

Chameleon fields, wave function collapse and quantum gravity

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Abstract. Chameleon fields are quantum (usually scalar) fields, with a density-dependent mass. In a high-density environment, the mass of the chameleon is large. On the contrary, in a small-density environment (e.g. on cosmological distances), the chameleon is very light. A model where the collapse of the wave function is induced by chameleon fields is presented. During this analysis, a Chameleonic Equivalence Principle (CEP) will be formulated: in this model, quantum gravitation is equivalent to a conformal anomaly. Further research efforts are necessary to verify whether this proposal is compatible with phenomenological constraints.

1. Introduction

In this work we discuss a connection between the collapse of the wave function, quantum gravity and chameleon fields. A more detailed discussion can be found in the original proposal [1]. We start with the question: what are chameleon fields? They are quantum fields, typically scalar, with a density-dependent mass and a coupling to baryons [2,3]: in a large-density environment they are massive, while in a small-density environment (for example on cosmological distances), chameleon fields are very light. Here is one of the possible actions that can give us this result:

$$S = \int d^4x \sqrt{-g} \left\{ \frac{M_{Pl}^2 R}{2} - \frac{(\partial\phi)^2}{2} - V(\phi) \right\} + \int d^4x \mathcal{L}_m(\psi_m^{(i)}, g_{\mu\nu}^{(i)}) \quad (1)$$

where the g -metric is the Einstein frame (E-frame) metric, ϕ is the chameleon field, V is a potential for the chameleon and the last term is a matter lagrangian where several different species of particles know gravity through several different metrics. So this is a multi-metric theory by construction. The crucial point about chameleon fields is to understand that their dynamical behaviour in the Einstein frame is not determined only by a potential V but it is determined by an *effective* potential that is the sum of two different contributions. On the one hand, a bare potential V , on the other hand, a matter branch written in the form $\rho B(\phi)$ where ρ is the matter density and B is a function encoding the coupling between matter and chameleon. If there is a competition between V and the matter branch, then we can construct a minimum where the scalar field can sit. Consequently, if we change the matter density, we modify the position of the minimum and also the mass of the chameleon. The ground state and its energy are related to the matter density. The harmonic approximation is valid around one single ground state but the theory is *non-linear*. These comments will be useful in the remaining part of this work.



2. The model

Let us discuss the model for the collapse of the wave function. This model can be obtained, at least partially, from heterotic-M-theory [4]. The non-perturbative string frame (S-frame) lagrangian is

$$\mathcal{L} = \mathcal{L}_{\text{SI}} + \mathcal{L}_{\text{SB}} \quad (2)$$

where

$$\mathcal{L}_{\text{SI}} = \sqrt{-g} \left(\frac{1}{2} \xi \phi^2 R - \frac{1}{2} \epsilon g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - \frac{1}{2} g^{\mu\nu} \partial_\mu \Phi \partial_\nu \Phi - \frac{1}{4} f \phi^2 \Phi^2 - \frac{\lambda_\Phi}{4!} \Phi^4 \right) \quad (3)$$

is a Scale Invariant lagrangian, ϕ is the string dilaton, Φ is another scalar field representative of matter fields and

$$\mathcal{L}_{\text{SB}} = \sqrt{-g} \left(a \phi^2 + b + c \frac{1}{\phi^2} \right) \quad (4)$$

is a Symmetry Breaking (SB) part, namely a stabilizing S-frame potential which breaks scale invariance. All the parameters of the lagrangian are of the order of one (no fine-tuning is present). The set-up we obtain in the S-frame is given by a stabilized dilaton with a very large vacuum energy (much larger than the Dark Energy scale).

Now we move to the E-frame and we ask: what happens to the mass of the dilaton and to the vacuum energy? It has been shown [5] that in the E-frame the dilaton is a chameleon in this model and the E-frame vacuum energy is small in the IR region including all quantum corrections and without fine-tuning. To illustrate these points, let us further analyze the model in the E-frame. Since our intention is to quantize the lagrangian, we want to regularize the theory and we will use dimensional regularization. Therefore, let us write the E-frame lagrangian in D=2d dimensions:

$$\mathcal{L}_* = \sqrt{-g_*} \left(\frac{1}{2} R_* - \frac{1}{2} g_*^{\mu\nu} \partial_\mu \sigma \partial_\nu \sigma + \mathcal{L}_{*matter} \right), \quad (5)$$

where $\mathcal{L}_{*matter}$ turns out to be

$$\mathcal{L}_{*matter} = -\frac{1}{2} g_*^{\mu\nu} D_\mu \Phi_* D_\nu \Phi_* - e^{\frac{2(d-2)}{d-1} \zeta \sigma} \left(\xi^{-1} \frac{f}{4} M_p^2 \Phi_*^2 + \frac{\lambda_\Phi}{4!} \Phi_*^4 \right) \quad (6)$$

and $D_\mu = \partial_\mu + \zeta \partial_\mu \sigma$. σ is the E-frame dilaton. As we can see from formula (6), when the number of spacetime dimensions is different from 4, a direct interaction between dilaton and matter is present and, for this reason, we can write many one-loop Feynman diagrams exploiting this interaction. An explicit calculation shows that, taking into account the various diagrams, a finite result in 4 dimensions is obtained. In other words, when we perform the limit to $D = 4$ in the loop calculation, a factor $D - 4$ cancels a pole in a gamma function and, consequently, a finite interaction vertex in $D = 4$ between dilaton and matter is obtained. This is one of the possible ways an anomaly may present itself. This conformal anomaly induced vertex can be written as

$$\mathcal{L}_{\Phi\Phi\sigma} = -\frac{1}{2} \frac{I}{M_p} \tilde{\Phi}^2 \sigma, \quad (7)$$

where, I is a factor coming from the evaluation of the integrals related to the loops and $\tilde{\Phi}$ comes from the splitting of the matter field in a expectation value and a fluctuating component, $\Phi_* = v + \tilde{\Phi}$. The anomaly induced interaction vertex has the form of a matter branch $\rho\sigma$, where ρ is the matter density. This vertex can be exploited to obtain an infinite number of Feynman diagrams that are an expansion where all loops are taken into account and the final result is

that the E-frame dilaton is a chameleon (see [5] for a detailed discussion of these points). In this model, the E-frame dilaton parametrizes the amount of scale invariance: in this room scale invariance is broken and the dilaton is heavy because the matter density is large, but, on the contrary, in a small density background scale invariance is almost restored and the dilaton is very light. In this way the cosmological constant is under control in this model including all quantum corrections and without fine-tuning of the parameters. For a detailed discussion of these results the reader is referred to [5].

Remarkably, the cosmological constant is under control only in the E-frame and, for this reason, the non-equivalence of different conformal frames at the quantum level has been pointed out in [5]. The E-frame is the physical one. One more remark is necessary. The careful reader may be worried by the absence of a ϕ^4 term in the S-frame lagrangian, because this term is expected from loop calculations. However, as already mentioned in [6], this is not a problem, because the Planck mass is running in this model. In other words, we can include a ϕ^4 term because, after the conformal transformation to the E-frame, this term will correspond to M_p^4 and the (renormalized) Planck mass is exponentially suppressed in the IR [6]. Therefore, ϕ^4 does not clash with the cosmological constant.

3. Chameleonic wave function collapse

Let us discuss the connection between chameleon fields and wave function collapse in this model. How can we give a mass to σ ? The mass of the E-frame dilaton is related to an explicit breaking of scale invariance and this result can be obtained in various ways. The first possibility (let us call it PATH1) is to exploit the anomaly-induced interaction vertex, however, the matter density is an exponential function of σ . Is this run-away behaviour problematic? It seems, at first sight, that it might be difficult to obtain the chameleonic minima. Happily, this is not the case, because we have a second possibility (let us call it PATH2) to stabilize σ : we can exploit gauge fields. Indeed, σ is coupled to the F^2 -term of gauge fields and performing the variation of the action we find

$$\delta S = \int d^4x \sqrt{-g_*} \{ -V_{,\sigma}(\sigma) \delta\sigma - \frac{1}{16\pi} \frac{\partial \alpha_g^{-1}}{\partial \sigma} 2(B^2 - E^2) \delta\sigma \} \quad (8)$$

where we introduced explicitly the electric and magnetic fields through the formula $F_{\mu\nu} F^{\mu\nu} = 2(B^2 - E^2)$. We define $\rho_\gamma = \frac{B^2 - E^2}{8\pi}$. Do not confuse $\rho_\gamma \propto B^2 - E^2$ with the electromagnetic energy density (proportional to the *sum* $B^2 + E^2$). If we require $\delta S = 0$ we thus have the following term in the equation of motion for σ :

$$-V_{,\sigma}(\sigma) + \frac{1}{\alpha^2(\sigma)} \frac{\partial \alpha}{\partial \sigma} \rho_\gamma. \quad (9)$$

From this formula we infer that the chameleonic competition with the F^2 -term of gauge fields is present granted that we switch off the couplings in the large σ region (this a rather natural requirement in this model because the large σ region is the weak coupling region of the string). In this way we can construct chameleonic minima, for example, inside standard matter the chameleonic minimum is guaranteed by the F^2 -term of gluons.

These comments are related to the collapse of the wave function. When we perform a quantum measurement, we induce a chameleonic jump from one ground state to a different ground state and we break the superposition principle for a short time because the harmonic approximation is not valid during the jump. PATH1 is useful when a shift of matter density is part of a measurement. For example, in a electronic diffraction experiment, when electrons enter into the screen, the matter density is shifted to a larger value and, consequently, the dilaton jumps from a low-density ground state to a high-density one and the superposition principle is broken during

the jump. PATH2 is useful to rediscuss the Stern-Gerlach (SG) experiment. Indeed, when particles enter into the magnetic field of a SG, ρ_γ is switched on and the chameleon mechanism will induce a dilatonic jump. In both cases (PATH1 and PATH2), the chameleonic jump can be summarized by a conformal anomaly, because when we modify the value of σ , we change also the matter density ($\rho \simeq e^{-4k\sigma}$, where k is a constant) and, therefore, we modify the anomaly induced interaction vertex $\rho\sigma$.

We know that during a measurement the superposition principle is broken. However, this is not enough to claim the existence of a (non-unitary) projection operator. Let us further elaborate this point. Consider a no-particles vacuum. To create particles we exploit creation operators. Once particles have been created, the number density (hence the local vacuum energy in the chameleonic effective potential) is non-vanishing and the state of minimum energy (in this room) is *not* annihilated by all the annihilation operators. Our system is similar to the Free Electron Gas Model (FEGM) granted that we compare (1) the electron in FEGM with the matter particle in the chameleon model and (2) the Fermi energy in FEGM with the non-vanishing local vacuum energy. Now the matter energy density is non-vanishing. We can create more particles, but we have to use creation operators which are different with respect to the creation operators we started with. The two sets of operators (hence the two sets of quantum fields, before and after measurement) are related to each other by a NON-UNITARY (see e.g. [7]) Bogoliubov transformation: this is the projection operator for the collapse. Happily, an alternative route gives the same result: projective representations of the conformal group [1]. In this way a superselection rule is obtained [1] when the conformal anomaly is non-negligible (i.e. when the dilaton is stabilized).

4. Chameleonic Equivalence Principle

The lagrangian of this chameleonic model satisfies a Chameleonic Equivalence Principle (CEP) pointed out in [1]. Here is the CEP:

For each pair of vacua $V1$ and $V2$ allowed by the theory there is a conformal transformation that connects them and such that the mass of matter fields $m0, V1$ is mapped to $m0, V2$. When a conformal transformation connects two vacua with a different amount of conformal symmetry, an additional term (in the form of a conformal anomaly) must be included in the field equations and this additional term is equivalent to the quantum gravitational field.

Some comments are in order. 1) This is not a postulate, it is a principle. In other words, the CEP is a property satisfied by our lagrangian. 2) The CEP is reminiscent of the Faraggi-Matone equivalence principle for quantum mechanics [8]. 3) There are a number of consequences of the CEP, for example, we can discuss (a) chameleonic matter [1], (b) quantum helioseismology [9] and (c) quantum gravity. Let us further analyze quantum gravitation.

How can we describe a complete absence of gravity? Our general-relativity-based intuition tells us that we must remove all the masses and all the energy sources (including vacuum energy). We can switch on a small *gravitational field* by adding a massive (or even massless) particle, the chameleon mechanism will slightly reduce the amount of conformal symmetry and the jump can be summarized by a *conformal anomaly*. In this way a connection between gravity and conformal anomaly is present in this model. In general relativity (GR) when we move from an inertial to a non-inertial frame, additional terms must be included and these terms describe gravity in harmony with Einstein's equivalence principle. To proceed further, let us consider the following strategy: let us replace the inertial frame of GR with a conformal ground state of the chameleonic model and let us summarize this replacement writing symbolically

Inertial frame \implies Conformal ground state.

Moreover, let us consider various replacements together (once again GR is before the arrow, while the chameleon model is after the arrow):

Non inertial frame \implies Non conformal ground state

General coordinate transformation \implies Conformal transformation

Metric and connection (i.e. the additional terms mentioned above) \implies Conformal anomaly

In this way a dictionary between GR and chameleonic quantum gravity is obtained. In the chameleonic model, conformal anomaly describes quantum gravitation in harmony with the CEP.

5. Conclusions

In this model, quantum gravitation is equivalent to a conformal anomaly and the collapse of the wave function is, in this model, a quantum gravity effect.

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