Detecting Dark Energy: from Cosmology to the Laboratory

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Outline:

Dark energy and screened fifth forces

Atom interferometry

Dark energy in the laboratory

How far away is a galaxy?

We want a ‘standard candle’ that burns with the same brightness everywhere in the universe

Image Credit: www.universeadventure.org

Type 1a supernovae

A white dwarf in a binary system accretes material from its companion

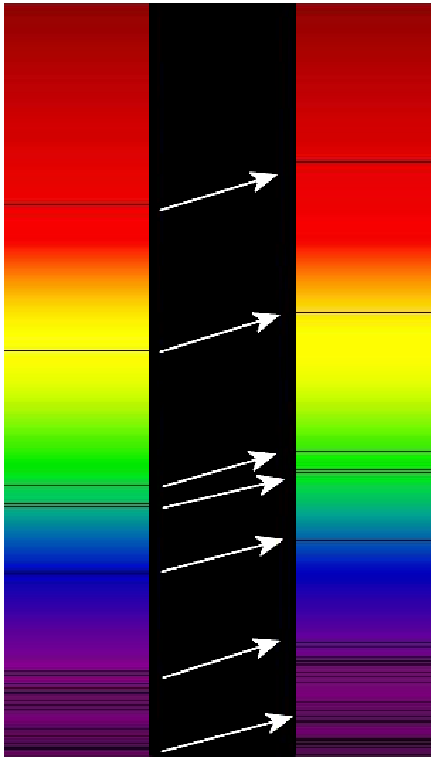
- As the mass approaches ~1.4 solar masses it becomes unstable, and runaway thermo-nuclear reactions result in an explosion

The Pinwheel Galaxy and SN2011fe. Image Credit: BJ Fulton

How fast is a galaxy moving?

Movement of the source changes the colour of the light
This changes the position of spectral lines

Spectrum from the Sun



Spectrum from Supercluster BAS11

Image Credit: Georg Wiora

How are distance and velocity related?

Einstein's General Theory of Relativity is our best current understanding of gravity

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

How the Universe evolves depends on what it is made of

The Accelerating Universe

The deceleration parameter:

$$q = -\frac{\ddot{a}a}{\dot{a}^2} = -\frac{\ddot{a}}{a}\frac{1}{H^2}$$

In a flat universe:

$$q = \frac{1}{2} - \frac{3}{2}\Omega_\Lambda$$

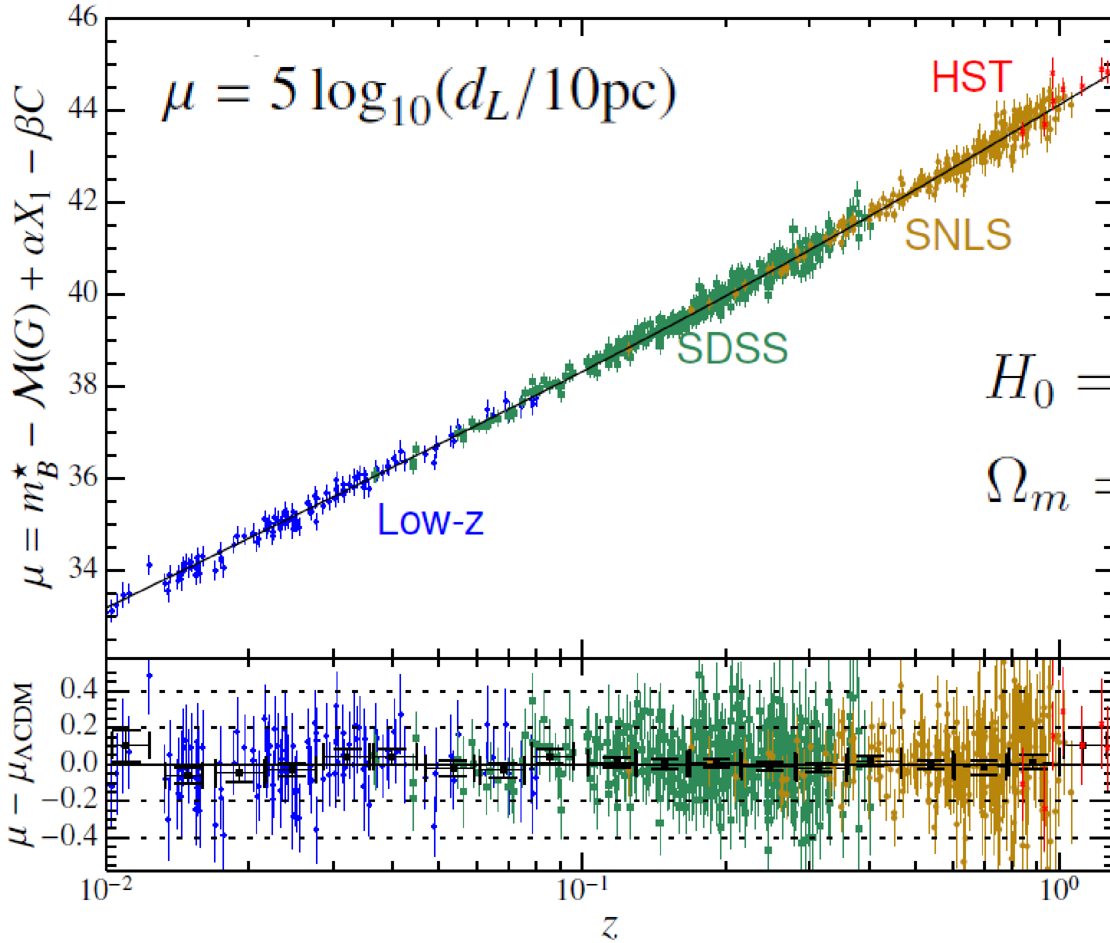
where

$$\Omega_\Lambda = \frac{\Lambda c^2}{3H^2}$$

If the cosmological constant contributes sufficiently to the energy budget of the universe it will accelerate

Supernova Hubble Diagram - 2014

740 Type 1a Supernovae

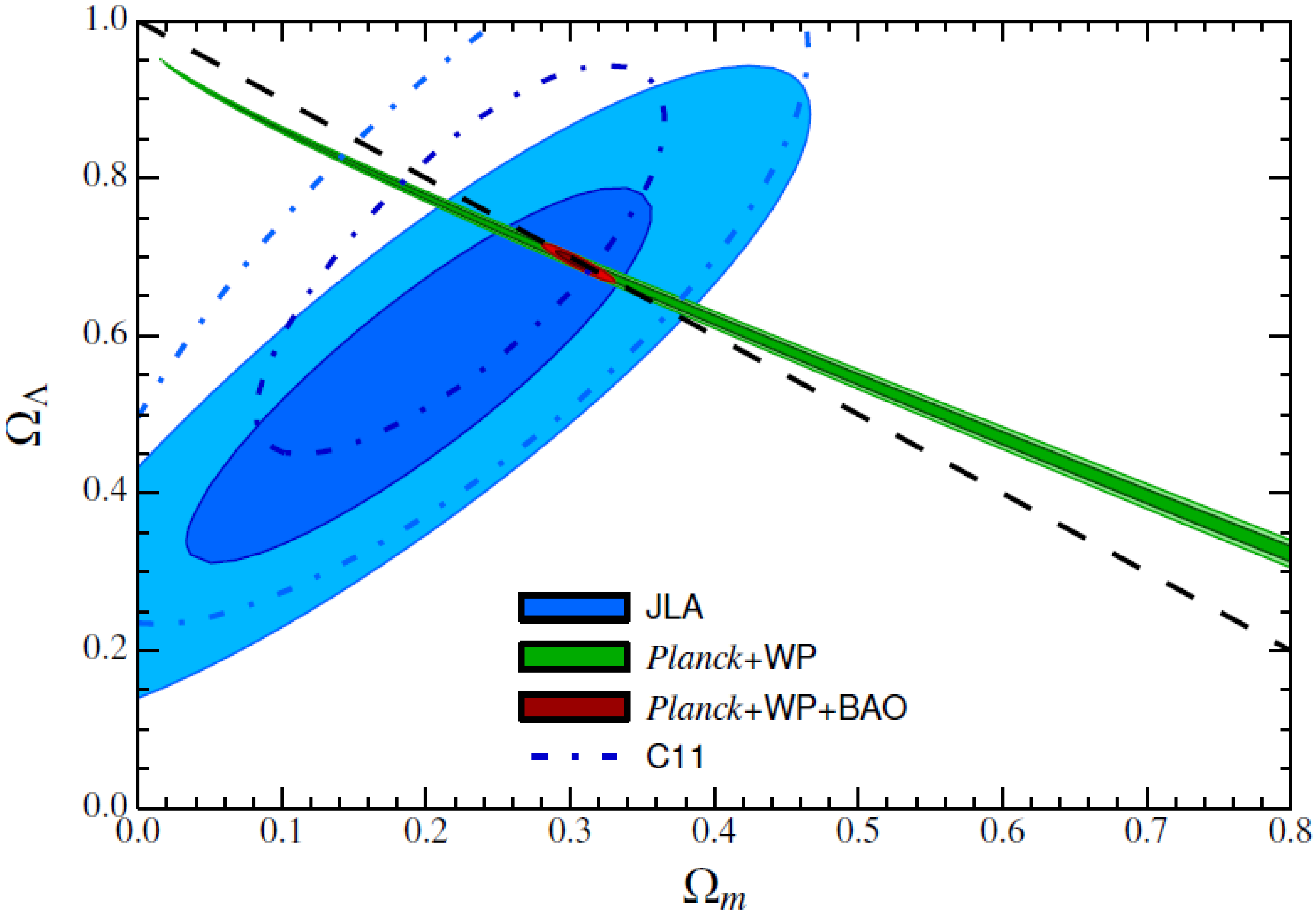


$$H_0 = 70\ \text{kms}^{-1}\text{Mpc}^{-1}$$

$$\Omega_m = 0.295$$

Betoule et al. 2014

The Contents of the Universe - 2014

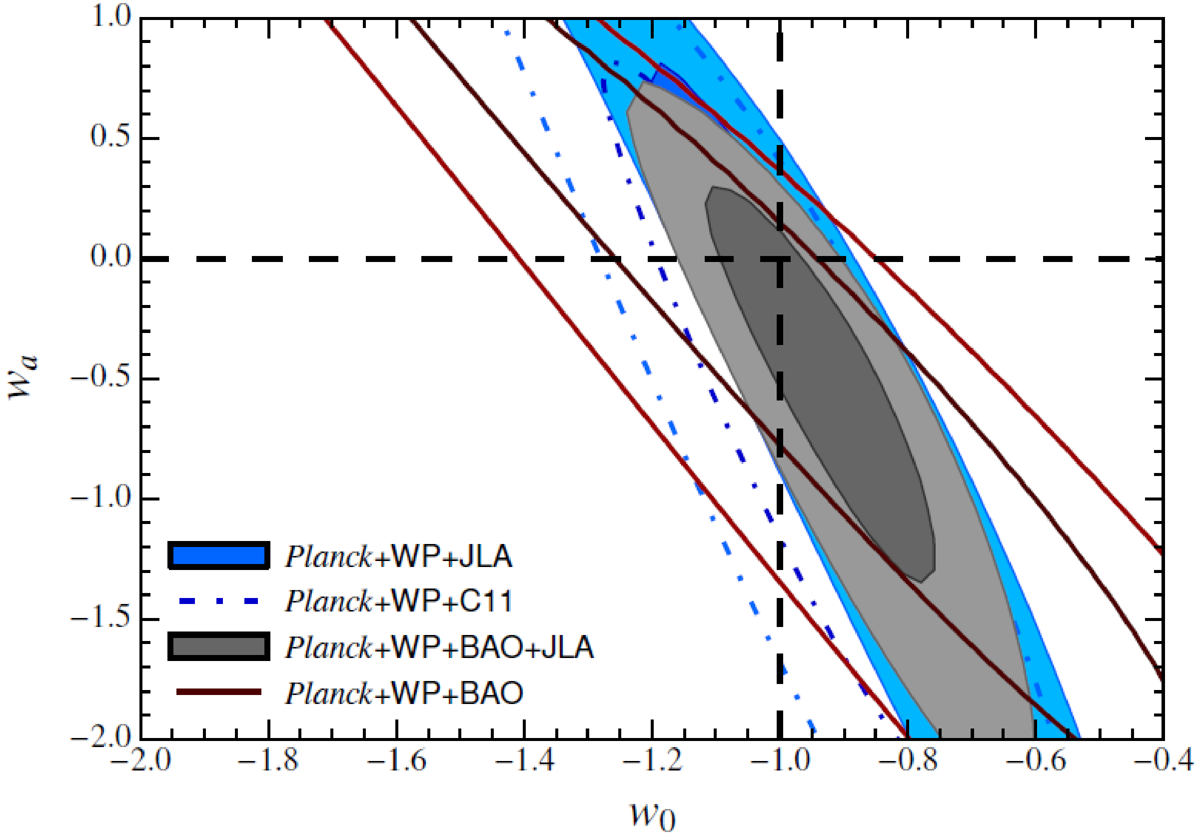


Betoule et al. 2014

Is it Really a Cosmological Constant?

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

Dashed lines = cosmological constant



Betoule et al. 2014

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

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

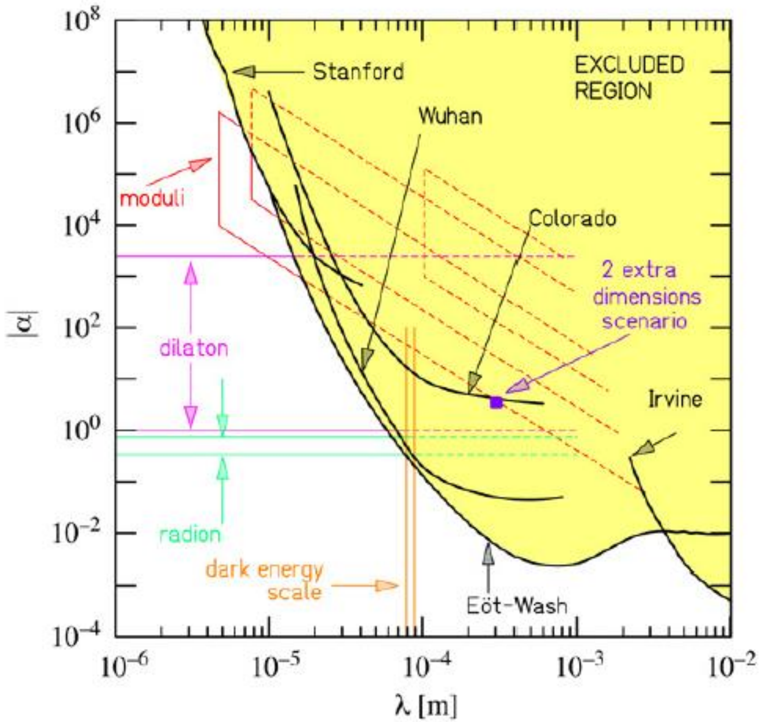
Papapetrou (1948). Weinberg (1965).

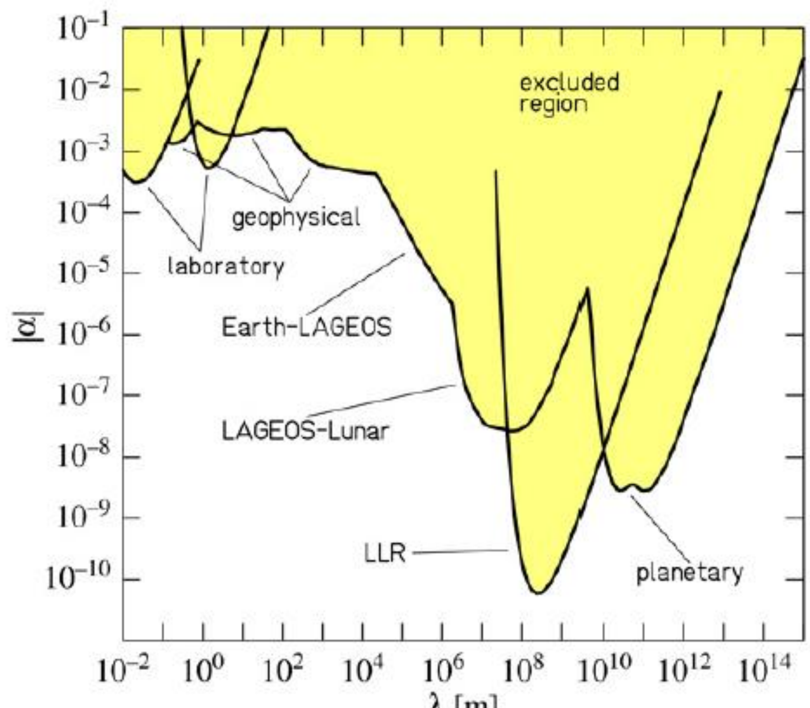
- New physics in the gravitational sector will introduce new degrees of freedom, typically Lorentz scalars

Problem: New Fields and New Forces

The existence of a fifth force is excluded to a high degree of precision

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





Adelberger et al. (2009)

Screening Mechanisms

Start with a non-linear scalar field theory

$$\mathcal{L} = -\frac{1}{2}Z^{\mu\nu}(\phi, \partial\phi, ...)\partial_\mu\phi\partial_\nu\phi - V(\phi) + g(\phi)T^\mu_\mu$$

Split the field into background and perturbation

$$\phi = \bar{\phi} + \varphi$$

Where the perturbation is sourced by a static, non-relativistic point mass

$$\rho = \mathcal{M}\delta^3(\vec{x})$$

Screening Mechanisms

Euler-Lagrange equation

$$Z(\bar{\phi})\left(\ddot{\varphi} - c_s^2(\bar{\phi})\nabla^2\varphi\right) + m^2(\bar{\phi})\varphi = g(\bar{\phi})\mathcal{M}\delta^3(\vec{x})$$

where

$$Z(\bar{\phi}) = Z^\mu_\mu(\bar{\phi}) \quad c_s^2(\bar{\phi}) = Z_{ii}(\bar{\phi})/Z(\bar{\phi}) \quad m^2(\bar{\phi}) \equiv \frac{d^2V}{d\phi^2}|_{\bar{\phi}}$$

Resulting in a scalar potential for a test mass

$$V(r) = -\frac{g^2(\bar{\phi})}{Z(\bar{\phi})c_s^2(\bar{\phi})}\frac{e^{-\frac{m(\bar{\phi})}{\sqrt{Z(\bar{\phi})}c_s(\bar{\phi})}r}}{4\pi r}\mathcal{M}$$

Screening Mechanisms

- **Locally weak coupling**

Symmetron and varying dilaton models

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

- **Locally large kinetic coefficient**

Vainshtein mechanism, Galileon and k-mouflage models

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

- **Locally large mass**

Chameleon models

Khoury, Weltman (2004).

The Chameleon

Spherically symmetric, static equation of motion

$$\frac{1}{r^2}\frac{d}{dr}[r^2\phi(r)] = \frac{dV}{d\phi} + \frac{\rho(r)}{M} \equiv V_{\rm eff}(\phi)$$

Chameleon screening relies on a non-linear potential, e.g.

$$V(\phi) = \frac{\Lambda^5}{\phi} \qquad\qquad V(\phi) = \frac{\lambda}{4}\phi^4$$

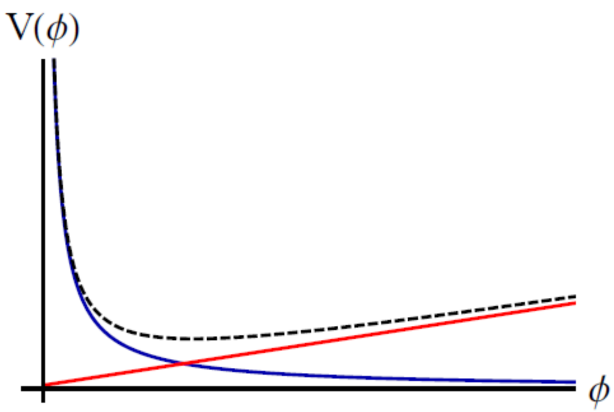
Khoury, Weltman. (2004). Image credit: Nanosanchez

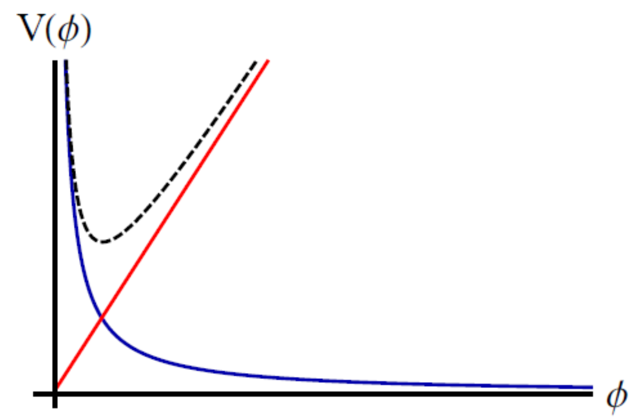
Varying Mass

The mass of the chameleon changes with the environment

Field is governed by an effective potential

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





Warning: Non-renormalisible theory

No known embedding in a more complete UV theory

(But see Hinterbichler, Khoury, Nastase 2010)

Symmetron Screening

Canonical scalar with potential and coupling to matter

$$V(\phi) = \frac{\lambda}{4}\phi^4 - \frac{\mu^2}{2}\phi^2 \qquad \mathcal{L} \supset \frac{\phi^2}{2M^2} T^\mu_\mu$$

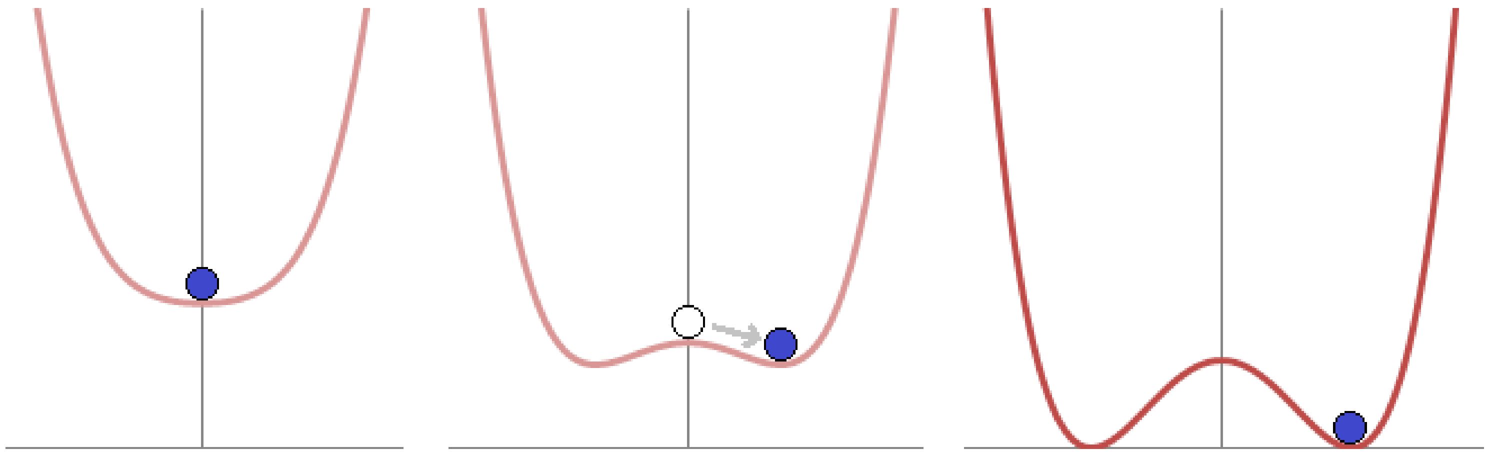
Effective potential

$$V_{\rm eff}(\phi) = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 + \frac{1}{4}\lambda\phi^4$$

Symmetry breaking transition occurs as the density is lowered

Hinterbichler, Khoury. (2010).

Symmetron Screening



Force on test particle vanishes when symmetry is restored

$$F = \phi \nabla \phi / M^2$$

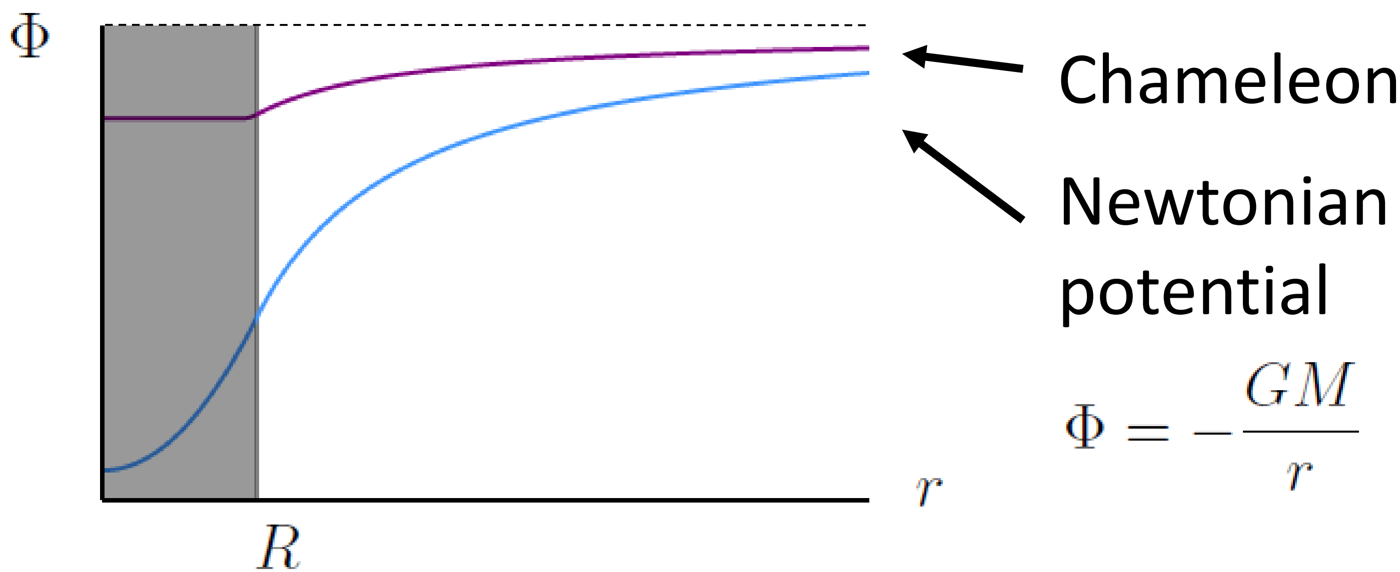
Radiatively stable model has been constructed

CB, Copeland, Millington. (2016).

How to Search for Screened Forces

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 cannoical light scalar fields

The Scalar Potential

Around a static, spherically symmetric source of constant density

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

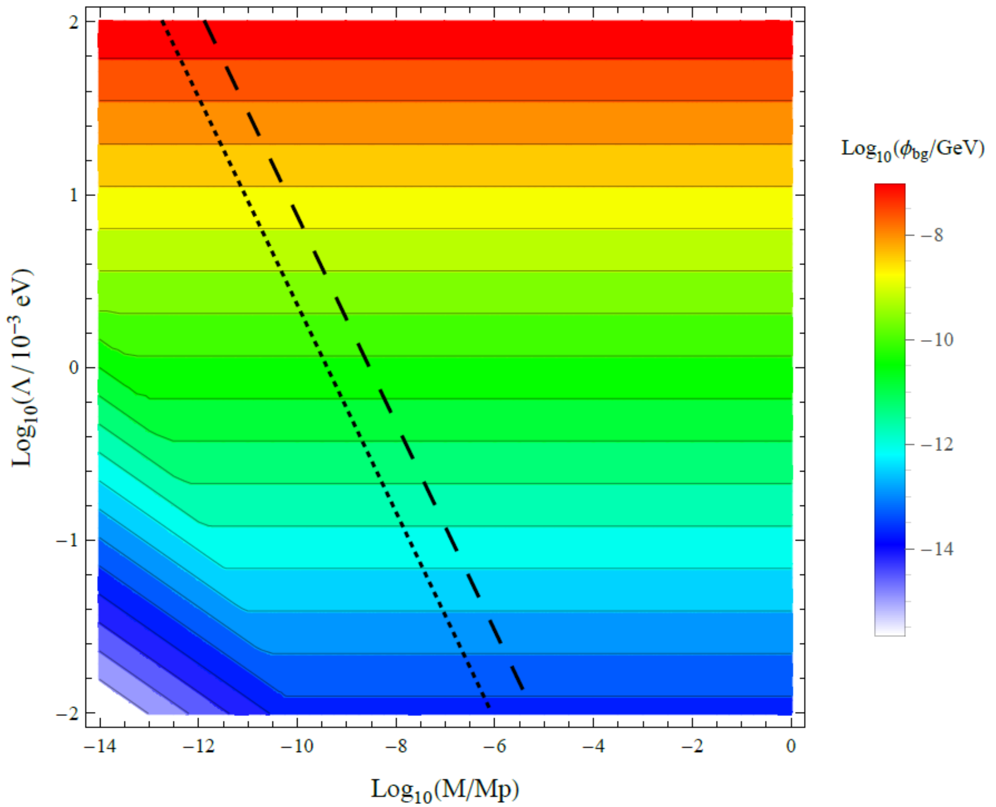
$$\lambda_A = \begin{cases} 1\,, & \rho_A R_A^2 < 3M\phi_{\rm bg} \\ 1 - \frac{S^3}{R_A^3} \approx 4\pi R_A \frac{M}{M_A}\phi_{\rm bg}\,, & \rho_A R_A^2 > 3M\phi_{\rm bg} \end{cases}$$

This determines how 'screened' an object is from the chameleon field

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)



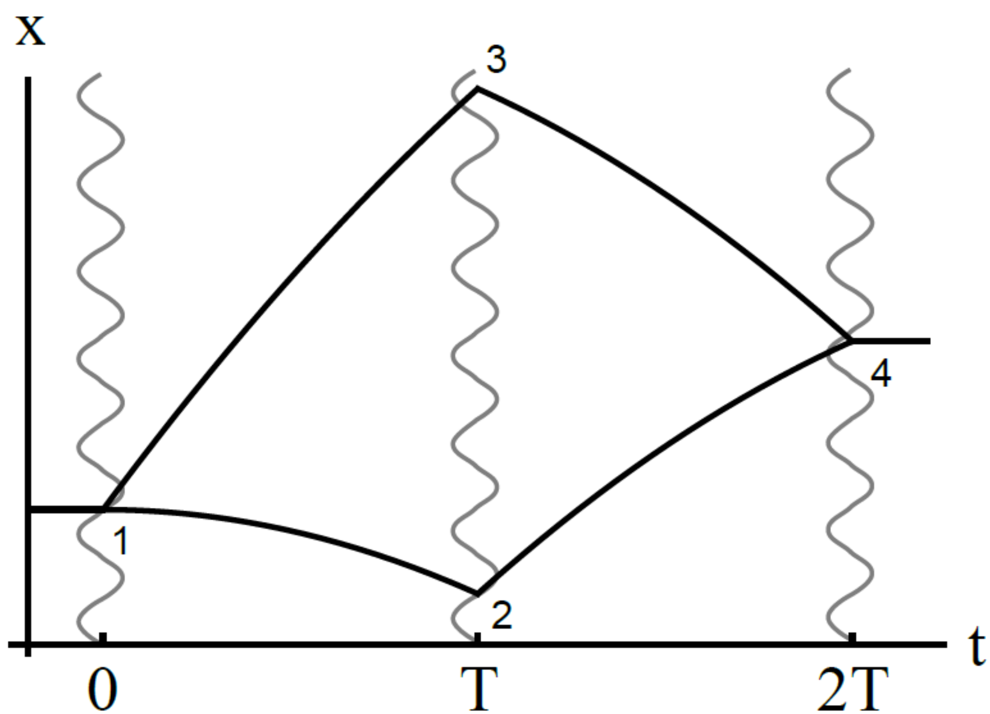
CB, Copeland, Hinds. (2015)

What is Atom Interferometry?

An interferometer where the wave is made of atoms

Atoms can be moved around by absorption of laser photons

An Atom Interferometer



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

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

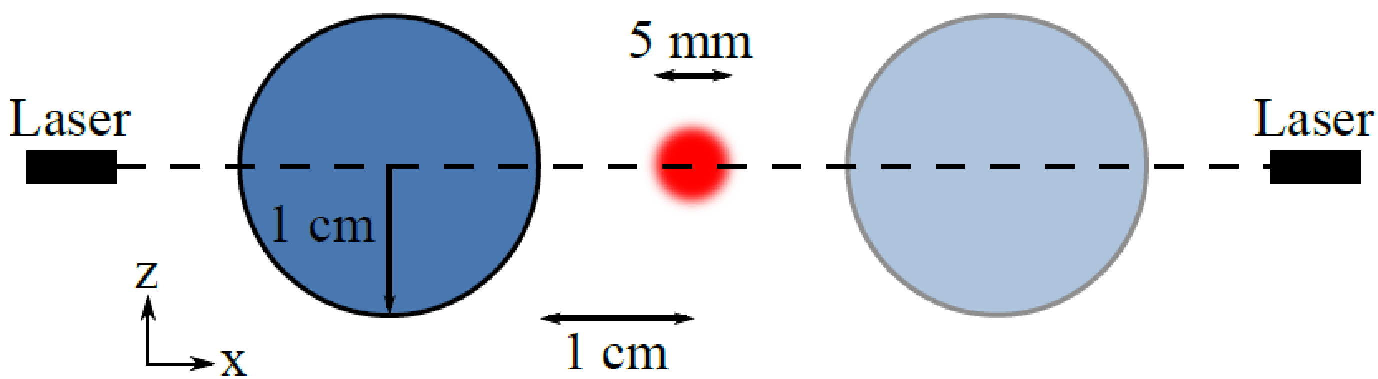
Additional contributions from interactions with photons, proportional to

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

Atom Interferometry for Chameleons

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

Macroscopic spherical mass (blue), produces chameleon potential felt by cloud of atoms (red)

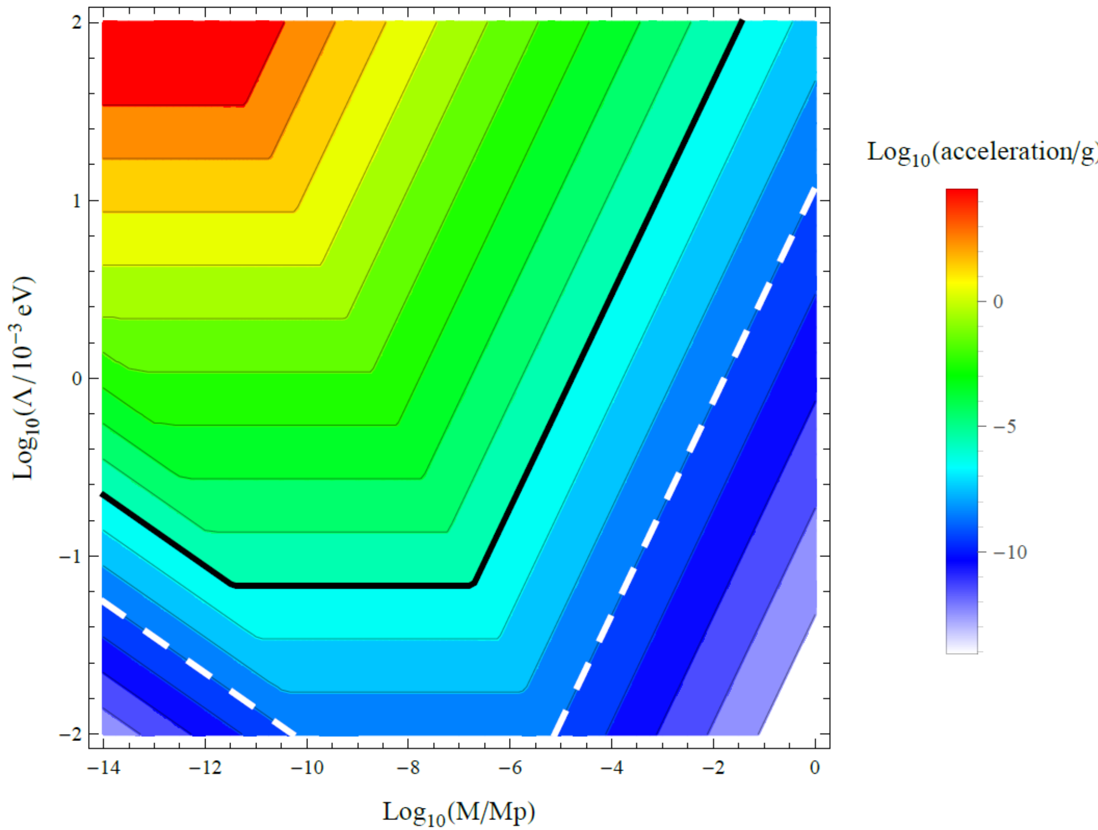


Proposed Sensitivity

Systematics: Stark effect, Zeeman effect, phase shifts due to scattered light, movement of beams

All negligible at 10^{-6} g sensitivity (solid black line)

Controllable down to 10^{-9} g (dashed white line)

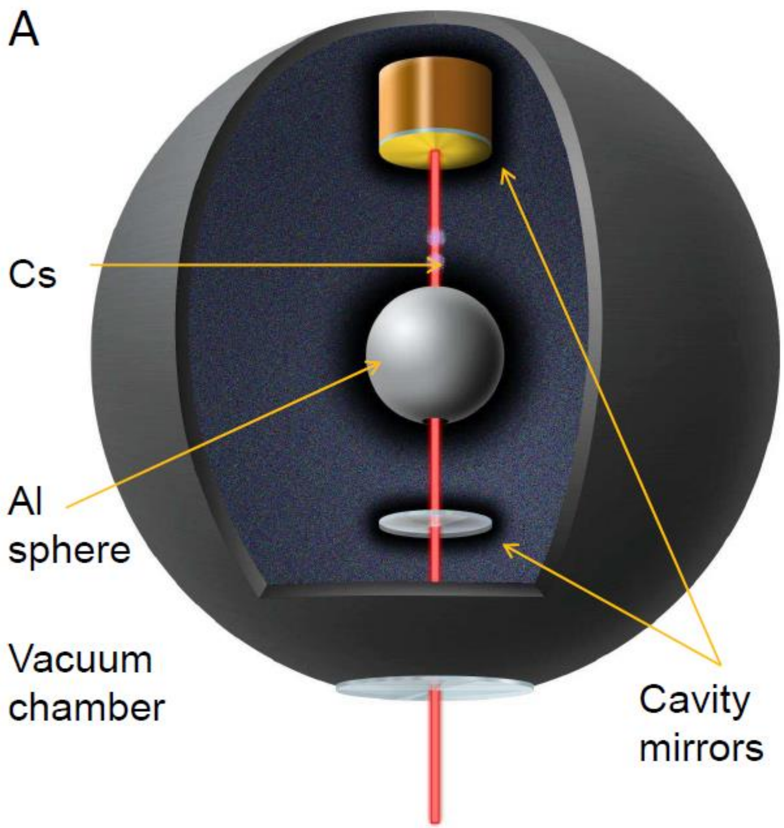


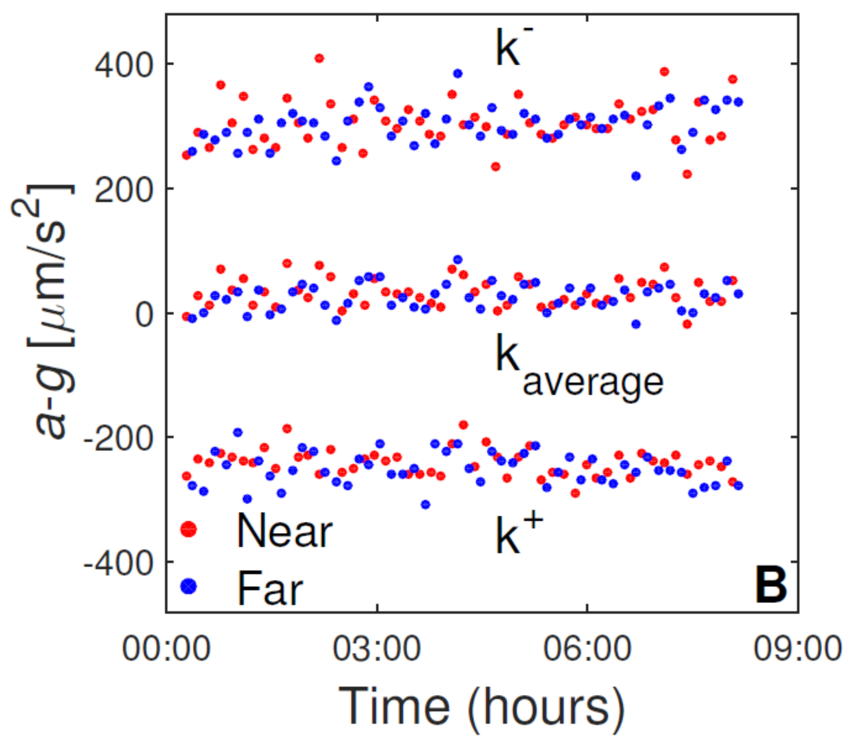
CB, Copeland, Hinds. (2015)

For numerical estimates see: Schlögel, Clesse, Füzfa (2015). Elder et al. (2016).

Berkley Experiment

Using an existing set up with an optical cavity
The cavity provides power enhancement, spatial filtering, and a precise beam geometry





Hamilton et al. (2015)

New Results

Aluminium sphere replaced by cylindrical tungsten source, mass 0.19 kg, height = diameter = 2.54 cm

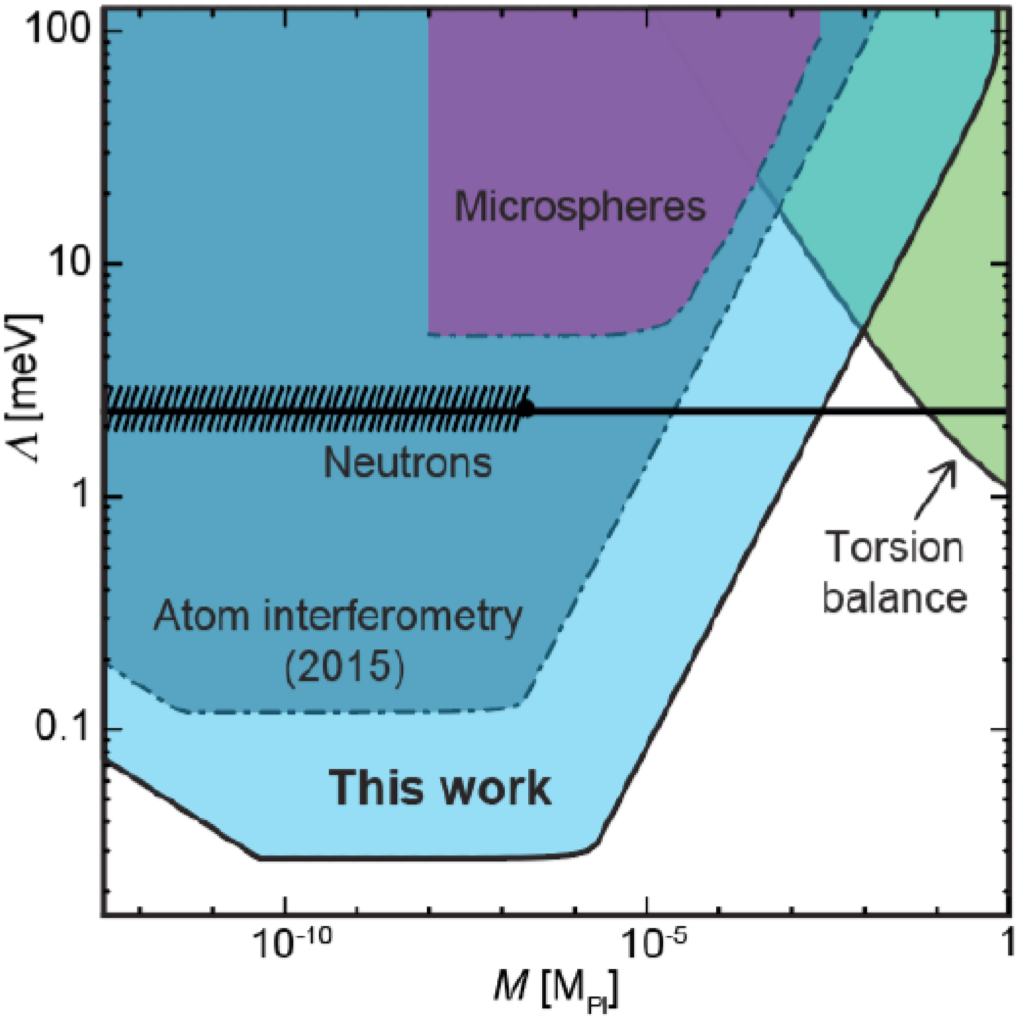
Additional vibration isolation and control of systematics

Detection of the gravitational force between the cylinder and caesium atoms at 2σ

$$F \sim 10^{-32}\ N$$

Jaffe et al. (2016)

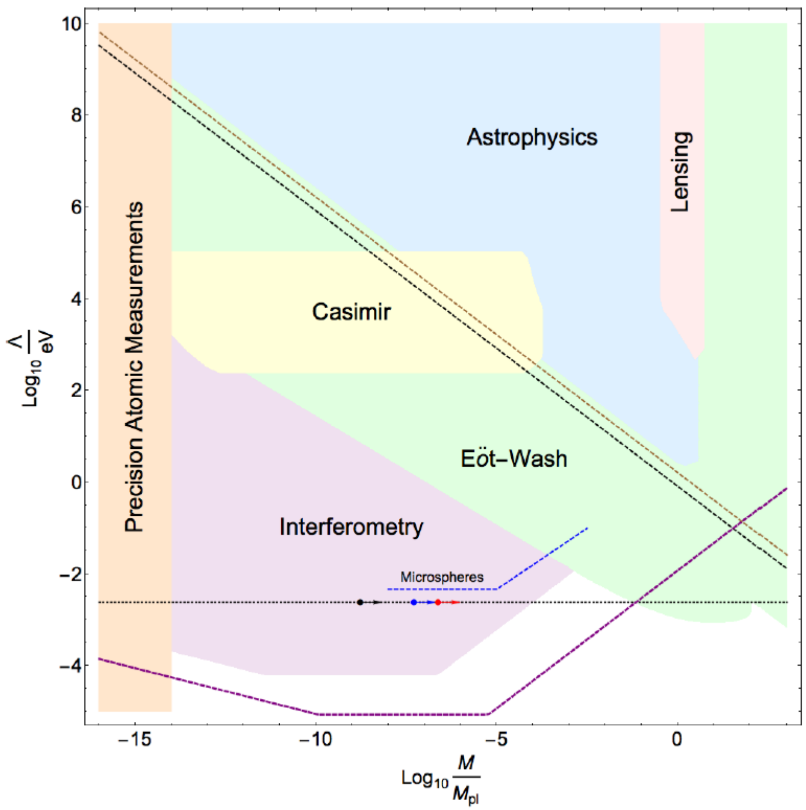
Berkley Experiment



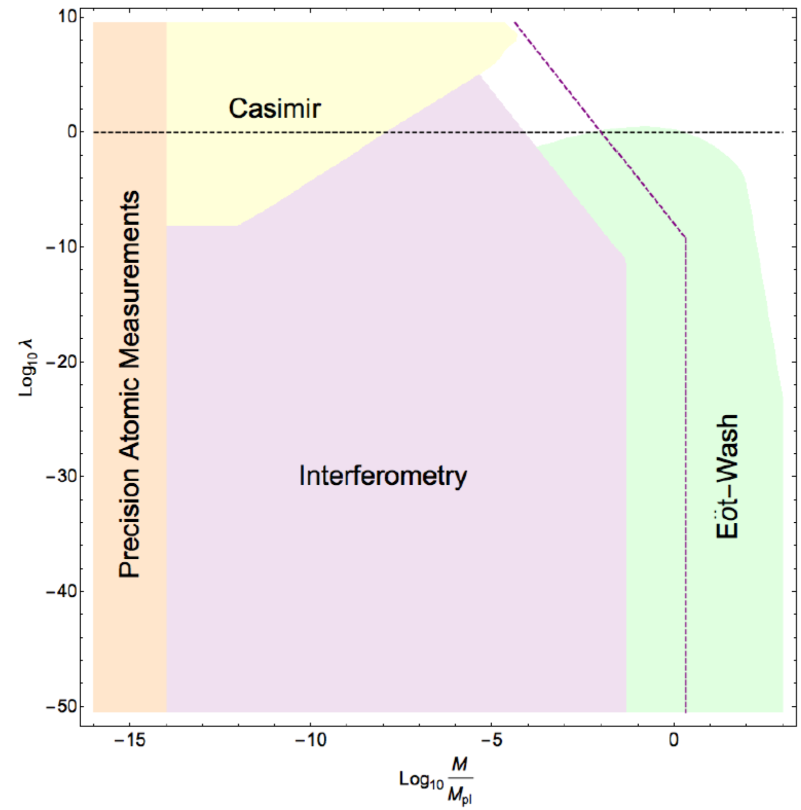
Hamilton et al. (2015) Jaffe et al. (2016)
See also: Neutron interferometry experiments: Lemmel et al. (2015)
Optically levitated microspheres: Rider et al. (2016)

Combined Chameleon Constraints

$$V(\phi) = \frac{\Lambda^5}{\phi}$$



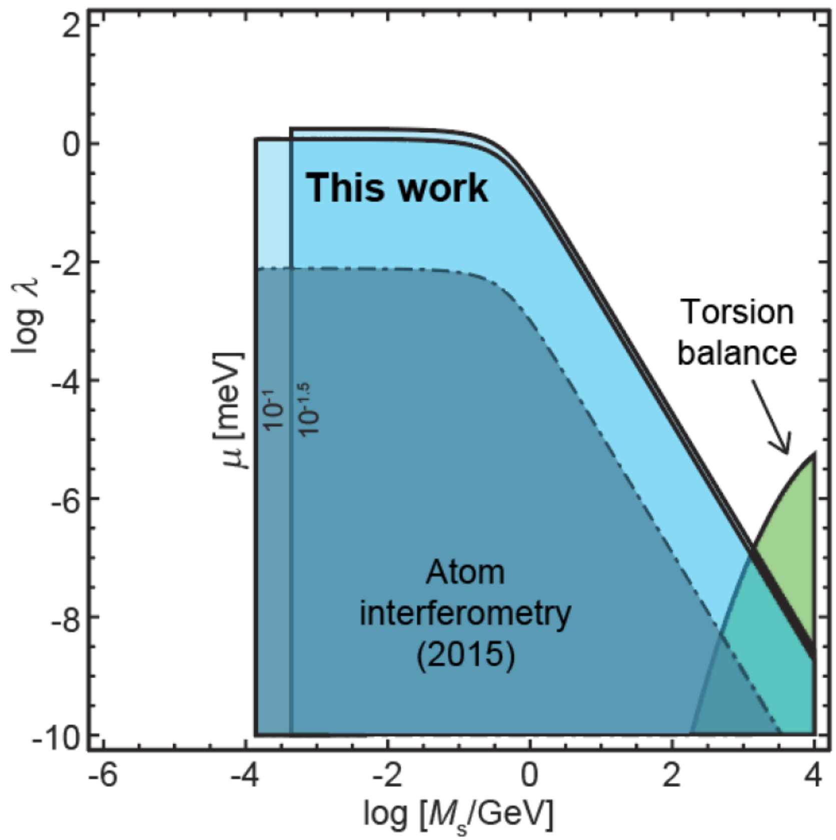
$$V(\phi) = \frac{\lambda}{4}\phi^4$$



CB, Sakstein. (2016)

Symmetron Constraints

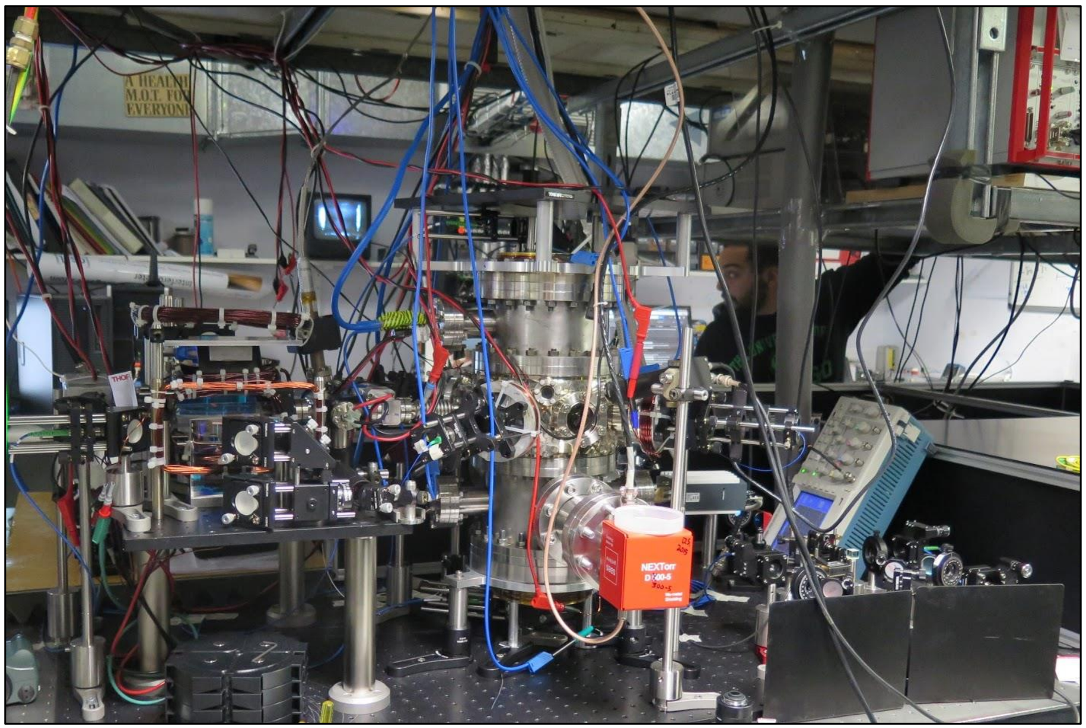
$$V_{\rm eff}(\phi) = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 + \frac{1}{4}\lambda\phi^4$$



Jaffe et al. (2016). CB, Kuribayashi-Coleman, Stevenson, Thrussell. (2016)

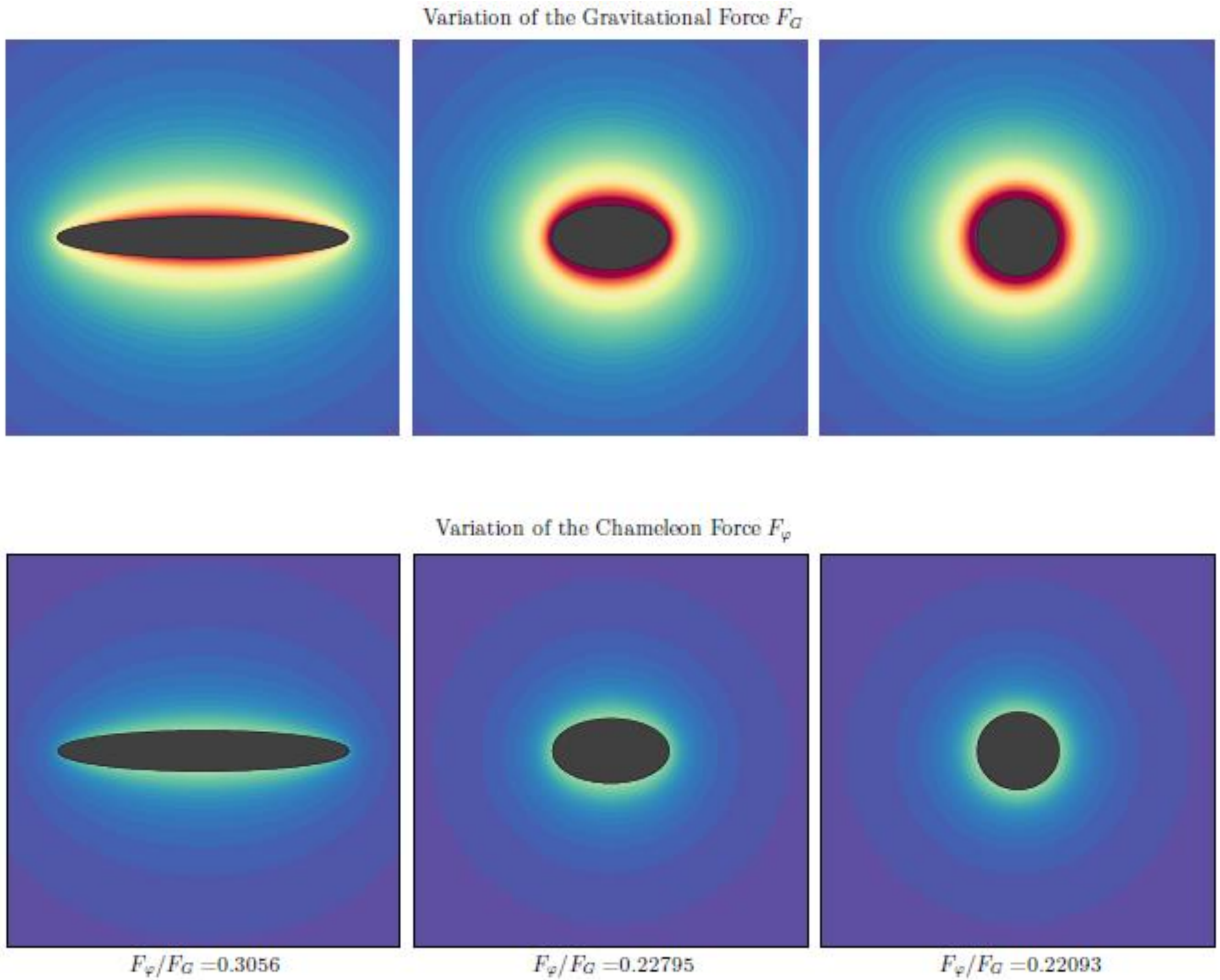
Imperial Experiment

Development underway at the Centre for Cold Matter, Imperial College (Group of Ed Hinds)



Experiment rotated by 90 degrees from the Berkeley experiment, so that no sensitivity to Earth’s gravity

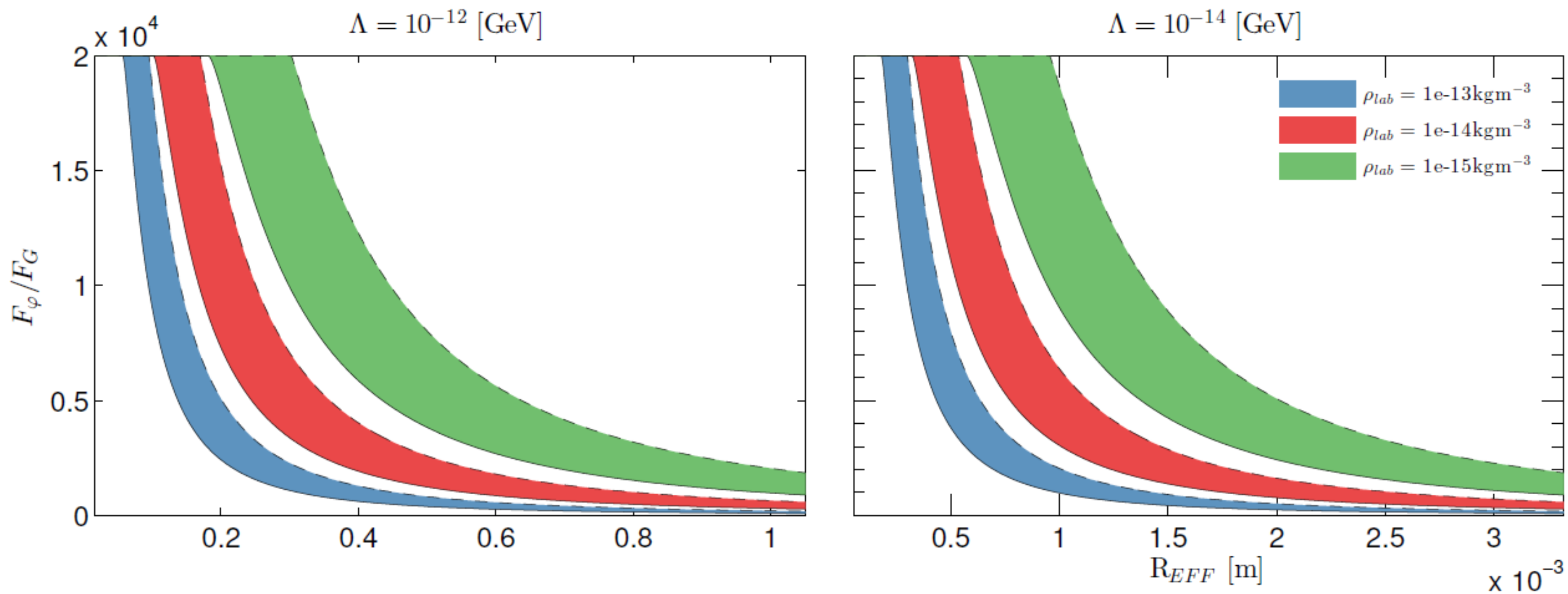
Future Prospects: Source Shape



CB, Copeland, Stevenson (2015)

Shape Dependence of Chameleon Force

Deviations from spherical symmetry impede the formation of a thin shell



CB, Copeland, Stevenson (2015)

Summary

Solutions to the cosmological constant problem include introducing new types of matter and modifying gravity

- Introduces new scalar fields but the corresponding forces are not seen

Screening mechanisms are required to hide these forces from fifth force searches

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