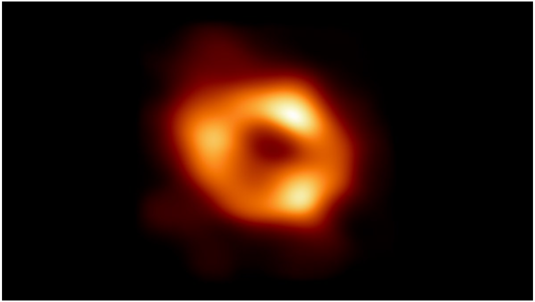


The crucial importance of black hole images for cosmology

Vyacheslav I. Dokuchaev

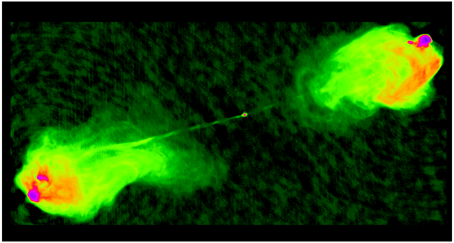
Institute for Nuclear Research of the Russian Academy of Sciences

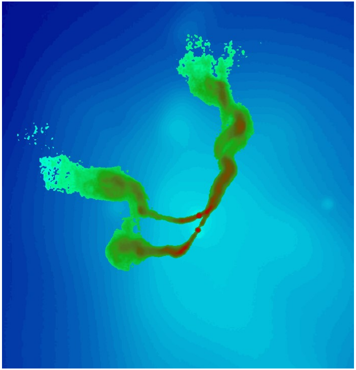
Dubna — 2022

Radio jets from astrophysical black holes

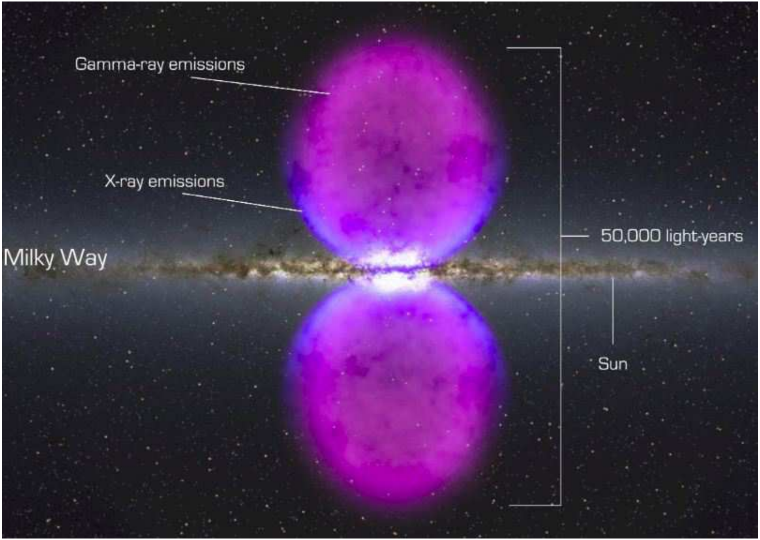
Cygnus A

3C 75





Milky Way: dormant quasar
"Fermi bubble"



Active galaxy M87: relativistic radio jet

The Astrophysical Journal, 855:128 (36pp), 2018 March 10 Walker et al.

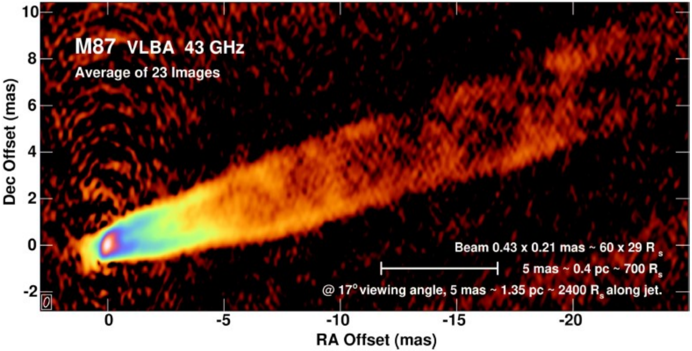


Figure 1. 23-epoch average radio image of the jet and counterjet in M87 based on data from 2007 and 2008. Angular to linear scales (in pc and in Schwarzschild radii R_S) are indicated for distances in the sky plane and for distances along the axis of the jet assuming that it is oriented at 17° to the line of sight. The beam with resolution 0.43×0.21 mas elongated in position angle $-16°$ is shown at the lower left. The off-source noise level is 62 μJy beam^{-1}, and the image peak is 0.83 Jy.

Active galaxy M87: HST optical jet

Active galaxy M87*: all images

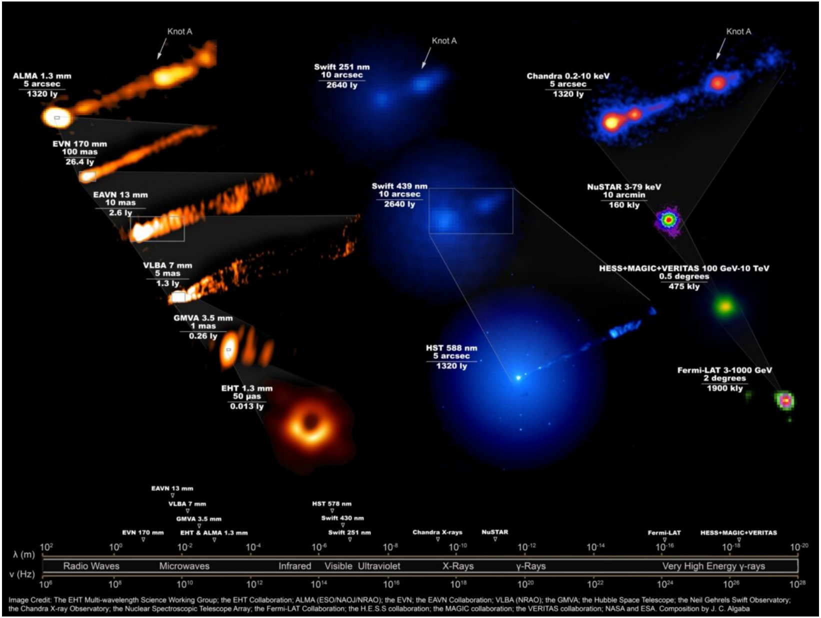
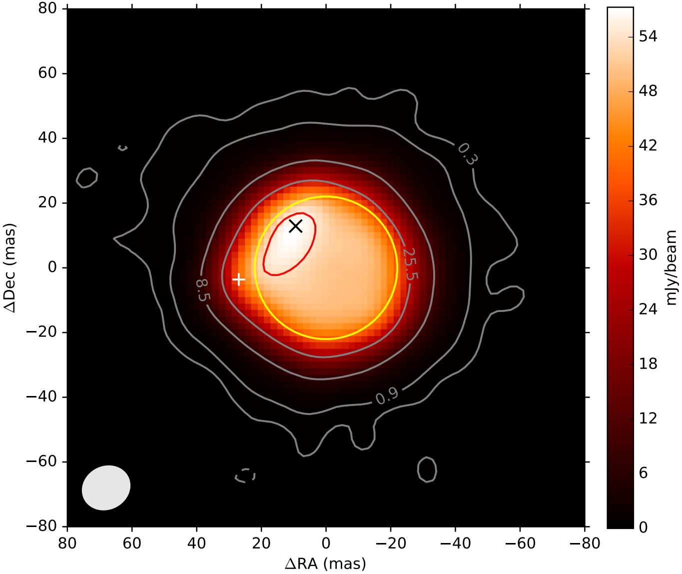


Image of the object which is not a black hole

ALMA: Star Betelgeuse arXiv:1706.06021



Equations of motion in the Kerr metrics B. Carter 1968

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

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

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

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

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

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

A.Strominger arXiv:1710.11112

Integral equations of motion C.T.Cunninghan & J.M.Bardeen 1973

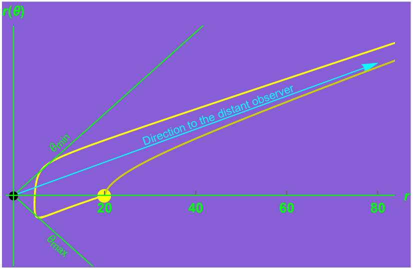
$$\fint^{\theta} \frac{d\theta}{\sqrt{V_\theta}} = \fint^{r} \frac{dr}{\sqrt{V_r}}, \quad V_\theta(\theta_{min}) = 0, \quad V_r(r_{min}) = 0$$

The integrals are understood to be path integrals along the trajectory

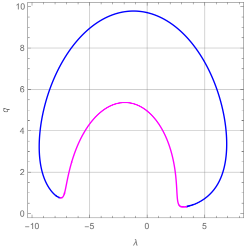
Integral equation with respect to $\lambda = \Phi/E$ and $q = Q^{1/2}/E$

for the trajectories of the first light echo:

$$\int_{\theta_s}^{\theta_{max}} \frac{d\theta}{\sqrt{V_\theta}} + \int_{\theta_{min}}^{\theta_{max}} \frac{d\theta}{\sqrt{V_\theta}} + \int_{\theta_0}^{\theta_{min}} \frac{d\theta}{\sqrt{V_\theta}} = \int_{r_s}^{r_{min}} \frac{dr}{\sqrt{V_r}} + \int_{r_{min}}^{r_0} \frac{dr}{\sqrt{V_r}}$$



2D photon trajectory $r(\theta)$



Solutions (λ, q)

Shapes of black hole images depend on the distribution of emitting matter around black holes

Astrophysical Case 1: radiation outside photon spheres

Luminous stationary background behind the black hole

Classical black hole shadow is viewed, which is a capture photon cross-section in the black hole gravitational field

Astrophysical Case 2: radiation inside photon spheres

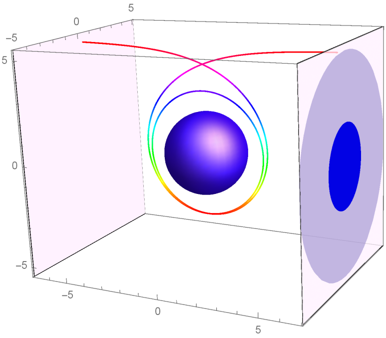
Luminous accretion inflow near the black hole event horizon

Event horizon shadow is viewed, which is a lensed image of the event horizon globe

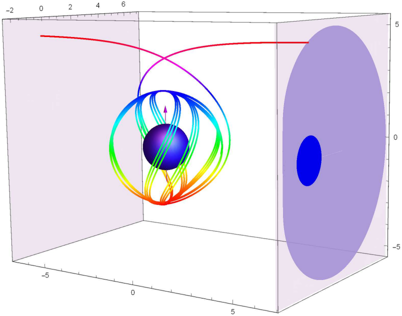
Astrophysical Case 1 : Stationary background

Shadow (magenta region)

Euclidean image (blue disk) of the event horizon



Schwarzschild

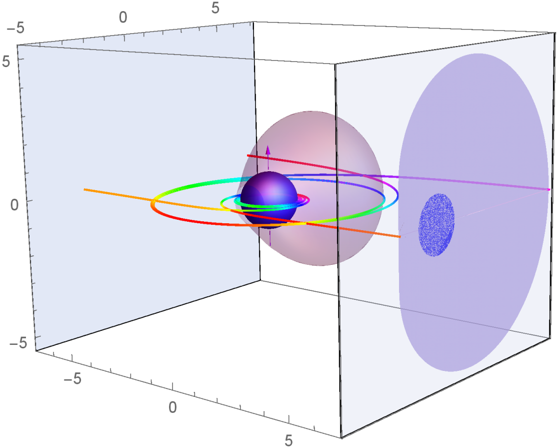


near extreme Kerr

Astrophysical Case 1: Stationary distant background

(Radiation outside purple photon spheres r_{ph} at $a = 1$)

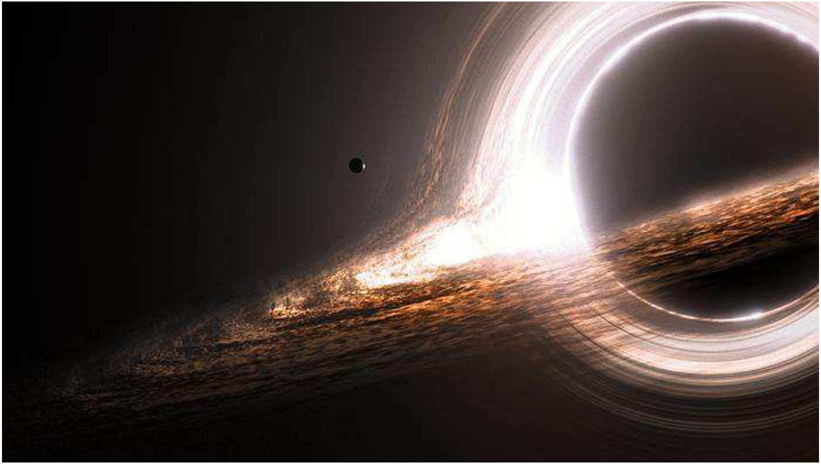
Classical black hole shadow is viewed: magenta region r_{sh}



Photon trajectories (multicolored 3D-curve) near the shadow outline with the return points at $r_{min} = 1$ (co-rotating) and $r_{min} = 4$ (counter-rotating). Closed purple region — boundary of photon spheres

Interstellar

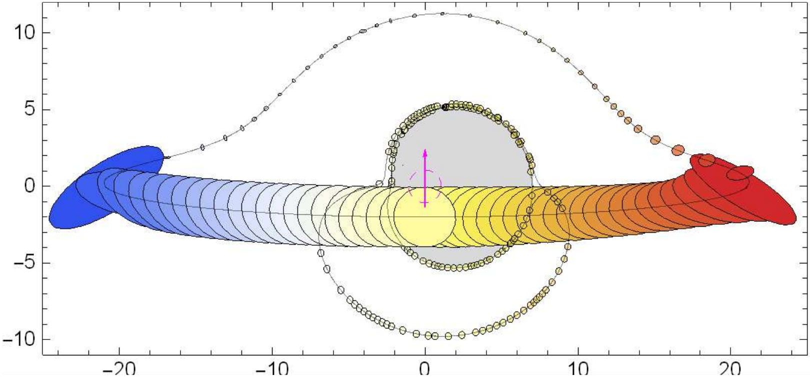
Classical black hole shadow inside accretion disk



This black hole image is wrong!

Astrophysical Case 1 : Compact star on the equatorial circular orbit with radius $r_s = 20M_hG/c^2$ around SgrA*, observed by a distant telescope (Millimetron)

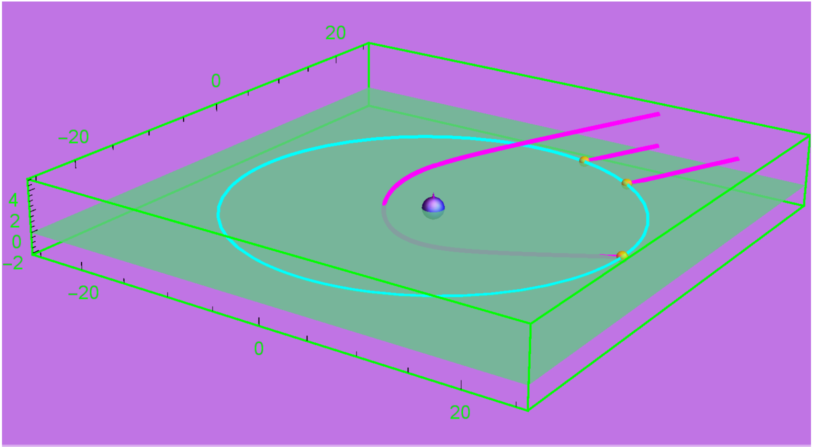
Radiation outside the photon spheres r_{ph}



w/ N.O.Nazarova arXiv:1802.00817

3D photon trajectories

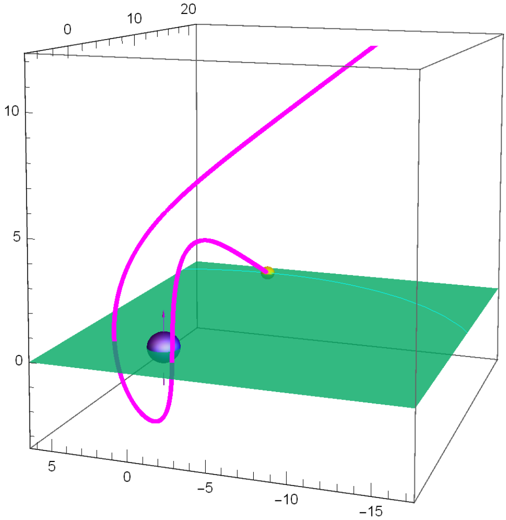
Prime image: no intersections of equatorial plane
First light echo: 1 intersection of equatorial plane



3D photon trajectory

Second light echo: 2 intersections of equatorial plane

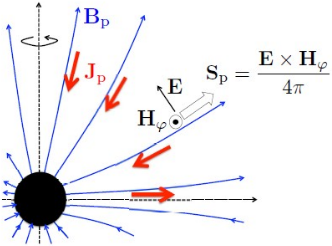
$$\lambda = -1.78, \quad q = 5.2, \quad r_h = 1, \quad r_s = 20, \quad r_{min} = 3.11$$

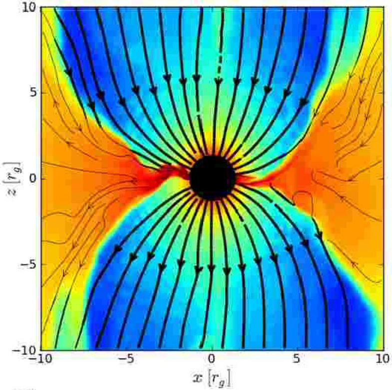


Astrophysical Case 2 : GRMHD accretion simulation!!!

Radiation from both the outside and inside photon spheres r_{ph}

The Blandford-Znajek process (quite different from the α-disk!) is a suitable model for the General Relativistic Magnetohydrodynamics (GRMHD) accretion onto black holes, in which the inflowing plasma is strongly heated even in the vicinity of the event horizon by the radial electric current

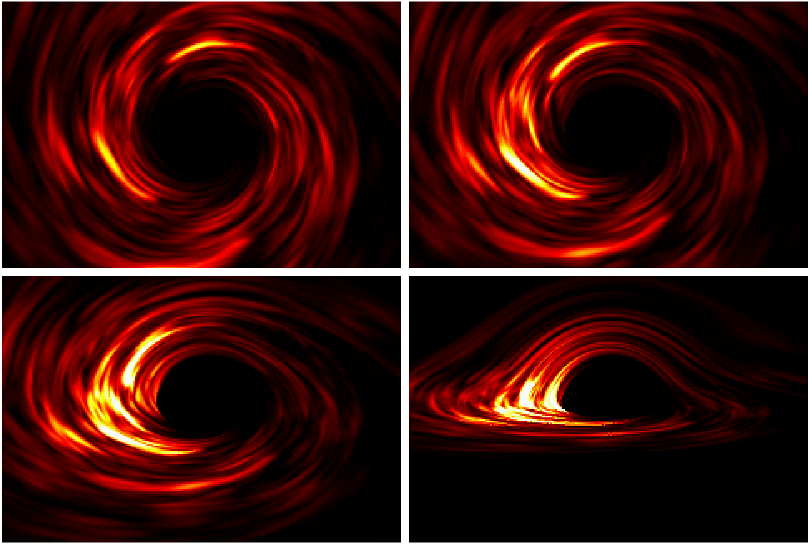




J.C.McKinney, A.Tchekhovskoy, R.D.Blandford (2012)

Astrophysical Case 2 : GRMHD accretion simulation

Radiation from both the outside and inside photon spheres r_{ph}

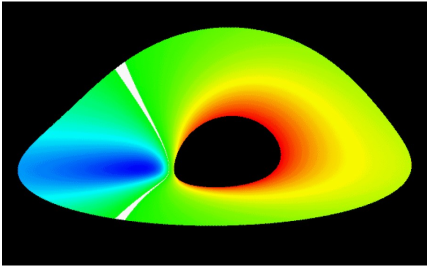


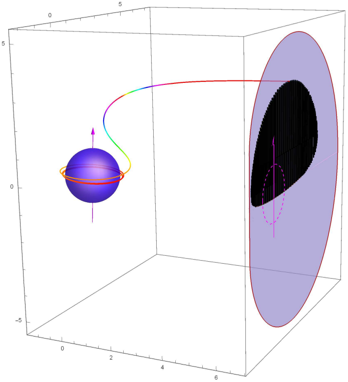
Fe Kα line at 6.4 keV

Armitage & Reynolds 2003

Astrophysical Case 2 : Line emission from accretion disk

Radiation from both the outside and inside photon spheres r_{ph}





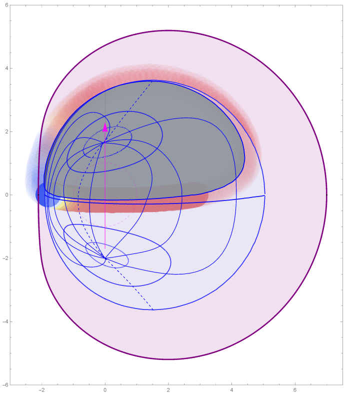
B.C.Bromley, K.Chen, W.A.Miller 1997

SgrA*

Lensed image (silhouette) of the event horizon

Purple curve — boundary of the classical black hole shadow

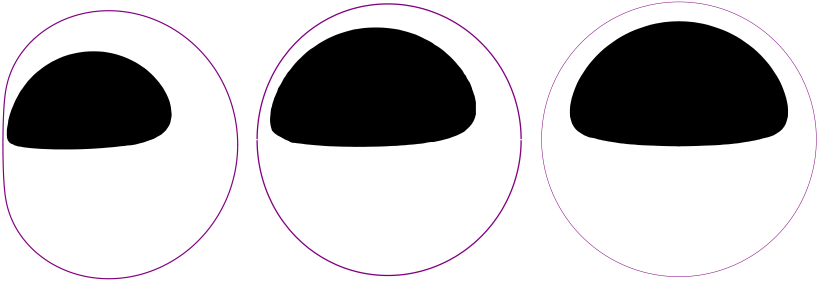
Dark region — lensed image of the northern hemisphere of the event horizon globe (boundary of this dark region is the equator at the event horizon globe)



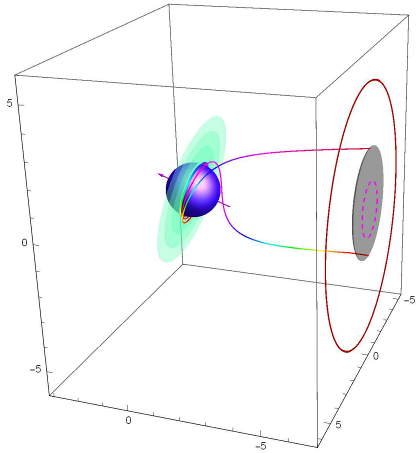
w/ N.O.Nazarova & V.P.Smirnov arXiv:1903.09594

SgrA*, $\theta_0 = 82.2°$: silhouettes of the northern hemisphere of event horizon (black region) projected inside an outline of the black hole shadow (purple closed curves)

Black holes (from left to right) with spin a = 0.9982, 0.65 and 0



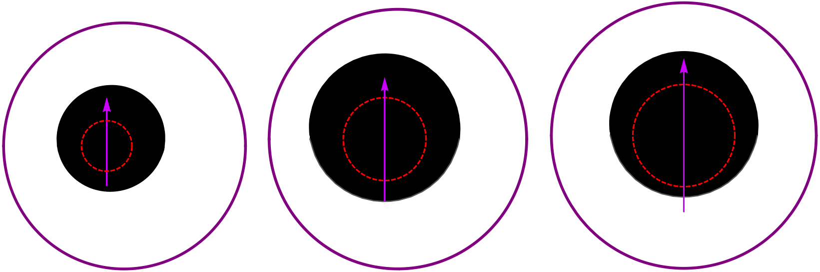
M87*, $\theta_0 = 17°$: Silhouettes of the southern hemisphere of event horizon (gray region) projected inside the black hole shadow (purple closed curves)



Green oval — thin accretion disk around M87*

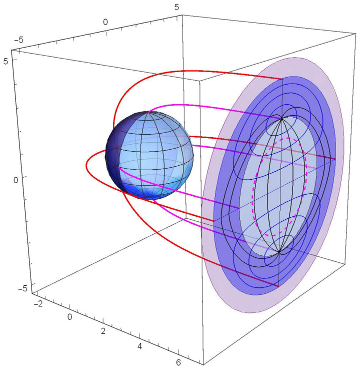
M87*, $\theta_0 = 17°$: Silhouettes of the southern hemisphere of event horizon (black region) projected inside a outline of the black hole shadow (purple closed curves)

Black holes (from left to right) with spin $a = 0.9982$, 0.65 and 0

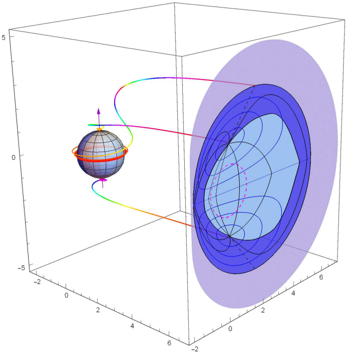


SgrA*: silhouette of the event horizon globe

(dark and light blue regions) projected inside the classical black hole shadow (purple closed curve)



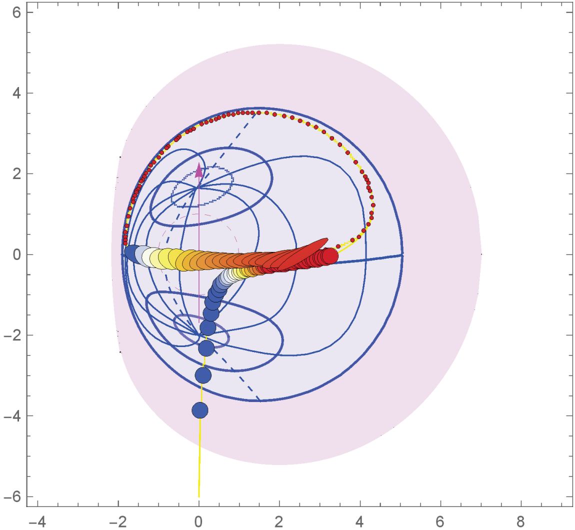
a = 0



a = 0.9982

SgrA*, a = 0.9982: gravitational lensing of the compact emitting source falling into black hole

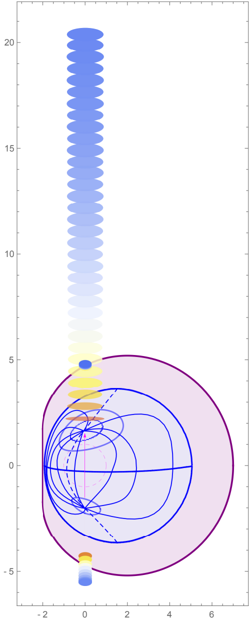
Distant observer is placed at $\cos\theta = 0.1,\ \theta_0 = 82.2°$



w/ N.O.Nazarova https://youtu.be/fps-3frL0AM

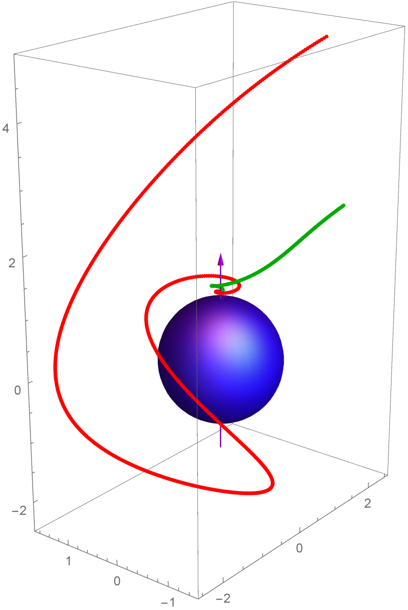
Moving hot spot in the jet from black hole SgrA*:

Direct image and 1-st light echoes in discrete time intervals



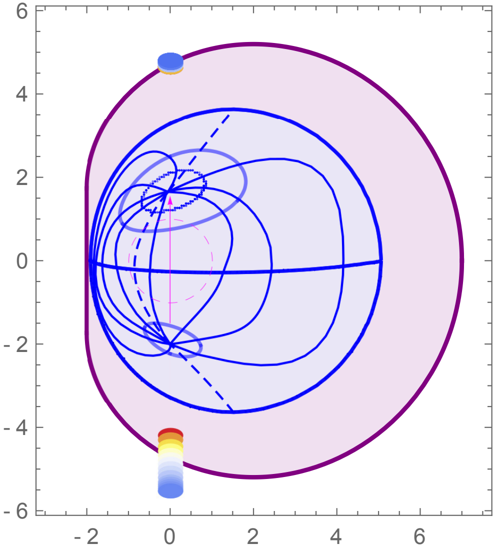
3D photons trajectories, starting at $r = 1.1r_h$

Prime image and second light echo: 2 intersections of equatorial plane



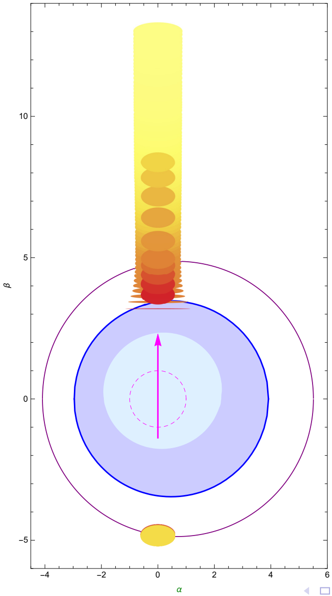
Moving hot spot in the jet from black hole SgrA*:

1-st light echoes near the outlet of the black hole shadow (closed purple curve)

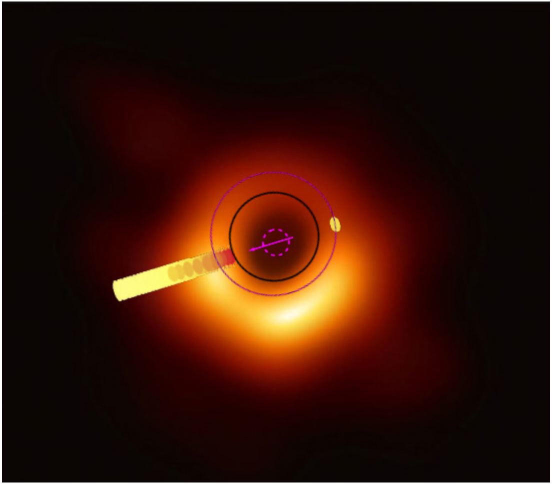


Moving hot spot in the jet from black hole M87*:

1-st light echoes near the outlet of the black hole shadow (closed purple curve)



Direct image and 1-st light echoes of the moving hot spot in the jet from the supermassive black hole M87* in discrete time intervals



Closed purple curve — outlet of the black hole shadow
Closed black curve — outlet of the lensed event horizon image

Conclusions

Unique information for the verification of strong gravity will be provided by the detailed observations of black hole images, including the motion of bright spots in jets.
(Millimetron Space Observatory?)

ArXiv for details:
2010.01885, 2007.14121, 1911.07695, 1906.07171, 1903.09594, 1812.06787, 1804.08030, 1802.00817

YouTube for animationsy:
youtube.com/watch?v=P6DneV0vk7U
youtu.be/zQzC-lVgdjg
youtu.be/fps-3frL0AM
youtu.be/7j8f_vlTul8

Thanks to all