The nature of the Fermi surface observed in the recently discovered family of unconventional insulators starting with SmB$_6$ is a subject of intense inquiry. Here we shed light on this question by accessing quantum oscillations in the high magnetic field-induced metallic regime above $\approx 47$ T in YbB$_{12}$, which we compare with the unconventional insulating regime. In the field-induced metallic regime, we find prominent quantum oscillations in the electrical resistivity characterised by multiple frequencies and heavy effective masses. The close similarity in Lifshitz-Kosevich low-temperature growth of quantum oscillation amplitude in insulating YbB$_{12}$ to field-induced metallic YbB$_{12}$ points to an origin of quantum oscillations in insulating YbB$_{12}$ from in-gap neutral low energy excitations. Higher frequency Fermi surface sheets of heavy quasiparticle effective mass emerge in the field-induced metallic regime of YbB$_{12}$ in addition to multiple heavy Fermi surface sheets observed in both insulating and metallic regimes. $f$-electron hybridisation is thus observed to persist from the unconventional insulating to the field-induced metallic regime of YbB$_{12}$, in contrast to the unhybridised conduction electron Fermi surface observed in unconventional insulating SmB$_6$. Our findings thus require an alternative model for YbB$_{12}$, of neutral in-gap low energy excitations, wherein the $f$-electron hybridisation is retained.

**RESULTS**

Quantum oscillations in field-induced metallic YbB$_{12}$

Figure 1a shows quantum oscillations in the contactless electrical resistivity of a single crystal of YbB$_{12}$ measured using the proximity detector oscillator (PDO) technique, at high magnetic fields above the insulator-metal transition at $\mu_0H \approx 47$ T. Prominent quantum oscillations are visible in the measured contactless electrical resistivity before background subtraction. Figure 1b shows quantum oscillations after smooth, monotonic backgrounds have been subtracted from the contactless electrical resistivity (measured by the resonant frequency) above 50 T at various temperatures, where the quantum oscillation periodicity in inverse magnetic field can be seen. Multiple frequency peaks between 500(200) and 3000(200) T are revealed by Fast Fourier Transforms (FFT) of the background-subtracted quantum oscillations, as shown in Fig. 2a. Plotting the quantum oscillation amplitude as a function of temperature down to 0.6 K yields a Lifshitz-Kosevich (LK) temperature dependence with cyclotron effective masses $m^*/m_e$ between 8.5(1) and 17(3), as shown in Fig. 2b.

**DISCUSSION**

Figure 3 shows multiple quantum oscillation frequencies in the insulating phase of YbB$_{12}$ measured through capacitive magnetic hybridisation in the unconventional insulating and field-induced metallic regimes.
torque and contacted electrical transport. Figure 2a shows the quantum oscillation frequency spectrum in the field-induced metallic phase, comprising multiple frequencies extending up to at least 3000(200) T. We note that even higher frequencies may exist, especially in view of the high value of linear specific heat \( C = 67 \text{ mJ mol}^{-1} \text{ K}^{-2} \) measured in the field-induced metallic regime of YbB\(_{12}\). Multiple comparable quantum oscillation frequencies between \( \sim 300 \) and 800 T are measured in both the metallic and insulating phases (Table 1); the multiple frequencies measured by magnetic torque in the insulating phase of YbB\(_{12}\) had previously been reported, which, through a comparison of the absolute amplitude of quantum oscillations with the expectation from the bulk volume in the infinite field limit, and the observation that more insulating samples exhibit larger amplitude quantum oscillations, have been shown to be intrinsic to the insulating bulk of YbB\(_{12}\). Curiously, these multiple frequencies were missed in other reports of a single quantum oscillation frequency in the insulating phase of YbB\(_{12}\). Such a quantum oscillation spectrum comprising multiple frequencies is expected from numerical Fermi surface simulations of metallic YbB\(_{12}\) involving hybridised f-electrons. In these theoretical simulations of the Fermi surface, multiple Fermi surface pockets located away from the centre of the Brillouin zone would be expected to yield a series of frequency branches; multiple frequencies would further be expected from a multiplicity of
Fig. 3  FFT of quantum oscillations in insulating YbB₁₂. FFT of quantum oscillations measured on insulating YbB₁₂ at a temperature of 0.3 K and field range of 35 T < µ₀H < 45 T in (a) magnetic torque, with the applied field aligned close to the [001] crystallographic direction, and (b) electrical resistivity, with the applied field aligned 3.5° away from the [001] crystallographic direction in the [001]-[111]-[110] rotation plane. The horizontal dashed lines indicate the FFT noise floors. Similar frequencies can be discerned in the two measured physical quantities.

A summary of the multiple observed frequencies and their respective quasiparticle effective masses is shown in Table 1. An FFT decomposition involving LK simulations identifies a frequency ≈ 450 T in electrical resistivity that is visible as a shoulder of the main peak.

Table 1. Observed multiple quantum oscillation frequencies and effective masses in the insulating and metallic phases of YbB₁₂.

| Frequency (T) | Mass (mₑ) | Frequency (T) | Mass (mₑ) | Frequency (T) | Mass (mₑ) |
|--------------|-----------|--------------|-----------|--------------|-----------|
| dHvA (θ ~ [001]) | 150 (90) | SdH (θ = 3.5° / [001] | 500 (200) | 8.5 (1) | PDO (θ ~ [001]) |
| 300 (70) | 4.5 (5) | 450 (80) | 6.1 (6) | 800 (200) | 9.2 (2) |
| 700 (90) | 7 (2) | 800 (90) | 7.9 (8) | 1300 (200) | 12.1 (3) |
| | | | | 1700 (200) | 16 (5) |
| | | | | 2300 (200) | 17 (3) |
| | | | | 3000 (200) | 14 (3) |

Multiple quantum oscillation frequencies and cyclotron effective masses measured with capacitive torque magnetisation (de Haas-van Alphen (dHvA) oscillations) and four-point contacted resistivity (Shubnikov-de Haas (SdH) oscillations) in the insulating phase of YbB₁₂, and with proximity detector oscillator (PDO) contactless electrical transport in the magnetic field-induced metallic phase of YbB₁₂. The applied magnetic field was aligned close to the [001] crystallographic direction for dHvA and PDO measurements, and was aligned 3.5° from the [001] crystallographic direction in the [001]-[111]-[110] rotational plane for the SdH measurements. The FFT field range was 30 T < µ₀H < 68 T for PDO, 23 T < µ₀H < 45 T for the 700 T frequency in dHvA, 35 T < µ₀H < 45 T for the 800 T frequency in SdH, and 28 T < µ₀H < 45 T for other frequencies in dHvA and SdH. For contacted resistivity in the insulating phase, we subtract away a smooth monotonic polynomial resistivity background at each temperature and use the relative change in resistivity to determine the quantum oscillation amplitude as a function of temperature. The effective mass obtained from contact resistivity and magnetic torque quantum oscillations for similar frequencies are in good agreement.

Landau level indexing assuming a single dominant frequency. In this work, therefore, we focus instead on a robust treatment involving comparison between the multiple quantum oscillation frequencies identified by Fourier transforms, and the temperature-dependence of the quantum oscillation amplitudes corresponding to these multiple frequencies observed in both the unconventional insulating and field-induced metallic regimes.

Broad classes of models that have been proposed to explain bulk quantum oscillations in unconventional insulators include categories of gapped models, and models characterised by in-gap low energy excitations. An analysis of the temperature-dependence of the quantum oscillation amplitude provides us with vital information to distinguish between classes of gapped and gapless models to describe quantum oscillations in the unconventional insulating phase.

At the simplest level of weakly interacting gapped systems, these systems are characterised by a single particle gap. Models in this category have for example been proposed for BCS superconductors and for weakly interacting insulators. For this category of gapped models of quantum oscillations in weakly interacting insulators, the quantum oscillation amplitude exhibits a non-LK flattening or decrease at low temperatures (Supplementary Information, Fig. 4a lower inset). Other models of weakly interacting gapped systems invoke quantum oscillations arising from modulation of the gap resulting from an inverted band structure.

This picture is modified in the case of strongly correlated insulators. The emergence of an in-gap density of states has been modelled by various theories applicable to these insulators that are driven by strong interactions. For instance, models of single-band Mott insulators involve low energy excitations of chie spin character. Models of Majorana fermions proposed for Kondo insulators include those in refs. In these models, low energy excitations involve Majorana fermion bands, that can be a linear equal combination of a canonical particle and anti-particle operators, crossing the chemical potential. Another model has been proposed for quantum oscillations from composite fermion excitations in Kondo insulators. In this case, mixed-valence insulators are proposed to host a fractionalised neutral Fermi electron and hole pockets. Fourier analysis in the high magnetic field range over which we measure quantum oscillations in this work reveals a complex spectrum in the metallic phase comprising a large number of constituent frequencies with similar amplitudes (shown in Fig. 2), rendering inappropriate analysis methods such as...
sea, which develops an emergent magnetic field in the presence of a physical magnetic field. The quantum oscillation amplitude in these gapless models is expected to increase at low temperatures, for instance obeying an LK form in the case of low energy excitations characterised by Fermi-Dirac statistics (Supplementary Information, Fig. 4a lower inset). It is also of interest to consider the case of unconventional superconductors, in which quantum oscillations are experimentally observed in the vortex regime. Quantum oscillations in a Kondo insulator may arise in a regime potentially analogous to such a vortex state, but one in which the two-component collective hybridisation order parameter of the Kondo lattice could play a role similar to the two-component superconducting order parameter.

Figure 2 shows the quantum oscillation amplitude as a function of temperature in field-induced metallic YbB_{12}, growing in accordance to the LK form down to the lowest measured temperatures, as expected for a metal characterised by Fermi-Dirac statistics. We obtain the cyclotron effective mass for multiple quantum oscillation frequencies in the field-induced metallic phase of YbB_{12} from an LK fit to the quantum oscillation amplitude as a function of temperature (Fig. 2b). Table 1 shows a range of moderately high effective masses m_*/m_e up to at least 17(3) observed for multiple quantum oscillation frequencies up to at least 30000(200) T. The heavy effective masses observed in the field-induced metallic phase indicate its correspondence to an f-electron hybridised metallic Fermi surface.

The presence of low-energy excitations in the gap that do not participate in longitudinal charge transport would be expected to yield an increase in quantum oscillation amplitude at low temperatures in strongly correlated models, which distinguishes them from gapped models of quantum oscillations in weakly interacting insulators in which the quantum oscillation amplitude is expected to exhibit non-LK flattening or decrease at low temperatures (Supplementary Information, Fig. 4a lower inset). Figure 4 shows the temperature dependence of quantum oscillation amplitude for multiple representative frequencies in magnetic torque and electrical transport measured in the insulating phase of YbB_{12}. Similar to our observation in the metallic phase, the quantum oscillation amplitude of both magnetic torque and electrical resistivity in the insulating phase grows in accordance with the LK form down to the lowest measured temperatures, below the gap temperature beneath which gapped models of quantum oscillations predict a non-LK flattening or decrease in amplitude. LK fits to the quantum oscillation amplitude as a function of temperature of quantum oscillation frequencies between 300 and 800 T observed in the insulating phase yield moderately heavy effective masses m_*/m_e between ~4.5 and 9, which are similar to the effective masses observed in the field-induced metallic phase for a similar range of quantum oscillation frequencies (Table 1). The growth in quantum oscillation amplitude down to the lowest measured temperatures is clearly evidenced in the two upper insets in Fig. 4, which highlight low temperature growth of the torque and transport quantum oscillation amplitude measured in the insulating phase. This striking observation of a steep increase in quantum oscillation amplitude down to the lowest temperature is in clear contrast to the non-LK flattening or decrease expected for gapped Fermi surface models, a simulation of which is shown in the lower inset of Fig. 4 for various gap values, exhibiting non-LK finite activation behaviour for a finite gap. We are thus able to identify quantum oscillation signatures in the unconventional insulator YbB_{12} that reveal an origin from low-energy excitations in the gap that do not participate in longitudinal charge transport, as yielded by correlated insulator models.

Our comparison of measured quantum oscillations between the unconventional bulk insulating regime and field-induced metallic regime of YbB_{12} shows that an application of magnetic fields yields a spectrum of multiple quantum oscillation frequencies that appear prominently in magnetic field-induced metallic YbB_{12}, encompassing similar frequencies below 1000 T observed in
insulating YbB₁₂, but extending to higher frequencies up to at least 3000(200) T (Table 1). The comparable quantum oscillation frequency range observed in both metallic and insulating regimes is characterised by similar moderately heavy effective masses in both regimes, while higher frequencies in the field-induced metallic phase are characterised by heavy effective masses m₁/₄ up to at least 17(3). This appearance of multiple additional heavy Fermi surface sheets in the magnetic field-induced metallic regime of YbB₁₂ would explain the steep increase in the linear quantum oscillation frequencies in the unconventional insulating regime of YbB₁₂ points to a multi-component Fermi surface characterised by f-electron hybridisation that persists from the unconventional insulating regime to the high field metallic regime. We note a crucial distinction between the band structure of unconventional insulators SmB₆ and YbB₁₂. While in the case of SmB₆, a single half-filled unhybridised conduction d-electron band crosses the Fermi energy and hybridises with the f-electron band to yield the Kondo gap (Fig. 5a), the situation is different in YbB₁₂. In the case of YbB₁₂, two partially filled unhybridised s-p conduction electron bands that are cumulatively half-filled cross the Fermi energy with electron-like character, and are gapped by hybridisation with the f-electron band (Fig. 5b). We find this difference leads to a distinct contrast between the case of the unconventional insulator YbB₁₂, where heavy Fermi surface sheets are characterised by f-electron hybridisation, and the case of SmB₆, in which the observed light Fermi surface sheets correspond to an unhybridised conduction electron band. Our findings in YbB₁₂ are a challenge to correlated models of in-gap states that are expected to yield a Fermi surface corresponding to an unhybridised conduction electron band. An alternative possibility is suggested by the close proximity of the underlying bandstructure to a semimetallic bandstructure comprising heavy f-electron hybridised electron and hole pockets (Fig. 5). For weak correlations between electrons and holes, metallic electrical conduction would be expected. In contrast, for strong correlations, the electrons and holes may be expected to combine, such that they cannot be readily decoupled, thus impeding longitudinal electrical conduction. Despite the electrically insulating behaviour in such a strongly correlated case where electrons and holes are coupled, the Lorentz force could potentially still drive orbital currents, which would yield quantum oscillations corresponding to a heavy f-electron hybridised semimetallic Fermi surface of the kind observed.

**METHODS**

**Sample preparation**

Source polycrystalline YbB₁₂ powder was synthesised using borothermal reduction of 99.998% mass purity Yb₂O₃ powder and 99.9% mass purity amorphous B at 1700 °C under vacuum. The synthesised powder was isostatically pressed into a cylindrical rod and sintered at 1600 °C in Ar gas flow for several hours. Single crystals of YbB₁₂ were grown by the travelling solvent floating zone technique under conditions similar to those in ref. using a four-mirror Xe arc lamp (3 kW) optical image furnace from Crystal Systems Incorporated, Japan. The growths were performed in a reducing atmosphere of Ar with 3% H₂ at a rate of 18 mm hr⁻¹ with the feed and seed rods counter-rotating at 20–30 rpm. Samples for all measurement techniques were cut to size using a wire saw and electropolished to remove heat damage and surface strain.

**Proximity detector oscillator**

Contactless electrical transport measurements using the proximity detector oscillator (PDO) technique were performed using a long-pulse magnet capable of generating up to 68 T at the Hochfeld Magnetlabor Dresden (HLD) in Dresden, Germany. The capacitor bank-driven magnet has a pulse duration of 150 ms, and is fitted with a custom made ¹⁸¹He system with a base temperature of ~600 mK. The PDO circuit was made in accordance to ref. using a hand-wound sensing coil with 10 turns. The raw frequency output from the PDO circuit was ~20 MHz, which was passed through a processing circuit before being recorded at ~1 MHz using a National Instruments PXI system recording at 15 MHz.

**Capacitive torque magnetometry**

Torque magnetometry measurements were performed in DC magnetic fields at the National High Magnetic Field Laboratory in Tallahassee,
Florida, USA. The 45T hybrid magnet was operated with a 4He system capable of reaching temperatures as low as 300 mK.

Cantilevers were cut from 20 μm or 50 μm thick pieces of BeCu into flexible T-shaped pieces. Samples of dimensions approximately 1 x 1 x 0.5 mm³ were secured on the wide end of the cantilever using epoxy, which was thermally matched to the sample to minimise strain. The narrow end of the cantilever was isolated using such that the wide end of the cantilever hovered above a Cu baseplate, forming the two plates of a capacitor. The change in capacitance between the two plates was measured using a General Radio analogue capacitance bridge with a lock-in amplifier.

Density functional theory calculations

Density functional theory bandstructures were calculated with the Wien2k augmented plane wave plus local orbital (APW+lo) code. The modified Becke-Johnson (mBJ) potential was used, which is a semi-local approximation capable of reaching temperatures as low as 300 mK.

Fermi surfaces. The bandstructure for boron was calculated by shifting the $f$-bands out of the energy range of the $p$-bands. A non-self-consistent calculation with a 30 x 30 x 30 mesh for calculation of the bandstructure resulted in a strong reordering of the bands. Self-consistent potential produced a semimetal with overlapping valence and conduction bands.

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AUTHOR CONTRIBUTIONS

H.L., A.J.H., M.H., A.J.D., A.G.E., and S.E.S. conducted the experiments and analyzed the results, N.S., M.C.H., and G.B. grew single crystal...
samples, M.D.J. performed bandstructure calculations, T.F., J.W., and T.P.M. provided support for high field experiments, S.E.S. and H.L. wrote the manuscript with inputs from co-authors, S.E.S. designed and oversaw the project.

COMPETING INTERESTS
The authors declare no competing interests.

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