Soliton boson stars as compact objects

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EuCAPT workshop "Gravitational wave probes of black hole environments"
17.06.2022

European Research Council
Established by the European Commission
ERC-2018-COG GRAMS 815673

Based on:

I MB, Barausse [2111.03870]

II Bezares, MB, Liebling, Palenzuela, Pani, Barausse [2201.06113]

(Pseudo-)soliton stars: what and why

- (Pseudo-)soliton stars: localized, finite-energy and stable (long living) solutions of the EoM of a field theory incld. gravity
- Simplest example: boson star (BS) - self-gravitating complex scalar w. $U(1)$ Liebling, Palenzuela [1202.5809]
- Motivation 1: connection with dark matter and EU models
  - ⋆ cosmo evolution of axion DM Hui [2101.11735], inflation relics, phase transitions, solitosynthesis Bertone+ [1907.10610]
- Motivation 2: ECO paradigm ("no stone unturned")
  Giudice, McCullough, Urbano [1605.01209], Cardoso, Pani [1904.05363]
  - ⋆ Consistent with known & tested physics? Formation mechanism? Stable (on astro/cosmo scales)?
- Motivation 3: toy model of matter in strong gravity
  - ⋆ Everything is in the action

Outline

i What sets the maximal compactness of (S)BS?

ii How does the form of the potential map onto structural properties of (S)BS?

iii Can rotating (S)BS form (in the binary collision)?

(i) Buchdahl bound and beyond

- WEC* + micro stability** $\implies$ Buchdahl bound $C_B \leq 0.44$ (constant density star); $C = GM/(Rc^2)$
- Causality condition $c_s = \sqrt{\partial P/\partial \rho} \leq 1$ lowers the Buchdahl bound:
  - ⋆ saturated by LinEoS $\rho \propto P$: $C_{\mathrm{B+C}} = 0.354$ Urbano, Veermäe [1810.07137]
  - ⋆ radially stable elastic objects must satisfy $C_{\mathrm{EOmax}} < 0.376$ Alho+ [2107.12272, 2202.00043]

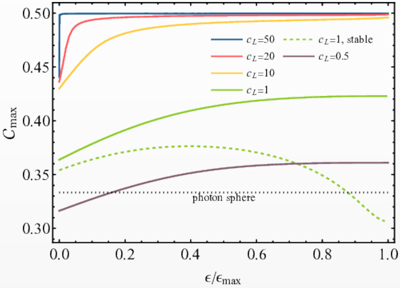


Fig: Alho+ [2202.00043]

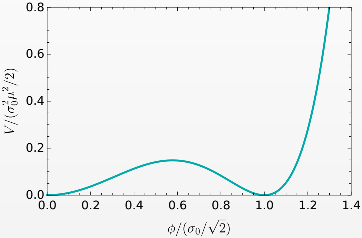
$^*\rho \geq 0 \wedge \rho + P \geq 0$, $^{**}P \geq 0 \wedge dP/d\rho \geq 0$

(i) (Soliton) boson stars

- Complex scalars w. $U(1)$: $\mathscr{L}_\Phi = -\partial_\mu \Phi^\dagger \partial^\mu \Phi - V(|\Phi|)$
- Mini BS $[\mu^2|\Phi|^2] \to C_{\rm max} \approx 0.11$ ("quantum pressure"), Self-interacting BS $[\lambda|\Phi|^4] \to C_{\rm max} \approx 0.16$ (radial pressure)
- SBS def by a (multiple) false/degenerate vacua. Simplest: Friedberg, Lee, Pang (1987), Macedo+ [1307.4812]

$$V = \mu^2 |\Phi|^2 \left(1 - 2\frac{|\Phi|^2}{\sigma_0^2}\right)^2$$

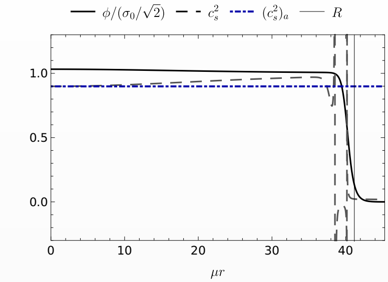
- Minkowski limit $M_{\rm Pl} \to \infty$: Q-balls Coleman (1985)

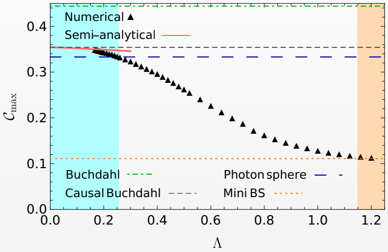


Review: Liebling, Palenzuela [1202.5809]

(i) SBSs are maximally stiff and compact

- Thin wall regime: bulk of the star is in the degenerate vacuum
- Effective LinEoS in the bulk $\varphi \approx 1 \to \varphi' \approx V \approx 0 \to P \approx \rho \quad [\varphi \equiv \phi/(\sigma_0/\sqrt{2})]$
- $(c_s)_a \approx 1 - 4(\varphi_c - 1) + \mathscr{O}[(\varphi_c - 1)^2]$
- Parameter space scanned w. $\Lambda = \sigma_0/M_{\rm Pl}$; thin wall realizable in the ultra-compact subspace: $\Lambda \lesssim 0.25$

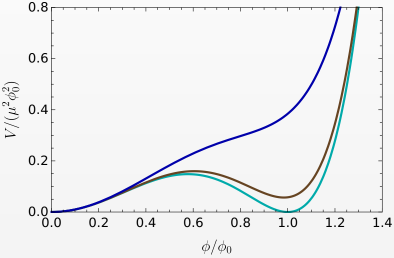


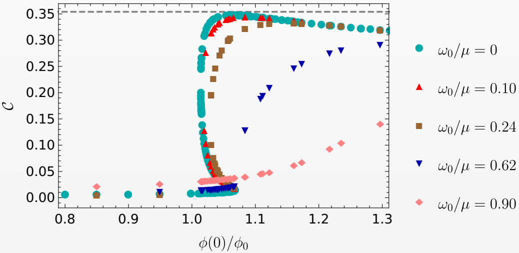


Consistent with the subsequent work of Cardoso+ [2112.05750], Collodel, Doneva [2203.08203]

(ii) It's not the full potential but the presence of a false vacuum that counts [1/2]: false vacuum

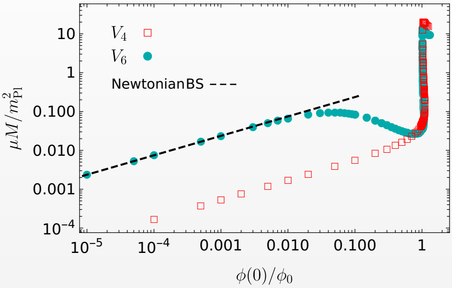
- General sextic potential: false vacuum
- Parametrized deviation from the degenerate vacuum
  $V_6 = \phi_0^2 \left[(\mu^2 - \omega_0^2)\varphi^2(1-\varphi^2)^2 + \omega_0^2 \varphi^2 \right] \;, \varphi = \phi/\phi_0$
- Effective LinEoS in the thin wall regime
  $(c_s^2)_a = \frac{2-(\omega_0/\mu)^2}{2+(\omega_0/\mu)^2} + \mathcal{O}[(\varphi_c - 1)] \;, C_{\max} \lesssim C_{\mathrm{B+C}} - 0.06(\omega_0/\mu)^2$

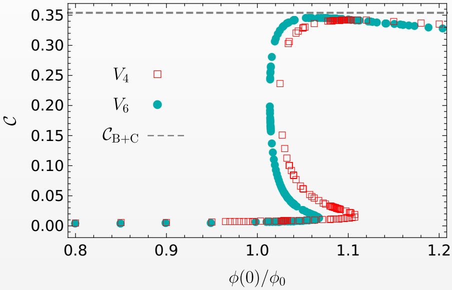




(ii) It's not the full potential but the presence of a false vacuum that counts [2/2]: quartic potential

- Non-polynomial quartic potential:
  $V_4(|\Phi|) = \mu^2|\Phi|^2 - g(|\Phi|^2)^{3/2} + \lambda|\Phi|^4$
  - ⋆ Low-compactness regime (V_6): Mini BS regime
  - ⋆ Low-compactness regime (V_4): Q-ball stable branch
  - ⋆ High-compactness regime: LinEoS universality





(iii) (S)BSs abhor angular momentum [1/3]

- BS have quantized angular momentum $J = kQ$, $k \in \mathbb{N}$
- Rotating BS generically suffer from non-axisymmetric instability Sanchis-Gual+ [1907.12565] ...
- ... which can be quenched w. sufficiently strong self-interactions, incl. SBS Siemonsen, East [2011.08247], Dmitriev+ [2104.00962]
- Can rotating SBS form from the binary inspiral of the non-rotating ones?

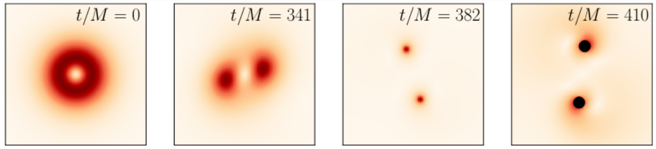
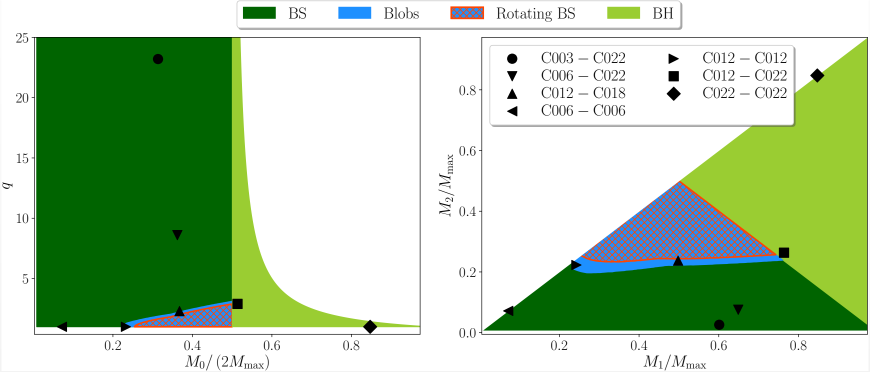


Fig: Siemonsen, East [2011.08247]

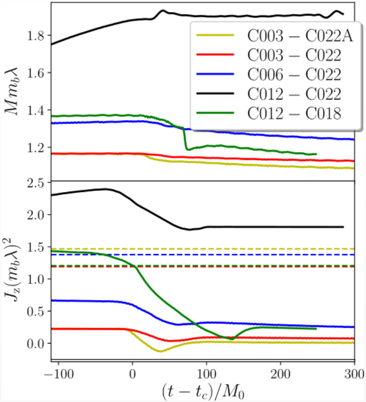
(iii) (S)BSs abhor angular momentum [2/3]

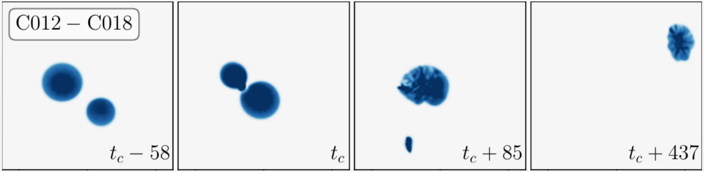
- Binary SBS simulations from Palenzuela+ [1710.09432], Paper II
- Catalogue: $3 \times q = 1$, $4 \times q \sim 2-30$
- If $M < M_{\rm max}$ BS will form; else - BH
- Parameterized condition for the rotating remnant
  $\frac{J_{c,K}(1+e_J)}{N(M_1)+N(M_2)} > 1 + e_N \quad \& \quad C > C_{\rm NAI}$



(iii) (S)BSs abhor angular momentum [3/3]

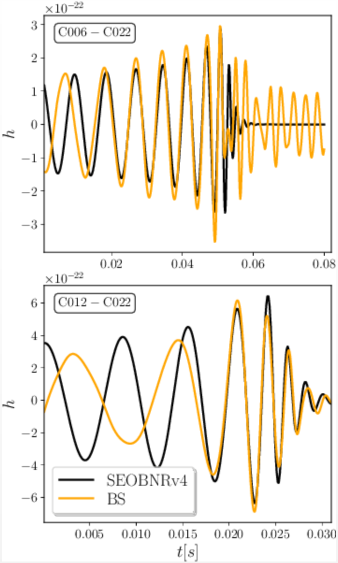
- For $\mathrm{BS} + \mathrm{BS} \to \mathrm{BS}$ exces angular momentum is dashed trough scalar radiation (gravitational cooling) and GW
- Instead of rotating remnants, in two cases exces angular momentum is emitted in the form of blobs
- For $q > 1$, blobs can induce superkicks $v \sim 0.05c$
- Do rotating remnants ever form? If not, why?





Other topics addressed

- MB, Barausse [2111.03870]
  - ⋆ "SBS are Q-balls in the time-dependent potential" (analytical solution)
  - ⋆ SBS w. multiple vacua ["axion BS"] also saturate $C_{\mathrm{B+C}}$
- Bezares, MB+ [2201.06113]
  - ⋆ SBS stable under large perturbations (SBS+anti-SBS collision)
  - ⋆ GW signal from SBS binaries
  - ⋆ SBS binaries in the LIGO band: distinguishability w.r.t. BH signal via $\mathrm{SNR}(\mathrm{h_{BS}} - \mathrm{h_{BH}}) \to$ missed detections/biases



Conclusions

- SBSs are maximally stiff and compact
  - ⋆ Beyond $C_{\mathrm{B+C}}$: Physical candidate allowing for positive pressure anisotropicity?
- It's not the full potential but the presence of a false vacuum that counts
  - ⋆ Plethora of models $\rightarrow$ universality in the macroscopic properties
- (S)BSs abhor angular momentum
  - ⋆ $a \neq 0$ probably indicates $\mathrm{ECO} \neq \mathrm{BS}$ (also axion star)

Supplementary material

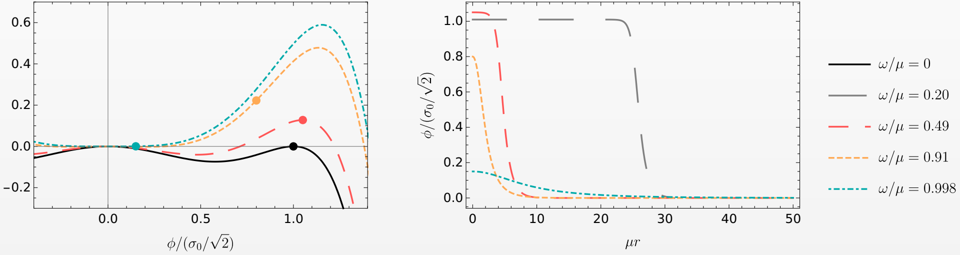
(i) Q-balls

- Analogue particle perspective: Newtonian dynamics

$$\phi'' + \frac{2}{r}\phi' = -\frac{dU_\omega}{d\phi}, \quad (1)$$

$$U_\omega = \frac{1}{2}(\omega^2\phi^2 - V(\phi)). \quad (2)$$

- Thin wall regime $\phi \sim \sigma_0/\sqrt{2}$, $\omega \ll \mu$
- Thick wall regime $\omega \sim \mu$



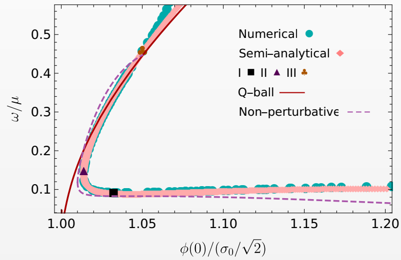
(i) SBSs are Q-balls in the time-dependent potential

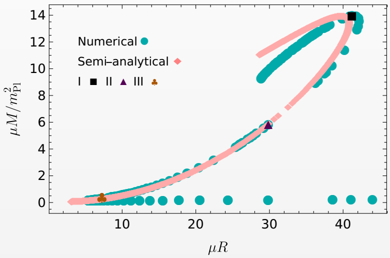
- SBS in the analogue perspective: Newtonian dynamics in the "time"-dependent potential

$$\varphi'' + \left(\frac{2}{r} - \frac{W'}{W}\right)\varphi' = \left[m^2(1-4\varphi^2+3\varphi^4) - W^2\right]\varphi\,,$$

$\mu W = \omega e^{(u-v)/2}$, $\mu m = \mu e^{u/2}$, $\varphi = \phi/(\sigma_0/\sqrt{2})$,
$ds^2 = -e^v dt^2 + e^u dr^2 + r^2 d\Omega^2$

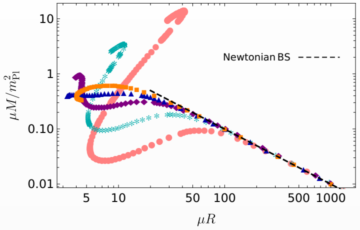
- Analytical solution for arbitrary $\Lambda \ll 1$

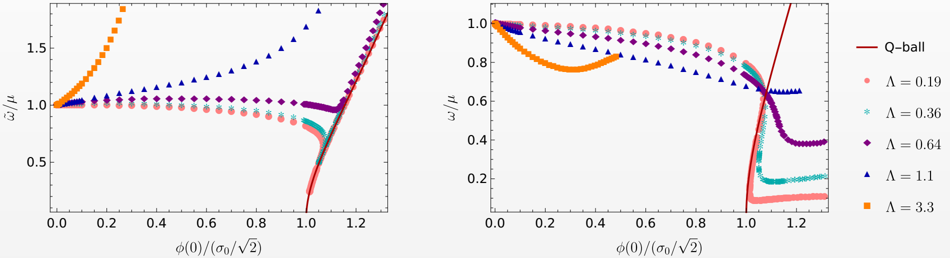




(i) SBS parameter space

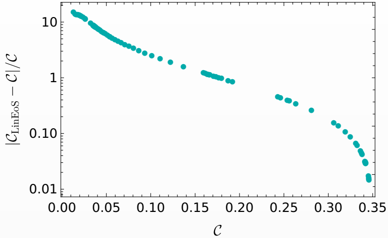
- Parameter space ($\Lambda \ll 1$): stable
  mini boson star (MBS) branch
  (quantum pressure) $\to$ unstable
  Q-ball branch $E > \mu Q \to$ stable
  Q-ball branch $\to$ stable
  strong-gravity branch $\to$ unstable
  strong-gravity branch
- $\Lambda \gtrsim 1$ MBS ($V = \mu^2 |\Phi|^2$) regime

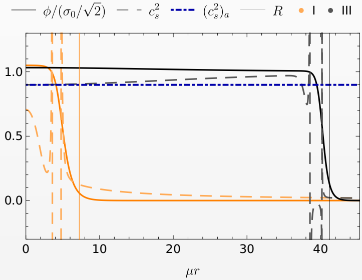




(i) SBSs are maximally stiff and compact [2/2]

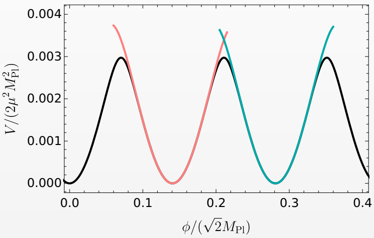
- Thin-wall estimates $\langle c_s^2(r) \rangle \to C_{\mathrm{B+C}}[c_s]$ compare well with the numerical results when $C \to C_{\mathrm{B+C}}$
- In the thick wall regime bulk and the wall commensurable: $C \ll C_{\mathrm{B+C}}$





(ii) It's not the full potential but the presence of a false vacuum that counts [3/3]: multiple vacua

- What about multiple vacua?
- Axion stars: pseudo-solitons with the cos potential $V \sim 1 - \cos(\phi/f_a)$ Helfer+ [1609.04724]
- "axion" BS as an axion star proxy Guerra, Macedo, Pani [1909.05515]
- "axion" BS maps to stacked vanila SBS $\Lambda_n = \frac{f_a}{m_{\rm Pl}} 2n\pi\sqrt{16\pi}, n \in \mathbb{N}$



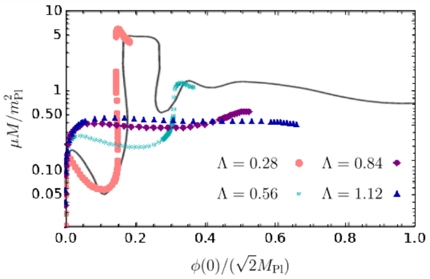


Fig (R): Guerra, Macedo, Pani [1909.05515] (background)

(iii) (S)BSs abhor angular momentum

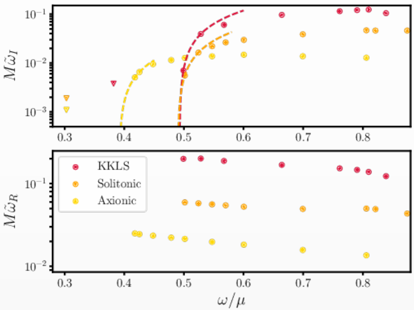
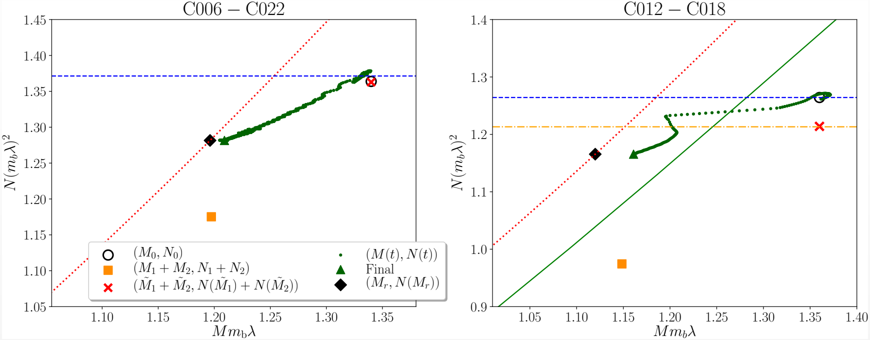
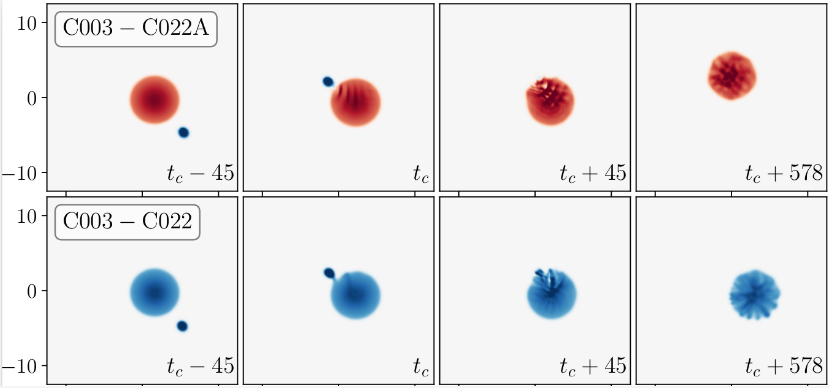


Fig: Siemonsen, East [2011.08247]

(iii) Mass-charge parameter space

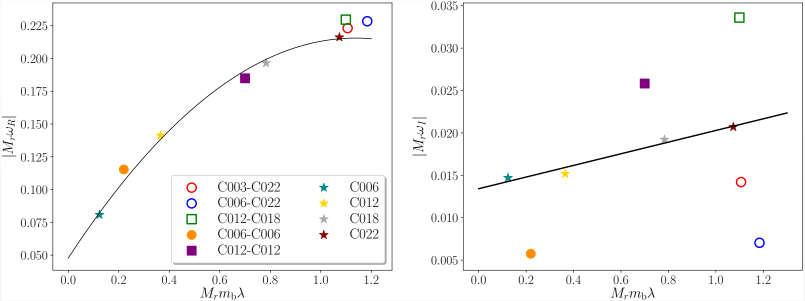


(iii) BS-anti-BS case



(iii) SBS QNMs in isolation vs. post-merger

- ω_R: good agreement between isolated SBS and post-merger remnants
- ω_I: significant discrepancy; it appears that direction correlates w. presence of blobs



(iii) SBS in the LIGO band

- SNR

$$\rho(\Delta) = \left[4 \int \frac{|\tilde{\Delta}(f)|^2}{S_n(f)} df\right]^{1/2}$$

- Two noise models: O3b single-detector sensitivity (solid), the single-detector design LIGO sensitivity (dashed)
- Large residual SNRs imply missed detections or biases in the parameter estimation