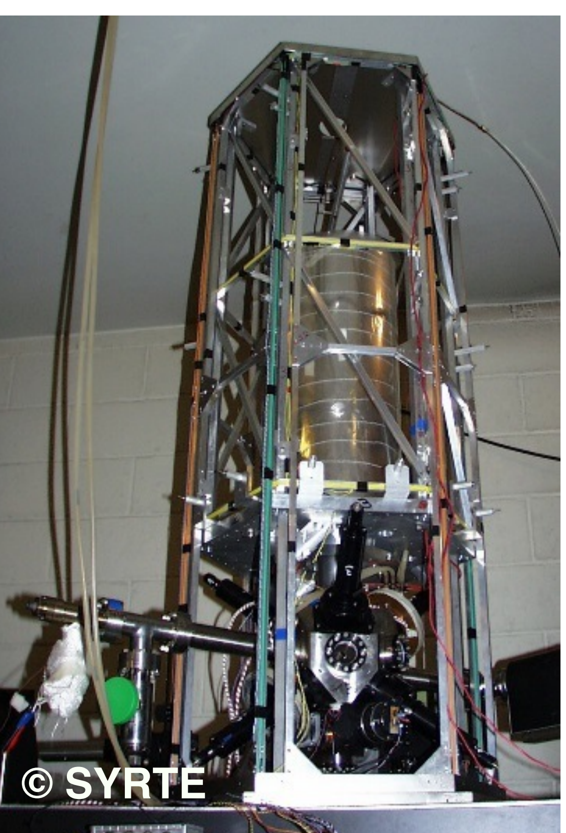
Can laboratory experiments help to characterize Dark Energy?

A. Hees, M. Abgrall, S. Bize, P. Delva, J. Guéna, B. Roberts, E. Savalle, P. Wolf

SYRTE, Paris Obs., Université PSL, Sorbonnes Univ.

O. Minazzoli, *Centre Scientifique de Monaco and OCA*

Y. Stadnik, *Helmoltz Institute Mainz*

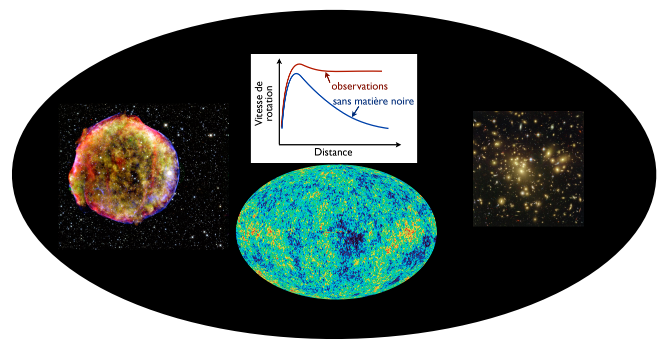


Colloque nat. Dark Energy
24 October 2018

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 ?

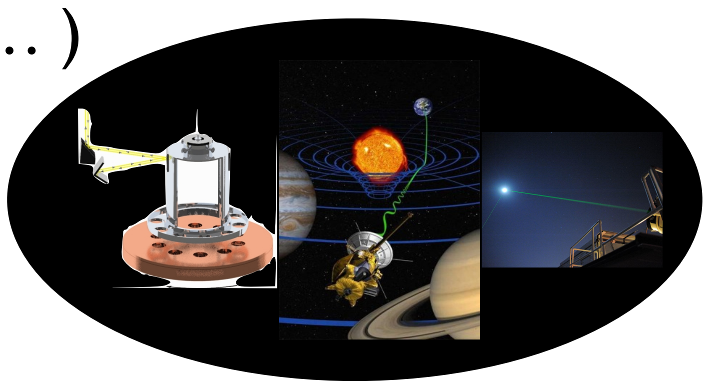


Astronomy & cosmology

(Grav. waves, SNIa, CMB, structure formation, galactic dynamics, …)

Local physics

(Solar System, **lab tests**, GNSS, …)



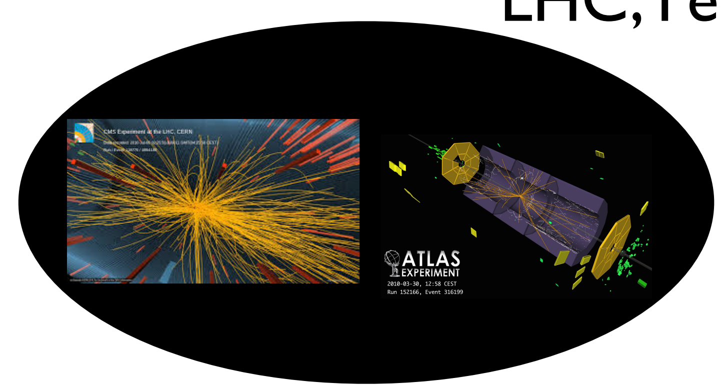
Quantum Gravity

Unification

DM and DE

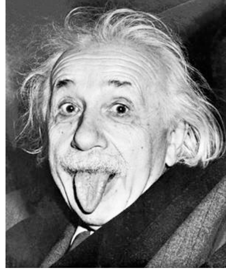
High energy

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



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

Why looking at lab scales?



Einstein Equivalence Principle

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

Principle of "minimal coupling"

see K. Thorne et al, PRD, 1972

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

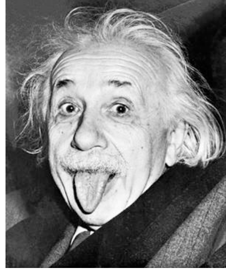
Einstein Field Equations

Space-time geometry ⟷ Energy/Matter content

Can be derived from the action

$$S_{\rm grav} = \frac{1}{2\kappa}\int d^4x \sqrt{-g}\,(R - 2\Lambda)$$

Why looking at lab scales?



Einstein Equivalence Principle

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

Principle of "minimal coupling"

see K. Thorne et al, PRD, 1972

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

Einstein Field Equations

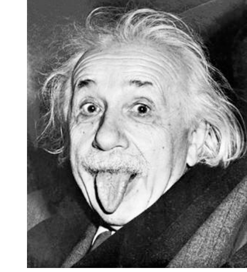
Space-time geometry ⟷ Energy/Matter content

Can be derived from the action

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

Models of DM or DE typically introduce new fields in this part of the action

Why looking at lab scales?



Einstein Equivalence Principle

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

Principle of "minimal coupling"

see K. Thorne et al, PRD, 1972

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

Einstein Field Equations

Space-time geometry ⟷ Energy/Matter content

Can be derived from the action

$$S_{\rm grav} = \frac{1}{2\kappa}\int d^4x \sqrt{-g}\,(R - 2\Lambda)$$

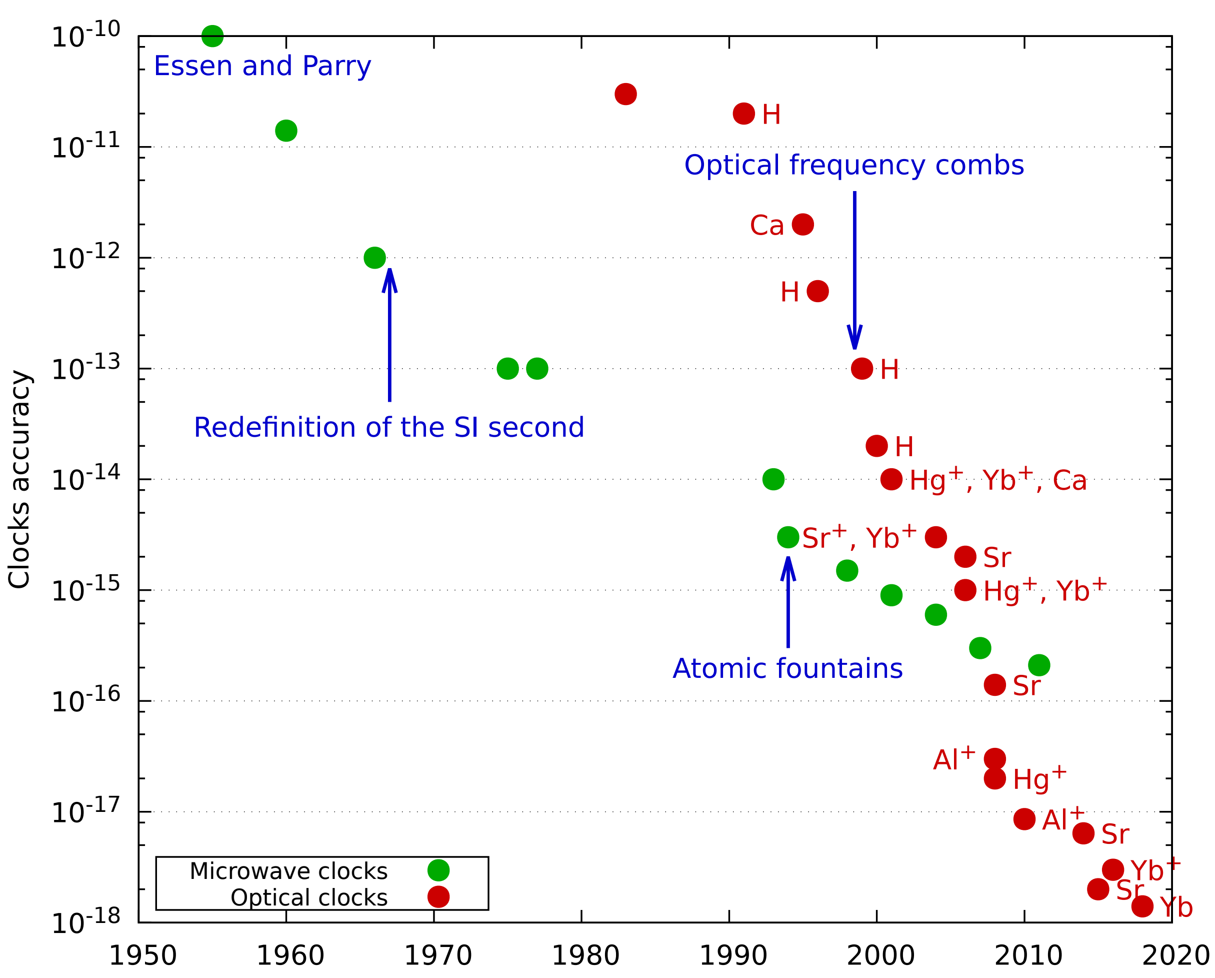
Models of DM or DE typically introduce new fields in this part of the action

What are the impacts of these additional fields on local experiments?

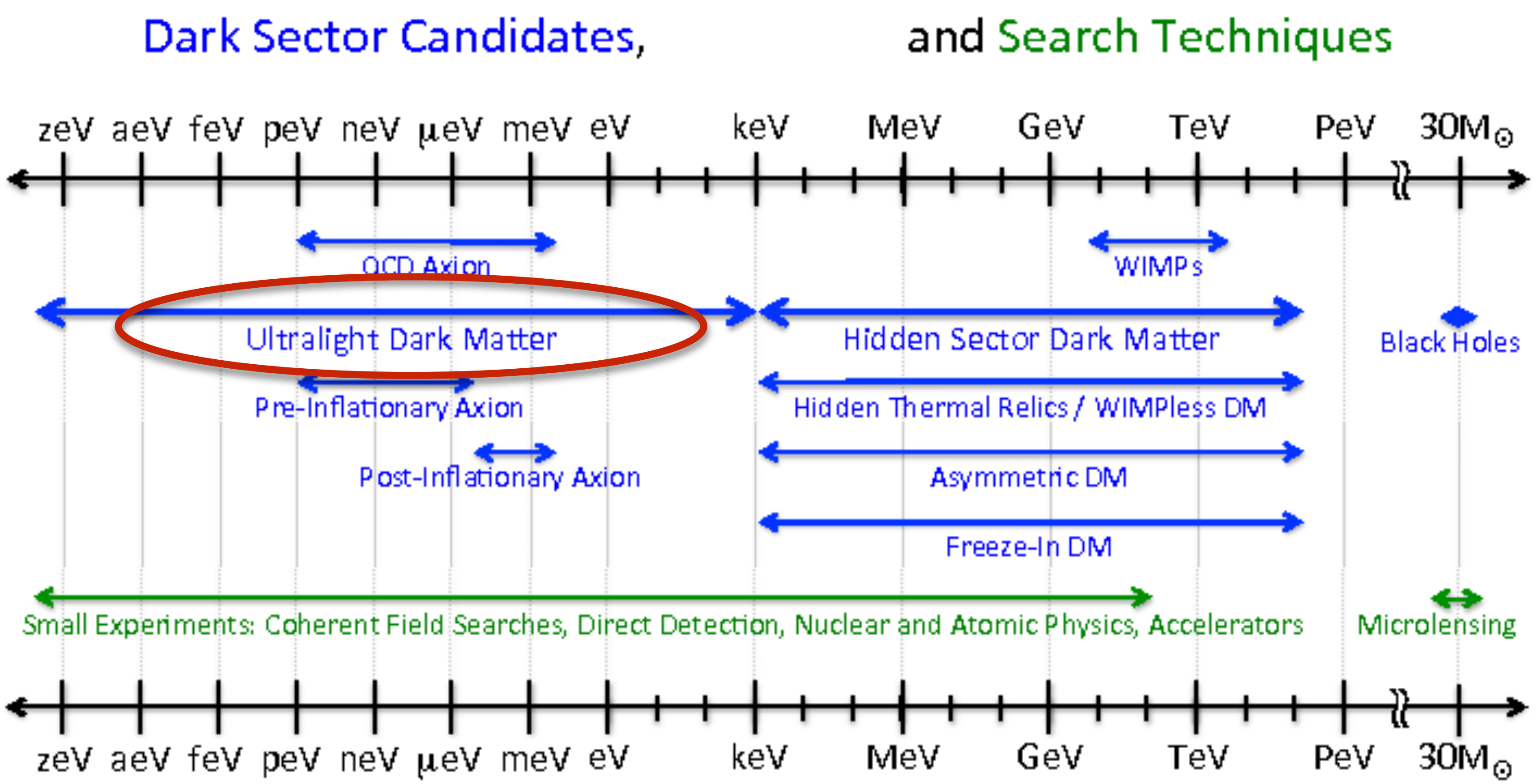
A priori no reason why there would be no coupling with SM

Laboratory experiments have several advantages

- Very high accuracy/stability
- Extremely good control over the systematics
- Reproducibility (even by different labs)
- Can easily be optimized to search for specific signatures
- “Affordable”



One example: UltraLight DM



Dark Matter can be made out of a bosonic scalar particles

Fig. from *US cosmic vision: new idea for Dark Matter*, 2017, arXiv:1707:04591

A light scalar Dark Matter model

- A massive scalar field $V(\varphi) \propto m^2\varphi^2$

$$S = \frac{1}{c}\int d^4x \frac{\sqrt{-g}}{2\kappa}\left[R - 2g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - V(\varphi)\right] + S_{\mathrm{mat}}\left[g_{\mu\nu}, \varphi\right]$$

- For low masses (< 0.1 eV), it behaves as a classical field and at cosmo scales:

$$\varphi = \varphi_0 \cos\left[\frac{mc^2}{\hbar}t\right]$$

- similar to pressureless fluid with $\rho \propto m^2\varphi_0^2$

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

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

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

This DM is expected to break the equivalence principle

- An effective Lagrangian for the scalar-matter coupling

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

see Damour and Donoghue, PRD, 2010

- Most usual couplings: linear (cfr Damour-Donoghue) or quadratic (cfr Stadnik et al)
- This leads to a space-time dependance of some constants of Nature to the scalar field

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

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

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

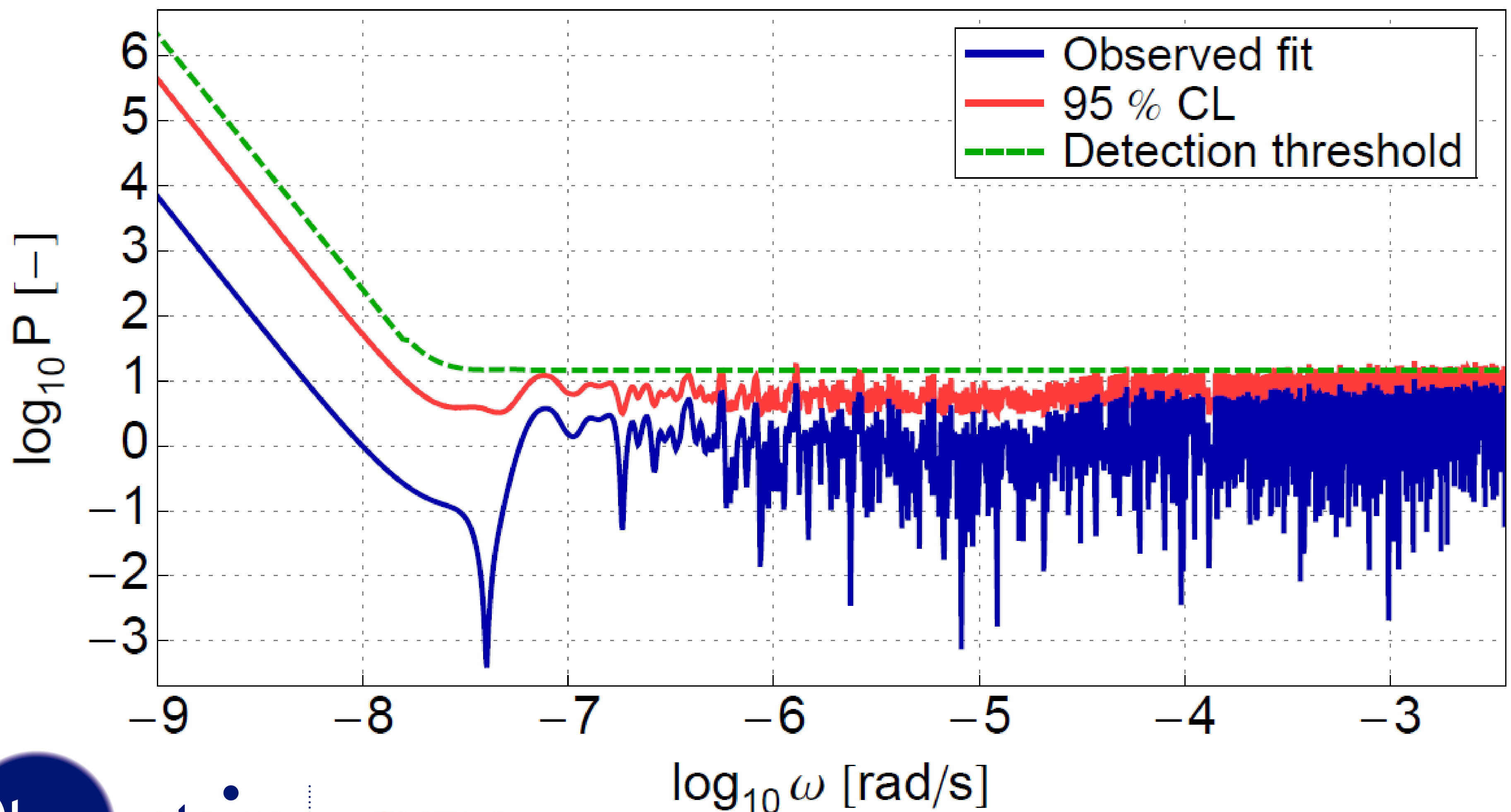
A signature of a violation of the Einstein Equivalence Principle that can be searched with atomic clocks!

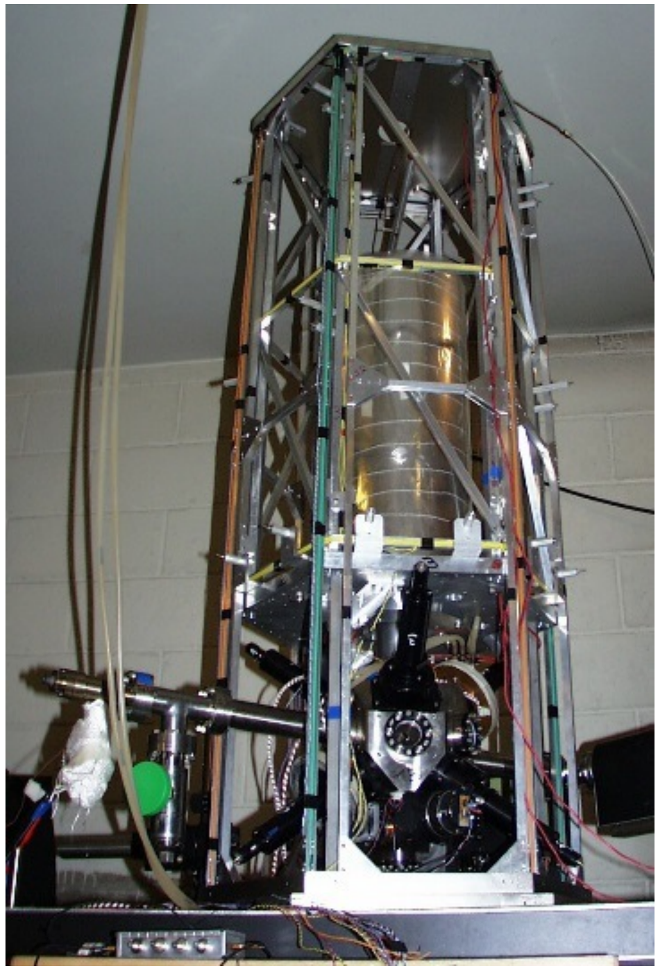
Violation of the EEP can be searched with atomic sensors

- use of more than 8 years of Cs/Rb FO2 atomic fountain data from SYRTE: high accuracy and high stability

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





No positive detection

l'Observatoire de Paris | SYRTE

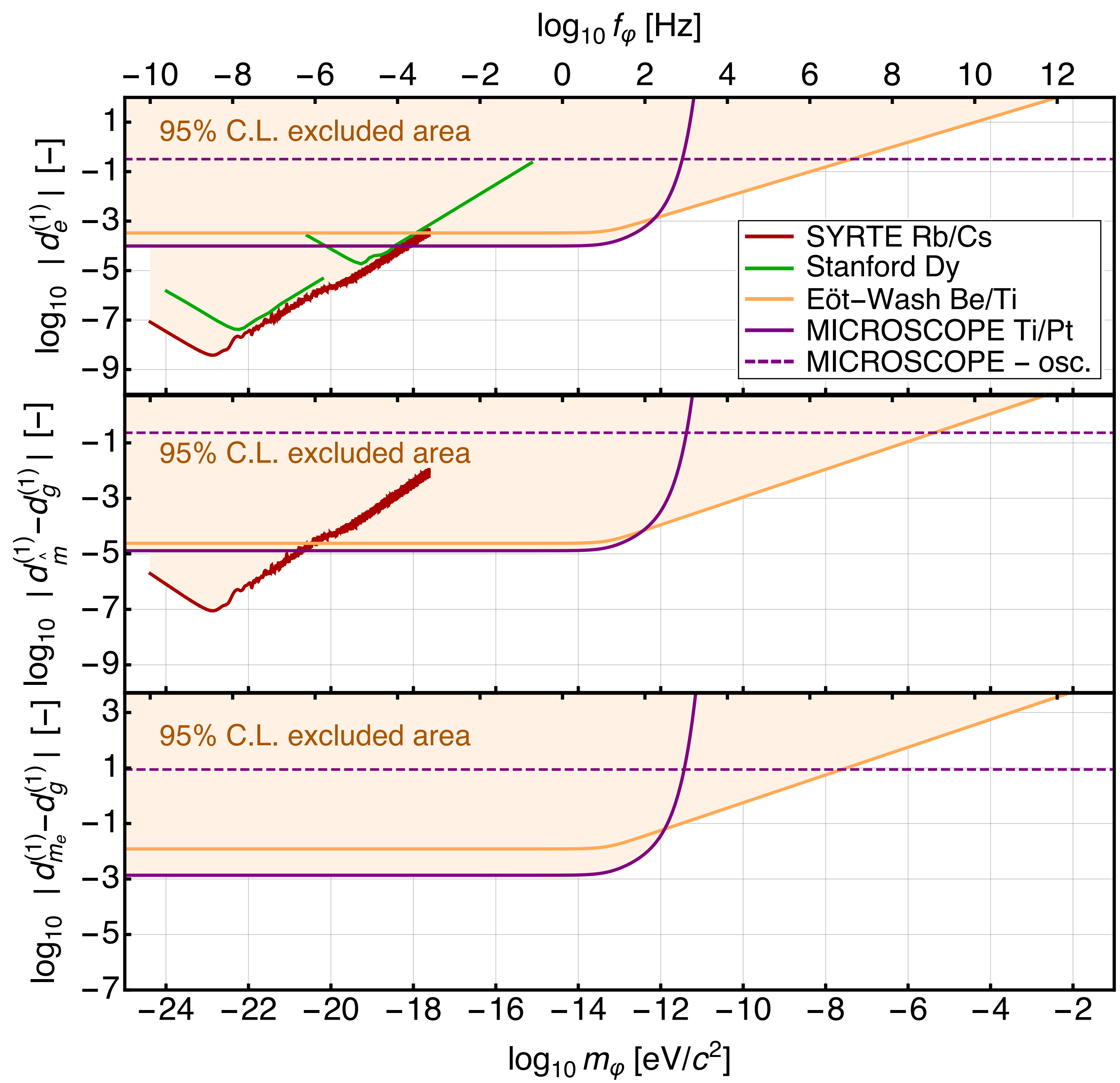
Systèmes de Référence Temps-Espace

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

Constraints on the linear couplings

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

see A. Hees et al, PRL, 2016
A. Hees et al, PRD, 2018

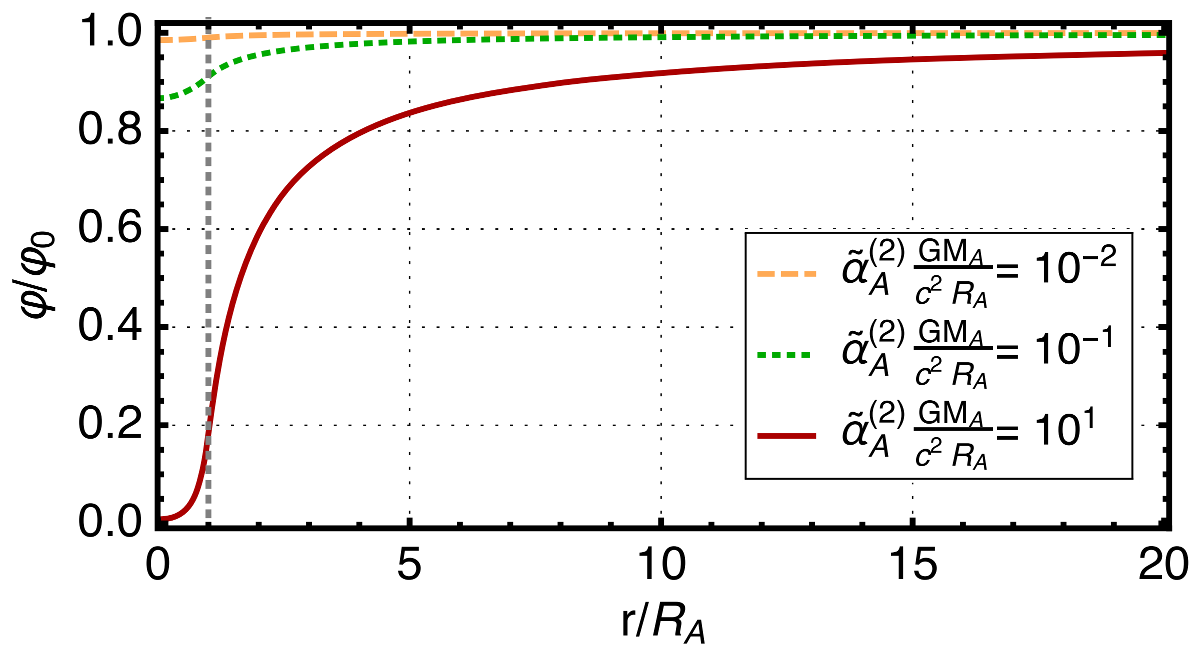


l'Observatoire de Paris | SYRTE
Systèmes de Référence Temps-Espace

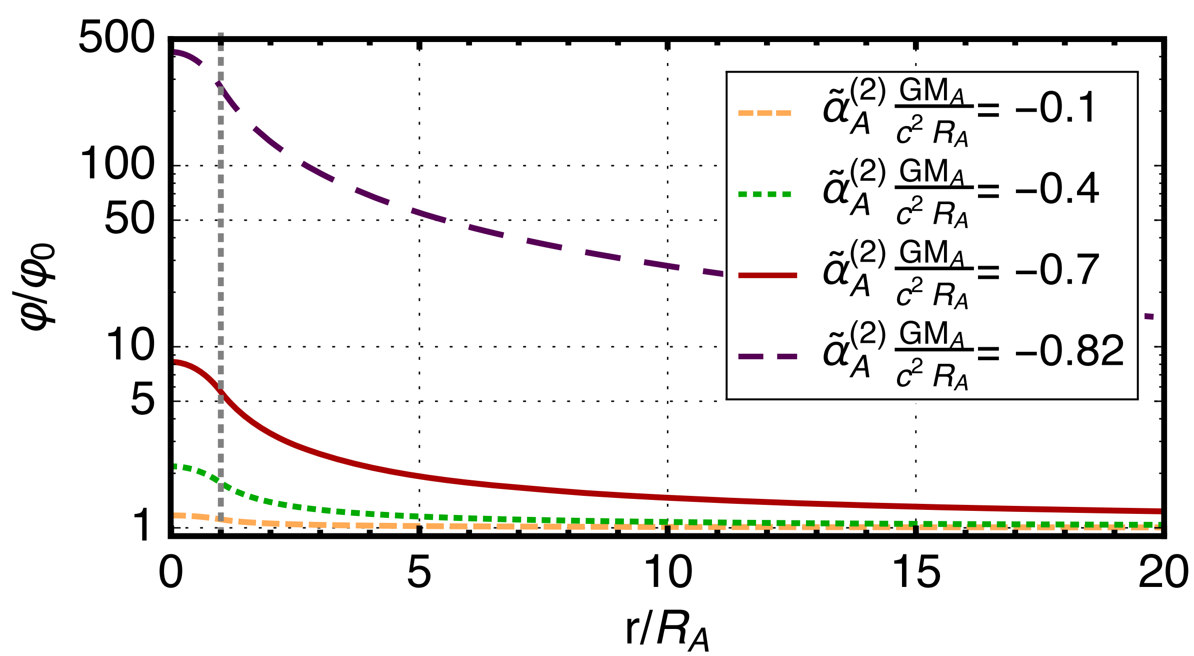
The phenomenology for the quadratic coupling is richer

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

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



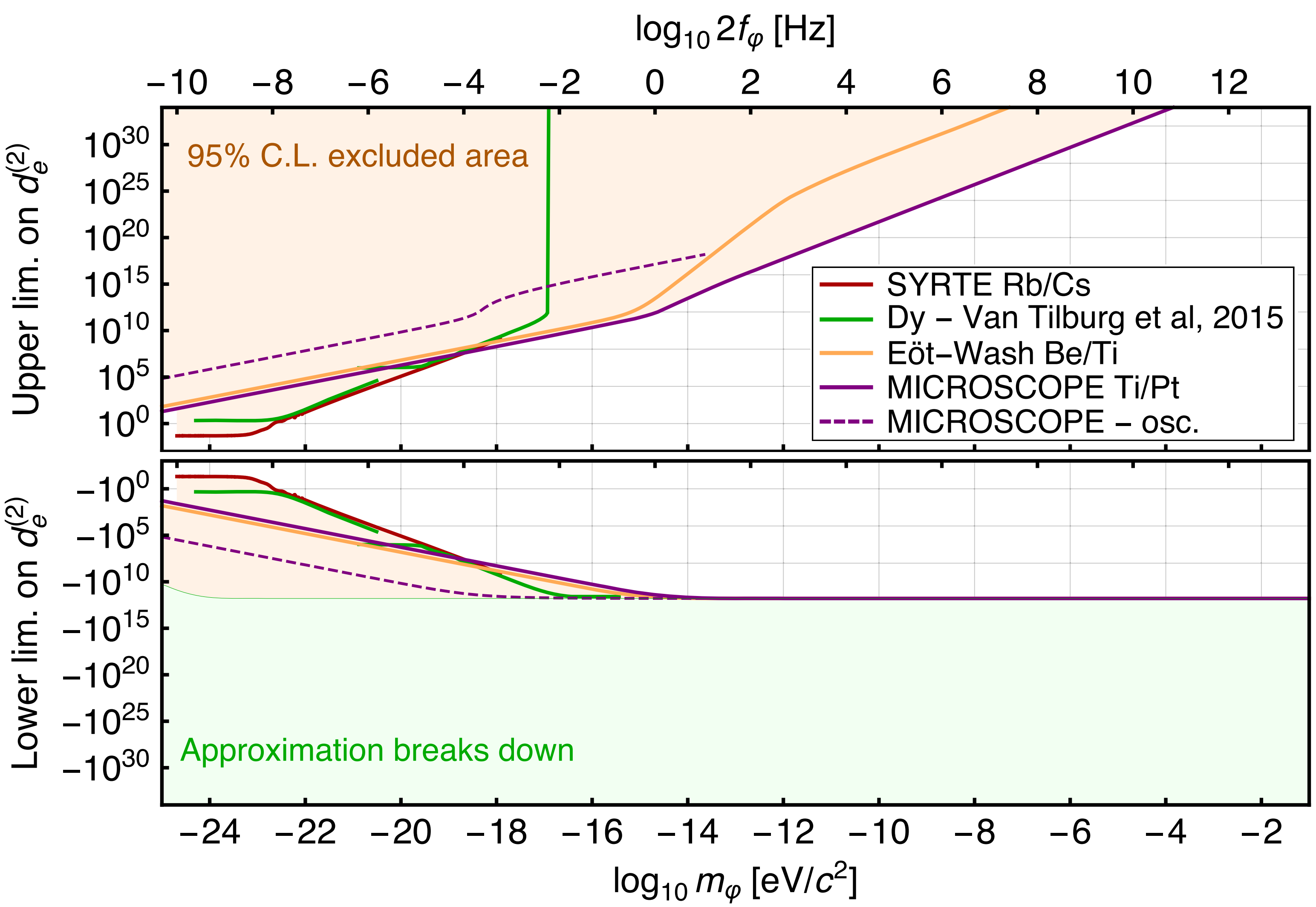
- Rich phenomenology: scalarization / screening



see A. Hees et al, PRD, 2018

Constraints on the quadratic couplings

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



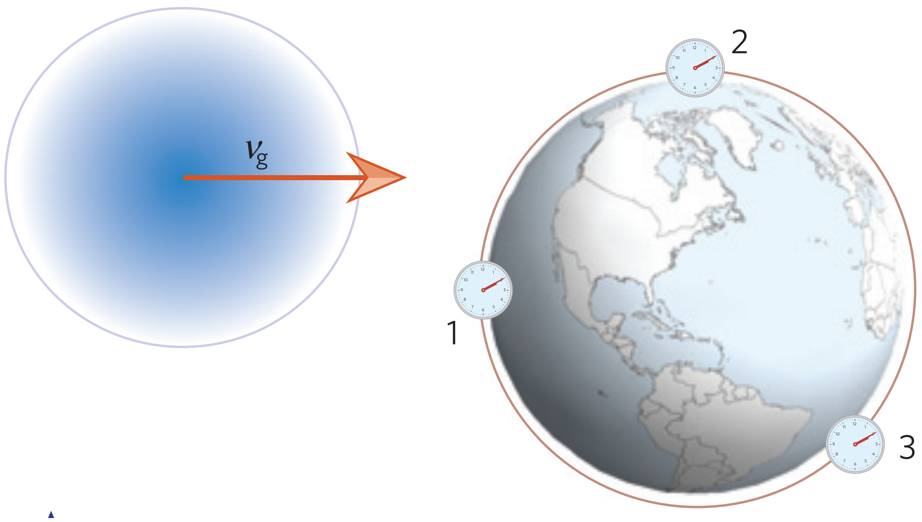
- Similar results obtained for the other couplings

See A. Hees et al, PRD, 2018

l'Observatoire de Paris | SYRTE

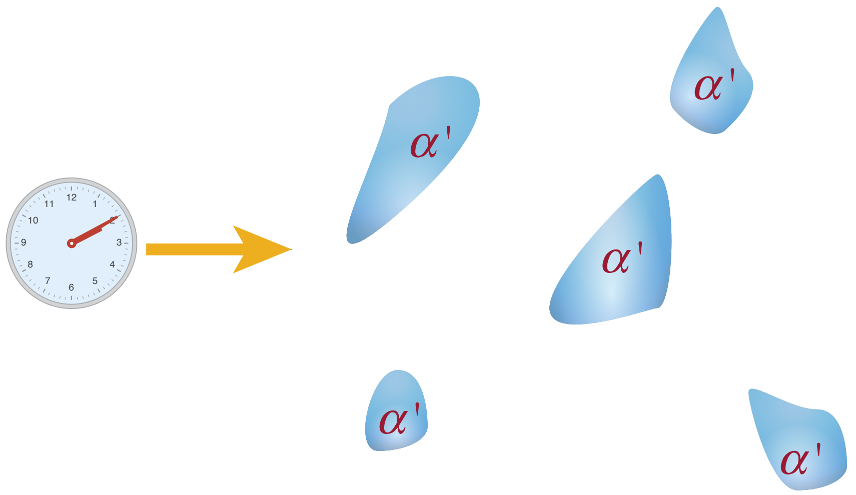
Systèmes de Référence Temps-Espace

Example II: DM as a scalar topological default



- Topological defect: carry energy and can be a DM candidate

- Frequencies of the clocks will change when topological defaults cross the Earth

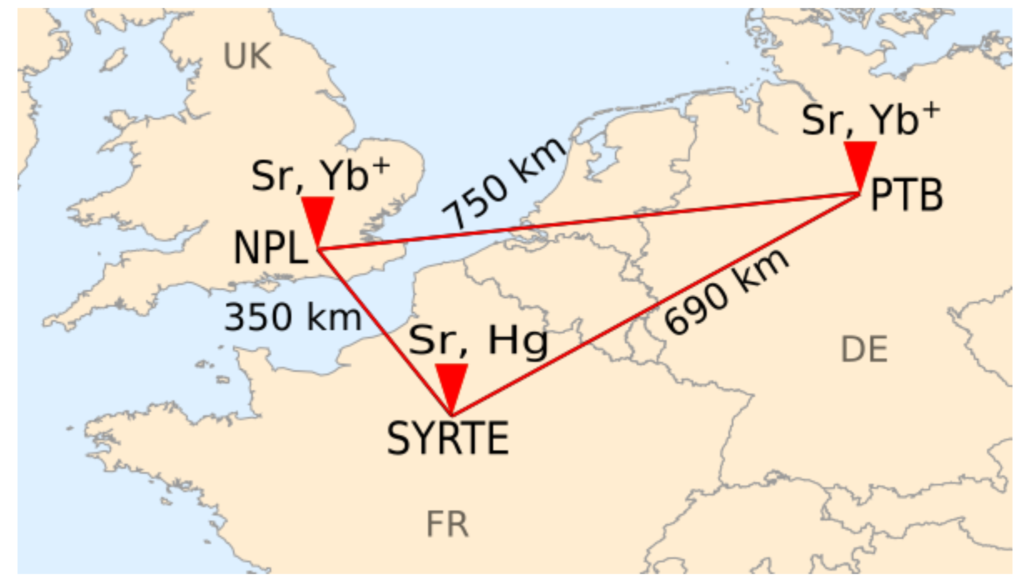


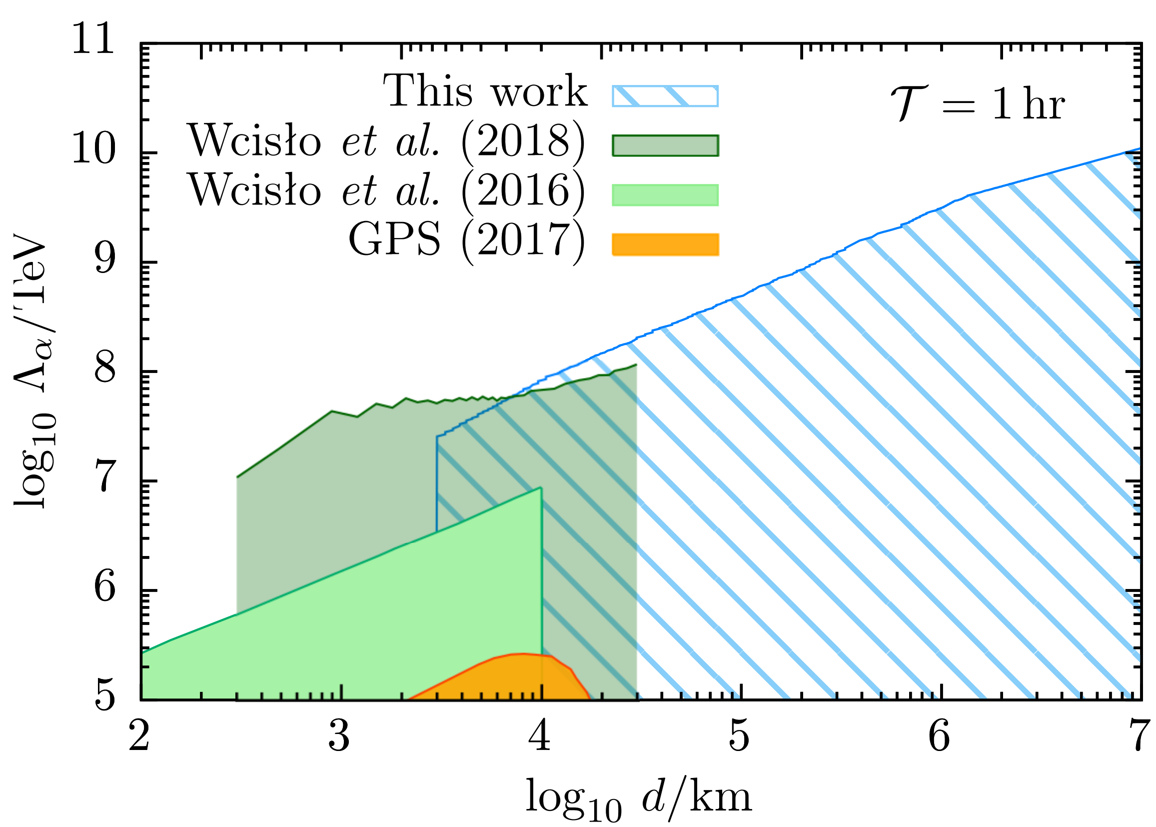
From Derevianko and Pospelov, Nature Phys., 2014

Example II: DM as a scalar topological default

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

- Fiber network: high accuracy long-distance clocks comparison
- Different clocks: Hg/Sr/Yb





- Simulations show that this dataset is very promising
- Data analysis on-going

Work by Benjamin Roberts @SYRTE

Temporal variations of fundamental constants seem unaffected by "screening mechanism"

- Screening mechanism: deviations from GR "hidden" in the Solar System $\gamma_{\mathrm{PPN}} \approx 1$

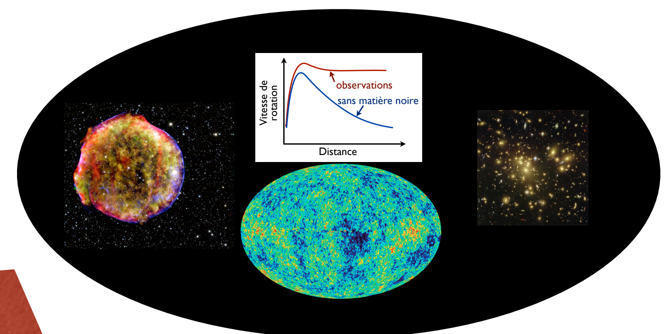
PRL **107,** 251102 (2011) PHYSICAL REVIEW LETTERS week ending 16 DECEMBER 2011

Constraints on Shift-Symmetric Scalar-Tensor Theories with a Vainshtein Mechanism from Bounds on the Time Variation of *G*

Eugeny Babichev,[1,2] Cédric Deffayet,[2,3] and Gilles Esposito-Farèse[3]
[1]*Laboratoire de Physique Théorique d'Orsay, Bâtiment 210, Université Paris-Sud 11, F-91405 Orsay Cedex, France*
[2]*AstroParticule & Cosmologie, UMR 7164-CNRS, Université Denis Diderot-Paris 7, CEA, Observatoire de Paris, 10 rue Alice Domon et Léonie Duquet, F-75205 Paris Cedex 13, France*
[3]*GReCO, Institut d'Astrophysique de Paris, UMR 7095-CNRS, Université Pierre et Marie Curie-Paris 6, 98 bis boulevard Arago, F-75014 Paris, France*

- *"This mechanism, if efficient to hide the effects of the scalar field at short distance and in the static approximation can in general not alter the cosmological time evolution of the scalar field"*

Are there other signatures to be searched in lab data that can help constraining DE models?



Astronomy & cosmology

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

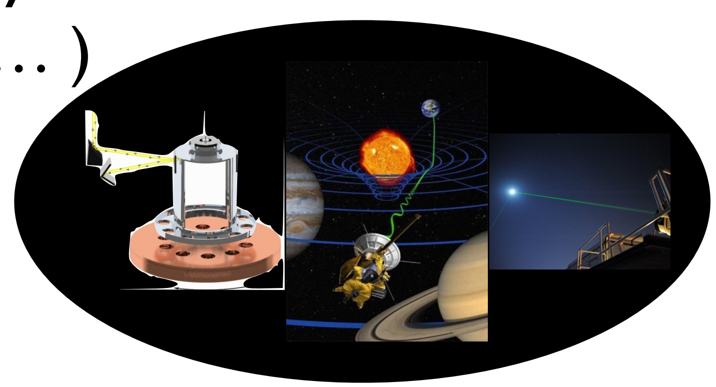
Quantum Gravity

Unification

DM and DE

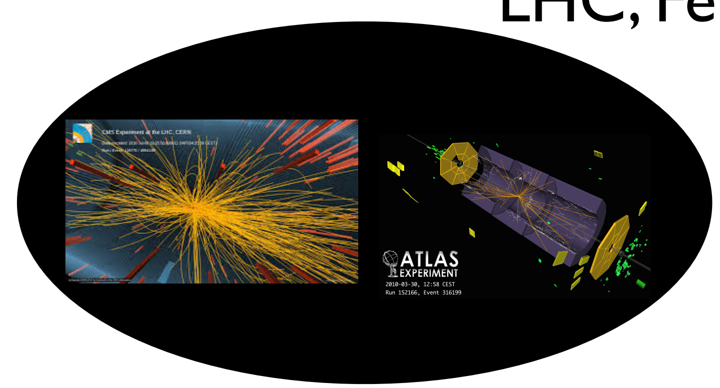
Local physics

(Solar System, **lab tests**, GNSS, …)



High energy

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



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

Another example: the chameleon

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{2\kappa} - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right] + S_{\rm mat}\left[\Psi, e^{2\phi/M}g_{\mu\nu}\right]$$

with $$V(\phi) = \Lambda^4 + \frac{\Lambda^{4+n}}{M_{pl}^n\phi^n}$$

- Screening mechanism: explain cosmic expansion while hiding the scalar field in region of "high density"

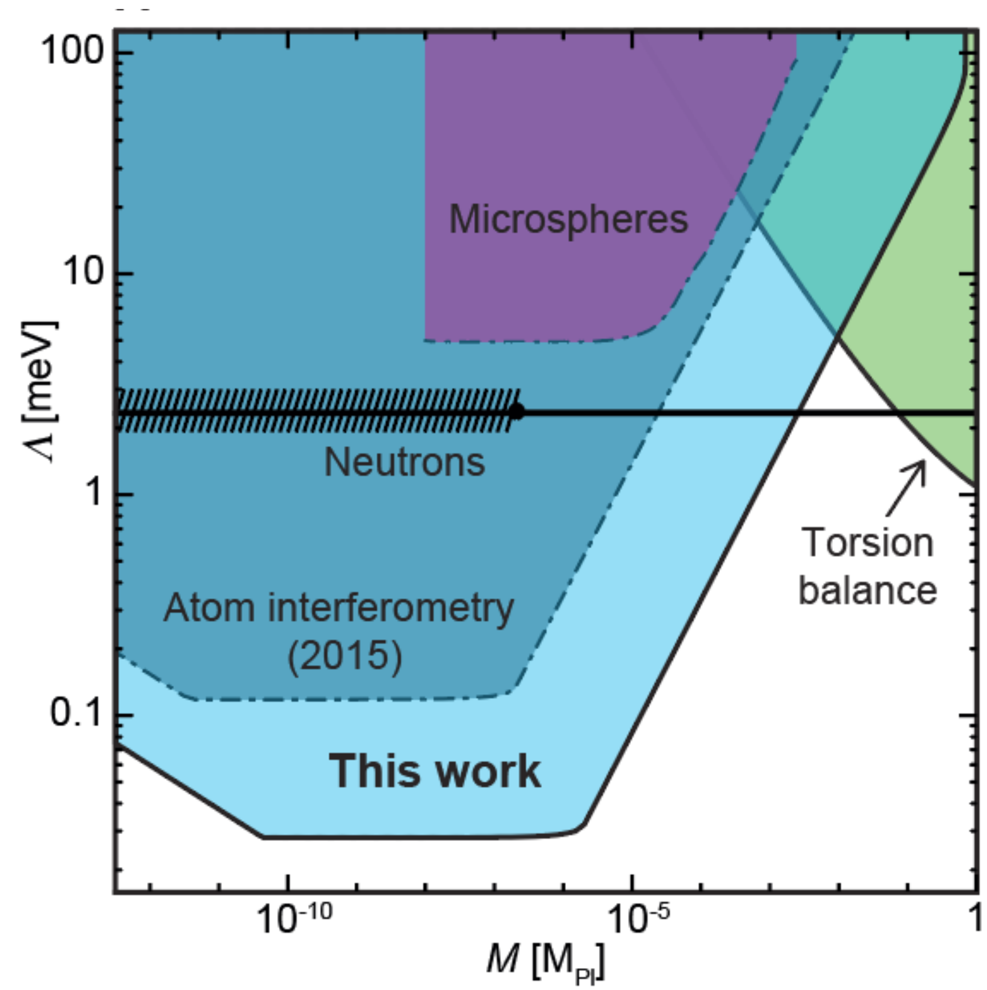
Khoury and Weltmann, PRL and PRD, 2004

Atom-interferometry constraints on dark energy

P. Hamilton,[1*] M. Jaffe,[1] P. Haslinger,[1] Q. Simmons,[1] H. Müller,[1,2]† J. Khoury[3]

Science, 2013

Jaffe, M., et al, Nature Physics, 2017



Some of the best constraints on chameleons are from laboratory experiments

Another example: a scalar model of DE

from Martins et al, JCAP 08, 47, 2015

$$\mathcal{L} = \frac{R}{16\pi G} - \frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1 + d_e\phi}{4} F_{\mu\nu}F^{\mu\nu} + \ldots$$

Constraints on DE in a specific model

from Martins et al, JCAP 08, 47, 2015

- Considered to model Dark Energy. The DE equation of state is characterized by

$$w(z) = \frac{p}{\rho} = \frac{\dot{\phi}^2 - 2V(\phi)}{\dot{\phi}^2 + 2V(\phi)}$$

- Combining cosmological data with clocks (1-2-3σ conf. level)

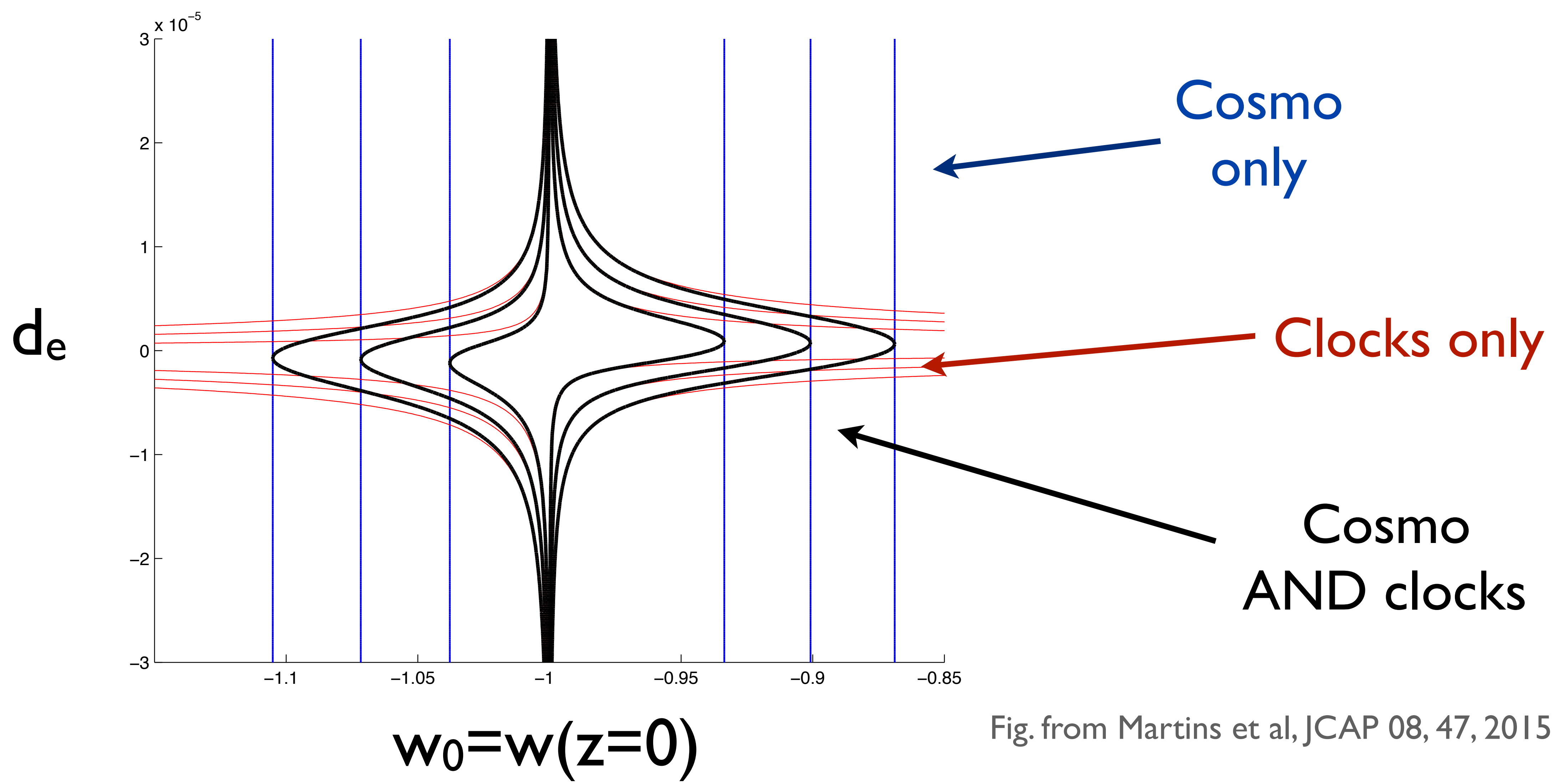


Fig. from Martins et al, JCAP 08, 47, 2015