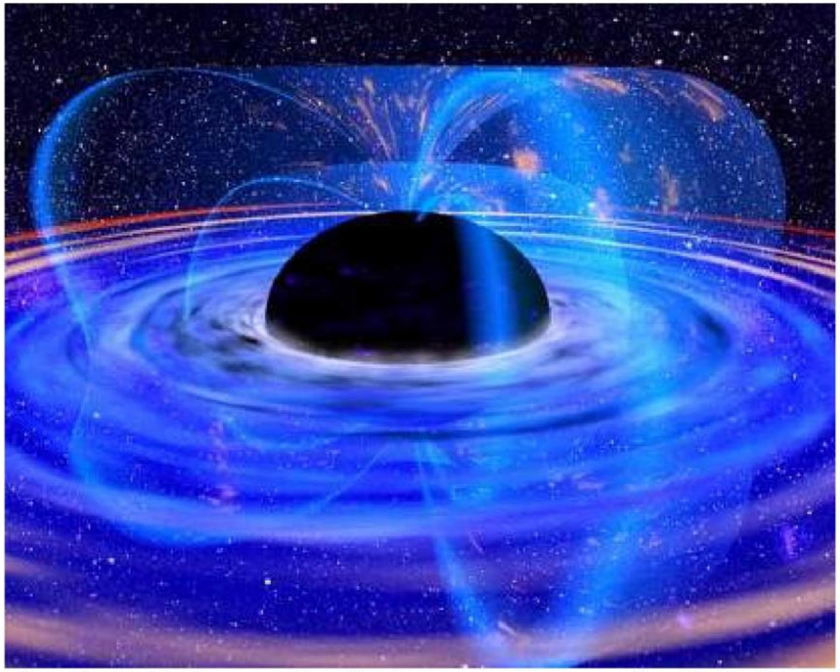
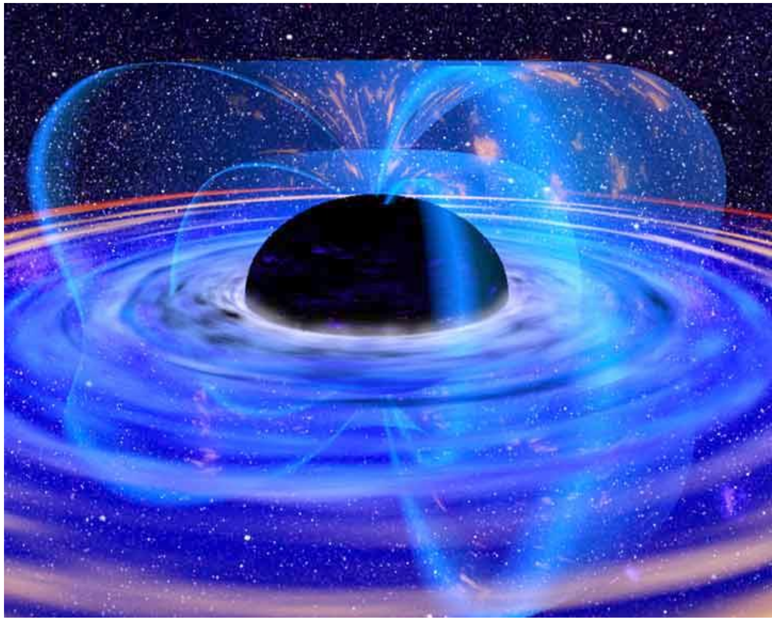
XMM-Newton observations of MCG-6-30-15 in the 2-10 keV band



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



- 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

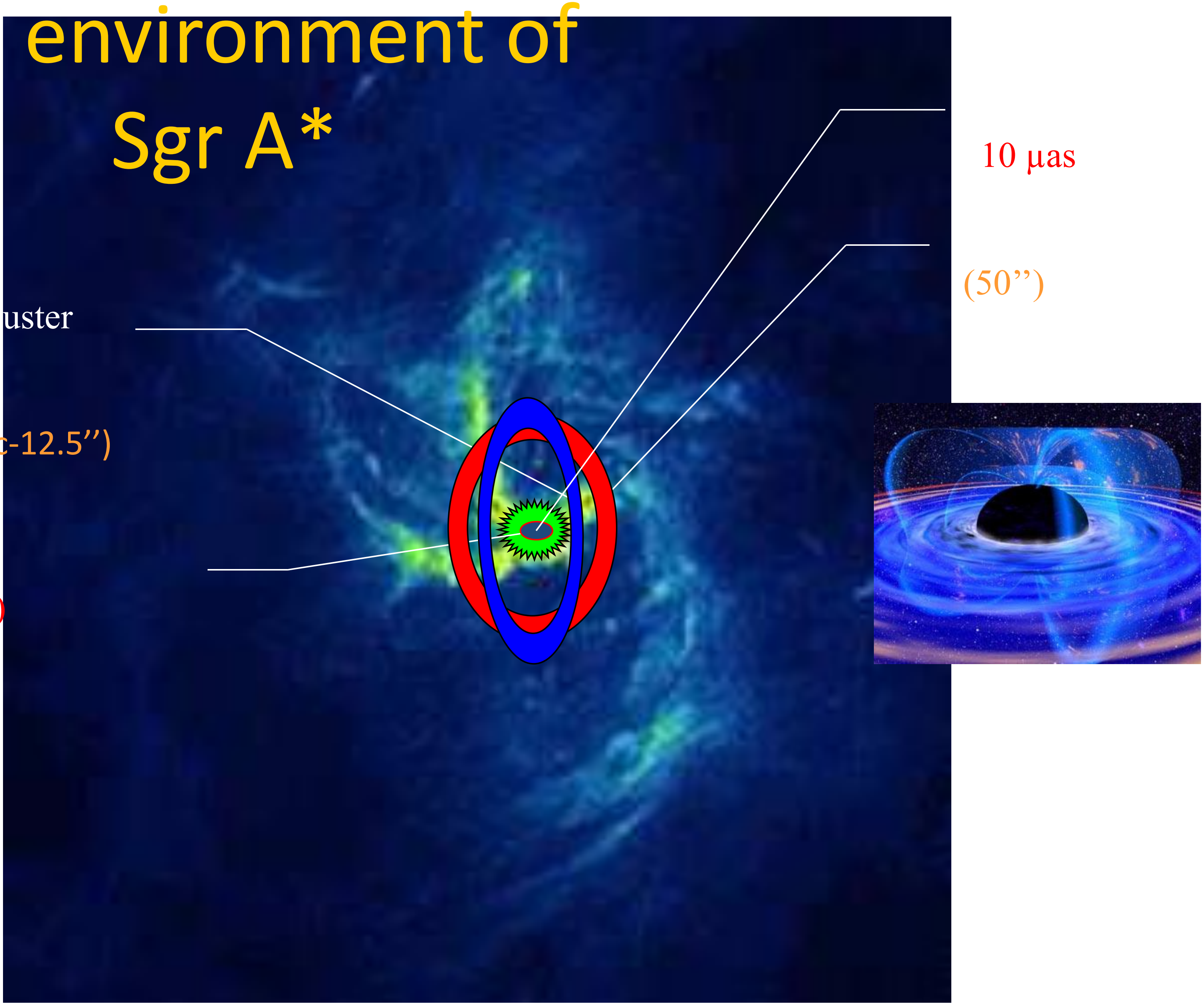
For the vast majority of objects thought to be black holes such information is not available

  - 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

The environment of Sgr A*



uster

(0.5 pc-12.5”)

(12-400 mas)

10 µas

(50”)

1973ApJ...183..237C

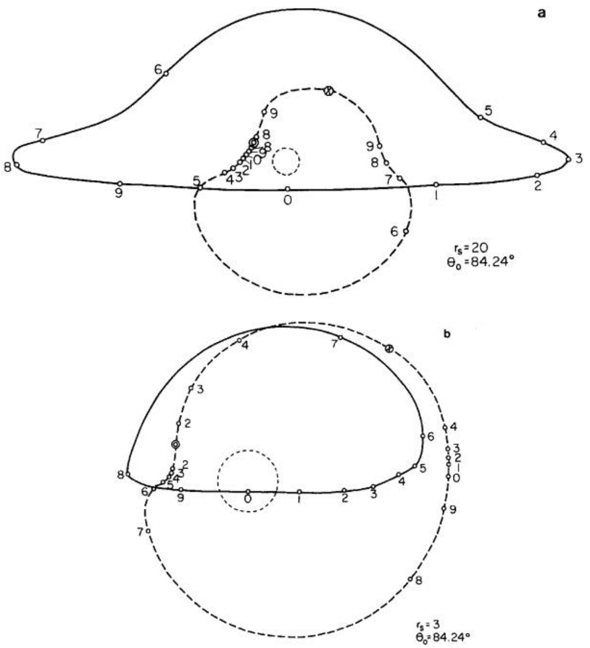


FIG. 8.—Apparent positions of the two brightest images as functions of time for two orbital radii and an observer at a polar angle $\theta_0 = 84\overset{\circ}{.}24$. The small, dashed circle in each plot is the locus $\alpha^2 + \beta^2 = 1$ and gives the scale of the plot. The direct image moves along 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 ⊗. 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.

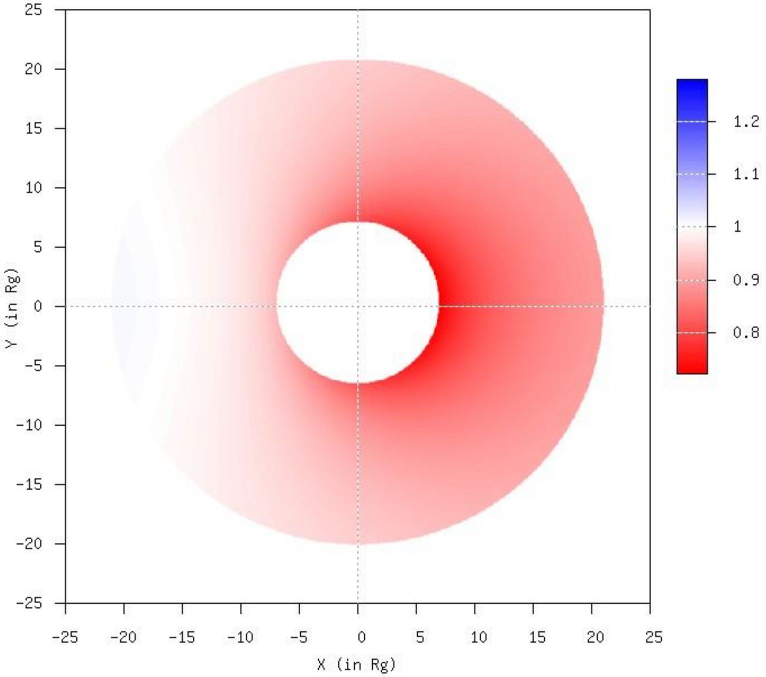
As the apparent position of the image seen by the distant observer changes, so does the corresponding direction of emission in the local rest frame of the star. If the instantaneous direction of emission of the beam of radiation which reaches the observer is represented by a point in figure 3 (for $r_s = 1.5$), this point moves along the $\cos\theta_0 =$ 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 ⊗. For $r_s = 1.5$ there is no retrograde image and, hence, no creation and destruction of images for observers with $\theta_0 \lesssim 40°$.

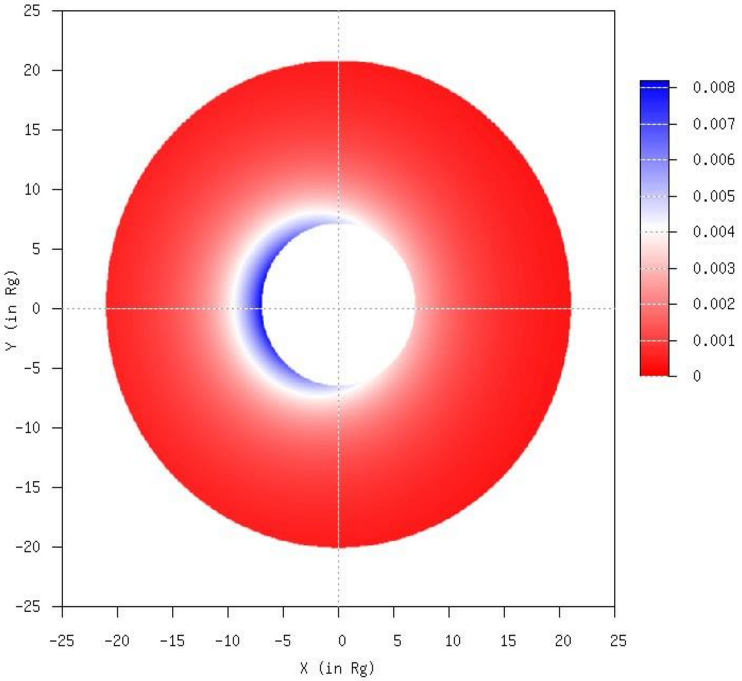
When r_s is not much larger than unity, the images move very slowly on the parts of the curves nearest the backward ϕ-direction and very rapidly on the remainder of the

Schwarzschild black hole images (P. Jovanovic , L.C. Popovic & A.F.Z. in preparation)

- θ=15 deg
- Redshift map

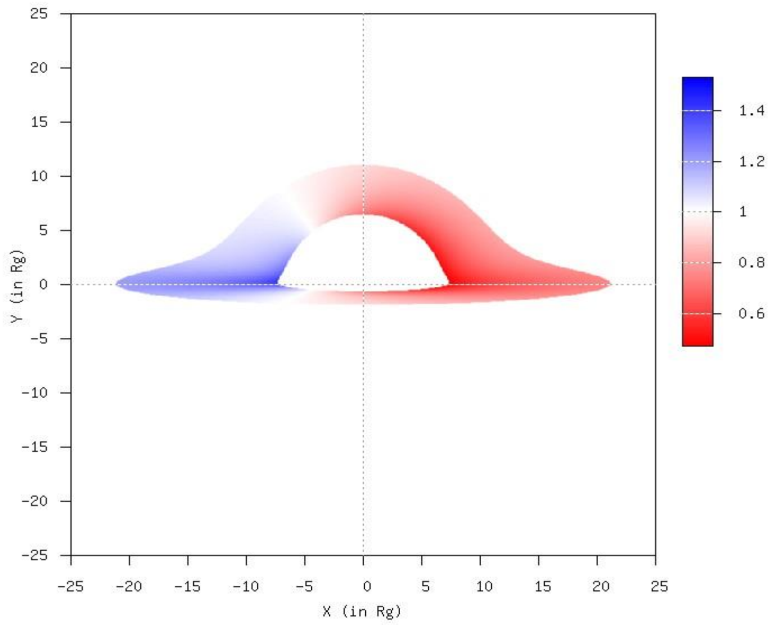
Intensity map

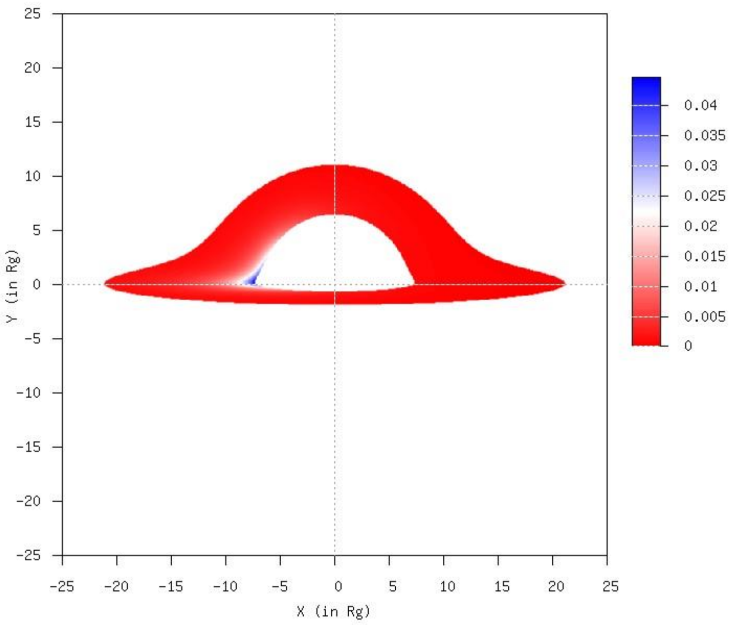




Schwarzschild black hole images: $\theta=85$ deg

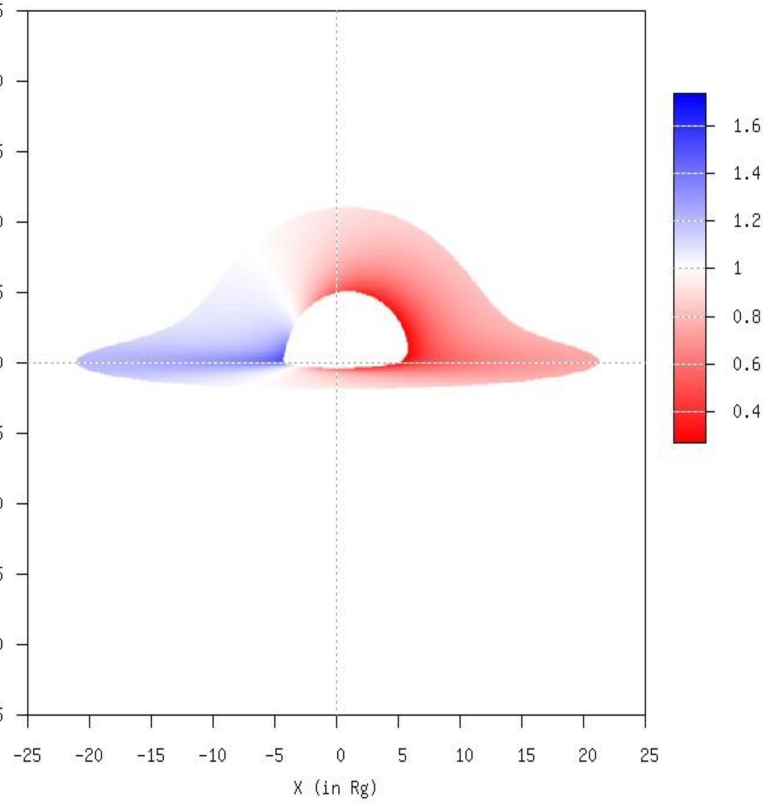
- Redshift map
- Intensity map

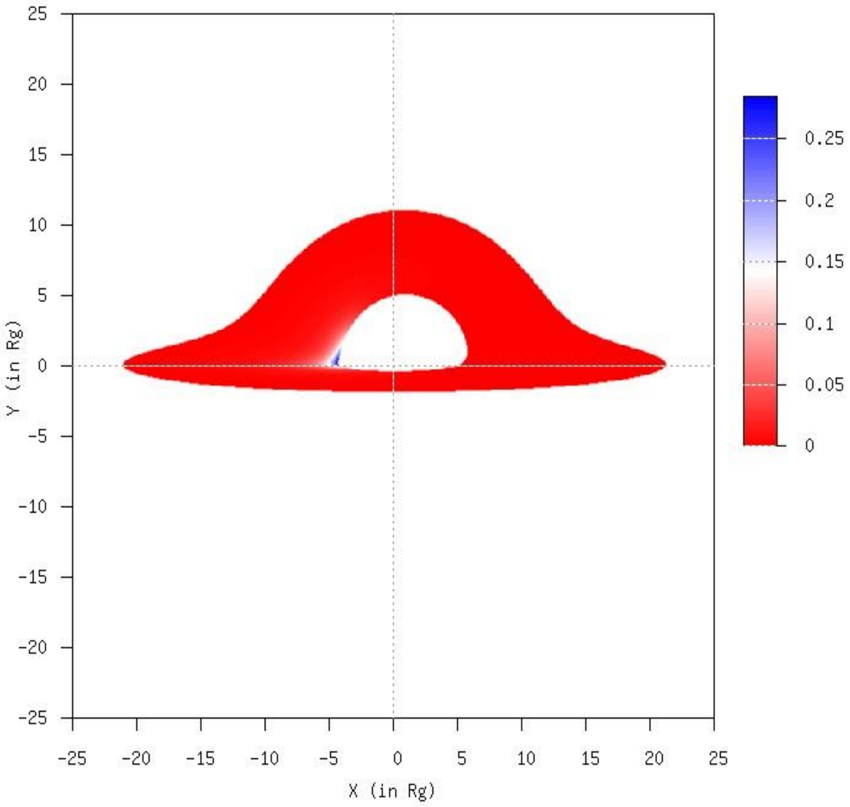




Kerr black hole images (a=0.75): θ**=85 deg**

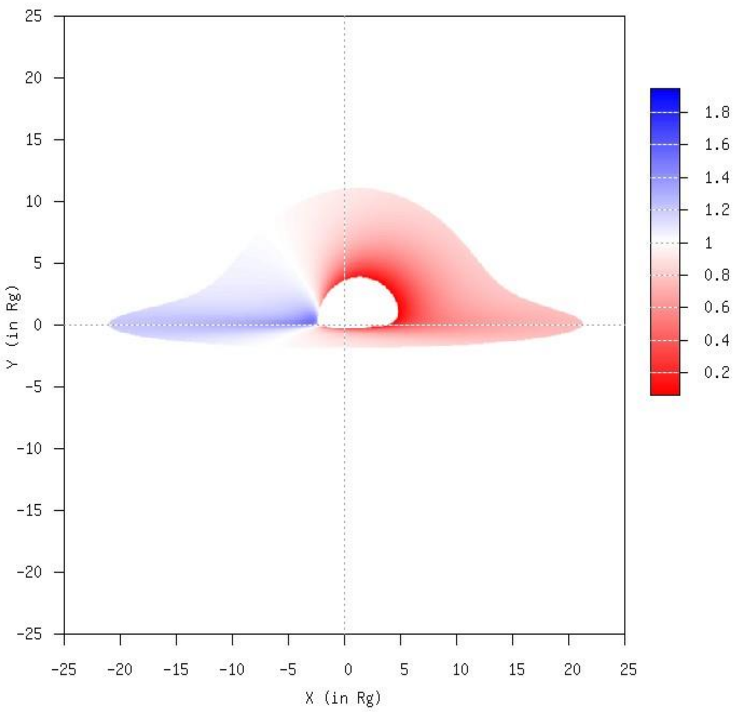
- Redshift map
- Intensity map



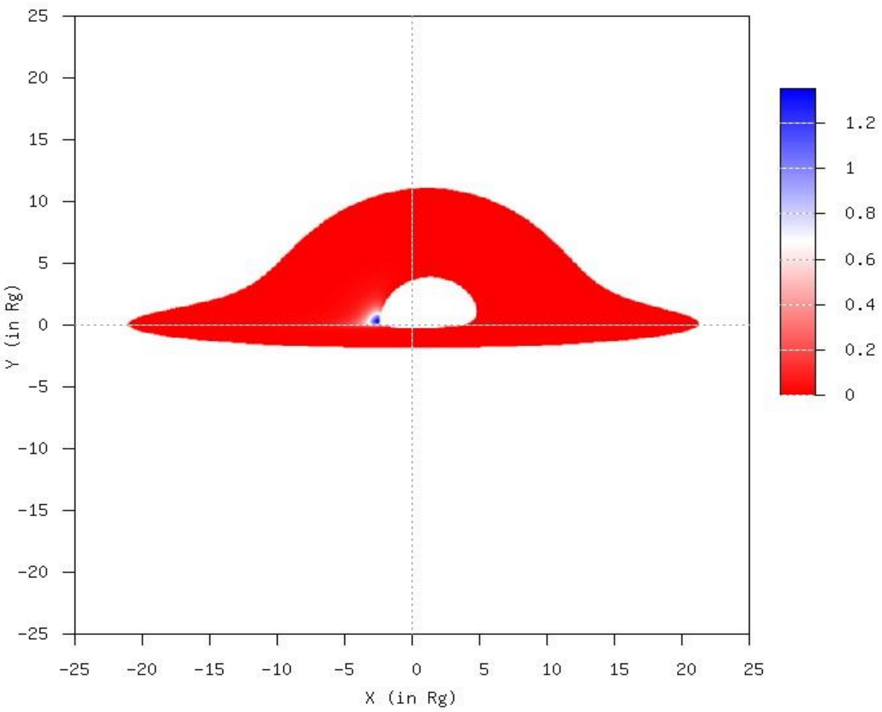


Kerr black hole images ($a=0.99$): $\theta=$**85 deg**

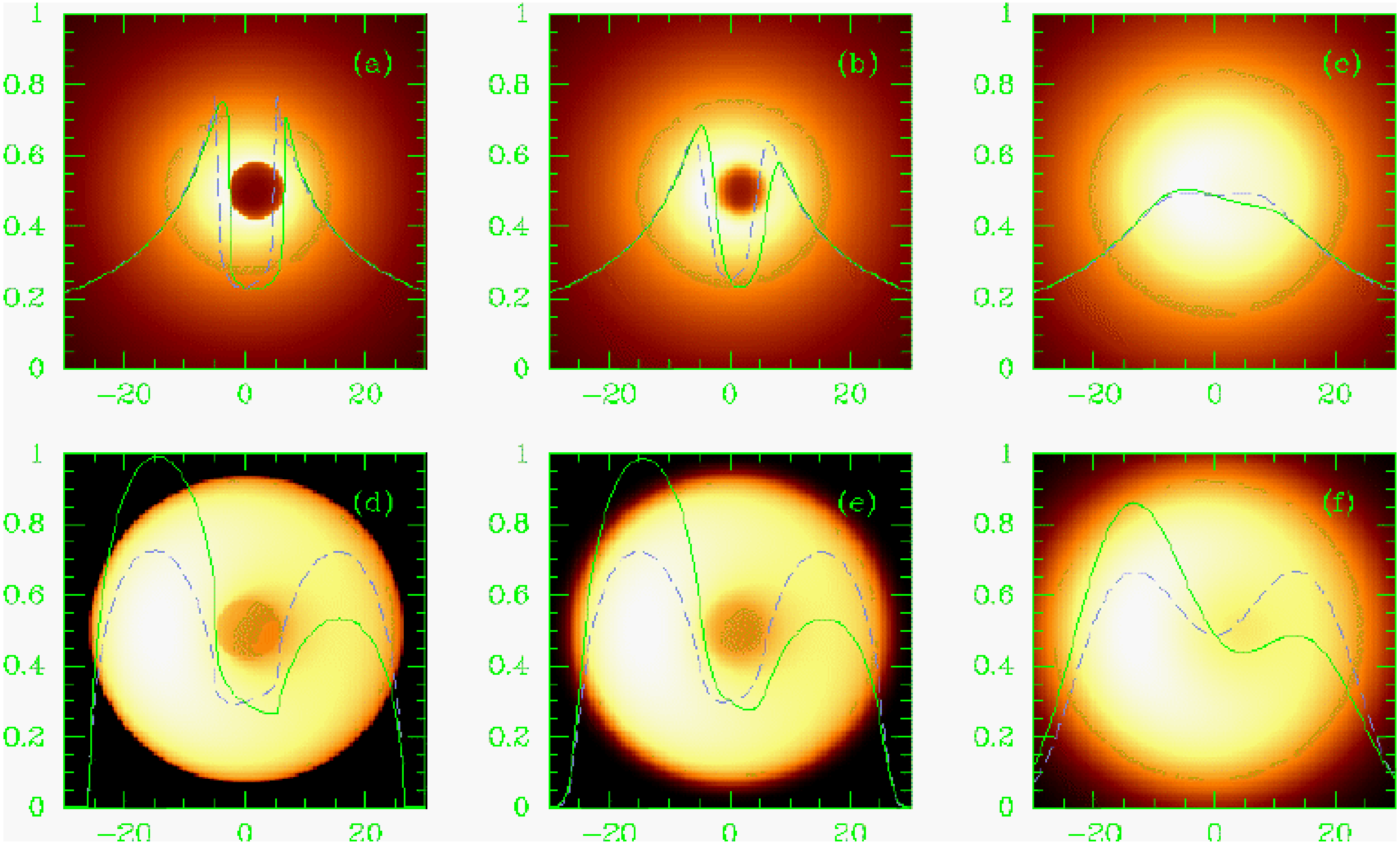
- Redshift map



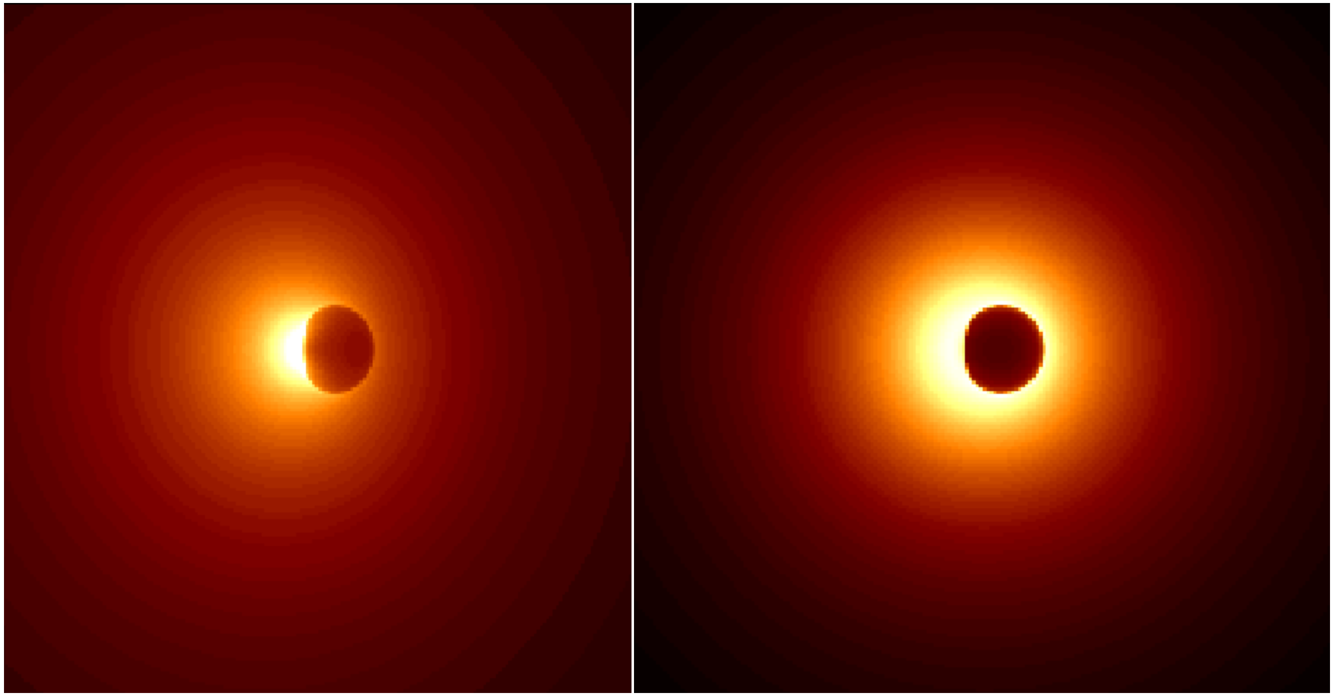
- Intensity map

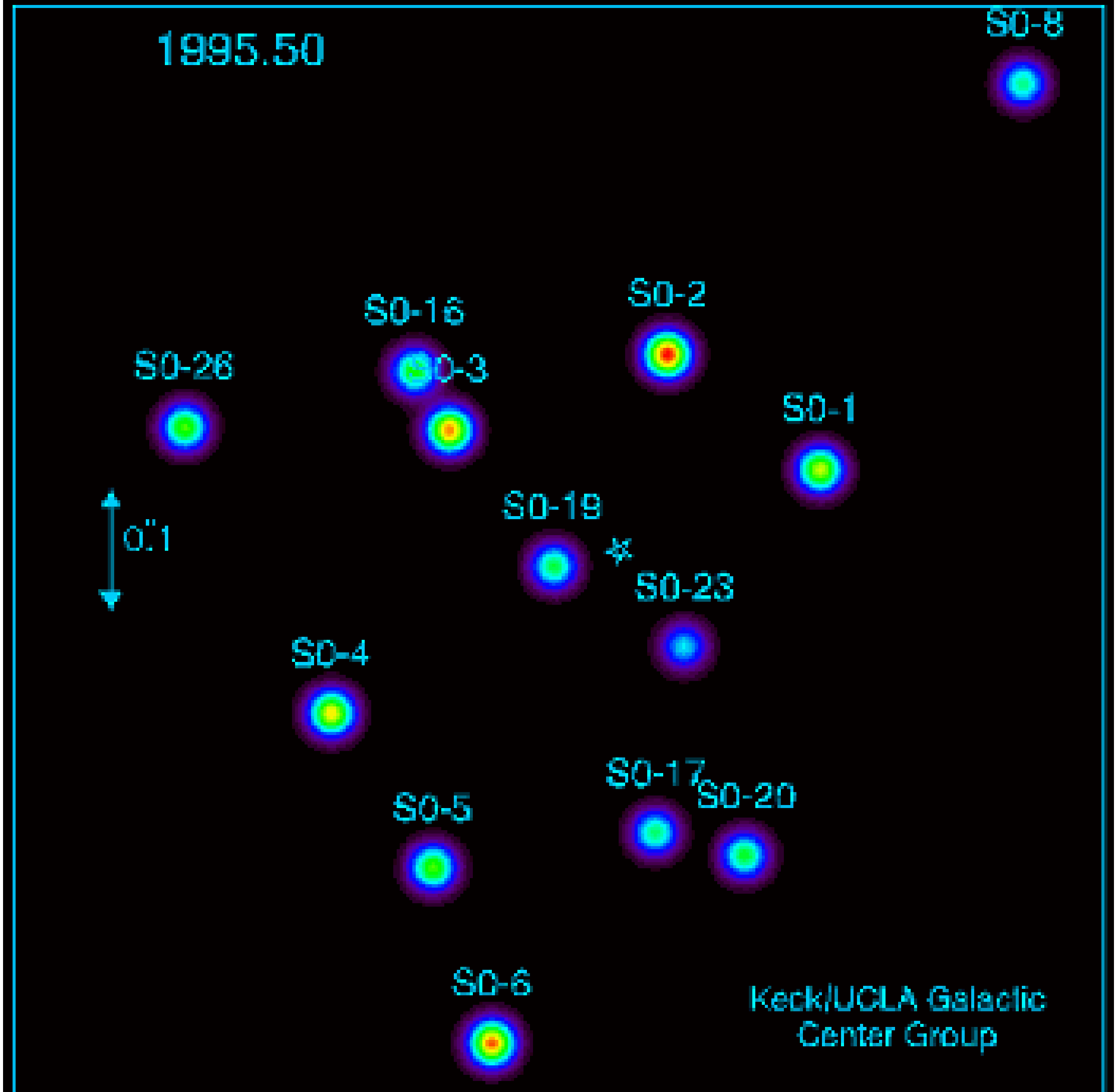


Falcke, Melia, Agol



Shadows from Melia





1995.50

Keck/UCLA Galactic
Center Group

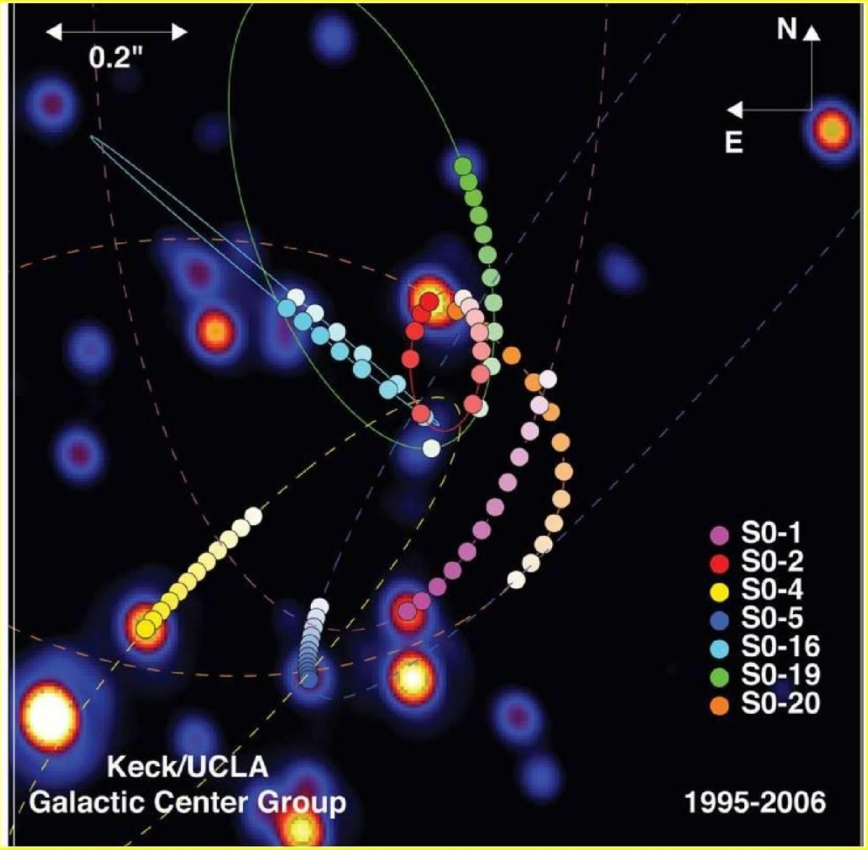


Figure 19: Bright stars near the Galactic Centre.

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Preprint typeset using LaTeX style emulateapj v. 03/07/07

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

S. Gillessen[1], F. Eisenhauer[1], S. Trippe[1], T. Alexander[3], R. Genzel[1,2], F. Martins[4], T. Ott[1]

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 $\approx 300\,\mu$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 $(4.31 \pm 0.06|_{\rm stat} \pm 0.36|_{R_0}) \times 10^6 M_\odot$ 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 $(3.95 \pm 0.06) \times 10^6 (R_0/8\,{\rm kpc})^{2.19} M_\odot$. 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

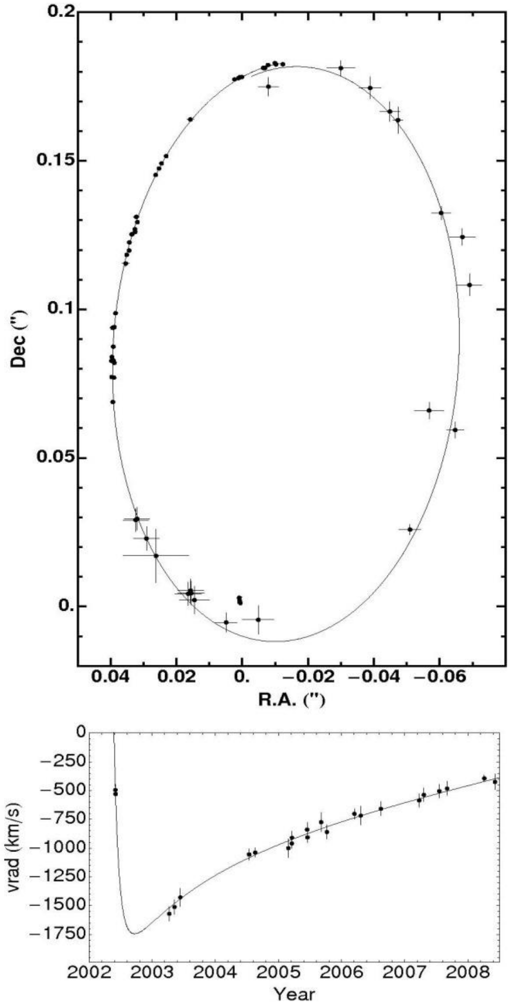


FIG. 13.— Top: The S2 orbital data plotted in the combined coordinate system and fitted with a Keplerian model in which the velocity of the central point mass and its position were free fit parameters. The non-zero velocity of the central point mass is the reason why the orbit figure does not close exactly 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.

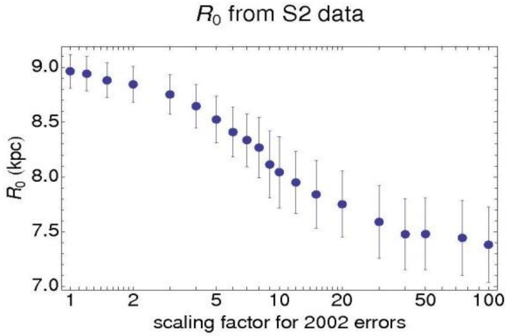


FIG. 14.— Fitted value of R_0 for various scaling factors of the S2 2002 data, using a fit with the coordinate system priors. The factor by which the 2002 astrometric errors of the S2 data is scaled up strongly influences the distance. The mean factor determined in Figure 9 is ≈ 7, corresponding to $R_0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

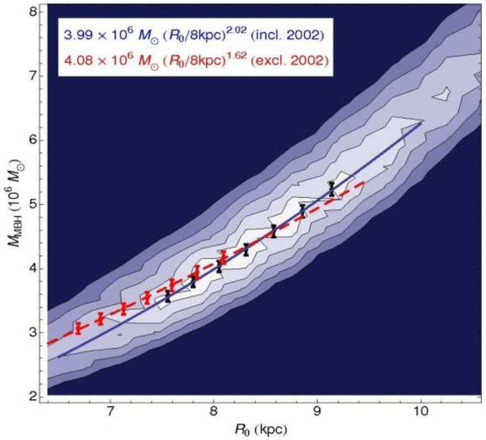


FIG. 15.— Contour plot of χ^2 as function of R_0 and central point mass. The two parameters are strongly correlated. The contours are generated from the S2 data including the 2002 data; fitting at each point all other parameters both of the potential and the orbital elements. The black dots indicate 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

An Expanded View of the Universe

Science with the European Extremely Large Telescope

Black Holes

Black holes are some of the most bizarre objects in the Universe, challenging the imaginations of even the most creative scientists. They are places where gravity trumps all other forces in the Universe, pushing our understanding of physics to the limit. Even more strangely, supermassive black holes seem to play a key role in the formation of galaxies and structures in the Universe.

Galactic Centre

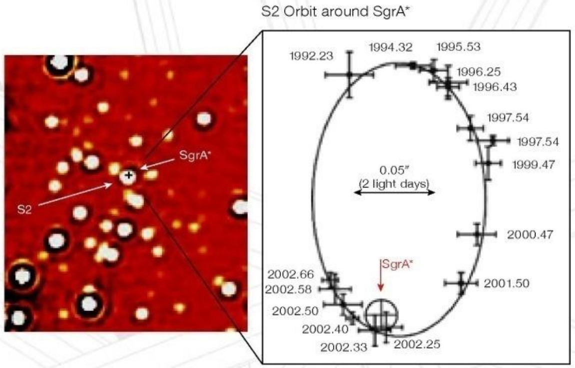
Over the last 15 years or so, an enormous amount of work has gone into improving our understanding of the closest supermassive black hole — Sagittarius A* at the centre of the Milky Way.

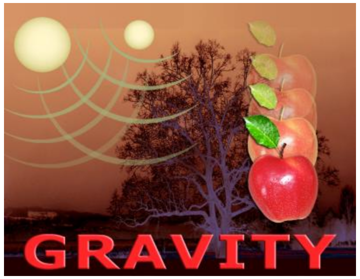
Technological progress, in particular in the areas of adaptive optics and high angular resolution with ground-based 8-metre-class telescopes, has allowed impressive progress in understanding supermassive black holes and their surroundings. Key progress was made in proving the very existence of a supermassive black hole at the centre of the Milky Way, in refining our knowledge of how matter falls into black holes, and in identifying gas discs and young stars in the immediate vicinity of the black hole. The Galactic Centre was thus established as the most important laboratory for the study of supermassive black holes and their surroundings.

But its potential for progress in fundamental physics and astrophysics is far from being fully exploited. The Galactic Centre remains the best place to test general relativity directly in a strong gravitational field. The E-ELT will enable extremely accurate measurements of the positions of stars (at the 50–100 microarcsecond level over fields of tens of arcseconds), as well as radial velocity measurements with about 1 km/s precision, pushing our observations ever closer to the black hole event horizon. Stars can then be discovered at 100 Schwarzschild radii, where orbital velocities approach a tenth of the speed of light. This is more than ten times closer than can be achieved with the current generation of telescopes. Such stellar probes will allow us to test the predicted relativistic signals of black hole spin and the gravitational redshift caused by the black hole, and even to detect gravitational wave effects. Further out, the dark matter distribution around the black hole, predicted by cold dark matter cosmologies (ΛCDM), can be explored. The distance to the Galactic Centre can be measured to 0.1%, constraining in turn the size and shape of the galactic halo and the Galaxy's local rotation speed to unprecedented levels. Crucial progress in our understanding of the interaction of the black hole with its surroundings will be made. The puzzling stellar cusp around the Galactic Centre, as well as the observed star formation in the vicinity of the black hole will be studied in detail for the first time.

Left: Very Large Telescope (VLT) observations have revealed that the supermassive black hole closest to us is located in the centre of the Milky Way.

The Milky Way's central supermassive black hole has been weighed by measuring the proper motions of stars in its vicinity.





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

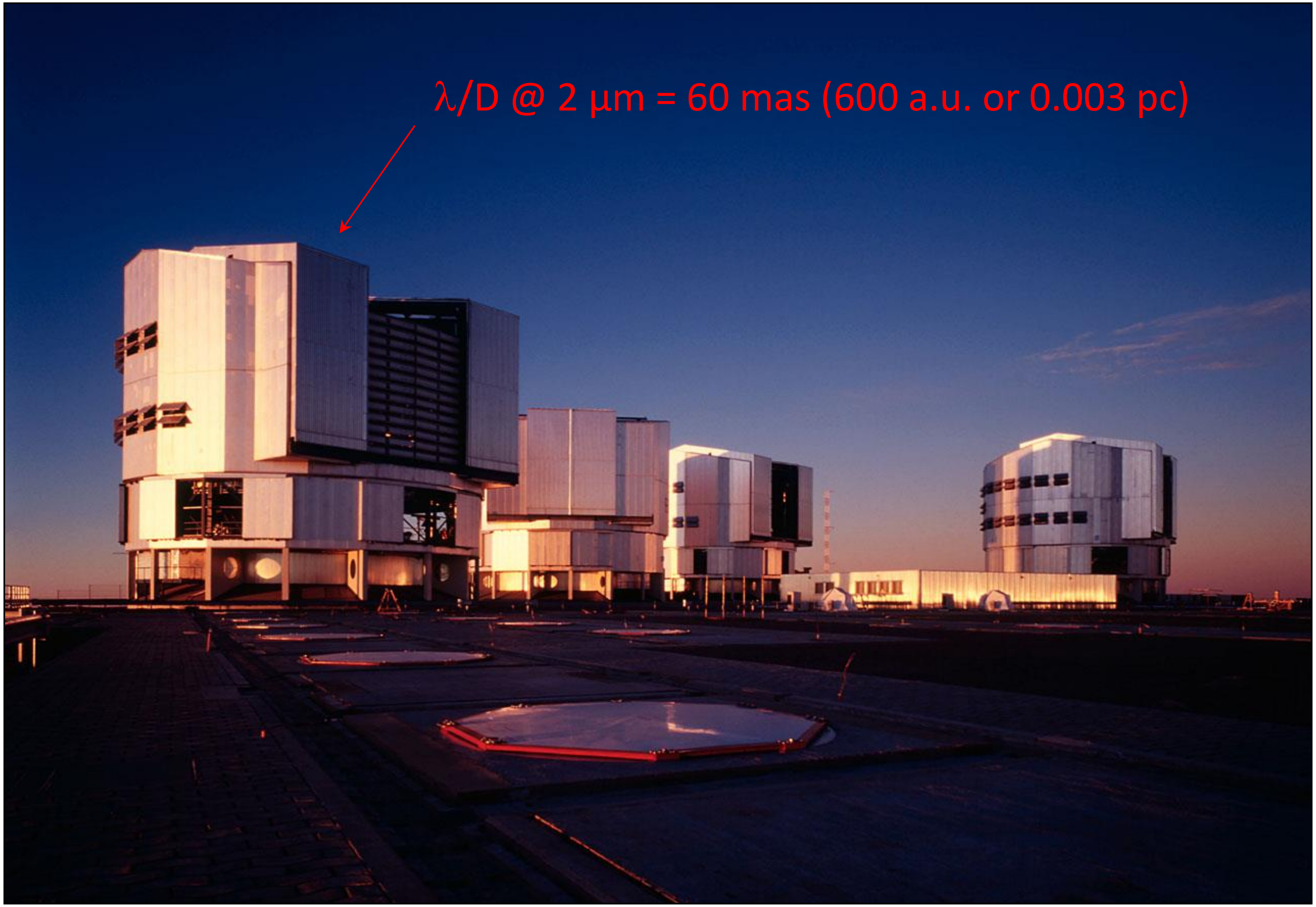
Guy Perrin and the GRAVITY consortium

l'Observatoire de Paris
LESIA

Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

Thursday 25 March 2011

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


λ/D @ 2 µm = 60 mas (600 a.u. or 0.003 pc)

GRAVITY – 4 giant telescope interferometer
(***G***eneral ***R***elativity vi***A*** ***V***lt ***I***nterferome***T***r***Y***)

λ/B @ 2 µm = 3 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 ~ 1 R_s 10 µas

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

Scale ~ 100 R_s 1 mas