New theory draws connections between Planckian metals and black holes

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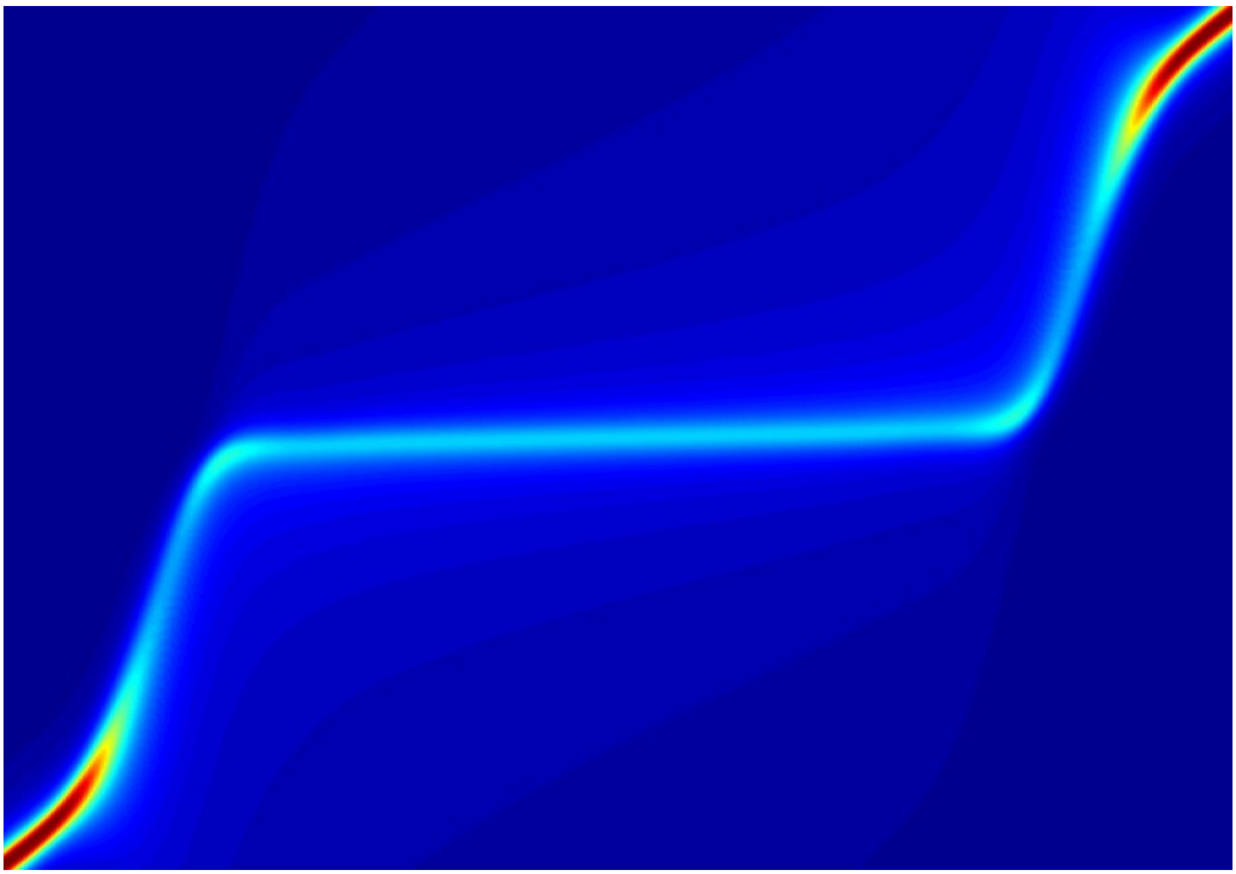

A plot of the electron spectral function for the important current-carrying electrons in energy-momentum space. Credit: Patel & Sachdev.

Two researchers at Harvard University, Aavishkar A. Patel and Subir Sachdev, have recently presented a new theory of a Planckian metal that could shed light on previously unknown aspects of quantum physics. Their paper, published in *Physical Review Letters*, introduces a lattice model of fermions that describes a Planckian metal at low temperatures ($T \to 0$).

Metals contain numerous electrons, which carry electric current. When physicists consider the electrical resistance of metals, they generally perceive it as arising when the flow of current-carrying electrons is interrupted or degraded due to electrons scattering off impurities or off the crystal lattice in the metal.

"This picture, put forth by Drude in 1900, gives an equation for the electrical resistance in terms of how much time electrons spend moving freely between successive collisions," Patel told Phys.org. "The length of this time interval between collisions, called the 'relaxation time,' or 'electron liftetime,' is typically long enough in most common metals for the electrons to be defined as distinct, mobile objects to a microscopic observer, and the Drude picture works remarkably well."

Although the theory proposed by Drude has been found to be applicable to several metals, there are other metals that exhibit different behavior, most notably those produced when high-temperature superconductors are heated above their superconducting transition temperature or when superconductivity is suppressed by applying a magnetic field. In these unconventional metals, the apparent relaxation time is very short, specifically of the order of Planck's constant divided by Boltzmann's constant times temperature (i.e. $\hbar/(k_B T)$).

This phenomenon is known as Planckian dissipation, and these metals are consequently referred to as Planckian metals. The short electron lifetime observed in these metals suggests that individual electrons can no longer be seen as well-defined objects, which makes describing them mathematically more challenging.

"What is really surprising is that in a variety of such materials with differing electron-electron interaction strengths (although all of them have strongly interacting electrons), the numerical value of the electron lifetime seems to be very close to exactly $\hbar/(k_B T)$," Patel explained. "This means that there is a universal theory that describes all such 'strange metals,' which has continued to elude scientists thus far."

Aware of this gap in the literature, Patel and Sachdev set out to develop a mathematically accurate quantum mechanical description of these strange metals. The key assumption behind their work was that interactions between electrons do not conserve momentum, and that this typically happens in a system with microscopic irregularities, known as disorder.

Past studies found that all materials that display this 'strange metal behavior' present significant amounts of disorder. In their study, Patel and Sachdev separately considered interactions between electrons that conserve energy and interactions between those that do not.

"The energy non-conserving interactions 'renormalize' the electrons (i.e., they change their mass), whereas the energy conserving (or 'resonant') interactions, whose effects we compute exactly, lead to an electron lifetime of almost exactly $\hbar$/(kBT) when we attempt to express the electrical resistance using the Drude formula," Patel said. "Furthermore, we find that this lifetime is independent of the exact strength of the electron-electron interactions in accordance with experimental observations."

In addition to providing a mathematically accurate and solvable model for Planckian dissipation, the theory developed by Patel and Sachdev outlines a unique signature in the electron spectral function, which is a mathematical quantity that measures the number of single-electron quantum states available at a particular energy. Interestingly, this characteristic signature can be measured in photoemission experiments.

"The velocity of the electrons that are responsible for carrying current is greatly slowed down to a quantity proportional to the temperature of the system," Patel explained. "This should be visible experimentally by observing the dispersion of the peak in the electron spectral function."

A further intriguing aspect of the new theory proposed by the researchers is that the quantum mechanical wave functions presented within it are closely related to those of the Sachdev-Ye-Kitaev model, which is connected to the physics of black holes. If their ideas are valid, they would also suggest that there are deep physical connections between black holes and strange metals.

"The connection to the Sachdev-Ye-Kitaev model highlights the importance of many-particle quantum entanglement," Sachdev said. "Sometimes called 'spooky action at a distance,' quantum entanglement is perhaps the most novel characteristic of the quantum theory: the ability to create states in which observation of one particle can influence the state of all other particles, even those very far away. Our work shows that the flavor of quantum entanglement created by the Sachdev-Ye-Kitaev model is closely connected to that in strange metals, and in black holes."

In the future, the model proposed by Patel and Sachdev could have important implications for the physics field. In fact, in addition to providing a theory that could shed light on the behavior of Planckian metals, their paper points to a possible connection between these 'unusual' metals and black holes. The researchers hope that their study will eventually answer some of the fundamental questions associated with quantum theories of black holes, including Hawking's information paradox.

"We now plan to examine how the specific exactly solvable form of electron-electron interactions that we use in our theory can arise from conventional approaches for studying interacting disordered electrons, perhaps by making some unconventional assumptions that can be justified a posteriori," Patel said. "There are also other quantum mechanical materials which are electrical insulators (not metals), but show analogs of the phenomenon of metallic Planckian dissipation in their thermal conductivities. It would be interesting to see if our strategies could develop workable theories for them, too, in a similar fashion."

More information: Aavishkar A. Patel et al. Theory of a Planckian Metal, *Physical Review Letters* (2019). DOI: 10.1103/PhysRevLett.123.066601

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