Observing black holes: a new astrophysics

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based on a collaboration with

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Conférence-débat
Les trous noirs: leur nature, et leur rôle en physique et en astrophysique
Académie des Sciences, Paris
13 February 2018

Black holes in the sky

Three kinds of black holes (candidates) are known in the Universe :

- **Stellar black holes** : remnants of massive stars :
  $M \sim 10 - 40\ M_\odot$ and $R \sim 30 - 120$ km

  examples : Cyg X-1 : $M = 15\ M_\odot$; $R = 45$ km

  GW150914 : $M_1 = 36 \pm 5\ M_\odot$, $M_2 = 29 \pm 4\ M_\odot$

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

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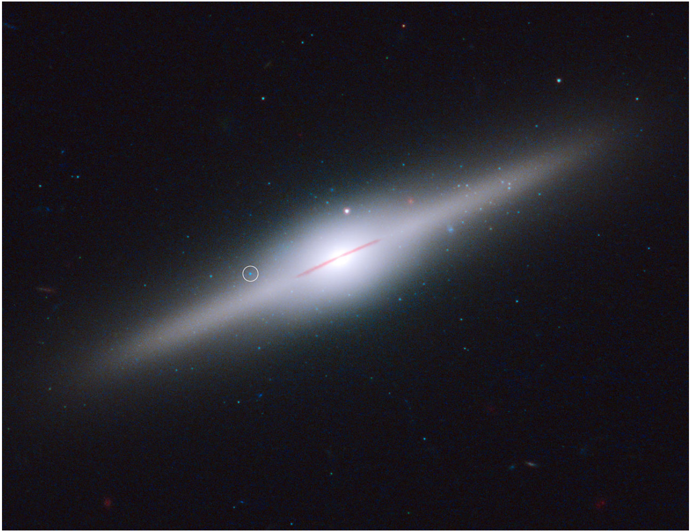
- **Intermediate mass black holes**, as ultra-luminous X-ray sources :
  $M \sim 10^2 - 10^5\ M_\odot$ and $R \sim 300\ \mathrm{km} - 3 \times 10^5\ \mathrm{km}$

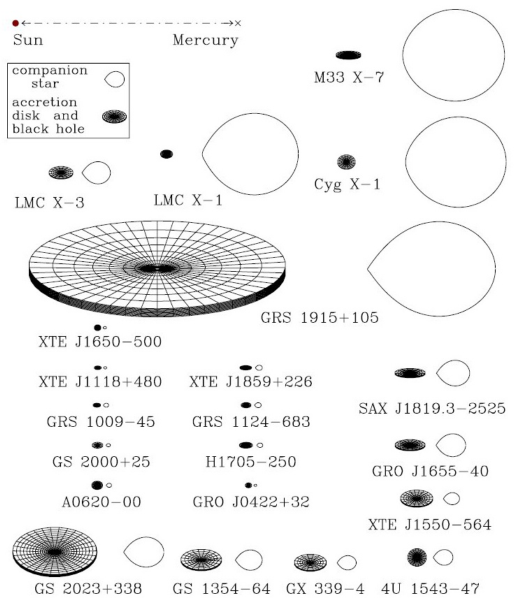
  example : ESO 243-49 HLX-1 : $M \sim 10^4\ M_\odot$; $R \sim 3 \times 10^4\ \mathrm{km}$

ESO 243-49 HLX-1 : an intermediate mass black hole ?



HST image [NASA/ESA/S. Farrel (2012)]

Stellar black holes in X-ray binaries



[McClintock et al. (2011)]

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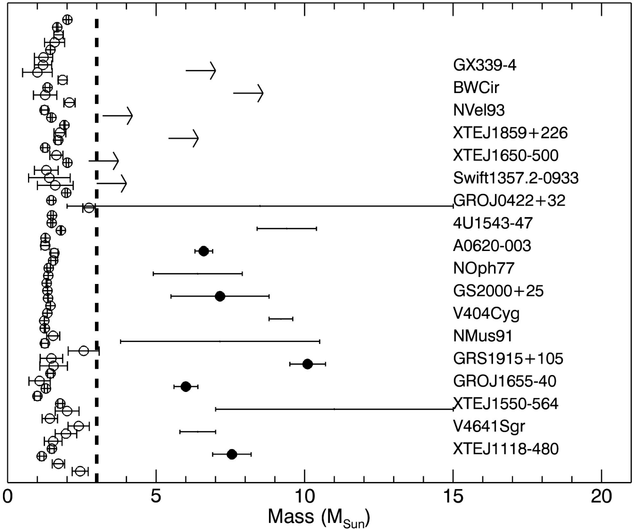
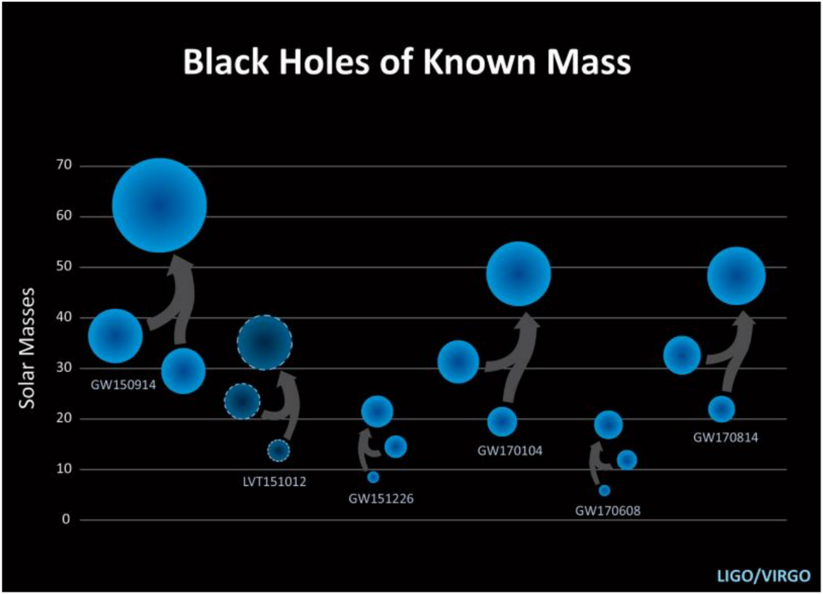


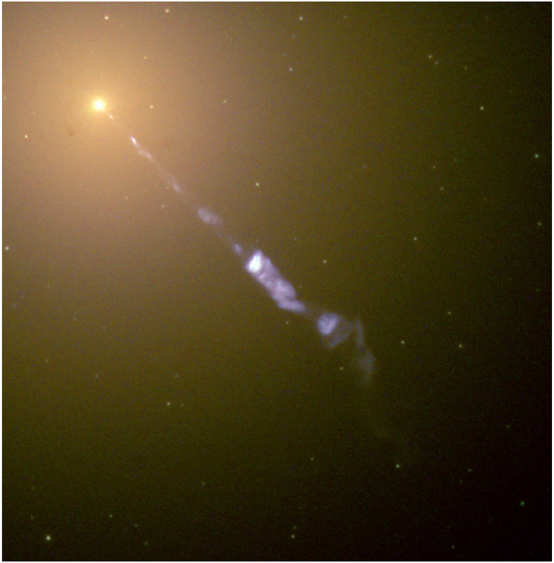
Dynamically measured masses of black holes in transient low-mass X-ray binaries (right), compared with measured masses of neutron stars (left)

[Corral-Santana et al., A&A **587**, A61 (2016)]

Black holes masses in gravitational wave events



Supermassive black holes in active galactic nuclei (AGN)

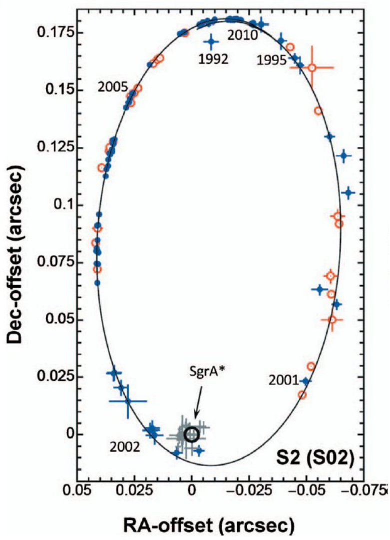


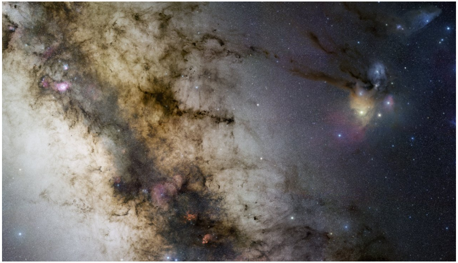
Jet emitted by the nucleus of the giant elliptic galaxy M87, at the centre of Virgo cluster [HST]

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

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

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





[ESO (2009)]

Mass of Sgr A* black hole deduced from 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, Eisenhauer & Gillessen, RMP **82**, 3121 (2010)]

Next periastron passage : May 2018 !

Can we see it from the Earth ?

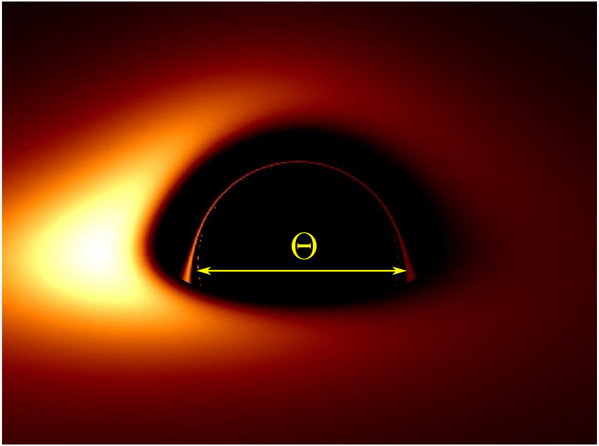


Image of a thin accretion disk around a Schwarzschild BH
[Vincent, Paumard, Gourgoulhon & Perrin, CQG **28**, 225011 (2011)]

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

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

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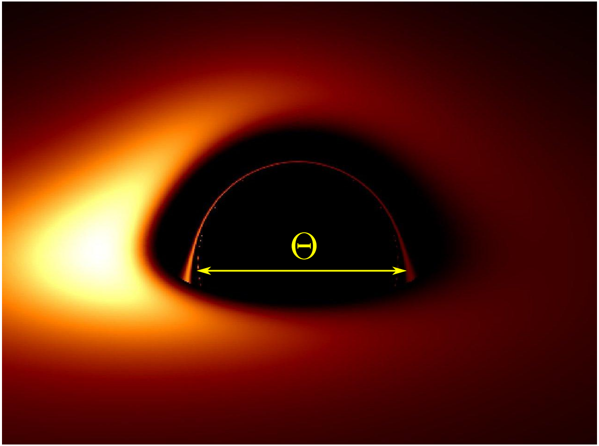

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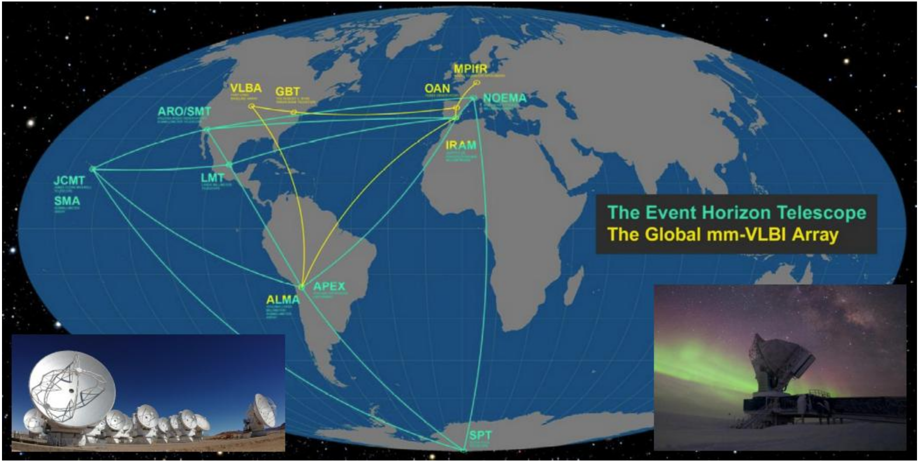
Largest black holes in the Earth's sky :

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 $\Theta \propto M/d$

Reaching μas resolution : the Event Horizon Telescope



http://eventhorizontelescope.org/

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

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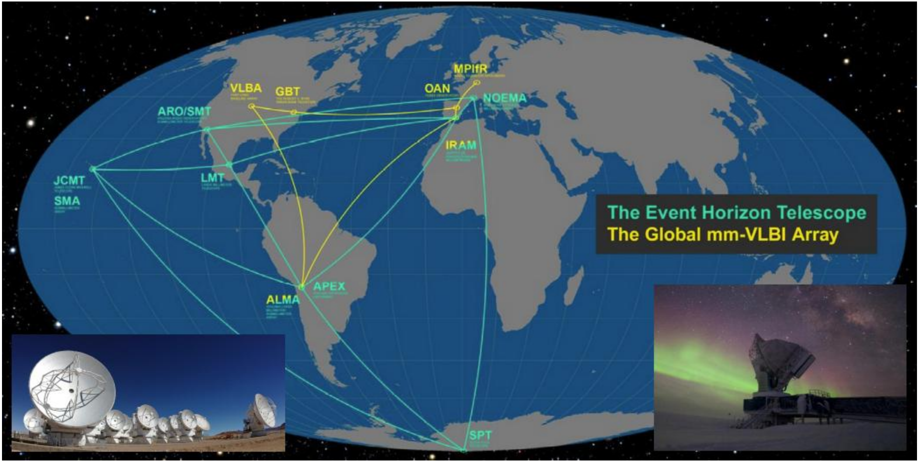

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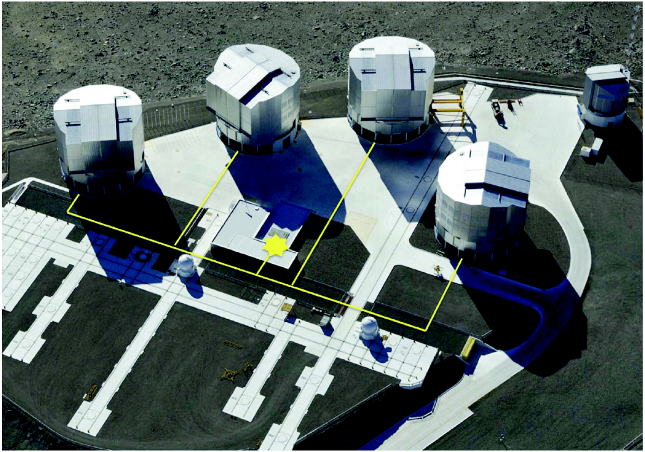
Very Large Baseline Interferometry (VLBI) at $\lambda = 1.3$ mm

April 2017 : large observation campaign $\Longrightarrow$ first image soon ?

Near-infrared optical interferometry : GRAVITY



[Gillessen et al. 2010]

GRAVITY instrument at VLTI (start : 2016)

Beam combiner (the four 8 m telescopes + four auxiliary telescopes)

astrometric precision on orbits : $10\ \mu as$

The no-hair theorem

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 $a = J/(Mc)$
- the total electric charge Q

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

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Astrophysical black holes have to be electrically neutral :

- $Q = 0$: Kerr solution (1963)

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)

The no-hair theorem : a precise mathematical statement

Any spacetime $(\mathscr{M}, \boldsymbol{g})$ that

- is 4-dimensional
- is asymptotically flat
- is pseudo-stationary
- is a solution of the vacuum Einstein equation : $\mathrm{Ric}(\boldsymbol{g}) = 0$
- contains a black hole with a connected regular horizon
- has no closed timelike curve in the domain of outer communications
- is analytic

has a domain of outer communications that is isometric to the domain of outer communications of the Kerr spacetime.

domain of outer communications : black hole exterior

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domain of outer communications : black hole exterior

Possible improvements : remove the hypotheses of analyticity and non-existence of closed timelike curves (analyticity removed recently but only for slowly rotating black holes [Alexakis, Ionescu & Klainerman, Duke Math. J. **163**, 2603 (2014)])

Lowest order no-hair theorem : quadrupole moment

Asymptotic expansion (large r) of the metric in terms of multipole moments $(\mathcal{M}_k, \mathcal{J}_k)_{k\in\mathbb{N}}$ [Geroch (1970), Hansen (1974)] :

- $\mathcal{M}_k$: mass 2^k-pole moment
- $\mathcal{J}_k$: angular momentum 2^k-pole moment

$\Longrightarrow$ For the Kerr metric, all the multipole moments are determined by (M, a) :

- $\mathcal{M}_0 = M$
- $\mathcal{J}_1 = aM = J/c$
- $$\boxed{\mathcal{M}_2 = -a^2 M = -\frac{J^2}{c^2 M}} \qquad (1)$$ $\leftarrow$ mass quadrupole moment
- $\mathcal{J}_3 = -a^3 M$
- $\mathcal{M}_4 = a^4 M$
- $\cdots$

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- $\cdots$

Measuring the three quantities M, J, $\mathcal{M}_2$ provides a compatibility test w.r.t. the Kerr metric, by checking (1)

Theoretical alternatives to the Kerr black hole

Within general relativity

The compact object is not a black hole but

- boson stars
- gravastar
- dark stars
- ...

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Beyond general relativity

The compact object is a black hole but in a theory that differs from 4-dimensional GR :

- Horndeski theories
- Chern-Simons gravity
- Hořava-Lifshitz gravity
- Higher-dimensional GR
- ...

Viable scalar-tensor theories after GW170817

$$\text{GW170817} \Longrightarrow \left| \frac{c_{\rm gw} - c}{c} \right| < 5\ 10^{-16}$$

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [42] Brans-Dicke/$f(R)$ [43, 44] Kinetic Gravity Braiding [46]	quartic/quintic Galileons [13, 14] Fab Four [15, 16] de Sitter Horndeski [45] $G_{\mu\nu}\phi^\mu\phi^\nu$ [47], Gauss-Bonnet
beyond H.	Derivative Conformal (20) [18] Disformal Tuning (22) DHOST with $A_1 = 0$	quartic/quintic GLPV [19] DHOST [20, 48] with $A_1 \neq 0$
	Viable after GW170817	Non-viable after GW170817

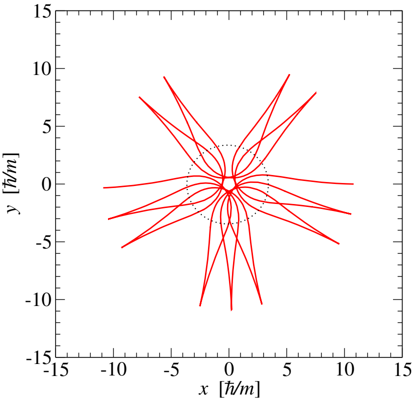
[Ezquiaga & Zumalacárregui, PRL **119**, 251304 (2017)]

An example : rotating boson stars

Boson star = localized configurations of a self-gravitating massive complex scalar field Φ ≡ *"Klein-Gordon geons"*
[Bonazzola & Pacini (1966), Kaup (1968)]

Boson stars may behave as black-hole mimickers

- Solutions of the *Einstein-Klein-Gordon* system computed by means of Kadath
  [Grandclément, JCP **229**, 3334 (2010)]
- Timelike geodesics computed by means of Gyoto
  [Vincent et al., CQG **28**, 225011 (2011)]

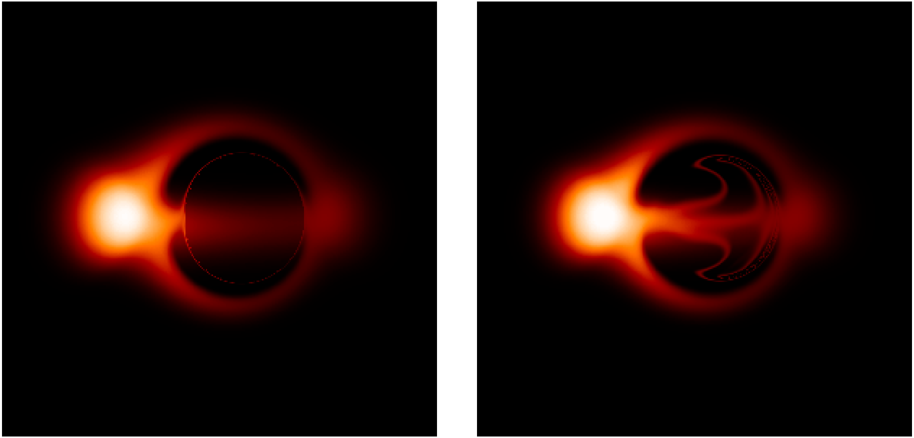


Pointy petal orbit around a rotating boson star for a free scalar field
$\Phi = \phi(r,\theta) e^{i(\omega t + 2\varphi)}$, $\omega = 0.75\, m/\hbar$

[Granclément, Somé & Gourgoulhon, PRD **90**, 024068 (2014)]

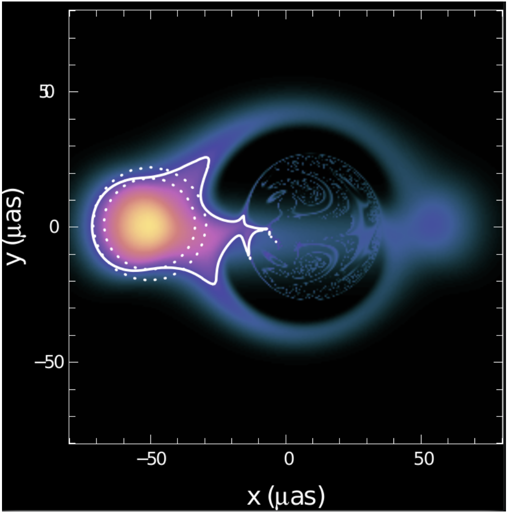
Image of an accretion torus : comparing with a Kerr BH

Kerr BH $a/M = 0.9$ Boson star $k = 1,\ \omega = 0.70\, m/\hbar$



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

Hairy black hole

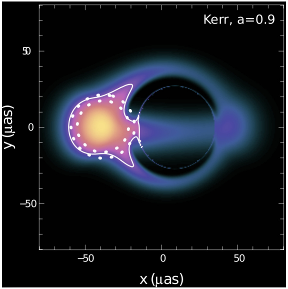


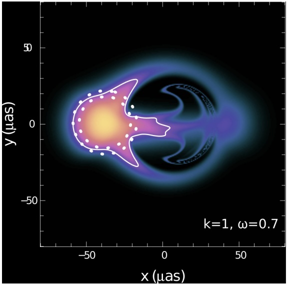
Accretion torus around a scalar-field-hairy rotating black hole

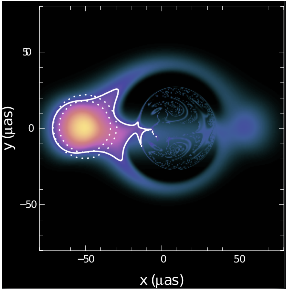
[Vincent, Gourgoulhon, Herdeiro & Radu, Phys. Rev. D **94**, 084045 (2016)]

Alternatives to the Kerr black hole

Kerr black hole	boson star [[1]]	hairy black hole [[2]]
$a/M = 0.9$	$k=1,\ \omega=0.7\, m/\hbar$	$a/M = 0.9$







Kadath → metric

Gyoto → ray-tracing

HR code → metric

(via Lorene)

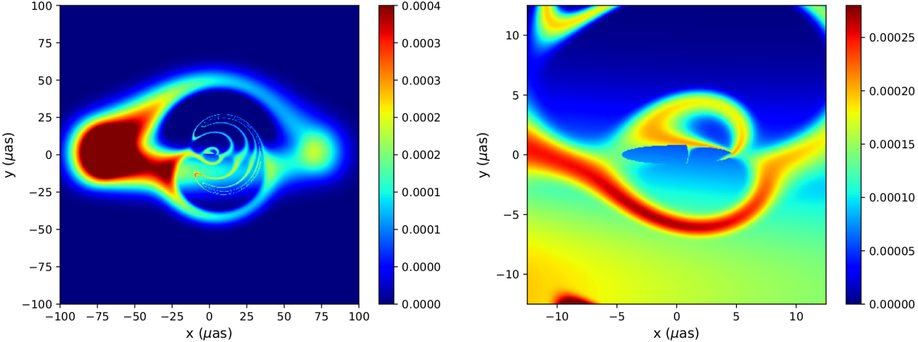
Gyoto → ray-tracing

[[1] Vincent, Meliani, Grandclément, Gourgoulhon & Straub, Class. Quantum Grav. **33**, 105015 (2016)]

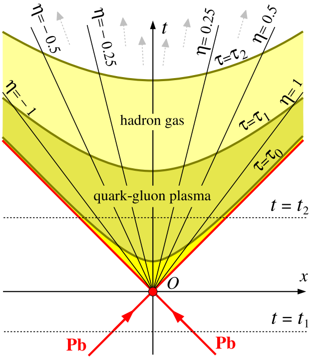
[[2] Vincent, Gourgoulhon, Herdeiro & Radu, Phys. Rev. D **94**, 084045 (2016)]

A more exotic alternative : naked rotating wormhole

Regular (singularity-free) spacetime with wormhole topology ($\mathbb{R}^2 \times \mathbb{S}^2$), sustained by exotic matter, asymptotically close a to Kerr spacetime with a naked singularity ($a > M$).



[Lamy, Gourgoulhon, Paumard & Vincent, arXiv:1802.01635]



Spacetime diagram of a heavy-ion collision (LHC)

$\tau_0 \simeq 0.2 \text{ fm}/c = 6\ 10^{-25}$ s

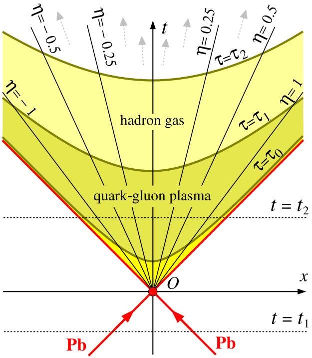
$\tau_1 \sim 10\tau_0$

Gauge/gravity duality ("holographic principle")

4D strongly-coupled gauge theory $\equiv$ 5D gravitation

Prototype : AdS/CFT correspondence

Black holes and gauge/gravity duality



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Prototype : AdS/CFT correspondence

Example : Quark-gluon plasma (QGP) in heavy-ion collisions : low-viscosity fluid with *anisotropic* pressure $(p_x < p_y)$
[Aref'eva, Golubtsova & Gourgoulhon, J. High Ener. Phys. **09(2016)**, 142 (2016)]

Thermalization of QGP $\equiv$ 5D black hole formation

Gauge theory : QCD
Gravity : 5D Lifshitz-like spacetime (*anisotropic* generalization of AdS_5) with formation of a black brane (Vaidya-type collapse)
Results : faster thermalization in the transversal direction ; evolution of the entanglement entropy

Conclusions

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Apart from astrophysics and gravitation theories, black holes play a key role in theoretical physics, via the gauge/gravity duality.