Testing dark energy models with atom interferometry

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Outline:

Dark energy and screened fifth forces

How to search for screening

Atom interferometry constraints

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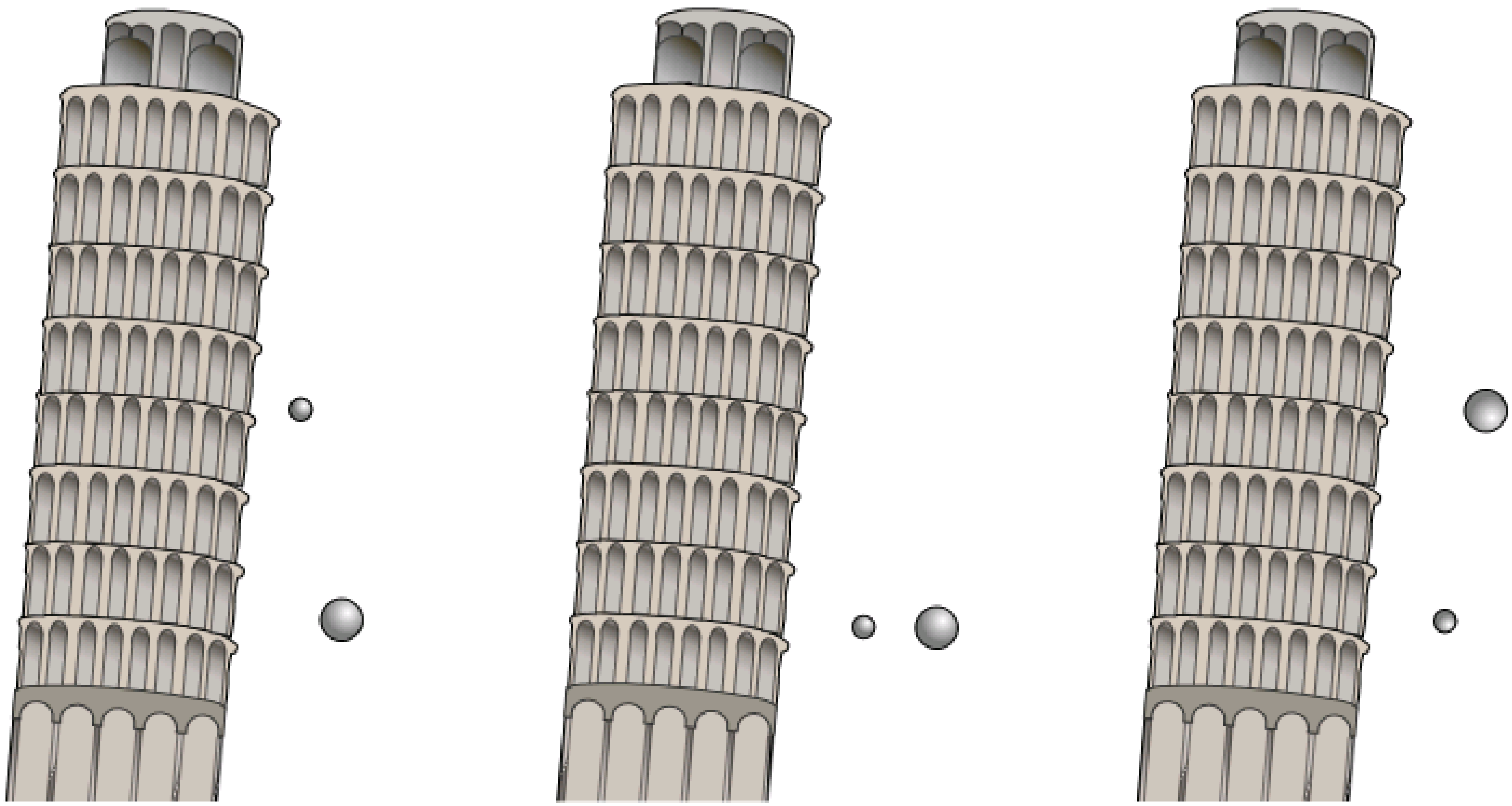
LEVERHULME TRUST

A Very Old Idea

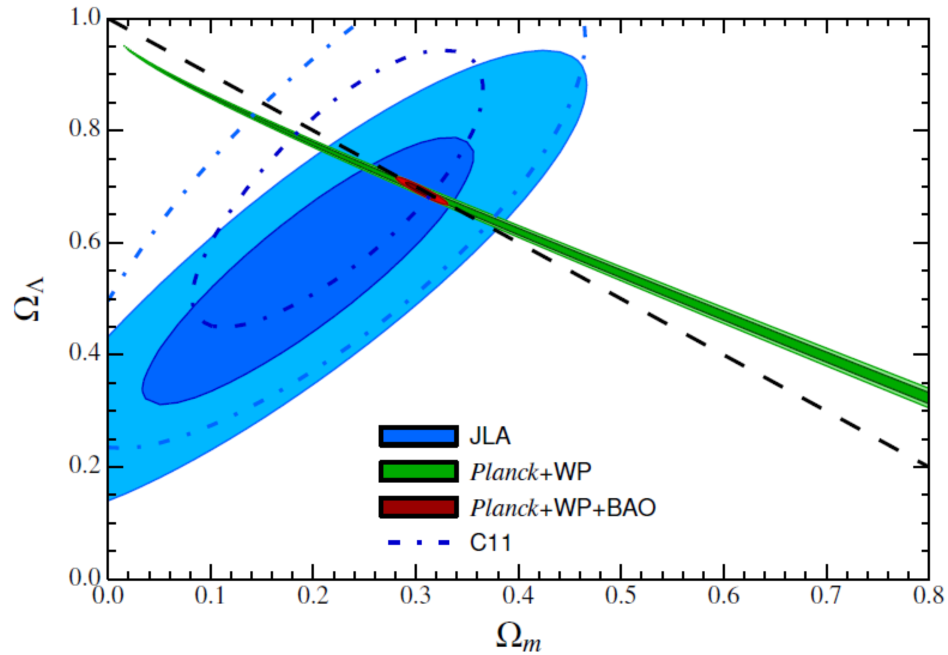
Do large objects and small objects fall at the same rate?



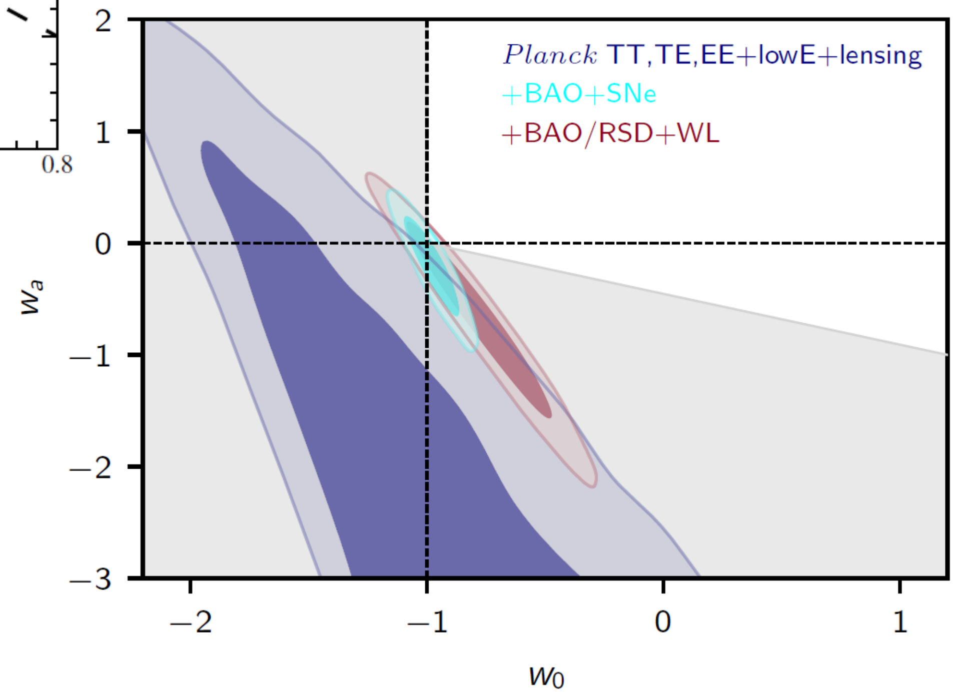
Old idea | Galileo | Dark Energy?

Image credit: Theresa Knott

Dark Energy Today



$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$



Equation of state:

$$w = w_0 + (1 - a)w_a$$

Betoule et al. (2014) Planck Collaboration. (2018)

The Cosmological Constant Problem

Vacuum fluctuations of standard model fields generate a large cosmological constant-like term

Expected:

$$\rho^{vac} \sim M^4$$

Observed:

$$\rho_\Lambda \sim (10^{-3}\ \mathrm{eV})^4$$

Phase transitions in the early universe also induce large changes in the vacuum energy

Such a large hierarchy is not protected in a quantum theory

Solutions to the Cosmological Constant Problem

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

There are new types of matter in the universe

- Quintessence directly introduces new fields
- New, light (fundamental or emergent) scalars

The theory of gravity is wrong

- General Relativity is the unique interacting theory of a Lorentz invariant, massless, helicity-2 particle

  Papapetrou (1948). Weinberg (1965).

- New physics in the gravitational sector will introduce new degrees of freedom, typically Lorentz scalars

Simple Scalar Tensor Theories

Jordan and Einstein frame for a Brans-Dicke theory

$$S = \int d^4x \sqrt{-\tilde{g}} \phi \tilde{R} + S_m[\tilde{g}_{\mu\nu}, \psi_m]$$

$$= \int d^4x \sqrt{-g} \left[R + \frac{3\Box\phi}{\phi} - \frac{9}{2}(\nabla \ln \phi)^2 \right] + S_m[\phi^{-1} g_{\mu\nu}, \psi_m]$$

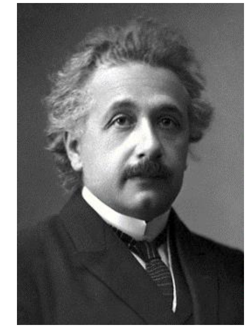
More general coupling

$$S = \int d^4x \sqrt{-g} F(\phi) R = \int d^4x \sqrt{-\tilde{g}} \tilde{R}$$

$$\tilde{g}_{\mu\nu} = F(\phi) g_{\mu\nu}$$

Dicke, Brans (1961). Jordan (1959)

Jordan vs Einstein Frame



Jordan Frame

- Scalar field coupled directly to gravity
- No direct coupling to matter
- Matter fields move on geodesics of a metric which depends on spin 0 and spin 2 fields

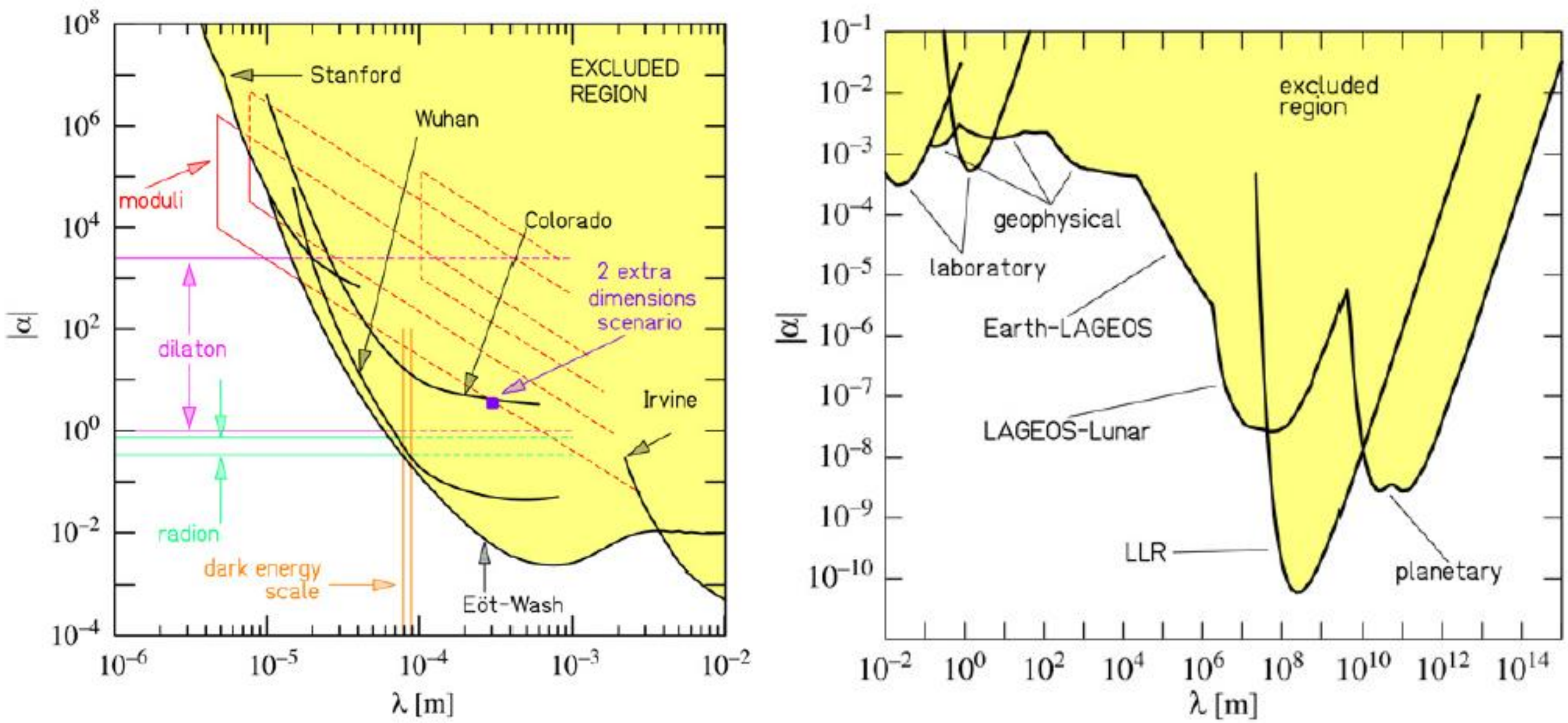
Einstein Frame

- Scalar field coupled directly to matter
- No non-minimal couplings to gravity
- Matter fields don’t move on geodesics of the metric, as they also experience a fifth force

New Fields and New Forces

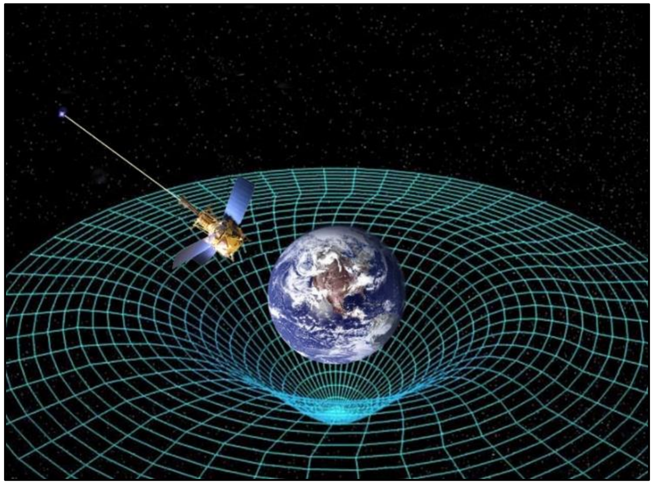
If the new physics is linear, a fifth force is excluded to a high degree of precision in the solar system

$$V(r) = -\frac{G\alpha m_1 m_2}{r} e^{-m_\phi r}$$



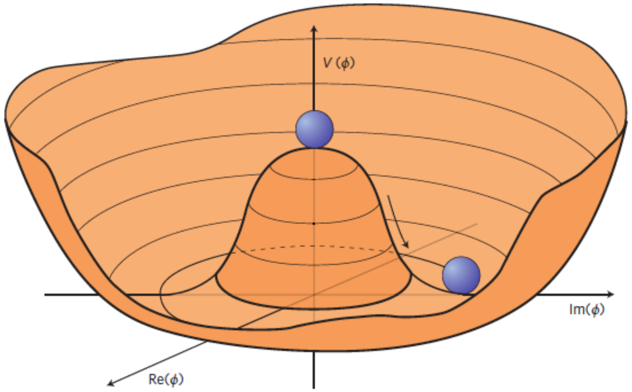
Adelberger et al. (2009)

Is the New Physics Linear?



General relativity is a non-linear theory

Higgs scalar has a non-linear potential



[I will return to the question of whether you can forbid a coupling to matter at the end of this talk]

Image credits: NASA, John Ellis (1312.5672)

New Physics is Non-linear: Screening Mechanisms

- **Locally weak coupling**

Symmetron and varying dilaton models

Pietroni (2005). Olive, Pospelov (2008). Hinterbichler, Khoury (2010). Brax et al. (2011).

- **Locally large mass**

Chameleon models

Khoury, Weltman (2004).

- **Locally large kinetic coefficient**

Vainshtein mechanism, Galileon and k-mouflage models

Vainshtein (1972). Nicolis, Rattazzi, Trincherini (2008).
Babichev, Deffayet, Ziour (2009).

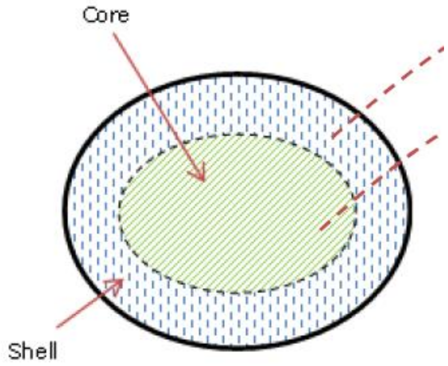
Screening Phenomenology

Compare to Yukawa fifth force

$$V(r) = -\frac{G\alpha m_1 m_2}{r} e^{-m_\phi r}$$

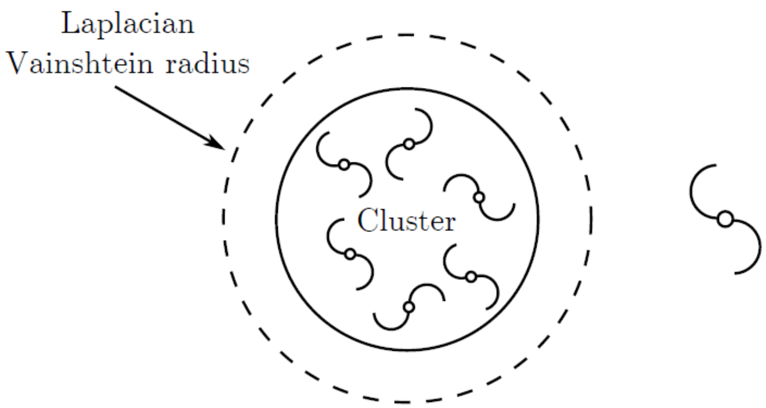
Change the way in which matter sources the scalar field

- thin-shell effect



Change the dependence on distance

- Vainshtein screening



The Chameleon

A scalar field with canonical kinetic terms, non-linear potential, and direct coupling to matter

$$S_\phi = \int \mathrm{d}^4x\sqrt{-g}\left(-\frac{1}{2}(\partial\phi)^2 - V(\phi) - A(\phi)\rho_\mathrm{m}\right)$$

$$V(\phi) = \frac{\Lambda^5}{\phi}, \quad A(\phi) = \frac{\phi}{M} \ ,$$

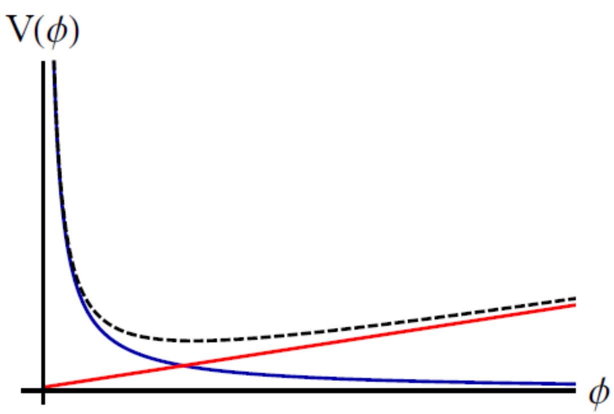
Khoury, Weltman. (2004). Image credit: Nanosanchez
Equivalent description as Higgs portal model:
CB, Copeland, Millington, Spannowsky. (2018)

Varying Mass

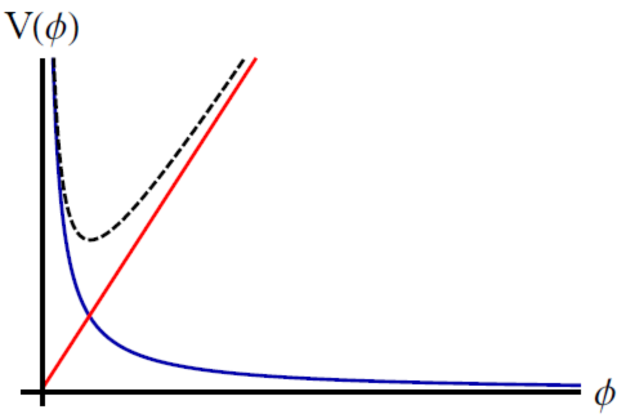
Dynamics governed by an effective potential

$$V_{\text{eff}} = \frac{\Lambda^5}{\phi} + \frac{\phi}{M}\rho$$

Non-linearities in the potential mean that the mass of the field depends on the local energy density



Low density

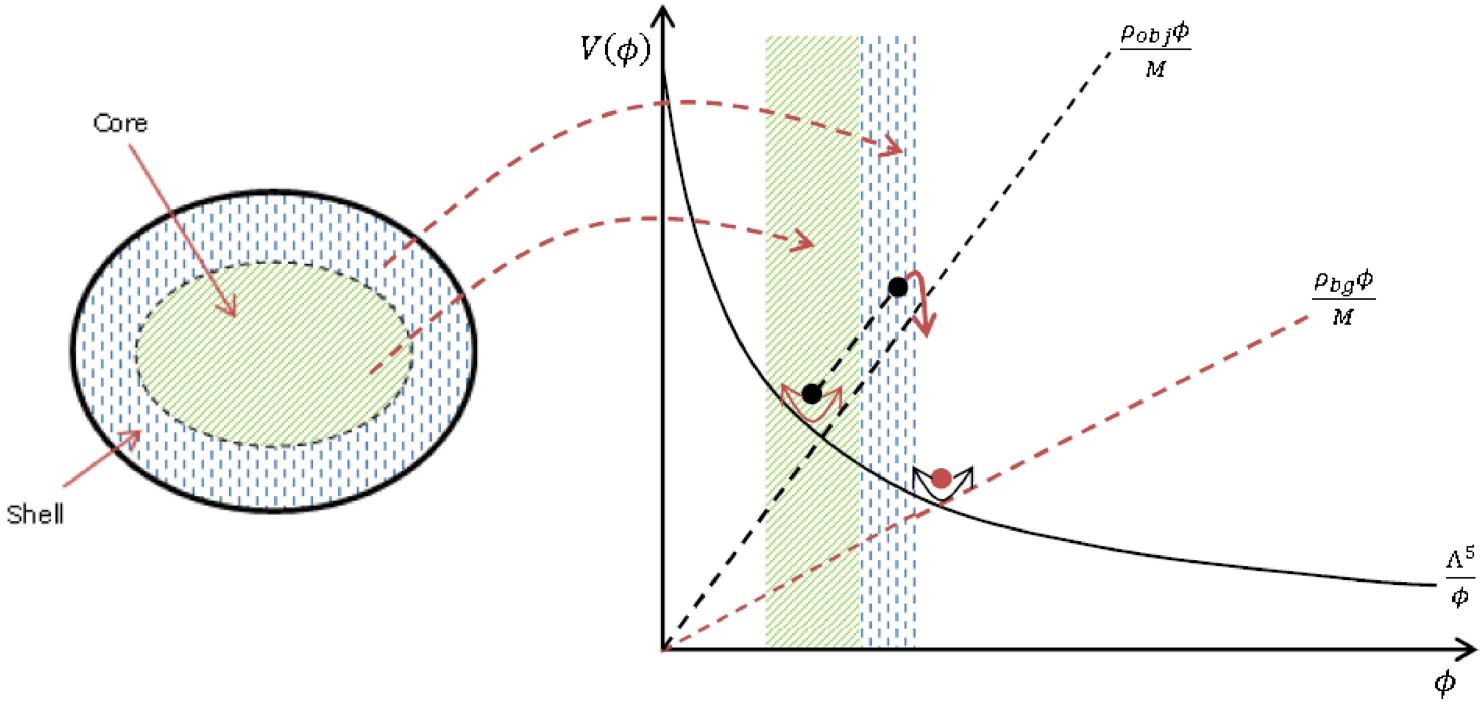


High density

Equivalent description as Higgs portal model:
CB, Copeland, Millington, Spannowsky. (2018)

Chameleon Screening

The increased mass makes it hard for the chameleon field to adjust its value



The chameleon potential well around ‘large’ objects is shallower than for canonical light scalar fields

CB, Copeland, Stevenson. (2015)

The Scalar Potential

Around a static, spherically symmetric source of constant density

$$\phi = \phi_{\rm bg} - \lambda_A \frac{1}{4\pi R_A} \frac{M_A}{M} \frac{R_A}{r} e^{-m_{\rm bg} r}$$

$$\lambda_A = \begin{cases} 1 \, , & \rho_A R_A^2 < 3M\phi_{\rm bg} \\ 1 - \frac{S^3}{R_A^3} \approx 4\pi R_A \frac{M}{M_A}\phi_{\rm bg} \, , & \rho_A R_A^2 > 3M\phi_{\rm bg} \end{cases}$$

This determines how ‘screened’ an object is from the chameleon field

Ideal experiments use unscreened test masses e.g. atomic nuclei, neutrons, microspheres

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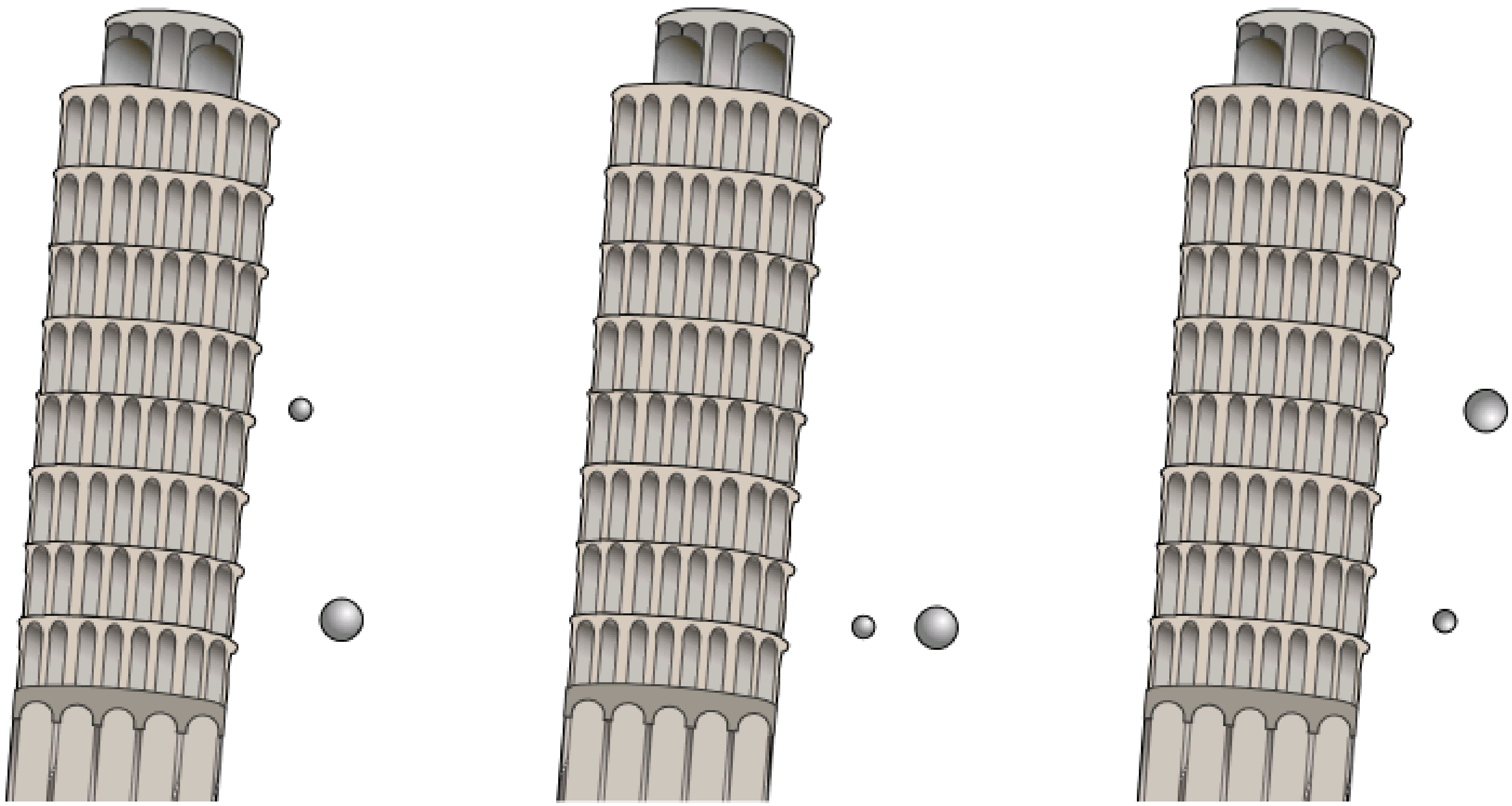


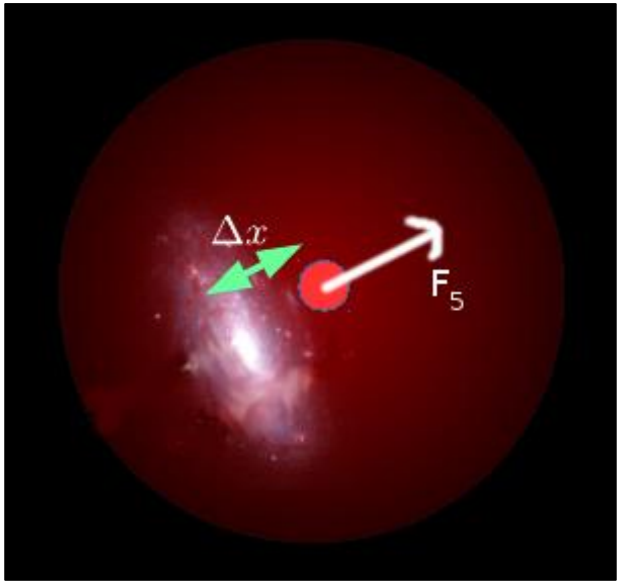
Old idea | Galileo | Dark Energy?

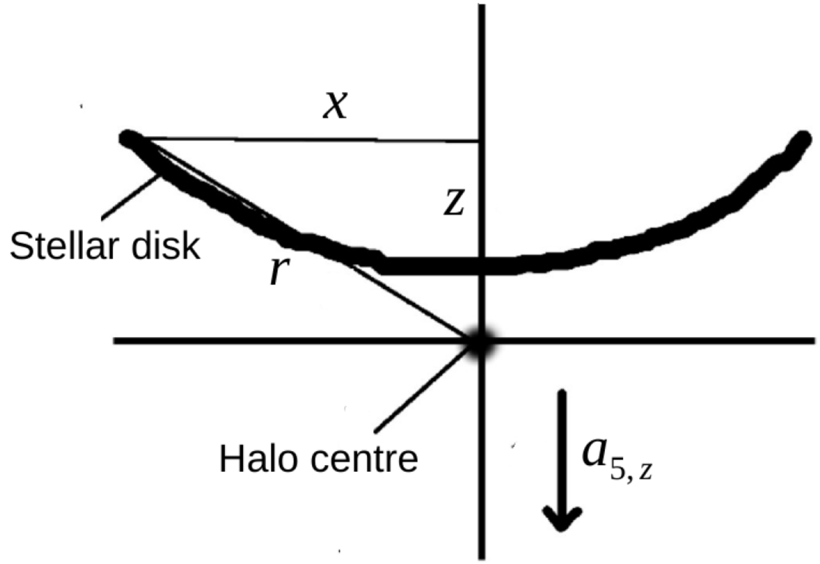
Image credit: Theresa Knott

Astrophysical Hints

Different components of a dwarf galaxy may fall in a gravitational field at different rates

- Stars are screened, gas and dark matter are not
- Look for gas-star offsets & warping of galactic discs





Desmond, Ferreira, Lavaux, Jasche. (2018)
Tests proposed by Hui, Nicolis, Stubbs. (2009). Jain, VanderPlas. (2011)

Astrophysical Hints

Correlated with expected direction of 5th force:

Evidence for offsets using ~10,000 HI detections from the ALFALFA survey

Evidence for galaxy warps using ~4,000 images from the Nasa Sloan Atlas

Both consistent with screened force, $M \sim 10\, M_{Pl}$, and background Compton wavelength ~1.8 Mpc

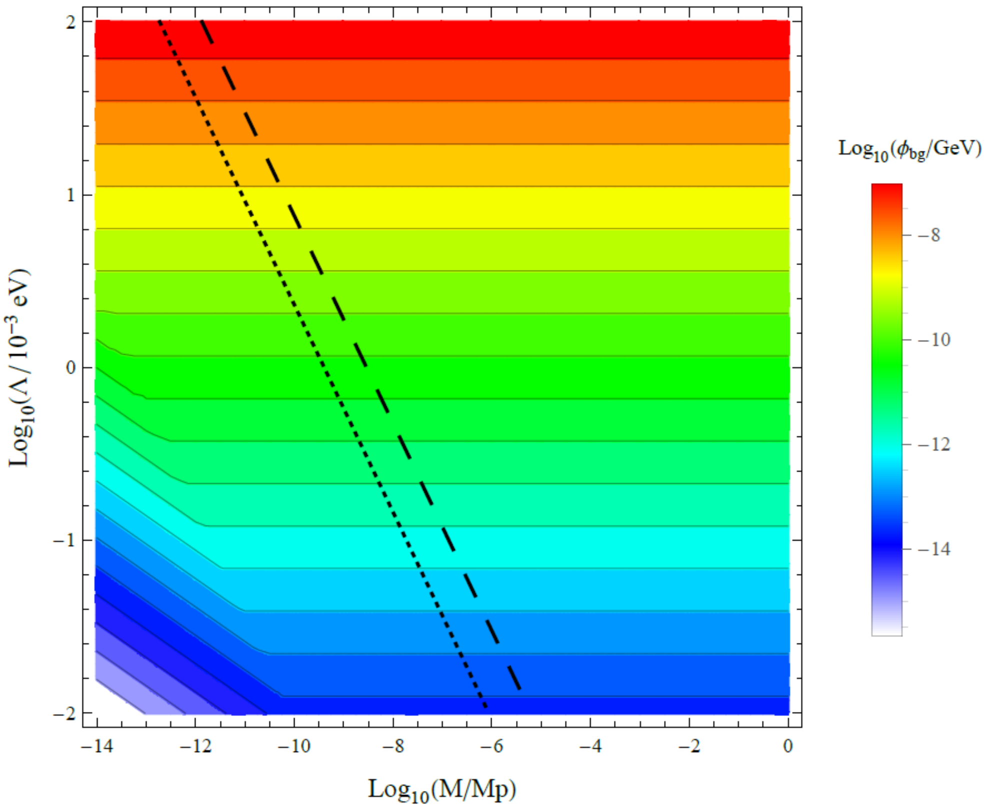
~7σ significance, but potentially challenging systematics

Desmond, Ferreira, Lavaux, Jasche. (2018)
Tests proposed by Hui, Nicolis, Stubbs. (2009). Jain, VanderPlas. (2011)

Why Atom Interferometry?

In a spherical vacuum chamber, radius 10 cm, pressure 10^{-10} Torr

Atoms are unscreened above black lines
(dashed = caesium, dotted = lithium)



CB, Copeland, Hinds. (2015)

Atom Interferometry

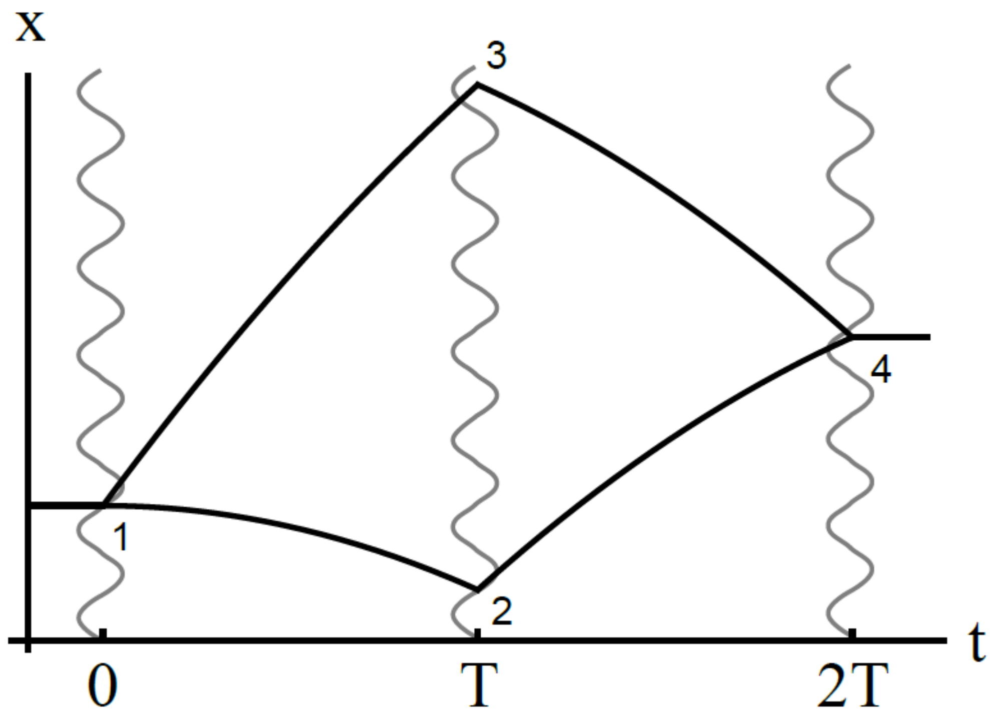
An interferometer where the wave is made of atoms

Atoms can be moved around by absorption of laser photons

Photon Momentum = k
Atom in ground state

Atom in excited state
with velocity = V

Atom Interferometry



Probability measured in excited state at output

$$P = \cos^2\left(\frac{kaT^2}{2}\right)$$

The Atomic Wavefunction

The probability of measuring atoms in the unexcited state at the output of the interferometer is a function of the wave function phase difference along the two paths

$$P \propto \cos^2\left(\frac{\varphi_1 - \varphi_2}{2}\right)$$

For freely falling atoms the contribution of each path has a phase proportional to the classical action

$$\theta[x(t)] = Ce^{(i/\hbar)S[x(t)]}$$

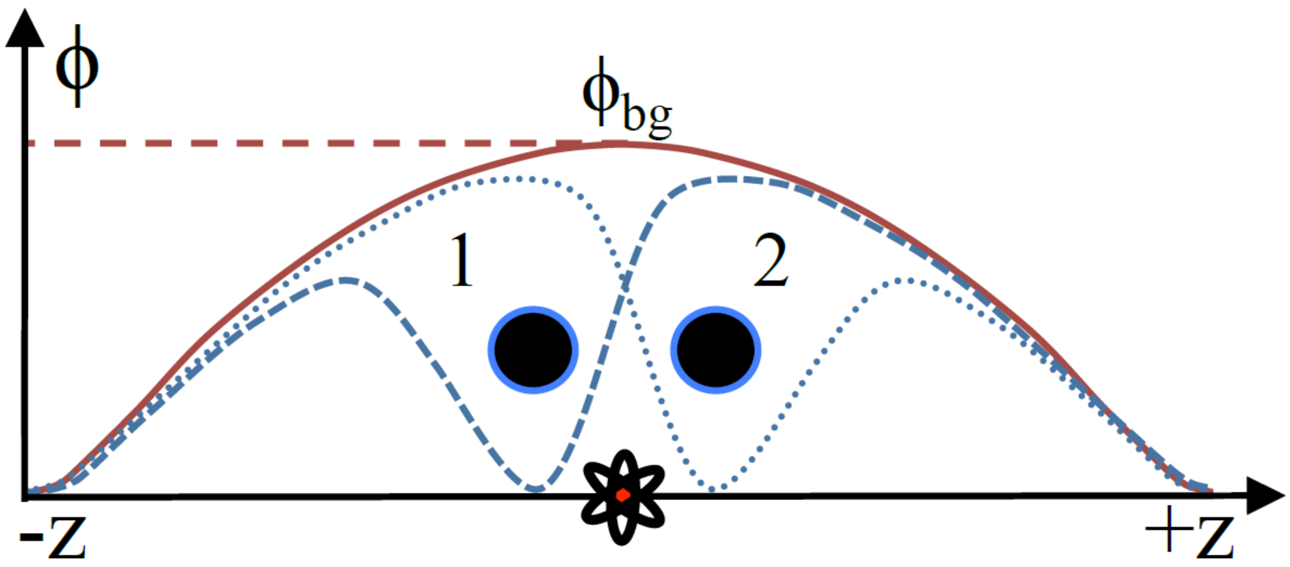
Additional contributions from interactions with photons, proportional to

$$(i/\hbar)(\omega t - \vec{k} \cdot \vec{x})$$

Atom Interferometry for Chameleons

The walls of the vacuum chamber screen out any external chameleon forces

Macroscopic spherical mass, produces chameleon potential felt by cloud of atoms

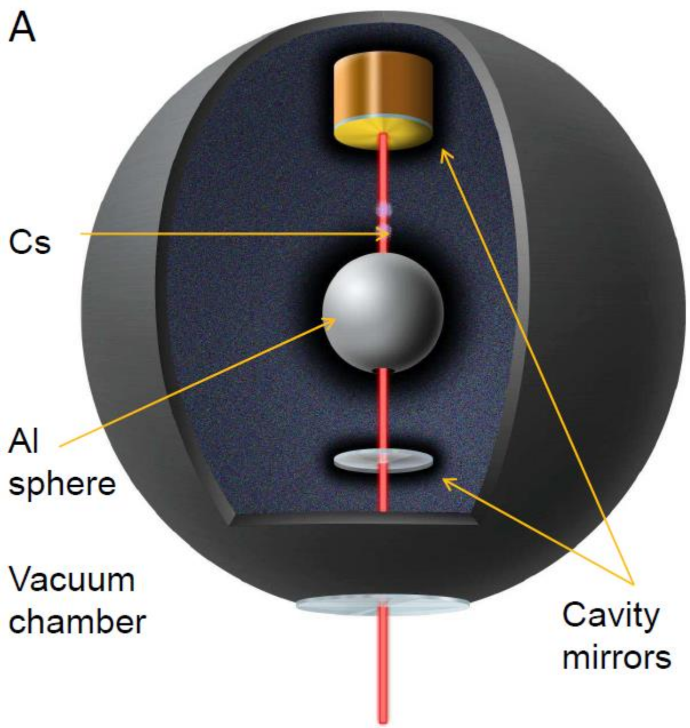


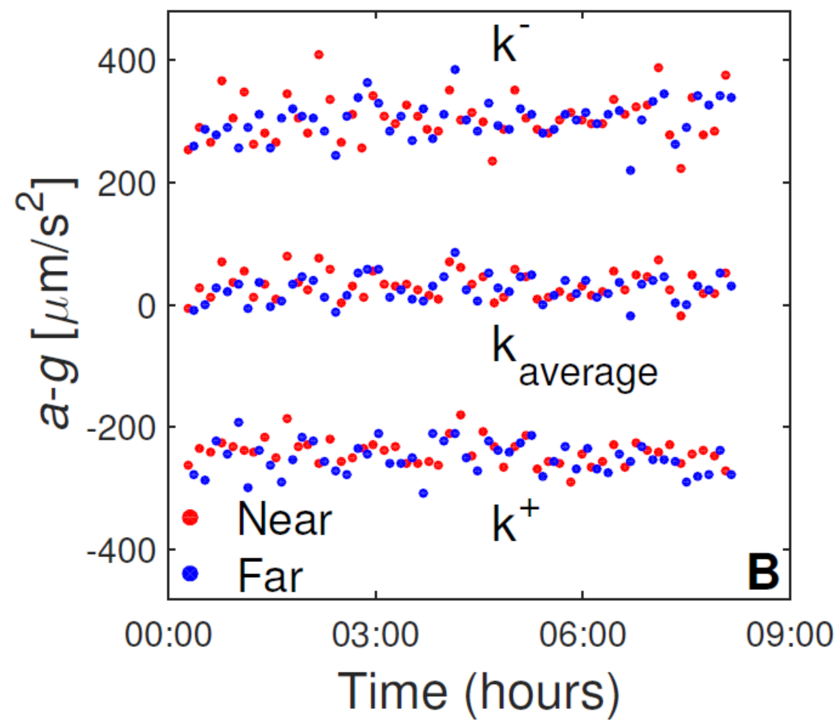
Sabulsky, Dutta, Hinds, Elder, CB, Copeland. arXiv:1812.08244

Berkley Experiment

Using an existing set up with an optical cavity, looking for a signal on top of the Earth's magnetic field

Anomalous acceleration = 11 ± 24 nm s^{-2}





Jaffe, Haslinger, Xu, Hamilton, Upadhye, Elder, Khoury, Müller. (2017)
Elder, Khoury, Haslinger, Jaffe, Müller, Hamilton. (2016)

Imperial Experiment

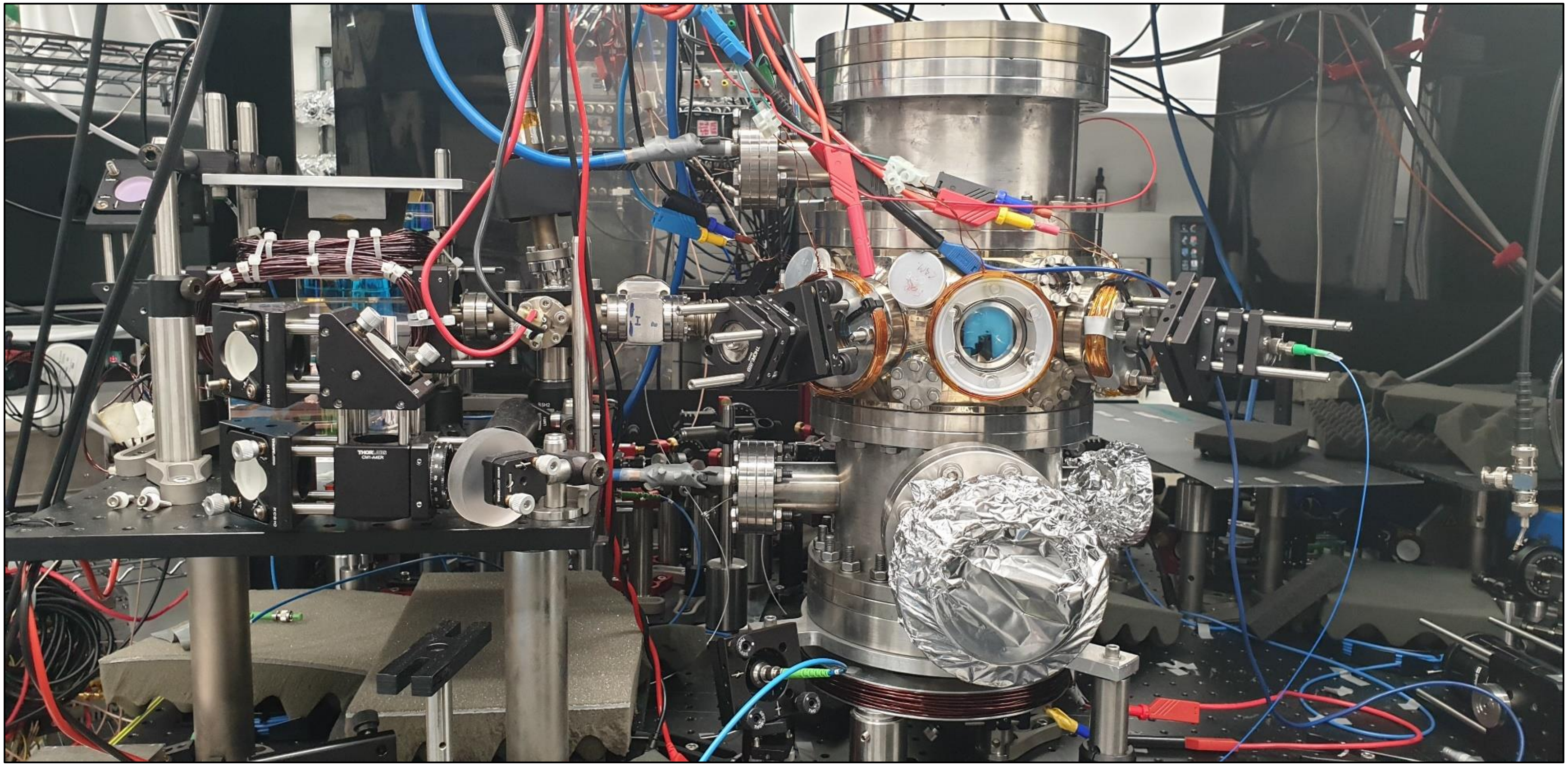
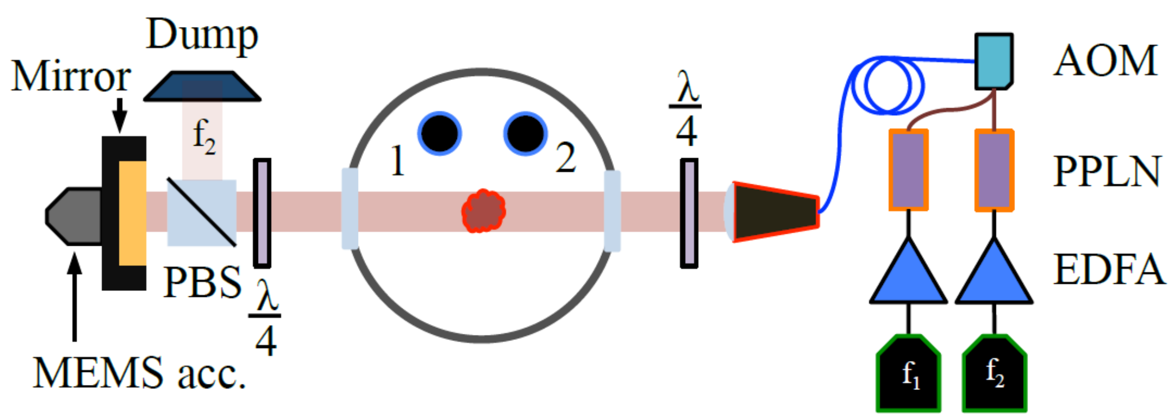


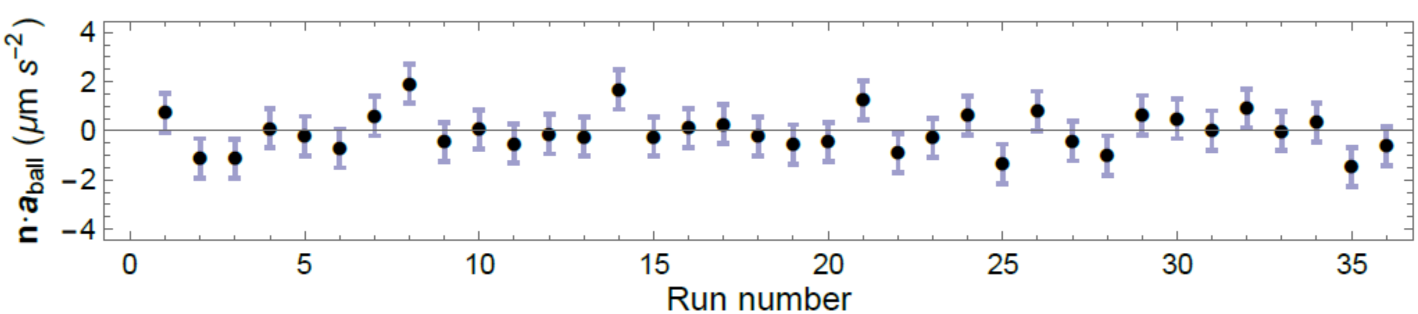
Image credit: E. Hinds

Imperial Experiment

Dedicated chameleon experiment, insensitive to the Earth’s gravitational field

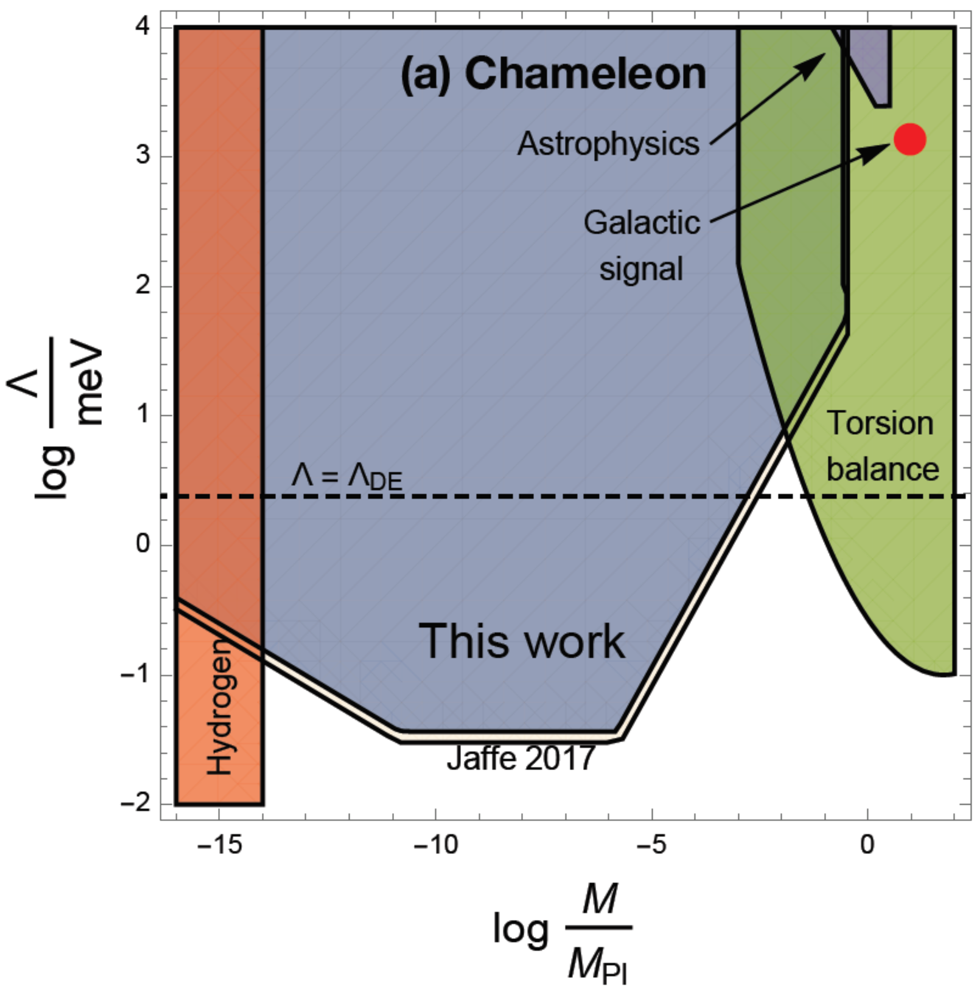
Anomalous acceleration = -77 ± 201 nm s^{-2}





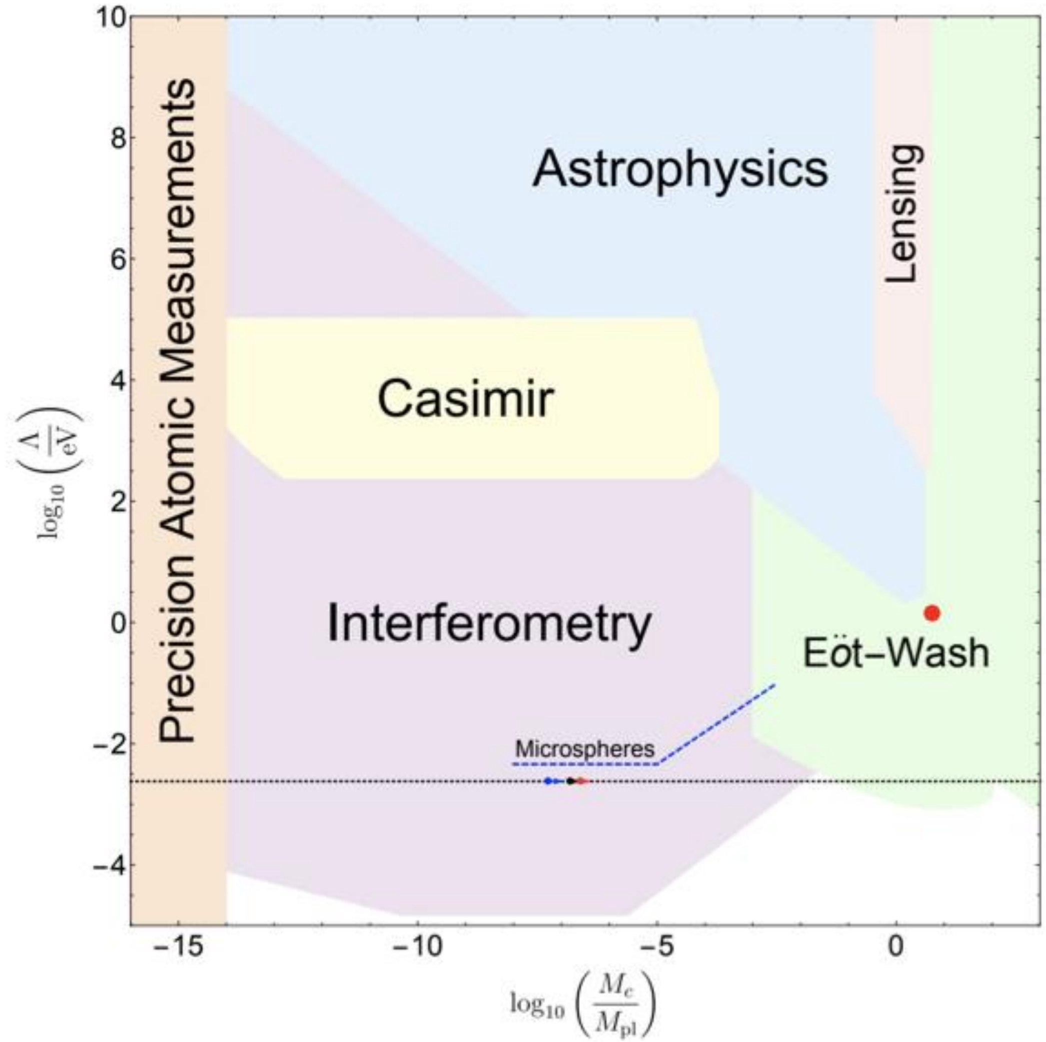
Sabulsky, Dutta, Hinds, Elder, CB, Copeland. arXiv:1812.08244
See also: Jaffe et al. (2017)

Imperial Experiment



Sabulsky, Dutta, Hinds, Elder, CB, Copeland. arXiv:1812.08244

Combined Constraints

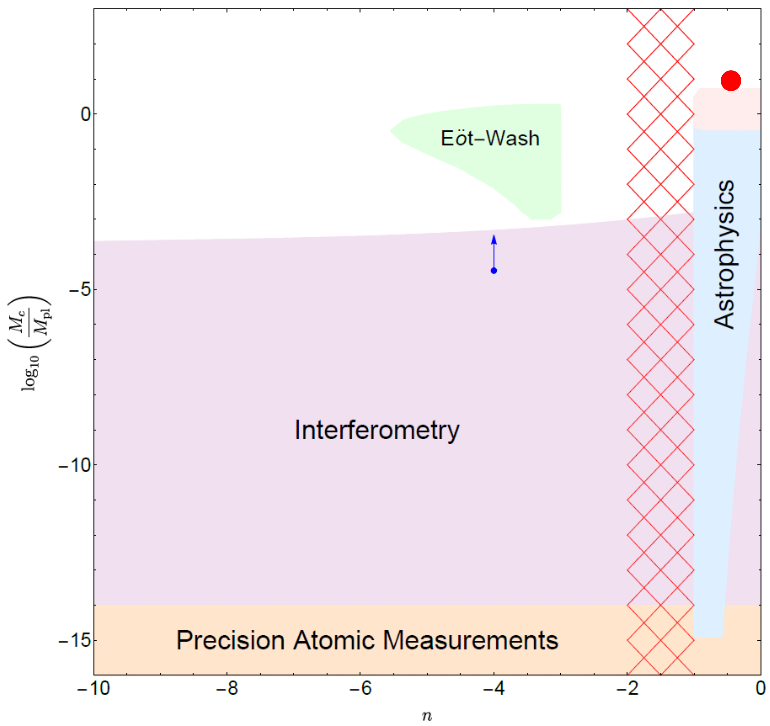


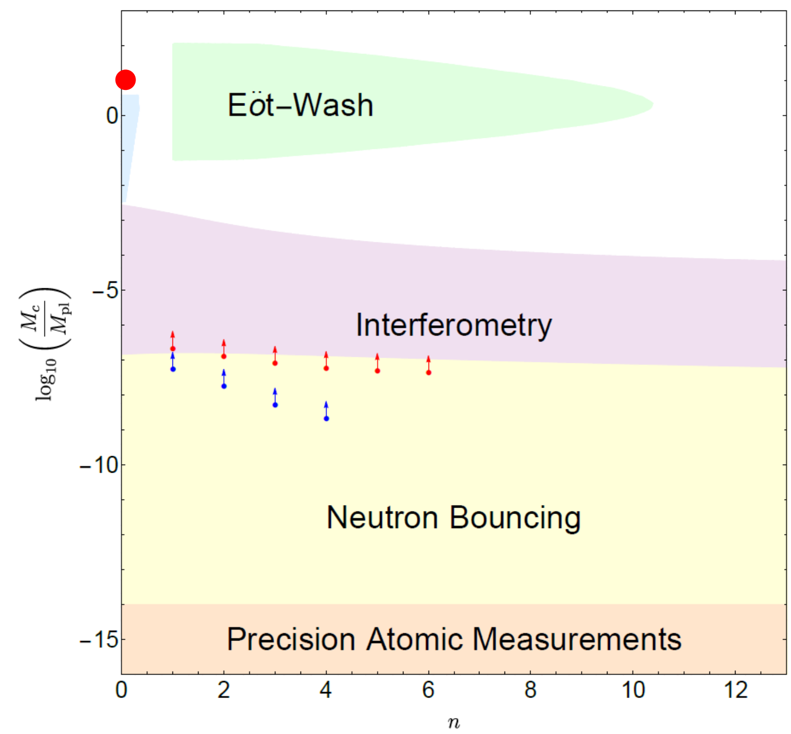
CB, Sakstein. (2017). With thanks to Ben Elder

Combined Chameleon Constraints

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

$$\Lambda = \Lambda_{\rm DE} = 2.4 \text{ meV}$$





CB, Sakstein. (2017). With thanks to Ben Elder

Summary

Explanations for dark energy typically introduce new scalar fields but the corresponding long range forces are not seen

Screening mechanisms (non-linearities) hide these forces from fifth force searches

- Can still be detected in suitably designed experiments
- Atom interferometry a particularly powerful technique

Complementary to large scale cosmological surveys e.g. Euclid, LSST