Publ. Astron. Obs. Belgrade No. 99 (2020), 287 - 290 *Contributed Paper*

KINEMATICAL PROPERTIES OF ELLIPTICAL GALAXIES IN YUKAWA-LIKE GRAVITY

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Abstract. Fundamental plane of elliptical galaxies can be used to constrain theories of gravity, i.e. to obtain observational constraints on the parameters of the theories of modified gravity. The fundamental plane is connected to global properties of ellipticals and also can be connected with the parameters of extended theories of gravity. On the other hand several extended gravitation potentials in the weak field limit have Yukawa-like form. That is why in this paper we first analyze the velocity distribution of elliptical galaxies comparing theoretical results in case of Yukawa-like gravity with astronomical data for elliptical galaxies. In that way we constrain the Yukawa parameters α and λ, and analyze the properties of elliptical galaxies in Yukawa-like gravity.

1. THE KINEMATICS OF ELLIPTICAL GALAXIES

There are three main global observables of elliptical galaxies: the central projected velocity dispersion of elliptical galaxies σ_0, the effective radius r_e, and the mean effective surface brightness (within r_e) I_e (Borka Jovanović et al. 2016a,b; Borka Jovanović et al. 2019). Elliptical galaxies do not populate uniformly these three dimensional parameter space, but they are rather confined to a narrow logarithmic plane. Any of the three parameters may be estimated from the other two, and together they describe a plane that falls within their more general three-dimensional space. This correlated plane is now referred to as the fundamental plane (FP) (Dressler et al. 1987; Ciotti et al. 1996). It was defined and discussed in more detail in e.g Bender et al. 1992; Bender et al. 1993; Busarello et al. 1997; Saulder et al. 2013; Taranu et al. 2015 and references therein. The important empirical relation (Busarello et al. 1997):

$$\log(r_e) = a\,\log(\sigma_0) + b\,\log(I_e) + c, \tag{1}$$

gives us the possibility to obtain unique observational constraints on the structure, formation, and evolution of early-type galaxies, as well as on the parameters of the theories of modified gravity.

Besides, in order to describe the velocity of populations of stars, one can define rotational velocity of a group of stars v_c, and a dispersion σ which represents the characteristic random velocity of stars. The relation v_c/σ characterizes the kinematics of the galaxies. It was shown that it is the main characteristic which differentiates spiral from elliptical galaxies. In case of spiral galaxies $v_c/\sigma \gg 1$, and they are regarded as kinematically cold systems, while elliptical galaxies are characterized with $0 < v_c/\sigma < 1$, and they are kinematically hot systems.

2. STELLAR KINEMATICS IN YUKAWA-LIKE GRAVITY

Several theories of modified gravity in the weak field limit has the Yukawa-like form (Capozziello et al. 2020):

$$\Phi(r) = -\frac{GM(r)}{r}\left[1 + \alpha e^{-\lambda r}\right], \tag{2}$$

where λ^{-1} is the range of Yukawa interaction (scale length) and α is a universal constant which gives the strength of the correction.

In order to use this type of corrections to the gravitational potential for modeling the stellar kinematics in the elliptical galaxies, we assumed that the mass distribution within them may be described by the singular isothermal sphere (SIS) model: $M(r) = 2\sigma_{SIS}^2\, G^{-1}\, r$. In that case $\sqrt{2}\sigma_{SIS} = \sigma_0$, and the expression for circular velocity v_c at the effective radius r_e has the following form (Capozziello et al. 2020):

$$v_c^2(r_e) = \sigma_0^2\left(1 + \alpha\,(1 + w)\,e^{-w}\right), \quad w = \lambda r_e, \tag{3}$$

from which one can obtain the following v_c/σ relation at r_e for the ellipticals in the Yukawa-like gravity:

$$\frac{v_c}{\sigma} = \frac{v_c(r_e)}{\sigma_0} = \sqrt{1 + \alpha\,(1 + w)\,e^{-w}}. \tag{4}$$

3. FUNDAMENTAL PLANE IN YUKAWA-LIKE GRAVITY

In this section we are going to constrain the parameters α and λ considering a sample of elliptical galaxies given in Busarello et al. 1997. The observations and the method that we are using are described in Capozziello et al. 2020 and references therein. For this purpose, we will study the v_c/σ relation given by the expression (4) for this sample of ellipticals.

In Fig. 1, we show numerically calculated value of the v_c/σ relation for ellipticals as a function of parameter α and product of Yukawa parameter λ and effective radius r_e in case of Yukawa-like potential. With increasing v_c/σ ratio, when approaching to 1, values of α approaches to 0, which is in accordance with our earlier finding (Capozziello et al. 2020). Also, we can notice that for larger values of $\lambda \cdot r_e$ product ($\lambda \cdot r_e \geq 4$) we are in allowed region of parameter space. It means that for this choice of parameters we will expect good agreement between theory and observations.

The theoretical values for the velocity dispersion of elliptical galaxies σ^{theor}, which is assumed to be equal to $v_c(r_e)$, are presented in Fig. 2 as a function of the effective radius r_e, for four different values of the $\lambda \cdot r_e$ product: 2, 3, 4 and 5, and for the three values of Yukawa parameter α: -0.5, -1.5 and -2.0.

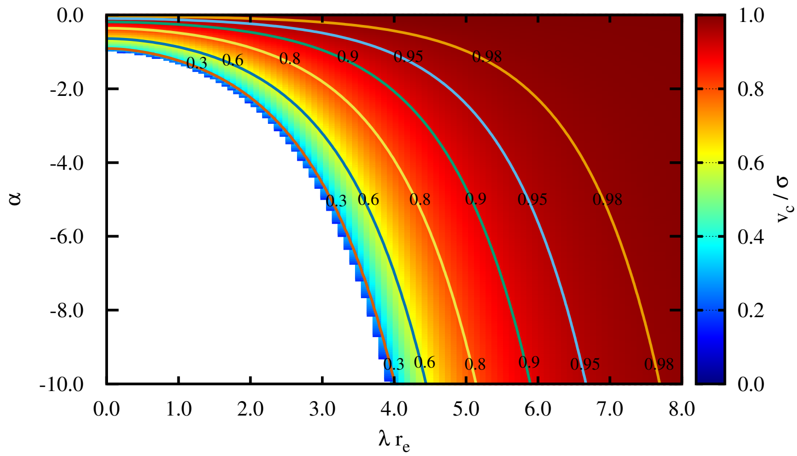

Figure 1: The v_c/σ relation for the elliptical galaxies in the Yukawa-like gravity, given by eq. (4) and represented by different color shades, as well as its dependence on the (λ, α) parameter space of the gravitational potential (2).

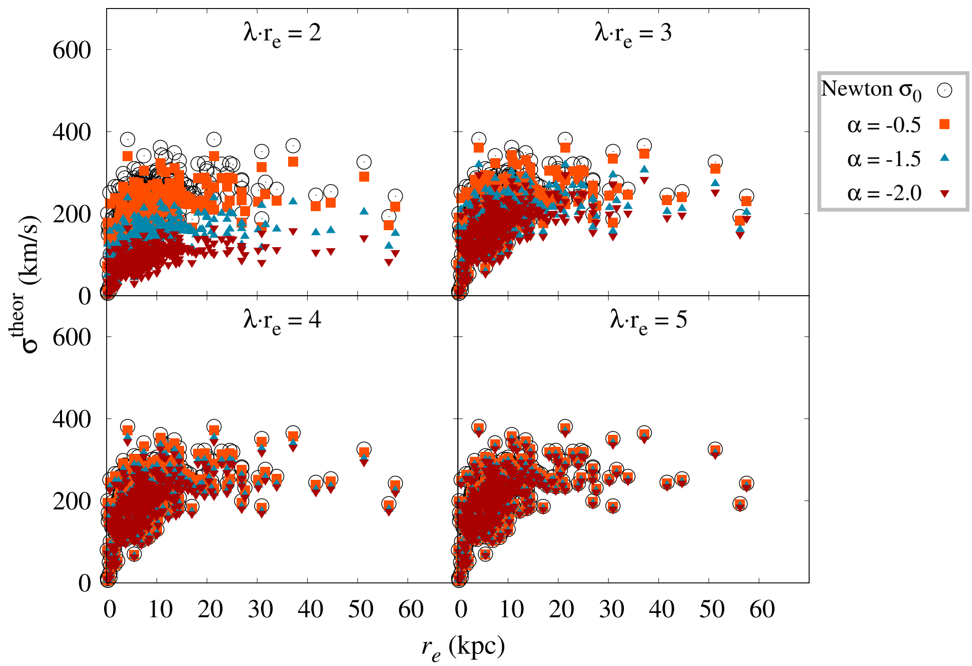

Figure 2: Velocity dispersion σ^{theor} as a function of the effective radius r_e for eliptical galaxies, for four different values of the $\lambda \cdot r_e$ product: 2, 3, 4 and 5. The Newtonian velocity dispersion at the effective radius σ_0 is taken from (Burstein et al. 1997). Theoretical values of velocity dispersion σ^{theor} are calculated for the three values of Yukawa parameter α: -0.5, -1.5 and -2.0.

For all three studied values of Yukawa parameter α, a good agreement is achieved for larger values of $\lambda \cdot r_e$ product of 4 and 5, while in the case of smaller $\lambda \cdot r_e$ product of 2 and 3, agreement is not so good, but it is still satisfactory when parameter α is smaller by magnitude. The values of v_c/σ ratio for different combinations of $(\alpha, \lambda \cdot r_e)$ parameters of Yukawa-like gravity from Fig. 2 are given in Table 1.

α \ λr_e	2	3	4	5
-0.5	0.89	0.95	0.98	0.99
-1.5	0.63	0.84	0.93	0.97
-2.0	0.43	0.78	0.90	0.96

Table 1: The values of v_c/σ ratio for different combinations of (α,λr_e) parameters of Yukawa-like gravity, presented in Fig. 2.

The obtained results show that the Yukawa-like gravity is able to explain elliptical galaxies with different stellar kinematics described by v_c/σ relations shown in Fig. 1 and Table 1, without introducing the dark matter hypothesis. Besides, we can notice from Fig. 2 that the Yukawa-like correction has strong influence on the FP of the elliptical galaxies, and that better agreement with observations is obtained for those gravity parameters α and λ which give a larger v_c/σ relation closer to 1 (i.e. for kinematically less hot systems). Therefore, the v_c/σ relation and the FP can be used as standard tools to probe the Yukawa-like gravity in the weak field limit, as well as to constrain its parameters α and λ.

Acknowledgments. This work is supported by Ministry of Education, Science and Technological Development of the Republic of Serbia. P.J. wishes to acknowledge the support by this Ministry through the project contract No. 451-03-68/2020/14/20002.

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