# Stable excited scalar boson-stars and astrophysical consequences

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# Boson stars overview

# Boson stars

- In General Relativity, complex boson fields can become localized due to their own self gravity.
- Boson stars are self-gravitating configurations of such fields.
- If made of ultralight bosons (scalar or vector) they can have masses in the astrophysical black hole mass range (specially if they have self-interactions)
- They are candidates for black holes mimickers.

# Boson stars

- Since they are not collapsed objects, they have different optical properties from BHs.
- BS are optically transparent and don't have an horizon.
- For certain levels of compactness they might exhibit light rings or ISCOs.
- Some supposed black hole mergers could be well modelled as two boson stars collisions **Bustillo *et al.* (2021)**.

# Why self-interacting boson stars?

- BS with self-interactions, have larger masses, putting them in the stellar mass range.
- Such stars have increased pressure which can avoid the collapse into a BH.
- Elementary scalar particles have self-interactions, such as the Higgs field or the hypothetical QCD axions.

# Self-interacting scalar boson stars

- Self-interacting BS are solutions to the Einstein-Klein-Gordon.
- Considering a quartic self-interaction the action is

$$S[g_{\mu\nu}, \Phi, \Phi^*] = \int_{\mathcal{M}} \left[ \frac{R}{16\pi} - \frac{1}{2} \left( \Phi^*_{,\mu} \Phi^{,\mu} + U(\Phi^* \Phi) \right) \right] \sqrt{-g} \mathrm{d}^4 x,$$

  where $U(\Phi^*\Phi) = \mu^2 |\Phi|^2 + \frac{\lambda}{2} |\Phi|^4$, where $\mu$ is the inverse reduced Compton wavelength of the particle and $\lambda$ is the self-interaction coupling constant.
- We define now $\Lambda = \lambda / 4\pi\mu^2$ and use units where $\mu = 1$.

# Excited states

- In spherical symmetry we have an infinite number of solutions each labelled by the number of radial nodes $n$ in $|\Phi(t, r)|$.
- Similar to the H atom, we have the fundamental ($n = 0$) and excited states ($n > 0$).
- Excited stars are unstable, either decaying or collapsing into a BH.
- These models might have interesting properties that impact GW emission.

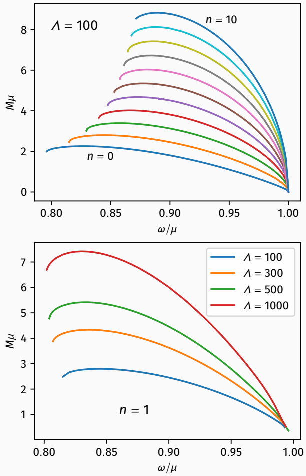


**Figure 1:** Candidate stable branches.

# Excited states

- The maximum mass doesn't guarantee their stability. Non-axisymmetric instabilities might have a role to play.
- This requires the numerical evolution of these models.
- They can be made stable with self-interactions up to $n = 10$ (**Sanchis-Gual *et al.* (2022)** $n = 1$ stars).

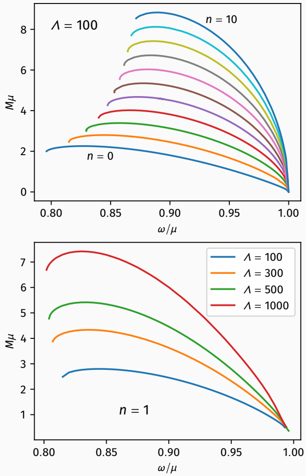


**Figure 1:** Candidate stable branches.

# Dynamical evolution and stability

# Evolution and generic outcomes

- Using the static spherical symmetric solutions to the EKG equations, we can evolve such models in time, using numerical truncation error as a perturbation.
- We analyse the evolution for a time window of $10^4$ in our units.
- Depending on the value of $\omega$ or $\Lambda$ the stars collapse to black holes, decay to a lower $n$ state, or become stable.
- It is possible that at the end the star isn't yet fully relaxed.
- We consider stars to be stable at the end the radial profile coincides with the initial one, notwithstanding the existence of oscillations in intermediate times.

# Collapse to black hole

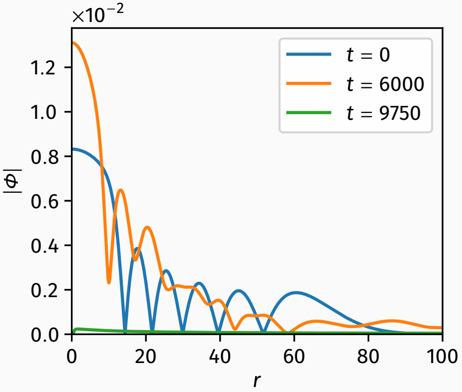


**Figure 2:** Radial profile of $n = 5$, $\Lambda = 400$, $\omega = 0.92$.

**Figure 3:** Evolution of $n = 5$, $\Lambda = 400$, $\omega = 0.92$.

# Stable solution

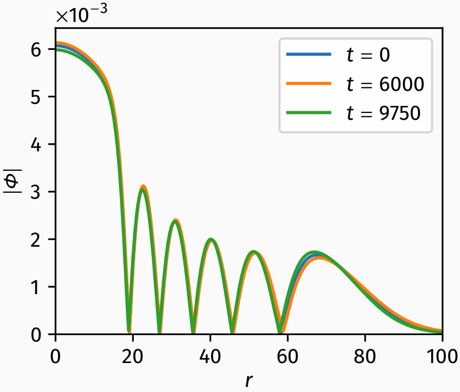


**Figure 4:** Radial profile of $n = 5$, $\Lambda = 700$, $\omega = 0.92$.

**Figure 5:** Evolution of $n = 5$, $\Lambda = 700$, $\omega = 0.92$.

# Threshold of stability

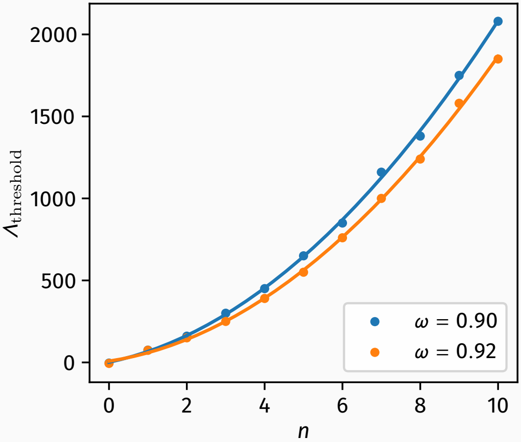


**Figure 6:** The $\Lambda_{\text{threshold}}$ as a function of $n$.

- For every studied model, after a certain value of $\Lambda$ all the stars are stable.
- This happens for all $n$ and $\omega$, each model having a different $\Lambda_{\text{threshold}}$.
- In fact there is a quadratic relation between $\Lambda_{\text{threshold}}$ and $n$:

$$\Lambda_{\omega=0.90} = 1.31 + 49.79n + 15.84n^2, R^2 = 0.9997$$
$$\Lambda_{\omega=0.92} = 7.82 + 36.16n + 14.97n^2, R^2 = 0.9997.$$

# Astrophysical features

# Compactness

- Since the self-interaction is repulsive, and the mass increases with $\Lambda$, the compactness increases as expected.
- It seems that it reaches an asymptotic value for large $\Lambda$.
- For large $\Lambda$, stars with lower $n$ seem more compact.

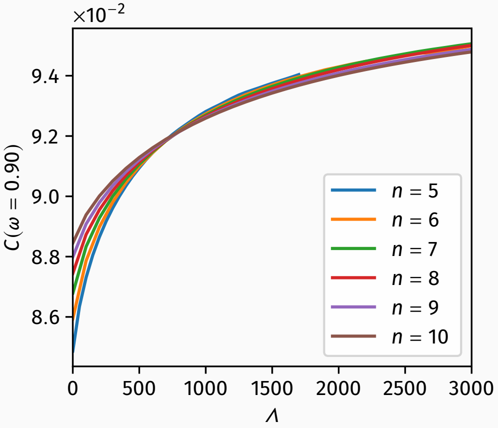


**Figure 7:** Compactness as a function of $\Lambda$.

# Compactness

- The maximum compactness in the stable branch for $n = 0$, was determined by **Amaro-Seoane *et al.* (2010)** to be $C \approx 0.16$.
- This is consistent so far with our results.
- If a star is compact enough special orbits like the ISCO (at $R = 6M$) might appear.
- However, our boson stars aren't compact enough, since $C_{\max}^{-1} = R/M \approx 10 > 6$.

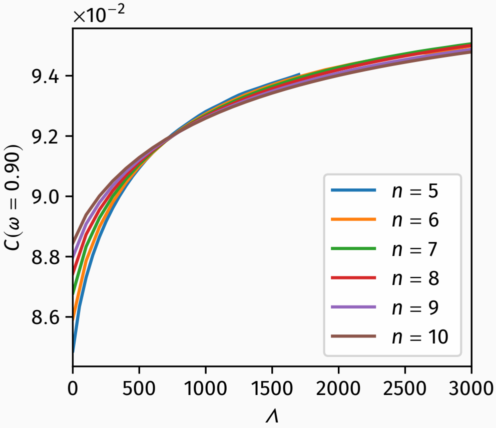


**Figure 7:** Compactness as a function of $\Lambda$.

# Galactic rotation curves

- As is well known, the rotational velocity of stars in galaxies do not follow the expected Keplerian behaviour $v_{\mathrm{rot}}(r) \simeq \sqrt{GM(r)/r}$.
- Instead we find that the rotational velocity increases way past the region which contains the luminous matter.
- One hypothesis is that the galactic dark matter halos can be modelled by a boson star, first noted by **Lee and Koh (1996)**.

# Galactic rotation curves

- Near the nodes, $v_{\mathrm{rot}}(r)$ increases in a Keplerian way since the particle is in a vacuum.
- This is followed by a decrease since there the particle is surrounded by matter.
- In the region with the nodes we find that $v_{\mathrm{rot}}$ increases almost linearly, with some oscillations.
- This **might** explain qualitatively, at least, the observed linear increase in the galactic rotational velocities.

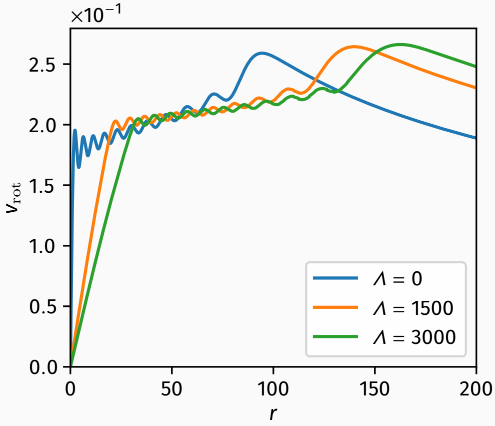


**Figure 8:** Velocity rotation curves for $n = 10$, $\omega = 0.92$.

# Final remarks

# Main results

- Spherical symmetric scalar excited boson stars can be made stable at least up to $n = 10$.
- This just depends on how strong the repulsive self-interaction is.
- The compactness of this stars reaches an asymptotic value as a function of $\Lambda$ and seems to sligty increase with $n$.
- There are no ISCOs. Stable circular orbits are allowed up to the very centre.
- Galactic rotation curves can be explained, at least qualitatively, by a scalar boson star.

# In the future

- Since these stars are stable, we could consider them in astrophysical scenarios.
- One interesting possibility is the collision of these objects and obtaining the respective GW signal.
- This is important to elaborate templates of GW signals to compare with observational evidence.

# References

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# Extra Material

# Stable Boson star

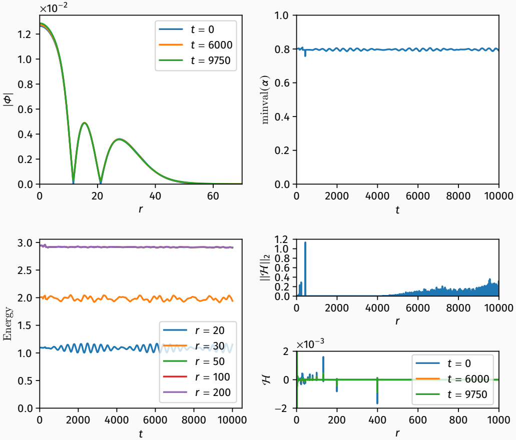


**Figure 9:** Summary of results for boson star model $n = 2$, $\Lambda = 150$ and $\omega = 0.92$.

# Angular velocity of particles

- The angular velocity of a particle orbiting a boson star is given, in Schwarzschild coordinates as $\Omega(r_{\rm orbit}) = \sqrt{(e^{F_0}/r)\ (de^{F_0}/dr)\big|_{r_{\rm orbit}}}$.
- If there is a maximum in $\Omega(r)$, this can quench the MRI of accretion disks, creating an effective shadow **Olivares *et al.*, 2020**.
- Instead of a Keplerian behaviour for $\Omega(r)$, we instead obtain plateaus in between the nodes.

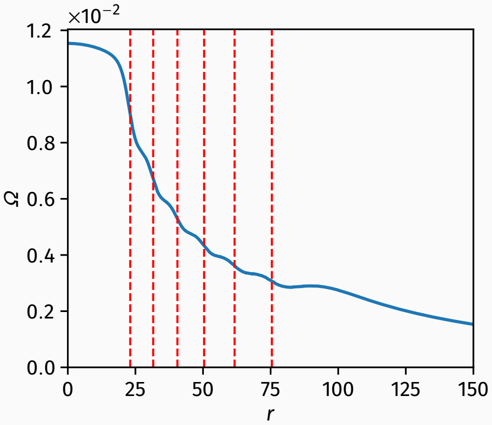


**Figure 10:** Angular velocity as a function of $r_{\rm orbit}$ for $n = 6$, $\Lambda = 800$, $\omega = 0.92$.

# Angular velocity of particles

- At the location of the nodes, $\Omega(r)$ increases in a Keplerian way since it is in a vacuum.
- At the location of the plateaus, the behaviour is different since the particle is surrounded by matter.

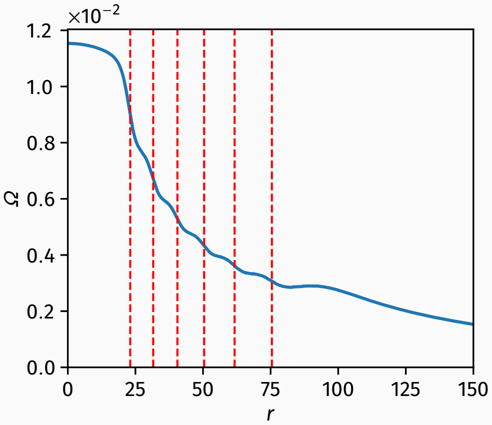


**Figure 10:** Angular velocity as a function of $r_{\mathrm{orbit}}$ for $n = 6$, $\Lambda = 800$, $\omega = 0.92$.

# Angular velocity of particles

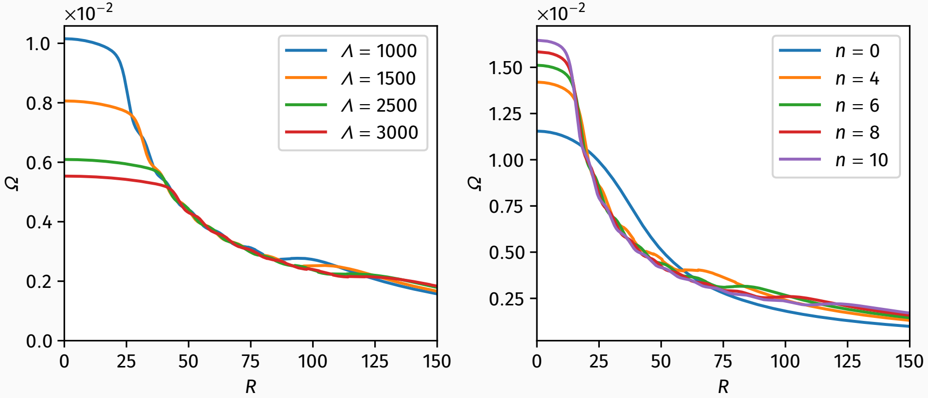


**Figure 11:** Angular velocity as a function of $R_{\mathrm{orbit}}$ for $n = 6$, $\omega = 0.92$ for several $\Lambda$ (left). Angular velocity as a function of $R_{\mathrm{orbit}}$ for $\Lambda = 300$, $\omega = 0.92$ for several $n$ (right). Same qualitative behaviour for $\omega = 0.90$.