Observation of quantum oscillations near the Mott-Ioffe-Regel limit in $CaAs_3$

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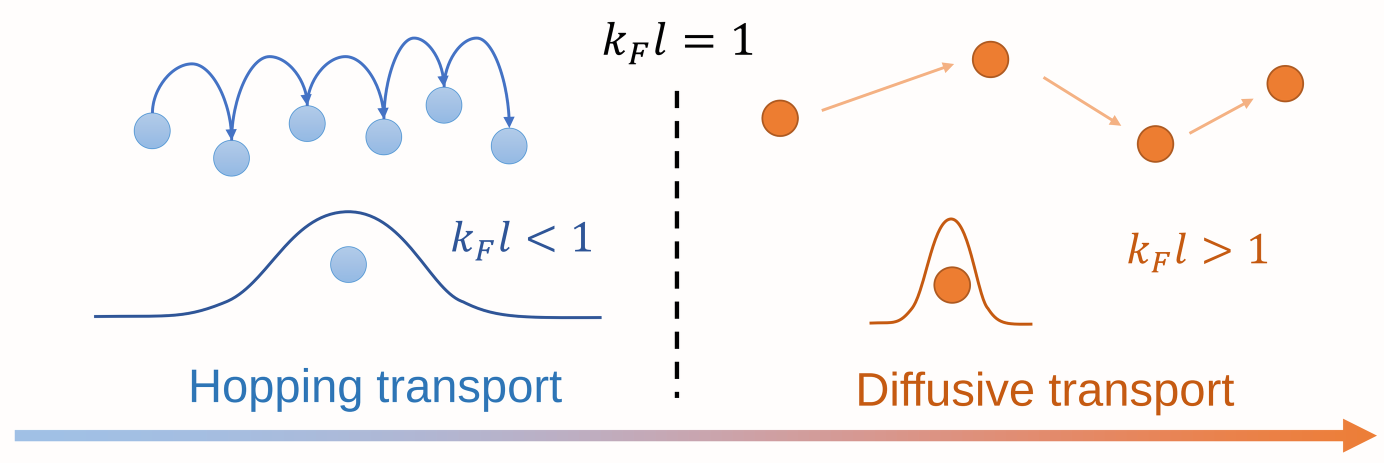
Introduction

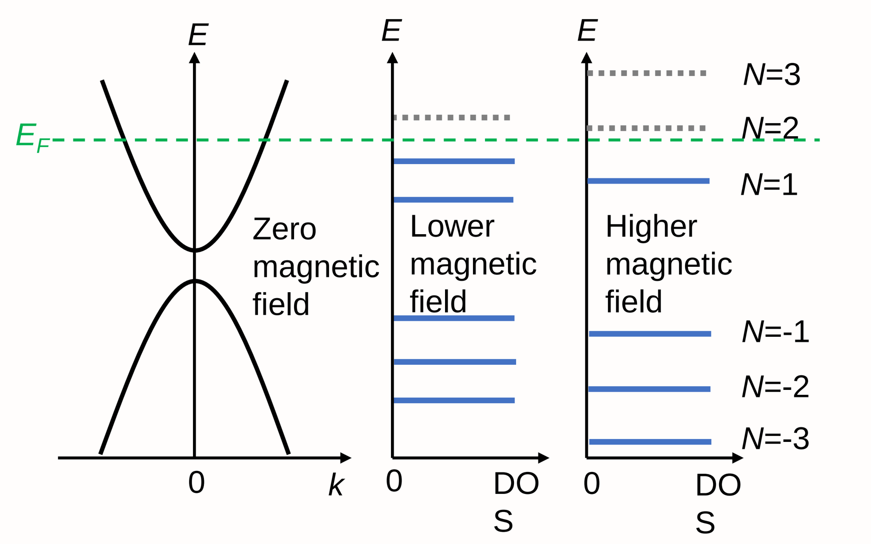
Mott-Ioffe-Regel (MIR) limit: $k_F l = 1$



k_F : Fermi wave vector l : Mean free path

MIR limit sets a boundary for metal where l should exceed the Fermi wavelength. Below this limit, a metal-to-insulator transition occurs due to electron localization.

Landau levels and quantum oscillations



Lifshitz-Kosevich (LK) formula

$$\frac{\Delta\rho_{xx}}{\rho_{xx}(B=0)} \propto R_T\, R_D \cos[2\pi(\frac{F}{B}+\varphi)]$$

F: oscillation frequency

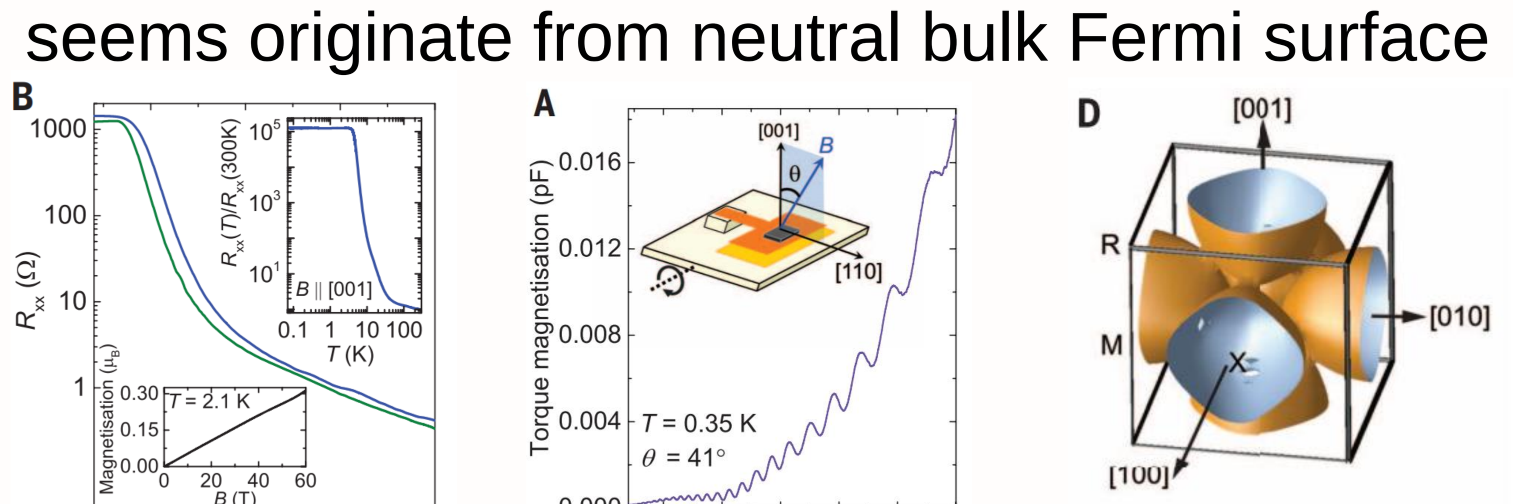
$$R_T = \frac{2\pi^2(k_BT/\hbar\omega)}{\sinh(2\pi^2 k_BT/\hbar\omega)}$$

↓

m^* effective mass

Comparison

Quantum oscillations in Kondo insulator SmB_6 seems originate from neutral bulk Fermi surface



B.S.Tan. Science 349 (6245).

Quantum oscillations usually appear in metal with highly coherent transport. However, quantum oscillations were observed in electrically insulating SmB_6, which reveal a large three-dimensional Fermi surface. Interestingly, quantum oscillations only appear in torque measurement but not in conductivity, which indicates a charge-neutral bulk Fermi surface.

Quantum oscillations in $CaAs_3$ come from a small Fermi surface and are absent in torque

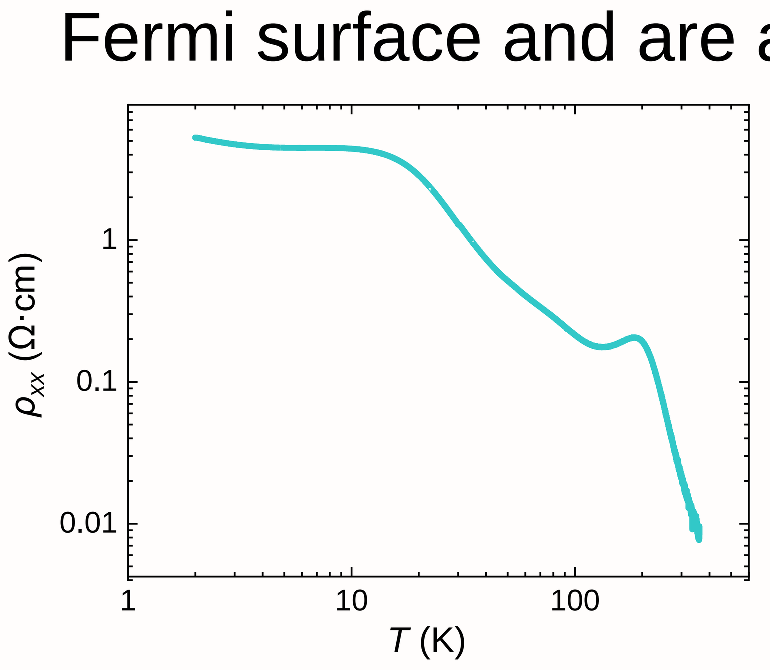


Fig. 7. Insulator-like R-T of $CaAs_3$

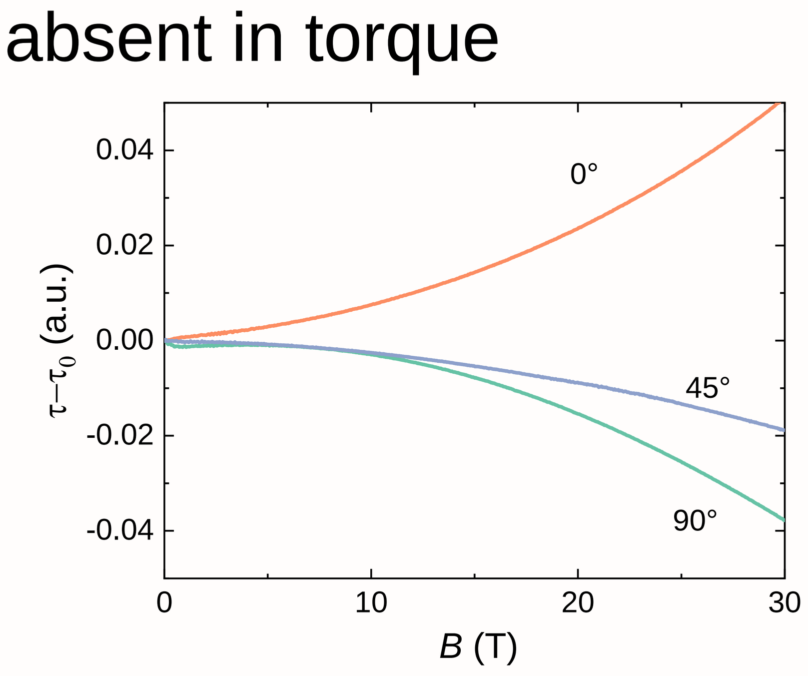
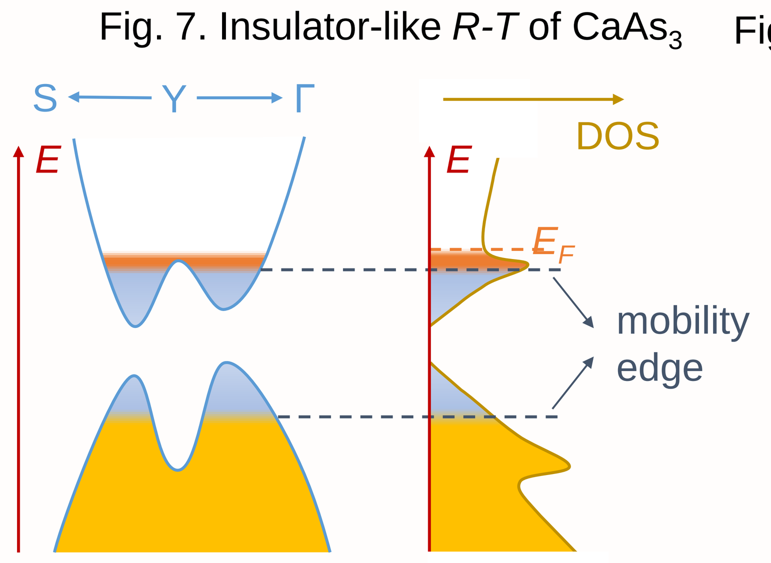


Fig. 8. Torque measurement of $CaAs_3$ at 1.4 K



Most electrons are localized by mobility gap while remnant mobile electrons beyond the mobility edge are coherent and contribute to quantum oscillations. Those localized electrons (incoherent) contribute to torque but not to conductivity, which may overwhelm dHvA oscillations of mobile electrons.

Results

Quantum oscillations and field-enhanced mass

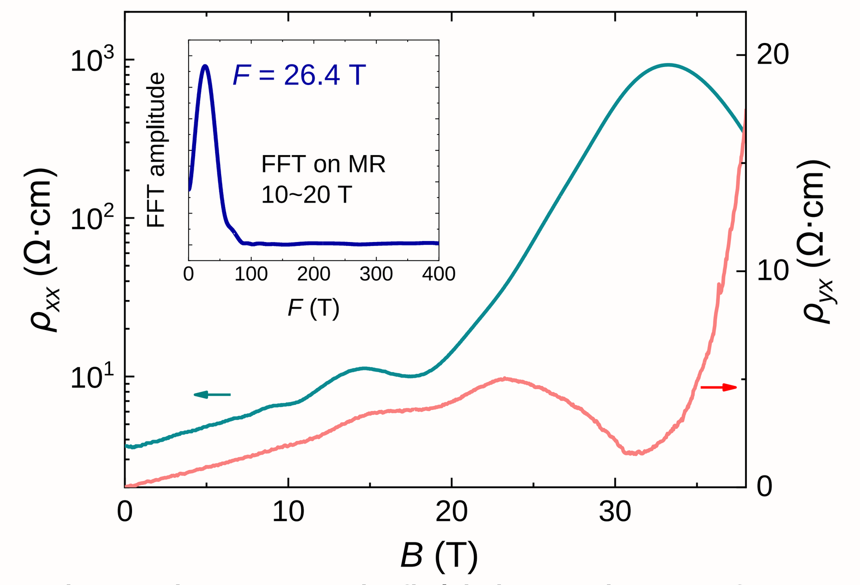


Fig. 1.The magnetic field dependence of ρ_{xx} and ρ_{yx} at 0.3 K with prominent SdH oscillations

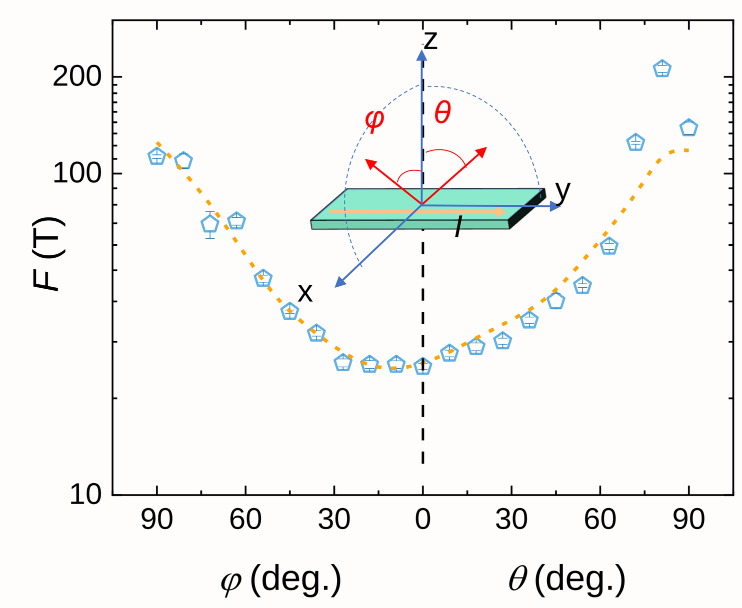


Fig. 2. The angle dependence of SdH oscillation frequencies gives density $n_{FS} = 3.8\times10^{18}$ cm^{-3}, which is three orders of magnitude larger than n_H.

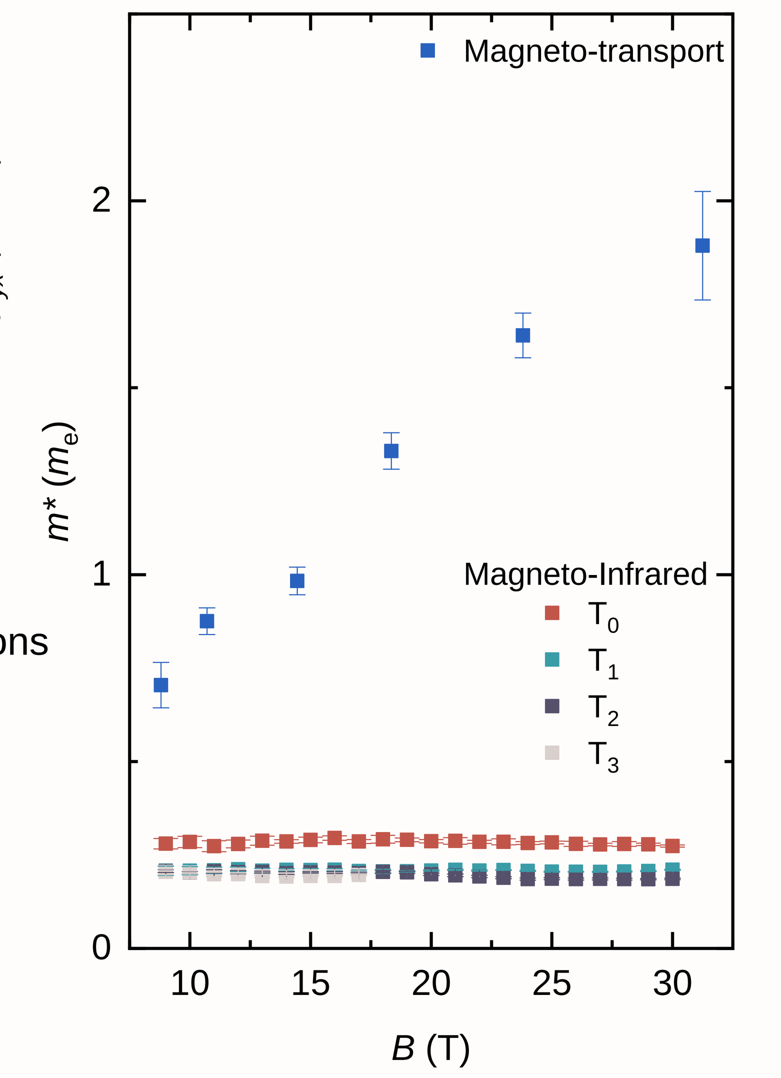


Fig. 3. The comparison between effective mass extracted from the quantum oscillations and interband-Landau-level transition indicates a strong renormalization effect near the Fermi surface. The transport effective mass increases systematically from $0.74m_e$ at 8.73 T to 2.19 m_e at 31.25 T.

Carrier sign reversal due to van Hove singularity

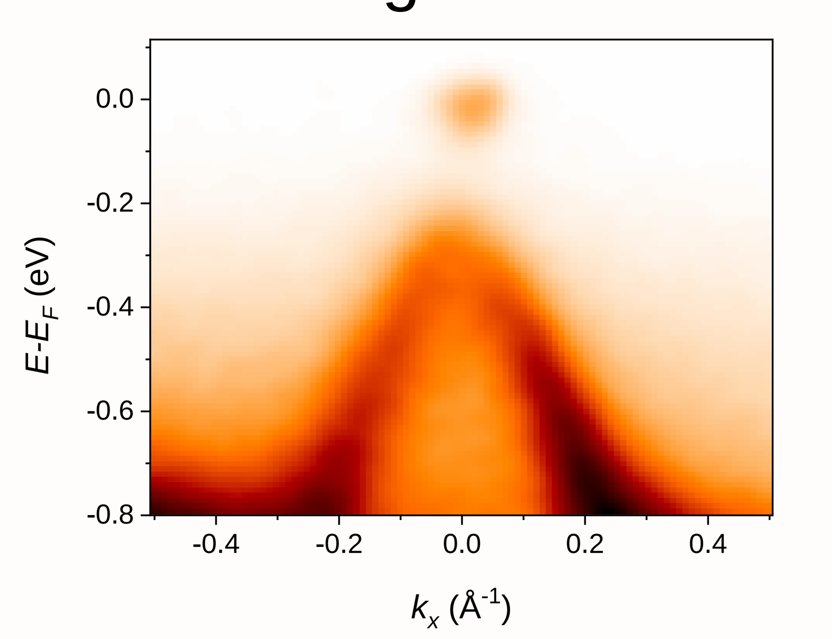


Fig. 4. Band dispersion at 10 K measured by ARPES with the photon energy of 98 eV.

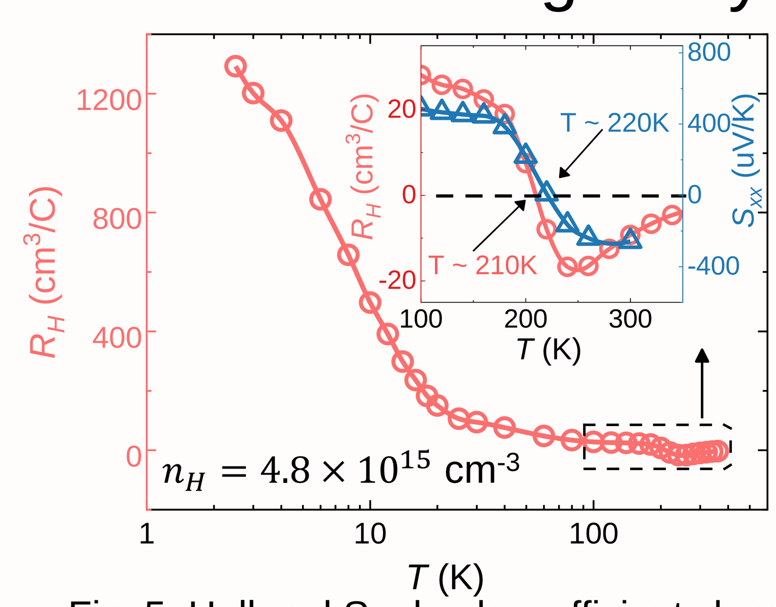


Fig. 5. Hall and Seebeck coefficient show sign reversal from n-type to p-type below 210 K, which conflicts with the result of ARPES and SdH oscillations.

Scaling plot with smallest $k_F l = 1.2$ of $CaAs_3$

Drude model: $\sigma = n\mu e = \frac{e^2}{3\pi^2\hbar}k_F^2 l$ ⟶ $\sigma/k_F = \frac{e^2}{3\pi^2\hbar}k_F l$ (linear)

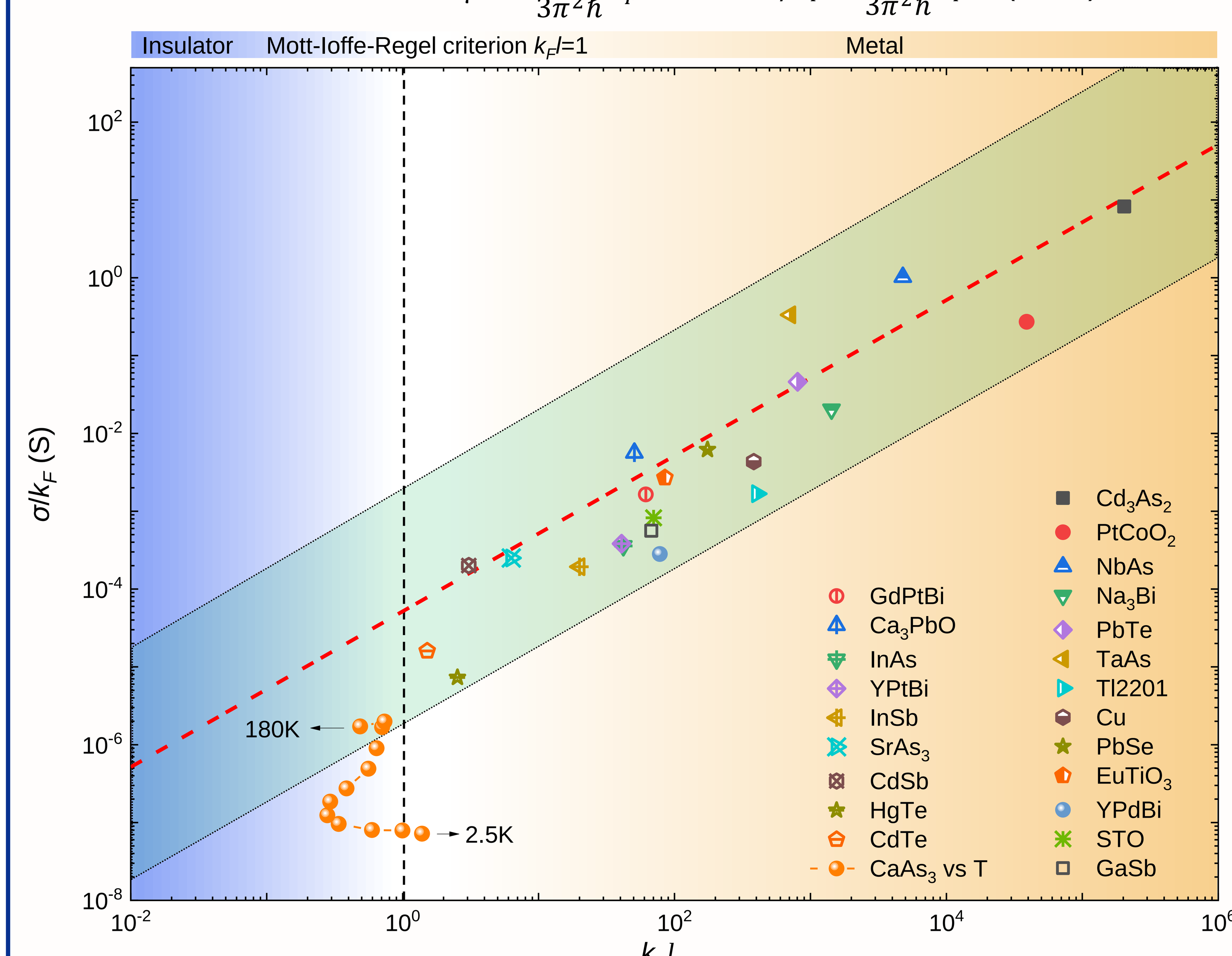


Fig. 6. The scaling plot of σ/k_F against the metallicity parameter $k_F l$ among these materials at the temperatures where quantum oscillations persist.

Conclusion

1. Electrons in $CaAs_3$ show the smallest metallicity parameter among all the materials with 3D quantum oscillations.
2. The transport effective mass increases systematically with magnetic fields, suggesting a strong many-body renormalization effect near the Fermi surface.
3. Distinct from strange metals, mobile electrons near the MIR limit manifest the metallic characteristic of quasiparticle coherence.

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