Cosmic Tsunamis Wrecking Screening Mechanisms in Modified Gravity

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High energy astrophysical phenomena, such as supernovae explosions or collapse of domain walls, create waves in the new degrees of freedom of modified theories of gravity. The propagation of such waves into our galaxy and solar system significantly impacts the efficiency of screening mechanisms, thereby threatening the viability of these theories.

1 Introduction

Any modification to Einstein's gravity must include a screening mechanism to hide the new extra degree of freedom and reduce the theory to general relativity in the well tested regimes [1]. The common feature to all the screening mechanisms is that they are built, and their efficiency tested, assuming the so called quasistatic approximation for the field equations. We find that, when relaxing the quasistatic approximation, the presence of waves may result in striking consequences for the efficiency and viability of the screening mechanism. In particular, we show that energetic waves in the extra degree of freedom strongly weaken the screening process for a theory with a standard kinetic term. Therefore, modified gravity theories previously considered viable may, in fact, be ruled out by the present days gravity experiments and observational data. To understand the implications of these waves in greater detail, we simulate a scalar degree of freedom with externally generated waves. The waves propagate radially in towards a spherically symmetric matter distribution, modeled after the Milky Way halo.

1.1 The symmetron

As a working example, we implement a specific form of modified gravity called the *symmetron* [2]. In spite of this specificity, the results presented here should be considered for any modified gravity theories that have extra degrees of freedom with wave-type equations of motion. We consider the following general scalar-tensor action for canonical scalar fields:

$$S = \int \left[\sqrt{-g} \left(\frac{R}{16\pi G} - \frac{1}{2}\phi^{,\mu}\phi_{,\mu} - V(\phi) \right) + \sqrt{-\tilde{g}}\tilde{\mathcal{L}}_m \right] \mathrm{d}^4 x, \tag{1}$$

$V(\phi)$ is the quartic symmetron potential with the three free parameters μ, λ, and V_0

$$V(\phi) = -\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4 + V_0. \tag{2}$$

The Jordan frame metric $\tilde{g}$ is related to the Einstein frame metric according to the conformal transformation $\tilde{g}_{\mu\nu} = C(\phi)\, g_{\mu\nu}$. The specific form of C for the symmetron is $C(\phi) = 1 + (\phi/M)^2$. The mass scale M is a free parameter that gives the strength of the interaction with the matter fields. The equation of motion for the scalar field is

$$\ddot{\phi} + 3H\dot{\phi} - \frac{1}{a^2}\nabla^2\phi = -\rho\frac{C_{,\phi}(\phi)}{2C(\phi)} - V_{,\phi}(\phi)\,, \tag{3}$$

The Einstein frame metric is assumed to be a flat Friedmann-Lemaître-Robertson-Walker metric with a single scalar perturbation Ψ_E, specifically

$$\mathrm{d}s^2 = -\left(1 + 2\Psi_E\right)\mathrm{d}t^2 + a^2(t)\left(1 - 2\Psi_E\right)\mathrm{d}r^2. \tag{4}$$

As a working example, we fix the symmetron parameters such that $\beta = 1$, $a_{\mathrm{SSB}} = 0.5$, and $\lambda_0 = 0.25\,\mathrm{Mpc}/h$. This is equivalent to a symmetron mass
$M = 3.4 \times 10^{-4}\,M_{\mathrm{pl}}$. These parameters are being widely assumed to represent a viable model that evades all the bounds from both Solar System and astrophysical data. With this choice of parameters, we aim to prove that even such a model may, in fact, be ruled out when one fully integrates the equations of motion of the field without the quasistatic assumption and, thereby, allow for the effects of the scalar waves.

2 Solar System constraints

To test how screening mechanisms work in the Solar System, the community generally chooses a static, spherically symmetric matter distribution to mimic the Galaxy. We follow this approach and choose the Navarro-Frenk-White density profile with the characteristics to represent the Milky Way Galaxy, specifically with a virial radius of $r_{\mathrm{vir}} = 137\,\mathrm{kpc}/h$ and concentration $c = 28$, resulting in a halo mass of $1.0 \times 10^{12} M_{\odot}$ and a circular velocity of 220 km/s at 8 kpc. The reason for the high value of the concentration is simply that we are modeling not only dark matter, but the total matter of the Milky Way, which is more concentrated than the pure dark matter halo [5].

One of the most precisely measured gravity parameters to probe deviations from general relativity is the parametrized post-Newtonian (PPN) parameter γ. It can be expressed as the ratio of the metric perturbations in the Jordan frame, Ψ_J and Φ_J:

$$\gamma - 1 = -\frac{\phi^2}{M^2}\frac{2}{\frac{\phi^2}{M^2} - 2\Psi_E - 2\Psi_E\frac{\phi^2}{M^2}}. \tag{5}$$

In general relativity, $\gamma = 1$ exactly. The strongest constraint to date, measured by the Cassini spacecraft, is $\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5}$.

The symmetron screening works by modifying the effective potential such that the field value is pushed towards zero in high density regions – like the inner regions of the Galaxy. This results in $\gamma - 1 \to 0$, such that the deviations from general relativity in the proximity of the Solar System are small. The same occurs for the fifth force F_ϕ associated to the scalar field [3,4].

3 Results

Figure 1 shows an example of how the PPN parameter γ changes when a wave enters the inner 100 kpc of the Milky Way. The vertical line shows the position of the Solar System, which we assume to be 8 kpc from the Galactic center. The modifications to gravity are initially screened very well in the regions around this position, with $|\gamma - 1| < 10^{-8}$ (blue dashed line). However, after the wave has arrived (black solid line), the scalar field is perturbed enough to breach the Solar System constraints, $|\gamma - 1| > 2 \times 10^{-5}$. In other words, the screening mechanism breaks down under these circumstances. The wave in this particular simulation has an amplitude $A = 0.01$ and a frequency $\omega = 40\ \mathrm{Myr}^{-1}$. The cusps are regions where the scalar field is zero, which exist since the wave oscillates both above and below $\chi = 0$.

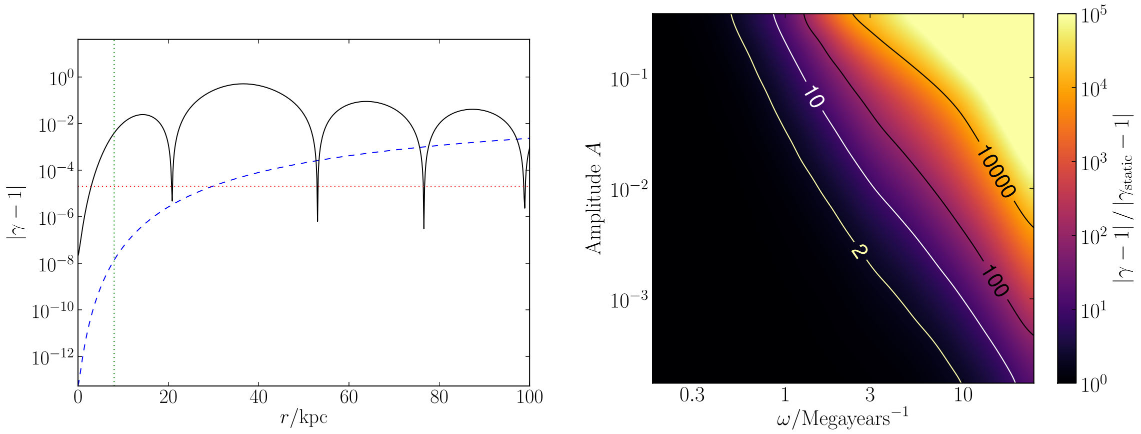

Figure 1 – LEFT: The PPN parameter $|\gamma-1|$, plotted against distance from the center of the Galaxy. The curves show $|\gamma-1|$ in the quasistatic case (blue dashed line), as well as after a scalar wave has entered the halo (black solid line). The vertical (green dotted) line indicates the position of the Solar System, and the horizontal (red dotted) line indicates the highest allowed value of $\gamma-1$ in the Solar System from the Cassini experiment. When the wave enters the Milky Way, it increases the value of $|\gamma-1|$ by several orders of magnitude. RIGHT: Maximum increase in the PPN parameter $|\gamma-1|$ due to incoming scalar field waves at the position of the Sun in the Galaxy (8 kpc from the center) as a function of amplitude and frequency of the incoming waves. The color indicates by which factor $|\gamma-1|$ is increased when compared to the quasistatic case with no waves.

When measuring γ arising from a single sinusoidal wave with low frequency, there is a possibility that the local wave is between two extrema at the time of measurement. This could render this kind of detection difficult for several thousand years. Nevertheless, given that various astrophysical events—such as supernovae—can generate waves, the probability that one of the wavefronts would bring us away from the minima at the present time is not negligible [6]. In order to investigate how our result depends on the frequency ω and amplitude A of the waves, we simulate incoming waves with several values of these two parameters. Figure 1 shows the maximum growth of $|\gamma-1|$ that we found at 8 kpc from the Galactic center. Brighter colors mean a larger increase of $|\gamma-1|$ compared to the quasistatic approximation. The values of the frequency and amplitude that lie in the black region of the plot, give waves that do not significantly impact γ compared to the quasistatic solution. Therefore, in this region of parameter space, the screening mechanism is efficient and hides the extra degree of freedom from gravity experiments.

From Figure 1, one concludes that higher frequencies and amplitudes for the incoming scalar waves give larger deviations from the general relativity result (i.e., $\gamma = 1$). The limit where amplitude and frequency go to zero is equivalent to the quasistatic limit, where no waves are produced and their energy is zero. As one goes into the high frequency and amplitude regime, the waves carry more energy, and therefore, the PPN parameter γ starts deviating significantly from the quasistatic limit. Note that, since in the symmetron model, the fifth force is $F_\phi \propto \nabla\phi^2/M^2$, these values can be immediately extrapolated to the impact of the waves on this quantity.

The dependence of the γ PPN parameter on the wave amplitude is straightforward to understand: When a wave propagates through the screened regions of the halo, a larger amplitude wave will lead to larger displacements of the field from the screening value $\phi \approx 0$. Therefore, $|\gamma-1| \underset{\sim}{\propto} \phi^2$ will increase accordingly.

The frequency dependence of the γ parameter is a consequence of the following: The effective potential of the symmetron grows steeper and narrower in high density areas. In other words, the mass of the field increases towards the center of the halo. Therefore, it becomes more difficult to perturb the field away from the minimum, and a higher wave energy is needed to displace it. Specifically, if the energy of the external waves is small compared to the mass of the field, the field will not be perturbed and the γ parameter will not be affected.

The results obtained imply that if waves with sufficient amplitude or frequency can somehow be generated in a given model for modified gravity, they will have to be taken into account when constraining the model parameters. Cosmic tsunamis, resulting from extreme events, could even completely ruin the screening mechanisms in modified gravity by increasing the deviations from general relativity by several orders of magnitude compared to the quasistatic case. A subject that that must be discussed now is the generation of such waves. Extreme events on small scales, such as collision of neutron stars, stellar, or super-massive black holes are obvious examples. Generation of waves by pulsating stars are another possibility.

In the specific case of the symmetron model, it is possible to obtain waves from events that occur on cosmological scales. First, the symmetron model undergoes a phase transition when the density falls below a specific threshold. This transition first occurs in voids when the expansion factor is close to a_{SSB}. When this happens, the scalar field receives a kick, which produces waves traveling from the center of the voids towards the dark matter halos. We find that, in a symmetron model with slightly different parameters, the amplitude of cosmological waves is typically smaller that 0.1 and the associated frequencies are of the order of 1/Myr. Note that these values depend on the model parameters and, hence, must be taken only as indicative. Scalar waves can also be created through the collapse of topological defects, which are known to exist in any model in which such phase transition occurs.

4 Conclusions

The viability of modified theories of gravity is strongly dependent on the existence of a screening mechanism that suppresses any extra degrees of freedom at these scales. Here, we show that waves propagating in an additional gravity degree of freedom, may significantly spoil the screening mechanism and, hence, jeopardize the viability of the given modified gravity theory. Specifically, we show that waves in a given model can increase the amplitude of the fifth force and the PPN parameter $|\gamma - 1|$ by several orders of magnitude, rendering theories previously assumed to be viable unfeasible. To demonstrate that similar effects can be expected in other theories, we propose a simple calculation regarding a viable chameleon model ($n = 1$, $M = 10^{-3} M_{\mathrm{Pl}}$, $\Lambda = 2\,\mathrm{meV}$). When a white dwarf explodes as a type Ia supernova, waves in the chameleon field will be measurable at several Mpc distance.

The applicability of the quasistatic approximation should be carefully analyzed when obtaining constraints for modified gravity theories from Solar System experiments. Our results show that, in modified gravity, the Solar System—and indeed, the Galaxy—can not be studied in isolation; events that occur on cosmological scales might actually impact events that happen in the inner Solar System. While our conclusions make it more difficult to build viable modified gravity theories based on screening mechanisms, the existence of nonstatic effects opens a completely new window for developing new tests of gravity.

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