Constraining screening mechanisms with MICROSCOPE

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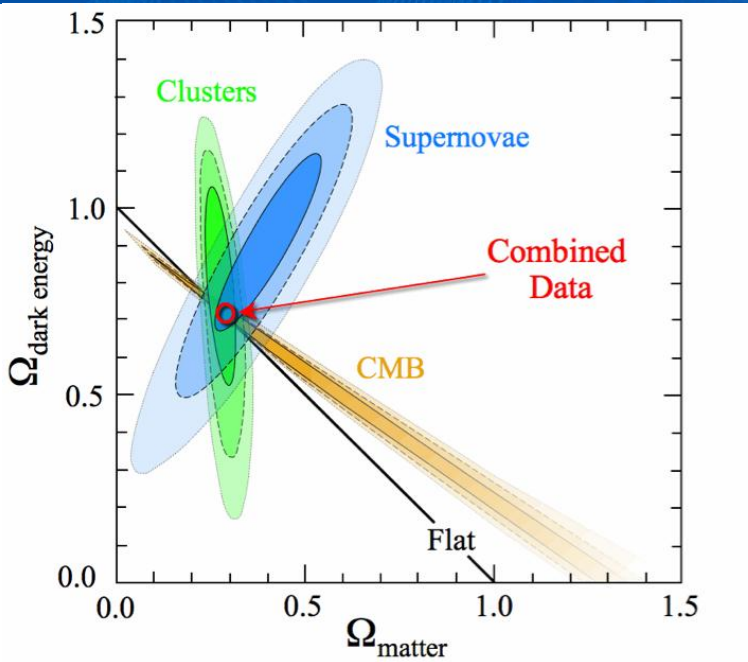
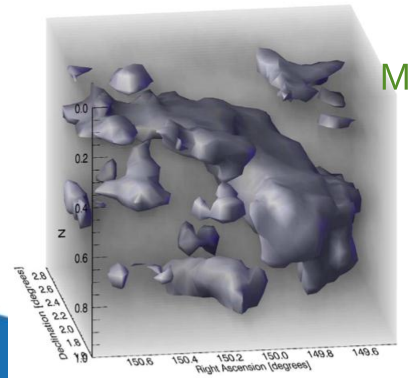
return on innovation

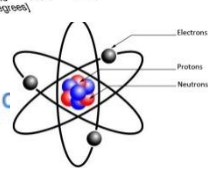
Do we need new physics?



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

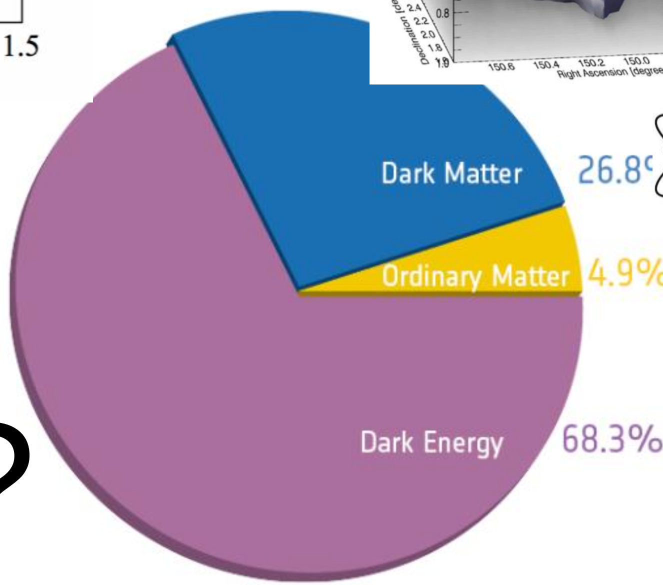


Massey+ 2007



Dark sector...

?



...or new physics?

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

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New physics

- Modified gravity
  - Scalar-vector-tensor theories
  - Modified action theories (generalizes GR's action), eg f(R)
  - ...

$$S_{\mathrm{GR}} = \int \sqrt{-g}\, R\, \mathrm{d}^4 x$$

- Loop quantum gravity
- String theory
- Extra scalar field associated to a long range fifth force, coupled to matter (CDM and matter) -- chameleon, dilaton...
- ...

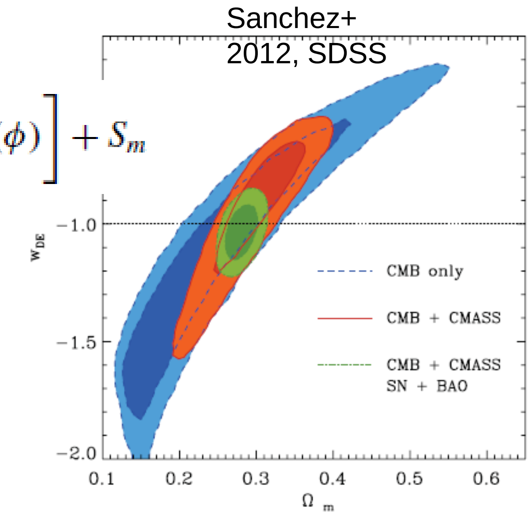
Predict Equivalence Principle violation e.g. due to coupling's dependence on matter species => finding such a violation will be a smoking gun for new physics beyond GR.

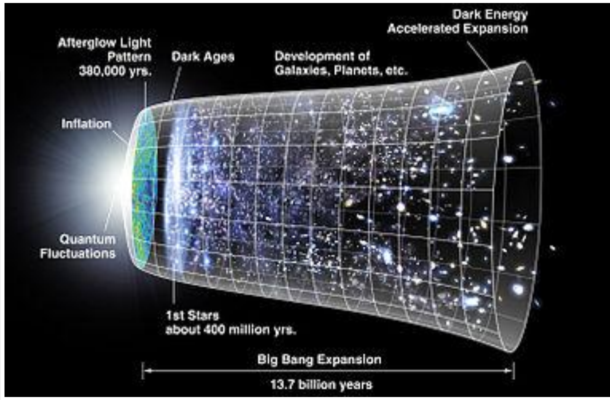
Motivations for new scalar fields

- Dark Energy, quintessence

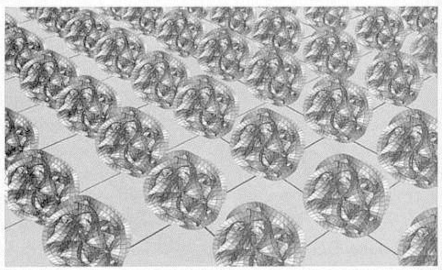
$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{1}{2}M_{\rm pl}^2 R - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right] + S_m$$

$$w \equiv \frac{P_\phi}{\rho_\phi} = \frac{\dot\phi^2/2 - V(\phi)}{\dot\phi^2/2 + V(\phi)}$$





- String theory: compactification into our low-energy, 4D space results in several massless scalar fields



According to string theory, the universe has extra dimensions curled up into a Calabi-Yau shape.

- Variation of constants

Some claims of variation of the fine structure in time of some parts in 10^{15} (Uzan 2012)

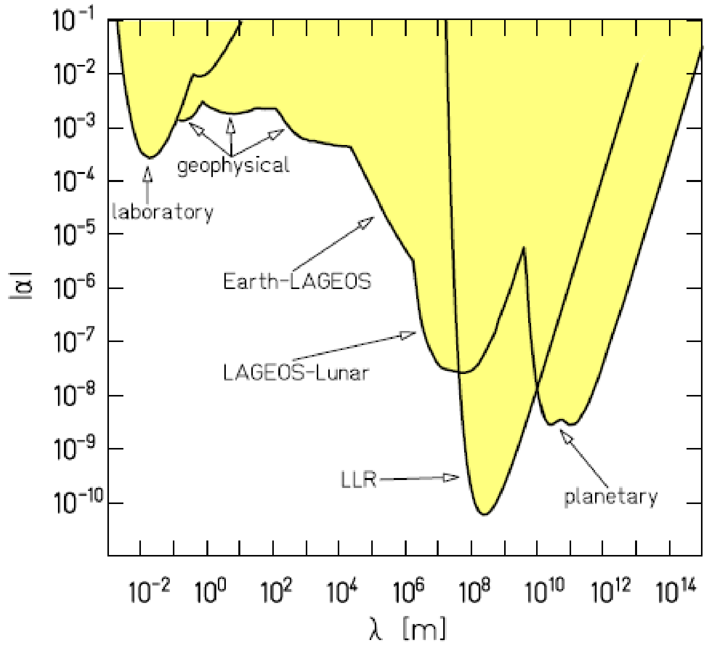
-> modeled as a coupling between matter and a scalar field

The problem with massless scalar fields

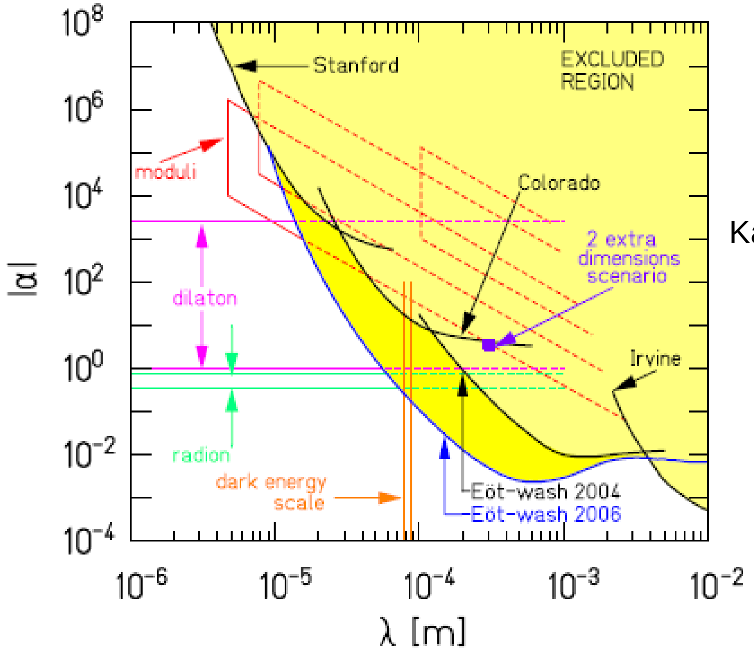
Long range => should be easily seen in Solar System / Earth experiments of $1/r^2$ law and EP tests.

But we don't see them.

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



Gubser & Khoury 2004



Kapner+ 2006

Don't they exist, or do they just hide themselves?

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: *symmetron*, *Galileon*, *dilaton*
- Mass / coupling depends on local gravitational acceleration: *MOND*-type theories
- Coupling depends on local curvature: *Vainshtein* mechanism

Chameleon in short (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:

- 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

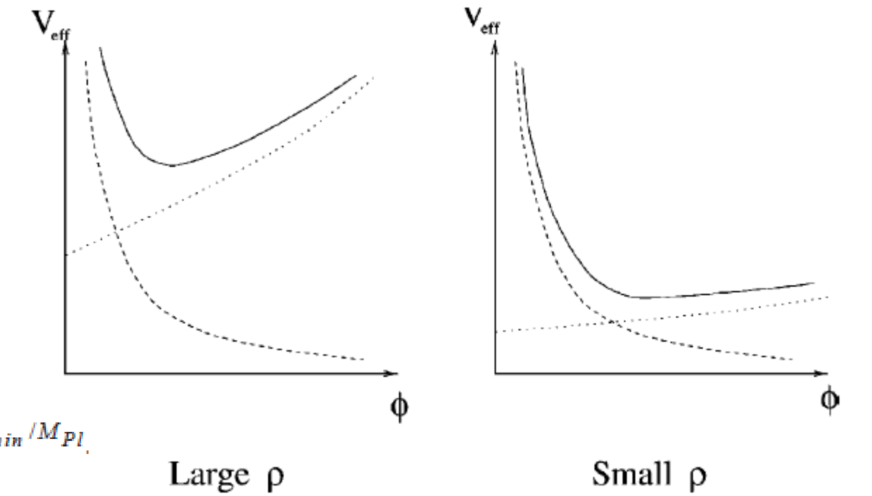
Potential $V(\phi)$ of the runaway form. E.g Ratra-Peebles $V(\phi)=M^{4+n}\phi^{-n}$.

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:

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



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

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

ϕ_{min} and m_{min} depend on local density: 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!).

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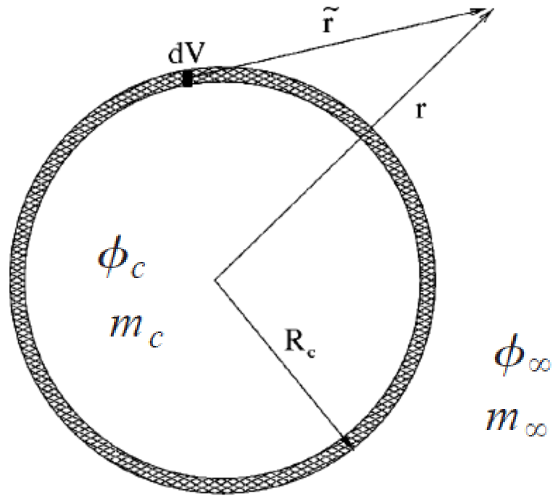
Chameleon: profile and thin-shell screening

Goal: 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 $\frac{d\phi}{dr}=0$ at $r=0$, $\phi\rightarrow\phi_\infty$ as $r\rightarrow\infty$

Inside the object, m_c >> m_∞, $\phi \sim \phi_c$, 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	$m_{atm}^{-1} \lesssim 1 \text{ mm} - 1 \text{ cm},$
Solar System	$m_G^{-1} \lesssim 10 - 10^4 \text{ AU},$
Cosmological scales	$m_0^{-1} \lesssim 0.1 - 10^3 \text{ pc},$

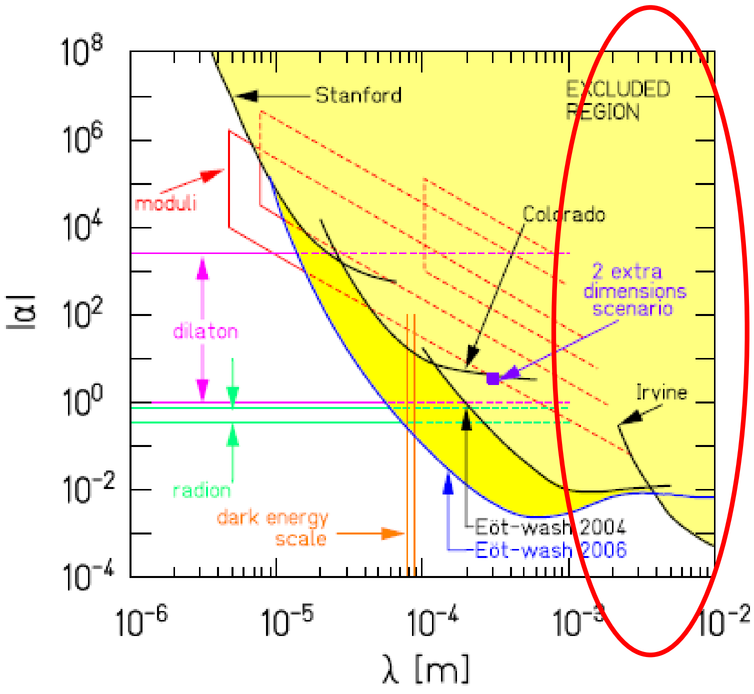
Behavior significantly different in space!

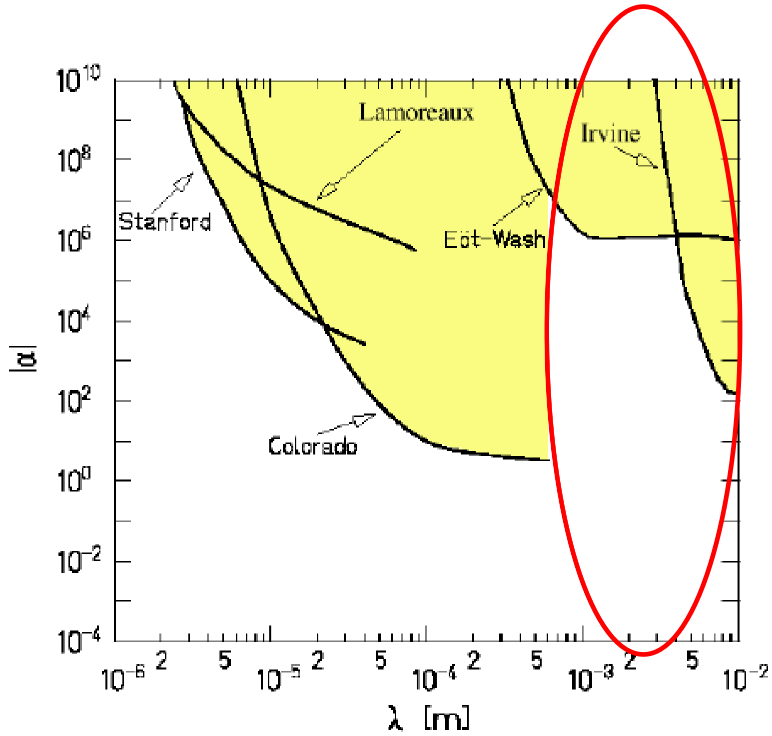
Looser constraints on fifth force

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





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

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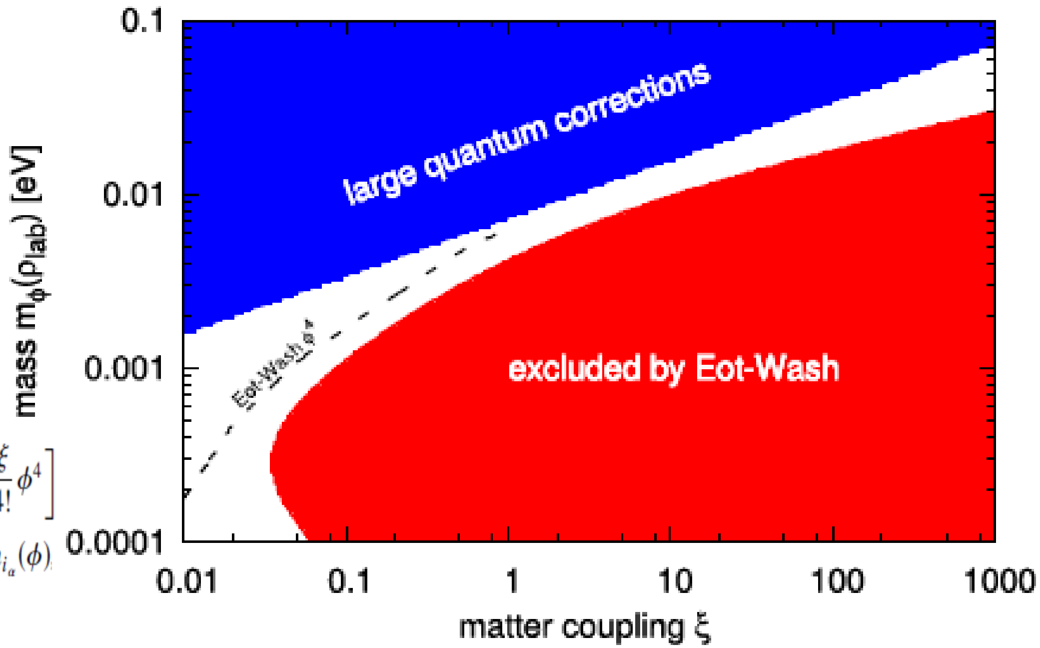
Allowed mass and coupling values

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

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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

- Pick up our preferred screening mechanism(s)
- Derive trustworthy field equations in the satellite and precise expected physical effect on EP test.
- Link to full instrument (electronics and mechanics) simulator.

- Bricks already exist:
  - Simulink model of the instrument (performance group)
  - Physics simulation (OCA –G. Metris, L. Serron-- CMS)
  - Payload simulator at CNES

The envisioned team

- Core members
  - Joel Bergé: ONERA Research scientist, member of MICROSCOPE CMS group, member of MICROSCOPE performance group
  - Jean-Philippe Uzan: IAP theoretical physicist
  - Quentin Baghi: ONERA PhD student
- A PhD student starting fall 2015?

- Performance group
- CMS

- Anyone interested

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
- 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.