The extreme strange metal $YbRh_2Si_2$

Silke Paschen
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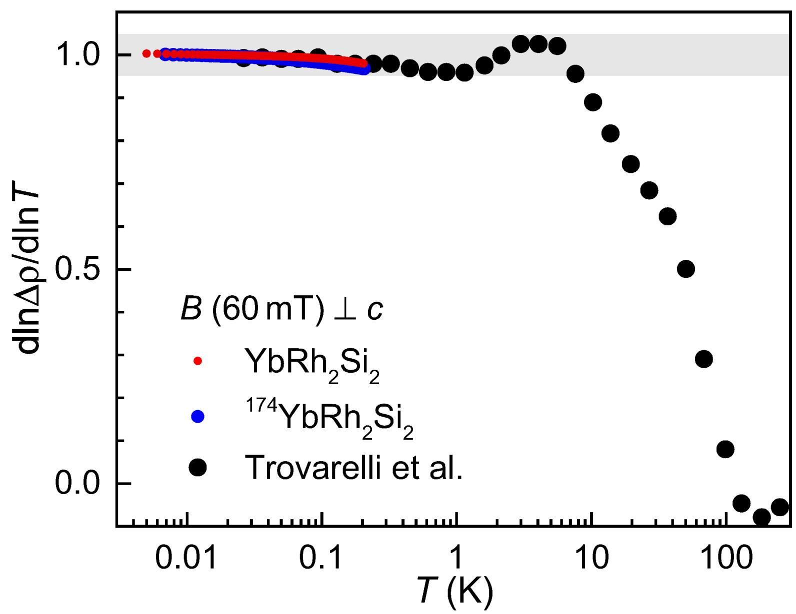
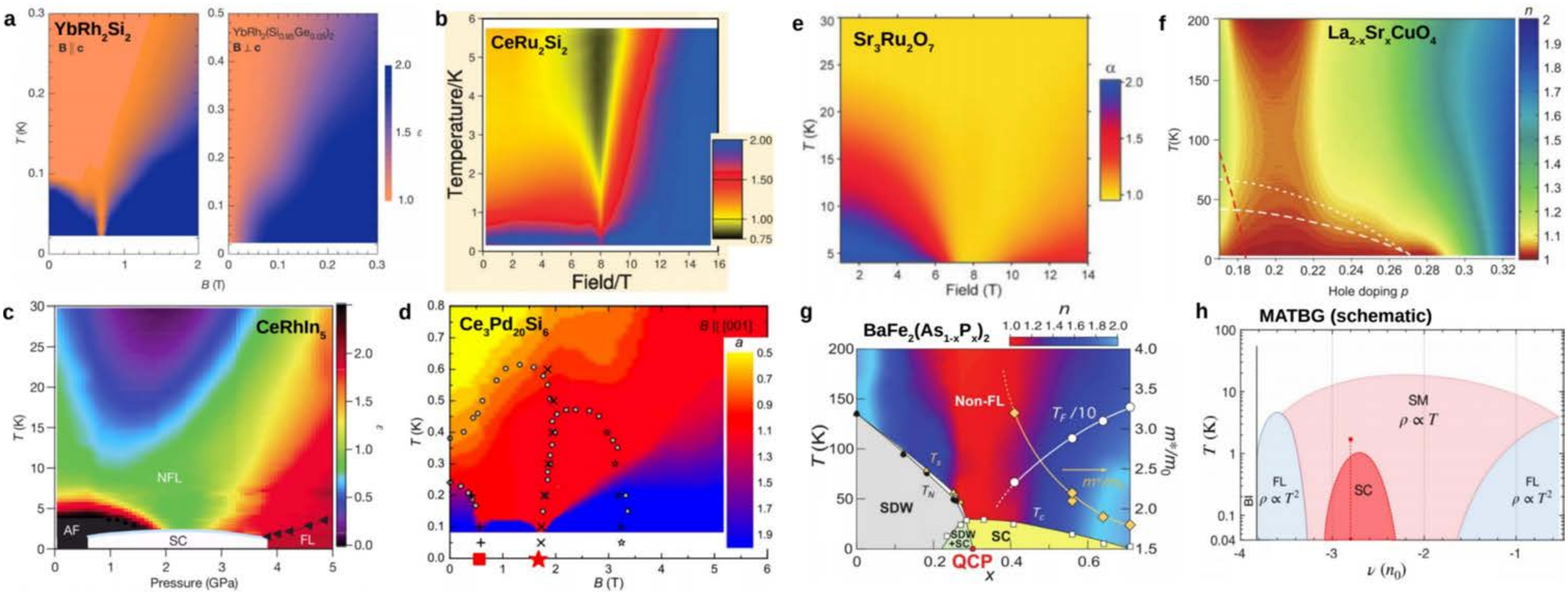


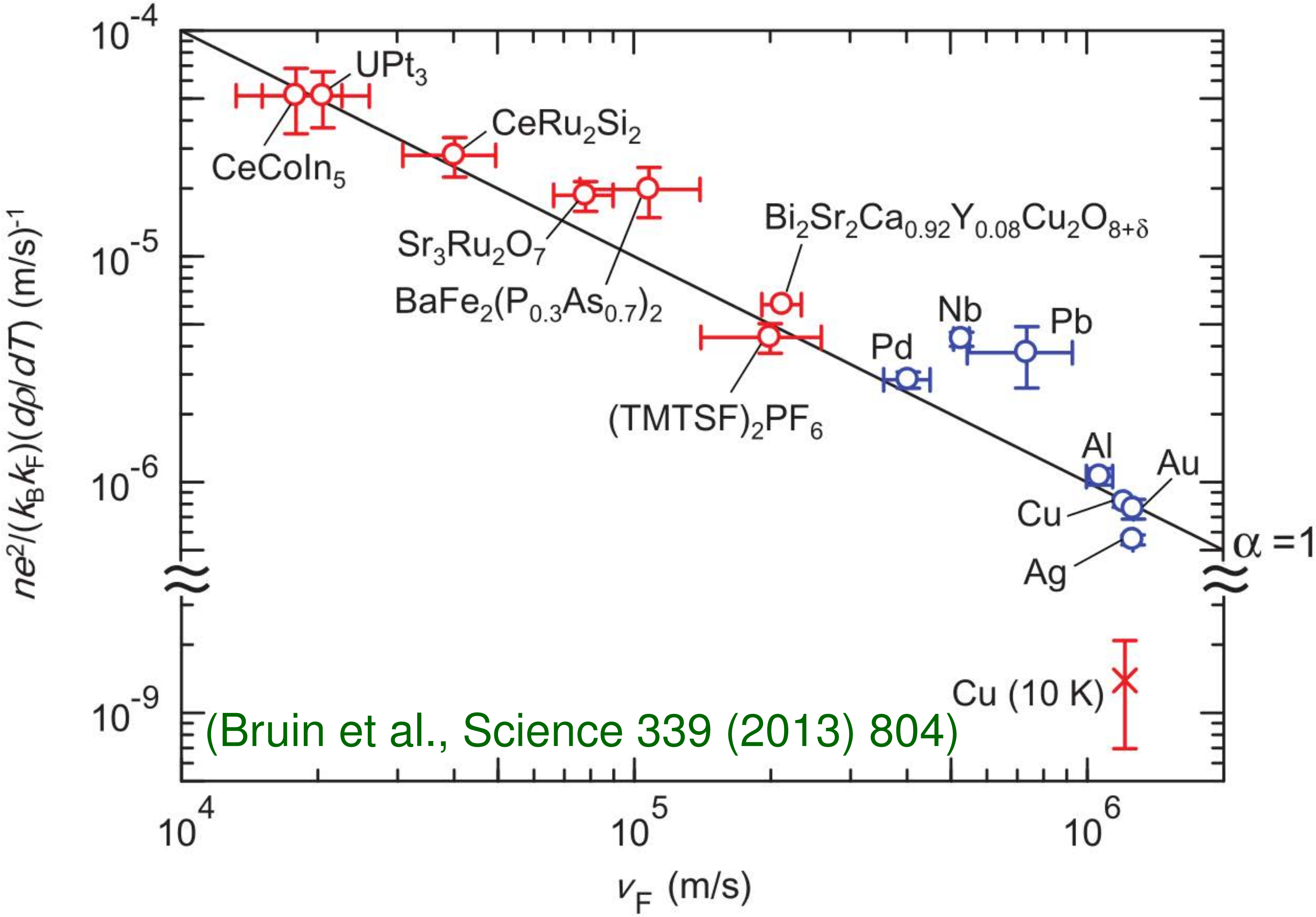
Strange metal behaviour in SCES



(Taupin & SP, Crystals 12 (2022) 251)

$$\rho = \rho_0 + A'T$$

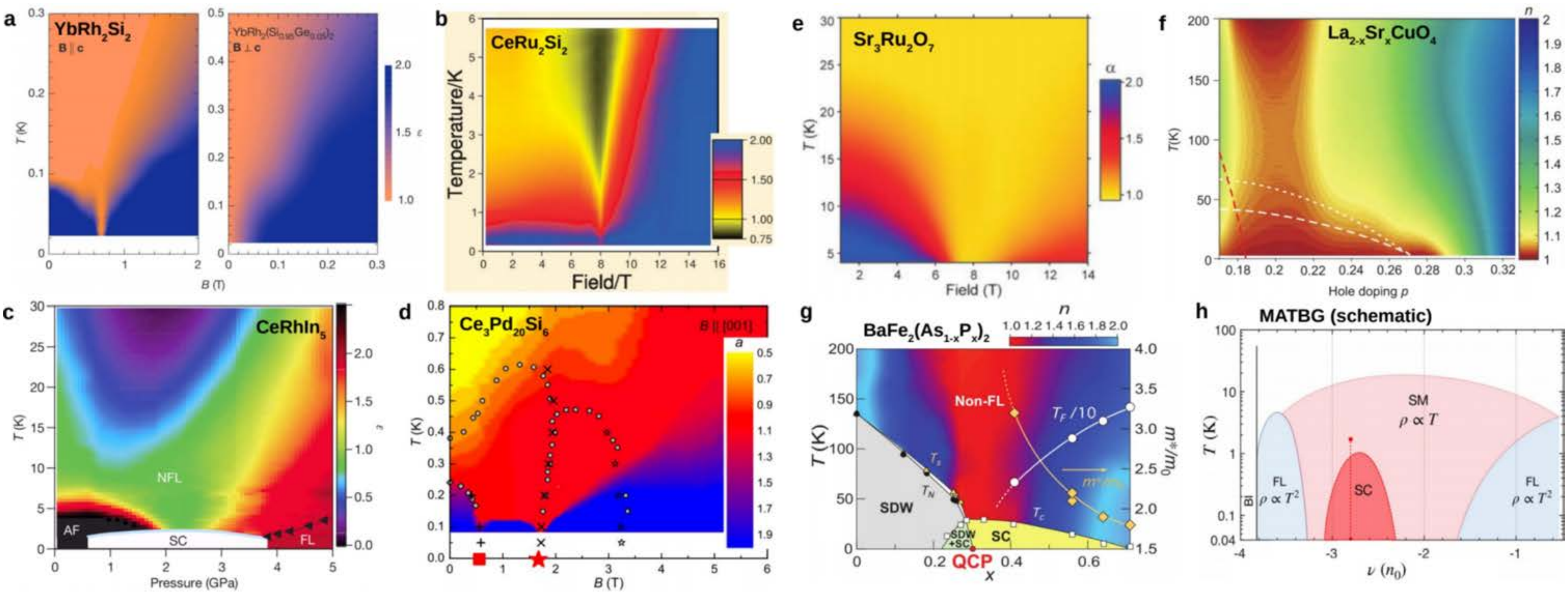
Planckian dissipation?



$$\rho = \rho_0 + \rho_{in} = \rho_0 + A'T = \rho_0 + \frac{m}{ne^2}\frac{1}{\tau} = \rho_0 + \frac{m}{ne^2}\alpha\frac{k_B T}{\hbar}$$

Drude model with $\frac{1}{\tau} \sim T$

Motivations to understand strange metal behaviour in SCES



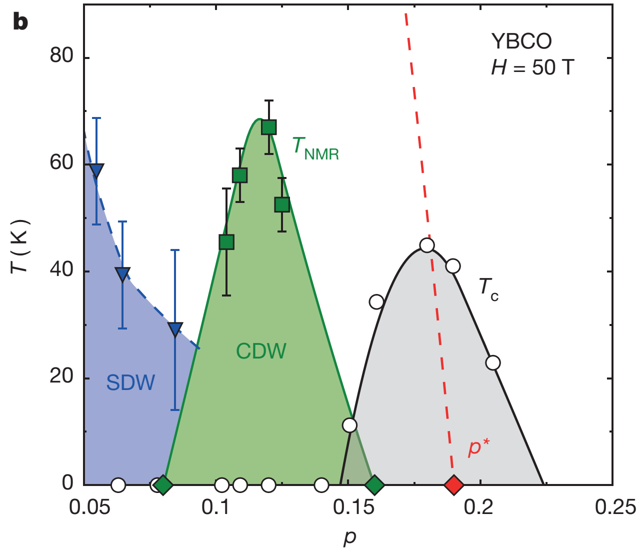
(Taupin & SP, Crystals 12 (2022) 251)

Non-Fermi liquid states of interest in their own right

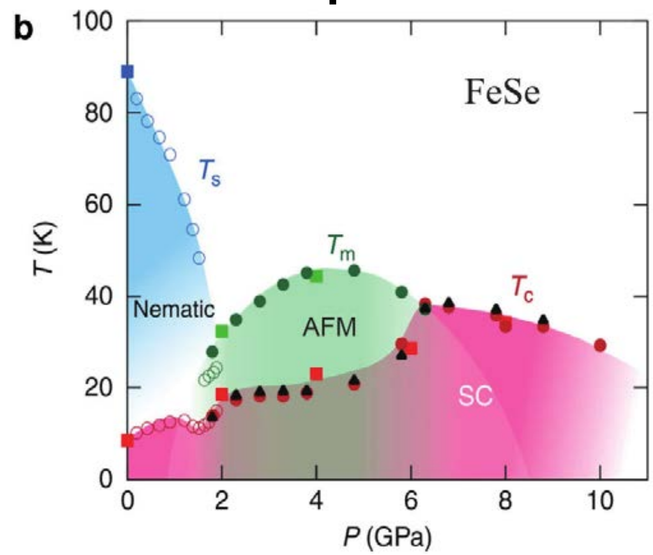
***p* and *x* tuned strange metals have a superconducting dome**

Superconducting domes in SCES

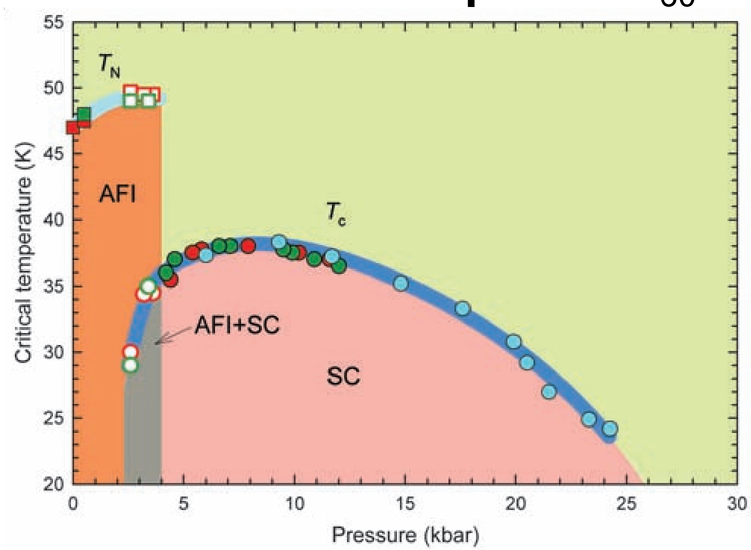
The cuprate $YBaCuO_{6-\delta}$



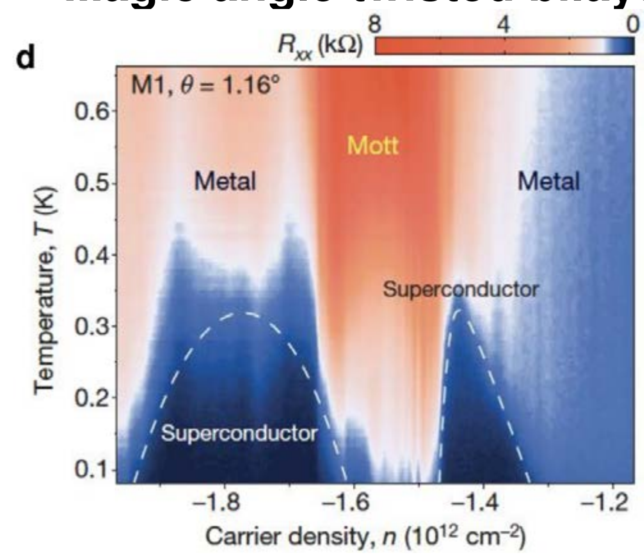
The iron pnictide FeSe



The fulleride compound C_{60}



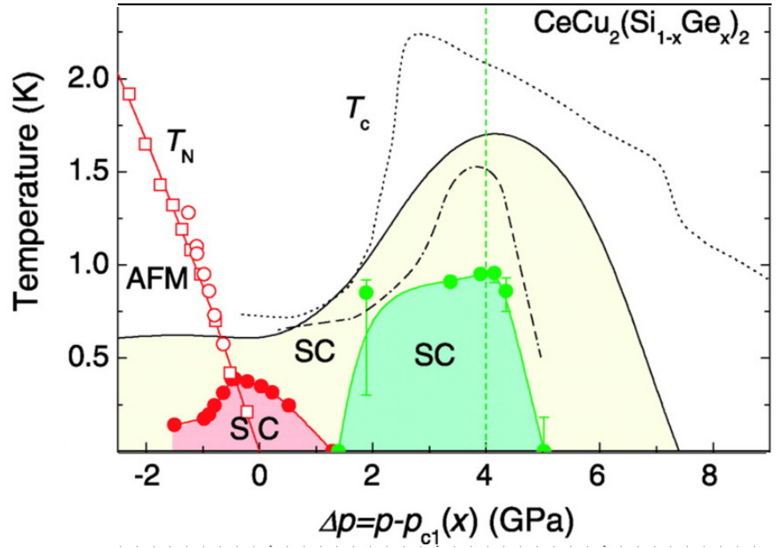
Magic angle twisted bilayer graphene

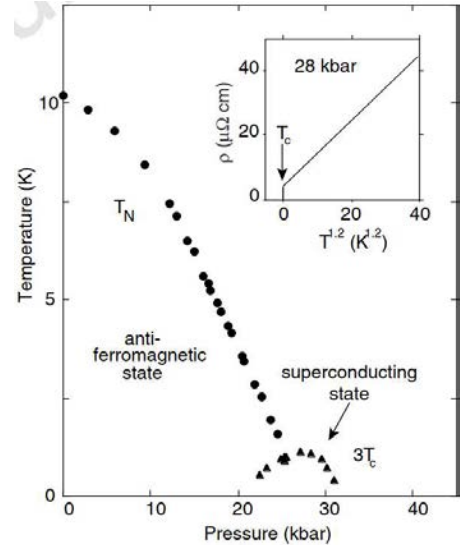


(SP & Si, Nat. Rev. Phys. 3 (2021) 9, and refs. therein)

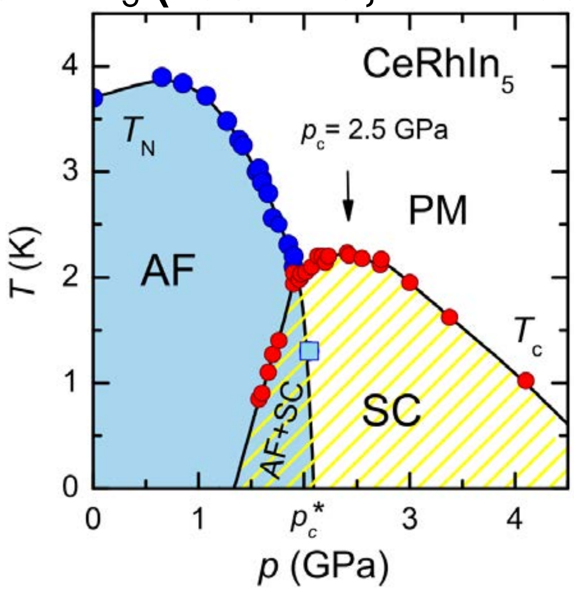
Superconducting domes in heavy fermion metals

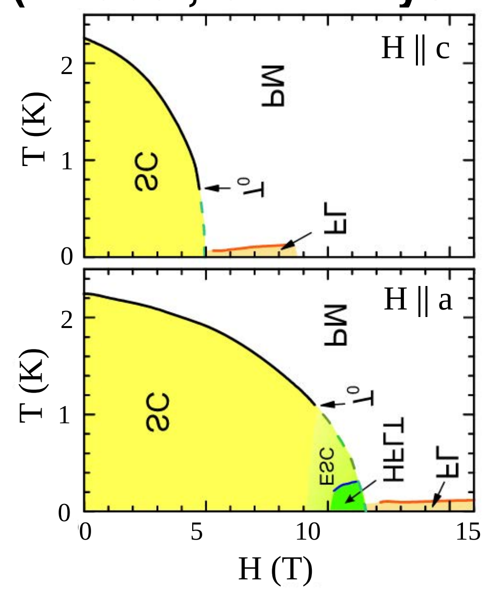
$CeCu_2Si_2$ (Yuan et al., Science 2003) **$CePd_2Si_2$ (Mathur et al., Nature 1998)**



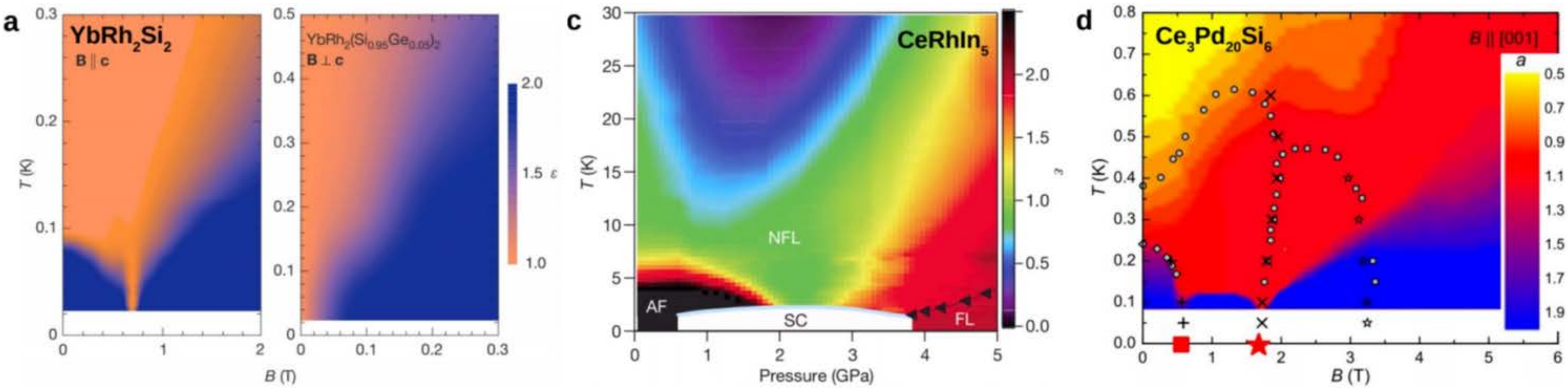


$CeRhIn_5$ (Yashima, PRB 2007) **$CeCoIn_5$ (Knebel, C. R. Phys. 2011 & refs.)**

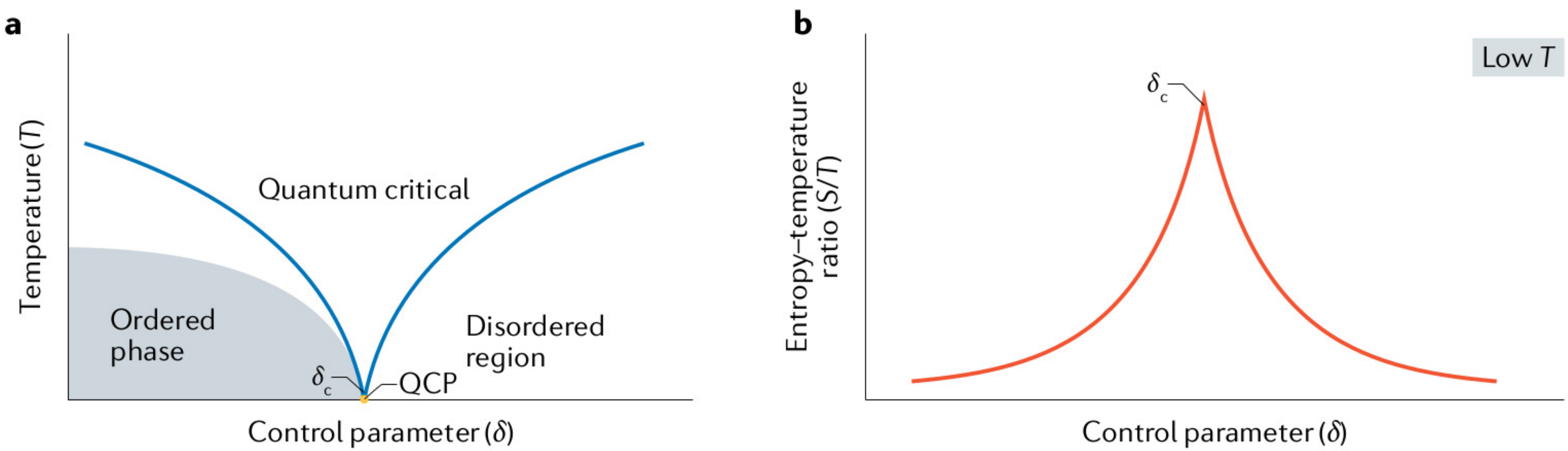




Quantum critical point scenario: Entropy accumulation

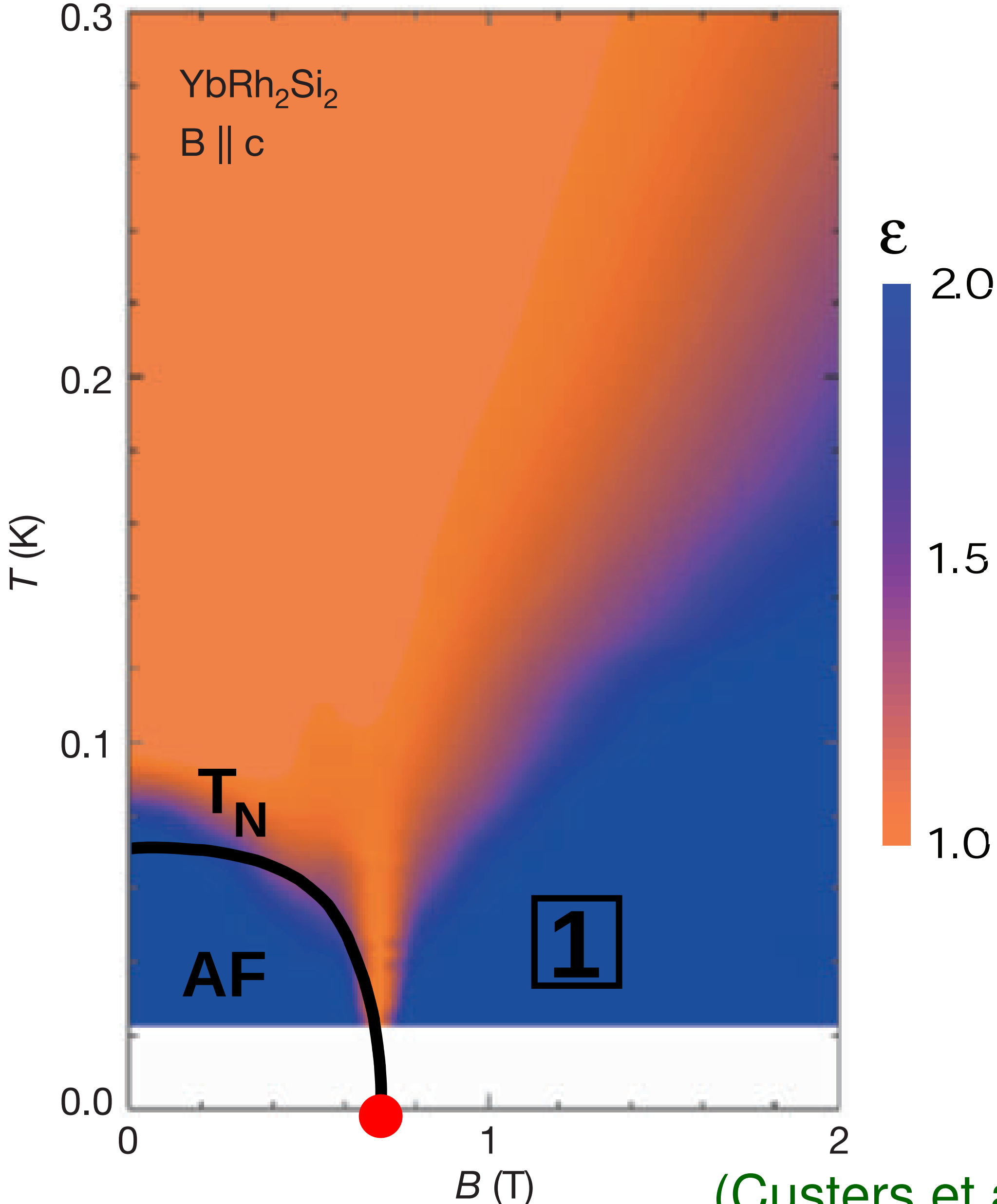


(Taupin & SP, Crystals 12 (2022) 251)



(SP & Si, Nat. Rev. Phys. 3 (2021) 9)

$YbRh_2Si_2$: A model quantum critical heavy fermion metal



$$\rho = \rho_0 + AT^{\epsilon}$$

ϵ = 2

(Custers et al., Nature **424** (2003) 524)

Heavy Fermi liquids

$$\rho = \rho_0 + AT^2$$

$$C/T = \gamma$$

$$A \sim (m^*)^2$$

$$\gamma \sim m^*$$

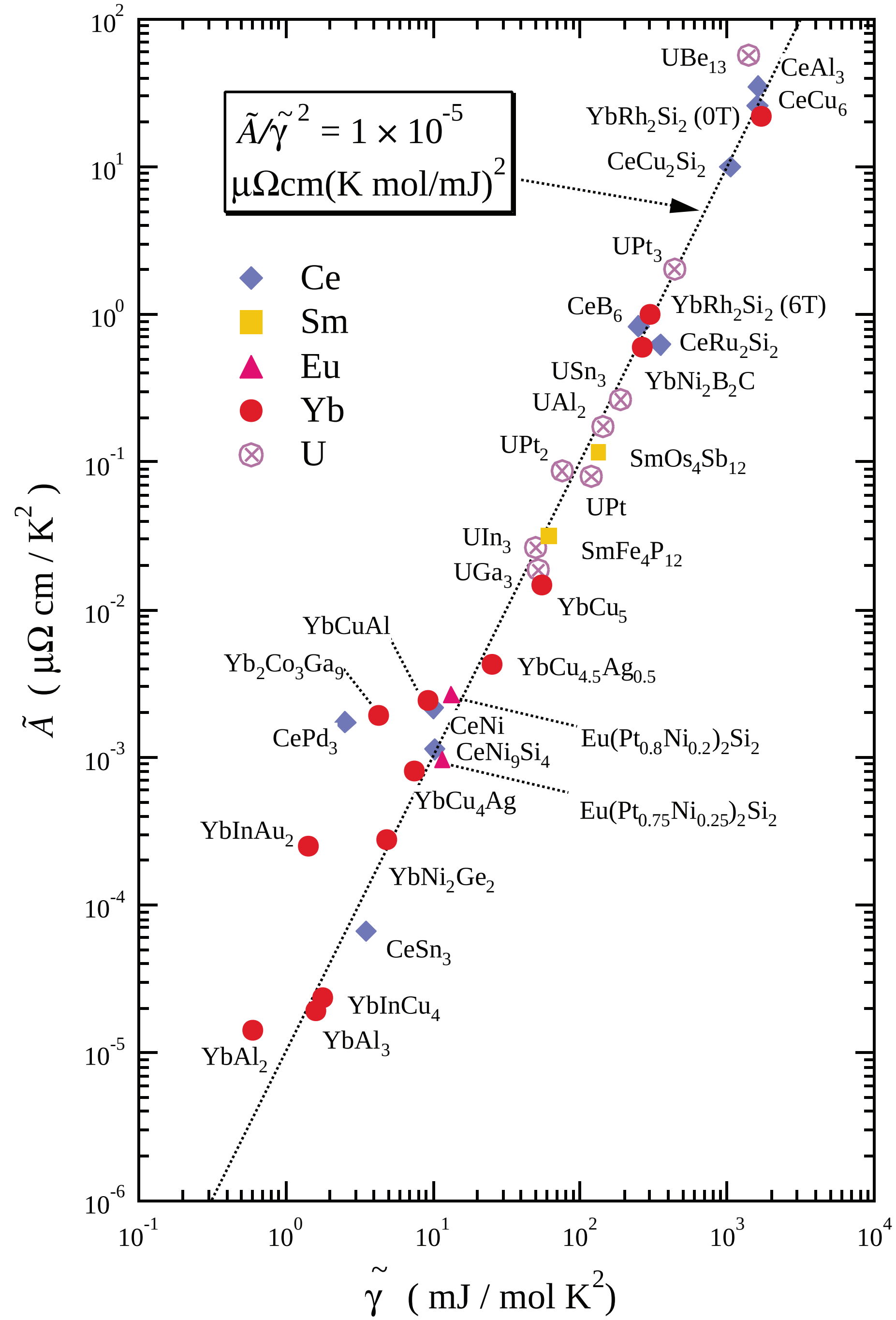
$$m^* = m(1 + \tfrac{1}{3}F_1^s)$$

With orbital degeneracy:

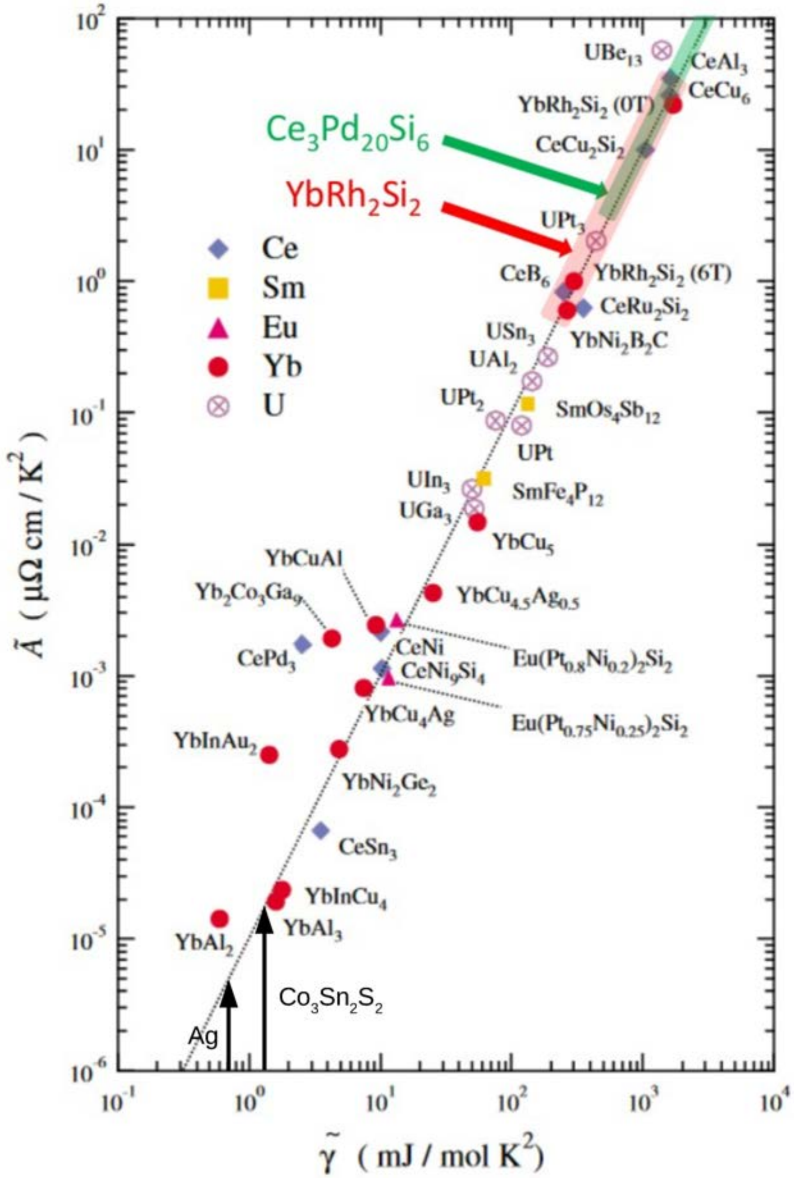
$$\tilde{A} = \frac{A}{\frac{1}{2}N(N-1)}$$

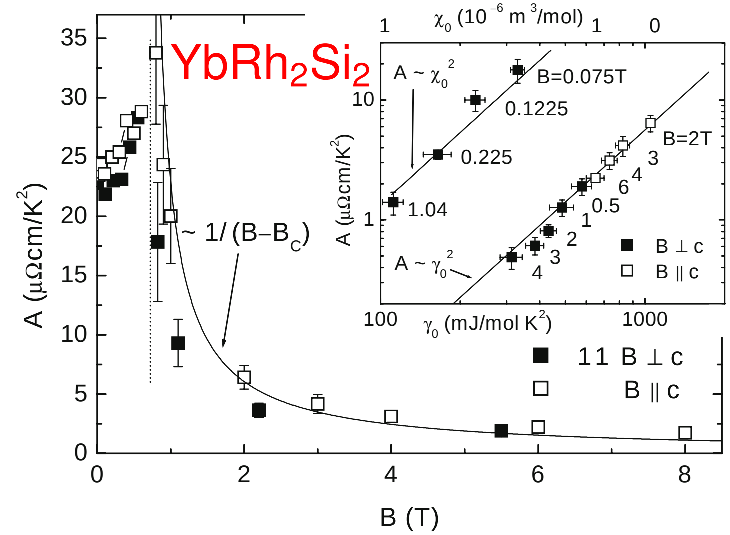
$$\tilde{\gamma} = \frac{\gamma}{\frac{1}{2}N(N-1)}$$

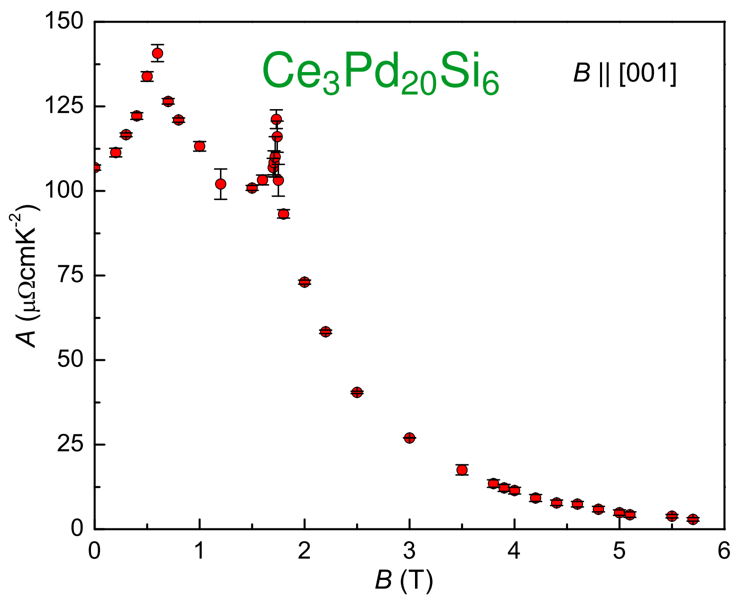
(Tsujii et al., Phys. Rev. Lett. 94 (2005) 057201) ⟶



Discontinuities appear upon tuning: FL parameters diverge

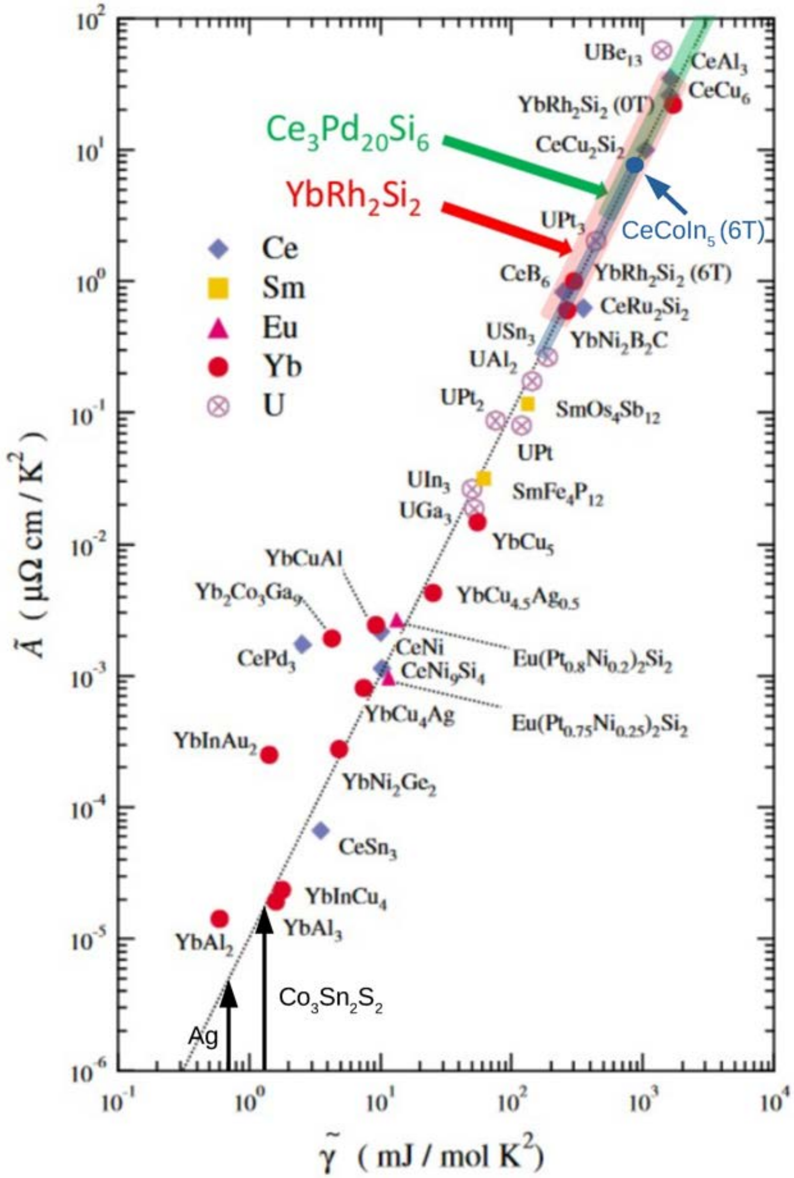


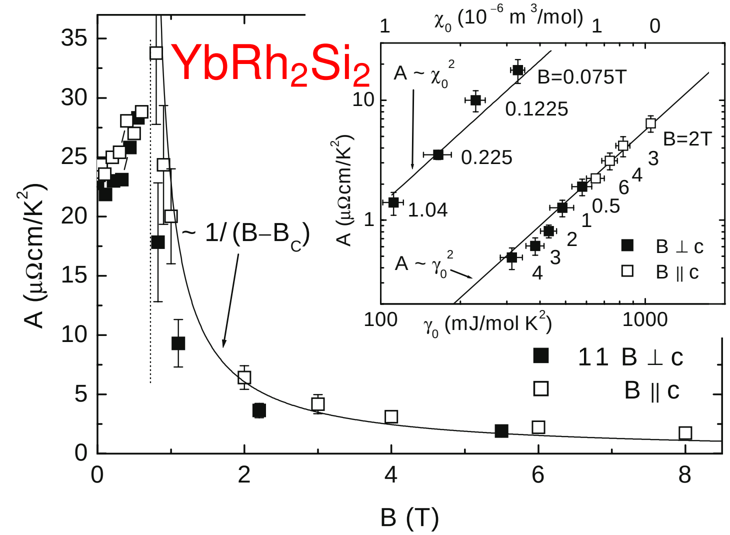


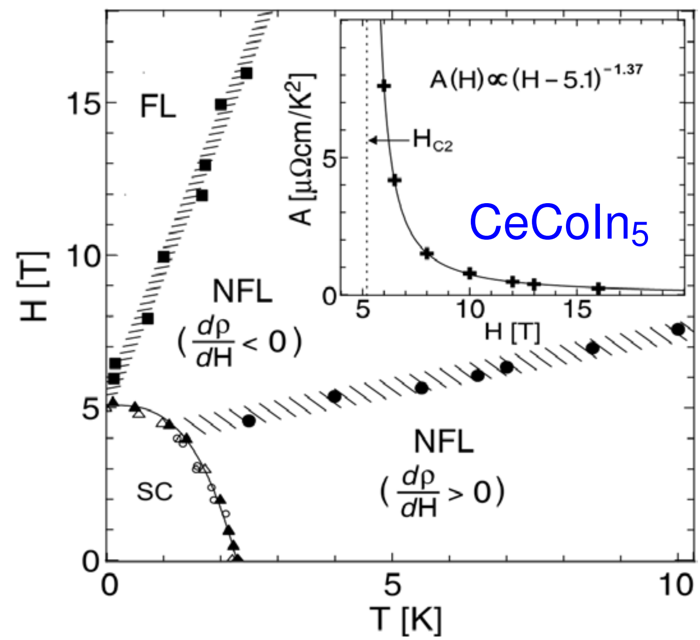


(SP & Si, Nat. Rev. Phys. 3 (2021) 9, and refs. therein)

Discontinuities appear upon tuning: FL parameters diverge

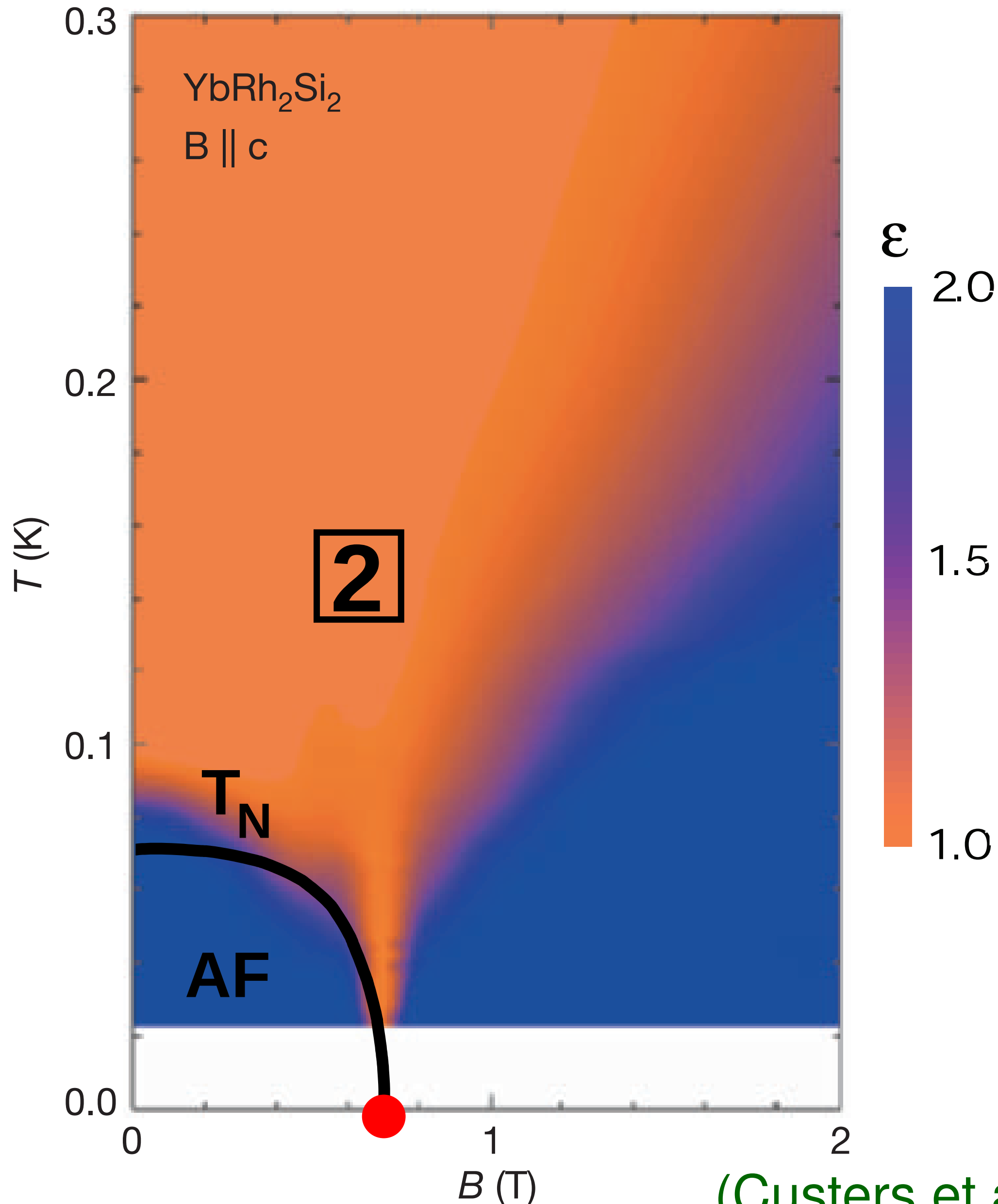






(Nat. Rev. Phys. 3 (2021) 9; Paglione et al., Phys. Rev. Lett. 24 (2003) 246405)

$YbRh_2Si_2$: A model quantum critical heavy fermion metal



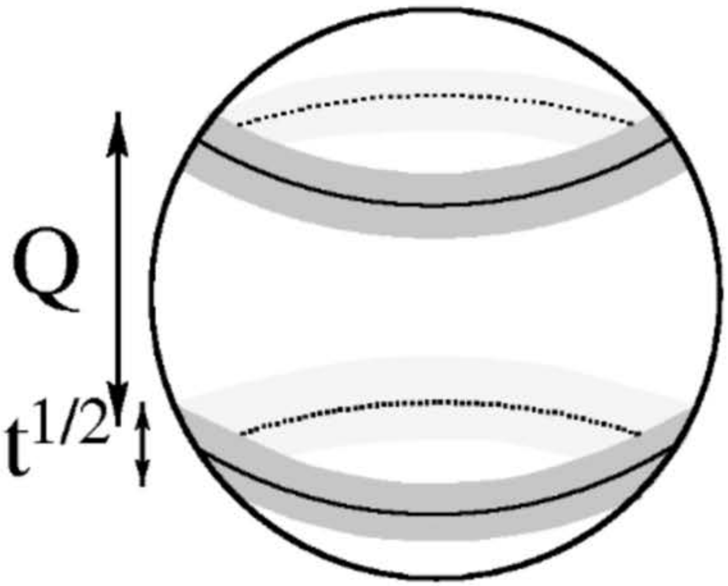
$$\rho = \rho_0 + AT^{\epsilon}$$

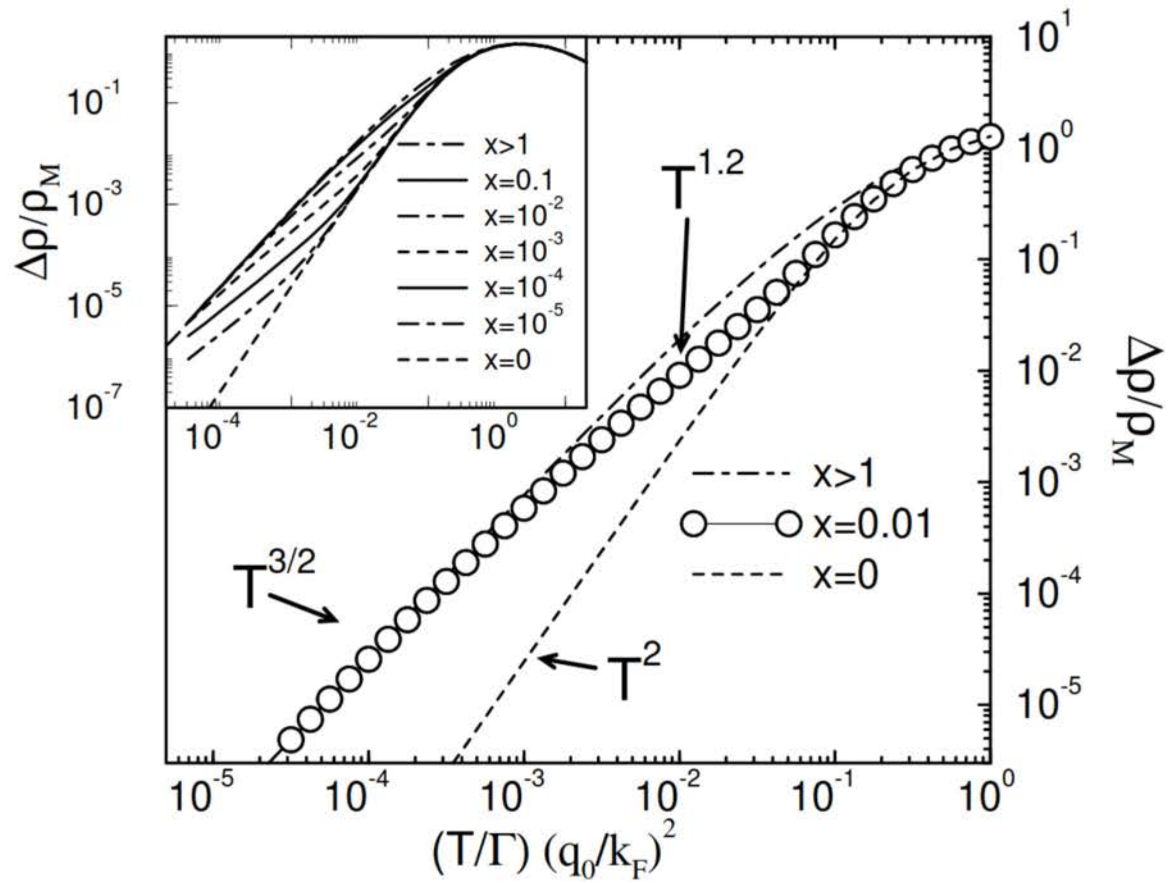
ϵ **= 1**

(Custers et al., Nature **424** (2003) 524)

"Normal" QCPs follow Ginzburg, Landau, Wilson paradigm

Predictions for electrical resistivity





No linear resistivity ***x*** **= 0**: clean limit ***x*** **> 1**: dirty limit

(Rosch, Phys. Rev. Lett. 82 (1999) 4280)

“Normal” QCPs follow Ginzburg, Landau, Wilson paradigm

Predictions for some thermodynamic properties

	$d=2$, $z=2$	$d=3$, $z=2$	$d=2$, $z=3$	$d=3$, $z=3$
$\alpha_{\rm cr} \sim$	$\ell n \ell n \frac{1}{T}$	$T^{1/2}$	$\ell n \frac{1}{T}$	$T^{1/3}$
$C_{\rm cr} \sim$	$T \ell n \frac{1}{T}$	$-T^{3/2}$	$T^{2/3}$	$T \ell n \frac{1}{T}$
$\Gamma_{r,{\rm cr}} \sim$	$\frac{\ell n \ell n \frac{1}{T}}{T \ell n \frac{1}{T}}$	$-T^{-1}$	$T^{-2/3} \ell n \frac{1}{T}$	$\left(T^{2/3} \ell n \frac{1}{T}\right)^{-1}$

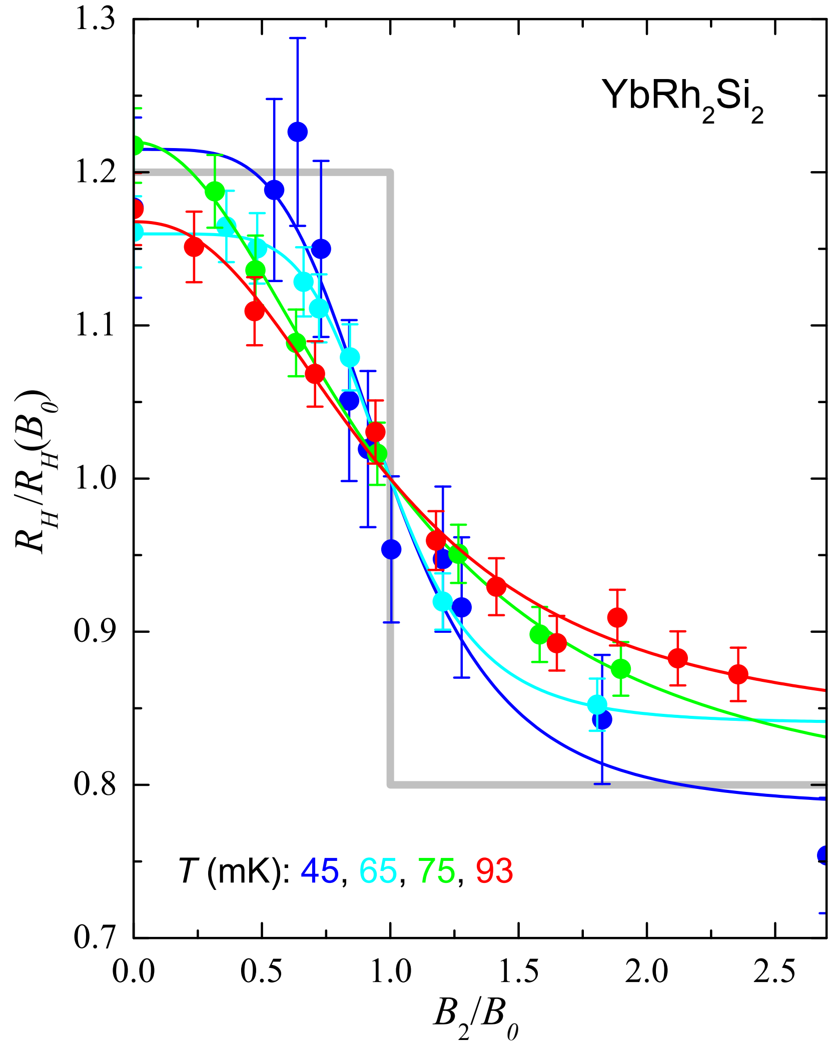
d: dimension, z = 2: AFM metal, z = 3: FM metal

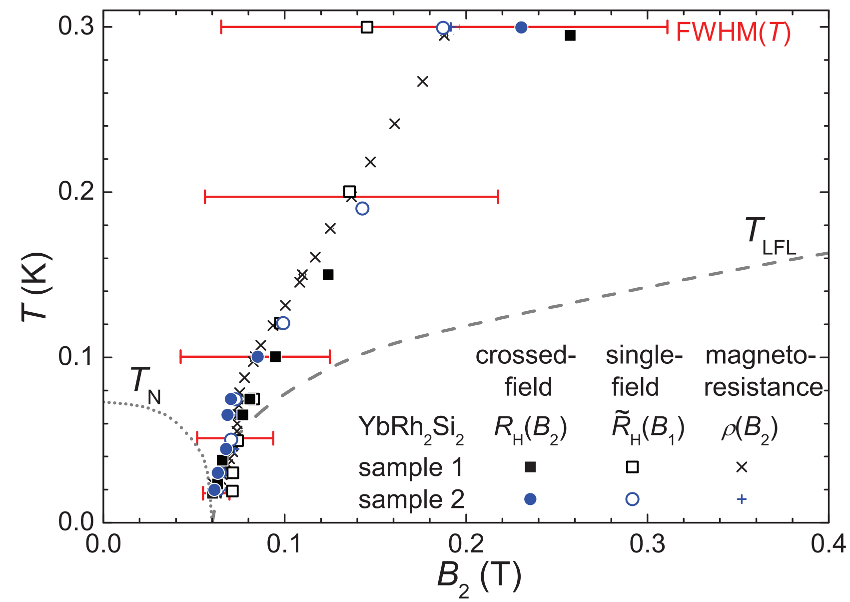
α: thermal expansion, *C*: specific heat, Γ = α/C: Grüneisen ratio

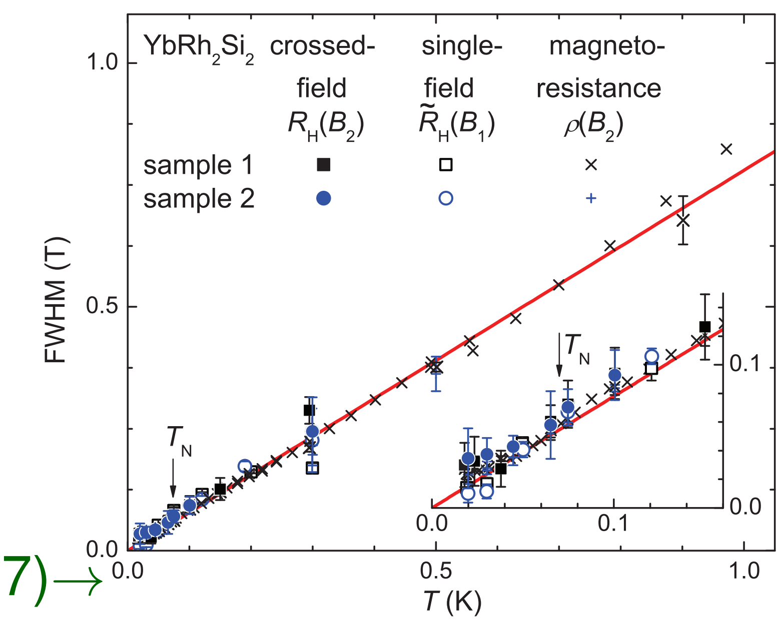
No hyperscaling above the upper critical dimension

(v. Löhneysen et al., Rev. Mod. Phys. 79 (2007) 1015; Hertz & Millis)

Evolution of Hall effect across the QCP: $YbRh_2Si_2$



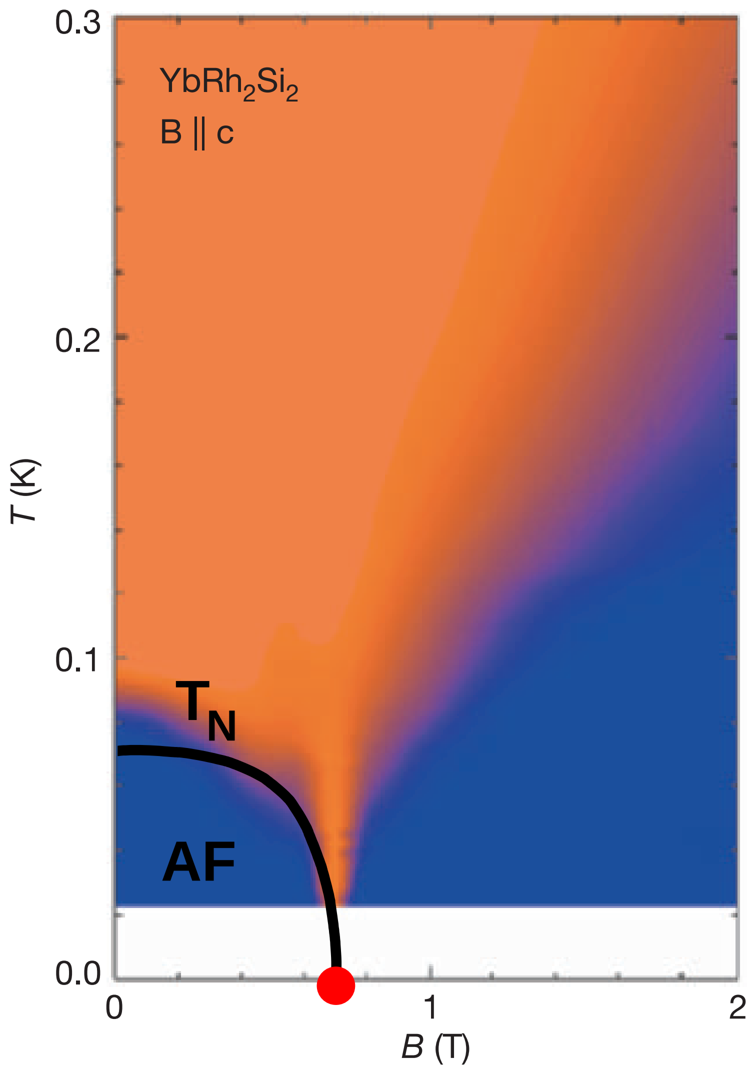


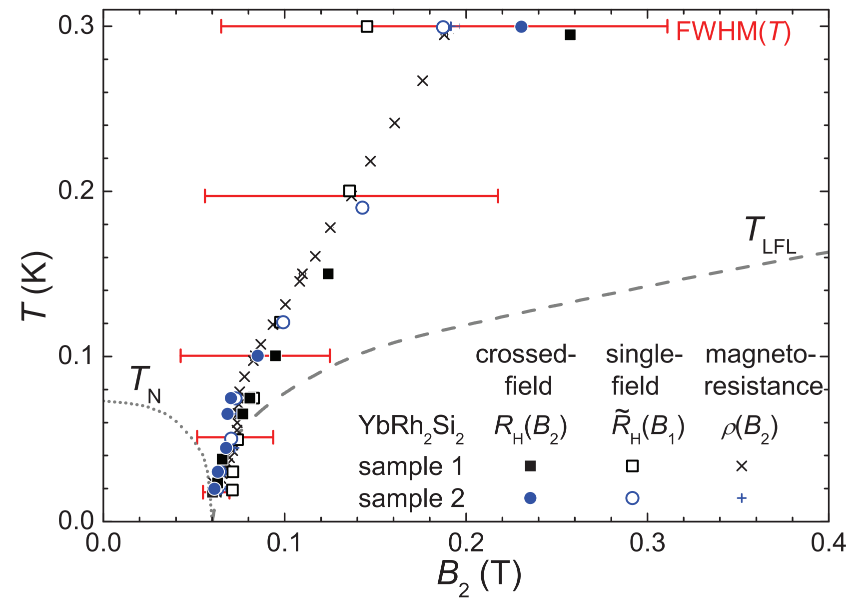


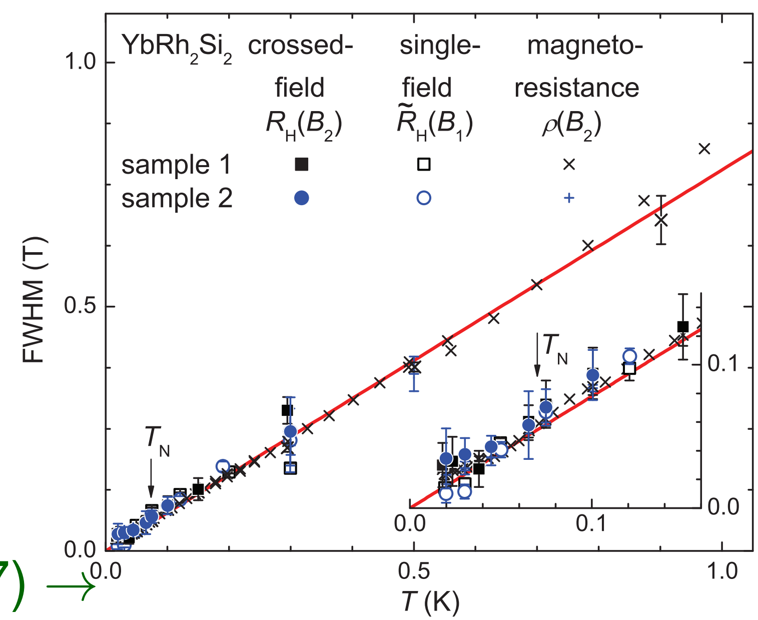
(SP et al., Nature 432 (2004) 881) ↑

(Friedemann et al., PNAS 107 (2010) 14547)→

Relation of Hall crossover and NFL behavior in $\rho(T)$



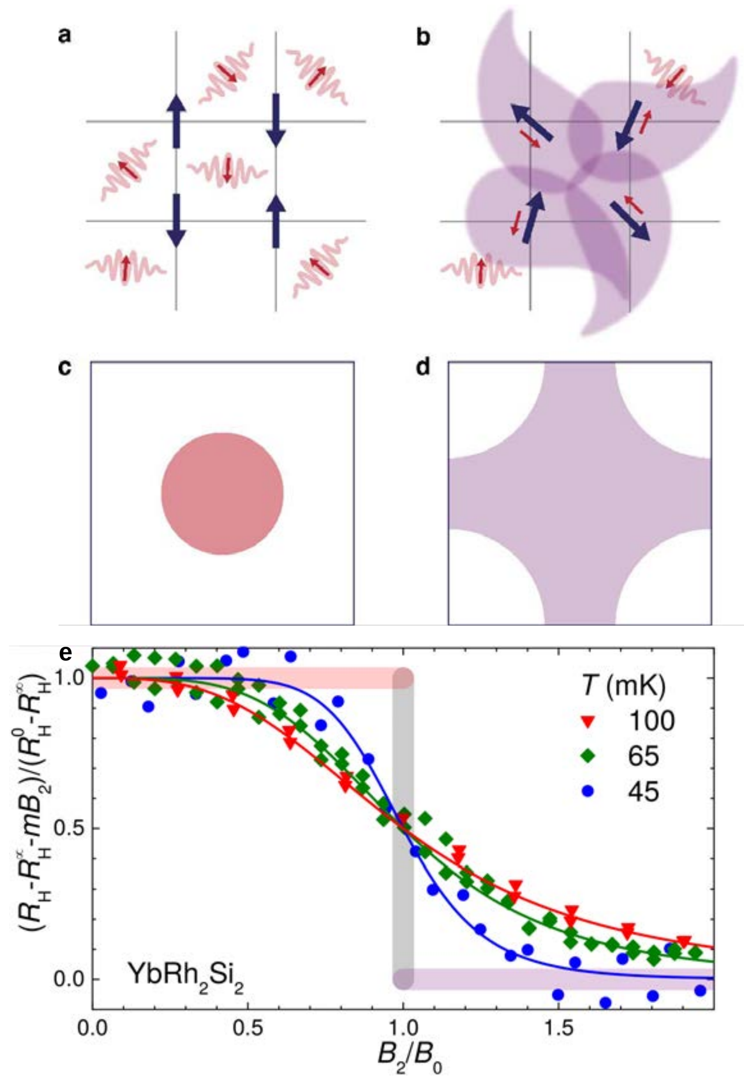


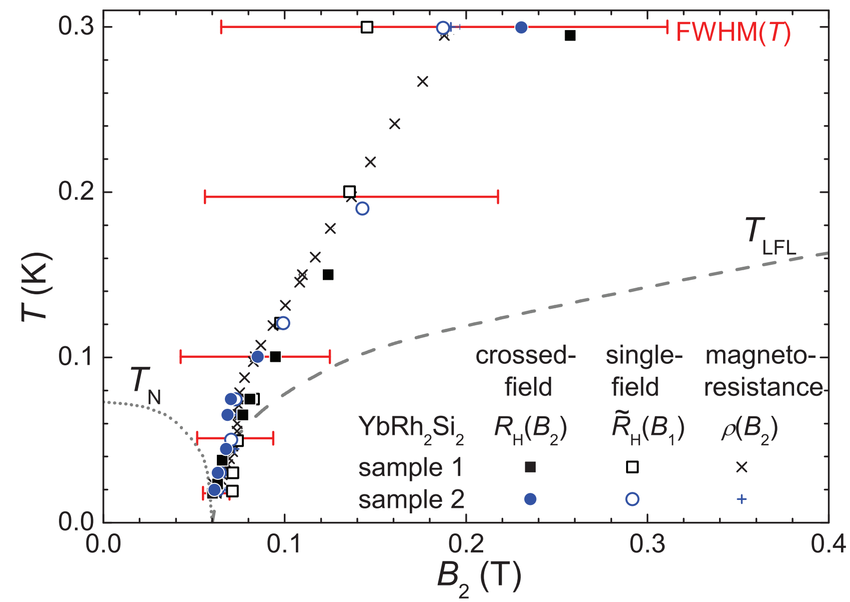


(Custers et al., Nature 424 (2003) 524) ↑

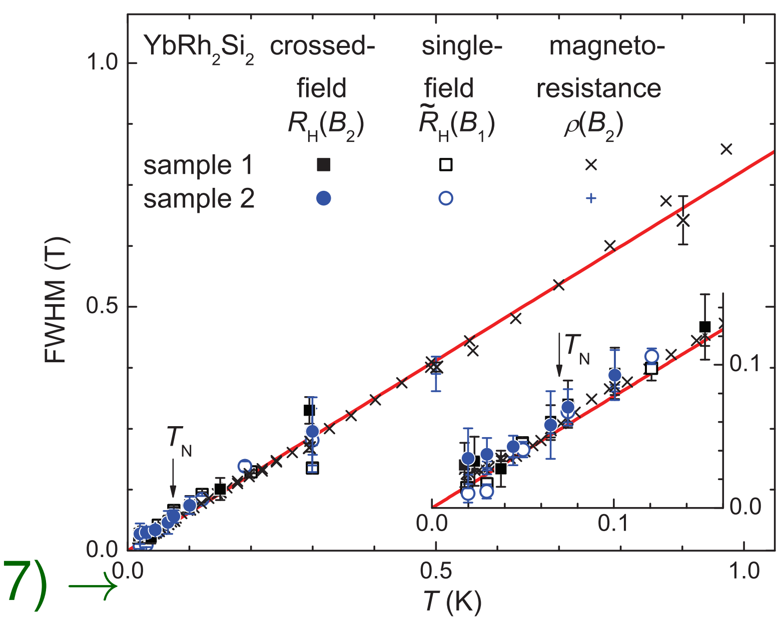
(Friedemann et al., PNAS **107** (2010) 14547) →

Kondo destruction QCP scenario



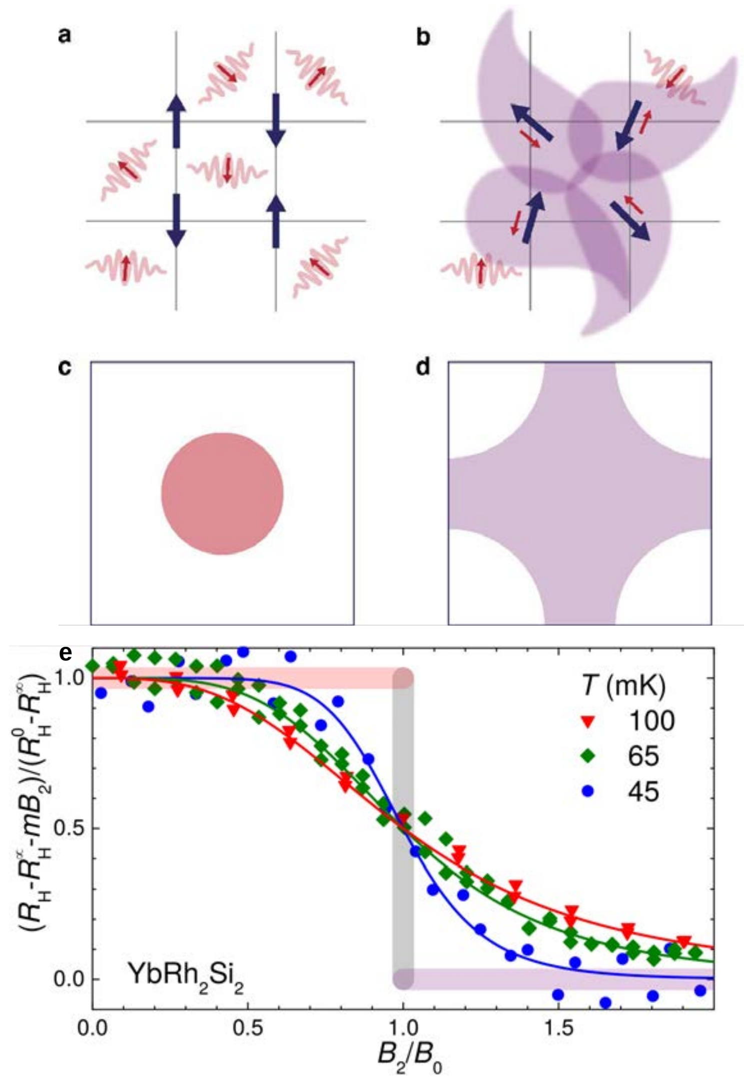


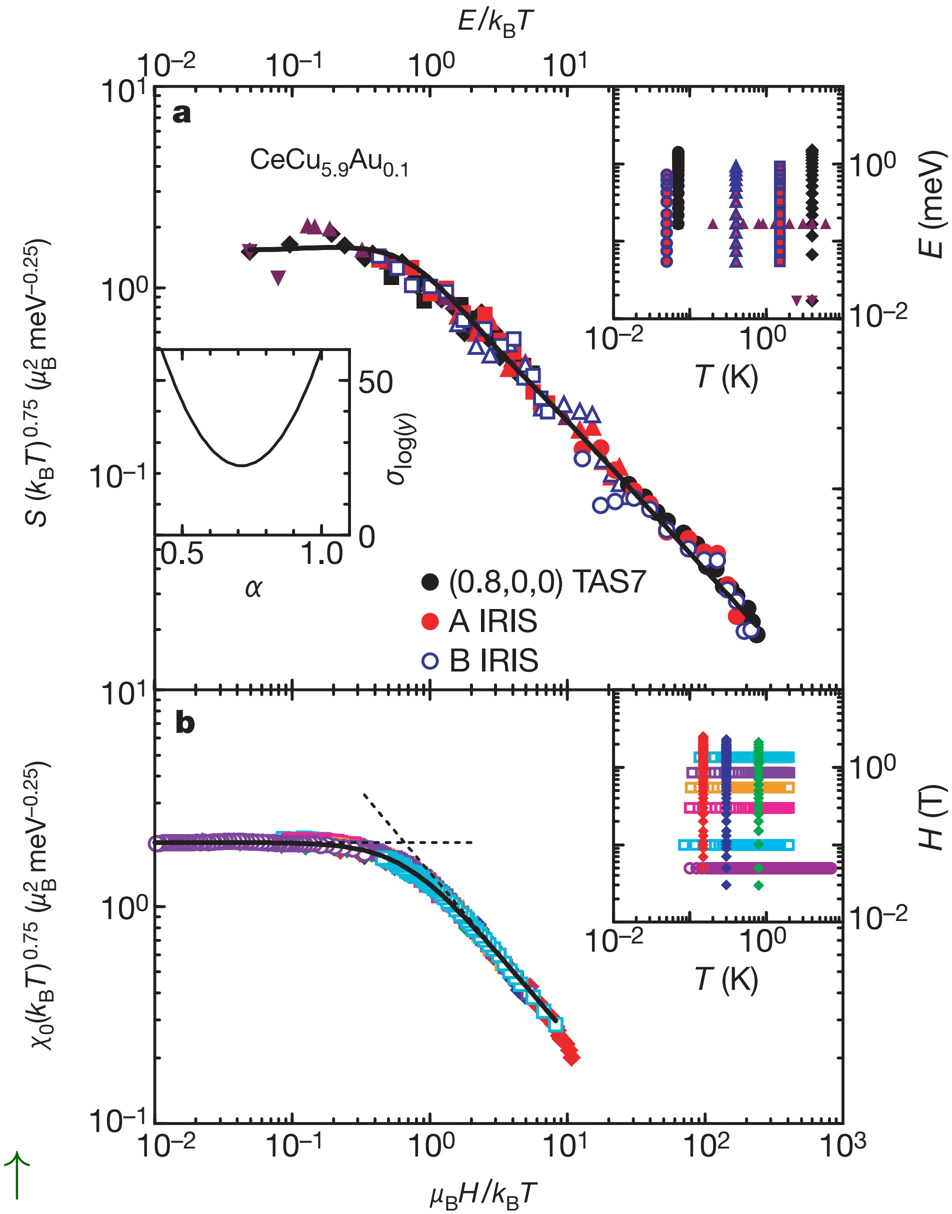
(SP & Si, Nat. Rev. Phys. 3 (2021) 9) ↑



(Friedemann et al., PNAS **107** (2010) 14547) →

Kondo destruction QCP scenario

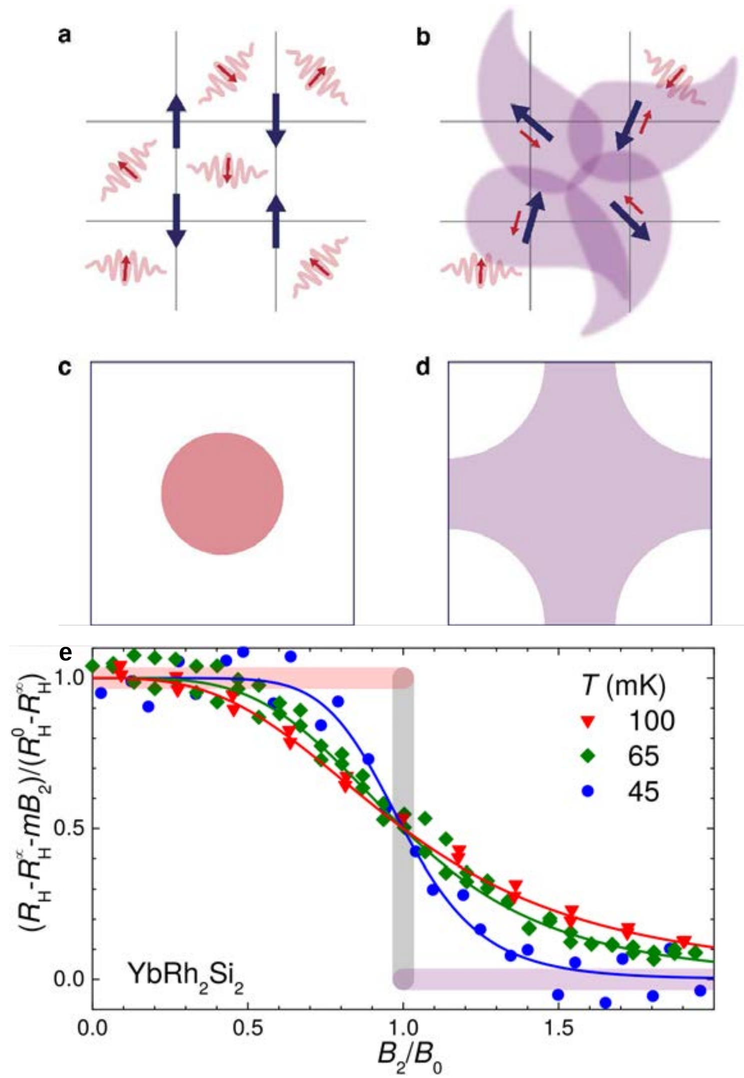


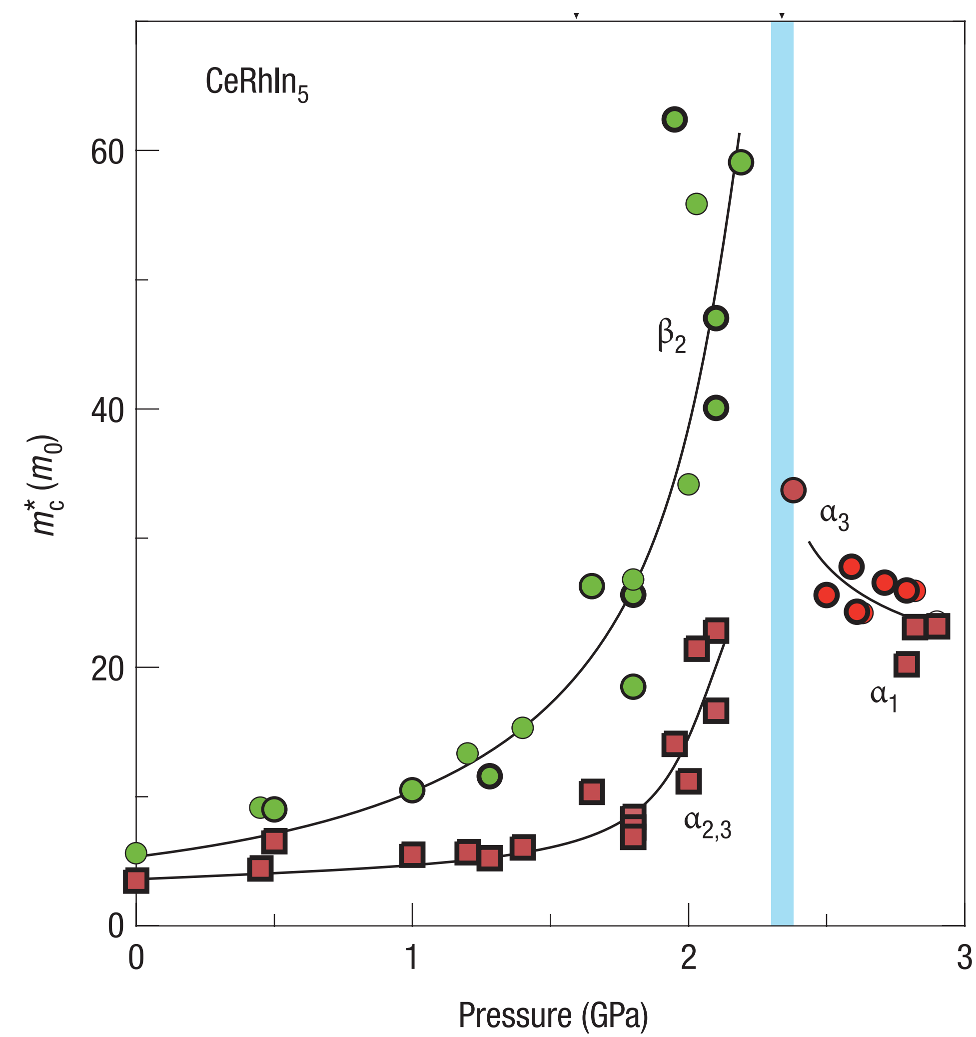


(SP & Si, Nat. Rev. Phys. 3 (2021) 9) ↑

(Coleman et al., JPCM 13 (2001) R723; Schröder et al., Nature 407 (2000) 351)

Kondo destruction QCP scenario



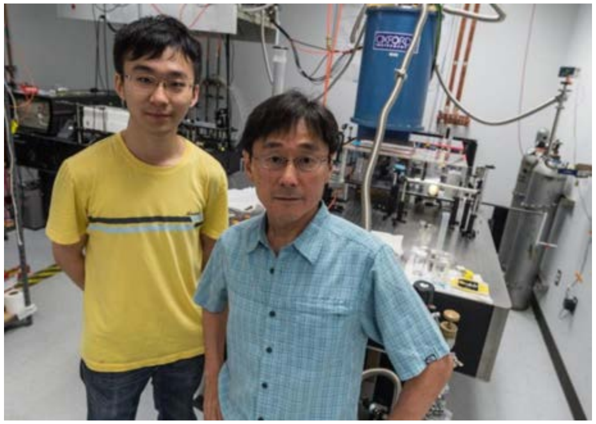


(SP & Si, Nat. Rev. Phys. 3 (2021) 9) ↑

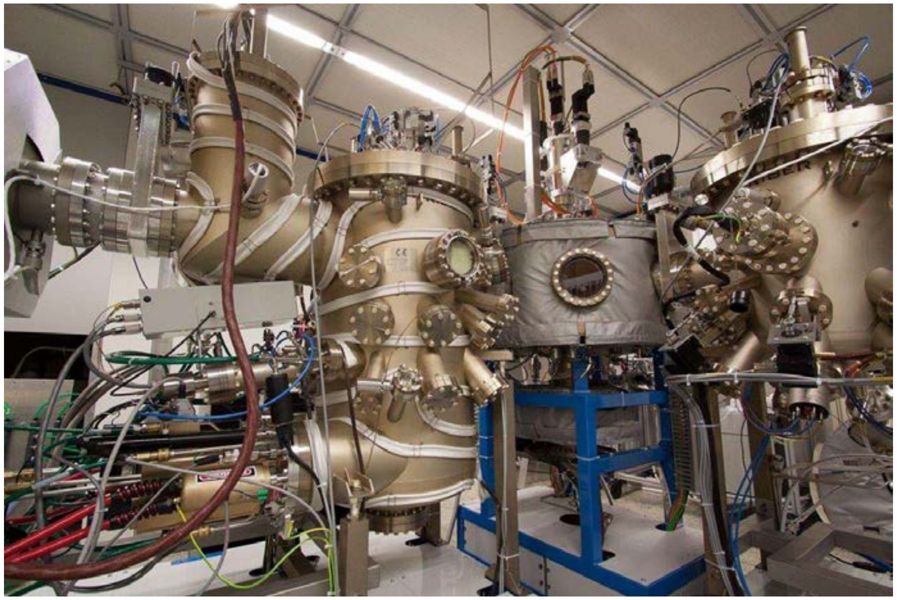
(Coleman et al., JPCM 13 (2001) R723; Shishido et al, JPSJ 74 (2005) 1103)

Dynamical response: THz time-domain transmission spectroscopy

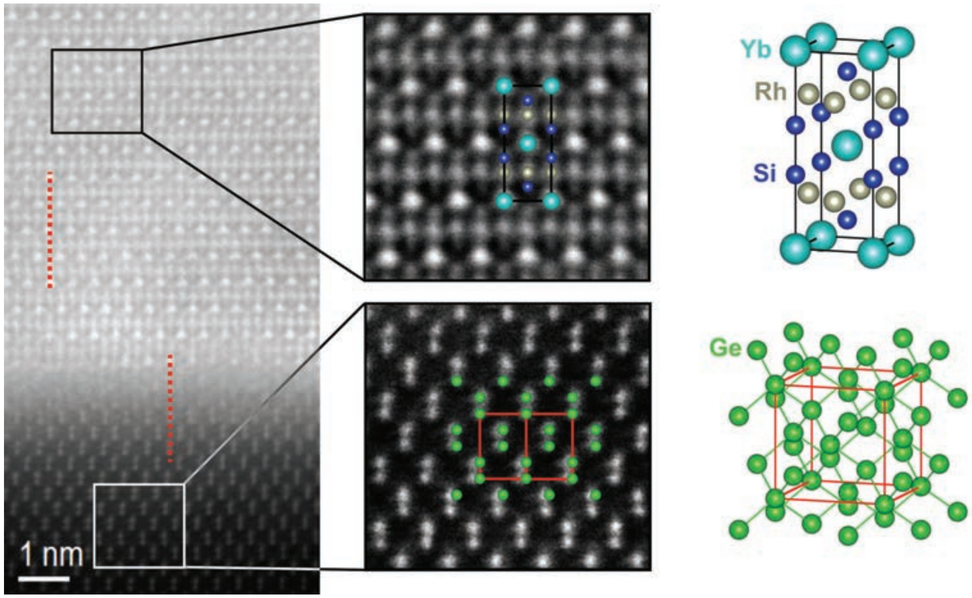
- Real and imag. part of $\sigma(\omega)$
- No Kramers-Kronig transformation
- Thin films needed!



Molecular beam epitaxy system



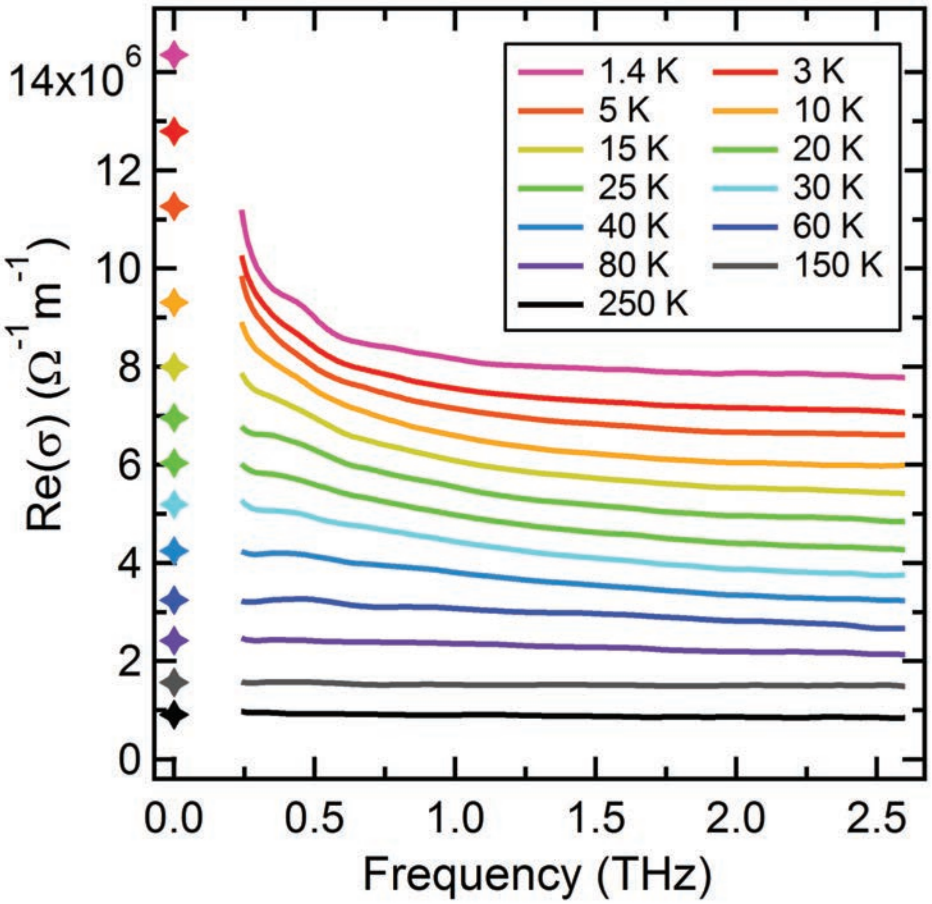
HAADF-STEM image

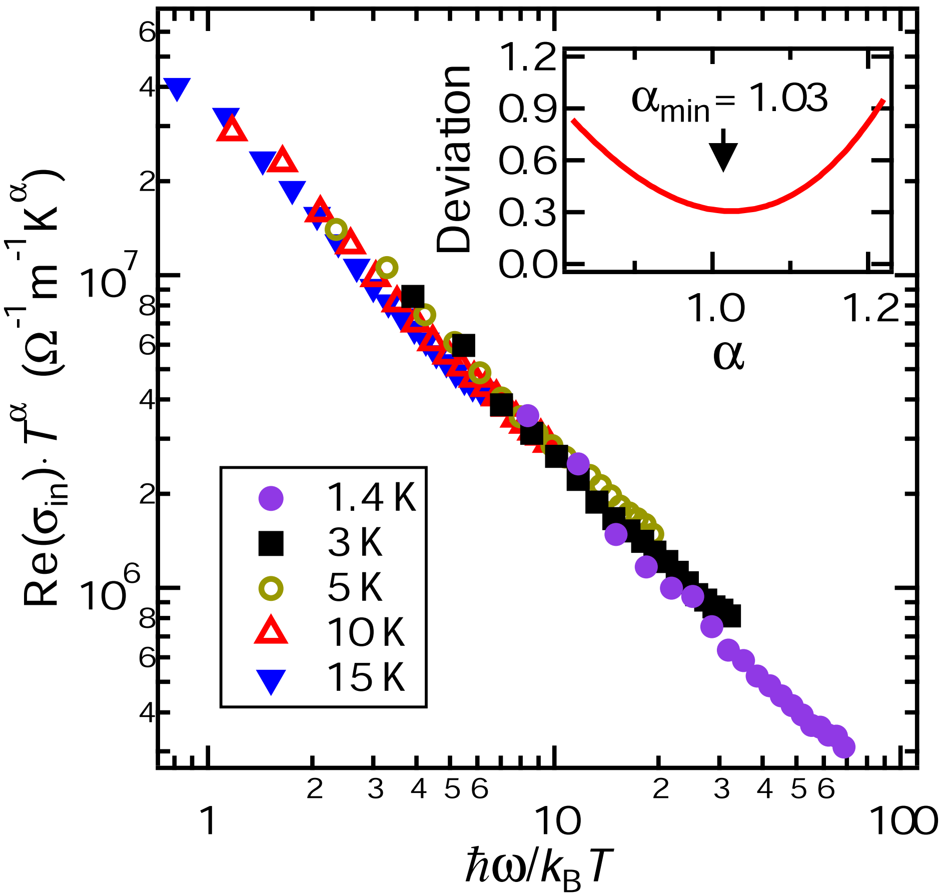


(Prochaska et al., Science 367 (2020) 285)

Dynamical scaling in quantum critical $YbRh_2Si_2$

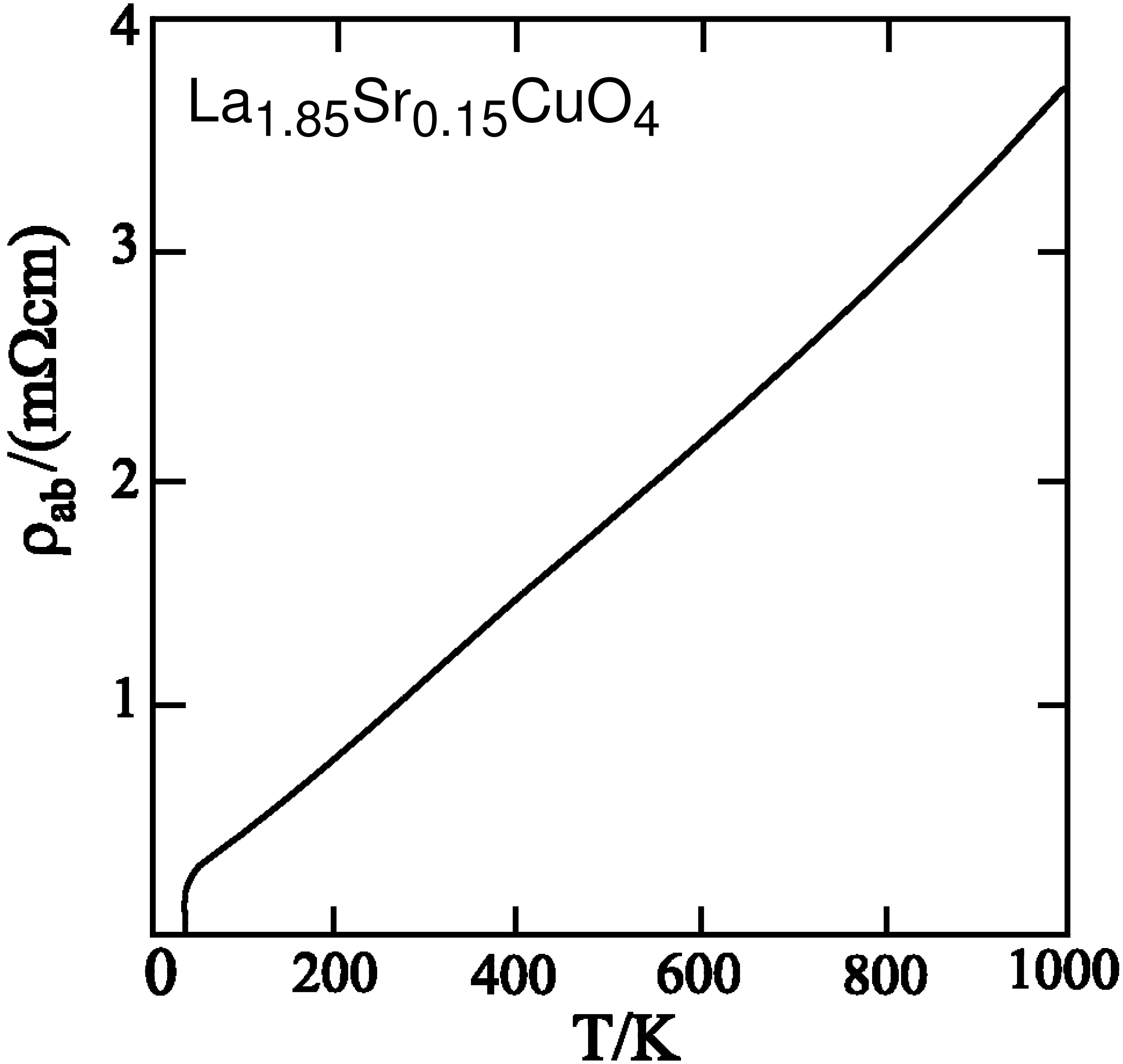
THz time-domain transmission spectroscopy on MBE films of $YbRh_2Si_2$





(Prochaska et al., Science 367 (2020) 285)

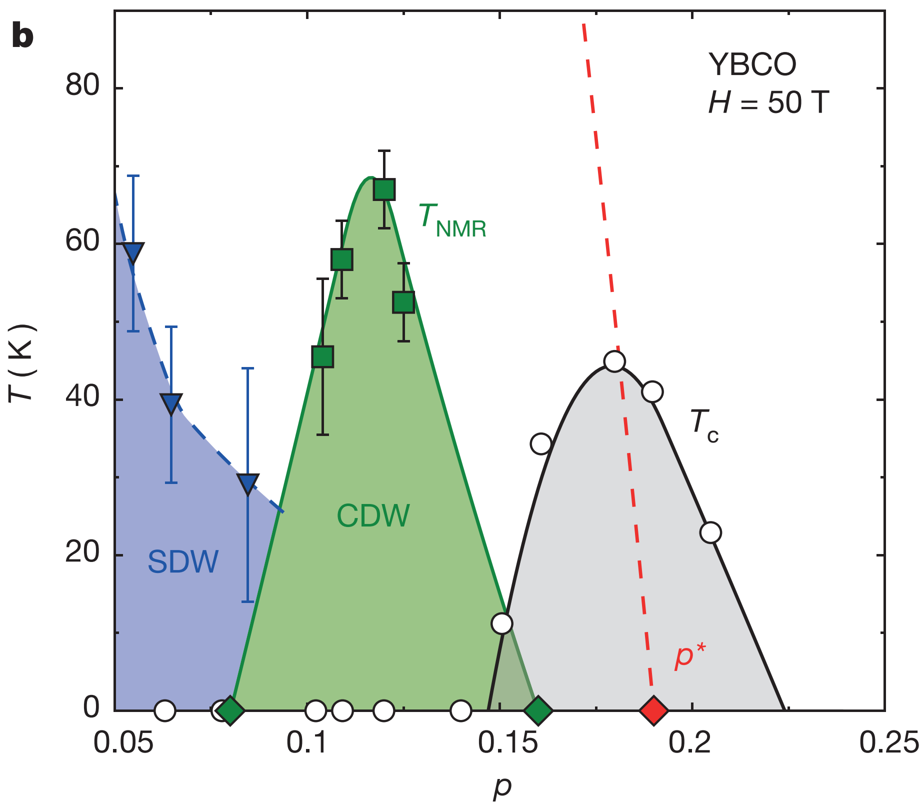
Relation to the high-T_c cuprates: Strange metal behavior



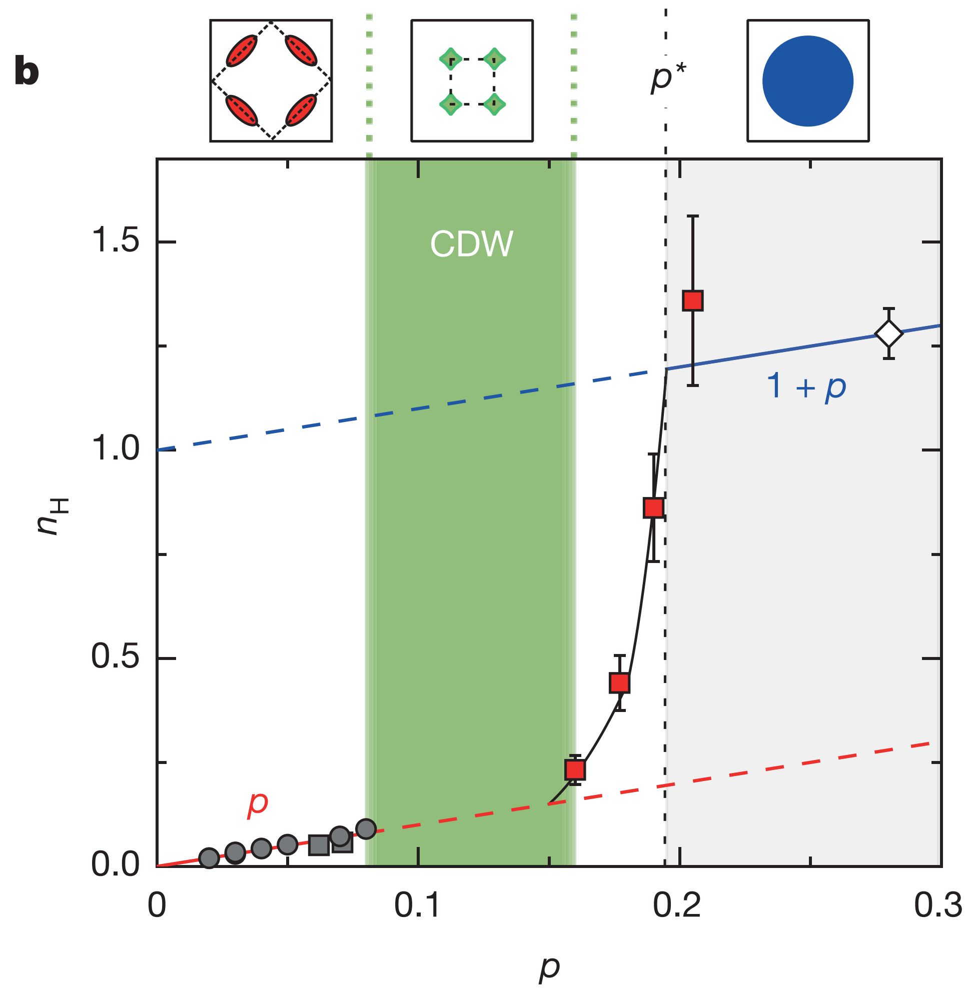
(Takagi et al., Phys. Rev. Lett. 69 (1992) 2975)

Relation to the high-T_c cuprates: Carrier (de)localization

Phase diagram at 50 T



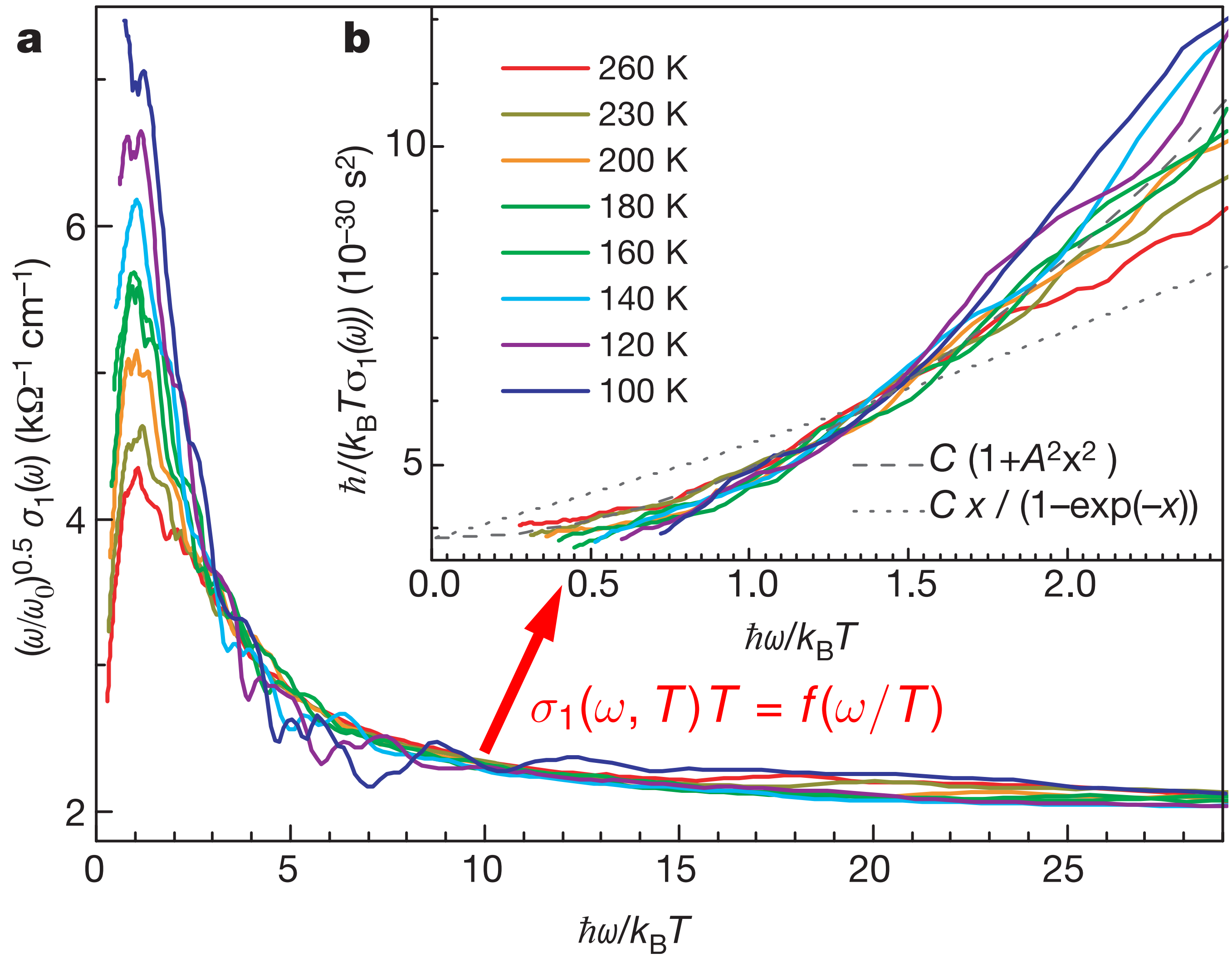
Change of carrier concentration

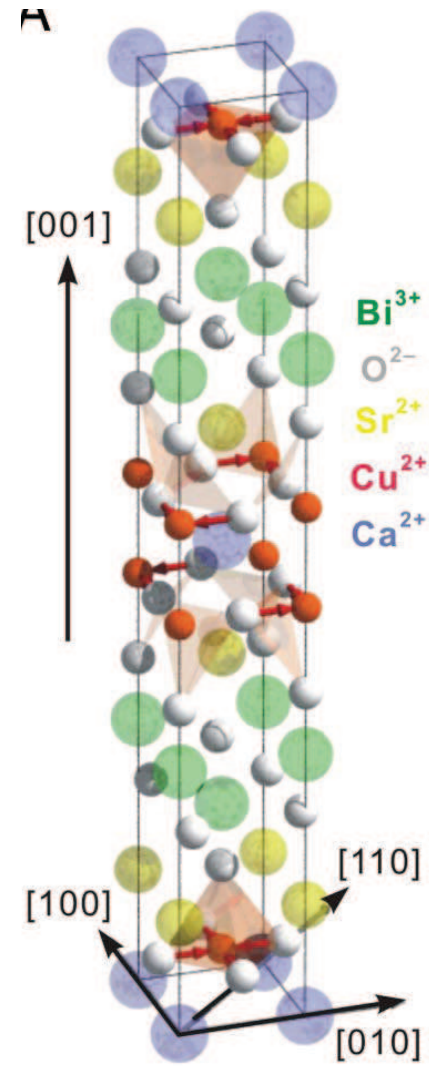


(Badoux et al., Nature 531 (2016) 210)

Relation to the high-T_C cuprates: Dynamical scaling in $\sigma(\omega)$

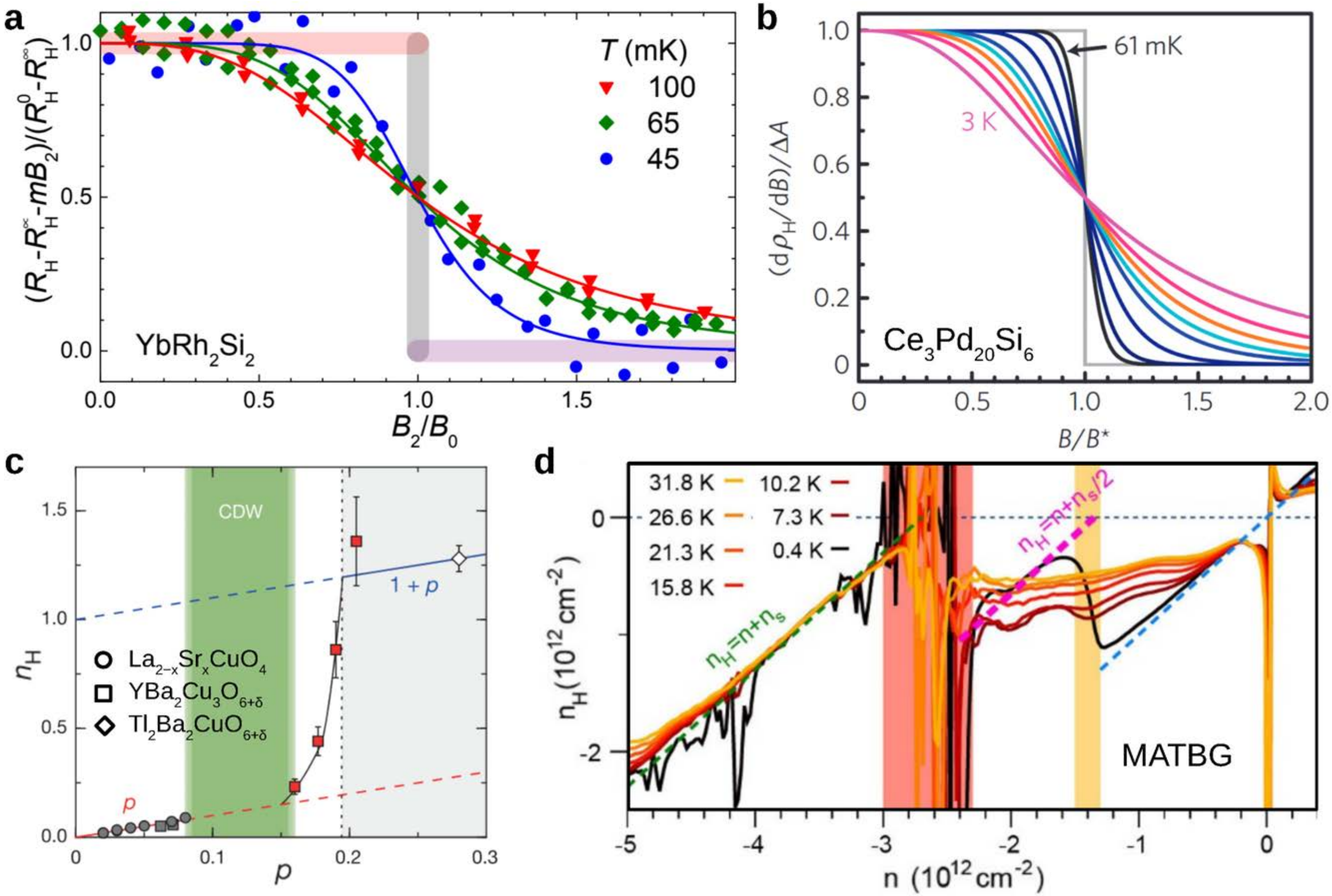
Optical conductivity of optimally doped $Bi_{2.23}Sr_{1.9}Ca_{0.96}Cu_2O_{8+\delta}$





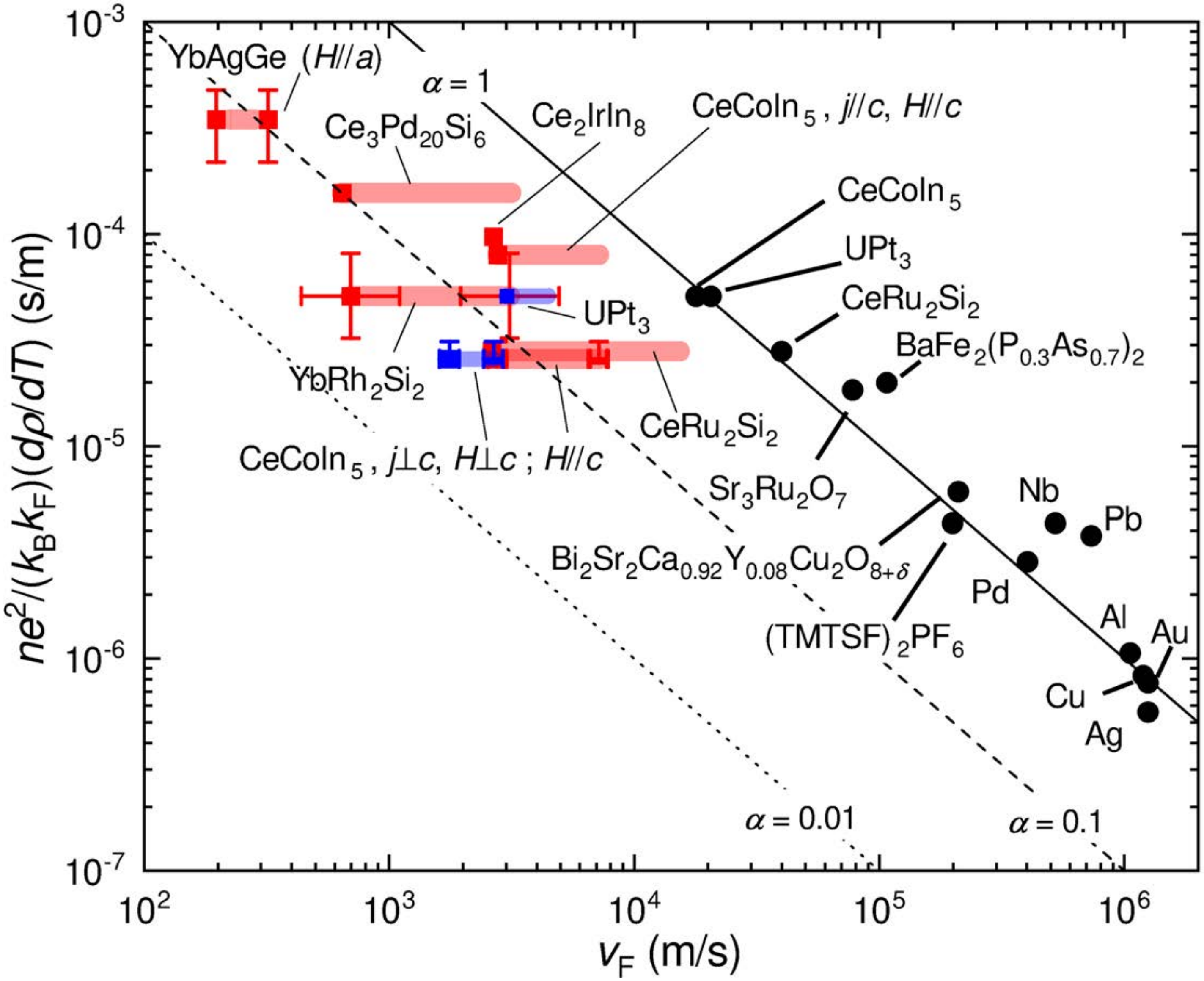
(van der Marel et al., Nature 425 (2003) 271) (Carbone et al., PNAS 2008)↑

Carrier (de)localization in other SCES?



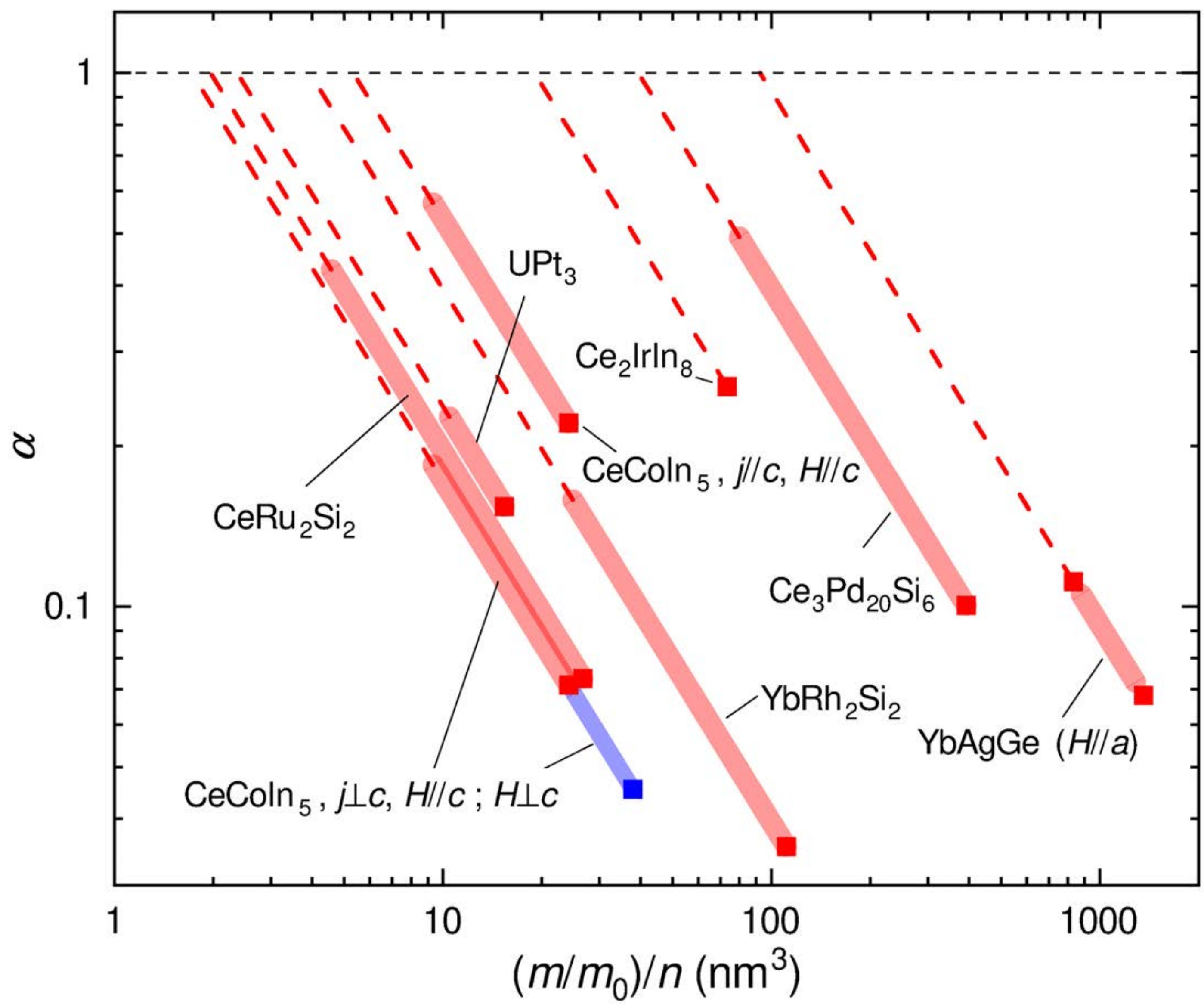
(Taupin & SP, Crystals 12 (2022) 251)

Planckian dissipation in electrical transport?



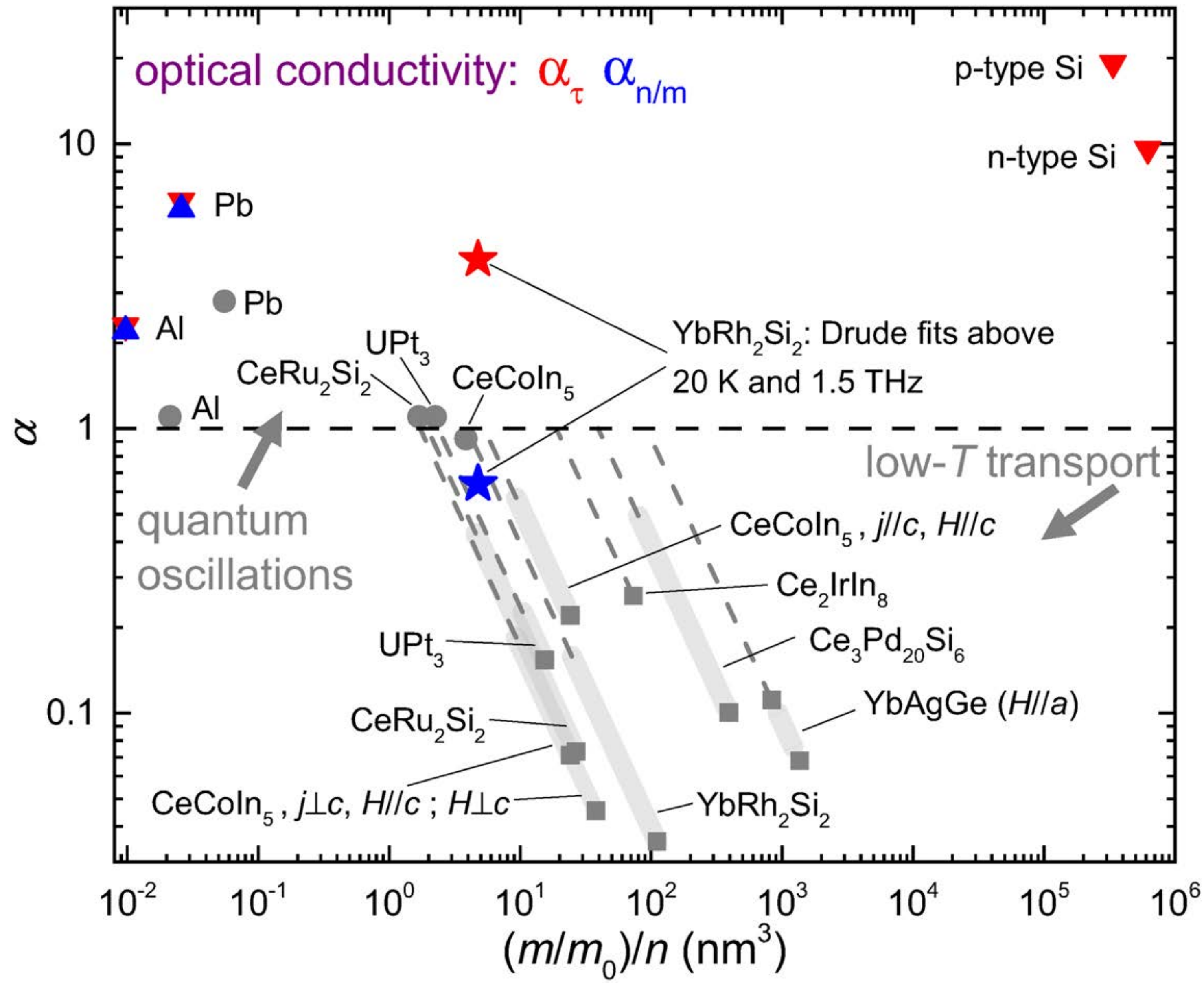
(Taupin & SP, Crystals 12 (2022) 251)

Planckian dissipation in electrical transport?



(Taupin & SP, Crystals 12 (2022) 251)

Planckian dissipation in optical conductivity?

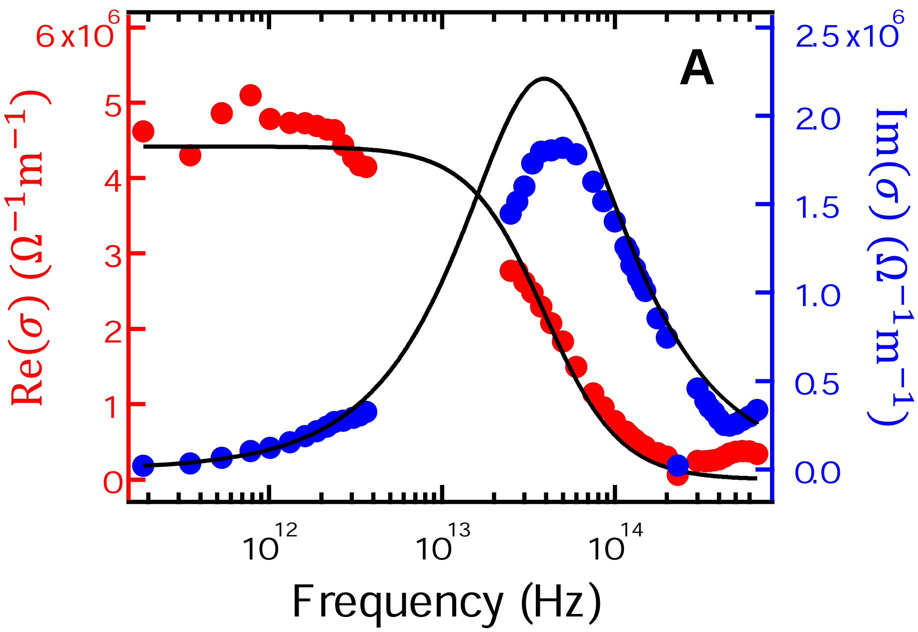


(Li, Kono, Si & SP, arXiv:2205.13382)

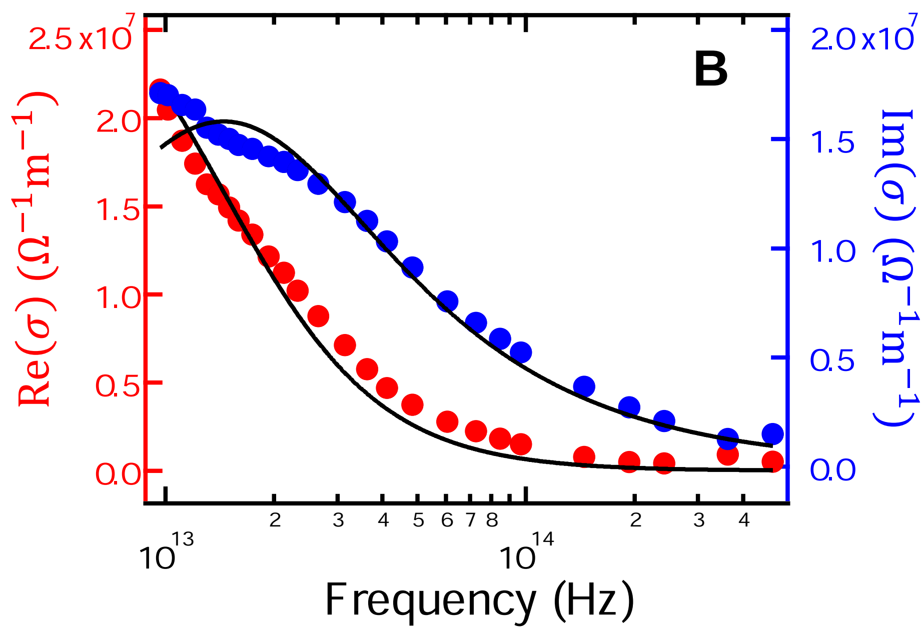
Planckian dissipation in optical conductivity?

$$\mathrm{Re}[\sigma(\omega)] = \sigma_1 = \frac{ne^2\tau}{m}\frac{1}{1+\omega^2\tau^2} \qquad \mathrm{Im}[\sigma(\omega)] = \sigma_2 = \frac{ne^2\tau}{m}\frac{\omega\tau}{1+\omega^2\tau^2}$$

Pb at room temperature



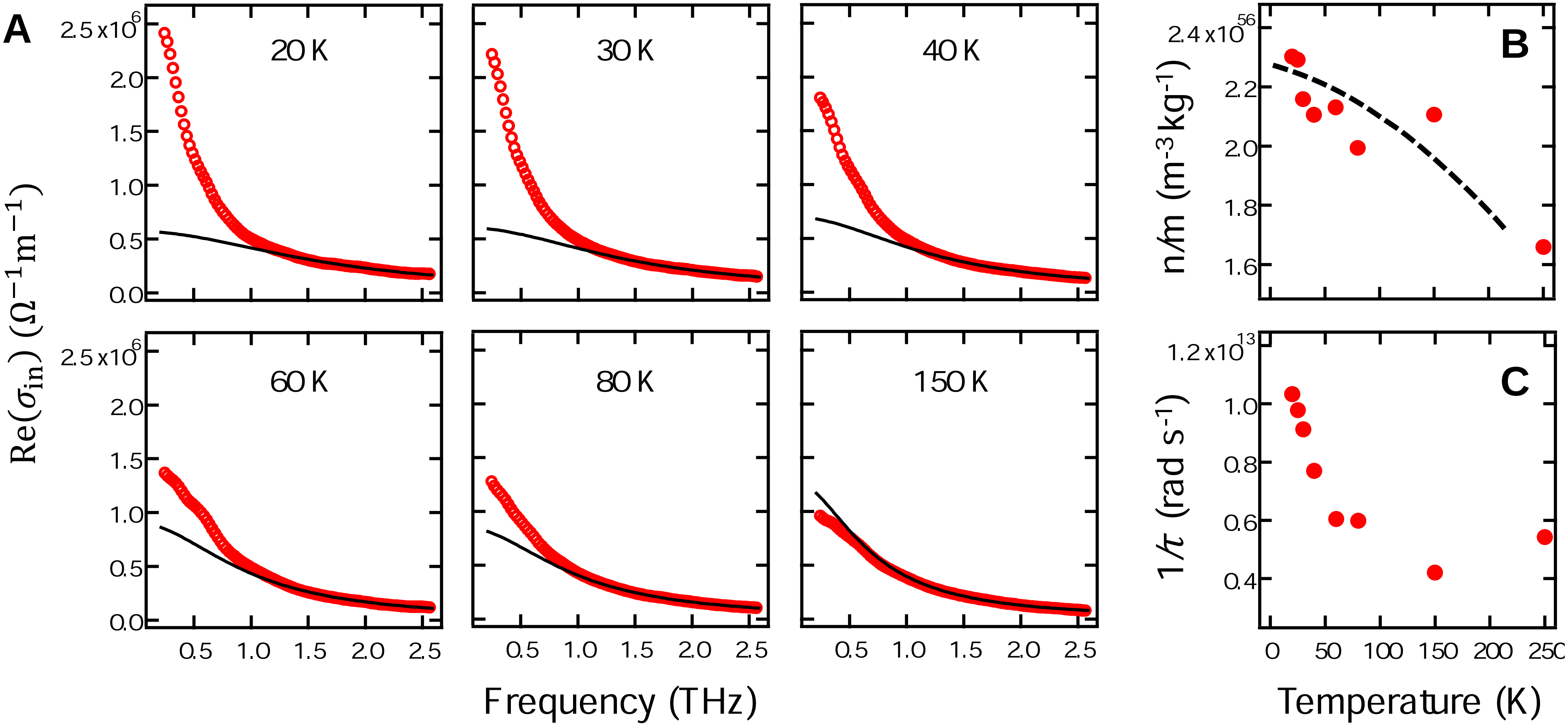
Al at room temperature



(Li, Kono, Si & SP, arXiv:2205.13382)

Planckian dissipation in optical conductivity?

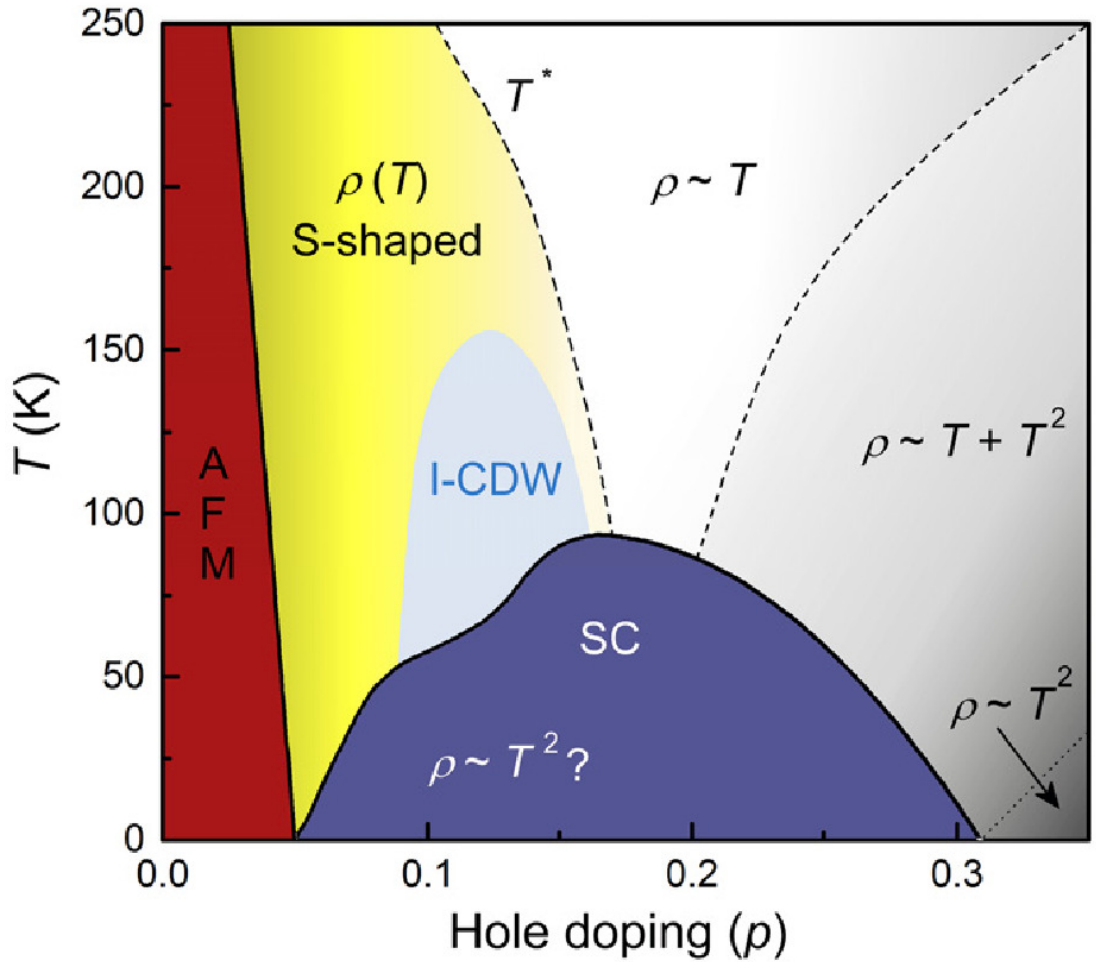
$YbRh_2Si_2$: highly non-Drude behavior in strange metal regime



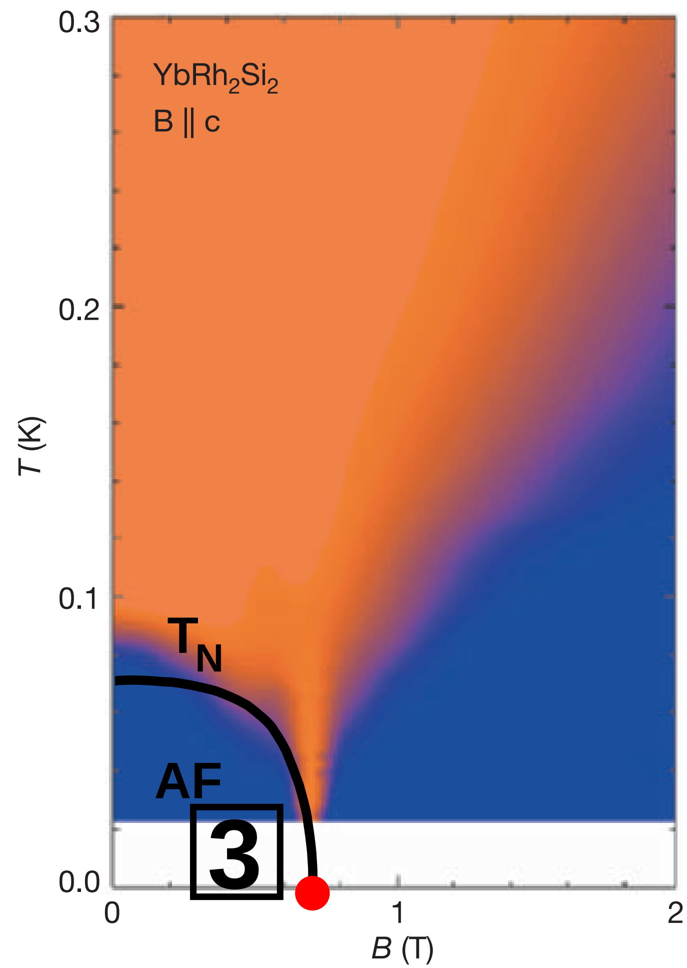
(Li, Kono, Si & SP, arXiv:2205.13382)

Is there superconductivity at the QCP of $YbRh_2Si_2$?

Generic phase diagram of the cuprates

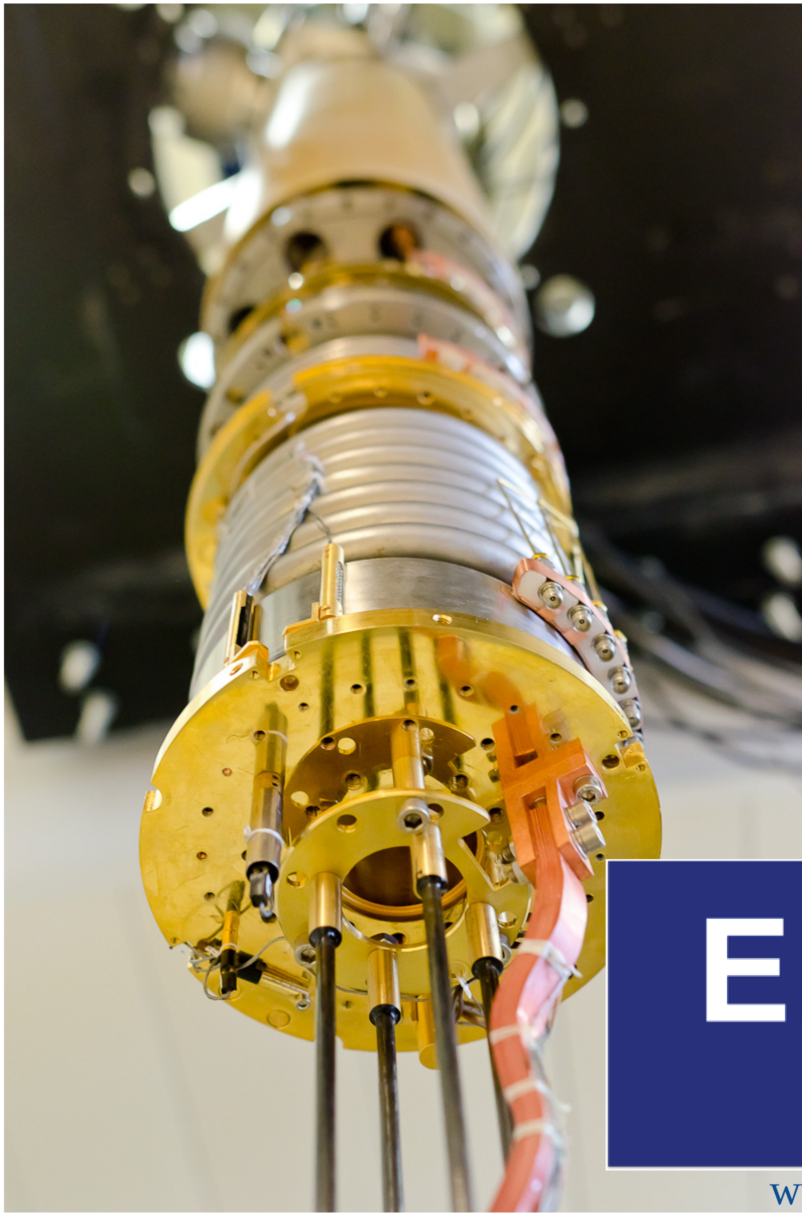


Phase diagram of $YbRh_2Si_2$



(Proust et al., PNAS 113 (2016) 13654) (Custers et al., Nature 424 (2003) 524)

The Vienna Microkelvin Laboratory



EMP

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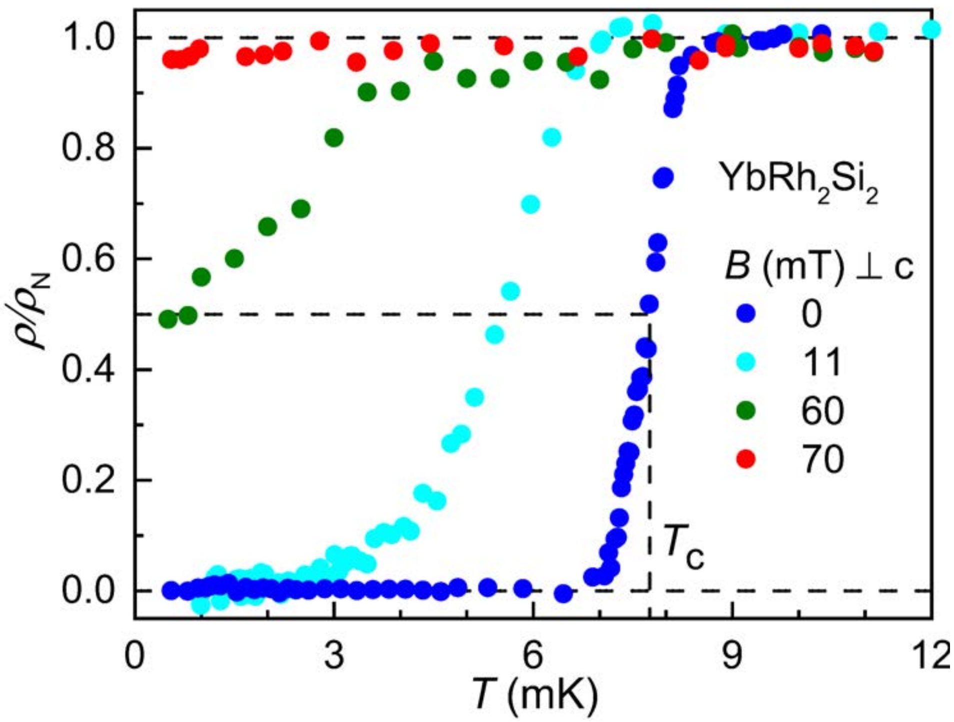
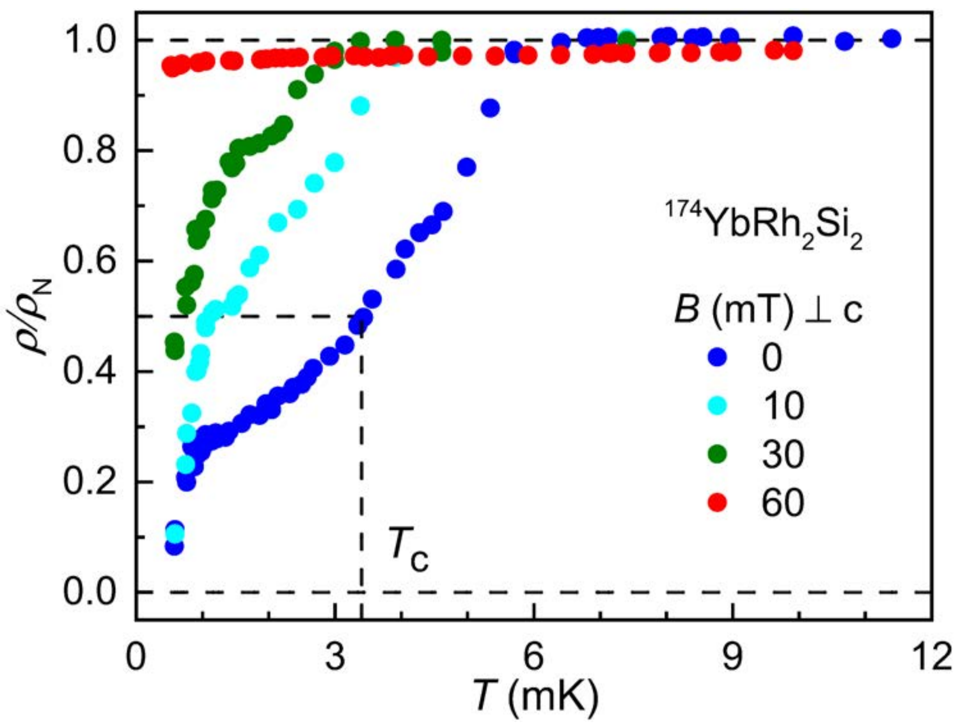
Electrical resistivity at ultralow temperatures: Iso-*B* curves

$YbRh_2Si_2$



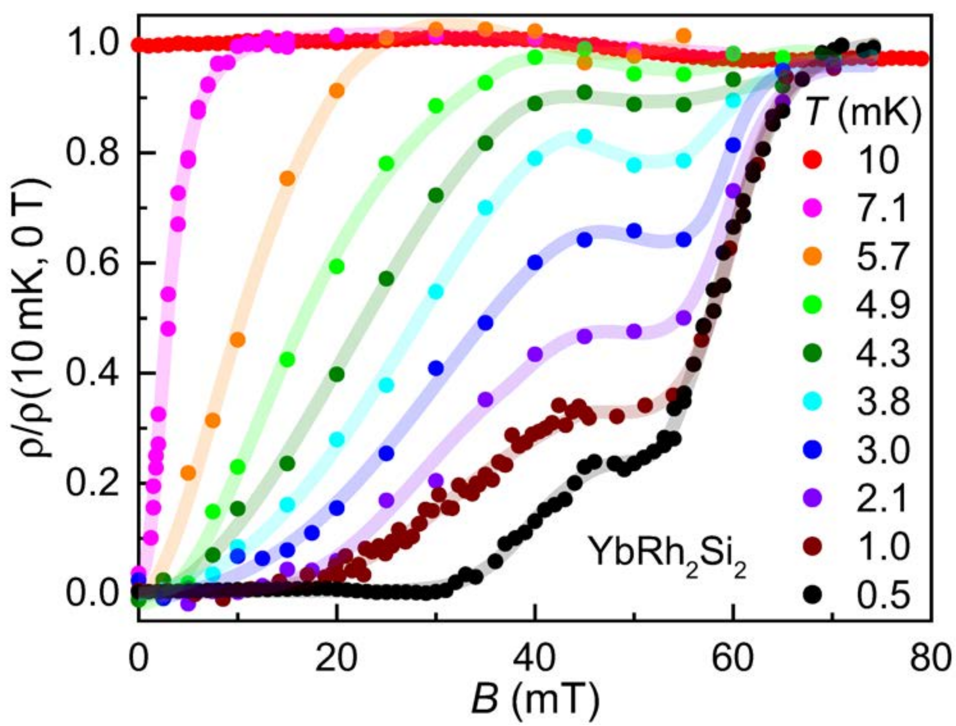
$^{174}YbRh_2Si_2$



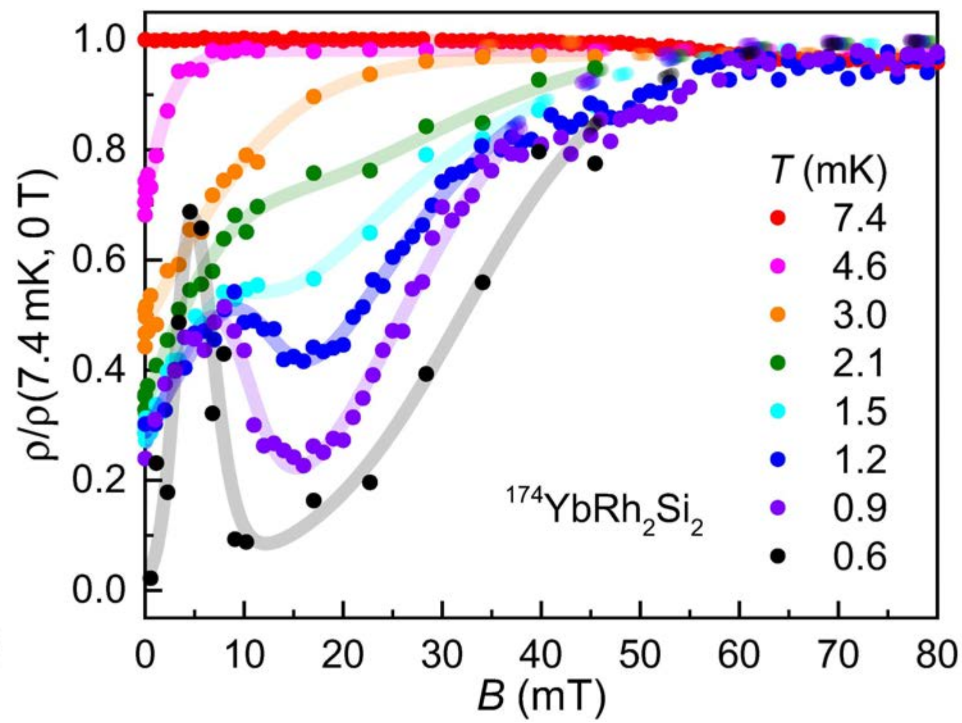
(Nguyen et al., Nat. Commun. 12 (2021) 4341)

Electrical resistivity at ultralow temperatures: Iso-*T* curves

$YbRh_2Si_2$



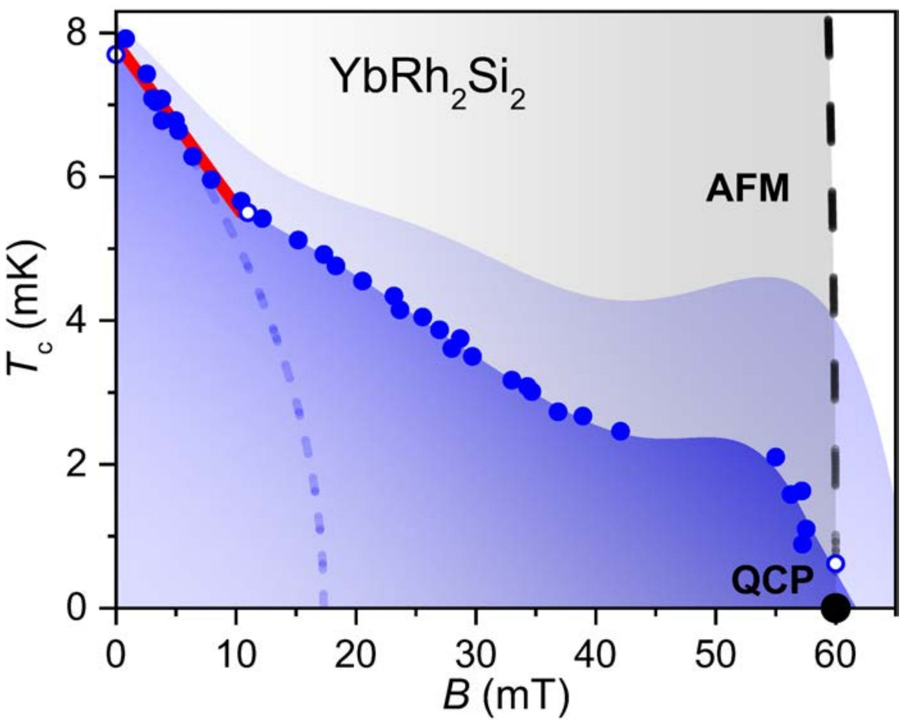
$^{174}YbRh_2Si_2$

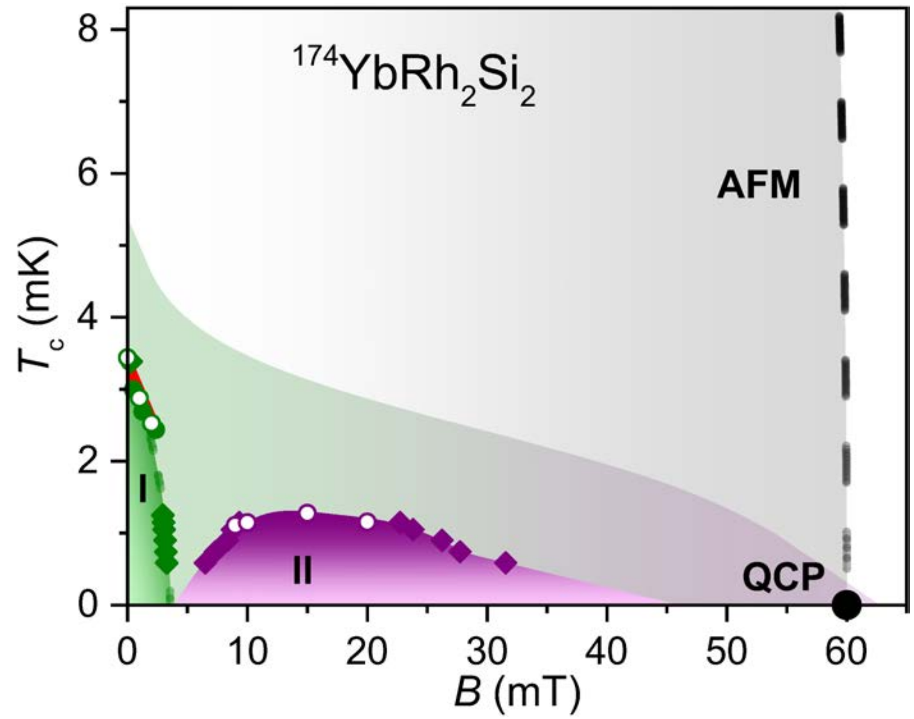


(Nguyen et al., Nat. Commun. 12 (2021) 4341)

Temperature–magnetic field phase diagrams

$YbRh_2Si_2$ $^{174}YbRh_2Si_2$

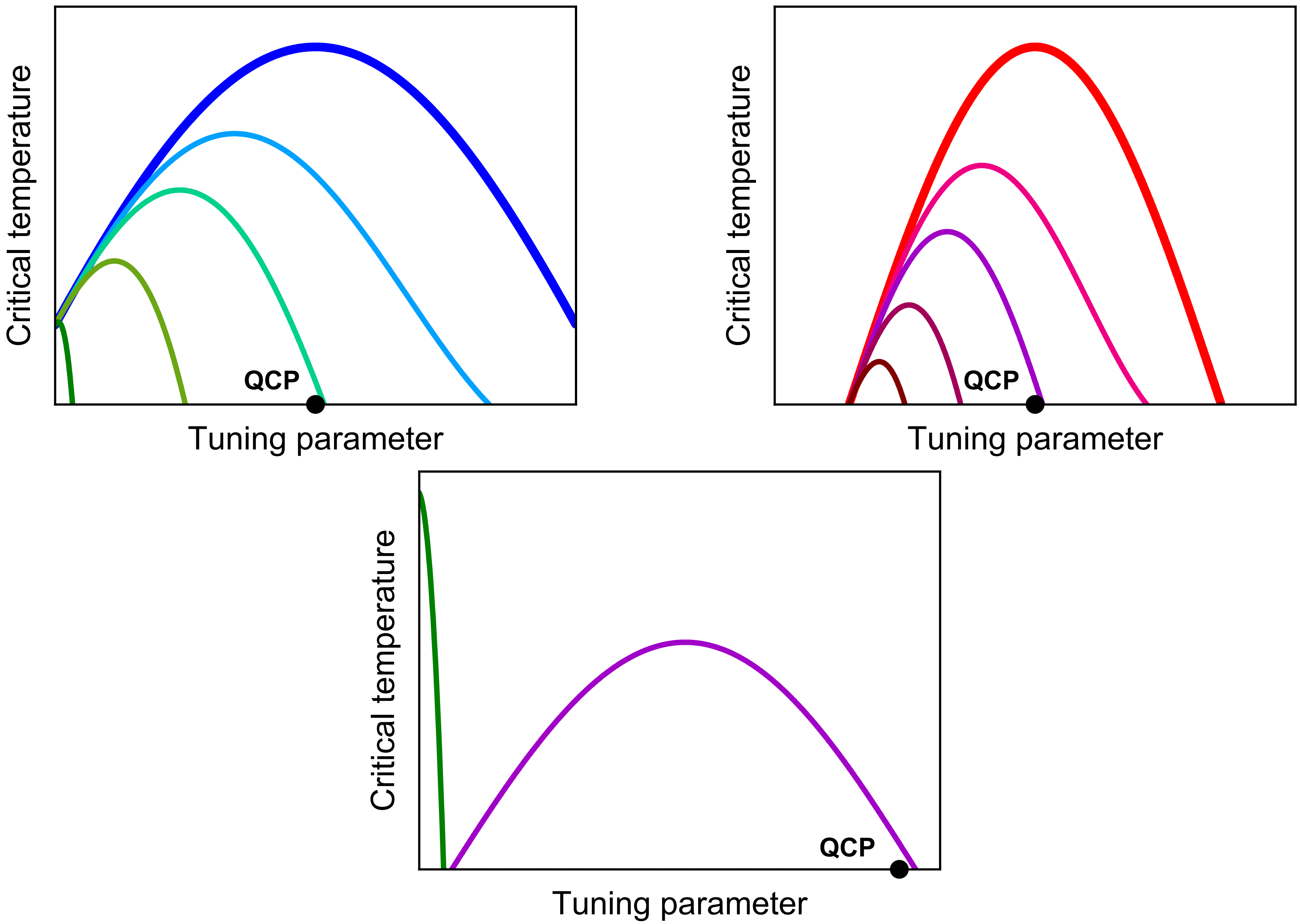




Orbital-limiting fields: 24 mT (5 mT)
Pauli-limiting fields: 15 mT (6.4 mT)

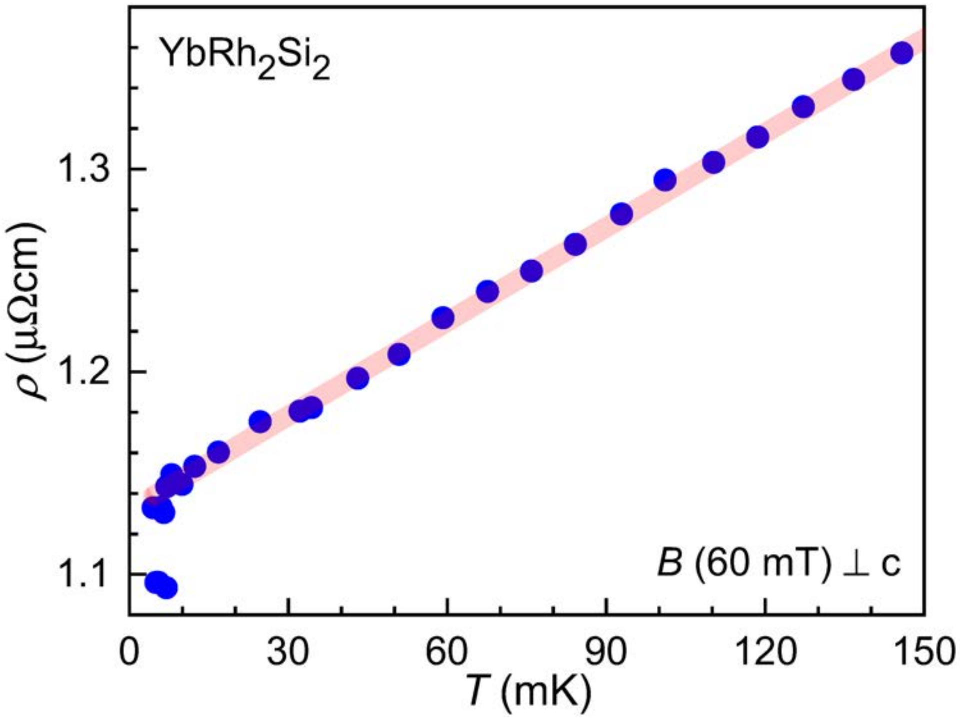
(Nguyen et al., Nat. Commun. 12 (2021) 4341)

Magnetic field effect on “dome” structure

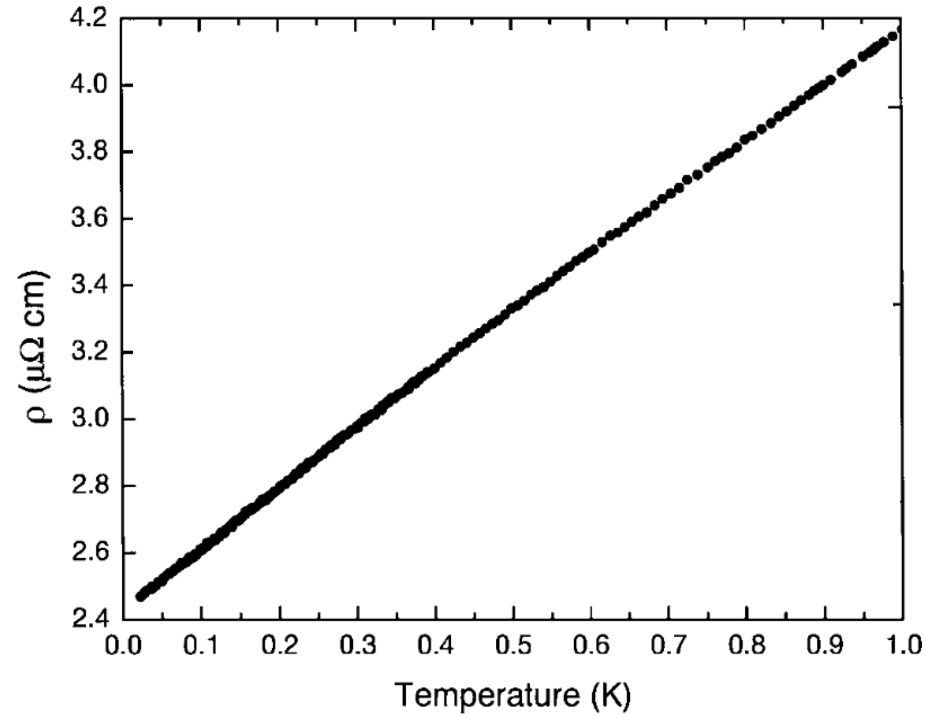


Linear-in-T electrical resistivity down to T_c at QCP

$YbRh_2Si_2$



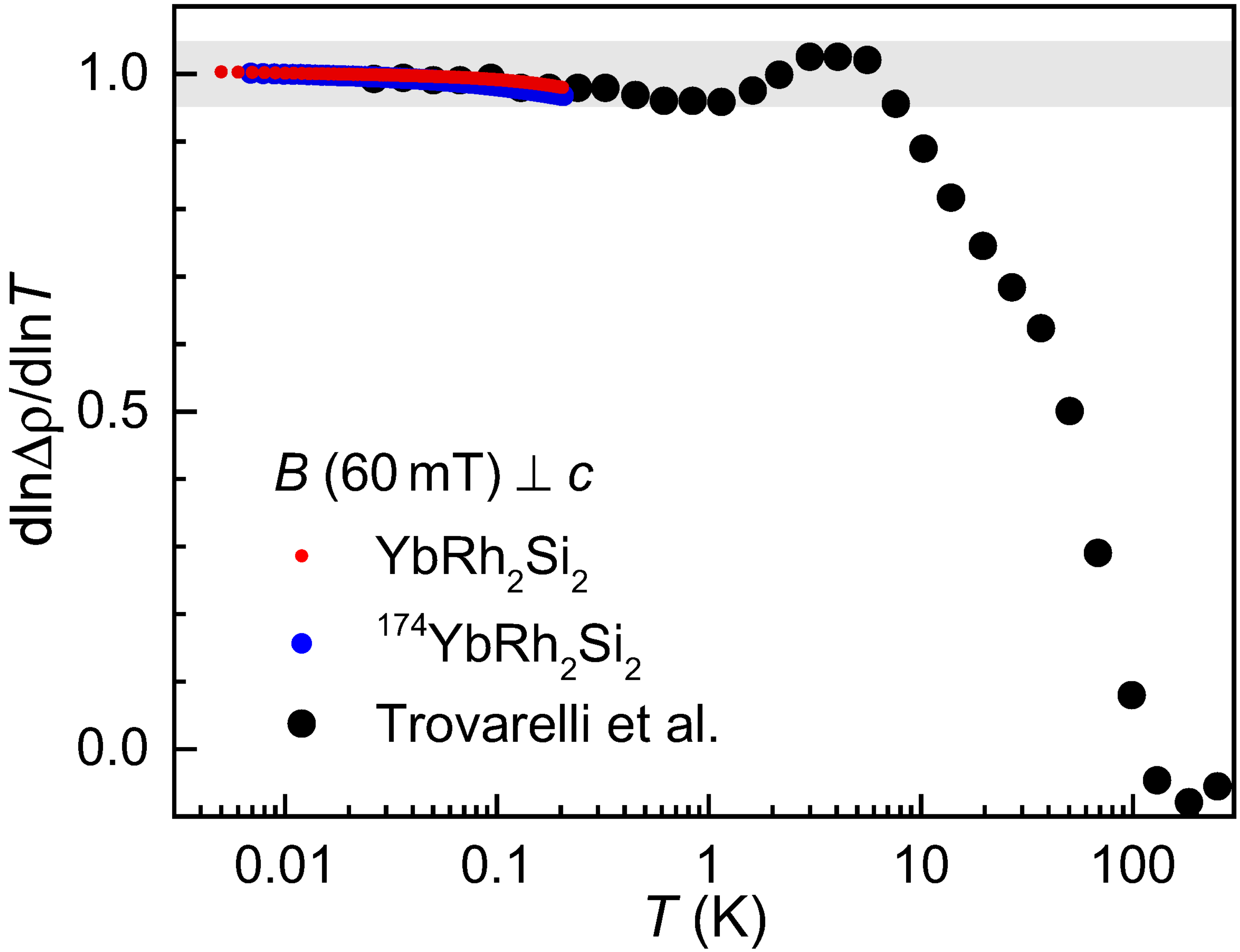
$YbRh_2Si_2$ (earlier batch)



(Nguyen et al., Nat. Commun. 12 (2021) 4341)

(Trovarelli et al., Phys. Rev. Lett. 85 (2000) 626)

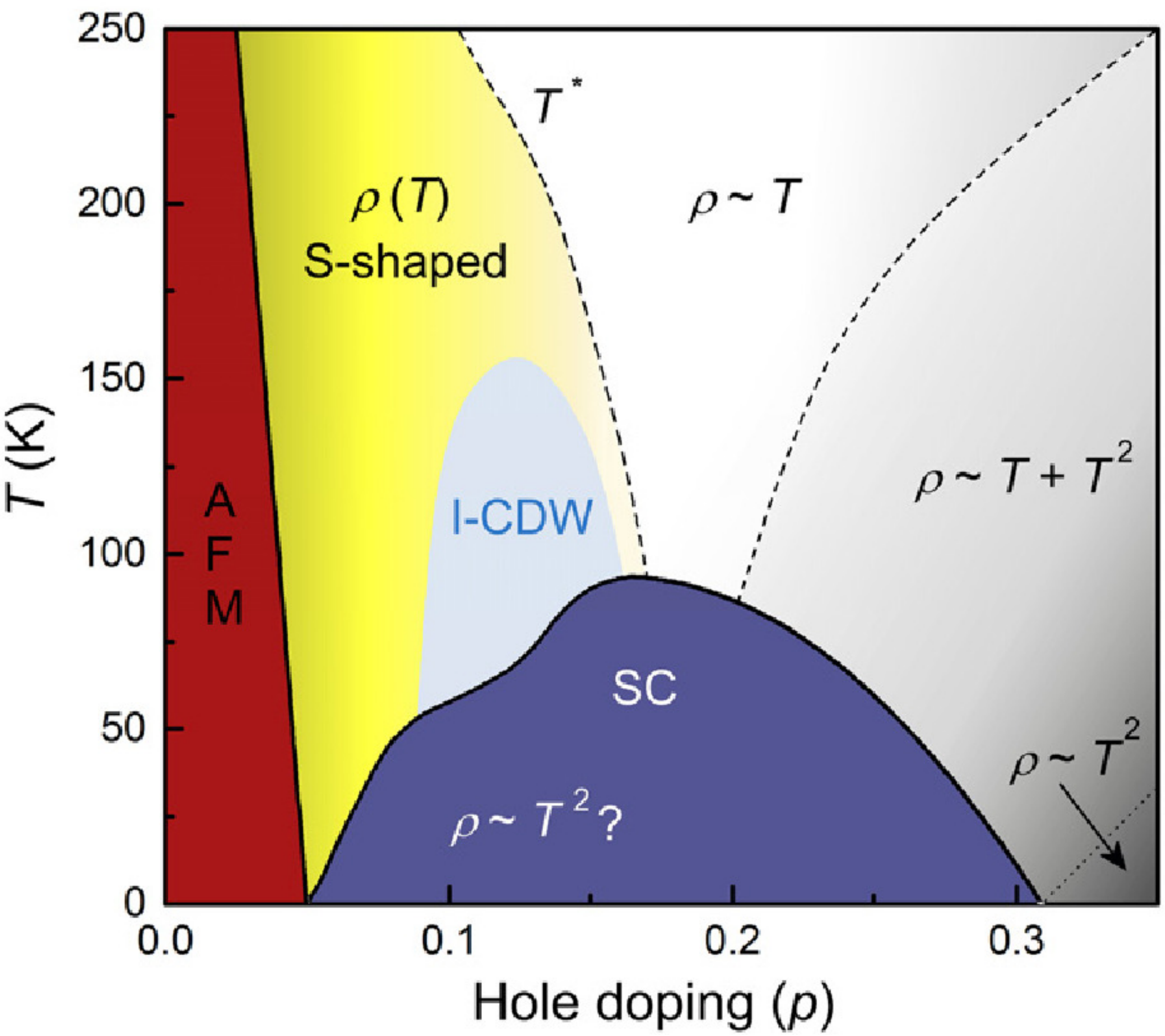
$YbRh_2Si_2$: An extreme strange metal (3.5 order of magnitude)



(Nguyen et al., Nat. Commun. 12 (2021) 4341)

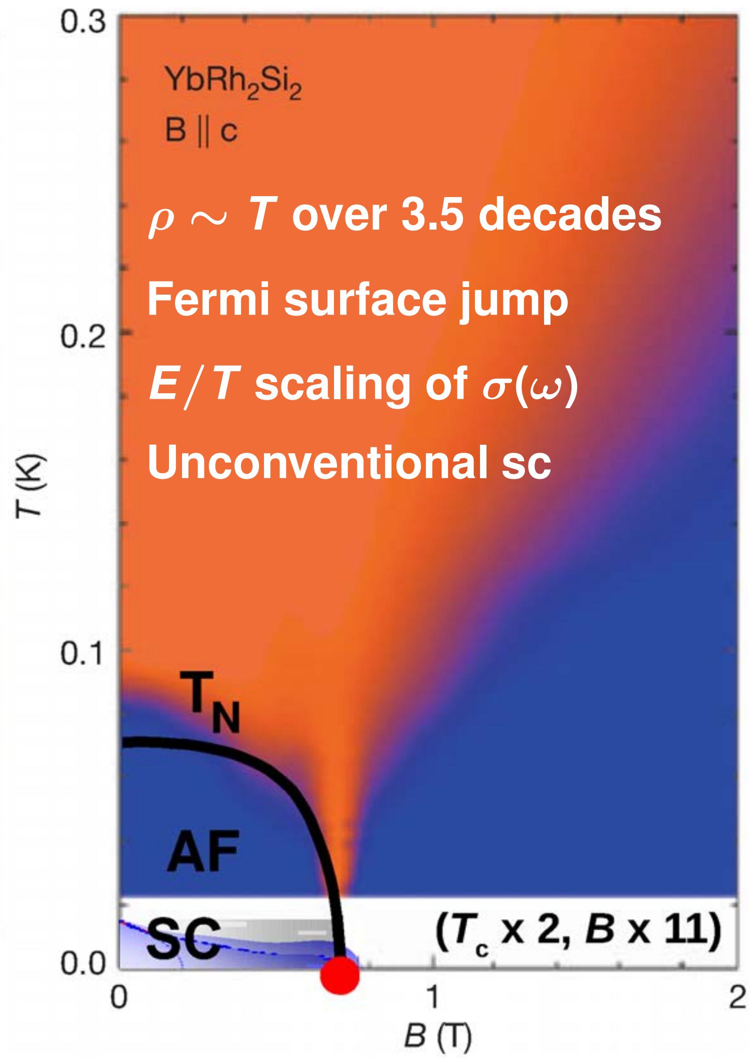
Advance understanding by connecting the various platforms!

Generic phase diagram of the cuprates



(Proust et al., PNAS 113 (2016) 13654)

Phase diagram of $YbRh_2Si_2$



(Refs. in this talk)

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