Searching for new particles with astrophysical compact objects

Supervisors: Carlos Herdeiro and Eugen Radu

Etevaldo dos Santos Costa Filho

Astrophysical motivation

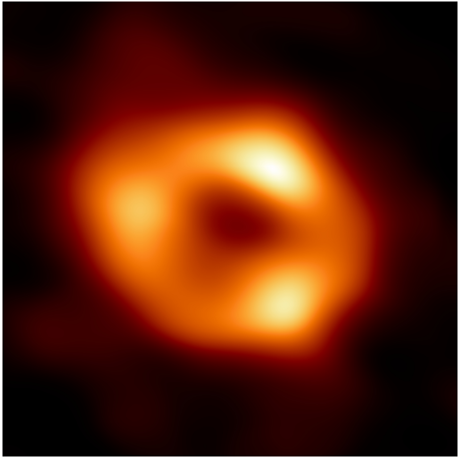
Certain observed astronomical objects formerly thought to be black holes may be massive boson stars.

EHT(2019)

Astrophysical motivation

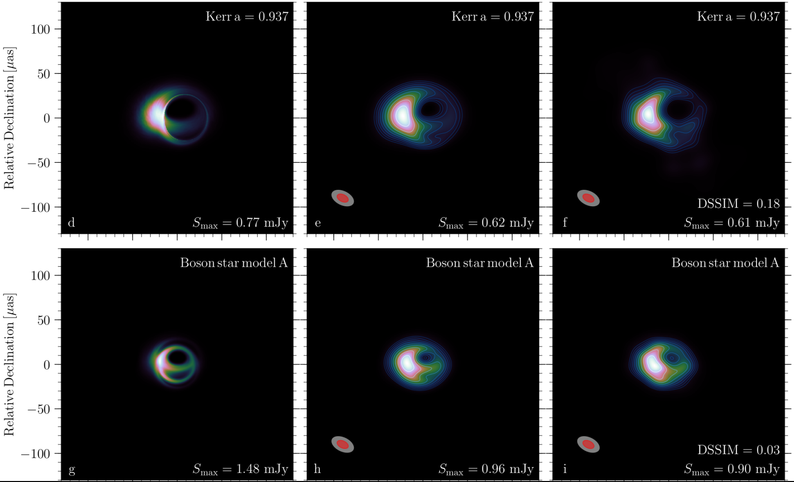
Certain observed astronomical objects formerly thought to be black holes may be massive boson stars.

EHT(2022)



Astrophysical motivation

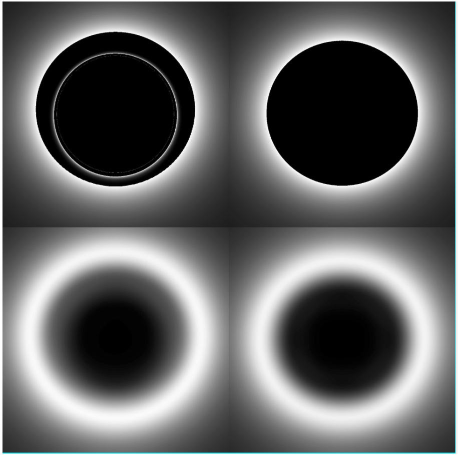
This boson star would not be able to be a black hole mimicker, because the size of the hole would be too small for the expected mass.



Olivares et al. MNRAS (2020)

Astrophysical motivation

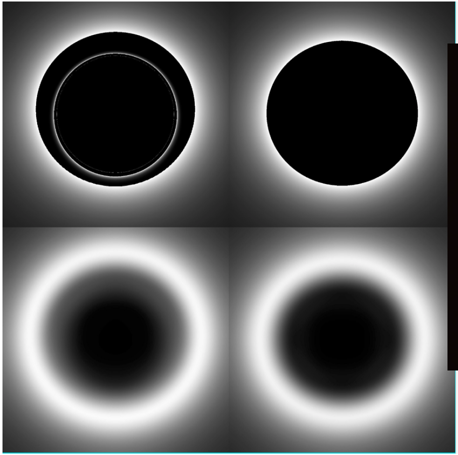
Proca star would be able to be a plack hole mimicker, because the size of the hole would be comparable with the Schwarzschild black hole for the same mass.



Herdeiro et al.
JCAP (2021)

Astrophysical motivation

Proca star would be able to be a plack hole mimicker, because the size of the hole would be comparable with the Schwarzschild black hole for the same mass.



Herdeiro et al.
JCAP (2021)

Astrophysical motivation

GW190521: A Binary Black Hole Merger with a Total Mass of 150 $M_\odot$

R. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 30 May 2020; revised 19 June 2020; accepted 9 July 2020; published 2 September 2020)

On May 21, 2019 at 03:02:29 UTC Advanced LIGO and Advanced Virgo observed a short duration gravitational-wave signal, GW190521, with a three-detector network signal-to-noise ratio of 14.7, and an estimated false-alarm rate of 1 in 4900 yr using a search sensitive to generic transients. If GW190521 is from a quasicircular binary inspiral, then the detected signal is consistent with the merger of two black holes with masses of $85^{+21}_{-14}\ M_\odot$ and $66^{+17}_{-18}\ M_\odot$ (90% credible intervals). We infer that the primary black hole mass lies within the gap produced by (pulsational) pair-instability supernova processes, with only a 0.32% probability of being below 65 $M_\odot$. We calculate the mass of the remnant to be $142^{+28}_{-16}\ M_\odot$, which can be considered an intermediate mass black hole (IMBH). The luminosity distance of the source is $5.3^{+2.4}_{-2.6}$ Gpc, corresponding to a redshift of $0.82^{+0.28}_{-0.34}$. The inferred rate of mergers similar to GW190521 is $0.13^{+0.30}_{-0.11}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$.

DOI: 10.1103/PhysRevLett.125.101102

Astrophysical motivation

GW190521 as a Merger of Proca Stars: A Potential New Vector Boson of 8.7×10^{-13} eV

Juan Calderón Bustillo,[1,2,3,4,*] Nicolas Sanchis-Gual,[5,6,†] Alejandro Torres-Forné,[7,8,9] José A. Font,[8,9] Avi Vajpeyi,[3,4] Rory Smith,[3,4] Carlos Herdeiro,[6] Eugen Radu,[6] and Samson H. W. Leong[2]

[1]*Instituto Galego de Física de Altas Enerxías, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Galicia, Spain*
[2]*Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong*
[3]*Monash Centre for Astrophysics, School of Physics and Astronomy, Monash University, Victoria 3800, Australia*
[4]*OzGrav: The ARC Centre of Excellence for Gravitational-Wave Discovery, Clayton, Victoria 3800, Australia*
[5]*Centro de Astrofísica e Gravitação—CENTRA, Departamento de Física, Instituto Superior Técnico—IST, Universidade de Lisboa—UL, Avenida Rovisco Pais 1, 1049-001, Portugal*
[6]*Departamento de Matemática da Universidade de Aveiro and Centre for Research and Development in Mathematics and Applications (CIDMA), Campus de Santiago, 3810-183 Aveiro, Portugal*
[7]*Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Am Mühlenberg 1, Potsdam 14476, Germany*
[8]*Departamento de Astronomía y Astrofísica, Universitat de València, Dr. Moliner 50, 46100, Burjassot (València), Spain*
[9]*Observatori Astronòmic, Universitat de València, C/ Catedrático José Beltrán 2, 46980, Paterna (València), Spain*

(Received 26 September 2020; revised 20 November 2020; accepted 14 January 2021; published 24 February 2021)

Advanced LIGO-Virgo have reported a short gravitational-wave signal (GW190521) interpreted as a quasicircular merger of black holes, one at least populating the pair-instability supernova gap, that formed a remnant black hole of $M_f \sim 142\ M_\odot$ at a luminosity distance of $d_L \sim 5.3$ Gpc. With barely visible pre-merger emission, however, GW190521 merits further investigation of the pre-merger dynamics and even of the very nature of the colliding objects. We show that GW190521 is consistent with numerically simulated signals from head-on collisions of two (equal mass and spin) horizonless vector boson stars (aka Proca stars), forming a final black hole with $M_f = 231^{+13}_{-17}\ M_\odot$, located at a distance of $d_L = 571^{+348}_{-181}$ Mpc. This provides the first demonstration of close degeneracy between these two theoretical models, for a real gravitational-wave event. The favored mass for the ultralight vector boson constituent of the Proca stars is $\mu_V = 8.72^{+0.73}_{-0.82} \times 10^{-13}$ eV. Confirmation of the Proca star interpretation, which we find statistically slightly preferred, would provide the first evidence for a long sought dark matter particle.

DOI: 10.1103/PhysRevLett.126.081101

Research Gap

- Natural BSM extensions suggest models with non-Abelian fields.
- The corresponding bosonic stars remains almost unexplored.

The Einstein-Klein-Gordon model

We consider the action for Einstein's gravity minimally coupled to a complex massive scalar field.

$$\mathcal{S} = \int d\,x^4 \sqrt{-g}\,(\mathcal{L}_G + \mathcal{L}_M)\,, \tag{1}$$

here, g is the determinant of the metric, $\mathcal{L}_G$ is the Einstein-Hilbert Lagrangian density

$$\mathcal{L}_G = \frac{1}{4\alpha^2} R, \qquad\qquad \alpha^2 = 4\pi G, \tag{2}$$

R is the Ricci scalar and G is the gravitational constant. By its turn, $\mathcal{L}_M$ is Lagrangian density for the matter fields, in which is given by

$$\mathcal{L}_M = -\left(\nabla_\mu \Phi \nabla^\mu \Phi^* + U(|\Phi|)\right)\,, \tag{3}$$

in which Φ is a complex scalar field and U is the potential of the theory, that only depends on the modulus of the field.

Scalar boson Stars

1. We are interested in those potentials that only depend on the modulus of the scalar field, $U = U(\Phi)$, so that we have a unitary symmetry group $U(1)$.

Scalar boson Stars

1. We are interested in those potentials that only depend on the modulus of the scalar field, $U = U(\Phi)$, so that we have a unitary symmetry group $U(1)$.
2. Boson stars described by different potentials can exhibit behaviors significantly different in several physical aspects

Scalar boson Stars

1. We are interested in those potentials that only depend on the modulus of the scalar field, $U = U(\Phi)$, so that we have a unitary symmetry group $U(1)$.
2. Boson stars described by different potentials can exhibit behaviors significantly different in several physical aspects
3. We assume the ansatz

$$\Phi = \boldsymbol{\varphi}(r, \boldsymbol{\theta})e^{-i\omega t+im\varphi}$$

Scalar boson Stars

1. We are interested in those potentials that only depend on the modulus of the scalar field, $U = U(\Phi)$, so that we have a unitary symmetry group $U(1)$.

2. Boson stars described by different potentials can exhibit behaviors significantly different in several physical aspects

3. We assume the ansatz

$$\Phi = \boldsymbol{\varphi}(r, \boldsymbol{\theta}) e^{-i\omega t + im\varphi}$$

4. So far, we have been manly focused on the potential of the form

$$U(|\Phi|) = \mu^2|\Phi|^2 + \frac{\lambda}{2}|\Phi|^4$$

Scalar boson Stars

1. Compact self-gravitating objects made up of scalars that are held together by the balance between the attractive force of gravity and the dispersive effects of a wave equation.

Scalar boson Stars

1. Compact self-gravitating objects made up of scalars that are held together by the balance between the attractive force of gravity and the dispersive effects of a wave equation.
2. The scalar field is complex and satisfies the Klein-Gordon equation, and the system has field solutions with different numbers of nodes.

Scalar boson Stars

1. Compact self-gravitating objects made up of scalars that are held together by the balance between the attractive force of gravity and the dispersive effects of a wave equation.
2. The scalar field is complex and satisfies the Klein-Gordon equation, and the system has field solutions with different numbers of nodes.
3. The lowest energy state, or ground state, is characterized by a field distribution that has no nodes.

Scalar boson Stars

1. Compact self-gravitating objects made up of scalars that are held together by the balance between the attractive force of gravity and the dispersive effects of a wave equation.
2. The scalar field is complex and satisfies the Klein-Gordon equation, and the system has field solutions with different numbers of nodes.
3. The lowest energy state, or ground state, is characterized by a field distribution that has no nodes.
4. Boson stars solutions can either be dynamically stable or unstable depending on its physical parameters.

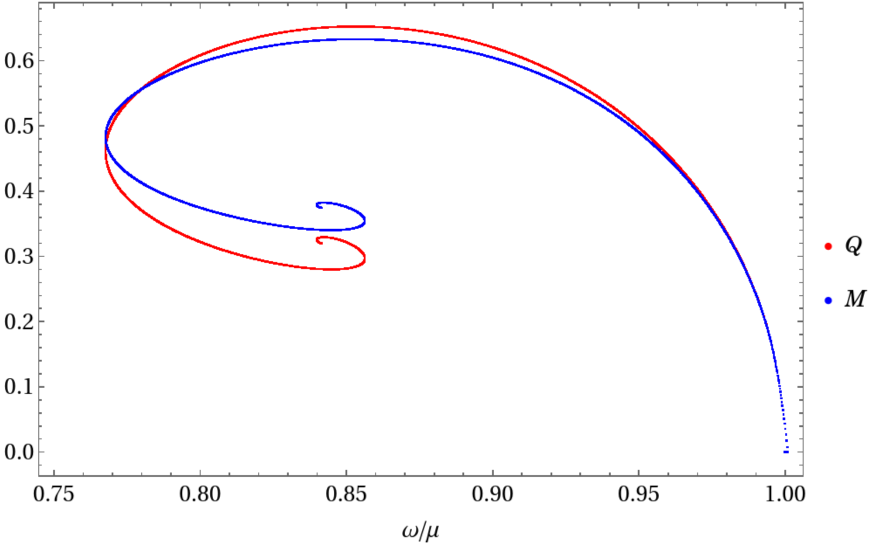
Complex scalar field BS models			
Model name	Potential U	m	Max. stable mass
Mini BS	$\mu^2\|\Phi\|^2$	0	$0.633 M_{pl}^2/\mu$
		1	$1.315 M_{pl}^2/\mu$
BS	$\mu^2\|\Phi\|^2 + \frac{\lambda}{2}\|\Phi\|^4$	0	$0.22\Lambda^{1/2} M_{pl}^2/\mu$
		1	$3.14 M_{pl}^2/\mu$, $\Lambda = 200$
Axion	$\frac{2\mu^2 f^2}{B}\left(1 - \sqrt{1 - 4B\sin^2\left(\frac{\|\Phi\|}{2f}\right)}\right)$	0	$0.632 M_{pl}^2/\mu$, $f = 10$, $B = 0.22$

Guerra et al. JCAP (2019), Schunck et al. CQG (2003)

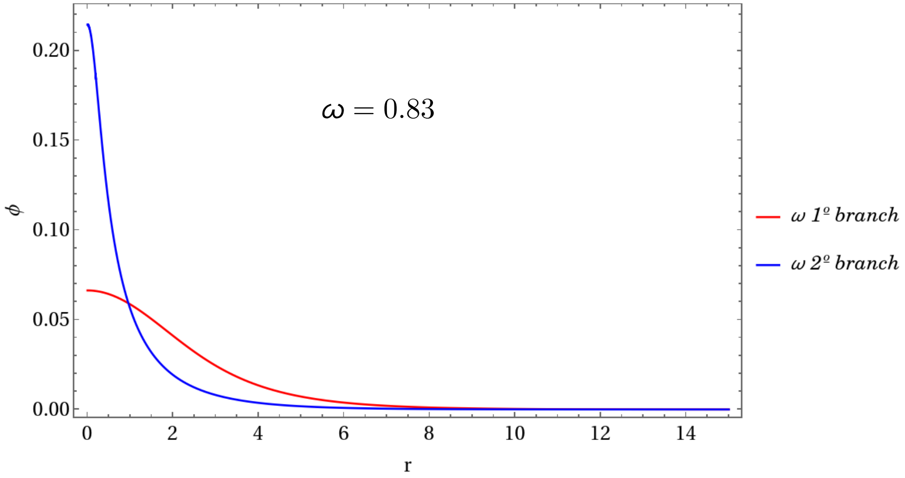
- **Can scalar fields lead to astrophysical compact objects?**
  If a ultralight scalar field exist in nature, under certain conditions, they can form Bose-Einstein condensates, confined by gravity.

$$M_{\rm ADM}^{\rm max} = \alpha_{\rm BS}^{(s)} \frac{M_{\rm pl}^2}{\mu} = \alpha_{\rm BS}^{(s)} 1.34 \times 10^{-19} M_{\odot} \left(\frac{\rm GeV}{\mu}\right) \tag{4}$$

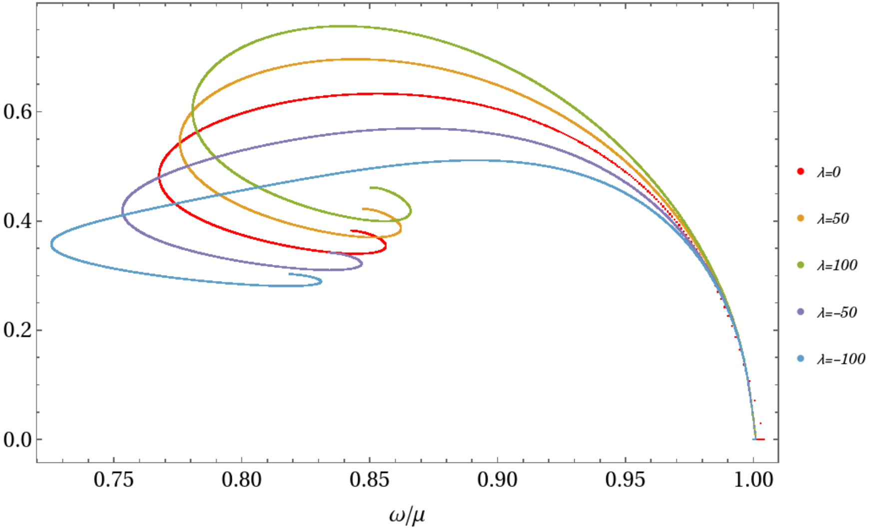
Spherical mini boson stars



Spherical mini boson stars



Spherical boson stars

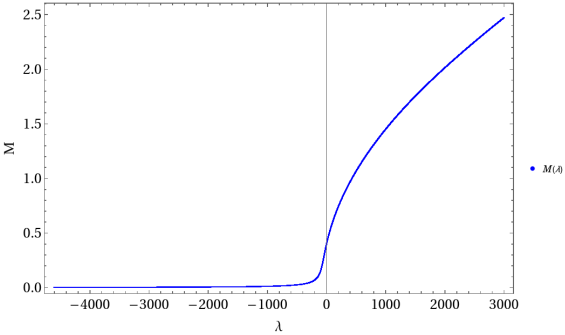


Spherical boson stars

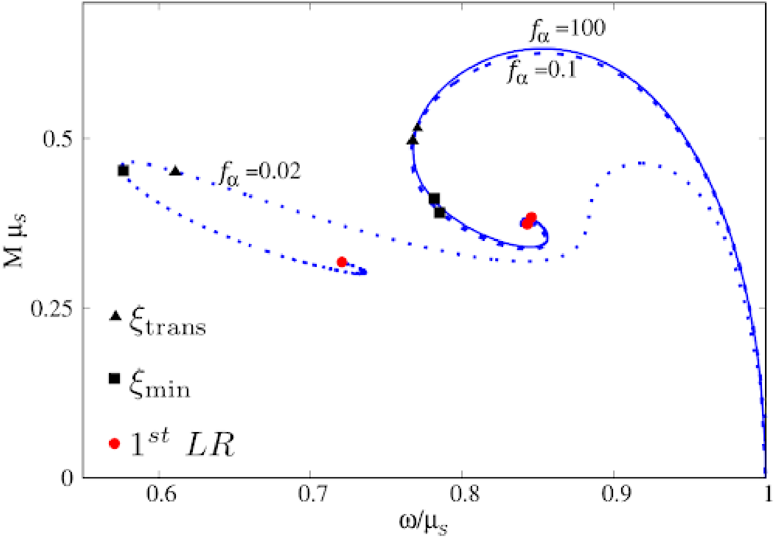
Moreover, we have found that some properties of boson stars depend on the sign of the coupling constant λ, a feature that to our knowledge, has not been reported in the literature

$$M \simeq \begin{cases} 0.022\sqrt{\lambda}, & \text{for } \lambda > 0 \text{ (repulsive interaction)} \\ 0.633, & \text{for } \lambda = 0 \text{ (non-interacting)} \\ \frac{1}{\sqrt{|\lambda|}} & \text{for } \lambda < 0 \text{ (attractive interaction)} \end{cases} \tag{5}$$

Preliminary Results



Spherical axion stars



Herdeiro et al.
JCAP (2021)

The Einstein-Proca model

If we think of boson stars being made of a condensate of massive spin 0 bosonic particles modeled by a complex scalar field, then it is natural to conceive a complex vector field A_μ, made of massive spin 1 particles (massive photons). That is, to study Einstein's gravity minimally coupled to an Abelian Proca field.
The fields are described by the Lagrangian

$$\mathcal{L}_{\mathcal{M}} = -\frac{1}{4} F_{\mu\nu} F^{*\mu\nu} - U(|A|). \tag{6}$$

Similar to scalar boson stars, we consider a potential which is the sum of a mass term plus a quartic interaction

$$U(|A|) = \mu^2 A^\mu A^*{}_\mu + \frac{\lambda}{2} \left(A^\mu A^*{}_\mu \right)^2 , \tag{7}$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ and A_μ is the Proca vector potential.

The Einstein-Proca model

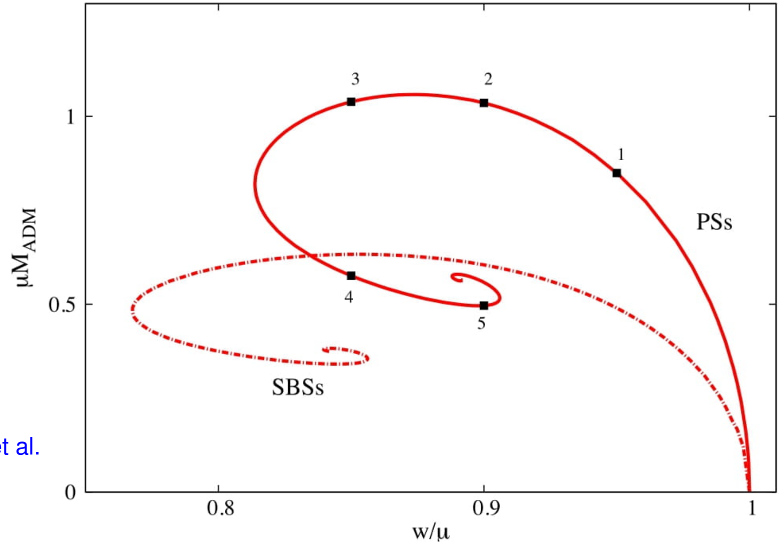
The energy momentum tensor is given by

$$T_{\mu\nu} = \frac{1}{2}\left(F_{\mu\rho}F^{*\rho}_{\nu} + F^{*}{}_{\mu\rho}F^{\rho}_{\nu}\right) - \frac{1}{4}g_{\mu\nu}F^{\rho\sigma}F^{*}{}_{\rho\sigma} + \mu^2\left[A_\mu A^{*}{}_{\nu} + A_\nu A^{*}{}_{\mu} - g_{\mu\nu}A^{*\rho}A_\rho\right]$$
$$+ \lambda\left[\left(A^{*\rho}A_\rho\right)\left(A_\mu A^{*}{}_{\nu} + A_\nu A^{*}{}_{\mu}\right) - \frac{1}{2}g_{\mu\nu}\left(A^{*\rho}A_\rho\right)^2\right]. \quad (8)$$

The equations of motion for the Proca field are

$$\nabla^\mu F_{\mu\nu} = 2\left[\mu^2 + \lambda\left(A^{*\rho}A_\rho\right)\right]A_\nu. \quad (9)$$

Spherical Proca stars



Sanchis-Gual et al.
PRD (2017)

Research Proposal

The main goal of this thesis is two-fold:

1. Construction of new solutions describing bosonic stars and hairy black holes

- to construct new bosonic star solutions, both static and spinning, based on non-Abelian global or gauge symmetries suggested by simple BSM extensions and study their basic mathematical and physical properties and phenomenology.
- to study hairy black hole solutions in the same models, which are counterparts of the spinning bosonic stars. In particular, we shall consider models that copy the electroweak sector of the standard model and could thus, be interpreted in that context.

Research Proposal

The main goal of this thesis is two-fold:

1. Construction of new solutions describing bosonic stars and hairy black holes
2. Interface the solutions constructed in 1 with state of the art techniques for GW and electromagnetic observables

- use the constructed solutions as starting points of numerical evolutions to extract waveform templates from the collision and merger of such bosonic stars.
- use the constructed solutions to obtain possible electromagnetic smoking guns for the bosonic DM particles, e.g., via its impact on black hole shadows.

universidade
de aveiro

Etevaldo dos Santos Costa Filho

Searching for new particles with astrophysical compact objects

Supervisors: Carlos Herdeiro and Eugen Radu