The strange metal is an enigmatic phase whose properties are irreconcilable with the established Fermi liquid theory of conductors. A fundamental question is whether a strange metal and a Fermi liquid are distinct phases of matter, or whether a material can be intermediate between or in a superposition of the two. We studied the collective density response of the correlated metal Sr$_2$RuO$_4$ by momentum-resolved electron energy-loss spectroscopy (M-EELS). We discovered that a broad continuum of non-propagating charge fluctuations (a characteristic of strange metals) and also a dispersing Fermi liquid-like collective mode at low energies and long wavelengths coexist in the same material at the same temperature. These features exhibit a spectral weight redistribution and velocity renormalization when we cool the material through the quasiparticle coherence temperature. Our results show not only that strange metal and Fermi liquid phenomena can coexist but also that Sr$_2$RuO$_4$ serves as an ideal test case for studying the interaction between the two.
Strange metals behave in ways that Fermi liquid theory cannot explain. This category of materials includes transition metal oxides, iron pnictides, and organic superconductors above their transition temperature $T_c$; magic-angle graphene; and many heavy fermion compounds, both superconducting and non-superconducting. The resistivity of strange metals increases linearly with temperature, and it continues to do so well beyond the Mott-Ioffe-Regel limit until the apparent mean free path of electrons becomes shorter than either the lattice constant or the electron-to-electron distance.

The electron scattering rate of strange metals, $r^{-1}$, depends only on two universal constants $\left( r^{-1} = k_B T / \hbar \right)$. This value seems to represent a fundamental limit. It holds true irrespective of material-specific parameters such as the crystal structure, the density of electrons, or the density of impurities. The apparently universal value of $r^{-1}$ describes a quantum-limited rate of electron scattering or thermal equilibration. It says that strange metals dissipate the energy from electron collisions as quickly as nature will allow (i.e., they exhibit “Planckian dissipation”).

This behavior rules out the existence of quasiparticles and so raises the question of what carries charge in strange metals. One hypothesis is that electrons in strange metals occupy a state of maximum long-range quantum entanglement, where the properties of each electron depend on those of every other electron. In the words of one author, “literally everything is entangled with everything.”

Strange metals exhibit deep parallels with the physics of black holes. When an external disturbance perturbs a black hole, its oscillation modes decay at a characteristic rate $k_B T_H / \hbar$, where $T_H$ is the Hawking temperature. In other words, black holes, like strange metals, return to thermal equilibrium at the maximum rate that nature will permit, a fundamental speed limit imposed by quantum mechanics. The origin of the strange metal state has therefore attracted interest from researchers studying condensed matter physics, astrophysics, quantum materials, and quantum information. It remains one of the great unsolved problems in theoretical physics, with future studies of dynamics being key.

No conceptual framework yet exists that can explain the behavior of materials with a maximally dissipative sea of unknown charge carriers. To understand the origin of the strange metal phase, we must clarify its relationship to the Fermi liquid. One promising path forward is to identify a material that occupies an intermediate space between a Fermi liquid and a strange metal. Such a material would enable us to study the crossover between the two phases and their interactions.

One such candidate intermediate or hybrid material is Sr$_2$RuO$_4$, a layered perovskite that exhibits exotic superconductivity below $T_c = 1.5$ K. At temperatures below about 40 K, Sr$_2$RuO$_4$ is an excellent Fermi liquid: it exhibits a $T^2$ resistivity, well-defined quantum oscillations, the expected scaling form for low-frequency conductivity, and other signatures of long-lived quasiparticles. At higher temperature, however, these quasiparticles disappear, and the material shows the defining features of a strange metal; i.e., the resistivity becomes linear in
temperature and eventually exceeds the Mott-Ioffe-Regel limit.\textsuperscript{29} $\text{Sr}_2\text{RuO}_4$ therefore seems an ideal vehicle in which to study the crossover between Fermi liquid behavior and strange metal behavior as a function of energy scale.

Here, we describe momentum-resolved electron energy loss spectroscopy (M-EELS) experiments on $\text{Sr}_2\text{RuO}_4$. In an M-EELS experiment, low-energy electrons strike the surface of a material. An analyzer measures the energy and momentum of the scattered electrons to determine the material’s dynamic charge susceptibility $\chi^\prime(q,\omega)$,\textsuperscript{1,30} where $q$ and $\omega$ are, respectively, the energy and momentum transferred to the sample by the electron. The susceptibility represents how the material’s charge density $\rho$ (in units of charge per unit volume) responds to a charge disturbance (an incident electron) as a function of position and time.

The signature of Fermi liquid behavior is the presence of a valence plasmon, a ripple of density that propagates through the bulk or across the surface of a material. A plasmon indicates long-lived quasiparticles near the Fermi surface. In M-EELS data, it appears as a peak in $\chi^\prime(q,\omega)$ whose energy shifts with increasing $q$.\textsuperscript{1}

We recently showed that the strange metal phase of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+x}$ (Bi-2212) does not exhibit a propagating plasmon.\textsuperscript{31,32} In fact, the plasmon is overdamped and observable only over about 8\% of the Brillouin zone.\textsuperscript{31,32} The rest of momentum space exhibits a featureless continuum of charge fluctuations that is independent of both frequency and momentum. This continuum resembles, semi-quantitatively, the hypothesized marginal Fermi liquid (MFL) continuum invoked many years ago to explain the properties of strange metals.\textsuperscript{33} The continuum also resembles the susceptibility of the model of Sachdev, Ye, and Kitaev (SYK),\textsuperscript{34,35} which various research groups have invoked to explain both the $T$-linear resistivity of strange metals\textsuperscript{36} and the behavior of quantum particles near the event horizon of a black hole.\textsuperscript{37,38,39} M-EELS is therefore an ideal way to investigate the microscopic “strangeness” of correlated metals and their connection to concepts in quantum information and cosmology.

Our M-EELS studies of $\text{Sr}_2\text{RuO}_4$ reveal the coexistence of two phenomena: a) broad, non-dispersing charge fluctuations that resemble those of the strange metal phase of Bi-2212\textsuperscript{31,32} and b) a dispersing plasmon-like collective mode at low energies and long wavelengths, as we would expect in a Fermi liquid. This coexistence is schematically shown in Figure 1 which displays the qualitative behavior of the dynamic charge susceptibility of $\text{Sr}_2\text{RuO}_4$ in energy and momentum. When we cool $\text{Sr}_2\text{RuO}_4$ below its Fermi liquid coherence temperature $T_{FL}\~\sim40\,\text{K}$,\textsuperscript{27} the spectral weight of the strange metal fluctuations shifts from low to high energy, and the dispersion of the collective mode dramatically renormalizes. These observations identify $\text{Sr}_2\text{RuO}_4$ as a crossover material in which we can study how the Fermi liquid and strange metal phases coexist and interact.

Figure 2 shows high energy ($\omega > 0.1\,\text{eV}$) M-EELS measurements of $\text{Sr}_2\text{RuO}_4$ at 300 K with an energy resolution of 6 meV along the (1,0) direction for momenta up to the Brillouin zone boundary. The spectra are nearly identical to the strange metal phase of Bi-2212: we observe an overdamped plasmon for $q < 0.16\,\text{r.l.u.}$, while the rest of momentum space exhibits a frequency-independent continuum with an MFL\textsuperscript{33} or SYK\textsuperscript{34}-like form. The only discernable
difference is the cutoff energy of the continuum, which we found to be 1.2 eV for Sr$_2$RuO$_4$ as compared to 1.0 eV for Bi-2212. To verify that this continuum is a bulk property and not a surface effect, we conducted transmission EELS measurements at 10 meV resolution with a Nion UltraSTEM. These data agree with M-EELS data and demonstrate the bulk character of the effect (Fig. 2c). Our observations indicate that we can consider Sr$_2$RuO$_4$ to be a strange metal at $\omega > 0.1$ eV.

It is surprising that the charge excitations of Sr$_2$RuO$_4$ resemble so closely those of Bi-2212. Sr$_2$RuO$_4$ is a 4$d$ Hund’s metal with large spin-orbit coupling, multiple Fermi surfaces, and weak disorder. In contrast, Bi-2212 is a single-band doped Mott insulator with strong disorder. The similarity of the charge excitations suggests that the M-EELS continuum arises from universal physics that depends on few microscopic details about the material.

At lower energies and longer wavelengths, a different collective electronic excitation emerges for $\omega < 70$ meV and $q < 0.08$ r.l.u.. This excitation resembles that of an ideal Fermi liquid (Figure 3). In contrast to the non-propagating strange metal fluctuations, it disperses on a characteristic scale of about 0.7 eVÅ, near the average quasiparticle Fermi velocity of 0.56 eVÅ. This similarity of scale suggests a Fermi liquid-like origin based on quasiparticle scattering across the Fermi surface. The large dispersion of 0.7 eVÅ establishes the electronic origin of this mode, since acoustic phonons propagate at the sound velocity, which is orders of magnitude smaller in Sr$_2$RuO$_4$ (about 0.008 eVÅ). Since M-EELS is a surface probe, we adopt the simplest interpretation: this excitation is a surface plasmon, the characteristic collective mode of the surface of a conventional Fermi liquid metal. As Figure 1 illustrates, Sr$_2$RuO$_4$ exhibits dual behavior with propagating Fermi liquid excitations at low energy and long wavelengths, and incoherent local strange metal fluctuations at high energy and short wavelengths.

To explore the impact of increasing quasiparticle coherence on the M-EELS response, we repeated the experiment at $T = 30$ K, just below the Fermi liquid coherence temperature $T_{FL} = 40$ K. The Fermi liquid collective mode sharply renormalizes; its dispersion drops from about 0.7 eVÅ (at 300 K) to 0.5 eVÅ (at 30 K) (Figures 3a-c). Since the carrier density of Sr$_2$RuO$_4$ does not change with temperature, we attribute this change in dispersion to the known renormalization of the quasiparticle self-energy at low temperature.

On the strange metal part of the spectrum (Figure 4a,b), at 30 K the spectral weight of the continuum increases above 1 eV and diminishes below 0.9 eV. Remarkably, this depletion of low-energy spectral weight occurs over energy scales much larger than the thermal energy $k_B T$. This spectral weight transfer resembles that of the overdoped cuprate Bi-2212, in which the continuum loses spectral weight at low energy as the material is cooled into the more Fermi liquid-like phase at low temperature (Figure 4c). We conclude that the continuum acts as a decay channel for quasiparticles, causing them to become more coherent in both materials at low temperature when spectral weight in the continuum is depleted. Note that the total spectral weight reduction is significantly lower in Sr$_2$RuO$_4$ than in highly overdoped Bi-2212. We attribute this fact to its lower coherence temperature of Sr$_2$RuO$_4$ (40 K compared to ~200 K).
The strong continuum of charge fluctuations in Sr$_2$RuO$_4$ is unexpected. The modern view is that Sr$_2$RuO$_4$ is a correlated Hund’s metal in which the charge density is primarily modulated by orbital fluctuations,$^{50}$ which are visible in M-EELS at nonzero $q$. However, the research community believes that the orbitals are static below $T_{\text{orb}} \sim 1000K$ and that only the spins remain active down to the spin coherence temperature of $T_{\text{spin}} \sim 25K$. Our M-EELS studies demonstrate that charge fluctuations in Sr$_2$RuO$_4$ are significant even at low temperature and that they span a wide range of energy scales.

Recently, a model of Hund’s metals that retains both spin and orbital degrees of freedom provided evidence that coupled spin and orbital fluctuations remain present down to $T_{\text{FL}} \sim 40K$ and that these fluctuations play a crucial role in the appearance of a non-Fermi liquid fixed point.$^{48}$ Our M-EELS study supports this view and suggests a parallel with coexisting local and nonlocal spin excitations observed with inelastic neutron scattering.$^{49,50}$ Future studies of the dynamic charge response in Sr$_2$RuO$_4$ will clarify the interplay between spin and charge excitations in this material.

In the broader context of strange metals, our study of Sr$_2$RuO$_4$ demonstrates that a strange metal is not a distinct phase from a Fermi liquid and that the two phenomena may coexist in the same material on different energy scales. In Sr$_2$RuO$_4$, the excitations at energies above 100 meV are strange metal-like, forming a continuum like that in Bi-2212.$^{31,32}$ At energies below 60 meV, the system exhibits a coherent, propagating collective mode—very likely a surface plasmon, a defining property of a Fermi liquid. These observations resemble qualitatively recent predictions from holography,$^{51,52}$ which suggest that the collective response of strongly interacting metals consists of two sectors: a coherent plasmon mode and a “quantum critical” continuum that cannot be described in terms of particle-like concepts.$^{53}$ Moreover, we find that the dispersion of the plasmon dramatically renormalizes at low temperature as the spectral weight in the continuum redistributes, indicating that the normal and strange metal sectors interact in an intricate way.

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**List of Supplementary Materials**
Materials and Methods
Fig S1 – S7
References S1 – S5
Fig. 1. Summary sketch of the collective charge excitations of Sr$_2$RuO$_4$. The color scale represents the magnitude of the dynamic charge susceptibility, $\chi''(q,\omega)$, as measured by momentum-resolved electron energy-loss spectroscopy (M-EELS). The momentum is shown in units of $2\pi/a$ or reciprocal lattice units (r.l.u.), with 0.5 r.l.u. corresponding to the Brillouin zone boundary ($a = 3.873$ Å). A broad continuum of strange metal fluctuations dominates the charge response up to 1.2 eV. In addition, a dispersive, Fermi liquid-like collective mode, perhaps a surface plasmon, manifests at much lower energy and momentum. Our study demonstrates that both types of collective excitation exist in Sr$_2$RuO$_4$, a hybrid material in which researchers can investigate the interaction between the two phenomena.
Fig. 2. Strange metal fluctuations in Sr$_2$RuO$_4$. (A) M-EELS spectra of Sr$_2$RuO$_4$ at 300 K for a selection of momenta ranging from $q = 0.12$ r.l.u. up to the Brillouin zone boundary along the (1,0) direction. The curves are normalized by $q^2$ and offset by 0.05 eV$^{-1}$ Å$^{-1}$ for clarity. The primary feature is a broad continuum, a defining characteristic (32) of strange metals (phonons cause the abrupt rise below 0.1 eV). (B) Schematic drawing of the M-EELS scattering process. A monochromatic beam of electrons with well-defined momentum scatters inelastically from a single crystal sample, and we measure the resulting signal as a function of both transferred energy $\omega$ and momentum $q$ to obtain $\chi^\prime(q, \omega)$ (30). (C) Comparison between surface M-EELS and bulk-sensitive EELS measurements of Sr$_2$RuO$_4$ with a scanning transmission electron microscope (STEM) (40) verifies the bulk nature of the strange metal continuum. (Inset: high-angle annular dark field image of the sample region used for STEM-EELS measurements confirms its crystallinity.)
Fig. 3. Dispersing Fermi liquid collective mode in Sr$_2$RuO$_4$. (A) Color plot of the M-EELS intensity along the (1,0) direction as a function of momentum and energy at 300 K. (To improve visibility, the intensity at each $q$ value was normalized by the integrated intensity above 6 meV). The weakly dispersing mode (yellow points) at about 67 meV is an optical phonon (44). The dispersing curve (red points) is an electronic Fermi liquid mode with characteristic dispersion of about 0.7 eV·Å. (B) Same color plot as (A) for $T = 30$ K. The dispersion of the collective mode (blue points) reduces to about 0.5 eV·Å at this temperature. (C) Summary plot comparing the collective mode dispersion at 300 K along (1,1) (green), at 300 K along (1,0) (red), and at 30 K along (1,0) (blue). The mode exhibits some anisotropy, perhaps because of the anisotropy of the Fermi surface. (D) Fermi surface of Sr$_2$RuO$_4$ with the momentum directions of the M-EELS spectra presented in panel (C) indicated by colored arrows.
Fig. 4. Spectral weight transfer below the Fermi liquid coherence temperature. (A) M-EELS spectra in the strange metal region at two temperatures, 300 K (red) and just below $T_{FL}$ at 30 K (blue). The spectra show a small but statistically significant suppression of spectral weight below 0.9 eV throughout momentum space. (B) Log plot of the M-EELS spectra at $q = 0.24$ r.l.u., emphasizing the spectral weight change. (C) Strange metal continuum in overdoped Bi-2212 reproduced for comparison from ref. (32). Sr$_2$RuO$_4$ behaves like overdoped Bi-2212, but with a lower Fermi liquid coherence temperature.
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