Detecting Dark Energy with Atom Interferometry

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Outline:

Dark energy and screened fifth forces

Atom interferometry

Dark energy in the laboratory

Bonus: Rotation curves and screened fifth forces

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

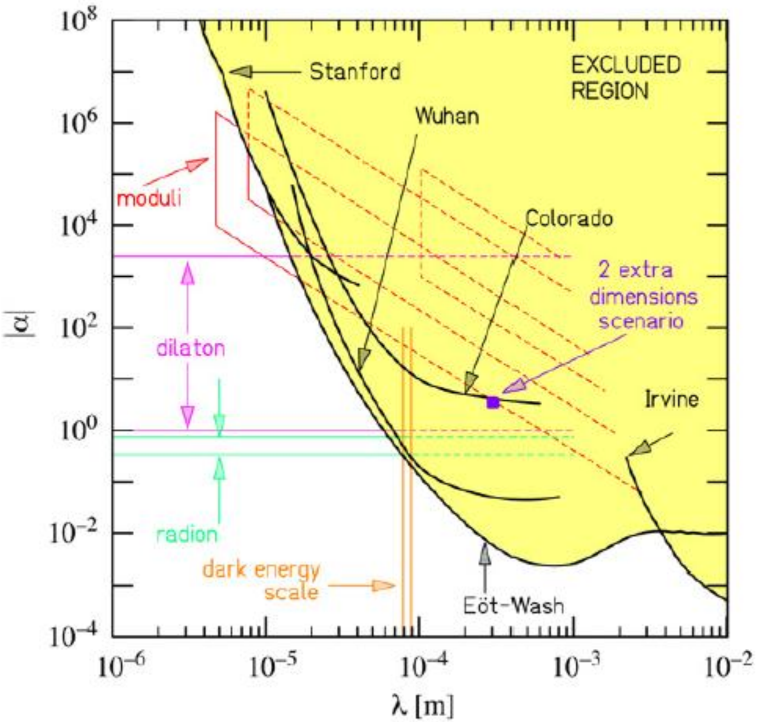
  Papapetrou (1948). Weinberg (1965).

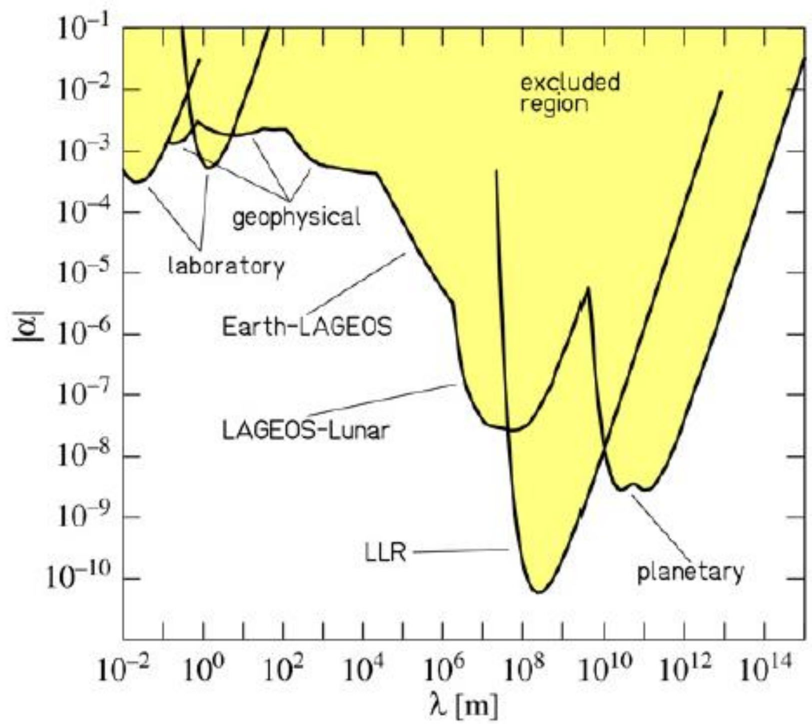
- New physics in the gravitational sector will introduce new degrees of freedom, typically Lorentz scalars

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.

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

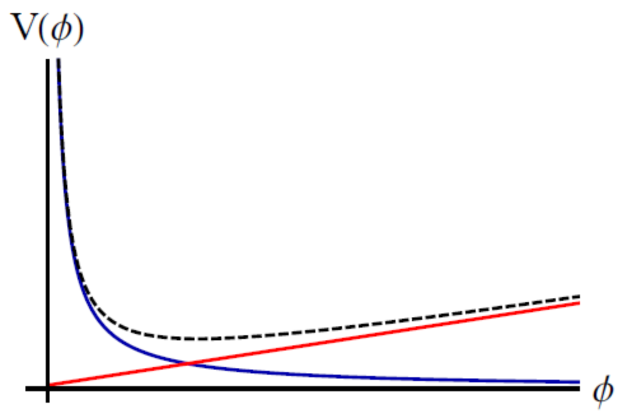
Khoury, Weltman. (2004). Image credit: Nanosanchez

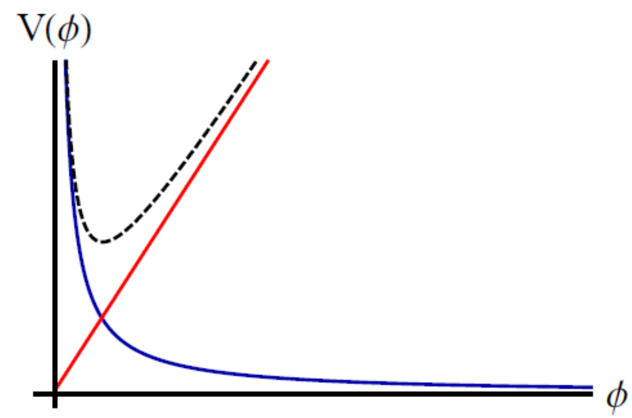
Varying Mass

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

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

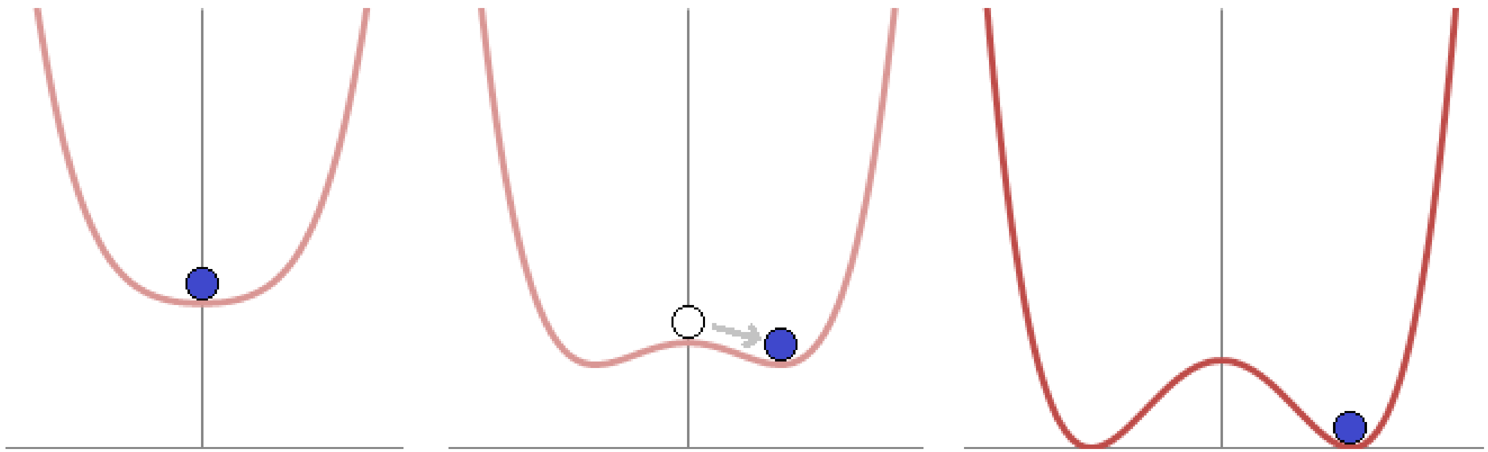
Effective potential

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

Symmetry breaking transition occurs as the density is lowered

Hinterbichler, Khoury. (2010).

Symmetron Screening



Force on test particle vanishes when symmetry is restored

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

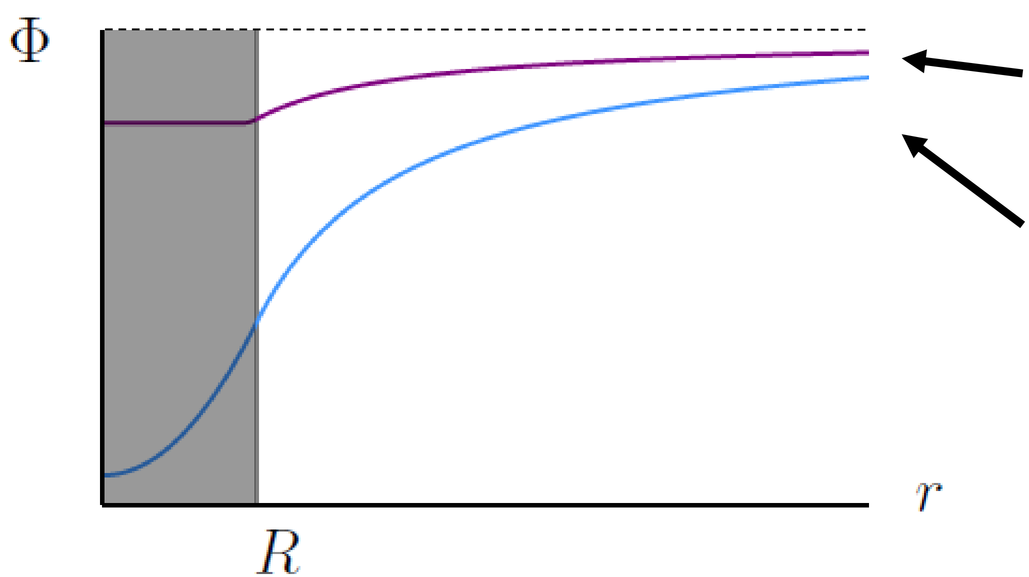
Radiatively stable model has been constructed

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



$$\Phi = -\frac{GM}{r}$$

The chameleon potential well around 'large' objects is shallower than for standard 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 responsive an object is to the chameleon field

Why Atom Interferometry?

Recall that for a chameleon:

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

Where the screening is controlled by

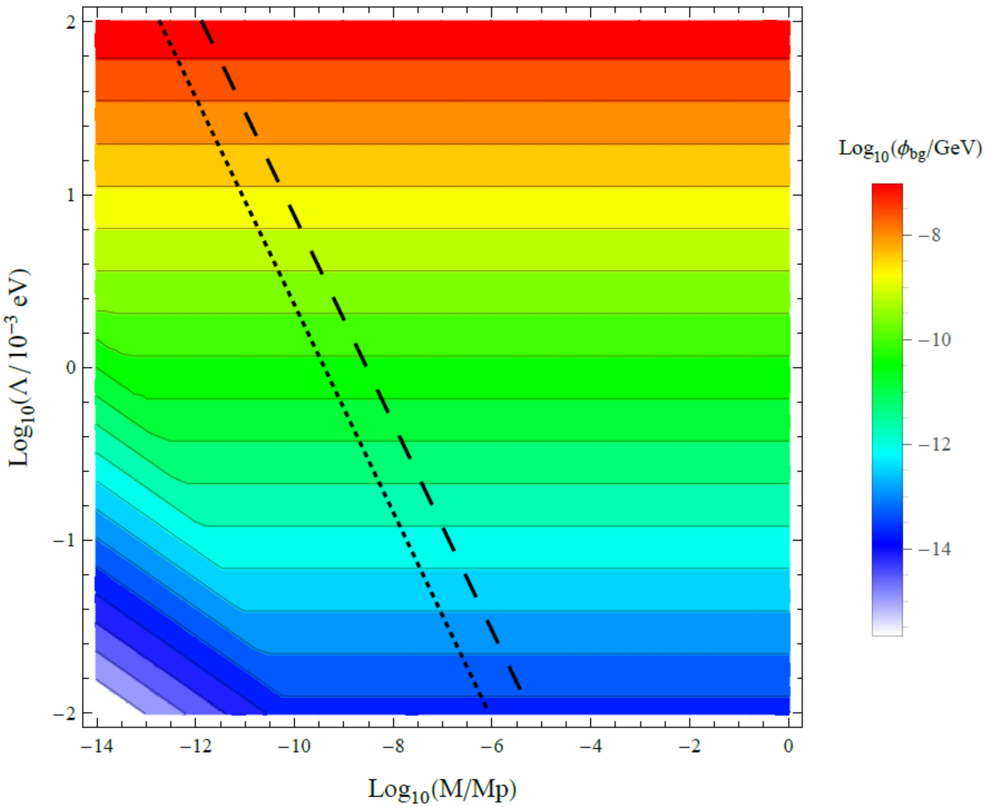
$$\lambda_A = \begin{cases} 1 \, , & \rho_A R_A^2 < 3M\phi_{\mathrm{bg}} \\ 1 - \frac{S^3}{R_A^3} \approx 4\pi R_A \frac{M}{M_A} \phi_{\mathrm{bg}} \, , & \rho_A R_A^2 > 3M\phi_{\mathrm{bg}} \end{cases}$$

Over a large part of the chameleon parameter space atoms are unscreened in a laboratory vacuum

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)



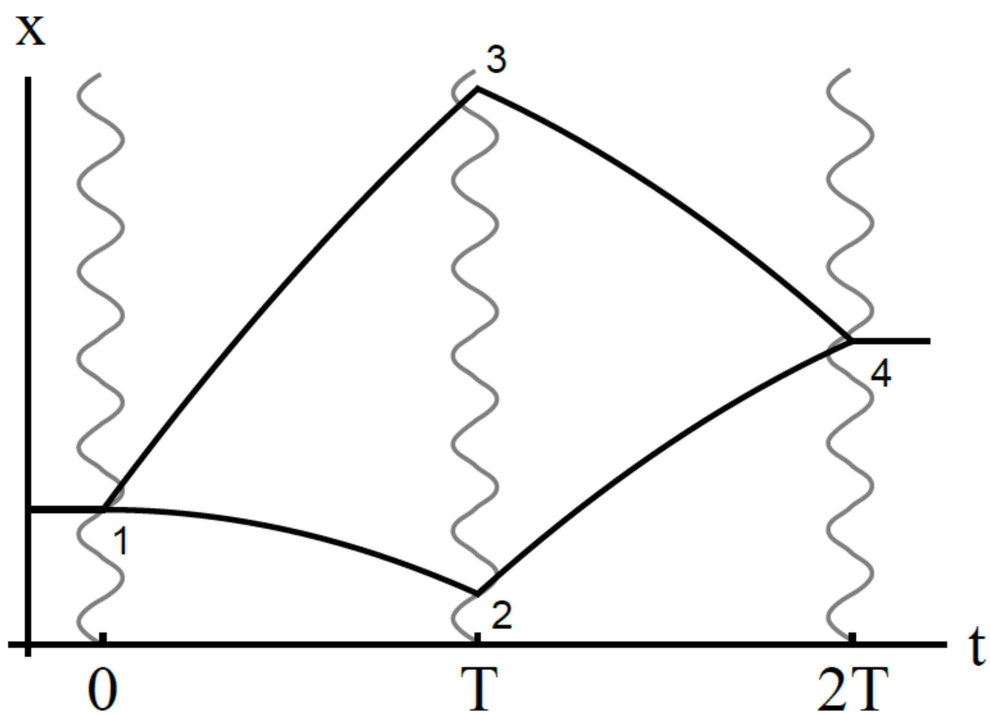
CB, Copeland, Hinds. (2015)

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

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

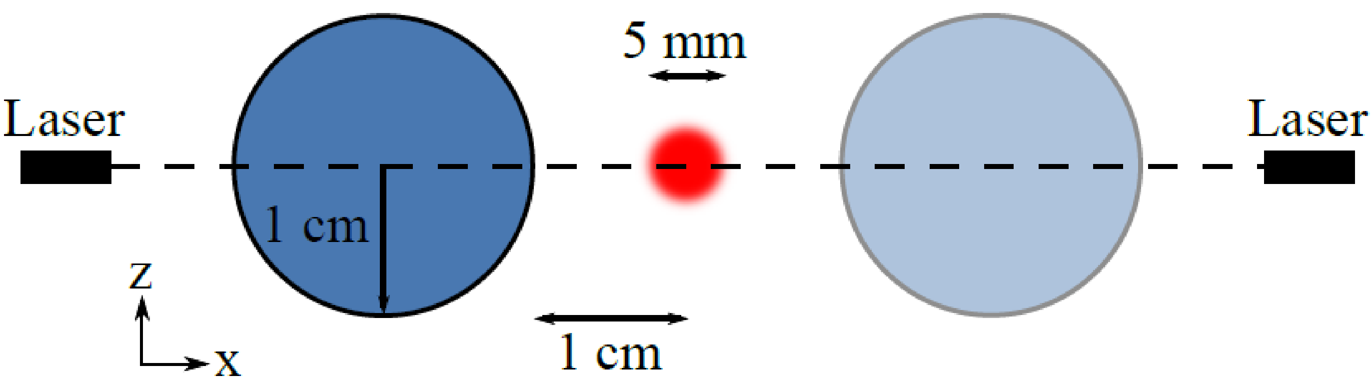
Additional contributions from interactions with photons, proportional to

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

Atom Interferometry for Chameleons

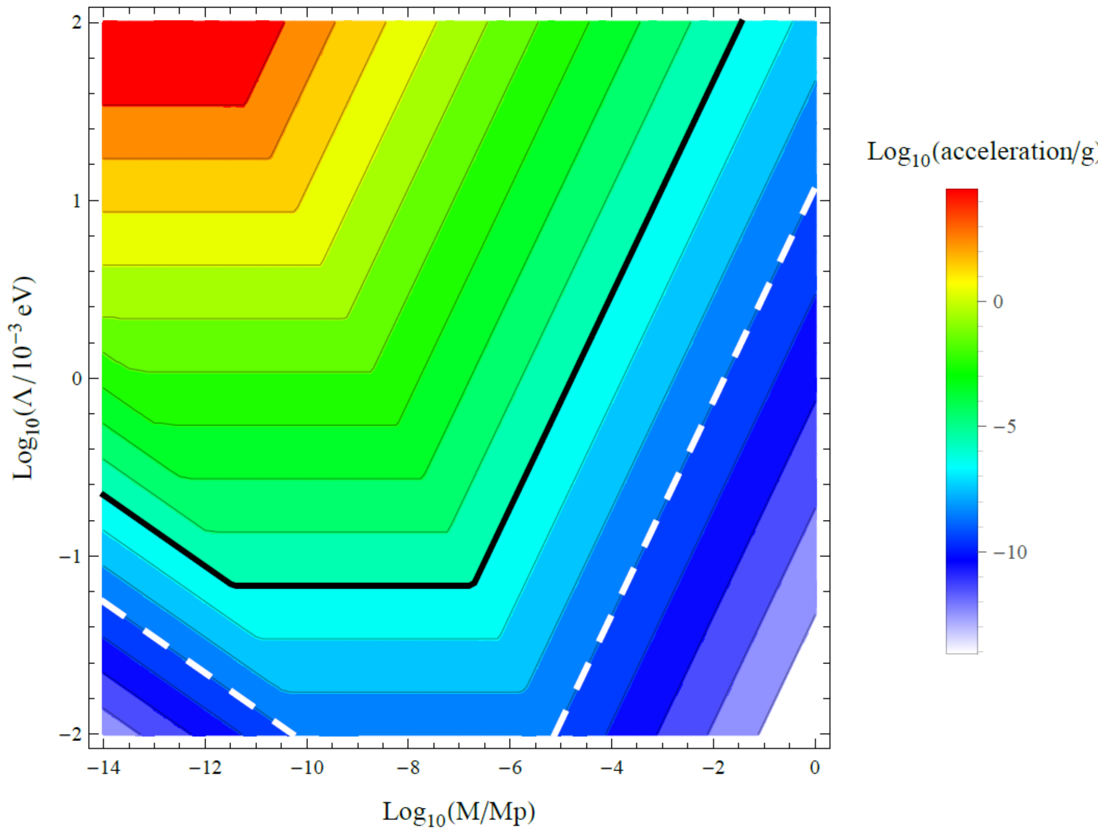
The walls of the vacuum chamber screen out any external chameleon forces

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)

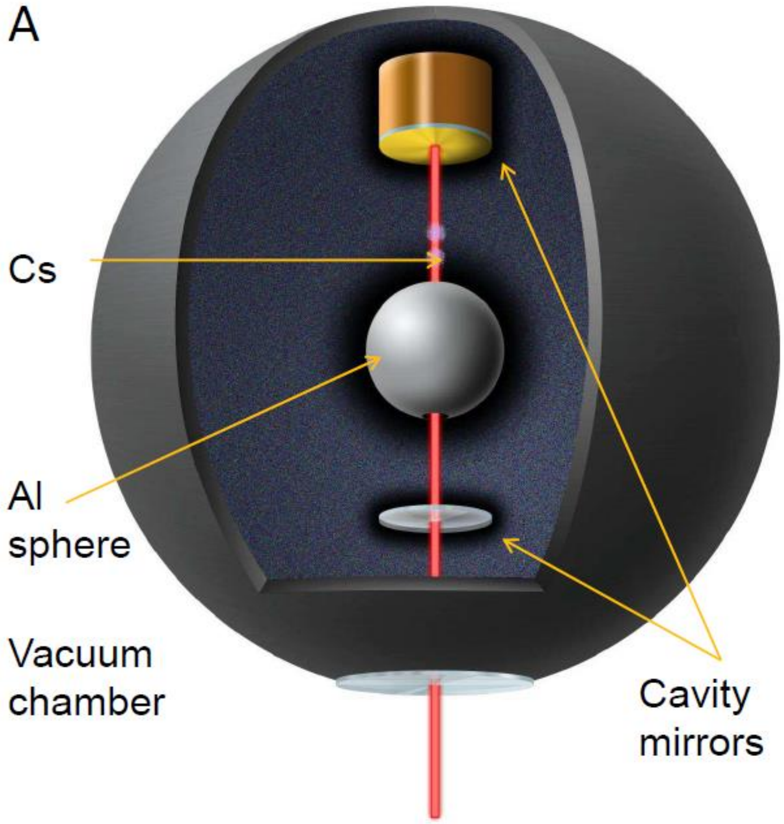


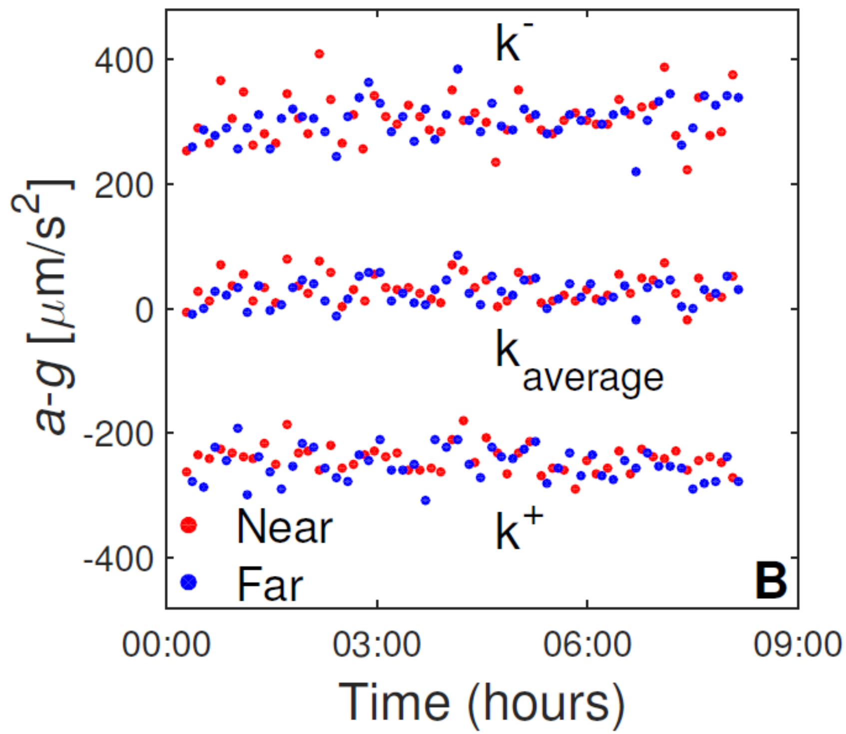
CB, Copeland, Hinds. (2015)

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

Berkley Experiment

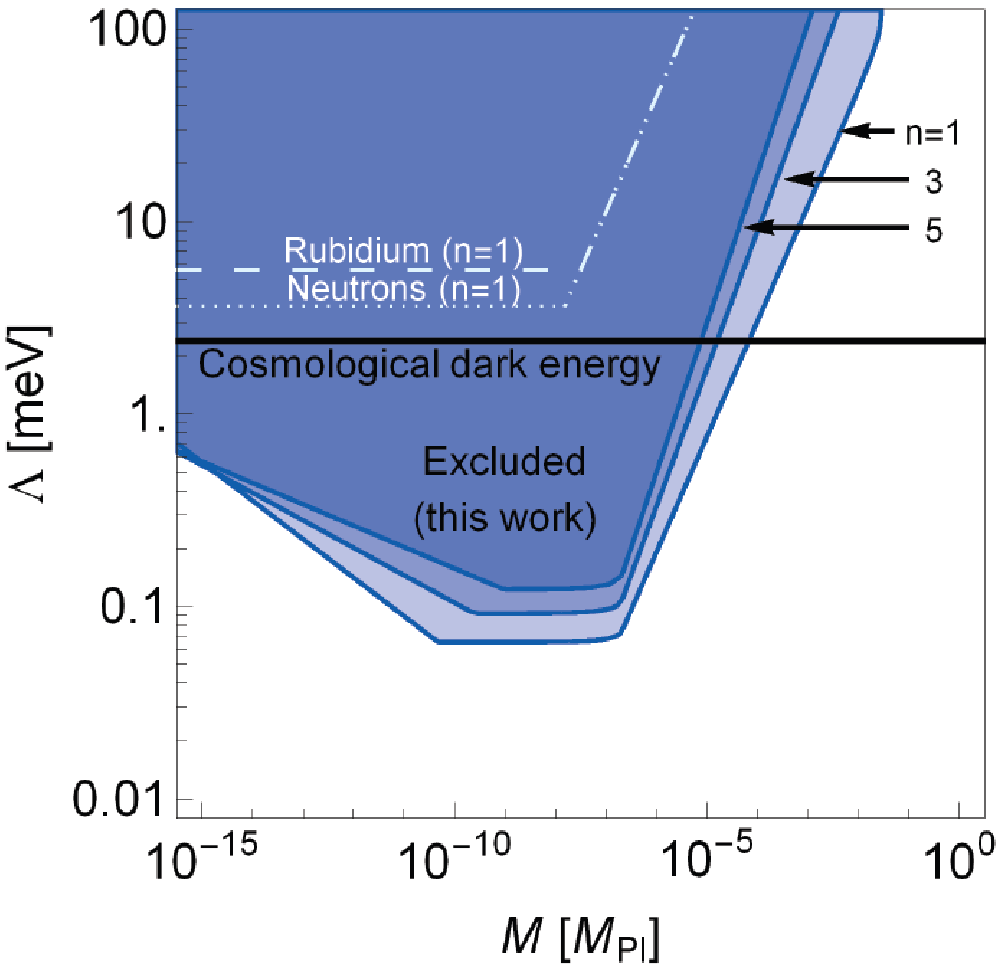
Using an existing set up with an optical cavity
The cavity provides power enhancement, spatial filtering, and a precise beam geometry





Hamilton et al. (2015)

Berkley Experiment



Hamilton et al. (2015)

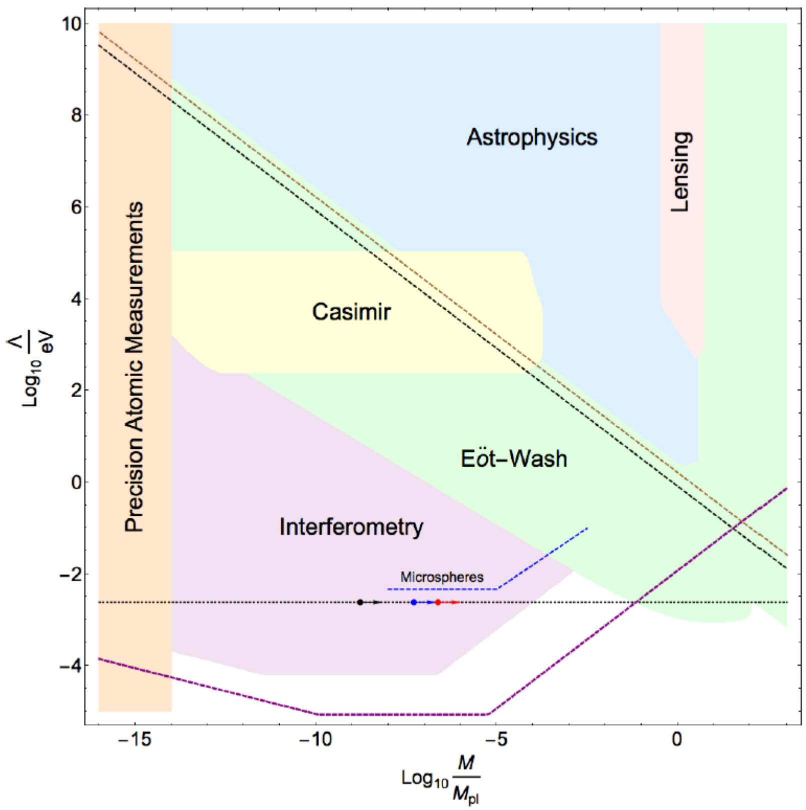
See also: Neutron interferometry experiments: Lemmel et al. (2015)

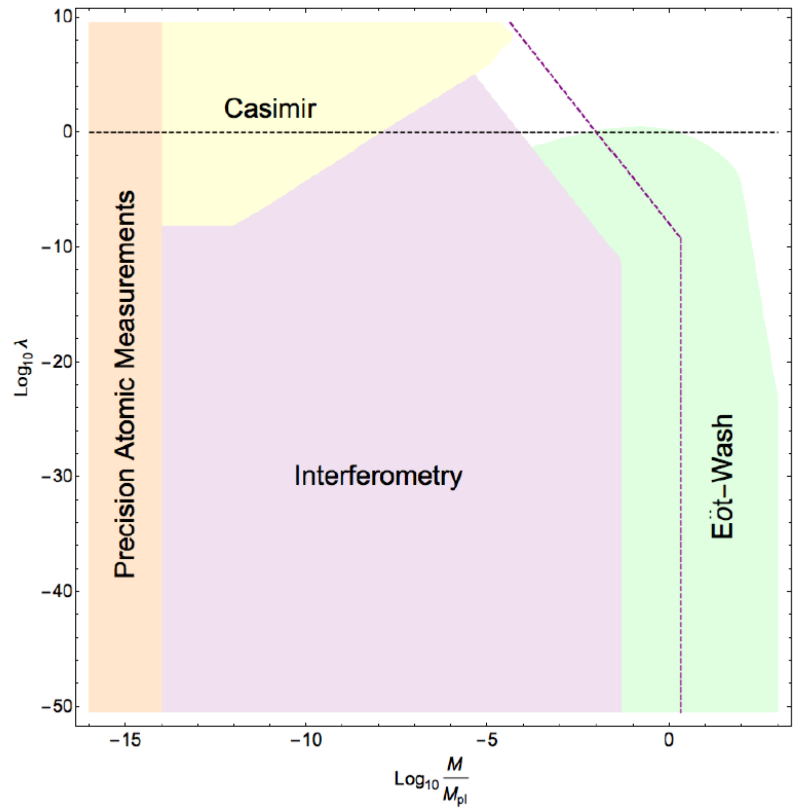
Optically levitated microspheres: Rider et al. (2016)

Combined Chameleon Constraints

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

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



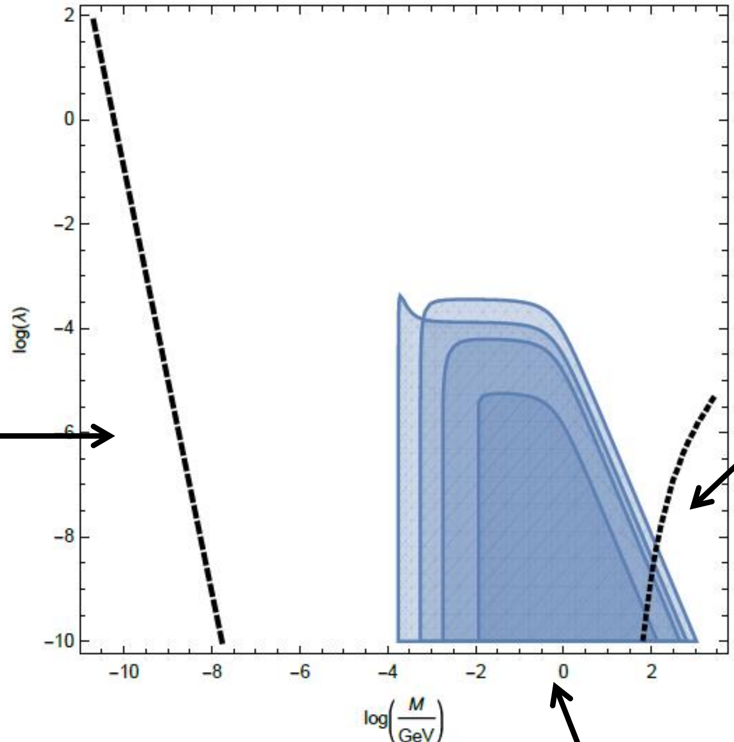


CB, Sakstein. (2016)

Symmetron Constraints

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

Excluded by exoplanet orbits $\mu \to 0$ [Santos & Mota 2016]



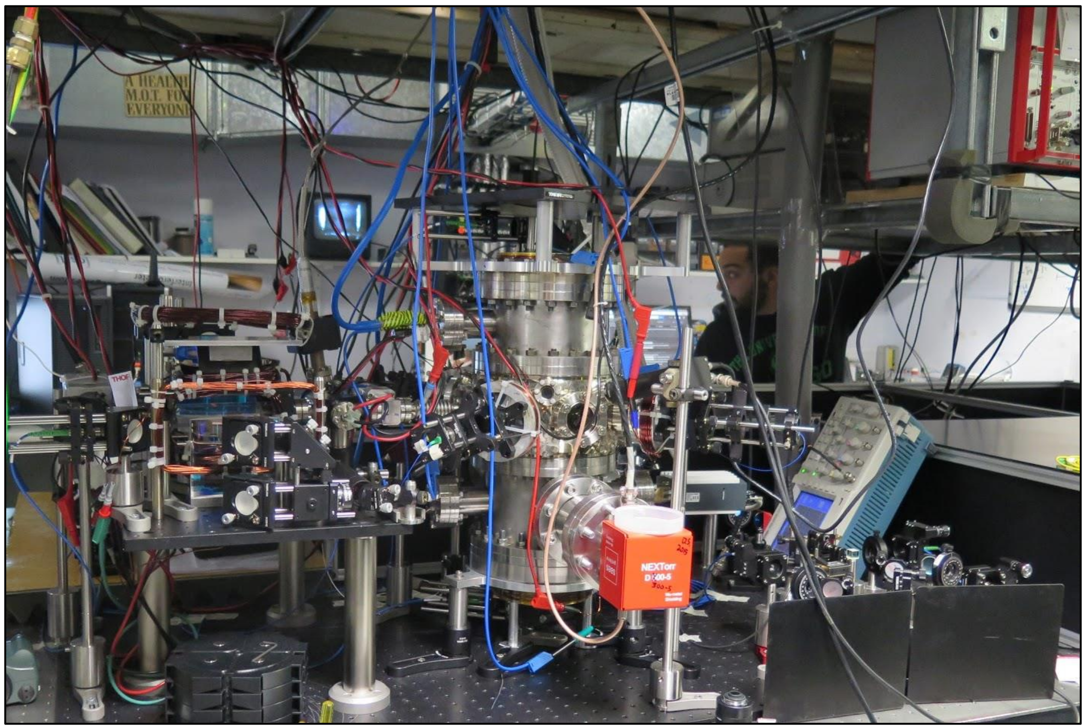
Excluded by torsion balance $\mu = 10^{-4}$ eV [Upadhye 2013]

Excluded by atom interferometry for $\mu = 10^{-4}, 10^{-4.5}, 10^{-5}, 10^{-5.5}$ eV

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

Screened Forces in Galaxies

Galaxy rotation curves – M33

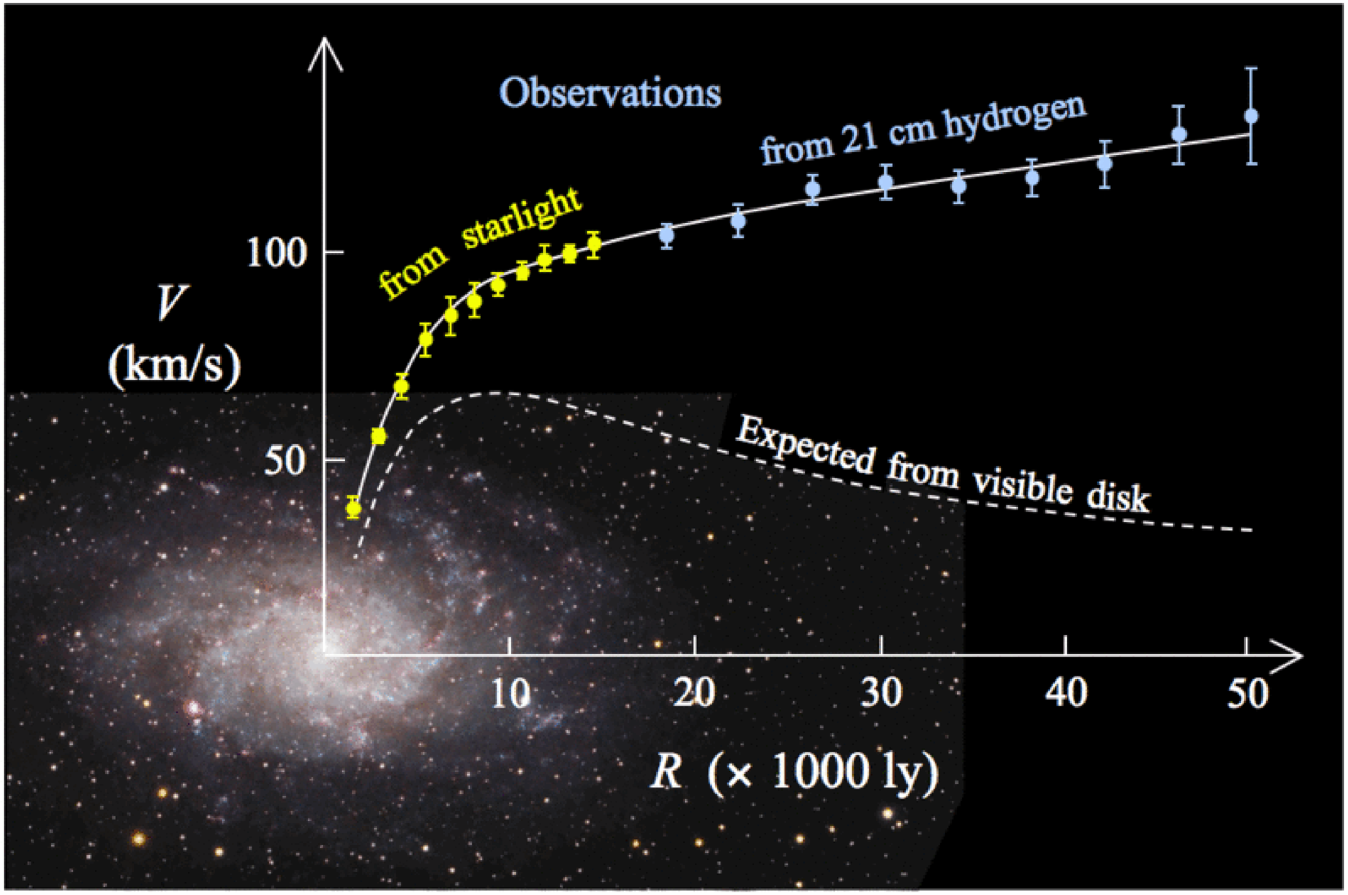
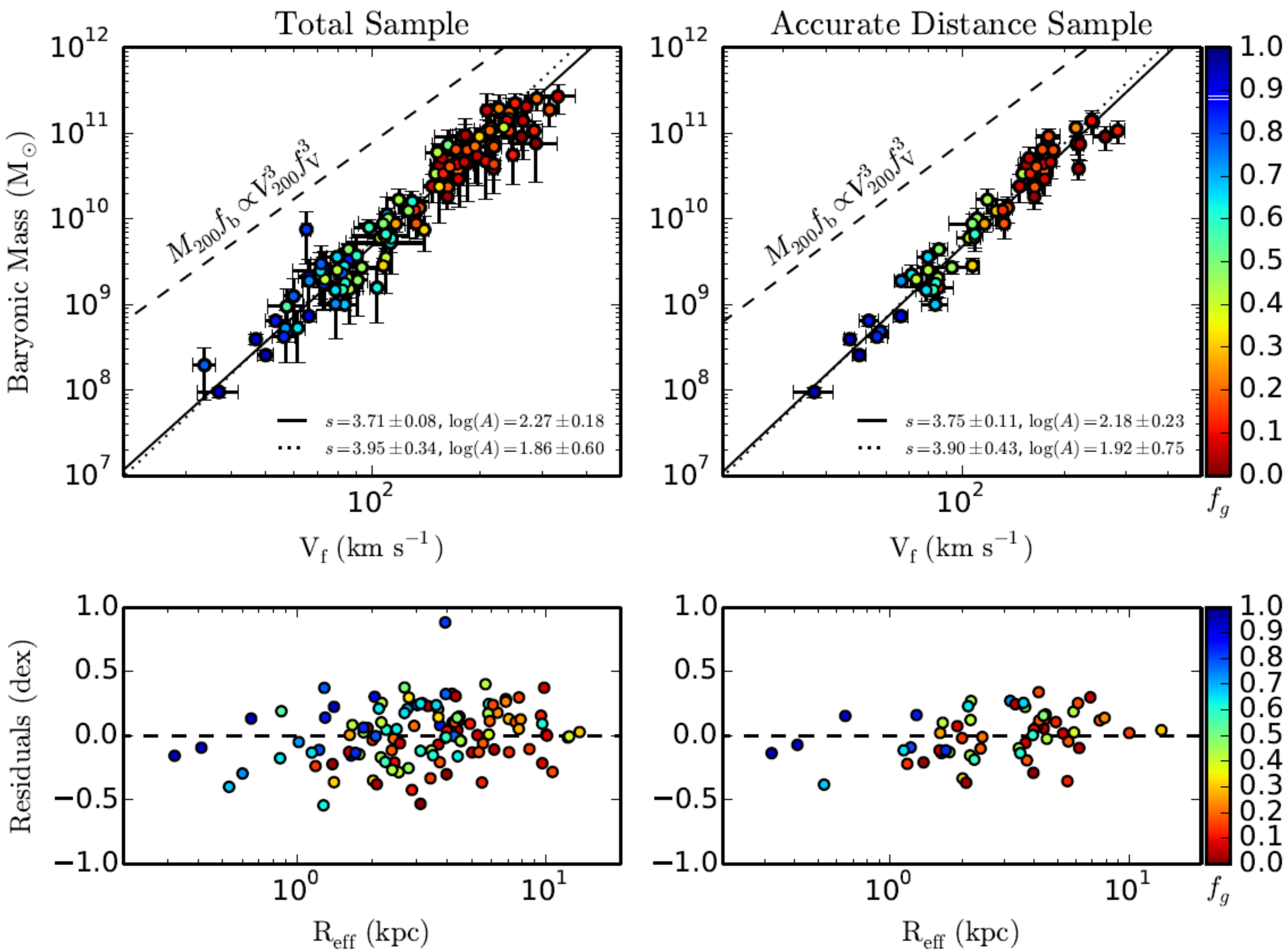


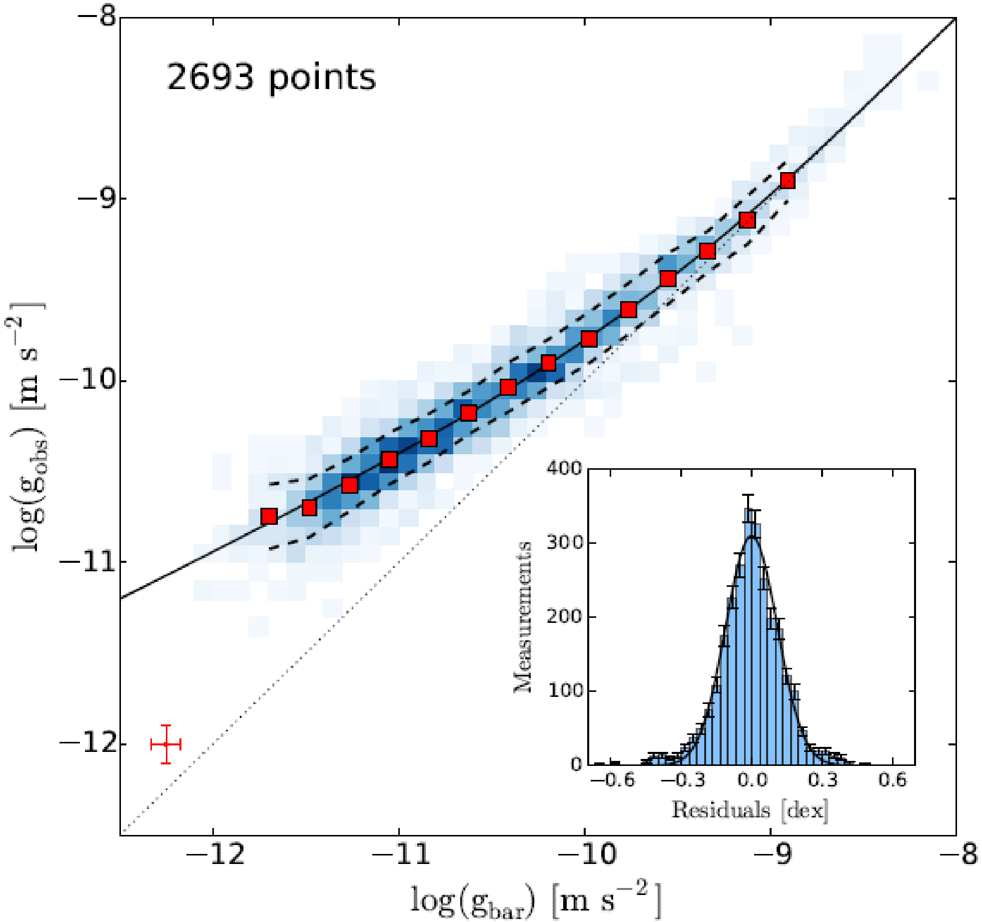
Image Credit: Stefania.deluca

Baryonic Tully-Fisher Relation



Lelli, McGaugh, Schombert. 2015

Radial Acceleration Relation



153 galaxies,

~ 2700 data points

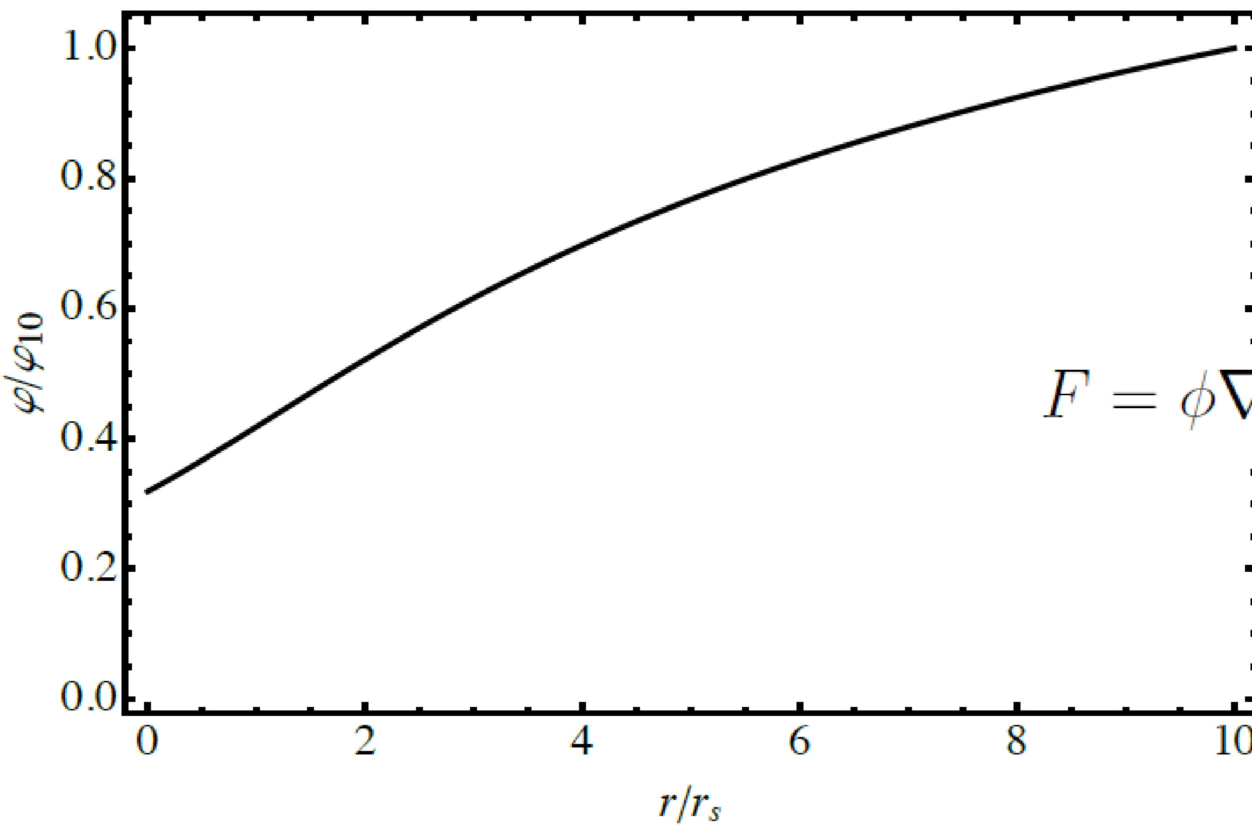
$$g_{obs} = \frac{V^2(R)}{R}$$

$$g_{obs} = \mathcal{F}(g_{bar}) = \frac{g_{bar}}{1 - e^{-\sqrt{g_{bar}/g_{\dagger}}}}$$

McGaugh, Lelli, Schombert. 2016. See also Keller and Wadsley 2016.

Symmetron Field Profile for a Galaxy

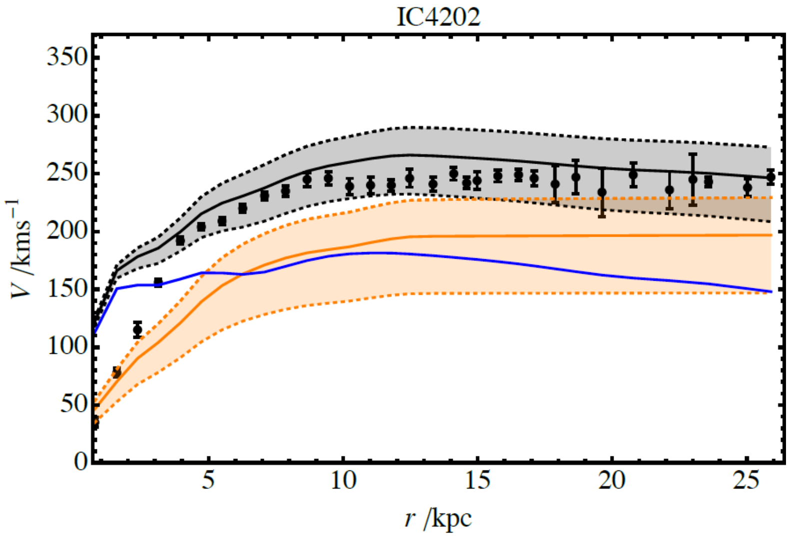
To explain rotation curves and the acceleration relation with only a symmetron force and no dark matter

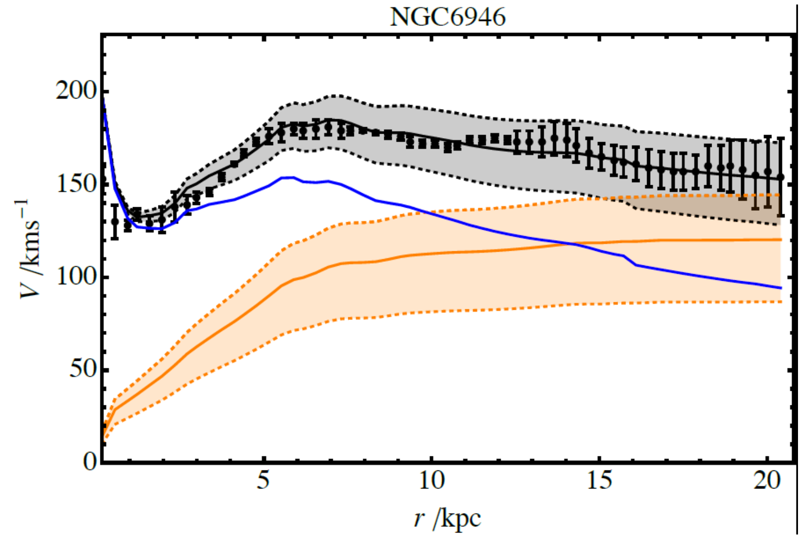


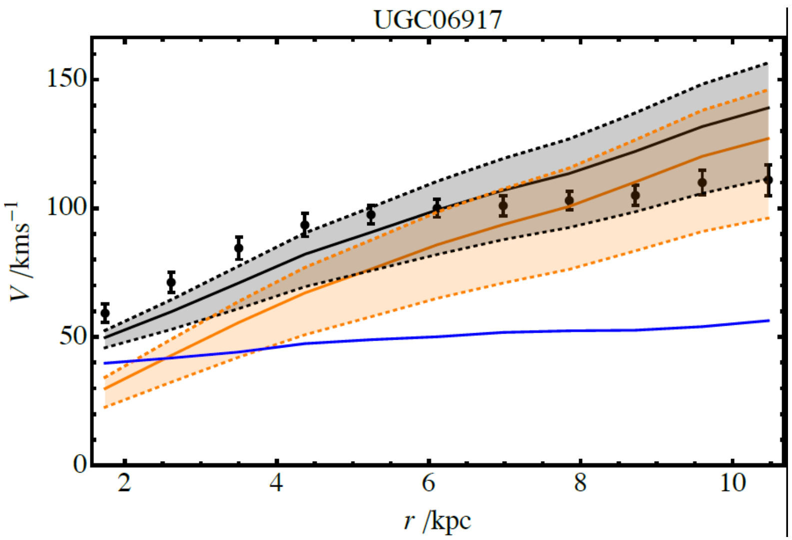
$$F = \phi \nabla \phi / M^2$$

CB, Copeland, Millington. (2016)

Galaxy Rotation Curves







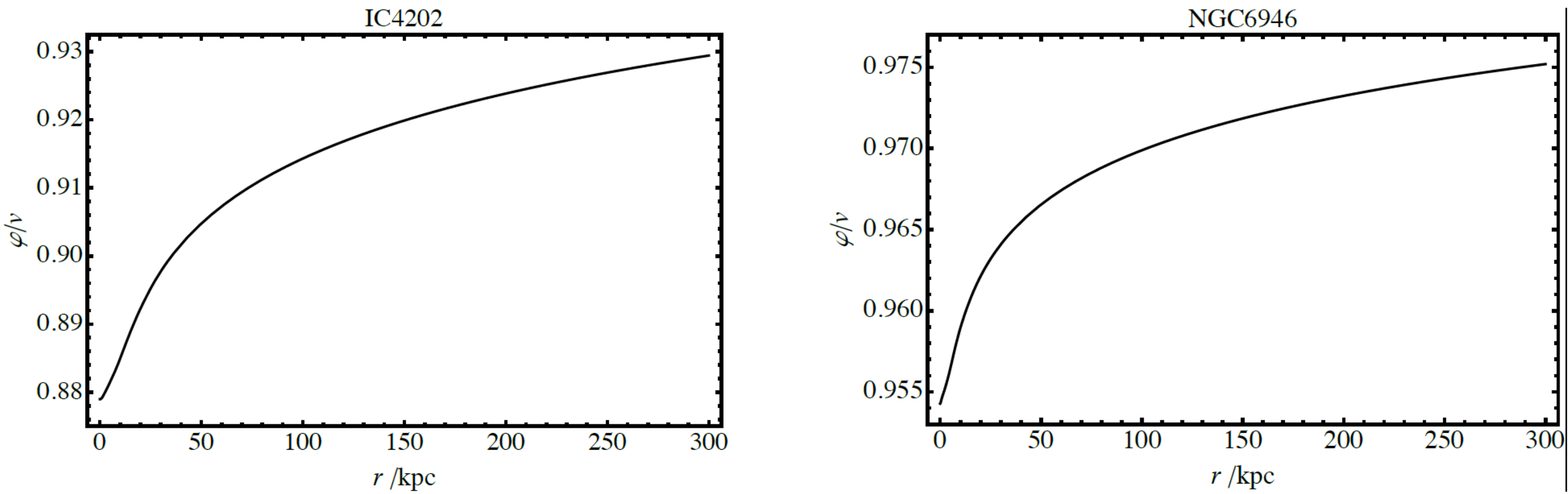
$$\mu = 10^{-40}\ \mathrm{GeV}$$

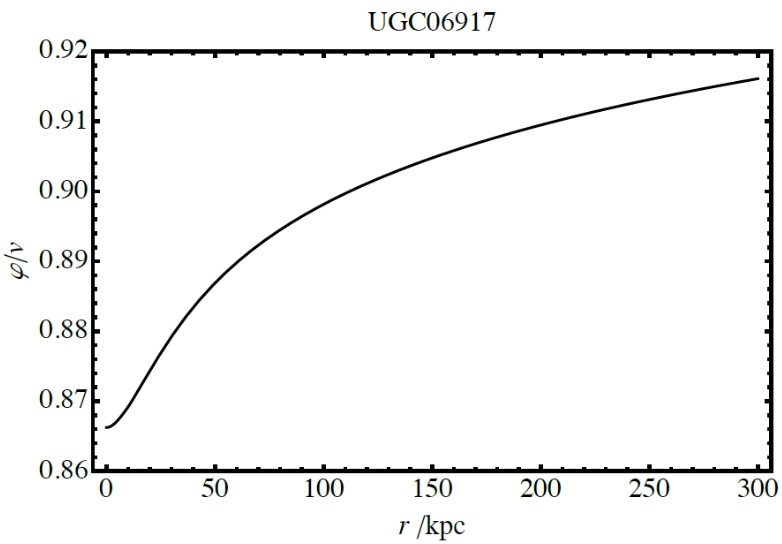
$$M = M_{\mathrm{Pl}}/10$$

$$v = M/170$$

CB, Copeland, Millington. (2016)

Symmetron Field Profiles





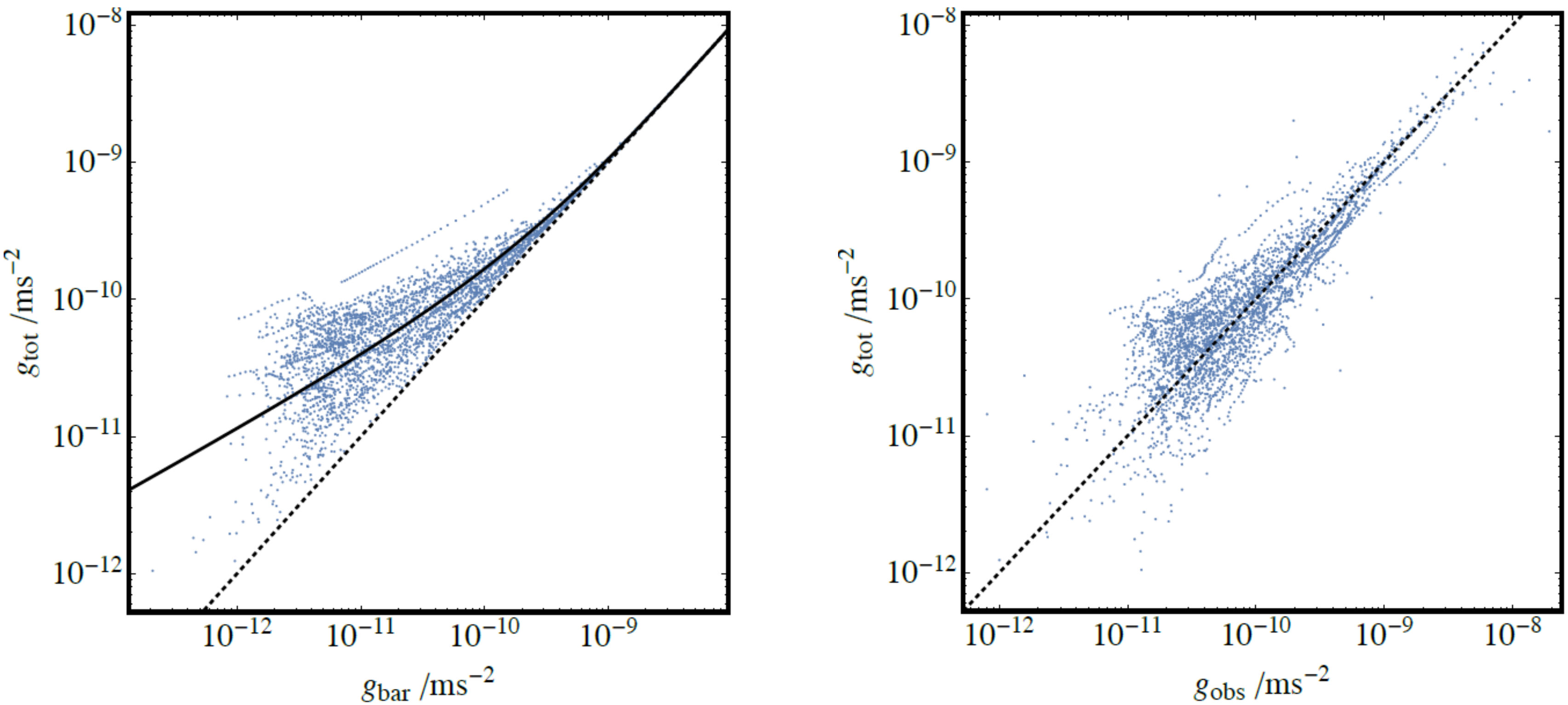
$$\mu = 10^{-40}\ \text{GeV}$$

$$M = M_{\text{Pl}}/10$$

$$v = M/170$$

CB, Copeland, Millington. (2016)

Symmetron Acceleration Relation



CB, Copeland, Millington. (2016)

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

Symmetron fifth forces could explain correlations between rotation curves and baryonic properties of galaxies