

No slip gravity

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No slip gravity

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Abstract. A subclass of the Horndeski modified gravity theory we call No Slip Gravity has particularly interesting properties: 1) a speed of gravitational wave propagation equal to the speed of light, 2) equality between the effective gravitational coupling strengths to matter and light, G_{matter} and G_{light} , hence no slip between the metric potentials, yet difference from Newton's constant, and 3) suppressed growth to give better agreement with galaxy clustering observations. We explore the characteristics and implications of this theory, and project observational constraints. We also give a simple expression for the ratio of the gravitational wave standard siren distance to the photon standard candle distance, in this theory and others, and enable a direct comparison of modified gravity in structure growth and in gravitational waves, an important crosscheck.

Keywords: modified gravity, cosmological parameters from LSS, dark energy theory, galaxy clustering

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1 Introduction

Modified gravity theories are becoming increasingly tested by current and forthcoming observations. A main motivation for considering alternatives to general relativity is the observation of cosmic acceleration, but modified gravity such as scalar-tensor theories have other degrees of freedom that allow scalar (density) and tensor (gravitational wave) perturbations to behave in ways not purely governed by the expansion, unlike general relativity.

Recent measurement of the speed of propagation of gravitational waves from GW170817 relative to its electromagnetic counterpart GRB170817A [1] severely limit its deviation from the speed of light, strongly disfavoring theories that generically predict a difference [2–7]. This leaves only a subset out of the Horndeski class of gravity, one of the most general scalar tensor theories with second order field equations, a key testing ground for cosmology.

Interestingly, in the remaining theories there is a unique subclass that makes another definite observational prediction: that another signature of deviation from general relativity, the slip between metric potentials, should vanish and yet the gravity theory does not reduce to general relativity. Indeed, discussion of the slip itself [8, 9] and the relation between slip and the speed of propagation of gravitational waves has highlighted important connections between the scalar and tensor sectors of modified gravity (e.g. see [10–12]). We explore the characteristics and implications of this subclass, No Slip Gravity.

In section 2 we define this theory in terms of the property functions, the equivalent effective field theory functions, and the Horndeski Lagrangian functions. We demonstrate the conditions for stability of the theory in section 3, and give specific model examples. Section 4 ties this to observations of growth of structure, for current data and projecting constraints from future cosmic structure surveys. We conclude in section 5.

2 No slip gravity theory

The effects of gravity on observations of cosmic matter and light can fruitfully be described (in the subhorizon, quasistatic limit; see section 3) by modified Poisson equations relating the time-time metric potential ψ and space-space metric potential ϕ (in Newtonian gauge)

to the matter perturbations. These equations are

$$\nabla^2\psi = 4\pi G_N\delta\rho \times G_{\text{matter}} \quad (2.1)$$

$$\nabla^2(\psi + \phi) = 8\pi G_N\delta\rho \times G_{\text{light}}, \quad (2.2)$$

where the first equation governs the growth of structure, with a gravitational strength G_{matter} , and the second governs the deflection of light, with a gravitational strength G_{light} .

The offset between G_{matter} and G_{light} , or ψ and ϕ , is referred to as the gravitational slip, with

$$\bar{\eta} \equiv \frac{G_{\text{matter}}}{G_{\text{light}}} = \frac{2\psi}{\psi + \phi} = \frac{2\eta}{1 + \eta} \quad (2.3)$$

$$\eta \equiv \frac{\psi}{\phi} = \frac{G_{\text{matter}}}{2G_{\text{light}} - G_{\text{matter}}} = \frac{\bar{\eta}}{2 - \bar{\eta}}. \quad (2.4)$$

Note that when $\bar{\eta} = 1$ then $\eta = 1$ and the converse. This corresponds to vanishing slip.

The expressions for G_{matter} , G_{light} , and slip in Horndeski gravity, or the equivalent effective field theory (EFT) approach, are given in, e.g., [13–15]. Imposing that the speed of propagation of gravitational waves equals the speed of light, $c_T = 1$ or $\alpha_T \equiv c_T^2 - 1 = 0$, simplifies the equations and we find a simple criterion for no slip:

$$\alpha_B = -2\alpha_M \quad (2.5)$$

$$m_0^2\dot{\Omega} = \bar{M}_1^3 \quad (2.6)$$

$$G_{4\phi} = -XG_{3X}. \quad (2.7)$$

Here the second two equations give the equivalent conditions in the EFT and Horndeski function approaches; we work in the α_i parameter approach but show the others for convenience. The first equation relates the property functions $\alpha_i(t)$, with α_B the braiding function mixing scalar and tensor properties and α_M the running of the Planck mass. The second relates two EFT functions, the conformal factor $m_0^2\Omega(t)$ multiplying the Ricci scalar and the $\bar{M}_1^3(t)$ function multiplying the product of the trace of the extrinsic curvature and the lapse function, $\delta K \delta g^{00}$. The third relates different terms in the Horndeski Lagrangian, where a subscript ϕ denotes a derivative with respect to the scalar field ϕ (not the metric potential) and a subscript X denotes a derivative with respect to the scalar kinetic energy $X = -g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi/2$.

The implications of No Slip Gravity for the gravitational strengths are quite simple also:

$$G_{\text{matter}} = G_{\text{light}} = \frac{m_p^2}{M_\star^2}, \quad (2.8)$$

where m_p is the Planck mass in general relativity, and $M_\star^2 (= m_0^2\Omega)$ is the effective, time dependent Planck mass in the modified gravity. Note that $\alpha_M = (1/H)d\ln M_\star^2/dt$. Thus matter growth and light propagation are modified in step, as time dependent effects, and are distinct from general relativity. Such a simple theory provides an excellent test ground for the ability of future cosmic surveys to look for deviations from general relativity and constrain their magnitude.

3 Viability conditions

For any theory of gravity it is important to make sure it has a firm foundation, without pathologies or instabilities. In terms of the property functions, the condition for no ghosts

is [13]

$$\alpha_K + \frac{3}{2}\alpha_B^2 > 0. \quad (3.1)$$

Since gravitational waves propagate at the speed of light the tensor sector is also free of ghosts. The quasistatic approximation is discussed in detail in [13, 16, 17]; this basically reduces to $\alpha_B k/(aH) \gg 1$, satisfied for modes well within the horizon if α_B is not so small that we would see no modified gravity effect anyway.

One must also check for instabilities in the scalar sector, with the stability condition $c_s^2 \geq 0$. Expressions for the sound speed c_s are given in the property function and EFT approaches in, e.g., [13, 18–20]. Within the property function approach, imposing $\alpha_T = 0$ yields

$$c_s^2 = \frac{(1 - \alpha_B/2)[H^2(2\alpha_M + \alpha_B) - 2\dot{H}] + H\dot{\alpha}_B - \rho_m - p_m}{H^2(\alpha_K + 3\alpha_B/2)} \quad (3.2)$$

where H is the Hubble parameter, and ρ_m and p_m are the matter energy density and pressure. We are free to choose the background expansion separately from the perturbation terms, and we adopt a Λ CDM background, in good agreement with current observations. This cancels terms involving the matter fields and \dot{H} .

Within the EFT approach,

$$c_s^2 \propto \frac{-3\dot{\Omega}}{H\Omega} + \frac{\bar{M}_1^3}{Hm_0^2\Omega} + \frac{2\dot{\Omega}/(H\Omega) + \ddot{\Omega}/(H^2\Omega) + \dot{\bar{M}}_1^3/(H^2m_0^2\Omega)}{1 + \dot{\Omega}/(2H\Omega) + \bar{M}_1^3/(2Hm_0^2\Omega)}, \quad (3.3)$$

where we omit the denominator, which must be positive by the no ghost condition.

For No Slip Gravity with $\alpha_B = -2\alpha_M$ or $\bar{M}_1^3 = m_0^2\dot{\Omega}$ the stability condition takes the simple, equivalent forms

$$(H\alpha_M)' < 0 \quad (3.4)$$

$$(\dot{\Omega}/\Omega)' < 0, \quad (3.5)$$

in the property function and EFT approach respectively. Using the definitions of α_M and $m_0^2\Omega$ in terms of M_\star^2 shows these conditions are indeed equivalent. Indeed, they are just

$$\frac{d^2 \ln M_\star^2}{dt^2} < 0. \quad (3.6)$$

We now have a one function theory, similar to $f(R)$ gravity (which has $\alpha_B = -\alpha_M$ and so does have slip), for a given background expansion. Note that the stability condition is quite restrictive. If we write

$$(H\alpha_M)' = \dot{H}\alpha_M + H\dot{\alpha}_M < 0, \quad (3.7)$$

then we can see that since $\dot{H} < 0$ for all times, and $\alpha_M \rightarrow 0$ as the universe approaches its de Sitter asymptote, that stability must break down at some time when $\alpha_M < 0$. That is, negative α_M must climb back to zero, either to cross to positive α_M or to reach the de Sitter limit, giving $\dot{\alpha}_M > 0$ and this will violate stability. In the early universe we want gravity to restore to general relativity, with $\alpha_M = 0$. So the simplest viable form is a “hill” in α_M , where it is always positive or zero. Note that a form such as $\alpha_M = \mu\Omega_\Lambda$, proportional to the effective dark energy density $\Omega_\Lambda(t)$, is immediately ruled out as it does not approach zero at late times as required, while $\alpha_M = \mu\Omega_\Lambda(1 - \Omega_\Lambda)$ is unstable.

For the one function determining the theory, we can choose either M_\star^2 or α_M . Note that in No Slip Gravity the condition $\alpha_B = -2\alpha_M$ determines that

$$G_{\text{matter}} = G_{\text{light}} = \frac{m_p^2}{M_\star^2}, \quad (3.8)$$

an extraordinarily simple result. In the early universe, we take $M_\star^2 \rightarrow m_p^2$ so the gravitational strength agrees with general relativity. In the asymptotic future, M_\star^2 freezes to its de Sitter value, and so does the gravitational strength.

Let us explore parametrizing $M_\star^2(t)/m_p^2$. We need it to transition from unity in the past to some constant value $1+\mu$ in the future. Other than that, a wide variety of functional forms is possible. We take the following as purely illustrative examples satisfying these conditions. One such simple function is the e-fold or $1 + \tanh$ form

$$\frac{M_\star^2}{m_p^2} = 1 + \frac{\mu}{1 + e^{-\tau(\ln a - \ln a_t)}} = 1 + \frac{\mu}{1 + (a/a_t)^{-\tau}} \quad (3.9)$$

$$= 1 + \mu \frac{1 + \tanh[(\tau/2) \ln(a/a_t)]}{2}, \quad (3.10)$$

where a is the cosmic scale factor. Here μ gives the amplitude of the transition, a_t the scale factor when it occurs, and τ its rapidity. For this form, the stability condition requires $0 < \tau \leq 3/2$.

Using $\alpha_M = d \ln M_\star^2 / d \ln a$ we find

$$\alpha_M = \left[1 + \frac{\mu}{1 + e^{-\tau(\ln a - \ln a_t)}} \right]^{-1} \frac{\tau \mu e^{-\tau(\ln a - \ln a_t)}}{[1 + e^{-\tau(\ln a - \ln a_t)}]^2}. \quad (3.11)$$

This vanishes at early and late times as required, and reaches a maximum in the vicinity of a_t , with amplitude $\alpha_M \approx \mu\tau/4$. The results for the evolutions of G_{matter} and α_M are presented in figure 1.

An alternate approach is to parametrize α_M , and derive M_\star^2 by integration. Recalling that we want α_M to be a hill, vanishing at early and late times, we adopt the (again, purely illustrative) form

$$\alpha_M = A (1 - \tanh^2[(\tau/2) \ln(a/a_t)]) = \frac{4A (a/a_t)^\tau}{[(a/a_t)^\tau + 1]^2}. \quad (3.12)$$

Again, for this form the stability condition requires $0 < \tau \leq 3/2$. This is easy to understand since at early times $\alpha_M \sim a^\tau$, as for the form of eq. (3.11), and during matter domination the Hubble parameter $H \sim a^{-3/2}$, so $(H\alpha_M)' \sim (a^{\tau-3/2})' \leq 0$ requires $\tau \leq 3/2$.

For this approach, α_M reaches a maximum of A at a_t , and vanishes in the past and future. We can write the corresponding M_\star^2 analytically as

$$\frac{M_\star^2}{m_p^2} = e^{(2A/\tau)(1 + \tanh[(\tau/2) \ln(a/a_t)])}. \quad (3.13)$$

Note that the form in eq. (3.10) is basically the first order expansion of this. In the past, this goes to unity, and in the future it goes to a constant $e^{4A/\tau}$. The results for the evolutions of G_{matter} and α_M are presented in figure 2.

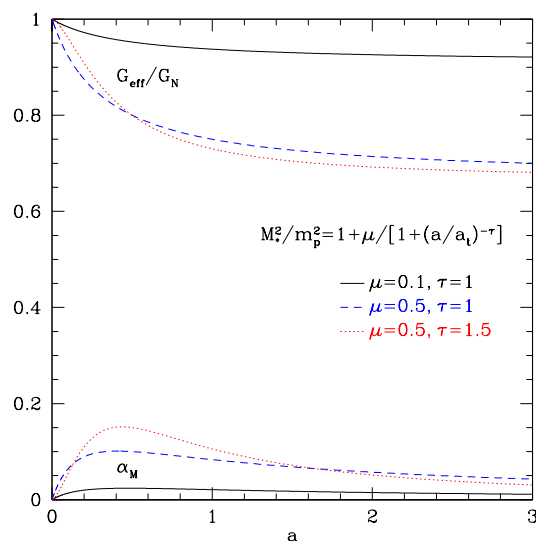


Figure 1. A model for $M_*^2(t)$ determines the theory. Here we plot $G_{\text{eff}}(a)/G_N = G_{\text{matter}} = G_{\text{light}}$ and α_M for various values of the model amplitude μ and evolution rapidity τ , for fixed transition time $a_t = 0.5$.

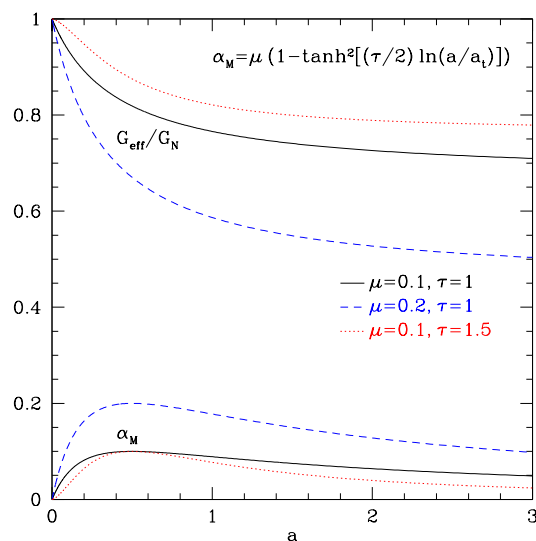


Figure 2. A model for $\alpha_M(t)$ determines the theory. Here we plot $G_{\text{eff}}(a)/G_N = G_{\text{matter}} = G_{\text{light}}$ and α_M for various values of the model amplitude A and evolution rapidity τ , for fixed transition time $a_t = 0.5$.

A major consequence of the stability condition that we have seen in figures 1 and 2 is that the gravitational strength is weaker than in general relativity! This follows, independent of the functional forms, because stability requires that $\alpha_M \geq 0$. Recall that

$$\ln \frac{M_*^2(a)}{m_p^2} = \int_0^a d \ln \tilde{a} \alpha_M(\tilde{a}). \quad (3.14)$$

Since $\alpha_M(a) \geq 0$ for all a , then $M_*^2(a)/m_p^2 \geq 1$, and so by eq. (3.8), $G_{\text{matter}} = G_{\text{light}} \leq 1$.

This is quite unusual for scalar-tensor theories, which generically increase the strength of gravity. However, it arises in No Slip Gravity due to the strength of the braiding, which mixes the scalar sector into the tensor sector (cf. [21–23]).

As we see in the next section, this weakening of gravity, despite the presence of cosmic acceleration, has important and potentially beneficial consequences for observations.

4 Observational constraints

Recently, [24] showed that binned values of G_{matter} gave highly accurate reconstructions of the observable growth quantities. Since in the No Slip Gravity case $G_{\text{matter}} = (m_p^2/M_\star^2)$ then one can directly read off from the binned G_{matter} the central quantity of the theory,

$$\alpha_M = -\Delta \ln G_{\text{matter}} / \Delta \ln a. \quad (4.1)$$

We have verified that for both the $M_\star^2(a)$ and $\alpha_M(a)$ models the binned approach delivers the redshift space distortion growth rate observable $f\sigma_8$ to 0.2% accuracy.

A closely related observational relation concerns the gravitational wave (GW) standard siren distance. Following [25, 26] we see that the GW strain amplitude

$$h = h^{GR} e^{-(1/2) \int_{\text{em}}^{\text{obs}} d \ln a \alpha_M(a)} = h^{GR} e^{-(1/2) \int_{\text{em}}^{\text{obs}} d \ln M_\star^2(a)} \quad (4.2)$$

$$= h^{GR} \left[\frac{M_{\star, \text{em}}^2}{M_{\star, \text{obs}}^2} \right]^{1/2}. \quad (4.3)$$

Since the strain is inversely proportional to the standard siren luminosity distance, one has¹

$$d_{L, \text{GW}}(a) = d_L^{GR}(a) \left[\frac{M_\star^2(a=1)}{M_\star^2(a)} \right]^{1/2}. \quad (4.4)$$

This is a quite general expression for Horndeski gravity and some other theories. Note in particular that the photon luminosity distance is simply d_L^{GR} so a comparison of the GW standard siren distance and the photon standard candle distance gives a simple test of gravity. Thus one can in principle measure the evolution of $M_\star(a)$; the running α_M would require a derivative of noisy data. For No Slip Gravity we have the further simplification that

$$d_{L, \text{GW}}(a) = d_L^{GR}(a) \left[\frac{G_{\text{matter}}(a)}{G_{\text{matter}}(a=1)} \right]^{1/2}, \quad (4.5)$$

and one could compare the modified gravity derived from GW in the tensor sector to that from growth of structure in the scalar sector. (After this article first appeared, [28] showed the same relation holds in a theory of nonlocal gravity.)

Returning to growth observables, galaxy redshift surveys already have a slew of measurements of the growth rate quantity $f\sigma_8$. We can apply our illustrative forms to examine the impact on this observable; we emphasize this is meant as a demonstration of principle regarding suppression of growth and not a fully quantitative likelihood analysis. Figure 3 compares the predictions of No Slip Gravity, where we use the exact solution of growth, with the cosmic expansion fixed to the best fit Planck cosmology (i.e. flat Λ CDM with $\Omega_m = 0.31$), to a compendium of current observations.

¹During the late stages of this work, [27] appeared with an equivalent expression.

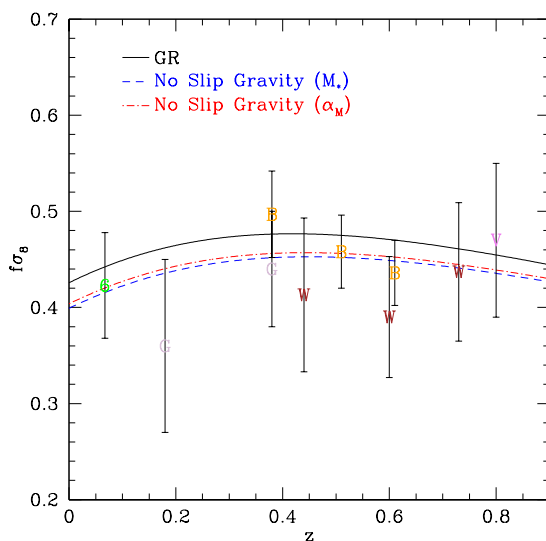


Figure 3. Current measurements of the cosmic structure growth rate $f\sigma_8$ are compared with the general relativity prediction for the Planck cosmology ($\Omega_m = 0.31$; solid black curve) and the No Slip Gravity models of M_* (dashed blue) and α_M (dot dashed red) functions. The data points come from 6dFGRS (6; [29]), GAMA (G; [30]), BOSS (B; [31]), WiggleZ (W; [32]), and VIPERS (V; [33]).

The fits of the two representative models of No Slip Gravity, employing a motivated functional form for $M_*^2(a)$ and $\alpha_M(a)$ respectively, appear to improve over the concordance cosmology. Recall they have the same expansion history as the Planck cosmology, and so will fit distance data as well as the concordance, general relativity cosmology. Figure 3 illustrates they provide fits more in accord with the growth rate data coming from redshift space distortion measurements, however. We find that current observations are in agreement with the M_*^2 model with $\mu = 0.1$ or the α_M model with $A = 0.03$, both with transition time $a_t = 0.5$ and $\tau = 1.5$. Again, these numbers are meant to give an indication of the characteristics, not a detailed analysis.

We can further highlight the deviation from general relativity by employing the conjoined expansion and growth history visualization of [34]. Figure 4 illustrates that the modification of gravity is distinct from a change in the background cosmological model. Recall that for the No Slip Gravity models we adopted the Planck cosmology of flat Λ CDM with $\Omega_m = 0.31$, but we see the modified gravity conjoined growth-expansion history in terms of $f\sigma_8$ vs H does not lie along the general relativity curves. While one can change the background to match the modified gravity prediction over a narrow range of redshifts, the modified gravity model has its own characteristic behavior.

Next we consider the leverage of next generation observations, such as from the Dark Energy Spectroscopic Instrument (DESI [35]), with percent level measurements of $f\sigma_8$ to test gravitation theory. We carry out a Fisher information analysis following the approach of [36] in testing early modified gravity. The data is taken to be future measurements of $f\sigma_8$ in 18 redshift bins over $z = 0.05$ – 1.85 as projected by [35]. Only linear modes are used, out to $k_{\max} = 0.1 h/\text{Mpc}$. We include a Gaussian prior on the matter density Ω_m of 0.01 to represent external data such as Planck CMB measurements.

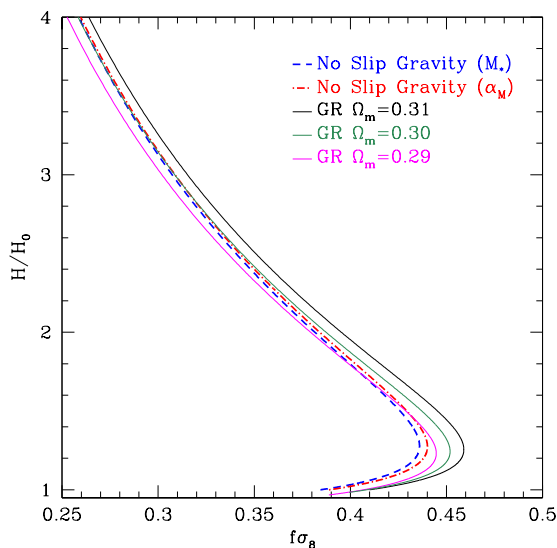


Figure 4. Using the conjoined growth-expansion approach illustrates the distinction between modified gravity and general relativity, in terms of the evolution in the $f\sigma_8(z)$ vs $H(z)/H_0$ plane. The behavior of the No Slip Gravity models of M_* (dashed blue) and α_M (dot dashed red) functions have characteristic deviations from the general relativity predictions for the Planck cosmology ($\Omega_m = 0.31$; solid black curve) and other background cosmologies ($\Omega_m = 0.3$ thin solid green and $\Omega_m = 0.29$ thin solid magenta). Note that H_0 here is that of the $\Omega_m = 0.31$ case and other cases are scaled to preserve the CMB sound horizon.

For the gravity model we take the fit parameters as exhibited in figure 3, for the two cases. In each case we fix $a_t = 0.5$ as a reasonable transition time and $\tau = 1.5$ as the maximum allowed rapidity. Constraints weaken for early or late transitions, and slow ones, due to parameter degeneracies so we present an optimistic scenario for searching for modifications to gravity; we seek an indication of the sensitivity, not meaning this as a detailed likelihood fit. We fit for the matter density and amplitude of the deviation from general relativity, either μ in the M_*^2 model or A in the α_M model. Both correspond to the maximum deviation over time of the functions from the general relativity limit.

Figures 5 and 6 show the results. The marginalized constraints on the modified gravity amplitudes are $\mu = 0.1 \pm 0.028$ and $A = 0.03 \pm 0.010$ respectively. Next generation data could see signatures of modification of gravity at the $\sim 3\sigma$ level in either model, if either model is correct and redshift space distortion data continue to lie along the current best fit.

5 Conclusions

The constraint on the speed of propagation of gravitational waves from GW170817/GRB170817A severely limited theories of modified gravity. Many conformal scalar-tensor theories still remain but only two carry particularly significant observational implications. The class of $f(R)$ gravity predicts that $G_{\text{light}} = 1$ (assuming $f_R \ll 1$ as required from solar system and astrophysical tests). Here we presented the other — No Slip Gravity — which makes the gravitational slip vanish so $G_{\text{matter}} = G_{\text{light}}$, though they can still differ from general relativity.

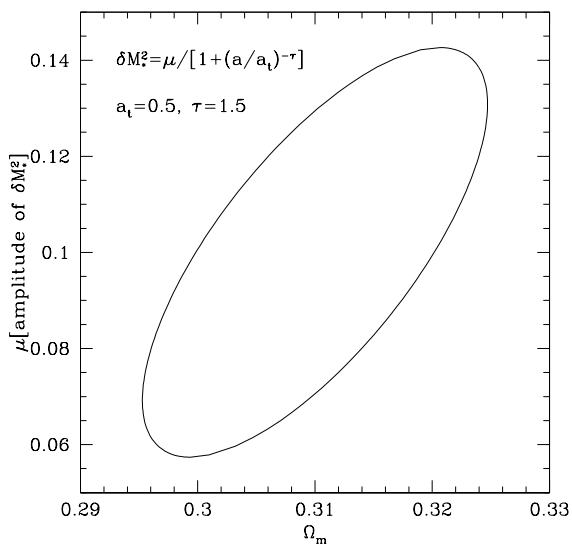


Figure 5. 68% joint confidence level constraints from future DESI redshift space distortion data on the No Slip Gravity model with $M_*^2/m_p^2 = 1 + \mu/[1 + (a/a_t)^{-\tau}]$ are shown in the Ω_m - μ plane, centered on the current best fit values. This can give a $\sim 3\sigma$ detection of μ , i.e. a deviation from general relativity.

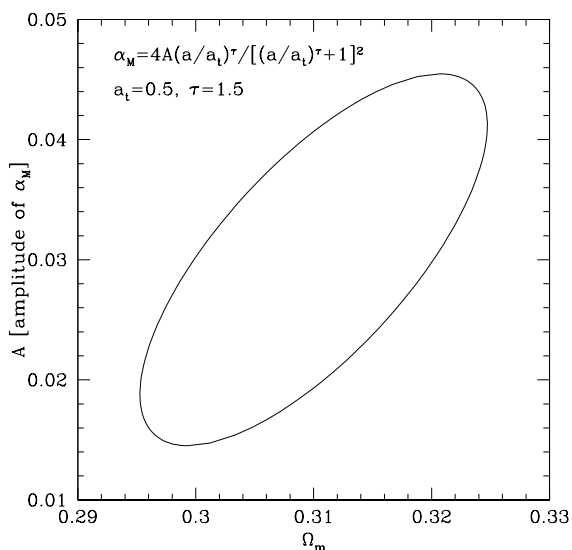


Figure 6. 68% joint confidence level constraints from future DESI redshift space distortion data on the No Slip Gravity model with $\alpha_M = 4A(a/a_t)^\tau / [(a/a_t)^\tau + 1]^2$ are shown in the Ω_m - A plane, centered on the current best fit values. This can give a $\sim 3\sigma$ detection of A , i.e. a deviation from general relativity.

(Since $f(R)$ has $\alpha_B = -\alpha_M$ and $G_{\text{light}} = 1$, and No Slip Gravity has $\alpha_B = -2\alpha_M$ and $\eta = 1$, one might imagine studying an interpolation (or extrapolation) $\alpha_B = -R\alpha_M$ but there is no equivalent physics motivation.)

No Slip Gravity is a simple one function theory, and the form of the function with time is strongly constrained by the stability condition $c_s^2 \geq 0$. In particular this implies that the

running of the Planck mass $\alpha_M \geq 0$ at all times. We presented two representative models, one in terms of a viable Planck mass function $M_\star^2(a)$ and one in terms of a viable running $\alpha_M(a)$.

Unlike many scalar-tensor theories, No Slip Gravity makes the definite observational prediction that gravity should be weaker than in general relativity, despite giving cosmic acceleration. We showed that this is in excellent agreement with current redshift space distortion data measuring the cosmic structure growth rate $f\sigma_8(a)$, better than general relativity for the Planck cosmology. Potentially it could also inform the tension on the weak lensing quantity $S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$ [37–40] and the value of E_G lower than general relativity [41] though we leave that for future study.

We also gave a simple expression for the ratio of the gravitational wave standard siren distance to the photon standard candle distance, in this theory and others. This enables a comparison of modified gravity in structure growth and in gravitational waves, an important crosscheck.

Next generation galaxy redshift survey data could distinguish between general relativity and No Slip Gravity at the $\sim 3\sigma$ level, if the percent level measurements of $f\sigma_8$ lie along the current best fit. Next generation imaging surveys, such as Euclid and LSST, could test the prediction of No Slip Gravity that there is no slip. Such tests would be an exciting development, searching for signatures of modified gravity that makes definite predictions.

Acknowledgments

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A No running

One might notice that another way to obtain zero slip (assuming $\alpha_T = 0$) is to impose $\alpha_M = 0$. This gives

$$G_{\text{matter}} = G_{\text{light}} = \frac{2\alpha_B + 2\alpha'_B}{(2 - \alpha_B)\alpha_B + 2\alpha'_B} \quad (\text{A.1})$$

$$c_s^2 \propto (H\alpha_B) + [1 - (\alpha_B/2)]\alpha_B H^2 > 0. \quad (\text{A.2})$$

This restores to general relativity in the early universe when $\alpha_B \ll 1$. (Also see [7].) In the late time de Sitter limit, the gravitational strength reaches $G_{\text{eff,dS}} = 1/(1 - \alpha_B/2)$. Stability requires that $\alpha_B > 0$ in this limit. However, at early times one can obtain stability with either sign of α_B . For example, α_B can deviate from 0 to positive values, and continue to its de Sitter asymptote. This will be stable at early times if $\alpha'_B/\alpha_B > 1/2$. If α_B initially deviates to negative values, it can be stable at early times with $\alpha'_B/\alpha_B < 1/2$, but will force G_{eff} negative at some time later before α_B crosses zero on the way to its positive de Sitter asymptote. Thus we require $\alpha_B \geq 0$.

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