Detecting Dark Energy in the Laboratory

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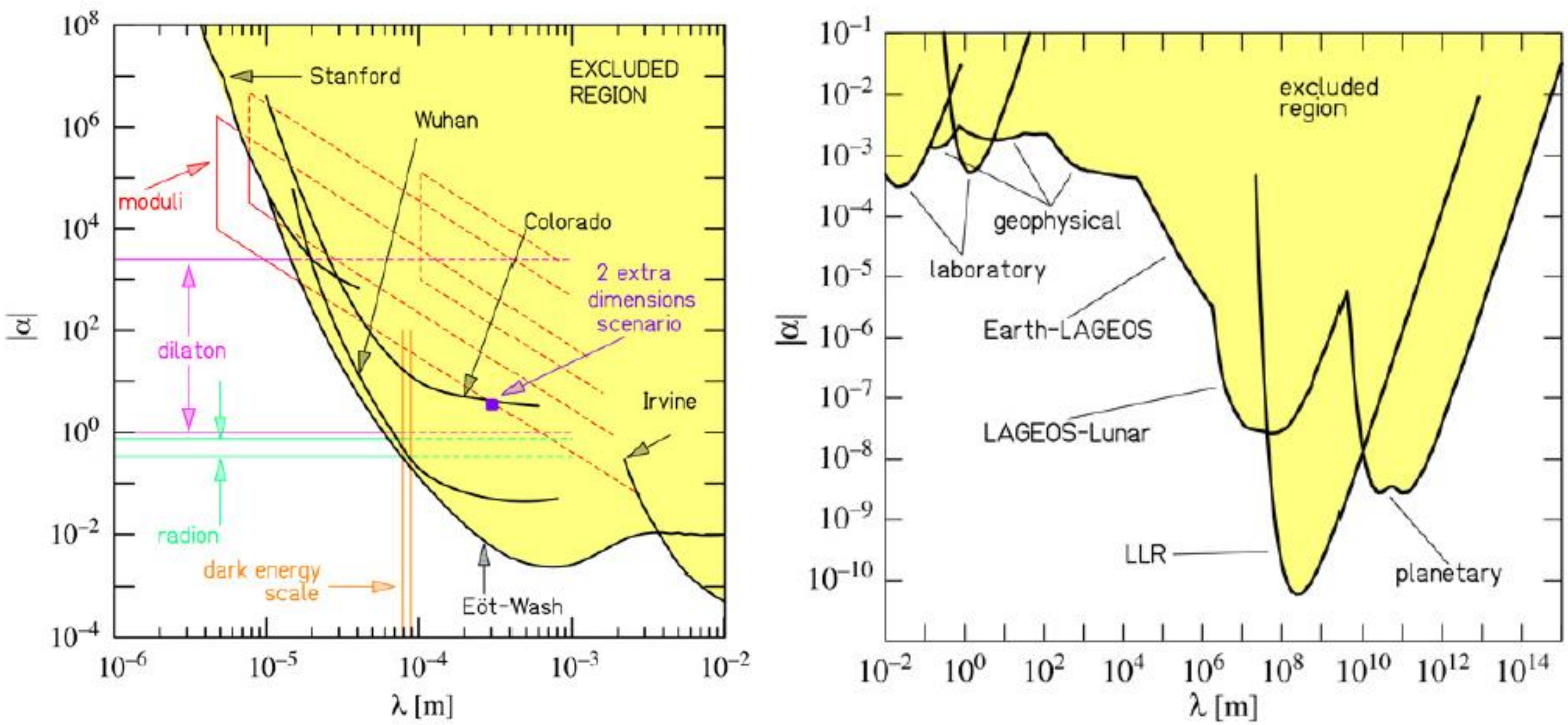
- Dark energy scalars require a screening mechanism
- Chameleon is the archetypal example
- Atoms are unscreened
- Atomic experiments have the potential to detect dark energy

Dark Energy Scalar Fields

Explanations of the current accelerated expansion of the universe often introduce new, light scalars

But we do not see long range Yukawa fifth forces



Adelberger et al. (2009)

The Chameleon

V.

Scalar field theory with non-trivial self interactions and coupling to matter

The spherically symmetric, static equation of motion is

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

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

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

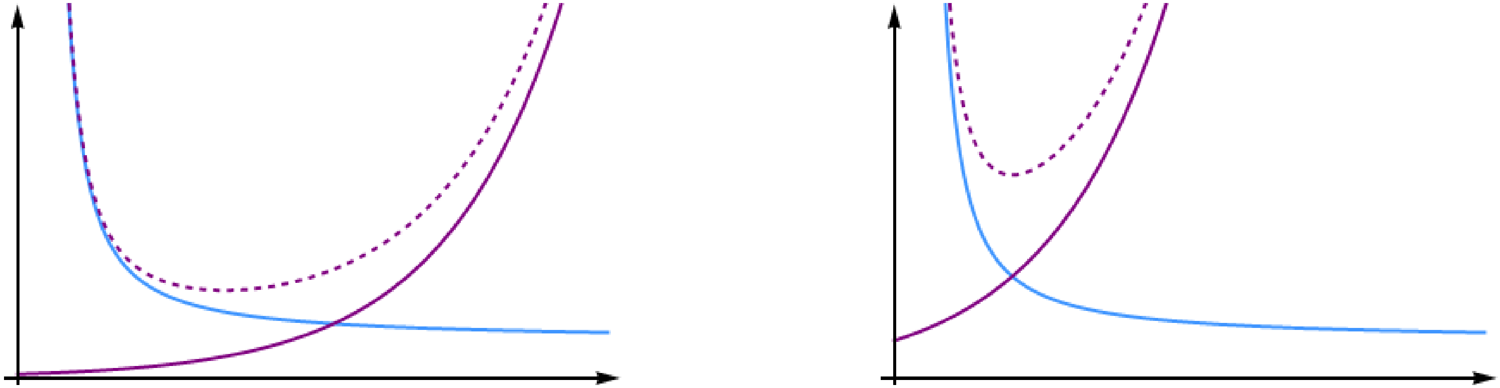
Khoury, Weltman. (2004). Image credit: Nanosanchez

Varying Mass

The mass of the chameleon changes with the environment

Field is governed by an effective potential

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



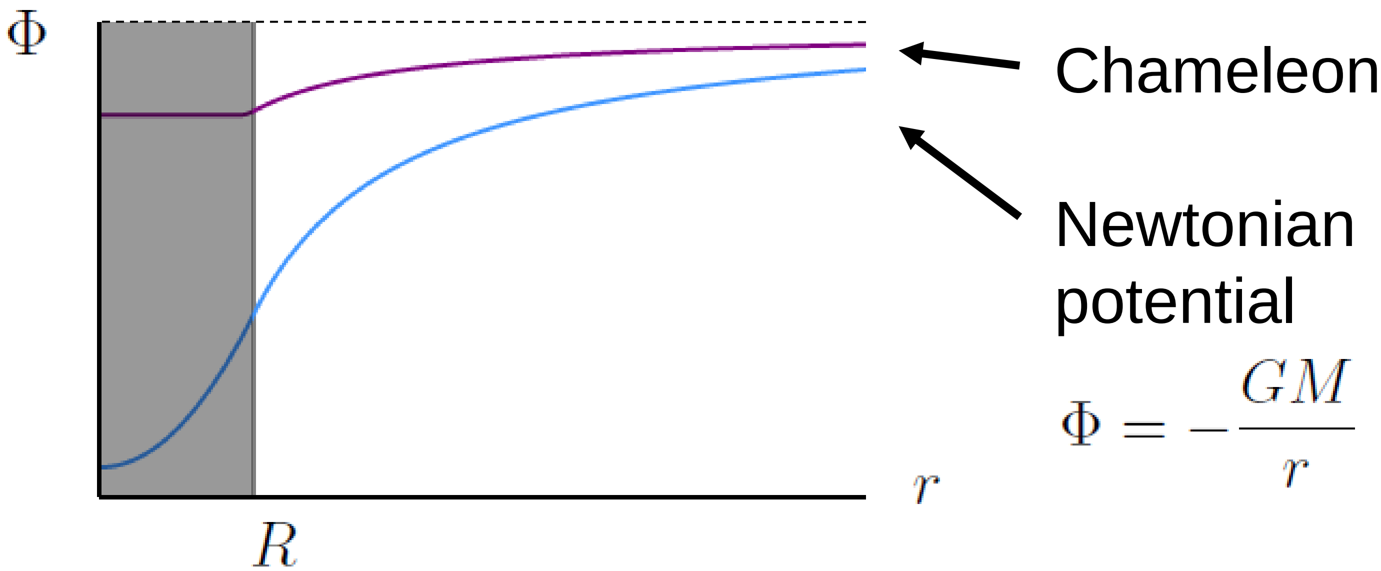
Low density High density

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

See also A. Erickcek talk on Wednesday

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 sufficiently large objects is shallower than for standard light scalar fields

A Universal Form for the Scalar Potential

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

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

The parameter λ 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:

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

Laboratory Experiments

The chameleon effects are not screened for ‘small’ objects that do not probe the scalar non-linearities. This requires:

$$\frac{1}{4\pi R_A}\frac{M_A}{M} \ll \phi_{\rm bg}$$

We want an experiment where:

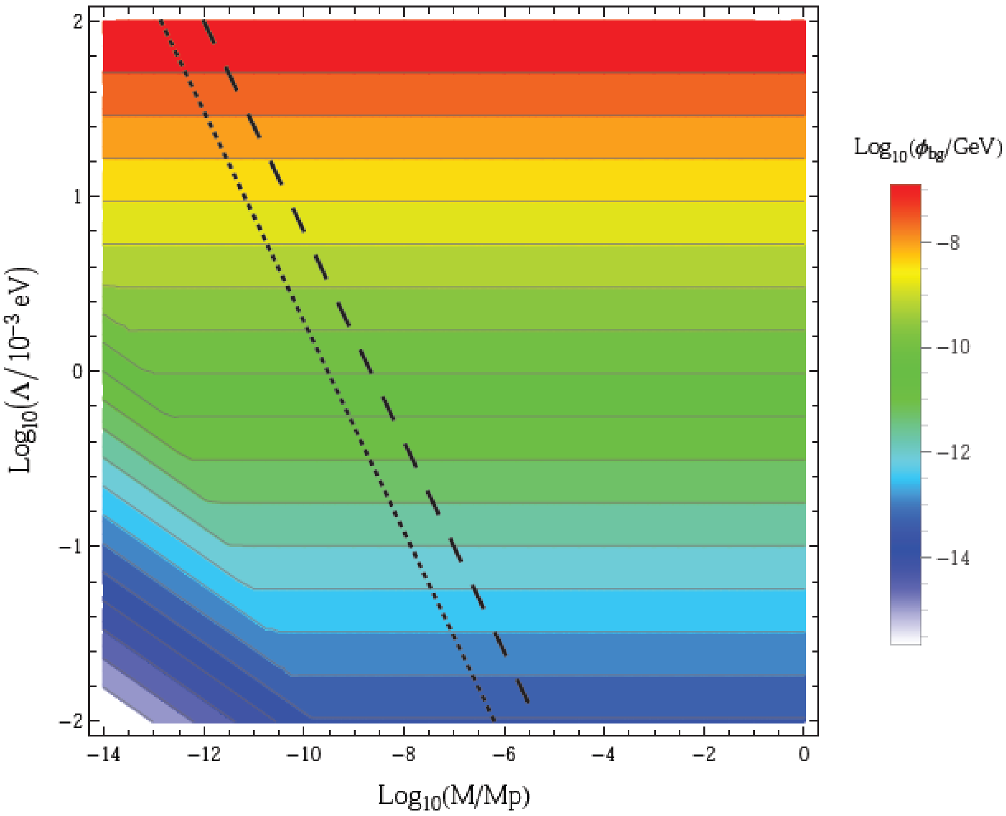
ϕ_{bg} is large – high quality vacuum

M_A/R_A is small – atoms

If the walls of the chamber are thick enough, the interior is screened from external chameleon fluctuations

cf. electrostatic shielding

Are Atoms Screened?



Vacuum chamber: Radius = 10 cm. Pressure = 10^{-10} Torr

Atoms unscreened above black lines: Dashed = caesium. Dotted = lithium

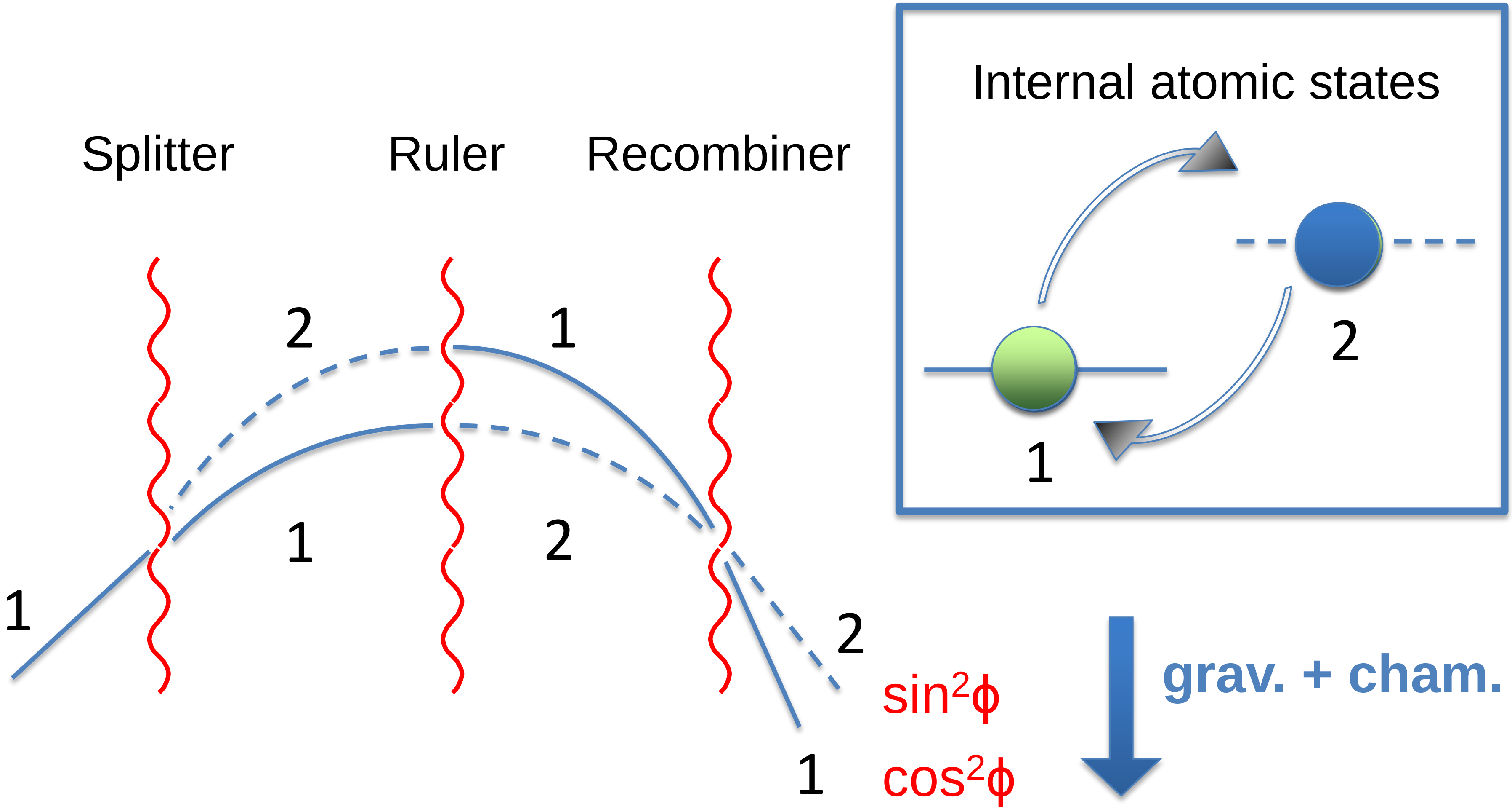
New Constraints

We can constrain the chameleon with any measurement of interactions between atoms and macroscopic objects / surfaces in high vacuum environments

Measurements of:

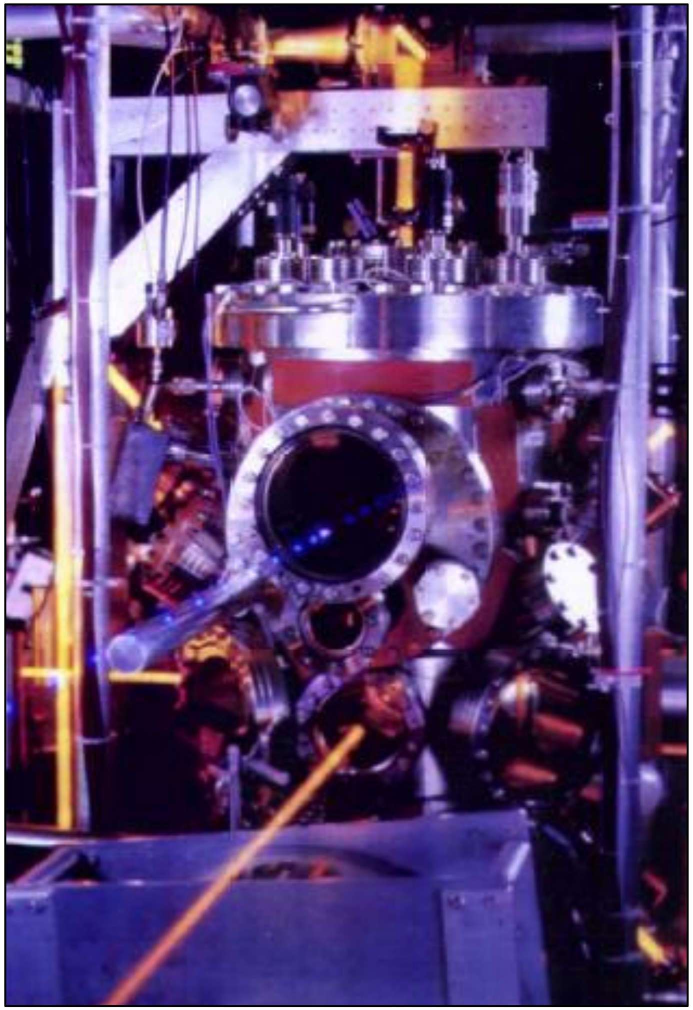
- van der Waals forces
  Shih (1974), Shih et al. (1975), Anderson et al. (1988)
- Casimir-Polder forces
  Sukenik et al. (1993)
- Gravitational forces on atoms above a chip
  Baumgärtner et al. (2010)
- Quantisation of gravitational energy levels of a neutron when bouncing above a plate
  Jenke et al. (2014)

Atom interferometry



Interference determines whether atoms come out in state 1 or state 2

Proposed Chameleon Experiment



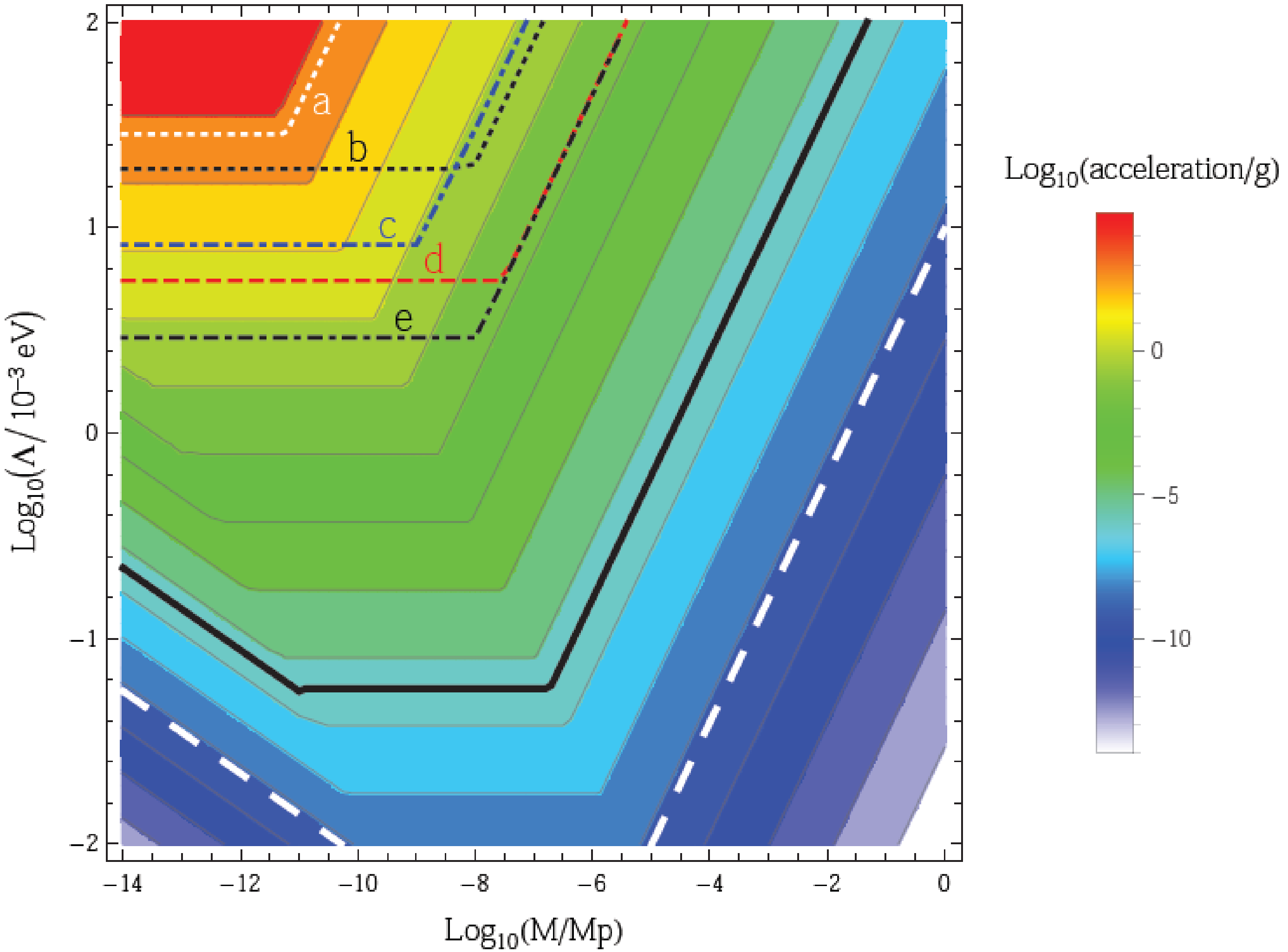
Launch Rb atoms in a fountain, height 5 mm, held 1 cm from a source mass of 1 cm radius

Accelerations of 10^{-6} g produce a detectable, $^{1}/_{7}$ radian, phase shift

Stark effect, Zeeman effect, phase shifts due to scattered light and movement of beams all negligible at this level

Image credit: Center for Cold Matter, Imperial College

Expected Sensitivity



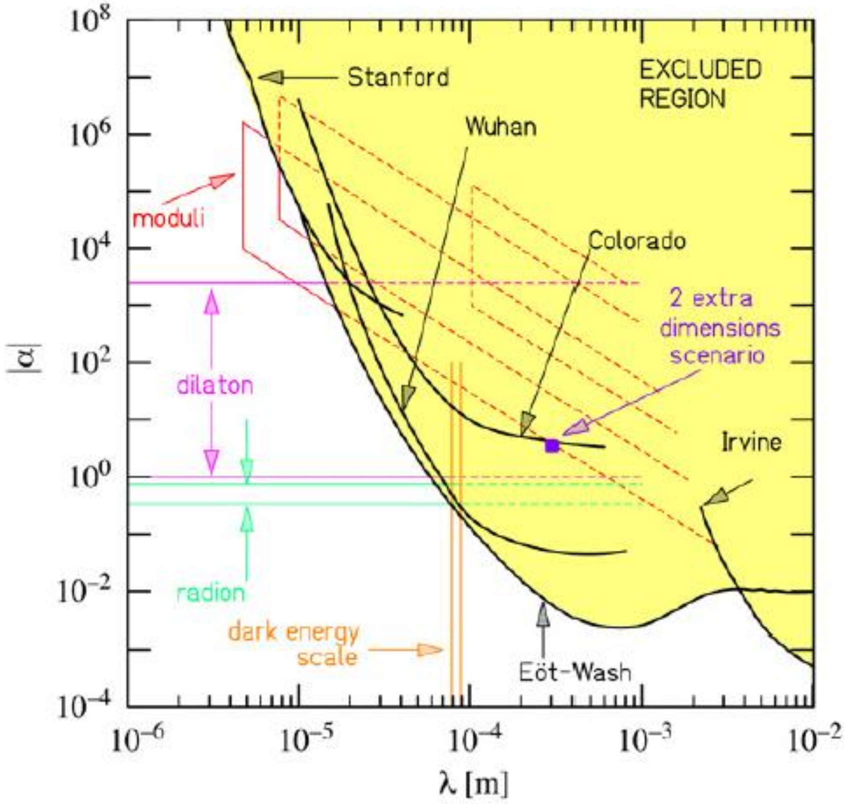
Conclusions

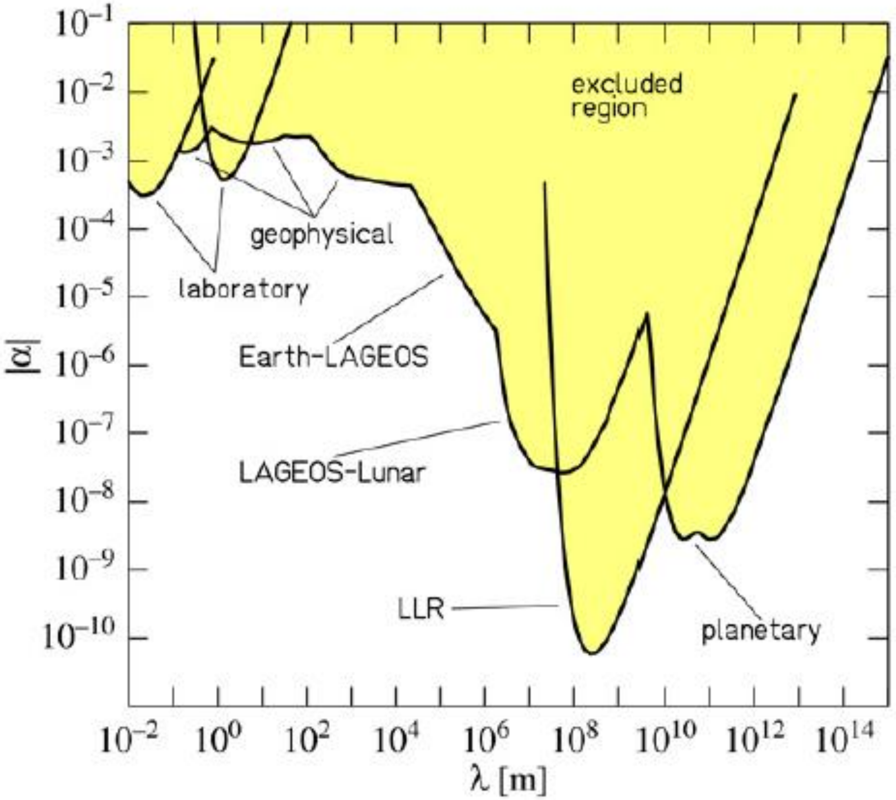
- The accelerated expansion of the universe motivates the introduction of new light scalar fields

- Theories with screening mechanisms hide the scalar force dynamically
- The chameleon screening mechanism relies on the mass of the scalar field varying with the density of the environment

- Chameleon forces on atoms in high vacuum are unscreened
- Current technology can significantly constrain the parameter space

Constraints on Yukawa Forces





Adelberger et al. (2009)

Inside the Vacuum Chamber

The field can only reach the minimum of the effective potential in vacuum if the chamber is large enough

Otherwise the field value depends on the size of the chamber:

$$\phi_{\rm bg} = \left(\frac{8\Lambda^5 L^2}{\pi^2}\right)^{1/3}$$

If the walls of the chamber are strongly perturbing, the interior is screened from external chameleon fluctuations

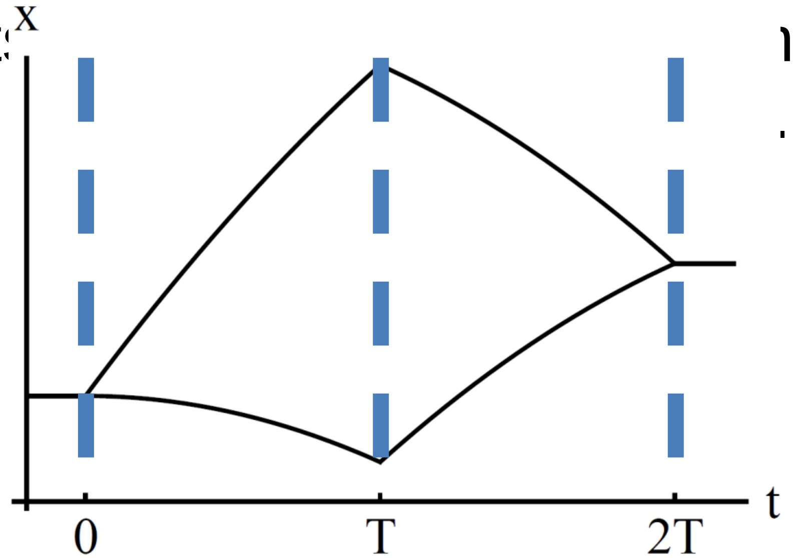
cf. electrostatic shielding

Atom Interferometry

Use Raman interferometry to split the wavefunction.

The two parts

moving under a



A phase difference is imprinted by interactions with the Raman beams at different spatial positions.

The wave function is recombined and the phase difference measured.

Raman Interferometry

Total phase difference between paths depends on:

(1) The free evolution

$$\Delta\varphi = \frac{1}{\hbar}(S_{\mathrm{cl}}^{B} - S_{\mathrm{cl}}^{A})$$

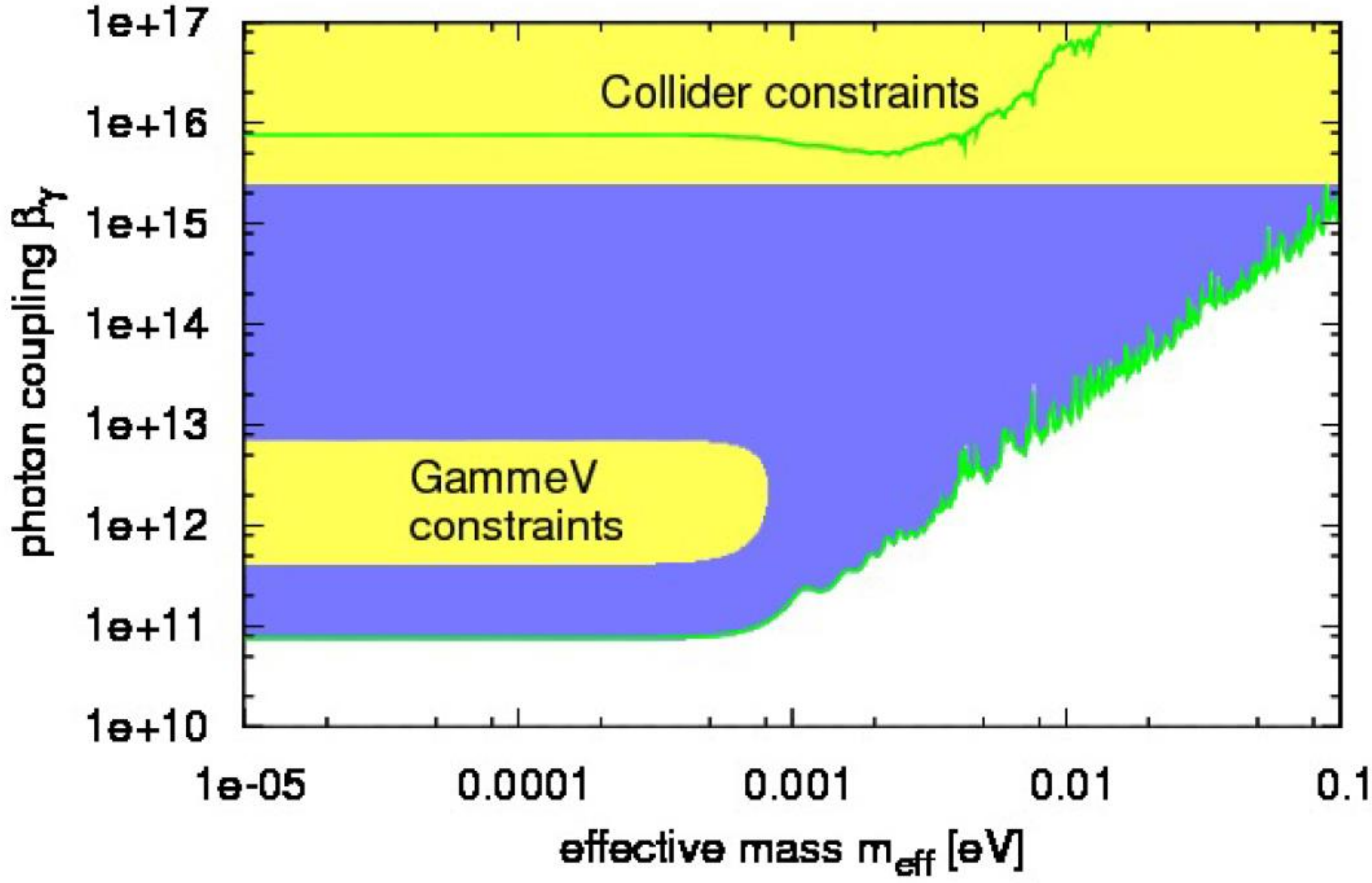
Vanishes for uniform gravitational / chameleon fields

(2) The interaction with Raman beams

Depends on the position and time of the interactions
Δφ is proportional to the gravitational / chameleon acceleration

GammeV-CHASE

Results from the Gammev Chameleon Afterglow Search at Fermilab



Steffen et al. 2010

The Chameleon

Constraints of Casimir, Fifth force, and atomic structure constraints require:

$$\Lambda < 100\,\mathrm{meV}$$
$$10^4\ \mathrm{GeV} \lesssim M \lesssim M_P$$

In the Jordan frame the chameleon becomes an f(R) model

Warning: The chameleon relies on the presence of non-renormalisible operators, and is not protected from quantum corrections

See also A. Erickcek talk on Wednesday