Black hole physics: recent developments and observational perspectives

Éric Gourgoulhon

Laboratoire Univers et Théories (LUTH)
CNRS / Observatoire de Paris / Université Paris Diderot
92190 Meudon, France

eric.gourgoulhon@obspm.fr

http://luth.obspm.fr/~luthier/gourgoulhon/

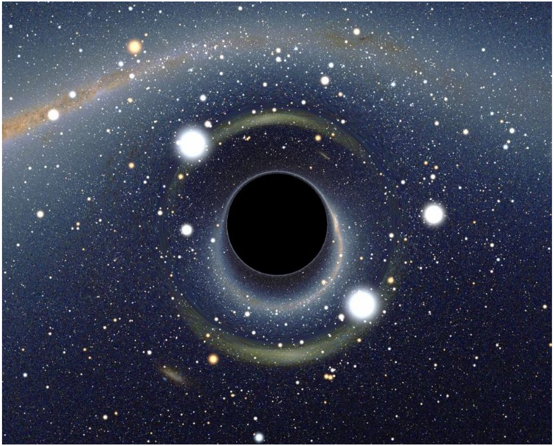
Semaine de l'Astrophysique Française
Montpellier, France
5 May 2013

Outline

Outline

Outline

What is a black hole ?



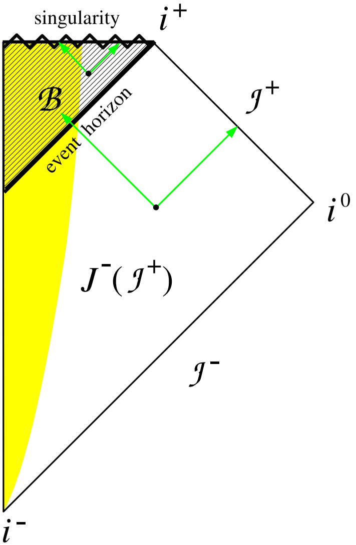
[Alain Riazuelo, 2007]

... for the layman:

A **black hole** is a region of spacetime from which nothing, not even light, can escape.

The (immaterial) boundary between the black hole interior and the rest of the Universe is called the **event horizon**.

What is a black hole ?



... for the mathematical physicist:

black hole: $\mathcal{B} := \mathscr{M} - J^-(\mathscr{I}^+)$

i.e. the region of spacetime where light rays cannot escape to infinity

- $(\mathscr{M}, \boldsymbol{g})$ = asymptotically flat manifold
- $\mathscr{I}^+$ = future null infinity
- $J^-(\mathscr{I}^+)$ = causal past of $\mathscr{I}^+$

event horizon: $\mathcal{H} := \partial J^-(\mathscr{I}^+)$ (boundary of $J^-(\mathscr{I}^+)$)

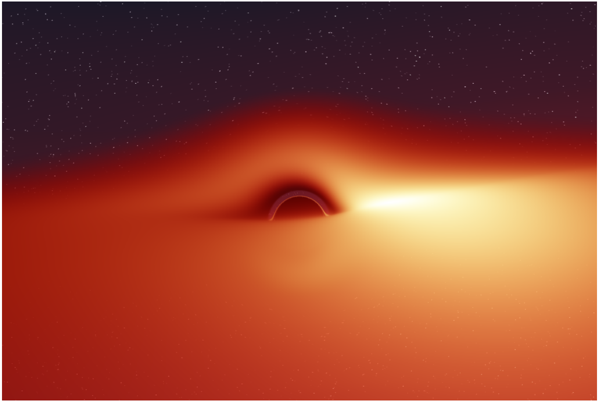
$\mathcal{H}$ smooth $\Longrightarrow$ $\mathcal{H}$ null hypersurface

What is a black hole ?

... for the astrophysicist: a very deep gravitational potential well

Release of potential gravitational energy by **accretion** on a black hole: up to 42% of the mass-energy mc^2 of accreted matter !

NB: thermonuclear reactions release less than 1% mc^2



Matter falling in a black hole forms an **accretion disk** [Lynden-Bell (1969), Shakura & Sunayev (1973)]

[J.-A. Marck (1996)]

Outline

Astrophysical black holes

Three kinds of black holes are known in the Universe:

- **Stellar black holes**: supernova remnants:
  $M \sim 10 - 30\ M_\odot$ and $R \sim 30 - 90\ \mathrm{km}$

  example: Cyg X-1 : $M = 15\ M_\odot$ and $R = 45\ \mathrm{km}$

Astrophysical black holes

Three kinds of black holes are known in the Universe:

- **Stellar black holes**: supernova remnants:
  $M \sim 10 - 30\ M_{\odot}$ and $R \sim 30 - 90\ \mathrm{km}$

  example: Cyg X-1 : $M = 15\ M_{\odot}$ and $R = 45\ \mathrm{km}$

- **Supermassive black holes**, in galactic nuclei:
  $M \sim 10^5 - 10^{10}\ M_{\odot}$ and $R \sim 3 \times 10^5\ \mathrm{km} - 200\ \mathrm{UA}$

  example: Sgr A* : $M = 4.3 \times 10^6\ M_{\odot}$ and
  $R = 13 \times 10^6\ \mathrm{km} = 18\, R_{\odot} = 0.09\ \mathrm{UA} = \frac{1}{4}\ \times$ radius of Mercury's orbit

Astrophysical black holes

Three kinds of black holes are known in the Universe:

- **Stellar black holes**: supernova remnants:
  $M \sim 10 - 30\ M_\odot$ and $R \sim 30 - 90\ \mathrm{km}$

  example: Cyg X-1 : $M = 15\ M_\odot$ and $R = 45\ \mathrm{km}$

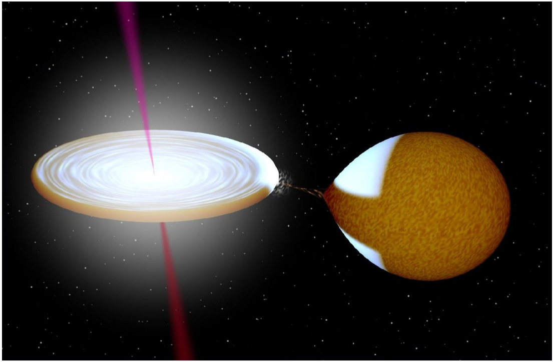
- **Supermassive black holes**, in galactic nuclei:
  $M \sim 10^5 - 10^{10}\ M_\odot$ and $R \sim 3 \times 10^5\ \mathrm{km} - 200\ \mathrm{UA}$

  example: Sgr A* : $M = 4.3 \times 10^6\ M_\odot$ and
  $R = 13 \times 10^6\ \mathrm{km} = 18\, R_\odot = 0.09\ \mathrm{UA} = \frac{1}{4} \times$ radius of Mercury's orbit

- **Intermediate mass black holes**, as ultra-luminous X-ray sources (?):
  $M \sim 10^2 - 10^4\ M_\odot$ and $R \sim 300\ \mathrm{km} - 3 \times 10^4\ \mathrm{km}$

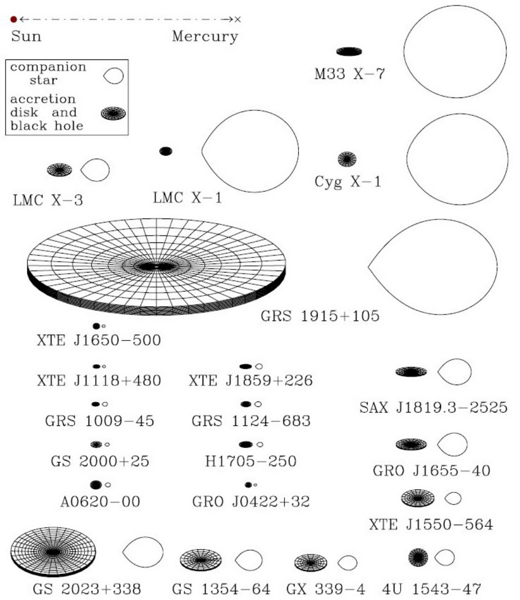
  example: ESO 243-49 HLX-1 : $M > 500\ M_\odot$ and $R > 1500\ \mathrm{km}$

Stellar black holes in X-ray binaries



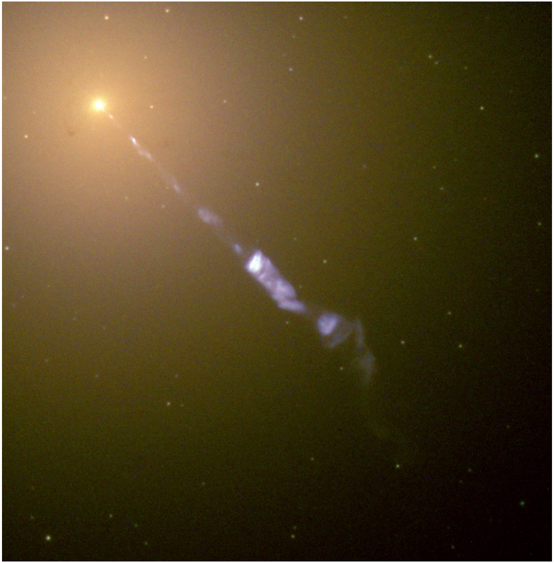
$\sim$ 20 identified stellar black holes in our galaxy

Stellar black holes in X-ray binaries



[McClintock et al. (2011)]

Supermassive black holes in active galactic nuclei (AGN)

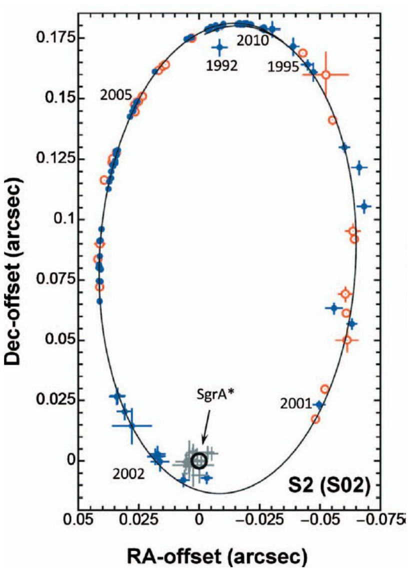


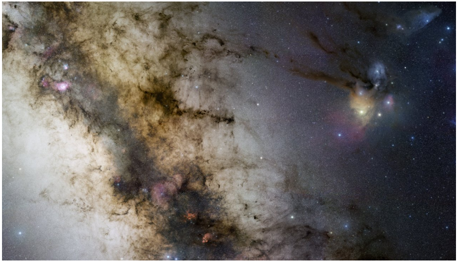
Jet emitted by the nucleus of the giant elliptic galaxy M87, at the centre of Virgo cluster [HST]

$M_{\rm BH} = 3 \times 10^9 \, M_\odot$

$V_{\rm jet} \simeq 0.99 \, c$

The black hole at the centre of our galaxy: Sgr A*





[ESO (2009)]

Determination of the mass of Sgr A* black hole by stellar dynamics:

$$M_{\rm BH} = 4.3 \times 10^6 \, M_\odot$$

← Orbit of the star S2 around Sgr A*

$P = 16\,{\rm yr}$, $r_{\rm per} = 120\,{\rm UA} = 1400\,R_{\rm S}$, $V_{\rm per} = 0.02\,c$

[Genzel, Einsenhauer & Gillessen, RMP **82**, 3121 (2010)]

Outline

Outline

Can we see a black hole from the Earth ?

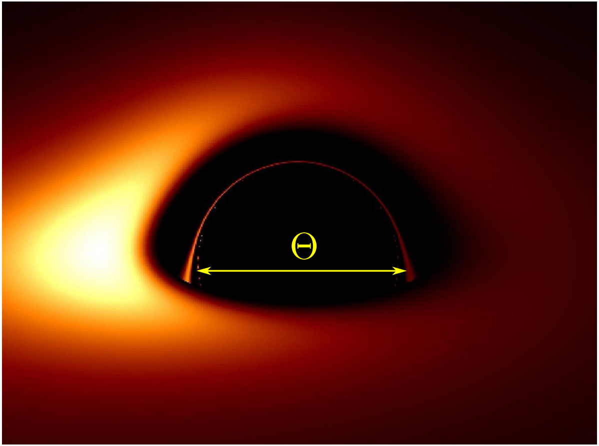


Image of a thin accretion disk around a Schwarzschild BH
[Vincent, Paumard, Gourgoulhon & Perrin, CQG **28**, 225011 (2011)]

Angular diameter of the event horizon of a Schwarzschild BH of mass M seen from a distance d:

$$\Theta = 6\sqrt{3}\,\frac{GM}{c^2 d} \simeq 2.60\,\frac{2R_S}{d}$$

Can we see a black hole from the Earth ?

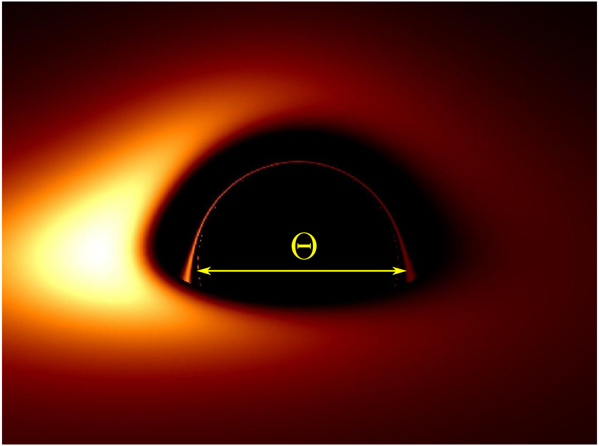


Image of a thin accretion disk around a Schwarzschild BH
[Vincent, Paumard, Gourgoulhon & Perrin, CQG **28**, 225011 (2011)]

Angular diameter of the event horizon of a Schwarzschild BH of mass M seen from a distance d:

$$\Theta = 6\sqrt{3}\,\frac{GM}{c^2 d} \simeq 2.60\,\frac{2R_S}{d}$$

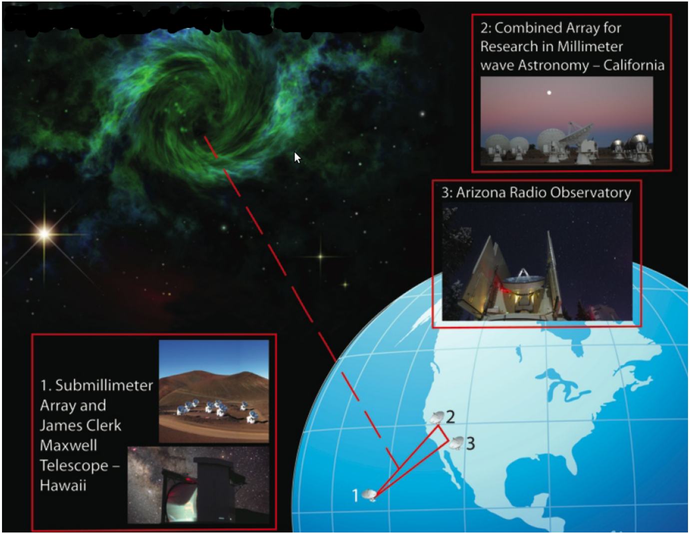
Largest black holes in the Earth's sky:

Sgr A* : $\Theta = 53\ \mu\mathrm{as}$
M87 : $\Theta = 21\ \mu\mathrm{as}$
M31 : $\Theta = 20\ \mu\mathrm{as}$

Remark: black holes in X-ray binaries are $\sim 10^5$ times smaller, for $\Theta \propto M/d$

Outline

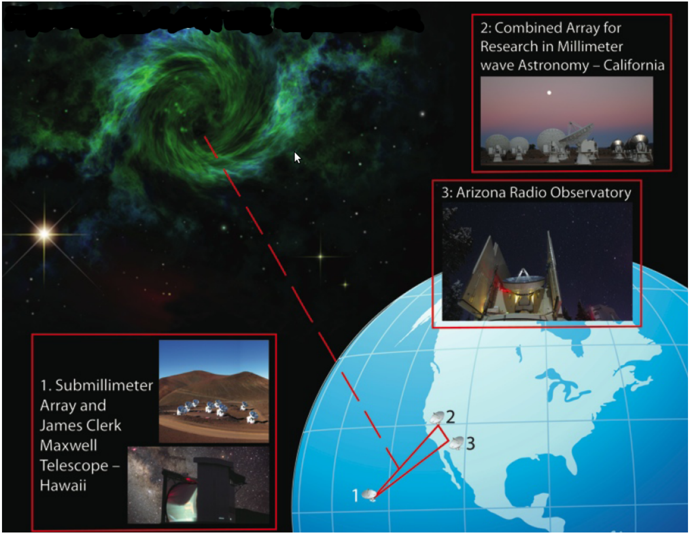
The solution to reach the μas regime: interferometry !



Existing American VLBI network [Doeleman et al. 2011]

Very Large Baseline Interferometry (VLBI) in (sub)millimeter waves

The solution to reach the μas regime: interferometry !



Existing American VLBI network [Doeleman et al. 2011]

Very Large Baseline Interferometry (VLBI) in (sub)millimeter waves

The best result so far: VLBI observations at 1.3 mm have shown that the size of the emitting region in Sgr A* is only $37\ \mu$as

[Doeleman et al., Nature **455**, 78 (2008)]

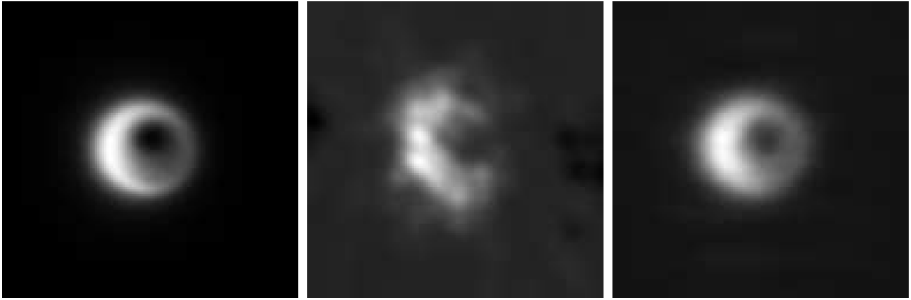
The near future: the Event Horizon Telescope

To go further:

- shorten the wavelength: $1.3\ \mathrm{mm} \to 0.8\ \mathrm{mm}$
- increase the number of stations; in particular add ALMA

Atacama Large Millimeter Array (ALMA)
part of the Event Horizon Telescope (EHT) to be completed by 2020

The near future: the Event Horizon Telescope



Simulations of VLBI observations of Sgr A* at $\lambda = 0.8$ mm

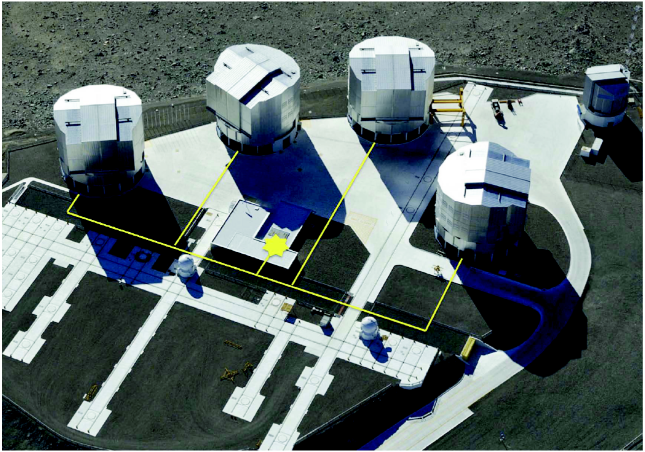
left: perfect image, *centre:* 7 stations (~ 2015), *right:* 13 stations (~ 2020)

$a = 0,\ i = 30^\circ$

[Fish & Doeleman, Proc. IAU Symp 261 (2010)]

Outline

Near-infrared optical interferometry: GRAVITY



[Gillessen et al. 2010]

GRAVITY instrument at VLTI (2015)

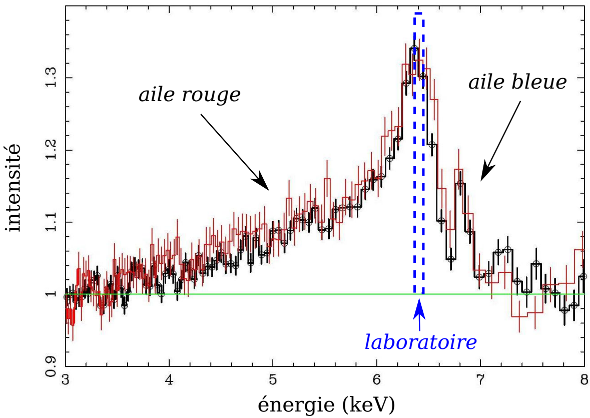
Beam combiner (the four 8 m telescopes + four auxiliary telescopes) $\Longrightarrow$ astrometric precision of $10\ \mu\text{as}$

cf. P. Kervella's talk in session S04

Outline

X-ray observations (Athena+)

The accretion disk as a spacetime probe



Kα line in the nucleus of the galaxy MCG-6-30-15 observed by XMM-Newton (red) and Suzaku (black) (adapted from [Miller (2007)])

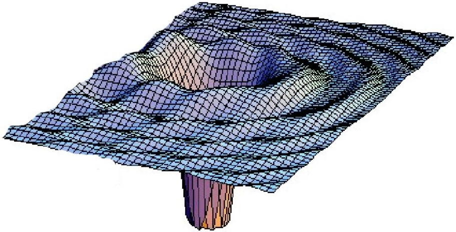
Kα line: X fluorescence line of Fe atoms in the accretion disk (the Fe atoms are excited by the X-ray emitted from the plasma corona surrounding the disk)

Redshift ⇒ time dilatation

cf. D. Barret's talk about Athena+ in session S15

Outline

Another way to "see" BHs: gravitational waves



Link between black holes and gravitational waves:

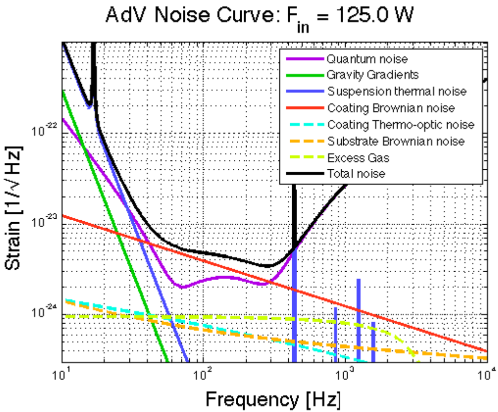
Black holes and gravitational waves are both spacetime distortions:

- extreme distortions (black holes)
- small distortions (gravitational waves)

In particular, black holes and gravitational waves are both vacuum solutions of general relativity equations (Einstein equations)

Advanced VIRGO

Advanced VIRGO: dual recycled (power + signal) interferometer with laser power $\sim$ 125 W

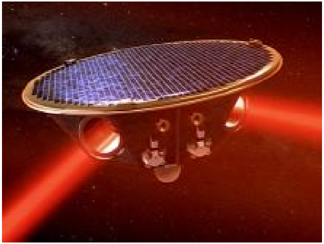


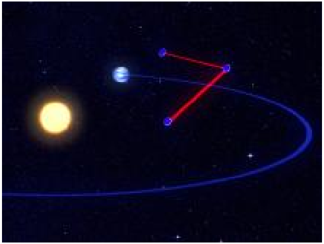
[CNRS/INFN/NIKHEF]

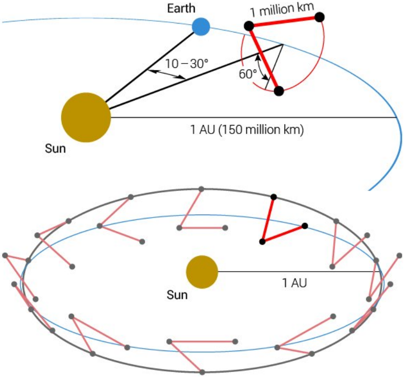
- VIRGO+ decommissioned in Nov. 2011
- Construction of Advanced VIRGO underway
- First lock in 2015
- Sensitivity $\sim 10 \times$ VIRGO
- $\Longrightarrow$ explored Universe volume 10^3 times larger !

eLISA

Gravitational wave detector in space $\Longrightarrow$ low frequency range: $[10^{-3}, 10^{-1}]$ Hz







[http://www.elisascience.org/]

- Selection in Nov. 2013 ? (ESA L2 mission) $\Longrightarrow$ launch in 2028
- LISA Pathfinder to be launched in 2015

Outline

Outline

The "No-Hair" Theorem

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

Within 4-D general relativity, a stationary black hole is necessarily a Kerr-Newmann black hole, which is a vacuum solution of Einstein equation described by only three parameters:

- the total mass M
- the total angular momentum J
- the total electric charge Q

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

- $Q = 0$ and $J = 0$: Schwarzschild solution (1916)
- $Q = 0$: Kerr solution (1963)

Theoretical alternatives to the Kerr black hole

Within general relativity

- boson stars
- gravastar
- Q-star
- dark stars
- ...

Beyond general relativity

black holes in

- Einstein-Yang-Mills
- Einstein-Gauss-Bonnet with dilaton
- Chern-Simons gravity
- Hořava-Lifshitz gravity
- ...

How to test the alternatives ?

Search for

- stellar orbits deviating from Kerr timelike geodesics (GRAVITY)
- accretion disk spectra different from those arising in Kerr metric (X-ray observatories)
- images of the black hole shadow different from that of a Kerr black hole (EHT)

How to test the alternatives ?

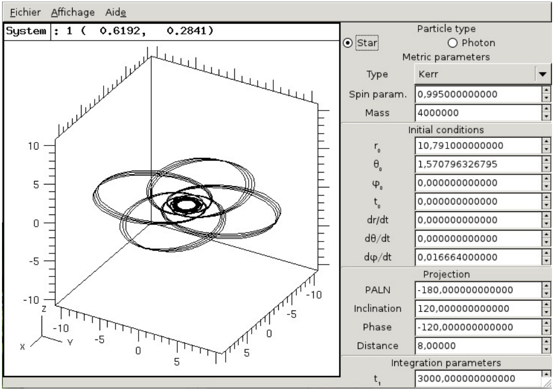
Search for

- stellar orbits deviating from Kerr timelike geodesics (GRAVITY)
- accretion disk spectra different from those arising in Kerr metric (X-ray observatories)
- images of the black hole shadow different from that of a Kerr black hole (EHT)

Need for a good and versatile geodesic integrator
to compute timelike geodesics (orbits) and null geodesics (ray-tracing) in any kind of metric

Outline

Gyoto code



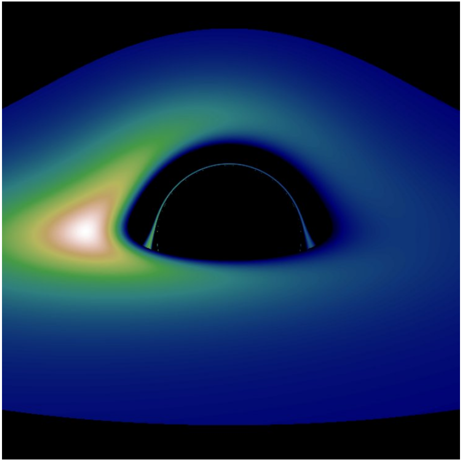
- Integration of geodesics in Kerr metric
- Integration of geodesics in any numerically computed 3+1 metric
- Radiative transfer included in optically thin media
- Very modular code (C++)
- Yorick interface
- Free software (GPL) : http://gyoto.obspm.fr/

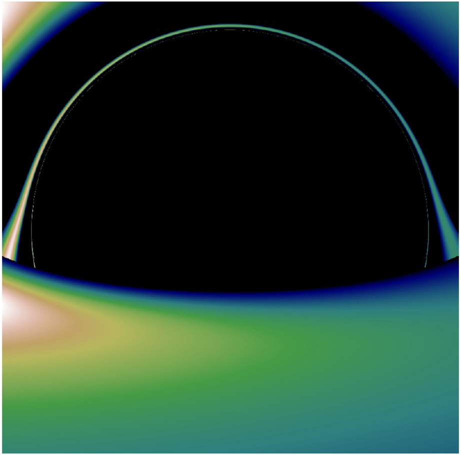
[Vincent, Paumard, Gourgoulhon & Perrin, CQG **28**, 225011 (2011)]

[Vincent, Gourgoulhon & Novak, CQG **29**, 245005 (2012)]

cf. F. Vincent's talk in session S15

Gyoto code



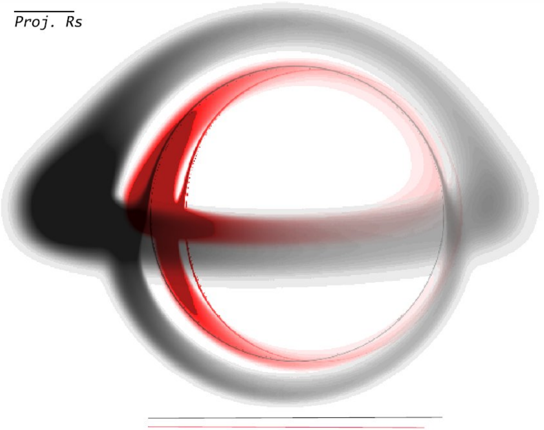


Computed images of a thin accretion disk around a Schwarzschild black hole

Measuring the spin from the black hole silhouette

Ray-tracing in the Kerr metric (spin parameter a)

Accretion structure around Sgr A* modelled as a ion torus, derived from the *polish doughnut* class [Abramowicz, Jaroszynski & Sikora (1978)]



Radiative processes included: thermal synchrotron, bremsstrahlung, inverse Compton

← Image of an ion torus computed with Gyoto for the inclination angle $i = 80°$:

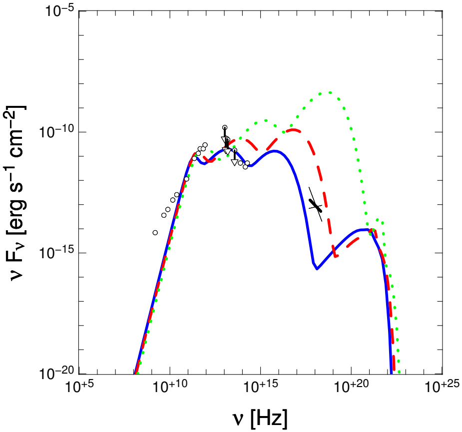
- black: $a = 0.5M$
- red: $a = 0.9M$

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

Measuring the spin from the accretion disk spectrum

Ray-tracing in the Kerr metric (spin parameter a)

Accretion structure around Sgr A* modelled as a ion torus, derived from the *polish doughnut* class [Abramowicz, Jaroszynski & Sikora (1978)]



Radiative processes included: thermal synchrotron, bremsstrahlung, inverse Compton

← Spectrum of an ion torus computed with Gyoto for the inclination angle $i = 80°$:

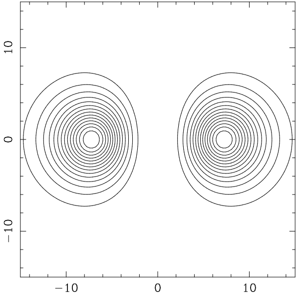
- blue: $a = 0$
- red: $a = 0.5M$
- green: $a = 0.9M$

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

An alternative to Kerr BH: boson star

Boson star = localized configurations of a self-gravitating complex scalar field Φ $\equiv$ "Klein-Gordon geons" [Kaup (1968), Ruffini & Bonazzola (1969)]

- Scalar field Lagrangian: $\mathcal{L} = -\frac{1}{2}\left[\nabla_\mu \bar{\Phi} \nabla^\mu \Phi + V(|\Phi|^2)\right]$
- Field equation: $\nabla_\mu \nabla^\mu \Phi = V'(|\Phi|^2)\,\Phi$
- Einstein equation: $R_{\alpha\beta} - \frac{1}{2} R g_{\alpha\beta} = 8\pi T_{\alpha\beta}(\Phi)$



Stationary and axisymmetric solutions computed by means of Kadath [Grandclément, JCP **229**, 3334 (2010)]

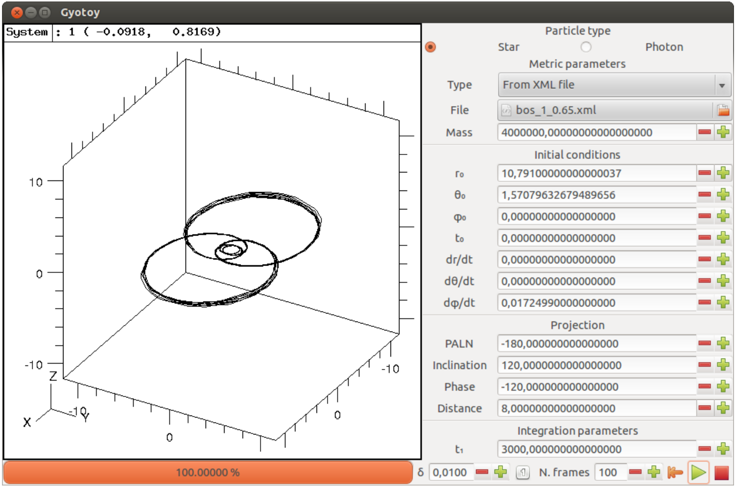
$\Phi(t, r, \theta, \varphi) = \Phi_0(r, \theta) e^{i(\omega t + k\varphi)}$

$\Longrightarrow$ rotating boson stars have a toroidal topology

Orbits in a rotating-boson-star spacetime

Rotating boson star computed by Kadath

Integration of timelike geodesics performed in 3+1 form by Gyoto

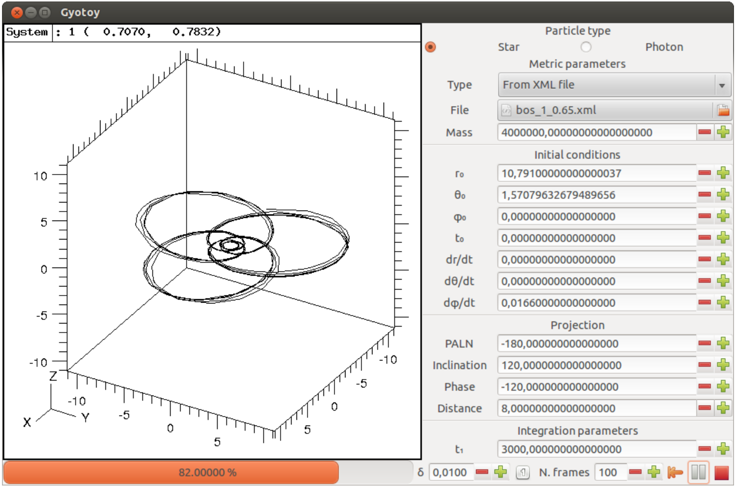


$k = 1$, $\omega = 0.65\, m/\hbar$ [Somé et al., in preparation]

Orbits in a rotating-boson-star spacetime

Rotating boson star computed by Kadath

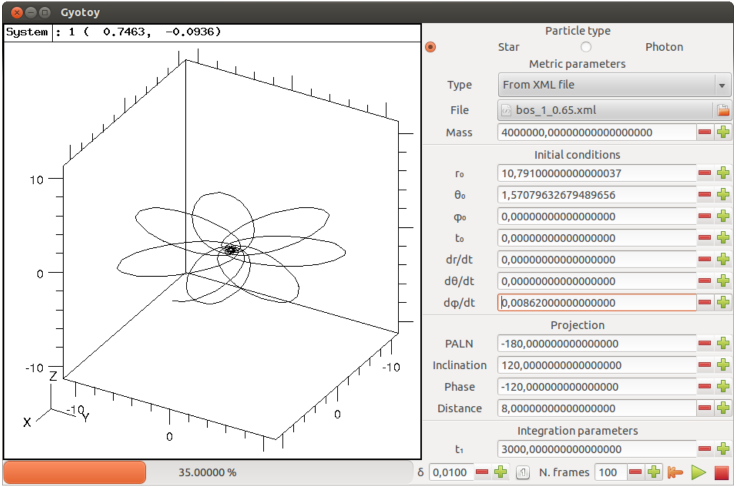
Integration of timelike geodesics performed in 3+1 form by Gyoto



$k = 1$, $\omega = 0.65\, m/\hbar$ [Somé et al., in preparation]

Orbits in a rotating-boson-star spacetime

Rotating boson star computed by Kadath
Integration of timelike geodesics performed in 3+1 form by Gyoto

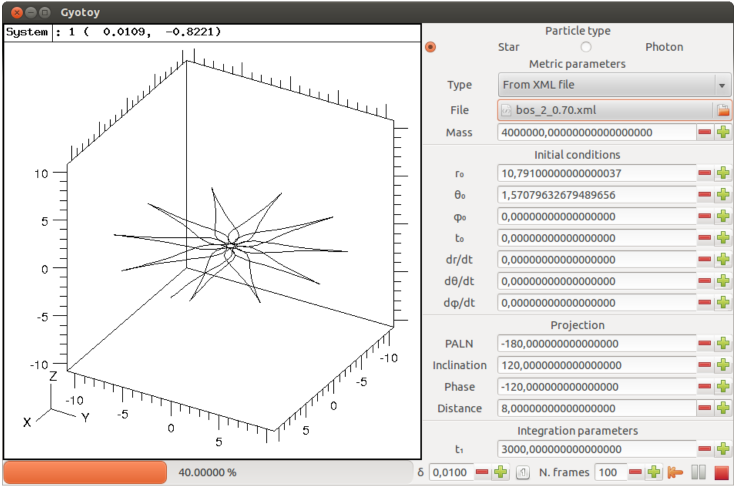


$k = 1$, $\omega = 0.65\, m/\hbar$ [Somé et al., in preparation]

Orbits in a rotating-boson-star spacetime

Rotating boson star computed by Kadath

Integration of timelike geodesics performed in 3+1 form by Gyoto



$k = 2$, $\omega = 0.70\, m/\hbar$, $\ell = 0$ [Somé et al., in preparation]

Outline

Conclusions and perspectives

- Black hole physics is entering into a new observational era:
  we are going to see/explore the close vicinity of the event horizon
- Observational tests regarding Sgr A* or the core of M 87 will become feasible. These tests address the nature of the central object or the theory of gravity
- To devise the tests, we have developed a ray-tracing code, `Gyoto`, capable of integrating timelike and null geodesics in any spacetime, either provided in analytical form (e.g. Kerr spacetime) or in 3+1 numerical form
- This code is free and downloadable at `http://gyoto.obspm.fr/`
- Alternatives to the standard Kerr black hole are currently explored in our group: computations are in progress for boson stars and black holes in Hořava-Lifshitz gravity