Probing scalar particles and forces with compact objects

Mateja Bošković

SISSA & IFPU (Trieste)

XV Black Holes Workshop
20.12.2022.

ERC-2018-COG GRAMS 815673

Based on:

I MB, Barausse [2111.03870]

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

III MB, Barausse [2301.xxxxx]

Outline

i. Microphysics (scalar field interactions) $\rightarrow$ 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** $\implies$ 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 $\rho \propto P$: $C_{B+C} = 0.354$ Urbano, Veermäe [1810.07137]
  - ⋆ radially stable elastic objects must satisfy $C_{EOmax} < 0.376$ Alho+ [2107.12272, 2202.00043]

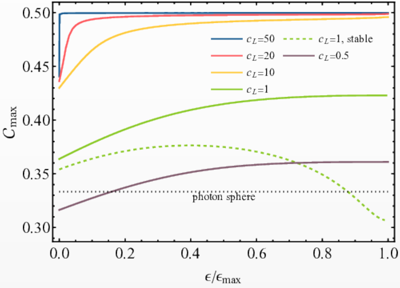


Fig: Alho+ [2202.00043]

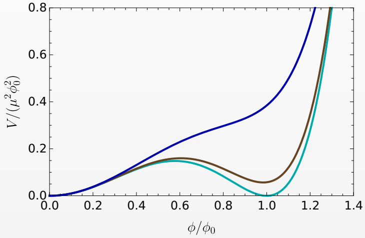
$^{*}\rho \geq 0 \wedge \rho + P \geq 0$, $^{**}P \geq 0 \wedge dP/d\rho \geq 0$

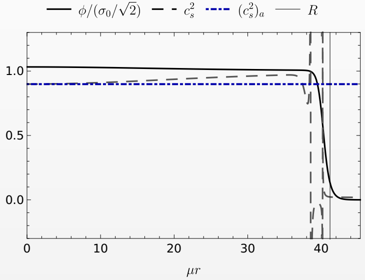
(i) (Soliton) boson stars

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

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

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

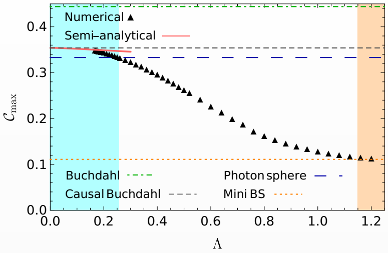


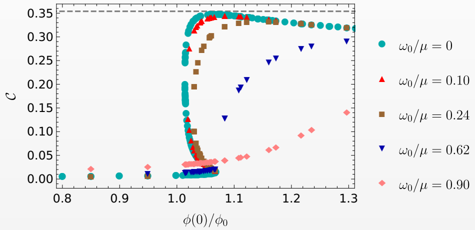


Review: Liebling, Palenzuela [1202.5809]

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

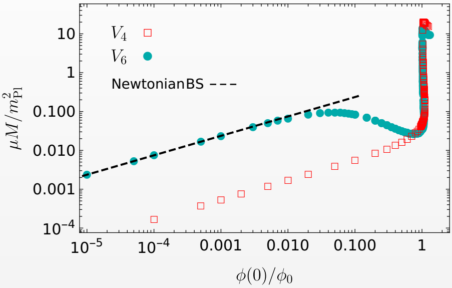


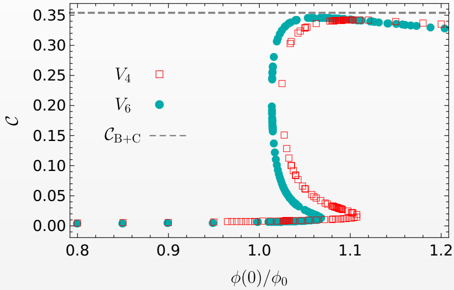


Consistent with the subsequent results in
Cardoso+ [2112.05750], Collodel, Doneva [2203.08203]

(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?

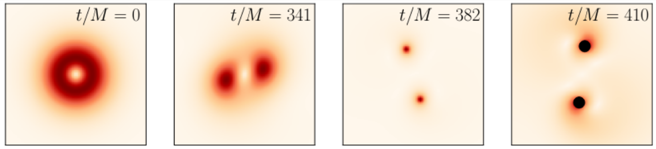
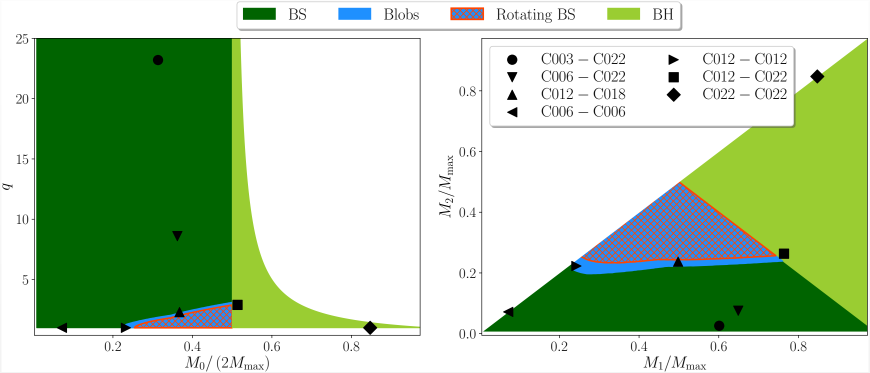


Fig: Siemonsen, East [2011.08247]

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

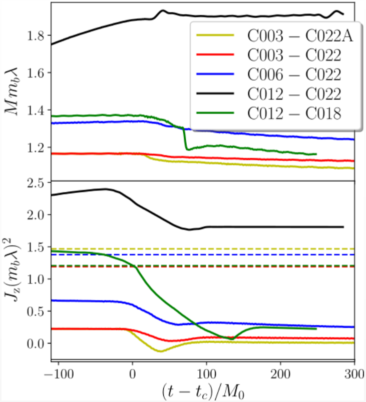
- Binary SBS simulations from Palenzuela+ [1710.09432], Paper II
- Catalogue: $3 \times q = 1$, $4 \times q \sim 2 - 30$
- If $M < M_{\rm max}$ BS will form; else - BH
- Parameterized condition for the rotating remnant

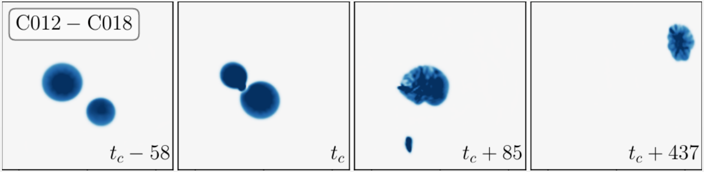
$$\frac{J_{c,K}(1+e_J)}{N(M_1)+N(M_2)} > 1 + e_N \quad \& \quad C > C_{\rm NAI}$$



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

- For $\mathrm{BS} + \mathrm{BS} \to \mathrm{BS}$ excess angular momentum is dashed trough 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?





(iii) Scalar fifth forces

- Is the phenomenon of *gravity* = 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 $\mathscr{L} = [K(X) + \frac{\alpha}{M_{Pl}} \varphi T]$
  $K = -\frac{1}{2}X + \frac{\beta}{4\Lambda^4}X^2 - \frac{\gamma}{8\Lambda^8}X^3 + \ldots$, $X = (\partial\varphi)^2$
  $\{|\beta|, \gamma, \ldots\} \sim \mathscr{O}(1)$
- Cosmological values of $\Lambda \sim \sqrt{H_0 M_{\rm Pl}} \sim {\rm meV}$
- Kinetic screening: turns off the fifth force when $|\boldsymbol{a}| \gtrsim \Lambda^2$

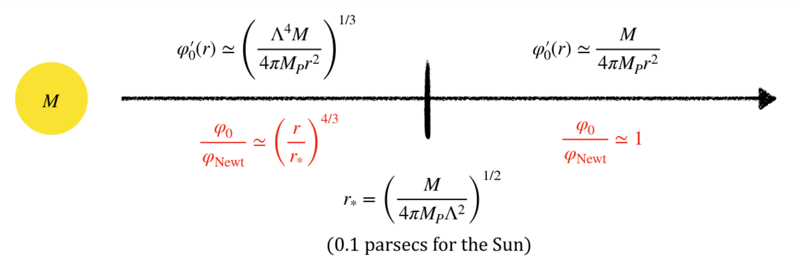
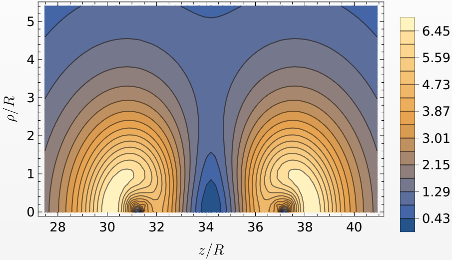
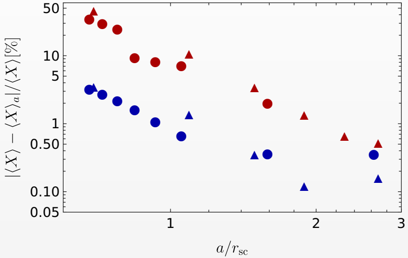


Fig: Kuntz (2021)

(iii) k-essence in binaries

- Numerical simulations indicate that screening can be less effective beyond spherical-symmetry and staticity (*)
- Stationary limit $\boldsymbol{\nabla}\left(K'\boldsymbol{\nabla}\varphi\right) = 4\pi\rho$
- Helmholtz decomposition: $K'\boldsymbol{\nabla}\varphi = \boldsymbol{\nabla}\chi + \boldsymbol{B}$ & $\nabla^2\chi = 4\pi\rho$
  - ⋆ $\boldsymbol{B}$ suppressed perturbatively; non-negligible in the deep screening regime
- Pockets of the linear regime $\delta r \sim (\Lambda^2/M_{\rm Pl})\omega^{-2}(1+\sqrt{q})^{-1}$





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

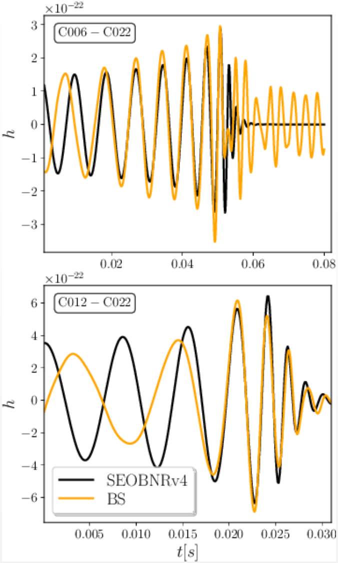
Conclusions

- 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 $\mathrm{ECO} \neq \mathrm{BS}$ (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 $C_{\mathrm{B+C}}$
- 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 $\mathrm{SNR}(\mathrm{h_{BS}} - \mathrm{h_{BH}}) \rightarrow$ missed detections/biases



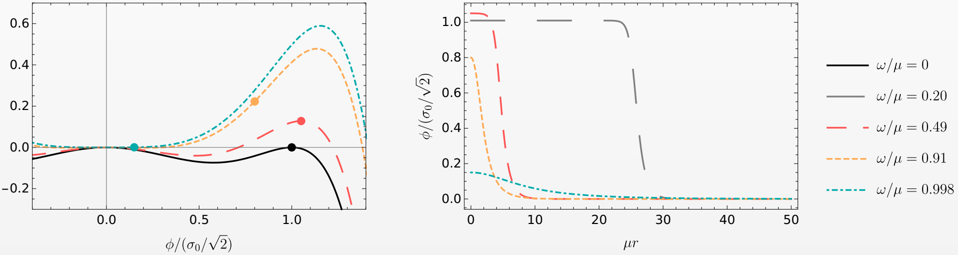
(i) Q-balls

- Analogue particle perspective: Newtonian dynamics

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

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

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



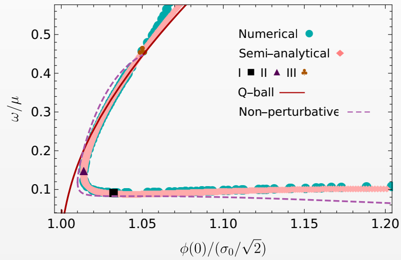
(i) SBSs are Q-balls in the time-dependent potential

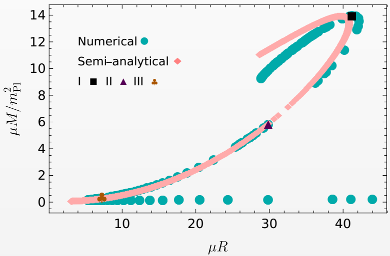
- SBS in the analogue perspective: Newtonian dynamics in the "time"-dependent potential

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

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

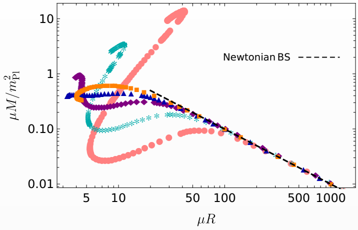
- Analytical solution for arbitrary $\Lambda \ll 1$



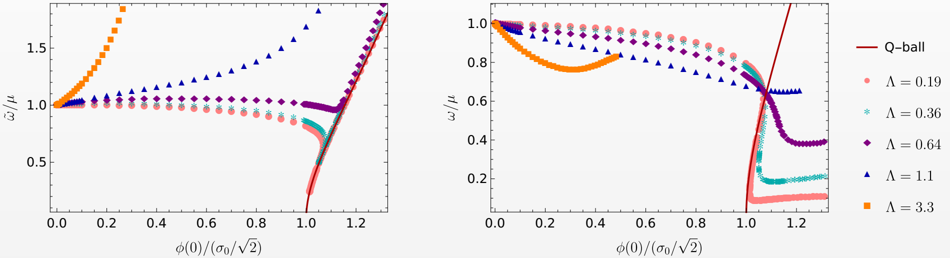


(i) SBS parameter space

- Parameter space ($\Lambda \ll 1$): stable mini boson star (MBS) branch (quantum pressure) $\rightarrow$ unstable Q-ball branch $E > \mu Q$ $\rightarrow$ stable Q-ball branch $\rightarrow$ stable strong-gravity branch $\rightarrow$ unstable strong-gravity branch

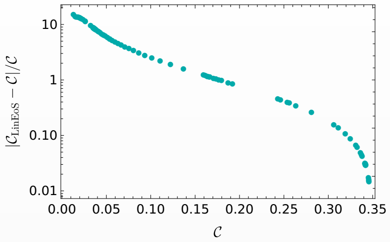


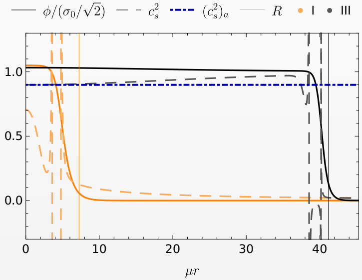
- $\Lambda \gtrsim 1$ MBS ($V = \mu^2|\Phi|^2$) regime



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

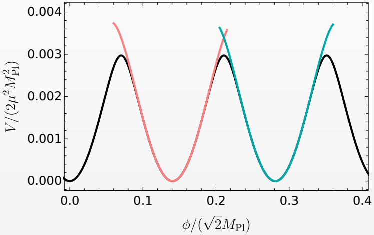
- Thin-wall estimates $\langle c_s^2(r)\rangle \to C_{\mathrm{B+C}}[c_s]$ compare well with the numerical results when $C \to C_{\mathrm{B+C}}$
- In the thick wall regime bulk and the wall commensurable: $C \ll C_{\mathrm{B+C}}$





(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 $\Lambda_n = \frac{f_a}{m_{\rm Pl}} 2n\pi\sqrt{16\pi}, n \in \mathbb{N}$



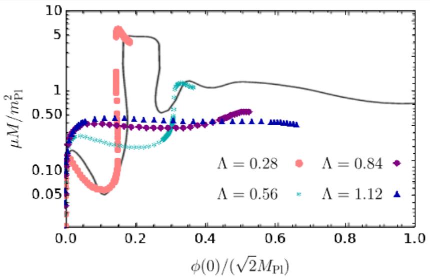


Fig (R): Guerra, Macedo, Pani [1909.05515] (background)

(iii) (S)BSs abhor angular momentum

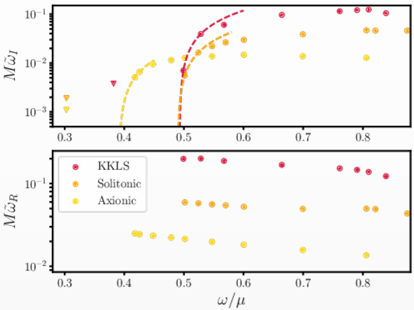
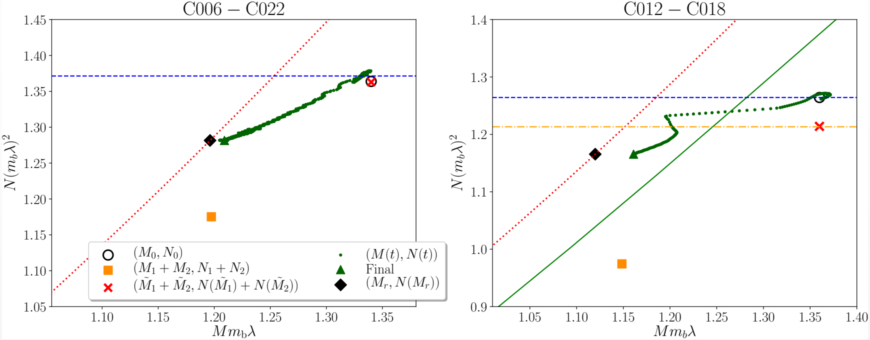
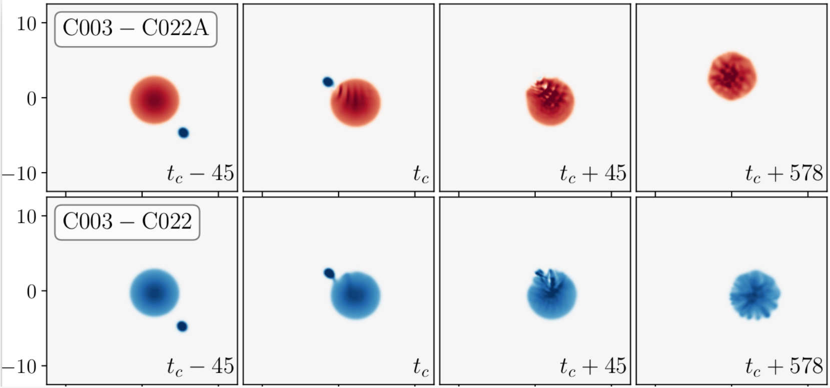


Fig: Siemonsen, East [2011.08247]

(iii) Mass-charge parameter space

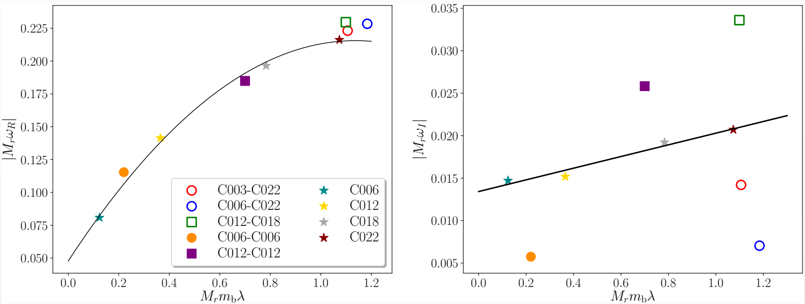


(iii) BS-anti-BS case



(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