Alternative theories of gravity and observed flares from Sgr A*

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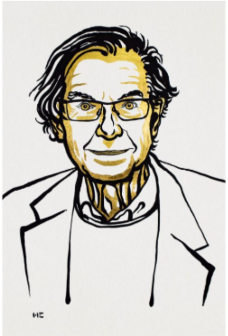
The Nobel Prize in Physics 2020



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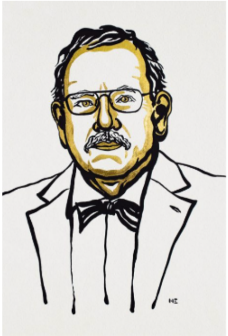
Roger Penrose

Prize share: 1/2



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Reinhard Genzel

Prize share: 1/4

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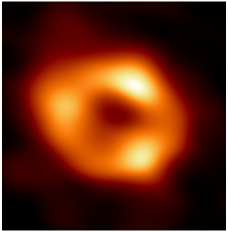
Andrea Ghez

Prize share: 1/4

Roger Penrose: *"for the discovery that black hole formation is a robust prediction of the general theory of relativity"*; Reinhard Genzel and Andrea Ghez: *"for the discovery of a supermassive compact object at the centre of our galaxy"*

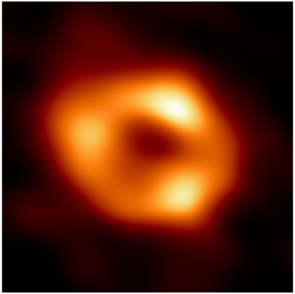
What we know about Sgr A* source?



- 1933 strong radio source in Sagittarius constellation (Galactic Center)
- 1974 bright and very compact component - Sgr A* (supermassive black hole?)
- 2002 Keplerian orbit of S2 star is giving central mass $\sim 4.1 \times 10^6\,\mathrm{M}_\odot$, distance to Earth ~ 8200 pc
- 2022 first image of the accretion disk around Sgr A* compact object

General relativity & compact object in our Galactic Center

Duck test: *"If it looks like a duck, swims like a duck, and quacks like a duck, then it probably is a duck."*



these observation can help us to determine *"supermassive compact object"* spacetime

- observed flares in Sgr A*
- Quasi-Periodic Oscillation for Sgr A*?
- Sgr A* BH shadow
- Extreme Mass Ratio Inspiral (GW overtones), broad K_α iron line, continuum-fitting method, ...

we try to do all calculations for general stationary and axisymmetric spacetime

$$\mathrm{d}s^2 = g_{tt}\mathrm{d}t^2 + 2g_{t\phi}\mathrm{d}t\mathrm{d}\phi + g_{\phi\phi}\mathrm{d}r^2 + g_{rr}\mathrm{d}r^2 + g_{\theta\theta}\mathrm{d}\theta^2$$

...we can automatically test any new spacetime $g_{\alpha\beta}$

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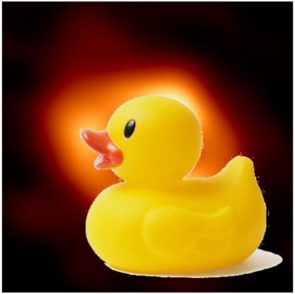

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List of stat. & axisym. spacetimes we can find in literature

Classical BHs in GR

Kerr BHs

Charged BHs in GR

kerr-Newman, Braneworld, Dyonic, Kerr-Taub-Nut, kerr-Newman-Taub-Nut, ...

BHs in alternative MOG

Kerr-Sen, Einstein-Born-Infeld, Weyl, Kalb-Ramond, Einstein-Gauss-Bonnet, Konoplya-Rezzolla-Zhidenko, BHs with Weyl corrections, BHs in Rastall gravity, Kerr-MOG, Kaluza-Klein, regular BHs in Einstein-Yang-Mills theory, Hairy BHs, ...

Regular BHs in GR

Bardeen, ABG, Hayward, ...

Bumpy spacetimes in GR

Johannsen-Psaltis, Kerr-Q, Hartle-Thorne, Quasi-Kerr, Accelerating-rotating, ...

BHs modified by matter field

BHs in DM (dirty BHs), BHs in PFDM , BHs in cold DM halo, BHs in scalar field DM halo, Hayward BHs in PFDM, BHs in DM spike, Deformed BHs in DM spike, BHs in quintessence, ...

Observations can determine spacetime around Sgr A*

- the most important parameter is compact object mass M
- Sgr A* spin $a \sim 0.4$ is not so high (Kerr $\sim$ Schwarzschild)
- restrict parameters determining deviation from Kerr (classical GR)
- deviation from Kerr will be more visible at smaller radii (strong gravity regime)

	distance	
EMRI	horizon	future space based GW detectors (LISA) - solarmass compact object inspiral into supermassive Sgr A* - overtones from ringdown are spacetime sensitive
shadow	photon sph.	dark region encircled by a bright light ring
iron line	ISCO	relativistic shift and broadening of K_α iron line
QPOs	$r = 10$M	resonant peaks in lightcurve spectra
flares	$r = 10$M	flares observed by the GRAVITY instrument

this talk: observed flares in Sgr A* ‖ (QPOs for Sgr A*? ‖ Sgr A* BH shadow)

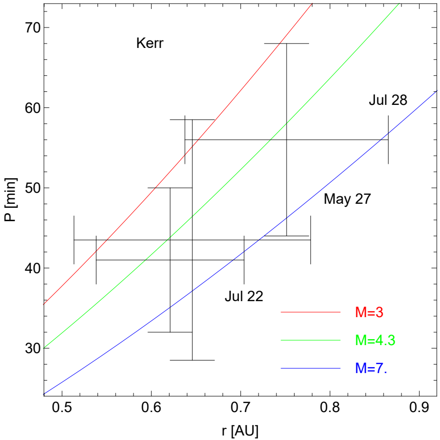
Three flares from Sgr A* (2018)

- hot-spot on geodesic orbit around BH
- distance and orbital periods known - fit!
- test effects of non-GR theories
  we used all stationary, axisymmetric, and asymp. flat BH metric we can found

$$\Omega_\phi(r) = \frac{-g_{t\phi,r} \pm \sqrt{(g_{t\phi,r})^2 - g_{tt,r}\ g_{\phi\phi,r}}}{g_{\phi\phi,r}}$$

hot-spot orbital frequency is given by $g_{\alpha\beta}$ only

$$P = \left(\frac{2\pi}{60}\right)\left(\frac{GM}{c^3}\right)\frac{1}{\Omega_\phi}$$



Kerr metric is OK and well ... more data / decrease error?
Restrictions on parameters of nonGR metric

• M.Shahzadi, M.Kološ, Z.Stuchlík, Y.Habib: *Testing alternative theories of gravity by fitting the hot-spot data of Sgr A**, The European Physical Journal C, 82, 407 (2022)

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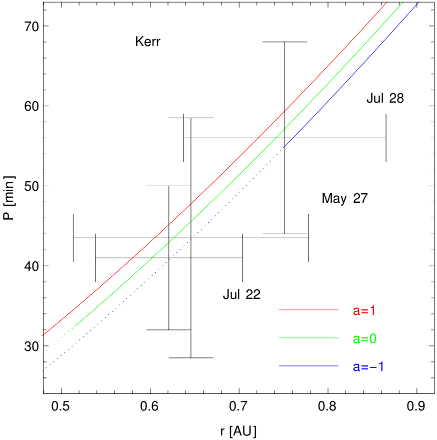

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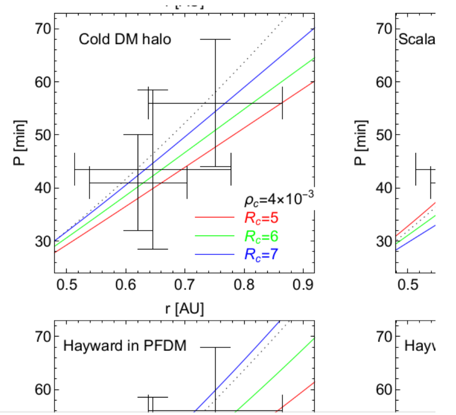

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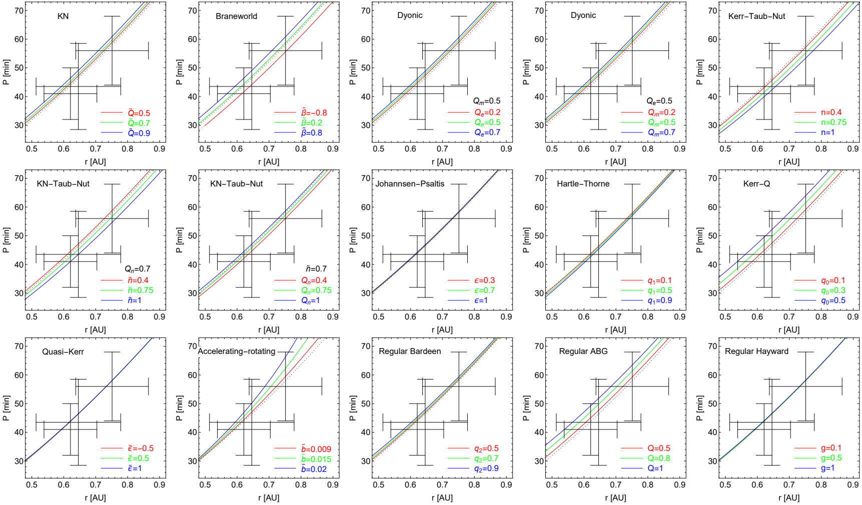
Fitting to the Flares data



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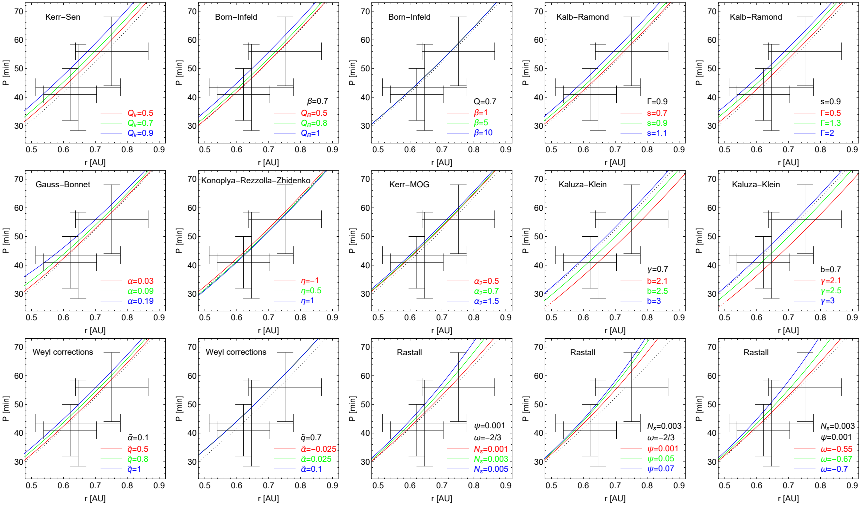

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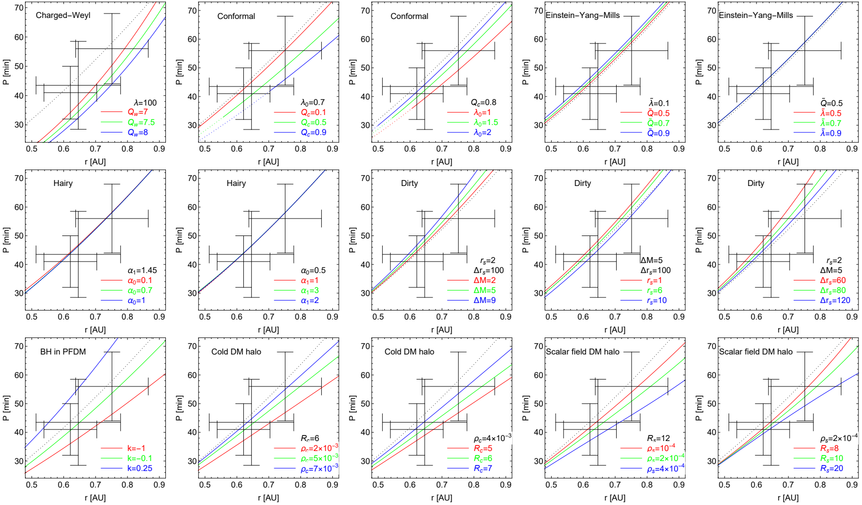


Spacetime	Parameter
KN	$\tilde{Q} \in (0, 1.70]$
Braneworld	$\tilde{\beta} \in [-8.30, 2.90]$
Dyonic	$Q_e \in (0, 1.64]$
	$Q_m \in (0, 1.64]$
Kerr-Taub-Nut	$n \in (0, 2.35]$
KN-Taub-Nut	$Q_n \in (0, 1.95]$,
	$\tilde{n} \in (0, 2.45]$
Dirty	$r_s \in (0, 24]$,
	$\Delta r_s \in (0, \infty)$,
	$\Delta M \in (0, 18]$
BH in PFDM	$k \in [-1.50, 0.29]$
Cold DM halo	$R_{\rm c} \in [3.50, \infty)$,
	$\rho_c \in [0.002, 0.02]$
Scalar field DM halo	$R_{\rm s} \in [2, 25]$,
	$\rho_s \in (0, 0.0004]$
Hayward in PFDM	$\tilde{k} \in [-1.50, 0.28]$,
	$Q_{\rm h} \in (0, 2.90]$
BH in DM spike	$\rho_d \in (0, 0.05]$
Deformed BH in DM	$\tilde{\alpha} \in (0, 2.65]$
BH in quintessence	$\tilde{c} \in (0, 0.007]$,

Johannsen-Psaltis	$\epsilon \in [-70, 20]$
Hartle-Thorne	$q_1 \in [-5.25, 27]$
Kerr-Q	$q_0 \in [-2, 1]$
Quasi-Kerr	$\tilde{\epsilon} \in [-35, 150]$
Accelerating-rotating	$\tilde{b} \in [-0.03, 0.03]$
Kerr-Sen	$Q_K \in (0, 1.25]$
Born-Infeld	$Q_{\rm B} \in (0, 1.30]$,
	$\beta \in (0, \infty)$
Kalb-Ramond	$s \in (0, 1.65]$,
	$\Gamma \in (0, 4.05]$
Gauss-Bonnet	$\alpha \in [-0.7, 0.47]$
KRZ BH	$\eta \in [-12, 55]$
Kerr-MOG	$\alpha_2 \in (0, \infty)$
Kaluza-Klein	$\gamma \in [1.25, 7.95]$,
	$b \in [1.25, 7.50]$
Weyl corrections	$\tilde{\alpha} \in (-\infty, \infty)$,
	$\tilde{q} \in (0, 1.73]$
Rastall	$N_{\rm s} \in (0, 0.10]$,
	$\psi \in (0, 0.12]$
Charged-Weyl	$Q_w \in [5, 8.80]$
Conformal	$Q_c \in (0, 1.20]$,
	$\lambda \in (0, \infty)$

(preliminary) Quasi-Periodic Oscillations and Sgr A* source

Sgr A*: $\nu_{\mathrm{upp}} = 1.445 \pm 0.16$ mHz; $\nu_{\mathrm{down}} = 0.886 \pm 0.04$ mHz; $M = 4.1 \times 10^6 \mathrm{M}_\odot$

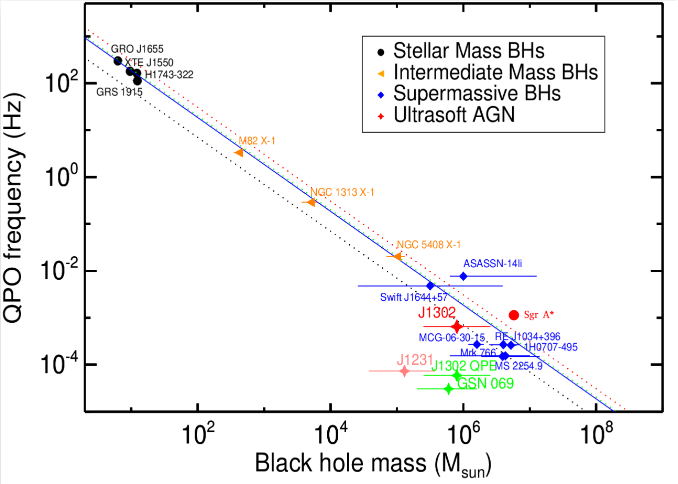
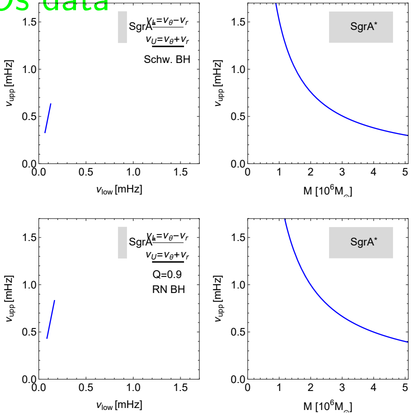


fig. taken from (Song+, 2022), updated with Sgr A* QPOs data from (Török, 2005)

(preliminary) Fitting to the HF QPOs data



hot-spot dynamics, (super)Hamiltonian

$$H = \frac{1}{2} g^{\alpha\beta} u_\alpha u_\beta + \frac{1}{2} m^2 = H_{\rm D} + H_{\rm P}$$

dynamical $H_{\rm D}$ (p_r, p_θ), potential $H_{\rm P}$ (m, $\mathcal{E}$, $\mathcal{L}$)

- conserved quantities $\mathcal{E}$, $\mathcal{L}$ for circular orbit
- perturbation of particle circular orbit (effective potential minima) leads to oscillations with frequencies: radial $\Omega_{\rm r}$, vertical Ω_θ, orbital Ω_ϕ.
- observed frequency in [Hz] $\Omega \to \nu$.

$$\Omega_{\rm r}^2 = \frac{\partial_r^2 H_{\rm P}}{g_{rr}(u^t)^2}, \quad \Omega_\theta^2 = \frac{\partial_\theta^2 H_{\rm P}}{g_{\theta\theta}(u^t)^2}, \quad \Omega_\phi = \frac{u^\phi}{u^t} \qquad \nu_\alpha = \frac{1}{2\pi}\frac{c^3}{GM}\Omega_\alpha$$

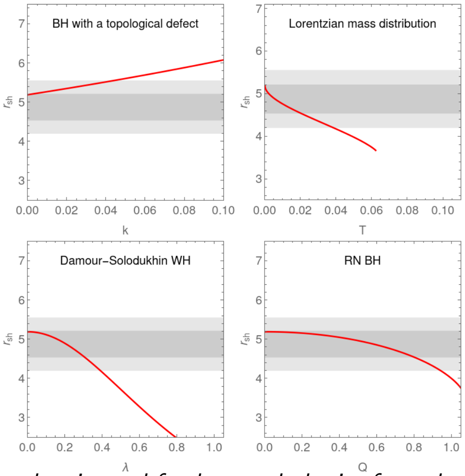
- Unable to fit Sgr A* HF QPOs data for any given spacetime?

(preliminary) Sgr A* shadow and alternative theories of gravity

- photon radius ($r_{\rm ph}$): $\sqrt{\frac{g_{\theta\theta}}{-g_{tt}}} = 0$
- shadow radius ($r_{\rm sh}$): $\sqrt{\frac{g_{\theta\theta}}{-g_{tt}}}\Big|_{r\to r_{\rm ph}}$

radius Sgr A* shadow can be used once again as restrictions on deviation for Kerr spcacetime (restrictions on new spacetime parameters)

- image of Sgr A* shadow
  is more restrictive than flares



for spherically symmetric spacetime see:

• S.Vagnozzi+++: *Horizon-scale tests of gravity theories and fundamental physics from the Event Horizon Telescope image of Sagittarius A**, arXiv (2022) [arXiv:2205.07787]

Summary & Future work

- three flares observed by the GRAVITY instrument at Sgr A* on May 27, July 22, July 28, 2018 are fitted by hot-spot dynamics orbiting various modifications of the standard Kerr black hole
- general formalism for any stationary, axially symmetric spacetime
- current data restrict deviations Kerr black hole only partially - more data needed

- we are now trying to do the same general method for Sgr A* shadow, ...

Thank you for your attention

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for magnetic field influence on hot-spot (flare) dynamics, see:
• A.Tursunov, M.Zajaček, A.Eckart, M.Kološ, S.Britzen, Z.Stuchlík, B.Czerny, V.Karas: *Effect of Electromagnetic Interaction on Galactic Center Flare Components*, ApJ 897 99 (2020)