Modified Gravity vs General Relativity: Observational and Experimental tests

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Colaborators

- Equivalence principle in chameleon theories and $f(R)$
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- Dwarfs galaxies in MOG
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Outline

- Motivation for studying alternative theories to GR
- Equivalence between $f(R)$,chameleons and Brans-Dicke theories
- Calculation of the PPN using the equation of motion for R in the Jordan frame
- Equivalence Principle in Chameleon Models
- Simulations of dwarf galaxies in chameleon models

Motivation

- Data from supernovae type Ia indicate that the present expansion of the Universe is accelerating.
- Two proposals are currently being considered to explain these data:

$$R_{\mu\nu} = 4\pi G T_{\mu\nu}$$

  - Add a new term to the energy momentum tensor with $P = \omega\rho$ and $-1 < \omega < -1/3$.
    - Add a constant term: Λ_{CDM} cosmology
    - Add a scalar field with an appropiate potential: quintessence, k-essence,etc
  - Consider an alterative gravity theory to GR
    - f(R), etc
    - chameleons, Moffat's MOG
    - Massige gravity: DGP, galileon, K-mouflage

The action in $f(R)$ gravity can be expressed:

$$S = \frac{1}{2\kappa^2}\int \mathrm{d}^4x\sqrt{-g}\,f(R) + \int \mathrm{d}^4x\mathcal{L}_M(g_{\mu\nu},\Psi_M)\,,$$

where $\kappa^2 = 8\pi G$, g is the determinant of the metric $g_{\mu\nu}$, and $\mathcal{L}_M$ is a matter Lagrangian. The Ricci scalar R is defined by $R = g^{\mu\nu}R_{\mu\nu}$.
The field equation can be derived by varying the action with respect to $g_{\mu\nu}$:

$$\Sigma_{\mu\nu} \equiv f'(R)R_{\mu\nu}(g) - \frac{1}{2}f(R)g_{\mu\nu} - \nabla_\mu\nabla_\nu f'(R) + g_{\mu\nu}\Box f'(R) = \kappa^2 T^{(M)}_{\mu\nu}\,,$$

where $f'(R) \equiv \partial f/\partial R$. $T^{(M)}_{\mu\nu}$ is the energy-momentum tensor of the matter fields defined by the variational derivative of $\mathcal{L}_M$ in terms of $g^{\mu\nu}$:

$$T^{(M)}_{\mu\nu} = -\frac{2}{\sqrt{-g}}\frac{\delta\mathcal{L}_M}{\delta g^{\mu\nu}}\,.$$

Friedmann equation in $f(R)$

In a the flat FLRW background the field equations are expressed:

$$\begin{aligned} 3FH^2 &= (FR - f)/2 - 3H\dot{F} + \kappa^2 \rho_M \,, \\ -2F\dot{H} &= \ddot{F} - H\dot{F} + \kappa^2(\rho_M + P_M) \,, \end{aligned}$$

where $F = \frac{\partial f}{\partial R}$ and the perfect fluid satisfies the continuity equation

$$\dot{\rho}_M + 3H(\rho_M + P_M) = 0 \,.$$

Equivalence between $f(R)$ and Brans-Dicke theories

Let us consider the following action with a new field χ,

$$S = \frac{1}{2\kappa^2} \int \mathrm{d}^4x \sqrt{-g}\, \left[f(\chi) + f_{,\chi}(\chi)(R-\chi) \right] + \int \mathrm{d}^4x \mathcal{L}_M(g_{\mu\nu}, \Psi_M)\,.$$

Varying this action with respect to χ, we obtain

$$f_{,\chi\chi}(\chi)(R-\chi) = 0\,.$$

Provided $f_{,\chi\chi}(\chi) \neq 0$ it follows that $\chi = R$.

If we define

$$\varphi \equiv f_{,\chi}(\chi)\,,$$

the action can be expressed as

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{1}{2\kappa^2}\varphi R - U(\varphi)\right] + \int \mathrm{d}^4x\mathcal{L}_M(g_{\mu\nu}, \Psi_M)\,,$$

where $U(\varphi)$ is a field potential given by

$$U(\varphi) = \frac{\chi(\varphi)\,\varphi - f(\chi(\varphi))}{2\kappa^2}\,.$$

Meanwhile the action in BD theory with a potential $U(\varphi)$ is given by

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{1}{2}\varphi R - \frac{\omega_{\mathrm{BD}}}{2\varphi}(\nabla\varphi)^2 - U(\varphi)\right] + \int \mathrm{d}^4x\mathcal{L}_M(g_{\mu\nu}, \Psi_M)\,,$$

where ω_{BD} is the BD parameter and $(\nabla\varphi)^2 \equiv g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi$.

Equivalence of chameleon models in the Jordan frame with BD theories

The action of a chameleon field in the Jordan frame can be written us:

$$S = M_{\rm Pl}^2 \int d^4x\sqrt{-g}\Big[\tfrac{1}{2}\Omega^2(\varphi)R - \tfrac{1}{2}h(\varphi)\nabla_\mu\varphi\nabla^\mu\varphi$$
$$-\Omega^4(\varphi)V\Big]$$
$$+\int d^4x\,\mathcal{L}_m(\psi_m, g_{\mu\nu})$$

where

$$h(\varphi) \equiv \Omega^2\left[1 - \frac{3}{2}\left(\frac{\partial \ln \Omega^2}{\partial\varphi}\right)^2\right]\,.$$

Equivalence of chameleon models in the Jordan frame with BD theories

We define

$$\varphi_{\rm BD} \equiv \Omega^2(\varphi) = \exp\left[-\frac{2\beta\varphi}{M_{\rm pl}}\right] .$$

The action in the Jordan frame becomes

$$\begin{aligned} S &= \int d^4x\sqrt{-g}\frac{1}{16\pi}\left[\varphi_{\rm BD}R - \frac{\omega_{\rm BD}}{\varphi_{\rm BD}}\nabla_\mu\varphi_{\rm BD}\nabla^\mu\varphi_{\rm BD}\right] \\ &+ \int d^4x\,\mathcal{L}_m(\psi_m, g_{\mu\nu}) \end{aligned}$$

where

$$\omega_{\rm BD} \equiv \frac{1-6\beta^2}{4\beta^2} .$$

Equivalence between $f(R)$ theories and chameleons in the Einstein frame

We define φ by

$$\exp\left(-\frac{2\beta\varphi}{M_{\rm Pl}}\right) = f'(R),$$

where $\beta = \sqrt{1/6}$. We also define the *Einstein frame* metric $\bar{g}_{\mu\nu}$ by a conformal transformation $\bar{g}_{\mu\nu} = e^{-\frac{2\beta\varphi}{M_{\rm Pl}}} g_{\mu\nu}$ and let $\bar{R}$ be the scalar curvature of $\bar{g}_{\mu\nu}$. When rewritten in terms of $\bar{g}_{\mu\nu}$ and φ, the action becomes:

$$\begin{aligned} S_{\rm ST} = \quad & \int {\rm d}^4 x \sqrt{-\bar{g}} \left(\frac{M_{\rm Pl}^2}{2}\bar{R} - \frac{1}{2}\bar{g}^{\mu\nu}\nabla_\mu\varphi\nabla_\nu\varphi - V(\varphi)\right) \\ & + S_{\rm matter}[e^{\frac{2\beta\varphi}{M_{\rm Pl}}}\bar{g}_{\mu\nu}, \Psi_i], \end{aligned}$$

where the potential $V(\varphi)$ is given by:

$$V(\varphi) = \frac{M_{\rm Pl}^2 \left(R f'(R) - f(R)\right)}{2 f'(R)^2}.$$

Differences between Einstein and Jordan frames

- In the Einstein frame $f'(R) = \exp\left(-\frac{2\beta\varphi}{M_{\rm Pl}}\right)$ and

$$V(\varphi) = \frac{M_{\rm Pl}^2\left(Rf'(R) - f(R)\right)}{2f'(R)^2}.$$

- In the Jordan frame $f'(R) = \varphi$ and

$$V(\varphi) = M_{\rm Pl}^2\left(R\varphi - f(R)\right).$$

THE SPATIAL EQUATION FOR R IN THE JORDAN FRAME

The spatial equation for R can be written as:

$$\Box_r R + \frac{f_{RRR}}{f_{RR}}(\nabla R)^2 = V'_{\text{eff}}(R)$$

where

$$V'_{\text{eff}}(R) = \frac{dV_{\text{eff}}(R)}{dR} = \frac{1}{3f_{RR}}(\kappa T + 2f - Rf_R),$$

We consider Starobinsky's model:

$$f(R) = R + \lambda R_0 \left[\left(1 + \frac{R^2}{R_0^2} \right)^{-n} - 1 \right]$$

:

Metric in Einstein and Jordan frames

The spherically symmetric metric in the Einstein frame can be written as:

$$\mathrm{d}\tilde{s}^2 = \tilde{g}_{\mu\nu}\mathrm{d}\tilde{x}^\mu \mathrm{d}\tilde{x}^\nu = -[1 - 2\tilde{\mathcal{A}}(\tilde{r})]\mathrm{d}t^2 + [1 + 2\tilde{\mathcal{B}}(\tilde{r})]\mathrm{d}\tilde{r}^2 + \tilde{r}^2\mathrm{d}\Omega^2 \,,$$

In the weak gravitational background ($\tilde{\mathcal{A}}(\tilde{r}) \ll 1$ and $\tilde{\mathcal{B}}(\tilde{r}) \ll 1$) the metric outside the spherically symmetric body with mass M_c is given by $\tilde{\mathcal{A}}(\tilde{r}) \simeq \tilde{\mathcal{B}}(\tilde{r}) \simeq GM_c/\tilde{r}$.

Let us transform the metric to that in the Jordan frame. $g_{\mu\nu} = e^{\frac{2\beta\varphi}{M_{\mathrm{pl}}}}\tilde{g}_{\mu\nu}$.

$$\mathrm{d}s^2 = e^{\frac{2\beta\varphi}{M_{\mathrm{pl}}}}\mathrm{d}\tilde{s}^2 = -[1 - 2\mathcal{A}(r)]\mathrm{d}t^2 + [1 + 2\mathcal{B}(r)]\mathrm{d}r^2 + r^2\mathrm{d}\Omega^2 \,.$$

The PPN parameter γ can be expressed as:

$$\gamma = \frac{\mathcal{B}(r)}{\mathcal{A}(r)}$$

The Post Newtoniana Parameter γ.

- In the standard approach, γ is calculated using the solution for the chameleon scalar field in the Einstein frame and the following expression

$$\tilde{r} = e^{\frac{\beta\varphi}{M_{\rm pl}}} r\,, \quad \mathcal{A}(r) \simeq \tilde{\mathcal{A}}(\tilde{r}) - \frac{\beta\varphi(\tilde{r})}{M_{\rm pl}}\,, \quad \mathcal{B}(r) \simeq \tilde{\mathcal{B}}(\tilde{r}) - \frac{\beta\tilde{r}}{M_{\rm pl}}\frac{{\rm d}\varphi(\tilde{r})}{{\rm d}\tilde{r}}\,.$$

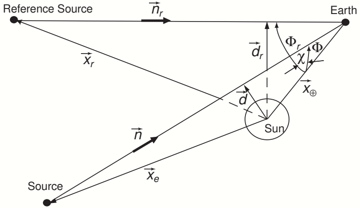
valid if $|\frac{\beta\varphi}{M_{\rm pl}}| \ll 1$

- In our approach, we solve the equation for R in the Jordan frame and $A(r)$ and $B(r)$ can be expressed in terms of $f(R)$ and its derivatives:

$$\mathcal{A}(r) \simeq \tilde{\mathcal{A}}(\tilde{r}) + \ln(f'(R)), \quad \mathcal{B}(r) \simeq \tilde{\mathcal{B}}(\tilde{r}) + r\frac{f''(R)}{f'(R)}\,.$$

where $f'(R) = \frac{\partial f}{\partial R}$ and $f''(R) = \frac{\partial^2 f}{\partial R^2}$

Solar System Tests: The deflection of light



The relative angular separation between an observed source of light and a nearby reference source as both rays pass near the Sun:

$$\delta\theta = \frac{1}{2}(1+\gamma)\left[-\frac{4\,M_\odot}{d}\cos\chi + \frac{4\,M_\odot}{d_{\rm r}}\left(\frac{1+\cos\varphi_{\rm r}}{2}\right)\right],$$

where d and $d_{\rm r}$ are the distances of closest approach of the source and reference rays respectively, $\varphi_{\rm r}$ is the angular separation between the Sun and the reference source, and χ is the angle between the Sun-source and the Sun-reference directions, projected on the plane of the sky.

Solar Sistem Tests:Time delay of light

A radar signal sent across the solar system past the Sun to a planet or satellite and returned to the Earth suffers an additional non-Newtonian delay in its round-trip travel time,

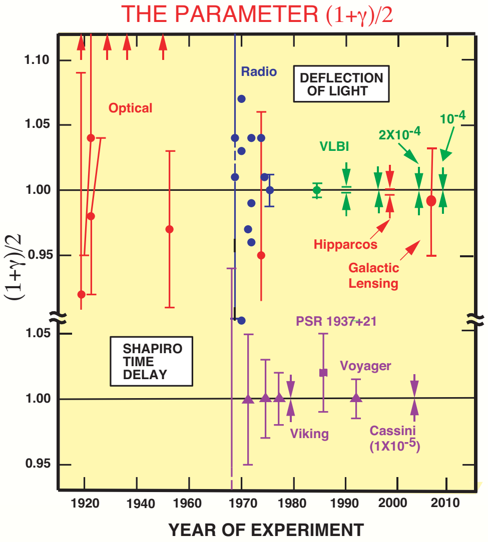
$$\delta t = 2(1+\gamma)M_{\odot}\ln\left(\frac{(r_{\oplus}+\mathbf{x}_{\oplus}\cdot\mathbf{n})(r_{\mathrm{e}}-\mathbf{x}_{\mathrm{e}}\cdot\mathbf{n})}{d^2}\right),$$

where $\mathbf{x}_{\mathrm{e}}$ $(\mathbf{x}_{\oplus})$ are the vectors, and r_{e} $(r_{\oplus})$ are the distances from the Sun to the source (Earth), respectively . For a ray which passes close to the Sun,

$$\delta t \approx \frac{1}{2}(1+\gamma)\left[240 - 20\ln\left(\frac{d^2}{r}\right)\right]\ \mu\mathrm{s},$$

where d is the distance of closest approach of the ray in solar radii, and r is the distance of the planet or satellite from the Sun.

Experimental constraints on γ



Summary and work in progress.

- It has been proved that $f(R)$ theories are equivalent to Brans-Dicke models with $\omega = 0$. On the other hand, chameleon models in the Jordan frame are also equivalent to Brans-Dicke models with $\omega_{\text{BD}} \equiv \frac{1-6\alpha^2}{4\alpha^2}$. Therfore, the equivalence between $f(R)$ models can be regarded as chameleon models with $\alpha = \frac{1}{\sqrt{6}}$ and a potential that depends on the particular choice of $f(R)$.
- Solar systems tests constrain the value of the PPN parameter γ which describes how much space-time curvature is produced by a unit rest mass. Each modified theory of gravity has a specific prediction for this parameter.
- We intent to calculate the prediction of γ in some particular $f(R)$ models using an alternative approach. We will not use the equivalence between $f(R)$ theories and STT. The proposal consists in solving the equation for R in the Jordan frame.

The chameleon model

The model involves a scalar-field φ that couples minimally to gravity via a fiducial metric $g_{\mu\nu}$:

$$S[g_{\mu\nu}, \Psi_m^{(i)}, \varphi] = \int d^4x\sqrt{-g}\left[\frac{M_{pl}^2}{2}R - \frac{1}{2}g^{\mu\nu}(\nabla_\mu\varphi)(\nabla_\nu\varphi) - V(\varphi)\right] - \int d^4x L_m\left(\Psi_m^{(i)}, g_{\mu\nu}^{(i)}\right),$$

where M_{pl} is the reduced Planck mass,R is the Ricci scalar associated with $g_{\mu\nu}$, and $\Psi_m^{(i)}$ represents the different matter fields. The scalar field φ couples *non-minimally* to the matter through a conformal factor that relates each metric $g_{\mu\nu}^{(i)}$ with the Einstein metric $g_{\mu\nu}$:

$$g_{\mu\nu}^{(i)} = \exp\left[\frac{2\beta_i\varphi}{M_{pl}}\right]g_{\mu\nu}.$$

The chameleon model

We consider the potential for the chameleon field:

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

where M is a constant, and n is a free parameter that can be taken to be either a positive integer or a negative even integer and $\lambda = 1$ for all values of n except when $n = -4$ where $\lambda = \frac{1}{4!}$.
The equation of motion for the the chameleon φ is

$$\Box\varphi = \frac{\partial V_{\text{eff}}}{\partial \varphi},$$

where V_{eff} represents the effective potential defined by:

$$V_{\text{eff}} = V(\varphi) - T^m \frac{\beta\varphi}{M_{pl}},$$

For a perfect fluid model, $T^m = -\rho + 3P$.

The one body problem

Let us consider a spherically-symmetric and *homogeneous* body of radius R and density $\rho_{\rm in}$ immersed in an external medium of density $\rho_{\rm out}$.

$$\rho = \begin{cases} \rho_{\rm in} & r \leq R \\ \\ \rho_{\rm out} & r > R \end{cases} ,$$

where R is the radius of the body.

Approximations to the effective potential

There are two regimes analyzed in the literature:

- *Thin shell* regime

$$V_{\rm eff}^{\rm in,out}(\varphi) \simeq V_{\rm eff}^{\rm in,out}(\varphi_{\rm min}^{\rm in,out}) + \frac{1}{2}\partial_{\varphi\varphi}V_{\rm eff}^{\rm in,out}(\varphi_{\rm min}^{\rm in,out})[\varphi - \varphi_{\rm min}^{\rm in,out}]^2,$$

and therefore the effective mass of the chameleon is defined :

$$m_{\rm eff}^{2\rm in,out}(\varphi_{\rm min}^{\rm in,out}, \beta_i, \rho^{in,out}) = \partial_{\varphi\varphi}V_{\rm eff}^{\rm in,out}(\varphi_{\rm min}^{\rm in,out}).$$

- *Thick shell* regime

$$V_{\rm eff}^{\rm in,out}(\varphi) \simeq \frac{\beta\varphi\rho^{in,out}}{M_{pl}}$$

The solution for the one body problem

The solution obtained by the standard approach for $r < R$ reads:

$$\varphi^{\rm in}(r) = \frac{(\varphi_0 - \varphi_c)\sinh(m_{\rm eff}^{\rm in} r)}{m_{\rm eff}^{\rm in} r} + \varphi_c \qquad (r \leq R) \ ,$$

where $\varphi_c := \varphi_{\rm min}^{\rm in}$ and φ_0 is a constant. and for $r > R$:

$$\varphi^{\rm out}(r) = C\frac{\exp\left[-m_{\rm eff}^{\rm out} r\right]}{r} + \varphi_\infty \qquad (r \geq R) \ ,$$

where

$$C = -\frac{3\beta\mathcal{M}}{4\pi M_{pl}}\frac{\Delta R}{R}\exp\left[m_{\rm eff}^{\rm out}R\right]f(x) \ ,$$

and

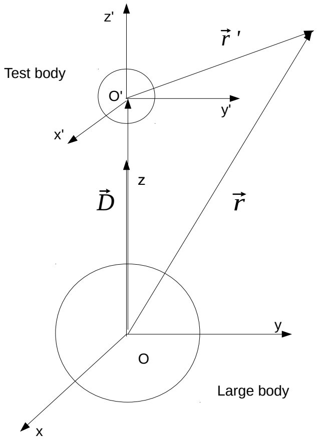
$$\frac{\Delta R}{R} = -\frac{(\varphi_c - \varphi_\infty)}{6\beta M_{pl}\varphi_N} \ ,$$

and $f(x)$ is a constant

The one body solution in the *thin shell* approximation

The so called *thin-shell* effect appears when $1 \ll m_{\rm eff}^{\rm in} R$. And the expressions for the field are:

$$\begin{aligned}
\varphi^{\rm in}(r) &\approx \frac{2(\varphi_\infty - \varphi_c)\exp\left[-R m_{\rm eff}^{\rm in}\right]\sinh(m_{\rm eff}^{\rm in} r)}{m_{\rm eff}^{\rm in} r} + \varphi_c \qquad (r \leq R) \ , \\
\varphi^{\rm out}(r) &\approx R(\varphi_c - \varphi_\infty)\frac{\exp\left[-m_{\rm eff}^{\rm out}(r-R)\right]}{r} + \varphi_\infty \qquad (r \geq R) \ .
\end{aligned}$$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y
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Large body
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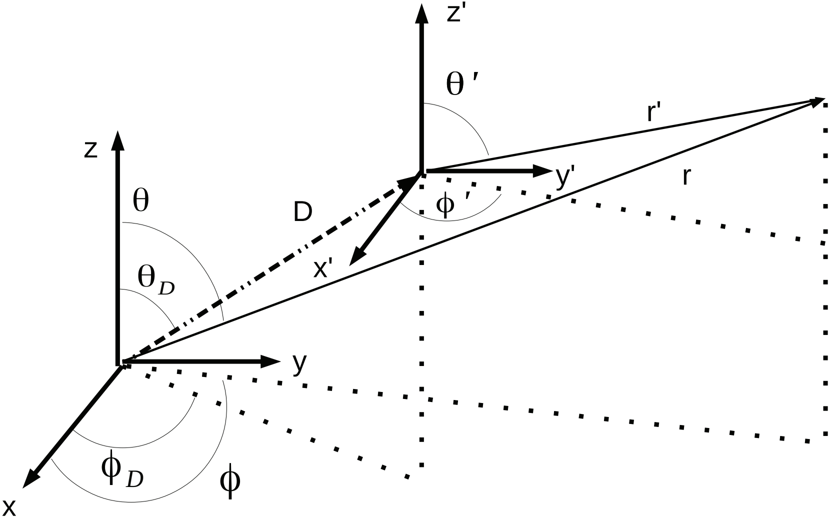
Our solution to the two body problem arXiv:1511.06307

We expand the most general solution in complete sets of solutions of the differential equation in the inside and outside regions determined by the two bodies:

$$\varphi = \begin{cases} \varphi_{\text{in1}} = \sum_{lm} C_{lm}^{\text{in1}} i_l(\mu_1 r) Y_{lm}(\theta,\phi) + \phi_{1\text{min}}^{\text{in}} & (r \leq R_1) \\ \varphi_{\text{out}} = \sum_{lm} C_{lm}^{\text{out1}} k_l(\mu_{\text{out}} r) Y_{lm}(\theta,\phi) + C_{lm}^{\text{out2}} k_l(\mu_{\text{out}} r') Y_{lm}(\theta',\phi') & \\ \qquad +\varphi_\infty \qquad \text{(exterior solution)} & \\ \varphi_{\text{in2}} = \sum_{lm} C_{lm}^{\text{in2}} i_l(\mu_2 r') Y_{lm}(\theta',\phi') + \varphi_{2\text{min}}^{\text{in}} & (r' \leq R_2) \end{cases}$$

where $\mu_1 = m_{\text{eff}}^{\text{large body}}$, $\mu_{\text{out}} = m_{\text{eff}}^{\text{out}}$, $\mu_2 = m_{\text{eff}}^{\text{test body}}$ and R_1, R_2 are the radii of the *large* and *test* bodies, respectively, and i_l and k_l are Modified Spherical Bessel Functions (MSBF).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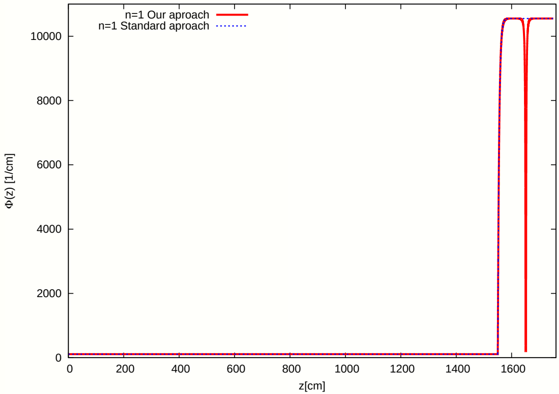
n=1 Our aproach
n=1 Standard aproach
Φ(z) [1/cm]
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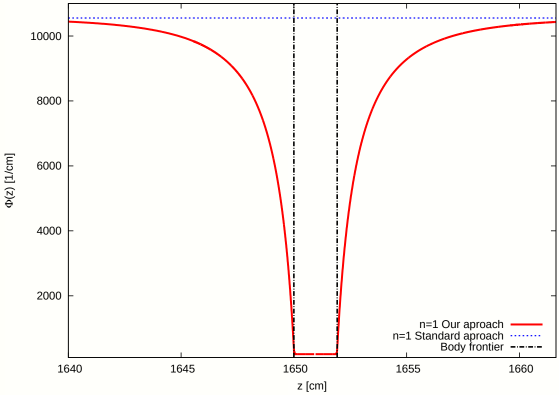
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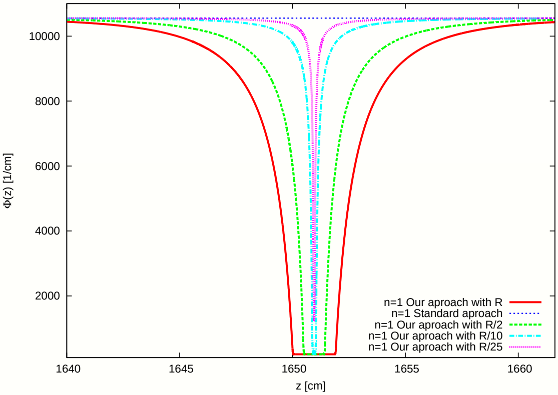
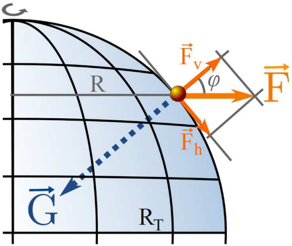
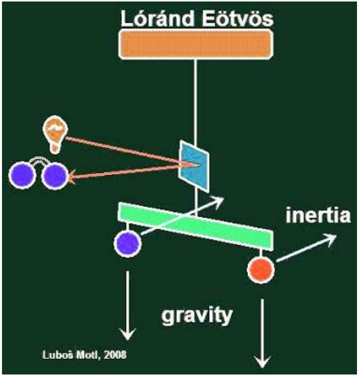
THE TWO BODY PROBLEM FOR $R \to 0$



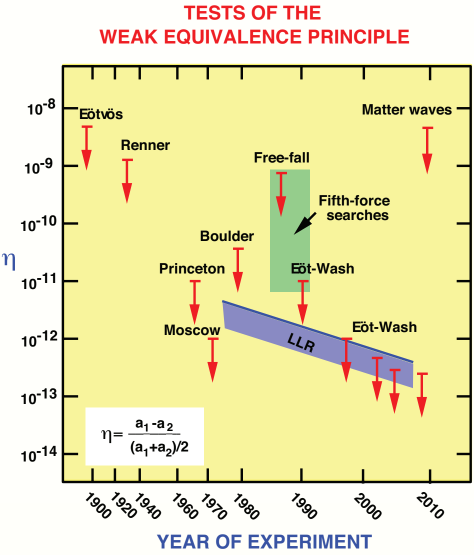




$$\tau \sim \eta = 2\frac{|a_1 - a_2|}{a_1 + a_2} = 2\frac{\frac{m_{g2}}{m_{i2}} - \frac{m_{g1}}{m_{i1}}}{\frac{m_{g2}}{m_{i2}} + \frac{m_{g1}}{m_{i1}}}$$

$$\vec{a}_i = \vec{a}_{i\varphi} + \vec{g}$$

Experimental constraints on WEP



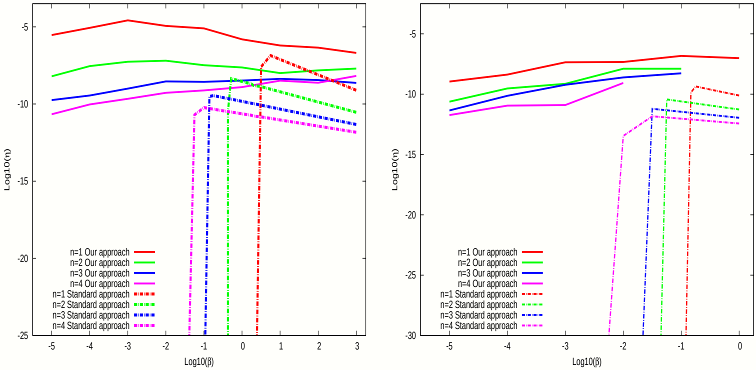
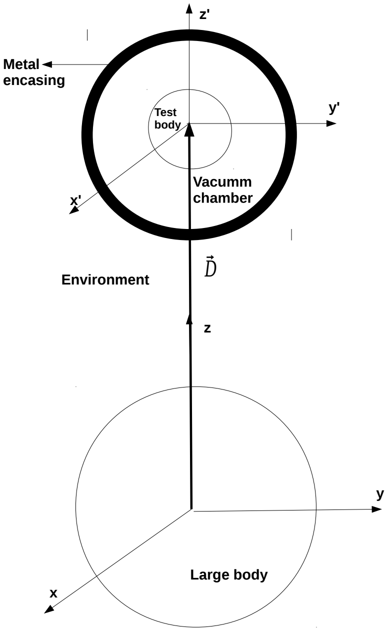


FIGURE: $M = 2.4 \times 10^{-3}\mathrm{eV}$. Left: $\rho_{\rm out} = 10^{-7}\mathrm{g\ cm}^{-3}$; Right: $\rho_{\rm out} = 10^{-3}\mathrm{g\ cm}^{-3}$. The predictions computed by Khoury & Weltman are also included and labeled as the *standard approach*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Results including the metal shell

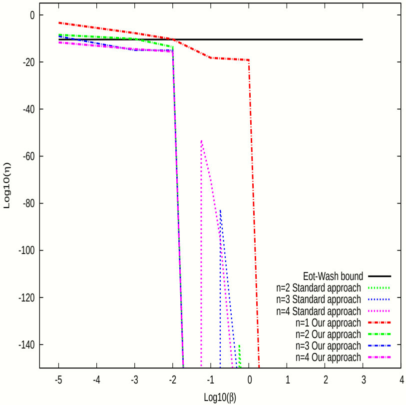


Figure: $\rho_{\rm out} = 10^{-7}{\rm g\ cm}^{-3}$. Also shown are the predictions computed by Khoury & Weltman with the effect of the metal encasing modeled by multiplying their estimates of η by the factor ${\rm sech}(2{\rm m}_{\rm shell}{\rm d})$.

Results including the metal shell

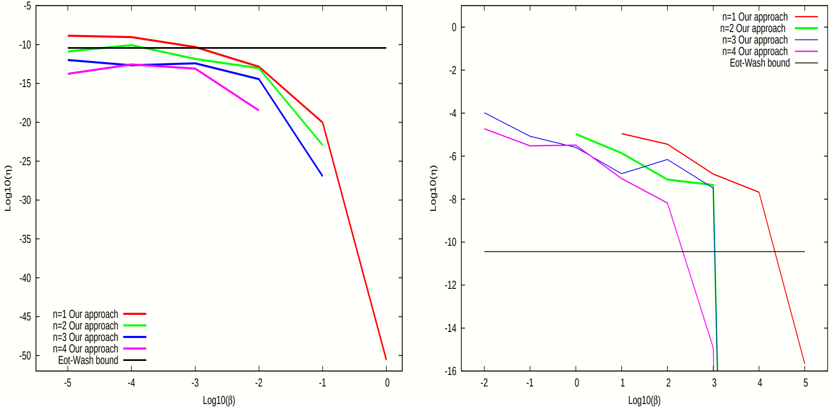
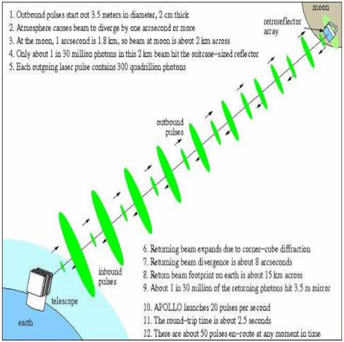


FIGURE: The density of the environment surrounding the Earth ρ_{out} is assumed to be equal the Earth's atmosphere $\rho_{\text{out}} = 10^{-3}\text{g cm}^{-3}$; the density of the environment inside the vacuum chamber is assumed to be $\rho_{\text{vac}} = 10^{-7}\text{g cm}^{-3}$; Left: $M = 2.4 \times 10^{-3}\text{eV}$ (cosmological chameleon); Right: $M = 10$ eV.

- Reflectors placed on the lunar surface allow the measurement of the round-trip travel time of short pulses of laser light, and thus set limits on the differential acceleration of the Earth-Moon system in free fall towards the Sun.



Results for the Lunar Laser Ranging Experiment

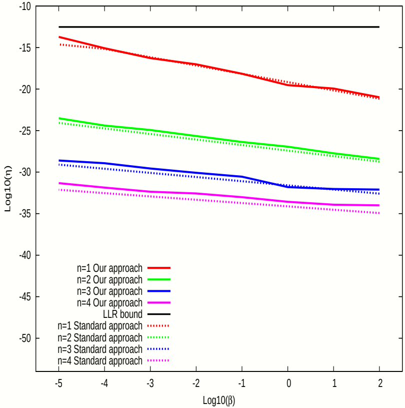


Figure: All bodies are surrounded by the interstellar medium. $M = 2.4 \times 10^{-3}\mathrm{eV}$ (cosmological chameleon).

Results for the Lunar Laser Ranging Experiment

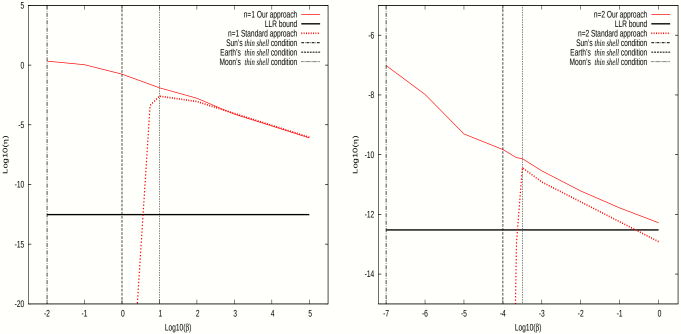


Figure: Left: $n = 1$; Right: $n = 2$. All bodies are surrounded by the interstellar medium. $M = 10$ eV.

Summary and work in progress.

- We have examined, in a critical manner, the degree to which the chameleon models evade existing bounds on the violation of UFF as a result of the famous *thin shell* effects.
- We have proposed a method to solve the two body problem for the chameleon fiedl, using a quadratic approximation for the the potential.
- We confirm that the force on the test body depends on the test body composition and for some values of the free parameters the estimates are varios orders of magnitude larger than predictions made in the literature.
- We have also compared our predictions with the available bounds from experiments that test violations of the WEP. We were able to restrict a new region in the plane $n - \beta$.
- The effect of the metal shell surrounding the test bodies in the experimental setup, is to reduce the predicted effect
- We will extend the analysis for the cases where the *thick shell* approximation for the large body is appropiate

MOG effects in dwarf galaxies

- Alternative gravity theories predict the existence of a fifth force in low density enviroments.
- Dwarf galaxies in low density environments are ideal laboratories to test this effects.
- Vikram et al. have analyzed the following effects
  - Differences in the rotation curves of stellar and gaseous disks.
  - Distinct morphological and dynamical effects in the stellar disk.
  - An asymmetry in the rotation velocity curve of the stellar disks along the direction of infall.
  - The spatial separation of the stellar disk from the dark matter and gas

Stellar and Gaseous Rotation curves in Dwarf galaxies

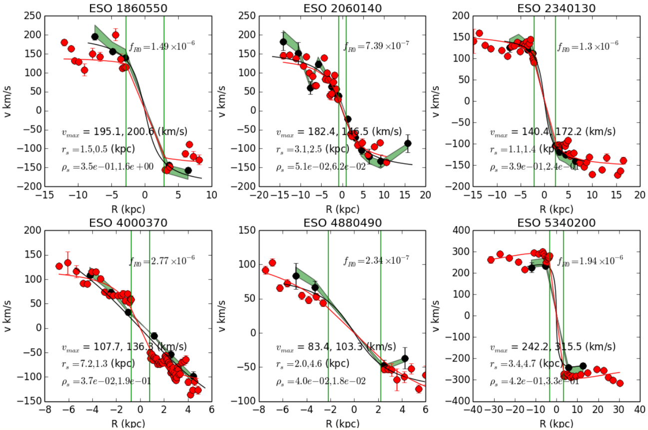


Figure: Vikram et al 2014

Simulations of MOG in dwarf galaxies

- We will use a modified version of ECOSMOG: include baryons
  1. Dwarf galaxies in Λ_{CDM}
  2. Dwarf galaxies in MOG.

Obrigado !!!! Muchas gracias!!!