

Implications of GW241011 for Rotating Exotic Compact Objects

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Several theoretical proposals describe horizonless compact objects that can mimic black holes in their gravitational wave signatures; however, their spin-induced quadrupole moments (SIQMs) may reveal their distinct nature. Using the tight bounds on the SIQM of GW241011, we place constraints on the nature of its primary. Across exotic compact object models considered in this Letter, we find that rotating boson stars with quartic self-interactions cannot explain the nature of the primary, whereas models of sufficiently large compactness, $C \gtrsim 0.24$, may still be viable contenders.

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Introduction—The latest LIGO-Virgo-KAGRA [1–3] gravitational wave (GW) transient catalog reported over 200 compact binary coalescences [4]. Owing to increased sensitivity and several exceptional events [5–11], we are in the position to perform unprecedented tests of general relativity and the standard model of particle physics [12]. One such exemplary event is GW241011 [10,13], a compact binary with a highly spinning primary (dimensionless spin $\chi_1 \sim 0.78^{+0.09}_{-0.09}$) that is roughly three times more massive than the secondary (primary mass $m_1 \sim 19.6^{+3.6}_{-2.5} M_\odot$ and mass ratio $q \sim 0.30^{+0.09}_{-0.08}$). These properties, together with its high signal strength, make GW241011 a perfect laboratory for investigating the fundamental question at the center of this work: do compact objects beyond the realm of black holes (BHs), neutron stars (NSs), and white dwarfs populate our Universe?

There have been a variety of proposed models for such exotic compact objects (ECOs) [14–17]. Among the most studied are scalar and vector boson stars (BSs) [18,19], while other proposals, such as gravastars (GSs) [20–25] and anti-de Sitter (AdS) black shells [26,27], are still being developed. While the GW phenomenology of BSs has been explored through numerical relativity in some regions of the parameter space [28–32], much of the landscape of ECO signatures still awaits a systematic study. Given the present challenges associated with accurately modeling of GW signatures of ECOs, agnostic parametrized tests of general finite-size signatures [14,33–40], i.e., effects related to the body’s internal structure, currently provide the most robust approach to probing the nature of these compact objects.

Spin-induced multipole moments are one class of finite-size effects. They arise when the spin of a compact object deforms its shape and generates a hierarchy of multipoles that imprint characteristic signatures on the emitted GW signal. While these multipoles are uniquely determined for Kerr BHs by their mass and spin [41–45], non-BH compact objects can have spin-induced deformations distinct from that of BHs [14,46–52], allowing for tests of the Kerr geometry through the GW signal of compact binaries. In particular, the leading-order spin-induced multipole—the spin-induced quadrupole moment (SIQM)—can be used to constrain the NS equation of state (EOS) [53], or various models of ECOs [54]. The SIQM (and higher-order moments) of *spinning* ECOs is less well-studied than that of NSs. Current efforts have focused on computing SIQM for certain BS models in the large self-interaction approximation [48,52] and from numerically computed spacetimes [49,55,56], as well as slowly rotating thin-shell GSs [50,57].

Remarkably, GW241011 [10] placed the most stringent constraint on beyond-Kerr corrections to the SIQM of the primary to date [10]. Here, we utilize this measurement to constrain the parameter space of ECO models that are still compatible with the primary of GW241011. In particular,

we compute the SIQMs of spinning BSs and place constraints on their potential and the scalar mass. We also extend our constraints to exotic fluid stars (EFSs) with sound speed equal to the speed of light. Finally, we comment on the implications for existing spinning gravastar models, dynamically scalarized BHs, and Proca stars, as well as the limitations of current modeling assumptions.

Unless otherwise stated, we use geometric units with $G = c = 1$.

SIQM measurements from GW241011—The post-Newtonian (PN) formalism provides a framework to describe the inspiral dynamics of a spinning compact binary [58–60]. Within this formalism, leading-order SIQM corrections to the GW phase appear at 2PN order [41,61]. The SIQM of each compact object scales as $Q_i = -\kappa_i \chi_i^2 m_i^3$ [41,43,44], where $i \in \{1, 2\}$, corresponding to the more or less massive object, respectively, and κ_i denotes the *reduced* quadrupole. For Kerr BHs, $\kappa_i = 1$, but alternative objects can have different values [46–51]. By explicitly introducing parametric coefficients κ_i in the inspiral phase, we can therefore test the binary progenitors for deviations from the Kerr hypothesis. We use the implementation of the SIQM corrections at 2PN and 3PN orders developed in Ref. [62] within the IMRPhenomXPHM waveform model [63], which includes double-spin precession, higher harmonics, and a complete inspiral-merger-ringdown treatment for binary black holes. As the waveform model does not readily support super-extremal spins $\chi > 1$ predicted by some BS and GS configurations, we restrict our discussion to subextremal spins, i.e., $\chi_{1,2} \in [0, 0.99]$.

In Fig. 1, we illustrate the κ_1 posterior probability distributions from GW241011 [10] and highlight the 95% credible interval (CI) with black dashed lines. The curves in the background are obtained by varying the maximum cutoff frequency f_{cut} when evaluating the likelihood function. For lower values of f_{cut} , posteriors on κ_1 are

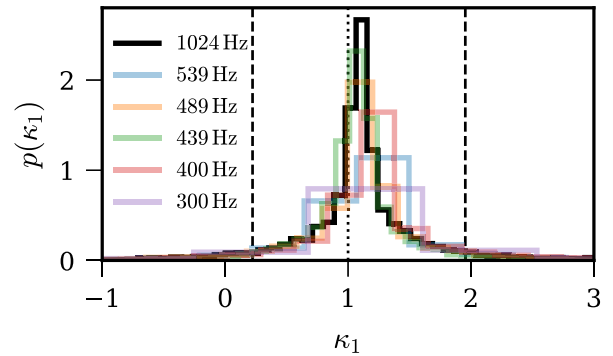


FIG. 1. The one-dimensional posterior distribution of κ_1 from GW241011. The colored lines represent posteriors obtained from the likelihood truncated at different frequencies f_{cut} , whereas the black line corresponds to the full inference. The dashed vertical lines represent the 95% CL bounds, and the dotted vertical line denotes the corresponding Kerr BH value of $\kappa_1 = 1$.

wider as a result of the reduced signal. The qualitative behavior of the posteriors remains unchanged across different f_{cut} , highlighting the robustness of the κ constraints (see the Supplemental Material for more details [64]). The SIQM of the secondary, κ_2 , on the other hand, is not constrained away from its prior; we therefore do not discuss it here.

We utilize the SIQM measurement from GW241011 to put stringent constraints on ECO models. For a broad range of ECOs, we identify models that are consistent with the spin constraints of the primary in GW241011 and then compare the inferred SIQM measurement with their theoretical predictions. As such, our constraints only apply to the primary object in GW241011 and do *not* rule out the existence of ECOs in other systems. In what follows, our comparisons use the full two-dimensional 95% isocontours of the $\kappa_1 - \chi_1$ posterior of the primary object in GW241011. Unless otherwise stated, all ECO parameters we constrain are quoted within the 95% CI.

Boson stars—Scalar boson stars arise from a massive complex scalar field φ , characterized by a potential $V(|\varphi|)$, that is minimally coupled to gravity. We adopt the three commonly studied potentials: (i) repulsive, $V_{\text{rep}}(|\varphi|) = \mu^2|\varphi|^2 + \lambda|\varphi|^4$; (ii) solitonic, $V_{\text{sol}}(|\varphi|) = \mu^2|\varphi|^2[1 - (2|\varphi|^2/\sigma^2)]^2$; and (iii) axionic, $V_{\text{axion}}(|\varphi|) = \mu^2 f^2 \{1 - \cos[\sqrt{2}|\varphi|^2 f^{-1}]\}$. Here, μ denotes the mass parameter, whilst λ/μ^2 , σ , and f are dimensionless coupling constants that quantify self-interactions. Our μ relates to the boson mass m_b via $\mu = m_b c/\hbar$. Spinning BSs are modeled by the scalar ansatz $\varphi = A(r, \theta)e^{i(\omega_{\text{BS}}t + m\phi)}$, where A denotes the amplitude, ω_{BS} the BS frequency, and m the azimuthal number.

For a fixed potential and coupling, we compute a family of BS solutions and their SIQMs (cf. the Supplemental Material for more details [64]). However, not all configurations we construct are viable candidates for ECOs due to stability considerations. We therefore exclude unstable stars, as indicated by (i) catastrophe theory turning-point arguments [76], and (ii) numerical simulations, identifying linear nonaxisymmetric instabilities in models with no or small self-interactions [65,77]. Additionally, we explicitly set $m = 1$ in the scalar field ansatz, as no dynamically stable boson star configurations with $m > 1$ have been obtained yet.

For item (ii), we determine the regions of dynamical stability using the results of numerical simulations of Ref. [65]. For instance, for repulsive stars, we extract the minimum threshold on the coupling to be $\lambda > 210/M_{\text{BS}}^2$, where M_{BS} is the BS mass. [A similar estimate of $\lambda > 168/M_{\text{BS}}^2$ has been reported in Ref. [78] for (Newtonian) Bose stars, which is in remarkably good agreement with our relativistic threshold.] For solitonic and axionic stars, we determine dynamical stability by the critical BS frequency $\omega_{\text{BS},c}$: the stars tend to stabilize at lower frequencies $\omega_{\text{BS}} < \omega_{\text{BS},c}$, corresponding to more

compact solutions (see, e.g., Fig. 5 of Ref. [65]). For solitonic models, we expect models consistent with GW241011 to be dynamically stable for $\sigma \lesssim 0.1$, whilst for axionic stars we do not have enough simulation data to draw concrete conclusions.

Repulsive stars: We first start our discussion on constraints with the repulsive potential. In the top panel of Fig. 2, we illustrate our numerically constructed families of repulsive BSs for different couplings $\lambda/\mu^2 \in [150, 1000]$ in the $\kappa - \chi$ space. All models (apart from solutions with $\lambda/\mu^2 = 150$ and $\chi > 0.86$) consistent with the χ_1 measurement of GW241011 permit dynamically stable solutions according to our relativistic stability criterion. If a repulsive potential is to remain consistent with the primary mass and

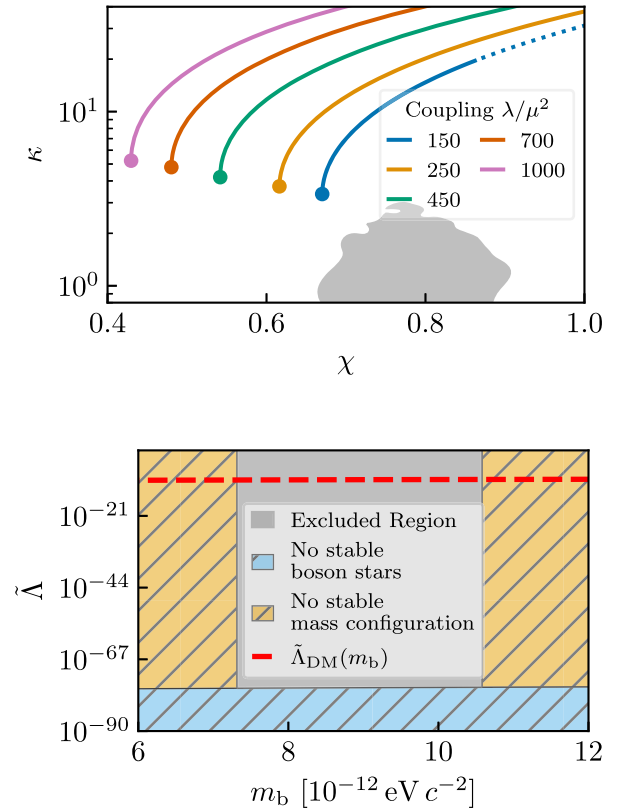


FIG. 2. Top: sequences of repulsive BSs in the $\chi - \kappa$ plane (solid lines), with different colors denoting the coupling values, λ/μ^2 , and dots the maximum mass solution. The dotted lines indicate dynamically unstable solutions according to our relativistic criterion (see the main text). The gray shaded region denotes the $\kappa - \chi$ measurement (at 95% credible level). Bottom: exclusion regions in the $m_b - \tilde{\Lambda}$ plane, where m_b is the boson mass in physical units, $\tilde{\Lambda} = \Lambda(\hbar c)$ is dimensionless, and Λ is the coupling in physical units. Gray denotes the region excluded by GW241011, yellow corresponds to stars with masses incompatible with GW241011, whereas blue contains only unstable solutions. For reference, we also overplot the $\tilde{\Lambda}$ and m_b values corresponding to a hypothetical dark matter particle with cross section per unit mass of $0.1 \text{ cm}^2 \text{ g}^{-1}$ in dashed red line.

spin measurements of GW241011, we find that the boson mass would lie within the range $m_b \in [7.32\text{--}10.6] \times 10^{-12} \text{ eV } c^{-2}$. However, the smallest theoretically allowed κ consistent with the primary spin of GW241011 is ~ 3 (corresponding to a smaller coupling $\lambda/\mu^2 = 150$)—much larger than the limits derived from GW241011. We thus conclude that the primary of GW241011 cannot be explained by a repulsive BS, and exclude $\lambda/\mu^2 \geq 150$ for the aforementioned μ range. For very large couplings $\lambda/\mu^2 \gtrsim 450$, solutions compatible with the spin of GW241011 have larger radii and achieve maximum compactness of $C_{\text{max}} \leq 0.08$. Naturally, these models are therefore unlikely to explain the nature of GW241011. However, for $\lambda/\mu^2 \leq 250$, we find $C_{\text{max}} \sim 0.11\text{--}0.17$, corresponding to more slowly spinning models. In the Supplemental Material [64], we show that there is significant coherent power in the signal past the nominal cutoff frequencies for these compactness values, further suggesting that such low compactness values are ruled out.

In the bottom panel of Fig. 2, we additionally map the constraints on the repulsive potential onto the exclusion region in $m_b\text{--}\tilde{\Lambda}$ plane, where $\tilde{\Lambda}$ is the coupling in physical units and $\tilde{\Lambda} = \Lambda(\hbar c)$ is dimensionless. We then compare it to the upper limits on the cross section of self-interacting dark matter $\sigma_{\text{cross}}^{\text{max}}/m_b \approx 0.1 \text{ cm}^2 \text{ g}^{-1}$ from various observations (see, e.g., Refs. [79–81]). Using the tree-level expression for the cross section per unit mass [82], $\sigma_{\text{cross}}/m_b = 3(32\pi m_b)^{-1}(\Lambda\hbar^2/m_b)^2$, we find that couplings corresponding to cross sections below $\sigma_{\text{cross}}^{\text{max}}/m_b$ are excluded by the data within the boson mass range probed by GW241011. We stress again that these exclusion regions *only* apply to the primary in GW241011 and cannot be extended to other objects in the Universe.

Solitonic stars: The constraints are more subtle for the solitonic potential, as illustrated in the top panel of Fig. 3. First, for smaller self-interactions ($\sigma > 0.1$), there are no solutions consistent with χ_1 of GW241011 (these solutions are also likely to be dynamically unstable). Larger self-interactions ($\sigma \leq 0.1$), on the other hand, do permit stable solutions that are consistent with both χ_1 and κ_1 measurements. The relatively low values of κ here arise from higher compactness ($C \gtrsim 0.26$) of these solitonic stars, in contrast to repulsive models. The allowed gray region in fact even intersects with some ultracompact stars with light rings [83]. Apart from some models with $\sigma = 0.05$ and $\sigma = 0.04$ at high spins, we conclude that, overall, solitonic stars with large self-interactions $\sigma_0 \lesssim 0.1$ and boson masses $m_b \in [1.4\text{--}4.5] \times 10^{-11} \text{ eV } c^{-2}$ are generally consistent with GW241011.

Axionic stars: Similar to the solitonic case, large self-interactions of $f \leq 0.01$ in the axionic potential also lead to highly compact models ($C \gtrsim 0.3$) that are consistent with the spin region of GW241011, and therefore the κ_1 measurement (see the middle panel of Fig. 3). These models have $m_b \in [2.6\text{--}5.0] \times 10^{-11} \text{ eV } c^{-2}$. On the other

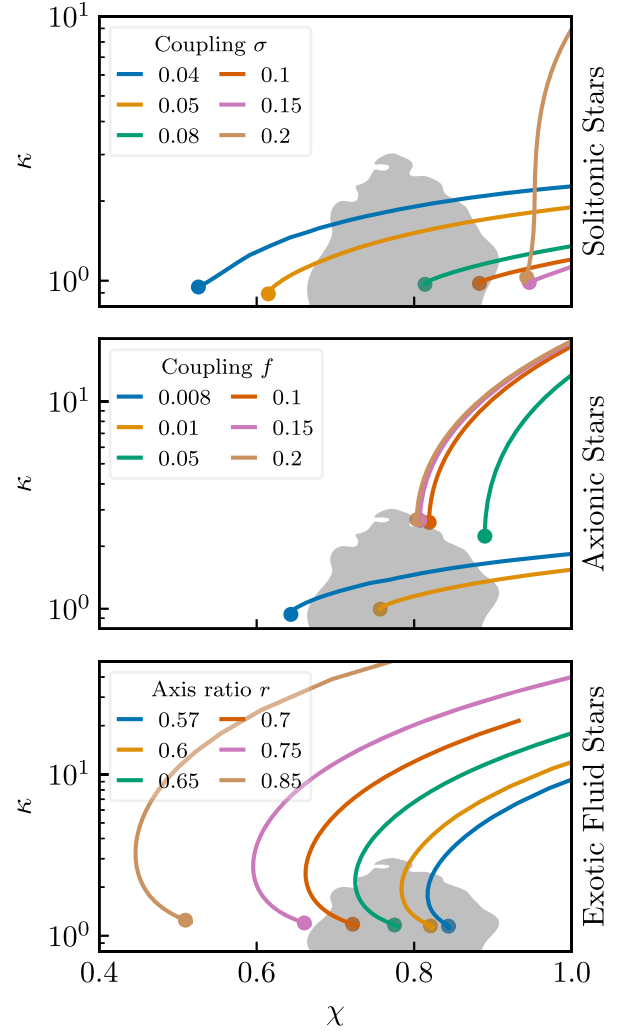


FIG. 3. Same as Fig. 2, but for solitonic stars (top), axionic stars (middle), and exotic fluid stars (bottom), with colors corresponding to values of σ , f , and r respectively (For solitonic $\sigma = 0.04$ models the dot corresponds to the end of the numerically computed sequence.). Here, however, we do not indicate solutions that suffer from dynamical instabilities.

hand, for smaller self-interactions of $f \gtrsim 0.05$, axionic models compatible with GW241011 are ruled out; these models have $C \leq 0.17$ and $m_b \in [7.1\text{--}9.5] \times 10^{-12} \text{ eV } c^{-2}$. However, solutions with $f > 0.1$ are more likely to suffer from dynamical instabilities [65].

Exotic fluid stars—As a toy model for ECOs, we additionally consider EFSs with a compressible EOS at the causal limit of stiffness (i.e., the sound speed equals the speed of light) [84–86]. The pressure is

$$P = \begin{cases} (\epsilon - \epsilon_s), & \epsilon \geq \epsilon_s, \\ 0, & \epsilon < \epsilon_s, \end{cases} \quad (1)$$

where ϵ is the total energy density and ϵ_s some critical energy density, setting the scale of the problem. We construct solutions with uniform rotation by varying the

ratio of polar to equatorial radius, i.e., the axis ratio r , using the RNS package [87–89] (see the Supplemental Material [64]). Changing ϵ_s corresponds to a simple rescaling of dimensionful quantities, e.g., mass $M_{\text{EFS}} \propto (\sqrt{\epsilon_s})^{-1}$, radius $R_{\text{EFS}} \propto (\sqrt{\epsilon_s})^{-1}$, and angular momentum $J_{\text{EFS}} \propto \epsilon_s^{-1}$. We therefore focus on dimensionless quantities, e.g., compactness, when placing constraints using GW241011.

In the bottom panel of Fig. 3, we illustrate families of solutions at different axis ratios, where smaller r typically results in more rapidly spinning and compact stars. We find solutions with spins compatible with GW241011 to have $r \gtrsim 0.55$; note that we exclude unstable configurations beyond the maximum-mass turning point from our analysis. Models compatible with GW241011 therefore enable us to place a lower limit on the allowed compactness of EFSs of $C \gtrsim 0.24$ (using a sequence of more oblate EFSs corresponding to the smallest r); however, this limit increases to $C \gtrsim 0.34$ for more spherical stars ($r \sim 0.7$).

Other ECOs—SIQMs have also been computed for a range of other ECO models that we now discuss here. For these models we are unable to place any meaningful constraints using the primary of GW241011 due to either their incompatible spin predictions, or their SIQM values lying close to the Kerr value.

For example, AdS black shells and their corresponding SIQMs have been computed to sixth order in angular momentum [90]. The configurations are considered reliable up to $\chi \leq 0.45$, which lies below GW241011 spin measurement. Likewise, slowly rotating solutions of thin-shell GSs (with de Sitter cores) have been constructed in Refs. [50,51]. In contrast to AdS shells, these GSs were found to encompass spins beyond the Kerr range. A comprehensive understanding of the stability of GSs and AdS black shells further remains an open question [50,91–93]. However, at least for GSs, it was argued that membranes, with density and pressure having the same sign and obeying the weak energy condition, are unstable against high frequency oscillations [94].

Scalarized BH solutions, arising in modifications to Einstein gravity that add couplings between a new scalar degree of freedom and curvature invariants [95], also predict SIQMs different from Kerr BHs. However, within the range of coupling strengths where these solutions are known to exist, the differences in κ from the Kerr value tend to be smaller than the range ruled out by GW241011—on the order of $\lesssim 10\%$ within the relevant range, e.g., for Einstein-scalar-Gauss-Bonnet [96] and dynamical Chern-Simons gravity [97].

Finally, Proca stars (PSs)—vector analogs of BSs [98]—are natural extensions to the cases considered above. Focusing on solutions with no self-interactions [99], we compute SIQMs for rotating $m = 1$ models using the methods outlined in Ref. [30]. We find no models satisfying the $\chi < 1$ bound. Further, all of the models constructed in the sequence (even less compact ones) have $\kappa \sim \mathcal{O}(1)$. PSs

are therefore a special case where the SIQM is weakly correlated with compactness.

Discussion—By employing the remarkably precise measurement of the SIQM, we placed constraints on various ECO proposals being the primary in the GW241011 merger event. Our analysis uncovered that BSs with repulsive potential (i.e., with quartic self-interactions) can be completely ruled out, whilst highly compact ($C \gtrsim 0.3$) solitonic and axionic stars may still be viable exotic contenders. We additionally ruled out exotic fluid stars with the EOS at the causal limit with compactnesses of $C \lesssim 0.24$. In general, over the models considered here, we found that all compact objects still permitted by GW241011 primary had compactnesses above this limit. Finally, we revisited theoretical predictions for SIQMs for GSs, AdS black shells, Proca stars, and dynamically scalarized BHs; however our constraints for these models were less conclusive.

Echoing Heisenberg [100]—“what we observe is not nature itself, but nature exposed to our method of questioning”—our results should be interpreted with care. Our analysis tests for one specific *finite-size* effect relating to SIQMs, and by construction does not account for other possible effects, such as tidal deformability [17,33,101] or BS-specific short-range interactions, that are known to play an important role in binary BS dynamics [28–30]. Furthermore, our waveform does not incorporate super-extremal spins (possible in most rotating BS and GS models). In the future, our analysis should include these effects, as well as higher PN orders [61] and higher multipole moments—such as the spin-induced octupole—which altogether could offer additional insights into the current constraints. Our results are further limited solely to SIQM projections of ECO models we consider here and should *not* be interpreted as ruling out all possible ECO proposals. However, our methods can be extended to other possible ECO constructions (and, e.g., BS potentials with higher-order self-interactions).

A complete program for probing the nature of compact objects through inspiral, merger, and ringdown would ideally require (i) numerical and phenomenological construction of ECO template banks, (ii) cross verification of consistency across various tests of general relativity and the standard model [102], (iii) simultaneous probing of the true nature of compact objects using population inference [103], and/or (iv) complementary findings from other observational channels. In particular, item (i) can be mainly driven by phenomenological modeling, and supplemented by numerics in some parts of the parameter space. For example, in analogy to NSs [104], (quasi) universal relations for ECOs may provide an efficient means to constrain quantities that are otherwise not directly observable.

GW241011 marks a crucial stepping stone toward probing the nature of compact objects and scrutinizing

models of ECOs. Looking ahead, future GW observations and detectors promise exciting dialogues between theory and experiment, enabling increasingly stringent tests of the Kerr nature of compact objects.

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Data availability—The data that support the findings of this article are openly available [106].

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