

Shadows around black holes as a tool to evaluate black hole parameters and spacetime dimensions

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- **Seminar of High Energy Density in Matter,**

- **FAIR-Russia Research Center, 21 November, 2011**

- 02.09.2011 20:24
- <http://www.vesti.ru/videos?vid=358242&cid=9>

• **Вблизи Земли обнаружены две черные дыры**

- Автор: Ася Семёнова
- *Недалеко от Земли обнаружены сразу две чёрные дыры, впечатляющие кадры запечатлел американский орбитальный телескоп "Чандра". Конечно, "недалеко" - понятие относительное, речь идёт о 160 миллионах световых лет. **Но это самые близкие к нашей планете черные дыры.** Повлиять на нас они, конечно, не могут, но у ученых появилась возможность изучить слияние двух галактик, во время которого и появились эти две дыры.*
- Свежие снимки из галактики NGC-3393. Они сделаны относительно недалеко от Земли - 160 миллионов световых лет. Астрономы поймали в объектив космического телескопа "Чандра" сразу пару черных дыр. Снимок крайне удачный. **По земным представлениям, в галактике, где не происходит межгалактических слияний, места для двух черных дыр не предусмотрено.**
- "Было известно, что в этой галактике черная дыра существует, но никто не подозревал, что там не одна, а две. То, что было довольно неожиданно обнаружено, это то, что двойная черная дыра была найдена в галактике, выглядящей довольно пристойно, то есть не видно было, чтобы она с чем-то сливалась", - отмечает профессор кафедры астрофизики и звездной астрономии Государственного астрономического института имени П.К. Штернберга МГУ М.В. Ломоносова Анатолий Засов.

- Увидеть черные дыры невозможно. Они не излучают, а только поглощают энергию. Вокруг них замедляется время, а гравитация максимальна, максимальна настолько, насколько это только допустимо законами природы.
- **Черную дыру обнаруживают по излучению тех космических объектов, которые она в данный момент засасывает.** Зафиксировать подобные явления можно с помощью рентгеновского телескопа "Чандра". **Названный в честь бога Луны в индуистской мифологии, телескоп постоянно находится в космосе на особой вытянутой орбите. Максимальное приближение к Земле - 16 тысяч километров.**
- "Чаще всего в оптическом диапазоне излучение не очень сильное, потому что значительная часть энергии перехватывается пылью, которая прячет очень яркое ядро. А рентгеновское излучение может пробивать значительную толщину веществ, и рентгеновские лучи до нас доходят", - поясняет Анатолий Засов.
- Будущее дыр вполне предсказуемо: они будут кружиться вокруг друг друга, пока не станут единым целым. Тем более, что между ними небольшое расстояние - 490 световых лет.
- Но любопытно, сколько еще подобных объектов скрывается в окрестностях нашей галактики? Сами ученые не отрицают: обнаружить эту пару удалось только потому, что галактика, в которой они находятся, по космическим меркам довольно близко от Млечного пути.

Research Note

Binary black holes in Mkns as sources of gravitational radiation for space based interferometers

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Received 30 April 2003 / Accepted 8 August 2003

Abstract. The possibility that some Markarian objects (e.g. Mkn 501, Mkn 421 and Mkn 766) host massive binary black hole systems with eccentric orbits at their centers has been considered. These systems could be sources of gravitational radiation for space-based gravitational wave interferometers like LISA and ASTROD. In the framework of the Lincoln–Will approximation we simulate coalescence of such systems, calculate gravitational wave templates and discuss parameters of these binary black hole systems corresponding to the facilities of LISA and ASTROD. We discuss also the possibility to extract information about parameters of the binary black hole systems (masses, of components, distances between them, eccentricity and orbit inclination angle with respect to line of sight) from future gravitational wave measurements.

Key words. black hole physics – gravitational waves

1. Introduction

BL Lacertae objects, also known as Markarian objects (hereafter Mkns), belong to the class of active galaxies according to the well-established unified model on radio-loud active galactic nuclei (Urry & Padovani 1995). These objects are thought to be dominated by relativistic jets seen at small angles to the line of sight.

Until now, several astrophysical phenomena have been attributed to binary black holes, like precession of jets (Begelman et al. 1980), misalignment (Conway & Wroble 1995), periodic outburst activity in the Quasar OJ 287 (Sillanpää et al. 1988; Lehto & Valtonen 1996) and precession of the accretion disk under gravitational torque (Katz 1997).

It has been recently observed that some Mkns show a periodic behavior in the radio, optical, X-ray and γ -ray light curves that is possibly related to the presence of a massive binary black hole with a jet along the line of sight or interacting with an accretion disk (Yu 2002). Therefore, the search for light curve variability, mainly in X-ray and γ -ray wavelengths, can be considered as a method to probe the existence of a massive binary black hole in the center of a galaxy.

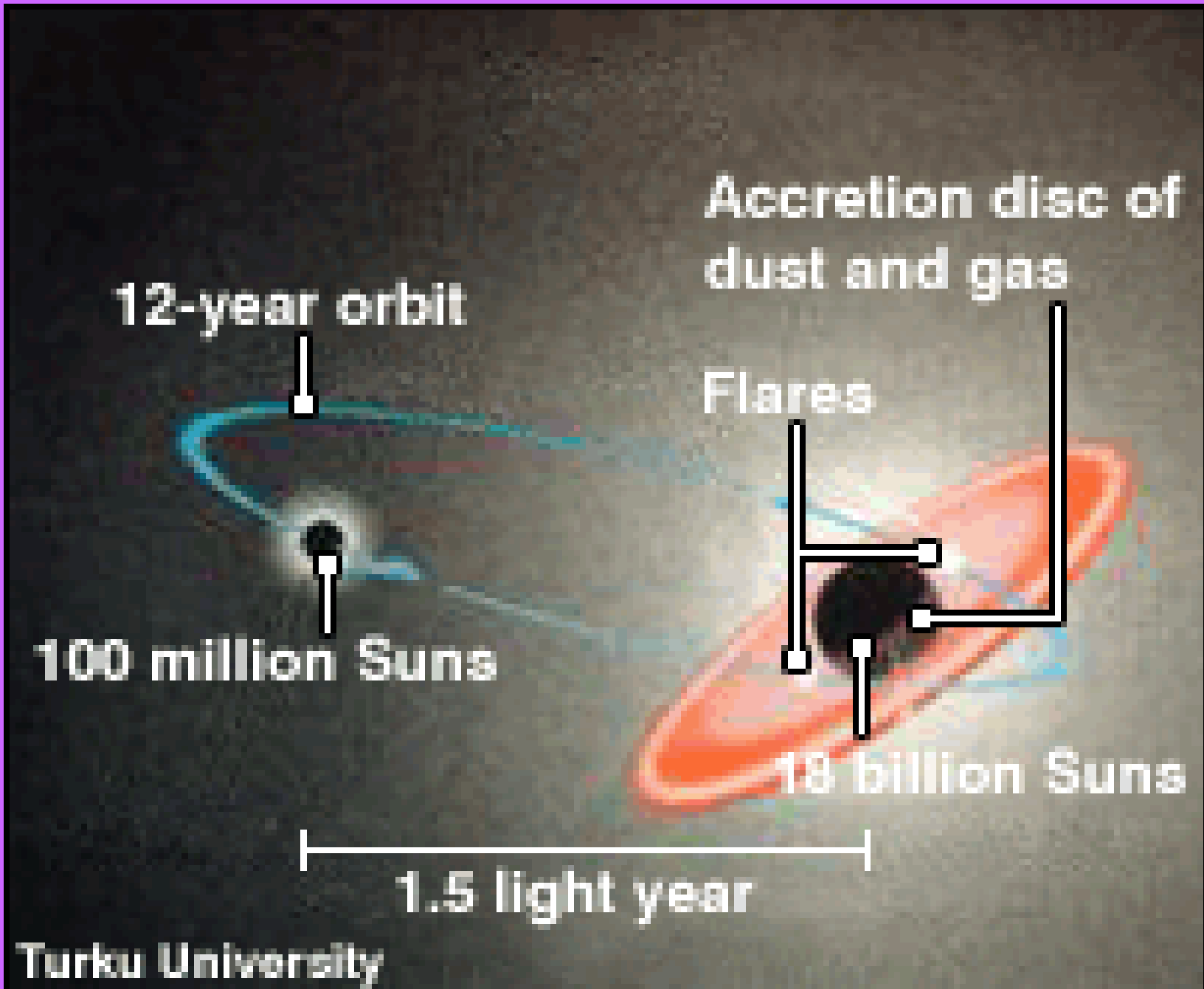
Send offprint requests to: A. A. Nucita,
e-mail: nucita@le.infn.it

A question naturally arises: how can a binary system of massive black holes be formed? The answer to this problem can be found in the framework of the hierarchical vision of the universe (White 1997), for example if massive black hole systems form as a result of merging processes between galaxies, each of them may contain in the center a massive black hole (Rees 1984; Kormendy & Richstone 1995; Richstone et al. 1998). Recent observational signatures¹ of such hypothesis were discussed, for example by Yu & Lu (2001) who analyzed typical features of Fe K α line shapes.

At least three Mkns (i.e. Mkn 501, Mkn 421 and Mkn 766) are particularly well studied at high energies, revealing a possible periodic behavior in their light curves.

Mkn 501, at $z = 0.034$, shows a clear well-correlated 23 day periodicity in X-ray and TeV energy bands with an observed TeV flux ratio $f \approx 8$ between the maximum and minimum of the signal (Protheroe et al. 1998; Hayashida et al. 1998; Kranich et al. 1999; Nishikawa et al. 1999; Kranich et al. 2001), while evidence for correlations in the optical U -band is rather weak (Catanese et al. 1997; Aharonian et al. 1999a,b). It has

¹ The gravitational wave spectrum from coalescing massive black hole binaries formed by merging processes of their host galaxies has been studied by Jaffe & Backer (2003).



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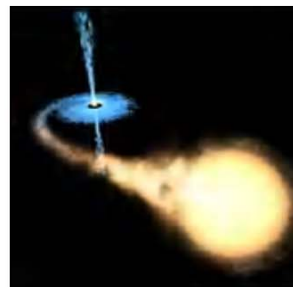
Published online: 31 March 2005; | doi:10.1038/news050328-8

Black holes 'do not exist'

[Philip Ball](#)

These mysterious objects are dark-energy stars, physicist claims.

Black holes are staples of science fiction and many think astronomers have observed them indirectly. But according to a physicist at the Lawrence Livermore National Laboratory in California, these awesome breaches in space-time do not and indeed cannot exist.



Black holes, such as the one pictured in this artist's impression, may in fact be pockets of 'dark energy'.

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Over the past few years, observations of the motions of galaxies have shown that some 70% the Universe seems to be composed of a strange 'dark energy' that is driving the Universe's accelerating expansion.

George Chapline thinks that the collapse of the massive stars, which was long believed to generate black holes, actually leads to the formation of stars that contain dark energy. "It's a near certainty that black holes don't exist," he claims.

Black holes are one of the most celebrated predictions of Einstein's general theory of relativity, which explains gravity as the warping of space-time caused by massive objects. The theory suggests that

a sufficiently massive star, when it dies, will collapse under its own gravity to a single point.

But Einstein didn't believe in black holes, Chapline argues. "Unfortunately", he adds, "he couldn't articulate why." At the root of the problem is the other revolutionary theory of twentieth-century physics, which Einstein also helped to formulate: quantum mechanics.

“ It's a near certainty that black holes don't exist. ”

George Chapline
Lawrence Livermore National
Laboratory

In general relativity, there is no such thing as a 'universal time' that makes clocks tick at the same rate everywhere.

Instead, gravity makes clocks run at different rates in

different places. But quantum mechanics, which describes physical phenomena at infinitesimally small scales, is meaningful only if time is universal; if not, its equations make no sense.

This problem is particularly pressing at the boundary, or event horizon, of a black hole. To a far-off observer, time seems to stand still here. A spacecraft falling into a black hole would seem, to someone watching it from afar, to be stuck forever at the event horizon, although the astronauts in the spacecraft would feel as if they were continuing to fall. "General relativity predicts that nothing happens at the event horizon," says Chapline.

Quantum transitions

However, as long ago as 1975 quantum physicists argued that strange things do happen at an event horizon: matter governed by quantum laws becomes hypersensitive to slight disturbances. "The result was quickly forgotten," says Chapline, "because it didn't agree with the prediction of general relativity. But actually, it was absolutely correct."

This strange behaviour, he says, is the signature of a 'quantum phase transition' of space-time. Chapline argues that a star doesn't simply collapse to form a black hole; instead, the space-time inside it becomes filled with dark energy and this has some intriguing gravitational effects.

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'surface' of a

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dark-energy star, it behaves much like a black hole, producing a strong gravitational tug. But inside, the 'negative' gravity of dark energy may cause matter to bounce back out again.

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If the dark-energy star is big enough, Chapline predicts, any electrons bounced out will have been converted to positrons, which then annihilate other electrons in a burst of high-energy radiation. Chapline says that this could explain the radiation observed from the centre of our galaxy, previously interpreted as the signature of a huge black hole.

He also thinks that the Universe could be filled with 'primordial' dark-energy stars. These are formed not by stellar collapse but by fluctuations of space-time itself, like blobs of liquid condensing spontaneously out of a cooling gas. These, he suggests, could be stuff that has the same gravitational effect as normal matter, but cannot be seen: the elusive substance known as dark matter.

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<http://xxx.arxiv.org/abs/astro-ph/0503200>
(2005).

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BHs is a consequence of black failure in knowledge of mathematics

шно продолжать заниматься важной и интересной научной работой, не остав-
своих прочих интересов.

Коллеги по кафедре общей ядерной физики

«Черные дыры» — это следствие черного провала в знаниях математики

общей теории относительности
рждается, что уравнения ОТО со-
кат решения, отвечающие «чер-
дырам». Это некие сферически-
метричные материальные объекты,
редоточенные в области, из которой
жду никакие сигналы выйти не мо-
Они проявляют себя лишь в гравитационном взаимодействии с другими
ми. Их внутренняя структура ока-
ается недоступной для изучения. Т.е.
онные дыры» — непознаваемые объ-
ы!

та непознаваемость уже сама по себе
жна была бы вызвать подозрение, так
объект создавался природой по за-
ам причинно-связанных процессов.
жна была бы возникнуть потреб-
ть более внимательно проанализиро-

ход рассуждений, приведших к шварцшильдовскому решению для метриче-
х коэффициентов в галилеевых координатах, содержащему «черные дыры».
Так в чем же там дело? А дело в следующем. При получении решения Шварц-
льда в галилеевых координатах в качестве внешнего решения некоего кусочно-
рерывного линейного дифференциального уравнения второго порядка бралось
общее решение с двумя константами интегрирования, а *частное* решение с
ой константой, определяемой граничным условием на бесконечности (вопрос
шивании с внутренним решением не поднимался). В результате получались
чения метрических коэффициентов риманова пространства, допускающие су-



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Outline of my talk

- Introduction
- Shadows for Kerr as a tool to evaluate BH characteristics
- Shadows around Reissner-Nordstrom BHs
- Observations of BH at Sgr A and a tidal Reissner-Nordstrom BH
- Bright star trajectories around BH at GC as a tool to evaluate BH parameters and DM cluster
- Conclusions

Rev. John Michell: *Phil. Trans. R. Soc. London*, 74, 35–57 (1784):

VII. *On the Means of discovering the Distance, Magnitude, &c. of the Fixed Stars, in consequence of the Diminution of the Velocity of their Light, in case such a Diminution should be found to take place in any of them, and such other Data should be procured from Observations, as would be farther necessary for that Purpose. By the Rev. John Michell, B. D. F. R. S. In a Letter to Henry Cavendish, Esq. F. R. S. and A. S.*

Read November 27, 1783.

Rev. John Michell: *Phil. Trans. R. Soc. London*, 74, 35–57 (1784):

42 *Mr. MICHELL on the Means of discovering the*

16. Hence, according to article 10, if the semi-diameter of a sphaere of the same density with the sun were to exceed that of the sun in the proportion of 500 to 1, a body falling from an infinite height towards it, would have acquired at its surface a greater velocity than that of light, and consequently, supposing light to be attracted by the same force in proportion to its vis inertiae, with other bodies, all light emitted from such a body would be made to return towards it, by its own proper gravity.

Mirages around Kerr black holes and retro-gravitational lenses

- Let us consider an illumination of black holes. Then retro-photons form caustics around black holes or mirages around black holes or boundaries around shadows.
- (Zakharov, Nucita, DePaolis, Ingrosso,
- *New Astronomy* 10 (2005) (479-489);
astro-ph/0411511)

RETRO-MACHOS: π IN THE SKY?

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Draft version September 20, 2004

ABSTRACT

Shine a flashlight on a black hole, and one is greeted with the return of a series of concentric rings of light. For a point source of light, and for perfect alignment of the lens, source, and observer, the rings are of infinite brightness (in the limit of geometric optics). In this manner, distant black holes can be revealed through their reflection of light from the Sun. Such retro-MACHO events involve photons leaving the Sun, making a π rotation about the black hole, and then returning to be detected at the Earth. Our calculations show that, although the light return is quite small, it may nonetheless be detectable for stellar-mass black holes at the edge of our solar system. For example, all (unobscured) black holes of mass M or greater will be observable to a limiting magnitude \bar{m} , at a distance given by: $0.02 \text{ pc} \times \sqrt[3]{10^{(\bar{m}-30)/2.5}} (M/10 M_{\odot})^2$. Discovery of a Retro-MACHO offers a way to *directly* image the presence of a black hole, and would be a stunning confirmation of strong-field general relativity.

Subject headings: gravitational lensing—black hole physics—relativity

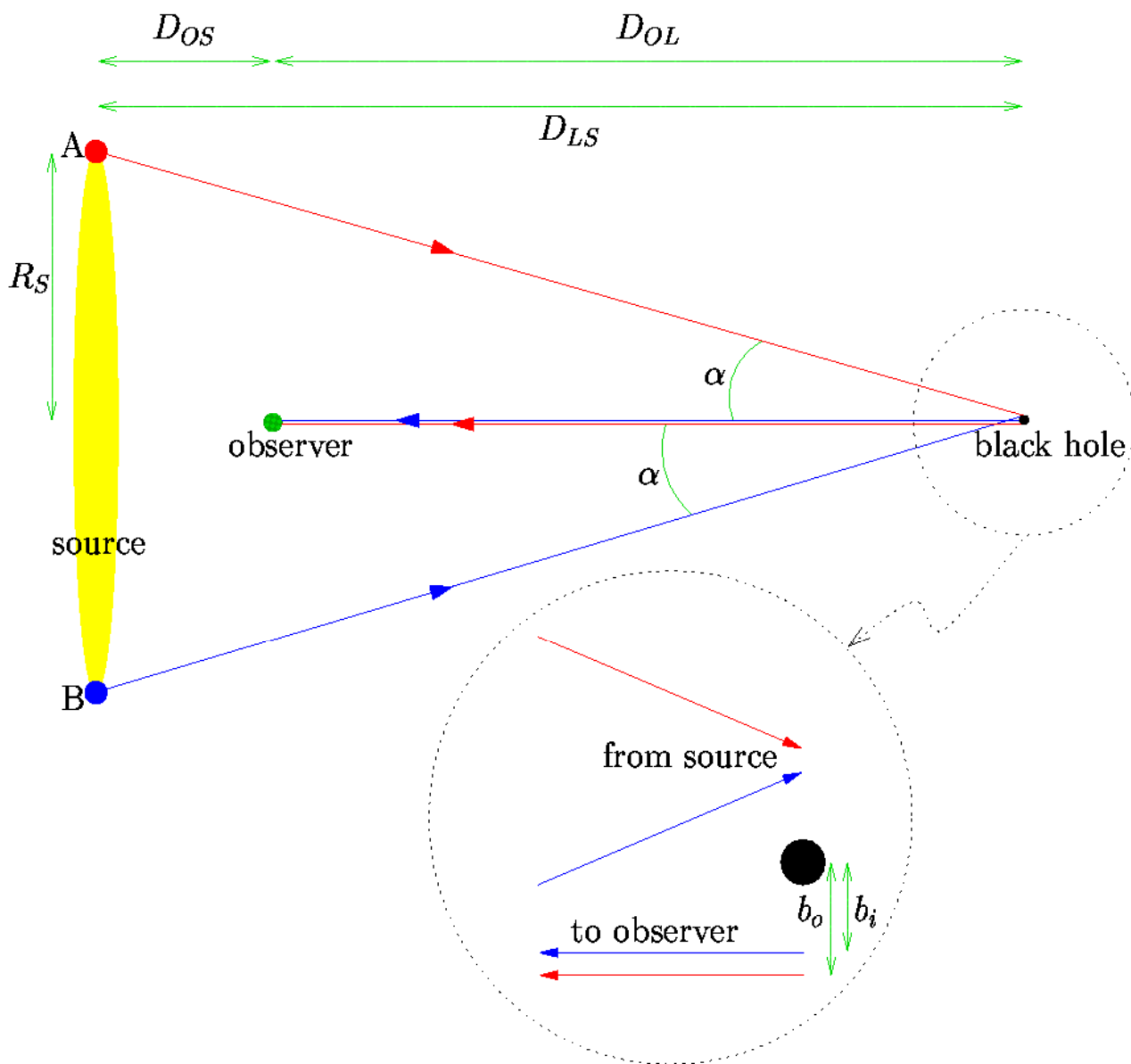


FIG. 1.— Perfect alignment: the (extended) source, observer, and lens are colinear. The resulting image of the source, as lensed by the black hole, is a ring. (The angles in this figure are greatly exaggerated.)

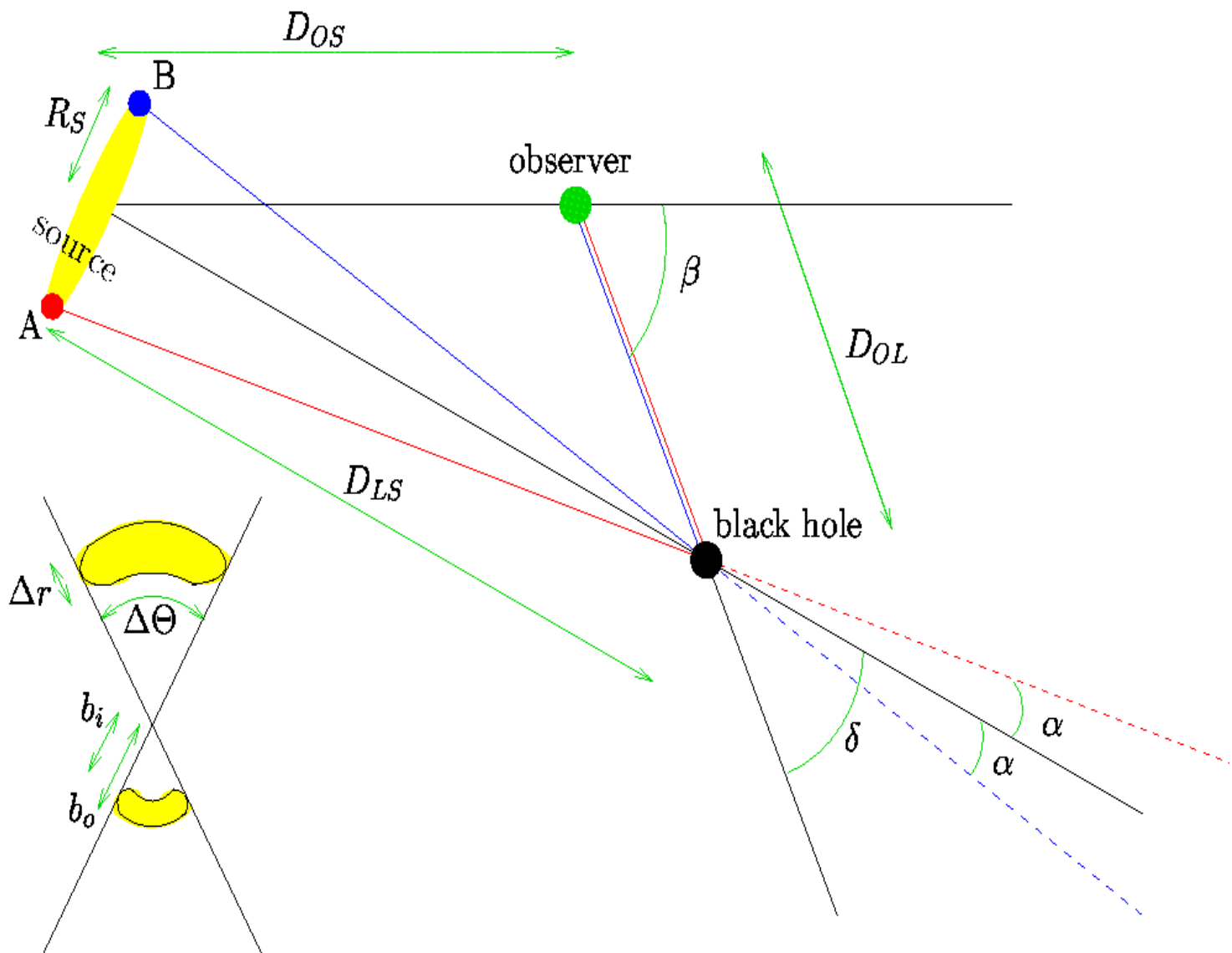


FIG. 2.— Imperfect alignment: the source, observer, and lens are not colinear. Pairs of images are produced, centered on the source–observer–lens plane, on opposite sides of the lens (see inset).

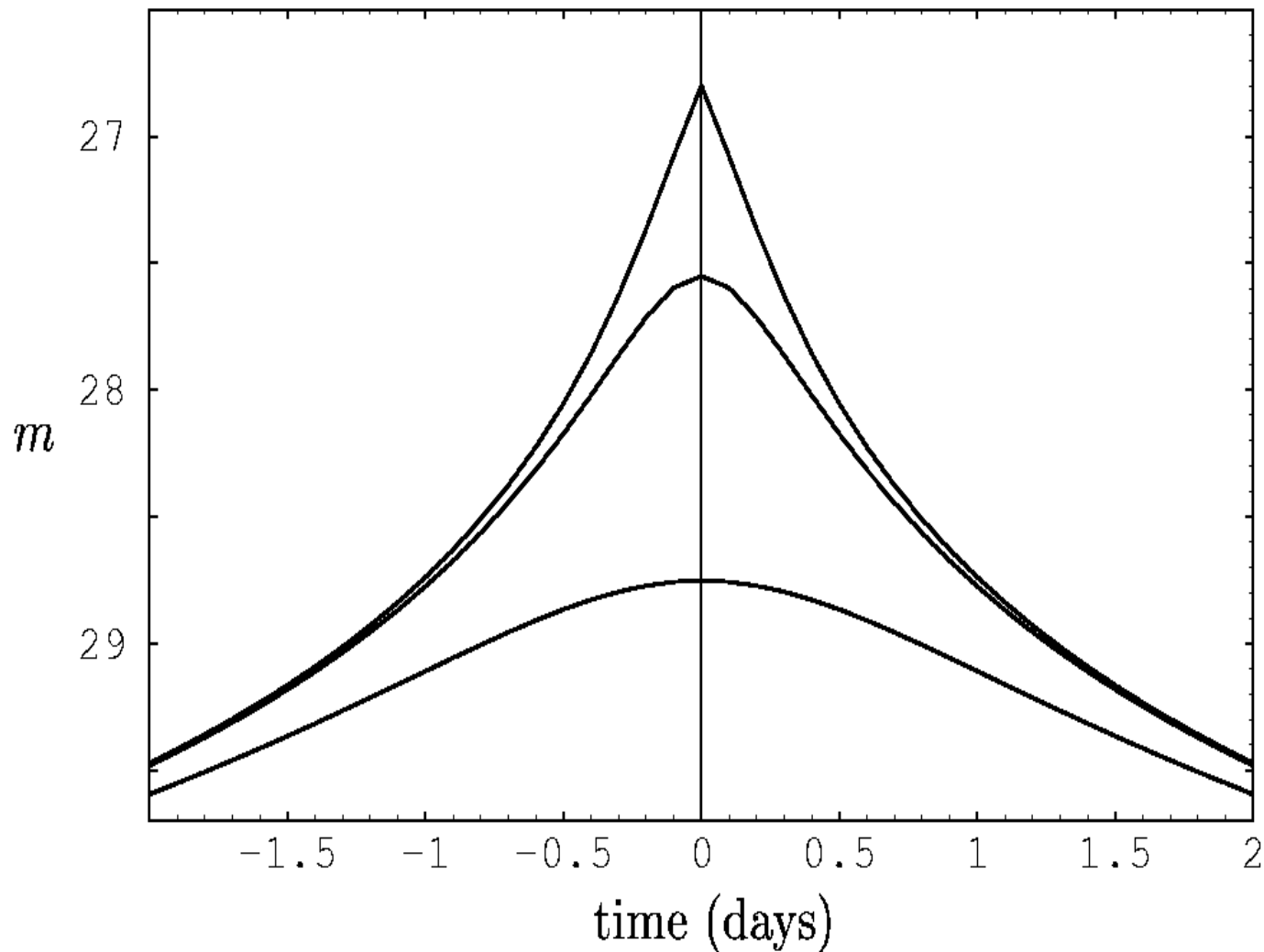


FIG. 3.— Solar retro-MACHO lightcurves: The apparent visual magnitude, m , of the Sun, imaged in a $10 M_{\odot}$ black hole at a distance of 0.01 pc. The different curves are for the black hole at angular displacements from the ecliptic plane of 0, $R_{\odot}/1 \text{ AU}$, and 1° respectively (top to bottom).

TABLE 1
RETRO-MACHO BRIGHTNESSES OF THE SUN

BH mass (M_{\odot})	BH distance (pc)	$\beta = 0$ (perfect alignment)	$\beta = R_{\odot}/1 \text{ AU}$ (edge alignment)	$\beta = 1^{\circ}$	$\beta = \pi/4$	$\beta = \pi/2$ (max misalignment)
1	10^{-2}	31.0	32.6	34	38	38
1	10^{-1}	38.6	40.1	41	45	46
10	10^{-2}	26.1	27.6	29	33	33
10	10^{-1}	33.6	35.1	36	40	41
10	1	41.1	42.6	44	48	48

The full classification of geodesic types for Kerr metric is given by Zakharov (1986). As it was shown in this paper, there are three photon geodesic types: capture, scattering and critical curve which separates the first two sets. This classification fully depends only on two parameters $\xi = L_z/E$ and $\eta = Q/E^2$, which are known as Chandrasekhar's constants (Chandrasekhar 1983). Here the Carter constant Q is given by Carter (1968)

$$Q = p_\theta^2 + \cos^2 \theta [a^2 (m^2 - E^2) + L_z^2/\sin^2 \theta], \quad (1)$$

where $E = p_t$ is the particle energy at infinity, $L_z = p_\phi$ is z -component of its angular momentum, $m = p_i p^i$ is the particle mass. Therefore, since photons have $m = 0$

$$\eta = p_\theta^2/E^2 + \cos^2 \theta [-a^2 + \xi^2/\sin^2 \theta]. \quad (2)$$

The first integral for the equation of photon motion (isotropic geodesics) for a radial coordinate in the Kerr metric is described by the following equation (Carter 1968; Chandrasekhar 1983; Zakharov 1986, 1991a)

$$\rho^4 (dr/d\lambda)^2 = R(r),$$

where

$$R(r) = r^4 + (a^2 - \xi^2 - \eta)r^2 + 2[\eta + (\xi - a)^2]r - a^2\eta, \quad (3)$$

and $\rho^2 = r^2 + a^2 \cos^2 \theta$, $\Delta = r^2 - 2r + a^2$, $a = S/M^2$. The constants M and S are the black hole mass and angular momentum, respectively. Eq. (3) is written in dimensionless variables (all lengths are expressed in black hole mass units M).

If we fix a black hole spin parameter a and consider a plane (ξ, η) and different types of photon trajectories corresponding to (ξ, η) , namely, a capture region, a scatter region and the critical curve $\eta_{\text{crit}}(\xi)$ separating the scatter and capture regions. The critical curve is a set of (ξ, η) where the polynomial $R(r)$ has a multiple root (a double root for this case). Thus, the critical curve $\eta_{\text{crit}}(\xi)$ could be determined from the system (Zakharov 1986, 1991a)

$$\begin{aligned} R(r) &= 0, \\ \frac{\partial R}{\partial r}(r) &= 0, \end{aligned} \tag{4}$$

for $\eta \geq 0, r \geq r_+ = 1 + \sqrt{1 - a^2}$, because by analysing of trajectories along the θ coordinate we know that for $\eta < 0$ we have $M = \{(\xi, \eta) | \eta \geq -a^2 + 2a|\xi| - \xi^2, -a \leq \xi \leq a\}$ and for each point $(\xi, \eta) \in M$ photons will be captured. If instead $\eta < 0$ and $(\xi, \eta) \notin M$, photons cannot have such constants of motion, corresponding to the forbidden region (see, (Chandrasekhar 1983; Zakharov 1986) for details).

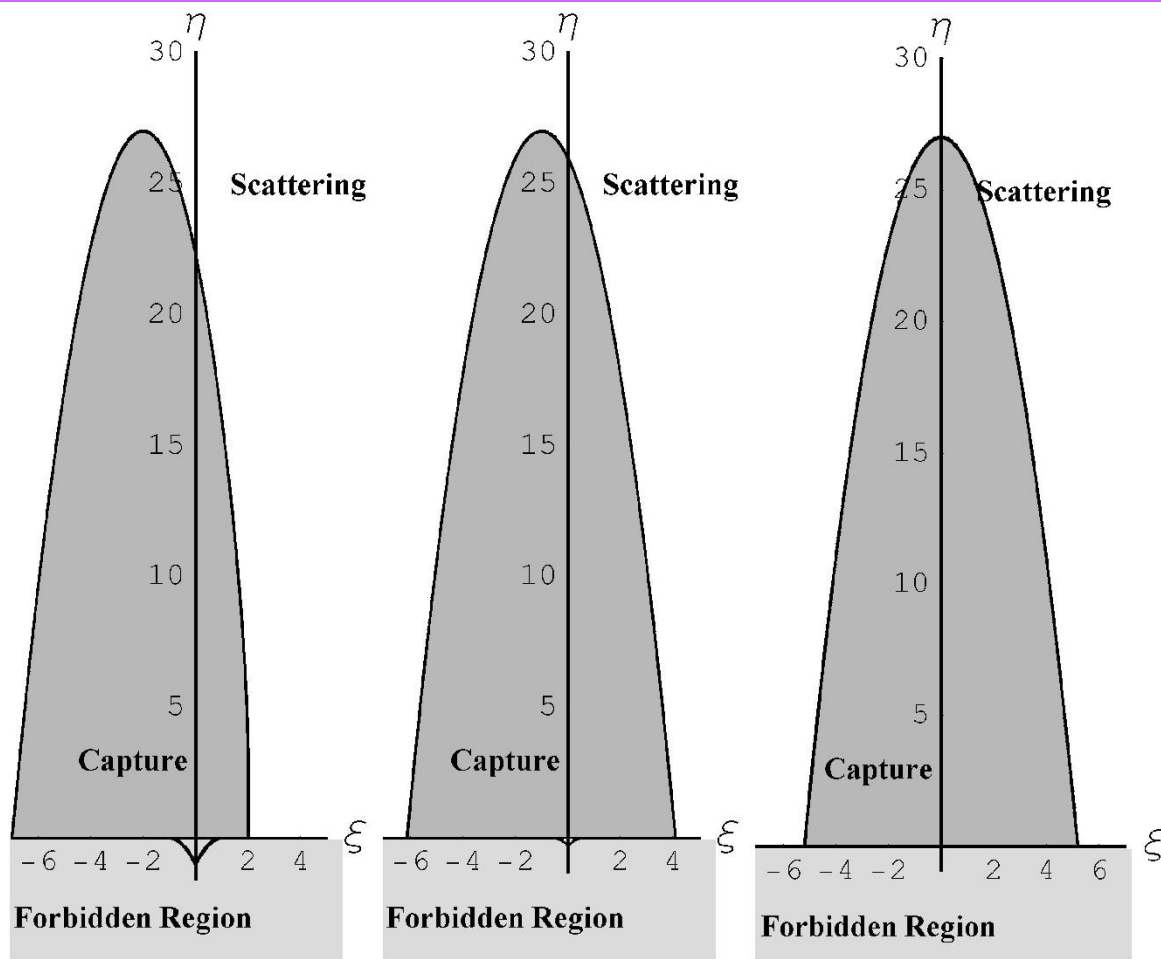


Fig. 1. Different types for photon trajectories and spin parameters ($a = 1, a = 0.5, a = 0$). Critical curves separate capture and scatter regions. Here we show also the forbidden region corresponding to constants of motion $\eta < 0$ and $(\xi, \eta) \in M$ as it was discussed in the text.

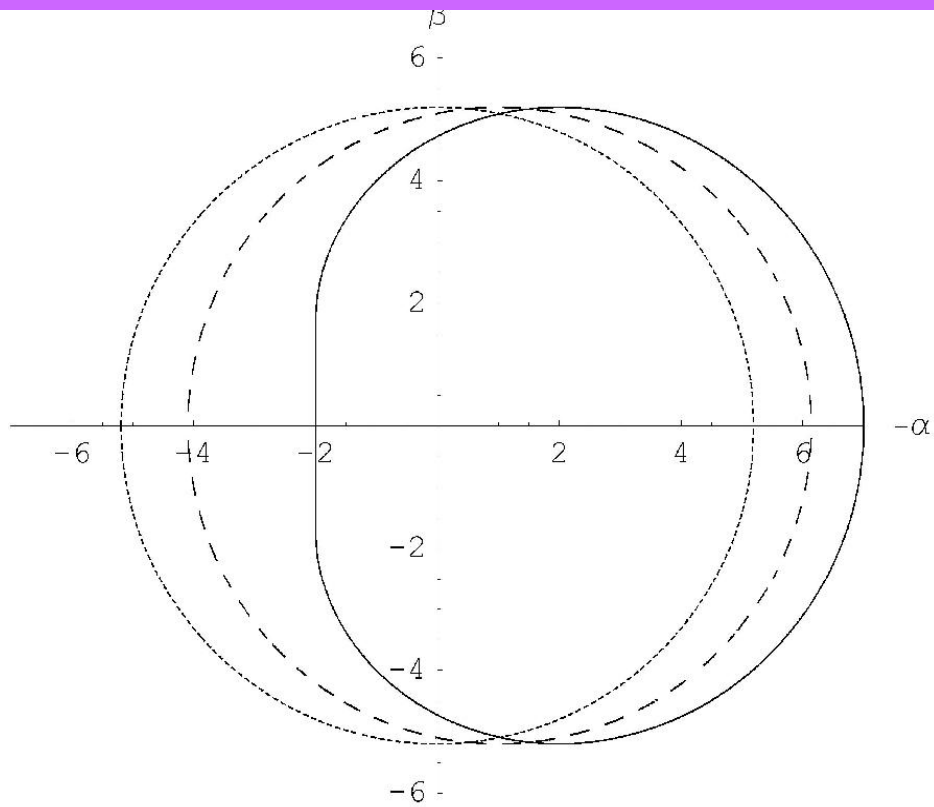


Fig. 2. Mirages around black hole for equatorial position of distant observer and different spin parameters. The solid line, the dashed line and the dotted line correspond to $a = 1$, $a = 0.5$, $a = 0$ correspondingly

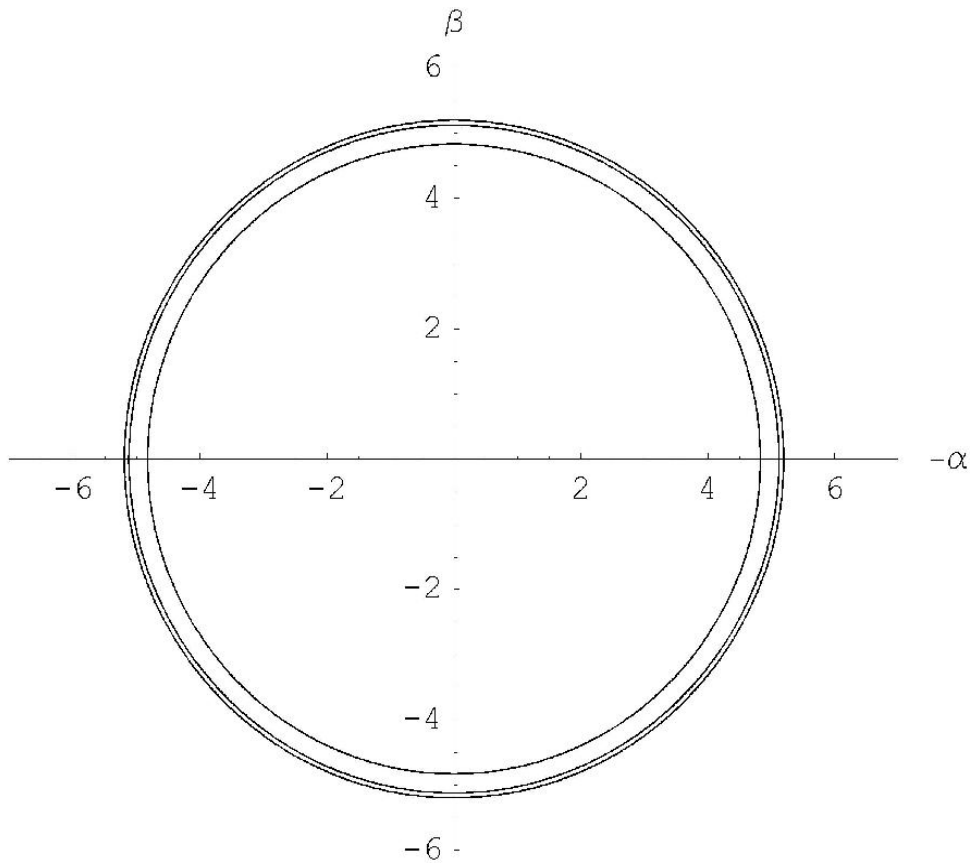


Fig. 3. Mirages around a black hole for the polar axis position of distant observer and different spin parameters ($a = 0, a = 0.5, a = 1$). Smaller radii correspond to greater spin parameters.

Table 1. Dependence of $\eta(0)$ and mirage radii $R_{\text{circ}} = (\eta(0) + a^2)^{1/2}$ on spins.

a	0	0.2	0.4	0.5	0.6	0.8	1.
$\eta(0)$	27	26.839	26.348	25.970	25.495	24.210	22.314
R_{circ}	5.196	5.185	5.149	5.121	5.085	4.985	4.828

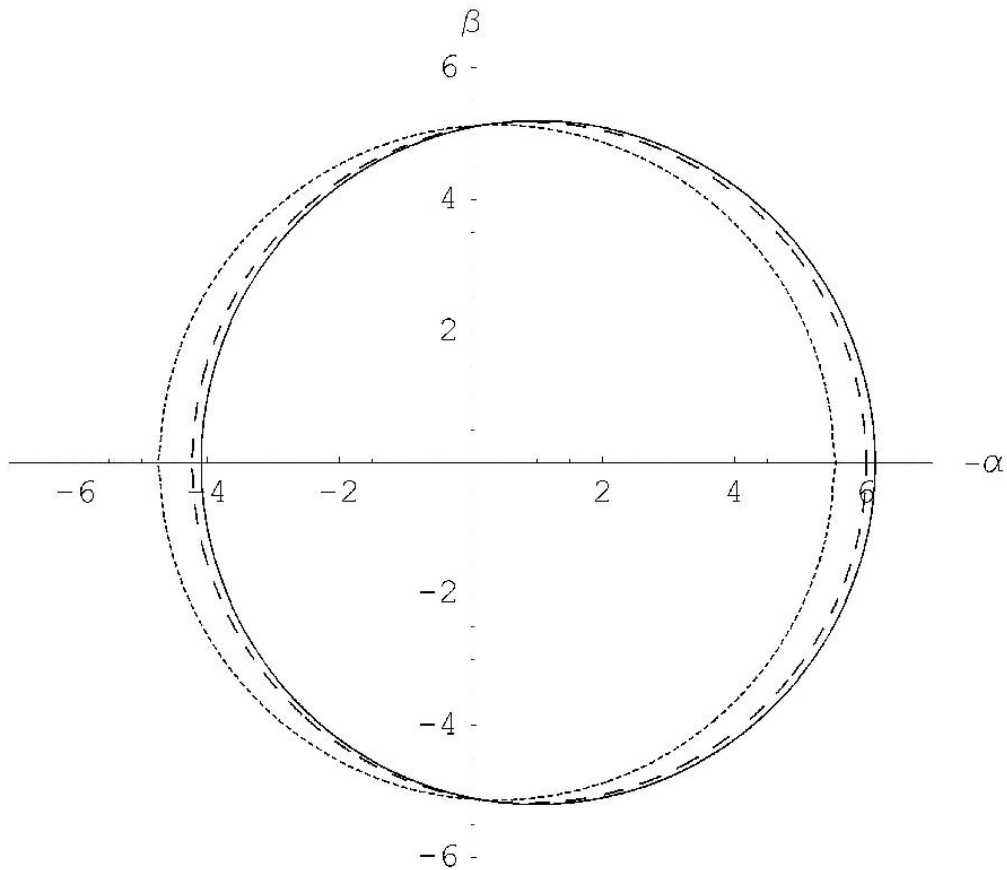


Fig. 4. Mirages around black hole for different angular positions of a distant observer and the spin $a = 0.5$. Solid, dashed and dotted lines correspond to $\theta_0 = \pi/2, \pi/3$ and $\pi/8$, respectively.

- **gr-qc/0604093, April 21, 2006**
 - Title: **Kerr black hole lensing for generic observers in the strong deflection limit**
 - Authors: V. Bozza, F. De Luca, G. Scarpetta

found by Carter [9]

$$\begin{aligned} \pm \int \frac{dx}{\sqrt{R}} &= \pm \int \frac{d\theta}{\sqrt{\Theta}} \quad (4) \\ \phi_f - \phi_i &= a \int \frac{x^2 + a^2 - aJ}{\Delta\sqrt{R}} dx - a \int \frac{dx}{\sqrt{R}} \\ &\quad + J \int \frac{\csc^2 \theta}{\sqrt{\Theta}} d\theta, \quad (5) \end{aligned}$$

where

$$\Theta = Q + a^2 \cos^2 \theta - J^2 \cot^2 \theta \quad (6)$$

$$\begin{aligned} R = x^4 + (a^2 - J^2 - Q)x^2 + (Q + (J - a)^2)x \\ - a^2 Q, \quad (7) \end{aligned}$$

and ϕ_i is the initial value of the azimuthal coordinate of the photon.

The roots of R represent inversion points in the radial motion. In gravitational lensing we consider photons coming from infinity, grazing the black hole and going back to infinity. For such trajectories there is only one inversion point x_0 , representing the closest approach distance. The minimum allowed value of x_0 can be found solving the equations $R(x) = 0$ and $R'(x) = 0$ simultaneously. However, in Kerr black hole, we do not have a unique minimum closest approach x_m , but rather a continuous family of values which depend on the approach trajectory followed by the photon. In particular, it is possible to establish a relation among the minimum closest approach x_m and the corresponding values of the constants of motion J and Q , that we shall indicate by J_m and Q_m (see e.g. Ref. [21])

$$J_m = \frac{x_m^2(2x_m - 3) + a^2(1 + 2x_m)}{a(1 - 2x_m)} \quad (8)$$

$$Q_m = \frac{x_m^3 [2a^2 - x_m(x_m - 3/2)^2]}{a^2(x_m - 1/2)^2}. \quad (9)$$

x_m also represents the radius of the unstable circular photon orbit. This radius is fixed to $3/2$ when $a = 0$ (Schwarzschild black hole). In the case of Kerr black holes, x_m may vary between two limiting values x_{m+} , x_{m-} , depending on the incoming direction of the photon. The two limiting values can be analytically obtained solving the equation $Q_m = 0$. To the third order in a , they read [16]

$$x_{m\pm} = \frac{3}{2} \mp \frac{2}{\sqrt{3}}a - \frac{4}{9}a^2 \mp \frac{20}{27\sqrt{3}}a^3 + O(a^4). \quad (10)$$

For example, photons whose orbit lies on the equatorial plane may turn either in the same sense of the black hole (prograde photons) or in the opposite sense (retrograde photons). Prograde photons are allowed to get closer to the black hole, with a minimum closest approach given by x_{m+} , while retrograde photons must stay farther than x_{m-} , in order to be deflected without falling into the black hole. Photons whose orbit does not lie

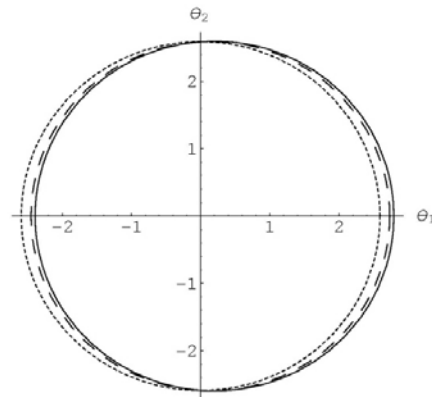


FIG. 2: The shadow of the black hole in the observer sky for $a = 0.1$ and different values of the observer position θ_o . The solid line is for $\theta_o = \pi/2$ (equatorial observer), the dashed line is for $\theta_o = \pi/4$ and the dotted line is for $\theta_o = 0$ (polar observer).

on the equatorial plane are characterized by intermediate values of x_m , with $Q_m > 0$. Thus x_m can be used to parametrize the family of unstable photon orbits allowed in Kerr metric or, equivalently, the incoming direction of the photon. The corresponding values of the constants of motion are uniquely determined by Eqs. (8) and (9).

Although exact expressions for x_{m+} and x_{m-} are available, it is convenient to start with a perturbative expansion *ab initio* in order to be prepared to face more complicated quantities in the following [16]. Throughout our treatment, only for x_m we need to push the expansion to the third order, in order to obtain some quantities to the second order in a .

III. THE SHADOW OF A KERR BLACK HOLE

The constants of motion J and Q have an immediate link to the position in the sky where the observer detects the photon. In fact, we can define angular coordinates (θ_1, θ_2) on the observer sky centered on the black hole position. We choose the orientation of these coordinates in such a way that the spin axis of the black hole is projected on the θ_2 -axis (see Fig.2).

As shown in Ref. [21], photons detected by the observer at angular coordinates (θ_1, θ_2) are characterized by constants of motion given by

$$J = -\theta_1 D_{OL} \sqrt{1 - \mu_o^2}, \quad (11)$$

$$Q = \theta_2^2 D_{OL}^2 + \mu_o^2 (\theta_1^2 D_{OL}^2 - a^2). \quad (12)$$

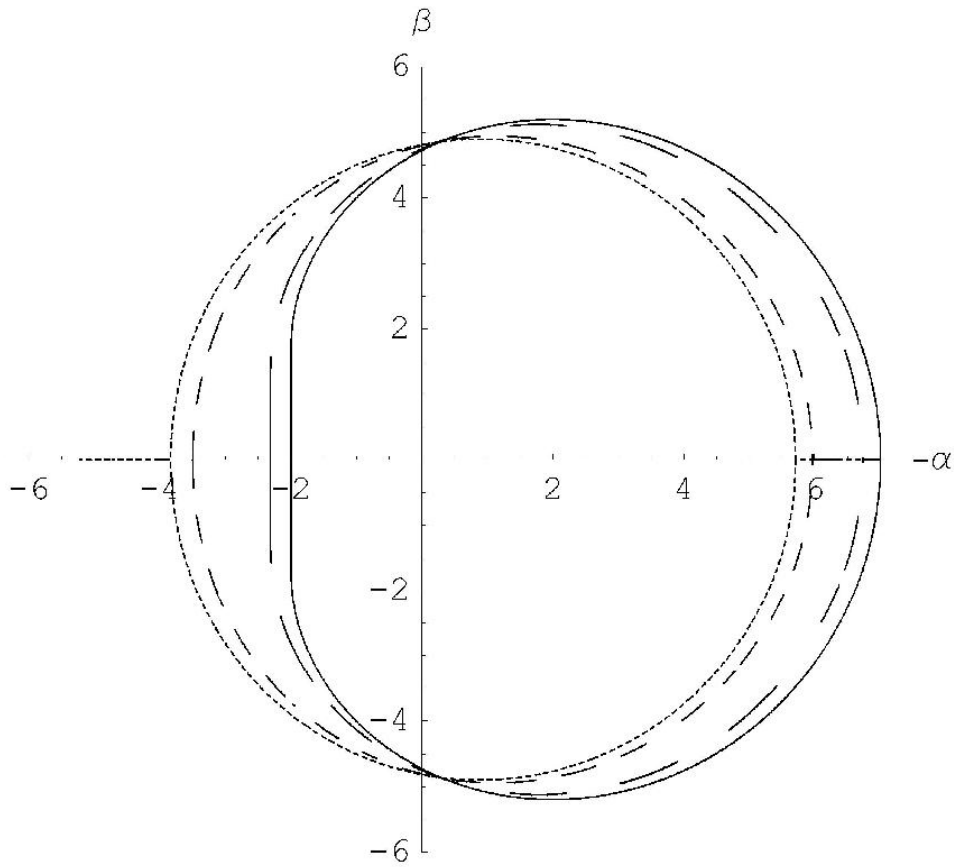


Fig. 5. Mirages around black hole for different angular positions of a distant observer and the spin $a = 1$. Solid, long dashed, short dashed and dotted lines correspond to $\theta_0 = \pi/2, \pi/3, \pi/6$ and $\pi/8$, respectively.

Direct Measurements of Black Hole Charge with Future Astrometrical Missions

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Received / accepted

Abstract. Recently, Zakharov et al. (2005a) considered the possibility of evaluating the spin parameter and the inclination angle for Kerr black holes in nearby galactic centers by using future advanced astrometrical instruments. A similar approach which uses the characteristic properties of gravitational retro-lensing images can be followed to measure the charge of Reissner-Nordström black hole. Indeed, in spite of the fact that their formation might be problematic, charged black holes are objects of intensive investigations. From the theoretical point of view it is well-known that a black hole is described by only three parameters, namely, its mass M , angular momentum J and charge Q . Therefore, it would be important to have a method for measuring all these parameters, preferably by model independent way. In this paper, we propose a procedure to measure the black hole charge by using the size of the retro-lensing images that can be revealed by future astrometrical missions. A discussion of the Kerr-Newmann black hole case is also offered.

In this paper we focus on the possibility to measure the black hole charge as well and we present an analytical dependence of mirage size on the black hole charge. Indeed, future space missions like Radioastron in radio band or MAXIM in X-ray band have angular resolution close to the shadow size for massive black holes in the center of our and nearby galaxies.

2. Basic Definitions and Equations

The expression for the Reissner - Nordström metric in natural units ($G = c = 1$) has the form

$$ds^2 = -(1 - 2M/r + Q^2/r^2)dt^2 + (1 - 2M/r + Q^2/r^2)^{-1}dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2). \quad (1)$$

$$R(r_{max}) = 0, \quad \frac{\partial R}{\partial r}(r_{max}) = 0, \quad (6)$$

as it was done, for example, by Chandrasekhar (1983) to solve similar problems.

Introducing the notation $\xi^2 = l$, $Q^2 = q$, we obtain

$$R(r) = r^4 - lr^2 + 2lr - qr. \quad (7)$$

The discriminant Δ of the polynomial $R(r)$ has the form (as it was shown by Zakharov (1991a,b, 1994a)):

$$\Delta = 16l^3[l^2(1 - q) + l(-8q^2 + 36q - 27) - 16q^3]. \quad (8)$$

The polynomial $R(r)$ thus has a multiple root if and only if

$$l^3[l^2(1 - q) + l(-8q^2 + 36q - 27) - 16q^3] = 0. \quad (9)$$

Excluding the case $l = 0$, which corresponds to a multiple root at $r = 0$, we find that the polynomial $R(r)$ has a multiple root for $r \geq r_+$ if and only if

$$l^2(1 - q) + l(-8q^2 + 36q - 27) - 16q^3 = 0. \quad (10)$$

If $q = 0$, we obtain the well-known result for a Schwarzschild black hole (Misner, Thorne and Wheeler 1973; Wald 1984; Lightman et al. 1975), $l = 27$, or $L_{cr} = 3\sqrt{3}$. If $q = 1$, then $l = 16$, or $L_{cr} = 4$, which also corresponds to numerical results given by Young (1976).

The photon capture cross section for an extreme charged black hole turns out to be considerably smaller than the capture cross section of a Schwarzschild black hole. The critical value of the impact parameter, characterizing the capture cross section for a Reissner - Nordström black hole, is determined by the equation (Zakharov 1991a,b, 1994a)

$$l = \frac{(8q^2 - 36q + 27) + \sqrt{(8q^2 - 36q + 27)^2 + 64q^3(1 - q)}}{2(1 - q)}. \quad (11)$$

A.F. Zakharov & F. De Paolis, A.A. Nucita, G.Ingrosso, **Astron. & Astrophys., 442, 795 (2005)**

As it was explained by Zakharov et al. (2005a,b) this leads to the formation of shadows described by the critical value of L_{cr} or, in other words, in the spherically symmetric case, shadows are circles with radii L_{cr} . Therefore, measuring the shadow size, one could evaluate the black hole charge in black hole mass units M .

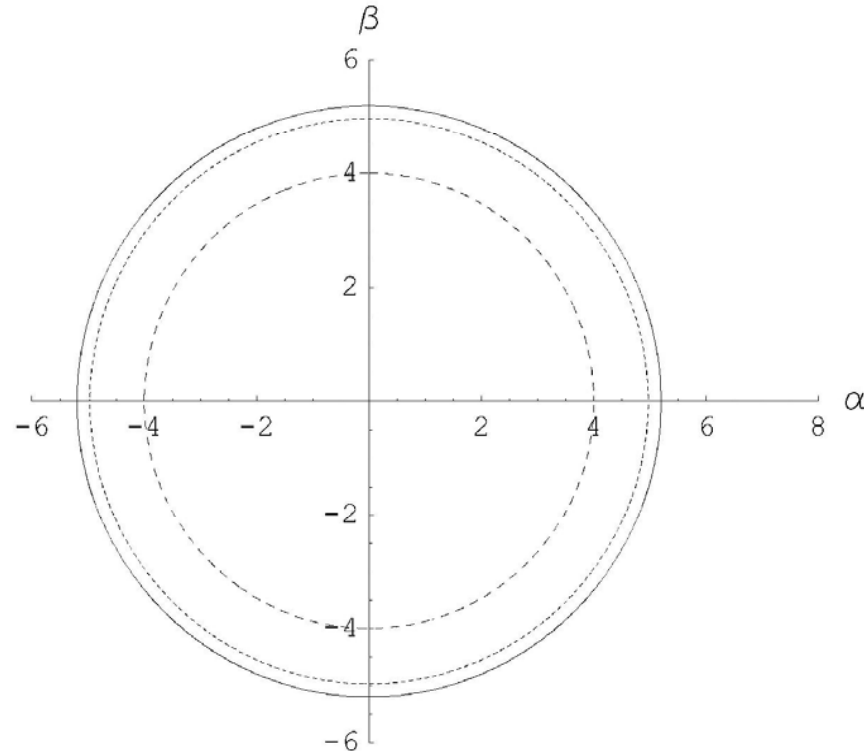
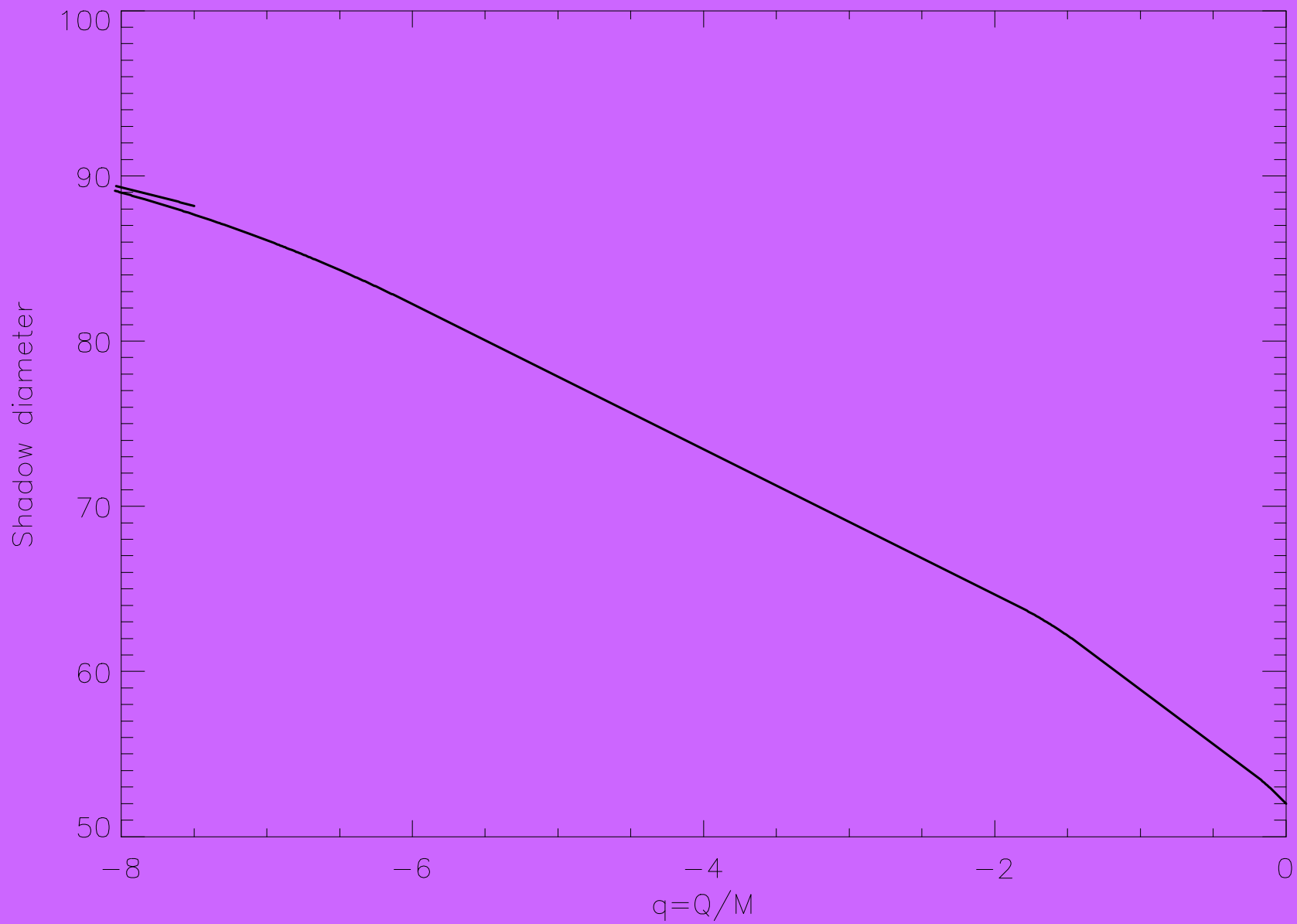


Fig. 1. Shadow (mirage) sizes are shown for selected charges of black holes $Q = 0$ (solid line), $Q = 0.5$ (short dashed line) and $Q = 1$ (long dashed line).

Recently, Bin-Nun (2010) discussed an opportunity that the black hole at the Galactic Center is described by the tidal Reissner--Nordstrom metric which may be admitted by the Randall--Sundrum II braneworld scenario. Bin-Nun suggested an opportunity of evaluating the black hole metric analyzing (retro-)lensing of bright stars around the black hole in the Galactic Center. Doeleman et al. (2008) evaluated a shadow size for the black hole at the Galactic Center. Measurements of the shadow size around the black hole may help to evaluate parameters of black hole metric Zakharov et al (2005). We derive an analytic expression for the black hole shadow size as a function of charge for the tidal Reissner--Nordstrom metric. We conclude that observational data concerning shadow size measurements are not consistent with significant negative charges, in particular, the significant negative charge $Q/(4M^2)=-1.6$ (discussed by Bin-Nun (2010) is practically ruled out with a very probability (the charge is roughly speaking is beyond 9σ confidence level, but a negative charge is beyond 3σ confidence level).



Наша галактика вращается вокруг чёрной дыры



В четверг китайские астрономы заявили, что в самом центре нашей галактики находится чёрная дыра.

Как пишет журнал «Нэйчер», таинственный объект под названием «Стрелец-А» давно был известен ученым. Однако только сейчас с помощью новейших радиотелескопов было доказано, что это — чёрная дыра.

Уже подсчитано, что «Стрелец» в несколько миллионов раз тяжелее Солнца, и может легко поглощать соседние космические тела. Впрочем, как заверяют астрономы, для нашей планеты он не опасен — от Земли до центра галактики слишком большое расстояние, почти 30 тысяч световых лет.

LETTERS

A size of ~ 1 AU for the radio source Sgr A* at the centre of the Milky Way

Zhi-Qiang Shen¹, K. Y. Lo², M.-C. Liang³, Paul T. P. Ho^{4,5} & J.-H. Zhao⁴

Although it is widely accepted that most galaxies have super-massive black holes at their centres^{1–3}, concrete proof has proved elusive. Sagittarius A* (Sgr A*), an extremely compact radio source at the centre of our Galaxy, is the best candidate for proof^{4–7}, because it is the closest. Previous very-long-baseline interferometry observations (at 7 mm wavelength) reported that Sgr A* is ~ 2 astronomical units (AU) in size⁸, but this is still larger than the ‘shadow’ (a remarkably dim inner region encircled by a bright ring) that should arise from general relativistic effects near the event horizon of the black hole⁹. Moreover, the measured size is wavelength dependent¹⁰. Here we report a radio image of Sgr A* at a wavelength of 3.5 mm, demonstrating that its size is ~ 1 AU. When combined with the lower limit on its mass¹¹, the lower limit on the mass density is $6.5 \times 10^{21} M_{\odot} \text{pc}^{-3}$ (where M_{\odot} is the solar mass), which provides strong evidence that Sgr A* is a super-massive black hole. The power-law relationship between wavelength and intrinsic size (size \propto wavelength^{1.09}) explicitly rules out explanations other than those emission models with stratified structure, which predict a smaller emitting region observed at a shorter radio wavelength.

Past very-long-baseline interferometry (VLBI) observations^{12–16} of Sgr A* have revealed an east–west elongated structure whose apparent angular size at longer wavelengths is dominated by the interstellar scattering angle, that is, $\theta_{\text{obs}} = \theta_{\text{obs}}^{\text{cm}} \lambda^2$, where θ_{obs} is the observed size in milliarcseconds (mas) at wavelength λ in cm, and equals $\theta_{\text{obs}}^{\text{cm}}$ at 1 cm. Thus, VLBI observations at shorter millimetre wavelengths, where the intrinsic structure of Sgr A* could become comparable to the pure scattering size, are expected to show deviations of the observed size from the scattering law. This has been demonstrated by the recent detection of the intrinsic size at 7 mm (ref. 8). On 20 November 2002, we successfully carried out an observation of Sgr A* with the Very Long Baseline Array (VLBA) at its shortest wavelength of 3.5 mm (ref. 10). Our observation, with the steadily improved performance of the VLBA system, has produced the first (to our knowledge) high-resolution image of Sgr A* made at 3.5 mm (Fig. 1), which exhibits an elongated structure too.

To yield a quantitative description of the observed structure, we tried a model fitting procedure¹⁷ in which the amplitude closure relation is applied. Compared to the conventional VLBI

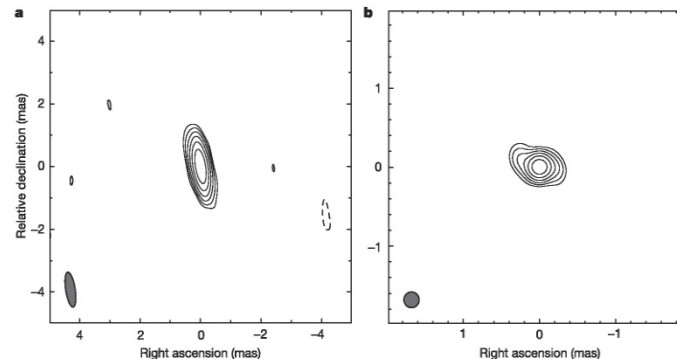


Figure 1 High-resolution VLBI image of Sgr A* at 3.5 mm obtained with the VLBA on 20 November 2002. The observations were flexibly scheduled to ensure good weather conditions at most sites, and the data were recorded at the highest possible recording rate of 512 Mbit s⁻¹. Standard visibility amplitude calibration including the elevation-dependent opacity correction was done, and the final image was obtained after several iterations of the self-calibration and cleaning procedures. The calibrated total flux density is

about 1.2 Jy. **a**, A uniformly weighted image with the restoring beam (indicated at the lower left corner) of $1.13 \text{ mas} \times 0.32 \text{ mas}$ at 9° . The peak flux density is $1.08 \text{ Jy beam}^{-1}$. Contour levels are drawn at $3\sigma \times (-1, 1, 2, 4, 8, 16, 32)$; $3\sigma = 17.5 \text{ mJy beam}^{-1}$. **b**, A super-resolution image with a circular beam of 0.20 mas from which an east–west elongated structure can be seen (see Table 1). Note the different scales. The contour levels are the same as that in **a** with the corresponding peak flux density of $1.01 \text{ Jy beam}^{-1}$.

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LETTERS

Event-horizon-scale structure in the supermassive black hole candidate at the Galactic Centre

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The cores of most galaxies are thought to harbour supermassive black holes, which power galactic nuclei by converting the gravitational energy of accreting matter into radiation¹. Sagittarius A* (Sgr A*), the compact source of radio, infrared and X-ray emission at the centre of the Milky Way, is the closest example of this phenomenon, with an estimated black hole mass that is 4,000,000 times that of the Sun^{2,3}. A long-standing astronomical goal is to resolve structures in the innermost accretion flow surrounding Sgr A*, where strong gravitational fields will distort the appearance of radiation emitted near the black hole. Radio observations at wavelengths of 3.5 mm and 7 mm have detected intrinsic structure in Sgr A*, but the spatial resolution of observations at these wavelengths is limited by interstellar scattering^{4–7}. Here we report observations at a wavelength of 1.3 mm that set a size of 37_{-10}^{+16} microarcseconds on the intrinsic diameter of Sgr A*. This is less than the expected apparent size of the event horizon of the presumed black hole, suggesting that the bulk of Sgr A* emission may not be centred on the black hole, but arises in the surrounding accretion flow.

The proximity of Sgr A* makes the characteristic angular size scale of the Schwarzschild radius ($R_{\text{Sch}} = 2GM/c^2$) larger than for any other black hole candidate. At a distance of ~ 8 kpc (ref. 8), the Sgr A* Schwarzschild radius is 10 μas , or 0.1 astronomical unit (AU). Multi-wavelength monitoring campaigns^{9–11} indicate that activity on scales of a few R_{Sch} in Sgr A* is responsible for observed short-term variability and flaring from radio to X-rays, but direct observations of structure on these scales by any astronomical technique has not been possible. Very-long-baseline interferometry (VLBI) at 7 mm and 3.5 mm wavelength shows the intrinsic size of Sgr A* to have a wavelength dependence, which yields an extrapolated size at 1.3 mm of 20–40 μas (refs 6, 7). VLBI images at wavelengths longer than 1.3 mm, however, are dominated by interstellar scattering effects that broaden images of Sgr A*. Our group has been working to extend VLBI arrays to 1.3 mm wavelength, to reduce the effects of interstellar scattering, and to utilize long baselines to increase angular resolution with a goal of studying the structure of Sgr A* on scales commensurate with the putative event horizon of the black hole. Previous pioneering VLBI work at 1.4 mm wavelength detected Sgr A* on 980-km projected baselines, but calibration

uncertainties resulted in a range for the derived size of 50–170 μas (ref. 12).

On 10 and 11 April 2007, we observed Sgr A* at 1.3 mm wavelength with a three-station VLBI array consisting of the Arizona Radio Observatory 10-m Submillimetre Telescope (ARO/SMT) on Mount Graham in Arizona, one 10-m element of the Combined Array for Research in Millimeter-wave Astronomy (CARMA) in Eastern California, and the 15-m James Clerk Maxwell Telescope (JCMT) near the summit of Mauna Kea in Hawaii. A hydrogen maser time standard and high-speed VLBI recording system were installed at both the ARO/SMT and CARMA sites to support the observation. The JCMT partnered with the Submillimetre Array (SMA) on Mauna Kea, which housed the maser and the VLBI recording system and provided a maser-locked receiver reference to the JCMT. Two 480-MHz passbands sampled to two-bit precision were recorded at each site, an aggregate recording rate of 3.84×10^9 bits per second (Gbit s^{-1}). Standard VLBI practice is to search for detections over a range of interferometer delay and delay rate. Six bright quasars were detected with high signal to noise on all three baselines allowing array geometry, instrumental delays and frequency offsets to be accurately calibrated. This calibration greatly reduced the search space for detections of Sgr A*. All data were processed on the Mark4 correlator at the MIT Haystack Observatory in Massachusetts.

On both 10 and 11 April 2007, Sgr A* was robustly detected on the short ARO/SMT–CARMA baseline and the long ARO/SMT–JCMT baseline. On neither day was Sgr A* detected on the CARMA–JCMT baseline, which is attributable to the sensitivity of the CARMA station being about a third that of the ARO/SMT (owing to weather, receiver temperature and aperture efficiency). Table 1 lists the Sgr A* detections on the ARO/SMT–JCMT baseline. The high signal to noise ratio, coupled with the tight grouping of residual delays and delay rates, makes the detections robust and unambiguous.

There are too few visibility measurements to form an image by the usual Fourier transform techniques; hence, we fit models to the visibilities (shown in Fig. 1). We first modelled Sgr A* as a circular Gaussian brightness distribution, for which one expects a Gaussian relationship between correlated flux density and projected baseline length. The weighted least-squares best-fit model (Fig. 1) corresponds to a Gaussian with total flux density of 2.4 ± 0.5 Jy and full

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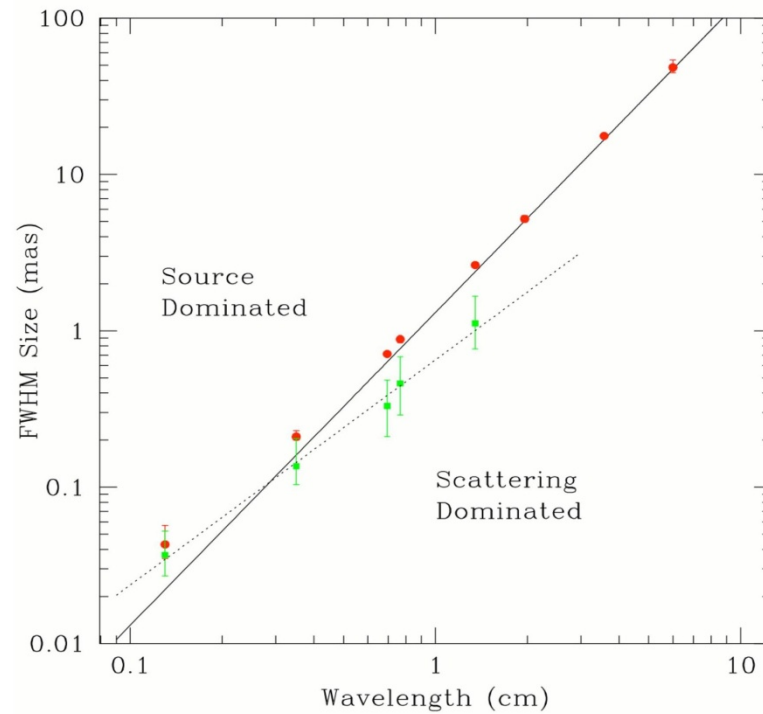


Fig 2

Figure 2 Observed and intrinsic size of Sgr A* as a function of wavelength. Red circles show major-axis observed sizes of Sgr A* from VLBI observations (all errors 3σ). Data from wavelengths of 6 cm to 7 mm are from ref. 13, data at 3.5 mm are from ref. 7, and data at 1.3 mm are from the observations reported here. The solid line is the best-fit λ^2 scattering law from ref. 13, and is derived from measurements made at $\lambda > 17$ cm. Below this line, measurements of the intrinsic size of Sgr A* are dominated by scattering effects, while measurements that fall above the line indicate intrinsic structures that are larger than the scattering size (a ‘source-dominated’ regime). Green points show derived major-axis intrinsic sizes from $2 \text{ cm} < \lambda < 1.3 \text{ mm}$ and are fitted with a λ^α power law ($\alpha = 1.44 \pm 0.07$, 1σ) shown as a dotted line. When the 1.3-mm point is removed from the fit, the power-law exponent becomes $\alpha = 1.56 \pm 0.11$ (1σ).

RADIO INTERFEROMETER MUCH LARGER THE EARTH

"SPECTR-R" (Mission "RadioAstron")

Main scientific tasks of the mission -

syntheses of high-precision images of various Universe objects, its coordinates measurements and search their variability with the time.
A fringe width of the system is up to 7 micro arc seconds.

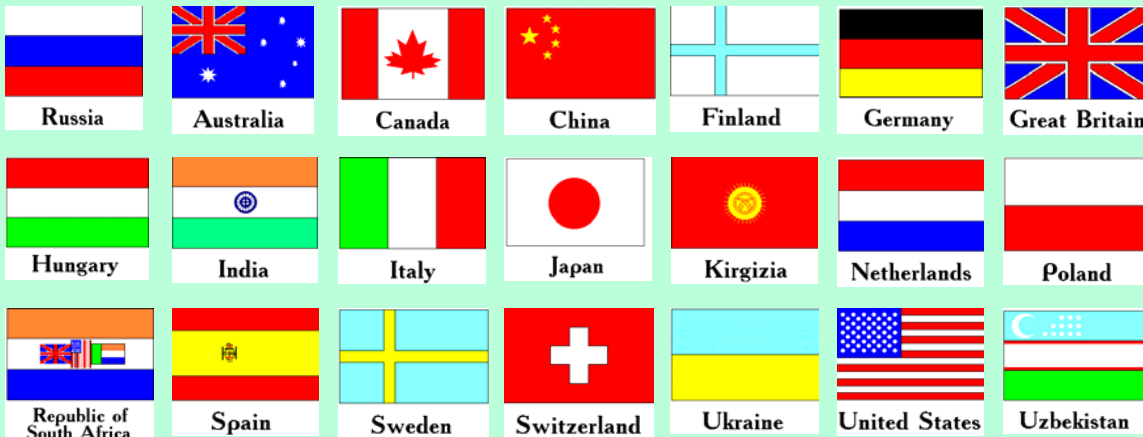
Main characteristics of the space radio telescope

Spectral band:

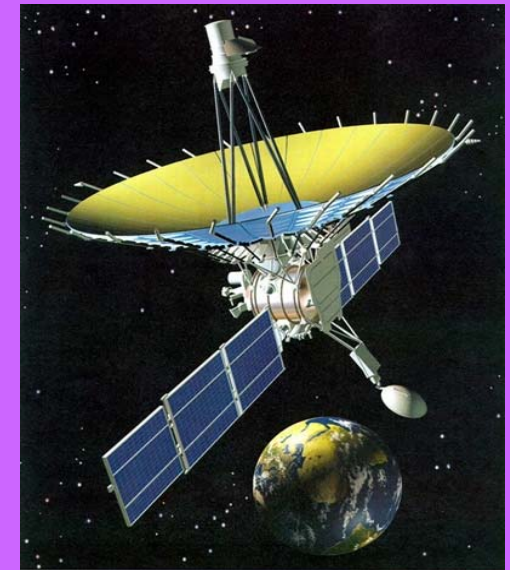
- wavelength (cm) - 92; 18; 6.2; 1.19-1.63
- frequency (GHz) - 0.327; 1.66; 4.83; 18-26

Main organizations:

on scientific complex - **Astro Space Center of Lebedev Physical Institute of Russian Academy of Science;**
of spacecraft - **Lavochkin Research Production Association of Russian Space Agency.**

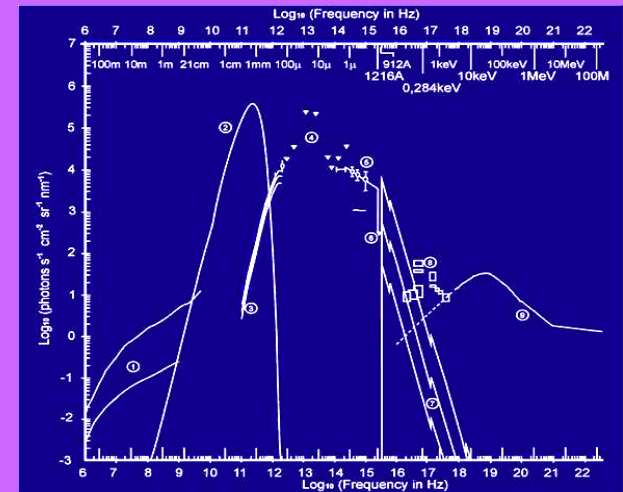


Planned launch date of the mission is **2007**.



The orbit of the mission :

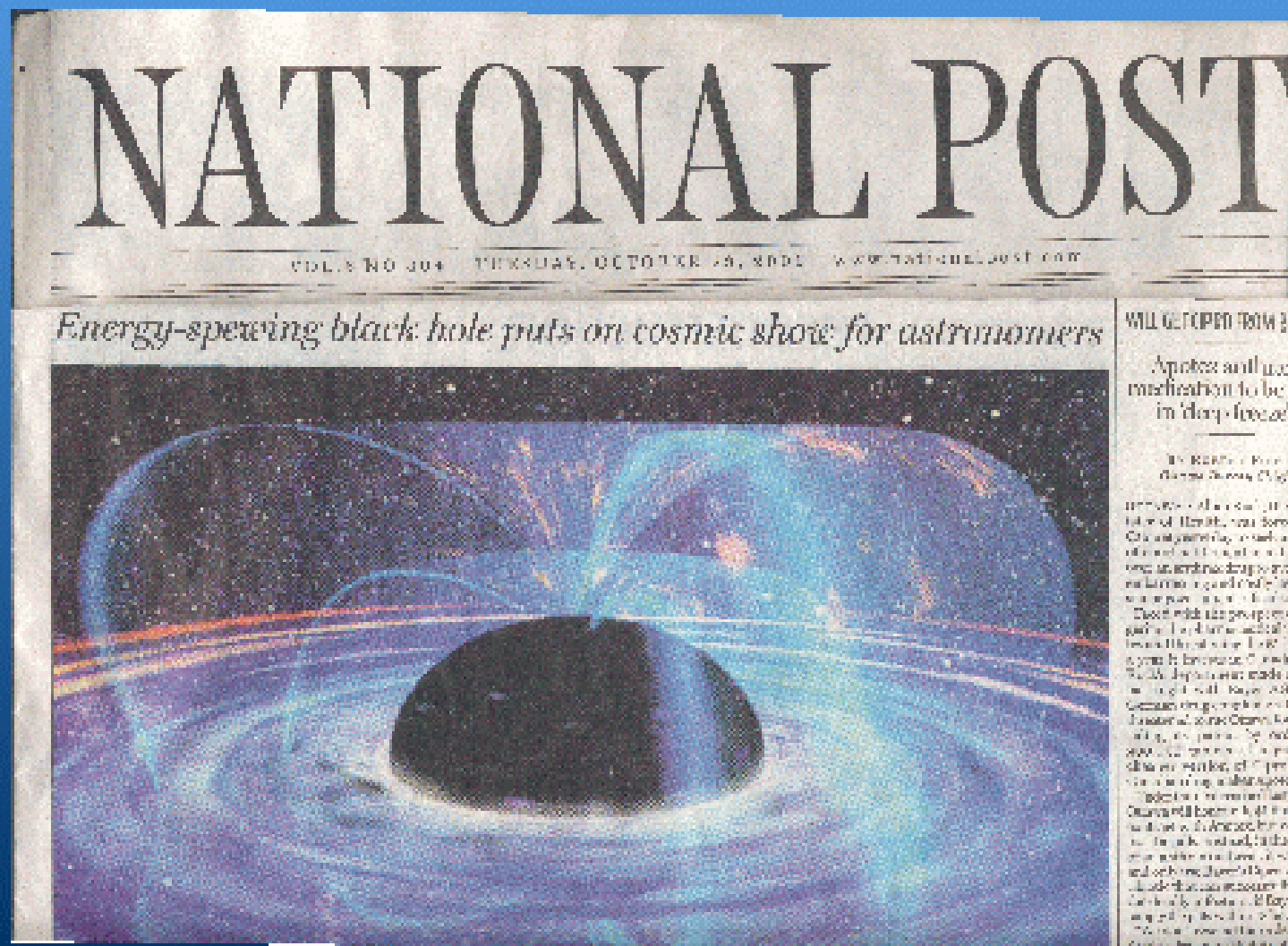
- apogee - 310 000 – 370 000 km
- perigee - 10 000 – 70 000 km
- declination - 51.6°
- period variation - 7 – 10 days
- Guaranteed time of activity - 5 years
- Scientific payload mass - 2100 kg
- Pointing accuracy of radio telescope - 35"

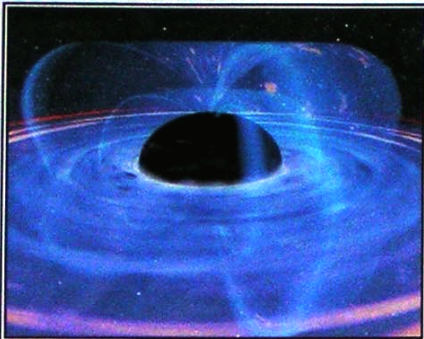




What is a black hole?

Everyone already seems to know!





学术报告

北京大学天文系
北京天体物理中心

Prof. Alexander Zakharov

**Institute of Theoretical and Experimental Physics,
Moscow, Russia**

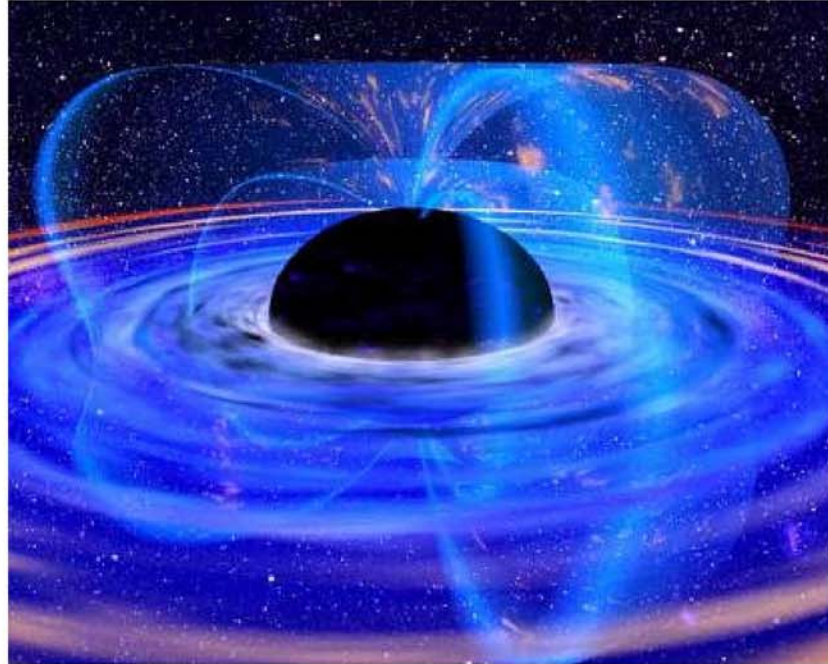
Measuring Parameters of Supermassive Black Holes with Present and Future Space Missions

时间: 2005年10月20日(星期四), 下午 3:30

地点: 北京大学理科二号楼 2907(天文系会议室)

欢迎参加

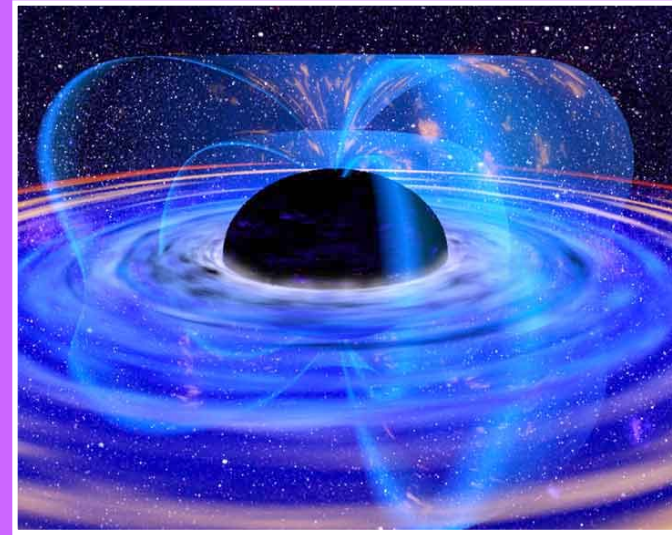
XMM-Newton observations of MCG-6-30-15 in the 2-10 keV band



Wilms et al 2002; Fabian et al 2002;
Vaughan et al 2002; Fabian & Vaughan
2002; Ballantyne et al 2003; Reynolds et al
2003; Vaughan & Fabian 2004

Understanding the spectral behaviour

What Makes them Black Holes



- Other than the classical Rees argument about **efficiency, size and luminosity** what observational properties make these objects black holes ?

- High mass in a small volume via direct measurements
SGR A*, NGC4258 etc
- Mass functions of stellar systems

For the vast majority of objects thought to be black holes such information is not available

- We must use indirect observational data
 - Spectra
 - Timing
 - Spectral/timing (reverberation mapping)
 - Imaging (micro-lensing)

Why are black hole interesting today

- Black Holes and Strong Gravity
 - Spectral and timing probes of strong gravity
 - Astrophysics in the strong gravity region
- AGN Winds & effect of BHs on cosmic structure
 - Outflows from AGN
 - Cooling flow and cluster entropy problems
 - Role of AGN in galaxy formation
- Evolution of AGN and SMBH growth
 - Paradigm shift in AGN evolution

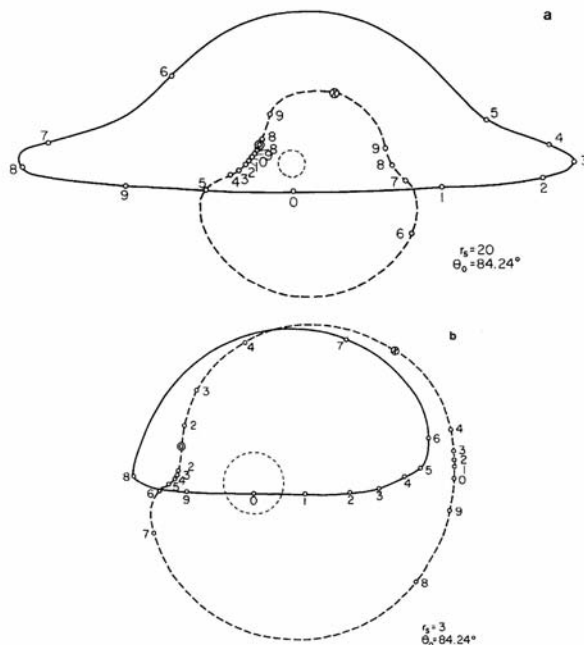


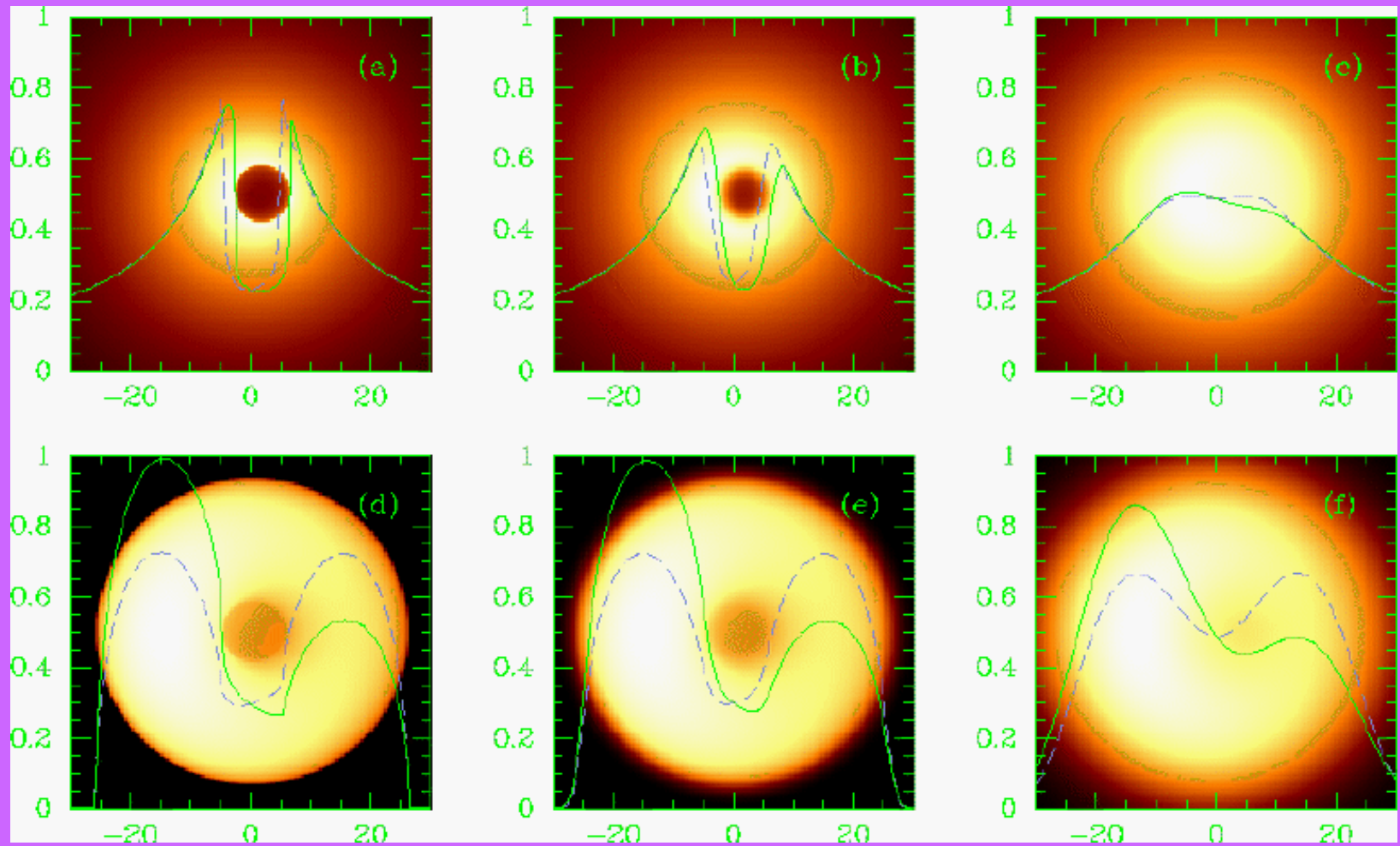
FIG. 8.—Apparent positions of the two brightest images as functions of time for two orbital radii and an observer at a polar angle $\theta_0 = 84^\circ 24'$. The small, dashed circle in each plot is the locus $\alpha^2 + \beta^2 = 1$ and gives the scale of the plot. The direct image moves along the solid line; the one-orbit image, along the dashed line. Ticks mark the positions of the images at 10 equally spaced times. A pair of one-orbit images appears to be created at the points @ and annihilated at the points X. See text.

fore of α) and the variation in surface brightness increase more rapidly for the one-orbit image than for the direct image as we consider stars of progressively smaller orbital radii.

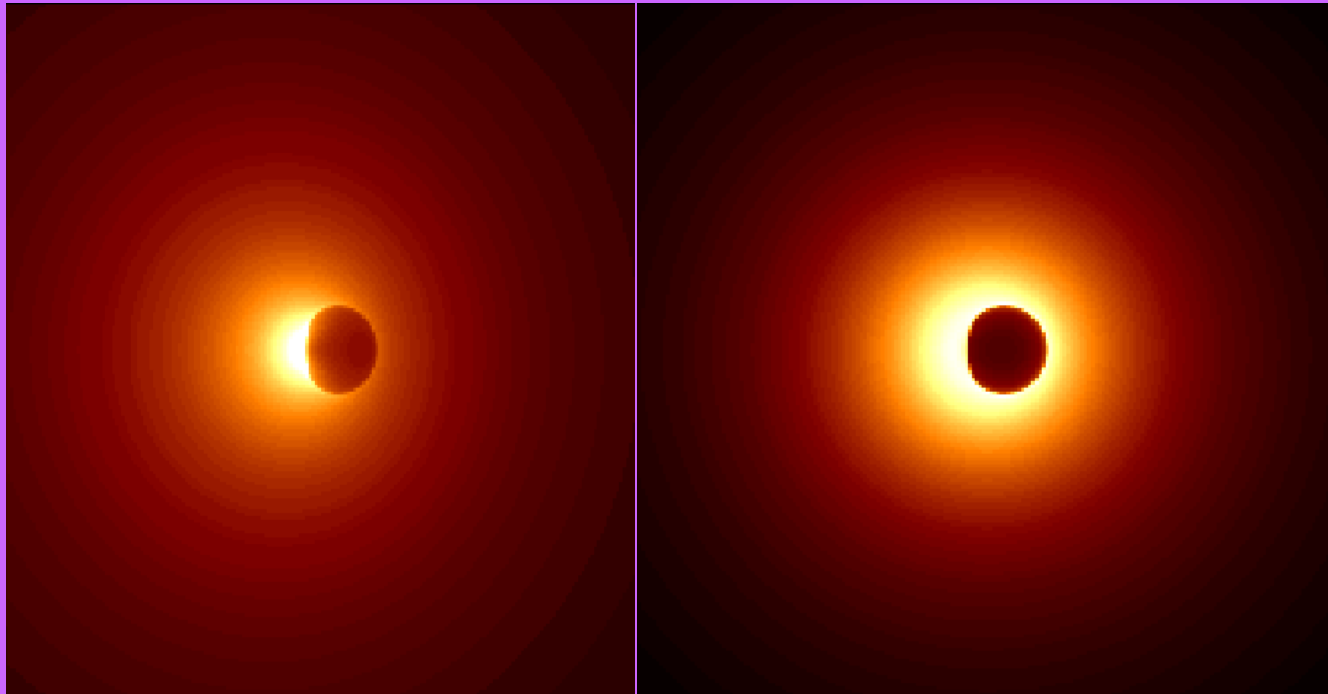
As the apparent position of the image seen by the distant observer changes, so does the corresponding direction of emission in the local rest frame of the star. If the instantaneous direction of emission of the beam of radiation which reaches the observer is represented by a point in figure 3 (for $r_s = 1.5$), this point moves along the $\cos \theta_0 = \text{const.}$ curve corresponding to the given type of image in the direction indicated by the arrows. Creation of pairs of images on the one-orbit curves is at the points marked @; destruction, at points X. For $r_s = 1.5$ there is no retrograde image and, hence, no creation and destruction of images for observers with $\theta_0 \leq 40^\circ$.

When r_s is not much larger than unity, the images move very slowly on the parts of the curves nearest the backward ϕ -direction and very rapidly on the remainder of the

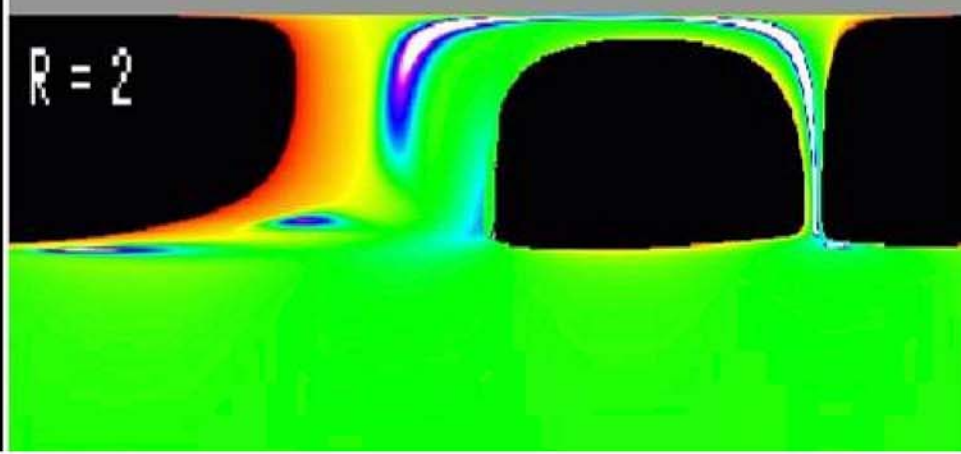
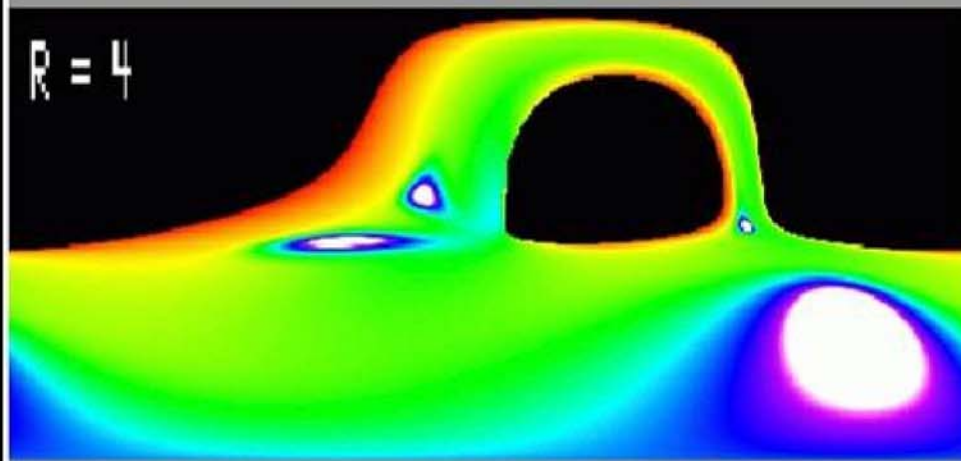
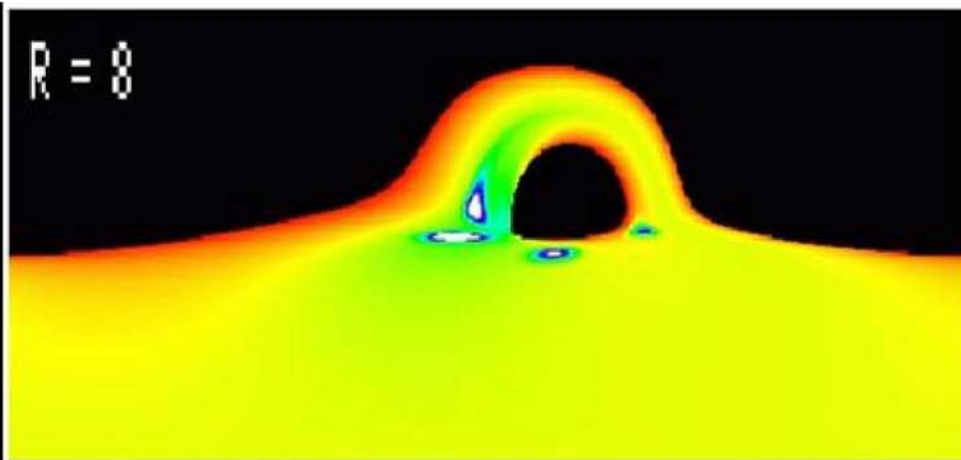
Falcke, Melia, Agol



Shadows from Melia



Kevin
Rauch
JHU

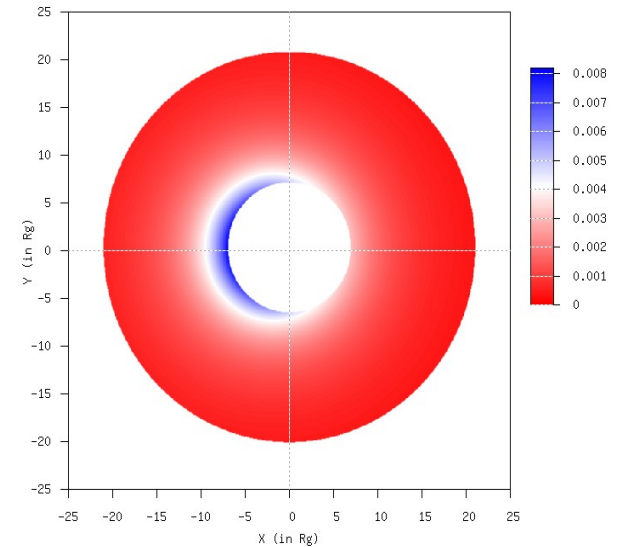
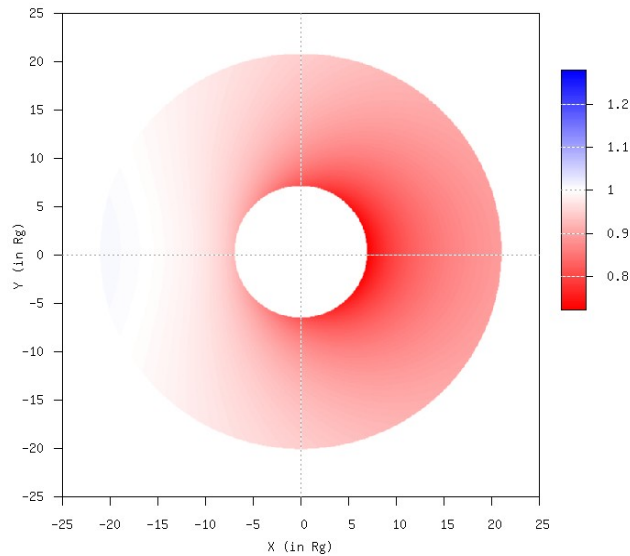


Schwarzschild black hole images

(P. Jovanovic , L.C. Popovic & A.F.Z. in preparation)

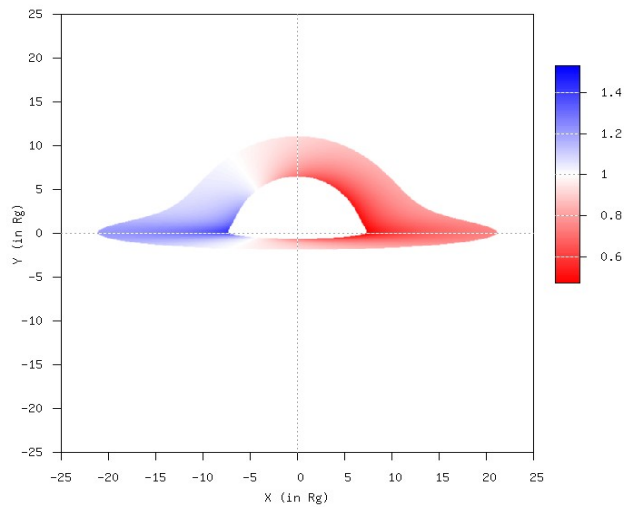
- $\theta=15$ deg
- Redshift map

Intensity map

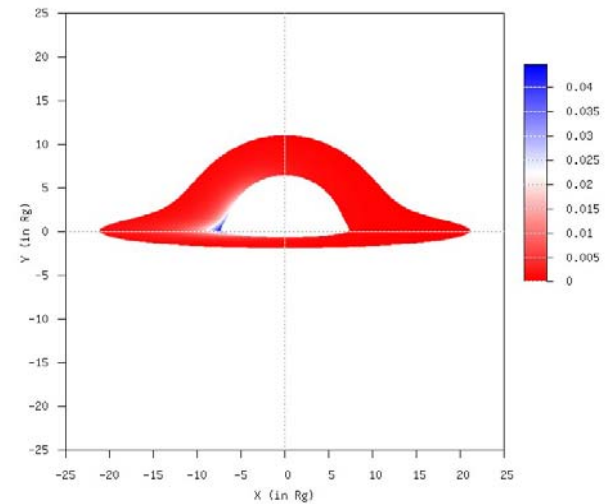


Schwarzschild black hole images: $\theta=85$ deg

- Redshift map

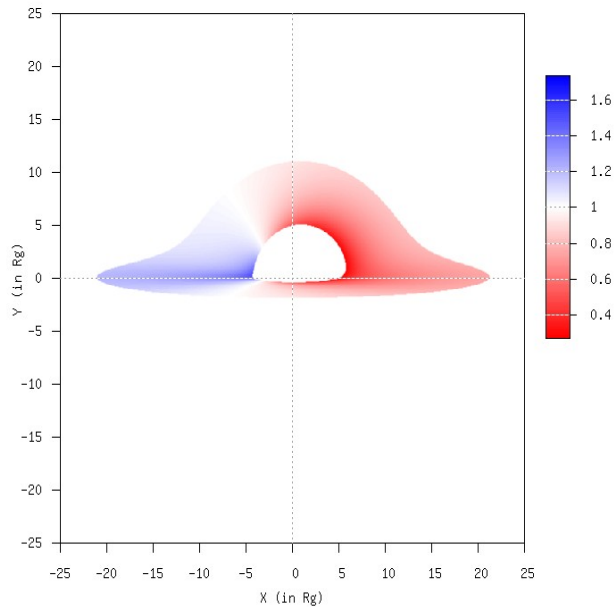


- Intensity map

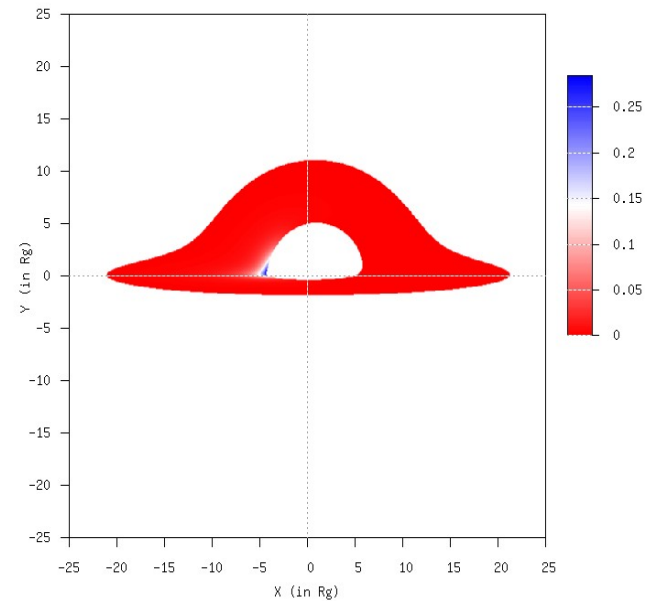


Kerr black hole images ($a=0.75$): $\theta=85$ deg

- Redshift map

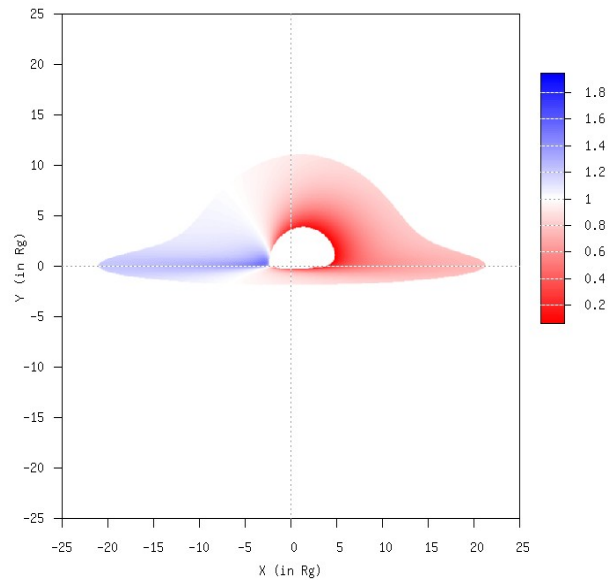


- Intensity map

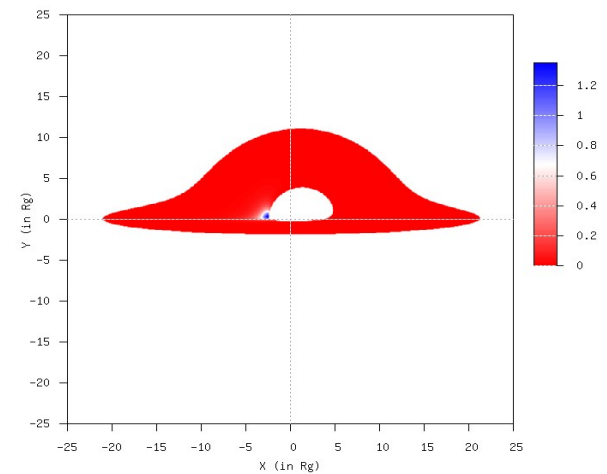


Kerr black hole images ($a=0.99$): $\theta=85$ deg

- Redshift map

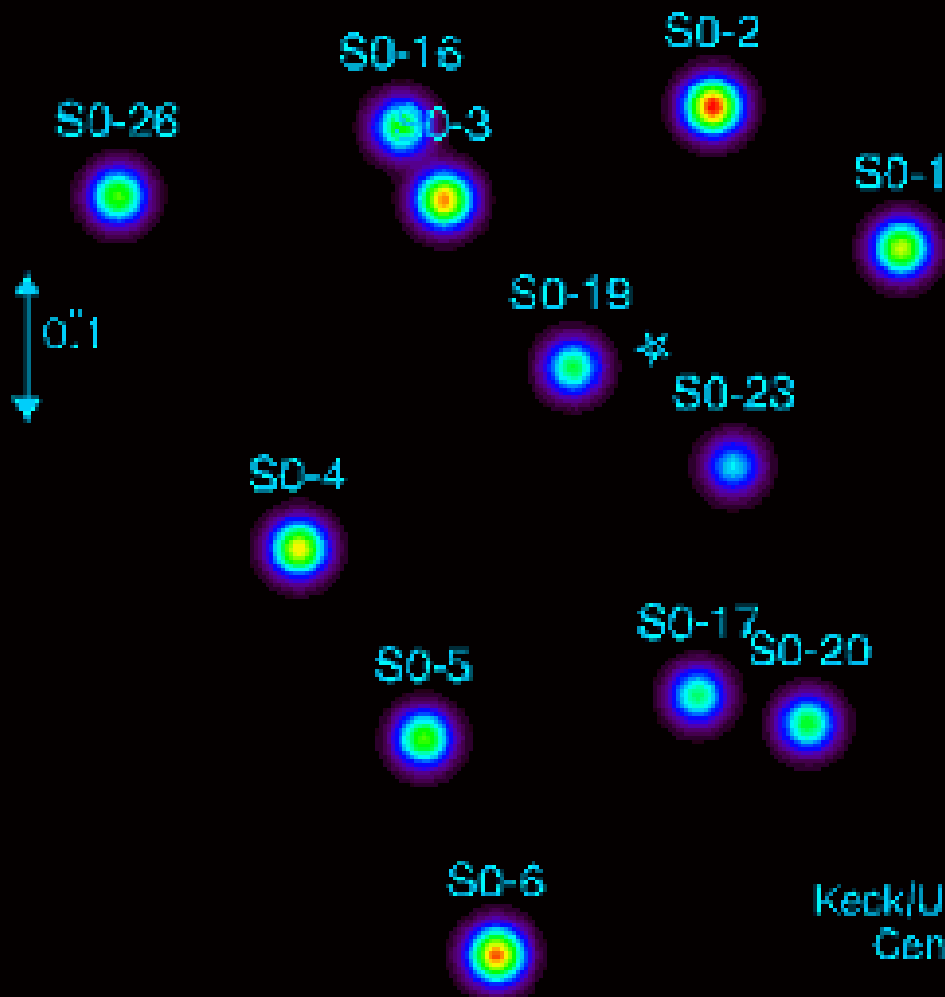


- Intensity map



1995.50

S0-8



Keck/UCLA Galactic
Center Group

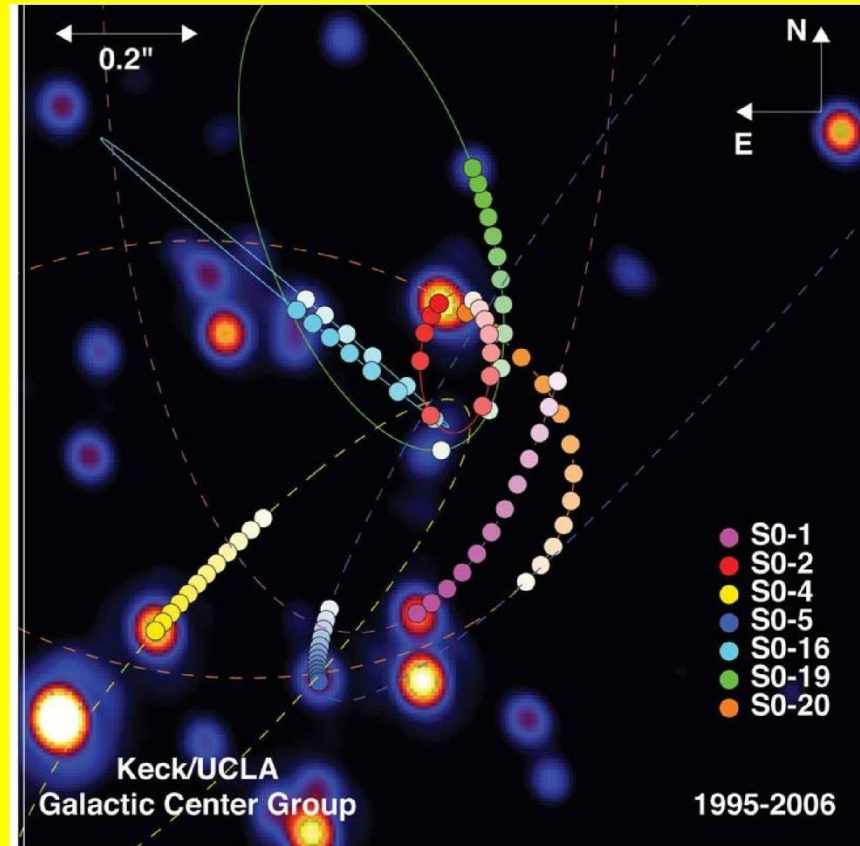


Figure 19: Bright stars near the Galactic Centre.

MONITORING STELLAR ORBITS AROUND THE MASSIVE BLACK HOLE IN THE GALACTIC CENTER

S. GILLESSEN¹, F. EISENHAUER¹, S. TRIPPE¹, T. ALEXANDER³, R. GENZEL^{1,2}, F. MARTINS⁴, T. OTT¹*Draft version October 26, 2008*

ABSTRACT

We present the results of 16 years of monitoring stellar orbits around the massive black hole in center of the Milky Way using high resolution near-infrared techniques. This work refines our previous analysis mainly by greatly improving the definition of the coordinate system, which reaches a long-term astrometric accuracy of $\approx 300 \mu\text{as}$, and by investigating in detail the individual systematic error contributions. The combination of a long time baseline and the excellent astrometric accuracy of adaptive optics data allow us to determine orbits of 28 stars, including the star S2, which has completed a full revolution since our monitoring began. Our main results are: all stellar orbits are fit extremely well by a single point mass potential to within the astrometric uncertainties, which are now $\approx 6\times$ better than in previous studies. The central object mass is $(4.31 \pm 0.06)_{\text{stat}} \pm 0.36_{R_0} \times 10^6 M_\odot$ where the fractional statistical error of 1.5% is nearly independent from R_0 and the main uncertainty is due to the uncertainty in R_0 . Our current best estimate for the distance to the Galactic Center is $R_0 = 8.33 \pm 0.35$ kpc. The dominant errors in this value is systematic. The mass scales with distance as $(3.95 \pm 0.06) \times 10^6 (R_0/8 \text{ kpc})^{2.19} M_\odot$. The orientations of orbital angular momenta for stars in the central arcsecond are random. We identify six of the stars with orbital solutions as late type stars, and six early-type stars as members of the clockwise rotating disk system, as was previously proposed. We constrain the extended dark mass enclosed between the pericenter and apocenter of S2 at less than 0.066, at the 99% confidence level, of the mass of Sgr A*. This is two orders of magnitudes larger than what one would expect from other theoretical and observational estimates.

Subject headings: blackhole physics — astrometry — Galaxy: center — infrared: stars

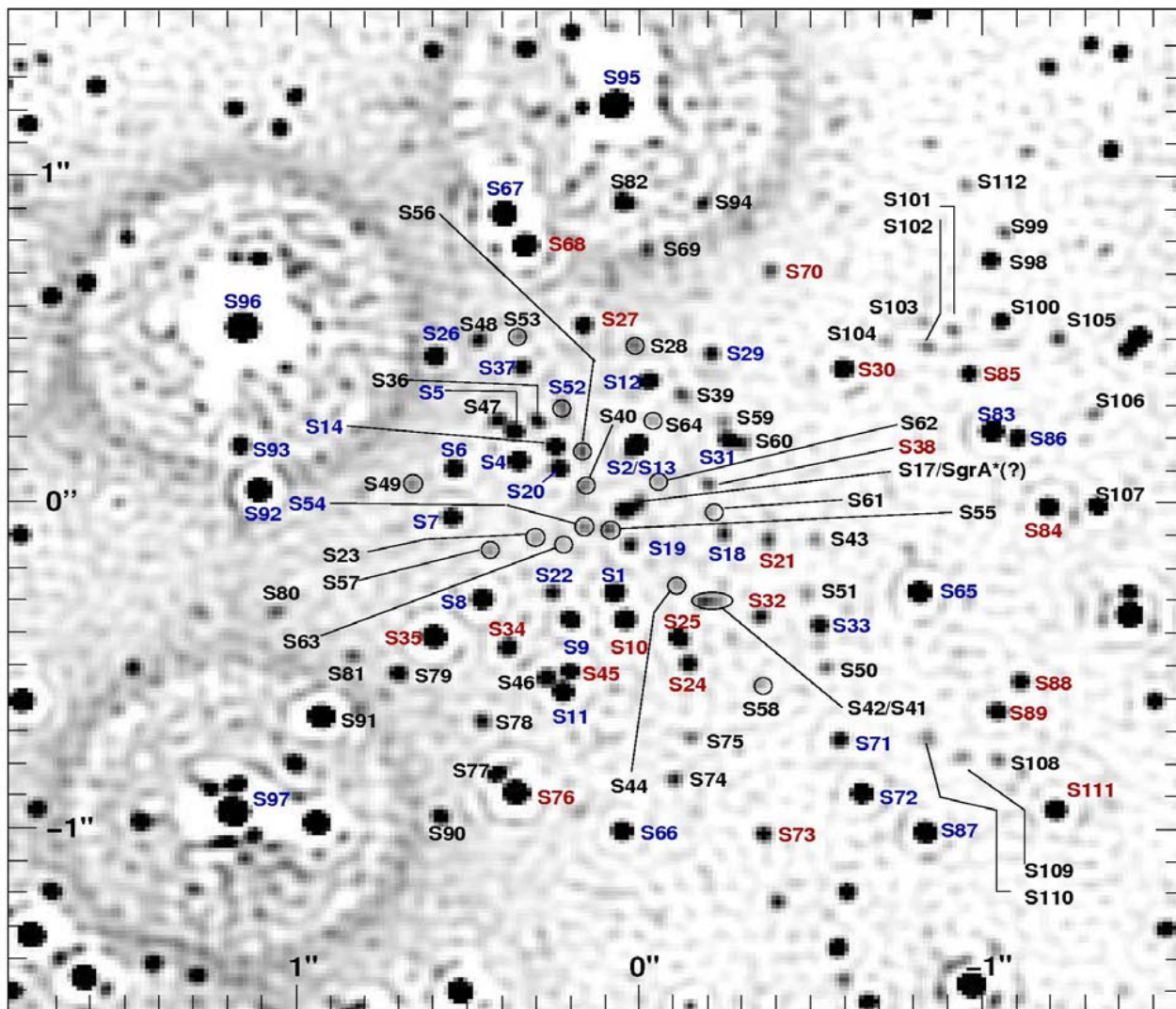


FIG. 1.— Finding chart of the S-star cluster. This figure is based on a natural guide star adaptive optics image obtained as part of this study, using NACO at UT4 (Yepun) of the VLT on July 20, 2007 in the H-band. The original image with a FWHM of ≈ 75 mas was deconvolved with the Lucy-Richardson algorithm and beam restored with a Gaussian beam with FWHM = 2 pix = 26.5 mas. Stars as faint as $m_H = 19.2$ (corresponding roughly to $m_K = 17.7$) are detected at the 5σ level. Only stars that are unambiguously identified in several images have designated names, ranging from S1 to S112. Blue labels indicate early-type stars, red labels late-type stars. Stars with unknown spectral type are labelled in black. At the position of Sgr A* some light is seen, which could be either due to Sgr A* itself or due to a faint, so far unrecognized star being confused with Sgr A*.

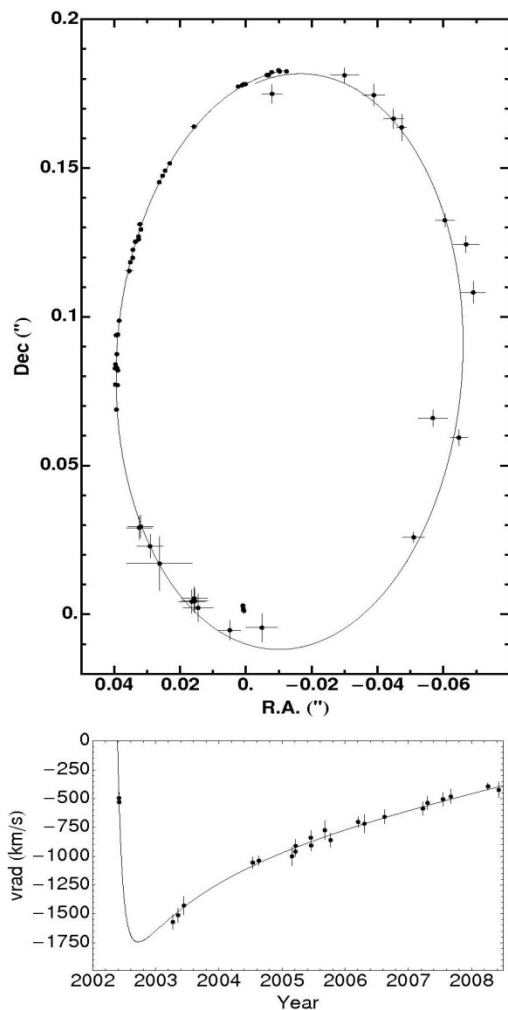


FIG. 13.— Top: The S2 orbital data plotted in the combined coordinate system and fitted with a Keplerian model in which the velocity of the central point mass and its position were free fit parameters. The non-zero velocity of the central point mass is the reason why the orbit figure does not close exactly in the overlap region 1992/2008 close to apocenter. The fitted position of the central point mass is indicated by the elongated dot inside the orbit near the origin; its shape is determined from the uncertainty in the position and the fitted velocity, which leads to the elongation. Bottom: The measured radial velocities of S2 and the radial velocity as calculated from the orbit fit.

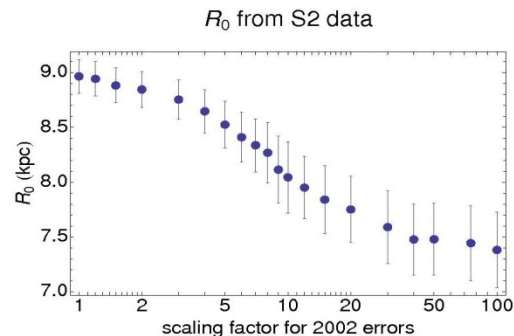


FIG. 14.— Fitted value of R_0 for various scaling factors of the S2 2002 data, using a fit with the coordinate system priors. The factor by which the 2002 astrometric errors of the S2 data is scaled up strongly influences the distance. The mean factor determined in Figure 9 is ≈ 7 , corresponding to $R_0 \approx 8.1$ kpc.

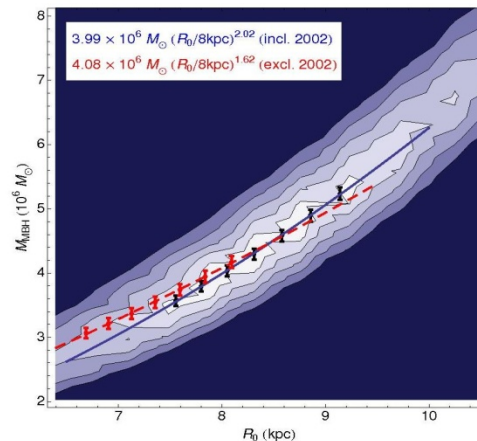
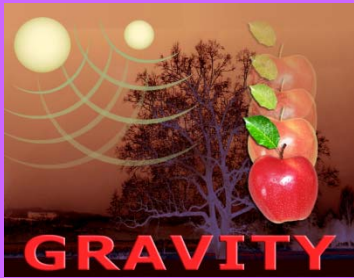


FIG. 15.— Contour plot of χ^2 as function of R_0 and central point mass. The two parameters are strongly correlated. The contours are generated from the S2 data including the 2002 data; fitting at each point all other parameters both of the potential and the orbital elements. The black dots indicate the position and errors of the best fit values of the mass for the respective distance; the blue line is a power law fit to these points; the corresponding function is given in the upper row of the text box. The central point is chosen at the best fitting distance. The red points and the red dashed line are the respective data and fit for the S2 data excluding the 2002 data; the fit is reported in the lower row of the text box. The contour levels are drawn at confidence levels corresponding to 1σ , 3σ , 5σ , 7σ , 9σ .

From the numbers it seems that the fit excluding the



GRAVITY

Studying the supermassive black hole at the center of the Galaxy

46th Rencontres de Moriond and GPHyS colloquium 2011
Gravitational Waves and Experimental Gravity

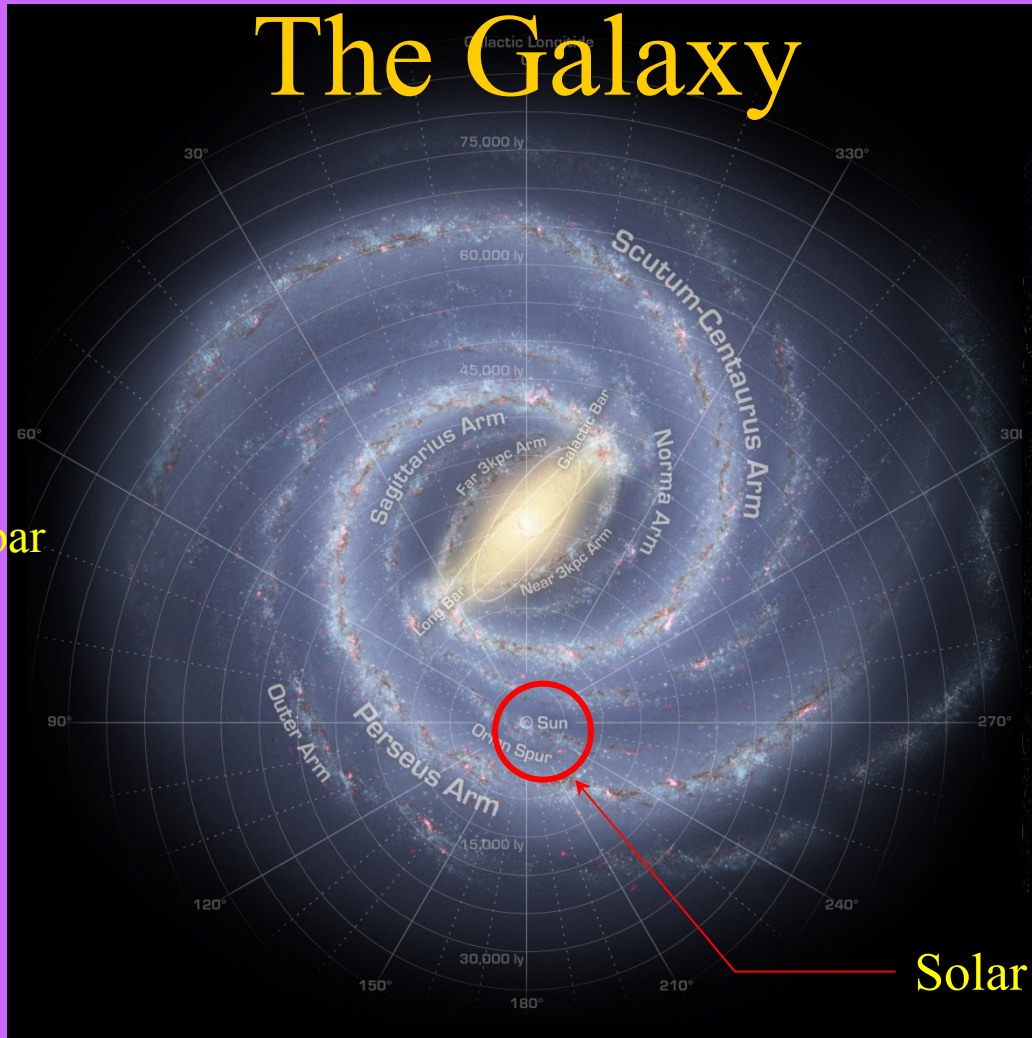
Guy Perrin and the GRAVITY consortium



Thursday 25 March 2011

The Galaxy

Diameter: 25 kpc
Spiral galaxy with bar



Solar system



Milky Way

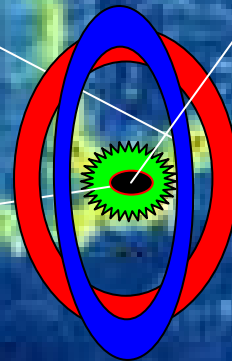
The environment of Sgr A*

Sgr A*
10 μ as

Mini spiral
(50'')

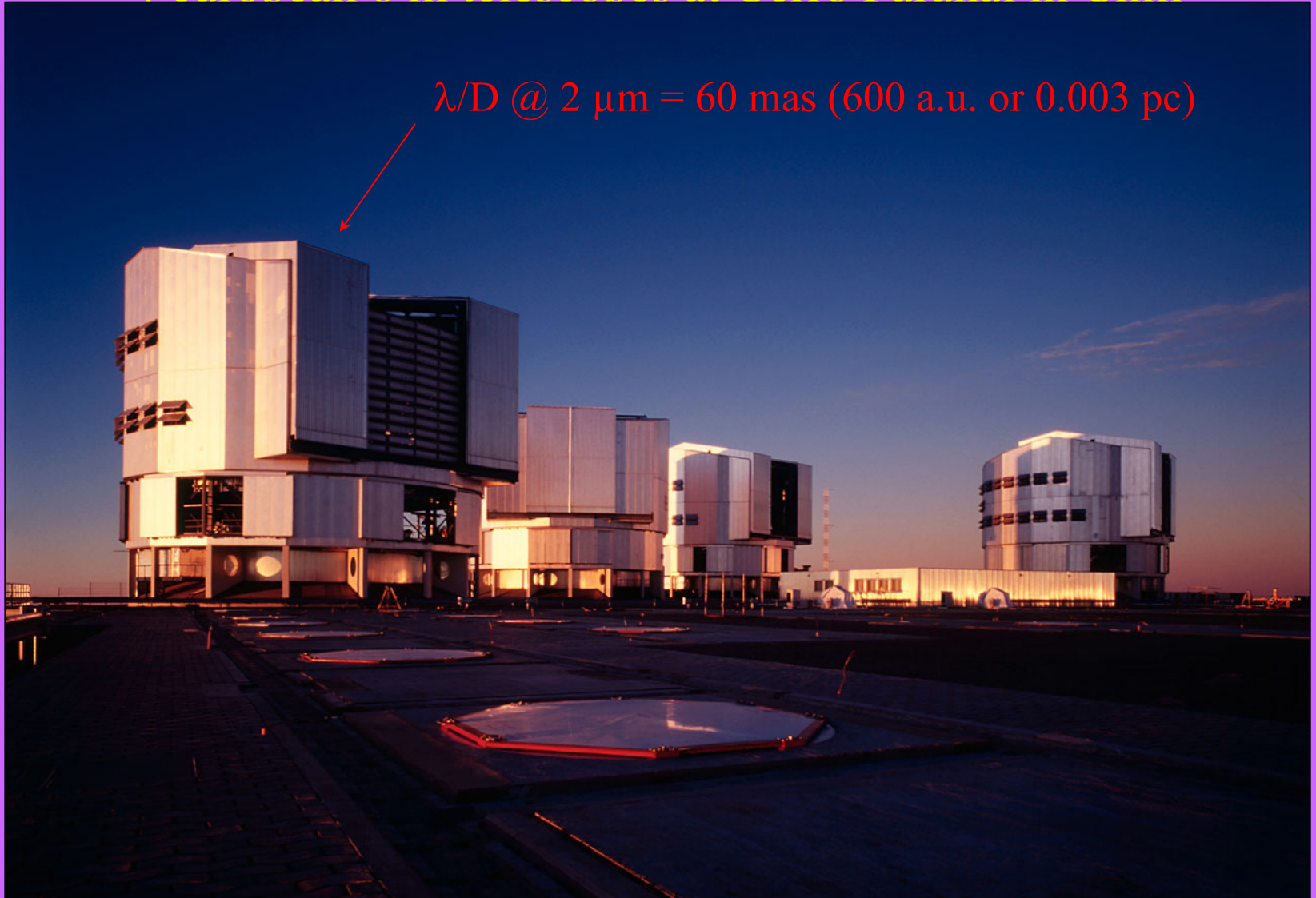
Central cluster
(2 disks)
(0.5 pc-12.5'')

S star cluster
(12-400 mas)



The VLT, *Very Large Telescope*
4 european 8 m telescopes at Cerro Paranal in Chili

$\lambda/D @ 2 \mu\text{m} = 60 \text{ mas (600 a.u. or 0.003 pc)}$



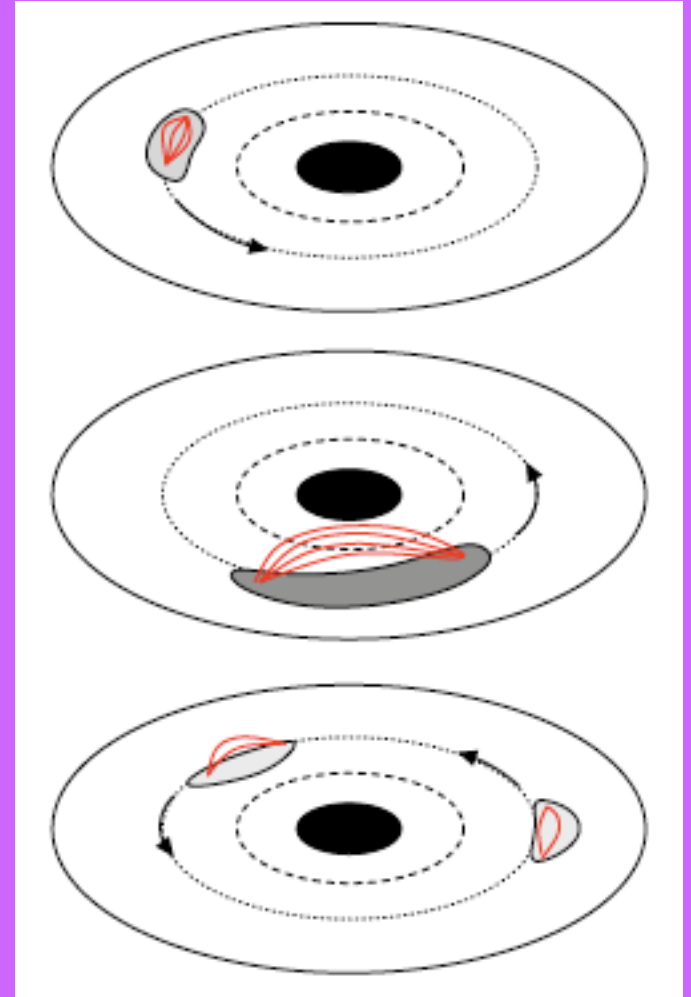
Possible origin of flares

Flare: matter is heated on a (the innermost stable) circular orbit ($30 \mu\text{as}$ if $J=0$)

Flare period: period of the orbit

Fantastic tool to study general relativity in the strong field regime.

The *hot spot* will be used as a test particle to measure the space time around Sgr A*.



Eckart et al. A&A 500, 935 (2009)

GRAVITY – 4 giant telescope interferometer (*General Relativity via VLTI Interferometry*)

$\lambda/B @ 2 \mu\text{m} = 3 \text{ mas}$ (30 a.u. or 0.00015 pc)



Going beyond boundaries thanks to accurate spatial information

- Bring the ultimate evidence that Sgr A* is a black hole: the mass is contained in the Schwarzschild radius.
- Understand the nature of flares.
- Use the black hole as a tool to study general relativity in the strong field regime

Scale $\sim 1 R_s$

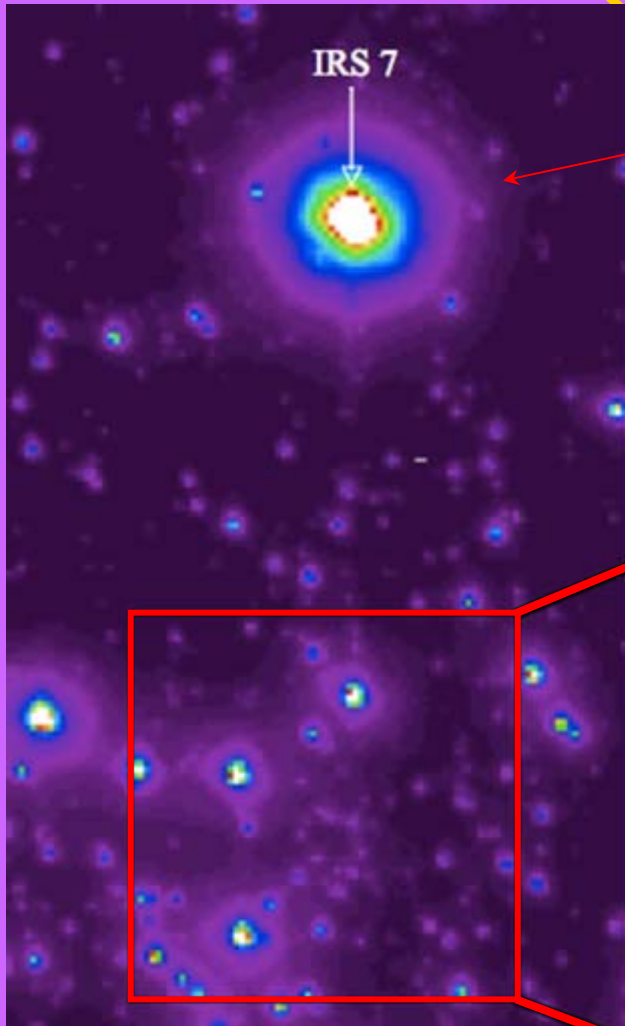
10 μ as

- Study relativistic effects on nearby stars
- Understand the nature of S stars and their distribution

Scale $\sim 100 R_s$

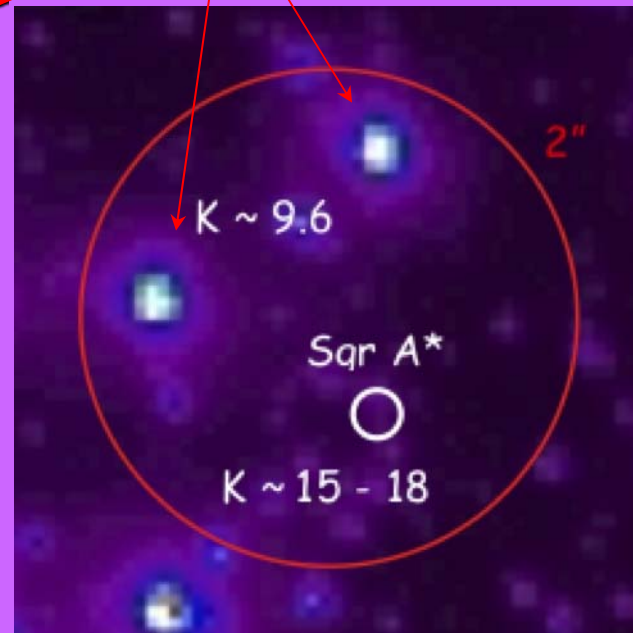
1 mas

Principle of the measurements with GRAVITY



Reference source for infrared
adaptive optics

Reference sources for $10 \mu\text{s}$
astrometry and 3 mas phase
reference imaging



GRAVITY Consortium



Amorim, Araujo-Hauck, Bartko, Baumeister, Berger, Brandner, Carvas, Cassaing, Chapron, Choquet, Clénet, Collin, Dodds-Eden, Eckart, Eisenhauer, Fédou, Fischer, Gendron, Genzel, Gillessen, Gräter, Hamaus, Haubois, Haug, Hippler, Hofmann, Hormuth, Houairi, Ihle, Jocu, Kellner, Kervella, Klein, Kolmeder, Lacour, Lapeyrère, Laun, Lenzen, Lima, Moratschke, Moulin, Naranjo, Neumann, Patru, Paumard, Perraut, Perrin, Pfuhl, Rabien, Ramos, Reess, Rohloff, Rousset, Sevin, Sturm, Straubmeier, Thiel, Vincent, Wiest, Zanker-Smith, Ziegleder, Ziegler

Where do we stand now ?

Concept Design Review: December
2007

Preliminary Design Review:
December 2009

Final Design Review: October
2011

First tests at Paranal: 2014

Hopefully first results on Sgr A* in 4 years.

In the last years intensive searches for dark matter (DM), especially its non-baryonic component, both in galactic halos and at galaxy centers have been undertaken (see for example Bertone et al. (2005,2005a) for recent results). It is generally accepted that the most promising candidate for the DM non-baryonic component is neutralino. In this case, the γ -flux from galactic halos (and from our Galactic halo in particular) could be explained by neutralino annihilation (Gurevich et al. 1997, Bergstrom et al. 1998, Tasitsiomi et al. 2002, Stoehr et al. 2003, Prada et al. 2004, Profumo et al. 2005, Mambrini et al. 2005). Since γ -rays are detected not only from high galactic latitude, but also from the Galactic Center, there is a wide spread hypothesis (see, Evans (2004) for a discussion) that a DM concentration might be present at the Galactic Center. In this case the Galactic Center could be a strong source of γ -rays and neutrinos (Bouquet 1989, Stecker 1988, Berezhinsky et al. 1994, Bergstrom et al. 1998, Bertone et al. 2004, Gnedin et al. 2004, Bergstrom et al. 2005, Horns 2005, Bertone et al. 2005) due to DM annihilation. Since it is also expected that DM forms spikes at

galaxy centers (Gondolo & Silk 1999, Ullio et al. 2001, Merritt et al. 2003) the γ -ray flux from the Galactic Center should increase significantly in that case.

At the same time, progress in monitoring bright stars near the Galactic Center have been reached recently (Genzel et al. 2003, Ghez et al. 2003, Ghez et al. 2005). The astrometric limit for bright stellar sources near the Galactic Center with 10 meter telescopes is today $\delta\theta_{10} \sim 1$ mas and the Next Generation Large Telescope (NGLT) will be able to improve this number at least down to $\delta\theta_{30} \sim 0.5$ mas (Weinberg et al. 2005) or even to $\delta\theta_{30} \sim 0.1$ mas (Weinberg et al. 2005) in the K-band. Therefore, it will be possible to measure the proper motion for about ~ 100 stars with astrometric errors several times smaller than errors in current observations.

The aim of this talk is to constrain the parameters of the DM distribution possible present around the Galactic Center by considering the induced apoastron shift due to the presence of this DM sphere and either available

data obtained with the present generation of telescopes (the so called *conservative* limit) and also expectations from future NGLT observations or with other advanced observational facilities.

Celestial mechanics of S2 like stars for BH+cluster (A.A. Nucita, F. De Paolis, G. Ingrosso, A. Qadir, AFZ, PASP, v. 119, p. 349 (2007))

GR predicts that orbits about a massive central body suffer periastron shifts yielding *rosette* shapes. However, the classical perturbing effects of other objects on inner orbits give an opposite shift. Since the periastron advance depends strongly on the compactness of the central body, the detection of such an effect may give information about the nature of the central body itself. This would apply for stars orbiting close to the GC, where there is a “dark object”, the black hole hypothesis being the most natural explanation of the observational data. A cluster of stars in the vicinity of the GC (at a distance < 1 arcsec) has been monitored by ESO and Keck teams for several years.

For a test particle orbiting a Schwarzschild black hole of mass M_{BH} , the periastron shift is given by (see e.g. Weinberg, 1972)

$$\Delta\phi_S \simeq \frac{6\pi GM_{\text{BH}}}{d(1-e^2)c^2} + \frac{3(18+e^2)\pi G^2 M_{\text{BH}}^2}{2d^2(1-e^2)^2 c^4}, \quad (9)$$

d and e being the semi-major axis and eccentricity of the test particle orbit, respectively. For a rotating black hole with spin parameter $a = |\mathbf{a}| = J/GM_{\text{BH}}$, the space-time is described by the Kerr metric and, in the most favorable case of equatorial plane motion ($(\mathbf{a}, \mathbf{v}) = 0$), the shift is given by (Boyer and Price (1965))

$$\Delta\phi_K \simeq \Delta\phi_S + \frac{8a\pi M_{\text{BH}}^{1/2} G^{3/2}}{d^{3/2}(1-e^2)^{3/2} c^3} + \frac{3a^2\pi G^2}{d^2(1-e^2)^2 c^4}, \quad (10)$$

which reduces to eq. (9) for $a \rightarrow 0$. In the more general case, $\mathbf{a} \cdot \mathbf{v} \neq 0$, the

expected periastron shift has to be evaluated numerically.

The expected periastron shifts (mas/revolution), $\Delta\phi$ (as seen from the center) and $\Delta\phi_E$ (as seen from Earth at the distance $R_0 \simeq 8$ kpc from the GC), for the Schwarzschild and the extreme Kerr black holes, for the S2 and S16 stars turn out to be $\Delta\phi^{S2} = 6.3329 \times 10^5$ and 6.4410×10^5 and $\Delta\phi_E^{S2} = 0.661$ and 0.672 respectively, and $\Delta\phi^{S16} = 1.6428 \times 10^6$ and 1.6881×10^6 and $\Delta\phi_E^{S16} = 3.307$ and 3.399 respectively. Recall that

$$\Delta\phi_E = \frac{d(1+e)}{R_0} \Delta\phi_{S,K} . \quad (11)$$

Notice that the differences between the periastron shifts for the Schwarzschild and the maximally rotating Kerr black hole is at most 0.01 mas for the S2 star and 0.009 mas for the S16 star. In order to make these measurements with the required accuracy, one needs to know the S2 orbit with a precision of at least $10 \mu\text{as}$.

The star cluster surrounding the central black hole in the GC could be sizable. At least 17 members have been observed within 15 mpc up to now (Ghez et al. (2005)). However, the cluster mass and density distribution, that is to say its mass and core radius, is still unknown. The presence of this cluster affects the periastron shift of stars orbiting the central black hole. The periastron advance depends strongly on the mass density profile and especially on the central density and typical length scale.

We model the stellar cluster by a Plummer model density profile (Binney & Tremaine (1987))

$$\rho_{CL}(r) = \rho_0 f(r) , \quad \text{with} \quad f(r) = \left[1 + \left(\frac{r}{r_c} \right)^2 \right]^{-\alpha/2} , \quad (12)$$

where the cluster central density ρ_0 is given by

$$\rho_0 = \frac{M_{CL}}{\int_0^{R_{CL}} 4\pi r^2 f(r) dr} , \quad (13)$$

R_{CL} and M_{CL} being the cluster radius and mass, respectively. According to dynamical observations towards the GC, we require that the total mass $M(r) = M_{BH} + M_{CL}(r)$ contained within $r \simeq 5 \times 10^{-3}$ pc is $M \simeq 3.67 \times 10^6 M_\odot$. Useful information is provided by the cluster mass fraction, $\lambda_{CL} = M_{CL}/M$, and its complement, $\lambda_{BH} = 1 - \lambda_{CL}$. As one can see, the requirement given in eq. (13) implies that $M(r) \rightarrow M_{BH}$ for $r \rightarrow 0$. The total mass density profile $\rho(r)$ is given by

$$\rho(r) = \lambda_{BH} M \delta^{(3)}(\vec{r}) + \rho_0 f(r) \quad (14)$$

and the mass contained within r is

$$M(r) = \lambda_{BH}M + \int_0^r 4\pi r'^2 \rho_0 f(r') dr' . \quad (15)$$

According to GR, the motion of a test particle can be fully described by solving the geodesic equations. Under the assumption that the matter distribution is static and pressureless, the equation of motion of the test particle becomes (see e.g. Weinberg 1972))

$$\frac{d\mathbf{v}}{dt} \simeq -\nabla(\Phi_N + 2\Phi_N^2) + 4\mathbf{v}(\mathbf{v} \cdot \nabla)\Phi_N - v^2\nabla\Phi_N . \quad (16)$$

For the S2 star, d and e given in the literature are 919 AU and 0.87 respectively. They yield the orbits of the S2 star for different values of the

black hole mass fraction λ_{BH} shown in Figure 20. The Plummer model parameters are $\alpha = 5$, core radius $r_c \simeq 5.8$ mpc. Note that in the case of $\lambda_{BH} = 1$, the expected (prograde) periastron shift is that given by eq. (9), while the presence of the stellar cluster leads to a retrograde periastron shift. For comparison, the expected periastron shift for the S16 star is given in Figure 31. In the latter case, the binary system orbital parameters were taken from Schödel et al. (2003) assuming also for the S16 mass a conservative value of $\simeq 10 M_{\odot}$.

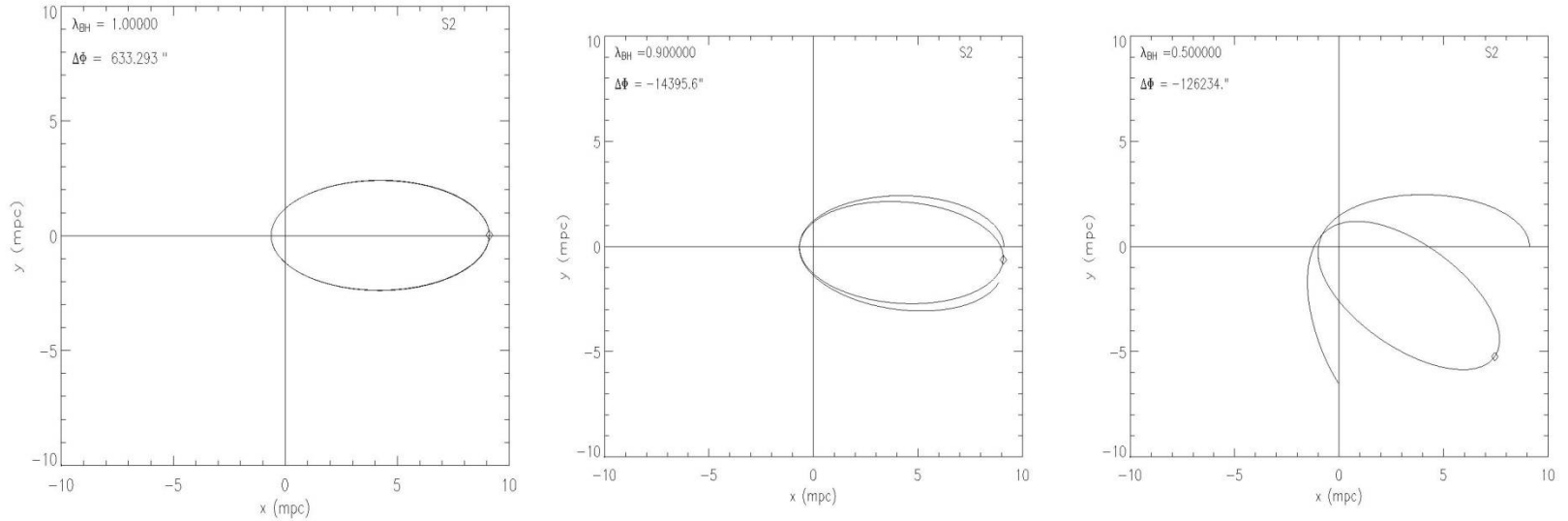


Figure 20: Post Newtonian orbits for different values of the black hole mass fraction λ_{BH} are shown for the S2 star (upper panels). Here, we have assumed that the Galactic central black hole is surrounded by a stellar cluster whose density profile follows a Plummer model with $\alpha = 5$ and a core radius $r_c \simeq 5.8$ mpc. The periastron shift values in each panel is given in arcseconds.

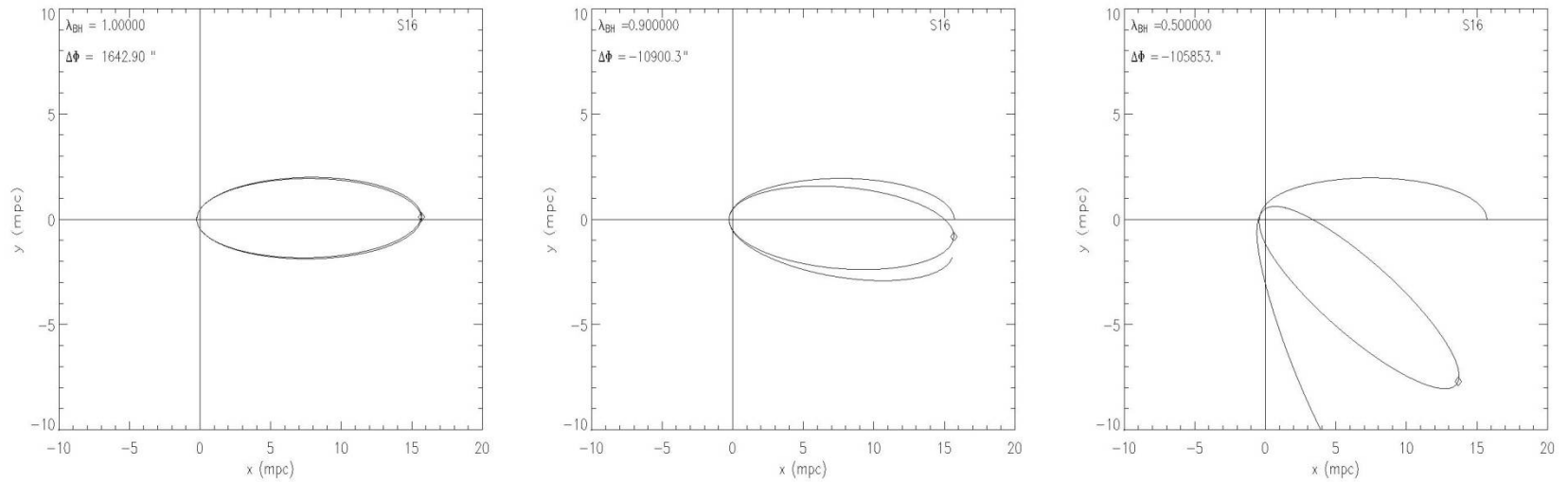


Figure 21: The same as in Figure 20 but for the S16–Sgr A* binary system. In this case, the binary system orbital parameters were taken from Ghez et al. (2005) assuming for the S16 mass a conservative value of $\simeq 10 M_{\odot}$.

The mass concentration at the Galactic Center

Recent advancements in infrared astronomy are allowing to test the scale of the mass profile at the center of our galaxy down to tens of AU. With the Keck 10 m telescope, the proper motion of several stars orbiting the Galactic Center black hole have been monitored and almost entire orbits, as for example that of the S2 star, have been measured allowing an unprecedented description of the Galactic Center region. Measurements of the amount of mass $M(< r)$ contained within a distance r from the Galactic Center are continuously improved as more precise data are collected. Recent observations (Ghez et al. (2003)) extend down to the periastron distance ($\simeq 3 \times 10^{-4}$ pc) of the S16 star and they correspond to a value of the enclosed mass within $\simeq 3 \times 10^{-4}$ pc of $\simeq 3.67 \times 10^6 M_{\odot}$. Several authors have used these observations to model the Galactic Center mass concentration. Here and in the following, we use the three component

model for the central region of our galaxy based on estimates of enclosed mass given by Ghez et al (2003, 2005) recently proposed by Hall and Gondolo (2006). This model is constituted by the central black hole, the central stellar cluster and the DM sphere (made of WIMPs), i.e.

$$M(< r) = M_{BH} + M_*(< r) + M_{DM}(< r) , \quad (17)$$

where M_{BH} is the mass of the central black hole Sagittarius A*. For the central stellar cluster, the empirical mass profile is

$$M_*(< r) = \begin{cases} M_* \left(\frac{r}{R_*} \right)^{1.6} , & r \leq R_* \\ M_* \left(\frac{r}{R_*} \right)^{1.0} , & r > R_* \end{cases} \quad (18)$$

with a total stellar mass $M_* = 0.88 \times 10^6 M_\odot$ and a size $R_* = 0.3878$ pc.

As far as the mass profile of the DM concentration is concerned, Hall & Gondolo (2006) have assumed a mass distribution of the form

$$M_{DM}(< r) = \begin{cases} M_{DM} \left(\frac{r}{R_{DM}} \right)^{3-\alpha}, & r \leq R_{DM} \\ M_{DM}, & r > R_{DM} \end{cases} \quad (19)$$

M_{DM} and R_{DM} being the total amount of DM in the form of WIMPs and the radius of the spherical mass distribution, respectively.

Hall and Gondolo (2006) discussed limits on DM mass around the black hole at the Galactic Center. It is clear that present observations of stars around the Galactic Center do not exclude the existence of a DM sphere with mass $\simeq 4 \times 10^6 M_{\odot}$, well contained within the orbits of the known stars, if its radius R_{DM} is $\lesssim 2 \times 10^{-4}$ pc (the periastron distance of the S16 star in the more recent analysis (Ghez et al. 2005)). However, if one

considers a DM sphere with larger radius, the corresponding upper value for M_{DM} decreases (although it tends again to increase for extremely extended DM configurations with $R_{DM} \gg 10$ pc). In the following, we will assume for definiteness a DM mass $M_{DM} \sim 2 \times 10^5 M_{\odot}$, that is the upper value for the DM sphere (Hall & Gondolo (2006)) within an acceptable confidence level in the range $10^{-3} - 10^{-2}$ pc for R_{DM} . As it will be clear in the following, we emphasize that even a such small value for the DM mass (that is about only 5% of the standard estimate $3.67 \pm 0.19 \times 10^6 M_{\odot}$ for the dark mass at the Galactic Center (Ghez et al. 2005)) may give some observational signatures.

Evaluating the S2 apoastron shift ¹ as a function of R_{DM} , one can further constrain the DM sphere radius since even now we can say that there is no evidence for negative apoastron shift for the S2 star orbit at the

¹We want to note that the periastron and apoastron shifts $\Delta\Phi$ as seen from the orbit center have the same value whereas they have different values as seen from Earth (see Eq. (23)). When we are comparing our results with orbit reconstruction from observations we refer to the apoastron shift as seen from Earth.

level of about 10 mas (Genzel et al. 2003). In addition, since at present the precision of the S2 orbit reconstruction is about 1 mas, we can say that even without future upgrades of the observational facilities and simply monitoring the S2 orbit, it will be possible within about 15 years to get much more severe constraints on R_{DM} .

Moreover, observational facilities will allow in the next future to monitor faint infrared objects at the astrometric precision of about 10 μ as (Eisenhauer et al. 2005) and, in this case, previous estimates will be sensibly improved since it is naturally expected to monitor eccentric orbits for faint infrared stars closer to the Galactic Center with respect to the S2 star.

In Fig. 30, the mass profile $M(< r)$ (Ghez et al. 2003) obtained by using observations of stars nearby the Galactic Center is shown (solid line). The dotted line represents the stellar mass profile as given in Eq. (18), while the dashed lines are for DM spheres with mass $M_{DM} \simeq 2 \times 10^5 M_{\odot}$ and

radii $R_{DM} = 10^{-3}$ and 10^{-2} pc, respectively.

Apoastron Shift Constraints

According to GR, the motion of a test particle can be fully described by solving the geodesic equations. Under the assumption that the matter distribution is static and pressureless, the equations of motion at the first post-Newtonian (PN) approximation become (see e.g. (Fock 1961, Weinberg 1972, Rubilar & Eckart 2001))

$$\frac{d\mathbf{v}}{dt} \simeq -\nabla(\Phi_N + 2\Phi_N^2) + 4\mathbf{v}(\mathbf{v} \cdot \nabla)\Phi_N - v^2\nabla\Phi_N . \quad (21)$$

We note that the PN-approximation is the first relativistic correction from which the apoastron advance phenomenon arises. In the case of the S2 star, the apoastron shift as seen from Earth (from Eq. (23)) due to the presence of a central black hole is about 1 mas, therefore not directly

detectable at present since the available precision in the apoastron shift is about 10 mas (but it will become about 1 mas in 10–15 years even without considering possible technological improvements). It is also evident that higher order relativistic corrections to the S2 apoastron shift are even smaller and therefore may be neglected at present, although they may become important in the future.

As it will be discussed below, the Newtonian effect due to the existence of a sufficiently extended DM sphere around the black hole may cause a apoastron shift in the opposite direction with respect to the relativistic advance due to the black hole. Therefore, we have considered the two effects comparing only the leading terms.

For the DM distribution at the Galactic Center we follow Eq. (19) as done in Hall & Gondolo (2006). Clearly, if in the future faint infrared stars (or spots) closer to the black hole with respect to the S2 star will be monitored (Eisenhauer, (2005)), this simplified model might well not hold

and higher order relativistic corrections may become necessary.

For a spherically symmetric mass distribution (such as that described above) and for a gravitational potential given by Eq. (20), Eq. (21) may be rewritten in the form (see for details Rubilar & Eckart (2001))

$$\frac{d\mathbf{v}}{dt} \simeq -\frac{GM(r)}{r^3} \left[\left(1 + \frac{4\Phi_N}{c^2} + \frac{v^2}{c^2} \right) \mathbf{r} - \frac{4\mathbf{v}(\mathbf{v} \cdot \mathbf{r})}{c^2} \right], \quad (22)$$

\mathbf{r} and \mathbf{v} being the vector radius of the test particle with respect to the center of the stellar cluster and the velocity vector, respectively. Once the initial conditions for the star distance and velocity are given, the rosetta shaped orbit followed by a test particle can be found by numerically solving the set of ordinary differential equations in eq. (22).

In Fig. 20, as an example, assuming that the test particle orbiting the Galactic Center region is the S2 star, we show the Post Newtonian orbits

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In Fig. 20, as an example, assuming that the test particle orbiting the Galactic Center region is the S2 star, we show the Post Newtonian orbits

obtained by the black hole only, the black hole plus the stellar cluster and the contribution of two different DM mass density profiles. In each case the S2 orbit apoastron shift is given. As one can see, for selected parameters for DM and stellar cluster masses and radii the effect of the stellar cluster is almost negligible while the effect of the DM distribution is crucial since it enormously overcome the shift due to the relativistic precession. Moreover, as expected, its contribution is opposite in sign with respect to that of the black hole (Nucita et al. (2007)).

We note that the expected apoastron (or, equivalently, periastron) shifts (mas/revolution), $\Delta\Phi$ (as seen from the center) and the corresponding values $\Delta\phi_E^\pm$ as seen from Earth (at the distance $R_0 \simeq 8$ kpc from the GC) are related by

$$\Delta\phi_E^\pm = \frac{d(1 \pm e)}{R_0} \Delta\Phi, \quad (23)$$

where with the sign \pm are indicated the shift angles of the apoastron (+)

and periastron (-), respectively. The S2 star semi-major axis and eccentricity are $d = 919$ AU and $e = 0.87$ (Ghez et al. 2005).

In Fig. 32, the S2 apoastron shift as a function of the DM distribution size R_{DM} is given for $\alpha = 0$ and $M_{DM} \simeq 2 \times 10^5 M_{\odot}$. Taking into account that the present day precision for the apoastron shift measurements is of about 10 mas, one can say that the S2 apoastron shift cannot be larger than 10 mas. Therefore, any DM configuration that gives a total S2 apoastron shift larger than 10 mas (in the opposite direction due to the DM sphere) is excluded. The same analysis is shown in Figs. 33 and 34 for two different values of the DM mass distribution slope, i.e. $\alpha = 1$ and $\alpha = 2$, respectively. In any case, we have calculated the apoastron shift for the S2 star orbit assuming a total DM mass $M_{DM} \simeq 2 \times 10^5 M_{\odot}$. As one can see by inspecting Figs. 32-34, the upper limit of about 10 mas on the S2 apoastron shift may allow to conclude that DM radii in the range about $10^{-3} - 10^{-2}$ pc are excluded by present observations.

We notice that the results of the present analysis allows to further constrain the results (Hall and Gondolo 2006) who have concluded that if the DM sphere radius is in the range $10^{-3} - 1$ pc, configurations with DM mass up to $M_{DM} = 2 \times 10^5 M_{\odot}$ are acceptable. The present analysis shows that DM configurations of the same mass are acceptable only for R_{DM} out the range between $10^{-3} - 10^{-2}$ pc, almost irrespectively of the α value.

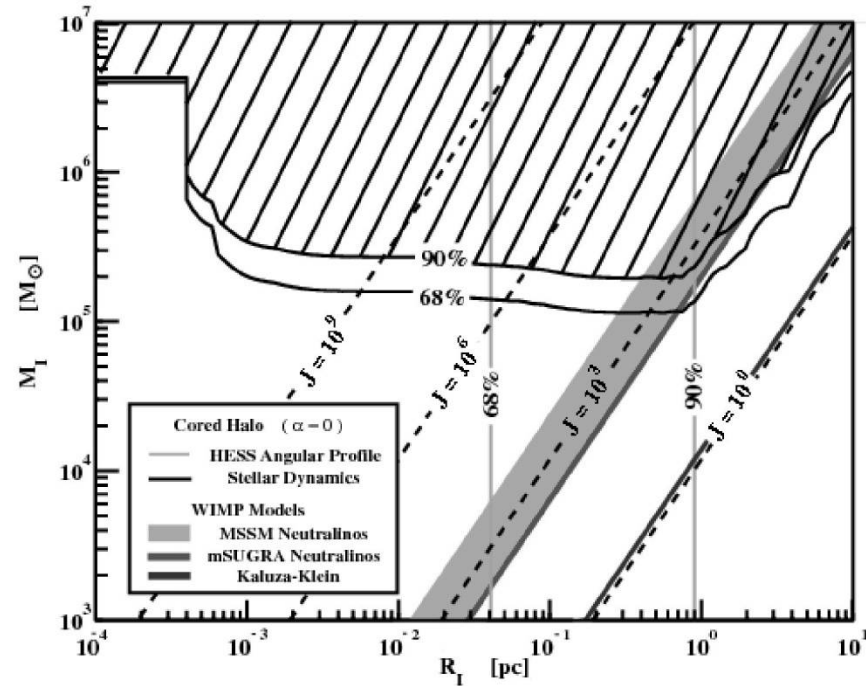


Figure 28: An allowed region for DM distribution from S2 like star trajectories near the Black Hole at the Galactic Center (Hall and Gondolo (2006)).

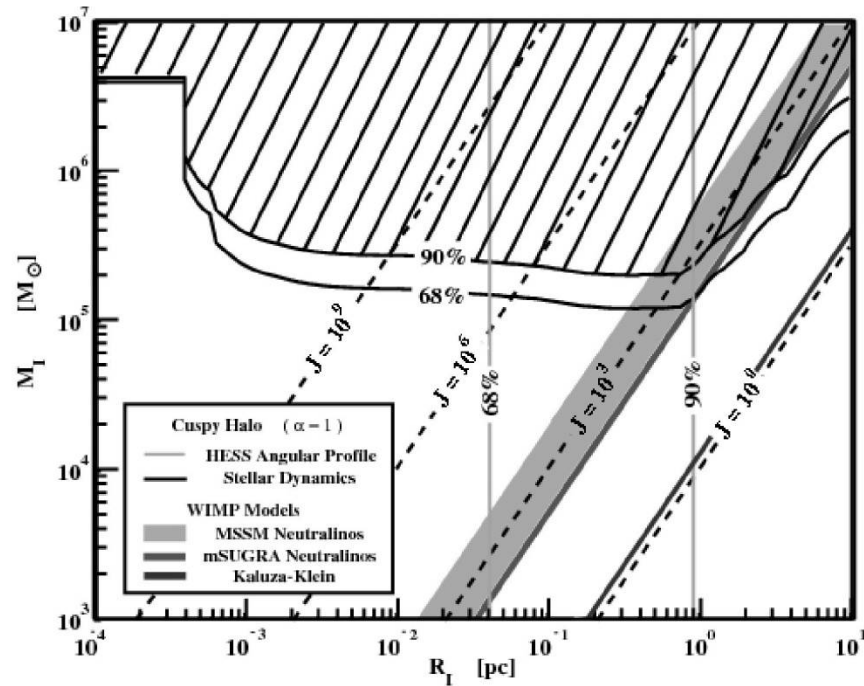


Figure 29: An allowed region for DM distribution from S2 like star trajectories near the Black Hole at the Galactic Center (Hall and Gondolo (2006)).

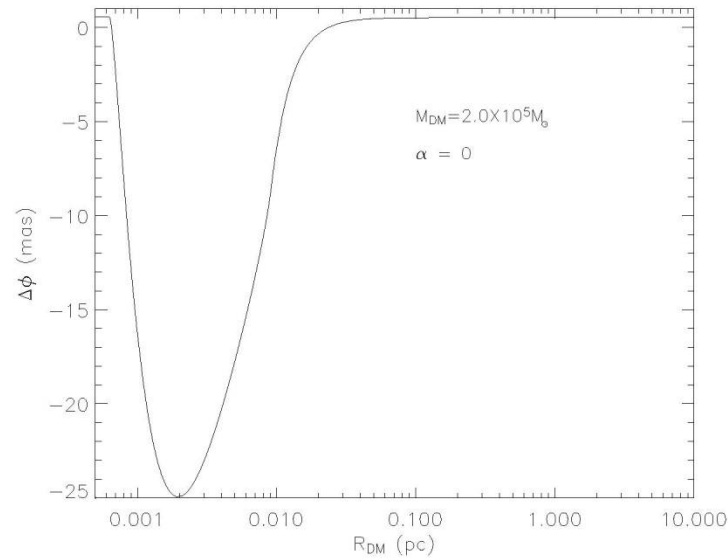


Figure 32: Apoastron shift as a function of the DM radius R_{DM} for $\alpha = 0$ and $M_{DM} \simeq 2 \times 10^5 M_{\odot}$. Taking into account present day precision for the apoastron shift measurements (about 10 mas) one can say that DM radii R_{DM} in the range $8 \times 10^{-4} - 10^{-2}$ pc are not acceptable.

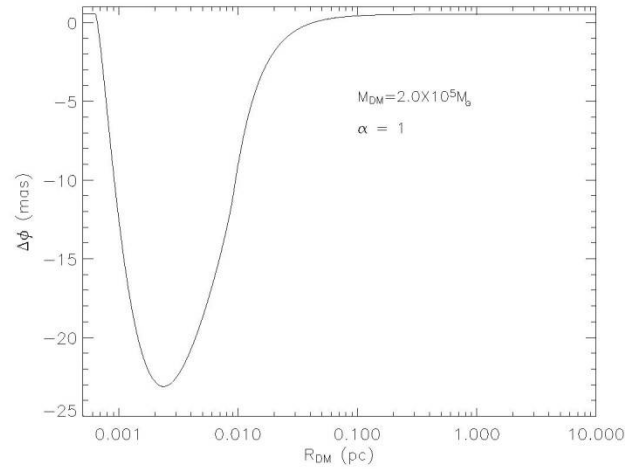


Figure 33: The same as in Fig. 32 for $\alpha = 1$ and $M_{DM} \simeq 2 \times 10^5 M_{\odot}$. As in the previous case one can say that the S2 apoastron shift put severe limits on the DM mass radii that are not acceptable in the range $9 \times 10^{-4} - 10^{-2}$ pc.

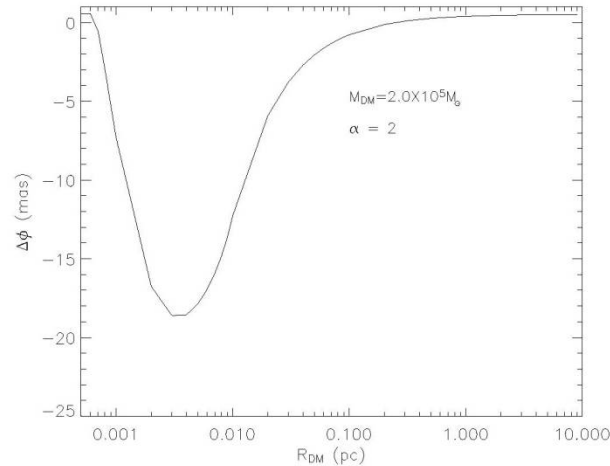


Figure 34: The same as in Fig. 32 for $\alpha = 2$ and $M_{DM} \simeq 2 \times 10^5 M_{\odot}$. As in the previous case one can say that the upper limit to the S2 apoastron shift allows to constrain the DM radius to be out the range $1.0 \times 10^{-3} - 1.1 \times 10^{-2}$ pc.

- **Conclusions**

- VLBI systems in mm and sub-mm bands or MAXIM could detect mirages (“faces”) around black holes.
- Shapes of images give an important information about BH parameter
- Trajectories of bright stars or bright spots around massive BHs are very important tool for an evaluation of BH parameters
- A significant tidal charge of the BH at GC is excluded by observations

- Thanks for your kind attention!

Event-horizon-scale structure in the supermassive black hole candidate at the Galactic Centre

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The cores of most galaxies are thought to harbour supermassive black holes, which power galactic nuclei by converting the gravitational energy of accreting matter into radiation¹. Sagittarius A*, the compact source of radio, infrared and X-ray emission at the centre of the Milky Way, is the closest example of this phenomenon, with an estimated black hole mass that is 4 million times that of the Sun^{2,3}. A long-standing astronomical goal is to resolve structures in the innermost accretion flow surrounding Sgr A* where strong gravitational fields will distort the appearance of radiation emitted near the black hole. Radio observations at wavelengths of 3.5 mm and 7 mm have detected intrinsic structure in Sgr A*, but the spatial resolution of observations at these wavelengths is limited by interstellar scattering⁴⁻⁷. Here we report observations at a wavelength of 1.3 mm that set a size of 37^{+16}_{-10} microarcseconds on the intrinsic diameter of Sgr A*. This is less than the expected apparent size of the event horizon of the presumed black hole, suggesting that the bulk of SgrA* emission may not be not centred on the black hole, but arises in the surrounding accretion flow.