Testing general relativity via observations of black hole surroundings

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based on a collaboration with
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Valencia, Spain
16 December 2016

Outline

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Can we see a black hole from the Earth ?

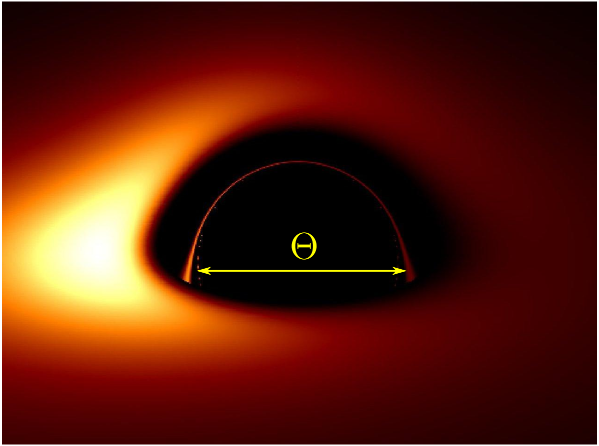

Image of a thin accretion disk around a Schwarzschild BH
[Vincent, Paumard, Gourgoulhon & Perrin, CQG **28**, 225011 (2011)]

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

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

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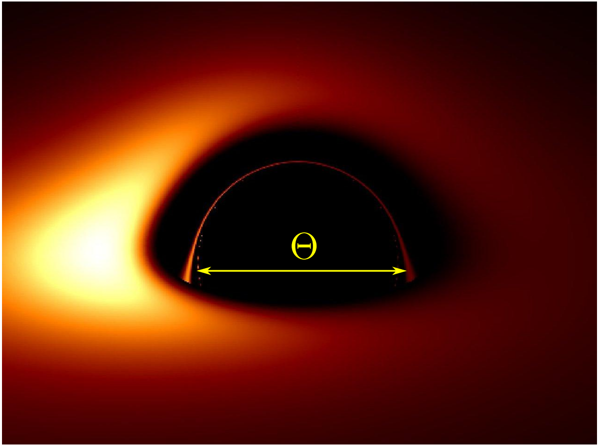

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Largest black holes in the Earth's sky :

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

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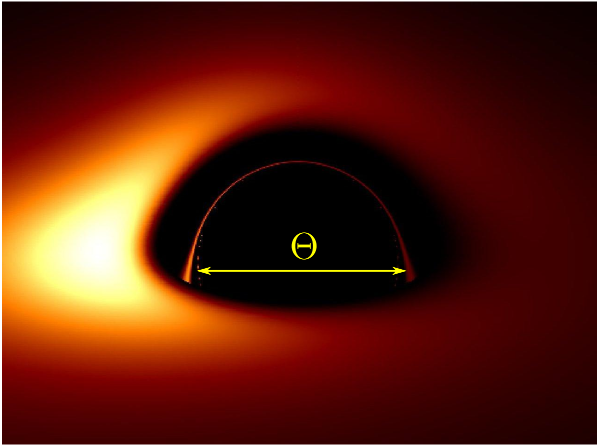

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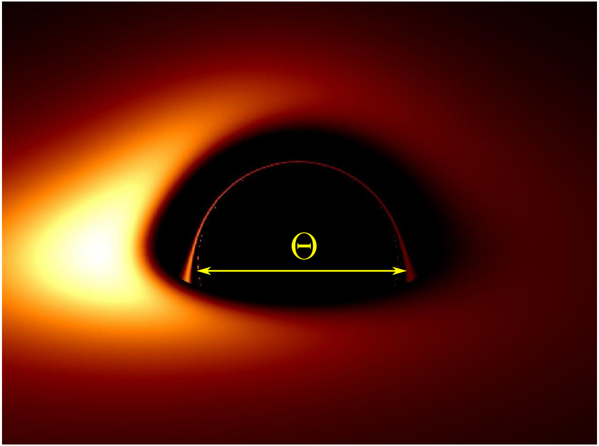

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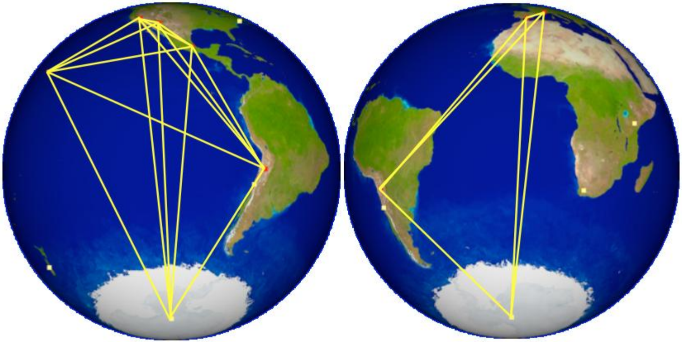
Remark : black holes in X-ray binaries are $\sim 10^5$ times smaller ($\Theta \propto M/d$)

Reaching the μas resolution with VLBI : the EHT



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

Event Horizon Telescope [Doeleman et al. 2011]

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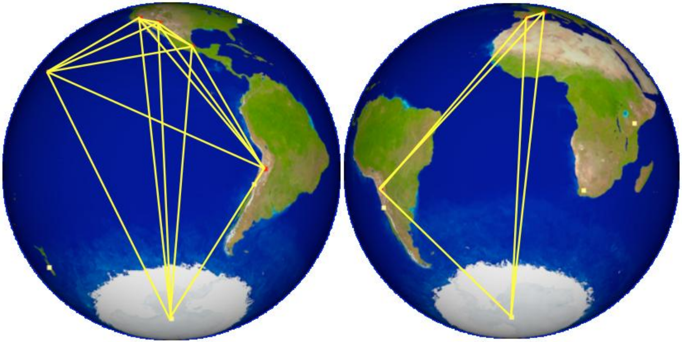

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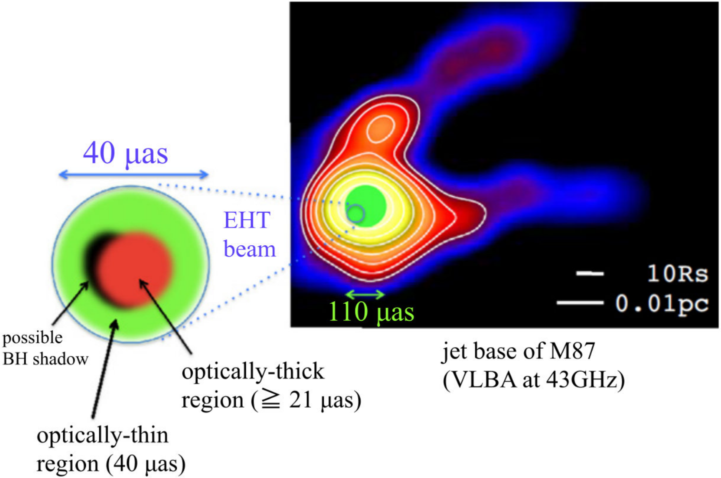
Very Large Baseline Interferometry (VLBI) in (sub)millimeter waves

One of 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

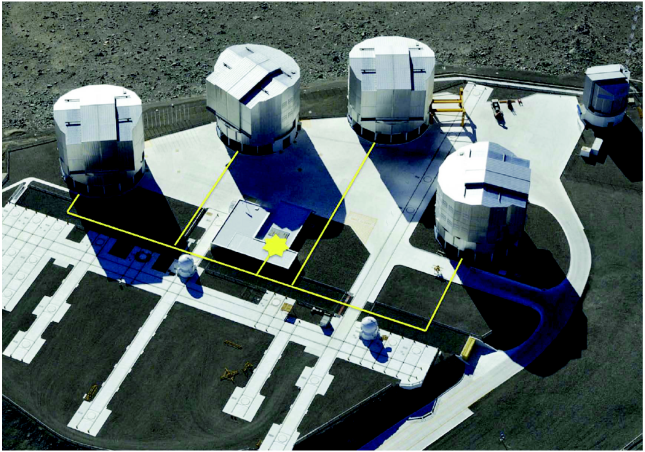
[Doeleman et al., Nature **455**, 78 (2008)]

VLBA and EHT observations of M87



[Kino et al., ApJ **803**, 30 (2015)]

Near-infrared optical interferometry : GRAVITY



[Gillessen et al. 2010]

GRAVITY instrument at VLTI (2016)

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

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

Near-infrared optical interferometry : GRAVITY

[MPE/GRAVITY team]

July 2015 : GRAVITY shipped to Chile and successfully assembled at Paranal Observatory

Fall 2016 : observations have started !

Outline

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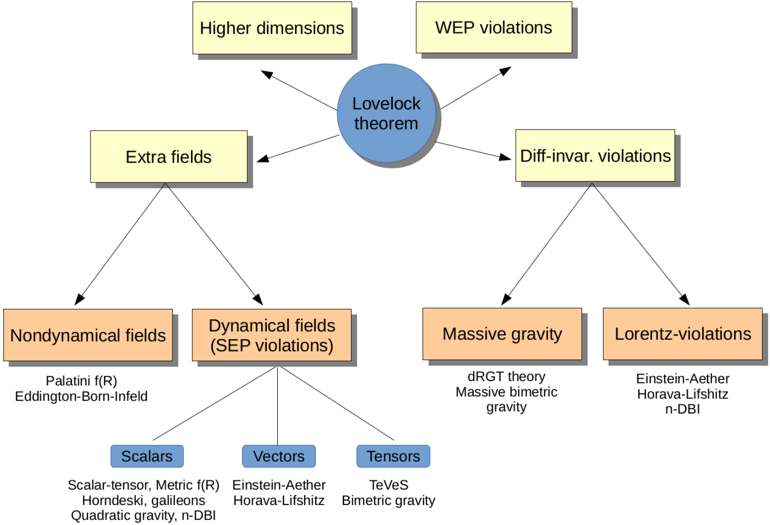
However, GR is certainly not the ultimate theory of gravitation :

- 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)]

An example : tensor-scalar theory

THE ASTROPHYSICAL JOURNAL, 533:392–405, 2000 April 10

GRAVITATIONAL WAVES FROM THE COLLAPSE AND BOUNCE OF A STELLAR CORE IN TENSOR-SCALAR GRAVITY

JÉRÔME NOVAK[1] AND JOSÉ M^A. IBÁÑEZ
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Received 1998 December 22; accepted 1999 November 17

ABSTRACT

Tensor-scalar theory of gravity allows the generation of gravitational waves from astrophysical sources, like supernovae, even in the spherical case. That motivated us to study the collapse of a degenerate stellar core, within tensor-scalar gravity, leading to the formation of a neutron star through a bounce and the formation of a shock. This paper discusses the effects of the scalar field on the evolution of the system, as well as the appearance of strong nonperturbative effects of this scalar field (the so-called spontaneous scalarization). As a main result, we describe the resulting gravitational monopolar radiation (form and amplitude) and discuss the possibility of its detection by the gravitational detectors currently under construction, taking into account the existing constraints on the scalar field. From the numerical point of view, it is worthy to point out that we have developed a combined code that uses pseudo-spectral methods for the evolution of the scalar field and High-Resolution Shock-Capturing schemes, as well as for the evolution of the hydrodynamical system. Although this code has been used to integrate the field equations of that theory of gravity, in the spherically symmetric case, a by-product of the present work is to gain experience for an ulterior extension to multidimensional problems in Numerical Relativity of such numerical strategy.

The link with **CoCoNuT** : first "Mariage des maillages"

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Test : are astrophysical black holes Kerr black holes ?

- No-hair theorem : GR $\Longrightarrow$ Kerr BH
- extension of GR $\Longrightarrow$ BH may deviate from Kerr

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Observational tests

Search for

- stellar orbits deviating from Kerr timelike geodesics (GRAVITY)
- accretion disk spectra different from those arising in Kerr metric (X-ray observatories, e.g. Athena)
- images of the black hole silhouette different from that of a Kerr BH (EHT)

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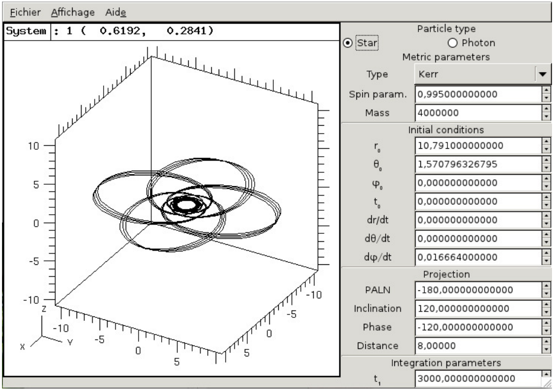
Need for a good and versatile geodesic integrator

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

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++)
- Python interface
- Free software (GPL) : http://gyoto.obspm.fr/

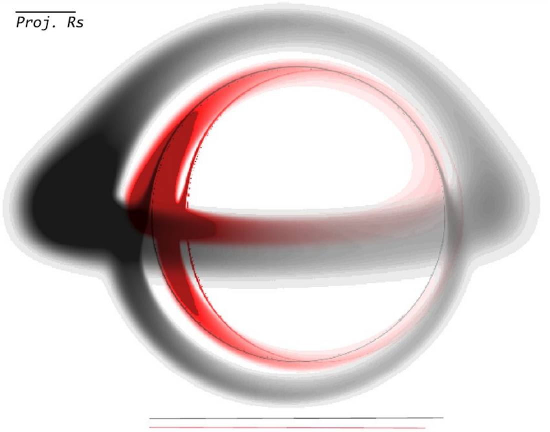
[Vincent, Paumard, Gourgoulhon & Perrin, CQG **28**, 225011 (2011)]

[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)]

Outline

Boson stars

Boson star = localized configurations of a self-gravitating complex scalar field Φ
≡ "Klein-Gordon geons" [Bonazzola & Pacini (1966), Kaup (1968), Ruffini & Bonazzola (1969)]

- Minimally coupled scalar field : $\mathcal{L} = \frac{1}{16\pi} R - \frac{1}{2} \left[\nabla_\mu \bar{\Phi} \nabla^\mu \Phi + V(|\Phi|^2) \right]$
- Field equation : $\nabla_\mu \nabla^\mu \Phi = V'(|\Phi|^2)\, \Phi$
- Einstein equation : $R_{\alpha\beta} - \frac{1}{2} R g_{\alpha\beta} = 8\pi T_{\alpha\beta}$

  with $T_{\alpha\beta} = \nabla_{(\alpha} \bar{\Phi} \nabla_{\beta)} \Phi - \frac{1}{2} \left[\nabla_\mu \bar{\Phi} \nabla^\mu \Phi + V(|\Phi|^2) \right] g_{\alpha\beta}$

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Examples :

- free field : $V(|\Phi|^2) = \frac{m^2}{\hbar^2} |\Phi|^2$, $\quad m$: boson mass

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Boson stars as black-hole mimickers

Boson stars can be very compact and are the less exotic alternative to black holes : they require only a scalar field and since 2012 we know that at least one fundamental scalar field exists in Nature : the Higgs boson !

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Maximum mass

- Free field : $M_{\max} = \alpha \frac{\hbar}{m} = \alpha \frac{m_{\rm P}^2}{m}$, with $\alpha \sim 1$
- Self-interacting field : $M_{\max} \sim \left(\frac{\lambda}{4\pi}\right)^{1/2} \frac{m_{\rm P}^2}{m} \times \frac{m_{\rm P}}{m}$

$m_{\rm P} = \sqrt{\hbar} = \sqrt{\hbar c/G} = 2.18\ 10^{-8}\ {\rm kg}$: Planck mass

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m	$M_{\rm max}$ (free field)	$M_{\rm max}$ $(\lambda = 1)$
125 GeV (Higgs)	$2\ 10^{9}$ kg	$2\ 10^{26}$ kg
1 GeV	$3\ 10^{11}$ kg	$2\ M_\odot$
0.5 MeV	$3\ 10^{14}$ kg	$5\ 10^{6}\ M_\odot$

Rotating boson stars

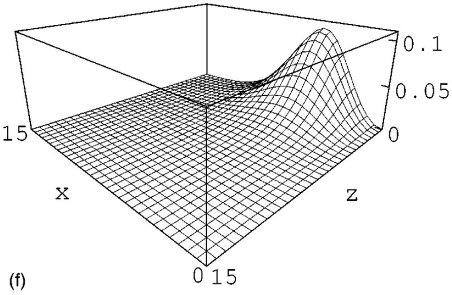
Ansatz for stationary and axisymmetric spacetimes [Schunck & Mielke (1996)] :

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

with $\Phi_0(r, \theta)$ real function, $\omega \in \mathbb{R}$ and $k \in \mathbb{N}$ (regularity on the rotation axis)

Solutions :

- $k = 0$: static and spherically symmetric boson stars
  $\Longrightarrow$ exterior spacetime = Schwarzschild (or close to it if Φ never vanishes)
- $k \geq 1$: stationary rotating "stars" with toroidal topology
  $\Longrightarrow$ exterior spacetime expected to be significantly different from Kerr



$\leftarrow$ Profile of $\Phi_0(r, \theta)$ for a free field with $k = 2$

z-axis = rotation axis :
$z = r \cos\theta$, $x = r \sin\theta \cos\varphi$

[Yoshida & Eriguchi, PRD **56**, 762 (1997)]

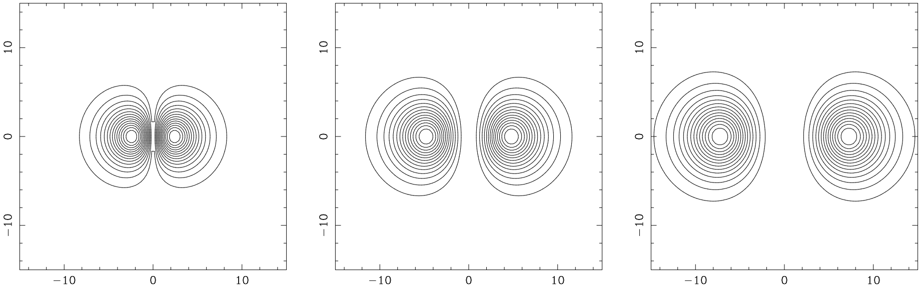
Rotating boson stars

Solutions computed by means of Kadath [Grandclément, JCP **229**, 3334 (2010)]

http://luth.obspm.fr/~luthier/grandclement/kadath.html

Isocontours of $\Phi_0(r,\theta)$ in the plane $\varphi = 0$ for $\omega = 0.8\frac{m}{\hbar}$:

$k = 1$ $k = 2$ $k = 3$

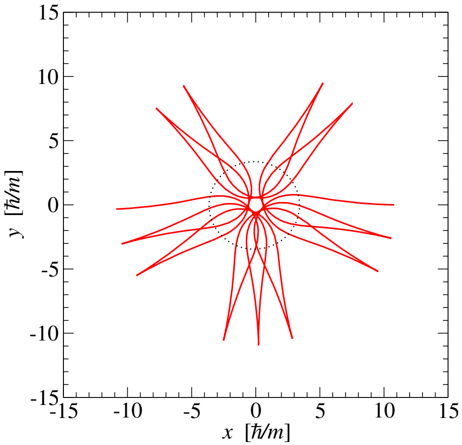


[Granclément, Somé & Gourgoulhon, PRD **90**, 024068 (2014)]

Zero-angular momentum orbits around rotating boson stars

$\ell = 0$ orbit around a rotating boson star based on the scalar field $\Phi = \Phi_0(r,\theta)e^{i(\omega t + k\varphi)}$ with $k = 2$ and $\omega = 0.75\, m/\hbar$

Orbit = timelike geodesic computed by means of Gyoto



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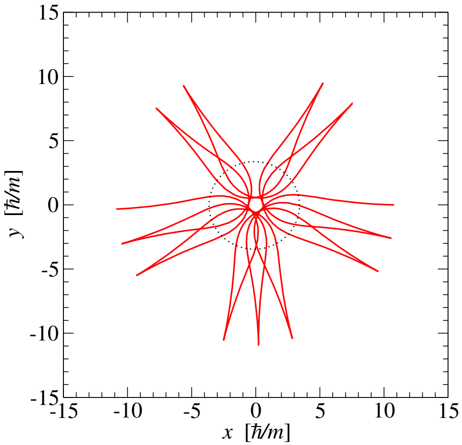

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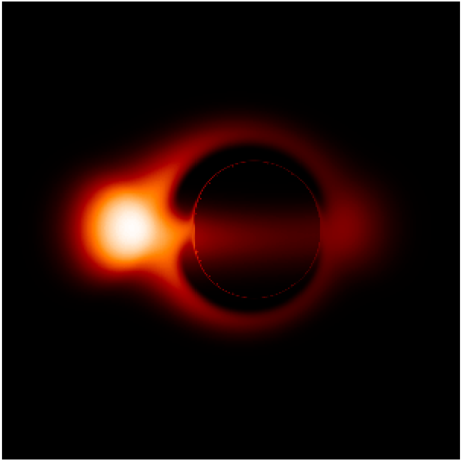
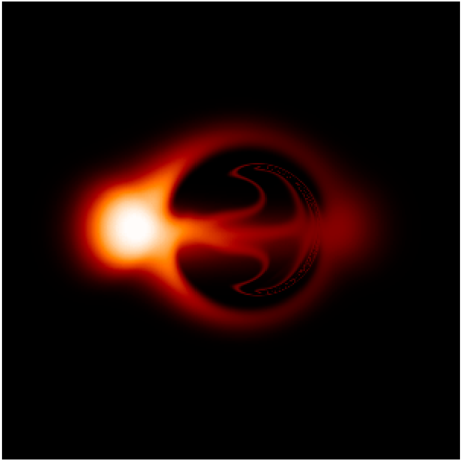
No equivalent in Kerr spacetime

Image of an accretion torus

Kerr BH $a/M = 0.9$

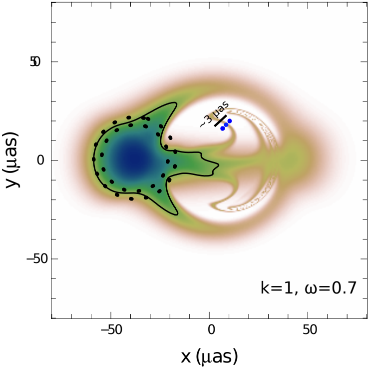


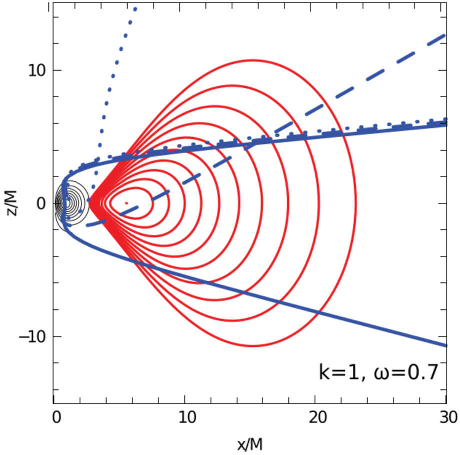
Boson star $k = 1$, $\omega = 0.70\, m/\hbar$



[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)]

Outline

Herdeiro-Radu hairy black holes

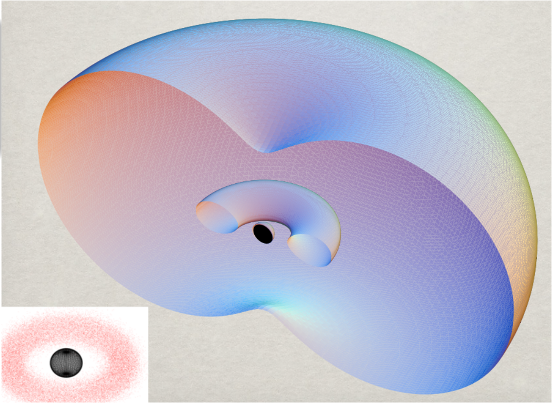
Herdeiro & Radu discovery (2014)

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

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

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



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

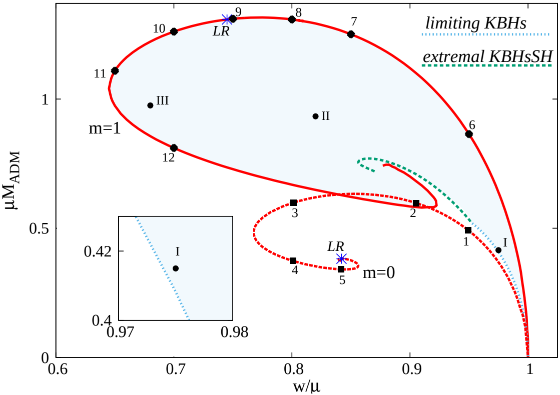
Herdeiro-Radu hairy black holes

- 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)]

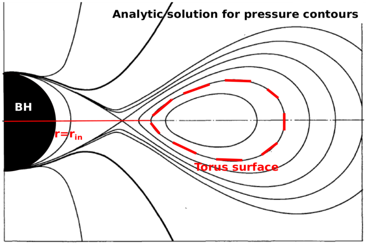
TABLE I. KBHsSH configurations considered in the present study. M is the ADM mass, $M_{\rm H}$ is the horizon's Komar mass, J is the total Komar angular momentum and $J_{\rm H}$ is the horizon's Komar angular momentum.

	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

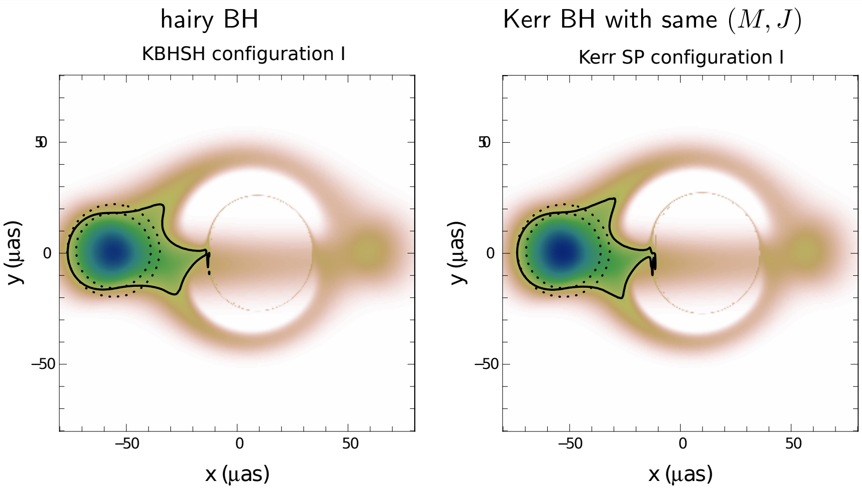
Accretion torus model of [Vincent, Yan, Straub, Zdziarski & Abramowicz, A&A **574**, A48 (2015)]

- 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

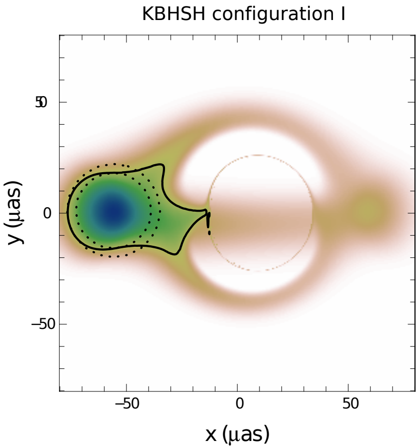


[Vincent, Gourgoulhon, Herdeiro & Radu, PRD **94**, 084045 (2016)]

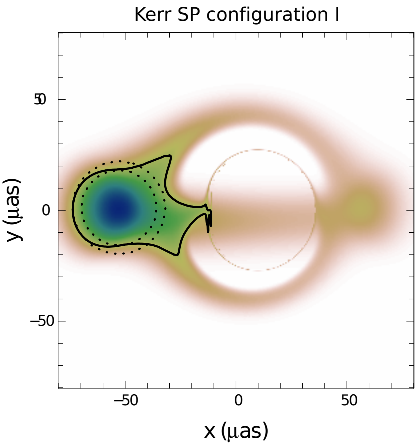
Configuration I

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

hairy BH



Kerr BH with same (M, J)

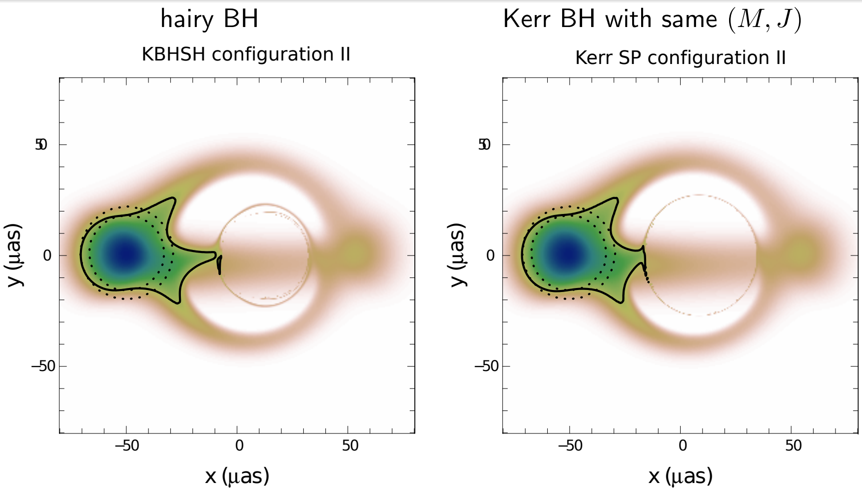


[Vincent, Gourgoulhon, Herdeiro & Radu, PRD **94**, 084045 (2016)]

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

Configuration II

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

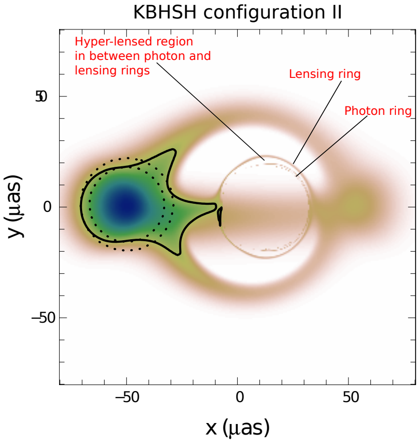


[Vincent, Gourgoulhon, Herdeiro & Radu, PRD **94**, 084045 (2016)]

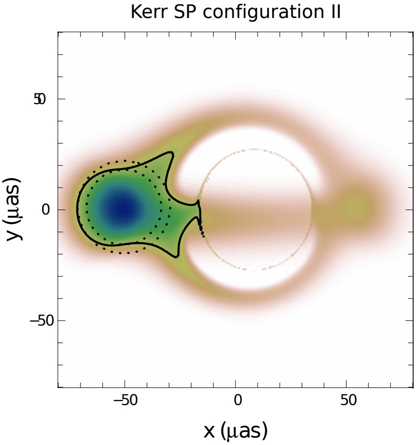
Configuration II

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

hairy BH



Kerr BH with same (M, J)

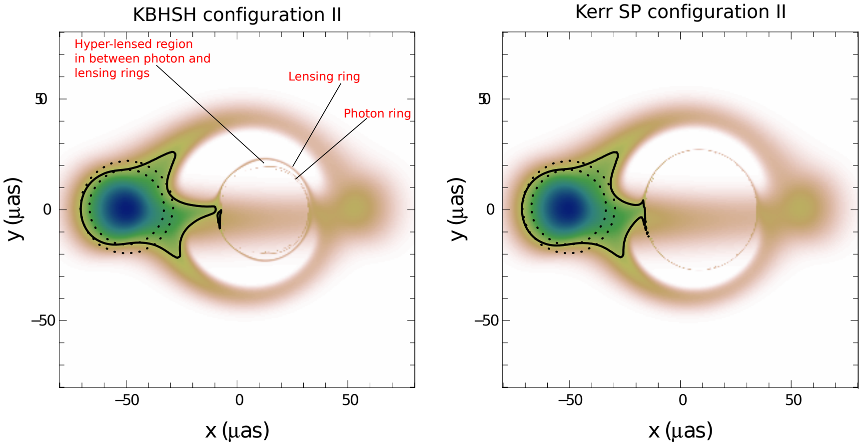


[Vincent, Gourgoulhon, Herdeiro & Radu, PRD **94**, 084045 (2016)]

Configuration II

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

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



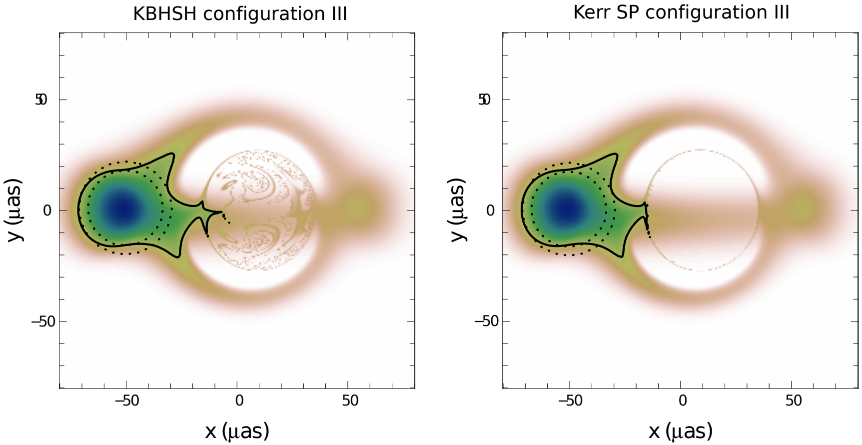
[Vincent, Gourgoulhon, Herdeiro & Radu, PRD **94**, 084045 (2016)]

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

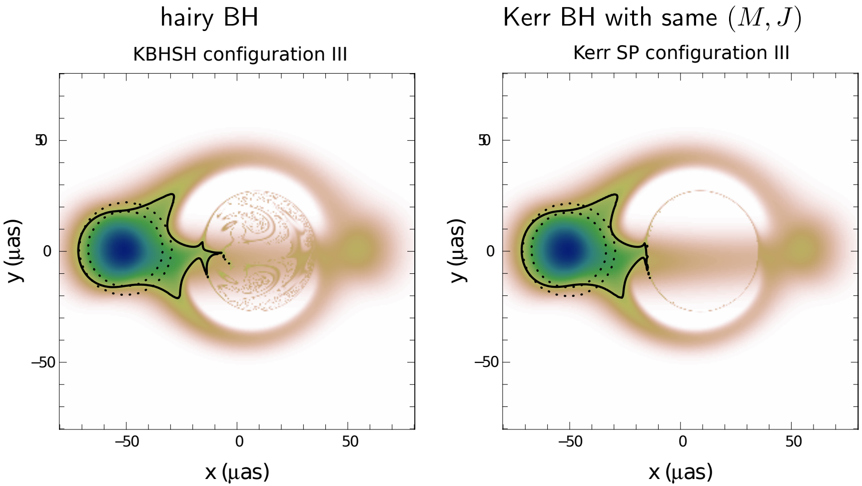
hairy BH | Kerr BH with same (M, J)



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

Configuration III

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



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

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

Outline

Conclusion and future prospects

After a century marked by the Golden Age (1965-1975), the first astronomical discoveries (1970-80's) and the ubiquity of black holes in high-energy astrophysics (1990's - present), black hole physics 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.

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We have investigated two alternatives to the Kerr black hole *within general relativity* : boson stars and black holes with scalar hair. Both show distinctive features, within the range of GRAVITY and EHT instruments.

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We have investigated two alternatives to the Kerr black hole *within general relativity* : boson stars and black holes with scalar hair. Both show distinctive features, within the range of GRAVITY and EHT instruments.

Future prospects

- Obtain rotating black hole solutions in extensions to GR, such as Einstein-Gauss-Bonnet gravity with dilaton [Kleihaus, Kunz & Radu, PRL **106**, 151104 (2011)] and Chern-Simons gravity
- Compute orbits and accretion disk/torus images and compare with Kerr BH