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DEPARTAMENTO DE ASTRONOMÍA Y ASTROFÍSICA - UNIVERSIDAD DE VALENCIA

NEW HORIZONS FOR PSI WORKSHOP – INSTITUTO SUPERIOR TÉCNICO – LISBOA– JULY 2024

DYNAMICAL BOSONIC STARS: STABILITY AND GRAVITATIONAL WAVES

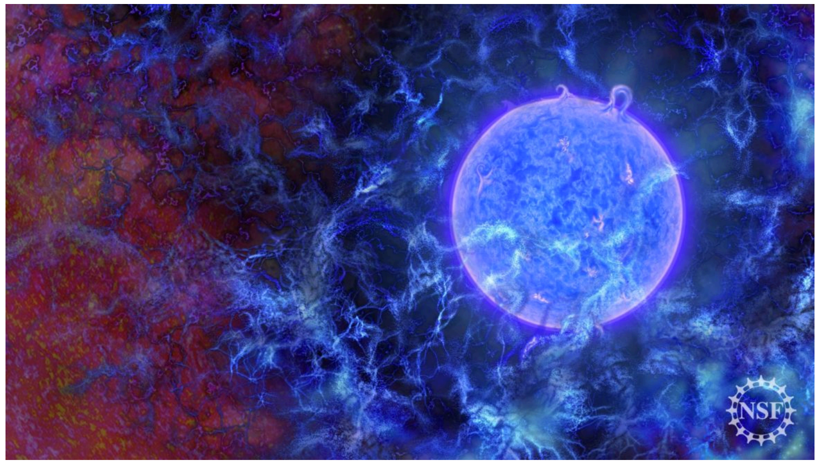
Bezares, M., & Sanchis-Gual, N. (2024). Exotic compact objects: a recent numerical-relativity perspective. *arXiv preprint arXiv:2406.04901*.

MOTIVATION

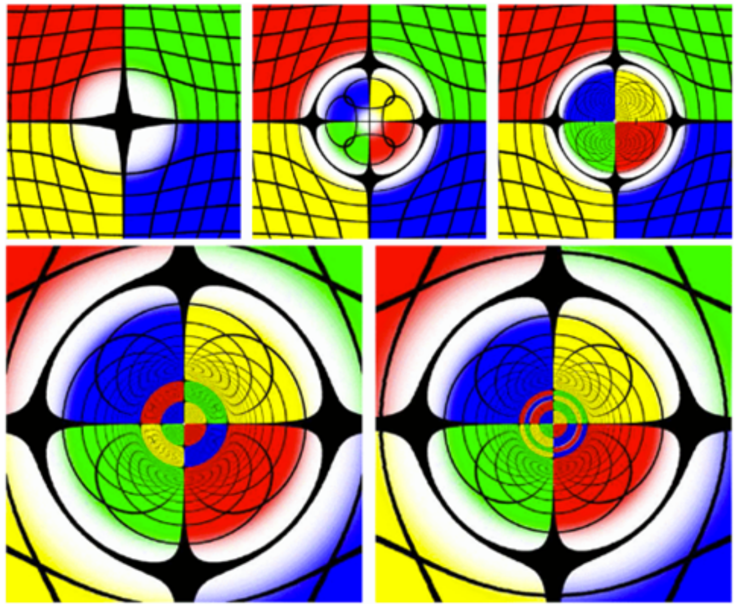
EXOTIC COMPACT OBJECTS

Cardoso, V., & Pani, P. (2019). *Living Reviews in Relativity*, *22*(1), 1-104.
Cardoso, V., Hopper, S., Macedo, C. F., Palenzuela, C., & Pani, P. (2016).. *Physical review D*, *94*(8), 084031.
Herdeiro, C. A. (2022). *arXiv preprint arXiv:2204.05640*.

- To what extent are all astrophysical, dark, compact objects **both black holes and described by the Kerr geometry**?
- **ECOs:** Involve extreme gravitational fields and may be the key to understand outstanding puzzles in fundamental physics.
- From **dark matter to quantum gravity:** Wormholes, scalarized BHs, gravastars, fuzzballs, quark stars, boson stars….
- In this talk I will focus on **boson stars**.



WHAT ARE BOSON STARS?



Kaup, D. J. (1968). Klein-gordon geon. *Physical Review*, *172*(5), 1331.
Ruffini, R., & Bonazzola, S. (1969). Systems of self-gravitating particles in general relativity and the concept of an equation of state. *Physical Review*, *187*(5), 1767.
Jetzer, P. (1992). Boson stars. *Physics Reports*, *220*(4), 163-227.
Brito, R., Cardoso, V., Herdeiro, C. A., & Radu, E. (2016). Proca stars: gravitating Bose–Einstein condensates of massive spin 1 particles. *Physics Letters B*, *752*, 291-295.

- **Scalar boson stars** and its vector “cousins”, known as **Proca stars**, are made of massive particles with **integer spin** following the Bose-Einstein statistics: **ultralight bosons**.
- At the lowest energy level state can be classically described by a **wavefunction**, characterized by the particle mass μ.
- Considering a **complex scalar field** with **harmonic dependence**:

$$\psi(t,r) = \psi_{\mathrm{Re}}(r,t) + i\psi_{\mathrm{Im}}(r,t) = \psi_0(r)\, e^{-i\omega t}$$

- The star forms **a stationary, soliton-like solution**.

ON THE STABILITY OF BOSON AND PROCA STARS

- Cunha, P. V., Font, J. A., Herdeiro, C., Radu, E., **Sanchis-Gual, N.**, & Zilhão, M. (2017). *Lensing and dynamics of ultracompact bosonic stars.* Physical Review D, 96(10), 104040.

- Escorihuela-Tomàs, A., **Sanchis-Gual, N.**, Degollado, J. C., & Font, J. A. (2017). *Quasistationary solutions of scalar fields around collapsing self-interacting boson stars.* Physical Review D, 96(2), 024015.

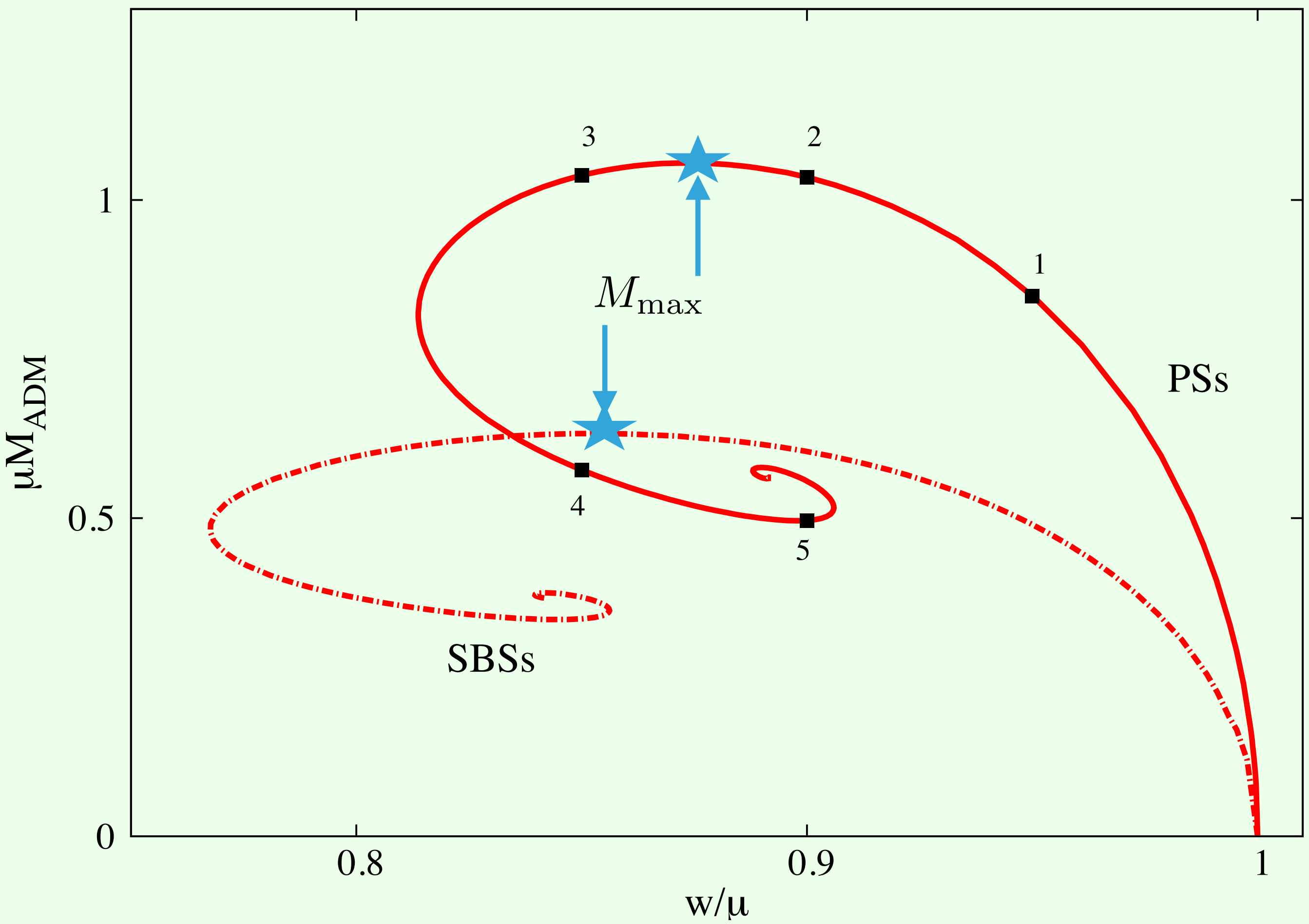
- **Sanchis-Gual, N.**, Herdeiro, C., Radu, E., Degollado, J. C., & Font, J. A. (2017). *Numerical evolutions of spherical Proca stars.* Physical Review D, 95(10), 104028.

BOSON AND PROCA STARS

Equilibrium solutions in spherical symmetry.

$$\phi(\mathbf{r}, t) = \phi_0 \, e^{-i\,\omega t}$$

$$\mathcal{A} = e^{-iwt}\left(iV dt + \frac{H_1}{r} dr\right)$$



$$M_{\rm max} \sim 0.633 \; M^2_{\rm Planck}/\mu$$

Liebling, S. L., & Palenzuela, C. (2017). Dynamical boson stars. *Living Reviews in Relativity*, *20*(1), 5.

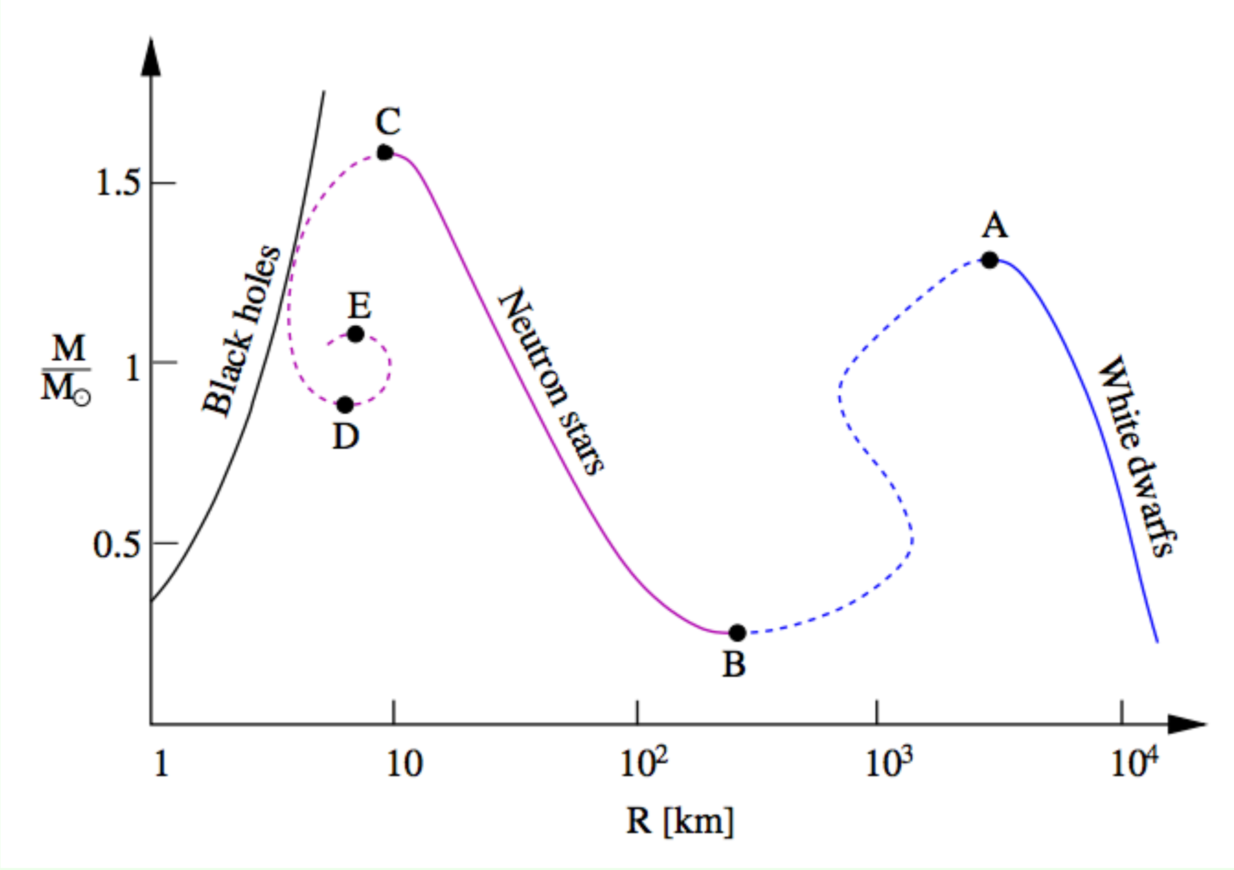
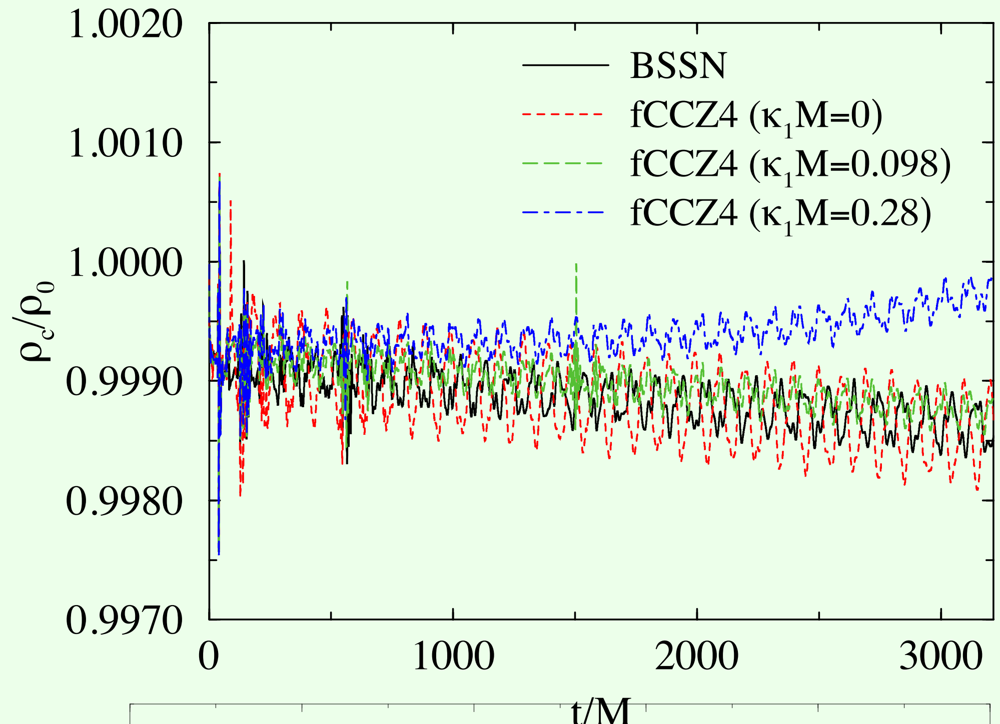
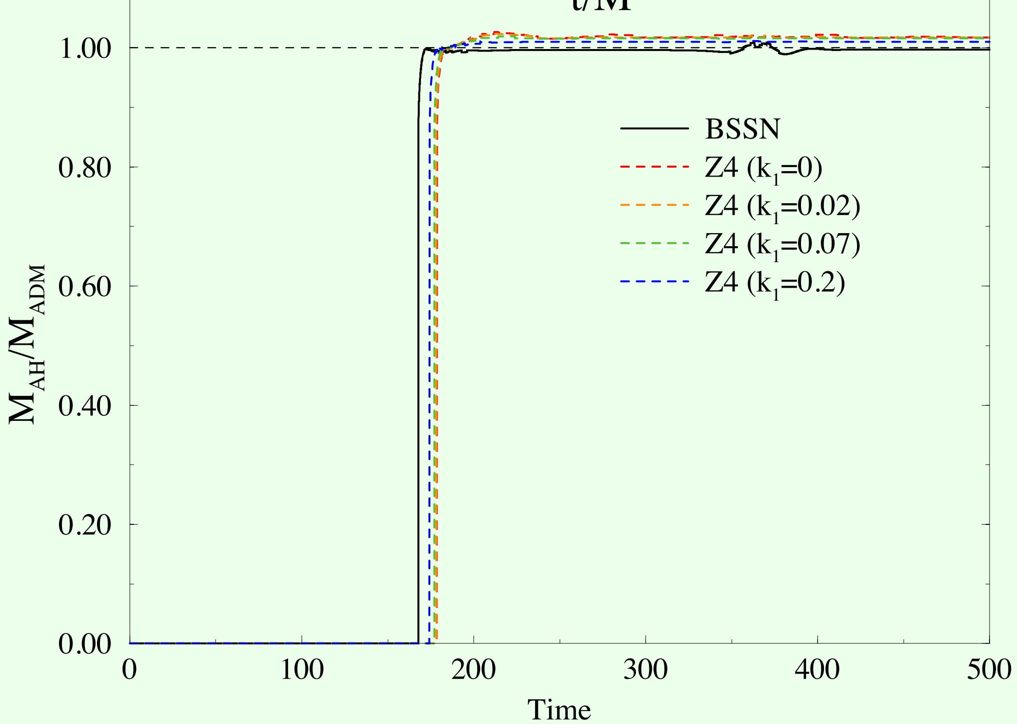


Figure extracted from: Guerra, D., Macedo, C. F., & Pani, P. (2019). Axion boson stars. *Journal of Cosmology and Astroparticle Physics*, *2019*(09), 061.

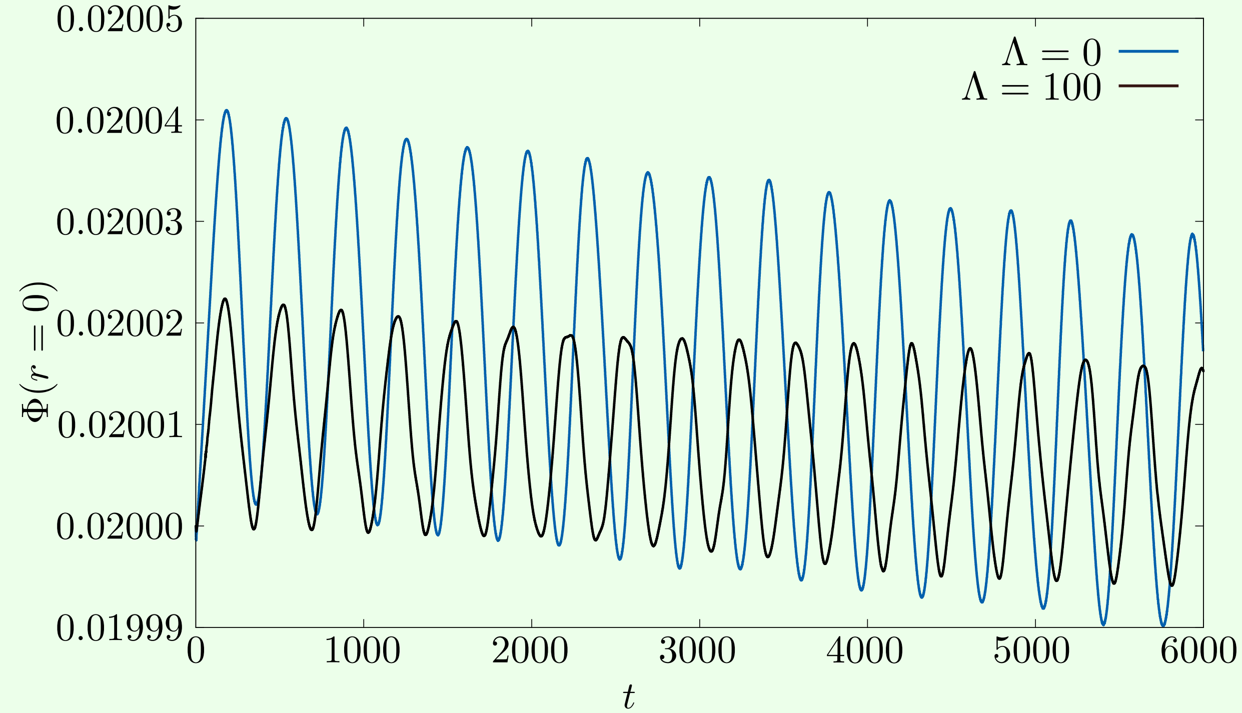
BOSON AND PROCA STARS

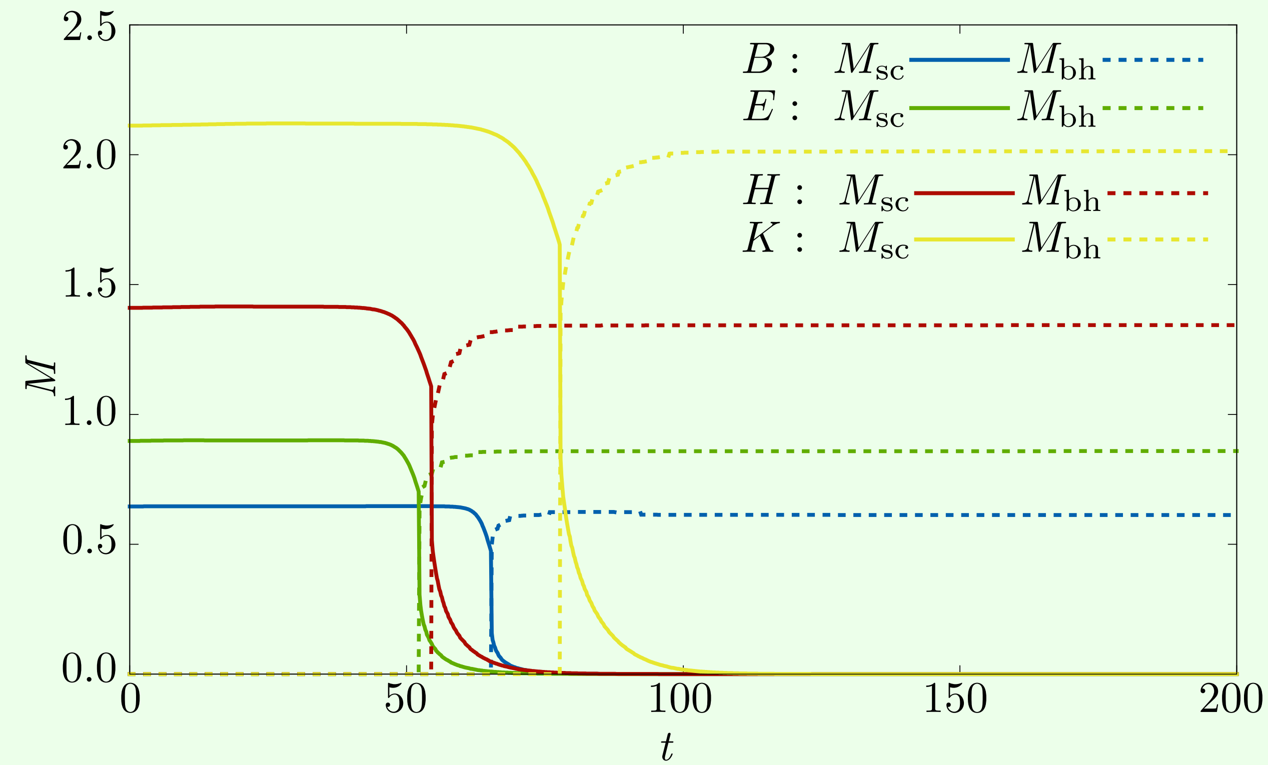
Neutron stars





Boson stars

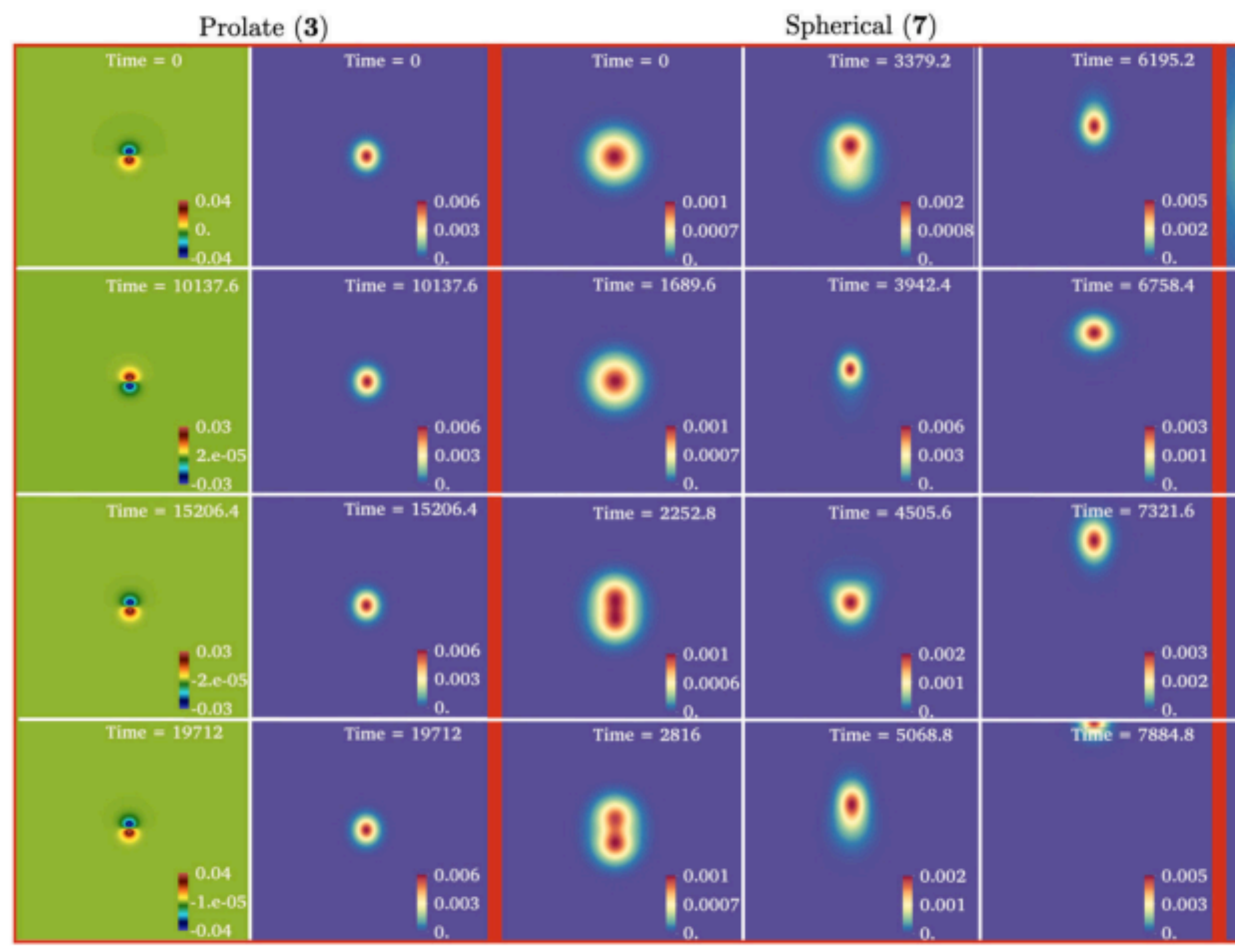




BOSON AND PROCA STARS

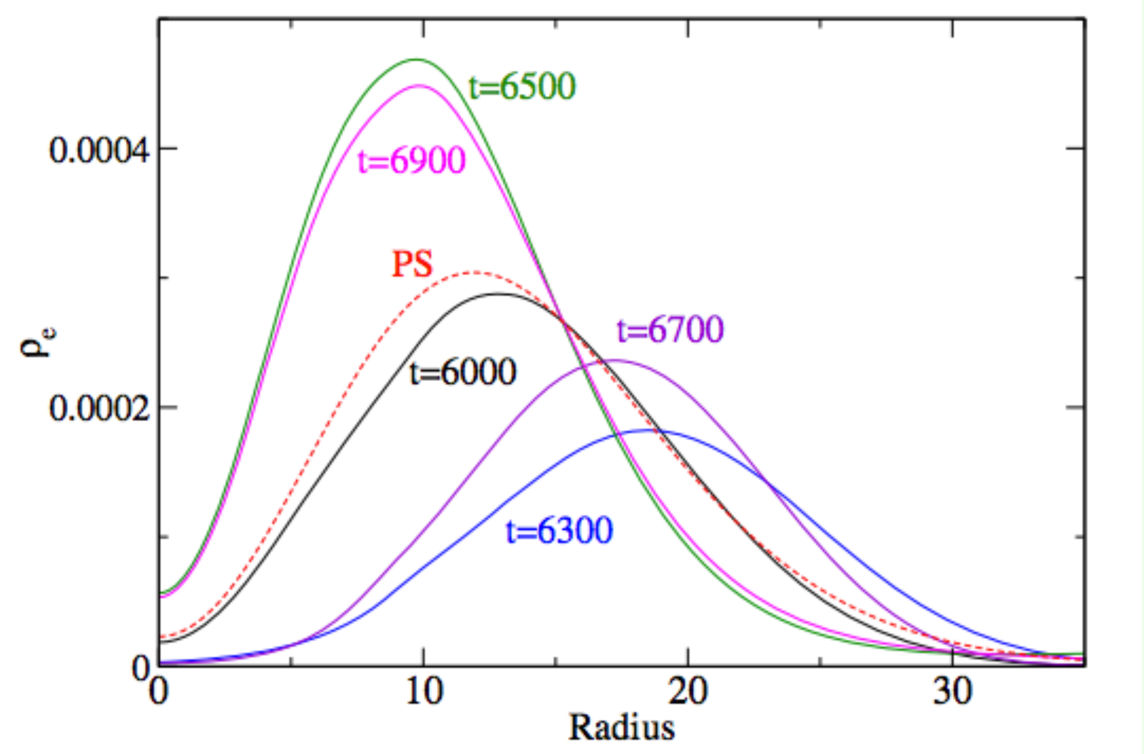
Spherical and prolate Proca stars

Spherical Proca stars decay to prolate Proca star configurations.

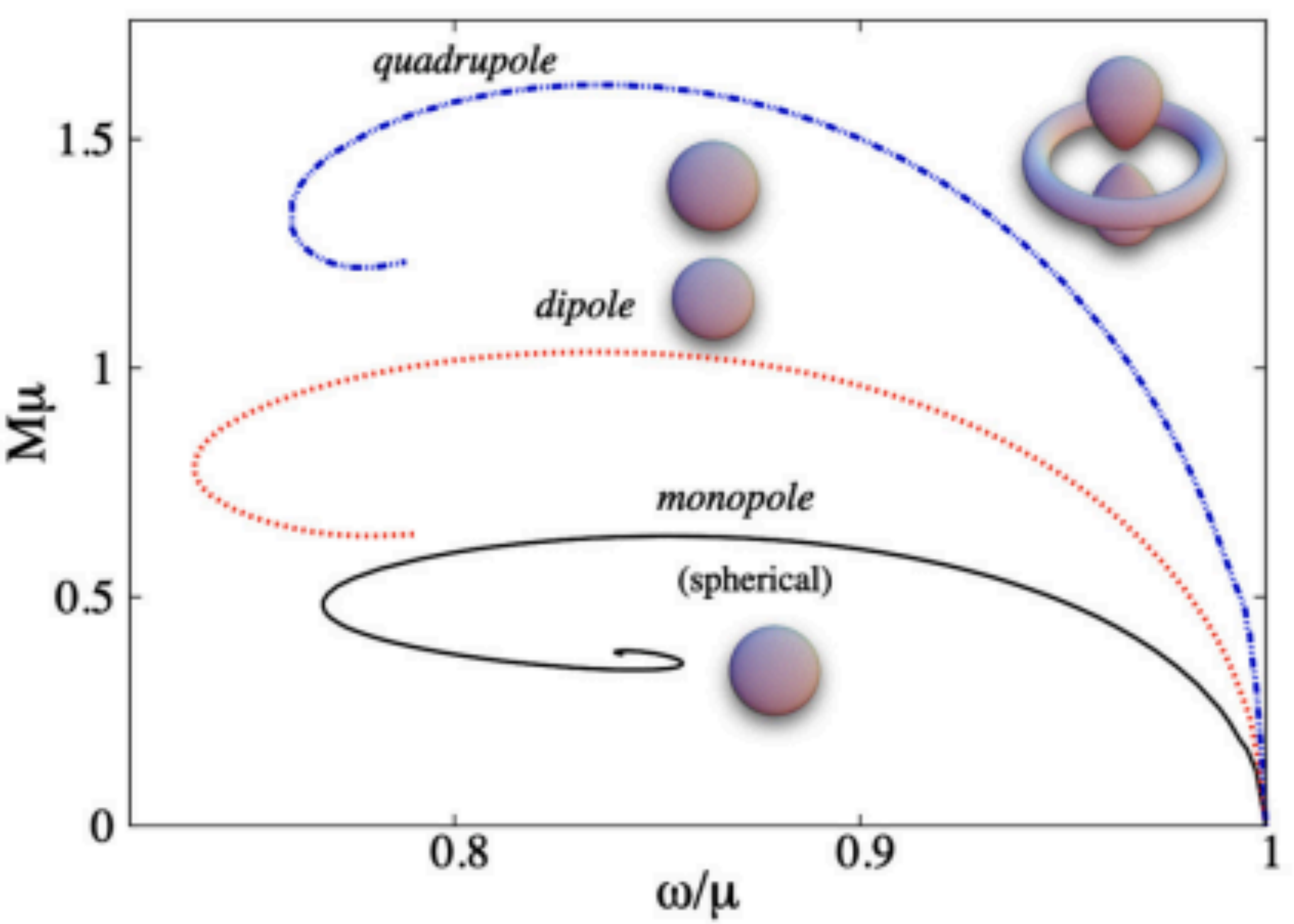


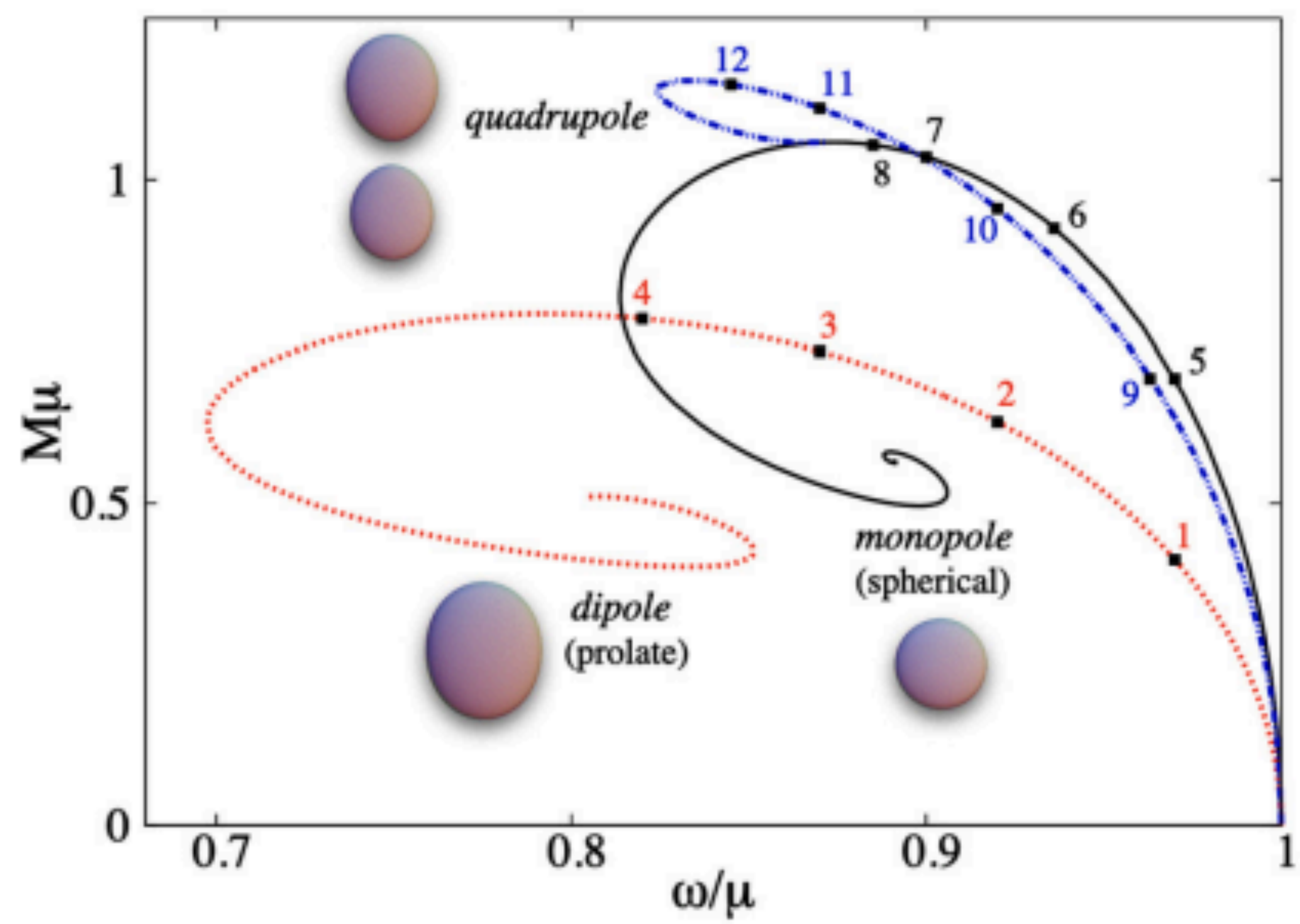
Herdeiro, C. A. R., Radu, E., Sanchis-Gual, N., Santos, N. M., & dos Santos Costa Filho, E. (2024). The non-spherical ground state of Proca stars. *Physics Letters B*, *852*, 138595.

BOSON AND PROCA STARS



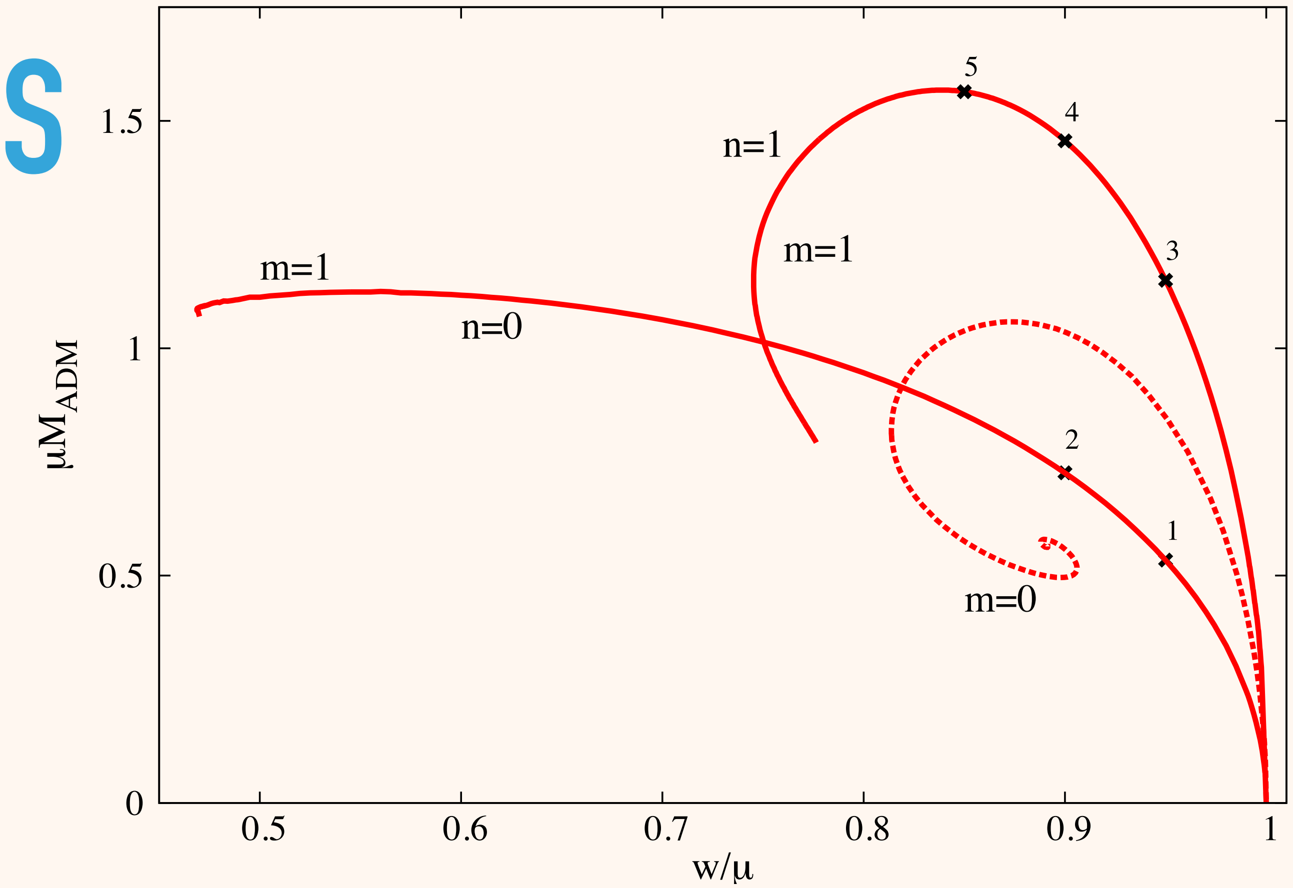
Static Boson and Proca stars





Herdeiro, C. A. R., Radu, E., Sanchis-Gual, N., Santos, N. M., & dos Santos Costa Filho, E. (2024). The non-spherical ground state of Proca stars. *Physics Letters B*, *852*, 138595.

SPINNING BOSONIC STARS



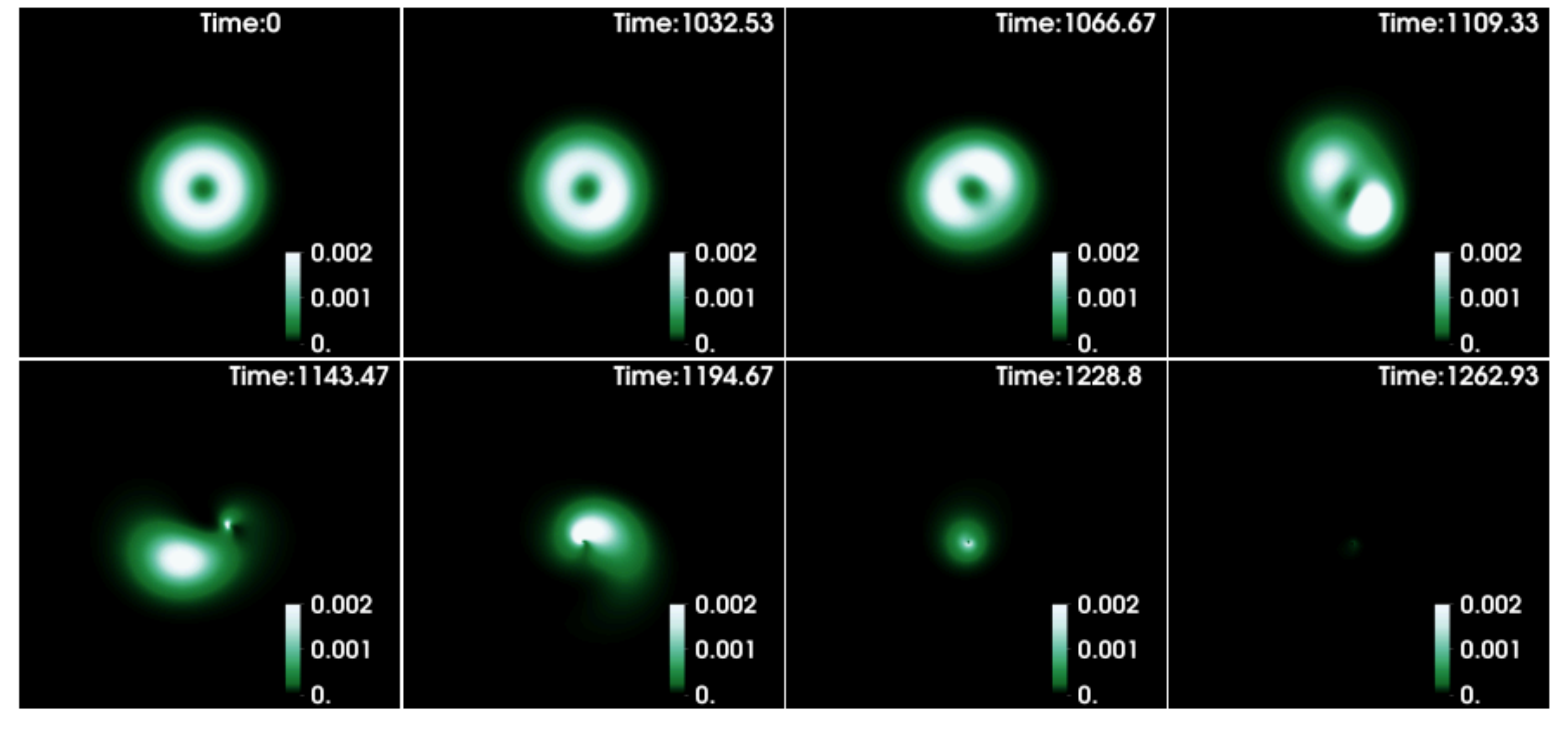
- The Proca field **ansatz**:

$$A = \left(\frac{H_1}{r} dr + H_2 d\theta + i H_3 \sin\theta d\varphi + i V dt \right) e^{i(m\varphi - \omega t)}$$

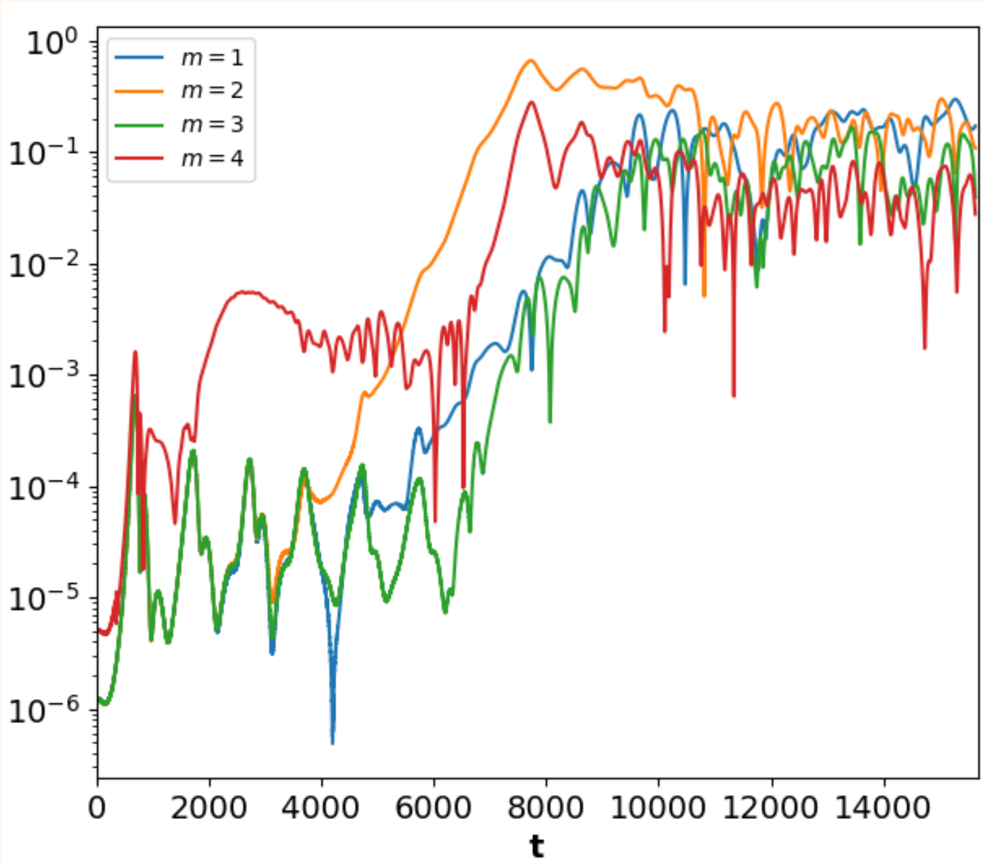
- and the scalar field **ansatz**:

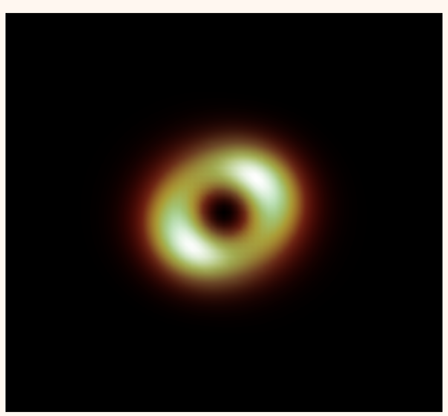
$$\psi(t, r, \theta, \varphi) = R(r)\Theta_{11}(\theta)\, e^{i(m\varphi - \omega t)}$$

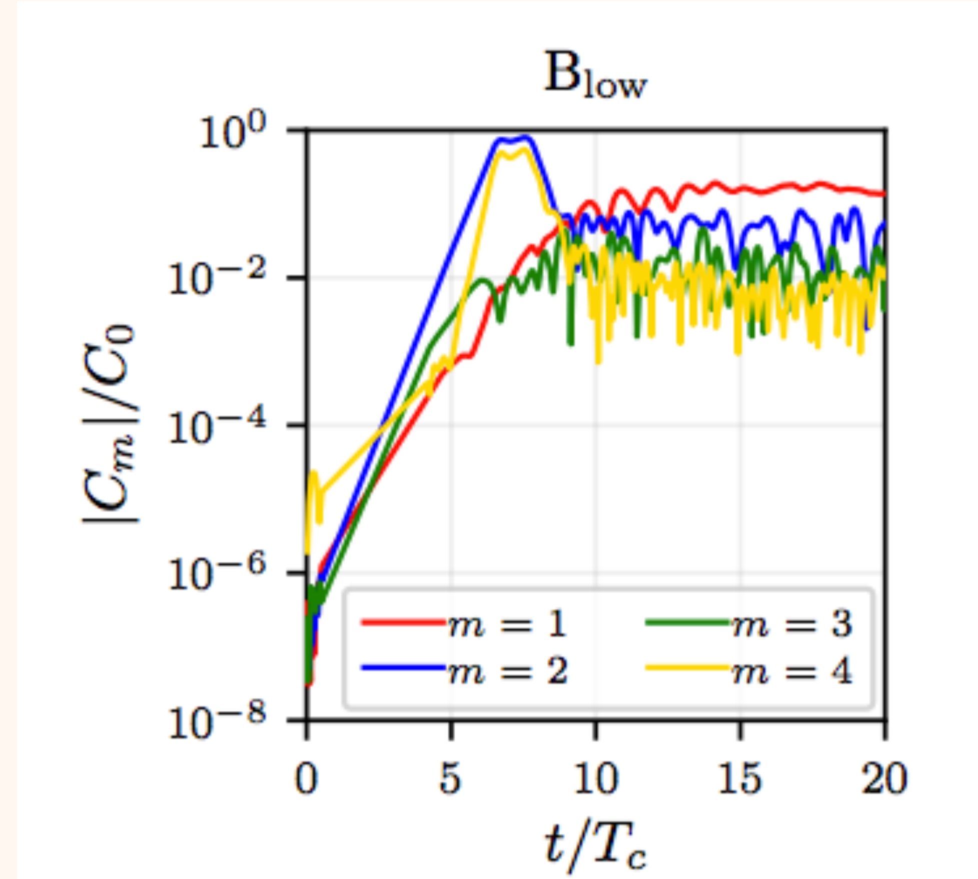
SPINNING BOSON STARS

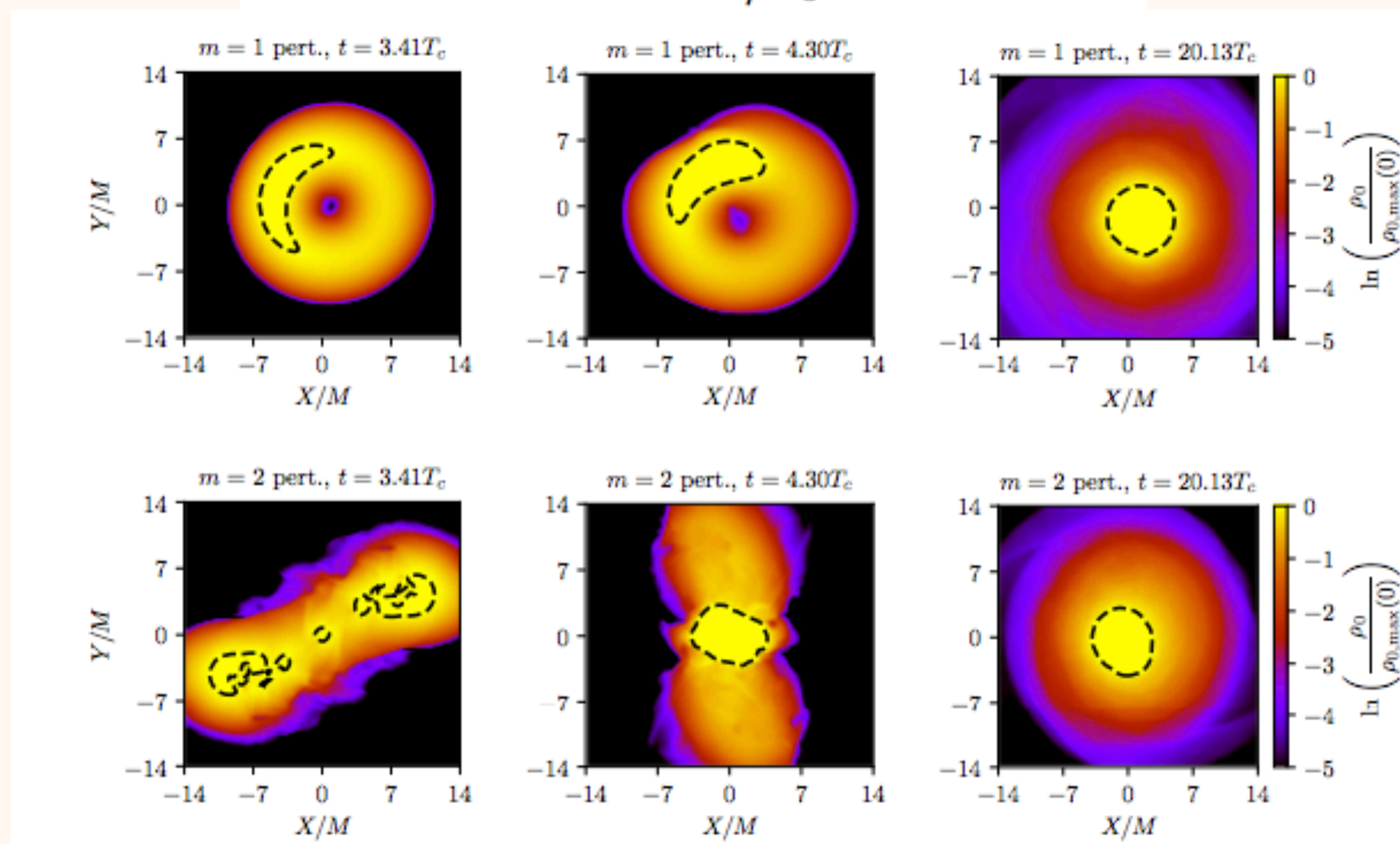


Sanchis-Gual, N., Di Giovanni, F., Zilhão, M., Herdeiro, C., Cerdá-Durán, P., Font, J. A., & Radu, E. (2019). Nonlinear dynamics of spinning bosonic stars: formation and stability. *Physical review letters*, *123*(22), 221101.



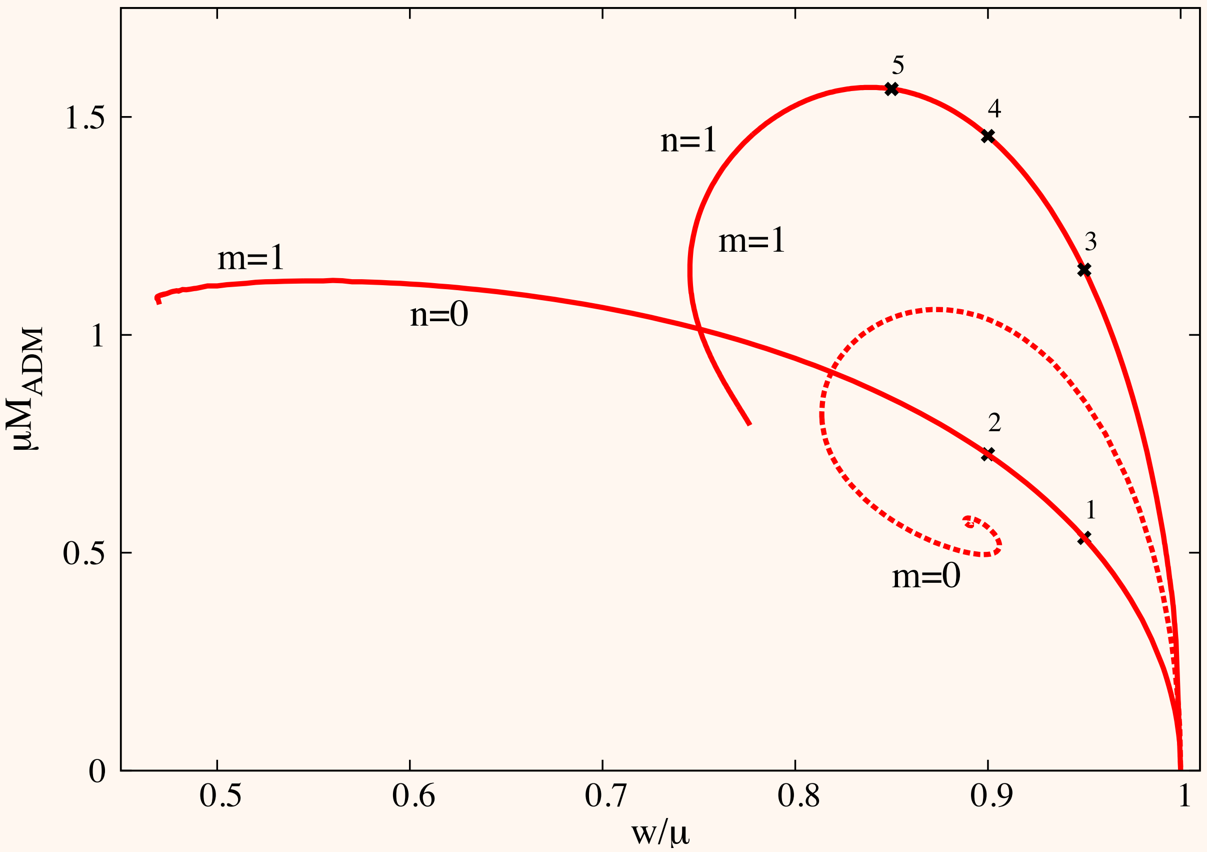


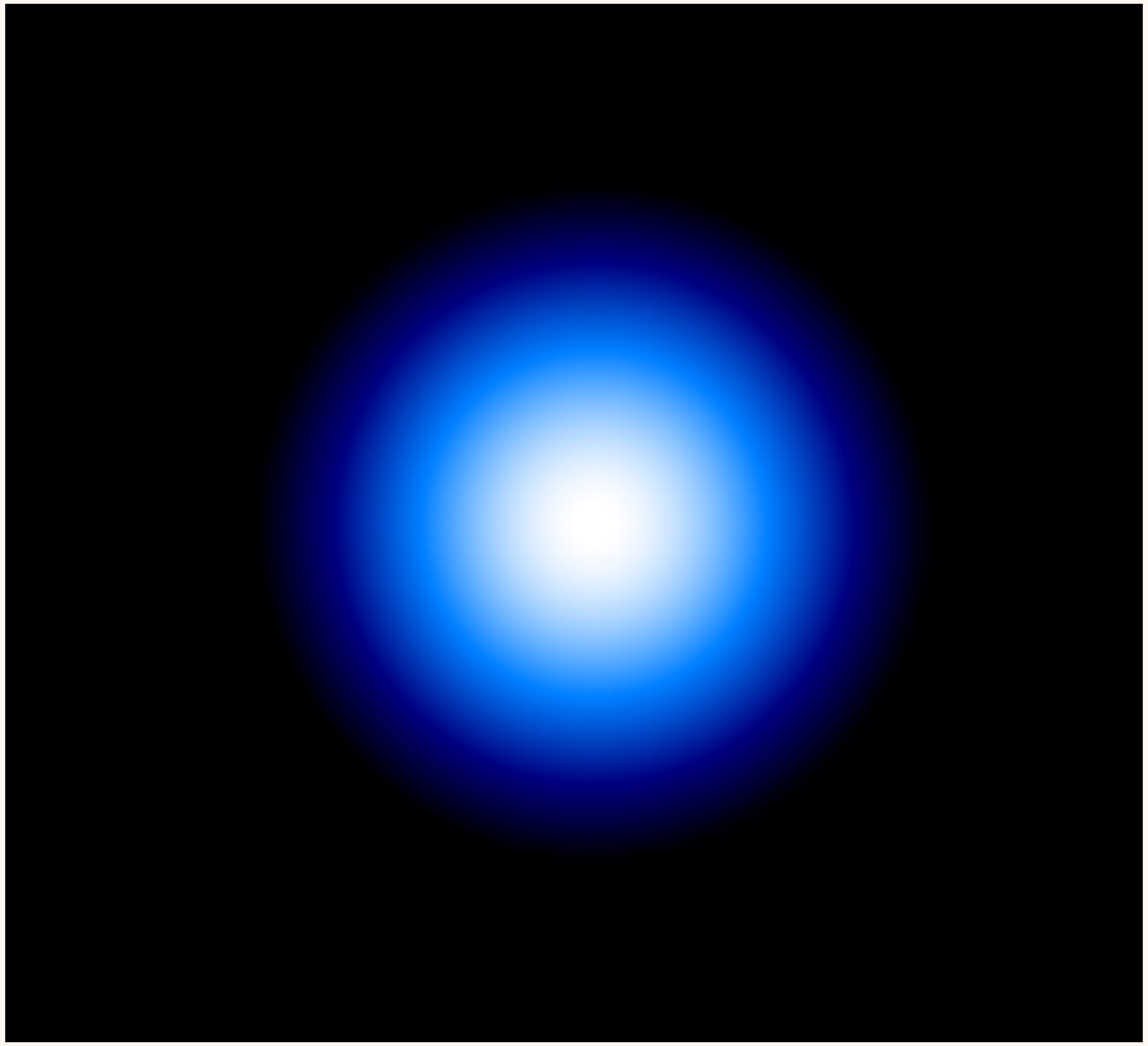




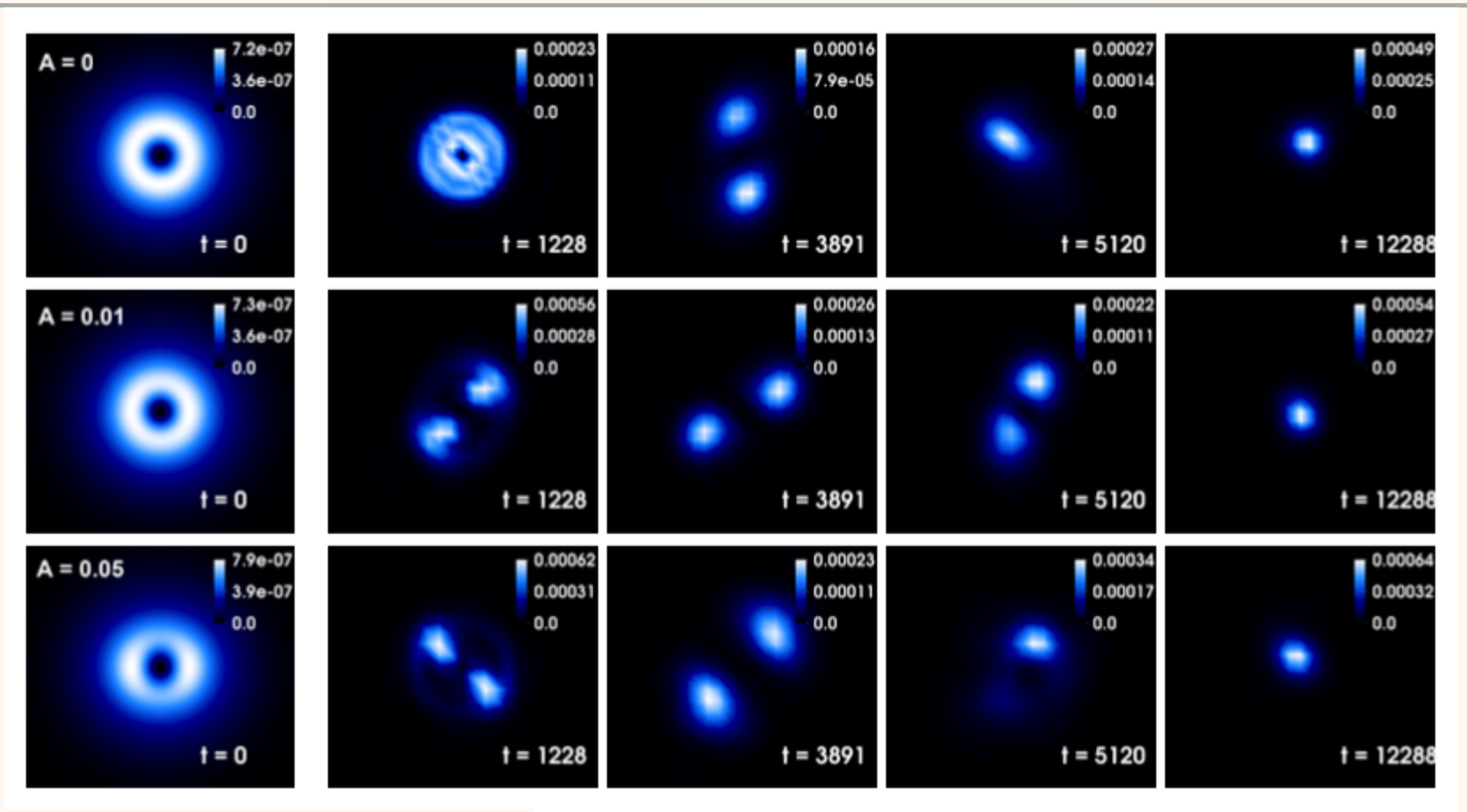
- (P. L. Espino, V. Paschalidis, T. W. Baumgarte, and S. L.Shapiro (2019), 1906.08786)

SPINNING PROCA STARS





Sanchis-Gual, N., Di Giovanni, F., Zilhão, M., Herdeiro, C., Cerdá-Durán, P., Font, J. A., & Radu, E. (2019). Nonlinear dynamics of spinning bosonic stars: formation and stability. *Physical review letters*, *123*(22), 221101.



Di Giovanni, F., Sanchis-Gual, N., Cerdá-Durán, P., Zilhão, M., Herdeiro, C., Font, J. A., & Radu, E. (2020). Dynamical bar-mode instability in spinning bosonic stars. *Physical Review D*, *102*(12), 124009.

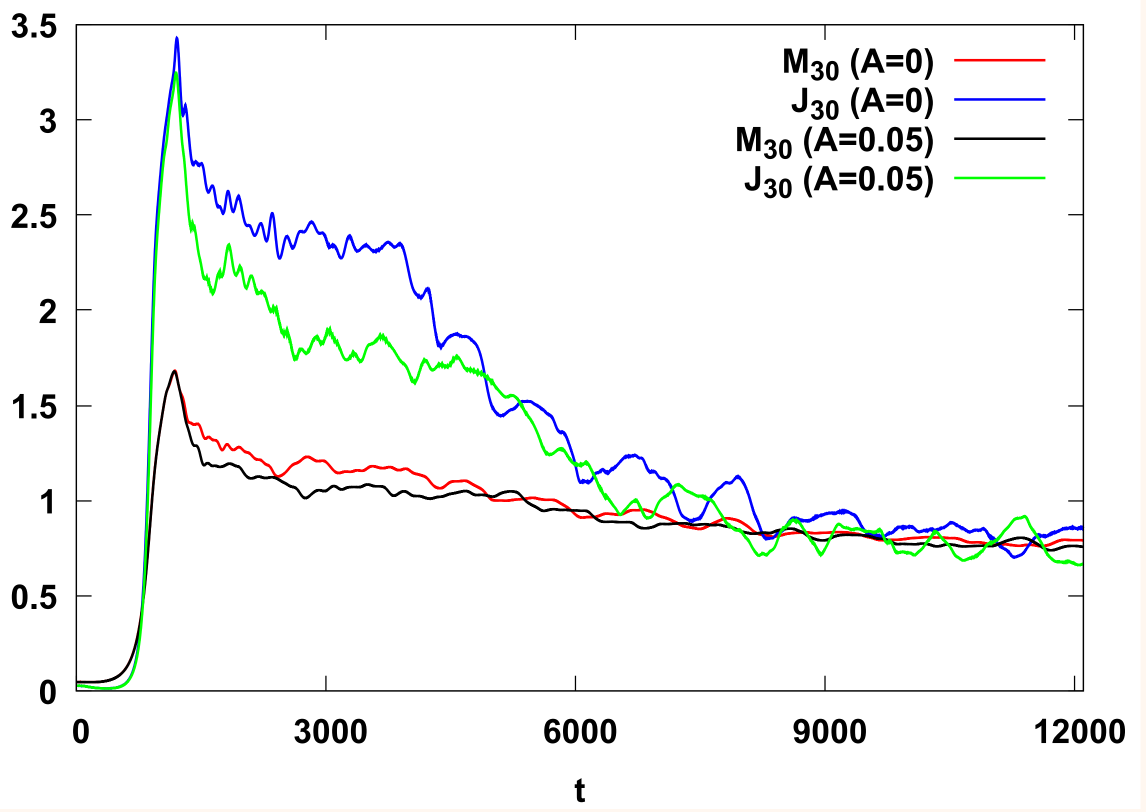
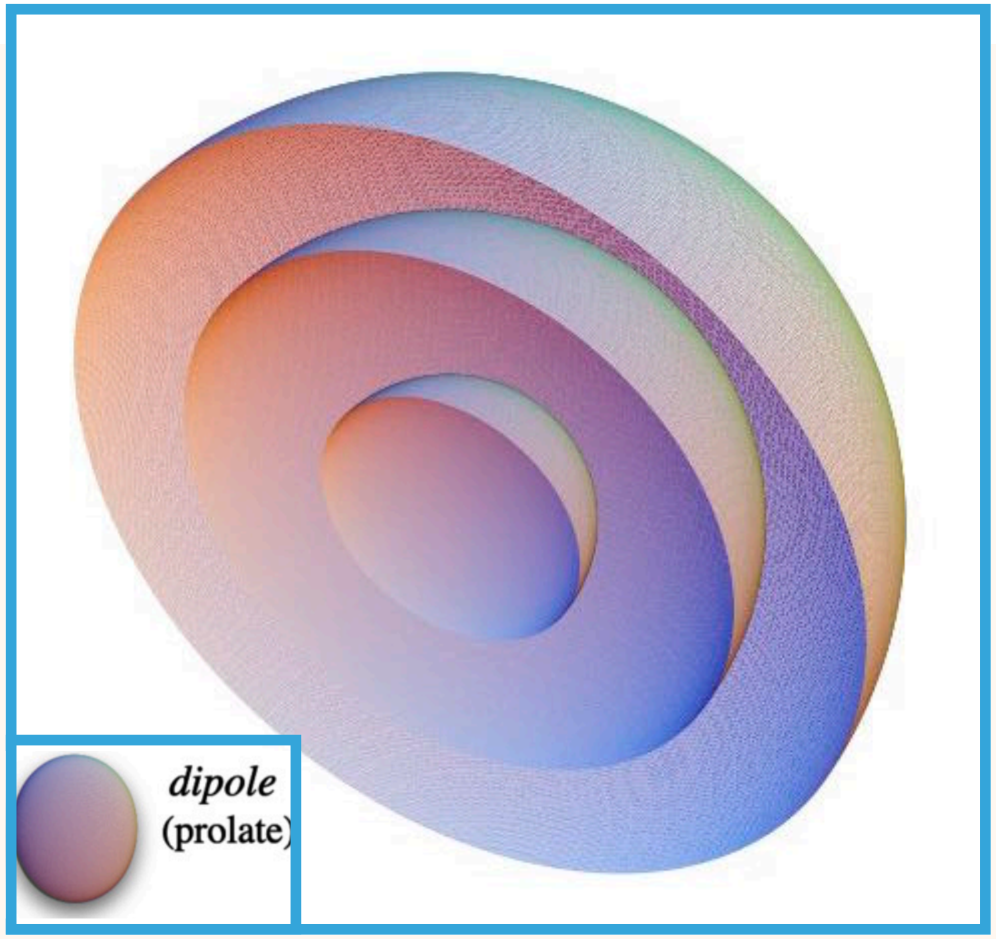
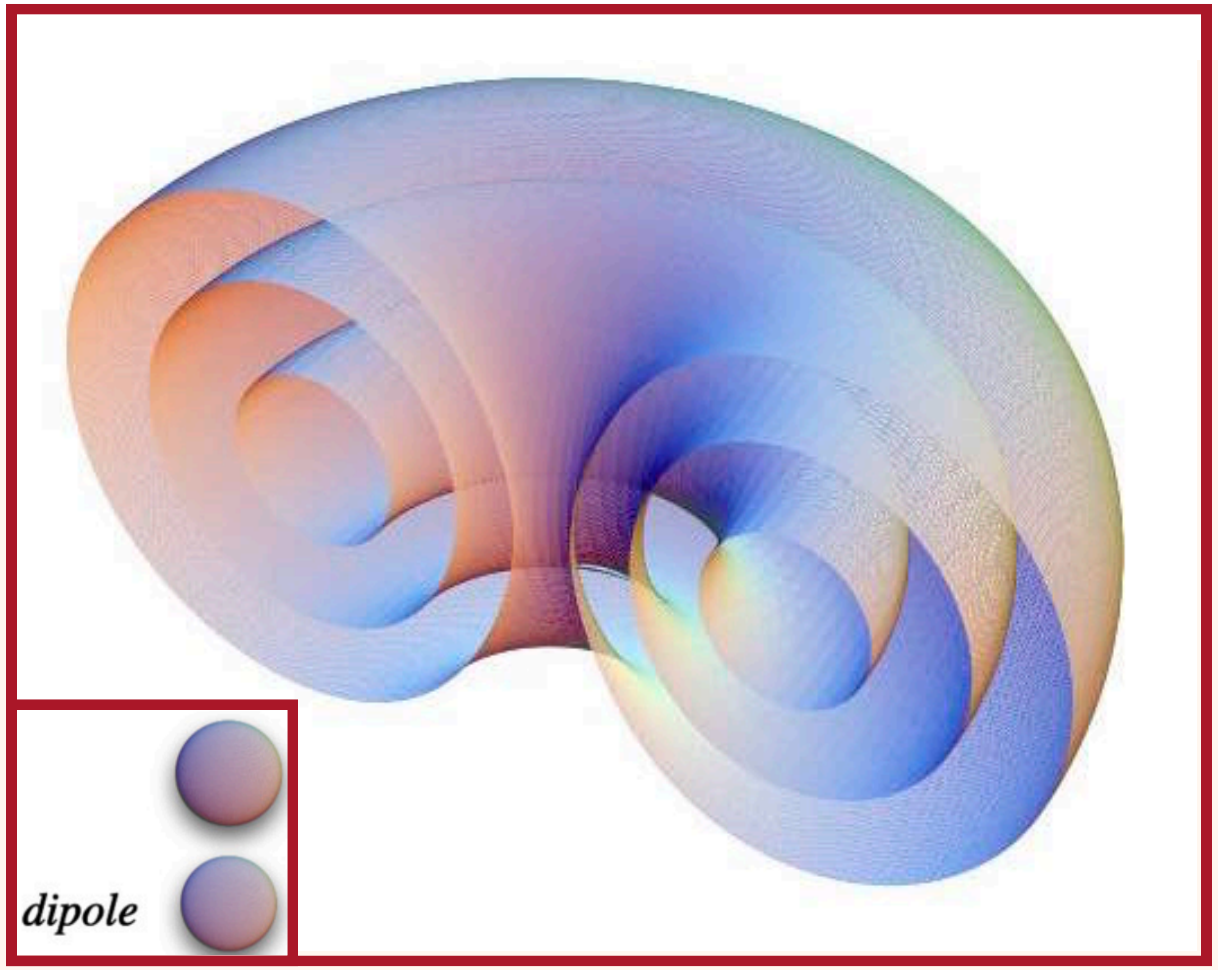


Table 1: *Bosonic stars.* Non-radial (in)stability of mini-bosonic stars on the stable branch.

Classes	Static $\ell = m = 0$	Static $\ell = 1, m = 0$	Rotating $\ell = 1, m = \pm 1$	Rotating $\ell = 2, m = \pm 2$
Scalar	Stable	Unstable	Unstable	Unstable
Proca	Unstable	Stable	Stable	Unstable





A STABILIZATION MECHANISM

MULTI-STATE BOSON STARS AND MIXED STARS

Bernal, A., Barranco, J., Alic, D., & Palenzuela, C. (2010). Multistate boson stars. *Physical Review D*, *81*(4), 044031.
Fabrizio Di Giovanni et al (2021), A stabilization mechanism for excited fermion–boson stars, Class. Quantum Grav. 38 194001

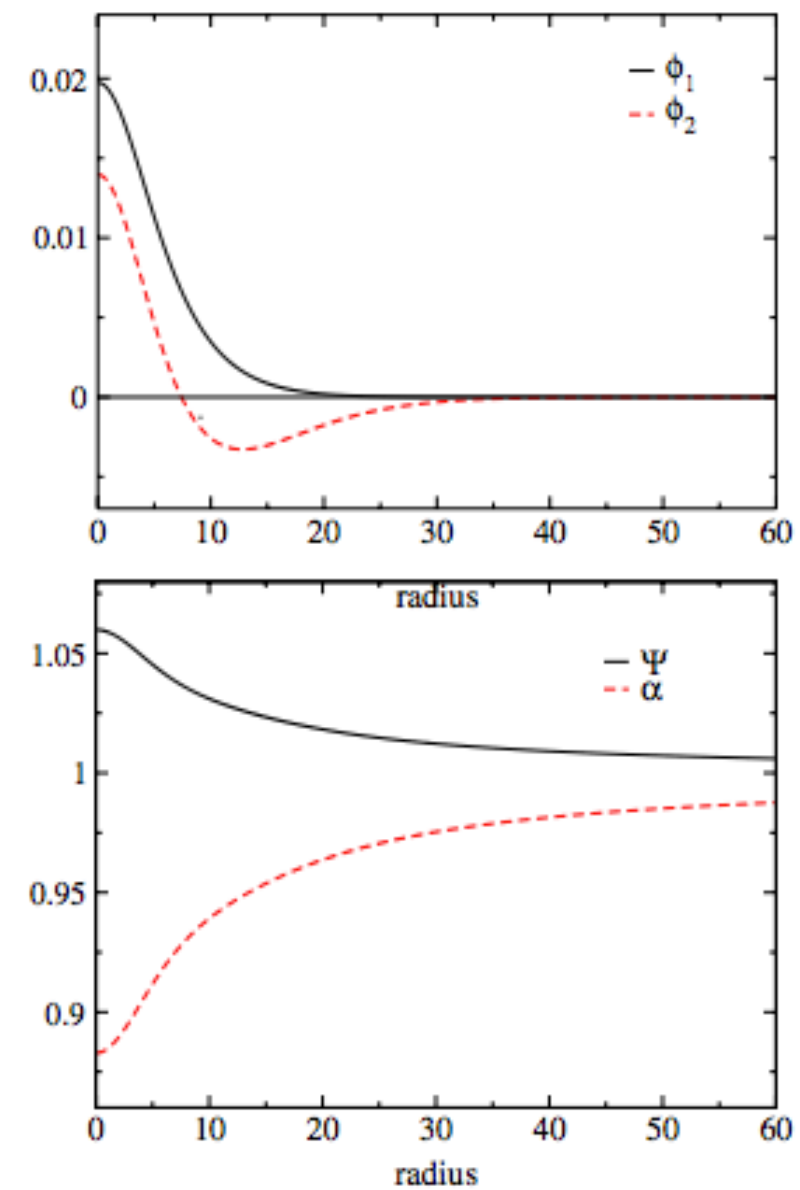


FIG. 1 (color online). Ground-1st excited configuration for $\phi_1(0) = 0.0197$ and fraction $\eta = 1$. The upper panel corresponds to the initial profiles of the two scalar fields, and the lower panel, to the lapse function α and the conformal factor Ψ.

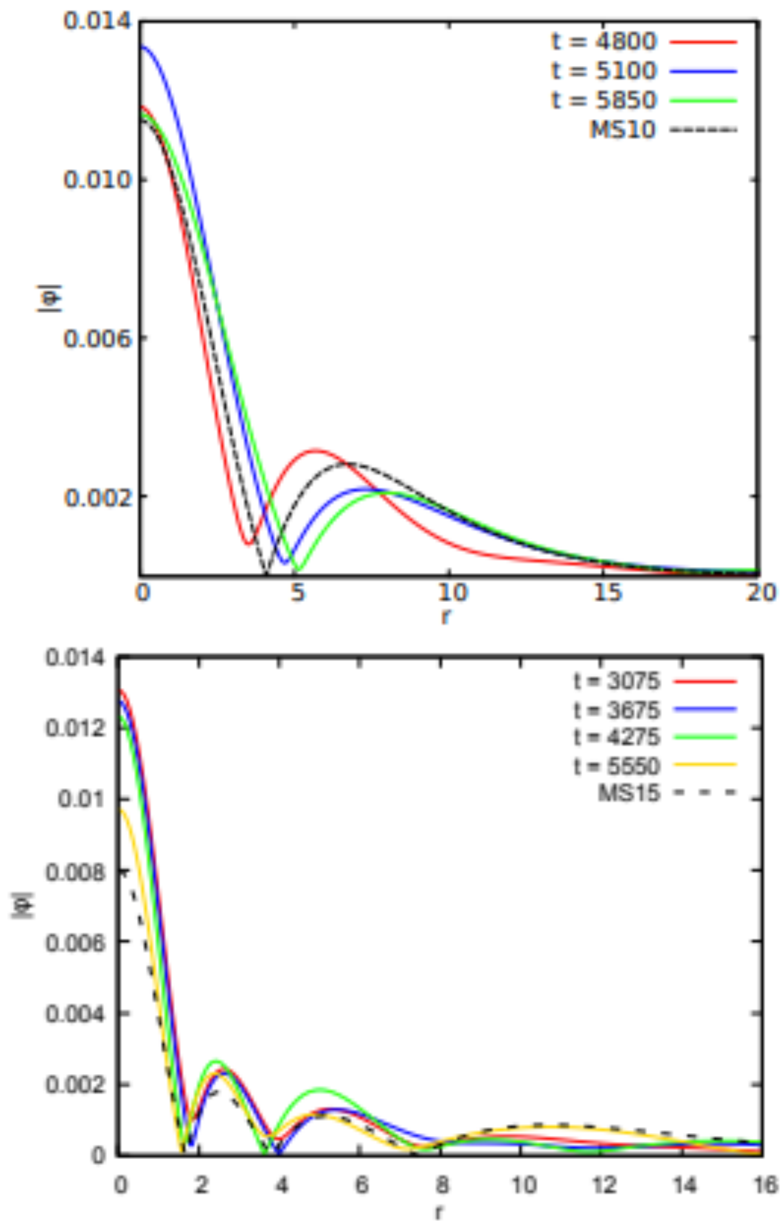
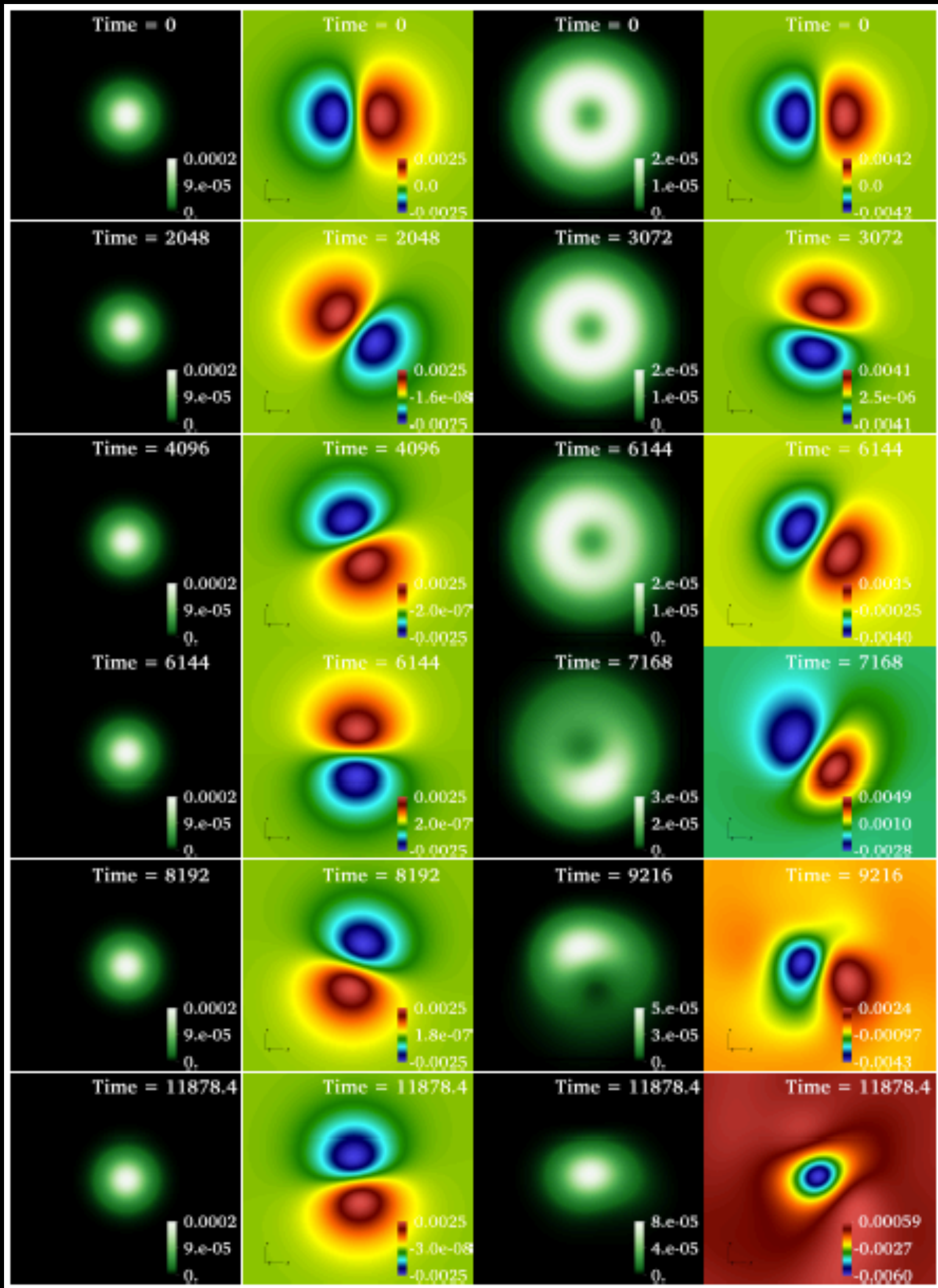
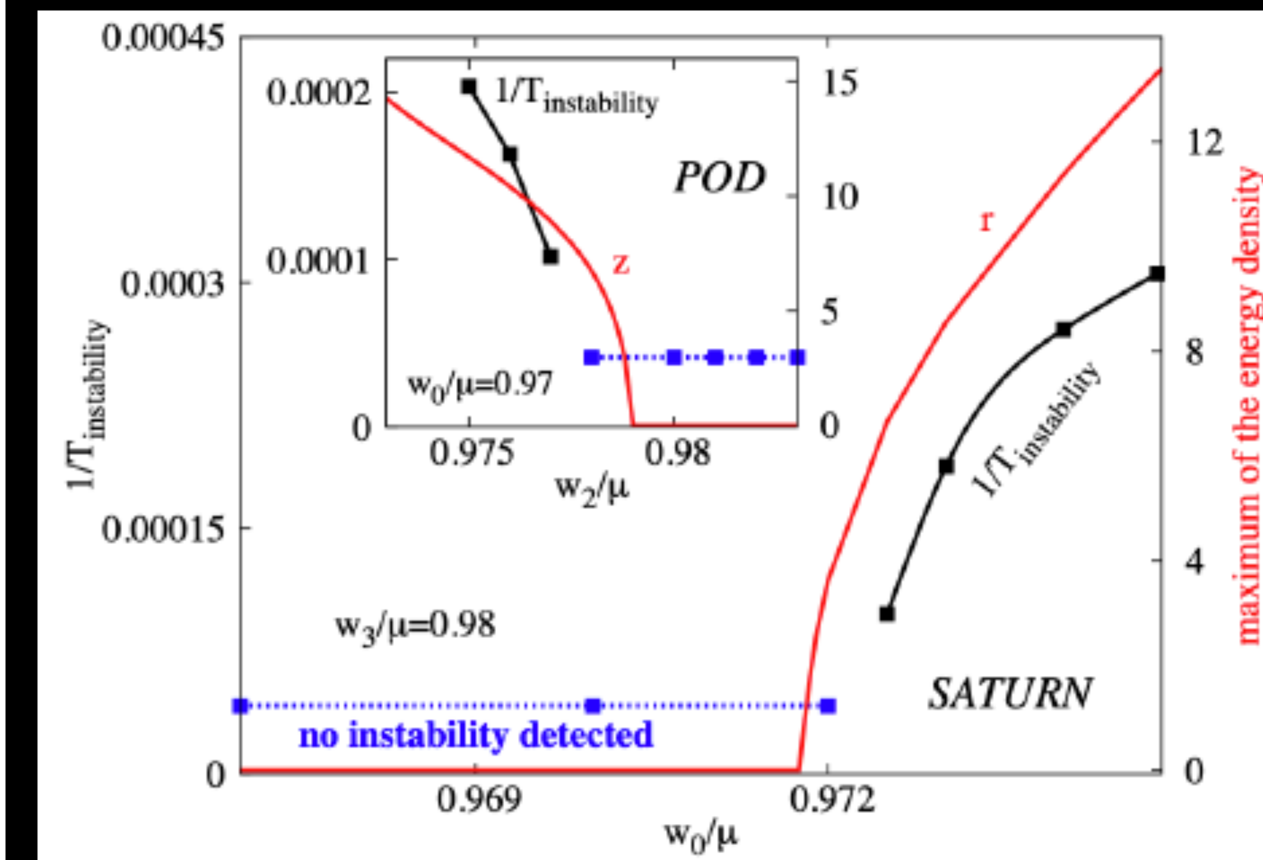


FIG. 6: Late-time snapshots of the radial profile of the module of the scalar field ϕ for models MS10 (top) and MS15 (bottom). The dashed black lines indicate the profiles of the corresponding static models with similar ρ_c and ϕ_c.

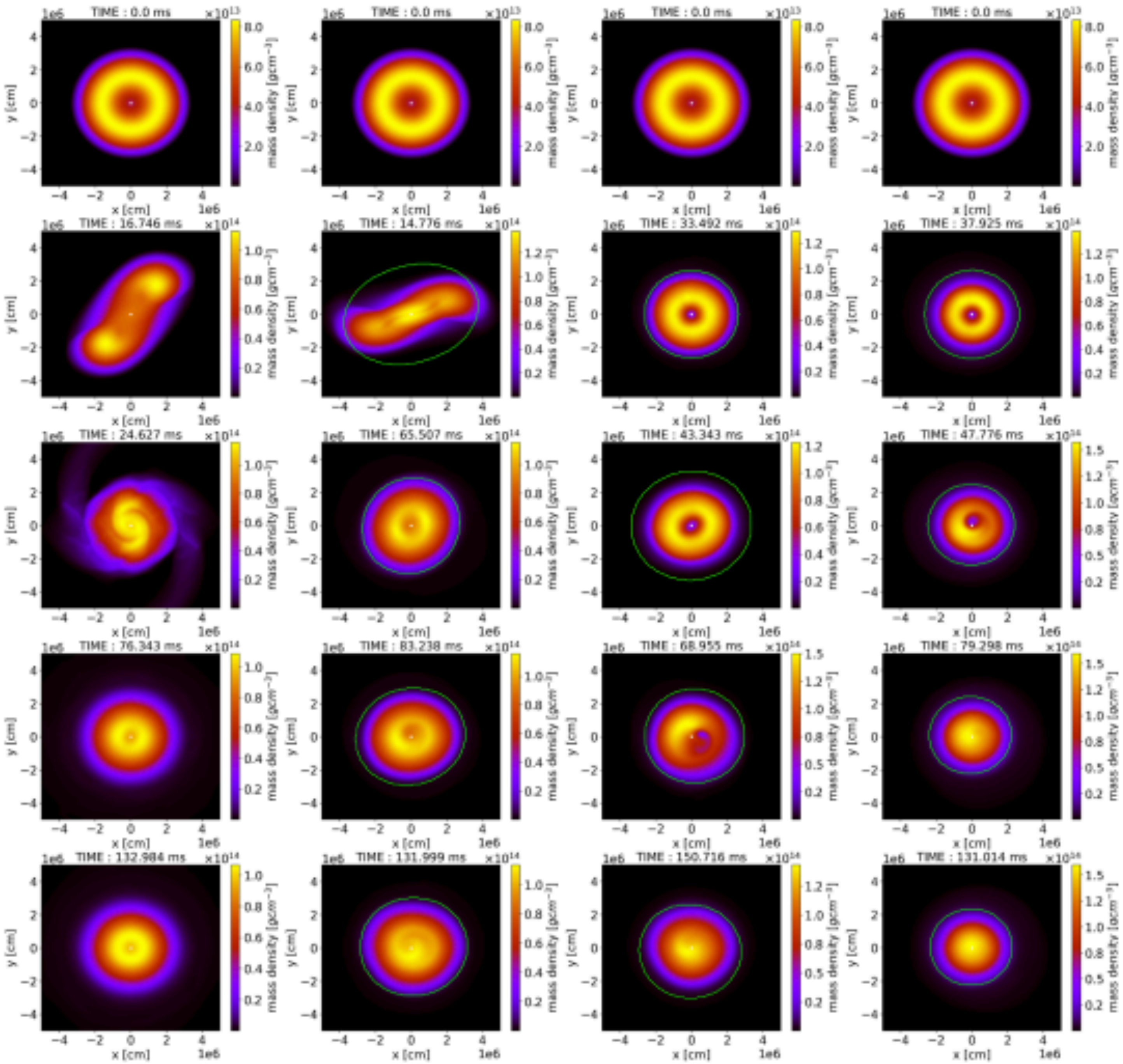
DYNAMICAL BOSONIC STARS AND GRAVITATIONAL WAVES

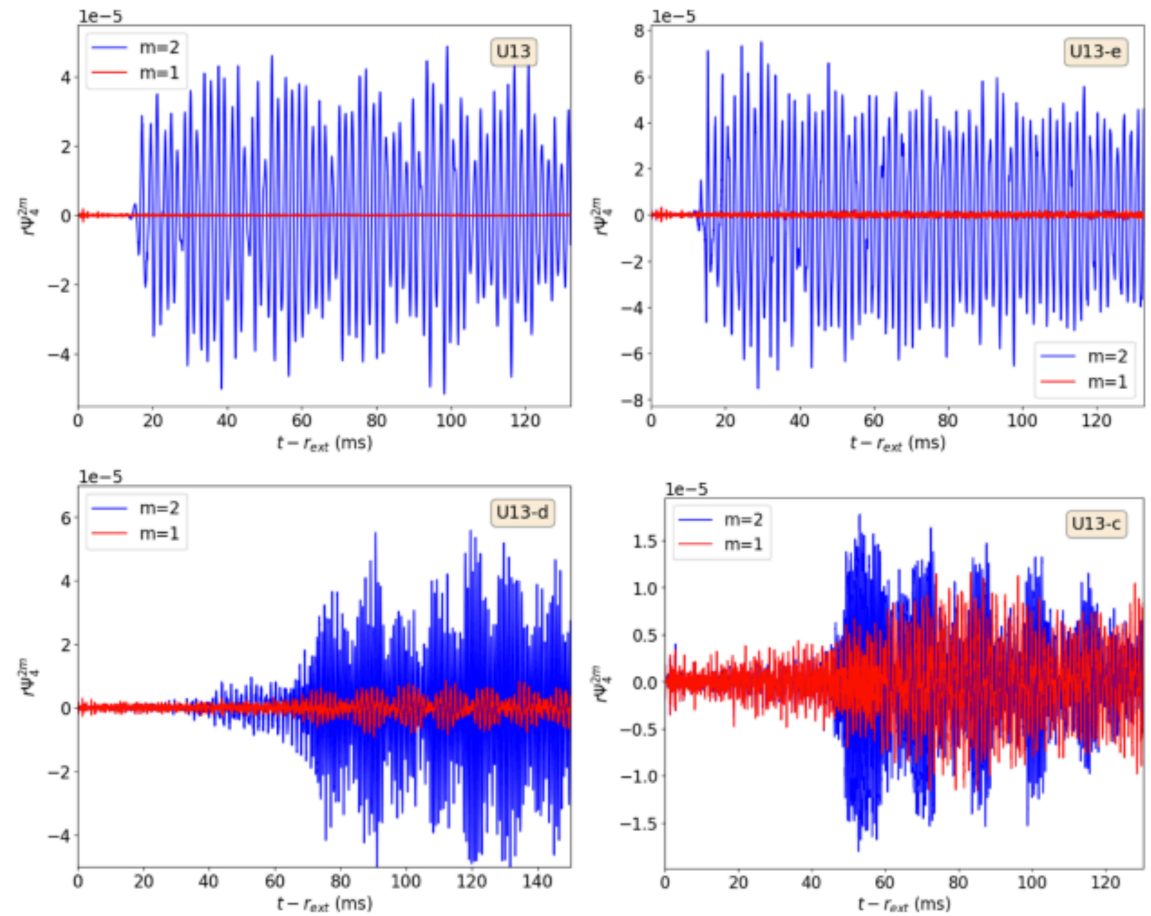




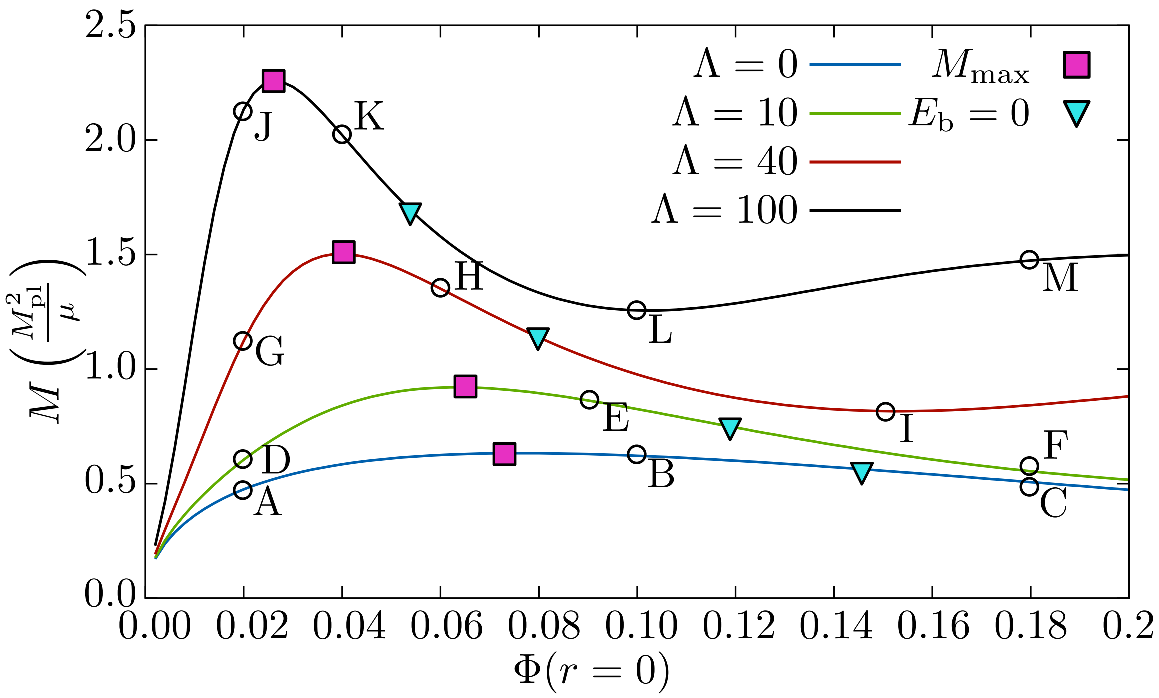
Sanchis-Gual, N., Di Giovanni, F., Herdeiro, C., Radu, E., & Font, J. A. (2021). Multifield, Multifrequency Bosonic Stars and a Stabilization Mechanism. *Physical Review Letters*, *126*(24), 241105.

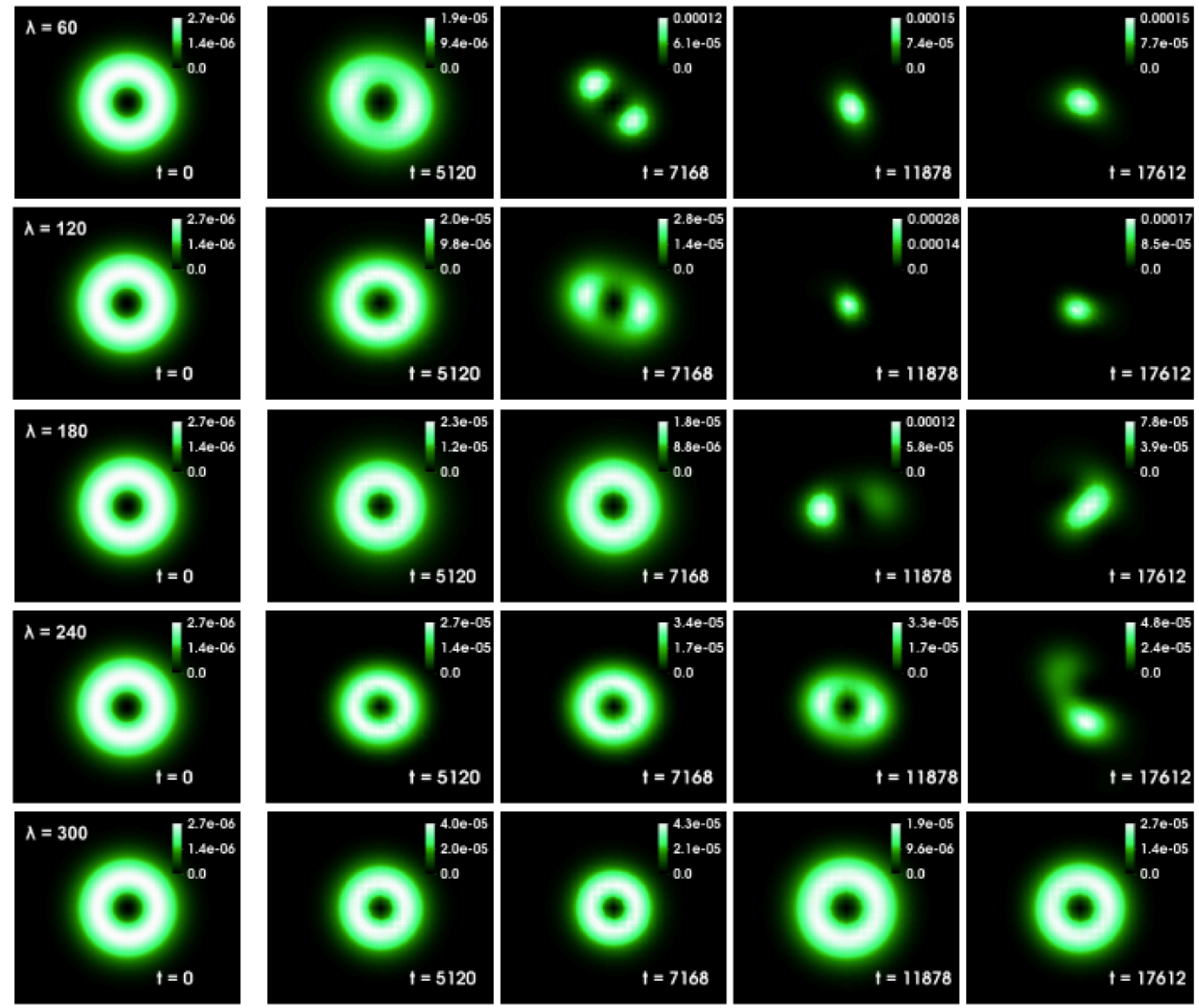
Bosonic dark matter and unstable rapidly rotating neutron star: impact on the instability and gravitational wave emission.





Di Giovanni, F., Sanchis-Gual, N., Guerra, D., Miravet-Tenés, M., Cerdá-Durán, P., & Font, J. A. (2022). Impact of ultralight bosonic dark matter on the dynamical bar-mode instability of rotating neutron stars. *Physical Review D*, *106*(4), 044008.



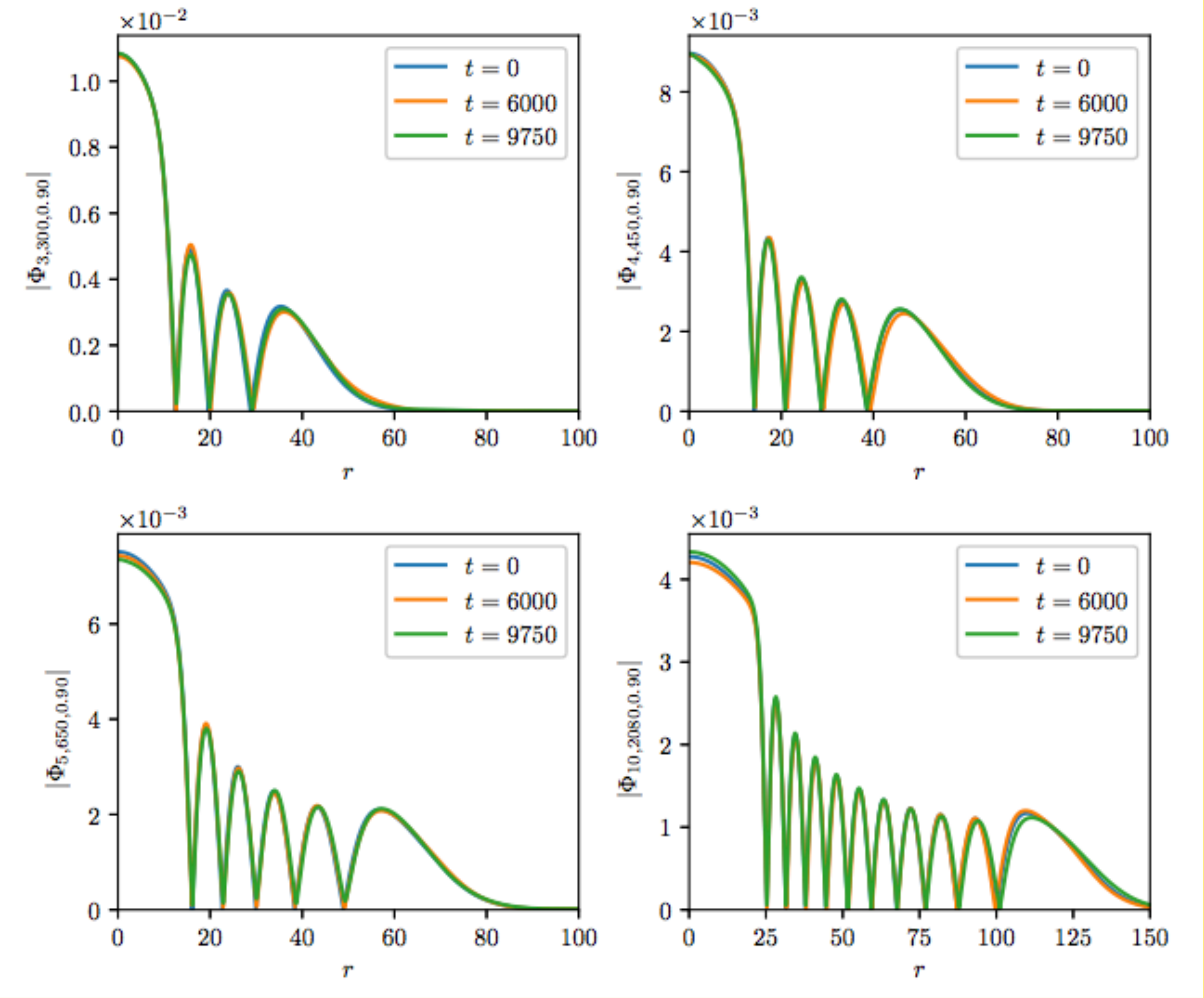


Di Giovanni, F., Sanchis-Gual, N., Cerdá-Durán, P., Zilhão, M., Herdeiro, C., Font, J. A., & Radu, E. (2020). Dynamical bar-mode instability in spinning bosonic stars. *Physical Review D, 102*(12), 124009.

Siemonsen, N., & East, W. E. (2021). Stability of rotating scalar boson stars with nonlinear interactions. *Physical Review D, 103*(4), 044022.

Dmitriev, A. S., Levkov, D. G., Panin, A. G., Pushnaya, E. K., & Tkachev, I. I. (2021). Instability of rotating Bose stars. *arXiv preprint arXiv:2104.00962*.

EXCITED BOSON STARS



Brito, M., Herdeiro, C., Radu, E., Sanchis-Gual, N., & Zilhão, M. (2023). Stability and physical properties of spherical excited scalar boson stars. *Physical Review D*, *107*(8), 084022.

MERGERS OF BOSONIC STARS

Palenzuela, C., Olabarrieta, I., Lehner, L., & Liebling, S. L. (2007). Head-on collisions of boson stars. *Physical Review D*, *75*(6), 064005.
Palenzuela, C., Lehner, L., & Liebling, S. L. (2008). Orbital dynamics of binary boson star systems. *Physical Review D*, *77*(4), 044036.
Bezares, M., Palenzuela, C., & Bona, C. (2017). Final fate of compact boson star mergers. *Physical Review D*, *95*(12), 124005.
Palenzuela, C., Pani, P., Bezares, M., Cardoso, V., Lehner, L., & Liebling, S. (2017). Gravitational wave signatures of highly compact boson star binaries. *Physical Review D, 96*(10), 104058.
Bezares, M., & Palenzuela, C. (2018). Gravitational waves from dark boson star binary mergers. *Classical and Quantum Gravity*, *35*(23), 234002.
Evstafyeva, T., Sperhake, U., Helfer, T., Croft, R., Radia, M., Ge, B. X., & Lim, E. A. (2023). Unequal-mass boson-star binaries: initial data and merger dynamics. *Classical and Quantum Gravity*, *40*(8), 085009.
Croft, R., Helfer, T., Ge, B. X., Radia, M., Evstafyeva, T., Lim, E. A., ... & Clough, K. (2022). The Gravitational Afterglow of Boson Stars. *Classical and Quantum Gravity*.
Siemonsen, N., & East, W. E. (2023). Binary boson stars: Merger dynamics and formation of rotating remnant stars. *Physical Review D*, *107*(12), 124018.

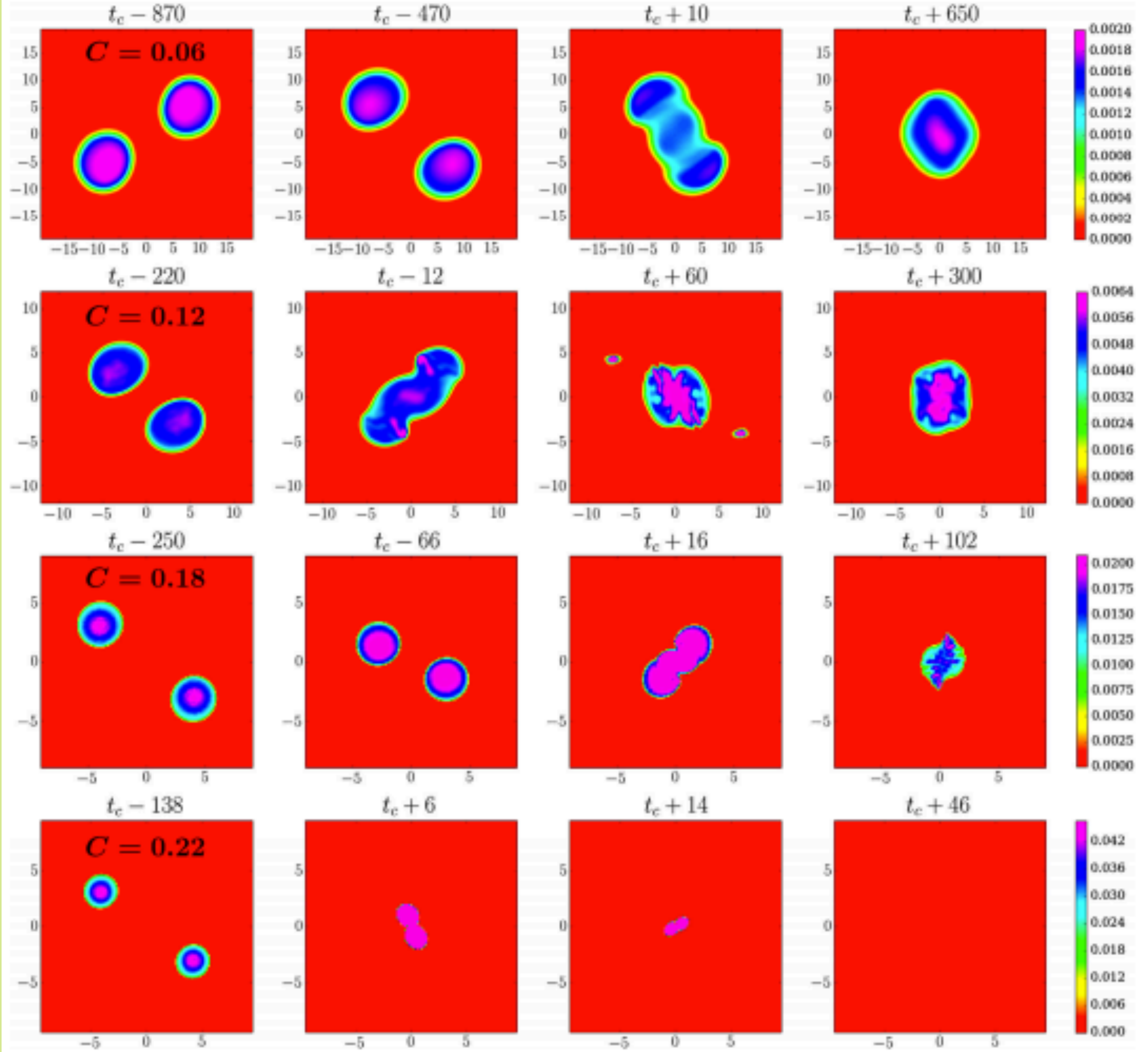
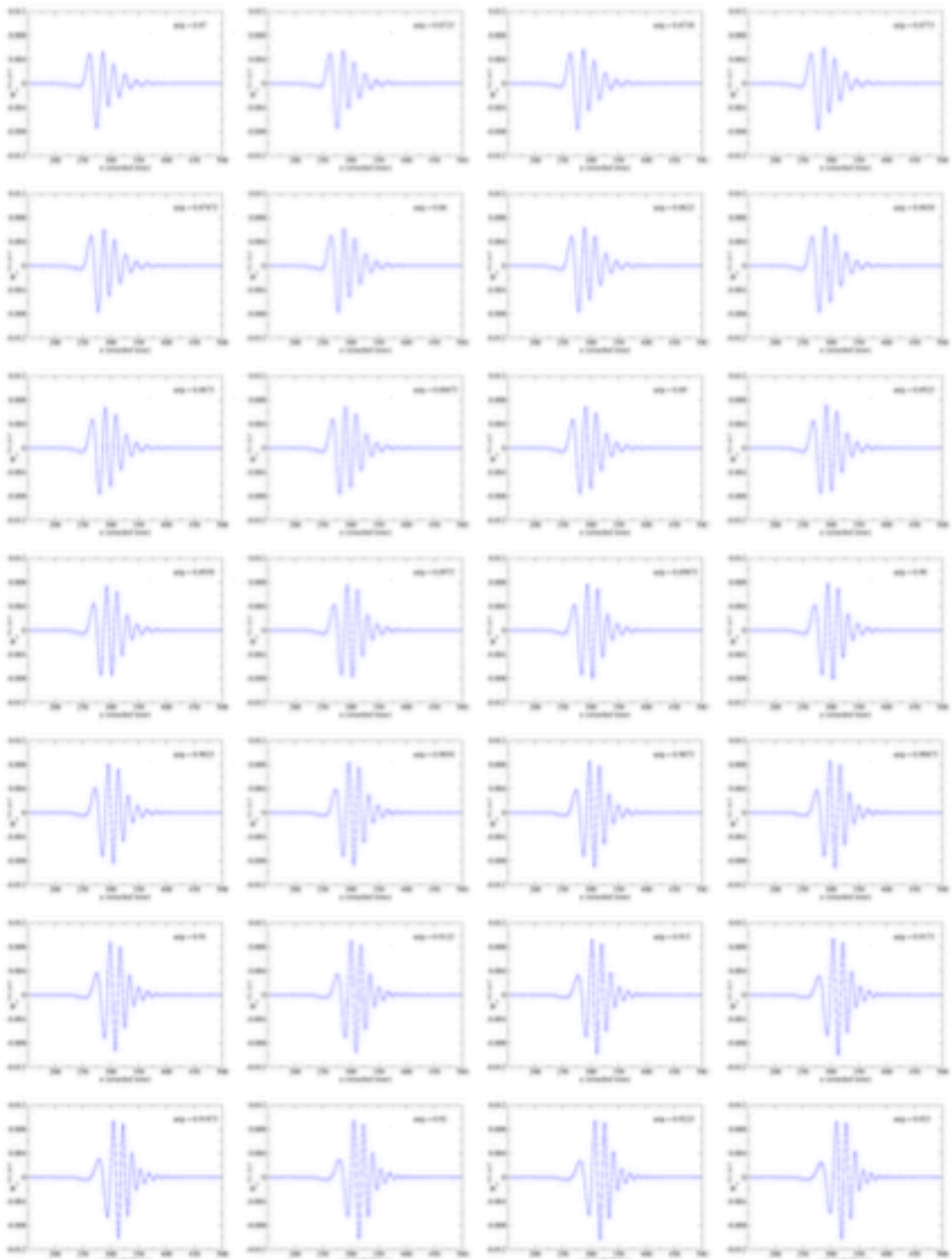
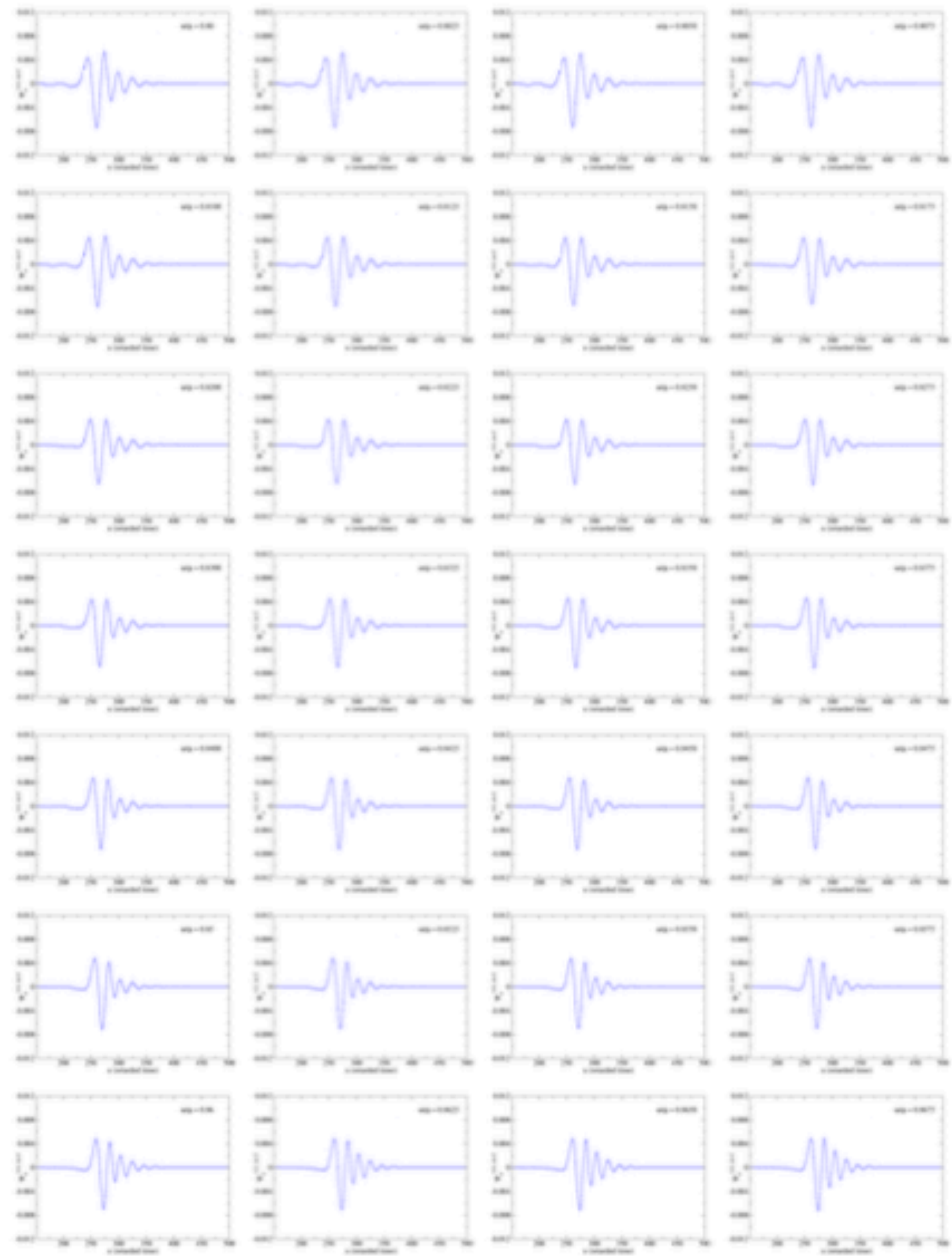


FIG. 2. Coalescence of binary BSs: Snapshots in time of the Noether charge density in the orbital plane. Each row corresponds to a different compactness (from top to bottom: 0.06, 0.12, 0.18, and 0.22). The collision of the stars happens at different times due to the different initial conditions and compactness of each case. Note the emission of two scalar blobs in the third panel of the $C = 0.12$ case.

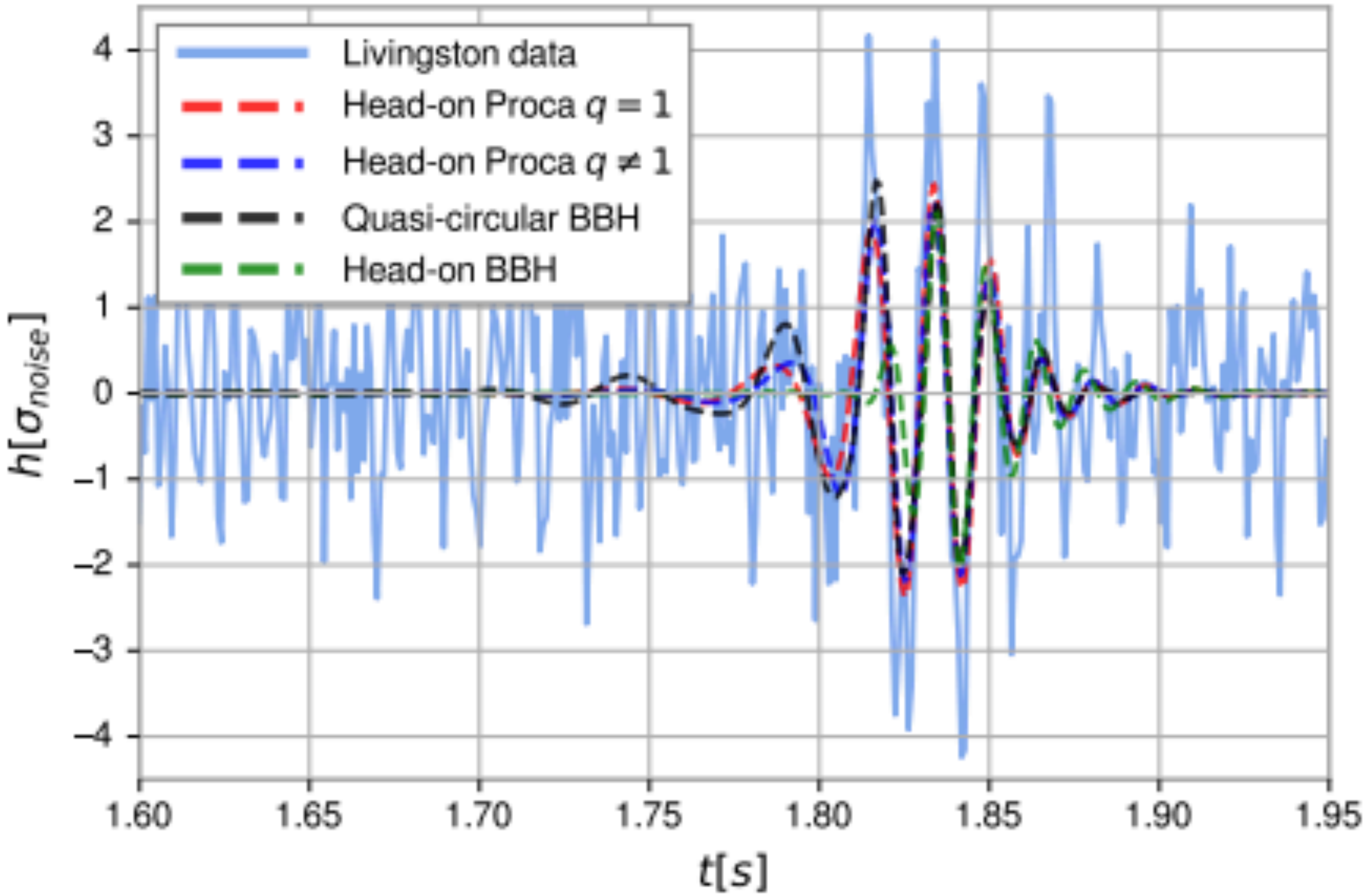
Palenzuela, C., Pani, P., Bezares, M., Cardoso, V., Lehner, L., & Liebling, S. (2017). Gravitational wave signatures of highly compact boson star binaries. *Physical Review D*, *96*(10), 104058.





Bustillo, J. C., Sanchis-Gual, N., Torres-Forné, A., Font, J. A., Vajpeyi, A., Smith, R., Herdeiro, C., Radu, E., & Leong, S. H. (2021). *GW190521 as a Merger of Proca Stars: A Potential New Vector Boson of 8.7× 10− 13 eV.* Physical Review Letters, 126(8), 081101.

Bustillo, J. C., Sanchis-Gual, N., Leong, S. H., Chandra, K., Torres-Forne, A., Font, J. A., ... & Li, T. G. (2022). Searching for vector boson-star mergers within LIGO-Virgo intermediate-mass black-hole merger candidates. *arXiv preprint arXiv:2206.02551*.



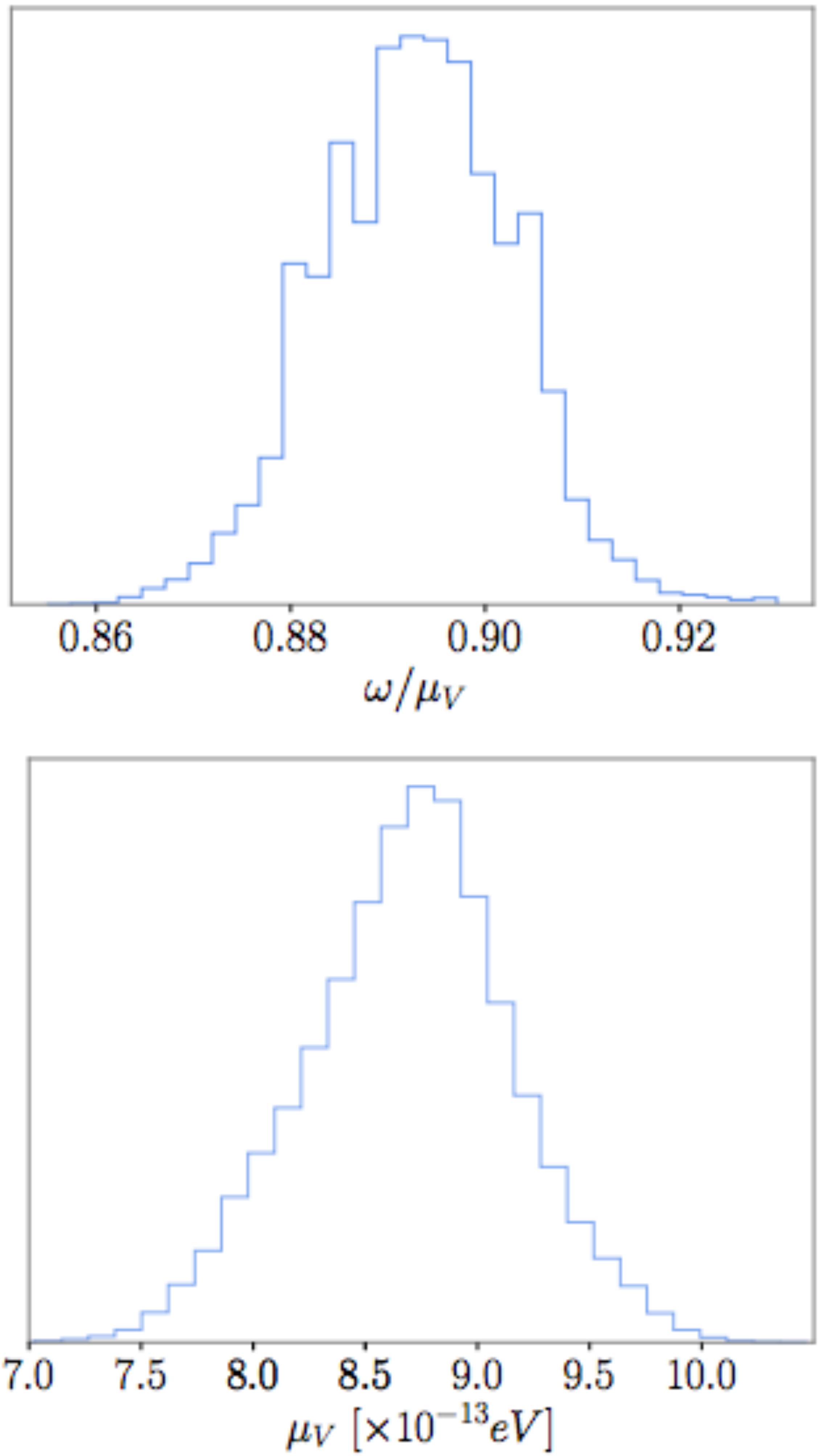
Proca stars?

Waveform model	$\log \mathcal{B}$	$\log \mathcal{L}_{Max}$
Quasi-circular Binary Black Hole	80.1	105.2
Head-on Equal-mass Proca Stars	80.9	106.7
Head-on Unequal-mass Proca Stars	82.0	106.5
Head-on Binary Black Hole	75.9	103.2

TABLE I. **Bayesian evidence for our GW190521 source models.** We report the natural Log Bayes Factor obtained for our different waveform models and corresponding maximum values of the Log Likelihood. We note that parameter estimation codes *are not* designed to find the true maximum of the likelihood, so that the values we report should be considered as approximate.

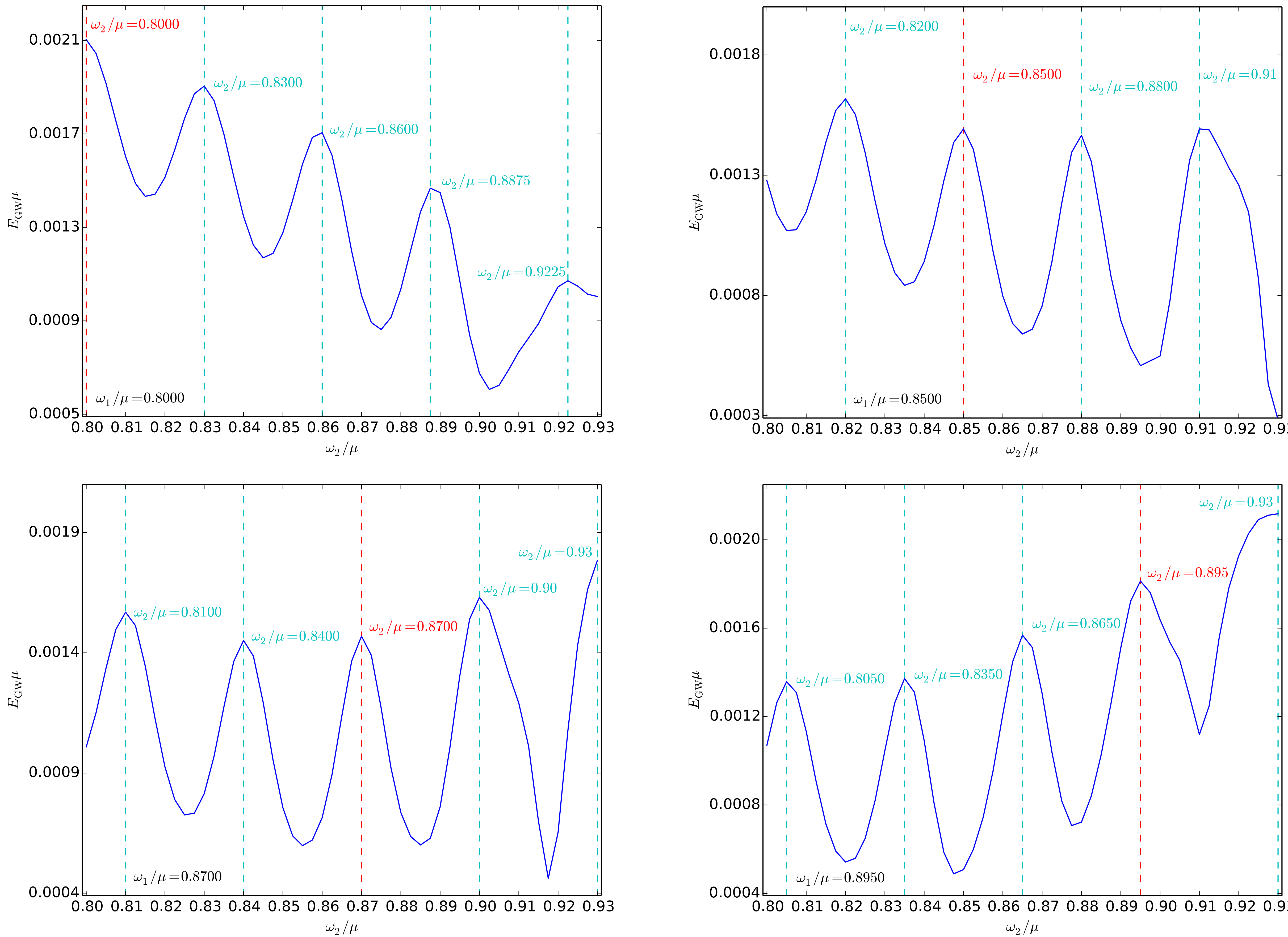
Parameter	$q = 1$ model	$q \neq 1$ model
Primary mass	$115^{+7}_{-8}\ M_\odot$	$115^{+7}_{-8}\ M_\odot$
Secondary mass	$115^{+7}_{-8}\ M_\odot$	$111^{+7}_{-15}\ M_\odot$
Total / Final mass	$231^{+13}_{-17}\ M_\odot$	$228^{+17}_{-15}\ M_\odot$
Final spin	$0.75^{+0.08}_{-0.04}\ M_\odot$	$0.75^{+0.08}_{-0.04}$
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	$\log \mathcal{B} \simeq 0.6$	—

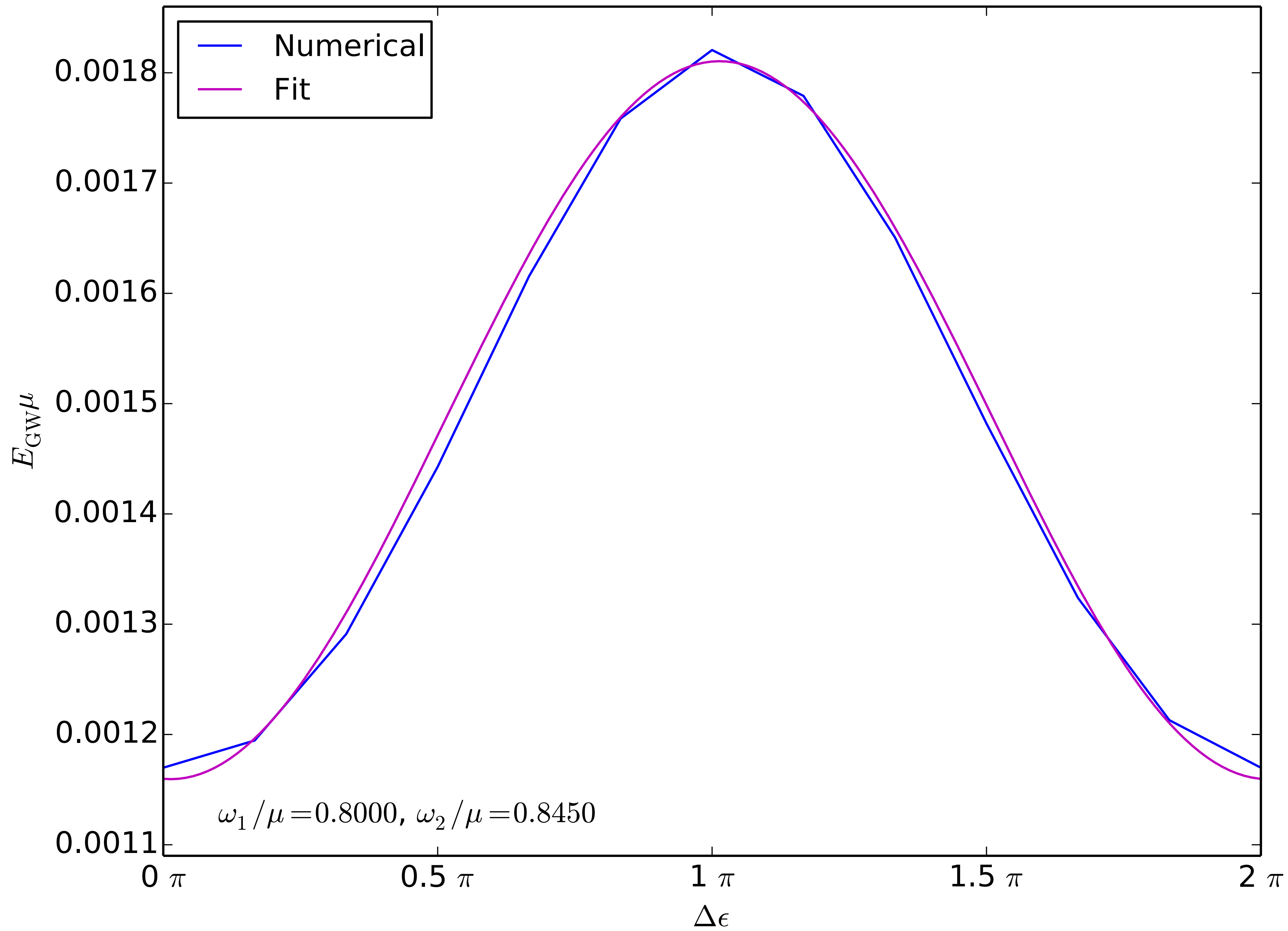
TABLE II. **Parameters of GW190521 assuming a head-on merger of Proca stars.** In the the first column we assume equal masses and spins. In the second column we allow for unequal masses, fixing the primary oscillation frequency to $\omega_1/\mu_V = 0.895$ and varying the second on an uniform grid. We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



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	$\log \mathcal{B} \simeq 0.6$	—

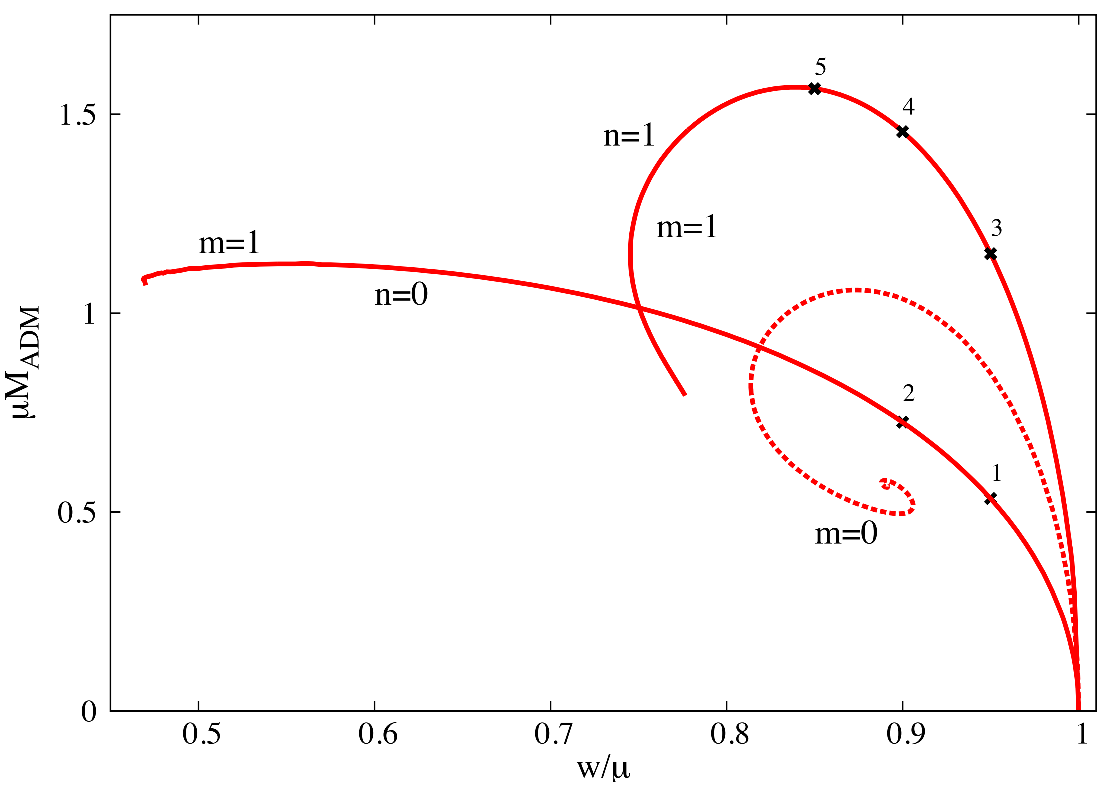
TABLE II. **Parameters of GW190521 assuming a head-on merger of Proca stars.** In the the first column we assume equal masses and spins. In the second column we allow for unequal masses, fixing the primary oscillation frequency to $\omega_1/\mu_V = 0.895$ and varying the second on an uniform grid. We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

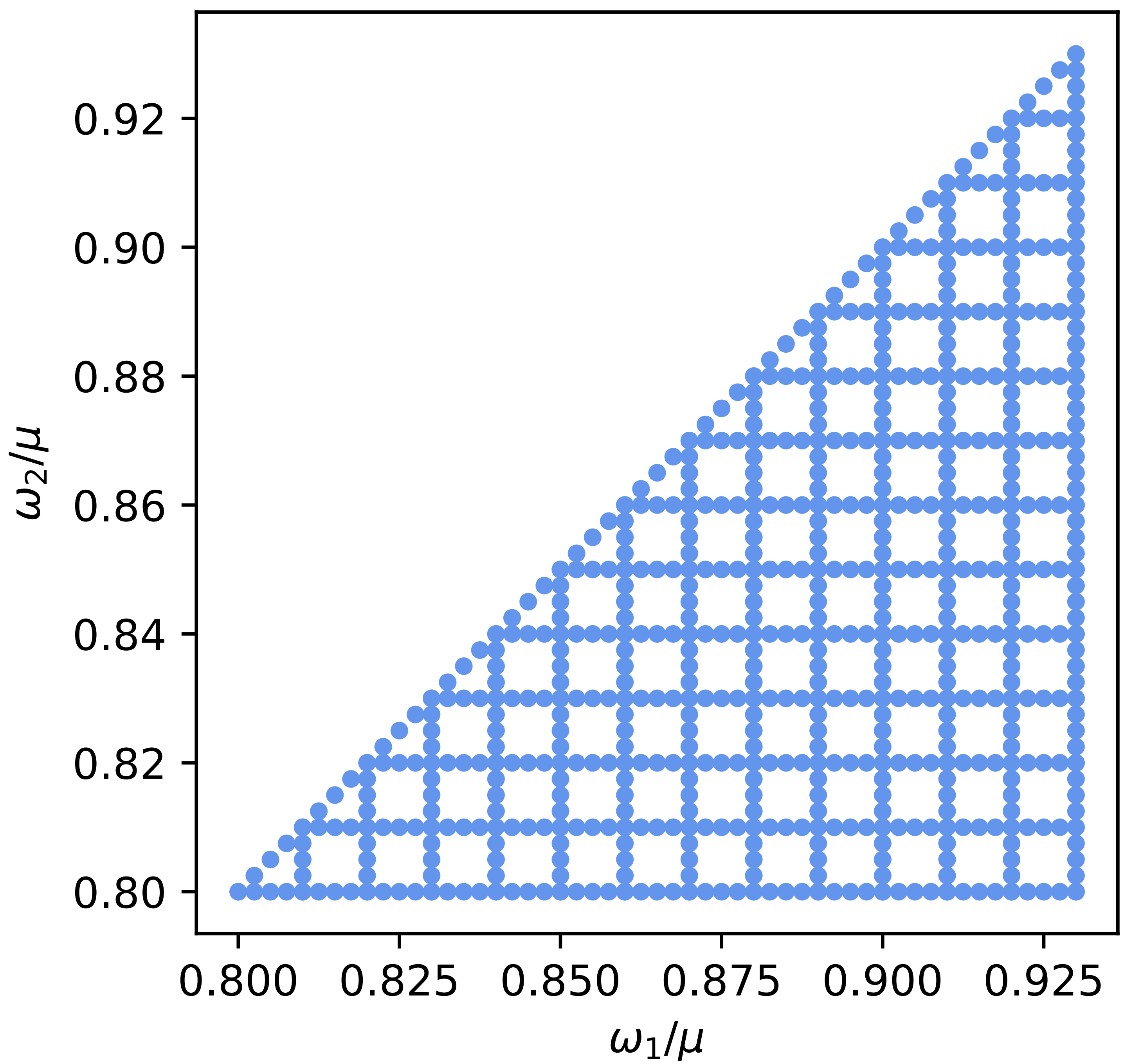

$\omega_2/\mu = 0.8000$
$\omega_2/\mu = 0.8300$
$\omega_2/\mu = 0.8600$
$\omega_2/\mu = 0.8875$
$\omega_2/\mu = 0.9225$
$\omega_1/\mu = 0.8000$
$E_{\rm GW}\mu$
ω_2/μ
$\omega_2/\mu = 0.8200$
$\omega_2/\mu = 0.8500$
$\omega_2/\mu = 0.8800$
$\omega_2/\mu = 0.91$
$\omega_1/\mu = 0.8500$
$\omega_2/\mu = 0.8100$
$\omega_2/\mu = 0.8400$
$\omega_2/\mu = 0.8700$
$\omega_2/\mu = 0.90$
$\omega_2/\mu = 0.93$
$\omega_1/\mu = 0.8700$
$\omega_2/\mu = 0.8050$
$\omega_2/\mu = 0.8350$
$\omega_2/\mu = 0.8650$
$\omega_2/\mu = 0.895$
$\omega_2/\mu = 0.93$
$\omega_1/\mu = 0.8950$



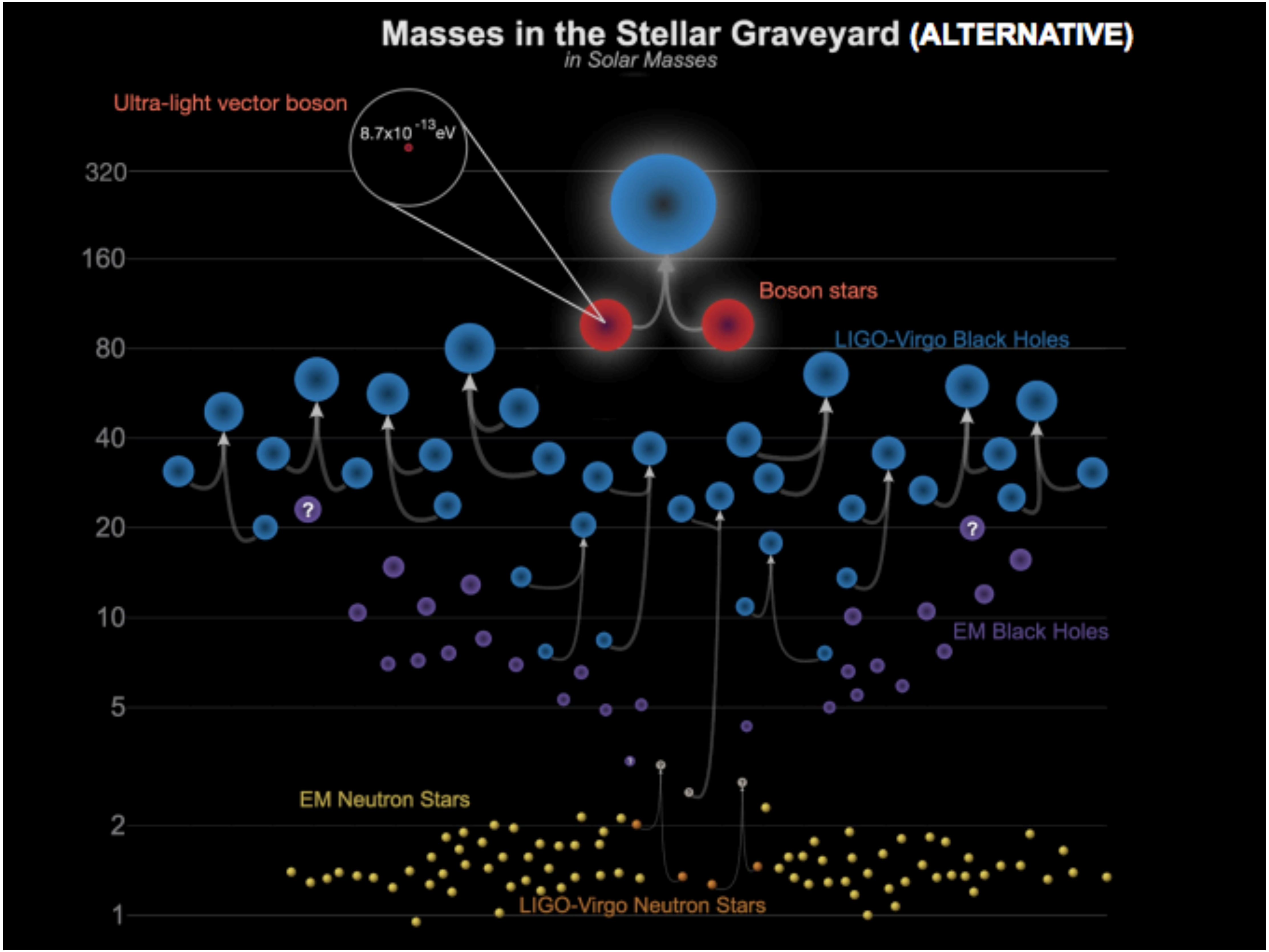
$$\mathcal{A} = \mathcal{A}(t, r, \theta)\, e^{i(\bar{m}\varphi - wt + \epsilon)}$$

$$1 + \cos\big((\omega_1 - \omega_2)t_{\rm col} + \Delta\epsilon\big)_{\rm max} = 2 \rightarrow (\omega_1 - \omega_2)_{\rm max} t_{\rm col} + \Delta\epsilon = 2k\pi$$





Luna, R., Llorens-Monteagudo, M., Lorenzo-Medina, A., Bustillo, J. C., Sanchis-Gual, N., Torres-Forné, A., ... & Radu, E. (2024). Numerical relativity surrogate models for exotic compact objects: the case of head-on mergers of equal-mass Proca stars. *arXiv preprint arXiv:2404.01395*.



Masses in the Stellar Graveyard (ALTERNATIVE)
in Solar Masses
Ultra-light vector boson
8.7x10^{-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

CONCLUSIONS

CONCLUSIONS

- **Dynamical robustness of exotic compact objects.**
- **Gravitational waves from BS binaries could be used to detect ultra-light boson particles (GW190521 and others).**
- **GW190521 has brought us in the realm of what are we really observing.**
- **Low significance trigger S200114**
- **More waveforms are needed. Surrogates.**
- **Is there (ultra-)light in the dark?**

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This work is supported by the Ramón y Cajal programme (grant RYC2022-037424-I), funded by MCIN/AEI/10.13039/501100011033 and by ``ESF Investing in your future”, by the Spanish Agencia Estatal de Investigaci\'on (Grant PID2021-125485NB-C21) funded by MCIN/AEI/10.13039/501100011033 and ERDF A way of making Europe,, and by the European Horizon Europe staff exchange (SE) programme HORIZON-MSCA2021-SE-01 Grant No. NewFunFiCO-101086251.

THANK YOU!
OBRIGADO!