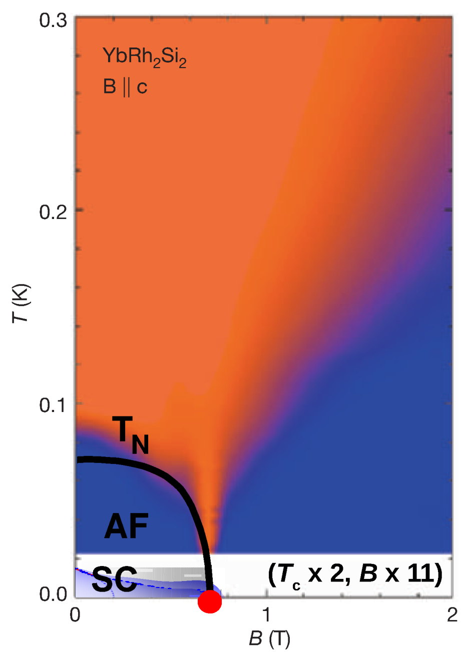
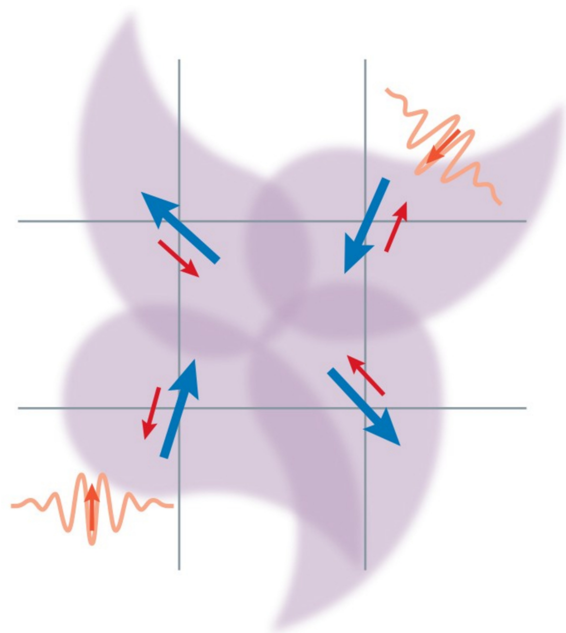
Heavy fermion systems
From quantum criticality to electronic topology

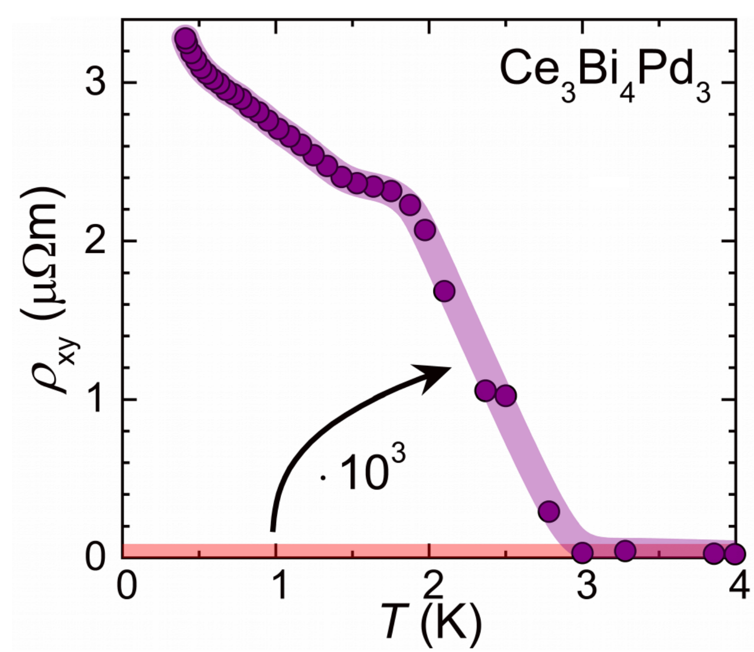
exosup2022 : School on Exotic Superconductivity

13-25 June 2022 Cargèse, Corse (France)

Silke Paschen
Vienna University of Technology







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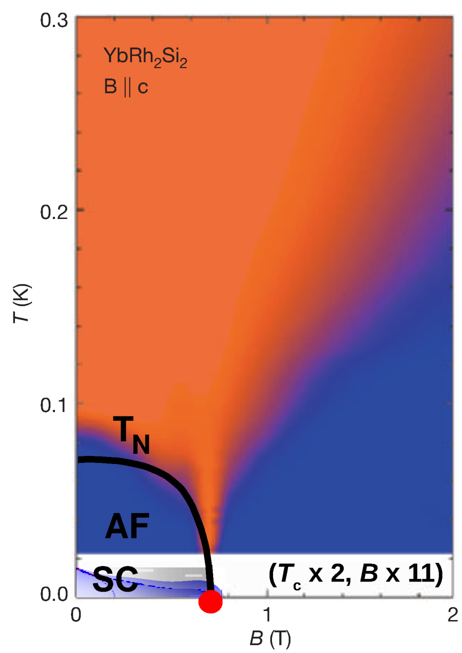

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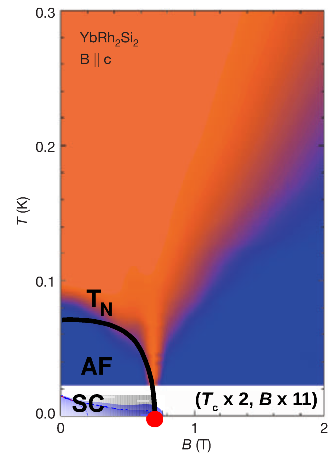

- **Tunable correlation strength**
- **Phase diagrams governed by quantum fluctuations**
- **Quantum criticality from vanishing order parameter**
- **Beyond order-parameter quantum criticality**
- **Global phase diagram of heavy fermion compounds**
- **Emergent phases: Unconventional superconductivity**

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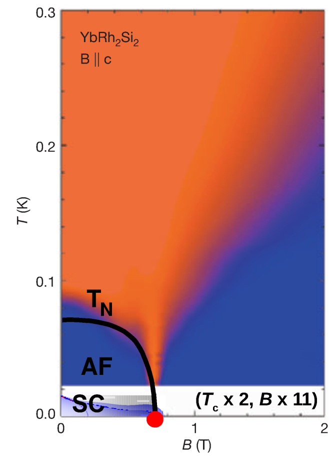

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Heavy Fermi liquids

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

$$C/T = \gamma$$

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

$$\gamma \sim m^*$$

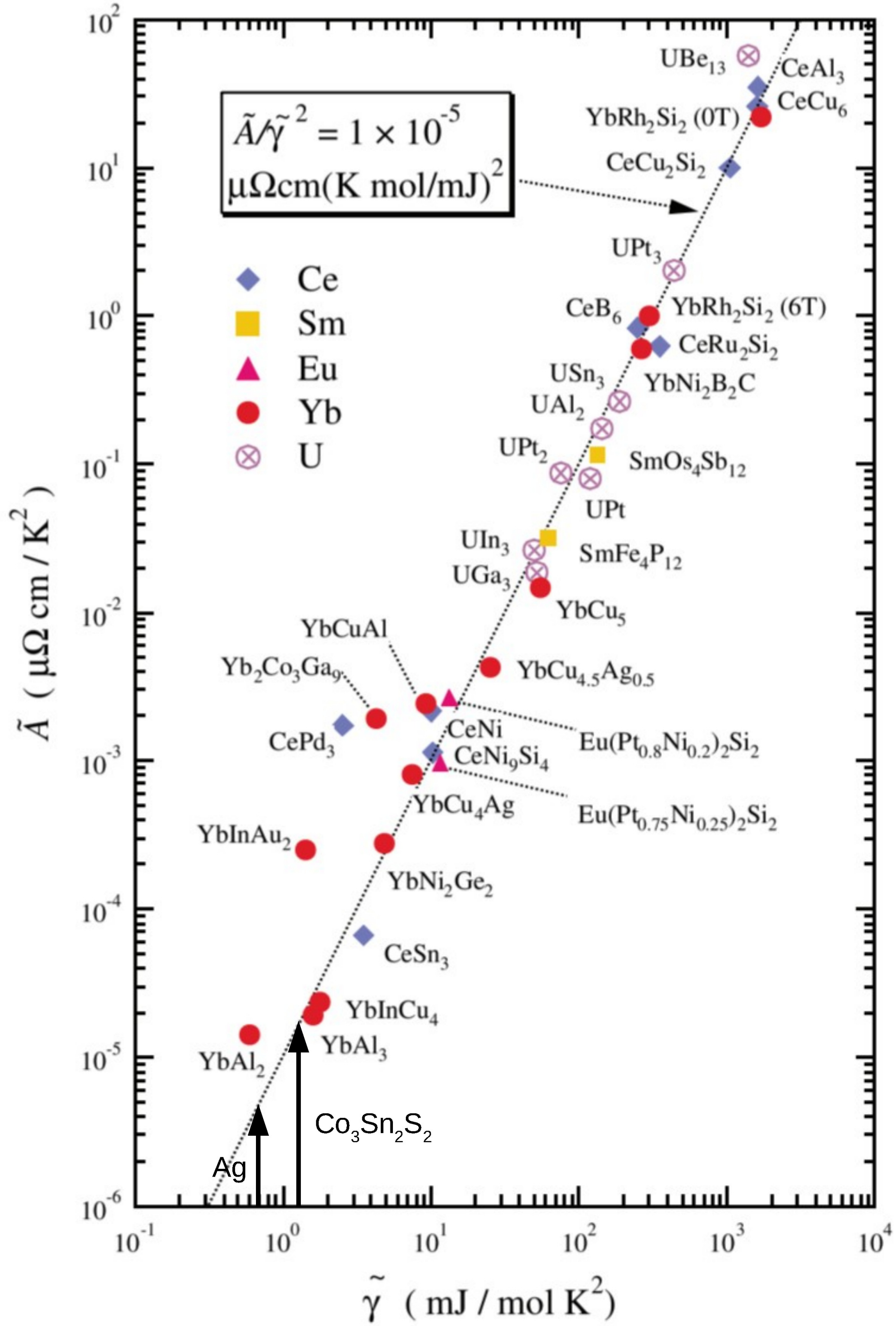
$$m^* = m(1 + \tfrac{1}{3}F_1^s)$$

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) $\longrightarrow$



Heavy Fermi liquids: Tuning

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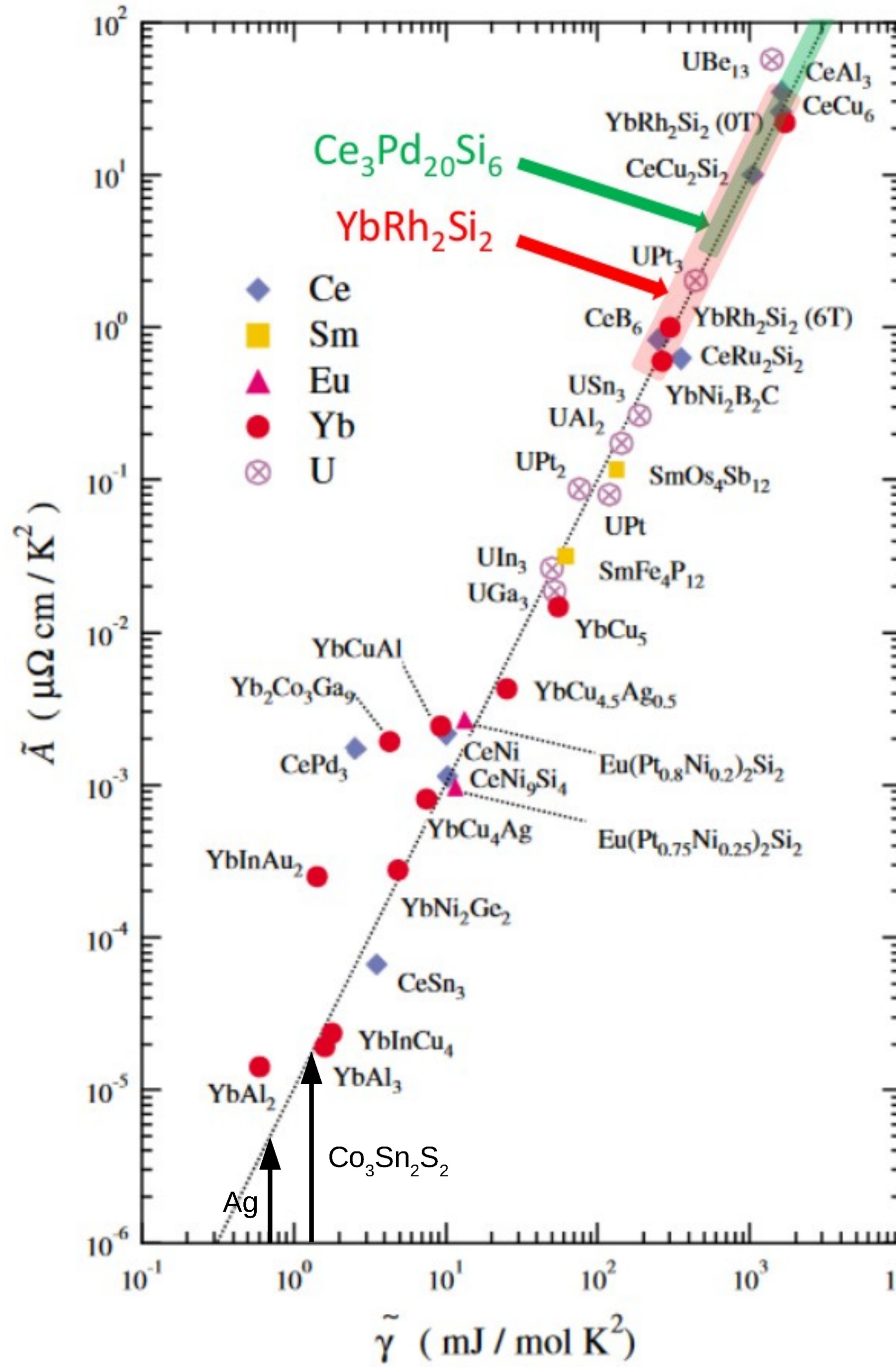
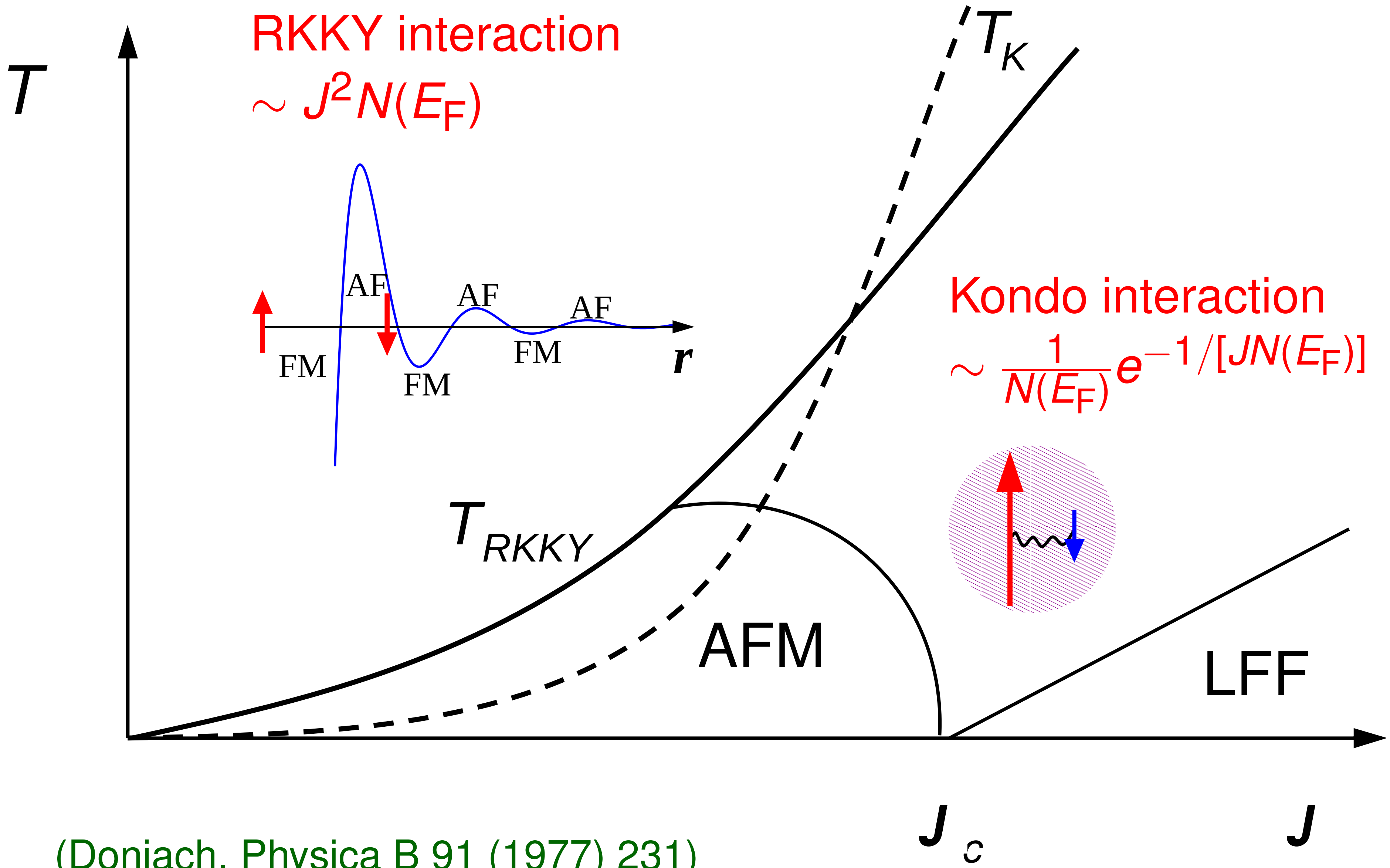
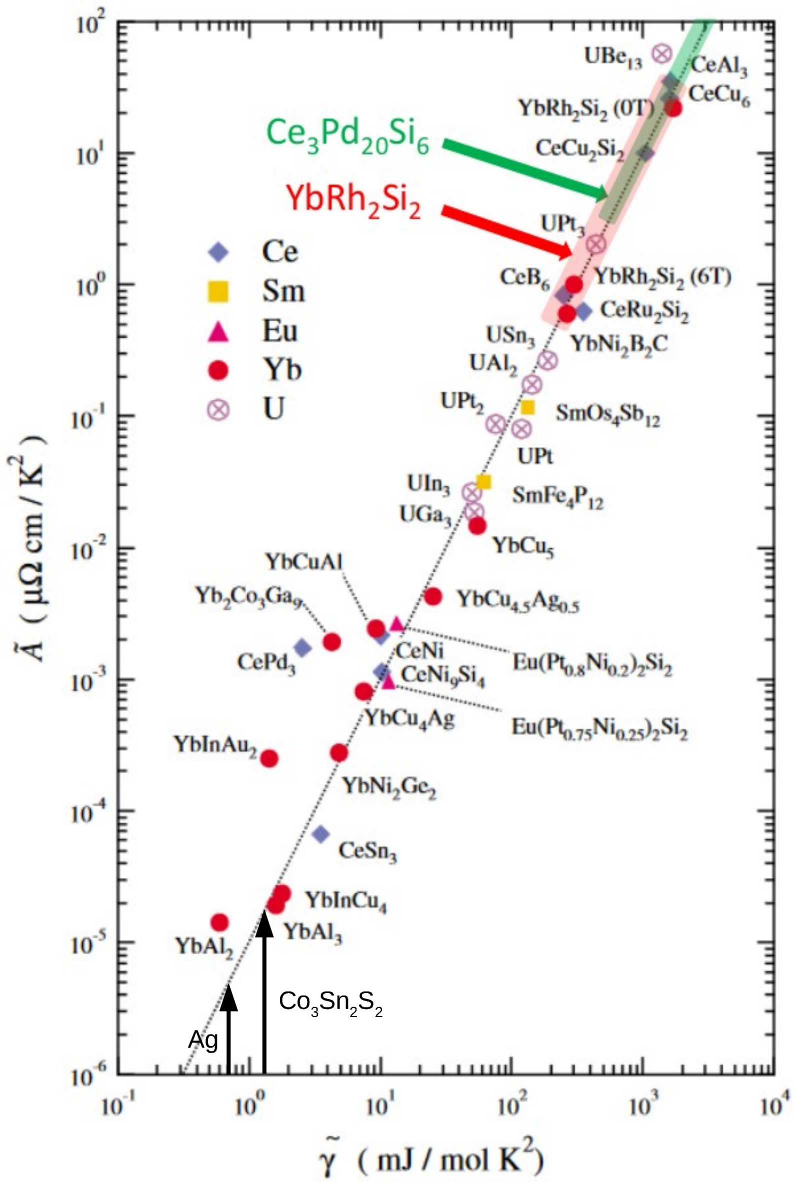


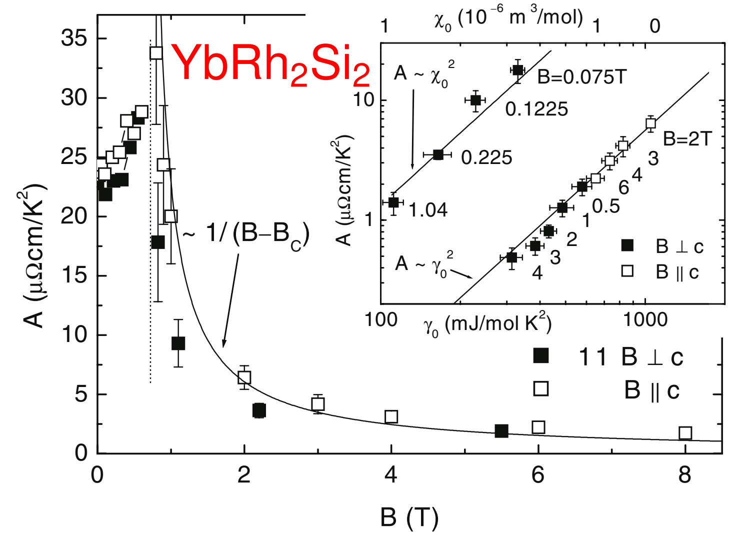
Tunability due to competing interaction: Kondo vs RKKY

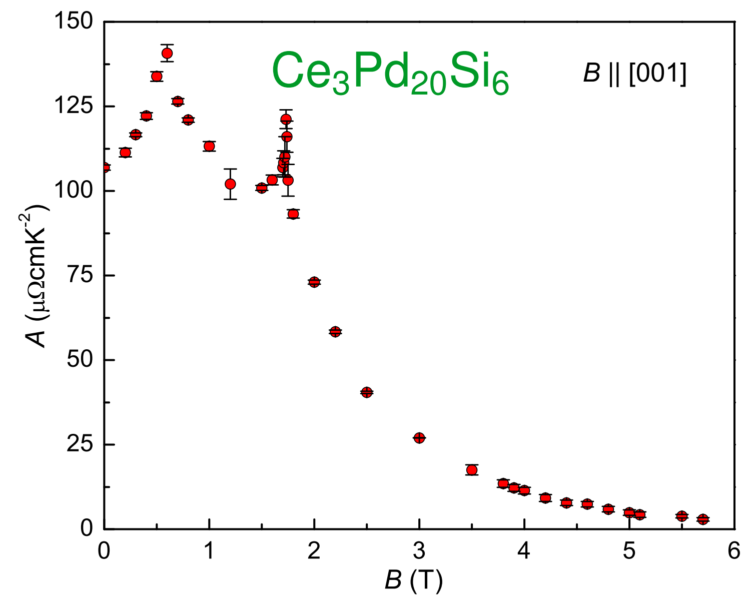


(Doniach, Physica B 91 (1977) 231)

Discontinuities appear upon tuning: FL parameters diverge

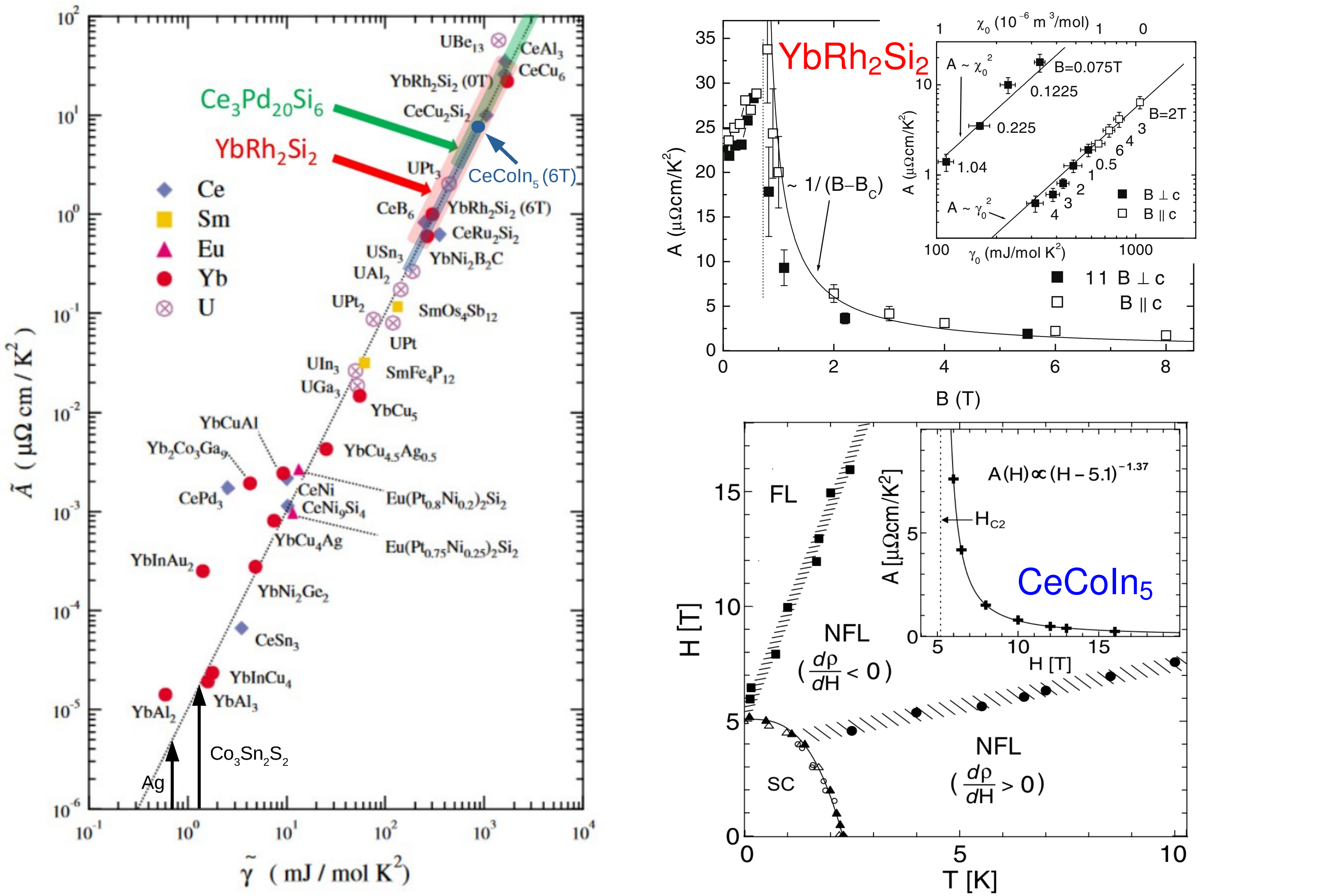






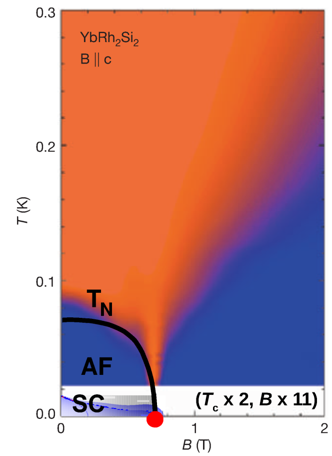
(SP & Si, Nat. Rev. Phys. 3 (2021) 9, and refs. therein)

Discontinuities appear upon tuning: FL parameters diverge



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

Heavy fermion systems
From quantum criticality to electronic topology



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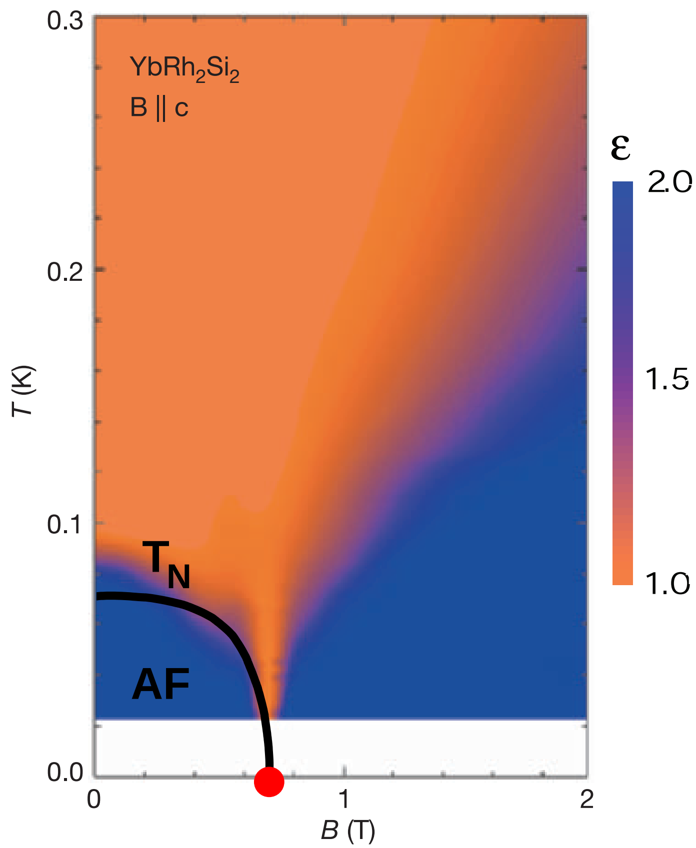
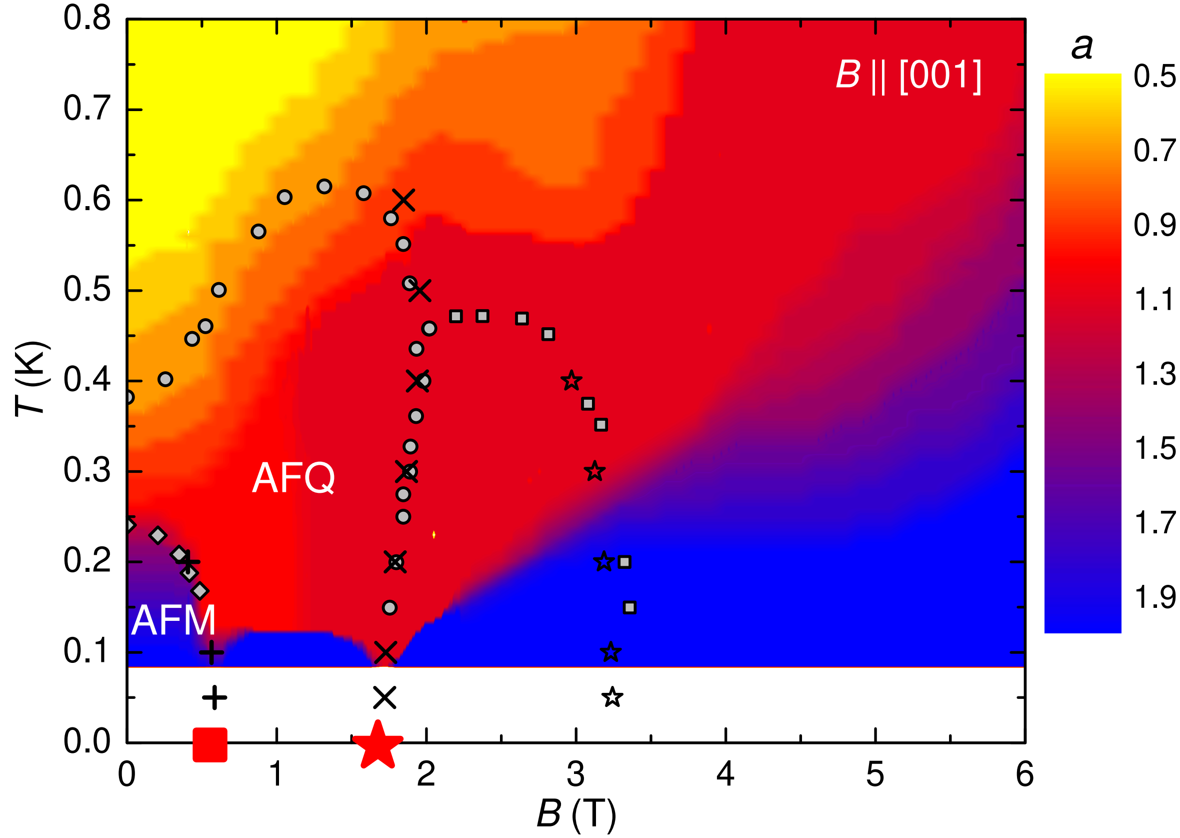
Origin of divergences: Quantum critical points

$YbRh_2Si_2$



$Ce_3Pd_{20}Si_6$



Fermi liquid: $\rho = \rho_0 + AT^2$ Non-Fermi liquid: $\rho = \rho_0' + A'T^1$

(Custers et al., Nature 424 (2003) 524; Martelli et al., PNAS 116 (2019) 08101)

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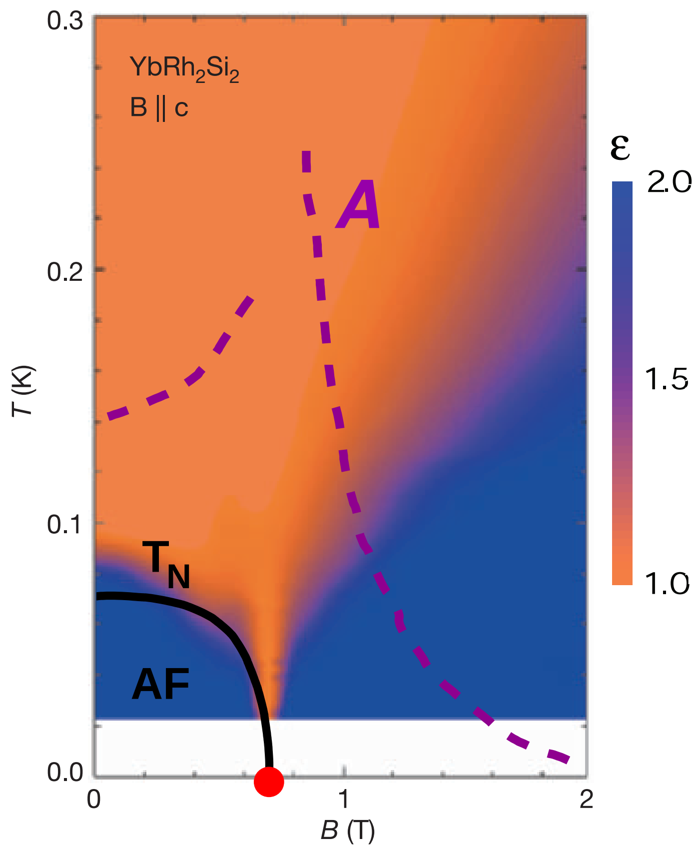

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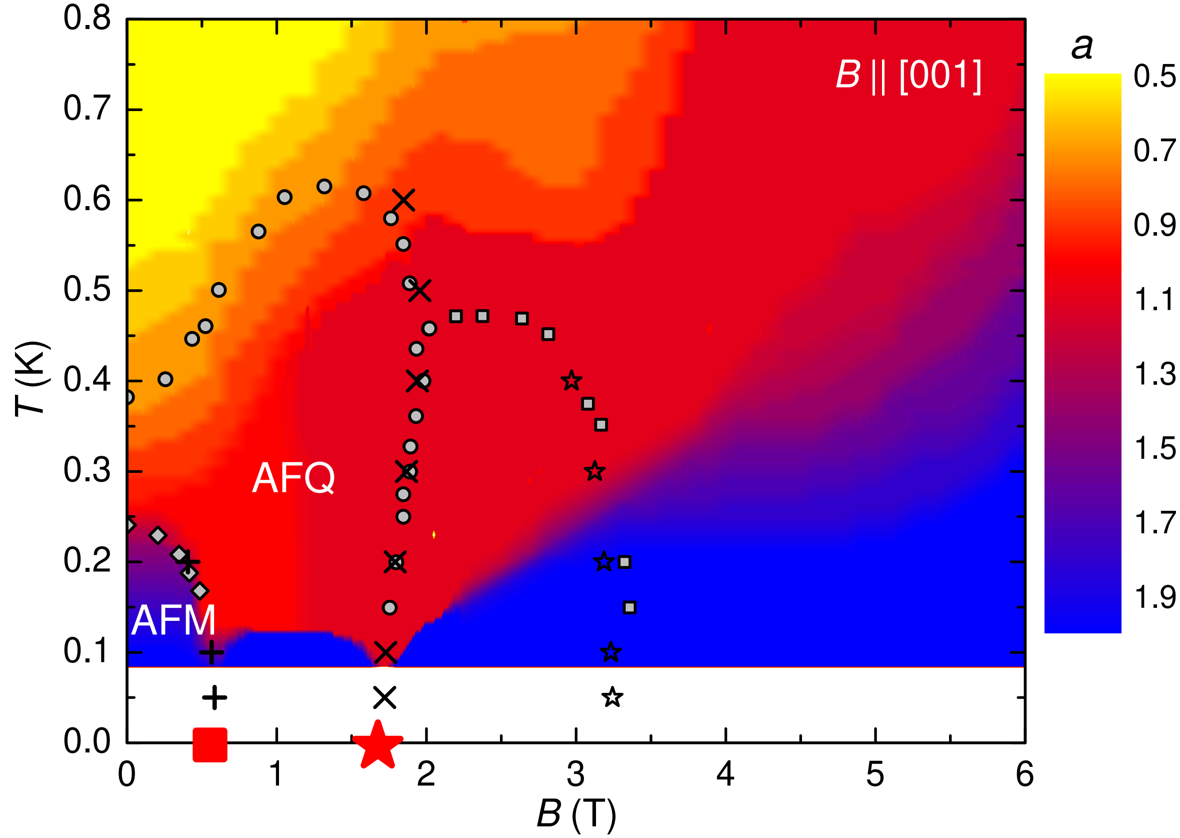

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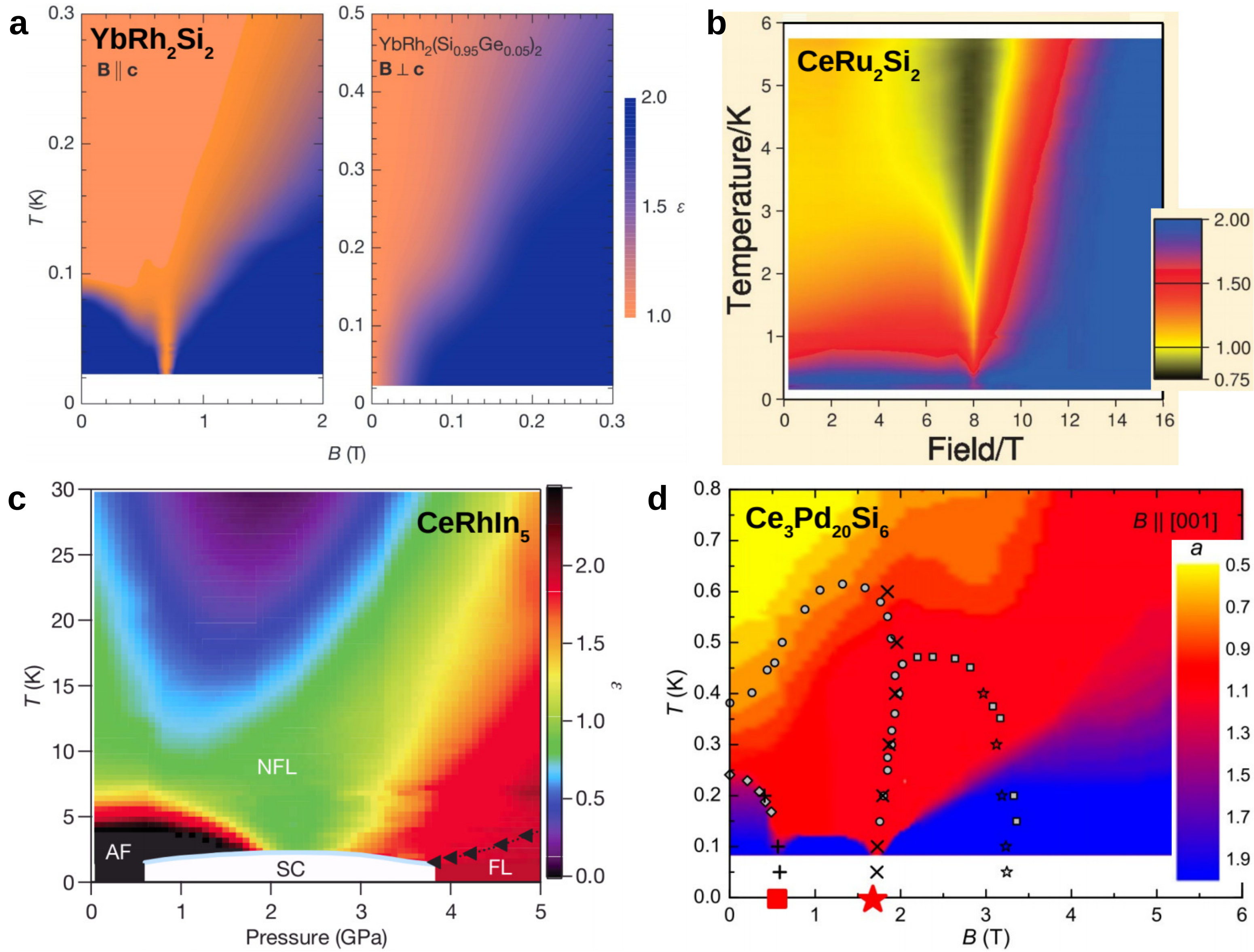
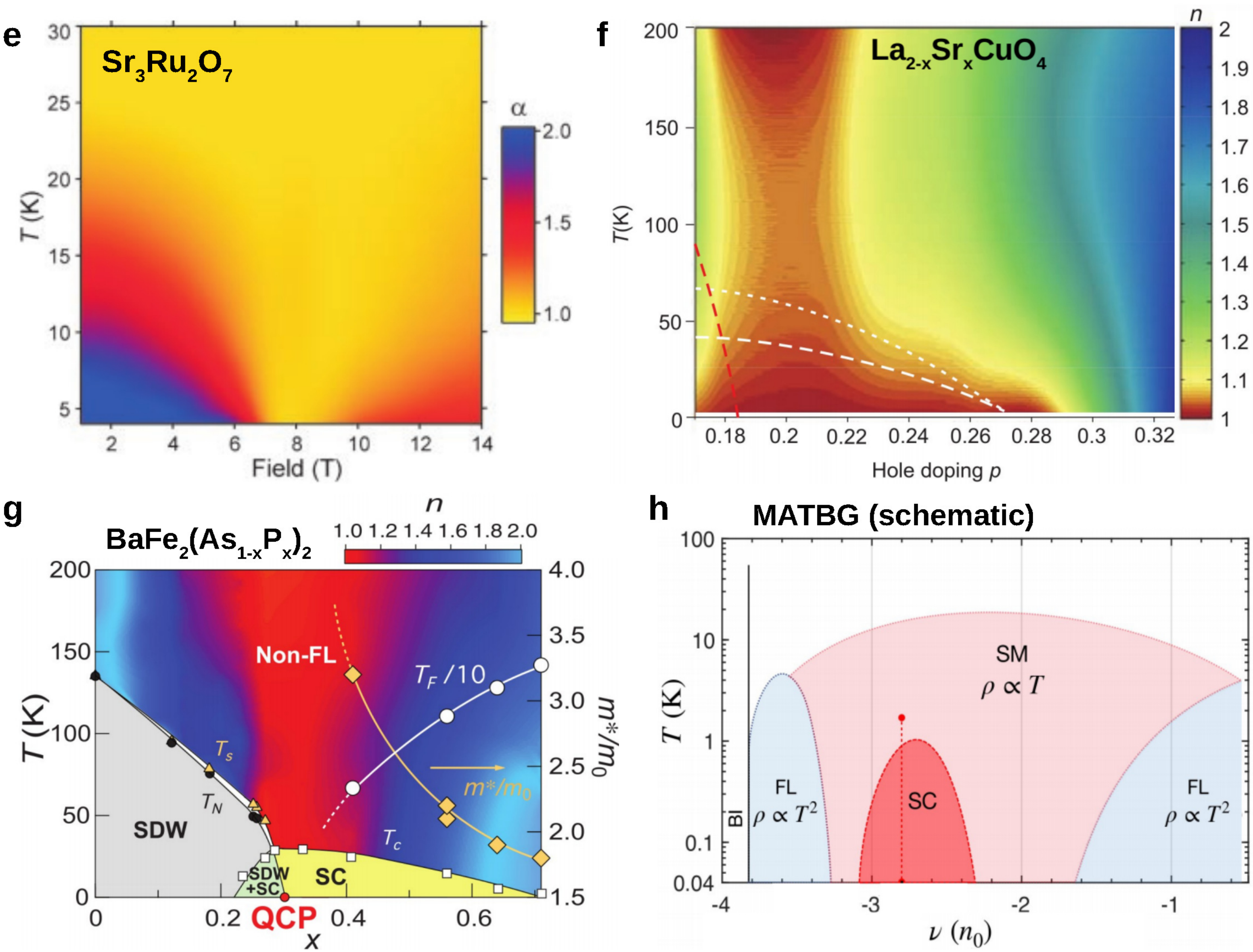
Phase diagrams governed by quantum fluctuations



(Taupin & SP, Crystals 12 (2022) 251 and refs. herein)

Phase diagrams governed by quantum fluctuations



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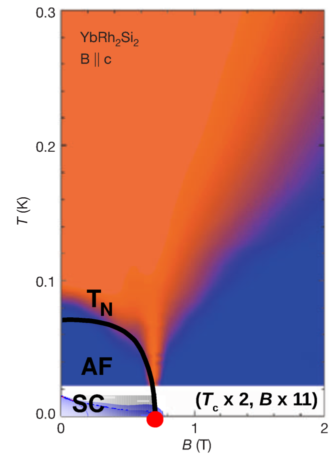
Heavy fermion systems

From quantum criticality to electronic topology



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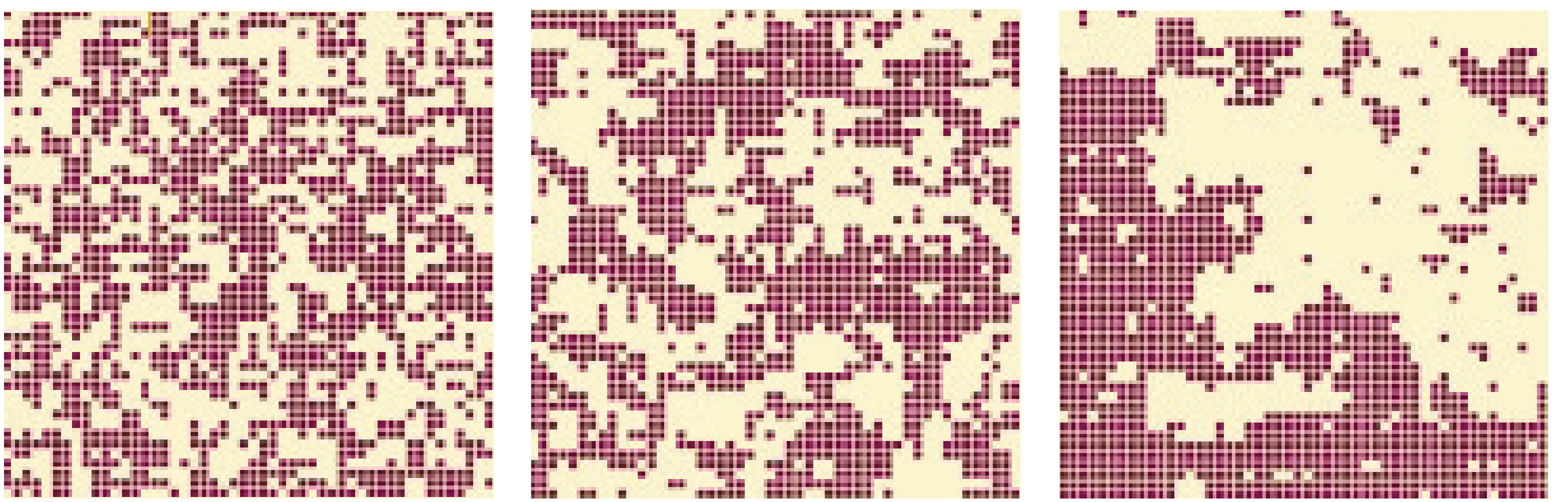
Classical continuous phase transitions

Classical criticality from order parameter fluctuations

- Order parameter: condensate wave function (normal conductor → superconductor), uniform magnetization (para- → ferromagnet), ...
- Correlation length: $\xi \sim |T - T_c|^{-\nu}$, correlation time: $\tau \sim |T - T_c|^{-\nu z}$
- Scale invariance, universality

$T = 2 \cdot T_c$ $\qquad$ $T = 1.3 \cdot T_c$ $\qquad$ $T = T_c$



(T. Vojta, Physik in unserer Zeit 32 (2001) 38: 2D Ising model)

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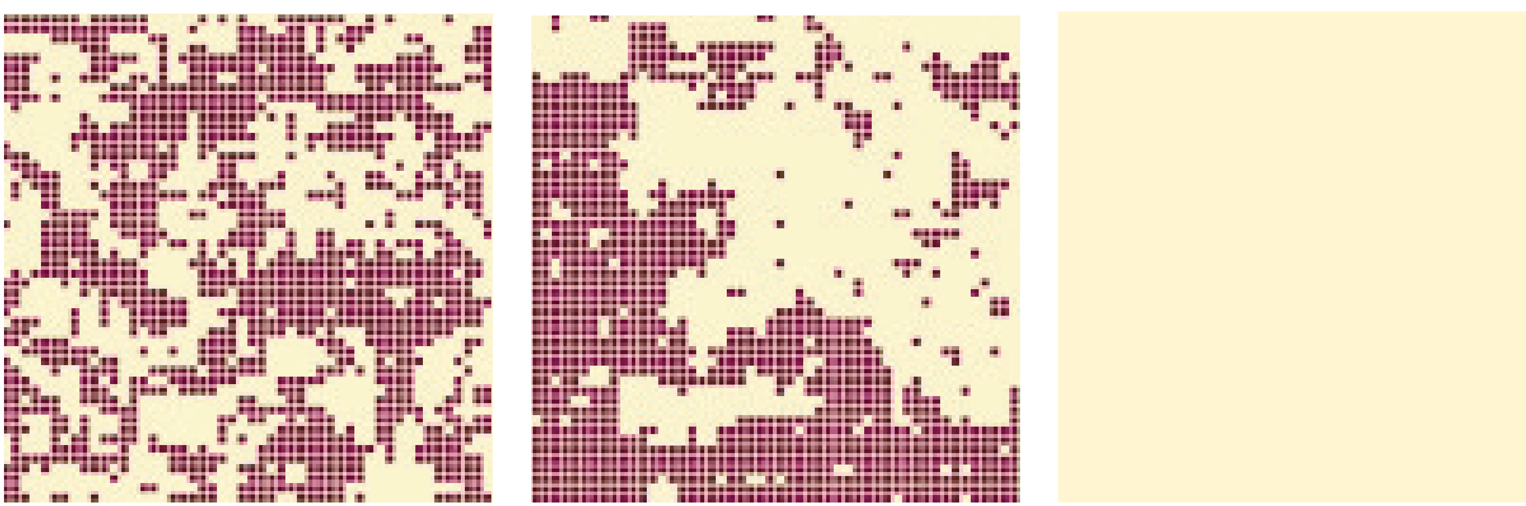
- Scale invariance, universality

$T = 1.3 \cdot T_c$ $\quad$ $T = T_c$ $\quad$ $T = 0\,\mathrm{K}$



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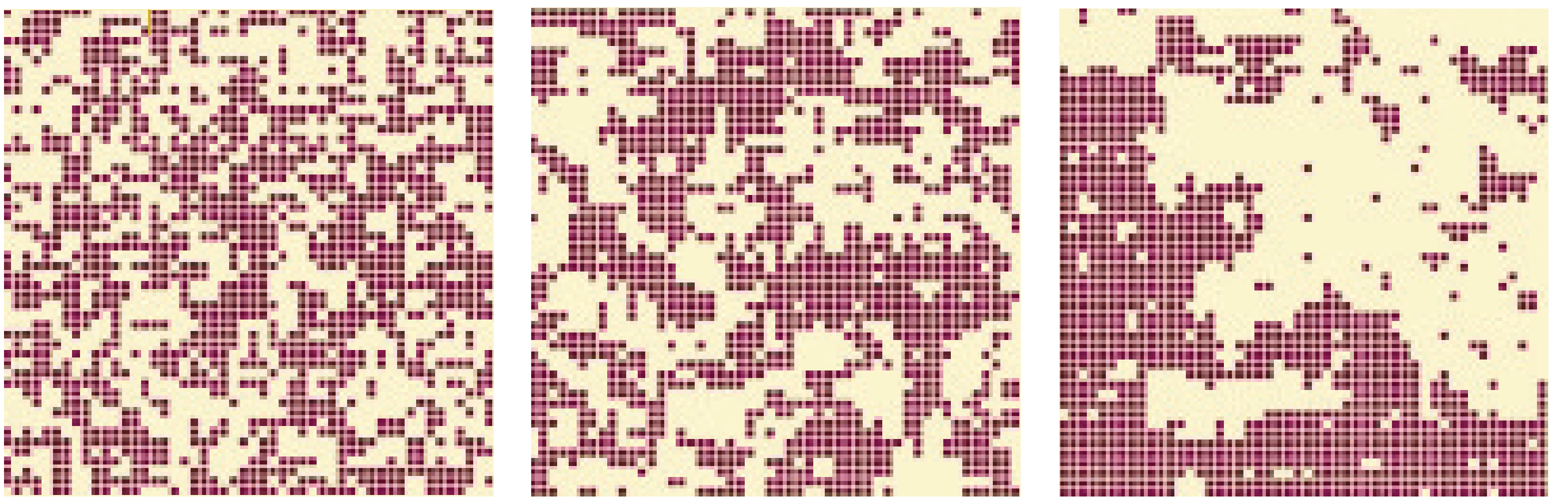
Continuous quantum phase transitions

Quantum criticality from order parameter fluctuations

- Order parameter: condensate wave function (normal conductor $\rightarrow$ superconductor), uniform magnetization (para- $\rightarrow$ ferromagnet), ...
- Correlation length: $\xi \sim |B - B_c|^{-\nu}$, correlation time: $\tau \sim |B - B_c|^{-\nu z}$
- Scale invariance, universality; $\nu_{qc} \neq \nu_{cc}$

At T = 0: $B = 2 \cdot B_c$ $B = 1.3 \cdot B_c$ $B = B_c$



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“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

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

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$C_{\rm cr}\sim$	$T \ell n \frac{1}{T}$	$-T^{3/2}$	$T^{2/3}$	$T \ell n \frac{1}{T}$
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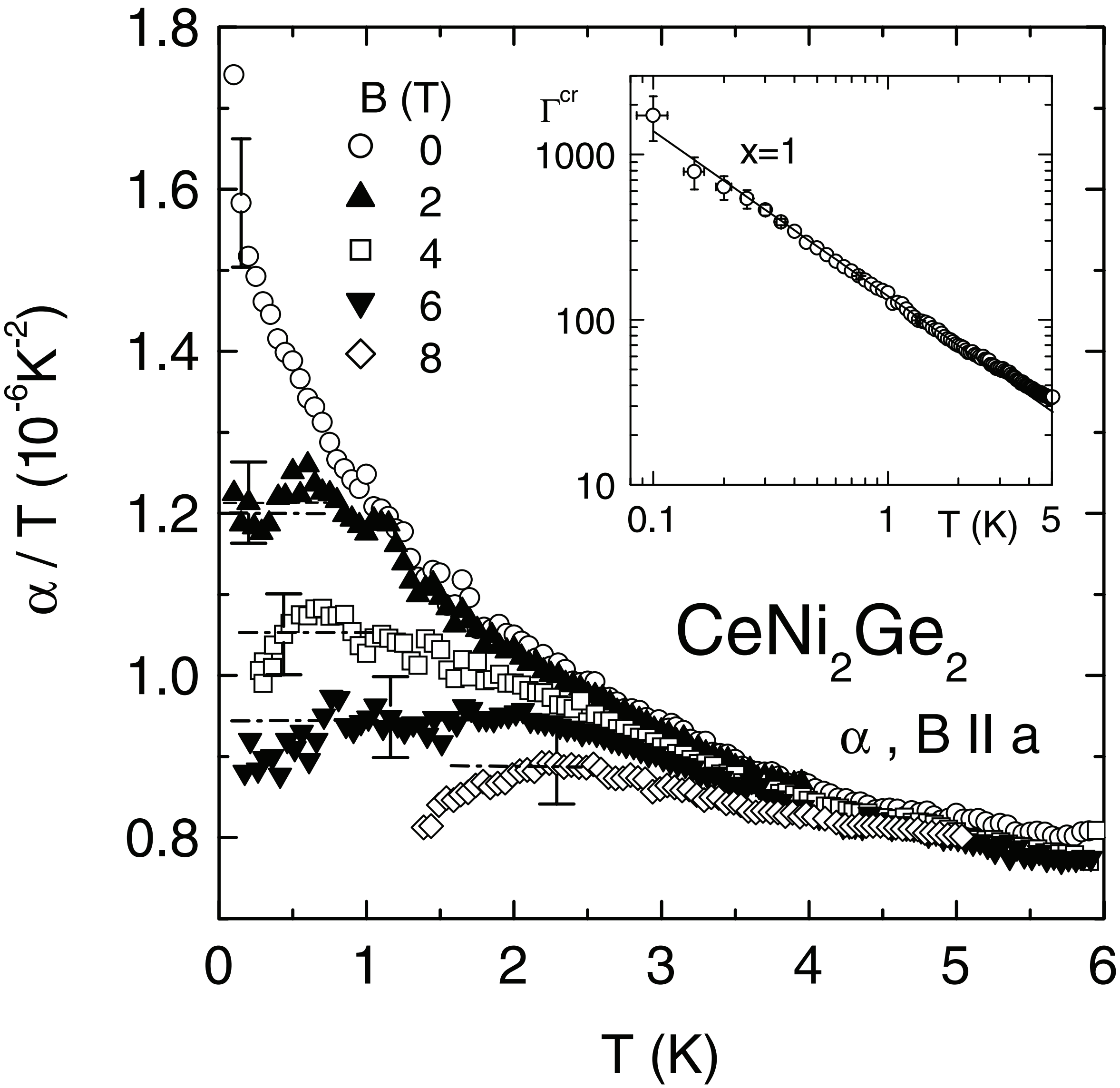
d: dimension, $z = 2$: AFM metal, $z = 3$: FM metal

α: thermal expansion, *C*: specific heat, $\Gamma = \alpha/C$: Grüneisen ratio

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

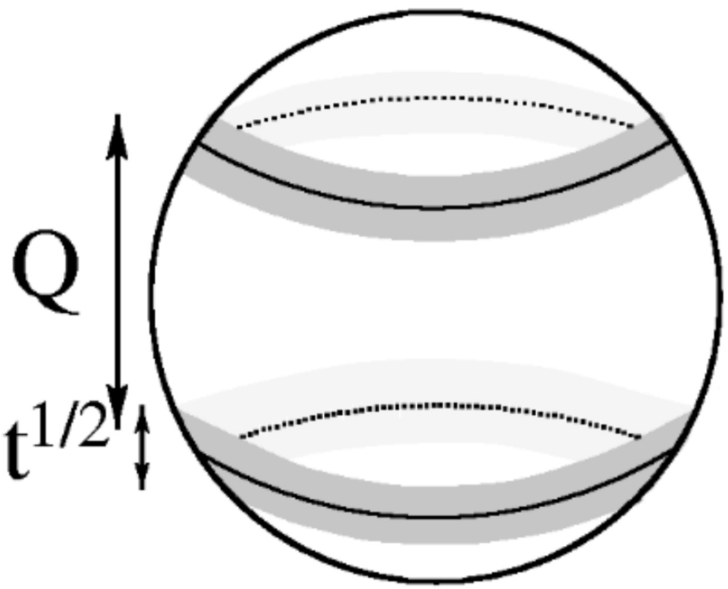
Thermal expansion and Grüneisen ratio: $CeNi_2Ge_2$

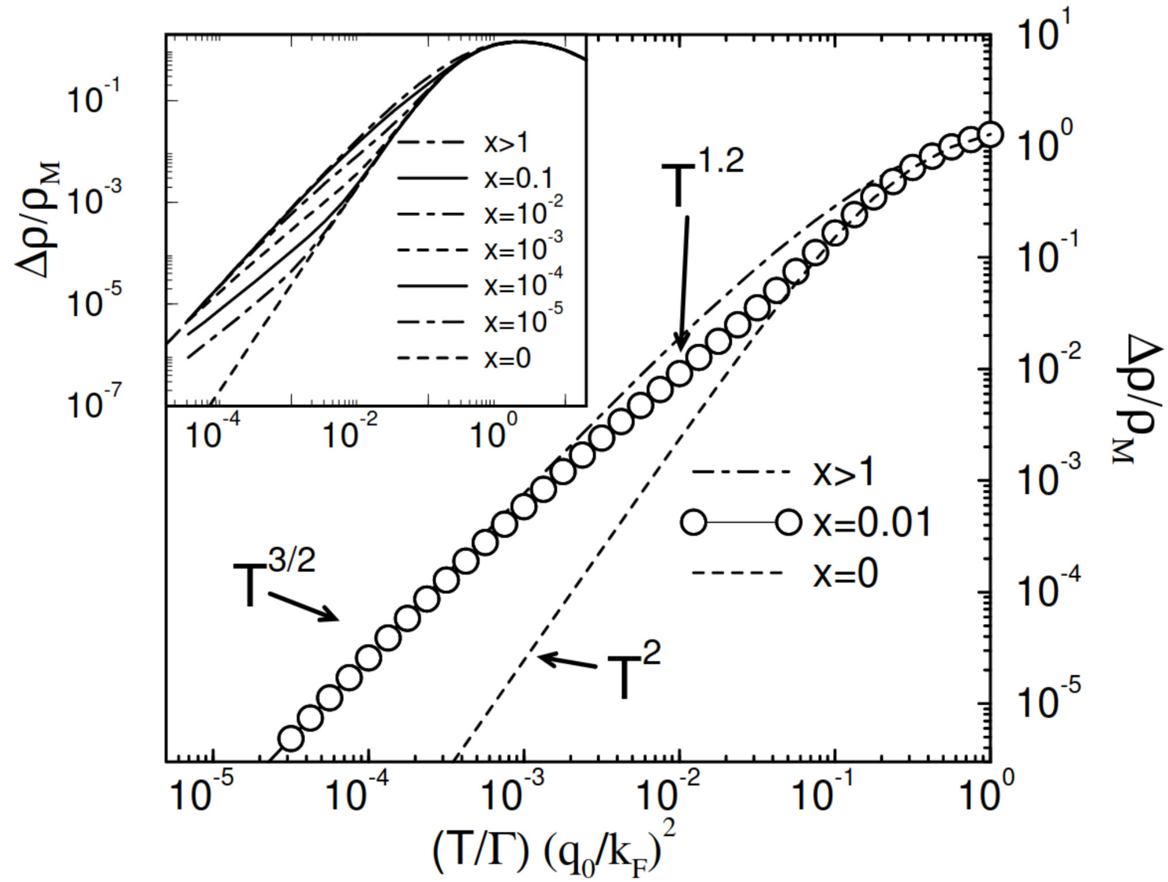


$\Gamma^{cr} \propto T^{-1}$, 3D AFM Metall (Küchler et al., PRL 91 (2003) 066405)

"Normal" QCPs follow Ginzburg, Landau, Wilson paradigm

Predictions for electrical resistivity



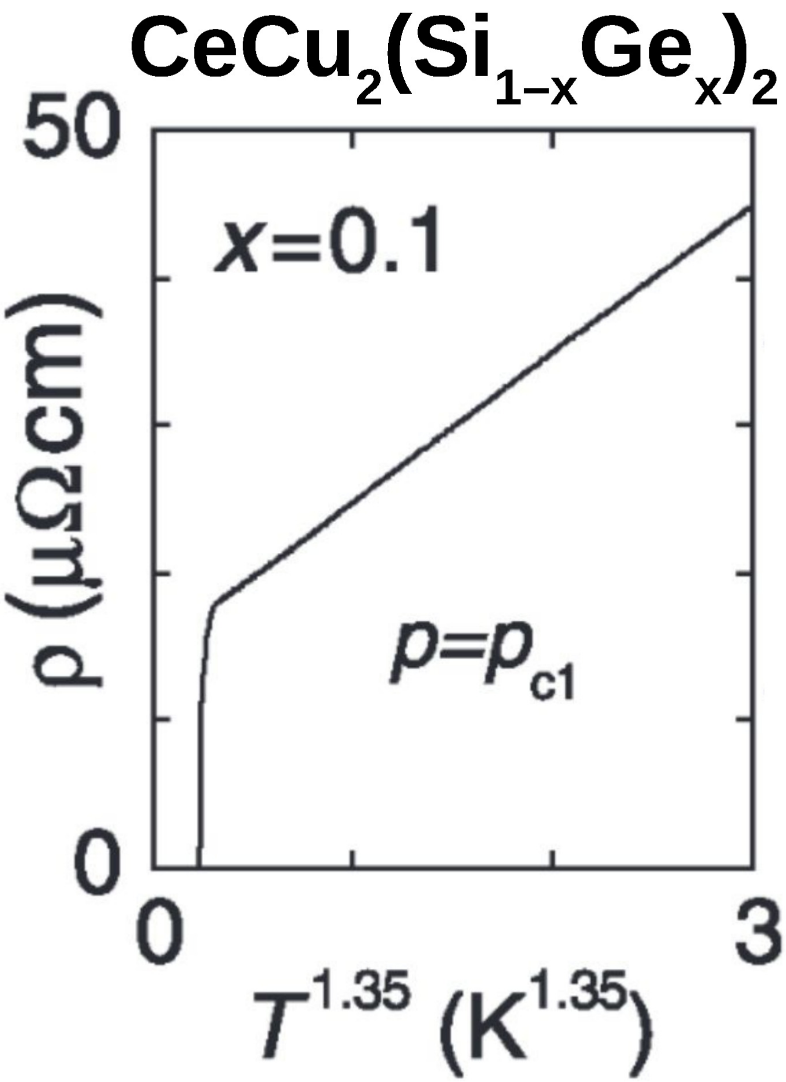


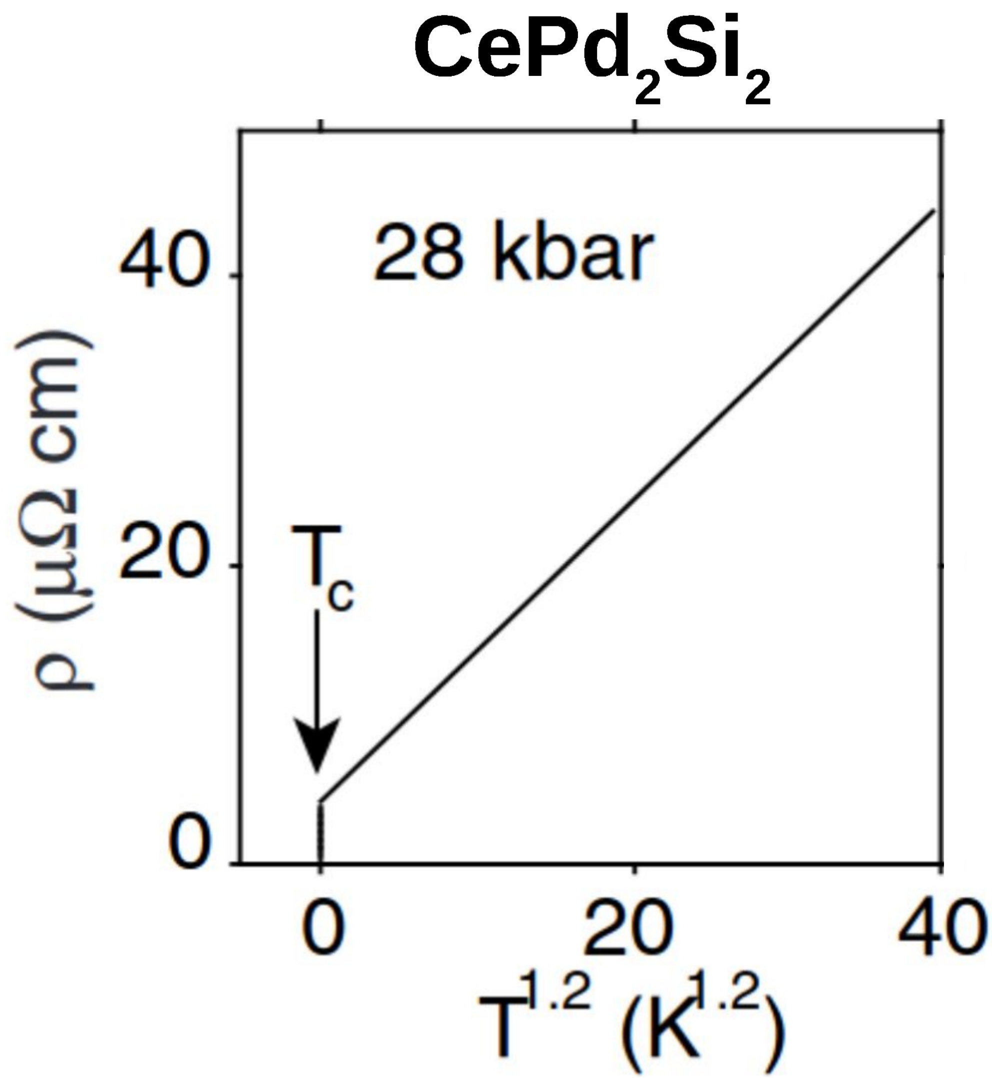
No linear resistivity

***x* = 0**: clean limit   ***x* > 1**: dirty limit

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

Electrical resistivity at "normal" QCPs





(Mathur et al., Nature 394 (1998) 39; Yuan et al., Science 302 (2003) 2104)

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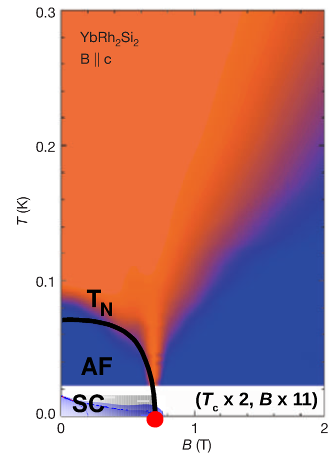

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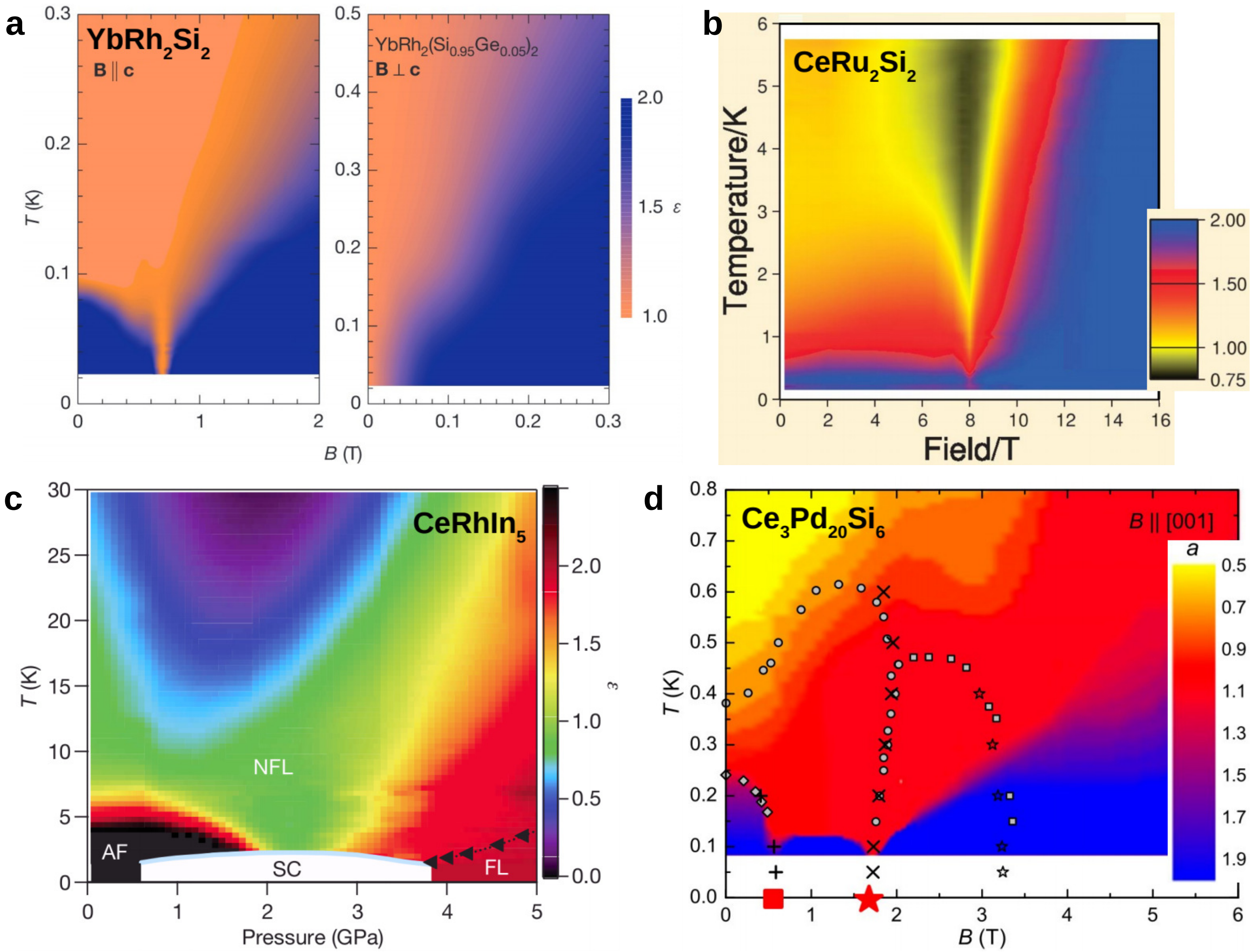
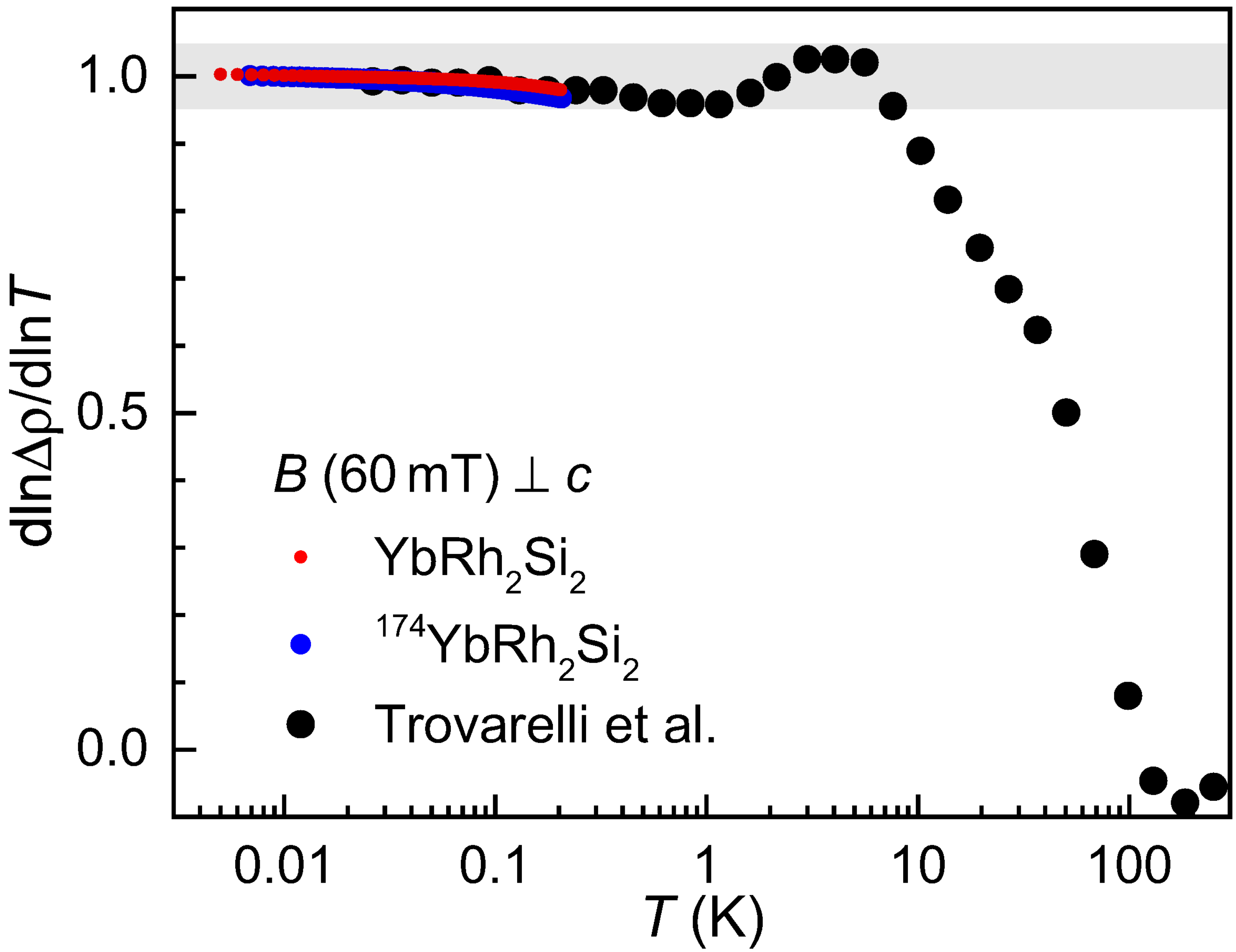
Deviations from GLW: Linear-in-*T* "strange metal" resistivity



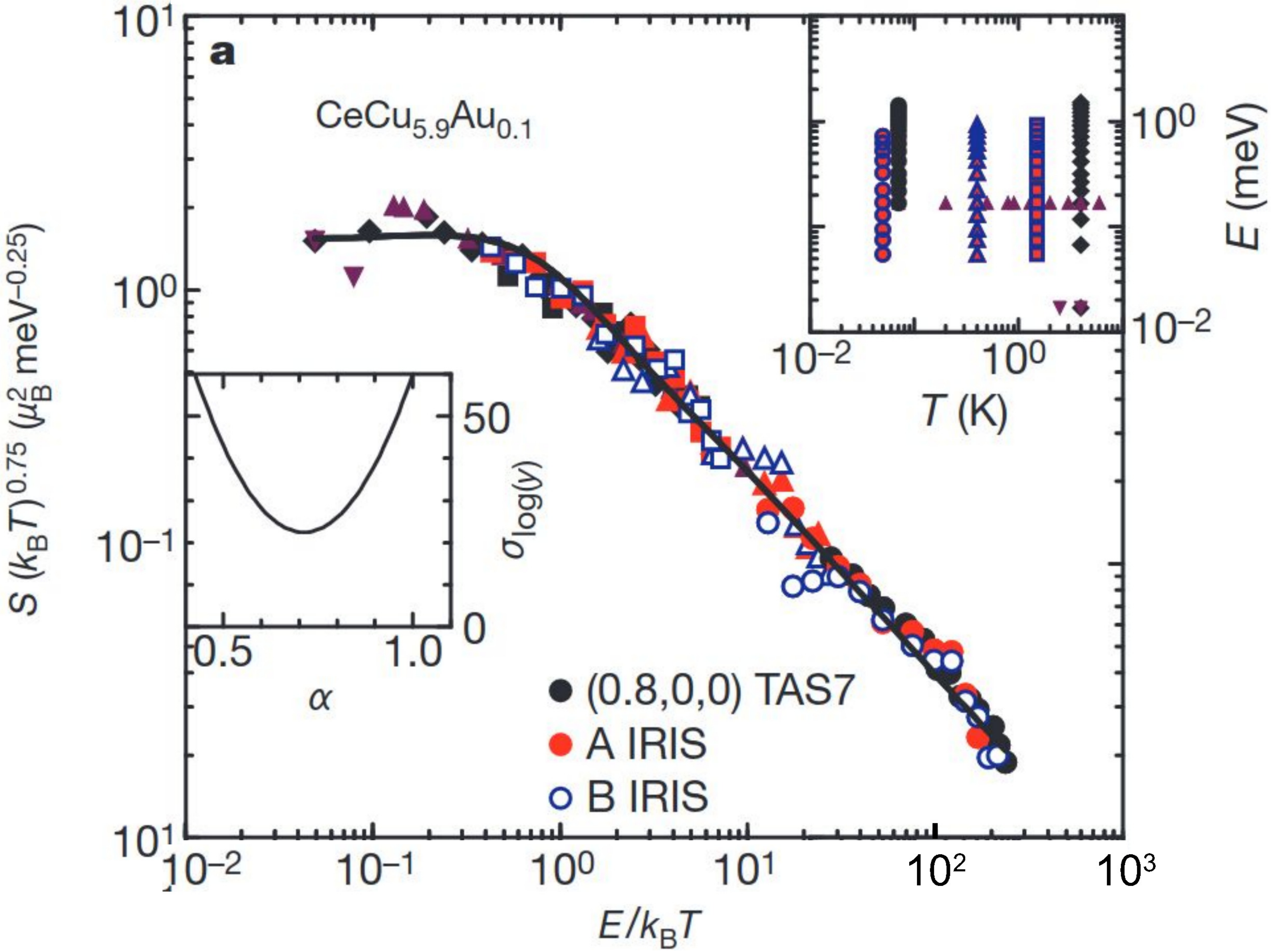
(Taupin & SP, Crystals 12 (2022) 251 and refs. herein)

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



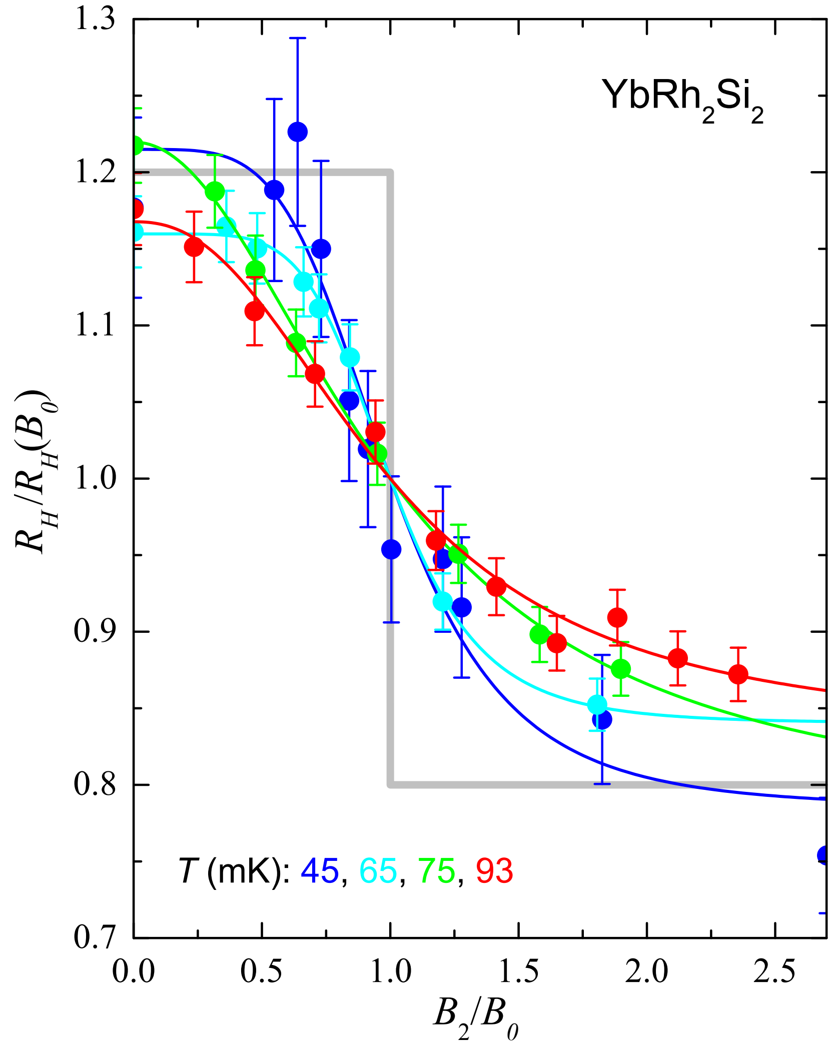
(Nguyen et al., Nat. Commun. 12 (2021) 4341)

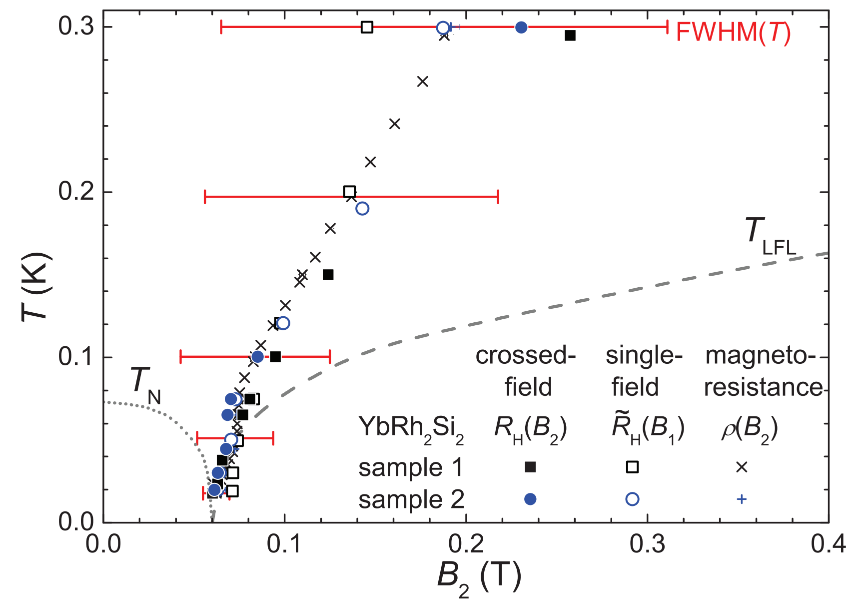
Deviations from GLW: E/T scaling in INS in $CeCu_{5.9}Au_{0.1}$

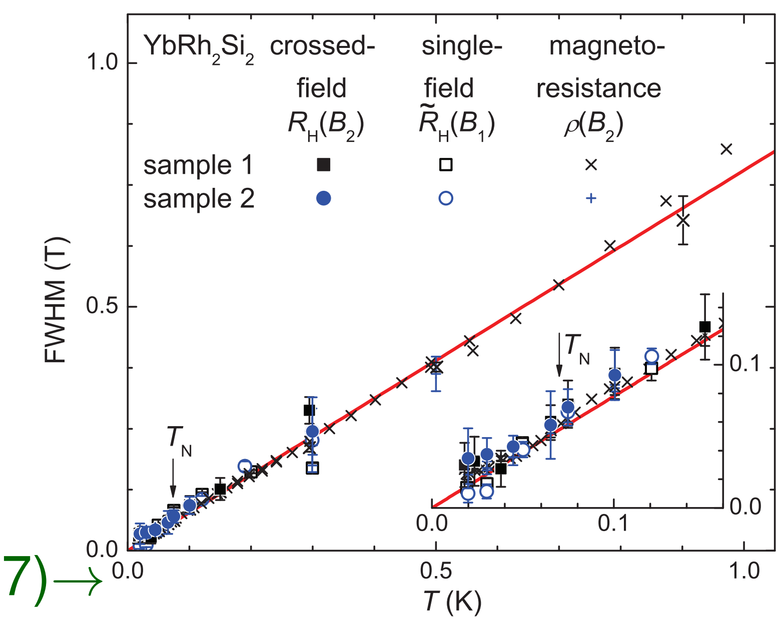


(Schröder et al., Nature 407 (2000) 351; theory: Si et al., ibid 413 (2001) 804)

Deviations from GLW: Jump in Hall effect in $YbRh_2Si_2$







(SP et al., Nature 432 (2004) 881) ↑

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

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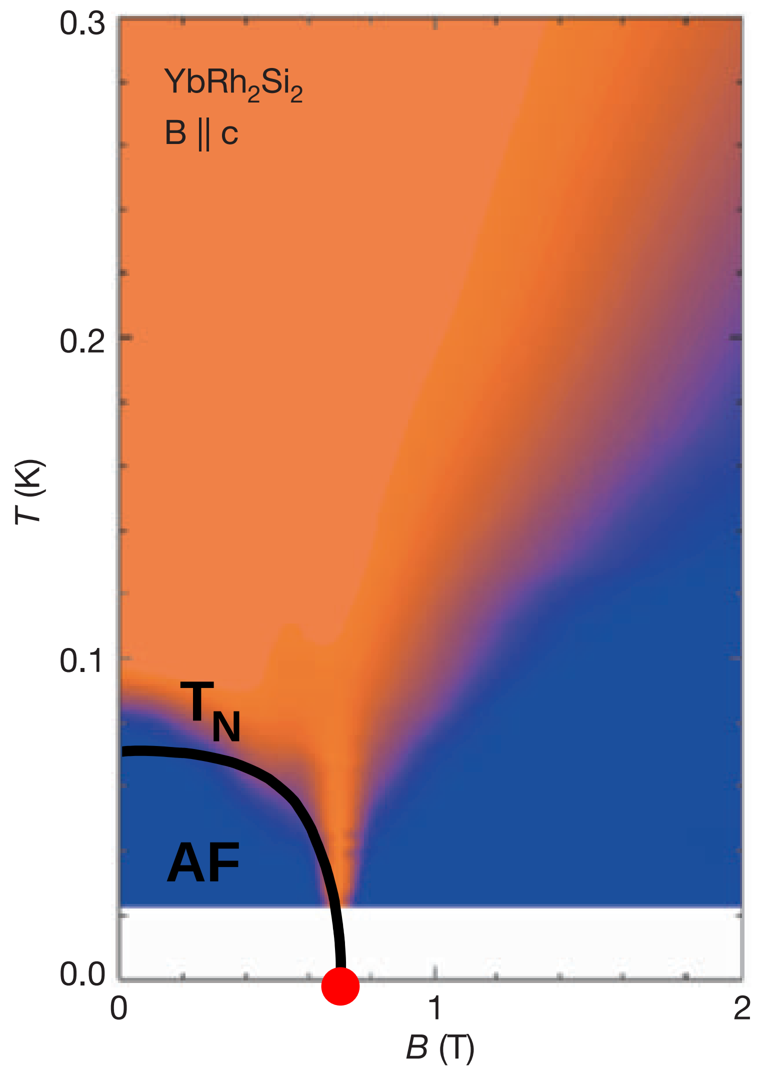
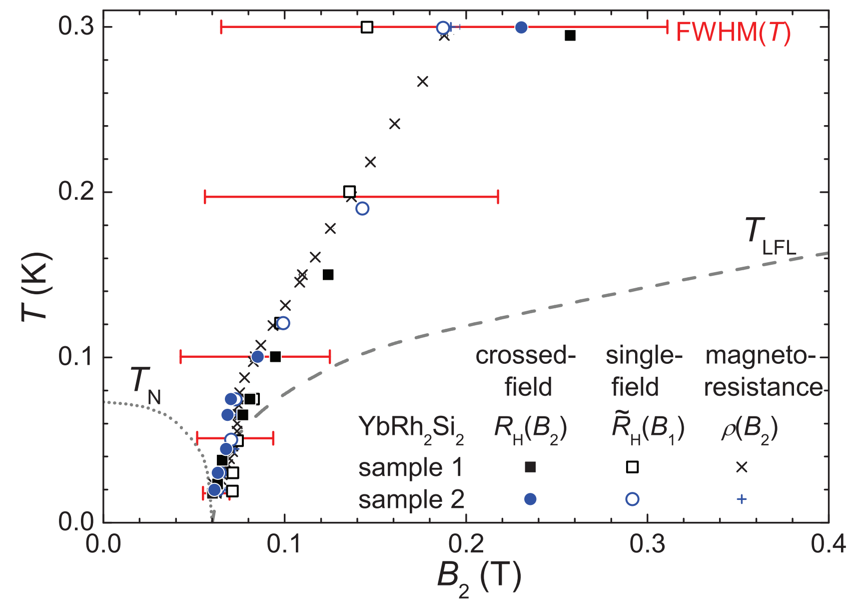
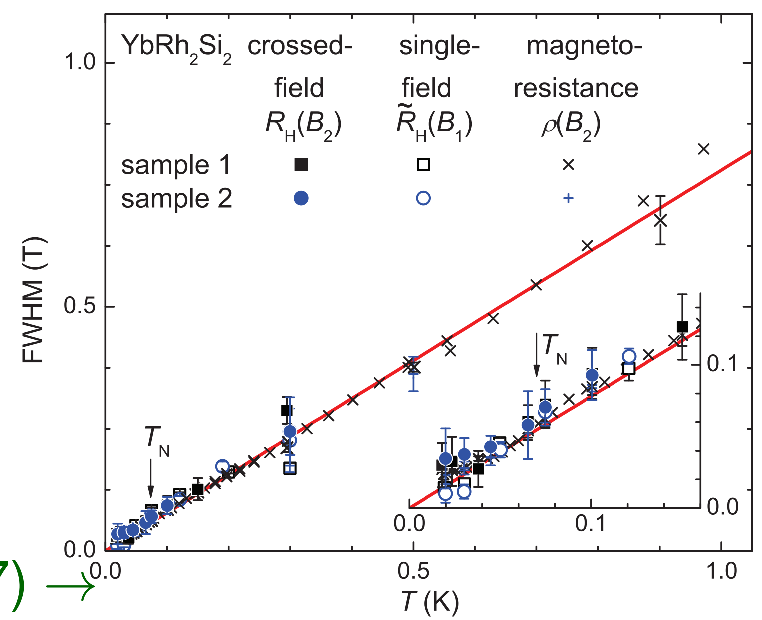


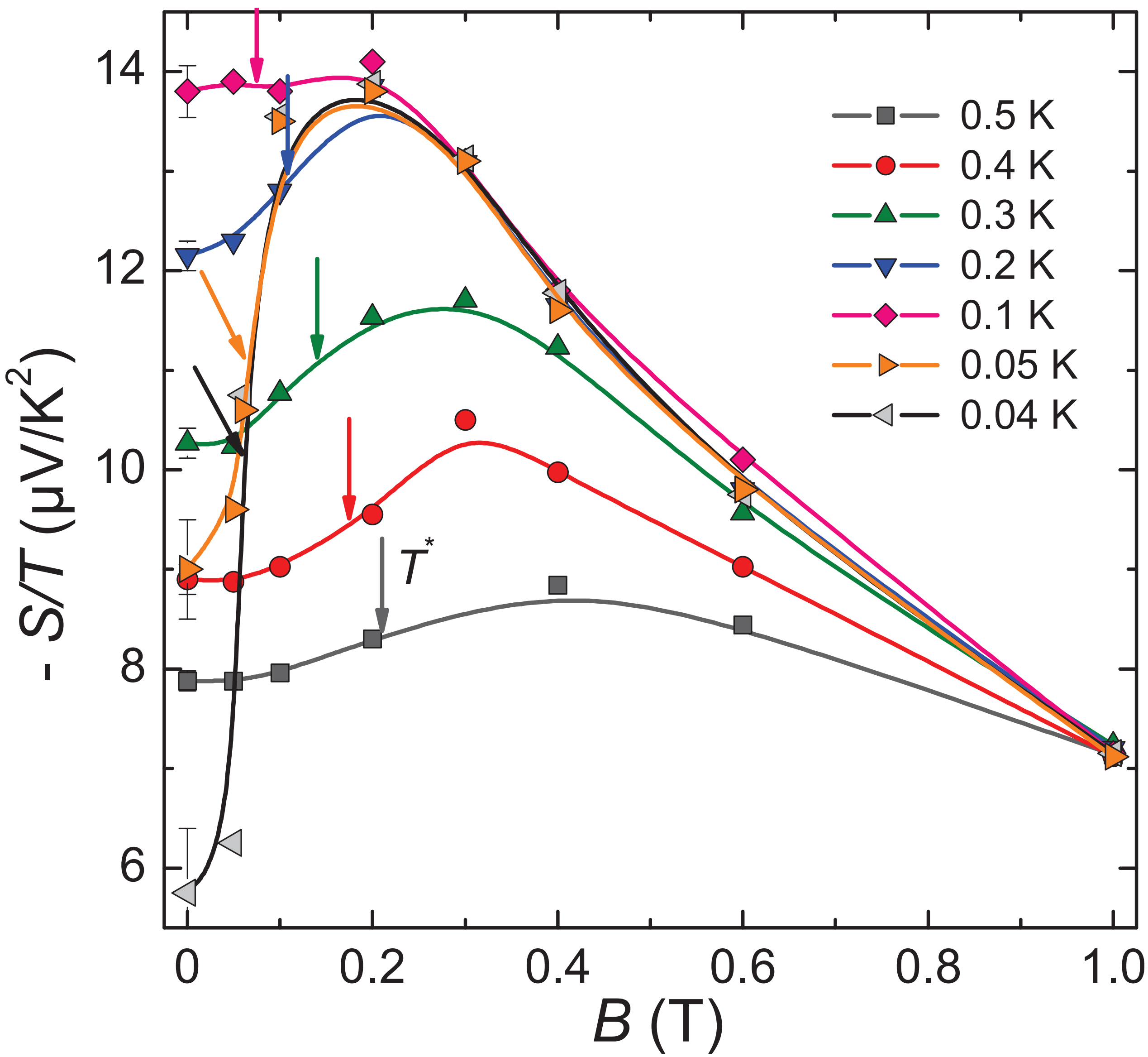




(Custers et al., Nature 424 (2003) 524) ↑

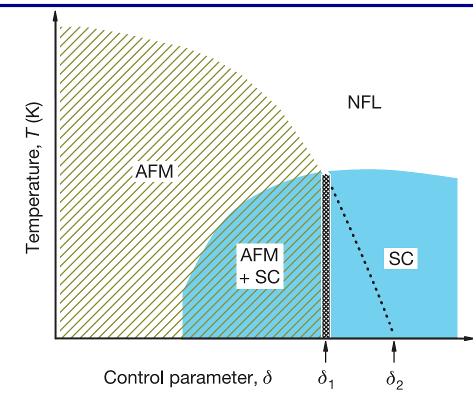
(Friedemann et al., PNAS **107** (2010) 14547) →

Deviations from GLW: Jump in thermopower in $YbRh_2Si_2$

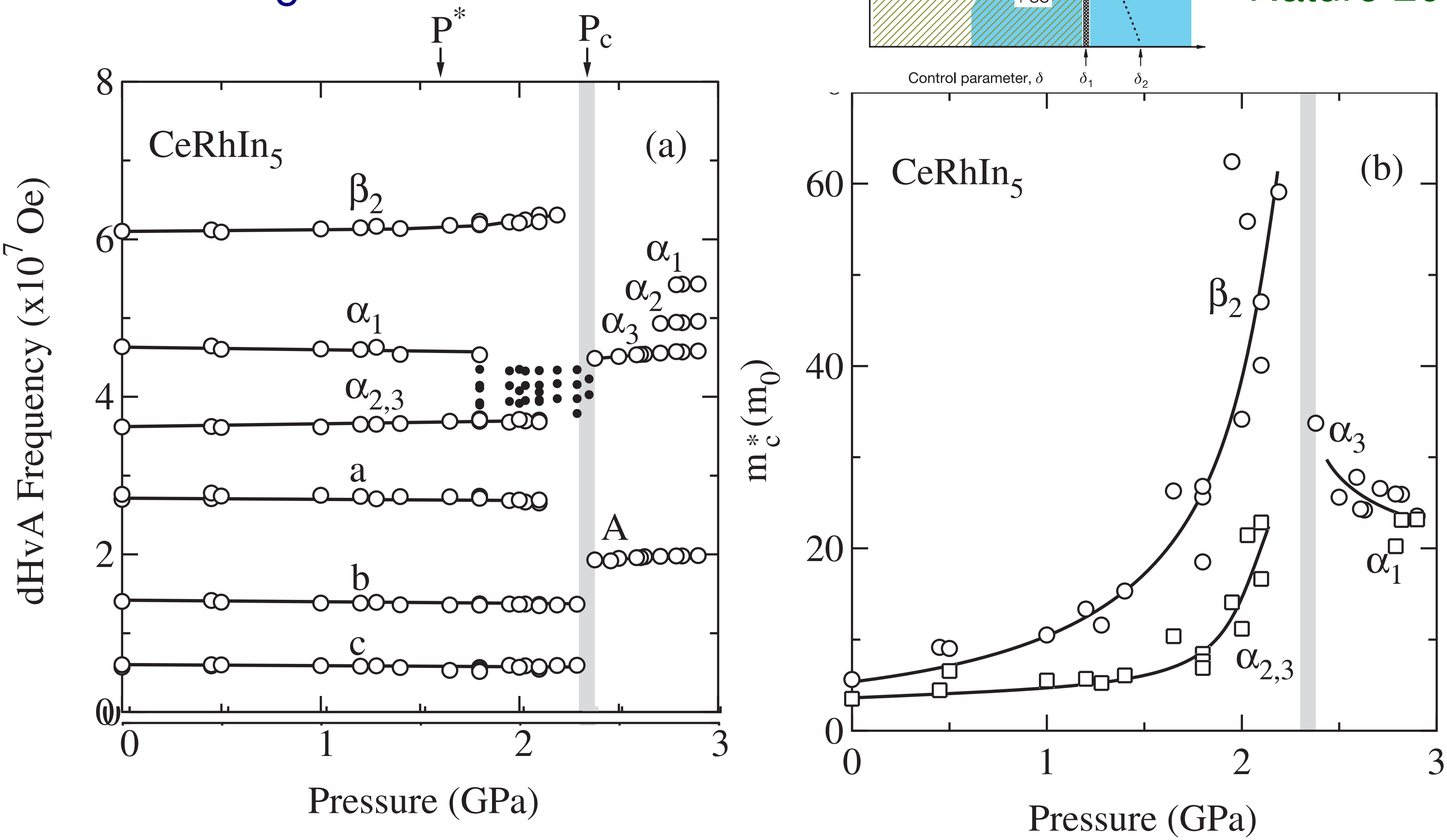


(Hartmann et al., Phys. Rev. Lett. 104 (2010) 096402)

Deviations from GLW: De Haas-van Alphen study in $CeRhIn_5$

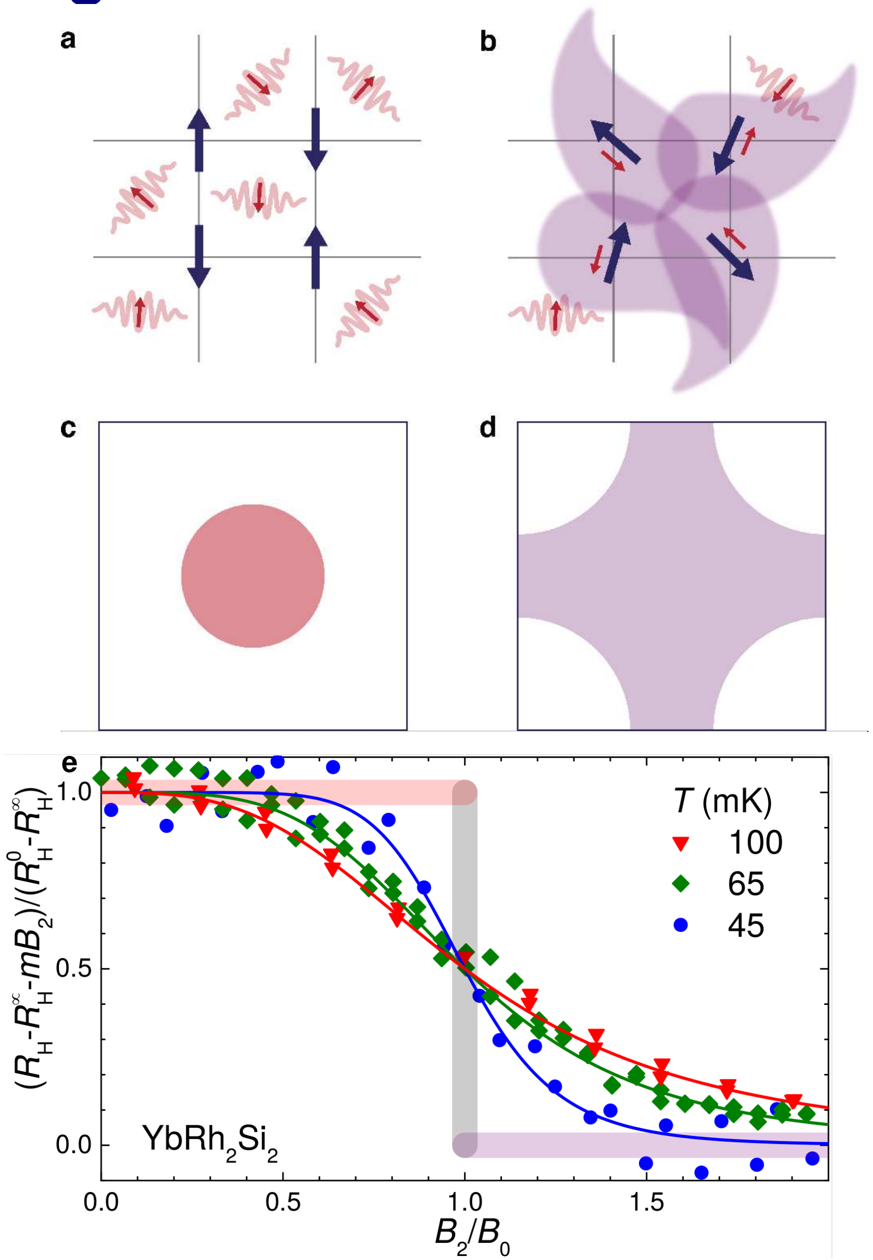


(Park et at. Nature 2006)



(Shishido et al., JPSJ 74 (2005) 1103)

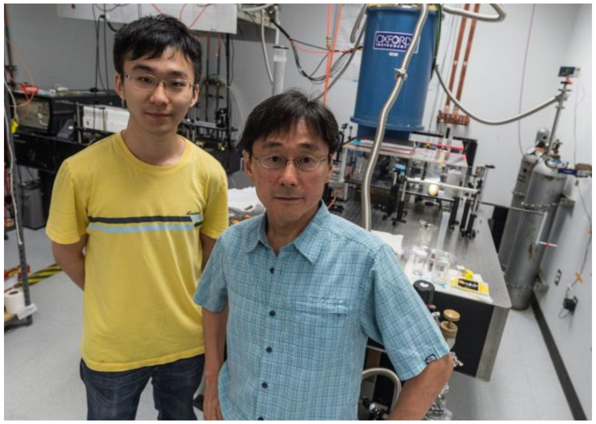
Understanding in terms of Kondo destruction



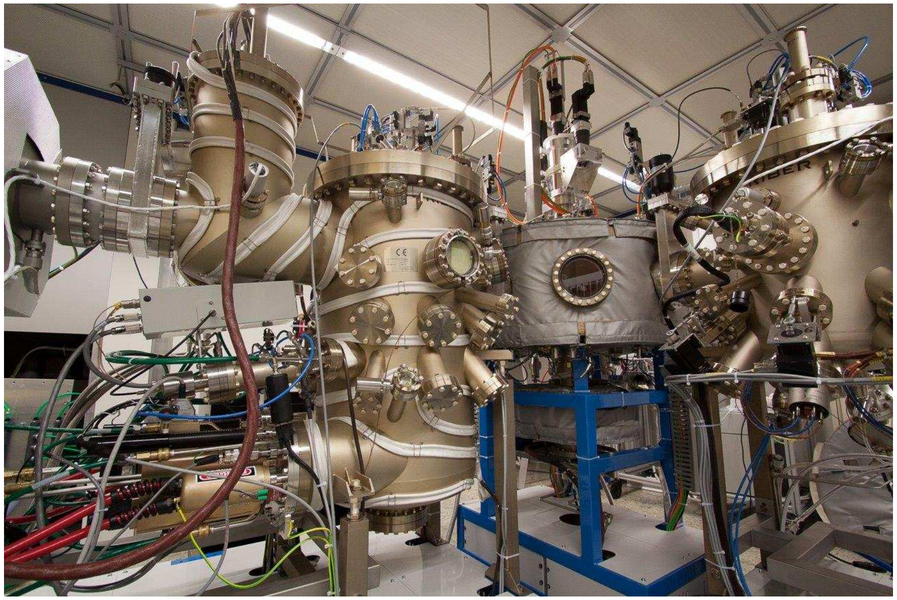
(SP & Si, Nat. Rev. Phys. 3 (2021) 9)

Dynamical charge response: THz time-domain transmission spectroscopy

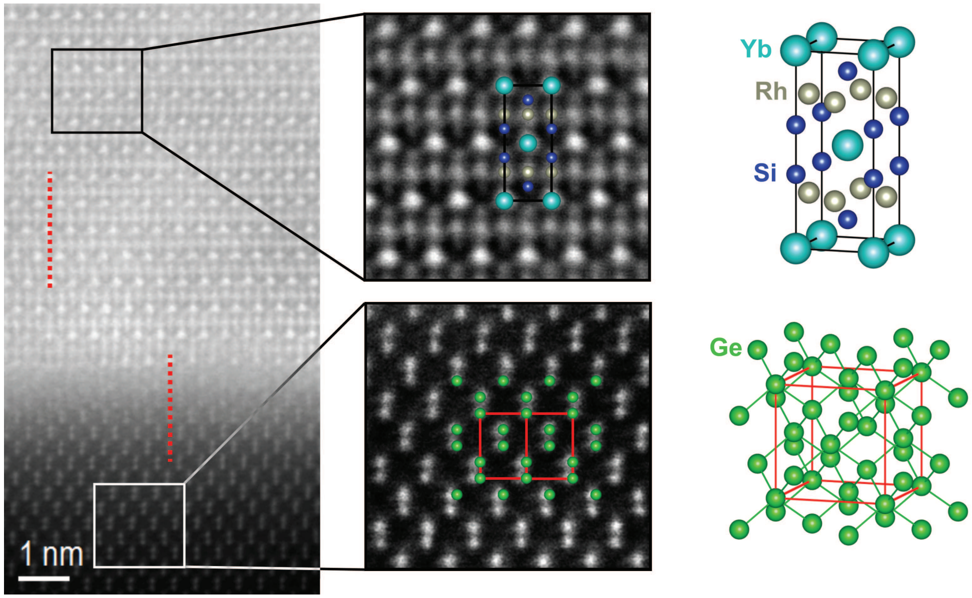
- Real and imag. part of $\sigma(\omega)$
- No Kramers-Kronig transformation
- Thin films needed!



Molecular beam epitaxy system



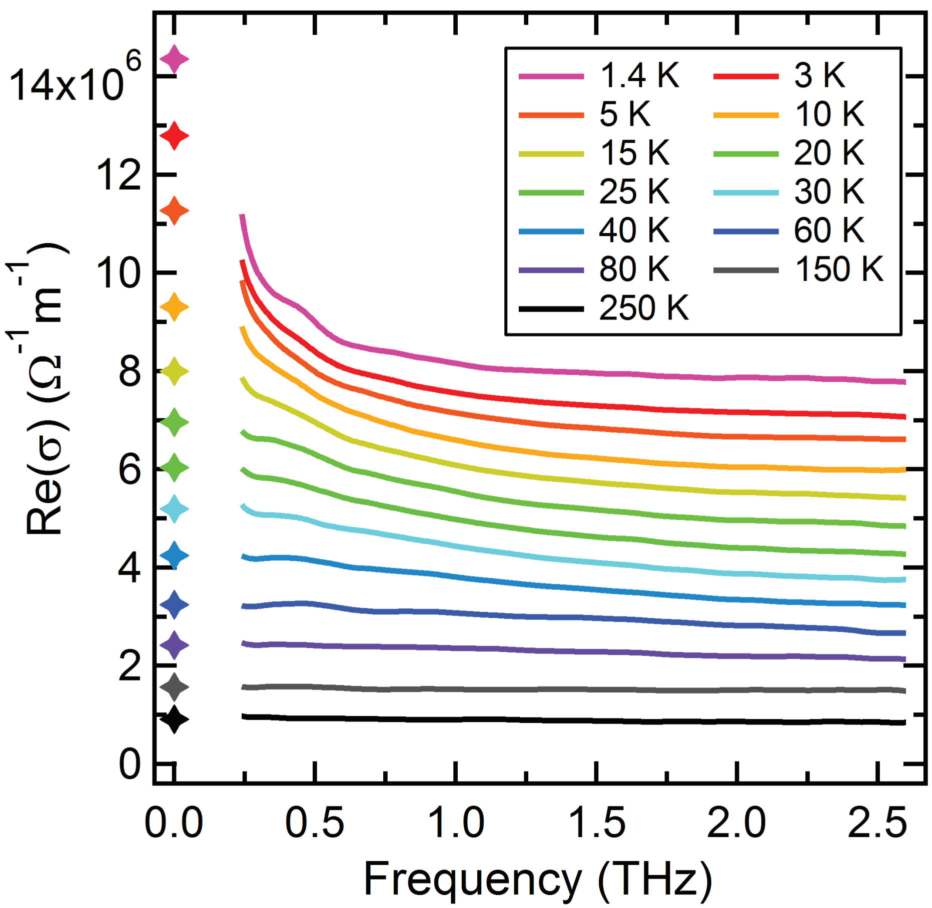
HAADF-STEM image

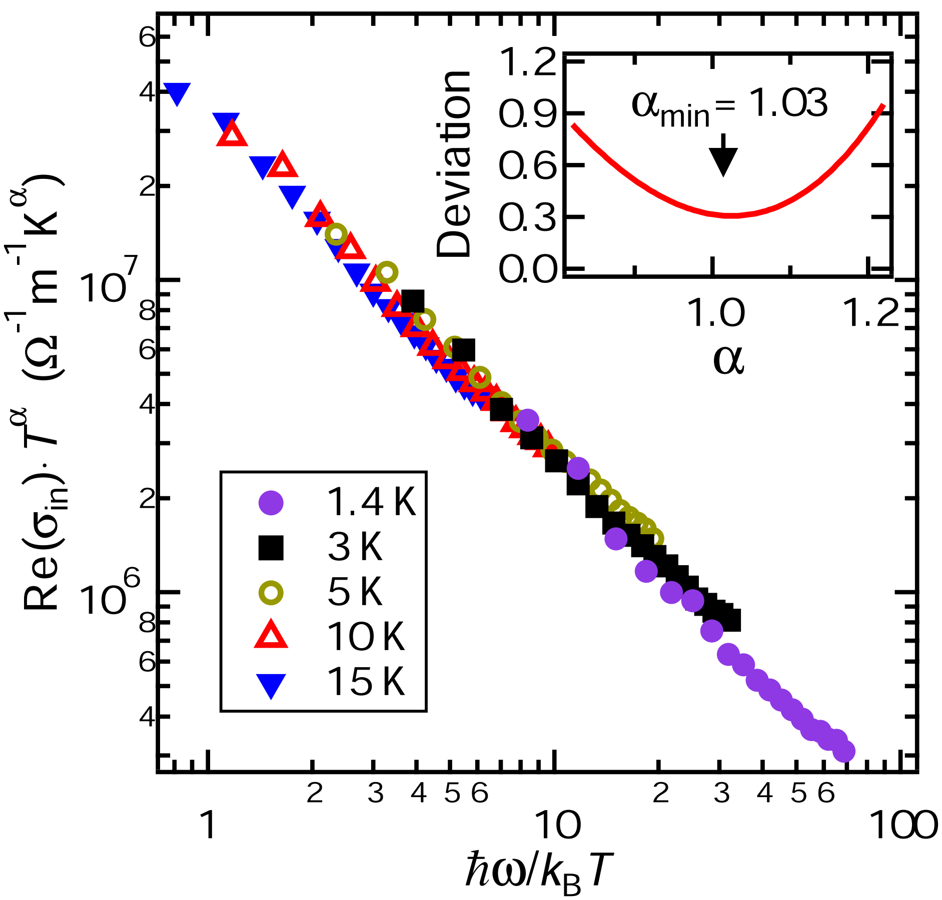


(Prochaska et al., Science 367 (2020) 285)

Dynamical scaling of optical conductivity in $YbRh_2Si_2$

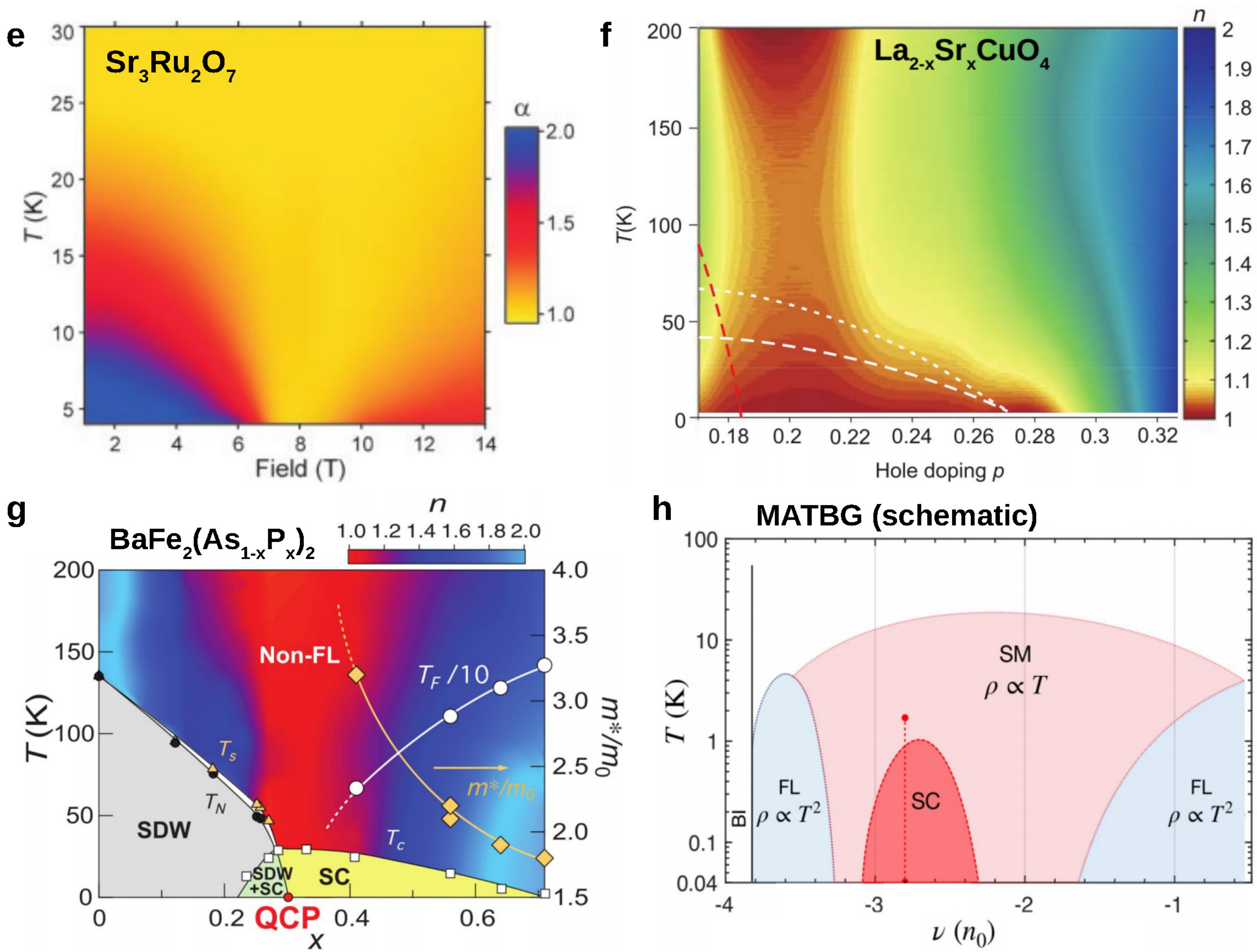
THz time-domain transmission spectroscopy on MBE films of $YbRh_2Si_2$





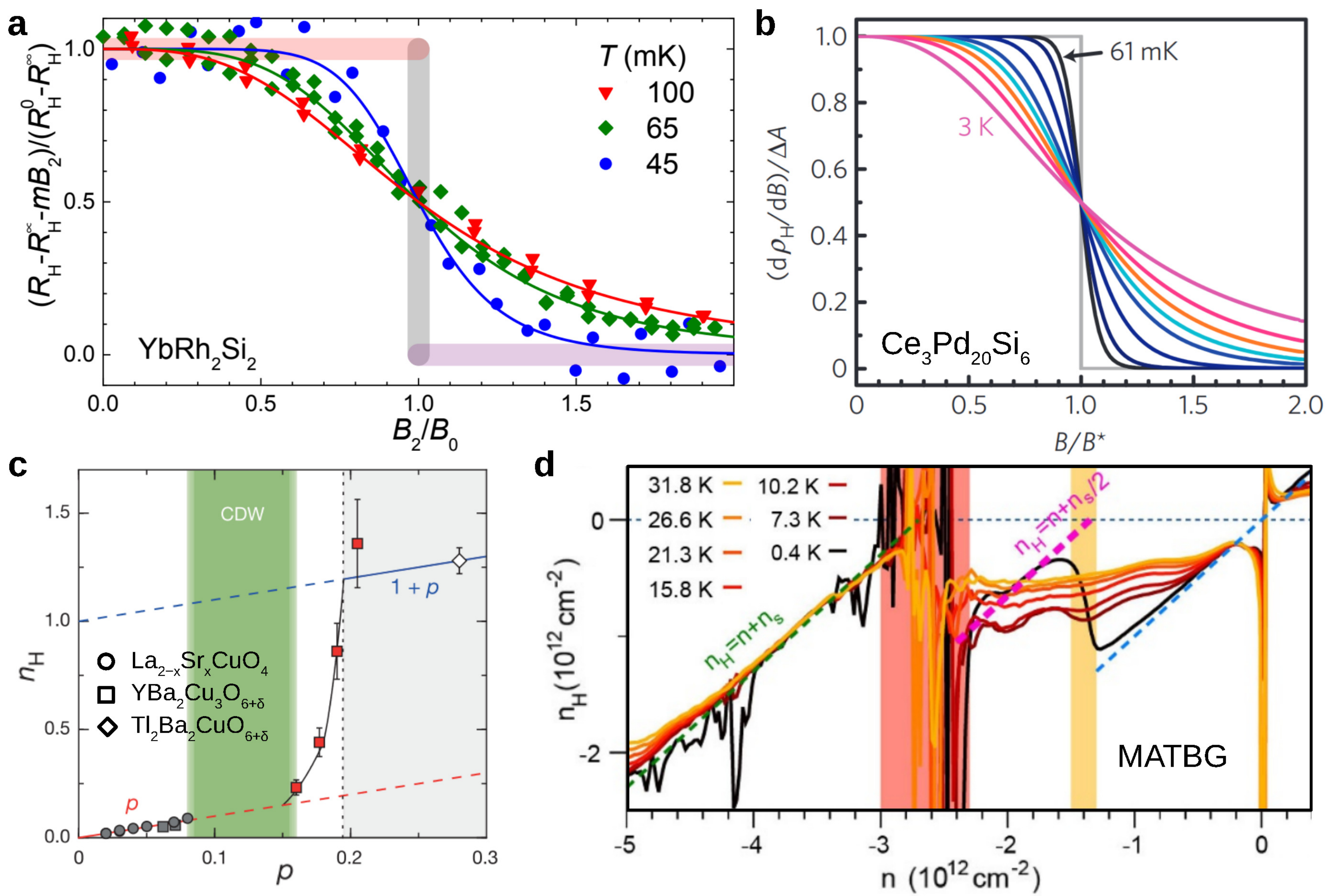
(Prochaska et al., Science 367 (2020) 285)

Relation to other SCES: Strange metal behavior



(Taupin & SP, Crystals 12 (2022) 251 and refs. herein)

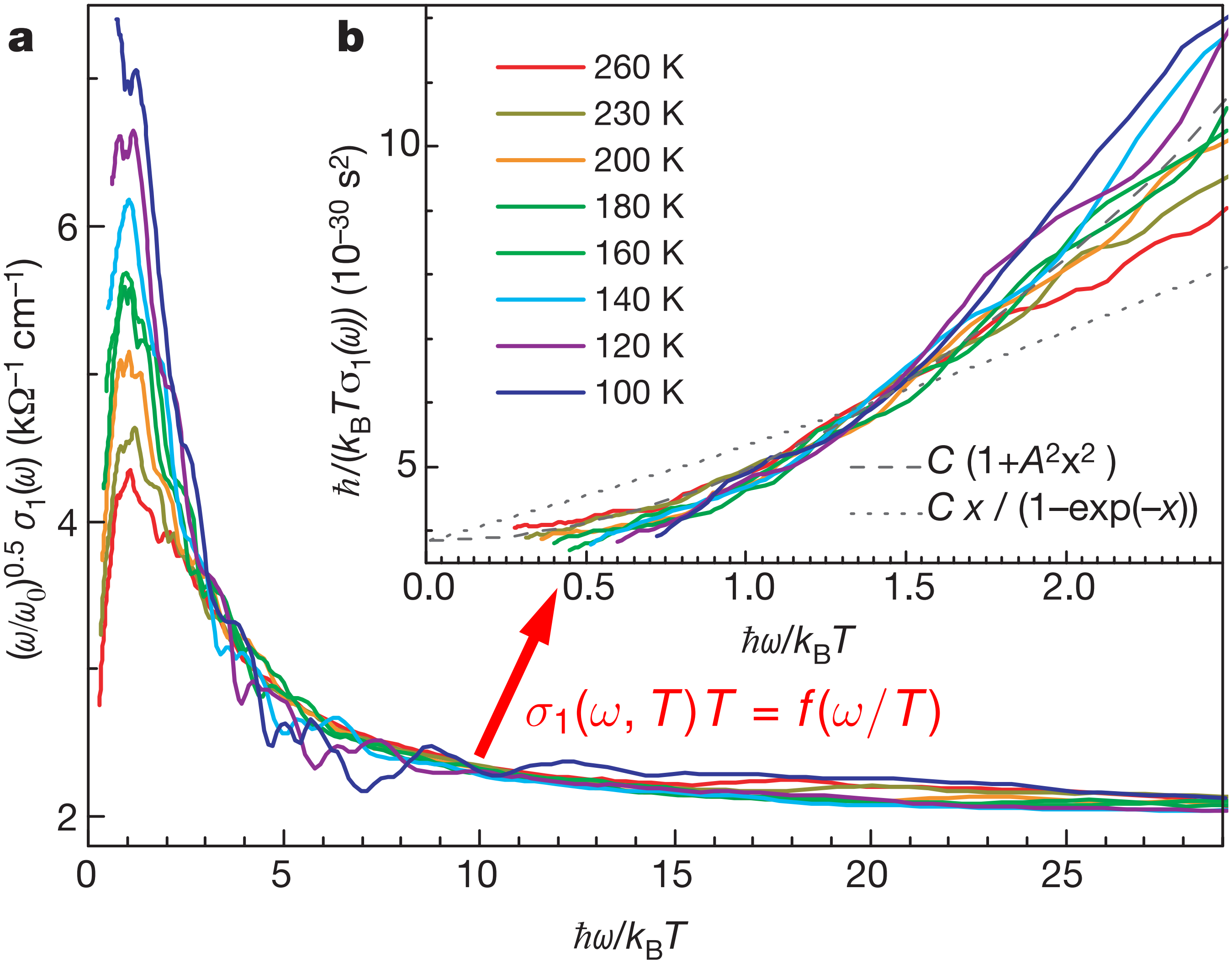
Relation to other SCES: Carrier (de)localization

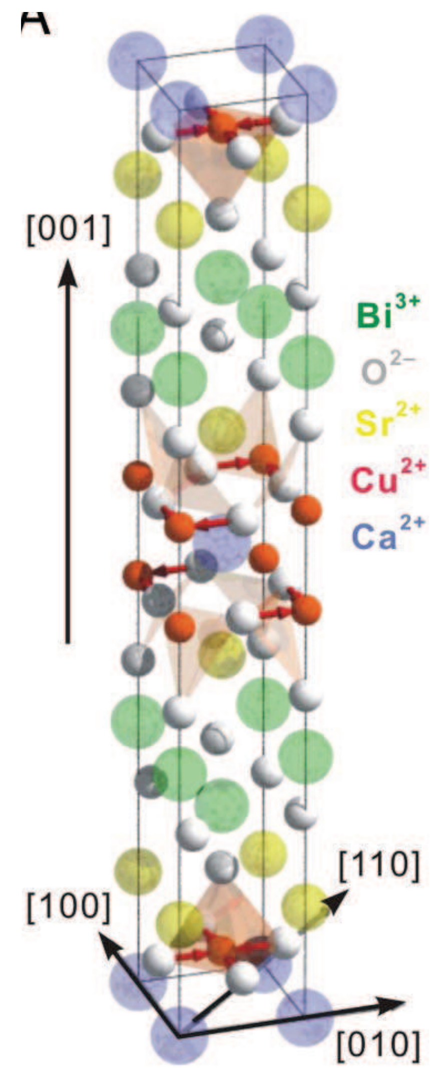


(M. Taupin & SP, Crystals 12 (2022) 251 and refs. herein)

Relation to other SCES: Dynamical scaling in $\sigma(\omega)$ in cuprates

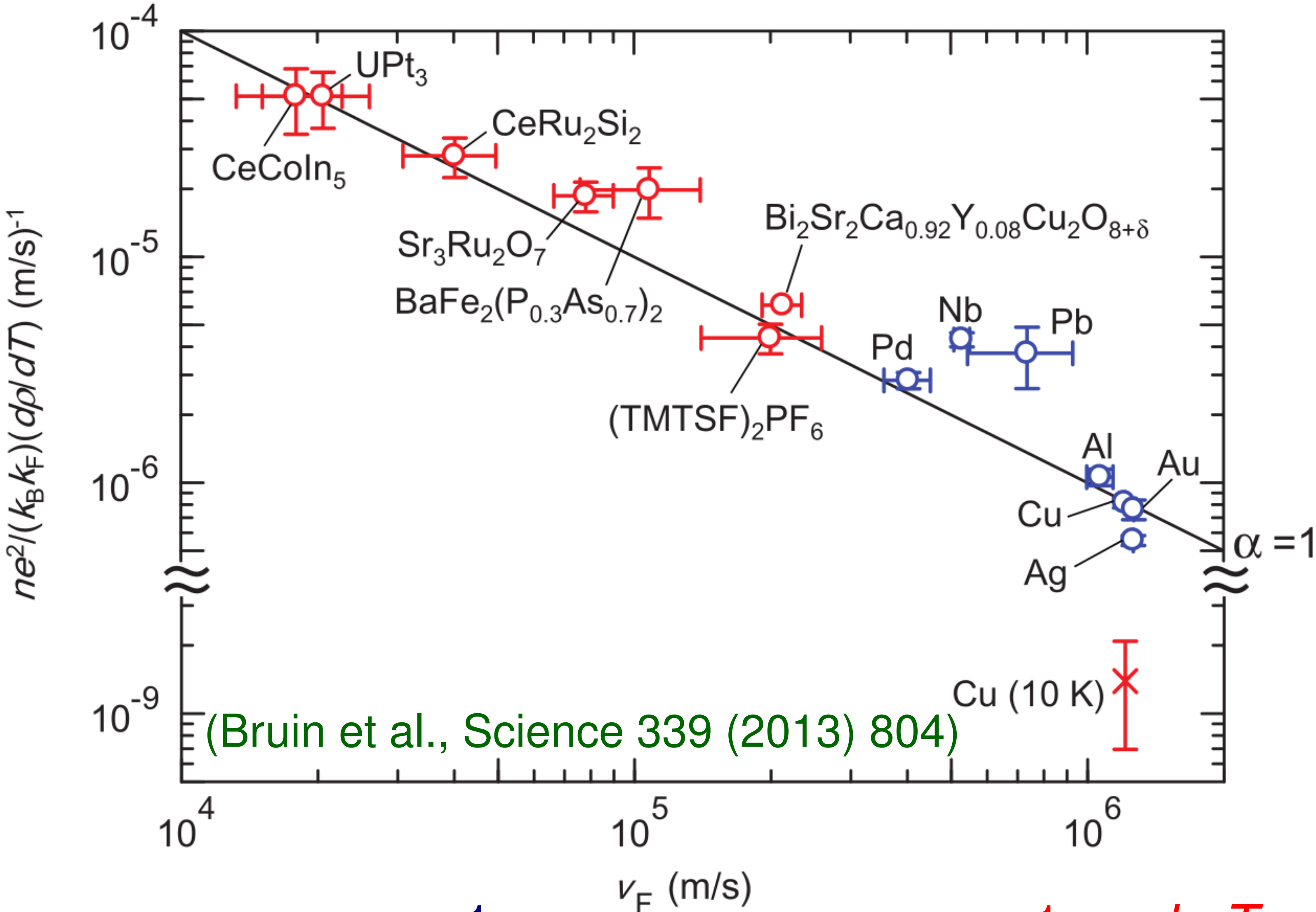
Optical conductivity of optimally doped $Bi_{2.23}Sr_{1.9}Ca_{0.96}Cu_2O_{8+\delta}$





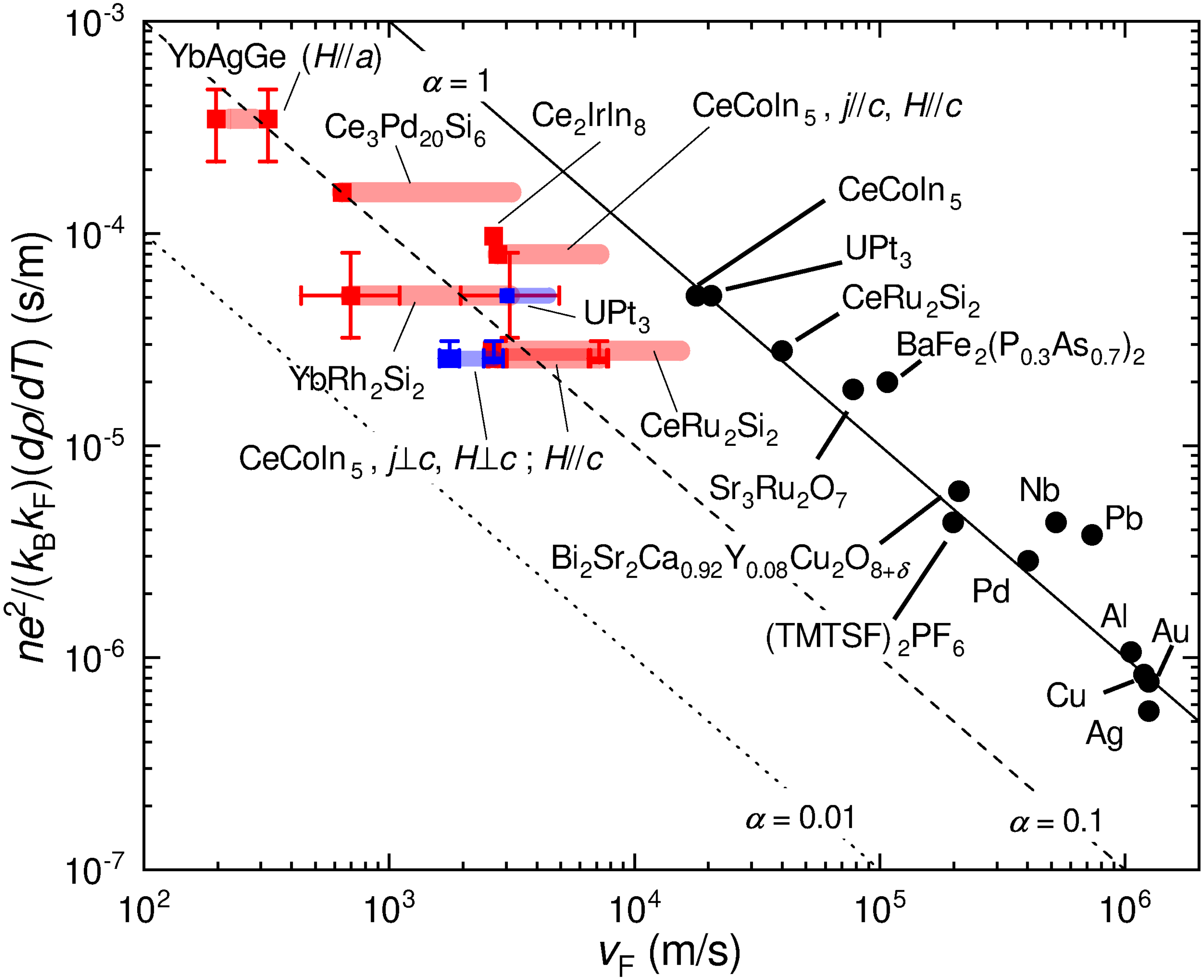
(van der Marel et al., Nature 425 (2003) 271) (Carbone et al., PNAS 2008)↑

Planckian dissipation? – Quantum oscillation data



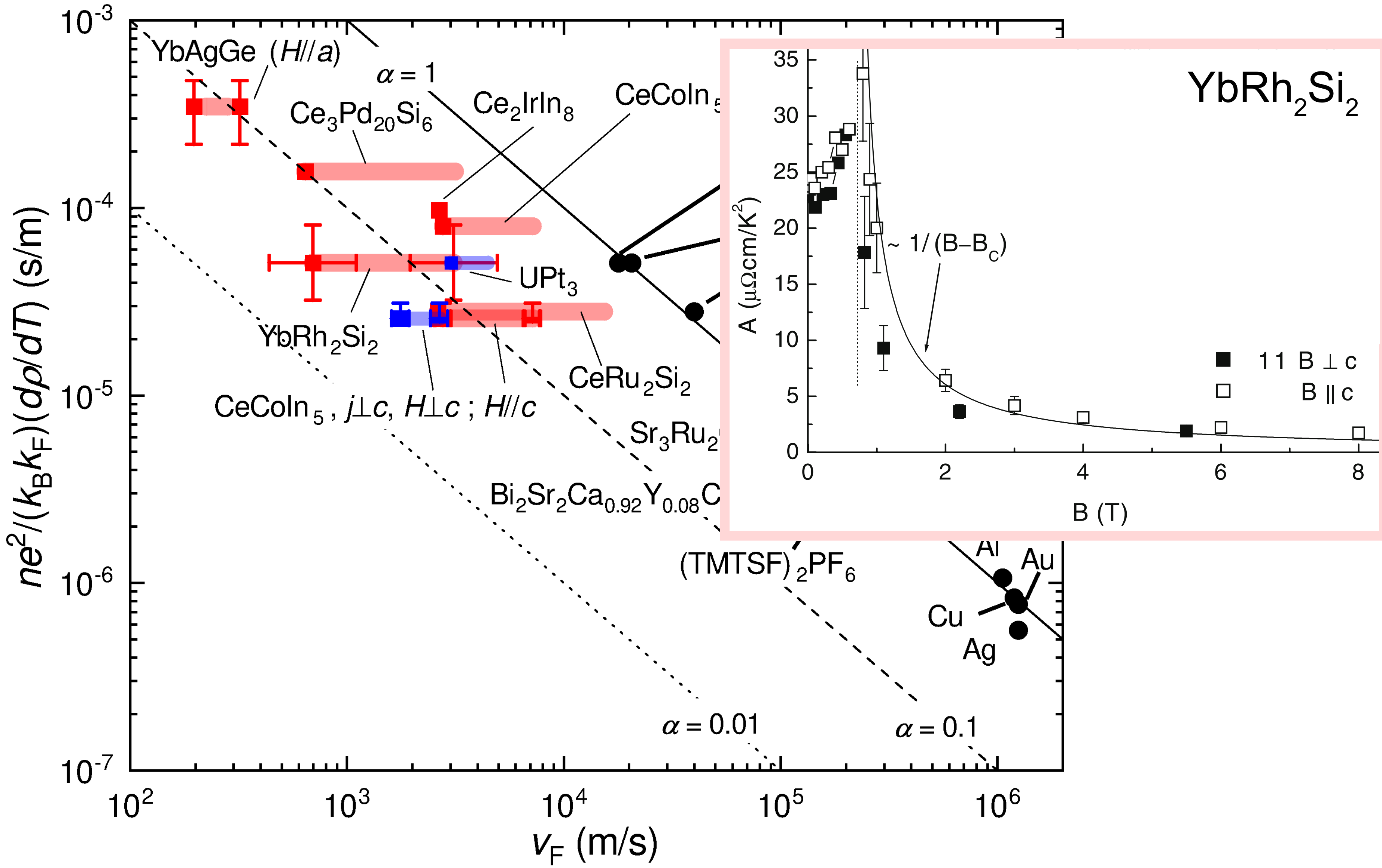
$$\rho - \rho_0 = A' T = \frac{m}{ne^2}\frac{1}{\tau}$$ Drude model with $$\frac{1}{\tau} = \alpha \frac{k_B T}{\hbar}$$

Planckian dissipation? – Low-T electrical transport



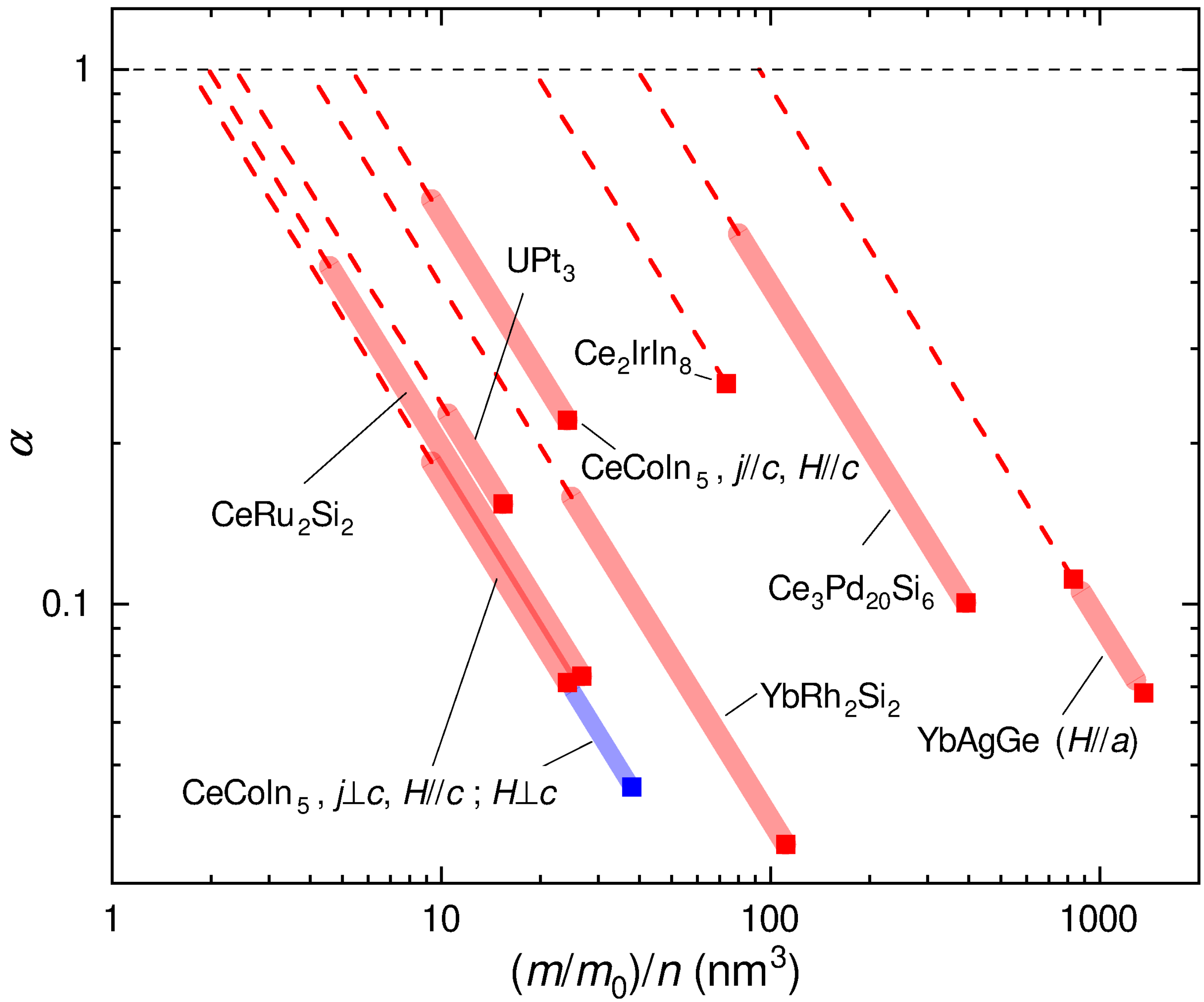
(M. Taupin & SP, Crystals 12 (2022) 251 and refs. herein)

Planckian dissipation? – Low-T electrical transport



(M. Taupin & SP, Crystals 12 (2022) 251 and refs. herein)

Planckian dissipation? – Low-T electrical transport

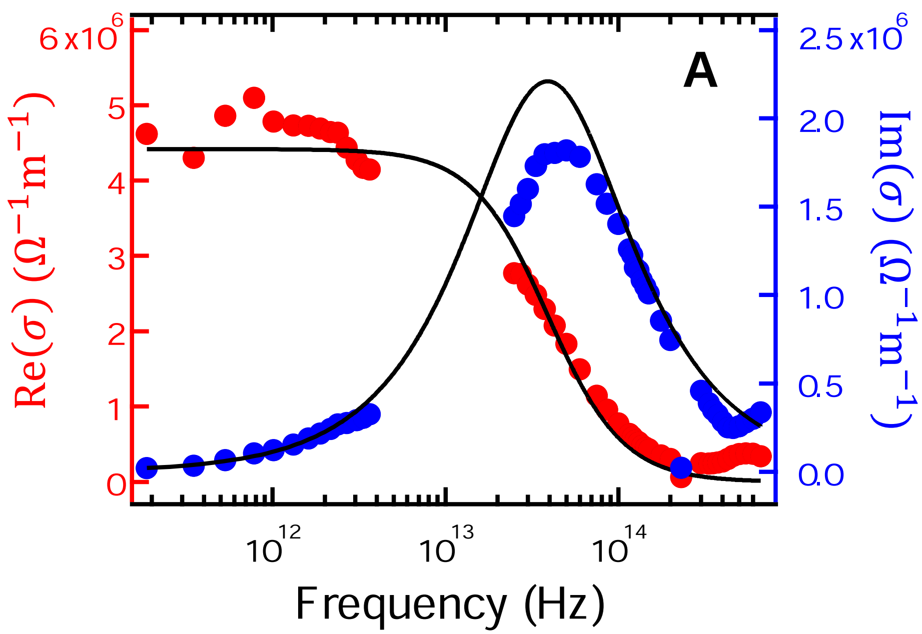


(M. Taupin & SP, Crystals 12 (2022) 251 and refs. herein)

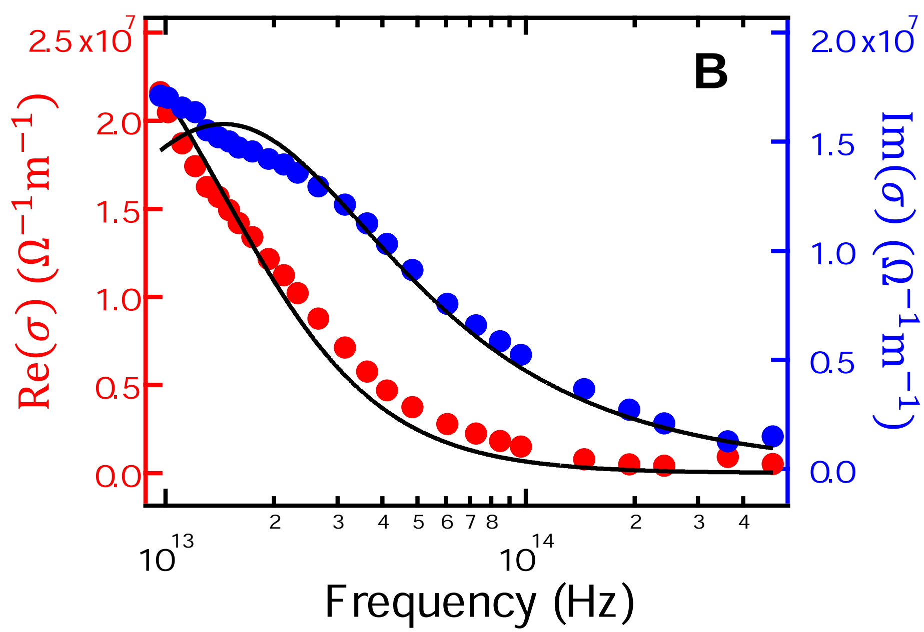
Planckian dissipation in optical conductivity?

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

Pb at room temperature

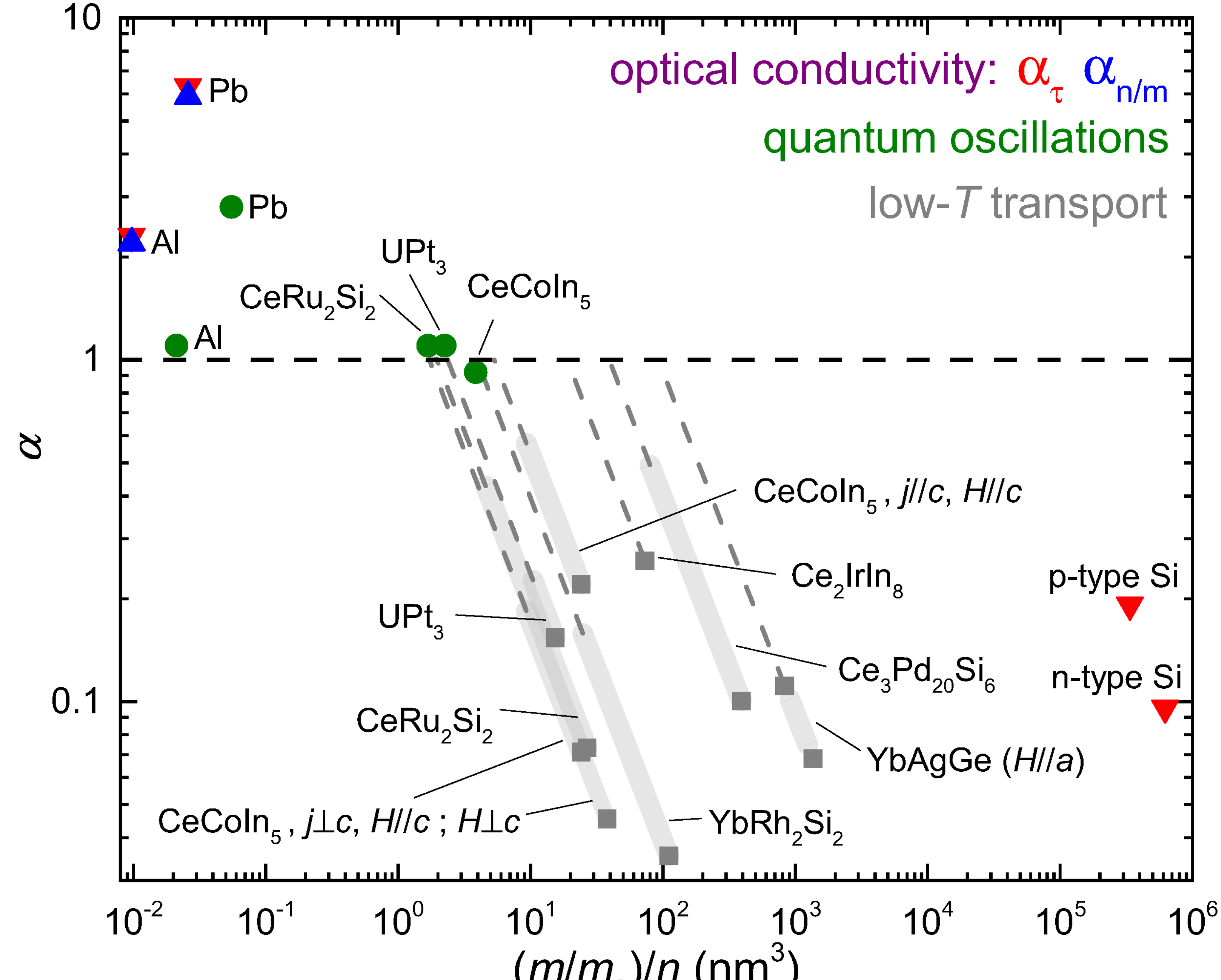


Al at room temperature



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

Planckian dissipation? – Optical conductivity data

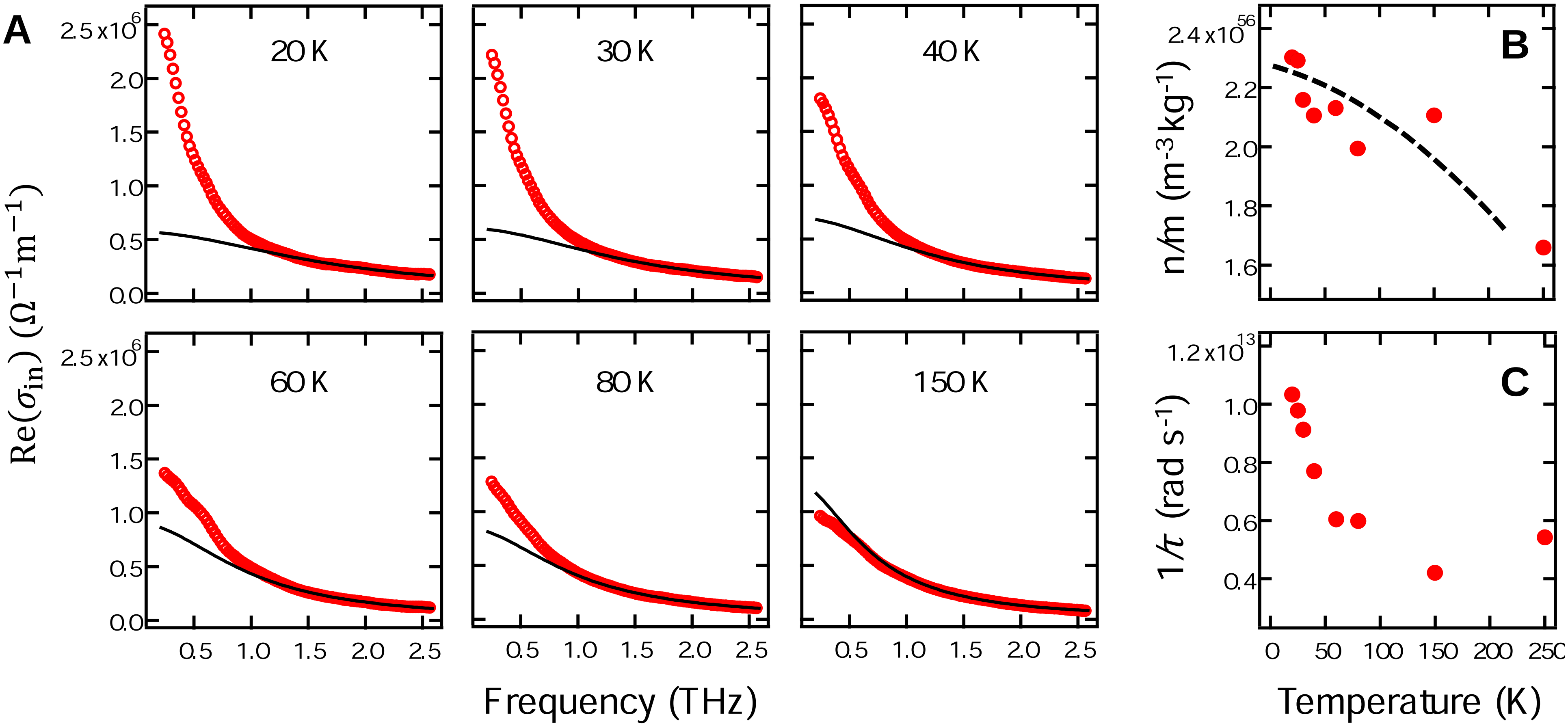


(Li, Kono, Si & SP, arXiv:2205.13382)

Planckian dissipation in optical conductivity?

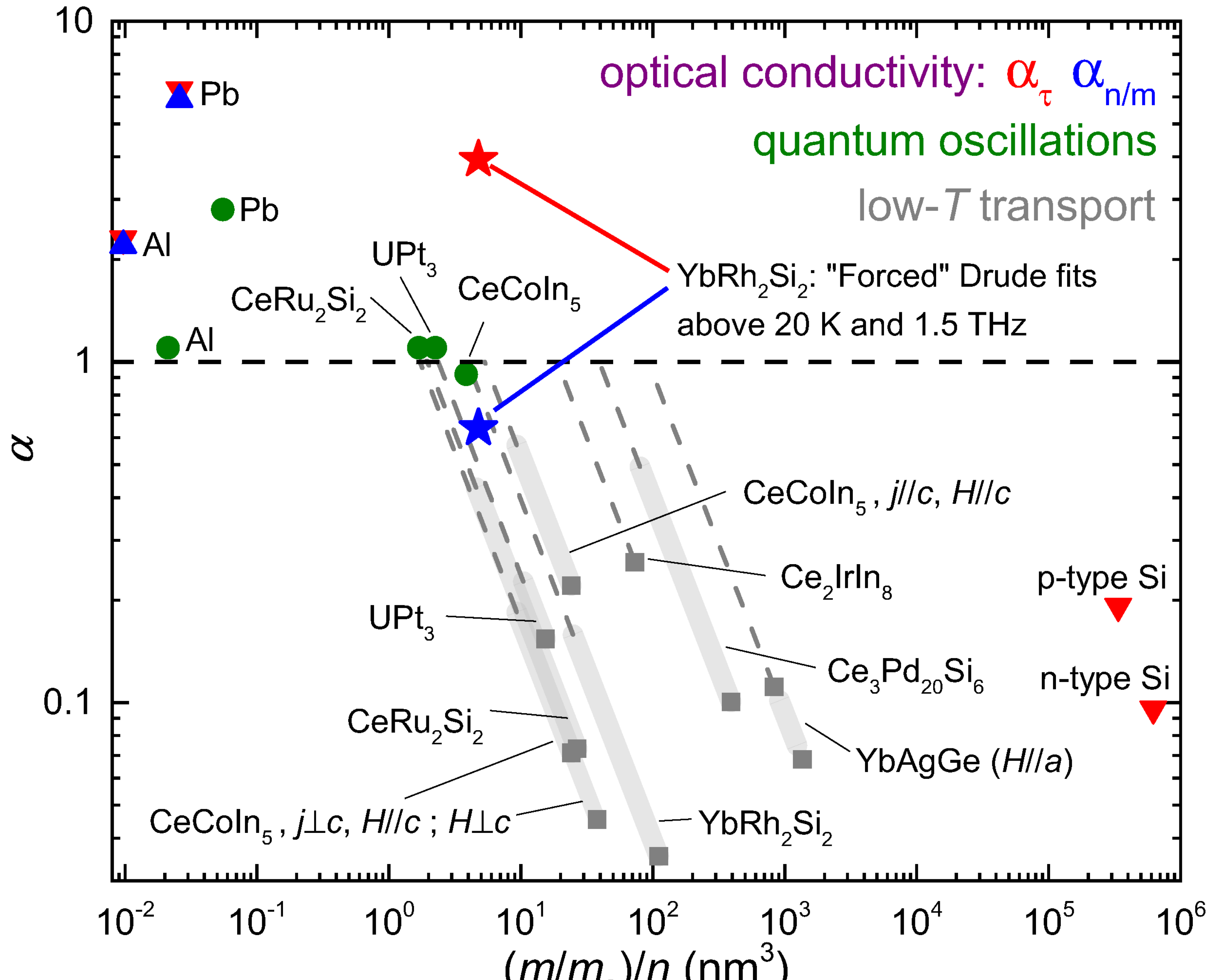
$YbRh_2Si_2$: Non-Drude behavior in strange metal regime

$\rightarrow$ Force Drude fit to high T and ω data



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

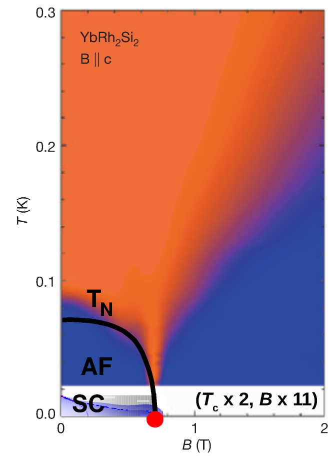
Planckian dissipation? – Optical conductivity data



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

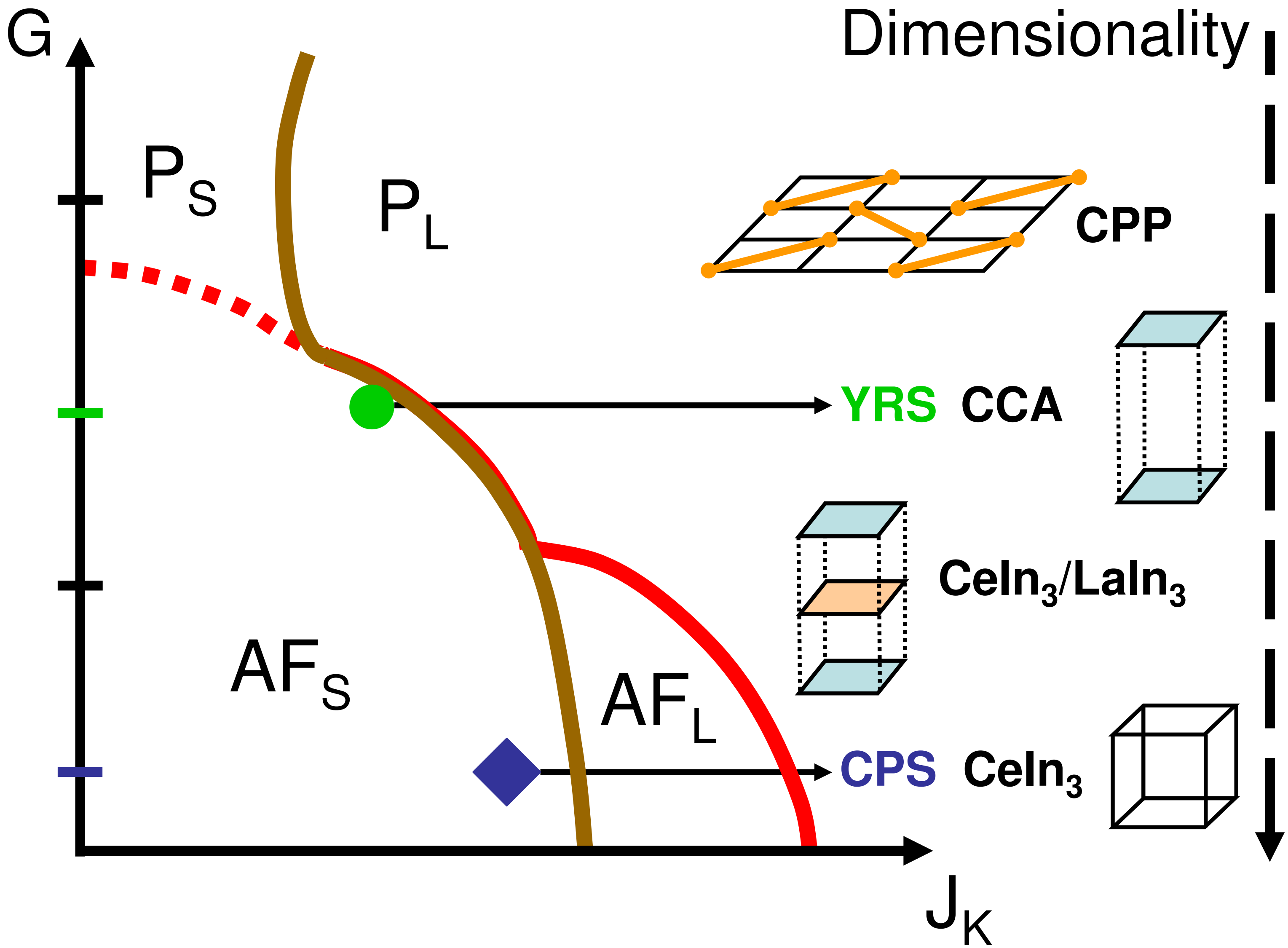
Heavy fermion systems

From quantum criticality to electronic topology



- Tunable correlation strength
- Phase diagrams governed by quantum fluctuations
- Quantum criticality from vanishing order parameter
- Beyond order-parameter quantum criticality
- **Global phase diagram of heavy fermion compounds**
- Emergent phases: Unconventional superconductivity

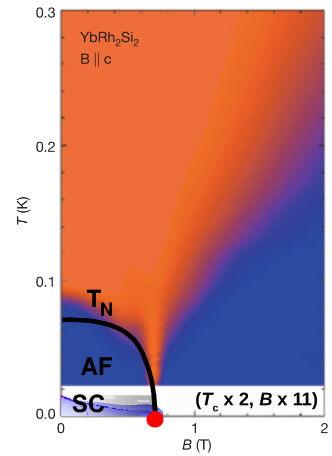
Global phase diagram of heavy fermion metals



(Custers et al., Nature Mater. 11 (2012) 189; Si, Physica B 378-380 (2006) 23)

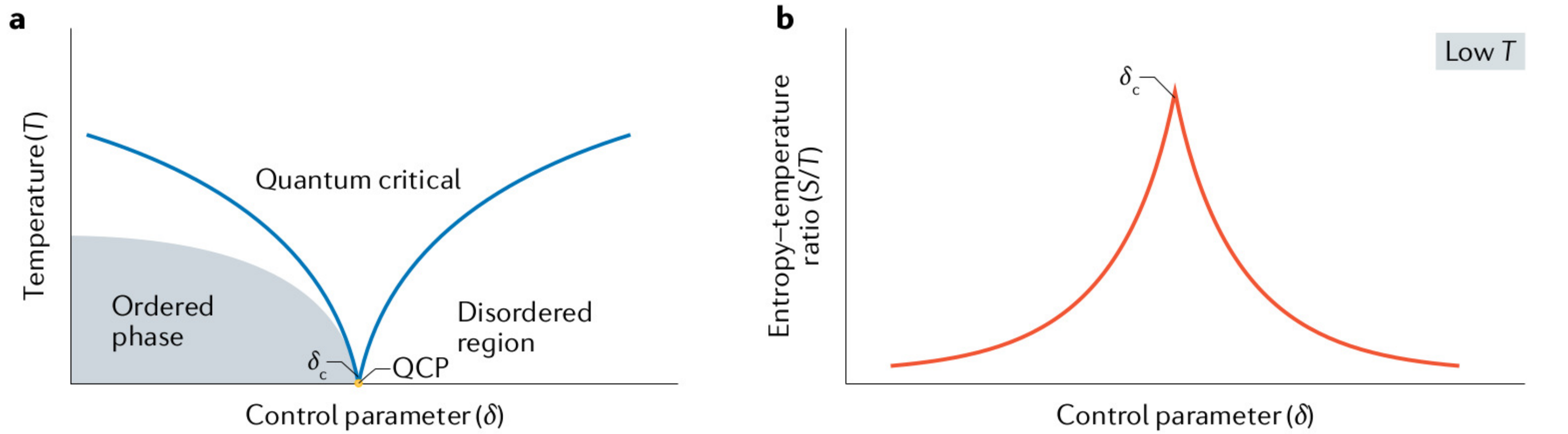
Heavy fermion systems

From quantum criticality to electronic topology

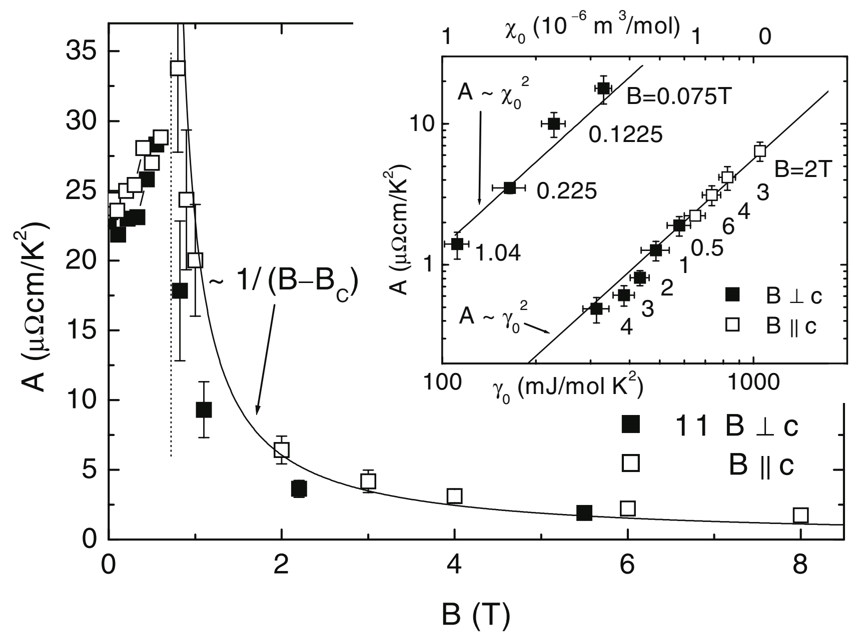


- Tunable correlation strength
- Phase diagrams governed by quantum fluctuations
- Quantum criticality from vanishing order parameter
- Beyond order-parameter quantum criticality
- Global phase diagram of heavy fermion compounds
- **Emergent phases: Unconventional superconductivity**

Entropy accumulation at quantum critical point

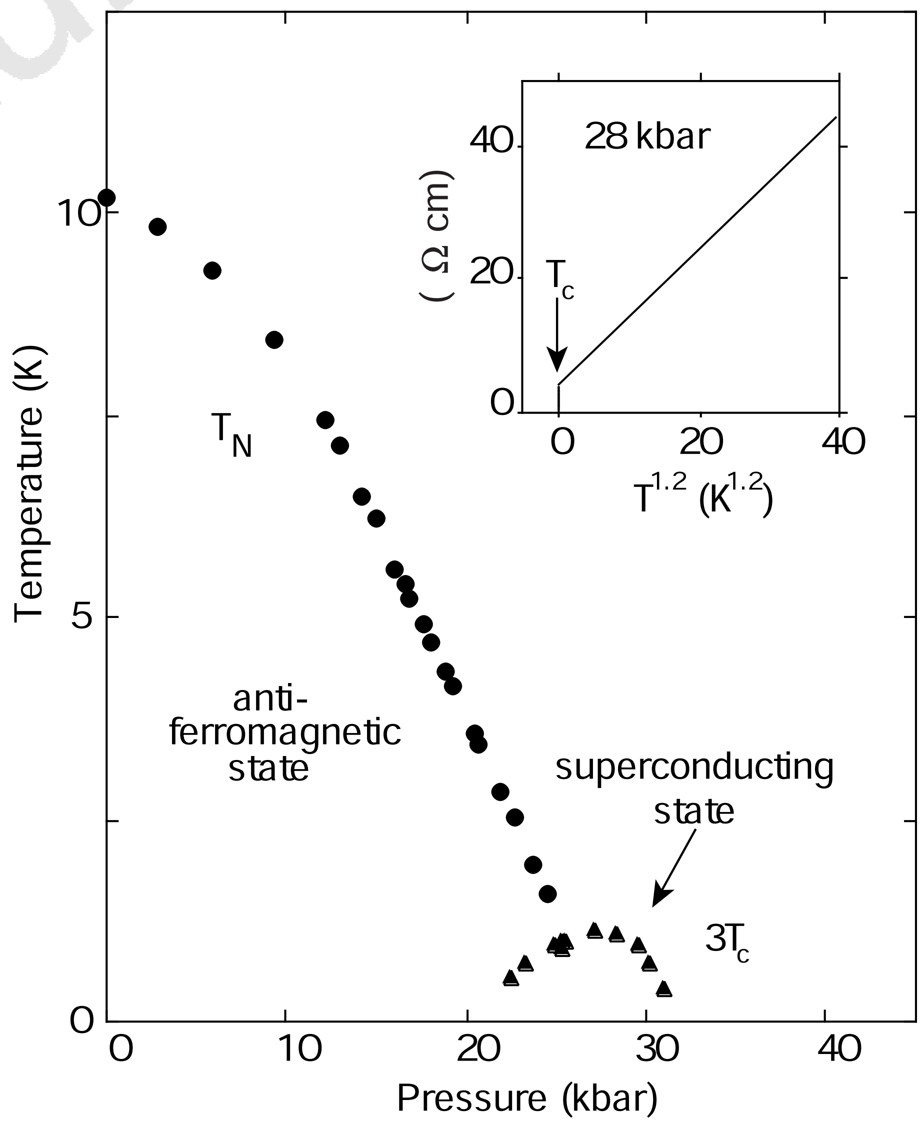


YbRh$_2$Si$_2$:



(SP & Si, Nat. Rev. Phys. 3 (2021) 9 (top); Gegenwart et al., Phys. Rev. Lett. 89 (2002) 056402 (bottom))

LGW QCPs lead to spin fluctuation mediated sc pairing

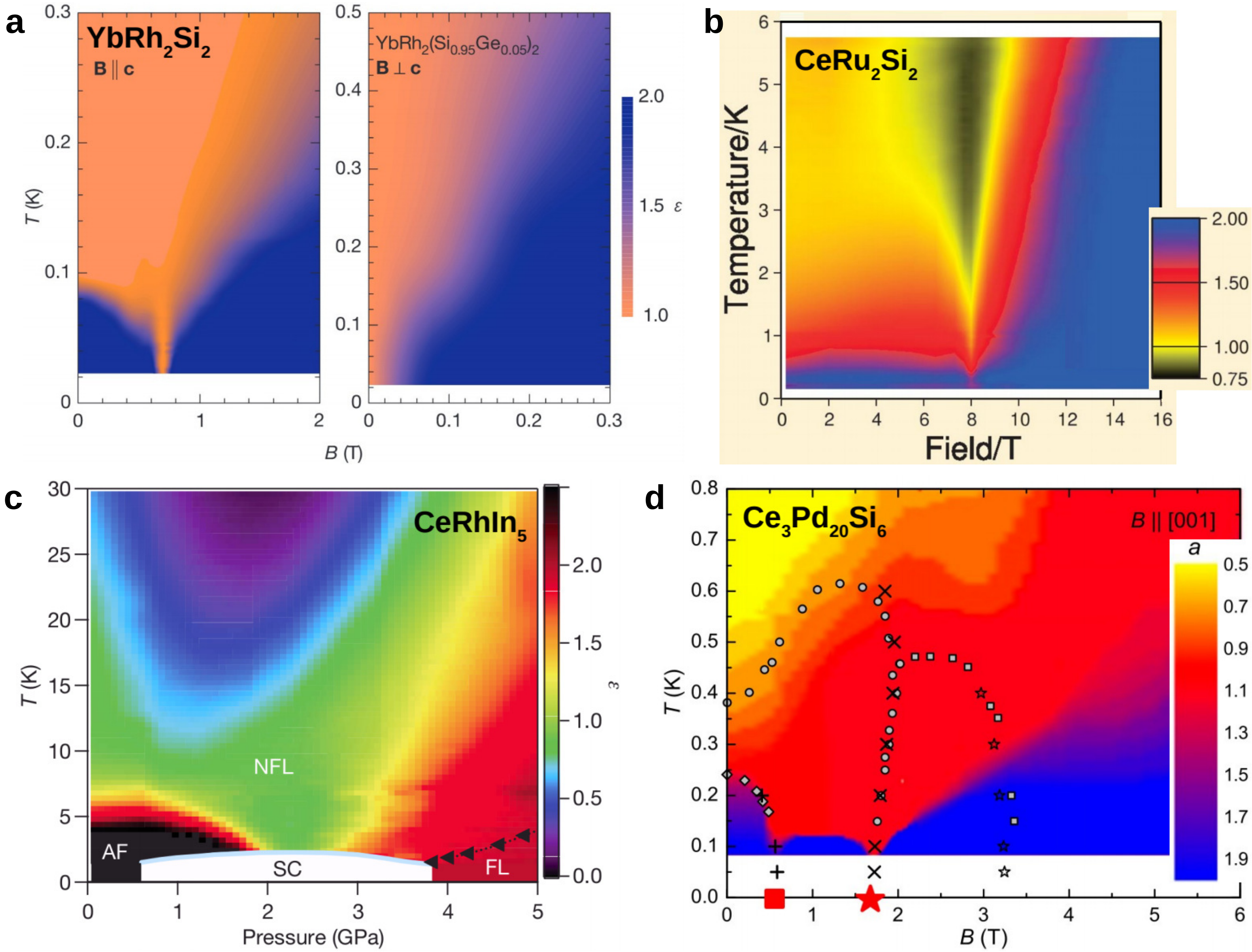


(Mathur et al., Nature 394 (1998) 39)

... it is still unconventional sc

- non-*f* reference compound does not superconduct
- $\Delta C/(\gamma_0 T_c) \sim 1$ and huge $dB_{c2}/dT(T_c)$: quasiparticles are heavy fermions
- BCS pairing unlikely: $v_F \sim v_{ph}$, no retardation, Coulomb interaction important $\rightarrow$ magnetic pairing
- strong pairbreaking by *non*magnetic impurities

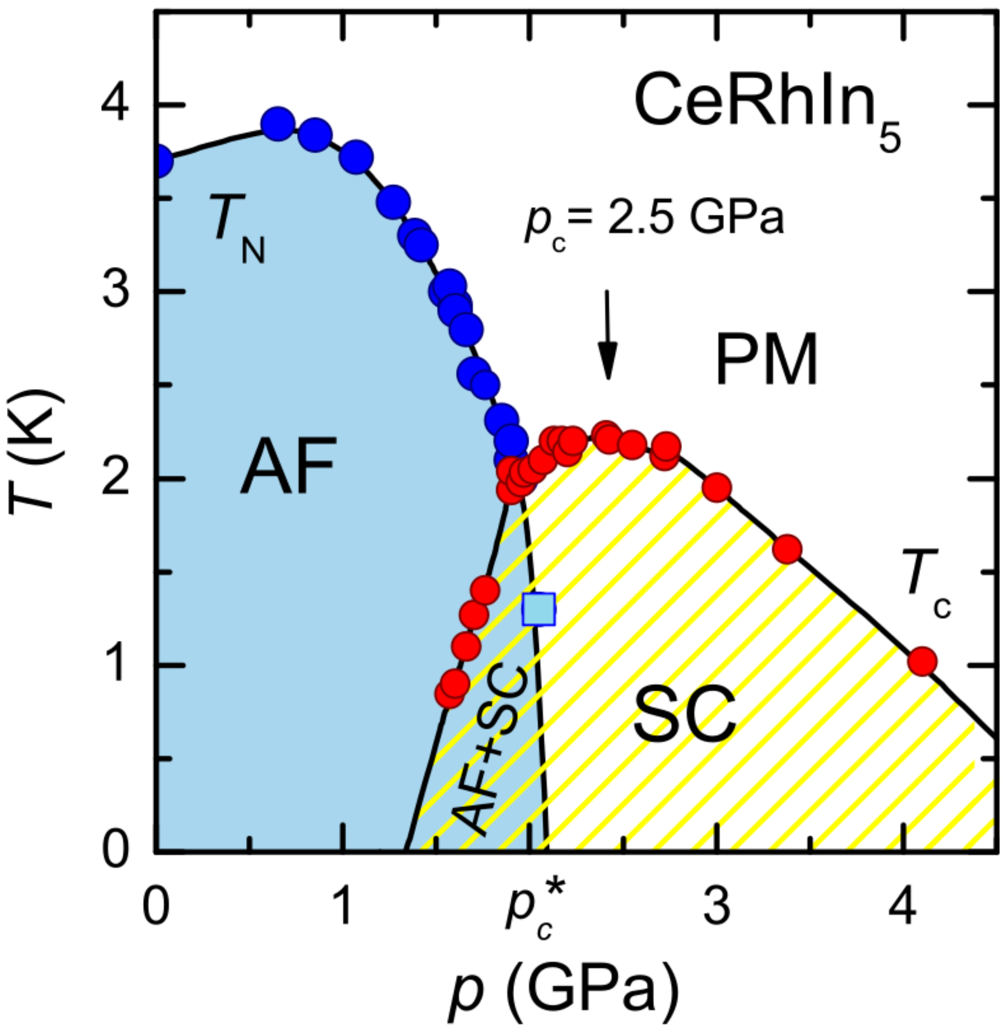
Superconductivity at a beyond-GLW QCP?



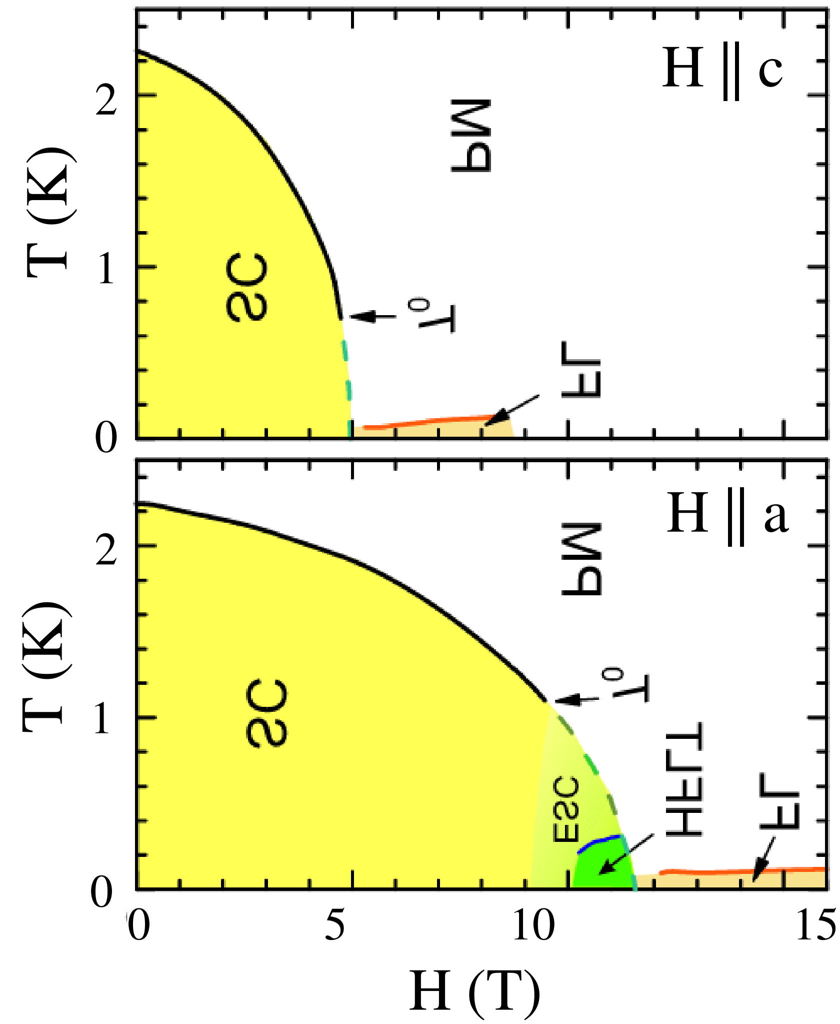
(Taupin & SP, Crystals 12 (2022) 251 and refs. herein)

Superconductivity at a beyond-GLW QCP

$CeRhIn_5$



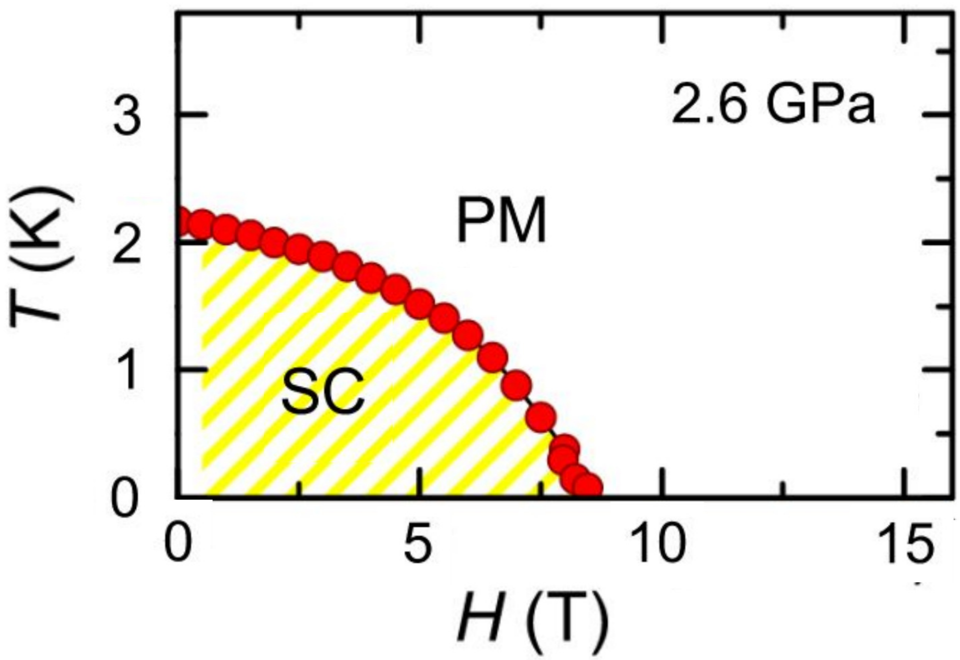
$CeCoIn_5$



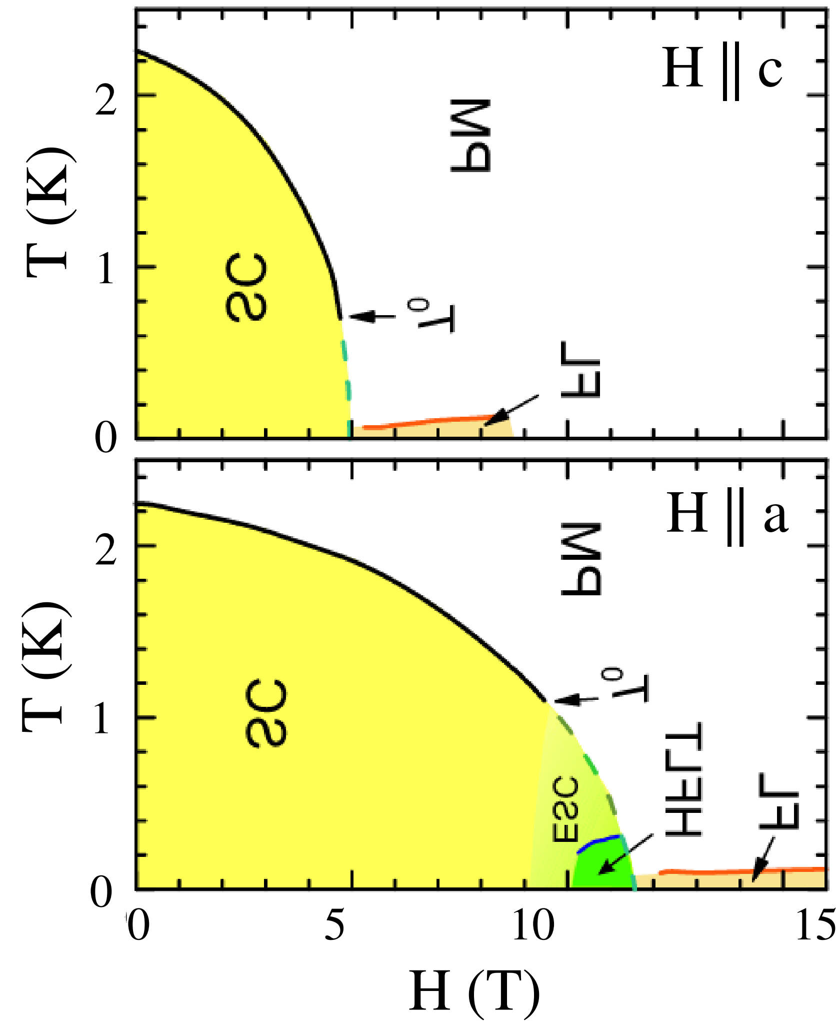
(Knebel et al., C. R. Physique 12 (2011) 542 and refs. herein)

Superconductivity at a beyond-GLW QCP

$CeRhIn_5$

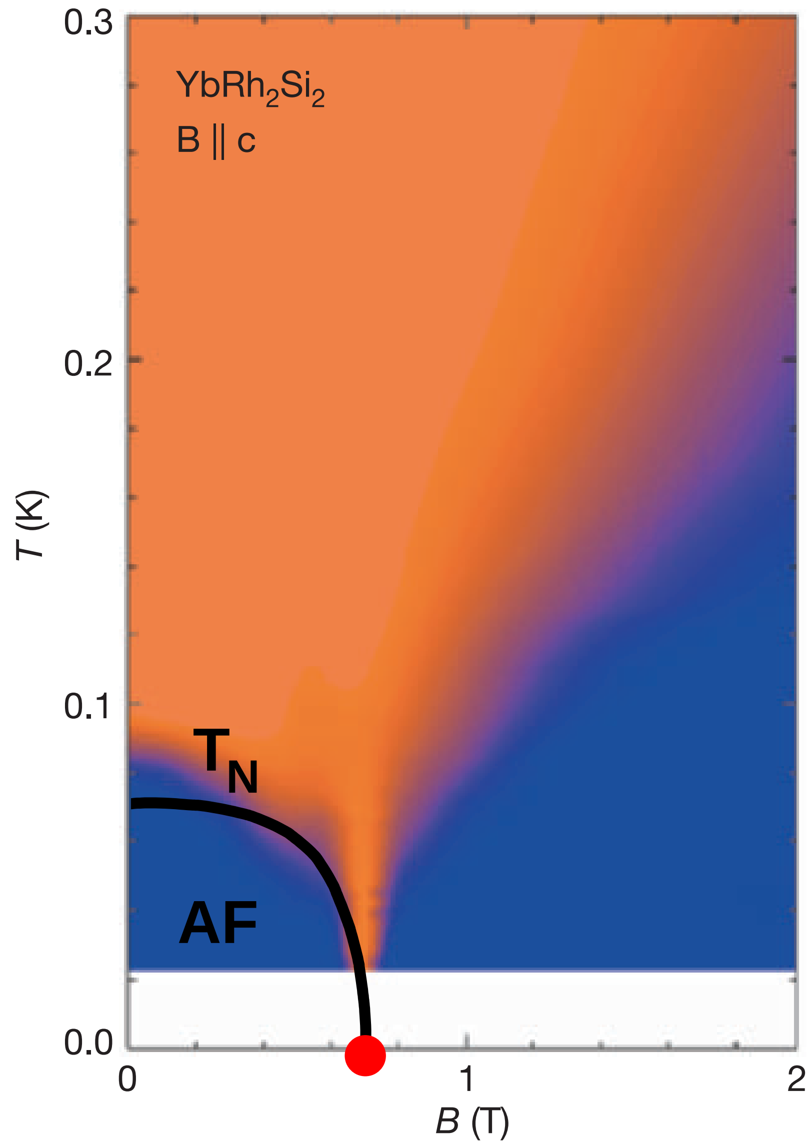


$CeCoIn_5$



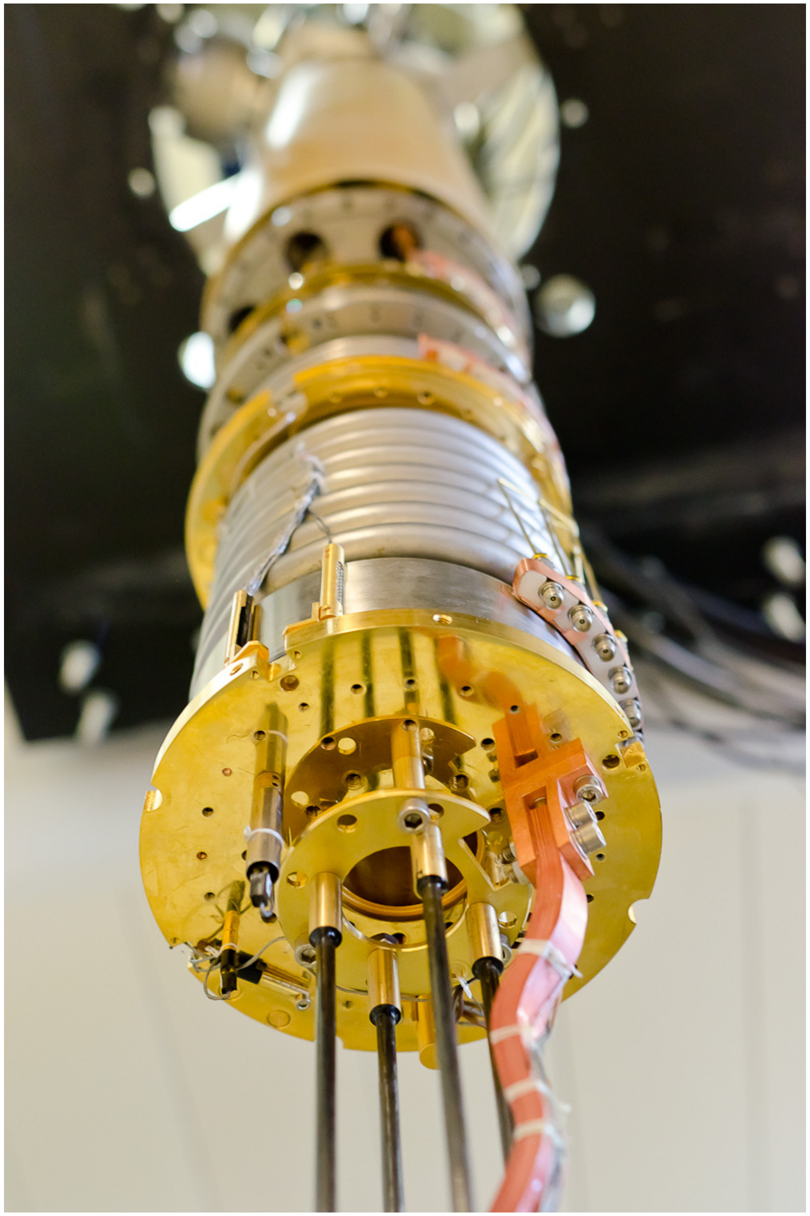
(Knebel et al., C. R. Physique 12 (2011) 542 and refs. herein)

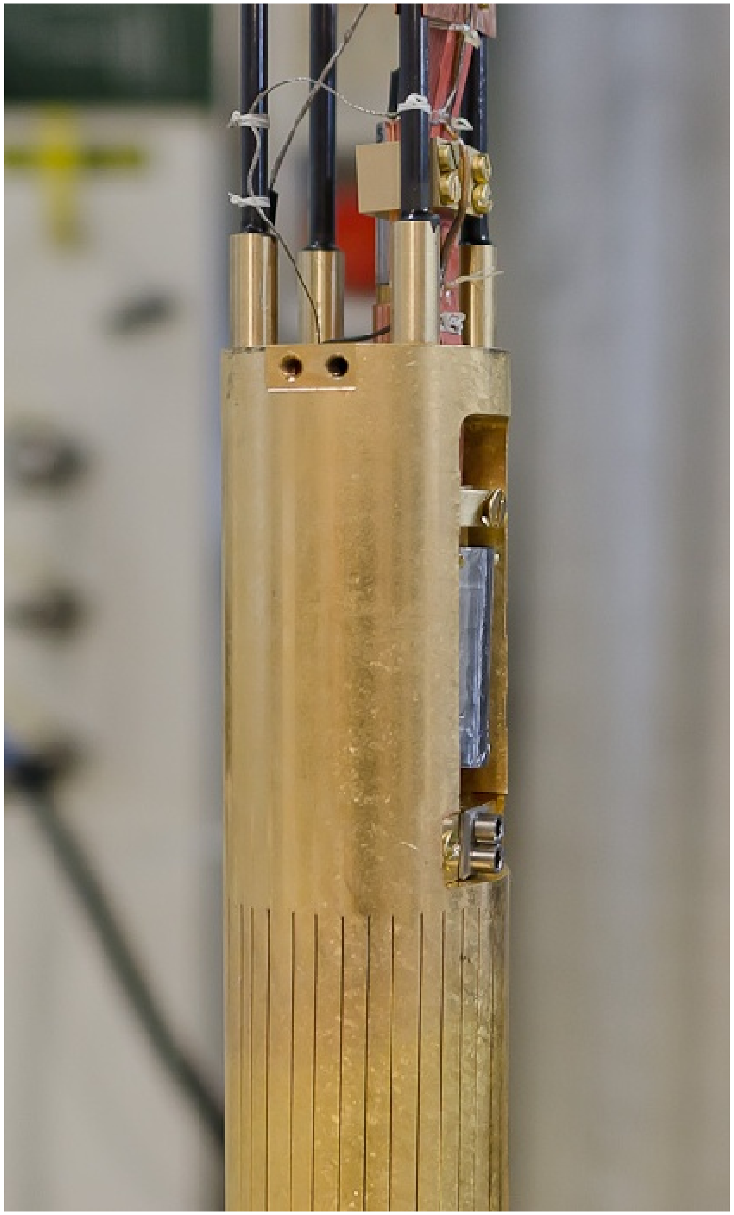
Is there superconductivity at the QCP of $YbRh_2Si_2$?



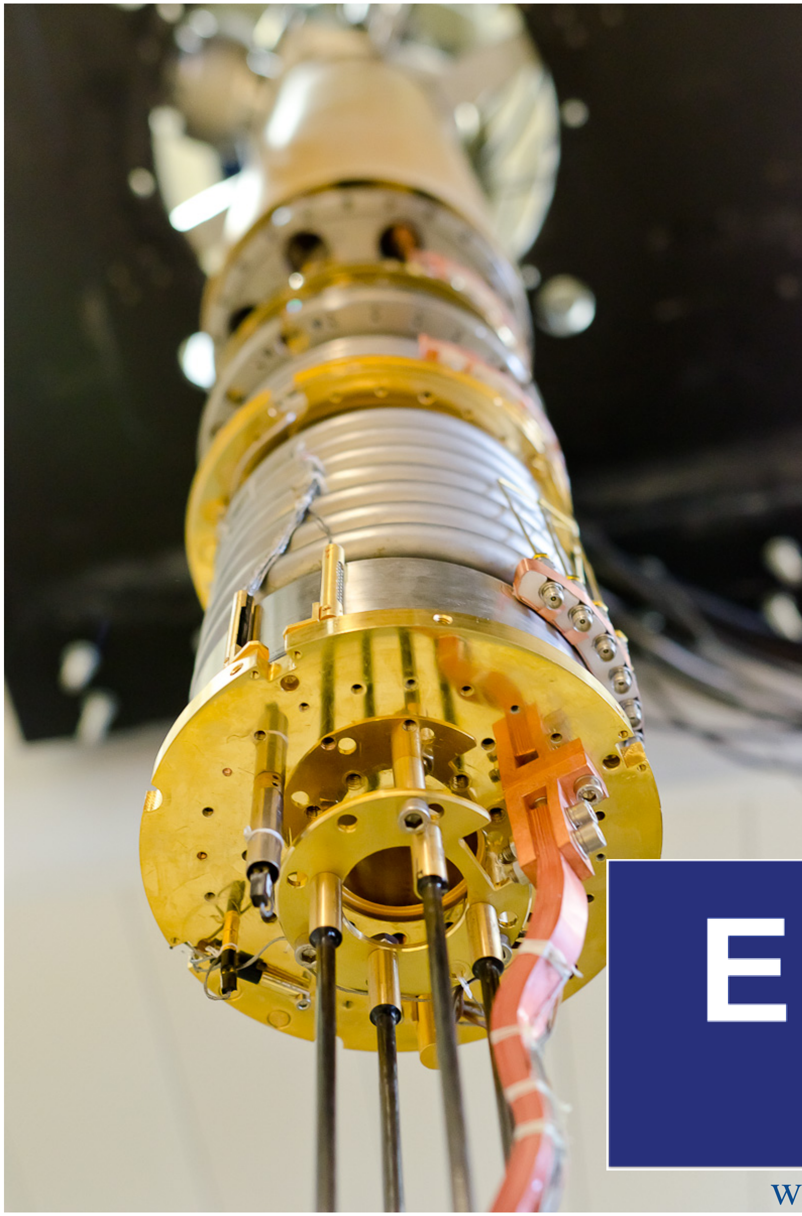
(Custers et al., Nature 424 (2003) 524)

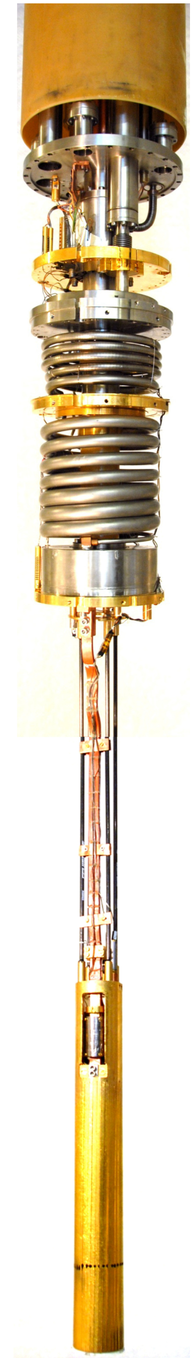
The Vienna Microkelvin Laboratory





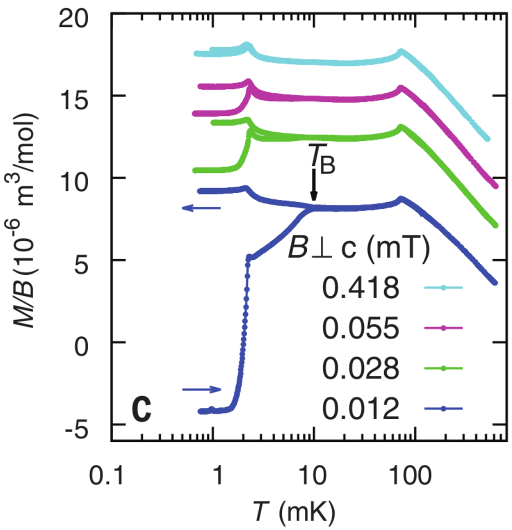
The Vienna Microkelvin Laboratory

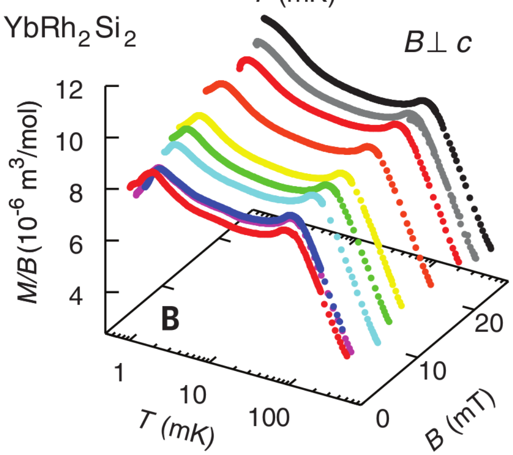


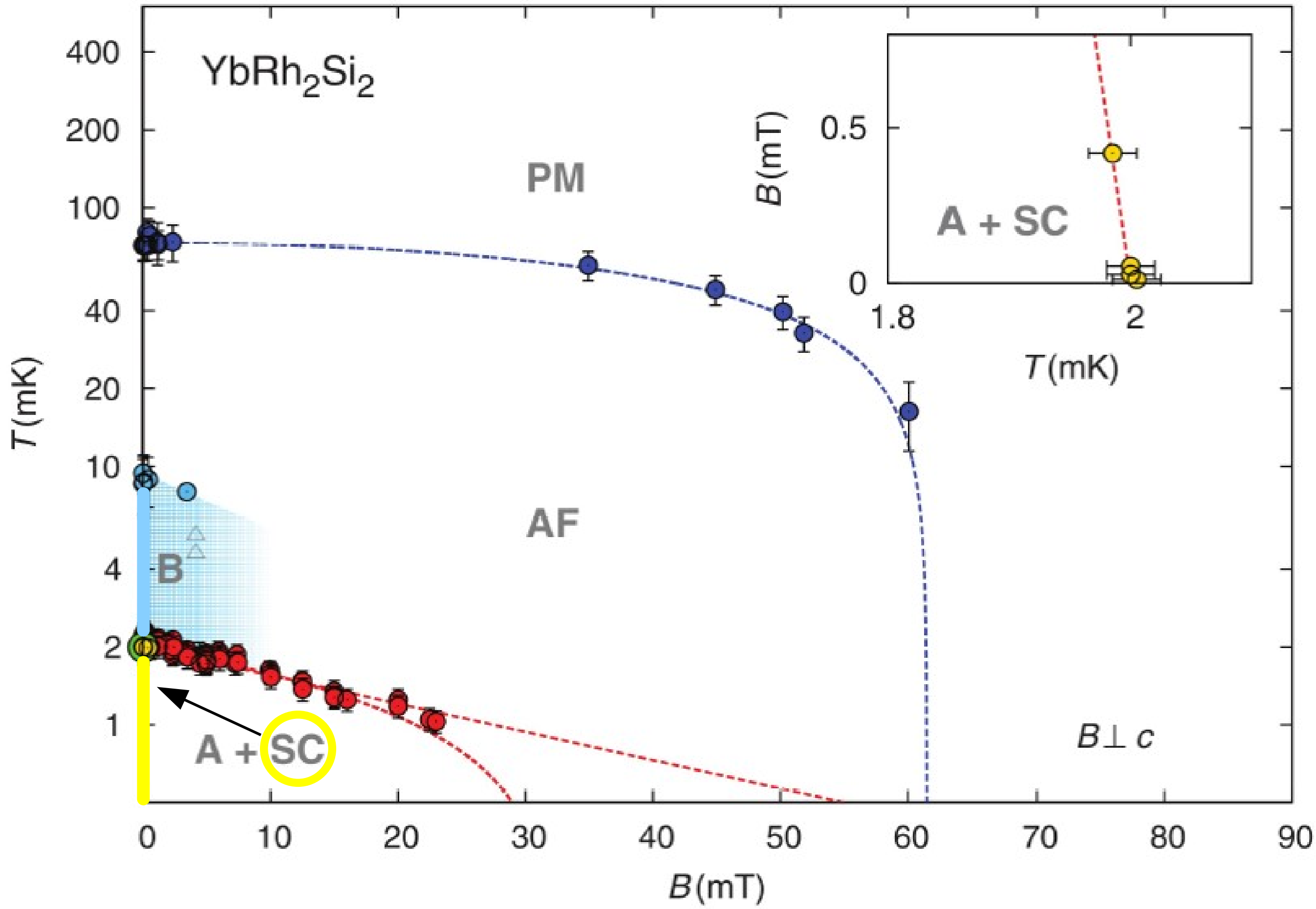


www.EMPlatform.eu

Magnetization measurements at ultralow temperatures





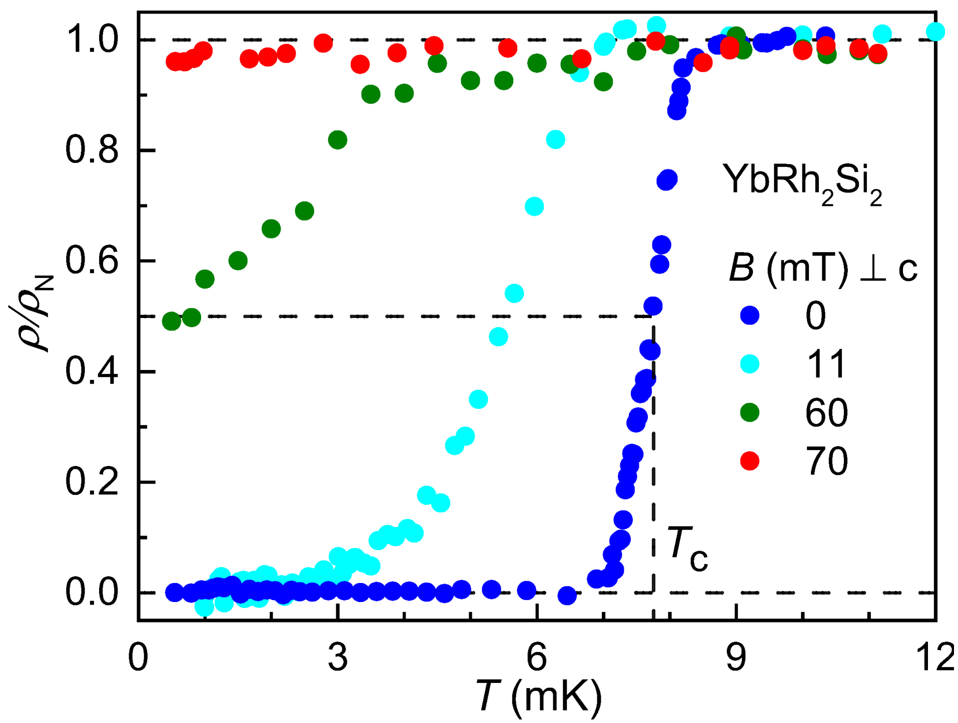


Shielding below 2 mK at $H = 0.012$ mT; field-cooled magnetization curves show kinks up to ~ 25 mT; hybrid electronic-nuclear spin order?

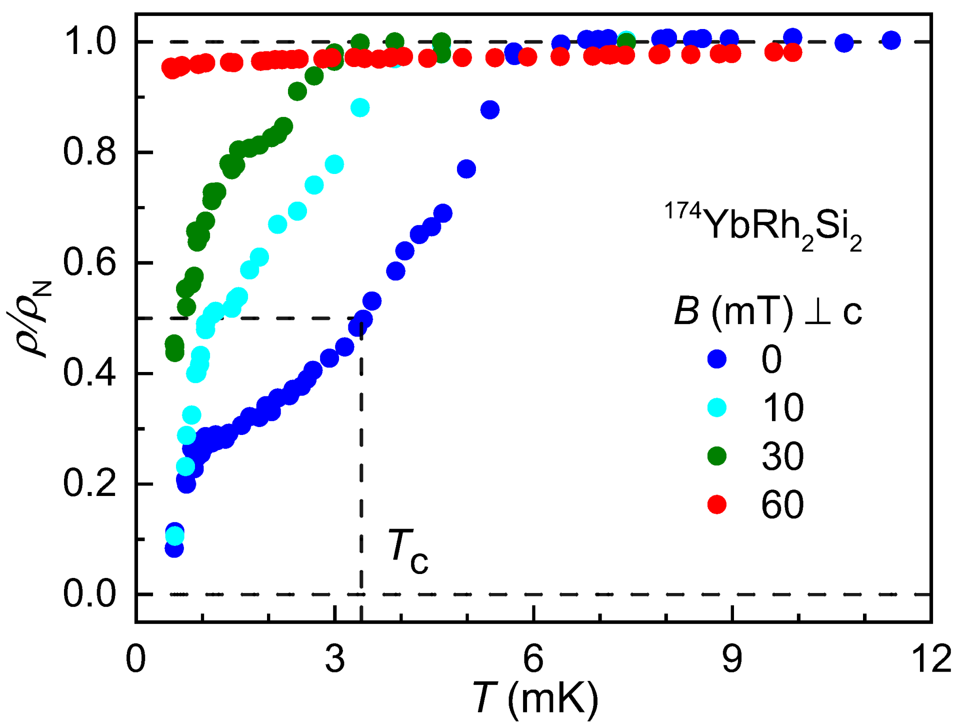
(Schuberth et al., Science 351 (2016) 485)

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

$YbRh_2Si_2$

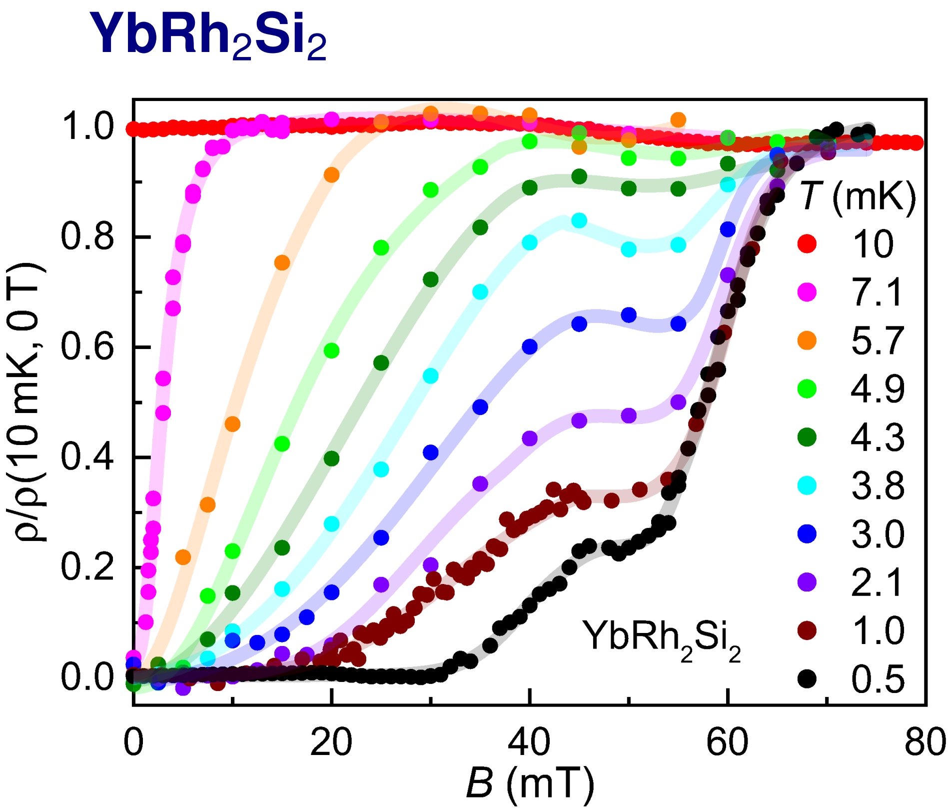


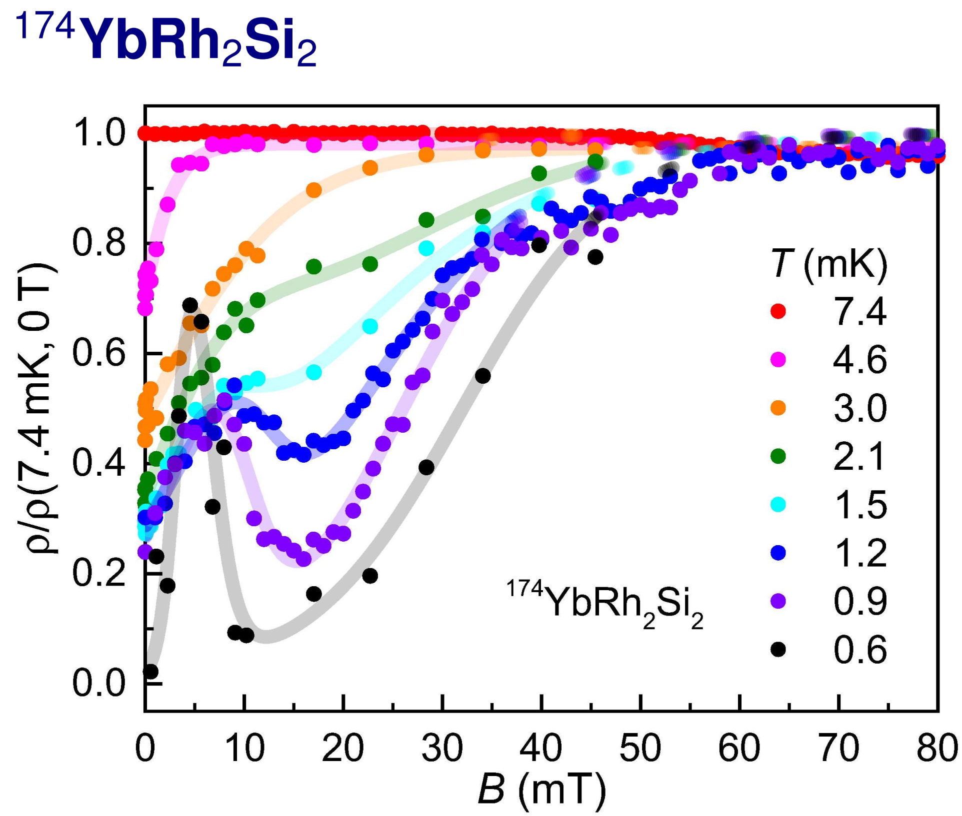
$^{174}YbRh_2Si_2$



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

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

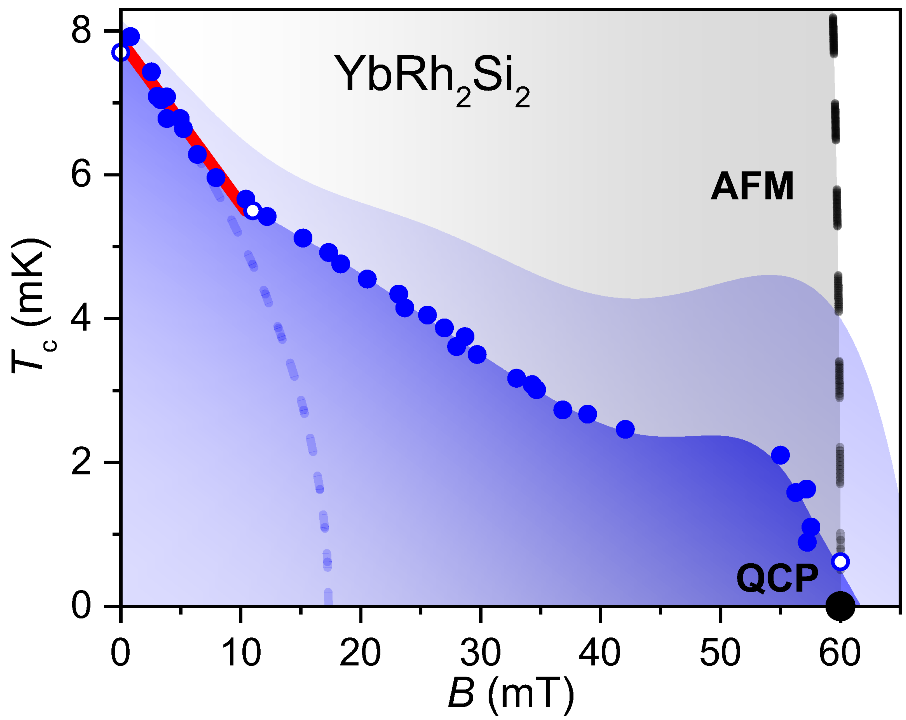




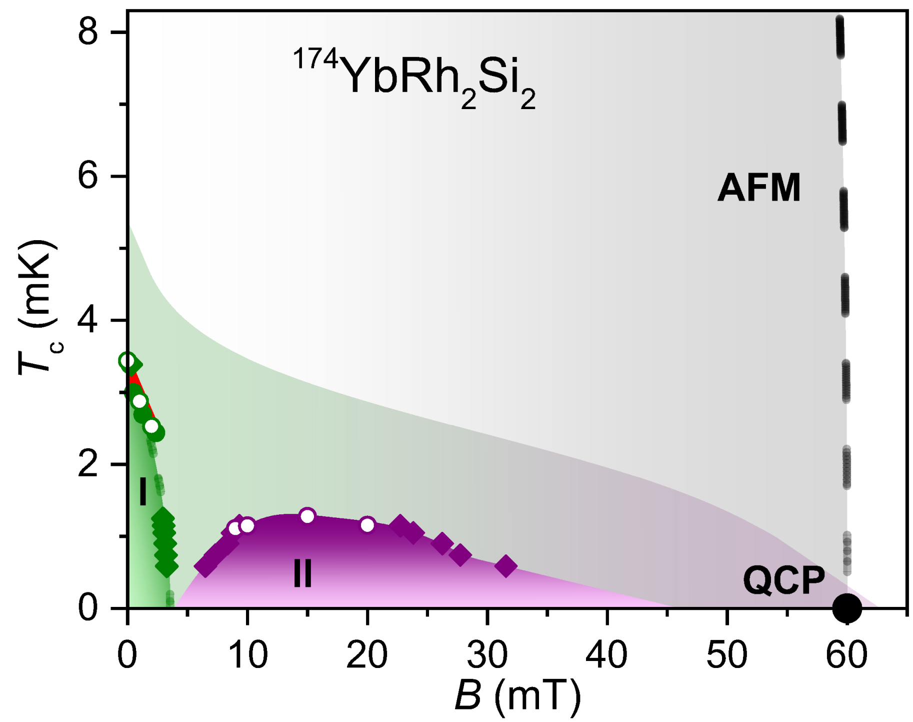
(Nguyen et al., Nat. Commun. 12 (2021) 4341)

Temperature–magnetic field phase diagrams

$YbRh_2Si_2$



$^{174}YbRh_2Si_2$

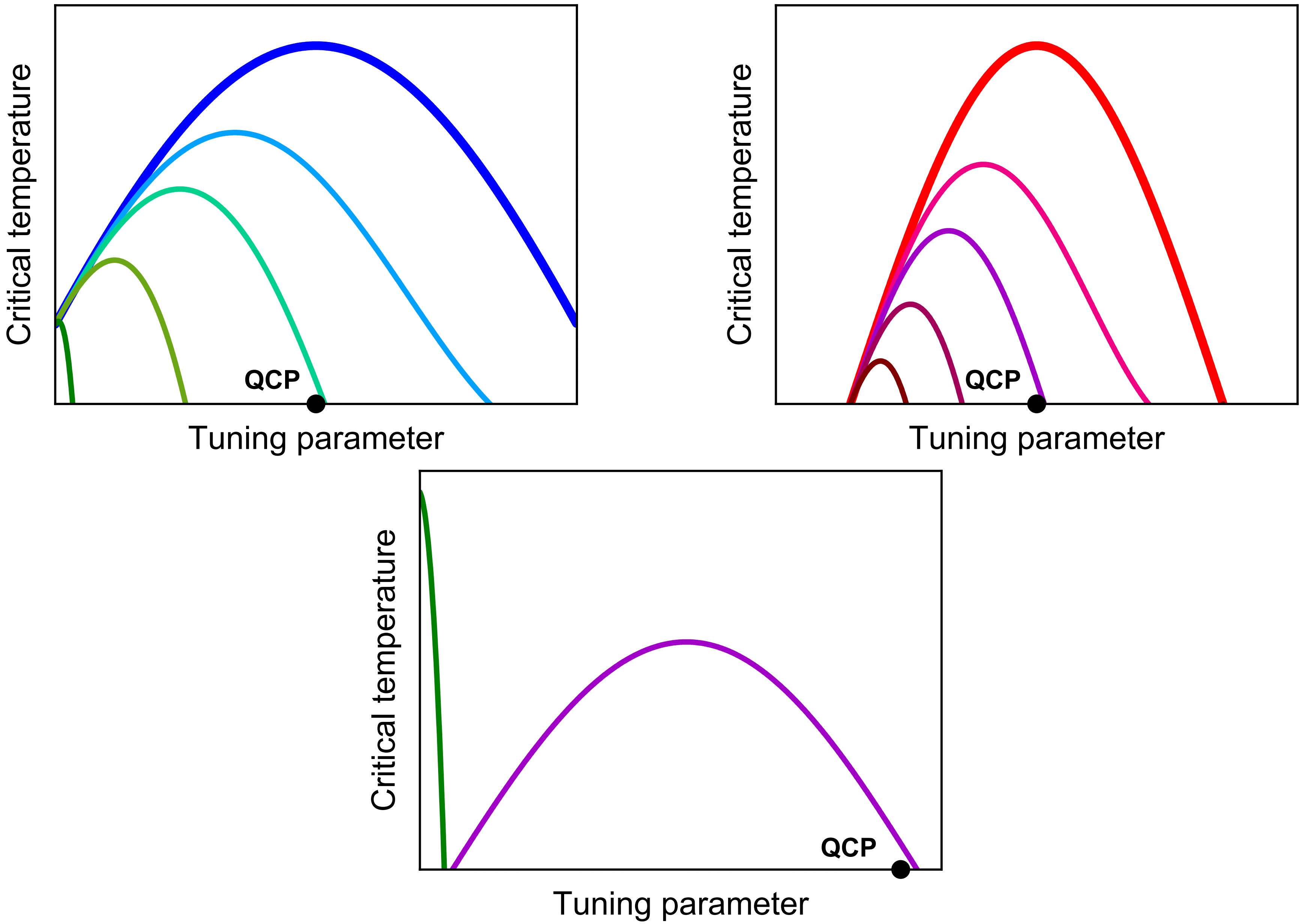


Orbital-limiting fields: 24 mT (5 mT)

Pauli-limiting fields: 15 mT (6.4 mT)

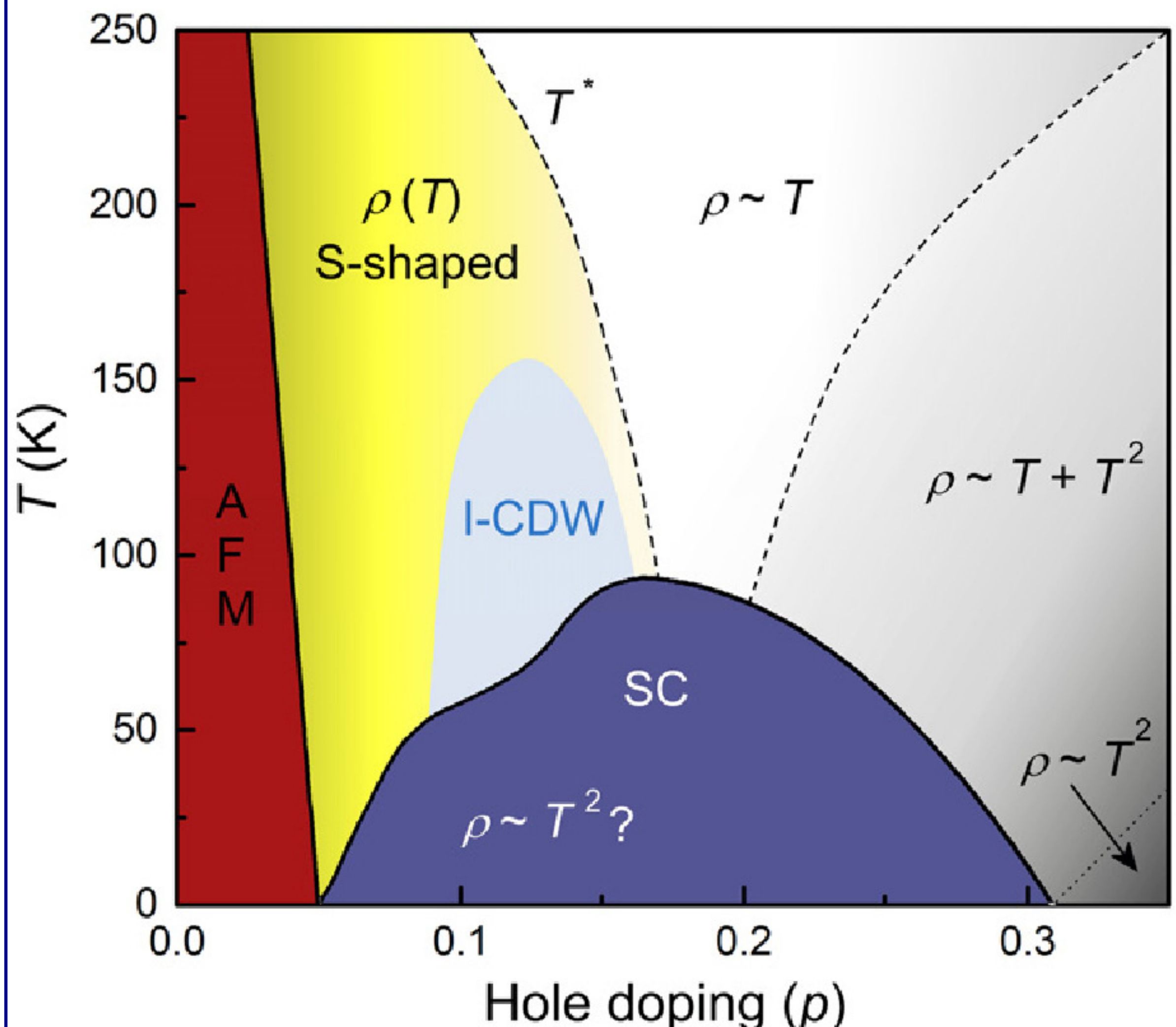
(Nguyen et al., Nat. Commun. 12 (2021) 4341)

Magnetic field effect on “dome” structure



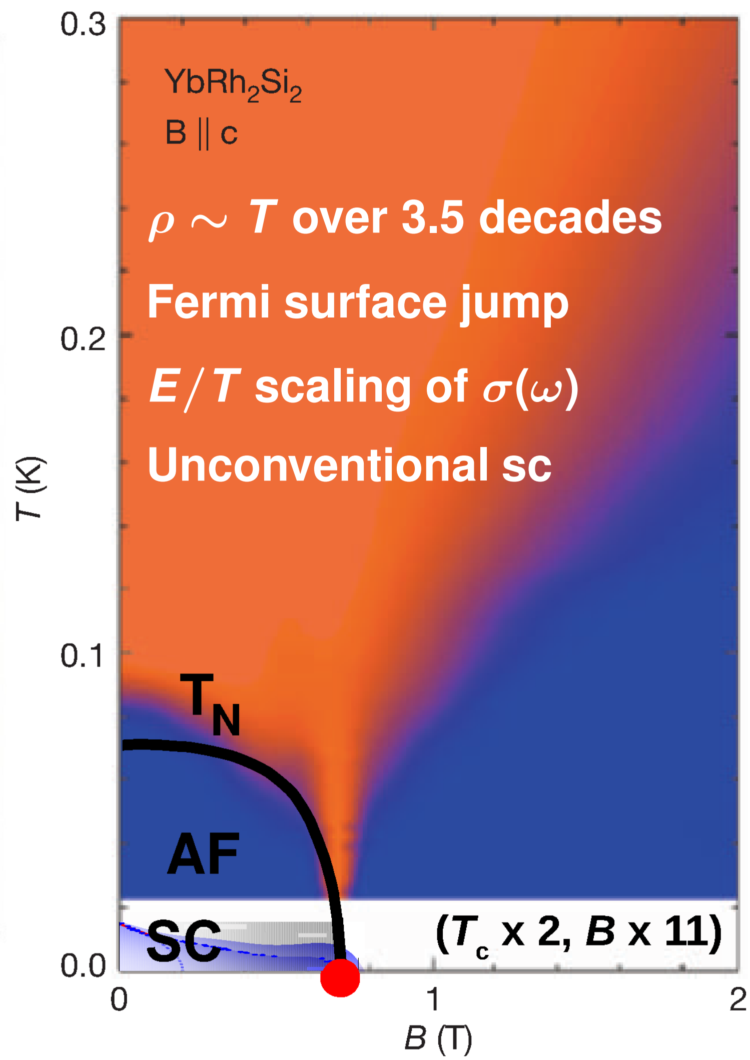
Advance understanding by connecting the various platforms!

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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Summary

- In heavy fermion compounds the correlation strength can be tuned
- Singulatities (can) appear at quantum critical points (QCPs)
- Some heavy fermion compounds are well described by GLW QCPs
- Beyond-GLW QCPs are accompanied by Kondo destruction physics
- AF (!) Kondo destruction QCP in finite *B*: Spin triplet pairing?