Тень Галактического центра: теоретическая концепция -- предсказание -- реализация

Александр Ф. Захаров

ИТЭФ – НИЦ “КИ”

ЛТФ имени Н. Н. Боголюбова, ОИЯИ, Дубна

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Black Hole Shadows as New Tests of General Relativity

A. F. Zakharov[1,2*]

[1] *National Research Center "Kurchatov Institute", Moscow, Russia*
[2] *Bogoliubov Laboratory for Theoretical Physics, JINR, 141980 Dubna, Russia*

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Abstract—Despite the fact that several alternative theories of gravity have been proposed, (many of them have been suggested in the recent years) the general relativity (GR), created more than 100 years ago, is still the best theory of gravity. Due to the great technological progress of observational and experimental facilities currently there are opportunities to test gravity theories in a strong gravitational field limit. In 2005 we proposed to use a shadow near the black hole at the Galactic Center (GC) as a GR test. We predicted also that the shadow can be reconstructed from observations of bright structures near the black hole. Our prediction concerning the shadow near the black hole at the Galactic Center has been confirmed since in 2022 the Event Horizon Telescope (EHT) collaboration reconstructed the shadow from EHT observations done in April 2017.

Keywords: supermassive black holes, Galactic Center, M87, Synchrotron radiation, VLBI observations

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1. INTRODUCTION

As it is known general relativity (GR) equations were found by A. Einstein and D. Hilbert in November 1915 [1, 2][1]. Slightly earlier, also in November 1915 Einstein explained the perihelion anomaly for the Mercury orbit [6] (the problem was formulated by U.J.J. Le Verrier in the mid of the XIX century). In one of his GR paper D. Hilbert appreciated V. Fredericks (Fréedericksz)[2] for useful communications.

Scientific knowledge about the universe in which we live is extremely important (at least within the framework of simplified models). The construction of realistic mathematical models of the structure of the Universe turned out to be possible only after A. Einstein created the general theory of relativity and built the first (static) model of the Universe [10]. Friedmann's cosmological solutions, which he found in 1922 and 1924, were of great importance [11, 12] and these results are among the most outstanding theoretical discoveries in physics [13, 14].

2. SOVIET INVESTIGATIONS IN GRAVITATION AND COSMOLOGY

As is known, the first cosmological model of the universe was proposed in the Einstein model, but the first evolving cosmological model was proposed by the Soviet mathematician and meteorologist A.A. Friedmann [11, 12]. Soon after that G. Lemaitre[3] showed that signs of an expanding

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[*] E-mail: `alex.fed.zakharov@gmail.com`

[1] An intensive correspondence between these two great scientists led to this wonderful discovery as it was discussed in [3–5].

[2] Friedmann's interest in GR and cosmological problems related to this theory was initiated by V.K. Fredericks, who worked as an assistant to D. Hilbert in Göttingen during the First World War and, came back to Russia in 1918. Fredericks was one of the from the pioneers of relativistic research in Soviet Russia [7, 8]. Practically, Fredericks and Friedmann established an outstanding relativity school in Petrograd (Leningrad) and V.A. Fock, G.A. Gamov, D.D. Ivanenko, A.D. Alexandrov belonged to this school. Frederics significantly contributed in liquid crystal physics and in particular, Frederics and his co-authors discovered a phenomenon which is called now Freedericksz (Fredericks) transitions [9].

[3] At the beginning of XX century Lemaitre spent some time in the USA and knew Slipher's results on positive redshifts for distant galaxies [15] and perhaps this knowledge helped Lemaitre to derive the cosmological expansion law which is called now the Hubble law. As a recognition of the Lemaitre contribution at the Thirtieth General Assembly of the International Astronomical Union (Vienna, 2018 August 20–31) astronomers suggested to rename the Hubble law as the Hubble–Lemaitre law and it was accepted that "from now on the expansion of the universe be referred to as the Hubble–Lemaitre law" [16].

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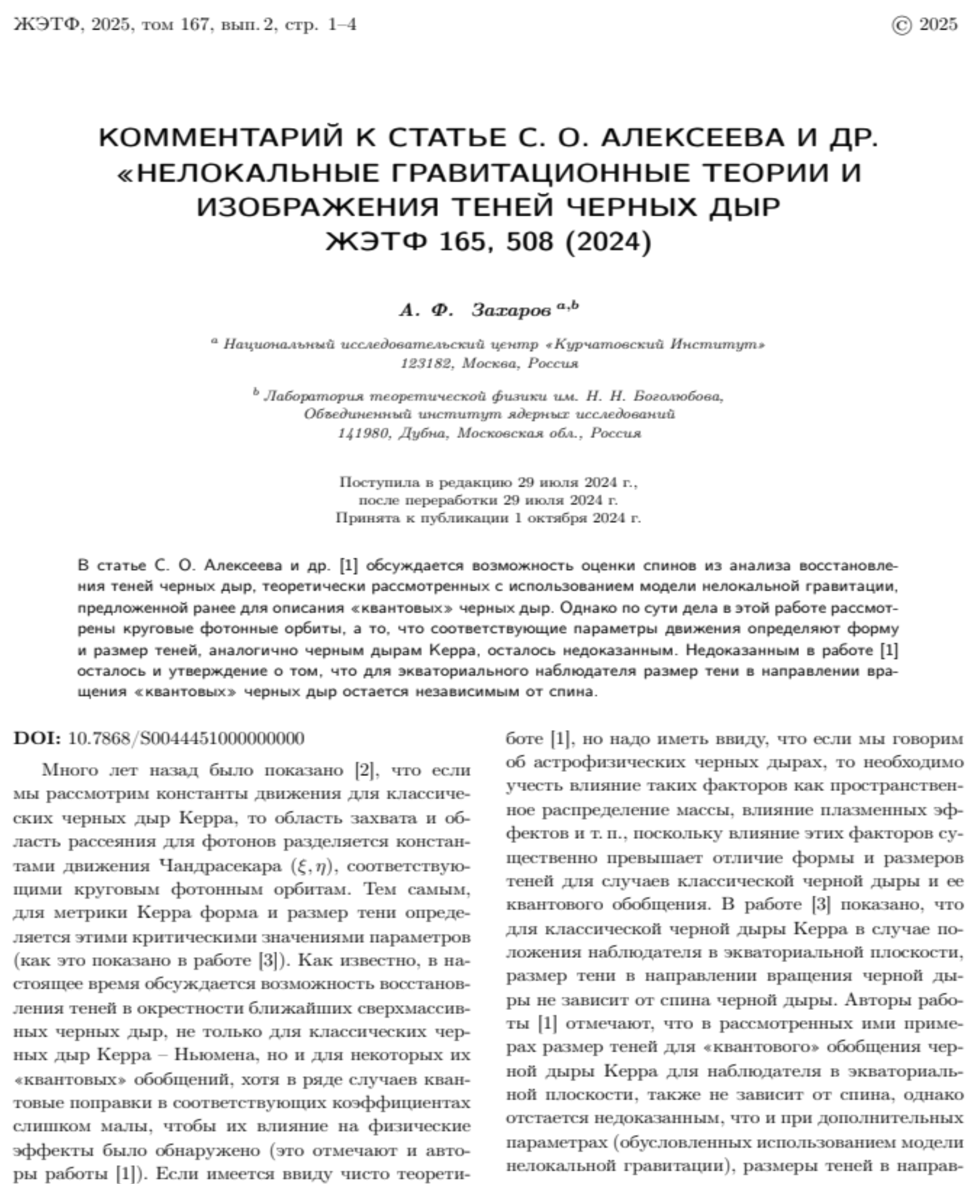

ЖЭТФ, 2025, том 167, вып. 2, стр. 1–4

КОММЕНТАРИЙ К СТАТЬЕ С. О. АЛЕКСЕЕВА И ДР. «НЕЛОКАЛЬНЫЕ ГРАВИТАЦИОННЫЕ ТЕОРИИ И ИЗОБРАЖЕНИЯ ТЕНЕЙ ЧЕРНЫХ ДЫР ЖЭТФ 165, 508 (2024)

А. Ф. Захаров [a,b]

[a] *Национальный исследовательский центр «Курчатовский Институт»*
123182, Москва, Россия

[b] *Лаборатория теоретической физики им. Н. Н. Боголюбова,*
Объединенный институт ядерных исследований
141980, Дубна, Московская обл., Россия

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В статье С. О. Алексеева и др. [1] обсуждается возможность оценки спинов из анализа восстановления теней черных дыр, теоретически рассмотренных с использованием модели нелокальной гравитации, предложенной ранее для описания «квантовых» черных дыр. Однако по сути дела в этой работе рассмотрены круговые фотонные орбиты, а то, что соответствующие параметры движения определяют форму и размер теней, аналогично черным дырам Керра, осталось недоказанным. Недоказанным в работе [1] осталось и утверждение о том, что для экваториального наблюдателя размер тени в направлении вращения «квантовых» черных дыр остается независимым от спина.

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Много лет назад было показано [2], что если мы рассмотрим константы движения для классических черных дыр Керра, то область захвата и область рассеяния для фотонов разделяется константами движения Чандрасекара (ξ, η), соответствующими круговым фотонным орбитам. Тем самым, для метрики Керра форма и размер тени определяется этими критическими значениями параметров (как это показано в работе [3]). Как известно, в настоящее время обсуждается возможность восстановления теней в окрестности ближайших сверхмассивных черных дыр, не только для классических черных дыр Керра – Ньюмена, но и для некоторых их «квантовых» обобщений, хотя в ряде случаев квантовые поправки в соответствующих коэффициентах слишком малы, чтобы их влияние на физические эффекты было обнаружено (это отмечают и авторы работы [1]). Если имеется ввиду чисто теорети-

боте [1], но надо иметь ввиду, что если мы говорим об астрофизических черных дырах, то необходимо учесть влияние таких факторов как пространственное распределение массы, влияние плазменных эффектов и т. п., поскольку влияние этих факторов существенно превышает отличие формы и размеров теней для случаев классической черной дыры и ее квантового обобщения. В работе [3] показано, что для классической черной дыры Керра в случае положения наблюдателя в экваториальной плоскости, размер тени в направлении вращения черной дыры не зависит от спина черной дыры. Авторы работы [1] отмечают, что в рассмотренных ими примерах размер теней для «квантового» обобщения черной дыры Керра для наблюдателя в экваториальной плоскости, также не зависит от спина, однако отстается недоказанным, что и при дополнительных параметрах (обусловленных использованием модели нелокальной гравитации), размеры теней в направ-

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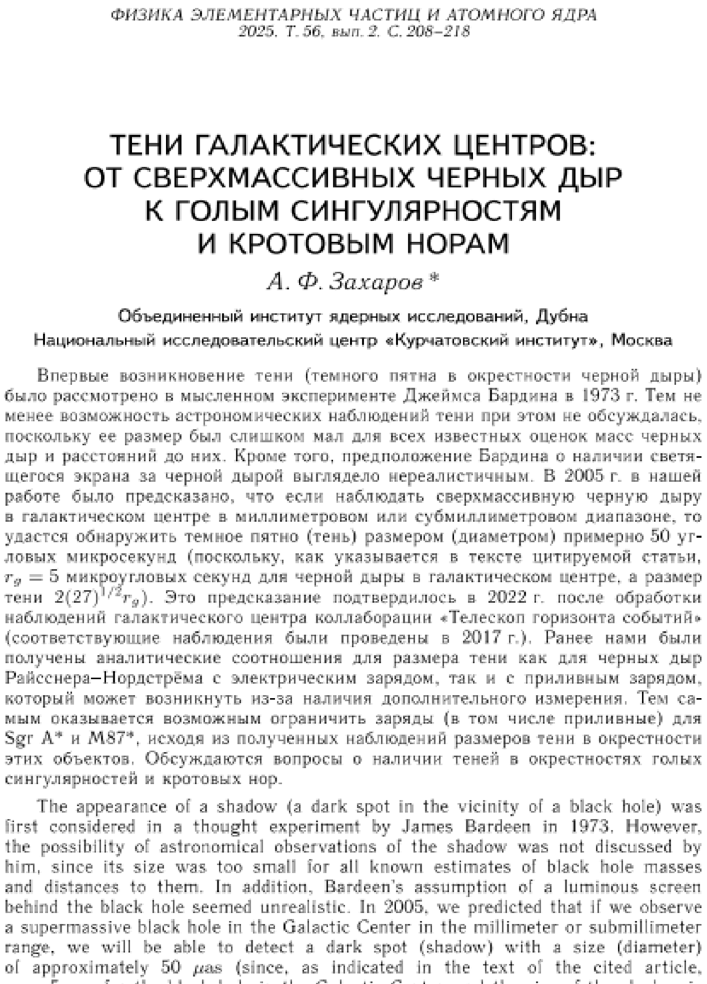

ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
2025. Т. 56, вып. 2. С. 208–218

ТЕНИ ГАЛАКТИЧЕСКИХ ЦЕНТРОВ: ОТ СВЕРХМАССИВНЫХ ЧЕРНЫХ ДЫР К ГОЛЫМ СИНГУЛЯРНОСТЯМ И КРОТОВЫМ НОРАМ

А. Ф. Захаров *

Объединенный институт ядерных исследований, Дубна
Национальный исследовательский центр «Курчатовский институт», Москва

Впервые возникновение тени (темного пятна в окрестности черной дыры) было рассмотрено в мысленном эксперименте Джеймса Бардина в 1973 г. Тем не менее возможность астрономических наблюдений тени при этом не обсуждалась, поскольку ее размер был слишком мал для всех известных оценок масс черных дыр и расстояний до них. Кроме того, предположение Бардина о наличии светящегося экрана за черной дырой выглядело нереалистичным. В 2005 г. в нашей работе было предсказано, что если наблюдать сверхмассивную черную дыру в галактическом центре в миллиметровом или субмиллиметровом диапазоне, то удастся обнаружить темное пятно (тень) размером (диаметром) примерно 50 угловых микросекунд (поскольку, как указывается в тексте цитируемой статьи, $r_g = 5$ микроугловых секунд для черной дыры в галактическом центре, а размер тени $2(27)^{1/2} r_g$). Это предсказание подтвердилось в 2022 г. после обработки наблюдений галактического центра коллаборации «Телескоп горизонта событий» (соответствующие наблюдения были проведены в 2017 г.). Ранее нами были получены аналитические соотношения для размера тени как для черных дыр Райсснера–Нордстрёма с электрическим зарядом, так и с приливным зарядом, который может возникнуть из-за наличия дополнительного измерения. Тем самым оказывается возможным ограничить заряды (в том числе приливные) для Sgr A* и *M*87*, исходя из полученных наблюдений размеров тени в окрестности этих объектов. Обсуждаются вопросы о наличии теней в окрестностях голых сингулярностей и кротовых нор.

The appearance of a shadow (a dark spot in the vicinity of a black hole) was first considered in a thought experiment by James Bardeen in 1973. However, the possibility of astronomical observations of the shadow was not discussed by him, since its size was too small for all known estimates of black hole masses and distances to them. In addition, Bardeen's assumption of a luminous screen behind the black hole seemed unrealistic. In 2005, we predicted that if we observe a supermassive black hole in the Galactic Center in the millimeter or submillimeter range, we will be able to detect a dark spot (shadow) with a size (diameter) of approximately 50 μas (since, as indicated in the text of the cited article,

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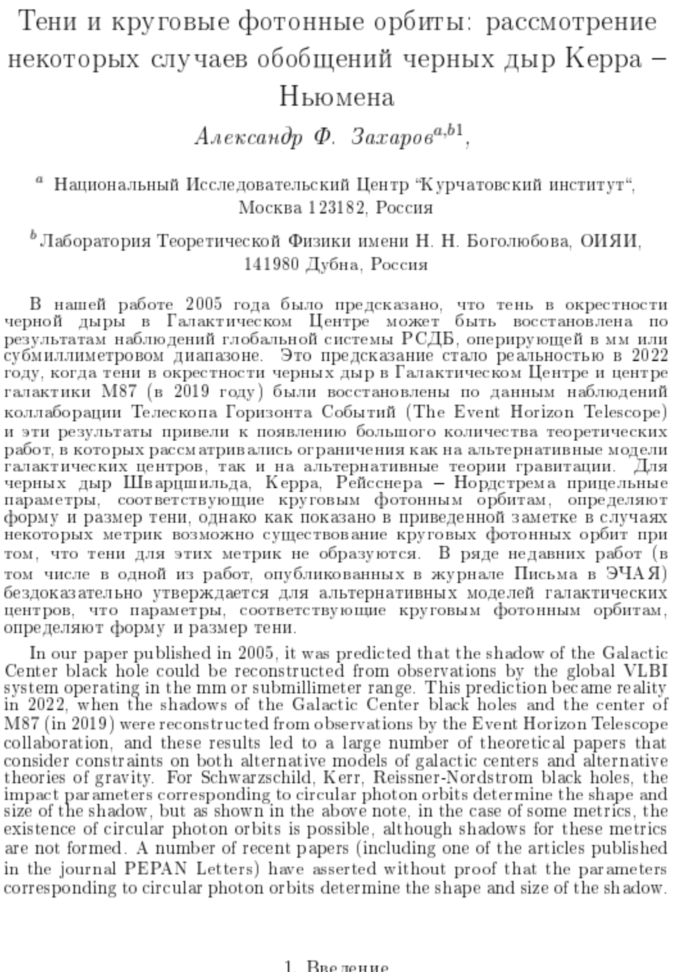


Тени и круговые фотонные орбиты: рассмотрение некоторых случаев обобщений черных дыр Керра – Ньюмена

Александр Ф. Захаров[a,b1],

[a] Национальный Исследовательский Центр "Курчатовский институт",
Москва 123182, Россия

[b] Лаборатория Теоретической Физики имени Н. Н. Боголюбова, ОИЯИ,
141980 Дубна, Россия

В нашей работе 2005 года было предсказано, что тень в окрестности черной дыры в Галактическом Центре может быть восстановлена по результатам наблюдений глобальной системы РСДБ, оперирующей в мм или субмиллиметровом диапазоне. Это предсказание стало реальностью в 2022 году, когда тени в окрестности черных дыр в Галактическом Центре и центре галактики M87 (в 2019 году) были восстановлены по данным наблюдений коллаборации Телескопа Горизонта Событий (The Event Horizon Telescope) и эти результаты привели к появлению большого количества теоретических работ, в которых рассматривались ограничения как на альтернативные модели галактических центров, так и на альтернативные теории гравитации. Для черных дыр Шварцшильда, Керра, Рейсснера – Нордстрема прицельные параметры, соответствующие круговым фотонным орбитам, определяют форму и размер тени, однако как показано в приведенной заметке в случаях некоторых метрик возможно существование круговых фотонных орбит при том, что тени для этих метрик не образуются. В ряде недавних работ (в том числе в одной из работ, опубликованных в журнале Письма в ЭЧАЯ) бездоказательно утверждается для альтернативных моделей галактических центров, что параметры, соответствующие круговым фотонным орбитам, определяют форму и размер тени.

In our paper published in 2005, it was predicted that the shadow of the Galactic Center black hole could be reconstructed from observations by the global VLBI system operating in the mm or submillimeter range. This prediction became reality in 2022, when the shadows of the Galactic Center black holes and the center of M87 (in 2019) were reconstructed from observations by the Event Horizon Telescope collaboration, and these results led to a large number of theoretical papers that consider constraints on both alternative models of galactic centers and alternative theories of gravity. For Schwarzschild, Kerr, Reissner-Nordstrom black holes, the impact parameters corresponding to circular photon orbits determine the shape and size of the shadow, but as shown in the above note, in the case of some metrics, the existence of circular photon orbits is possible, although shadows for these metrics are not formed. A number of recent papers (including one of the articles published in the journal PEPAN Letters) have asserted without proof that the parameters corresponding to circular photon orbits determine the shape and size of the shadow.

1. Введение

Our recent publications on the subject

AFZ, Phys. Part. Nucl. Lett. (2023)

AFZ, Universe (2022)

AFZ, Astron. Astrophys. Trans. (2022)

P. Jovanovic, D. Borka, V. Borka Jovanovic, AFZ, JCAP (2023)

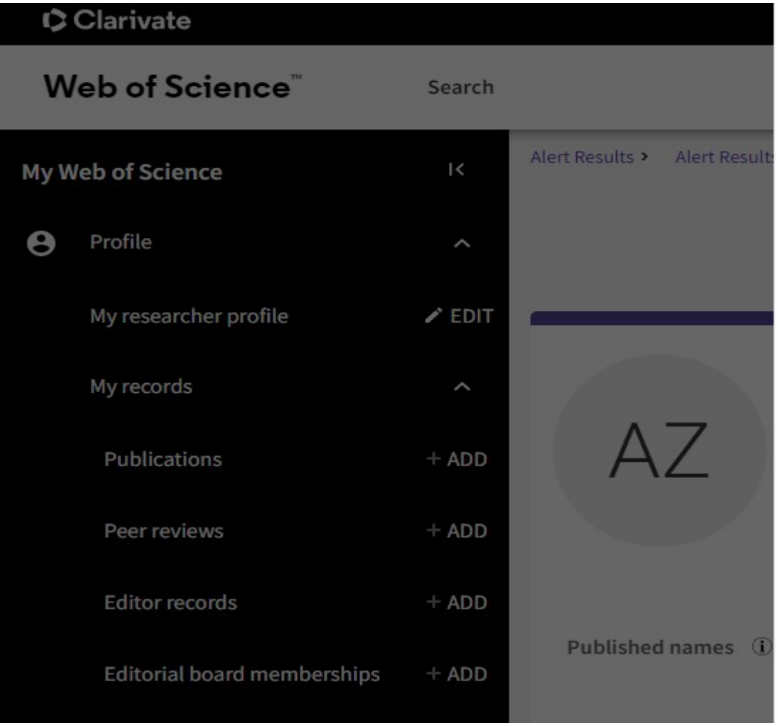
AFZ, Phys. Part. Nucl. (2023)

AFZ, IJMPD (2023)

AFZ, arxiv:2305.15446

P. Jovanovic, D. Borka, V. Borka Jovanovic, AFZ, PRD (2024)

P. Jovanovic, D. Borka, V. Borka Jovanovic, AFZ, Symmetry (2024)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М. И. Монастырский (2009) “...К слову сказать, у нас (в России) очень любят причитать по поводу недооценки русских учёных на Западе. Но тщательный анализ реальных фактов показывает, что больше всего признанию русских (советских) учёных мешают другие русские (советские) учёные...”

From Paradise Lost by A. A. Migdal

“...Some of us turned out to be more equal than others, and our Western friends, regardless how hard they tried to help us in isolation, could do nothing with the laws of a free market – if you are not present to explain and defend your ideas they will get stolen or simply ignored and reinvented...”

About citations

L. B. Okun said to young colleagues: “You have to prove that your studies are known in the world. Let me know a number of citations at your papers”.

A few year ago at ITEP seminar, a ITEP researcher informed people that a Nobel prize winner quoted his paper (and it was like a small sensation that Nobel prize winners knew papers from researchers of our Institute), and I decided to take a look how many Nobel prize winners quoted our paper and recognized that V. L. Ginzburg, S. Weinberg, G. Smoot, A. Ghez and her co-authors, R. Genzel and his co-authors. In particular, V. L. Ginzburg quoted my book and our paper on gravitational microlensing in his last reviews on the most interesting problems of physics and astrophysics.

I counted 23 citations on our papers from A. Ghez and R. Genzel groups in their papers on trajectories of bright stars near the GC.

Astron Astrophys Rev (2024)32:3
https://doi.org/10.1007/s00159-024-00154-z

REVIEW ARTICLE

Experimental studies of black holes: status and future prospects

Reinhard Genzel[1,2,3] · **Frank Eisenhauer**[1,4] · **Stefan Gillessen**[1]

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Abstract

More than a century ago, Albert Einstein presented his general theory of gravitation (GR) to the Prussian Academy of Sciences. One of the predictions of the theory is that not only particles and objects with mass, but also the quanta of light, photons, are tied to the curvature of space-time, and thus to gravity. There must be a critical compactness, above which photons cannot escape. These are black holes (henceforth BH). It took 50 years after the theory was announced before possible candidate objects were identified by observational astronomy. And another 50 years have passed, until we finally have in hand detailed and credible experimental evidence that BHs of 10 to 10^{10} times the mass of the Sun exist in the Universe. Three very different experimental techniques, but all based on Michelson interferometry or Fourier-inversion spatial interferometry have enabled the critical experimental breakthroughs. It has now become possible to investigate the space-time structure in the vicinity of the event horizons of BHs. We briefly summarize these interferometric techniques, and discuss the spectacular recent improvements achieved with all three techniques. Finally, we sketch where the path of exploration and inquiry may go on in the next decades.

Keywords Black holes · Galactic center · Interferometry · GRAVITY

Contents

Extended author information available on the last page of the article

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A&A, 692, A242 (2024)
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Astronomy & Astrophysics

Improving constraints on the extended mass distribution in the Galactic center with stellar orbits

GRAVITY Collaboration[*]: K. Abd El Dayem[1], R. Abuter[4], N. Aimar[1,7], P. Amaro Seoane[14,2,20,15], A. Amorim[8,7], J. Beck[2], J. P. Berger[3,4], H. Bonnet[4], G. Bourdarot[2], W. Brandner[5], V. Cardoso[7,17], R. Capuzzo Dolcetta[21], Y. Clénet[1], R. Davies[2], P. T. de Zeeuw, A. Drescher[2], A. Eckart[6,13], F. Eisenhauer[2,19], H. Feuchtgruber[2], G. Finger[2], N. M. Förster Schreiber[2], A. Foschi[1], F. Gao[13], P. Garcia[10,7], E. Gendron[1], R. Genzel[2,11], S. Gillessen[2], M. Hartl[2], X. Haubois[9], F. Haussmann[2], G. Heißel[16,1], T. Henning[5], S. Hippler[5], M. Horrobin[6], L. Jochum[9], L. Jocou[3], A. Kaufer[9], P. Kervella[1], S. Lacour[1,4], V. Lapeyrère[1], J.-B. Le Bouquin[3], P. Léna[1], D. Lutz[2], F. Mang[2], N. More[2], T. Ott[2], T. Paumard[1], K. Perraut[3], G. Perrin[1], O. Pfuhl[4,2], S. Rabien[2], D. C. Ribeiro[2], M. Sadun Bordoni[2,**], S. Scheithauer[5], J. Shangguan[2], T. Shimizu[2], J. Stadler[12,2], O. Straub[2,18], C. Straubmeier[6], E. Sturm[2], L. J. Tacconi[2], I. Urso[1], F. Vincent[1], S. D. von Fellenberg[13,2], F. Widmann[2], E. Wieprecht[2], J. Woillez[4], and F. Zhang[22,23,24]

(Affiliations can be found after the references)

Received 17 September 2024 / Accepted 12 November 2024

ABSTRACT

Studying the orbital motion of stars around Sagittarius A* in the Galactic center provides a unique opportunity to probe the gravitational potential near the supermassive black hole at the heart of our Galaxy. Interferometric data obtained with the GRAVITY instrument at the Very Large Telescope Interferometer (VLTI) since 2016 has allowed us to achieve unprecedented precision in tracking the orbits of these stars. GRAVITY data have been key to detecting the in-plane, prograde Schwarzschild precession of the orbit of the star S2 that is predicted by general relativity. By combining astrometric and spectroscopic data from multiple stars, including S2, S29, S38, and S55 – for which we have data around their time of pericenter passage with GRAVITY – we can now strengthen the significance of this detection to an approximately 10σ confidence level. The prograde precession of S2's orbit provides valuable insights into the potential presence of an extended mass distribution surrounding Sagittarius A*, which could consist of a dynamically relaxed stellar cusp comprising old stars and stellar remnants, along with a possible dark matter spike. Our analysis, based on two plausible density profiles – a power-law and a Plummer profile – constrains the enclosed mass within the orbit of S2 to be consistent with zero, establishing an upper limit of approximately $1200\,M_\odot$ with a 1σ confidence level. This significantly improves our constraints on the mass distribution in the Galactic center. Our upper limit is very close to the expected value from numerical simulations for a stellar cusp in the Galactic center, leaving little room for a significant enhancement of dark matter density near Sagittarius A*.

Key words. black hole physics – gravitation – instrumentation: interferometers – Galaxy: center

1. Introduction

Since 2016, the GRAVITY interferometer at ESO's Very Large Telescope (GRAVITY Collaboration 2017) has allowed us to obtain astrometric data with unprecedented accuracy (reaching in the best cases a 1σ uncertainty of 30 µas) of the S-stars orbiting around Sagittarius A* (Sgr A*) in the Galactic center (GC). This has turned them into a powerful tool to investigate the gravitational potential near the supermassive black hole (SMBH) at the center of our Galaxy, reaching distances from Sgr A* down to about a thousand times its Schwarzschild radius (R_S). Furthermore, astrometric and polarimetric observations of flares from Sgr A* with GRAVITY have revealed that the mass inside the flares' radius of a few R_S is consistent with the black hole mass measured from stellar orbits (GRAVITY Collaboration 2018b, 2023a). This, together with the radio-VLBI image of Sgr A* (Event Horizon Telescope Collaboration 2022), confirms that Sgr A* is a SMBH beyond any reasonable doubt.

For the S2 star, due to its short orbital period of 16 years and its brightness ($m_K \approx 14$), astrometric data are available for two complete orbital revolutions around Sgr A*, while spectroscopic data cover one and a half revolutions (Schödel et al. 2002; Ghez et al. 2003, 2008; Gillessen et al. 2017). At the pericenter, S2 reaches a distance of $\sim 1400\,R_S$ from the SMBH with a speed of $7700\,\mathrm{km\,s^{-1}} \simeq 0.026\,c$. Monitoring the star's motion on the sky and radial velocity with GRAVITY and SINFONI around the time of the pericenter passage in 2018, crucial data were obtained in order to detect the first-order effects in the post-Newtonian (PN) expansion of general relativity (GR) on its orbital motion. The first one is the gravitational redshift of spectral lines, which was detected together with the transverse Doppler effect, predicted by special relativity, with a $\approx 10\sigma$ significance in GRAVITY Collaboration (2018a) and a $\approx 5\sigma$ significance in Do et al. (2019). GRAVITY Collaboration (2019) improved the significance of the detection to $\approx 20\sigma$. The other effect is the prograde, in-plane precession of the orbit's pericenter angle; namely, the Schwarzschild precession (SP). It

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[*] GRAVITY is developed in collaboration by MPE, LESIA of Paris Observatory/CNRS/Sorbonne Université/Univ. Paris Diderot, and IPAG of Université Grenoble Alpes/CNRS, MPIA, Univ. of Cologne, CENTRA – Centro de Astrofisica e Gravitação, and ESO.

[**] Corresponding author; `mbordoni@mpe.mpg.de`

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corresponds to an advance of $\delta\varphi_{Schw} = \frac{3\pi R_S}{a(1-e^2)}$ per orbit, which for S2 is equal to 12.1 arcmin per orbit in the prograde direction. In GRAVITY Collaboration (2020), this effect was detected at the 5σ level, and improved in GRAVITY Collaboration (2022) to $\approx 7\sigma$ by combining the data of S2 with data of the stars S29, S38, and S55, which could be observed with GRAVITY around the time of their pericenter passage and whose pericenter distances are comparable to that of S2.

The Lense-Thirring effect, caused by the spin of the central SMBH, appears at a 1.5PN order and gives both an additional contribution to the in-plane precession and a precession of the orbital plane (Merritt et al. 2010). We define $A_{LT} = 4\pi\chi \left(\frac{R_S}{2a(1-e^2)}\right)^{3/2}$, which for S2 is equal to 0.11 arcminutes. Consequently, the in-plane precession per orbit becomes $\delta\varphi_{Kerr} = \delta\varphi_{Schw} - 2A_{LT}\cos(i)$, while the precession per orbit of the orbital plane is given by $\delta\Phi_{Kerr} = A_{LT}$, where χ is the dimensionless spin of the SMBH (with $0 \leq \chi \leq 1$) and i is the angle between the direction of the SMBH spin and that of the stellar orbital angular momentum. The effect is thus at least 50 times smaller than the SP, assuming a SMBH with maximum spin, and is out of reach for current measurements. In order to measure the spin of Sgr A*, we would need to observe a star with a pericenter distance that is at least three times smaller than that of S2, given the astrometric accuracy achievable with GRAVITY (Waisberg et al. 2018; Capuzzo-Dolcetta & Sadun-Bordoni 2023).

Any extended mass distribution around Sgr A*, following a spherically symmetric density profile, would add a retrograde precession of the stellar orbits, counteracting the prograde SP (GRAVITY Collaboration 2020, 2022). This mass distribution is expected to be composed mainly of a dynamically relaxed cusp of old stars and stellar remnants. Peebles (1972); Frank & Rees (1976); Bahcall & Wolf (1976) first addressed the problem of the distribution of stars around a central massive BH. Bahcall & Wolf (1976) found that a single-mass stellar population around a central massive BH reaches a stationary density distribution over the two-body relaxation timescale, which is a power law, $\rho(r) \propto r^s$, with slope $s = -1.75$. In the GC, the old stellar population can be approximately represented by light stars with masses around $1\,M_\odot$ and heavier stellar black holes with masses around $10\,M_\odot$ (Alexander 2017). For such a population, mass segregation occurs, where heavier objects tend to concentrate toward the center due to dynamical interactions with lighter objects. The mass-segregation solution for the steady-state distribution of stars around a massive BH is derived in Alexander & Hopman (2009). It has two branches, weak and strong segregation, based on the dominance of heavier or lighter objects in the scattering interactions. In the weak segregation branch, the heavy objects settle into a power-law distribution with a slope of -1.75, while the lighter objects exhibit a shallower profile with a slope of -1.5, as was already heuristically derived in Bahcall & Wolf (1977). Conversely, the strong segregation branch results in steeper slopes and a larger difference between the light and heavy masses. The heavy masses settle into a much steeper cusp with $-2.75 \lesssim s \lesssim -2$, while the light masses settle into a cusp with $-1.75 \lesssim s \lesssim -1.5$. Preto & Amaro-Seoane (2010) provided a clear realization through N-body simulations of the strong mass segregation solution, showing also that the stellar cusp can develop on timescales that are much shorter than the relaxation time, which is shorter than the Hubble time for the GC (Alexander & Hopman 2009; Genzel et al. 2010). In Linial & Sari (2022), it is argued that weak segregation must exist interior to a certain break radius, r_B, where the massive population dominates the scattering, while for radii larger than r_B the light objects dominate the scattering and strong segregation occurs.

The existence of such a stellar cusp in the GC is also validated by the observational results of Gallego-Cano et al. (2018) and Schödel et al. (2018) for the distribution of giant, subgiant, and main-sequence stars within the central few parsecs. They find that the density distribution of the light objects is shallower than $s = -1.5$, being compatible with a power-law with slope between -1.4 and -1.15. This is impossible in the steady state, Bahcall & Wolf framework in order to maintain an equilibrium distribution, but could be explained by a number of factors, such as stellar collisions (Rose & MacLeod 2024), taking into account the complex star formation history of the nuclear star cluster (Baumgardt et al. 2018), or by diffusion in angular momentum leading to tidal disruptions; namely, diffusion into the loss cone (Zhang & Amaro-Seoane 2024). Red giant stars, instead, do not show a cusp but a distribution that appears to flatten toward the central ~0.3 pc (Buchholz et al. 2009; Do et al. 2009; Bartko et al. 2010; Gallego-Cano et al. 2018), possibly due to the stripping of red giant envelopes due to the interaction with a star-forming disk (Amaro-Seoane & Chen 2014).

In addition to the stellar cusp, an intermediate-mass black hole (IMBH) companion of Sgr A* could be present in the GC. It has been shown that an IMBH enclosed within the orbit of S2 can only have a mass of $<10^3\,M_\odot$ (GRAVITY Collaboration 2023b; Will et al. 2023). Moreover, it was predicted by Gondolo & Silk (1999) that dark matter particles could be accreted by the SMBH to form a dense spike, increasing the dark matter density in the GC by up to ten orders of magnitude with respect to the expected density in the case of a Navarro–Frenk–White (NFW) profile. In this scenario, the spike could contribute to the extended mass distribution around Sgr A*, while in the absence of such a spike, the contribution of dark matter within the radial range of the S-stars' orbits would be negligible under an NFW profile. The dark matter spike would also follow a power-law distribution, $\rho(r) \propto r^s$, with slope $-2.5 < s < -2.25$ in the case of a generalized NFW profile (Gondolo & Silk 1999; Shen et al. 2024). Another possibility that has been investigated is that dark matter could exist in the form of an ultralight scalar field or a massive vector field cloud that clusters around Sgr A* (Foschi et al. 2023; GRAVITY Collaboration 2024), or as a compact fermion ball supported by degeneracy pressure (Viollier et al. 1993; Argüelles et al. 2019; Becerra-Vergara et al. 2020).

Additionally, a deviation from general relativity, such as the one introduced by massive gravity theories or $f(R)$-gravity, could modify the gravitational potential through a Yukawa-like correction in the Newtonian limit, adding an additional precession of the stellar orbits to the prograde SP and the retrograde precession induced by an extended mass distribution (Hees et al. 2017; De Martino et al. 2021; Tan & Lu 2024; Jovanović et al. 2024a,b). For the specific case of massive gravity, the additional precession would be prograde and equal to $\delta\varphi_Y = \pi\sqrt{1-e^2}\frac{a^2}{\lambda^2}$ (Jovanović et al. 2024a), where $\lambda = \frac{\hbar}{m_g c}$ is the Compton wavelength of the massive graviton, m_g the mass of the graviton, and $\hbar$ the reduced Planck constant. From the observed precession of the S2 star, it is thus possible to derive a lower limit on λ and an upper limit on m_g, as is done in Hees et al. (2017); Jovanović et al. (2024a,b).

In GRAVITY Collaboration (2022), the 1σ upper limit on any extended mass distributed within the orbit of S2 is found to be $\approx 3000\,M_\odot$, assuming a Plummer density profile (Plummer 1911). In this paper, we use S-star data, including one more year orbit is consistently compatible with zero. We set a strong upper limit of approximately 1200 $M_\odot$ with a 1σ confidence level, significantly improving upon the limits established in GRAVITY Collaboration (2022). Our findings align with theoretical predictions for a dynamically relaxed stellar cusp in the GC, composed of stars, brown dwarfs, white dwarfs, neutron stars, and stellar black holes, according to numerical simulations using an updated version of the code developed in Zhang & Amaro-Seoane (2024). This analysis predicts an enclosed mass of approximately 1210 $M_\odot$ within S2's orbit. Given that our upper limit is very close to this predicted value, we conclude that we find no evidence for a significant dark matter spike in the GC.

S2 is currently moving toward the apocenter of its orbit, which it will reach in 2026. We expect that GRAVITY data collected in the coming years, combined with ERIS spectroscopy, will further refine our constraints on the extended mass distribution in the GC, as the mass distribution primarily influences stellar orbits in the apocenter half (Heißel et al. 2022). This will allow us to refine the comparison with the theoretical predictions for the stellar cusp, which is of fundamental importance in order to understand the distribution of the faint, old main-sequence stars and subgiants in the GC. These stars are too faint to be currently detected with GRAVITY, but their detection could be in reach of future observations with the GRAVITY+ upgrade at the VLTI (GRAVITY+ Collaboration 2022) and the MICADO instrument at the ELT (Davies et al. 2018). These stars could potentially be in tighter orbits around Sgr A* and could allow us to measure its spin and quadrupole moment. Furthermore, the comparison between our observational constraints and theoretical predictions is also important to better understand the distribution of compact objects in the GC and in galactic nuclei in general. This could offer precious insights in view of the future LISA mission (Amaro-Seoane et al. 2017), which will be able to detect the inspirals of compact objects into SMBHs (EMRIs) (Amaro-Seoane et al. 2007). In fact, the rate of EMRIs depends strongly on the density distribution of compact remnants within ~10 mpc of the central SMBH (Preto & Amaro-Seoane 2010), which corresponds to the apocenter distance of S2 for the GC.

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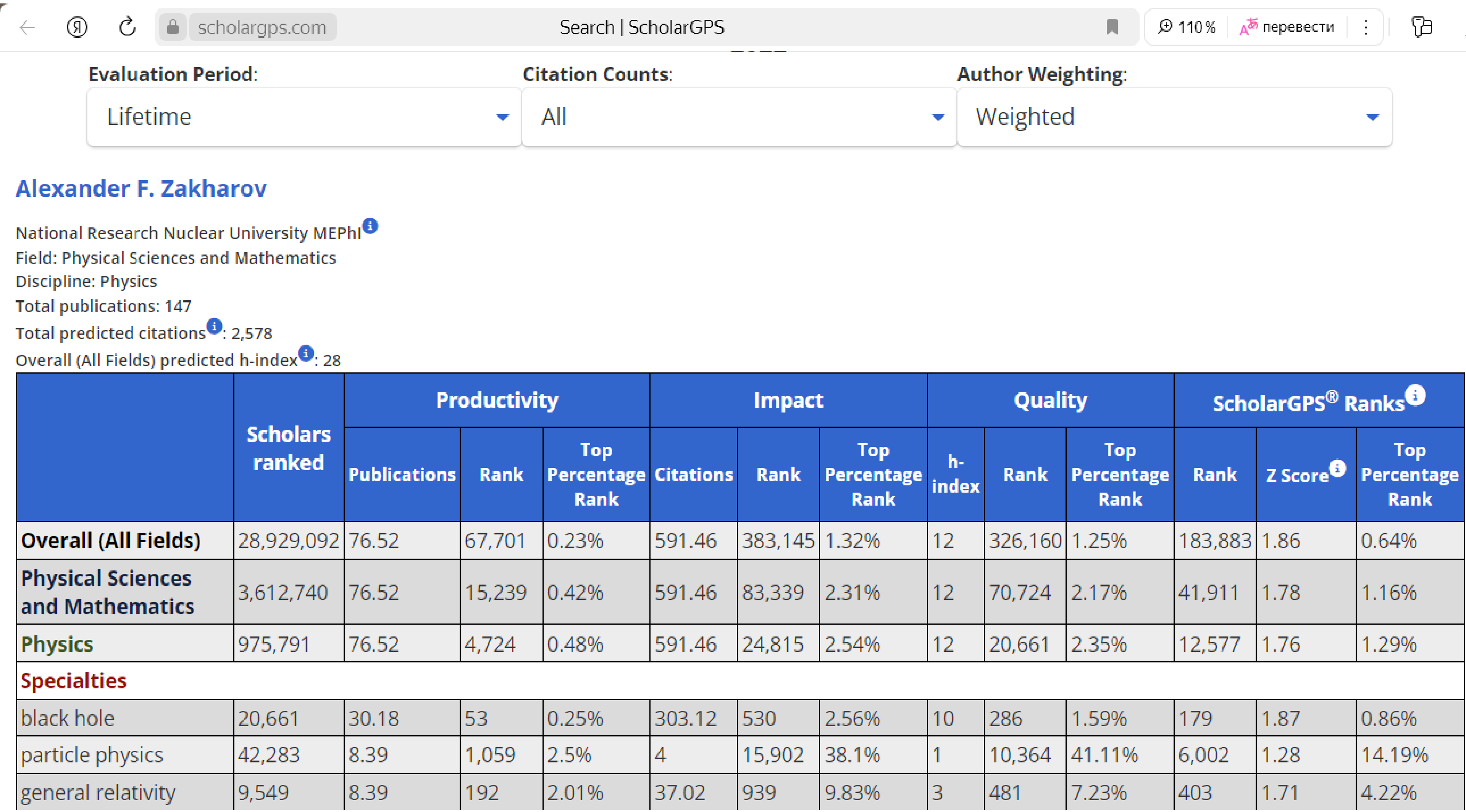
[1] LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université de Paris, 5 place Jules Janssen, 92195 Meudon, France
[2] Max Planck Institute for Extraterrestrial Physics, Giessenbachstraße 1, 85748 Garching, Germany
[3] Univ. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France
[4] European Southern Observatory, Karl-Schwarzschild-Straße 2, 85748 Garching, Germany



Evaluation Period: Lifetime

Citation Counts: All

Author Weighting: Weighted

Alexander F. Zakharov

National Research Nuclear University MEPhI
Field: Physical Sciences and Mathematics
Discipline: Physics
Total publications: 147
Total predicted citations: 2,578
Overall (All Fields) predicted h-index: 28

	Scholars ranked	Productivity			Impact			Quality			ScholarGPS® Ranks		
		Publications	Rank	Top Percentage Rank	Citations	Rank	Top Percentage Rank	h-index	Rank	Top Percentage Rank	Rank	Z Score	Top Percentage Rank
Overall (All Fields)	28,929,092	76.52	67,701	0.23%	591.46	383,145	1.32%	12	326,160	1.25%	183,883	1.86	0.64%
Physical Sciences and Mathematics	3,612,740	76.52	15,239	0.42%	591.46	83,339	2.31%	12	70,724	2.17%	41,911	1.78	1.16%
Physics	975,791	76.52	4,724	0.48%	591.46	24,815	2.54%	12	20,661	2.35%	12,577	1.76	1.29%
Specialties													
black hole	20,661	30.18	53	0.25%	303.12	530	2.56%	10	286	1.59%	179	1.87	0.86%
particle physics	42,283	8.39	1,059	2.5%	4	15,902	38.1%	1	10,364	41.11%	6,002	1.28	14.19%
general relativity	9,549	8.39	192	2.01%	37.02	939	9.83%	3	481	7.23%	403	1.71	4.22%

НЕЗАВИСИМАЯ

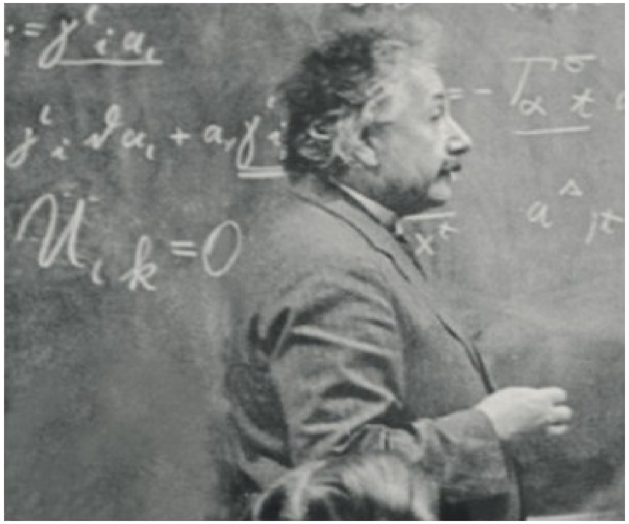
25.11.2015 00:01:15

Гравитация раскрыла не все свои тайны

Михаил Сажин (/authors/50542/)

Об авторе: Михаил Васильевич Сажин - доктор физико-математических наук, профессор, главный научный сотрудник Отдела релятивистской астрофизики Государственного астрономического института им. П.К. Штернберга МГУ им. М.В. Ломоносова. Ольга Сергеевна Сажина - доктор физико-математических наук, ведущий научный сотрудник Отдела релятивистской астрофизики Государственного астрономического института им. П.К. Штернберга МГУ им. М.В. Ломоносова.

Тэги: эйнштейн (/search/tags/?tags=эйнштейн), теория относительности (/search/tags/?tags=теория относительности), гравитация (/search/tags/?tags=гравитация), физика (/search/tags/?tags=физика)



Альберт Эйнштейн проводит лекцию. Фото 1921 года

25 ноября 2015 года исполняется ровно 100 лет со дня выступления Альберта Эйнштейна в Прусской Государственной библиотеке с докладом «Уравнения гравитационного поля», в котором он дал красивейшую геометрическую интерпретацию гравитационных сил. Статья под тем же названием была принята к печати 2 декабря 1915 года.

Рождение общей теории относительности (ОТО) не стало бы возможным без математического аппарата искривленной (неэвклидовой) геометрии - плода усилий многих математиков того времени. И точно так же научное понимание физической сути явлений было результатом работы многих физиков. Эйнштейн смог собрать все воедино и сформулировать теорию, которая по прошествии века не только не утратила своей актуальности, но прочно вошла в технологию, прежде всего космическую, и породила множество научных направлений, в том числе космологию - науку о Вселенной.

Эволюция относительности

Однажды родившись, любая физическая теория проходит несколько стадий развития. Сначала она всего лишь одна из многих других. Будучи хорошо обоснована математически, она вступает в конкуренцию с другими теориями. И только те из них, которые находят сначала одно наблюдательное или экспериментальное подтверждение, а потом еще и еще, становятся жизнеспособными на фоне всех остальных. Создатели и защитники той или иной теории постоянно ищут для нее подтверждений, стараясь совместить с данными экспериментов, и передают свою убежденность молодым коллегам.

Так теория может просуществовать довольно долго, однако статус общепринятой она приобретает только после выхода на технологический уровень. Теория, дошедшая до этой последней стадии «эволюции» и ставшая востребованной технологией, подтверждается тысячами ежедневных рутинных и обыденных измерений. Такая теория больше не требует апологетов и становится невосприимчива к попыткам ее ниспровергнуть. Никому не придет в голову вести дискуссии против теории электромагнетизма Максвелла, поскольку горящая лампочка и другие работающие бытовые электрические приборы защищают ее истинность лучше всяких ученых-апологетов.

Так и ОТО успешно преодолела все стадии развития и стала общепризнанной. Это случилось после того, как ее выводы стали востребованы в космических навигационных технологиях.

Теория относительности не стала конечным пунктом развития физики. Продемонстрировав прорыв в понимании природы, от «наивной наглядности светоносного эфира» до постулата о конечности скорости света, она указала возможные пути

Наследие ОТО

Одним из признанных мировых центров изучения ОТО и космологии стал Государственный астрономический институт им. П.К. Штернберга Московского государственного университета им. М.В. Ломоносова (ГАИШ МГУ). Это связано прежде всего с фигурой академика АН СССР Якова Зельдовича, ученого необыкновенной эрудиции, разноплановости пионерских работ и высочайшего интеллектуального уровня. ЯБ - как его называли многочисленные ученики и коллеги - вместе с Виталием Гинзбургом и Иосифом Шкловским организовали Объединенный астрофизический семинар, который в течение длительного времени был местом пересечения и дискуссий всех интересовавшихся ОТО и космологией.

На семинаре выступали известные ученые со всего мира - достаточно упомянуть таких выдающихся советских ученых, как Андрей Сахаров, Игорь Новиков, Анатолий Черепащук, а также зарубежных ученых: Кип Торн, Стивен Хокинг, Джон Уилер… На нем были впервые доложены классические работы Николая Шакуры и Рашида Сюняева, в которых был объяснен феномен рентгеновских источников излучения в нашей Галактике. На этом семинаре с изложением своих работ выступали основоположники теории ранней Вселенной Андрей Линде, Валерий Рубаков и Алексей Старобинский. На этом семинаре было впервые оглашено открытие анизотропии реликтового излучения, которое совершил советский спутник «Реликт» (авторы И. Струков, А. Брюханов, Д. Скулачев, Институт космических исследований АН СССР, и М. Сажин, ГАИШ МГУ).

Одно из важных предсказаний ОТО - существование черных дыр, объектов с гравитационным полем такой силы, что даже свет не может покинуть их. Открытие черных дыр - тоже заслуга советских ученых. Еще в 70-х годах прошлого века коллектив астрономов (В. Лютый, Р. Сюняев, А. Черепащук) измерили массу двойной системы в созвездии Лебедя, масса невидимой компоненты показала, что она является черной дырой. Этот результат также был доложен впервые на семинаре Зельдовича.

Сейчас астрономам известно много таких объектов и в нашей Галактике, и в других галактиках. Открыты также сверхмассивные черные дыры с массами от нескольких миллионов масс Солнца до миллиарда масс Солнца. Они «поселились» в центрах галактик. Так, в центре нашей Галактики Млечный Путь существует черная дыра с массой 4 млн солнечных масс. Сейчас астрономы с помощью гигантского телескопа-интерферометра пытаются измерить «тень» черной дыры в центре нашей Галактики, предсказанную российским физиком А. Захаровым. Такие наблюдения позволят измерить характеристики «горизонта» черной дыры.

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Regular Article - Theoretical Physics

Relativistic orbits of S2 star in the presence of scalar field

Parth Bambhaniya[1,2,a], **Ashok B. Joshi**[2,b], **Dipanjan Dey**[2,3,c], **Pankaj S. Joshi**[1,2,d], **Arindam Mazumdar**[4,e], **Tomohiro Harada**[5,f], **Ken-ichi Nakao**[6,7,g]

[1] International Centre for Space and Cosmology, Ahmedabad University, Ahmedabad, GUJ 380009, India
[2] International Center for Cosmology, Charusat University, Anand, Gujarat 388421, India
[3] Department of Mathematics and Statistics, Dalhousie University, Halifax NS, B3H 3J5, Canada
[4] Centre for Theoretical Studies, Indian Institute of Technology, Kharagpur, West Bengal 721302, India
[5] Department of Physics, Rikkyo University, Toshima, Tokyo 171-8501, Japan
[6] Department of Physics, Graduate School of Science, Osaka Metropolitan University, Sugimoto 3-3-138, Sumiyoshi, Osaka 558-8585, Japan
[7] Nambu Yoichiro Institute of Theoretical and Experimental Physics, Osaka Metropolitan University, Sugimoto 3-3-138, Sumiyoshi, Osaka 558-8585, Japan

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Abstract The general theory of relativity predicts the relativistic effect in the orbital motions of S-stars which are orbiting around our Milky-way Galactic Center. The post-Newtonian or higher-order approximated Schwarzschild black hole models have been used by GRAVITY and UCLA Galactic Center groups to carefully investigate the S2 star's periastron precession. In this paper, we investigate the scalar field effect on the orbital dynamics of S2 star. Hence, we consider a spacetime, namely Janis-Newman-Winicour (JNW) spacetime which is seeded by a minimally coupled, mass-less scalar field. The novel feature of this spacetime is that one can retain the Schwarzschild spacetime from JNW spacetime considering zero scalar charge. We constrain the scalar charge of JNW spacetime by best fitting the astrometric data of S2 star using the Monte-Carlo–Markov-Chain (MCMC) technique assuming the charge to be positive. Our best-fitted result implies that similar to the Schwarzschild black hole spacetime, the JNW naked singularity spacetime with an appropriate scalar charge also offers a satisfactory fitting to the observed data for S2 star. Therefore, the JNW naked singularity could be a contender for explaining the nature of Sgr A* through the orbital motions of the S2 star.

1 Introduction

The idea of reconstructing the shadow of a black hole in the Galactic Center using global interferometers operating in the millimeter wavelength was initially suggested in [1]. Recently, the Event Horizon Telescope collaboration has announced a major breakthrough in the imaging of an ultra-compact object at the centre of our Galaxy [2–7]. A bright emission ring around a core brightness depression in VLBI horizon-scale images of Sgr A*, with the latter linked to the shadow of black hole. The shadow boundary of the Sgr A* marks the visual image of the photon region and differentiates capture orbits from scattering orbits on the plane of a distant observer. The radius of the bright ring can be used as an approximation for the black hole shadow radius under specific conditions and after proper calibration, with little reliance on the details of the surrounding accretion flux. While there is strong evidence that there is a high concentration of mass in the center of our Milky Way Galaxy, the question of whether or not it is a black hole is still open. They have considered various alternatives such as naked singularities and regular black holes. They favorably acknowledge that the naked singularity with a photon sphere Joshi-Malafarina-Narayan (JMN-1) naked singularity could be the best black hole mimicker [7]. The central object and its nature remain mysterious. This is because just like a black hole case, the JMN-1 naked singularity would create a similar shadow, and therefore it is very difficult to distinguish between the two. Therefore, in this paper, we study the relativistic orbits of stars that are orbiting around our own Galactic Center.

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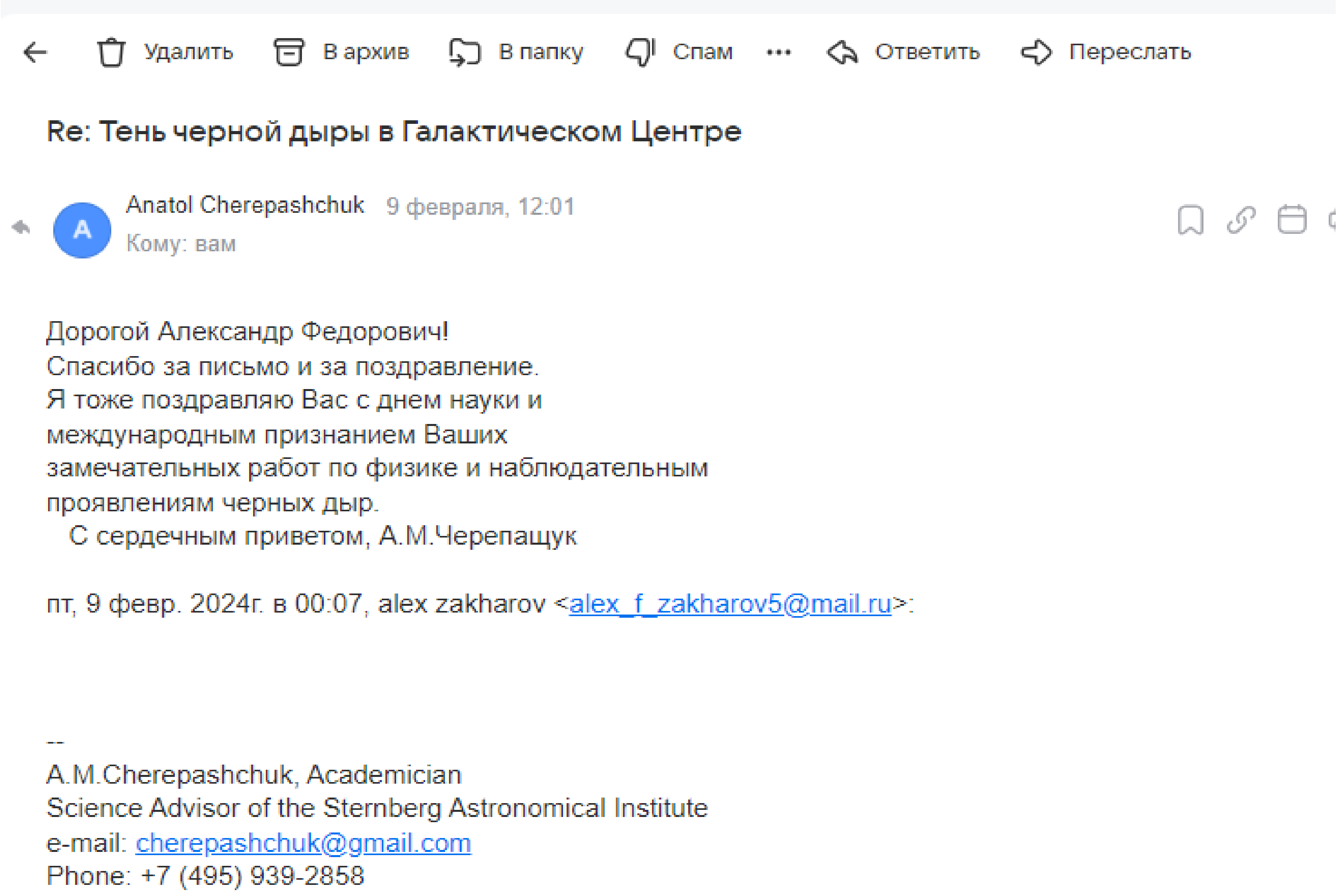
[a] e-mail: grcollapse@gmail.com (corresponding author)
[b] e-mail: gen.rel.joshi@gmail.com
[c] e-mail: deydipanjan7@gmail.com
[d] e-mail: psjcosmos@gmail.com
[e] e-mail: arindam.mazumdar@iitkgp.ac.in
[f] e-mail: harada@rikkyo.ac.jp
[g] e-mail: knakao@omu.ac.jp



Re: Тень черной дыры в Галактическом Центре

Anatol Cherepashchuk 9 февраля, 12:01
Кому: вам

Дорогой Александр Федорович!
Спасибо за письмо и за поздравление.
Я тоже поздравляю Вас с днем науки и
международным признанием Ваших
замечательных работ по физике и наблюдательным
проявлениям черных дыр.
С сердечным приветом, А.М.Черепащук

пт, 9 февр. 2024г. в 00:07, alex zakharov <alex_f_zakharov5@mail.ru>:

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A.M.Cherepashchuk, Academician
Science Advisor of the Sternberg Astronomical Institute
e-mail: cherepashchuk@gmail.com
Phone: +7 (495) 939-2858

Black hole types

- Black holes with stellar masses 10 -- 10^2 M_{Sun}

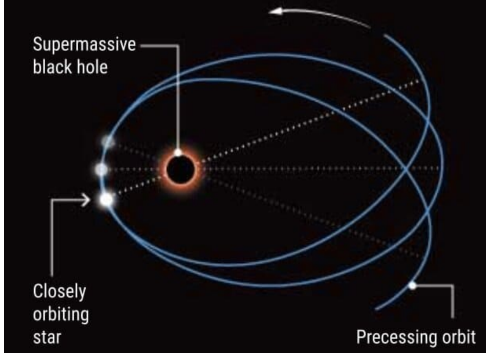
- Massive black holes 10^2 -- 10^5 M_{Sun}
- Supermassive black holes 10^5 – 10^{10} M_{sun}

How to probe a black hole

Albert Einstein's theory of gravity, general relativity, predicts that the collapse of enough mass can leave a self-sustaining gravitational field so strong that, inside a distance called the event horizon, nothing can escape, not even light. But are black holes exactly the inscrutable things general relativity predicts? Observers may now have the tools to find out.

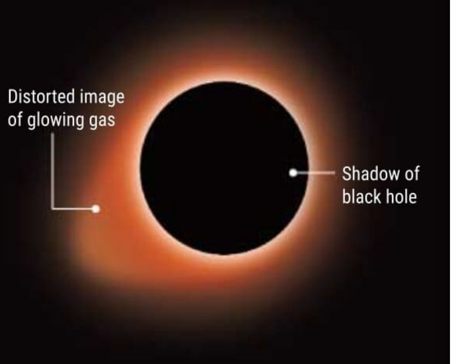
1. Trace the stars

Tracking the orbits of stars around the black hole in our Galaxy's center can reveal whether the black hole warps space and time exactly as general relativity predicts.



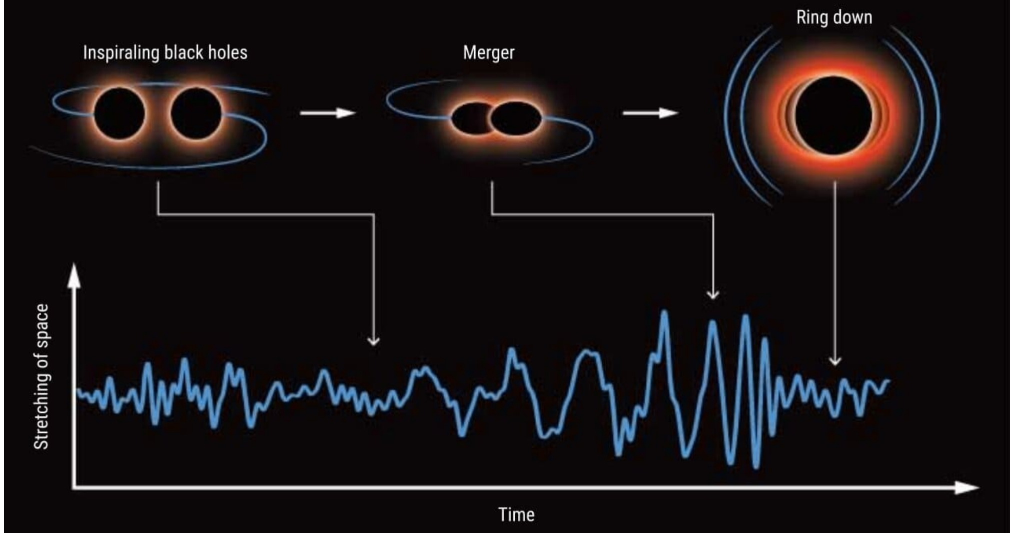
2. Take a picture

An image of a supermassive black hole holds clues to whether, as general relativity predicts, it has an event horizon rather than a surface, and mass and spin are its sole properties.



3. Catch the waves

When two small black holes spiral together, they radiate gravitational waves, which could reveal whether the supposed black holes are instead material objects. The final black hole reverberates at frequencies and overtones that provide another test of whether its only properties are mass and spin.



Great success of relativistic astrophysics

Three Nobel prizes in last five years (2017, 2019, 2020)

LIGO-Virgo: BBHs, BNS (kilonova) GW 170817;

GRAVITY, Keck and new tests of GR (gravitational redshift for S2 near its periapsis passage)

The confirmation of relativistic precession for S2 (GRAVITY)

Shadow reconstructions in M87* and Sgr A*

Young BHs discovered with JWST

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

John Kormendy[1] and Luis C. Ho[2]

[1]Department of Astronomy, University of Texas at Austin,
2515 Speedway C1400, Austin, TX 78712-1205; email: kormendy@astro.as.utexas.edu

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

Abstract

Supermassive black holes (BHs) have been found in 87 galaxies by dynamical modeling of spatially resolved kinematics. The *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 $M_\bullet$ and the velocity dispersion σ 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 $M_\bullet \sim 10^{9.5}\ M_\odot$ in brightest cluster ellipticals to $M_\bullet \sim 10^6\ M_\odot$ 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 $10^5 - 10^6\ M_\odot$ 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 $M_\bullet$ 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 $M_\bullet$ 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-disky 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-boxy ellipticals. Their properties, including their tight correlations between $M_\bullet$ 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 $M_\bullet$ correlations from the large values observed in bulgeless and pseudobulge galaxies to the small values observed in giant elliptical galaxies.

Table 1 Mass measurements of supermassive black holes in our Galaxy, M 31, and M 32

Galaxy (1)	D (Mpc) (2)	σ_e (km s^{-1}) (3)	$M_\bullet$ ($M_{\rm low}, M_{\rm high}$) ($M_\odot$) (4)	r$_{\rm infl}$ (arcsec) (5)	σ_* (arcsec) (6)	r$_{\rm infl}/\sigma_*$ (7)	Reference (8)
Galaxy			4.41(3.98–4.84) e6		0.0146	2868.	Meyer et al. 2012
Galaxy			4.2 (3.9 –4.6) e6		0.0139	3013.	Yelda et al. 2011
Galaxy	0.00828	105	4.30(3.94–4.66) e6	41.9	0.0146	2868.	Genzel, Eisenhauer & Gillessen 2010
Galaxy	0.00828	105	4.30(3.94–4.66) e6	41.9	0.0146	2868.	Gillessen et al. 2009a
Galaxy			4.09(3.74–4.43) e6		0.0148	2829.	Gillessen et al. 2009b
Galaxy			4.25(3.44–4.79) e6		0.0139	3013.	Ghez et al. 2008
Galaxy			3.80(3.60–4.00) e6		0.0056	7478.	Ghez et al. 2005
Galaxy			3.7 (3.3 –4.1) e6		0.0075	5583.	Ghez et al. 2003
Galaxy			3.8 (2.3 –5.4) e6		0.0155	2702.	Schödel et al. 2002
Galaxy			2.1 (1.3 –2.8) e6		0.113	371.	Chakrabarty & Saha 2001
Galaxy			3.1 (2.6 –3.6) e6		0.26	161.	Genzel et al. 2000
Galaxy			2.7 (2.5 –2.9) e6		0.39	107.	Ghez et al. 1998
Galaxy			2.70(2.31–3.09) e6		0.39	107.	Genzel et al. 1997
Galaxy			2.55(2.12–2.95) e6		0.39	107.	Eckart & Genzel 1997
Galaxy			2.8 (2.5 –3.1) e6		2.4	17.4	Genzel et al. 1996
Galaxy			2.0 (0.9 –2.9) e6		4.9	8.5	Haller et al. 1996
Galaxy			2.9 (2.0 –3.9) e6		3.4	12.3	Krabbe et al. 1995
Galaxy			2. e6		5	8.4	Evans & de Zeeuw 1994
Galaxy			3. e6		5	8.4	Kent 1992
Galaxy			5.4 (3.9 –6.8) e6		15	2.8	Sellgren et al. 1990
M 31	0.774	169	1.4 (1.1–2.3) e8	5.75	0.053	109.	Bender et al. 2005
M 31			1.0 e8		0.297	19.4	Peiris & Tremaine 2003
M 31			6.1 (3.6–8.7) e7		0.052	111.	Bacon et al. 2001
M 31			3.3 (1.5–4.5) e7		0.297	19.4	Kormendy & Bender 1999
M 31			6.0 (5.8–6.2) e7		0.297	19.4	Magorrian et al. 1998
M 31			9.5 (7 – 10) e7		0.42	13.7	Emsellem & Combes 1997
M 31			7.5 e7		0.56	10.3	Tremaine 1995
M 31			8.0 e7		0.42	13.7	Bacon et al. 1994
M 31			5 (4.5–5.6) e7		0.59	9.7	Richstone, Bower & Dressler 1990
M 31			3.8 (1.1– 11) e7		0.56	10.3	Kormendy 1988a
M 31			5.6 (3.4–7.8) e7		0.59	9.7	Dressler & Richstone 1988
M 32	0.805	77	2.45(1.4–3.5) e6	0.46	0.052	8.76	van den Bosch & de Zeeuw 2010
M 32			2.9 (2.7–3.1) e6		0.052	8.76	Verolme et al. 2002
M 32			3.5 (2.3–4.6) e6		0.052	8.76	Joseph et al. 2001
M 32			2.4 (2.2–2.6) e6		0.23	1.98	Magorrian et al. 1998
M 32			3.9 (3.1–4.7) e6		0.050	9.11	van der Marel et al. 1998a
M 32			3.9 (3.3–4.5) e6		0.050	9.11	van der Marel et al. 1997a, 1997b
M 32			3.2 (2.6–3.7) e6		0.23	1.98	Bender, Kormendy & Dehnen 1996
M 32			2.1 (1.8–2.3) e6		0.34	1.34	Dehnen 1995
M 32			2.1 e6		0.34	1.34	Qian et al. 1995
M 32			2.1 (1.7–2.4) e6		0.34	1.34	van der Marel et al. 1994a
M 32			2.2 (0.8–3.5) e6		0.59	0.77	Richstone, Bower & Dressler 1990
M 32			9.3 e6		0.59	0.77	Dressler & Richstone 1988
M 32			7.5 (3.5–11.5) e6		0.76	0.60	Tonry 1987
M 32			5.8 e6		1.49	0.31	Tonry 1984

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 $r_{\rm infl}$ 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 $\sigma_{*\rm tel}$ of a Gaussian fitted to the core of the average radial brightness profile of the PSF. In particular, the HST PSF has $\sigma_{*\rm tel} \sim 0\farcs036$ from a single-Gaussian fit to the PSF model in van der Marel, de Zeeuw & Rix (1997a).

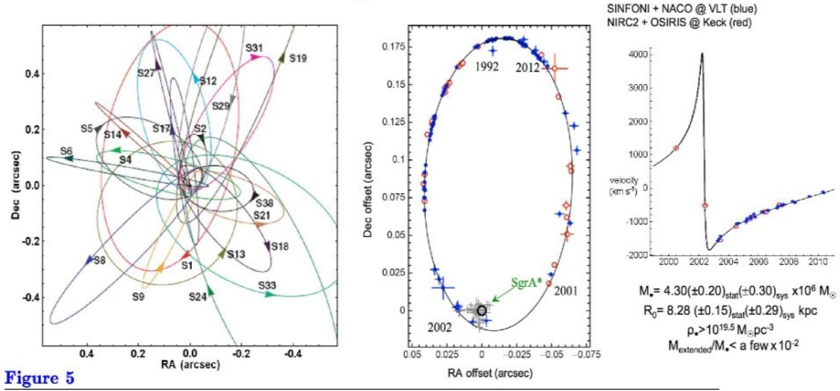


Figure 5

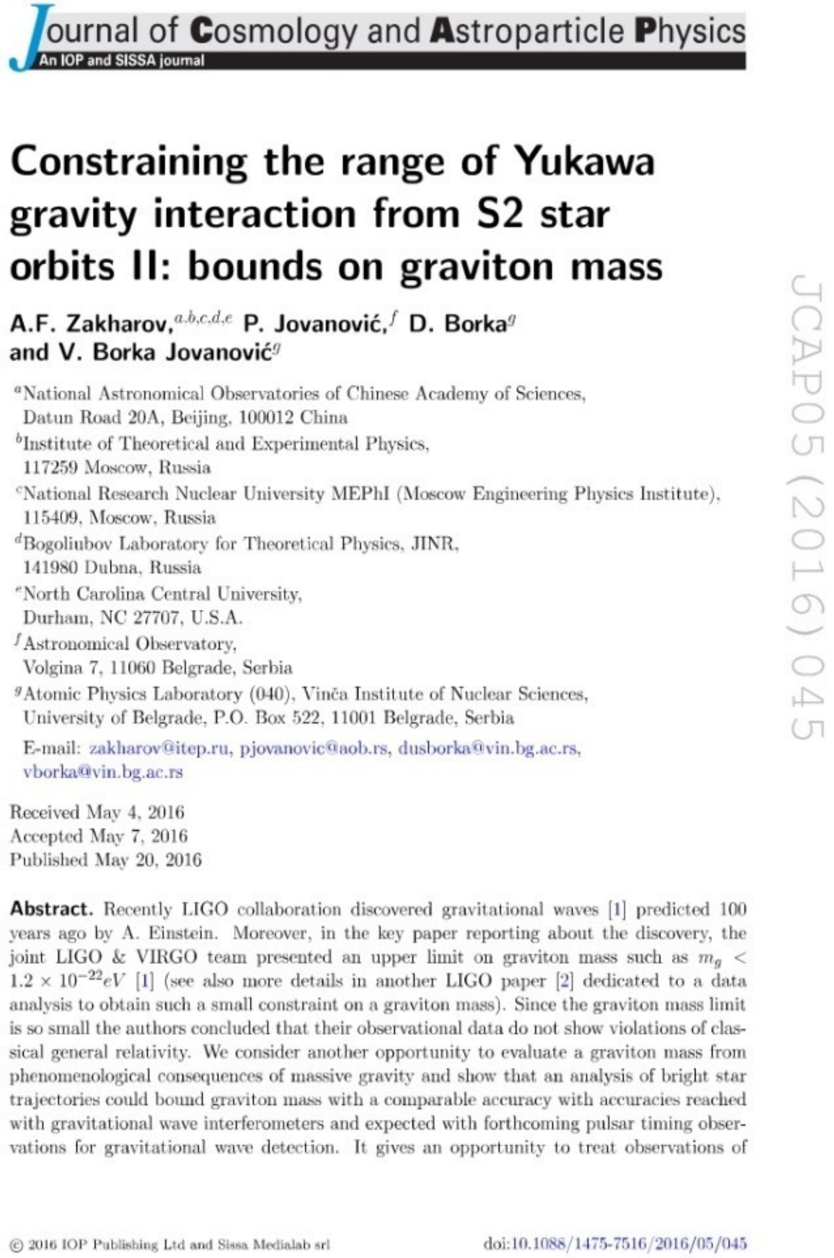
(*left*) Orbits of individual stars near the Galactic center. (*right*) Orbit of star S2 around the BH and associated radio source Sgr A* based on observations of its position from 1992 to 2012. Results from the Ghez group using the Keck telescope and from the Genzel group using the Europen Very Large Telescope (VLT) are combined. This figure is updated from Genzel, Eisenhauer & Gillessen (2010) and is kindly provided by Reinhard Genzel.

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 & Palenzuela 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 Sołtan (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 dark 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.

KR95 was titled "Inward Bound – The Search for Supermassive Black Holes in Galactic Nuclei." 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.

Massive graviton theories

- M. Fierz and W.Pauli-1939
- Zakharov; Veltman, van Dam – 1970
- Vainshtein - 1972
- Boulware, Deser -- 1972
- Logunov, Mestvirishvili, Gershtein et al. (RTG)
- Visser – 1998 (review on such theories)
- Rubakov, Tinyakov – 2008
- de Rham et al.—2011 -- 2016



Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

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

A.F. Zakharov,[a,b,c,d,e] **P. Jovanović,**[f] **D. Borka**[g]
and V. Borka Jovanović[g]

[a]National Astronomical Observatories of Chinese Academy of Sciences,
Datun Road 20A, Beijing, 100012 China
[b]Institute of Theoretical and Experimental Physics,
117259 Moscow, Russia
[c]National Research Nuclear University MEPhI (Moscow Engineering Physics Institute),
115409, Moscow, Russia
[d]Bogoliubov Laboratory for Theoretical Physics, JINR,
141980 Dubna, Russia
[e]North Carolina Central University,
Durham, NC 27707, U.S.A.
[f]Astronomical Observatory,
Volgina 7, 11060 Belgrade, Serbia
[g]Atomic Physics Laboratory (040), Vinča Institute of Nuclear Sciences,
University of Belgrade, P.O. Box 522, 11001 Belgrade, Serbia

E-mail: zakharov@itep.ru, pjovanovic@aob.rs, dusborka@vin.bg.ac.rs,
vborka@vin.bg.ac.rs

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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 trajectories could bound graviton mass with a comparable accuracy with accuracies reached with gravitational wave interferometers and expected with forthcoming pulsar timing observations for gravitational wave detection. It gives an opportunity to treat observations of

doi:10.1088/1475-7516/2016/05/045

Constraints on graviton mass from S2 trajectory

- AFZ, D. Borka, P. Jovanovic, V. Borka Jovanovic gr-qc: 1605.00913v; JCAP (2016) :
- $\lambda_g > 2900$ AU = 4.3×10^{11} km with P=0.9 or
- $m_g < 2.9 \times 10^{-21}$ eV $= 5.17 \times 10^{-54}$ g
- Hees et al. PRL (2017) slightly improved our estimates with their new data $m_g < 1.6 \times 10^{-21}$ eV (see discussion below)

pdgLive Home > graviton > graviton MASS

graviton MASS

INSPIRE search

It is likely that the graviton is massless. More than fifty years ago Van Dam and Veltman (VANDAM 1970), Iwasaki (IWASAKI 1970), and Zakharov (ZAKHAROV 1970) almost simultaneously showed that in the linear approximation a theory with a finite graviton mass does not approach GR as the mass approaches zero. Attempts have been made to evade this "vDVZ discontinuity" by invoking modified gravity or nonlinear theory by De Rahm (DE-RHAM 2017) and others. More recently, the analysis of gravitational wave dispersion has led to bounds that are largely independent of the underlying model, even if not the strongest. We quote the best of these as our best limit.

Experimental limits have been set based on a Yukawa potential (YUKA), dispersion relation (DISP), or other modified gravity theories (MGRV).

The following conversions are useful: 1 eV = 1.783×10^{-33} g = $1.957 \times 10^{-6} m_e$; λ_C = (1.973×10^{-7} m)×(1 eV/m_g).

VALUE (eV)	*DOCUMENT ID*		*TECN*	*COMMENT*
$\mathbf{< 5 \times 10^{-23}}$	[1] ABBOTT	2019	DISP	LIGO Virgo catalog GWTC-1
• • We do not use the following data for averages, fits, limits, etc. • •				
$< 3.2 \times 10^{-23}$	[2] BERNUS	2020	YUKA	Planetary ephemeris INPOP19a
$< 2 \times 10^{-28}$	[3] SHAO	2020	DISP	Binary pulsar Galileon radiation
$< 7 \times 10^{-23}$	[4] BERNUS	2019	YUKA	Planetary ephemeris INPOP17b
$< 3.1 \times 10^{-20}$	[5] MIAO	2019	DISP	Binary pulsar orbital decay rate
$< 1.4 \times 10^{-29}$	[6] DESAI	2018	YUKA	Gal cluster Abell 1689
$< 5 \times 10^{-30}$	[7] GUPTA	2018	YUKA	Using SPT-SZ
$< 3 \times 10^{-30}$	[7] GUPTA	2018	YUKA	Using Planck all-sky SZ
$< 1.3 \times 10^{-29}$	[7] GUPTA	2018	YUKA	Using redMaPPer SDSS-DR8
$< 6 \times 10^{-30}$	[8] RANA	2018	YUKA	Weak lensing in massive clusters
$< 8 \times 10^{-30}$	[9] RANA	2018	YUKA	SZ effect in massive clusters
$< 1.0 \times 10^{-23}$	[10] WILL	2018	YUKA	Perihelion advances of planets
$< 7 \times 10^{-23}$	[1] ABBOTT	2017	DISP	Combined dispersion limit from three BH mergers
$< 1.2 \times 10^{-22}$	[1] ABBOTT	2016	DISP	Combined dispersion limit from two BH mergers
$< 2.9 \times 10^{-21}$	[11] ZAKHAROV	2016	YUKA	S2 star orbit
$< 5 \times 10^{-23}$	[12] BRITO	2013	MGRV	Spinning black holes bounds
$< 6 \times 10^{-32}$	[13] GRUZINOV	2005	MGRV	Solar System observations
$< 6 \times 10^{-32}$	[14] CHOUDHURY	2004	YUKA	Weak gravitational lensing
$< 9.0 \times 10^{-34}$	[15] GERSHTEIN	2004	MGRV	From Ω_{tot} value assuming RTG
$< 8 \times 10^{-20}$	[16,17] FINN	2002	DISP	Binary pulsar orbital period decrease
$< 7 \times 10^{-23}$	TALMADGE	1988	YUKA	Solar system planetary astrometric data
$< 1.3 \times 10^{-29}$	[18] GOLDHABER	1974	YUKA	Rich clusters
$< 7 \times 10^{-28}$	HARE	1973	YUKA	Galaxy
$< 8 \times 10^{4}$	HARE	1973	YUKA	2γ decay

[1] ABBOTT 2019 , ABBOTT 2017 , and ABBOTT 2016 limits assume a dispersion relation for gravitational waves modified relative to GR.

[2] BERNUS 2020 use the latest solution of the ephemeris INPOP (19a) in order to improve the constraint in BERNUS 2019 on the existence of a Yukawa suppression to the Newtonian potential, generically associated to a gravitons mass.

[3] SHAO 2020 sets limit, 95% CL, based on non-observation of excess gravitational radiation in 14 well-timed binary pulsars in the context of the cubic Galileon model.

[4] BERNUS 2019 use the planetary ephemeris INPOP 17b to constraint the existence of a Yukawa suppression to the Newtonian potential, generically associated to a gravitons mass.

[5] MIAO 2019 90% CL limit is based on orbital period decay rates of 9 binary pulsars using a Bayesian prior uniform in graviton mass. Limit becomes $< 5.2 \times 10^{-21}$ eV for a prior uniform in ln(m_g).

[6] DESAI 2018 limit based on dynamical mass models of galaxy cluster Abell 1689.

[7] GUPTA 2018 obtains graviton mass limits using stacked clusters from 3 disparate surveys.

[8] RANA 2018 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.

[9] RANA 2018 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.

[10] WILL 2018 limit from perihelion advances of the planets, notably Earth, Mars, and Saturn. Alternate analysis yields $< 6 \times 10^{-24}$.

[11] ZAKHAROV 2016 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 $\delta = 100$.

[12] BRITO 2013 explore massive graviton (spin-2) fluctuations around rotating black holes.

[13] GRUZINOV 2005 uses the DGP model (DVALI 2000) showing that non-perturbative effects restore continuity with Einstein's equations as the gravition mass approaches zero, then bases his limit on Solar System observations.

[14] CHOUDHURY 2004 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.

[15] GERSHTEIN 2004 use non-Einstein field relativistic theory of gravity (RTG), with a massive graviton, to obtain the 95% CL mass limit implied by the value of $\Omega_{tot} = 1.02 \pm 0.02$ current at the time of publication.

[16] FINN 2002 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.

[17] As of 2020, limits on dP/dt are now about 0.1% (see T. Damour, “Experimental tests of gravitational theory,” in this *Review*).

[18] GOLDHABER 1974 establish this limit considering the binding of galactic clusters, corrected to Planck $h_0 = 0.67$.

References:

BERNUS	2020	PR D102 021501	Constraint on the Yukawa suppression of the Newtonian potential from the planetary ephemeris INPOP19a
SHAO	2020	PR D102 024069	New Graviton Mass Bound from Binary Pulsars
ABBOTT	2019	PR D100 104036	Tests of General Relativity with the Binary Black Hole Signals from the LIGO-Virgo Catalog GWTC-1
BERNUS	2019	PRL 123 161103	Constraining the mass of the graviton with the planetary ephemeris INPOP
MIAO	2019	PR D99 123015	Bounding the mass of graviton in a dynamic regime with binary pulsars
DESAI	2018	PL B778 325	Limit on graviton mass from galaxy cluster Abell 1689
GUPTA	2018	ANP 399 85	Limit on graviton mass using stacked galaxy cluster catalogs from SPT-SZ, Planck-SZ and SDSS-redMaPPer
RANA	2018	PL B781 220	Bounds on graviton mass using weak lensing and SZ effect in galaxy clusters
WILL	2018	CQG 35 17LT01	Solar system versus gravitational-wave bounds on the graviton mass
ABBOTT	2017	PRL 118 221101	GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2
ABBOTT	2016	PRL 116 061102	Observation of Gravitational Waves from a Binary Black Hole Merger
ZAKHAROV	2016	JCAP 1605 045	Constraining the range of Yukawa gravity interaction from S2 star orbits II: Bounds on graviton mass
BRITO	2013	PR D88 023514	Massive Spin-2 Fields on Black Hole Spacetimes: Instability of the Schwarzschild and Kerr Solutions and Bounds on the Graviton Mass
GRUZINOV	2005	NAST 10 311	On the Graviton Mass
CHOUDHURY	2004	ASP 21 559	Probing Large Distance Higher Dimensional Gravity from Lensing Data
GERSHTEIN	2004	PAN 67 1596	Graviton Mass, Quintessence and Oscillatory Character of the Universe Evolution
FINN	2002	PR D65 044022	Bounding the Mass of the Graviton using Binary Pulsar Observations
TALMADGE	1988	PRL 61 1159	Model Independent Constraints on Possible Modifications of Newtonian Gravity
GOLDHABER	1974	PR D9 1119	Mass of the Graviton
HARE	1973	CJP 51 431	Mass of the Graviton

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modification $\mu(a)$ of Kepler's third law:

$$\frac{a^3}{T^2} = \frac{M_\odot(1+\mu(a))}{4(2\pi)^3 M_{\rm Pl}^2}, \tag{3.10}$$

where a and T are the semi-major axis and the period of the planet's orbit. In GR, $\mu = 0$, while in models of modified gravity, μ can depart from unity in some regime and acquire a non-trivial radius dependence, $\mu = \mu(a)$. Comparing the ratio a^3/T^2 of various planets provides a powerful way to test GR with the best bounds given by comparison of the ratio for the Earth and the Moon (Talmadge *et al.*, 1988).

Besides modifying Kepler's third law and including fifth force effects, modifications of the standard Newtonian potential can lead to an additional precession beyond that expected from GR and the fifth forces. This implies that even theories that do not involve any additional degrees of freedom or carry no fifth force effects can still lead to an additional advance of the perihelion on top of GR's expected precession. These effects are typically less constrained than the corrections to Kepler's third law but should still be under control.

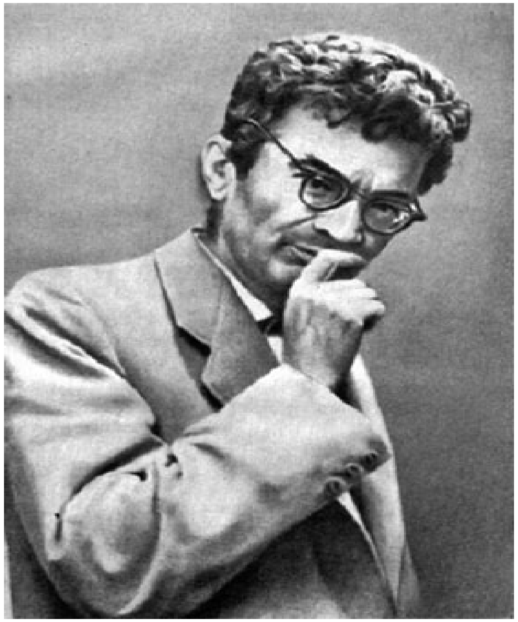
3.4.5 *Black holes and stellar solutions*

All of the constraints on planetary orbits within the solar system are also applicable to the orbits of stars in the vicinity of black holes, including Sagittarius A*, with S2-like stars orbiting the black hole within distances comparable to that in the solar system as observed by the **W.M. KECK observatory** (Eckart and Genzel, 1996; Ghez *et al.*, 2005a,b; Gillessen *et al.*, 2009; Meyer *et al.*, 2012) leading to competitive tests of modified gravity (Borka *et al.*, 2012, 2013; Zakharov *et al.*, 2016).

In parallel, the modification of the black hole solution itself in theories of modified gravity can be matched against its shadow as observed by the **Event Horizon Telescope** (Akiyama *et al.*, 2022a) and has already been used to constrain models of modified gravity (Akiyama *et al.*, 2022b; Psaltis *et al.*, 2020; Shaikh, 2023; Vagnozzi *et al.*, 2022; Zakharov, 2022). The potential presence of hair, superradiance and other effects modifying the black hole structure near the horizon could provide competitive tests of modified gravity in the future.

In addition, modifications of gravity can affect the **sequence of stars** and structure of other astrophysical systems. The presence of additional degrees of freedom that often go along with modified gravity, when equilibrated in a stellar core, can drive new stellar instabilities which would manifest in **mass gaps in black hole populations** (see Straight *et al.*, 2020 for an example). Modified gravity effects can also change the equilibrium structure of main sequence stars, modifying the relation between their mass and luminosity (stars are typically brighter in theories of gravity involving a Chameleon-like screened scalar field like in $f(R)$), an effect which is then reflected in their radii and ages (Davis *et al.*, 2012). Reviews on other astrophysical tests of modified gravity can be found in Alves Batista *et al.* (2021); Baker *et al.* (2021); Sakstein (2020).

Shadow reconstructions for M87* and Sgr A* are based on three pillars: Synchrotron radiation, VLBI concept, GR in a strong gravitational field



I. Pomeranchuk, The maximum energy that primary cosmic ray electrons can have on the Earth's surface due to radiation in the Earth's magnetic field, J. Phys. USSR, 2, 356 (1940)

D. Ivanenko and I. Pomeranchuk, On the Maximal Energy Attainable in a Betatron, Phys. Rev. 65, 343 (1944)

L.A. Artsimovich and I. Pomeranchuk, The maximum energy that primary cosmic ray electrons can have on the Earth's surface due to radiation in the Earth's magnetic field, J. Phys. USSR, 2, 267 (1945)

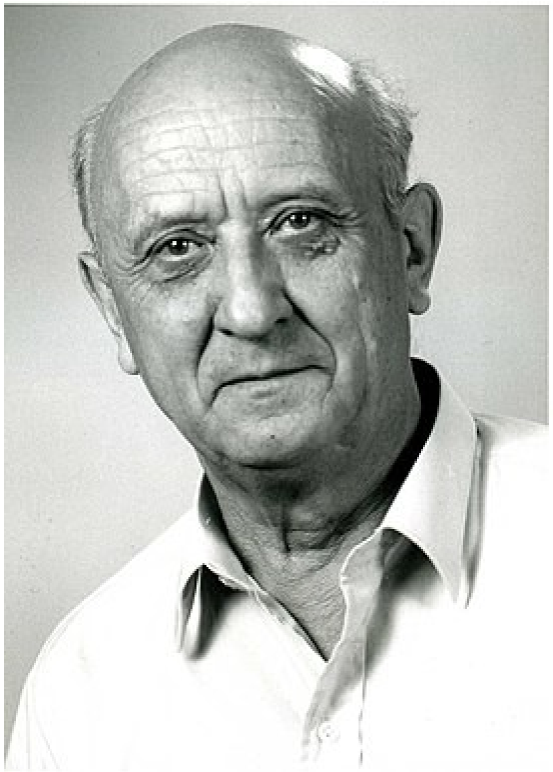
Elder, F. R., Gurewitsch, A. M., Langmuir, R. V., & Pollock, H. C. Radiation from Electrons in a Synchrotron. Physical Review, 71(11), 829 (1947)

In 1950 D. Ivanenko, A. A. Sokolov and I. Pomeranchuk were awarded the State prize of the second grade for works on synchrotron radiation, presented in book “Classical Field Theory”

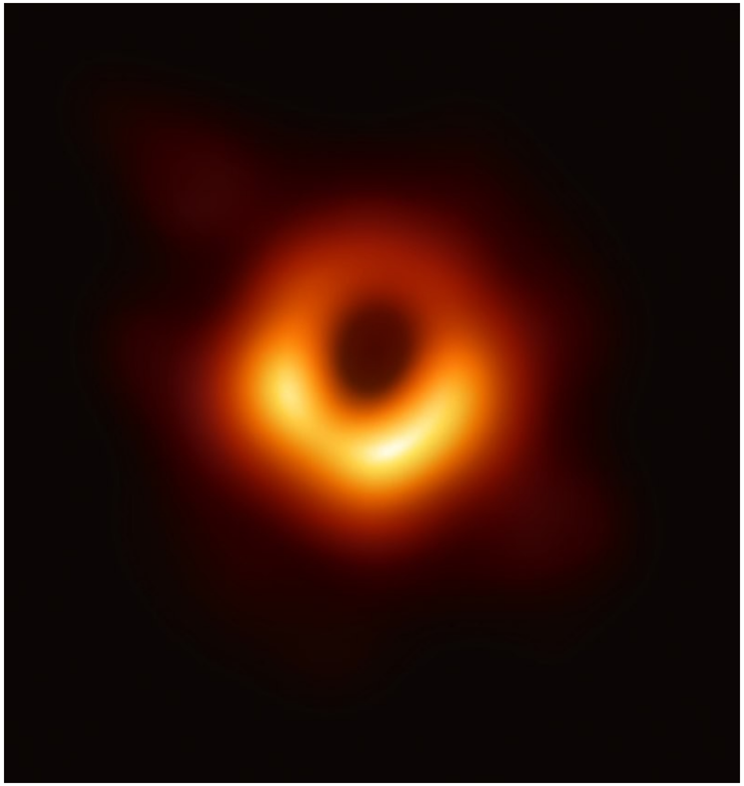
Synchrotron radiation plays a key role in many astrophysical objects (including BH's and pulsars (Crab Nebula)) . In 1946 they predicted emission in radio band from solar corona. In May 1947 they participated in Brazil expedition

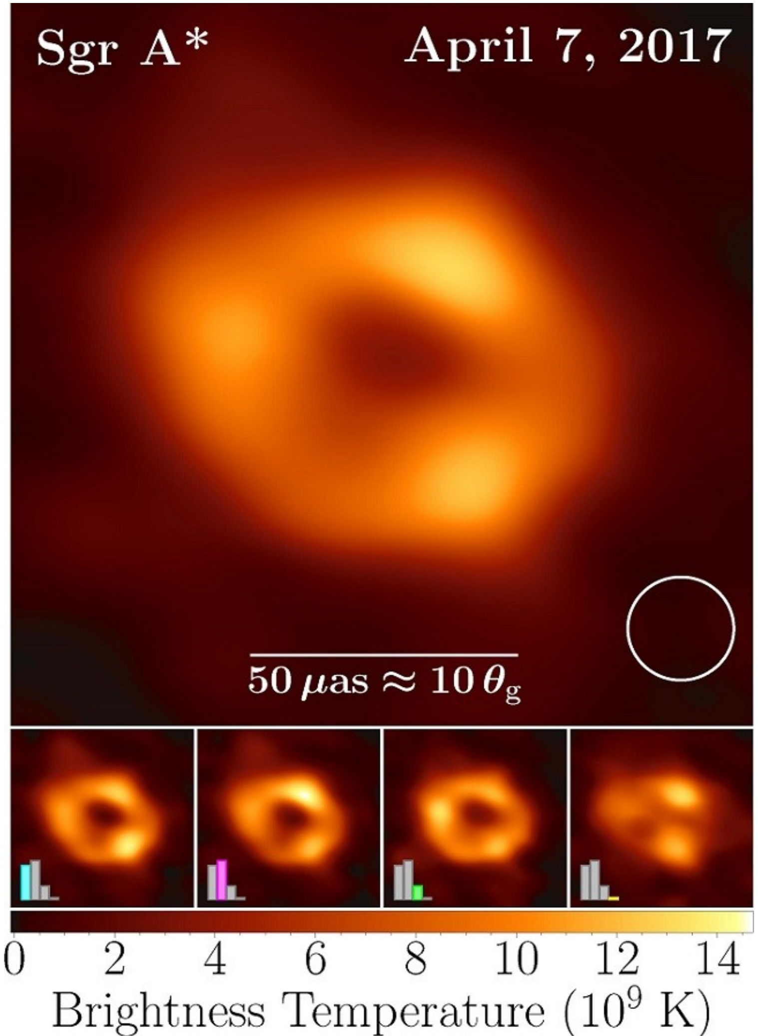
The Soviet expedition in Brazil for solar eclipse observations in 20 May 1947 where S. E. Khaikin and B. M. Chikhachev discovered radio emission from solar corona during the solar eclipse aboard the “Griboedov” ship

The idea of VLBI observation was introduced by L. I. Matveenko (1929—2019) in 1960s and it was realized in Soviet – US joint radio observations in 1970s. Matveenko proposed also a project of a ground – space interferometer. This idea was realized later by Japanese (HALCA, VSOP, 1997) and Russian Astronomers (Radioastron, 2011) .



EHT shadow reconstruction for M87* and Sgr A* observed in April 2017





Подтверждено предсказание ученого НИЦ "Курчатовский институт" о существовании "тени" в центре нашей Галактики

15.06.2022 ПРЕСС-ЦЕНТР НИЦ "КУРЧАТОВСКИЙ ИНСТИТУТ"

Фото: Ana Torres Kampos

В 2005 году физик-теоретик **Александр Захаров** и его соавторы предложили с помощью наблюдений подтвердить присутствие сверхмассивной черной дыры в Центре нашей Галактики и проверить предсказания общей теории относительности в сильном гравитационном поле. А. Захаров и его итальянские коллеги предположили, что в случае наличия черной дыры в Галактическом центре (ГЦ) наблюдатели в направлении на ГЦ увидят тень размером порядка 52 микроарксекунд. Работа была опубликована в журнале New Astronomy.

"Понятие "черная дыра" для теоретика и наблюдателя отличается, – поясняет ведущий научный сотрудник лаборатории физики плазмы и астрофизики НИЦ "Курчатовский институт" Александр Захаров (в 2005 г. – сотрудник ИТЭФ). – *Для теоретика черная дыра – это определенная метрика, описывающая пространство-*

https://www.gazeta.ru/science/news/2022/06/15/17937578.shtml

- 15 июня 2022, 16:03
- **Сбылось предсказание российского ученого о загадочной тени**
- Борис Ганьжин
-
- Первое изображение сверхмассивной черной дыры в центре Млечного Пути, о получении которого в мае 2022 года сообщила коллаборация Телескопа горизонта событий Event Horizon Telescope, послужило подтверждением предсказания ведущего научного сотрудника лаборатории физики плазмы и астрофизики ККТЭФ НИЦ «Курчатовский институт» Александра Захарова и его итальянских коллег, сделанного в 2005 году. Об этом «Газете.Ru» сообщили в НИЦ «Курчатовский институт».

For about 20 years we declared black holes (for theorists) are dark spots (shadows) for observers and reported these ideas in many institutes located in different countries (Russia, Serbia, China, Bulgaria, Switzerland, Italy, Greece, Germany, USA, UK, India, Pakistan, Australia, Spain, France). These ideas were also reported at EHT meetings.

When our predictions concerning GC shadow were confirmed a majority of colleagues forgot them and did not mention them. Similarly, when I noted in a comment that an opportunity for GC shadow using Millimetron space – ground observations was firstly discussed in our paper (2005), three (!!!) anonymous referees did not disprove a correctness of my statement but they reacted in a negative way and they simultaneously wrote that it was not modest and ethic to request an additional citation.

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Shadows near supermassive black holes: From a theoretical concept to GR test

Alexander F. Zakharov

https://doi.org/10.1142/S0218271823400047 | **Cited by:** 1 **(Source: Crossref)**

Abstract

General relativity (GR) passed many astronomical tests but in majority of them GR predictions have been tested in a weak gravitational field approximation. Around 50 years ago a shadow was introduced by Bardeen as a purely theoretical concept but due to an enormous progress in observational and computational facilities this theoretical prediction has been confirmed and the most solid argument for an existence of supermassive black holes in Sgr A* and M87* has been obtained.

At the initial stage of development of GR and quantum mechanics gedanken(thought) experiments were very popular in a discussion of specific features of new theories. To discuss observations signatured of black holes J. M. Bardeen considered features of an existence of bright screen which is located behind a Kerr black hole in the case of an observer is located in the equatorial plane. In these considerations it was assumed that photons emitted by a luminous screen do not interact with a matter around a black hole.

Clearly, this gedanken experiment looked rather artificial since first, there are no luminous screens behind astrophysical black holes, second, masses of black holes were estimated not precisely and a majority of astrophysical black holes were black holes with stellar masses but even now shadows around these black holes are too small to be detected, third, it was not clear how to detect a darkness or to distinguish it from a faintness.

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Measuring the black hole parameters in the galactic center with RADIOASTRON

A.F. Zakharov [a,b,c,*], A.A. Nucita [d], F. DePaolis [d], G. Ingrosso [d]

[a] *Institute of Theoretical and Experimental Physics, 25, B. Cheremushkinskaya st., Moscow 117259, Russia*
[b] *Space Research Centre of Lebedev Physics Institute, Moscow, Russia*
[c] *Joint Institute for Nuclear Research, Dubna, Russia*
[d] *Dipartimento di Fisica, Universita di Lecce and INFN, Sezione di Lecce, Italy*

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Communicated by F. Melchiorri

Abstract

Recently, Holz and Wheeler (2002) [ApJ 578, 330] considered a very attracting possibility to detect retro-MACHOs, i.e., retro-images of the Sun by a Schwarzschild black hole. In this paper, we discuss glories (mirages) formed near rapidly rotating Kerr black hole horizons and propose a procedure to measure masses and rotation parameters analyzing these forms of mirages. In some sense that is a manifestation of gravitational lens effect in the strong gravitational field near black hole horizon and a generalization of the retro-gravitational lens phenomenon. We analyze the case of a Kerr black hole rotating at arbitrary speed for some selected positions of a distant observer with respect to the equatorial plane of a Kerr black hole. Some time ago Falcke, Melia, Agol (2000) [ApJ 528, L13S] suggested to search shadows at the Galactic Center. In this paper, we present the boundaries for shadows. We also propose to use future radio interferometer RADIOASTRON facilities to measure shapes of mirages (glories) and to evaluate the black hole spin as a function of the position angle of a distant observer.

PACS: 97.60.L; 04.70; 95.30.S; 04.20; 98.62.S

Keywords: Black hole physics; Gravitational lenses; Microlensing

1. Introduction

Recently Holz and Wheeler (2002) have suggested that a Schwarzschild black hole may form retro-images (called retro-MACHOs) if it is illuminated by the Sun. We analyze a rapidly rotating

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[*] Corresponding author. Tel.:+7 095 1299759; fax: +7 095 8839601.
E-mail address: zakharov@itep.ru (A.F. Zakharov).

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For the paper entitled:

"Measuring the black hole parameters in the galactic center with RADIOASTRON"

This paper was published in:

New Astronomy, Volume 10, Issue 6, 2005

David Clark
Senior Vice President, Physical Sciences I
Amsterdam, The Netherlands

Our proposal

In 2004-2005 we proposed a way to test GR predictions with Radioastron:

Since angular resolution of Radioastron at 1.3 cm is around 8 uas and the size of darkness (shadow) could help us to evaluate a charge, while shape could help us to evaluate a spin (good!)

The shortest wavelength is 1.3 cm (it is too long to detect shadow) (not good for Radioastron!)

So, we propose to test GR predictions about shape and size of BH images with observations. Astronomy is dealing with images. Therefore, establishing the correspondence of theoretical image and reconstructed image using observational data is an aim for further observations.

AFZ et al., NA (2005): “In our old paper
https://ui.adsabs.harvard.edu/.../2005NewA...10.../abstract

we wrote at the end "In spite of the difficulties of measuring the shapes of images near black holes is so attractive challenge to look at the ‘‘faces’’ of black holes because namely the mirages outline the ‘‘faces’’ and

correspond to fully general relativistic description of a region near black hole horizon without any assumption about a specific model for astrophysical processes around black holes (of course we assume that there are sources illuminating black hole surroundings). No doubt that the rapid growth of observational facilities will give a chance to measure the mirage shapes using not only RADIOASTRON facilities but using also other instruments and spectral bands (for example, X-ray interferometer MAXIM (White, 2000; Cash et al., 2000) or sub-mm VLBI array (Miyoshi, 2004)). Astro Space Centre of Lebedev Physics Institute proposed except the RADIOASTRON mission and developed also space based interferometers (Millimetron and Sub-millimetron) for future observations in mm and sub-mm bands. These instruments could be used for the determination of shadow shapes.“

Therefore, the shadows may be reconstructed from ground or space -- ground VLBI observations in mm or sub-mm bands. EHT results confirmed these predictions.

Measuring the black hole parameters in the Galactic Center with Radioastron

- Let us consider an illumination of black holes. Then retro-photons form caustics around black holes or mirages around black holes or boundaries around shadows.
- (Zakharov, Nucita, DePaolis, Ingrosso,
- New Astronomy 10 (2005) 479; astro-ph/0411511)

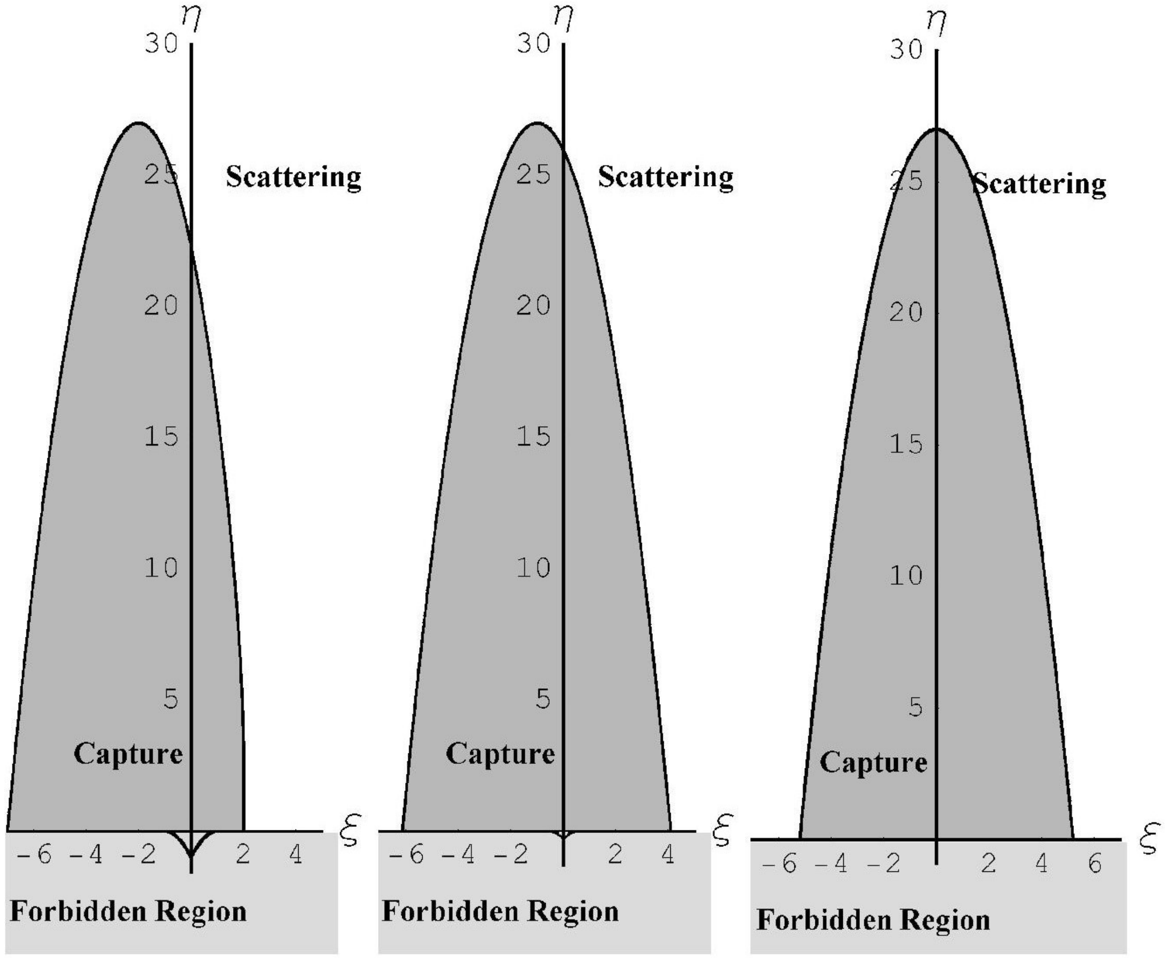
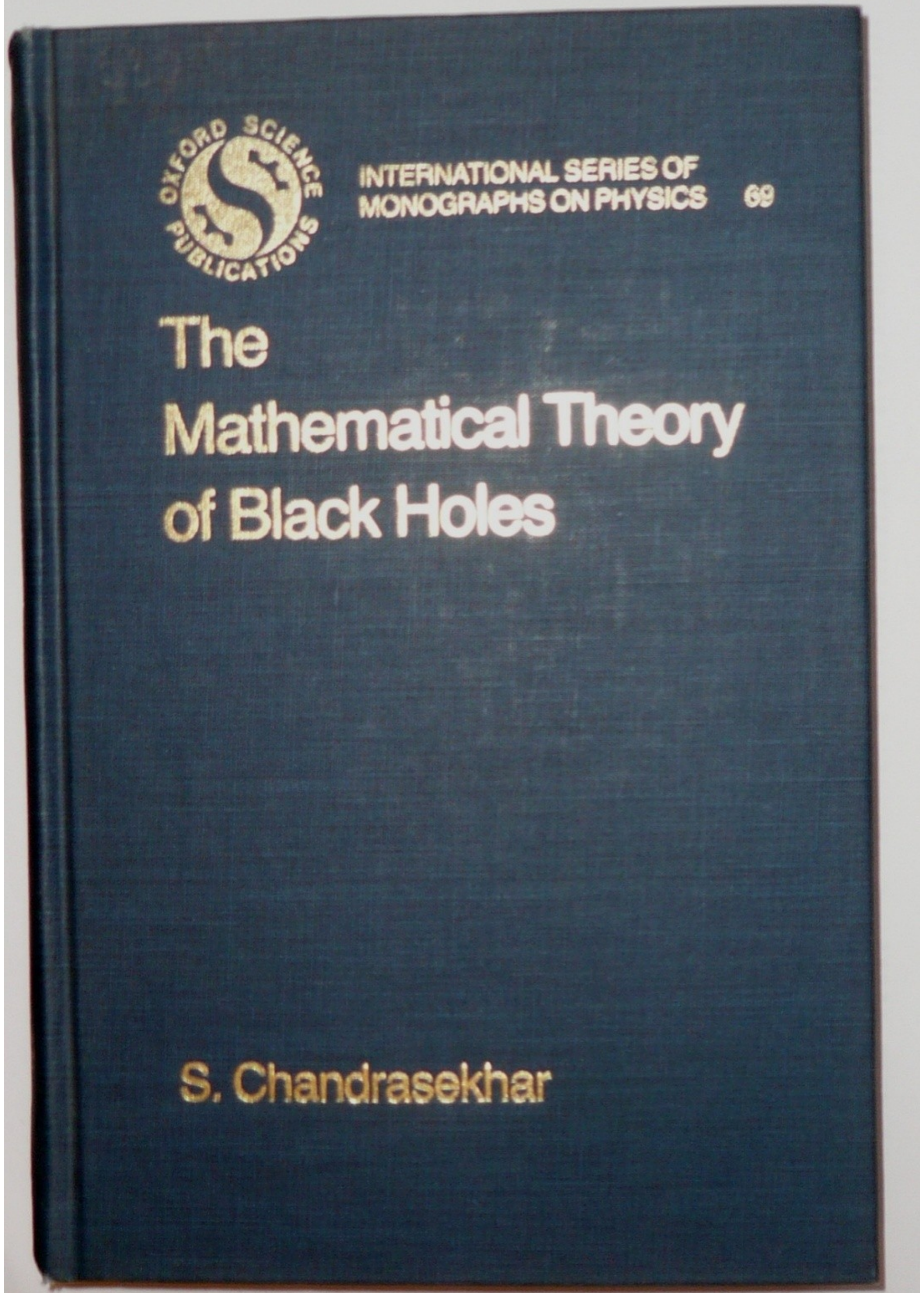


Fig. 1. Different types for photon trajectories and spin parameters ($a = 1., a = 0.5, a = 0.$). Critical curves separate capture and scatter regions. Here we show also the forbidden region corresponding to constants of motion $\eta < 0$ and $(\xi, \eta) \bar{\in} M$ as it was discussed in the text.



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The Mathematical Theory of Black Holes

S. Chandrasekhar

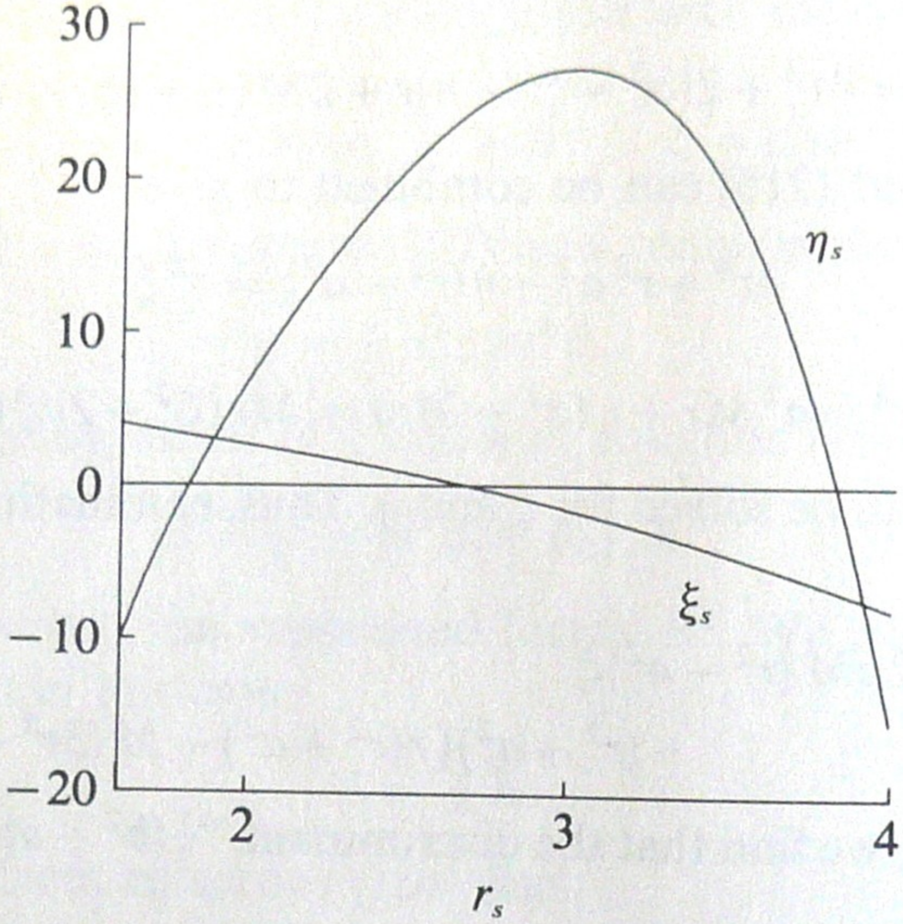

FIG. 34. The locus (ξ_s, η_s) determining the constants of the motion for three-dimensional orbits of constant radius described around a Kerr black-hole with $a = 0.8$. The unit of length along the abscissa is M.

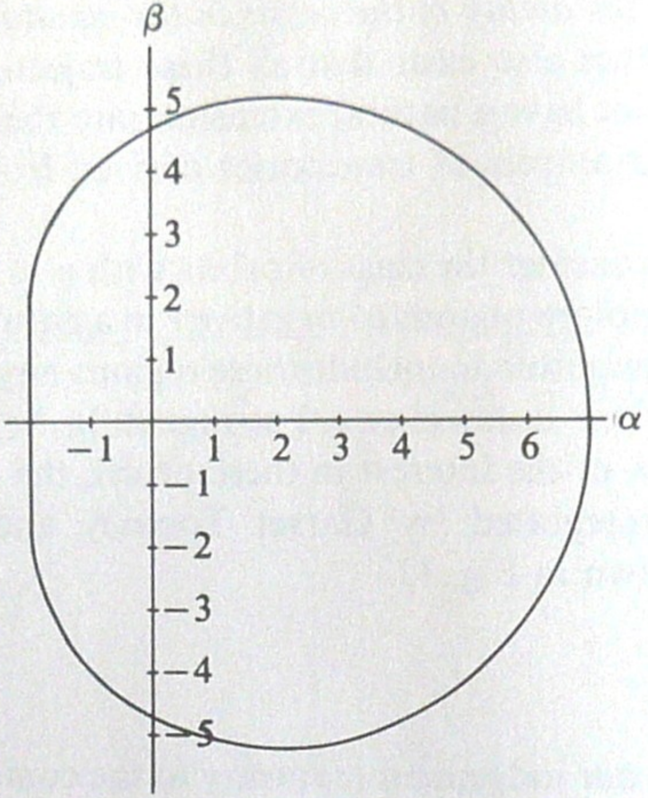

FIG. 38. The apparent shape of an extreme ($a = M$) Kerr black-hole as seen by a distant observer in the equatorial plane, if the black hole is in front of a source of illumination with an angular size larger than that of the black hole. The unit of length along the coordinate axes α and β (defined in equation (241) is M.

black hole from infinity, the apparent shape will be determined by

$$(\alpha, \beta) = [\xi, \sqrt{\eta(\xi)}]. \tag{242}$$

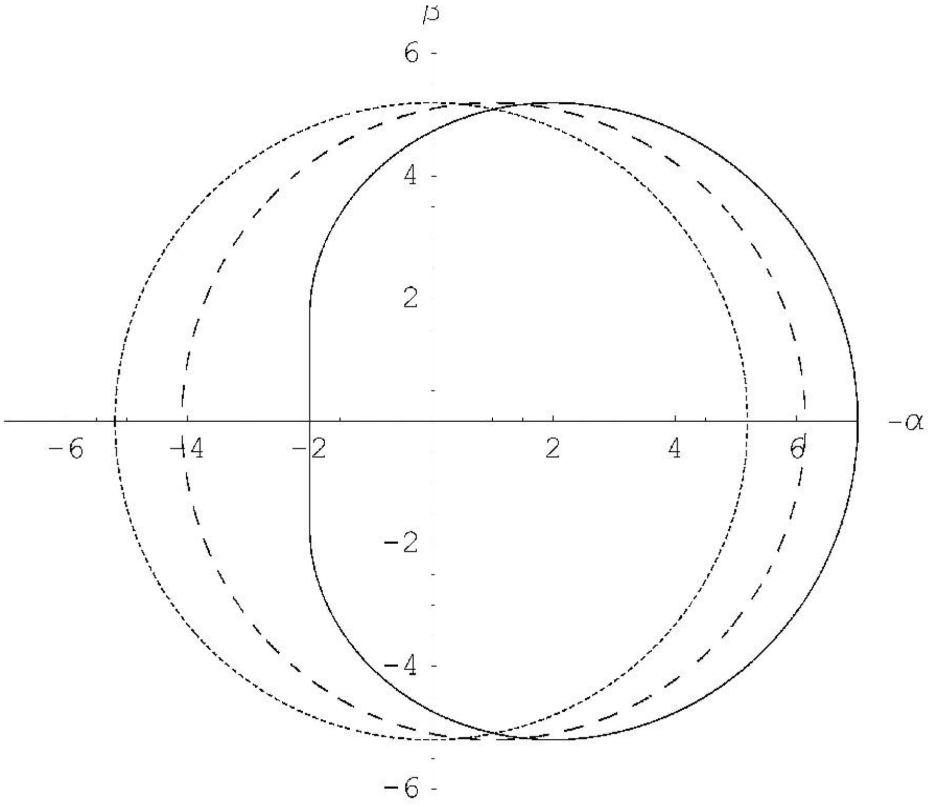

Fig. 2. Mirages around black hole for equatorial position of distant observer and different spin parameters. The solid line, the dashed line and the dotted line correspond to $a = 1, a = 0.5, a = 0$ correspondingly

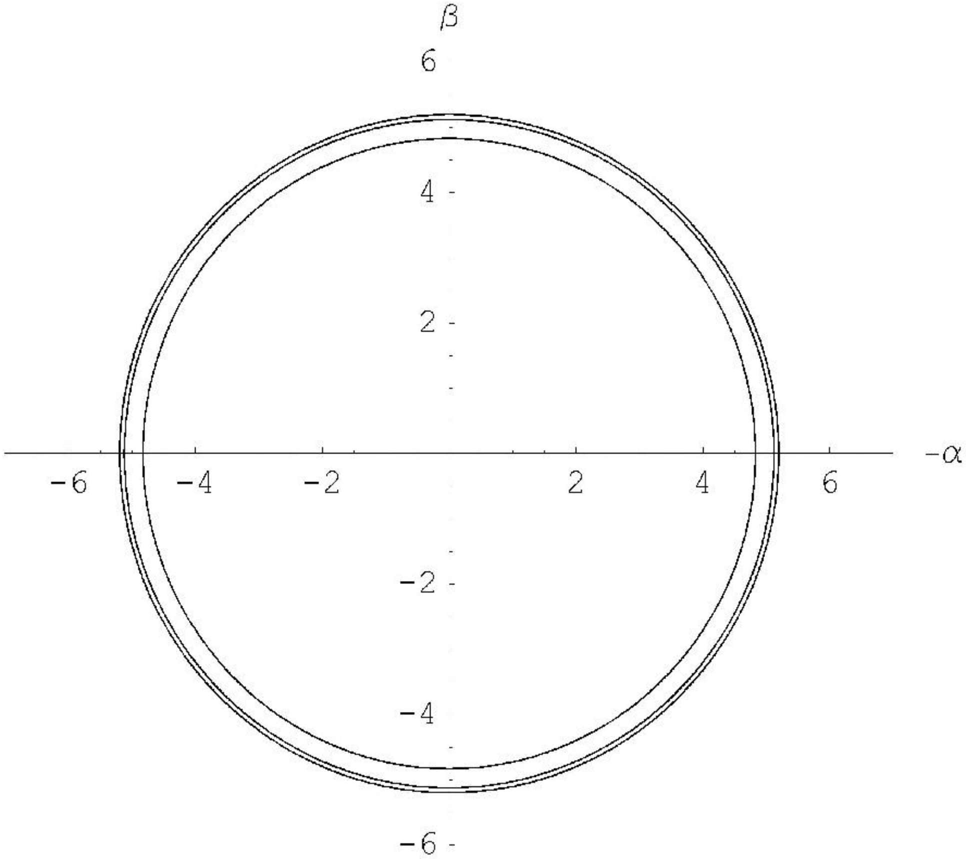

Fig. 3. Mirages around a black hole for the polar axis position of distant observer and different spin parameters ($a = 0, a = 0.5, a = 1$). Smaller radii correspond to greater spin parameters.

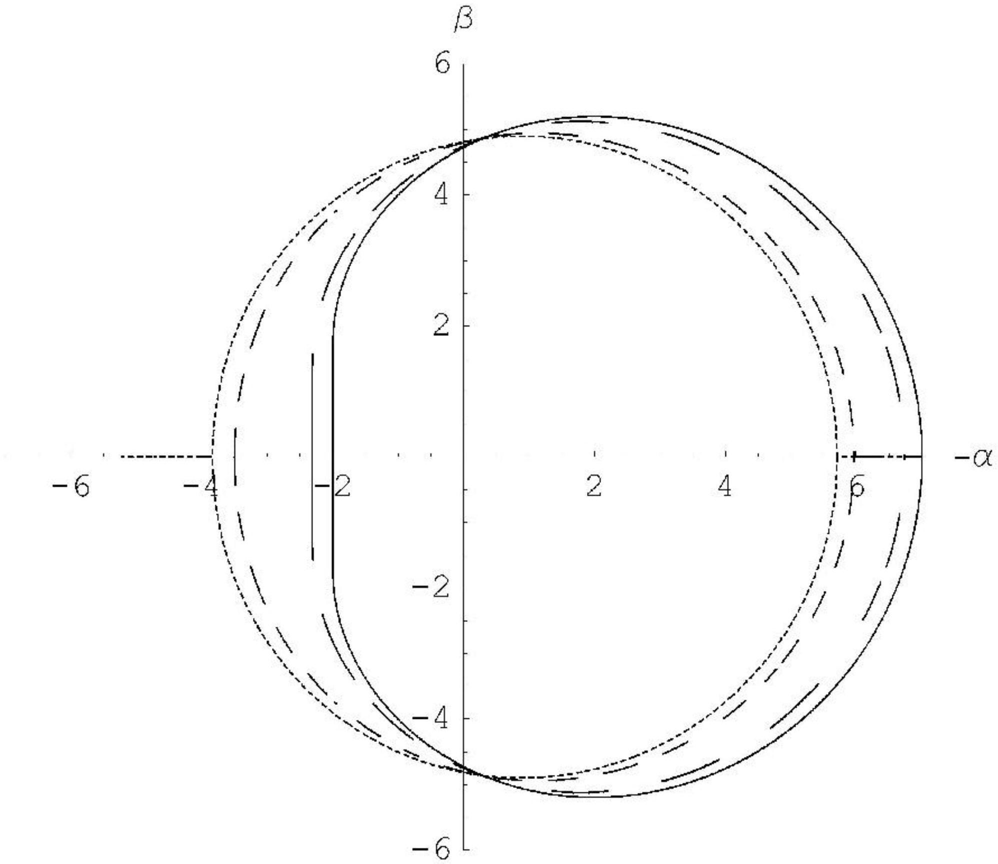

Fig. 5. Mirages around black hole for different angular positions of a distant observer and the spin $a = 1$. Solid, long dashed, short dashed and dotted lines correspond to $\theta_0 = \pi/2, \pi/3, \pi/6$ and $\pi/8$, respectively.

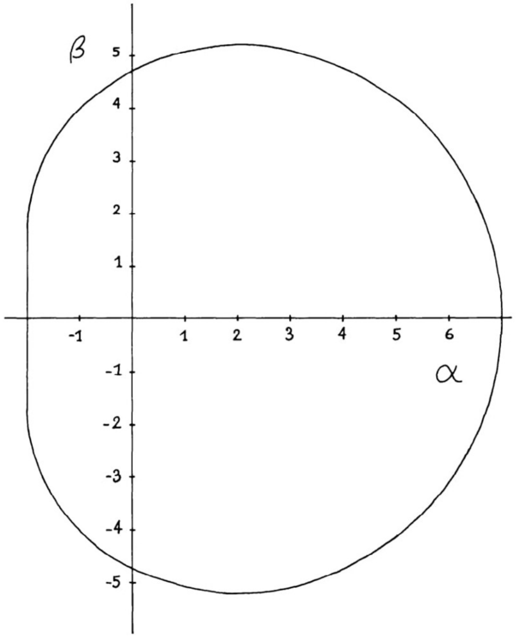

Figure 6. The apparent shape of an extreme ($a = m$) Kerr black hole as seen by a distant observer in the equatorial plane, if the black hole is in front of a source of illumination with an angular size larger than that of the black hole.

is largest there and because of the gravitational focusing effects associated with the bending of the rays toward the equatorial plane. Note that the radiation comes out along the flat portion of the apparent boundary of the extreme black hole as plotted in Figure 6.

D. Geometrical Optics

A detailed calculation of the brightness distribution coming from a source near a Kerr black hole requires more of geometrical optics than the calculation of photon trajectories. I will now review some techniques which are useful in making astrophysical calculations in connection with black holes.

The fundamental principle can be expressed as the conservation of photon density in phase space along each photon trajectory. A phase space element $d^3x\, d^3p$, the product of a proper spatial volume element and a physical momentum-space volume element in a local observer's frame of reference, is a Lorentz invariant, so the particular choice of local observer is arbitrary. The density $N(x^a, p^{(\beta)})$ is defined

James Maxwell Bardeen passed away on June 20, 2022
(Shadows +Kerr BHs as engines for quasars)

John Bardeen (1908 -1991), the father of J. M. Bardeen. E. Wigner was J. Bardeen’ supervisor

Direct Measurements of Black Hole Charge with Future Astrometrical Missions

A.F. Zakharov[1,2,3], F. De Paolis[4], G. Ingrosso[4], A.A. Nucita[4]

[1] Institute of Theoretical and Experimental Physics, 25, B.Cheremushkinskaya st., Moscow, 117259, Russia,

[2] Astro Space Centre of Lebedev Physics Institute, 84/32, Profsoyuznaya st., Moscow, 117810, Russia,

[3] Joint Institute for Nuclear Research, Dubna, Russia

[4] Department of Physics, University of Lecce and INFN, Section of Lecce, Via Arnesano, I-73100 Lecce, Italy

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Abstract. Recently, Zakharov et al. (2005a) considered the possibility of evaluating the spin parameter and the inclination angle for Kerr black holes in nearby galactic centers by using future advanced astrometrical instruments. A similar approach which uses the characteristic properties of gravitational retro-lensing images can be followed to measure the charge of Reissner-Nordström black hole. Indeed, in spite of the fact that their formation might be problematic, charged black holes are objects of intensive investigations. From the theoretical point of view it is well-known that a black hole is described by only three parameters, namely, its mass M, angular momentum J and charge Q. Therefore, it would be important to have a method for measuring all these parameters, preferably by model independent way. In this paper, we propose a procedure to measure the black hole charge by using the size of the retro-lensing images that can be revealed by future astrometrical missions. A discussion of the Kerr-Newmann black hole case is also offered.

Table 1. The fringe sizes (in micro arcseconds) for the standard and advanced apogees $B_{\max}$ (350 000 and 3 200 000 km, respectively).

$B_{\max}$(km)\λ(cm)	92	18	6.2	1.35
3.5×10^5	540	106	37	8
3.2×10^6	59	12	4	0.9

4. The space RADIOASTRON interferometer

The space-based radio telescope RADIOASTRON[1] is planned to be launched within few next years[2]. This space-based 10-m radio telescope will be used for space – ground VLBI observations. The measurements will have extremely high angular resolutions, namely about 1–10 μas (in particular about 8 μas at the shortest wavelength of 1.35 cm and a standard orbit[3], and could be about 0.9 μas for the high orbit configuration at the same wavelength. Four wave bands will be used corresponding to λ = 1.35 cm, λ = 6.2 cm, λ = 18 cm, λ = 92 cm (see Table 1). A detailed calculation of the high-apogee evolving orbits ($B_{\max}$) can be done, once the exact launch time is known.

After several years of observations, it should be possible to move the spacecraft to a much higher orbit (with apogee radius about 3.2 million km), by additional spacecraft maneuvering using the gravitational force of the Moon. The fringe sizes (in μas) for the apogee of the above-mentioned orbit and for all RADIOASTRON wavelengths are given in Table 1.

By comparing Figs. 1, 2 and Table 1, one can see that there are non-negligible chances to observe such mirages around the black hole at the Galactic Center and in nearby AGNs and microquasars in the radio-band using RADIOASTRON facilities.

We also mention that this high resolution in radio band will be achieved also by Japanese VLBI project VERA (VLBI Exploration of Radio Astrometry), since the angular resolution aimed at will be at the 10 μas level (Sawad-Satoh 2000; Honma 2001). Therefore, the only problem left is to have a powerful enough radio source to illuminate a black hole in order to have retro-lensing images detectable by such radio VLBI telescopes as RADIOASTRON or VERA.

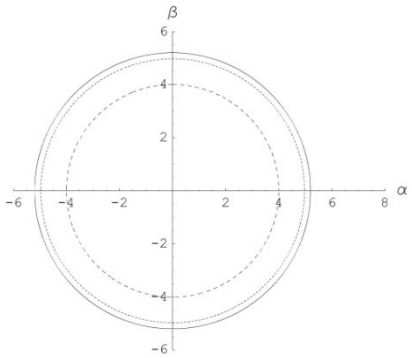

Fig. 1. Shadow (mirage) sizes are shown for selected charges of black holes $Q = 0$ (solid line), $Q = 0.5$ (short dashed line), and $Q = 1$ (long dashed line).

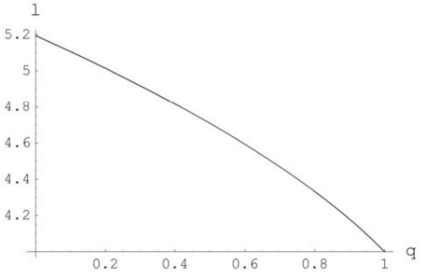

Fig. 2. The mirage radius l is shown as a function of the black hole charge q (l and q are given in units of M).

5. Searches for mirages near Sgr A^* with RADIOASTRON

Radio, near-infrared, and X-ray spectral band observations are developing very rapidly (Lo et al. 1998, 1999; Genzel et al. 2003; Ghez et al. 2004; Baganoff et al. 2001, 2003; Bower et al. 2002, 2003; Narayan 2003; Bower et al. 2004)[4], and it is known that Sgr A^* harbors the closest massive black hole with mass estimated to be $4.07 \times 10^6\ M_\odot$ (Bower et al. 2004; Melia & Falcke 2001; Ghez et al. 2003; Schodel et al. 2003).

Following the idea of Falcke et al. (2000) and of Zakharov et al. (2005a,b,c,d) we propose to use the VLBI technique to observe mirages around massive black holes and, in particular, towards the black hole at Galactic Center. To evaluate the shadow shape Falcke et al. (2000) used the ray-tracing technique. The boundaries of the shadows are black hole mirages.

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[1] See web-site `http://www.asc.rssi.ru/radioastron/` for more information.

[2] This project was proposed by the Astro Space Center (ASC) of Lebedev Physical Institute of the Russian Academy of Sciences (RAS) in collaboration with other institutions of RAS and RosAviaKosmos. Scientists from 20 countries are developing the scientific payload for the satellite by providing by ground-based support to the mission.

[3] The satellite orbit will have high apogee, and its rotation period around Earth will be 9.5 days, which evolves as a result of the weak gravitational perturbations from the Moon and the Sun. The perigee has been planned to be between 10^4 and 7×10^4 km and the apogee between 310 and 390 thousand kilometers. The basic orbit parameters will be the following: the orbital period is P = 9.5 days, the semi-major axis is a = 189 000 km, the eccentricity is e = 0.853, the perigee is H = 29 000 km.

[4] An interesting idea to use radio pulsars to investigate the region nearby black hole horizon was proposed recently by Pfahl & Loeb (2003).

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Constraints on a charge in the Reissner-Nordström metric for the black hole at the Galactic Center

Alexander F. Zakharov[*]

North Carolina Central University, Durham, North Carolina 27707, USA; Institute of Theoretical and Experimental Physics, Moscow 117218, Russia; Joint Institute for Nuclear Research, Dubna 141980, Russia; Institute for Computer Aided Design of RAS, 123056 Moscow, Russia; and National Research Nuclear University (NRNU MEPHI), 115409 Moscow, Russia

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Using an algebraic condition of vanishing discriminant for multiple roots of fourth-degree polynomials, we derive an analytical expression of a shadow size as a function of a charge in the Reissner-Nordström (RN) metric [1,2]. We consider shadows for negative tidal charges and charges corresponding to naked singularities $q = \mathcal{Q}^2/M^2 > 1$, where $\mathcal{Q}$ and M are black hole charge and mass, respectively, with the derived expression. An introduction of a negative tidal charge q can describe black hole solutions in theories with extra dimensions, so following the approach we consider an opportunity to extend the RN metric to negative $\mathcal{Q}^2$, while for the standard RN metric $\mathcal{Q}^2$ is always non-negative. We found that for $q > 9/8$, black hole shadows disappear. Significant tidal charges $q = -6.4$ (suggested by Bin-Nun [3–5]) are not consistent with observations of a minimal spot size at the Galactic Center observed in mm-band; moreover, these observations demonstrate that a Reissner-Nordström black hole with a significant charge $q \approx 1$ provides a better fit of recent observational data for the black hole at the Galactic Center in comparison with the Schwarzschild black hole.

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I. INTRODUCTION

Soon after the discovery of general relativity (GR), the first solutions corresponding to spherical symmetric black holes were found [1,2,6]; however, initially people were rather sceptical about possible astronomical applications of the solutions corresponding to black holes [7] (see also, for instance, one of the first textbooks on GR [8]). Even after an introduction to the black hole concept by Wheeler [9] (he used the term in his public lecture in 1967 [10]), we did not know too many examples where we really need GR models with strong gravitational fields that arise near black hole horizons to explain observational data. The cases where we need strong field approximation are very important since they give an opportunity to check GR predictions in a strong field limit; therefore, one could significantly constrain alternative theories of gravity.

One of the most important options to test gravity in the strong field approximation is analysis of relativistic line shape as it was shown in [11], with assumptions that a line emission is originated at a circular ring area of a flat accretion disk. Later on, such signatures of the Fe $K\alpha$ line have been found in the active galaxy MCG-6-30-15 [12]. Analyzing the spectral line shape, the authors concluded the emission region is so close to the black hole horizon that one has to use Kerr metric approximation [13] to fit observational data [12]. Results of simulations of iron $K\alpha$ line formation are given in [14,15] (where we used our approach [16]); see also [17] for a more recent review of the subject.

Now there are two basic observational techniques to investigate a gravitational potential at the Galactic Center, namely, (a) monitoring the orbits of bright stars near the Galactic Center to reconstruct a gravitational potential [18] (see also a discussion about an opportunity to evaluate black hole dark matter parameters in [19] and an opportunity to constrain some class of an alternative theory of gravity [20]) and (b) measuring in mm band, with VLBI technique, the size and shape of shadows around the black hole, giving an alternative possibility to evaluate black hole parameters. The formation of retro-lensing images (also known as mirages, shadows, or "faces" in the literature) due to the strong gravitational field effects nearby black holes has been investigated by several authors [21–24].

Theories with extra dimensions admit astrophysical objects (supermassive black holes in particular) which are rather different from standard ones. Tests have been proposed when it would be possible to discover signatures of extra dimensions in supermassive black holes since the gravitational field may be different from the standard one in the GR approach. So, gravitational lensing features are different for alternative gravity theories with extra dimensions and general relativity.

Recently, Bin-Nun [3–5] discussed the possibility that the black hole at the Galactic Center is described by the tidal Reissner-Nordström metric which may be admitted by the Randall-Sundrum II braneworld scenario [25]. Bin-Nun suggested an opportunity of evaluating the black hole

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[*] zakharov@itep.ru

$$\mathrm{Dis}(s_1,s_2,s_3,s_4)=\begin{vmatrix}1 & 1 & 1 & 1\\ X_1 & X_2 & X_3 & X_4\\ X_1^2 & X_2^2 & X_3^2 & X_4^2\\ X_1^3 & X_2^3 & X_3^3 & X_4^3\end{vmatrix}^2 = \begin{vmatrix}4 & p_1 & p_2 & p_3\\ p_1 & p_2 & p_3 & p_4\\ p_2 & p_3 & p_4 & p_5\\ p_3 & p_4 & p_5 & p_6\end{vmatrix}. \qquad (20)$$

Expressing the polynomials $p_k (1 \le k \le 6)$ in terms of the polynomials $s_k (1 \le k \le 4)$ and using Newton's equations we calculate the polynomials and discriminant of the family X_1, X_2, X_3, X_4 in roots of the polynomial $R(r)$; we obtain

$$\begin{aligned} &p_1 = s_1 = 0, \qquad p_2 = -2s_2, \qquad p_3 = 3s_3,\\ &p_4 = 2s_2^2 - 4s_4, \qquad p_5 = -5s_3s_2,\\ &p_6 = -2s_2^3 + 3s_3^2 + 6s_4s_2, \end{aligned} \qquad (21)$$

where $s_1 = 0$, $s_2 = -l$, $s_3 = -2l$, $s_4 = -ql$, corresponding to the polynomial $R(r)$ in Eq. (8). The discriminant Dis of the polynomial $R(r)$ has the form

$$\begin{aligned}\mathrm{Dis}(s_1,s_2,s_3,s_4) &= \begin{vmatrix}4 & 0 & 2l & -6l\\ 0 & 2l & -6l & 2l(l+2q)\\ 2l & -6l & 2l(l+2q) & -10l^2\\ -6l & 2l(l+2q) & -10l^2 & 2l^2(l+6+3q)\end{vmatrix}\\ &= 16l^3[l^2(1-q) + l(-8q^2+36q-27) - 16q^3]. \end{aligned} \qquad (22)$$

The polynomial $R(r)$ thus has a multiple root if and only if

$$l^3[l^2(1-q) + l(-8q^2+36q-27) - 16q^3] = 0. \qquad (23)$$

Excluding the case $l = 0$, which corresponds to a multiple root at $r = 0$, we find that the polynomial $R(r)$ has a multiple root for $r \ge r_+$ if and only if

$$l^2(1-q) + l(-8q^2+36q-27) - 16q^3 = 0. \qquad (24)$$

If $q = 0$, we obtain the well-known result for a Schwarzschild black hole [38,39,49], $l_{\mathrm{cr}} = 27$, or $\xi_{\mathrm{cr}} = 3\sqrt{3}$ [where l_{cr} is the positive root of Eq. (24)]. If $q = 1$, then $l = 16$, or $\xi_{\mathrm{cr}} = 4$, which also corresponds to numerical results given in paper [50]. The photon capture cross section for an extreme charged black hole turns out to be considerably smaller than the capture cross section of a Schwarzschild black hole. The critical value of the impact parameter, characterizing the capture cross section for a RN black hole, is determined by the equation

$$l_{\mathrm{cr}} = \frac{(8q^2-36q+27) + \sqrt{D_1}}{2(1-q)}, \qquad (25)$$

where $D_1 = (8q^2-36q+27)^2 + 64q^3(1-q) = -512(q-\frac{9}{8})^3$. It is clear from the last relation that there are circular unstable photon orbits only for $q \le \frac{9}{8}$ (see also results in [37] about the same critical value). Substituting Eq. (25) into the expression for the coefficients of the polynomial $R(r)$ it is easy to calculate the radius of the unstable circular photon orbit (which is the same as the minimum periastron distance). The orbit of a photon moving from infinity with the critical impact parameter, determined in accordance with Eq. (25) spirals into circular orbit. To find a radius of photon unstable orbit we will solve Eq. (7) substituting l_{cr} in the relation. From trigonometric formula for roots of cubic equation we have

$$r_{\mathrm{crit}} = 2\sqrt{\frac{l_{\mathrm{cr}}}{6}}\cos\frac{\alpha}{3}, \qquad (26)$$

where

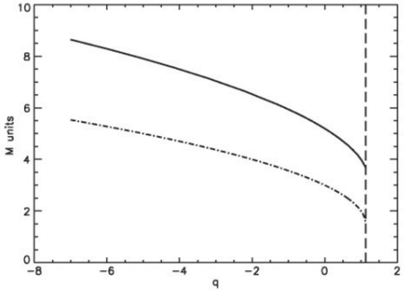

FIG. 1. Shadow (mirage) radius (solid line) and radius of the last circular unstable photon orbit (dot-dashed line) in M units as a function of q. The critical value $q = 9/8$ is shown with dashed vertical line.

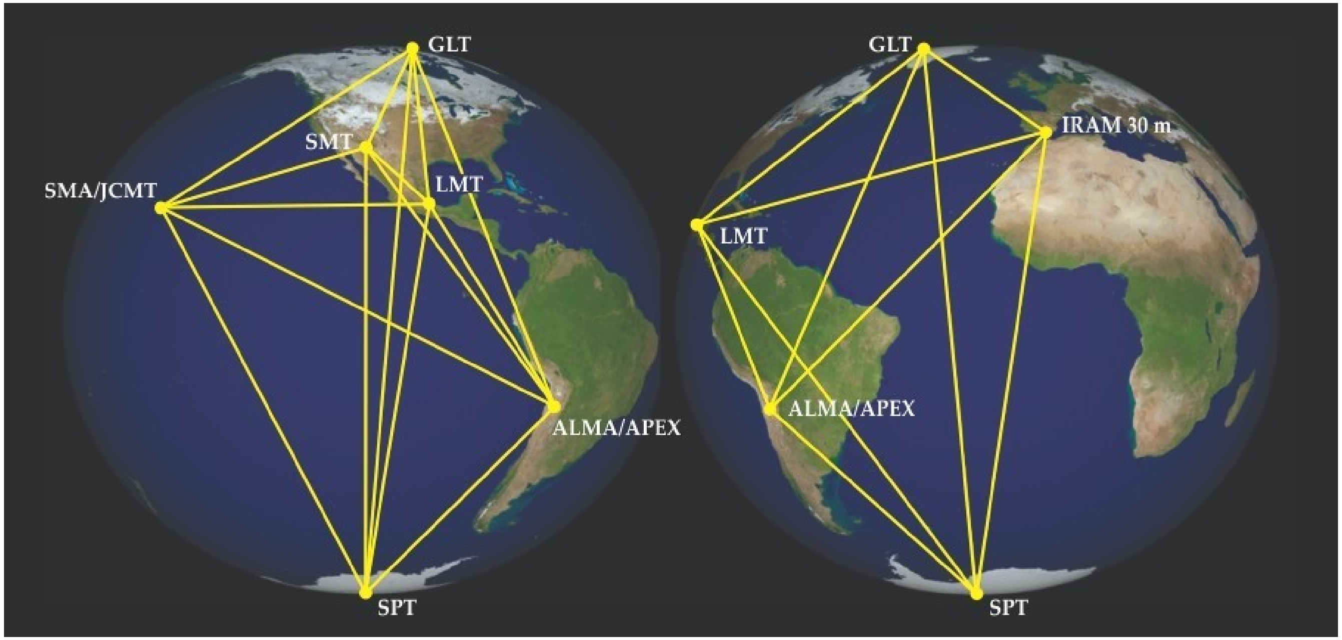

Figure 2. ***The Event Horizon Telescope*** *is a global array of millimeter telescopes (see http://eventhorizontelescope.org/array) that aims to take the first pictures of black holes. (Courtesy of Dan Marrone/University of Arizona.)*

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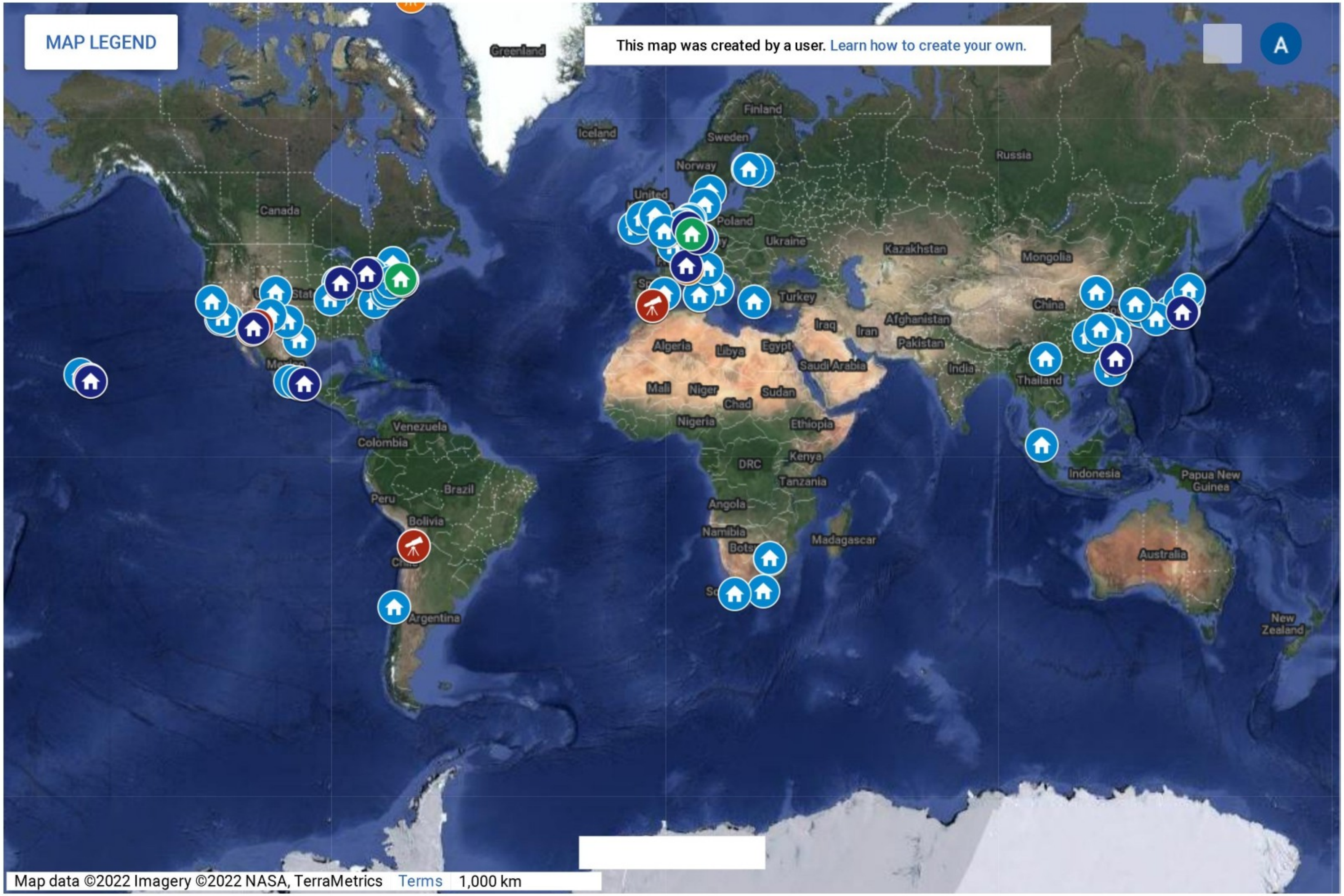
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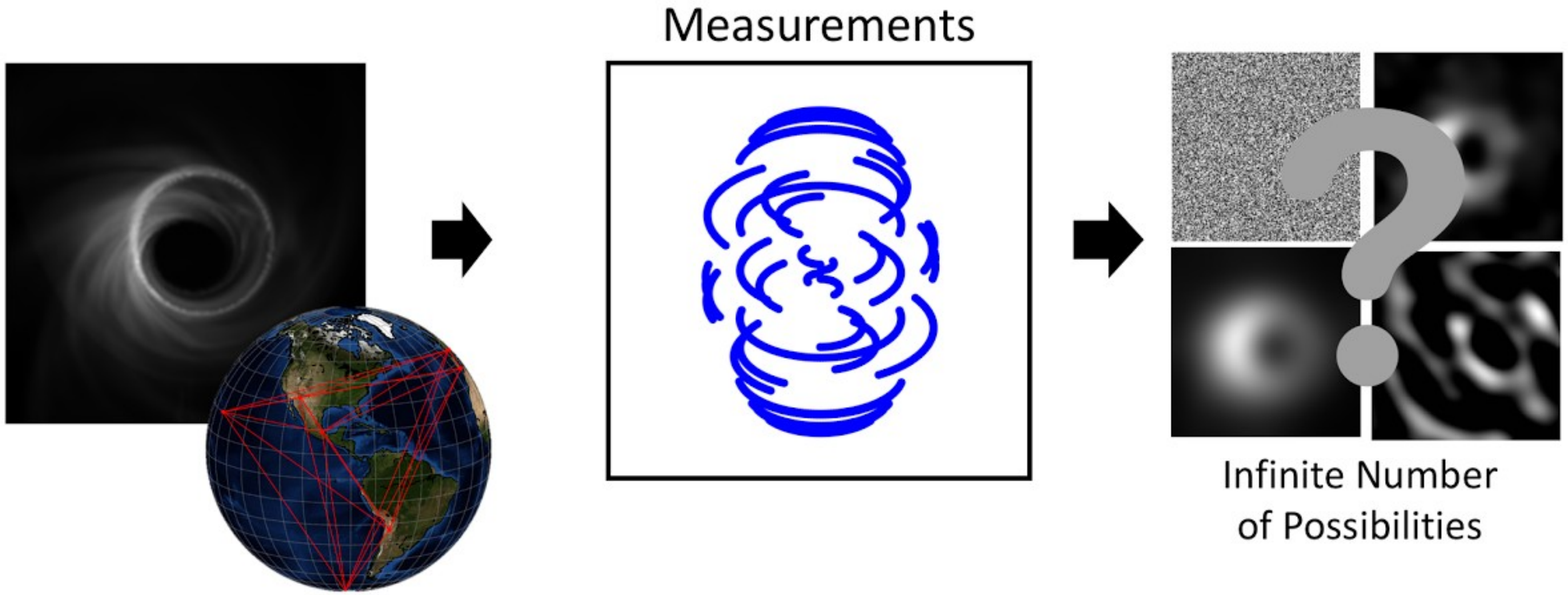
1,000 km

EHT team: “Similarly, for the EHT, the data we take only tells us only a piece of the story, as there are an infinite number of possible images that are perfectly consistent with the data we measure. But not all images are created equal— some look more like what we think of as images than others. To chose the best image, we essentially take all of the infinite images that explain our telescope measurements, and rank them by how reasonable they look. We then choose the image (or set of images) that looks most reasonable. “



PHYSICAL REVIEW D **103,** 104047 (2021)

Constraints on black-hole charges with the 2017 EHT observations of M87*

Prashant Kocherlakota,[1] Luciano Rezzolla,[1–3] Heino Falcke,[4] Christian M. Fromm,[5,6,1] Michael Kramer,[7]
Yosuke Mizuno,[8,9] Antonios Nathanail,[9,10] Héctor Olivares,[4] Ziri Younsi,[11,9] Kazunori Akiyama,[12,13,5] Antxon Alberdi,[14]
Walter Alef,[7] Juan Carlos Algaba,[15] Richard Anantua,[5,6,16] Keiichi Asada,[17] Rebecca Azulay,[18,19,7] Anne-Kathrin Baczko,[7]
David Ball,[20] Mislav Baloković,[5,6] John Barrett,[12] Bradford A. Benson,[21,22] Dan Bintley,[23] Lindy Blackburn,[5,6]
Raymond Blundell,[6] Wilfred Boland,[24] Katherine L. Bouman,[5,6,25] Geoffrey C. Bower,[26] Hope Boyce,[27,28]
Michael Bremer,[29] Christiaan D. Brinkerink,[4] Roger Brissenden,[5,6] Silke Britzen,[7] Avery E. Broderick,[30–32]
Dominique Broguiere,[29] Thomas Bronzwaer,[4] Do-Young Byun,[33,34] John E. Carlstrom,[35,22,36,37] Andrew Chael,[38,39]
Chi-kwan Chan,[20,40] Shami Chatterjee,[41] Koushik Chatterjee,[42] Ming-Tang Chen,[26] Yongjun Chen (陈永军),[43,44]
Paul M. Chesler,[5] Ilje Cho,[33,34] Pierre Christian,[45] John E. Conway,[46] James M. Cordes,[41] Thomas M. Crawford,[22,35]
Geoffrey B. Crew,[12] Alejandro Cruz-Osorio,[9] Yuzhu Cui,[47,48] Jordy Davelaar,[49,16,4] Mariafelicia De Laurentis,[50,9,51]
Roger Deane,[52–54] Jessica Dempsey,[23] Gregory Desvignes,[55] Sheperd S. Doeleman,[5,6] Ralph P. Eatough,[56,7]
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Colin Lonsdale,[12] Ru-Sen Lu (路如森),[43,44,7] Nicholas R. MacDonald,[7] Jirong Mao (毛基荣),[90–92] Nicola Marchili,[86,7]
Sera Markoff,[42,93] Daniel P. Marrone,[20] Alan P. Marscher,[76] Iván Martí-Vidal,[18,19] Satoki Matsushita,[17]
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Monika Moscibrodzka,[4] Cornelia Müller,[7,4] Gibwa Musoke,[42,4] Alejandro Mus Mejías,[18,19] Hiroshi Nagai,[13,48]
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Bart Ripperda,[106,16] Freek Roelofs,[4] Alan Rogers,[12] Eduardo Ros,[7] Mel Rose,[20] Arash Roshanineshat,[20] Helge Rottmann,[7]
Alan L. Roy,[7] Chet Ruszczyk,[12] Kazi L. J. Rygl,[86] Salvador Sánchez,[107] David Sánchez-Arguelles,[66,67] Mahito Sasada,[47,108]
Tuomas Savolainen,[109,110,7] F. Peter Schloerb,[97] Karl-Friedrich Schuster,[29] Lijing Shao,[7,71] Zhiqiang Shen (沈志强),[43,44]
Des Small,[79] Bong Won Sohn,[33,34,111] Jason SooHoo,[12] He Sun (孙赫),[25] Fumie Tazaki,[47] Alexandra J. Tetarenko,[112]
Paul Tiede,[31,32] Remo P. J. Tilanus,[4,64,113,20] Michael Titus,[12] Kenji Toma,[114,115] Pablo Torne,[7,107] Tyler Trent,[20]
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Maciek Wielgus,[5,6] George N. Wong,[62] Qingwen Wu (吴庆文),[120] Doosoo Yoon,[42] André Young,[4] Ken Young,[6]
Feng Yuan (袁峰),[43,68,121] Ye-Fei Yuan (袁业飞),[122] J. Anton Zensus,[7] Guang-Yao Zhao,[14] and Shan-Shan Zhao[43]

(EHT Collaboration)

[1]*Institut für Theoretische Physik, Goethe-Universität,*
Max-von-Laue-Strasse 1, 60438 Frankfurt, Germany
[2]*Frankfurt Institute for Advanced Studies, Ruth-Moufang-Strasse 1, 60438 Frankfurt, Germany*
[3]*School of Mathematics, Trinity College, Dublin 2, Ireland*
[4]*Department of Astrophysics, Institute for Mathematics, Astrophysics and Particle Physics (IMAPP),*
Radboud University, P.O. Box 9010, 6500 GL Nijmegen, Netherlands
[5]*Black Hole Initiative at Harvard University, 20 Garden Street, Cambridge, Massachusetts 02138, USA*

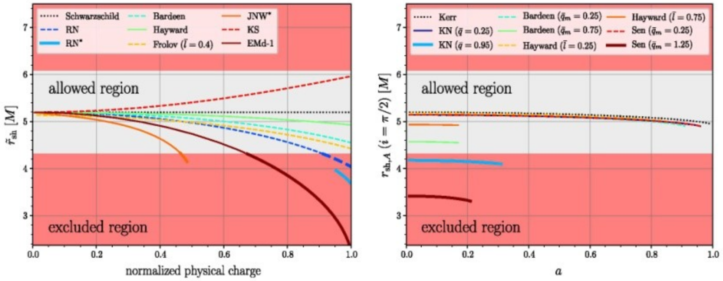


FIG. 2. Left: shadow radii $\tilde{r}_{\rm sh}$ for various spherically symmetric black-hole solutions, as well as for the JNW and RN naked singularities (marked with an asterisk), as a function of the physical charge normalized to its maximum value. The gray/red shaded regions refer to the areas that are 1-σ consistent/inconsistent with the 2017 EHT observations and highlight that the latter set constraints on the physical charges (see also Fig. 3 for the EMd-2 black hole). Right: shadow areal radii $r_{{\rm sh},A}$ as a function of the dimensionless spin a for four families of black-hole solutions when viewed on the equatorial plane ($i = \pi/2$). Also in this case, the observations restrict the ranges of the physical charges of the Kerr-Newman and the Sen black holes (see also Fig. 3).

independent charges—can also produce shadow radii that are incompatible with the EHT observations; we will discuss this further below. The two EMd black-hole solutions (1 and 2) correspond to fundamentally different field contents, as discussed in [70].

We report in the right panel of Fig. 2 the shadow areal radius $r_{{\rm sh},A}$ for a number of stationary black holes, such as Kerr [72], Kerr-Newman (KN) [73], Sen [74], and the rotating versions of the Bardeen and Hayward black holes [75]. The data refers to an observer inclination angle of $i = \pi/2$, and we find that the variation in the shadow size with spin at higher inclinations (of up to $i = \pi/100$) is at most about 7.1% (for $i = \pi/2$, this is 5%); of course, at zero-spin the shadow size does not change with inclination. The shadow areal radii are shown as a function of the dimensionless spin of the black hole $a := J/M^2$, where J is its angular momentum, and for representative values of the additional parameters that characterize the solutions. Note that—similar to the angular momentum for a Kerr black hole—the role of an electric charge or the presence of a de Sitter core (as in the case of the Hayward black holes) is to reduce the apparent size of the shadow. Furthermore, on increasing the spin parameter, we recover the typical trend that the shadow becomes increasingly noncircular, as encoded, e.g., in the distortion parameter $\delta_{\rm sh}$ defined in [57,83] (see Appendix). Also in this case, while the regular rotating Bardeen and Hayward solutions are compatible with the present constraints set by the 2017 EHT observations, the Kerr-Newman and Sen families of black holes can produce shadow areal radii that lie outside of the 1-σ region allowed by the observations.

To further explore the constraints on the excluded regions for the Einstein-Maxwell-dilaton 2 and the Sen black holes, we report in Fig. 3 the relevant ranges for these two solutions. The Einstein-Maxwell-dilaton 2 black holes are nonrotating but have two physical charges expressed by the coefficients $0 < \bar{q}_e < \sqrt{2}$ and $0 < \bar{q}_m < \sqrt{2}$, while the Sen black holes spin (a) and have an additional electromagnetic charge $\bar{q}_m$. Also in this case, the gray/red shaded regions refer to the areas that are consistent/inconsistent with the 2017 EHT observations. The figure shows rather easily that for these two black-hole families there are large

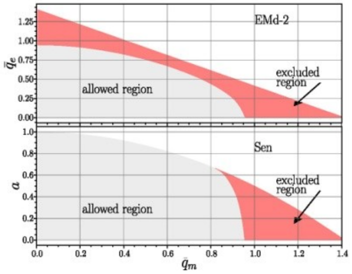
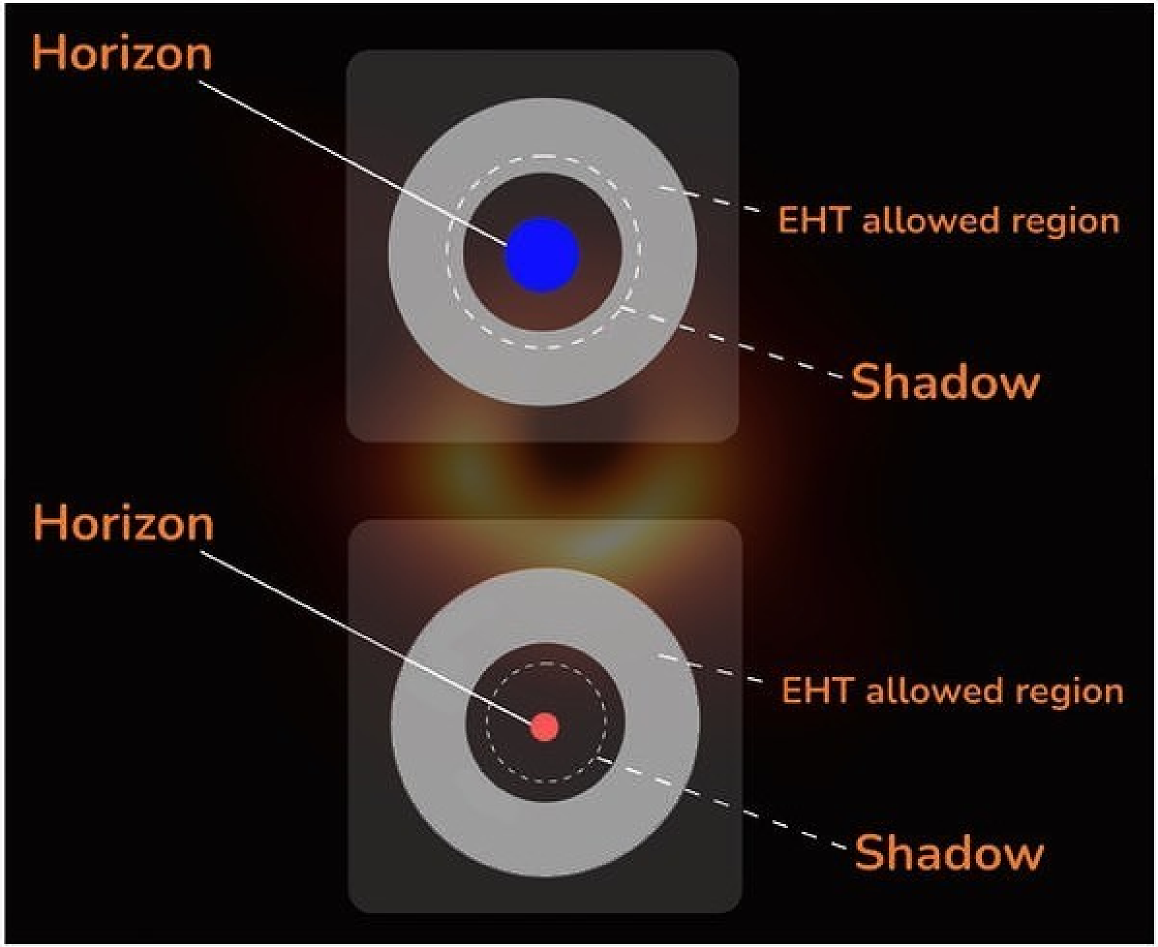
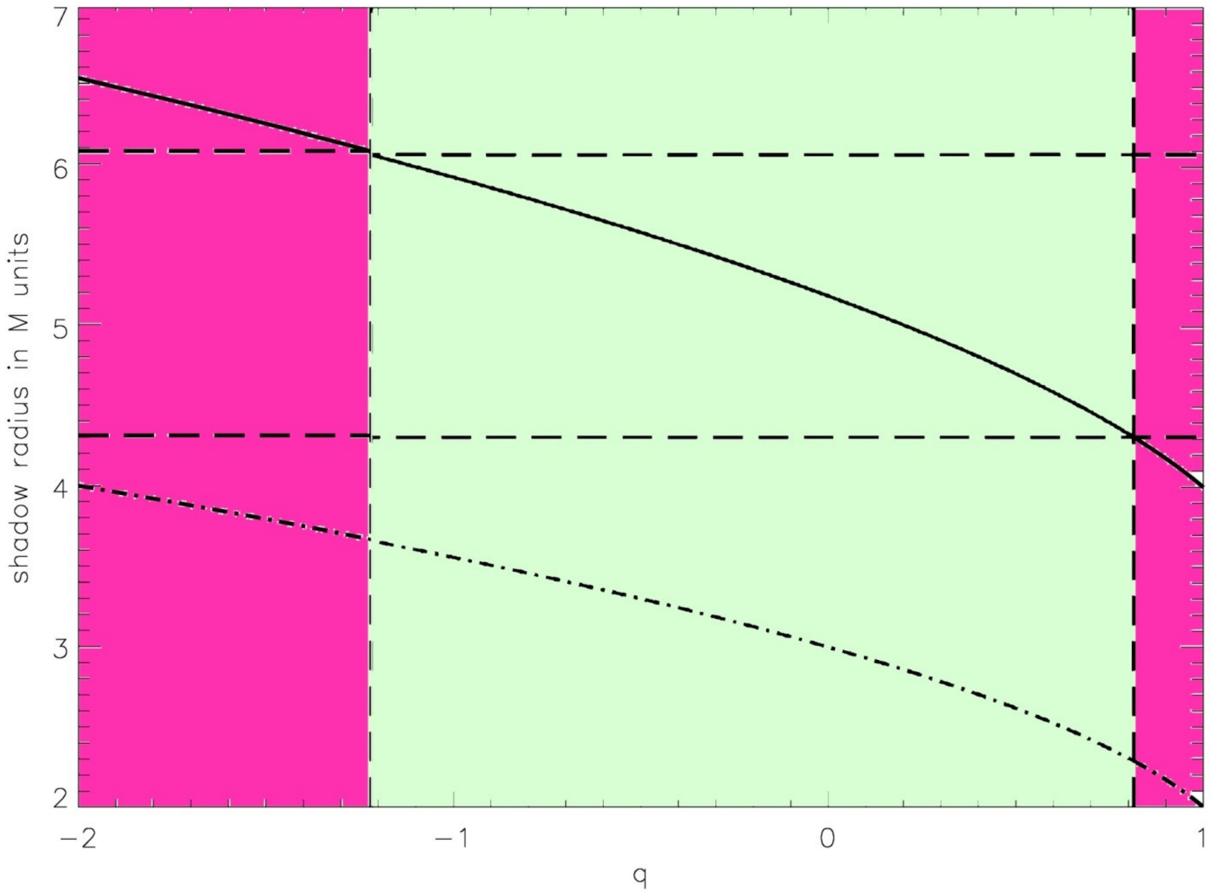


FIG. 3. Constraints set by the 2017 EHT observations on the nonrotating Einstein-Maxwell-dilaton 2 and on the rotating Sen black holes. Also in this case, the gray/red shaded regions refer to the areas that are 1-σ consistent/inconsistent with the 2017 EHT observations).


Horizon
EHT allowed region
Shadow
Horizon
EHT allowed region
Shadow

Zakharov, Universe, 2022; arxiv:2108.01533; charge constraint on M87* (for Sgr A* D=51.8±2.3 uas, 12.05.2022). For M87 D=D_Sch (1±0.17)

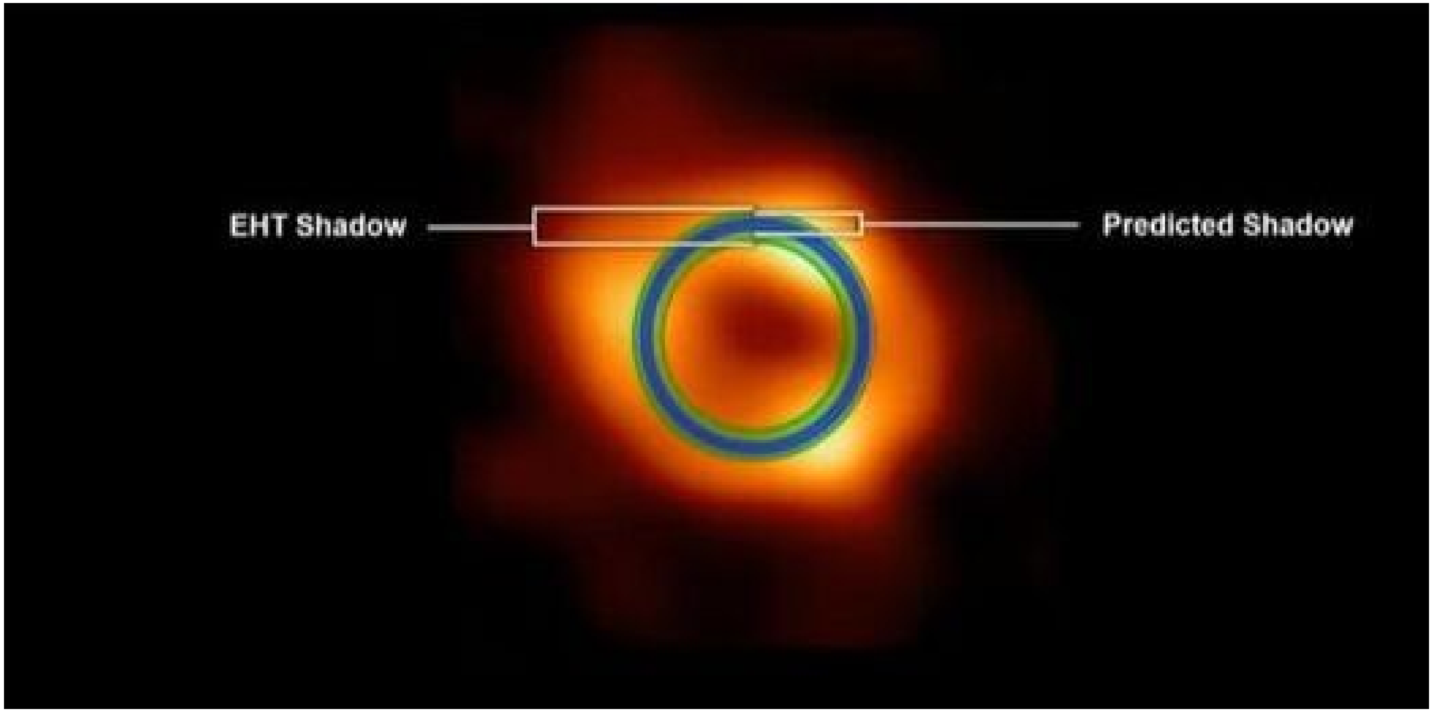


Sgr A* shadow discovery by EHT (reported on May 12, 2022)

Press Conferences around the world (Video Recordings):

Garching, Germany - European Southern Observatory
Madrid, Spain - Consejo Superior de Investigaciones Científicas
México D.F., Mexico - Consejo Nacional de Ciencia y Tecnología
Rome, Italy - Istituto Nazionale di Astrofisica
Santiago de Chile - ALMA Observatory
Washington D.C., USA - National Science Foundation
Tokyo, Japan - National Astronomical Observatory of Japan

For Sgr A* D=51.8±2.3 uas, (EHT collaboration, 12.05.2022)



A. F. Zakharov, Physics of Particle and Nuclei Lett. (2023)

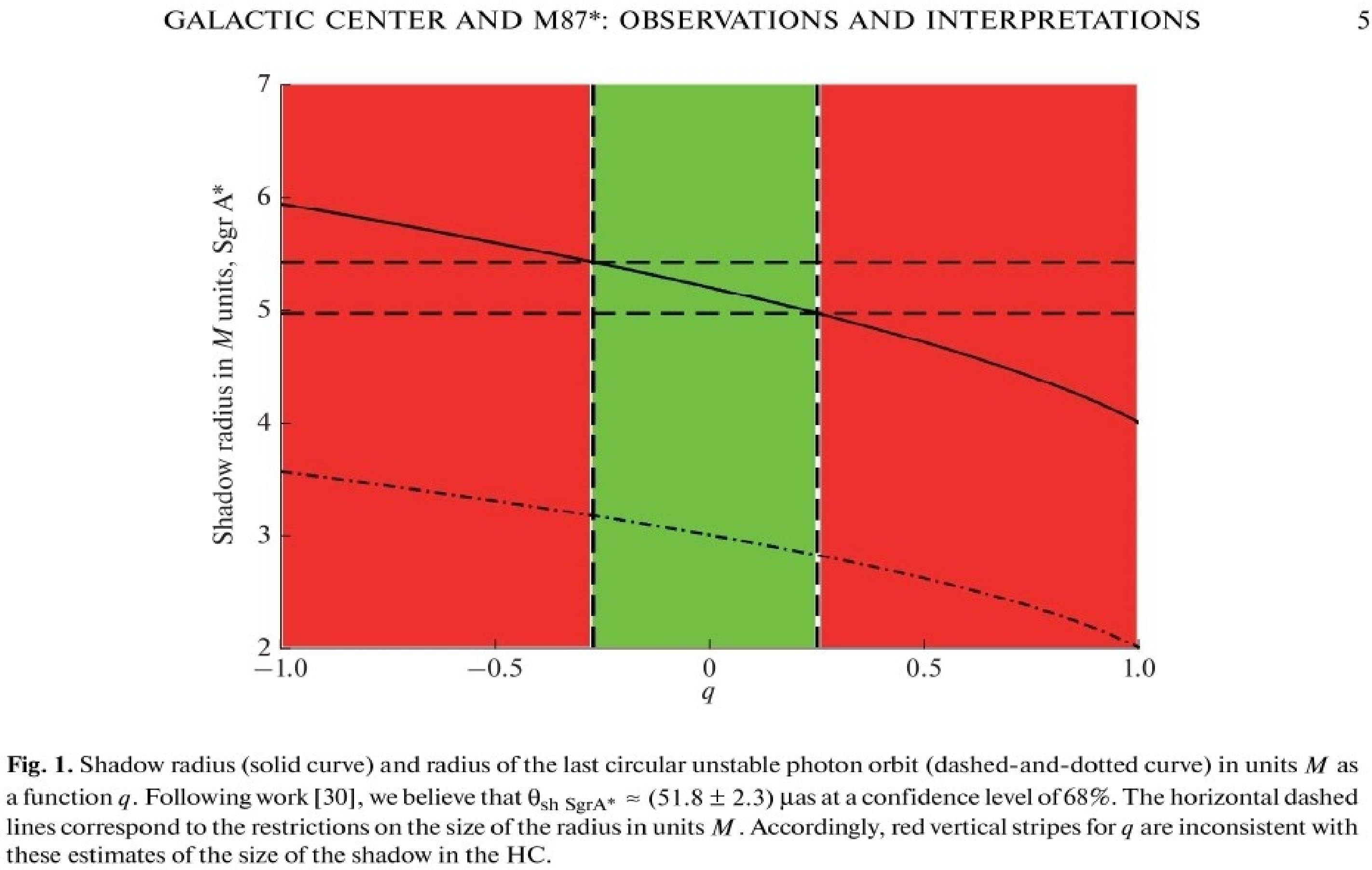


Fig. 1. Shadow radius (solid curve) and radius of the last circular unstable photon orbit (dashed-and-dotted curve) in units M as a function q. Following work [30], we believe that $\theta_{\text{sh SgrA*}} \approx (51.8 \pm 2.3)$ μas at a confidence level of 68%. The horizontal dashed lines correspond to the restrictions on the size of the radius in units M. Accordingly, red vertical stripes for q are inconsistent with these estimates of the size of the shadow in the HC.

Physics and Astronomy

In contrast to experimental physics we cannot control all parameters in astronomical system. In astronomy we have an opportunity only to observe, therefore we have to point out what, where and when to observe in the sky.

Example. All astrophysical BHs are surrounded with bulk distribution of matter (dust, gas, DM and stellar clusters near SMBH). If uncertainties in shadow reconstruction due bulk matter distribution are around 10^{-6} there is no reason to consider shadow deviation at a level 10^{-7}.

ЖЭТФ, 2024, том 165, вып. 4, стр. 508–515

НЕЛОКАЛЬНЫЕ ГРАВИТАЦИОННЫЕ ТЕОРИИ И ИЗОБРАЖЕНИЯ ТЕНЕЙ ЧЕРНЫХ ДЫР

С.О. Алексеев [a,b*], *А.А. Байдерин* [b], *А.В. Немтинова* [c], *О.И. Зенин* [b]

[a] *Государственный астрономический институт им. П. К. Штернберга,*
Московский государственный университет им. М. В. Ломоносова
119234, Москва, Россия

[b] *Кафедра квантовой теории и физики высоких энергий, физический факультет,*
Московский государственный университет им. М. В. Ломоносова
119234, Москва, Россия

[c] *Уральский федеральный университет им. первого Президента России Б. Н. Ельцина*
620002, Екатеринбург, Россия

Поступила в редакцию 28 ноября 2023 г.,
после переработки 4 декабря 2023 г.
Принята к публикации 4 декабря 2023 г.

С помощью метода Ньюмена–Яниса получено новое вращающееся решение «черная дыра» (ЧД) в гравитации с нелокальными поправками. Предложен способ учета поправок от квантовой гравитации при моделировании теней ЧД с использованием вращающихся метрик ЧД. Метод применим и для других нелокальных моделей с аналогичной структурой ЧД-решений. Показано, что в будущем при увеличении точности наблюдений и, следовательно, необходимости более точного их теоретического моделирования в некоторых случаях удобнее учитывать полевые и/или нелокальные поправки вместо введения новых полей.

DOI: 10.31857/S0044451024040059

1. ВВЕДЕНИЕ

Идея использования нелокальных членов в действии расширенных моделей гравитации обсуждается довольно продолжительное время [1]. Использование такого подхода дает еще одну возможность построить модель темной энергии. Нелокальные конструкции использовались, например, в моделях Рэндалл – Сандрума [2]. Отметим, что рассмотрение нелокальных членов позволило установить новые ограничения на гравитационные модели, используя

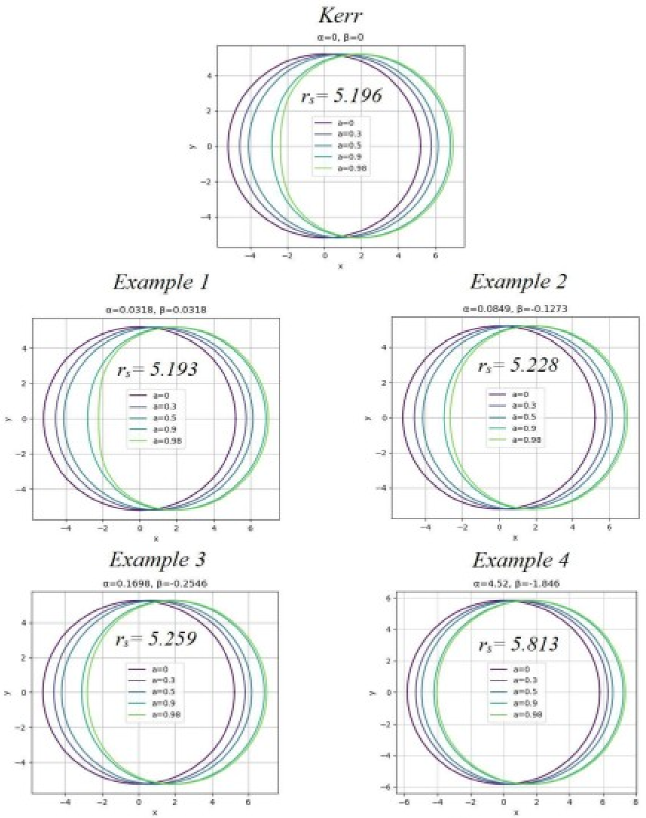
$$L = R + c_1 R^2 + c_2 R_{\mu\nu} R^{\mu\nu} + c_3 R_{\mu\nu\alpha\beta} R^{\mu\nu\alpha\beta} + \\ + \alpha R \log\frac{\Box}{\mu^2} R + \beta R_{\mu\nu} \log\frac{\Box}{\mu^2} R^{\mu\nu} + \\ + \gamma R_{\mu\nu\alpha\beta} \log\frac{\Box}{\mu^2} R^{\mu\nu\alpha\beta}, \tag{1}$$

где R — скаляр Риччи, $R_{\mu\nu}$ и $R_{\mu\nu\alpha\beta}$ — тензоры Риччи и Римана соответственно, c_i, α, β и γ — числовые коэффициенты, определенные в [4]. Решения вида «черная дыра» для действия (1) получено и имеет вид (в сигнатуре $(-,+,+,+)$)

$$ds^2 = -f_t dt^2 + f_r dr^2 + r^2 d\Omega^2, \tag{2}$$

где f_t, f_r — метрические функции,

$$f_t \simeq \left(1 - \frac{2G_n M}{r}\right) - \frac{\hat{\alpha}\hbar G_n^2 M}{r^3} + O(G_n^3),$$



ис. 2. Профили тени черной дыры при различных a для случая метрики Керра и различных фиксированных полей при угле наклона плоскости вращения $\theta_0 = \pi/2$

4. МОДЕЛИРОВАНИЕ ТЕНИ ЧЕРНОЙ ДЫРЫ ДЛЯ МЕТРИКИ (19)

После нескольких предварительных замечаний можно приступить к расчету зависимости разме-ра тени от α и β. Применяя гравитационные по-правки к метрике стабильной звезды, удовлетворя-ющей уравнению Толмена – Оппенгеймера – Волкова 18], мы вводим новые переменные $\alpha = \hat{\alpha}$ и $\beta = \hat{\beta}$, которые являются модельно-независимыми.

Необходимо отметить, что в качестве примеров мы используем значения коэффициентов из [4]. Та-ким образом, получены изображения теней ЧД для $M = 1$[1] и различных значений a для метрики Керра и ее расширения, определенные в [18] (в скалярном поле $\xi = 1/3$), см. рис. 2. Угол плоскости вращения равен $\theta_0 = \pi/2$. Заметим две основные особенности: во-первых, тень смещается от оси симметрии с увеличением a и, во-вторых, тень становится асимметричной вдоль направления x для больших значений a. Обе особенности исчезают при $a \to 0$, когда круглая тень для метрики Шварцшильда восстанавливается. Также заметим, что при угле $\theta_0 = \pi/2$ размер

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[1] Поскольку в реальном случае $M = 10^{44}$, эффект исчезает, как было указано во Введении.

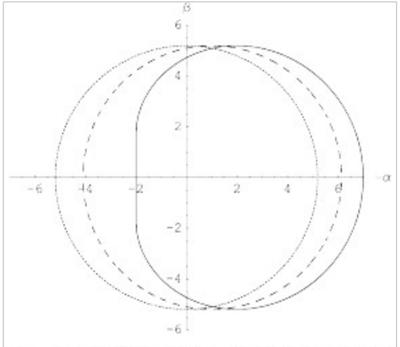


Fig. 2. Mirages around black hole for equatorial position of distant observer and different spin parameters. Solid line, dashed line and dotted lines correspond to $a = 1$, $a = 0.5$, $a = 0$, respectively.

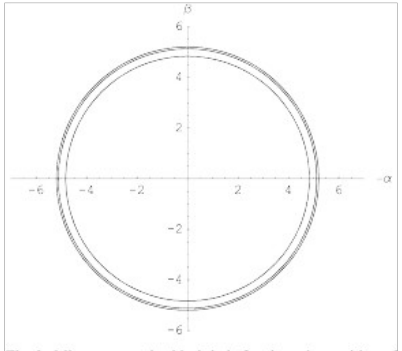


Fig. 3. Mirages around a black hole for the polar position of distant observer and different spin parameters ($a = 0$, $a = 0.5$, $a = 1$). Smaller radii correspond to greater spin parameters.

4. Polar axis observer case

If the observer is located along the polar axis we have $\theta_0 = 0$ and from Eq. (6), we obtain

$$\beta(\alpha) = (\eta_{\text{crit}}(0) + a^2 - \alpha^2(\xi))^{1/2}. \tag{9}$$

or

$$\beta^2(\alpha) + \alpha^2 = \eta_{\text{crit}}(0) + a^2.$$

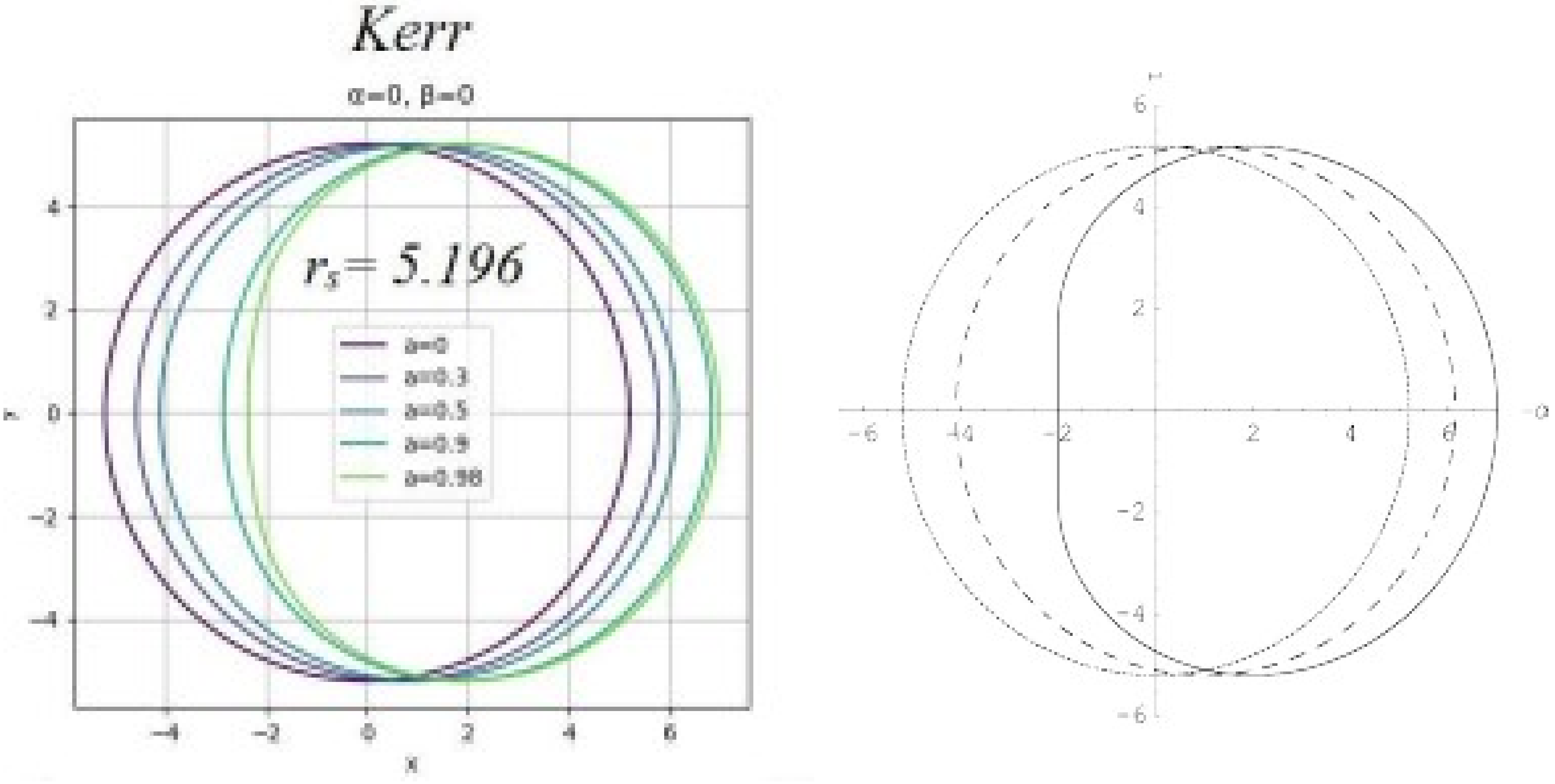
Thus, mirages around Kerr black hole
cles and even for this case in princi
evaluate the black hole spin (if the bla
is known) taking into account that rad
cles weakly depend on the black hole
ter. However, one should mention th
small difference between radii for di
even in the future it is unlikely to be ab
black hole spins in this way (see Tabl

5. General case for the angular positio observer

Let us consider different values fo
positions of a distant observer $\theta =$
π/8 for the spin parameter $a = 0.5$
θ = π/2, π/3, π/4 and π/6 for $a = 1$. (F
these figures one can see that angu
of a distant observer could be evalua
mirage shapes only for rapidly rotatin
($a \sim 1$), but there are no chances to
angles for slowly rotating black ho
even for $a = 0.5$ the mirage shape d
too small to be distinguishable by
Indeed, mirage shapes weakly depen
server angle position for moderate bl
parameters.

6. Projected parameters of the space RADIOASTRON interferometer

During this decade the space ra
RADIOASTRON will be launched.
was initiated by Astro Space Cent
Lebedev Physical Institute of Russi
of Sciences (RAS) in collaboration
institutions of RAS and RosAviaKo
tists from 20 countries develop the s
load for the satellite and will provi
base support of the mission. The pro
proved by RAS and RosAviaKos
smoothly developing. This space ba
radio telescope will be used for



Comparison of these figures Alexeyev et. al (2024) [*a=0, a=0.3, a=0.5, 0.9, 0.98*] and Zakharov et al. (2005) [*a=0, a=0.5, a=1*.]

Concerns on Alexeyev et al. paper (2024)

1. The conventional model for SMBH is describing by Kerr metric (even electric charge is usually considered as negligible). No hair theorem for BHs. There are no observational arguments to violate no hair theorem conditions.

2. “Quantum” black holes approach is applicable for microscopic objects while shadows could observable only for SMBHs. Therefore, such objects look like centaurs which do not exist in nature. The authors increased “quantum” parameters in 10^{44} times but they ignored natural astronomical factors such as bulk distribution of matter. Therefore, the authors from observable phenomena came back to thought experiments. «One step forward, two steps back».

3. The authors discussed an invariance of shadow size in the rotation axis direction for Kerr metric and an equatorial observer (this property was proven in Zakharov et al. (NA, 2005)). The property was discussed for “quantum” rotational black holes without a proof.

4. For K-N BHs circular photon orbits determine shadows but for generalizations of K-N these metrics these two categories are not equivalent. There are examples of circular photon orbits without shadows and shadows without black holes. The authors did not prove that they really deal with shadows (not with circular photon orbits).

5. The authors did not mention that GC shadow was reconstructed by EHT as it was predicted by Zakharov et al. (NA, 2005) in spite of the fact that predictions are realized extremely rarely (usually after observing a phenomenon, its interpretations appear).

COMMENT ON THE ARTICLE "NON-LOCAL GRAVITATIONAL CORRECTIONS IN BLACK HOLE SHADOW IMAGES" BY S. O. ALEXEYEV ET AL.

Alexander F. Zakharov [a,b]

[a] *National Research Center – "Kurchatov Institute", Moscow*

[b] *Bogoliubov Laboratory of Theoretical Physics, JINR, 141980 Dubna, Russia*

Recently Alexeyev et al. published paper (J. Theor. Exper. Phys. v. 165, N 4, p. 508 in Russian; arXiv:2404.16079 [gr-qc], the reference is given also in [1]). In the paper the authors discussed an opportunity of estimating spins from the analysis of the shadow reconstruction of black holes, theoretically considered using the nonlocal gravity model proposed earlier for the description of "quantum" black holes. However, in essence, this paper considered circular photon orbits, and the fact that the corresponding motion parameters determine the shape and size of shadows, similarly to Kerr black holes, remained unproven. It is also remained unproven the statement that for an equatorial observer the shadow size in the direction of rotation of "quantum" black holes remains independent of spin. A long time ago the shadow property was established for the Kerr black hole case.

Many years ago it was shown [2] that if we consider the constants of motion for classical Kerr black holes, the capture region and the scattering region for photons are separated by the Chandrasekar constants of motion (ξ, η) corresponding to circular photon orbits. Thus, for the Kerr metric, the shape and size of the shadow is determined by these critical parameter values (as shown in [3]). As is known, the possibility of shadow reconstruction in the neighborhood of the nearest supermassive black holes is currently under discussion, not only for classical Kerr–Newman black holes, but also for some of their "quantum" generalizations, although in some cases quantum corrections are used to recover shadows in the vicinity of the nearest supermassive black holes. in some cases quantum corrections in the corresponding coefficients are too small for their influence on the physical effects to be detected (this is also noted by the authors of the paper [1]).

If we mean a purely theoretical discussion, we can analyze the differences of shadows for the classical Kerr black hole and its "quantum" generalization, considered in the work of [1], but it is necessary to keep in mind that if we speak about astrophysical black holes, it is necessary to take into account the influence of such factors as the spatial mass distribution, the influence of plasma effects, etc., since the influence of these factors significantly exceeds the difference in the shape and size of shadows for the cases of a classical black hole and its quantum generalization. In paper [3] it is shown that for a classical Kerr black hole in the case of the observer's position in the equatorial plane, the size of the shadow in the direction of the black hole's rotation does not depend on the spin of the black hole. The authors of the paper [1] note that in the examples considered by them the size of shadows for the "quantum" generalization of the Kerr black hole for an observer in the equatorial plane is also independent of spin, however it remains unproven that for additional parameters (due to the use of the model of nonlocal gravitation), the sizes of shadows in the rotation direction for the considered "quantum" generalization of the Kerr black hole for an observer in the equatorial plane, do not depend on spin.

After the discovery of any physical (or astronomical) phenomenon, there is also its theoretical explanation, but very often theoretical predictions are not realized in experiments or astronomical observations. are realized in experiments or astronomical observations, so it is useful to recall that the the idea to use ground-based and ground-based space-based VLBI operating in the millimeter or submillimeter range to reconstruct the shadow in the vicinity of the Galactic center was proposed in [3] (which can naturally be generalized to other supermassive black holes, such as the black hole at the center of the galaxy M87). The possibility of reconstructing the shadow of a black hole at the Galactic Center using global ground-space (and ground-based) interferometers operating in the mm band was *firstly*

nature

NEWS | 04 September 2024

Publishing nightmare: a researcher's quest to keep his own work from being plagiarized

A scientist reviewing a study spotted figures that looked identical to his own, leading to a frustrating campaign to prevent its publication.

By Dan Garisto

When bioinformatician Sam Payne was asked to review a manuscript on a topic relevant to his own work, he agreed – not anticipating just how relevant it would be.

When bioinformatician Sam Payne was asked to review a manuscript on a topic relevant to his own work, he agreed – not anticipating just how relevant it would be.

The manuscript, which was sent to Payne in March, was about a study on the effect of cell sample sizes for protein analysis. “I immediately recognized it,” says Payne, who is at Brigham Young University in Provo, Utah. The text, he says, was similar to that of a paper[1] he’d authored three years earlier, but the most striking feature was the plots: several were identical down to the last data point. He fired off an e-mail to the journal, *BioSystems*, which promptly rejected the manuscript.

In July, Payne discovered that the manuscript had been published[2] in the journal *Proteomics*, and he alerted the editors. On 15 August, the journal retracted the paper. An accompanying statement cited “major unattributed overlap between the figures” in it and Payne’s work. In response to questions from *Nature*, a spokesperson for Wiley, which publishes *Proteomics*, said, “This paper was simultaneously submitted to multiple journals and included plagiarized images.”

The retraction statement also stated that four of the authors said they “did not participate in the writing and submission of the article and gave no consent for publication”, and that the fifth author did not respond. However, *Nature*’s news team found links between several of the authors and International Publisher, a paper mill based in Moscow. Neither the authors nor International Publisher responded to *Nature*’s requests for comment.

RELATED

AI is complicating plagiarism. How should scientists respond?

A VERY CLOSE MATCH

The figure on the left appears in a paper published in 2021 by bioinformatician Sam Payne and his co-authors. The figure on the right appears in a paper published in the journal *Proteomics* in May 2024 by other authors. The *Proteomics* paper was retracted in August.

Fig. 1a Boekwig *et al.* 2021

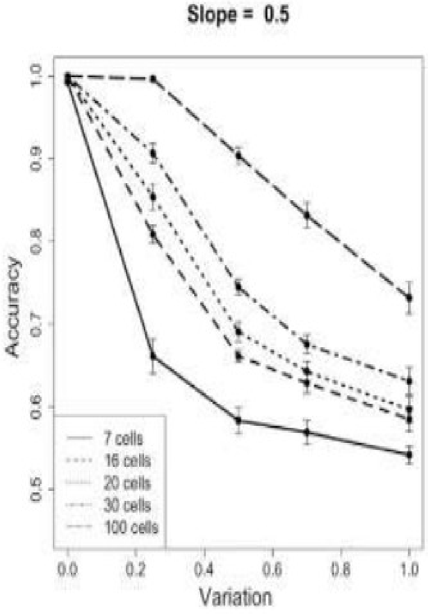
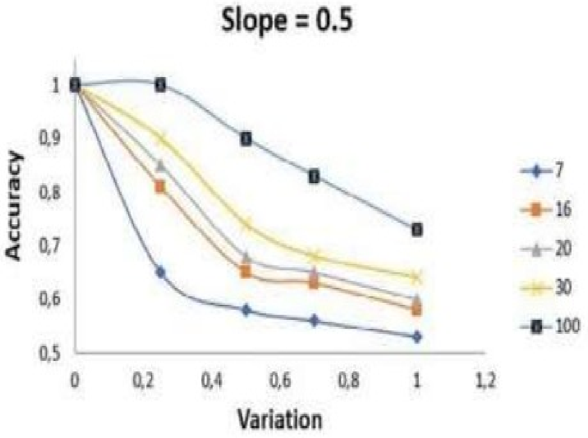


Fig. 3a Popova *et al.* 2024



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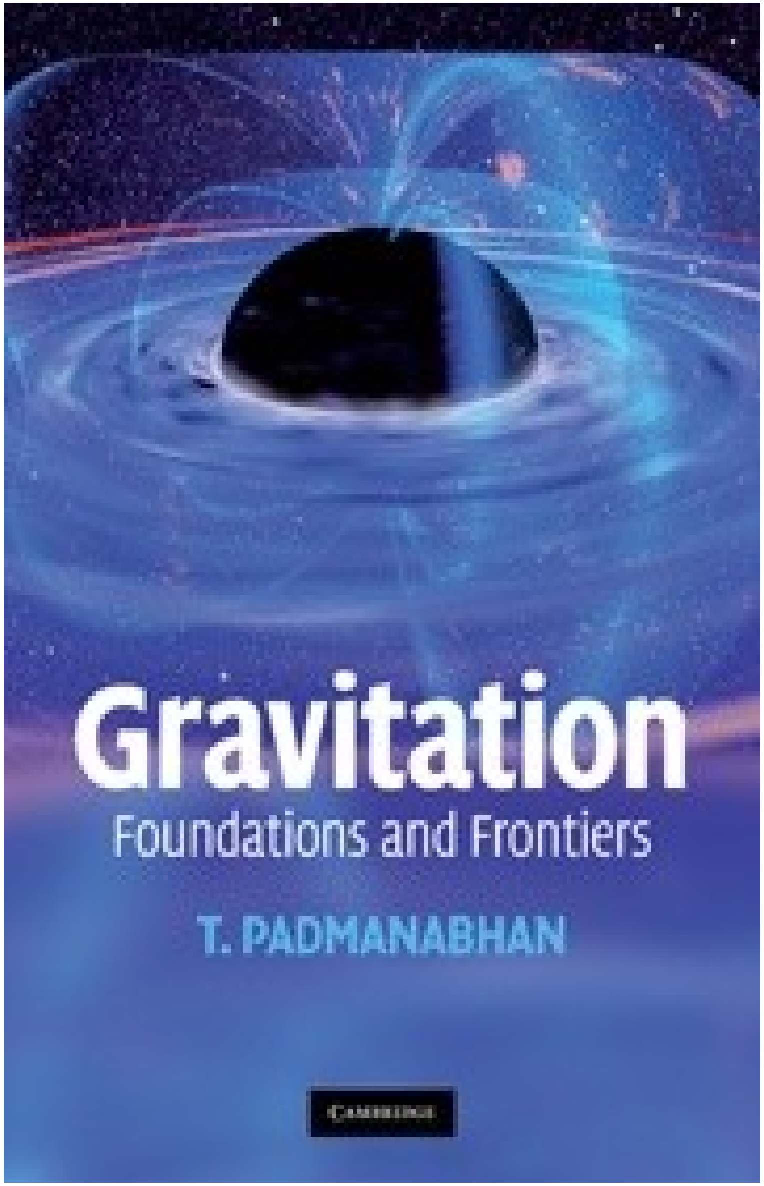
Source: Ref. 1 and Ref. 2

When, months later, he discovered the *Proteomics* paper, he posted a follow-up. "Well. It REALLY happened" — the paper that he had been asked to review had been published. Two weeks later, *Proteomics* retracted the paper, citing


Nature's
10

[Anna Abalkina]... She was shocked to find that a PhD student had plagiarized two of her papers, copying large parts of the works. When she complained, the journal issued only a correction, saying that the author forgot to reference her work. (The student later gave up their degree after Abalkina applied pressure to their university.)



Gravitation
Foundations and Frontiers

T. PADMANABHAN

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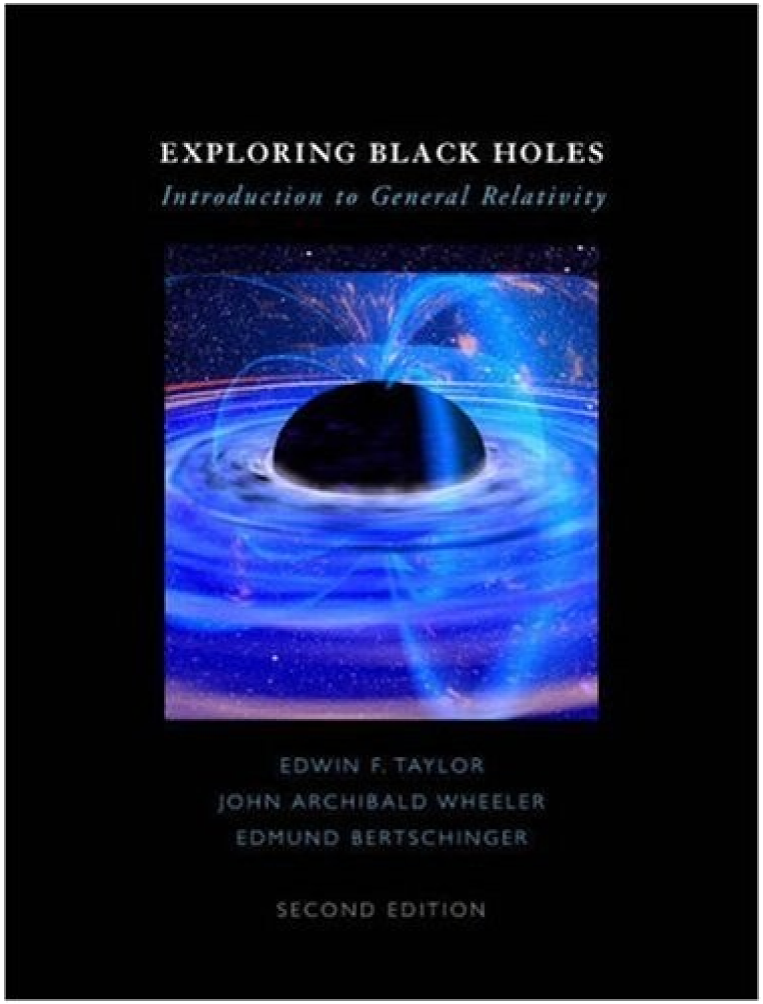
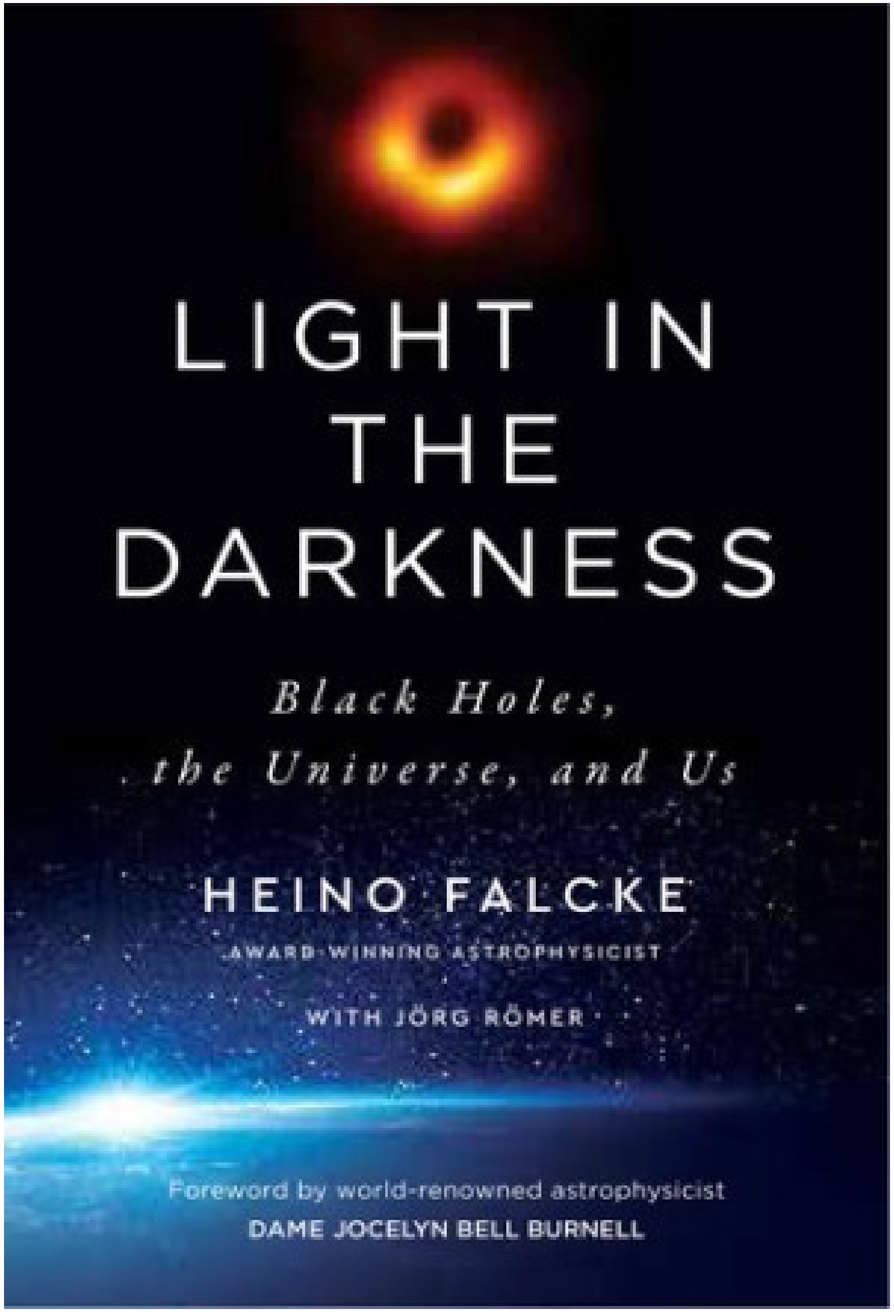


EXPLORING BLACK HOLES

Introduction to General Relativity

EDWIN F. TAYLOR
JOHN ARCHIBALD WHEELER
EDMUND BERTSCHINGER

SECOND EDITION



LIGHT IN
THE
DARKNESS

Black Holes,
the Universe, and Us

HEINO FALCKE

AWARD-WINNING ASTROPHYSICIST

WITH JÖRG RÖMER

Foreword by world-renowned astrophysicist
DAME JOCELYN BELL BURNELL

ХАЙНО ФАЛЬКЕ

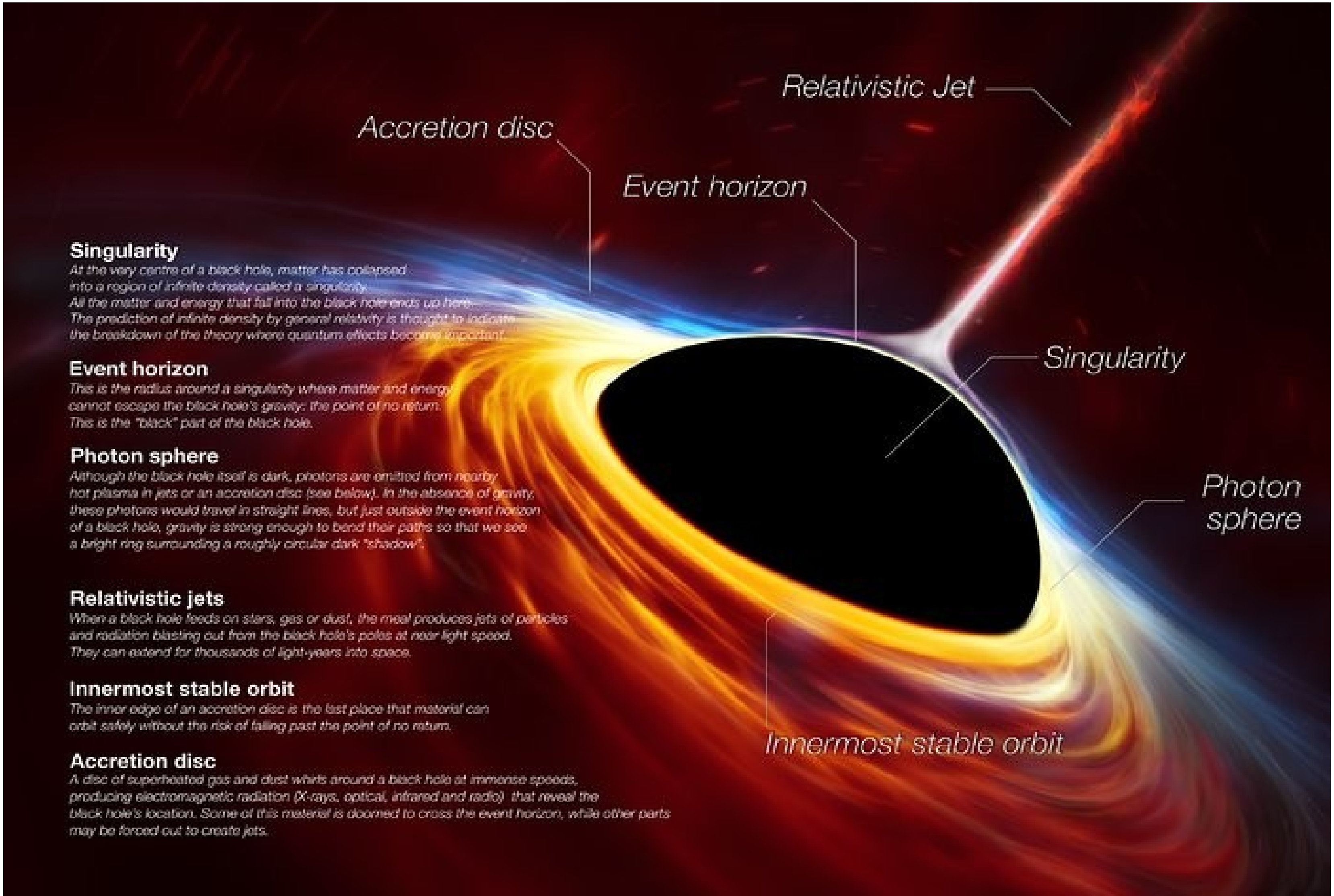
ПРИ УЧАСТИИ ЙОРГА РЕМЕРА

СВЕТ
ВО
ТЬМЕ

ЧЕРНЫЕ ДЫРЫ,
ВСЕЛЕННАЯ И МЫ

КНИГИ ПОЛИТЕХА

The Event Horizon Telescope Picture



Singularity
At the very centre of a black hole, matter has collapsed into a region of infinite density called a singularity. All the matter and energy that fall into the black hole ends up here. The prediction of infinite density by general relativity is thought to indicate the breakdown of the theory where quantum effects become important.

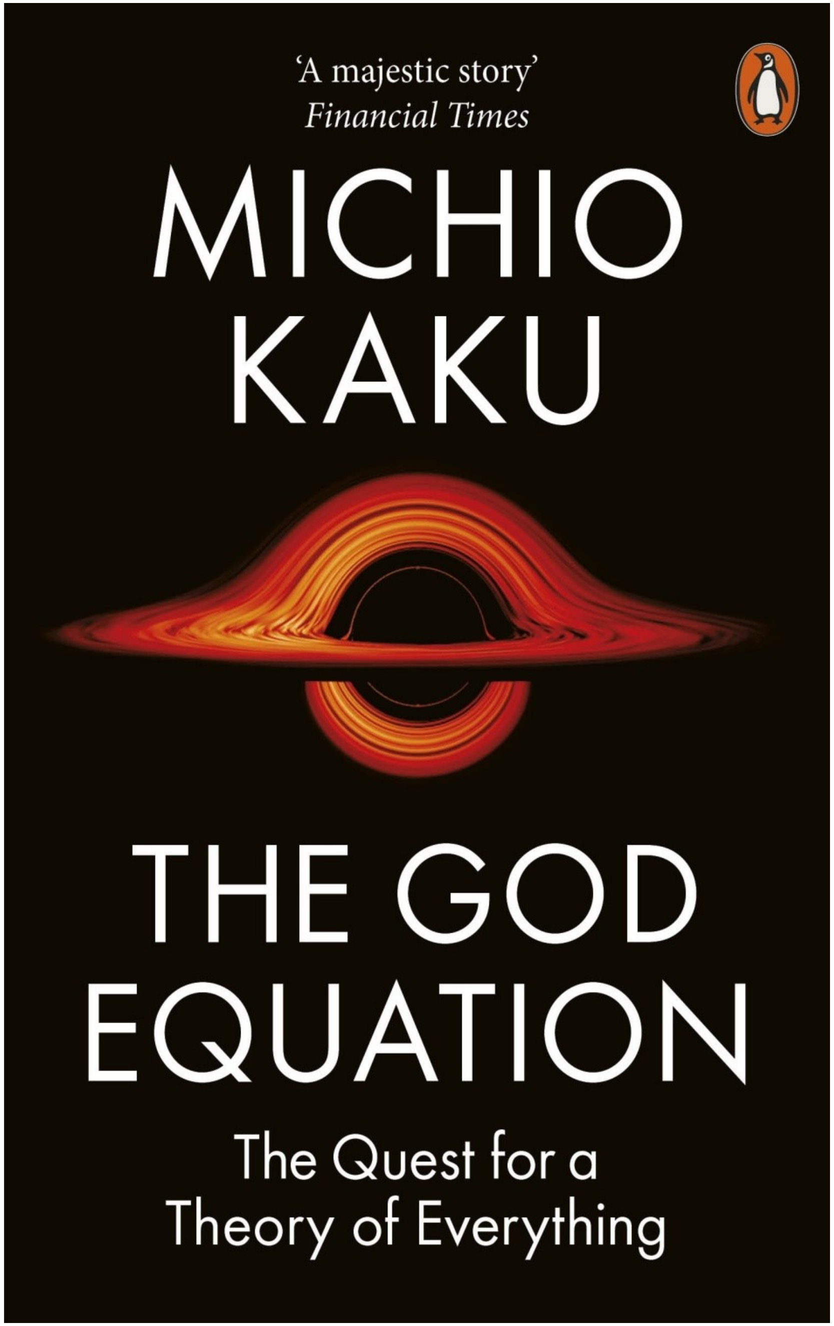
Event horizon
This is the radius around a singularity where matter and energy cannot escape the black hole's gravity: the point of no return. This is the "black" part of the black hole.

Photon sphere
Although the black hole itself is dark, photons are emitted from nearby hot plasma in jets or an accretion disc (see below). In the absence of gravity, these photons would travel in straight lines, but just outside the event horizon of a black hole, gravity is strong enough to bend their paths so that we see a bright ring surrounding a roughly circular dark "shadow".

Relativistic jets
When a black hole feeds on stars, gas or dust, the meal produces jets of particles and radiation blasting out from the black hole's poles at near light speed. They can extend for thousands of light-years into space.

Innermost stable orbit
The inner edge of an accretion disc is the last place that material can orbit safely without the risk of falling past the point of no return.

Accretion disc
A disc of superheated gas and dust whirls around a black hole at immense speeds, producing electromagnetic radiation (X-rays, optical, infrared and radio) that reveal the black hole's location. Some of this material is doomed to cross the event horizon, while other parts may be forced out to create jets.



'A majestic story'
Financial Times

MICHIO
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THE GOD
EQUATION

The Quest for a
Theory of Everything

Circular photon orbits and shadows

Canonical (Kerr – Newman) BHs: Existence of photon rings means Shadow Existence.

NS: It is possible an existence of photon rings without an existence of shadows.

For BH mimickers, “generalizations” of BHs and compact objects without event horizons relations between circular photon rings and shadows must be carefully analysed.

BHs, Naked Singularities (NSs), WHs

Canonical (Kerr – Newman) BHs: Existence of photon rings means Shadow Existence.

NS: It is possible an existence of photon rings without an existence of shadows.

WHs: For photons emitted only from Universe 1 shadows could exist, while if they are emitted from Universe 2 shadows are disappeared.

Conclusion

As we predicted the shadow concept has been transformed from a purely theoretical category into an observable quantity which may be reconstructed from astronomical observations.

Therefore, VLBI observations and image reconstructions for M87* and Sgr A* are in a remarkable agreement with an existence of supermassive black holes in centers of these galaxies.

Thanks for your kind attention!

Figure 13. Inset: paint-swatch accretion disk with inner and outer radii $r = 9.26M$ and $r = 18.70M$ before being placed around a black hole. Body: this paint-swatch disk, now in the equatorial plane around a black hole with $a/M = 0.999$, as viewed by a camera at $r_c = 74.1M$ and $\theta_c = 1.511$ (86.56°), ignoring frequency shifts, associated colour and brightness changes, and lens flare. (Figure from *The Science of Interstellar* [40], used by permission of W. W. Norton & Company, Inc, and created by our Double Negative team, $^{\mathrm{TM}}$ & © Warner Bros. Entertainment Inc. (s15)). This image may be used under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs 3.0 (CC BY-NC-ND 3.0) license. Any further distribution of these images must maintain attribution to the author(s) and the title of the work, journal citation and DOI. You may not use the images for commercial purposes and if you remix, transform or build upon the images, you may not distribute the modified images.

itself. This entire image comes from light rays emitted by the disk's bottom face: the wide bottom portion of the image, from rays that originate behind the hole, and travel under the hole and back upward to the camera; the narrow top portion, from rays that originate on the disk's front underside and travel under the hole, upward on its back side, over its top, and down to the camera—making one full loop around the hole.

There is a third disk image whose bottom portion is barely visible near the shadow's edge. That third image consists of light emitted from the disk's top face, that travels around the hole once for the visible bottom part of the image, and one and a half times for the unresolved top part of the image.

In the remainder of this section 4 we deal with a moderately realistic accretion disk—but a disk created for *Interstellar* by Double Negative artists rather than created by solving astrophysical equations such as [32]. In appendix A.6 we give some details of how this and other Double Negative accretion disk images were created. This artists' *Interstellar* disk was chosen to be very anemic compared to the disks that astronomers see around black holes and that astrophysicists model—so the humans who travel near it will not get fried by x-rays and gamma-rays. It is physically thin and marginally optically thick and lies in the black hole's equatorial plane. It is not currently accreting onto the black hole, and it has cooled to a position-independent temperature $T = 4500$ K, at which it emits a black-body spectrum.

Figure 14 shows an image of this artists' disk, generated with a gravitational lensing geometry and computational procedure identical to those for our paint-swatch disk, figure 13

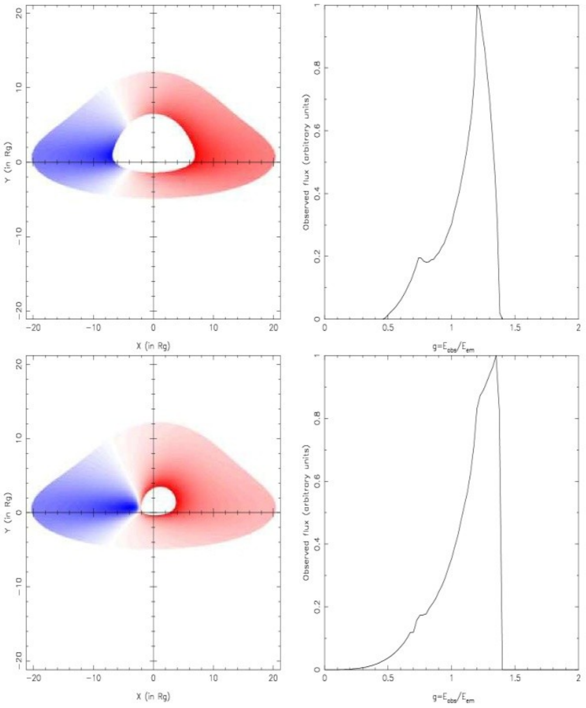

Fig. 2 (online colour at: www.fp-journal.org) The same as in Fig. 1 but for a highly inclined disk with $i = 75^\circ$.

asymmetric (see Fig. 3). If the line emission is originating at larger distances from the BH, the red peak of the line becomes brighter and line profile narrower and more symmetric. In majority of AGN, where the broad Fe Kα line is observed[1], its profile is more similar to the modeled profile as obtained under assumption that the line emitters are located close to the central BH. Therefore, comparisons between the observed and modeled Fe Kα line profiles can bring us some essential information about strong gravitational field in vicinity of central supermassive BH of AGN.

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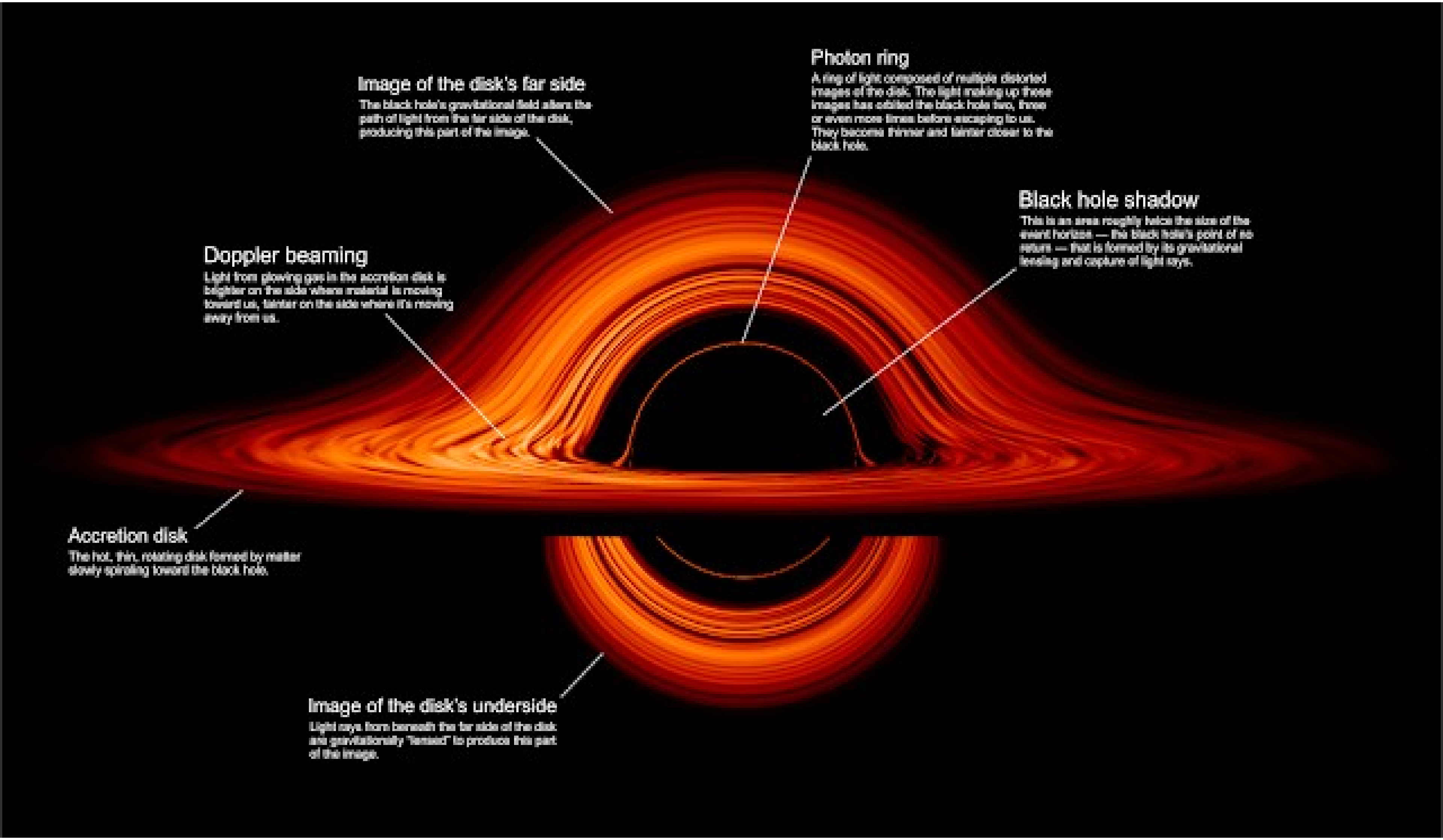
[1] Note here that in some AGN only the narrow Fe Kα line is observed, but it is supposed to be emitted in the disk corona that is located farther from the disk, and therefore, these relativistic effects cannot be detected in the line profile



Photon ring

A ring of light composed of multiple distorted images of the disk. The light making up these images has orbited the black hole two, three or even more times before escaping to us. They become thinner and fainter closer to the black hole.

Image of the disk's far side

The black hole's gravitational field alters the path of light from the far side of the disk, producing this part of the image.

Black hole shadow

This is an area roughly twice the size of the event horizon — the black hole's point of no return — that is formed by its gravitational lensing and capture of light rays.

Doppler beaming

Light from glowing gas in the accretion disk is brighter on the side where material is moving toward us, fainter on the side where it's moving away from us.

Accretion disk

The hot, thin, rotating disk formed by matter slowly spiraling toward the black hole.

Image of the disk's underside

Light rays from beneath the far side of the disk are gravitationally "lensed" to produce this part of the image.

1. Fig. From Alexeyev et al. (2024) with a proper attribution was presented in talk by Alexeyev in conference https://indico.jinr.ru/event/4174/

and in talks by Zenin at conference https://indico.quarks.ru/event/2024/timetable/#all.detailed and

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