Physics Letters B 769 (2017) 491–497

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Constraining spatial variations of the fine-structure constant in symmetron models

A.M.M. Pinho [a,b,c], M. Martinelli [d], C.J.A.P. Martins [a,e,*]

[a] Centro de Astrofísica, Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal
[b] Faculdade de Ciências, Universidade do Porto, Rua do Campo Alegre 687, 4169-007 Porto, Portugal
[c] Institut für Theoretische Physik, Ruprecht-Karls-Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany
[d] Institute Lorentz, Leiden University, PO Box 9506, Leiden 2300 RA, The Netherlands
[e] Instituto de Astrofísica e Ciências do Espaço, CAUP, Rua das Estrelas, 4150-762 Porto, Portugal

ARTICLE INFO

Article history:
Received 13 February 2017
Received in revised form 11 April 2017
Accepted 12 April 2017
Available online 14 April 2017
Editor: M. Trodden

Keywords:
Cosmology
Fundamental couplings
Fine-structure constant
Astrophysical observations

ABSTRACT

We introduce a methodology to test models with spatial variations of the fine-structure constant α, based on the calculation of the angular power spectrum of these measurements. This methodology enables comparisons of observations and theoretical models through their predictions on the statistics of the α variation. Here we apply it to the case of symmetron models. We find no indications of deviations from the standard behavior, with current data providing an upper limit to the strength of the symmetron coupling to gravity ($\log\beta^2 < -0.9$) when this is the only free parameter, and not able to constrain the model when also the symmetry breaking scale factor a_{SSB} is free to vary.

1. Introduction

Astrophysical tests of the stability of dimensionless fundamental couplings such as the fine-structure constant α are a powerful probe of cosmology as well as of fundamental physics [1,2]. The analysis of a dataset of 293 archival data measurements from the Keck and VLT telescopes by Webb et al. provided an indication of spatial variations with an amplitude of a few parts per million, with a statistical significance of $4-\sigma$ [3]. Even though there are concerns about possible systematic effects in this dataset [4] and the statistical significance itself decreases when this dataset is analyzed jointly with more recent data [5], it is important to consider the theoretical implications of such results, also bearing in mind that forthcoming astrophysical facilities will enable much more precise tests in the near future.

At a phenomenological level it is common to fit the astrophysical measurements with a simple dipole, with or without an additional dependence on redshift or look-back time [3,5]. On the other hand, from a theoretical point of view simplistic dipole models would require strong fine-tuning to explain such a behavior, and a physically motivated approach would rely on environmental dependencies [6]. This therefore calls for more robust methodologies which enable accurate comparisons between models and observations. Early work along these lines was done by Murphy et al., who calculated the two-point correlation function of the Keck subsample of the aforementioned archival data, finding it to be consistent with zero [7]. In this paper we move from the two point angular correlation function to the calculation of the angular power spectrum of these measurements. The aim of adopting this approach is to be able to compress the data information in such a way to allow for comparison with the predictions of theoretical models. As a proof of concept, in this paper we apply this method to the case of the symmetron model, for which the environmental dependence of α has been previously studied using N-body simulations [8].

In Section 2 we present a concise overview of the symmetron model. Section 3 presents the methodology used to compress the α measurements into angular power spectra. In section 4 we calculate the theoretical power spectrum for the symmetron model and present our analysis methodology, leading to the results discussed in Section 5. Finally, in Section 6 we summarize our results and the outlook for this methodology.

2. Symmetron model

The symmetron model is a scalar-tensor modification of gravity, introduced in order to achieve an additional long range scalar

* Corresponding author at: Centro de Astrofísica, Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal.
E-mail addresses: am.pinho@thphys.uni-heidelberg.de (A.M.M. Pinho), martinelli@lorentz.leidenuniv.nl (M. Martinelli), Carlos.Martins@astro.up.pt (C.J.A.P. Martins).

http://dx.doi.org/10.1016/j.physletb.2017.04.027

force while still satisfying local gravity constraints thanks to the environment density dependence of its coupling to matter. This modification of gravity is described by the action [9]

$$S = \int dx^4 \sqrt{-g}\Big[\frac{R}{2}M_{pl}^2 - \frac{1}{2}(\partial\phi)^2 - V(\phi)\Big] + S_m(\Psi_m; g_{\mu\nu}A^2(\phi)) \quad (1)$$

where $g = \det(g_{\mu\nu})$, $M_{pl} = 1/\sqrt{8\pi G}$ and S_m is the matter-action. The conformal coupling between the scalar field and the matter fields Ψ_m expressed by $\tilde{g}_{\mu\nu} = g_{\mu\nu}A^2(\phi)$, is assumed to be the simplest one consistent with the potential symmetry,

$$A(\phi) = 1 + \frac{1}{2}\left(\frac{\phi}{M}\right)^2, \quad (2)$$

with M and μ arbitrary mass scales. This coupling leads to a fifth force, which in the non-relativistic limit is given by

$$\vec{F}_\phi \equiv \frac{dA(\phi)}{d\phi}\vec{\nabla}\phi = \frac{\phi\vec{\nabla}\phi}{M^2}. \quad (3)$$

The potential is chosen to be of the symmetry breaking form

$$V(\phi) = -\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4. \quad (4)$$

The dynamics of the scalar field ϕ is determined by an effective potential which in the non-relativistic limit (relevant for the astrophysical measurements) has the form

$$V_{eff}(\phi) = V(\phi) + A(\phi)\rho_m = \frac{1}{2}\left(\frac{\rho_m}{\mu^2 M^2} - 1\right)\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4; \quad (5)$$

this means that in the early Universe or, in general, when the matter density is high, the effective potential has a minimum $\phi = 0$ where the field will reside. As the Universe expands, the matter density dilutes until it reaches a critical density $\rho_{SSB} = \mu^2 M^2$ for which the symmetry breaks and the field moves to one of the two new minima $\phi = \pm\phi_0 = \pm\mu/\sqrt{\lambda}$.

The fifth-force between two test particles residing in a region of space where the field has the value $\phi = \phi_{local}$ can be calculated to be [9]

$$\frac{F_\phi}{F_{gravity}} = 2\beta^2\left(\frac{\phi_{local}}{\phi_0}\right)^2 \sim 2\beta^2\left(1 - \frac{\rho}{\mu^2 M^2}\right), \quad (6)$$

for separations of the Compton wavelength $\lambda_{local} = 1/\sqrt{V_{eff,\phi\phi}(\phi_{local})}$, where the coupling strength to gravity is given by

$$\beta = \frac{\phi_0 M_{pl}}{M^2} \quad (7)$$

For larger separations or in the cosmological background before symmetry breaking, $\phi_{local} \approx 0$ and the force is suppressed. After symmetry breaking, the field moves towards $\phi = \pm\phi_0$ and the force is comparable to gravity for $\beta = \mathcal{O}(1)$. Non-linear effects in the field-equation ensure that the force is effectively screened in high density regions. The symmetry breaks at the scale factor $a_{SSB} = (\rho_{m,0}/\rho_{SSB})$ and the range of the fifth-force when the symmetry is broken is given by $\lambda_{\phi 0} = 1/(\sqrt{2}\mu)$, where local gravity constrains satisfy $\lambda_{\phi 0} \lesssim 1$ Mpc/h for symmetry breaking close to today, i.e. $a_{SSB} \approx 1$ [10].

Since the symmetron scalar field is a dynamical degree of freedom, one naturally expects it to couple to the other degrees of freedom in the Lagrangian, unless a new symmetry is postulated to suppress these couplings. In particular, we can assume that it couples with the electromagnetic sector of the theory [8]

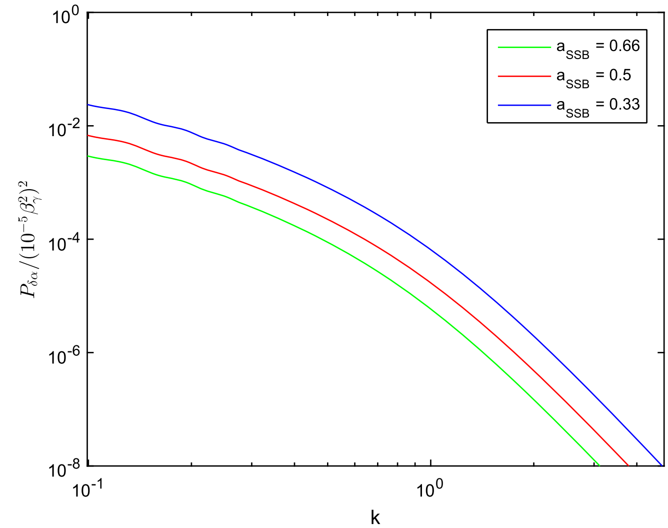

Fig. 1. Theoretical power spectrum $P_{\delta\alpha}(k, a)$ given by eq. (10) as a function of the wavenumber k for $a = 1, \beta = 1, \lambda_{\phi 0} = 1$ Mpc/h and different symmetry breaking scale factors $a_{SSB} = [0.33, 0.5, 0.66]$. Note that strictly speaking eq. (10) only applies in the linear regime, so the behavior beyond this should be taken with care. Following [8] a normalization factor $x = 0.06(0.5/a_{SSB})$ was used. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$$S_{EM} = -\int dx^4 \sqrt{g} B_F(\phi)\frac{1}{4}F_{\mu\nu}^2, \quad (8)$$

where B_F is the gauge kinetic function which leads to $\alpha = \alpha_0 B_F^{-1}(\phi)$. With the same choice of quadratic coupling $B_F^{-1}(\phi) = 1 + \frac{1}{2}\beta_\gamma^2\left(\frac{\phi}{M}\right)^2$ one gets the following variation of the fine structure constant

$$\delta_\alpha \equiv \frac{\Delta\alpha}{\alpha} = \frac{\alpha(\phi) - \alpha_0}{\alpha_0} = B_F^{-1}(\phi) - 1 = \frac{1}{2}\left(\frac{\beta_\gamma\phi}{M}\right)^2. \quad (9)$$

Considering perturbations of the scalar field in Fourier space, the power spectrum for variations of α in the linear regime can be connected to the matter power spectrum $P_m(k, a)$ as follows [8]

$$P_{\delta_\alpha}(k, a) = \left[\frac{3\Omega_m H_0^2 \beta_\gamma^2 \beta^2}{a(k^2 + a^2 m_\phi^2)}\left(\frac{\bar{\phi}}{\phi_0}\right)^2\right]^2 P_m(k, a), \quad (10)$$

where Ω_m and H_0 are the present-day matter density and Hubble parameter, β_γ is the scalar-photon coupling relative to the scalar-matter coupling, k is the co-moving wavenumber, $m_\phi^2 = V_{eff,\phi\phi}(\bar{\phi})$ is the scalar mass in the cosmological background, and $(\bar{\phi}/\phi_0)$ is the background scalar field value. For $a \geq a_{SSB}$ we can write

$$\left(\frac{\overline{\phi(a)}}{\phi_0}\right)^2 = \left(1 - \left(\frac{a_{SSB}}{a}\right)^3\right),$$
$$m_\phi^2(a) = \frac{1}{\lambda_{\phi 0}^2} = \left(1 - \left(\frac{a_{SSB}}{a}\right)^3\right). \quad (11)$$

P_{δ_α} is plotted in Fig. 1; it is also useful to write it as

$$P_{\delta_\alpha}(k, a) = \left[\frac{0.33\Omega_m 10^{-6}\beta_\gamma^2\beta^2}{a((k/m_\phi)^2 + a^2)}\left(\frac{\lambda_{\phi 0}}{Mpc/h}\right)^2\right]^2 P_m(k, a). \quad (12)$$

3. Observational data

Currently available astrophysical measurements of α come from high-resolution spectroscopy of absorption clouds along the line