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Laboratory searches for dark energy

C. Burrage
University of Geneva
Switzerland

Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it

Laboratory Searches for Dark Energy

Clare Burrage
Université de Genève

with Philippe Brax, Anne-Christine Davis, David Seery, Amanda Weltman

Dark Energy

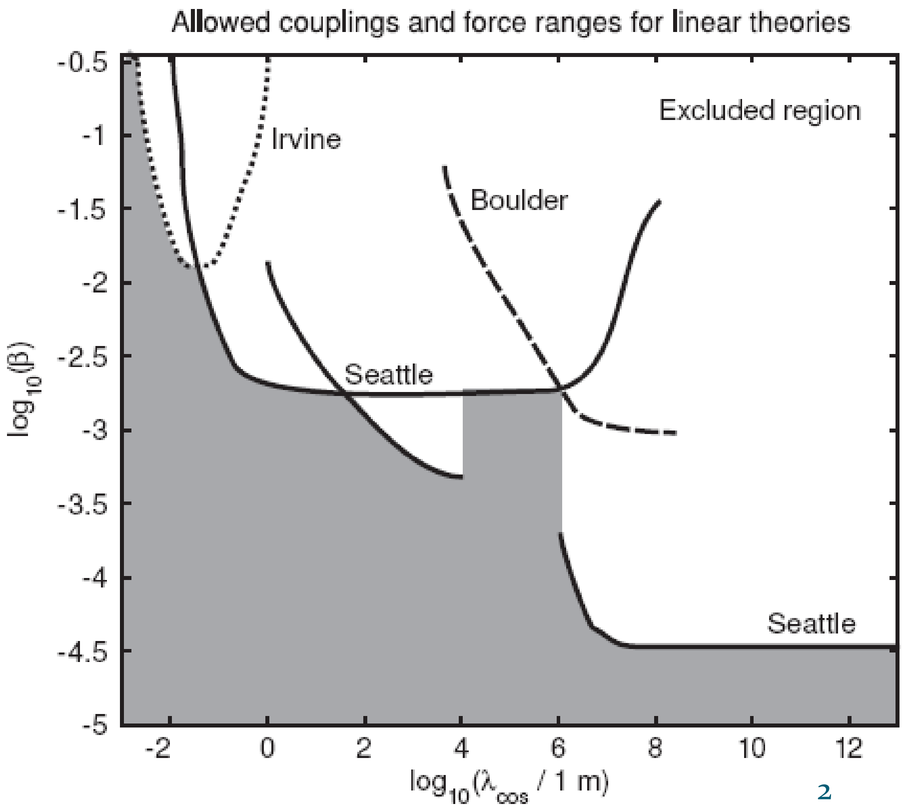
- The acceleration of the expansion of the universe is explained by a (slowly rolling) scalar field
  - Mass $m_\phi \lesssim 10^{-33}\ \mathrm{eV}$
  - Interaction range

$$\sim 10^{26}\ \mathrm{m} \sim 10^{4}\ \mathrm{Mpc}$$

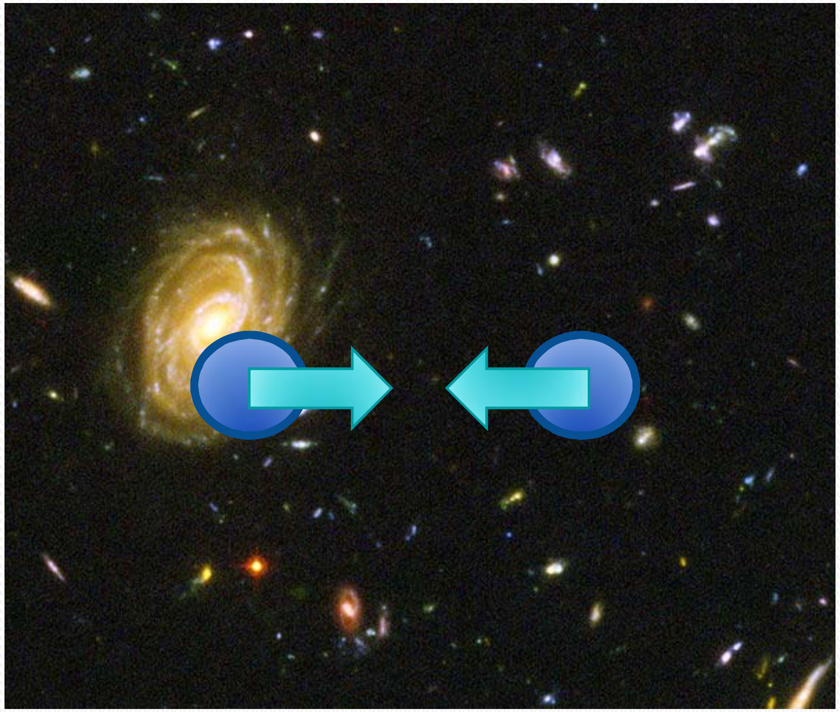
- New light scalar fields mediate long range fifth forces

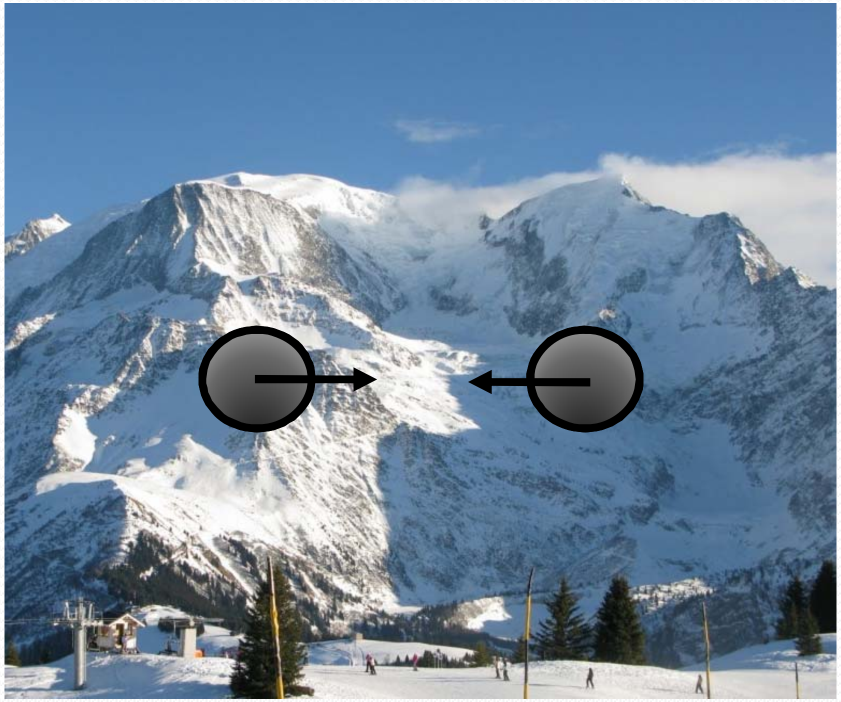
$$\mathcal{L}_\phi = -\frac{1}{2}(\partial\phi)^2 - m^2\phi^2 - \frac{\beta\phi}{M_P}T$$

(Mota, Shaw 2007)



“Chameleon” particles





Outline

- Screening Mechanisms
  - The Chameleon
  - The Symmetron
  - The Galileon

- Hunting in the Laboratory
  - Parallel Plate Experiments
  - Particle Colliders
  - Atomic Precision Measurements

The Chameleon

- The chameleon is a scalar field with non minimal couplings to matter

$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi)\right] - \int d^4x \mathcal{L}_m(\psi^{(i)}, g_{\mu\nu}^{(i)})$$

$$g_{\mu\nu}^{(i)} = B\left(\frac{\phi}{M}\right) g_{\mu\nu}$$

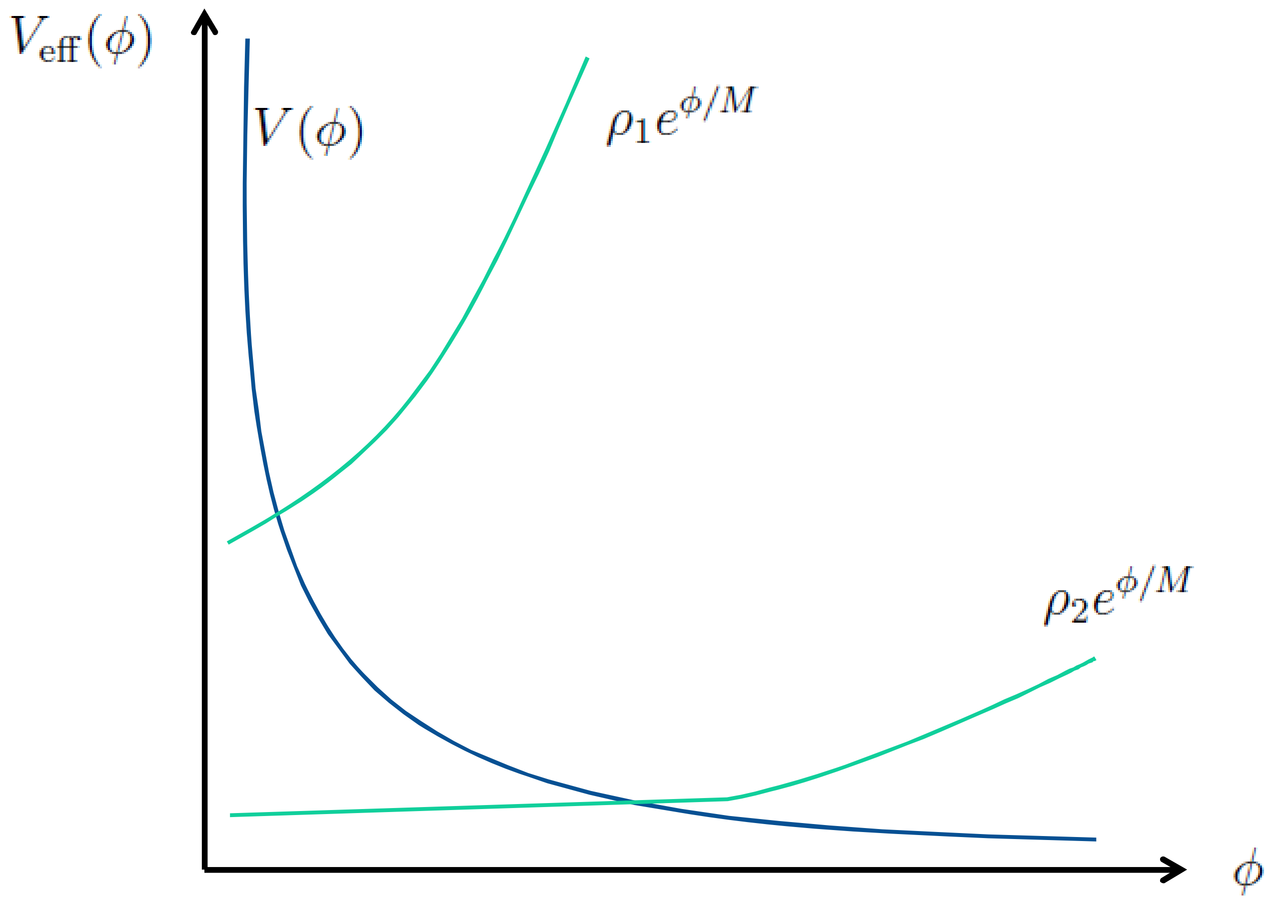
- This gives rise to an effective potential

$$V_{\text{eff}}(\phi) = V(\phi) + \rho B\left(\frac{\phi}{M}\right)$$

  - Need self-interaction terms in the potential
  - The mass of the field depends on the local density

(Khoury, Weltman 2004)

The Chameleon



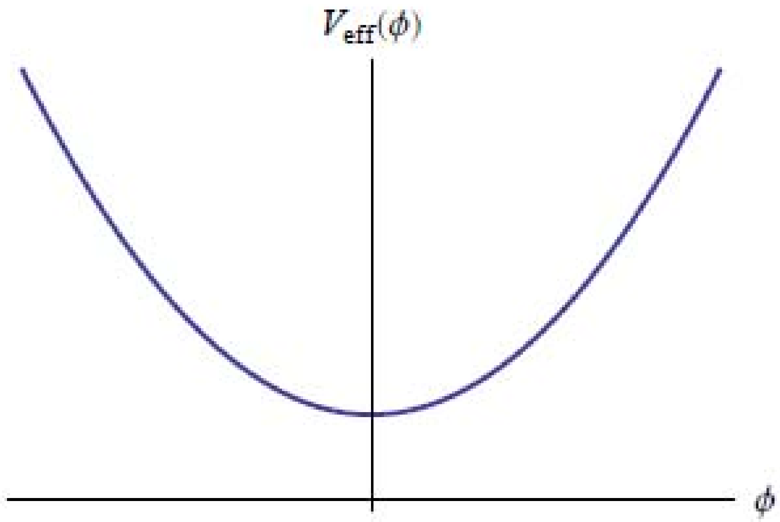
The Symmetron

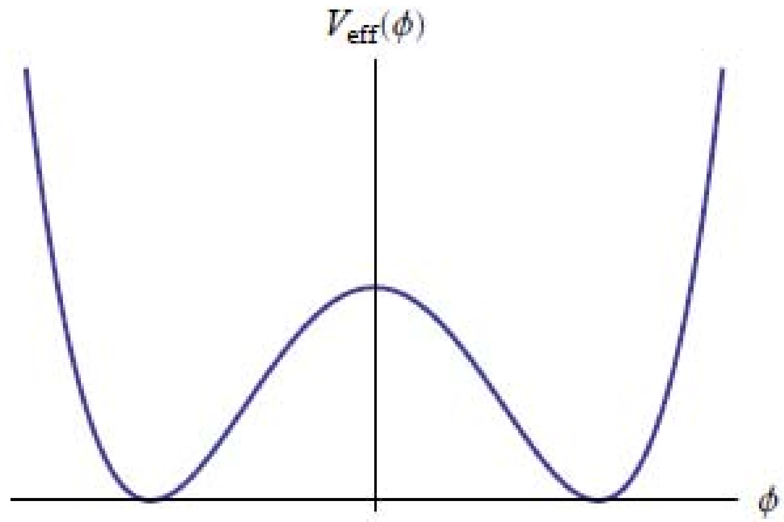
- Potential

$$V(\phi) = -\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4 \,,$$

Coupling to matter

$$B(\phi) = 1 + \frac{\phi^2}{M^2}$$





(Hinterbichler, Khoury 2004)

The Galileon Model

- Galileon model
  - Respects the symmetry

$$\pi(x) \to \pi(x) + b_\mu x^\mu + c,$$

  - Equations of motion are second order in derivatives

- In four dimensions only five possible operators

$$\mathcal{L}_\pi = \sum_{i=1}^{5} c_i \mathcal{L}_i, \qquad [c_i] = [M]^{2(3-i)}$$

- Galileon action

$$S_\pi = \int \mathrm{d}^4 x \left(\mathcal{L}_\pi + \pi T^\mu{}_\mu \right)$$

(Nicolis, Rattazzi, Trincherini. 2008)

The Vainshtein Effect

- Spherically symmetric, static equations of motion, near an object of mass M

$$c_2\left(\frac{\pi'}{r}\right)+2c_3\left(\frac{\pi'}{r}\right)^2+2c_4\left(\frac{\pi'}{r}\right)^3=\frac{M_c}{4\pi r^3}$$

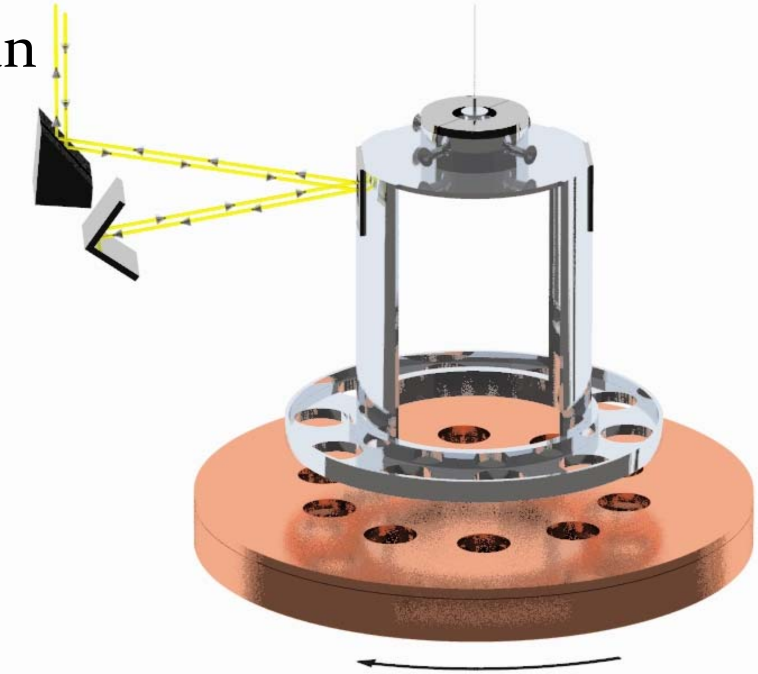
- Force can be made substantially weaker than gravity if non-linearities become important

$$F_\pi=\frac{\mathrm{d}\pi(r)}{\mathrm{d}r}$$

(Nicolis, Rattazzi, Trincherini. 2008)

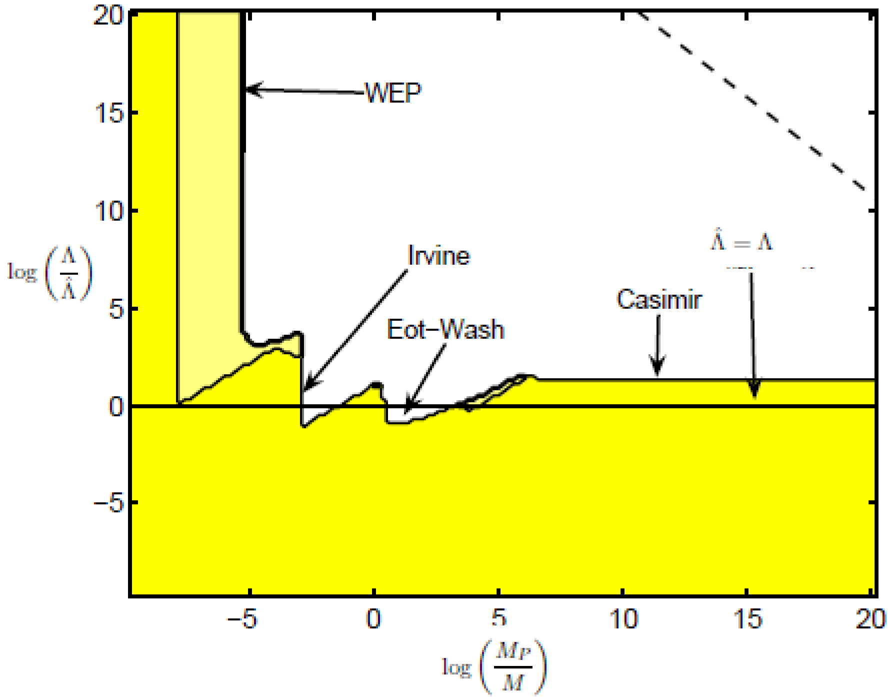
Eöt-Wash

- Looks for deviations from Newtonian gravitational potential
  - Area of overlap changes as the plates are rotated
  - Null experiment:
    No force if only Newtonian gravity present



Eöt-Wash: The Chameleon

- Only weak constraints on the chameleon
  - Force due to thin shell object only weakly depends on coupling strength



$$V(\phi) = \hat{\Lambda}^4 \left[1 + \left(\frac{\Lambda}{\phi}\right)^n\right]$$

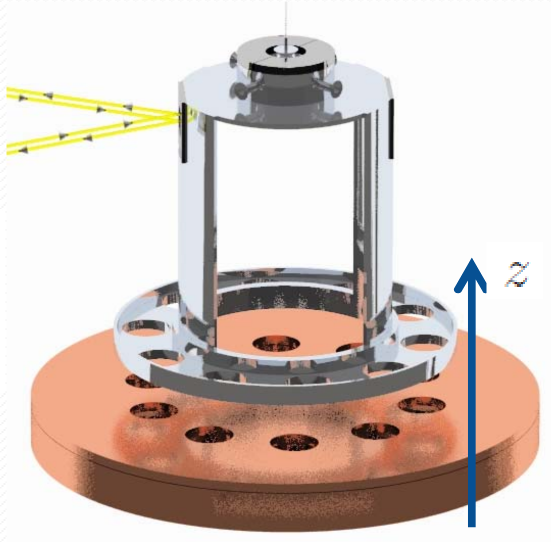
(Mota, Shaw. 2007)

Eöt-Wash: The Galileon

- Have to expand around the background due to the Earth

$$\pi(\vec{x}) = \pi_\oplus(r) + \phi(z),$$

- No Vainshtein mechanism in a 1D system



$$\frac{d^2\phi}{dz^2}\underbrace{\left[c_2 + 4c_3\frac{\pi'_\oplus}{r} + 12c_4\left(\frac{\pi'_\oplus}{r}\right)^2 + 32c_5\left(\frac{\pi'_\oplus}{r^3}\right)^3\right]}_{Z_\oplus} = -T\ .$$

- Torque from beyond standard model physics

$$T < 0.87 \times 10^{-17}\ \text{Nm}.$$

- Constrains

$$Z_\oplus > 6.05 \times 10^{40}\text{GeV}^2\ , \quad > (20m_P)^2\ ,$$

if $c_4 = 0, \quad c_5 = 0$

$$c_3 > 10^{96}$$

Scalar Fields Couple to Gauge Bosons

- Conformally coupled scalar fields

$$g^{(i)}_{\mu\nu} = B\left(\frac{\phi}{M}\right) g_{\mu\nu}$$

  - Classically no coupling to kinetic terms of gauge bosons

- But quantisation and conformal rescaling do not commute!

- In a quantum theory we should always include a coupling

$$\mathcal{L} \supset \frac{\phi}{M_\gamma} F_{\mu\nu} F^{\mu\nu}$$

Scalar fields at Colliders

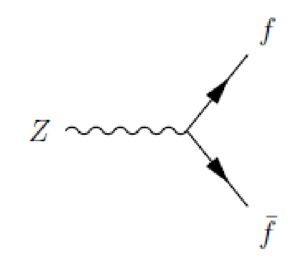
- Effective Lagrangian

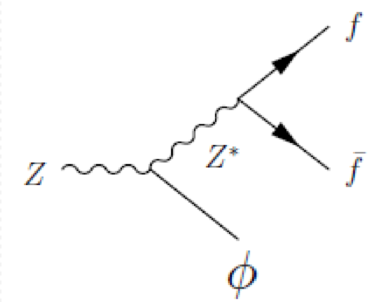
$$S = -\frac{1}{4}\int d^4x\, 2B_\gamma\left(\frac{\phi}{M_\gamma}\right)\left[(\partial^a W^{+b} - \partial^b W^{+a})(\partial_a W_b^- - \partial_b W_a^-) + W \leftrightarrow Z + W \leftrightarrow A\right] + 2B_H\left(\frac{\phi}{M_H}\right)\left[2m_W^2 W^{+a} W_a^- + m_Z^2 Z^a Z_a\right]$$

  - Preserves that the Lagrangian descends from unbroken $SU(2) \times U(1)$ at high energies, and gauge boson masses from spontaneous symmetry breaking
- Contributes
  - New processes - scalar in final state
  - Corrections to SM processes - scalar only in intermediate state

Scalar Bremsstrahlung

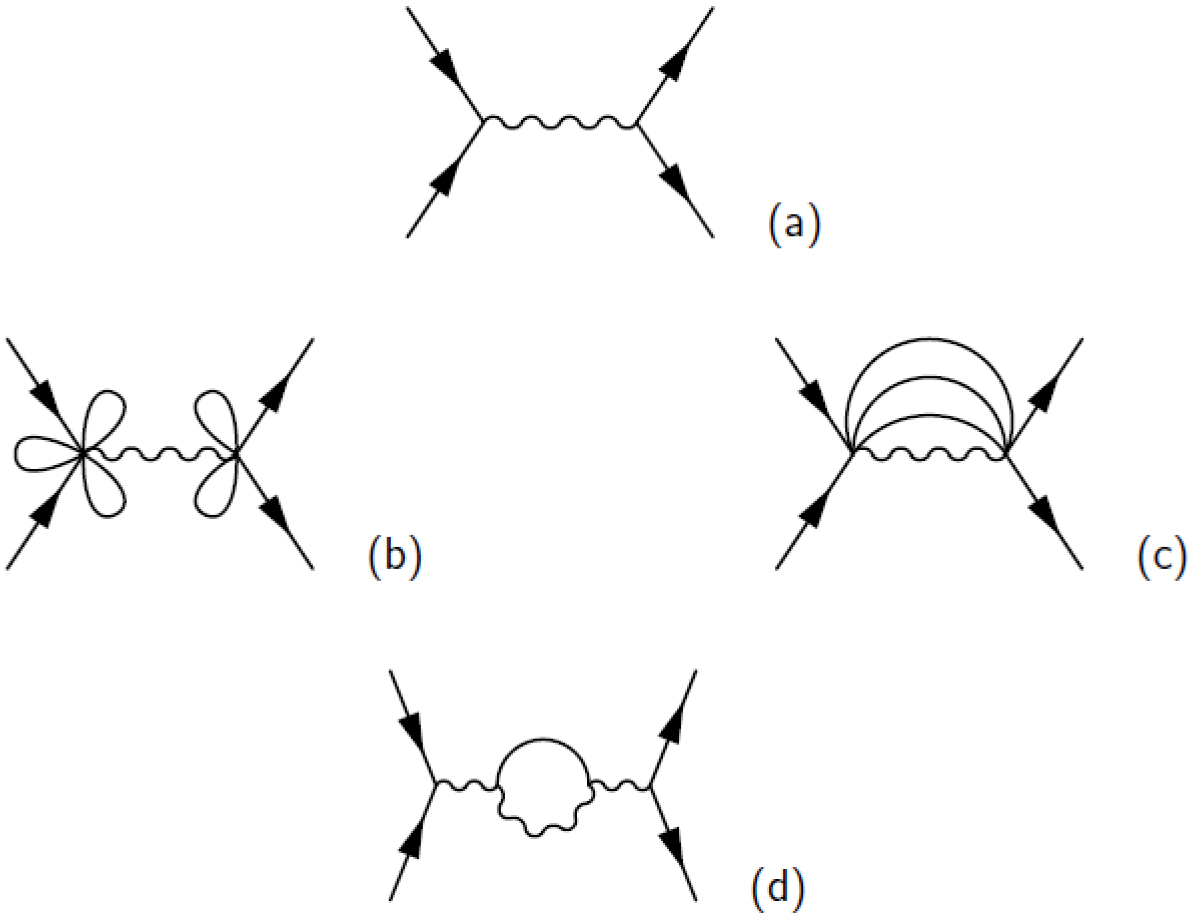
- Contribution to the width of Z decay





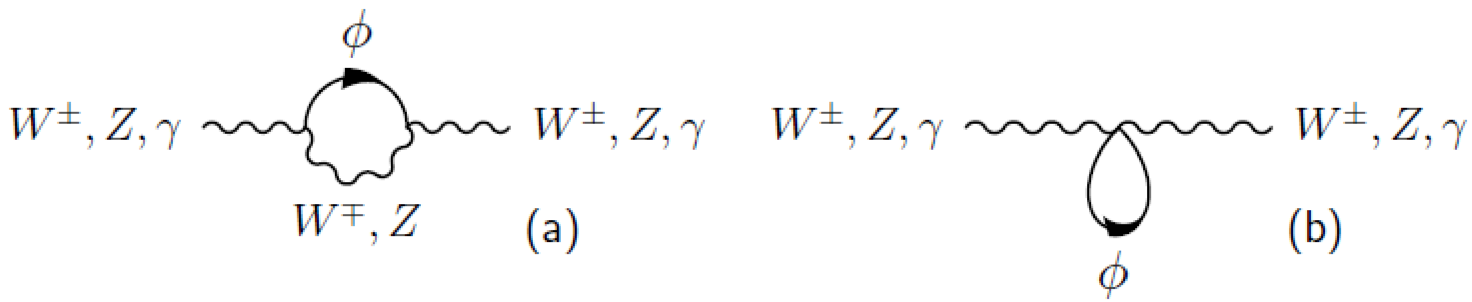
- Decay rate: $\frac{\Gamma(Z \to \phi f \bar{f})}{\Gamma(Z \to f \bar{f})} = \frac{1}{16\pi^3} \frac{m_Z^2}{M_\gamma^2} I_{\phi f \bar{f}}$ $I_{\phi f \bar{f}} \approx 0.2$
- Width of the Z
  - Prediction from the standard model $\Gamma_Z = 2.4952 \text{ GeV}$
  - Known from observation $\Gamma_Z = (2.4952 \pm 0.0023) \text{ GeV}$
- Dark Energy correction negligible if $M_\gamma \gtrsim 10^2 \text{ GeV}$

Corrections to Electroweak Processes



Corrections to Electroweak Processes

- Leading order scalar effects occur as oblique corrections



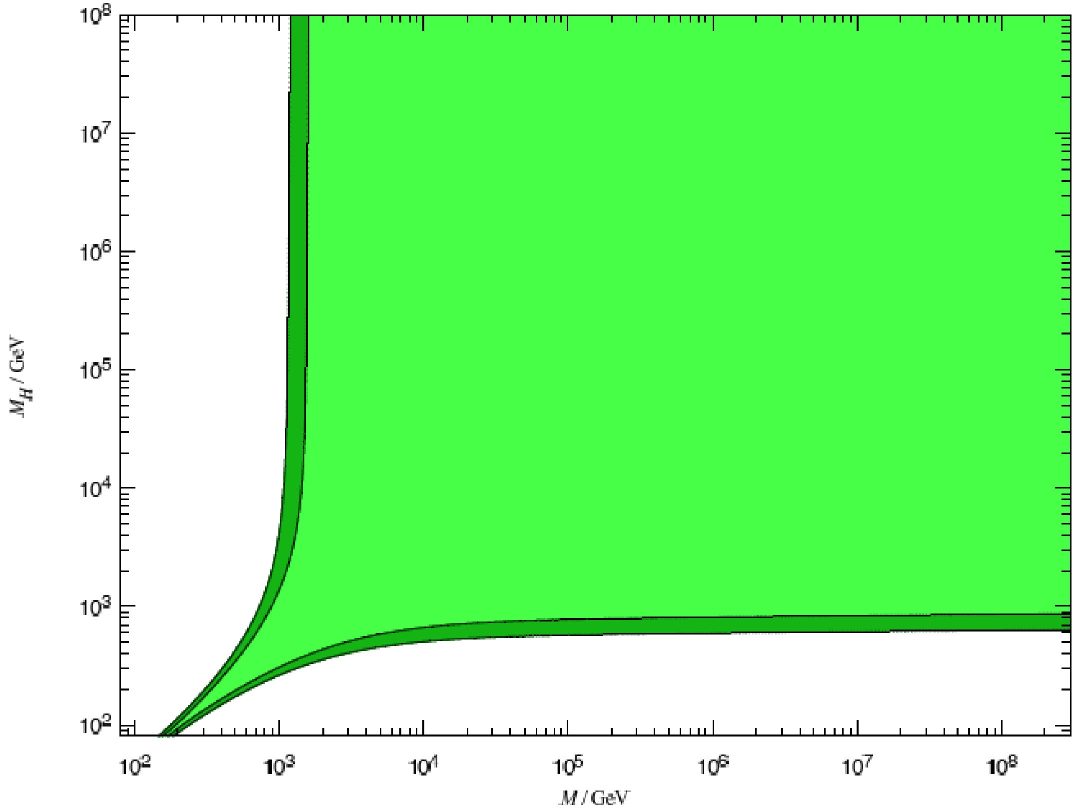
  - The corrected propagator is

$$\Delta(k^2) = \frac{1}{k^2 + m_A^2 - \Pi_{AA}^{(0)}(k^2)}$$

Electroweak precision observables

- Constraints on scalar couplings from EW precision observables at LEP

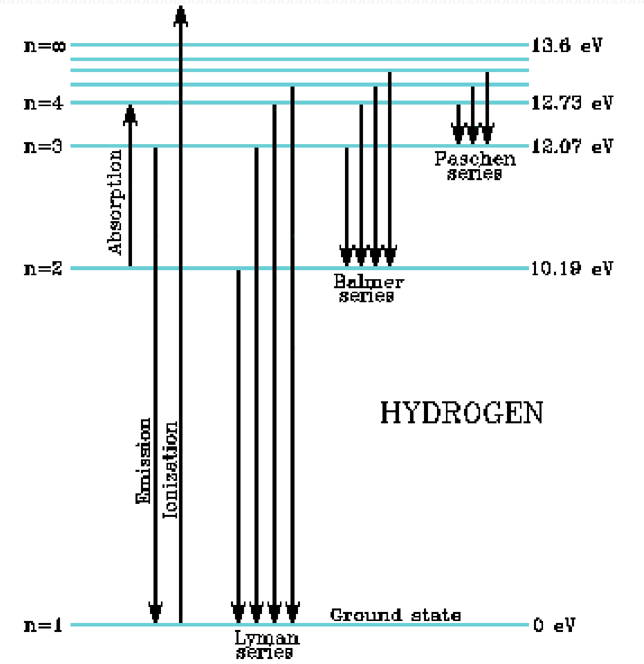
- Possible corrections to Higgs production



Atomic precision measurements

- Perturbations of the scalar fields are sourced by
  - Nuclear electric field
  - Density of the atomic nucleus

$$\delta\phi = -\frac{m_N}{4\pi M_m r} - \frac{Z^2\alpha}{8\pi M_\gamma r^2}.$$



- Fermion masses are scalar field dependent

$$m_f(\phi) = m_f\left(1 + \frac{\delta\phi}{M_m}\right).$$

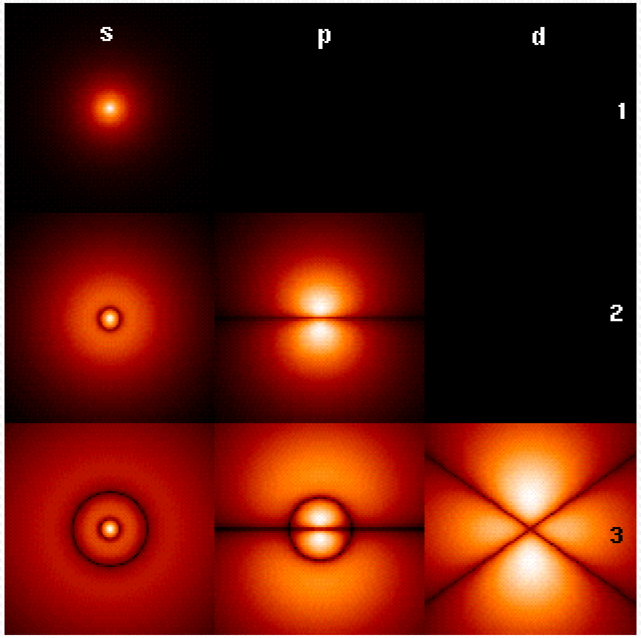
- Leads to a perturbed Schrodinger equation

$$H = \frac{p^2}{2m} + W + m - \frac{1}{2mM_m}\left(\delta\phi p^2 + (\sigma\cdot p)\delta\phi(\sigma\cdot p)\right) + \frac{m}{M_m}\delta\phi,$$

Atomic precision measurements

- Perturbs atomic energy levels

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

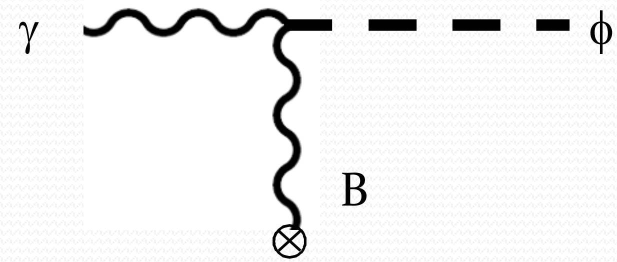


- 1 sigma uncertainty on the 1s to 2s transition in hydrogen of order 10^{-9} eV

- Constrains: $10 \text{ TeV} \lesssim M_m$

Astrophysical Constraints

- The interaction $$\mathcal{L} \supset \frac{\phi}{M_\gamma} F_{\mu\nu} F^{\mu\nu}$$
- Leads to mixing in magnetic fields



- Changes the polarization and luminosity of sources viewed through magnetic fields
  - Constraints from observations of AGN

$$10^{11}\ \text{GeV} \lesssim M_\gamma$$

(CB, Davis, Shaw. 2009)

  - Laboratory searches not yet competitive

Dark Energy in the Laboratory

- If the acceleration expansion of the universe is caused by a scalar field it must couple to matter
- For linear theories gravitational strength couplings are excluded by fifth force experiments
- Nonlinear theories are ok!

- Best Constraints

$$10^{11}\ \text{GeV} \lesssim M_\gamma$$

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

Electroweak precision observables

- The vacuum polarization for each boson is

$$\Pi_{AA}(k^2) \sim a(k^2)\Lambda^2 + b(k^2)\ln\left(\frac{\Lambda^2}{M_A^2}\right) + c(k^2)$$

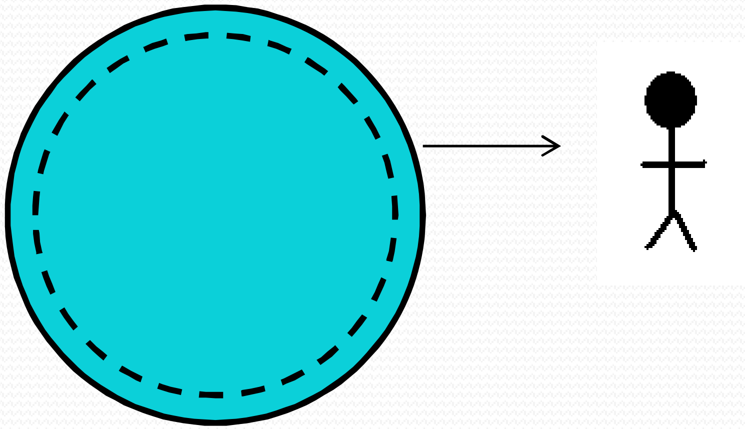
  - These are sensitive to the cut off scale

- Leads to Log divergences in observables
  - Typically differences of the wavefunction renormalisation of different bosons, or bosons at different momenta

The Chameleon

- Thin shell suppression of forces
  - The chameleon force sourced by a massive body is produced only by a thin shell near the surface

$$\frac{F_\phi}{F_N} = -\underbrace{\frac{M_P^2}{M^2}\frac{\Delta R}{R}}_{\sim \frac{1}{\Phi_N}\left(\frac{\phi_\infty}{M} - \frac{\phi_c}{M}\right)}(1 + m_\infty r)e^{-m_\infty (r-R)}$$



(Khoury, Weltman 2004)

Lunar Laser Ranging Constraints

- Assuming $c_2 \lesssim M_P^2$
- Lunar Laser Ranging bounds on the precession of the perihelion of the moon $|\delta\phi| < 2.4 \times 10^{-11}$
- Galileon

$$\delta\phi = \frac{M_P^2 r^2}{M_\oplus}(2\pi'_\oplus + r\pi''_\oplus)|_{\mathrm{Moon}}$$

  - If $c_4 = 0, \quad c_5 = 0$

$$10^{120} < c_3 \ ,$$

The Galileon Model

$$\mathcal{L}_1 = \pi$$

$$\mathcal{L}_2 = -\frac{1}{2}\partial\pi\cdot\partial\pi$$

$$\mathcal{L}_3 = -\frac{1}{2}(\Box\pi)\partial\pi\cdot\partial\pi$$

$$\mathcal{L}_4 = -\frac{1}{4}[(\Box\pi)^2\partial\pi\cdot\partial\pi - 2(\Box\pi)\partial\pi\cdot\Pi\cdot\partial\pi - (\Pi\cdot\Pi)(\partial\pi\cdot\partial\pi) + 2\partial\pi\cdot\Pi\cdot\Pi\cdot\partial\pi]$$

$$\mathcal{L}_5 = -\frac{1}{5}[(\Box\pi)^3\partial\pi\cdot\partial\pi - 3(\Box\pi)^2\partial\pi\cdot\Pi\cdot\partial\pi - 3\Box\pi(\Pi\cdot\Pi)(\partial\pi\cdot\partial\pi) + 6(\Box\pi)\partial\pi\cdot\Pi\cdot\Pi\cdot\partial\pi + 2(\Pi\cdot\Pi\cdot\Pi)(\partial\pi\cdot\partial\pi) + 3(\Pi\cdot\Pi)\partial\pi\cdot\Pi\cdot\partial\pi - 6\partial\pi\cdot\Pi\cdot\Pi\cdot\Pi\cdot\partial\pi]$$

$$\Pi^\mu_\nu \equiv \partial^\mu\partial_\nu\pi$$

(Nicolis, Rattazzi, Trincherini. 2008)

Screening Mechanisims: Summary

- Non-linear terms dominate in regions of high density
- This changes
  - The vacuum and the mass (chameleon)
  - The coupling strength (Galileon)

- No UV completion of the chameleon
- Galileon shown to arise from
  - DGP (Dvali, Gabadadze, Porrati. 2000)
  - Probe brane world scenarios (de Rham, Tolley. 2010)
  - Massive gravity (de Rham, Gabadadze. 2008)

Scalar fields at Colliders

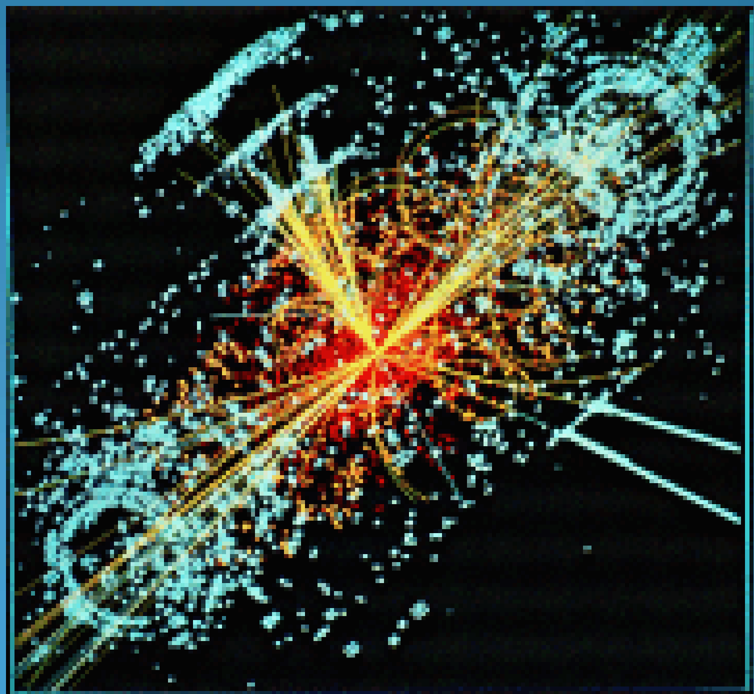
- All fermions and bosons entitled to radiate into scalar fields
  - May introduce large corrections to currently observable interactions
- Focus on Electroweak sector
  - Also a correction to QCD processes, but calculations more difficult (work in progress)

Electroweak precision observables

- Six parameters to describe oblique corrections
  - S measures the difference between wavefunction renormalisation of Z and photon
  - T measures additional isospin breaking at zero momentum (difference between charged and neutral current interactions)
  - U measures difference between W and Z wavefunction renormalisations
  - V measures the difference between Z wavefunction renormalisation on shell and at zero momentum
  - W measures the difference between W wavefunction renormalisation on shell and at zero momentum
  - X measures additional mixing between Z and photon (not present for conformally coupled scalars)

(Peskin, Takeuchi 1992. Maksymyk, Burgess, London 1994)

Higgs Production

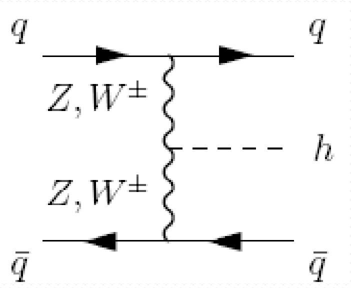


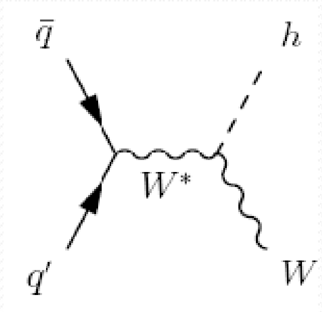
Higgs Production

- Can the scalar give large corrections to Higgs production cross sections?

$$S \supset -\frac{1}{2}\int d^4x \left[B_H\left(\frac{\phi}{M_H}\right)|(\partial_a + i\vec{A}_a\cdot\vec{t} - iB_a y)H|^2 - C_H\left(\frac{\phi}{M_H}\right)\mu^2 H^\dagger H + \mathcal{O}([H^\dagger H]^2)\right]$$

  - Focus on production mechanisms with gauge bosons





Higgs Production

- Enhancement of Higgs production rate

$$\frac{\Gamma(ZZ \to h)}{\tilde{\Gamma}(ZZ \to h)} = 1 + 2\frac{\Pi_{ZZ}(-M_Z^2)}{M_Z^2} - \frac{\Pi_{WW}(0)}{M_W^2} + 2\Pi'_{ZZ}(-M_Z^2) + \Pi'_{HH}(-M_H^2)$$
$$= 1 + \alpha(2V + R).$$

- New oblique parameter

$$\alpha R \equiv \frac{\mathrm{d}}{\mathrm{d}k^2}\,\Pi_{HH}(k^2)\big|_{k^2=-M_H^2} + \frac{\Pi_{ZZ}(0)}{M_Z^2}.$$

- Higgs vacuum polarisation

$$\Pi_{HH}(k^2) \sim d(k^2)\Lambda^2 + e(k^2)\ln\left(\frac{\Lambda^2}{M_H^2}\right) + f(k^2)$$

Higgs Production

- Oblique parameter

$$\alpha R = \frac{\beta_H^2 \Lambda^2}{32\pi^2} \frac{\bar{B}_H'^2}{\bar{B}} \left[\frac{1}{2} \left(1 + \frac{\bar{B}}{\bar{B}_H} \right) - 2 \frac{\bar{B}_H'' \bar{B}}{\bar{B}_H'^2} \right] + \text{finite terms of order O} \left(\beta_H^2 M_{\text{EW}}^2 \right).$$

- Leads to corrections to Higgs production
  - Gluon-gluon fusion corrections possibly enhanced (work in progress)

The Vainshtein Effect

- A perturbation around the spherically symmetric background $$\pi(\vec{x}) \to \pi_0(\vec{x}) + \phi(\vec{x})$$
- Within the Vainshtein radius renormalisations from the background alter coefficient of the kinetic term
  - eg $c_4 = 0, \quad c_5 = 0$

$$\mathcal{L}_\phi = Z_{\mu\nu}\partial^\mu\phi\partial^\nu\phi - \frac{c_3}{2}\Box\phi(\partial\phi)^2 + \phi T$$

$$Z_{\mu\nu} \sim Z\delta_{\mu\nu}$$

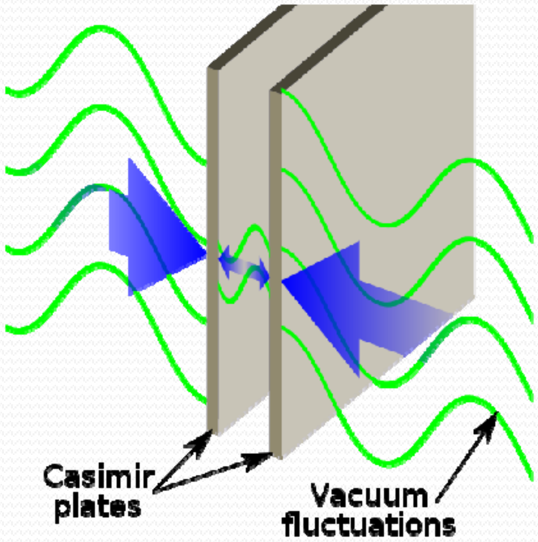
$$Z \sim -\frac{c_2}{2}\left[1 - \frac{1}{2}\left(\frac{R_1}{r}\right)^{3/2}\right]$$

- Canonically normalising
  - The coupling strength is suppressed

$$\mathcal{L}_{\hat{\phi}} = (\partial\hat{\phi})^2 - \frac{c_3}{2Z^{3/2}}\Box\hat{\phi}(\partial\hat{\phi})^2 + \frac{\hat{\phi}}{Z^{1/2}}T$$

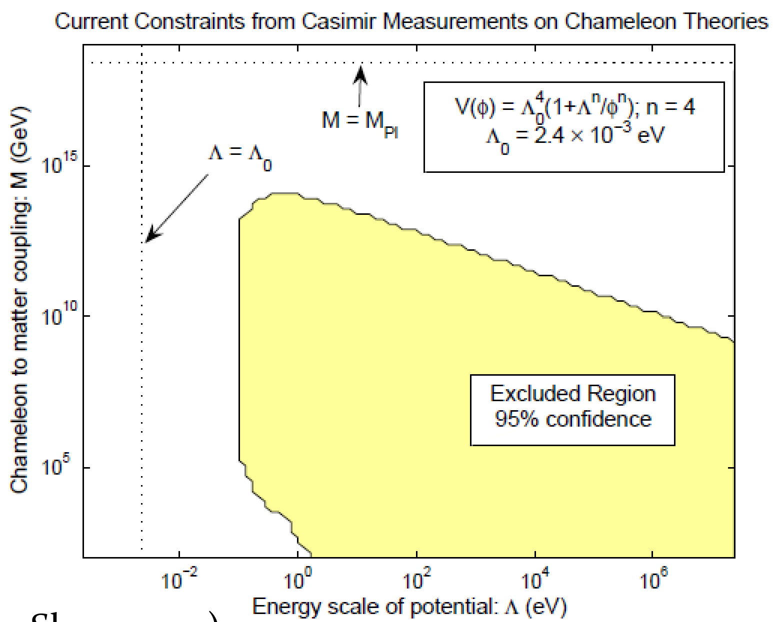
Casimir Experiments

- Casimir force arises between two uncharged plates in a vacuum due to the quantisation of the electromagnetic field



- Constrains form of chameleon potential, but not coupling

- Current experimental set-ups not suitable to look for Galileons



(Brax, van de Bruck, Davis, Mota Shaw. 2007)

The Vainshtein Effect

- Writing $\pi' = \frac{M_c}{4\pi c_2 r^2} g(r)$

- The equation of motion can be written as

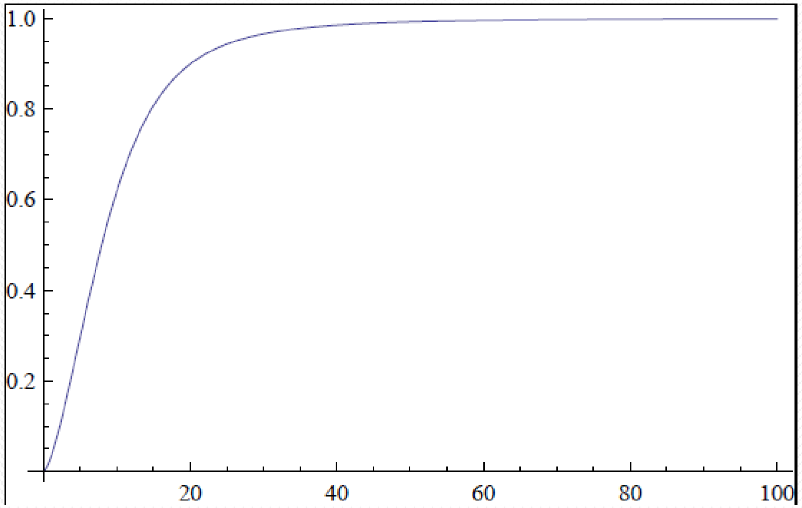
$$g + \left(\frac{R_1}{r}\right)^3 g^2 + \left(\frac{R_2}{r}\right)^6 g^3 = 1.$$

0411113

  - Suppression of the force when g<1

$$R_1^3 \sim \frac{c_3 M_c}{c_2^2}$$

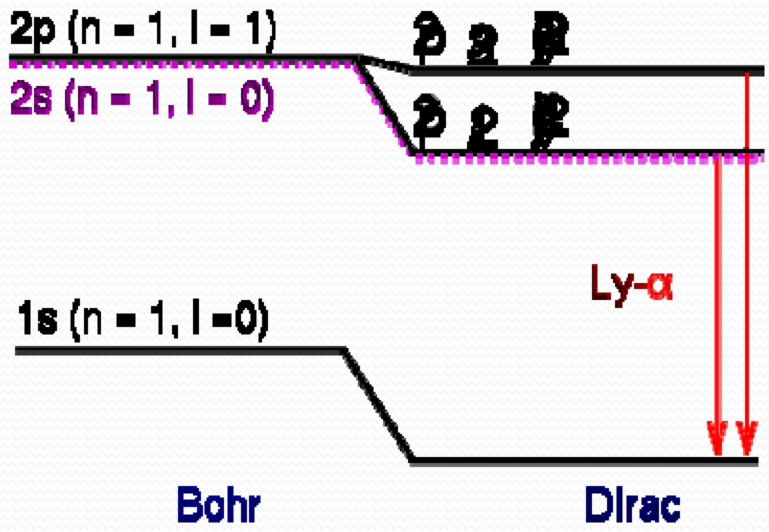
$$R_2^6 \sim \frac{c_4 M_c^2}{c_2^3}$$



Atomic precision measurements

- Lamb shift is the splitting between the 2s and 2p energy levels due to QED effects

$$\delta E_{2s-2p} = \frac{Z^4 \alpha}{48\pi a_0^2 M^2} m.$$



- The electronic Lamb Shift bounds

$$10^{-4}\ \mathrm{GeV} \lesssim (M_\gamma M_m)^{1/2}$$

- Current bounds mean that a new scalar field cannot explain the anomalous Lamb shift of muonic hydrogen

Scalar Fields Couple to Gauge Bosons

- Start with a coupling only to fermions

$$\mathcal{L} \supseteq B^2\bar{\lambda}(\not{e}^\mu D_\mu)\lambda + \text{h.c.}$$

- Conformal rescaling of the metric

$$g_{\mu\nu} = B^{-2}(\phi)\tilde{g}_{\mu\nu}.$$

- Canonically normalised spinors are related by

$$\lambda_E = B^{3/2}\lambda_J$$

- This makes the measure of the path integral scalar field dependent
  - The Jacobian is not invariant under rescaling

$$[\mathrm{d}\lambda\ \mathrm{d}\bar{\lambda}]_J = \left|\frac{\partial(a,\bar{b})}{\partial(c,\bar{d})}\right| [\mathrm{d}\lambda\ \mathrm{d}\bar{\lambda}]_E.$$

Scalar Fields Couple to Gauge Bosons

- Computing the Jacobian

$$\left|\frac{\partial(a,\bar{b})}{\partial(c,\bar{d})}\right| \propto \exp\operatorname{tr}\frac{3\alpha}{2}\int \mathrm{d}^4x\,\sqrt{-g}\,\delta\phi\,(\bar{\psi}_m\psi_n + \bar{\psi}_n\psi_m),$$

$$\left|\frac{\partial(a,\bar{b})}{\partial(c,\bar{d})}\right| = \mathrm{e}^{\mathrm{i}\delta S}.$$

$$\mathrm{i}\delta S = -3\alpha\mu^4\int \mathrm{d}^4x\,\delta\phi\int\frac{\mathrm{d}^4k}{(2\pi)^4}\,\mathrm{e}^{-k^2} \times\left(4 - \frac{e^2}{32\mu^4}\operatorname{Tr}[\gamma^a,\gamma^b][\gamma^c,\gamma^d]F_{ab}F_{cd} + \cdots\right),$$

- Leading to a term in the Lagrangian

$$\mathcal{L}_E \supset \frac{\delta\phi}{M_\gamma}F^{ab}F_{ab}$$

- Quantisation and conformal rescaling do not commute!