Constraining the chameleon screening mechanism with MICROSCOPE

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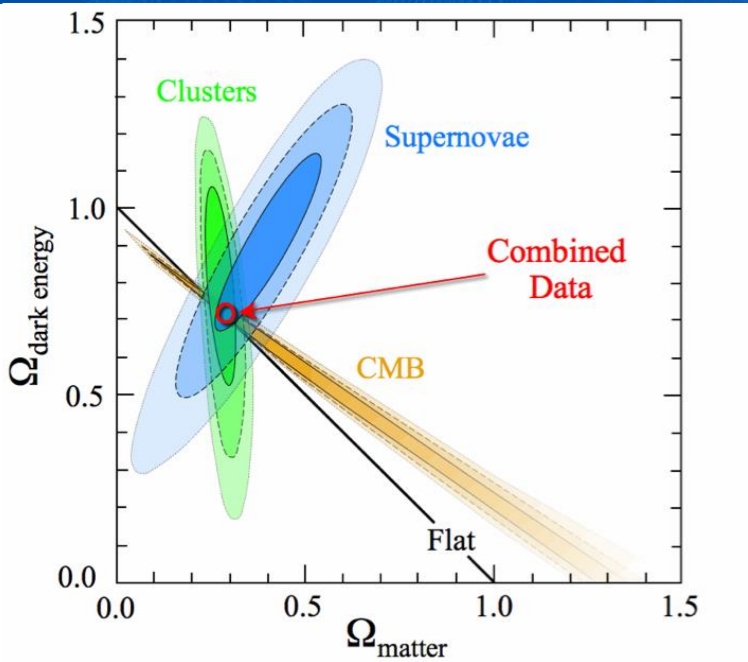
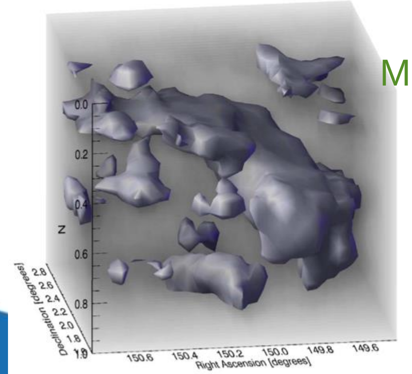
return on innovation

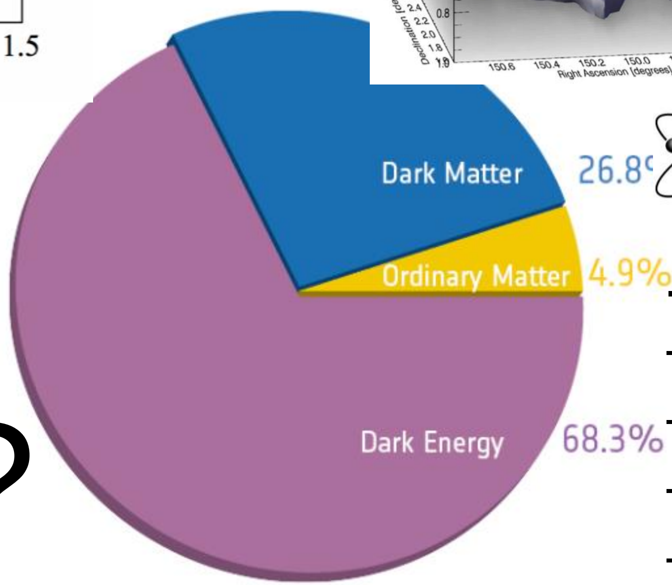
Fundamental physics at a crossroad

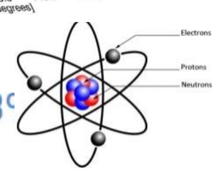


ΛCDM model: explains acceleration of the Universe's expansion. But, is it the end of the road?



Massey+ 2007





Dark sector...

?

...or new physics?

- Modified gravity
- String theory
- New interaction
- ...

Tests of GR in the Solar System

Parametrized-Post Newtonian formalism: 10 parameters to approximate Einstein's equations in the weak field limit

Allows one to easily test theories.

$$g_{00} = -1 + \frac{2Gm}{rc^2} - 2\beta^{\rm PPN}\left(\frac{2Gm}{rc^2}\right)^2 \qquad g_{ij} = \left(1 + 2\gamma^{\rm PPN}\frac{2Gm}{rc^2}\right)\delta_{ij}$$

Nonlinearity in superposition law for gravity

Curvature from a unit mass

Cassini probe tracking (time delay and deflection of light), Lunar Laser Range: γ-1 = 2.1+/-2.3x10^{-5}

Mercury perihelion's shift: $|\beta-1| < 3 \times 10^{-3}$

Deviations from GR pretty well constrained…

But difficult to use PPN formalism to reconcile constraints on cosmological scales and on Solar System scale (b/c of the absence of characteristic scales).

In particular for scalar-tensor theories…

Scalar-tensor theories

Idea: add an extra scalar degree of freedom to GR

$$\tilde{I} = (16\pi G)^{-1} \int \left[\tilde{R} - 2\tilde{g}^{\mu\nu}\partial_\mu\varphi\,\partial_\nu\varphi - V(\varphi)\right](-\tilde{g})^{1/2}\,d^4x + I_{\rm m}\left(\psi_{\rm m}, A^2(\varphi)\tilde{g}_{\mu\nu}\right)$$

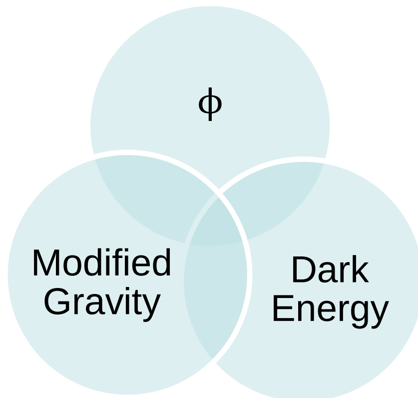
$$\phi \equiv A(\varphi)^{-2},$$
$$3 + 2\omega(\phi) \equiv \alpha(\varphi)^{-2},$$
$$\alpha(\varphi) \equiv \frac{d(\ln A(\varphi))}{d\varphi}.$$

PPN parameters $\omega \equiv \omega(\phi_0),\qquad \lambda \equiv \left[\frac{\phi\, d\omega/d\phi}{(3+2\omega)(4+2\omega)}\right]_{\phi_0},$

$\gamma = \frac{1+\omega}{2+\omega}$ => ω > 40000 (Bertotti+ 2003) => makes scalar-tensor theories difficult to reconcile with Solar System tests

But very well motivated for:

- Unification of GR and Quantum Physics
- Explain cosmic acceleration: dark energy

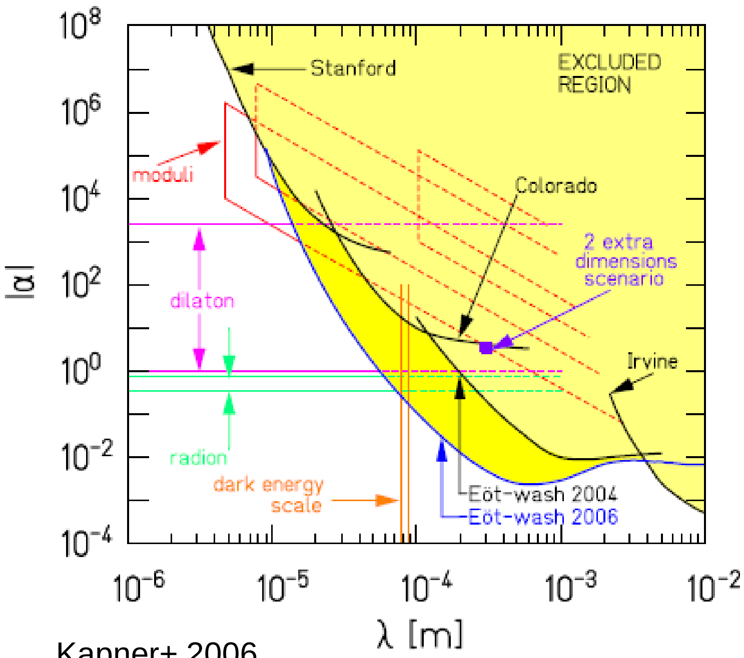


The problem with massless scalar fields

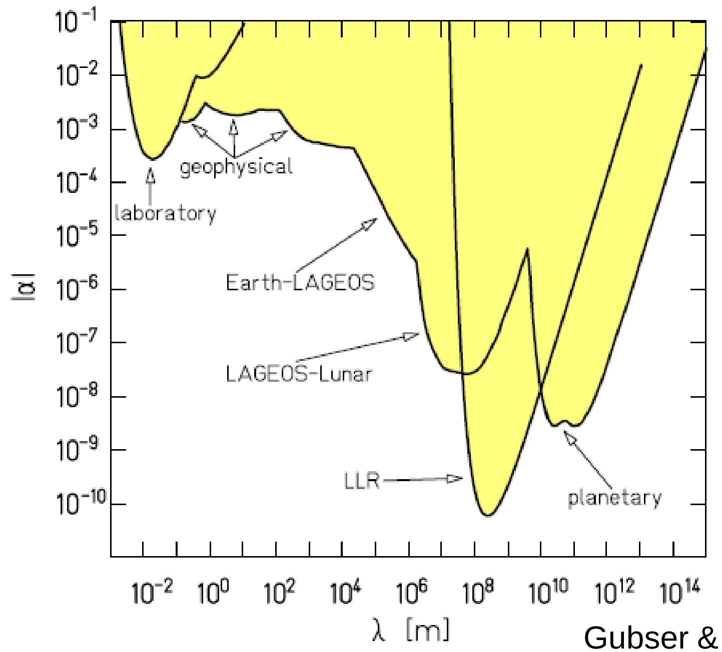
Massless scalar fields create a long range fifth force => should be easily seen in Solar System / Earth experiments of $1/r^2$ law and EP tests.

But we don't see them.

$$V(r) = -G\frac{m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$



Kapner+ 2006



Gubser & Khoury 2004

Don't they exist, or do they hide?

Screening

Under some conditions, a scalar field which couples to matter can become hidden to our measurements and evade the constraints

$\Rightarrow$ The field has no detectable signature in these conditions, but behaves differently in other conditions. E.g., long-range in low-density regions (cosmological scales) but small-range in high-density regions (Earth, Solar System).

Zoology of screening mechanisms:

- Mass depends on local density: *chameleon*
- Coupling with matter depends on local density: *Damour-Polyakov mechanism; symmetron*, *dilaton*
- Mass / coupling depends on local gravitational acceleration: *MOND*-type theories
- Coupling depends on local curvature: *Vainshtein* mechanism

The effect of the environment

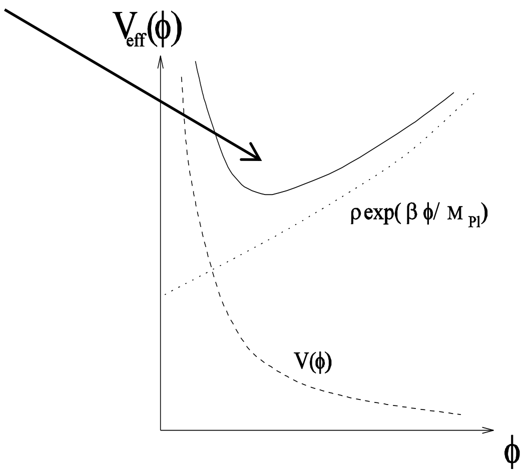
When coupled to matter, scalar fields have a matter dependent effective potential

$$V_{eff}(\phi) = V(\phi) + \rho_m (A(\phi) - 1)$$

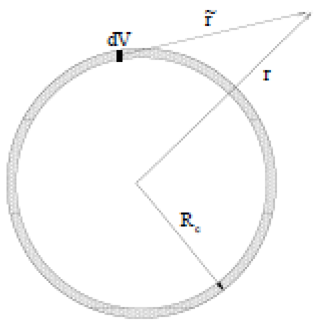
Chameleon

$$V(\varphi) = V_0 \left(\frac{M_{\rm Pl}}{\varphi}\right)^n \qquad A(\varphi) = e^{\beta_0 \varphi / M_{\rm Pl}}$$

Environment dependent minimum



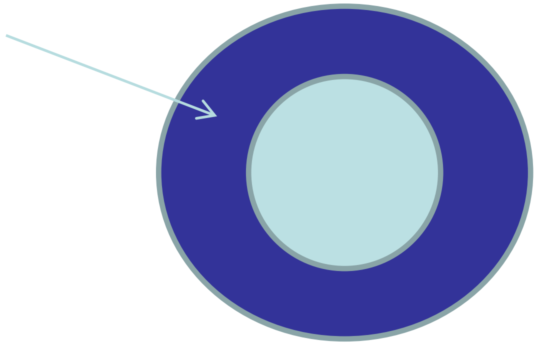
Chameleon=constant coupling



The field generated from deep inside is Yukawa suppressed. Only a thin shell radiates outside the body. Hence suppressed scalar contribution to the fifth force.

Chameleon, Symmetron, Dilaton

Brax+ 2012



For chameleons, when objects are big enough/dense enough, the field is screened outside. Inside it is nearly constant apart from inside thin shell whose size is inversely proportional to Newton's potential at the surface.

Chameleon $$V(\varphi) = V_0 \left(\frac{M_{\rm Pl}}{\varphi}\right)^n \qquad A(\varphi) = e^{\beta_0 \varphi / M_{\rm Pl}}$$

Symmetron $$V(\phi) = V_0 - \frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^2, \;\; A(\phi) = 1 + \frac{A_2}{2m_{\rm Pl}^2}\phi^2$$

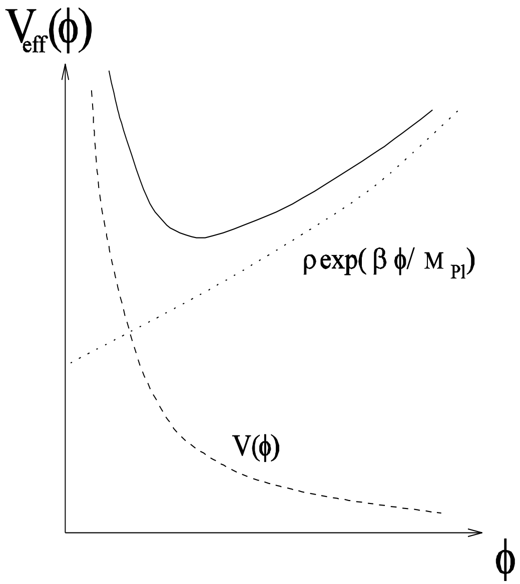
Dilaton $$V(\phi) = V_0 e^{-\phi/m_{\rm Pl}}, \quad A(\phi) = 1 + \frac{A_2}{2m_{\rm Pl}^2}(\phi - \phi_\star)^2$$

For all chameleon, dilaton, symmetron models where either the potential and/or the coupling is a non-linear function of ϕ, dense bodies are screened when their gravitational charge is small.

Unified description of screening mechanisms

Brax+ 2012

The family of screened modified gravity models (excluding Vainshtein) can be much more easily analysed using a reconstruction procedure.



The existence of a minimum for a medium of density ρ allows one to define a mapping between ρ and the value of the field and the value of the potential at the minimum. This implicit way of defining V(φ) is very useful as ρ itself can be parameterised by the expansion rate of the Universe

This implicit definition of the models depends only on the mass m(a) and the coupling β(a) at the minimum.

Unified description of screening mechanisms

The non-linear potential of the model and the values of the field can be evaluated using:

$$\phi(a) = \phi_i + \frac{3}{m_{\rm Pl}} \int_{a_i}^{a} da \frac{\beta(a)\rho(a)}{am^2(a)}$$
$$V(a) = V_i - \frac{3}{m_{\rm Pl}} \int_{a_i}^{a} da \frac{\beta^2(a)\rho^2(a)}{am^2(a)}$$

The full non-linear dynamics is reconstructed parametrically using the mass and the coupling function as a function of redshift! It works explicitly for chameleons, f(R), dilatons, symmetrons and one can invent new models!

As the Universe evolves from pre-BBN to now, the density of matter goes from the density of ordinary matter (10g/cm3) to cosmological densities. The minimum of the effective potential experiences all the possible minima from sparse densities (now) to high density (pre-BBN).

Large-scale effects

The loosest screening conditions require that the Milky way is marginally screened, this corresponds to the absence of disruption of the galactic halo dynamics:

$$\frac{9\Omega_{m0}H_0^2}{m_0^2}\left(\int_{a_G}^{1}\frac{da}{a^4}\frac{\beta(a)}{\beta_0}\frac{m_0^2}{m^2(a)}\right) \leq 2\Phi_G$$

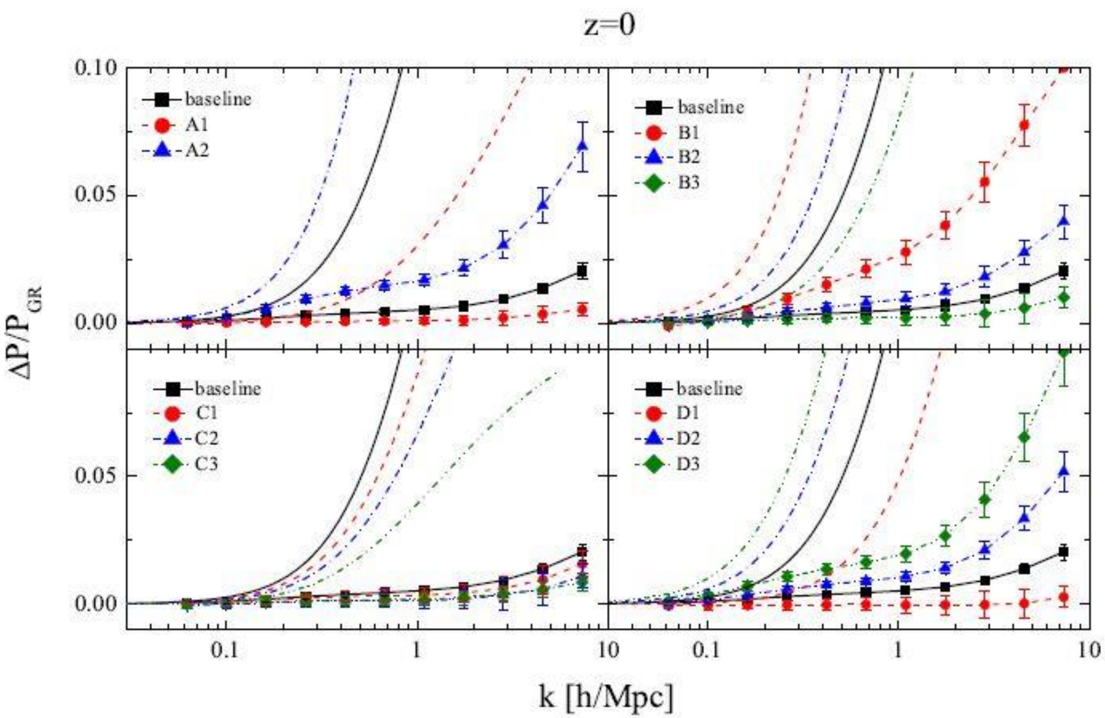
This implies the crucial bound:

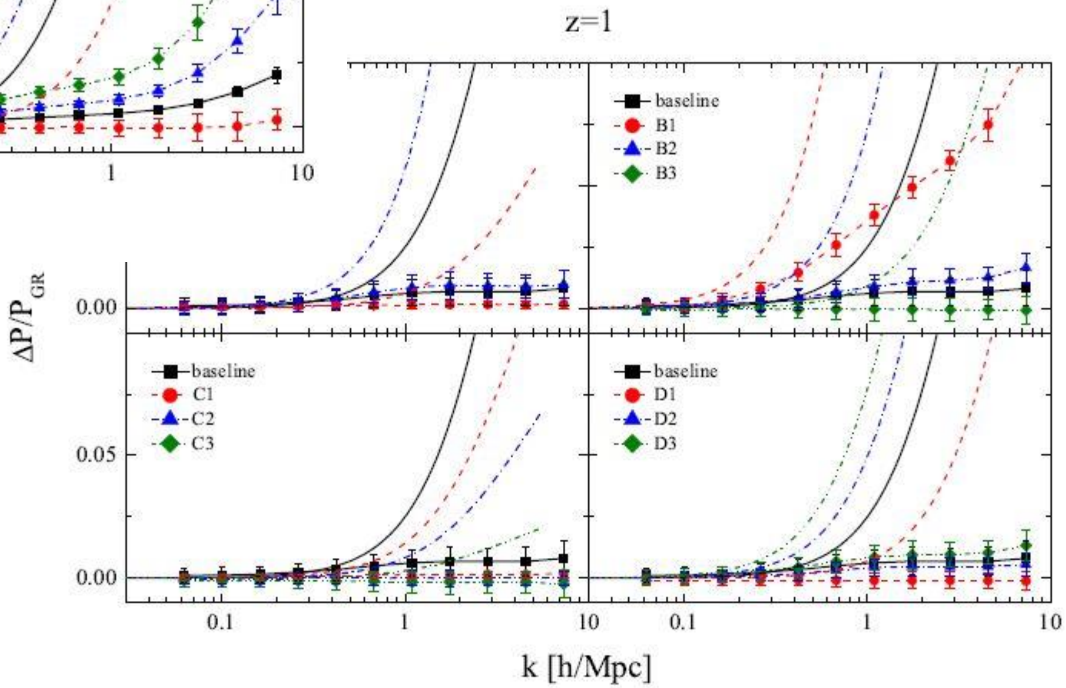
$$\frac{m_0}{H_0} \geq 10^3$$

Effects of modified gravity can appear at most on the Mpc scale.

Cosmological effects: power spectrum

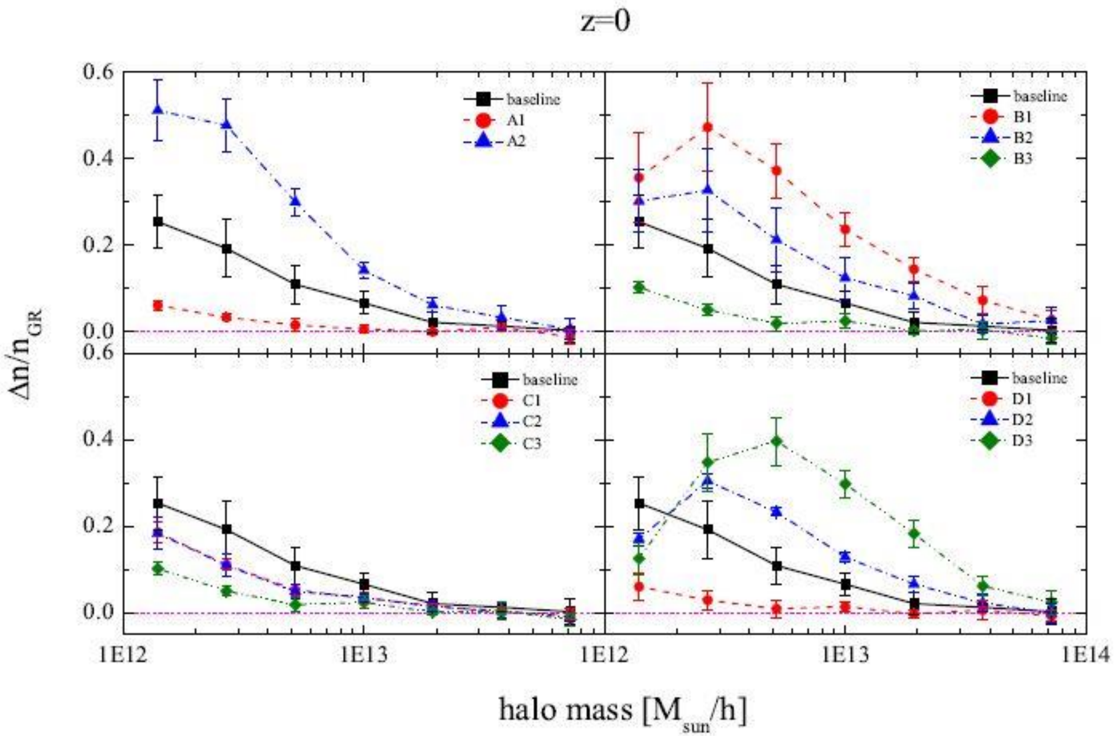
Brax+ 2013

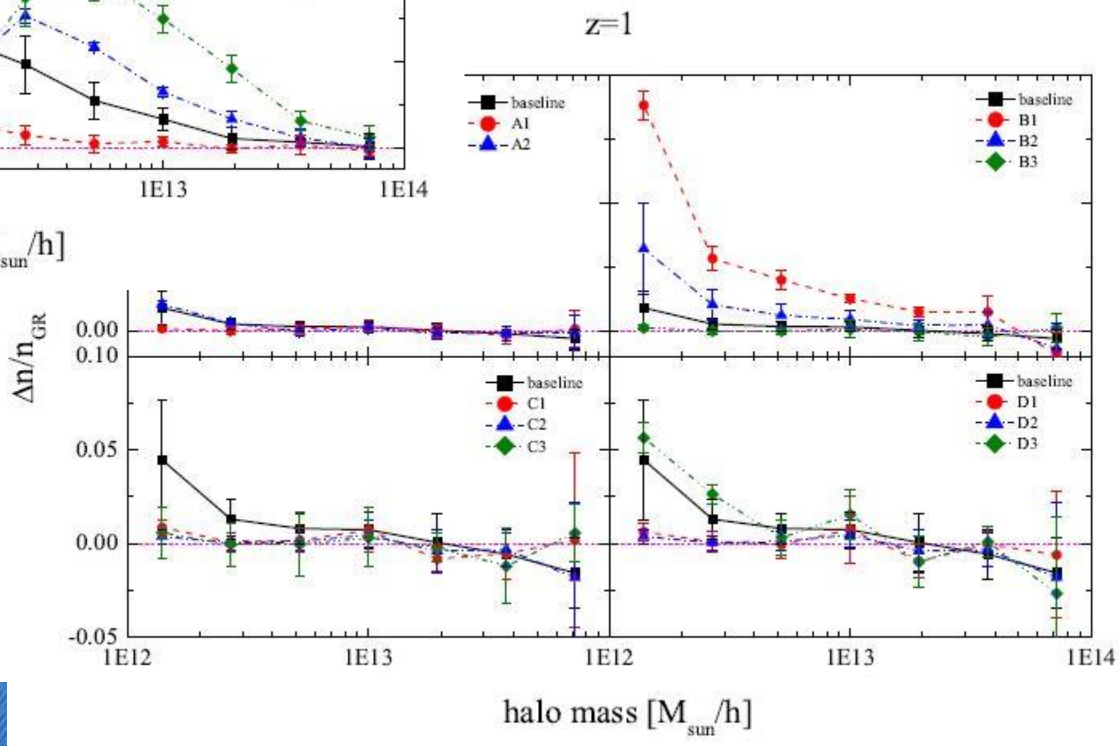




Cosmological effects: mass function

Brax+ 2013





Test screening mechanisms with MICROSCOPE

Given this unified description, we can test several models out of those that are allowed by cosmological constraints.

In particular, it is expected that chameleon models may be detected by experimental tests of gravitation in space.

=> By MICROSCOPE

Reminder from previous slides -- Chameleon in a nutshell

Khoury & Weltman 2004

- Scalar field coupled to matter (with possibly different couplings between different matter species => can violate Equivalence Principle)
- Runaway potential, monotonic, decreasing
- Mass depends on local density
- Additional screening through thin-shell screening

Abundant literature:

Original KW04 papers cited 700+ times

- Fifth force searches on Earth (Eöt-Wash)
- Solar System tests (Hees+ 2012)
- Cosmology (Brax+)

Chameleon: more details (Khoury & Weltman 2004)

Action: $S=\int d^4x\sqrt{-g}\left\{\frac{M_{Pl}^2}{2}\mathcal{R}-\frac{1}{2}(\partial\phi)^2-V(\phi)\right\}-\int d^4x\,\mathcal{L}_m(\psi_m^{(i)},g_{\mu\nu}^{(i)})$ $\psi_m^{(i)}$: matter fields

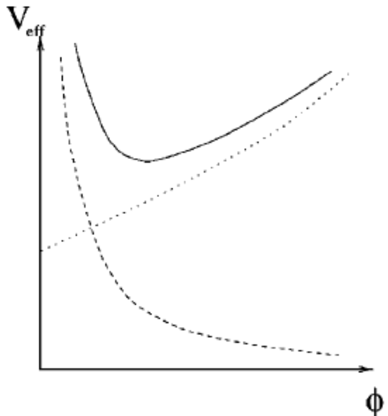
Potential *V(ϕ)* of the runaway form. E.g Ratra-Peebles $V(\phi)=M^{4+n}\phi^{-n}$.

Coupling to matter fields of the form $e^{\beta_i\phi/M_{Pl}}$ β_i: dimensionless constants ~1

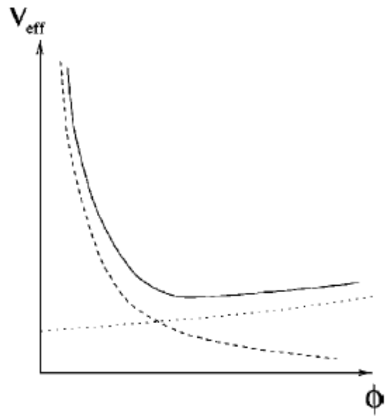
Equation of motion $\nabla^2\phi=V_{,\phi}+\sum_i\frac{\beta_i}{M_{Pl}}\rho_i e^{\beta_i\phi/M_{Pl}}$

=> dynamics of ϕ are governed by the effective potential:

$$V_{eff}(\phi)\equiv V(\phi)+\sum_i\rho_i e^{\beta_i\phi/M_{Pl}}$$



Large ρ



Small ρ

Mass of the field: $m_{min}^2=V_{,\phi\phi}(\phi_{min})+\sum_i\frac{\beta_i^2}{M_{Pl}^2}\rho_i e^{\beta_i\phi_{min}/M_{Pl}}$

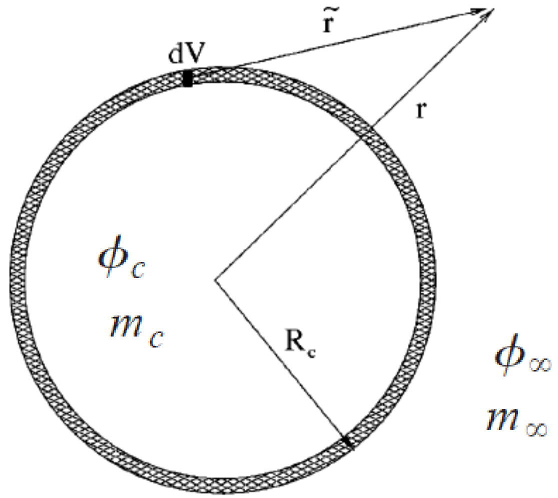
$$V_{,\phi}(\phi_{min})+\sum_i\frac{\beta_i}{M_{Pl}}\rho_i e^{\beta_i\phi_{min}/M_{Pl}}=0$$

<u>ϕ_{min} and m_{min} depend on local density</u>: larger ρ correspond to smaller ϕ_{min} and larger mass => field can be massive enough on Earth to evade constraints but light enough in space to affect the gravitational dynamics (with no fine-tuning of β!).

Chameleon: profile and thin-shell screening

<u>Goal</u>: derive chameleon profile for a spherical compact object of mass M_c, radius R_c and density profile $\rho(r)$:

$$\rho(r)=\begin{cases}\rho_c & \text{for } r<R_c\\ \rho_\infty & \text{for } r>R_c\end{cases}$$



Equation of motion: $$\frac{d^2\phi}{dr^2}+\frac{2}{r}\frac{d\phi}{dr}=V_{,\phi}+\frac{\beta}{M_{Pl}}\rho(r)e^{\beta\phi/M_{Pl}}$$

with initial conditions $\frac{d\phi}{dr}=0 \quad \text{at } r=0$, $\phi\to\phi_\infty \quad \text{as } r\to\infty$

Inside the object, $m_c >> m_\infty$, $\phi \sim \phi_c$, a volume element *dV* contributes exp($-m_c r$) => exponentially suppressed. Only the volume elements close enough (ΔR_c) from the surface contribute to the exterior profile.

$$\phi(r)\approx-\left(\frac{\beta}{4\pi M_{Pl}}\right)\left(\frac{3\Delta R_c}{R_c}\right)\frac{M_c e^{-m_\infty r}}{r}+\phi_\infty \qquad \frac{\Delta R_c}{R_c}=\frac{\phi_\infty-\phi_c}{6\beta M_{Pl}\Phi_c}$$

assuming thin-shell condition $\frac{\Delta R_c}{R_c}\leqslant 1$

Thin-shell suppression factor

For small objects, $\frac{\Delta R_c}{R_c}>1$ and $$\phi(r)\approx-\left(\frac{\beta}{4\pi M_{Pl}}\right)\frac{M_c e^{-m_\infty r}}{r}+\phi_\infty$$

No thin-shell screening

Chameleon: fifth force, EP test and constraints

Chameleon force on a test particle of mass *M*: $\vec{F}_\phi = -\frac{\beta}{M_{Pl}} M \vec{\nabla}\phi$

Profile on Earth + atmosphere (thin-shelled) and beyond:

$$\phi(r) \approx \begin{cases} \phi_\oplus & \text{for} \quad 0 < r \lesssim R_\oplus, \\ \phi_{atm} & \text{for} \quad R_\oplus \lesssim r \lesssim R_{atm}, \\ -\left(\frac{\beta}{4\pi M_{Pl}}\right)\left(\frac{3\Delta R_\oplus}{R_\oplus}\right)\frac{M_\oplus e^{-m_G(r-R_{atm})}}{r} + \phi_G & \text{for} \quad r \gtrsim R_{atm}, \end{cases}$$

$$\frac{\Delta R_\oplus}{R_\oplus} \equiv \frac{\phi_G - \phi_{atm}}{6\beta M_{Pl}\Phi_\oplus} < 10^{-7}$$

=> Fifth force on a test particle of mass *M* and coupling β_i:

$$|\vec{F}_\phi| = 2\beta\beta_i\left(\frac{3\Delta R_\oplus}{R_\oplus}\right)\frac{M_\oplus M}{8\pi M_{Pl}^2 r^2}$$

Magnitude of EP violation: $\eta \equiv 2\frac{|a_1 - a_2|}{a_1 + a_2} \sim 10^{-4}\beta^2\frac{\Delta R_\oplus}{R_\oplus}$

Constraints on the chameleon-mediated interaction's range for a Ratra-Peebles potential

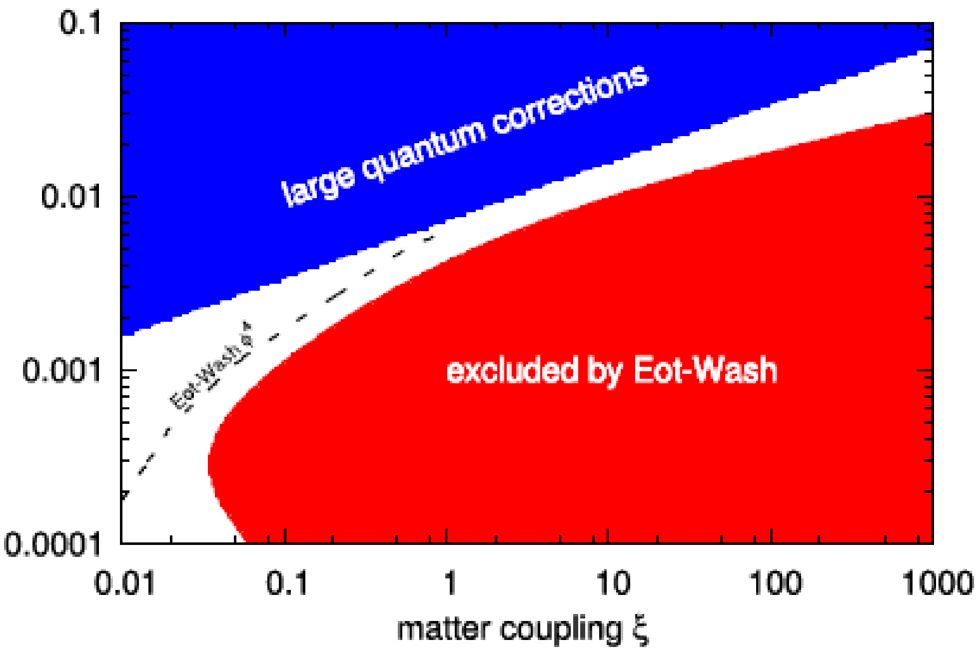
$$V(\phi) = M^{4+n}\phi^{-n},$$

Atmosphere	$m_{atm}^{-1} \lesssim 1 \quad \text{mm} - 1 \quad \text{cm},$
Solar System	$m_G^{-1} \lesssim 10 - 10^4 \quad \text{AU},$
Cosmological scales	$m_0^{-1} \lesssim 0.1 - 10^3 \quad \text{pc},$

Behavior significantly different in space!

Allowed mass and coupling values

Chameleon theories are effective field theories => quantum corrections should remain small compared to the classical potential => cannot have too large a mass



Upadhye+ 2012

$$S = \int d^4x\sqrt{g}\left[\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{\xi}{4!}\phi^4\right] - \sum_\alpha \int_{\gamma_\alpha} ds\, m_{i_\alpha}(\phi)$$

Model-independent constraints from $1/r^2$ law experiments

Chameleon fields already very much constrained: a small improvement in experiments could rule out all chameleon models

Expectation for chameleon detection with MICROSCOPE

Order of magnitude estimate, based on Khoury & Weltman 2004

MICROSCOPE can see a chameleon-induced WEP violation if it is not thin-shelled, i.e. if $\Delta R_{MIC}/R_{MIC} > 1$

Chameleon (the Earth is thin-shelled):

$$\phi(r) \approx \begin{cases} \phi_\oplus & \text{for} \quad 0 < r \lesssim R_\oplus , \\ \phi_{atm} & \text{for} \quad R_\oplus \lesssim r \lesssim R_{atm} , \\ -\left(\frac{\beta}{4\pi M_{Pl}}\right)\left(\frac{3\Delta R_\oplus}{R_\oplus}\right)\frac{M_\oplus e^{-m_G(r-R_{atm})}}{r} + \phi_G & \text{for} \quad r \gtrsim R_{atm} , \end{cases}$$

$$\frac{\Delta R_\oplus}{R_\oplus} = \frac{\phi_G - \phi_{atm}}{6\beta M_{Pl}\Phi_\oplus} < 10^{-7}$$

At r=700km, $\phi(r) \sim \phi_G$

MICROSCOPE's Newtonian potential ~ $10^{-15}\Phi_\oplus$

$\Delta R_{MIC}/R_{MIC} > 1$ if $\frac{\Delta R_\oplus}{R_\oplus} > 10^{-15}$

=> MICROSCOPE has no thin shell if $10^{-15} < \frac{\Delta R_\oplus}{R_\oplus} < 10^{-7}$

=> EP violation $\eta \approx 10^{-4}\beta^2 \frac{\Delta R_\oplus}{R_\oplus}$

$$\beta^2 \times 10^{-19} < \eta < \beta^2 \times 10^{-11}$$

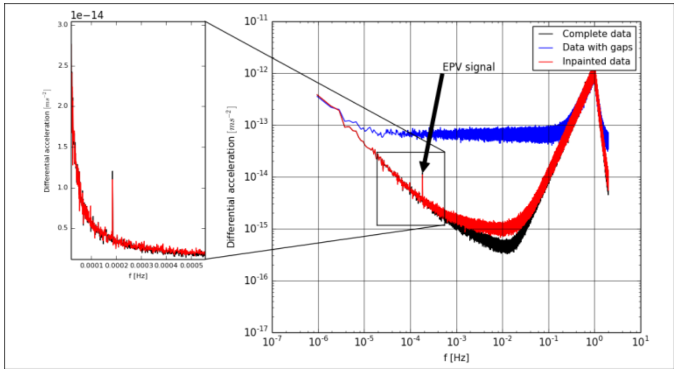
Roadmap

We need MICROSCOPE-specific predictions…

- Derive trustworthy field equations in the satellite (within the Earth-Moon system) and precise expected physical effect on EP test.
- Link to full instrument (electronics and mechanics) simulator => importance of geometry
- Bricks already exist:
  - Physics simulation (OCA –G. Metris, L. Serron-- CMSM)
  - Simulink model of the instrument (performance group)

… and robust data analysis methods…

- Precise and robust data analysis: e.g. work within SPG (inpainting to correct for missing data: Q. Baghi's talk tomorrow)



… and instrument's house-keeping data

- To make sure we understand the data correctly: e.g. work from and within CMSM

The team

- Core members
  - Jean-Philippe Uzan: IAP, theoretical physicist
  - Joel Bergé: ONERA, member of CMSM and SPG groups, data analysis, phenomenology
  - Philippe Brax: IPhT/CEA, theoretical physicist
  - Sandrine Pires: SAp/CEA, data analysis expert
- A PhD student starting fall 2016?

- Performance group
- CMSM

Conclusion

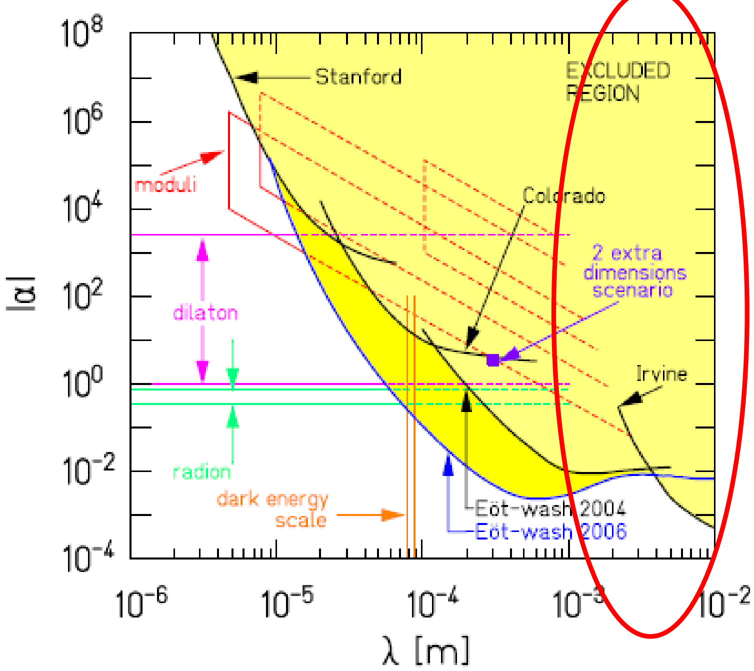
- We have good reasons to add new scalar fields in physics
- To account for current tests of gravity, those scalar fields must either be very fine-tuned or remain hidden
- Several screening mechanisms have been proposed, that allow us to still add scalar fields
- Unified description allows for various models and simulations => effect on structure formation
- EP violations are expected
- Significant EP violation (bigger than on Earth) could be seen with MICROSCOPE if a chameleon field exists.
- Otherwise, possibility to rule out all chameleons models.
- MICROSCOPE can be a unique experiment in the near future to make progress on constraining screening mechanisms.

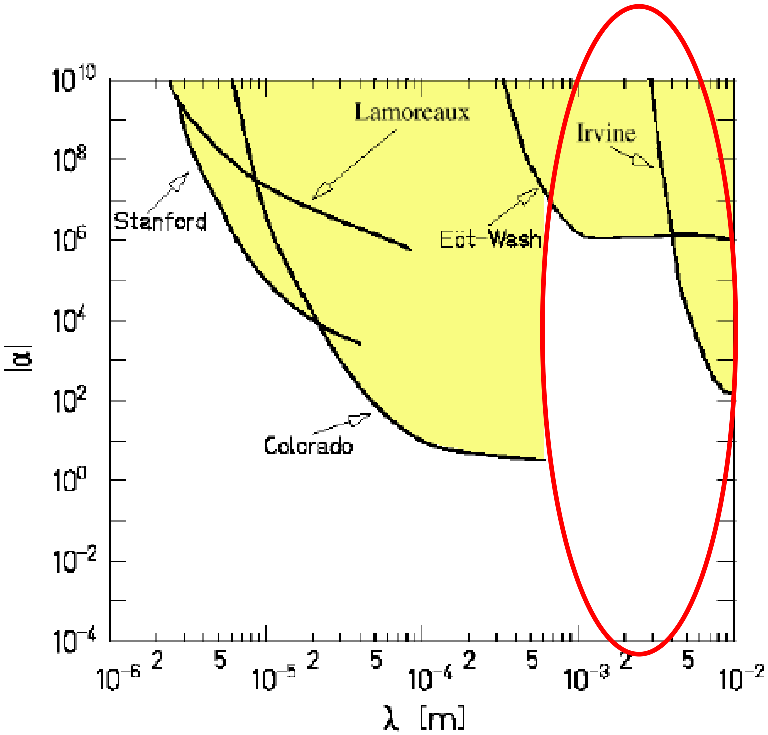
Looser constraints on fifth force

Gubser & Khoury 2004

$$S = \int d^4x\sqrt{g}\left[\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{\xi}{4!}\phi^4\right] - \sum_\alpha \int_{\gamma_\alpha} ds\, m_{i_\alpha}(\phi)$$

Thin-shelled





$$V(r) = -G\,\frac{m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$