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Graviton mass evaluation with trajectories of bright stars at the Galactic Center

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Abstract. One could use trajectories of test particles to evaluate a gravitational potential. In particular, in the case of the Galactic Center one could use photon trajectories to analyze a shadow structure. Another way is to use bright stars near the Galactic Center to evaluate a gravitational potential and constrain parameters of a model for the Galactic Center. In particular, one could obtain constraints on parameters of black hole, stellar cluster and dark matter concentration. Earlier, we constrained parameters of R^n and a Yukawa potential from observational data for the S2 star trajectory. Now gravity theories with a massive graviton are a subject of intensive studies. People proposed different experimental ways to evaluate a graviton mass. Recently, the joint LIGO & VIRGO collaboration reported not only a discovery of gravitational waves and binary black holes, but the team claimed also that found a constraint on a graviton mass as 1.2×10^{-22} eV. We show that an analysis of the S2 star trajectory could constrain a graviton mass with a comparable accuracy and this constraint is consistent with LIGO's one.

1. Introduction

In spite of a great success of a general relativity (GR) development in a more than a century we know only a few cases where we really need a strong gravitational field approximation to describe a physical reality. If we speak about observable manifestations of black hole features we need models with a strong gravitational field to describe 1) a final stage of inspiraling (merging and ring down) binary black holes; and 2) shapes of shadows around black holes. Perhaps, very soon observers will need GR corrections and later a full GR approach to fit observational data for bright stars near the Galactic Center. Assuming that a radiation in a spectral line is emitted from a region near a black hole horizon, it was found (and after that it was observed the X-ray K_{α} -line) that an observed shape of the spectral line can be an important indicator of a strong gravitational field near a black hole, moreover, one can evaluate a black hole spin analyzing a

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spectral line structure [1, 2, 3]⁸ (see also more recent reviews [11, 12] on the subject). Another phenomenon, where one really needs a strong gravitational field approach, is simulations of a shadow formation started since [13, 14, 15, 16] (see also calculations of shadows for different cases [17, 18, 19, 20, 21, 22] and recent reviews on the subject [23, 24]).

The problem is connected with attempts to resolve the smallest spot at the Galactic Center with VLBI interferometry in mm-band [25]. As it was noted earlier, observations of bright star trajectories near the Galactic Center could provide an efficient tool to evaluate a gravitational potential in particular, analyzing these trajectories one can obtain constraints on parameters of black hole and stellar cluster [26] and on parameters of dark matter distribution [27, 28, 29].

Two groups of astronomers with VLT and Keck telescopes observe stars near the Galactic Center, see [30, 31, 32] and references therein. An analysis of S2 like star trajectories gives an opportunity to obtain stringent constraints on alternative theories of gravity, including R^n theory which is a generalization of the classical GR and $n = 1$ corresponds to GR [33, 34] (there are also stringent constraints from Solar system data [35]), and Yukawa gravity [36]. In the paper we will obtain a graviton mass constraint from analysis of trajectories of bright stars at the Galactic Center.

2. Gravity Theories with Massive Graviton

A gravity theory with massive graviton was introduced in M. Fierz and W. Pauli [37]. However, later on some unexpected properties of such theories have been found such as van Dam–Veltman–Zakharov (vDVZ) discontinuity [38, 39, 40] (however, nonlinear solution was constructed for the Schwarzschild problem [41] providing a continuity at $m \rightarrow 0$ with the massless Einstein theory) and a presence of ghosts (and related instabilities) and other pathologies from quantum field theory point of view [42]. However, there is a significant progress to overcome such problem and build a consistent theory without Boulware – Deser ghosts [43, 44, 45, 46] (a great step has been done in the paper [47] where the authors developed a ghost free massive gravity). Here, we will not discuss theoretical aspects of massive gravity theory and we will consider only observational features of such an approach.

In spite of the problems of current theoretical models of massive gravity in seventies Goldhaber and Nieto obtained a graviton mass constraint based on the assumption that a Compton wave length of graviton is around $\lambda_g = 580$ kpc (it is around a typical distance between galaxies), and $m_g < 2 \times 10^{-62}$ g = 1.1×10^{-29} eV [48]. It was shown that in the relativistic theory of gravitation (RTG), developed by Logunov and his group, a non-vanishing mass of graviton substitutes Λ -term in the conventional Λ CDM cosmological model and one could find that a Compton wave length for graviton has a cosmological value, so that $m_g < (1.3 - 3.2) \times 10^{-66}$ g (depending on a way for an evaluation of the quantity) [49, 50, 51], see also estimates obtained recently $m_g < 5.2 \times 10^{-66} - 1.2 \times 10^{-65}$ g taking into account constraints on quintessence parameters [52]. Constraints on λ in Yukawa potential from Solar system data is given in [53] and analyzing these data, C. Will obtained a graviton mass constraint $m_g < 7.2 \times 10^{-23}$ eV at the 2σ level [54]. Analyzing weak gravitational lensing data (gravitational potential reconstruction for galactic clusters based on image deformations of background galaxies), Choudhury et al. found that a Compton wavelength of massive graviton has to be $\lambda > 100$ Mpc = 3×10^{21} km [55], therefore, $m_g < 6 \times 10^{-32}$ eV. Finn and Sutton suggested to use binary pulsars PSR B1913+116 and PSR B1534+112 to evaluate a graviton mass and they obtained $m_g < 7.6 \times 10^{-20}$ eV with 90% confidence level [56]. Larson and Hiscock proposed to use future LISA data for observations of gravitational radiation from interacting white dwarf binary star systems, including helium cataclysmic variable (HeCV) systems and in this case one can expect to reach the following graviton mass bound $m_g < 1 \times 10^{-24}$ eV [57]. For a subsample of 400 close white dwarf binaries

⁸ Results of iron K_{α} -line simulations in the framework of a simple model are given in [4, 5, 6, 7, 8, 9, 10].

with high signal-to-noise ratio gravitational wave and optical data with magnitudes brighter than 25, the combined upper limit on the graviton mass is at the level of $m_g = 6 \times 10^{-24}$ eV [58]. One can expect even a better estimates for ASTROD-I mission [59] because it will be possibly a next generation of space borne gravitational interferometers in space for gravitational wave detections. Many years ago, Sazhin proposed to use pulsar timing for gravitational wave detection [60] (see, also a more detailed discussion in [61]). Graviton mass constraints were obtained in [62], but later in erratum the authors noted that their approach was not correct [63], however, in paper [64] it was concluded, that one can obtain a graviton mass bound at a level $m_g = 3 \times 10^{-22}$ eV, if bi-weekly observation of 60 pulsars is performed for 5 years with a pulsar rms timing accuracy of 100 ns and the estimate can be improved in the case if more observations for more pulsars a longer observation period would be done, moreover, such an estimate will be improved with a pulsar array technique [65]. There are other suggestions to evaluate a graviton mass, some of them are rather exotic and based on hardly verified assumptions [46]. Systematics of proposed experiments and observations is not well investigated, moreover, some weaknesses of the proposals for a graviton mass evaluation are pointed out in the review [46].

3. Graviton Mass Estimate from Gravitational Wave Signal

If a graviton has a mass m_g , then in this case a speed of gravitational wave propagation could differ from c and we have a dispersion relation [54, 66, 67]

$$\frac{v_g^2}{c^2} = 1 - \frac{m_g^2 c^4}{E^2}, \quad (1)$$

where E is a graviton energy. Gravitons with different energies propagate with different velocities. Assume that we have gravitational waves and electromagnetic waves from the same source (from supernovae explosion, for instance). In this case we have [54, 66, 67]

$$1 - \frac{v_g}{c} = 5 \times 10^{-17} \left(\frac{200 \text{ Mpc}}{D} \right) \left(\frac{\Delta t}{1 \text{ s}} \right), \quad (2)$$

where $\Delta t = \Delta t_a - (1+z)\Delta t_e$ is the time difference, where Δt_a and Δt_e are the differences in arrival time and emission time of the two signals, respectively, and z is the redshift of the source. Usually Δt_e is unknown, however, one could find an upper limit for Δt_e (for instance from a theoretical model), therefore, one could evaluate $1 - \frac{v_g}{c}$, therefore, m_g . Following [54, 66, 67] and assuming that the frequency of gravitational wave is ν and $h\nu \gg m_g c^2$ (h is Planck's constant), therefore, we have $\frac{v_g}{c} \approx 1 - \frac{1}{2} \frac{h}{\lambda_g \nu}$, where $\lambda_g = \frac{h}{m_g c}$ or $\lambda_g \approx \frac{1}{2} \frac{1}{\sqrt{1 - v_g/c}}$. If one has an upper limit for $1 - v_g/c$, it can be re-written as a lower limit for λ_g , as the following expression [54, 66, 67]

$$\lambda_g = 3 \times 10^{12} \text{ km} \left(\frac{200 \text{ Mpc}}{D} \frac{\nu}{100 \text{ Hz}} \right) \left(\frac{1}{\nu \Delta t} \right). \quad (3)$$

It is a lucky case if one observe electromagnetic and gravitational radiation from the same source. But even in the case if only gravitational radiation has been detected as it was noted [54] because gravitational wave signal with a massive graviton will be different from signal for a graviton with a vanishing mass and in this case for $D \approx 200 \text{ Mpc}$, $\nu \approx 100 \text{ Hz}$, $\nu \Delta t \sim \rho^{-1} \approx 0.1$ The result is $\lambda_g > 10^{13} \text{ km}$. Based on ideas expressed in [54, 66, 67], the LIGO/VIRGO collaboration obtained the same estimate for the Compton wavelength of a massive graviton [68, 69, 70].

4. Graviton Mass Estimates from Trajectories of Bright Stars near the Galactic Center

We use a modification of the Newtonian potential corresponding to a massive graviton case [71, 54, 67]:

$$V(r) = -\frac{GM}{(1+\delta)r} \left[1 + \delta e^{-\left(\frac{r}{\lambda}\right)} \right], \quad (4)$$

where δ is a universal constant (we put $\delta = 1$). In our previous studies [36] we found constraints on parameters of Yukawa gravity. As it was described in [72, 73] we used observational data from NTT/VLT [30]. If we wish to find a limiting value for λ_x , so that $\lambda > \lambda_x$ with a probability $P = 1 - \alpha$ (where we select $\alpha = 0.1$) normalized depending on λ_x has to be equal to the threshold depending on degree of freedom ν and parameter α or in other words, $\chi^2(\lambda_x) = \chi^2_{\nu, \alpha}$. Computing these quantities we obtain $\lambda_x = 2900$ AU $\approx 4.3 \times 10^{11}$ km. Now we obtain the upper limit on a graviton mass and we could claim that with a probability $P = 0.9$, a graviton mass should be less than $m_g = 2.9 \times 10^{-21}$ eV (since $m_g = h c / \lambda_x$) in the case of $\delta = 1$ [72].

5. Conclusions

As it was noted earlier, our graviton mass estimate is slightly greater than estimate with LIGO interferometer, however, a) our estimate was obtained in independent way with other observational data; b) our estimate is consistent with LIGO's one; c) our estimate will definitely improved with forthcoming facilities such as GRAVITY, E-ELT and TMT because more precise observations of bright star orbits will give an opportunity to reconstruct a gravitational potential at the Galactic Center in a more accurate way, therefore, one can expect a better estimates for λ parameter and a graviton mass. However, such a progress will be not very rapid because of an exponential dependence of a potential on λ .

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