A STABILIZATION MECHANISM FOR EXCITED FERMION-BOSON STARS

Fabrizio Di Giovanni

in collaboration with S. Fakhry, N. Sanchis-Gual, J.C. Degollado, and J.A. Font

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Introduction

◇ Boson stars (**BSs**) are **stationary**, **soliton-like** solutions of the Einstein system coupled to Klein-Gordon (scalar BSs) or Proca (vector BSs) for a **massive complex** field which has an harmonic time dependence.

$$\mathcal{L}_S = \frac{R}{16\pi G} - \frac{1}{2} g^{\alpha\beta} \partial_\alpha \Phi^* \partial_\beta \Phi - \frac{1}{2}\mu_S^2 \Phi^* \Phi - V(\Phi)$$

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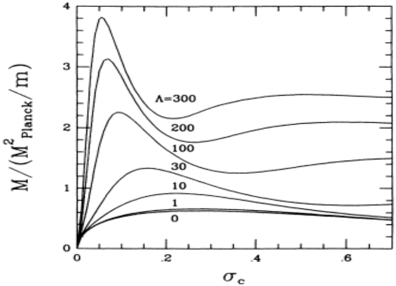
- If we consider a **real field** coupled to gravity, we obtain a soliton-like solution but the spacetime will not be stationary. These solutions are known as **oscillatons**, and are considered to be **quasi-stationary**. If we consider a **complex field** we obtain a stationary spacetime and the solutions are known as **boson stars**.

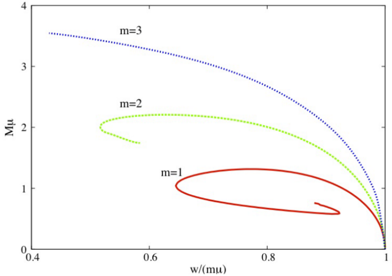
Introduction

BSs are Bose-Einstein condensates of **ultralight** particles with integer spin, with a large occupation number. The maximum ADM mass depend on the mass parameter μ

$$M^{max} = \alpha_s \times 10^{-19} M_\odot \left(\frac{GeV}{\mu} \right)$$



M. Colpi et al., Physical Review Letters, Volume 57, N. 20 (1986)



C. Herdeiro and E. Radu, Classical and Quantum Gravity, Volume 32, N. 14 (2015)

Fermion-boson stars

- Compact objects like neutron stars and white dwarfs may accrete bosonic dark matter, resulting in objects known as **fermion-boson stars**. They can be modeled by a **perfect fluid** minimally coupled to a **complex scalar field**.

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F. Di Giovanni, S. Fakhry, N. Sanchis-Gual, J. C. Degollado, and J. A. Font, “Dynamical formation and stability of fermion-boson stars”, Phys. Rev. D 102, 084063 (2020)
F. Di Giovanni, S. Fakhry, N. Sanchis-Gual, J. C. Degollado, and J. A. Font, “A stabilization mechanism for excited fermion-boson stars”, arXiv:2105.00530 (2021)

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We solve numerically the set of ODEs describing the perfect fluid and the complex scalar field, under the following assumptions:

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- ◇ We used units such as $G = c = \bar{h} = 1$, and we set the bosonic particle mass μ to be unitary for the models described in this talk; we considered a quartic self-interaction term in the scalar potential $V(\Phi) = \frac{1}{4}\lambda(\Phi\Phi^*)^2$.

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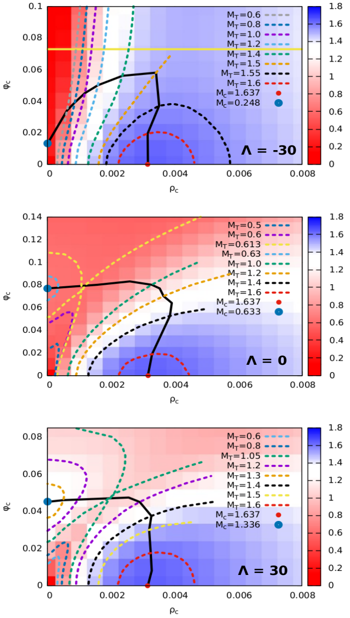
- ◇ The construction of equilibrium configurations require a two-parameters shooting method to extract the frequency of the field ω. The parameters are the central scalar field ϕ_c and the central rest-mass density ρ_c

Equilibrium configurations

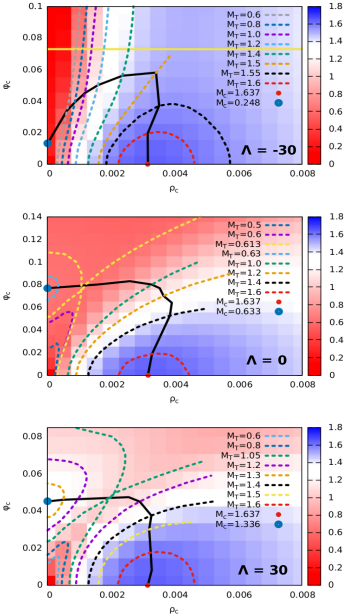


$$\Lambda = \frac{M_{Pl}^2 \lambda}{4\pi\mu^2}$$

Total gravitational mass

$$M_T = \lim_{r \longrightarrow \infty} \frac{r}{2}\left(1 - \frac{1}{\tilde{a}^2}\right)$$

Equilibrium configurations



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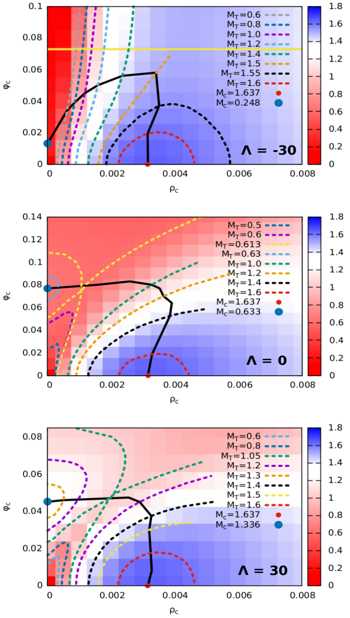

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Number of bosonic and fermionic particles

$$N_B = 4\pi \int \frac{\tilde{a}\omega\phi^2 r^2}{\alpha} dr$$

$$N_F = 4\pi \int \tilde{a}\rho r^2 dr$$

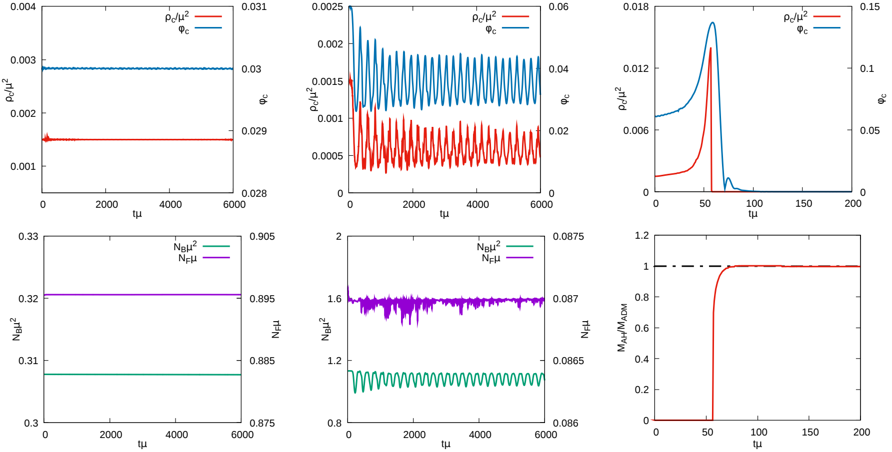
Critical points:

$$\frac{\partial N_B}{\partial \rho_c}\bigg|_{M=\text{const}} = \frac{\partial N_F}{\partial \rho_c}\bigg|_{M=\text{const}} = 0$$

$$\frac{\partial N_B}{\partial \phi_c}\bigg|_{M=\text{const}} = \frac{\partial N_F}{\partial \phi_c}\bigg|_{M=\text{const}} = 0$$

Numerical evolutions

$$\rho_c = 1.5 \times 10^{-3}$$



$\phi_c = 0.03$ $\phi_c = 0.06$ $\phi_c = 0.06(+2\%)$

Dynamical formation

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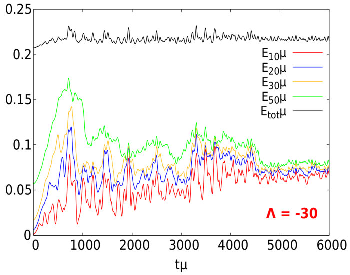
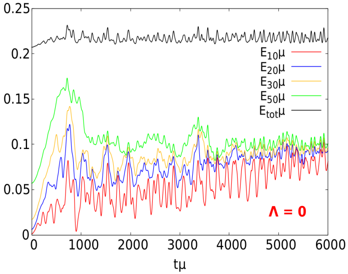
- Intuitively, this process can lead to two possible outcomes: either to the **formation of a fermion-boson star** or, if the mass of the entire system is above a certain threshold, to the **formation of a Schwarzschild black hole**.

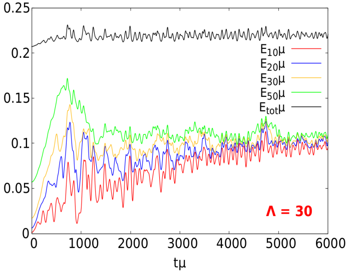
Dynamical formation





$$E^{\phi}_{r*} = 4\pi \int_0^{r^*} \mathcal{E}^{\phi} \sqrt{\gamma} dr$$

$$\mathcal{E}^{\phi} = \frac{1}{2}\left(\bar{\Pi}\,\Pi + \frac{\bar{\Psi}\Psi}{e^{4\chi}a}\right) + \frac{1}{2}\mu^2\bar{\phi}\phi + \frac{1}{4}\lambda(\bar{\phi}\phi)^2$$



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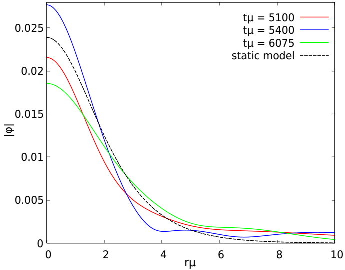
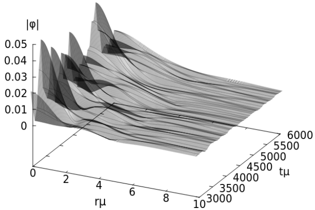
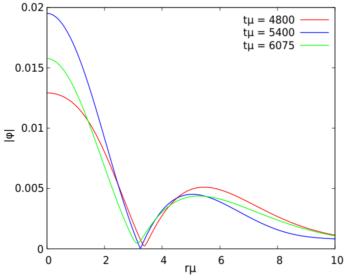
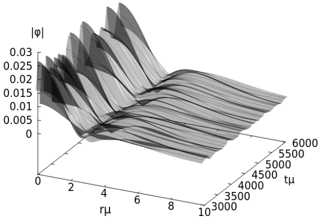




Model MS3	
ρ_c	1.28×10^{-3}
A_0	4.0×10^{-4}
σ	90
Λ	-30

Dynamical formation





Model MS5	
ρ_c	1.28×10^{-3}
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σ	90
Λ	30

Excited fermion-boson stars

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- Similar results were shown in a previous work where the authors studied boson stars composed by two coexisting states of the scalar field.

A. Bernal, J. Barranco, D. Alic and C. Palenzuela, “Multistate boson stars”, Phys. Rev. D 81,044031 (2010)

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- ◇ Similar results were shown in a previous work where the authors studied boson stars composed by two coexisting states of the scalar field.
- ◇ As there is no direct interaction between the perfect fluid and the scalar field, this effect must be purely gravitational.

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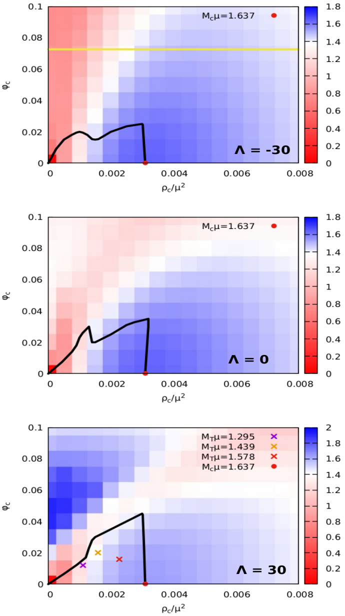

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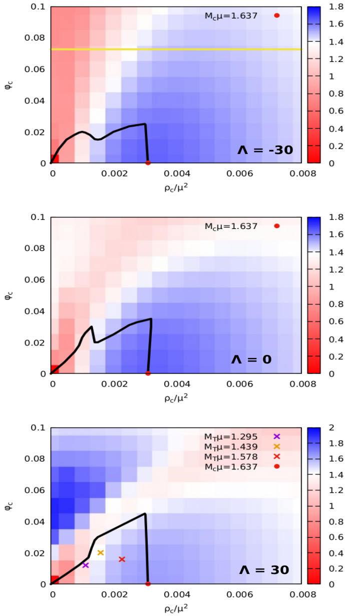

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The stability of the model is evaluated by means of nonlinear numerical evolutions.

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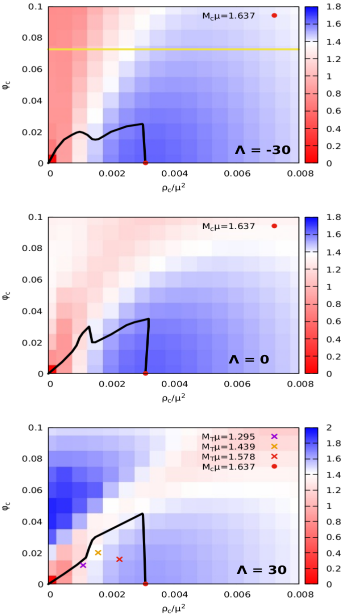

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The couloured crosses represent models formed dynamically.

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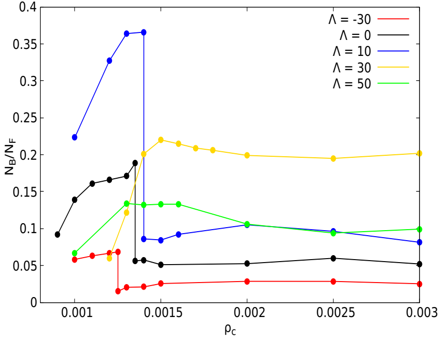
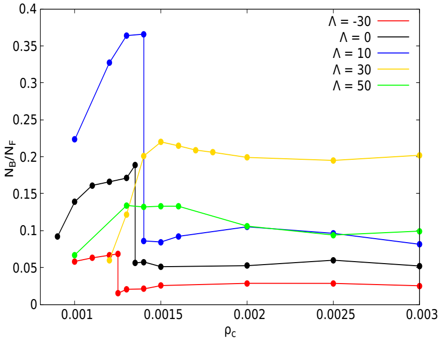


Values of N_B/N_F for models living on the critical black solid line depicted in the existence plot

Equilibrium configurations



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Monotonical behaviour of N_B/N_F up to a certaint threshold value ρ_{crit}, and then saturation regime.

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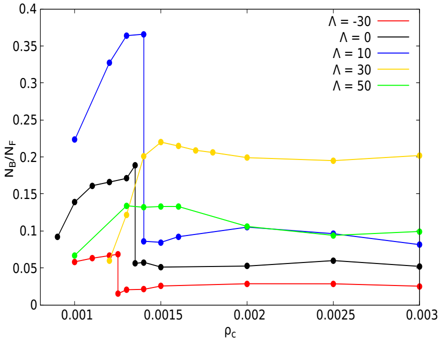

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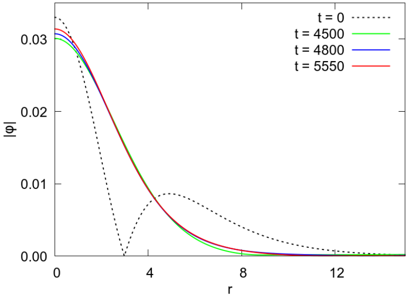
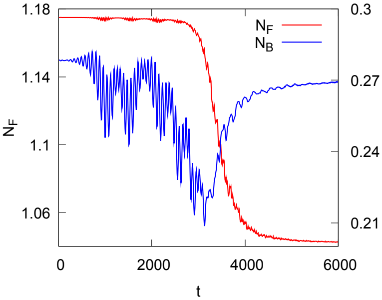
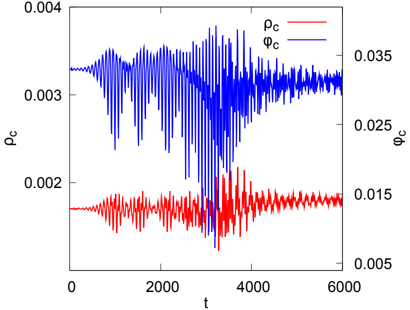
ρ_{crit} increases monotonically with Λ; for low values of Λ we observe a drop in N_B/N_F.

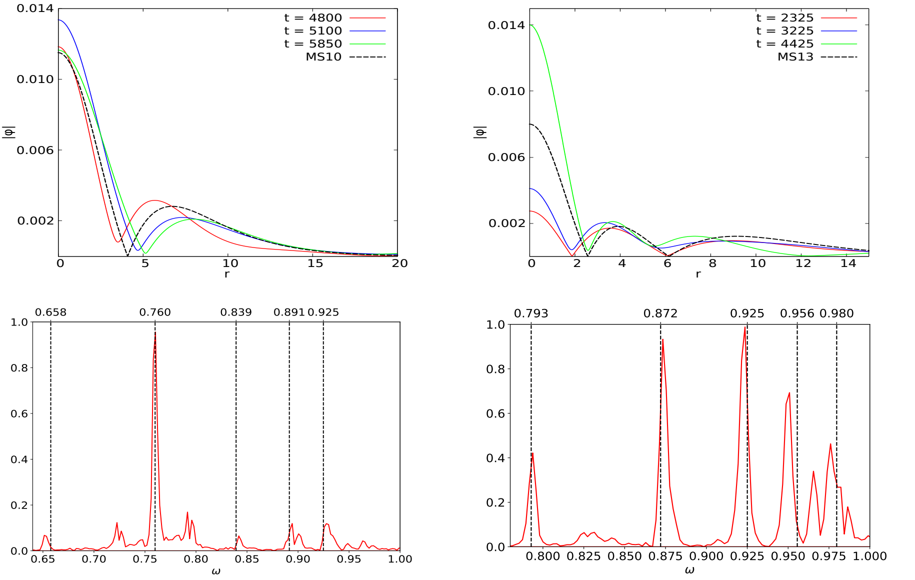
Dynamical migration to the ground state



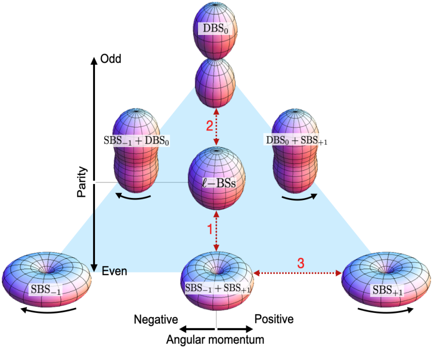




Dynamical formation from a generic boson cloud



Multifield, multifrequency boson stars



$\ell = 1$ boson stars family

$$\Phi^{(j)} = \phi_j(r, \theta)e^{-i(\omega_j t - m_j \varphi)}.$$

1-field configurations at the corners.

2-field configurations at the sides.

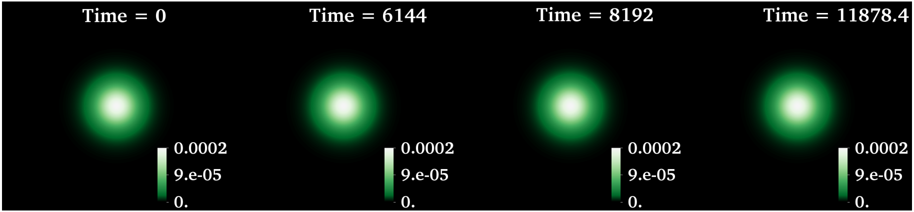
$\ell-$boson star at the center.

Multifrequency configurations inside the triangle.

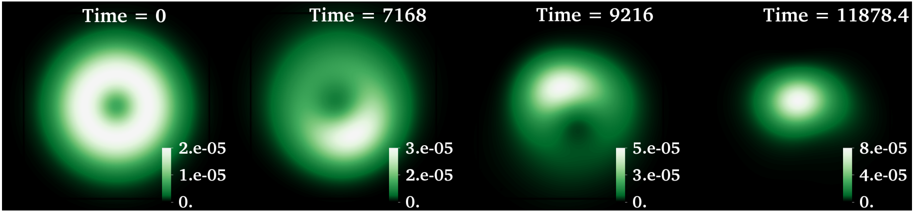
N. Sanchis-Gual, F. Di Giovanni, C. Herdeiro, E. Radu, and J. A. Font, "Multifield, Multifrequency Bosonic Stars and a Stabilization Mechanism", Phys. Rev. Lett. 126, 241105 (2021)

Multifield, multifrequency boson stars

$MBS_0 + SBS_1$, $\omega = 0.967$ (closer to MBS_0)



$MBS_0 + SBS_1$, $\omega = 0.974$ (closer to SBS_1)



Conclusions

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- Succeeded in constructing equilibrium configurations for ground-state and excited fermion-boson stars;
- Studied the dynamical properties of these objects, assessing their stability and their dynamical formation mechanism;
- Observed that unstable excited scalar field can be stabilized due to the presence of another stable source of matter, through a purely gravitational effect;
- A future work would be considering a more realistic equation of state and studying the effect of the scalar field on the NS physical properties; another interesting work would be studying fermion-boson stars in rotation;

Thank you for listening!