NICOLÁS SANCHIS-GUAL

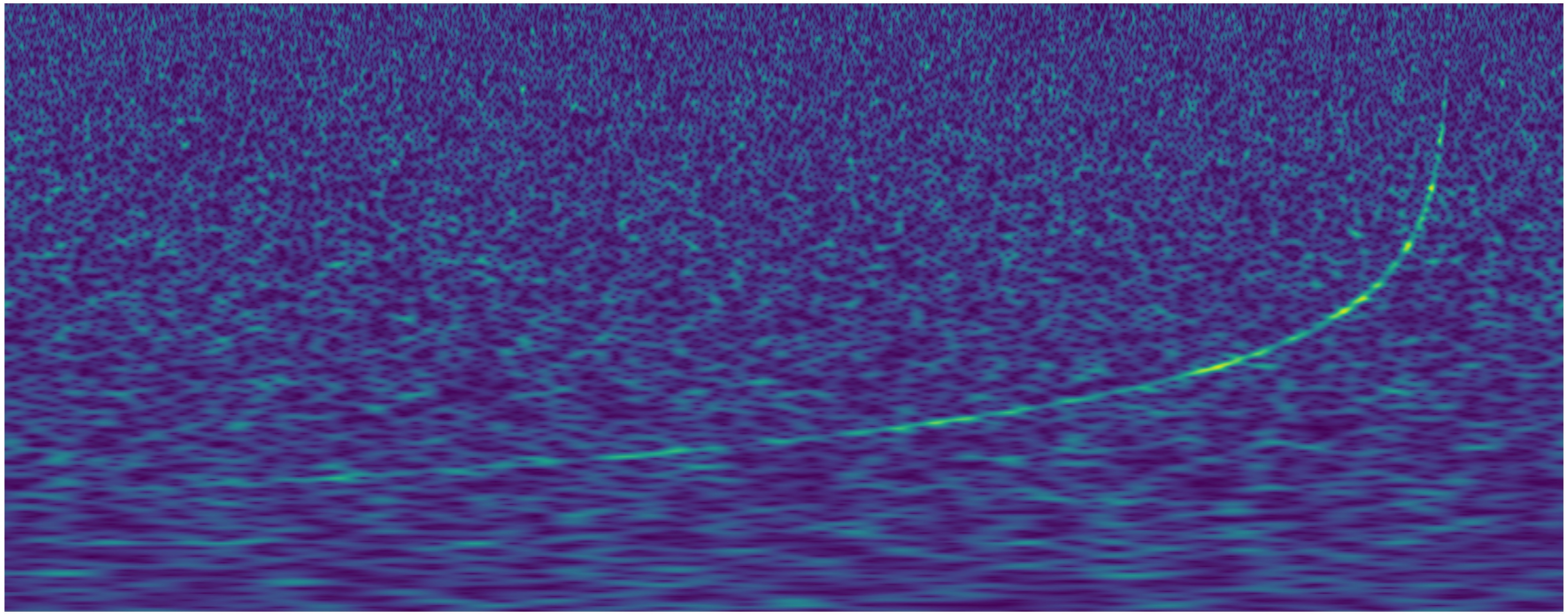
DEPARTAMENTO DE ASTRONOMÍA Y ASTROFÍSICA - UNIVERSITY OF VALENCIA

12TH IBERIAN GRAVITATIONAL WAVES MEEETING - BRAGA - PORTUGAL

A NUMERICAL-RELATIVITY GRAVITATIONAL-WAVE CATALOGUE OF SPINNING PROCA-STAR COLLISIONS

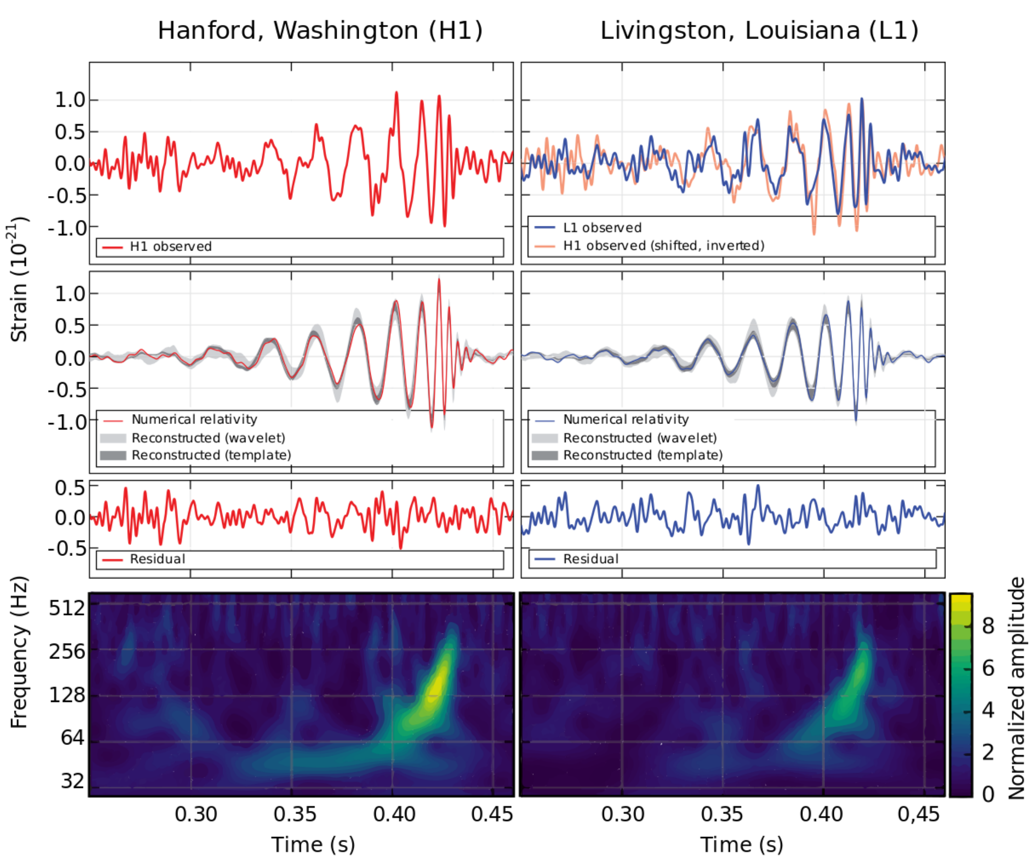
MOTIVATION

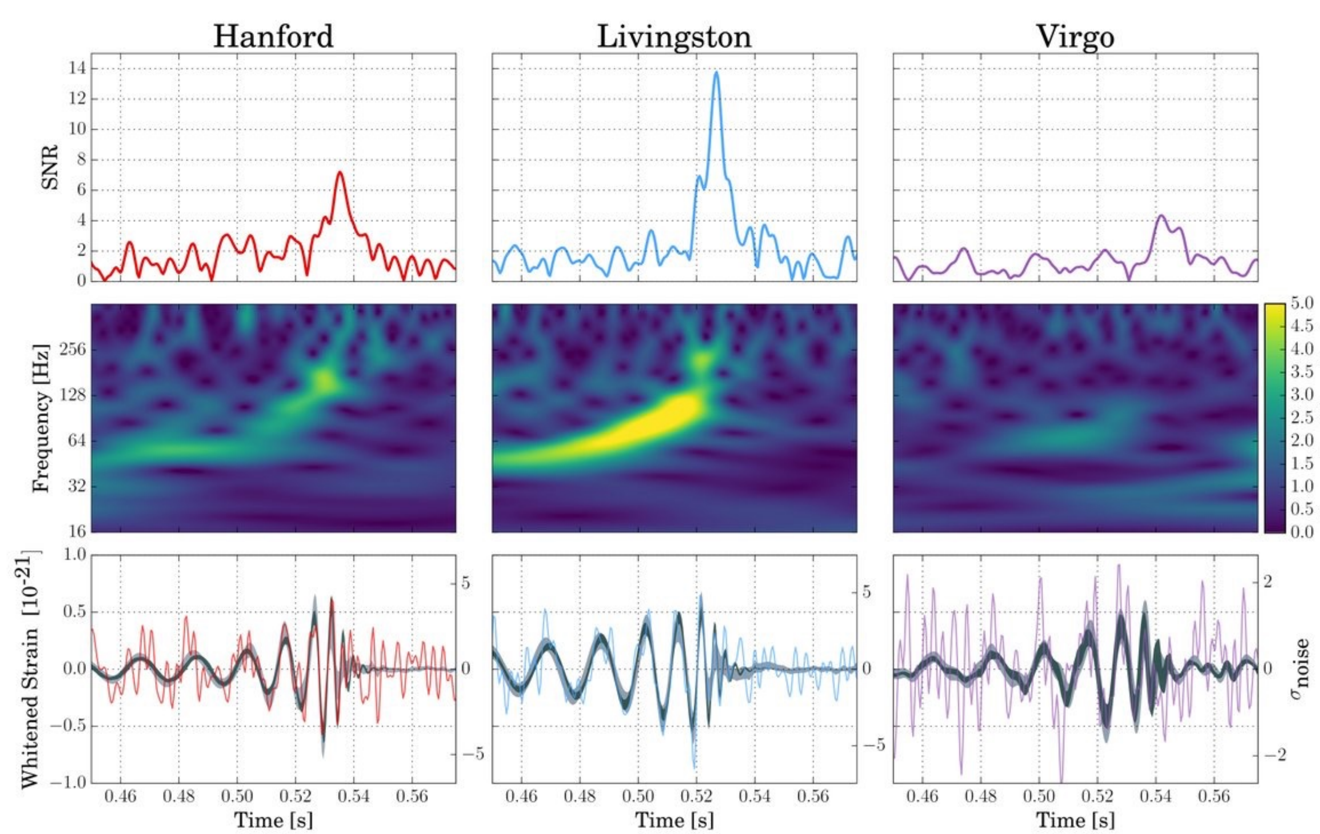
Abbott, B. P., Abbott, R., Abbott, T. D., Acernese, F., Ackley, K., Adams, C., ... & Affeldt, C. (2017). GW170817: observation of gravitational waves from a binary neutron star inspiral. *Physical Review Letters*, *119*(16), 161101.



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.

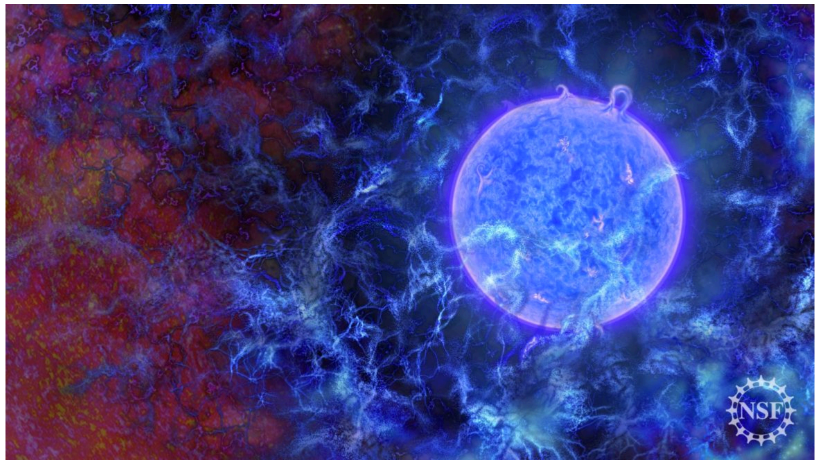




EXOTIC COMPACT OBJECTS

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 strong gravitational fields and may be the key to understand open questions in fundamental physics.
- From **dark matter to quantum gravity:** Wormholes, dark stars, 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.
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 macroscopic self-gravitating Bose-Einstein condensates described by 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**:

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

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: $\lambda = h/(mc)$

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

- 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 $10^{23}\ \mathrm{M}_{\odot}$

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*.

ON THE STABILITY OF BOSON AND PROCA STARS

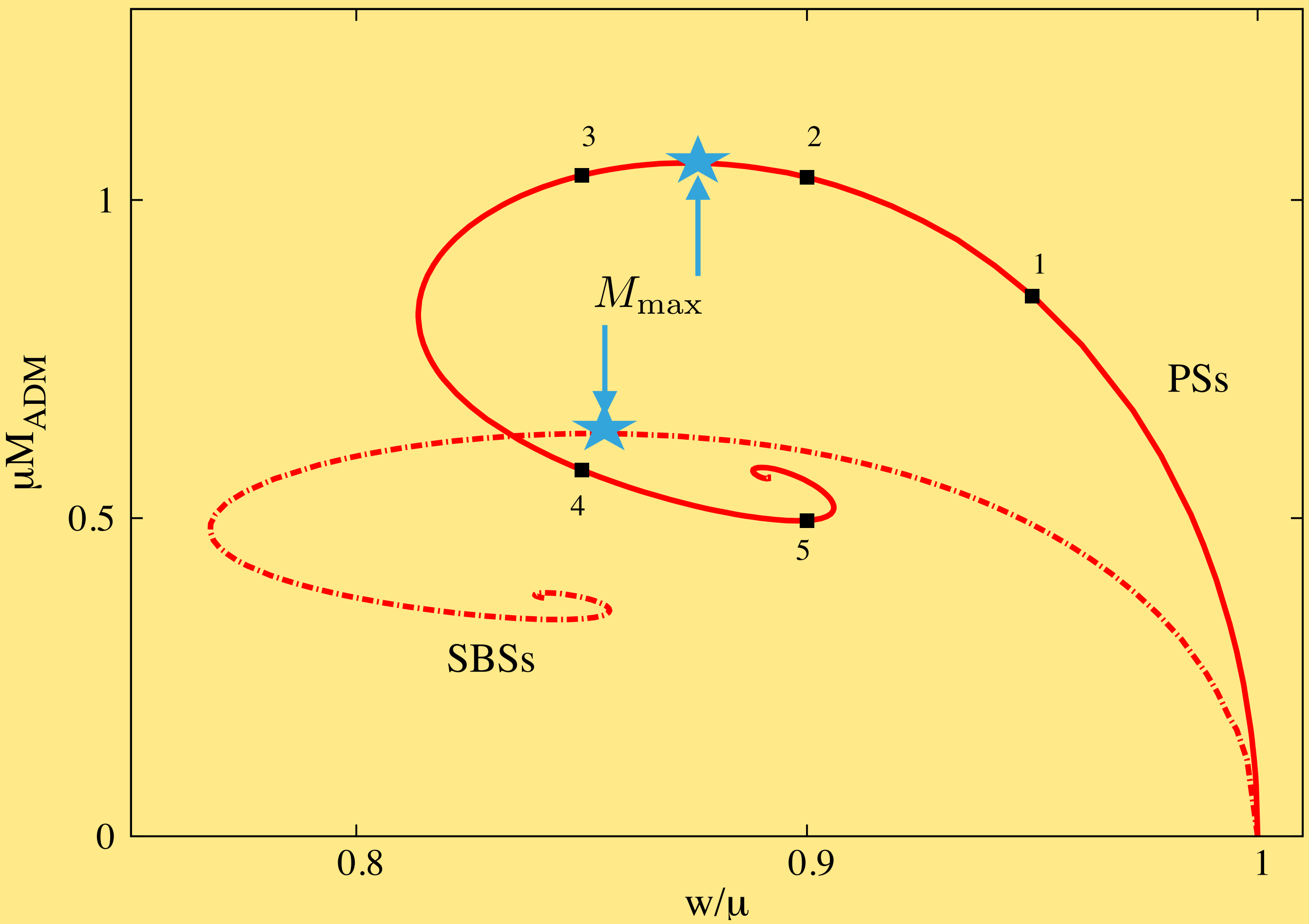
- Cunha, P. V., Font, J. A., Herdeiro, C., Radu, E., **Sanchis-Gual, N.**, & Zilhão, M. (2017). *Lensing and dynamics of ultracompact bosonic stars.* Physical Review D, 96(10), 104040.

- 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.



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

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

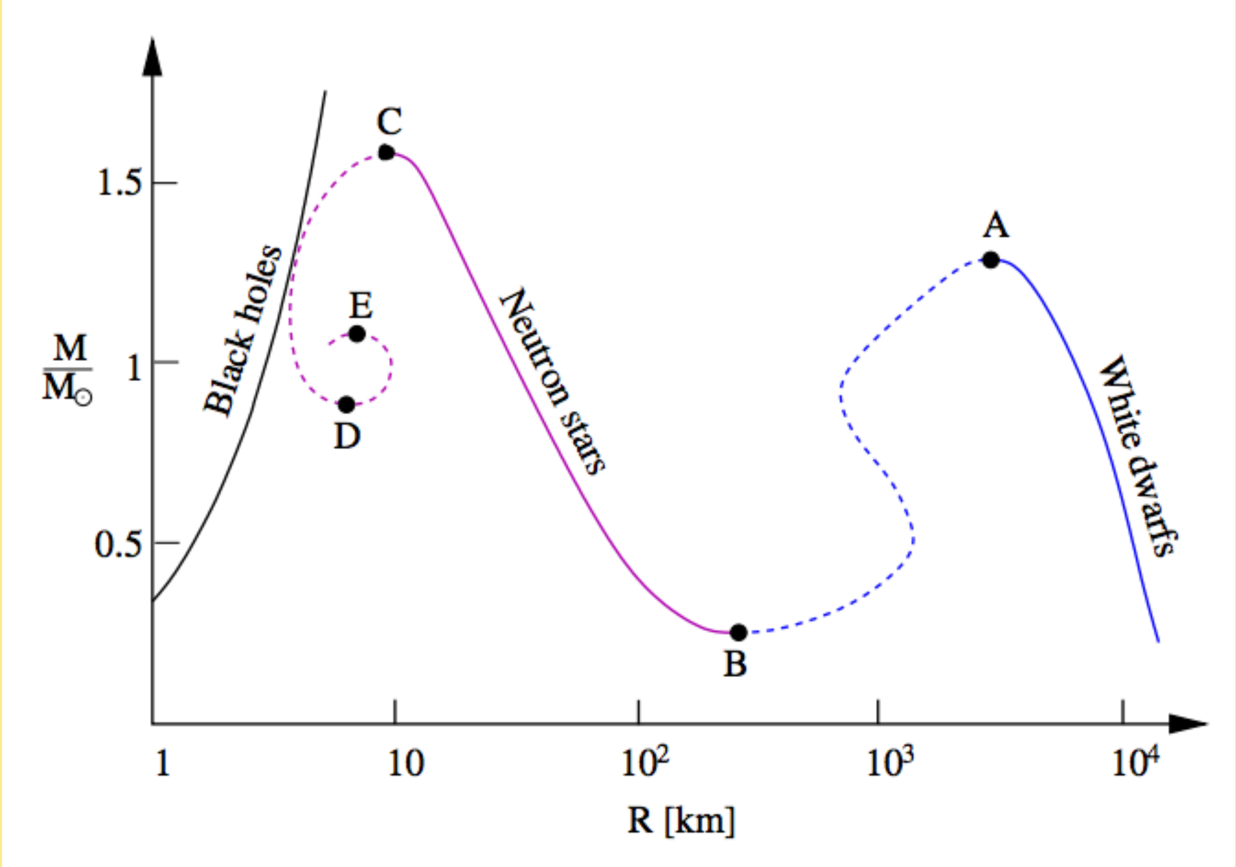
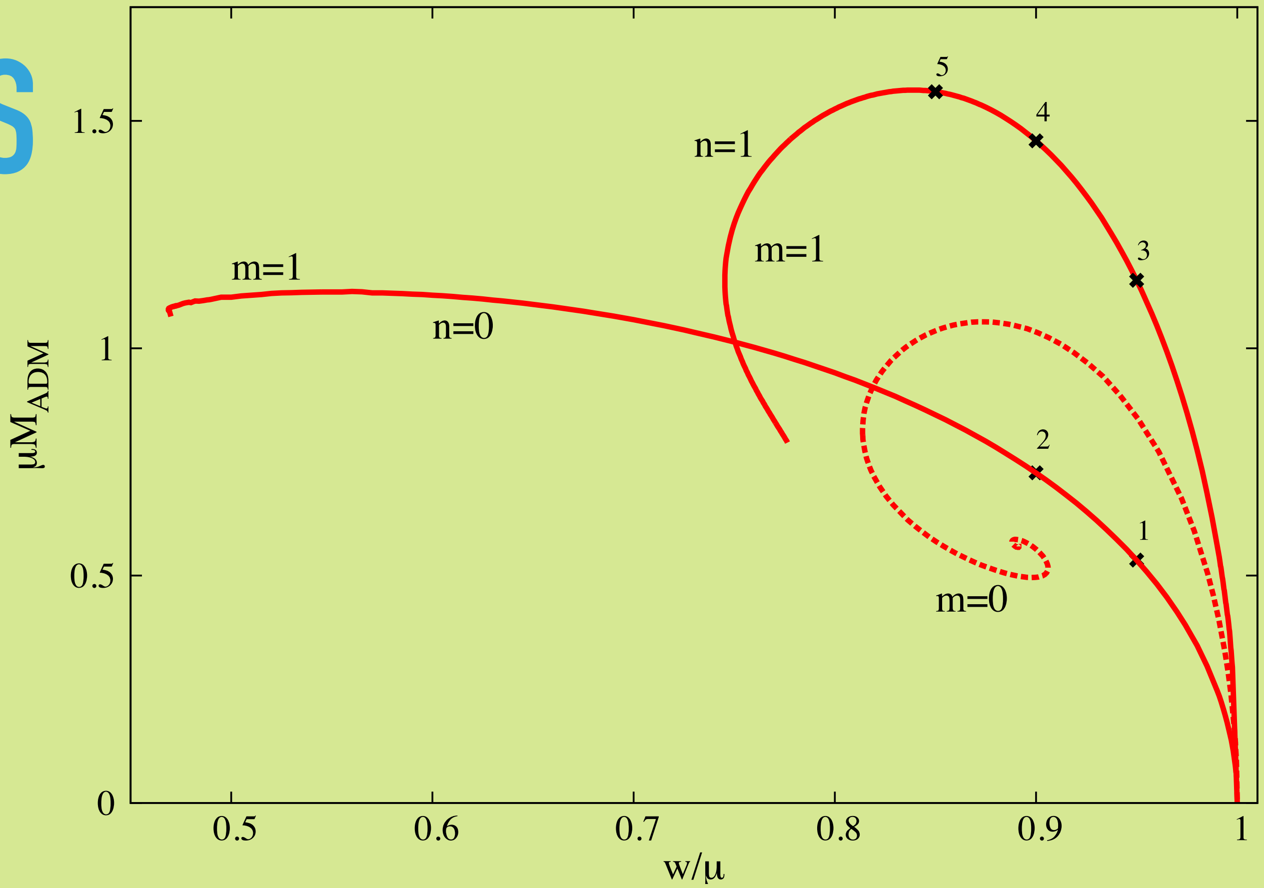


Figure extracted from: Guerra, D., Macedo, C. F., & Pani, P. (2019). Axion boson stars. *Journal of Cosmology and Astroparticle Physics*, *2019*(09), 061.

SPINNING BOSONIC STARS

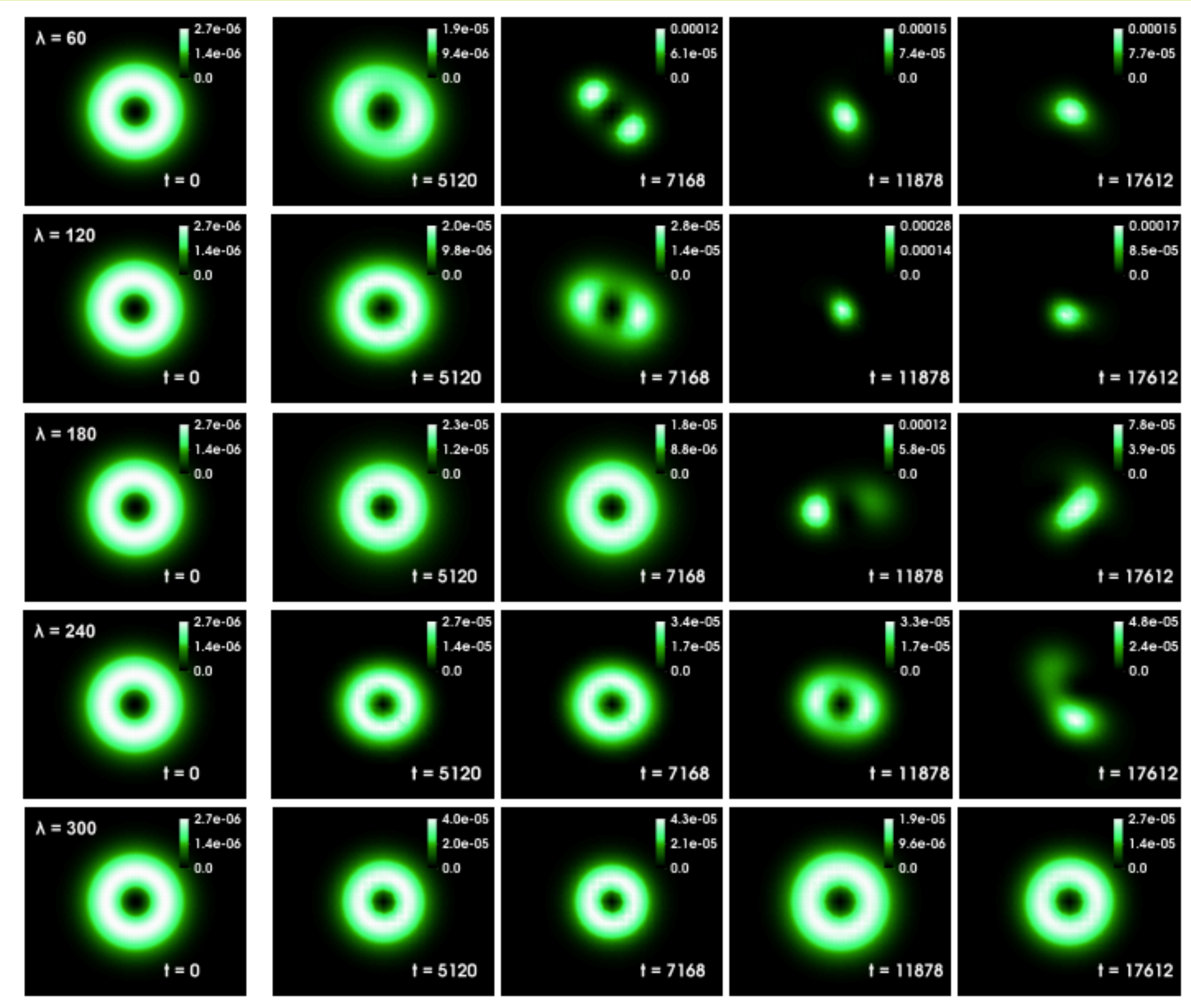


- The Proca field **ansatz**:

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

- and the scalar field **ansatz**:

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



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.

NR GW CATALOGUE OF BOSONIC STAR MERGERS

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.

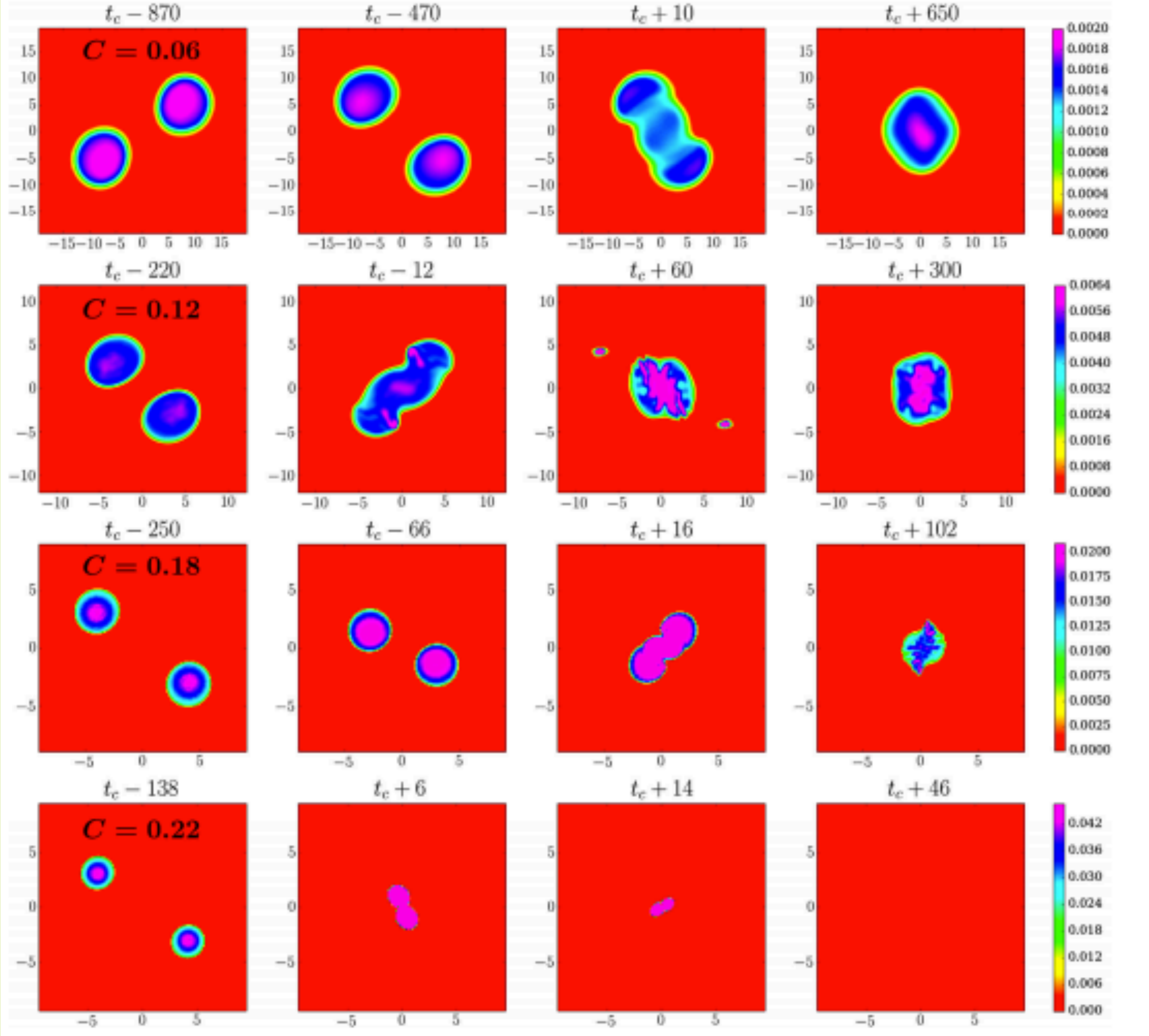
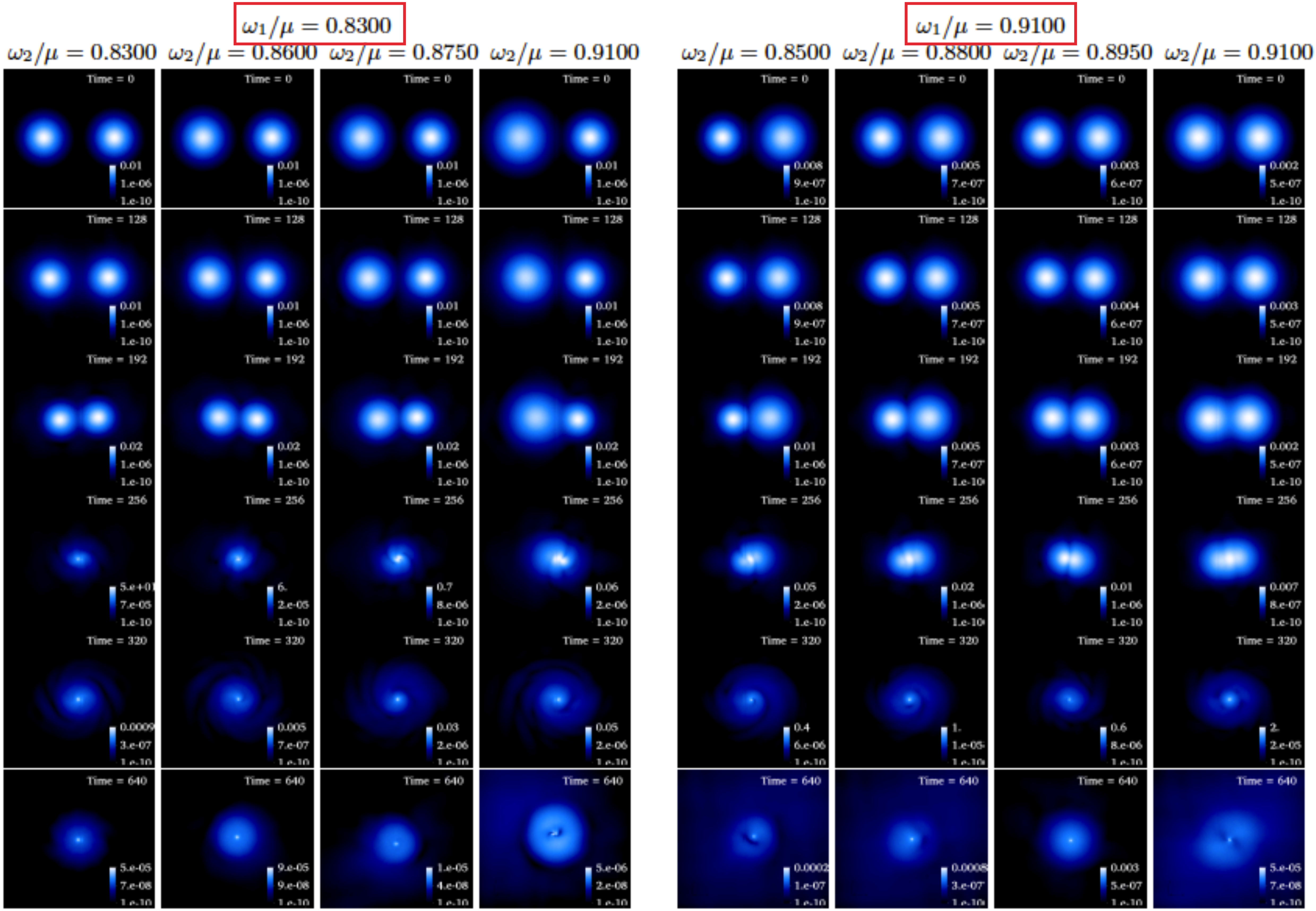
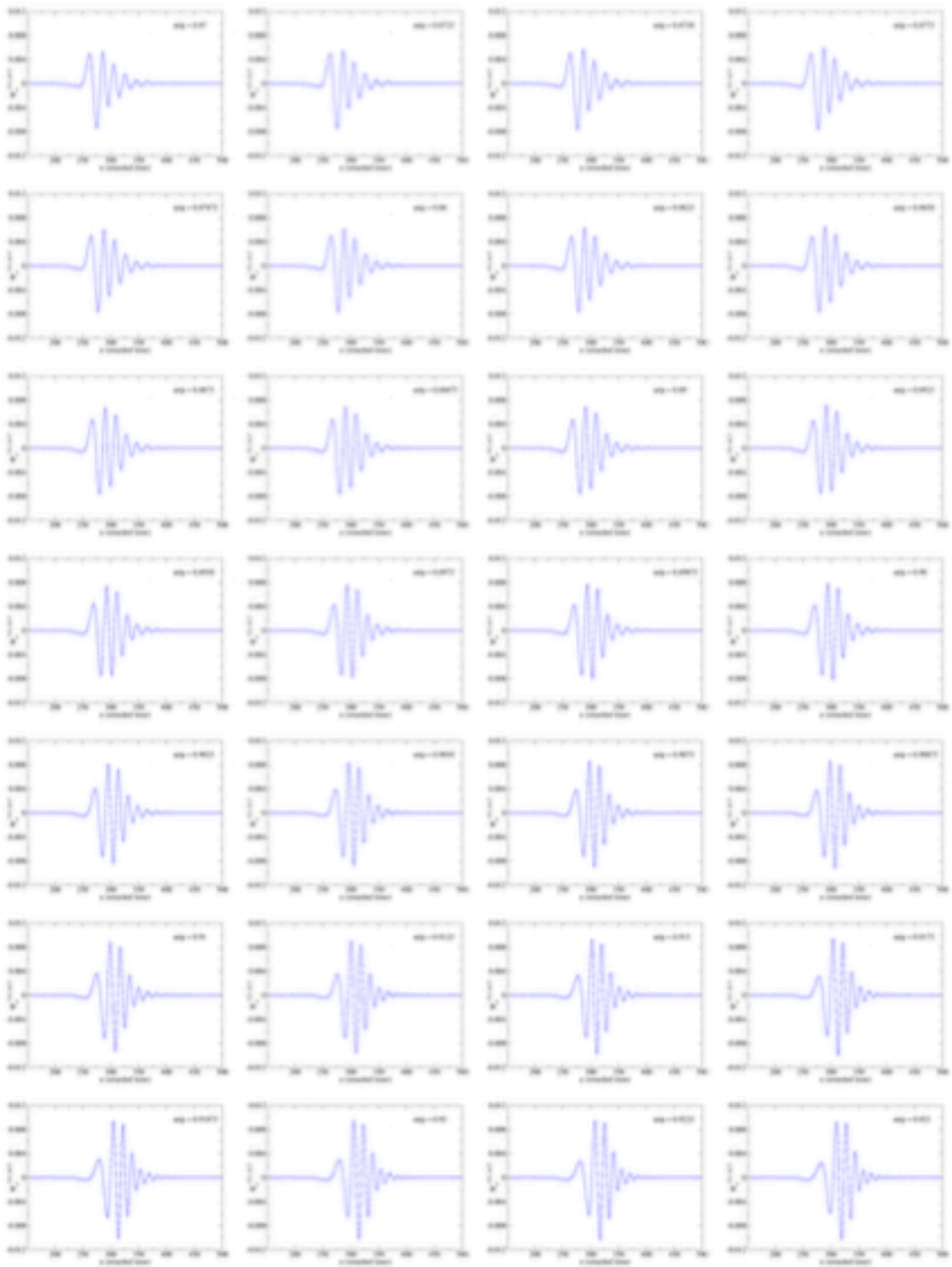
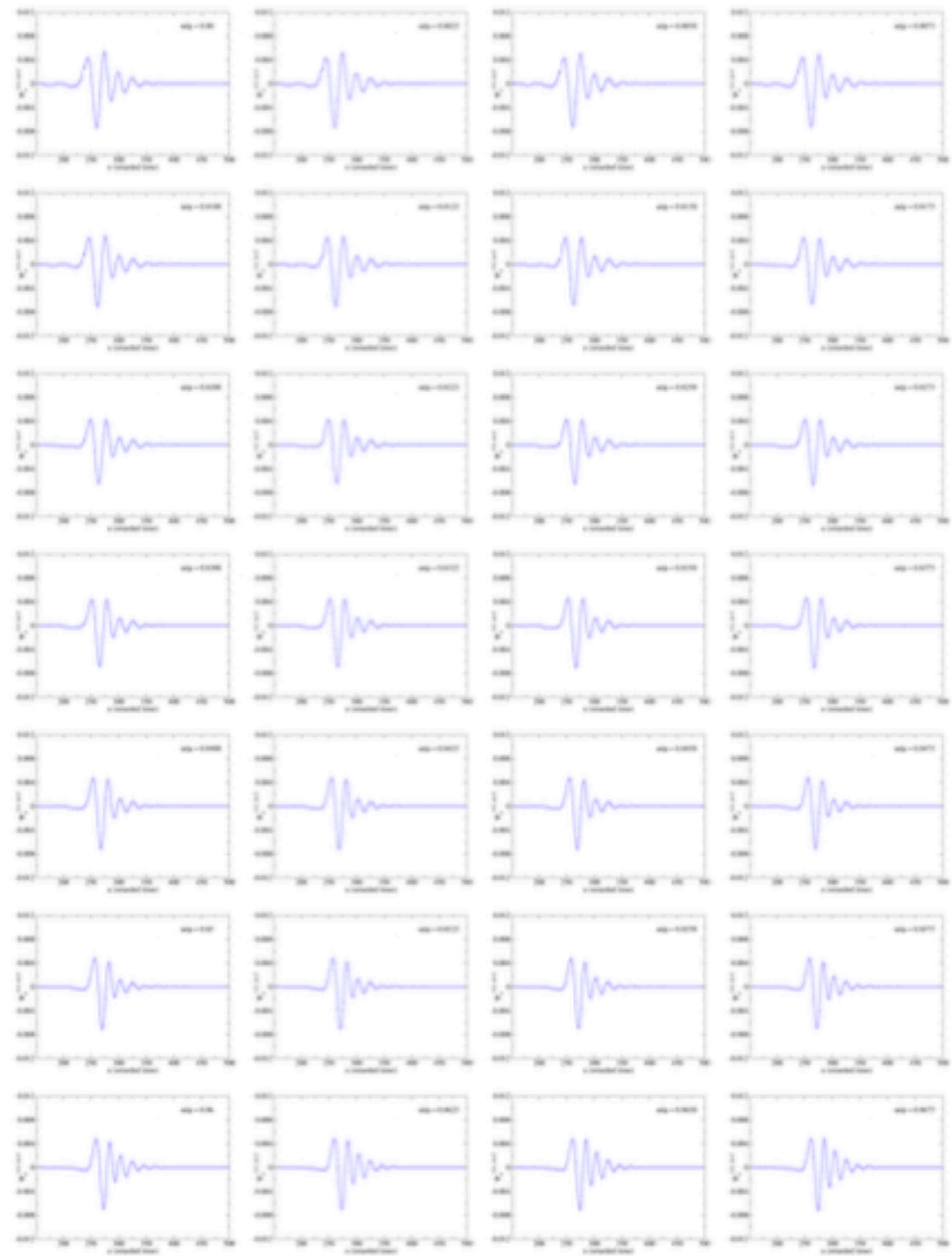


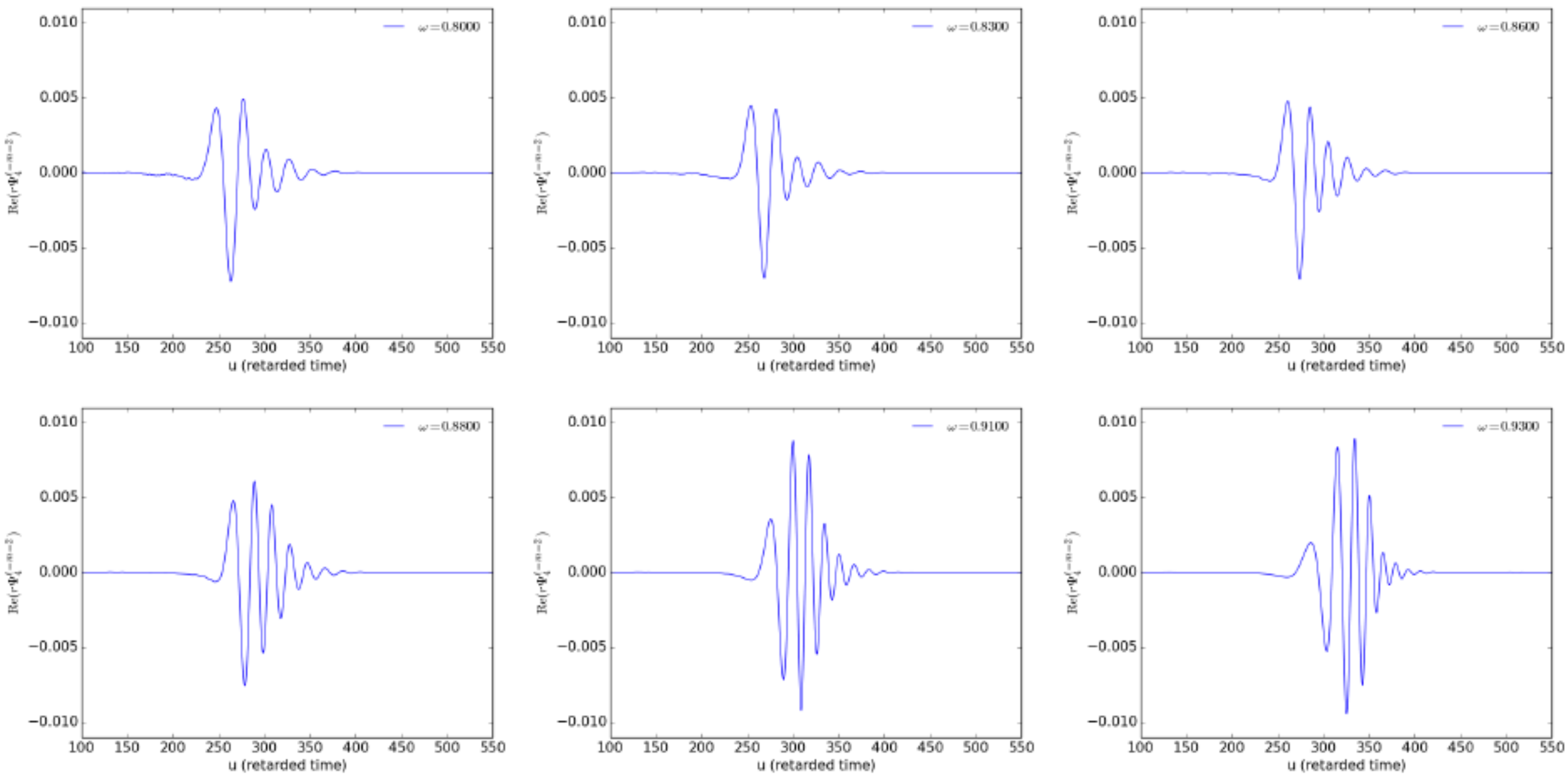
FIG. 2. Coalescence of binary BSs: Snapshots in time of the Noether charge density in the orbital plane. Each row corresponds to a different compactness (from top to bottom: 0.06, 0.12, 0.18, and 0.22). The collision of the stars happens at different times due to the different initial conditions and 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.

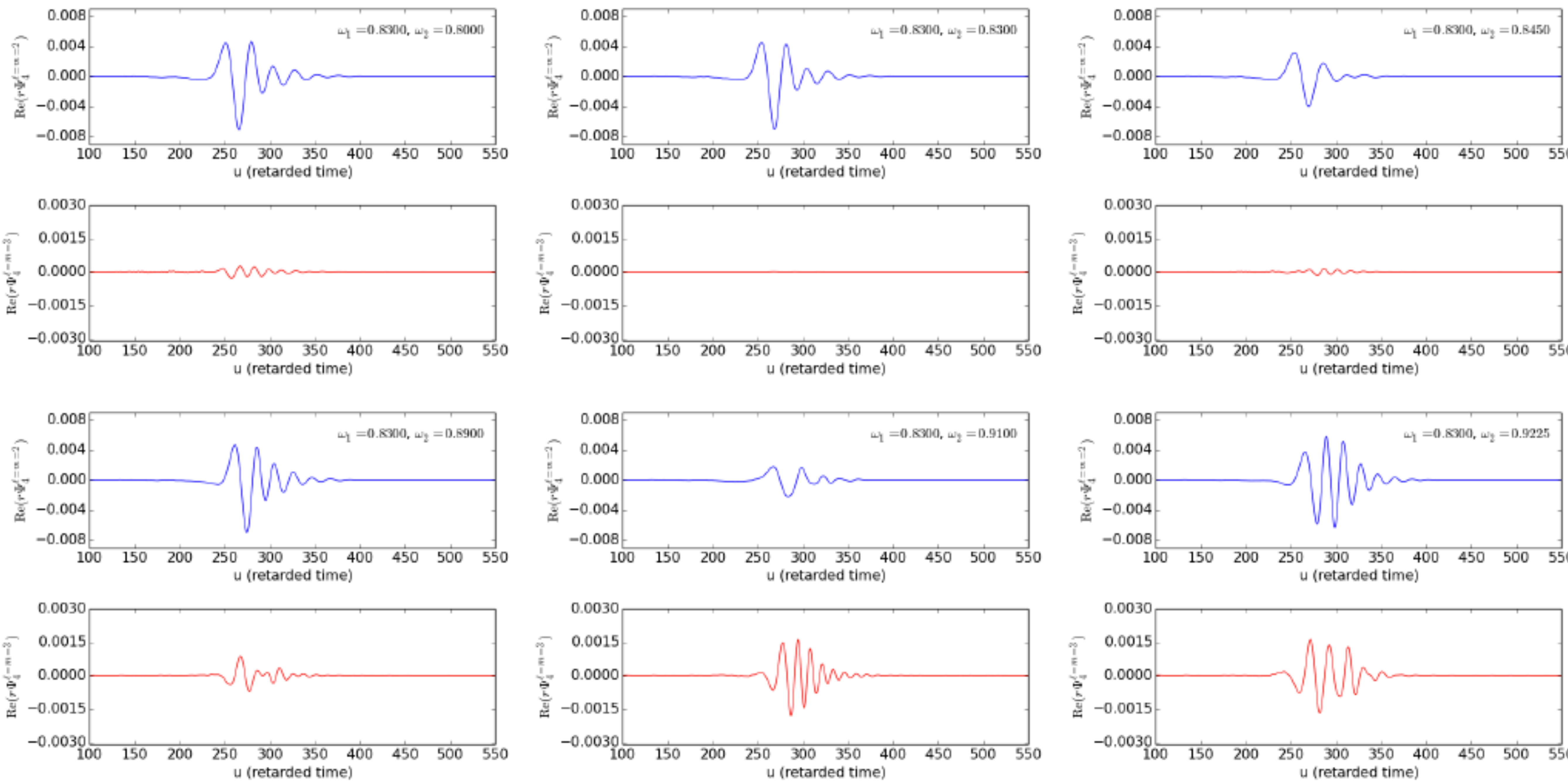

$\omega_1/\mu = 0.8300$
$\omega_2/\mu = 0.8300$ $\omega_2/\mu = 0.8600$ $\omega_2/\mu = 0.8750$ $\omega_2/\mu = 0.9100$
$\omega_1/\mu = 0.9100$
$\omega_2/\mu = 0.8500$ $\omega_2/\mu = 0.8800$ $\omega_2/\mu = 0.8950$ $\omega_2/\mu = 0.9100$
Time = 0
Time = 128
Time = 192
Time = 256
Time = 320
Time = 640

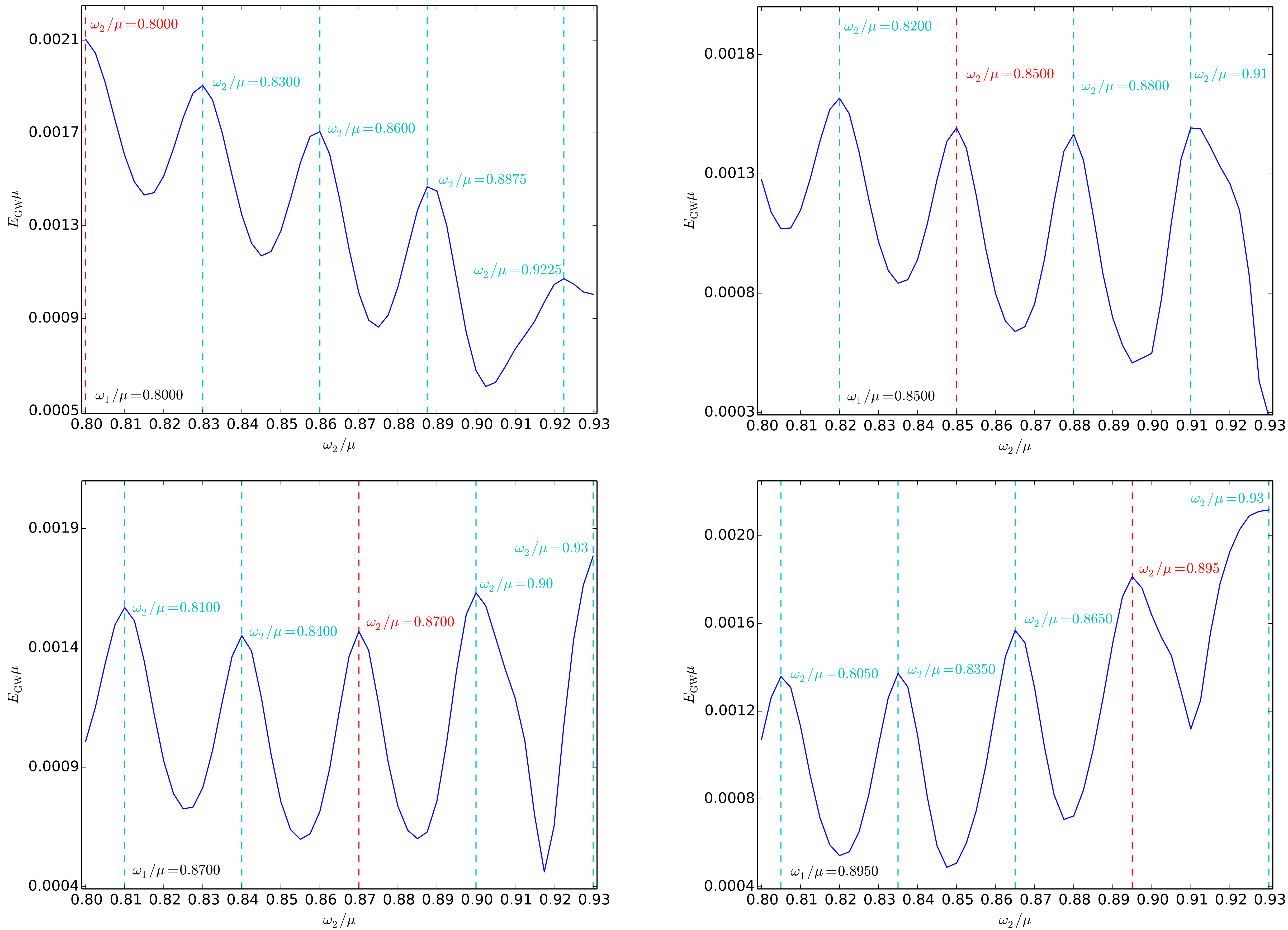



Equal-mass collisions



Unequal-mass collisions



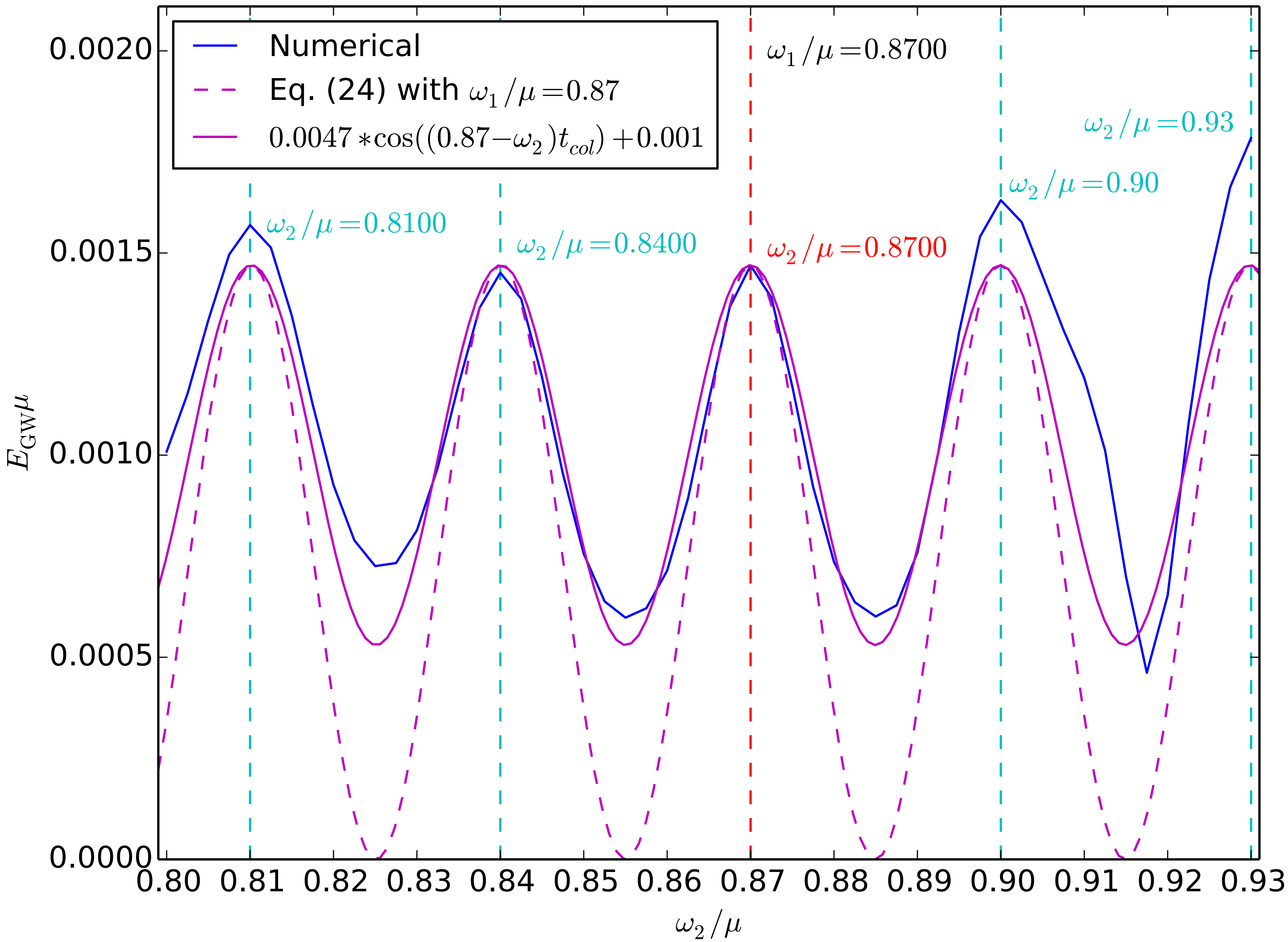

$\omega_2/\mu = 0.8000$
$\omega_2/\mu = 0.8300$
$\omega_2/\mu = 0.8600$
$\omega_2/\mu = 0.8875$
$\omega_2/\mu = 0.9225$
$\omega_1/\mu = 0.8000$
0.0021
0.0017
0.0013
0.0009
0.0005
$E_{\rm GW}\mu$
0.80 0.81 0.82 0.83 0.84 0.85 0.86 0.87 0.88 0.89 0.90 0.91 0.92 0.93
ω_2/μ
$\omega_2/\mu = 0.8200$
$\omega_2/\mu = 0.8500$
$\omega_2/\mu = 0.8800$
$\omega_2/\mu = 0.91$
$\omega_1/\mu = 0.8500$
0.0018
0.0013
0.0008
0.0003
$E_{\rm GW}\mu$
0.80 0.81 0.82 0.83 0.84 0.85 0.86 0.87 0.88 0.89 0.90 0.91 0.92 0.93
ω_2/μ
$\omega_2/\mu = 0.8100$
$\omega_2/\mu = 0.8400$
$\omega_2/\mu = 0.8700$
$\omega_2/\mu = 0.90$
$\omega_2/\mu = 0.93$
$\omega_1/\mu = 0.8700$
0.0019
0.0014
0.0009
0.0004
$E_{\rm GW}\mu$
0.80 0.81 0.82 0.83 0.84 0.85 0.86 0.87 0.88 0.89 0.90 0.91 0.92 0.93
ω_2/μ
$\omega_2/\mu = 0.8050$
$\omega_2/\mu = 0.8350$
$\omega_2/\mu = 0.8650$
$\omega_2/\mu = 0.895$
$\omega_2/\mu = 0.93$
$\omega_1/\mu = 0.8950$
0.0020
0.0016
0.0012
0.0008
0.0004
$E_{\rm GW}\mu$
0.80 0.81 0.82 0.83 0.84 0.85 0.86 0.87 0.88 0.89 0.90 0.91 0.92 0.93
ω_2/μ

$$\mathrm{Re}(\mathcal{A}) \sim \cos(\omega_1\, t) + \cos(\omega_2\, t) = 2\cos\left(\frac{(\omega_1+\omega_2)}{2}t\right)\cos\left(\frac{(\omega_1-\omega_2)}{2}t\right)$$

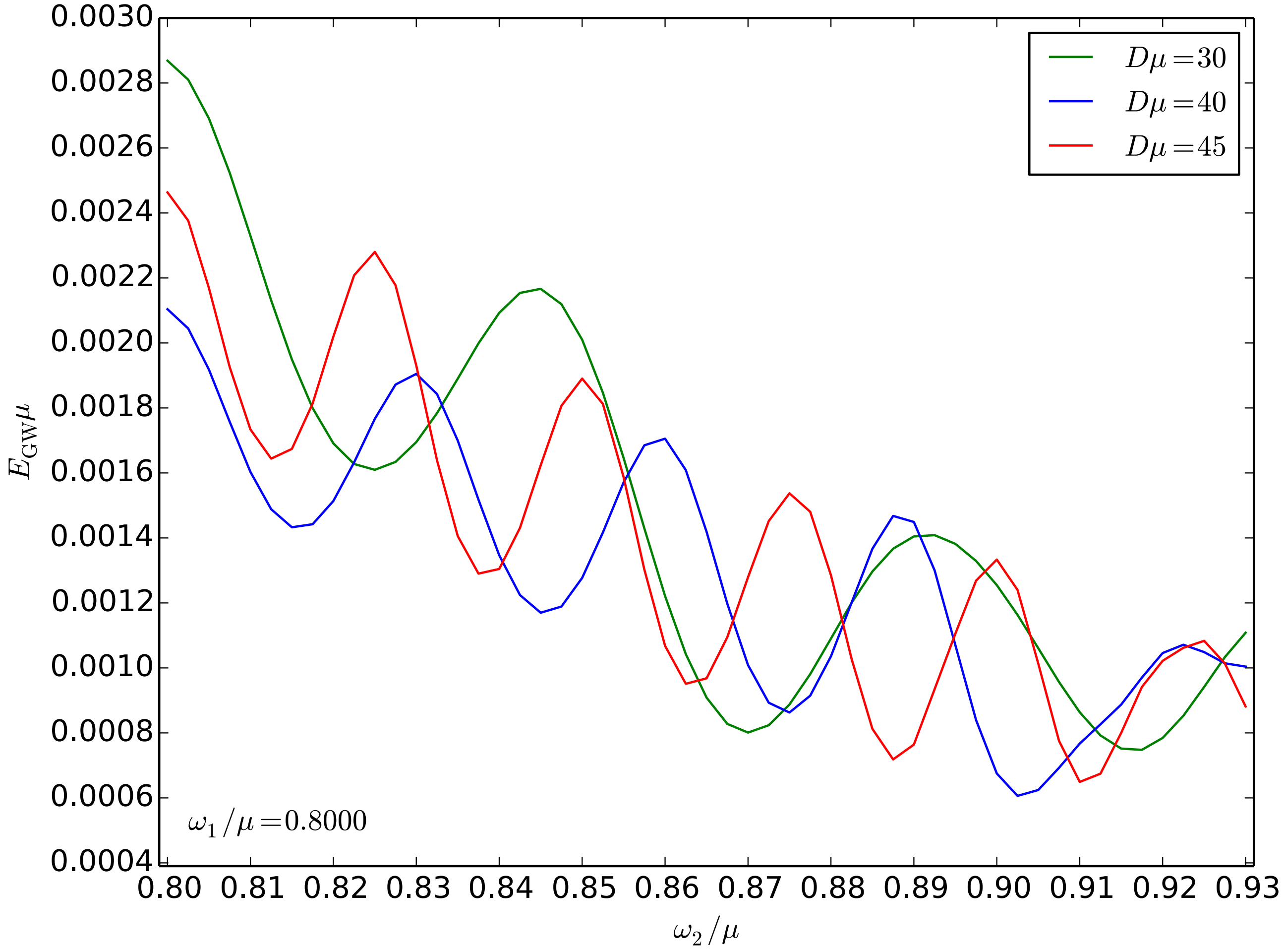
$$\mathrm{Im}(\mathcal{A}) \sim \sin(\omega_1\, t) + \sin(\omega_2\, t) = 2\sin\left(\frac{(\omega_1+\omega_2)}{2}t\right)\cos\left(\frac{(\omega_1-\omega_2)}{2}t\right).$$

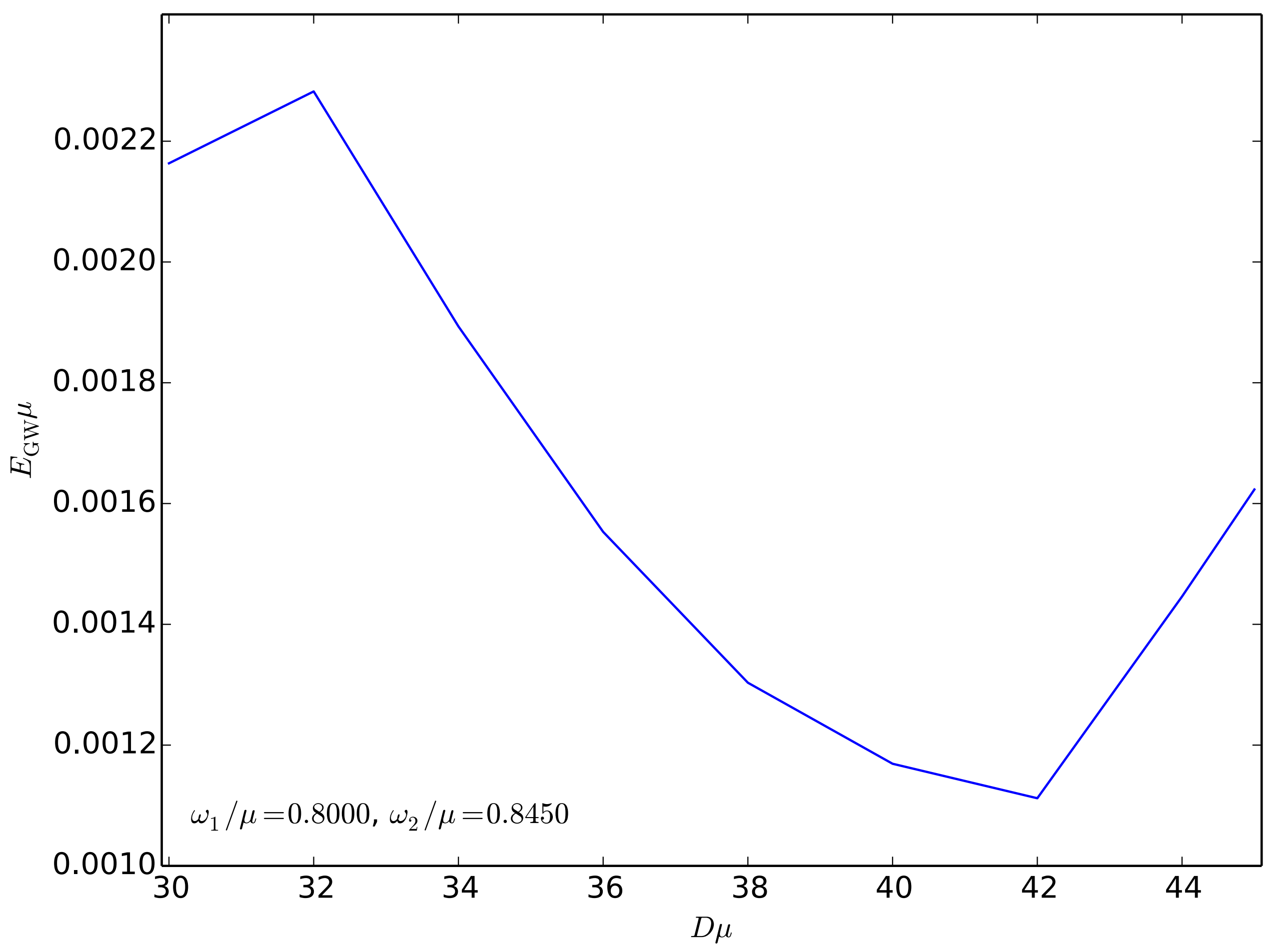
$$|\mathcal{A}|^2 = \mathrm{Re}(\mathcal{A})^2 + \mathrm{Im}(\mathcal{A})^2 \sim 4\cos^2\left(\frac{(\omega_1-\omega_2)}{2}t\right) = 2\big[1+\cos\big((\omega_1-\omega_2)t\big)\big].$$

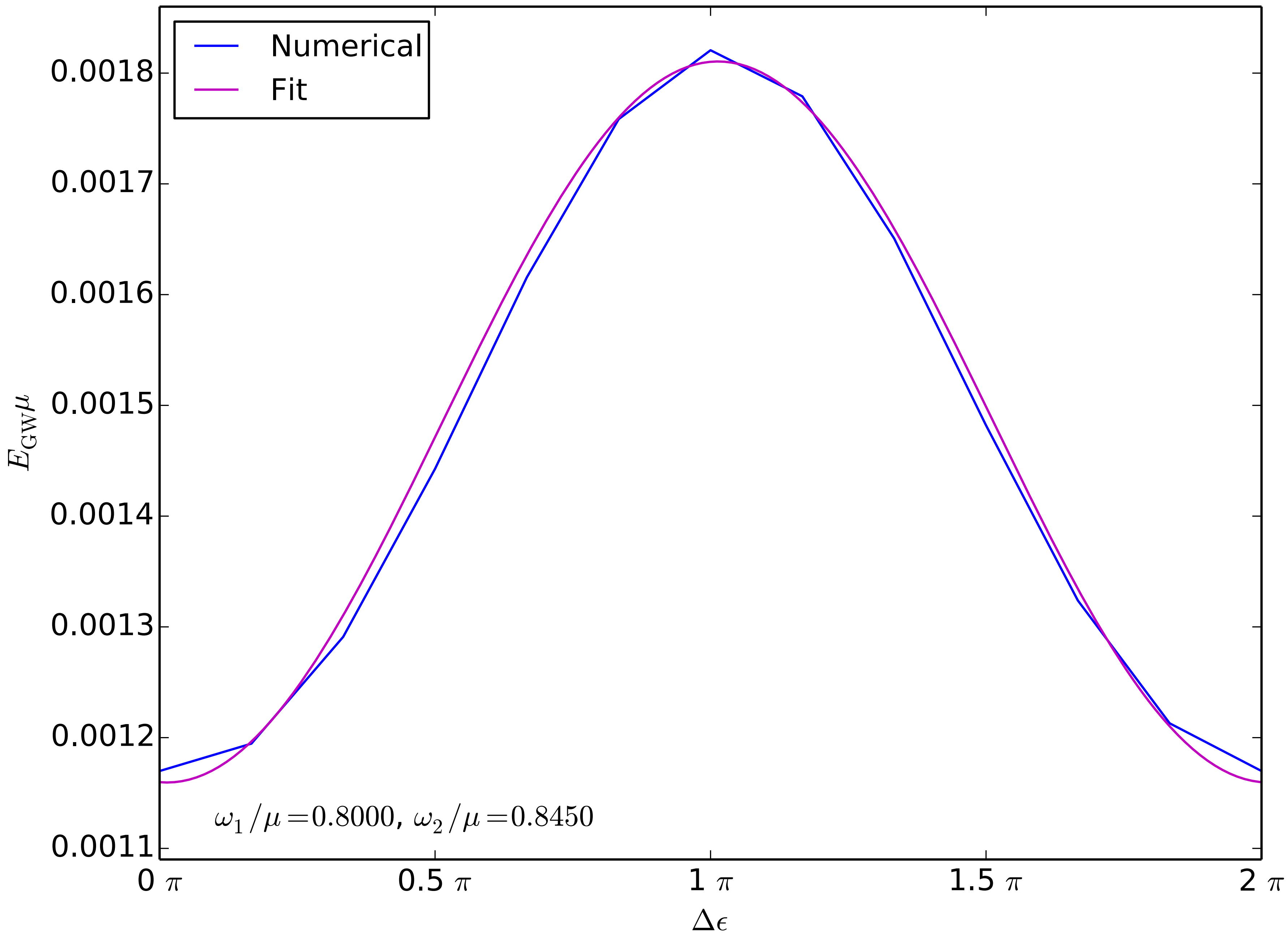
$$1+\cos\big((\omega_1-\omega_2)t_{\rm col}\big)_{\rm max} = 2 \rightarrow (\omega_1-\omega_2)_{\rm max}t_{\rm col} = 2k\pi,$$



$$|\mathcal{A}|^2 = \mathrm{Re}(\mathcal{A})^2 + \mathrm{Im}(\mathcal{A})^2 \sim 4\cos^2\left(\frac{(\omega_1 - \omega_2)}{2} t\right) = 2\left[1 + \cos\big((\omega_1 - \omega_2)t\big)\right].$$


$D\mu = 30$
$D\mu = 40$
$D\mu = 45$
$\omega_1/\mu = 0.8000$
$E_{\rm GW}\mu$
ω_2/μ
0.0030
0.0028
0.0026
0.0024
0.0022
0.0020
0.0018
0.0016
0.0014
0.0012
0.0010
0.0008
0.0006
0.0004
0.80 0.81 0.82 0.83 0.84 0.85 0.86 0.87 0.88 0.89 0.90 0.91 0.92 0.93


$\omega_1/\mu = 0.8000$, $\omega_2/\mu = 0.8450$
$E_{\rm GW}\mu$
$D\mu$
0.0022
0.0020
0.0018
0.0016
0.0014
0.0012
0.0010
30 32 34 36 38 40 42 44



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

$$|\mathcal{A}|^2 = \mathrm{Re}(\mathcal{A})^2 + \mathrm{Im}(\mathcal{A})^2 \sim 4\cos^2\left(\frac{(\omega_1 - \omega_2)}{2}t\right) = 2\left[1 + \cos\left((\omega_1 - \omega_2)t\right)\right].$$

CONCLUSIONS

CONCLUSIONS

- **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.**
- **The wave-like nature of the BSs has an important impact.**
- **Is there (ultra-)light in the dark?**

This work is supported by the Spanish Ministerio de Universidades, reference UP2021-044, within the European Union-Next Generation EU.

THANK YOU!