Testing general relativity
via observations of black hole surroundings

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based on a collaboration with
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Thibaut Paumard, Guy Perrin, Eugen Radu, Claire Somé, Odele Straub and
Frédéric H. Vincent

CoCoNuT Meeting 2016
Valencia, Spain
16 December 2016
1. A new observational era

2. Testing general relativity with black holes

3. Boson stars

4. Black holes with scalar hair

5. Conclusion and future prospects
Outline

1. A new observational era

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5. Conclusion and future prospects
Can we see a black hole from the Earth?

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

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

Image of a thin accretion disk around a Schwarzschild BH

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

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Compare: HST resolution $\sim 10^5 \mu\text{as}$!
A new observational era

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Compare : HST resolution $\sim 10^5 \mu\text{as}$!

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

Reaching the \( \mu \text{as} \) resolution with VLBI: the EHT

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

Event Horizon Telescope [Doeleman et al. 2011]
A new observational era

Reaching the $\mu$as resolution with VLBI: the EHT

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)]
A new observational era

VLBA and EHT observations of M87

Éric Gourgoulhon (LUTH)

Testing GR via BH observations


40 μas

optically-thick region (≥ 21 μas)

optically-thin region (40 μas)

possible BH shadow

EHT beam

110 μas

jet base of M87
(VLBA at 43GHz)

A new observational era
Near-infrared optical interferometry: GRAVITY

GRAVITY instrument at VLTI (2016)
Beam combiner (the four 8 m telescopes + four auxiliary telescopes)
astrometric precision on orbits: 10 μas

[Gillessen et al. 2010]
A new observational era

Near-infrared optical interferometry: GRAVITY

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

Fall 2016: observations have started!

[MPE/GRAVITY team]
Outline

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2. Testing general relativity with black holes
3. Boson stars
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Is general relativity unique?

Yes if we assume

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

The above is a consequence of Lovelock theorem (1972).
Testing general relativity with black holes

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- diffeomorphism invariance
- $\nabla \cdot T = 0$ (⇒ weak equivalence principle)

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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
- …
Testing general relativity with black holes

Extensions of general relativity

- Higher dimensions
- WEP violations
- Lovelock theorem
- Diff-invar. violations
- Extra fields

Nondynamical fields
- Palatini $f(R)$
- Eddington-Born-Infeld

Dynamical fields (SEP violations)
- Scalars
  - Scalar-tensor, Metric $f(R)$
  - Horndeski, galileons
  - Quadratic gravity, n-DBI
- Vectors
  - Einstein-Aether
  - Horava-Lifshitz
- Tensors
  - TeVeS
  - Bimetric gravity

Massive gravity
- dRGT theory
- Massive bimetric gravity

Lorentz-violations
- Einstein-Aether
- Horava-Lifshitz
- n-DBI

[Berti et al., CGQ 32, 243001 (2015)]
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 pseudospectral 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.
Testing general relativity with black holes

The link with CoCoNuT: first “Mariage des maillages”

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

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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 pseudospectral 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.
Test: are astrophysical black holes Kerr black holes?

- **No-hair theorem**: GR $\Rightarrow$ Kerr BH
- Extension of GR $\Rightarrow$ BH may deviate from Kerr
Test: are astrophysical black holes Kerr black holes?

- No-hair theorem: GR $\implies$ Kerr BH
- Extension of GR $\implies$ BH may deviate from Kerr

**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)
Testing general relativity with black holes

Test: are astrophysical black holes Kerr black holes?

- **No-hair theorem**: $\text{GR} \implies \text{Kerr BH}$
- extension of $\text{GR} \implies \text{BH}$ may deviate from Kerr

**Observational tests**

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

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

Radiative processes included: thermal synchrotron, bremsstrahlung, inverse Compton

$\leftarrow$ 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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Boson stars

**Boson star** = localized configurations of a self-gravitating complex scalar field $\Phi$

$\equiv$ “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: $V(|\Phi|^2) = \frac{m^2}{\hbar^2} |\Phi|^2$, $m$: boson mass

  $\implies$ field equation = Klein-Gordon equation: $\nabla_\mu \nabla^\mu \Phi = \frac{m^2}{\hbar^2} \Phi$

- a standard self-interacting field: $V(|\Phi|^2) = \frac{m^2}{\hbar^2} |\Phi|^2 + \lambda |\Phi|^4$
Boson stars

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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:** \( M_{\text{max}} = \alpha \frac{\hbar}{m} = \alpha \frac{m_P^2}{m} \), with \( \alpha \sim 1 \)

- **Self-interacting field:** \( M_{\text{max}} \sim \left( \frac{\lambda}{4\pi} \right)^{1/2} \frac{m_P^2}{m} \times \frac{m_P}{m} \)

\[
m_P = \sqrt{\hbar} = \sqrt{\hbar c/G} = 2.18 \times 10^{-8} \text{ kg} : \text{Planck mass}
\]
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<table>
<thead>
<tr>
<th>$m$</th>
<th>$M_{\text{max}}$ (free field)</th>
<th>$M_{\text{max}}$ ($\lambda = 1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>125 GeV (Higgs)</td>
<td>2 $10^9$ kg</td>
<td>2 $10^{26}$ kg</td>
</tr>
<tr>
<td>1 GeV</td>
<td>3 $10^{11}$ kg</td>
<td>$2 M_\odot$</td>
</tr>
<tr>
<td>0.5 MeV</td>
<td>3 $10^{14}$ kg</td>
<td>$5 \times 10^6 M_\odot$</td>
</tr>
</tbody>
</table>
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
  \[ \Rightarrow \text{exterior spacetime} = \text{Schwarzschild (or close to it if } \Phi \text{ never vanishes)} \]
- \( k \geq 1 \): stationary rotating “stars” with toroidal topology
  \[ \Rightarrow \text{exterior spacetime expected to be significantly different from Kerr} \]

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

\[ z \text{-axis} = \text{rotation axis} : \]
\[ z = r \cos \theta, \ x = r \sin \theta \cos \varphi \]

[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 $\omega = 0.8 \frac{m}{\hbar}$:

$k = 1$

$k = 2$

$k = 3$

[Grandclément, Somé & Gourgoulhon, PRD 90, 024068 (2014)]
$\ell = 0$ 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

[Granclément, Somé & Gourgoulhon, PRD 90, 024068 (2014)]
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with \( k = 2 \) and \( \omega = 0.75 \, m/\hbar \)

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

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

\[ x(\mu\text{as}) \quad y(\mu\text{as}) \approx 3 \mu\text{as} \quad k=1, \omega=0.7 \]

[Vincent, Meliani, Grandclément, Gourgoulhon & Straub, CQG 33, 105015 (2016)]
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Black holes with scalar hair

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 $\Phi$ and an event horizon

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

$$\omega = k\Omega_H$$

[Herdeiro & Radu, PRL 112, 221101 (2014)]
Black holes with scalar hair

Herdeiro-Radu hairy black holes

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

\[ \mu = \frac{m}{\hbar} = \frac{m}{m^2_{Pl}} = \mathcal{M}^{-1} \]

- \( m = 0 \): non-rotating boson stars
- \( m = 1 \): rotating boson stars with \( k = 1 \)

---

**TABLE I.** KBHsSH configurations considered in the present study. \( M \) is the ADM mass, \( M_H \) is the horizon’s Komar mass, \( J \) is the total Komar angular momentum and \( J_H \) is the horizon’s Komar angular momentum.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>( M )</th>
<th>( M_H )</th>
<th>( J )</th>
<th>( J_H )</th>
<th>( \frac{M_H}{M} )</th>
<th>( \frac{J_H}{J} )</th>
<th>( \frac{J}{M^2} )</th>
<th>( \frac{J_H}{M_H^2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.415M</td>
<td>0.393M</td>
<td>0.172M^2</td>
<td>0.150M^2</td>
<td>95%</td>
<td>87%</td>
<td>0.999</td>
<td>0.971</td>
</tr>
<tr>
<td>II</td>
<td>0.933M</td>
<td>0.234M</td>
<td>0.740M^2</td>
<td>0.115M^2</td>
<td>25%</td>
<td>15%</td>
<td>0.850</td>
<td>2.10</td>
</tr>
<tr>
<td>III</td>
<td>0.975M</td>
<td>0.018M</td>
<td>0.85M^2</td>
<td>0.002M^2</td>
<td>1.8%</td>
<td>2.4%</td>
<td>0.894</td>
<td>6.20</td>
</tr>
</tbody>
</table>

[Cunha, Herdeiro, Radu Rúnarsson, PRL 115, 211102 (2015)]
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 $r_{\text{in}} \simeq 5.5 \ M$
- max electron density : $n_e = 6.3 \ 10^{12} \ \text{m}^{-3}$
- max electron temperature : $T_e = 5.3 \ 10^{10} \ \text{K}$
- isotropized magnetic field $\Rightarrow$ synchrotron radiation
- gas-to-magnetic pressure ration $\beta = 10$
- observer inclination angle : $\theta = 85^\circ$
Black holes with scalar hair

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

hairy BH

Kerr BH with same $(M, J)$

KBHSH configuration I
Kerr SP configuration I

[$\text{Vincent, Gourgoulhon, Herdeiro & Radu, PRD 94, 084045 (2016)}$]
5% difference in photon ring size $\implies$ barely observable

[Vincent, Gourgoulhon, Herdeiro & Radu, PRD 94, 084045 (2016)]
Configuration II
Gyoto-simulated images of Sgr A* at $f = 250$ GHz

hairy BH
KBHSH configuration II

Kerr BH with same $(M, J)$
Kerr SP configuration II

[Vincent, Gourgoulhon, Herdeiro & Radu, PRD 94, 084045 (2016)]
Black holes with scalar hair

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

hairy BH

Kerr BH with same $(M, J)$

Hyper-lensed region in between photon and lensing rings

[Vincent, Gourgoulhon, Herdeiro & Radu, PRD 94, 084045 (2016)]
Configuration II
Gyoto-simulated images of Sgr A* at $f = 250$ GHz

Black holes with scalar hair

hairy BH

Kerr BH with same $(M, J)$

Hyper-lensed region in between photon and lensing rings

Lensing ring

Photon ring

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

20% difference between HBH-lensing and BH-photon rings $\implies$ observable by EHT
**Configuration III**

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

- **hairy BH**
  - KBHSH configuration III

- **Kerr BH with same $(M, J)$**
  - Kerr SP configuration III

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

Éric Gourgoulhon (LUTH)  
Testing GR via BH observations  
Black holes with scalar hair

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 $\implies$ detectable by EHT
Conclusion and future prospects

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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