Testing dark energy in gravitationally bound systems: The case of Non-local Gravity

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Introduction

The forthcoming generation of astrophysical and cosmological surveys are expected to generate an extensive and groundbreaking collection of data. The unmatched quantity and quality of these observations should boost our knowledge of the Universe, especially in regards to the dark sector. The true nature of the dark energy, either gravitational or related to fundamental fields, may therefore be unveiled in the next decades.

A complementary approach for delving into the zoo of dark energy models relies on the analysis of the impact within the non-linear regime resulting from the introduction of extra degrees of freedom (DoF) in the theory. Therefore, the investigation of the dynamics of gravitationally bound systems emerges as the ideal framework to explore the feasibility of any modification of the standard Λ Cold Dark Matter (ΛCDM) paradigm.

Even though the ΛCDM model clearly is the best fit model for cosmology, several shortcomings and recently risen tensions make room for alternative cosmological models as well as extended theories of gravity. The presence of singularities, along with the inconsistency at quantum level, plagues General Relativity (GR) on ultraviolet (UV) scales. In addition, the ineffective effort to find out the true nature of the dark fluids as well as the so-called cosmological tensions pose severe challenges to the reliability of the ΛCDM paradigm in the infrared (IR) regime. To tackle these issues, one potential approach is to reinterpret the discrepancy between observations and GR predictions as a missing geometry rather than a missing matter/energy.

According to the Lovelock's theorem, there exist only five options to extend the geometrical content of our theory of gravity: in this poster, we investigate the physical consequences of giving up locality, thus following a quantum-inspired path. Non-locality is introduced at the dynamical level through the addition of non-local operators into the gravitational lagrangian. It can be seen as either a fundamental feature of gravity or an effective approach to ameliorate the behaviour of the gravitational interaction both in the UV and IR regime, where the GR might be breaking down.

Galaxy clusters (based on arXiv:2205.03216)

The additional DoF of the non-local model affect the nonlinear regime, hence the cosmic structures. The astrophysical systems therefore emerge as the optimal framework to benchmark non-local gravity against GR. In order to yield the non-local theoretical predictions to be compared with the astrophysical data, it is necessary to specify the form of the distortion function. $f(\eta)$ is derived by leveraging the existence of Noether symmetries in a spherically symmetric spacetime:

$$f(\eta) = 1 + e^{\eta}\,.$$

Once provided an explicit form for the non-local action, the weak field limit can be performed to derive the Newtonian potentials

$$\Phi(r) = -\frac{GM}{r} + \frac{G^2M^2}{2c^2r^2}\left[\frac{14}{9} + \left(\frac{3}{r_\eta} - \frac{11}{6r_\xi}\right)r\right],$$

$$\Psi(r) = -\frac{GM}{3r} + \frac{G^2M^2}{2c^2r^2}\left[\frac{2}{9} + \left(\frac{3}{2r_\xi} - \frac{1}{r_\eta}\right)r\right].$$

These potentials have been used to test the non-local scenario at galaxy cluster scales. The clusters of galaxies, being the most prominent density peaks of the large-scale structure in the Universe, act as powerful cosmic lenses, hence privileged systems to test both the standard cosmological model and the underlying theory of gravity. The modelling of the lensing phenomenology within the Non-local Gravity framework yields

$$\kappa(R) = \frac{1}{c^2}\frac{D_{ls}D_l}{D_s}\int_{-\infty}^{+\infty}\nabla_r^2\left[\frac{\Phi(R,z)+\Psi(R,z)}{2}\right]dz$$

CLASH sample

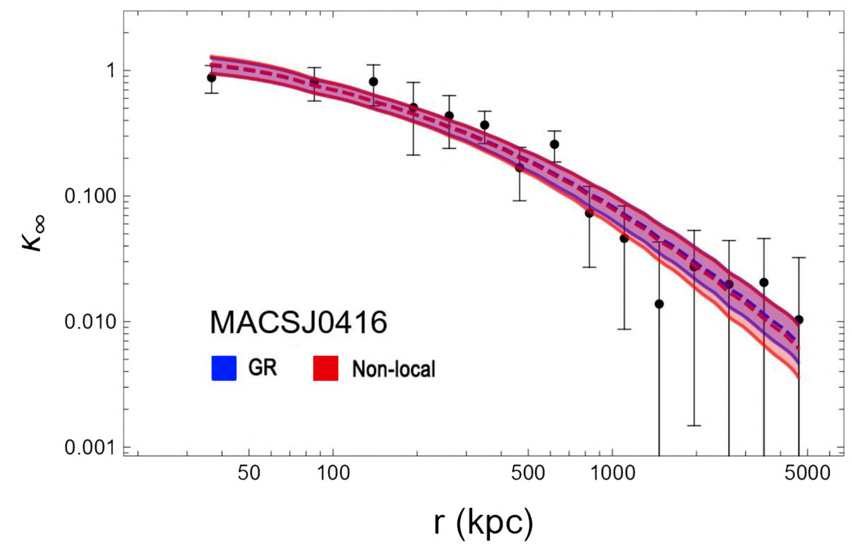
$5 \lesssim M_{200}/10^{14}M_\odot \lesssim 30$

$0.187 < z < 0.686$

4 measures of $\kappa(R_i)$ from strong lensing

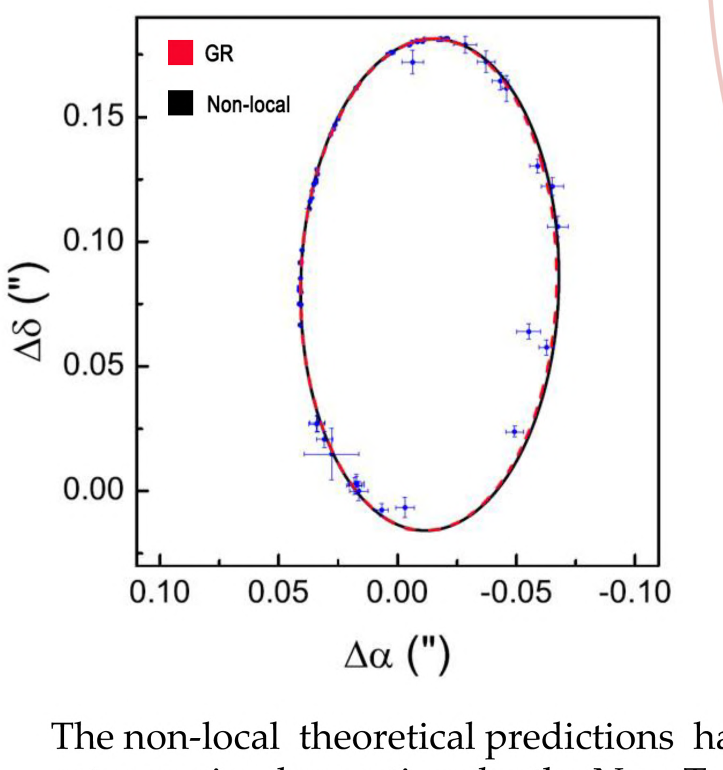
11 measures of $\kappa(R_i)$ from weak lensing

The Markov Chain Monte Carlo analysis of the non-local model in light of the CLASH data provides lower bounds on the non-local radii (see the figure in the Conclusions). Moreover, our analysis clearly shows that there is no evidence in favour of General Relativity with respect to Non-local Gravity in the context of galaxy cluster lensing: $-0.03 \leq \ln \mathcal{B}_{GR}^{NL} \leq 1.01$, where $\mathcal{B}_{GR}^{NL}$ is the Bayes factor.



S2 star (based on arXiv:1812.09289)

The non-local model has also been tested through the orbit of the star S2 around the Galactic center. The theoretical predictions have been achieved by performing two-body simulations in the non-local gravity potential $\Phi(r)$, assuming that the distance from S2 is 8.3 kpc, and the mass of SgrA* is 4.3×10^6 M$_\odot$. Since the goal was not to make a new estimate of the black hole mass using non-local gravity, but instead studying the possible deviations from the Keplerian orbit of the star S2, the black hole parameters have been fixed to the best fit values from an independent analysis.



The non-local theoretical predictions have been compared to the astronomic observations by the New Technology Telescope (NTT) and the Very Large Telescope (VLT). The non-local parameters have been inferred by minimizing the χ^2 through a modified Marquardt-Levenberg algorithm (see the figure in the Conclusions), and no spoiling effects on the orbit have been found.

Non-local gravity

In this poster we focus on a specific non-local gravity model, originally proposed by Deser and Woodard

$$S = \frac{1}{2\kappa}\int d^4x\,\sqrt{-g}\,R[1 + f(\Box^{-1}R)]\,.$$

Here, non-locality is introduced through the ***distortion function*** $f(\Box^{-1}R)$. Note that any transcendental functions of the geometric fields can be rewritten as the integral kernel of a differential operator. The non-locality therefore has integral nature and give rise to long-range effects that are usually applied for addressing the IR issues of GR.

Moreover, the non-locality can be encoded in two auxiliary scalar fields

$$S = \frac{1}{2\kappa}\int d^4x\,\sqrt{-g}\,\{R[1 + f(\eta) - \xi] - \partial_\mu\xi\,\partial^\mu\eta\}\,,$$

where the Klein-Gordon equations for the two scalar fields are

$$\Box\,\eta = R\,, \qquad \Box\,\xi = -R\,\frac{\partial f(\eta)}{\partial\eta}\,.$$

This non-local model shows an extremely appealing cosmological phenomenology. It indeed provides a viable mechanism to account for the late time cosmic acceleration through a delayed response to the radiation-to-matter dominance transition. The non-local contribution vanishes during the radiation epoch, and then starts to grow. However, it remains subdominant until very low redshift. Around z = 1, the gravitational correction finally becomes non-negligible and drives the onset of the cosmic acceleration, thus preventing the introduction of DE.

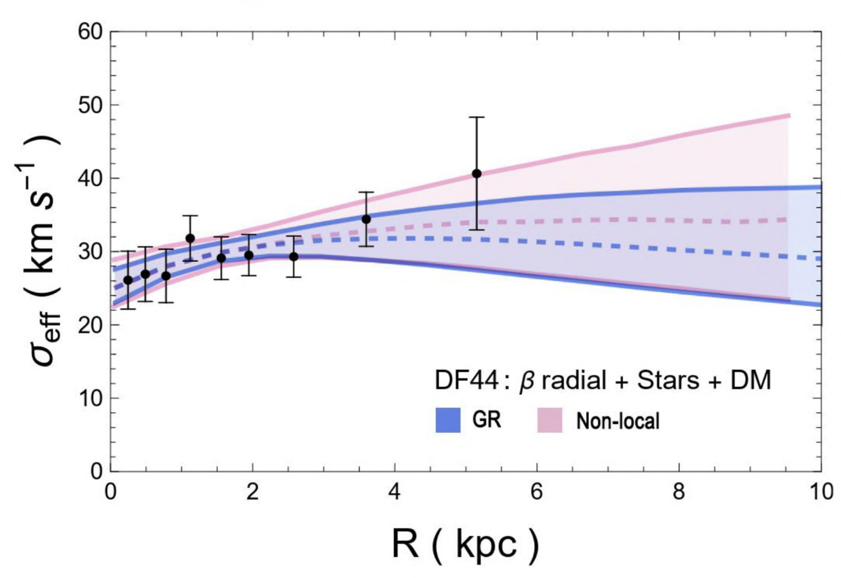
Ultra-Diffuse Galaxies (in preparation)

The Ultra-Diffuse Galaxies are a specific class of low surface brightness galaxies, characterized by either the the lack of star-forming gas or a very low star formation efficiency. They recently emerged as ideal systems to test theories of gravity due to their wide variety of matter contents. Here we consider the galaxy DF-44, dark matter dominated (M_{DM} / M_{gal} ~ 1), and the galaxies DF-2 and DF-4, baryon dominated (M_{DM} / M_{stars} ≤ 1). UDGs are characterized by a high number of globular clusters, through which the galaxy kinematics can be traced.

The non-local gravity potential can be used to define an effective mass that enters the line-of-sight velocity dispersion

$$\sigma_{los}^2 = \frac{2G_N}{I(R)}\int_R^\infty dr\,K\left(\frac{r}{R}\right)l(r)\frac{M_{eff}(r)}{r}$$

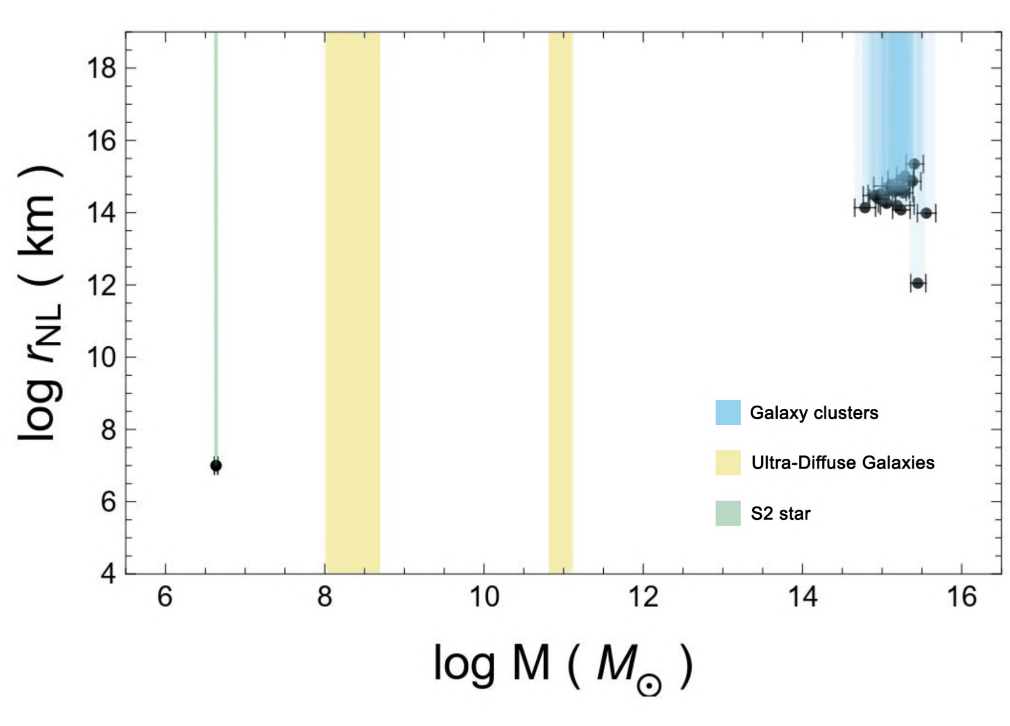
Through an MCMC analysis, the non-local model has been tested against the Dragonfly Array Telescope data, and then compared to GR to investigate possible spoiling effects at galaxy scales. Moreover, constraints on the non-local radii will be set at new mass scales (see the figure in Conclusions).



Conclusions

Throughout this poster, I have presented a non-local metric model of gravity, which is able to perfectly reproduce the cosmic expansion history without any additional dark energy component. This model is currently facing a severe challenge as its original screening mechanism has been disproven. However, the non-local terms can be localized, thus resulting in effective scalar fields depending on the scale and mediating the additional gravitational effects. The screening mechanism usually applied in the Extended Theories of Gravity could be therefore suitable for Non-local Gravity as well.

While waiting for the data of the IV generation cosmological surveys, that may break the degeneracy among dark energy models, the gravitationally bound systems represent a rewarding test bench for those models based upon extensions of GR. The Non-local Gravity model under consideration has been therefore tested on a wide range of astrophysical scales, ranging from the galactic center up to massive galaxy clusters, showing no evidence for spoiling effects. Moreover, the additional gravitational radii provided by the theory may be constrained by future analysis at intermediate mass scales (UDGs and others), thus yielding a fundamental tool to investigate the formation and evolution of cosmic structures within the Non-local Gravity framework.



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arXiv:1812.09289 – Dialektopoulos, Borka, Capozziello et al., *''Constraining nonlocal gravity by S2 star orbits''*, PRD 99 (2019) 4