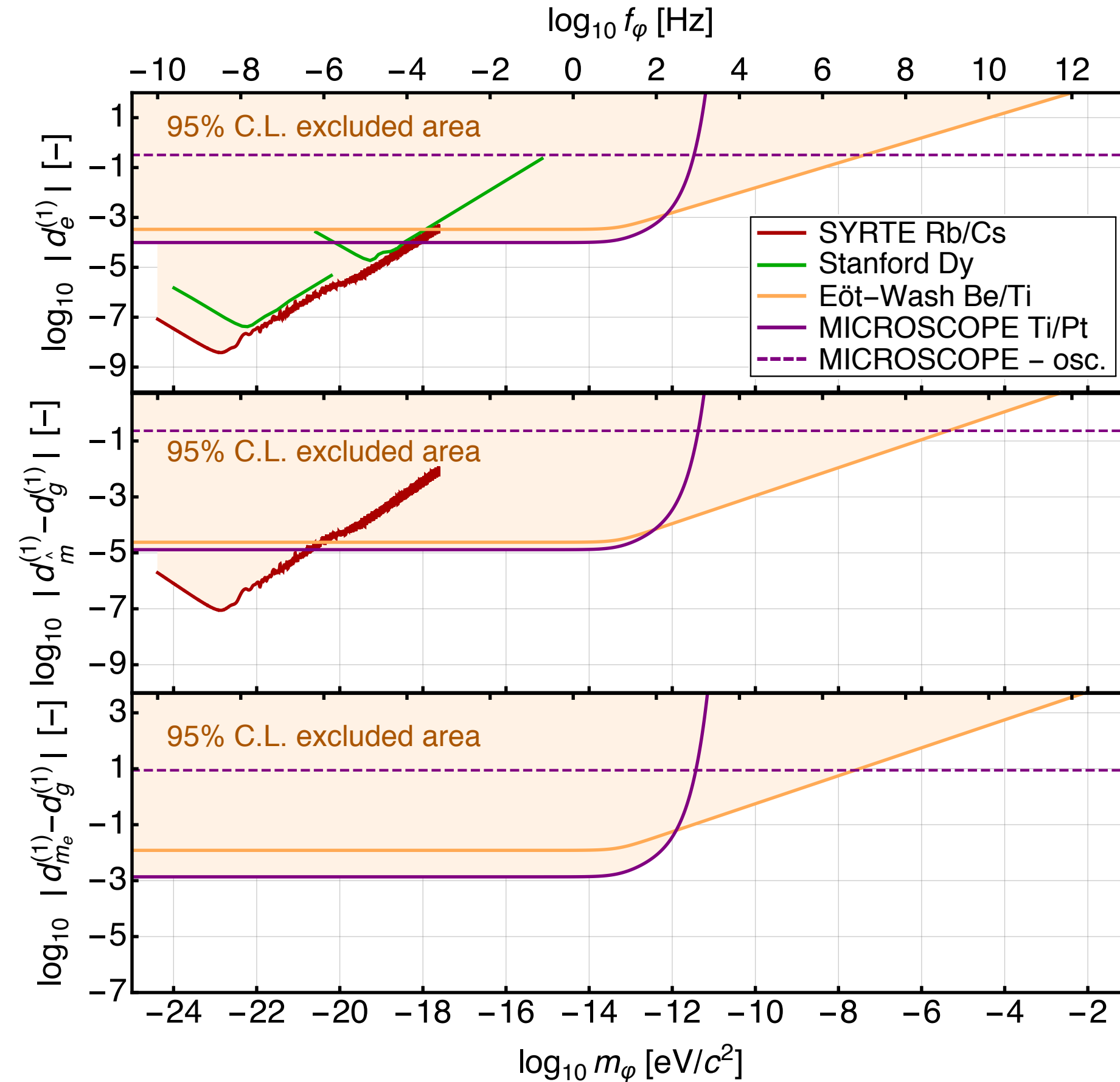
- QUADRATIC: no Yukawa interaction ! Very rich phenomenology

$$\varphi^{(2)}(t, \boldsymbol{x}) = \varphi_0 \cos\left(\frac{m_\varphi c^2}{\hbar} t + \delta\right) \left[1 - s_A^{(2)} \frac{GM_A}{c^2 r}\right]$$

Legend:
- $\tilde{\alpha}_A^{(2)} \frac{GM_A}{c^2 R_A} = 10^{-2}$
- $\tilde{\alpha}_A^{(2)} \frac{GM_A}{c^2 R_A} = 10^{-1}$
- $\tilde{\alpha}_A^{(2)} \frac{GM_A}{c^2 R_A} = 10^{1}$

Non-linearities: scalarization and screening mechanism

Favorable to be in space!
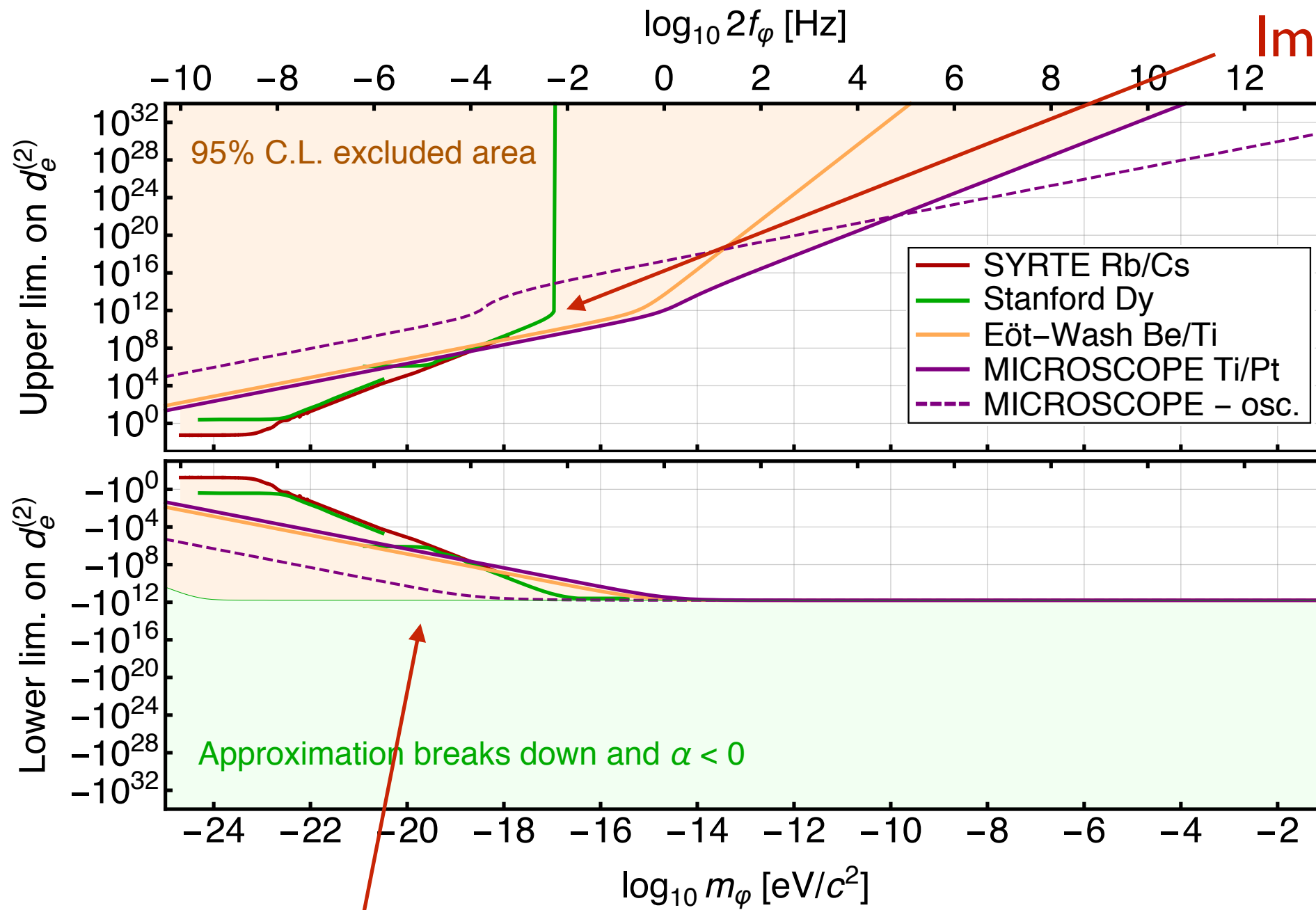
see Hees et al, PRD, 2018

Constraints on the linear couplings

see A. Hees et al, PRD, 2018
and J. Bergé et al, PRL, 2018

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Constraints on the quadratic couplings

Impact of screening

95% C.L. excluded area

Legend:
- SYRTE Rb/Cs
- Stanford Dy
- Eöt–Wash Be/Ti
- MICROSCOPE Ti/Pt
- MICROSCOPE – osc.

Approximation breaks down and $\alpha < 0$

Impact of amplification

Being in space is favorable ! Scalar field tends to vanish at the Earth surface

see A. Hees et al, PRD, 2018

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  - M4 mission and payload
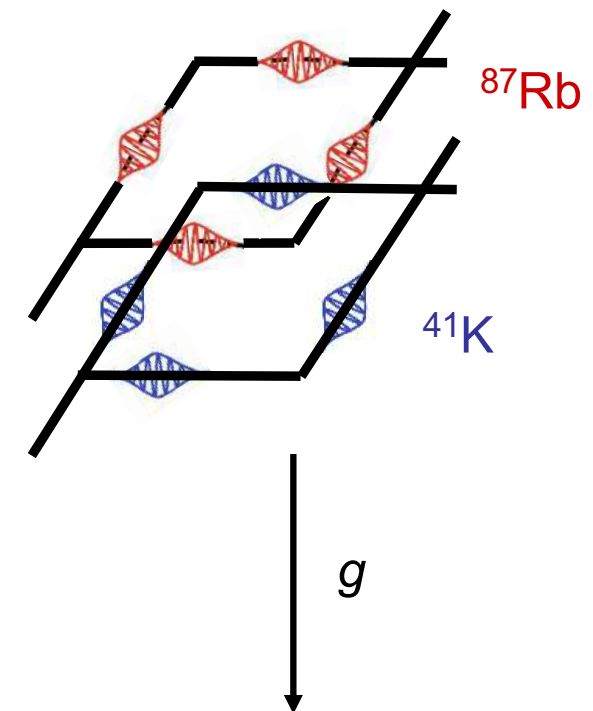
  - Science objectives

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STE-QUEST (Space-Time Explorer and QUantum Equivalence principle Space Test)

- The main scientific goal: to test the UFF with quantum objects @10^{-17}

^{87}Rb

^{41}K

g

"STE-QUEST performs the experiment of the motion of Rb and K in a quantum superposition"
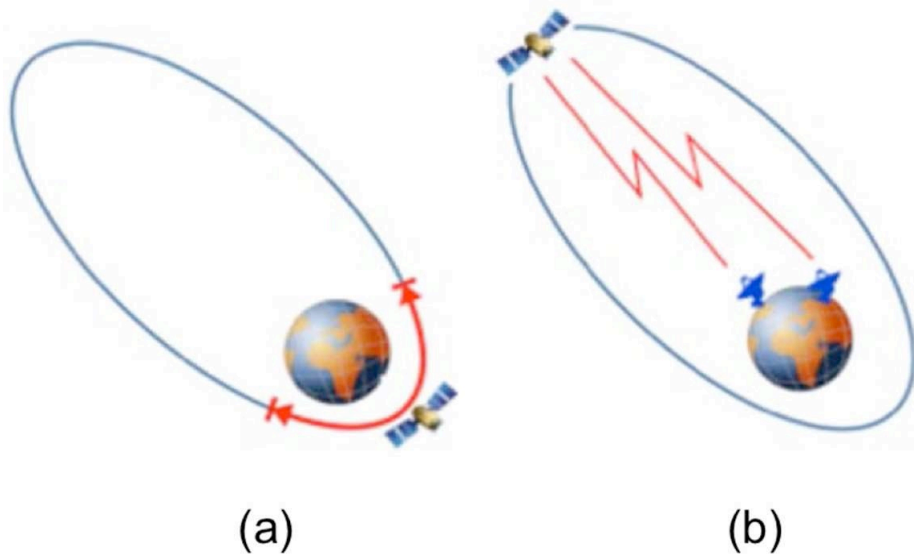
L. Catani, "Galileo performs the experiment of the motion of weights from the Tower of Pisa in the presence of the Grand Duke", Gallery of Modern Art of the Pitti Palace, Florence

M4 mission and payload

- Proposed in different versions to M3 and M4

- Pre-selected in M3, not selected in M4

(a)   (b)

- Elliptic orbit, 2500x33600 km, 63° inclination

- 3.5 yr mission lifetime

- ^{41}K - ^{87}Rb double atom interferometer

- MWL for intercontinental ground clock comparison

Main science objective: test of the UFF
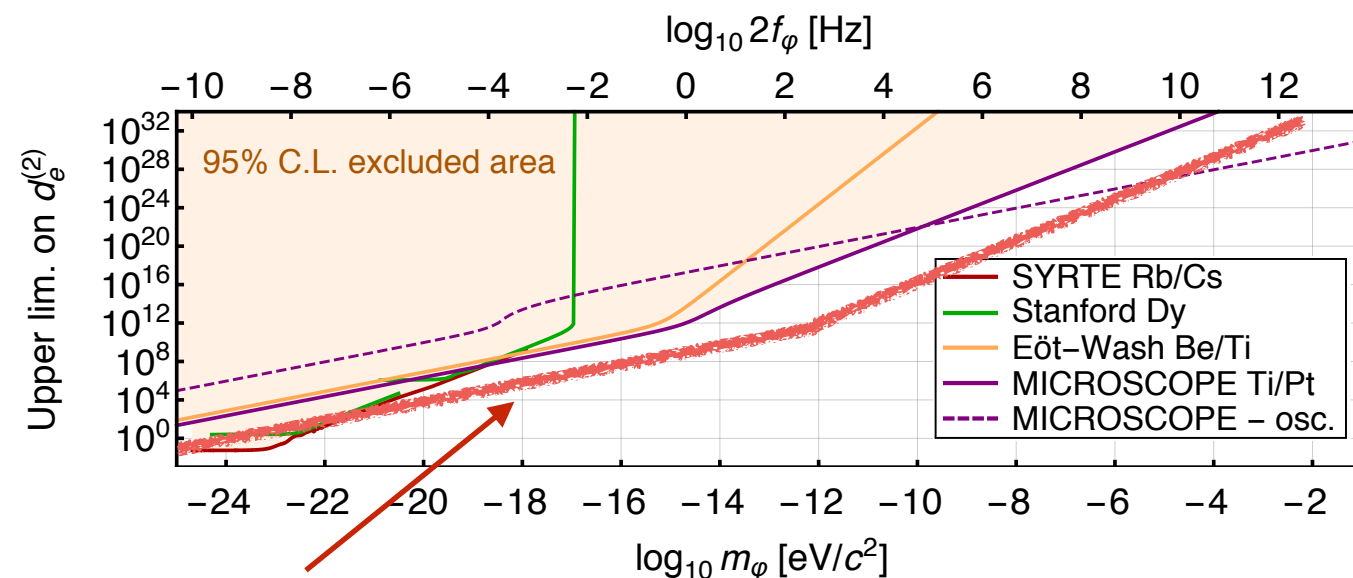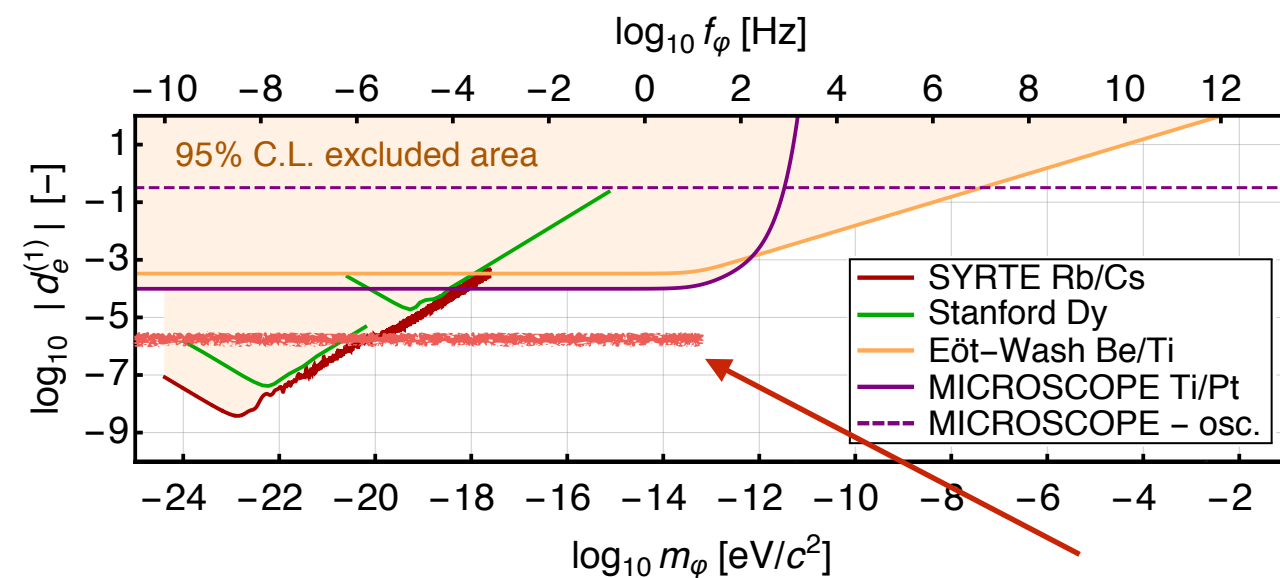
- Test using quantum objects @10^{-17}

- To be compared with

  Classic
  - Torsion balances: 2×10^{-13} Schlamminger, 2008
  - MICROSCOPE: 10^{-14} Touboul, 2017

  Hybrid
  - Comparison macro vs micro 7×10^{-9} Peters, 2001, Merlet, 2010

  Quantum
  - Atom interferometry 3×10^{-8} Zhou, 2015, Schlippert, 2014, Tarallo, 2014

- Interpreted as a search for DM

STE-QUEST @ 10^{-17}
and 700 km perigee

Evolution since 2014

- TRL issues have been, and are being tackled, evolve towards a micro-g demonstration !

- Microscope (2016-18) and LISA-Pathfinder (2015-17) missions have demonstrated "beyond expectation" drag-free performance, and determination of test-mass offsets at 0.1 μm level.

- A seminal paper (PRL 2017) has suggested a method that cancels gravity gradient issues in quantum accelerometers (GGC). Demonstrated experimentally by two groups since.
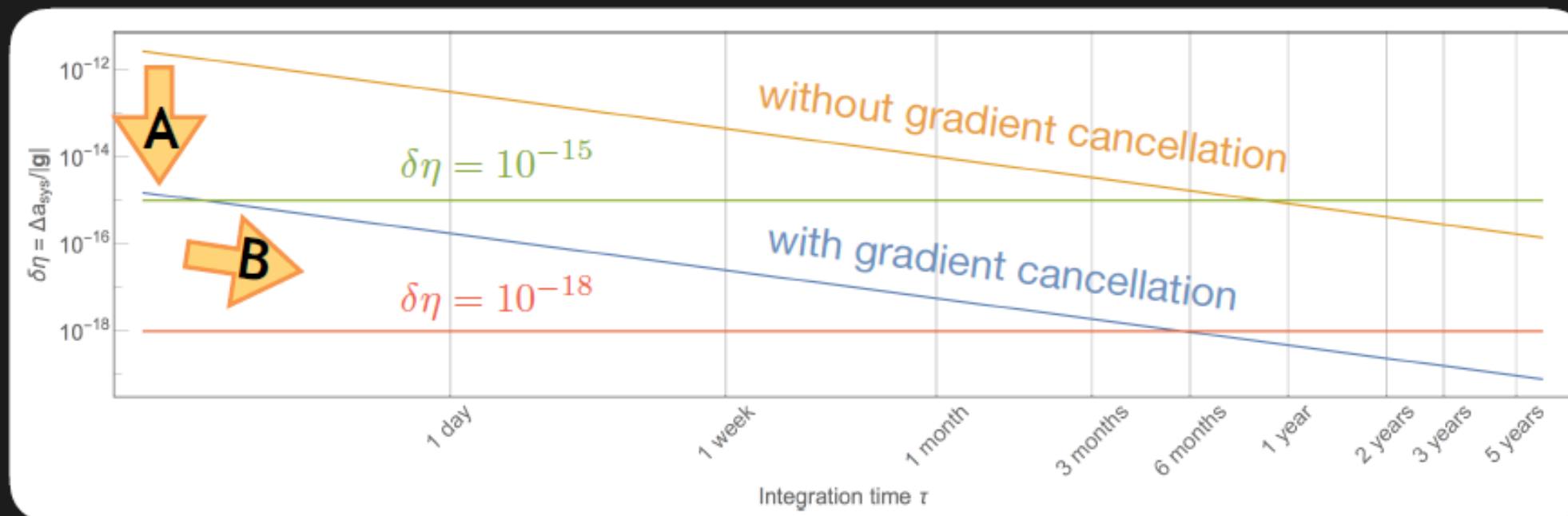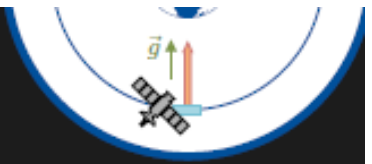
see Roura, PRL, 2017 and Overstreet et al, PRL, 2018 ; D'amico et al, PRL, 2017

- We (SYRTE+LUH) have started developing a full mission simulator that integrates these developments (and many other features) for the design of future quantum sensor UFF/WEP test missions and other applications.

Evolution since 2014

Study case: WEP test with atom interferometry

- inertial configuration on circular orbit
- A) GGC: reduces verification time & improves contrast
- B) Demodulation: reduces residual uncertainties

without gradient cancellation

$\delta\eta = 10^{-15}$

with gradient cancellation

$\delta\eta = 10^{-18}$

A

B

$\delta\eta = \Delta a_{sys}/|g|$

1 day   1 week   1 month   3 months   6 months   1 year   2 years   3 years   5 years

Integration time τ

assumptions:
$\delta r_0 = 1\mu m$
$\delta v_0 = 1\mu m/s$
altitude = 700km
T = 5s
$\delta\theta$ = 100nrad
δf = 10MHz
$\delta\Omega$ = 10nrad
$\delta\gamma = 10^{-3} \gamma$

Preliminary results: statistical uncertainty of 10^{-18} reachable by using the GGC…

On-going work by Sina Loriani, with N. Gaaloul and P. Wolf

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

Secondary science objectives

- Test of the gravitational redshift: in the field of the Moon and of the Sun: universality of clock rate

  2 orders of magnitude improvement
  compared to what is expected from ACES

- Test of Lorentz/CPT symmetry:

  2 orders of magnitude improvement on several
  SME coefficients (in particular on the $\bar{a}^J$)

- Geodesy: unification of the reference frames

  @ sub-cm level

- T/F metrology: distant clock comparisons @10^{-18} level after a few days of integration

  Essential for synchronization of next generation
  of ground clocks

Conclusion

- Several recent experimental and theoretical results have advanced the field significantly in recent years.

- A mission for a UFF/WEP test with a Rb-K dual atom interferometer at the 10^{-17} level has become realistic.

- This would improve the expected final Microscope results (10^{-15}) by 2-3 orders of magnitude, entering a region no other experiments can reach.

Explore completely uncharted territory with potential for a major discovery !

Thank you for your attention
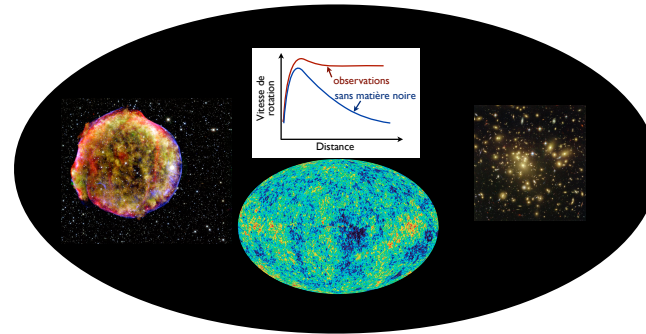
Astronomy & cosmology

(gravitational waves, 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, …)