Some of the highest-transition-temperature superconductors across various materials classes exhibit linear-in-temperature ‘strange metal’ or ‘Planckian’ electrical resistivities in their normal state. It is thus believed by many that this behavior holds the key to unlock the secrets of high-temperature superconductivity. However, these materials typically display complex phase diagrams governed by various competing energy scales, making an unambiguous identification of the physics at play difficult. Here we use electrical resistivity measurements into the micro-Kelvin regime to discover superconductivity condensing out of an extreme strange metal state—with linear resistivity over 3.5 orders of magnitude in temperature. We propose that the Cooper pairing is mediated by the modes associated with a recently evidenced dynamical charge localization–delocalization transition, a mechanism that may well be pertinent also in other strange metal superconductors.
The phenomenon of superconductivity has fascinated scientists since its discovery in 1911. It had to await microscopic understanding, achieved in the BCS theory, for almost 50 years. Conventional superconductors such as aluminum and niobium are now key players in the race for realizing the quantum computer. Understanding superconductivity that goes beyond this framework, as first seen in the heavy fermion compound CeCu$_2$Si$_2$ and since then considered for numerous materials classes, is the next grand challenge.

In several of these “unconventional” superconductors—across high-$T_c$ cuprates, iron pnictides and organic conductors, heavy fermion metals, and, very recently, infinite-layer nickelates, twisted bilayer graphene, and WSe$_2$—the normal state shows a linear-in-temperature “strange metal” electrical resistivity, at least in certain temperature ranges. This suggests that to decipher this type of superconductivity requires understanding the mechanism of the underlying strange metal normal state. However, because of the complexity of the phase diagrams of many of these systems, this has proven challenging. Multiple competing effects, crossovers between different scaling behaviors, possible trivial linear-in-temperature resistivity contributions, or simply the fact that strong superconductivity covers much of the normal-state phase space and needs to be suppressed by external parameters, which may modify the original normal state, are inhibiting consensus on the key mechanism at play.

On the other hand, there is a material—the heavy fermion compound YbRh$_2$Si$_2$—where such complications are absent and linear-in-temperature strange metal behavior has recently been pinned down as resulting from a dynamical electron localization–delocalization transition as underlying the strange metal behavior. This mechanism seems unlikely, because no localization cryostat, a setup for high-resolution electrical resistivity measurements expand the previously established strange metal behavior, now covering 3.5 orders of magnitude in temperature, with a high accuracy of 5% below about 10 K, this mechanism seems unlikely, because no localization cryostat, a setup for high-resolution electrical resistivity measurements to temperatures well below 1 mK (see Methods), and used it to measure state-of-the-art YbRh$_2$Si$_2$ single crystals. To assess the previously discussed role of Yb nuclear moments, in addition to samples with natural abundance Yb (containing 14.2% $^{171}$Yb with a nuclear moment $I = 1/2$ and 16.1% $^{173}$Yb with a nuclear moment $I = 5/2$), we also studied $^{174}$YbRh$_2$Si$_2$, which is free of nuclear Yb moments. In zero magnetic field, both samples show the characteristic kink near the Néel temperature $T_N$, as well as linear-in-temperature behavior above and Fermi liquid $T^2$ behavior below (Fig. 1a, b). The parameters extracted from these fits (Table 1) are in good agreement with previous results, confirming the high reproducibility of the properties in state-of-the-art YbRh$_2$Si$_2$ single crystals. At the lowest temperatures, a pronounced drop of the resistivity signals the onset of superconductivity. It is fully displayed in Fig. 1c, d. In YbRh$_2$Si$_2$, the transition is rather sharp ($T_c/T_N = 0.10$ for a resistance change from 90% to 10% of the value above the transition), with an onset somewhat below 9 mK. In $^{174}$YbRh$_2$Si$_2$, the onset is shifted to below 6 mK, and the transition is broadened, even though the residual resistance ratio of this sample is almost twice that of the normal YbRh$_2$Si$_2$ sample (Table 1), an effect that will be discussed later.

Application of magnetic fields within the $a$-$a$ plane of the tetragonal crystal successively suppresses superconductivity in both samples (Fig. 1c, d). Note, however, that clear signs of superconductivity are visible even at the quantum critical field (see Fig. 1c, green curve, for YbRh$_2$Si$_2$, and Fig. 2b for $^{174}$YbRh$_2$Si$_2$), thus demonstrating superconductivity that nucleates directly out of the strange metal state (Fig. 2a, b). Our measurements expand the previously established strange metal regime to a record span of linear electrical resistivity over 3.5 orders of magnitude in temperature, with a high accuracy of 5% in the linear exponent $c$ (Fig. 2c).

To characterize the superconductivity further, we performed isothermal magnetic field sweeps. In YbRh$_2$Si$_2$, all traces of superconductivity disappear only in fields beyond 70 mT, which is well above the quantum critical field of 60 mT (Fig. 3a). The unusual two-step-like shape of the resistivity isotherms below 5 mK, which is distinct from normal broadening in applied fields, suggests that two different superconducting phases might be involved. This is corroborated by the results on $^{174}$YbRh$_2$Si$_2$, where the lowest-temperature isotherms show clear signs of reentrance (Fig. 3b). We note that no current dependence was observed, ruling out that flux-flow resistivity is at the origin of these characteristics. Next, we present color-coded temperature–magnetic field phase diagrams of YbRh$_2$Si$_2$ and $^{174}$YbRh$_2$Si$_2$ (Fig. 3c, d), constructed from a large number of isotherms. Their merit is to give a general and fully unbiased impression of the phases present: an “S-shaped” superconducting region in YbRh$_2$Si$_2$ and two possibly separated superconducting regions in $^{174}$YbRh$_2$Si$_2$.

For more quantitative phase diagrams, a definition of the (field-dependent) transition temperatures $T_c$ and (temperature-dependent) upper critical fields $B_{c2}$ has to be adopted. We choose the midpoints of the resistive transitions, as sketched in Fig. 1c, d. For YbRh$_2$Si$_2$ this leads to the phase boundary delineated by the full ($B_{c2}$) and open (T$_c$) blue circles in Fig. 4a, which closely
resembles the shape drawn by the yellow color code (50% resistance) in Fig. 3c. An initial rapid suppression of \( T_c \) is followed by a much more gradual one, indicating that moving toward the QCP boosts the superconductivity against the general trend of field suppression associated with the Pauli- and/or orbital-limiting effect of the magnetic field (for cartoons of this field effect, see Supplementary Fig. 3). This is seen even more clearly in the 90% resistance line (boundary of the pale shading in Fig. 4a) that exhibits a local maximum at a magnetic field only slightly below the QCP. This evidences that at least a component of the superconductivity in YbRh\(_2\)Si\(_2\) is promoted by the same quantum effect, see Supplementary Fig. 3). This is seen even more clearly in \( T \) behavior above the Neel temperature \( T_N \), \( T^2 \) behavior below it, and the onset of superconductivity at the lowest temperatures. c, d Electrical resistivity below 12 mK, scaled to its normal-state resistivity \( \rho_N \) just above the transition, showing the superconducting transition at \( T_c \), which we define as the temperature where \( \rho(T) \) has dropped to \( \rho_N/2 \). Magnetic fields (applied within the tetragonal \( a-a \) plane) successively suppress \( T_c \). The 10 and 30 mT curves for \(^{174}\text{Yb}Rh_2Si_2\) were extracted from isothermal field sweeps (Fig. 3b); all other curves were recorder as function of temperature.

### Table 1 Characteristics of the investigated YbRh\(_2\)Si\(_2\) and \(^{174}\text{Yb}Rh_2Si_2\) single crystals.

| Sample             | Batch   | RRR\(_{10\text{mK}}\) | \( \rho_0 \) (\( \mu \Omega \text{cm} \)) | \( A \) (\( \mu \Omega \text{cm} \text{K}^2 \)) | \( A' \) (\( \mu \Omega \text{cm} \text{K} \)) | \( \rho_0/ AT \) (J/molK\(^2\)) |
|--------------------|---------|------------------------|------------------------------------------|---------------------------------|---------------------------------|----------------------------------|
| YbRh\(_2\)Si\(_2\) | 63113_1 | 67                     | 1.19                                     | 20.2                            | 1.23                            | 1.17                             | 1.42                            |
| \(^{174}\text{Yb}Rh_2Si_2\) | Lap0288 | 123                    | 0.55                                     | 14.8                            | 0.59                            | 0.85                             | 1.22                            |

Both samples are from batches studied in detail previously\(^{17,32}\). Their residual resistance ratios RRR\(_{10\text{mK}}\) \( \approx R(300 \text{K})/R(10\text{mK}) \), as well as the zero-field Fermi liquid behavior \( \rho = \rho_0 + AT^2 \) below \( T_N \) and the non-Fermi liquid behavior \( \rho = \rho_0 + AT \) at the quantum critical field of 60 mT confirm high sample quality. To remove uncertainties in the geometric factors, we have assumed \( R(300 \text{K}) = 80 \mu \Omega \text{cm} \). The Sommerfeld coefficient in zero field \( \gamma_0 \), calculated from \( A \) via the universal Kadowaki-Woods ratio \( A/\gamma \approx 10^{-3} \mu \Omega \text{cm(K)}^2/(\text{mJ})^2 \), is a good estimate of the non-quantum critical contribution (see Supplementary Note 2: Estimates on Planckian dissipation).

In what follows we give a few simple estimates of characteristics of the superconductivity in YbRh\(_2\)Si\(_2\) and \(^{174}\text{Yb}Rh_2Si_2\) (see Table 2). From the zero-field \( T_c \) values (7.9 and 3.4 mK for YbRh\(_2\)Si\(_2\) and \(^{174}\text{Yb}Rh_2Si_2\), respectively) and upper critical field slopes \( -dB_c/dT \) (4.4 and 2.1 T/K, much larger than in conventional superconductors), which we determined from line fits in Fig. 4 (see red lines), we estimate the weak-coupling BCS Ginzburg–Landau coherence lengths \( \xi_{\text{GL}} \) (97 and 215 nm). Together with the relevant (non-quantum critical) Sommerfeld
Fig. 2 Strange metal behavior of YbRh$_2$Si$_2$ and $^{174}$YbRh$_2$Si$_2$. 

**a, b** Temperature-dependent electrical resistivity at the quantum critical field of 60 mT applied within the tetragonal a-a plane. Superconductivity develops out of a strange metal $\rho$ - $T$ normal state. The parameters of the linear-in-$T$ fits are given in Table 1. 

**c** Electrical resistivity exponent $\epsilon$ of the non-Fermi liquid form $\rho = \rho_0 + A' T^\epsilon$, determined as $\epsilon = \frac{d \ln \Delta \rho}{d \ln T}$, shown together with literature data up to high temperatures$^{15}$. This establishes linear-in-$T$ resistivity, evidenced by $\epsilon = 1 \pm 0.05$, over 3.5 orders of magnitude in temperature. Note that this presentation visualizes the temperature dependence of the exponent with great sensitivity, and that the error bar of $\pm 0.05$ corresponds to a high precision in the exponent’s closeness to the value of 1 (for comparison see, e.g., Fig. 12 of ref. $^8$).

Fig. 3 Magnetic field dependence of the electrical resistivity of YbRh$_2$Si$_2$ and $^{174}$YbRh$_2$Si$_2$. 

**a, b** Selected isotherms of the electrical resistivity $\rho(B)$, revealing reentrant superconductivity at low temperatures in $^{174}$YbRh$_2$Si$_2$ (b) and remnants thereof in YbRh$_2$Si$_2$ (a). Lines are guides-to-the-eyes in (a) and fits to a multi-transition model (Supplementary Note 1: Analysis of resistivity vs magnetic field isotherms and Supplementary Fig. 1) in (b). 

**c, d** Temperature--magnetic field phase diagrams of the two samples, with the reduced electrical resistance $R/R(9$ mK) as color code. The yellow color corresponds to the resistive midpoint. As a measure of $T_c(B)$ it indicates a phase boundary of unusual shape for YbRh$_2$Si$_2$, and two possibly distinct phases for $^{174}$YbRh$_2$Si$_2$. 
that the perfect overlap of the full and open symbols demonstrates the high reproducibility of the results. Full diamonds represent the \(B_{c2}\) values extracted from a multi-transition model (Supplementary Note 1: Analysis of resistivity vs magnetic field isotherms and Supplementary Fig. 1) for the three involved transitions (green for leaving phase I, violet for entering and leaving phase II). The good agreement between diamonds and circles in the regions of minimal multi-phase interference justifies this procedure. The upper boundaries of the pale shaded areas away from data points represent 90% resistance lines. The black dashed line in both panels indicates the boundary of the antiferromagnetic (AFM) phase. It represents an extrapolation of data from refs. 28,29, to \(T = 0\), the quantum critical point (QCP, black dot). The red lines are linear fits to the low-field (50%) data, and determine both the upper critical field slopes \(-dB_{c2}/dT_{c}\) and the zero-field superconducting transition temperatures \(T_c = \frac{-\pi}{\sqrt{2}}H(0)\). The dashed lines represent (inverted) \(B_{c2}(T) = B_{c2}(T = 0) \cdot \left[1 - \frac{T}{(T/T_{c})}\right]\) mean-field curves determined from \(-dB_{c2}/dT_{c}\) and \(T_c\), as estimates of the (low-field) phase boundaries. Below 0.5 mK, all other phase/shading boundaries correspond to linear-in-B extrapolations of fits to the lowest \(T\) data points. Note that the perfect overlap of the full and open symbols demonstrates the high reproducibility of the results.

Table 2 Characteristics of the superconducting phase(s) in YbRh\(_2\)Si\(_2\) and \(^{174}\)YbRh\(_2\)Si\(_2\).

| Sample       | \(T_c\) (mK) | \(-\frac{dB_{c2}}{dT_{c}}\) | \(\xi_{GL}\) (nm) | \(k_F \left(\frac{m}{\hbar}\right)^{\frac{1}{2}}\) | \(l_{tr}\) (nm) | \(\lambda_{GL}\) (\(\mu\)m) | \(B_{c2}\) (mT) | \(B_{p}\) (mT) | \(\alpha\)  |
|--------------|--------------|-----------------|------------------|----------------------------------|-------------|----------------|----------------|----------------|------------|
| YbRh\(_2\)Si\(_2\) | 7.9          | 4.4             | 97               | 5.2                             | 371         | 1.8            | 24             | 15             | 0.011      |
| \(^{174}\)YbRh\(_2\)Si\(_2\) | 3.4          | 2.1             | 215              | 4.8                             | 976         | 2.0            | 5.0             | 6.4             | 0.0065     |

Both \(T_c(B)\) and \(B_{c2}(T)\) are defined as the midpoints of the resistive transitions (see Figs 1c, d and 2a, b). The zero-field values \(T_c\) \([\sim T_c(H=0)]\) as well as the upper critical field slopes \(-dB_{c2}/dT_{c}\) are determined from linear fits to the data at small fields (red lines in Fig. 4). Listed are also estimates of the Ginzburg-Landau coherence length \(\xi_{GL}\), the Ginzburg-Landau penetration depth \(\lambda_{GL}\), the orbital (limiting) upper critical field \(B_{c2}\), and the Pauli limiting field \(B_{p}\) (see text). \(\alpha\) is the prefactor of the scattering rate \(1/\tau = \alpha_0 T/k_B\) of a simple Drude conductor, estimated from \(T_c\), \(\xi_{GL}\) (both below), and \(\mu_0 B_{p}\) (from Table 1), as explained in the Supplementary Note 2: Estimates on Planckian dissipation; “Planckian dissipation” refers to \(\alpha = 1\).
We start by recapitulating our results that make the BCS mechanism extremely unlikely: (i) superconductivity in YbRh$_2$Si$_2$ condenses out of an extreme strange metal state, with linear-in-temperature resistivity right down to the onset of superconductivity (Fig. 2a); (ii) the upper critical field slope (Table 2) as well as the directly measured critical field (Fig. 4a) strongly overshoot both the Pauli and the orbital limiting fields; (iii) the low-temperature resistivity isotherms exhibit a two-step transition (Fig. 3a), evidencing that one component is much less field sensitive than the other; (iv) the superconducting phase boundary deviates strongly from a mean-field shape (Figs 3a and 4a), evidencing that the field boosts (at least part of) the superconductivity against the general trend of field suppression; (v) superconductivity is strongly suppressed by substituting the natural abundance Yb (of atomic mass 173.04) by $^{174}$Yb, though the isotope effect in a BCS picture would have a minimal effect (a reduction of $T_c$ by 0.1%). It is thus natural to assume that quantum critical fluctuations are involved in stabilizing (at least the high-field part of) the superconductivity in YbRh$_2$Si$_2$. Very recently, in a two-impurity Anderson model of Yb, features Kondo destruction$^{20}$, the singlet-pairing susceptibility was found to be strongly enhanced by critical local moment fluctuations$^{34}$. Because singlet pairing may be subject to Pauli limiting, this phase—though stabilized by quantum critical fluctuations—might be suppressed by the applied magnetic field even well before the QCP is reached. Thus, phase I of $^{174}$YbRh$_2$Si$_2$, and the putative corresponding low-field phase of YbRh$_2$Si$_2$ are promising candidates for this type of superconductivity. Interestingly, in this context, unconventional superconductivity is also discussed in the spin-triplet channel$^{35,36}$. It is tempting to consider phase II of $^{174}$YbRh$_2$Si$_2$ and the putative corresponding high-field phase of YbRh$_2$Si$_2$ to be of this kind, which would provide a compelling link to recently discovered candidate spin-triplet topological superconductors$^{37,38}$. Of course, any model for superconductivity in YbRh$_2$Si$_2$ (and $^{174}$YbRh$_2$Si$_2$) should also correctly capture the high-temperature dc resistivity, and linear-in-frequency and linear-in-frequency-over-temperature scaling, with a critical exponent of 1, of the optical resistivity$^{30}$. When the magnetic field applied to the samples (as opposed to the typical situation of Ce-based systems under pressure or doping tuning), nor the QCP being governed by effects beyond order parameter fluctuations inhibits superconductivity. Instead, we propose that critical modes associated with a dynamical electron localization–delocalization transition mediate the strange-metal unconventional superconductivity in YbRh$_2$Si$_2$. Future experiments, ideally in conjunction with ab initio-based theoretical work, shall ascertain this assignment, disentangle the different superconducting phases, determine the symmetry of the order parameter, clarify further important details such as the single vs multiband nature of the superconductivity, and even explore the possibility of exotic surface phases.

Finally, we relate our discovery to strange-metal unconventional superconductors in other materials classes. It has been pointed out that the strange metal behavior in many of these is compatible with "Planckian dissipation", i.e., with the transport scattering rate $1/r$ in a simple Drude conductor being equal to $a_k \tau k T / h$, with $a \sim 10$. For YbRh$_2$Si$_2$ and $^{174}$YbRh$_2$Si$_2$, we estimate much smaller $a$ values (see Table 2, and Supplementary Note 2: Estimates on Planckian dissipation), suggesting that linear-in-temperature resistivity—even in the extended form observed here—does not require the Planckian limit to be reached. Whether this is related to the very strongly correlated nature of this compound (with effective masses above 1000 $m_0$, much beyond those in the materials considered in ref. 40) or its pronounced deviation from Drude-like behavior (see Supplementary Materials of ref. 19) is an interesting question for future studies. As to a microscopic understanding of the phenomenon, we point out that charge delocalization transitions, similar to those observed in YbRh$_2$Si$_2$, are being discussed also in other strange-metal superconductors, including the high-$T_c$ cuprates$^{21,22}$, an organic conductor$^{23}$ and, tentatively, even magic angle bilayer graphene$^{24}$. Our results thus point to the exciting possibility that a dynamical electron localization–delocalization transition may mediate strange-metal unconventional superconductivity in a broad range of materials classes.

Methods

Refrigerator and thermometry. All measurements were carried out in the Vienna nuclear demagnetization refrigerator$^{31}$. We use resistance thermometry (Pt resistance thermometers Pt–1000, RuO$_2$ thermometers, and sliced Speer carbon resistance thermometers) for temperatures above 10 mK and magnetic thermometry (CmN, pulsed Pt-NMR, thermometers, via the pulsed nuclear magnetic resonance of $^{197}$Au nuclei) for temperature below 20 mK. For the presented results, we used a CMN thermometer between 20 and 2 mK, a Speer thermometer above, and a Pt-NMR thermometer below.

Filters. To attenuate radiofrequency radiation, a series of filters and thermalization stages consisting of thermo-coax cables (from room temperature to the 50 mK plate), silver-epoxy filters, and RC filters were installed. The silver-epoxy filters are also used for thermalization (down to the mixing chamber temperature).

Sample holders and thermalization. Machined silver sample holders made from a 5N silver rod were annealed to reach a residual resistance ratio of 2000. They are directly screwed to the nuclear stage using home-made silver screws. To thermalize the samples, one of the two outer contact points (of the 4-point technique, see Fig. 4a) was connected by 50 cm gold wires to the silver holder, via spot welding on the sample and screwing to the silver holder. A separate grounding point of excellent quality (anchored 600 m below ground level) was used. The different stages of the cryostat (4 and 1 K plate, still, 50 mK plate, mixing chamber, copper nuclear stage) were all connected via NbTi/CuNi superconducting wires to the same ground, such that the ground potential was highly uniform. To avoid ground loops, all measurements devices were connected via opto-couplers. During the measurements at ultralow temperatures (below 10 mK), all measurement devices were powered by 4 x 12 V – 150 A batteries with floating ground. For electrical isolation (away from the ground point), Vespel was used on the sample holder, the superconducting coil, and the Nb-superconducting shield.

Magnetic field applied to the samples. A dc magnetic field coil made of superconducting NSTi wire ($T_c = 9.2$ K), a superconducting Nb cylinder ($10$ cm diameter, $10$ cm length), and the sample holder are concentrically assembled. The field coil and the superconducting shield are thermalized to the mixing chamber,
the sample holder to the nuclear stage. Magnetic fields at the position of the samples up to 80 mT were generated by applying a dc current, with the precision of a few μT. For the highest fields, a current above 1 A was passed through the self-made coil. Because this represented a considerable risk of quenching and breaking the magnet, only a final set of experiments was done up to the highest fields. In particular, most of the measurements on $^{174}$YbRh$_2$Si$_2$ were done up to 45 mT only.

**Resistivity measurements.** Electrical resistivity measurements were done with a 7124 Precision Lock-in Amplifier. Electrical currents were sourced by a CS580 voltage-controlled current source. The lowest measurement current in our experiments was 10 μA. To increase the signal to noise ratio, low-temperature transformers (encapsulated in a lead shield) with a gain of 1000 were used. They were installed at and thermalized to the mixing chamber. In addition, a SR560 low noise transimpedance pre-amplifier was used at room temperature. Electrical contacts for these measurements were made by spot-welding gold wires to the samples, in a standard 4-point geometry. Carefully derived measurement protocols (electrical current densities, sweep rates, waiting times, etc.) for a good thermalization of the samples to the nuclear stage were followed for all presented measurements; the good thermalization is confirmed by the reproducibility of the results between different types of experiments (e.g., temperature vs magnetic-field sweeps, cooling vs warming curves). Applying larger currents leads to overheating effects at the lowest temperatures, but no evidence for flux-flow resistance could be revealed.

**Data availability**

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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