The Equivalence Principle in the Dark Sector

N. Mohapi

with A. Hees, J. Larena

Department of Mathematics
Rhodes University

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Is the the EEP valid for Dark Matter?

- DM has not been directly detected
- Direct tests of the EEP with DM not possible
- DM effects noticeable on galactic and larger scales
- Indirect constraints can be reached in different metric theories of gravity
- One of the simplest has a matter action of the form

$$S_{mat} = S_l \left[A_l^2(\varphi) g_{\mu\nu}, \Psi_l\right] + S_d \left[A_d^2(\varphi) g_{\mu\nu}, \Psi_d\right]$$

- Corresponding simplest geometrical action with a scalar field

$$S_{geom} = \int \frac{1}{2\kappa} \left[R - 2g_{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi\right] \sqrt{-g}\; d^4x$$

The EEP in a Non-Universally Coupled Theory

- The PPN parameter, γ, can be related to the coupling in the following way (Damour and Esposito-Farèse [1996])

$$\gamma - 1 = -2\frac{\alpha^2_{LM,\varphi_0}}{1+\alpha^2_{LM,\varphi_0}}$$

- A difference in coupling strengths leads to a violation of the EEP

$$\alpha_{i,\infty} = \left.\frac{\partial \ln A_i(\varphi)}{\partial\varphi}\right|_{\varphi=\varphi_\infty}$$

- The differential acceleration of a SM body and a DM body falling under the gravitational field of a SM body takes the form

$$\left(\frac{\Delta a}{a}\right)_{l;l-d} = \frac{(\alpha_{l,\infty} - \alpha_{d,\infty})\alpha_{l,\infty}}{1+\frac{1}{2}\left(\alpha^2_{l,\infty} + \alpha_{d,\infty}\alpha_{l,\infty}\right)},$$

Galactic Model

- Static, spherically symmetric space-time in weak field gravitational limit
- Dust galaxies with power law densities
  - Luminous density - $r^{-\delta}\rho_0^{(\delta)}$
  - Total density - $r^{-\gamma}\rho_0^{(\gamma)}$
- Weak field

$$\frac{A_I(\varphi)}{A_{I,\infty}} \approx 1 + \alpha_{I,\infty}(\varphi - \varphi_\infty)\,.$$

- Analytical solution for $\varphi = \varphi_\gamma + \varphi_\delta + \varphi_\infty$

Gravitational Lensing and Velocity Dispersion

- The Einstein radius has two contributions

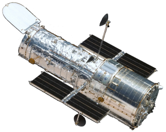
$$\theta_E = \theta_{E,GR} + \theta_{E,\varphi}$$
$$\theta_{E,\varphi} = \alpha_{l,\infty}^2 n_1 + \left(\alpha_{l,\infty}^2 - \alpha_{l,\infty}\alpha_{d,\infty}\right) n_2.$$

- Similarly, for the Velocity dispersion averaged over the line-of-sight luminosity weighted over the spectroscopic aperture $w(R) = e^{\frac{-R^2}{2\bar{\sigma}_{atm}^2}}$:

$$\sigma_\star^2 = \sigma_{\star,GR}^2 + \sigma_{\star,\varphi}^2$$
$$\sigma_{\star,\varphi}^2 = \alpha_{l,\infty}^2 m_1 + \left(\alpha_{l,\infty}^2 - \alpha_{l,\infty}\alpha_{d,\infty}\right) m_2,$$

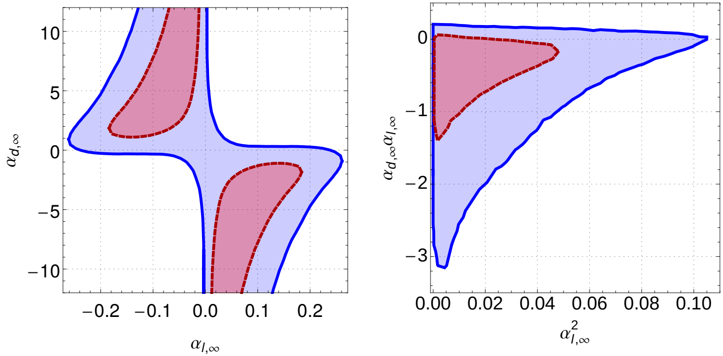
Data

- Galactic quantities (SDDS Gavazzi et al. [2007]):
  - Luminous matter profile parameter
  - Redshift to the lens and to the source
  - Luminosity of each galaxy
  - The effective radius of each galaxy
- Cosmological quantities H_0 and Ω_Λ

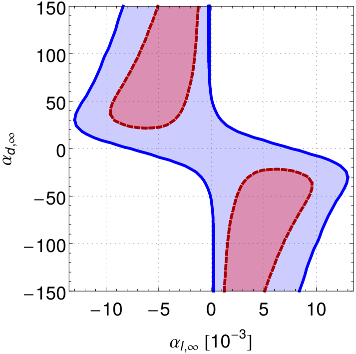


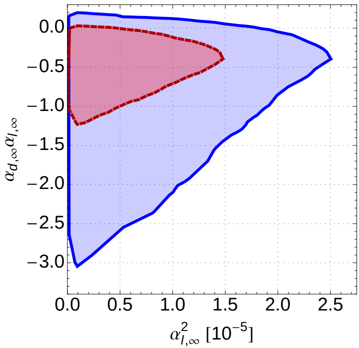
- The remaining galactic quantities will be marginalized over

Analysis Using Only Galactic Observations I



Combined Solar System and Galactic Observations Analysis I





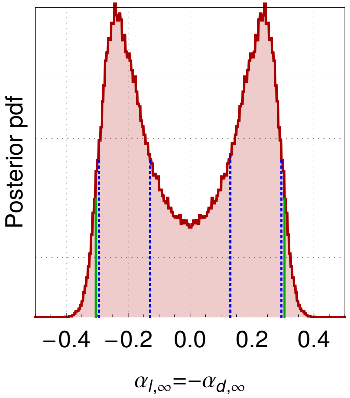
Side by Side Comparison

Table : Estimation of the 1σ and 2σ marginal credible intervals obtained using galactic observations alone.

Parameter	1σ	2σ
$\alpha^2_{l,\infty}$	[0 , 0.023]	[0 , 0.063]
$\alpha_{l,\infty}\alpha_{d,\infty}$	[-0.67 , 0.0]	$[-1.91\,,\,0.17]$
$(\Delta a/a)_{l;l-d}$	$[-0.004\,,\,0.84]$	$[-0.19\,,\,3.53]$

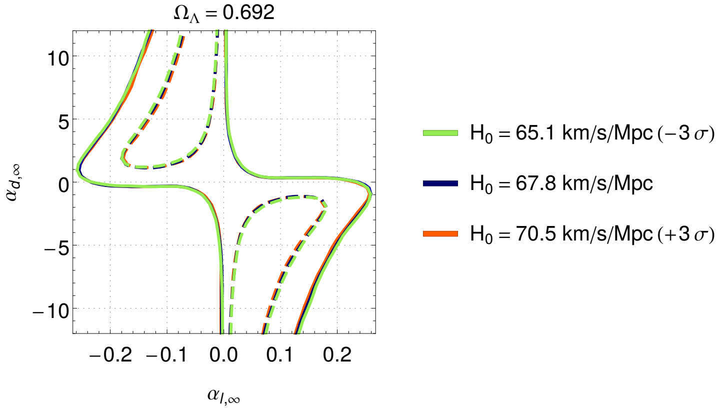
Parameter	1σ	2σ
$\alpha_{l,\infty}\alpha_{d,\infty}$	$[-0.81\,,\,-0.07]$	$[-2.15\,,\,0.10]$
$(\Delta a/a)_{l;l-d}$	$[-0.003\,,\,0.98]$	$[-0.14\,,\,4.09]$

Coupling strengths of same magnitude but opposite signs

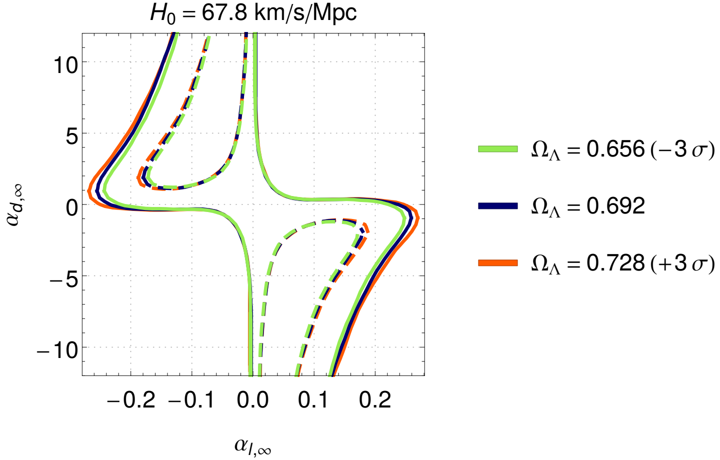


Parameter	1σ	2σ
$\alpha_{l,\infty}$	$\pm[0.128\,,0.295]$	$[-0.304\,,0.304]$

Influence of the H_0 and Ω_Λ I



Influence of the H_0 and Ω_Λ II



Summary

- Tension between the framework for gravity and the other fundamental forces motivates experimental tests of the EEP
- Cosmological observations support the existence of a Dark Sector the physics of which is little understood
- We have examined the EEP in the dark sector on galactic scales within the framework of a generic non-universally coupled STT
  - We have constrained $\left(\frac{\Delta a}{a}\right)_{l;l-d}$ at 10^{-1} on galactic scales
  - $\alpha_{d,\infty}$ remains poorly constrained
  - The constraints may be improved by using observables dominated by the dynamics of DM
  - $\left(\frac{\Delta a}{a}\right)_{l;l-d}$ is compatible with GR at 1-σ
- See arXiv:1510.06198