# Probing scalar particles and forces with compact objects

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# (Averaged) trajectory


- BSc, MSc in Theoretical Physics @ Uni Belgrade; MSc thesis w Vitor Cardoso at Tecnico Lisboa
- PhD in Astroparticle Physics w Enrico Barausse at SISSA

# Overview

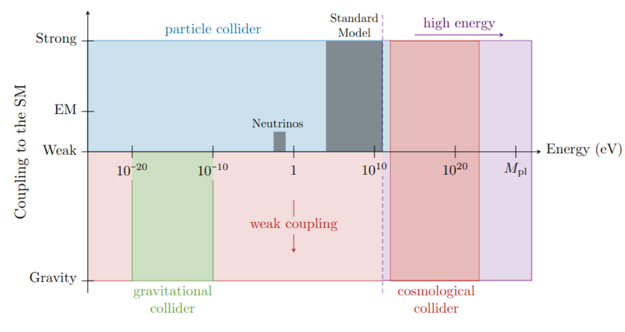
- Understanding the nature of DM and DE $\rightarrow$ search for new particles; we focus on massive and massless, force-mediating, scalars
- GW astronomy allows one to probe some of these models by studying the coalescence of compact object binaries
- Alternative motivation: Scalars are accessible models of matter under strong gravity conditions

# Overview

- Gravitational probes of ultra-light bosons
- Solitons in strong gravity
- Gravitational probes of scalar fifth forces

# (i) Gravitational probes of ultra-light bosons (1/3)

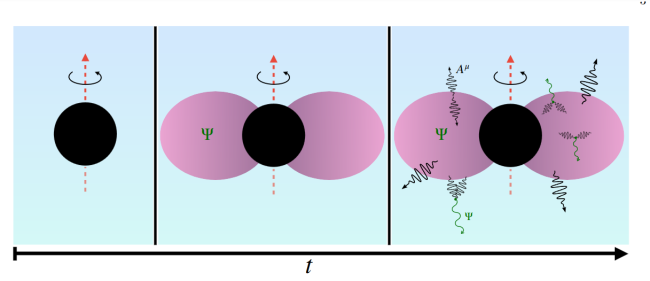
- Compton/De Broglie wavelengths on astrophysical scales - from stellar BHs to galaxies
- Large occupancies in the case of DM halos, superradiant clouds etc.
- e.g. Motion in time-periodic background generated by axion DM MB+ [1806.07331]




Reviews: Hui [2101.11735], Brito, Cardoso, Pani [1501.06570];
Fig: Baumann+ [1912.04932]

# (i) Gravitational probes of ultra-light bosons (2/3)

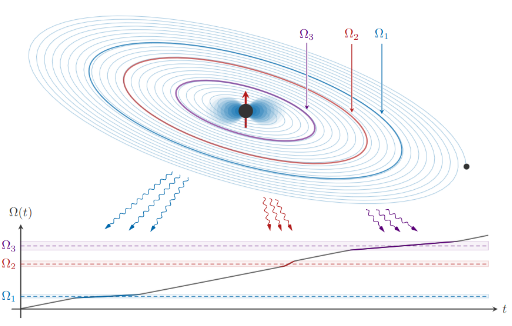
- Axion-photon coupling and BH superradiance (parametric instability) MB+ [1811.04945]
- $\mathscr{L} \supset \frac{\beta}{f_a} a^* FF$ , $R > \lambda_*^{-1}$ , $\lambda_* \sim \frac{\beta}{f_a} \mu \langle a \rangle_c$
- Typically plasma-blocked for $\omega_{\rm pl} \gtrsim \mu$




Refs: Rosa, Kephart [1709.06581], Sen [1805.06471], MB+ [1811.04945];
Fig/further development: Spieksma+ [2306.16447]

# (i) Gravitational probes of ultra-light bosons (3/3)

- Resonantly enhanced level transitions; ionization
- Significantly enriches phenomenology; cloud survival entangled with the orbit formation
- Ongoing work [w. Koschnitzke, Porto]




Refs: Baumann+ [1804.03208, 1912.04932, 2112.14777], Tomaselli, Spieksma, Bertone [2305.15460], Brito, Shah [2307.16093]; Fig: Baumann+ [1912.04932]

# (ii) (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
- Motivation 1: connection with dark matter and EU models
  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

# (ii) Buchdahl bound and beyond

- WEC* + micro stability** $\implies$ Buchdahl bound $C_B \leq 0.44$ (constant density star); $C = GM/(Rc^2)$
- Subluminal 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]
- What microphysics can saturate these conditions?

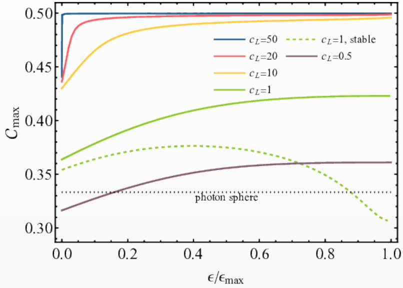



Fig: Alho+ [2202.00043]

$^*\rho \geq 0 \wedge \rho + P \geq 0$ ,

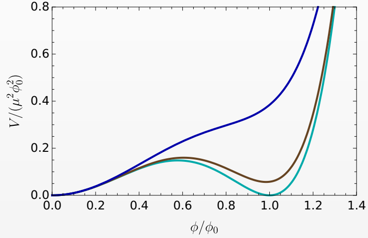
$^{**}P \geq 0 \wedge dP/d\rho \geq 0$

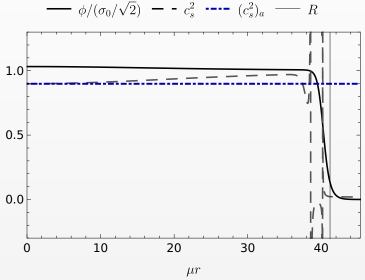
# (ii) (Soliton) boson stars

- Complex scalars w. $U(1)$: $\mathscr{L}_\Phi = -\partial_\mu \Phi^\dagger \partial^\mu \Phi - V(|\Phi|)$
- Parametrized deviation from the degenerate vacuum (gravitating Q-balls)

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

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

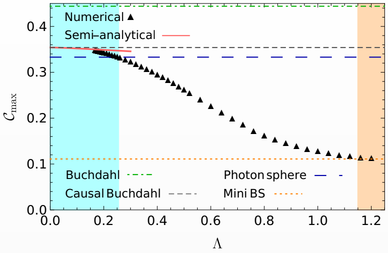


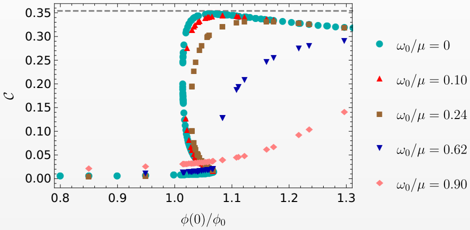




Review: Liebling, Palenzuela [1202.5809]

# (ii) 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. $\Lambda = \sigma_0 / M_{\rm Pl}$; thin wall realizable in the ultra-compact subspace: $\Lambda \lesssim 0.25$
- False vacuum $\omega_0 \neq 0$
  - ⋆ $(c_s^2)_a \approx \frac{2-(\omega_0/\mu)^2}{2+(\omega_0/\mu)^2}$
  - ⋆ $C_{\rm max} \lesssim C_{\rm B+C} - 0.06(\omega_0/\mu)^2$




Ref: MB, Barausse [2111.03870]; Consistent with the subsequent results of Cardoso+ [2112.05750], Collodel, Doneva [2203.08203]

# (ii) (S)BSs abhor angular momentum [1/2]

- BS have quantized angular momentum $J = kQ$, $k \in \mathbb{N}$
- Rotating BSs 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?

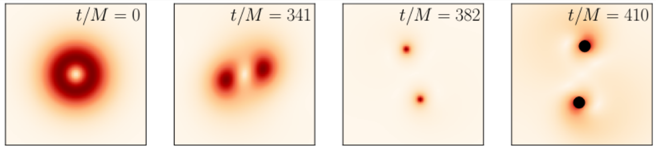
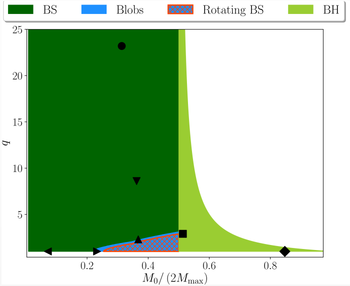


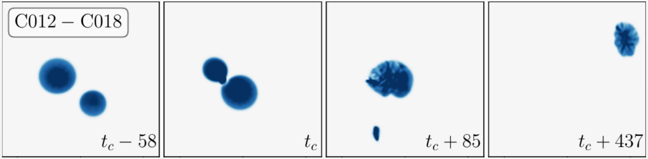

Fig: Siemonsen, East [2011.08247]

# (ii) (S)BSs abhor angular momentum [2/2]

- If $M < M_{\max}$ BS will form; else - BH
- Parameterized condition for the rotating remnant $J_{c,K} \gtrsim N(M_1) + N(M_2)$ & $C > C_{\rm NAI}$
- Instead of rotating remnants, in two cases excess angular momentum is emitted in the form of blobs
- For $q > 1$, blobs can induce superkicks $v \sim 0.05c$
- Subsequent work: formation of rotating BS possible but not generic Siemonsen, East [2302.06627]

- Binary SBS simulations from Palenzuela+ [1710.09432], Bezares, MB+ [2201.06113]



# (iii) Fifth force screening

- Fifth force screening necessary to evade Solar System bounds
- Is screening effective beyond staticity and spherical symmetry?
- General scalar theory in the decoupling limit $\varphi = \bar{\varphi} + \bar{\pi}$
  $\mathscr{L} = -\frac{1}{2}\bar{Z}^{\mu\nu}\partial_\mu \pi \partial_\nu \pi - \frac{1}{2}\bar{m}^2\pi^2 + \bar{g}\,T + \ldots$ ,
  $\bar{Z} = \bar{Z}(\partial\bar{\phi}, \partial^2\bar{\phi}, \ldots)$
- Fifth-force potential of a point source (all functions of $\bar{\varphi}$):
  $\hat{\pi} \sim \frac{\bar{g}}{\sqrt{\bar{Z}}} \frac{\exp\left(-\frac{\bar{m}}{\sqrt{\bar{Z}}} r\right)}{r}$
- Varieties of screening:
  - ⋆ $\hat{\pi}$ as a trigger (via potential): weak coupling $\bar{g}$ (symmetron), large mass $\bar{m}$ (chameleon)
  - ⋆ $\partial\hat{\pi}$ as a trigger (via acceleration) $\bar{Z}$: kinetic screening
  - ⋆ $\partial^2\hat{\pi}$ as a trigger (via curvature) $\bar{Z}$: Vainshtein mechanism

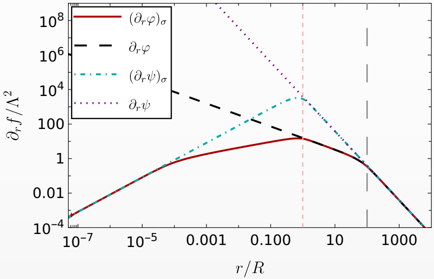
Review: Joyce+ [1407.0059]

# (iii) $k$-essence

- $k$-essence action $\mathscr{L} = K(X)$

$$K = -\frac{1}{2}X + \Lambda^4 \sum_{n=2}^{N} \frac{c_n}{2n}\left(\frac{X}{\Lambda^4}\right)^n, X = g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi$$

- Cosmological context
  $\Lambda \sim \sqrt{H_0 M_{\rm Pl}} \sim \mathrm{meV}$
  - ⋆ Only unconstrained sector of Horndeski after GW170817 and requiring GW $\nrightarrow$ DE
    Creminelli+ ['17, '18, '19]

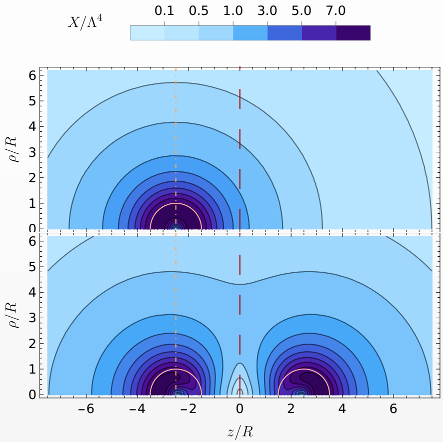



- $k$-mouflage $K(X)$: turns off the fifth force when $X \gtrsim \Lambda^4$
- Radiative stability for large $X$
  de Rham, Ribeiro [1405.5213]

Review: Joyce+ [1407.0059]

# (iii) Screening in a binary

- At the Newtonian order $\partial_i(K_X \partial^i \varphi) = \frac{\alpha}{2M_{\rm Pl}} T$
- Helmholtz decomposition: $\boldsymbol{\chi} \equiv K_X \boldsymbol{\nabla}\varphi$ , $\boldsymbol{\chi} = -\frac{1}{2}\boldsymbol{\nabla}\psi + \boldsymbol{B}$
- Identified the regime where $\boldsymbol{B}$ can be ignored: $q \gg 1$ , $\left(\frac{r_{\rm sc}}{D}\right)^2 \ll 1$
- Checked numerically; qualitatively fine when $q \approx 1$
- Saddle point: attractive forces cancel, breakdown of screening $\frac{\delta}{D} \simeq \frac{1}{\kappa}\frac{q^{3/2}}{(1+\sqrt{q})^4}$
- e.g. Earth-Moon ($\delta \approx 0.2{\rm km}$), Sun-Earth ($\delta \approx 1{\rm km}$) [$\Lambda \sim {\rm meV}$]




Ref: MB, Barausse [2305.07725]

# On-going interests

- Phenomenology with gravitational two-body problem
  - ⋆ Are scalar clouds robust? New signatures?
  - ⋆ Beyond boson clouds and ECOs
- Classical non-linearities and EFTs
  - ⋆ Screening vs. positivity bounds
  - ⋆ Breakdown of the well-posedness of the Cauchy problem