Физика фундаментальных взаимодействий

Секция-конференция отделения ядерной физики ОФН РАН, посвященная 70 летию В.А.Рубакова

Президиум РАН, 17-21 февраля 2025 года

Ограничения на теории гравитации с помощью астрономических данных

С.О.Алексеев, О.И.Зенин

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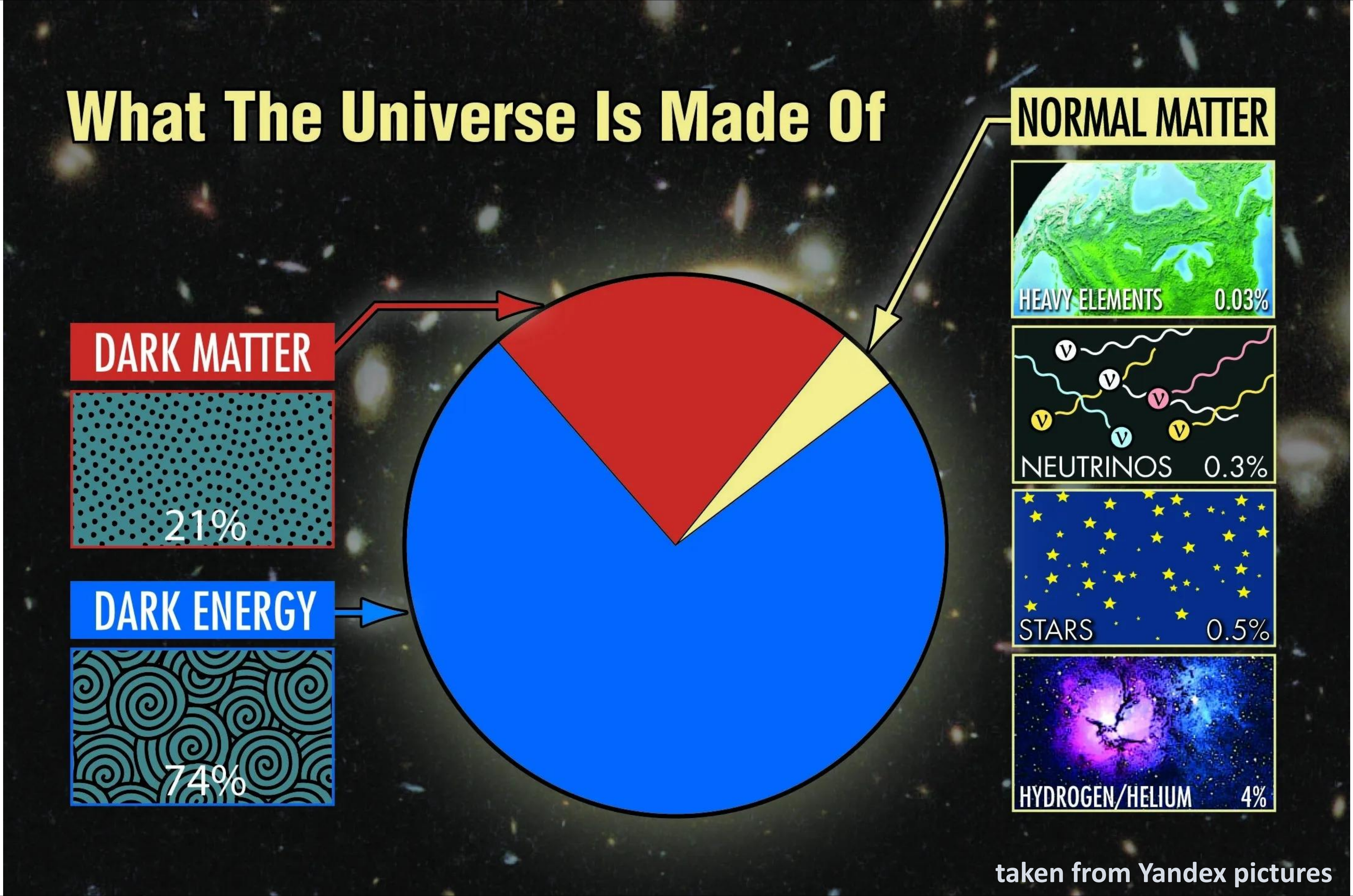

What The Universe Is Made Of
NORMAL MATTER
DARK MATTER
21%
DARK ENERGY
74%
HEAVY ELEMENTS 0.03%
NEUTRINOS 0.3%
STARS 0.5%
HYDROGEN/HELIUM 4%
taken from Yandex pictures

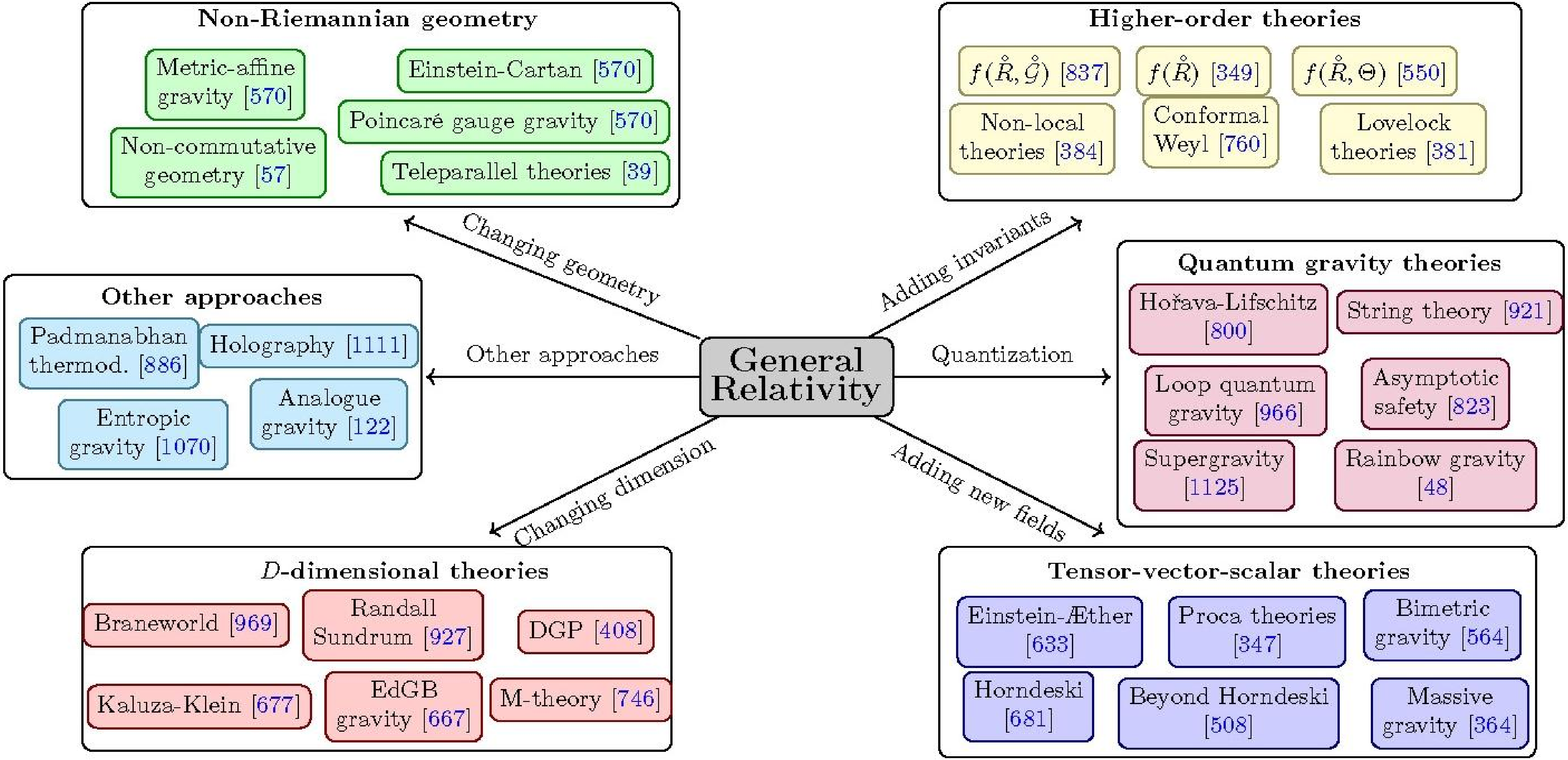


Figure 8: Representation of some possible ways of modifying GR through breaking the Lovelock's theorem along with some examples.

@ Rept.Prog.Phys. 86, 026901 (2023)

Extending PPN to different energy ranges

↓

A system of tests to constrain an extended gravity theory on different energy scales with astronomical data

universe
MDPI

Review

Extended Gravity Constraints at Different Scales

Stanislav Alexeyev [1,2,*] and Vyacheslav Prokopov [1,3]

1 Sternberg Astronomical Institute, Lomonosov Moscow State University, Universitetskii Prospekt, 13, 119234 Moscow, Russia; slaprok777@gmail.com
2 Department of Quantum Theory and High Energy Physics, Physics Faculty, Lomonosov Moscow State University, Leninskie Gory, 1/2, 119234 Moscow, Russia
3 Department of Astrophysics and Stellar Astronomy, Physics Faculty, Lomonosov Moscow State University, Leninskie Gory, 1/2, 119234 Moscow, Russia
* Correspondence: alexeyev@sai.msu.ru
† This paper is an extended version of our paper published in An extended version of a conference paper The paper represents an extended version of the lecture presented by SA at XXII International Meeting "Physical Interpretations of Relativity Theory-2021" (5–9 July 2021), held at Bauman Moscow State Technical University.

Simple Summary: Simple summary We review a set of the possible ways to constrain extended gravity models at Galaxy clusters scales (the regime of dark energy explanations and comparison with ΛCDM), for black hole shadows, gravitational wave astronomy, binary pulsars, the Solar system and a Large Hadron Collider (consequences for high-energy physics at TeV scale).

Abstract: We review a set of the possible ways to constrain extended gravity models at Galaxy clusters scales (the regime of dark energy explanations and comparison with ΛCDM), for black hole shadows, gravitational wave astronomy, binary pulsars, the Solar system and a Large Hadron Collider (consequences for high-energy physics at TeV scale). The key idea is that modern experimental and observational precise data provide us with the chance to go beyond general relativity.

Keywords: general relativity; extended gravity; black hole; turnaround radius; shadow of black hole; gravitational waves; binary pulsars

PACS: 04.50.+h; 04.50.Gh; 04.80.Cc

check for updates

Citation: Alexeyev, S.; Prokopov, V. Extended Gravity Constraints at Different Scales. *Universe* **2022**, *8*, 283. https://doi.org/10.3390/universe8050283

Academic Editor: Salvatore Capozziello and Daniele Vernieri

Received: 9 March 2022
Accepted: 11 May 2022
Published: 15 May 2022

1. Introduction

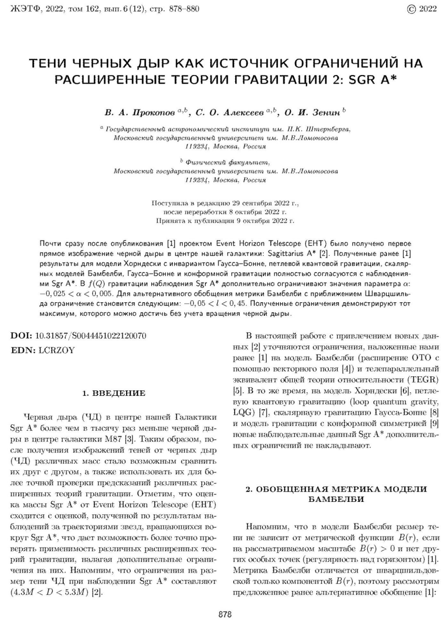
The theory of General Relativity (GR) is confirmed in all projects of experimental astronomy. However, the problems of dark energy, dark matter, the evolution of the early Universe, and the quantum theory of gravity remain open. For example, the theoretical description of the Universe's accelerated expansion (i.e., dark energy) is realised by adding the cosmological constant to the GR action L as

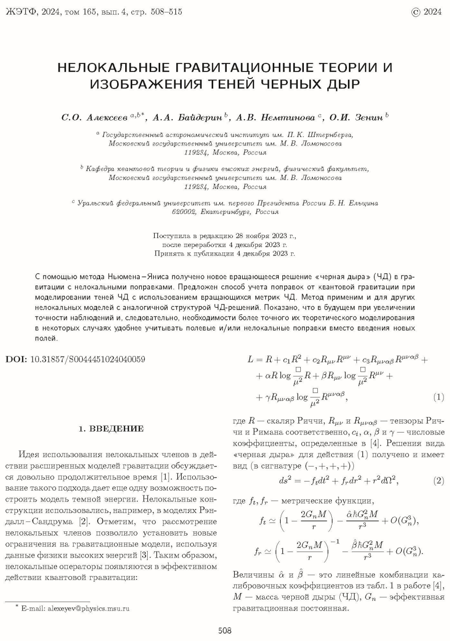
$$L_{GR\Lambda} = \sqrt{-g}(R + \Lambda), \quad (1)$$

where R is Ricci scalar and Λ is the cosmological constant. The problem is that Λ-term is the best fit for the observational data. On the other hand, from the fundamental point of view, it appears to be a pure fine-tuning parameter. The next step is to consider an additional scalar field ϕ in the form of Brans–Dicke model

$$L_{BD} = \sqrt{-g}\left(\phi R + \frac{\omega}{\phi}\partial_\mu\phi\partial^\mu\phi + V(\phi)\right). \quad (2)$$

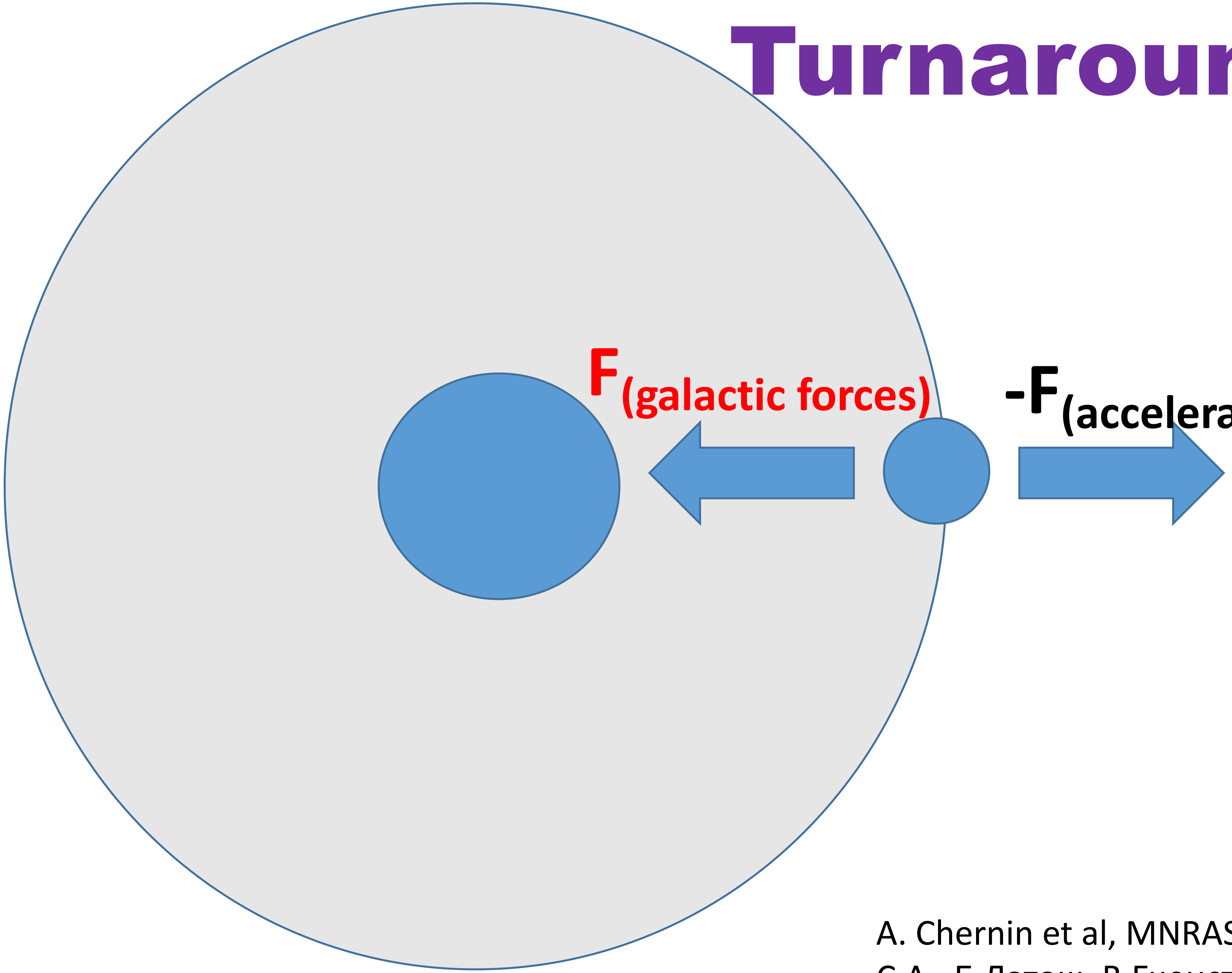
Such a model can reproduce the cosmological constant contribution with the help of taking the appropriate form of $V(\phi)$. Now, one has to find the origin of the scalar field in Equation (2). The same problem occurs with the inflation stage: accelerated expansion of





- Galaxy clusters scales: ways to explain dark energy & comparing with ΛCDM.
- Shadows of black holes: deviations from GR.
- Gravitational wave astronomy: deviations from GR.
- Binary pulsars: deviations from GR.
- Solar system: Newtonian limit and deviations from it.
- Large Hadron Collaider: gravity at TeV scale.

Turnaround radius



A. Chernin et al, MNRAS, Vol.449 , P.2069 (2015),
С.А., Б.Латош, В.Ечеистов, ЖЭТФ, т.152, с.1271 (2017),
S.A., K.Kovalkov, IJMP A, v.35, p.204057 (2020).

Idea:

to calculate turnaround radius using 2 independent methods

- To calculate gravitational potential **ϕ**. At turnaround radius **$d\phi/dr=0$, $d^2\phi/dr^2 > 0$**.
- ***To use astronomical data on gravitational lensing for the experimental estimation of turnaround radius value.***
- At 1st step to use **ΛCDM** asymptote for estimation.

NOTE: Calculations of **ϕ** are based on metrics **==>** one can compare different models.

Horndeski theory (*see O.Zenin's talk for details*)

Constrainss from turnaround radius (*О.Зенин, СА, ЖЭТФ, принято к печати (2025)*)

+

Constrains from GW200115 (*E.Babichev, C. Charmousis, M. Hassaine and N. Lecoeur, PRD 108, 024019 (2023)*)

+

Constrains from PSR J1915+1606 (*P. Dyadina, N. Avdeev, SA, MNRAS 483, 947 (2019)*)

↓

Additional separate constrains on α_4, α_5, η

DGP model (*see O.Zenin's talk for details*)

Constrainss from turnaround radius (*О.Зенин, СА, ЖЭТФ, принято к печати (2025)*)

+

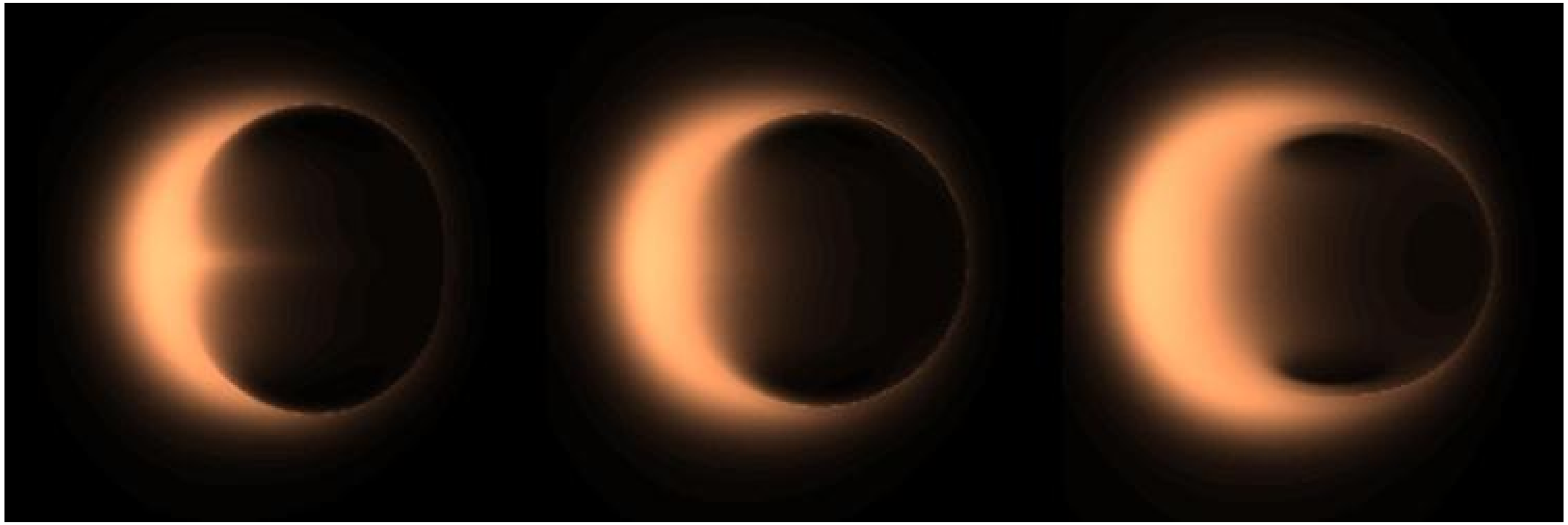
Constrainss from solution by itself (*R. Gannouji, EPJ C 78, 318 (2018)*)

⇓

Confirmation of DGP (4+)D regime at high scale (near Vainstein radius)

- Galaxy clusters scales: ways to explain dark energy & comparing with ΛCDM.
- Shadows of black holes: deviations from GR.
- Gravitational wave astronomy: deviations from GR.
- Binary pulsars: deviations from GR.
- Solar system: Newtonian limit and deviations from it.
- Large Hadron Collaider: gravity at TeV scale.

Constraints on gravity models from black hole shadows



Pic is taken from https://www.eso.org/public/images/shadow-evt/

$$ds^2 = -\left(1 - \frac{2M}{r}\right)dt^2 + \frac{dr^2}{\left(1 - \frac{2M}{r}\right)} + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

$\Rightarrow$

$$ds^2 = -\left(1 - \frac{2M}{r} + \frac{Q^2}{r^2}\right)dt^2 + \frac{dr^2}{\left(1 - \frac{2M}{r} + \frac{Q^2}{r^2}\right)} + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

A. F. Zakharov, Sov. Phys. JETP, 64, 1 (1986).
A. F. Zakharov, A. A. Nucita, F. De Paolis, G. Ingrosso, New Astron. 10, 479 (2005)
A. F. Zakharov, IJMP D 54, 2340004 (2023)
A.Zakharov, Phys. Rev. D, Vol.90, P.062007 (2014)
V.Prokopov, SA, O.Zenin, JETP, Vol.135, p.842 (2022) ...
С.А, А. Байдерин, А.Немтинова, О.Зенин, ЖЭТФ 165, 508 (2024)

Idea:

- **The general form of spherically-symmetric metrics:**

$$ds^2 = -A(r)dt^2 + B(r)dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2).$$

- **Equation of motion:** $\left(\frac{d\hat{r}}{d\tau}\right)^2 + \frac{L^2}{B(\hat{r})\hat{r}^2} = \frac{E^2}{A(\hat{r})B(\hat{r})}, \qquad \frac{d\phi}{d\tau} = \frac{L}{\hat{r}^2},$

- **Introduce:** $D = L/E$

- **To calculate the shadow size one has to find maximal root of**

$$u(r) = \left(\frac{d\hat{r}}{d\phi}\right)^2 = \frac{\hat{r}^4}{D^2 A(\hat{r})B(\hat{r})} - \frac{\hat{r}^2}{B(\hat{r})},$$

$$u(r) = 0, \quad \frac{du(r)}{dr} = 0, \quad \frac{d^2u(r)}{d^2r} > 0.$$

Horndesky Model

$$A(r) = 1 - \frac{2M}{r} - \frac{2C_7}{7r^7}$$

$$B(r)^{-1} = 1 - \frac{2M}{r} - \frac{C_7}{r^7}$$

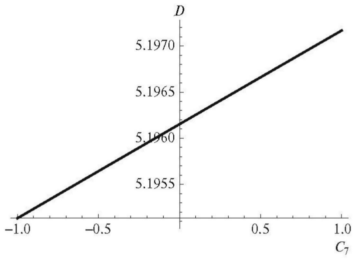


Fig. 3. The dependence of shadow size (D) versus the combination of model constants C_7 for Horndesky theory coupled with Gauss–Bonnet invariant (in the units of M, $M = 1$).

E. Babichev, C. Charmousis, and A. Lehebel. JCAP, 2017. arXiv:1702.01938 V.Prokopov, SA, O.Zenin, **JETP**, Vol.135, P. 91 (2022), ***ibid***, p.842 (2022)

Loop quantum gravity

$$A(r) = \left(1 - \frac{2Mr^2}{r^3 + 2Ml^2}\right)\left(1 - \frac{\alpha\beta M}{\alpha r^3 + \beta M}\right),$$

$$B(r)^{-1} = 1 - \frac{2Mr^2}{r^3 + 2Ml^2},$$

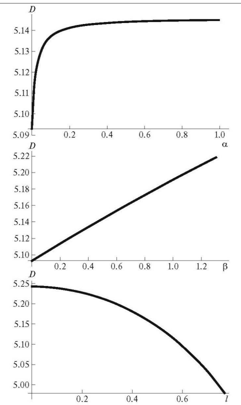


Fig. 4. The dependence of shadow size D upon the time delay α when $l = 0.5M$ and $\beta = 0.5$ (top image), upon the 1-loop quantum corrections β when $l = 0.5M$, $\alpha = 0.5$ (central image), upon the central energy density l when $\alpha = 0.5$, $\beta = 0.5$ (bottom image) for BH in modified Hayward metric in the units of M, $M = 1$.

J. Hu, L. Shi, Y. Zhang, and P. Duan. Astrophysics and Space Science, 2018. arXiv:2104.07523 V.Prokopov, SA, O.Zenin, **JETP**, Vol.135, P. 91 (2022), ***ibid***, p.842 (2022)

Conformal gravity

$$A(r) = 1 - \frac{2M}{r} + \frac{Q_s^2}{r^2} + \frac{Q_s^2\left(-M^2 + Q_s^2 + \frac{6}{m_2^2}\right)}{3r^4} + \ldots,$$

$$B(r)^{-1} = 1 - \frac{2M}{r} + \frac{Q_s^2}{r^2} + \frac{2Q_s^2\left(-M^2 + Q_s^2 + \frac{6}{m_2^2}\right)}{3r^4} + \ldots,$$

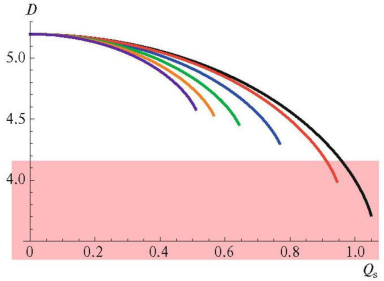


Fig. 5. The dependence of the shadow size D against the scalar charge Q_s for in new massive conformal gravity with different values of massive spin-2 mode m_2 (in the units of M, $M = 1$). Black line corresponds to $m_2 \to \infty$, red one corresponds to $m_2 = 2$, blue one corresponds to $m_2 = 1$, green one corresponds to $m_2 = 0.707$, orange one corresponds to $m_2 = 0.577$, purple one corresponds to $m_2 = 0.5$.

Y. S. Myung and D. Zou. PRD 2019. arXiv:1907.09676 V.Prokopov, SA, O.Zenin, **JETP**, Vol.135, P. 91 (2022), ***ibid***, p.842 (2022)

Conformal gravity

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}[R - \alpha(\phi^2 R + 6\partial_\mu\phi\partial^\mu\phi] - \frac{1}{2m_2^2}C^{\mu\nu\rho\sigma}C_{\mu\nu\rho\sigma}]$$

$$A(r) = 1 - \frac{2M}{r} + \frac{Q_s^2}{r^2} + \frac{Q_s^2\left(-M^2 + Q_s^2 + \frac{6}{m_2^2}\right)}{3r^4} + \ldots,$$

$$B(r)^{-1} = 1 - \frac{2M}{r} + \frac{Q_s^2}{r^2} + \frac{2Q_s^2\left(-M^2 + Q_s^2 + \frac{6}{m_2^2}\right)}{3r^4} + \ldots,$$

Bumblebee model

$$S_B = \int d^4x\sqrt{-g}\mathcal{L}_B = \int d^4x\sqrt{-g}(\mathcal{L}_g + \mathcal{L}_{gB} + \mathcal{L}_K + \mathcal{L}_V + \mathcal{L}_M)$$

$$\mathcal{L}_B = \frac{e}{2\kappa}R + \frac{e}{2\kappa}\xi B^\mu B^\nu R_{\mu\nu} - \frac{1}{4}eB_{\mu\nu}B^{\mu\nu} - eV(B^\mu) + \mathcal{L}_M$$

$$A(r) = \left(1 - \frac{2M}{r}\right),$$

$$B(r) = \frac{1 + l}{1 - \frac{2M}{r}},$$

f(Q) gravity

$$S[g, \Gamma; \lambda, \rho] = \int_{\mathcal{M}} d^4x\left(\frac{1}{2}\sqrt{-g}f(\mathbb{Q}) + \lambda_\alpha^{\beta\mu\nu}R^\alpha_{\beta\mu\nu} + \rho_\alpha^{\mu\nu}T^\alpha_{\mu\nu}\right) + S_{matter}$$

$$A(r) = 1 - \frac{2M_{\text{ren}}}{r} - \alpha\frac{32}{r^2},$$

$$B(r)^{-1} = 1 - \frac{2M_{\text{ren}}}{r} - \alpha\frac{96}{r^2},$$

$$2M_{\text{ren}} = 2M - \alpha\left(\frac{32}{3M} + c_1\right),$$

Scalar Gauss-Bonnet gravity

$$S = \int d^4x\sqrt{-g}\left[\kappa R + \alpha_1 f_1(\vartheta)R^2 + \alpha_2 f_2(\vartheta)R_{ab}R^{ab} + \alpha_3 f_3(\vartheta)R_{abcd}R^{abcd} + \alpha_4 f_4(\vartheta)R_{abcd} * R^{abcd} - \frac{\beta}{2}\left(\nabla_a\vartheta\nabla^a\vartheta + 2V(\vartheta)\right) + \mathcal{L}_{mat}\right]$$

$$A = -f(r)\left[1 + \frac{\zeta}{3r^3 f(r)}h(r)\right],$$

$$B = \frac{1}{f(r)}\left[1 - \frac{\zeta}{r^3 f(r)}k(r)\right],$$

where

$$h(r) := 1 + \frac{26}{r} + \frac{66}{5r^2} + \frac{96}{5r^3} - \frac{80}{r^4},$$

$$k(r) := 1 + \frac{1}{r} + \frac{52}{3r^2} + \frac{2}{r^3} + \frac{16}{5r^4} - \frac{368}{3r^5},$$

$$f(r) := 1 - \frac{2}{r},$$

Bumblebee model

$$A(r) = \left(1 - \frac{2M}{r}\right),$$

$$B(r) = \frac{1 + l}{1 - \frac{2M}{r}},$$

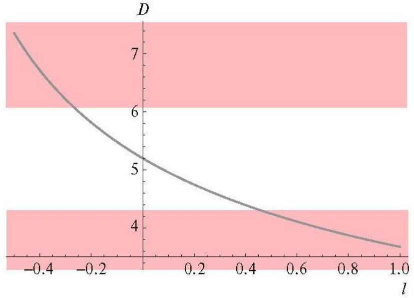


Fig. 6. The dependence of the shadow size D upon parameter l in alternative Bumblebee generalization with Schwarzschild approximation (in the units of M, $M = 1$).

R. Casana, A. Cavalcante, et al., PRD 2018 arXiv:1711.02273 V.Prokopov, SA, O.Zenin, **JETP**, Vol.135, P. 91 (2022), ***ibid***, p.842 (2022)

f(Q) gravity

$$A(r) = 1 - \frac{2M_{\text{ren}}}{r} - \alpha\frac{32}{r^2},$$

$$B(r)^{-1} = 1 - \frac{2M_{\text{ren}}}{r} - \alpha\frac{96}{r^2},$$

$$2M_{\text{ren}} = 2M - \alpha\left(\frac{32}{3M} + c_1\right),$$

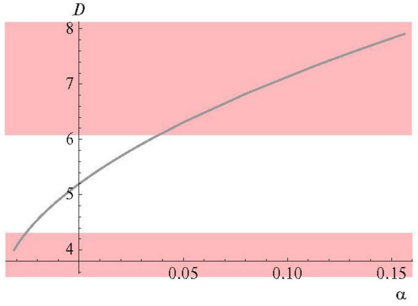


Fig. 7. The dependence of the shadow size D upon parameter α in $f(Q)$ gravity in M_{ren} units.

F. D'Ambrosio, S. D. B. Fell, L. Heisenberg, and S. Kuhn. PRD, 2022.arXiv:2109.03174 V.Prokopov, SA, O.Zenin, **JETP**, Vol.135, P. 91 (2022), ***ibid***, p.842 (2022)

Scalar Gauss-Bonnet gravity

$$A = -f(r)\left[1 + \frac{\zeta}{3r^3 f(r)}h(r)\right],$$

$$B = \frac{1}{f(r)}\left[1 - \frac{\zeta}{r^3 f(r)}k(r)\right],$$

where

$$h(r) := 1 + \frac{26}{r} + \frac{66}{5r^2} + \frac{96}{5r^3} - \frac{80}{r^4},$$

$$k(r) := 1 + \frac{1}{r} + \frac{52}{3r^2} + \frac{2}{r^3} + \frac{16}{5r^4} - \frac{368}{3r^5},$$

$$f(r) := 1 - \frac{2}{r},$$

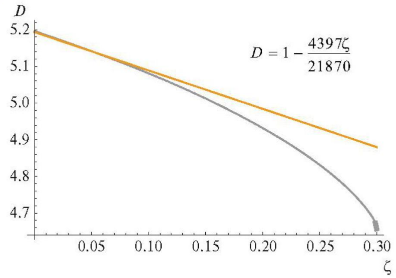
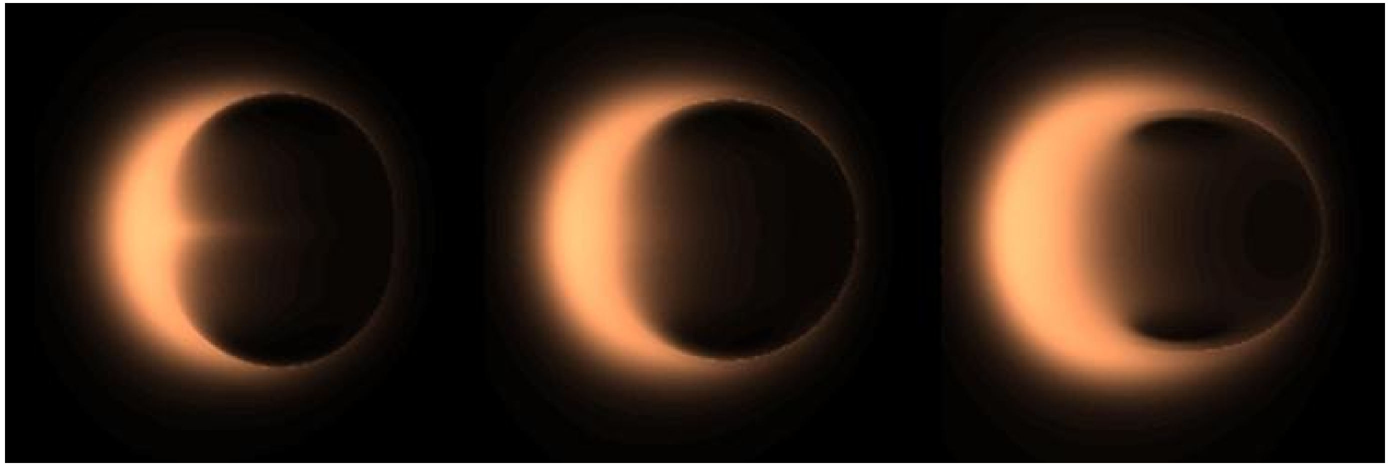


Fig. 8. The lower curve is the dependence of the shadow size D upon parameter ζ in scalar Gauss–Bonnet gravity (in the units of M, $M = 1$). The top line is the first order approximation.

N. Yunes and L. C. Stein. PRD 2011. arXiv:1101.2921 V.Prokopov, SA, O.Zenin, **JETP**, Vol.135, P. 91 (2022), ***ibid***, p.842 (2022)

Constraints on gravity models from black hole shadows



Pic is taken from https://www.eso.org/public/images/shadow-evt/

$$ds^2 = \left(1 - \frac{2M}{r} + \frac{Q^2}{r^2}\right)dt^2 - \frac{dr^2}{\left(1 - \frac{2M}{r} + \frac{Q^2}{r^2}\right)} - r^2 d\Omega^2$$

$$ds^2 = \frac{\Delta}{\rho^2}\left(dt - a\sin^2\theta d\tilde{\varphi}\right)^2 - \frac{\sin^2\theta}{\rho^2}\left((r^2 + a^2)d\tilde{\varphi} - a dt\right)^2 - \frac{\rho^2}{\Delta}dr^2 - \rho^2 d\theta^2$$

Newman-Janis algorythm (NJA) --> Approved NJA

AIP Journal of Mathematical Physics

Note on the Kerr SpinningParticle Metric

E. T. Newman and A. I. Janis

Citation: J. Math. Phys. **6**, 915 (1965); doi: 10.1063/1.1704350
View online: http://dx.doi.org/10.1063/1.1704350
View Table of Contents: http://jmp.aip.org/resource/1/JMAPAQ/v6/i6
Published by the American Institute of Physics.

Eur. Phys. J. C (2014) 74:2865
DOI 10.1140/epjc/s10052-014-2865-8

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

From static to rotating to conformal static solutions: rotating imperfect fluid wormholes with(out) electric or magnetic field

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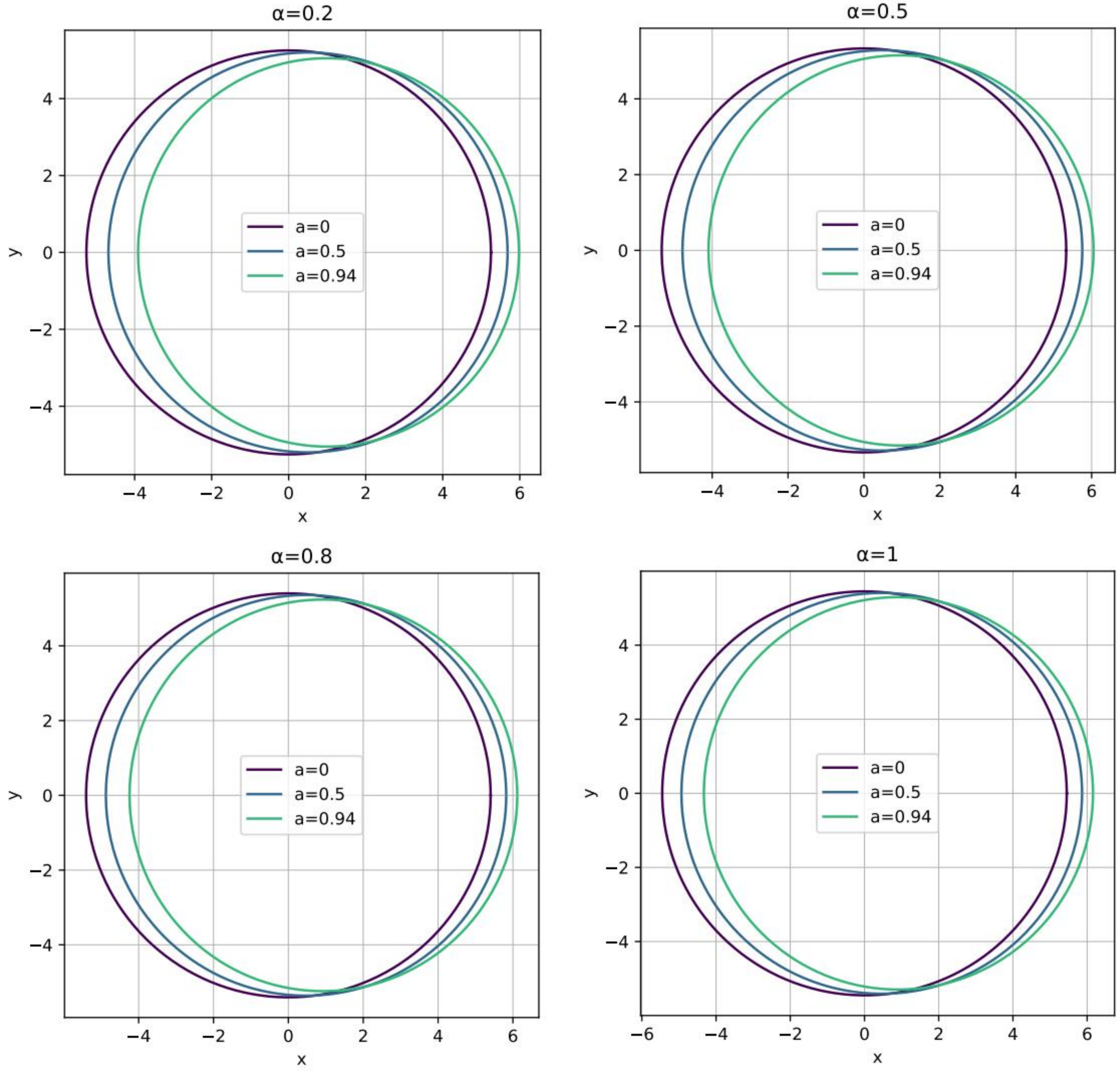
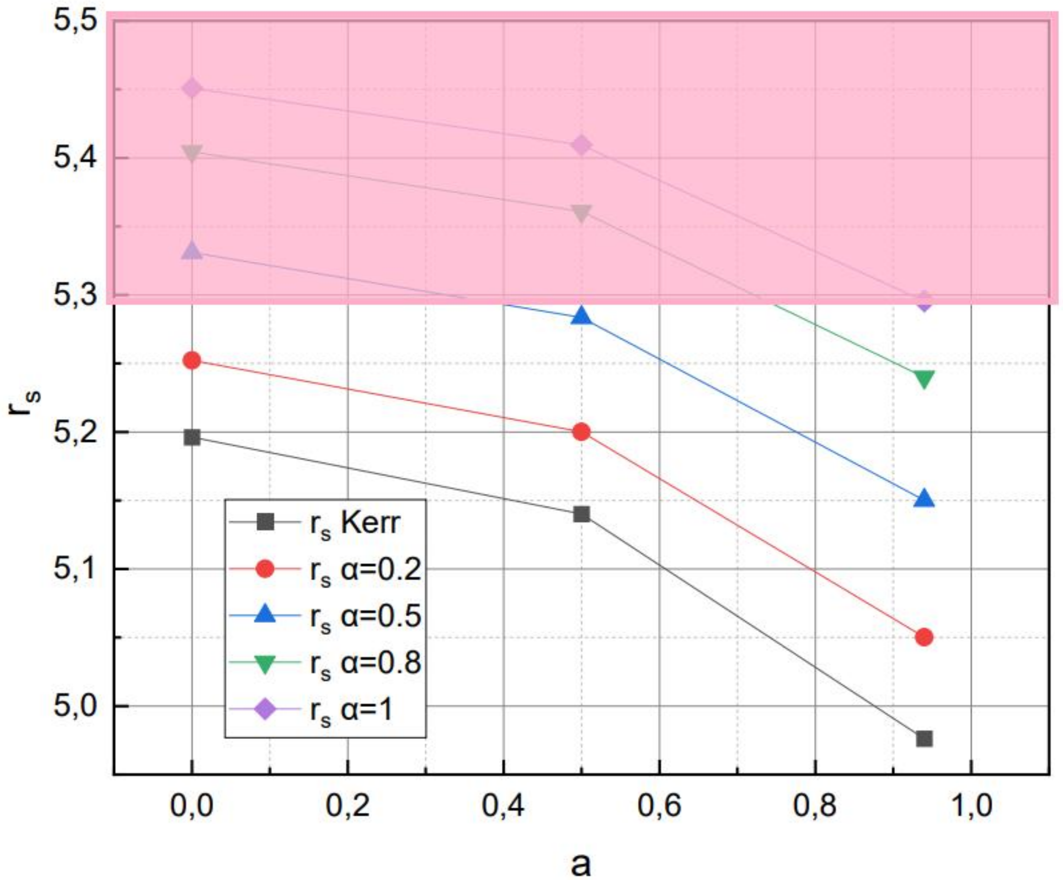
Department of Mathematics, Başkent University, Bağlıca Campus, Ankara, Turkey

Received: 31 January 2014 / Accepted: 16 April 2014 / Published online: 6 May 2014

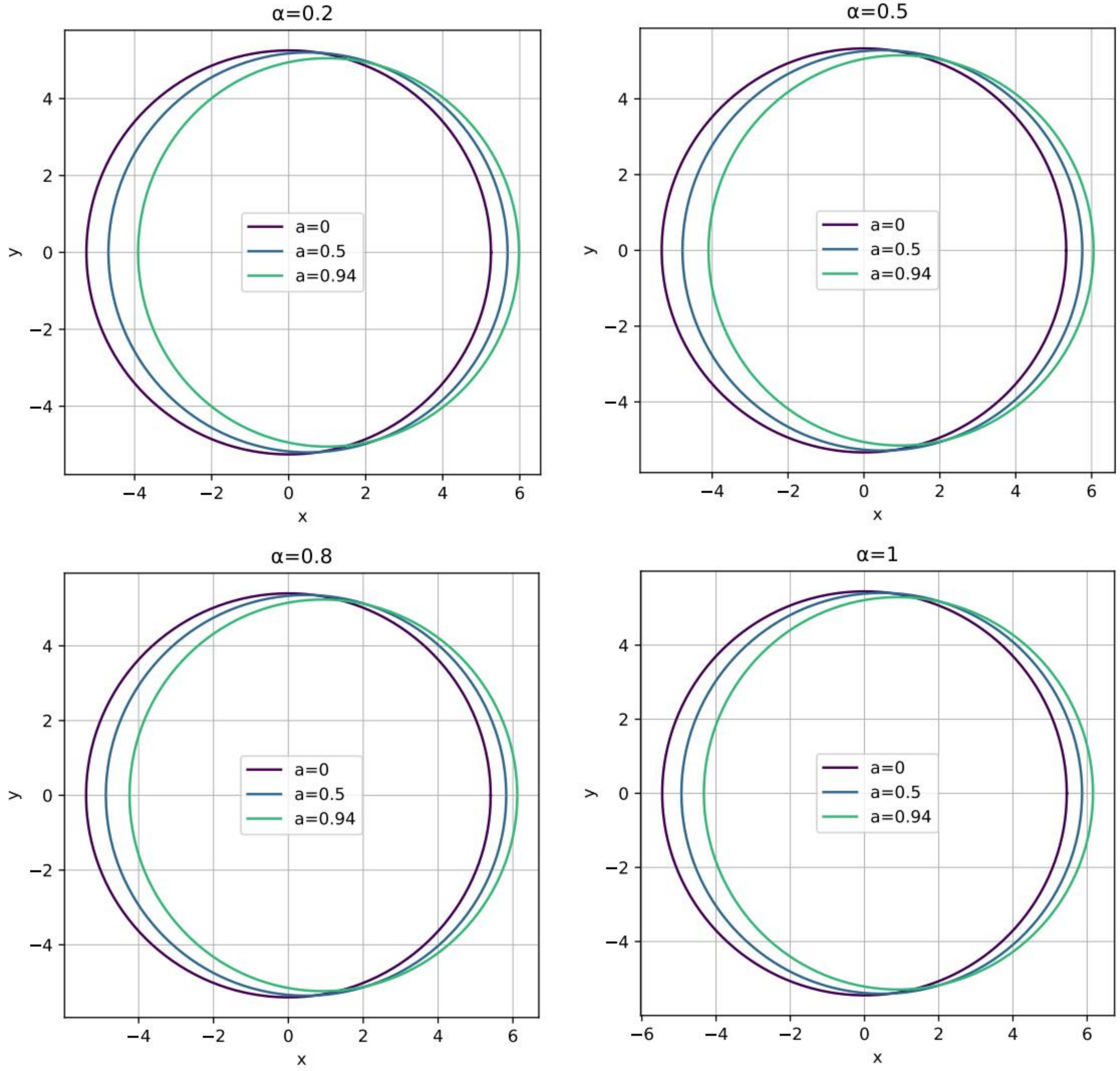
Horndesky theory

The dependence of the shadow size r_s against rotation a



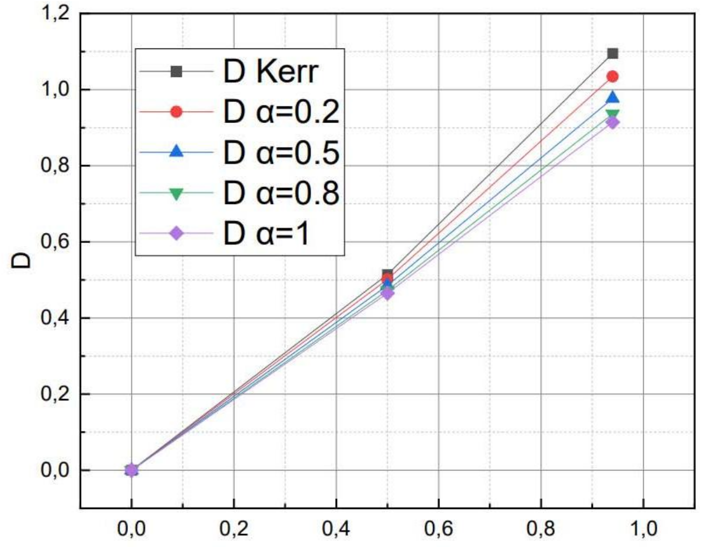


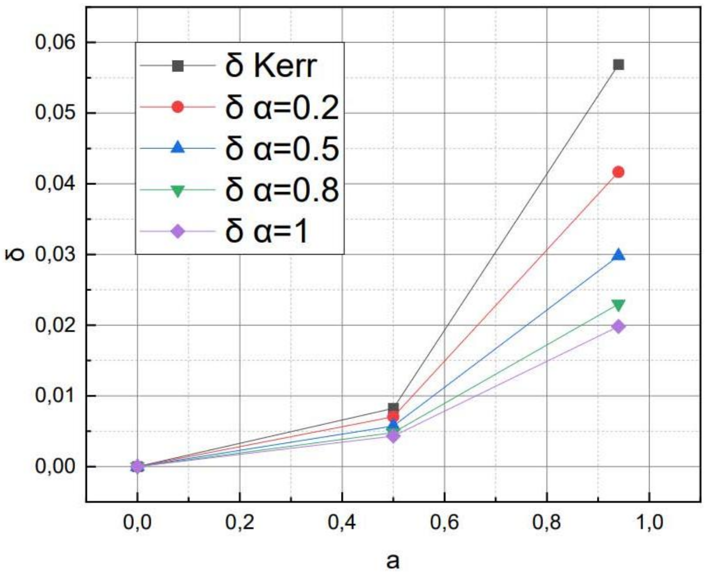
SA, A.Baiderin, O.Zenin, submitted to JETP



Horndesky theory

The dependence of shift **D** and distortion **δ** against rotation **a**

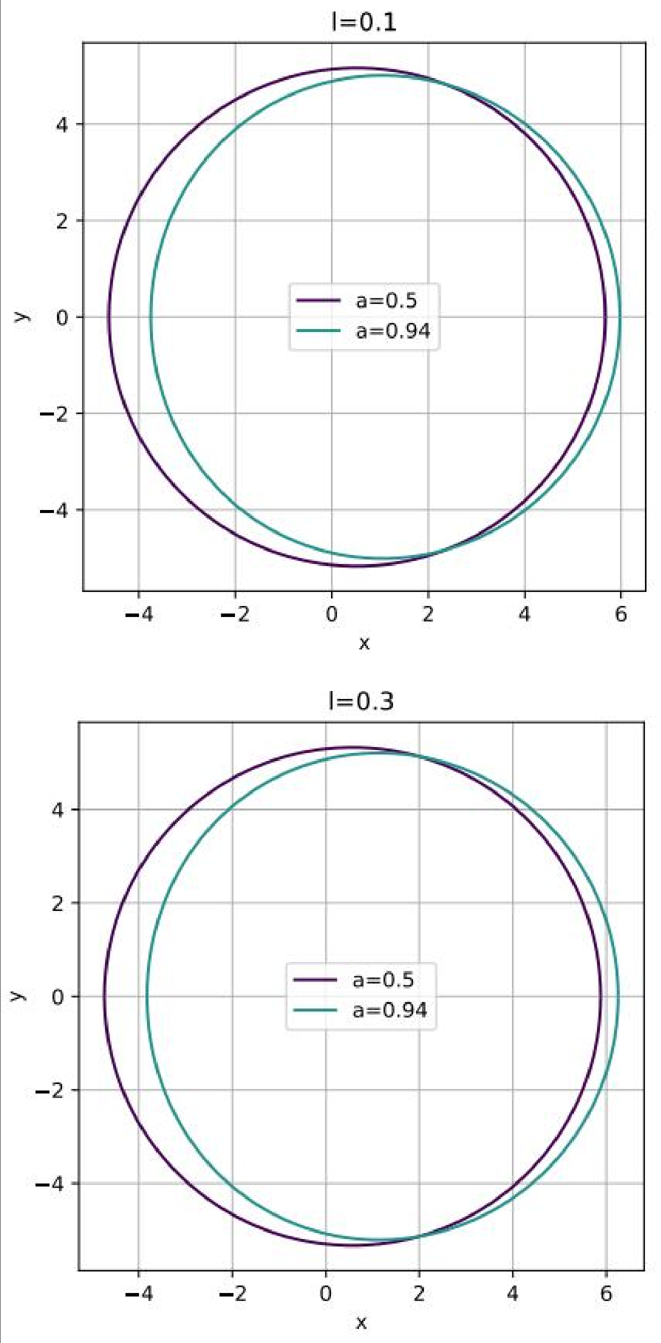


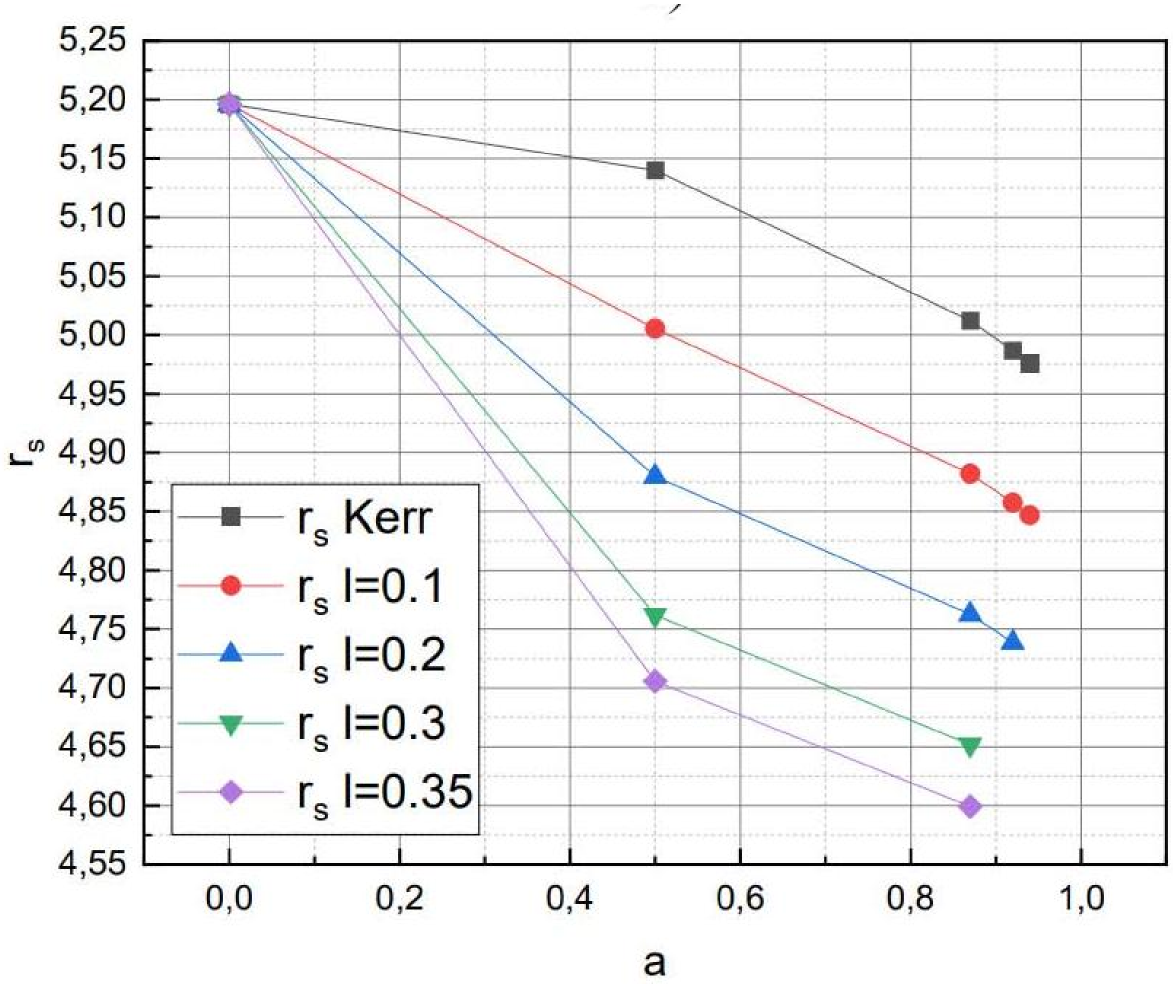


SA, A.Baiderin, O.Zenin, submitted to JETP

Bumblebee model

The dependence of the shadow size r_s against rotation **a**

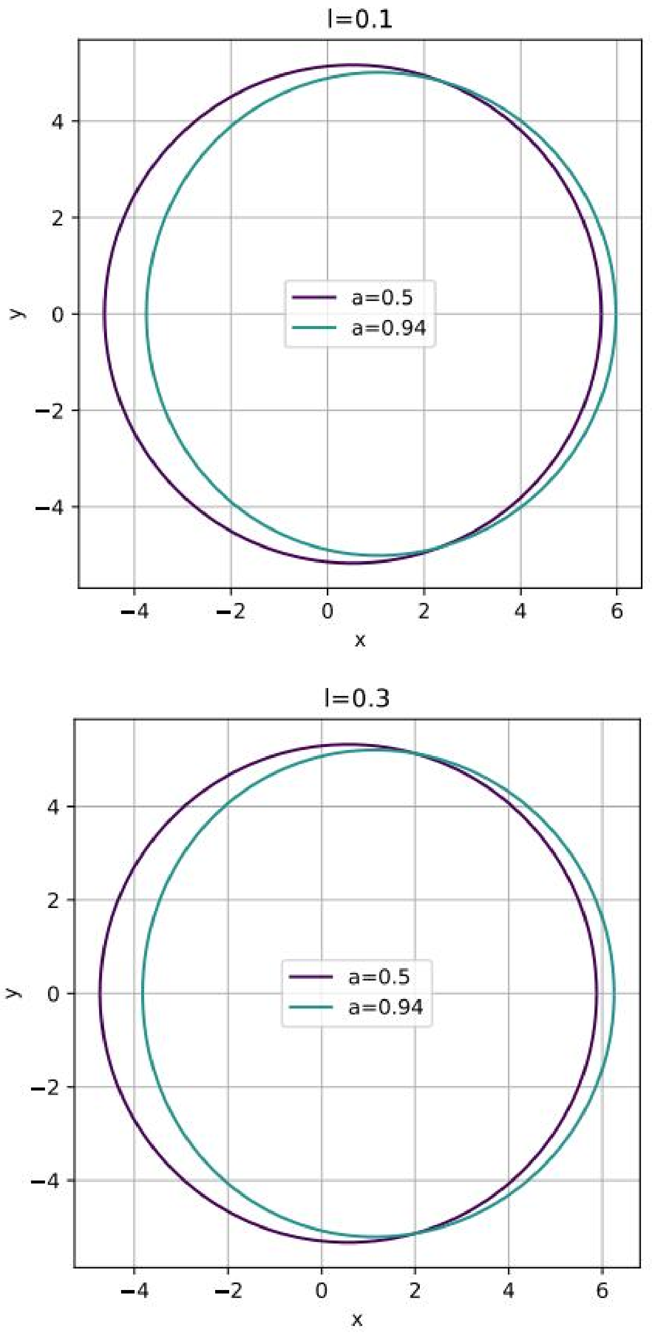


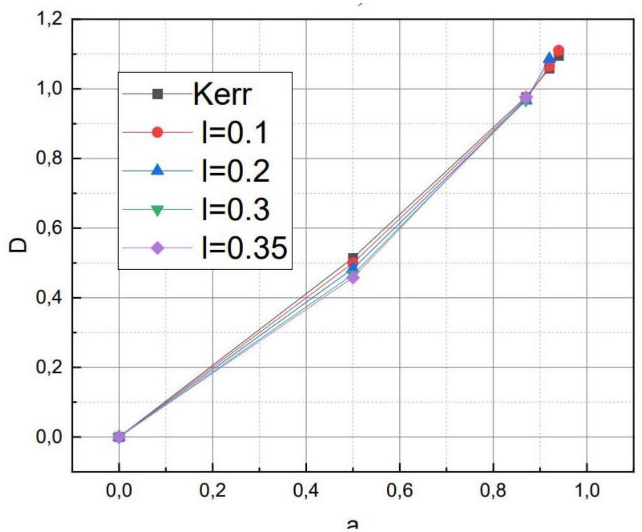


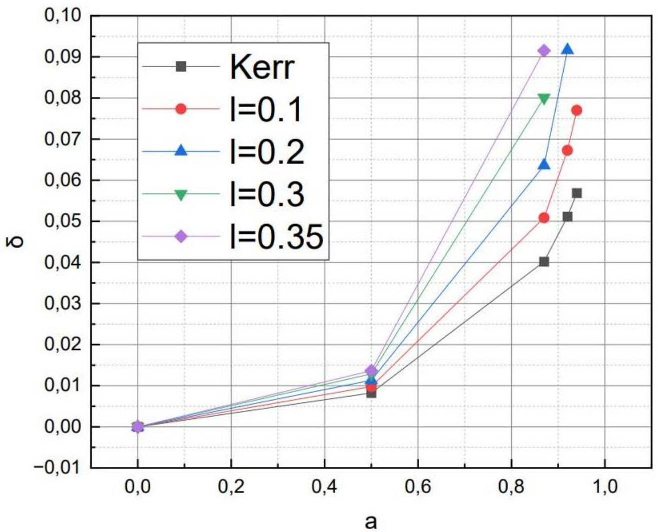
SA, A.Baiderin, O.Zenin, submitted to JETP

Bumblebee model

The dependence of shift D and distortion δ against rotation a



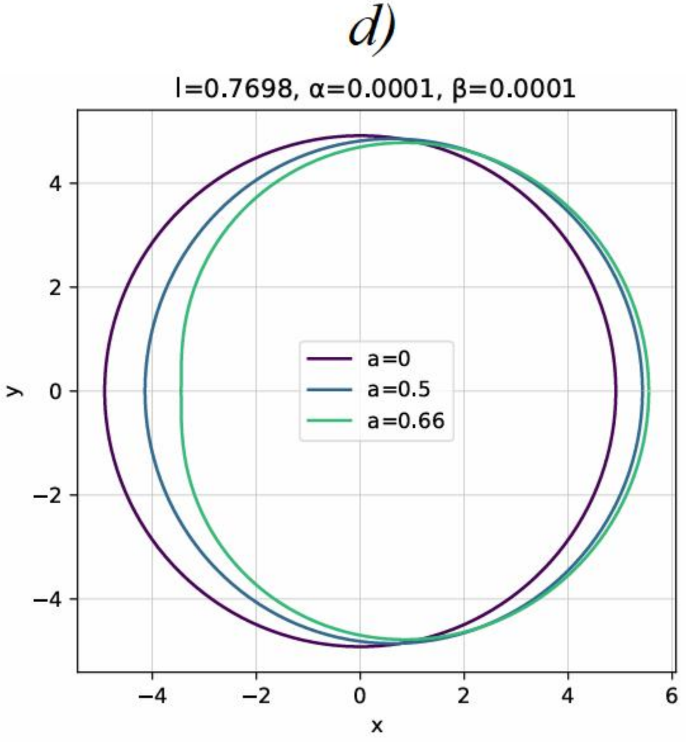


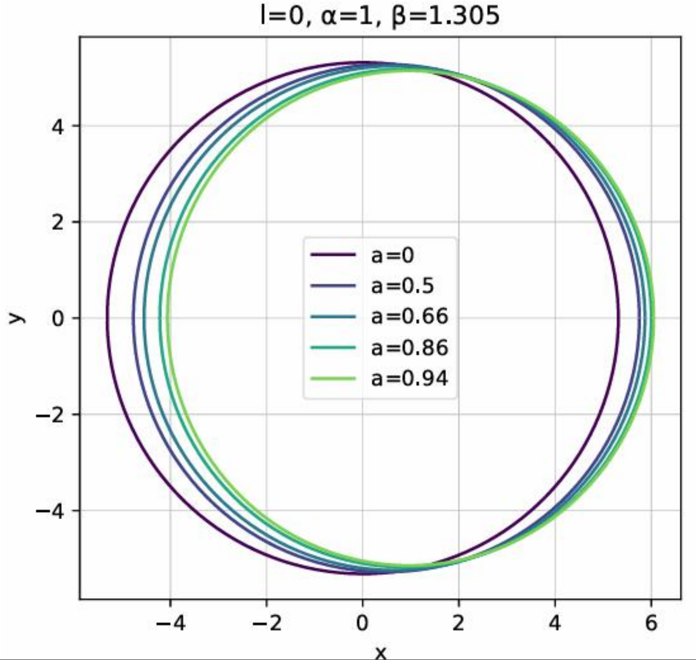


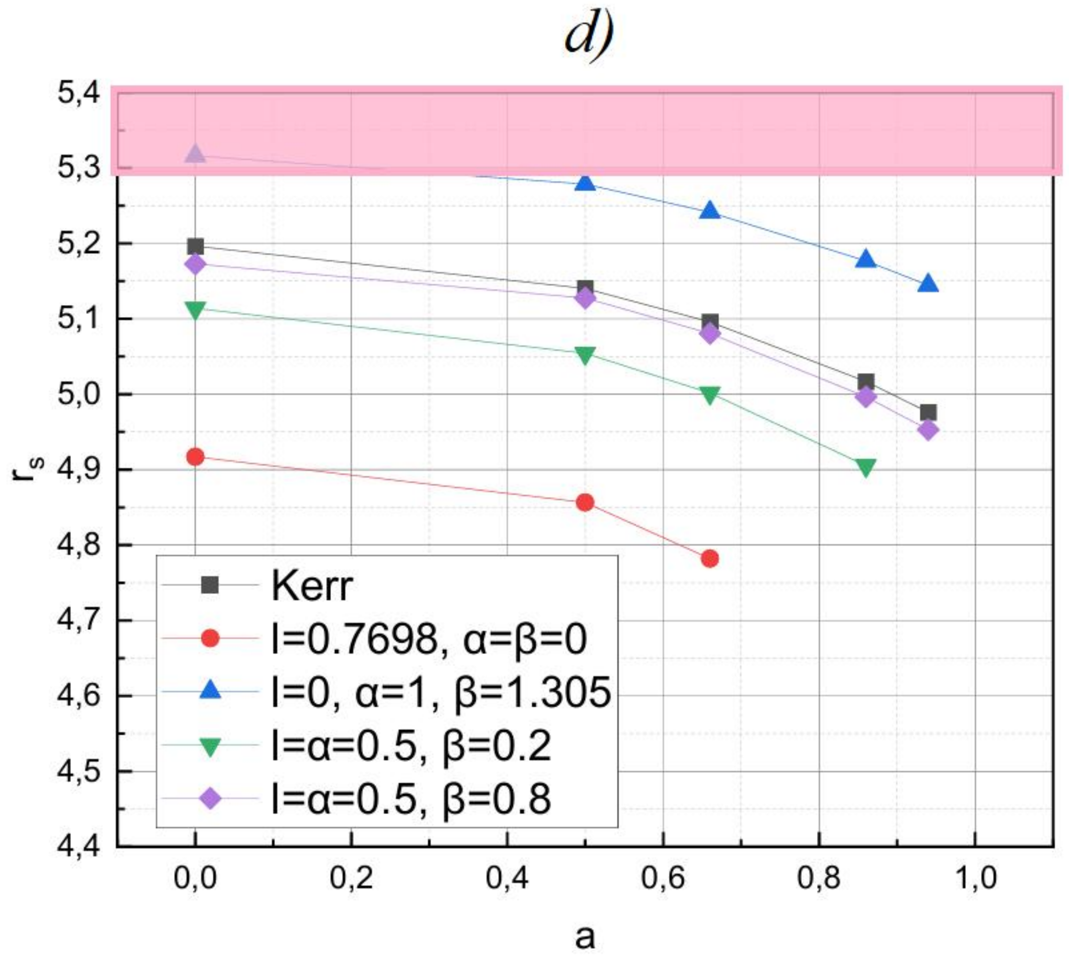
SA, A.Baiderin, O.Zenin, submitted to JETP

Loop Quantum Gravity

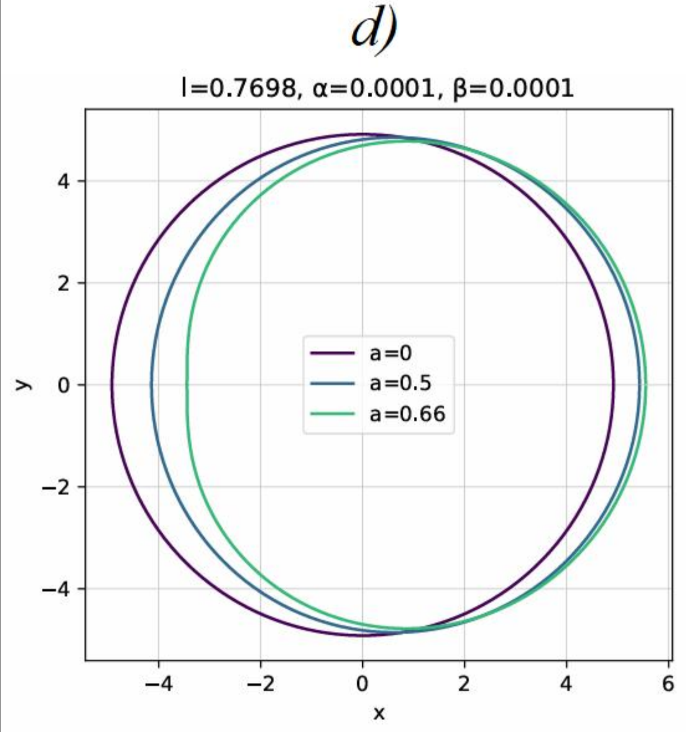
The dependence of the shadow size r_s against rotation a

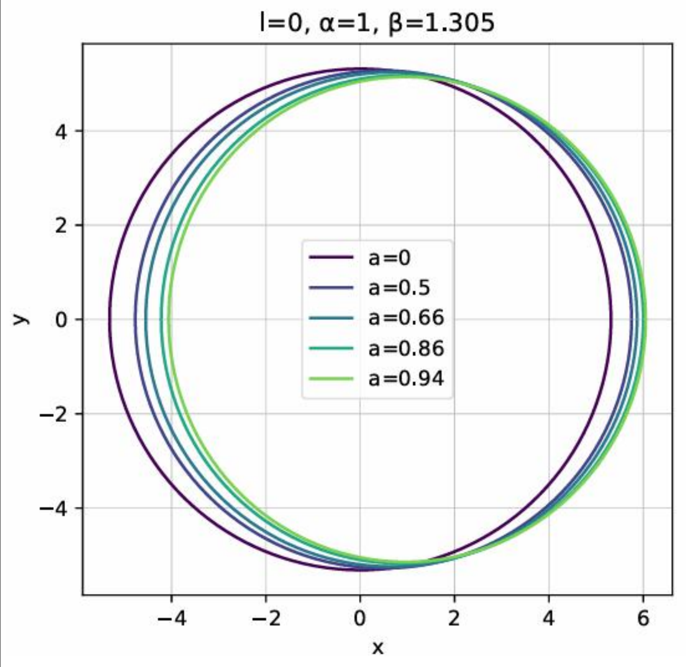






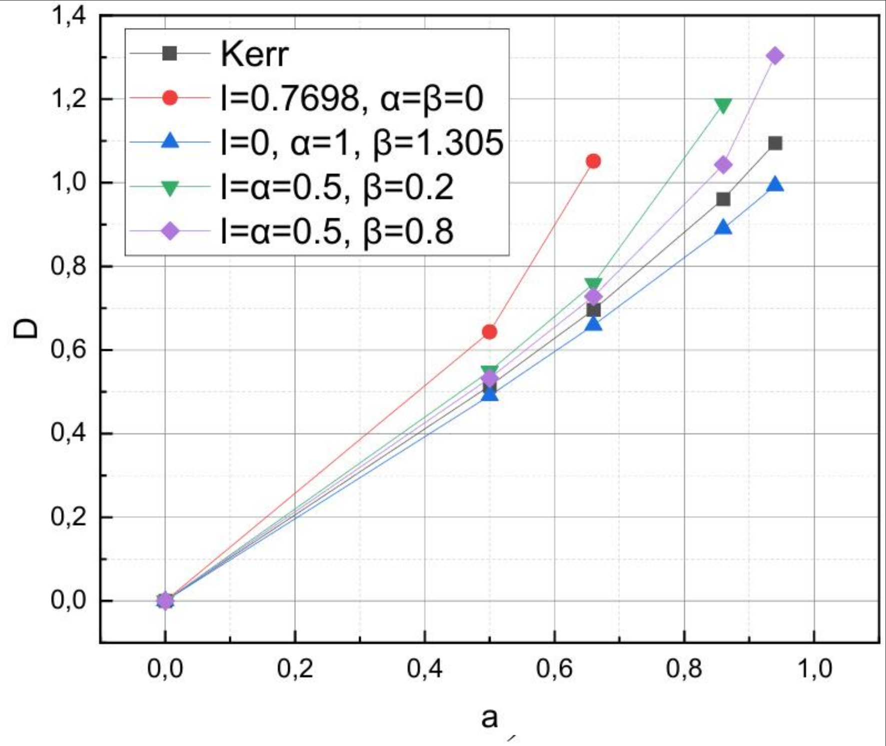
SA, A.Baiderin, O.Zenin, submitted to JETP

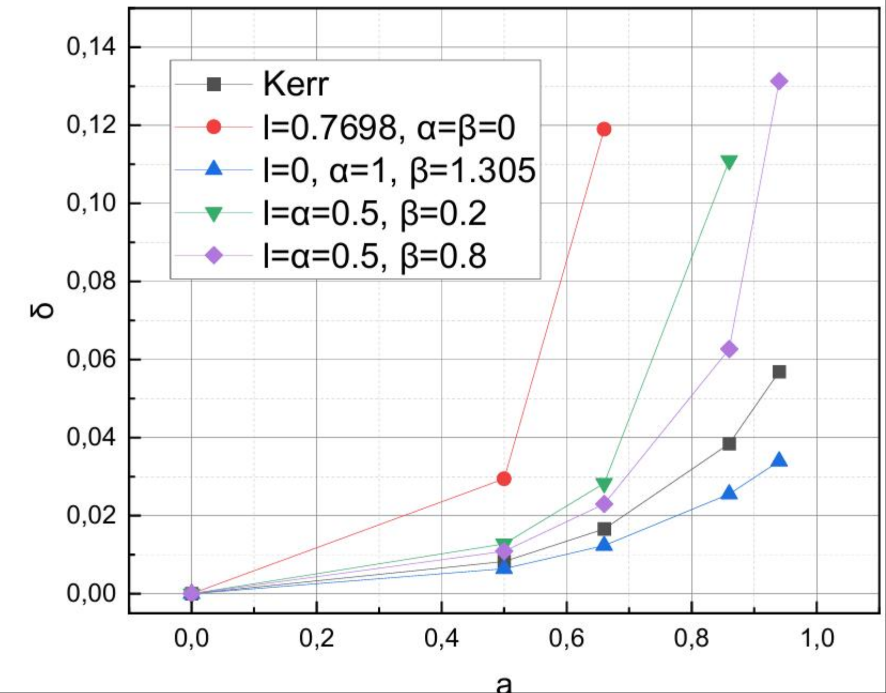




Loop Quantum Gravity

The dependence of shift **D** and distortion **δ** against rotation **a**

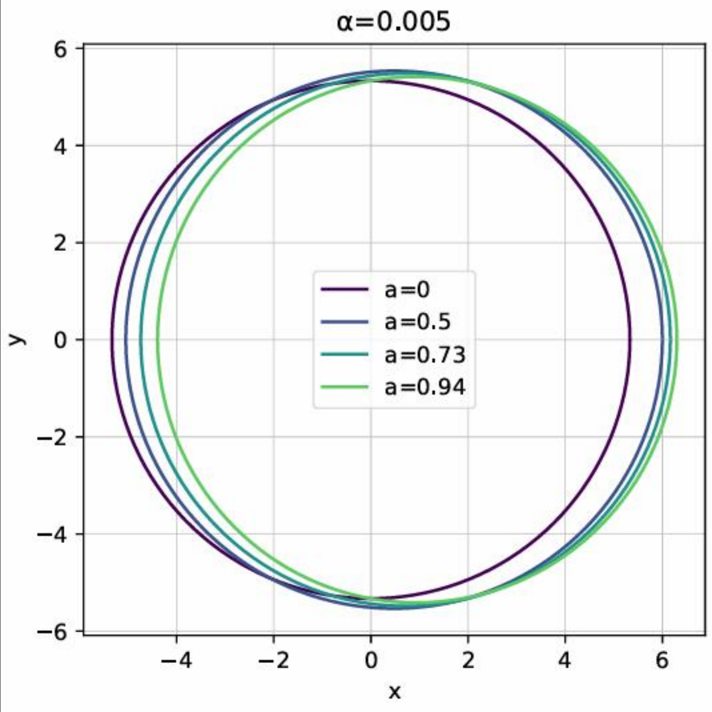


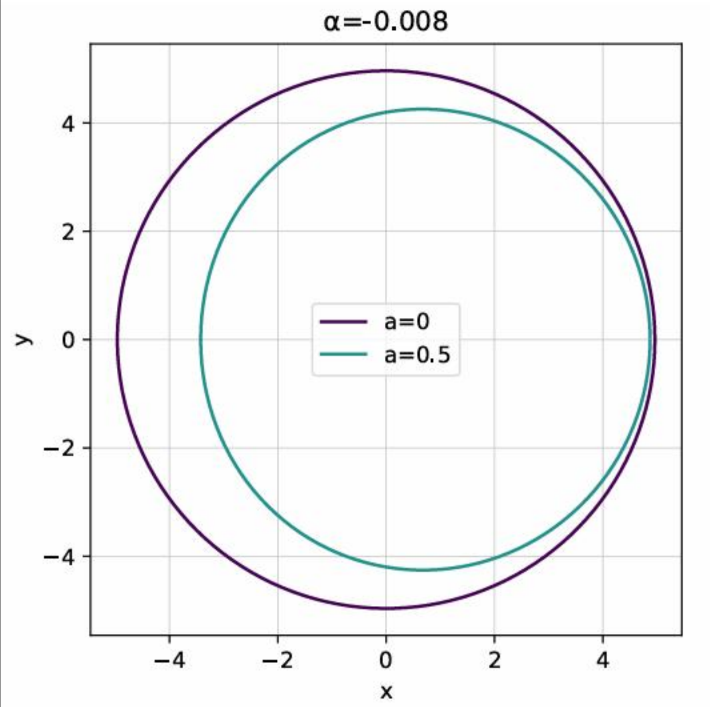


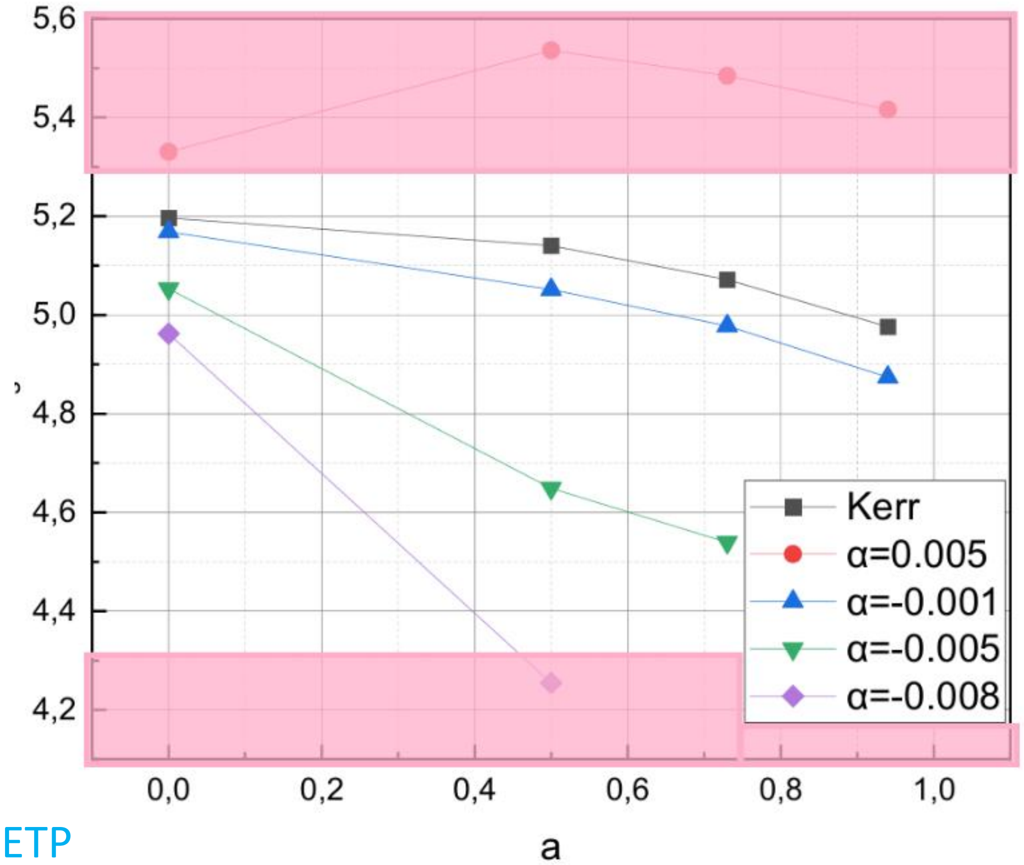
SA, A.Baiderin, O.Zenin, submitted to JETP

f(Q) gravity

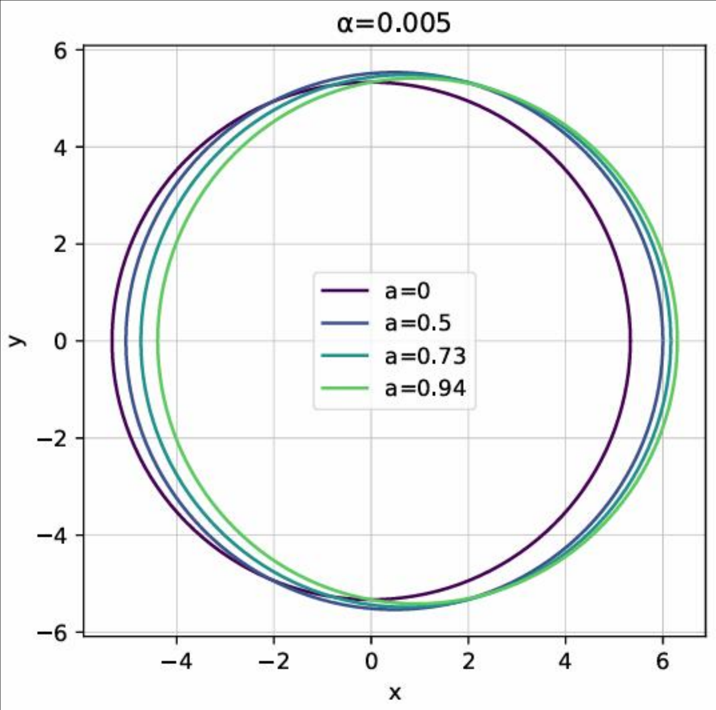
The dependence of the shadow size r_s against rotation a

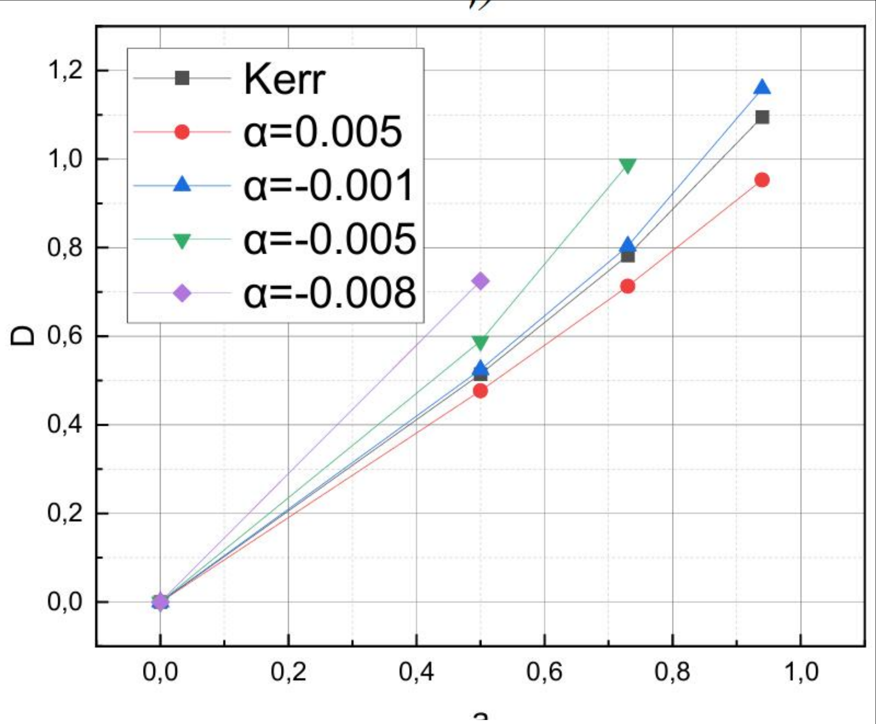






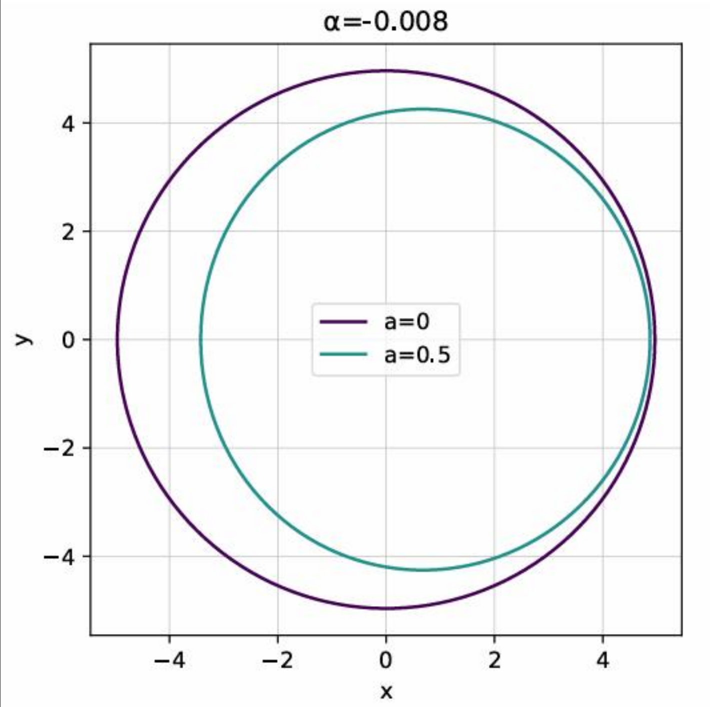
SA, A.Baiderin, O.Zenin, submitted to JETP

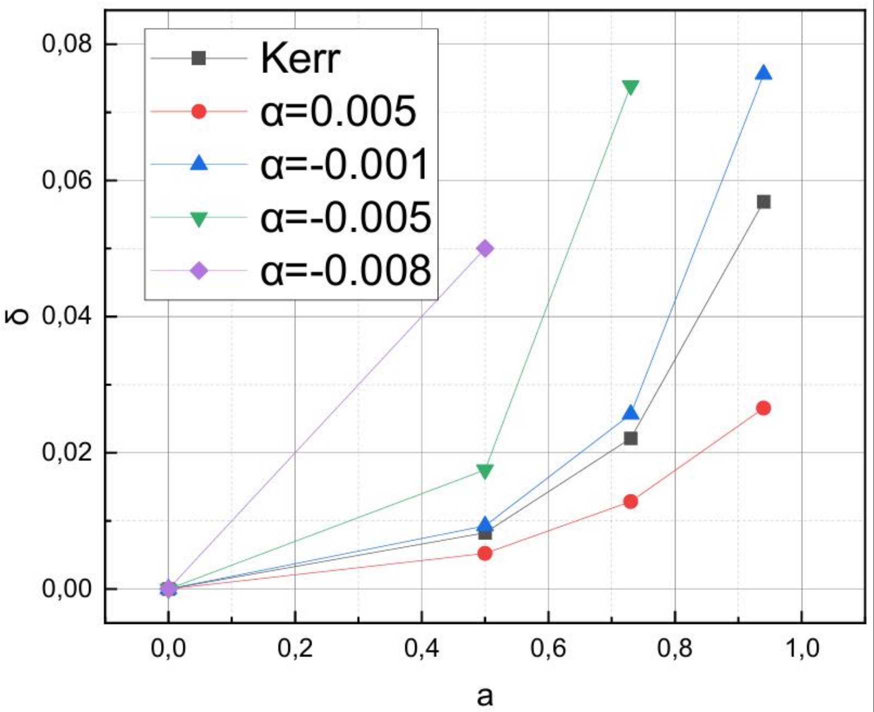




f(Q) gravity

The dependence of shift (up case) and distortion (down case) against rotation a





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- Generally for considered models some of them (Horndesky model and Gauss-Bonnet scalar gravity) weaken the effect of rotation and bumblebee model enhances it.

- This conclusion matches the previous one at non-local gravity models study: extended gravity theories by themselves correct the effect of rotation in both directions. This fact seems to be important as the accuracy of shadow images permanently increases.

Comment on the Newman-Janis algorithm status

$$r^2 \dashrightarrow r^2 + a^2 \cos^2\theta$$

partial symmetry group of rotating solution

- Galaxy clusters scales: ways to explain dark energy & comparing with ΛCDM.
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- Gravitational wave astronomy: deviations from GR.
- Binary pulsars: deviations from GR.
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Thank you for your attention!