μSR Signatures of Pseudogap and Critical Spin Dynamics in the Kondo Condensate of P-Doped Silicon

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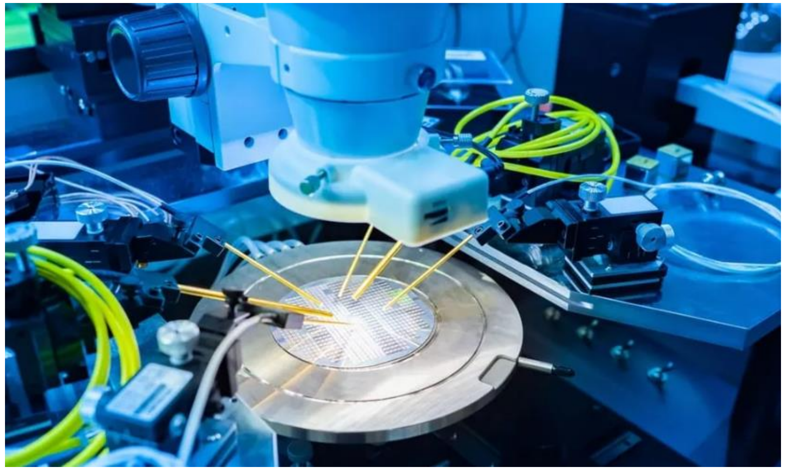
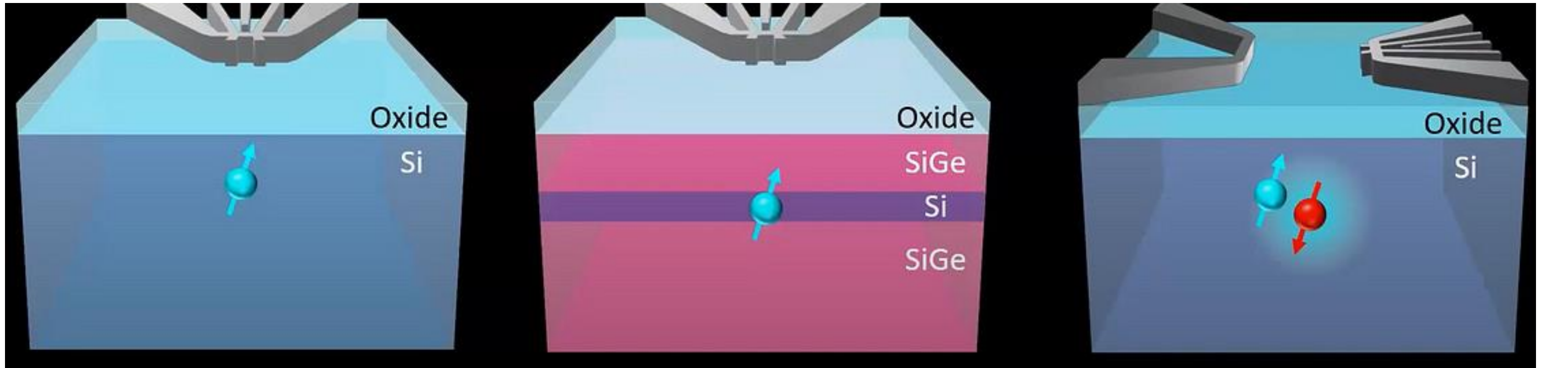
▶ Si: platforms for semiconductor and qantum technologies

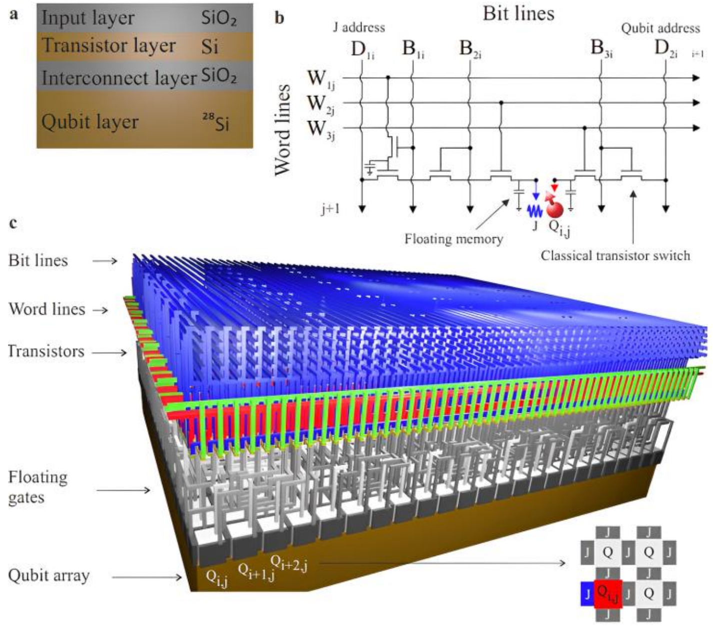




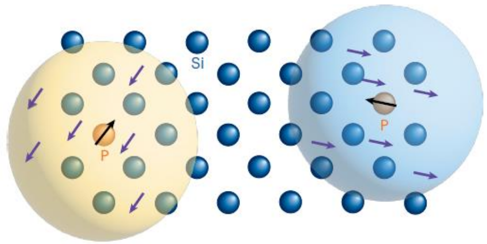
M. Veldhorst et al., Nature Nano. 9, 981 (2014)

E. Kawakami et al., Nature Nano. 9, 666 (2014)

B. E. Kane et al., Nature 393, 133 (1998)

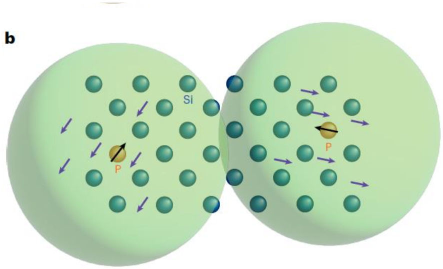


▶ Si:P Model system to explore Anderson localization + Mott physics



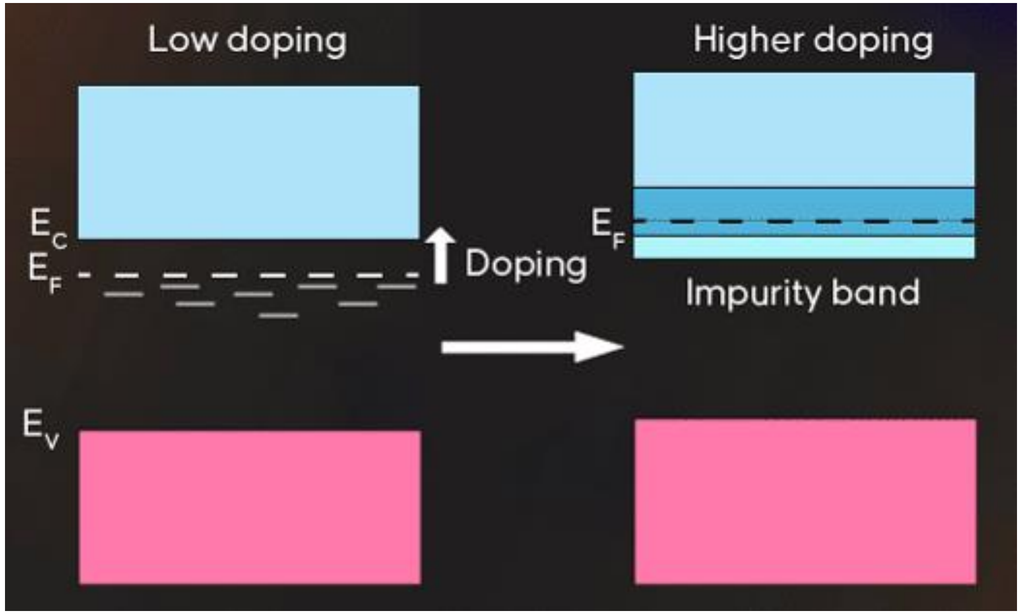
Isolated impurity level

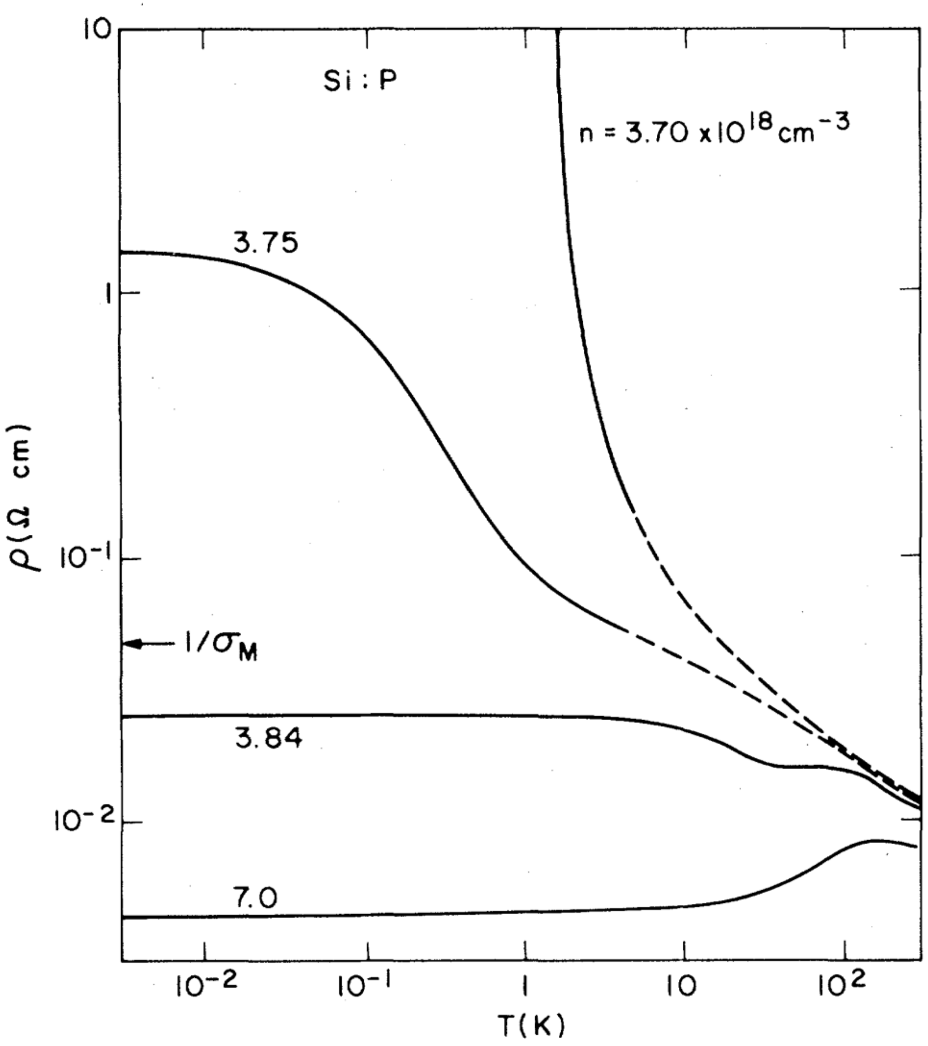
localized moments



impurity band

Coulomb correlations + disorder

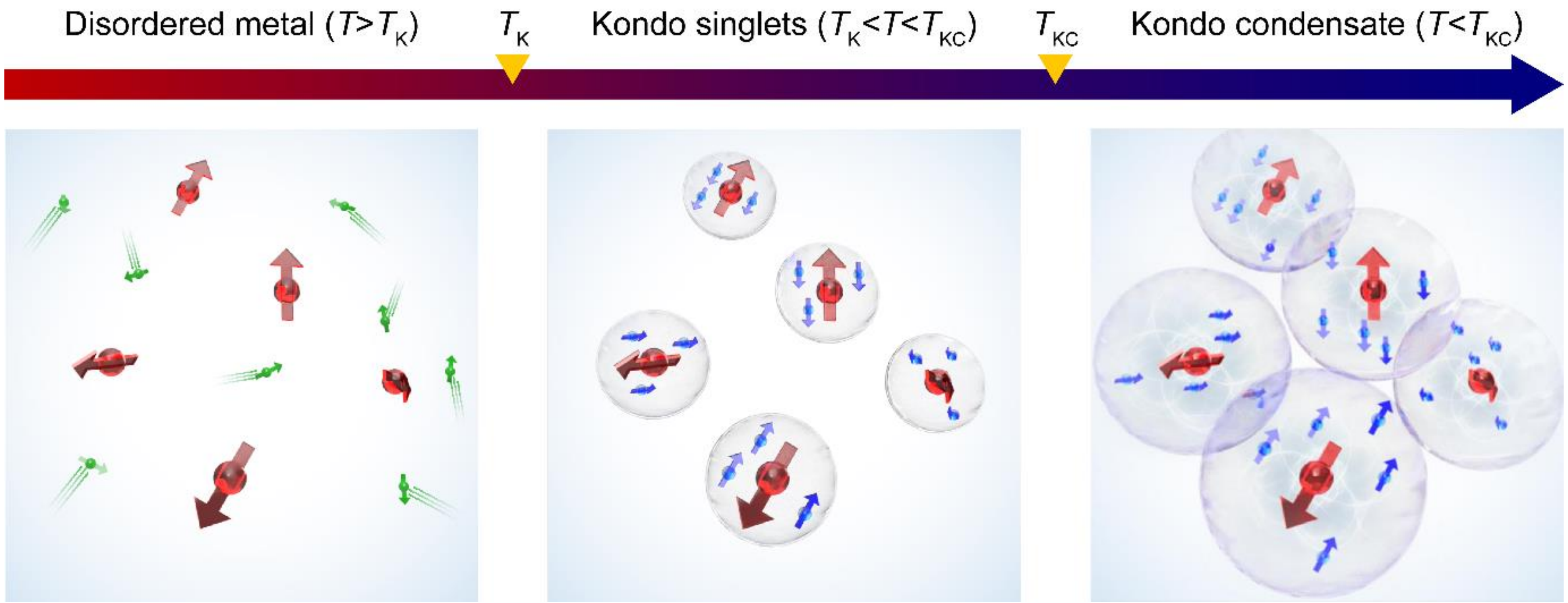




T. F. Rosenbaum et al., PRB **27**, 7509 (83)

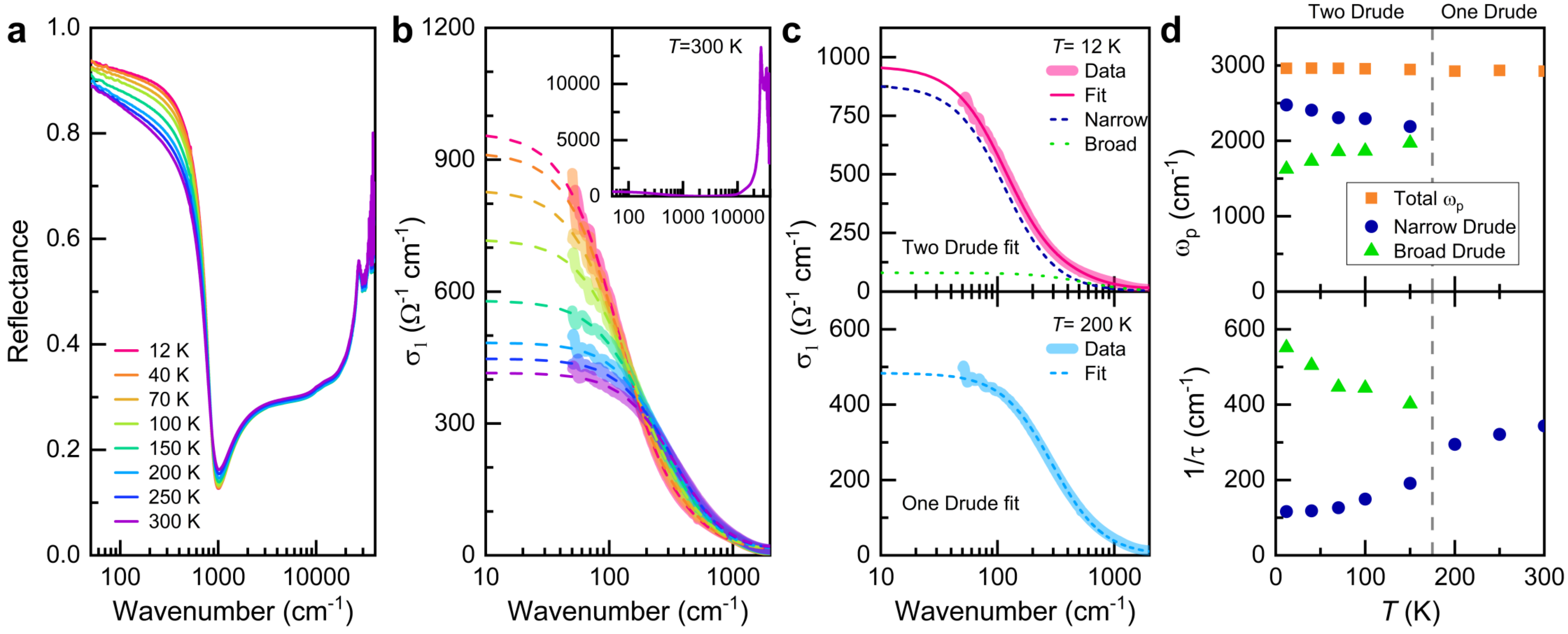
Kondo effect in degenerately P-doped Si (Si:P)

Degenerately doped Si: doping level, typically above 10^{19} cm^{-3}
A 10^{-5} fraction of the total impurities induce unscreened localized moments.
Non-degenerately doped Si: a doping range of 10^{14}–10^{18} cm^{-3}



A mean distance between the local moments is less than 1 μm, comparable the size of a Kondo cloud.

▶ Optical conductivity of Si:P



Two-mode Drude model

$$\sigma_1(\omega) = \frac{\omega_{\mathrm{p,n}}^2}{4\pi}\frac{1/\tau_{\mathrm{n}}}{\omega^2+(1/\tau_{\mathrm{n}})^2} + \frac{\omega_{\mathrm{p,b}}^2}{4\pi}\frac{1/\tau_{\mathrm{b}}}{\omega^2+(1/\tau_{\mathrm{b}})^2}$$

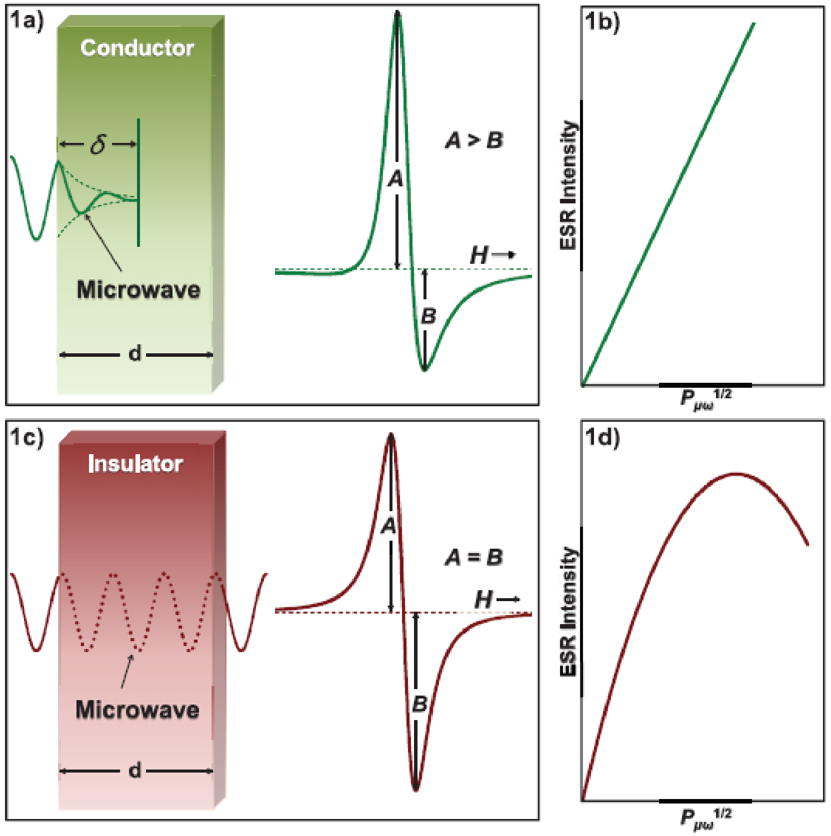
The total plasma frequency

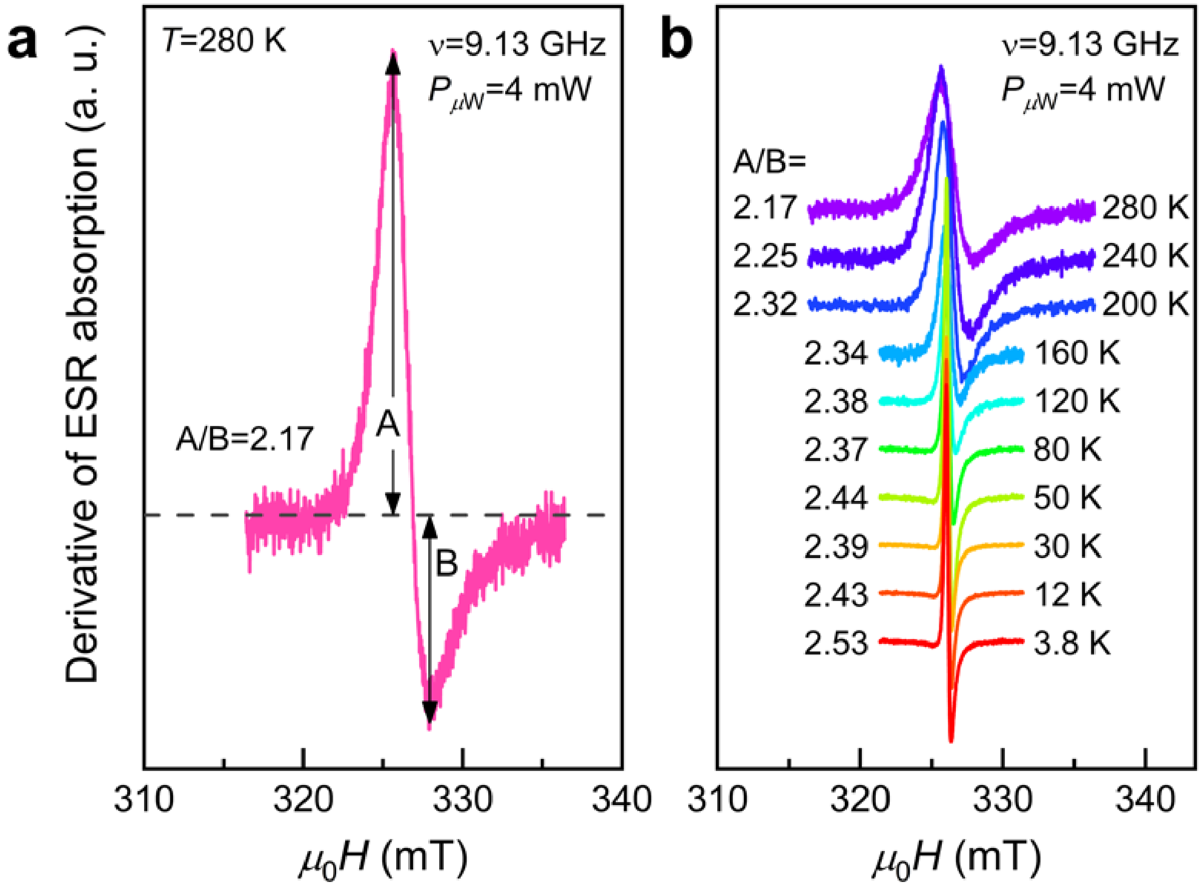
$$\omega_{\mathrm{p,t}} = \sqrt{\omega_{p,n}^2 + \omega_{\mathrm{p,b}}^2} = \frac{4\pi n e^2}{m_e}$$

→ $n \sim 9.4\times10^{19}\ \mathrm{cm}^{-3}$

Two-mode Drude model
→ Two scattering channels
delocalized and localized electrons

▶ ESR signatures of spin correlations in Si:P



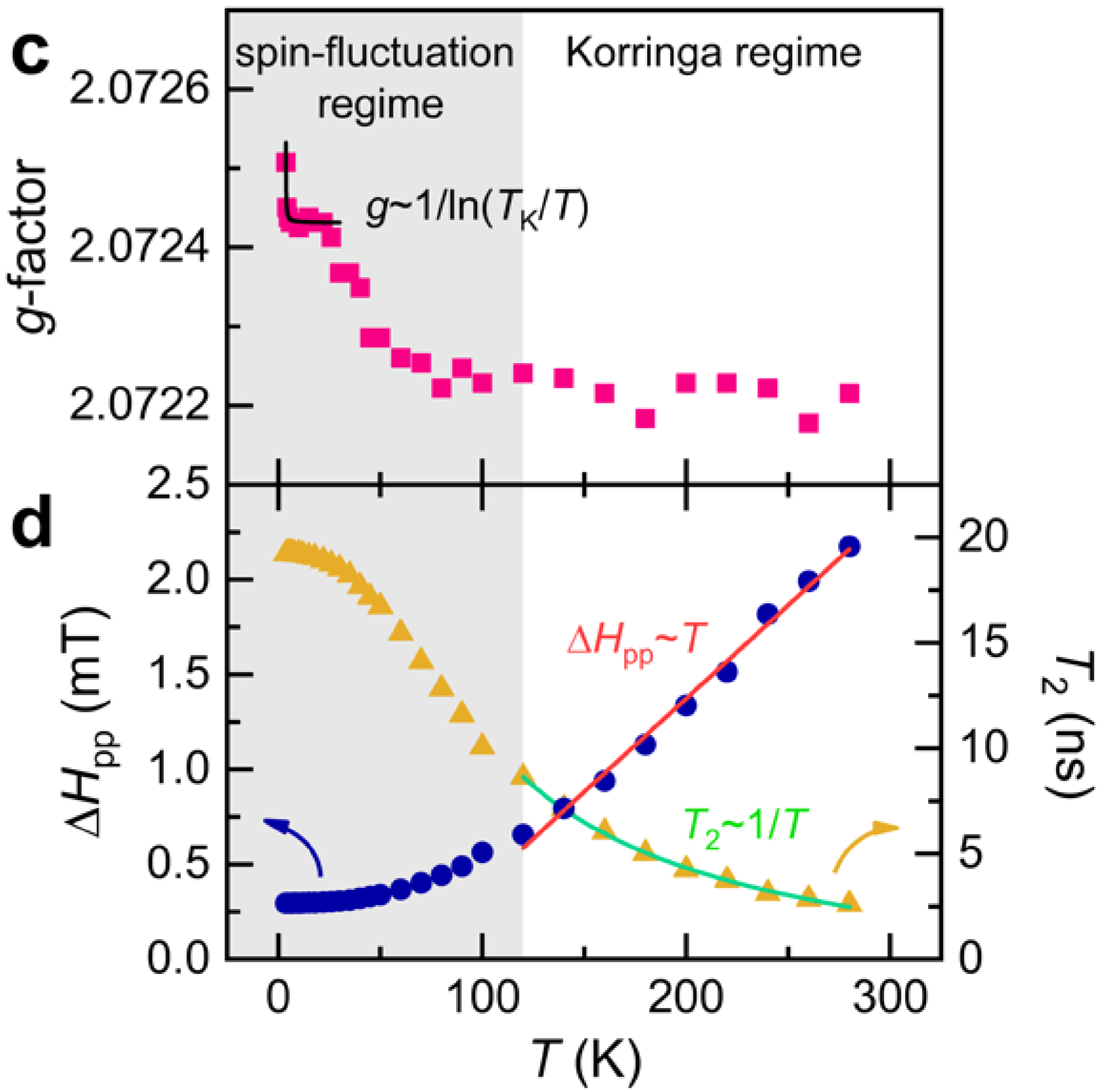


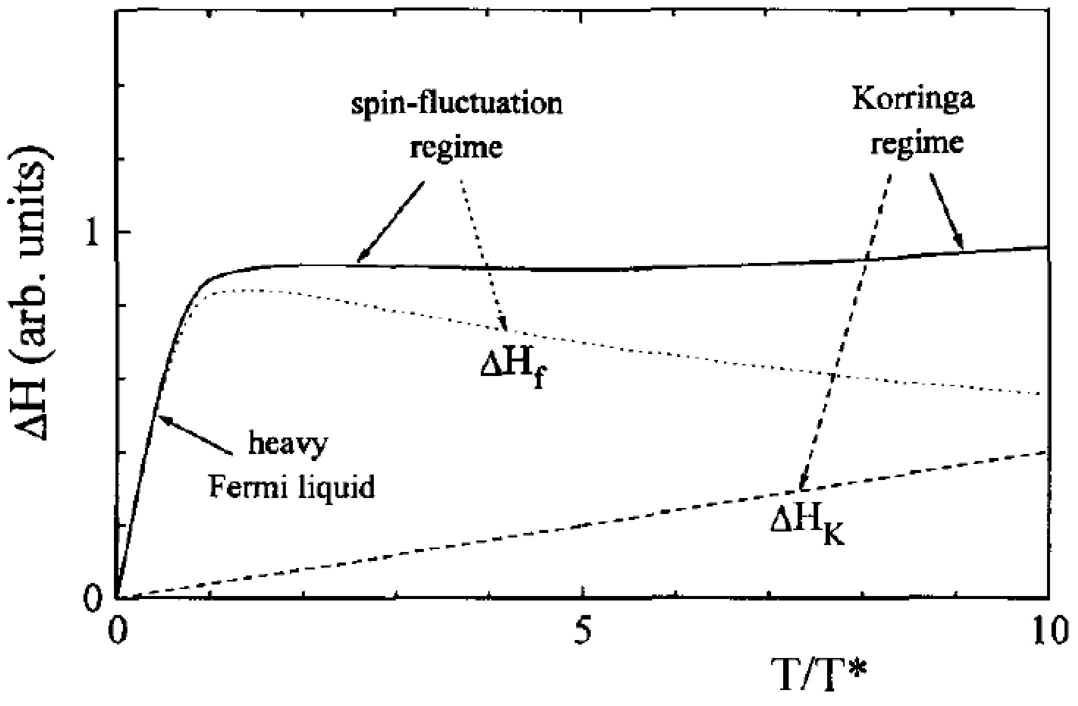
In the diffusionless limit with $1 \leq A/B \leq 2.6$ and $T_D/T_2 \gg 1$

→ The electron spin relaxation times are much shorter than the timescales associated with the electron's diffusive motion.

$$\frac{d[(1-\alpha)\chi'' + \alpha\chi']}{dH} = \chi_0 H_{\mathrm{res}} \gamma^2 T_2^2 \left[\frac{2(1-\alpha)x}{(1+x^2)^2} + \frac{\alpha(1-x^2)}{(1+x^2)^2}\right]$$

ESR evidence of spin fluctuations in Si:P





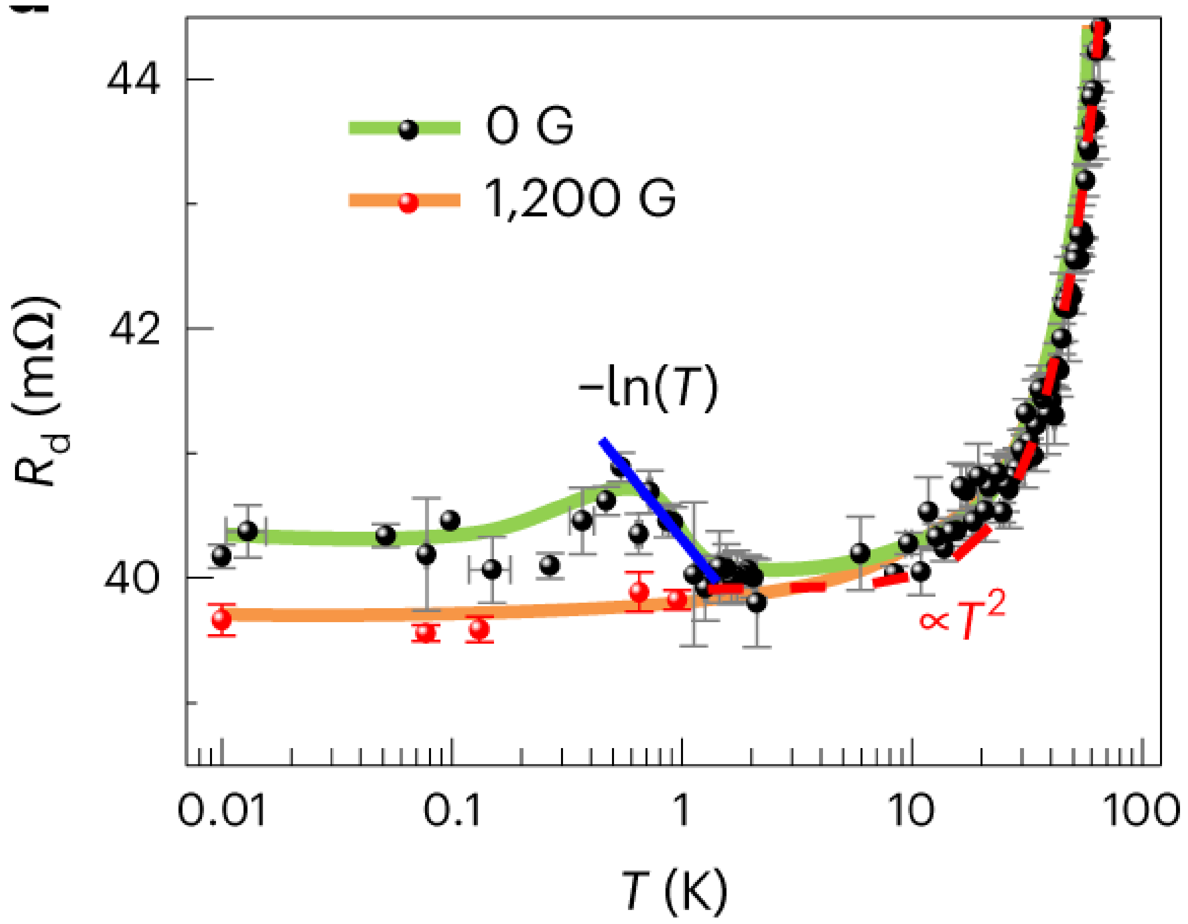
H.-A. Krug von Nidda et al., Appl. Magn. Reson. 12, 287 (97)

$$\Delta g \propto N(E_F) J_{ce-S}(q=0) \qquad \Delta H \propto \langle J^2_{CE-ls}(q) \rangle N^2(E_F) T,$$

J_{ce-S} is the exchange integral between the conduction electrons and the local moments.

$N(E_F)$ is the electronic density of states at the Fermi energy E_F.

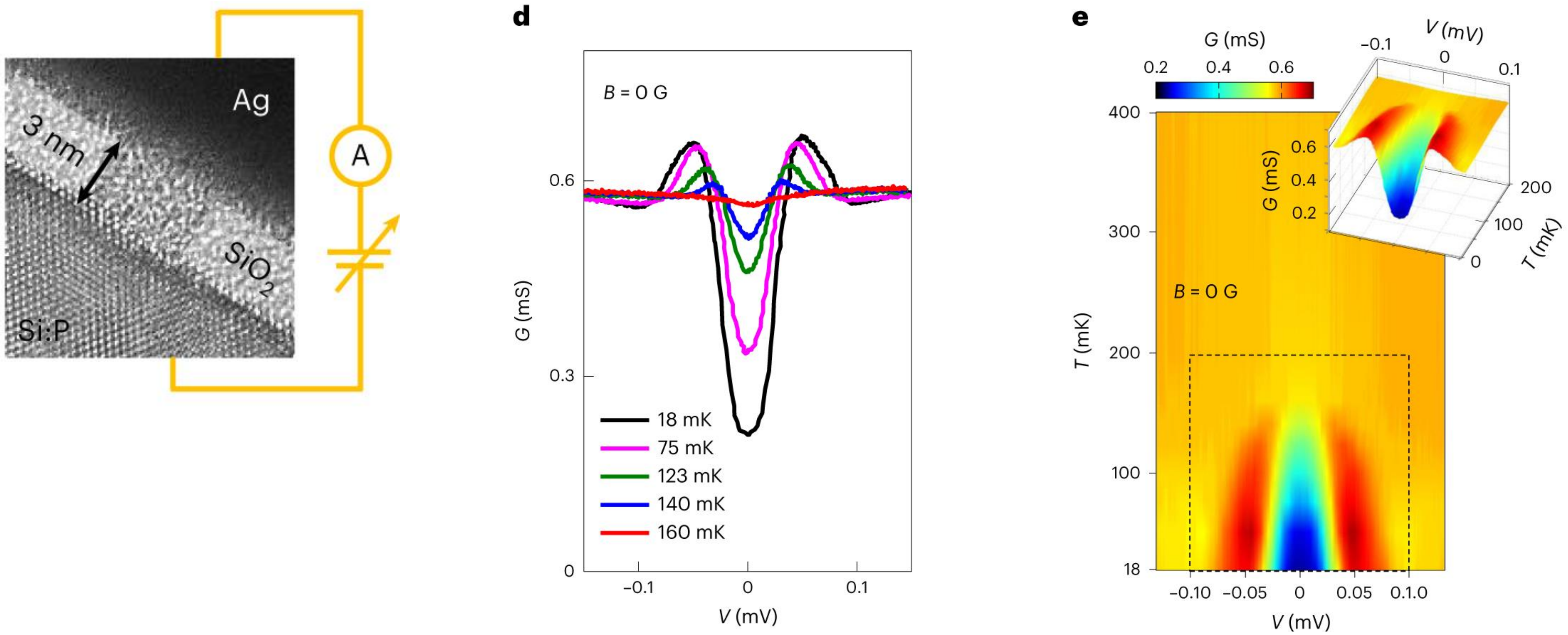
Differential resistance R_d of Si:P



H. Im et al., Nat. Phys. **19**, 676 (23)

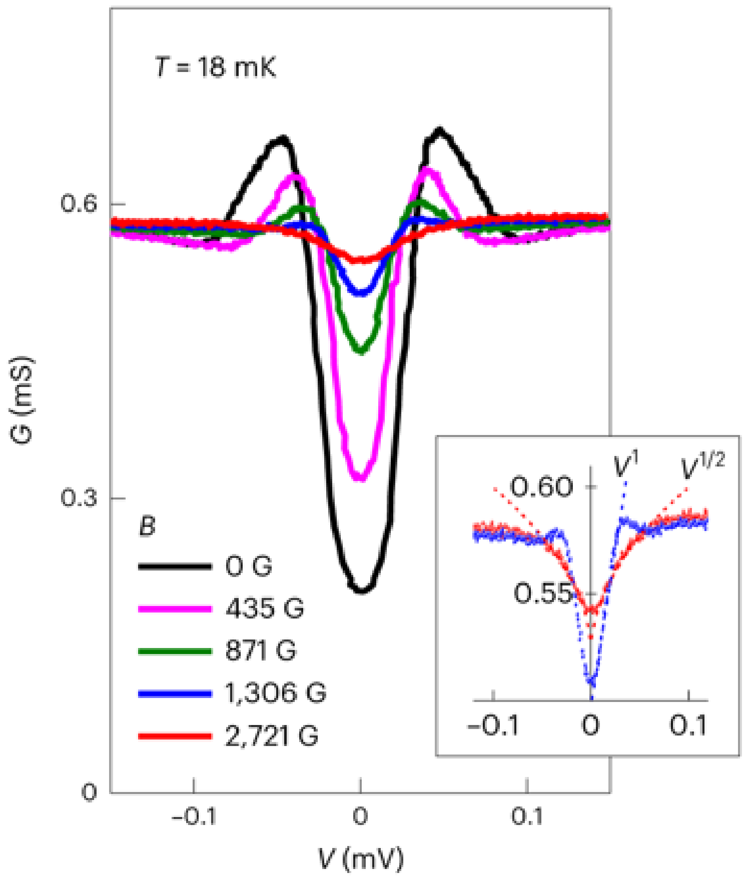
The increase in ln(T) and the subsequent decrease in the resistivity at B=0 is reminiscent of those of a Kondo lattice compound with disorder.

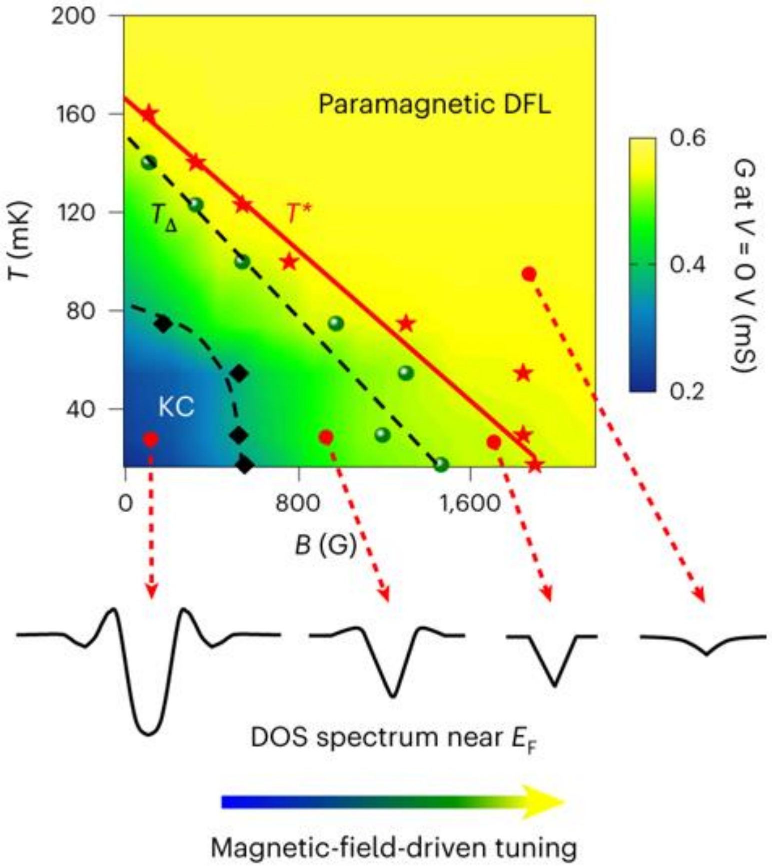
▶ Tunneling DOS spectroscopy of Si:P

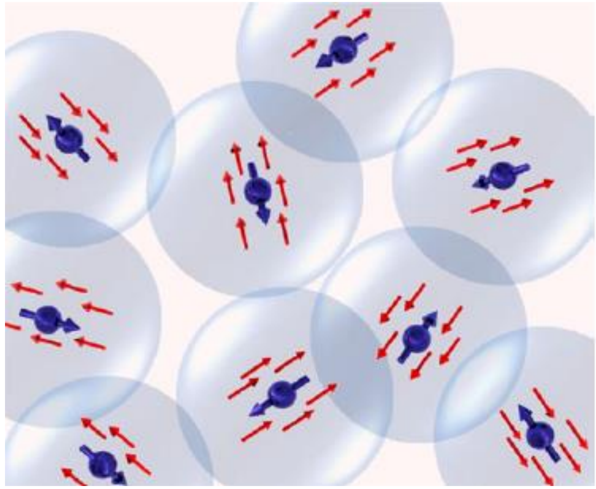


Above 160 mK, the U-shaped pseudogap with the side peaks changes into a $V^{1/2}$-type Altshuler–Aronov gap (paramagnetic, disordered Fermi liquid).

▶ Field-temperature phase diagram of Si:P



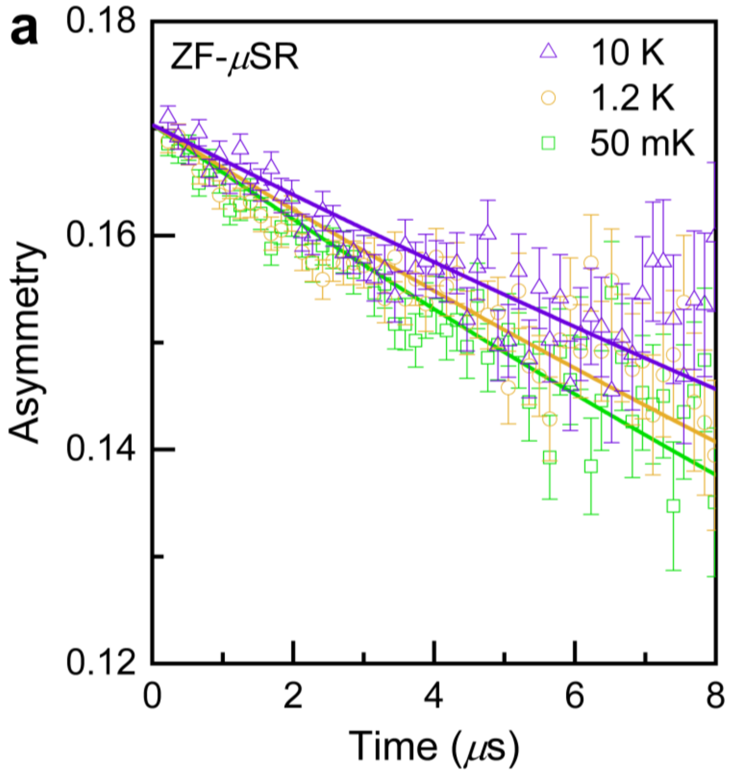


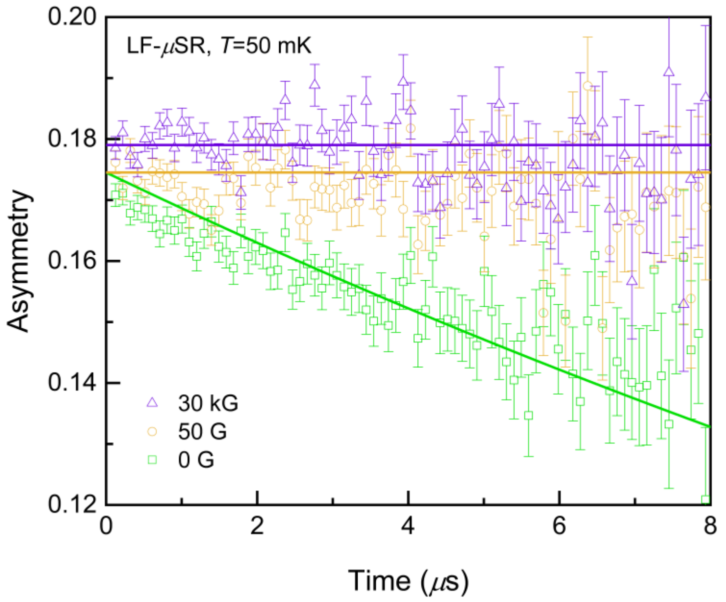


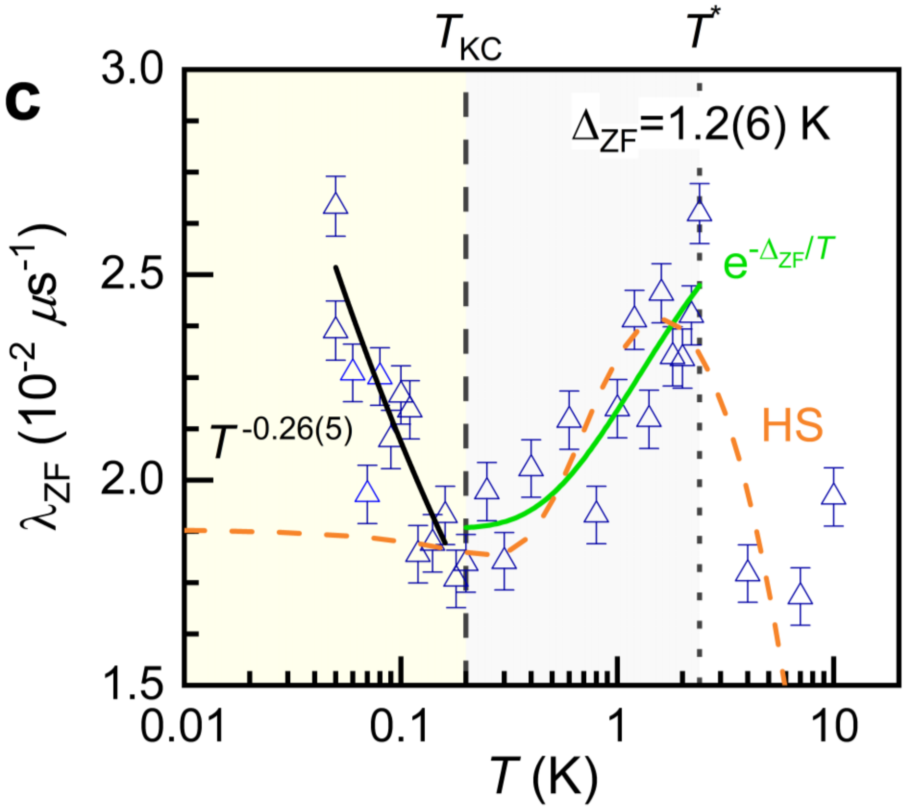
H. Im et al., Nat. Phys. **19**, 676 (23)

In randomly disordered many-impurity Kondo systems, the BCS-like pseudogap without hidden superconductivity implies macroscopic coherence, called **Kondo condensation**.

▶ ZF and LF-μSR of Si:P

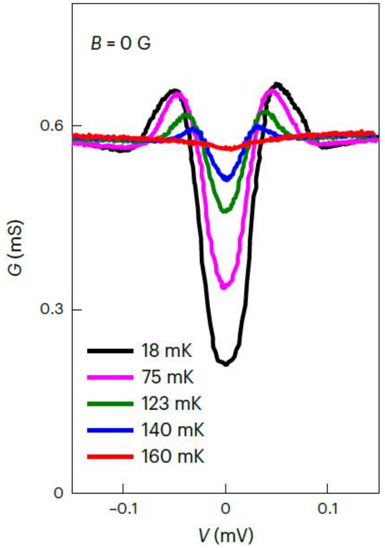


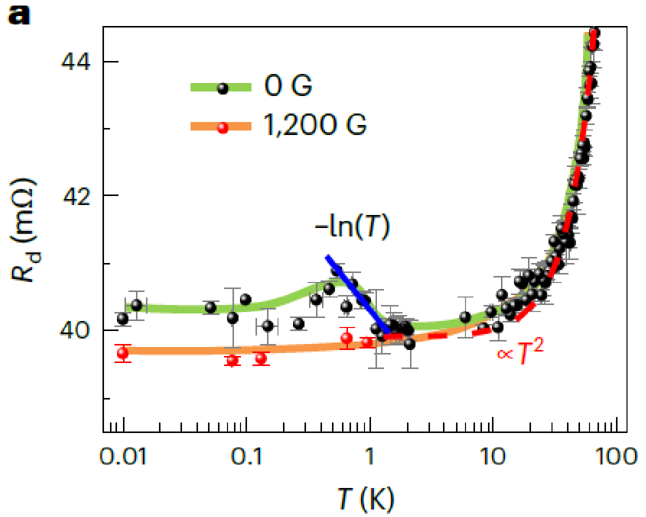




$$P_z^{\mathrm{ZF}}(t) = P_z(0)\exp(-\lambda_{\mathrm{ZF}} t)$$

^{28}Si (I=0) ~92.23%
+ no Gaussian relaxation component
→ dynamic magnetism





$$\lambda_{\mathrm{ZF}}(T)$$
$$\propto 1 + \exp(-\Delta_{\mathrm{ZF}}/T)$$

S. Lee et al.,
submitted (25)

SCIENCE ADVANCES | RESEARCH ARTICLE

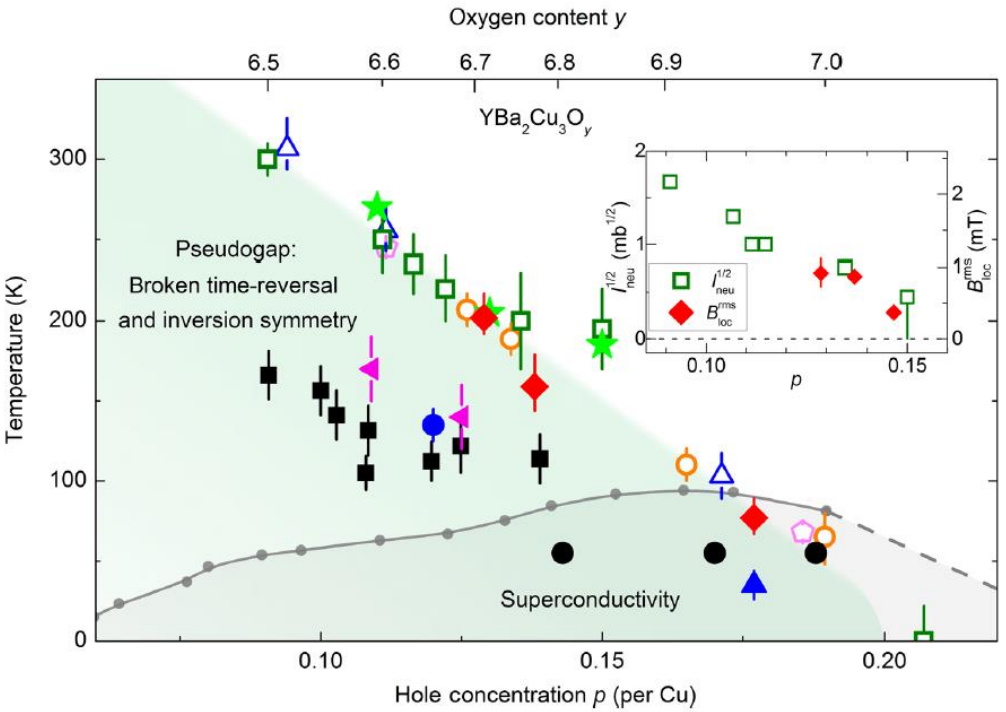
CONDENSED MATTER PHYSICS

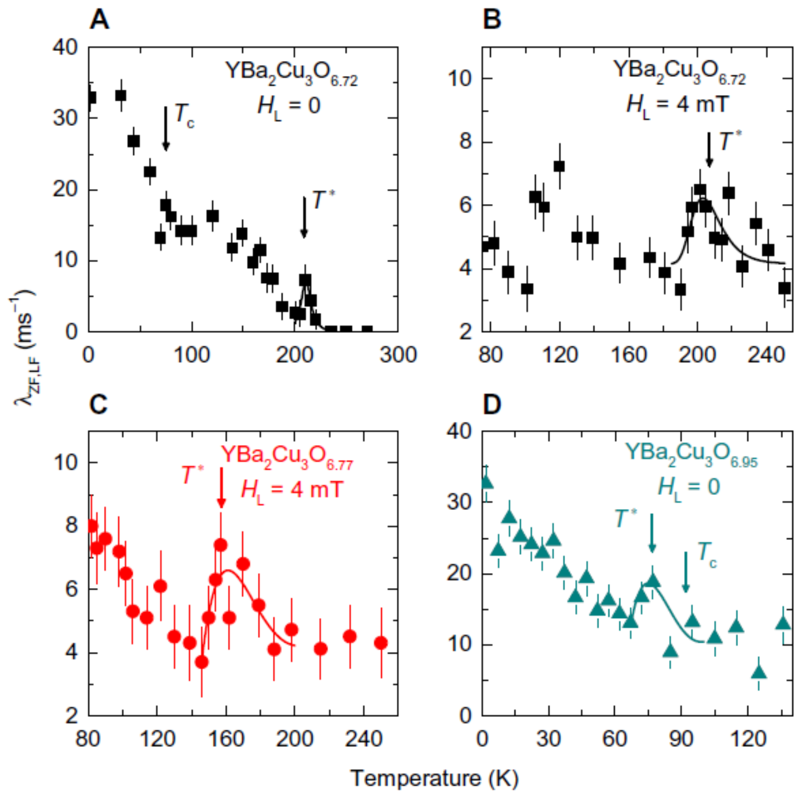
Discovery of slow magnetic fluctuations and critical slowing down in the pseudogap phase of $YBa_2Cu_3O_y$

Jian Zhang,[1] Zhaofeng Ding,[1] Cheng Tan,[1] Kevin Huang,[1*] Oscar O. Bernal,[2] Pei-Chun Ho,[3] Gerald D. Morris,[4] Adrian D. Hillier,[5] Pabitra K. Biswas,[5] Stephen P. Cottrell,[5] Hui Xiang,[6] Xin Yao,[6,7] Douglas E. MacLaughlin,[8] Lei Shu[1,7†]

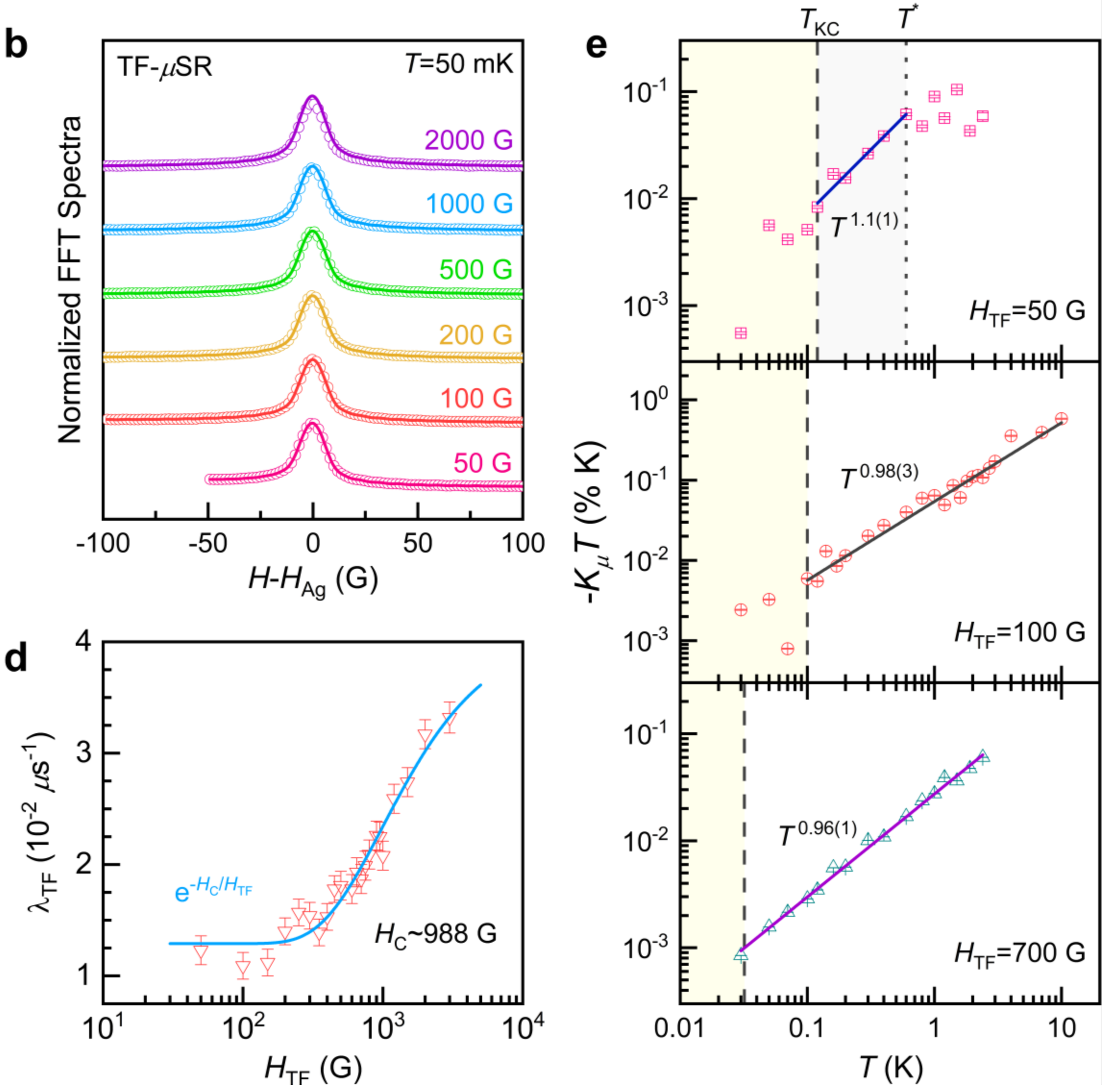
Table 1. Correlation times τ_c and rms muon local fields B_{loc}^{rms} from muon spin relaxation rates in $YBa_2Cu_3O_y$.

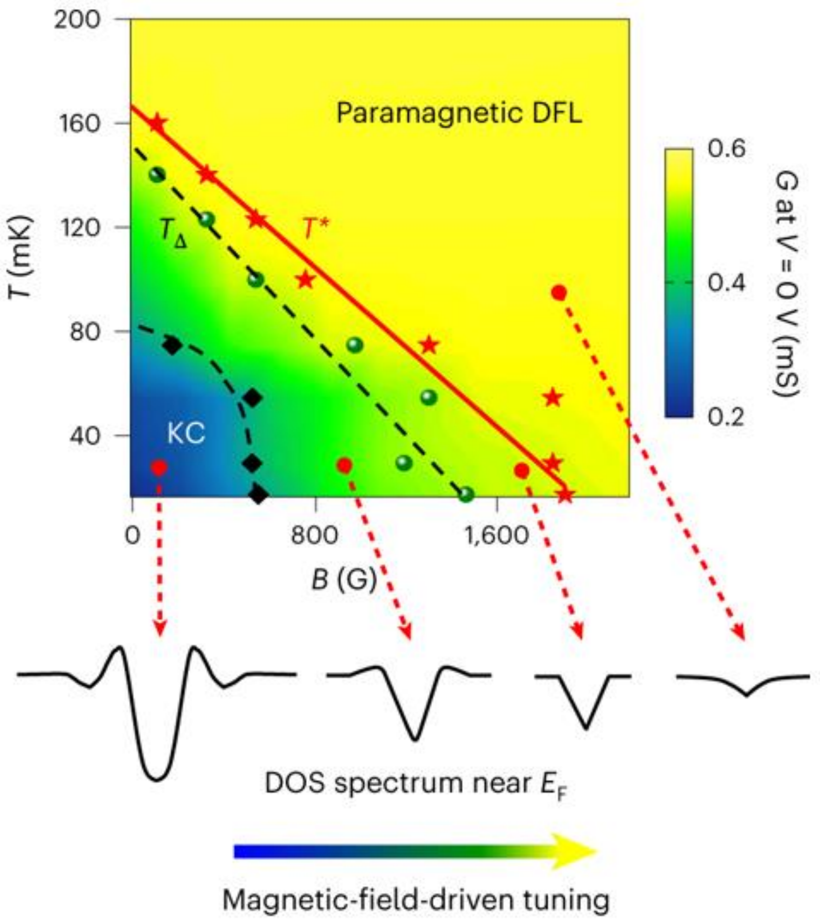
y	Temperature (K)	τ_c(ns)	B_{loc}^{rms} (mT)
6.72	80	5(2)	0.92(19)
6.77	85	10(3)	0.87(10)
6.83	93	25(10)	0.37(6)





TF-μSR: field-induced transition

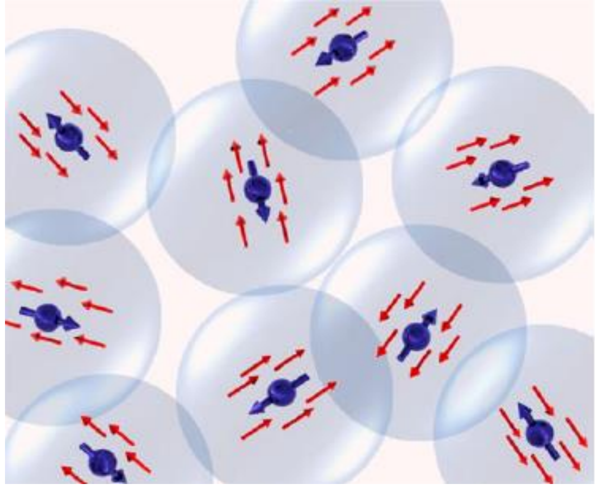




$$P_z^{\mathrm{TF}}(t) = P_z(0)\exp(-\lambda_{\mathrm{TF}} t)\cos\left(f_\mu t + \phi\right)$$

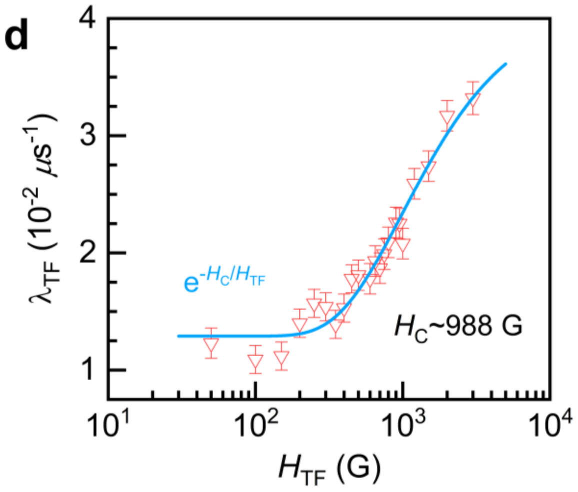
S. Lee et al., submitted (25)

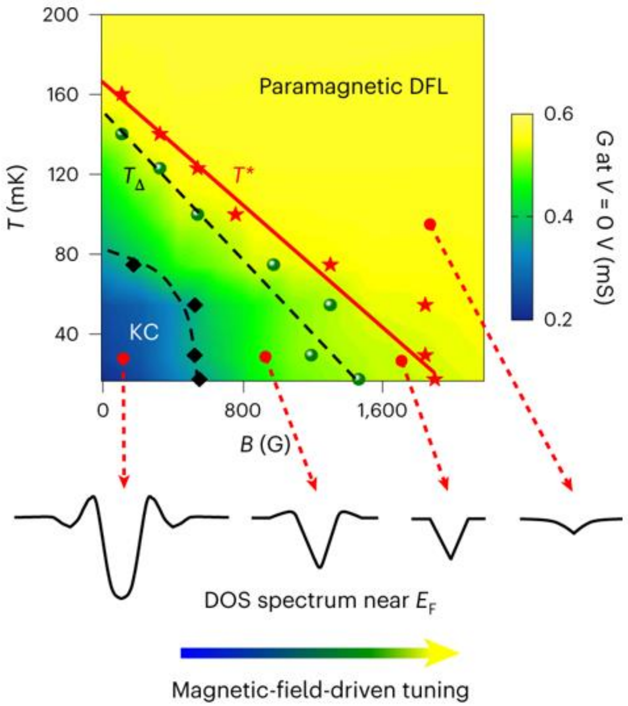
▶ Magnetic origin of pseudogap in the Kondo cloud condensation

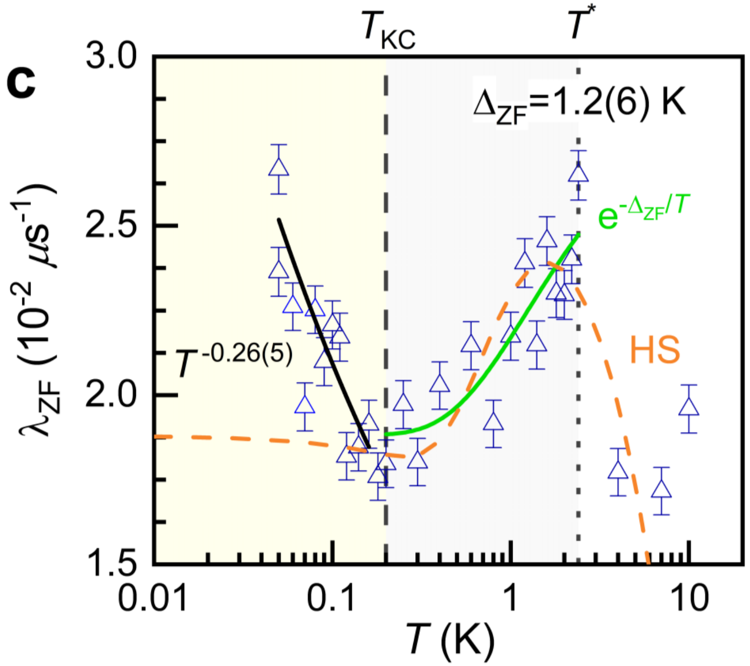


introduce the charge neutral scalar field $\varphi = < c_{\uparrow} f_{\downarrow}^{+} - c_{\downarrow} f_{\uparrow}^{+} >$, where c is an itinerant electron and f^{+} is an ion impurity with a net spin of 1/2. Kondo condensation is the configuration in which φ is non-vanishing.

Critical spin fluctuations are a control parameter of the charge coherence of overlapping Kondo singlets.







Summary

・The critical spin fluctuations of the Kondo condensate state act as a driving force for pseudogap formation within inhomogeneous Kondo clouds.

・Our findings broaden the scope of pseudogap phenomena, extending their relevance into the realm of doped semiconductors.

Thanks to my collaborators

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Yugo Oshima (RIKEN; ESR)

Jungseek Hwang (SKKU; optical spectroscopy)