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ON THE PRESENCE OF A FIFTH FORCE AT THE GALACTIC CENTER

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Abstract. The presence of a Yukawa-like correction to Newtonian gravity is investigated at the Galactic Center, leading to a new upper limit for the intensity of such a correction. We perform a Markov Chain Monte Carlo analysis using the astrometric and spectroscopic data of star S2 collected at the Very Large Telescope by GRAVITY, NACO and SINFONI instruments, covering the period from 1992 to 2022. The precision of the GRAVITY instrument allows us to derive the most stringent upper limit at the Galactic Center for the intensity of the Yukawa contribution ($\propto \alpha e^{-\lambda r}$) to be $|\alpha| < 0.003$ for a scale length $\lambda = 3 \cdot 10^{13}$ m (~ 200 AU). This improves by roughly one order of magnitude all estimates obtained in previous works.

Keywords: celestial mechanics, general relativity, galactic center

1 Introduction

It is well known that the current theory of gravity, General Relativity (GR) correctly reproduces the observations obtained at Solar System scales, such as the precession of Mercury, and predicts the gravitational waveforms expected from two compact objects coalescing, first observed by the LIGO/VIRGO collaboration in 2012 (Will 2018b).

Further evidences in favour of GR comes from the monitoring of the stellar motion around Sagittarius A* (SgrA*), the supermassive black hole (BH) at the center of the Milky Way, performed by the GRAVITY collaboration and the UCLA group, independently (Eckart & Genzel 1996; Schödel et al. 2002; Ghez et al. 2003; Gillessen et al. 2009b,a; Sabha et al. 2012) and from the first observation of SgrA* shadow by the Event Horizon Telescope collaboration (Akiyama et al. 2022).

However, it is equally known that GR fails in describing the accelerated expanding universe if not introducing an *ad hoc* cosmological constant, which causes several isssues (Weinberg 1989; Peebles & Ratra 2003), or the presence of the so-called dark matter effects, such as gravitational lensing effects and the rotational curve of galaxies (van Albada et al. 1985; Massey et al. 2010; Salucci 2019). To conclude, GR lacks a quantum description and fails completely when quantum scales are reached.

All those issues gave rise to a plethora of Extended Theories of Gravity (ETGs), which aim to create a more general theory that is able to explain all the effects mentioned above and of which GR represents only a *weak field* limit. Among those many theories we recall the scalar-tensor-vector theory (Moffat 2006), massive gravity theories (Visser 1998; Hinterbichler 2012), theories in higher dimensions with Kaluza-Klein compactification (Bars & Visser 1986; Hoyle et al. 2001), massive Brans-Dicke theories (Perivolaropoulos 2010; Alsing et al. 2012), or $f(R)$ theories (Capozziello et al. 2015).

A common characteristic of all those theories, which is also the only relevant information for this work, is the fact that when a new massive degree of freedom is introduced in the theory, then the weak field limit, that in GR is given by Newtonian gravity, is modified with the introduction of a Yukawa-like correction, i.e.

$$U = -\frac{GM}{r}\left(1 + \alpha e^{-\lambda r}\right) . \tag{1.1}$$

Due to the huge impact that a deviation from Newtonian gravity would have on our community, the presence of such a correction has been largely studied and explored with both Earth-based and space-based instruments

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(Konopliv et al. 2011; Hees et al. 2014; Bergé 2017; Hofmann & Müller 2018; Will 2018a; Touboul et al. 2022; Mariani et al. 2023; Fienga & Minazzoli 2024), with the most stringent upper limit found at $\lambda \sim 5 \cdot 10^8$ m (correspondent to Earth-Moon distance), where $|\alpha| \lesssim 10^{-10}$.

The discovery of orbiting stars around SgrA* (Eckart & Genzel 1996; Schödel et al. 2002; Ghez et al. 2003; Gillessen et al. 2009b,a; Sabha et al. 2012), all located within one arcsecond distance from it, allows us to test GR in a completely different environment from the Solar System.

The importance of looking for a fifth force at the Galactic Center (GC) lies in the fact that many ETGs that predict a Yukawa-like term also display a screening mechanism that suppresses the fifth force contribution at Solar System scales and prevents its detection. This would explain why it would be yet unobserved, while its effect may be different around supermassive BHs.

At the GC, a previous test was performed by the UCLA group using the orbit of star S2 (Hees et al. 2017), which found the best upper limit to be $\alpha \lesssim 0.01$ at scales comparable to the S2-SgrA* distance. ($\lambda \sim 10^{13} - 10^{14}$ m).

After the introduction of the GRAVITY instument (GRAVITY Collaboration 2017), that can reach up to a few tens of microarcsecond in astrometric precision, and the pericenter passage of S2 on May 2018 we decided to perform the analysis again aiming to improve the current upper bounds on α.

2 Methods

2.1 Available data

The set of available data D for star S2 can be organized according to the following criteria:

a) Astrometric data DEC, R.A.

- 128 data points collected using both the SHARP camera at the New Technology Telescope between 1992 and 2002 ($\sim$ 10 data points, accuracy of ≈ 4 mas) and the NACO imager at the VLT between 2002 and 2019 (118 data points, accuracy of ≈ 0.5 mas);
- 76 data points collected by GRAVITY at the VLT between 2016 and April 2022 (accuracy of $\approx 50\,\mu$as).

b) Spectroscopic data V_R

- 102 data points collected by SINFONI at the VLT (100 points) and NIRC2 at Keck (2 points) collected between 2000 and March 2022 (accuracy in good conditions of $\approx 10 - 15$ km/s).

2.2 Model

The potential we aim to test takes the form in Eq. (1.1), where α represents the strength of interaction and λ is a scale parameter, which depends on the specific theory considered. For example, when new massive fields are included in the theory, λ represents the Compton wavelength of the field, which is related to the mass by $m_\varphi = h/c\lambda$, being h the Planck constant.

In comparison to previous works, here the Schwarzschild precession in the S2 orbit is also included, since it has been formally detected at a 10σ confidence level by the GRAVITY Collaboration (GRAVITY Collaboration 2020; GRAVITY Collaboration 2024) and it is computed via

$$\boldsymbol{a}_{\rm 1PN} = \frac{GM}{c^2 r^2}\left[\left(\frac{4GM}{r} - v^2\right)\frac{\boldsymbol{r}}{r} + 4\dot{r}\boldsymbol{v}\right], \tag{2.1}$$

where $\boldsymbol{r} = r\hat{r}$, $\boldsymbol{v} = \left(\dot{r}\hat{r}, r\dot{\theta}\hat{\theta}, r\dot{\phi}\sin\theta\hat{\phi}\right)$ and $v = |\boldsymbol{v}|$.

We performed a Markov Chain Monte Carlo analysis using Emcee (Foreman-Mackey et al. 2013), with a Gaussian likelihood and fixing the value of λ at each run. The set of fitted parameters is given by:

$$\Theta_i = \{e, a_{\rm sma}, \Omega_{\rm orb}, i_{\rm orb}, \omega_{\rm orb}, t_p, R_0, M, x_0, y_0, v_{x_0}, v_{y_0}, v_{z_0}, \alpha\}, \tag{2.2}$$

where e is the eccentricity and $a_{\rm sma}$ the semi major axis of the star S2, while $\Omega_{\rm orb}$, $i_{\rm orb}$, and $\omega_{\rm orb}$ are the three angles used to project the star's orbital frame into the observer reference frame, t_p is the time of pericenter passage, and M and R_0 are SgrA* mass and GC distance, respectively. The additional parameters $\{x_0, y_0, v_{x_0}, v_{y_0}, v_{z_0}\}$ characterize the NACO/SINFONI data reference frame with respect to Sgr A* (Plewa et al. 2015).

3 Results

Analysing the posterior distribution of α, we were able to derive a 95% confidence level on it, which is reported in Figure 1 as function of the fixed lengthscale λ.

The minimum of the curve is reached at $\lambda \sim 3 \cdot 10^{13}$ m, where $|\alpha| < 0.003$, that represents our strongest constraint at the GC and it improves by roughly one order of magnitude the previous upper limit found by Hees et al. (2017).

The upper limits are much better for length scales that coincide with S2 orbital range, as one can expect. On the contrary, for $\lambda < r_{\rm S2}^{\rm peri}$ the exponential contribution goes to zero, leaving only the Newtonian potential in the equations of motion, while for for $\lambda > r_{\rm S2}^{\rm apo}$ the Yukawa contribution reduces to the monopolar contribution $M(1+\alpha)/r$ and the parameters M and α are completely degenerate.

If we assume that the gravitational interaction is mediated by a massive boson as in massive gravity theories (where $\alpha = 1$), an upper limit on the graviton's mass can be derived. Since $\alpha = 1$ is excluded at 95% confidence level for $\lambda \lesssim 8 \cdot 10^{14}$ m, this lower bound on the wavelength λ can be translated into an upper limit on the graviton mass, corresponding to $m_g \lesssim 2.5 \cdot 10^{-22}$ eV.

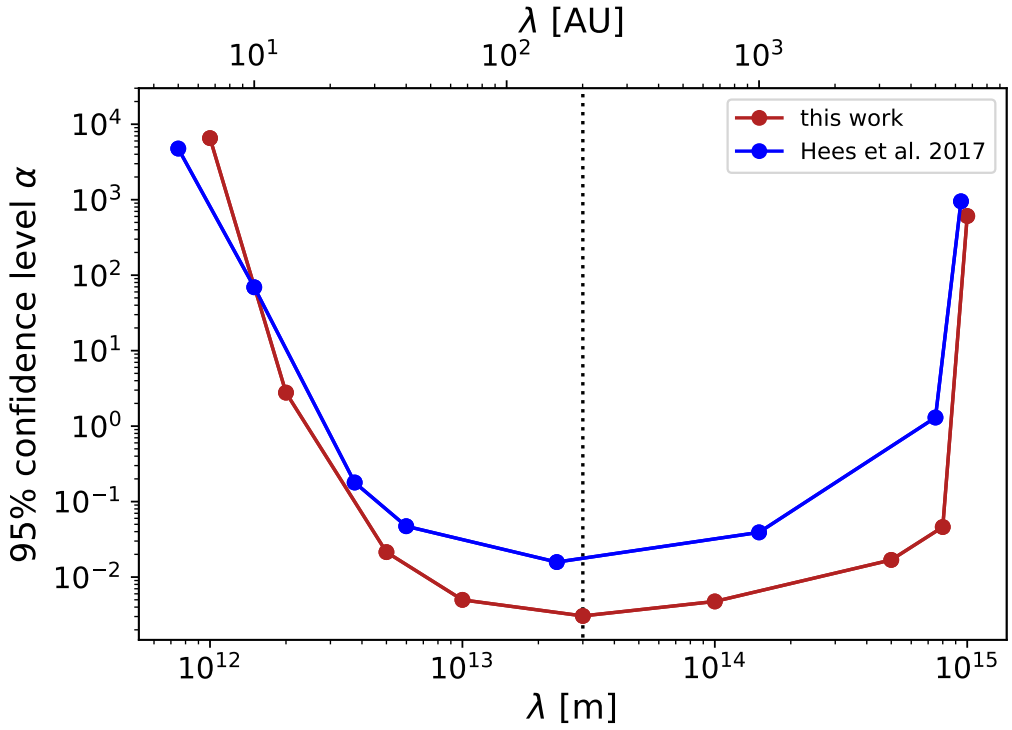

Fig. 1. 95% confidence level on $|\alpha|$ obtained in this work (red dots), compared with previous estimates by Hees et al. (2017) (blue dots). The dotted vertical line represents the minimum of the curve, in correspondence to $\lambda \sim 3 \cdot 10^{13}$ m $\sim$ 200 AU

4 Conclusions

In the work presented here, we update the current constraints on the fifth force intensity at the GC using GRAVITY data for S2 from 2017 to 2022, including the pericenter passage. These data have allowed us to significantly improve previous estimates on the same effect, giving a 95% confidence level curve that is one order of magnitude below the previous estimates (see Figure 1). Specifically, three different behaviors are found in the posterior distribution of α, according to the value of the length scale of the new interaction λ compared to S2 orbital range.

The minimum value of α is found for $\lambda = 3 \cdot 10^{13}$ m ($\sim$ 200 AU) where $|\alpha| < 0.003$. For comparison, in correspondence with the minimum found by Hees et al. (2017), $\lambda = 150$ AU $\sim 2.2 \cdot 10^{13}$ m, we found $|\alpha| < 0.0031$.

A complete analysis including all S-stars, specifically those with apocenter passage farther away than S2, is left for future work, with the aim of further improving the confidence level curve. This would allow us to possibly expand the range of λ and obtain additional and meaningful constraints at $\lambda \gtrsim 8 \cdot 10^{14}$ m.

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