Recent Developments in Modified Gravity

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Outline

Modified Gravity Models

Chameleon, Symmetron, Dilaton, Galileon

Laboratory Tests Chameleon, symmetron

Atomic Interferometry; Casimir

Gravitational Waves Galileons, Horndeski

Massive Gravity

Effect of uv completion

Main screening mechanisms can be written as

$$\mathcal{L} \supset -\frac{Z(\phi_0)}{2}(\partial\delta\phi)^2 - \frac{m^2(\phi_0)}{2}\delta\phi^2 + \frac{\beta(\phi_0)}{M_P}\delta\phi\delta T\ ,$$

The Vainshtein mechanism reduces the coupling to matter by increasing Z

The Damour Polyakov mechanism reduces the coupling β

The chameleon mechanism increases the mass

Screened Modified Gravity

consider the chameleon action

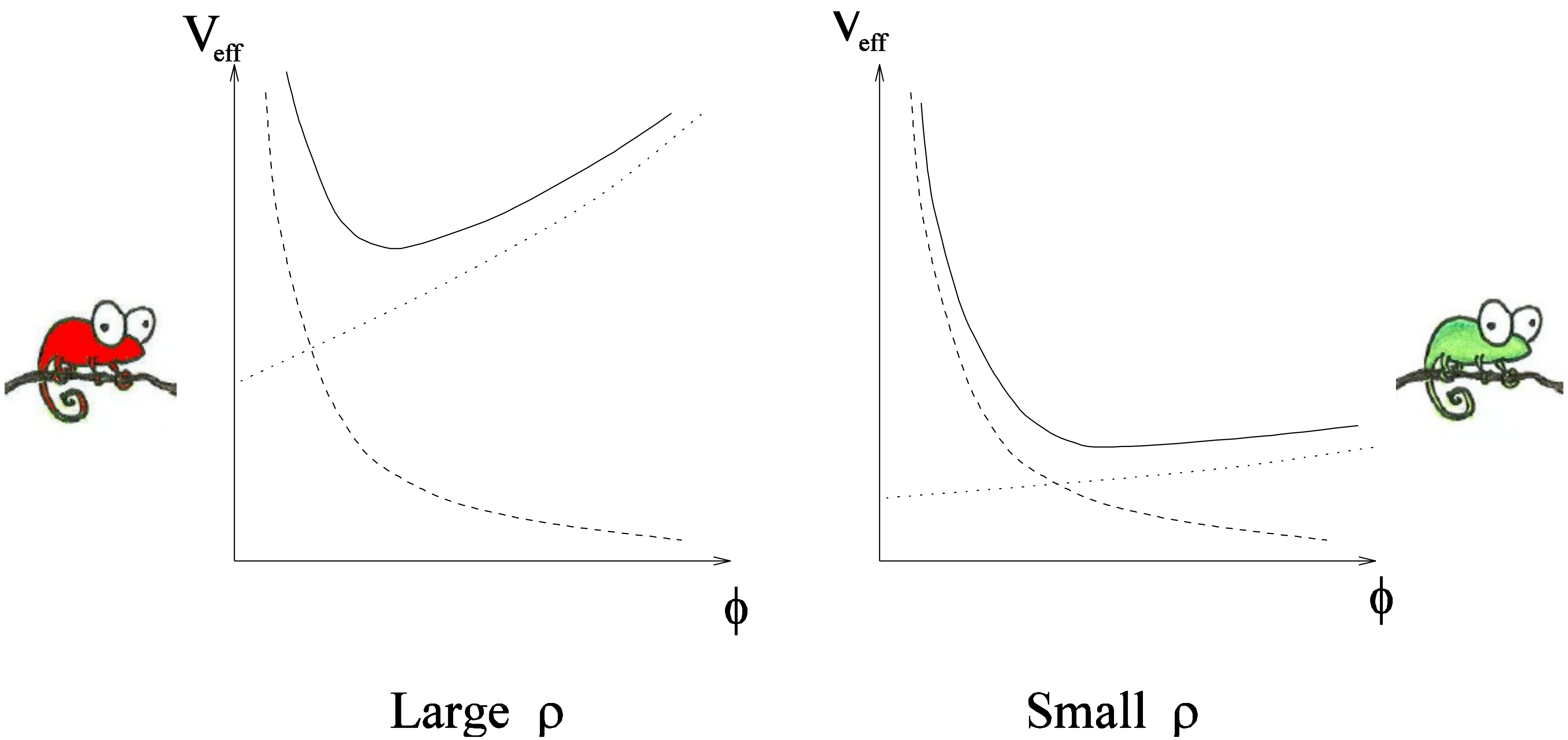
$$S = \int d^4x\sqrt{-g}(\frac{R}{16\pi G_N} - \frac{(\partial\phi)^2}{2} - V(\phi)) + S_m(\psi_i, A^2(\phi)g_{\mu\nu})$$

gives the effective potential

$$V_{\text{eff}}(\phi) = V(\phi) - (A(\phi) - 1)T$$

$$V(\phi) = \frac{\Lambda^{4+n}}{\phi^n} \qquad A(\phi) = e^{\beta\phi}$$

This should give fifth forces, but these are screened. Two types of screening. Chameleons - the mass depends on the environment; dilatons and symmetrons - the coupling to matter depends on the environment.
Both are considered. They have been constrained by solar system and lab tests.



mass is proportional to the second derivative of minimum of the potential
Hence it can be heavy when ρ is large and light when ρ is small

$$m_\phi^2(\rho) = \partial^2 V(\rho)/\partial\phi^2$$

Khoury&Weltman, astroph/039300;039411;
Brax et al astroph/0408415

Environmentally Dependent Dilaton

$$V(\phi) = V_0 e^{-\alpha\phi}$$

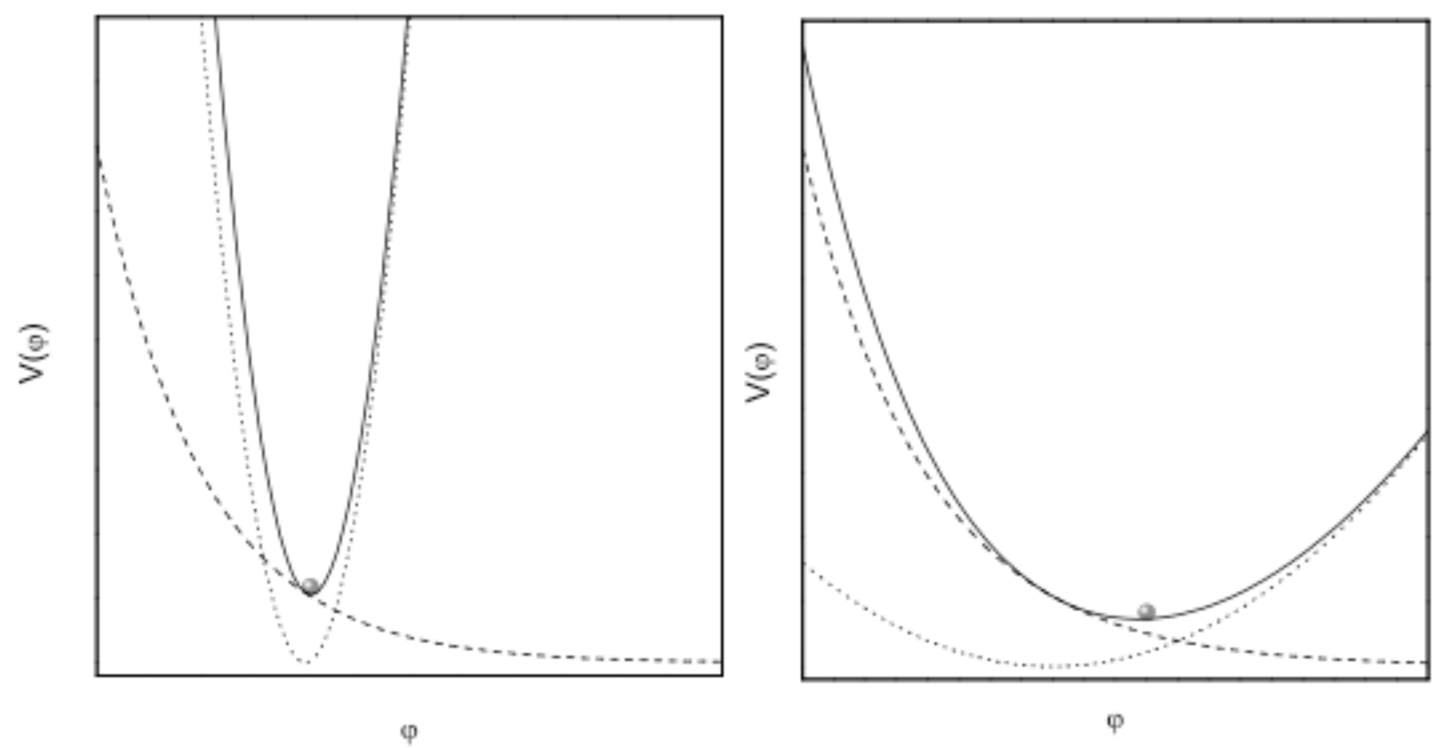
Where the potential is derived from string theory in the strong coupling limit. We chose the coupling to matter to be

$$A(\phi) = 1 + \frac{A_2}{2}(\phi - \phi_\star)^2$$

This keeps the scalar in the strong coupling regime as the Universe evolves. See Brax et al 1005.3735 for full details of the cosmological behaviour, local constraints and linear perturbation theory

$$S = \int d^4x\sqrt{-g}(\frac{1}{16\pi G_N}R - \frac{1}{2}(\partial\phi)^2 - V(\phi)) + \mathcal{S}_m(\psi_m, A^2(\phi)g_{\mu\nu}))$$

$$V_{eff}(\phi) = V(\phi) + \rho_m A(\phi)$$



Symmetrons

Khoury&Hinterbichler, 1001.4525

This has potential

$$V(\phi) = V_0 + \frac{\lambda}{4}\phi^4 - \frac{\mu^2}{2}\phi^2$$

and coupling function

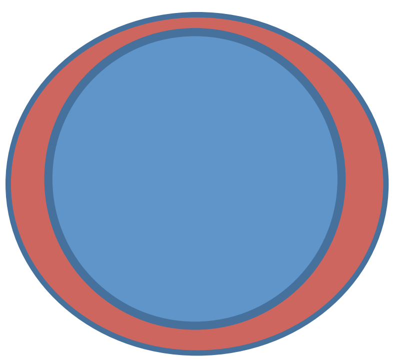
$$A(\phi) = 1 + \frac{\beta_\star}{2\phi_\star m_{\rm Pl}}\phi^2$$

In a dense environment the field is at the origin whilst in a sparser one the field is at the minimum of the potential with the transition happening at density

$$\rho_*$$

When objects are big enough/dense enough, or if they are surrounded by big objects, the field is screened. Inside it is nearly constant apart from inside thin shell whose size is inversely proportional to Newton's potential at the surface

Thin shell



the fifth force is proportional to the size of the thin shell

$$F_\phi \propto \Delta R/R\Phi_N$$

Atomic Interferomery

Originally proposed by Burrage, Copeland and Hinds; arxiv 1408.1409
experiment performed by Berkeley group of Muller et al arxiv 1603.06587

These experiments constrain the anomalous acceleration of an atom in the presence of an external ball of matter of radius 0.95cm. The atom is too small to have a thin shell, so feels the full extra force. The whole apparatus is embedded in a cavity of radius 6.1 cm

By computing the scalar charge of the source we can compute the extra acceleration on the atom for specific models. we can then bound models against the results of the Berkeley group

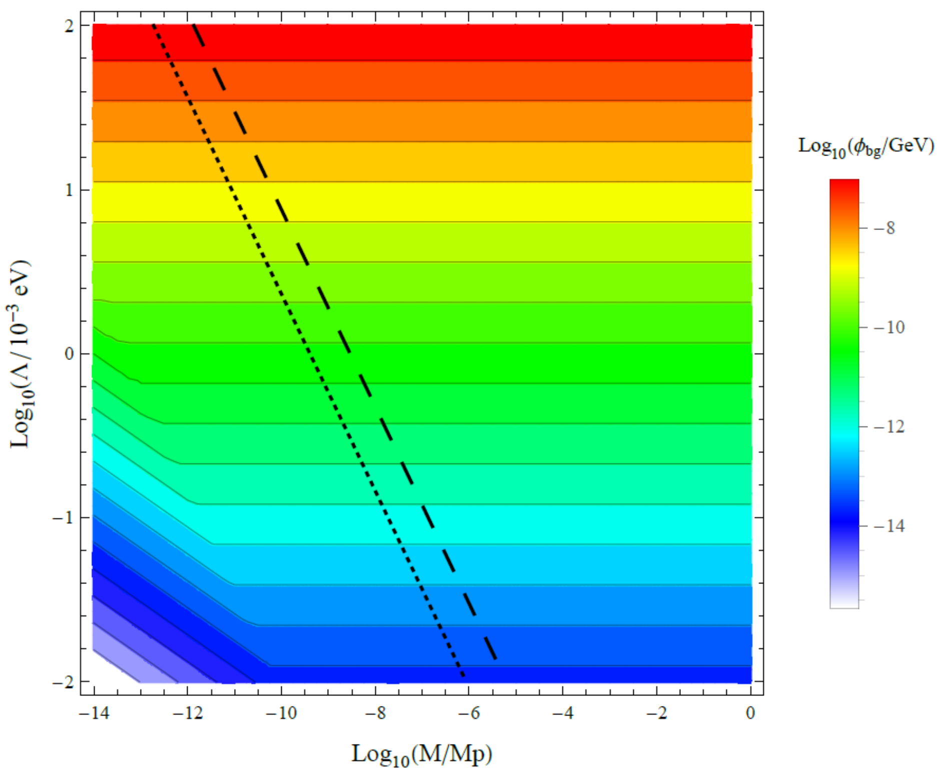
We find that for f(R) models and dilation existing constraints are stronger

Brax&ACD 1609.09242

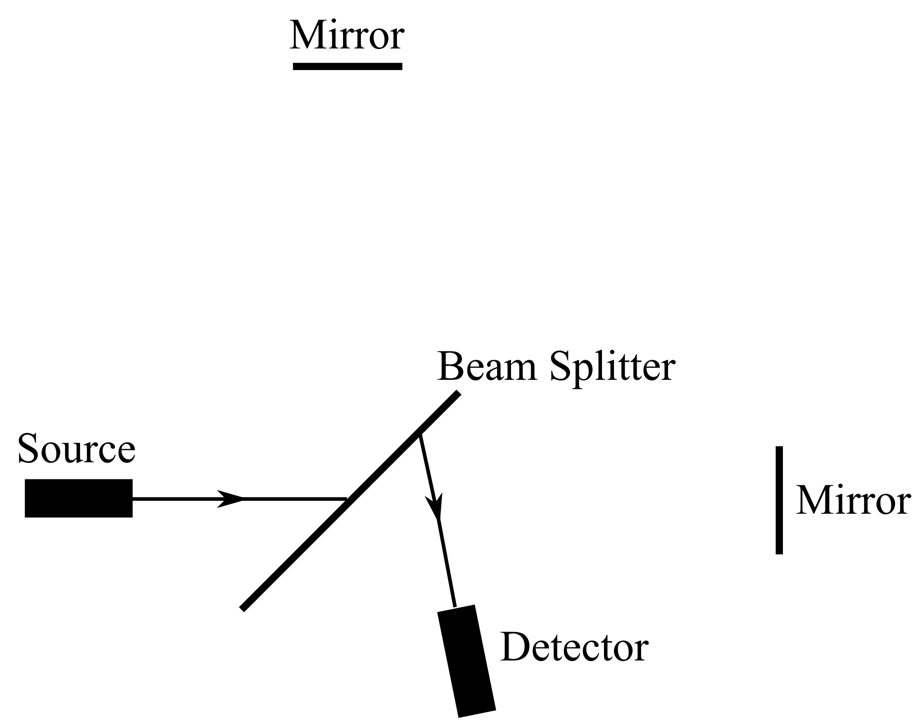
Why Atom Interferometry?

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

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

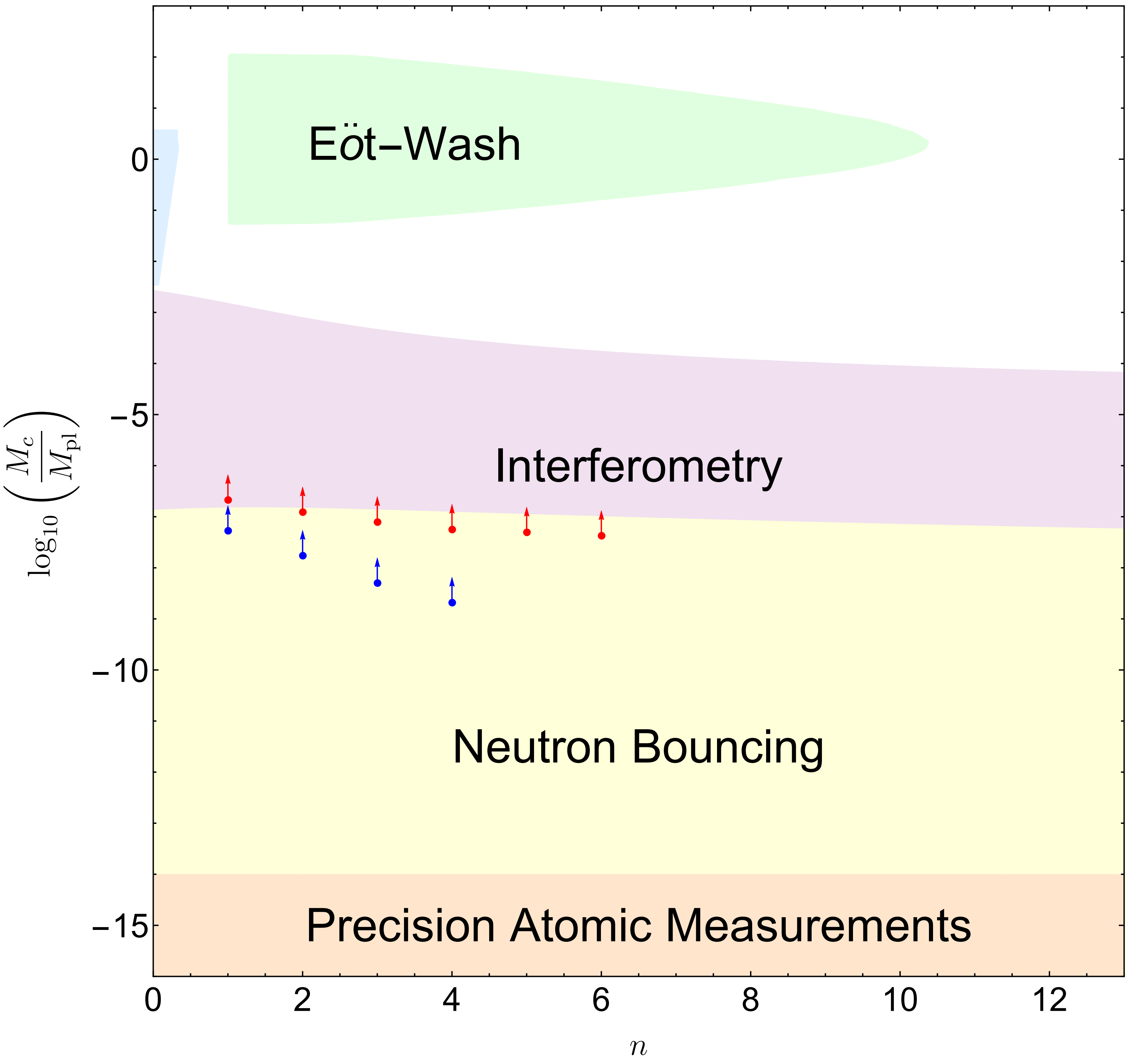


CB, Copeland, Hinds. (2015)


Mirror
Beam Splitter
Source
Mirror
Detector

Chameleon Constraints

Burrage&Sakstein;
1709.09071



Symmetron Constraints

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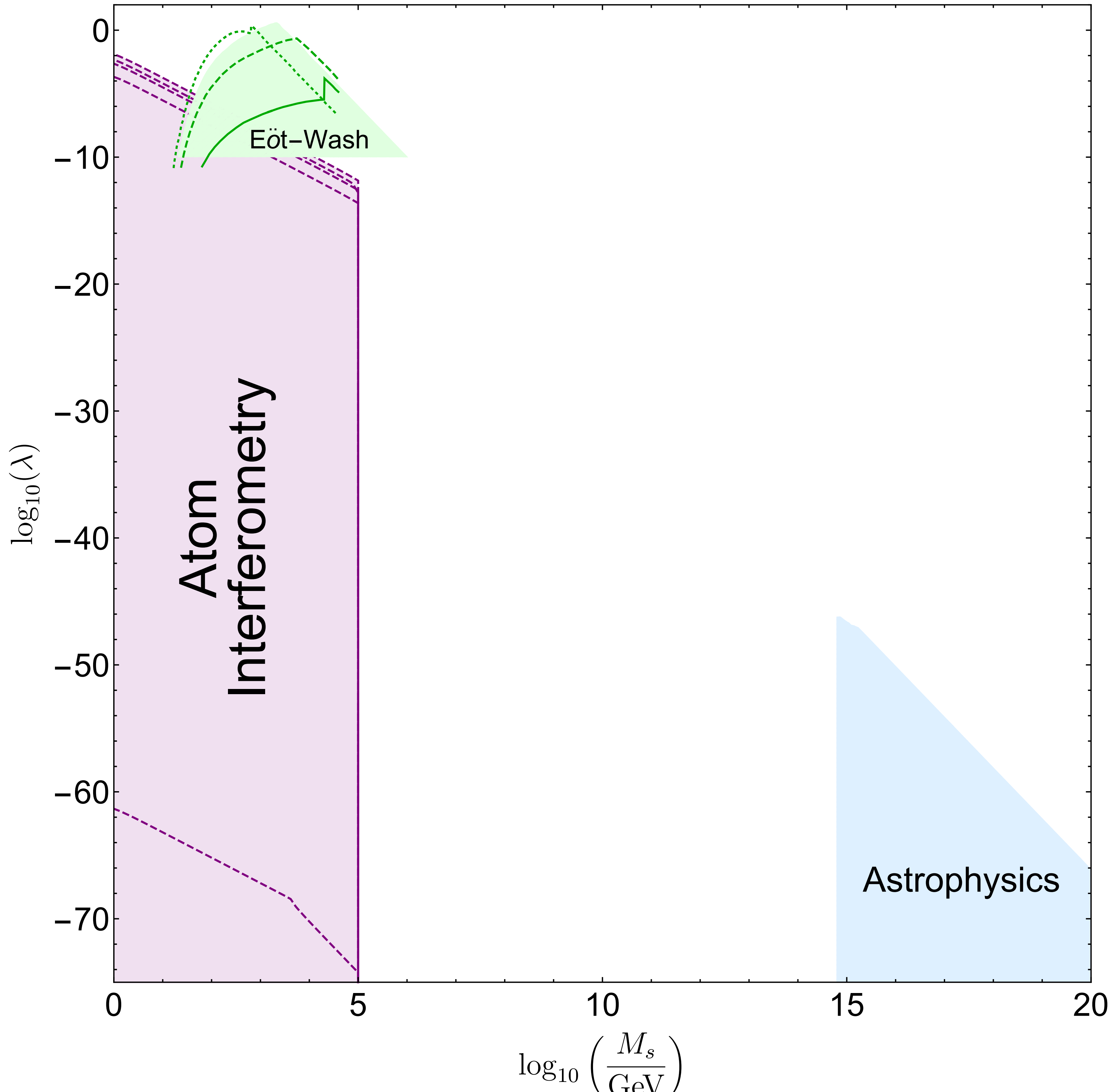
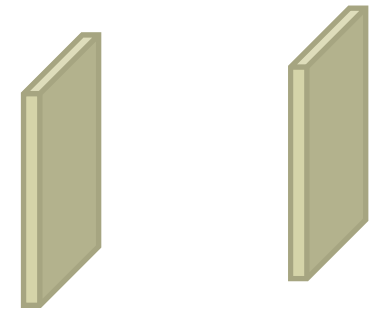


Casimir Force Experiments

Brax et al PRD76(07)124034

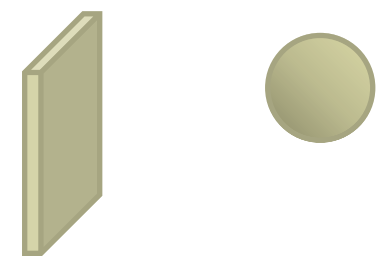
The scalar force could be detected in Casimir type experiments

force between parallel plates



$$F_{cas} \approx d^{-4}$$

force between a plate and a sphere

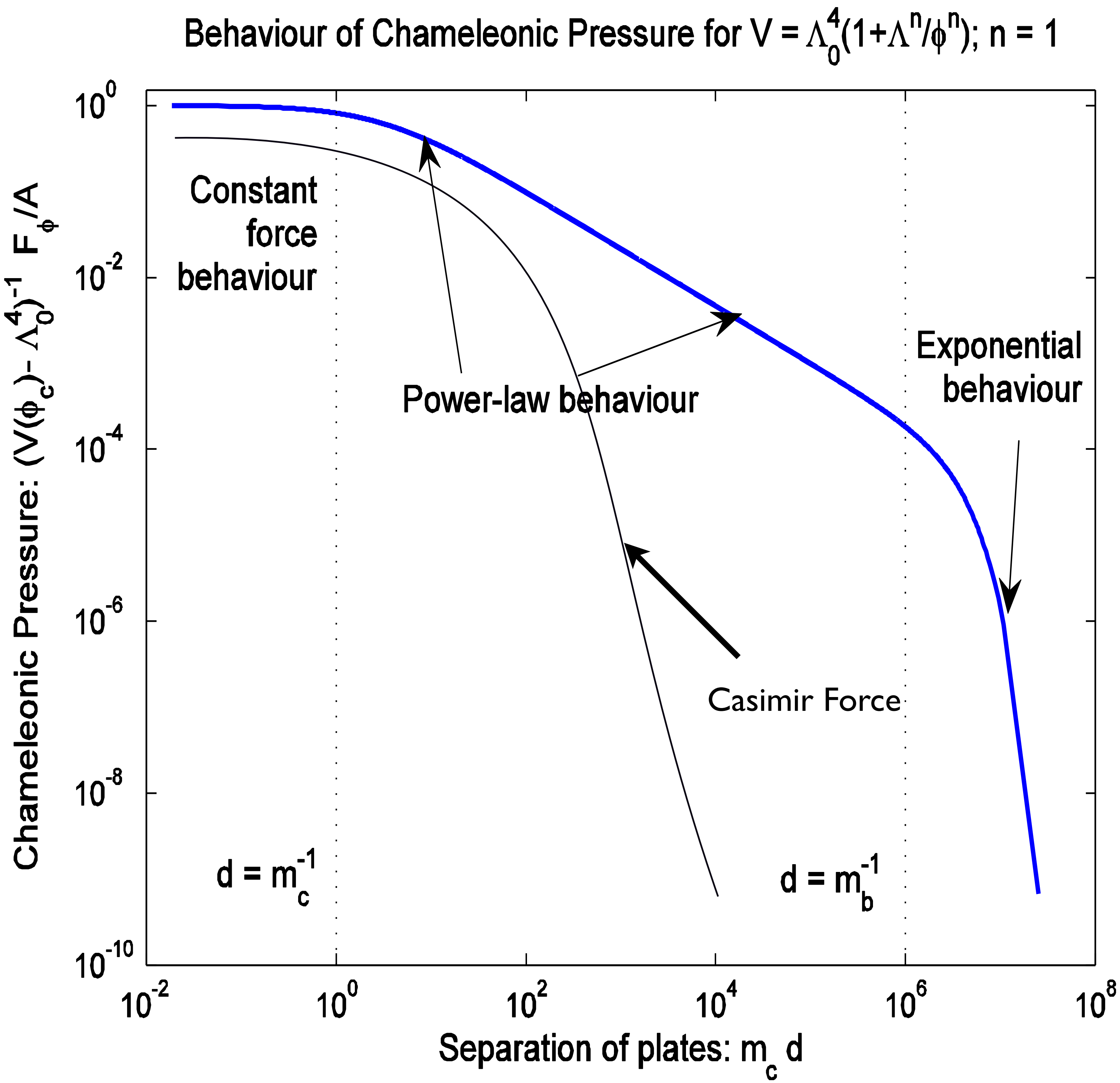


chameleonic force

$$\frac{F_\phi}{A} \sim \Lambda^4 (\Lambda d)^{-\frac{2n}{n+2}} \qquad \frac{F_\phi}{F_{\rm cas}} \sim \frac{240}{\pi^2} (\Lambda d)^{\frac{2(n+4)}{n+2}}$$

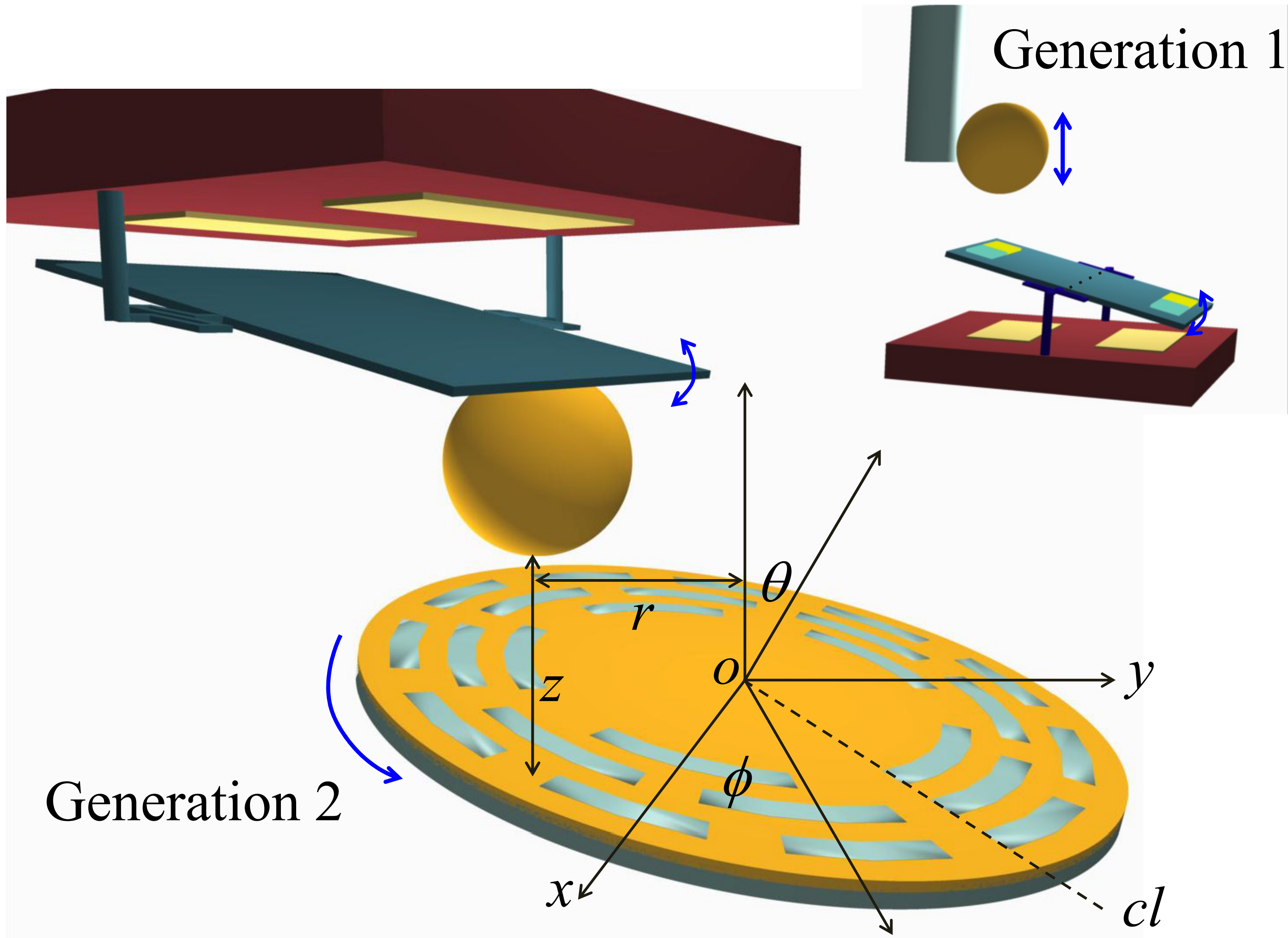
dark energy scale is

$$\Lambda^{-1} \sim 82 \mu m$$

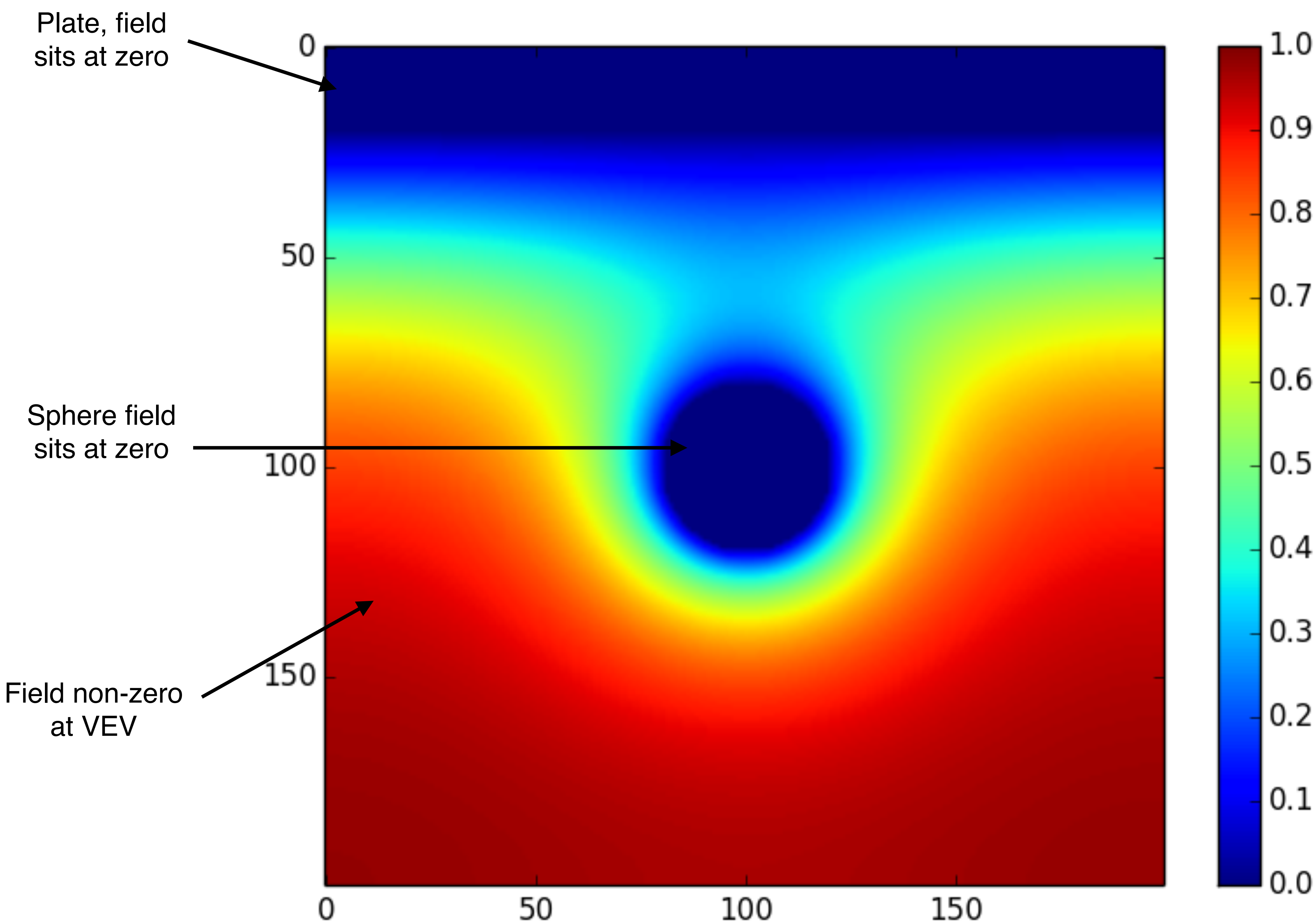


Behaviour of Chameleonic Pressure for $V = \Lambda_0^4(1+\Lambda^n/\phi^n)$; n = 1
Chameleonic Pressure: $(V(\phi_c) - \Lambda_0^4)^{-1}\ F_\phi/A$
Separation of plates: $m_c\, d$
Constant force behaviour
Power-law behaviour
Exponential behaviour
Casimir Force
$d = m_c^{-1}$
$d = m_b^{-1}$

Decca Experiment — 1410.7267; 1509.05349

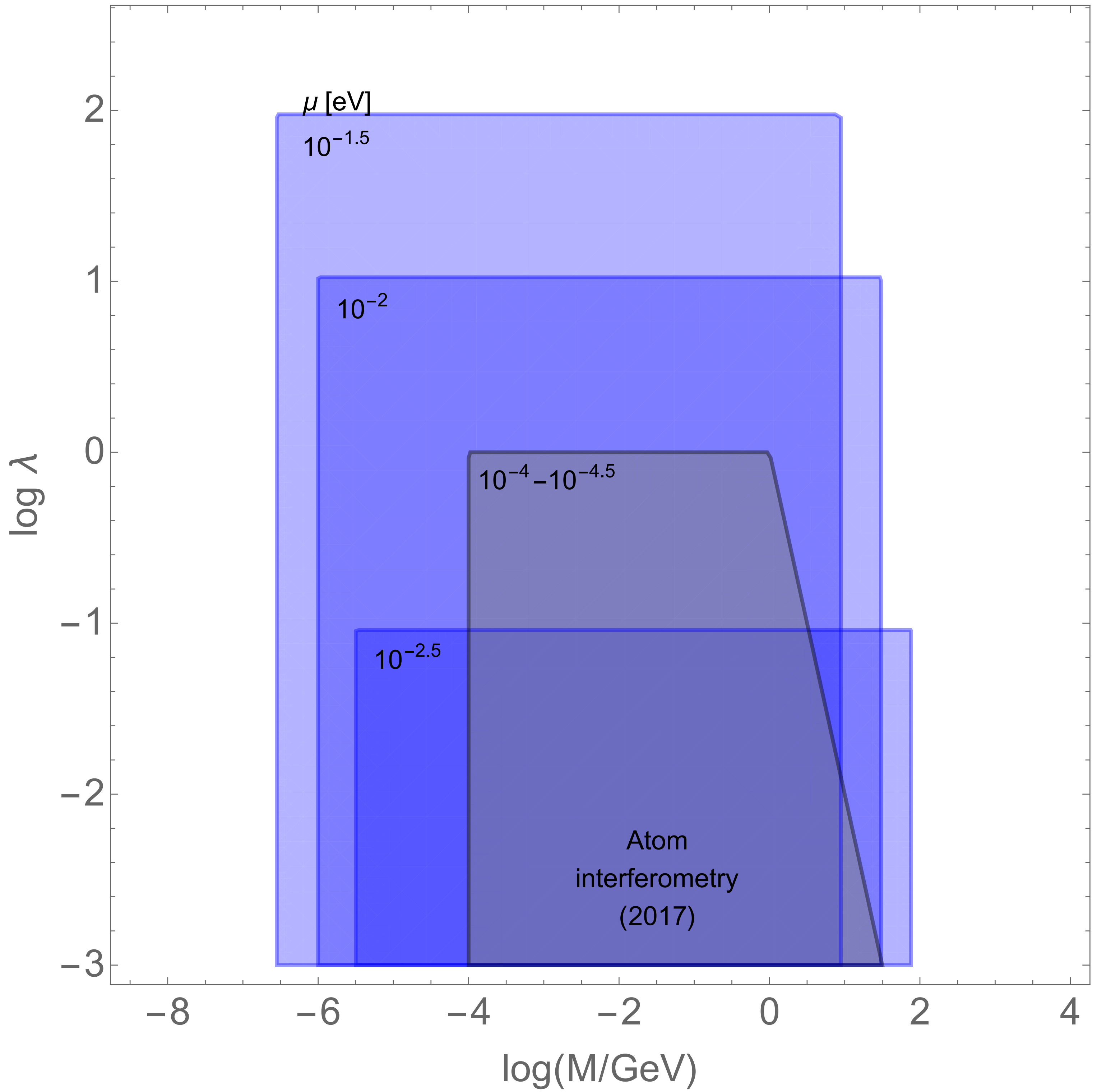


Akrami, Brax, Bsaibes, Davis, Decca, Elder & Vardanyan,
to appear



Symmetron Constraints

Akrami, Brax, Bsaibes, Davis, Decca, Elder & Vardanyan



Galileons Nicolis,RattazziTrincheri; 0811.2197

Galileon employs Vainshtein Screening ★ and highly non-linear Lagrangian, but equations of motion only have second order time derivatives

$$\mathcal{L} = -\frac{c_2}{2}(\partial\phi)^2 - \frac{c_3}{\Lambda^3}\Box\phi(\partial\phi)^2 - \frac{c_4}{\Lambda^6}\mathcal{L}_4 - \frac{c_5}{\Lambda^9}\mathcal{L}_5 + \sum_i \frac{c_0^i\phi}{m_{\rm Pl}}T_i - \sum_i \frac{c_G^i}{\Lambda^4}\partial_\mu\phi\partial_\nu\phi T_i^{\mu\nu} \ ,$$

where c_0 and c_G are the conformal and disformal couplings

we take $\Lambda^3 = H_0^2 m_{\rm Pl}$ to be of cosmological interest

and $c_2 > 0$ to avoid ghosts in Minkowski space

The coupling to the metric is $\tilde{g}^i_{\mu\nu} = A^i(\phi)g_{\mu\nu} + \frac{2}{M_i^4}\partial_\mu\phi\partial_\nu\phi \ .$ with $A^i(\phi) = 1 + \frac{c_0^i\phi}{m_{\rm Pl}}$

$$\mathcal{L}_4 = (\partial\phi)^2\left[2(\Box\phi)^2 - 2D_\mu D_\nu\phi D^\nu D^\mu\phi - R\frac{(\partial\phi)^2}{2}\right]$$

$$\mathcal{L}_5 = (\partial\phi)^2\left[(\Box\phi)^3 - 3(\Box\phi)D_\mu D_\nu\phi D^\nu D^\mu\phi + 2D_\mu D^\nu\phi D_\nu D^\rho\phi D_\rho D^\mu\phi \right.$$
$$\left. -6D_\mu\phi D^\mu D^\nu\phi D^\rho\phi G_{\nu\rho}\right]$$

these are the remaining terms and play a role cosmologially

Galileons

For cubic Galileon the Vainshtein radius is PLB39(1972)393

$$R_* = \frac{1}{\Lambda}\left(\frac{c_0^b m}{2\pi c_3 m_{\rm Pl}}\right)^{1/3}$$

choosing cosmological values gives the Vainshtein radius of the earth to be

$$R_* = 10^{14} km$$

The fifth force inside this radius is screened, so solar system screened and no effect in the Laboratory

Cosmological solutions require non-zero c4, which give the speed of gravitational waves to be different from that of photons

Brax, Burrage, ACD 1510.03701

$$c_{T0}^2 = \frac{1+\bar{c}_4}{1-3\bar{c}_4}$$

Old constraints from give

$c_T < c$ $$1 - \frac{c_T}{c} \leq 10^{-17}$$

$c_T > c$ $$\frac{c_T}{c} - 1 \leq 10^{-2}$$

New constraints strengthen the superluminal propogation, but not as strong as above for subluminal propagation. The LIGO/VIRGO detection of neutron star binary collision GW170817 and the electromagnetic counterpart now constrain

$$-3 \times 10^{-15} \leq \frac{c_T}{c_\gamma} - 1 \leq 7 \times 10^{-16}$$

Ghost-free Massive (Bi)gravity

$$S = -\frac{M_g^2}{2}\int d^4x\sqrt{-\det g}R(g) - \frac{M_f^2}{2}\int d^4x\sqrt{-\det f}R(f)$$
$$+ m^4\int d^4x\sqrt{-\det g}\sum_{n=0}^{4}\beta_n e_n\left(\sqrt{g^{-1}f}\right)$$

The action for the gravity sector.

$$\mathbb{X}^\mu{}_\alpha \mathbb{X}^\alpha{}_\nu \equiv g^{\mu\beta} f_{\beta\nu}$$
$$(\mathbb{X}^{-1})^\mu{}_\alpha (\mathbb{X}^{-1})^\alpha{}_\nu \equiv f^{\mu\beta} g_{\beta\nu}$$

Hassan and Rosen, JHEP 1202, 126 (2012)

Matter couplings

- Doubly-coupled scenario

$$\boxed{S_{\rm matter}[g^{\rm eff}_{\mu\nu}, \Psi]}$$ *

- Has interesting healthy solutions (see later).
- Strongly affected by the gravitational wave measurements.

*
$$\boxed{g^{\rm eff}_{\mu\nu} = \alpha^2 g_{\mu\nu} + 2\alpha\beta g_{\mu\gamma}(\sqrt{g^{-1}f})^{\gamma}{}_{\nu} + \beta^2 f_{\mu\nu}}$$

de Rham, Heisenberg, and Ribeiro, CQG 32, 035022 (2015), Brax,ACD&Noller;1606.05590

Cosmology

$$\gamma \equiv \frac{\beta}{\alpha}$$

Controls the relative importance of the two metrics.

- **Two metrics**

$$\mathrm{d}s_g^2 = -N_g^2\mathrm{d}t^2 + a_g^2\mathrm{d}x_i\mathrm{d}x^i$$
$$\mathrm{d}s_f^2 = -N_f^2\mathrm{d}t^2 + a_f^2\mathrm{d}x_i\mathrm{d}x^i$$

$$r \equiv \frac{a_f}{a_g}$$

- **The effective metric**

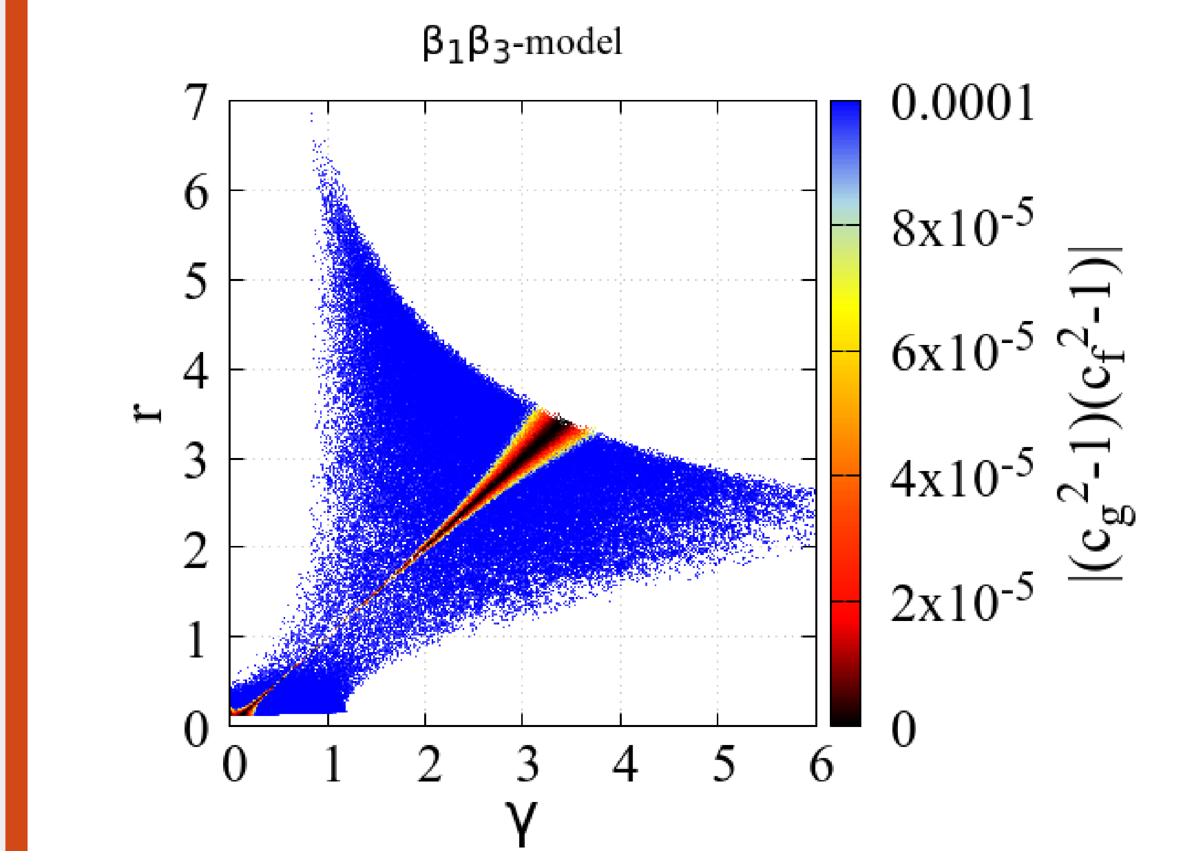
$$\mathrm{d}s_{\mathrm{eff}}^2 = -N^2\mathrm{d}t^2 + a^2\mathrm{d}x_i\mathrm{d}x^i$$

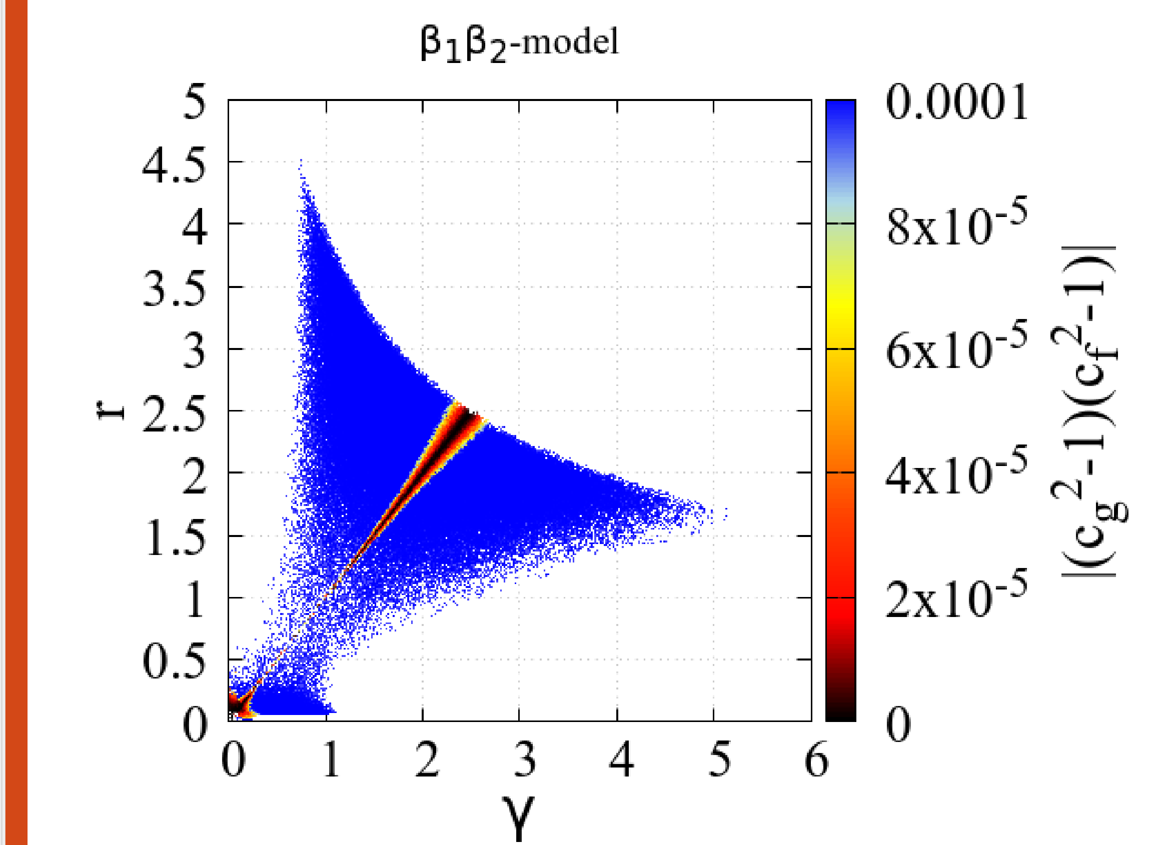
$$N \equiv \alpha N_g + \beta N_f\,,$$
$$a \equiv \alpha a_g + \beta a_f\,,$$

Brax,ACD&Noller;1703.08016

Proportional Metrics: two-parameter models

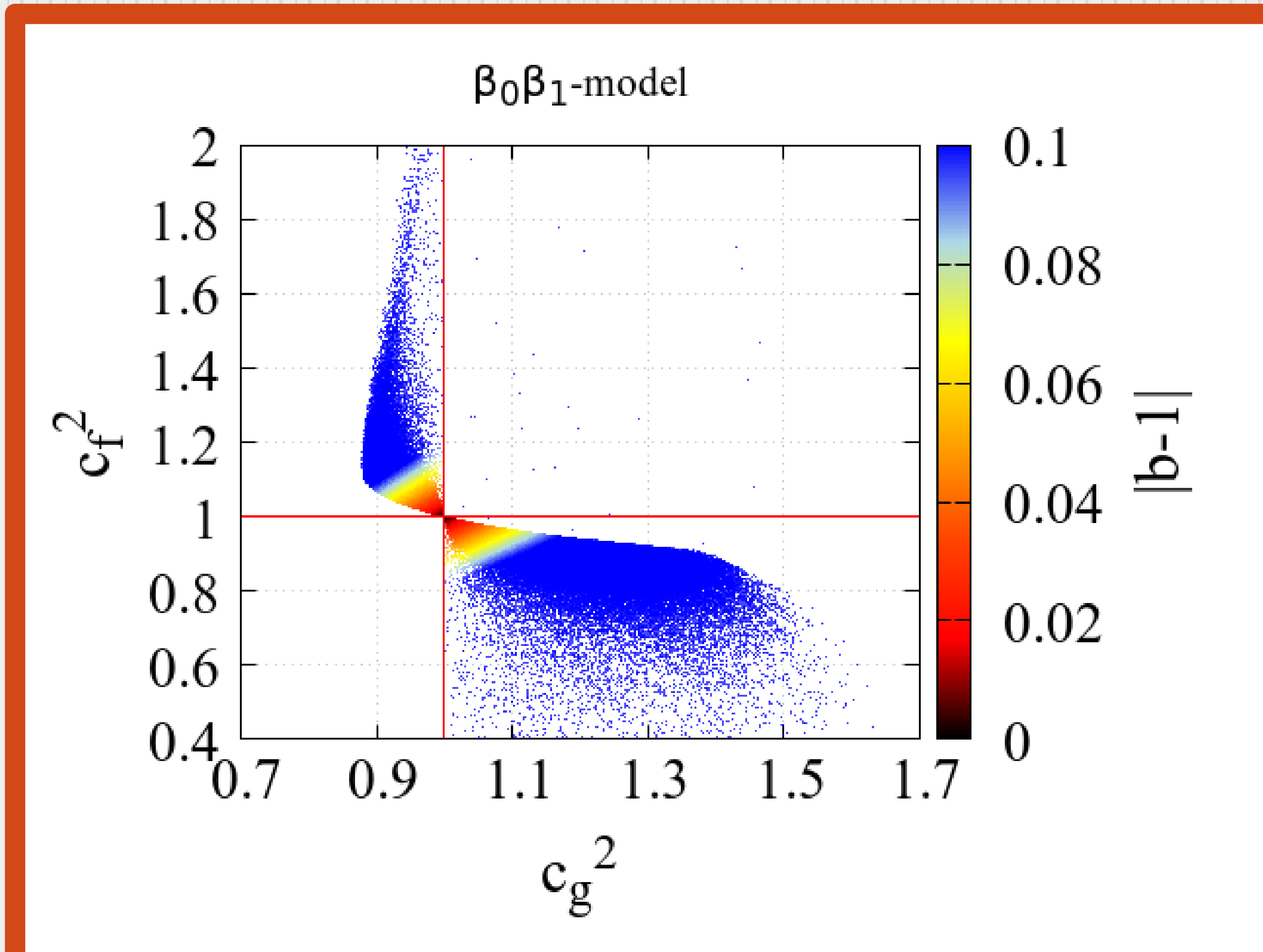
Akrami,Brax,ACD,Vardanyan;1803.09726





Note:

Both of the speeds become unity at the same point of the parameter space*



*Unless we are in the singly-coupled limit

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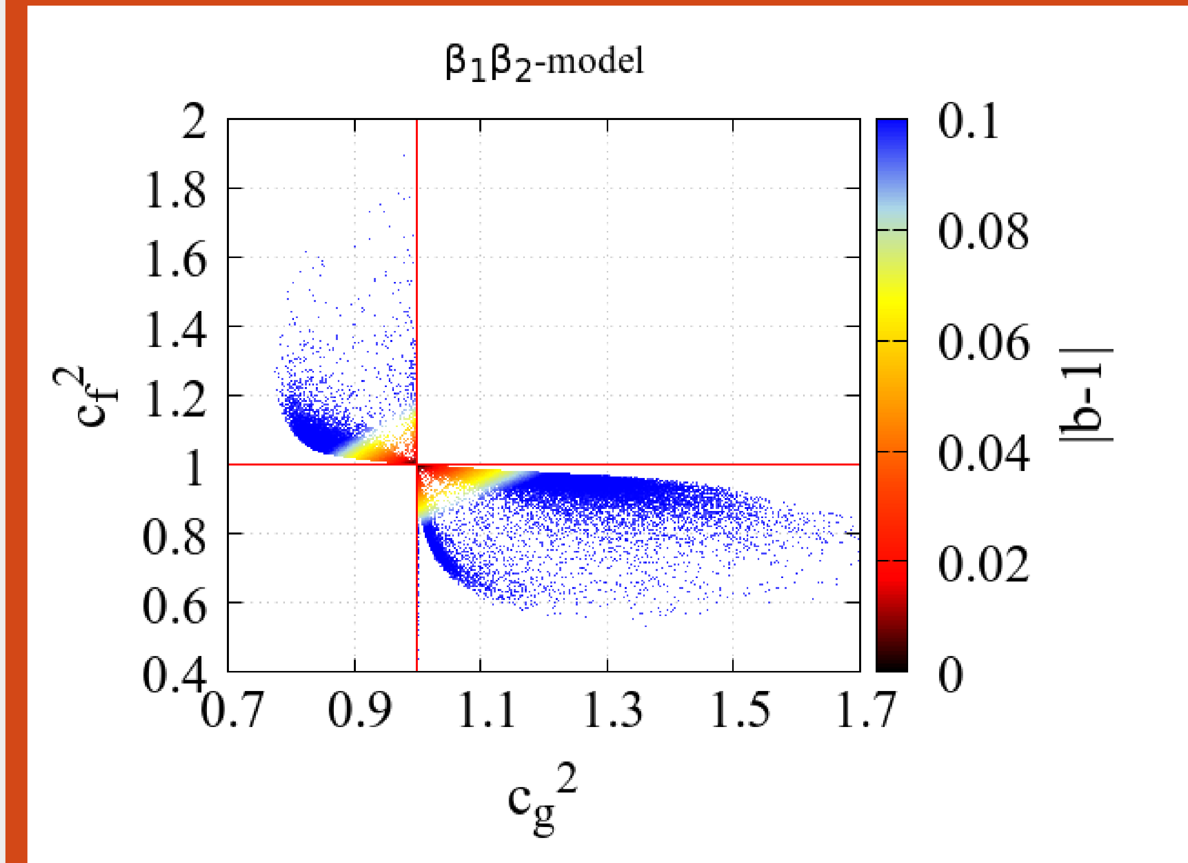

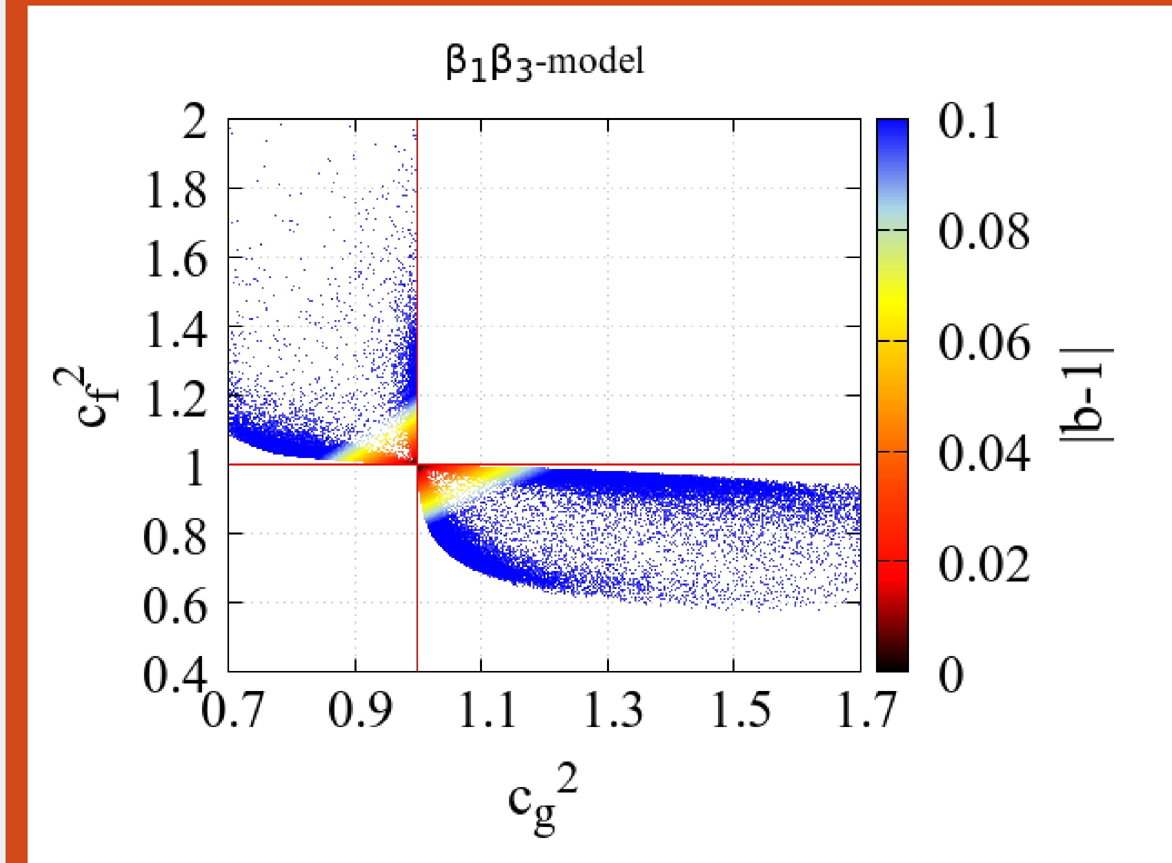

*Unless we are in the singly-coupled limit

UV Completion

de Rham and Melville; 1806.09417 pointed out that LIGO operated at 10-100Hz, which is 20 orders of magnitude higher than the EFTs for dark energy and any cut-off for Horndeski etc would be much lower than 100Hz.

They point out that any uv complete theory should be Lorentz invariant, in which case the phase velocity should be unity. In which case one might have c(k). Using examples of EFT they show how to reconcile LIGO with modified gravity models. Is this the way forward?

The need to understand uv completion is imperative, and very hard!

For c3 non-zero the spherically symmetric solution is

$$\frac{d\phi}{dr} = -\frac{\Lambda^3 r}{4}\left(1 - \sqrt{1 + \left(\frac{R_*}{r}\right)^3}\right) \ ,$$

Non-linearities dominate inside the Vainshtein radius to screen the fifth force

$$R_* = \frac{1}{\Lambda}\left(\frac{c_0^b m}{2\pi c_3 m_{\rm Pl}}\right)^{1/3} \qquad \frac{F_\phi}{F_N} = (c_0^b)^2\left(\frac{r}{R_*}\right)^{3/2}$$

Both conformal and disformal couplings to matter are severely constrained.

c_0 leads to large variations in particle masses when coupled to baryons

c_G coupled to baryons is constrained by LHC and to photons by variation of the speed of light

giving the duality relation $d_L = \left(\frac{c_{\rm obs}}{c_{\rm emit}}\right)^2 (1+z)^2 d_A$