Horndeski and the Sirens

Charles Dalang[1], Pierre Fleury[2] Lucas Lombriser[1]

[1]Département de Physique Théorique, Université de Genève

[2]Instituto de Física Teórica UAM-CSIC, Universidad Autónoma de Madrid

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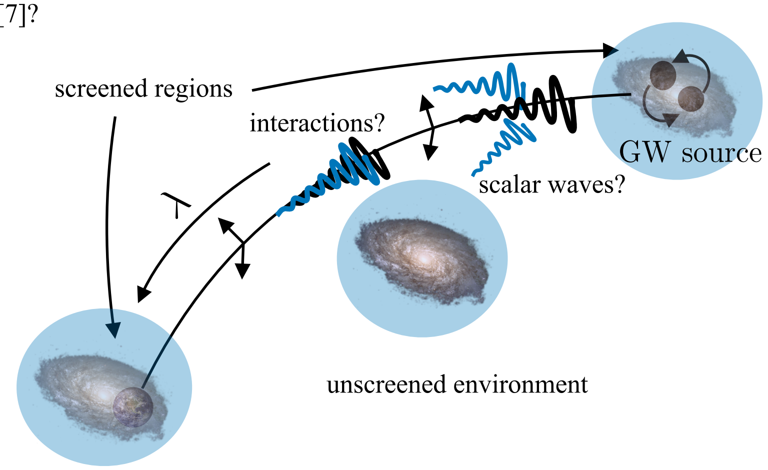
UNIVERSITÉ DE GENÈVE

Abstract

In dark-energy models where a scalar field is nonminimally coupled to the spacetime geometry, gravitational waves (GWs) are expected to be supplemented with a scalar mode. Such scalar waves may interact with the standard tensor waves, thereby affecting their observed amplitude and polarization. Understanding the role of scalar waves is thus essential in order to design reliable gravitational-wave probes of dark energy and gravity beyond general relativity (GR). We study gravitational wave propagation signatures from a large classe of alternative gravity theories and some possible limitations.

Introduction

Cosmologically viable scalar-tensor theories display so called screening mechanism, which allow for the approximate recovery of GR in high density regions such as galaxies or the Solar-System where tight constraints on gravity exist. If GWs are generated according to GR, can deviations appear during their propagation? In particular, is the polarization parallel transported along the geodesic? Are there extra polarizations? Do we expect GWs to decay into scalar waves? Is the amplitude affected by the scalar field or do GWs decay as the inverse of the luminosity distance as in GR providing *standard sirens* in analogy to standard candles such as supernovae type 1a or Cepheids [7]?



Reduced Horndeski theories

The lagrangian density of scalar-tensor theories predicting a GW speed $c_T = c$ and having enough freedom to screen deviations from GR in high density environment take on the following form [6]

$$\mathcal{L} = \underbrace{G_2(\varphi, X)}_{\substack{\text{Quintessence} \\ \text{K-essence} \\ \text{cosmo. constant}}} + \underbrace{G_3(\varphi, X)\Box\varphi}_{\substack{\text{Kinetic Gravity Braiding} \\ \text{Vainshtein screening}}} + \underbrace{G_4(\varphi)R}_{\substack{\text{Brans-Dicke} \\ \text{Chameleons}}}$$

$$X = -\partial_\mu\varphi\partial^\mu\varphi/2$$

Equations of motion on a curved background

We study linear perturbations on a generic curved background spacetime [1,2]

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}\,, \qquad ||h_{\mu\nu}|| \ll 1\,,$$
$$\varphi = \bar{\varphi} + \delta\varphi\,, \qquad |\delta\varphi| \ll 1\,.$$

and get complicated equations of motion after diagonalization

$$\gamma_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\bar{g}_{\mu\nu}h + \bar{G}_4^{-1}\left(\bar{G}_{3,X}\bar{\varphi}_{,\mu}\bar{\varphi}_{,\nu} - \bar{G}_{4,\varphi}\bar{g}_{\mu\nu}\right)\delta\varphi\,,$$

in a generalized harmonic gauge $\bar{\nabla}^\mu\gamma_{\mu\nu} = 0$,

$$\Bigg[\underbrace{\begin{pmatrix} K_\varphi{}^{\varphi\alpha\beta} & 0 \\ 0 & K_{\mu\nu}{}^{\rho\sigma\alpha\beta}\end{pmatrix}}_{\text{Kinetic}}\bar{\nabla}_\alpha\bar{\nabla}_\beta + \underbrace{\begin{pmatrix} A_\varphi{}^{\varphi\alpha} & A_\varphi{}^{\rho\sigma\alpha} \\ A_{\mu\nu}{}^{\varphi\alpha} & A_{\mu\nu}{}^{\rho\sigma\alpha}\end{pmatrix}}_{\text{Amplitude}}\bar{\nabla}_\alpha + \underbrace{\begin{pmatrix} M_\varphi{}^{\varphi} & M_\varphi{}^{\rho\sigma} \\ M_{\mu\nu}{}^{\varphi} & M_{\mu\nu}{}^{\rho\sigma}\end{pmatrix}}_{\text{Mass}}\Bigg]\begin{pmatrix}\delta\varphi \\ \gamma_{\rho\sigma}\end{pmatrix} = \begin{pmatrix}0 \\ 0\end{pmatrix}$$

The kinetic, amplitude and mass matrix depend on the functions, G_2, G_3 and G_4 and mix the scalar and tensor degrees of freedom. Do they impact the amplitude or polarization evolution?

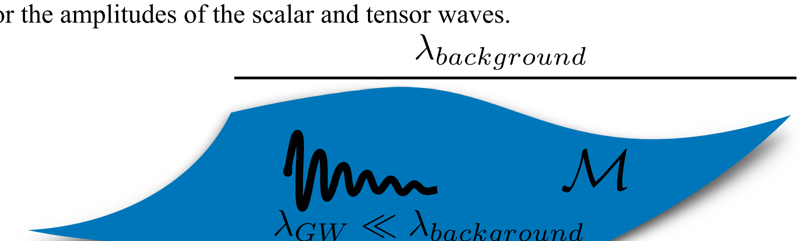
Short wavelength approximation

We make wave Ansätze

$$\delta\varphi(x) = \Phi(x)e^{i\omega v(x)}\,, \qquad v_{,\mu} \equiv p_\mu$$
$$\gamma_{\mu\nu}(x) = \Gamma_{\mu\nu}(x)e^{i\omega w(x)}\,, \qquad w_{,\mu} \equiv k_\mu$$

amplitude phase large ω

In the short wavelength approximation, the mass-like terms are negligible. This simplifies drastically the equations of motion and allows us to solve for the amplitudes of the scalar and tensor waves.



Gravitational distance

Solving for the amplitude, we find that the plus and cross modes decay as the inverse of the gravitational distance, related to the standard luminosity distance by [1,2]

$$D_G = \underbrace{\sqrt{\frac{\bar{G}_4(\bar{\varphi}(t_o, \boldsymbol{x}_o))}{\bar{G}_4(\bar{\varphi}(t_s, \boldsymbol{x}_s))}}}_{\simeq 1} D_L$$

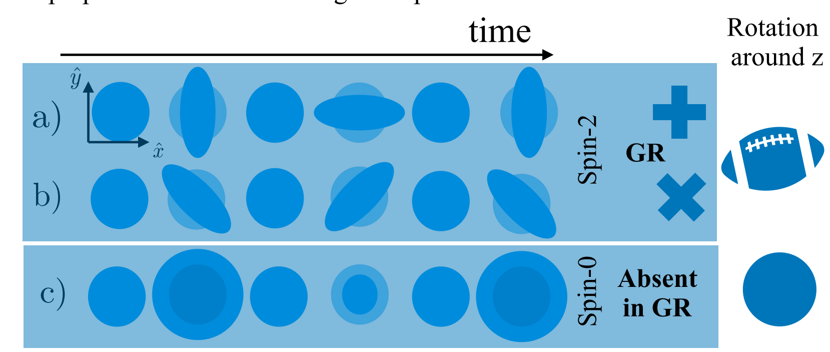
Popular screening mechanisms [3,4]

The measurement of D_G together with an associated redshift to the source to infer $D_L(z)$ was believed to set tight constraints on the evolution of G_4.

This is unfortunately jeopardize by the assumption of screening at the source for GR-like emission and at the observer to satisfy Solar-System and galactic tests of gravity.

Polarization content

High frequency Horndeski GWs carry three polarization modes, the plus, the cross polarization modes and an extra breathing mode. We find that those do not interact during their propagation in curved spacetime. For a wave travelling in the z direction, their impact on a sphere of particles is a superposition of the following three patterns



The signature of scalar waves survives chameleon screening in the limit of high frequency waves [2,5].

Conclusions

We find that standard sirens allow to probe the local value of G_4 at the source and observer [1,2], which have been assumed and constrained to be screened, respectively [8]. That means that in practice we do not expect any signature on the observed gravitational distance from the scalar field due to a coherent evolution of G_4 on cosmological scales [3,4]. There exists an extra polarization mode with respect to GR, the breathing mode, which if emitted, may give a signature at the observer, if the frequency of the scalar wave is high enough [2,5]. There is no energy exchange between scalar and tensor waves during the propagation of the waves such that even if the emission is GR-like, there is no leakage to scalar waves [2].

References

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