Spin and mass of the nearest supermassive black hole

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Rotating ($a \simeq 1$) black hole are welcomed !

There are no Schwarzschild black holes in the Universe

'Rotation' angular velocity of the Kerr-Newman metric: $(d\phi - \omega dt)^2$

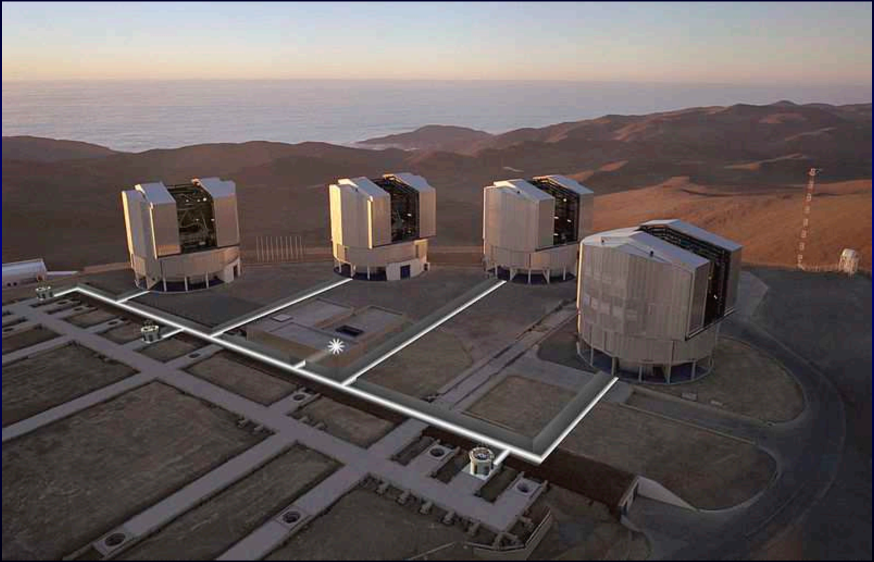
$$\omega = \frac{2Mr - e^2}{(r^2 + a^2)^2 - a^2 \Delta \sin^2 \theta} a, \quad \Delta = r^2 - 2r + a^2 + e^2$$

Relativistic jets, shocks, ultra-high-energy cosmic rays generation:

- Penrose mechanism
  Extraction of rotaion energy from black hole ergosphere
- Unipolar induction
  Electric potential of rotating black hole
- Blandford-Znajek mechanism
  Electromagnetic extraction of rotation energy from black hole

Very Large Telescope Array (interferometer)

Chile, ESO 2635 m, VLTA $= 4 \times ø8.2$ m $+ 4 \times ø1.8$ m



Sgr A*: Quaisi-periodic oscillations (QPO)

QPO observations in the near Infra-Red of the Galactic center by VLTA

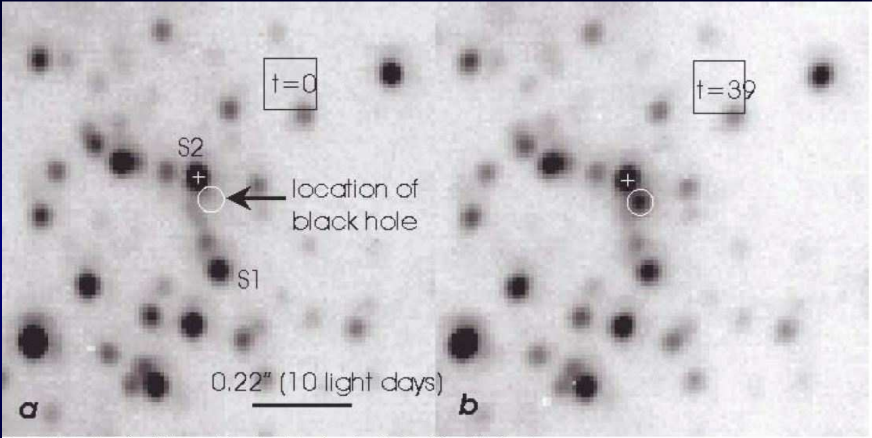
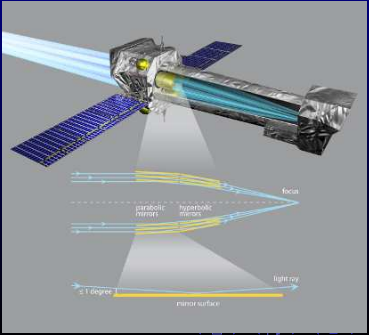


Figure 1 Detection of variable near-infrared emission from SgrA*. Raw H-band (1.65-µm) AO images (40 mas full-width at half-maximum, FWHM) of the central ,1" of the Milky

arXiv:astro-ph/0310821

X-ray Multi-Mirror Mission — Newton

NASA-ESA 1999, 3.8 **tons** ×10 **m** ×16 **m,** 0.2 – 12 **keV**



Sgr A*: Quasi-periodic oscillations (QPO)

QPO observations in the X-rays of the Galactic center by Newton telescope

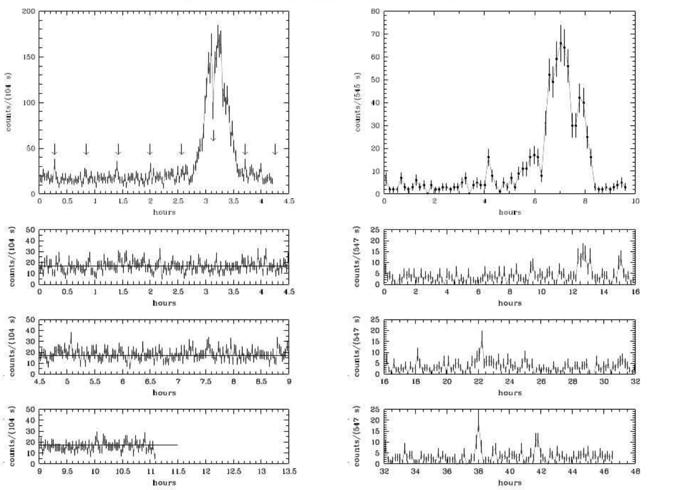


Fig. 1. EPIC light curves (MOS1+MOS2+PN) of the *XMM-Newton* observation of October 3, 2002 (upper panel, Fig. 1a) and the February 26, 2002 observation

Fig. 2. ACIS-I light curves of the *Chandra* observation of October 26, 2000 (upper panel, Fig. 2a) and the May 25, 2002 observation (lower three panels, Fig. 2b). Error bars

arXiv:astro-ph/0401589

Test particle motion in the Kerr-Newman metric

Parameters

- M — black hole mass
- $J = \frac{GM^2}{c} a$ — black hole angular moment
  $0 \leq a \leq 1$ — black hole spin parameter
- e — black hole electric charge
- μ — particle mass
- ϵ — particle electric charge

Integrals of motion

- E — total particle energy
- L — particle azimuthal angular momentum
- Q — Carter constant

At $Q = 0$ the motion is in the equatorial plane
At $a = 0$ the total particle angular momentum $\mathcal{J} = \sqrt{Q + L^2}$

Equations of motion of test particles

B. Carter 1968

in the Boyer-Lindquist coordinates

- $\rho^2 \frac{dr}{dL} = \pm\sqrt{V_r}$
- $\rho^2 \frac{d\theta}{dL} = \pm\sqrt{V_\theta}$
- $\rho^2 \frac{d\varphi}{dL} = L\sin^{-2}\theta + a(\Delta^{-1}P - E)$
- $\rho^2 \frac{dt}{dL} = a(L - aE\sin^2\theta) + (r^2 + a^2)\Delta^{-1}P$

$L = \frac{\tau}{\mu}$, τ — particle proper time

- Effective radial potential
  $V_r = P^2 - \Delta[\mu^2 r^2 + (L - aE)^2 + Q]$
- Effective latitude potential (nutation)
  $V_\theta = Q - \cos^2\theta[a^2(\mu^2 - E^2) + L^2\sin^{-2}\theta]$
- $P = E(r^2 + a^2) + \epsilon er - aL, \quad \rho^2 = r^2 + a^2\cos^2\theta$
- $\Delta = r^2 - 2r + a^2 + e^2$ Horizons $\Delta = 0, \quad r = r_\pm$

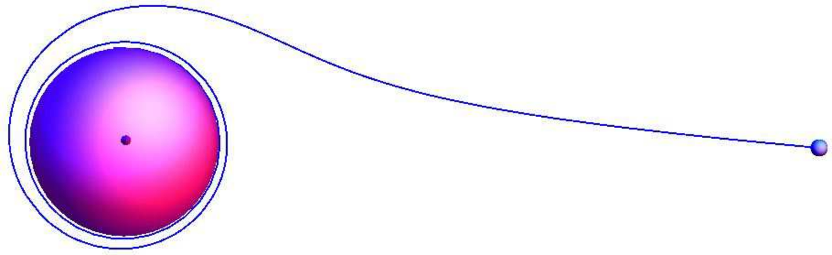
$r_+ = 1 + \sqrt{1 - a^2 - e^2}$ — external horizon (event horizon)

$r_- = 1 - \sqrt{1 - a^2 - e^2}$ — internal horizon (Cauchy horizon)

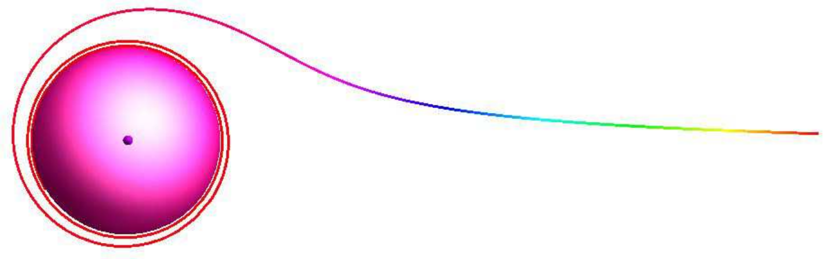
Infall to the rotating black hole

numerically calculated and viewed from the black hole north pole

Planet infall: parabolic orbit $E = 1$, zero angular momentum $L = 0$

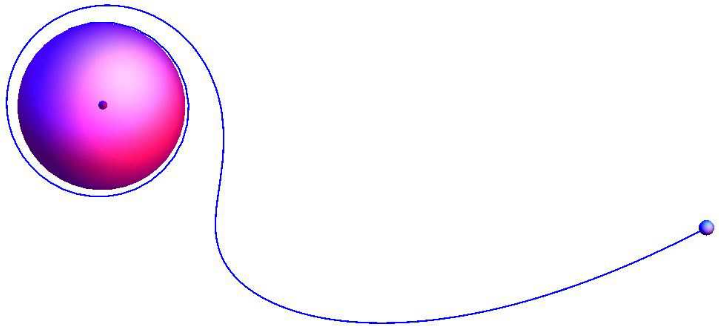


Photon infall: zero impact parameter $b = L/E = 0$

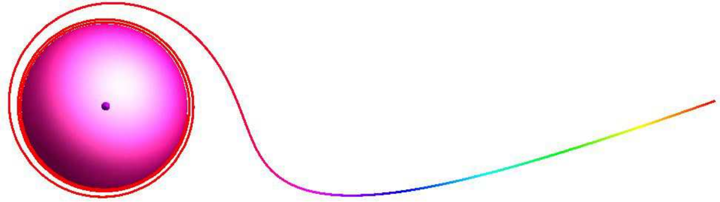


Infall to the rotating black hole

Planet infall: $L = -3$ (negative!), $E = 1$

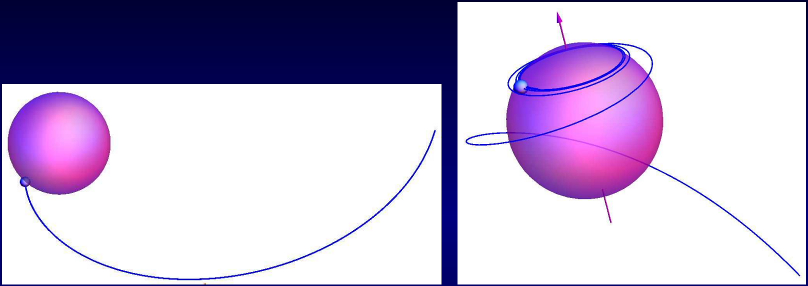


Photon infall: $b = L/E = -3$ (negative!)



Test particle infall trajectories to the black hole

$G = c = 1$, $Q = 0.3M^2\mu^2$, $E \Rightarrow E/M = 0.85$, $L \Rightarrow L/M = 1.7$, $r(0) \Rightarrow r(0)/M = 4.4$



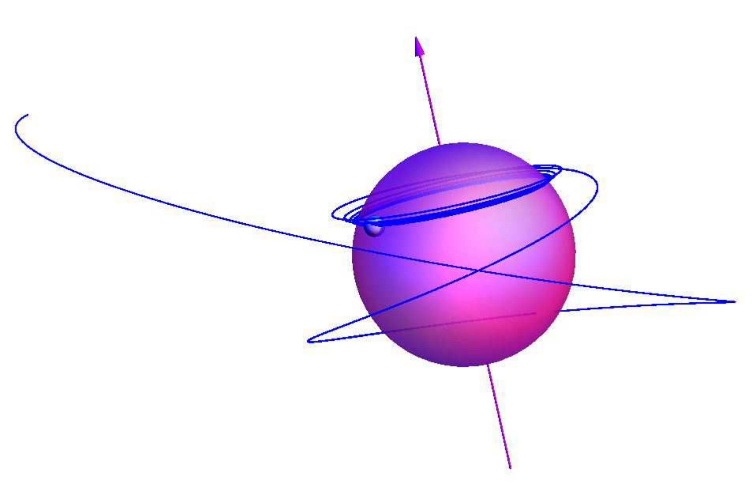
$a = 0$ $\qquad\qquad$ $a = 0.998$

Angular velocity $\Omega_{\rm h}$ and rotation period $T_{\rm h}$ of the horizon:

$$\Omega_{\rm h} = \omega(r_+) = \frac{2\pi}{T_{\rm h}} = \frac{a}{2(1+\sqrt{1-a^2})}$$

Planet infall trajectory to the rotating black hole

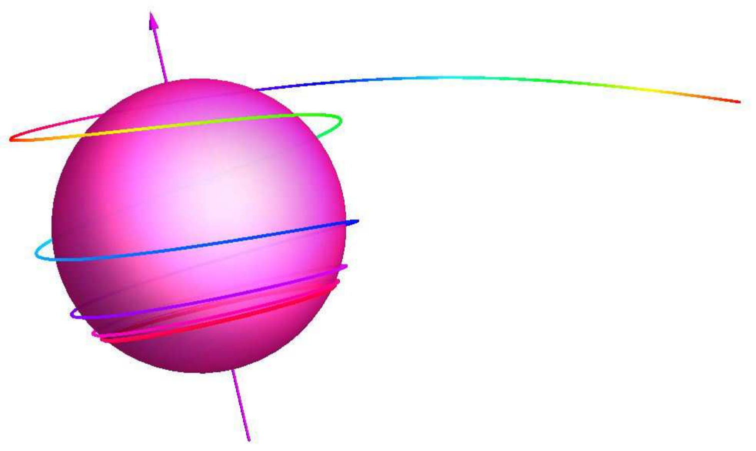
$a = 0.998,\ Q = 1,\ E = 0.85,\ L = 1.7,\ r(0) = 4.4$



$$\Omega_{\rm h} = \omega(r_+) = \frac{2\pi}{T_{\rm h}} = \frac{a}{2(1+\sqrt{1-a^2})}$$

Photon infall trajectory to the rotating black hole

$a = 0.998,\ Q = 2,\ b = 2,\ r_+ = 1.063$



$$\Omega_{\rm h} = \omega(r_+) = \frac{2\pi}{T_{\rm h}} = \frac{a}{2(1+\sqrt{1-a^2})}$$

‘Synchrotron’ focusing of outgoing radiation at $r \gtrapprox r_+$

Observed frequency modulation with the horizon rotation frequency $\simeq \mathbf{\Omega}_{\rm h}$

L140 C. T. CUNNINGHAM AND J. M. BARDEEN Vol. 173

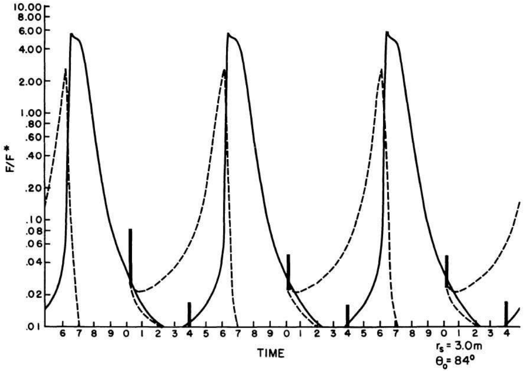


FIG. 2.—Light curves for $r_s = 3m$ and $\theta_0 = 84°$. The two brightest images are indicated by solid and dashed curves, as in fig. 1. The sharp spikes in the light curve for the one-orbit image mark the times at which the light curve doubles back on itself.

Light curve of the source at the circular orbit

C. W. Mizner, Phys. Rev. Lett. **28**, *994–997 (1972)*

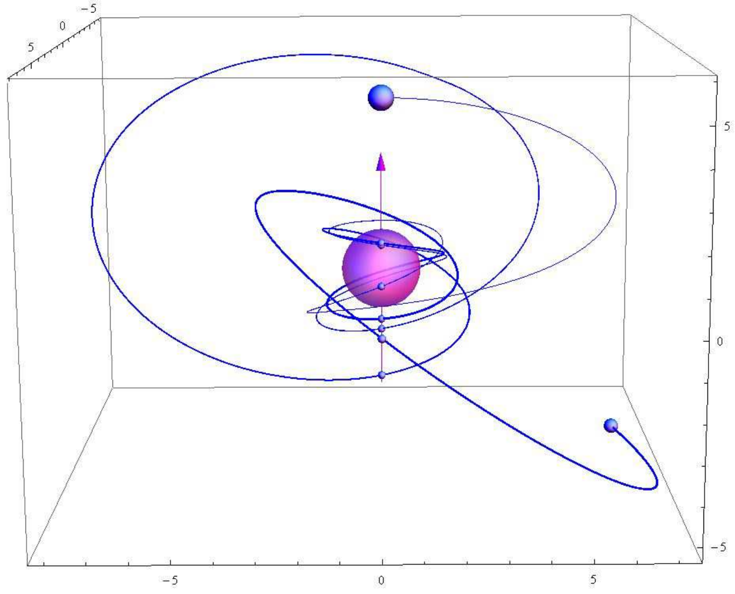
J. M. Bardeen, W. H. Press and S. A. Teukiolsky Astrophys. J **178** *347 (1972)*

C. T. Cunningham J. M. Bardeem, Astrophys. J. **173**, *L137 (1972)*

A. G. Polnarev, Astrophysics, **8**, *273 (1972)*

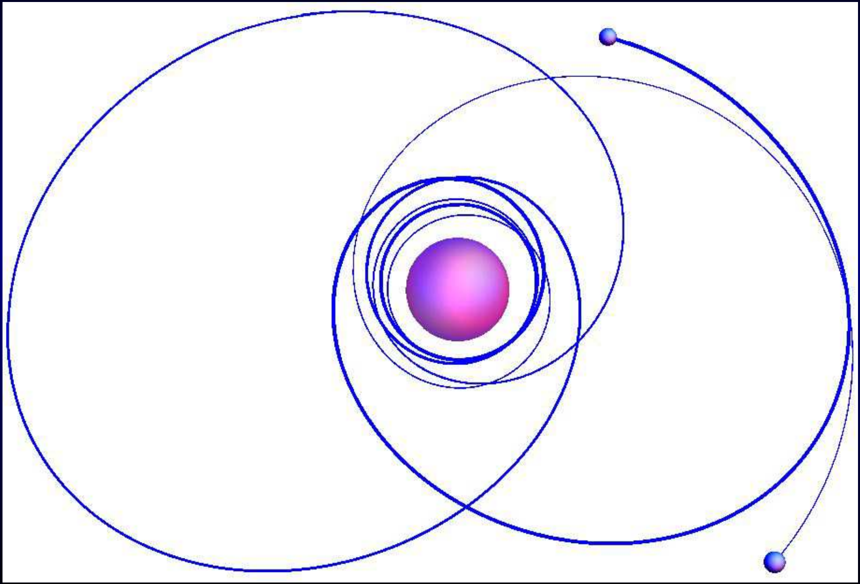
Quasi-periodic orbit, $n > 7$ turns (years)

$a = 0.9982$, $Q = 2$, $E = 0.92$, $L = 1.9$, $r_p = 1.74$, $r_a = 9.48$, $\theta_{\max} = 36.2^\circ$



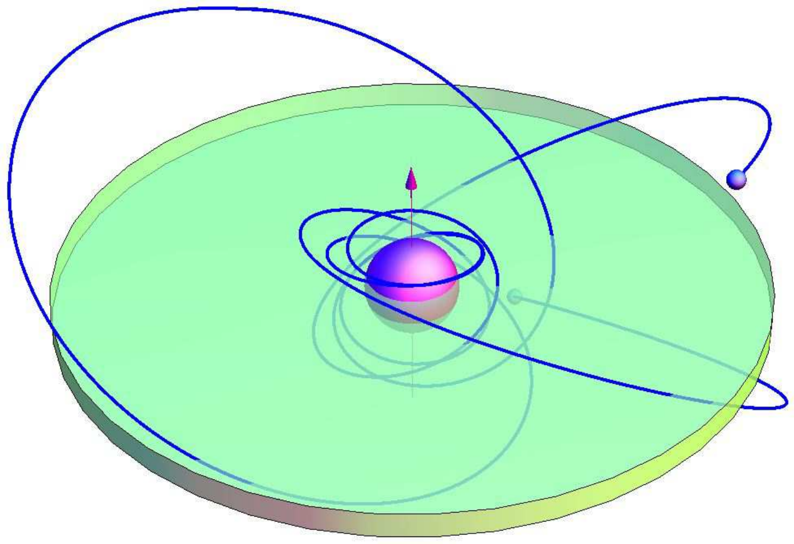
The same orbit, viewed from the north pole

$a = 0.9982$, $Q = 2$, $E = 0.92$, $L = 1.9$, $r_p = 1.74$, $r_a = 9.48$, $\theta_{\max} = 36.2°$



Latitude oscillation of the hot plasma clump

over the opaque accretion disk

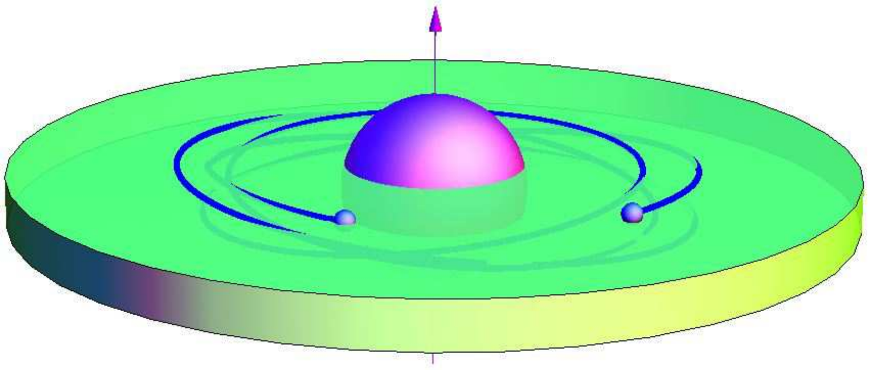


$a = 0.9982,\ Q = 2,\ E = 0.92,\ L = 1.9,$

$r_+ = 1.06,\ r_p = 1.74,\ r_a = 9.48,\ \theta_{\max} = \pm 36.2^\circ$

Latitude oscillation of the hot plasma clump

in the thin opaque accretion disk with a frequency Ω_θ



$a = 0.65,\ Q = 0.1,\ E = 0.91,\ L = 2.715,$
$r_+ = 1.76,\ r_p = 3.86,\ r_a = 5.01,\ \theta_{\max} = \pm 6.6^\circ$

Hot spots on the surface of the accretion disk R. A. Suynyaev 1972

Latitude oscillation frequency of the hot spot clump Ω_θ

$$\frac{\Omega_\theta}{\Omega_\varphi} = \frac{\pi}{2}(\beta z_+)^{1/2}\left[\frac{L}{a}\Pi(-z_-, k) + \frac{2xE - aL}{\Delta}K(k)\right]^{-1}$$

$$K(k) = \int_0^{\pi/2}\frac{dx}{(1-k^2\sin^2 x)^{1/2}}, \quad \Pi(n,k) = \int_0^{\pi/2}\frac{dx}{(1+n\sin^2 x)(1-k^2\sin^2 x)^{1/2}}$$

$$z_\pm = \cos^2\theta_\pm = (2\beta)^{-1}[\alpha + \beta \pm \sqrt{(\alpha+\beta)^2 - 4Q\beta}], \quad k^2 = z_-/z_+$$

$$\alpha = (Q + L^2)/a^2, \quad \beta = 1 - E^2$$

D. C. Wilkins, Phys. Rev. D, 5, 814 (1972)

$$\Omega_\varphi = \frac{x\sqrt{x^3(3Q - Qx + x^2) + a^2Q^2} - a(x^2 + 3Q)}{x^5 - a^2[x^2 + Q(x+3)]}, \qquad \Omega_\varphi(Q=0) = \frac{1}{x^{3/2} + a}$$

Thin accretion disk $(Q \to 0)$

VD, arXiv:1306.2033

$$\Omega_\theta\big|_{Q\to 0} = \frac{2\pi}{T_\theta} = \frac{\sqrt{x^2 - 4ax^{1/2} + 3a^2}}{x(x^{3/2} + a)}$$

Minimal radius of the stable circular orbits $x = x_{\rm ms}$

$$x_{\rm ms} = 3 + Z_2 - \sqrt{(3 - Z_1)(3 + Z_1 + 2Z_2)}, \qquad \Omega_{\rm ms} = \Omega_\varphi(x = x_{\rm ms})$$

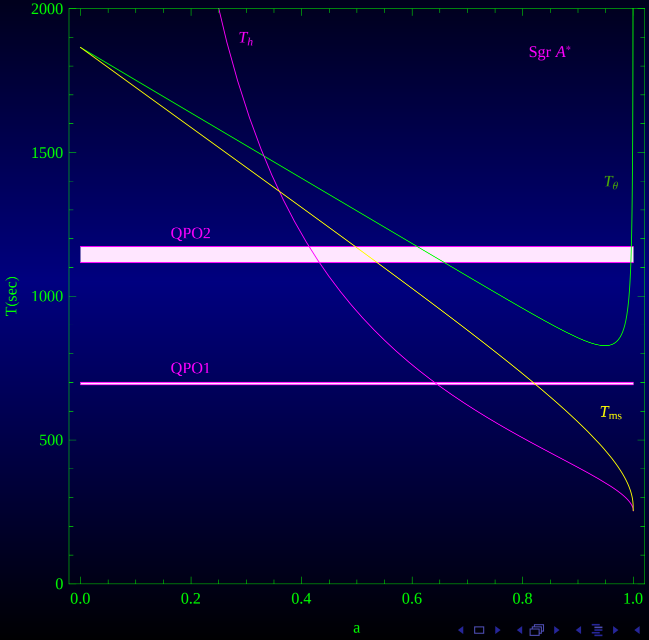
$$Z_1 = 1 + (1 - a^2)^{1/3}[(1+a)^{1/3} + (1-a)^{1/3}], \qquad Z_2 = \sqrt{3a^2 + Z_1^2}$$

Quasi-periodic oscillations of hot clumps

in the accretion disk

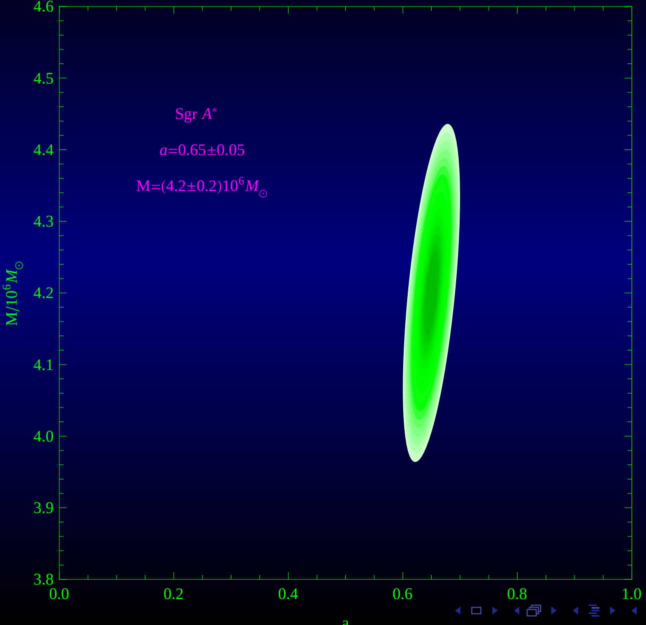
- Frequencies Ω_θ and $\Omega_{\rm h}$ are independent on the accretion model
- Frequencies Ω_θ and $\Omega_{\rm h}$ depend only on the black hole parameters (mass M and spin a)
- Modulation of accretion radiation with frequencies Ω_θ and $\Omega_{\rm h}$ (two spikes in the power spectrum)
- Modulation of accretion radiation with frequency Ω_φ is wide spreaded (absence of the corresponding spike in the power spectrum)

Sgr A*: observed quasi-periodic oscillations



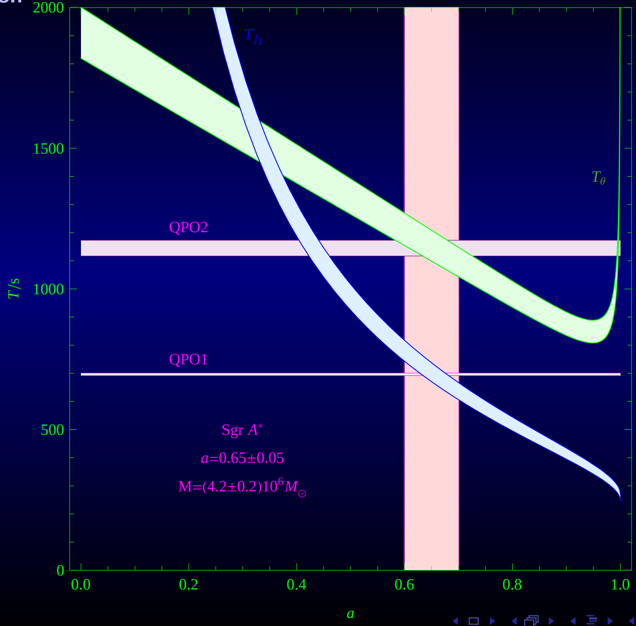
Supermassive black hole Sgr A*: spin and mass

1 σ-error region



Sgr A*: $M = (4.2 \pm 0.2)\,10^6 M_\odot$, $a = 0.65 \pm 0.05$!

1 σ-error region



Results and Conclusions

- Mass of the nearest supermassive black in the Galactic center
  $M = (4.2 \pm 0.2)\,10^6\,M_\odot$
  Previously known value: $M = (4.1 \pm 0.4)\,10^6\,M_\odot$
- The nearest supermassive black hole rotates not very fast
  $a = 0.65 \pm 0.05$
- Identification of quasi-periodic oscillations from Sgr A*
  Rotation period of black hole horizon
  $T_{\rm h} = 11.5$ мin
  Latitude oscillation period of hot spots in the accretion flow
  $T_\theta = 19$ min
- Moderately fast rotation is in agreement with the black hole evolution due to accretion of stars from the central cluster
- Black hole Sgr A* in the Galactic center is a moderately effective cosmic rays generator