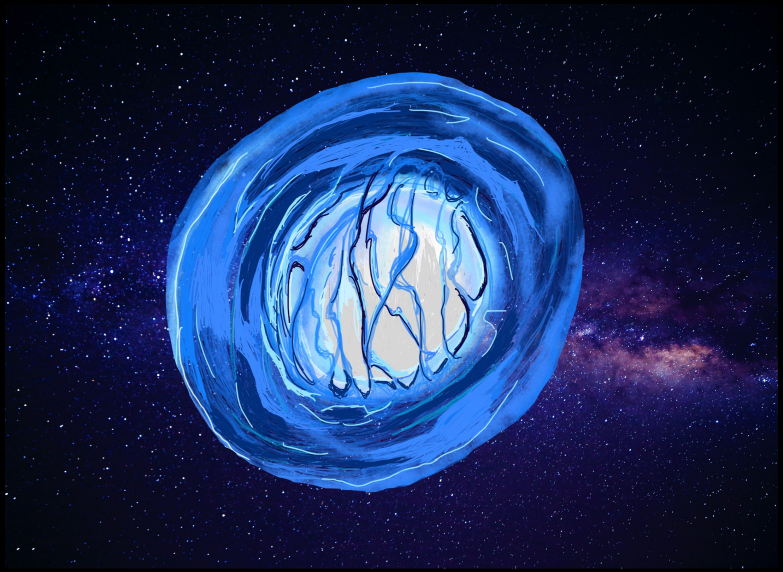


NICOLÁS SANCHIS-GUAL

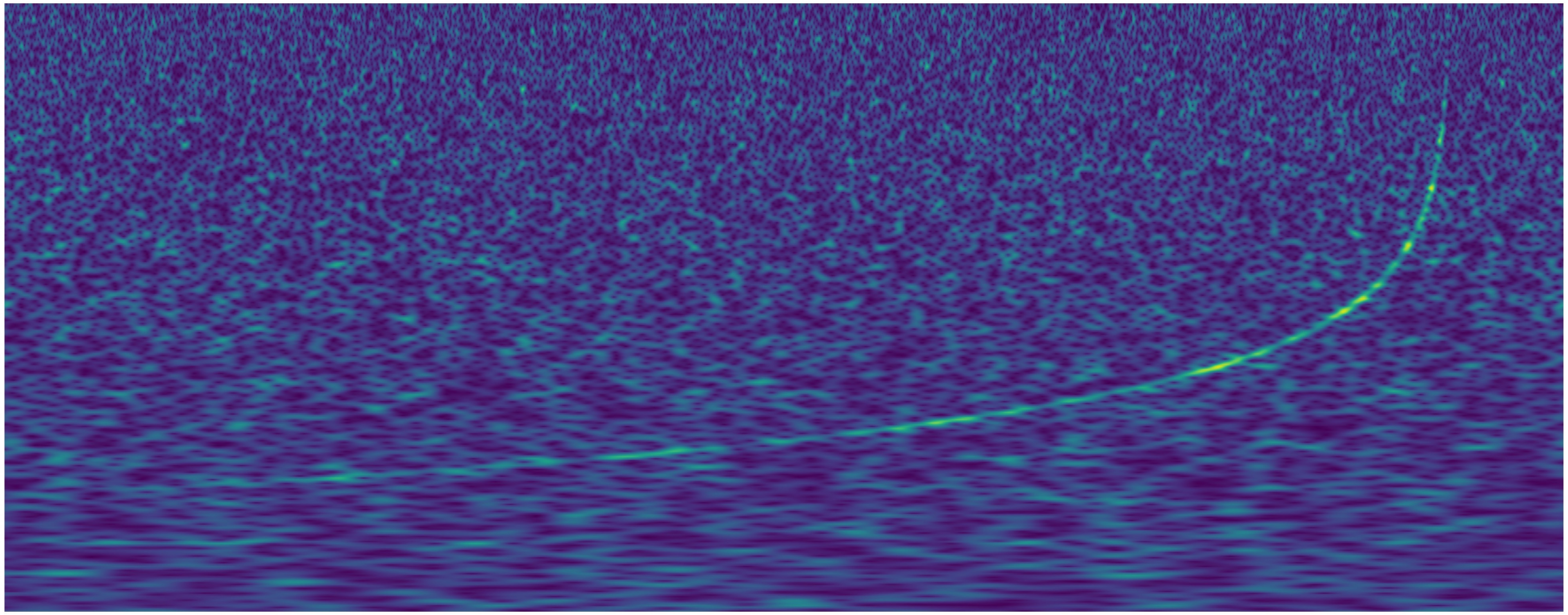
GRAVITATIONAL GEOMETRY AND DYNAMICS GROUP - CIDMA - UNIVERSIDADE DE AVEIRO

SPANISH PORTUGUESE RELATIVITY MEETING-ONLINE-AVEIRO-SEPTEMBER 2021

DYNAMICAL BOSONIC STARS AND GRAVITATIONAL WAVES

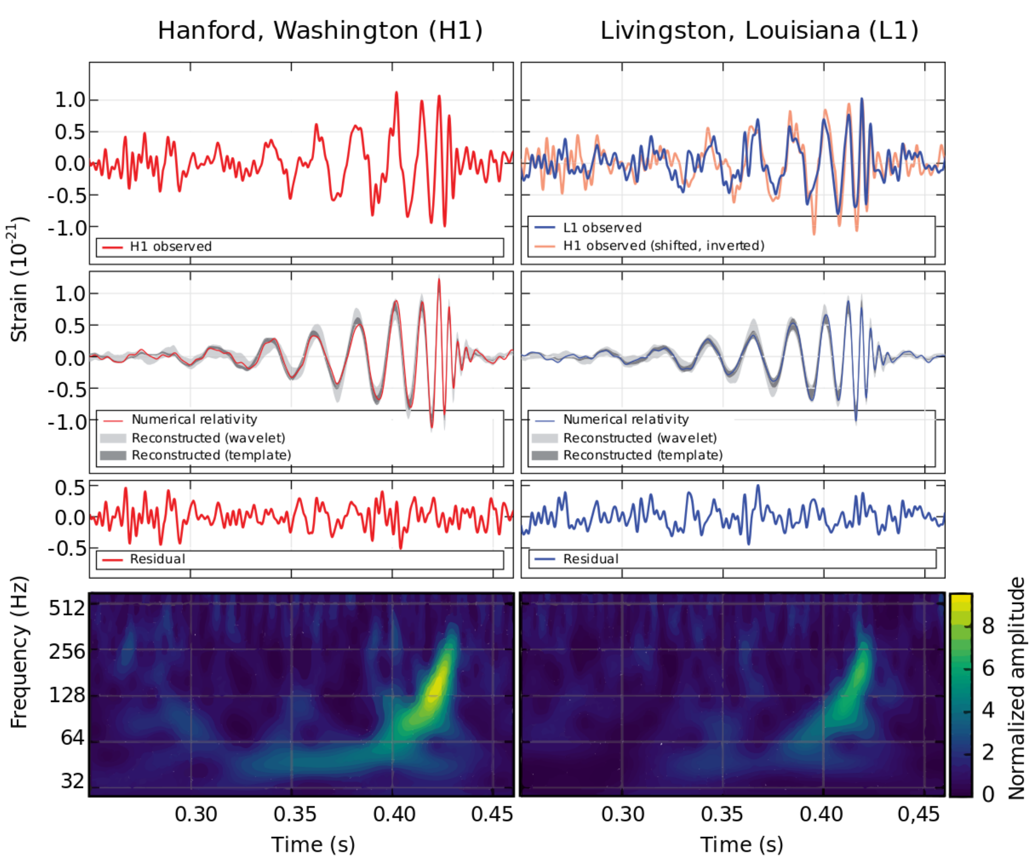
MOTIVATION

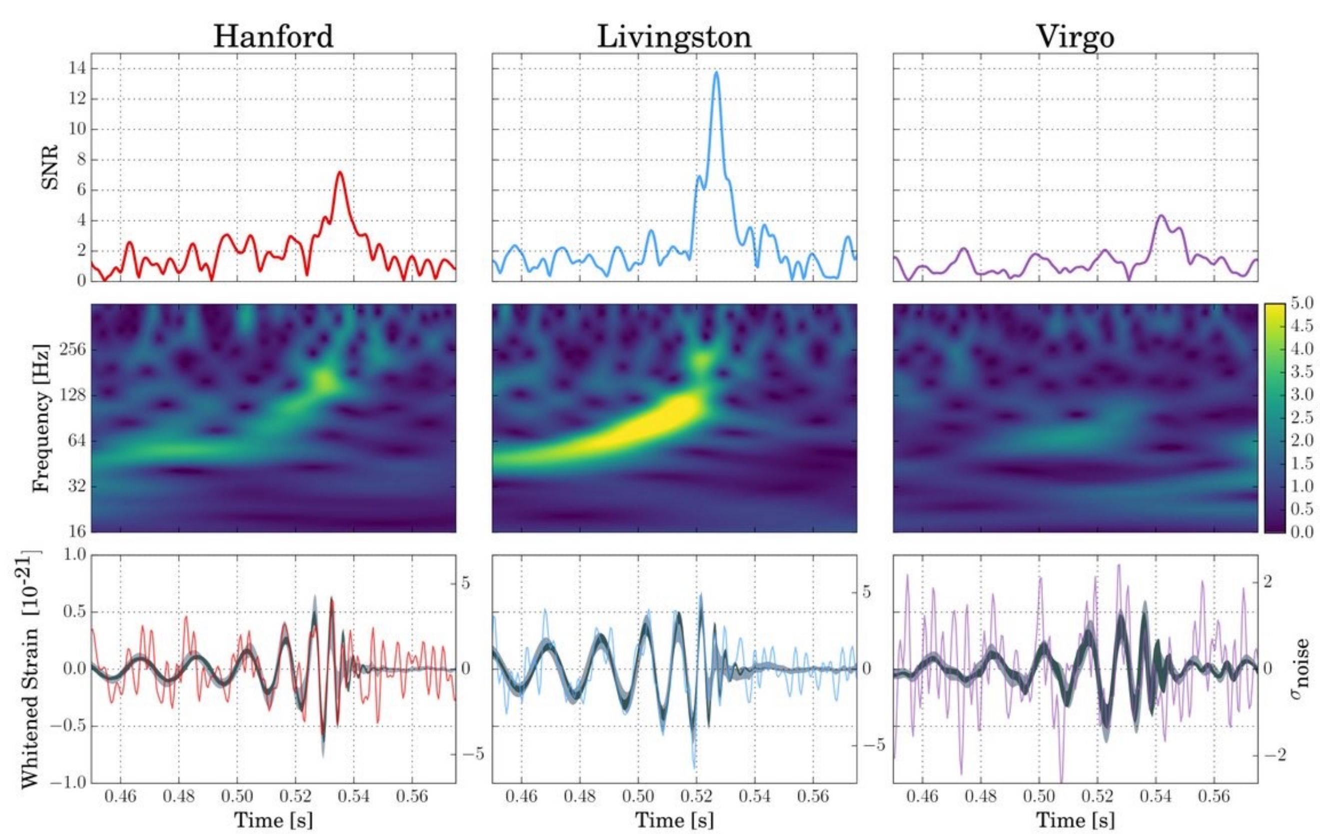
Abbott, B. P., Abbott, R., Abbott, T. D., Acernese, F., Ackley, K., Adams, C., ... & Affeldt, C. (2017). GW170817: observation of gravitational waves from a binary neutron star inspiral. *Physical Review Letters*, *119*(16), 161101.



Abbott, B. P., Abbott, R., Abbott, T. D., Abernathy, M. R., Acernese, F., Ackley, K., ... & Adya, V. B. (2016). Observation of gravitational waves from a binary black hole merger. *Physical review letters*, *116*(6), 061102.

Abbott, B. P., Abbott, R., Abbott, T. D., Acernese, F., Ackley, K., Adams, C., ... & Affeldt, C. (2017). GW170814: a three-detector observation of gravitational waves from a binary black hole coalescence. *Physical review letters*, *119*(14), 141101.





WHAT ARE 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.
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: **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**:

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

WHAT ARE BOSON STARS?

- **Fermions** cannot occupy the same energy level: **Pauli exclusion principle**.
- White dwarfs and neutron stars: supported against gravity by the **Fermi degeneracy pressure**.
- Boson stars**?**

WHAT ARE BOSON STARS?

- **Heisenberg uncertainty principle**: quantum mechanical principle to support boson stars.
- In a macroscopic quantum state:

$$\Delta x \Delta p \geq \hbar$$

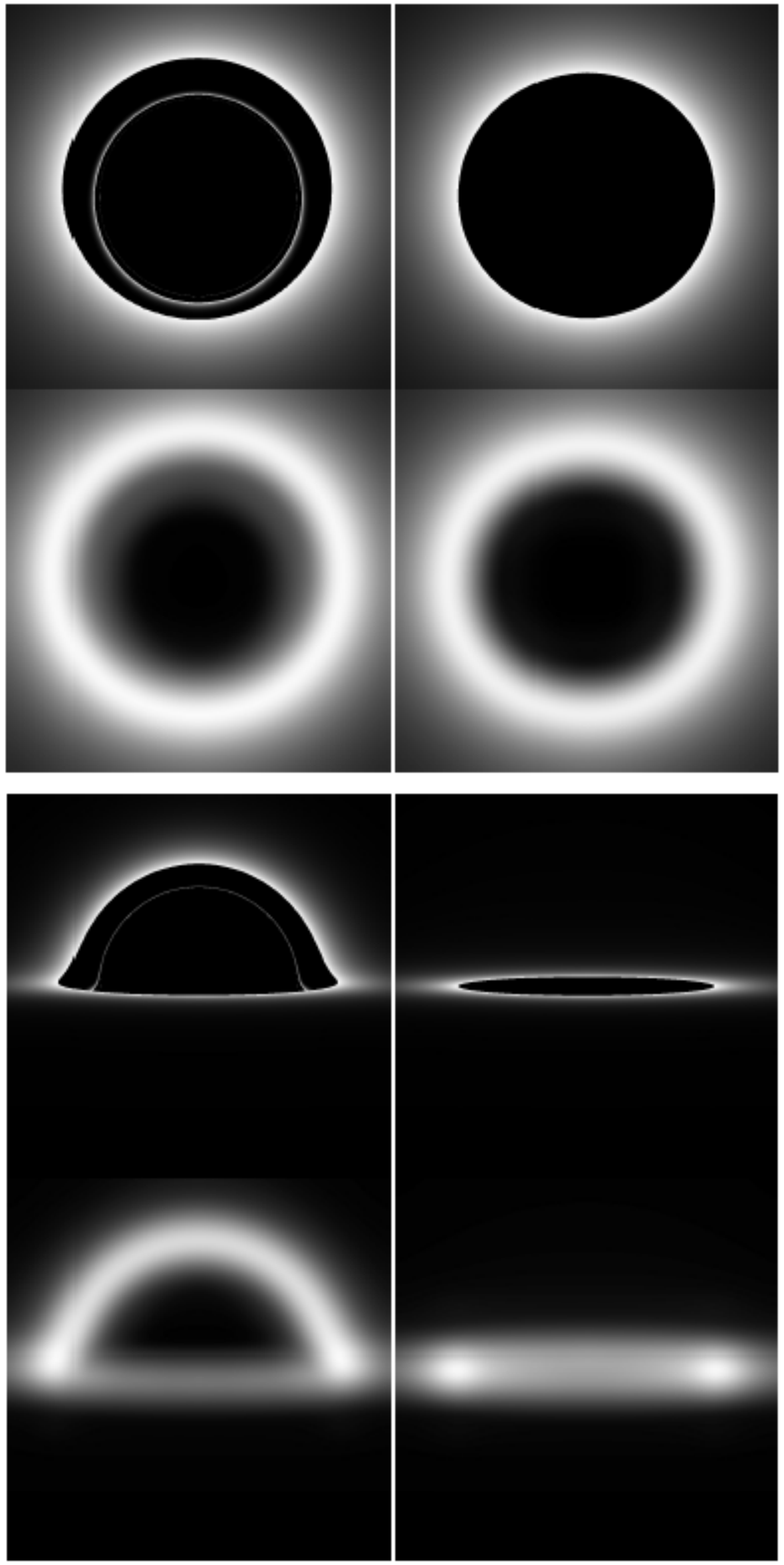
- **Maximum mass** estimate:

$$M_{\mathrm{max}} = \frac{1}{2}\frac{\hbar c}{G\mu} = 0.5\, M_{\mathrm{Planck}}^2/\mu$$

- **Correct maximum mass**:

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

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



Herdeiro, C. A., Pombo, A. M., Radu, E., Cunha, P. V., & Sanchis-Gual, N. (2021). The imitation game: Proca stars that can mimic the Schwarzschild shadow. *Journal of Cosmology and Astroparticle Physics*, *2021*(04), 051.

See Alexandre Pombo's talk

MOTIVATION

- **Dark matter** up to 27% of the energy content of the Universe.
- In a **cosmological** context, **scalar fields** have been proposed as constituents of **dark matter halos** in galaxies.
- Compton wavelength: $\lambda = h/(mc)$

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

- Schwarzschild BHs can develop **quasi-bound scalar field configurations** that may be very **long lived**.
- Astrophysical BHs could have **scalar or Proca hair** (Herdeiro & Radu 2014).
- **Axiverse**: from 10^{-33} to 10^{-10} eV this implies masses from 1 to $10^{23}\ M_\odot$

Arvanitaki, A., Dimopoulos, S., Dubovsky, S., Kaloper, N., & March-Russell, J. (2010). String axiverse. *Physical Review D*, *81*(12), 123530.
Freitas, F. F., Herdeiro, C. A., Morais, A. P., Onofre, A., Pasechnik, R., Radu, E., ... & Santos, R. (2021). Ultralight bosons for strong gravity applications from simple Standard Model extensions. *arXiv preprint arXiv:2107.09493*.

See António Morais' talk

ON THE STABILITY OF BOSON AND PROCA STARS

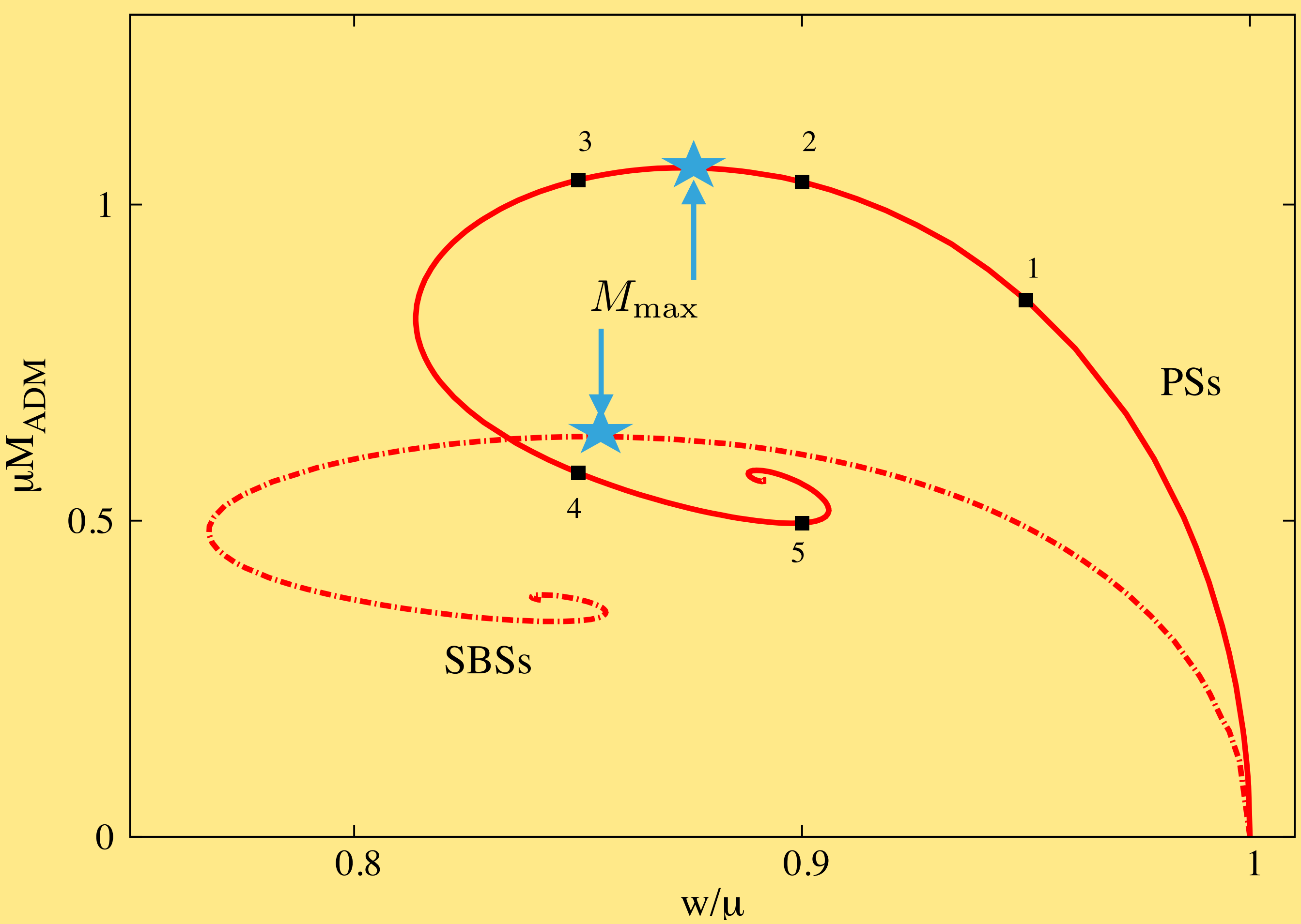
- Cunha, P. V., Font, J. A., Herdeiro, C., Radu, E., **Sanchis-Gual, N.**, & Zilhão, M. (2017). *Lensing and dynamics of ultracompact bosonic stars.* Physical Review D, 96(10), 104040.

- 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.



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

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

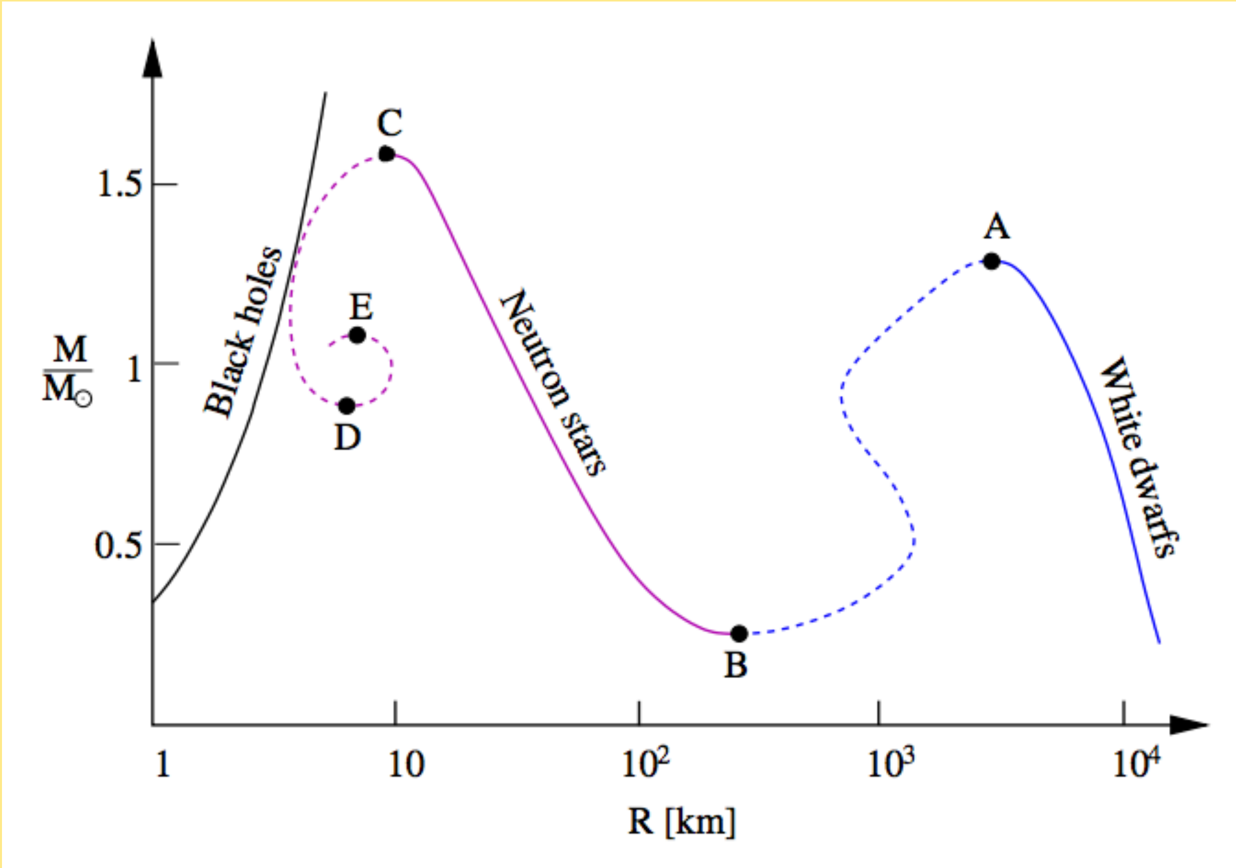
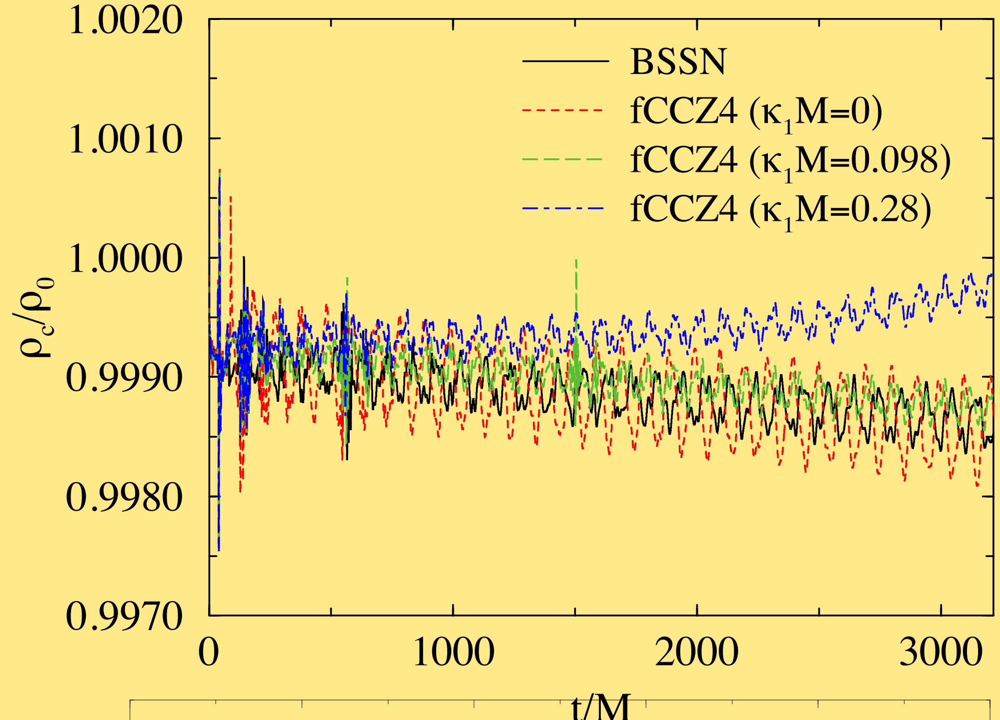
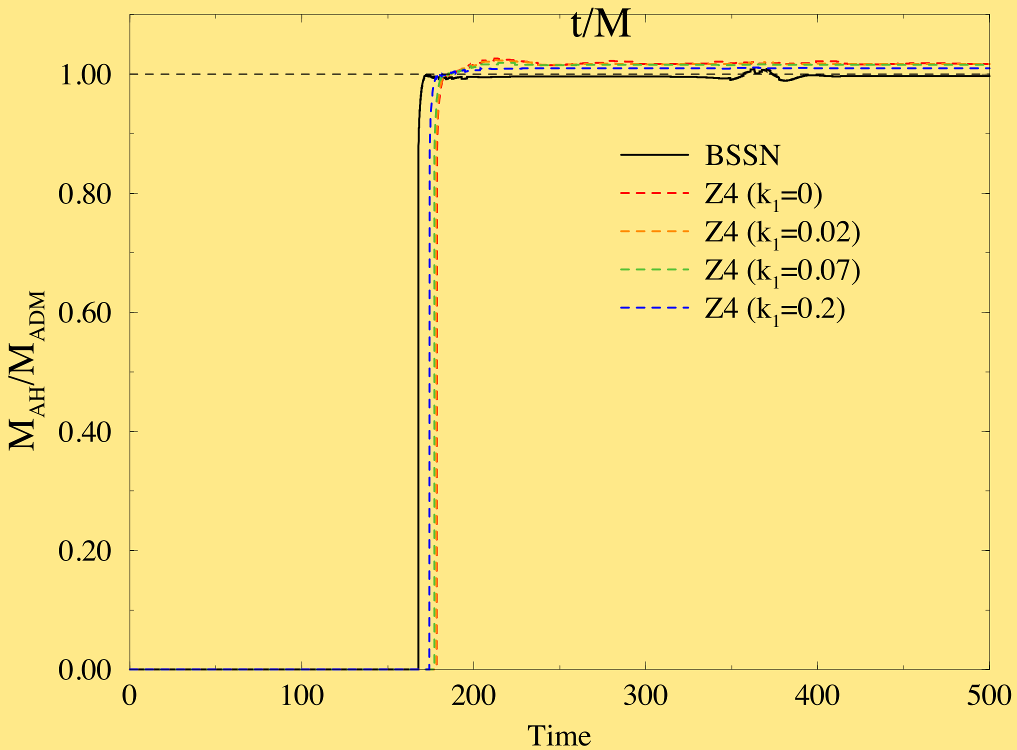


Figure extracted from: Guerra, D., Macedo, C. F., & Pani, P. (2019). Axion boson stars. *Journal of Cosmology and Astroparticle Physics*, *2019*(09), 061.

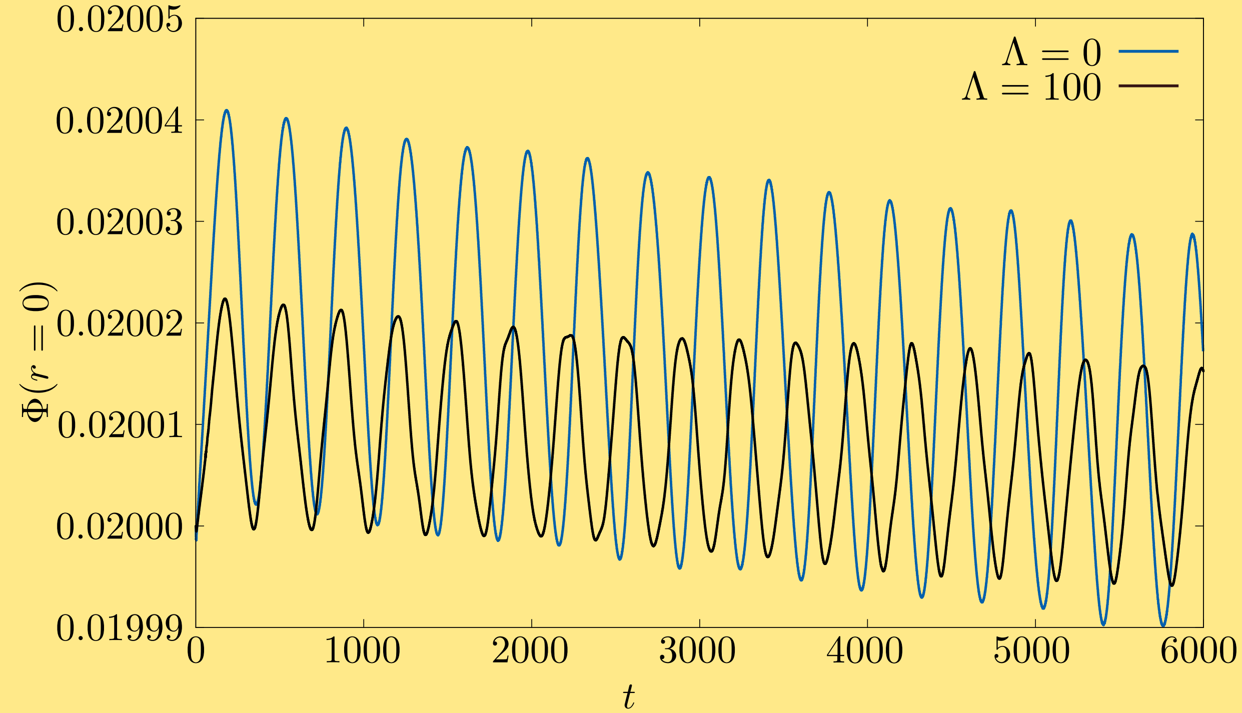
BOSON AND PROCA STARS

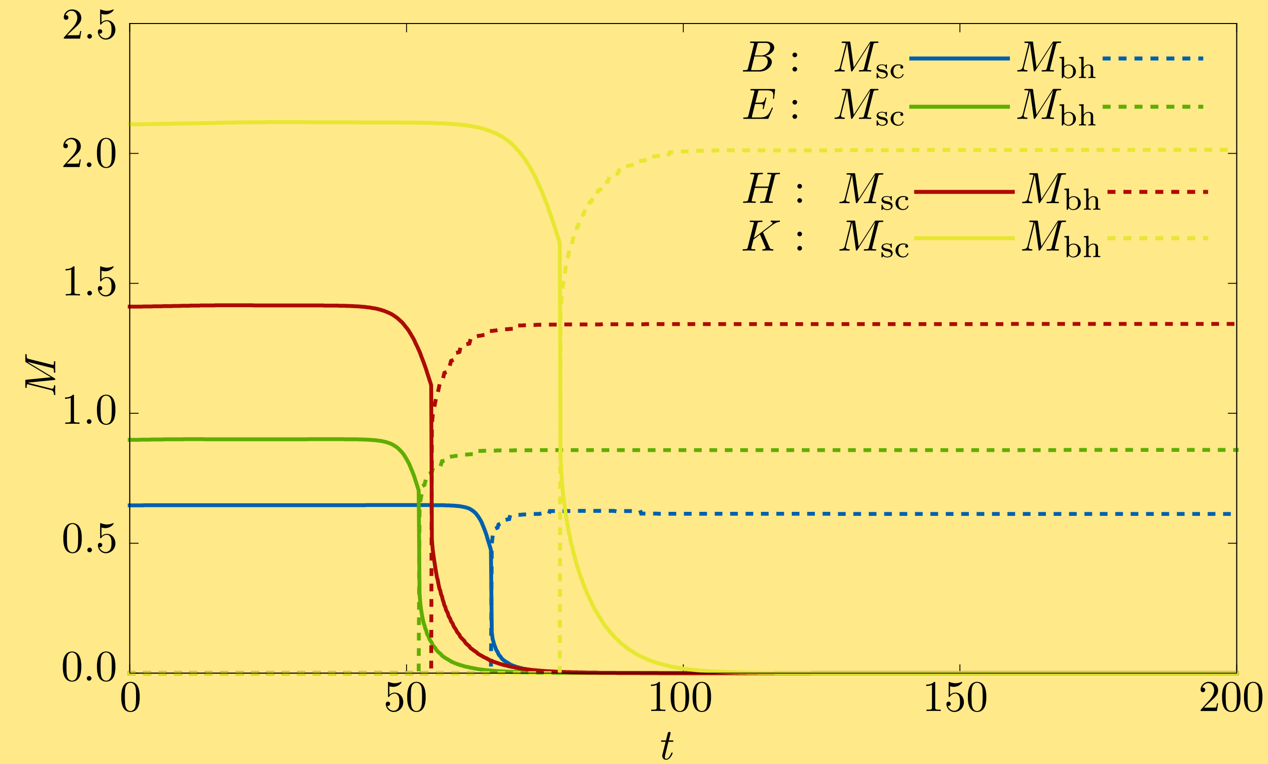
Neutron stars





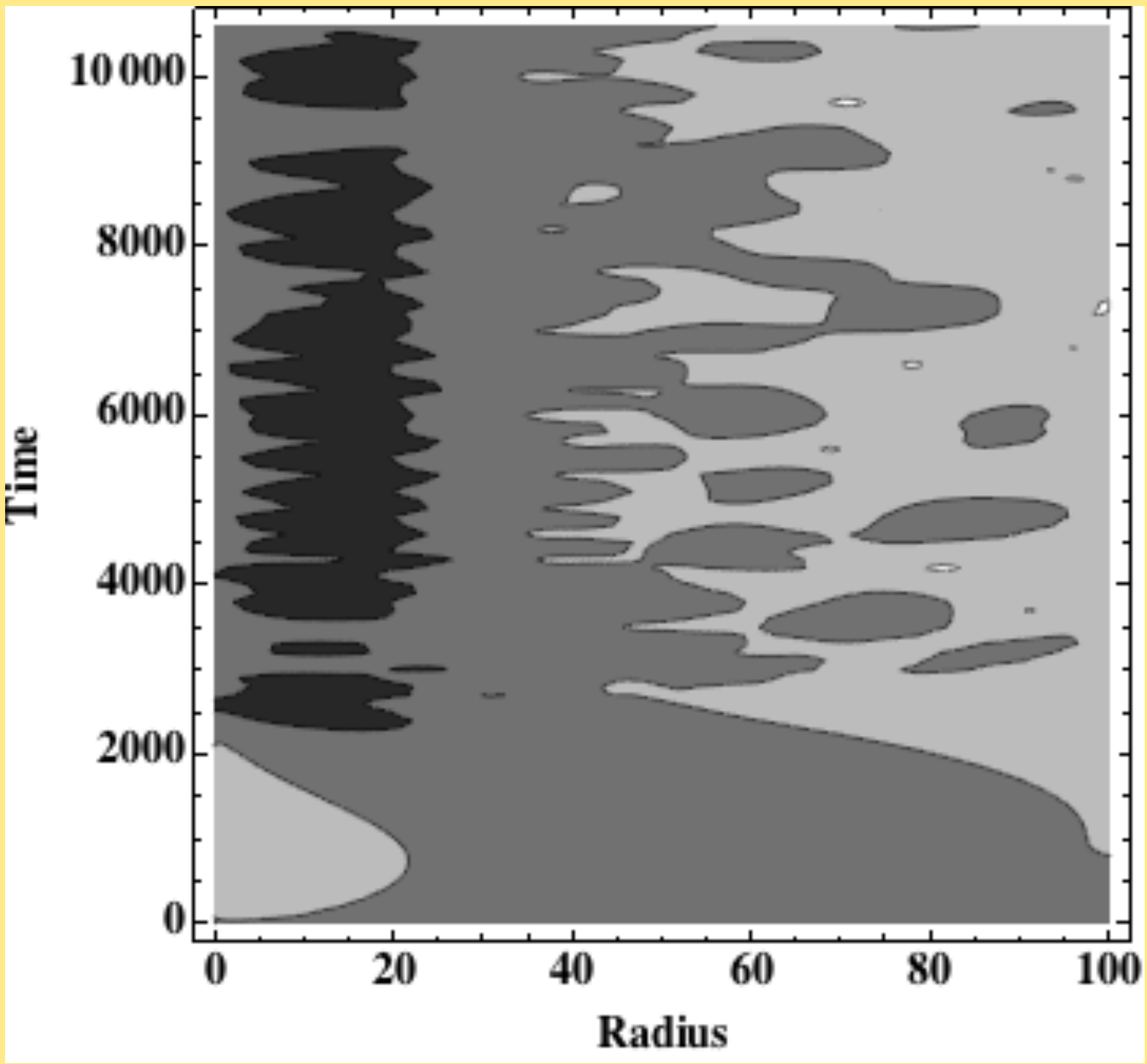
Boson and Proca stars

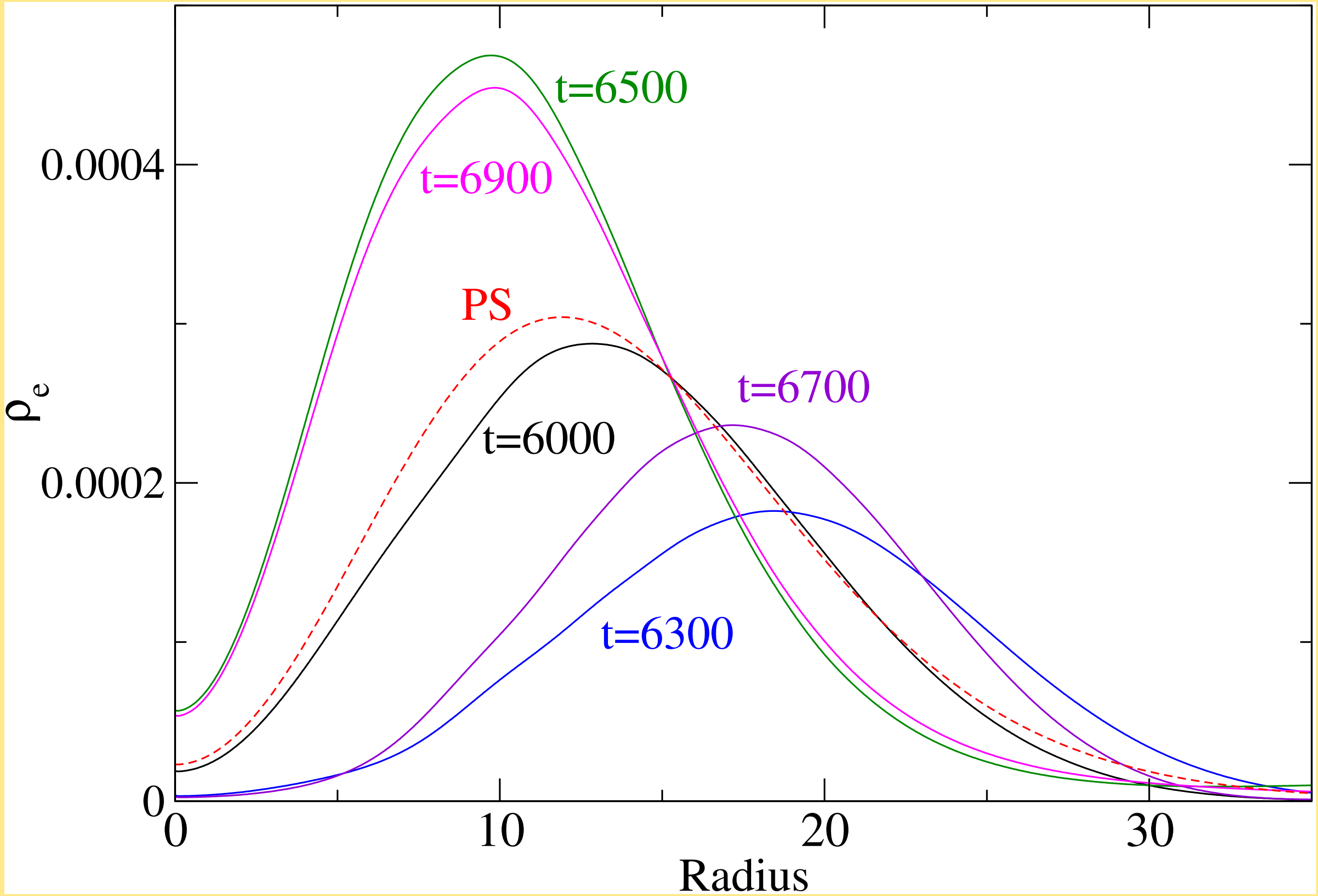




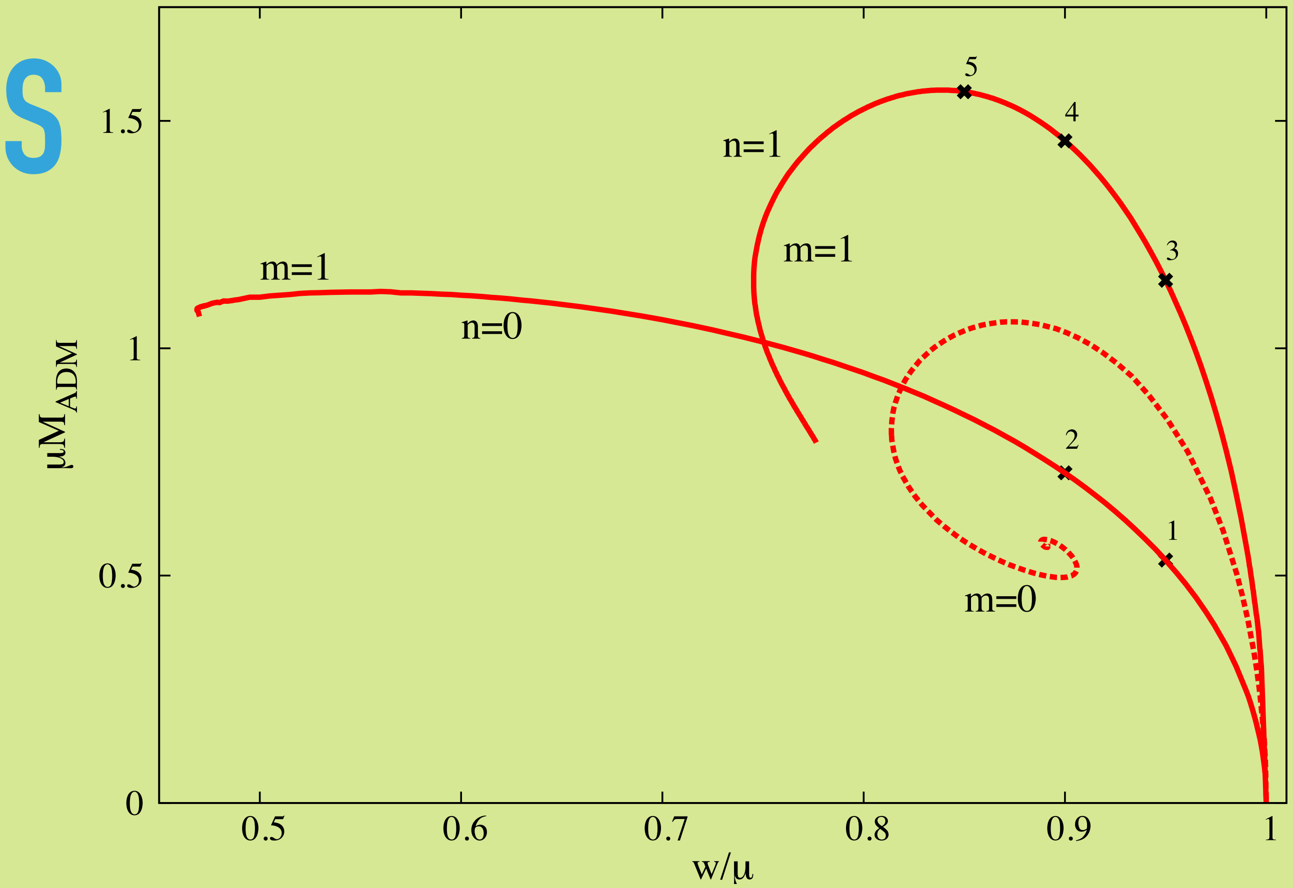
BOSON AND PROCA STARS

Seidel, E., & Suen, W. M. (1994). Formation of solitonic stars through gravitational cooling. *Physical review letters*, *72*(16), 2516.
Dynamical formation of Proca stars (Di Giovanni et al 2018)





SPINNING BOSONIC STARS



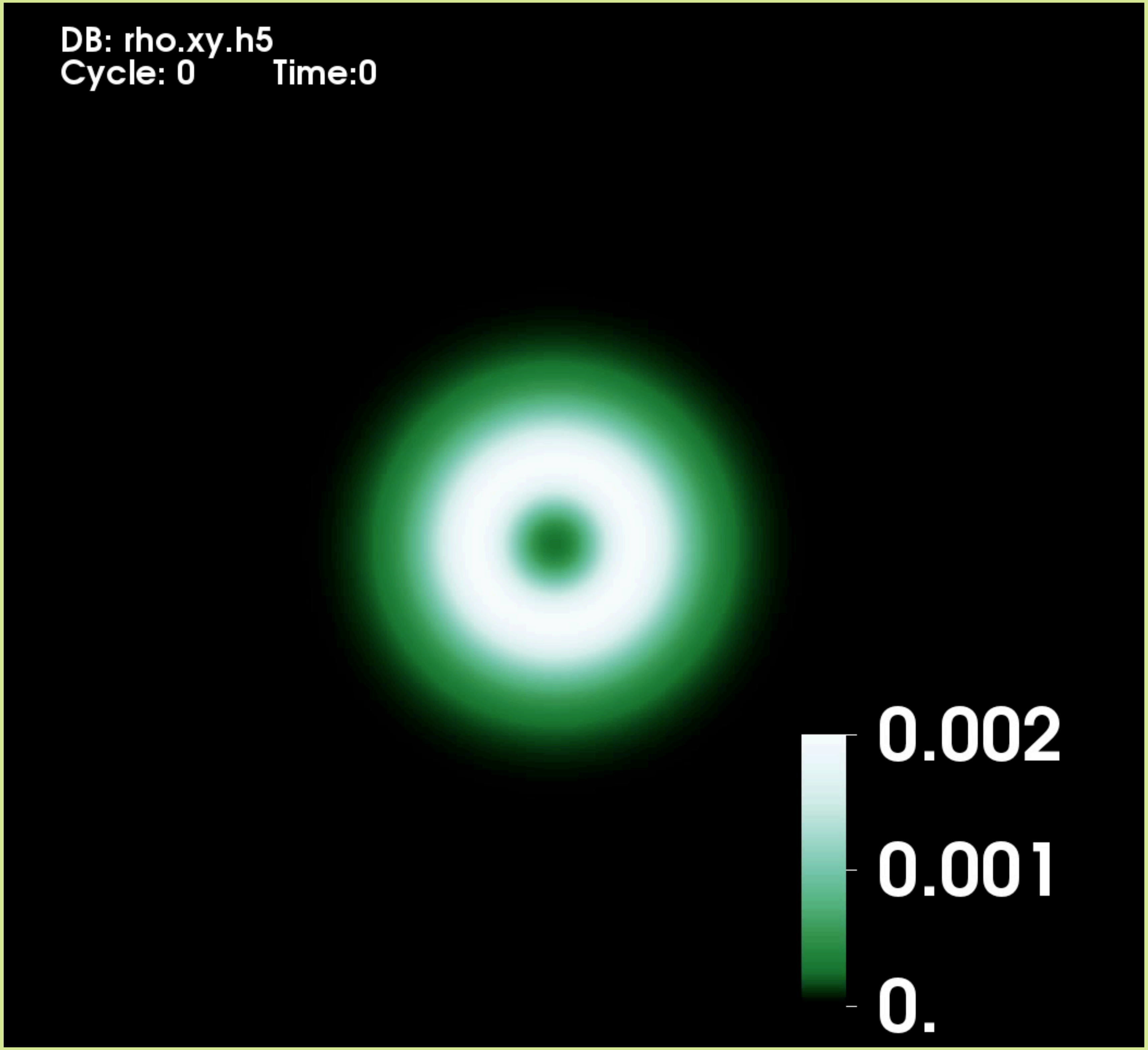
- The Proca field **ansatz**:

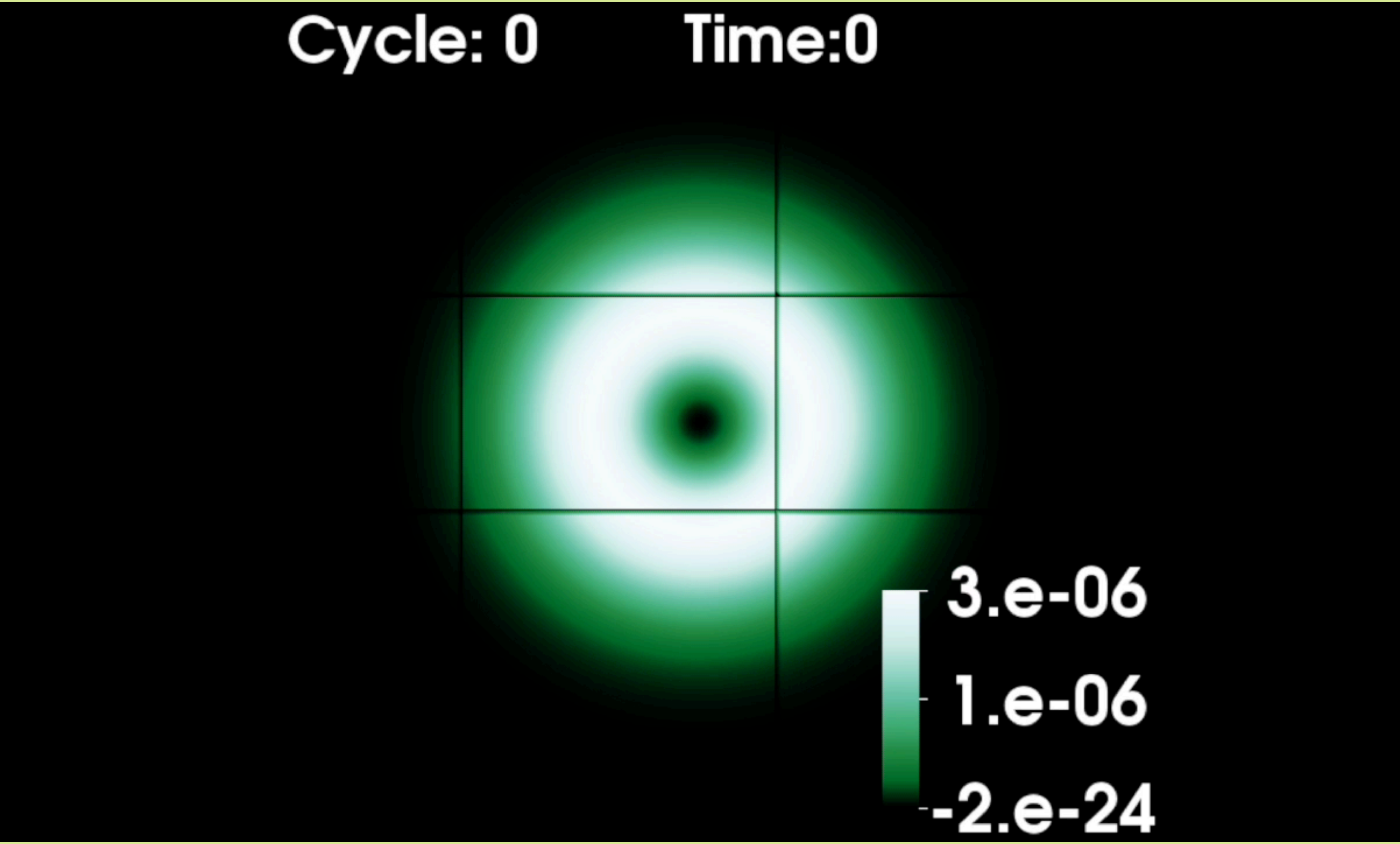
$$A = \left(\frac{H_1}{r} dr + H_2 d\theta + i H_3 \sin\theta d\varphi + i V dt \right) e^{i(m\varphi - \omega t)}$$

- and the scalar field **ansatz**:

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

SPINNING BOSON STARS

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1.e-06
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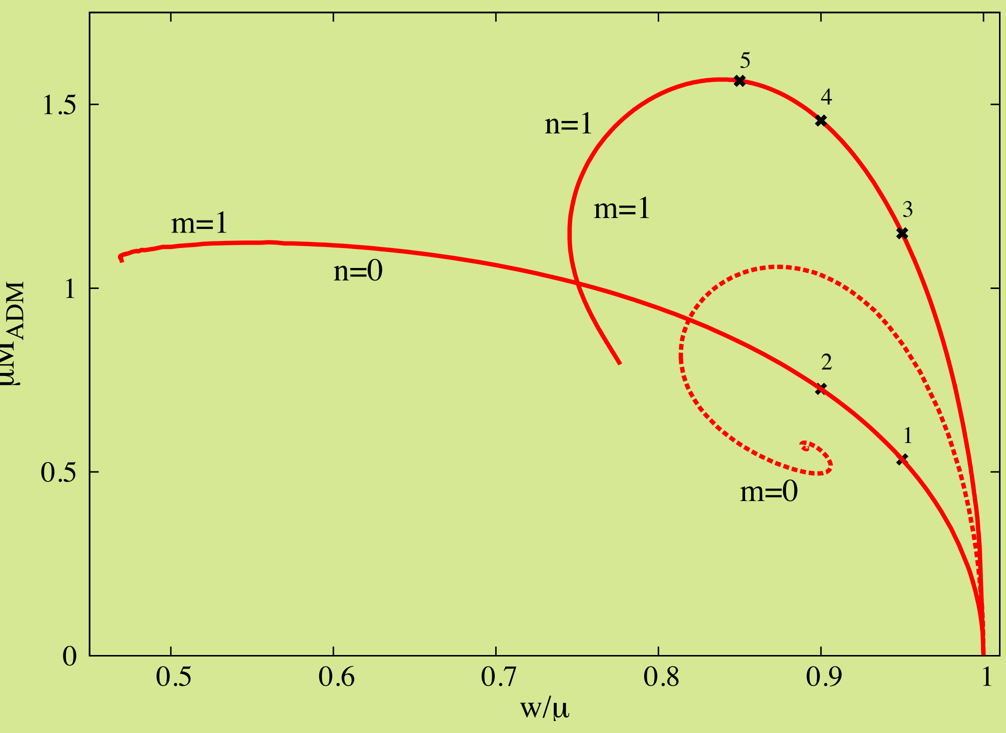
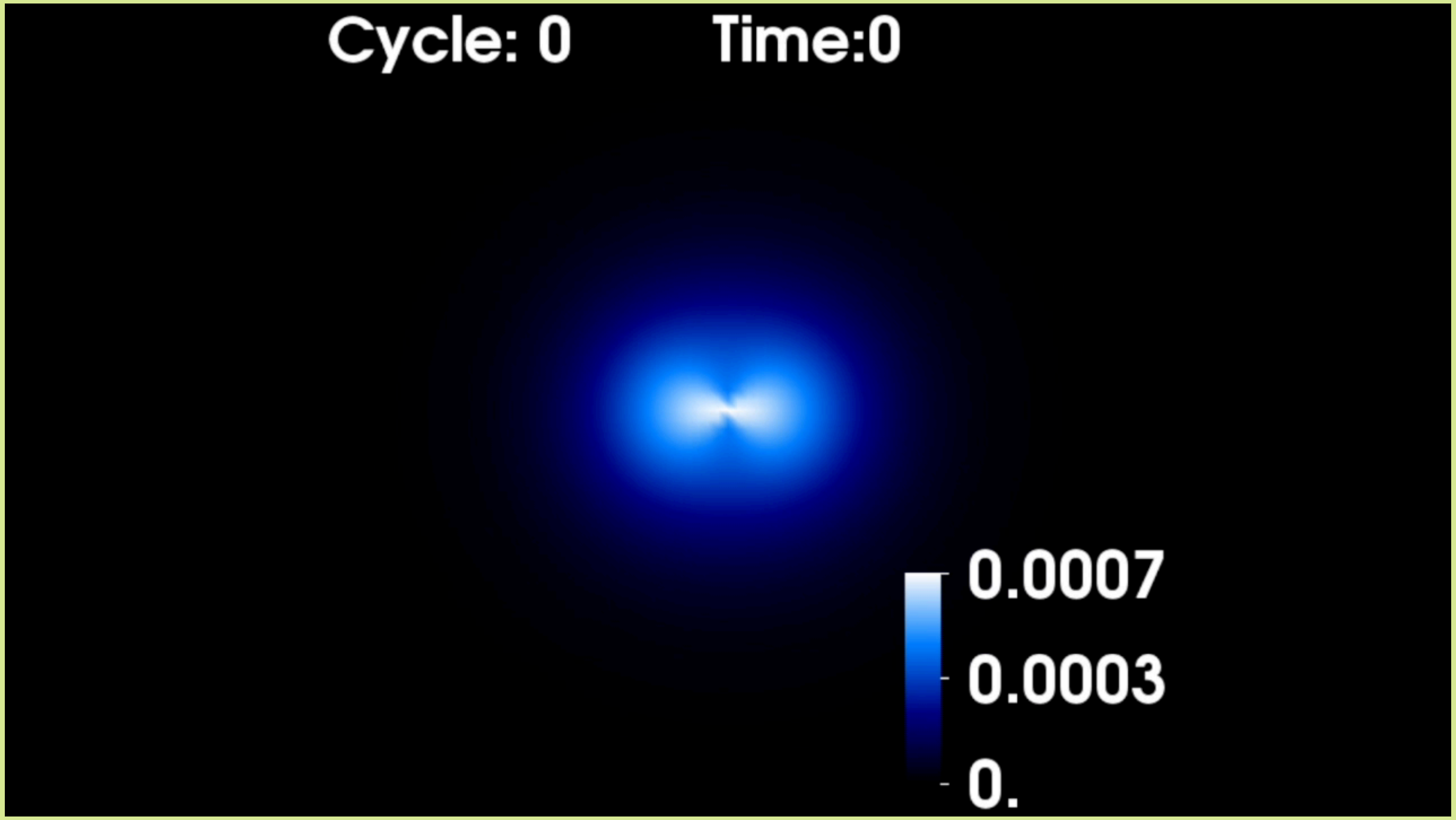
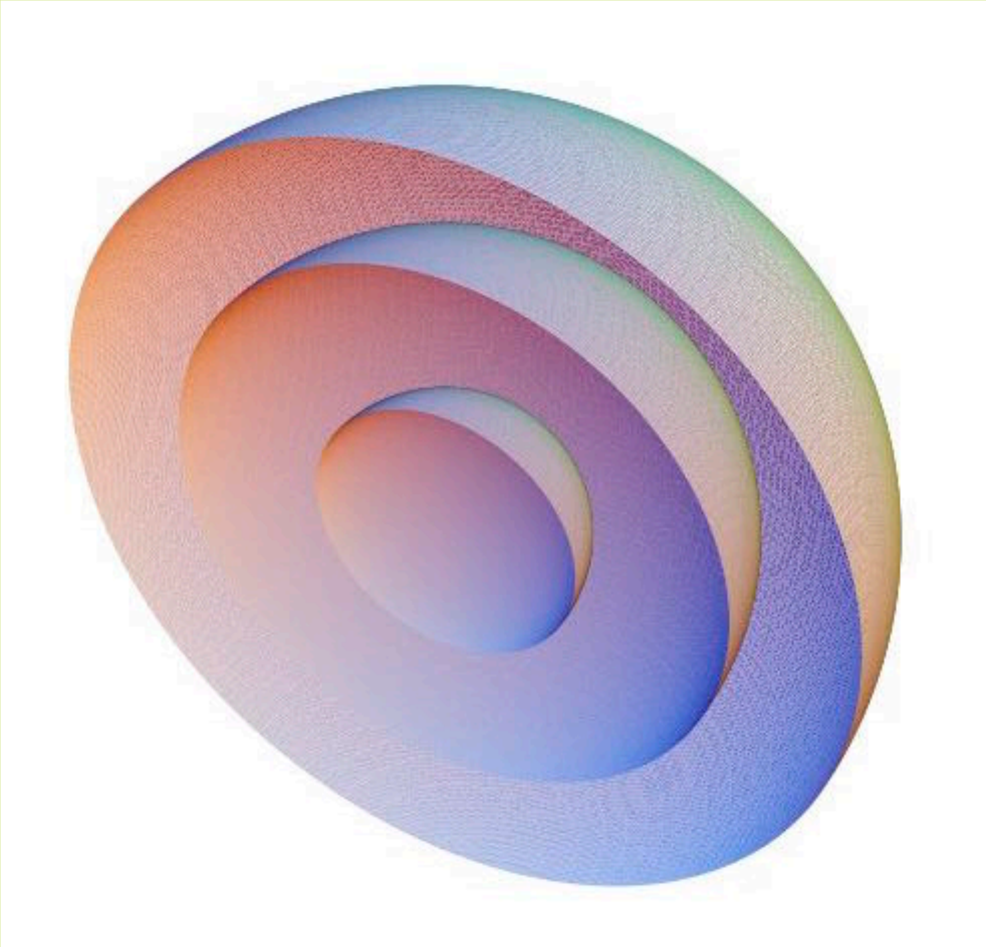
SPINNING PROCA STARS





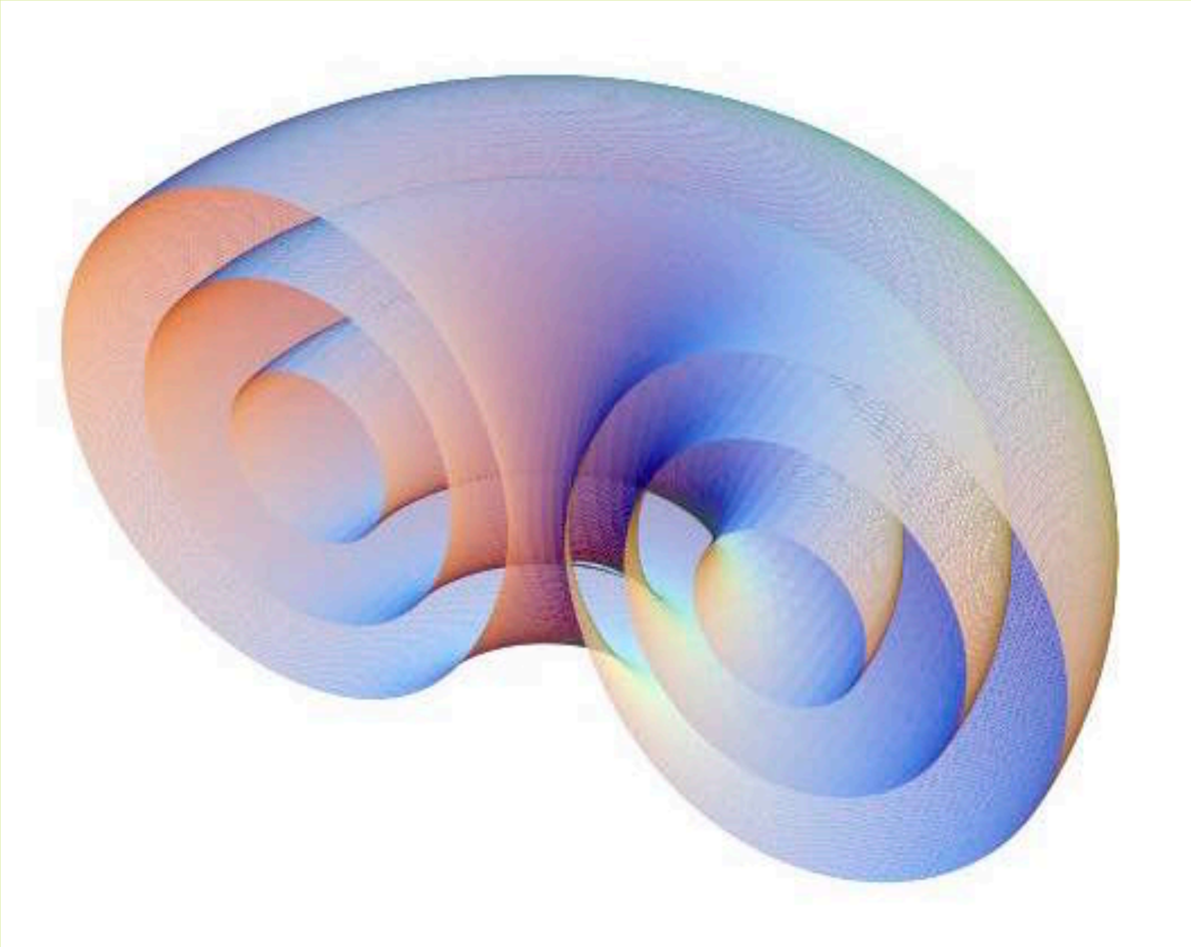
m=1 Proca star

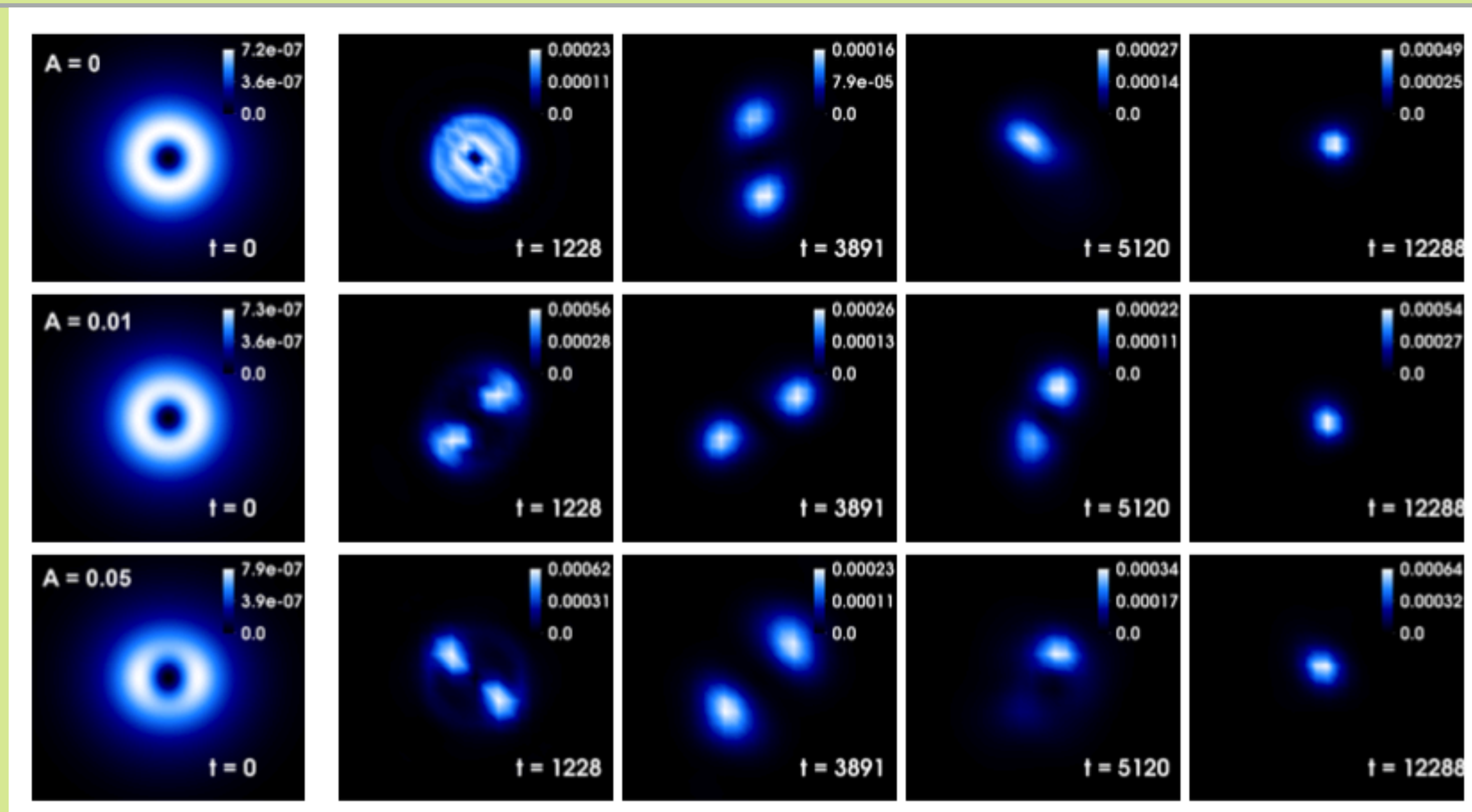
- **form dynamically**
- **stable**

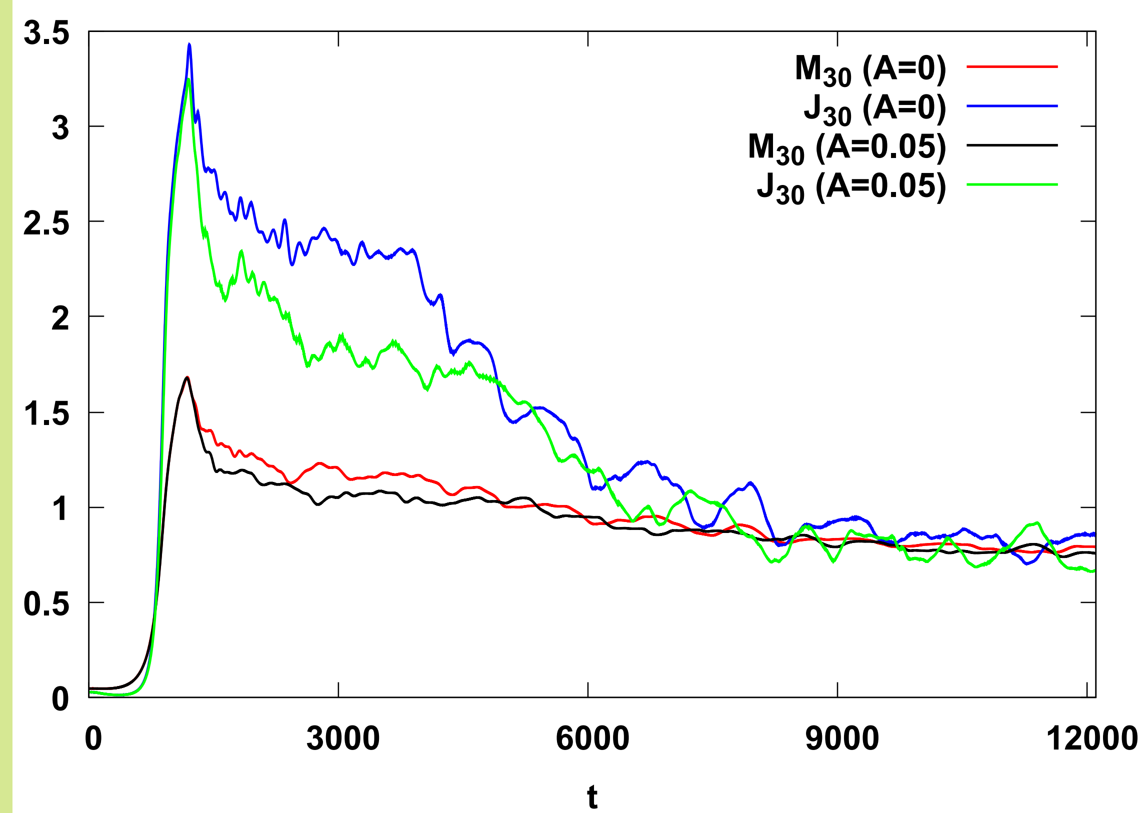


m=1 Boson star

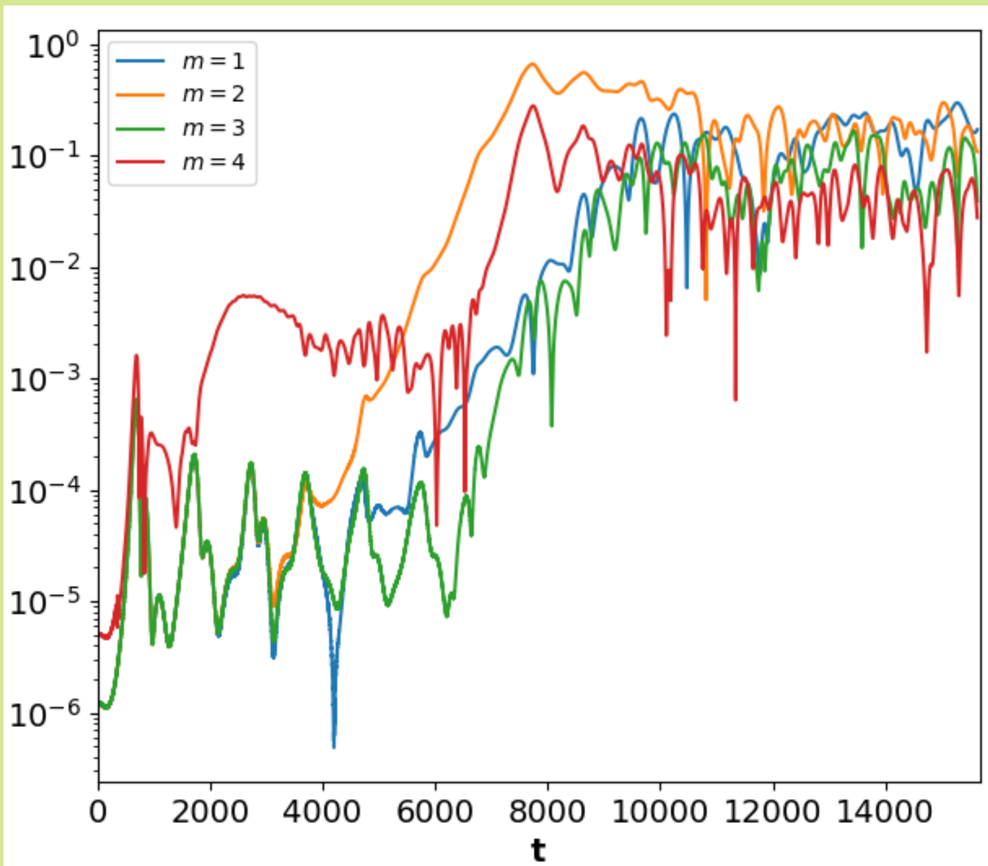
- **spherically symmetric boson star**
- **collapse to BH**

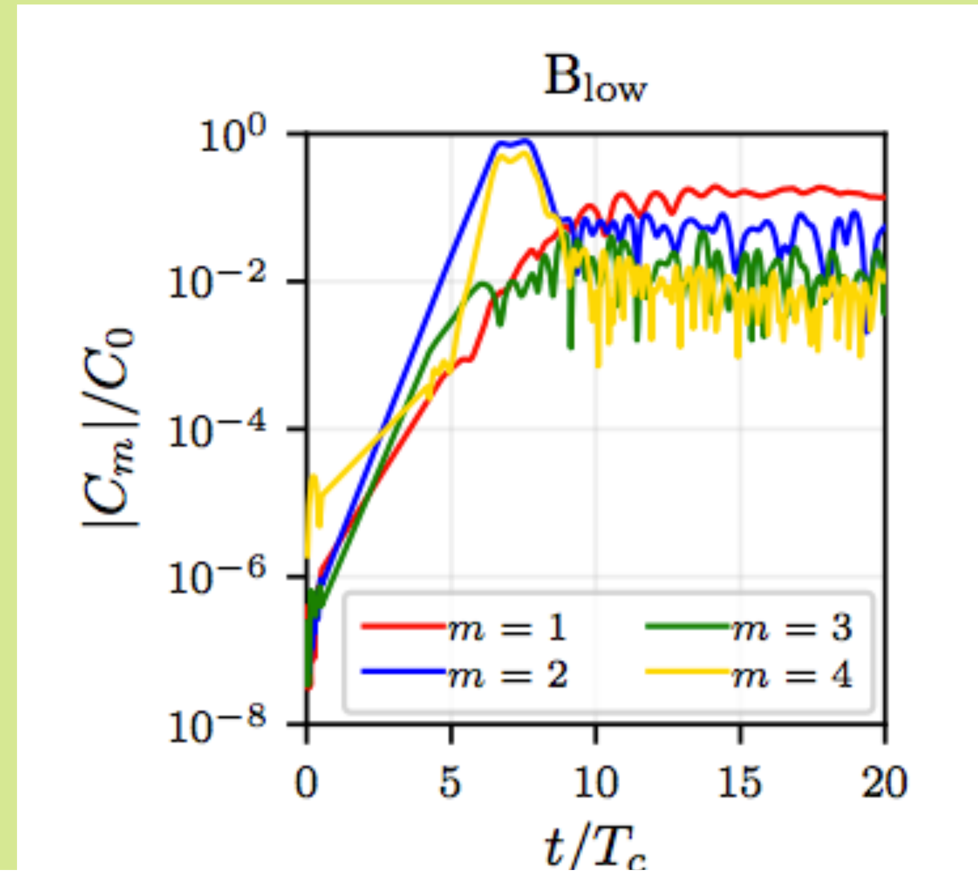


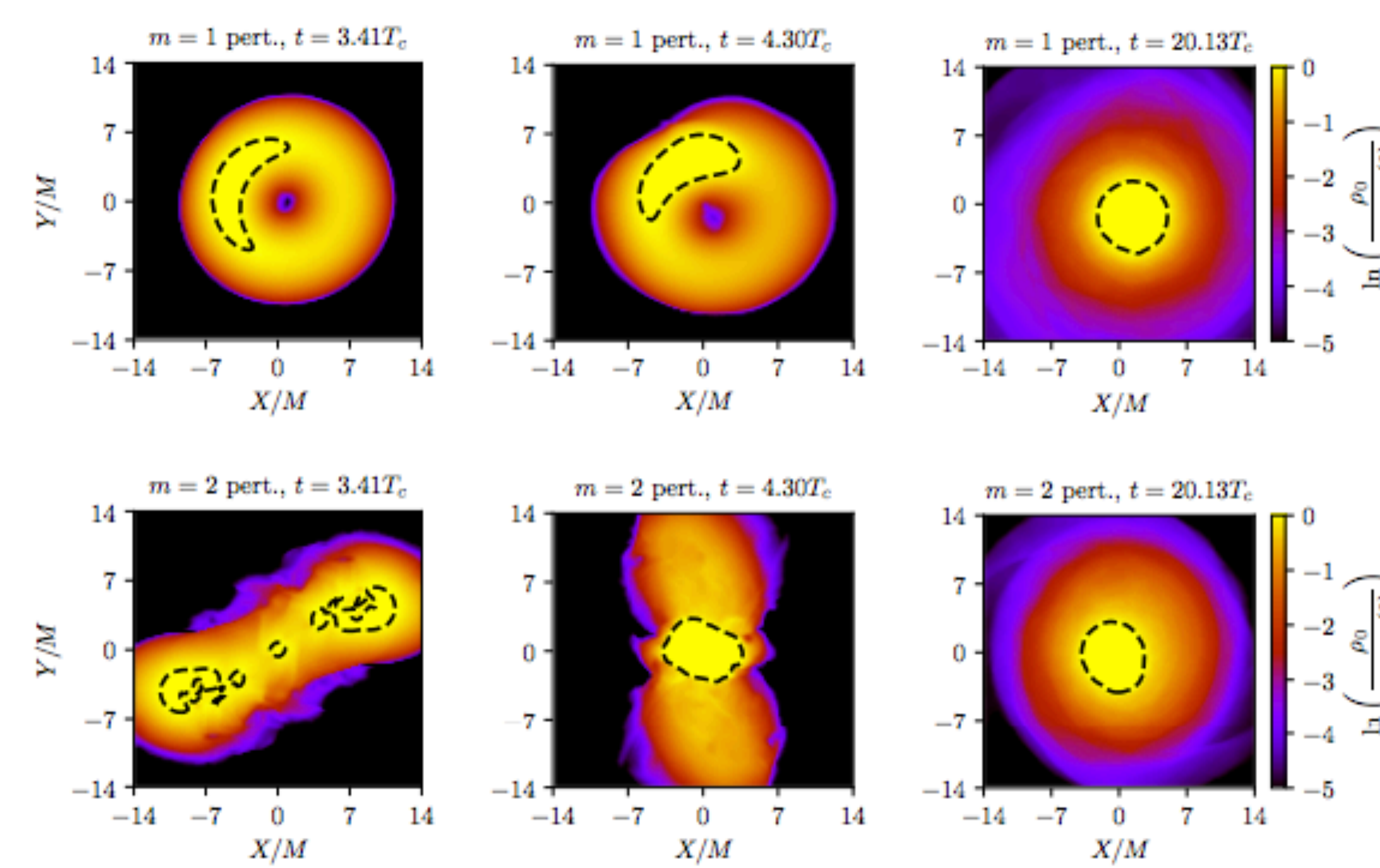




Di Giovanni, F., Sanchis-Gual, N., Cerdá-Durán, P., Zilhão, M., Herdeiro, C., Font, J. A., & Radu, E. (2020). Dynamical bar-mode instability in spinning bosonic stars. *Physical Review D*, *102*(12), 124009.





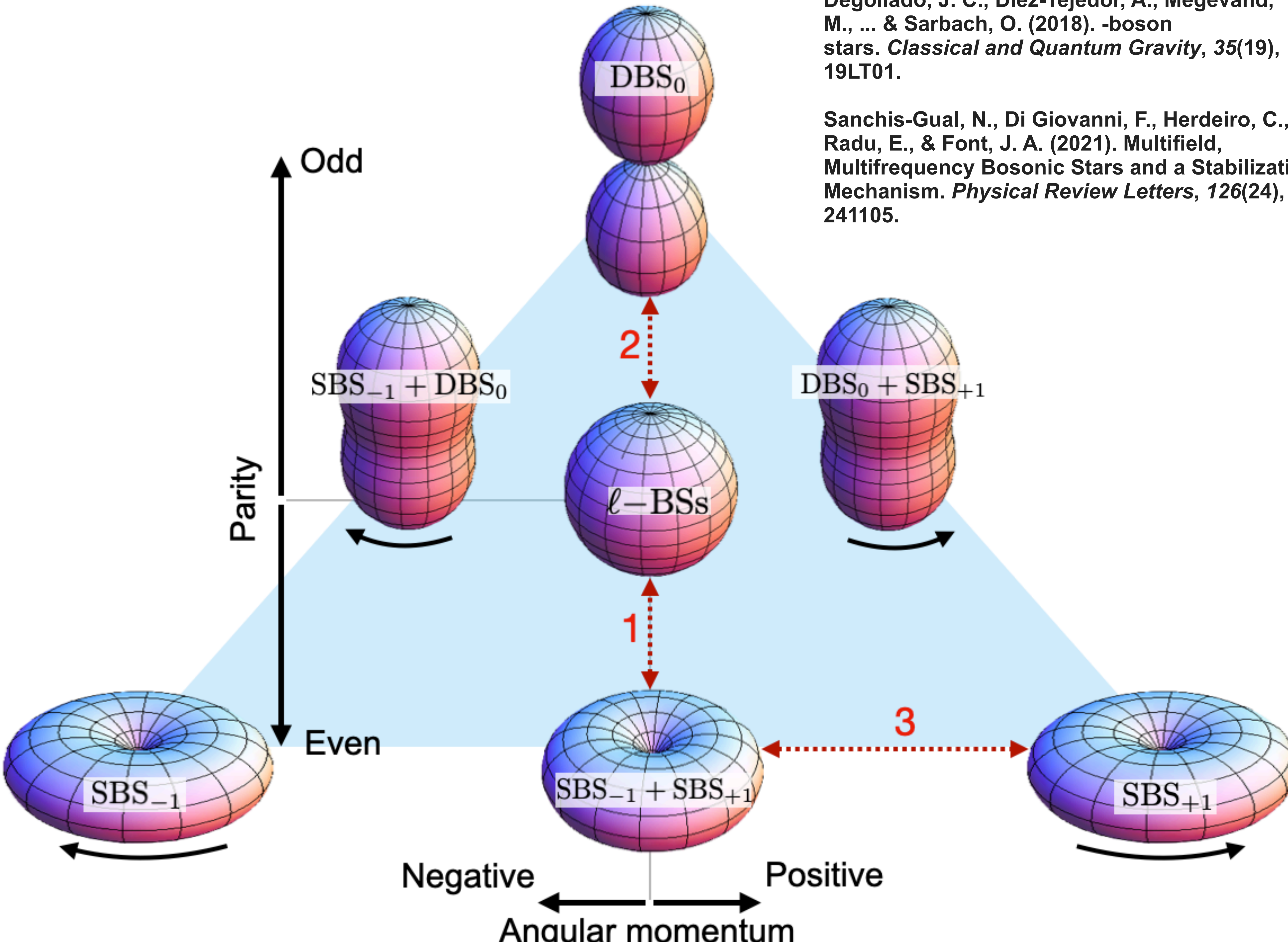


- **(P. L. Espino, V. Paschalidis, T. W. Baumgarte, and S. L.Shapiro (2019), 1906.08786)**

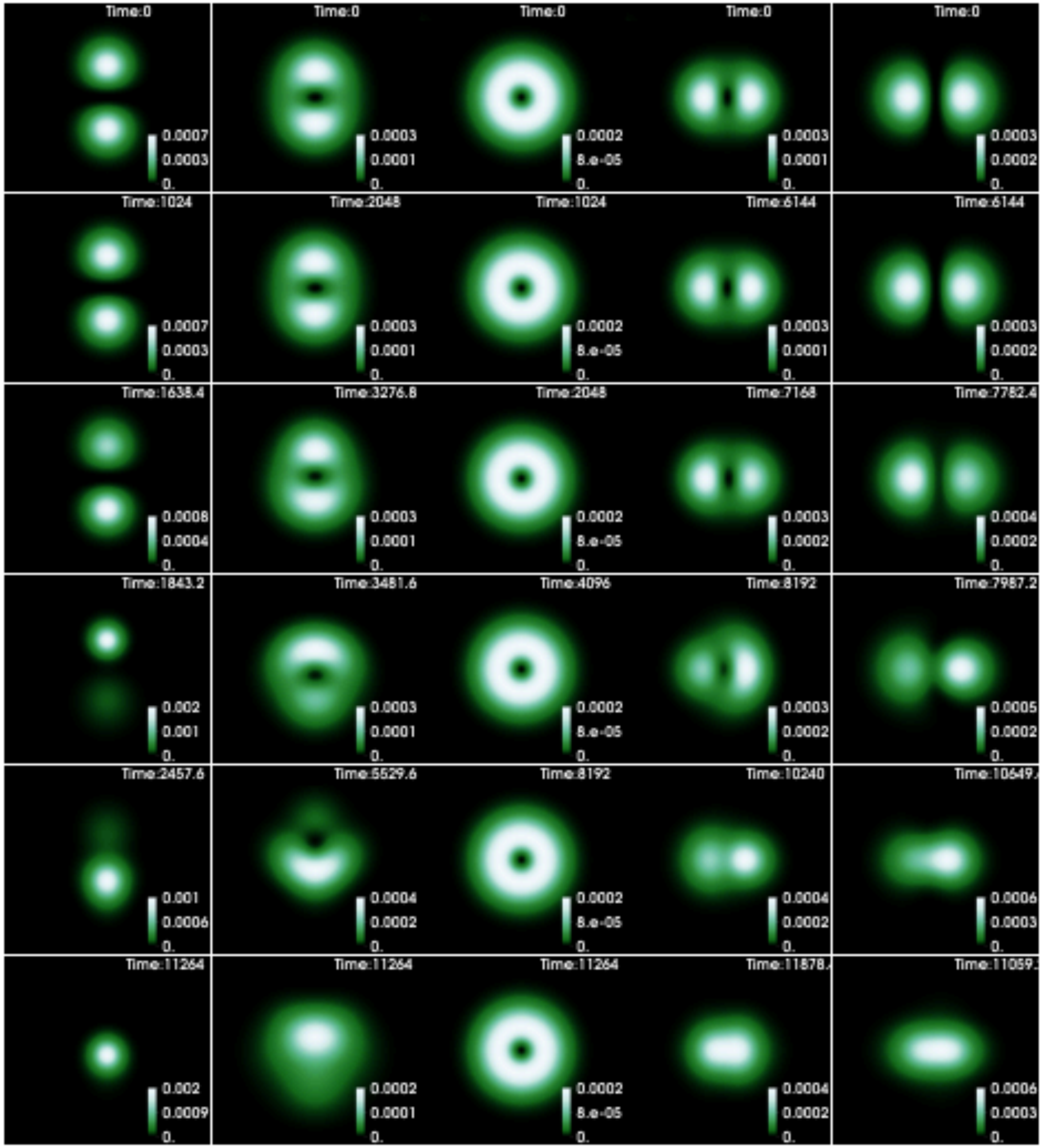
MORE BOSON STAR SOLUTIONS

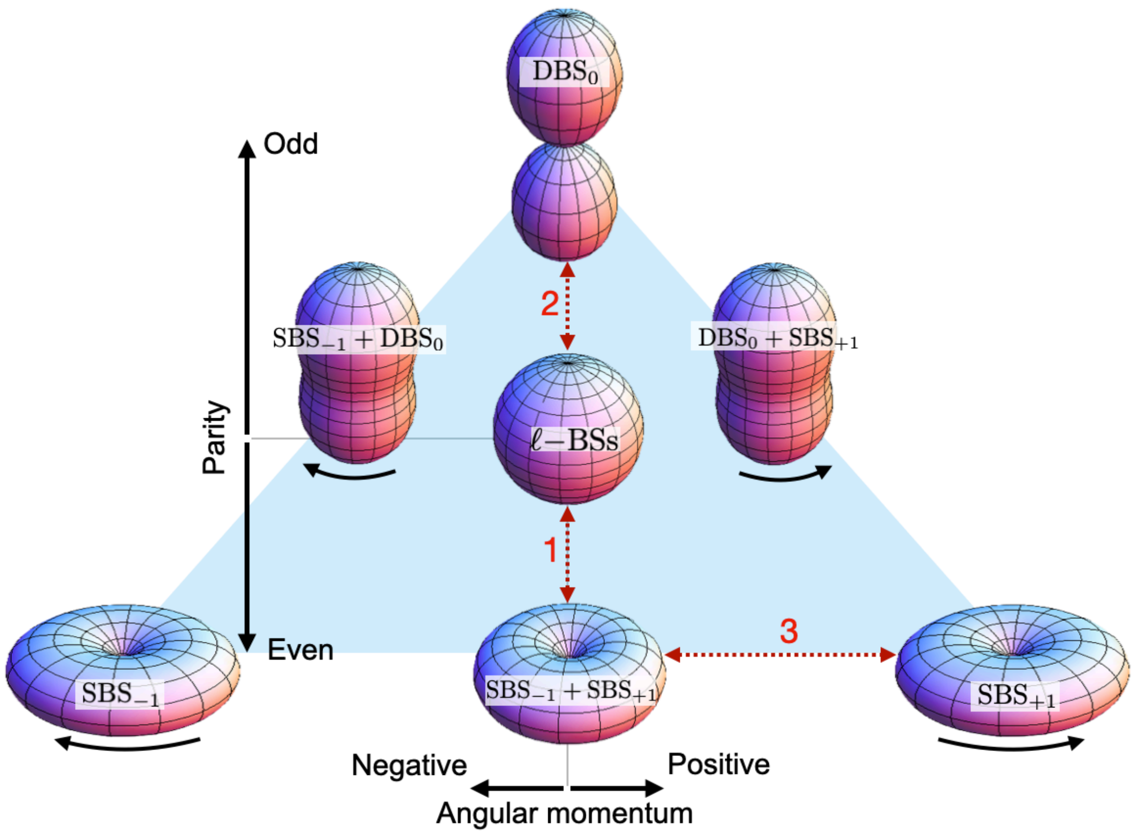
Alcubierre, M., Barranco, J., Bernal, A., Degollado, J. C., Diez-Tejedor, A., Megevand, M., ... & Sarbach, O. (2018). -boson stars. *Classical and Quantum Gravity*, *35*(19), 19LT01.

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.

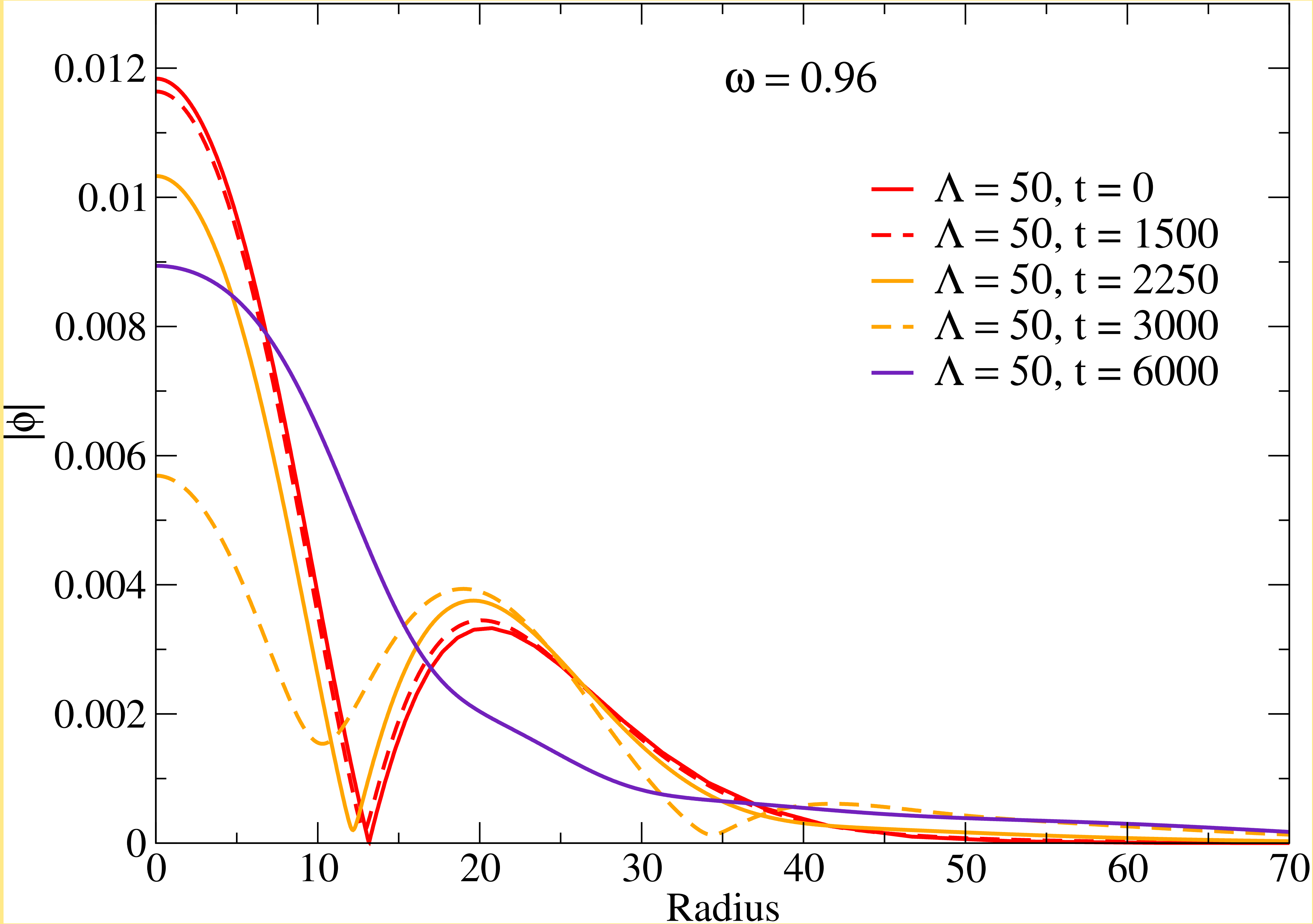


DYNAMICAL BOSONIC STARS AND GRAVITATIONAL WAVES





EXCITED BOSON STARS



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

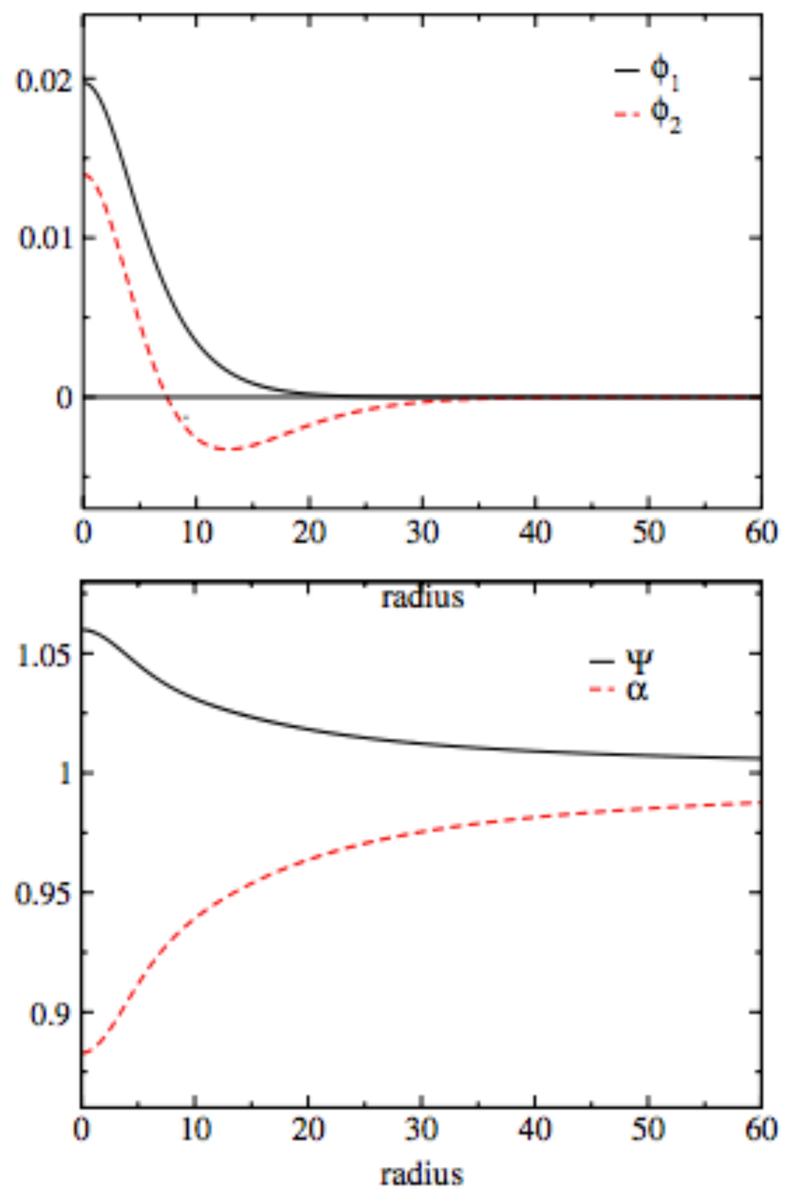


FIG. 1 (color online). Ground-1st excited configuration for $\phi_1(0) = 0.0197$ and fraction $\eta = 1$. The upper panel corresponds to the initial profiles of the two scalar fields, and the lower panel, to the lapse function α and the conformal factor Ψ.

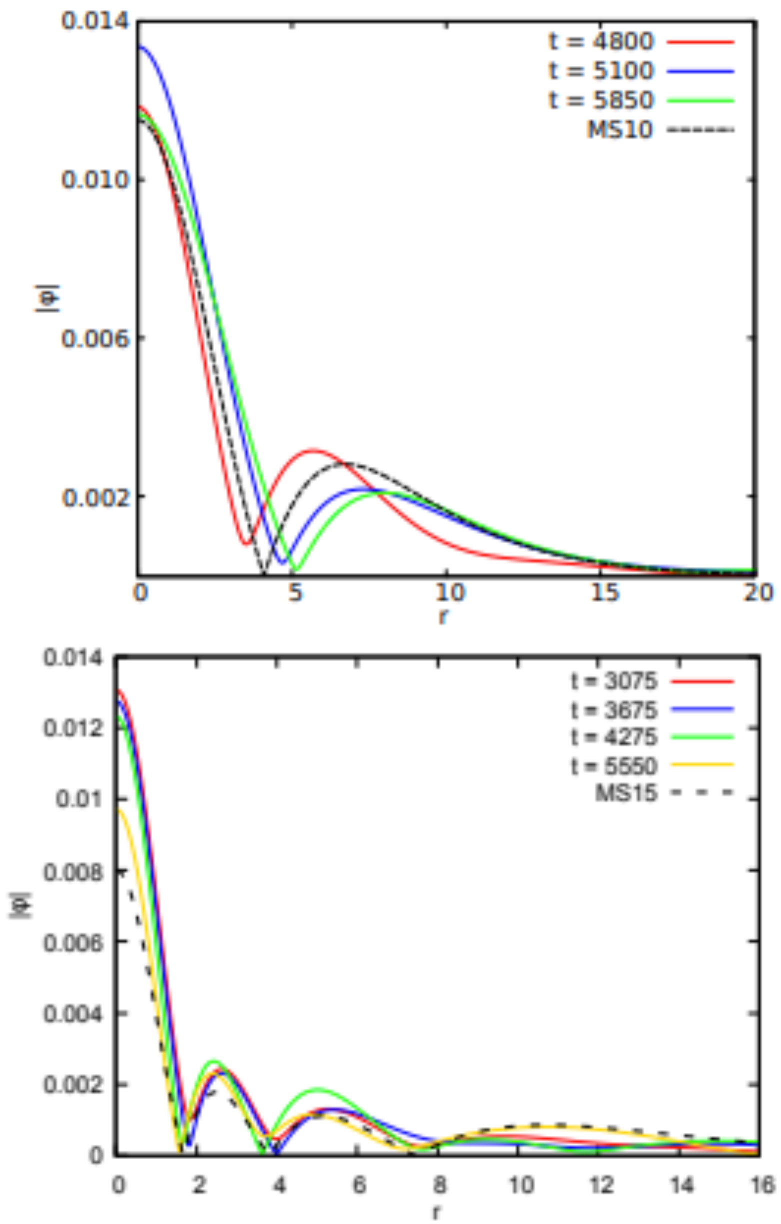
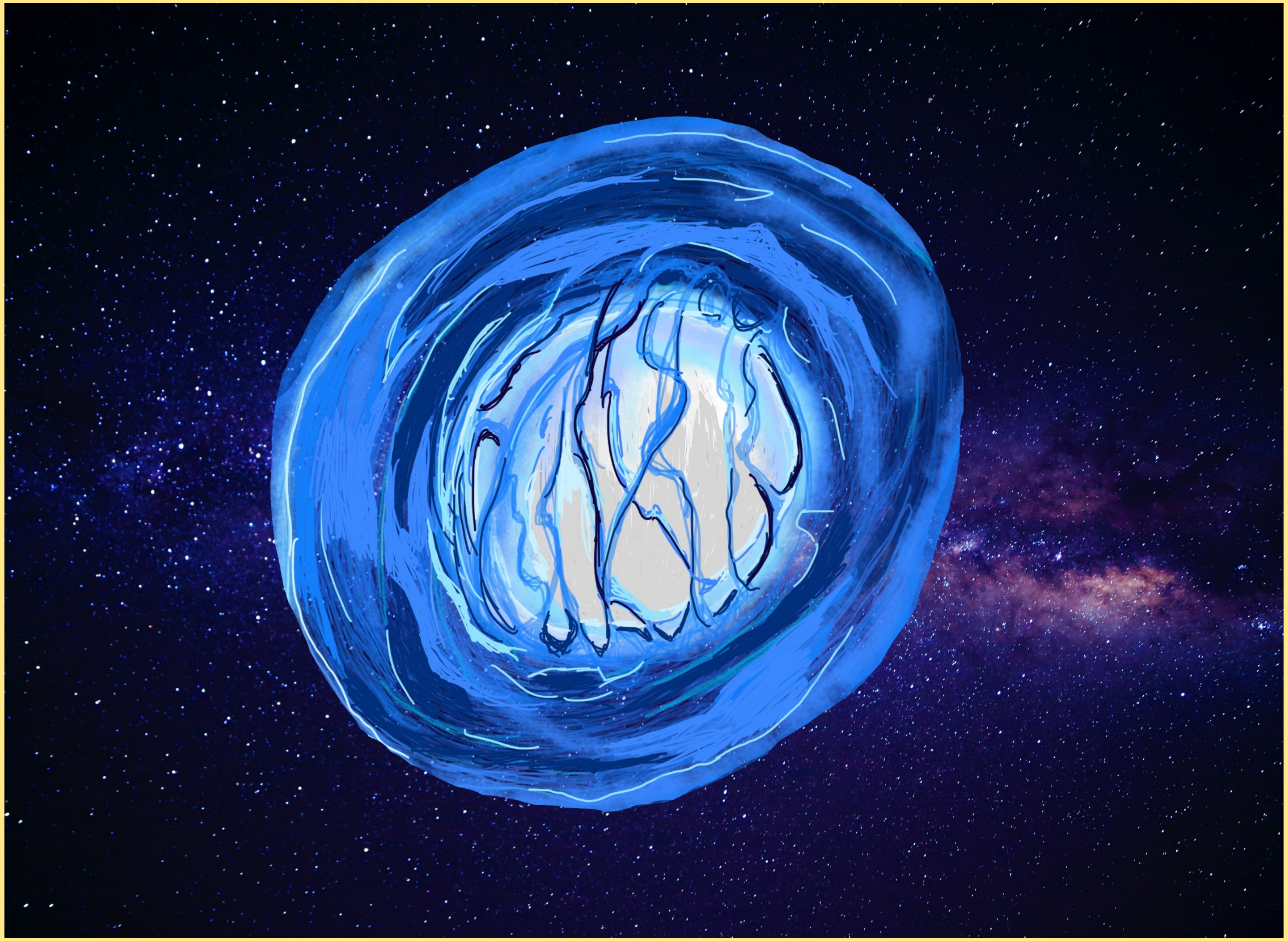
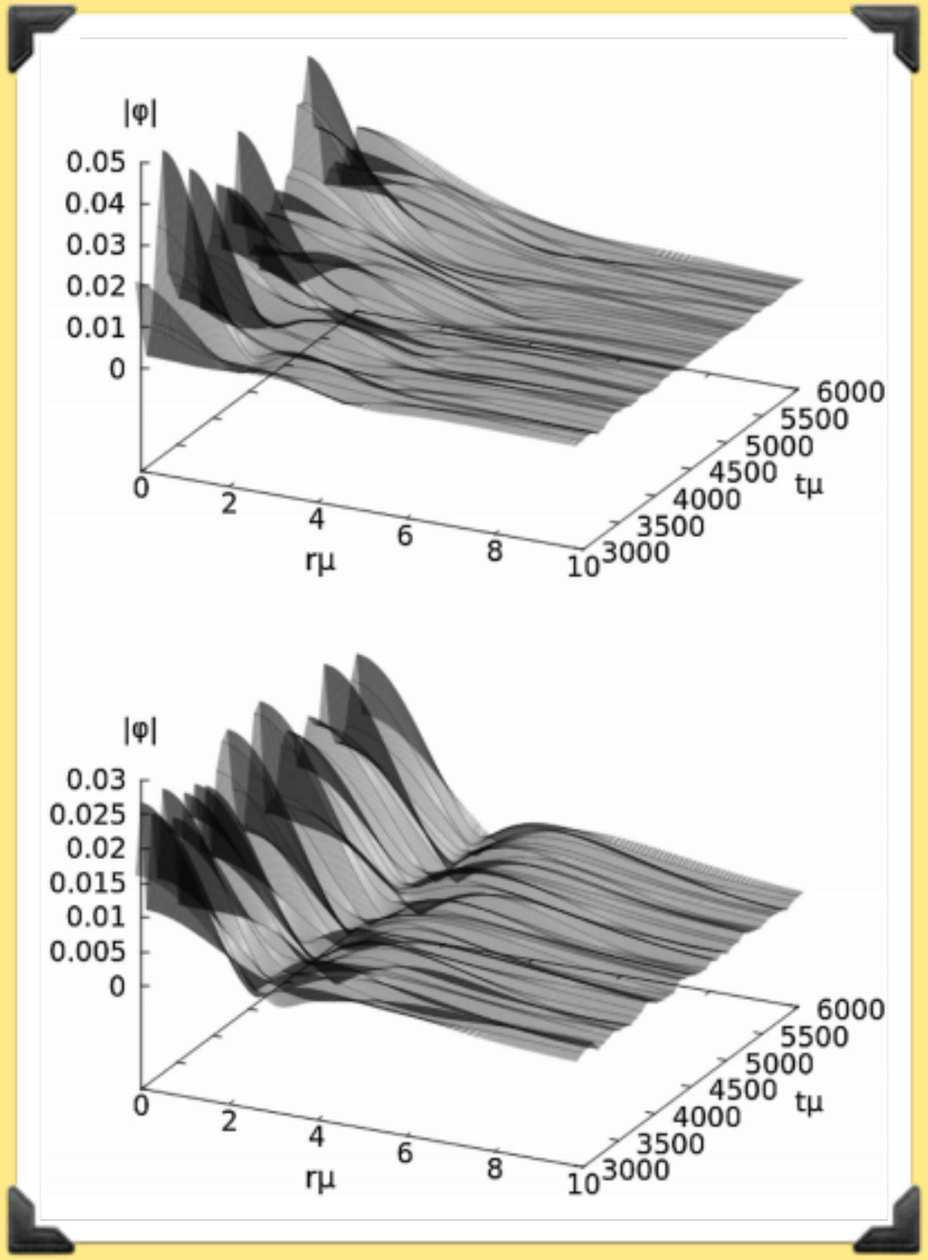


FIG. 6: Late-time snapshots of the radial profile of the module of the scalar field ϕ for models MS10 (top) and MS15 (bottom). The dashed black lines indicate the profiles of the corresponding static models with similar ρ_c and ϕ_c.

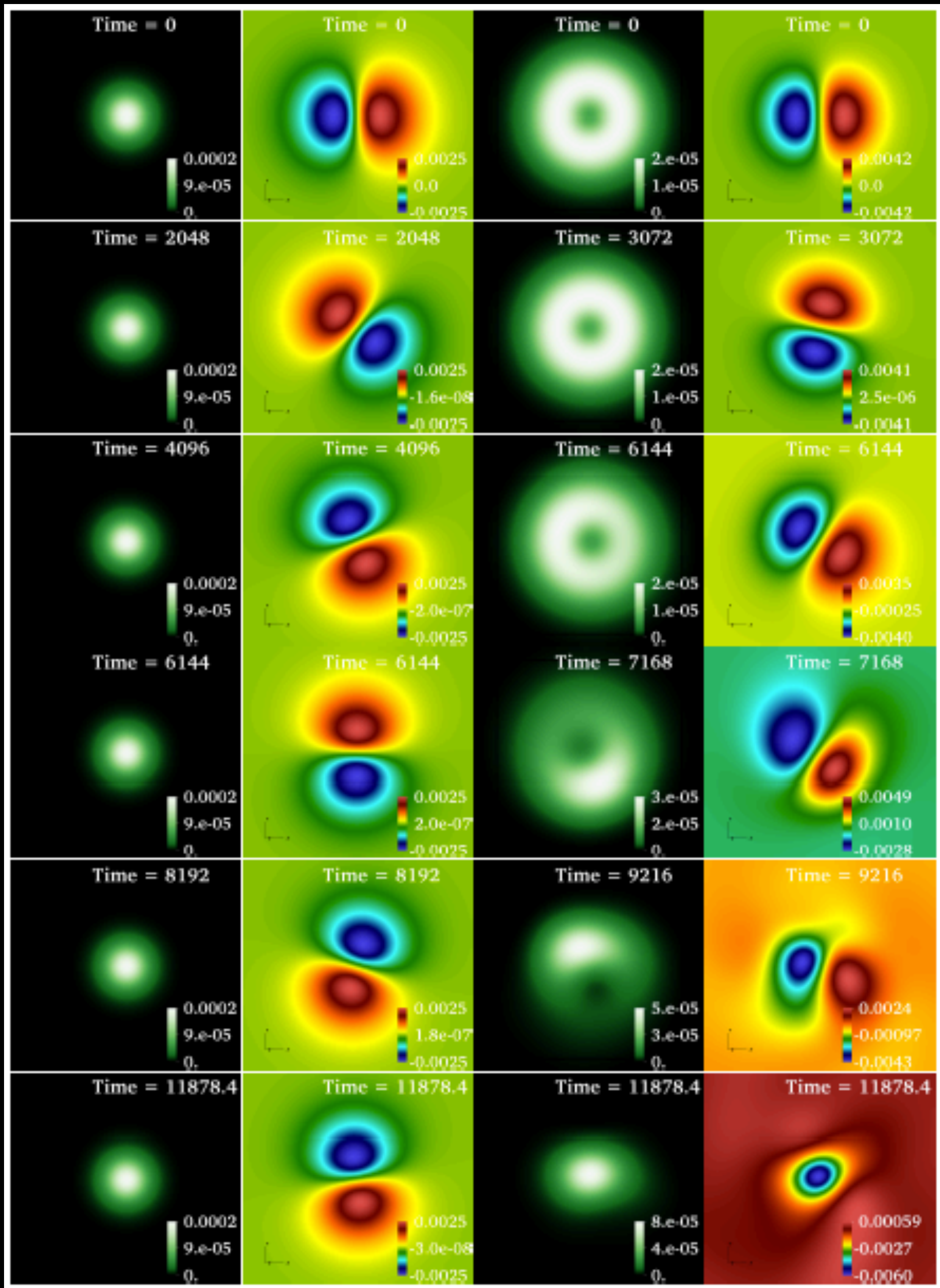
MIXED FERMION–BOSON STARS

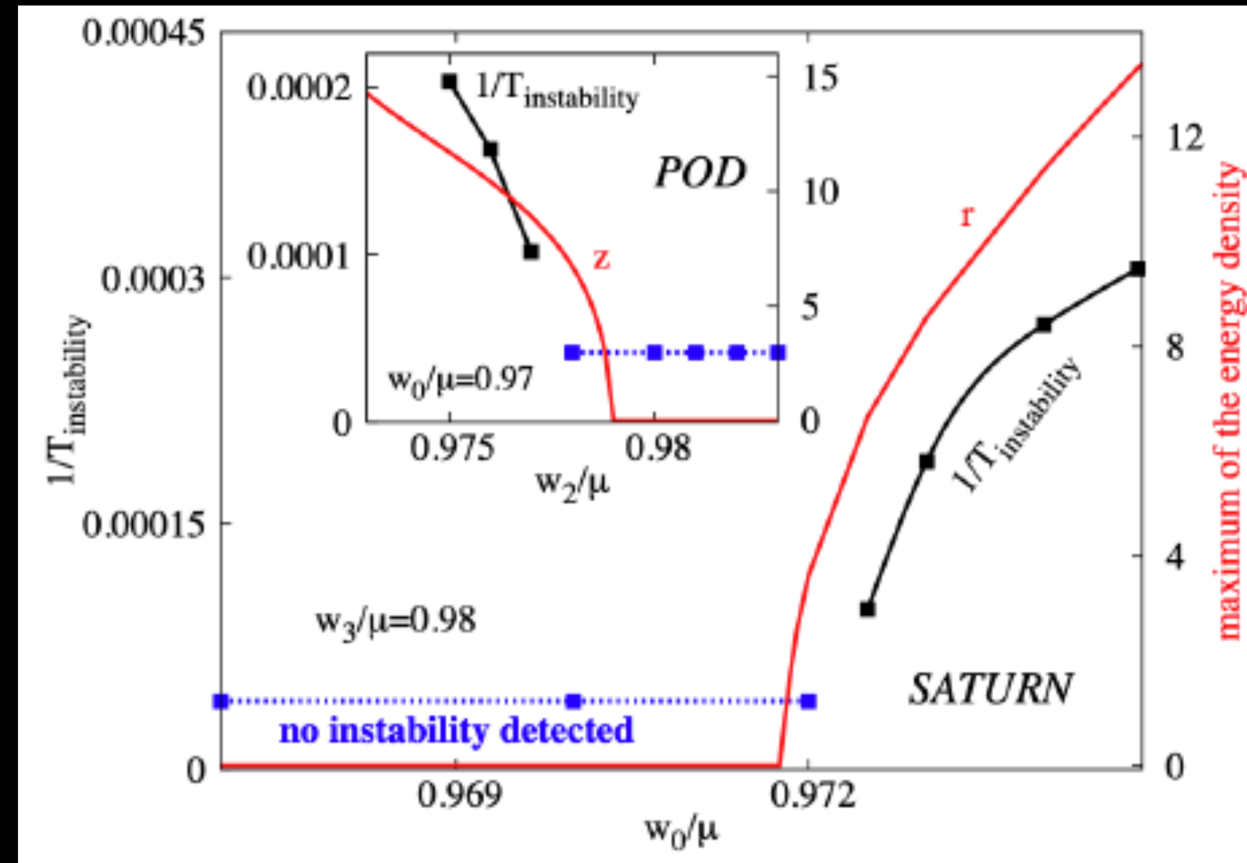
Valdez-Alvarado, S., Palenzuela, C., Alic, D., & Urena-López, L. A. (2013). Dynamical evolution of fermion-boson stars. Physical Review D, 87(8), 084040.
Valdez-Alvarado, S., Becerril, R., & Ureña-López, L. A. (2020). Fermion-boson stars with a quartic self-interaction in the boson sector. Physical Review D, 102(6), 064038.
Di Giovanni, F., Fakhry, S., Sanchis-Gual, N., Degollado, J. C., & Font, J. A. (2020). Dynamical formation and stability of fermion-boson stars. Physical Review D, 102(8), 084063.
Fabrizio Di Giovanni et al (2021), A stabilization mechanism for excited fermion–boson stars, Class. Quantum Grav. 38 194001

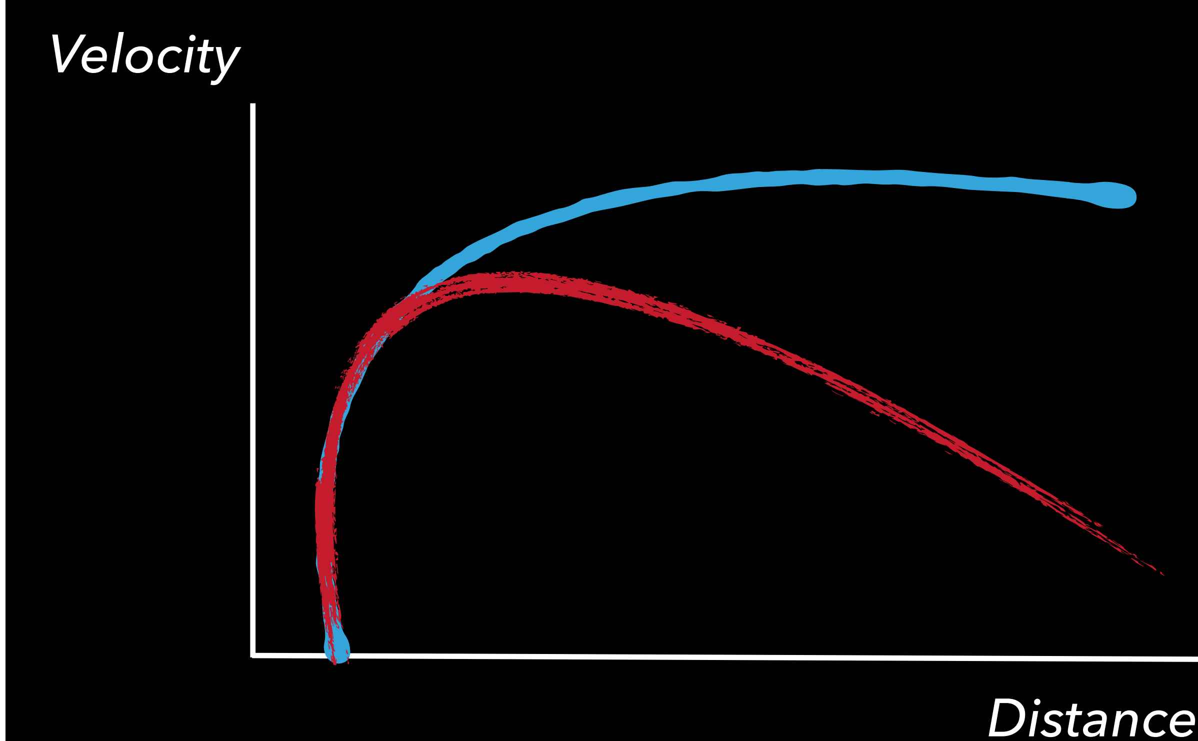


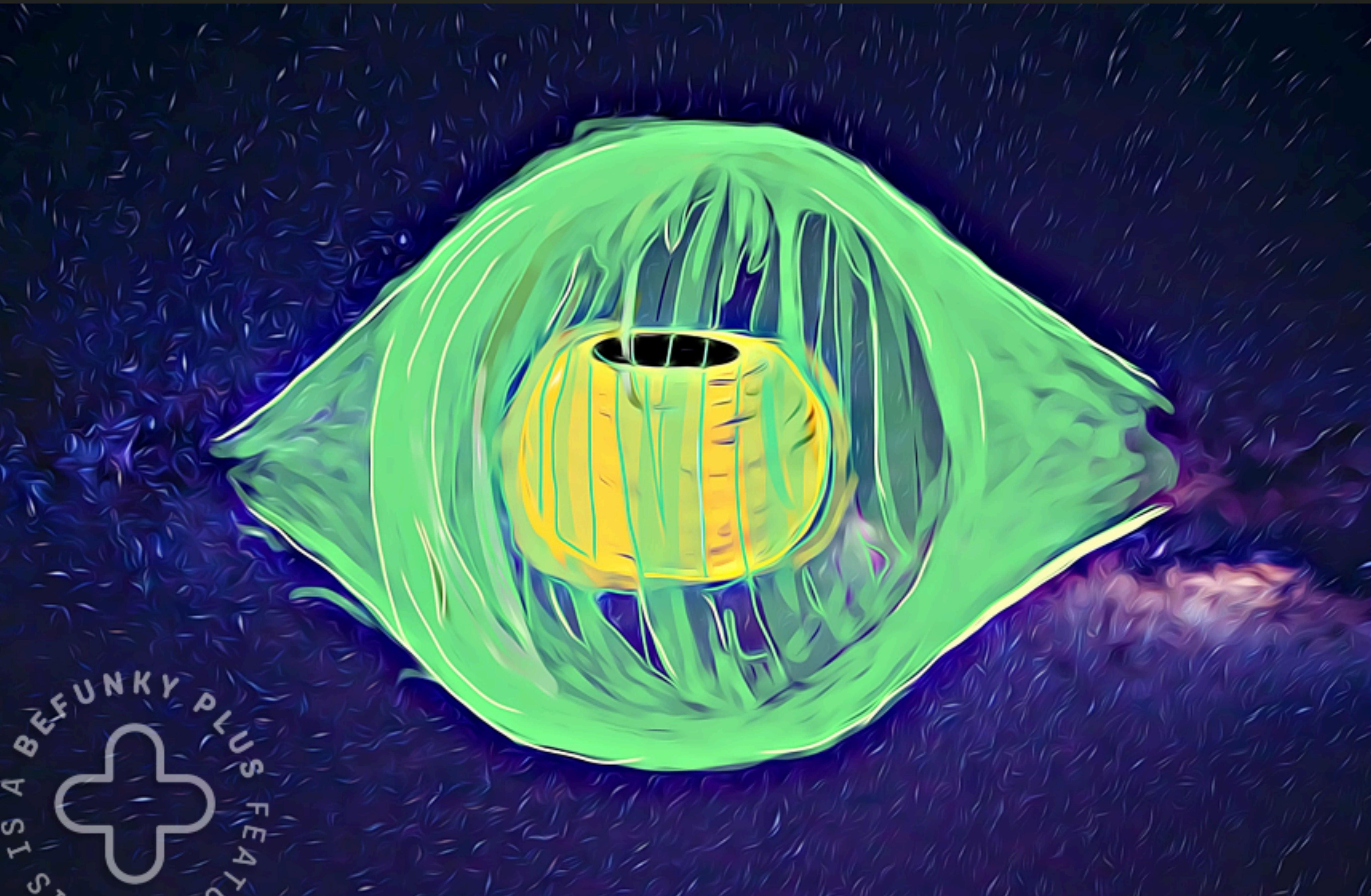


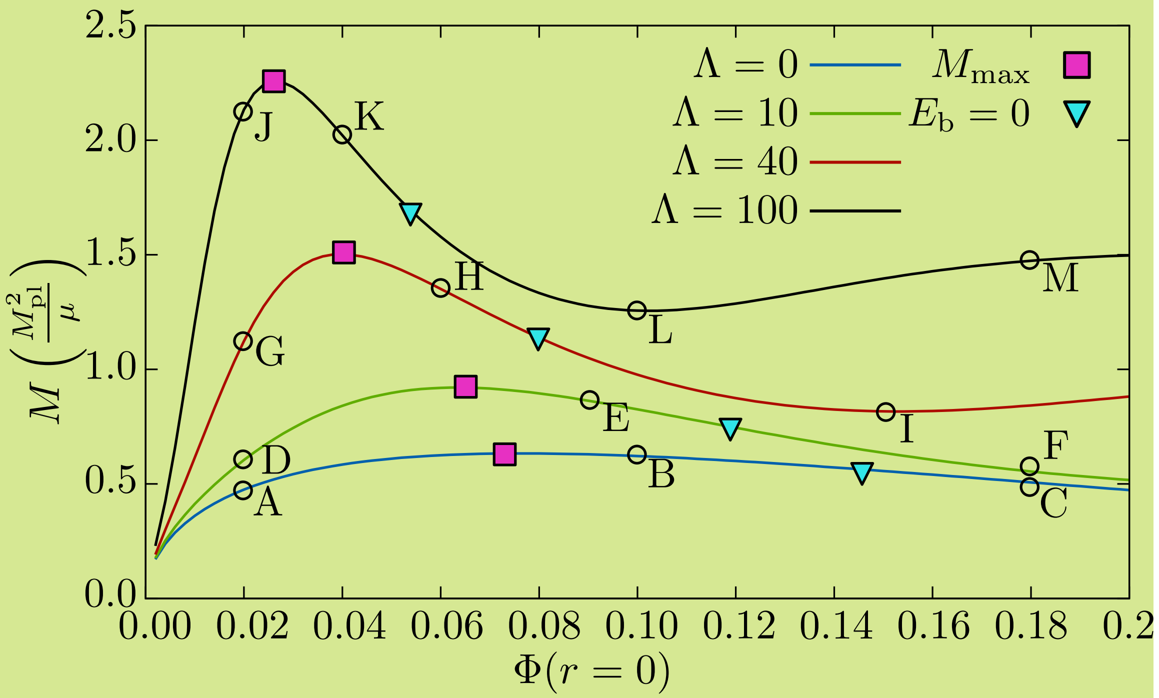
DYNAMICAL BOSONIC STARS AND GRAVITATIONAL WAVES

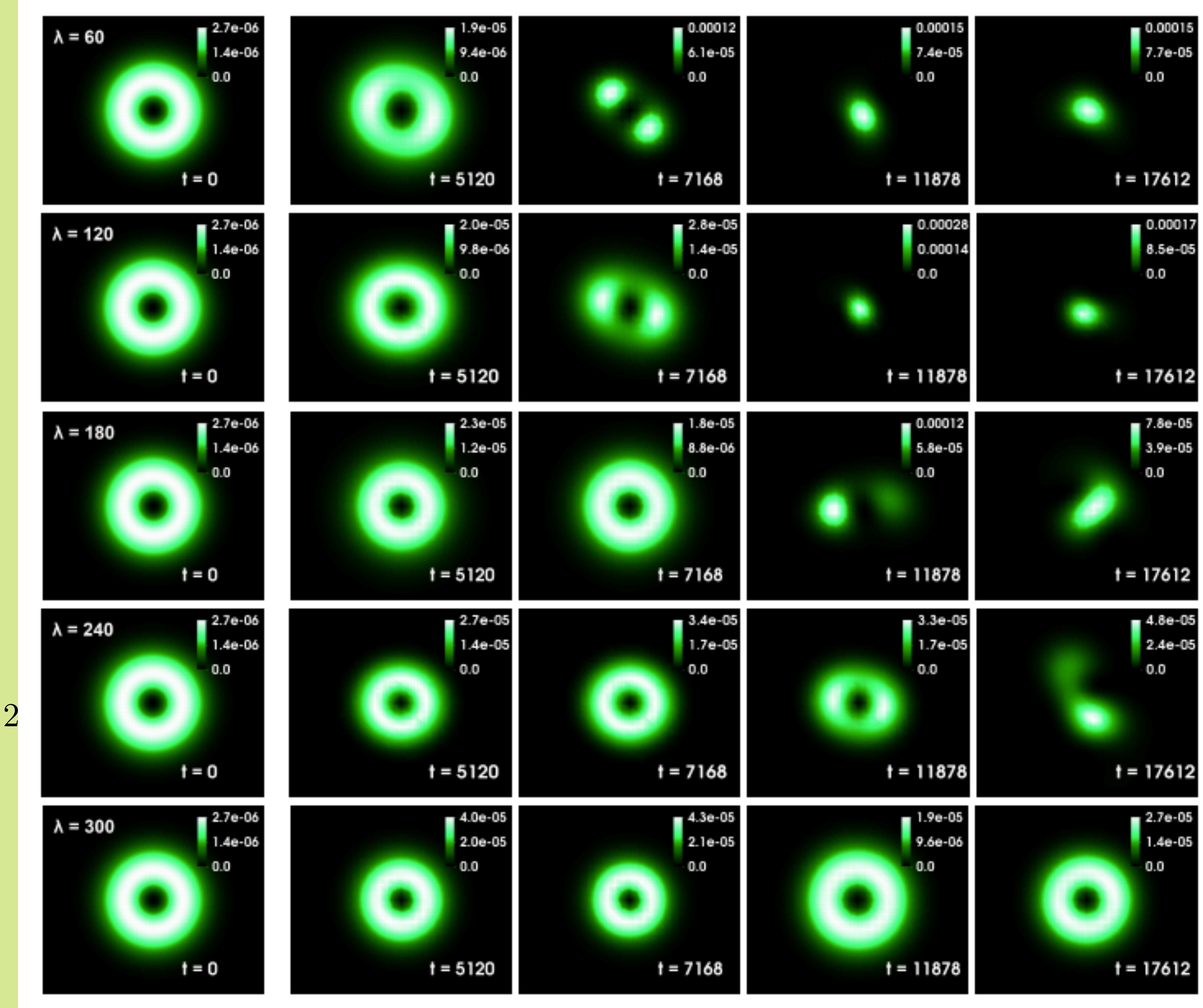







IS A BEFUNKY PLUS FEATU



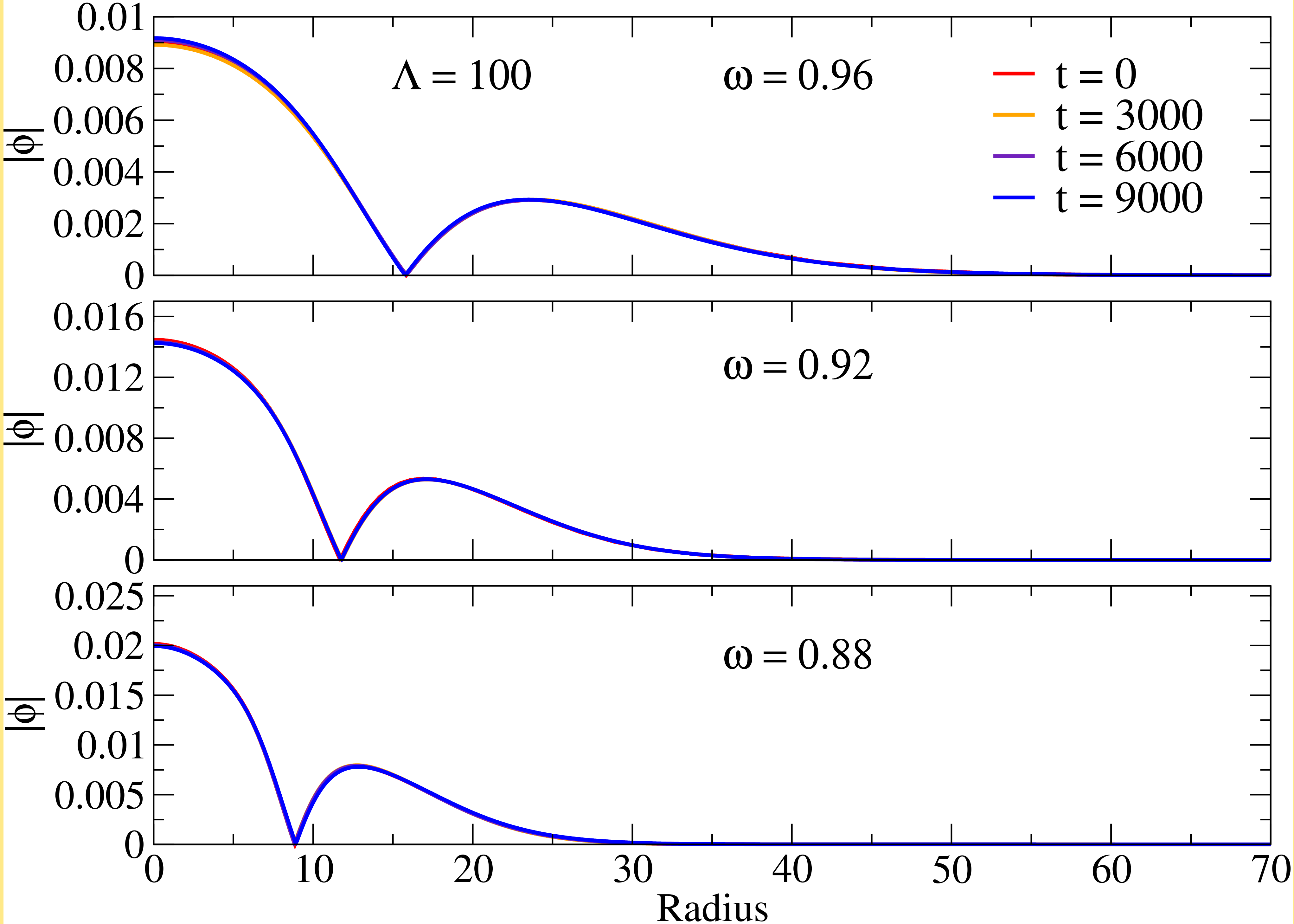


Di Giovanni, F., Sanchis-Gual, N., Cerdá-Durán, P., Zilhão, M., Herdeiro, C., Font, J. A., & Radu, E. (2020). Dynamical bar-mode instability in spinning bosonic stars. *Physical Review D, 102*(12), 124009.

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



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.

DYNAMICAL BOSONIC STARS AND GRAVITATIONAL WAVES

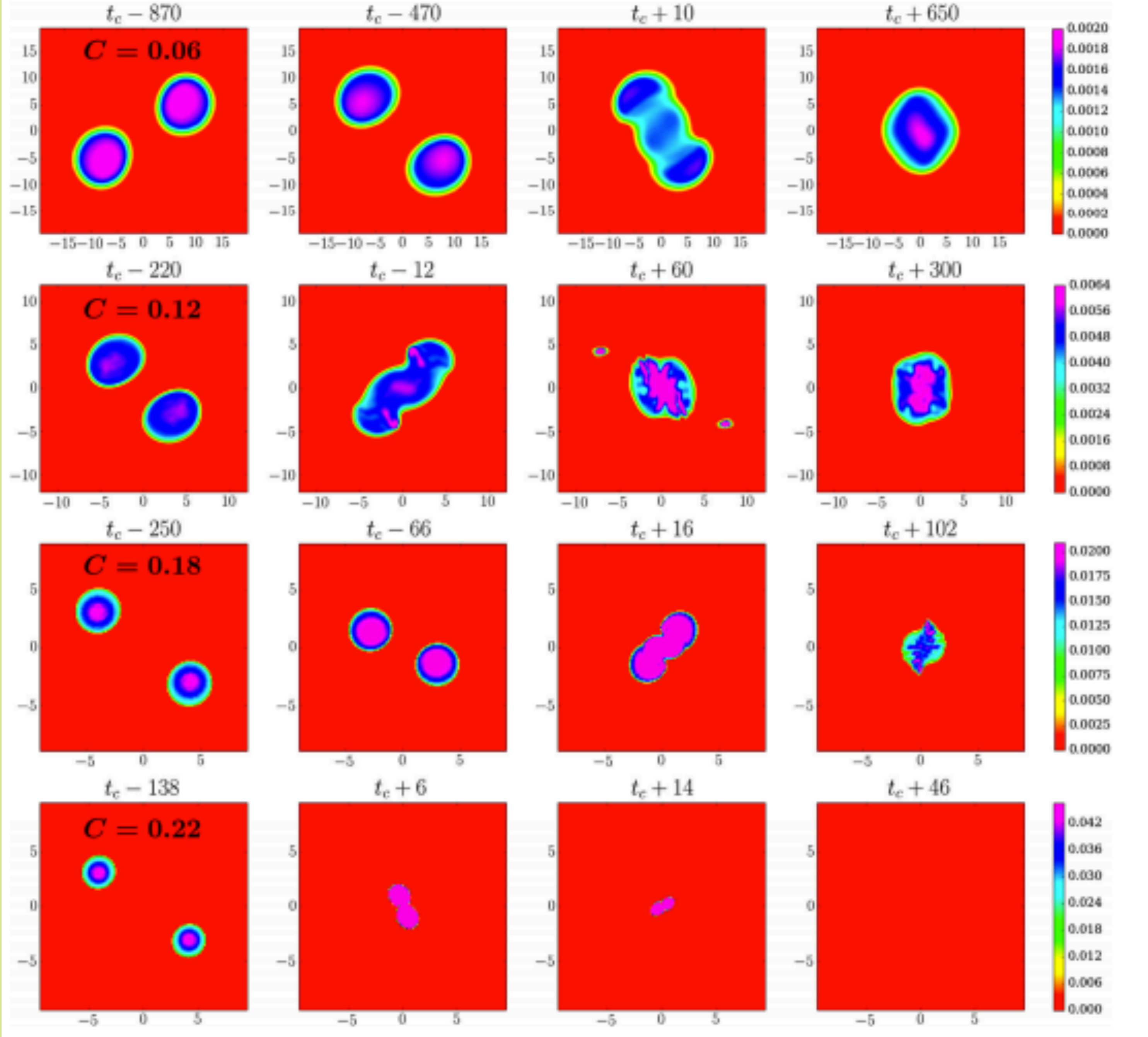
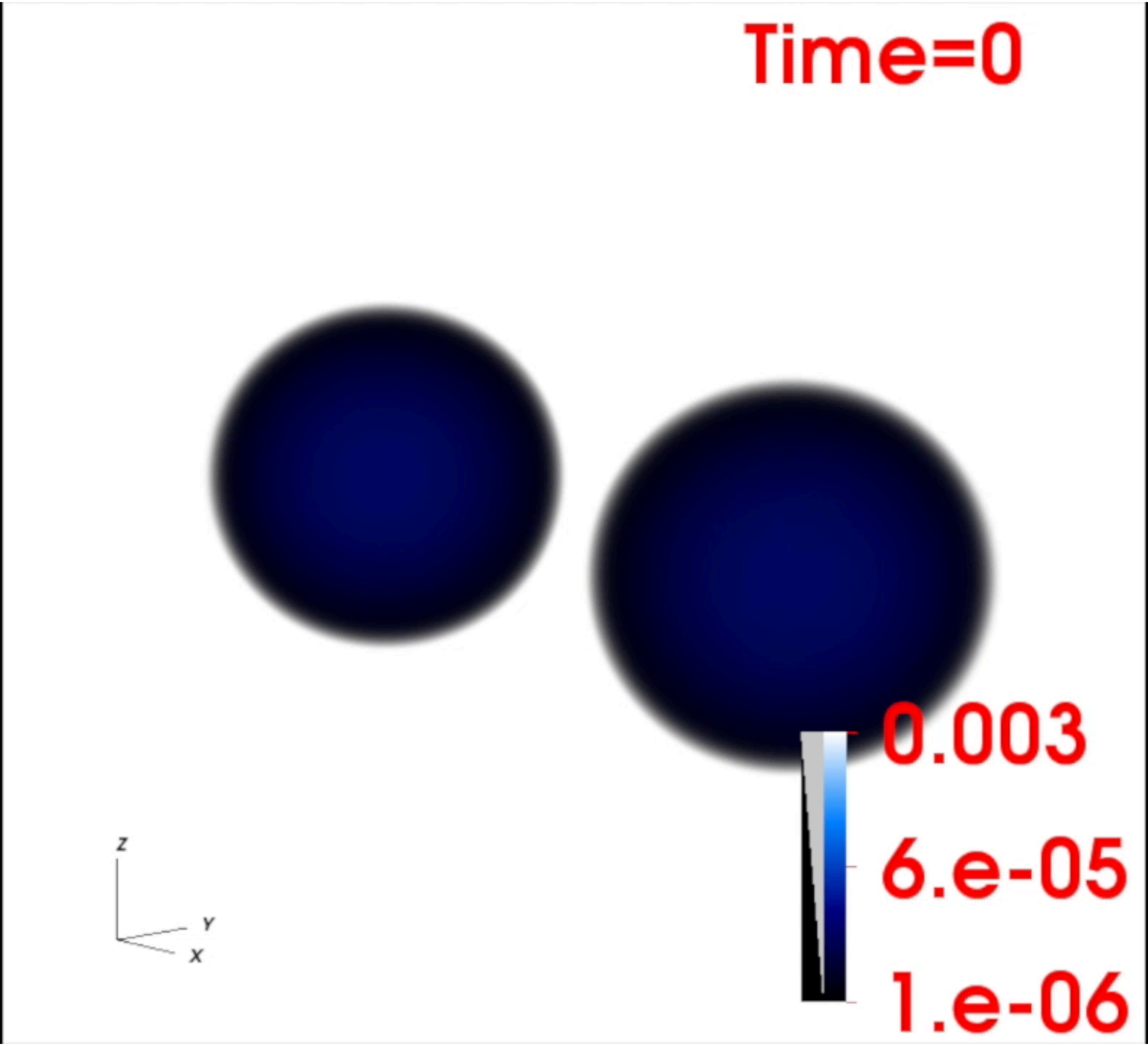


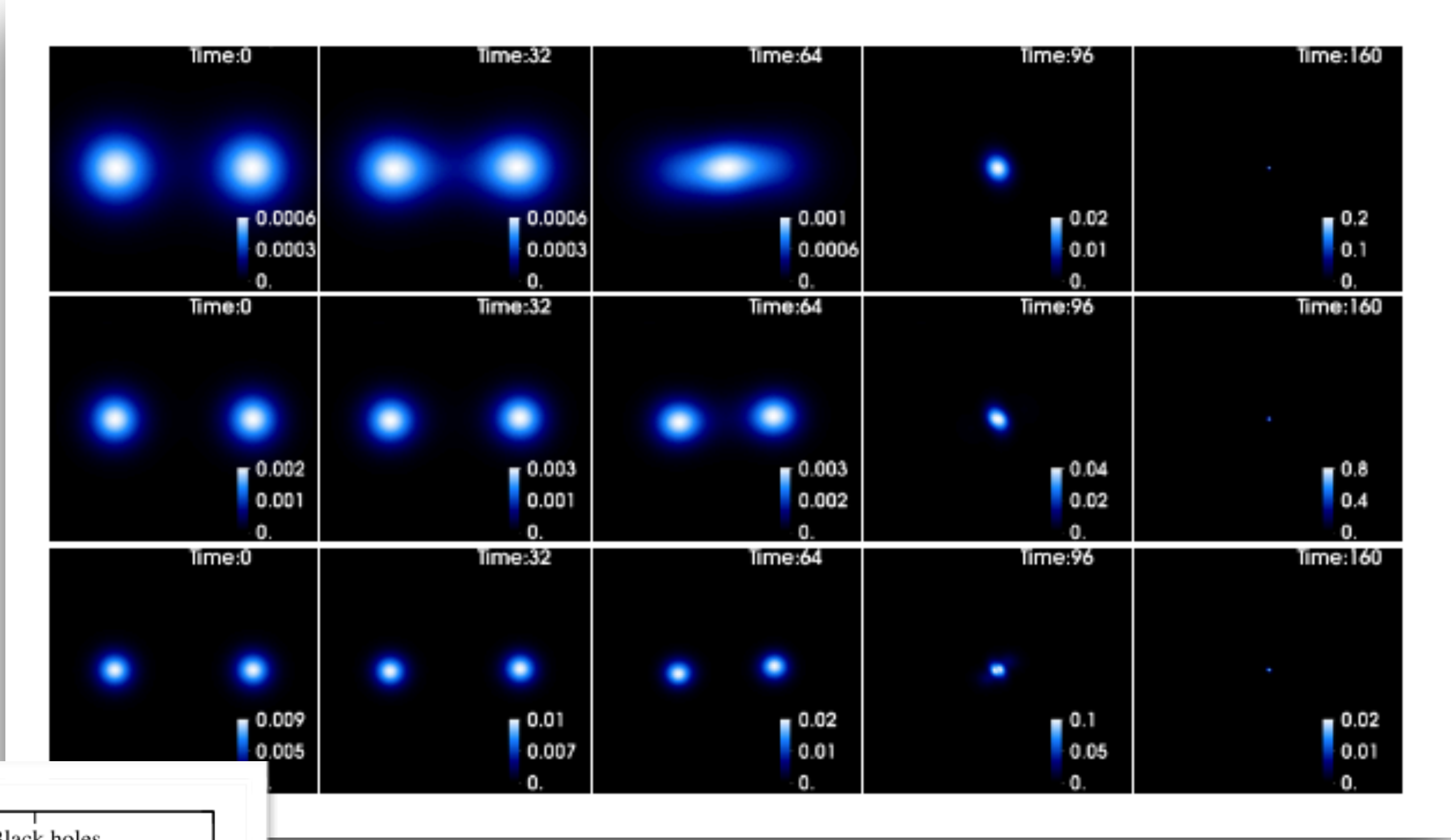
FIG. 2. Coalescence of binary BSs: Snapshots in time of the Noether charge density in the orbital plane. Each row corresponds to a different compactness (from top to bottom: 0.06, 0.12, 0.18, and 0.22). The collision of the stars happens at different times due to the different initial conditions and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

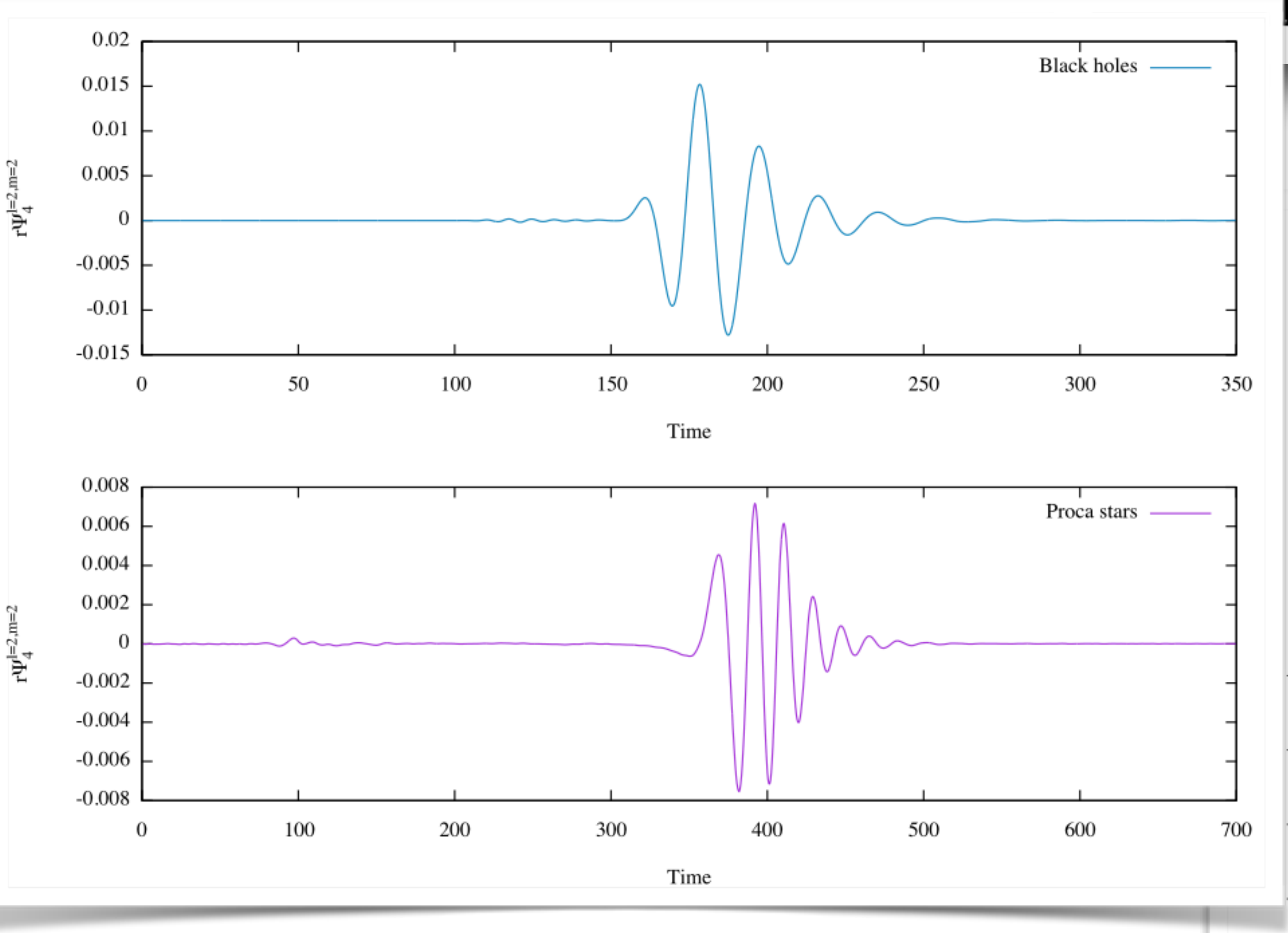
Palenzuela, C., Pani, P., Bezares, M., Cardoso, V., Lehner, L., & Liebling, S. (2017). Gravitational wave signatures of highly compact boson star binaries. ***Physical Review D*, *96***(10), 104058.

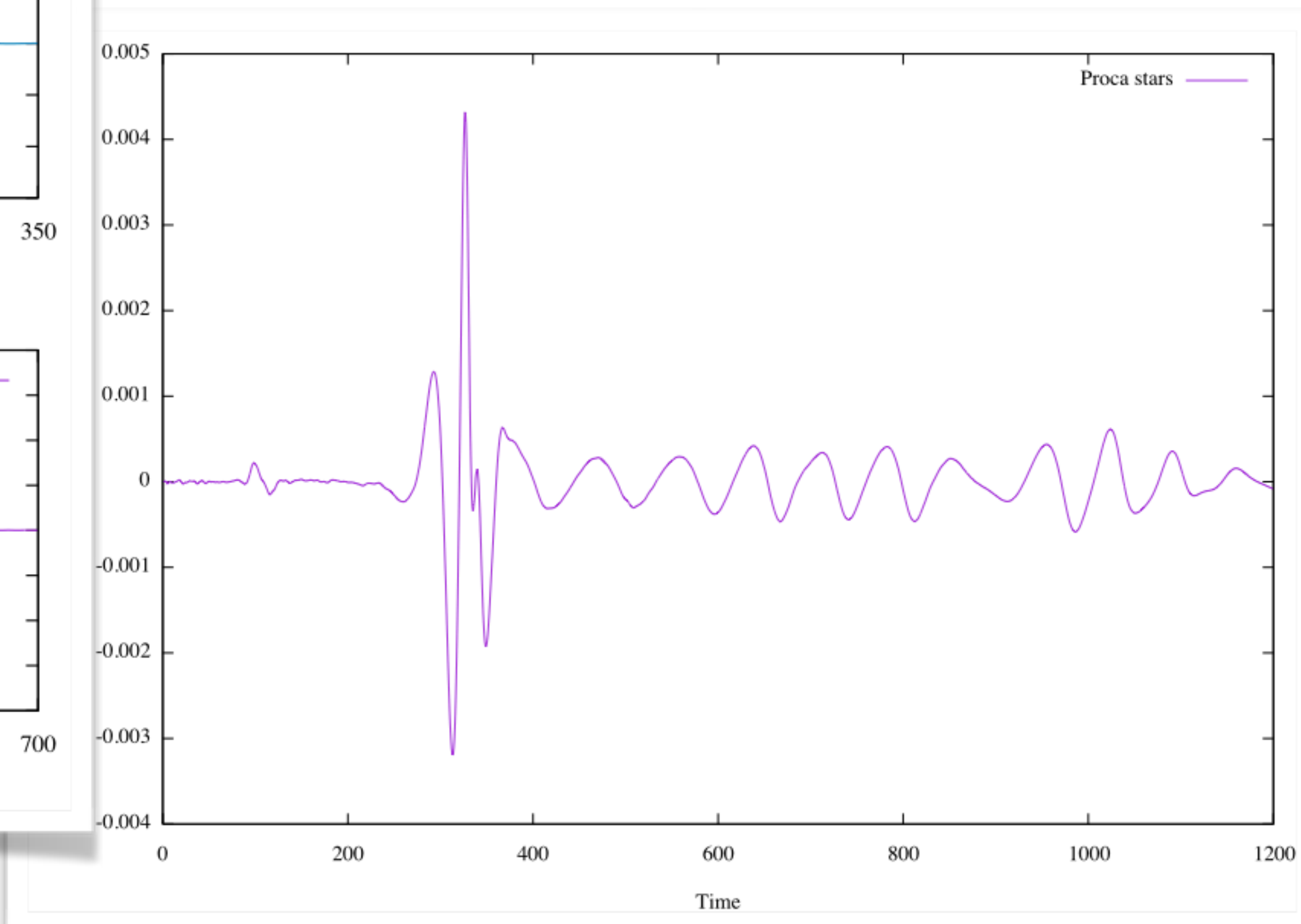


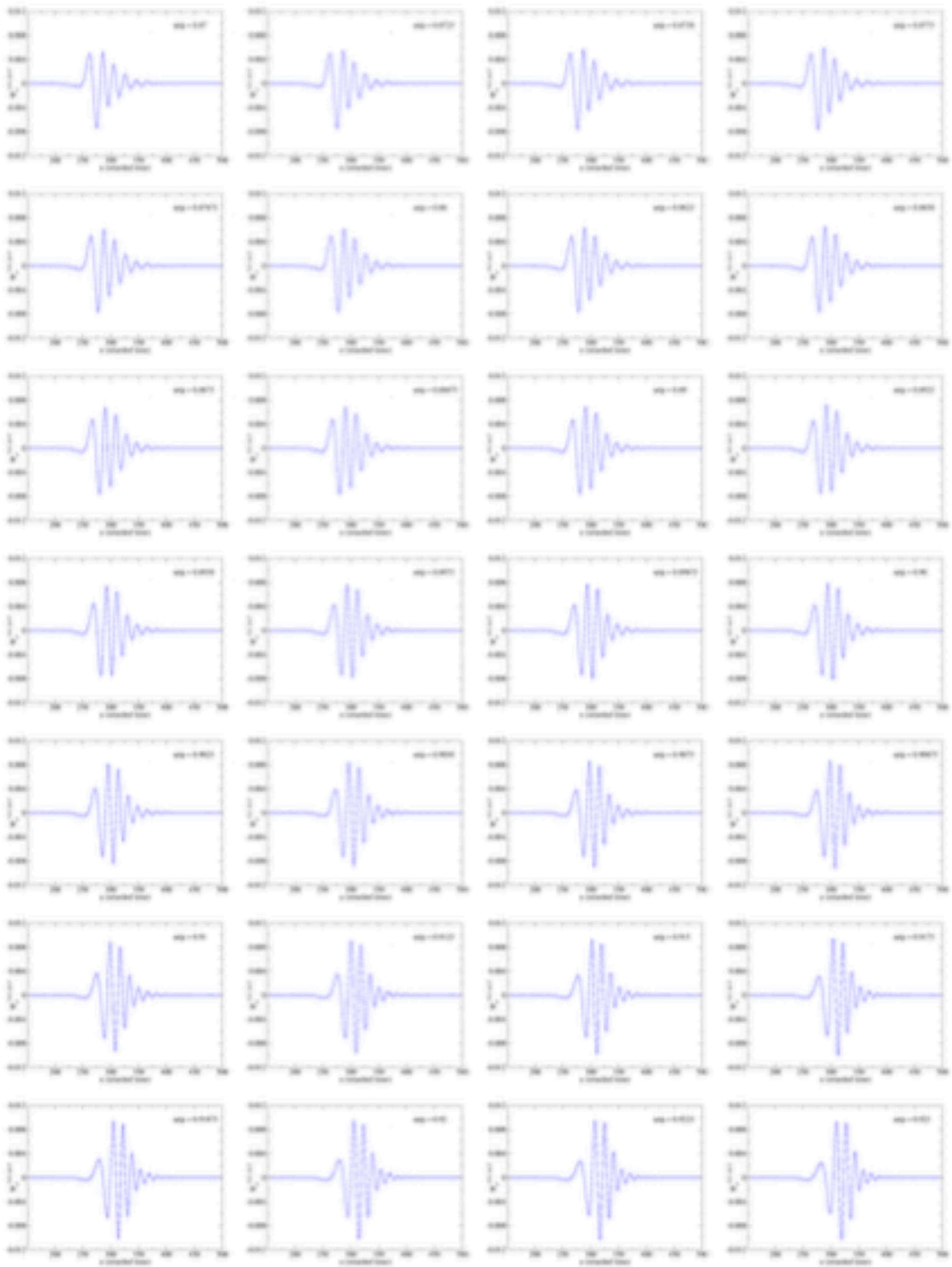
Time=0
0.003
6.e-05
1.e-06
Z
Y
X

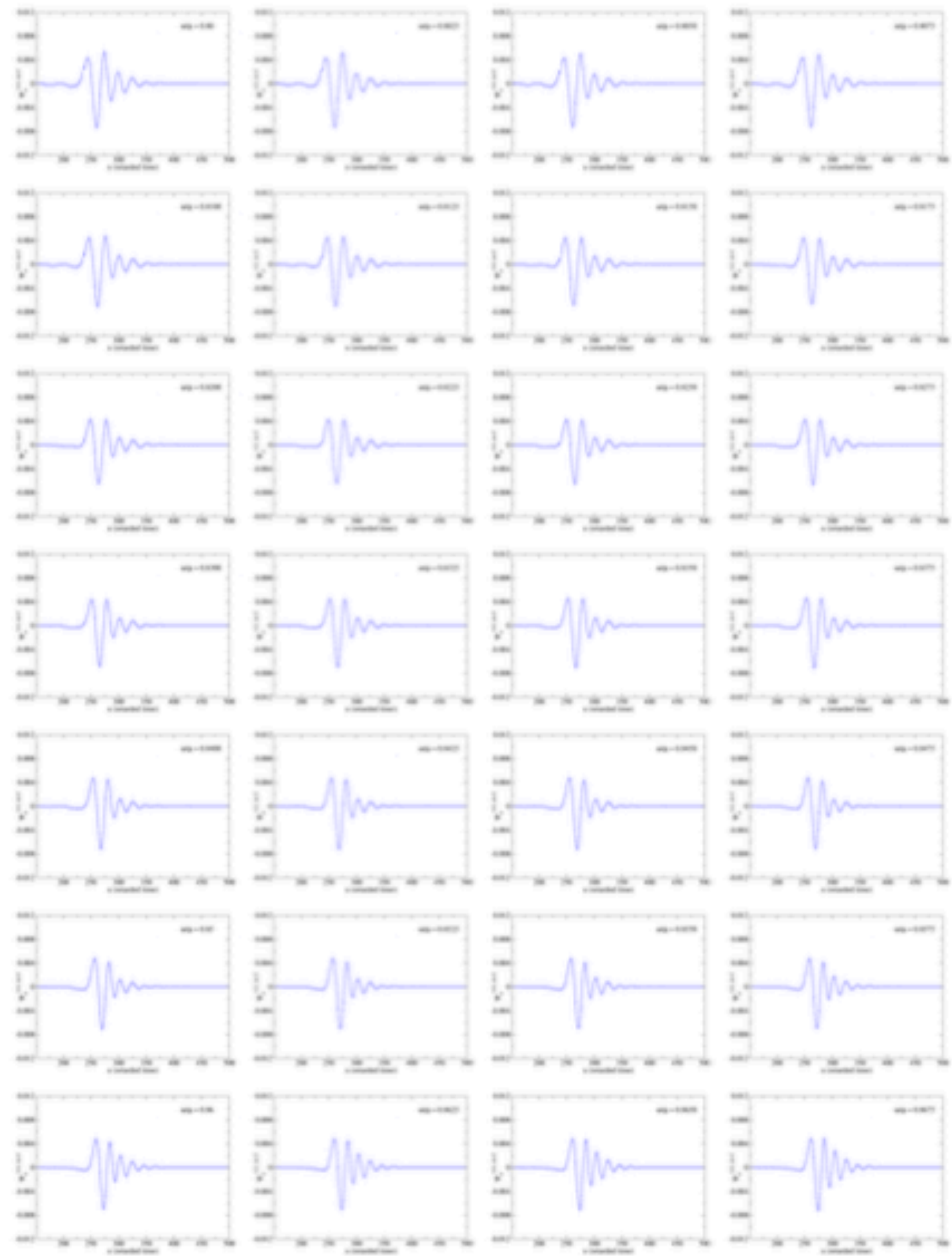
Head-on collisions of spinning Proca stars and Kerr black holes.

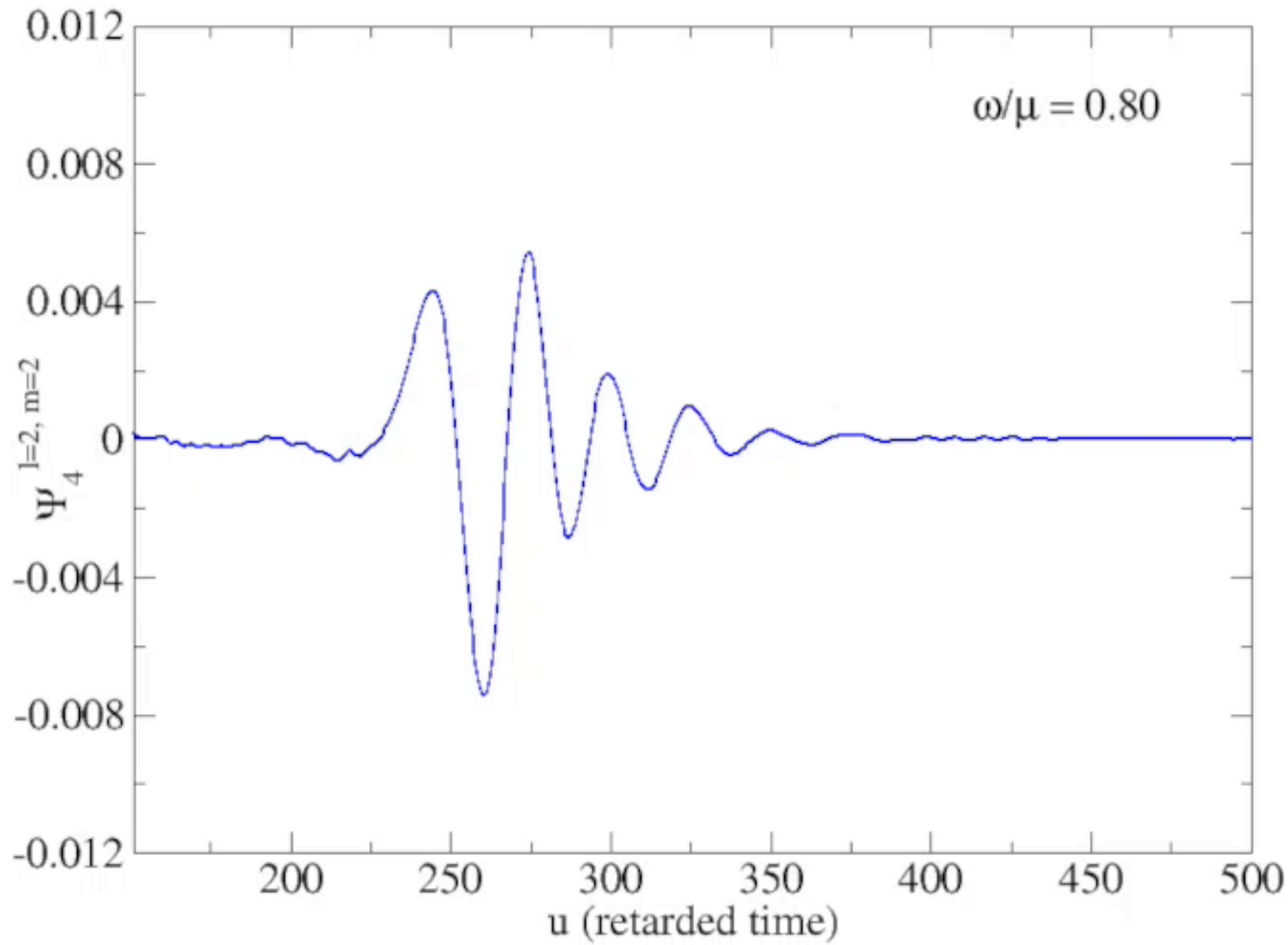




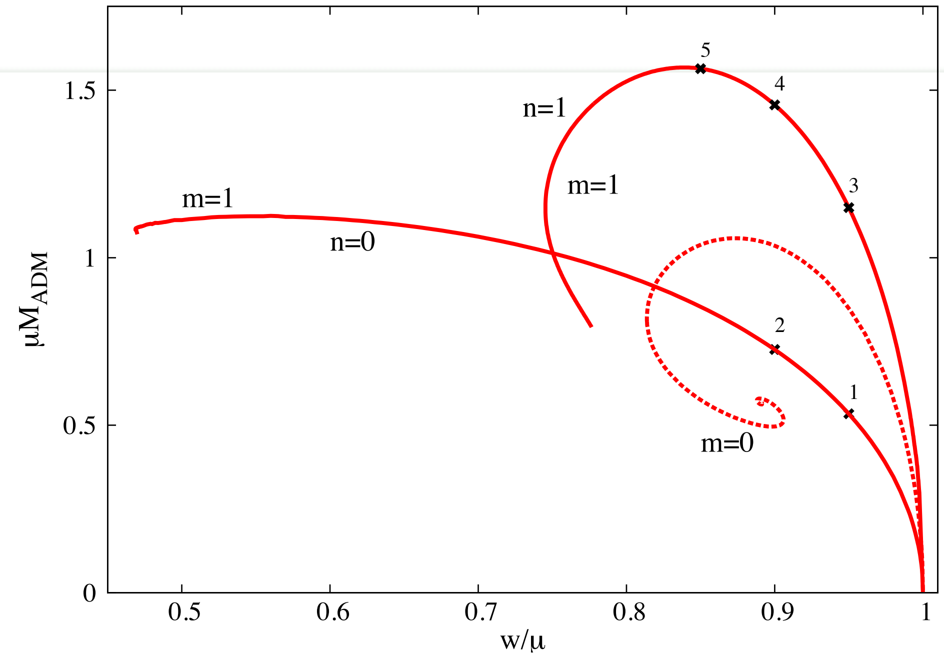




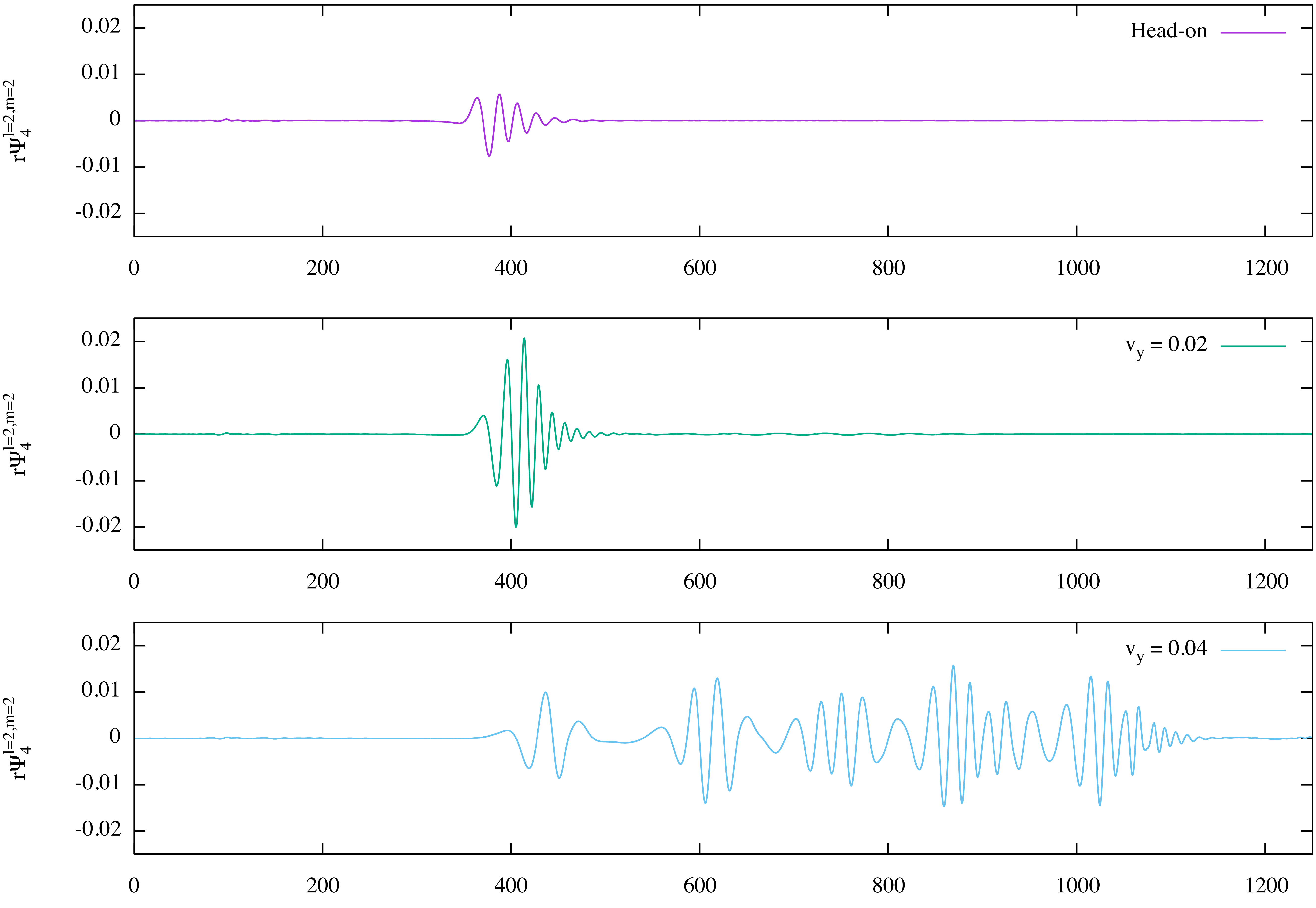




ω/μ = 0.80
$\Psi_4^{l=2,\ m=2}$
u (retarded time)
0.012
0.008
0.004
0
-0.004
-0.008
-0.012
200
250
300
350
400
450
500



μM_{ADM}
w/μ
n=1
m=1
m=1
n=0
m=0
1
2
3
4
5
0
0.5
1
1.5
0.5
0.6
0.7
0.8
0.9
1

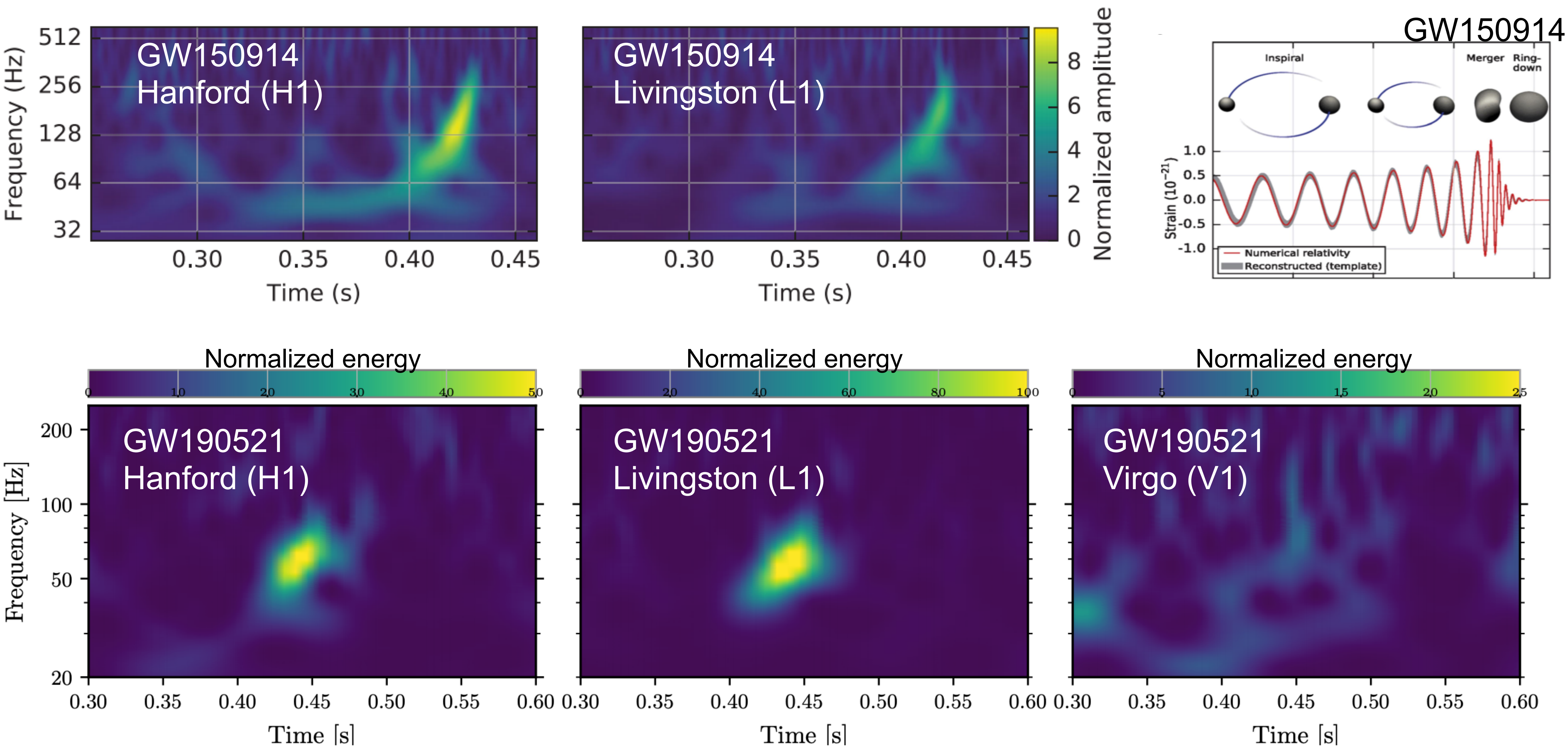


Head-on
$v_y = 0.02$
$v_y = 0.04$
$r\Psi_4^{l=2,m=2}$
$r\Psi_4^{l=2,m=2}$
$r\Psi_4^{l=2,m=2}$
0.02
0.01
0
-0.01
-0.02
0
200
400
600
800
1000
1200

GW EVENTS

GW190521 signal morphology

Slides from Juan Calderón-Bustillo's talk. Workshop on Compact Objects, Gravitational Waves and Deep Learning, 2020



centra
center for astrophysics and gravitation

OzGrav

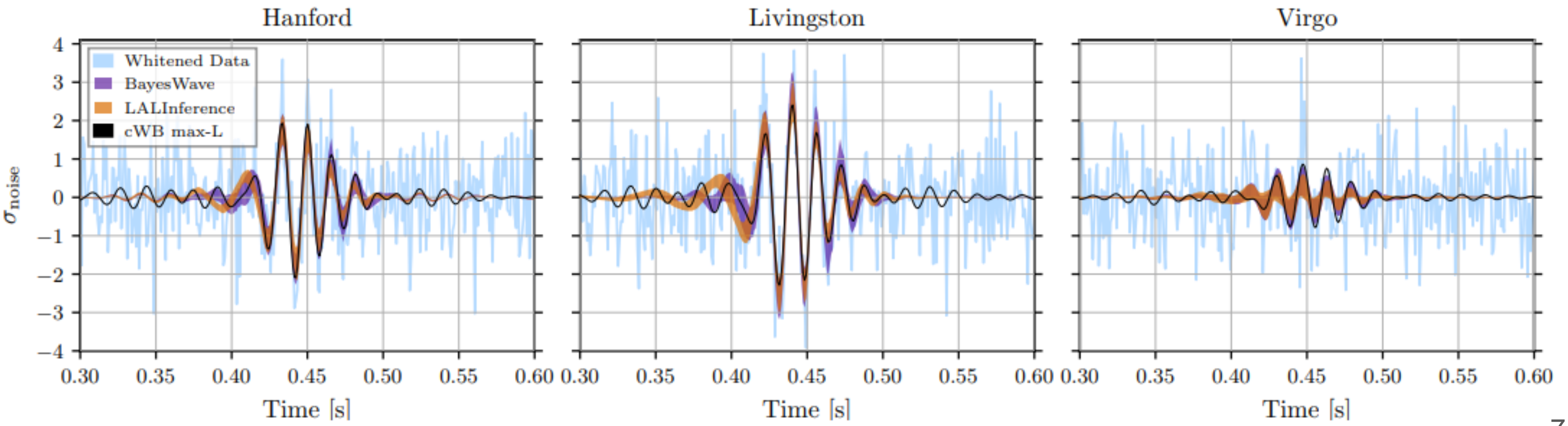
MONASH
University

GW190521 in LIGO Hanford, LIGO Livingston, Virgo

Slides from Juan Calderón-Bustillo's talk. Workshop on Compact Objects, Gravitational Waves and Deep Learning, 2020

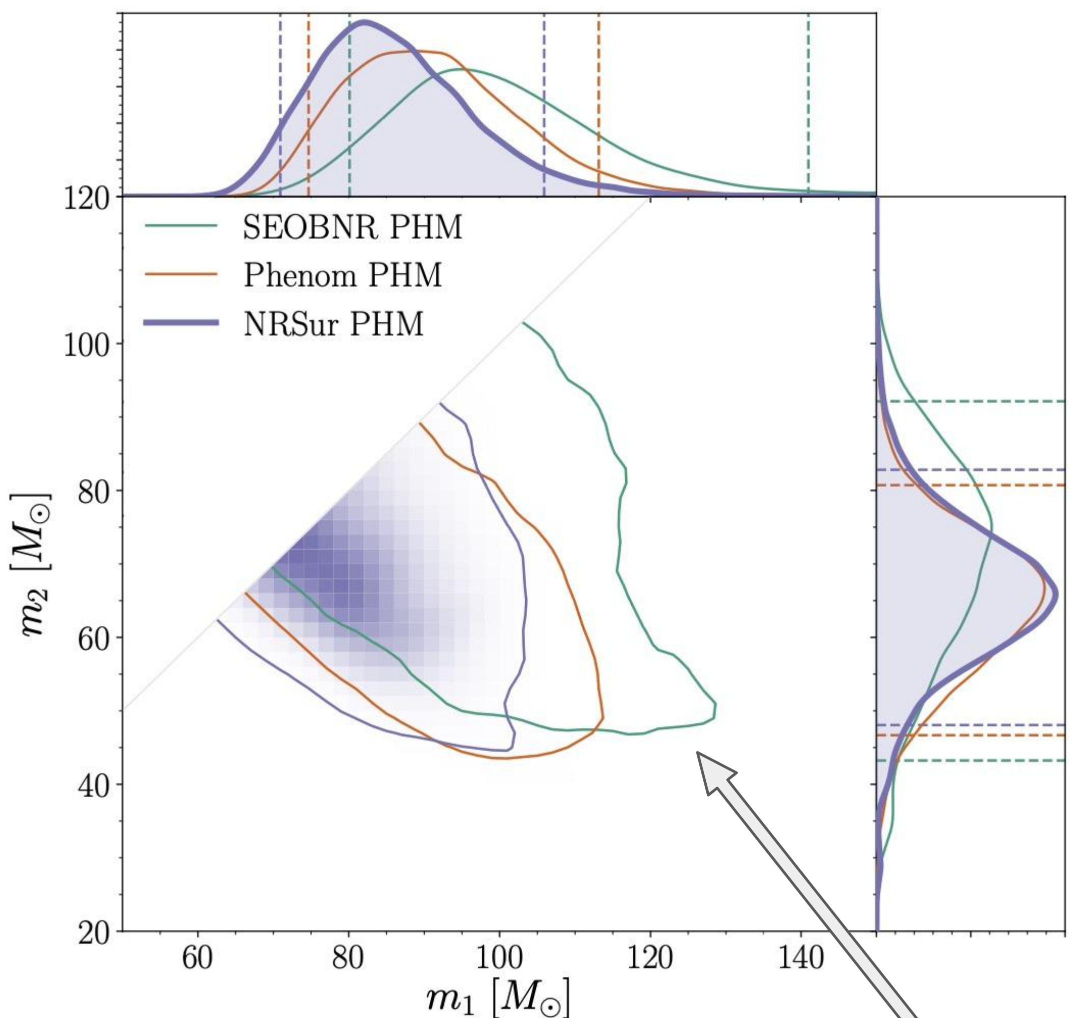
GW190521: A Binary Black Hole Merger with a Total Mass of $150M_{\odot}$

Properties and astrophysical implications of the $150\,M_{\odot}$ binary black hole merger GW190521



Masses

Slides from Juan Calderón-Bustillo’s talk. Workshop on Compact Objects, Gravitational Waves and Deep Learning, 2020



90% credible regions

- Most massive binary ever detected

$$M = 150^{+29}_{-17} M_\odot \qquad m_2/m_1 = 0.79^{+0.19}_{-0.29}$$

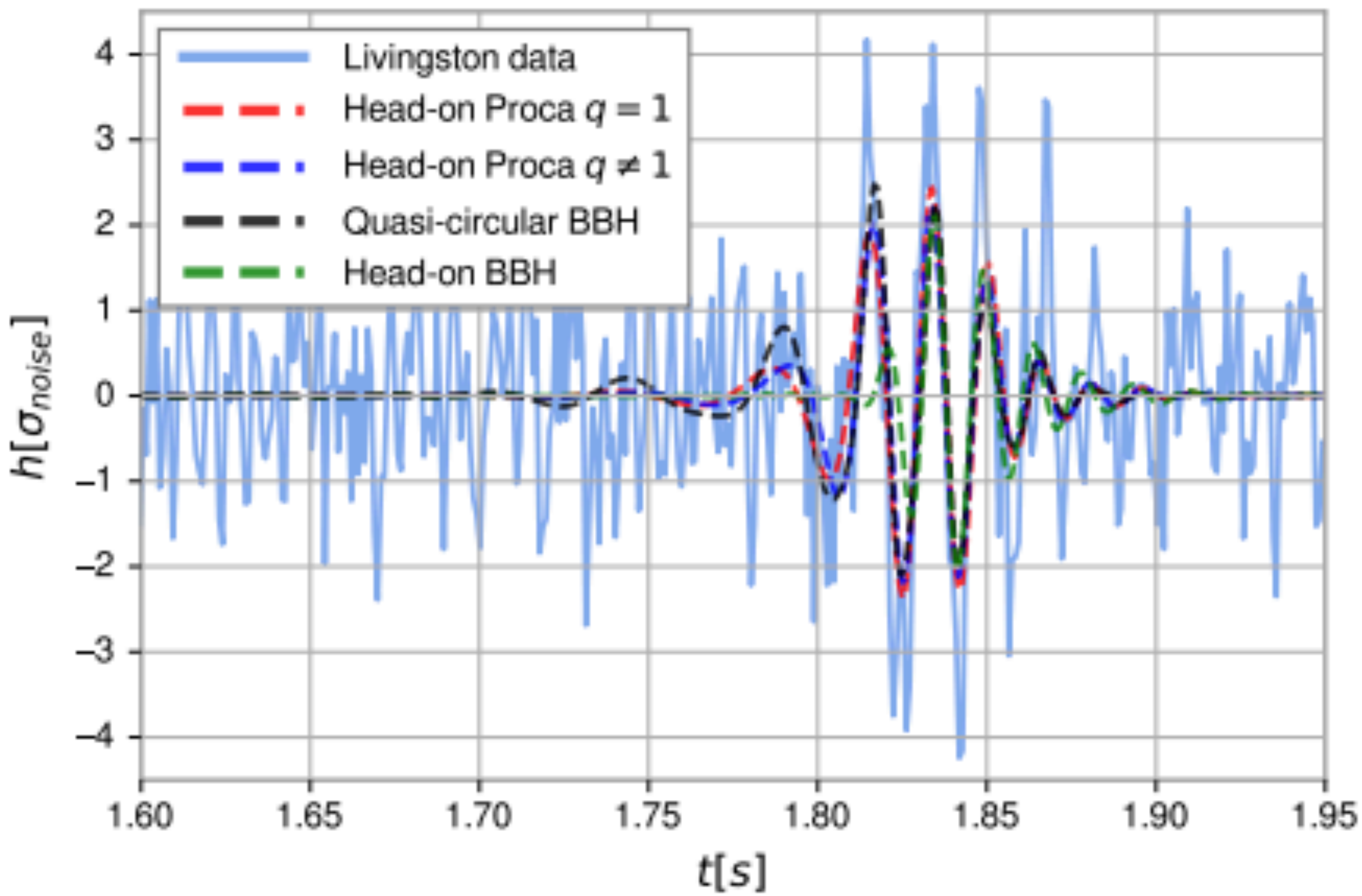
- Most massive colliding black holes

$$m_1 = 85^{+21}_{-14} M_\odot \qquad m_2 = 66^{+17}_{-18} M_\odot$$

- Masses within the pair instability supernova gap

$$P(m_1 < 65 M_\odot) = 0.32\%$$

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.



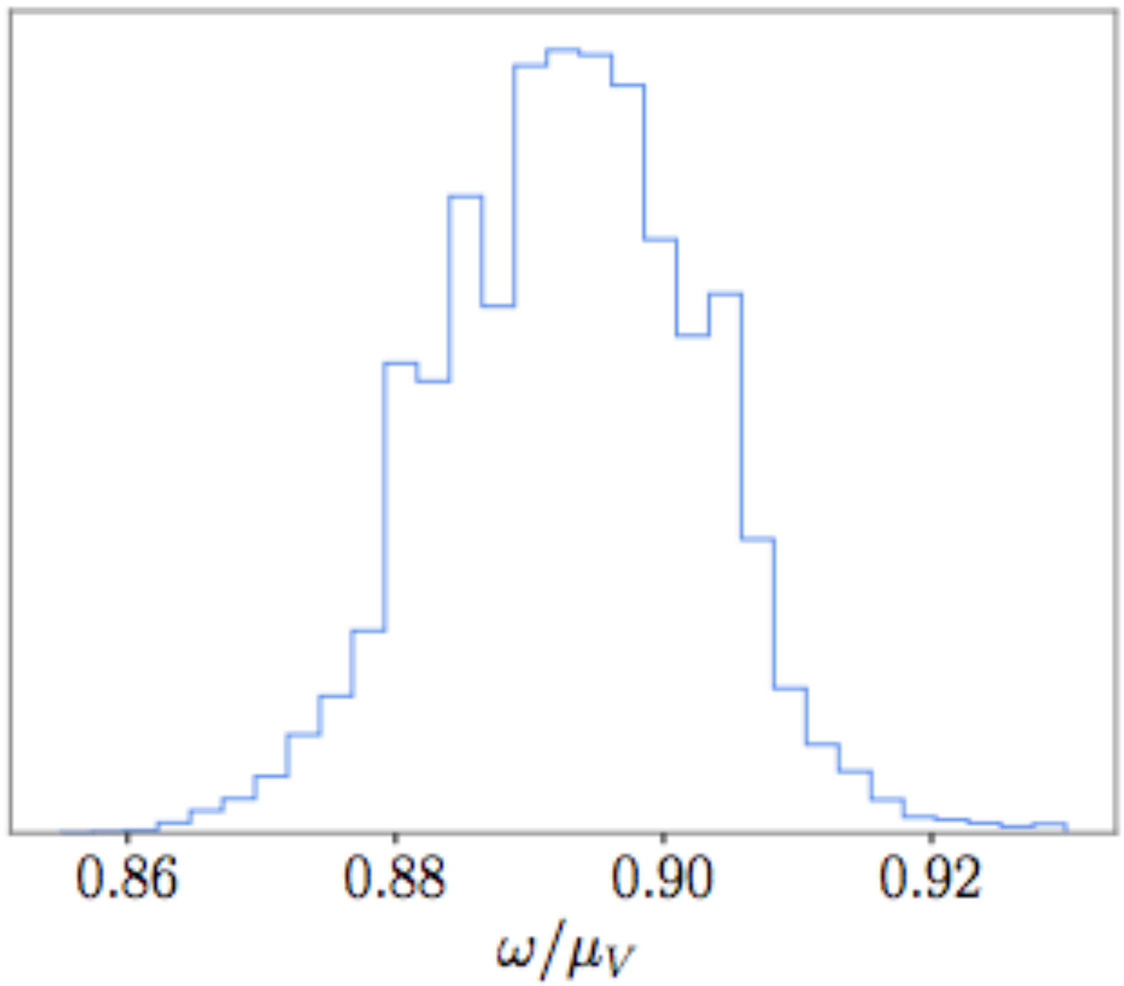
Proca stars?

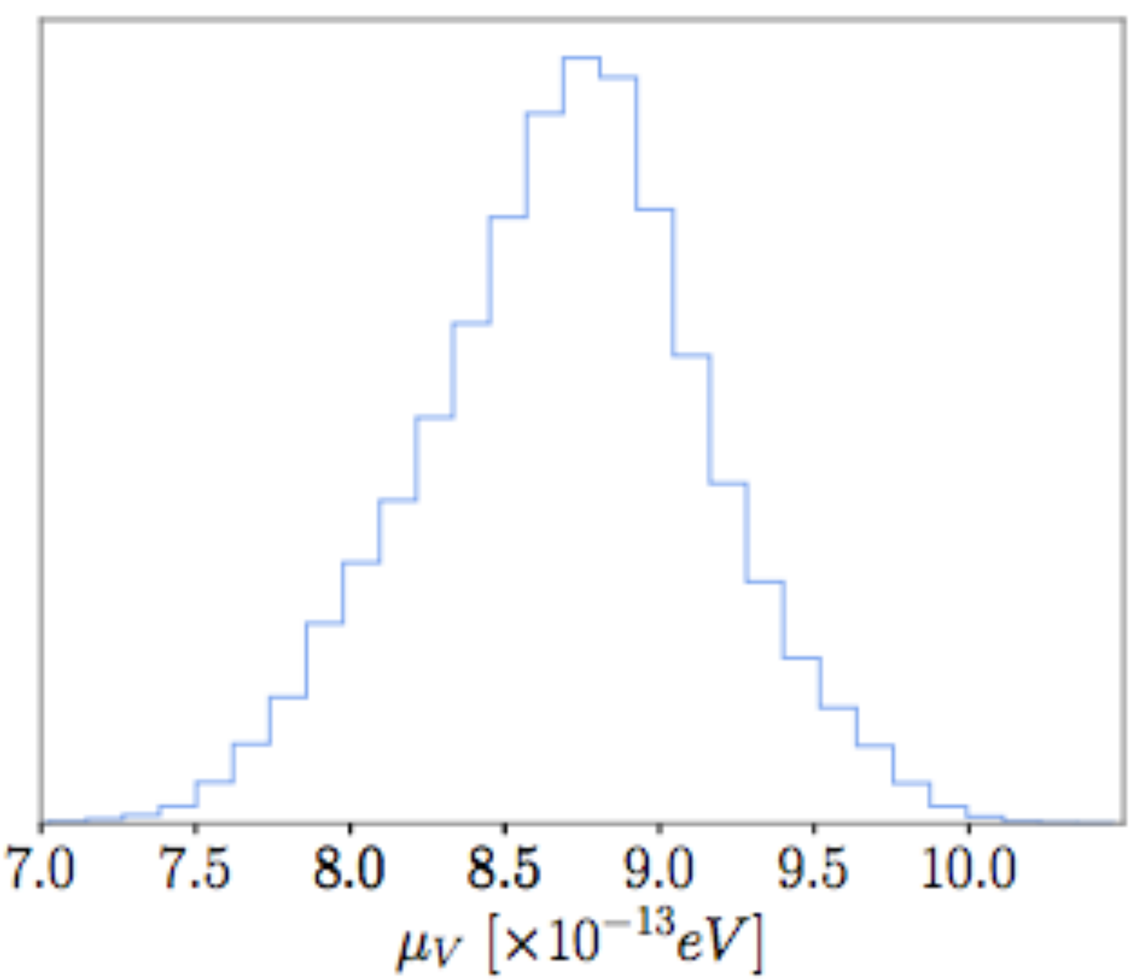
Waveform model	$\log \mathcal{B}$	$\log \mathcal{L}_{Max}$
Quasi-circular Binary Black Hole	80.1	105.2
Head-on Equal-mass Proca Stars	80.9	106.7
Head-on Unequal-mass Proca Stars	82.0	106.5
Head-on Binary Black Hole	75.9	103.2

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.





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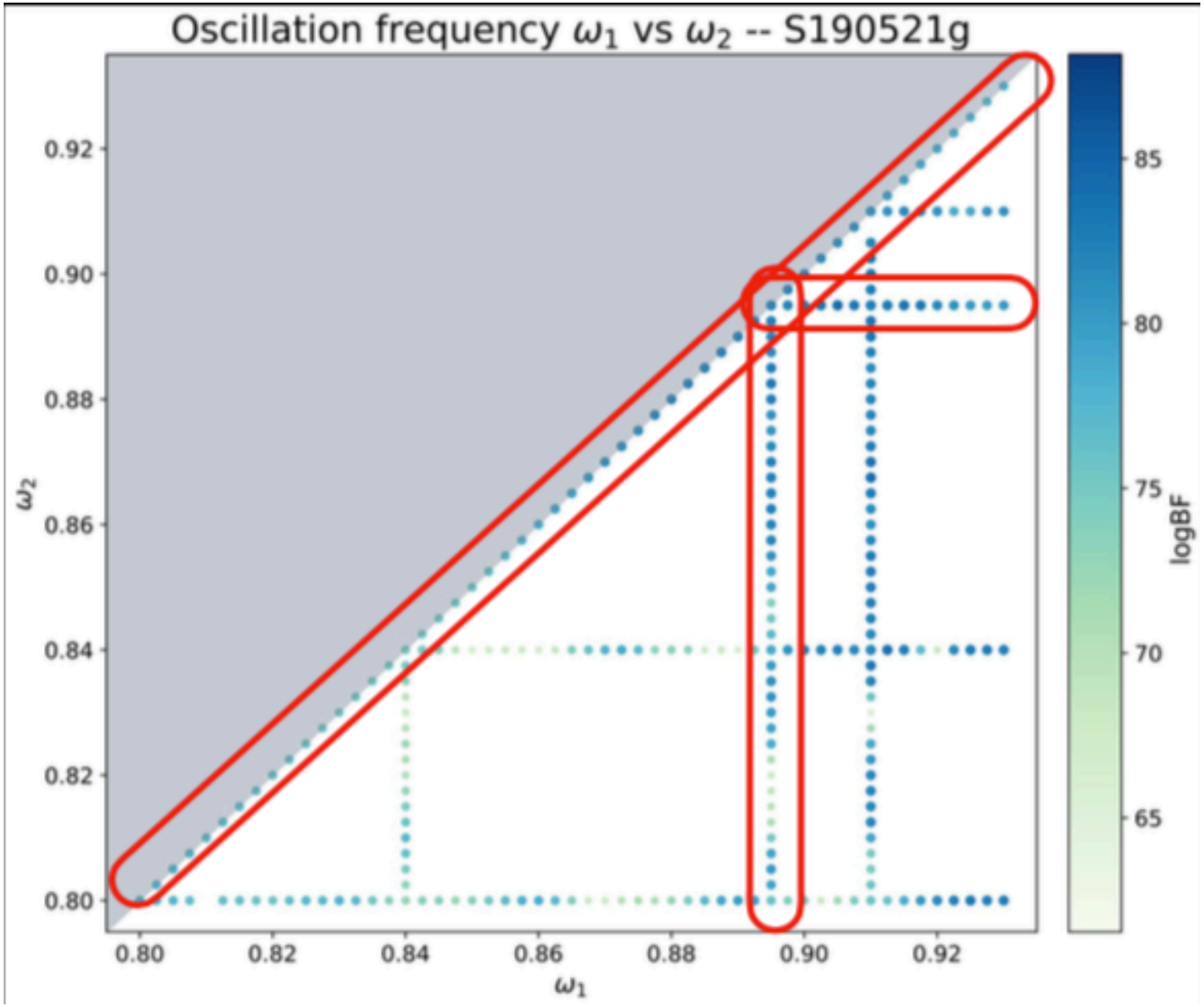
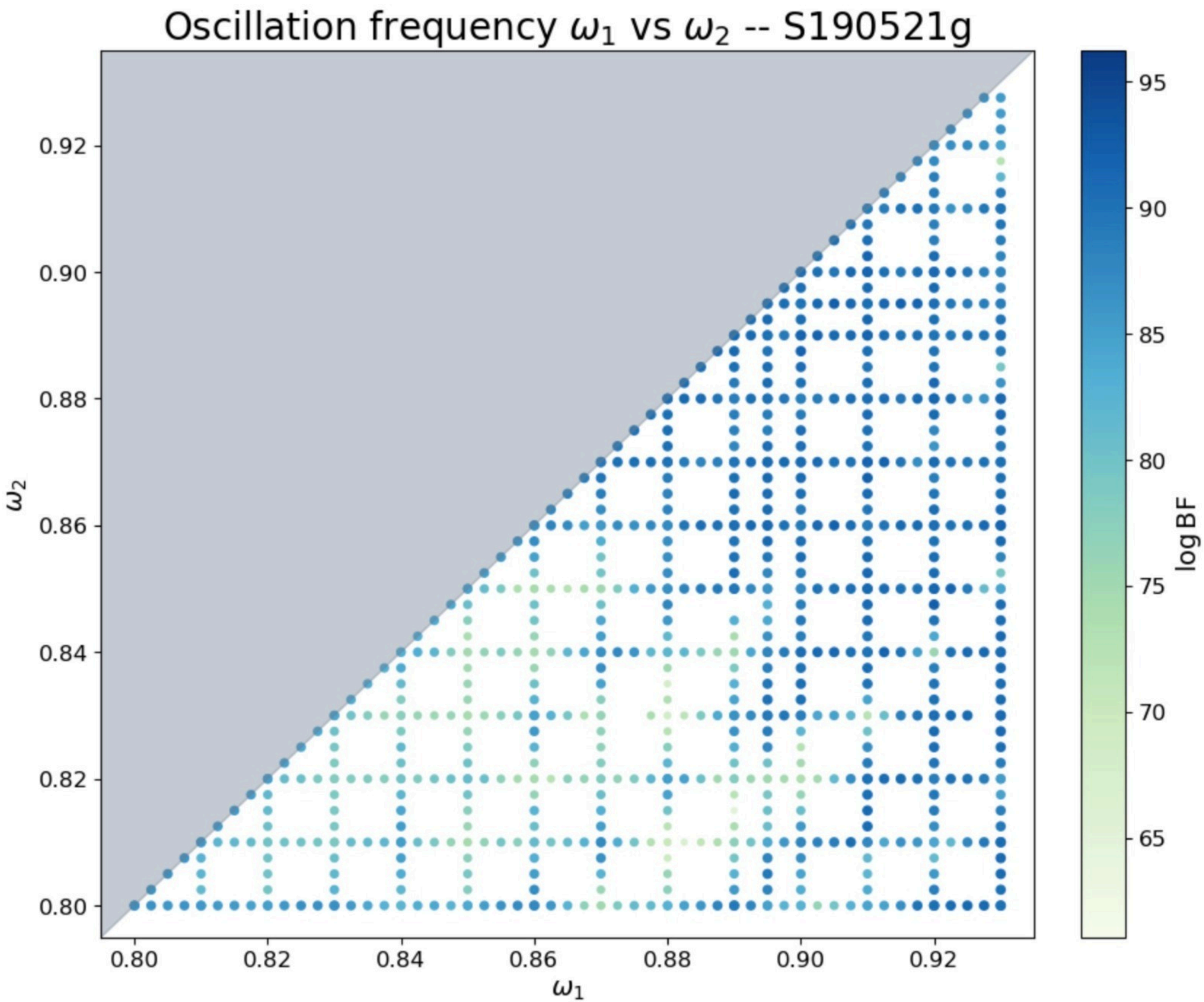
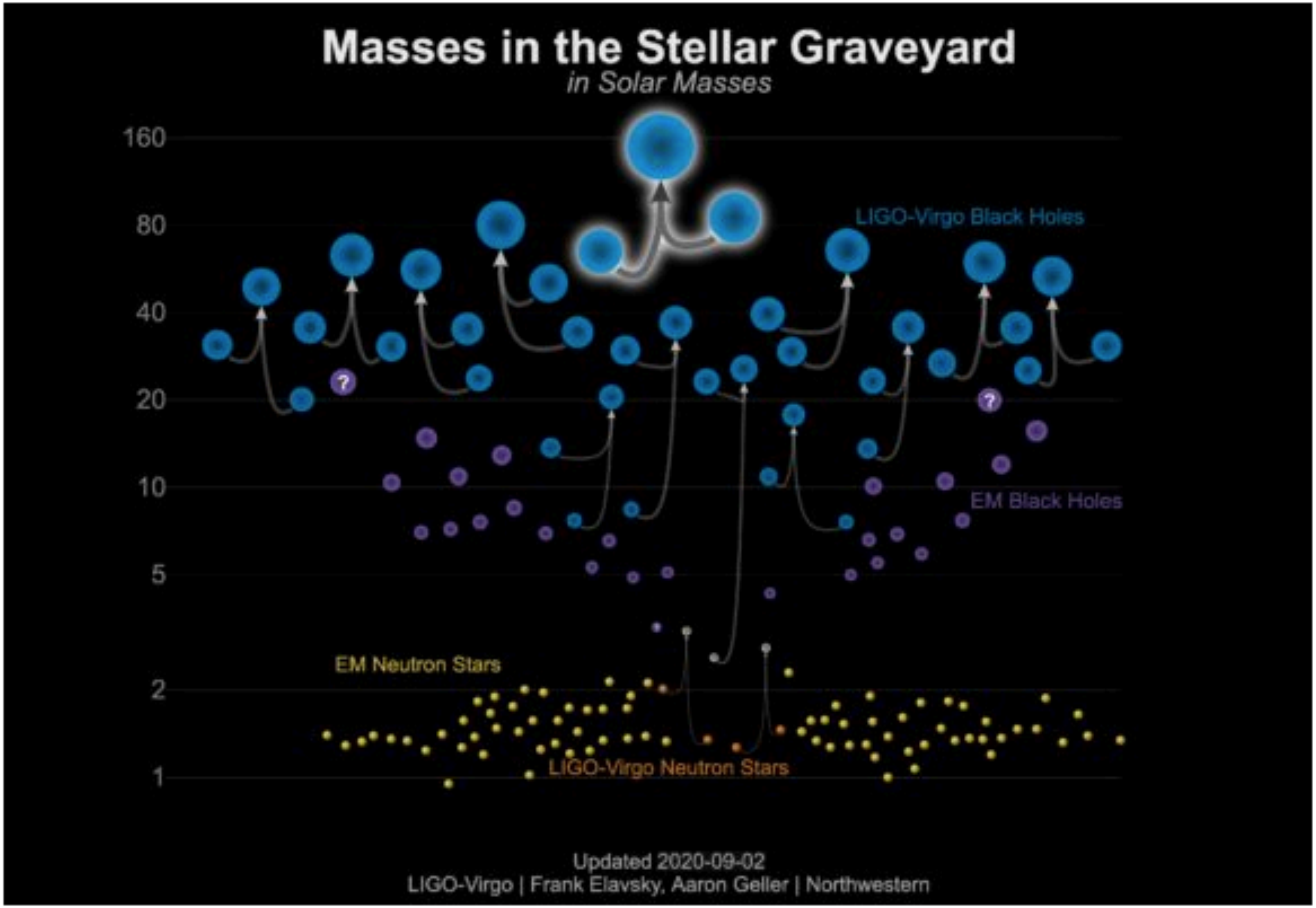
See Juan Calderón Bustillo's talk



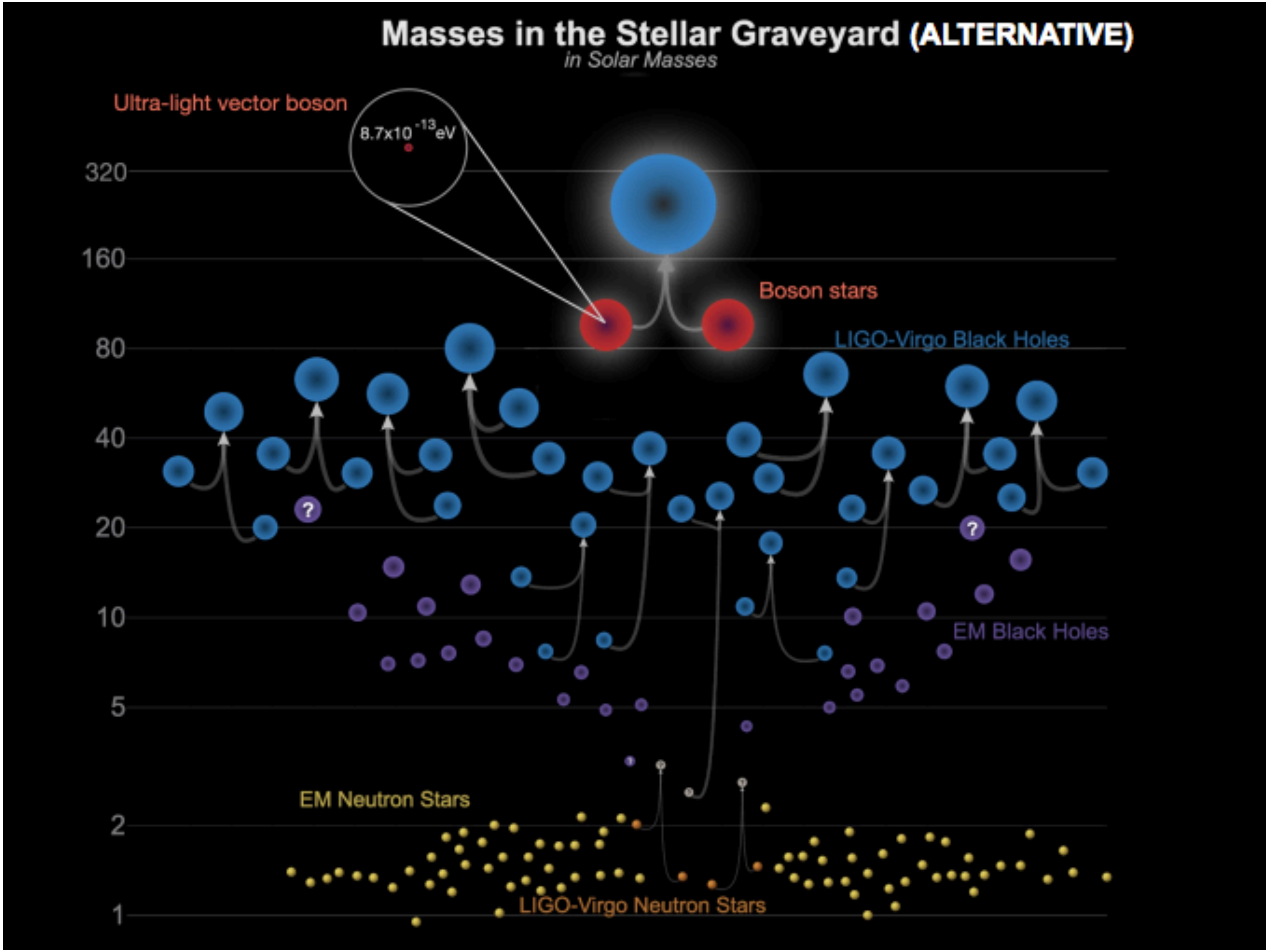
Oscillation frequency ω_1 vs ω_2 -- S190521g
ω_2
0.92
0.90
0.88
0.86
0.84
0.82
0.80
0.80
0.82
0.84
0.86
0.88
0.90
0.92
ω_1
85
80
75
70
65
logBF



Oscillation frequency ω_1 vs ω_2 -- S190521g
ω_2
0.80
0.82
0.84
0.86
0.88
0.90
0.92
ω_1
0.80
0.82
0.84
0.86
0.88
0.90
0.92
log BF
65
70
75
80
85
90
95



Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
Updated 2020-09-02
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern



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

200114_020818 (preliminary)

LIGO Scientific Collaboration, Virgo Collaboration, & KAGRA Collaboration. (2021). Search for intermediate mass black hole binaries in the third observing run of Advanced LIGO and Advanced Virgo. *arXiv preprint arXiv:2105.15120*.

200114_020818

- **Second IMBH** trigger reported by LVC (but low significance).
- **Not ruled out** as Proca star merger.
- $\mu_V = 10.23 \times 10^{-13}\,\mathrm{eV}$

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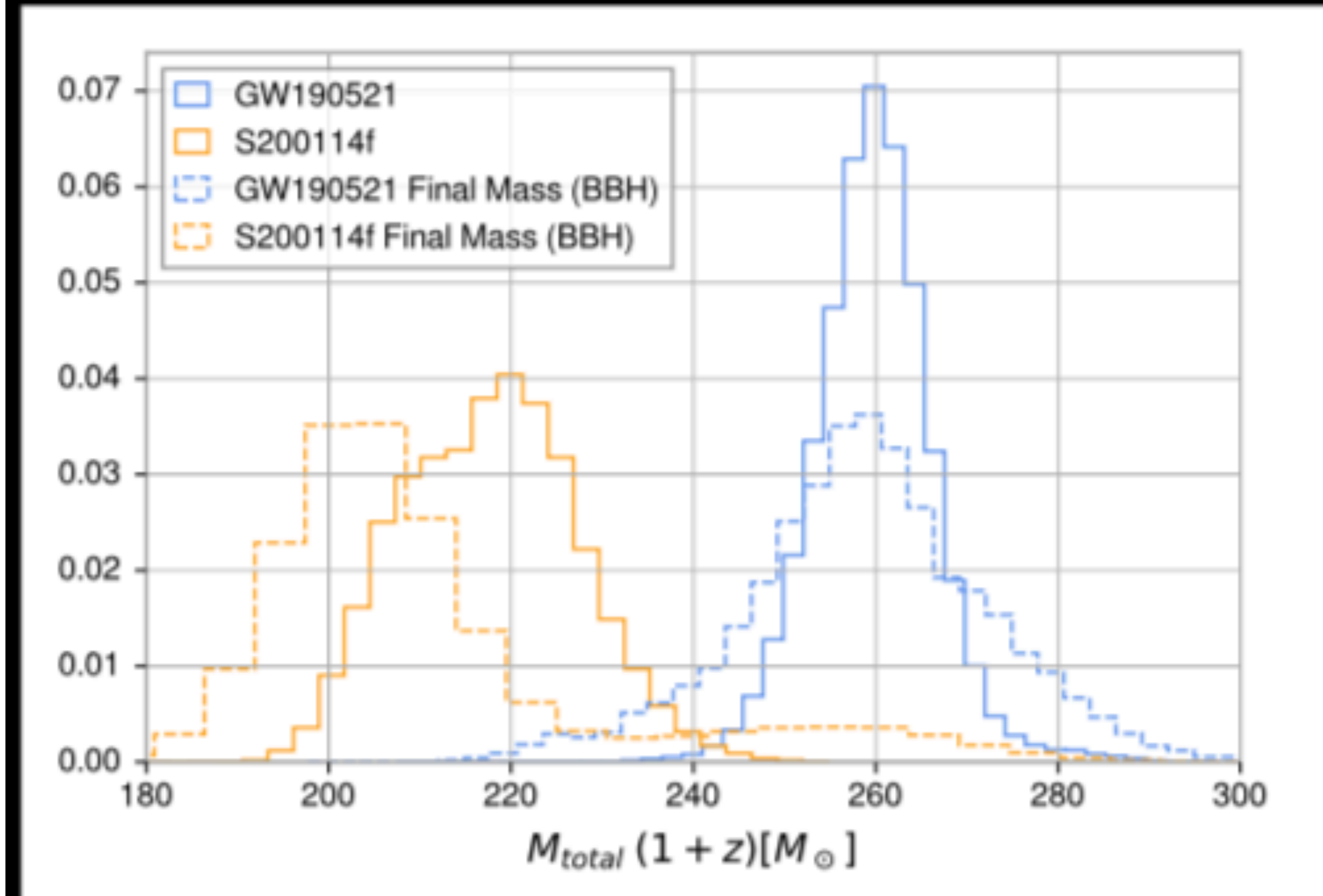
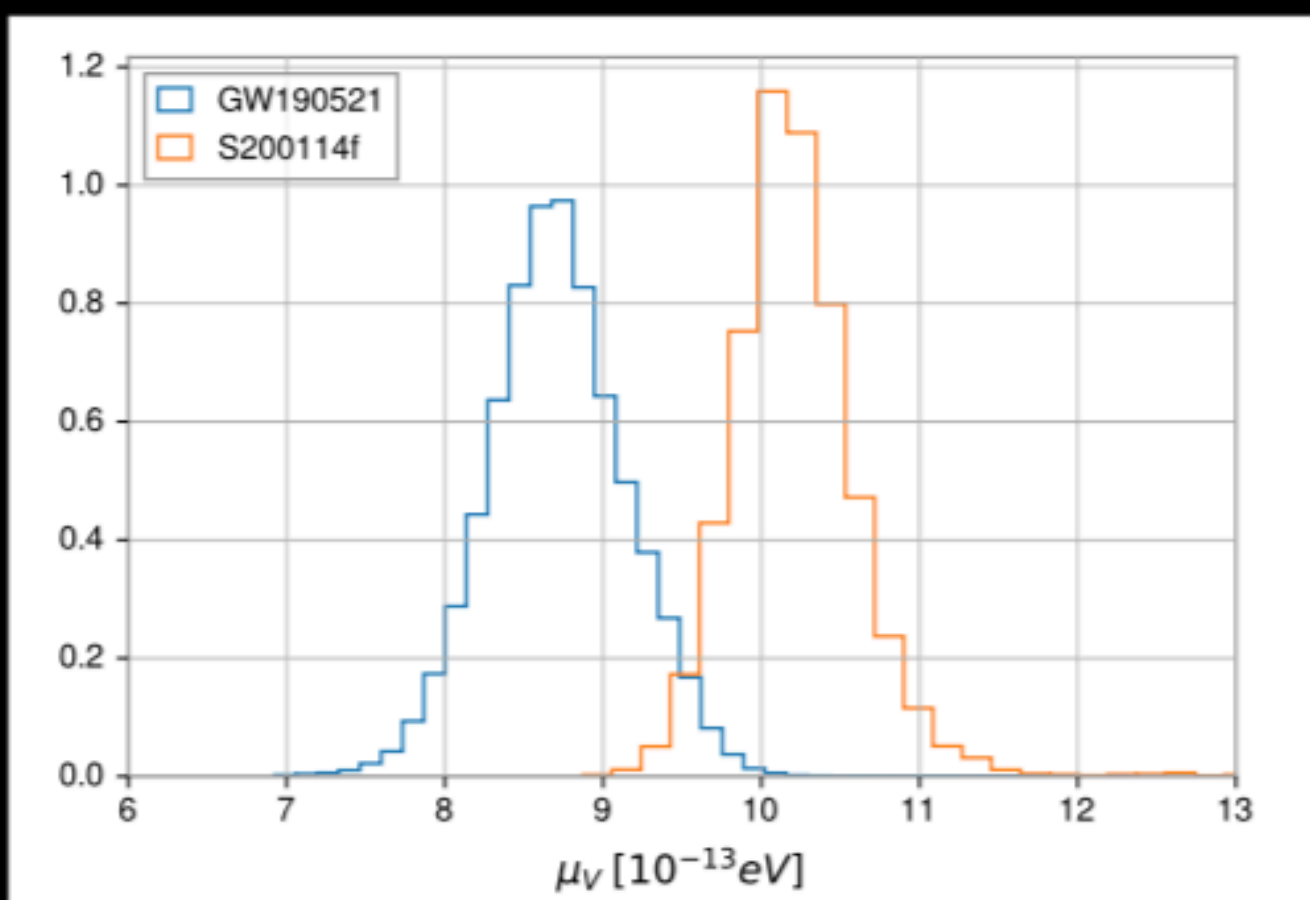


Parameter	GW190521	S200114f
Primary mass	$124^{+17}_{-12}\,M_\odot$	$113^{+9}_{-9}\,M_\odot$
Secondary mass	$95^{+10}_{-13}\,M_\odot$	$97^{+8}_{-10}\,M_\odot$
Total / Final mass	$231^{+15}_{-16}\,M_\odot$	$217^{+16}_{-16}\,M_\odot$
Final spin	$0.75^{+0.08}_{-0.04}$	$0.75^{+0.08}_{-0.04}$
Inclination $\pi/2 - \lvert\iota - \pi/2\rvert$	$0.66^{+0.37}_{-0.45}$ rad	$0.93^{+0.39}_{-0.29}$ rad
Azimuth	$0.65^{+0.86}_{-0.54}$ rad	$0.78^{+1.23}_{-1.20}$ rad
Luminosity distance	571^{+348}_{-181} Mpc	155^{+80}_{-52} Mpc
Redshift	$0.12^{+0.07}_{-0.05}$	$0.034^{+0.025}_{-0.012}$
Total / Final redshifted mass	$259^{+10}_{-10}\,M_\odot$	$217^{+16}_{-16}\,M_\odot$
Primary boson field frequency ω/μ_V	$0.880^{+0.032}_{-0.080}$	$0.845^{+0.020}_{-0.035}$
Secondary boson field frequency ω/μ_V	$0.910^{+0.015}_{-0.015}$	$0.895^{+0.017}_{-0.015}$
Boson mass μ_V [$\times 10^{-13}$]	$8.70^{+0.75}_{-0.69}$ eV	$10.19^{+0.65}_{-0.55}$ eV
Maximal boson star mass	$173^{+15}_{-14}\,M_\odot$	$147^{+8}_{-9}\,M_\odot$



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CONCLUSIONS

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- **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 observing**
- **Second, low significance trigger S200114**
- **Consistent masses at 90% C.I.**
- **Is there (ultra-)light in the dark?**
- **Is it time to *Proc & Roll*?**

THANK YOU!