Identity of the supermassive black hole at the Galactic Center

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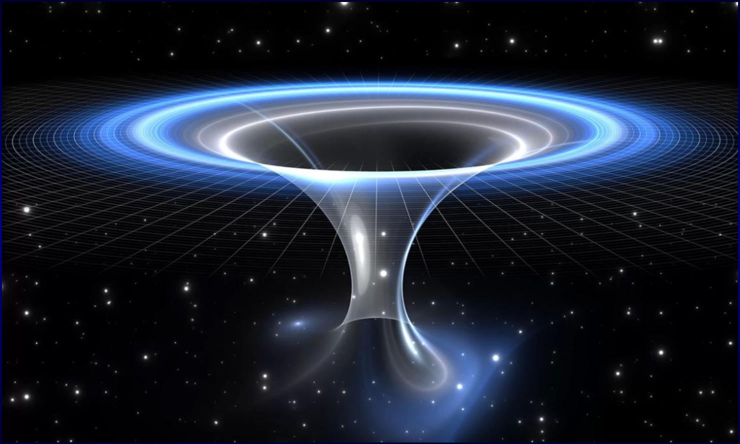
Standard Model in Astrophysics

Black hole is the essential element of the Standard Model



Black holes — most exotic objects in the Universe

(widely known, badly studied)

Standard Model in Astrophysics

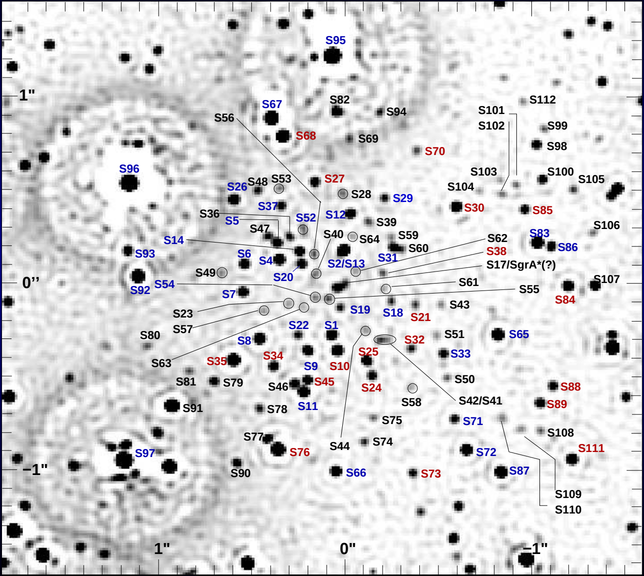
Experiment is requested for verification (or falsification) of the General Relativity in the strong field limit!

$$R > \frac{GM}{c^2}, \qquad \varphi \sim \frac{GM}{R} \sim v_{\rm vir}^2 < c^2, \qquad \boxed{\varphi \sim c^2}$$

Remember the first, second, and third cosmic velocities...

The first great galactographic discovery in the XXI century

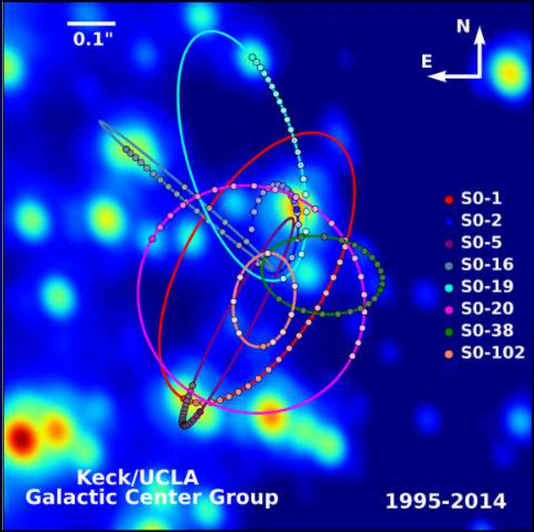
Direct measuring the mass of the black hole SgrA* in the Galactic Center



Stars in the Galactic Center in the near-infrared *Gillessen et al. 2008*

The first great galactographic discovery in the XXI century

Direct measuring the mass of the black hole SgrA* in the Galactic Center

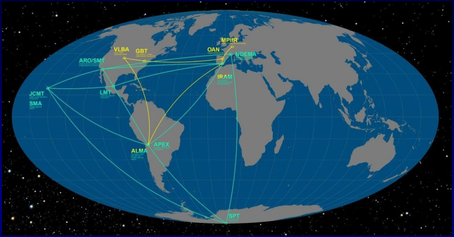


S0-102: $T = 11.5$ yrs, S0-2: $T = 16$ yrs, $M_h = (4.1 \pm 0.4)10^6 M_\odot$

The next (awaited) great galactographic discovery in the XXI century

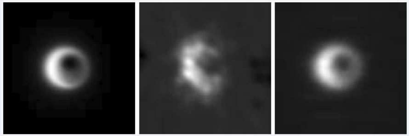
The Event Horizon Telescope (EHT) array for the black hole shadow $\sim$ 2020 yr

Submillimeter (0.87 – 1.3 mm) VLBI array for the EHT $\Rightarrow$ $\mathbf{10^{-6''}}$



EHT stations

Submillimeter array (ALMA)



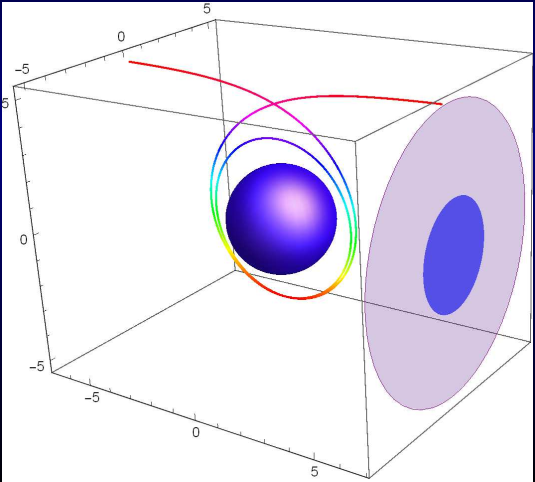
Black hole shadow (at left) and model images of SgrA*

EHT with 7 telescopes

Fish & Doeleman

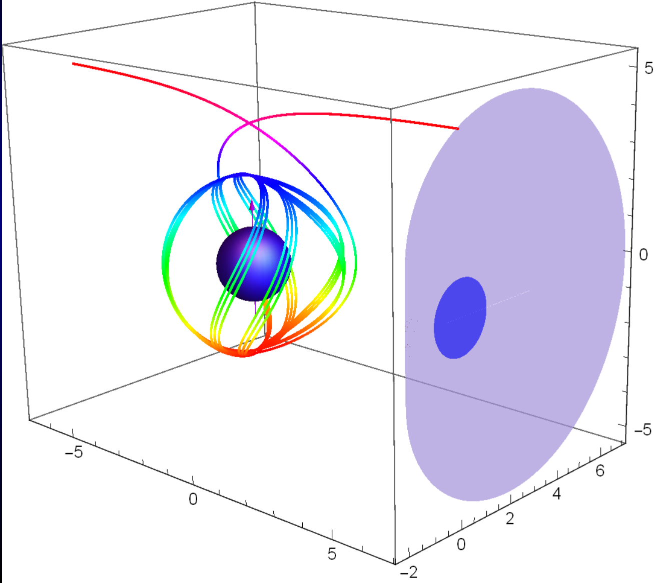
Black hole shadow (magenta disk) — photon capture cross section by luminous stationary background in the Schwarzschild case $(a = 0)$ with radius $r_{\rm sh} = 3\sqrt{3} \simeq 5.196$

Inside the black hole shadow is shown the image of the event horizon (blue disk) with radius $r_h = 2$ in the imaginary Euclidean space



Shadow (magenta region) of the extreme Kerr black hole $(a = 1)$

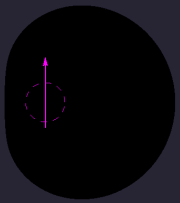
Inside the black hole shadow is shown the image of the event horizon (blue disk) with radius $r_h = 1$ in the imaginary Euclidean space



Crucial experiment for General Relativity verification in the strong field limit

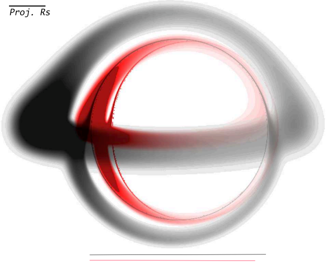
Direct evidence for existence of black holes in the Universe ~ 2020 yr

Shadow of the supermassive black hole SgrA* in the Galactic Center?

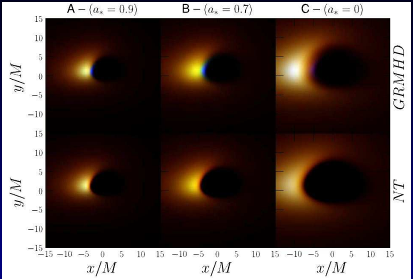


Invisible black hole horizon and visible black hole shadow

Experimental falsification of the Gravitation Theory models ~ 2020 yr

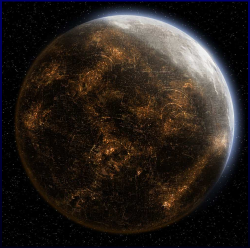


Polish disk (Ion tor) $a = 0.5; 0.9$



Typhoon eye $a = 0; 0.7; 0.9$ Zhu et al. 2012

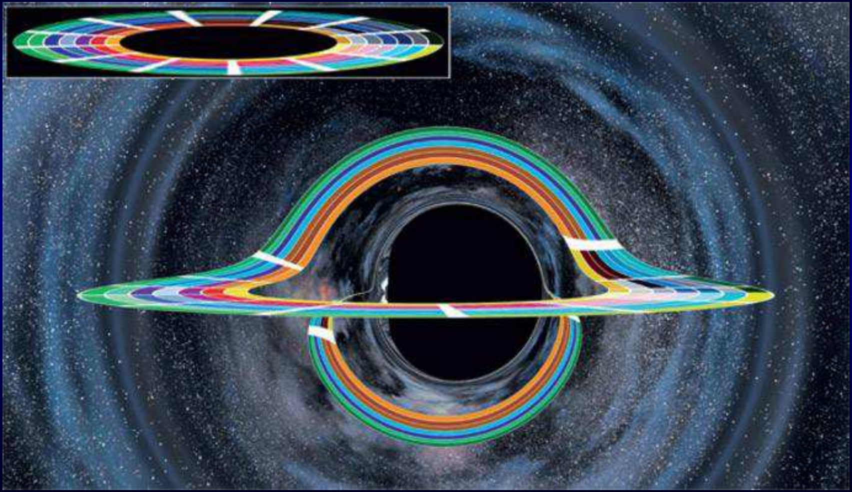
Cast-iron ball



Planet Coruscant — Capital of the Galactic Republic

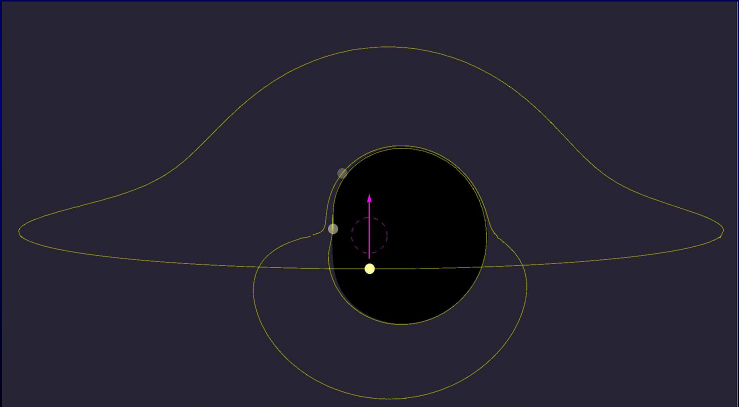
Thin accretion disk

Numerical modelling for cinema "Interstellsr" 2015 *K. S. Thorne et al.*



Star (probe) on the equatorial circular orbit close to SgrA* viewed by the distant telescope

Orbital radius $r_s = 20MG/c^2 \simeq 1.24\ 10^8$ km ~ 1 AU, orbital period $T = 3.22$ hrs, orbital velocity $v_s = 0.22c$, black hole spin $a = 0.998$. Infinite number of instant lensed images:



Prime image of the star and first and second light echoes

Optical appearance of a star

C. T. Cunninghan, J. M. Bardeen 1973

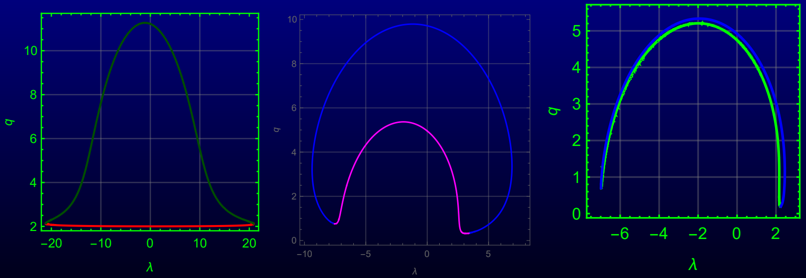
Prime image: 0 intersections of equatorial plane

First light echo: 1 intersection of equatorial plane

Second light echo: 2 intersections of equatorial plane

N-th light echo: $1 \leq N < \infty$ intersections of equatorial plane

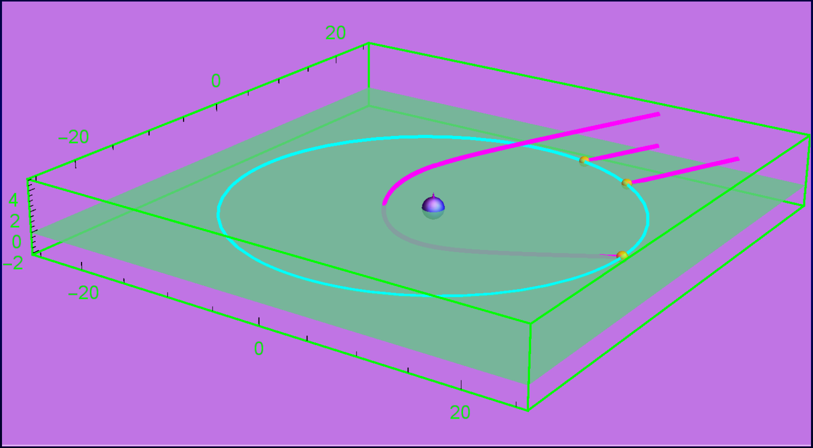
$$\int_{\theta_s}^{\theta_0} \frac{d\theta}{\sqrt{V_\theta}} = \int_{r_s}^{r_0} \frac{dr}{\sqrt{V_r}}, \qquad \sum_N \int_{\theta_{N1}}^{\theta_{N2}} \frac{d\theta}{\sqrt{V_\theta}} = \sum_N \int_{r_{N1}}^{r_{N2}} \frac{dr}{\sqrt{V_r}}$$



Solutions (λ, q) for prime images, first and second light echoes

3D photon trajectories

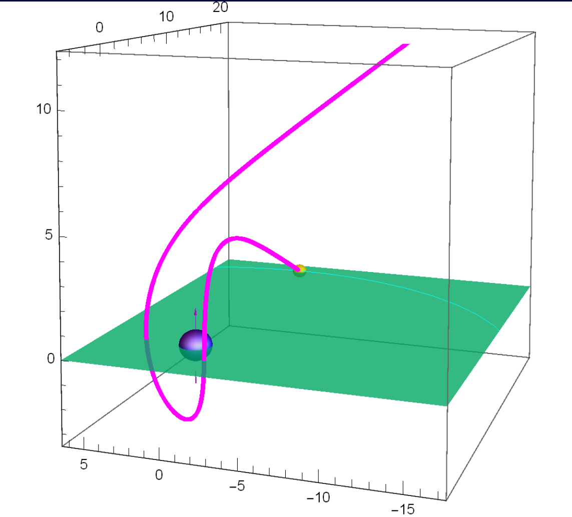
Prime image: no intersections of equatorial plane
First light echo: one intersection of equatorial plane



3D photon trajectory

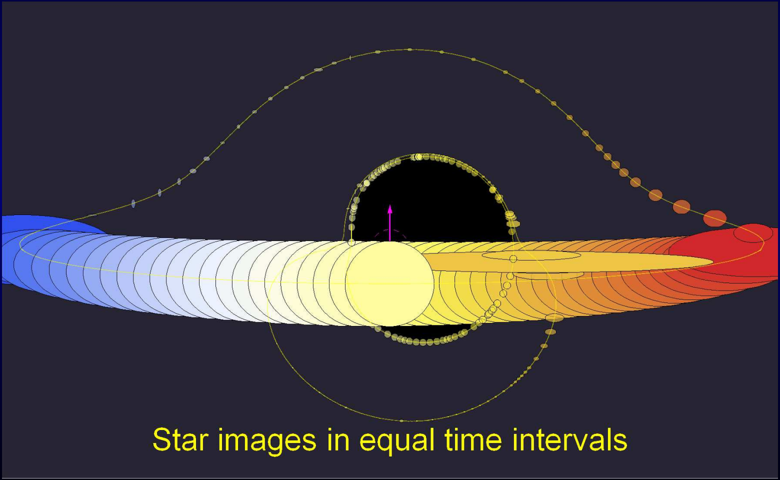
Second light echo: two intersections of equatorial plane

$\lambda = -1.78, \quad q = 5.2, \quad r_{\min} = 3.11$



Star (probe) on the equatorial circular orbit close to SgrA* viewed by the distant observer

Numerical calculation of the direct image and the first and second light echoes



VD & N. O. Nazarova 2017

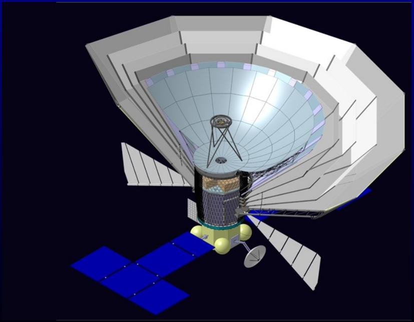
The next step: What is the Gravitation Theory?

Experimental verification or falsification of the gravity theories in the strong field limit:

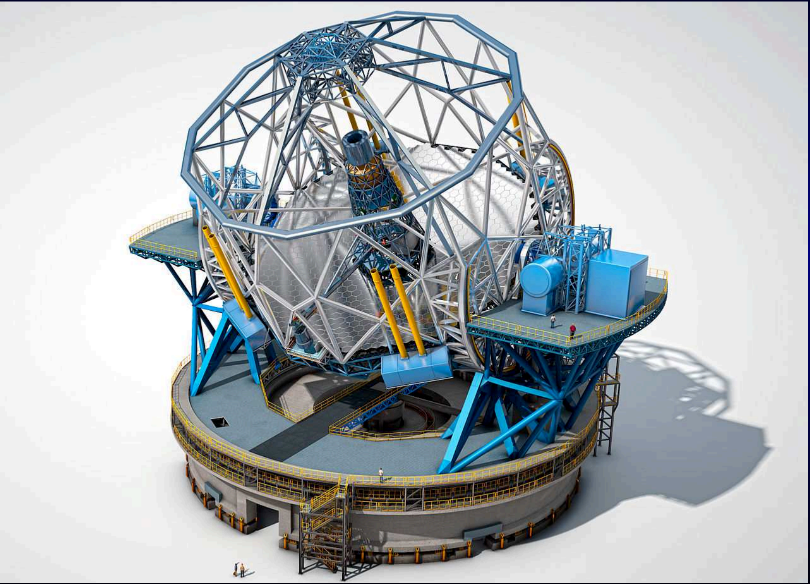
General Relativity, $f(R)$, C^2, Galileon, Horndesky, extra-dim or...?

New technologies are requested to view the SgrA* with the angular resolution $\sim 10^{-9''}$

Russian space project **Millimetron** is the most promising for developing of requested new technologies

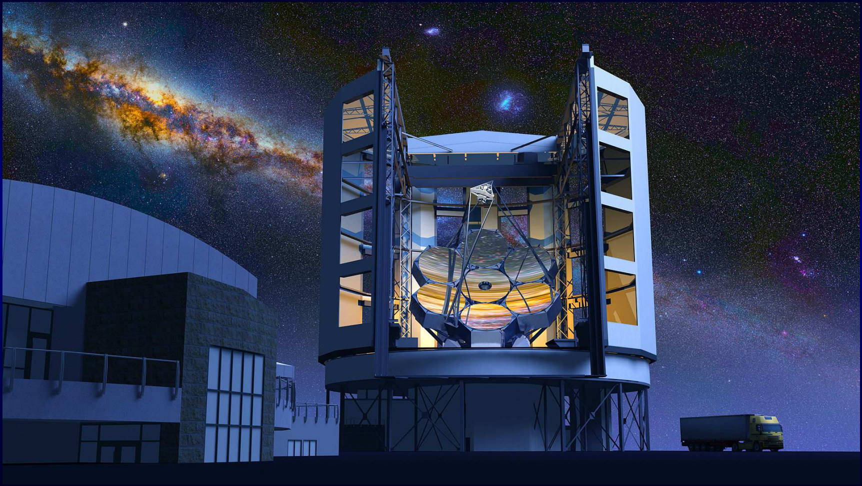


$\varnothing = 39.3$ m, European Extremely Large Telescope (ELT), Chile $\sim$ 2020



$\varnothing$ = 30 m, 492 segments, Thirty Meter Telescope (TMT), Hawaii 2021

$\varnothing = 24.5$ м (7×8.4 м) **Giant Magellan Telescope (GMT), Chile**



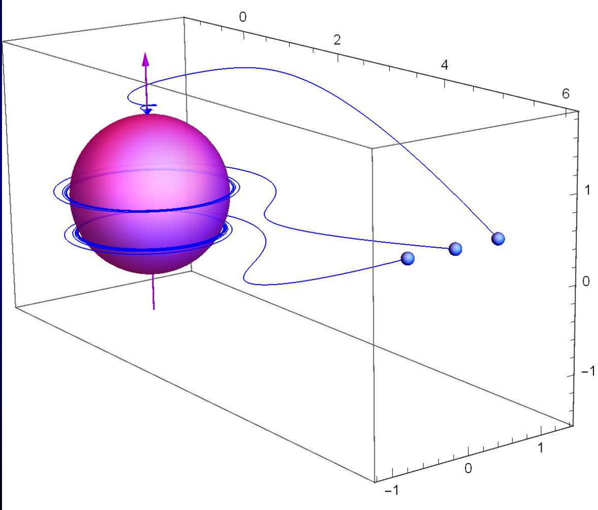
Event horizon is invisible,

but it can be identified
(groped in the dark)

inside the black hole shadow!

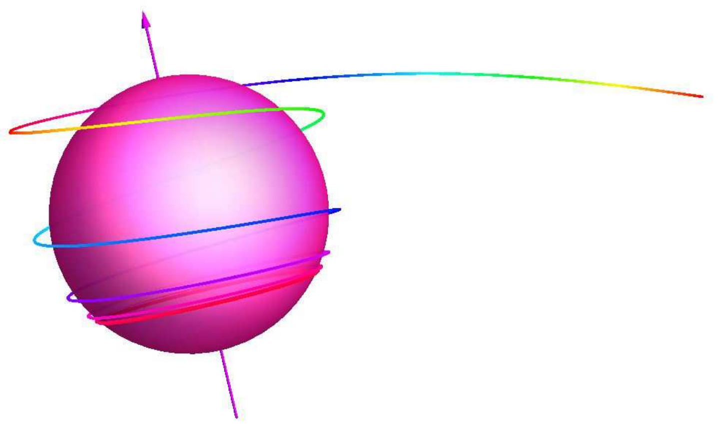
$3D$ **trajectories of test particles, plunging into rotating black hole:**

1. **near the north pole of the event horizon** ($\gamma = 1$, $\lambda = 0$, $q = 1.85$),
2. **near its equator** ($\gamma = 1$, $\lambda = -1.31$, $q = 0.13$)
3. **in its south hemisphere** ($\gamma = 1$, $\lambda = -1.31$, $q = 0.97$)



Photon infall into rotating black hole

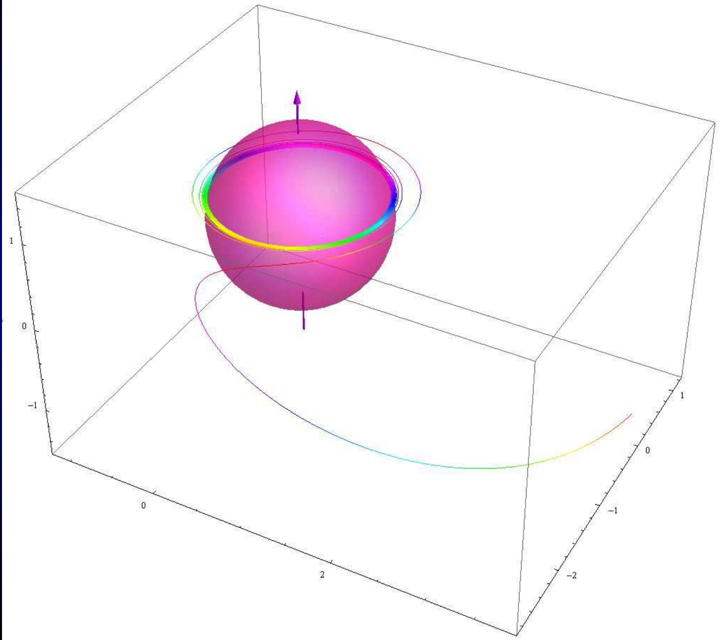
$a = 0.998, \quad \eta \equiv Q/E^2 = 2, \quad \lambda \equiv \Phi/E = 2, \quad r_+ = 1.063$



Horizon angular velocity Ω_h and horizon rotation period T_h:

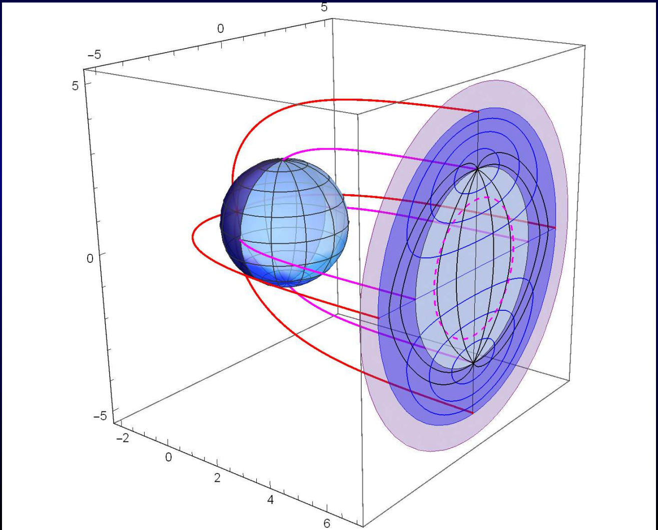
$$T_h = \frac{2\pi}{\Omega_h} = \frac{4\pi M}{a}(1 + \sqrt{1 - a^2})$$

Photon infall into rotating black hole: $\lambda = -6.5$, $\eta = 4$

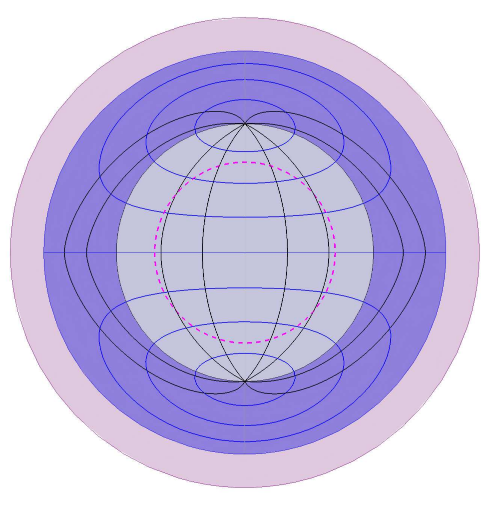


Event horizon image (blue disk) inside the black hole shadow (magenta disk) of the Schwarzschild black hole ($a = 0$)

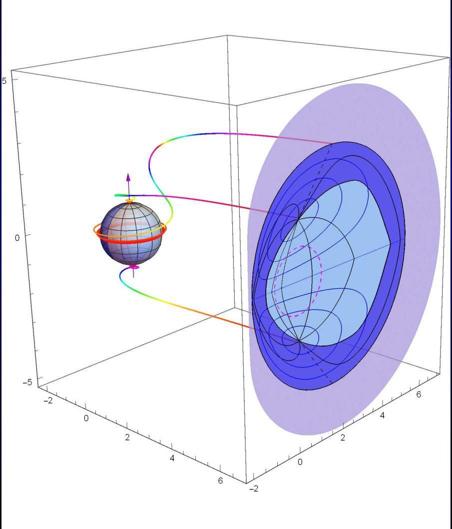
Photon trajectories forming the event horizon image inside the Schwarzschild black hole shadow



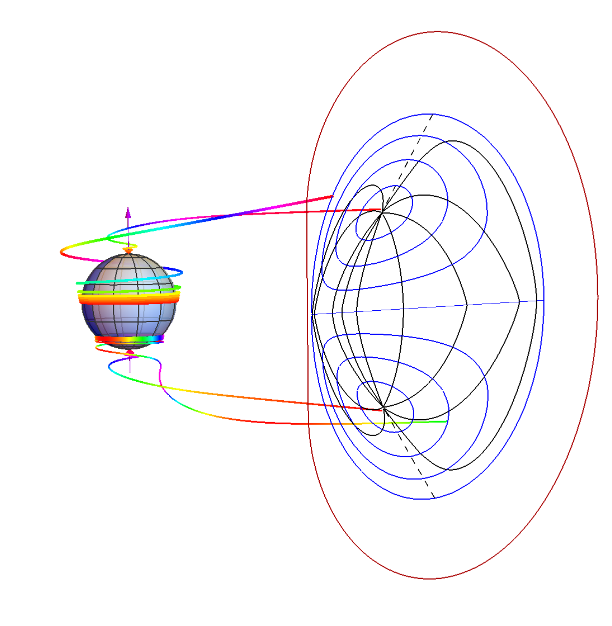
Gravitationally lensed image of the event horizon (light and dark blue disks) inside the Schwarzschild black hole shadow (magenta disk)



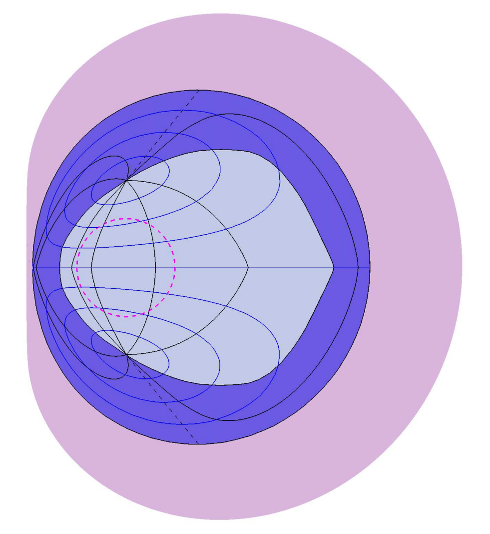
Event horizon image (light and dark blue regions) inside the black hole shadow (magenta region) of the Kerr black hole ($a = 1$)



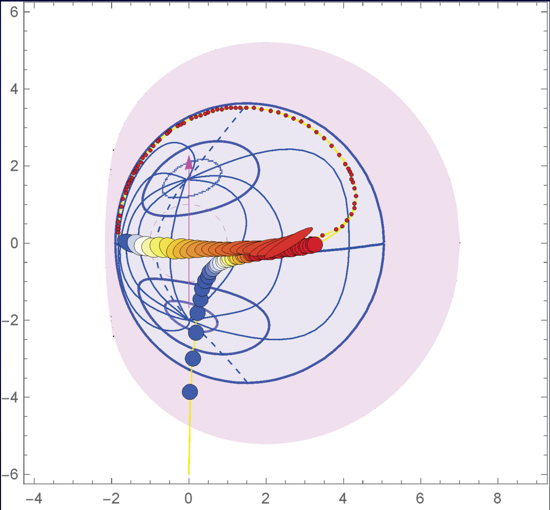
Event horizon image inside the black hole shadow of the Kerr black hole



Gravitationally lensed image of the event horizon (light and dark blue regions) inside the Kerr black hole shadow (magenta region)



Gravitational lensing of the luminous source plunging in the equatorial plane into rotating black hole. Distant observer is placed at the latitude $\cos\theta = 0.1$. At late times the observed image is fading $\propto exp(-\Omega_h t)$



VD & N. O. Nazarova 2018

Numerical simulation of MHD accretion

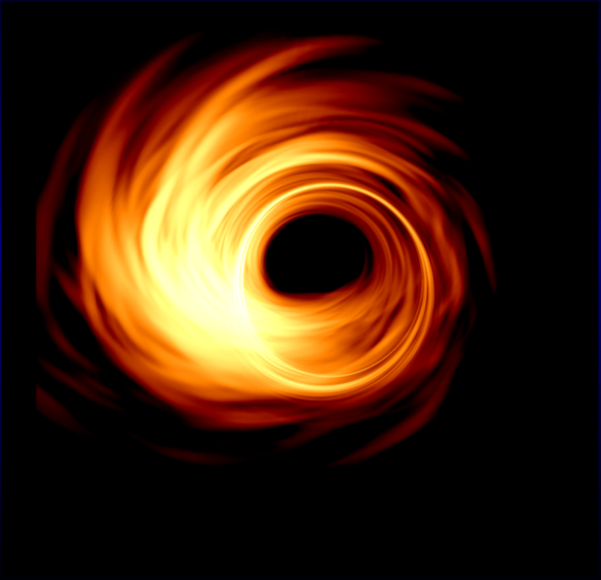
H. Shiokawa, EHT

https://www.youtube.com/watch?v=dlAEbvAUXYg

Numerical simulation of MHD accretion

H. Shiokawa, EHT

Hotaka Shiokawa: https://eventhorizontelescope.org/simulations-gallery



Numerical simulation of MHD accretion

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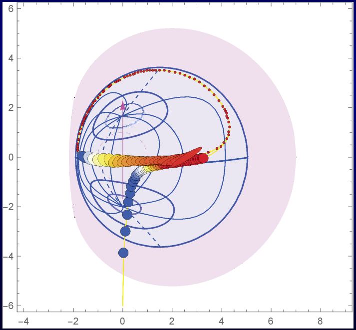
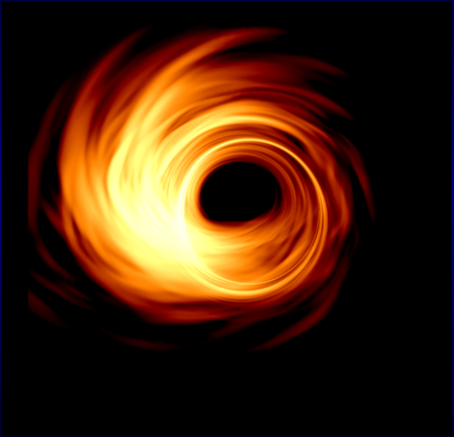




Conclusion

- The supermassive black hole SgrA* at the Galactic Center is an exclusive physical laboratory allowing the verification (or falsification) of the General Relativity and Modified Gravity Theories in the strong field limit
- A genuine image of the black hole viewed by a distant observer is not its shadow, but a more compact event horizon image
- Black holes are the unique objects in the Universe which may be viewed by distant observers at once from both the front and back sides

Thanks to all!

Kerr-Newman metric

$$ds^2 = \frac{\rho^2 \Delta}{\mathcal{A}} dt^2 - \frac{\mathcal{A} \sin^2\theta}{\rho^2}(d\varphi - \omega dt)^2 - \frac{\rho^2}{\Delta} dr^2 - \rho^2 d\theta^2$$

Potential $A = e\rho^{-2} r(du - a\sin^2\theta d\varphi), \quad u = t + r, \quad F = 2dA$

$$\rho^2 = r^2 + a^2\cos^2\theta, \ \Delta = r^2 - 2r + a^2 + e^2, \ \mathcal{A} = (r^2 + a^2)^2 - a^2 \Delta \sin^2\theta$$

Metric 'angular velocity'

$$\boxed{\omega = (2Mr - e^2)\frac{a}{\mathcal{A}}}$$

Horizons: $\Delta = 0, \quad r_\pm = 1 \pm \sqrt{1 - a^2 - e^2}$

R-regions $(\Delta > 0)$: $r > r_+, \qquad 0 < r < r_- < r_+$
T-region $(\Delta < 0)$: $r_- < r < r_+$

Locally Nonrotating Frame (LNRF):
$r = const, \quad \theta = const, \quad \varphi_0 = \omega t + const$

J. M. Bardeen 1970

Equations of motion of a test particle
B. Carter 1968

The final solution for the Hamilton-Jacobi equation
J. Bardeen 1972

$$S = \frac{1}{2}\mu^2\tau - Et + \Phi\varphi + \int^\theta \sqrt{V_\theta}\,d\theta + \int^r \frac{\sqrt{V_r}}{\Delta}dr$$

$$V_\theta = Q + a^2(E^2-\mu^2)\cos^2\theta - \Phi^2\cot^2\theta, \qquad \Delta = r^2 - 2r + a^2 + e^2$$

$$V_r = r[r(r^2+a^2)+2a^2]E^2 - 4arE\Phi - (r^2-2r)\Phi^2 - \Delta(r^2\mu^2+Q)$$

$$\int^r \frac{dr}{\sqrt{V_r}} = \int^\theta \frac{d\theta}{\sqrt{V_\theta}}, \qquad \tau = \int^\theta \frac{a^2\cos^2}{\sqrt{V_\theta}}d\theta + \int^r \frac{r^2}{\sqrt{V_r}}dr$$

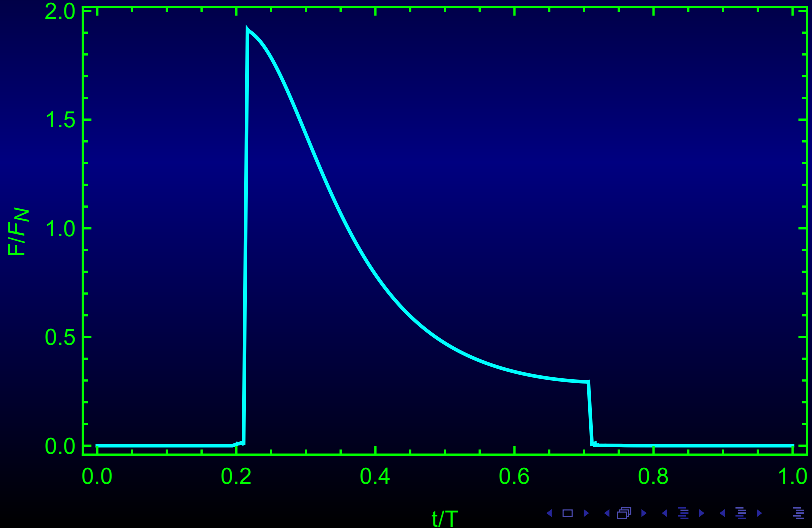
$$t = \int^\theta \frac{a^2E^2\cos^2\theta}{\sqrt{V_\theta}}d\theta + \int^r \frac{r^2(r^2+a^2)E + 2ar(aE-\Phi)}{\Delta\sqrt{V_r}}dr$$

$$\varphi = \int^\theta \frac{\Phi\cot^2\theta}{\sqrt{V_\theta}}d\theta + \int^r \frac{r^2\Phi + 2ar(aE-\Phi)}{\Delta\sqrt{V_r}}dr$$

Light curve of the prime (direct) image: $F(t)/F_N$

$F(t)$ — flux of energy, F_N — Newtonian flux of energy

T — orbital period



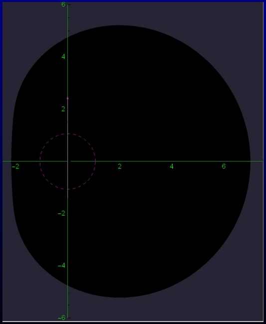
The apparent shape of the black hole
"Black hole shadow"

J. M. Bardeen 1972

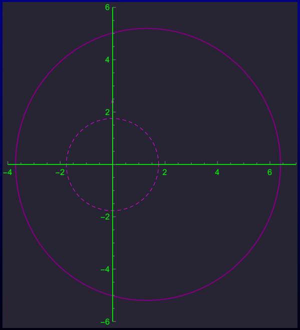
The verge of turning points ($r = const$ trajectories):

$$V_r = \frac{dV_r}{dr} = 0 \quad \Rightarrow \quad \text{parametric solution:}$$

$$\lambda = \frac{-r^3 + 3r^2 - a^2(r+1)}{a(r-1)}, \quad q = \sqrt{\frac{r^3[4a^2 - r(r-3)^2]}{a^2(r-1)}}$$



a=0.998



a=0.65