Detecting Dark Energy with Atom Interferometry

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Outline:

Chameleon dark energy

A brief review of atom interferometry

Dark energy in the laboratory

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

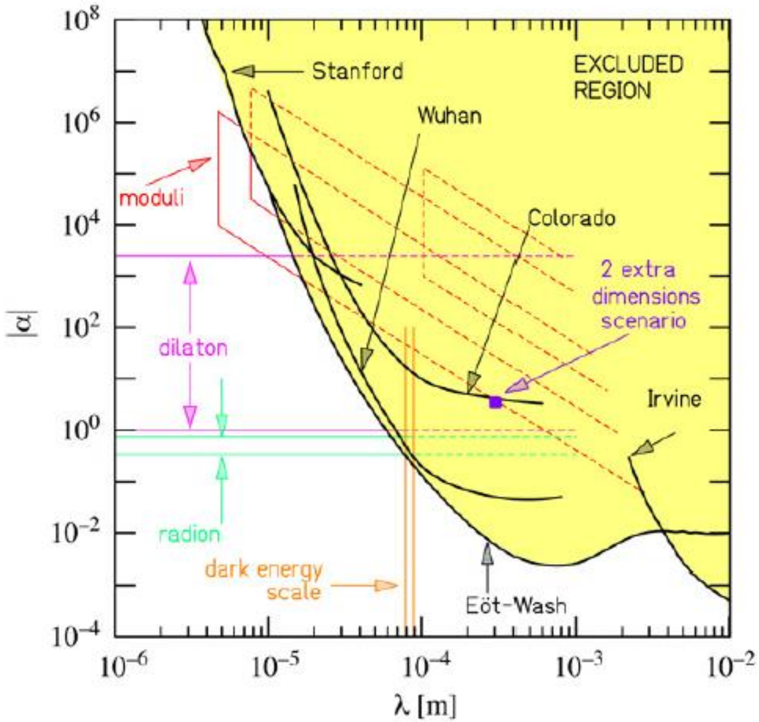
Papapetrou (1948). Weinberg (1965).

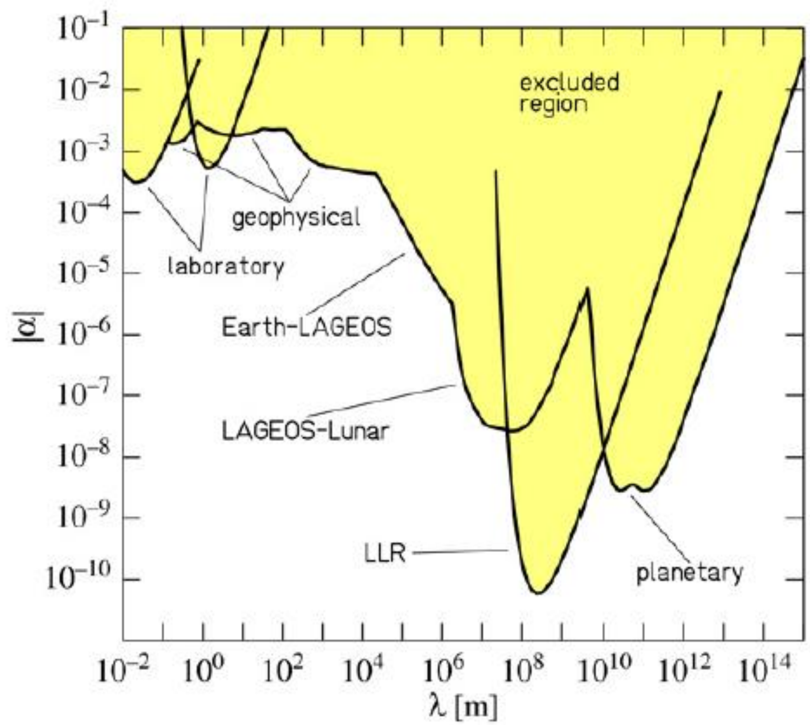
- New physics in the gravitational sector will introduce new degrees of freedom, typically Lorentz scalars

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

- **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 and f(R)

Khoury, Weltman (2004).

The Chameleon

Chameleon screening relies on a non-linear potential,

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

Non-relativistic, static, spherically symmetric equation of motion

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

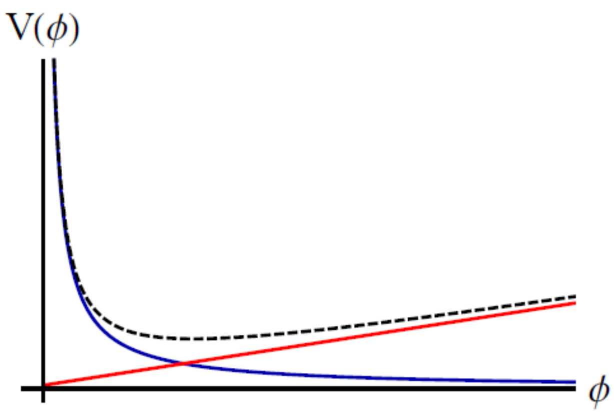
Khoury, Weltman. (2004). Image credit: Nanosanchez

Varying Mass

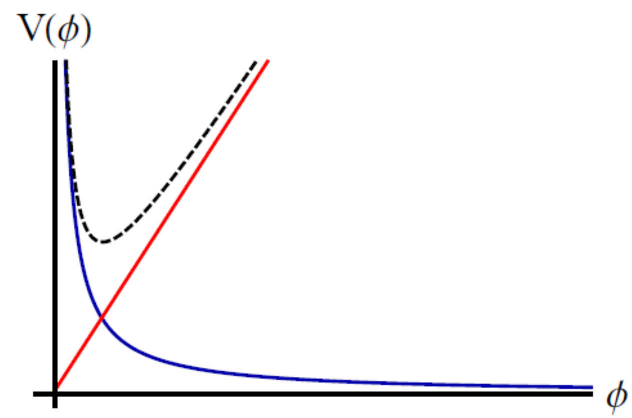
The mass of the chameleon changes with the environment

Field is governed by an effective potential

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



Low density



High density

Warning: Relies on non-renormalisible operators, no protection from quantum corrections

The Scalar Potential

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

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

This determines how responsive an object is to the chameleon field

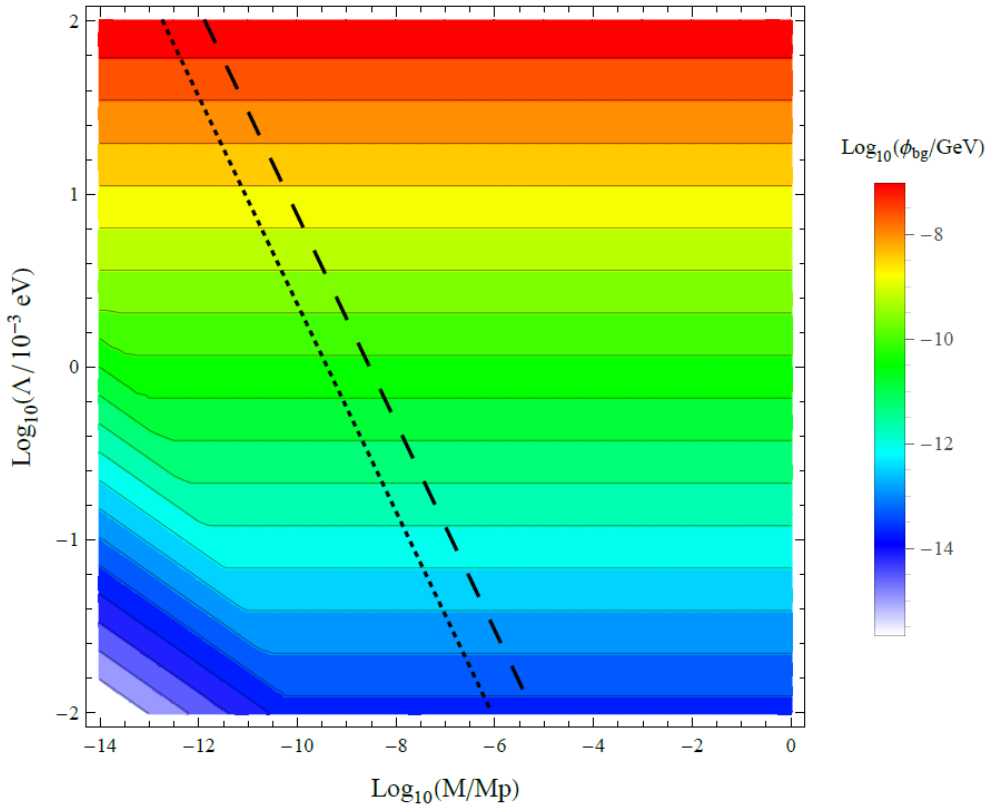
When $m_{bg}r$ is small the ratio of the acceleration of a test particle due to the chameleon and gravity is:

$$\frac{a_\phi}{a_N} = \frac{\partial_r \phi}{M} \frac{r^2}{G M_A} = 3\lambda_A \left(\frac{M_P}{M}\right)^2$$

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?

Interferometry – family of techniques in which waves are superimposed in order to extract information

In atom interferometry the wave is made of atoms

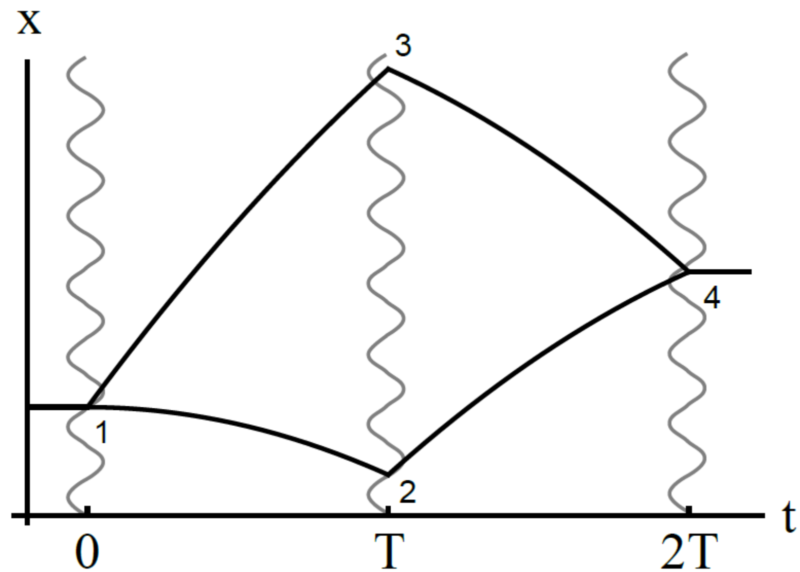
Atoms can be moved around by absorption of laser photons

Photon Momentum = k
Atom in ground state

Atom in excited state
with velocity = V

An Atom Interferometer

In between interactions with the laser, atoms move freely under a force acting in the x direction



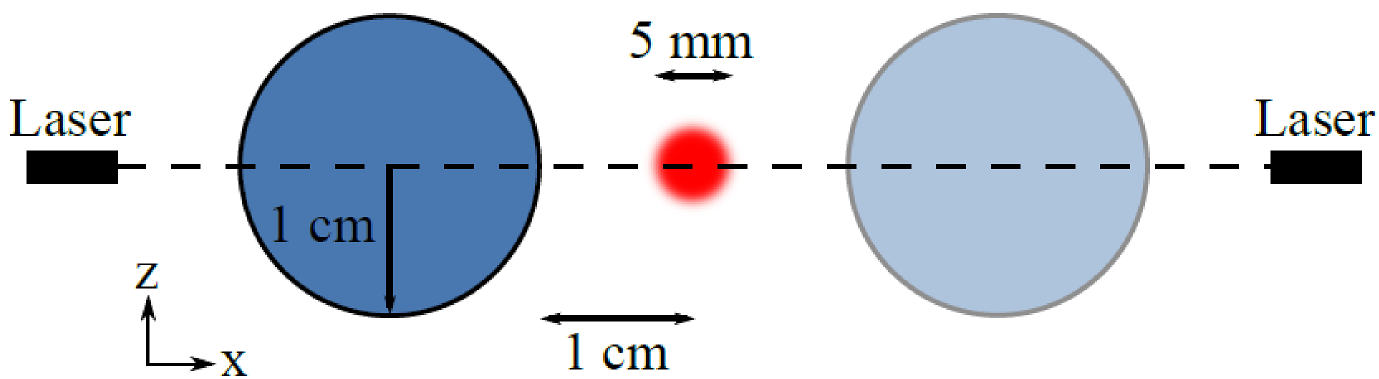
Probability of detecting atoms in an excited state

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

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)

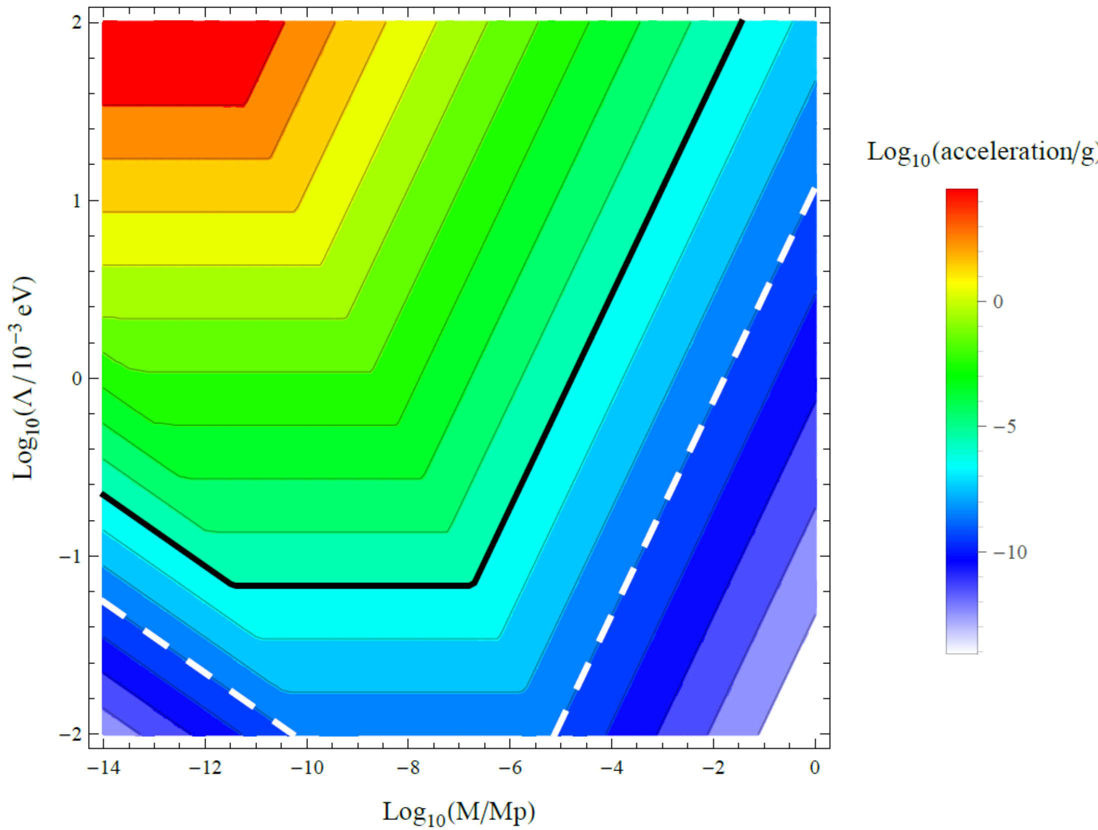


Proposed Sensitivity

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

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

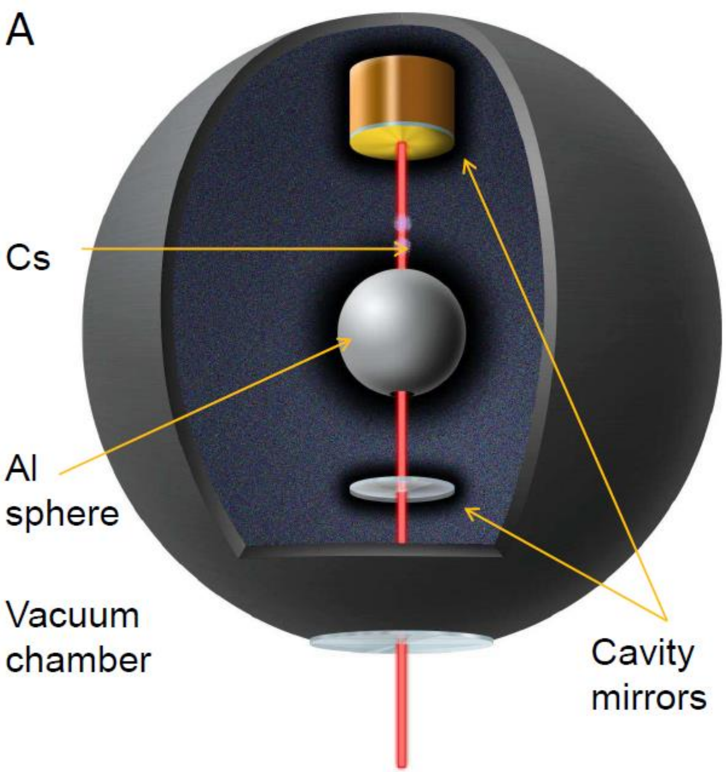
Controllable down to 10^{-9} g (dashed white line)

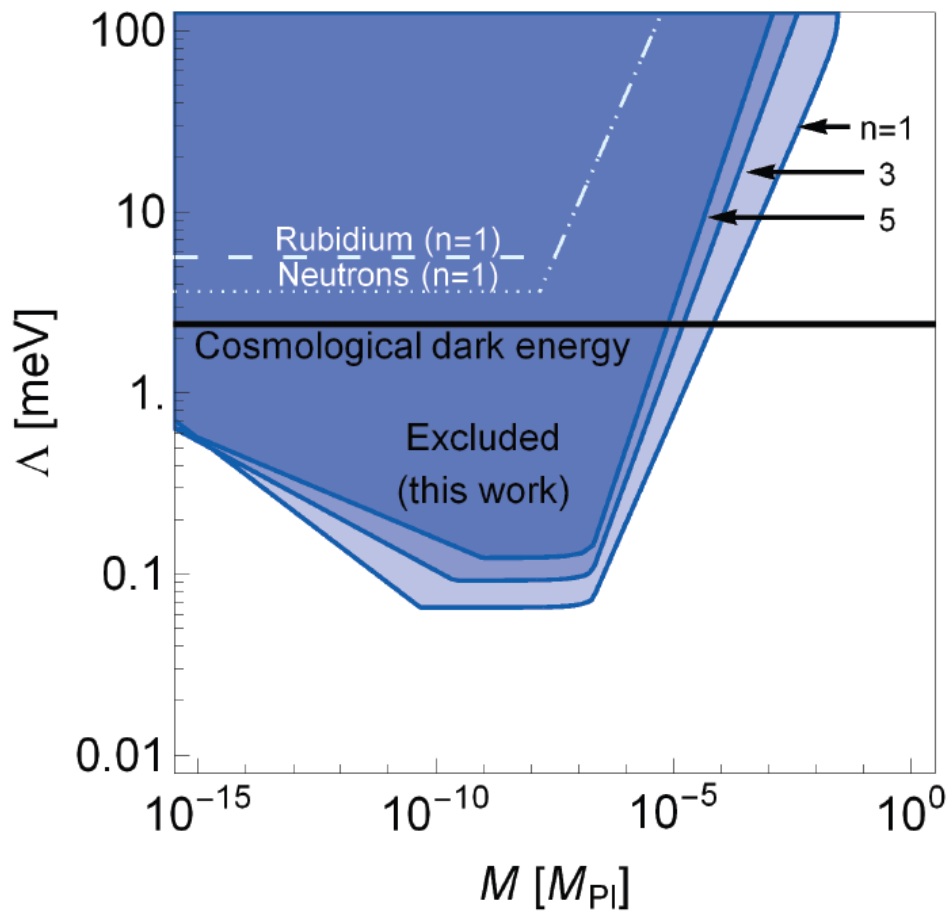


CB, Copeland, Hinds. (2015)

For numerical estimates see: Schlögel, Clesse, Füzfa (2015)

Berkley Experiment

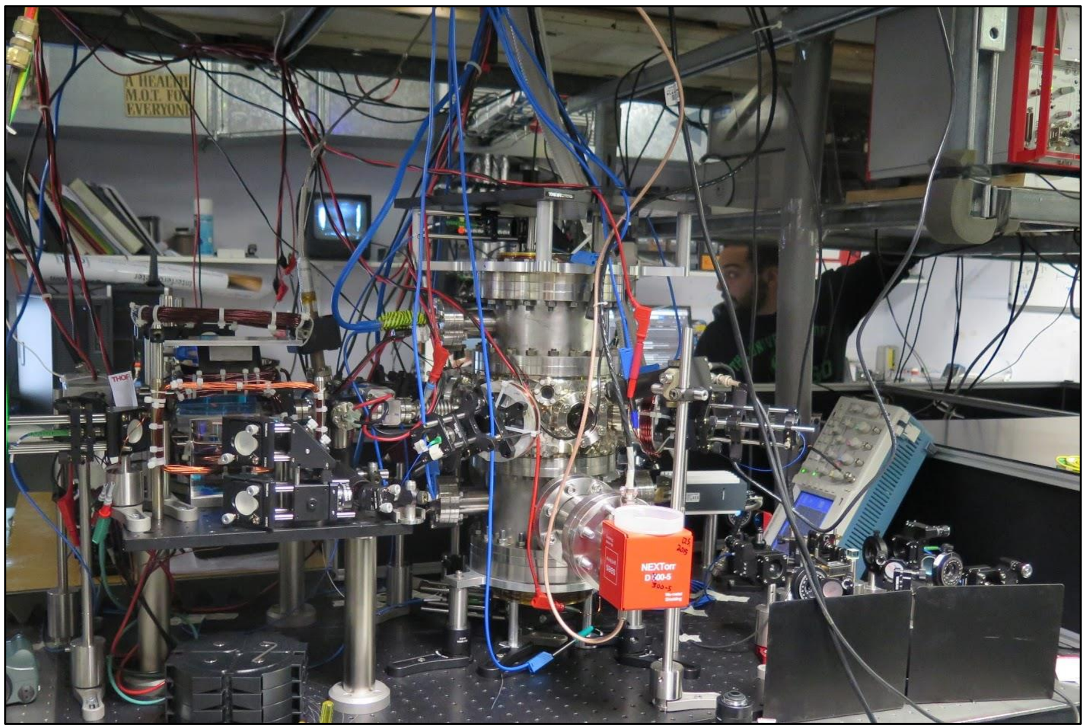




Hamilton et al. (2015)
See also: neutron interferometry experiments: Lemmel et al. 2015

Imperial Experiment

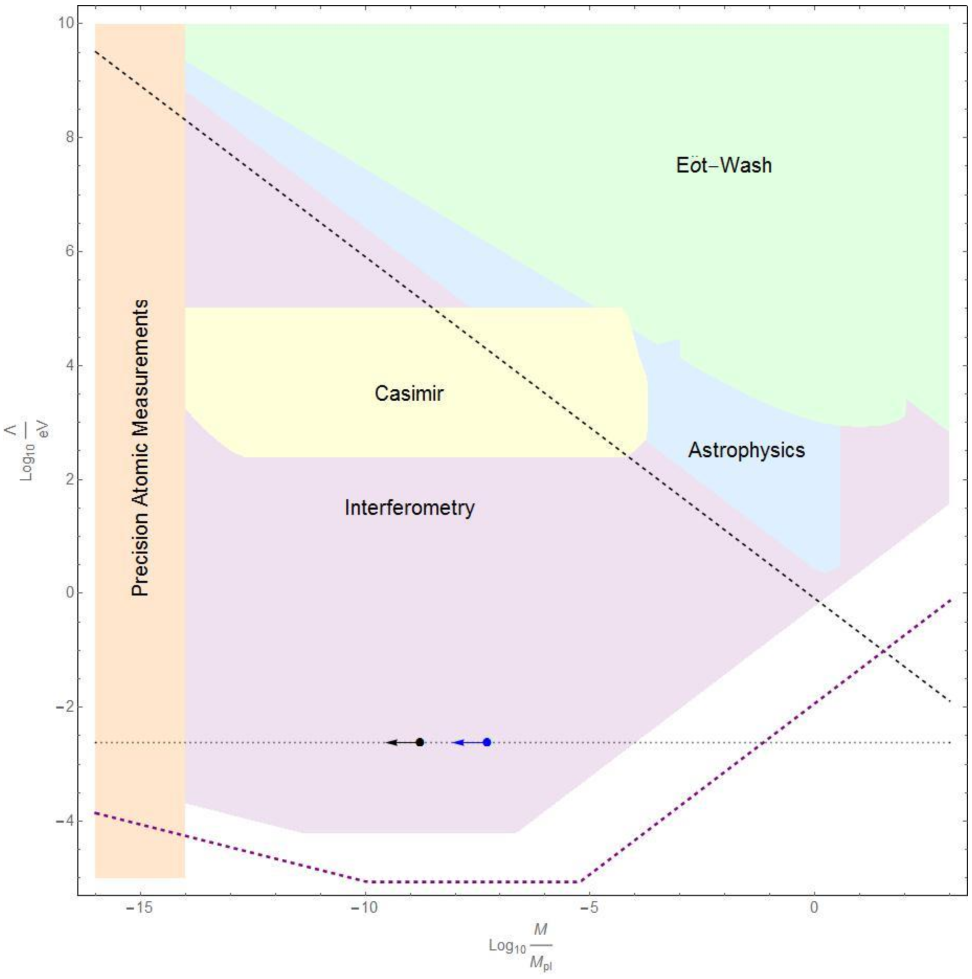
Development underway at the Centre for Cold Matter, Imperial College



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

Combined Constraints - PRELIMINARY

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



CB, Sakstein. (to appear)

Summary

Attempts to solve the cosmological constant problem introduce new types of matter or modify gravity

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

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

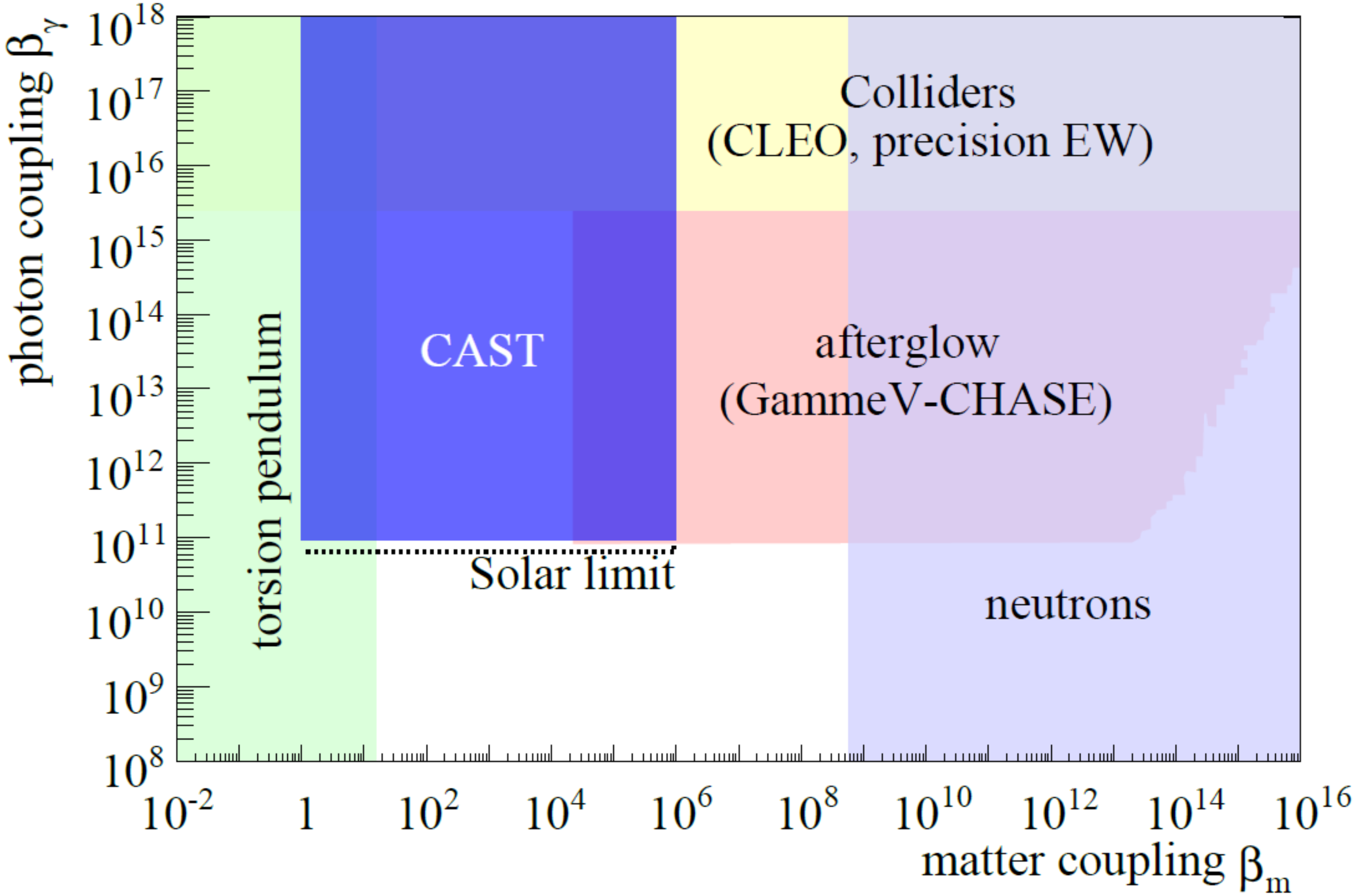
- Can still be detected in suitably designed experiments

Atom interferometry is a new and powerful technique

- When combined with other searches we could cover all of the interesting parameter space

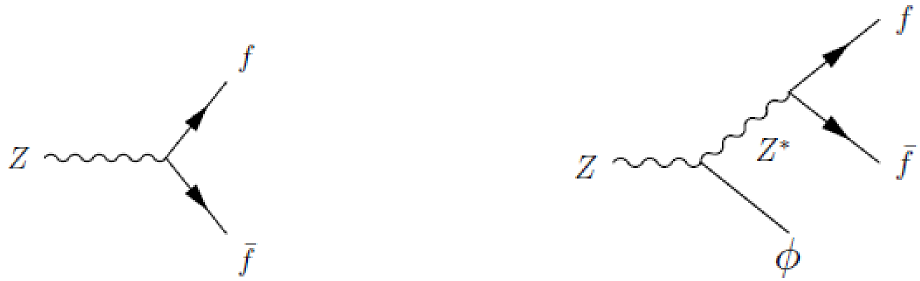
Matter vs Photon coupling

CAST collaboration 2015



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).

f(R) Chameleons

Attempt to modify gravity to explain the accelerated expansion of the universe

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

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

The extra degree of freedom can be made explicit

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

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

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

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Make the extra degree of freedom explicit

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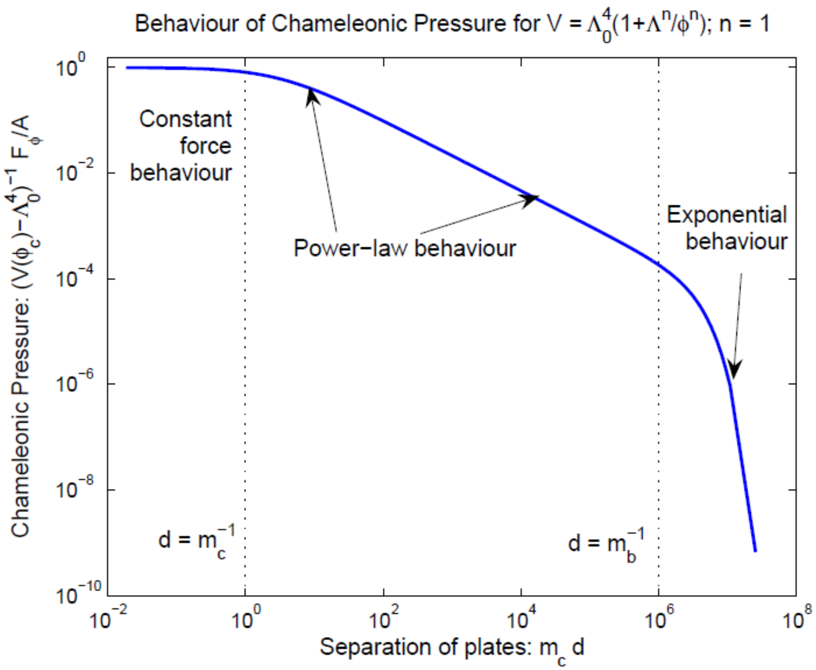
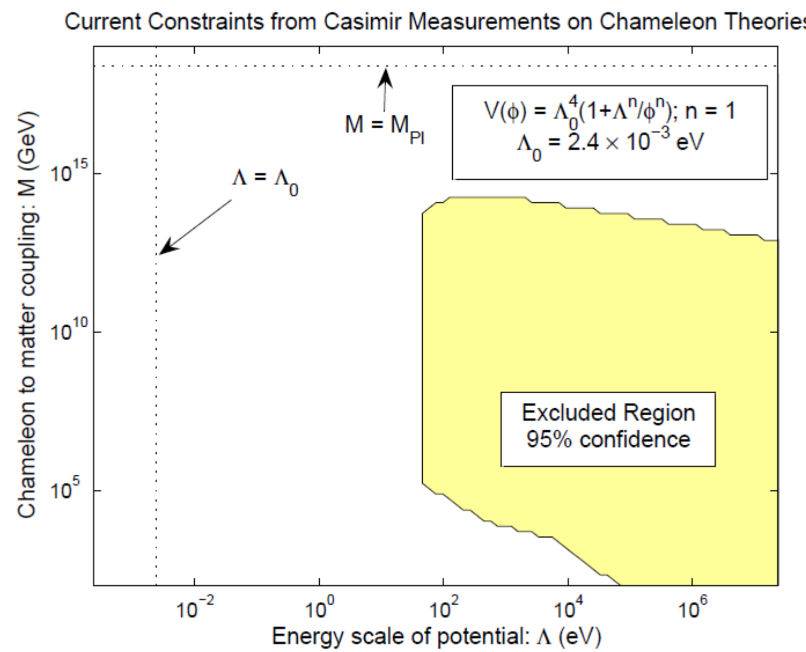
Casimir Searches





Tailor searches for chameleons by varying the density of gas between the plates

Chameleon Casimir experiment, CANNEX, underway in Amsterdam

Brax et al. (2007, 2010). Brax, Davis (2014).

Atomic Precision Measurements

A scalar potential is sourced by the nuclear mass and electric field

Scalar forces lead to perturbations of the Schrödinger equation and energy levels

$$\begin{aligned}
\delta E_{1s} &= -\frac{Z m_N}{4\pi M_m^2 a_0} m - \frac{Z^4\alpha}{4\pi a_0^2 M_m M_\gamma} m, \\
\delta E_{2s} &= -\frac{Z m_N}{16\pi M_m^2 a_0} m - \frac{Z^4\alpha}{32\pi a_0^2 M_m M_\gamma} m, \\
\delta E_{2p} &= -\frac{Z m_N}{16\pi M_m^2 a_0} m - \frac{Z^4\alpha}{96\pi a_0^2 M_m M_\gamma} m.
\end{aligned}$$

Precision measurements of 1s-2s transition constrain

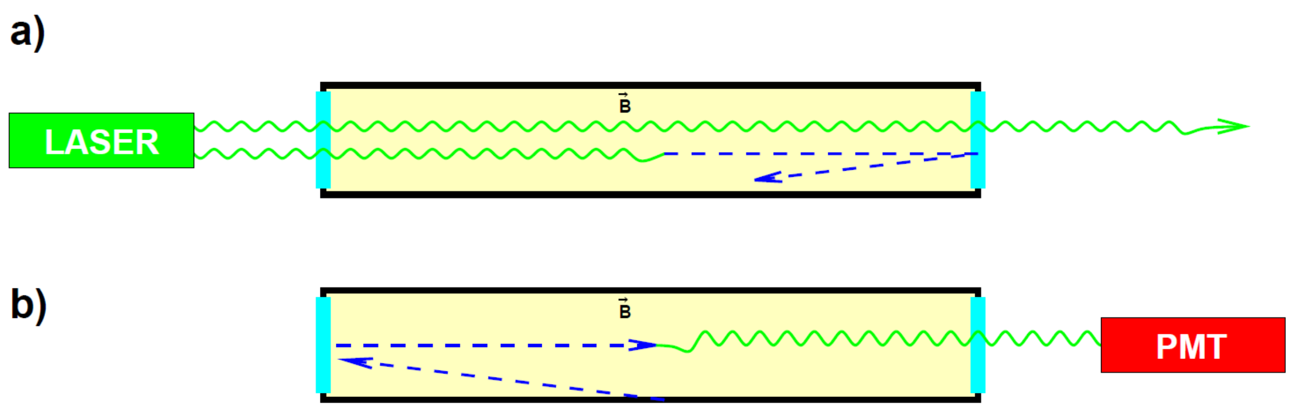
$$10 \text{ TeV} \lesssim M_m$$

Brax CB (2010)

Chameleon After-glow

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

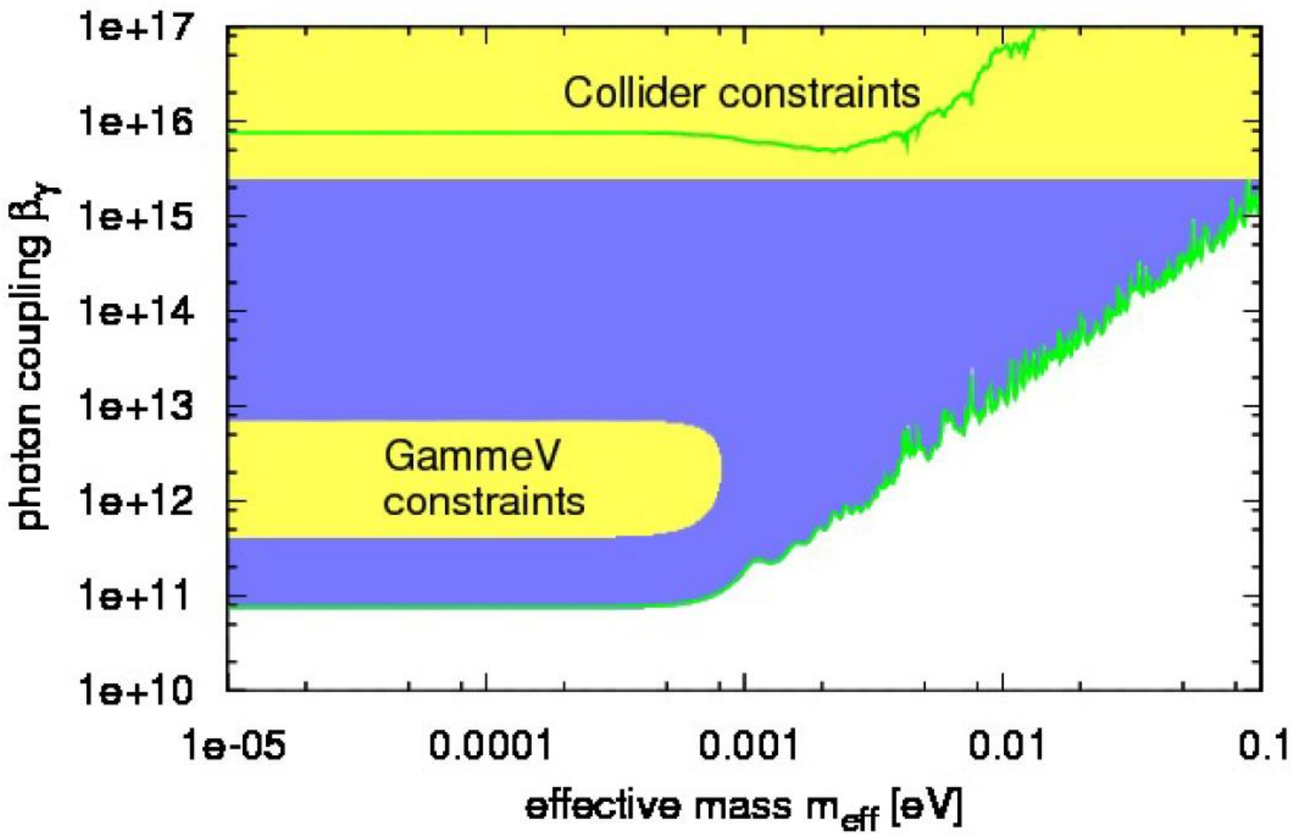
- To pass through the walls they need to become heavier
- If chameleons are not energetic enough this is forbidden and they remain trapped
- Reverse Primakov effect produces afterglow photons



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

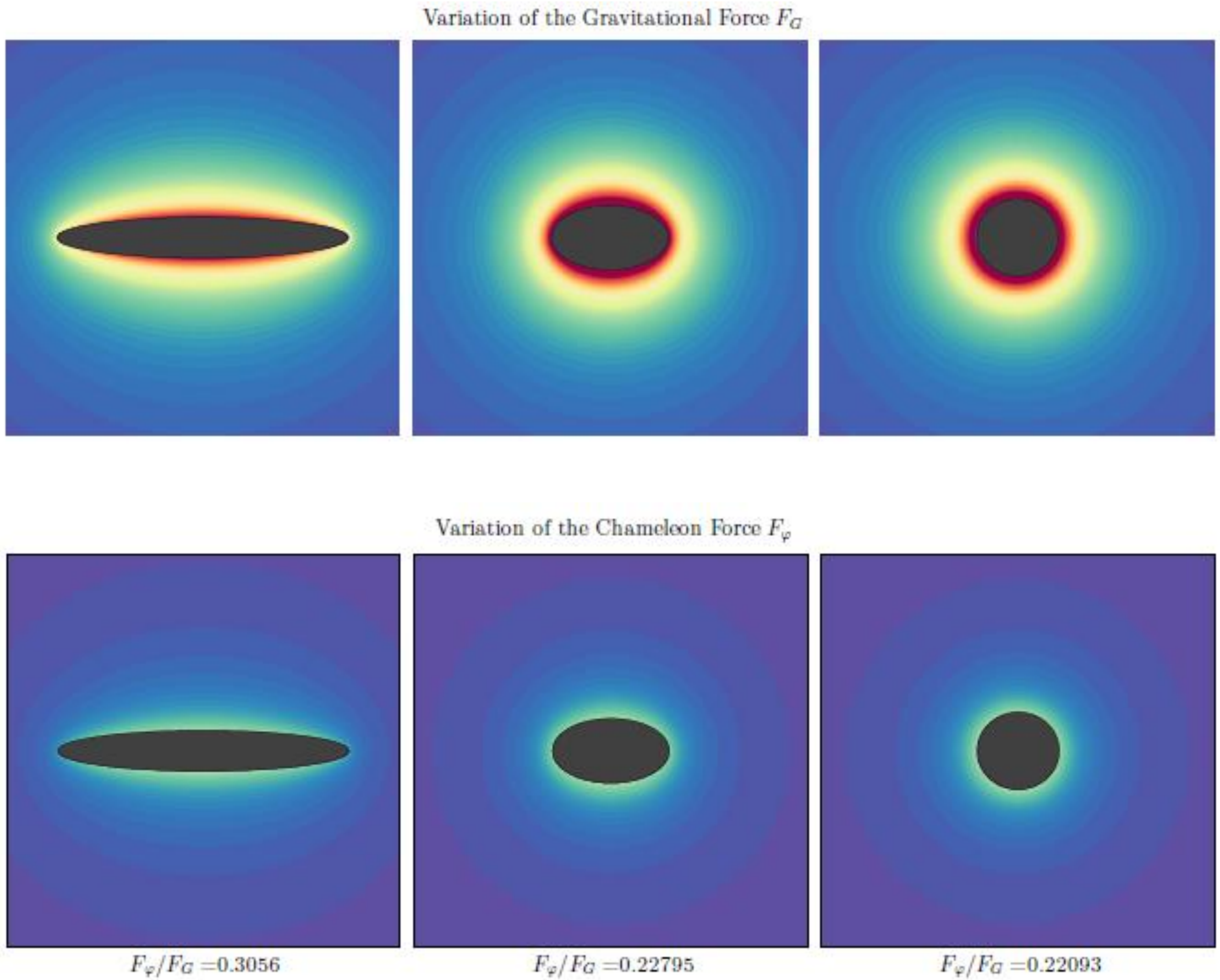
GammeV-CHASE

Results from the Gammev Chameleon Afterglow Search at Fermilab



Steffen et al. (2010)

Future Prospects: Source Shape



CB, Copeland, Stevenson (2014)