The black hole no-hair theorem

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based on a collaboration with
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Outline

1. The no-hair theorem
2. Theoretical alternatives to the Kerr black hole
3. Testing the no-hair theorem : some examples

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3. Testing the no-hair theorem : some examples

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 : precise mathematical statement

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

- is 4-dimensional
- is asymptotically flat
- is stationary
- is a solution of the vacuum Einstein equation : $\mathrm{Ric}(\boldsymbol{g}) = 0$
- contains a black hole with a connected regular horizon
- does not contain any 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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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)])

The Kerr solution

Roy Kerr (1963)

$$g_{\alpha\beta}\,\mathrm{d}x^\alpha\,\mathrm{d}x^\beta = -\left(1-\frac{2GMr}{c^2\rho^2}\right)c^2\mathrm{d}t^2 - \frac{4GMar\sin^2\theta}{c^2\rho^2}\,c\,\mathrm{d}t\,\mathrm{d}\varphi + \frac{\rho^2}{\Delta}\,\mathrm{d}r^2 + \rho^2\mathrm{d}\theta^2 + \left(r^2+a^2+\frac{2GMa^2r\sin^2\theta}{c^2\rho^2}\right)\sin^2\theta\,\mathrm{d}\varphi^2$$

where

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

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

→ 2 parameters : M : gravitational mass ; $a := \frac{J}{cM}$ reduced angular momentum

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$$+\rho^2 d\theta^2 + \left(r^2 + a^2 + \frac{2GMa^2r\sin^2\theta}{c^2\rho^2}\right)\sin^2\theta\,d\varphi^2$$

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→ Schwarzschild solution as the subcase $a = 0$:

$$g_{\alpha\beta}\,dx^\alpha\,dx^\beta = -\left(1-\frac{2GM}{c^2r}\right)c^2dt^2 + \left(1-\frac{2GM}{c^2r}\right)^{-1}dr^2 + r^2\left(d\theta^2+\sin^2\theta\,d\varphi^2\right)$$

Basic properties of Kerr metric

- Asymptotically flat ($r \to \pm\infty$)
- Stationary : metric components independent from t
- Axisymmetric : metric components independent from φ
- Not static when $a \neq 0$
- Contains a black hole $\iff$ $\boxed{0 \leq a \leq m}$, where $m := GM/c^2$

  event horizon : $r = r_+ := m + \sqrt{m^2 - a^2}$
- Contains a curvature singularity at $\rho = 0 \iff r = 0$ and $\theta = \pi/2$

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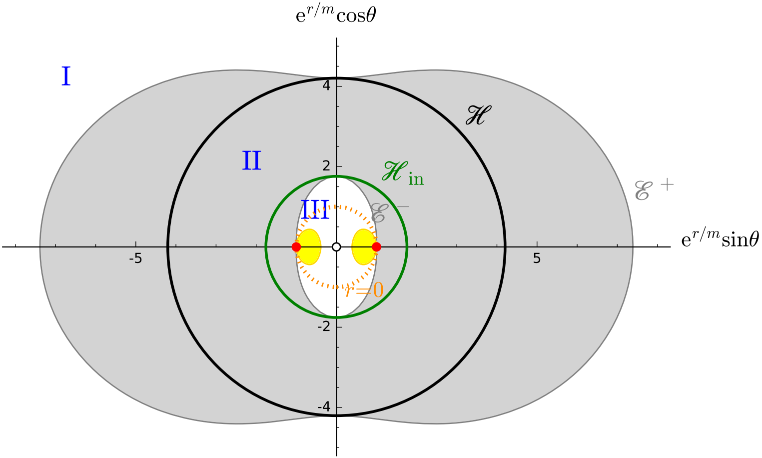
Remark : the radius of a black hole is not a well defined concept : it *does not* correspond to some distance between the black hole "centre" and the event horizon. A well defined quantity is the area of the event horizon, A.
The radius can be then defined from it : for a Schwarzschild black hole :

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

Kerr spacetime



Meridional view of a section $t = \text{const}$ of Kerr spacetime with $a/m = 0.90$

$\mathscr{E}^+$: ergosphere, $\mathscr{H}$: event horizon, $\mathscr{H}_{\rm in}$: inner horizon (Cauchy horizon)

● : ring singularity, (yellow) : Carter time machine

The Kerr metric is specific to black holes

Spherically symmetric (non-rotating) case :

Birkhoff theorem

Within 4-dimensional general relativity, the spacetime outside any spherically symmetric body is described by Schwarzschild metric

$\Longrightarrow$ No possibility to distinguish a non-rotating black hole from a non-rotating dark star by monitoring orbital motion or fitting accretion disk spectra

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Rotating axisymmetric case :

No Birkhoff theorem

Moreover, no "reasonable" matter source has ever been found for the Kerr metric (the only known source consists of two counter-rotating thin disks of collisionless particles [Bicak & Ledvinka, PRL **71**, 1669 (1993)])

$\Longrightarrow$ The Kerr metric is specific to rotating black holes (in 4-dimensional general relativity)

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) :

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

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

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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 GR :

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

Is general relativity unique ?

Yes if we assume

- a 4-dimensional spacetime
- gravitation only described by a metric tensor $\boldsymbol{g}$
- field equation involving only derivatives of $\boldsymbol{g}$ up to second order
- diffeomorphism invariance
- $\boldsymbol{\nabla} \cdot \boldsymbol{T} = 0$ ($\Longrightarrow$ weak equivalence principle)

The above is a consequence of Lovelock theorem (1972).

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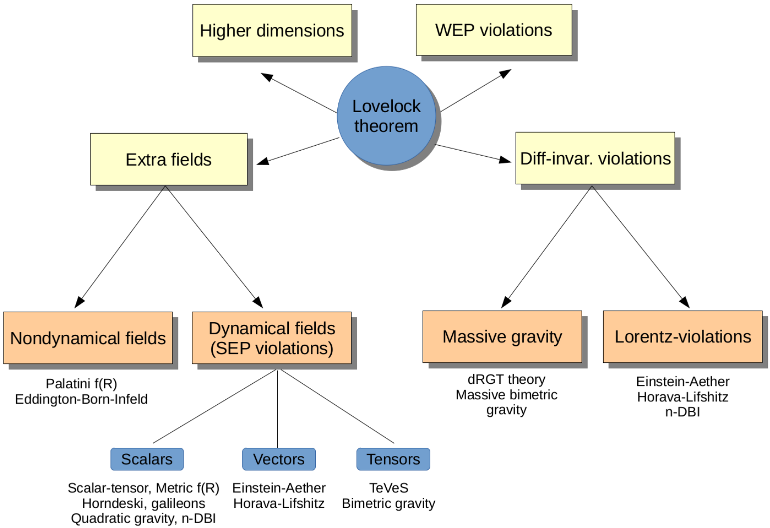
However, GR is certainly not the ultimate theory of gravitation :

- it is not a quantum theory
- cosmological constant / dark energy problem

GR is generally considered as a low-energy limit of a more fundamental theory :

- string theory
- loop quantum gravity
- ...

Extensions of general relativity



[Berti et al., CGQ **32**, 243001 (2015)]

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Test : are astrophysical black holes Kerr black holes ?

- GR $\Longrightarrow$ Kerr BH (no-hair theorem)
- extension of GR $\Longrightarrow$ BH may deviate from Kerr

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- gravitational waves :
  - ring-down phase of binary black hole mergers (LIGO, Virgo, LISA)
  - EMRI : extreme-mass-ratio binary inspirals (LISA)

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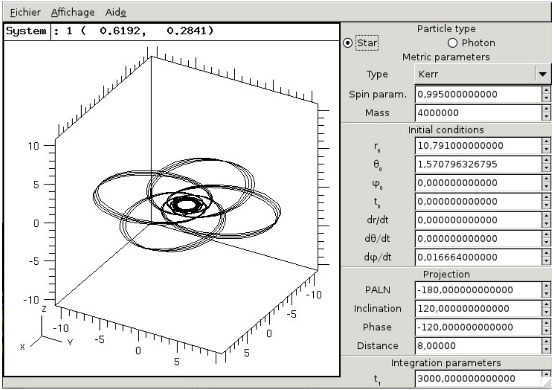
- pulsar orbiting Sgr A* : the Holly Grail !

Gyoto code

Main developers : T. Paumard & F. Vincent



- 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 and Python interfaces
- Free software (GPL) : http://gyoto.obspm.fr/

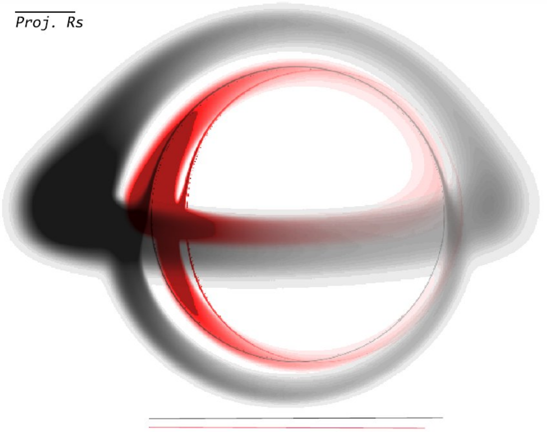
[Vincent, Paumard, Gourgoulhon & Perrin, CQG **28**, 225011 (2011)]

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

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 : $a = 0.9M$

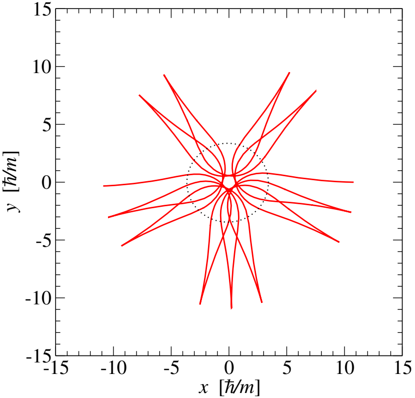
[Straub, Vincent, Abramowicz, Gourgoulhon & Paumard, A&A **543**, A83 (2012)]

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

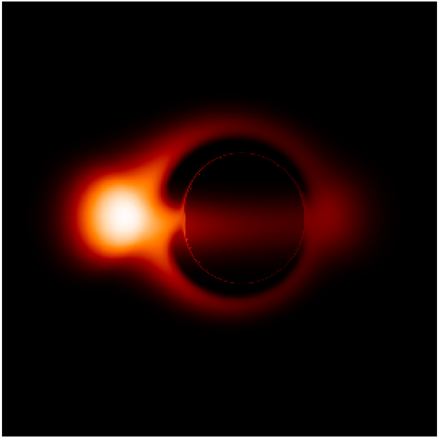


Intially-at-rest orbit around a rotating boson star based on a free scalar field $\Phi = \phi(r, \theta) e^{i(\omega t + 2\varphi)}$ with $\omega = 0.75\, m/\hbar$.

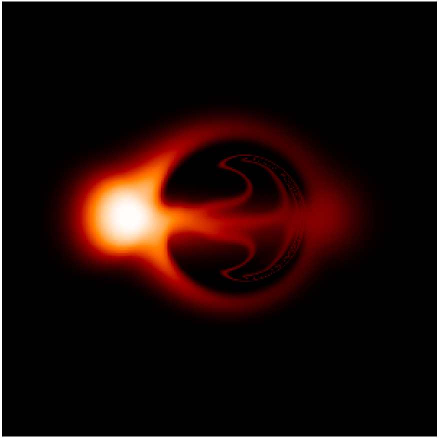
[Granclément, Somé & Gourgoulhon, PRD **90**, 024068 (2014)]

Image of an accretion torus : comparing with a Kerr BH

Kerr BH $a/M = 0.9$

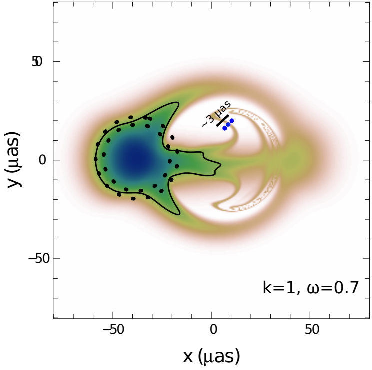


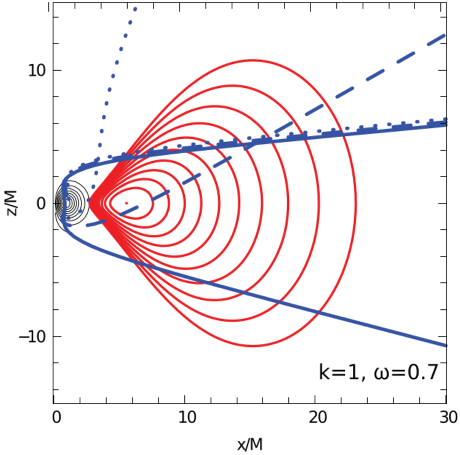
Boson star $k = 1,\ \omega = 0.70\, m/\hbar$



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

Strong light bending in rotating boson star spacetimes





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

Hairy black holes

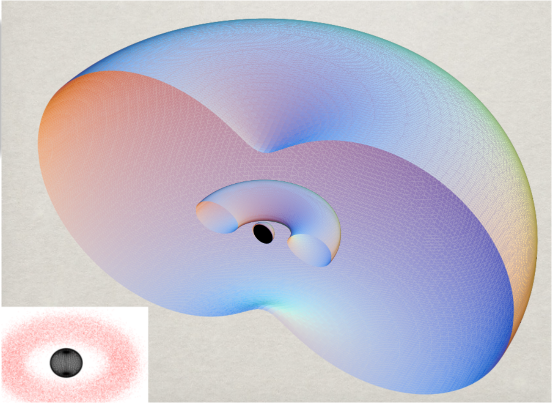
Herdeiro & Radu discovery (2014)

A black hole can have a complex scalar hair

Stationary axisymmetric configuration with a self-gravitating massive complex scalar field Φ and an event horizon

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

$$\omega = k\Omega_{\rm H}$$



[Herdeiro & Radu, PRL **112**, 221101 (2014)]

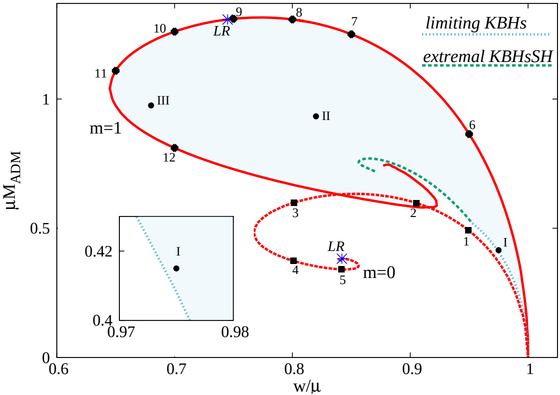
Herdeiro-Radu hairy black holes

- Configuration I : rather Kerr-like
- Configuration II : not so Kerr-like
- Configuration III : very non-Kerr-like

$\mu = \frac{m}{\hbar} = \frac{m}{m_{\rm Pl}^2} = \mathcal{M}^{-1}$

m = 0 : non-rotating boson stars

m = 1 : rotating boson stars with $k = 1$



[Cunha, Herdeiro, Radu Rúnarsson, PRL **115**, 211102 (2015)]

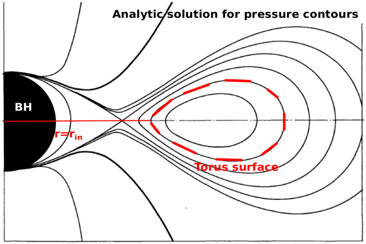
TABLE I. KBHsSH configurations considered in the present study. M is the ADM mass, $M_{\rm H}$ is the horizon's Komar mass, J is the total Komar angular momentum and $J_{\rm H}$ is the horizon's Komar angular momentum.

	M	$M_{\rm H}$	J	$J_{\rm H}$	$\frac{M_{\rm H}}{M}$	$\frac{J_{\rm H}}{J}$	$\frac{J}{M^2}$	$\frac{J_{\rm H}}{M_{\rm H}^2}$
Configuration I	$0.415\mathcal{M}$	$0.393\mathcal{M}$	$0.172\mathcal{M}^2$	$0.150\mathcal{M}^2$	95%	87%	0.999	0.971
Configuration II	$0.933\mathcal{M}$	$0.234\mathcal{M}$	$0.740\mathcal{M}^2$	$0.115\mathcal{M}^2$	25%	15%	0.850	2.10
Configuration III	$0.975\mathcal{M}$	$0.018\mathcal{M}$	$0.85\mathcal{M}^2$	$0.002\mathcal{M}^2$	1.8%	2.4%	0.894	6.20

Images of a magnetized accretion torus

Accretion torus model of [Vincent, Yan, Straub, Zdziarski & Abramowicz, A&A **574**, A48 (2015)]

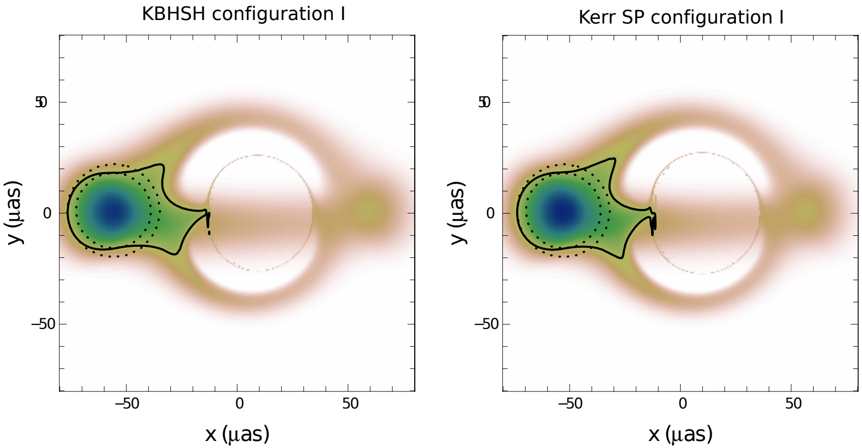
- non-self-gravitating perfect fluid
- polytropic EOS $\gamma = 5/3$
- constant specific angular momentum $\ell = u_\varphi/(-u_t) = 3.6\,M$ [Abramowicz, Jaroszynski & Sikora, A&A **63**, 221 (1978)]
- torus inner radius $r_{\rm in} \simeq 5.5\,M$
- max electron density : $n_{\rm e} = 6.3\ 10^{12}\ {\rm m}^{-3}$
- max electron temperature : $T_{\rm e} = 5.3\ 10^{10}\ {\rm K}$
- isotropized magnetic field $\Longrightarrow$ synchrotron radiation
- gas-to-magnetic pressure ration $\beta = 10$
- observer inclination angle : $\theta = 85°$



Configuration I

Gyoto-simulated images of Sgr A* at $f = 250$ GHz

hairy BH	Kerr BH with same (M, J)



[Vincent, Gourgoulhon, Herdeiro & Radu, PRD **94**, 084045 (2016)]

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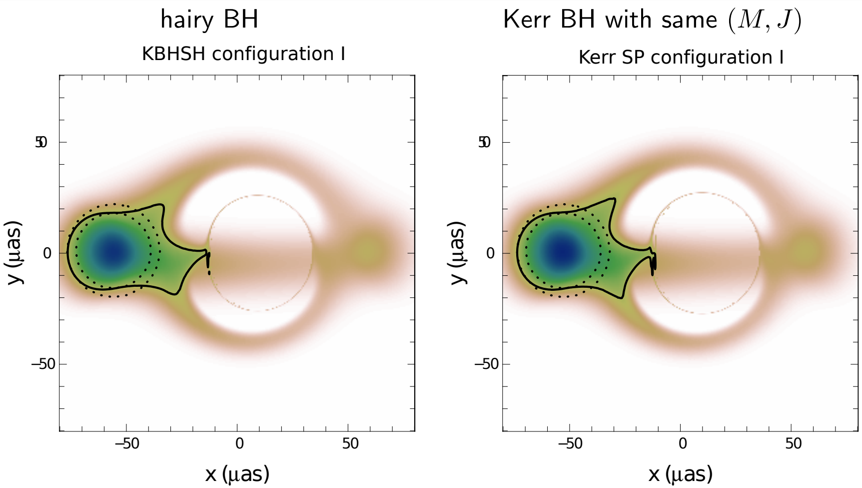


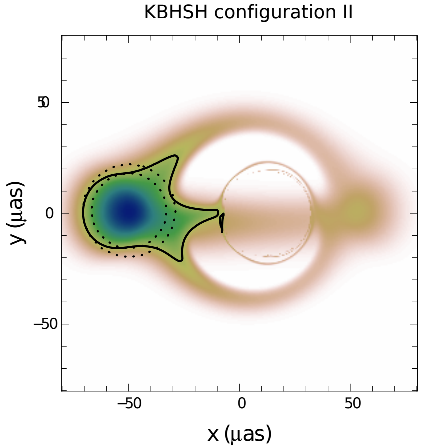
[Vincent, Gourgoulhon, Herdeiro & Radu, PRD **94**, 084045 (2016)]

5% difference in photon ring size $\Longrightarrow$ barely observable

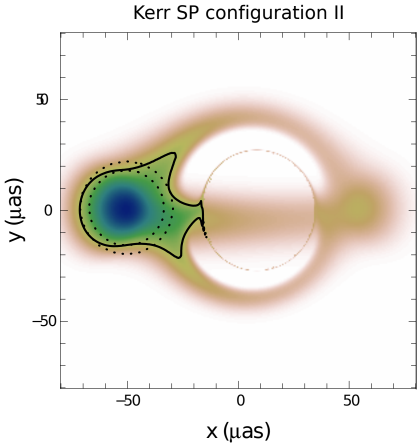
Configuration II

Gyoto-simulated images of Sgr A* at $f = 250$ GHz

hairy BH



Kerr BH with same (M, J)



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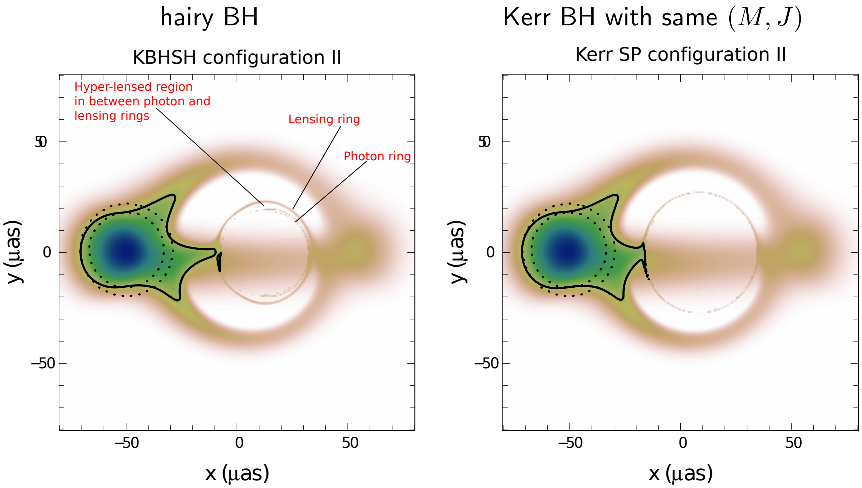

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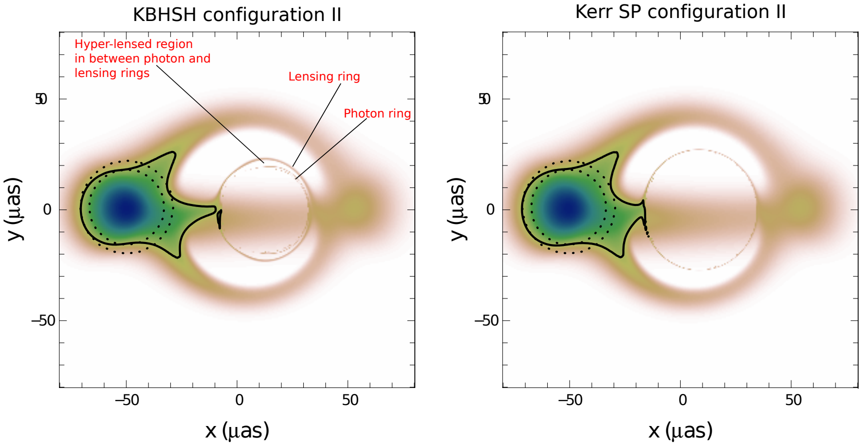
Gyoto-simulated images of Sgr A* at $f = 250$ GHz

hairy BH | Kerr BH with same (M, J)

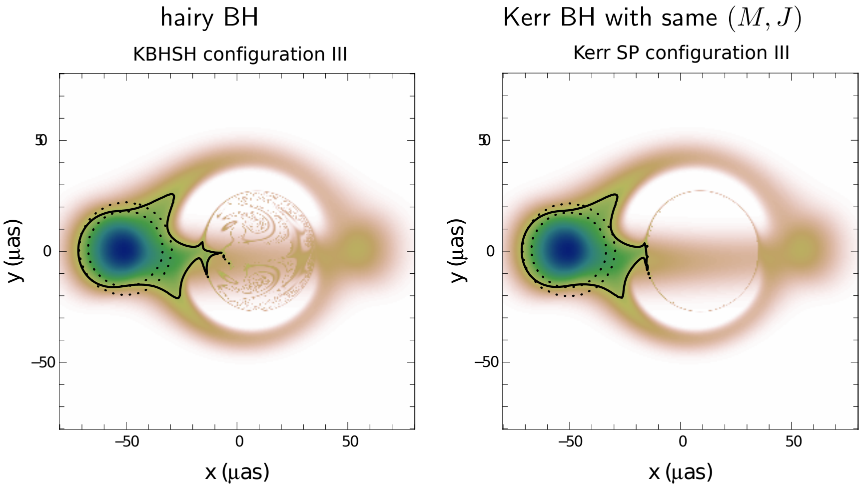


[Vincent, Gourgoulhon, Herdeiro & Radu, PRD **94**, 084045 (2016)]

20% difference between HBH-lensing and BH-photon rings $\Longrightarrow$ observable by EHT

Configuration III

Gyoto-simulated images of Sgr A* at $f = 250$ GHz



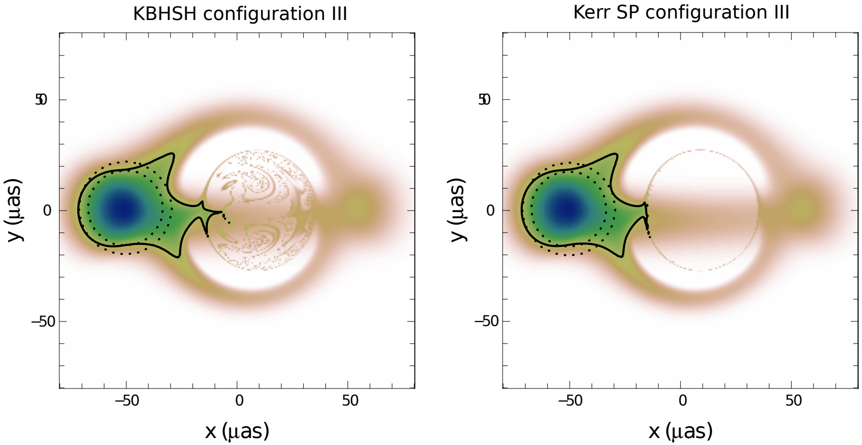
[Vincent, Gourgoulhon, Herdeiro & Radu, PRD **94**, 084045 (2016)]

Configuration III

Gyoto-simulated images of Sgr A* at $f = 250$ GHz

hairy BH

Kerr BH with same (M, J)



[Vincent, Gourgoulhon, Herdeiro & Radu, PRD **94**, 084045 (2016)]

HBH : no sharp edge in the intensity distribution $\Longrightarrow$ detectable by EHT

Conclusions

After a century marked by the Golden Age (1965-1975), which culminated with the no-hair theorem, the first astronomical discoveries and the ubiquity of black holes in high-energy astrophysics, black hole physics is very much alive.

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It is entering a new observational era, with the advent of high-angular-resolution telescopes and gravitational wave detectors, which provide unique opportunities to test general relativity in the strong field regime, notably by finding some voliation of the no-hair theorem.

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The GW150914 event was both the first direct detection of gravitational waves and the first observation of the merger of two black holes — the most dynamical event in relativistic gravity. The waveform was found consistent with general relativity.