Modified gravity versus shear viscosity: imprints on the scalar matter perturbations

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Cosmological scalar perturbation theory studied in the Newtonian gauge for cosmological scalar potentials, \( \Phi \) and \( \Psi \). In General Relativity (GR) they must coincide (\( \Phi = \Psi \)) in the absence of anisotropic stresses sourced by the energy momentum tensor. On the other hand, it is widely accepted in the literature that potential deviations from GR can be parameterized by \( \Phi \neq \Psi \). The latter feature is therefore present in both GR cosmologies equipped with shear viscous fluids or modified gravity. We study the evolution of scalar matter density perturbations using the redshift-space-distortion based \( f(z)\sigma_8(z) \) data as a tool to differentiate and characterize the imprints of both scenarios. We show that in the \( f(z)\sigma_8(z) \) evolution both scenarios yields to completely different imprints in comparison to the standard cosmology. While the current available data is not sensitive to distinguish modified gravity from viscous shear cosmologies, future precise data can be used to break this indistinguishability.

I. INTRODUCTION

The several available cosmological observables powerfully constrain the background expansion of the universe as the one dictated by the flat-\( \Lambda \)CDM model, i.e., a GR based description for gravity composed of baryonic plus dark matter (\( \Omega_{\text{m0}} \sim 0.3 \)) and a cosmological constant \( \Lambda \) (\( \Omega_{\Lambda} \sim 0.7 \)). However, the background expansion, which can be characterized by the Hubble term evolution \( H_\Lambda \) in the ACDM model, can also be achieved in modified gravity scenarios if suitable choices in their degrees of freedom are made. Therefore, investigation of the perturbative cosmological sector is necessary as an additional tool such as to increase our ability to distinguish GR from its possible candidate extensions.

The recent detection of gravitational waves from GW170817 [1] has set the bound on the gravitational wave speed \( c_{gw} \) compared to the light speed \( c \) as \( \left| \frac{c_{gw}}{c} - 1 \right| < 5 \times 10^{-15} \). This result severely reduces the available parameter space of generic Lorentz-breaking modifications of gravity, as for example some branches of the Horndeski (and Beyond-Horndeski) theory [2,3]. Hence, the radiative sector of gravitational theories seems to be tightly close to GR, but the potential sector could still have space to manifest some differences from the standard gravity.

Using the Newtonian gauge for cosmological scalar perturbations in an expanding, homogeneous and isotropic flat Universe, the line element reads

\[
d s^2 = a^2(\tau) \left[ -(1 + 2\Phi) d\tau^2 + (1 - 2\Psi) \delta_{ij} dx^i dx^j \right],
\]

where \( \tau \) is the conformal time and \( \Phi \) and \( \Psi \) are the metric perturbations. It is quite usual in the literature to parameterize phenomenological departures from GR in terms of a difference between the scalar potentials, \( \Phi \neq \Psi \) (see, e.g., Ref. [4] and references therein).

Apart from the perspective given above, the issue we want to stress out in this work is that \( \Phi \neq \Psi \) is also naturally achieved in GR cosmologies if the energy-momentum tensor \( T^{\mu\nu} \) of some of the energy components possesses anisotropic stresses like, e.g., shear viscosity. Then, we are left with the question: Is the possible inference of \( \Phi \neq \Psi \) from observational data actually indicating a manifestation of modified gravity or would it be due to some non-conventional aspect of the universe’s energy content? In order to investigate this question we develop scalar perturbations in two different cosmologies, namely, i) GR gravity equipped with a cosmological constant and viscous (shear) matter and ii) modified gravity theories via usual parameterizations of the Poisson equation. Then, we compare the predictions for the growth of matter perturbations via the redshift-space-distortion based \( f(z)\sigma_8(z) \) measurements [5]. In order to probe only the perturbative sector of these two approaches we will assume that both share the same background expansion as the one given by the standard flat-\( \Lambda \)CDM model. To some extent, similar strategies have been employed in Ref. [4,6].

Shear viscous effects in cosmology are in fact receiving interest in the recent literature as a possible way of understanding different physical phenomena that might be in play both in the late universe [7,10] as also in the early universe [11, 12]. These recent interests on shear viscous effects show that there are clear motivations for a deeper study of their possible effects and relevance in cosmology, which might eventually also provide relevant information about the nature of the dark matter itself. In the present work, our focus on the shear viscous effects is directly connected on how they contribute at the perturbation level and the issue of having \( \Phi \neq \Psi \) for the gravitational perturbed potentials as a consequence of the presence of a nonvanishing shear viscosity. Our main interest then is to understand how this compares with the apparent similar situation in the context of modified gravity models, quantifying the possible differences in the two cases.

This paper is organized as follows. In section [1] we de-
velop the perturbation dynamics of the model with shear viscosity. For this analysis, we take particular advantage of the results obtained in Ref. [7], where we have placed an upper bound on the magnitude of dark matter shear viscosity allowed by the matter clustering observations. In section [IV] we develop the perturbed scalar equations for the case of modified gravity and present the parameterizations that will be used in this work. In section [V] we give our analysis of the quantitative comparison between the GR plus shear viscosity case and contrast these results with the modified gravity case by making use of the evolution of the $f_{\sigma s}$ observable. Finally, in section [VI] we give our conclusions.

II. DYNAMICS OF THE VISCOS (SHEAR) DARK MATTER MODEL

We start by focusing on the ΛCDM model and by assuming that matter behaves as a viscous/dissipative component possessing shear viscosity. This type of approach has been used already a number of times in the recent literature (see, e.g., Refs. [7-19]). The general structure of this model is given by the field equations derived from GR,

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R - \Lambda g_{\mu\nu} = \frac{8\pi}{c^4}G T_{\mu\nu}, \quad (2.1)$$

where $T_{\mu\nu}$ stands for the total energy momentum tensor of the viscous matter. This tensor possesses the dissipative effect in the form of shear viscosity such that [13, 14]

$$T^{\mu\nu} = \rho_v u^\mu u^\nu - p_v (g^{\mu\nu} - u^\mu u^\nu) + \Delta T^{\mu\nu}, \quad (2.2)$$

where the component $\Delta T^{\mu\nu}$ is the viscous contribution to the fluid in the form of shear viscosity,

$$\Delta T^{\mu\nu} = \eta \left[ u^{\mu\nu} + u^{\nu\mu} - u^\mu u^\nu \right] - \frac{2}{3} (g^{\mu\nu} - u^\mu u^\nu) \nabla_\rho (u^\rho u^\nu), \quad (2.3)$$

and $\eta$ is the shear viscosity coefficient. The coefficient of shear viscosity, being a transport coefficient, is typically proportional to the particle free mean path as in any microscopic formulation of viscosity effects and it can also depend on the density and temperature of the fluid. This, however, implies on the knowledge of the microscopic physics of the interactions between the dark matter particles. As we do not have in mind specific candidates for dark matter particles, most of the time it is assumed for $\eta$ some simple functional form in terms of the fluid density, like $\eta \propto \rho_c^a$. This functional form has the advantage of allowing for a completely model independent analysis, where we do not need to specify properties related to the dark matter fluid inherent to its microscopic physics. Alternatively, we can also see $\eta \propto \rho_c^a$ as a consequence of appropriately choosing the dimensional scale as the fluid density itself and where all microscopic dimensional parameters are expressed in terms of this scale up to appropriate dimensionless constants. In the present work we will not be interested in these details and it will suffice for our objectives of the comparison of the shear viscous effects with those from modified gravity by simply adopting $\eta$ to be a constant parameter. For simplicity, we will also set the dark matter kinetic pressure to $p_v = 0$. This guarantees a pressureless matter fluid at the background level as in the standard cosmology. Indeed, shear viscosity does not act at the background level.

As already mentioned in the introduction, our starting point is based on setting the line element of a Friedmann-Lemaître-Robertson-Walker (FLRW) expansion up to first order in scalar perturbation according to Eq. (1.1). Hence, from Eq. (2.1), the expansion rate here follows the usual flat-ΛCDM model with

$$H^2 = H_0^2 \left[ \Omega_{\Lambda 0} (1 + z)^3 + 1 - \Omega_{\Lambda 0} \right]^{1/2}, \quad (2.4)$$

where the today’s viscous matter density adopted is $\Omega_{\Lambda 0} = 8\pi G \rho_c / 3H_0^2 = 0.3$. In the above equation the expansion rate is written in the more familiar form as $H = \dot{a} / a$, where the symbol dot (‘) represents the derivative with respect to the cosmic time ($t$).

Our next step is to review the perturbed equations for shear viscous cosmologies. We have developed it in great detail in Ref. [7], so below we only give the relevant expressions needed for the present study. Applying Eq. (1.1) to the Einstein equations we obtain, for example, the $(0,0)$-component, in momentum space. It reads

$$- k^2 \Psi - 3 \mathcal{H} (\Psi' + \mathcal{H} \Phi) = \frac{3}{2} \Omega_v \mathcal{H}_0^2 a^2 \Delta_v, \quad (2.5)$$

while the $(0,i)$-component is given by

$$- k^2 (\Psi' + \mathcal{H} \Phi) = \frac{3}{2} \mathcal{H}_0^2 \Omega_v a \theta_v, \quad (2.6)$$

where $\mathcal{H} = \dot{a} / a$, with the symbol ” ’ “ corresponding to a derivative with respect to the conformal time ($\tau$), $k$ is the (comoving) momentum and $\Omega_v = \Omega_{\rho c} / a^3$. When writing Eq. (2.5), we have also used the definition of the density contrast, $\Delta_v = \rho_v / \rho_c$. From the $(0,i)$-component of the Einstein’s equation (2.6), we obtain the definition for the velocity potential $\theta = \partial_t \theta_v$. Finally, the evolution of the perturbation potentials $\Psi \Phi$ are encoded in the $i-j$ component of the Einstein equation and given explicitly by the expression

$$\left[ \Psi'' + \mathcal{H} (2 \Psi + \Phi)' + (2 \mathcal{H}' + \mathcal{H}^2) \Phi + \frac{1}{2} \nabla(\Phi - \Psi) \right] \delta_j^i - \frac{1}{2} \partial_i \partial_j (\Phi - \Psi) = 4\pi G a^2 \delta T^i_j, \quad (2.7)$$

where the perturbed energy-momentum tensor is obtained from Eq. (2.2), which gives

$$\delta T^i_j = - \eta \delta_{jk} \delta_j^i \left( \delta u_{k,i} + \delta u_{i,k} - \frac{2}{3} a^2 \delta u_{m,m} \delta_{kl} \right). \quad (2.8)$$
and from the \( i \neq j \) case of the above equation, we find that Eq. (2.7) corresponds to

\[
-k^2 \frac{d^2}{d\tau^2} (\Phi - \Psi) = \frac{3H^2}{\rho} \eta \theta. \tag{2.9}
\]

Equation (2.9) makes it clear that when \( \eta \neq 0 \) we have that \( \Phi \neq \Psi \). This demonstrates a notable feature of the presence of the shear viscosity (anisotropic stress), i.e., the Newtonian potentials do not coincide. It is worth noting that \( \Phi \neq \Psi \) is also seen in general in the literature as a manifestation of modified gravity theories \[15–18\].

By combining the above relations (the interested reader can also consult Ref. [7] for further details), we obtain

\[
a^2 \frac{d^2 \Delta_v}{da^2} + \left( 3 - \frac{3}{2} \Omega_b \frac{H_0^2}{H^2} + A + k^2 B \right) \frac{d \Delta_v}{da} = 0,
\]

where the factors \( A \) and \( B \) appearing in the above equation are defined, respectively, as

\[
A = \frac{2i \eta H}{30 \Omega_b H_0}, \tag{2.11}
\]

\[
B = \frac{4i \eta}{27a^2 \Omega_b H H_0}. \tag{2.12}
\]

One can see explicitly that shear viscosity leads to contributions to the Hubble friction term in the differential equation for the matter density contrast.

### III. MODIFIED GRAVITY AT LINEAR PERTURBATIVE LEVEL

In the previous section we have obtained the equations for the case in which shear viscosity sets the magnitude of the inequality \( \Phi \neq \Psi \) via Eq. (2.9). Let us now see in this section how the effects of modified gravity can also be parameterized by differences between \( \Phi \) and \( \Psi \). In particular, we want to explore the consequences of choosing the usual parameterizations of modified gravity in which the \( \text{slip} \) parameter, defined by the ratio \( \Phi/\Psi \), is used to quantify deviations from GR. Then, we assume that the phenomenology for dealing with modifications of gravity at cosmological scales merely sets the inequality

\( \Phi \neq \Psi \) (Modified Gravity). \tag{3.1}

Even when adopting modifications of gravity, we assume that the theory is conservative and that the usual conservation laws apply, i.e., \( \nabla \mu T^{\mu \nu} = 0 \). Our approach for dealing with scalar perturbations in a parameterized modified gravity theory consists in combining the perturbed continuity equation for the density contrast \( \Delta \) for a pressureless fluid and in the modified gravity context, given by

\[
\Delta' + a \theta = 0, \tag{3.2}
\]

with the Euler equation

\[
(a \theta)' + H a \theta - k^2 \Phi = 0, \tag{3.3}
\]

to obtain the result

\[
\Delta'' + H \Delta' + k^2 \Phi = 0. \tag{3.4}
\]

Therefore, Eq. (3.4) tell us that the matter clustering growth (the observable we are interested in) depends only on the potential \( \Phi \). However, on sub-horizon scales we can also write down the Poisson equation as

\[
-k^2 \Phi = \frac{3}{2} \Omega_m H_0^2 a^2 \Delta. \tag{3.5}
\]

At this point, it is worth noting that the standard equation for the evolution of \( \Delta \) is obtained by assuming \( \Phi = \Psi \) and combining the above two equations. It is exactly this step we want to avoid. Instead, we will adopt typical parameterizations of Eq. (3.5) found in the literature to explore the phenomenology of modified gravity. The some possible choices for the functional parameterization that we will use in our study is explained next.

Equations (3.4) and (3.5) involve three different functions. Indeed, if anisotropic stresses are neglected in the energy-momentum tensor one obtains \( \Phi = \Psi \) and a homogeneous second order differential equation for \( \Delta \) is obtained. Departures from the standard model, i.e., the \( \Lambda \)CDM model, are usually parameterized in the literature by \( \Phi \neq \Psi \). Since we want to investigate small deviations from GR, which are relevant for the structure formation process, we will then follow an analogous strategy as used, e.g., in Refs. \[4, 6\] and set the background evolution to be the same as in \( \Lambda \)CDM. As in Ref. [1], we adopt a Poisson type equation for the potential \( \Phi \), such that

\[
-a^2 \frac{d^2 \Delta}{da^2} + \left( 3 - \frac{a}{H} \frac{dH}{da} \right) \frac{d \Delta}{da} \left( 6 - \frac{a}{H} \frac{dH}{da} \right) \frac{d \Delta}{da} = 0 \tag{3.6}
\]

where \( \mu(a,k) \), sometimes also denoted by the function \( Y(a,k) \), incorporates to the relativistic Poisson equation possible contributions from clustering dark energy.

Combining Eq. (3.4) with the parameterization Eq. (3.6) and using the scale factor as the dynamical variable we obtain the following equation for the evolution of the matter density contrast

\[
a^2 \frac{d^2 \Delta}{da^2} + \left( 3 + \frac{a}{H} \frac{dH}{da} \right) \frac{d \Delta}{da} \left( 6 + \frac{a}{H} \frac{dH}{da} \right) \frac{d \Delta}{da} = 0 \tag{3.7}
\]

The function \( \mu(a,k) \) can in principle depend on time (here given in terms of the scale factor \( a \) dependence) and the scale (via the wavenumber-mode \( k \)).

By comparing Eq. (2.10) with Eq. (3.7) one realizes one important difference between the shear viscous scenario and modified gravity. Shear viscosity acts by damping the Hubble friction term in Eq. (2.10). This
conclusion is in agreement with the recent study performed in Ref. [19], which also shows how shear viscosity damps the growth of structures. It is worth noting that such damping is not present in modified gravity scenarios. In fact, for example in $f(R)$-type of models for modified gravity, the resulting effect is rather usually associated with the boosting of the agglomeration rate [20] and of the matter power spectrum [21].

According to Ref. [4], one possible way to employ the parameterization in the form as given in Eq. (3.6), occurs by choosing the function $\mu(a, k)$ as

$$\mu(a, k) = 1 + \frac{cE}{aH/k^2},$$  \hspace{1cm} (3.8)

where $c$ and $\lambda$ are constant parameters. For the sake of simplicity and without loss of generality we will fix $\lambda = 1$. At small scales (large $k$), $\mu \to 1 + f(a)$, while for large scales (small $k$), $\mu \to 1 + f(a)c$. Then, in practice the scale dependence plays no decisive role for astrophysical applications we have in mind. Thus, we proceed now by adopting the following simpler structure,

$$\mu_1(a) = 1 + E_1 \frac{H_0^2}{H^2},$$ \hspace{1cm} (3.9)

where $E_1$ is a constant parameter, with the parameter $c$ absorbed in the definition of $E_1$. Equation (3.9) will be the first parameterization form we will use. For completeness, we will also use two more and that will be defined below.

The range of values of the parameters presented in the Eq. (3.8) depends on the modified gravity theory. For instance, in the case of the $f(R)$ theories, with a chameleon mechanism, the coefficients are positive, implying that the gravitational coupling is enhanced compared with the GR case [20]. An enhanced gravitational coupling leads to a stronger matter agglomeration. Even if such property of modified gravity theories must be verified case by case, it remains a quite general feature, at least to our knowledge. For this reason, we will also consider $E_1$ as a positive quantity. Hence, it is already possible, at this level, to predict that modified gravity acts on matter agglomeration in the opposite sense compared to shear viscosity: While the shear viscosity suppresses the matter agglomeration, modified gravity acts mainly in the sense of enhancing the formation of structures.

Besides the parameterization given by Eq. (3.9), we will also make use of two more that are conventionally considered in the literature. More specifically, we also consider the parameterization according to the proposal of Ref. [22] and define

$$\mu_2(a) = 1 + (E_2 e^{-\frac{a}{k_c^2}} - 1),$$ \hspace{1cm} (3.10)

where the scale $k = 0.1h Mpc^{-1}$ has been fixed. Indeed, it is a sub-horizon mode and still linear at $a_0$. The free constant parameters are $E_2$ and $k_c$. The GR limit occurs for $E_2 = 1$ and $k_c \to \infty$.

Finally, we also consider the parameterization proposed in Ref. [15] and studied recently by the authors of Ref. [23], given by

$$\mu_3(a) = 1 + E_3 \frac{2(1 + 2\Omega_m(a)^2)}{3[1 + \Omega_m(a)^2]},$$ \hspace{1cm} (3.11)

and which is inspired within the DGP gravity scenario [24].

IV. RESULTS

From the three forms of parameterizations, given by Eqs. (3.9), (3.10) and (3.11), respectively, we apply them to Eq. (3.7). The resulting equation for each case can then be solved numerically for the density contrast $\Delta$. Having also the result for the density contrast from the shear viscous case and obtained from Eq. (2.10), we can calculate the growth function $f(z)$ for all these different cases. The growth function $f(z)$ is defined as

$$f(z) \equiv \frac{d \ln \Delta(a)}{d \ln a} = -(1 + z) \frac{d \ln \Delta(z)}{dz},$$ \hspace{1cm} (4.1)

with $z = 1/a - 1$ and

$$\sigma_8(z) = \sigma_8(z_0) \frac{\Delta(z)}{\Delta(z_0)},$$ \hspace{1cm} (4.2)

is the redshift-dependent root-mean-square mass fluctuation in spheres with radius $8h^{-1}$ Mpc. The today’s scale factor is set to unity, $a_0 = 1$, thus, $z_0 = 0$. The today’s value adopted here for the variance of the density field at $z_0$ is $\sigma_8(z_0) = 0.8$, which is consistent with current observations.

Let us consider the results obtained by using the first parameterization given by Eq. (3.9). In Fig. 1, we show the $f\sigma_8$ observable as a function of the redshift. The light-red filled area corresponds to the shear viscous model. This region is set by using our previous results from Ref. [7] and corresponds to the range of the viscosity parameter $0 \leq \tilde{\eta} \leq 2.593 \times 10^{-6}$ at $2\sigma$ of statistical confidence level obtained in that reference. Here, for convenience, we have defined the dimensionless viscous parameter $\tilde{\eta} = 24\pi G\eta / H_0$ and $\eta$ is assumed to be a constant value, as we have already explained in Sec. II. The viscous shear model equals the $\Lambda$CDM (black line) curve for the case of vanishing viscosity, $\tilde{\eta} = 0$. The viscosity parameter, being physically a transport coefficient, should assume only positive values. Thus, its effect acts smoothing the matter clustering in comparison to the standard cosmology, which corresponds to the region below the black line. The value $\tilde{\eta} = 2.593 \times 10^{-6}$ is the maximum viscosity allowed by the available 21 data points shown in
FIG. 1: The $f \sigma_8$ observable as a function of the redshift. (a) For the shear viscous model the light-red area corresponds to the range of the viscous parameter $0 \leq \tilde{\eta}_0 \leq 2.593 \times 10^{-6}$. The green region shows the behavior of modified gravity model with the $\mu_1$ parameterization with the range $0 \leq E_1 \leq 0.225$. (b) Plot of the difference between top green line and bottom red line from (a). At $z = 0.54$ we have the largest difference between shear and the modified gravity model (detail shown in the inset).

FIG. 2: The $f \sigma_8$ observable as a function of the redshift. (a) For the shear viscous model the red lines correspond to the range of the viscous parameter $0 \leq \tilde{\eta}_0 \leq 2.593 \times 10^{-6}$. Green lines show the behavior of modified gravity models with the $\mu_2$ parameterization. Different values for $E_2$ parameter $1.1 \leq E_2 \leq 1.23$ and $1 \leq k_c \leq 1.1$. (b) Plot of the difference between top green line and bottom red line, from (a). At $z = 0.58$ we have the biggest difference between shear and the modified gravity model (detail shown in the inset).

this figure at 2$\sigma$ of statistical confidence level (see Ref. [7] for details). The shear model with $\tilde{\eta} = 2.593 \times 10^{-6}$ is the lowest light-red line plotted in Fig. 1a. The green filled area corresponds to modified gravity models based on $\mu_1$ and defined in Eq. (3.9). Since we expect the values for $\mu_1$ to be such that they increase the intensity of gravity [4], then $\mu_1$ only assumes positive values. The consequence of this imposition can be seen in Fig. 1b.
The green lines always stay above the ΛCDM line, while the red lines, corresponding to the shear viscosity effect, always stay below the ΛCDM line.

It is worth noting that both models share the same asymptotic behavior for high redshifts. In particular, the value \( E_1 = 0 \) corresponds to the ΛCDM model. Having the bound on \( \tilde{\eta}_0 \) given above in mind, we have plotted the green region in Fig. 1a according to the following criteria: We limit the maximum \( f\sigma_8(a = 1) \) given by the modified gravity model to yield the same departure in magnitude from the ΛCDM model, but in the opposite direction, in comparison to the shear model. Then, if combining both effects they approximately compensate the effect of each other both today and in the asymptotic past at high redshifts. The combination of both effects is seen in Fig. 1b. Although very tiny, the region around \( z = 0.54 \) is where one finds the largest difference between both effects (inset plot).

In Fig. 2 we present the results obtained by using the second parameterization for the modified gravity effects and given by Eq. (3.10). The color scheme follows the same as the one used in Fig. 1. We notice from Fig. 2a that now the modified gravity results spread at an uniform distance above the ΛCDM result for a given value of the constant \( E_2 \). In particular, at low redshifts we again observe a compensation of the modified gravity effect by the shear viscous (or vice-versa), as is apparent from Fig. 2b, where we plot the difference between the maximum differences for each case with respect to the ΛCDM result. However, at high redshifts the difference starts to get more and more appreciable.

Finally, in Fig. 3 we present the results obtained when considering the parameterization given by Eq. (3.11). Once again, the color scheme used in Fig. 3 follows the same as the one already used in the previous two figures. The trend observed is similar to the one obtained from the parameterization given by Eq. (3.10), where we have a tendency of shear viscous effects masking the modified gravity one and vice-versa at low redshifts, but the difference increases more appreciably at high redshifts, as seen in Fig. 3b.

V. CONCLUSIONS

We have studied in the present work the potential differences in the Newtonian scalar potentials \( \Psi \) and \( \Phi \) as resulting from both a possible derivation from the GR description for gravity and also by considering that the anisotropic stresses in the energy momentum tensor yield to \( \Psi \neq \Phi \). The latter effect due to a shear viscosity that dark matter might be endowed in the GR context. For this study, we have employed three different forms of parameterizing the modified gravity effects through the modification of the Poisson equation for the scalar potential \( \Phi \). This is a strategy commonly used in the literature to account the possible modifications generated by different physical scenarios to GR. We have then contrasted these modifications from modified gravity with...
those from the shear viscous effects when added to GR. To gauge these modifications in the context of the ΛCDM model, we have made use of the redshift-space-distortion based $f(z)\sigma_8(z)$ data, which gives a convenient probe of these different effects at the level of the perturbations.

Our results show that, in general, modified gravity and shear viscosity have opposing effects on the $f(z)\sigma_8(z)$ predicted by the ΛCDM model. While modified gravity tends to suppress the gravitational coupling to GR acts oppositely. This, thus, leads to an interesting possibility of the shear viscosity effects in GR masking those effects from modified gravity. We have seen that this tends to happen mostly effectively at low redshifts in all three cases of parameterizations of modified gravity that we have considered. This compensation effect is, however, less effective at high redshifts.

This points out then for a possible best way for differentiating these effects in future astrophysical searches and probes using high redshift data. In this case, very accurate data on the matter clustering via the $f(z)\sigma_8(z)$ measurements might then be able to distinguish the effects studied here.

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