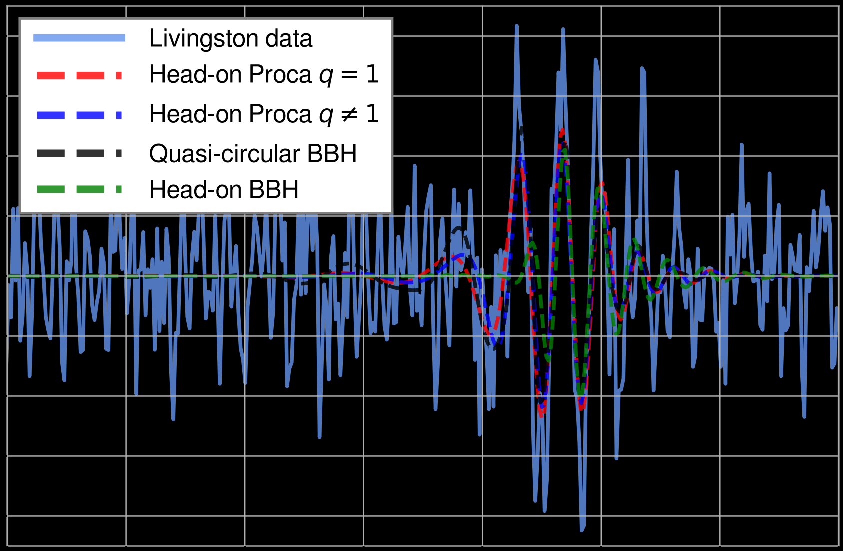
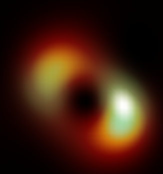


Nicolás Sanchis-Gual, on behalf of the GGD group

GRAV - UNIVERSIDADE DE AVEIRO



VIRTUAL IBERIAN GRAVITATIONAL WAVE MEETING - OCTOBER 2020

GRAVITATIONAL WAVES AND FUNDAMENTAL PHYSICS AT THE U. AVEIRO

Gravitational Geometry and Dynamics research group

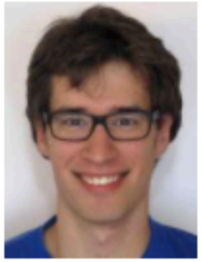
Gr@v is a team of researchers, based at the Mathematics and Physics Department of Aveiro University, Portugal, working on strong gravity, astrophysics and high energy physics. The group was established in 2010. In January 2015 Gr@v integrated the FCT funded CIDMA research unit (UIDB/04106/2020 and UIDP/04106/2020), as the Gravitational Geometry and Dynamics research group. The group scientific coordinator is C. Herdeiro.

Gr@v

The Gravity group @ Aveiro University, Portugal

RESEARCHERS


Sonia Antón


Pedro Cunha


Felipe Freitas


Carlos Herdeiro


António Morais


Eugen Radu


Nicolas Sanchis-Gual


Timothée Vaillant

GRADUATE STUDENTS


Jorge Delgado

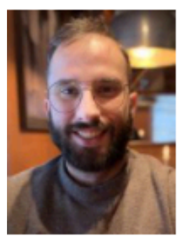

João Oliveira


João Pedro Pino

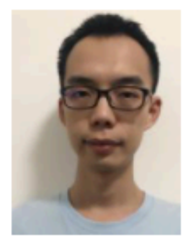

Alexandre Pombo


Nuno Santos


Ivo Sengo


Vasileios Vatellis


Rodrigo Vicente


Jianzhi Yang

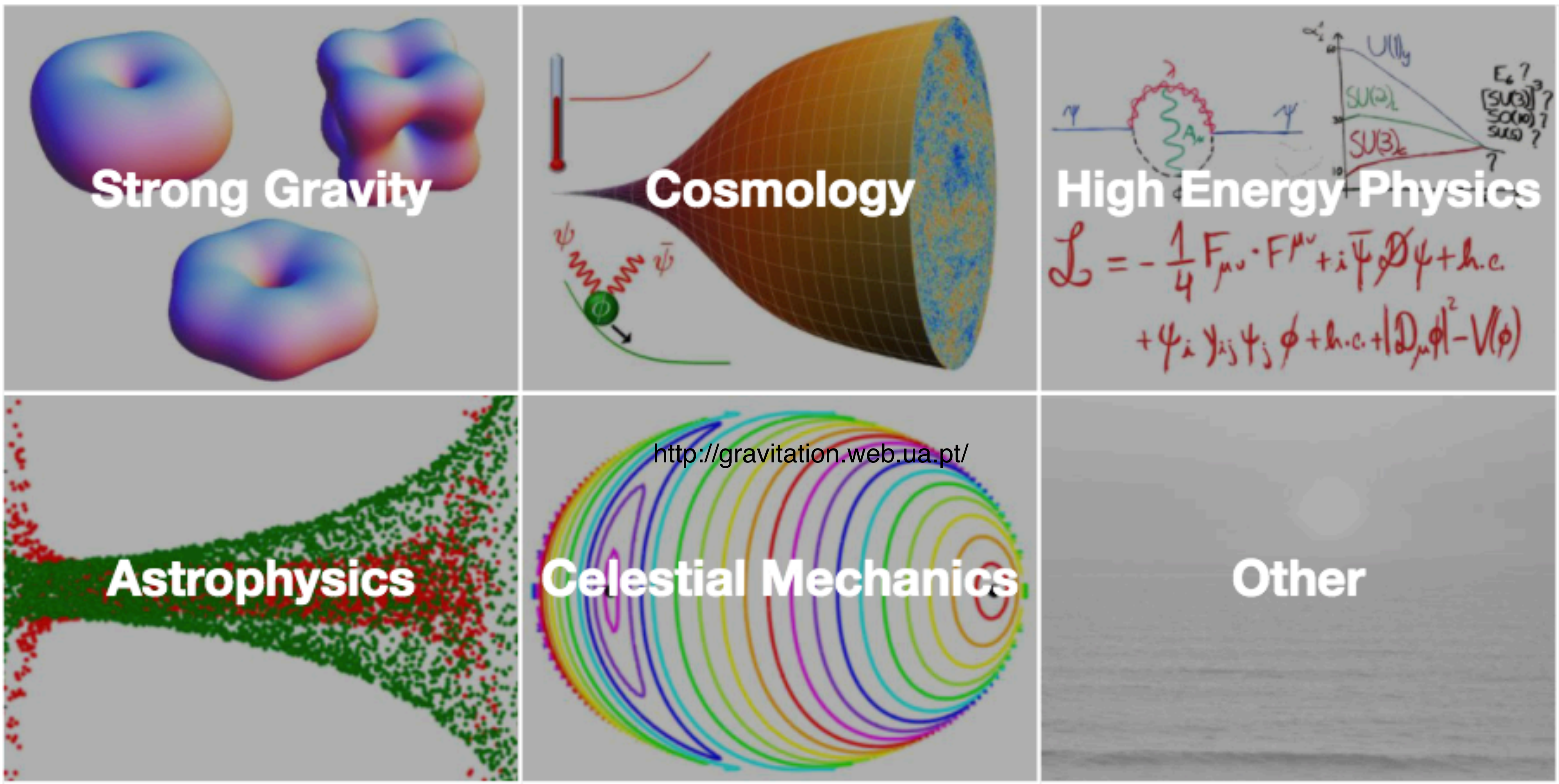
UNDERGRADUATE STUDENTS


Marco Brito


José Queirós

The Gravity group @ Aveiro University, Portugal

Gravitational Geometry and Dynamics research group



http://gravitation.web.ua.pt/

STRONG GRAVITY, FUNDAMENTAL FIELDS, AND GWS

Einstein equations

Train graveyard, Uyuni (Bolivia), 1999
Photography by Gianni Battimelli

Ultralight bosonic fields

- In a **cosmological** context, **scalar fields** have been proposed as constituents of **dark matter halos** in galaxies.
- Compton wavelength:

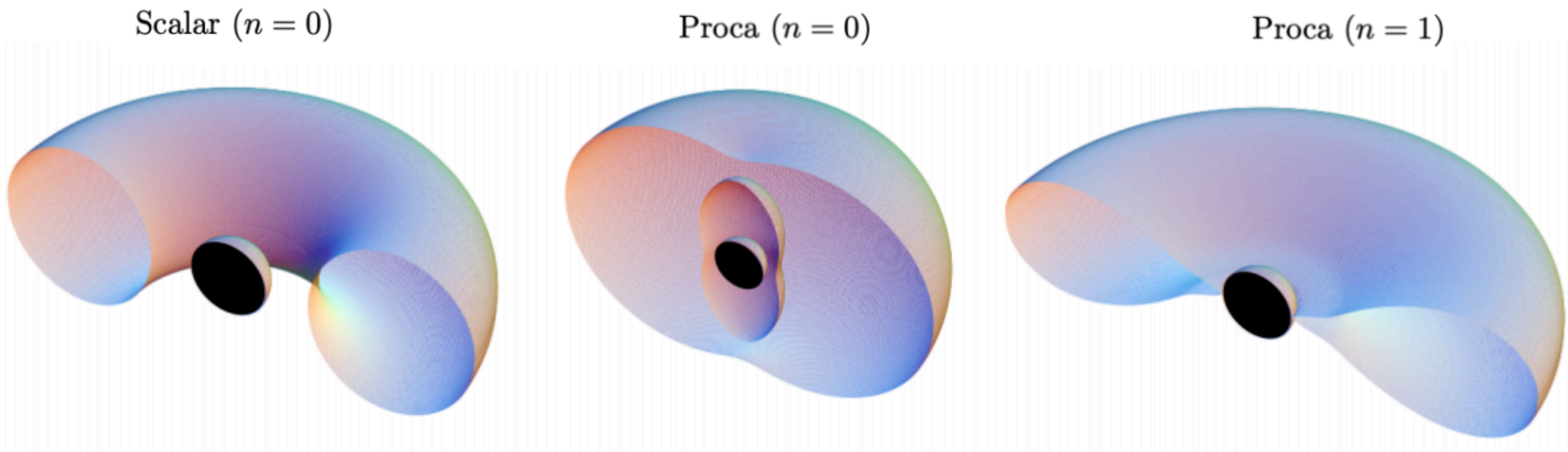
$$\lambda = h/(mc)$$

$$\hbar\mu \sim 10^{-22} - 10^{-24}\ \mathrm{eV}$$

- Black holes can develop **quasi-bound scalar field configurations** that may be very **long lived**.
- Astrophysical BHs could have **scalar or Proca hair** (Herdeiro & Radu 2014).

SOLUTIONS AND SHADOWS OF HAIRY BLACK HOLES AND BOSON STARS

Kerr black holes with bosonic hair



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Boson and Proca stars

- **Scalar boson stars** and its vector "cousins", known as **Proca stars**, are made of particles with **integer spin** following the Bose-Einstein statistics: **bosons**.

- At the lowest energy level state can be classically described by a **wavefunction**, characterized by the particle mass.

- Considering a **complex scalar field** with **harmonic dependence**:

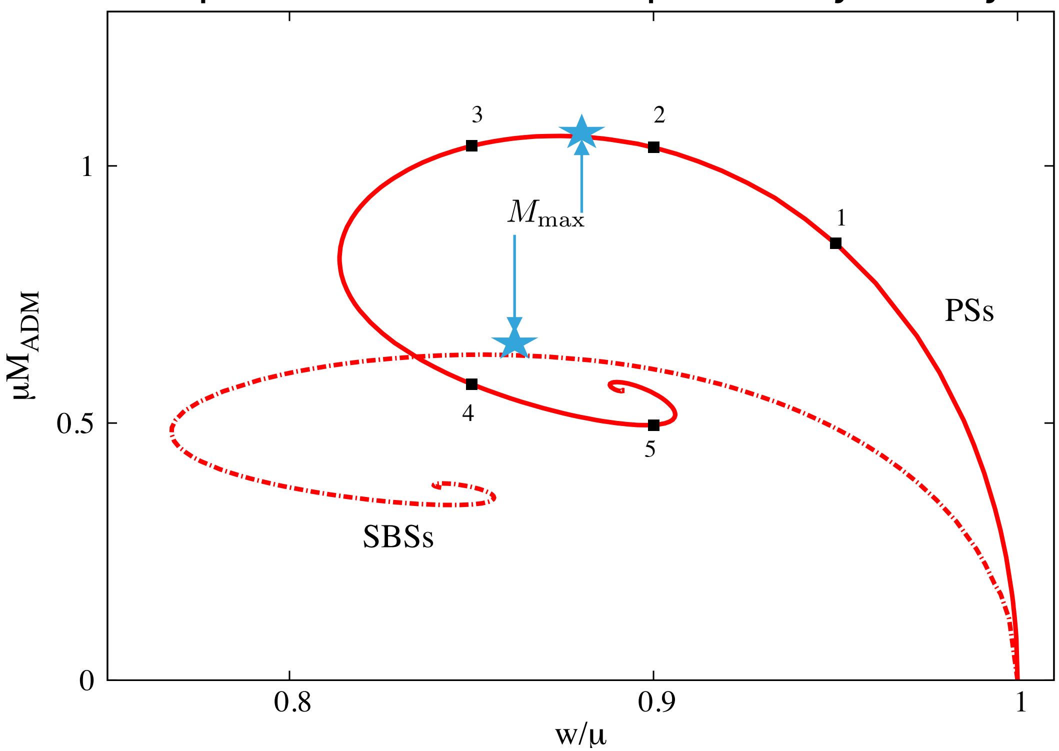
$$\phi(\mathbf{r},t) \equiv \phi_{\mathrm{Re}}(\mathbf{r},t) + i\,\phi_{\mathrm{Im}}(\mathbf{r},t) = \phi_0\, e^{-i\,\omega t}$$

- **Maximum mass**

$$M_{\mathrm{max}} \sim 0.633\ M_{\mathrm{Planck}}^2/\mu$$

Boson and Proca stars

Equilibrium solutions in spherical symmetry.



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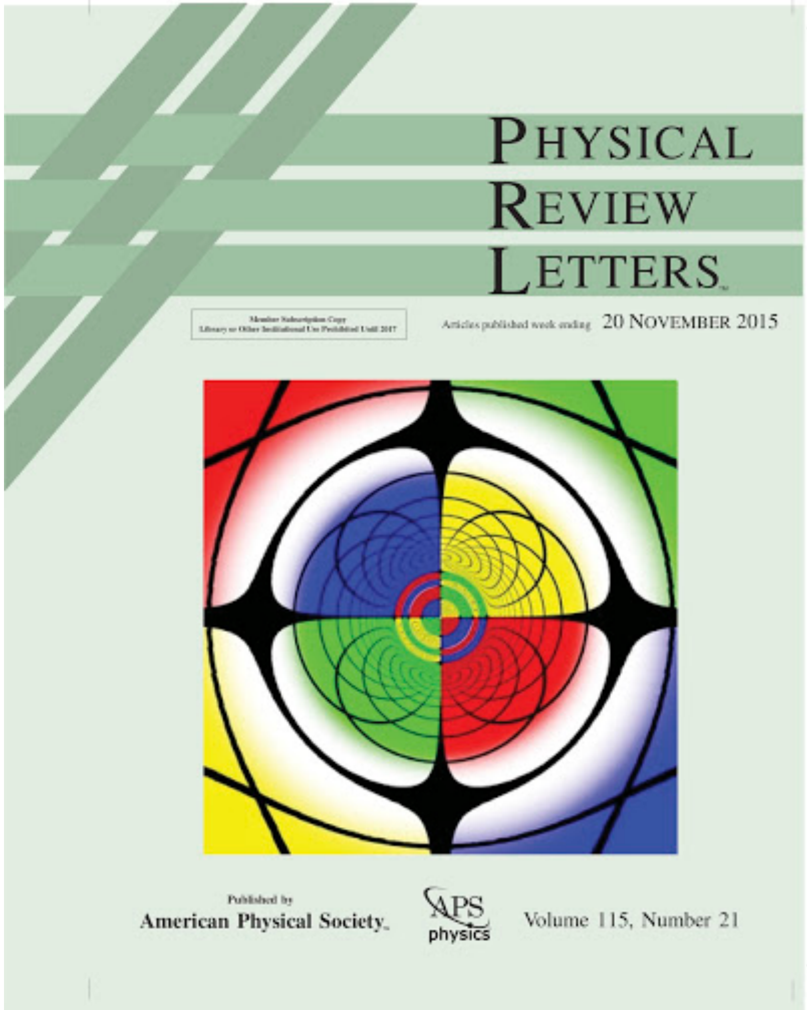

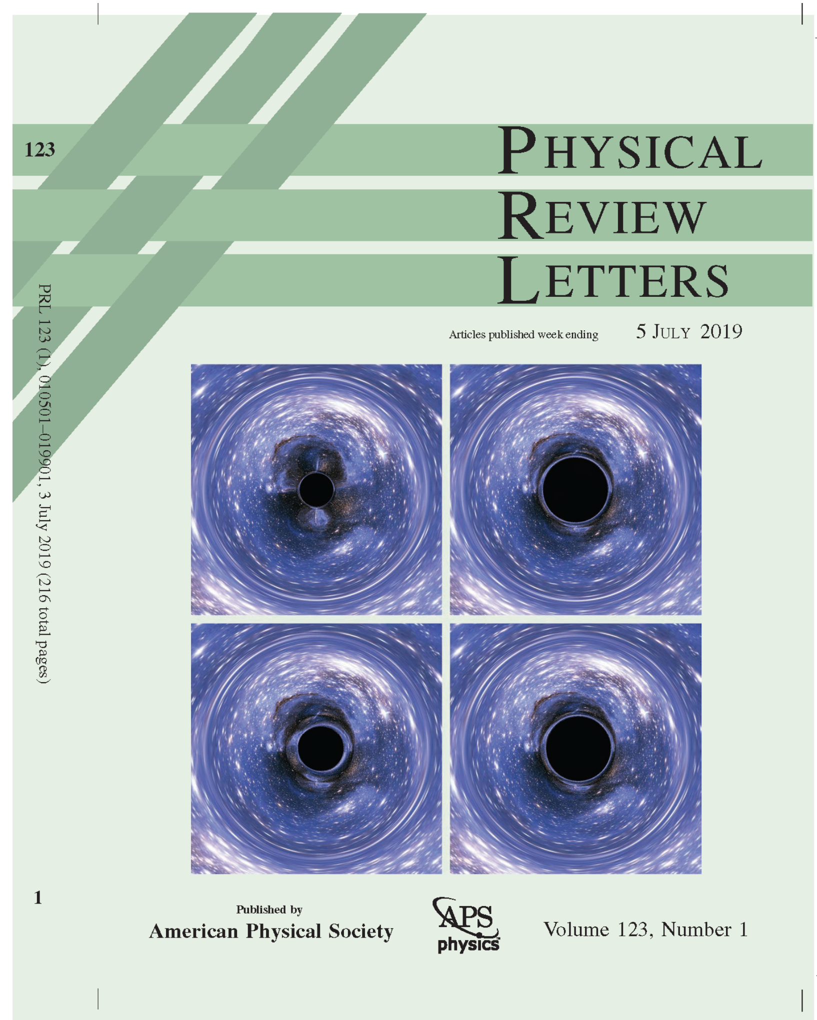

Cunha, P. V., Herdeiro, C. A., Radu, E., & Rúnarsson, H. F. (2015). Shadows of Kerr black holes with scalar hair. *Physical review letters*, *115*(21), 211102.

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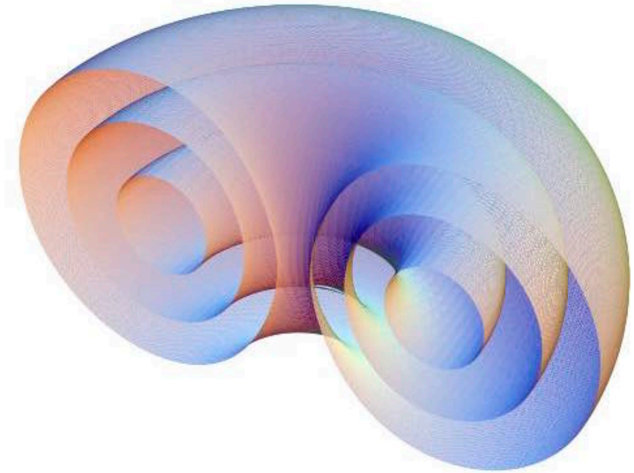
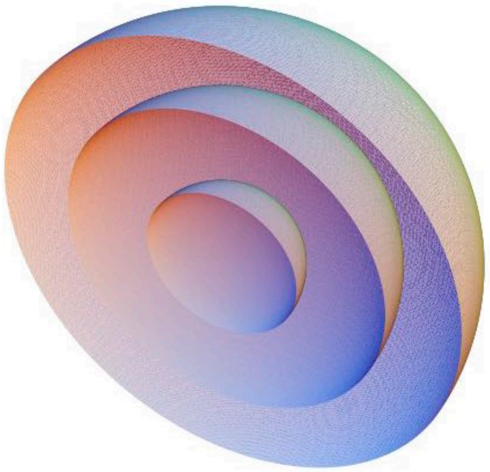
NUMERICAL RELATIVITY AND GWS





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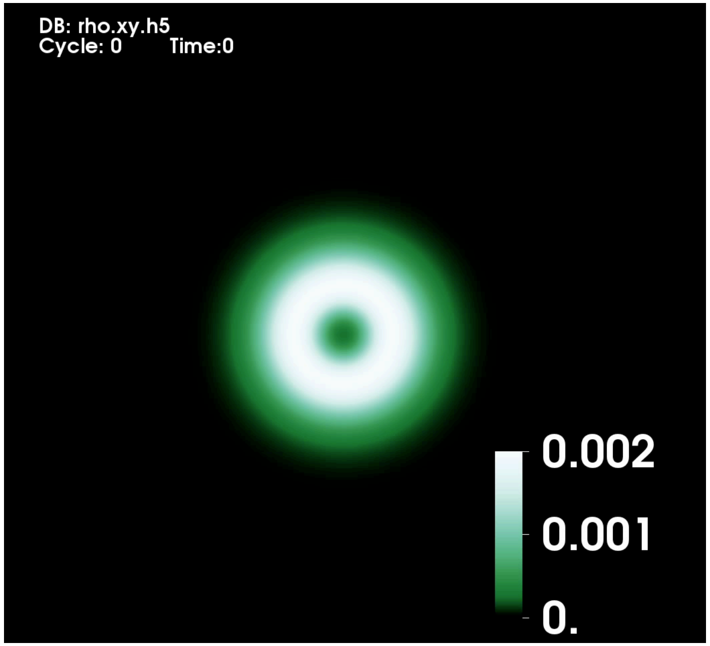
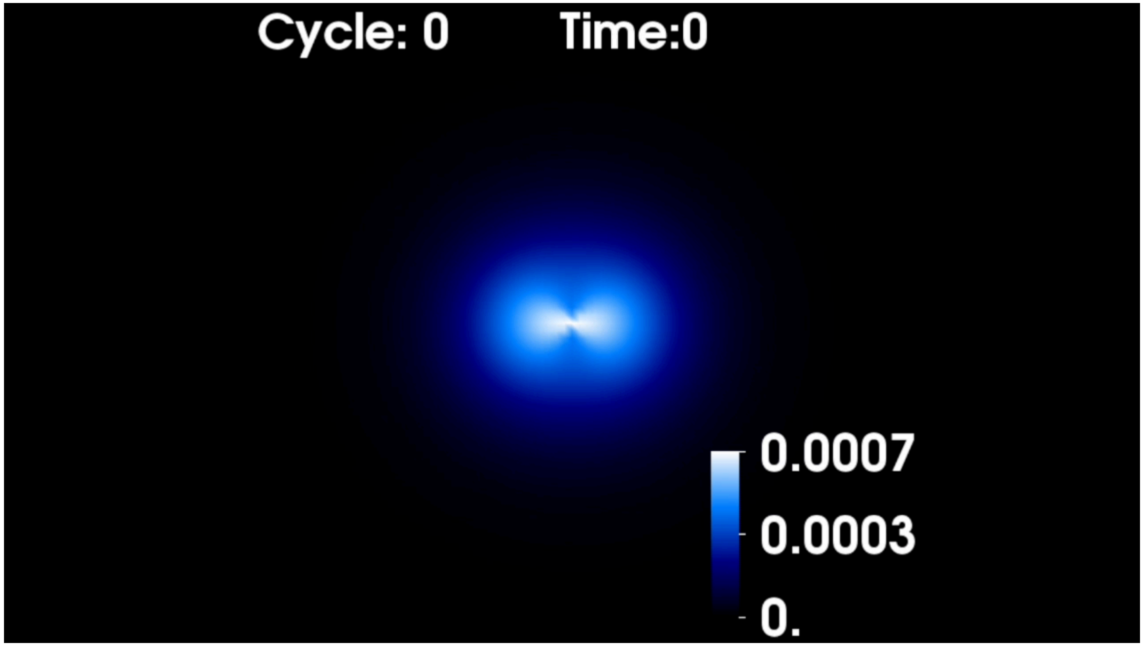
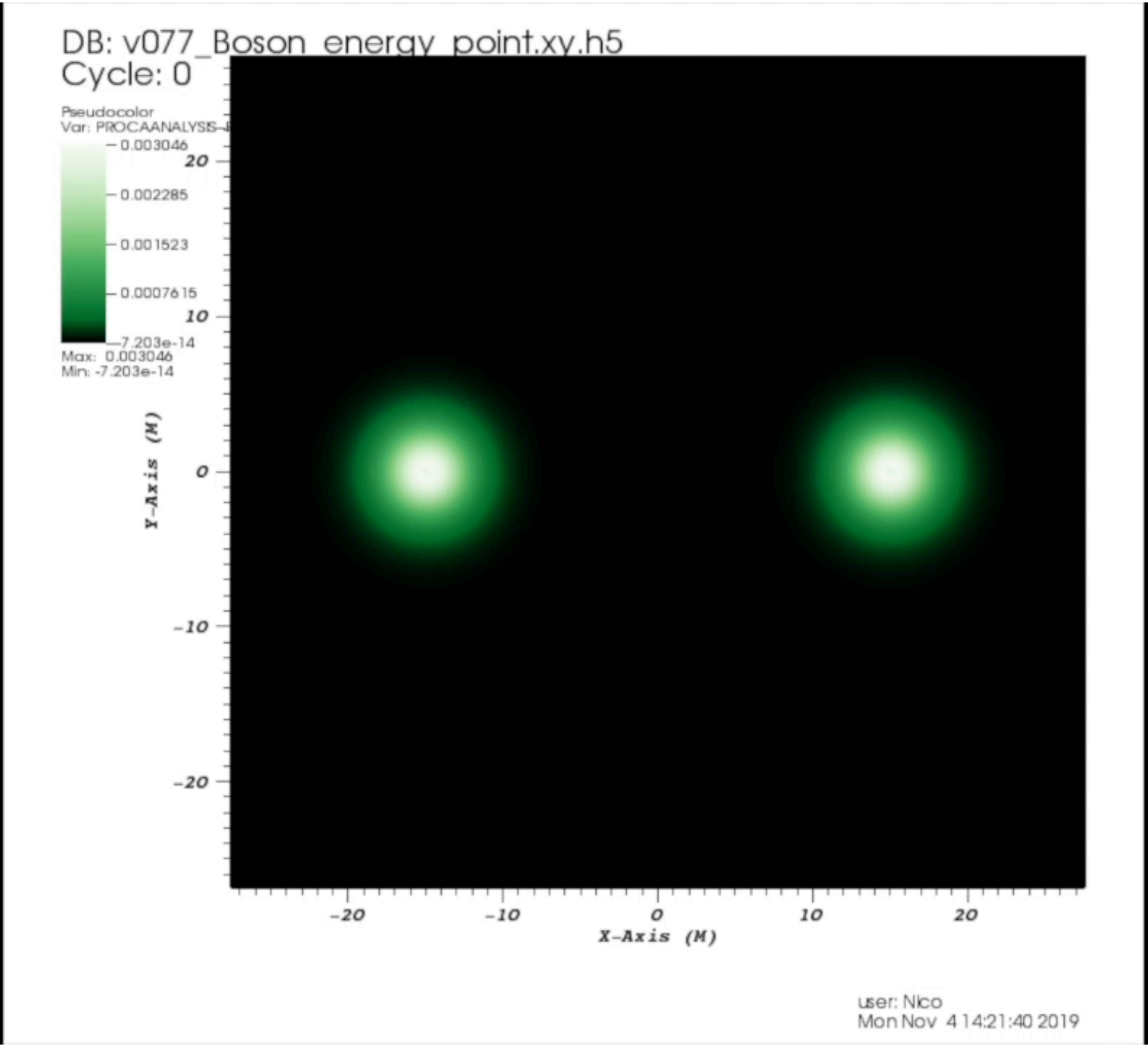
Santos, N. M., & Herdeiro, C. A. (2020). Stationary scalar and vector clouds around Kerr-Newman black holes. *arXiv preprint arXiv:2005.07201*.



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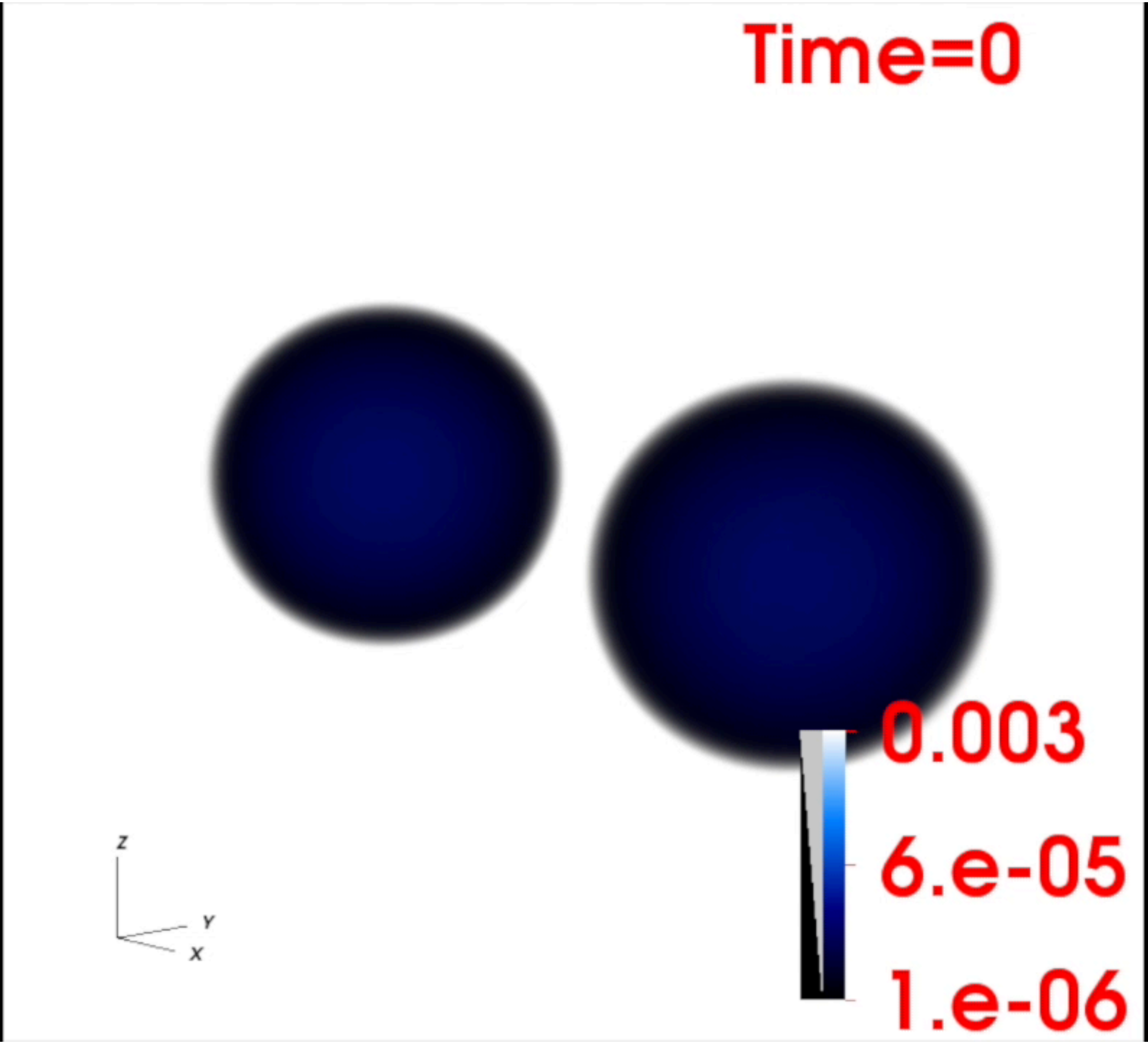
-10
-20
user: Nico
Mon Nov 4 14:21:40 2019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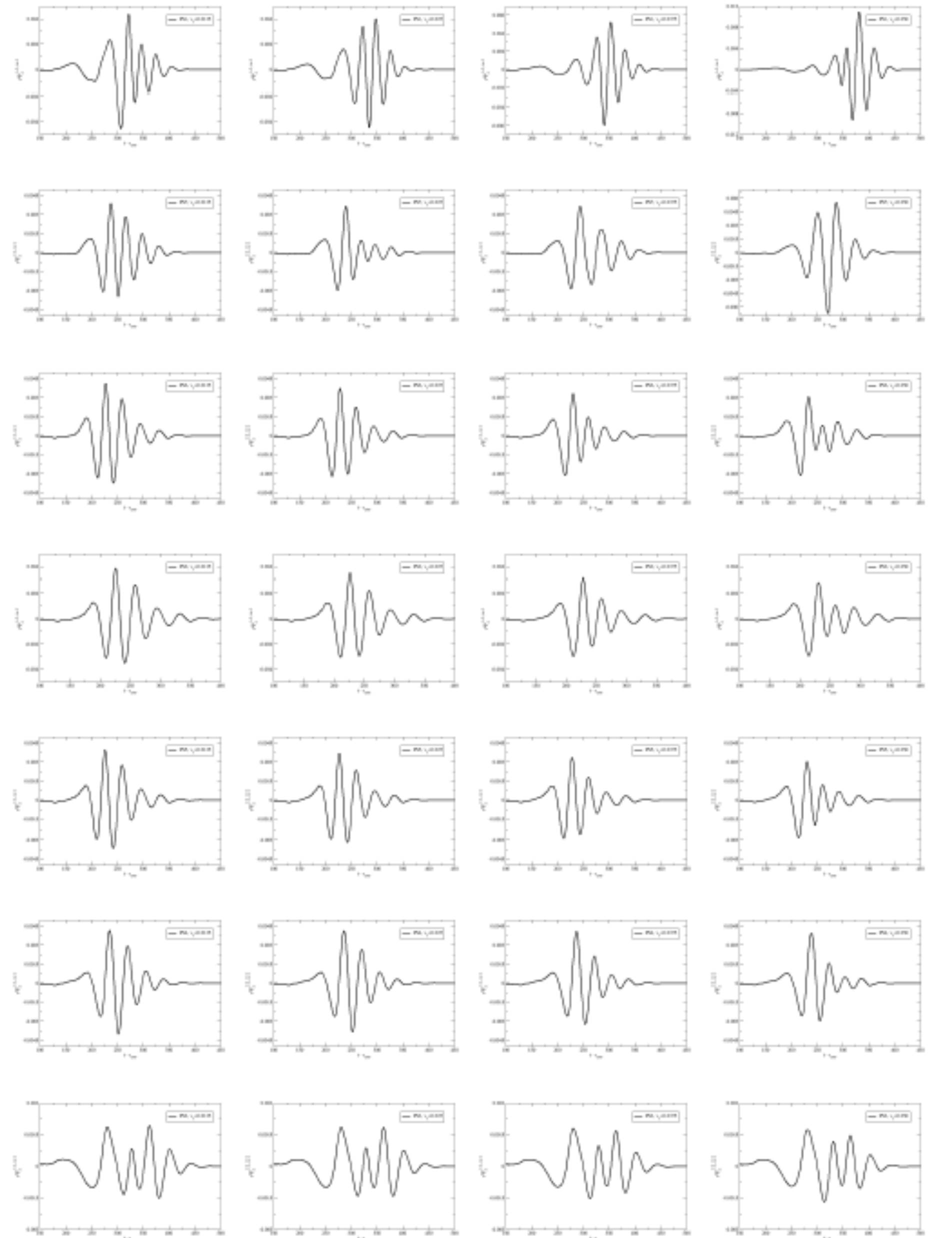
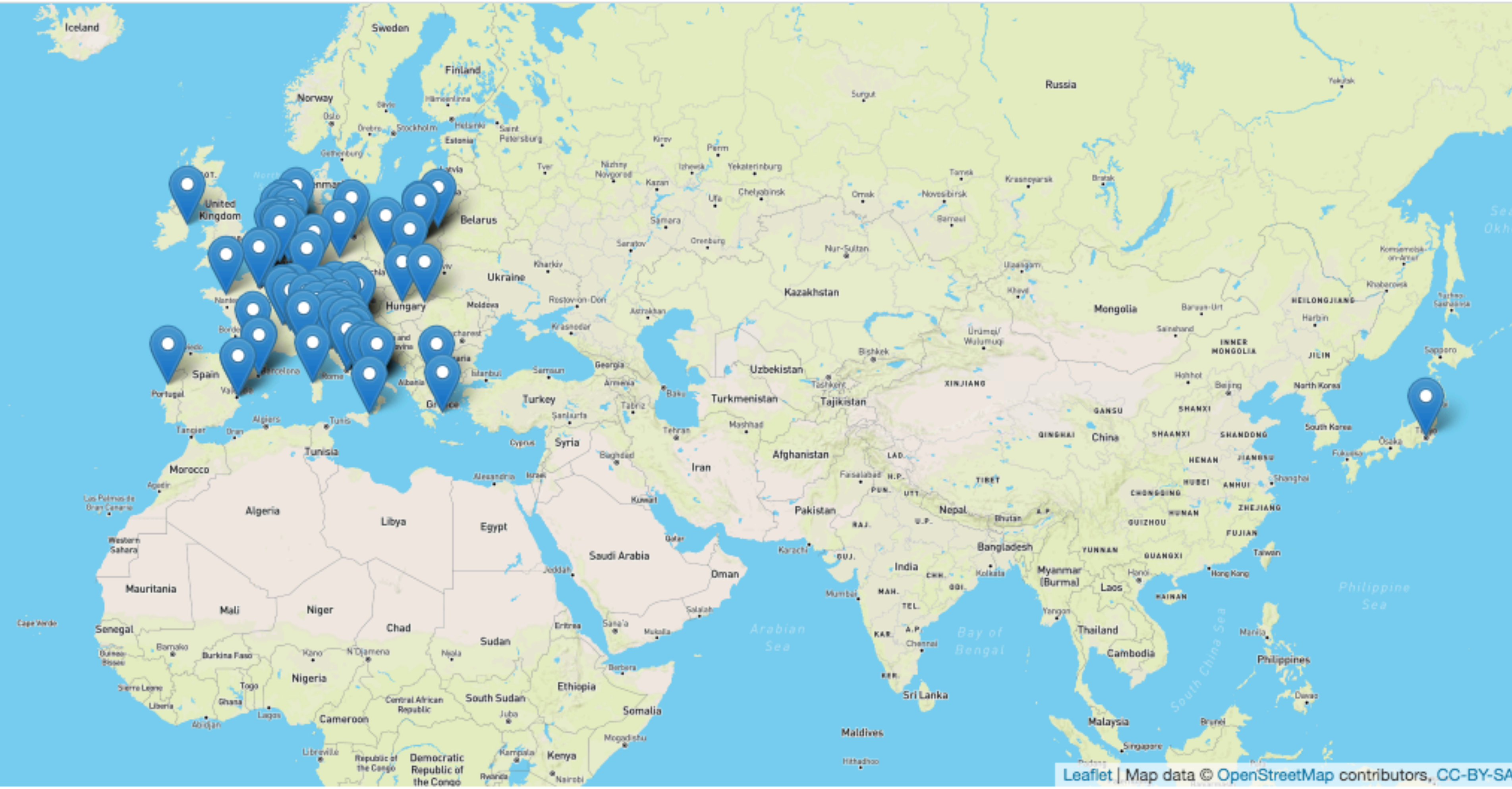
Sanchis-Gual, N., Herdeiro, C., Font, J. A., Radu, E., & Di Giovanni, F. (2019). Head-on collisions and orbital mergers of Proca stars. *Physical Review D*, *99*(2), 024017.
Bustillo, J. C., Sanchis-Gual, N., Torres-Forné, A., Font, J. A., Vajpeyi, A., Smith, R., …, Herdeiro, C., Radu, E., & Leong, S. H. (2020). The (ultra) light in the dark: A potential vector boson of 8.7×10^{-13} eV from GW190521. *arXiv preprint arXiv:2009.05376*.

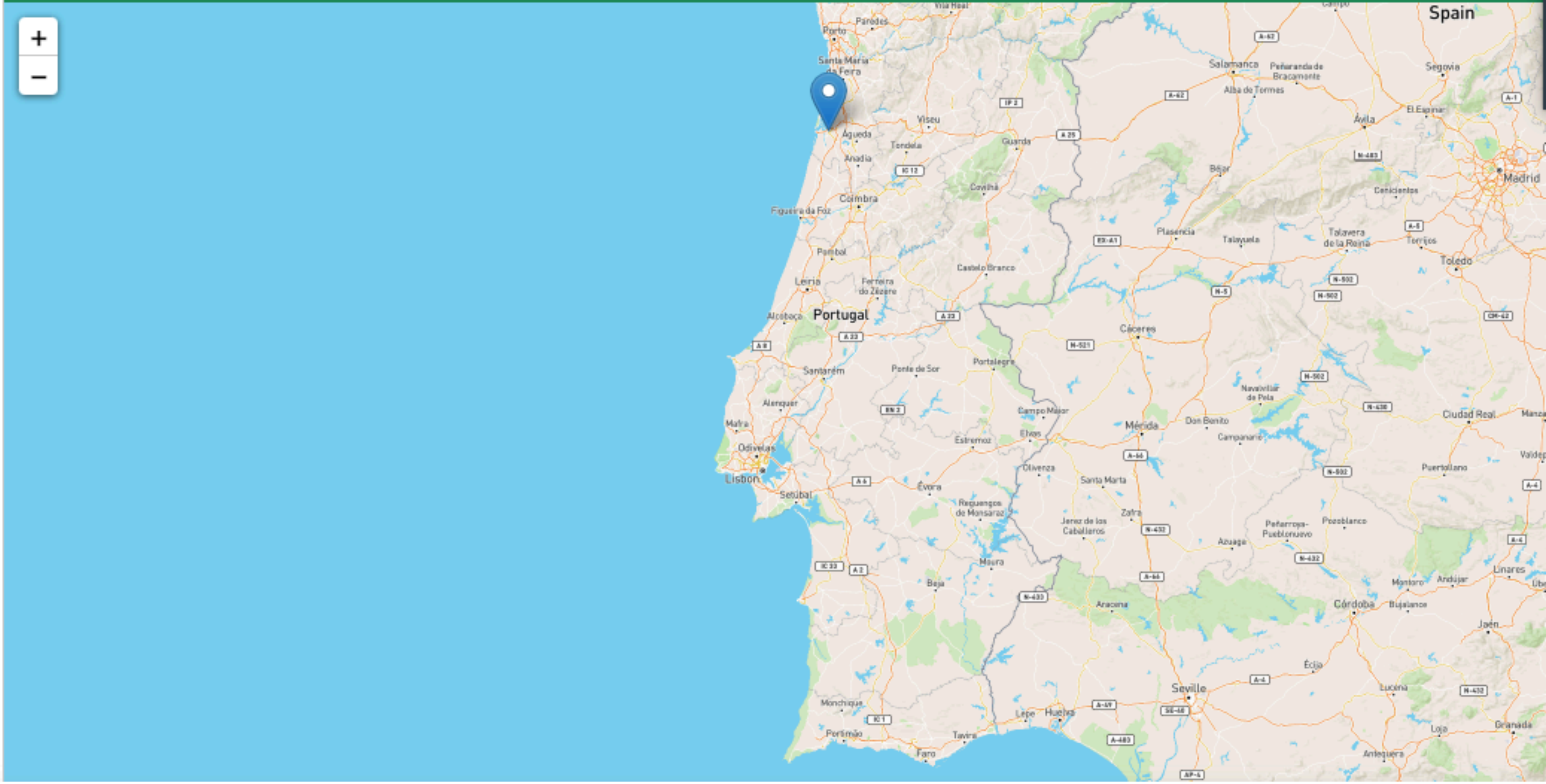


Virgo Valencia Group

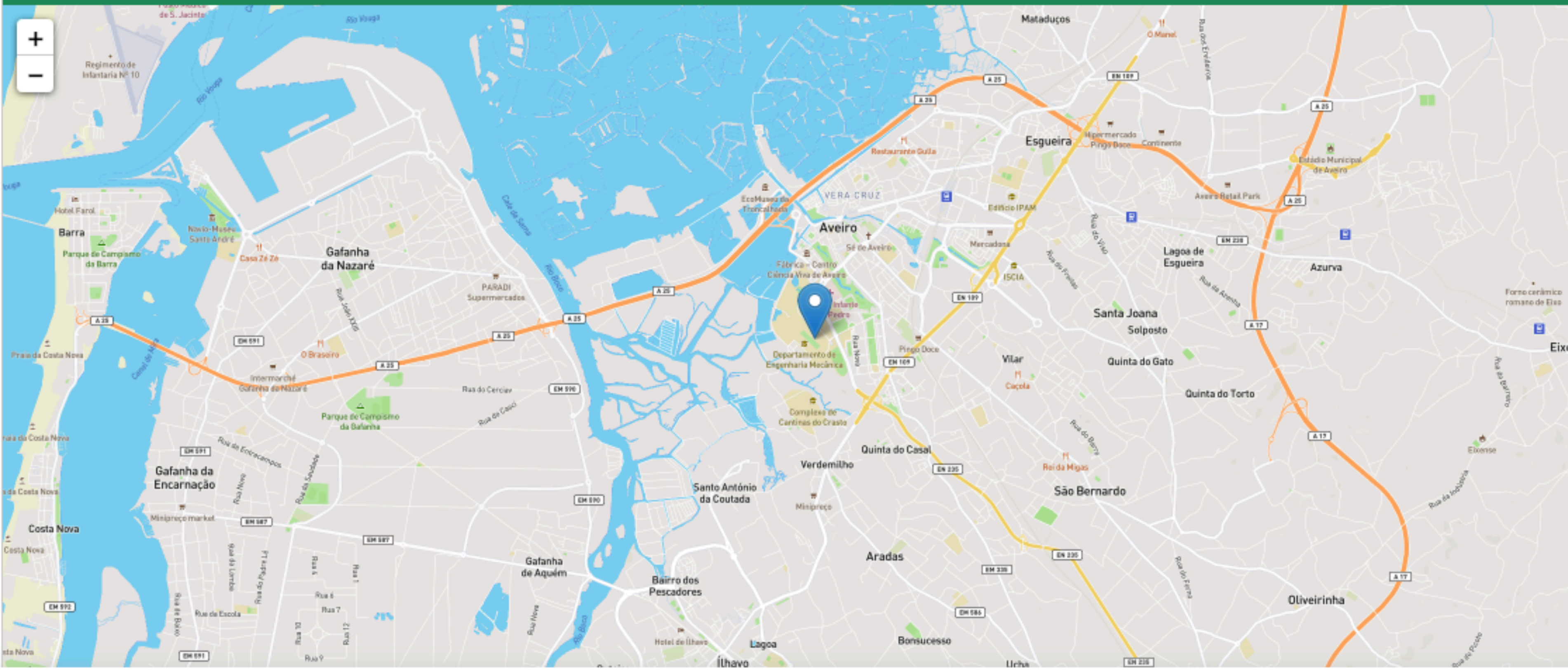


The Virgo Institutions

Map of the Institutions of the Virgo Collaboration

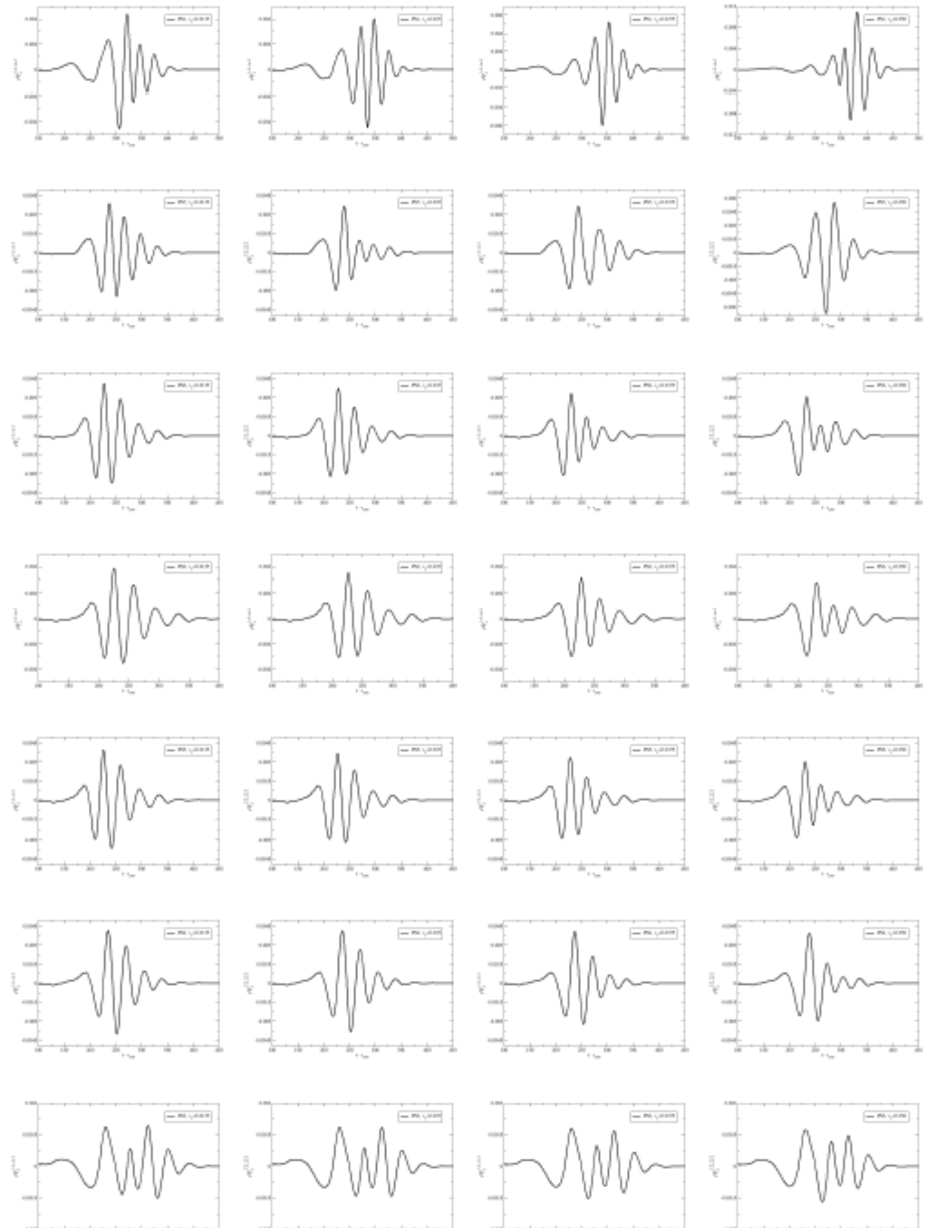


Map of the Institutions of the Virgo Collaboration

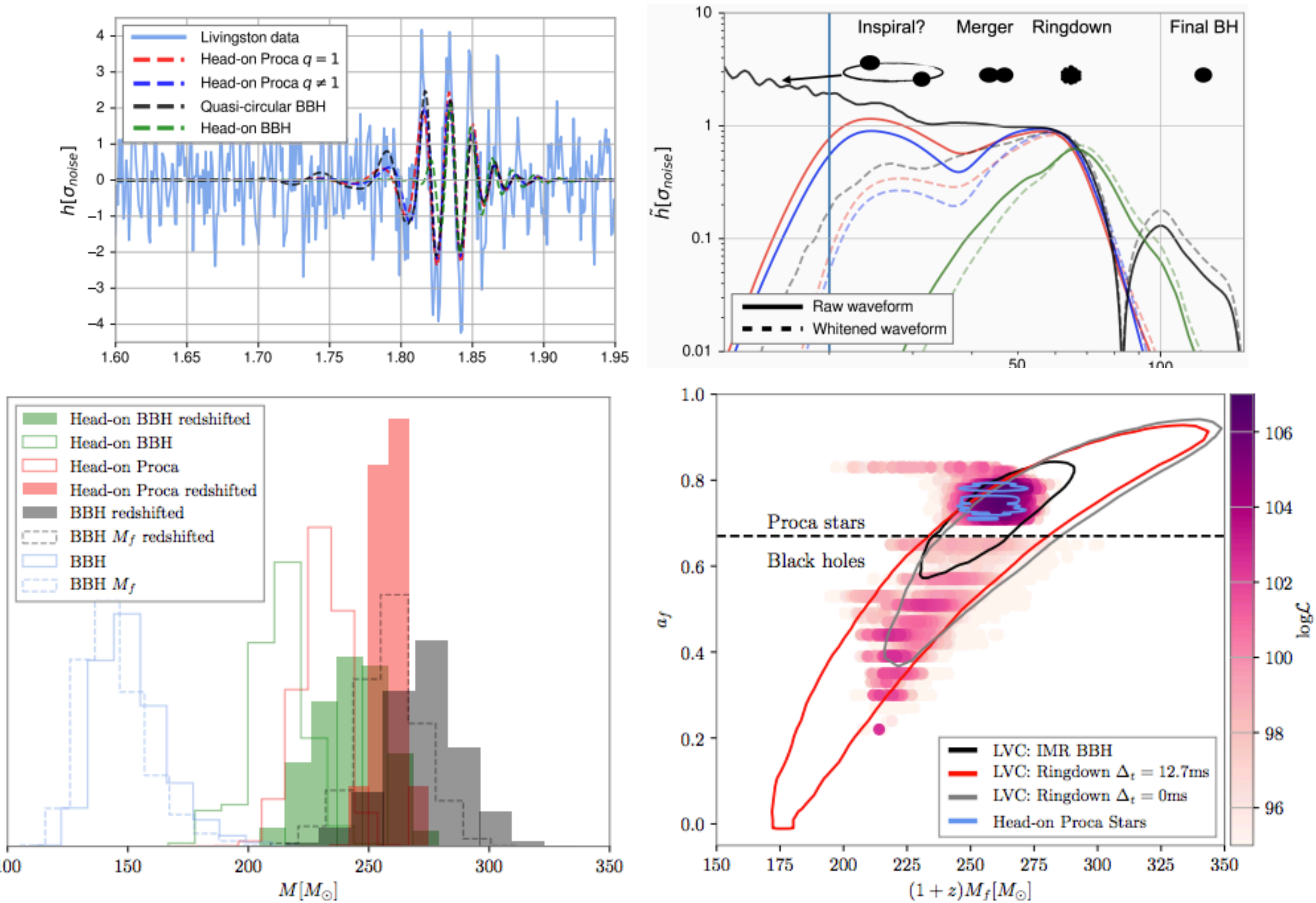


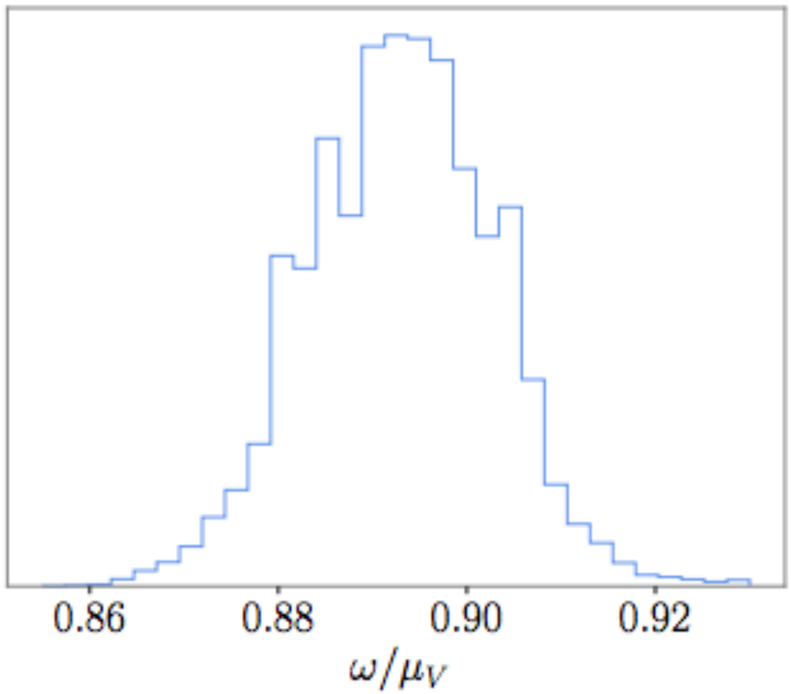
Sanchis-Gual, N., Herdeiro, C., Font, J. A., Radu, E., & Di Giovanni, F. (2019). Head-on collisions and orbital mergers of Proca stars. *Physical Review D*, *99*(2), 024017.

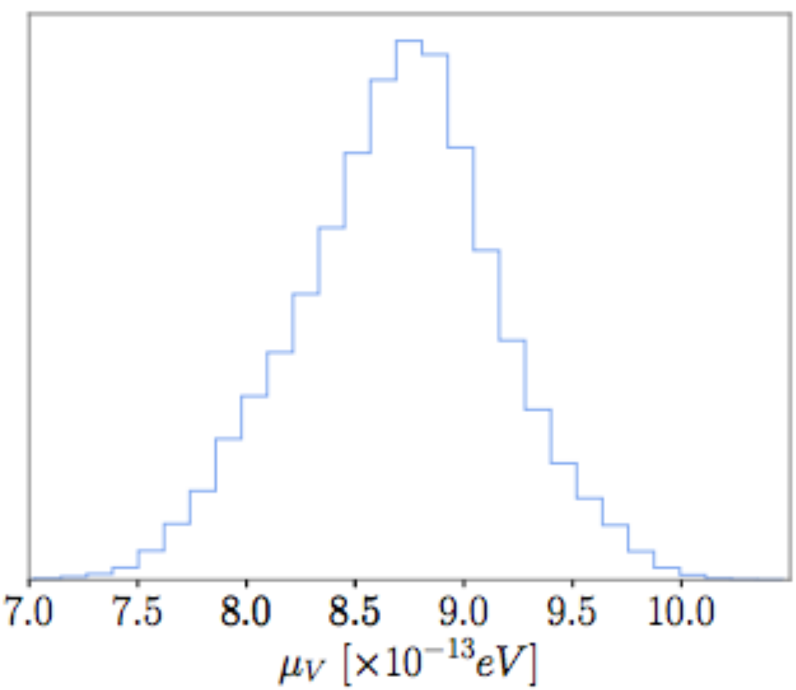
Bustillo, J. C., Sanchis-Gual, N., Torres-Forné, A., Font, J. A., Vajpeyi, A., Smith, R., …, Herdeiro, C., Radu, E., & Leong, S. H. (2020). The (ultra) light in the dark: A potential vector boson of $8.7\times 10^{-13} $ eV from GW190521. *arXiv preprint arXiv:2009.05376*.



GW190521 as a Proca star merger

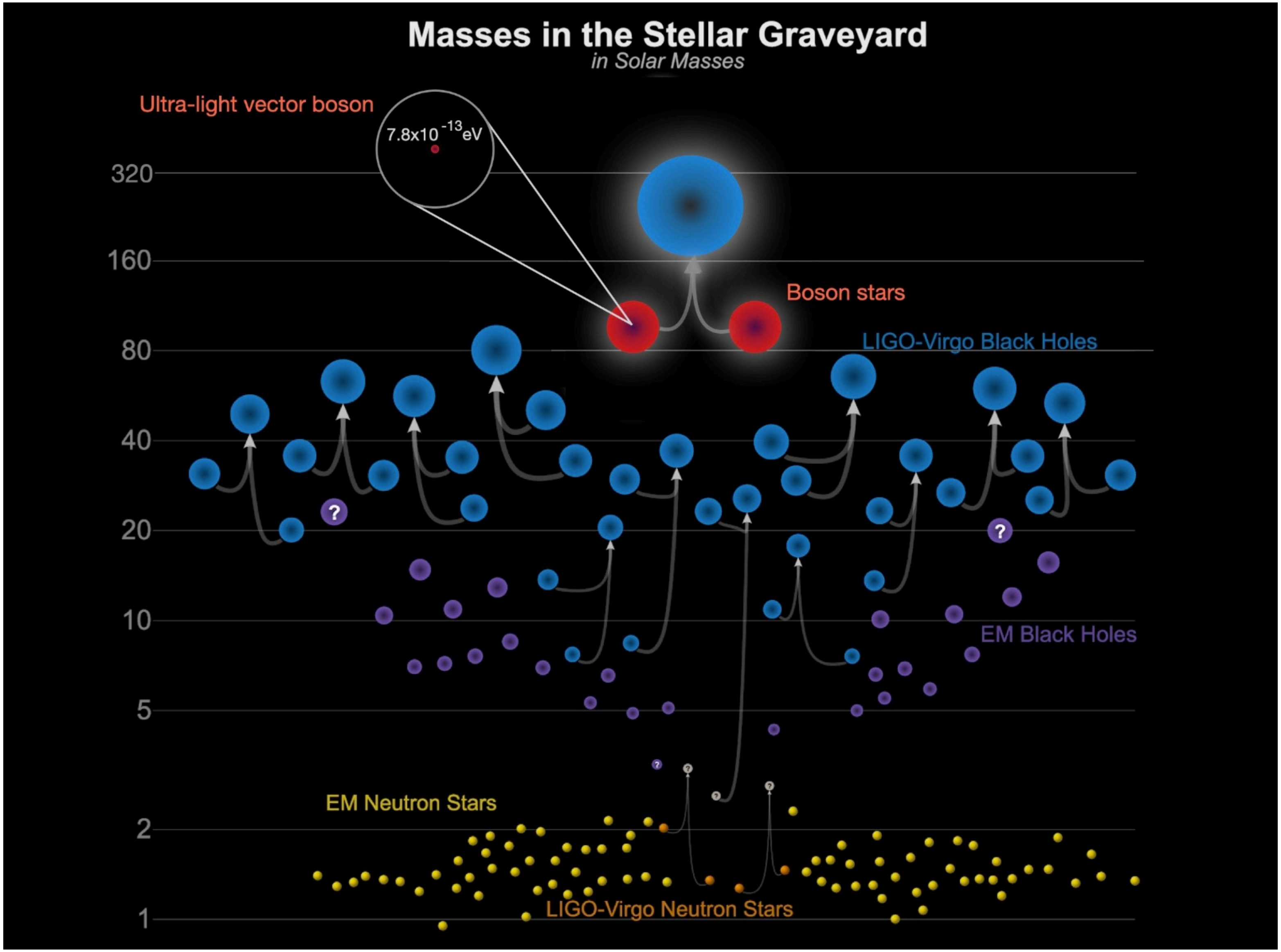






Parameter	$q = 1$ model	$q \neq 1$ model
Primary mass	$115^{+7}_{-8}\ M_\odot$	$115^{+7}_{-8}\ M_\odot$
Secondary mass	$115^{+7}_{-8}\ M_\odot$	$111^{+7}_{-15}\ M_\odot$
Total / Final mass	$231^{+13}_{-17}\ M_\odot$	$228^{+17}_{-15}\ M_\odot$
Final spin	$0.75^{+0.08}_{-0.04}\ M_\odot$	$0.75^{+0.08}_{-0.04}$
Inclination $\pi/2 - \lvert\iota - \pi/2\rvert$	$0.83^{+0.23}_{-0.47}$ rad	$0.58^{+0.40}_{-0.39}$ rad
Azimuth	$0.65^{+0.86}_{-0.54}$ rad	$0.78^{+1.23}_{-1.20}$ rad
Luminosity distance	571^{+348}_{-181} Mpc	700^{+292}_{-279} Mpc
Redshift	$0.12^{+0.05}_{-0.04}$	$0.14^{+0.06}_{-0.05}$
Total / Final redshifted mass	$258^{+9}_{-9}\ M_\odot$	$261^{+10}_{-11}\ M_\odot$
Bosonic field frequency ω/μ_V	$0.893^{+0.015}_{-0.015}$	$(*)0.905^{+0.012}_{-0.042}$
Boson mass μ_V [$\times 10^{-13}$]	$8.72^{+0.73}_{-0.82}$ eV	$8.59^{+0.58}_{-0.57}$ eV
Maximal boson star mass	$173^{+19}_{-14}\ M_\odot$	$175^{+13}_{-11}\ M_\odot$
Evidence for (2, 0) mode	$\log \mathcal{B} \simeq 0.6$	—

TABLE II. **Parameters of GW190521 assuming a head-on merger of Proca stars.** In the the first column we assume equal masses and spins. In the second column we allow for unequal masses, fixing the primary oscillation frequency to $\omega_1/\mu_V = 0.895$ and varying the second on an uniform grid. We estimate the secondary oscillation frequency ω_2/μ_V. We report median values and symmetric 90% credible intervals.


Masses in the Stellar Graveyard
in Solar Masses
Ultra-light vector boson
7.8x10^-13 eV
Boson stars
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
320
160
80
40
20
10
5
2
1

SCALARISED BLACK HOLES AND GWS

Herdeiro, C. A., Radu, E., Sanchis-Gual, N., & Font, J. A. (2018). Spontaneous scalarization of charged black holes. *Physical review letters*, *121*(10), 101102.
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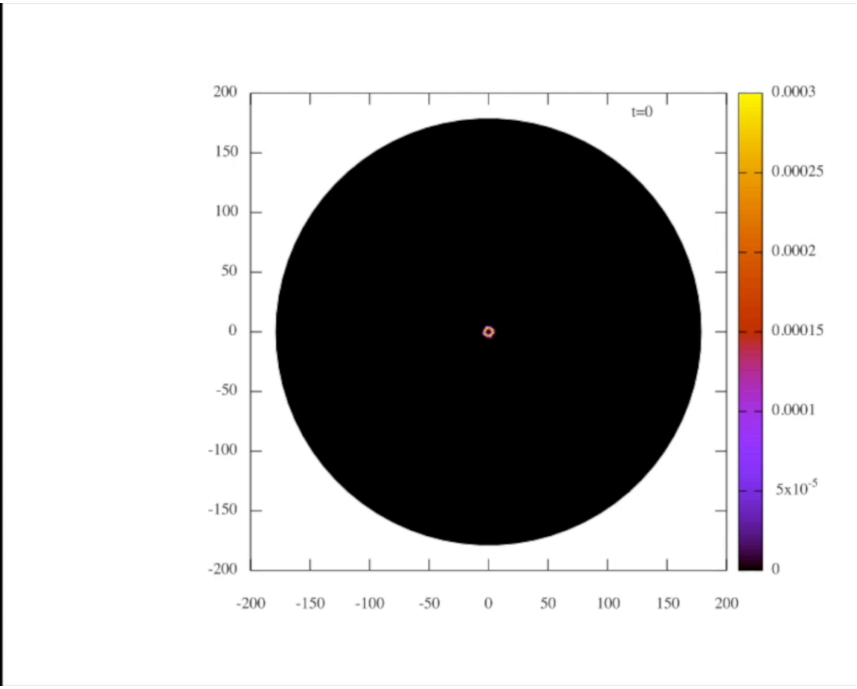

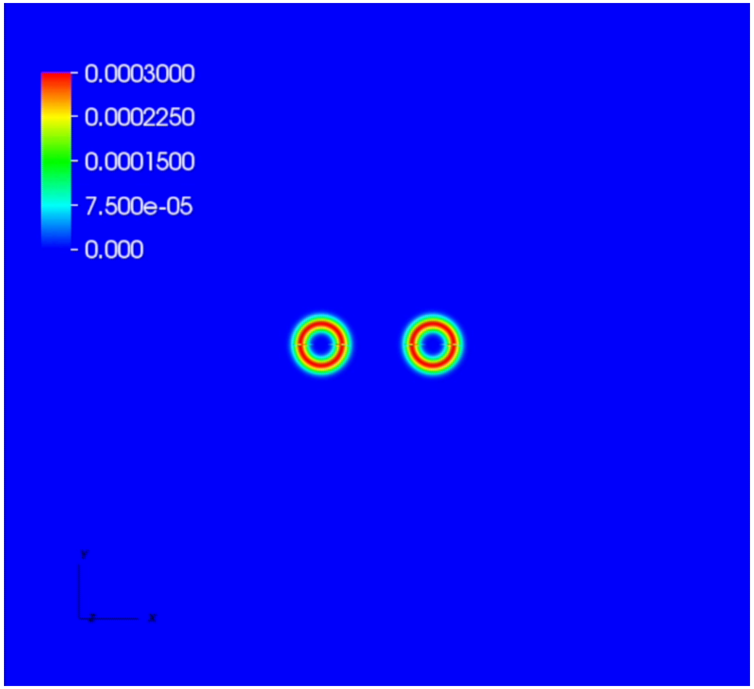

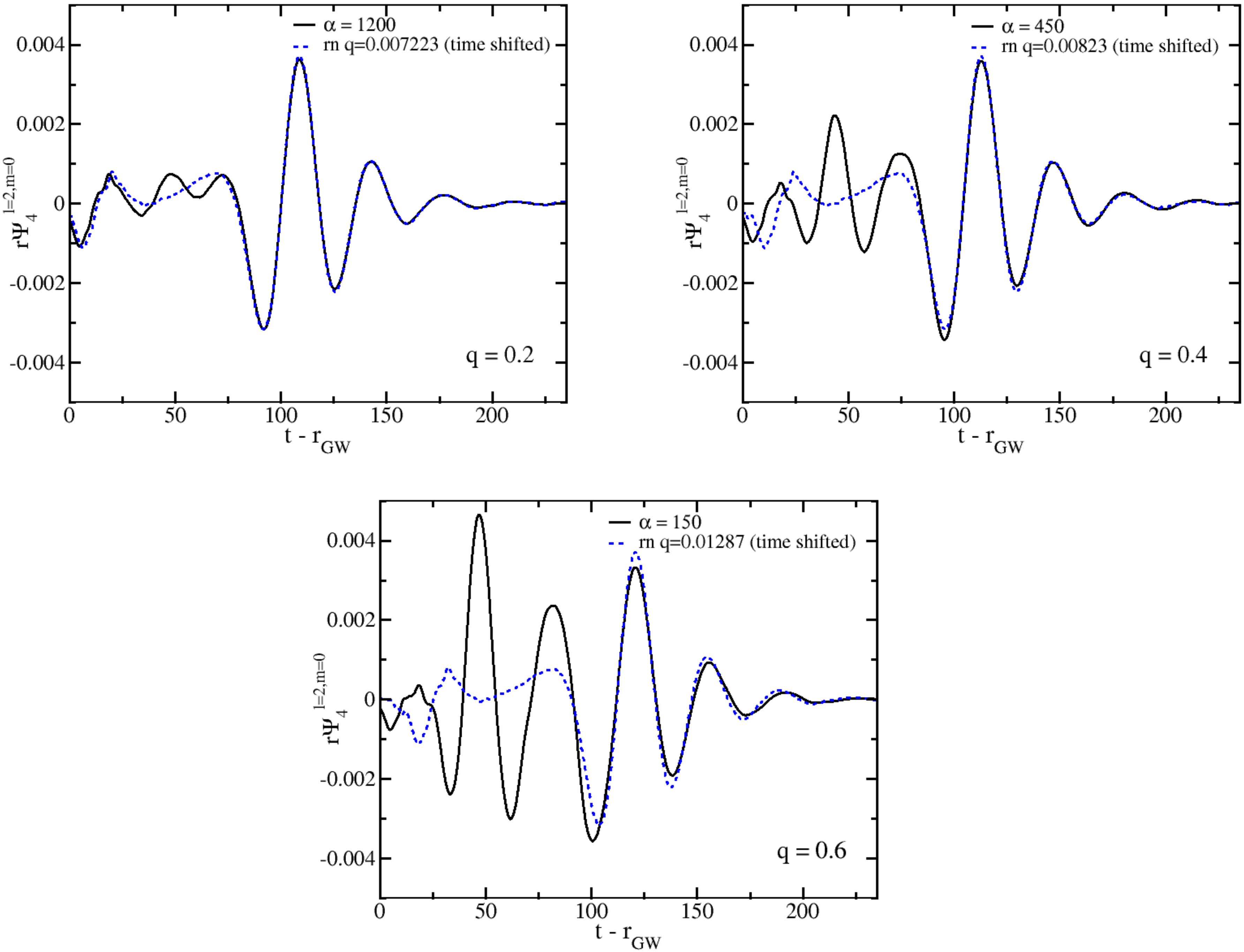

α = 1200
rn q=0.007223 (time shifted)
q = 0.2
α = 450
rn q=0.00823 (time shifted)
q = 0.4
α = 150
rn q=0.01287 (time shifted)
q = 0.6
$r\Psi_4^{l=2,m=0}$
t - r_{GW}
0.004
0.002
0
-0.002
-0.004
0
50
100
150
200

PHYSICAL REVIEW LETTERS **124**, 211301 (2020)

Spontaneous Creation of Circularly Polarized Photons in Chiral Astrophysical Systems

Adrian del Rio,[1] Nicolas Sanchis-Gual,[1] Vassilios Mewes,[2,3,4] Ivan Agullo,[5]
José A. Font,[6,7] and Jose Navarro-Salas[8]
[1]*Centro de Astrofísica e Gravitação—CENTRA, Instituto Superior Técnico, Universidade de Lisboa, Avenida Rovisco Pais 1, 1049-001, Lisboa, Portugal*
[2]*National Center for Computational Sciences, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee 37831-6164, USA*
[3]*Physics Division, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee 37831-6354, USA*
[4]*Center for Computational Relativity and Gravitation, and School of Mathematical Sciences, Rochester Institute of Technology, 85 Lomb Memorial Drive, Rochester, New York 14623, USA*
[5]*Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803-4001, USA*
[6]*Departamento de Astronomía y Astrofísica, Universitat de València, Doctor Moliner 50, 46100 Burjassot (València), Spain*
[7]*Observatori Astronòmic, Universitat de València, Catedrático José Beltrán 2, 46980 Paterna (València), Spain*
[8]*Departamento de Física Teórica and IFIC, Universitat de València-CSIC. Doctor Moliner 50, 46100 Burjassot (València), Spain*

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$$\frac{-1}{96\pi^2}\int_M d^4x\sqrt{-g}R_{\alpha\beta\mu\nu}\,{}^*R^{\alpha\beta\mu\nu} = \int_{-\infty}^{\infty} du\, f(u) \equiv \Delta Q$$

$$f(u) = \frac{1}{72\pi^2}\int_{-\infty}^{u} du' \sum_{lm} \mathrm{Im}\left[\Psi^0_{4,lm}(u)\bar{\Psi}^0_{4,lm}(u)\right]$$

$$\Psi^0_4(u,\theta,\phi) = \lim_{r\to\infty} r\Psi_4(u,r,\theta,\phi)$$

PRIMORDIAL GWS FROM COSMOLOGICAL PHASE TRANSITIONS

Primordial Gravitational Waves from cosmological Phase Transitions

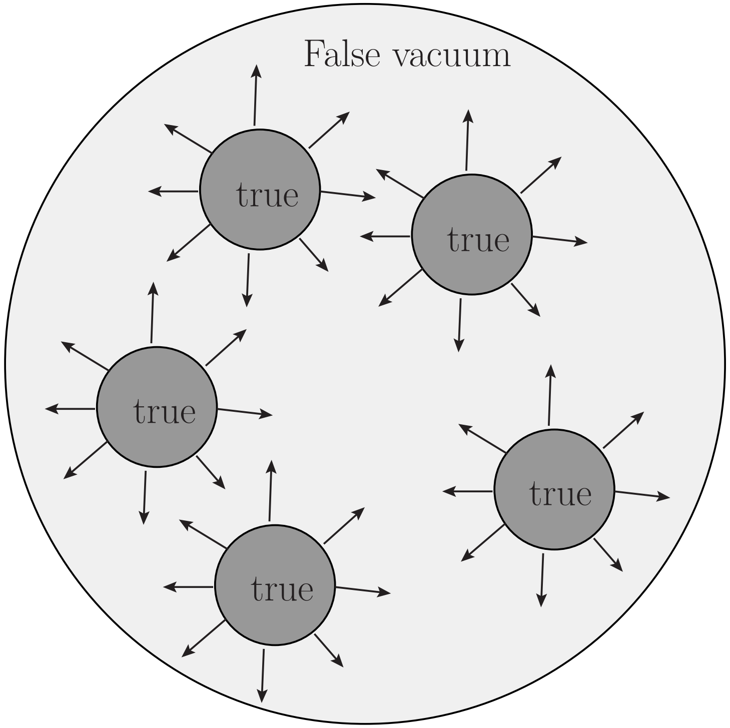
JCAP 07 (2018) 014; JCAP 04 (2020) 036; PLB 807 (2020) 135577; PoS(EPS-HEP2019)054

Team at Aveiro:
António P. Morais (leader), Felipe F. Freitas (responsible for machine learning implementations)
Students: Vasileios Vatellis, João Pino, Pedro Rodrigues

Current Collaborations:
Roman Pasechnik, Johan Rathsman and Marten Bertenstam (Lund U.),
Rui Santos and João Viana (Lisbon U.),
Antonino Marciano (Fudan U.)

Primordial Gravitational Waves from cosmological Phase Transitions

Generated by expanding vacuum bubbles of a true vacuum phase in a universe filled with a false vacuum phase



Primordial Gravitational Waves from cosmological Phase Transitions

JCAP 07 (2018) 014; JCAP 04 (2020) 036; PLB 807 (2020) 135577

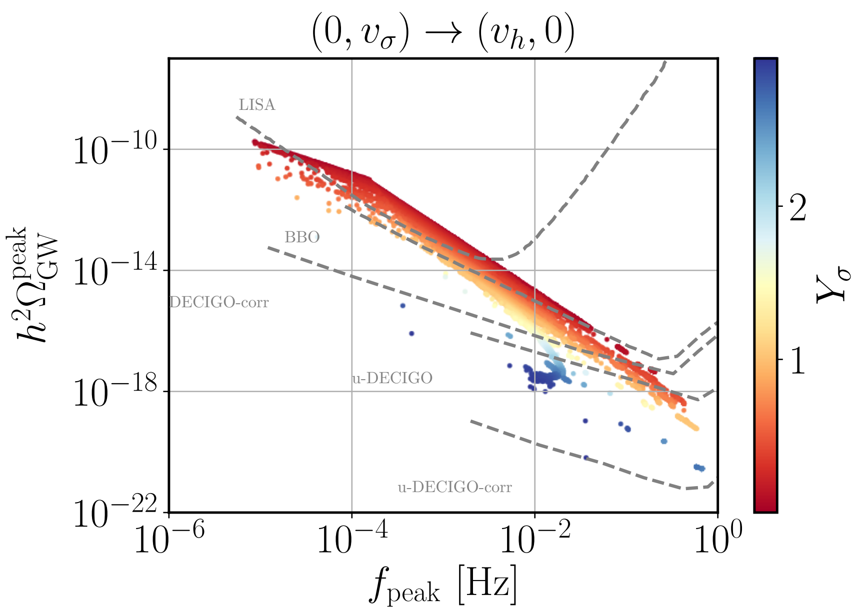
Generated by expanding vacuum bubbles of a broken phase in a universe filled with a symmetric phase

GW background as a gravitational probe for New Physics beyond the reach of collider experiments

Different Particle Physics models may leave distinctive GW footprints

PTs occurring close to the electroweak era yield GW frequencies within LISA range

Eg: Probing the $Y_\sigma \sigma SS$ coupling between a complex singlet scalar σ and a sterile neutrino S



- Typically, the main source of GW production results from sound waves
- We are developing deep-learning techniques aiming at ultra-fast data sampling (VAEs and GANs)

Particle Physics details encoded in $h^2\Omega_{\rm GW}(f)$ and f

$$h^2\Omega_{\rm GW}(f) = \frac{2\pi^2}{3} f^2 (h_c(f))^2$$

$h^2\Omega_{\rm GW}(f) \to$ energy density per logarithmic frequency,

$h_c(f) \to$ characteristic strain.

THANK YOU!
¡GRACIAS!
OBRIGADO!