Detecting Dark Energy with Atom Interferometry

Clare Burrage
University of Nottingham
Clare.Burrage@nottingham.ac.uk

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:

\[ \rho_{\text{vac}} \sim M^4 \]

Observed:

\[ \rho_\Lambda \sim (10^{-3} \text{ eV})^4 \]

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
- 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

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

where

\[ Z(\phi) = Z^\mu_\mu(\phi) \quad c_s^2(\phi) = \frac{Z_{\phi\phi}}{Z(\phi)} \quad m^2(\phi) \equiv \frac{d^2V}{d\phi^2} |_{\phi} \]

Resulting in a scalar potential for a test mass

\[ V(r) = -\frac{g^2(\phi)}{Z(\phi)c_s^2(\phi)} e^{-\frac{m(\phi)}{\sqrt{Z(\phi)c_s(\phi)}} r} \frac{\mathcal{M}}{4\pi r} \]
Screening Mechanisms

• **Locally weak coupling**
  Symmetron and varying dilaton models

• **Locally large kinetic coefficient**
  Vainshtein mechanism, Galileon and k-mouflage models
  Babichev, Deffayet, Ziour (2009).

• **Locally large mass**
  Chameleon models
  Khoury, Weltman (2004).
The Chameleon

Spherically symmetric, static equation of motion

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

Chameleon screening relies on a non-linear potential,

e.g.

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

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

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-renormalisable 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

\[ V(\phi) = \frac{\lambda}{4} \phi^4 - \frac{\mu^2}{2} \phi^2 \]

\[ \mathcal{L} \supset \frac{\phi^2}{2M^2} T^\mu_\mu \]

Effective potential

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

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 standard light scalar fields

\[ \Phi = -\frac{GM}{r} \]
The Scalar Potential

Around a static, spherically symmetric source of constant density

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

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

This determines how responsive an object is to the chameleon field
Why Atom Interferometry?

Recall that for a chameleon:

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

Where the screening is controlled by

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

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.

1. Photon Momentum = k
2. Atom in excited state with velocity = V

Atom in ground state
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

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

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)
Berkley Experiment

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

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

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

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

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

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

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

\[ \mu = 10^{-40} \text{ GeV} \]
\[ M = M_{\text{Pl}}/10 \]
\[ v = M/170 \]

CB, Copeland, Millington. (2016)
Symmetron Field Profiles

\[ \frac{\varphi}{\Lambda} \]

\[ r \, / \text{kpc} \]

IC4202

NGC6946

UGC06917

\[ \mu = 10^{-40} \text{ GeV} \]

\[ M = M_{\text{Pl}}/10 \]

\[ \nu = M/170 \]

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