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TESTS OF GRAVITY AT GALACTIC AND EXTRAGALACTIC SCALES: THEORY VS OBSERVATIONS

V. BORKA JOVANOVIĆ[1], P. JOVANOVIĆ[2], D. BORKA[1] and S. CAPOZZIELLO[3,4,5]

[1] *Atomic Physics Laboratory (040), Vinča Institute of Nuclear Sciences,*
University of Belgrade, P.O. Box 522, 11001 Belgrade, Serbia
E–mail: vborka@vinca.rs, dusborka@vinca.rs

[2] *Astronomical Observatory, Volgina 7, P.O. Box 74, 11060 Belgrade, Serbia*
E–mail: pjovanovic@aob.rs

[3] *Dipartimento di Fisica "E. Pancini", Università di Napoli "Federico II", Compl. Univ.*
di Monte S. Angelo, Edificio G, Via Cinthia, I-80126, Napoli, Italy
E–mail: capozzie@na.infn.it

[4] *Istituto Nazionale di Fisica Nucleare (INFN) Sez. di Napoli, Compl. Univ.*
di Monte S. Angelo, Edificio G, Via Cinthia, I-80126, Napoli, Italy

[5] *Gran Sasso Science Institute, Viale F. Crispi, 7, I-67100, L'Aquila, Italy*

Abstract. We present a short overview of our results considering a possibility to explain the observed galactic and extragalactic dynamics using gravitational potentials derived from Extended Theories of Gravity (ETGs) without dark matter (DM) hypothesis. These theories can have observational signatures at astrophysical and cosmological scales, and thus we consider different ETG potentials within the Galactic Central Parsec, as well as on extragalactic scales. The simulated stellar orbits, obtained by modified gravity potentials, are compared with astrometric observations of S2 star orbit around the central suppermassive black hole of the Milky Way. The obtained results give strong constraints on the gravity interaction parameters. We also used ETGs to investigate the baryonic Tully-Fisher relation of spiral galaxies and the fundamental plane of ellipticals, and found that these empirical relations could be theoretically explained by the existence of a further gravitational radius predicted by ETGs and without the DM hypothesis. This gravitational radius plays an analogous role, in the case of weak gravitational field, like the Schwarzschild radius in the case of strong gravitational field.

1. INTRODUCTION

In this paper we present the primary scientific objectives of the project 176003 "Gravitation and the large scale structure of the Universe", as well as the research team of the project, and we describe realized scientific aims. The project is proposed in the frame of fundamental research programme for 2011-2017 period and it is supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia.

The results of the work within the project are presented at many national and international conferences (poster sections, talks, invited lectures) and at the seminars, and there are published papers in national and international refereed journals.

2. BASIC RESEARCH PROJECT 176003

Research team. Our research team consists of seven researchers:

- Dr. Predrag P. Jovanović, leader of the project, Full Research Professor, Astronomical Observatory (AOB), engaged with 10 research months (RM) per year
- Dr. Luka Č. Popović, Full Research Professor, AOB, 2 RM
- Dr. Edi A. Bon, Assistant Research Professor, AOB, 6 RM
- Dr. Nataša Ž. Bon, Assistant Research Professor, AOB, 4 RM
- Dr. Marko T. Stalevski, Assistant Research Professor, AOB, 6 RM
- Dr. Duško V. Borka, Full Research Professor, Vinča Institute of Nuclear Sciences, 4 RM
- Dr. Vesna V. Borka Jovanović, Assistant Research Professor, Vinča Institute of Nuclear Sciences, 8 RM

We are a team of seven researchers, with total 40 research months per year, which would correspond to about 3.33 × 12 research months per year.

As it can be seen from the list of authors in our published papers, we developed international collaboration with colleagues from abroad, which had multiple benefits in the sense of transfer of knowledge, improving learning performances, as well as the professional training and development of young researchers.

Project tasks within 176003. One part of the project topics is organized into three project tasks:

1. "*Variability of the radiation in the spectra of active galaxies.*" (leader Dr. Edi Bon)
2. "*Radio sources and structure of the matter at cosmological scales.*" (leader Dr. Vesna Borka Jovanović)
3. "*Effects of the modified theories of gravity at large scales.*" (leader Dr. Duško Borka)

Theses and awards. In the frame of the project, during the period 2011-2017, several researchers defended their PhD theses and were awarded for their scientific contribution. Also, a number of foreign students defended their MSc theses under the supervision by the members of our research team. Below is a list of these results regarding the professional training and development of researchers.

defended PhD theses

- Dr. Nataša Bon, 2011: *The contribution of stellar populations to AGN spectra.*
- Dr. Marko Stalevski, 2012: *Research of the structure of AGNs: dusty torus.*

awards

- Dr. Vesna Borka Jovanović, 2008: Annual Award of the Institute of Nuclear Sciences "Vinča", for scientific contributions in basic research.
- Dr. Duško Borka, 2012: Annual Award of the Institute of Nuclear Sciences "Vinča", for scientific contributions in basic research.
- Dr. Predrag Jovanović, 2012: Annual Award of the Astronomical Observatory Belgrade, for scientific contributions in basic research.

defended MSc theses - AstroMundus students

- MSc. Miika Pursiainen (Finland), 2017: *The shape of the broad iron Kα line and the effect of the accretion disc parameters.*
- MSc. Miriam Gudino (Mexico), 2017: *The Hubble constant from time-delays of gravitationally lensed quasars.*

defended MSc theses - ERASMUS students

- MSc. Stefania Gravina (Italy), 2017: *The Galactic Center as a gravitational laboratory.*
- MSc. Anna D'Addio (Italy), 2017: *Testing theories of gravity by Sgr A*.*

Participations in European projects. Members of our research team had very intensive international collaboration and actively participated in several European projects which are listed below.

ERASMUS+ Mobility Program

- For higher education student and staff mobility (2016-2018);
- inter-institutional agreement between: Dipartimento di Fisica, Università di Napoli "Federico II", Italy and Vinča Institute of Nuclear Sciences, University of Belgrade, Serbia.

Bilateral cooperation

- No. 451-03-01231/2015-09/1, "Testing Extended Theories of Gravity at different astrophysical scales", for period 2016-2018;
- between Serbia and Italy.

COST actions

- MP1304: "Exploring fundamental physics with compact stars" (NewCompStar), 2014-2017.

- CA15117: "Cosmology and Astrophysics Network for Theoretical Advances and Training Actions" (CANTATA), 2016-2019.

AstroMundus

- A 2-years Erasmus programme, with joint masters degree in Astronomy and Astrophysics (Austria, Italy, Germany, Serbia), 2012-2018.

3. OBJECTIVES OF THE PROJECT 176003

In the scope of our project there are several lines of research (theoretical investigations, numerical simulations and the comparison of the modelled results with astronomical observations) which include the following gravitational phenomena at galactic and extragalactic scales:

1. supermassive black holes,
2. supermassive black hole binaries,
3. gravitational lenses, and
4. modified gravity as alternative to dark matter.

Here, we will just briefly mention the main results from the first three topics, while the last one will be discussed in more detail.

3. 1. SUPERMASSIVE BLACK HOLES

Supermassive black holes (SMBHs) are considered to be located in the centers of most of galaxies, and therefore, the formation and evolution of host galaxies is fundamentally influenced by properties of their central SMBHs. Within our project, we investigate the effects of strong gravity in the vicinity of SMBHs, their activity and radiation from their accretion disks. Also, there are investigations of infrared radiation from the dusty torus and polarization in active galactic nuclei and in quasars.

For more details about obtained results see Jovanović et al. 2011, 2016, Jovanović 2012, Popović et al. 2012, Stalevski et al. 2016, 2017, Peest et al. 2017, and references therein.

3. 2. SUPERMASSIVE BLACK HOLE BINARIES

Supermassive black hole binaries (SMBHBs) originate in the galactic mergers, and their coalescences represent the most powerful sources of gravitational waves. We study electromagnetic counterparts of gravitational waves because SMBHBs in Active Galactic Nuclei (AGNs) can be detected by periodicity in electromagnetic radiation from their host-galaxies.

From this field, the significant results were obtained and published in Bon et al. 2012, 2016 and Jovanović et al. 2014.

3. 3. GRAVITATIONAL LENSES

Gravitational lenses (GLs) are massive astronomical objects in which gravitational field light bending is induced and as a consequence, either the appearance of multiple images of some background source (macrolensing), or its amplification (microlensing). We focus on gravitational lensing effects on radiation from AGN in different spectral bands, and on application of GL in observational cosmology.

For an example about the investigations and the obtained results in this field, see e.g. Stalevski et al. 2012.

3. 4. MODIFIED GRAVITY AS ALTERNATIVE TO DARK MATTER

Modified gravity gives the possibility for explaining the observed galactic and extragalactic dynamics using gravitational potentials derived from Extended Theories of Gravity (ETGs), without taking into account presence of dark matter (DM). ETGs may have observational effects at astronomical and cosmological scales. We tested the following modified gravities: R^n, Yukawa, Sanders, hybrid, scalar-tensor, nonlocal gravity, using astronomical observations of motion of S-stars around SMBH in the center of our Galaxy, as well as at extragalactic scales. Here we present a short overview of these investigations.

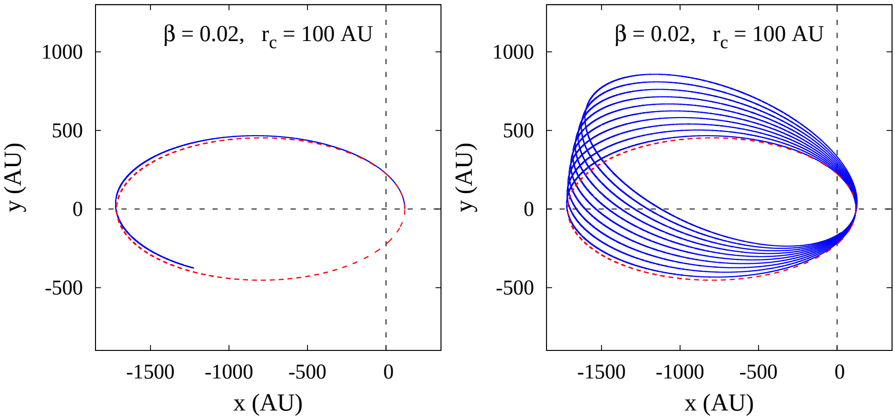

Figure 1: The orbits of S2-like star around massive black hole in R^n gravity (blue solid line) and in Newtonian gravity (red dashed line) for $r_c = 100$ AU and $\beta = 0.02$ during 0.8 periods (left) and 10 periods (right) (Borka et al. 2012).

R^n modified gravity. One of the straightforward generalizations of Einstein's General Relativity, where the function $f(R)$ is not linear in the Ricci scalar R ($f(R) \neq$ R), would be $f(R)$ modified gravity. Furthermore, there is the power-law version of this gravity: R^n modified gravity, which we used in our investigations. About considerations of the power-law fourth-order theories of gravity see in Capozziello et al. 2007. In the weak field limit, R^n gravity potential (generated by a pointlike mass m at the distance r) is Capozziello et al. (2007):

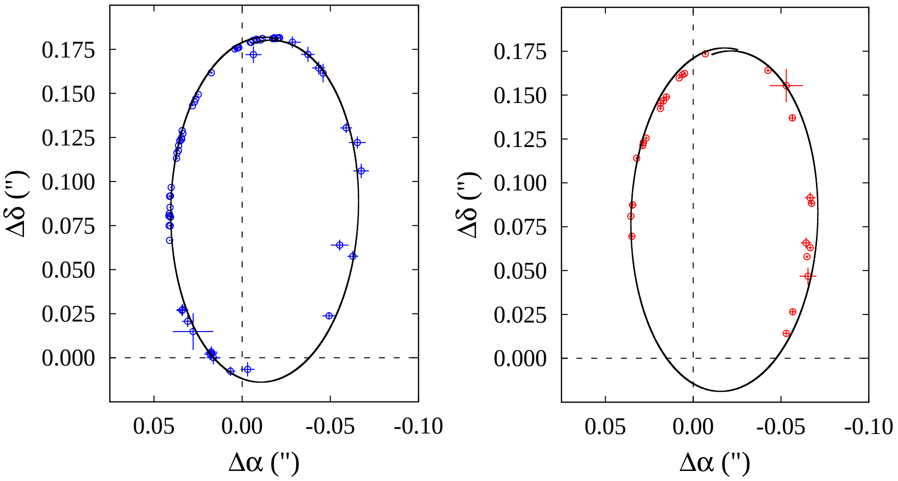

Figure 2: The fitted orbit of S2 star around massive black hole in R^n gravity for r_c = 100 AU and β = 0.01 (black solid lines in both panels). The NTT/VLT astrometric observations are presented in the left panel by blue circles, while the Keck measurements are denoted by red circles in the right panel (Borka et al. 2012).

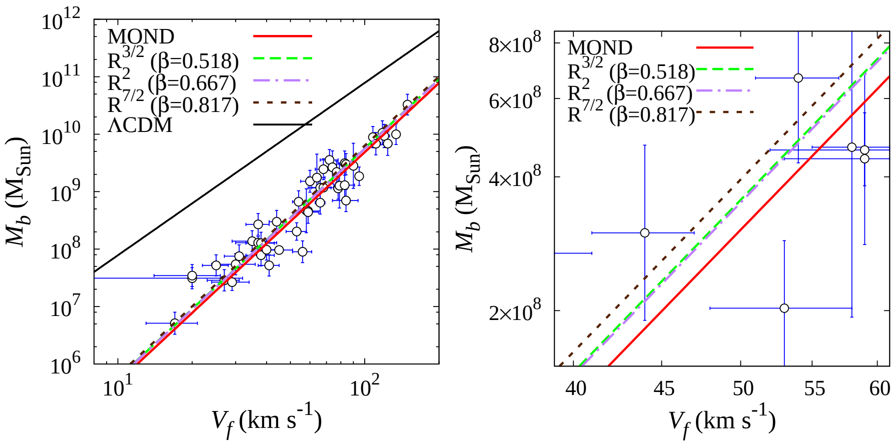

Figure 3: *Left*: Comparison between best fit BTF relations of gas-rich galaxies, in MOND, R^n gravity for values of n = 1.5, 2 and 3.5 (corresponding β are 0.518, 0.667 and 0.817, respectively) and ΛCDM. *Right*: A zoomed part of the figure, for one small range of parameters (Capozziello et al. 2017).

$$\Phi(r) = -\frac{Gm}{2r}\left[1 + \left(\frac{r}{r_c}\right)^{\beta}\right], \tag{1}$$

where r_c is scalelength depending on the gravitating system properties and β is universal constant which depends on power n:

$$\beta = \frac{12n^2 - 7n - 1 - \sqrt{36n^4 + 12n^3 - 83n^2 + 50n + 1}}{6n^2 - 4n + 2}. \tag{2}$$

Our results considering the simulated S2 star orbits around the SMBH in the Galactic Center (GC), obtained using the power-law fourth-order theories of gravity, as well as about determining of the parameter space of $f(R)$ gravity, can be found in the following papers: Borka et al. 2012, Borka et al. 2013, Zakharov et al. 2014, Borka et al. 2015. The comparison between the observed and simulated orbit of S2 star is given in Figs. 1 and 2. We obtained that the orbital precession is about -1° per orbital period.

In the paper Borka Jovanović et al. 2016 we showed that the fundamental plane (FP) of galaxies can be recovered in the framework of $f(R)$ gravity, avoiding the issues related to DM, to fit the observations. Also, our results point out that the gravitational corrections induced by $f(R)$ can lead photometry and dynamics of the system, i.e. the effective radius (observationally derived from photometry), actually is a gravitational radius. In Capozziello et al. 2017 we showed that it is possible to explain the baryonic Tully-Fisher relation and the rotation curve of gas-rich galaxies without the dark matter hypothesis. A graphical comparison between the best fit BTF relations in R^n gravity, MOND and ΛCDM is presented in Fig. 3.

Yukawa-like and Sanders-like modified gravity. We also investigated the possibility of explaining theoretically the observed deviations of S2 star orbit around the GC using gravitational potentials derived from modified gravity models in the absence of DM. To this aim, an analytic fourth-order theory of gravity, nonminimally coupled with a massive scalar field, is considered (Capozziello et al. 2014). As discussed in that paper, in $f(R)$-gravity, the scalar curvature R of the Hilbert - Einstein action, is replaced by a generic function $f(R)$. As a result, in the weak field limit, the gravitational potential is found to be Yukawa-like:

$$\Phi\left(r\right) = -\frac{GM}{(1+\delta)r}\left[1 + \delta e^{-\left(\dfrac{r}{\Lambda}\right)}\right], \tag{3}$$

where Λ is an arbitrary parameter (usually referred to as the range of interaction), depending on the typical scale of the system under consideration and δ is a universal constant.

In case of $f(R,\phi)$-gravity, we can consider a generic function of Ricci scalar and scalar field (e.g. Stabile & Capozziello 2013). The gravitational potential is found by setting the gravitational constant as

$$G = \left(\frac{2\,\omega(\phi^{(0)})\,\phi^{(0)} - 4}{2\,\omega(\phi^{(0)})\,\phi^{(0)} - 3}\right)\frac{G_\infty}{\phi^{(0)}}, \tag{4}$$

where $\phi^{(0)}$ is the first term of the series expansion of the scalar field ϕ, and G_∞ is the gravitational constant as measured at infinity, and by imposing $\alpha^{-1} = 3 - 2\,\omega(\phi^{(0)})\,\phi^{(0)}$ and $\omega(\phi^{(0)}) = 1/2$, the gravity potential is (see e.g. Stabile & Capozziello 2013, Capozziello et al. 2014):

$$\Phi_{ST}(\mathbf{x}) = -\frac{G_\infty M}{|\mathbf{x}|}\left\{1+\alpha\, e^{-\sqrt{1-3\alpha}\, m_\phi |\mathbf{x}|}\right\}. \tag{5}$$

In case of $f(R,\phi)$-gravity, parameters that we want to determine are α and m_ϕ.

The simulated orbits of S2 star around the Galactic Centre in Sanders gravity potential are shown in Fig. 4. The orbital precession is about 3.1° per orbital period.

In Zakharov et al. 2016 we considered opportunity to evaluate a graviton mass from χ^2 statistical test of fitting the S2-star orbit around central SMBH of our Galaxy in the gravitational potential which was derived from Yukawa theory of massive gravity. The obtained results showed that such stellar trajectories could constrain the range of Yukawa interaction i.e. the Compton wavelength of graviton, and hence its mass. The derived upper bound for graviton mass was consistent with the corresponding constraints obtained from a gravitation wave signal recently detected by LIGO (Abbott et al. 2016).

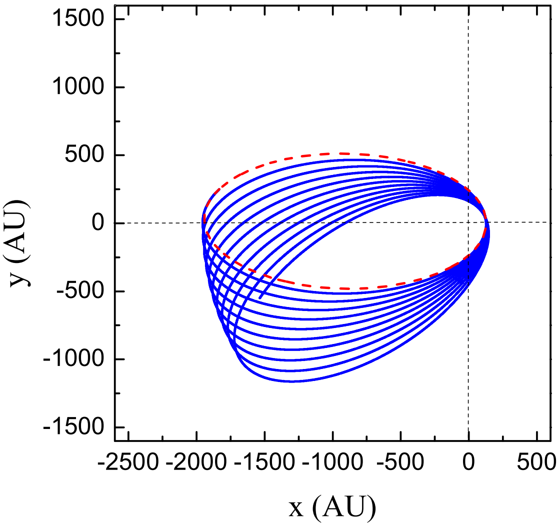

Figure 4: Comparison between the orbit of S2 star in Newtonian potential (red dashed line) and Sanders-like potential for the best fit parameters (the absolute minimum of reduced χ^2 = 1.5011) α = 0.00018 and m_ϕ = -0.0026 during 10 orbital periods (blue solid line) (Capozziello et al. 2014).

Hybrid modified gravity. The possible signatures for the so called hybrid gravity within the Galactic Central Parsec, are considered in Borka et al. 2016. The simulations of S2 star orbital precession resulted with constraints on the range of hybrid gravity interaction parameter ϕ_0. We used the modified gravitational potential, with the leading parameters m_ϕ and ϕ_0, in the form:

$$\Phi\left(r\right)=-\frac{G}{1+\phi_0}\left[1-\left(\phi_0/3\right)e^{-m_\phi r}\right]M/r. \tag{6}$$

The hybrid gravity effective potential is very good candidate among the other considered models of gravity because it is able to explain gravitational phenomena at different astronomical scales.

Scalar-tensor modified gravity. In Gravina et al. 2017, D'Addio et al. 2017 we discussed the general case of scalar-tensor-higher-order gravity, where the standard Hilbert-Einstein action is replaced by a more general action containing a scalar field and curvature invariants, like the Ricci scalar R and the Ricci tensor $R_{\alpha\beta}$.

All these results show that theories of modified gravity represent a good alternative to DM, and they are a good basis to construct an effective theory of gravity.

4. THE PLANS FOR FUTURE WORK

This was an overview of some of the most important results within the project 176003 "Gravitation and the large scale structure of the Universe", and the remaining ones can be seen from the bibliography of the published papers. Our plan for future work would be (a) to continue with the investigations of gravitation at different scales, as well (b) to continue and improve our international collaboration. Therefore, our plans for future work include the following issues:

(a)
- further research of possible alternatives to DM through different theories of modified gravity,
- testing these theories using astronomical observations in our Galaxy, and also at large, extragalactic scales,
- research of the observed effects of the strong gravitational field in the vicinity of SMBHs - single and binaries,
- theoretical models of areas in the vicinity of central SMBHs in active galaxies;

(b)
- achieving partnerships between educational institutions,
- foster of collaboration,
- mobility of young researchers.

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