Probing scalar particles and forces with compact objects

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Based on:
I MB, Barausse [2111.03870]
II Bezares, MB, Liebling, Palenzuela, Pani, Barausse [2201.06113]
III MB, Barausse [2301.xxxxx]
i Microphysics (scalar field interactions) → macroscopic properties of exotic compact objects (ECO)

ii ECOs coalescence: can boson stars (BS) sustain angular momentum?

iii How the kinetic screening of scalar fifth forces operates in binary systems?
(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: 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
(i) Buchdahl bound and beyond

- **WEC** + micro stability\(^*\) + micro stability\(^**\) \(\implies\) Buchdahl bound \(C_B \leq 0.44\) (constant density star);
  \[ C = \frac{GM}{(Rc^2)} \]

- **Subluminal condition**
  \[ c_s = \sqrt{\frac{\partial P}{\partial \rho}} \leq 1 \]
  lowers the Buchdahl bound:
  - saturated by LinEoS \(\rho \propto P\):
    \[ C_{B+C} = 0.354 \]
    Urbano, Veermäe [1810.07137]
  - radially stable elastic objects must satisfy \(C_{EO\text{max}} < 0.376\)
    Alho+ [2107.12272, 2202.00043]

Fig: Alho+ [2202.00043]

\* \(\rho \geq 0 \land \rho + P \geq 0\)
\** \(P \geq 0 \land \frac{dP}{d\rho} \geq 0\)
(i) (Soliton) boson stars

- Complex scalars w. $U(1)$: $\mathcal{L}_\Phi = -\partial_\mu \Phi^\dagger \partial^\mu \Phi - V(|\Phi|)$
- Mini BS $[\mu^2 |\Phi|^2] \rightarrow C_{\text{max}} \approx 0.11$ ("quantum pressure"), Self-interacting BS $[\lambda |\Phi|^4] \rightarrow C_{\text{max}} \approx 0.16$ (radial pressure)
- Parametrized deviation from the degenerate vacuum

$$V_6 = \phi_0^2 \left[ (\mu^2 - \omega_0^2) \phi^2 (1 - \phi^2)^2 + \omega_0^2 \phi^2 \right], \phi = \phi / \phi_0$$

- Thin wall regime: bulk of the star is in the degenerate vacuum

Review: Liebling, Palenzuela [1202.5809]
(i) SBSs are maximally stiff and compact

- **Degenerate vacuum** \( \omega_0 = 0 \)
  - Effective LinEoS in the bulk \( \varphi \approx 1 \to \varphi' \approx V \approx 0 \) \( \to P \approx \rho \)
  - \( (c_s)_a \approx 1 - 4(\varphi_c - 1) \)
  - Parameter space scanned w. \( \Lambda = \sigma_0/M_{Pl} \); thin wall realizable in the ultra-compact subspace: \( \Lambda \lesssim 0.25 \)

- **False vacuum** \( \omega_0 \neq 0 \)
  - \( (c_s^2)_a \approx \frac{2 - (\omega_0/\mu)^2}{2 + (\omega_0/\mu)^2} \)
  - \( C_{\text{max}} \lesssim C_{B+C} - 0.06(\omega_0/\mu)^2 \)

Consistent with the subsequent results in Cardoso+ [2112.05750], Collodel, Doneva [2203.08203]
(i) It’s not the full potential but the presence of a false vacuum that counts

- 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
(ii) (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]]
(ii) (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 \(M < M_{\text{max}}\) BS will form; else - BH
- Parameterized condition for the rotating remnant

\[
\frac{J_{c,K}(1+e_J)}{N(M_1)+N(M_2)} > 1 + e_N \quad & \quad C > C_{\text{NAI}}
\]
(ii) (S)BSs abhor angular momentum [3/3]

- For BS + BS → BS excess angular momentum is dashed through scalar radiation (gravitational cooling) and GW
- Instead of rotating remnants, in two cases excess 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?

![Graph and images]
(iii) Scalar fifth forces

▶ Is the phenomenon of \( \text{gravity} = \text{GR} + \) additional attractive universal long-range interaction (fifth force)?

▶ Motivations
  - i Cosmological constant problem; behavior of DM in galaxies (e.g. superfluid DM Berezhiani, Khoury [1507.01019])
  - ii Gravitational probes allow us to constrain fifth forces

▶ Simplest extension: massless scalar (Brans-Dicke)

▶ How to “hide” the scalar at the solar system scales w.o. fine-tuning: screening mechanism

Review: Joyce+ [1407.0059]
(iii) k-essence

- k-essence $\mathcal{L} = [K(X) + \frac{\alpha}{M_{Pl}} \varphi T]$
  
  $K = -\frac{1}{2} X + \frac{\beta}{4 \Lambda^4} X^2 - \frac{\gamma}{8 \Lambda^8} X^3 + ...$, $X = (\partial \varphi)^2$

  $\{|\beta|, \gamma, ...\} \sim \mathcal{O}(1)$

- Cosmological values of $\Lambda \sim \sqrt{H_0 M_{Pl}} \sim \text{meV}$

- Kinetic screening: turns off the fifth force when $|a| \gtrsim \Lambda^2$

\[ q_0'(r) \simeq \left( \frac{\Lambda^4 M}{4 \pi M_{Pl} r^2} \right)^{1/3} \]

\[ \frac{q_0}{q_{\text{Newt}}} \simeq \left( \frac{r}{r_*} \right)^{4/3} \]

\[ \frac{q_0}{q_{\text{Newt}}} \simeq 1 \]

\[ r_* = \left( \frac{M}{4 \pi M_{Pl} \Lambda^2} \right)^{1/2} \]

(0.1 parsecs for the Sun)

Fig: Kuntz (2021)
Numerical simulations indicate that screening can be less effective beyond spherical-symmetry and staticity (*)

Stationary limit: $\nabla (K' \nabla \phi) = 4\pi \rho$

Helmholtz decomposition: $K' \nabla \phi = \nabla \chi + B \& \nabla^2 \chi = 4\pi \rho$

$B$ suppressed perturbatively; non-negligible in the deep screening regime

Pockets of the linear regime $\delta r \sim (\Lambda^2 / M_{Pl}) \omega^{-2} (1 + \sqrt{q})^{-1}$

(*) gravitational collapse Bezares+ [2105.13992], Shibata, Traykova [2210.12139]; binary in the stationary limit Kuntz [1905.07340]; compact binary coalescence Bezares+ [2107.05648]
Conclusions

- **SBSs are maximally stiff and compact motivated ECOs** [2111.03870]
  - It's not the full potential but the presence of a false vacuum that counts
- **(S)BSs abhor angular momentum** [2201.06113]
  - $a \neq 0$ probably indicates $\text{ECO} \neq \text{BS}$ (also axion star)
- **In screening, more is different** [2301.xxxxx]
  - Pockets of the linear regime and solenoidal component in the near zone
Supplementary material
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 $C_{B+C}$

▶ 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 $\text{SNR}(h_{BS} - h_{BH}) \rightarrow$ missed detections/biases
(i) Q-balls

- Analogue particle perspective: Newtonian dynamics

\[ \phi'' + \frac{2}{r} \phi' = -\frac{dU_\omega}{d\phi}, \]  
\[ U_\omega = \frac{1}{2}(\omega^2 \phi^2 - V(\phi)). \]  

- 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

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

\[ \mu W = \omega e^{(u-v)/2}, \quad \mu m = \mu e^{u/2}, \quad \varphi = \phi / (\sigma_0 / \sqrt{2}), \]

- Analytical solution for arbitrary \( \Lambda \ll 1 \)
(i) SBS parameter space

- Parameter space ($\Lambda \ll 1$): stable mini boson star (MBS) branch (quantum pressure) → unstable Q-ball branch $E > \mu Q$ → stable Q-ball branch → stable strong-gravity branch → 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 $\langle c_s^2(r) \rangle \rightarrow C_{B+C}[c_s]$ compare well with the numerical results when $C \rightarrow C_{B+C}$

- In the thick wall regime bulk and the wall commensurable: $C \ll C_{B+C}$
(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
  \[ V \sim 1 - \cos \left( \frac{\phi}{f_a} \right) \]  
  Helfer+ [1609.04724]
▶ "axion" BS as an axion star proxy Guerra, Macedo, Pani [1909.05515]
▶ "axion" BS maps to stacked vanila SBS
  \[ \Lambda_n = \frac{f_a}{m_{Pl}} \frac{2n\pi \sqrt{16\pi}}{n}, n \in \mathbb{N} \]

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

- \( \omega_R \): good agreement between isolated SBS and post-merger remnants
- \( \omega_I \): significant discrepancy; it appears that direction correlates with 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