Black holes: from theory to the first image

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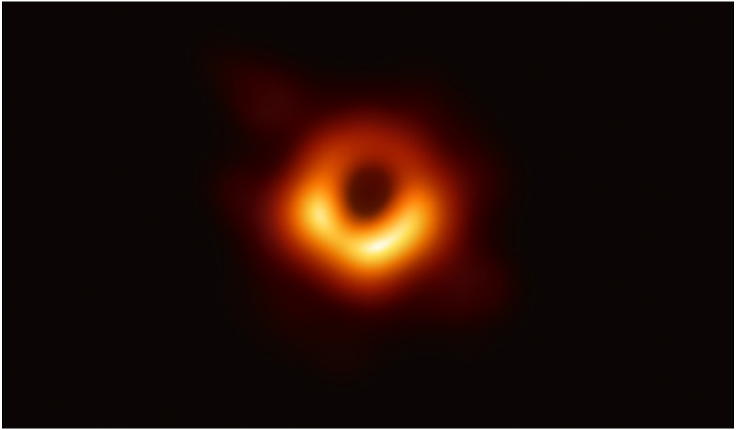
GANIL
Université Caen Normandie
Caen, France
17 June 2019

10 April 2019: first image released!



Event Horizon Telescope image of M87 central black hole

[EHT Collaboration, ApJ **875**, L1 (2019)]

Outline

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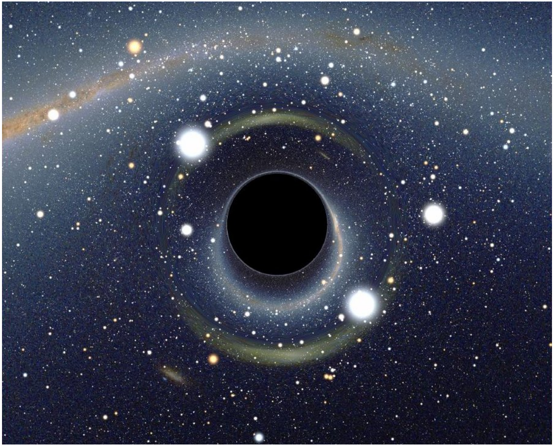
Qu'est-ce qu'un trou noir ?



[Alain Riazuelo, 2007]

Une définition en quelques mots:

Un **trou noir** est une région de l'espace-temps d'où rien, pas même la lumière, ne peut s'échapper.

La frontière (immatérielle) entre l'intérieur du trou noir et le reste de l'Univers est appelée **horizon des événements**.

Black hole prehistory...

$$\boxed{V_{\rm esc} > c} \iff \frac{2GM}{R} > c^2 \iff \frac{2G}{R} \times \frac{4}{3}\pi R^3 \rho > c^2 \iff \boxed{R > \sqrt{\frac{3c^2}{8\pi G\rho}}}$$

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John Michell (1784)

"If there should really exist in nature any bodies, whose density is not less than that of the sun, and whose diameters are more than 500 times the diameter of the sun, since their light could not arrive at us, ..., we could have no information from sight"

[Phil. Trans. R. Soc. Lond. **74**, 35 (1784)]

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Pierre Simon de Laplace (1796)

"Un astre lumineux, de la même densité que la Terre, et dont le diamètre serait 250 fois plus grand que le Soleil, ne permettrait, en vertu de son attraction, à aucun de ses rayons de parvenir jusqu'à nous. Il est dès lors possible que les plus grands corps lumineux de l'univers puissent, par cette cause, être invisibles."

[Exposition du système du monde (1796)]

Limits of the Newtonian concept of black hole

- No privileged role of the velocity of light in Newtonian theory: nothing forbids $V > c \Longrightarrow$ Michell & Laplace's "invisible stars" are not causally disconnected from the rest of the Universe

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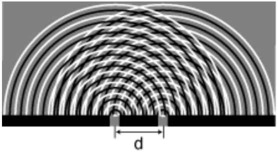
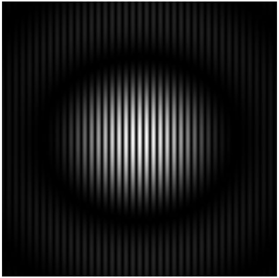
- $V_{\rm esc} \sim c \Longrightarrow$ gravitational potential energy $\sim$ mass energy Mc^2 $\Longrightarrow$ a *relativistic* theory of gravitation is necessary !
- No clear action of the gravitation field on electromagnetic *waves* in Newtonian gravity





[R. Taillet]

104 years ago: a relativistic theory of gravitation

844 Sitzung der physikalisch-mathematischen Klasse vom 25. November 1915

Die Feldgleichungen der Gravitation.

Von A. Einstein.

In zwei vor kurzem erschienenen Mitteilungen[1] habe ich gezeigt, wie man zu Feldgleichungen der Gravitation gelangen kann, die dem Postulat allgemeiner Relativität entsprechen, d. h. die in ihrer allgemeinen Fassung beliebigen Substitutionen der Raumzeitvariabeln gegenüber kovariant sind.

$$\boxed{\boldsymbol{R} - \frac{1}{2} R\, \boldsymbol{g} = \frac{8\pi G}{c^4} \boldsymbol{T}}$$

[A. Einstein, Sitz. Preuss. Akad. Wissenschaften Berlin, 844 (1915)]

The Schwarzschild solution (1915)

Karl Schwarzschild (letter to Einstein 22 Dec. 1915; publ. submitted 13 Jan 1916)
Über das Gravitationsfeld eines Massenpunktes nach der Einsteinschen Theorie, Sitz. Preuss. Akad. Wiss., Phys. Math. Kl. 1916, 189 (1916)

$\Longrightarrow$ First exact non-trivial solution of Einstein equation found while seeking the gravitational field of a point mass:

$$\mathrm{d}s^2 = -\left(1 - \frac{2M}{r}\right) c^2 \mathrm{d}t^2 + \left(1 - \frac{2M}{r}\right)^{-1} \mathrm{d}r^2 + r^2 \left(\mathrm{d}\theta^2 + \sin^2\theta \, \mathrm{d}\varphi^2\right)$$

M: gravitational mass of the “point mass”

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- Black hole character recognized in 1920 (Alexander Anderson)
- Formation by gravitational collapse: Georges Lemaître (1932), Robert Oppenheimer & Hartlad Snyder (1939)

The Kerr solution (1963)

Roy Kerr (1963)

Expression in Boyer-Lindquist coordinates:

$$
\begin{aligned}
g_{\alpha\beta}\,\mathrm{d}x^\alpha\,\mathrm{d}x^\beta = \; & -\left(1 - \frac{2Mr}{\rho^2}\right)\mathrm{d}t^2 - \frac{4Mar\sin^2\theta}{\rho^2}\,\mathrm{d}t\,\mathrm{d}\varphi + \frac{\rho^2}{\Delta}\,\mathrm{d}r^2 \\
& + \rho^2\mathrm{d}\theta^2 + \left(r^2 + a^2 + \frac{2Ma^2r\sin^2\theta}{\rho^2}\right)\sin^2\theta\,\mathrm{d}\varphi^2
\end{aligned}
$$

where $\rho^2 := r^2 + a^2\cos^2\theta$, $\Delta := r^2 - 2Mr + a^2$ and $\boxed{r \in (-\infty, \infty)}$

→ spacetime manifold: $\mathscr{M} = \mathbb{R}^2 \times \mathbb{S}^2 \setminus \{r = 0 \ \& \ \theta = \pi/2\}$

→ describes a rotating black hole

→ 2 parameters: M: gravitational mass; $a := J/M$ reduced angular momentum

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$$g_{\alpha\beta}\, dx^\alpha\, dx^\beta = -\left(1 - \frac{2Mr}{\rho^2}\right) dt^2 - \frac{4Mar\sin^2\theta}{\rho^2}\, dt\, d\varphi + \frac{\rho^2}{\Delta}\, dr^2 + \rho^2 d\theta^2 + \left(r^2 + a^2 + \frac{2Ma^2 r\sin^2\theta}{\rho^2}\right) \sin^2\theta\, d\varphi^2$$

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→ Schwarzschild solution recovered as the subcase $a = 0$ (static limit)

The no-hair theorem: all black holes are Kerr

Dorochkevitch, Novikov & Zeldovitch (1965), Israel (1967), Carter (1971), Hawking (1972)

Within 4-dimensional general relativity, a *stationary* black hole in an otherwise empty universe is necessarily a Kerr-Newmann black hole, which is an electro-vacuum solution of Einstein equation described by only 3 numbers:

- the total mass M
- the total specific angular momentum $a = J/M$
- the total electric charge Q

$\Longrightarrow$ *"a black hole has no hair"* (John A. Wheeler)

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Other special cases:

- $a = 0$: Reissner-Nordström solution (1916, 1918)
- $a = 0$ and $Q = 0$: Schwarzschild solution (1916)
- $a = 0$, $Q = 0$ and $M = 0$: Minkowski metric (1907)

Physical meaning of the parameters M and J

- mass M: *not* a measure of the "amount of matter" inside the black hole, but rather a *characteristic of the external gravitational field*
  $\rightarrow$ measurable from the orbital period of a test particle in far circular orbit around the black hole *(Kepler's third law)*

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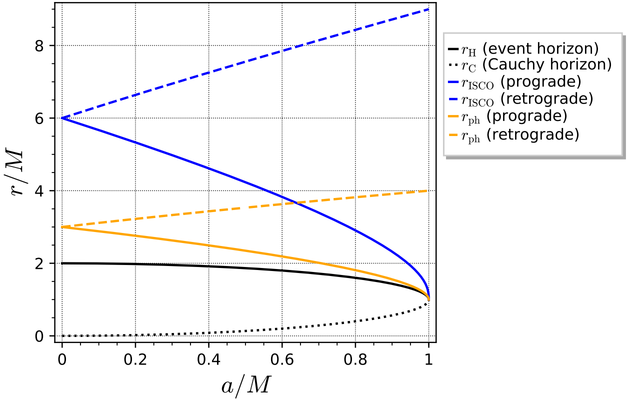
Remark: the radius of a black hole is not a well defined concept: it *does not* correspond to some distance between the black hole "centre" and the event horizon. A well defined quantity is the area of the event horizon, A.
The radius can be then defined from it: for a Schwarzschild black hole:

$$R := \sqrt{\frac{A}{4\pi}} = \frac{2GM}{c^2} \simeq 3 \left(\frac{M}{M_\odot} \right) \ \mathrm{km}$$

Circular orbits in the equatorial plane of a Kerr black hole

Circular orbits exist and are stable for $r \geq r_{\rm ISCO} = \begin{cases} 6M & \text{for } a = 0 \\ M & \text{for } a = M \end{cases}$



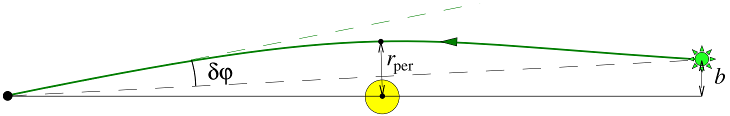
$r_{\rm ISCO}$: radius of the innermost stable circular orbit

$r_{\rm ph}$: radius of circular photon orbit

- $a/M = 0$: Schwarzschild black hole (non-rotating)
- $a/M = 1$: extreme Kerr black hole (maximally rotating)

Outline

Light bending in a gravitational field



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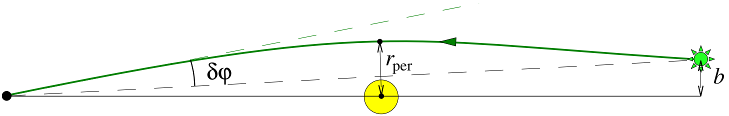

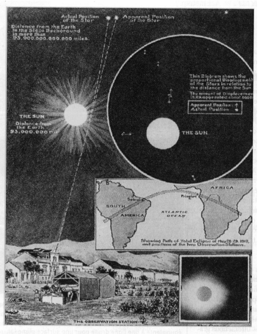

1919 solar eclipse (observed by A. Eddington)

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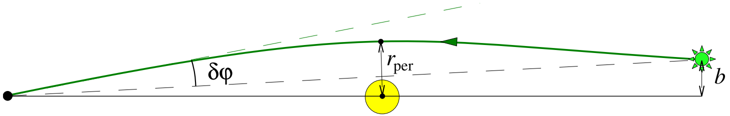

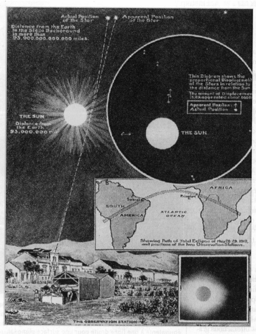

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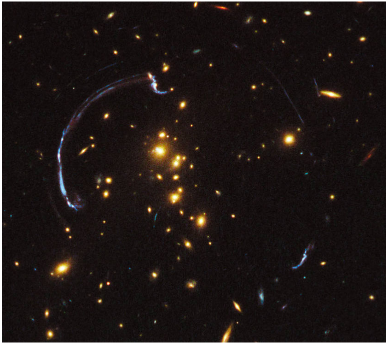


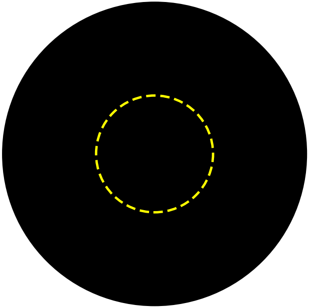
[HST (Nasa/ESA/STSCI)]
Gravitational lensing by galaxy cluster

David Hilbert (1917): shadow of a Schwarzschild black hole

Light rays with impact parameter $b < 3\sqrt{3}M \simeq 2.60M$ are absorbed by the black hole

[Hilbert, Nachricht. König. Gesel. Wissen. Göttingen, Mathematisch-Ph 1917, p. 53]

$\Longrightarrow$ black hole "shadow"



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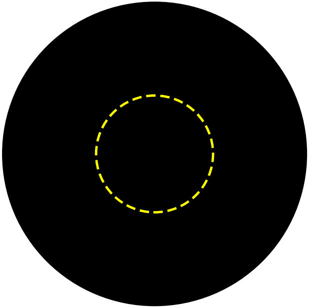

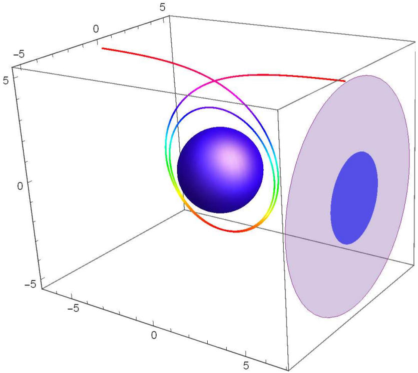

Trajectory of a photon arising from the edge of the black hole shadow

[Dokuchaev, IJMPD **28**, 1941005 (2019)]

James M. Bardeen (1972): shadow of a Kerr black hole

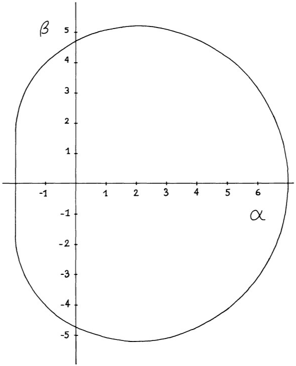

Figure 6. The apparent shape of an extreme ($a = m$) Kerr black hole as seen by a distant observer in the equatorial plane, if the black hole is in front of a source of illumination with an angular size larger than that of the black hole.

Shadow of a maximally rotating Kerr black hole

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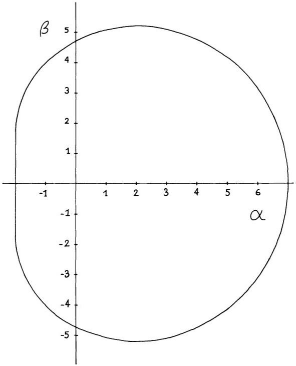

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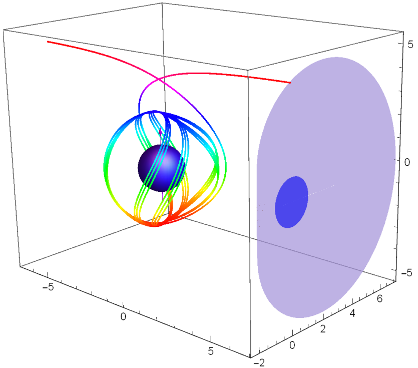

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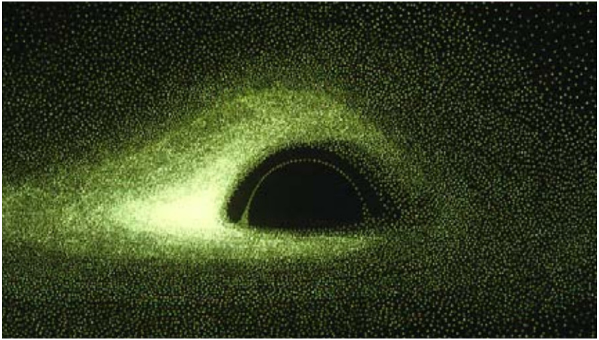
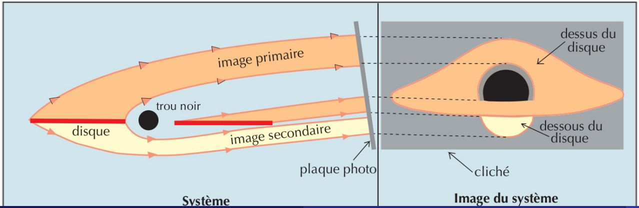
Jean-Pierre Luminet (1979): the first (computed) image

Groupe d'Astrophysique Relativiste, Observatoire de Paris, Meudon



First image of an accretion disk around a Schwarzschild black hole

[Luminet, A&A **75**, 228 (1979)]



Light ray trajectories

https://luth.obspm.fr/~luminet/

Jean-Alain Marck (1991, 1996): the first movie

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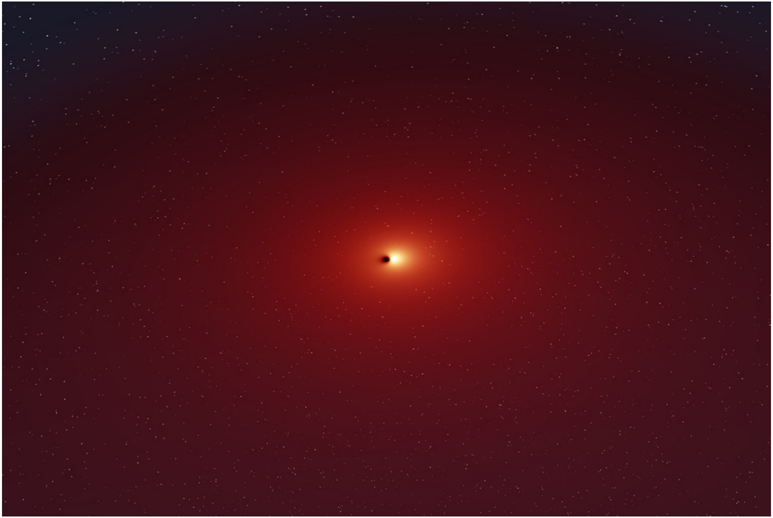

Flight to a black hole, [Marck, CQG **13**, 393 (1996)]

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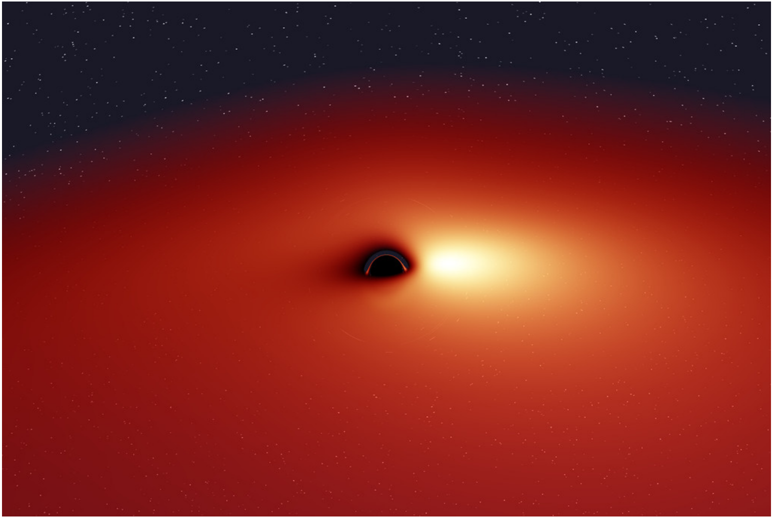

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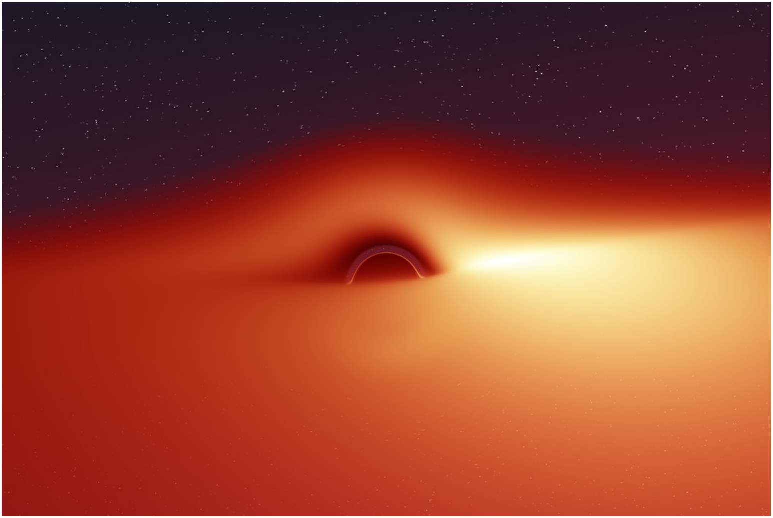

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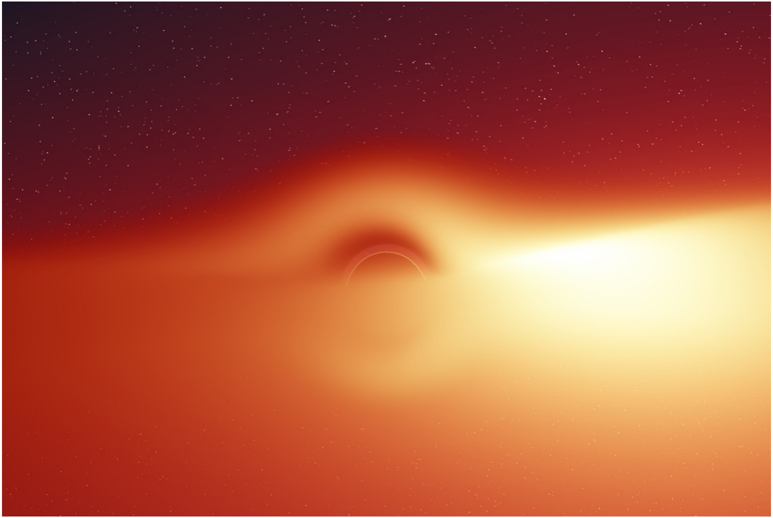

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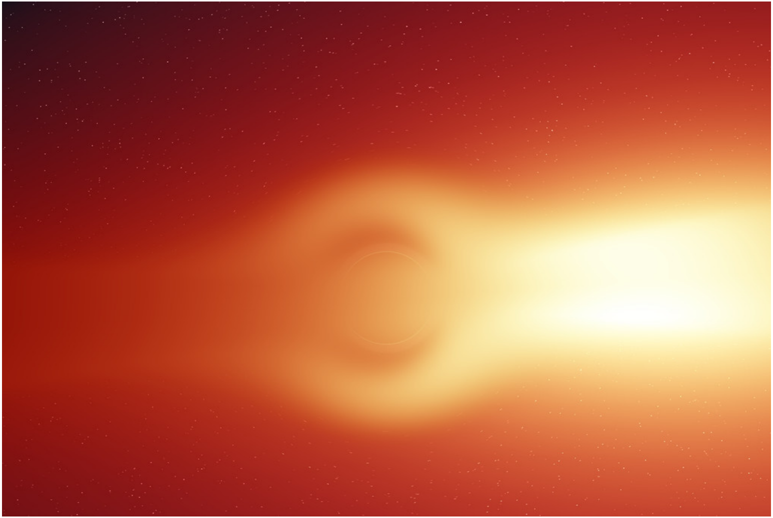

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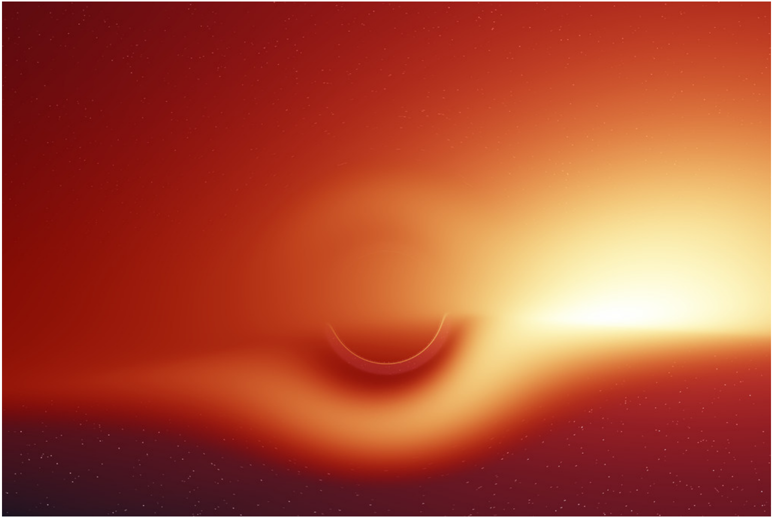

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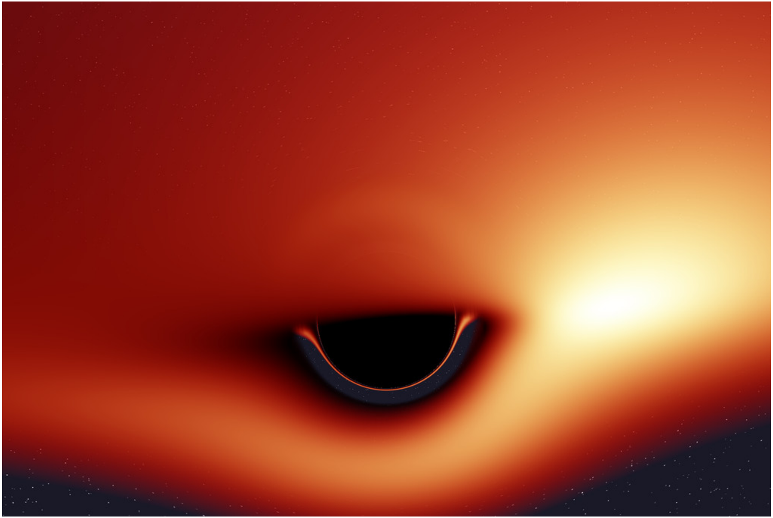

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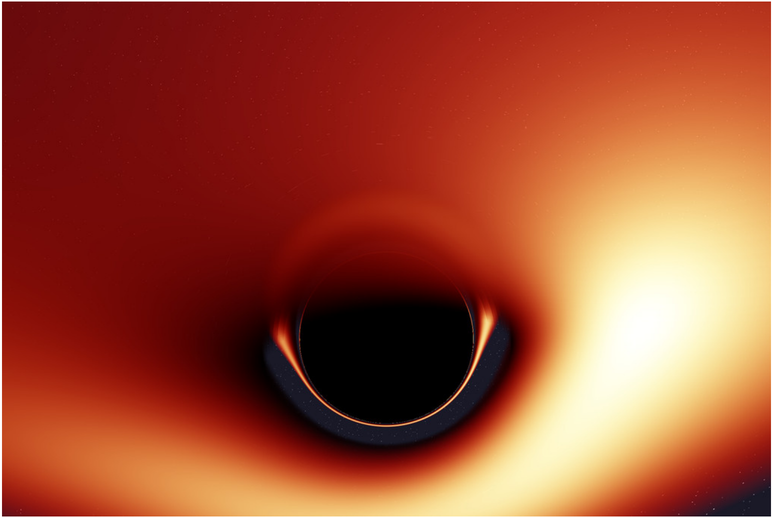

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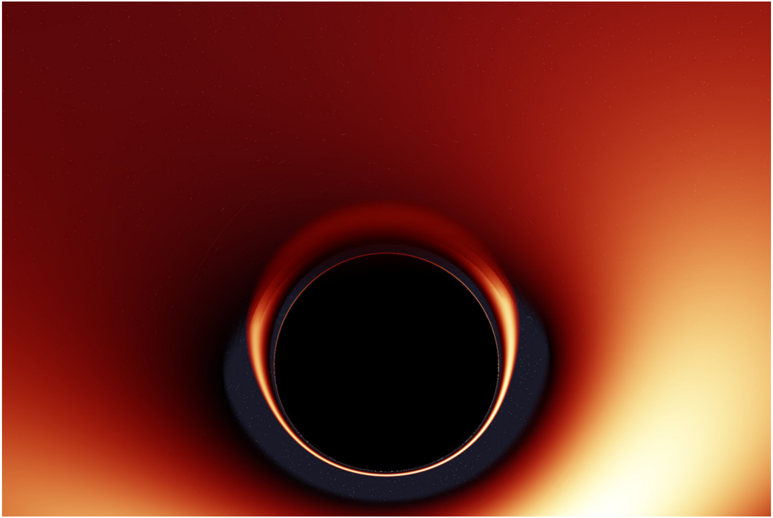

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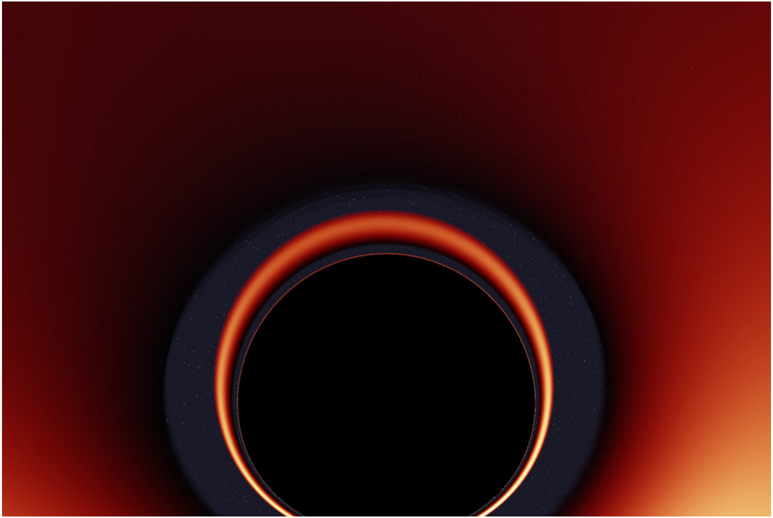

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Jean-Alain Marck (1991, 1996): the first movie

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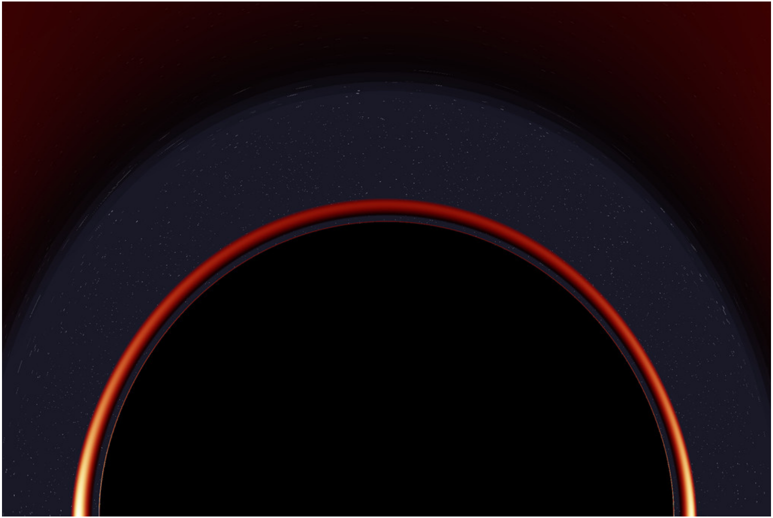
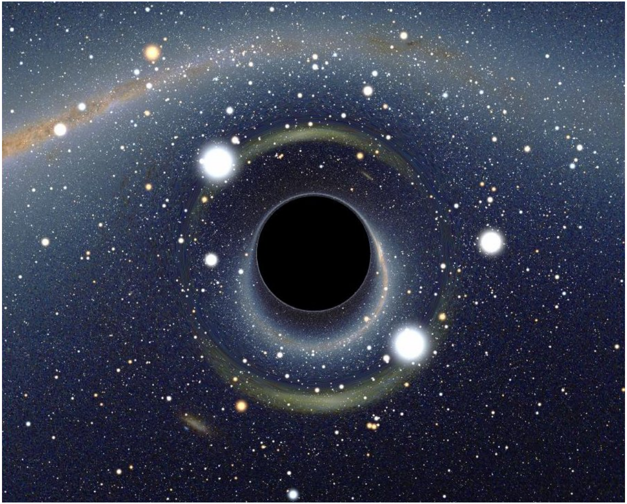


Flight to a black hole, [Marck, CQG **13**, 393 (1996)]

Alain Riazuelo (2007): the black hole in the sky

Institut d'Astrophysique de Paris

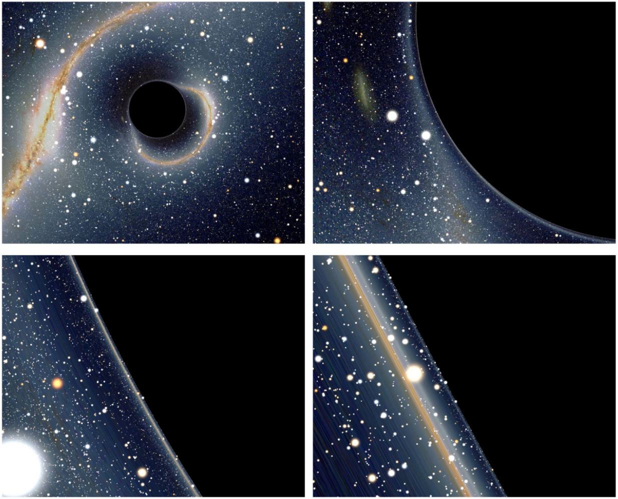


Schwarzschild black hole

[Riazuelo (2007)]; [Riazuelo, IJMPD **28**, 1950042 (2019)]

Alain Riazuelo (2007): very high precision computations

Institut d'Astrophysique de Paris

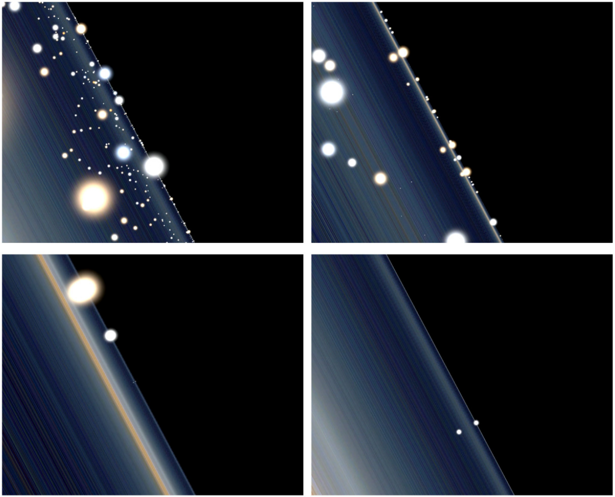


Zoom 1

[Riazuelo (2007)]; [Riazuelo, IJMPD **28**, 1950042 (2019)]

Alain Riazuelo (2007): very high precision computations

Institut d'Astrophysique de Paris



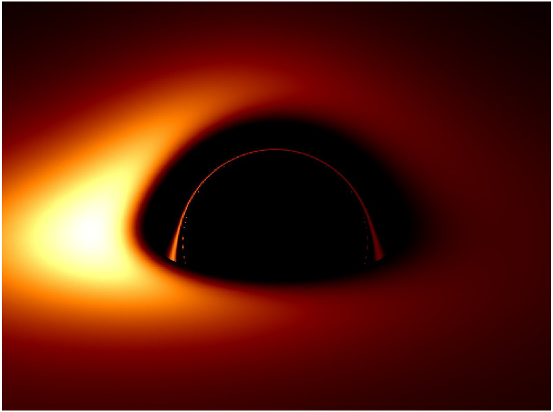
Zoom 2

[Riazuelo (2007)]; [Riazuelo, IJMPD **28**, 1950042 (2019)]

GYOTO: Frédéric Vincent, Thibaut Paumard et al. (2011)

LESIA & LUTH, Observatoire de Paris, Meudon

https://gyoto.obspm.fr/



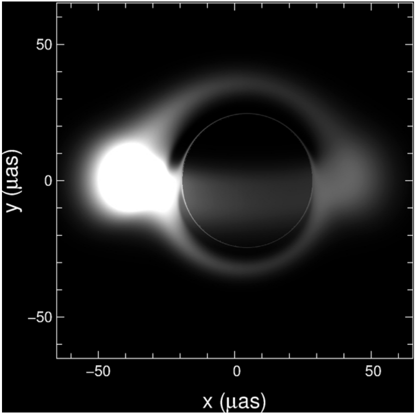
Thin accretion disk around a Schwarzschild black hole

[Vincent, Paumard, Gourgoulhon & Perrin, CQG **28**, 225011 (2011)]

GYOTO (2012): an open-source and flexible code

LESIA & LUTH, Observatoire de Paris, Meudon

https://gyoto.obspm.fr/

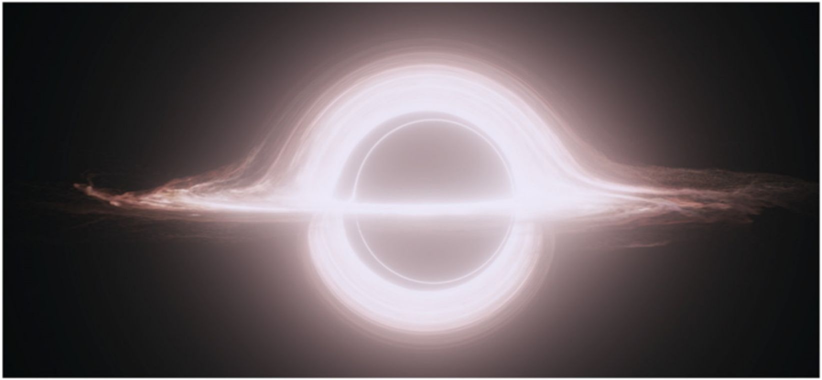


Ionised torus around a Schwarzschild black hole

[Straub, Vincent, Abramowicz, Gourgoulhon & Paumard, A&A **543**, A83 (2012)]

Oliver James, Eugénie von Tunzelmann, Paul Franklin & Kip S Thorne (2015): the *Interstellar* black hole

Double Negative Visual Effects, London

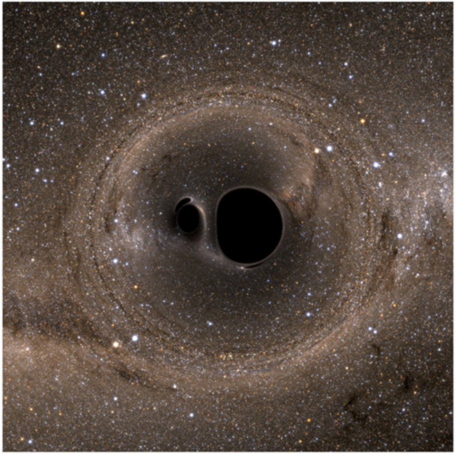


Thin accretion disk around a Kerr black hole with $a/M = 0.6$ for the movie *Interstellar* (Christopher Nolan, 2014)

[James, von Tunzelmann, Franklin & Thorne, CQG **32**, 065001 (2015)]

Andy Bohn et al. (2015): movie of a binary black hole

Cornell University



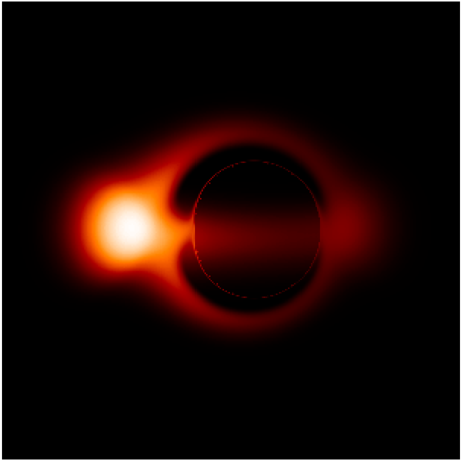
Binary black hole with mass ratio $m_1/m_2 = 3$
seen along an axis perpendicular to the orbital plane

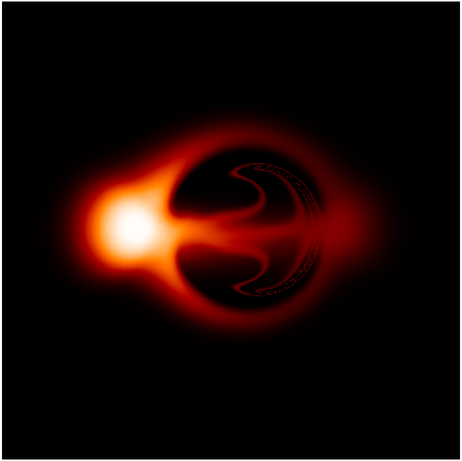
[Bohn et al., CQG **32** 065002 (2015)]

GYOTO (2016): alternatives to the Kerr black hole

Kerr black hole $a/M = 0.9$

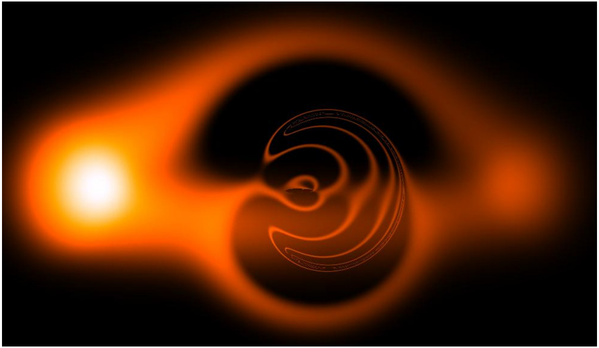
Boson star $k = 1$, $\omega = 0.70\, m/\hbar$

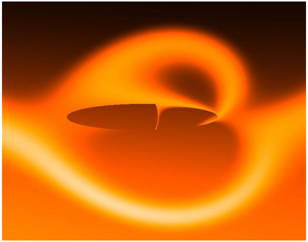




[Vincent, Meliani, Grandclément, Gourgoulhon & Straub, CQG **33**, 105015 (2016)]

GYOTO (2018): alternatives to the Kerr black hole





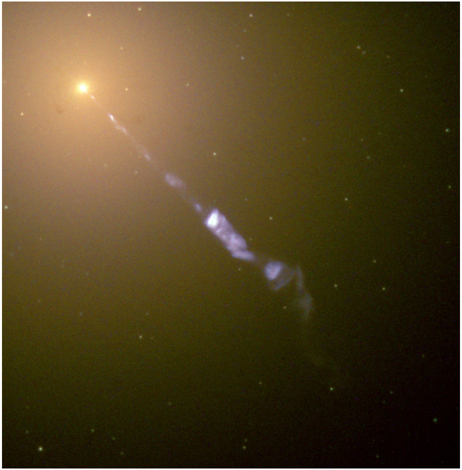
zoom on the central region

Rotating naked wormhole

[Lamy, Gourgoulhon, Paumard & Vincent, CQG **35**, 115009 (2018)]

Outline

M87: a galaxy with an active nucleus



[HST]

M87

Giant elliptical galaxy at the center of Virgo cluster

- M87 = Meissier 87: the 87th object in Charles Meissier's *Catalogue des nébuleuses et amas d'étoiles* (1774)
- Jet discovered by H. Curtis (1918)
  $V_{\rm jet} \simeq 0.99\, c$
- Bright radio source (Virgo A) (Bolton et al. 1949)
- distance: $d = 16.7\ \mathrm{Mpc} = 54.5\ \mathrm{Mly}$

M87*: the supermassive black hole in M87 nucleus

- Mass determined by stellar dynamics (velocity dispersion): $\boxed{M \simeq 6.2 \times 10^9 M_\odot}$
- Spin $a = J/M$ unknown yet

M87*: the supermassive black hole in M87 nucleus

- Mass determined by stellar dynamics (velocity dispersion):
  $\boxed{M \simeq 6.2 \times 10^9 M_\odot}$
- Spin $a = J/M$ unknown yet

$\Longrightarrow$ black hole areal radius ($a = 0$): $R \simeq 120\ \mathrm{AU}$ ($4\times$ Neptune's orbit)

$\Longrightarrow$ orbital period at the innermost stable circular orbit:
$T = 33\ \mathrm{d}$ ($a = 0$) down to $T = 4.4\ \mathrm{d}$ ($a = M$)

$\Longrightarrow$ angular diameter of the shadow ($a = 0$):

$$\Theta = 6\sqrt{3}\,\frac{GM}{c^2 d} \simeq 1.8 \times 10^{-10}\ \mathrm{rad} = 38\ \mu\mathrm{as}\ !$$

For comparison: angular resolution of Hubble Space Telescope: $0.1\ \mathrm{as} = 10^5\ \mu\mathrm{as}$

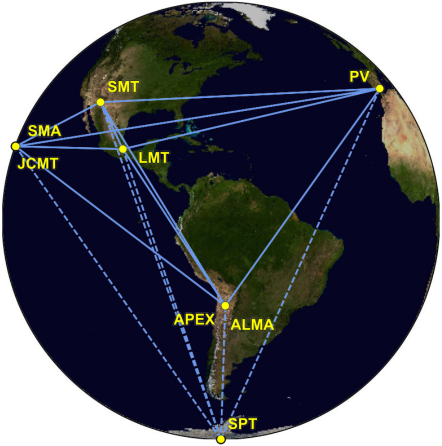
Reaching μas resolution: VLBI interferometry

Angular resolution of an interferometer of baseline D observing at wavelength λ:

$$\theta \sim \frac{\lambda}{D}$$

$$\left.\begin{array}{l} \lambda = 1\ \mathrm{mm} = 10^{-3}\ \mathrm{m} \\ D = 10,000\ \mathrm{km} = 10^{7}\ \mathrm{m} \end{array}\right\} \Longrightarrow \theta \sim 10^{-10}\ \mathrm{rad} \sim 21\ \mu\mathrm{as}$$

Reaching μas resolution: the Event Horizon Telescope



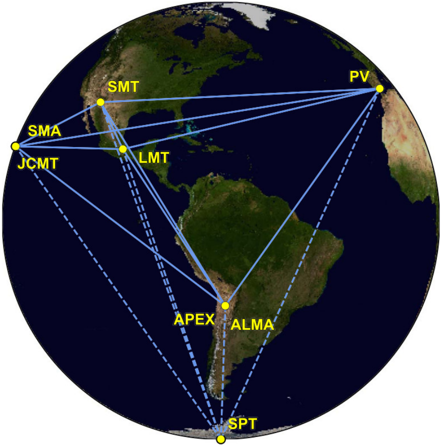
https://eventhorizontelescope.org/

IRAM 30 m (Pico Veleta, Spain)

ALMA (Atacama, Chile)

Very Large Baseline Interferometry (VLBI) at $\lambda = 1.3$ mm

Reaching μas resolution: the Event Horizon Telescope



https://eventhorizontelescope.org/

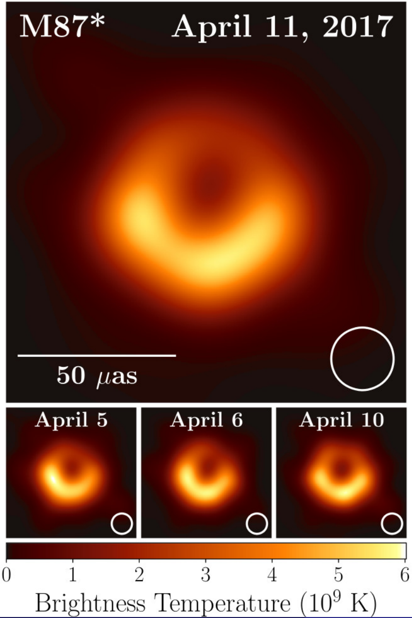
IRAM 30 m (Pico Veleta, Spain)

ALMA (Atacama, Chile)

Very Large Baseline Interferometry (VLBI) at $\lambda = 1.3$ mm

Two observation campaigns: April 2017 and April 2018

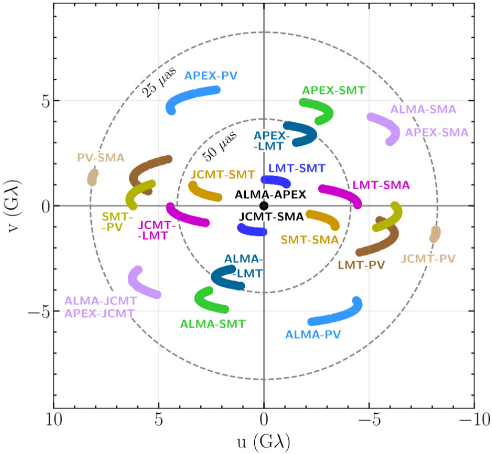
The image of M87* from the EHT 2017 data



EHT observations of M87* black hole

[EHT Collaboration, ApJ **875**, L1 (2019)]

M87*: the true data

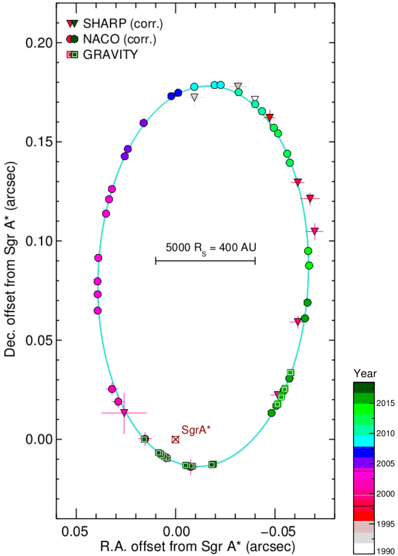


Coverage of the Fourier plane

[EHT Collaboration, ApJ **875**, L1 (2019)]

Unsufficient coverage to get a unique image by inverse Fourier transform
$\Longrightarrow$ image reconstruction by statistical algorithms

The next image: the Galactic center black hole (Sgr A*)?



- distance: $d = 8.12\ \mathrm{kpc}$
- mass:

$$\begin{aligned} M &= 4.10 \times 10^6\, M_\odot \\ &= 20.2\ \mathrm{s} \qquad (c = G = 1) \\ &= 6.06 \times 10^9\ \mathrm{m} \\ &= 4.05 \times 10^{-2}\ \mathrm{au} \\ &= 1.96 \times 10^{-7}\ \mathrm{pc} \end{aligned}$$

$$\iff 1\ \mathrm{pc} = 5.10 \times 10^6 M$$

- spin $J = aM$ unknown yet...

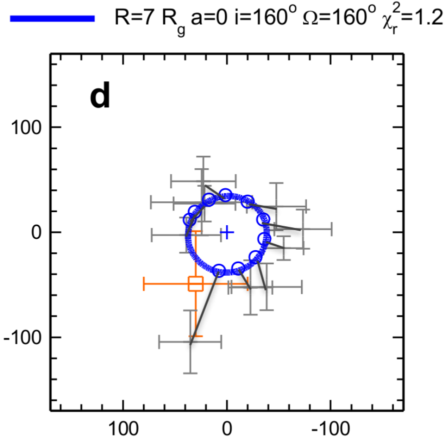
$\Longrightarrow$ shadow size $\Theta \sim 53\ \mu\mathrm{as}$

$\leftarrow$ Orbit of star S2 around Sgr A*
S2: main-sequence B star
orbital period: $P = 16.05\ \mathrm{yr}$
periastron (May 2018):

- $r_{\rm per} = 120\ \mathrm{au} = 3 \times 10^3 M$
- $v_{\rm per} = 7650\ \mathrm{km\,s^{-1}} = 0.025\, c$

[GRAVITY team, A&A **615**, L15 (2018)]

GRAVITY instrument at VLT has observed orbital motion very close to the black hole



Orbital motion of a flare in the accretion flow at $r \sim 7M$

[GRAVITY team, A&A **618**, L10 (2018)]

Outline

Conclusions and perspectives

- The image of M87* is the very first image showing a black hole shadow
- The black hole mass M estimated from the size of the ring is consistent with the mass determined from stellar dynamics in M87 nucleus
  $\Longrightarrow$ (broad) confirmation of general relativity in the strong field regime
- Future images should be sharper:
  - spring 2020: EHT observations with augmented array: NOEMA (IRAM, Plateau de Bures) and Greenland Telescope
  - near future: VLBI with antennas in space

$\Longrightarrow$ measure the spin of the black hole and test the black hole hypothesis and/or general relativity