Detecting Dark Energy with Atom Interferometry

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Outline:

Dark energy and its interactions

How to screen fifth forces

Dark energy in the laboratory

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

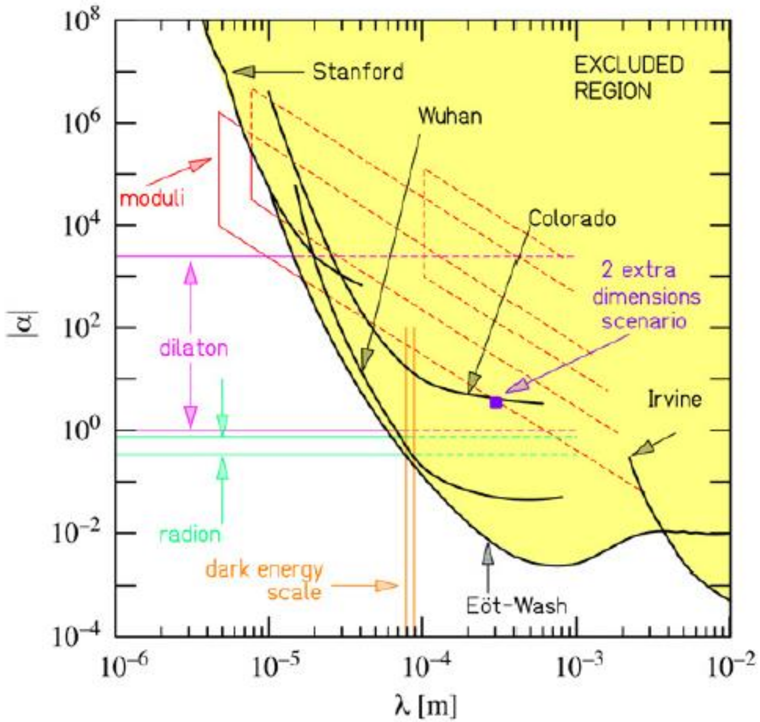
  Papapetrou (1948). Weinberg (1965).

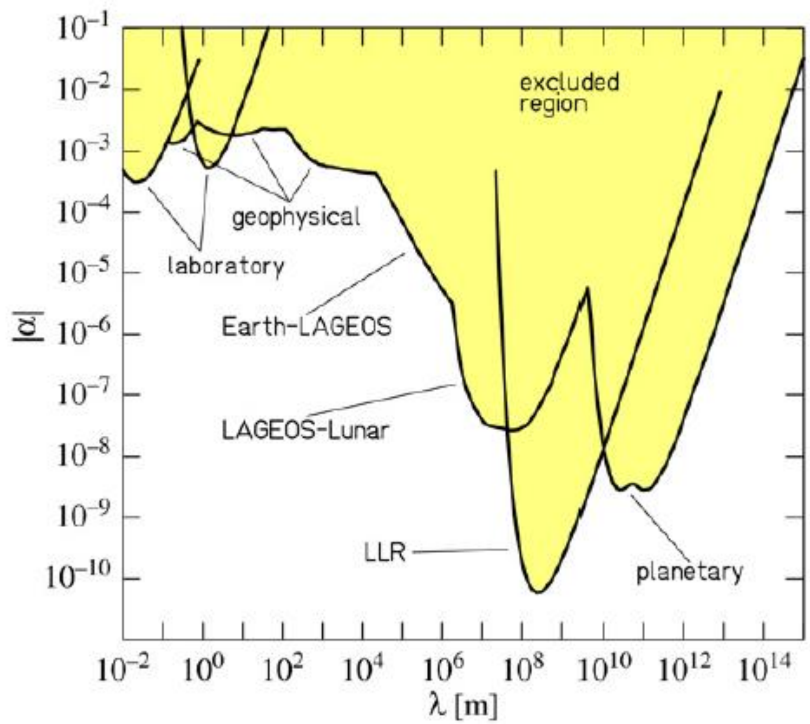
- New physics in the gravitational sector will introduce new degrees of freedom, typically Lorentz scalars

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

Split the field into background and perturbation

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

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

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.

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

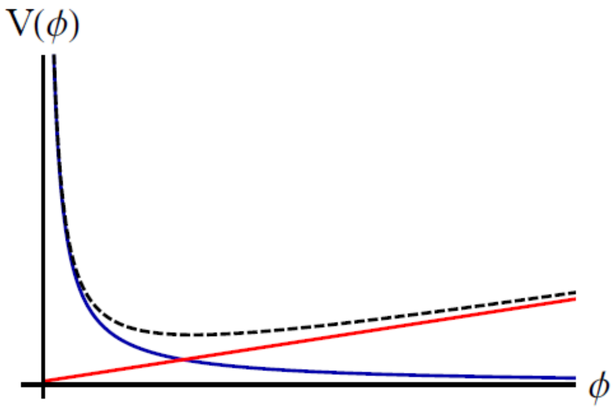
Khoury, Weltman. (2004). Image credit: Nanosanchez

Varying Mass

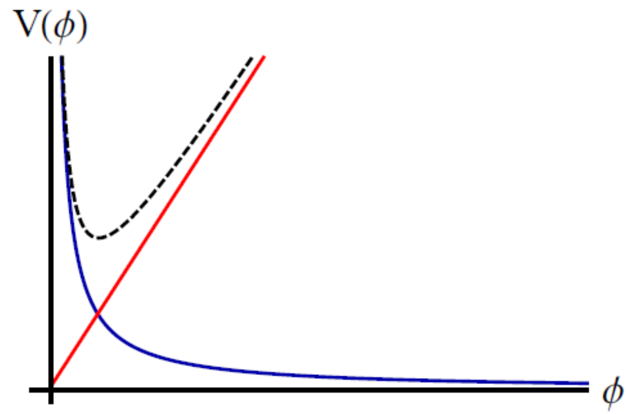
The mass of the chameleon changes with the environment

Field is governed by an effective potential

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



Low density



High density

Warning: Non-renormalisible theory, no protection from quantum corrections (But see arXiv:1604.06051)

The Scalar Potential

Around a static, spherically symmetric source of constant density

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

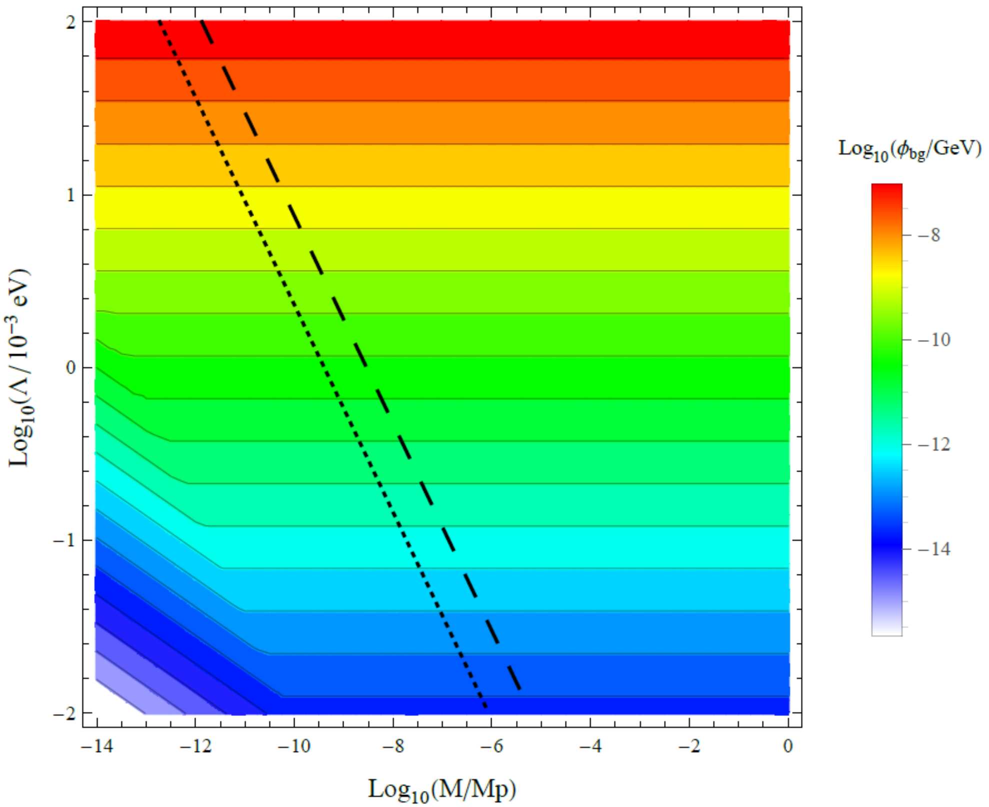
$$\lambda_A = \begin{cases} 1\,, & \rho_A R_A^2 < 3M\phi_{\rm bg} \\ 1 - \frac{S^3}{R_A^3} \approx 4\pi R_A \frac{M}{M_A}\phi_{\rm bg}\,, & \rho_A R_A^2 > 3M\phi_{\rm bg} \end{cases}$$

This determines how responsive an object is to the chameleon field

Why Atom Interferometry?

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

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



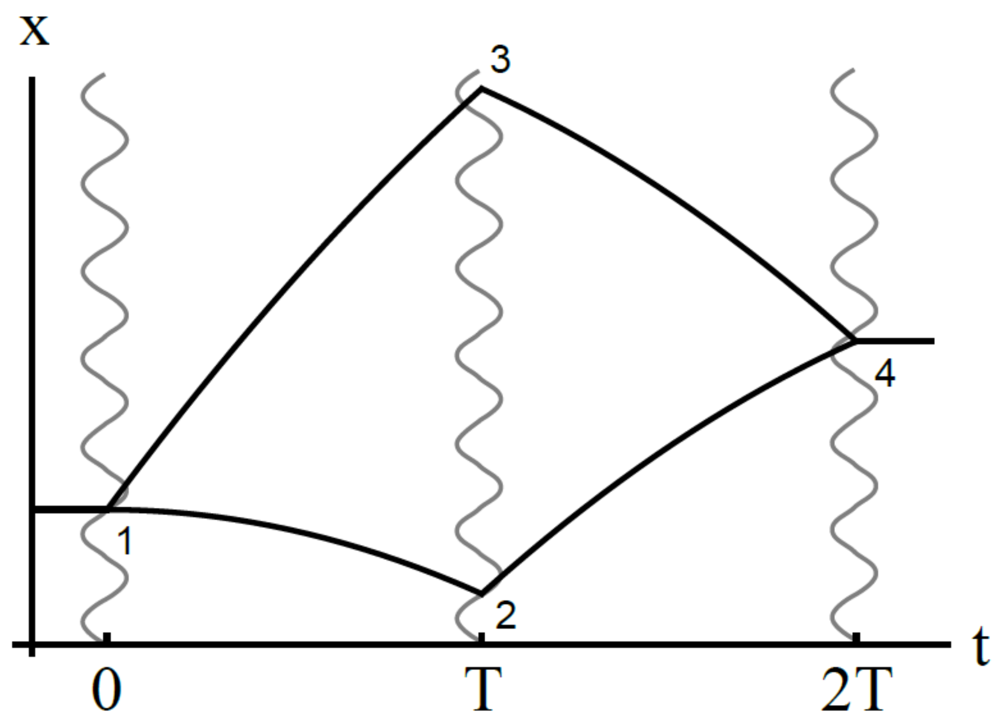
CB, Copeland, Hinds. (2015)

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



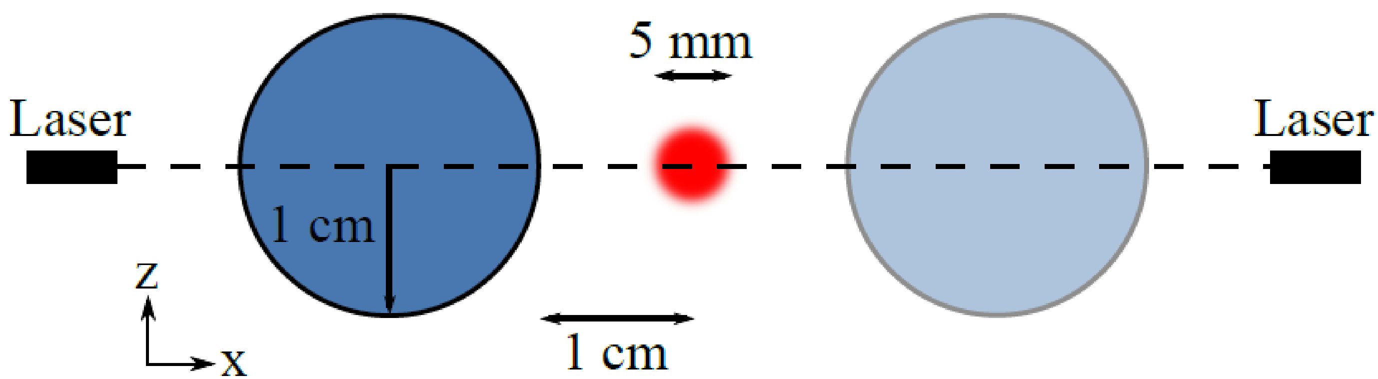
Probability measured in excited state at output

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

Atom Interferometry for Chameleons

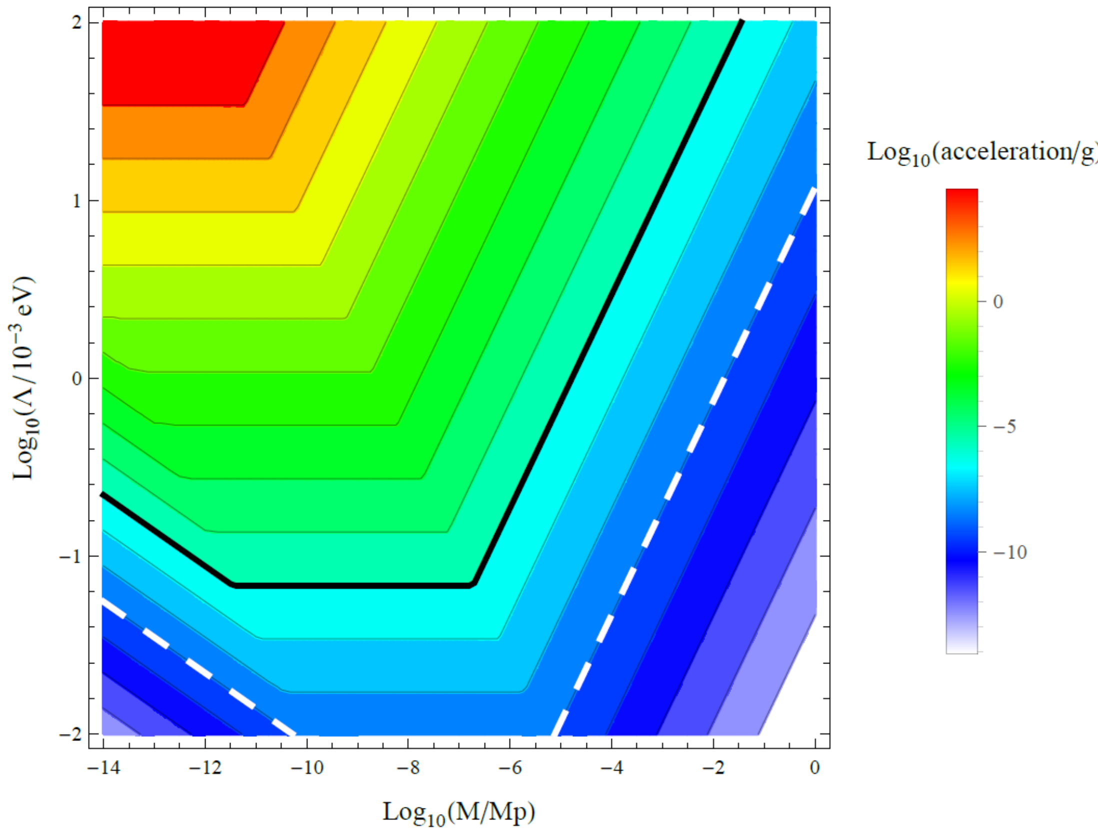
The walls of the vacuum chamber screen out any external chameleon forces

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



Proposed Sensitivity

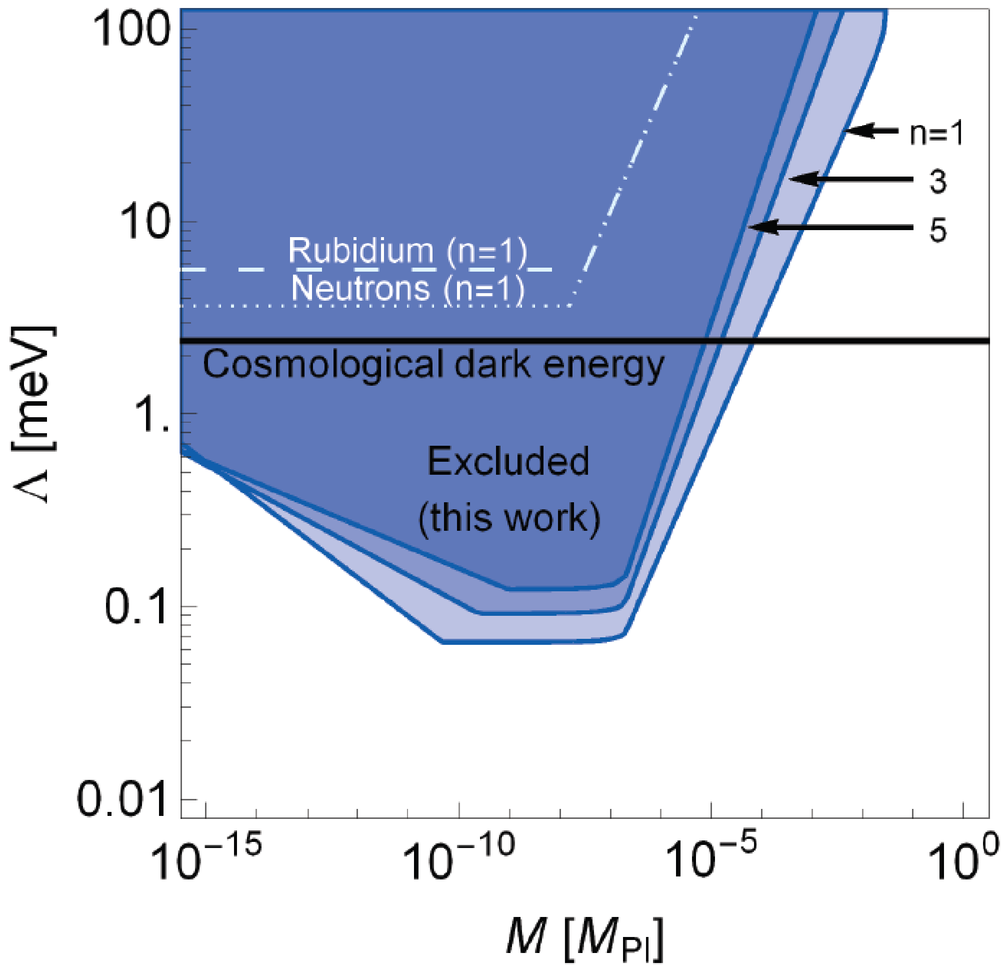
- Systematics: Stark effect, Zeeman effect, phase shifts due to scattered light, movement of beams
- All negligible at 10^{-6} g sensitivity (solid black line)
- Controllable down to 10^{-9} g (dashed white line)



CB, Copeland, Hinds. (2015)

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

Berkley Experiment



Hamilton et al. (2015)

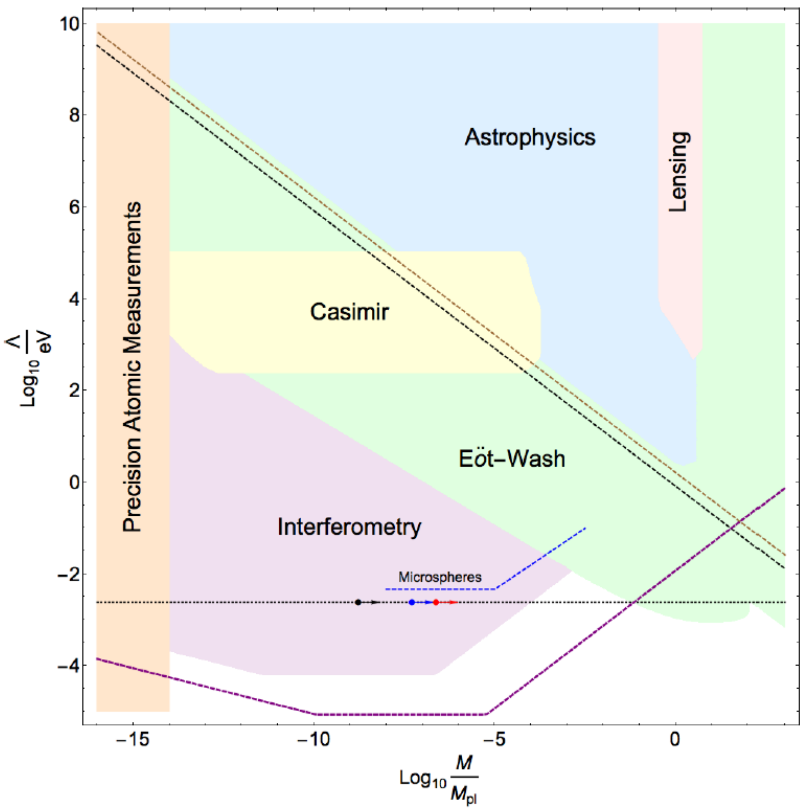
See also: Neutron interferometry experiments: Lemmel et al. (2015)

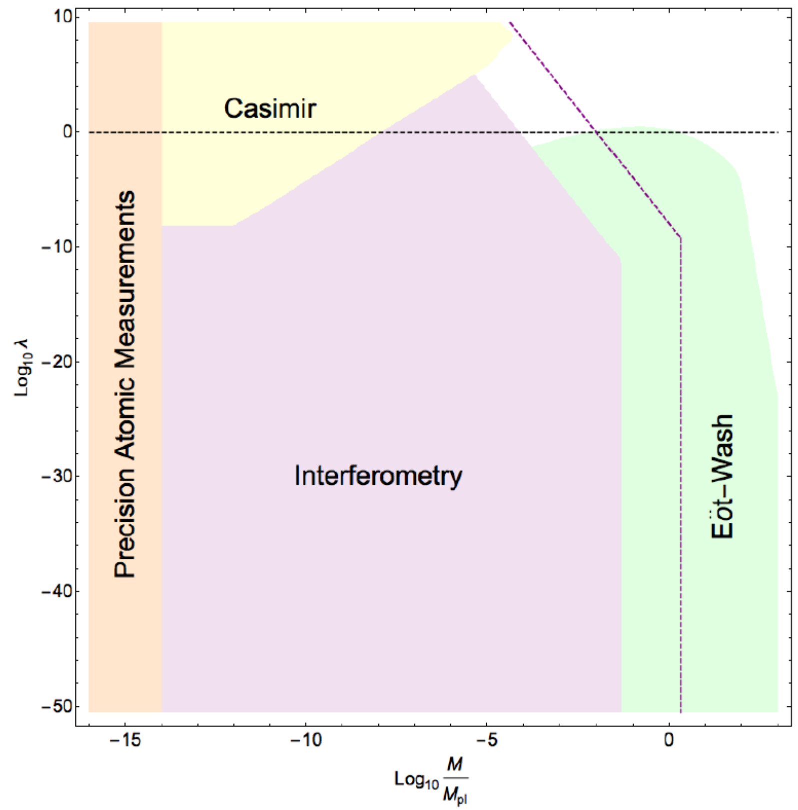
Optically levitated microspheres: Rider et al. (2016)

Combined Constraints

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

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

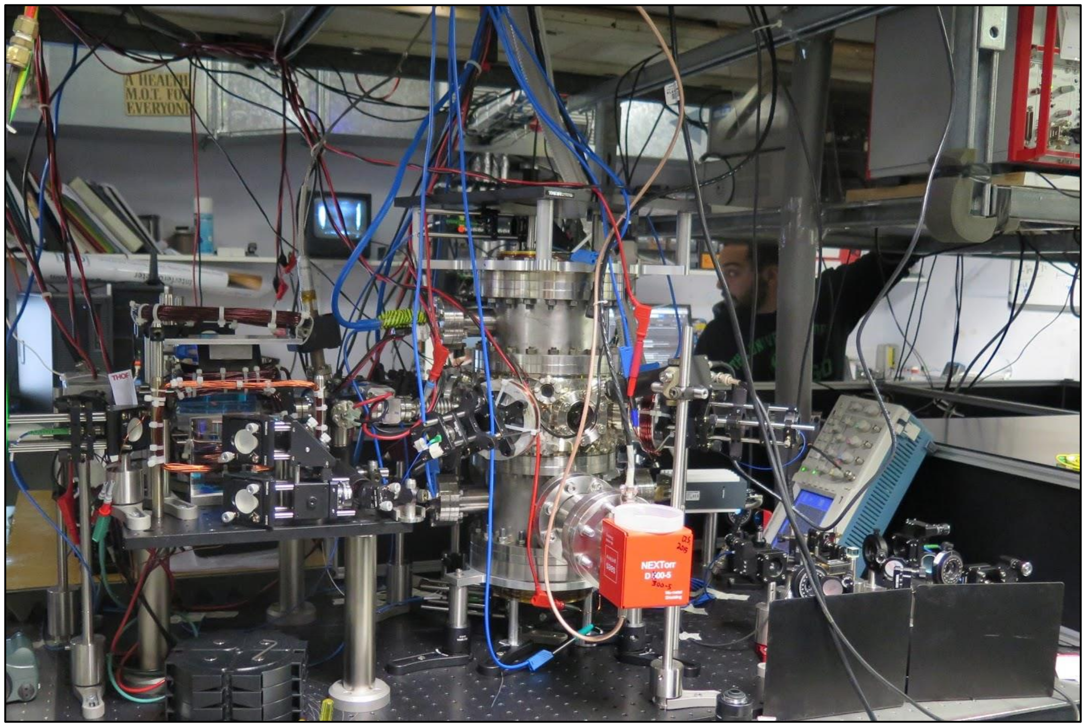




CB, Sakstein. arXiv:1609.01192

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

Related Ideas and Experiments

Interactions of chameleons with photons studied by GammeV, CAST

Steffen et al. (2010) Anastassopoulos et al. (2015)

Detecting chameleons with novel force sensors – see talk of Giovanni Cantatore

Karuza et al. (2016)

Is it possible to detect vacuum fluctuations directly with atom interferometry? – speak to Jon Coleman

Adler, Mueller, Perl. (2011)

LHC signatures of scalar dark energy

Brax, CB, Englert, Spannowsky. (2016)

Summary

Dark energy makes up ~ 70% of the Universe

- Theory predicts a value for the cosmological constant significantly larger than observed

Solutions 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

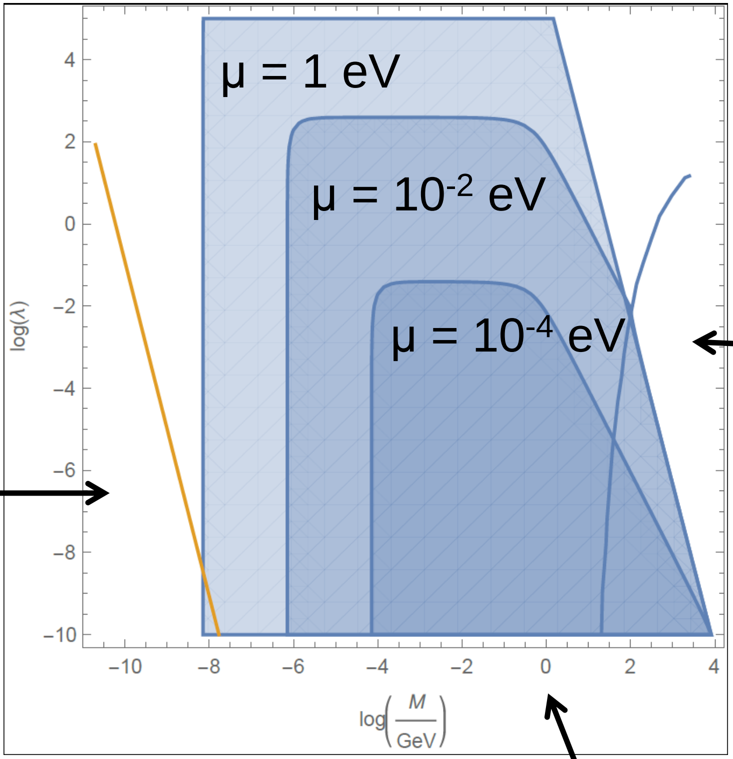
- Can still be detected in suitably designed experiments
- Atom interferometry a particularly powerful technique.

Symmetron 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 [Santos & Mota 2016]

$\mu \to 0$



Excluded by torsion balance [Upadhye 2013]

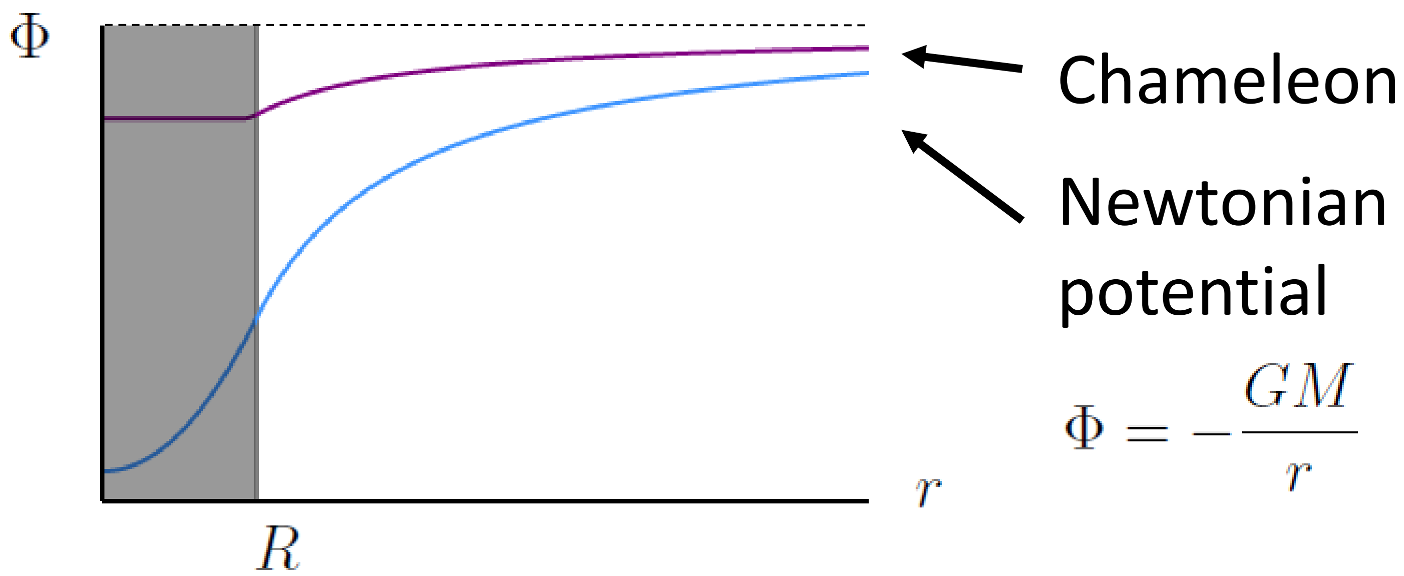
$\mu = 10^{-2}$ eV

Excluded by atom interferometry $\mu = 10^{-2}$ eV

CB, Kuribayashi-Coleman, Thrussell (to appear)

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

f(R) Chameleons

In the Einstein frame

$$\bar{g}_{\mu\nu} = e^{-\frac{2\beta\phi}{M_{\rm Pl}}} g_{\mu\nu}$$

$$S_{\rm ST} = \int {\rm d}^4 x \sqrt{-\bar{g}} \left(\frac{M_{\rm Pl}^2}{2} \bar{R} - \frac{1}{2} \bar{g}^{\mu\nu} \nabla_\mu \phi \nabla_\nu \phi - V(\phi) \right) + S_{\rm matter}[e^{\frac{2\beta\phi}{M_{\rm Pl}}} \bar{g}_{\mu\nu}, \Psi_i],$$

Scalar field has potential and coupling

$$V(\phi) = \frac{M_{\rm Pl}^2 (R f'(R) - f(R))}{2 f'(R)^2} \qquad \beta = \sqrt{1/6}$$

Only f(R) theories with a chameleon mechanism are observationally acceptable

Hu, Sawicki (2007). Brax, van de Bruck, Davis, Shaw (2008).

f(R) Chameleons

Attempt to modify gravity to explain accelerated expansion

$$S_{f(R)} = \int \mathrm{d}^4 x \sqrt{-g} \frac{M_{\mathrm{Pl}}^2}{2} f(R) + S_{\mathrm{matter}}[g_{\mu\nu}, \Psi_i]$$

Field equations are second order in derivatives of R

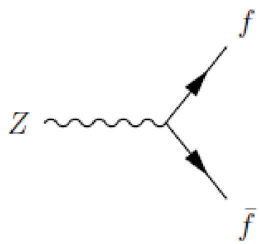
- Fourth order in derivatives of the metric
- By Ostrogradski's theorem there are hidden degrees of freedom

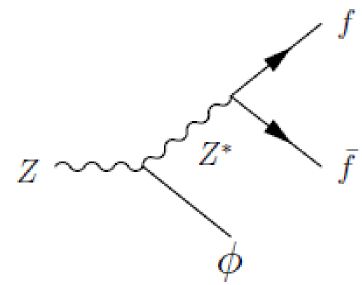
Make the extra degree of freedom explicit

$$\exp\left(-\frac{2\beta\phi}{M_{\mathrm{Pl}}}\right) = f'(R)$$

Scalar Bremsstrahlung

Contribution to the width of Z decay





$$\frac{\Gamma(Z \to \phi f \bar{f})}{\Gamma(Z \to f \bar{f})} = \frac{1}{16\pi^3} \frac{m_Z^2}{M_\gamma^2} I_{\phi f \bar{f}} \qquad I_{\phi f \bar{f}} \approx 0.2$$

- Prediction from the Standard Model:

$$\Gamma_Z = 2.4952 \ \text{GeV}$$

- Measurement at LEP:

$$\Gamma_Z = (2.4952 \pm 0.0023) \ \text{GeV}$$

Dark Energy correction negligible if

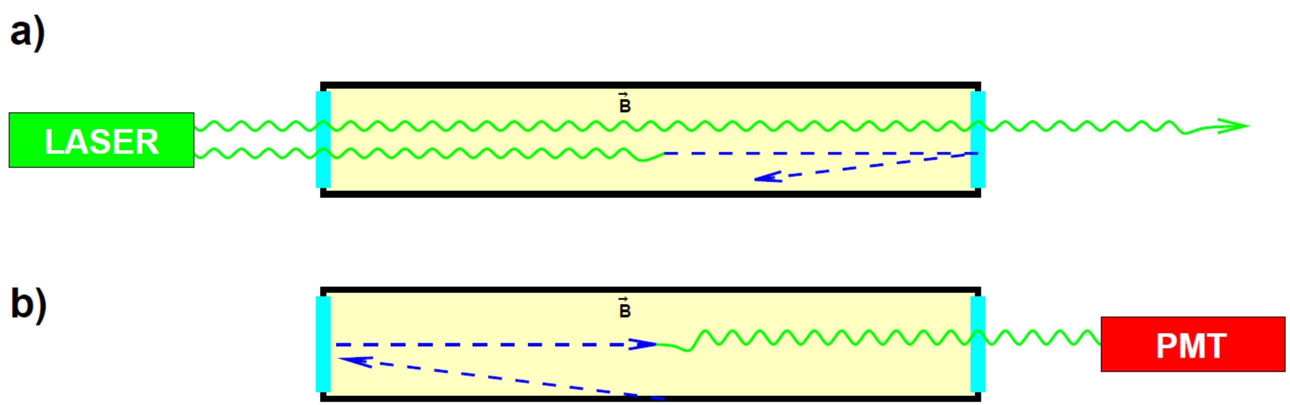
$$M_\gamma \gtrsim 10^2 \ \text{GeV}$$

Brax, CB, Davis, Seery, Weltman. (2009).

Chameleon After-glow

Chameleons could be made in a vacuum chamber through the Primakov effect

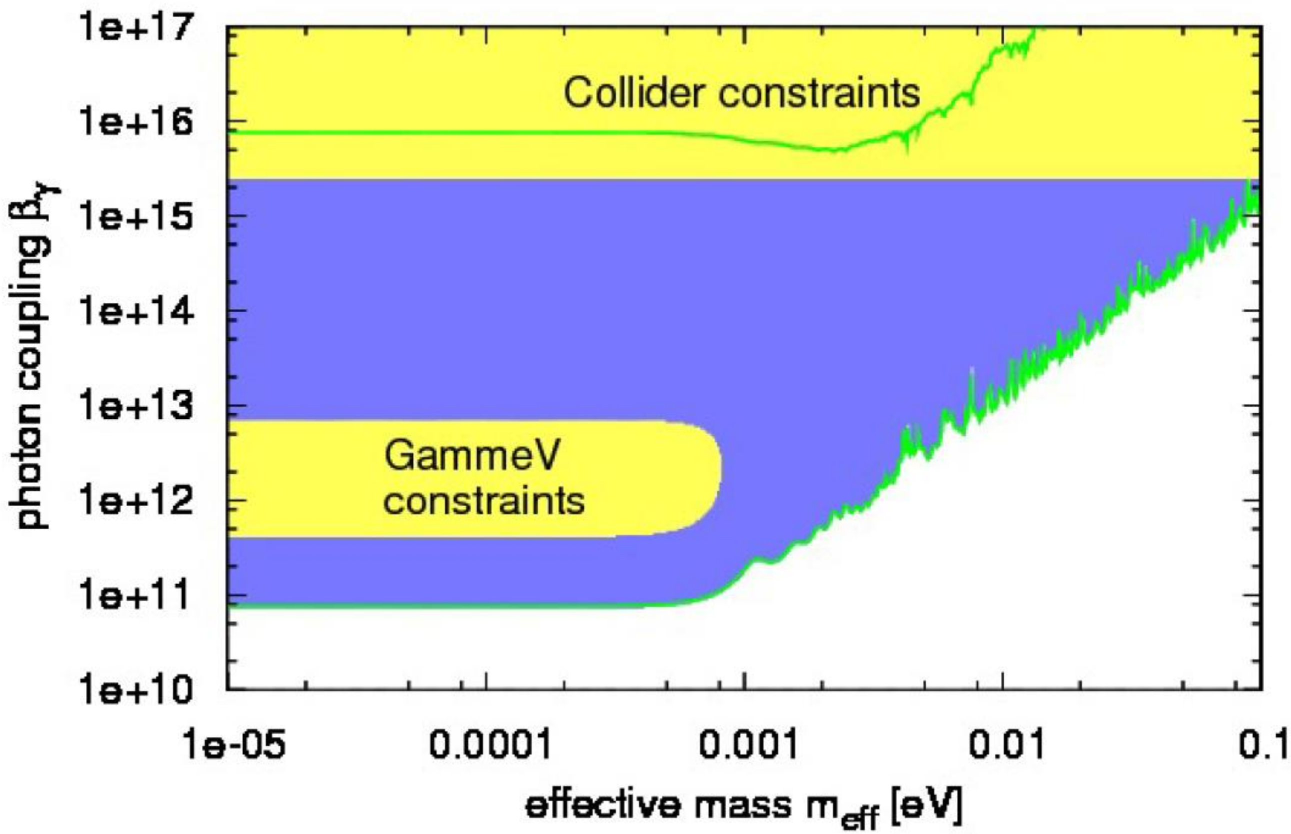
- To pass through the walls they need to become heavier
- If chameleons are not energetic enough this is forbidden and they remain trapped
- Reverse Primakov effect produces afterglow photons



Gies, Mota, Shaw. (2008). Ahlers, Lindner, Ringwald, Schrempp, Weniger. (2008).
Image credit: Upadhye, Steffen, Chou. (2012).

GammeV-CHASE

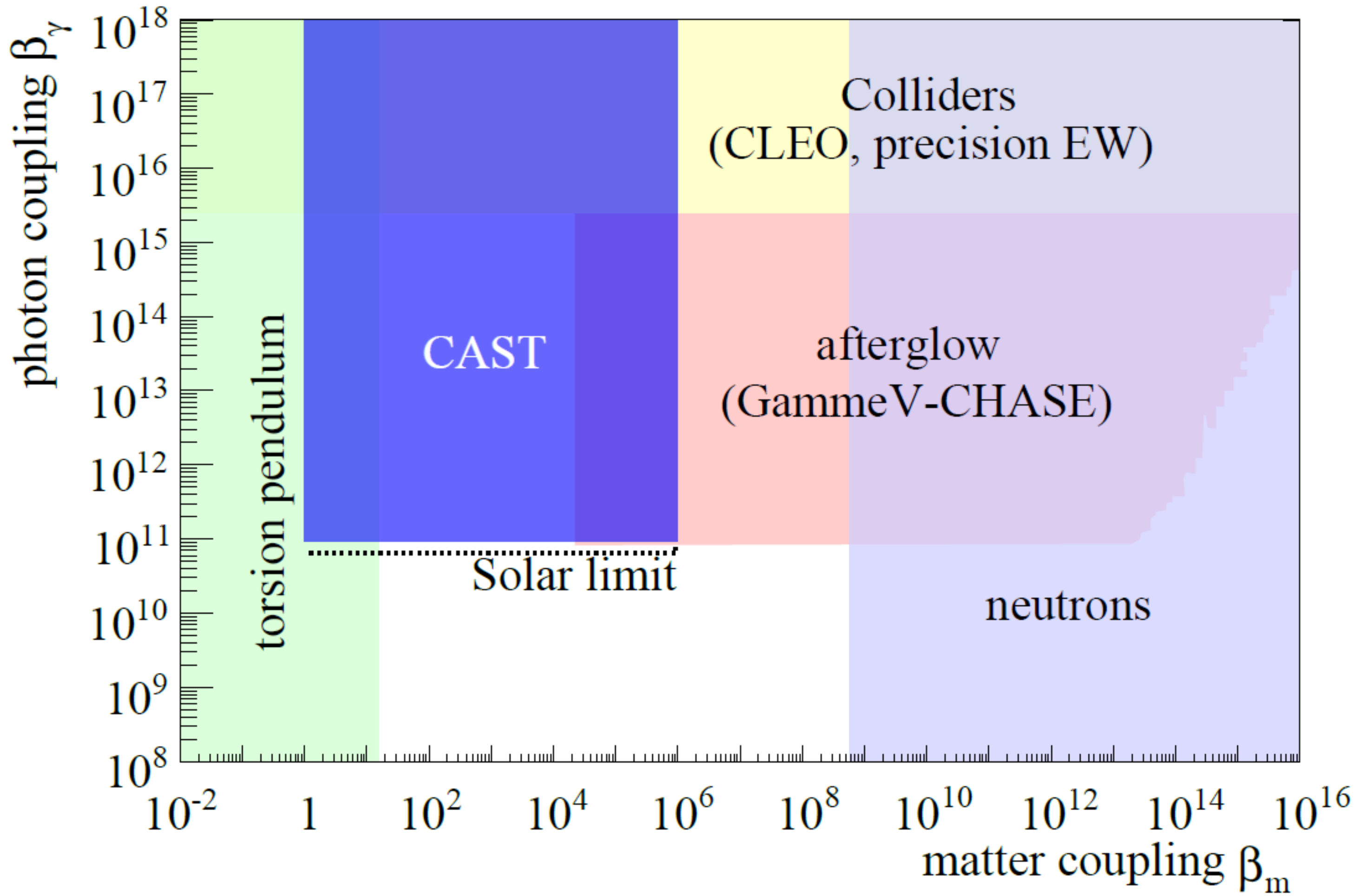
Results from the Gammev Chameleon Afterglow Search at Fermilab



Steffen et al. (2010)

Matter vs Photon coupling

CAST collaboration 2015



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

The Phase Difference

For a constant force, the atomic Lagrangian is

$$\mathcal{L} = \frac{m}{2}\dot{x}^2 + \frac{m}{2}\dot{z}^2 - max$$

Total action accumulated along each path is identical

$$S = \frac{mT}{2}\left(\frac{16}{3}aT^2 - 4aV + V^2 + 2U^2\right)$$

Where V the velocity imparted by interactions with the laser and U the velocity orthogonal to the force

No overall phase difference

Interactions With Photons

Continuity of the wave function means that atoms pick up a phase proportional to

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

each time they interact with a photon

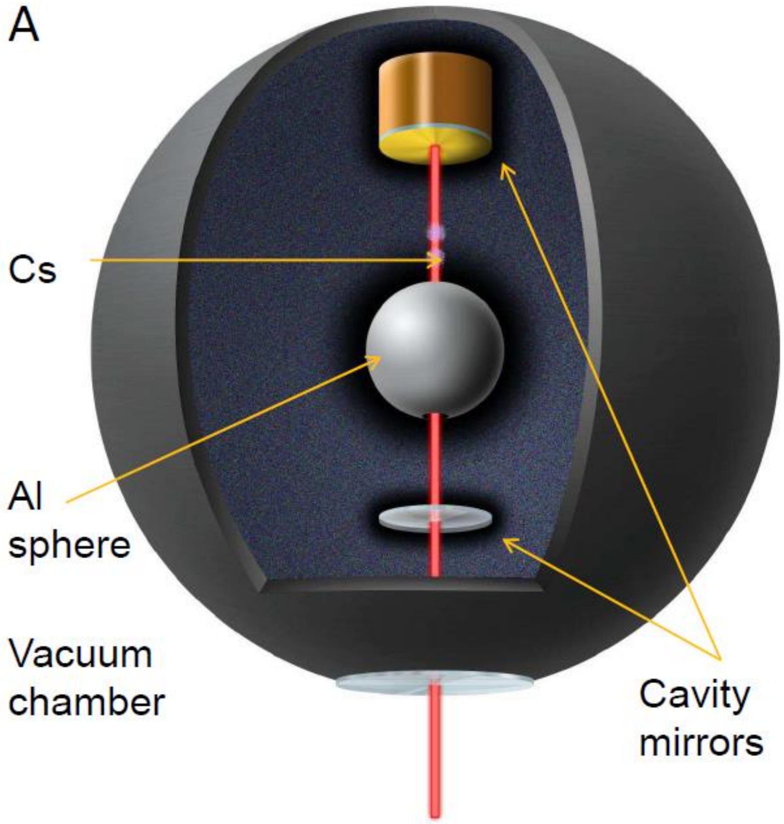
Assuming constant acceleration, the probability of measuring an atom in the ground state at the output of the interferometer is

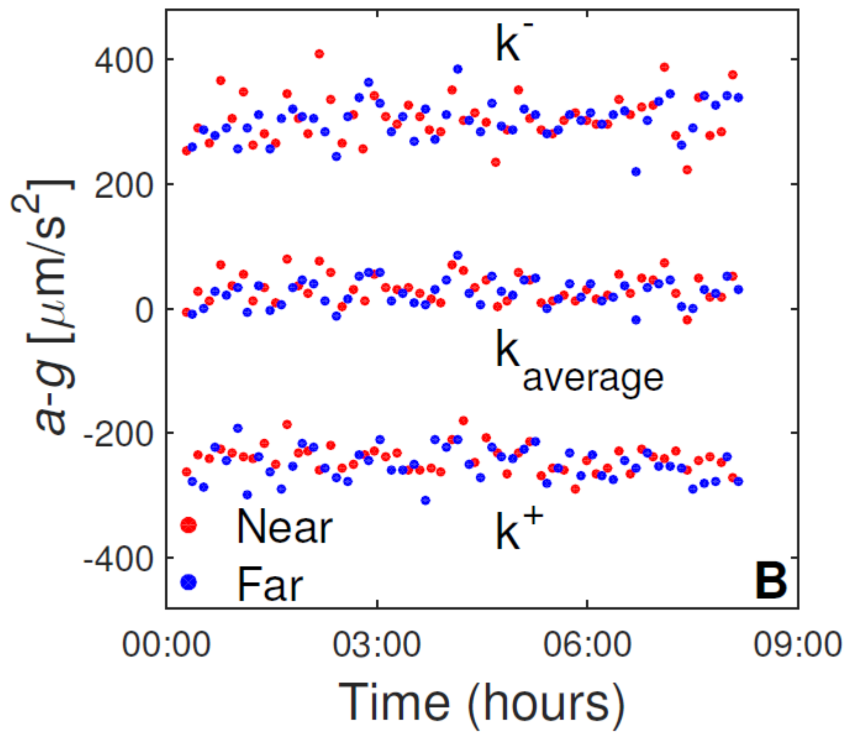
$$\Delta\varphi \propto \omega(t_1 + t_4 - t_2 - t_3) - k(x_1 + x_4 - x_2 - x_3)$$

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

Berkley Experiment

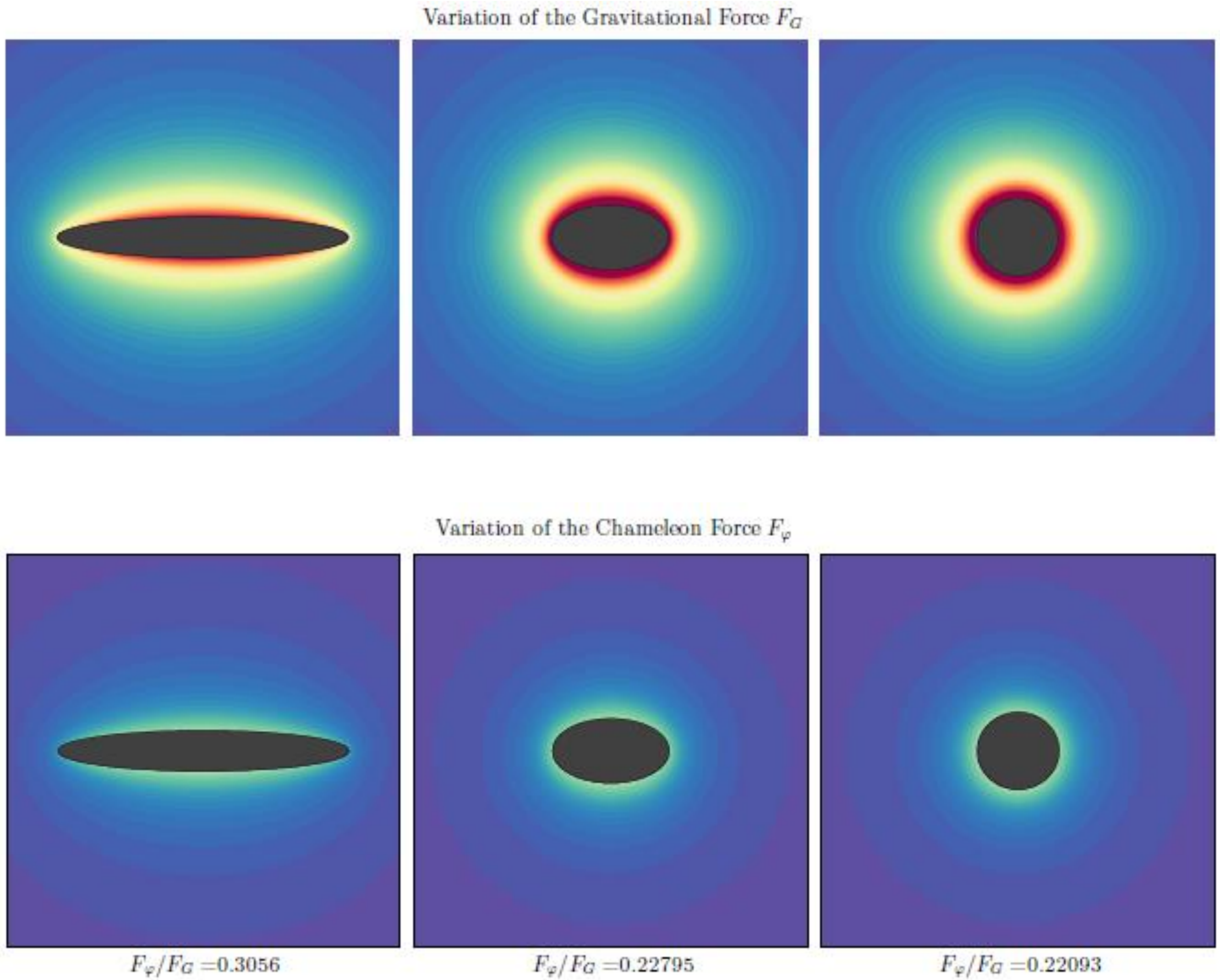
Using an existing set up with an optical cavity
The cavity provides power enhancement, spatial filtering, and a precise beam geometry





Hamilton et al. (2015)

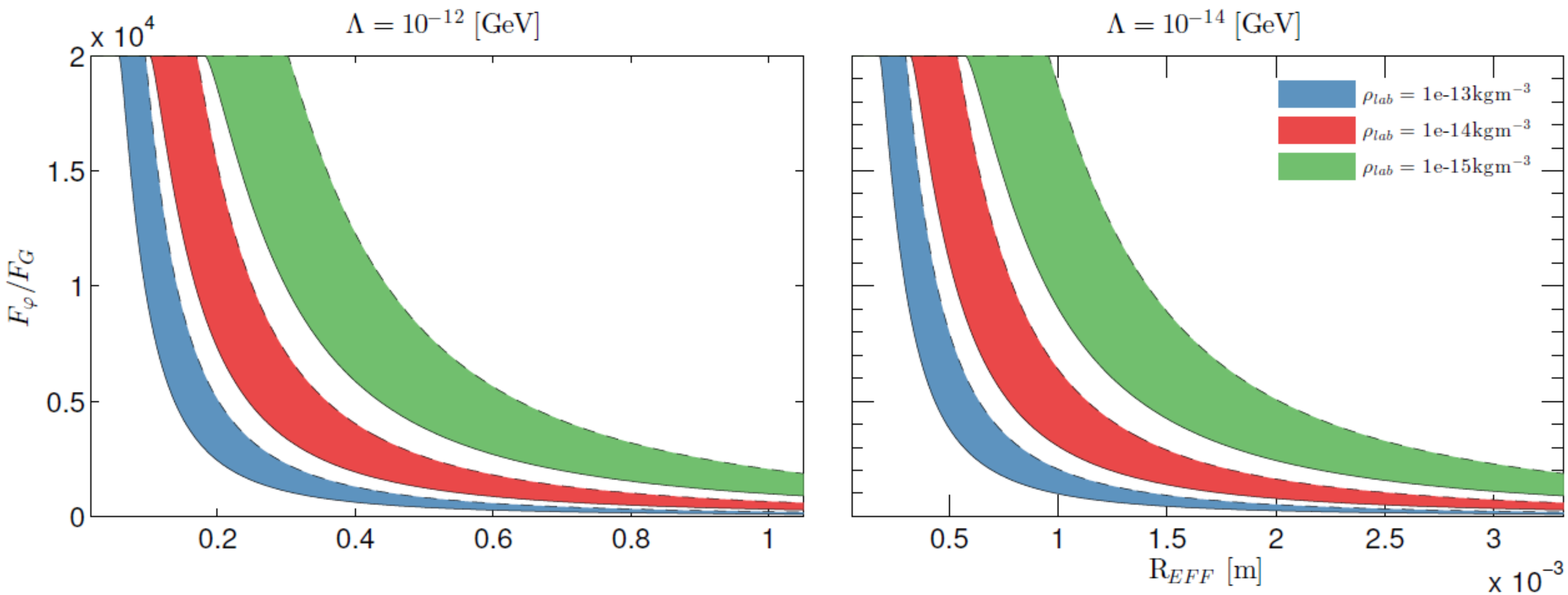
Future Prospects: Source Shape



CB, Copeland, Stevenson (2014)

Shape Dependence of Chameleon Force

Deviations from spherical symmetry impede the formation of a thin shell



CB, Copeland, Stevenson (2015)