Chasing chameleons

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Motivations

- The greatest surprise of modern cosmology was the observation that the Universe is accelerating in its expansion.
- While the data are consistent with the expansion being driven by a Λ, dark energy is more generally modeled by a scalar field rolling down an almost flat potential.
  - It is expected that such field to be essentially massless on solar system scales.
- If this field exists, why it has not been detected in local tests of the EP and $5th$ force searches?

Motivations

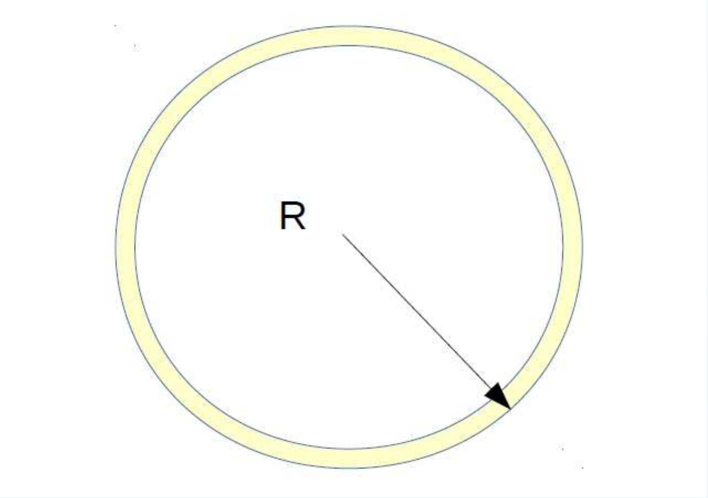
- Khoury $\&$ Weltman 2004, proposed novel solution to this problem, the “chameleon effect” whereby the coupling of a light scalar field to matter is effectively suppressed via a background dependent induced effective mass for these fields:
  - in places where $\rho_{\rm matter}$ is high, the particle interaction is weak;
  - in places where $\rho_{\rm matter}$ is low, the particle interaction is strong;

The Universe could be being pushed by the Chameleon´s force.

Motivations

- According to Mota & Shaw 2007 update;
  - The most simple models break the Weak Equivalence Principle (WEP).
  - This violation does not happen in the no-linear regimen; the chameleon fields and/or their interactions with matter are independent of the composition of bodies in free fall because these effects are only relevant in a small region on the surface of bodies.

THIN SHELL



Motivations

- The WEP is incorporated *ab initio* by pure metric-based theories while it is violated by construction by models such as “chameleons” even when referring to *point test particles*.

- This violation might not be observable in experiments due to the “screening phenomenon” BUT can be exacerbated when considering *test bodies*.

- We shall analyze the two body problem (both extended) embedded in a light medium. Preliminary results show detectable violations of the WEP. However, when considering the test body encased in a shell of dense material (like the chamber in the experiment) this violations are strongly supressed.

Motivations

- With similar arguments to those proposed by Hui et al., we want to show:
  - difference in acceleration depends on the properties of the test bodies even when the coupling β_i is universal;
  - when the *thin shell* effect becomes relevant, the physical objects must be considered as extendend bodies, and an effective violation of the WEP appears.

Chameleon models

- In this scenario, the action is given by:

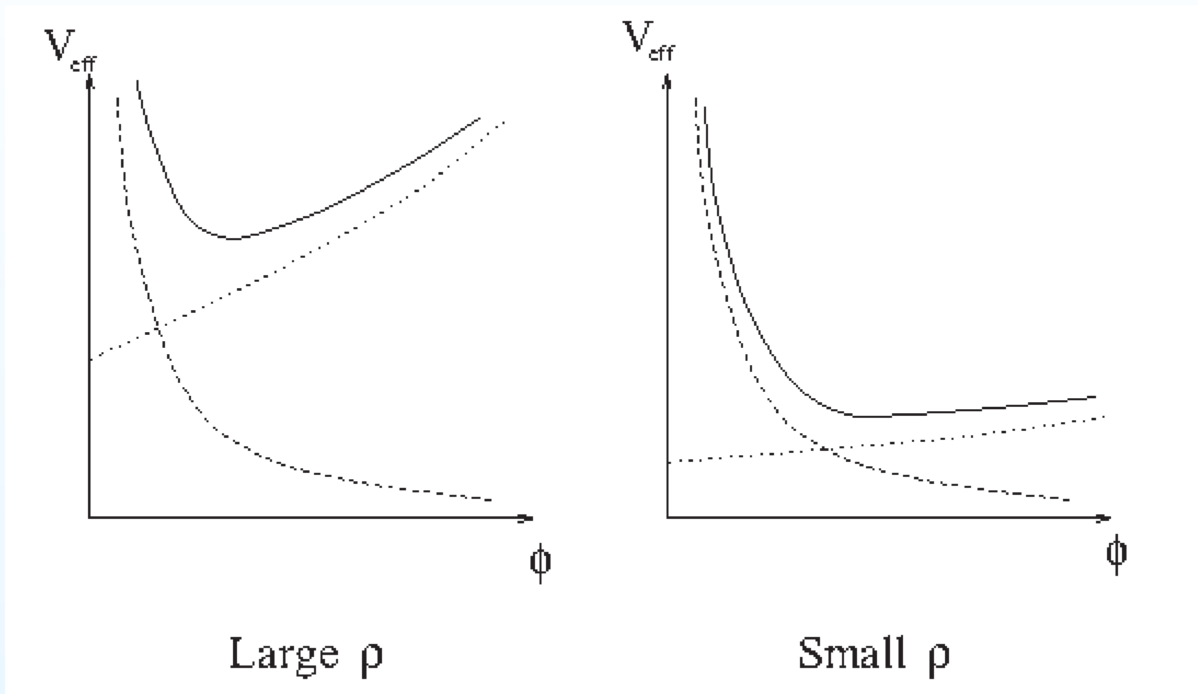
$$S = \int d^4x\sqrt{-g}\left[\frac{M_{pl}}{2}R - (\partial\Phi)^2 - V(\Phi)\right] - \int d^4x L_m\left(\Psi_m^{(i)}, g_{\mu\nu}^{(i)}\right)$$

L_m is the lagrangian of the matter fields and $g_{\mu\nu}^{(i)} = \exp\left[\frac{2\beta_i\Phi}{M_{pl}}\right]g_{\mu\nu}$. The potential $V(\Phi) \propto M_\Lambda^{n+4}\Phi^{-n}$; being $M_\Lambda \sim 10^{-3}$ eV the dark energy scale; n y β_i constant dimensionless parameters of the theory.

The key of the model: The no-linears effects are only relevant in a very small zone near the surface of the body called *thin shell*;

$$\frac{\Phi_\infty - \Phi_{\mathrm{C}}}{6\beta M_{pl}\Phi_{\mathrm{N}}} = \frac{\Delta R}{R} << 1$$

Chameleon models



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

$$V(\Phi) = \lambda M_\Lambda^{n+4}\Phi^{-n}, \qquad A(\Phi) = -T^m e^{\beta\Phi/M_{pl}}$$

Chameleon models

- The equation of motion is:

$$\Box\Phi = \frac{\partial V_{eff}}{\partial \Phi},$$

$$V_{eff}(\Phi) \simeq V_{eff}(\Phi_{\min}) + \frac{1}{2}\partial_{\Phi\Phi}V_{eff}(\Phi_{\min})[\Phi - \Phi_{\min}]^2.$$

- Defining the "effective mass":

$$m^2_{eff} = \partial_{\Phi\Phi}V_{eff}(\Phi_{\min}),$$

$$\frac{1}{r}\partial r[r^2\partial r\Phi] = m^2_{eff}[\Phi - \Phi_{\min}].$$

- The thin-shell condition becomes: $m_{eff}R >> 1$

Chameleon models

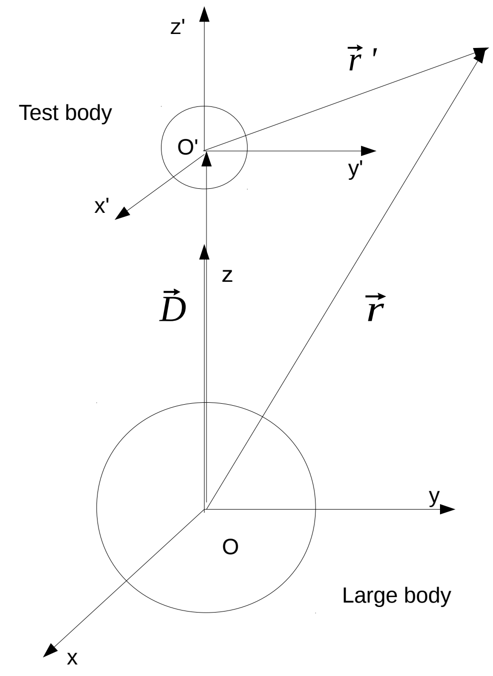
- The force mediated by the chameleon is:

$$F_\Phi = -\frac{\beta}{M_{pl}} M_{tp} \vec{\nabla} \Phi. \quad (1)$$

- The force due to a compact body of radius R and mass M_c is generated by the gradient of the chameleon field outside the body which interpolates between the minimum inside and outside the body.
- Inside the solution is nearly constant up to the boundary of the object and jumps over a thin shell $\frac{\Delta R}{R}$.
- Outside the field is given by,

$$\Phi \approx \Phi_\infty - \frac{\beta}{M_{pl}} \frac{3\Delta R}{R} \frac{M_c}{r} \quad (2)$$

The situation to analyze is given by,



Our proposal

- We take the complete solution of $\Box\Phi = m^2_{eff}[\Phi - \Phi_{\rm min}]$ in 3 regions:
  - Inside the massive body (MB) Φ_1, and the test body (TB) Φ_2; and outside both bodies Φ_3
- We analyze the case when the 2 bodies contribute to the external field.
- The boundary conditions are :

$$\lim_{r\to 0}\partial_r\Phi_{1,2} = 0 \quad \text{so as} \quad \lim_{r\to 0}\Phi_{1,2} = \Phi_{\mathrm{C}_{1,2}};$$
$$\lim_{r\to\infty}\partial_r\Phi_3 = 0 \quad \text{so as} \quad \lim_{r\to\infty}\Phi_3 = \Phi_\infty;$$
$$\Phi_j = \Phi_3|_{R_j}; \qquad \frac{\partial\Phi_j}{\partial r} = \frac{\partial\Phi_3}{\partial r}|_{R_j}, \qquad j = 1,2$$

Our proposal

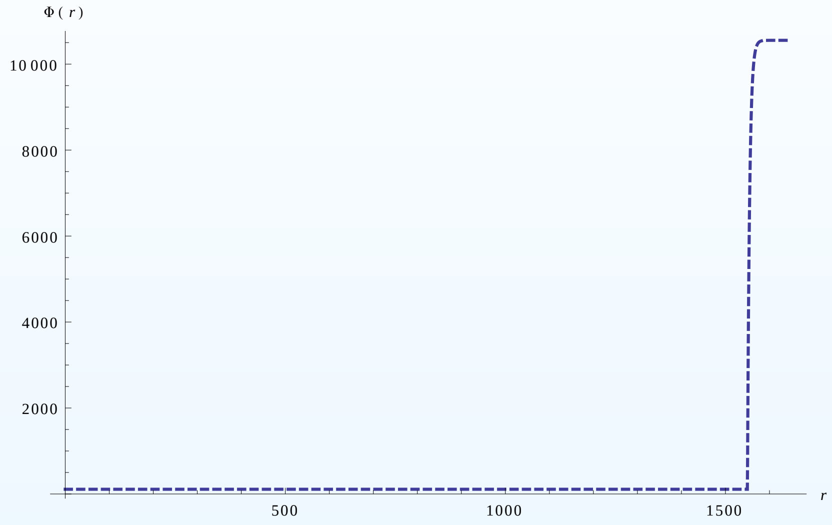
The most general solution is;

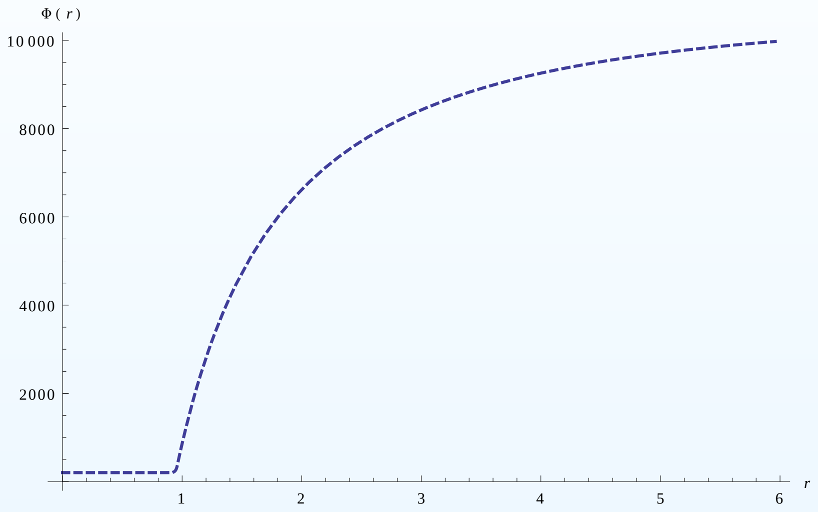
$$\Phi = \begin{cases} \Phi_1 = \sum_{lm} C^1_{lm} i_l(\mu_1 r) Y_{lm}(\theta,\phi) + \Phi_{C1} & r \leq R_1 \\ \Phi_3 = \sum_{lm} C^{3.1}_{lm} k_l(\hat{\mu} r) Y_{lm}(\theta,\phi) + & \text{outside both} \\ \qquad C^{3.2}_{lm} k_l(\hat{\mu} r') Y_{lm}(\theta',\phi') + \Phi_\infty & \text{bodies} \\ \Phi_2 = \sum_{lm} C^2_{lm} i_l(\mu_2 r') Y_{lm}(\theta',\phi') + \Phi_{C2} & r' \leq R_2 \end{cases}$$

$\mu_{1,2} = m_{1,2eff}$ and $\hat{\mu} = m_{3eff}$. We calculate the C^j_{lm} thanks to the next transformations with $|r| \leq |D|$ y $|r'| \leq |D|$; and we truncate the series with $N = \frac{e\hat{\mu}|D|}{2}$;

$$\begin{cases} k_l(\hat{\mu} r) Y_{lm}(\theta,\phi) = \sum_{vw} \alpha^{*lm}_{vw}(\vec{D}) i_v(\hat{\mu} r') Y_{vw}(\theta',\phi') \\ k_l(\hat{\mu} r') Y_{lm}(\theta',\phi') = \sum_{vw} \alpha^{lm}_{vw}(\vec{D}) i_v(\hat{\mu} r) Y_{vw}(\theta,\phi), \end{cases}$$

Our proposal





For the same length of interval, the “thin shell effect” is more notorious in the large body (hill) that in the test body (small sphere of aluminum). For this case, $n = \beta = 1$ and the bodies are immersed in the Earth’s atmosphere.

Our proposal

In order to calculate the force chameleon, we calculate the energy of the whole system which depends on Φ,

$$\begin{aligned} U_\Phi &= \int_V T_{00}^\Phi + T_{00}^m dV, \\ &= \int_V \Big\{ -\frac{\Phi}{2}\nabla^2\Phi + V_{eff}(\Phi) + \rho + \frac{\beta\Phi T^m}{M_{pl}} \Big\} dV, \\ &= \int_V \Big\{ -\frac{(2+n)}{2} V_{eff}(\Phi) + \frac{(3+n)\beta\Phi T^m}{2M_{pl}} + \rho \Big\} dV \end{aligned}$$

and derive it respect to the position between the bodies

$$\vec{F_\Phi} = -\frac{\partial U}{\partial \vec{D}}.$$

Taking the limit $R_{\rm TB} \to 0$, we recover the predictions for the “test particle” model.

Results

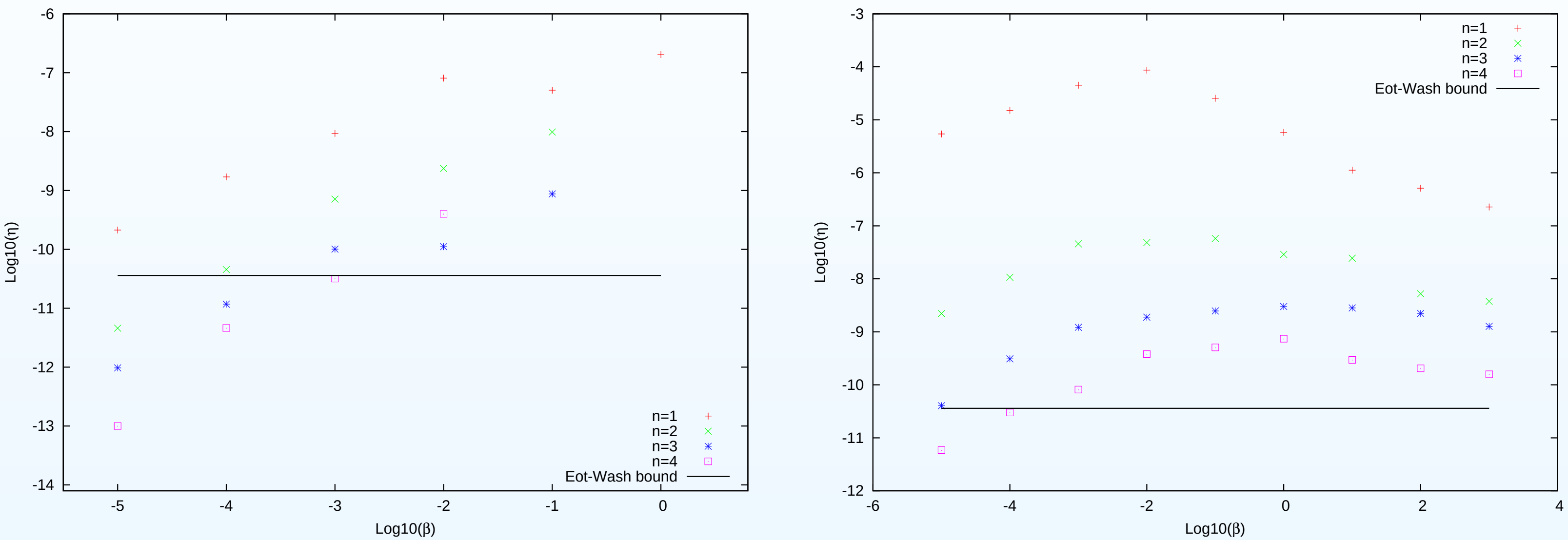
- We get the acceleration due to chameleon force $\vec{a_C}$ and so we can evaluate the expression

$$\eta \sim \frac{|\vec{a_T}_A - \vec{a_T}_B|}{|\vec{a_T}_A + \vec{a_T}_B|}$$

($\vec{a_T} = \vec{a_C} + \vec{g}$) to compare with Eöt-Wash torsion-balance experiments (WEP) (Be-Al-Hill).

- We use two different environments; the Earth´s atmosphere and the chamber´s vacumm.
- The test bodies no longer have thin shell for $\beta \leq 10^{-1.5}$, while in the cases of the massive body β can be much more smaller.

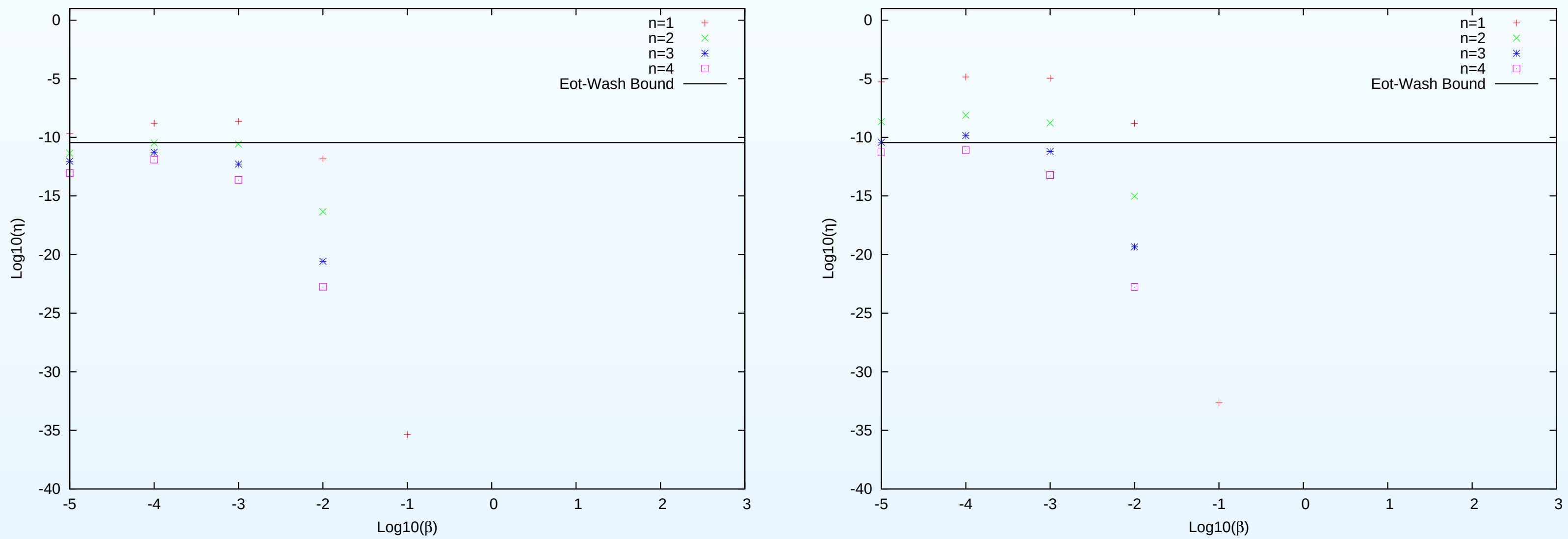
Results



In the left figure $\rho_{\rm out}$ is the Earth's atmosphere, and in the right one is the chamber's vacuum.

Results

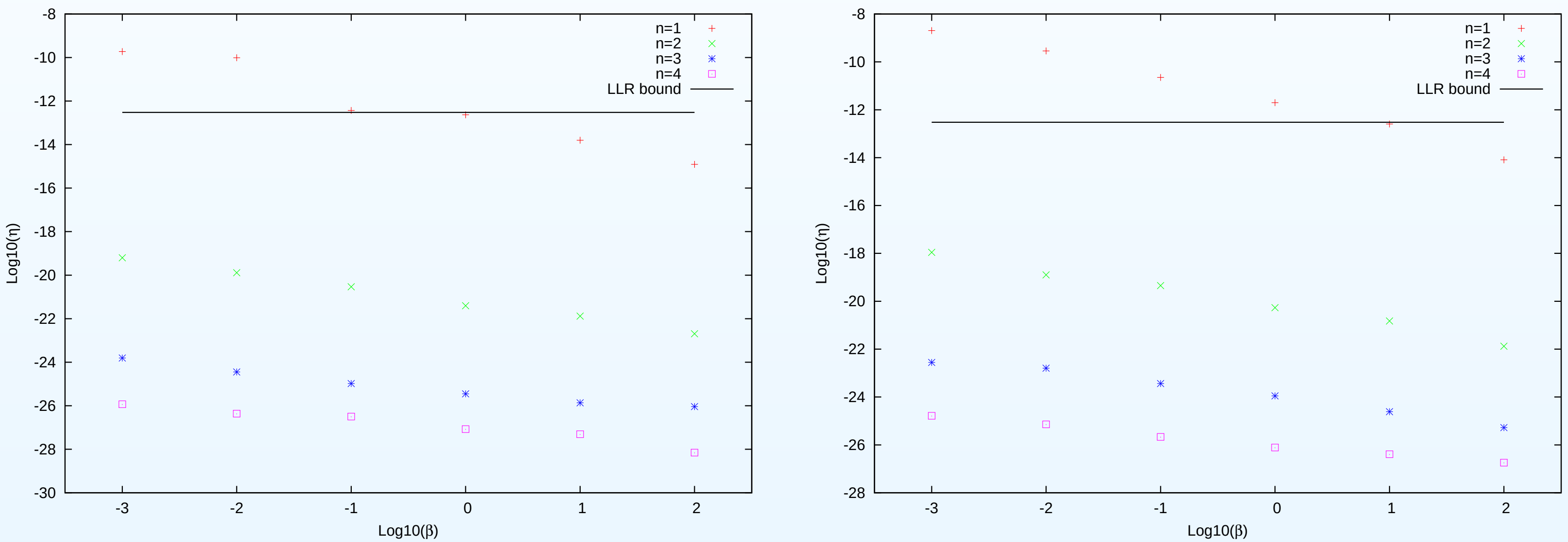
Brax made us notice that in these particular models, the effect of the layer of the vacuum chamber should be taken into account, Upadhye (2012).



In the left figure $\rho_{\rm out}$ is the Earth's atmosphere, and in the right one is the chamber's vacuum. The force suppression factor $\sim \mathrm{sech}(2m_{eff}^{\rm layer}d)$, being d the diameter of the layer.

Results

The LLR experiment test the WEP without the shielding between the test bodies and (Earth-Moon) and the source (Sun).



In the left figure the Earth and the Sun are surrounded by their atmospheres, and in the right not. In both cases $\rho_{\rm out}$ is density of the interstellar medium and the three bodies have thin shell.

Results

- We compare our results (LAp) for one body problem with the numerically ones obtained by Khoury, Upadhye et al. and we deduce:
  - LAp works better far from the large body.
  - At the test particle position there is an overestimation of the force by a factor 2.
- Conversely, at the large body surface, the forces and the WEP violation seem to be worse using the exact numerical solution than with the calculation using the LAp.
- We estimate the corrections introduced to V_{eff} approximation (LAp) by considering the effects of cubic term in the expansion as a perturbation for the one body problem and they are small in the regime $0 < n < 5$.

Conclusions

- We have performed a very carefull calculation considering the two body problem and obtained that there is a violation of the WEP at variance with the calculations of previos paper.
- However, for comparing with torsion balance experiments, the contribution of a metal encasing of the vacuum chamber surrounding the test body should be considered. In this case and considering a rough estimate, there is Yukawa type effect that screens the violations of the WEP. We conclude that this kind of experimets are not suitable for testing the WEP.
- The linear approximation is suitable for the one body problem with $0 < n < 5$. The two body problem is yet to be analized.

Future

- In order to test a wider range of paramenters:
  - improve either the numeric code (Matlab) or the coordinate transformation (oblates) considering the metal encasing;
  - calculate the effects of cubic term in the expansion as a perturbation for the two body problem.
- Although, MICROSCOPE will improve the bounds on the WEP, the encasement problem will continue.
- Test the WEP with other experiments for extended bodies:
  - peculiar motion of galaxies with redshift space distortions and voids;
  - internal motion in unscreened galaxies;
  - etc..

Thank you!