Black hole physics: recent developments and observational perspectives

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Semaine de l’Astrophysique Française
Montpellier, France
5 May 2013
The current observational status of black holes
- What is a black hole?
- Known black holes in the Universe

The near-future observations of black holes
- Can we “see” a black hole?
- The Event Horizon Telescope
- GRAVITY instrument at VLTI
- Athena+ X-ray observatory
- Gravitational wave observations

Tests of general relativity
- The theoretical framework
- Ongoing work at LUTH / LESIA / CAMK

Conclusions and perspectives
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Éric Gourgoulhon (LUTH)
What is a black hole?

... 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**.

[Alain Riazuelo, 2007]
What is a black hole?

... for the mathematical physicist:

**black hole:** \[ \mathcal{B} := \mathcal{M} - J^-(\mathcal{I}^+) \]

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

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

**event horizon:** \(\mathcal{H} := \partial J^-(\mathcal{I}^+)\)  

(boundary of \(J^-(\mathcal{I}^+)\))  

\(\mathcal{H}\) smooth \(\implies \mathcal{H}\) 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)]
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Astrophysical black holes

Three kinds of black holes are known in the Universe:

- **Stellar black holes**: supernova remnants:
  \[ M \sim 10 - 30 \, M_\odot \text{ and } R \sim 30 - 90 \, \text{km} \]
  
  example: Cyg X-1 : \( M = 15 \, M_\odot \text{ and } R = 45 \, \text{km} \)
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- **Supermassive black holes**, in galactic nuclei:
  \[ M \sim 10^5 - 10^{10} \, M_\odot \text{ and } R \sim 3 \times 10^5 \, \text{km} - 200 \, \text{UA} \]
  example: Sgr A* : \( M = 4.3 \times 10^6 \, M_\odot \text{ and } \)
  \[ R = 13 \times 10^6 \, \text{km} = 18 \, R_\odot = 0.09 \, \text{UA} = \frac{1}{4} \times \text{radius of Mercury’s orbit} \]
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- **Intermediate mass black holes**, as ultra-luminous X-ray sources (?):
  \[ M \sim 10^2 - 10^4 \, M_\odot \text{ and } R \sim 300 \text{ km} - 3 \times 10^4 \text{ km} \]
  example: ESO 243-49 HLX-1 : \( M > 500 \, M_\odot \) and \( R > 1500 \text{ km} \)
Stellar black holes in X-ray binaries

~ 20 identified stellar black holes in our galaxy
Stellar black holes in X-ray binaries

Known black holes in the Universe

- Stellar black holes in X-ray binaries

[McClintock et al. (2011)]
Jet emitted by the nucleus of the giant elliptic galaxy M87, at the centre of Virgo cluster [HST]

\[ M_{BH} = 3 \times 10^9 M_\odot \]
\[ V_{jet} \simeq 0.99 c \]
The black hole at the centre of our galaxy: Sgr A*

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

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

← Orbit of the star S2 around Sgr A*

$$P = 16 \text{ yr}, \quad r_{\text{per}} = 120 \text{ UA} = 1400 R_S, \quad V_{\text{per}} = 0.02 c$$

[Genzel, Eisenhauer & Gillessen, RMP 82, 3121 (2010)]
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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 $d$:

$$\Theta = 6\sqrt{3} \frac{GM}{c^2d} \simeq 2.60 \frac{2R_S}{d}$$
The near-future observations of black holes

Can we “see” a black hole?

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Largest black holes in the Earth’s sky:

**Sgr A**: $\Theta = 53 \mu$as

**M87**: $\Theta = 21 \mu$as

**M31**: $\Theta = 20 \mu$as

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

The Event Horizon Telescope

The solution to reach the $\mu$as regime: interferometry!

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

Existing American VLBI network [Doeleman et al. 2011]
The near-future observations of black holes

The Event Horizon Telescope

The solution to reach the $\mu$as regime: interferometry!

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)]

Existing American VLBI network [Doeleman et al. 2011]
The near future: the Event Horizon Telescope

To go further:
- shorten the wavelength: $1.3 \text{ mm} \rightarrow 0.8 \text{ mm}$
- 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 observations of black holes

The Event Horizon Telescope

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 ($\sim 2015$), *right:* 13 stations ($\sim 2020$)

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

[Fish & Doeleman, Proc. IAU Symp 261 (2010)]
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Near-infrared optical interferometry: GRAVITY

GRAVITY instrument at VLTI (2015)

Beam combiner (the four 8 m telescopes + four auxiliary telescopes) $\Rightarrow$ astrometric precision of 10 $\mu$as

cf. P. Kervella’s talk in session S04

[Gillessen et al. 2010]
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The accretion disk as a spacetime probe

**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 $\Rightarrow$ time dilatation

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

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

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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: dual recycled (power + signal) interferometer with laser power $\sim 125 \text{ W}$

- VIRGO+ decommissioned in Nov. 2011
- Construction of Advanced VIRGO underway
- First lock in 2015
- Sensitivity $\sim 10 \times$ VIRGO
- $\rightarrow$ explored Universe volume $10^3$ times larger!
The near-future observations of black holes

**Gravitational wave observations**

**eLISA**

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

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

- **Selection in Nov. 2013 ? (ESA L2 mission)** $\Rightarrow$ launch in 2028
- **LISA Pathfinder to be launched in 2015**
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Tests of general relativity

The theoretical framework

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The “No-Hair” Theorem

Uniqueness theorem

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 \( Q \)

\[ Q = 0 \text{ and } J = 0 : \text{Schwarzschild solution (1916)} \]
\[ Q = 0 : \text{Kerr solution (1963)} \]
### 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
- ...

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Éric Gourgoulhon (LUTH)  
Black hole physics: new perspectives  
SF2A, Montpellier, 5 May 2013  
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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?

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**Need for a good and versatile geodesic integrator**

to compute timelike geodesics (orbits) and null geodesics (ray-tracing) in any kind of metric
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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)]

$	ext{Proj. } Rs$

Radiative processes included: thermal synchrotron, bremsstrahlung, inverse Compton

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

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

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Radiative processes included: thermal synchrotron, bremsstrahlung, inverse Compton

← Spectrum of an ion torus computed with Gyoto for the inclination angle $i = 80^\circ$:
- blue: $a = 0$
- red: $a = 0.5M$
- green: $a = 0.9M$

An alternative to Kerr BH: boson star

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

- Scalar field Lagrangian: $\mathcal{L} = -\frac{1}{2} \left[ \nabla_\mu \Phi \nabla^\mu \Phi + V(|\Phi|^2) \right]$
- 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)]

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

⇒ rotating boson stars have a toroidal topology
Rotating boson star computed by **Kadath**

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

\[ k = 1, \ \omega = 0.65 \frac{m}{\hbar} \] [Somé et al., in preparation]
Rotating boson star computed by **Kadath**

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\[ k = 1, \ \omega = 0.65 \text{ m}/\hbar \]  

[Somé et al., in preparation]
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\[ k = 1, \ \omega = 0.65 \frac{m}{\hbar} \]
[Somé et al., in preparation]
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]
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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.