Tests of gravity theories with observations of Galactic Center and M87*. Advances in astronomy in 2019

А.Ф. Захаров (Alexander F. Zakharov)

E-mail: zakharov@itep.ru

Institute of Theoretical and Experimental Physics, B. Cheremushkinskaya, 25, 117218 Moscow

27. 11.2019

Workshop on Non-Ideal Plasma,
Presidium of RAS, Moscow, Russia
Growing Importance of GR

- LIGO-Virgo: BBHs, BNS (kilonova) GW 170817;
- GRAVITY, Keck and new tests of GR
- EHT and M87* images
- We consider shadows and trajectories of bright stars near the GC as tools to test gravity theories
- Nobel prize in physics 2019 (J. Peebles (physical cosmology); M. Mayor and D. Queloz (exoplanets))
• 2009: Ingrosso et al. discovered the first exoplanet in Andromeda galaxy
• 2019: Observers operating largest telescopes with AO use our ideas to constrain parameters of alternative theories of gravity
• (three citations of Keck group (Hees et al. PRL (2017) and 10 citations by GRAVITY collaboration (2019))
R. Hooke proof that $F \sim \frac{1}{r^2}$ could explain Kepler’s laws
Outline of my talk

• Introduction
• Bright star trajectories around BH at GC as a tool to evaluate BH parameters and DM cluster
• Constraints on massive graviton theories
• Forecasts for graviton mass improvements
• Constraints on tidal charge
• Applications for current and forthcoming observations
• Conclusions
References

• AFZ, F. De Paolis, G. Ingrosso, and A. A. Nucita, New Astronomy Reviews, 56, 64 (2012).
• AFZ, Physical Reviews D 90, 062007 (2014).
• AFZ, P. Jovanovic, D. Borka, V. Borka Jovanovic, gr-qc: 1605.00913v; JCAP (2016)
• AFZ, EPJ C (2018)
• AFZ, IJMPD (2019)
ON A STATIONARY SYSTEM WITH SPHERICAL SYMMETRY
CONSISTING OF MANY GRAVITATING MASSES

By Albert Einstein
(Received May 10, 1939)

If one considers Schwarzschild's solution of the static gravitational field of spherical symmetry

\[ ds^2 = -\left(1 + \frac{\mu}{2r}\right)^4 \left(dx_1^2 + dx_2^2 + dx_3^2\right) + \left(1 - \frac{\mu}{2r}\right)^2 dt^2 \]

it is noted that

\[ g_{tt} = \left(1 - \frac{\mu}{2r}\right)^2 \]

vanishes for \( r = \mu/2 \). This means that a clock kept at this place would go at the rate zero. Further it is easy to show that both light rays and material particles take an infinitely long time (measured in "co-ordinate time") in order to reach the point \( r = \mu/2 \) when originating from a point \( r > \mu/2 \). In this sense the sphere \( r = \mu/2 \) constitutes a place where the field is singular. (\( \mu \) represents the gravitating mass.)

There arises the question whether it is possible to build up a field containing such singularities with the help of actual gravitating masses, or whether such regions with vanishing \( g_{tt} \) do not exist in cases which have physical reality. Schwarzschild himself investigated the gravitational field which is produced by an incompressible liquid. He found that in this case, too, there appears a region with vanishing \( g_{tt} \) if only, with given density of the liquid, the radius of the field-producing sphere is chosen large enough.

This argument, however, is not convincing; the concept of an incompressible liquid is not compatible with relativity theory as elastic waves would have to travel with infinite velocity. It would be necessary, therefore, to introduce a compressible liquid whose equation of state excludes the possibility of sound signals with a speed in excess of the velocity of light. But the treatment of any such problem would be quite involved; besides, the choice of such an equation of state would be arbitrary within wide limits, and one could not be sure that thereby no assumptions have been made which contain physical impossibilities.

One is thus led to ask whether matter cannot be introduced in such a way that questionable assumptions are excluded from the very beginning. In fact this can be done by choosing, as the field-producing mass, a great number of
The following table gives $\mu$ and $2\nu$ for $M = 1$ as functions of $\nu$ (approximately):

<table>
<thead>
<tr>
<th>$\nu$</th>
<th>$\mu$</th>
<th>$2\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.</td>
<td>1.</td>
<td>$\infty$</td>
</tr>
<tr>
<td>.05</td>
<td>.988</td>
<td>19.76</td>
</tr>
<tr>
<td>.1</td>
<td>.948</td>
<td>9.48</td>
</tr>
<tr>
<td>.15</td>
<td>.977</td>
<td>6.56</td>
</tr>
<tr>
<td>.2</td>
<td>1.134</td>
<td>5.65</td>
</tr>
<tr>
<td>.23</td>
<td>1.322</td>
<td>5.63</td>
</tr>
<tr>
<td>.25</td>
<td>1.823</td>
<td>7.40</td>
</tr>
<tr>
<td>.26</td>
<td>2.634</td>
<td>10.1</td>
</tr>
<tr>
<td>.268</td>
<td>$\infty$</td>
<td>$\infty$</td>
</tr>
</tbody>
</table>

When the cluster is contracted from an infinite diameter its mass decreases at the most about 5%. This minimal mass will be reached when the diameter $2\nu$ is about 9. The diameter can be further reduced down to about 5.6, but only by adding enormous amounts of energy. It is not possible to compress the cluster any more while preserving the chosen mass distribution. A further addition of energy enlarges the diameter again. In this way the energy content, i.e. the gravitating mass of the cluster, can be increased arbitrarily without destroying the cluster. To each possible diameter there belong two clusters (when the number of particles is given) which differ with respect to the particle velocity.

Of course, these paradoxical results are not represented by anything in physical nature. Only that branch belonging to smaller $\nu$ values contains the cases bearing some resemblance to real stars, and this branch only for diameter values between $\infty$ and $9M$.

The case of the cluster of the shell type, discussed earlier in this paper, behaves quite similarly to this one, despite the different mass distribution. The shell type cluster, however, does not contain a case with infinite $\mu$, given a finite $M$.

The essential result of this investigation is a clear understanding as to why the "Schwarzschild singularities" do not exist in physical reality. Although the theory given here treats only clusters whose particles move along circular paths it does not seem to be subject to reasonable doubt that more general cases will have analogous results. The "Schwarzschild singularity" does not appear for the reason that matter cannot be concentrated arbitrarily. And this is due to the fact that otherwise the constituting particles would reach the velocity of light.

This investigation arose out of discussions the author conducted with Professor H. P. Robertson and with Drs. V. Bargmann and P. Bergmann on the mathematical and physical significance of the Schwarzschild singularity. The problem quite naturally leads to the question, answered by this paper in the negative, as to whether physical models are capable of exhibiting such a singularity.

The Institute for Advanced Study
Black holes in centers of galaxies

Coevolution (Or Not) of Supermassive Black Holes and Host Galaxies

John Kormendy\textsuperscript{1} and Luis C. Ho\textsuperscript{2}

\textsuperscript{1}Department of Astronomy, University of Texas at Austin, 2515 Speedway C1400, Austin, TX 78722-1025; email: kormendy@astro.as.utexas.edu

\textsuperscript{2}The Observatories of the Carnegie Institution for Science, 813 Santa Barbara Street, Pasadena, CA 91101; email: lho@obs.carnegiescience.edu

\textbf{Abstract}

Supermassive black holes (BHs) have been found in 87 galaxies by dynamical modeling of spatially resolved kinematics. The \textit{Hubble Space Telescope} revolutionized BH research by advancing the subject from its proof-of-concept phase into quantitative studies of BH demographics. Most influential was the discovery of a tight correlation between BH mass $M_s$ and the velocity dispersion $v$ of the bulge component of the host galaxy. Together with similar correlations with bulge luminosity and mass, this led to the widespread belief that BHs and bulges coevolve by regulating each other’s growth. Conclusions based on one set of correlations from $M_s \sim 10^{9.5} M_\odot$ in brightest cluster ellipticals to $M_s \sim 10^9 M_\odot$ in the smallest galaxies dominated BH work for more than a decade.

New results are now replacing this simple story with a richer and more plausible picture in which BHs correlate differently with different galaxy components. A reasonable aim is to use this progress to refine our understanding of BH–galaxy coevolution. BHs with masses of $10^8 - 10^9 M_\odot$ are found in many bulgeless galaxies. Therefore, classical (elliptical-galaxy-like) bulges are not necessary for BH formation. On the other hand, while they live in galaxy disks, BHs do not correlate with galaxy disks. Also, any $M_s$ correlations with the properties of disk-grown pseudobulges and dark matter halos are weak enough to imply no close coevolution.

The above and other correlations of host galaxy parameters with each other and with $M_s$ suggest that there are four regimes of BH feedback. (1) Local, secular, episodic, and stochastic feeding of small BHs in largely bulgeless galaxies involves too little energy to result in coevolution. (2) Global feeding in major, wet galaxy mergers rapidly grows giant BHs in short-duration, quasar-like events whose energy feedback does affect galaxy evolution. The resulting hosts are classical bulges and coreless rotating-disk ellipticals. (3) After these AGN phases and at the highest galaxy masses, maintenance-mode BH feedback into X-ray-emitting gas has the primarily negative effect of helping to keep baryons locked up in hot gas and thereby keeping galaxy formation from going to completion. This happens in giant, core-nonrotating-halo ellipticals. Their properties, including their tight correlations between $M_s$ and core parameters, support the conclusion that core ellipticals form by dissipationless major mergers. They inherit coevolution effects from smaller progenitor galaxies. Also, (4) independent of any feedback physics, in BH growth modes (2) and (3), the averaging that results from successive mergers plays a major role in decreasing the scatter in $M_s$ correlations from the large values observed in bulgeless and pseudobulge galaxies to the small values observed in giant elliptical galaxies.
<table>
<thead>
<tr>
<th>Galaxy</th>
<th>(D) (Mpc)</th>
<th>(\sigma_v) ((\text{km sec}^{-1}))</th>
<th>(M_\bullet) (M(_{\odot}))</th>
<th>(r_{\text{infl}}) (arcsec)</th>
<th>(\sigma_{r_{\text{infl}}})</th>
<th>(r_{\text{infl}}/\sigma_{r_{\text{infl}}})</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galaxy</td>
<td>110.1</td>
<td>3.2</td>
<td>5.0</td>
<td>0.21</td>
<td>0.22</td>
<td>0.71</td>
<td>Meyer et al. 2012</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.9</td>
<td>4.0</td>
<td>0.23</td>
<td>0.24</td>
<td>0.70</td>
<td>Yelda et al. 2011</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.6</td>
<td>4.5</td>
<td>0.26</td>
<td>0.27</td>
<td>0.70</td>
<td>Gillessen 2009a</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>4.0</td>
<td>4.5</td>
<td>0.27</td>
<td>0.28</td>
<td>0.70</td>
<td>Genzel et al. 2010</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.7</td>
<td>4.2</td>
<td>0.29</td>
<td>0.30</td>
<td>0.70</td>
<td>Genzel et al. 2009b</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.6</td>
<td>4.3</td>
<td>0.30</td>
<td>0.31</td>
<td>0.70</td>
<td>Genzel et al. 2009c</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.3</td>
<td>4.1</td>
<td>0.31</td>
<td>0.32</td>
<td>0.70</td>
<td>Genzel et al. 2009d</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.7</td>
<td>4.4</td>
<td>0.32</td>
<td>0.33</td>
<td>0.70</td>
<td>Genzel et al. 2009e</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.8</td>
<td>4.5</td>
<td>0.33</td>
<td>0.34</td>
<td>0.70</td>
<td>Genzel et al. 2009f</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.9</td>
<td>4.6</td>
<td>0.34</td>
<td>0.35</td>
<td>0.70</td>
<td>Genzel et al. 2009g</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.1</td>
<td>4.3</td>
<td>0.35</td>
<td>0.36</td>
<td>0.70</td>
<td>Genzel et al. 2009h</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.7</td>
<td>4.4</td>
<td>0.36</td>
<td>0.37</td>
<td>0.70</td>
<td>Genzel et al. 2009i</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.8</td>
<td>4.5</td>
<td>0.37</td>
<td>0.38</td>
<td>0.70</td>
<td>Genzel et al. 2009j</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.9</td>
<td>4.6</td>
<td>0.38</td>
<td>0.39</td>
<td>0.70</td>
<td>Genzel et al. 2009k</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.1</td>
<td>4.3</td>
<td>0.39</td>
<td>0.40</td>
<td>0.70</td>
<td>Genzel et al. 2009l</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.7</td>
<td>4.4</td>
<td>0.40</td>
<td>0.41</td>
<td>0.70</td>
<td>Genzel et al. 2009m</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.8</td>
<td>4.5</td>
<td>0.41</td>
<td>0.42</td>
<td>0.70</td>
<td>Genzel et al. 2009n</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.9</td>
<td>4.6</td>
<td>0.42</td>
<td>0.43</td>
<td>0.70</td>
<td>Genzel et al. 2009o</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.1</td>
<td>4.3</td>
<td>0.43</td>
<td>0.44</td>
<td>0.70</td>
<td>Genzel et al. 2009p</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.7</td>
<td>4.4</td>
<td>0.44</td>
<td>0.45</td>
<td>0.70</td>
<td>Genzel et al. 2009q</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.8</td>
<td>4.5</td>
<td>0.45</td>
<td>0.46</td>
<td>0.70</td>
<td>Genzel et al. 2009r</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.9</td>
<td>4.6</td>
<td>0.46</td>
<td>0.47</td>
<td>0.70</td>
<td>Genzel et al. 2009s</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.1</td>
<td>4.3</td>
<td>0.47</td>
<td>0.48</td>
<td>0.70</td>
<td>Genzel et al. 2009t</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.7</td>
<td>4.4</td>
<td>0.48</td>
<td>0.49</td>
<td>0.70</td>
<td>Genzel et al. 2009u</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.8</td>
<td>4.5</td>
<td>0.49</td>
<td>0.50</td>
<td>0.70</td>
<td>Genzel et al. 2009v</td>
</tr>
<tr>
<td>Galaxy</td>
<td>105</td>
<td>3.9</td>
<td>4.6</td>
<td>0.50</td>
<td>0.51</td>
<td>0.70</td>
<td>Genzel et al. 2009w</td>
</tr>
</tbody>
</table>

Lines based on HST spectroscopy are in red. Column 2 is the assumed distance. Column 3 is the stellar velocity dispersion inside the “effective radius” that encompasses half of the light of the bulge. Column 4 is the measured BH mass with the one-sigma range that includes 68% of the probability in parentheses. Only the top four \(M_\bullet\) values for the Galaxy include distance uncertainties in the error bars. Column 5 is the radius of the sphere of influence of the BH, the line that lists \(r_{\text{infl}}\) contains the adopted \(M_\bullet\). Column 6 is the effective resolution of the spectroscopy, estimated as in Kormendy (2004). It is a radius that measures the blurring effects of the telescope point-spread function or “PSF,” the slit width or aperture size, and the pixel size. The contribution of the telescope is estimated by the dispersion \(\sigma_{\text{psf}}\), the effective resolution of the core of the average radial brightness profile of the PSF. In particular, the HST PSF is the PSF taken from M31 (van den Bosch & de Zeeuw 2010).
These results establish the existence and mass of the central dark object beyond any reasonable doubt. They also eliminate astrophysical plausible alternatives to a BH. These include brown dwarfs and stellar remnants (e.g., Maoz 1995, 1998; Genzel et al. 1997, 2000; Ghez et al. 1998, 2005) and even fermion balls (Ghez et al. 2005; GEG10). Boson balls (Torres et al. 2000; Schunck & Mielke 2003; Liebling & Palenmuela 2012) are harder to exclude; they are highly relativistic, they do not have hard surfaces, and they are consistent with dynamical mass and size constraints. But a boson ball is like the proverbial elephant in a tree: it is OK where it is, but how did it ever get there? GEG10 argue that boson balls are inconsistent with astrophysical constraints based on AGN radiation. Also, the Sofian (1982) argument implies that at least most of the central dark mass observed in galaxies grew by accretion in AGN phases, and this quickly makes highly relativistic objects collapse into BHs. Finally (Fabian 2013), X-ray AGN observations imply that we see, in some objects, material interior to the innermost stable circular orbit of a non-rotating BH; this implies that these BHs are rotating rapidly and excludes boson balls as alternatives to all central objects. Arguments against the most plausible BH alternatives – failed stars and dead stars – are also made for other galaxies in Maoz (1995, 1998) and in Bender et al. (2005). Exotica such as sterile neutrinos or dark matter WIMPs could still have detectable (small) effects, but we conclude that they no longer threaten the conclusion that we are detecting supermassive black holes.

HST has taken us essentially one order of magnitude inward in radius. A few other telescopes take us closer. But mostly, we are still working at $10^4$ to $10^5$ Schwarzschild radii. In our Galaxy, we have observed individual stars in to $\sim 500$ Schwarzschild radii. Only the velocity profiles of relativistically broadened Fe Kα lines (e.g., Tanaka et al. 1995; Fabian 2013) probe radii that are comparable to the Schwarzschild radius. So we are still inward bound. Joining up our measurements made at thousands of $R_S$ with those probed by Fe Kα emission requires that we robustly integrate into our story the rich and complicated details of AGN physics; that is, the narrow- and broad-emission-line regions. That journey still has far to go.
Large telescopes, AO and bright stars in IR

Reinhard Genzel, Prof. Dr.

Max Planck Institute for Extraterrestrial Physics, Garching

Curriculum Vitae

Born on March 24, 1952 in Bad Homburg v.d.H. Study of physics Bonn Univ., doctorate Max Planck Institute for Radioastronomy Bonn (1978), Postdoctoral Fellow, Harvard-Smithsonian Center for Astrophysics (1978-1980), Cambridge, MA, Associate Professor of Physics and Associate Research Astronomer, Space Sciences Laboratory, University of California, Berkeley (1981-1985), Full Professor of Physics, University of California, Berkeley (1985-1986), Director and Scientific Member at the Max Planck Institute for Extraterrestrial Physics (since 1986), Honorary Professor Munich Univ. (since 1988), Full Professor of Physics University of California Berkeley (since 1999).
American citizen. Born 1965 in New York City, NY, USA. Ph.D. 1992 at California Institute of Technology, Pasadena, CA, USA. Professor at University of California, Los Angeles, CA, USA.
MEASURING DISTANCE AND PROPERTIES OF THE MILKY WAY’S CENTRAL SUPERMASSIVE BLACK HOLE WITH STELLAR ORBITS

A. M. Ghez1,2, S. Sales1,4, N. N. Weinberg1,2, J. R. Lu1, T. Do1, J. K. Dunn1, K. Matthews3, M. Morris2, S. Yelda1, E. E. Becklin1, T. Kremski1, M. Melo y Acevedo1, J. Naaman1

ABSTRACT

We report new precision measurements of the properties of our Galaxy’s supermassive black hole. Based on astrometric (1995-2007) and radial velocity (2000-2007) measurements from the W. M. Keck 10-meter telescopes, a fully unconstrained Keplerian orbit for the short period star S2-2 provides values for the distance (R0) of 8.0 ± 0.4 kpc, the enclosed mass (M4) of 4.3 ± 0.6 × 10^6 M⊙, and the black hole’s radial velocity, which is consistent with zero with 30 km/s uncertainty. If the black hole is assumed to be at rest with respect to the Galaxy (e.g., has no massive companion to induce motion), we can further constrain the fit and obtain R0 = 8.4 ± 0.4 kpc and M4 = 4.5 ± 0.4 × 10^6 M⊙. More complex models constrain the extended dark mass distribution to be less than 3.4 × 10^6 M⊙ within 0.01 pc, ~100 times higher than predictions from stellar and stellar remnant models. For all models, we identify transients violent shifts from source confusion (up to 5x the astrometric error) and the assumptions regarding the black hole’s radial motion as previously unrecognized limits on orbital accuracy and the usefulness of fainter stars. Future astrometric and RV observations will remedy these effects. Our estimates of R0 and the Galaxy’s local rotation speed, which it is derived from combining R0 with the apparent proper motion of Sgr A*, (θ0 = 229 ± 18 km s−1), are compatible with measurements made using other methods. The increased black hole mass found in this study, compared to that determined using projected mass estimators, implies a longer period for the innermost stable orbit, longer resonant relaxation timescales for stars in the vicinity of the black hole and a better agreement with the M4= relation.

Subject headings: black hole physics -- Galaxy center -- Galaxy kinematics and dynamics -- infrared stars -- technical high angular resolution

1. INTRODUCTION

Ever since the discovery of fast moving (v > 1000 km s⁻¹) stars within 0.13 (0.01 pc) of our Galaxy’s central supermassive black hole (Eckart & Genzel 1997; Ghez et al. 1998), the prospect of using stellar orbits to make precise measurements of the black hole’s mass (M4) and kinematics, the distance to the Galactic center (R0) and, more ambitiously, to measure post-newtonian effects has been anticipated (Jaroszynski 1998, 1999; Sales & Gould 1999; Fragile & Matthews 2000; Bohr & Eckart 2001; Weinberg, Melis et al. & Ghez 2005; Zucker & Alexander 2007; Krunzić et al. 2007; Will 2008). An accurate measurement of the Galaxy’s central black hole mass is useful for putting the Milky Way in context with other galaxies through the apparent relationship between the mass of the central black hole and the velocity dispersion, σ, of the host galaxy (e.g., Ferrarese & Merritt 2000; Gebhardt et al., 2000; Tremaine et al. 2002). It can also be used as a test of this scaling, as the Milky Way has the most convincing case for a supermassive black hole of any galaxy used to define this relationship. Accurate estimates of R0 impact a wide range of issues associated with the mass and structure of the Milky Way, including possible constraints on the shape of the dark matter halo and the possibility that the Milky Way is a lopsided spiral (e.g., Reid 1993; Olling & Merrifield 2000; Majewski et al. 2006). Furthermore, if measured with sufficient accuracy (~1%), the distance to the Galactic center could influence the calibration of standard candles, such as RR Lyrae stars, Cepheid variables and giants, used in establishing the extragalactic distance scale. In addition to estimates of M4 and R0, precision measurements of stellar kinematics offer the exciting possibility of detecting deviations from a Keplerian orbit. This would allow an exploration of a possible cluster of stellar remnants surrounding the central black hole, suggested by Morris (1993), Miralda-Escudé & Gould (2000), and Freitag et al. (2003). Estimates for the mass of the remnant cluster range from 10³–10⁴ M⊙, within a few 10⁴ times that of the central black hole. Absence of such a remnant cluster would be interesting in view of the hypothesis that the inspiral of intermediate-mass black holes by dynamical friction could deplete any centrally concentrated cluster of remnants. Likewise, measurements of post-newtonian effects would provide a test of general relativity, and, ultimately, could probe the spin of the central black hole. Tremendous observational progress has been made over the last decade towards obtaining accurate estimates of the orbital parameters for the fast moving stars at the
4.2. Point Mass Plus Extended Mass Distribution Analysis

Limits on an extended mass distribution within S0-
2's orbit are derived by assuming that the gravitational potential consists of a point mass and an extended mass distribution, and allowing for a Newtonian precession of the orbits (see, e.g., Rubilar & Eckart 2001). In order to do this, we use the orbit fitting procedure described in Weinberg et al. (2005), and adopt an extended mass distribution that has a power-law density profile \( \rho(r) = \rho_0 (r/r_0)^{-\gamma} \). This introduces two additional parameters to the model: the normalization of the profile and its slope \( \gamma \). The total enclosed mass is then given by

\[
M(< r) = MBH + M_{\text{ext}}(< r_0) \left( \frac{r}{r_0} \right)^{-\gamma},
\]

where we quote values for the normalization \( M_{\text{ext}}(< r_0) \) at \( r_0 = 0.01 \) pc, corresponding to the characteristic scale of the orbit. Figure 13 shows the constraint on \( M_{\text{ext}}(< r_0 = 0.01 \) pc) and \( \gamma \) from a fit to the astrometric and radial velocity measurements for S0-2. The 99.7% confidence upper-bound on the extended mass is \( M_{\text{ext}}(< 0.01 \) pc) \( \lesssim 3 - 4 \times 10^8 M_\odot \) and has only a weak dependence on \( \gamma \).

Mouawad et al. (2005) report a similar upper-bound on the extended mass in fits to the orbit of S0-2. Their analysis differs only slightly from that presented here in that it forces the focus to be at the inferred radio position of Sgr A*, assumes a Plummer model mass distribution, and is based on data presented in Eisenhauer et al. (2003). Similarly, Zakharov et al. (2007) use an order of magnitude analysis to show that if the total mass of the extended matter enclosed within the S0-2 orbit is \( \gtrsim 10^8 M_\odot \), then it would produce a detectable spocenter shift \( \Delta \theta \gtrsim 10 \) mas (see also § 3.2 in Weinberg et al. 2005). Hall & Gondolo (2006) fit the total measured mass concentration \( M(< r) \) given in Ghez et al. (2005) assuming a power-law density profile and obtain an upper bound of \( \lesssim 10^9 M_\odot \) between 0.001 - 1 pc.
The Galactic Center massive black hole and nuclear star cluster

Reinhard Genzel,* Frank Eisenhauer, and Stefan Gillessen
Max-Planck Institut für Extraterrestrische Physik, 85748 Garching, Germany

(20 January 2010)

The Galactic Center is an excellent laboratory for studying phenomena and physical processes that may be occurring in many other galactic nuclei. The center of our Milky Way is by far the closest galactic nucleus, and observations with exquisite resolution and sensitivity cover 16 orders of magnitude in energy of electromagnetic radiation. Theoretical simulations have become increasingly more powerful in explaining these measurements. This review summarizes the recent progress in observational and theoretical work on the central parsec, with a strong emphasis on the current empirical evidence for a central massive black hole and on the processes in the surrounding dense nuclear star cluster. Current evidence is presented, from the analysis of the orbits of more than two dozen stars and from the measurements of the size and motion of the central compact radio source, Sgr A*, that this radio source must be a massive black hole of about 4.4 × 10^6 M☉, beyond any reasonable doubt. What is known about the structure and evolution of the dense nuclear star cluster surrounding this black hole is reported, including the astounding fact that stars have been forming in the vicinity of Sgr A* recently, apparently with a top-heavy stellar mass function. A dense concentration of faster stars centered in the immediate vicinity of the massive black hole is discussed, three of which have orbital perihelia of less than one light day. This “S-star cluster” appears to consist mainly of young early-type stars, in contrast to the predicted properties of an equilibrium “stellar corona” around a black hole. This constitutes a remarkable and presently not fully understood “paradox of youth.” What is known about the emission properties of the surrounding gas onto Sgr A* is also summarized and how this emission is beginning to delineate the physical properties in the hot accretion zone around the event horizon.

PACS number(s): 98.35.Jk

DOE: 10.1103/RevModPhys.82.3121

CONTENTS

I. Introduction 3122
A. Massive black holes 3122
B. The Galactic Center laboratory 3124
II. The Nuclear Star Cluster 3125
A. The nuclear cluster of cool old stars 3125
B. The disk(s) of young massive stars 3125
1. The clockwise stellar disk 3125
2. More than one disk? 3127
3. Massive binaries in the disk(s) 3128
C. The central S-star cluster and the distribution of B stars 3129
D. Is there an “equilibrium” stellar corona? 3131
1. Radial distribution of different stellar components 3132
E. Stellar mass function 3135
F. Chemical abundances 3137
III. Observed Properties of the Nuclear Interstellar Matter 3139
A. Ionized gas in Sgr A West 3139
B. Neutral gas 3141
C. Dust and interstellar extinction toward the Galactic Center 3142
D. Hot gas and high-energy emission 3143
IV. Testing the Black-Hole Paradigm: Is Sgr A* a

---

*Also at Department of Physics, University of California, Berkeley, CA 94720.
Fig. 13.— Top: The S2 orbital data plotted in the combined coordinate system and fitted with a Keplerian model in which the velocity of the central point mass and its position were free fit parameters. The non-zero velocity of the central point mass is the reason why the orbit figure does not close exactly in the overlap region 1992/2008 close to apocenter. The fitted position of the central point mass is indicated by the elongated dot inside the orbit near the origin; its shape is determined from the uncertainty in the position and the fitted velocity, which leads to the elongation. Bottom: The measured radial velocities of S2 and the radial velocity as calculated from the orbit fit.

Fig. 14.— Fitted value of $R_0$ for various scaling factors of the S2 2002 data, using a fit with the coordinate system priors. The factor by which the 2002 astrometric errors of the S2 data is scaled up strongly influences the distance. The mean factor determined in Figure 9 is \(\approx 7\), corresponding to \(R_0 \approx 8.1\) kpc.

Fig. 15.— Contour plot of $\chi^2$ as function of $R_0$ and central point mass. The two parameters are strongly correlated. The contours are generated from the S2 data including the 2002 data; fitting at each point all other parameters both of the potential and the orbital elements. The black dots indicate the position and errors of the best fit values of the mass for the respective distance; the blue line is a power law fit to these points; the corresponding function is given in the upper row of the text box. The central point is chosen at the best fitting distance. The red points and the red dashed line are the respective data and fit for the S2 data excluding the 2002 data; the fit is reported in the lower row of the text box. The contour levels are drawn at confidence levels corresponding to 1σ, 3σ, 5σ, 7σ, 9σ.

From the numbers it seems that the fit excluding the
Keck telescope twins
VLTs with AO
Black Holes

Black holes are some of the most bizarre objects in the Universe, challenging the imaginations of even the most creative scientists. They are places where gravity trumps all other forces in the Universe, pushing our understanding of physics to the limit. Even more strangely, supermassive black holes seem to play a key role in the formation of galaxies and structures in the Universe.

Galactic Centre

Over the last 15 years or so, an enormous amount of work has gone into improving our understanding of the closest supermassive black hole — Sagittarius A* at the centre of the Milky Way.

Technological progress, in particular in the areas of adaptive optics and high angular resolution with ground-based 8-metre-class telescopes, has allowed impressive progress in understanding supermassive black holes and their surroundings. Key progress was made in proving the very existence of a supermassive black hole at the centre of the Milky Way, in refining our knowledge of how matter falls into black holes, and in identifying gas discs and young stars in the immediate vicinity of the black hole. The Galactic Centre was thus established as the most important laboratory for the study of supermassive black holes and their surroundings.

But its potential for progress in fundamental physics and astrophysics is far from being fully exploited. The Galactic Centre remains the best place to test general relativity directly in a strong gravitational field. The E-ELT will enable extremely accurate measurements of the positions of stars at the 0.1–100 microarcsecond level over fields of tens of arcseconds, as well as radial velocity measurements with about 1 km/s precision, pushing our observations ever closer to the black hole event horizon. Stars can then be discovered at 100 Schwarzschild radii, where orbital velocities approach a tenth of the speed of light. This is more than ten times closer than can be achieved with the current generation of telescopes. Such stellar probes will allow us to test the predicted relativistic signals of black hole spin and the gravitational redshift caused by the black hole, and even to detect gravitational wave effects. Further out, the dark matter distribution around the black hole, predicted by cold dark matter cosmologies (ΛCDM), can be explored. The distance to the Galactic Centre can be measured to 0.1%, constraining in turn the size and shape of the galactic halo and the Galaxy’s local rotation speed to unprecedented levels. Crucial progress in our understanding of the interaction of the black hole with its surroundings will be made. The puzzling stellar cusp around the Galactic Centre, as well as the observed star formation in the vicinity of the black hole will be studied in detail for the first time.
The VLT, Very Large Telescope
4 European 8 m telescopes at Cerro Paranal in Chile

\[ \lambda/D \ @ 2 \mu m = 60 \text{ mas} (600 \text{ a.u. or 0.003 pc}) \]
Parallel session: BH2 - Theoretical and observational studies of astrophysical black holes
type : Oral abstract
Title: The 2018 Peri-Passage of S2 - Testing General Relativity Near The Galactic Center Black Hole
Co-authors: GRAVITY

Abstract: The Galactic Center offers the unique possibility to quantitatively test general relativity in the so-far unexplored regime close to a super-massive black hole. Here we present the current status of measuring post-Newtonian effects in the orbit of the star S2 during its peri-passage in May 2018. As the star approaches the black hole as close as 17 light hours and a speed of almost 8000 km/s, we follow its orbit with infrared spectroscopy and interferometry at the ESO Very Large Telescope. The focus of the talk will be on the redshift measurements with SINFONI, and the deep interferometric imaging and astrometry with GRAVITY. This GRAVITY instrument, which we have developed specifically for the observations of the Galactic Center black hole and its orbiting stars, is now routinely achieving ~3milli-arcsec imaging interferometry, with a sensitivity several hundred times better than previous instruments, and an astrometric precision of few ten micro-arcseconds, which corresponds to only few Schwarzschild radii of Galactic Center massive black hole.
The mass concentration at the Galactic Center

Recent advancements in infrared astronomy are allowing to test the scale of the mass profile at the center of our galaxy down to tens of AU. With the Keck 10 m telescope, the proper motion of several stars orbiting the Galactic Center black hole have been monitored and almost entire orbits, as for example that of the S2 star, have been measured allowing an unprecedented description of the Galactic Center region. Measurements of the amount of mass $M(<r)$ contained within a distance $r$ from the Galactic Center are continuously improved as more precise data are collected. Recent observations (Ghez et al. (2003)) extend down to the periastron distance ($\simeq 3 \times 10^{-4}$ pc) of the S16 star and they correspond to a value of the enclosed mass within $\simeq 3 \times 10^{-4}$ pc of $\simeq 3.67 \times 10^6 M_\odot$. Several authors have used these observations to model the Galactic Center mass concentration. Here and in the following, we use the three component
For a test particle orbiting a Schwarzschild black hole of mass $M_{BH}$, the periastron shift is given by (see e.g. Weinberg, 1972)

$$\Delta \phi_S \simeq \frac{6\pi G M_{BH}}{d(1 - e^2)c^2} + \frac{3(18 + e^2)\pi G^2 M_{BH}^2}{2d^2(1 - e^2)^2c^4}, \quad (9)$$

$d$ and $e$ being the semi-major axis and eccentricity of the test particle orbit, respectively. For a rotating black hole with spin parameter $a = |a| = J/G M_{BH}$, the space-time is described by the Kerr metric and, in the most favorable case of equatorial plane motion ($(a,v) = 0$), the shift is given by (Boyer and Price (1965))

$$\Delta \phi_K \simeq \Delta \phi_S + \frac{8a\pi M_{BH}^{1/2}G^{3/2}}{d^{3/2}(1 - e^2)^{3/2}c^3} + \frac{3a^2\pi G^2}{d^2(1 - e^2)^2c^4}, \quad (10)$$

which reduces to eq. (9) for $a \to 0$. In the more general case, $a \cdot v \neq 0$, the
expected periastron shift has to be evaluated numerically.

The expected periastron shifts (mas/revolution), $\Delta \phi$ (as seen from the center) and $\Delta \phi_E$ (as seen from Earth at the distance $R_0 \approx 8$ kpc from the GC), for the Schwarzschild and the extreme Kerr black holes, for the \textit{S2} and \textit{S16} stars turn out to be $\Delta \phi^{S2} = 6.3329 \times 10^5$ and $6.4410 \times 10^5$ and $\Delta \phi^{S2}_E = 0.661$ and 0.672 respectively, and $\Delta \phi^{S16} = 1.6428 \times 10^6$ and $1.6881 \times 10^6$ and $\Delta \phi^{S16}_E = 3.307$ and 3.399 respectively. Recall that

$$\Delta \phi_E = \frac{d(1+e)}{R_0} \Delta \phi_{S,K}.$$  \hspace{1cm} (11)

Notice that the differences between the periastron shifts for the Schwarzschild and the maximally rotating Kerr black hole is at most 0.01 mas for the S2 star and 0.009 mas for the S16 star. In order to make these measurements with the required accuracy, one needs to know the S2 orbit with a precision of at least 10 $\mu$as.
The star cluster surrounding the central black hole in the GC could be sizable. At least 17 members have been observed within 15 mpc up to now (Ghez et al. (2005)). However, the cluster mass and density distribution, that is to say its mass and core radius, is still unknown. The presence of this cluster affects the periastron shift of stars orbiting the central black hole. The periastron advance depends strongly on the mass density profile and especially on the central density and typical length scale.

We model the stellar cluster by a Plummer model density profile (Binney & Tremaine (1987))

\[ \rho_{CL}(r) = \rho_0 f(r) , \quad \text{with} \quad f(r) = \left[ 1 + \left( \frac{r}{r_c} \right)^2 \right]^{-\alpha/2} , \quad (12) \]
and the mass contained within $r$ is

$$M(r) = \lambda_{BH} M + \int_0^r 4\pi r'^2 \rho_0 f(r') \, dr'.$$  \hfill (15)

According to GR, the motion of a test particle can be fully described by solving the geodesic equations. Under the assumption that the matter distribution is static and pressureless, the equation of motion of the test particle becomes (see e.g. Weinberg 1972))

$$\frac{dv}{dt} \simeq -\nabla(\Phi_N + 2\Phi_N^2) + 4v(v \cdot \nabla)\Phi_N - v^2 \nabla \Phi_N.$$

For the S2 star, $d$ and $e$ given in the literature are 919 AU and 0.87 respectively. They yield the orbits of the S2 star for different values of the
Figure 21: The same as in Figure 20 but for the S16–Sgr A* binary system. In this case, the binary system orbital parameters were taken from Ghez et al. (2005) assuming for the S16 mass a conservative value of $\sim 10 \, M_\odot$. 
model for the central region of our galaxy based on estimates of enclosed mass given by Ghez et al (2003, 2005) recently proposed by Hall and Gondolo (2006). This model is constituted by the central black hole, the central stellar cluster and the DM sphere (made of WIMPs), i.e.

\[ M(< r) = M_{BH} + M_*(< r) + M_{DM}(< r) , \]  

where \( M_{BH} \) is the mass of the central black hole Sagittarius A*. For the central stellar cluster, the empirical mass profile is

\[ M_*(< r) = \begin{cases} 
M_* \left( \frac{r}{R_*} \right)^{1.6} , & r \leq R_* \\
M_* \left( \frac{r}{R_*} \right)^{1.0} , & r > R_* 
\end{cases} \]  

with a total stellar mass \( M_* = 0.88 \times 10^6 \, M_\odot \) and a size \( R_* = 0.3878 \, \text{pc} \).
As far as the mass profile of the DM concentration is concerned, Hall & Gondolo (2006) have assumed a mass distribution of the form

\[
M_{DM}(< r) = \begin{cases} 
M_{DM} \left( \frac{r}{R_{DM}} \right)^{3-\alpha}, & r \leq R_{DM} \\
M_{DM}, & r > R_{DM}
\end{cases}
\] (19)

\(M_{DM}\) and \(R_{DM}\) being the total amount of DM in the form of WIMPs and the radius of the spherical mass distribution, respectively.

Hall and Gondolo (2006) discussed limits on DM mass around the black hole at the Galactic Center. It is clear that present observations of stars around the Galactic Center do not exclude the existence of a DM sphere with mass \(\simeq 4 \times 10^6 M_\odot\), well contained within the orbits of the known stars, if its radius \(R_{DM}\) is \(\lesssim 2 \times 10^{-4}\) pc (the periastron distance of the S16 star in the more recent analysis (Ghez et al. 2005)). However, if one
Apoastraon Shift Constraints

According to GR, the motion of a test particle can be fully described by solving the geodesic equations. Under the assumption that the matter distribution is static and pressureless, the equations of motion at the first post-Newtonian (PN) approximation become (see e.g. (Fock 1961, Weinberg 1972, Rubilar & Eckart 2001))

\[
\frac{dv}{dt} \simeq -\nabla (\Phi_N + 2\Phi_N^2) + 4v(v \cdot \nabla)\Phi_N - v^2 \nabla \Phi_N .
\]  

(21)

We note that the PN-approximation is the first relativistic correction from which the apoastron advance phenomenon arises. In the case of the S2 star, the apoastron shift as seen from Earth (from Eq. (23)) due to the presence of a central black hole is about 1 mas, therefore not directly
obtained by the black hole only, the black hole plus the stellar cluster and
the contribution of two different DM mass density profiles. In each case the
S2 orbit apoastron shift is given. As one can see, for selected parameters
for DM and stellar cluster masses and radii the effect of the stellar cluster
is almost negligible while the effect of the DM distribution is crucial since it
enormously overcome the shift due to the relativistic precession. Moreover,
as expected, its contribution is opposite in sign with respect to that of the
black hole (Nucita et al. (2007)).

We note that the expected apoastron (or, equivalently, periastron) shifts
(mas/revolution), $\Delta \Phi$ (as seen from the center) and the corresponding
values $\Delta \phi^\pm_E$ as seen from Earth (at the distance $R_0 \sim 8$ kpc from the GC)
are related by

$$\Delta \phi^\pm_E = \frac{d(1 \pm e)}{R_0} \Delta \Phi,$$

where with the sign $\pm$ are indicated the shift angles of the apoastron ($+$)
Figure 28: An allowed region for DM distribution from S2 like star trajectories near the Black Hole at the Galactic Center (Hall and Gondolo (2006)).
Figure 32: Apoastron shift as a function of the DM radius $R_{DM}$ for $\alpha = 0$ and $M_{DM} \approx 2 \times 10^5 \, M_\odot$. Taking into account present day precision for the apoastron shift measurements (about 10 mas) one can say that DM radii $R_{DM}$ in the range $8 \times 10^{-4} - 10^{-2}$ pc are not acceptable.
capabilities. They showed that the orbital precession can occur due to relativistic effects, resulting in a prograde shift and due to a possible extended mass distribution, producing a retrograde shift. Both prograde relativistic and retrograde Newtonian periastron shifts will result in rosette-shaped orbits. Weinberg et al. [12] discussed physical experiments achievable via the monitoring of stellar dynamics near the massive black hole at the Galactic center, with a diffraction-limited, next-generation, extremely large telescope. They demonstrated that the lowest order relativistic effects, such as the prograde precession, will be detectable if the astrometric precision becomes less than 0.5 mas.

In this paper we continue to investigate constraints on the parameters of this class of gravity theories using S2-like star orbits under the uncertainty of 10 mas. In Sec. II the type of gravitational potential we use is given. In Sec. III we present the S2-like star orbits, gravity parameters, and angles of orbital precession, and also compare theoretical results with observations. The main conclusions are pointed out in Sec. IV.

II. THEORY

$R^n$ gravity belongs to power-law fourth-order theories of gravity obtained by replacing the scalar curvature $R$ with $f(R) = R^\beta$ in the gravity Lagrangian [1,2]. As a result, in the weak field limit [13], the gravitational potential is found to be [1,2]

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

where $r_c$ is an arbitrary parameter, depending on the typical scale of the considered system, and $\beta$ is a universal parameter:

$$\beta = \frac{12n^2 - 7n - 1 - \sqrt{36n^4 + 24n^3 - 3n^2 + 1}}{6n^2 - 4n + 2}$$

This formula corresponds to a modification of the gravity action in the form

$$A = \int d^4x \sqrt{-g} f(R) + L_m$$

where $f(R)$ is a generic function of the Ricci scalar curvature and $L_m$ is the standard matter Lagrangian.

For $n = 1$ and $\beta = 0$ the $R^n$ potential reduces to the Newtonian one, as expected. Parameter $\beta$ controls the shape of the correction term and is related to $n$, which is part of the gravity Lagrangian. Since it is the same for all gravitating systems, as a consequence, $\beta$ must be the same for all of them and therefore it is a universal parameter [2]. The parameter $r_c$ is the scale length parameter, and it is related to the boundary conditions and the mass of the system [2].

III. RESULTS

A. Orbits of S2-like stars and parameters of $R^n$ gravity

In order to study the effects of $R^n$ gravity on the motion of S2, we performed two-body calculations of its orbit in the $R^n$ potential [Eq. (1)] during two periods. We assumed the following input parameters taken from the paper of Zukhovskii et al. [10]: orbital eccentricity of the S2-like star, $e = 0.87$; major semiaxis $a = 919$ AU; mass of the S2-like star, $M_s = 1M_\odot$; mass of the central black hole, $M_{\text{BH}} = 4.3 \times 10^6 M_\odot$ (where $M_\odot$ is the solar mass); and orbital period of the S2-like star is 15 years. We calculated the S2-like star orbit during two periods using Newtonian and $R^n$ potentials. We also investigated the constraints on the parameters $\beta$ and $r_c$ for which the deviations between the S2-like star orbits in the $R^n$ gravity potential [Eq. (1)] and its Keplerian orbit will stay within the maximum precision of the current instruments (about 10 mas), during one orbital period.

In Fig. 1 we present the trajectory of the S2-like star around a massive black hole in $R^n$ gravity (blue solid line) and in Newtonian gravity (red dashed line) for $r_c = 100$ AU and for the following nine values of parameter $\beta$: 0.005, 0.01, 0.015, 0.02, 0.025, 0.03, 0.035, 0.04, 0.0475. The black hole is assumed to be located at the coordinate origin. We fix a value of parameter $r_c$ at 100 AU, because this value corresponds to the maximal value of parameter $\beta$ in the parameter space (see Fig. 3), and vary values of parameter $\beta$. All nine orbits presented fulfill the request that the $R^n$ orbit and the corresponding Newtonian orbit differ by less than 10 mas (i.e. within the maximum precision of the current observations) during one orbital period. We can see that if parameter $\beta$ increases, the $R^n$ orbit differs more from the corresponding Newtonian orbit since the precession angle becomes larger. This indicates that the value of $\beta$ should be small, as inferred from Solar System data [9] and in contrast to the value $\beta = 0.817$ (obtained by [2], which gives excellent agreement between theoretical and observed rotation curves). In the future, with improvements in observational facilities, the precision on constraints of values of parameters $\beta$ and $r_c$ will increase, as will the accuracy of the S2 orbit.

The corresponding distances between the S2-like star and the black hole as a function of time for the same values of parameters $r_c$ and $\beta$ as in Fig. 1 are presented in Fig. 2. There is an additional requirement on parameter space: the period of the S2-like star orbit has to remain $\Delta t = 5 \pm 0.2$. Like in the previous case, with increasing observational accuracy of the period, the precision on constraints on values of parameters $\beta$ and $r_c$ will also increase.

In Fig. 3 we present the parameter space for $R^n$ gravity under the constraint that, during one orbital period, S2-like star orbits under $R^n$ gravity differ by less than 10 mas from their orbits under Newtonian gravity for ten values of parameter $\beta$: 0.001, 0.002, 0.003, 0.004, 0.005, 0.006, 0.007, 0.008.
The exact expression (7) is inappropriate for practical applications. However, it can be easily approximated for \( \beta = 0 \) and \( \beta \approx 1 \). In the case of \( \beta = 0 \) expansion in Eq. (7) in Taylor's series over \( \beta \), up to first order, leads to the following expression for the precession angle:

\[
\Delta \theta = \frac{\omega a d \beta (\sqrt{1 - e^2} - 1)}{e^2} = \frac{180^\circ \beta (\sqrt{1 - e^2} - 1)}{e^2}.
\]

(8)

The above expression in the case of the S2-like star orbit is presented in Fig. 9 as a blue dash-dotted line. Similarly, the expansion of Eq. (7) in power series for \( \beta \approx 1 \) leads to the following expression for the precession angle (red dotted line in Fig. 9):

\[
\Delta \theta = \frac{\omega a d \beta (\sqrt{1 - e^2} - 1 + e^2)}{r_e e^2} = \frac{180^\circ \beta (\sqrt{1 - e^2} - 1 + e^2)}{r_e e^2}.
\]

(9)

One can expect that, in general, the precession angle depends on the semimajor axis and eccentricity of the orbit (see e.g. Iorio and Ruggiero [17]), as well as on both potential parameters \( \beta \) and \( r_e \). This is indeed the case for \( \beta = 1 \) in Eq. (9). But as it can be seen from formula (8), the precession angle in the case when \( \beta \) is small (\( \beta \approx 0 \)) depends only on the eccentricity and the universal constant \( \beta \) itself.

In order to test if the approximation from Eq. (8) is satisfactory in the case of the S2-like star, we derived its precession angle in two ways:

(i) analytically from the approximative formula (8),
(ii) numerically from the calculated orbits presented in Fig. 8.

Comparison of the obtained precession angles by these two methods is presented in Table 1. As it can be seen from this table, the approximative formula (8) can be used for estimating the precession angle for all values of \( \beta \) from Fig. 8.

The above analysis indicates that \( R^\alpha \) gravity results in the retrograde shift of the S2-like star orbit. Ruhilgar and Eckart [11] showed that the orbital precession can be due to relativistic effects, resulting in a prograde shift, or due to an extended mass distribution, producing a retrograde shift. We can conclude that the perturbing potential \( V(r) \) has an
D. Borka, V. Borka Jovanovic, P. Jovanovic, AFZ

From an analysis of S2 orbit one can find signatures of Yukawa gravity (JCAP, 2013)
Figure 1. Comparisons between the orbit of S2 star in Newtonian gravity (red dashed line) and Yukawa gravity during 10 orbital periods (blue solid line) for \( \Lambda = 2.59 \times 10^3 \) AU. In the left panel \( \delta = +1/3 \), and in the right \( \delta = -1/3 \).

5. the reduced \( \chi^2 \) is minimized and the final values of initial positions and velocities are obtained.

Finally, we kept the value of \( \Lambda \) which resulted with the smallest value of minimized reduced \( \chi^2 \).

In order to obtain some more general constraints on the parameters of Yukawa gravity, we also varied both \( \delta \) and \( \Lambda \) and studied the simulated orbits of S2 star which give at least the same or better fits than the Keplerian orbit. For each pair of these parameters the reduced \( \chi^2 \) of the best fit is obtained and used for generating the \( \chi^2 \) maps over the \( \Lambda - \delta \) parameter space. These maps are then used to study the confidence regions in \( \Lambda - \delta \) parameter space.

3 Results and discussion

The simulated orbits of S2 star around the central object in Yukawa gravity (blue solid line) and in Newtonian gravity (red dashed line) for \( \Lambda = 2.59 \times 10^3 \) AU and \( \delta = +1/3 \) (left panel) and \( \delta = -1/3 \) (right panel) during 10 periods, are presented in Fig. 1. We can notice that for \( \delta = -1/3 \) the precession has negative direction and when \( \delta = +1/3 \) the precession has positive direction. Our analysis shows that the Yukawa gravity potential induces precession of S2 star orbit in the same direction as General Relativity for \( \delta > 0 \) and for \( \delta < -1 \), and in the opposite direction for \( -1 < \delta < 0 \) as in the case of extended mass distribution or in \( R^n \) gravity [22].

We used these simulated orbits to fit the observed orbits of S2 star. The best fit (according to NTT/VLT data) is obtained for the scale parameter: \( \Lambda = 2.59 \times 10^3 \) AU, for which even a significant strength of Yukawa interaction could be expected according to the planetary and Lunar Laser Ranging constraints [32].

In Fig. 2 we presented two comparisons between the fitted orbits in Yukawa gravity for \( \delta = +1/3 \) through the astrometric observations of S2 star by NTT/VLT alone (left) and NTT/VLT–Keck combination (right). In order to combine NTT/VLT and Keck data sets,
Figure 2. The fitted orbits in Yukawa gravity for $\delta = -1/3$ through the astrometric observations of S2 star (denoted by circles), obtained by NTT/VLT alone (left panel) and NTT/VLT+Keck (right panel). The best fits are obtained for $\Lambda = 2.59 \times 10^3$ AU and $\Lambda = 3.03 \times 10^3$ AU, respectively.

Figure 3. The comparison between the observed (open circles with error bars) and fitted (solid lines) coordinates of S2 star (top), as well as the corresponding O-C residuals (bottom). The left panel shows the results for $\Delta x$ and right panel for $\Delta \delta$ in the case of NTT/VLT observations and Yukawa gravity potential with $\delta = -1/3$ and $\Lambda = 2.59 \times 10^3$ AU.

the position of the origin of Keck observations is first shifted by $\Delta x = 3.7$ and $\Delta y = 4.1$ mas, following the suggestion given in [39]. In the first case the best fit is obtained for $\Lambda = 2.50 \times 10^3$ AU, resulting with reduced $\chi^2 = 1.54$, and in the second case for $\Lambda = 3.03 \times 10^3$ AU with reduced $\chi^2 = 2.24$. As one can see from these figures, in both cases there is a good agreement between the theoretical orbits and observations, although the higher value of reduced $\chi^2$ in
Figure 4. The same as in Fig. 3, but for NTT/VLT+Keck combined observations and for Yukawa gravity potential with $\Lambda = 3.03 \times 10^3$ AU.

Figure 5. The comparisons between the observed (circles with error bars) and fitted (solid lines) radial velocities of S2 star (top), as well as the corresponding O-C residuals (bottom). The left panel shows the results in the case of NTT/VLT observations and Yukawa gravity potential with $\Lambda = 2.50 \times 10^3$ AU, while the right panel shows the results for NTT/VLT+Keck combined observations and for Yukawa gravity potential with $\Lambda = 3.03 \times 10^3$ AU. In both cases $\delta = +1/3$.

The second case indicates possibly larger positional difference between the two coordinate systems, as also noted in [39]. These figures also show that the simulated orbits of S2 are not closed in vicinity of apocenter, indicating a possible orbital procession.

In Figs. 3 and 4 we presented the comparisons between the observed and fitted coordinates of S2 star and their O-C residuals in the case of NTT/VLT observations, as well as NTT/VLT–Keck combined data set, respectively. One can notice that in both cases, O-C
Figure 6. The reduced $\chi^2$ for $\delta = 1/3$ as a function of $A$ in case of NTT/VLT alone (left) and combined NTT/VLT+Keck (right) observations.

Figure 7. The maps of reduced $\chi^2$ over the $\Lambda - \delta$ parameter space in case of NTT/VLT observations. The left panel corresponds to $\delta \in [0, 1]$, and the right panel to the extended range of $\delta \in [0.01, 10]$. The shades of gray color represent the values of the reduced $\chi^2$ which are less than the corresponding value in the case of Keplerian orbit, and three contours (from inner to outer) enclose the confidence regions in which the difference between the current and minimum reduced $\chi^2$ is less than 0.0005, 0.005 and 0.05, respectively.

Figure 8. The same as in Fig. 7, but for the combined NTT/VLT+Keck observations.

residuals are higher in the first part of observing interval (up to the 12 mas) and much less in its second part (less than 2 mas). Due to adopted merit function given by expression (2.7), our fitting procedure assigned greater weight to these latter, more precise observations. Also, the O-C residuals are larger in the case of the combined NTT/VLT+Keck observations most likely due to the shift of the origin of the coordinate system, which was necessary in order to
Massive graviton theories

- M. Fierz and W. Pauli - 1939
- Zakharov; Veltman, van Dam – 1970
- Vainshtein - 1972
- Boulware, Deser -- 1972
- Logunov, Mestvirishvili, Gershtein et al.
- Visser – 1998 (review on such theories)
- Rubakov, Tinyakov – 2008
- DeRham --2016
Massive graviton theories (constraints)

• Sazhin (1978) GW’s could be detected with pulsar timing

• Lee et al. (2010) array of pulsars and timing 60 pulsars – 5 years with accuracy 100 ns -- $\lambda_g > 4 \times 10^{12}$ km
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott et al.

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of $1.0 \times 10^{-21}$. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203,000 years, equivalent to a significance greater than 5.1σ.

The source lies at a luminosity distance of $410^{+500}_{-300}$ Mpc corresponding to a redshift $z = 0.09^{+0.04}_{-0.02}$. In the source frame, the initial black hole masses were $36.2^{+5.8}_{-4.9} M_{\odot}$ and $29.4^{+2.9}_{-2.4} M_{\odot}$, and the final black hole mass is $62^{+7}_{-3} M_{\odot}$ with $3.8^{+1.6}_{-0.8} M_{\odot}$ radiated in gravitational waves. All uncertainties define 90% credible intervals.

These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

I. INTRODUCTION

In 1916, the year after the final formulation of the field equations of general relativity, Albert Einstein predicted the existence of gravitational waves. He found that the linearized weak-field equations had wave solutions: transverse waves of spatial strain that travel at the speed of light, generated by time variations of the mass quadrupole moment of the source [1,2]. Einstein understood that gravitational-wave amplitudes would be remarkably small; moreover, until the Chapel Hill conference in 1957 there was significant debate about the physical reality of gravitational waves [3].

Also in 1916, Schwarzschild published a solution for the field equations [4] that was later understood to describe a black hole [5,6], and in 1963 Kerr generalized the solution to rotating black holes [7]. Starting in the 1970s theoretical work led to the understanding of black hole quasinormal modes [8-10], and in the 1990s higher-order post-Newtonian calculations [11] preceded extensive analytical studies of relativistic two-body dynamics [12,13]. These advances, together with numerical relativity breakthroughs in the past decade [14-16], have enabled modeling of binary black hole mergers and accurate predictions of their gravitational waveforms. While numerous black hole candidates have now been identified through electromagnetic observations [17-19], black hole mergers have not previously been observed.

The discovery of the binary pulsar system PSR B1913 + 16 by Hulse and Taylor [20] and subsequent observations of its energy loss by Taylor and Weisberg [21] demonstrated the existence of gravitational waves. This discovery, along with emerging astrophysical understanding [22], led to the recognition that direct observations of the amplitude and phase of gravitational waves would enable studies of additional relativistic systems and provide new tests of general relativity, especially in the dynamic strong-field regime.

Experiments to detect gravitational waves began with Weber and his resonant mass detectors in the 1960s [23], followed by an international network of cryogenic resonant detectors [24]. Interferometric detectors were first suggested in the early 1960s [25] and the 1970s [26]. A study of the noise and performance of such detectors [27], and further concepts to improve them [28], led to proposals for long-baseline broadband laser interferometers with the potential for significantly increased sensitivity [29-32]. By the early 2000s, a set of initial detectors was completed, including TAMA 300 in Japan, GEO 600 in Germany; the Laser Interferometer Gravitational-Wave Observatory (LIGO) in the United States, and Virgo in Italy. Combinations of these detectors made joint observations from 2002 through 2011, setting upper limits on a variety of gravitational-wave sources while evolving into a global network. In 2015, Advanced LIGO became the first of a significantly more sensitive network of advanced detectors to begin observations [33-36].

A century after the fundamental predictions of Einstein and Schwarzschild, we report the first direct detection of gravitational waves and the first direct observation of a binary black hole system merging to form a single black hole. Our observations provide unique access to the
properties of space-time in the strong-field, high-velocity regime and confirm predictions of general relativity for the nonlinear dynamics of highly disturbed black holes.

II. OBSERVATION

On September 14, 2015 at 09:50:45 UTC, the LIGO Hanford, WA, and Livingston, LA, observatories detected the coincident signal GW150914 shown in Fig. 1. The initial detection was made by low-latency searches for generic gravitational-wave transients [41] and was reported within three minutes of data acquisition [43]. Subsequently, matched-filter analyses that use relativistic models of compact binary waveforms [44] recovered GW150914 as the most significant event from each detector for the observations reported here. Occurring within the 10-ms intense

![Graph showing strain and frequency over time for GW150914](image)

**FIG. 1.** The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors. Times are shown relative to September 14, 2015 at 09:50:45 UTC. For visualization, all time series are filtered with a 35–350 Hz bandpass filter to suppress large fluctuations outside the detectors' most sensitive frequency band, and band-reject filters to remove the strong instrumental spectral lines seen in the Fig. 3 spectra. Top row: left: H1 strain, Top row, right: L1 strain. GW150914 arrived first at L1 and 6.96 ± 0.02 ms later at H1; for a visual comparison, the H1 data are also shown, shifted in time by this amount and inverted (to account for the detectors' relative orientations). Second row: Gravitational-wave strain projected onto each detector in the 35–350 Hz band. Solid lines show a numerical relativity waveform for a system with parameters consistent with those recovered from GW150914 [37,38] confirmed to 99.9% by an independent calculation based on [35]. Shaded areas show 90%-credible regions for two independent waveform reconstructions. One (dark gray) models the signal using binary black hole template waveforms [39]. The other (light gray) does not use an astrophysical model, but instead calculates the strain signal as a linear combination of sine-Gaussian wavelets [40,41]. These reconstructions have a 94% overlap, as shown in [39]. Third row: Residuals after subtracting the filtered numerical relativity waveform from the filtered detector time series. Bottom row: A time-frequency representation [42] of the strain data, showing the signal frequency increasing over time.
propagation time, the events have a combined signal-to-
noise ratio (SNR) of 24 [45].

Only the LIGO detectors were observing at the time of
GW150914. The Virgo detector was being upgraded, and GEO 600, though not sufficiently sensitive to detect
this event, was operating but not in observational mode. With only two detectors the source position is
primarily determined by the relative arrival time and
localized to an area of approximately 600 deg² (90% credible region) [39,46].

The basic features of GW150914 point to it being
produced by the coalescence of two black holes—i.e.,
their orbital inspiral and merger, and subsequent final black
hole ringdown. Over 0.2 s, the signal increases in frequency
and amplitude in about 8 cycles from 35 to 150 Hz, where
the amplitude reaches a maximum. The most plausible
explanation for this evolution is the inspiral of two orbiting
masses, m₁ and m₂, due to gravitational-wave emission. At
the lower frequencies, such evolution is characterized by
the chirp mass [11]

\[ \mathcal{M} = \left( \frac{m_1 m_2}{m_1 + m_2} \right)^{3/5} \frac{c}{2} \left[ \frac{G}{c^3} \right]^{1/5} \]

where f and \( \dot{f} \) are the observed frequency and its time
derivative and G and c are the gravitational constant and
speed of light. Estimating f and \( \dot{f} \) from the data in Fig. 1,
we obtain a chirp mass of \( \mathcal{M} \approx 30 M_{\odot} \), implying that the
total mass \( M = m_1 + m_2 \approx 70 M_{\odot} \) in the detector frame.

This bounds the sum of the Schwarzschild radii of the
binary components to \( 2GM/c^2 \approx 210 \) km. To reach an
orbital frequency of 75 Hz (half the gravitational-wave
frequency) the objects must have been very close and very
compact; equal Newtonian point masses orbiting at this
frequency would be only \( \approx 350 \) km apart. A pair of
neutron stars, while compact, would not have the required
mass, while a black hole neutron star binary with the
deduced chirp mass would have a very large total mass,
and would thus merge at much lower frequency. This
leaves black holes as the only known objects compact
enough to reach an orbital frequency of 75 Hz without
contact. Furthermore, the decay of the waveform after it
peaks is consistent with the damped oscillations of a black
hole relaxing to a final stationary Kerr configuration.

Below, we present a general-relativistic analysis of
GW150914; Fig. 2 shows the calculated waveform using the
resulting source parameters.

III. DETECTORS

Gravitational-wave astronomy exploits multiple, widely
separated detectors to distinguish gravitational waves from
local instrumental and environmental noise, to provide
source sky localization, and to measure wave polarizations.
The LIGO sites each operate a single Advanced LIGO
detector [33], a modified Michelson interferometer (see
Fig. 3) that measures gravitational-wave strain as a differ-
ence in length of its orthogonal arms. Each arm is formed by
two mirrors, acting as test masses, separated by
\( L_x = L_y = L = 4 \) km. A passing gravitational wave effec-
tively alters the arm lengths such that the measured
difference is \( \Delta L(t) = \Delta L_x - \Delta L_y = h(t)L \), where h is the
gravitational-wave strain amplitude projected onto the
detector. This differential length variation alters the phase
difference between the two light fields returning to the
beam splitter, transmitting an optical signal proportional to
the gravitational-wave strain to the output photodetector.

To achieve sufficient sensitivity to measure gravitational
waves, the detectors include several enhancements to the
basic Michelson interferometer. First, each arm contains a
resonant optical cavity, formed by two test mass mirrors,
that multiplies the effect of a gravitational wave on the light
phase by a factor of 300 [40]. Second, a partially trans-
missive power-recycling mirror at the input provides addi-
tional resonant buildup of the laser light in the interferometer
as a whole [49,50]. 20 W of laser input is increased to 700 W
incident on the beam splitter, which is further increased to
100 kW circulating in each arm cavity. Third, a partially
transmissive signal-recycling mirror at the output opti-
Graviton Mass Estimate from Gravitational Wave Signal

Assuming that a graviton mass is small in comparison with energy of gravitational waves $\hbar f \gg m_g c^2$, then

$$v_g/c \approx 1 - \frac{1}{2} \left( \frac{c}{\lambda_g f} \right)^2,$$

(1)

where $\lambda_g = \hbar/(m_g c)$ is the graviton Compton wavelength and one could obtain (Will, 1998)

$$\lambda_g > 3 \times 10^{12} \text{km} \left( \frac{D}{200 \text{ Mpc}} \frac{100 \text{ Hz}}{f} \right)^{1/2} \left( \frac{1}{f \Delta t} \right)^{1/2},$$

(2)
\[ \Delta t = \Delta t_a - (1 + z) \Delta t_e, \]

where \( \Delta t_a = t_a^{EM} - t_a^{GW} \), \( \Delta t_e = t_e^{EM} - t_e^{GW} \), \( t_a^{EM}(t_e^{EM}) \) and \( t_a^{GW}(t_e^{GW}) \) are arrival (emission) instant of electromagnetic radiation and arrival (emission) instant for gravitational waves. As it was pointed out, one can use Eq. (2) if observers detected gravitational waves and electromagnetic radiations from one source and \( \Delta t_e \) is known or can be evaluated with a sufficient accuracy. Moreover, there is an opportunity to constrain a graviton mass in the case if there is only a gravitational wave signal. For numerical estimate, one can estimate \( f \Delta t \sim \rho^{-1} \approx 10 \) (where \( \rho \) is a signal-to-noise ratio) for LIGO-Virgo ground based interferometers, therefore, a graviton mass constraint can be at a level \( 2.5 \times 10^{-22} \) eV for ground based LIGO-Virgo detectors.

The LIGO-Virgo collaboration reported about the first detection of gravitational waves from a merger of two black holes (it was detected on September 14, 2015 and it is called GW150914). According to estimates
from the shape of gravitational wave signal the source is located at a luminosity distance of around 410 Mpc (which corresponds to a redshift $z \approx 0.09$), the initial black hole masses were $36M_\odot$ and $29M_\odot$ and the final black hole mass is $62M_\odot$, therefore, around $3M_\odot$ was emitted in gravitational waves in 0.1 s. The collaboration not only discovered gravitational waves but also detected the first binary black hole system and one of the most powerful source of radiation in the Universe and the energy was released in gravitational waves. Moreover, the team constrained the graviton Compton wavelength $\lambda_g > 10^{13}$ km which could be interpreted as a constraint for a graviton mass $m_g < 1.2 \times 10^{-22}$ eV (Abbott et al. 2016) (the estimate roughly coincides with theoretical predictions).

In June 2017 the LIGO-Virgo collaboration published a paper where the authors described a detection of gravitational wave signal from a merger of binary black hole system with masses of components $31.2M_\odot$ and $19.4M_\odot$ at distance around 880 Mpc which corresponds to $z \approx 0.18$ (Abbott 2017).
this case, around $2M_\odot$ was emitted in gravitational waves in around 0.4 s. The event is named GW170104. In this paper the authors significantly improved their previous graviton mass constraint, $m_g < 7.7 \times 10^{-23}$ eV.

On August 17, 2017 the LIGO-Virgo collaboration detected a merger of binary neutron stars with masses around $0.86M_\odot$ and $2.26M_\odot$ at a distance around 40 Mpc (GW170817) and after 1.7 s the Fermi-GBM detected $\gamma$-ray burst GRB 170817A associated with the GW170817. Since gravitational wave signal was observed before GRB 170817A one could conclude that the observational data are consistent with massless or very light graviton, otherwise, electromagnetic signal could be detected before gravitational one because in the case of relatively heavy gravitons gravitational waves could propagate slower than light.

In the consideration one assumes that photon is massless (but graviton may be massive). In the case of massive photon $m_\gamma > 0$ (see, (Jackson 1998) for introduction of Proca theory which describes a massive photon
case) to use the same logic at least we have to have \((c - v_\gamma) \ll (c - v_g)\) 
\((c\) is a limiting speed of ultra high energy quanta, \(v_\gamma\) and \(v_g\) are velocities of quanta and gravitons respectively) or

\[ m_g/f \gg m_\gamma/\nu, \]  

as we see from Eq. (1), where \(m_g\) and \(m_\gamma\) are masses of graviton and photon, respectively; \(f\) and \(\nu\) are their typical frequencies) and photon mass is constrained with another experimental (or observational) data. Different ways to evaluate photon mass are discussed in couple of reviews (Goldhaber and Nieto 2010, Tu et al. 2005, Okun 2006) and original papers. Laboratory experiments gave the upper limit as \(m_\gamma < 7 \times 10^{-19}\) eV (Luo et al. 2003) or \(m_\gamma < 5 \times 10^{-20}\) eV (Tu et al. 2006), while astrophysical constraint from analysis of plasma in Solar wind gave \(m_\gamma < 10^{-18}\) eV (Ryutov 2007), analysis of Fast Radio Bursts gave weaker constraints on photon mass \(m_\gamma < 10^{-14}\) eV.
One could roughly estimate frequency band for quanta where inequality (4) is hold. If we adopt the upper limit of graviton mass (around $10^{-22}$ eV) obtained by LIGO collaboration from the first GW events without electromagnetic counterpart and we assume $f \approx 100$, then the inequality (4) is hold for spectral band of quanta from radio up to higher frequencies if we use upper limit estimates from papers (Luo et al. 2003, Tu et al. 2006 and the inequality (4) is hold for spectral band of quanta from optical band up to higher frequencies if we use upper limit estimates from papers (Wu et al. 2016; Bonetti et al. 2016, 2017). Constraints on speed of gravitational waves have been found $-3 \times 10^{-15} < (v_g - c)/c < 7 \times 10^{-16}$ (Abbott et al., 2017). Graviton energy is $E = h f$, therefore, assuming a typical LIGO frequency range $f \in (10, 100)$, from the dispersion relation one could obtain a graviton mass estimate $m_g < 3 \times (10^{-21} - 10^{-20})$ eV which a slightly weaker estimate than previous ones obtained from binary black hole signals detected by the LIGO team.
GW170817
Binary neutron star merger
A LIGO / Virgo gravitational wave detection with associated electromagnetic events observed by over 70 observatories.

12:41:04 UTC
A gravitational wave from a binary neutron star merger is detected.

Gravitational wave signal
Two neutron stars, each the size of a city but with at least the mass of the sun, collided with each other.

Gamma ray burst
A short gamma ray burst is an intense beam of gamma ray radiation which is produced just after the merger.

GW170817 allows us to measure the expansion rate of the universe directly using gravitational waves for the first time.

Detecting gravitational waves from a neutron star merger allows us to find out more about the structure of these unusual objects.

This multimessenger event provides confirmation that neutron star mergers can produce short gamma ray bursts.

The observation of a kilonova allowed us to show that neutron star mergers could be responsible for the production of the heavy elements, like gold, in the universe.

Observing both electromagnetic and gravitational waves from the event provides compelling evidence that gravitational waves travel at the same speed as light.

Kilonova
Decaying neutron-rich material creates a glowing kilonova, producing heavy metals like gold and platinum.

Radio remnant
As material moves away from the merger it produces a shockwave in the interstellar medium - the tenuous material between stars. This produces emission which can last for years.

X-ray emission detected.

+ 2 seconds
A gamma ray burst is detected.

+ 10 hours 52 minutes
A new bright source of optical light is detected in a galaxy called NGC 4993, in the constellation of Hydra.

+ 11 hours 36 minutes
Infrared emission observed.

+ 15 hours
Bright ultraviolet emission detected.

+ 9 days
X-ray emission detected.

+ 16 days
Radio emission detected.
May 4, 2016 -- The Gruber Foundation has announced the award of the 2016 Gruber Cosmology Prize to LIGO's Ronald W.P. Drever (Caltech), Kip S. Thorne (Caltech), and Rainer Weiss (MIT) for the detection of gravitational waves.
Yuri Milner, a Russian Internet entrepreneur and philanthropist, announced that he was giving $3 million to the gravitational-wave discoverers. The award is a special addition to the $3 million Breakthrough Prizes in Fundamental Physics he awards every fall. The three ringleaders of the gravitational-wave experiment, known as LIGO, Ronald P. Drever and Kip. S. Thorne of the California Institute of Technology, and Rainer Weiss of the Massachusetts Institute of Technology, will split $1 million. The other $2 million will be split among 1,012 scientists who were authors of the article in Physical Review Letters, or who made major contributions to the study of gravitational waves.
GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2

B. P. Abbott et al. (LIGO Scientific and Virgo Collaboration)

(Received 9 May 2017; published 1 June 2017)

We describe the observation of GW170104, a gravitational-wave signal produced by the coalescence of a pair of stellar-mass black holes. The signal was measured on January 4, 2017 at 10:11:58.6 UTC by the twin advanced detectors of the Laser Interferometer Gravitational-Wave Observatory during their second observing run, with a network signal-to-noise ratio of 13 and a false alarm rate less than 1 in 70,000 years. The inferred component black hole masses are $31.2^{+1.9}_{-1.8} M_\odot$ and $19.4^{+3.1}_{-3.1} M_\odot$ (at the 90% credible level). The black hole spins are best constrained through measurement of the effective inspiral spin parameter, a mass-weighted combination of the spin components perpendicular to the orbital plane, $x_{\text{eq}} = -0.12^{+0.25}_{-0.26}$. This result implies that spin configurations with both component spins positively aligned with the orbital angular momentum are disfavored. The source luminosity distance is $880^{+190}_{-200}$ Mpc, corresponding to a redshift of $z = 0.20^{+0.04}_{-0.05}$. We constrain the magnitude of modifications to the gravitational-wave dispersion relation and perform null tests of general relativity. Assuming that gravitons are dispersed in vacuum like massive particles, we bound the graviton mass to $m_g < 7.7 \times 10^{-23}$ eV/c^2. In all cases, we find that GW170104 is consistent with general relativity.

I. INTRODUCTION

The first observing run of the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) [1] identified two binary black hole coalescence signals with high statistical significance, GW150914 [2] and GW151226 [3], as well as a less significant candidate LVT151012 [4,5]. These discoveries ushered in a new era of observational astronomy, allowing us to investigate the astrophysics of binary black holes and test general relativity (GR) in ways that were previously inaccessible [6,7]. We now know that there is a population of binary black holes with component masses $25 M_\odot$ [5,6], and that merger rates are high enough for us to expect more detections [5,8].

Advanced LIGO's second observing run began on November 30, 2016. On January 4, 2017, a gravitational-wave signal was detected with high statistical significance. Figure 1 shows a time-frequency representation of the data from the LIGO Hanford and Livingston detectors, with the signal GW170104 visible as the characteristic chirp of a binary coalescence. Detailed analyses demonstrate that GW170104 arrived at Hanford ~3 ms before Livingston, and originated from a coalescence of two stellar-mass black holes at a luminosity distance of $\sim 3 \times 10^9$ light-years.

GW170104's source is a heavy binary black hole system, with a total mass of $\sim 50 M_\odot$, suggesting formation in a subsolar metallicity environment [6]. Measurements of the black hole spins show a preference away from being (positively) aligned with the orbital angular momentum, but do not exclude zero spins. This is distinct from the case for GW151226, which had a strong preference for spins with positive projections along the orbital angular momentum [3]. The inferred merger rate agrees with previous calculations [5,8], and could potentially be explained by binary black holes forming through isolated binary evolution or dynamical interactions in dense stellar clusters [6].

Gravitational-wave observations of binary black holes are the ideal means to test GR and its alternatives. They provide insight into regimes of strong-field gravity where velocities are relativistic and the spacetime is dynamic. The tests performed with the sources detected in the first observing run showed no evidence of departure from GR's predictions [5,7]; GW170104 provides an opportunity to tighten these constraints. In addition to repeating tests performed in the first observing run, we also test for modifications to the gravitational-wave dispersion relation. Combining measurements from GW170104 with our previous results, we obtain new gravitational-wave constraints on potential deviations from GR.

II. DETECTORS AND DATA QUALITY

The LIGO detectors measure gravitational-wave strain using two dual-recycled Fabry-Perot Michelson interferometers at the Hanford and Livingston observatories [1,10].
• On June 2, 2017 LIGO (Abbott et al. PRL 118, 21101 (2017)) reported about the discovery of the third GW event from merging the BHs with 31 and 19 solar masses at redshift \( z=0.19 \)

• \( m_g < 7.7 \times 10^{-23} \text{ eV} \)
Black Holes of Known Mass

Solar Masses

X-Ray Studies

GW150914
LVT151012
GW170104
GW170814

LIGO/VIRGO
Constraining the range of Yukawa gravity interaction from S2 star orbits II: bounds on graviton mass

A.F. Zakharov, P. Jovanović, D. Borka, and V. Borka Jovanović

aNational Astronomical Observatories of Chinese Academy of Sciences, Datun Road 20A, Beijing, 100012 China
bInstitute of Theoretical and Experimental Physics, 117259 Moscow, Russia
cNational Research Nuclear University MEPhi (Moscow Engineering Physics Institute), 115409, Moscow, Russia
dBogoliubov Laboratory for Theoretical Physics, JINR, 141980 Dubna, Russia
eNorth Carolina Central University, Durham, NC 27707, U.S.A.
fAstronomical Observatory, Volgina 7, 11060 Belgrade, Serbia
gAtomic Physics Laboratory (040), Vinča Institute of Nuclear Sciences, University of Belgrade, P.O. Box 522, 11001 Belgrade, Serbia
E-mail: zakharov@itep.ru, pjoovanovic@aob.rs, dusborka@vin.bg.ac.rs, vborka@vin.bg.ac.rs

Received May 4, 2016
Accepted May 7, 2016
Published May 20, 2016

Abstract. Recently LIGO collaboration discovered gravitational waves [1] predicted 100 years ago by A. Einstein. Moreover, in the key paper reporting about the discovery, the joint LIGO & VIRGO team presented an upper limit on graviton mass such as $m_g < 1.2 \times 10^{-22} eV$ [1] (see also more details in another LIGO paper [2] dedicated to a data analysis to obtain such a small constraint on a graviton mass). Since the graviton mass limit is so small the authors concluded that their observational data do not show violations of classical general relativity. We consider another opportunity to evaluate a graviton mass from phenomenological consequences of massive gravity and show that an analysis of bright star orbits in our Galaxy together with LIGO data shows that graviton mass is strongly constrained with a new lower limit $m_g > 10^{-24} eV$. This new range on graviton mass further supports the idea that gravitons are massive and could be detectable in high energy accelerators.
modification of the Newtonian potential [5, 14]:

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

(1.1)

where \( \delta \) is a universal constant. In our previous paper [35], we found constraints on parameters of Yukawa gravity.

Will considered an opportunity to evaluate a graviton mass analyzing a time delay in electromagnetic waves such as supernova or gamma-ray burst [5], moreover he demonstrated a possibility to constrain a graviton mass from gravitational wave signal alone [4].

Pulsar timing may be used to evaluate a graviton mass [36]. In the paper it was concluded that, with 90% probability, massless gravitons can be distinguished from gravitons heavier than \( 3 \times 10^{-22} \text{eV} \) (Compton wavelength \( \lambda_c = 4.1 \times 10^{12} \text{km} \)), if bi-weekly observation of 60 pulsars is performed for 5 years with a pulsar rms timing accuracy of 100 ns and if 10 year observation of 300 pulsars with 100 ns timing accuracy would probe graviton masses down to \( 3 \times 10^{-23} \text{eV} \) (\( \lambda_c = 4.1 \times 10^{13} \text{km} \)). These conclusions are based on an analysis of cross-correlation functions of gravitational wave background. An idea to use pulsar timing for gravitational wave detection has been proposed many years ago [37]. An analysis of the cross-correlation function between pulsar timing residuals of pulsar pairs could give an opportunity to detect gravitational waves [38, 39]. If a graviton has a mass it gives an impact on cross-correlation functions [36]. However, as a first step people have to discover stochastic GW signal and only after a detailed analysis of cross-correlation it could help to put constraints on a graviton mass.

Here we show that our previous results concerning the constraints on parameters of Yukawa gravity, presented in the paper [35], can be extended in the way that one could also obtain a graviton mass bounds from the observations of trajectories of bright stars near the Galactic Center. As it is shown below our estimate of a graviton mass is slightly greater than the estimate obtained by the LIGO collaboration with the first detection of gravitational waves from the binary black hole system. However, we would like to note that: a) our estimate is consistent with the LIGO one; b) in principle, with analysis of trajectories of bright stars near the Galactic Center one could obtain such a graviton mass estimate before the LIGO report [1] about the discovery of gravitational waves and their estimate of a graviton mass; c) in the future our estimate may be improved with forthcoming observational facilities.

2 Graviton mass estimates from S2 star orbit

Two groups of observers are monitoring bright stars (including S2 one) to evaluate gravitational potential at the Galactic Center [40-48]. Recently, the astrometric observations of S2 star [49] were used to evaluate parameters of black hole and to test and constrain several models of modified gravity at mpc scales [50-54]. The simulations of the S2 star orbit around the supermassive black hole at the Galactic Centre (GC) in Yukawa gravity [35] and their comparisons with the NTT/VLT astrometric observations of S2 star [49] resulted with the constraints on the range of Yukawa interaction \( \lambda \) which showed that \( \lambda \) is most likely on the order of several thousand astronomical units. However, it was not possible to obtain the reliable constrains on the universal constant \( \delta \) because its values \( 0 < \delta < 1 \) were highly correlated to \( \lambda \) while the values \( \delta > 2 \) corresponded to a practically fixed \( \lambda \sim 5000-6000 \text{AU} \).
Constraints on graviton mass from S2 trajectory

- \( \lambda_g > 2900 \text{ AU} = 4.3 \times 10^{11} \text{ km with } P=0.9 \) or
- \( m_g < 2.9 \times 10^{-21} \text{ eV} = 5.17 \times 10^{-54} \text{ g} \)
- Hees et al. PRL (2017) slightly improved our estimates with their new data \( m_g < 1.6 \times 10^{-21} \text{ eV} \) (see discussion below)
Impact of our studies


A couple of our papers have been quoted in the second paper.
Testing General Relativity with Stellar Orbits around the Supersmassive Black Hole in Our Galactic Center

A. Hees,1 T. Do,1 A. M. Ghez,1,2 G. D. Martinez,1 S. Naoz,1 E. E. Becklin,1 A. Bohle,1 S. Chappell,1 D. Chu,1 A. Dehghanfar,1 K. Kovnir,1 J. R. Lu,2 K. Matthews,2 M. R. Morris,1 S. Sakai,1 R. Schödel,1 and G. Witze1

1Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA
2Astronomy Department, University of California, Berkeley, California 94720, USA
3Division of Physics, Mathematics, and Astronomy, California Institute of Technology, MC 101-17, Pasadena, California 91125, USA
4Instituto de Astrofisica de Andalucia (CSIC), Glorieta de la Astronomia S/N, 18008 Granada, Spain

(Received 22 December 2016; revised 14 March 2017; published 25 May 2017)

We demonstrate that short-period stars orbiting around the supermassive black hole in our Galactic center can successfully be used to probe the gravitational theory in a strong regime. We use 19 years of observations of the two best measured short-period stars orbiting our Galactic center to constrain a hypothetical fifth force that arises in various scenarios motivated by the development of a unification theory or in some models of dark matter and dark energy. No deviation from general relativity is reported and the fifth force strength is restricted to an upper 95% confidence limit of $|\alpha| < 0.016$ at a length scale of $\lambda = 150$ astronomical units. We also derive a 95% confidence upper limit on a linear drift of the argument of periastron of the short-period star S0-2 of $\dot{\omega}_{\text{S0-2}} < 1.6 \times 10^{-3}$ rad/yr, which can be used to constrain various gravitational and astrophysical theories. This analysis provides the first fully self-consistent test of the gravitational theory using orbital dynamics in a strong gravitational regime, that of a supermassive black hole. A sensitivity analysis for future measurements is also presented.

DOI: 10.1103/PhysRevLett.118.211101

The development of a quantum theory of gravitation or of a unification theory generically predicts deviations from general relativity (GR). In addition, observations requiring the introduction of dark matter and dark energy also challenge GR and the standard model of particle physics [1] and are sometimes interpreted as a modification of gravitational theory (see, e.g., Refs. [2,3]). It is thus important to test the gravitational interaction with different types of observations [4]. While GR is thoroughly tested in the Solar System (see, e.g., Refs. [5–8]) and with binary pulsars (see, e.g., Ref. [9]), observations of short-period stars orbiting the supermassive black hole (SMBH) at the center of our Galaxy allow one to probe gravity in a strong field regime unexplored so far, as shown in Fig. 1 (see also Refs. [10,11]). In this Letter, we report two results: (i) a search for a fifth force around our Galactic center and (ii) a constraint on the advance of the periastron of the short-period star S0-2 that can be used to constrain various gravitational and astrophysical theories in our Galactic center. This analysis provides the first fully self-consistent test of the gravitational theory using an orbital dynamic in a strong gravitational regime around a SMBH. The constraints presented in this Letter, resulting from 20 yr of observations, are therefore highly complementary with Solar System or binary pulsar tests of gravity and open a new window to study gravitation.

One phenomenological framework widely used to search for deviations from GR is the fifth force formalism [13–18], which considers deviations from Newtonian gravity in which the gravitational potential takes the form of a Yukawa potential

$$U = \frac{GM}{r} \left[1 + \alpha e^{-r/\lambda}\right],$$  \hspace{1cm} (1)

with $G$ the Newton’s constant, $M$ the mass of the central body, and $r$ the distance to the central mass. This potential is characterized by two parameters: a length $\lambda$ and a strength of interaction $\alpha$. A Yukawa potential appears in several theoretical scenarios, such as unification theories that predict new fundamental interactions with a massive

![FIG. 1. The gravitational potential probed by different tests of gravitation against the mass of the central body that generates gravity in these tests. Short-period stars, such as S0-2, around our Galactic center explore a new region in this parameter space. The figure is inspired by Ref. [12].](image-url)
stars are probing space-time in a higher potential and around a central body much more massive than in the other experiments. This is highlighted in the right panel of Fig. 2, where $\lambda$ is expressed in terms of the gravitational radius of the central body. Furthermore, short-period stars probe the space-time around a SMBH, which is conceptually different from Solar System tests where the space-time curvature is generated by weakly gravitating bodies. Specifically, some nonperturbative effects may arise around strongly gravitating bodies (see, e.g., Ref. [76]). In addition, in models of gravity exhibiting screening mechanisms, deviations from GR may be screened in the Solar System (see, e.g., Ref. [77]). In this context, searches for alternative theories of gravitation in other environments are important.

A specific theoretical model covered by the fifth force framework is a massive graviton. In that context, we found a 90% confidence limit $\lambda > 5000$ A.U. for $\alpha = 1$, which can be interpreted as a lower limit on the graviton's Compton wavelength $\lambda_G > 7.5 \times 10^{11}$ km or, equivalently, as an upper bound on the graviton's mass $m_G < 1.6 \times 10^{-21}$ eV/c^2 (see also Ref. [36]). This constraint is one order of magnitude less stringent than the recent bound obtained by LIGO [78], which, nevertheless, does not apply for all models predicting a fifth force. From an empirical perspective, one of the effects produced by a fifth force is a secular drift of the argument of periastron $\omega$ [31,79]. Several theoretical scenarios predict such an effect, which can be constrained by observations. We produced a new orbital fit using a model that includes seven global parameters (the SMBH $M_\bullet$, $R_G$, and the positions and velocities of the SMBH) and seven orbital parameters for each star, with the additional parameters being a linear drift of the argument of the periastron $\dot{\omega}$. As a result of our fit including the jackknife analysis, we obtained an upper confidence limit on a linear drift of the argument of periastron for S0-2 given by

$$|\dot{\omega}_{S0-2}| < 1.7 \times 10^{-3} \text{ rad/yr at 95\% C.L.}$$

(3)

This limit is currently one order of magnitude larger than the relativistic advance of the periastron $\dot{\omega}_{\text{GR}} = 6\pi G M_\bullet /[Pc^2(1 - e^2)] = 1.6 \times 10^{-3}$ rad/yr for S0-2 (with $a$ being the semimajor axis). Nevertheless, the limit from Eq. (3) can be used to derive a preliminary constraint on various theoretical scenarios (astrophysical or modified gravity) that predict an advance of the periastron for short-period stars in the Galactic center, like, for example, improve the current results. Figure 3 shows a sensitivity analysis based on a Fisher matrix approach performed to assess the improvement expected by observations with a TMT-like telescope. We have simulated 16 additional years of observations with two astrometric observations and one spectroscopic observation per year with the following astrometric (spectroscopic) accuracy for an S0-2-like star: current Keck accuracy, 0.5 mas (30 km/s); TMT-like improved accuracy, 15 μas (5 km/s).

FIG. 3. Statistical uncertainty on the fifth force strength $\alpha_5$ expected for various observational scenarios: the dashed green (light) line corresponds to the data used in this analysis, the continuous orange (light) line corresponds to data that will be available by the end of 2018. The two red (dark) lines indicate 16 additional years of observations with two astrometric observations and one spectroscopic observation per year with the following astrometric (spectroscopic) accuracy (as above) for an S0-2-like star: current Keck accuracy, 0.5 mas (30 km/s); TMT-like improved accuracy, 15 μas (5 km/s).

In conclusion, we have used 19 yr of observations of S0-2 and S0-38 reported in Ref. [44] to constrain a hypothetical fifth interaction around the SMBH in our Galactic center. The constraints obtained in our analysis are summarized in Fig. 2. Our results complement the ones obtained in the Solar System since they are obtained in a completely different and unexplored strong field regime. We have shown that future observations—and especially the next generation of telescopes—will improve our results substantially. In addition, we have derived a limit on an hypothetical advance of the periastron of the short-period


Constraining the range of Yukawa gravity interaction from S2 star orbits III: improvement expectations for graviton mass bounds

A.F. Zakharov, P. Jovanović, D. Borka and V. Borka Jovanović

1National Astronomical Observatories of Chinese Academy of Sciences, Datun Road 20A, Beijing, 100012 China
2Institute of Theoretical and Experimental Physics, 117259 Moscow, Russia
3National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 115409 Moscow, Russia
4Bogoliubov Laboratory for Theoretical Physics, JINR, 141600 Dubna, Russia
5North Carolina Central University, Durham, NC 27707, U.S.A.
6Astronomical Observatory, Volgajev 7, P.O. Box 71, 11000 Belgrade, Serbia
7Atomic Physics Laboratory (JAS), Vinca Institute of Nuclear Sciences, University of Belgrade, P.O. Box 522, 11001 Belgrade, Serbia

E-mail: zakharov@itep.ru, pjovanovic@nus.edu.sg, dborka@vinca.rs, vborka@vinca.rs

Received January 17, 2018
Revised February 14, 2018
Accepted March 9, 2018
Published 777, 2018

1Corresponding author.
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 (Visser, 1998; Will, 1998, 2014):

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

(5)

where $\delta$ is a universal constant (we put $\delta = 1$). In our previous studies we found constraints on parameters of Yukawa gravity. As it was described in we used observational data from NTT/VLT. If we wish to find a limiting value for $\lambda_x$, so that $\lambda > \lambda_x$ with a probability $P = 1 - \alpha$ (where we select $\alpha = 0.1$)
normalized $\chi^2$ depending on $\lambda_x$ has to be equal to the threshold depending on degree of freedom $\nu$ and parameter $\alpha$ or in other words, $\chi^2(\lambda_x) = \chi^2_{\nu,\alpha}$. Computing these quantities we obtain $\lambda_x = 2900 \text{ AU} \approx 4.3 \times 10^{11} \text{ km}$. 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 $m_g = 2.9 \times 10^{-21} \text{ eV}$ (since $m_g = \hbar c/\lambda_x$) in the case of $\delta = 1$. 
Orbital precession due to general central-force perturbations

A general expression for apocenter shifts for Newtonian potential and small perturbing potential is given as a solution of problem 3 in Section 15 in the classical Landau & Lifshitz (L & L) textbook [Mechanics].

Orbital precession $\Delta \varphi$ per orbital period, induced by small perturbations to the Newtonian gravitational potential $\Phi_N(r) = -\frac{GM}{r}$ could be evaluated as:

$$\Delta \varphi^{rad} = \frac{-2L}{GM e^2} \int \frac{z \cdot dz}{\sqrt{1 - z^2}} \frac{dV(z)}{dz},$$

(6)
while in the textbook it was given in the form

$$ \Delta \varphi^{rad} = \frac{-2L}{GM_e} \int_0^\pi \cos \varphi r^2 \frac{dV(r)}{dr} \, dr \, d\varphi, $$ \hspace{1cm} (7)$$

where \( V(z) \) is the perturbing potential, \( r \) is related to \( z \) via: \( r = \frac{L}{1 + e z} \)
in Eq. (6) (and \( r = \frac{L}{1 + c \cos \varphi} \) in Eq. (7)), and \( L \) being the semilatus rectum of the orbital ellipse with semi-major axis \( a \) and eccentricity \( e \):

$$ L = a \left(1 - e^2\right), $$ \hspace{1cm} (8)$$

while \( \Delta \varphi \) represents true precession in the orbital plane, and the corresponding apparent value \( \Delta s \), as seen from Earth at distance \( R_0 \),
is (assuming that stellar orbit is perpendicular to line of sight and taking into account an inclination of orbit one has to write an additional factor which is slightly less than 1 in the following expression):

$$\Delta s \approx \frac{a(1+e)}{R_0} \Delta \varphi.$$  \hspace{1cm} (9)

In order to compare the orbital precession of S-stars in both GR and Yukawa gravity, we applied the same procedure as described in to perform the two-body simulations of the stellar orbits in the framework of these two theories.
normalized $\chi^2$ depending on $\lambda_x$ has to be equal to the threshold depending on degree of freedom $\nu$ and parameter $\alpha$ 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 $\delta = 1$. 

Orbital precession in Yukawa gravity

In order to simulate orbits of S-stars in Yukawa gravity we assumed the following gravitational potential (Borka et al. 2013):

\[ \Phi_Y(r) = -\frac{GM}{(1 + \delta)r} \left[ 1 + \delta e^{-\frac{r}{\Lambda}} \right], \]  \hspace{1cm} (13)

where \( \Lambda \) is the range of Yukawa interaction and \( \delta \) is a universal constant. Here we will assume that \( \delta > 0 \), as indicated by data analysis of astronomical observations. Yukawa gravity induces a perturbation to the Newtonian gravitational potential described by the following perturbing potential:
\[ V_Y(r) = \Phi_Y(r) + \frac{GM}{r} = \frac{\delta}{1 + \delta} \frac{GM}{r} \left[ 1 - e^{-\frac{r}{\Lambda}} \right] \]  

(14)

The exact analytical expression for orbital precession in the case of the above perturbing potential could be presented in the integral form Eqs. (6) and (7), but we will calculate the approximate expression for \( \Delta \varphi \) using power series expansion of \( V_Y(r) \), assuming that \( r \ll \Lambda \):

\[ V_Y(r) \approx -\frac{\delta GMr}{2(1 + \delta)\Lambda^2} \left[ 1 - \frac{r}{3\Lambda} + \frac{r^2}{12\Lambda^2} - \ldots \right], \quad r \ll \Lambda, \]  

(15)

where we neglected the constant term since it does not affect \( \Delta \varphi \). By substituting the above expression into (6) we obtain the following approximation for the angle of orbital precession in Yukawa gravity:
\[ \Delta \varphi_{Y}^{rad} \approx \frac{\pi \delta \sqrt{1 - e^2}}{1 + \delta} \left( \frac{a^2}{\Lambda^2} - \frac{a^3}{\Lambda^3} + \frac{4 + e^2}{8} \frac{a^4}{\Lambda^4} - \ldots \right). \] (16)

The right-hand side in Eq. (16) could be presented as series of Gauss's hypergeometric function \( \genfrac{}{}{0pt}{}{2}{F_1} \) with different arguments.

Since \( r \ll \Lambda \) also implies that \( a \ll \Lambda \), we can neglect higher order terms in the above expansion. The first order term then yields the following approximate formula for orbital precession:

\[ \Delta \varphi_{Y}^{rad} \approx \frac{\pi \delta \sqrt{1 - e^2} \ a^2}{1 + \delta} \frac{a^2}{\Lambda^2}, \quad a \ll \Lambda. \] (17)

Both, \( \Delta \varphi_{GR} \) and \( \Delta \varphi_{Y} \) represent the angles of orbital precession per orbital period in the orbital plane (i.e. true precession). The corresponding
apparent values in Yukawa case $\Delta s_Y$, as seen from Earth at distance $R_0$ is (for $\delta = 1$) according to (Weinberg et al. 2005):

\[
\Delta s_Y \approx \frac{a(1+e)}{R_0} \Delta \varphi_{Y}^{\text{rad}} \approx 0.5\pi \frac{a^3}{R_0 \Lambda^2} (1+e) \sqrt{1-e^2}.
\]

(18)

If one believes that a gravitational field at the Galactic Center is described with a Yukawa potential, then the maximal $\Delta s_Y$ value corresponds to $e = 1/2$ when function $(1+e)\sqrt{1-e^2}$ has its maximal value (assuming that all other parameters are fixed).
Expectations to constrain the range of Yukawa gravity with future observations

We assume that in future GR predictions about precession angles for bright star orbits around the Galactic Center will be successfully confirmed, therefore, for each star we have a constraint on $\Lambda$ which can be obtained from the condition for $\Lambda$, so that Yukawa gravity induces the same orbital precession as GR. This constraint can be obtained directly from (11) and (17), assuming that $\Delta \varphi_Y = \Delta \varphi_{GR}$. In this way we obtain that:

\[
\Lambda \approx \sqrt{\frac{\delta c^2 (a \sqrt{1 - e^2})^3}{6(1 + \delta)GM}}.
\]  

(19)

As it can be seen from the above expression, taking into account that $\delta$ is
universal constant, the corresponding values of $\Lambda$ in the case of all S-stars depend only on the semi-major axes and eccentricities of their orbits. In order to stay in accordance with (Zakharov et al., 2016), here we will also assume that $\delta = 1$, in which case formula (19) reduces to:

$$\Lambda \approx \frac{c}{2} \sqrt{\frac{(a\sqrt{1-e^2})^3}{3GM}} \approx \sqrt{\frac{(a\sqrt{1-e^2})^3}{6R_S}},$$

(20)

Using Kepler law we could write the previous equation in the following form

$$\Lambda \approx \frac{T}{T_0} \sqrt{\frac{(a_0\sqrt{1-e^2})^3}{6R_S}}.$$  

(21)
Constraints on (tidal) charge of the supermassive black hole at the Galactic Center with trajectories of bright stars

In paper (Dadhich et al. 2001) it was shown that the Reissner – Nordström metric with a tidal charge could arise in Randall – Sundrum model with an extra dimension. Astrophysical of braneworld black holes are considered assuming that they could substitute conventional black holes in astronomy, in particular, geodesics and shadows in Kerr – Newman braneworld metric are analyzed in (Schee and Stuchlik, 2009a), while profiles of emission lines generated by rings orbiting braneworld Kerr black hole are considered in (Schee and Stuchlik, 2009a). Later it was proposed to consider signatures of gravitational lensing assuming a presence of the Reissner – Nordström black hole with a tidal charge at the Galactic Center (Bin-Nun
2010a, 2010b, 2011). In paper (Zakharov, 2014) analytical expressions for shadow radius of Reissner – Nordström black hole have been derived while shadow sizes for Schwarzschild – de Sitter (Köttler) metric have been found in papers (Stuchlik 1983, Zakharov 2014). In the paper we derive analytical expressions for Reissner – Nordström – de-Sitter metric in post-Newtonian approximation and discuss constraints on (tidal) charge from current and future observations of bright stars near the Galactic Center.
\[ V_{dS}(r) = -\frac{\Lambda r^2}{6} \quad (\alpha_2 = -\frac{\Lambda}{6}) \] and one has the corresponding apocenter (pericenter) shift (Adkins and McDonnell 2007) (see also, (Kerr et al. 2003, Sereno and Jetzer 2006)

\[ \Delta \theta(\Lambda) := \Delta \theta(2)_{dS} = \frac{\pi \Lambda a^3 \sqrt{1 - e^2}}{M}. \] (23)

Therefore, a total shift of a pericenter is

\[ \Delta \theta(\text{total}) := \frac{6\pi M}{L} - \frac{\pi Q^2}{ML} + \frac{\pi \Lambda a^3 \sqrt{1 - e^2}}{M}. \] (24)

and one has a relativistic advance for a tidal charge with \( Q^2 < 0 \) and apocenter shift dependences on eccentricity and semi-major axis are the same for GR and Reissner – Nordström advance but corresponding factors
\((6\pi M \text{ and } -\frac{\pi Q^2}{M})\) are different, therefore, it is very hard to distinguish a presence of a tidal charge and black hole mass evaluation uncertainties. For \(Q^2 > 0\), there is an apocenter shift in the opposite direction in respect to GR advance.
Estimates

As it was noted by the astronomers of the Keck group (Hees et al. 2017), pericenter shift has not be found yet for S2 star, however, an upper confidence limit on a linear drift is constrained

$$|\dot{\omega}| < 1.7 \times 10^{-3}\text{rad/yr.}$$ (25)

at 95% C.L., while GR advance for the pericenter is (Hees et al. 2017)

$$|\dot{\omega}_{GR}| = \frac{6\pi GM}{P c^2 (1 - e^2)} = 1.6 \times 10^{-4}\text{rad/yr},$$ (26)

where $P$ is the orbital period for S2 star (in this section we use dimensional constants $G$ and $c$ instead of geometrical units). Based on such estimates
one could constrain alternative theories of gravity following the approach used in (Hees et al. 2017).
Estimates of (tidal) charge constraints

Assuming $\Lambda = 0$ we consider constraints on $Q^2$ parameter from previous and future observations of S2 star. One could re-write orbital precession in dimensional form

$$\dot{\omega}_{RN} = \frac{\pi Q^2}{PGML},$$  \hspace{2cm} (27)

where $P$ is an orbital period. Taking into account a sign of pericenter shift for a tidal charge with $Q^2 < 0$, one has

$$\dot{\omega}_{RN} < 1.54 \times 10^{-3}\text{rad/yr} \approx 9.625 \dot{\omega}_{GR},$$  \hspace{2cm} (28)

therefore,

$$-57.75M^2 < Q^2 < 0,$$  \hspace{2cm} (29)
with 95% C. L. For $Q^2 > 0$, one has

$$|\dot{\omega}_{RN}| < 1.86 \times 10^{-3}\text{rad/yr} \approx 11.625 \dot{\omega}_{GR},$$

(30)

therefore,

$$0 < |Q| < 8.3516M,$$

(31)

with 95% C. L. As it was noted in (Hees et al. 2017) in 2018 after the pericenter passage of S2 star the current uncertainties of $|\dot{\omega}|$ will be improved by a factor 2, so for a tidal charge with $Q^2 < 0$, one has

$$\dot{\omega}_{RN} < 6.9 \times 10^{-4}\text{rad/yr} \approx 4.31 \dot{\omega}_{GR},$$

(32)

$$-25.875M^2 < Q^2 < 0,$$

(33)

For $Q^2 > 0$, one has

$$|\dot{\omega}_{RN}| < 9.1 \times 10^{-4}\text{rad/yr} \approx 5.69 \dot{\omega}_{GR},$$

(34)
therefore,

$$0 < |Q| < 5.80M, \quad (35)$$

One could expect that subsequent observations with VLT, Keck, GRAVITY, E-ELT and TMT will significantly improve an observational constraint on $|\dot{\omega}|$, therefore, one could expect that a range of possible values of $Q$ parameter would be essentially reduced.

As it was noted in paper (Hees et al. 2017), currently Keck astrometric uncertainty is around $\sigma = 0.16$ mas, therefore, an angle $\delta = 2\sigma$ (or two standard deviations) is measurable with around 95% C.L. In this case $\Delta\theta(GR)_{S2} = 2.59\delta$ for S2 star where we adopt $\Delta\theta(GR)_{S2} \approx 0.83$. Assuming that GR predictions about orbital precession will be confirmed in the next 16 years with $\delta$ accuracy (or $\left|\frac{\pi Q^2}{ML}\right| \lesssim \delta$), one could constrain $Q$ parameter

$$|Q^2| \lesssim 2.32M^2, \quad (36)$$
where we wrote absolute value of $Q^2$ since for a tidal charge $Q^2$ could be negative.

If we adopt for TMT-like scenario uncertainty $\sigma_{TMT} = 0.015$ mas as it was used in (Hees et al. 2017) ($\delta_{TMT} = 2\sigma_{TMT}$) or in this case $\Delta \theta(GR)_{S2} = 27.67 \delta_{TMT}$ for S2 star and assuming again that GR predictions about orbital precession of S2 star will be confirmed with $\delta_{TMT}$ accuracy (or $\left| \frac{\pi Q^2}{ML} \right| \lesssim \delta_{TMT}$), one could conclude that

$$|Q^2| \lesssim 0.216 M^2, \quad (37)$$

or based on results of future observations one could expect to reduce significantly a possible range of $Q^2$ parameter in comparison with a possible hypothetical range of $Q^2$ parameter which was discussed in (Bin-Nun 2010a, 2010b).
Estimates of $\Lambda$-term constraints

In this subsection we assume that $Q = 0$. One could re-write orbital precession in dimensional form

$$\dot{\omega}_\Lambda = \frac{\pi \Lambda c^2 a^3 \sqrt{1 - e^2}}{PGM},$$  \hspace{1cm} (38)

Dependences of functions $\omega_\Lambda$ and $\omega_{GR}$ on eccentricity and semi-major axis are different and orbits with higher semi-major axis and smaller eccentricity could provide a better estimate of $\Lambda$-term (the S2 star orbit has a rather high eccentricity). However, we use observational constraints for S2 star. For positive $\Lambda$, one has relativistic advance and

$$\omega_\Lambda < 1.54 \times 10^{-3}\text{rad/yr} \approx 9.625 \omega_{GR},$$  \hspace{1cm} (39)
or

\[ 0 < \Lambda < 3.9 \times 10^{-39}\text{cm}^{-2}, \]  

(40)

for \( \Lambda < 0 \) one has

\[ 0 < -\Lambda < 4.68 \times 10^{-39}\text{cm}^{-2}, \]  

(41)

if we use current accuracy of Keck astrometric measurements \( \sigma = 0.16 \text{ mas} \) and monitor S2 star for 16 years and assume that additional apocenter shift \( (2\sigma) \) could be caused by a presence of \( \Lambda \)-term, one obtains

\[ |\Lambda| < 1.56 \times 10^{-40}\text{cm}^{-2}, \]  

(42)

while for TMT-like accuracy \( \delta_{TMT} = 0.015 \text{ mas} \) one has

\[ |\Lambda| < 1.46 \times 10^{-41}\text{cm}^{-2}. \]  

(43)
As one can see, constraints on cosmological constant from orbital precession of bright stars near the Galactic Center are much weaker than not only its cosmological estimates but also than its estimates from Solar system data.
LETTER TO THE EDITOR

Detection of the gravitational redshift in the orbit of the star S2 near the Galactic centre massive black hole


(Affiliations can be found after the references)

Received 26 June 2018 / Accepted 29 June 2018

ABSTRACT

The highly elliptical, 16-year-period orbit of the star S2 around the massive black hole candidate Sgr A* is a sensitive probe of the gravitational field in the Galactic centre. Near periapsis at 120 AU = 1400 Schwarzschild radii, the star has an orbital speed of \( v_{\text{orb}} \approx 7500\) km s\(^{-1}\), such that the first-order effects of Special and General Relativity have now become detectable with current capabilities. Over the past 26 years, we have monitored the radial velocity and motion on the sky of S2, mainly with the SINFONI and NACO adaptive optics instruments on the ESO Very Large Telescope, and since 2016 up to and including periapsis, we robustly detect the combined gravitational redshift and relativistic transverse Doppler effect for S2 of \( \Delta v_{\text{rad}} \approx \pm 200\) km s\(^{-1}\) with different statistical analysis methods. When parameterising the post-Newtonian contribution from these effects by a factor \( f \), with \( f = 0 \) and \( f = 1 \) corresponding to the Newtonian and general relativistic limits, respectively, we find from posterior fitting with different weighting schemes \( f = 0.99 \pm 0.09\) or \( f = 0.75\). The S2 data are inconsistent with pure Newtonian dynamics.

Key words: Galaxy: center – gravitation – black hole physics

1. Introduction

General Relativity (GR) so far has passed all experimental tests with flying colours (Unruh 2014). The most stringent are tests that employ solar mass pulsars in binary systems (Kramer et al. 2006), and gravitational waves from 10 to 30 M\(_{\odot}\) black hole in-spiral events (Abbott et al. 2016a,b,c). These tests cover a wide range of field strengths and include the strong curvature limit (Fig. A.2). At much lower field strength, Earth laboratories probe planetary masses that are about a factor 10\(^6\) lower than the stellar mass scale. For massive black hole (MBH) candidates with masses of \( 10^6 - 10^8 M_{\odot}\), only indirect evidence for GR effects has been reported, such as relativistically broadened, redshifted iron K\(_{\alpha}\) line emission in nearby active galaxies (Tanaka et al. 1995; Fabian et al. 2000). The closest MBH is at the centre of the Milky Way (\( R_{\odot} = 8.25 \pm 0.4\) kpc, \( M_{\odot} = 4 \times 10^6 M_{\odot}\)), and its Schwarzschild radius subsumes the largest angle on the sky of all known MBHs (\( R_{\odot} = 10 \mu\text{as} = 0.08\) AU). It is coincident with a very compact, variable X-ray, infrared, and radio source, Sgr A*, which in turn is surrounded by a very dense cluster of orbiting young and old stars. Radio and infrared observations have provided detailed information on the distribution, kinematics, and physical properties of this nuclear star cluster and of the hot, warm, and cold interstellar gas interspersed in it (cf. Genzel et al. 2010; Morris et al. 2012; Falcke & Markoff 2013). High-resolution near-infrared (NIR) speckle and adaptive optics (AO) assisted imaging and spectroscopy of the nuclear star cluster over the past 26 years, mainly by two groups in Europe
and 26 additional spectroscopy epochs with SINFONI using the 25 mm pix$^{-1}$ scale and the combined H + K-band grating with a spectral resolution of R $\approx$ 1500.

For more details on the data analysis of all three instruments, we refer to Appendix A.

3. Results
3.1. Relativistic corrections

The left panel of Fig. 2 shows the combined single-telescope and interferometric astrometry of the 1992–2018 sky-projected orbital motion of S2, where the zero point is the position of the central mass and of Sgr A*. All NACO points were corrected for a zero-point offset and drift in RA/Dec, which are obtained from the orbit fit. The bottom right panel zooms into the 2018 section of the orbit around pericentre measured with GRAVITY. The zoom demonstrates the hundred-fold improvement of astrometry between SHARP in the 1990s (0.4 mas precision) and NACO in the 2000s (0.5 mas) to GRAVITY in 2018 (as small as $\approx$0.5mas). While the motion on the sky of S2 could be detected with NACO over a month, the GRAVITY observations detect the motion of the star from day to day. The upper right panel of Fig. 2 displays the radial velocity measurements with SINFONI at the VLT and NIRCam2 at Keck. S2 reached pericentre of its orbit at the end of April 2002, and then again on May 19th, 2018 (MJD 58257.67). The data before 2017 are taken from Ghez et al. (2008), Bothe et al. (2016), Chu et al. (2018), and Gillessen et al. (2017, 2009b). The 2017/2018 NACO/SINFONI and GRAVITY data are presented here for the first time. The cyan curve shows the best-fitting S2 orbit to all these data, including the effects of General and Special Relativity.
3.3. Posterior analysis

Because of the uncertainties in the parameters of $K_{\text{prior}}$, in particular, in the strongly correlated mass and distance, a more conservative approach is to determine the best-fit value of the parameter $f$ a posteriori, including all data and fitting for the optimum values of all parameters. In carrying out the fitting, it is essential to realise that the inferred measurement uncertainties are dominated by systematic effects, especially when evidence from three or more very different measurement techniques is combined (see Appendix A.6 for a more detailed discussion). In particular, the NACO measurements are subject to correlated systematic errors, for example from unrecognised confusion events (Plewa & Sari 2018), which typically last for one year and are comparable in size to the statistical errors. We therefore down-sampled the NACO data into 100 bins with equal path lengths along the projected orbit (Fig. 4, middle) and gave these data in addition a lower weight of 0.5. Depending on exactly which weighting or averaging scheme was chosen, the posterior analysis including all data between 1992 and 2018 yielded $f$ values between 0.85 and 1.09. With a weighting of 0.5 of the NACO data, we find $f = 0.90 \pm 0.09$ (Fig. 4). GR ($f = 1$) is favoured over pure Newtonian physics ($f = 0$) at the $\sim 10\sigma$ level.

The error on $f$ is derived from the posterior probability distributions (Fig. 4, bottom) of a Markov chain Monte Carlo (MCMC) analysis. Fig. A.1 shows the full set of correlation plots and probability distributions for the fit parameters. The distributions are compact and all parameters are well determined. The best-fit values and uncertainties are given in Table A.1.

The superb GRAVITY astrometry demonstrably improves the quality of the fits and is crucial for overcoming the source confusion between Sgr A* and S2 near pericentre. A minimal detection of PPN (1), (PPN (1)) is provided by a combination using only NACO and SINFONI data ($f_{\text{PPN (1)}} = 1.0 \pm 0.09, 3.6\sigma$), but the inclusion of the GRAVITY data very significantly improves the precision and significance of the fitted parameters: the improvement reaches a factor of 2-3.

A still more demanding test is to search for any Keplerian fit to all data and determine whether its goodness of fit is significantly poorer than the goodness of fit of the best-fitting GR-orbit. For linear models the formula presented in András et al. (2010) can be used to estimate the significance. However, the value for the degrees of freedom (d.o.f.) is not well defined for non-linear models (András et al. 2010). In our case, we have two models that only differ significantly over a very critical short time-span given the uncertainties in the underlying data. We therefore used the number of degrees of freedom as d.o.f. for which the two models predict significant differences. The difference in $\chi^2$ yields a formal significance of $5\sigma$ or greater in favour of the relativistic model.

For further comments on a Bayesian analysis of our data, see Appendix A.9.

4. Discussion

We have reported the first direct detection of the PPN(1) gravitational redshift parameter around the MBH in the Galactic centre from a data set that extends up to and includes the pericentre approach in May 2018. Three different analysis methods of our data suggest that this detection favours the post-Newtonian model with robust significance. Further improvement of our results is expected as our monitoring continues past pericentre. Still, there are reasons to be cautious about the significance of these early results, mainly because of the systematic uncertainties.
GRAVITY result about PN(1) correction for gravitational redshift

- For orbital precession $f = 0.94 \pm 0.09$ (2018)
- $R = 8178 \pm 13\text{stat.} \pm 22\text{sys.}$ parsecs
- Mass = $4.154 \pm 0.014 \times 10^6$ solar masses
  $f = 1.04 \pm 0.05$

Relativistic redshift of the star S0-2 orbiting the Galactic Center supermassive black hole

Tuan Do\textsuperscript{1}, Aurieles Hees\textsuperscript{2}, Andrea Ghez\textsuperscript{1}, Gregory D. Martinez\textsuperscript{1}, Devin S. Chu\textsuperscript{3}, Silyan Jia\textsuperscript{4}, Shoko Sakai\textsuperscript{5}, Jessica B. Lu\textsuperscript{1}, Abhimal K. Goharian\textsuperscript{6}, Kelly Kosmack\textsuperscript{7}, Erle E. Becklin\textsuperscript{1}, Mark R. Morris\textsuperscript{1}, Keith Matthews\textsuperscript{1}, Shogo Nishiyama\textsuperscript{8}, Randy Campbell\textsuperscript{9}, Samantha Chappell\textsuperscript{10}, Zhou Chen\textsuperscript{11}, Anna Chael\textsuperscript{12}, Aracel Delgado\textsuperscript{13}, Eulalia Gallego-Cano\textsuperscript{14}, Wolfgang E. Kerzendorf\textsuperscript{15,16}, James E. Lyke\textsuperscript{17}, Smaiur Naze\textsuperscript{18}, Hironomi Saita\textsuperscript{19}, Rainer Schirbel\textsuperscript{20}, Masahida Takahashi\textsuperscript{21}, Yutusuke Takami\textsuperscript{22}, Gunther Witte\textsuperscript{23}, Peter Wizinowich\textsuperscript{24}

The general theory of relativity predicts that a star passing close to a supermassive black hole should exhibit a relativistic redshift. In this study, we used observations of the Galactic center star S0-2 to test this prediction. We combined existing spectroscopic and astrometric measurements from 1995-2017, which cover S0-2’s 16-year orbit, with new measurements from March to September 2018, which cover three events during S0-2’s closest approach to the black hole. We detected a combination of special relativistic and gravitational redshift, quantified using the redshift parameter \(Y\). Our result, \(Y = 0.88 \pm 0.17\), is consistent with general relativity (\(Y = 1\)) and excludes a Newtonian model (\(Y = 0\)) with a statistical significance of 5\(\sigma\).

Central relativity (GR) has been thoroughly tested in weak gravitational fields in the Solar System (I), with binary pulsars (2) and with measurements of gravitational waves from stellar-mass black hole binaries (3, 4). Observations of short-period stars in our Galactic Center (GC) (5-8) allow GR to be tested in a different regime (9): the strong field near a supermassive black hole (SMBH) (10, 11). The star S0-2 (also known as S2) has a 16-year orbit around Sagittarius A (Sgr A), the SMBH at the center of the Milky Way. In 2018, S0-2 reached its point of closest approach, at a distance of 120 astronomical units with a velocity reaching 2.7% of the speed of light. Within a 6-month interval of that date, the star also passed through its maximum and minimum velocity (in March and September, respectively) along the line of sight, spanning 6000 km s\(^{-1}\) in radial velocity (RV) (Fig. 1). Here we present observations of all three events combined with data from 1995-2017 (Fig. 2).

During 2018, the close proximity of S0-2 to the SMBH caused the relativistic redshift, which is the combination of the transverse Doppler shift from special relativity and the gravitational redshift from GR. This deviation from a Keplerian orbit was predicted to reach 200 km s\(^{-1}\) (Fig. 3) and is detectable with current telescopes. The GRAVITY collaboration (12) previously reported a similar measurement. Our measurements are complementary in the following ways: (i) We took a complete set of independent measurements with three additional months of data, doubling the baseline for the year of closest approach and including the third turning point (RV minimum) in September 2018. (ii) We used three different spectroscopic instruments in 2018, enabling us to probe the presence of instrumental biases. (iii) To test for bias in the result, we analyzed the systematic errors that may arise from an experiment spanning more than 20 years. (iv) We publicly released the stellar measurements and the posterior probability distributions.

We used a total of 45 astrometric positional measurements (spanning 24 years) and 335 RVs (16 years) to fit the orbit of S0-2. Of these, 11 are new astrometric measurements of S0-2 from 2016 to 2018 and 28 are new RV measurements from 2017 and 2018 (Fig. 1). Astrometric measurements were obtained at the W. M. Keck Observatory by using speckle imaging (a technique to overcome blurring from the atmosphere by taking very short exposures and combining the images with software) from 1995–2005 and adaptive optics (AO) imaging (13) from 2007–2018. RV measurements were obtained from the W. M. Keck Observatory, Gemini North Telescope, and Subaru Telescope. All of our RV observations were taken using AO. We supplement our observations with previously reported RVs from Keck from 2006 (14) and the Very Large Telescope from 2003–2018 (15). This work includes data from two imaging instruments and six spectroscopic instruments (16).

We scheduled our 2018 observations using a tool designed to maximize the sensitivity of the experiment to the redshift signal (17). We predicted that, given the existing data (1995–2017), spectroscopic measurements at the RV maximum and minimum in 2018 would provide the most sensitivity and thus would be ideal for detecting the relativistic redshift (Fig. 3). Although they are less sensitive to the effect of the redshift, imaging observations of the sky position of S0-2 in 2018 also slightly improve the measurement of the relativistic redshift (R).

The RVs of S0-2 are measured by fitting a physical model (which includes properties of the star, such as its effective temperature, surface gravity, and rotational velocity in addition to RV) to its observed spectrum (17). The same procedure is applied to the new and archival observations. For the latter, this spectroscopic method improves the precision by a factor of 1.7 compared with previous analyses (18, 19).

We also characterized additional sources of uncertainties beyond the uncertainties in the fitted model. (i) The wavelength solution, which transforms locations on the detector to vacuum wavelengths, was characterized by comparing the observed wavelengths of atmospheric OH emission lines in the spectra of S0-2 and in observations of black sky to their known vacuum wavelengths. This comparison shows the uncertainty of the wavelength solution of the spectroscopic instrument to be ~2 km s\(^{-1}\), with some observations from 2002–2004 having lower accuracy between 2 and 26 km s\(^{-1}\).
• $f = 0.88 \pm 0.17$, is consistent with general relativity ($f = 1$) and excludes a Newtonian model ($f = 0$) with a statistical significance of 5 $\sigma$. 
Scalar field effects on the orbit of S2 star


1 CENTRA, Centro de Astronomia e Gravitation, Instituto Superior Técnico, Av. Rovisco Pais 1, 1049 Lisboa, Portugal
2 European Southern Observatory, Casilla 686, Sotillo, La Serena, Chile
3 Universidade de Lisboa, Faculdade de Engenharia, Rua Dr. Roberto Frias, 2000-417 Lisboa, Portugal
4 Max Planck Institute for Extraterrrestrial Physics (MPE), Hans-Kretschmer Str. 1, 85748 Garching, Germany
5 Univ. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France
6 LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université de Paris, 5 place Jules Janssen, 92190 Meudon, France
7 Hamburger Sternwarte, Universität zu Köln, Zöllnerstr. 1, 53121 Köln, Germany
8 Observatoire de Liège, Université de Liège, 43 Boulevard du Roi Baudouin, 4000 Liège, Belgium
9 Max Planck Institute für Astrophysik (MPA) und Haus der Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany

Accepted XXX. Received YYYY; in original form XXX

ABSTRACT

Precise measurements of the S-stars orbiting SgrA* have set strong constraints on the nature of the compact object at the centre of the Milky Way. The presence of a black hole in that region is well established, but its neighboring environment is still an open debate. In that respect, the existence of dark matter in that central region may be detectable due to its strong signatures on the orbits of stars: the main effect is a Newtonian precession which will affect the overall pericentre shift of S2, the latter being a target measurement of the GRAVITY instrument. The exact nature of this dark matter (e.g., stellar dark remnants or diffuse dark matter) is unknown. This article assumes it to be an scalar field of toroidal distribution, associated with ultra-light dark matter particles, surrounding the Kerr black hole. Such a field is a form of "hair" expected in the context of superradiance, a mechanism that extracts rotational energy from the black hole. Orbital signatures for the S2 star are computed and shown to be detectable by GRAVITY. The scalar field can be constrained because the variation of orbital elements depends both on the relative mass of the scalar field to the black hole and on the field mass coupling parameter.

Key words: black hole physics – celestial mechanics – dark matter – gravitation – Galaxy – centre – quasar: supermassive black holes.

* Corresponding author. E-mail: mcferrin@astro.ufl.edu
† Corresponding author. E-mail: pgarcia@bigfoot.com
Results from 9 our papers were used
Graviton

Van Dam and Veltman (VANDAM 70), Iwasaki (IWASAKI 70) and Zakharov (ZAKHAROV 70) almost simultaneously showed that "... there is a discrete difference between the theory with non-mass and a theory with finite mass, no matter how small as compared to all external momenta." The resolution of this "DDVZ discontinuity" has to do with whether the linear approximation is valid. De Rham et al. (DE-RHAM 11) have shown that nonlinear effects not captured in their linear treatment can give rise to a screening mechanism, allowing for massive gravity theories. See also GOLDHABER 10 and DE-RHAM 17 and references therein. Experimental limits have been set based on a Yukawa potential or signal dispersion. \( A_0 \) is the Hubble constant in units of 100 \( \text{km} \text{s}^{-1} \text{Mpc}^{-1} \).

The following conversions are useful: 1 eV = 1.731 \( \times 10^{-33} \) g = 1.667 \( \times 10^{-6} \) \( m_p \).

\( X_C = (1.975 \times 10^{-7}) \times (1 \text{ eV/mg}) \).

<table>
<thead>
<tr>
<th>VALUE (eV)</th>
<th>DOCUMENT ID</th>
<th>TECH</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;8 ( \times 10^{-32} )</td>
<td>CHoudhury 04</td>
<td>YUKA</td>
<td>Weak gravitational lensing</td>
</tr>
<tr>
<td>&lt;4 ( \times 10^{-30} )</td>
<td>DESAI 16</td>
<td>YUKA</td>
<td>Gal cluster Abell 1069</td>
</tr>
<tr>
<td>&lt;3 ( \times 10^{-28} )</td>
<td>GUPTA 16</td>
<td>YUKA</td>
<td>SPT-SZ</td>
</tr>
<tr>
<td>&lt;1.3 ( \times 10^{-29} )</td>
<td>GUPTA 16</td>
<td>YUKA</td>
<td>PLANCK all-sky SZ</td>
</tr>
<tr>
<td>&lt;6 ( \times 10^{-30} )</td>
<td>RANA 18</td>
<td>YUKA</td>
<td>redMapper SDSS-DRE</td>
</tr>
<tr>
<td>&lt;8 ( \times 10^{-30} )</td>
<td>RANA 18</td>
<td>YUKA</td>
<td>Weak lensing in massive clusters</td>
</tr>
<tr>
<td>&lt;5 ( \times 10^{-30} )</td>
<td>RANA 18</td>
<td>YUKA</td>
<td>S2 effect in massive clusters</td>
</tr>
<tr>
<td>&lt;7 ( \times 10^{-23} )</td>
<td>ABBOTT 17</td>
<td>DISC</td>
<td>Combined dispersion limit from three BH mergers</td>
</tr>
<tr>
<td>&lt;1.2 ( \times 10^{-22} )</td>
<td>ABBOTT 16</td>
<td>DISC</td>
<td>Combined dispersion limit from two BH mergers</td>
</tr>
<tr>
<td>&lt;1.9 ( \times 10^{-21} )</td>
<td>ZAKHAROV 16</td>
<td>YUKA</td>
<td>S2 star orbit</td>
</tr>
<tr>
<td>&lt;6 ( \times 10^{-25} )</td>
<td>Baskaran 06</td>
<td>YUKA</td>
<td>Graviton phase velocity fluctuations</td>
</tr>
<tr>
<td>&lt;7.9 ( \times 10^{-22} )</td>
<td>GRUZINOV 05</td>
<td>YUKA</td>
<td>Solar system observations</td>
</tr>
<tr>
<td>&lt;9.0 ( \times 10^{-24} )</td>
<td>Gershtein 04</td>
<td>YUKA</td>
<td>From D2g value assuming RTG</td>
</tr>
<tr>
<td>&lt;6 ( \times 10^{-14} )</td>
<td>HWALI 03</td>
<td>YUKA</td>
<td>Horizon scales</td>
</tr>
<tr>
<td>&lt;1.3 ( \times 10^{-12} )</td>
<td>Finn 02</td>
<td>DISC</td>
<td>Binary pulsar orbital period increases</td>
</tr>
<tr>
<td>&lt;1.5 ( \times 10^{-13} )</td>
<td>DLMOUR 90</td>
<td>YUKA</td>
<td>Binary pulsar PSR 1913+16</td>
</tr>
<tr>
<td>&lt;7 ( \times 10^{-26} )</td>
<td>Goldhaber 74</td>
<td>YUKA</td>
<td>Solar system planetary astrometric data</td>
</tr>
<tr>
<td>&lt;7 ( \times 10^{-28} )</td>
<td>Hare 73</td>
<td>YUKA</td>
<td>Rich clusters</td>
</tr>
<tr>
<td>&lt;7 ( \times 10^{-28} )</td>
<td>Hare 73</td>
<td>YUKA</td>
<td>Galaxy</td>
</tr>
<tr>
<td>&lt;3 ( \times 10^{-4} )</td>
<td>Hare 73</td>
<td>YUKA</td>
<td>2y decay</td>
</tr>
</tbody>
</table>
1. CHoudhury 04 concludes from a study of weak-lensing data that masses heavier than about the inverse of 100 Mpc seem to be ruled out if the gravitation field has the Yukawa form.

2. DESAI 18 limit based on dynamical mass models of galaxy cluster Abell 1689.

3. GUPTA 18 obtains graviton mass limits using stacked clusters from 3 disparate surveys.

4. RANA 18 limit, 68% CL, obtained using weak lensing mass profiles out to the radius at which the cluster density falls to 200 times the critical density of the Universe. Limit is based on the fractional change between Newtonian and Yukawa accelerations for the 50 most massive galaxy clusters in the Local Cluster Substructure Survey. Limits for other CL's and other density cuts are also given.

5. RANA 18 limit, 68% CL, obtained using mass measurements via the SZ effect out to the radius at which the cluster density falls to 500 times the critical density of the Universe for 182 optically confirmed galaxy clusters in an Altacama Cosmology Telescope survey. Limits for other CL's and other density cuts are also given.

6. ABBOTT 16 and ABBOTT 17 assumed a dispersion relation for gravitational waves modified relative to GR.

7. ZAKHAROV 16 constrains range of Yukawa gravity interaction from S2 star orbit about black hole at Galactic center. The limit is $< 2.9 \times 10^{-21}$ eV for $\delta = 100$.

8. BRITO 13 explore massive graviton (spin-2) fluctuations around rotating black holes.

9. BASKARAN 08 consider fluctuations in pulsar timing due to photon interactions ("surfing") with background gravitational waves.

10. GRUZINOV 05 uses the DGP model (DVALI 00) showing that non-perturbative effects restore continuity with Einstein’s equations as the graviton mass approaches 0, then bases his limit on Solar System observations.

11. GERShteIN 04 use non-Einstein field relativistic theory of gravity (RTG), with a massive graviton, to obtain the 95% CL mass limit implied by the value $\Omega_{\text{tot}} = 1.02 \pm 0.02$ current at the time of publication.

12. DVALI 03 suggest scale of horizon distance via DGP model (DVALI 00). For a horizon distance of $3 \times 10^{50}$ m (about age of Universe/c, GOLDHABER 10) this graviton mass limit is implied.

13. FINN 02 analyze the orbital decay rates of PSR B1913+16 and PSR B1534+12 with a possible graviton mass as a parameter. The combined frequentist mass limit is at 90% CL.

14. As of 2014, limits on dP/dt are now about 0.1% (see T. Damour, "Experimental tests of gravitational theory," in this Review).

15. DAmOUR 91 is an analysis of the orbital period change in binary pulsar PSR 1913+16, and confirms the general relativity prediction to 0.8%. “The theoretical importance of the [rate of orbital period decay] measurement has long been recognized as a direct confirmation that the gravitational interaction propagates with velocity c (which is the immediate cause of the appearance of a damping force in the binary pulsar system) and thereby as a test of the existence of gravitational radiation and of its quadrupolar nature.” TAYLOR 93 adds that orbital parameter studies now agree with general relativity to 0.5%, and set limits on the level of scalar contribution in the context of a family of tensor (spin-2)-bi-scalar theories.

**Graviton References**

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desai</td>
<td>PL 8778 325</td>
</tr>
<tr>
<td>Gupt</td>
<td>ANP 399 85</td>
</tr>
<tr>
<td>Rana</td>
<td>PL 781 229</td>
</tr>
<tr>
<td>Abbott</td>
<td>PRL 118 221101</td>
</tr>
<tr>
<td>de-Rham</td>
<td>HEP 89 025004</td>
</tr>
<tr>
<td>Abbott</td>
<td>PRL 116 061102</td>
</tr>
<tr>
<td>Zakharov</td>
<td>JCAP 1005 045</td>
</tr>
<tr>
<td>Brito</td>
<td>PR D68 093514</td>
</tr>
<tr>
<td>de-Rham</td>
<td>PRL 106 231101</td>
</tr>
<tr>
<td>Goldhaber</td>
<td>IMP 87 939</td>
</tr>
<tr>
<td>Baskaran</td>
<td>PR D76 044018</td>
</tr>
<tr>
<td>Gruzinov</td>
<td>NAST 10 311</td>
</tr>
</tbody>
</table>

**HTTP://PDG.LBL.GOV**

Page 2 Created: 5/22/2019 10:04
Main conclusions

• We found graviton mass constraints which are comparable with LIGO’s ones

• The observers working with largest telescopes with AO (Keck, VLT, GRAVITY, TMT, E-ELT) follow our ideas to improve current graviton mass constraints with current and forthcoming facilities. The current graviton mass LIGO constraint will be outperformed with current GRAVITY observation (private comm.)

• The observers use our ideas to constrain parameters of alternative theories of gravity with observations of bright stars near GC
J. Peebles, D. Queloz, M. Mayor
SECRETS IN THE BACKGROUND RADIATION

The universe was extremely hot and dense in its earliest moments, the Big Bang. Since then, the universe has been expanding, getting larger and colder. Almost 400,000 years after the Big Bang, the initial radiation began to travel through space. This radiation still fills the cosmos and, coded into it, many of the universe's secrets are hiding. Using his theoretical models, James Peebles was able to predict the shape of the universe and the matter and energy it contains (the below curve). His calculations were a good match with later measurements of background radiation.

The first peak shows that the universe is geometrically flat, i.e. two parallel lines will never meet.

The second peak shows that ordinary matter is just 5% of the matter and energy in the universe.

The third peak shows that 26% of the universe consists of dark matter.

From these three peaks, it is possible to conclude that if 31% (5%+26%) of the universe is composed of matter, then 69% must be dark energy in order to fulfill the requirement for a flat universe.
Sakharov’s oscillations (1185 citations Google Scholar)

SMALL-SCALE FLUCTUATIONS OF RELIC RADIATION

R. A. SUNYAEV and Y. A. ZELDOVICH
Institute of Applied Mathematics, Academy of Sciences of the U.S.S.R., Moscow, U.S.S.R.

(Received 11 September, 1969)

Abstract. Perturbations of the matter density in a homogeneous and isotropic cosmological model which leads to the formation of galaxies should, at later stages of evolution, cause spatial fluctuations of relic radiation. Silk assumed that an adiabatic connection existed between the density perturbations at the moment of recombination of the initial plasma and fluctuations of the observed temperature of radiation \( \delta T / T = \delta n / 3 n_e \). It is shown in this article that such a simple connection is not applicable due to:

1. The long time of recombination;
2. The fact that when regions with \( M < 10^{14} M_\odot \) become transparent for radiation, the optical depth to the observer is still large due to Thomson scattering;
3. The spasmodic increase of \( \delta n / n_e \) in recombination.

As a result the expected temperature fluctuations of relic radiation should be smaller than adiabatic fluctuations. In this article the value of \( \delta T / T \) arising from scattering of radiation on moving electrons is calculated; the velocity field is generated by adiabatic or entropy density perturbations. Fluctuations of the relic radiation due to secondary heating of the intergalactic gas are also estimated. A detailed investigation of the spectrum of fluctuations may, in principle, lead to an understanding of the nature of initial density perturbations since a distinct periodic dependence of the spectral density of perturbations on wavelength (mass) is peculiar to adiabatic perturbations. Practical observations are quite difficult due to the smallness of the effects and the presence of fluctuations connected with discrete sources of radio emission.

1. Introduction

In the contemporary ‘big-bang’ model of the Universe it is hypothesized that in the distant past, before recombination of the initial plasma at times corresponding to a red shift \( z \sim 1000 \), there were no galaxies and the origin of galaxies is connected with insignificant deviations from strict homogeneity existing in that period. In the first approximation it can be considered that after recombination of protons and electrons ‘matter’ – neutral atoms – do not interact with radiation and relic radiation (having at present an average temperature of 2.7 K) immediately gives us information about conditions for \( z \sim 1000 \). In particular, the dependence of deviations of temperature on the direction of observation now being performed from the Earth characterizes the dependence of physical values, i.e. deviations of density, on the spatial coordinates at an earlier stage. These deviations grow in the future (after recombination) due to gravitation instability. For the moment of formation of separate objects it is reasonable to take the time of origin of regions with densities at least twice the average density, i.e. \( \delta n / n \sim 1 \). It is assumed that this occurred relatively recently (on a logarithmic time scale) at \( z \sim 2 \times 10 \). In this case an estimate for the perturbation at the moment of recombination gives \( \delta n / n \sim 10^{-2} \), i.e., it is possible to speak about...
Acoustic peaks (1346 citations Google Scholar)
FINDING PLANETS USING THE RADIAL VELOCITY METHOD

The star moves as it is affected by the gravity of its planet. Seen from the Earth, the star wobbles backwards and forwards in the line of sight. The speed of this movement, its radial velocity, can be determined using the Doppler effect, because the light from a moving object changes colour.

THE STAR'S VELOCITY TOWARDS THE EARTH (M/S)

Periodic movement. The star's velocity varies as it moves to and from the Earth when the planet orbits it.

©Johan Jarnestad/The Royal Swedish Academy of Sciences
Otto Struve

Proposition for a Project of High-Precision Stellar Radial Velocity Work

By Otto Struve

With the completion of the great radial-velocity programmes of the major observatories, the impression seems to have gained ground that the measurement of Doppler displacements in stellar spectra is less important at the present time than it was prior to the completion of R. E. Wilson's new radial-velocity catalogue.

I believe that this impression is incorrect, and I should like to support my contention by presenting a proposal for the solution of a characteristic astrophysical problem.

One of the burning questions of astronomy deals with the frequency of planet-like bodies in the galaxy which belong to stars other than the Sun. K. A. Strand's discovery of a planet-like companion in the system of 61 Cygni, which was recently confirmed by A. N. Deitch at Pulkovo, and similar results announced for other stars by F. Van de Kamp and D. Renyi and E. Holmberg have stimulated interest in this problem. I have suggested elsewhere that the absence of rapid axial rotation in all normal solar-type stars (the only rapidly-rotating G and K stars are either W Ursae Majoris binaries or T Tauri nebular variables, or they possess peculiar spectra) suggests that these stars have somehow converted their angular momentum of axial rotation into angular momentum of orbital motions of planets. Hence, there may be many objects of planet-like character in the galaxy.

But how should we proceed to detect them? The method of direct photography by Strand is, of course, excellent for nearby binary systems, but it is quite limited in scope. There seems to be at present no way to discover objects of the mass and size of Jupiter; nor is there much hope that we could discover objects ten times as large in mass as Jupiter, if they are at distances of one or more astronomical units from their parent stars.
A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz
Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.

Five more than ten years, several groups have been examining the radial velocities of dozens of stars, in an attempt to identify orbiting companions induced by the presence of planetary companions. The precision of spectrographs optimised for Doppler studies and currently in use is limited to about 3 m s⁻¹. As the reflex motion of the Sun due to Jupiter is 13 m s⁻¹, all current searches are limited to the detection of objects with at least the mass of Jupiter (Mj). So far, all precise Doppler surveys have failed to detect any jovian planets or brown dwarfs.

Since April 1994 we have monitored the radial velocity of 142 G and K dwarf stars with a precision of 1.3 m s⁻¹. The stars in our survey are selected for their apparent constant radial velocity (at lower precision) from a larger sample of stars monitored for 35 years. After 18 months of measurements, a small number of stars show significant velocity variations. Although most candidates require additional measurements, we report here the discovery of a companion with a minimum mass of 0.5 Mj, orbiting at 0.05 au around the solar-type star 51 Peg. Constraints originating from the observed rotational velocity of 71 Peg and from its low chromospheric emission give an upper limit of 2 Mj for the mass of the companion. Alternative explanations to the observed radial velocity variation (pulsation or spot rotation) are unlikely.

The very small distance between the companion and 51 Peg is certainly not predicted by current models of giant planet formation. As the temperature of the companion is above 1,300 K, this object seems to be dangerously close to the Jeans thermal evaporation limit. Moreover, non-thermal evaporation effects are known to be dominant over thermal ones. This jovian-mass companion may therefore be the result of the stripping of a very-low-mass brown dwarf.

The short-period orbital motion of 51 Peg also displays a long-period perturbation, which may be the signature of a second low-mass companion orbiting at larger distance.

Discovery of Jupiter-mass companion(s)

Our measurements are made with the new fibre-fed echelle spectrograph ELODE of the Haute-Provence Observatory, France. This instrument permits measurements of radial velocity with an accuracy of about 1.3 m s⁻¹ of stars up to 9 mag in exposure time of <30 min. The radial velocity is computed...
with a cross-correlation technique that concentrates the Doppler information of about 5,000 stellar absorption lines. The position of the cross-correlation function (Fig. 1) is used to compute the radial velocity. The width of the cross-correlation function is related to the star's rotational velocity. The very high radial-velocity accuracy achieved is a result of the scrambling effect of the fibres, as well as monitoring by a calibration lamp of instrumental variations during exposure.

The first observations of 51 Peg started in September 1994. In January 1995 a first 4.23-day orbit was computed and confirmed by intensive observations during eight consecutive nights in July and September 1995. Nevertheless, a 24 m s^{-1} scatter of the orbital solution was measured. As this is incompatible with the accuracy of ELODIE measurements, we adjusted an orbit to four sets of measurements carried out at four different epochs with only the γ-velocity as a free parameter (see Fig. 2).

The γ-velocity in Fig. 3 shows a significant variation that cannot be the result of instrumental drift in the spectrograph. This slow perturbation of the short-period orbit is probably the signature of a second low-mass companion.

The long-period orbit cannot have a large amplitude. The 26 radial velocity measurements made during >12 years with the CORAVEL spectrometer do not reveal any significant variation at a 200 m s^{-1} level. Intensive monitoring of 51 Peg is in progress to confirm this long-period orbit.

In Fig. 4 a short-period circular orbit is fitted to the data after correction of the variation in υ-velocity. Leaving the eccentricity as a free parameter would have given e = 0.09 ± 0.06 with almost the same standard deviation for the r.m.s residual (13 m s^{-1}). Therefore we consider that a circular orbit cannot be ruled out. At present the eccentricity range is between 0 and about 0.15. Table 1 lists the orbital parameters of the circular-orbit solution.

An orbital period of 4.23 days is rather short, but short-period binaries are not exceptional among solar-type stars. (Five spectroscopic binaries have been found with a period <4 days in a volume-limited sample of 164 G-type dwarfs in the solar vicinity.) Although this orbital period is not surprising in binary stars, it is puzzling when we consider the mass obtained for the companion:

\[ M_2 \sin i = 0.47 \pm 0.02 M_\odot \]

where \( i \) is the (unknown) inclination angle of the orbit.

51 Peg (HR8729, HD217014 or Gliese 882) is a 5.5 mag star, quite similar to the Sun (see Table 2), located 13.7 pc (45 light yr) away. Photometric and spectroscopic analyses indicate a star slightly older than the Sun, with a similar temperature and slight overabundance of heavy elements. The estimated age\(^{10}\) derived from its luminosity and effective temperature is typical of an old galactic-disk star. The slight overabundance of heavy elements in such an old disk star is noteworthy. But this is certainly not a remarkable peculiarity in view of the observed scatter of stellar metallicities at a given age.

### Upper limit for the companion mass

\textit{A priori}, we could imagine that we are confronted with a normal spectroscopic binary with an orbital plane almost perpendicular to the line of sight. Assuming a random distribution of binary orbital planes, the probability is less than 1% that the companion mass is larger than 4 \( M_\odot \), and 1/40,000 that it is above the hydrogen...
Extragalactic Exoplanets

• Andromeda galaxy planets
• A team of scientists has used gravitational microlensing to come up with a tentative detection of an extragalactic exoplanet in Andromeda, our nearest large galactic neighbor. The lensing pattern fits a star with a smaller companion, PA-99-N2, weighing just around 6.34 times the mass of Jupiter. This suspected planet is the first announced in the Andromeda Galaxy (Ingrosso et al. 2009, 2010).

In his fundamental “The Exoplanet Handbook” by M. Perryman the author quoted four of our papers from thousands papers of other authors.
A planetary system around the millisecond pulsar PSR1257+12

A. Woloszczak* & A. D. A. Frail†

*National Astronomy and Ionosphere Center, Arecibo Observatory, Arecibo, Puerto Rico 00612, USA
†National Radio Astronomy Observatory, Socorro, New Mexico 87801, USA

MILLISECOND RADIO pulsars, which are old (~10^6 yr), rapidly rotating neutron stars believed to be spun up by accretion of matter from their stellar companions, are usually found in binary systems with other degenerate stars. Using the 305-m Arecibo radiotelescope to make precise timing measurements of pulses from the recently discovered 6.2-ms pulsar PSR1257+12 (ref. 2), we demonstrate that, rather than being associated with a stellar object, the pulsar is orbited by two or more planet-sized bodies. The planets detected so far have masses of at least 2.8 M_J and 3.4 M_J, where M_J is the mass of the Earth. Their respective distances from the pulsar are 0.47 AU and 0.36 AU, and they move in almost circular orbits with periods of 98.2 and 66.6 days. Observations indicate that at least one more planet may be present in this system. The detection of a planetary system around a nearby (~500 pc), old neutron star, together with the recent report on a planetary companion to the pulsar PSR1829–10 (ref. 3) raises the tantalizing possibility that a non-negligible fraction of neutron stars observable as radio pulsars may be orbited by planet-sized bodies.

The 6.2-ms pulsar PSR1257+12 (Fig. 1) was discovered during the search at high galactic latitudes for millisecond pulsars conducted in February 1990 with the 305-m Arecibo radiotelescope at a frequency of 430 MHz (ref. 2). The characteristics of this survey and the details of data analysis are described elsewhere. The confirming observations made on 5 July 1990 have been followed by routine pulse-time-of-arrival (TOA) observations which have been accumulated so far, with the Arecibo radiotelescope, the 48-MHz, three-level correlation spectrometer and the Princeton Mark III pulsar processor at 430 MHz and 1.400 MHz. A typical uncertainty in the TOAs derived from 1-min pulse integrations is ~15 μs.

The standard analysis of the timing data has been carried out using the model fitting program TEMPO* and the Center for Astrophysics Solar System ephemeris EPSP40R. With a growing time span of the TOA measurements, it has gradually become clear that the TOAs showed an unusual variability superimposed on an annual sinusoidal pattern caused by a small (~1°) error in the assumed pulsar position. To separate these effects unambiguously, a timing-independent, interferometric position of PSR1257+12 was measured with the Very Large Array (VLA) in its A-array configuration on 19 July and again on 18 September 1991. The ~0° accuracy of the resulting pulsar position was achieved by referencing the fringe phase to a point-source calibrator 17° away.

A least-squares fit of a simple model, which involved the pulsar's rotational period, P, and its derivative, P; as free parameters and the fixed VLA position (Table 1), to the timing data spanning the period of 486 days resulted in post-fit residuals shown in Fig. 2a. The residuals, which measure the difference between the predicted and the actual TOAs, show a quasiperiodic 'wandering' over the entire pulsar period. A closer examination of this effect has revealed that it occurred by two strict periodicities of 66.6 days and 98.2 days in the pulsar arrival times. This further demonstrated in Fig. 2b, which shows post-fit residuals after fitting of each of the two periods separately to the above data, assuming simple keplerian binary models involving a low-mass binary companion to the pulsar. Evidently, fitting only for the assumed binary periodicity leaves the other one as a post-fit residual, implying that the pulse arrival times of PSR1257+12 are indeed affected by two independent periodicities. Further detailed analysis has shown that the periodicities are independent of radio frequency and that other millisecond pulsars routinely observed at Arecibo with the same data acquisition equipment show no such effect in their timing residuals.

Millisecond pulsars are extremely stable rotators. Systematic timing observations of objects like the 1.5-ms pulsar 1937+21 (ref. 6) have not revealed any timing noise, quasiperiodic TOA variations or 'glitches' at the level often found in the population of younger pulsars and believed to be related to neutron star seismology. The frequency independence of the amplitude of
In 2008 *Gazeta Prawna* disclosed that from 1973 until 1988 Wolszczan was an informant (codenamed "Lange") for the Polish communist-era Służba Bezpieczeństwa, which he confirmed, but stressed that he was passing only unimportant information, usually publicly known, and that he did not harm anybody. The resulting controversy in Polish media resulted in his resignation from Nicolaus Copernicus University in Toruń.
• "If we want great discoveries, we have to pay for it". MIT President Leo R. Reif on the LIGO's discovery of the century.

• V.E. Fortov: “Always our authorities want a miracle and they want to get it for free.”
• Conclusions

• VLBI systems in mm and sub-mm bands could detect mirages (“faces”) around black holes (for BH@ GC in particular) (see, EHT pictures for M87*)
• Shapes of images give an important information about BH parameters
• Trajectories of bright stars or bright spots around massive BHs are very important tool for an evaluation of BH parameters
• Trajectories of bright stars or bright spots around massive BHs can be used to obtain constraints on alternative theories of gravity (f(R) theory, for instance)
• A significant tidal charge of the BH at GC is excluded by observations, but there signatures of extreme RN charge (perhaps non-electric one)
• Constraints on Yukawa potential has been found
• Constraints of graviton mass have been obtained (they are consistent with LIGO ones)
• Perspectives to improve the current graviton mass estimates with future observations (VLT, Keck, GRAVITY, E-ELT, TMT) are discussed
• Constraints of tidal charge have been obtained
• The EHT team will release a new image of the SMBH@GC shortly. Stay tuned!
• Thanks for your kind attention!
•
In a letter from Newton to Halley, June 20, 1686
Newton complained that “he [Hooke] knew not how to go about it. Now is not this very fine? Mathematicians that find out, settle & and do all the business must content themselves with being nothing but dry calculators & drudges & and another that does nothing but pretend & grasp at all things must carry away all the invention as well as those who were to follow him as of those that went before him.”
Scalar field effects on the orbit of S2 star

The GRAVITY Collaboration: A. Amorim,5,4 M. Bauböck,5 M. Benisty,6 J.-P. Berger,6 Y. Clénet,7 V. Coudé du Forest,7 T. de Zeeuw,8,5 J. Dexter,5 G. Duvert,6 A. Eckart,9 F. Eisenhauer,5 M. C. Ferreira,10 F. Gao,5 Paulo J.V. Garcia,1,2,3+ E. Gendron,7 R. Genzel,5,10 S. Gillessen,5 P. Gordo,1,4 M. Habibi,5 M. Horrobin,9 A. Jimenez-Rosales,5 L. Jocou,6 P. Kervella,7 S. Lacour,7,5 J.-B. Le Bouquin, P. Léna,7 T. Ott,5 M. Pütschel,11 T. Paumard,7 K. Perraut,6 G. Perrin,10 O. Pfuhl,5 G. Rodríguez Coira,7 G. Rousset,7 O. Straub,5 C. Straubmeier,6 E. Sturm,5 F. Vincent,7 S. von Fellenberg,5 I. Waisberg9 and F. Widmann5

1CENTRA, Centro de Astrofísica e Gravitação, Instituto Superior Técnico, Avenida Rovisco Pais 1, 1049-001 Lisboa, Portugal
2European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany
3Max Planck Institut für Extraterrestrische Physik (MPE), Giessenbachstr. 1, 85748 Garching, Germany
4Univ. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France
5LESIA, Observatoire de Paris, Univ. Paris Cité, CNRS, Sorbonne Université, Université de Paris, 7 place Jules Janssen, 92195 Meudon, France
6SRON Research Center, Leiden University, P.O. Box 9504, 2300 RA Leiden, The Netherlands
7Physikalisches Institut, Universität zu Köln, Zülpicher Str. 77, 50937 Köln, Germany
8Department of Physics and Astronomy, Le Conte Hall, University of California, Berkeley, CA 94720, USA
9Max Planck Institute for Astronomy (MPIA) and Heidelberg University, Königstraße 17, D-69120 Heidelberg, Germany

ABSTRACT
Precise measurements of the S-stars orbiting SgrA* have set strong constraints on the nature of the compact object at the centre of the Milky Way. The presence of a black hole in that region is well established, but its neighborhood environment is still an open debate. In that respect, the existence of dark matter in that central region may be detectable due to its strong signatures on the orbits of stars: the main effect is a Newtonian precession which will affect the overall pericentre shift of S2, the latter being a target measurement of the GRAVITY instrument. The exact nature of this dark matter (e.g., stellar dark remnants or diffuse dark matter) is unknown. This article assumes it to be an scalar field of spheroidal distribution, associated with ultra-light dark matter particles, surrounding the Kerr black hole. Such a field is a form of 'hair' expected in the context of superradiance, a mechanism that extracts rotational energy from the black hole. Orbital signatures for the S2 star are computed and shown to be detectable by GRAVITY. The scalar field can be constrained because the variation of orbital elements depends both on the relative mass of the scalar field to the black hole and on the field mass coupling parameter.

Key words: black hole physics - celestial mechanics - dark matter - gravitation - Galaxy: centre - quasars: supermassive black holes

* Corresponding author, e-mail: mich@astrotecnico.ist.utl.pt
+ Corresponding author, e-mail: jpa@mpia.de
Table 2. Literature computing extensions/alternatives to GR effects in the orbits of the S-stars.

<table>
<thead>
<tr>
<th>extension/alternative</th>
<th>results/comments</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>charged rotating black holes and plasma effects</td>
<td>upper limits from black hole mass, spin and local magnetic field.</td>
<td>Rajadsek et al. (2018)</td>
</tr>
<tr>
<td>boson “star”</td>
<td>Effects much smaller than GH at S2 orbit, only relevant at a few tens of Schwarzschild radii.</td>
<td>Amaro-Seoane et al. (2010), Bekenstein &amp; Melia (2019), Gould et al. (2017a)</td>
</tr>
<tr>
<td>Einstein-Maxwell-Dilaton-Axion gravity</td>
<td>Effects smaller than (10^{-3}) of GR for S2, need pulsars or inner stars for further tests.</td>
<td>De Laurentis et al. (2018a), Kalita (2018)</td>
</tr>
<tr>
<td>Brans-Dicke theory</td>
<td>Effects smaller than (10^{-3}) of GR for S2, need pulsars or inner stars for further tests.</td>
<td>Capozziello et al. (2014), De Laurentis et al. (2018a), De Laurentis et al. (2018b), Kalita (2018)</td>
</tr>
<tr>
<td>(f(R)) gravity</td>
<td>Effects smaller than (10^{-5}) of GR for S2, need pulsars or inner stars for further tests.</td>
<td>Capozziello et al. (2014)</td>
</tr>
<tr>
<td>nonlocal gravity</td>
<td>Precision compatible with observational upper limit, of the order of GR prediction.</td>
<td>Dialatepopoulos et al. (2019)</td>
</tr>
<tr>
<td>scalar tensor gravity</td>
<td>Precession is (13\times) GR value, ruled out by Hes et al. (2017).</td>
<td>Borka Jovanović et al. (2019)</td>
</tr>
<tr>
<td>(f(R,\phi)) gravity</td>
<td>Best fit precession prediction for S2 is (20\times) GR value, ruled out by Hes et al. (2017).</td>
<td>Capozziello et al. (2014)</td>
</tr>
<tr>
<td>hybrid gravity</td>
<td>Best fit precession prediction too high, ruled out by Hes et al. (2017).</td>
<td>Borka et al. (2016)</td>
</tr>
<tr>
<td>(R^n) gravity</td>
<td>When compared with Hes et al. (2017) upper value, the GR value ((n = 1)) is recovered to (&lt;1%), or smaller if extended mass distributions are present.</td>
<td>Borka et al. (2012), Zakharov et al. (2014)</td>
</tr>
<tr>
<td>quadratic Einstein-Gauss-Bonnet gravity</td>
<td>Derive expressions for gravitational redshift in function of theory coupling parameters (scalar/matter &amp; scalar/Gauss-Bonnet invariant).</td>
<td>Hes et al. (2019)</td>
</tr>
<tr>
<td>dark matter profiles (See Table 1 for dark matter + black hole studies.)</td>
<td>Dark matter mass required to explain TeV emission compatible with orbital upper limits. Limits on spatial distribution of non-annihilating dark matter.</td>
<td>de Paolis et al. (2011), Hall &amp; Gondolo (2006), Iorio (2013), Lacock (2018), Zakharov et al. (2007)</td>
</tr>
<tr>
<td>scalar fields and ultralight dark matter</td>
<td>Upper limits on scalar field mass (19% of black hole) for particles of mass (4 \times 10^{-19} \text{eV}/c^2)</td>
<td>Bar et al. (2019)</td>
</tr>
</tbody>
</table>

We will follow the analytic results of Detweiler (1980) and then translate the scalar field solution in an effective gravitational potential which can then be treated with the usual perturbation analysis of Keplerian orbits. In this section we will be using Planck units \((\hbar = c = G = 1)\) unless otherwise stated.

A black hole-scalar field system, in which the scalar field is minimally coupled to gravity, is described by the following action

\[
S = \int d^4x \sqrt{-g} \left( \frac{R}{16\pi} - \frac{1}{2} \partial\phi \partial\phi - \frac{\mu^2}{2} \phi^2 \right)
\]  

(1)

in which \(R\) is the Ricci scalar, \(\phi\) and \(\mu\) is the metric and coupling constant, respectively; \(\mu^2\) is the mass of the scalar field. The principle of least action results in the Einstein-Klein-Gordon system of equations

\[
\nabla_a \nabla^a \phi = \frac{8\pi G\rho}{M_p^2} - \frac{\partial^2 \phi}{\partial x^2}
\]

(2)

where \(G_{ab}\) is the Einstein tensor, \(\nabla_a\) represents the covariant derivative and

\[

abla^a \nabla_a \phi = \frac{\partial^2 \phi}{\partial x^2} - \frac{1}{2} \partial^2 \phi + \frac{\partial^2 \phi}{\partial x^2} - \mu^2 \phi
\]

(3)

is the energy-momentum of the scalar field. In this system, the relevant quantity is the dimensionless mass coupling

\[
\nu = \frac{\mu}{M_p}
\]

(4)

which must be determined from observations and can be related to the so-called Hubble constant.
News from the Galactic Center (12.09.19)
In its first major result, just over a year after its inauguration, a super-sensitive South African telescope has discovered two giant 'radio bubbles' above and below the central region of the Milky Way. The features stretch over a total of 430 parsecs (1,400 light years), about 5% of the distance between the Solar System and the Galaxy's centre.

The bubbles are gas structures that can be observed because electrons stirring inside them produce radio waves as they are accelerated by magnetic fields. This activity suggests that the bubbles are the remnants of an energetic eruption of hot gas several millions years ago, say the authors of a paper describing the features, published in *Nature* on 11 September.

One possible explanation is that the super-massive black hole at the centre of the Galaxy underwent a period of intense matter-gobbling that created the outburst, say the researchers. Another could be a 'starburst' event — the near-simultaneous formation and subsequent fiery death of around 100 large stars. The shock waves of their explosions could have combined to blow a hole through the thick interstellar matter of the Galaxy's central region.

Oliver Pfuhl, an astronomer at the European Southern Observatory in Garching, Germany, says that both starburst and black-hole activity might have been at play, even reinforcing each other. And researchers know of a starburst that took place in the region around 7 million years ago. "It is intriguing to relate the radio bubble to this star formation event," he says.

Researchers working with South Africa's MeerKAT radio telescope — a precursor to what will be the world's largest radio telescope, the Square Kilometre Array (SKA) — discovered the bubbles when they created an image of the Galactic centre to celebrate the observatory's inauguration and test drive their brand-new facility beginning in April 2018, says radioastronomer Fernando Camilo, the observatory's chief scientist. Typically, it takes years for researchers to get a new observatory to work properly and to produce science with it. But with MeerKAT, they were stunned by how smoothly things went. "It kind of worked right out of the box," Camilo says.

The bubbles could also solve an old puzzle in radioastronomy. It's possible that the electrons accelerating inside them are the source of bright 'filaments' of matter tens of parsecs long that stretch out of the Galactic centre, first seen in 1984. Even larger bubbles, towering over those seen by MeerKAT's, have been seen in the γ-ray part of the spectrum, and could have a similar

[Link to article]
Inflation of 430–parsec bipolar radio bubbles in the Galactic Centre by an energetic event

I. Heywood1,2,4, F. Camilo1,4, W. D. Cotton1,4, F. Yusof-Zadeh1, T. D. Abbott1, R. M. Adam1, A. M. Alder1, K. F. Bauermeister1, R. S. Booth1, A. G. Botha1, D. H. Botha1, L. S. Bredesen1, Z. B. Brits1, S. J. Buchner1, J. P. Burger1, J. M. Chalmers1, T. Cheetham1, D. de Villiers1, M. A. Dikgale-Mahlakoana1, L. du Toit1, S. W. P. Esterhuysen1, R. F. Frens1, D. J. Fourie1, R. G. Garnatt1, S. Goedhart1, S. Gouws1, A. H. Hooymans1, D. H. Horn1, J. M. Horrell1, R. Hug1, A. R. Isaacs1, A. J. Jonas1, J. T. R. Jordaan1, J. A. Joubert1, G. L. Józsa1, R. P. M. Julie1, F. Kapp1, J. S. Kenyon1, P. F. A. Krozek1, H. Kriel1, T. W. Kuijzel1, R. Lehmenkühler1, D. Liebenberg1, A. Loots1, H. J. Lord1, R. M. Lumsden1, P. S. Macfarlane1, J. G. Magnus1, C. M. Maguire1, J. P. L. Main1, J. A. Malan1, R. D. Malgas1, J. R. Markey1, M. D. J. Marre1, B. M. Merry2, R. Millenaar1, N. Mynard1, I. P. T. Moen1, T. E. Monama1, M. C. Mphego1, W. S. New1, B. Ngobethabha1, N. Oozeer1, A. J. Otto1, S. S. Pausma1, A. A. Patel1, A. Peens-Hough1, S. J. Perkins1, S. M. Rautliff1, K. Renil1, A. Rust1, S. Siebrits1, S. K. Siothwa1, O. M. Smits1, L. Soley1, P. S. Swart1, C. Tasse1, D. T. Taylor1, I. P. Theroux1, K. Thorat1, A. J. Tjipiday1, S. Ishongweni1, T. J. van Bal1, A. van der By1, C. van der Merwe1, C. L. van Dyk1, R. Van Rooyen1, V. Van Tonder1, D. V. Wyke1, B. H. Wallace1, M. G. Welz1 & L. P. Williams1

The Galactic Centre contains a supermassive black hole with a mass of several million solar masses within an environment that differs markedly from that of the Galactic disk. Although the black hole is essentially quiescent in the broader context of active galactic nuclei, X-ray observations have provided evidence for energetic outbursts from its surroundings. Also, although the levels of star formation in the Galactic Centre have been approximately constant over the past few hundred million years, there is evidence of increased short-duration bursts2, strongly influenced by the interaction of the black hole with the enhanced gas density present within the ring-like central molecular zone at Galactic longitude $|b| < 0.7$ degrees and latitude $|b| < 0.2$ degrees. The inner 200–parsec region is characterized by large amounts of warm molecular gas1, a high cosmic-ray ionization rate, unusual gas chemistry, enhanced synchrotron emission3, and a multitude of radio–emitting magnetized filaments1, the origin of which has not been established. Here we report radio imaging that reveals a bipolar bubble structure, with an overall span of 1 degree by 3 degrees (140 parsec $\times$ 430 parsec), extending above and below the Galactic plane and apparently associated with the Galactic Centre. The structure is edge–brightened and bounded, with symmetry implying creation by an energetic event in the Galactic Centre. We estimate the age of the bubbles to be a few million years, with a total energy of $7 \times 10^{47}$ ergs. We postulate that the progenitor event was a major contributor to the increased cosmic–ray density in the Galactic Centre, and is in turn the principal source of the relativistic particles required to power the synchrotron emission of the radio filaments within and in the vicinity of the bubble cavities. We observed the Galactic Centre region with the MeerKAT radio telescope2, resulting in a deep mosaic spanning several square degrees, with a central frequency of 1.284 MHz and 6 arcsec angular resolution (see Methods). Many new radio structures are revealed, the most important of which is the pair of bounded, bipolar bubbles, spanning 430 pc across the Galactic plane, shown in Fig. 1. The radio emission is non–thermal, with spectral–index measurements consistent with synchrotron radiation, with a cooling time of 1–2 Myr (see Methods). The symmetry of the bubbles about the Galactic Centre implies that the progenitor event took place in the vicinity of the strong radio source Sgr A*.
bubble appears to almost precisely bound the ionized plasma revealed by enhanced X-ray emission (Fig. 2).

Observations of H I, C I, and N I absorption lines imply a high cosmic-ray energy density ($e_{CR}$) in the central molecular zone, approximately two orders of magnitude higher than in the Galactic disk. It is reasonable to assume that this has a latitudinal decline away from the plane, consistent with the thermal pressure decline seen in X-rays. For a cylindrical volume of $4 \times 10^{10}$ cm$^3$ and an average $e_{CR} = 10$ eV cm$^{-3}$ throughout the bubbles (see Methods), we derive a total cosmic-ray energy within the cavities of $7 \times 10^{43}$ erg. This is comparable to the thermal energy derived from X-ray measurements of $4 \times 10^{43}$ erg. These observations are consistent with modelling of X-ray and radio synchrotron emission towards the Galactic Centre, which indicates that similar cosmic-ray and gas pressures are required to drive flows along the in situ magnetic field lines. Assuming that 10% of the energy emerges in the form of cosmic rays, we derive a total energy budget for the progenitor event of $7 \times 10^{43}$ erg.

Whatever the mechanism by which the progenitor event occurred, the creation of a large population of relativistic cosmic-ray particles is powering the radio synchrotron emission of the bubbles. The same population could thus also be driving the emission from the magnetized radio filaments of which more than 100 have been identified in the Galactic Centre region, and nowhere else, since their discovery 35 years ago (Fig. 2). The filaments are linearly polarized and have synchrotron spectra, their highly linear morphology tracing locally or globally ordered magnetic fields with strengths of the order of 100 μG. To date there has been no conclusive explanation for their origin.

One of the key unknowns is the mechanism by which particles are injected and accelerated to relativistic speeds in order to generate the observed synchrotron emission around the magnetic fields. Comparing the distribution and brightness of the filaments to the boundary of the radio bubbles reveals a clear spatial association between the two.