Visualization of black hole images

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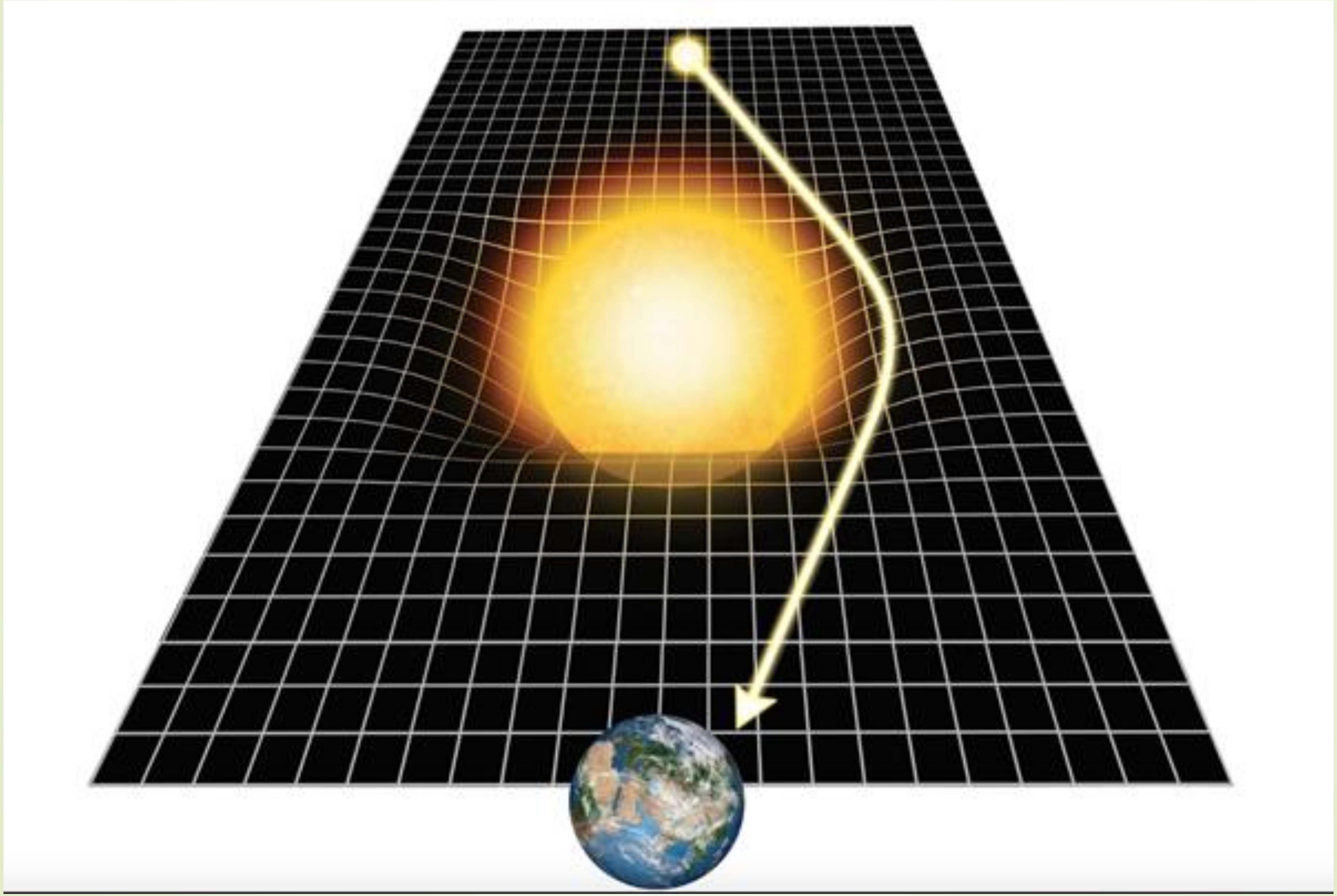
Flat space-time: the closer the light source to the object - the bigger it shadow on the distant wall

Curved space-time: the bending of light (gravitational lensing)



Kerr metric: equations of motion for test particles *B. Carter 1968*

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

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

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

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

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

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

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

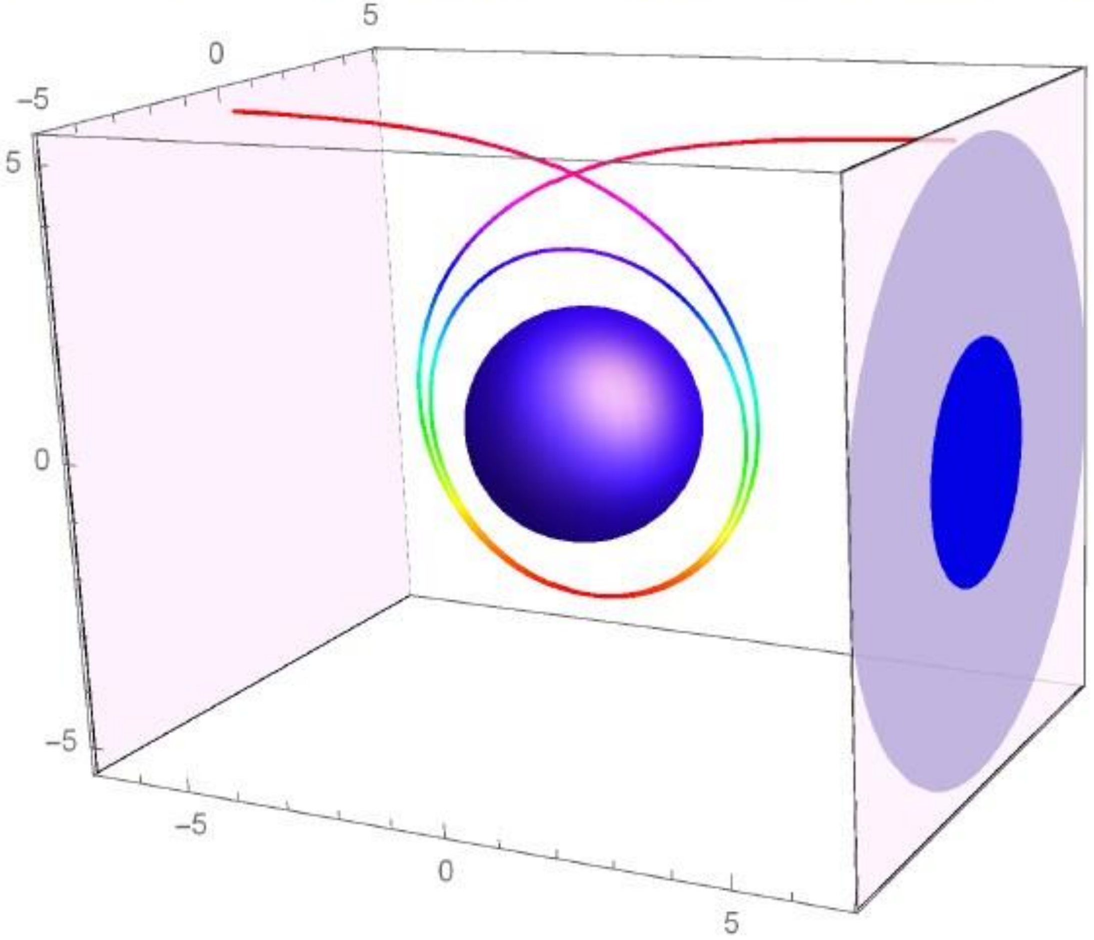
Luminous accretion inflow near the black hole event horizon

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

Astrophysical Case 1: Stationary background

Euclidean image (blue disk) of the event horizon, $r_h = 2$, $M_h G/c^2 = 1$

Classical shadow (magenta region) of the Schwarzschild black hole ($a = 0$), shadow radius $r_{sh} = 3\sqrt{3} \simeq 5.2$, radius of photon circular orbit $r_{ph} = 3$

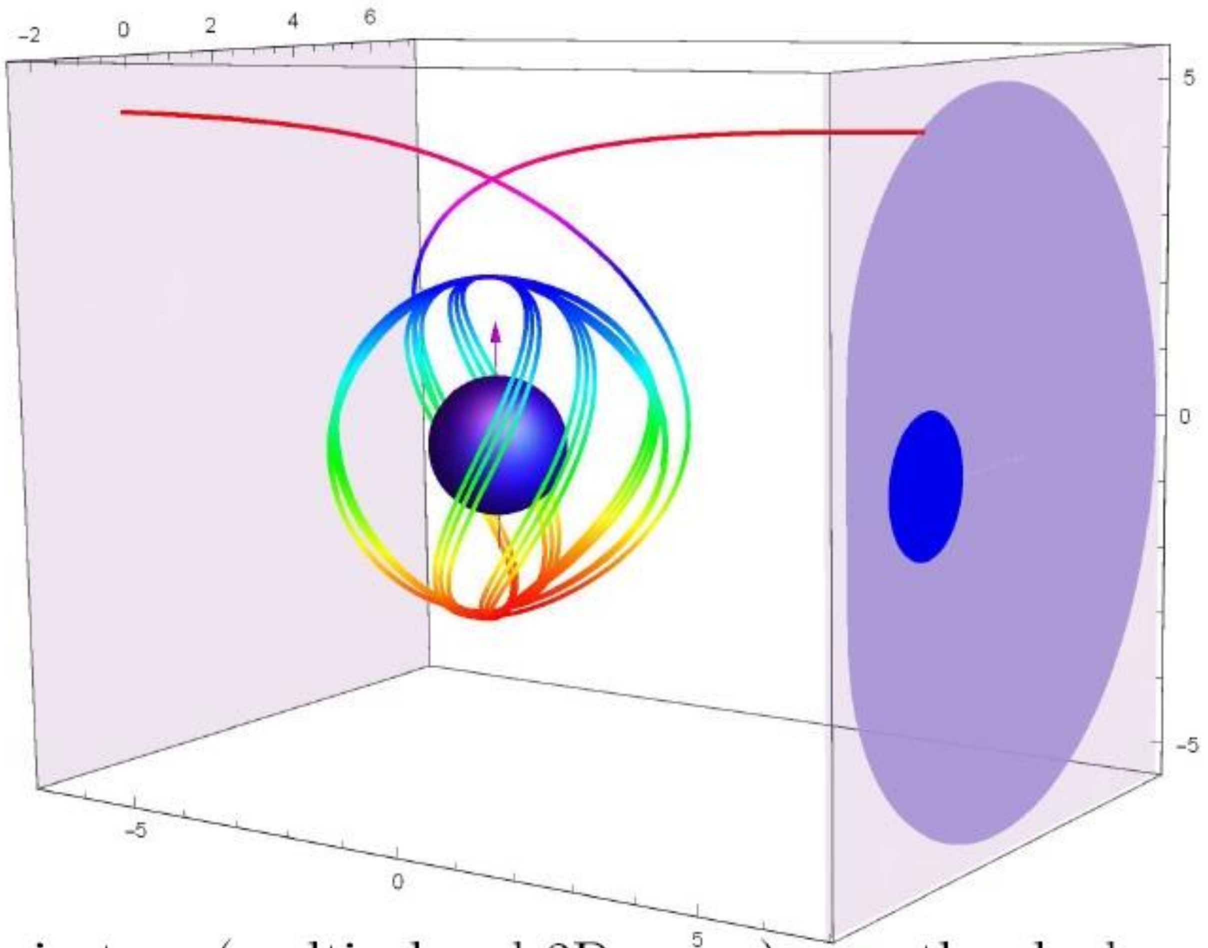


Photon trajectory (multicolored 3D-curve) with the return point $r_{min} = r_{ph} = 3$, impact parameters $\lambda = 0$, $q = \sqrt{Q} = r_{sh} = 3\sqrt{3} \simeq 5.2$

Astrophysical Case 1: Stationary background

Classical shadow (magenta region) of the Kerr black hole: $a = 1$, $r_h = 1$

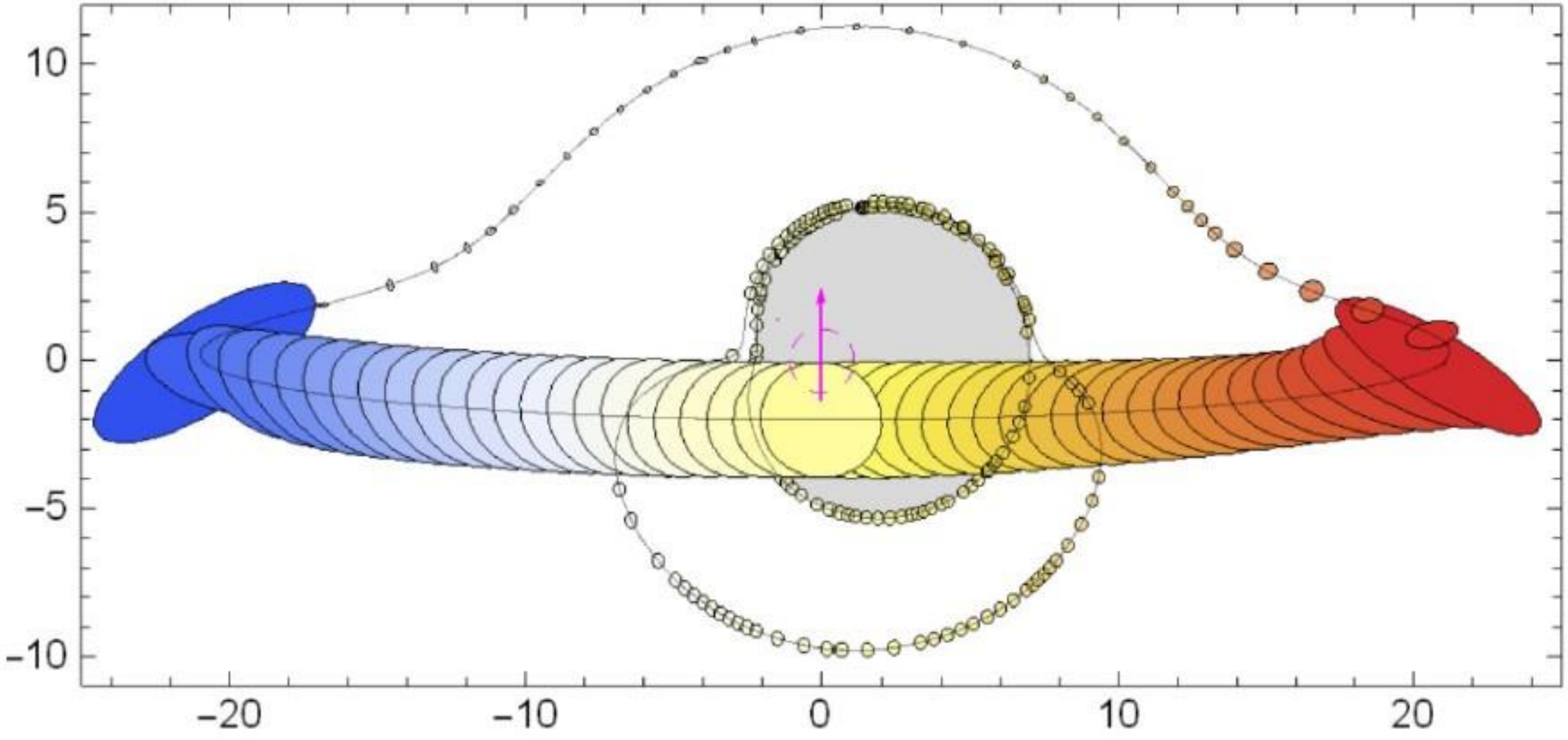
$\theta_0 = \pi/2$ — polar angle of a distant observer



Photon trajectory (multicolored 3D-curve) near the shadow outline with the return point $r_{min} = 1 + \sqrt{2}$ and impact parameters $\lambda = 0$ (horizontal) and $q = \sqrt{Q} = \sqrt{11 + 8\sqrt{2}} \simeq 4.72$ (vertical)

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

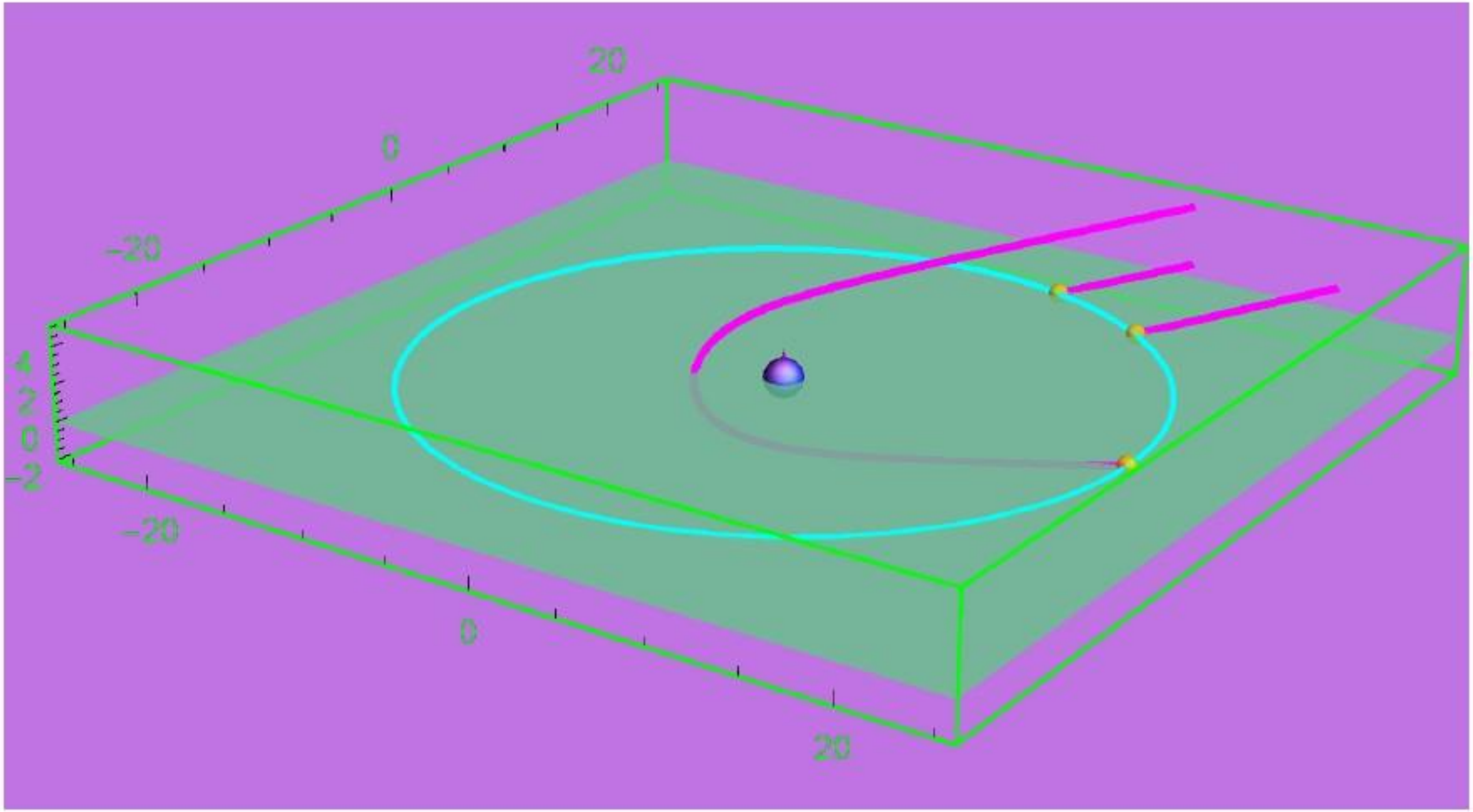
Radiation outside the photon spheres r_{ph}



VD, Natalia Nazarova arXiv:1802.00817

3D photon trajectories

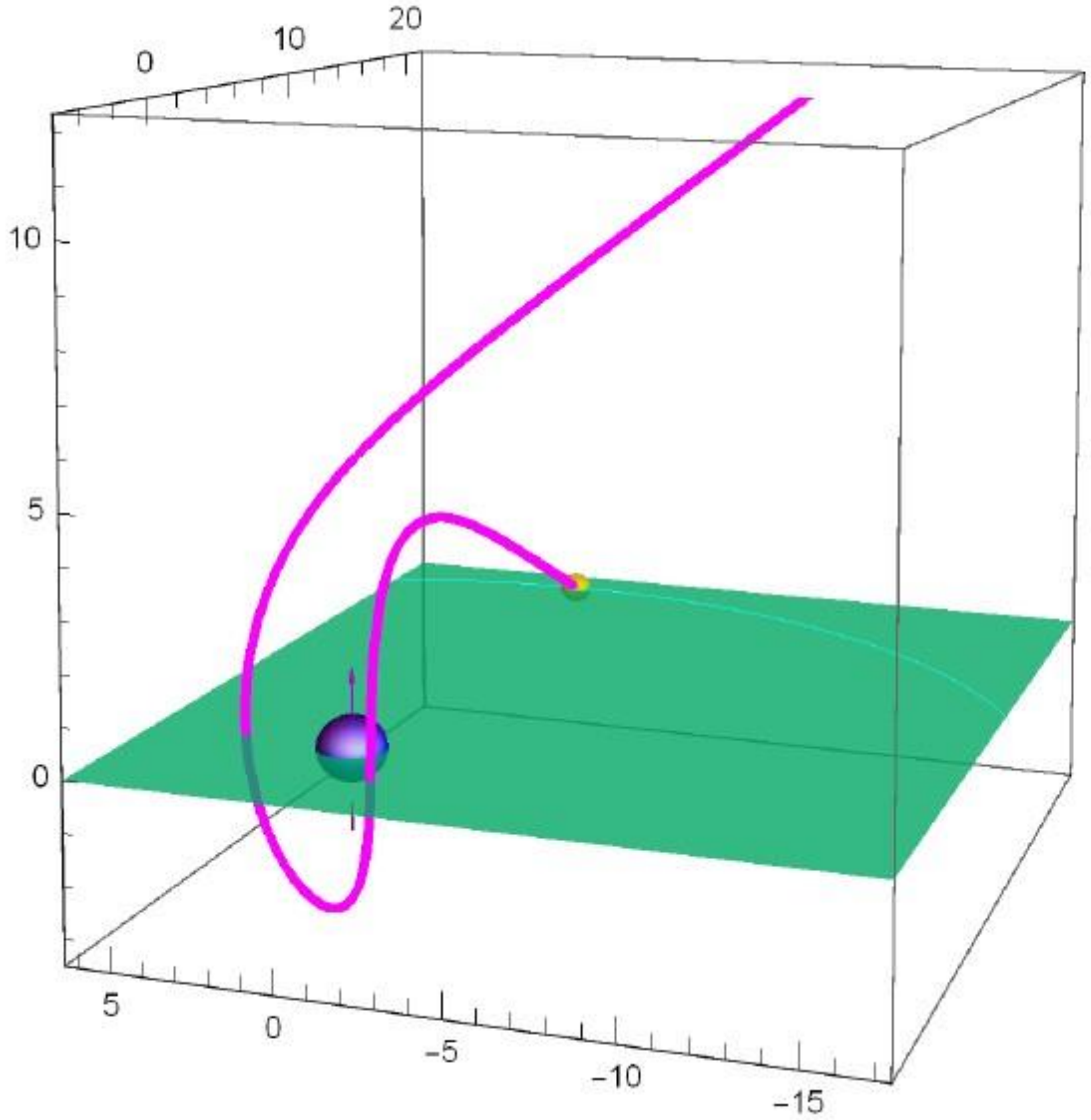
Prime image: no intersections of equatorial plane
First light echo: 1 intersection of equatorial plane



3D photon trajectory

Second light echo: 2 intersections of equatorial plane

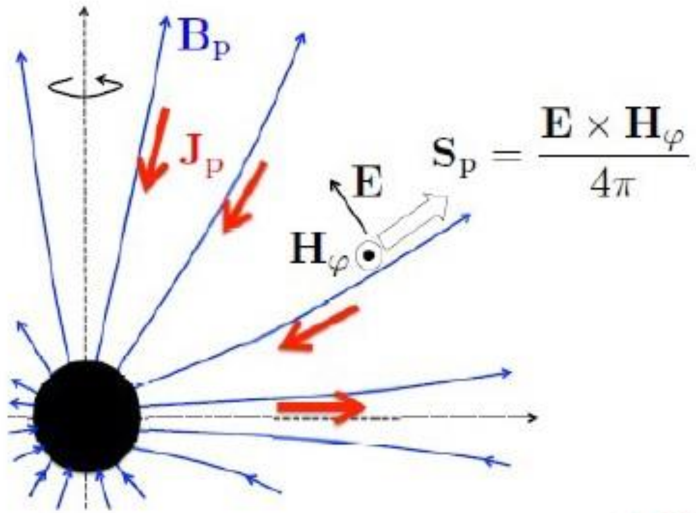
$$\lambda = -1.78,\ \ q = 5.2,\ \ r_h = 1,\ \ r_s = 20,\ \ r_{min} = 3.11$$

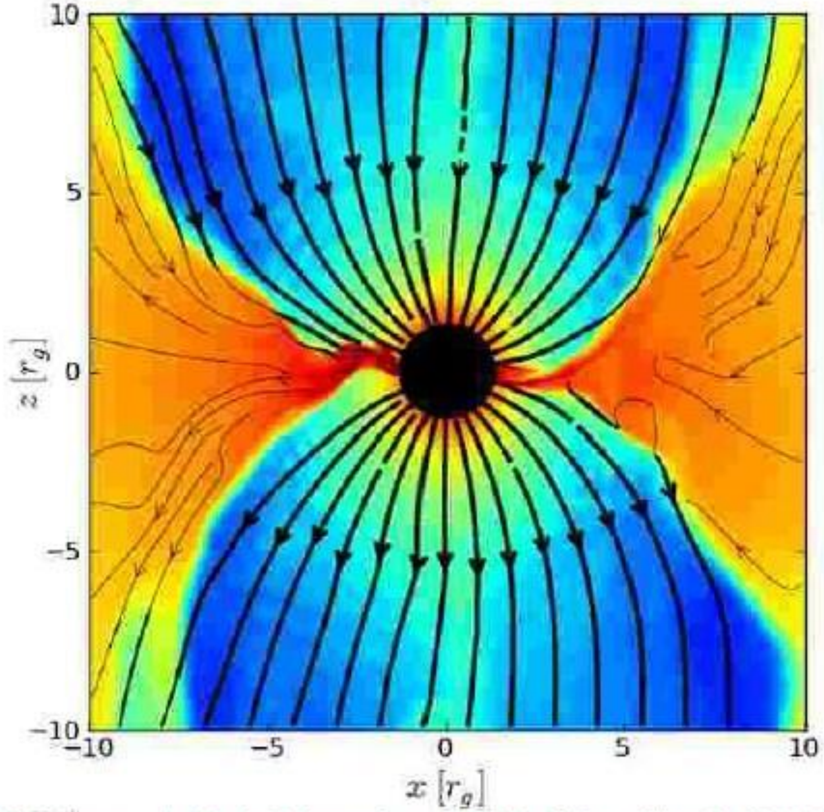


Astrophysical Case 2: GRMHD accretion simulation!!!

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

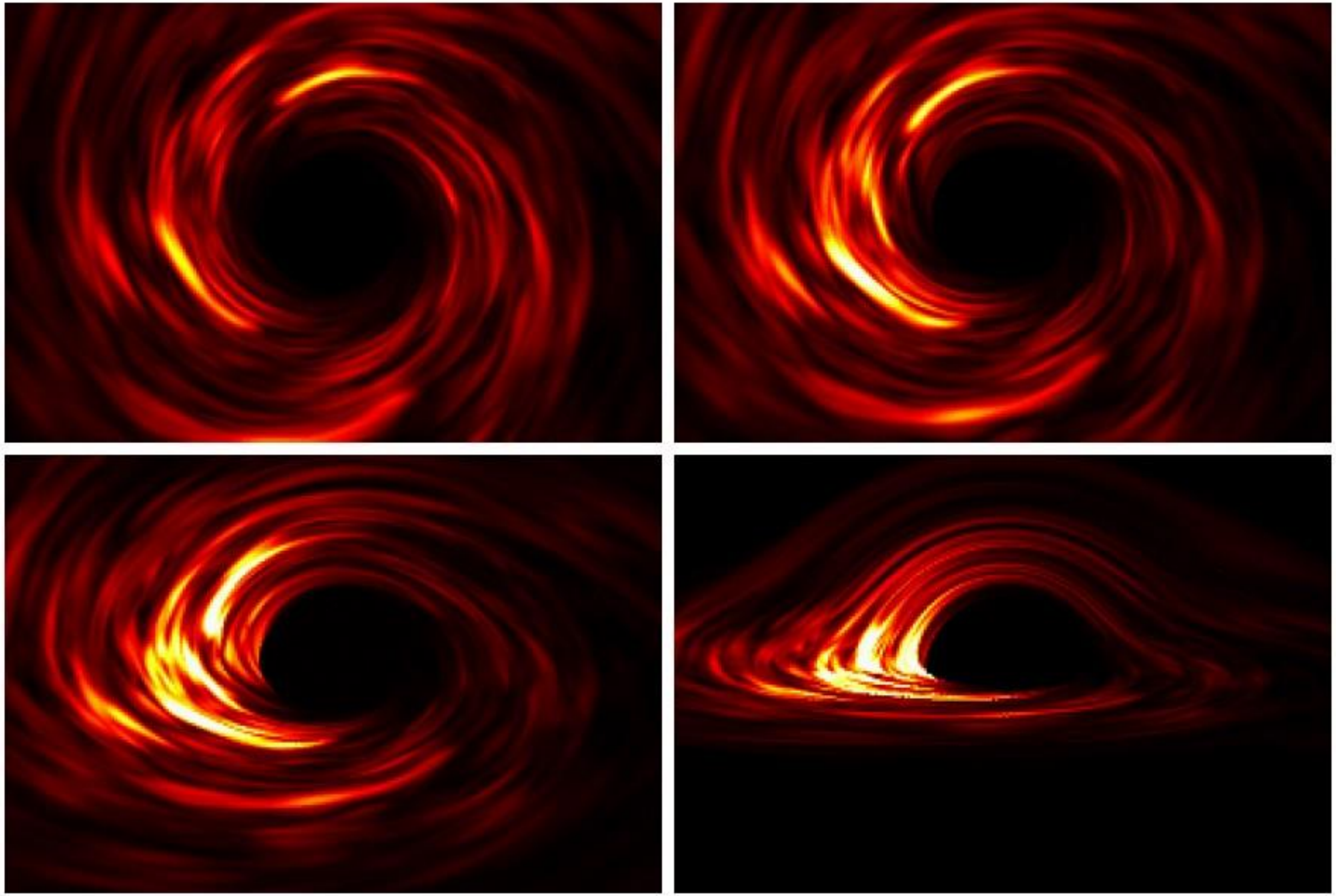




J.C.McKinney, A.Tchekhovskoy, R.D.Blandford (2012)

Astrophysical Case 2: GRMHD accretion simulation

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

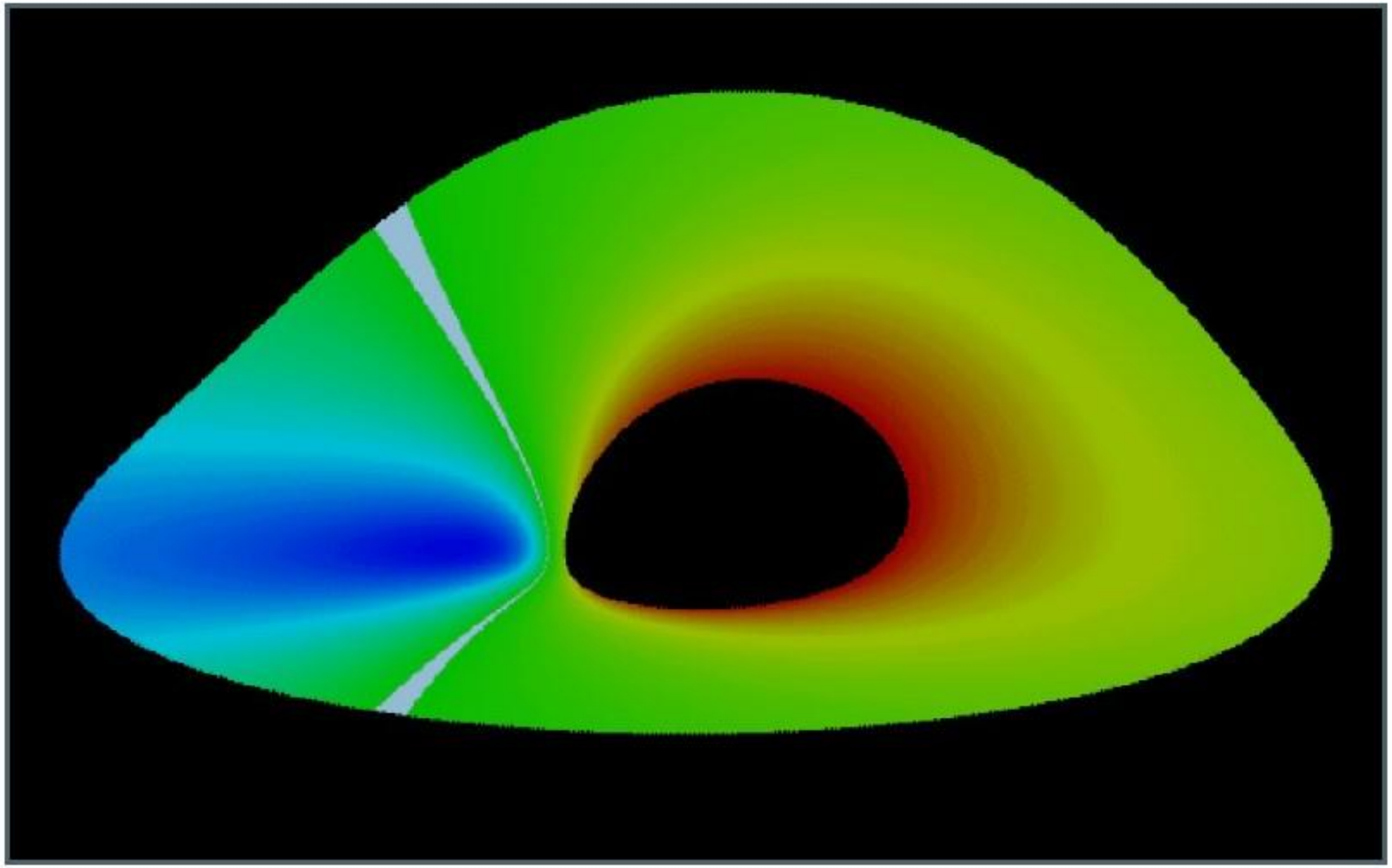


Fe Kα line at 6.4 keV

Armitage & Reynolds 2003

Astrophysical Case 2: Line emission from accretion disk

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



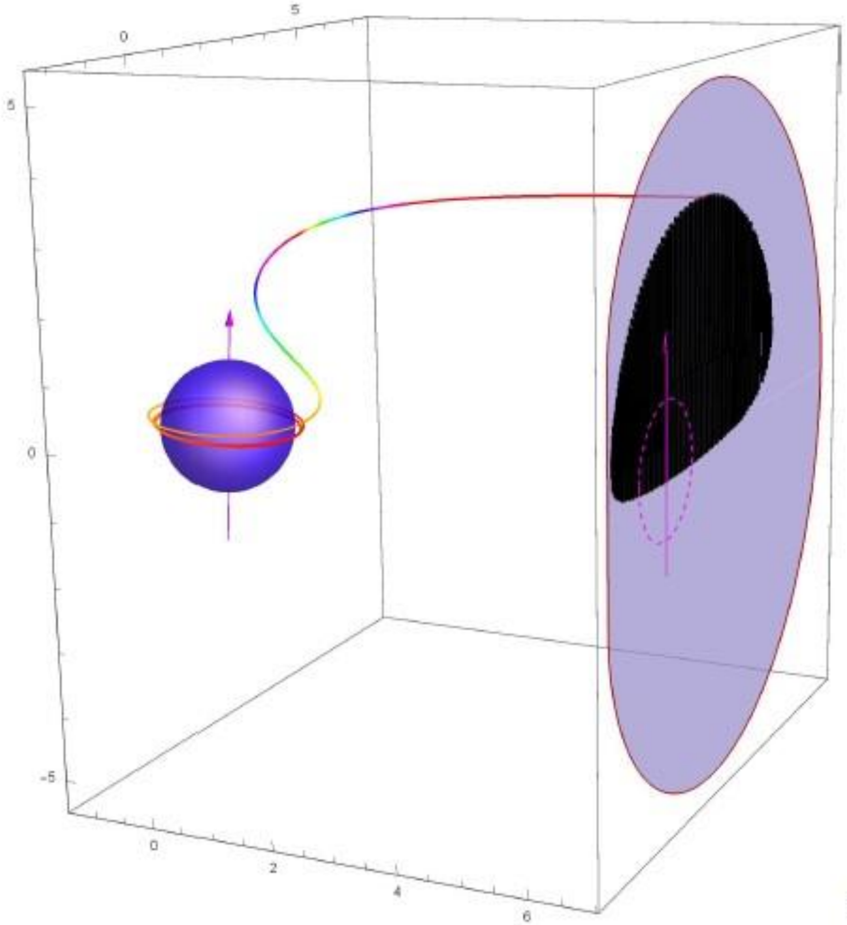
B.C.Bromley, K.Chen, W.A.Miller ApJ 475 57 (1997)

Astrophysical Case 2: Outgoing photon from $r = 1.01 r_h$

Radiation inside the photon spheres r_{ph}

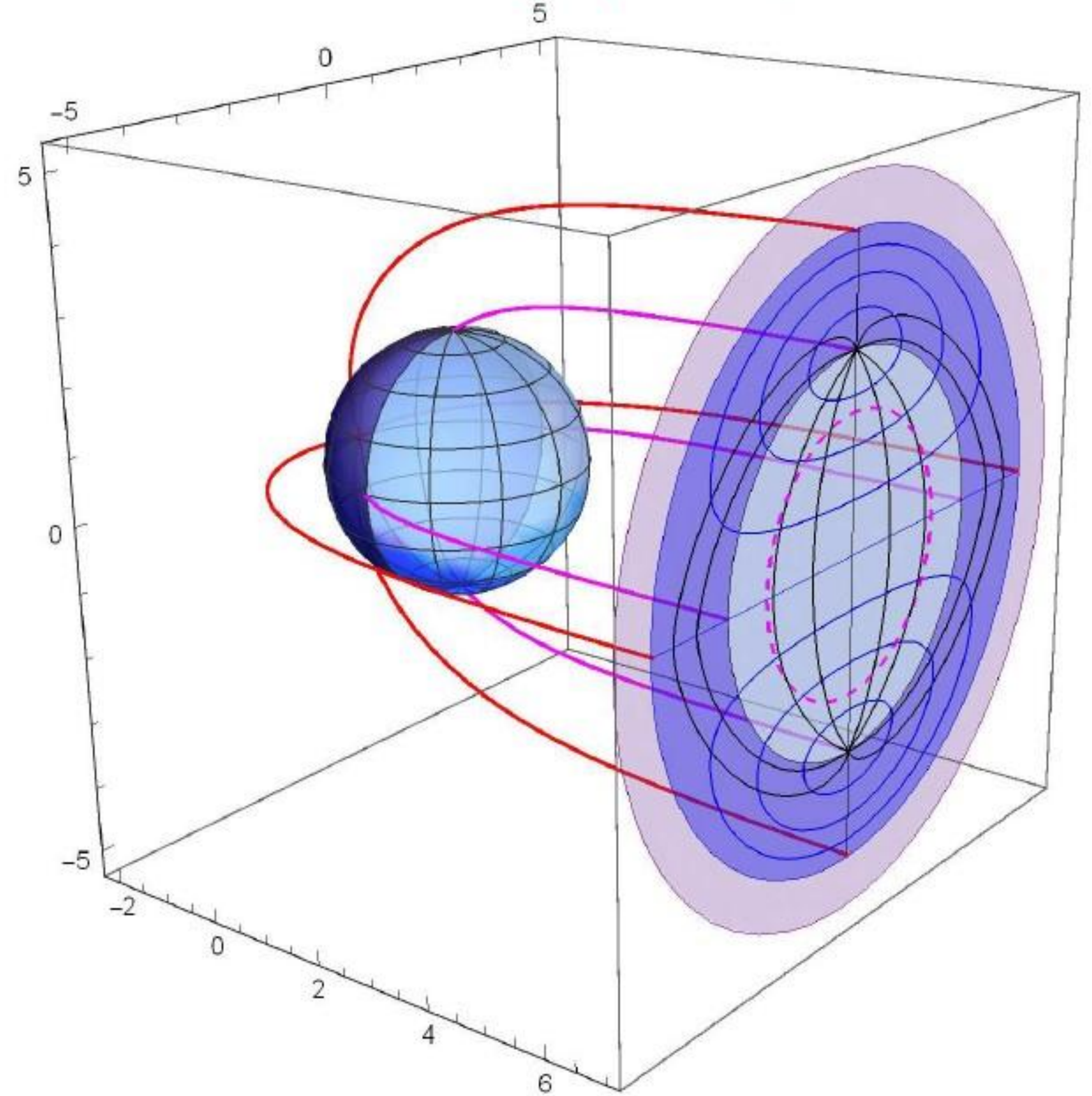
SgrA*, $a = 1$, $\theta_0 = 82.2^\circ$ — position angle of observer
Black hole shadow (black region) is recovered by emission of the nonstationary inner part of accretion disk adjoining the event horizon.

Photon trajectory with impact parameters $\lambda = -1.493$ and $q = 3.629$:

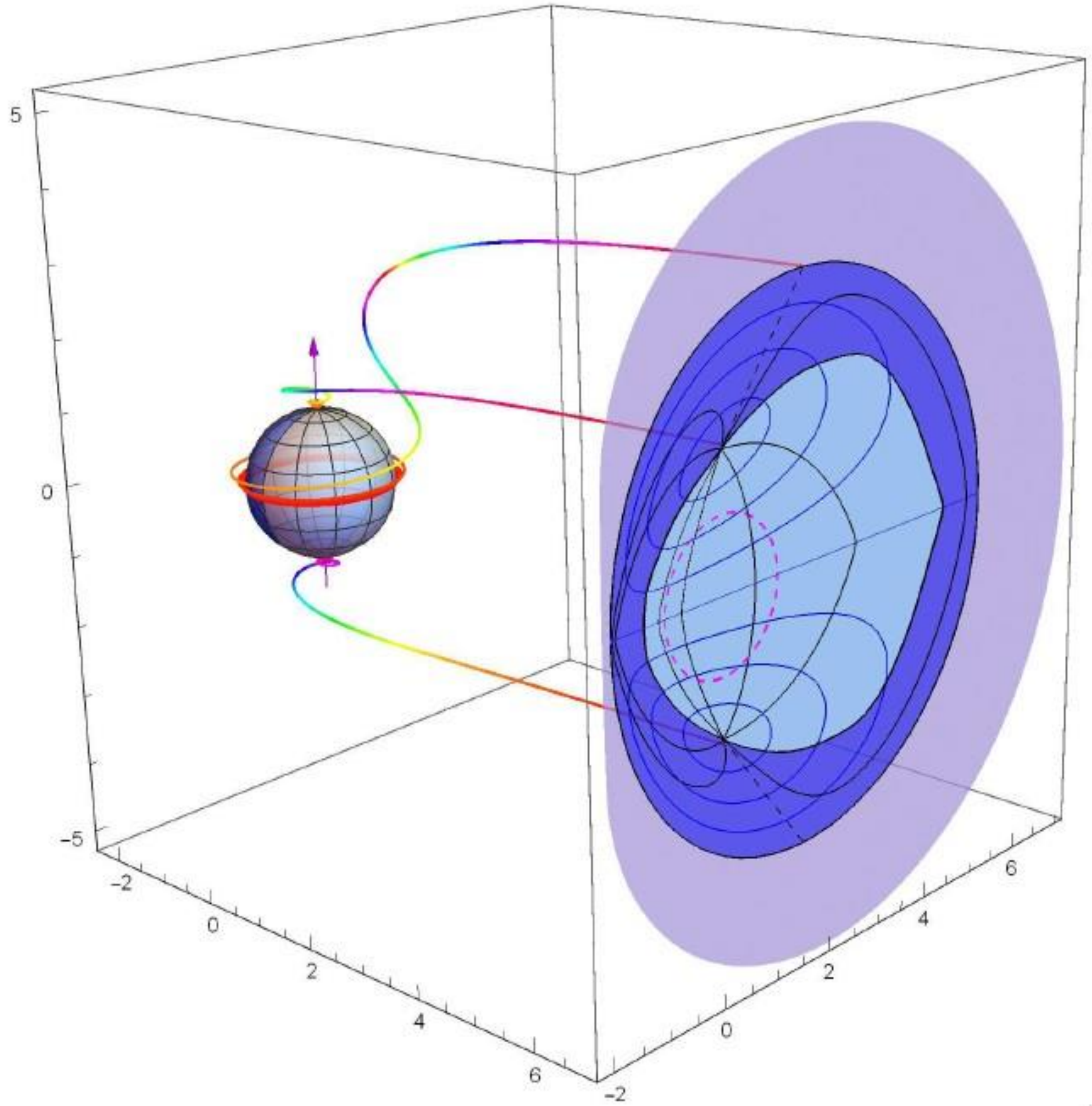


SgrA*, a = 0:

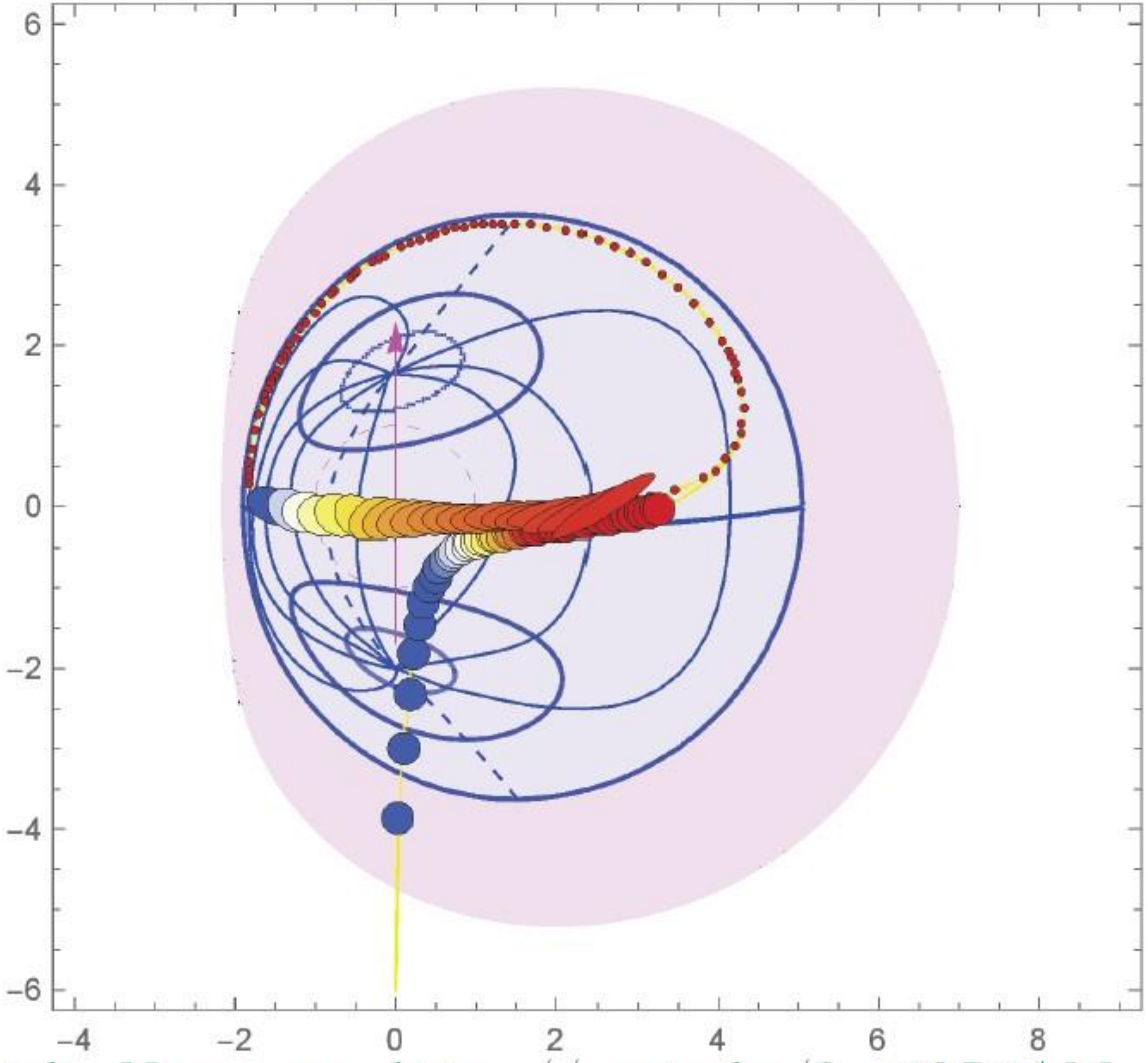
Silhouette of the event horizon globe (dark and light blue regions) projected inside the classical black hole shadow (purple disk)



SgrA*, $a = 0.9982$: outgoing photons from $r = 1.01 r_h$

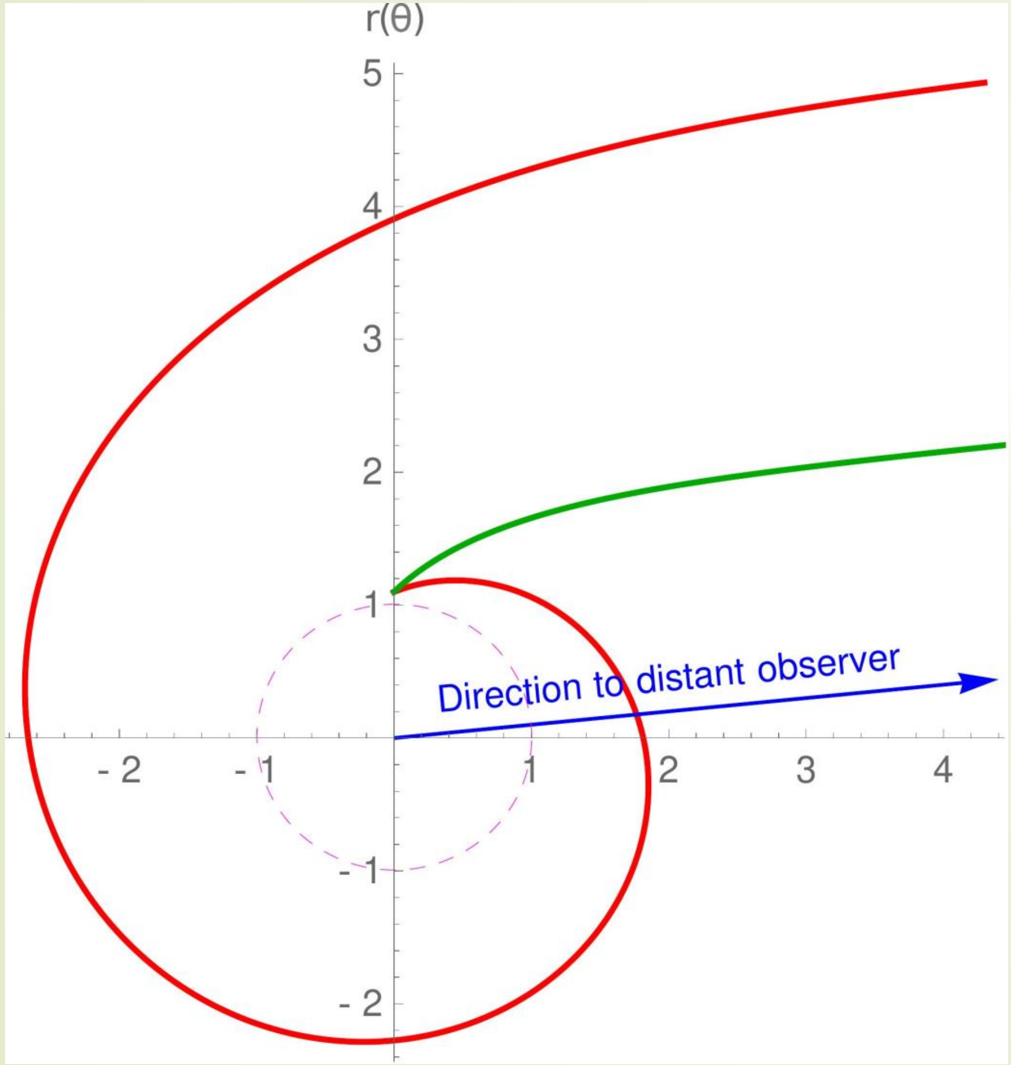


SgrA*, a = 0.9982: gravitational lensing of the compact emitting source falling into black hole, $\theta_0 = 82.2°$



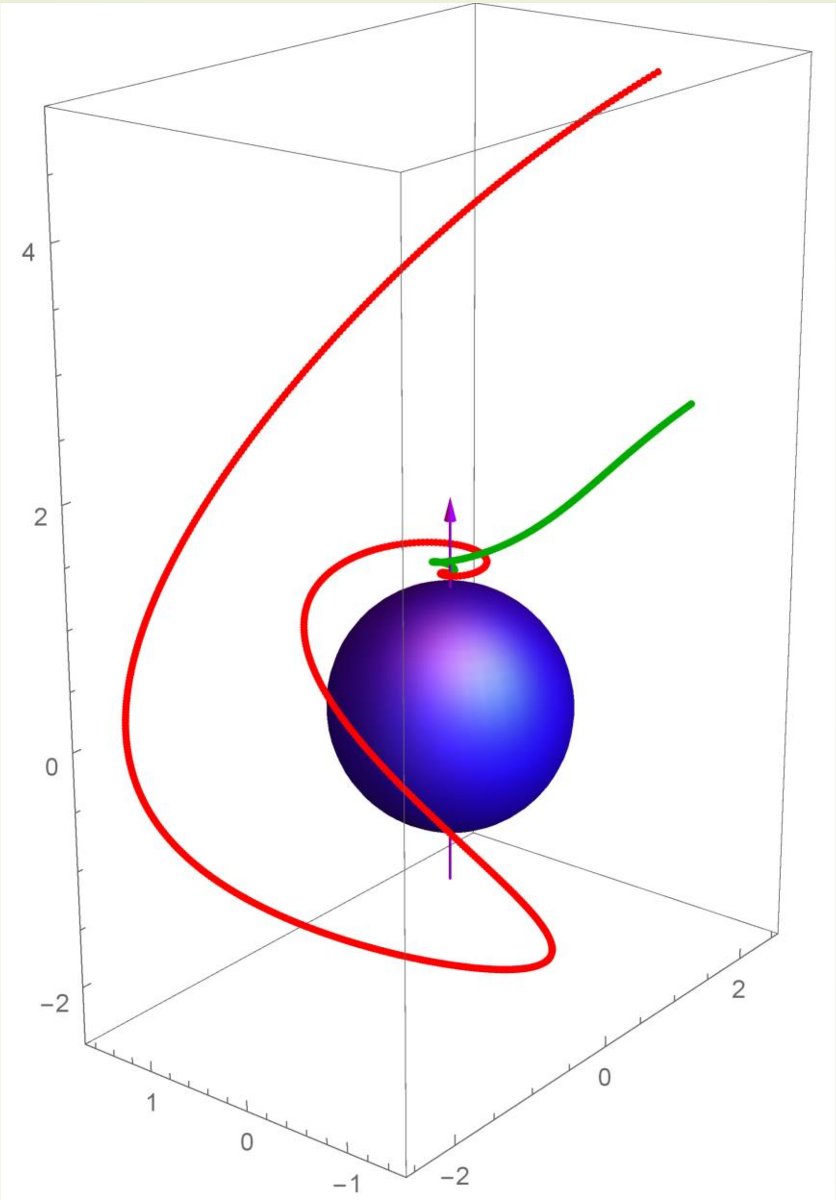
VD, Natalia Nazarova https://youtu.be/fps-3frL0AM

2D trajectories of two photons from moving hot spot, starting at $r = 1.1\ r_h$, ($r_h = 1+(1-a^2)^{1/2}$) from the rotation axis of the Kerr black hole ($a=1$) toward a distant observer and providing prime image (green curve) and 1-st light echo (red curve of clockwise moving photon)

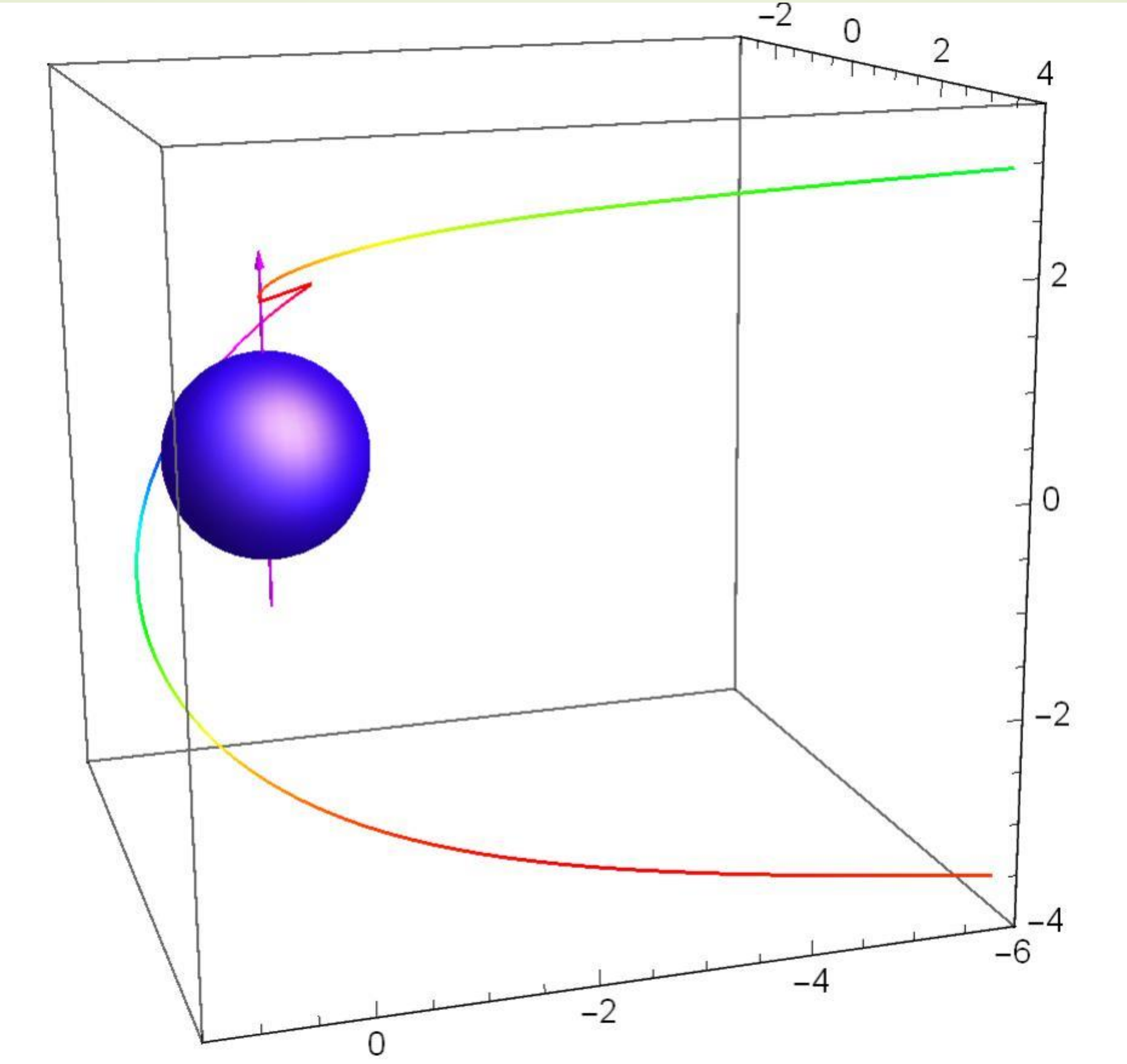


Dashed magenta circle – event horizon ($r_h = 1+(1-a^2)^{1/2}$) in the imaginary Euclidean space

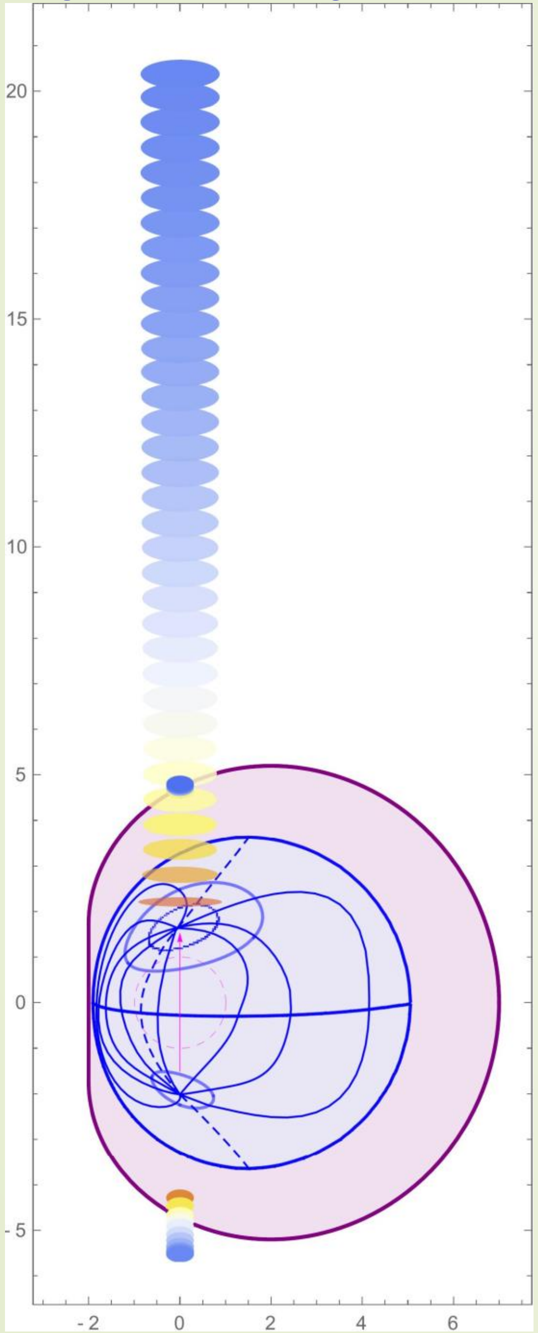
3D trajectories of the same photons from previous slide, starting at r = 1.1, and providing prime image (green curve) and 1-st light echo (red curve)



3D trajectories of photons from the outward moving hot spot, starting at r = 1.5, and providing the prime image and the 1-st light echo (counter-clockwise moving photon)



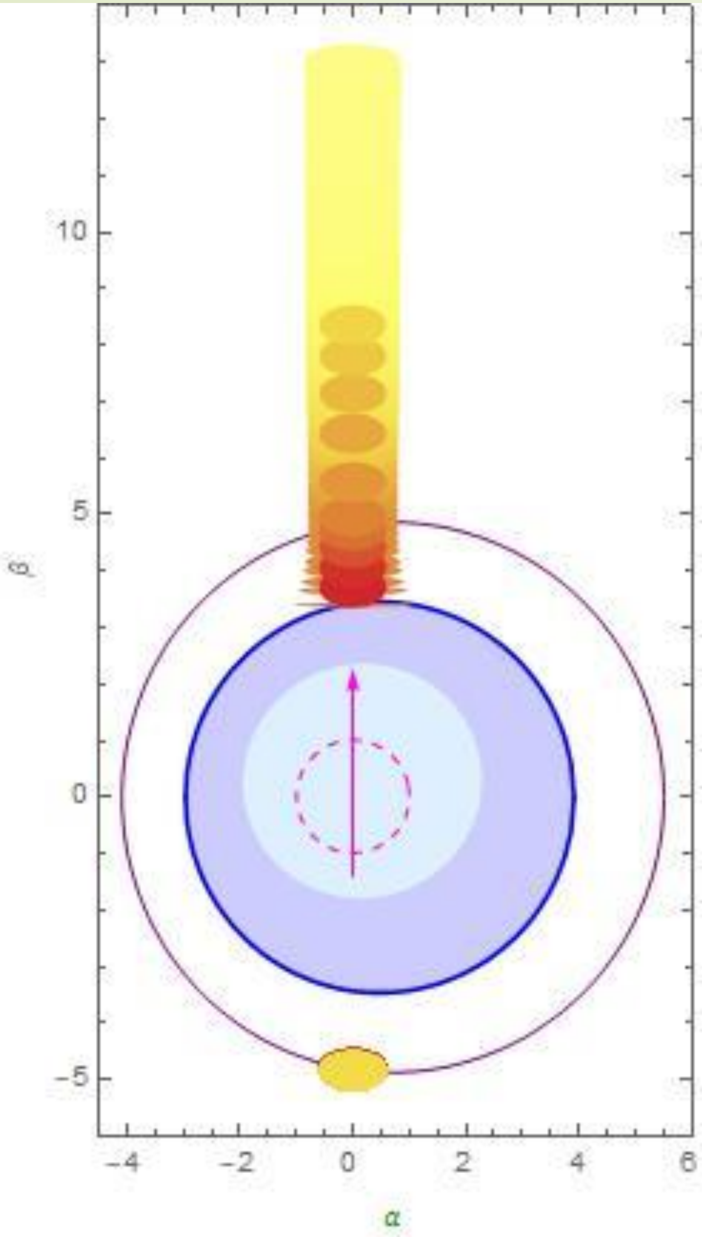
Moving hot spot in the jet from black hole SgrA* in discrete time intervals



- Closed purple curve – outline of the black hole shadow
- Dashed magenta circle – event horizon in the Euclidean space
- Magenta arrow – event horizon in the Euclidean space
- Light blue closed region – lensed event horizon globe
  ("direct view of the event horizon")
- Light blue closed curves – Meridians and parallels on the lensed event horizon globe

- Hot spot is starting from the north pole of the event horizon
- There are infinite number of lensed images of a separate hot spot (direct image and light echoes)
- It is shown direct images and 1-st light echoes of a hot spot in discrete time intervals
- 1-st light echoes produced by clockwise and counter-clockwise moving photons and viewed near the outline of the black hole shadow

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 – outline of the black hole shadow

Dashed magenta circle – event horizon in the Euclidean space

Magenta arrow – event horizon in the Euclidean space

Light blue and blue – "direct view of the event horizon":

Light blue closed region – lensed south hemisphere of the event horizon globe

Blue closed region – lensed north hemisphere of the event horizon globe

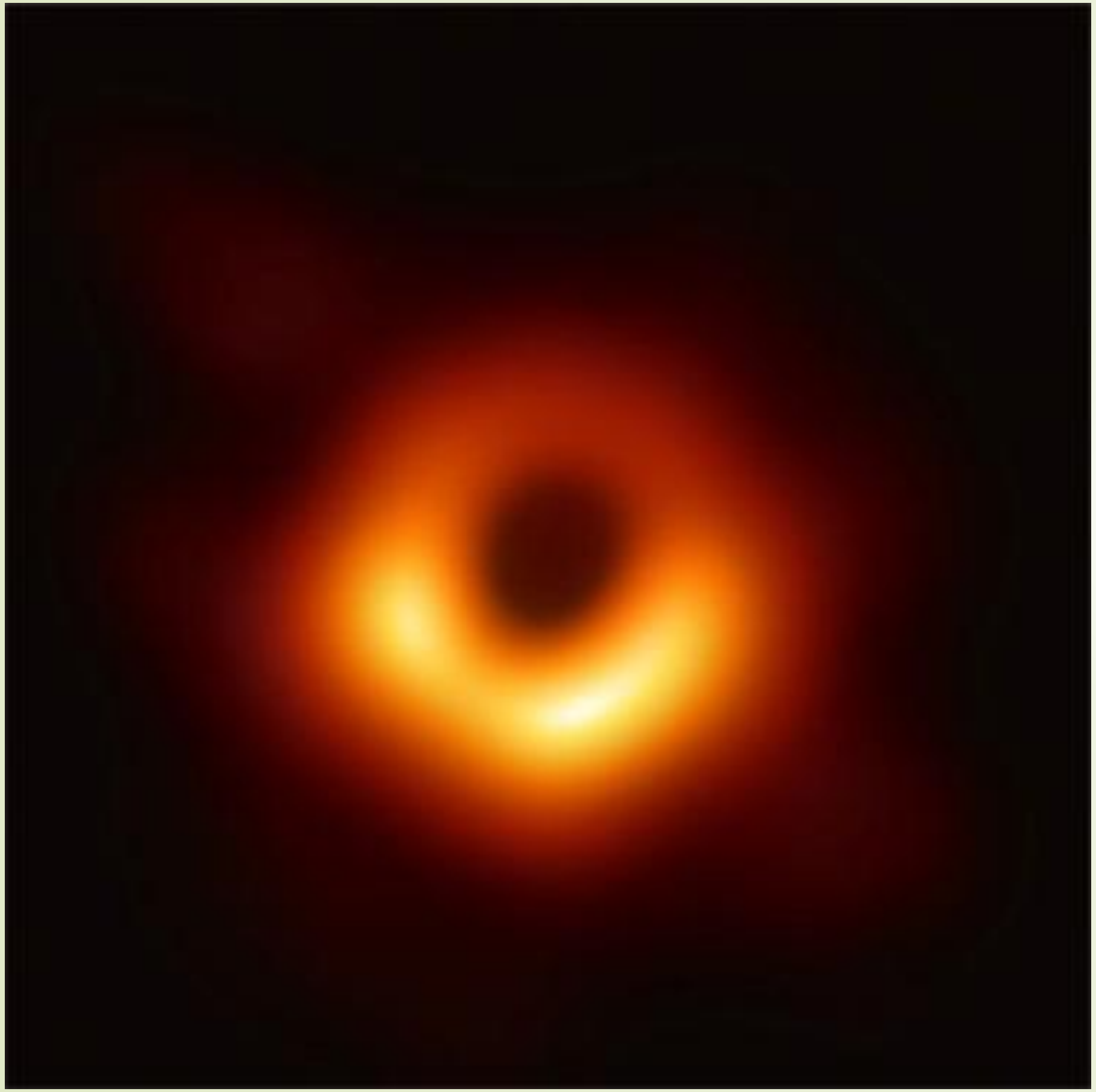
Hot spot is staring from the north pole of the event horizon

There are infinite number of lensed images of a separate hot spot (direct image and light echoes)

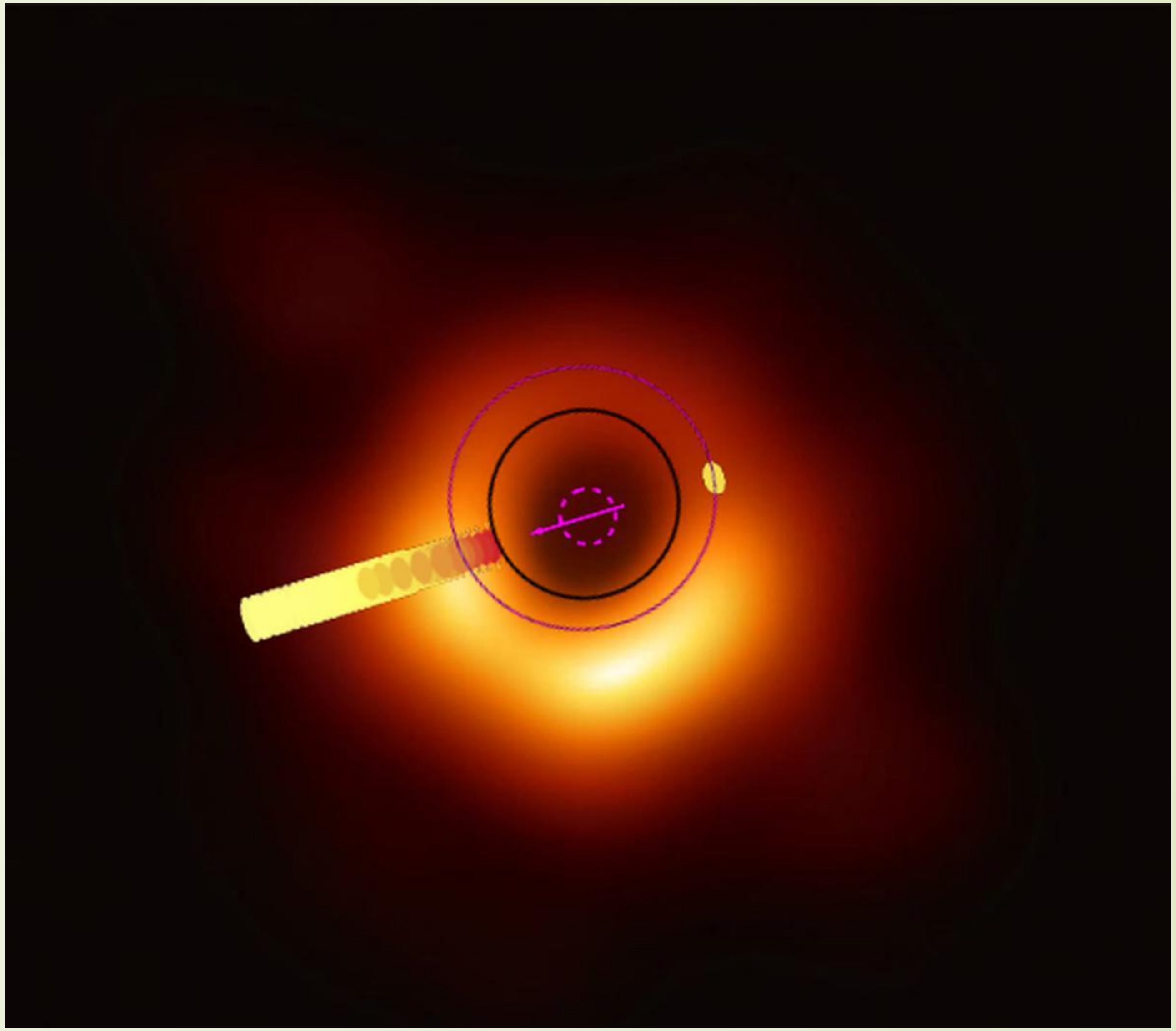
It is shown direct images and 1-st light echoes of a hot spot in discrete time intervals

1-st light echoes produced by clockwise and counter-clockwise moving photons and viewed near the outline of the black hole shadow

Event Horizon Telescope (2019)



Millimetron Space Observatory (2030?)



Closed magenta curve – the position of the classical black hole shadow

Closed black curve - the lensed north hemisphere of the event horizon

Conclusion

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.

Details in: 2010.01885, 2007.14121, 1911.07695, 1906.07171, 1903.09594, 1812.06787, 1804.08030, 1802.00817

Animations in: youtube.com/watch?v=P6DneV0vk7U
youtu.be/7j8f_vlTul8
youtu.be/zQzC-IVgdjg
youtu.be/fps-3frL0AM