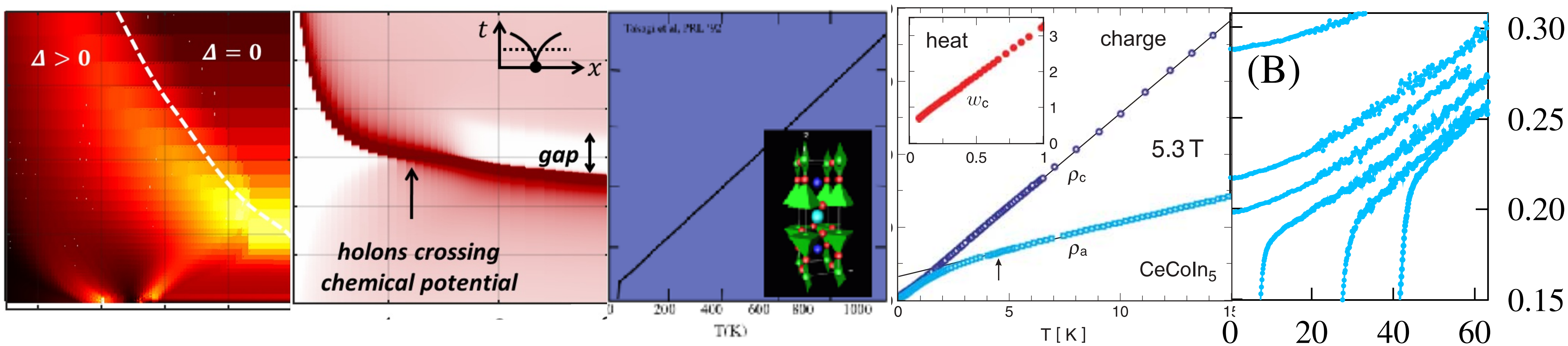
Kondo Breakdown and a possible connection with Strange and Bad metals.

Piers Coleman

Center for Materials Theory, Rutgers U, USA
Hubbard Theory Consortium, Royal Holloway, U. London



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Nanjing Conference on Quantum Materials
15-17th June, 2019

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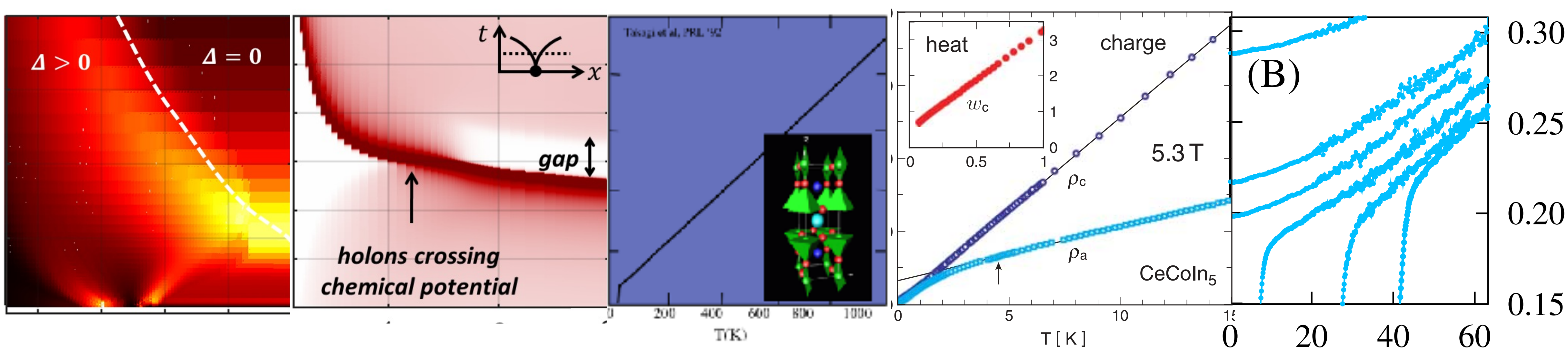
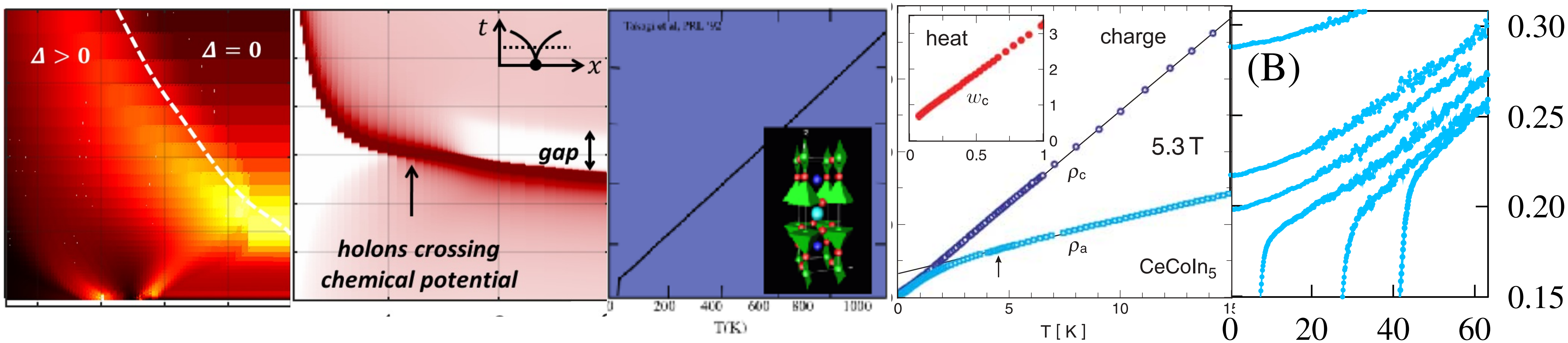


$\Delta > 0$
$\Delta = 0$
t
x
gap
holons crossing chemical potential
T(K)
heat
charge
w_c
5.3 T
ρ_c
ρ_a
$CeCoIn_5$
T [K]
(B)
0.30
0.25
0.20
0.15
0
20
40
60



- Heavy Fermions: tunable strange metals
- Schwinger Bosons and the Kondo Lattice
- Quantum Criticality in a simple KL
- Possible link with Strange Metals

Yashar Komijani & PC **PRL 122, 217001 (2019)**

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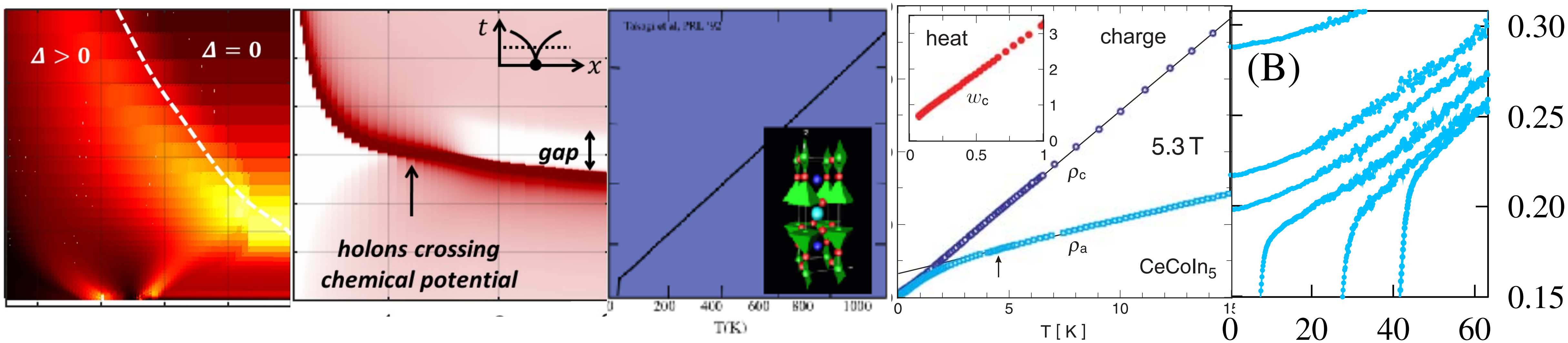

Collaborators

<u>Yashar Komijani</u> **CMT Rutgers**

Premi Chandra	CMT Rutgers
Satoru Nakatsuji	ISSP, Tokyo
Huiqiu Yuan	Zhejiang/Nanjing
Frank Steglich	MPICPFS/Zhejiang
Michael Smitman	Zhejiang U
Michael Nicklas	MPICPFS Dresden

Yashar Komijani & PC **PRL 122, 217001 (2019)**

physics.rutgers.edu/~coleman/talks/nanjing19.pdf

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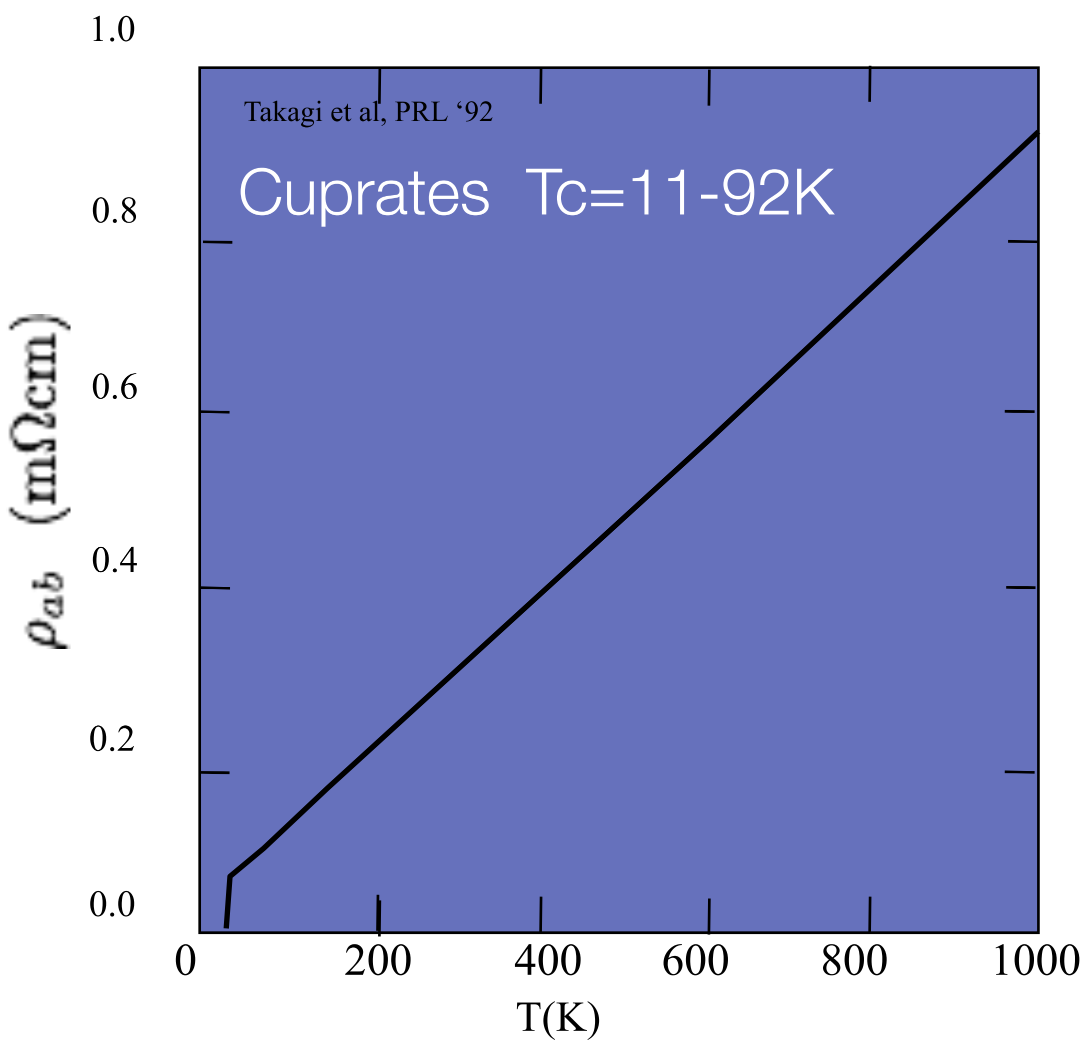
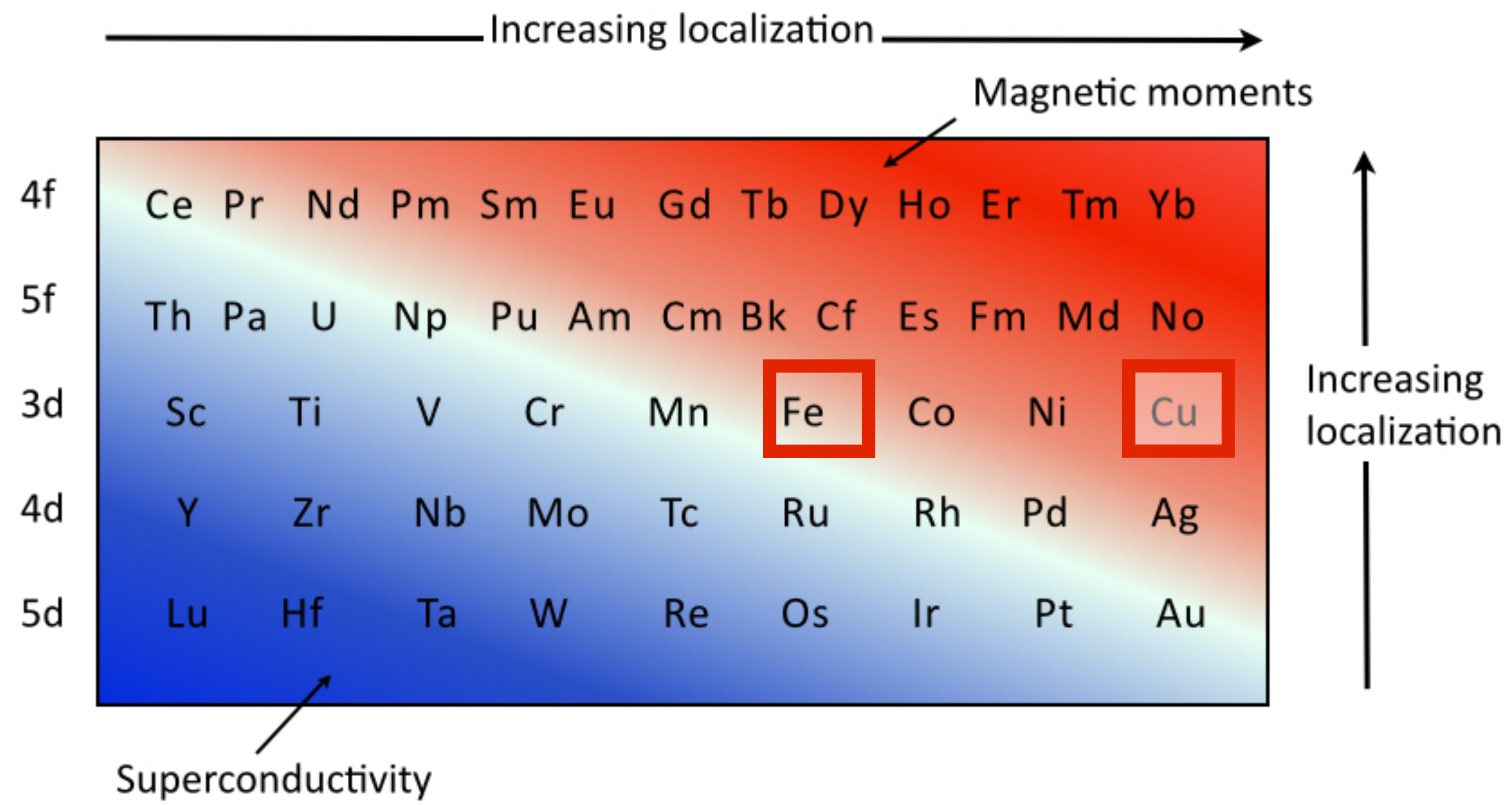
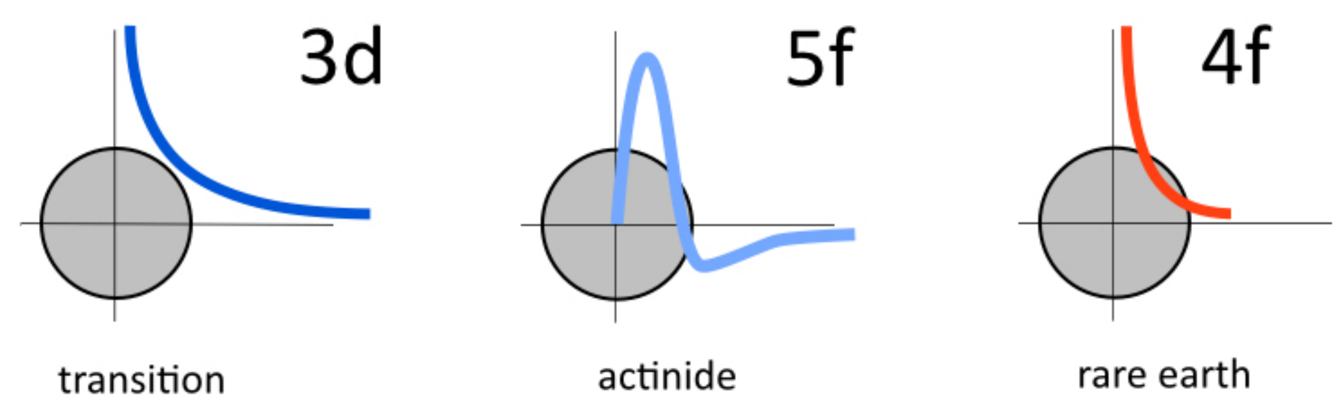
Heavy Fermions: Tunable Strange Metals

Strange Metals: Electrons at the Brink of Localization

- Mystery of Linear resistivity in strange metals







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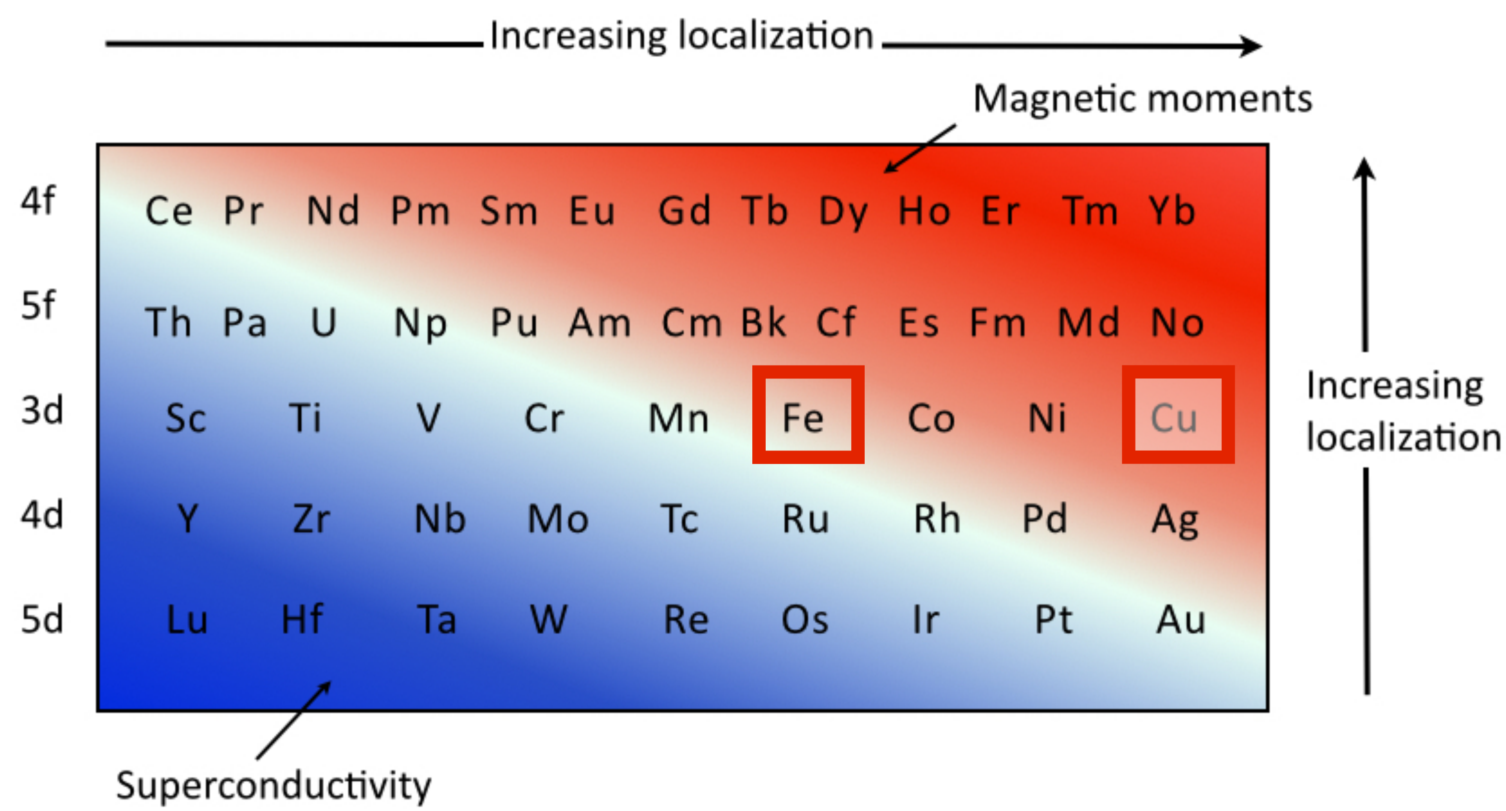
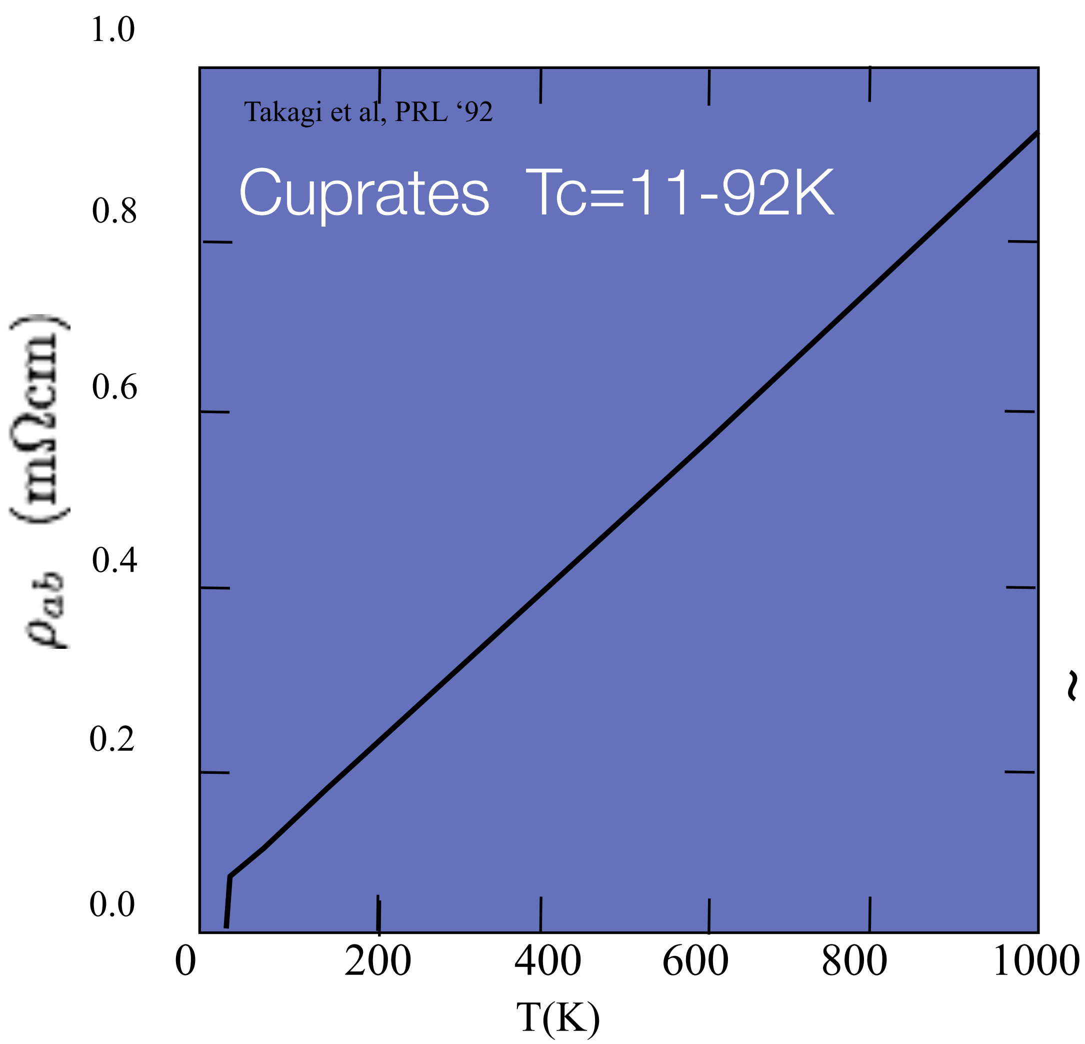
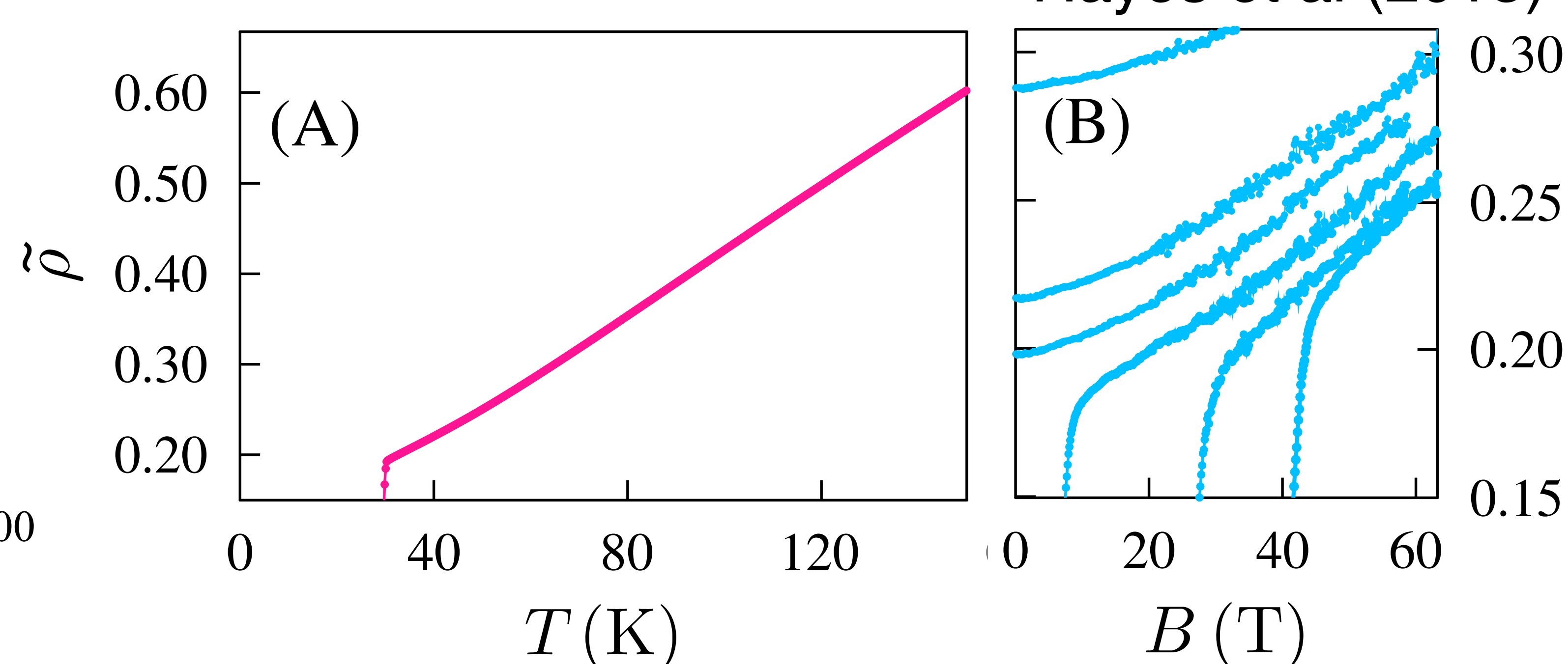




Iron-based SC Tc = 5-65K

$BaFe_2As_{2-x}P_x$ (x=0.31)

Hayes et al (2015)



Strange Metals: Electrons at the Brink of Localization

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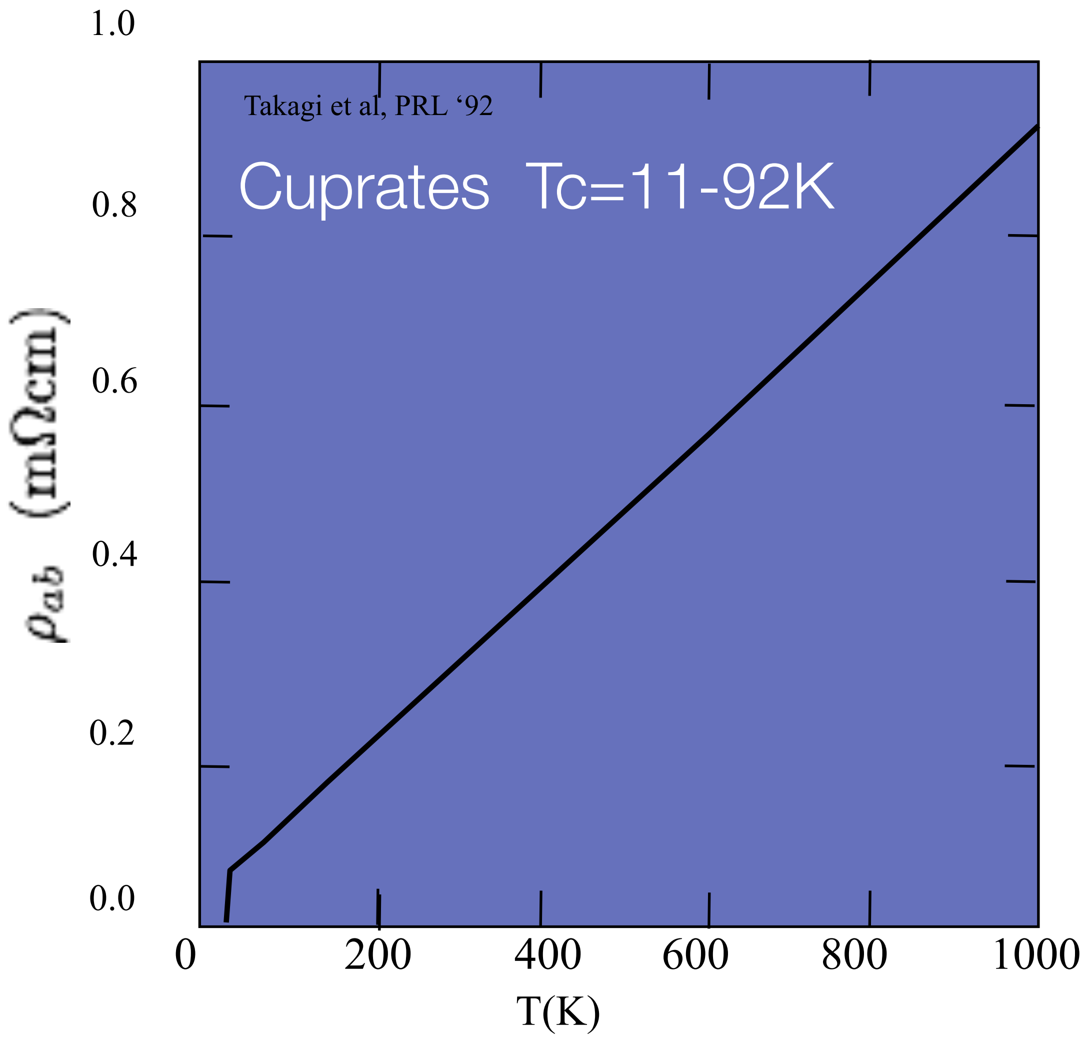
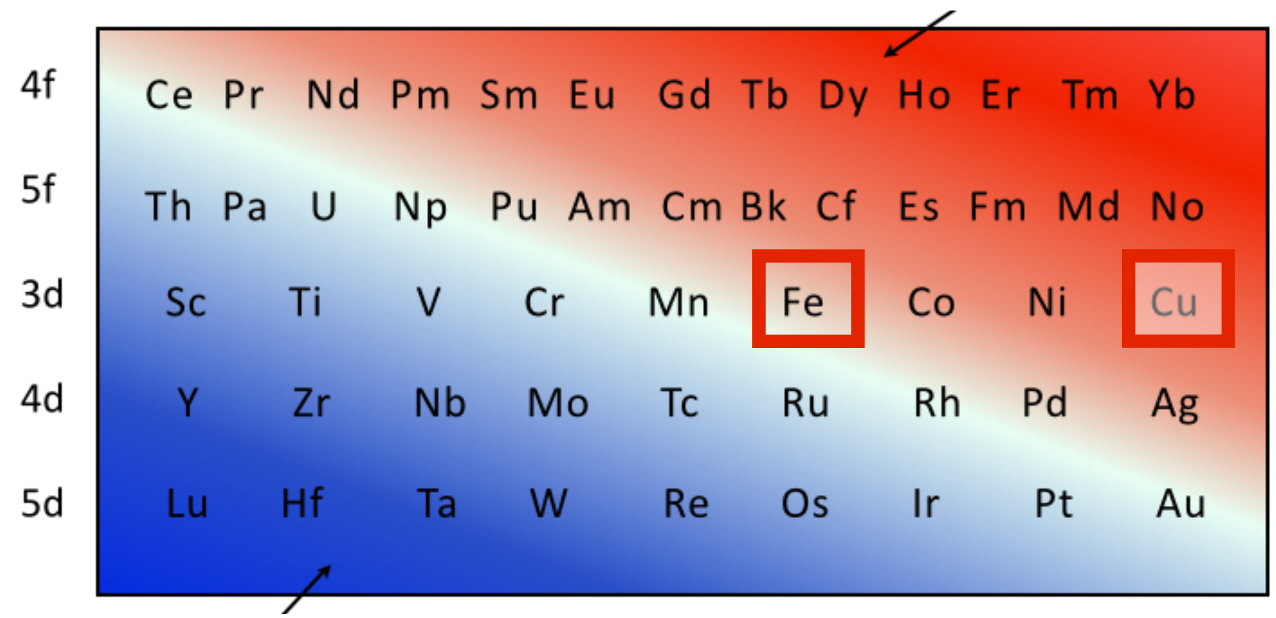
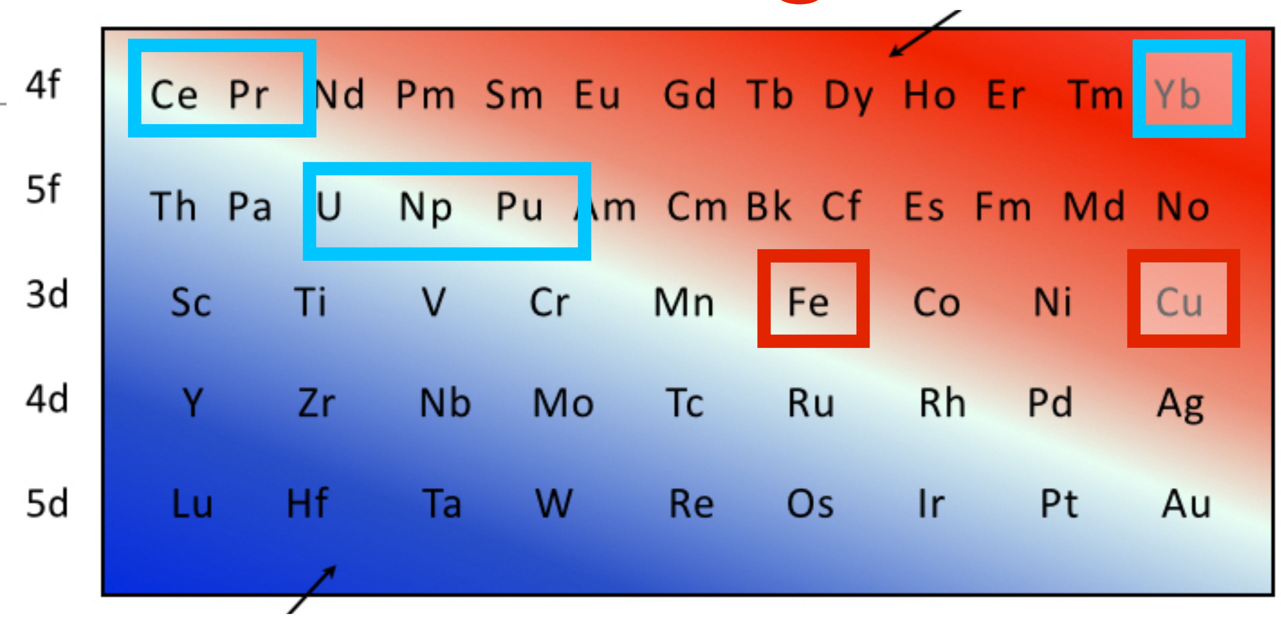
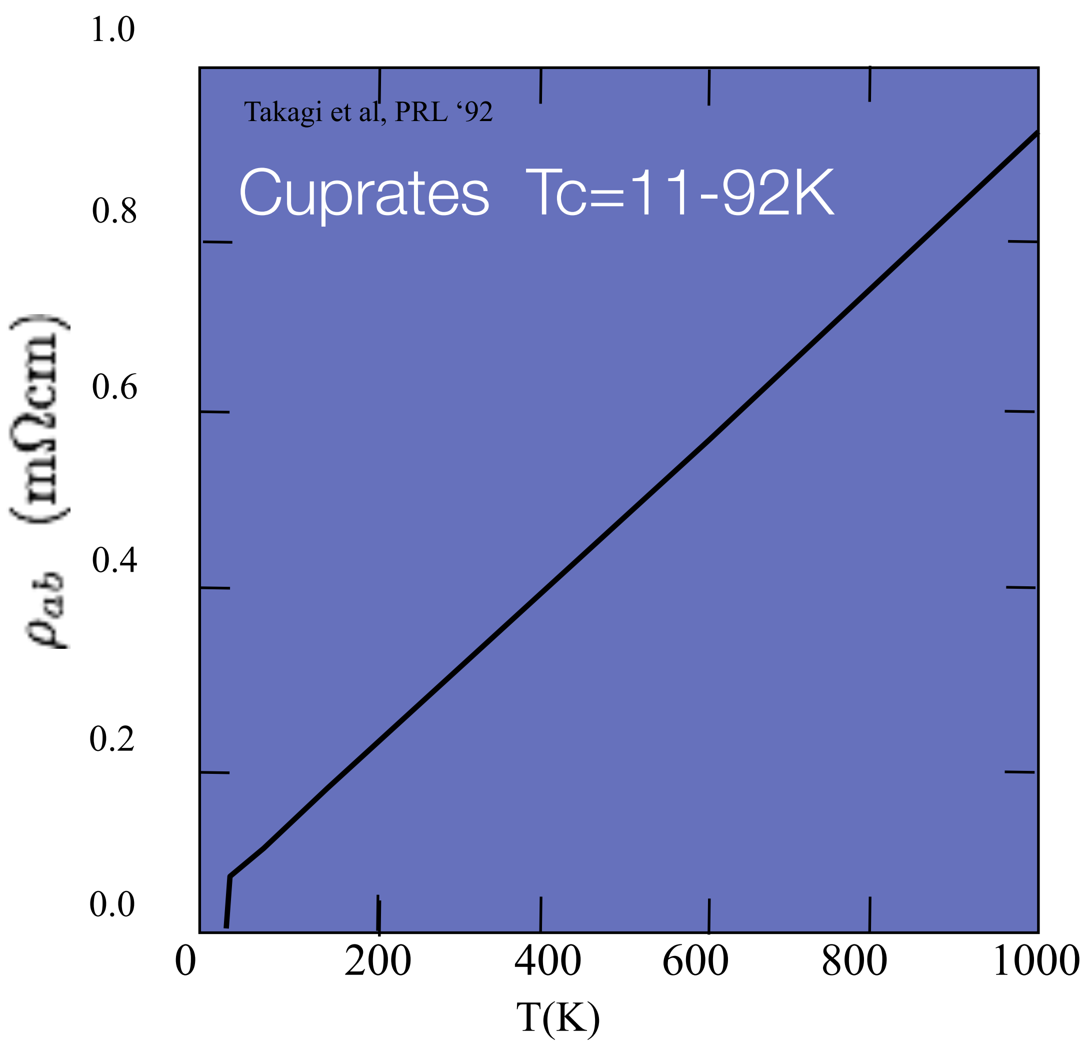


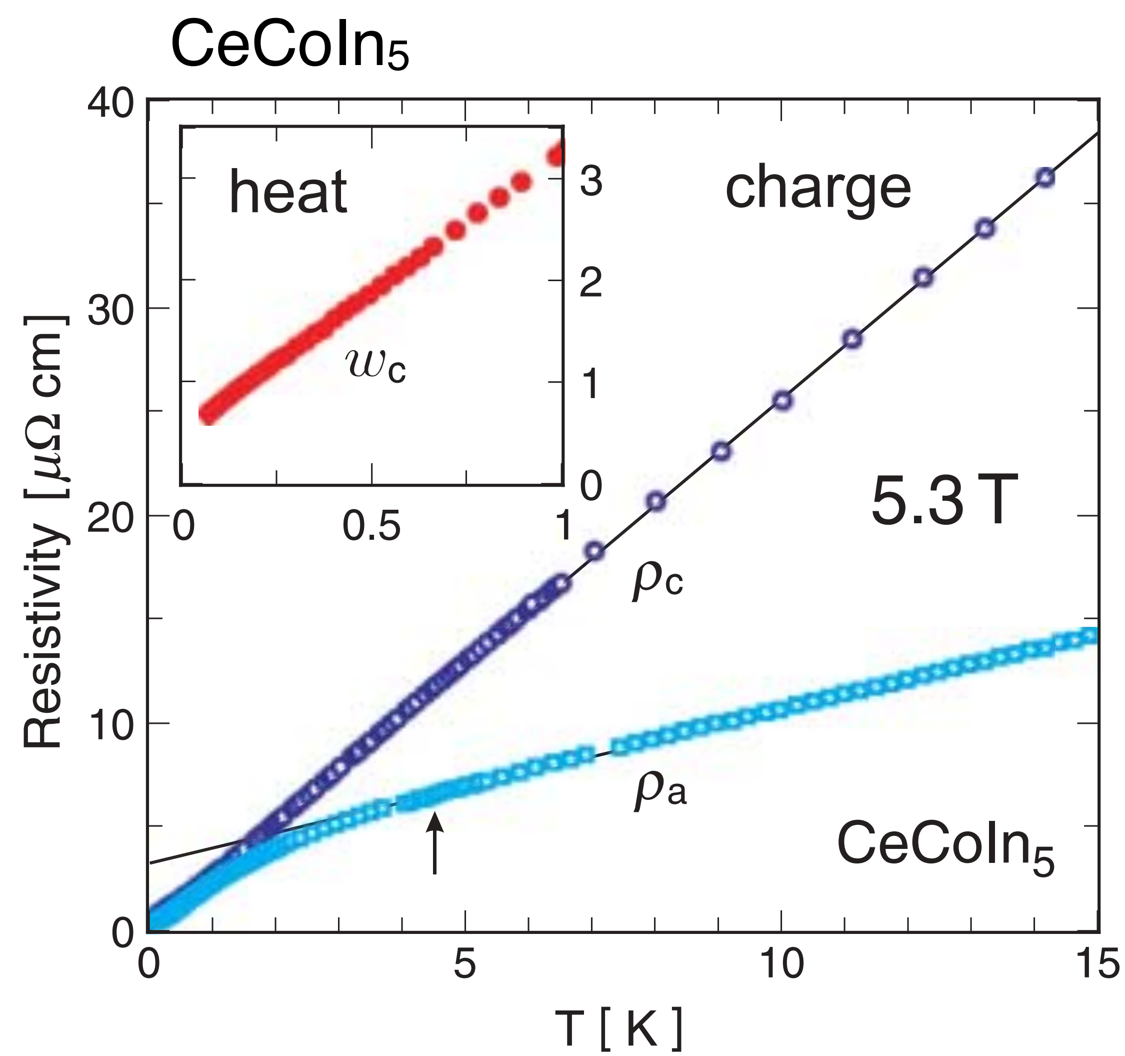


Heavy Fermions: Tunable Strange Metals

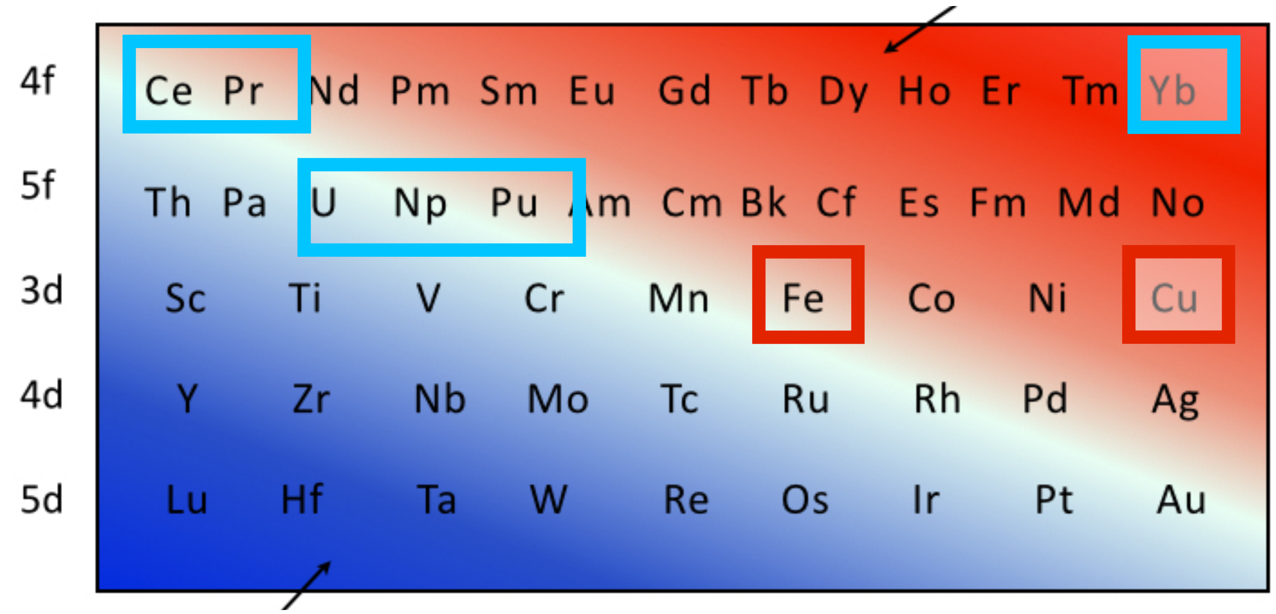
- Mystery of Linear resistivity in strange metals
- Heavy Fermions: highly tunable.

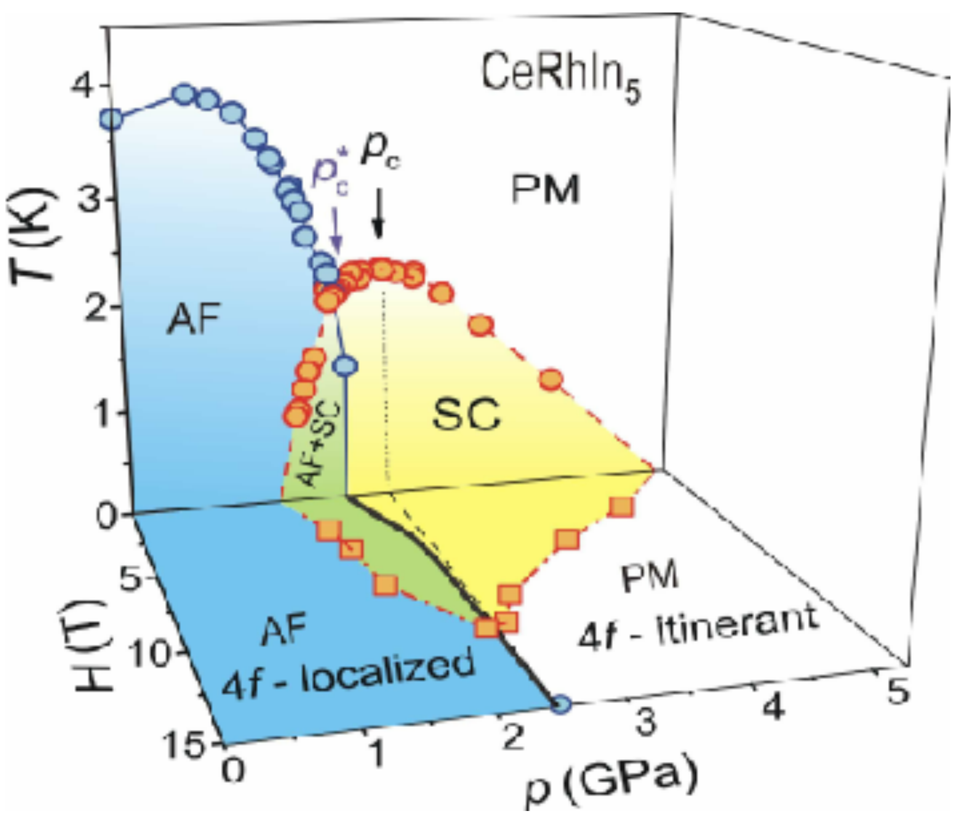






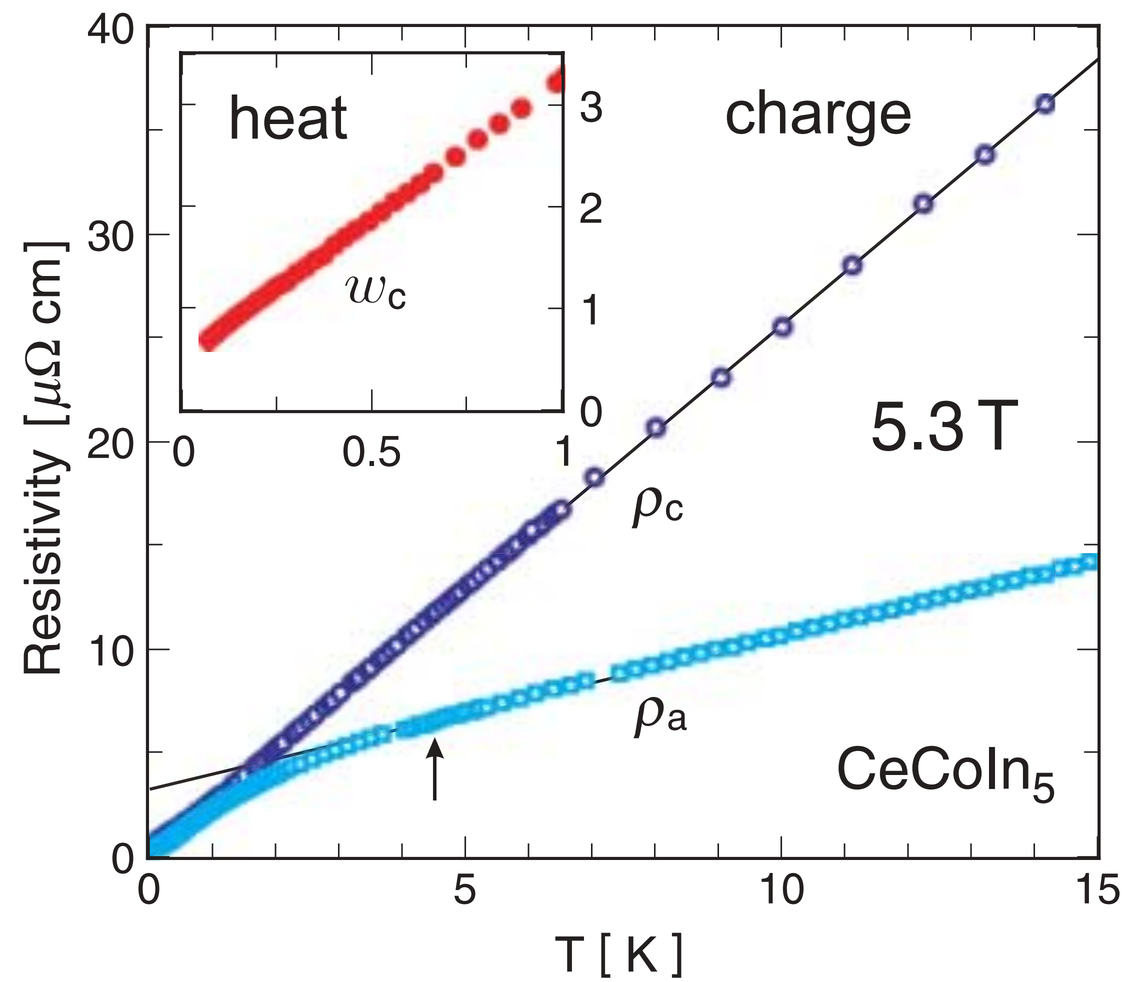
- Mystery of Linear resistivity in strange metals
- Heavy Fermions: highly tunable.
- Link with Quantum Criticality

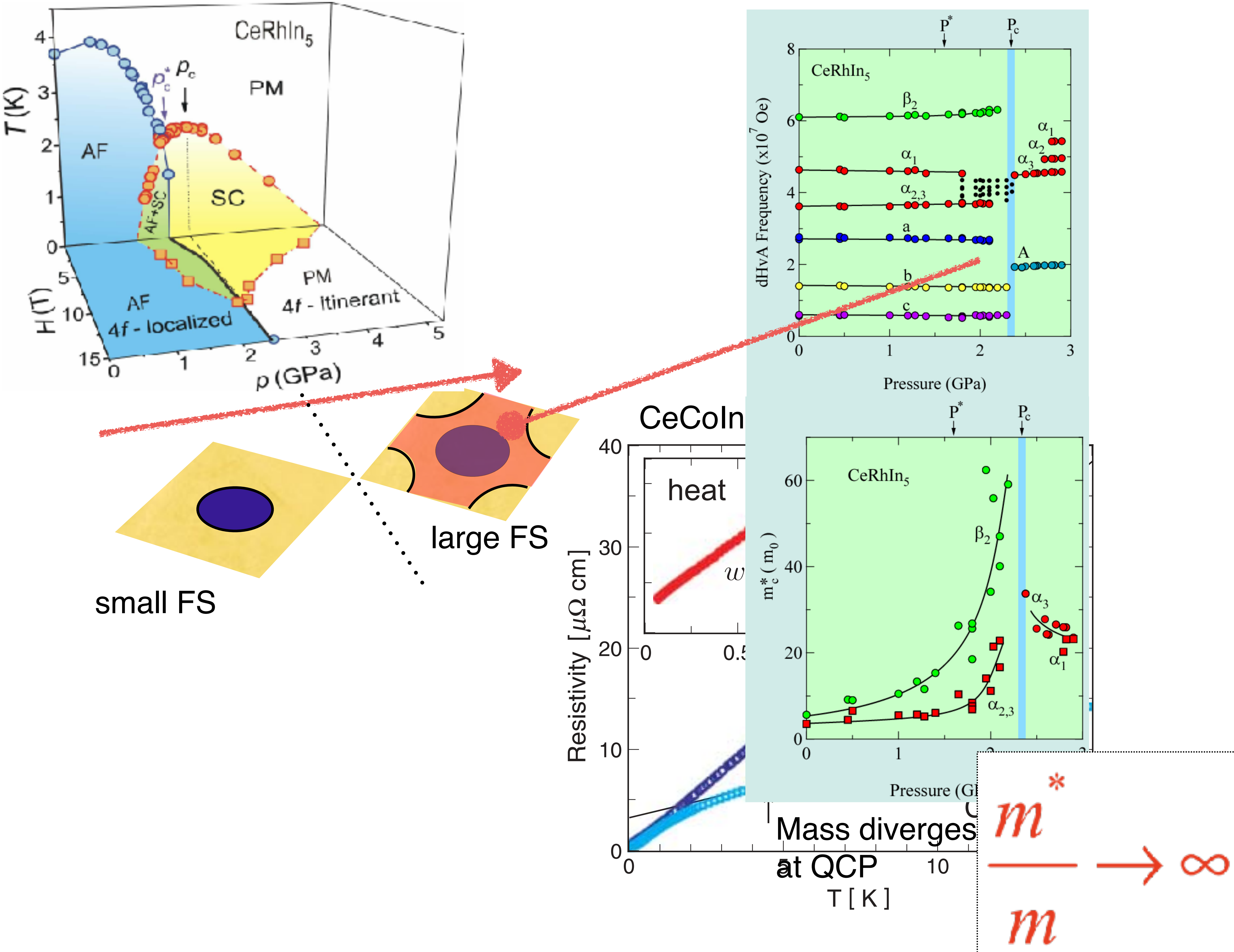


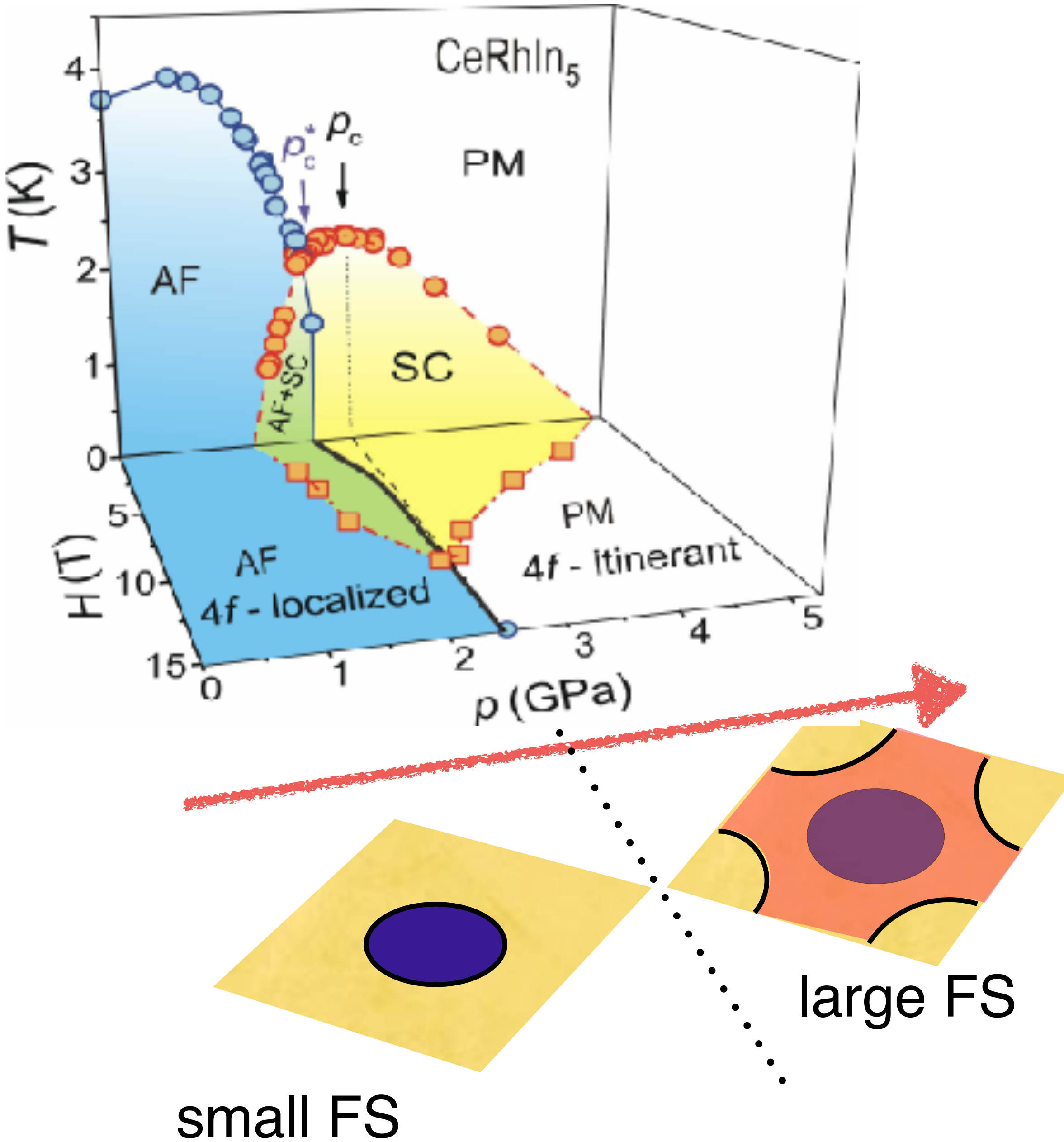


Knebel, Aoki, Floquet, arXiv:0911.5223 (2009)

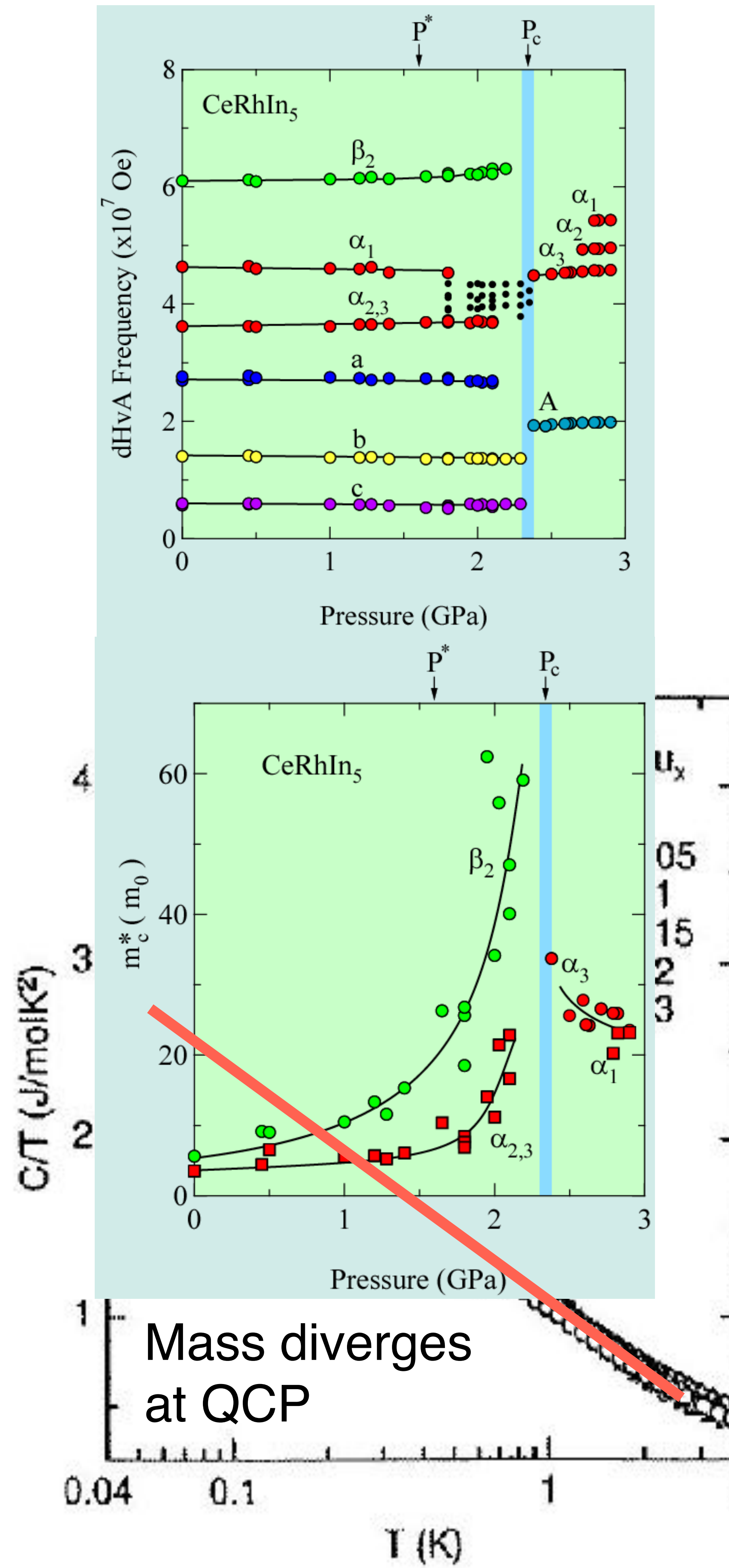
$CeCoIn_5$




CeRhIn$_5$
T (K)
PM
AF
SC
AF+SC
p_c^*
p_c
H (T)
AF
4f - localized
PM
4f - itinerant
p (GPa)
small FS
large FS
CeCoIn
heat
Resistivity [$\mu\Omega$ cm]
T [K]
P*
P$_c$
CeRhIn$_5$
dHvA Frequency (x10^7 Oe)
Pressure (GPa)
β_2
α_1
$\alpha_{2,3}$
a
b
c
A
α_1
α_2
α_3
CeRhIn$_5$
m_c^* (m_0)
Mass diverges
at QCP
$\frac{m^*}{m} \rightarrow \infty$

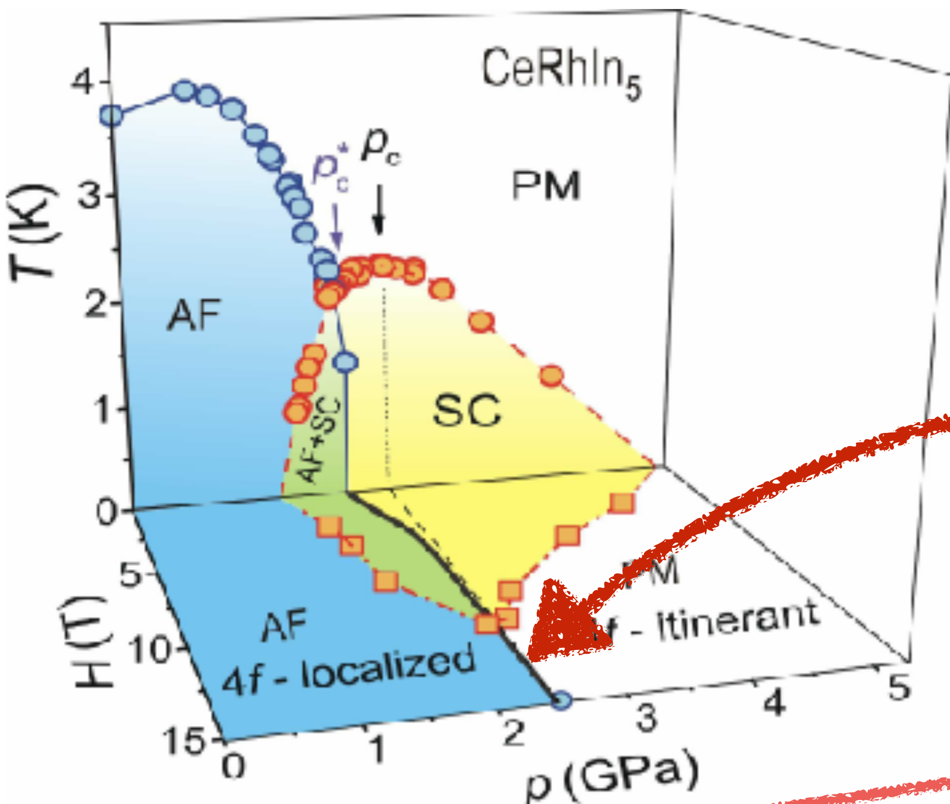


$\boxed{\begin{array}{l} C/T \sim S_0/T^* \ln(T^*/T) \\ S_0 \sim (0.1\text{-}0.3)\ \ R \ln 2 \end{array}}$

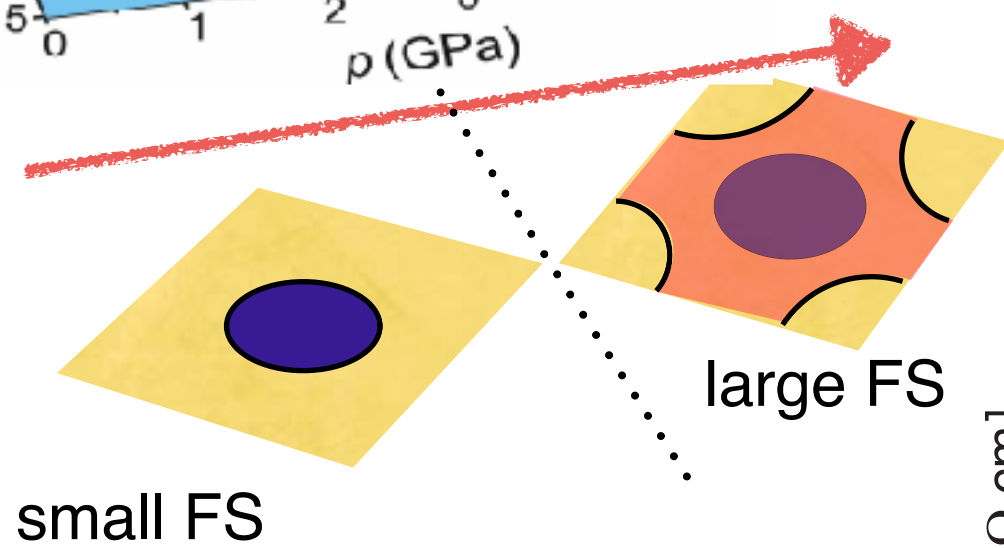


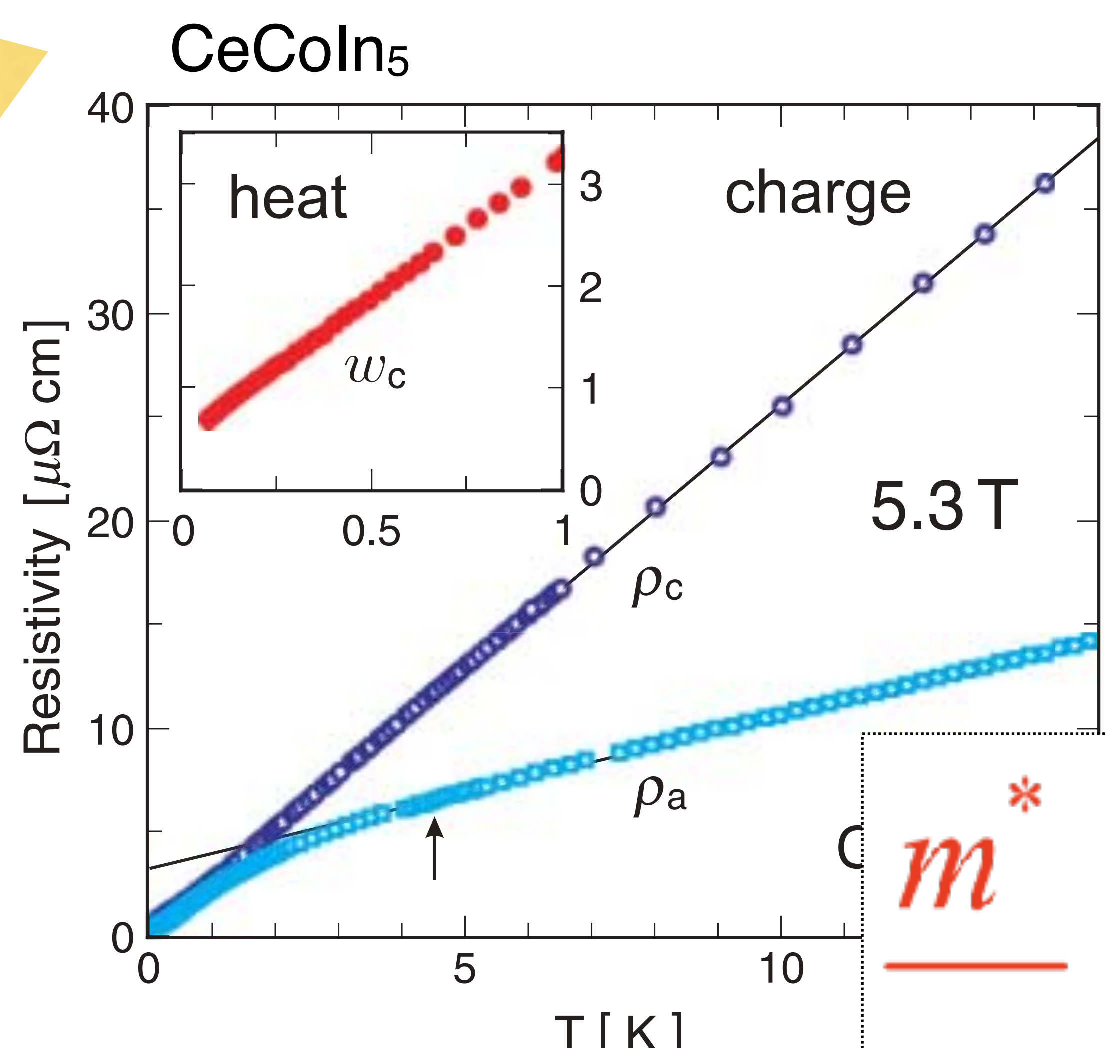
“Kondo Breakdown”

“Partial Mott Localization”

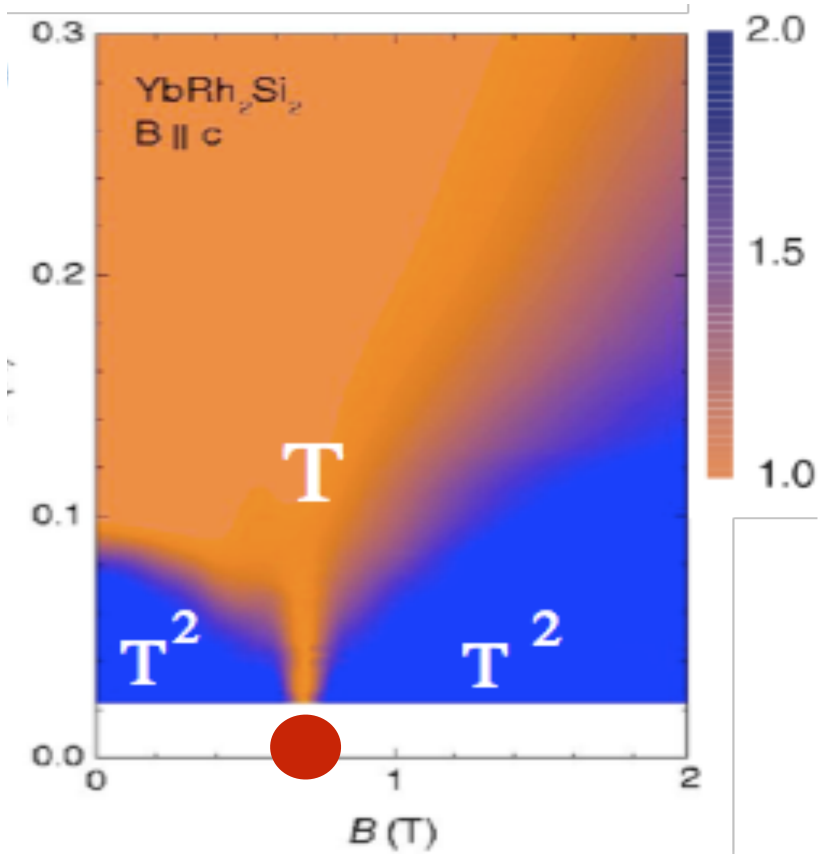


What happens to the charge fluctuations at a small-large FS transition?





$$\frac{m^*}{m} \longrightarrow \infty$$

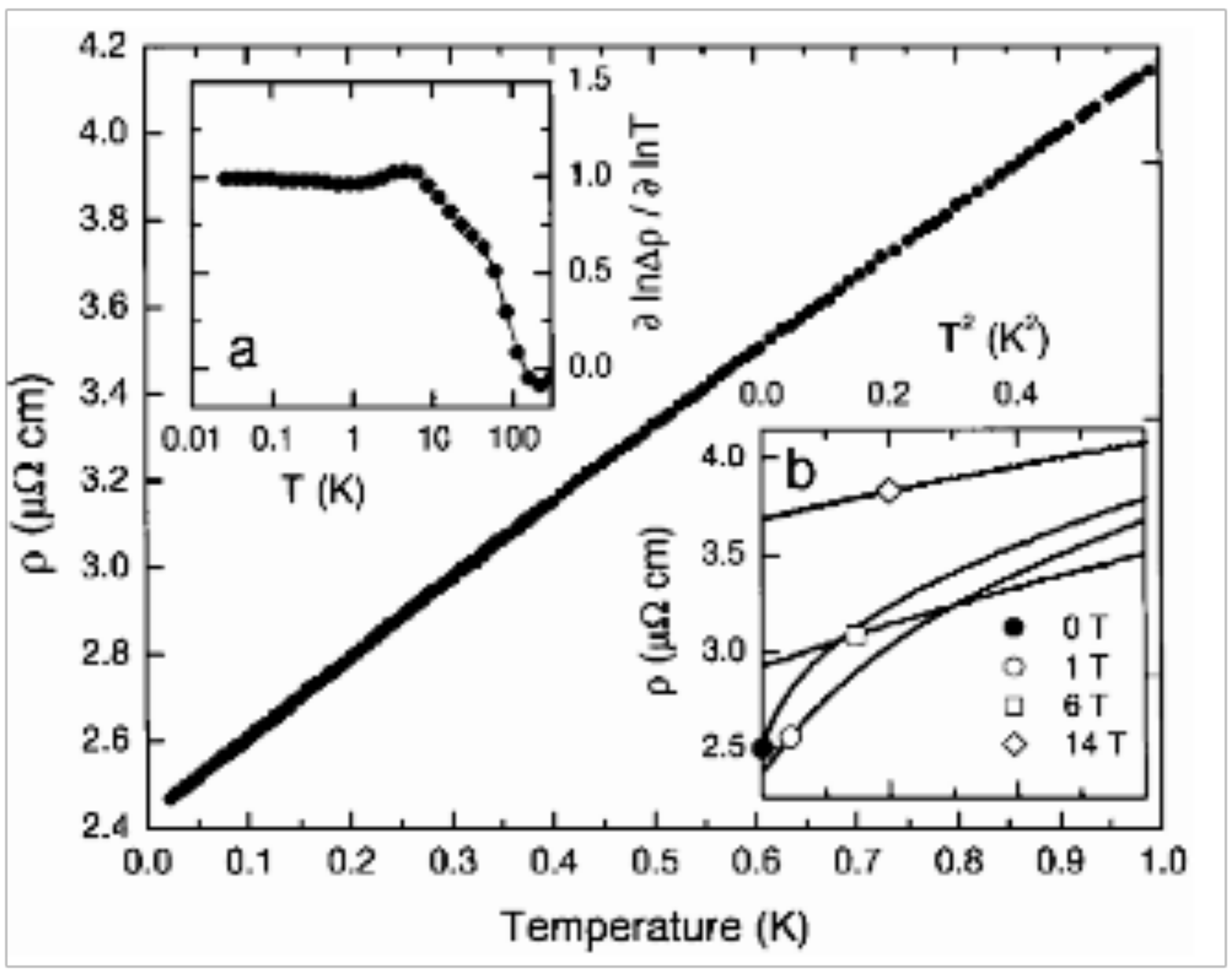


“Kondo Breakdown”

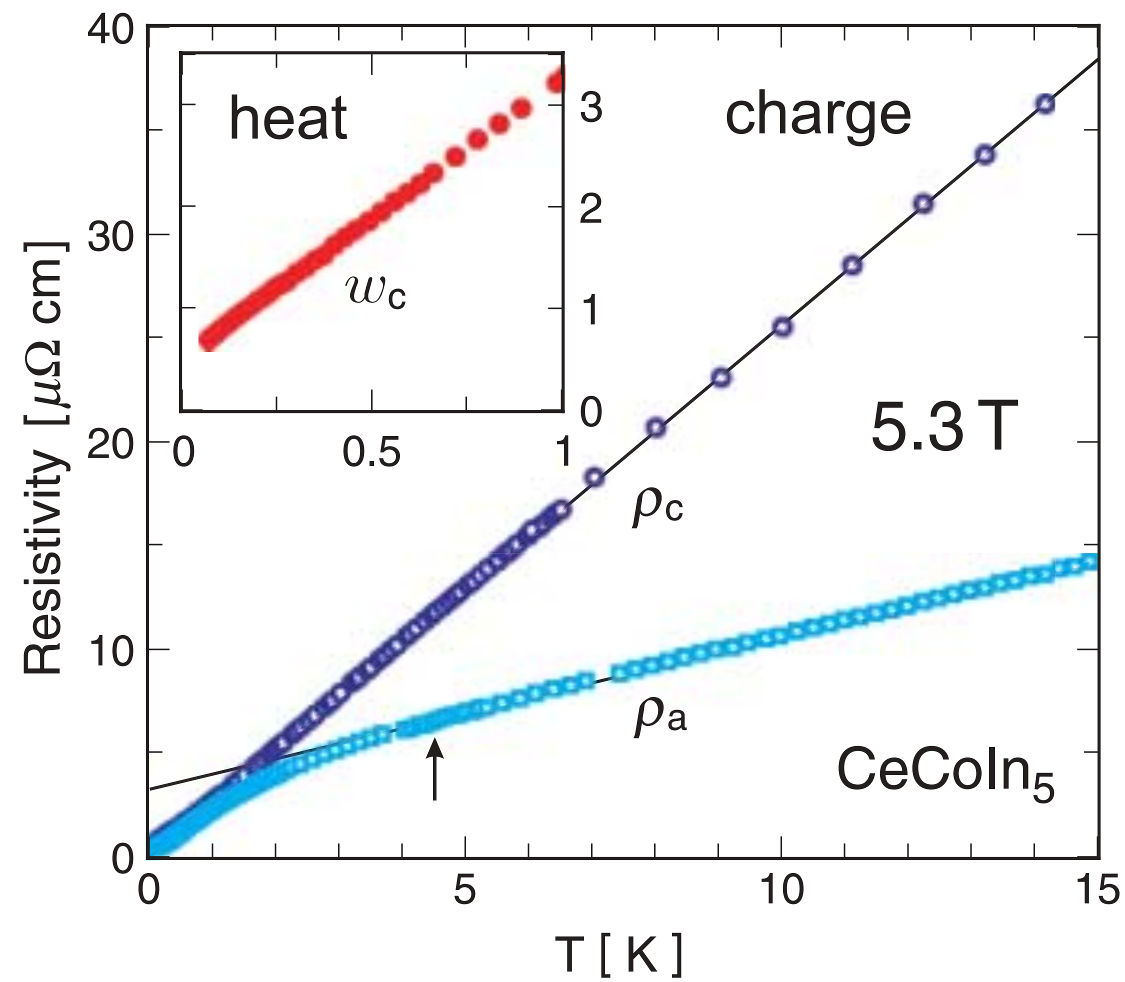
“Partial Mott Localization”

What happens to the charge fluctuations at a small-large FS transition?

$YbRh_2Si_2$



$CeCoIn_5$



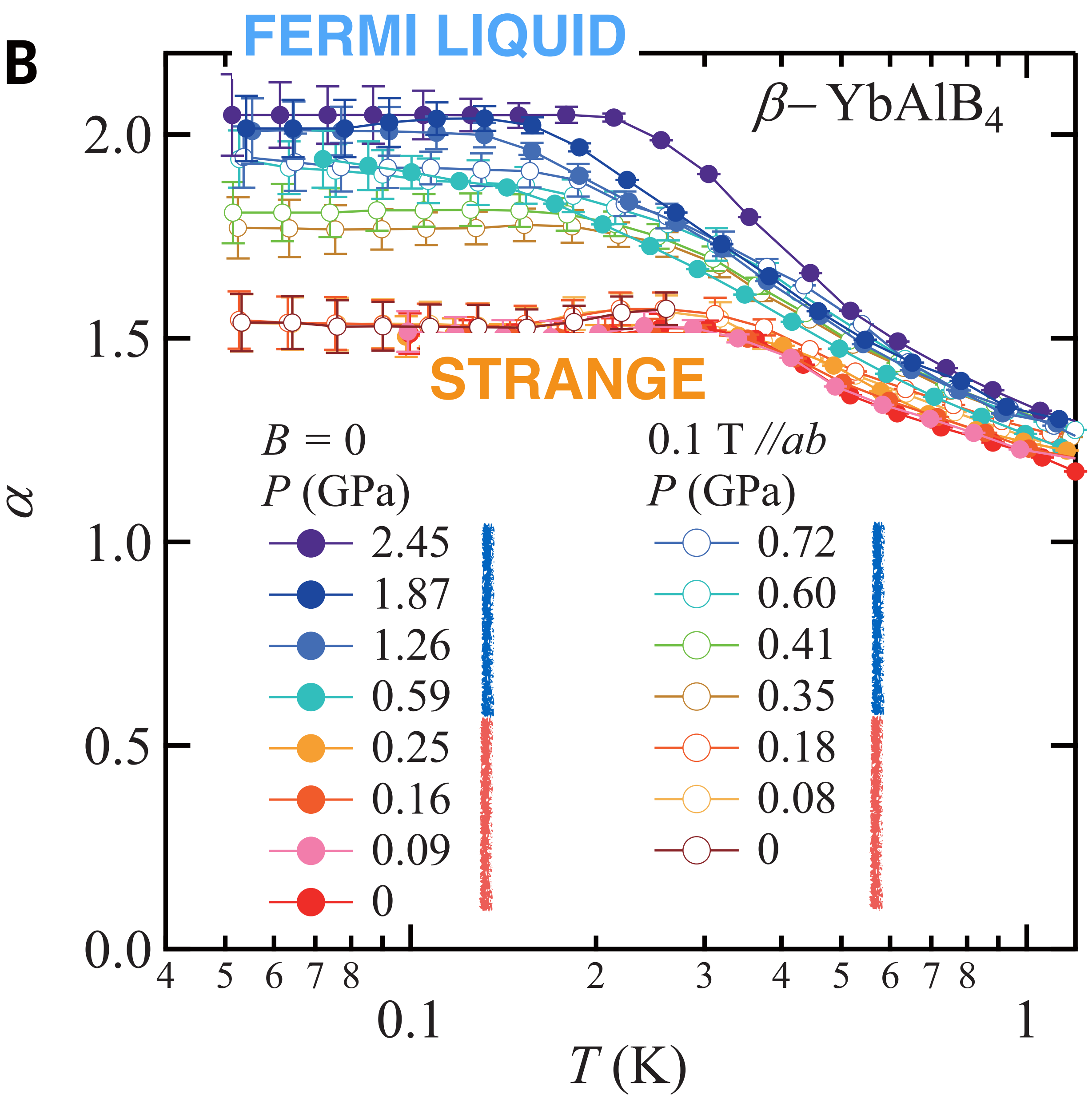
What are the requirements for strange metal behavior?

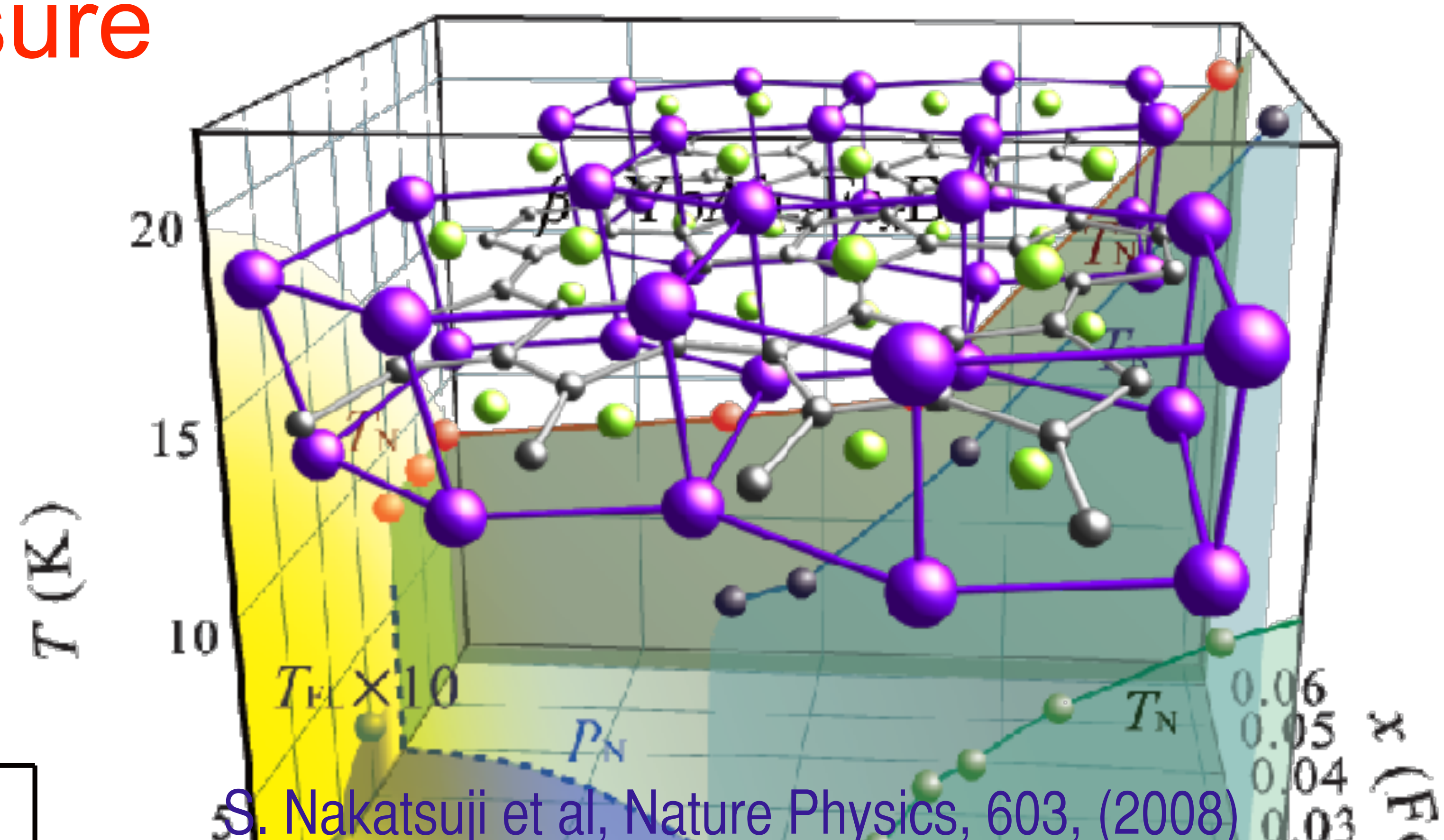
β-$YbAlB_4$: Effect of Pressure

T. Tomita, K. Kuga, et al.
Science **349**, 506 (2015)

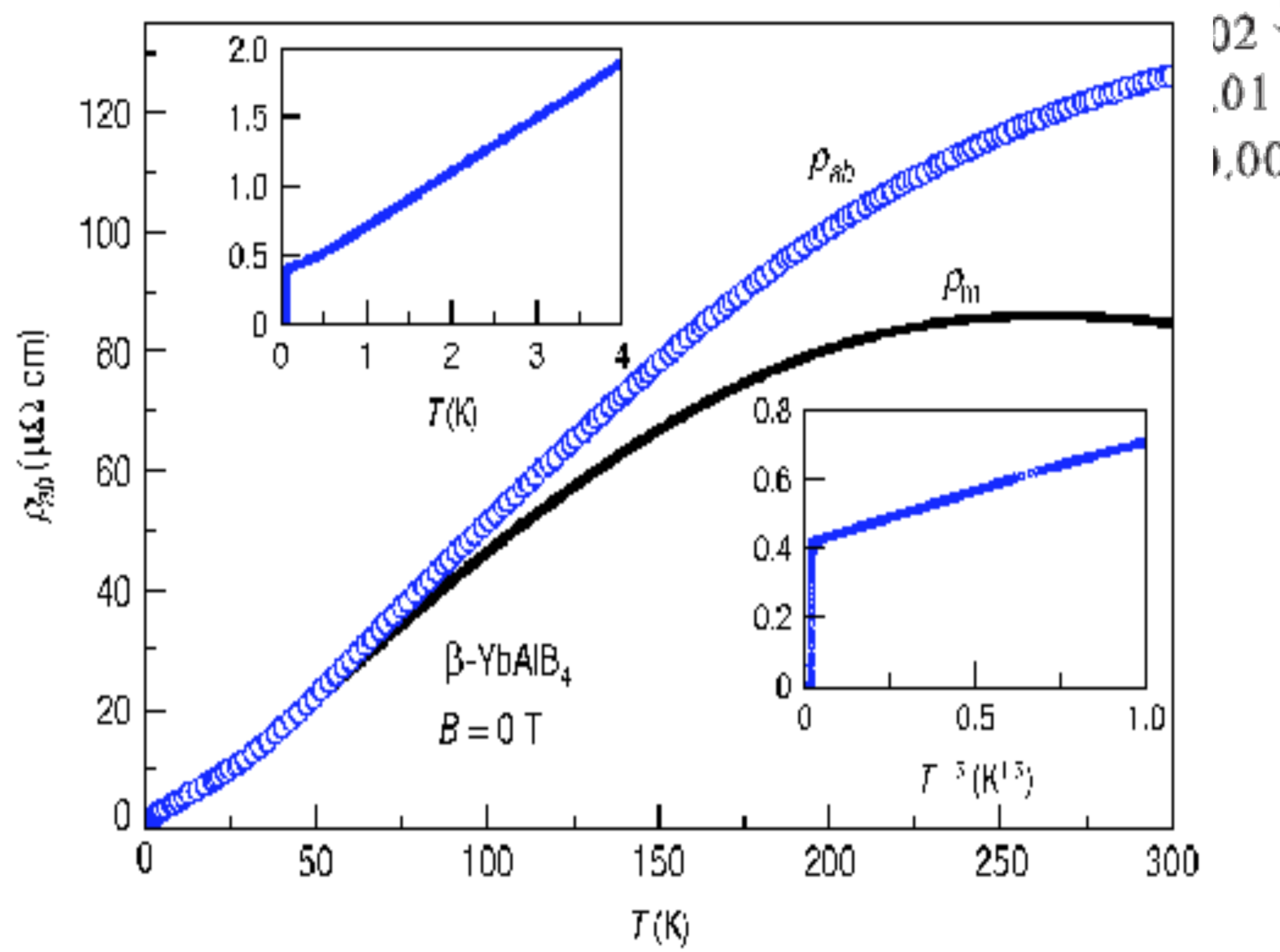
Resistivity under pressure
(piston/cubic anvil)

$$\boxed{\Delta\rho \sim T^{\alpha}}$$



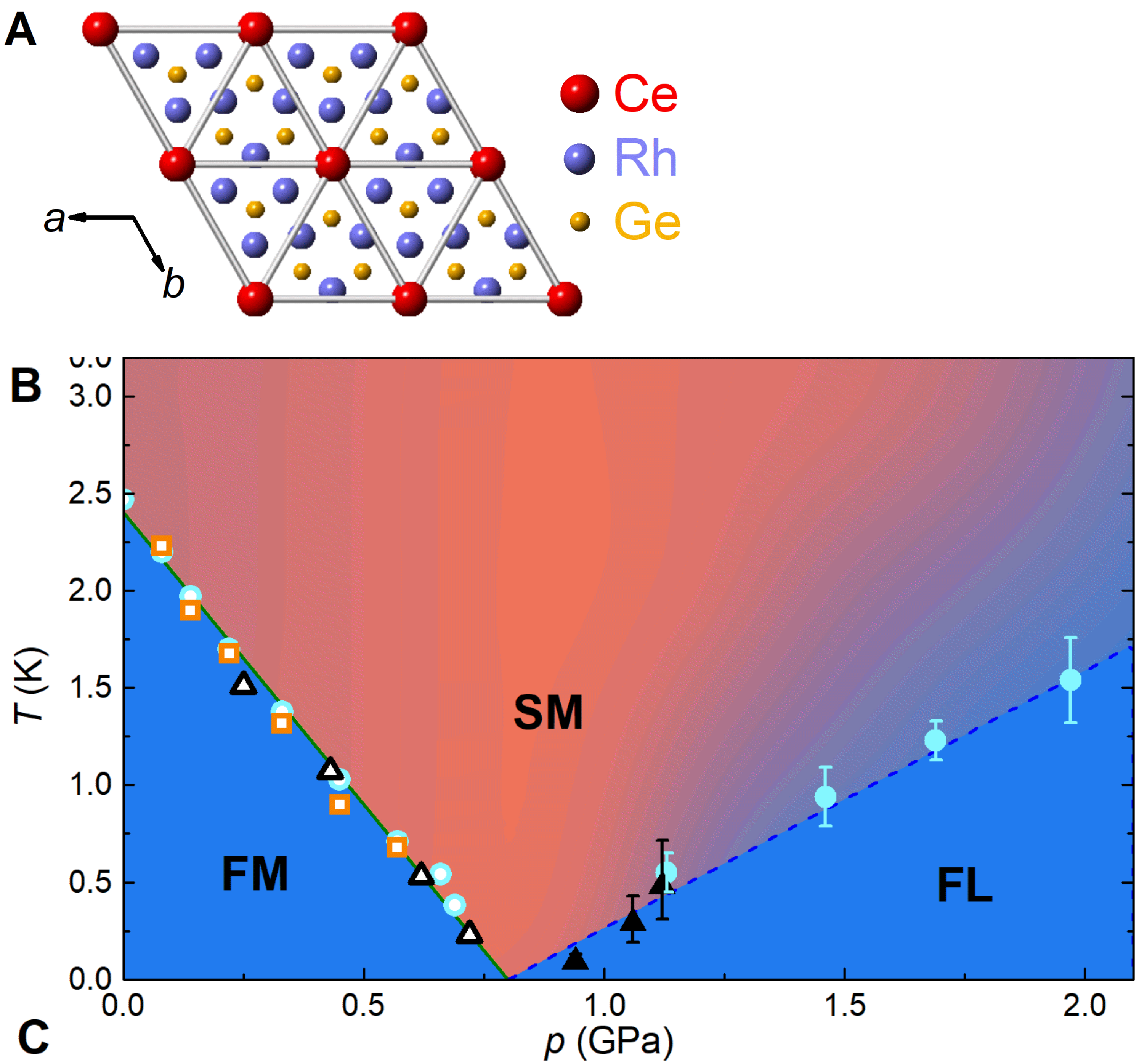


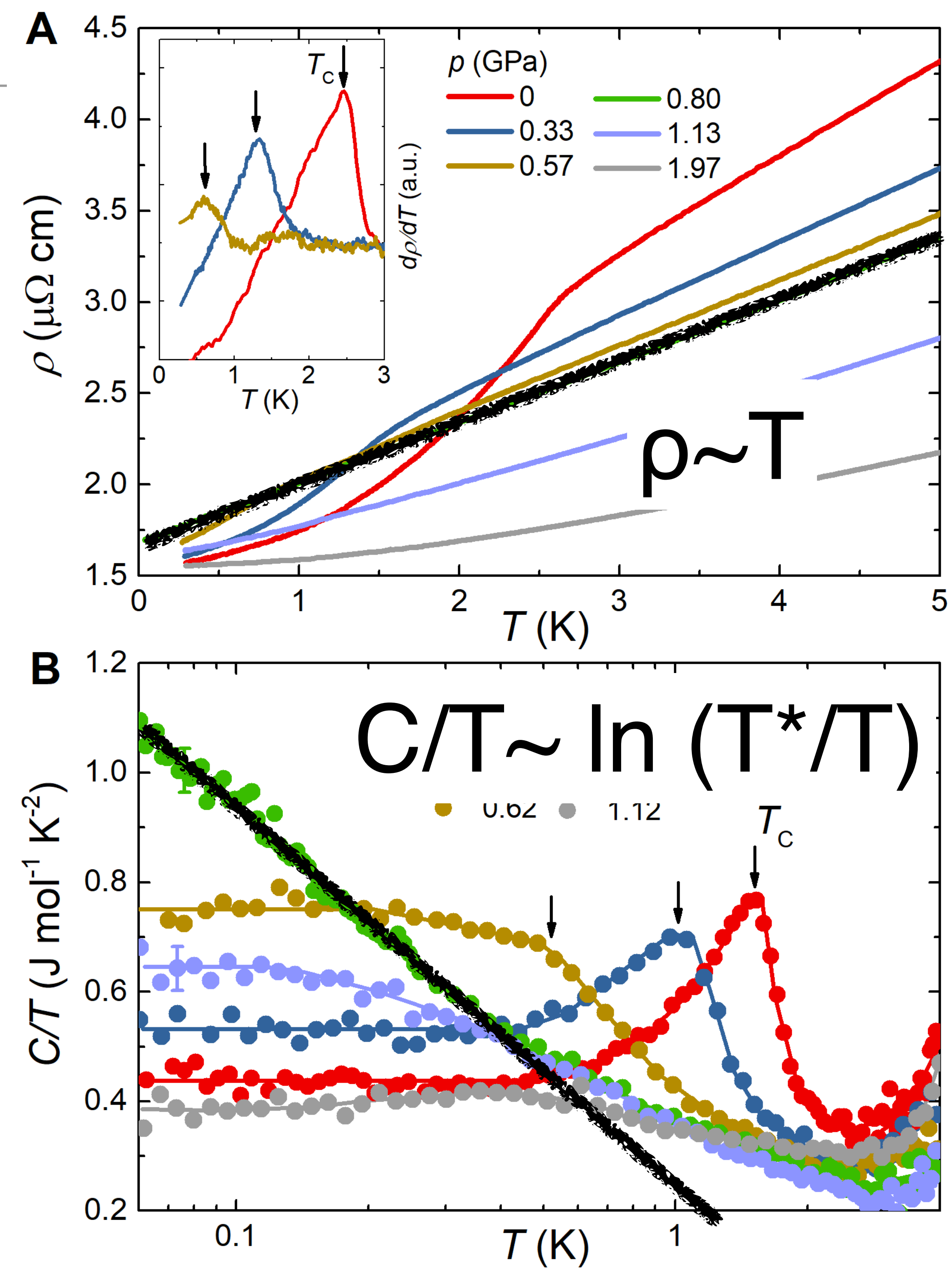
S. Nakatsuji et al, Nature Physics, 603, (2008)



$CeRh_6Ge_4$: Strange metal at a FM QCP

Bin Shen et al, preprint (2019)

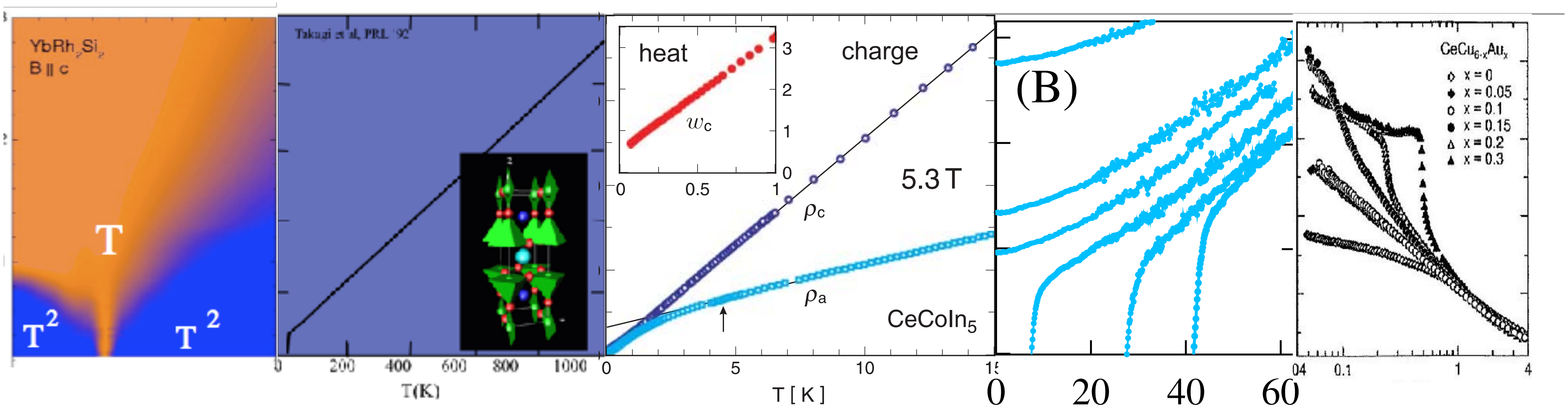




Strange metal behavior at a FM QCP

(Strong xy anisotropy: spin entanglement)

Strange Metals: Summary



- Ubiquity of strange metal behavior, in transition metal and rare-earth materials.
- Linear Resistivity can't be explained by spin fluctuations
- Logarithmic $C/T \sim S_0/T^* \log_e(T^*/T)$.
- AFM QCP not necessary: Kondo breakdown in FM in $CeRh_6Ge_4$ and away from QCP in $YbAlB_4$
- Common feature: partial Mott localization/Kondo Breakdown

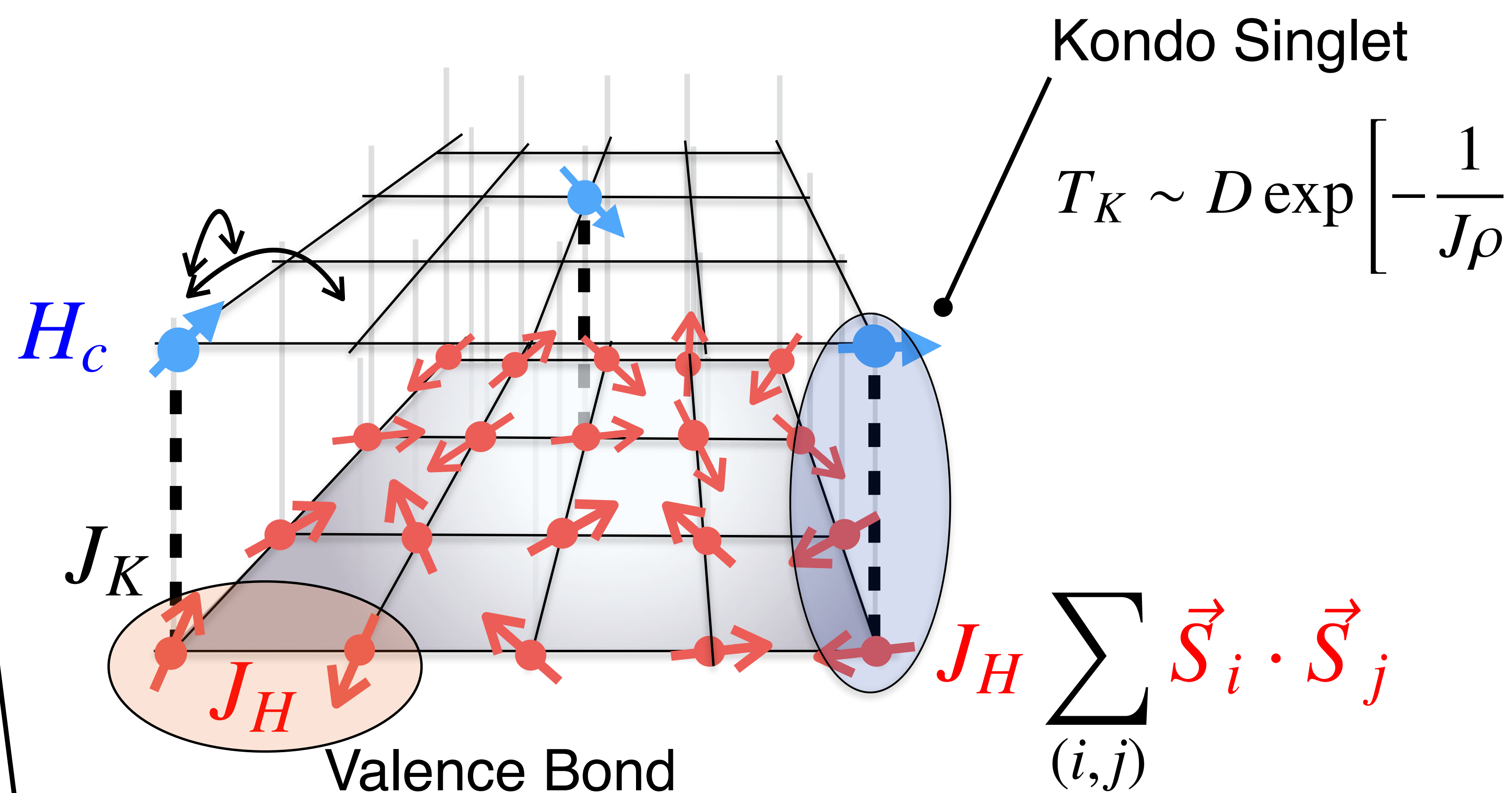
Schwinger Bosons and the Kondo Lattice

Kondo Lattice: introduction

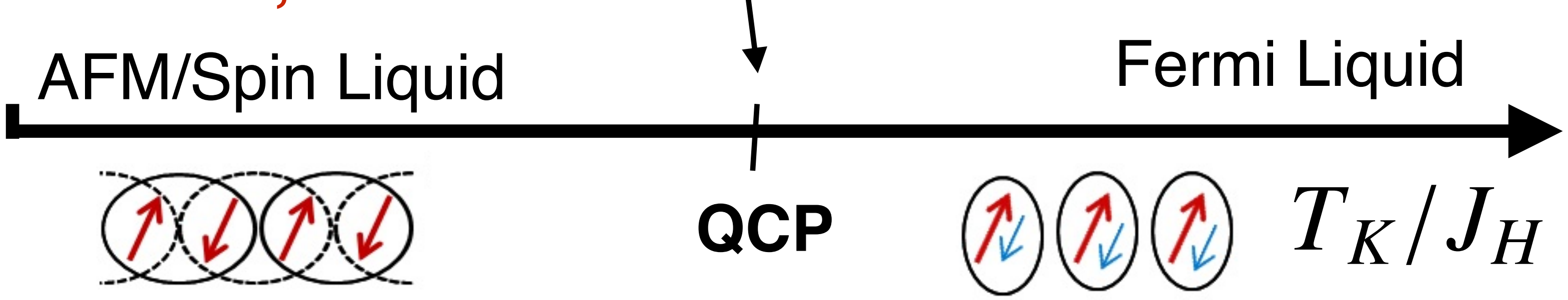
$$H = J_H \sum_{(i,j)} \vec{S}_i \cdot \vec{S}_j$$

QCP :

Transformation in pattern of entanglement



Doniach, 1976

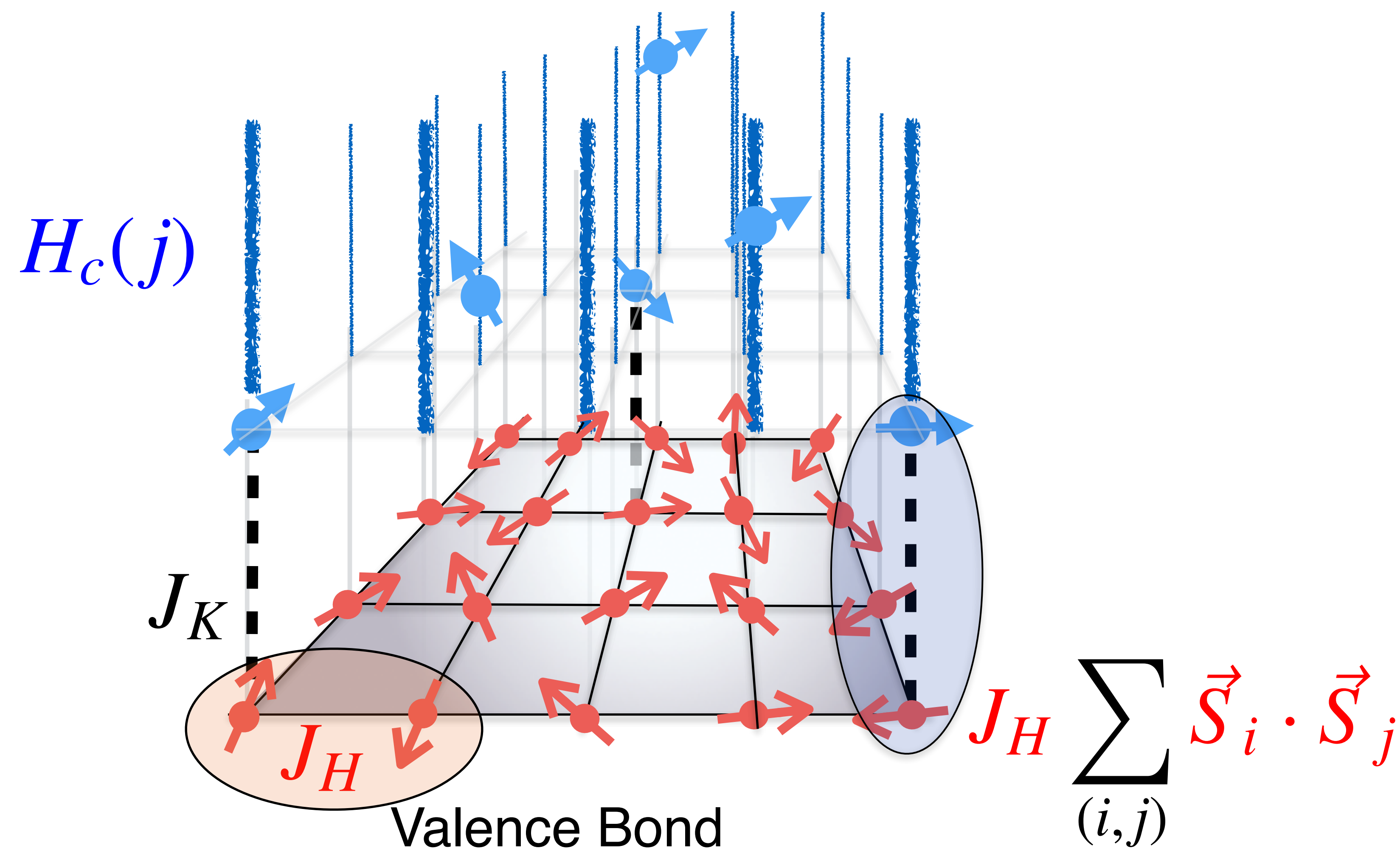


Simplified Kondo Lattice

A. M. Lobos, M. A. Cazalilla, and P. Chudzinski, **PRB 86, 035455 (2012).**
A. M. Lobos and M. A. Cazalilla, **J. Phys. Cond. Matt 25, 094008 (2013).**
Yashar Komijani & PC PRL **120, 157206**, (2018);
Yashar Komijani & PC PRL (2019)

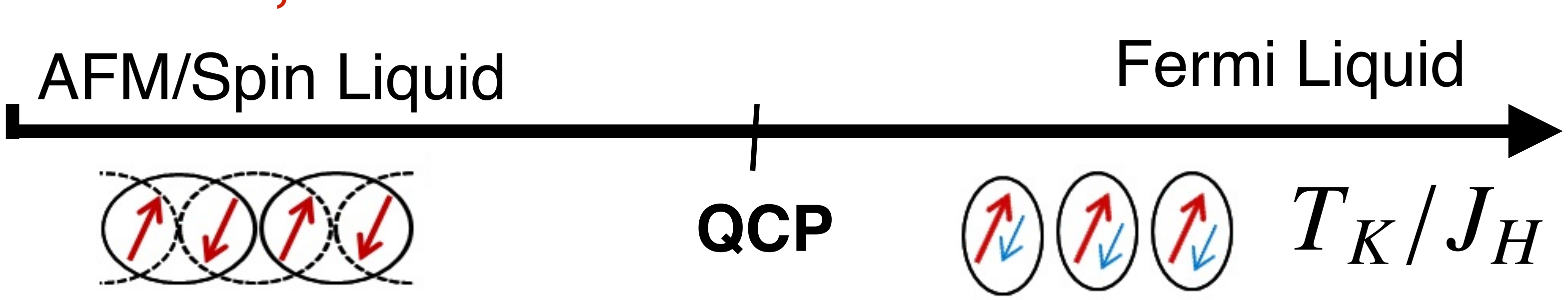
$$H = J_H \sum_{(i,j)} \vec{S}_i \cdot \vec{S}_j + \sum_j H_c(j) + J_K \sum_j \vec{\sigma}_j \cdot \vec{S}_j$$

Each magnetic site has its own conduction screening bath.

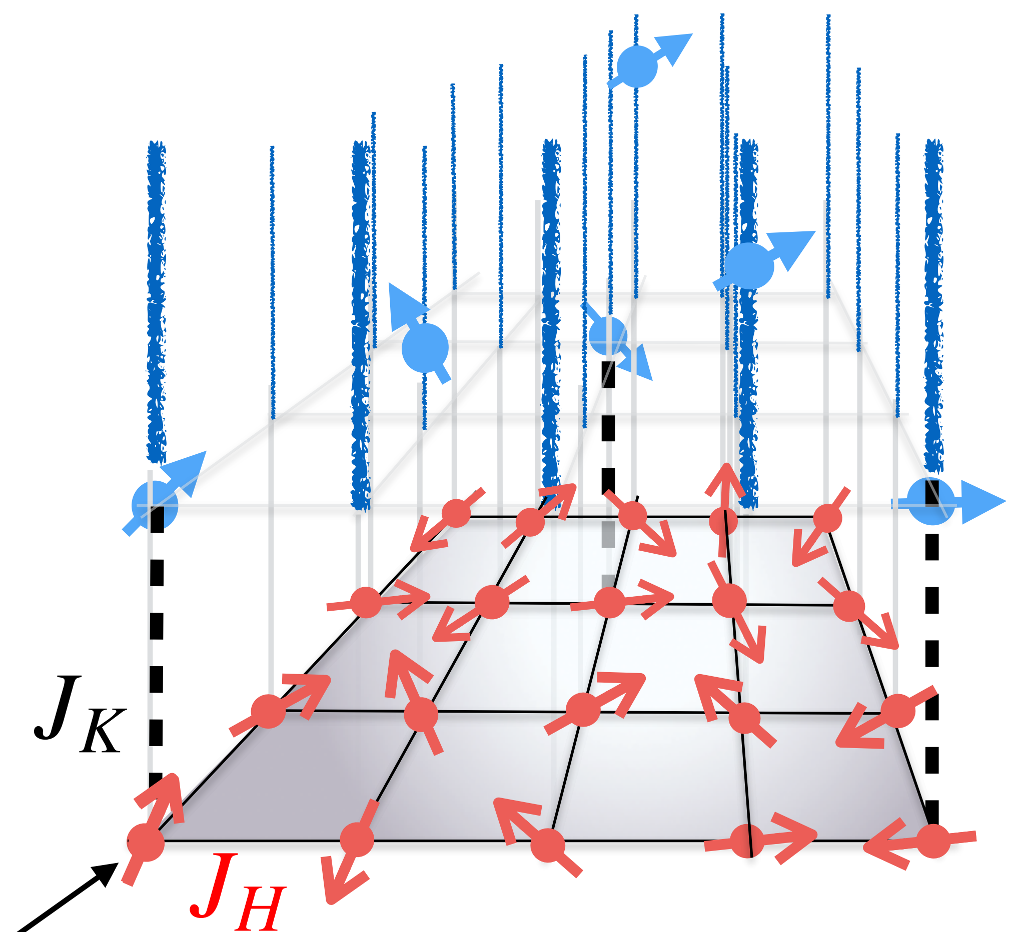


The model captures the essential competition between magnetic and Kondo entanglement

Doniach, 1976



Schwinger Bosons and the Kondo Lattice



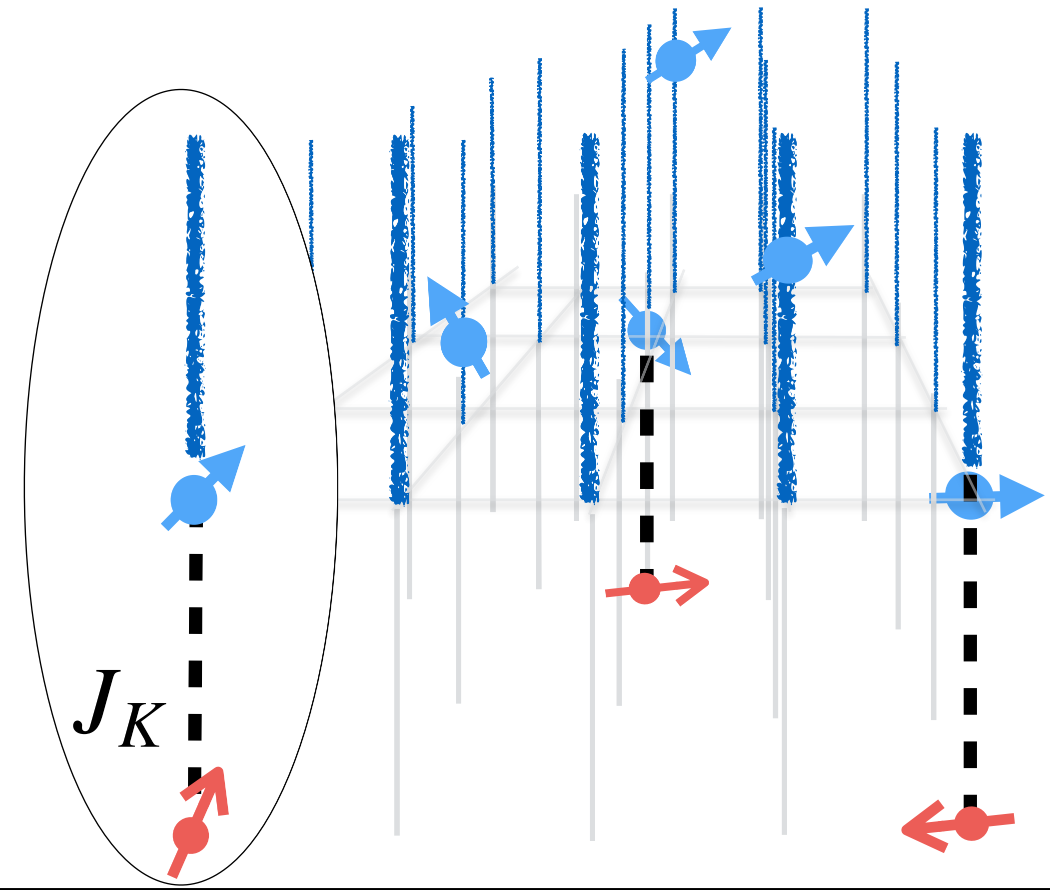
$$\boxed{\vec{S}_j = b_j^\dagger \left(\frac{\vec{\sigma}}{2}\right) b_j}$$

Schwinger Bosons and the Kondo Lattice

Parcollet-Georges Approach

O. Parcollet and A. Georges, **PRL 79, 4665 (1997).**

J. Rech, et al, **PRL 96, 016601 (2006).**



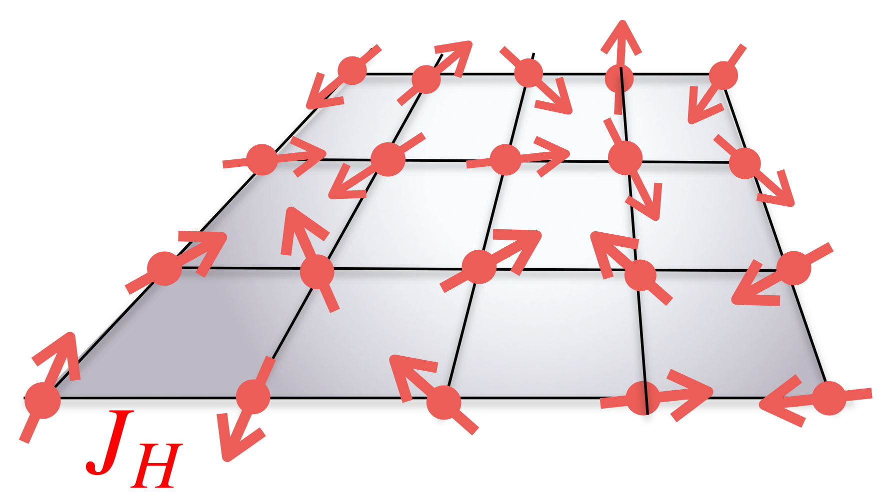
Arovas Auerbach Approach (Large N)

D. P. Arovas and A. Auerbach, **PRB 38, 316 (1988).**

$$J_H \vec{S}_i \cdot \vec{S}_j \longrightarrow \left[\bar{\Delta}_{ij} (\tilde{\sigma} b_{j\bar{\sigma}} b_{i\sigma}) + \mathrm{H.c} \right] + \frac{N|\Delta_{ij}|^2}{J_H}$$

Captures the physics of fluctuating magnetism in one and two dimensions as a bosonic RVB.

$$\boxed{\vec{S}_j = b_j^\dagger \left(\frac{\vec{\sigma}}{2} \right) b_j}$$



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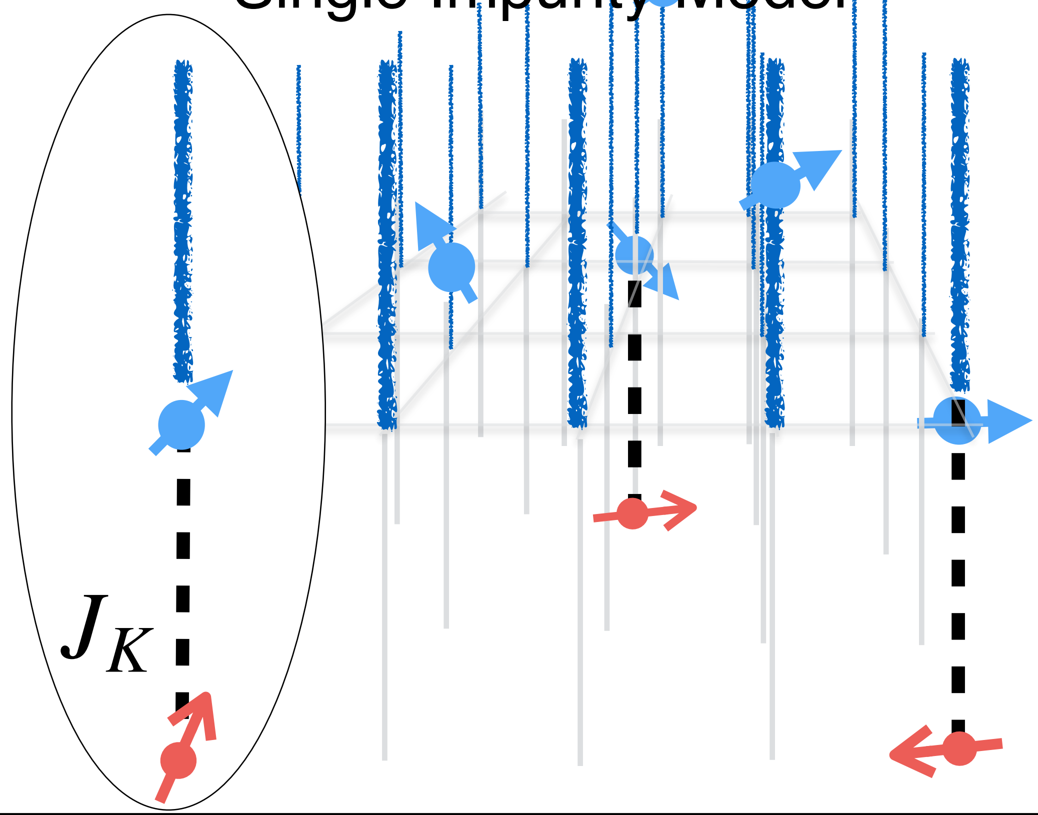
Single Impurity Model



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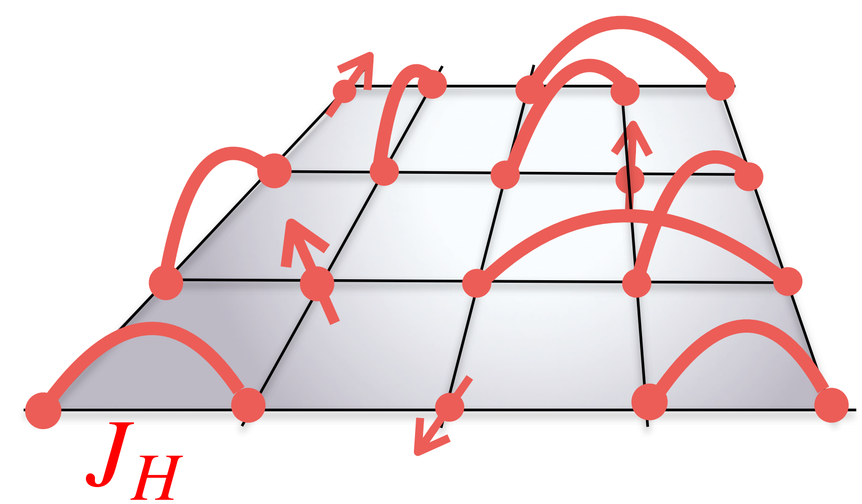

Schwinger Bosons and the Kondo Lattice

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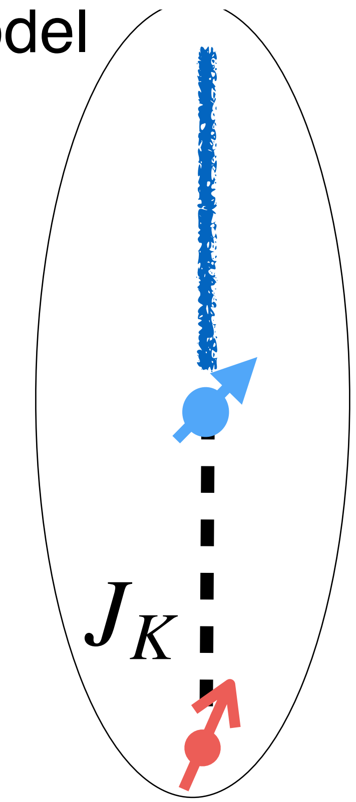

$$H_K(j) \rightarrow [(b^\dagger_{j\alpha}\psi_{ja\alpha})\chi_{ja} + \mathrm{h.c}] + \frac{N\bar{\chi}_{ja}\chi_{ja}}{J_K}$$

Treats the Kondo effect as an fractionalization of spins into heavy electrons and Kondo singlets

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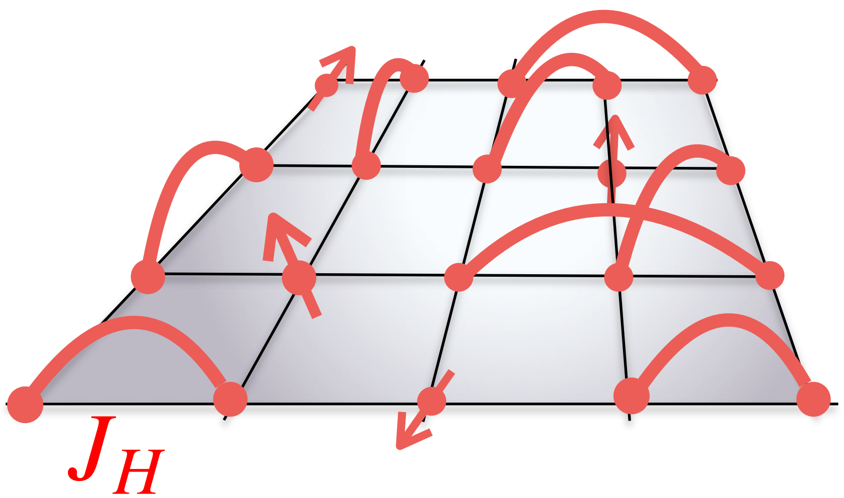

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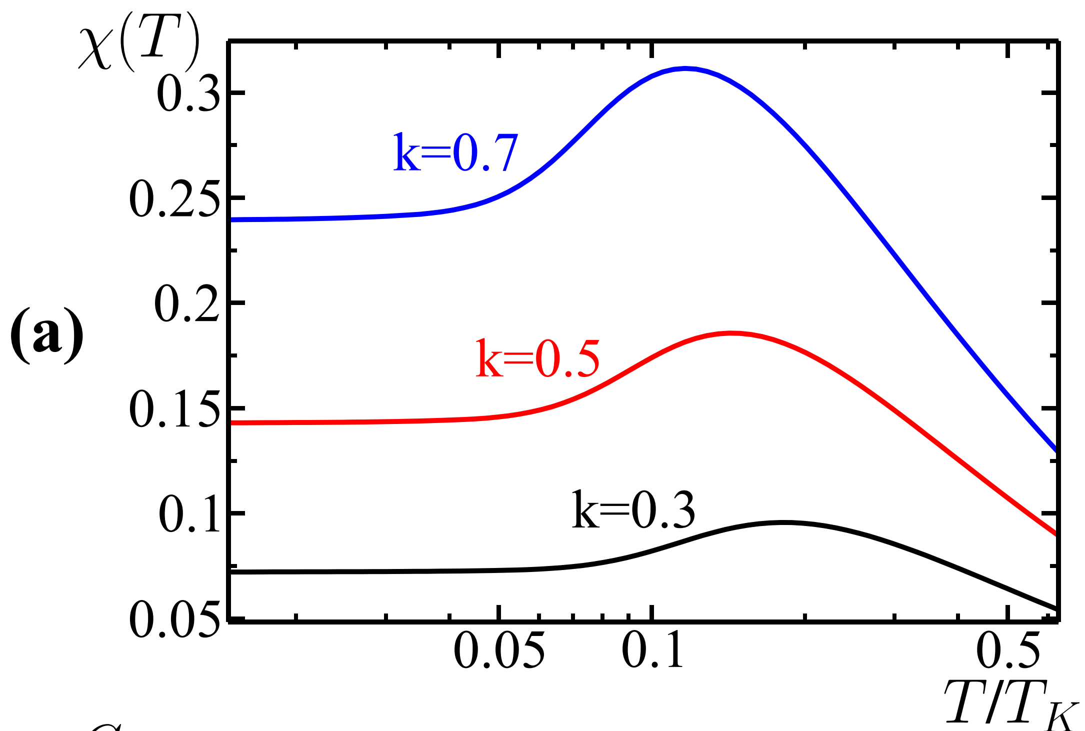
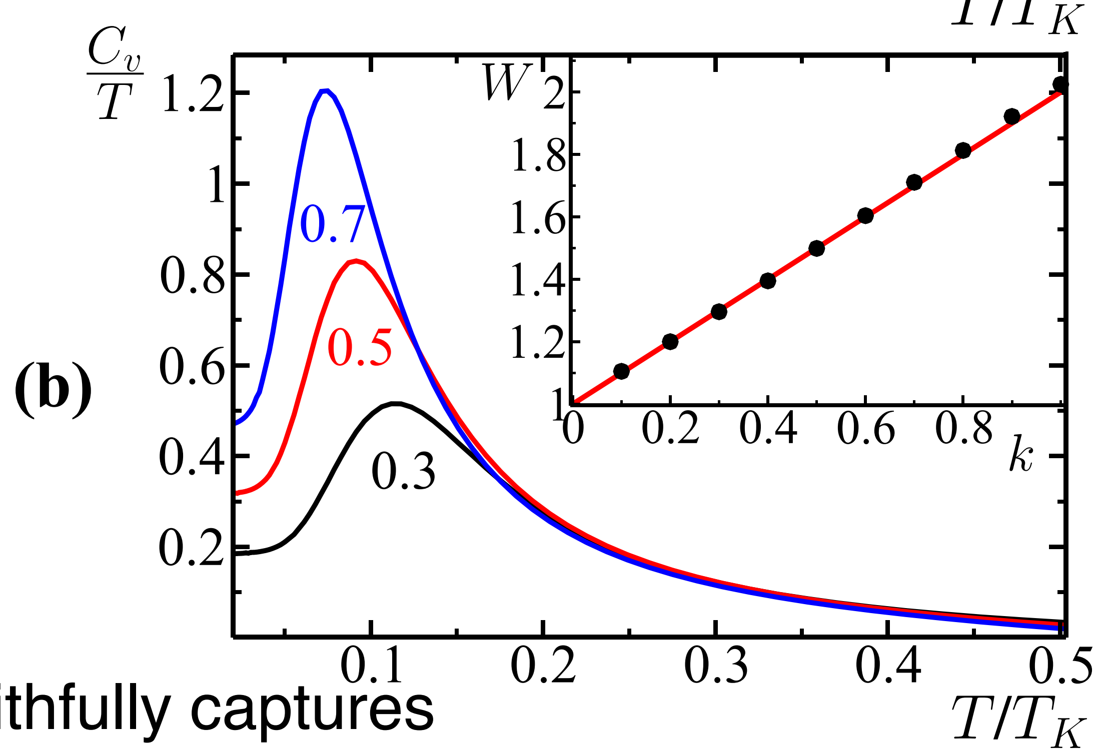
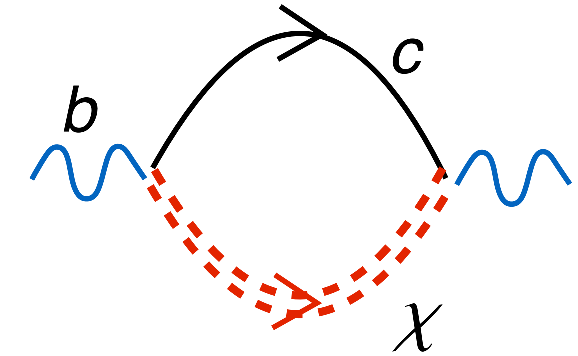


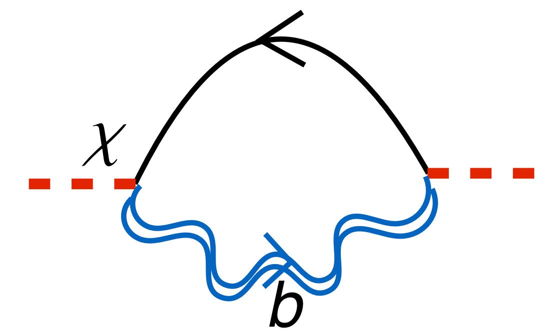


$$\Sigma_b(\omega) =$$

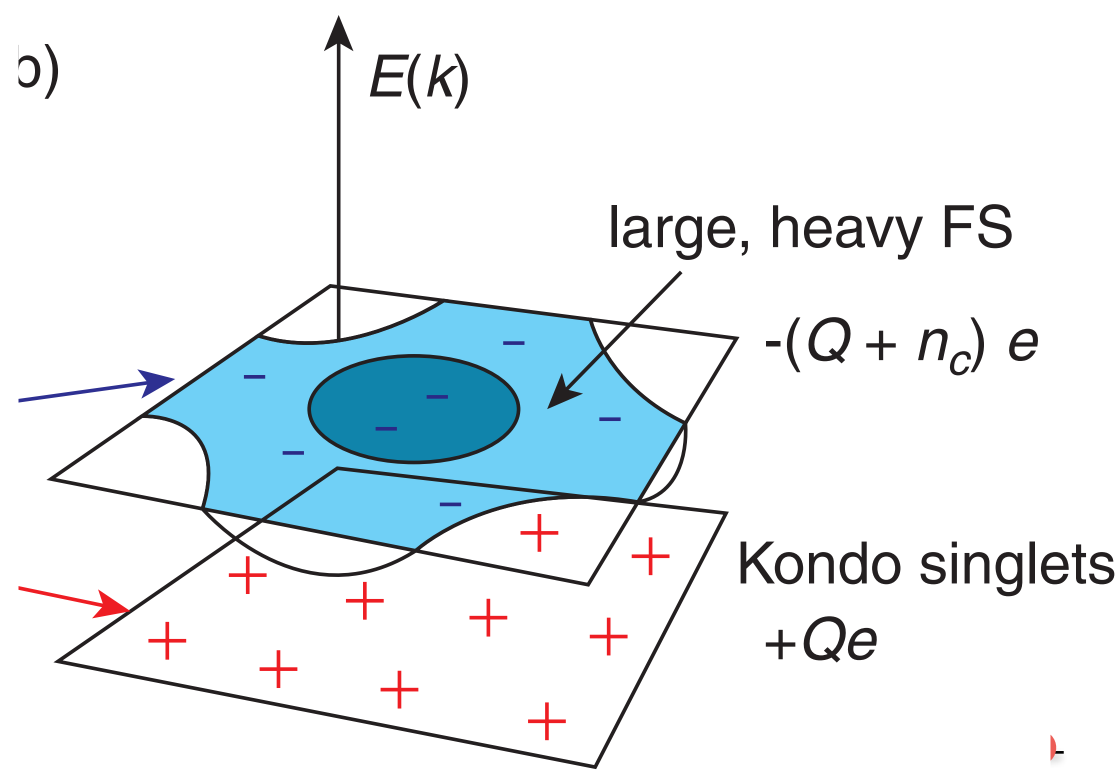


spinon self-energy

$$\Sigma_\chi(\omega) =$$



holon self-energy



Faithfully captures
Fully screened FL

Schwinger Bosons and the Kondo Lattice

$$\vec{S}_j = b^\dagger_j \left(\frac{\vec{\sigma}}{2}\right) b_j$$

Parcollet-Georges Approach

O. Parcollet and A. Georges, **PRL 79, 4665 (1997).**

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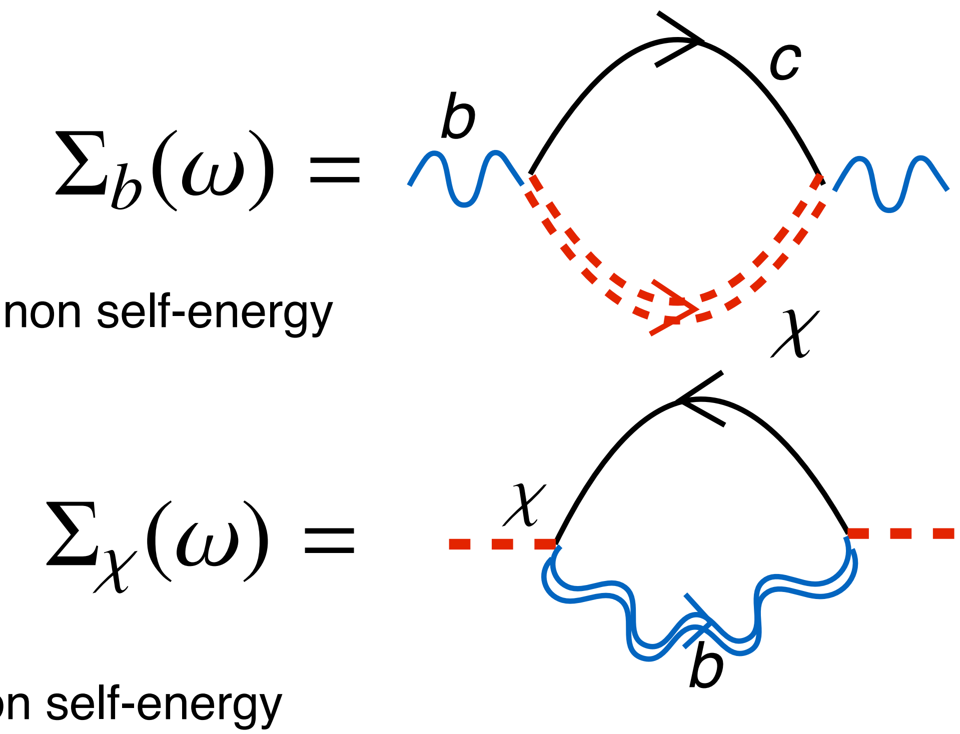
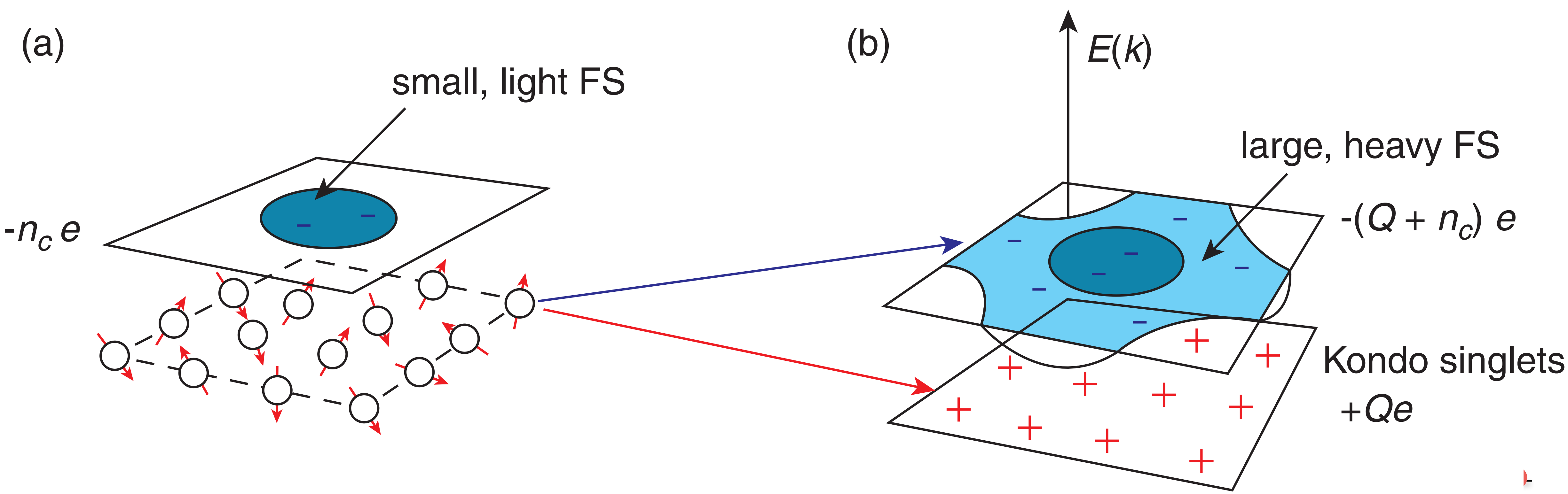


Kondo effect as an fractionalization of spins into heavy electrons and Kondo singlets (holons)



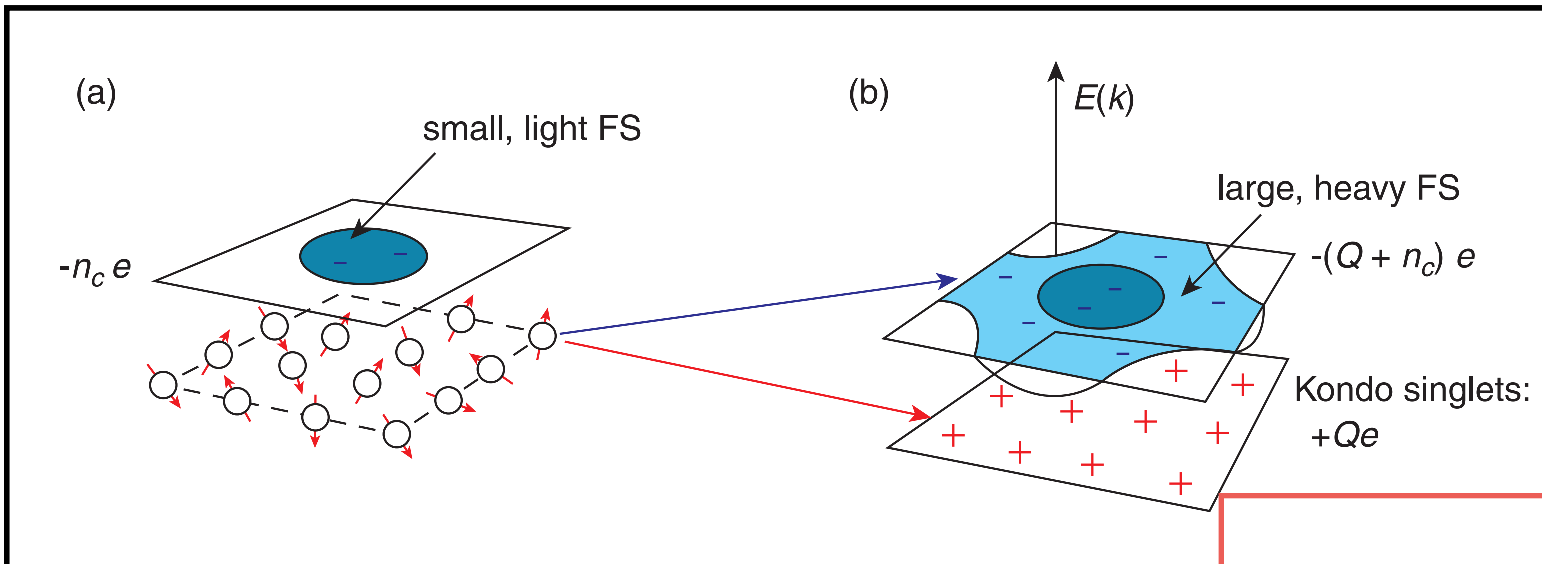
Schwinger Bosons and the Kondo Lattice

$$\vec{S}_j = b_j^\dagger \left(\frac{\vec{\sigma}}{2}\right) b_j$$

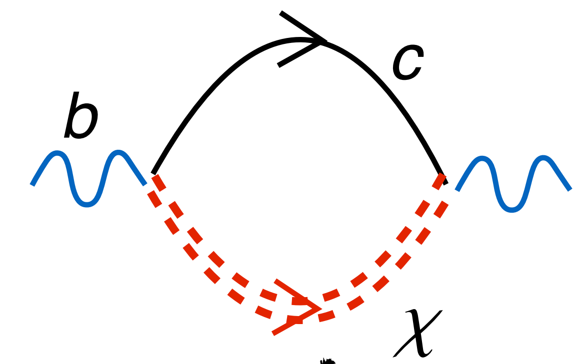
Parcollet-Georges Approach

O. Parcollet and A. Georges, **PRL 79, 4665 (1997).**

J. Rech, et al, **PRL 96, 016601 (2006).**



$$\Sigma_b(\omega) =$$



spinon self-energy

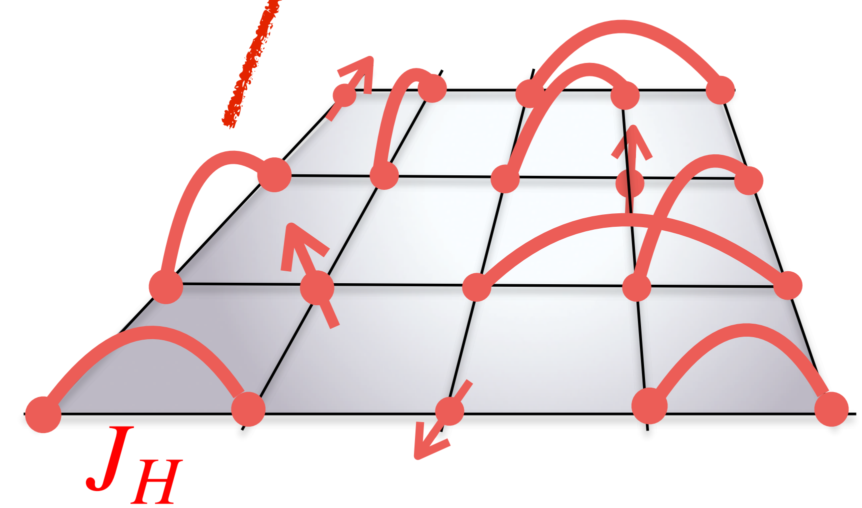
$$\mathcal{G}(\mathbf{q},\omega) = \left[\left(\omega\tau_3 - \lambda - i\Delta_{\mathbf{q}}\tau_2\right) - \Sigma_b(\omega)\right]^{-1}$$

Unified approach

Arovas Auerbach Approach (Large N)

D. P. Arovas and A. Auerbach, **PRB 38, 316 (1988).**

Captures the physics of fluctuating magnetism in one and two dimensions as a bosonic RVB.

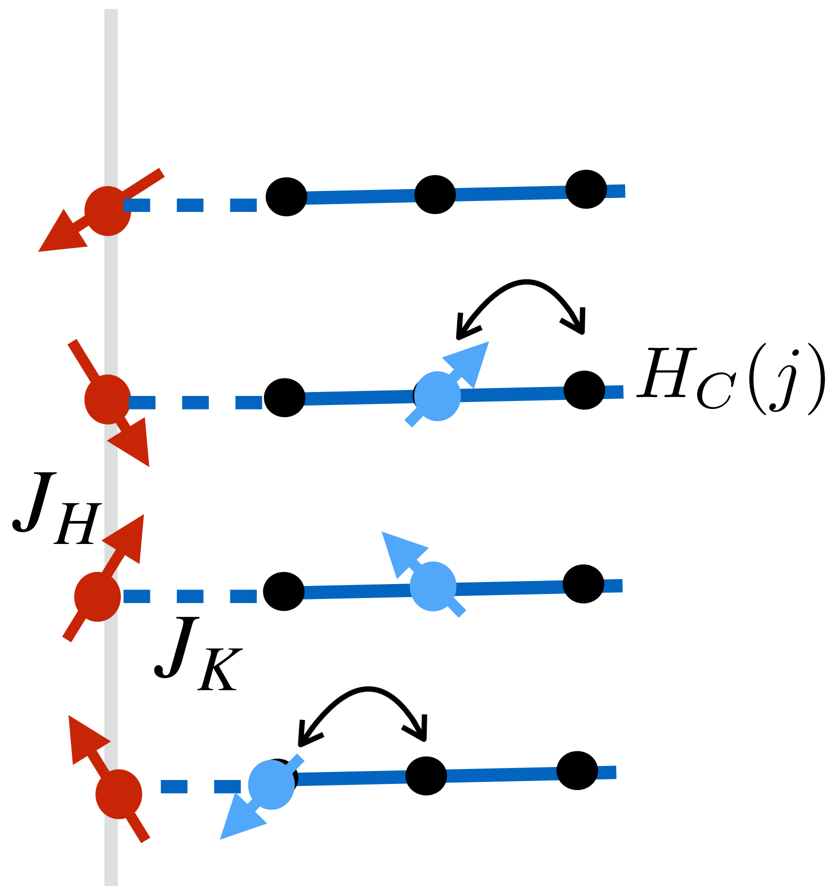


Application to 1D Kondo Lattices

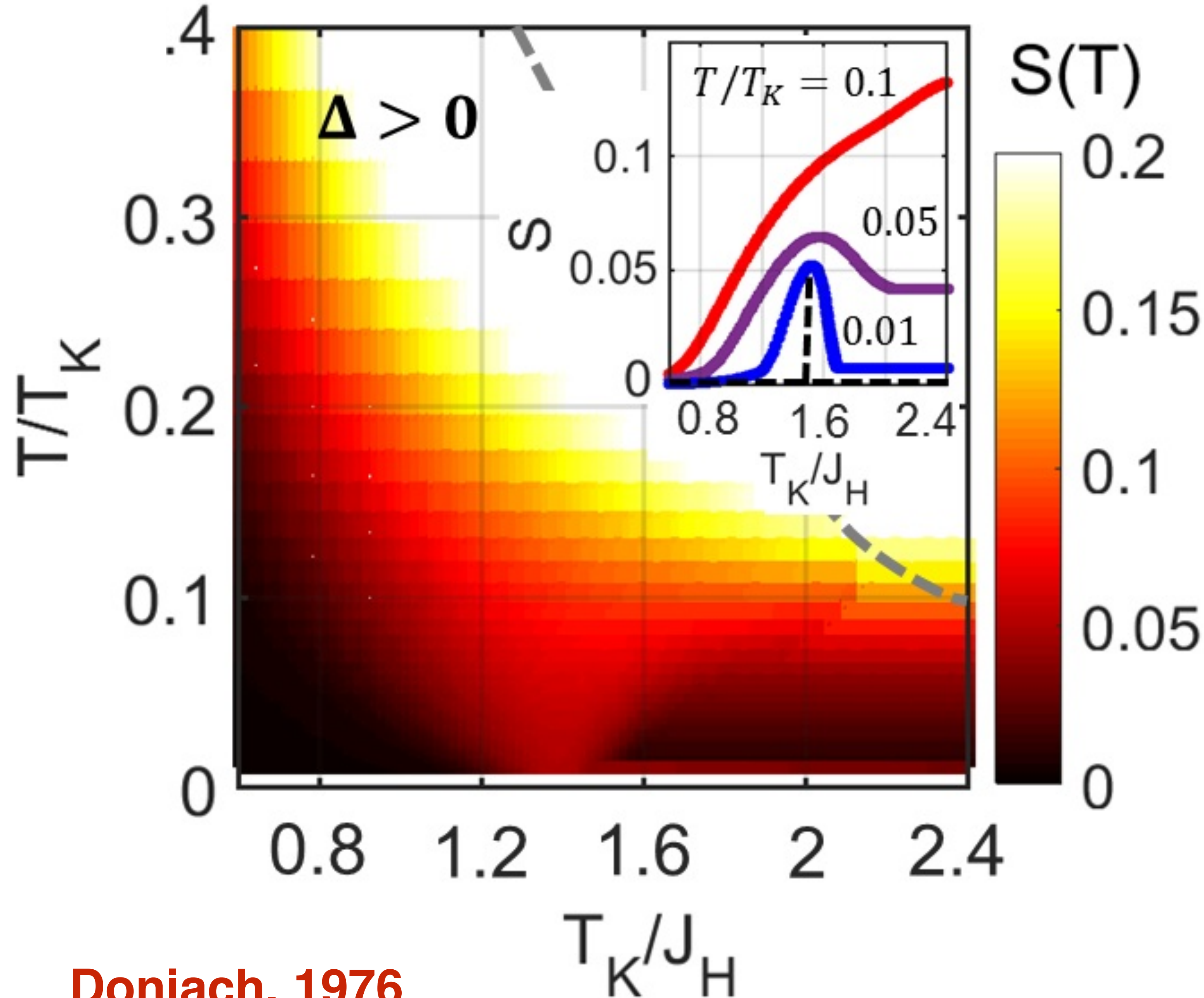
Schwinger Boson approach to the KL

Yashar Komijani & PC **PRL 122, 217001 (2019)**

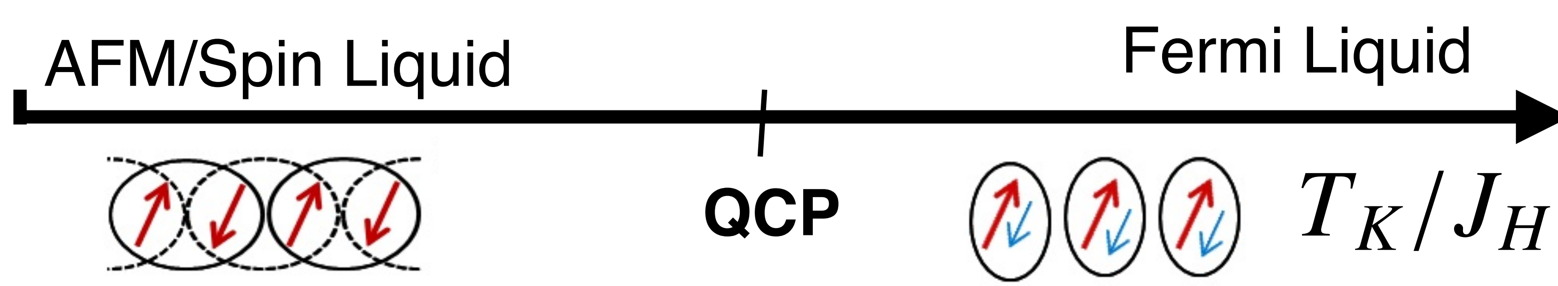
$$H = \sum_j \left[H_C(j) + J_K \vec{S}_j \cdot \vec{\sigma}_j + J_H \vec{S}_j \cdot \vec{S}_{j+1} \right].$$



Simplified 1D Kondo Lattice



Doniach, 1976



Schwinger Boson approach to the KL

Yashar Komijani & PC **PRL 122, 217001 (2019)**

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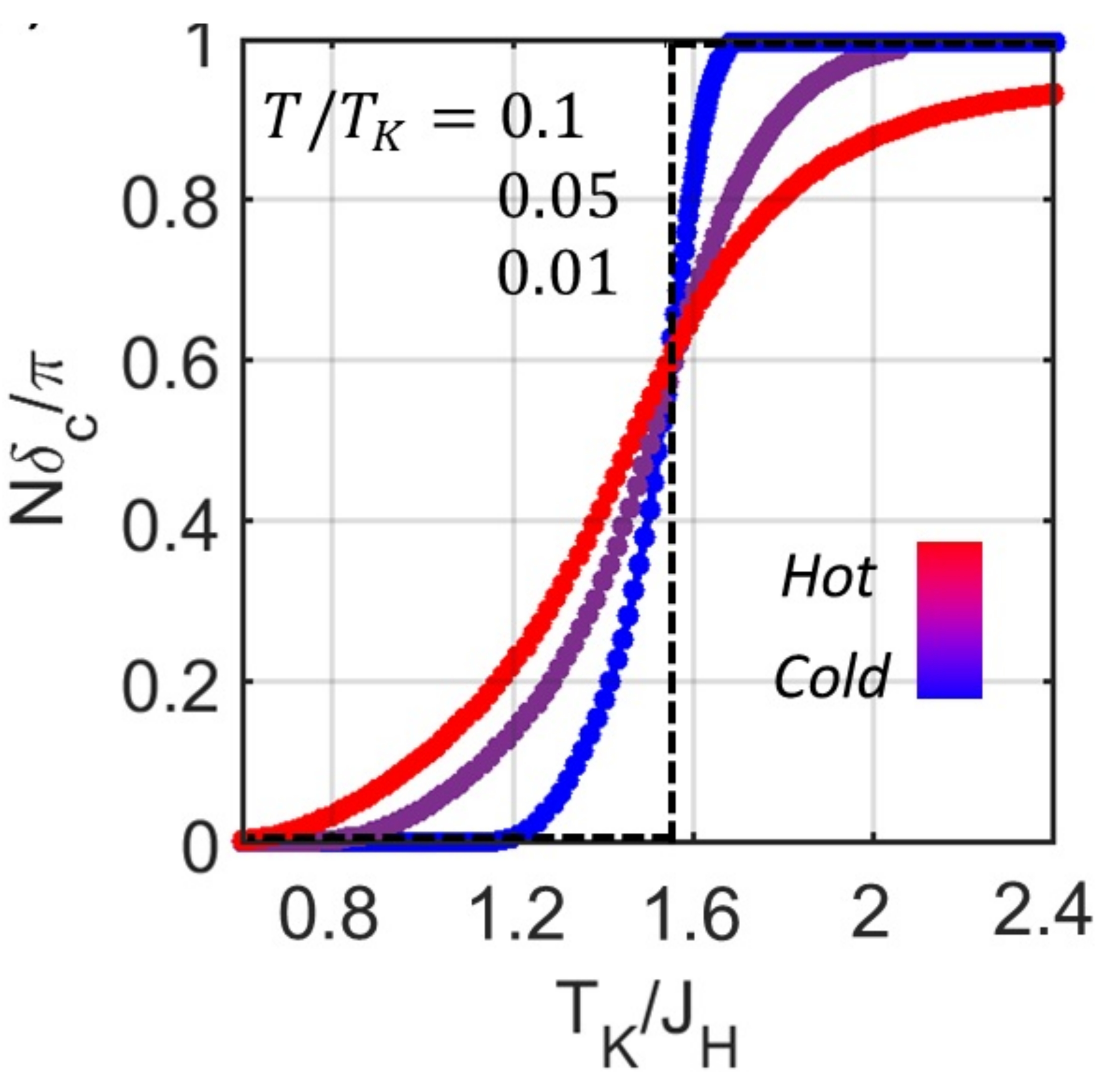
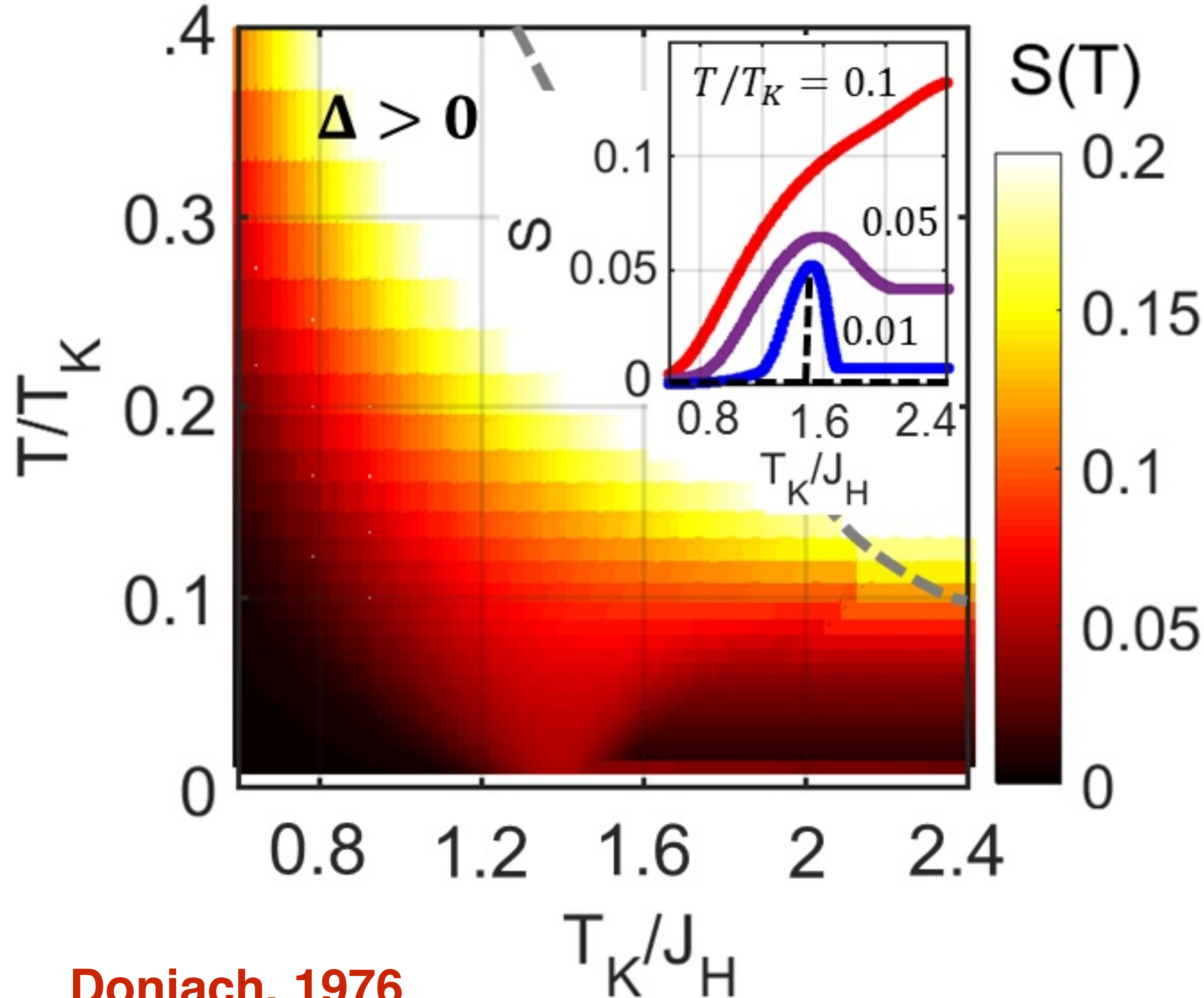
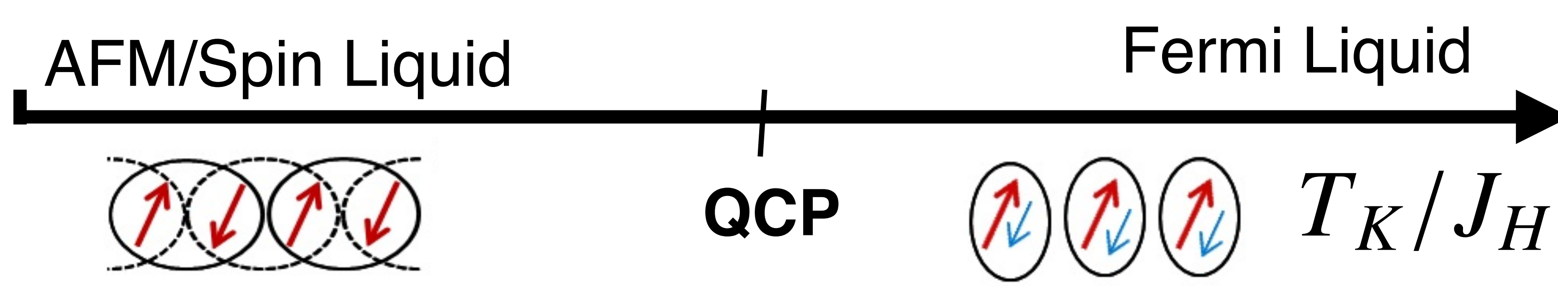




"Jump in the Fermi Surface"

Doniach, 1976



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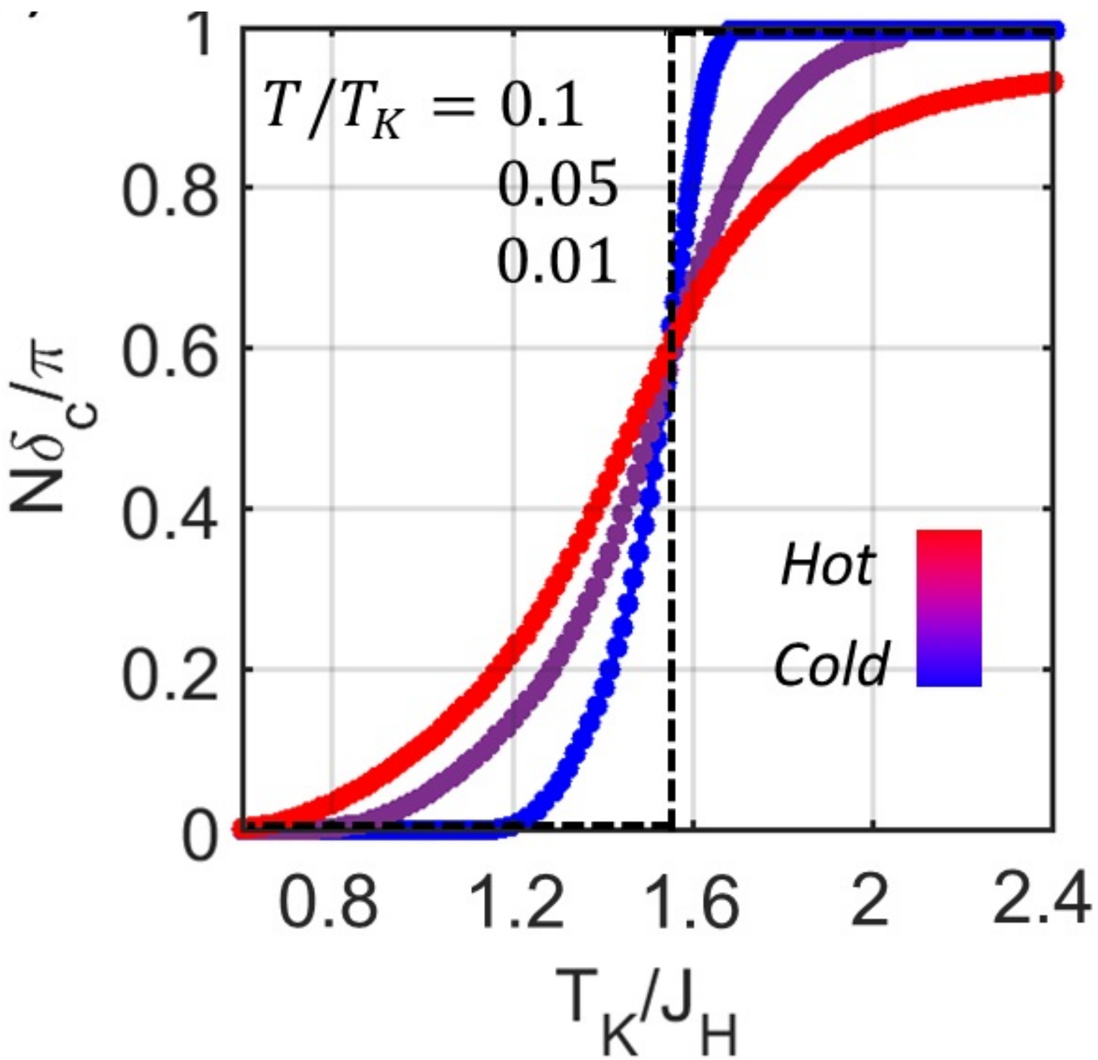

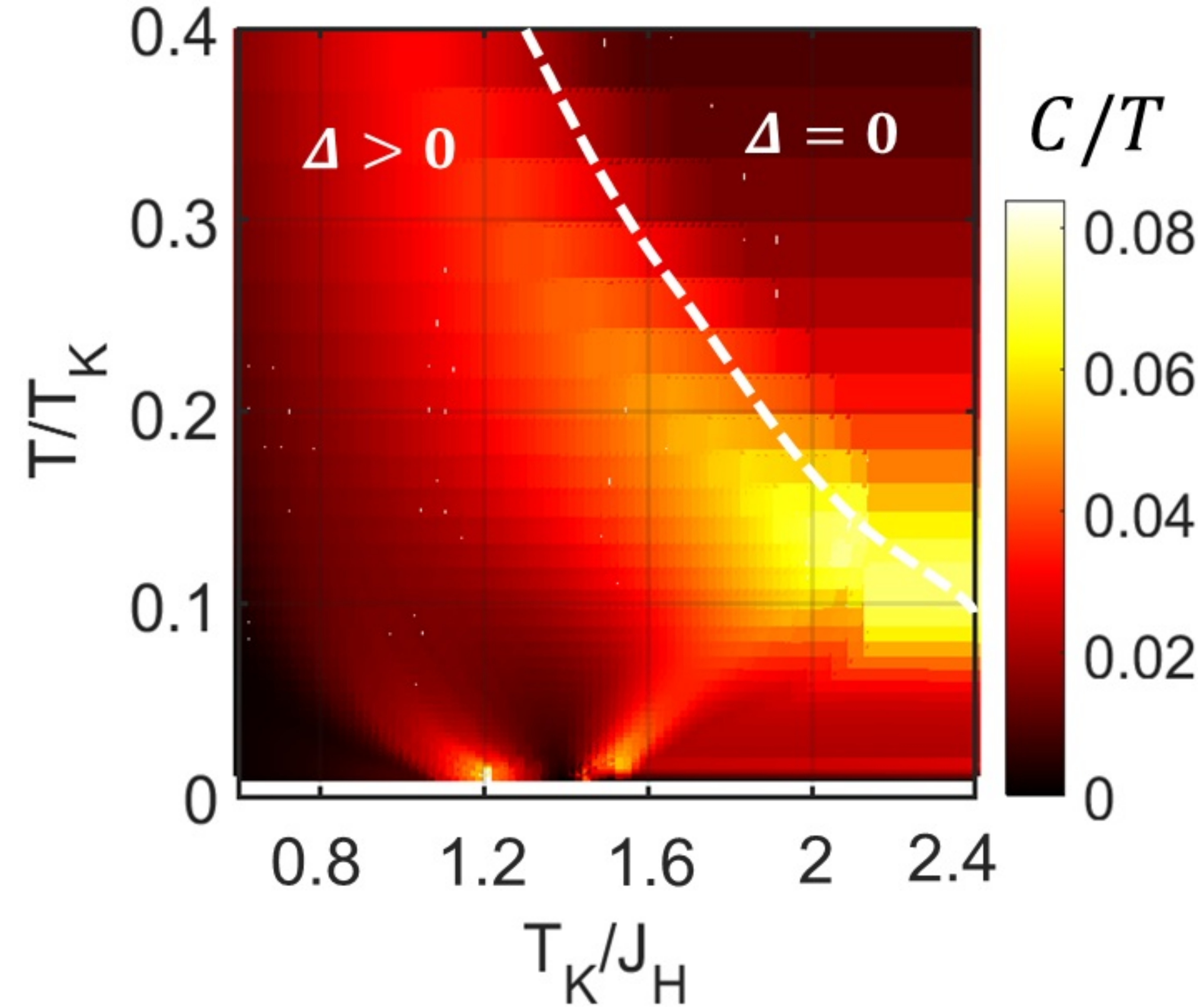

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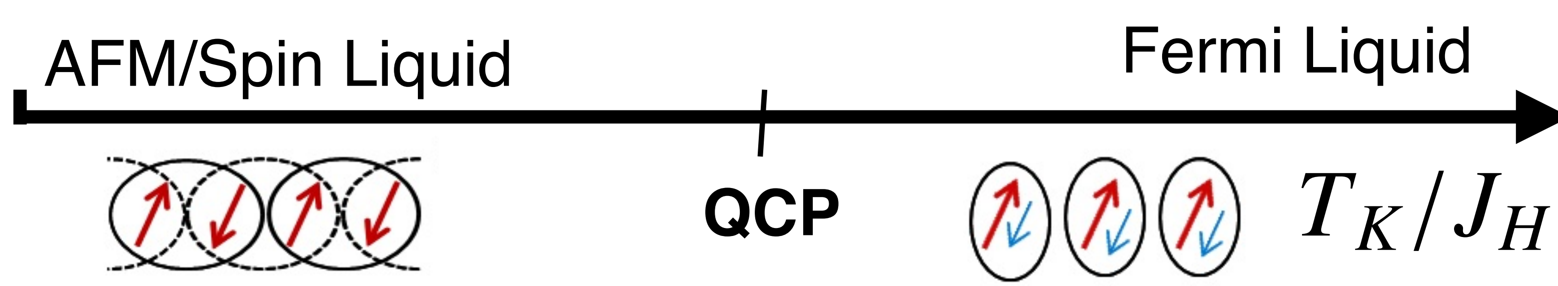

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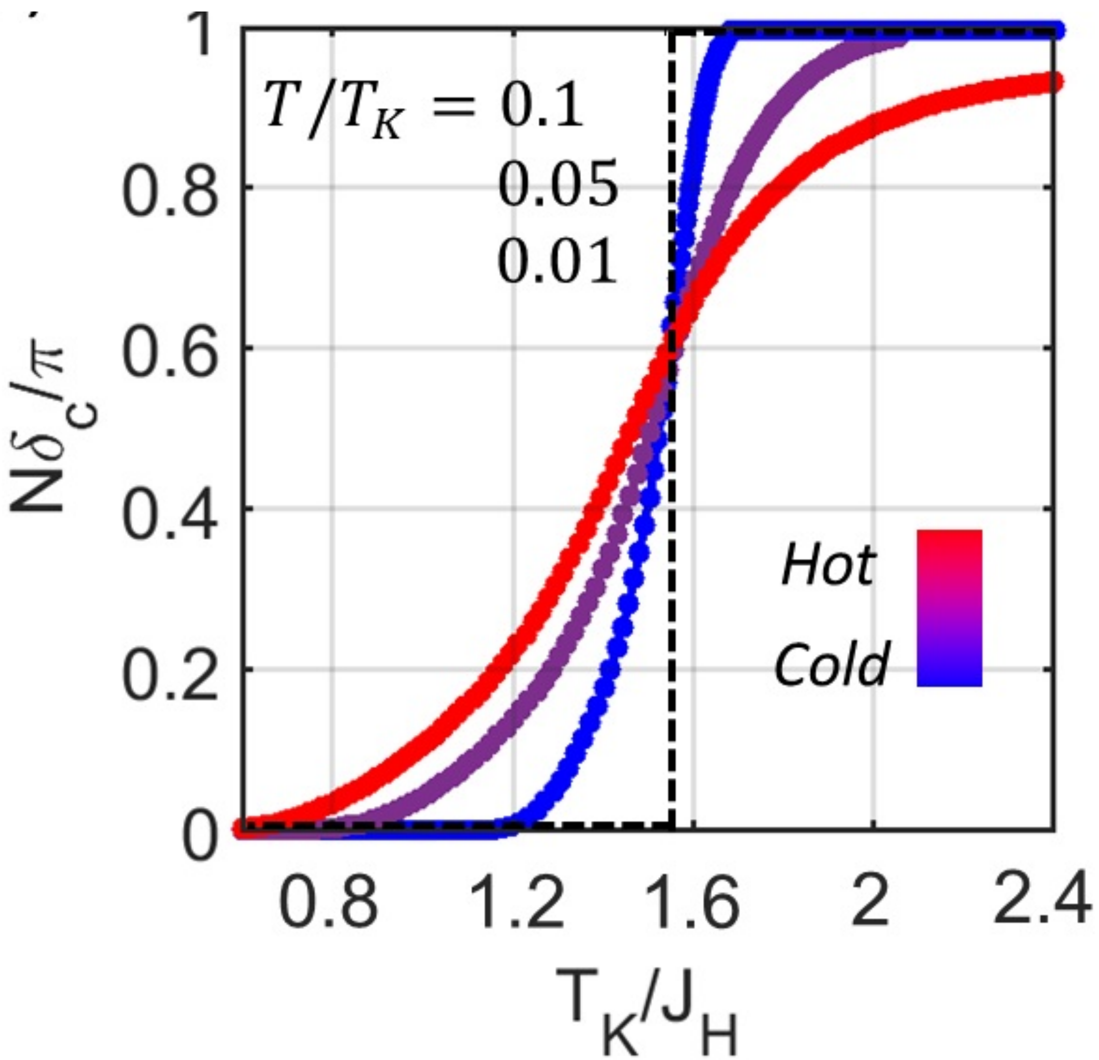

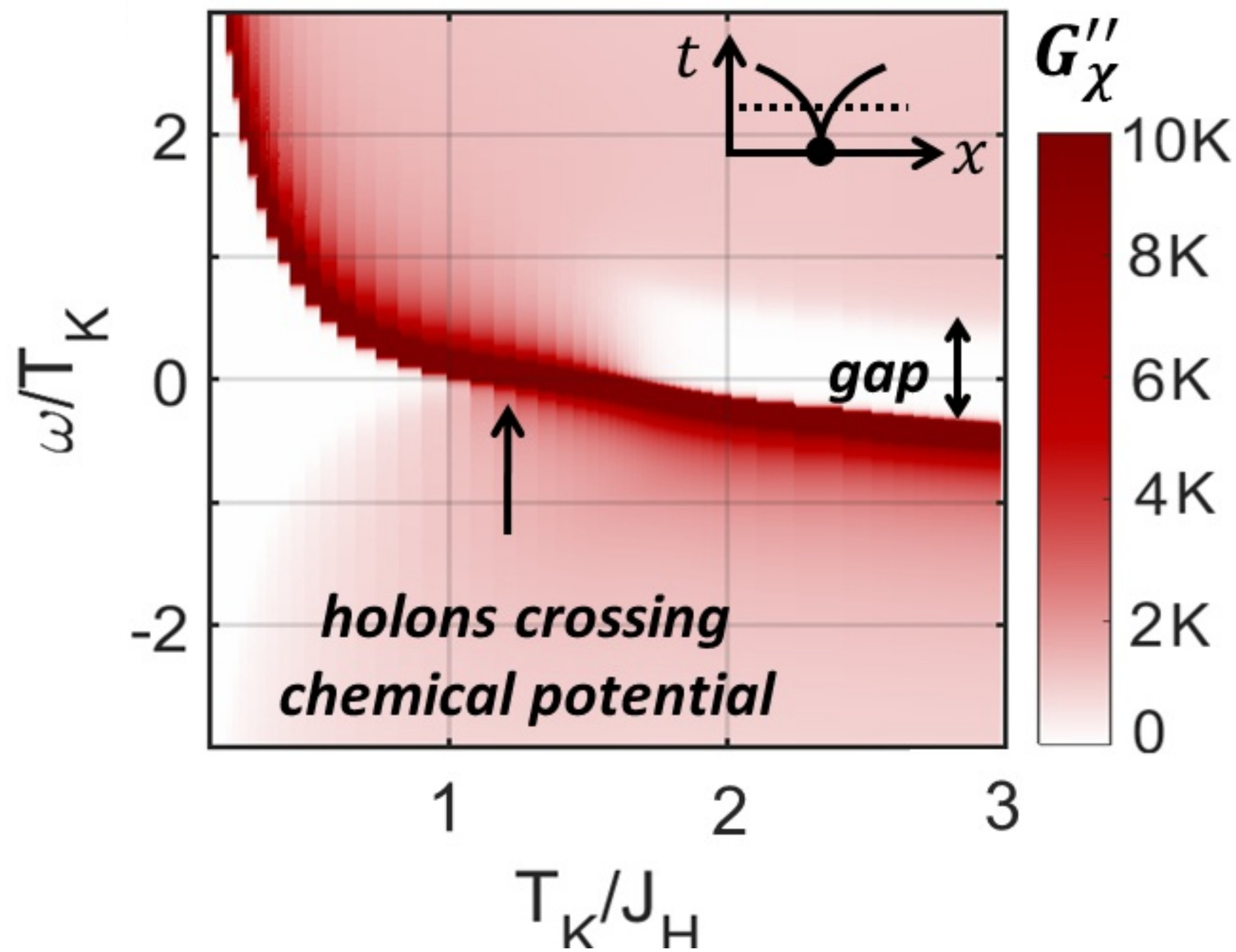

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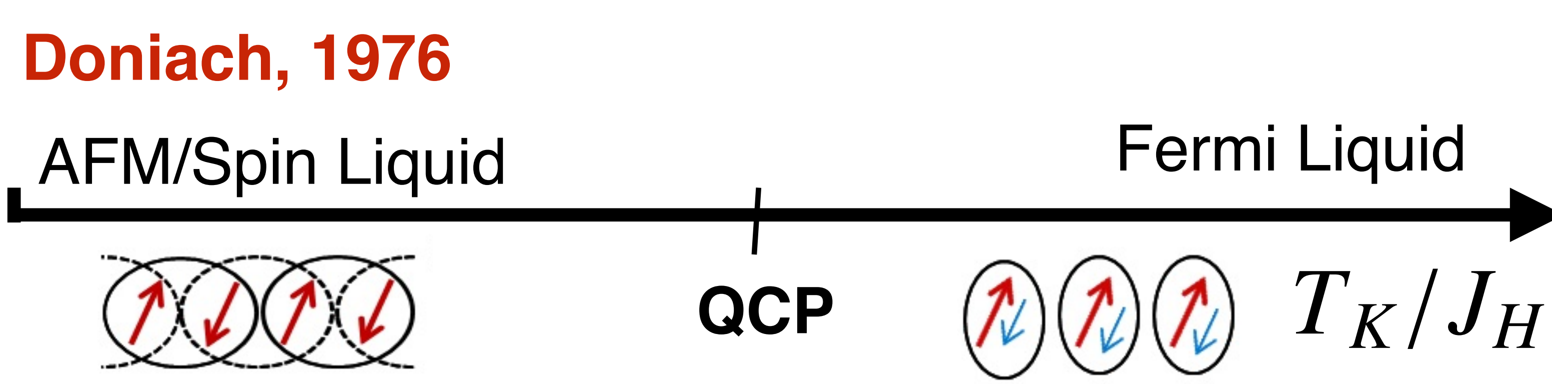
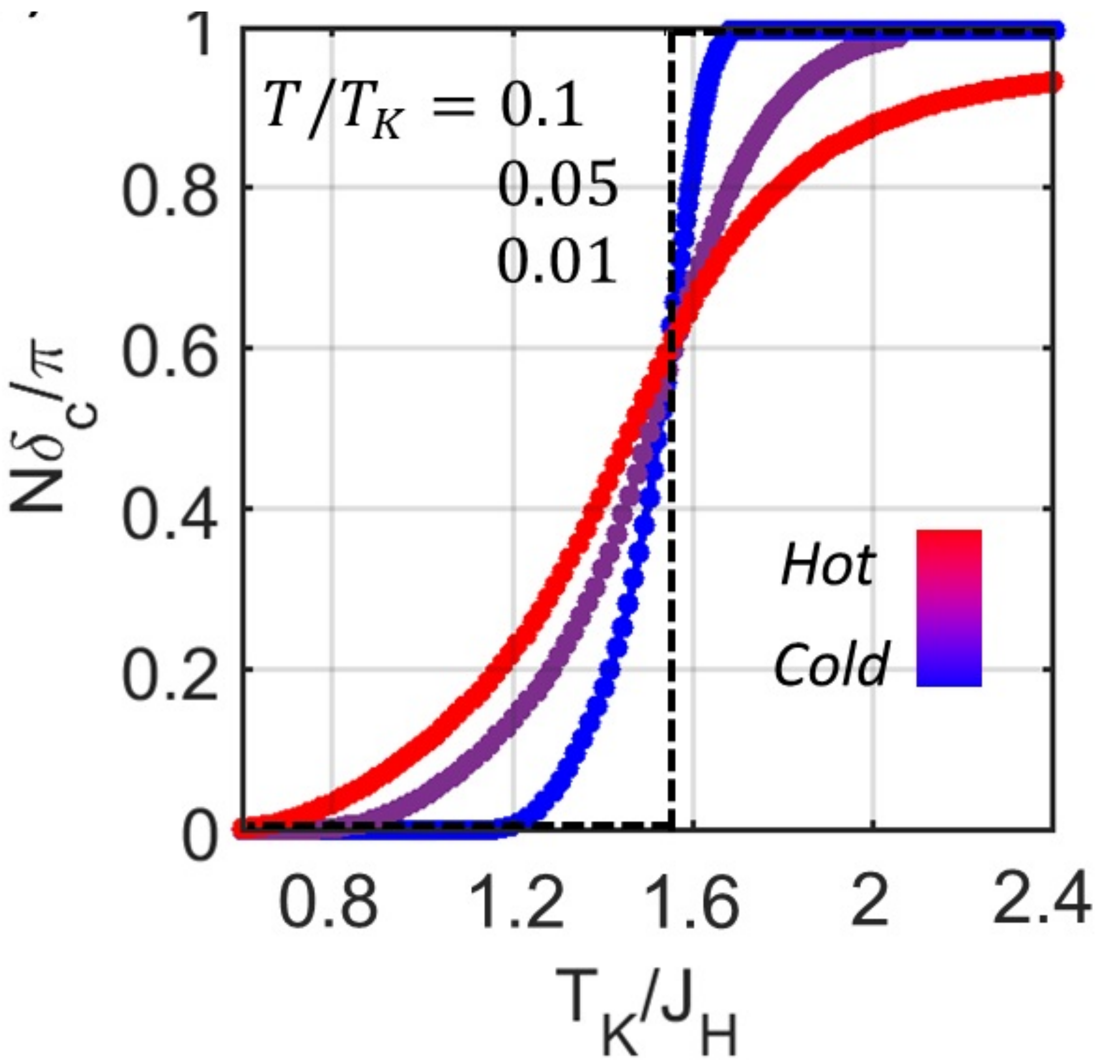
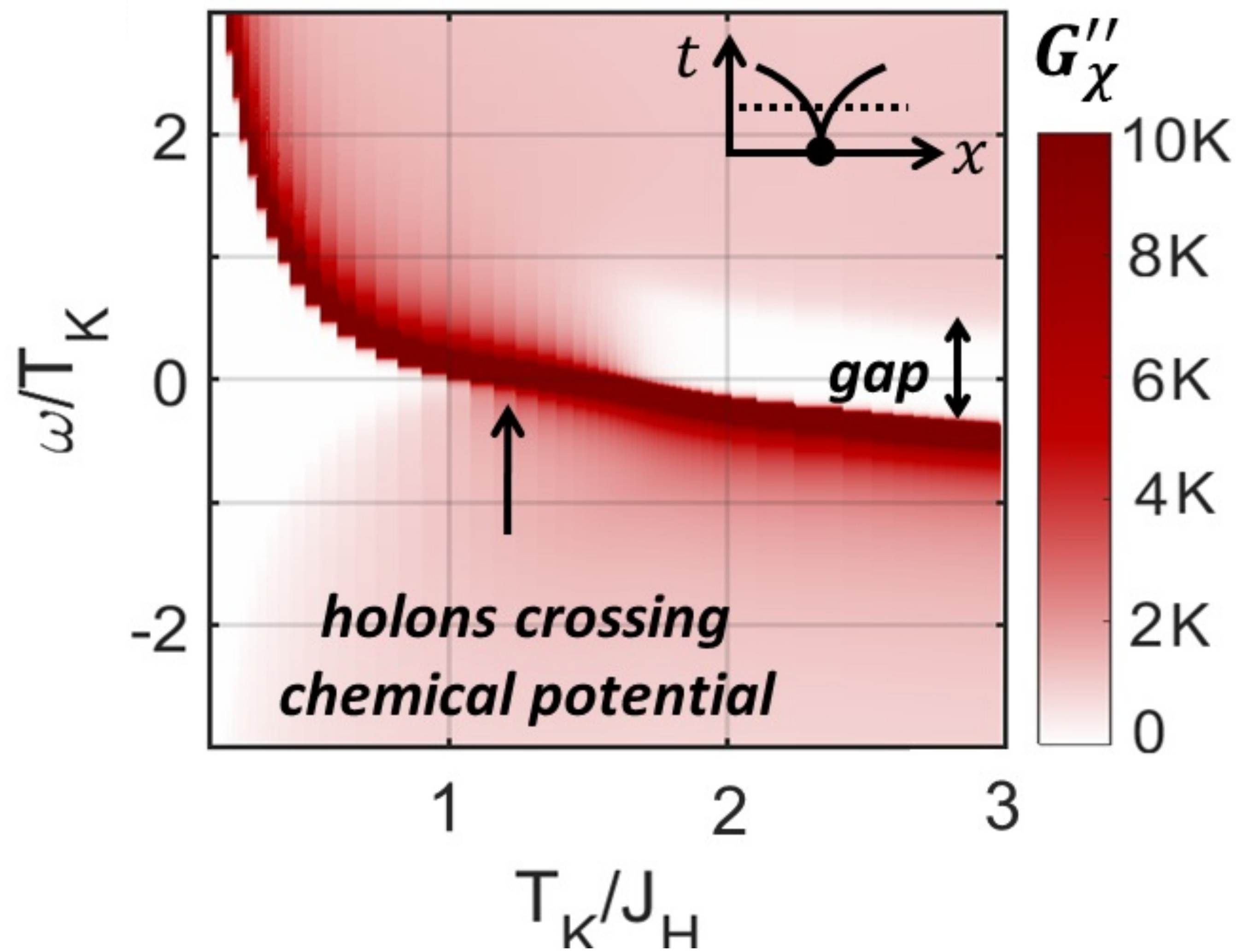


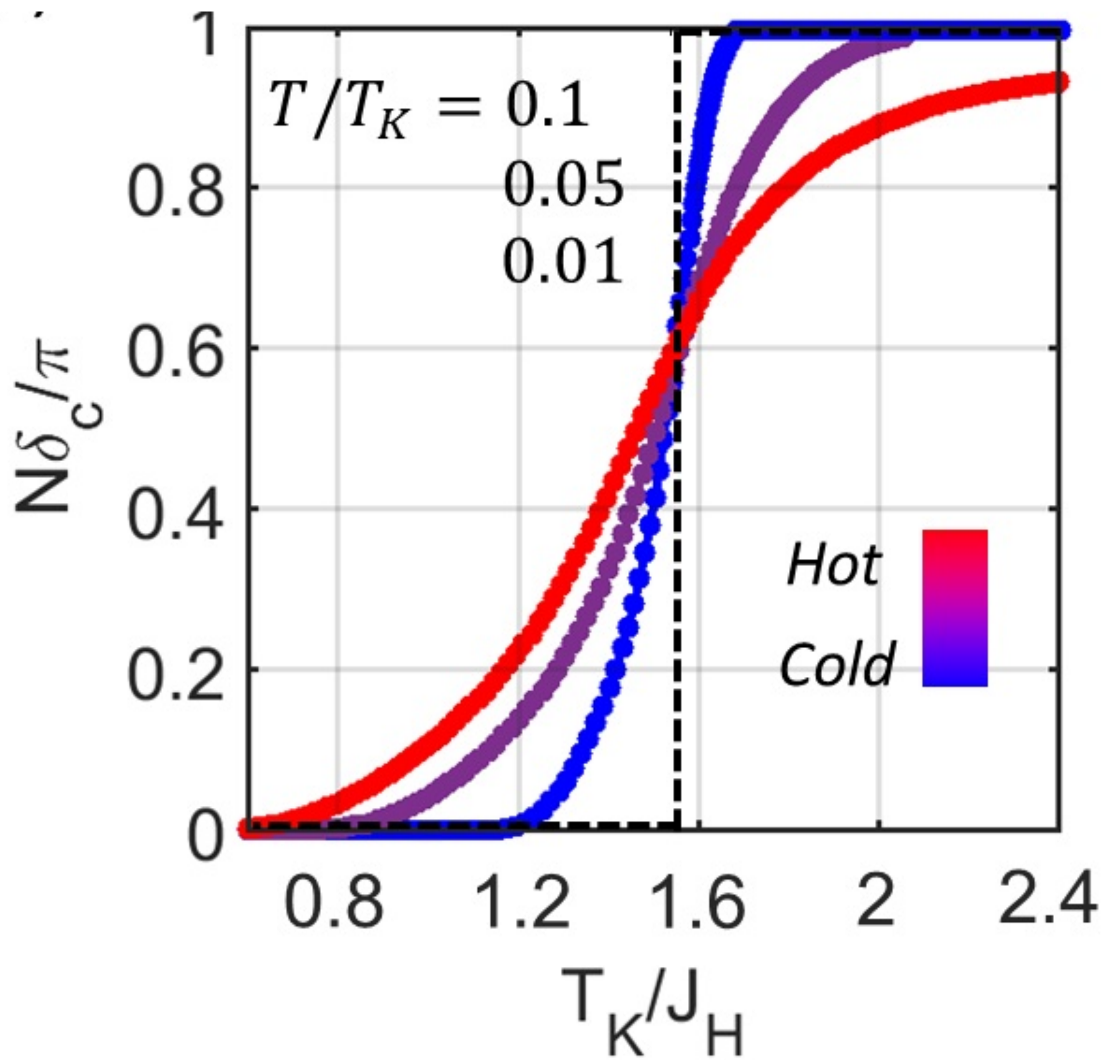
Yashar Komijani & PC **PRL 122, 217001 (2019)**

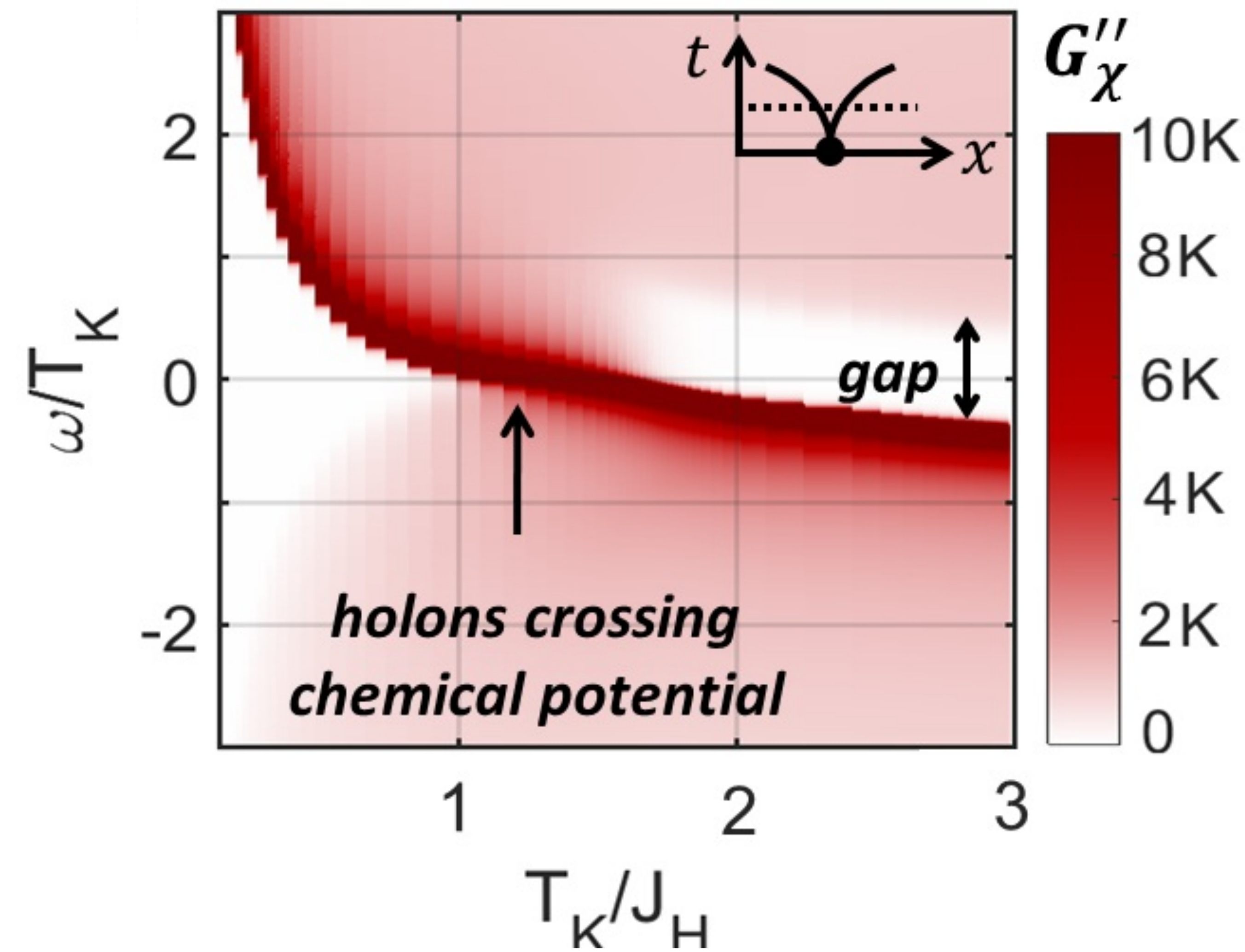


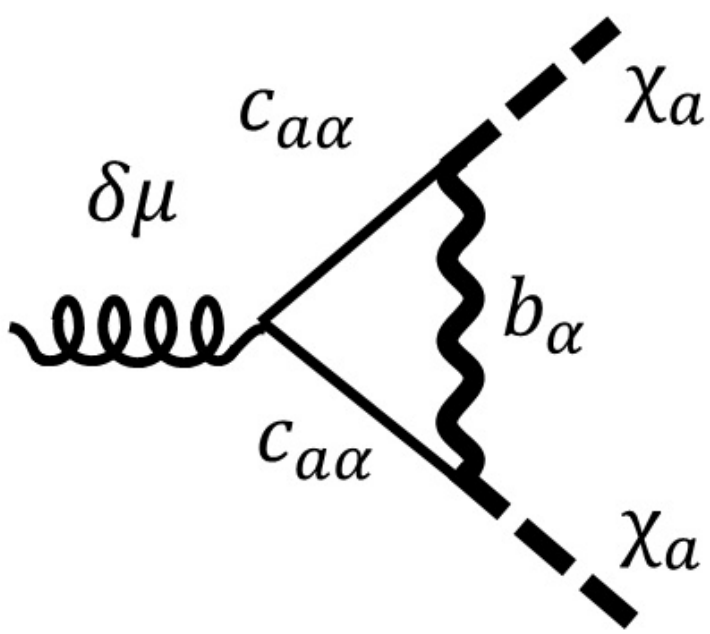


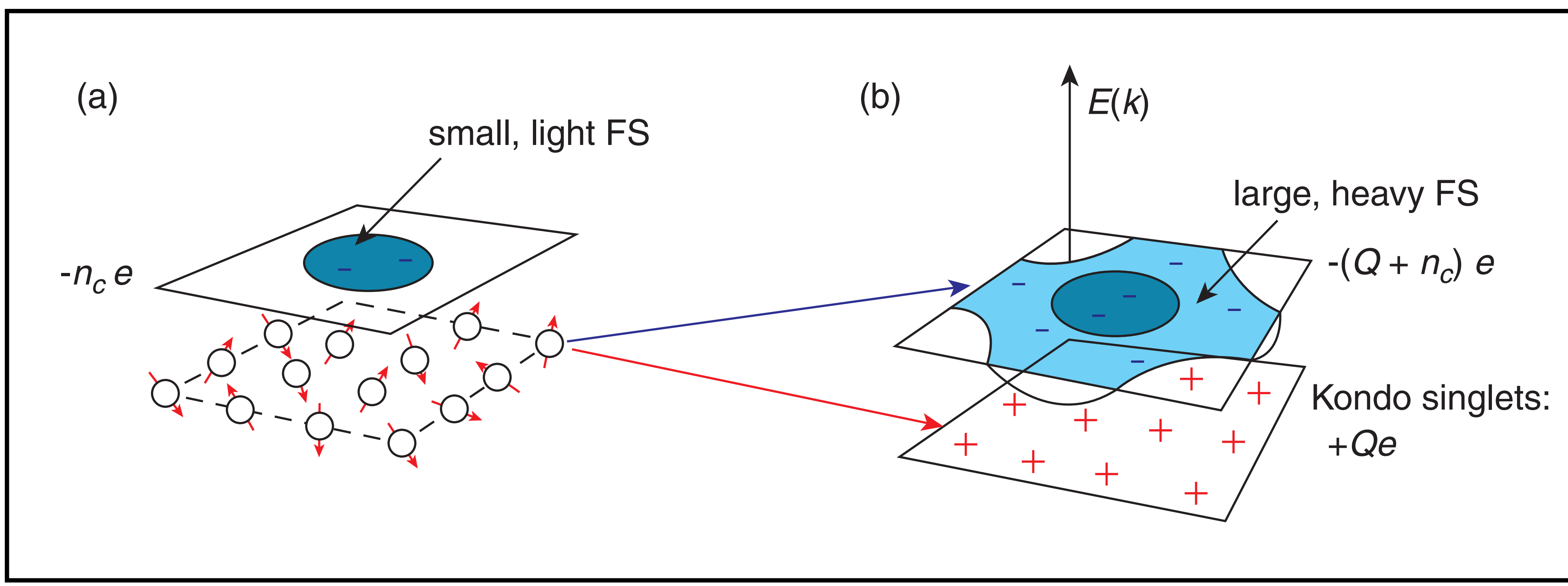
"Jump in the Fermi Surface"

[Yashar Komijani](#) & PC **PRL 122, 217001 (2019)**



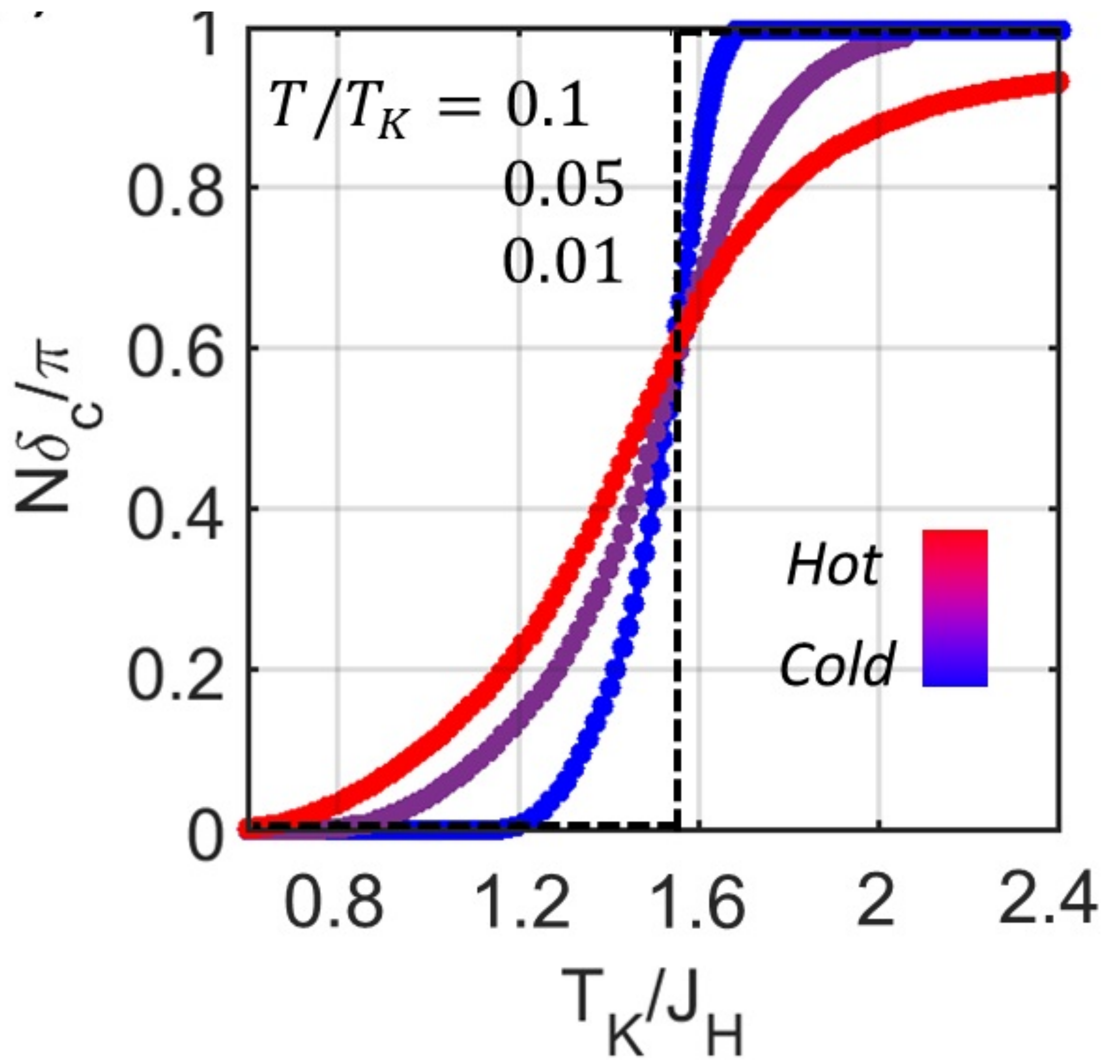


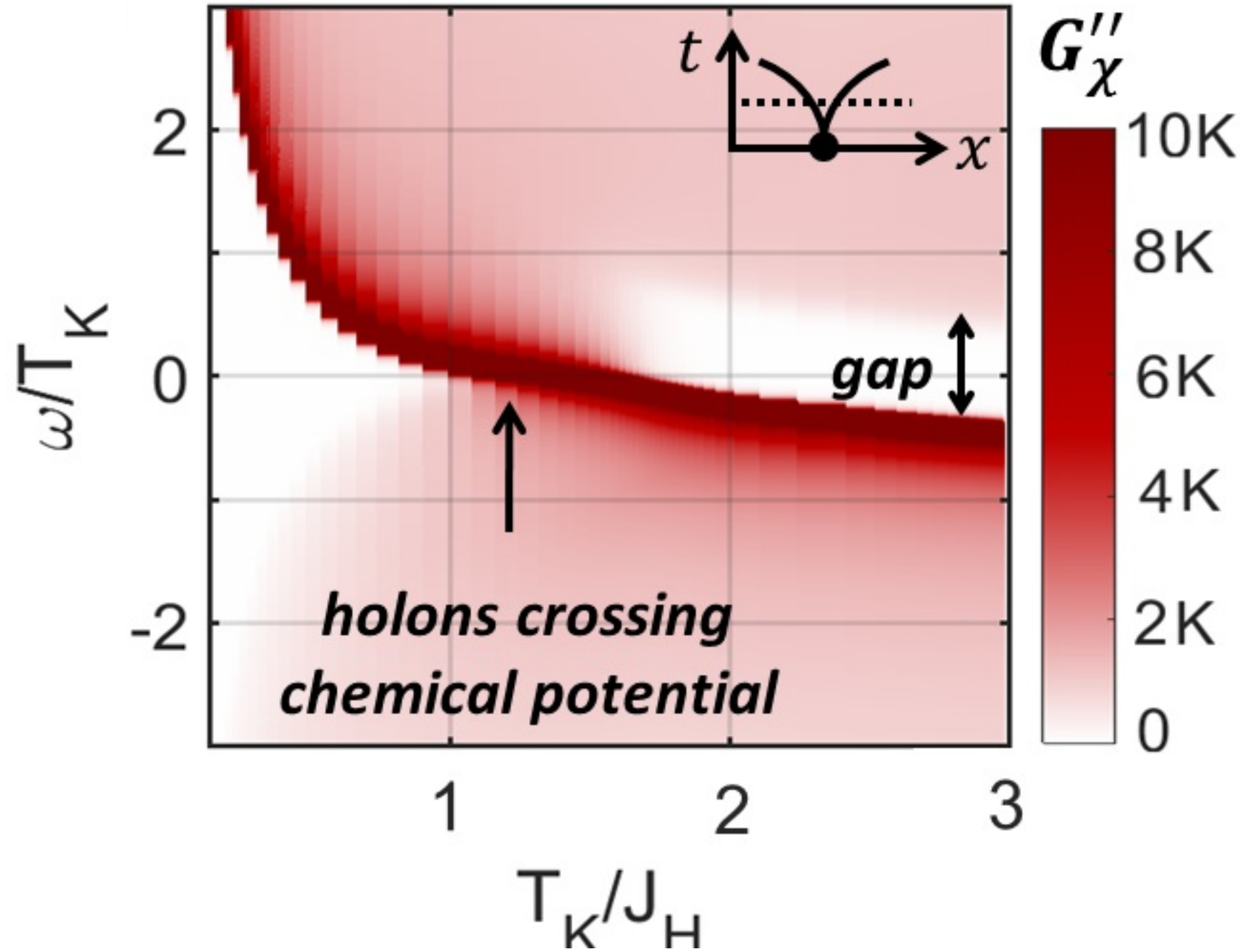


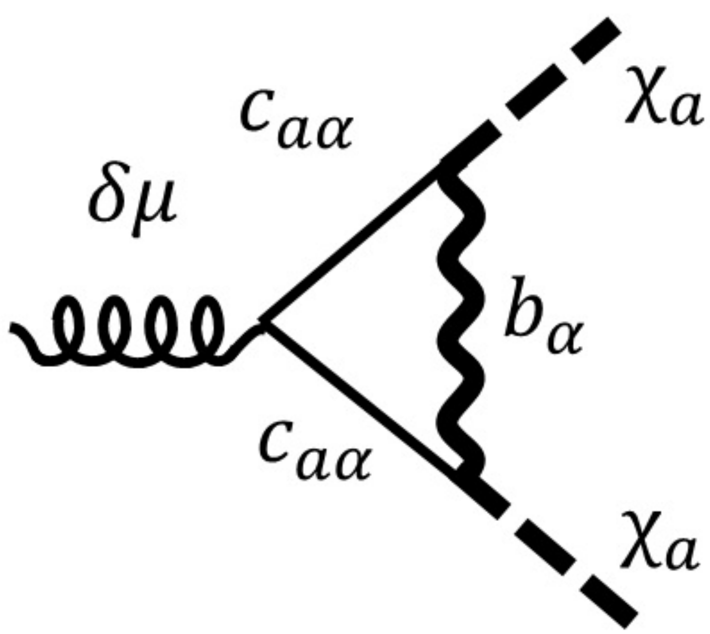


“Jump in the Fermi Surface”

Yashar Komijani & PC **PRL 122, 217001 (2019)**

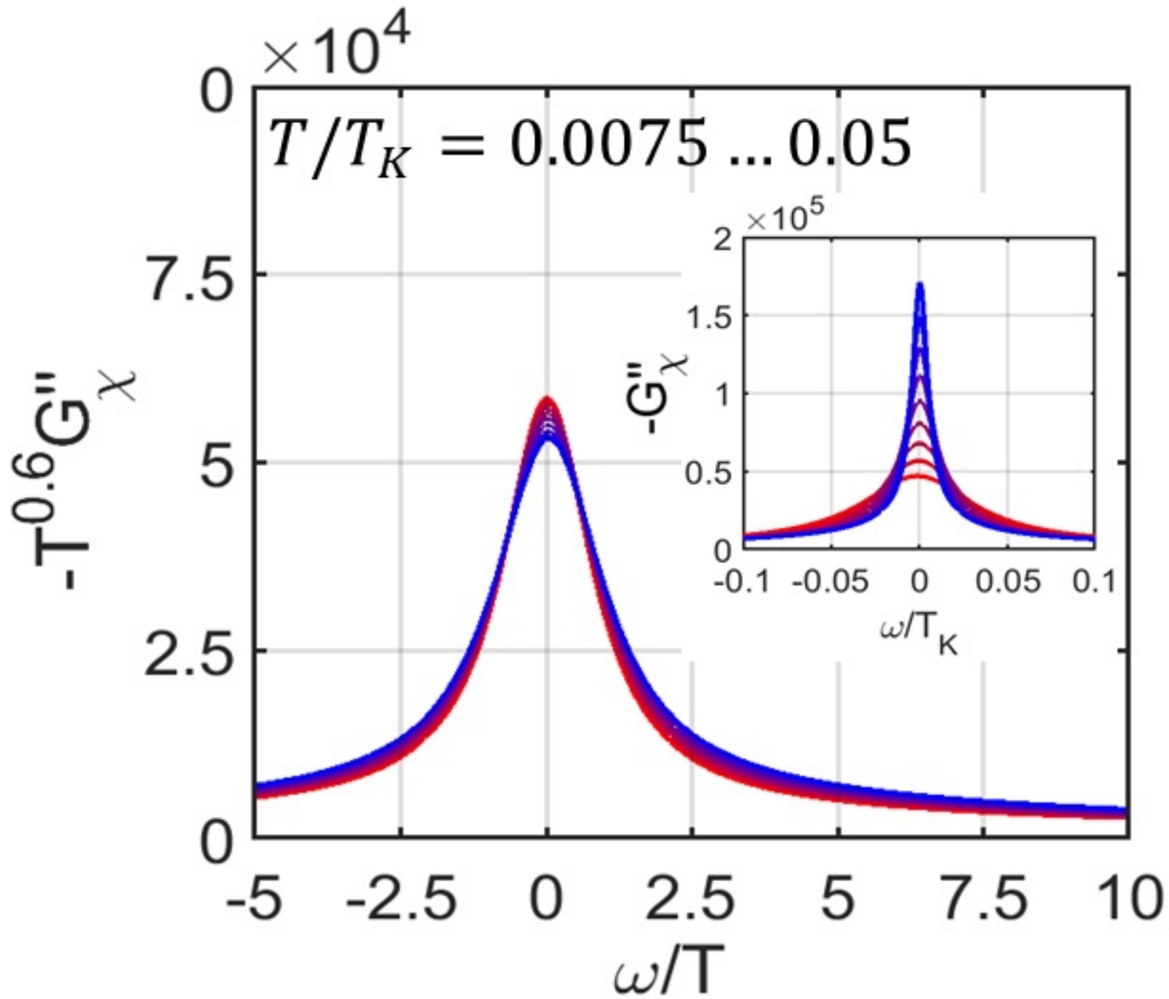


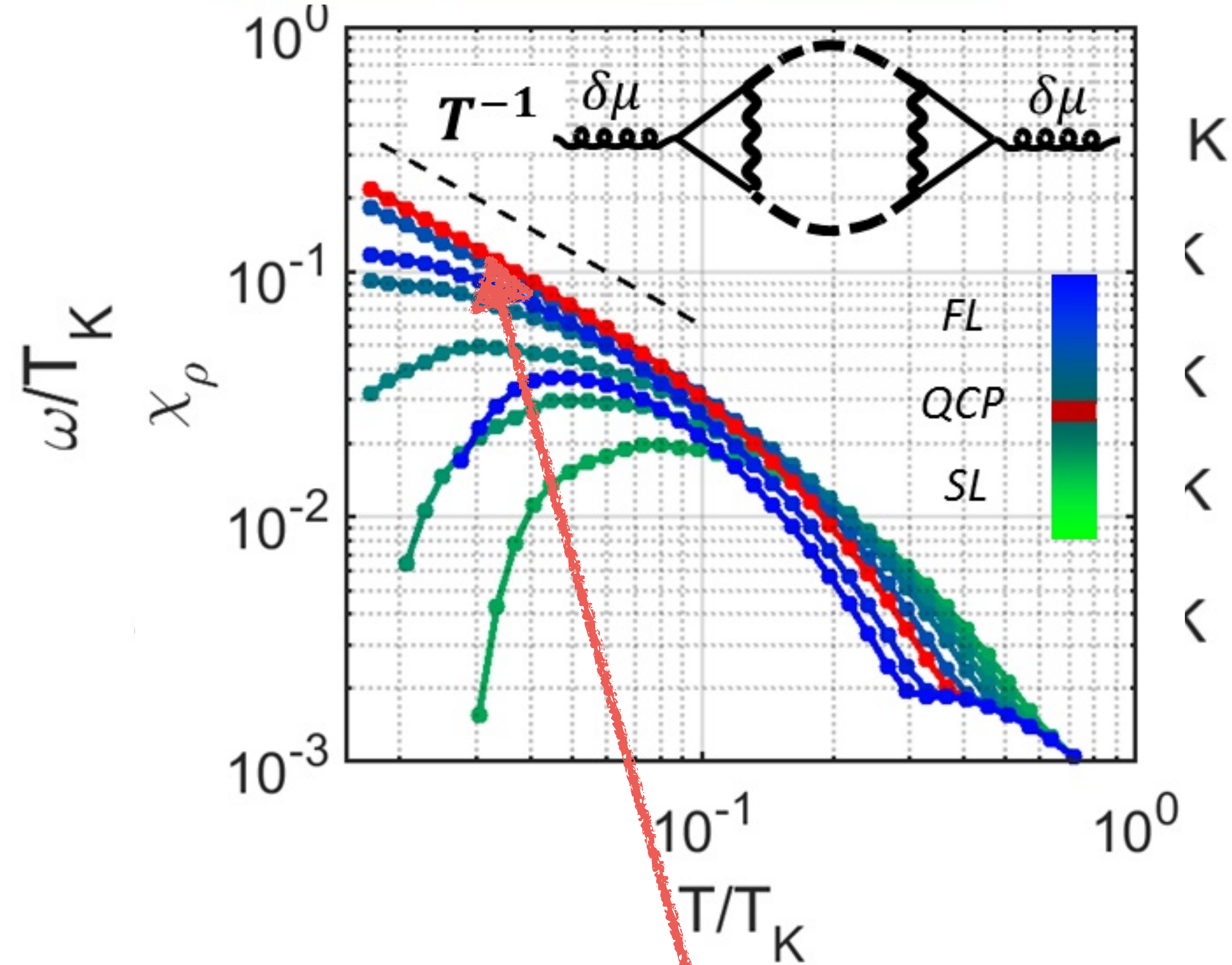




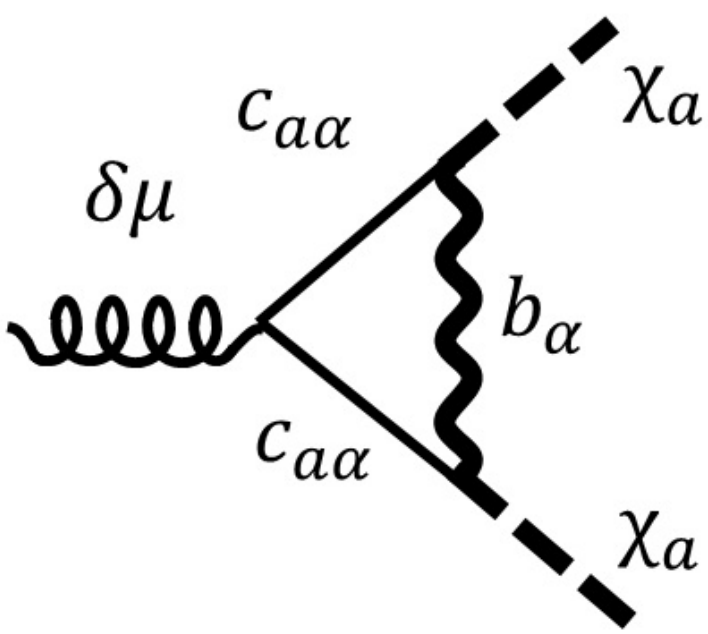
Holons Develop a Physical Charge

Yashar Komijani & PC **PRL 122, 217001 (2019)**





ω/T scaling at the QCP.



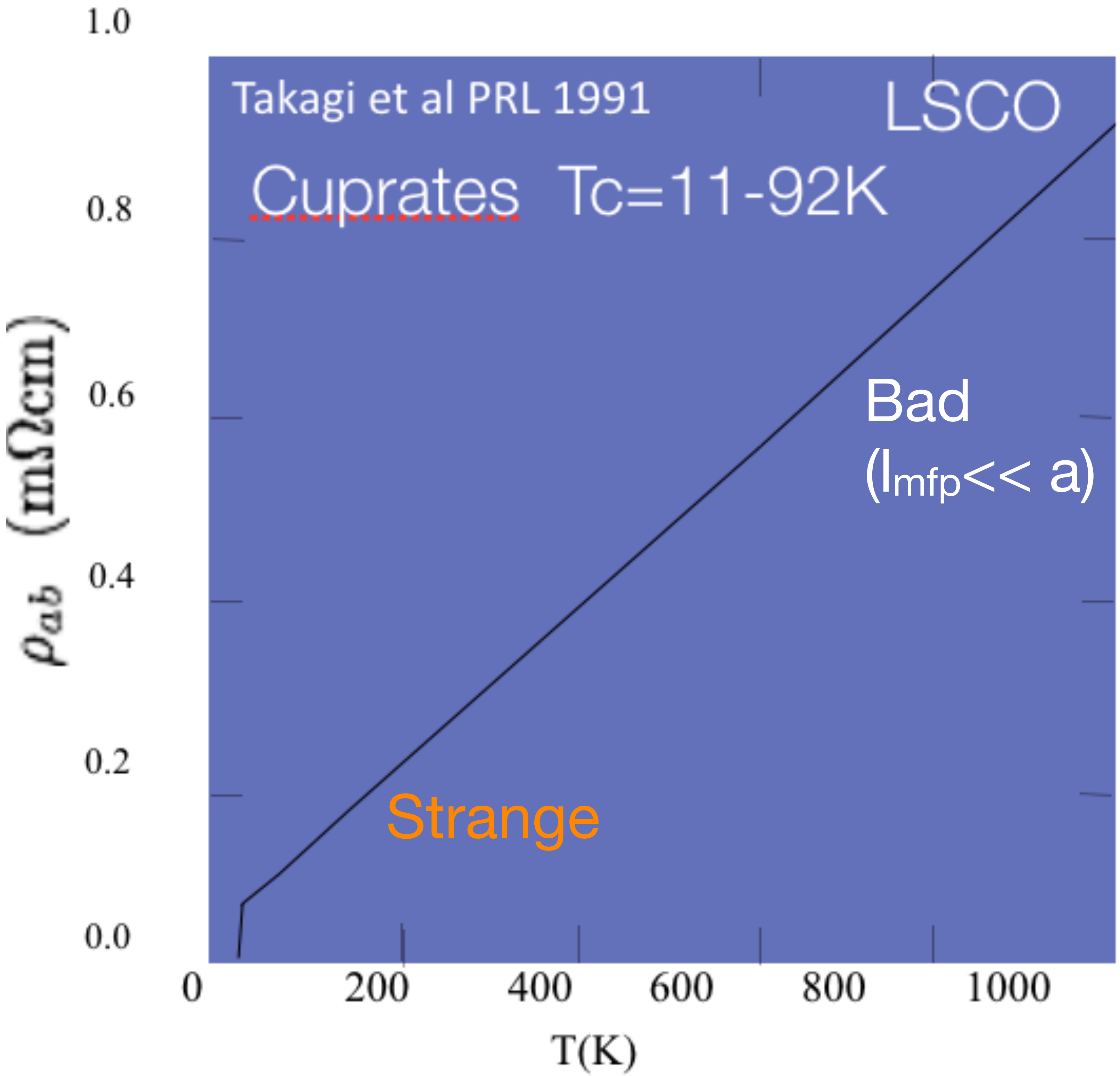
Holons Develop a Physical Charge

CURIE charge susceptibility at QCP

$$\boxed{\chi_c \sim \frac{n_h e^2}{k_B T}}$$

A possible link between Kondo Breakdown and Strange Metals

New Rule: Strange Metals are Bad Metals



Ubiquitous linear resistivity of strange metals is often regarded as a result of a marginal Fermi liquid with a Planckian relaxation time.

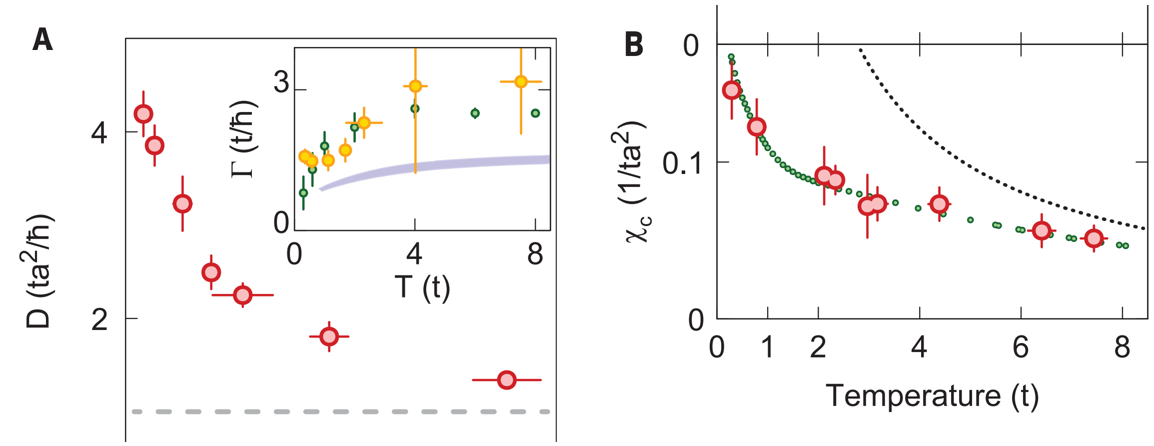
$$\tau = \frac{\hbar}{k_B T}$$

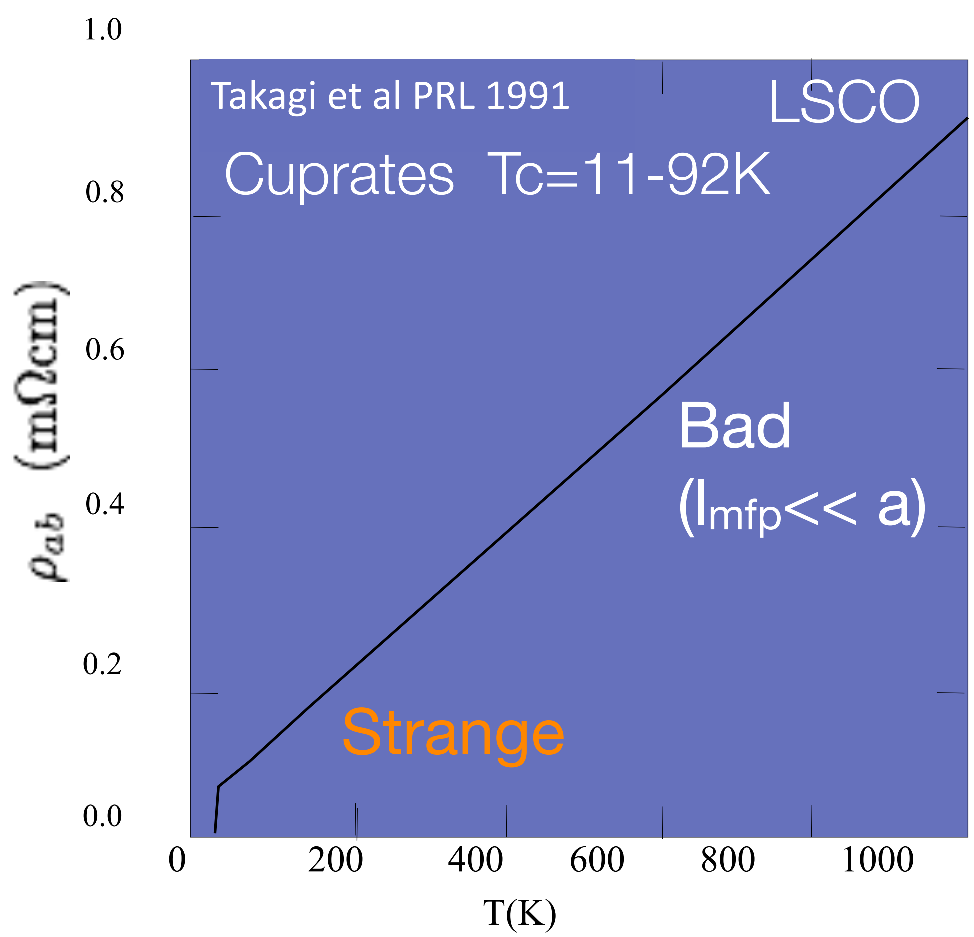
Varma et al, PRL 1989,
Legros et al, Nature Physics 15, 142 (2019)

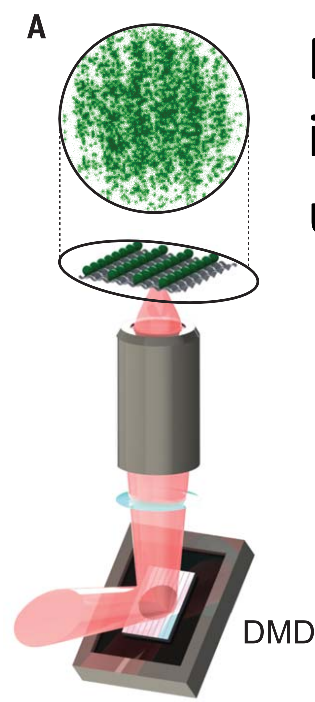
But the linear resistivity continues unabated from the strange metal regime to the bad metal regime.

New Rule: Strange Metals are Bad Metals

Brown et al,
Science 363, 379 (2019)







Measurement of conductivity in optical trap Hubbard model using Einstein-Nernst equation.

$$\sigma = D\chi_c$$

New Rule: Strange Metals are Bad Metals

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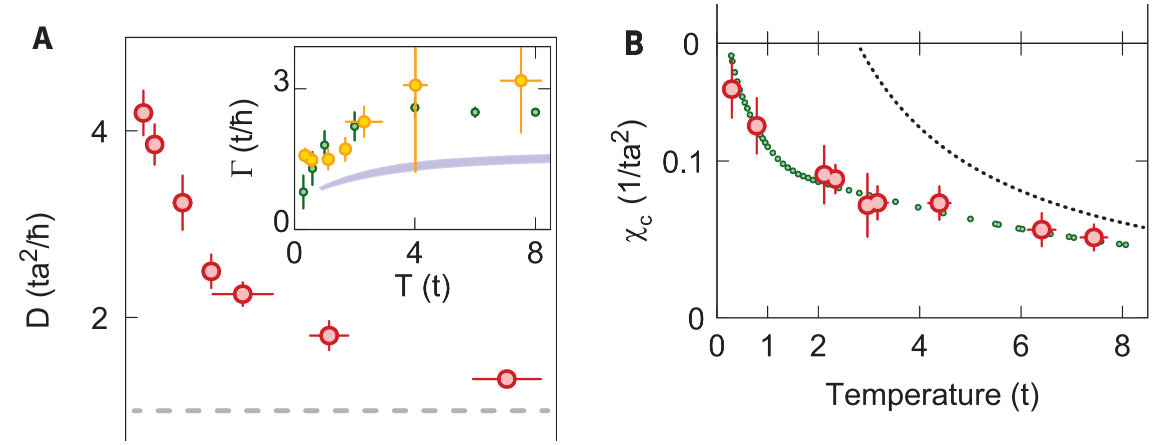
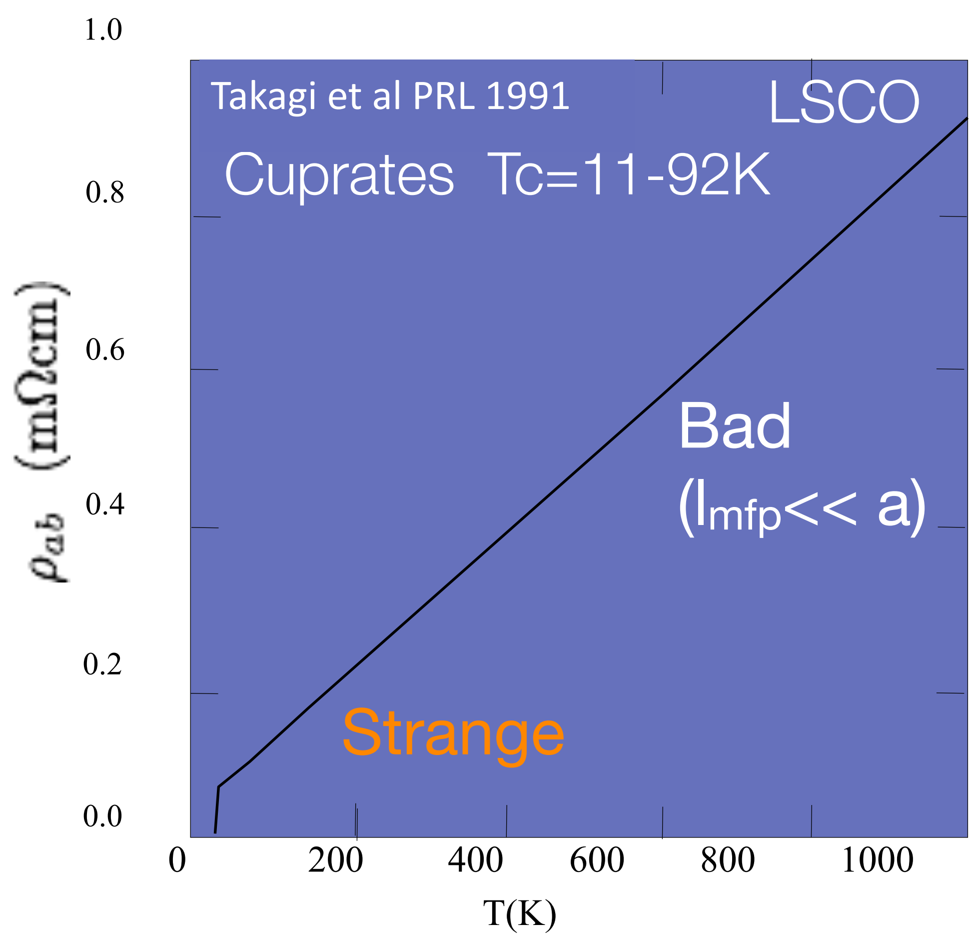
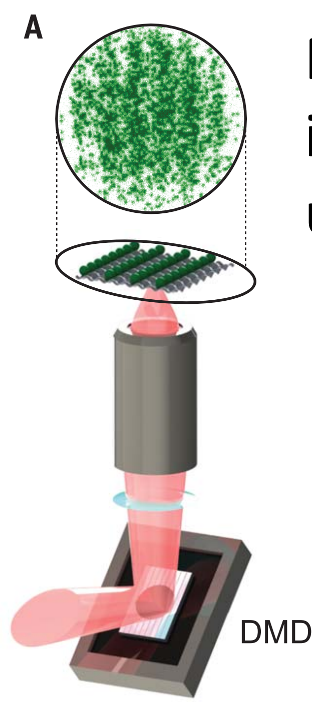






Measurement of conductivity in optical trap Hubbard model using Einstein-Nernst equation.

$$\sigma = D\chi_c$$

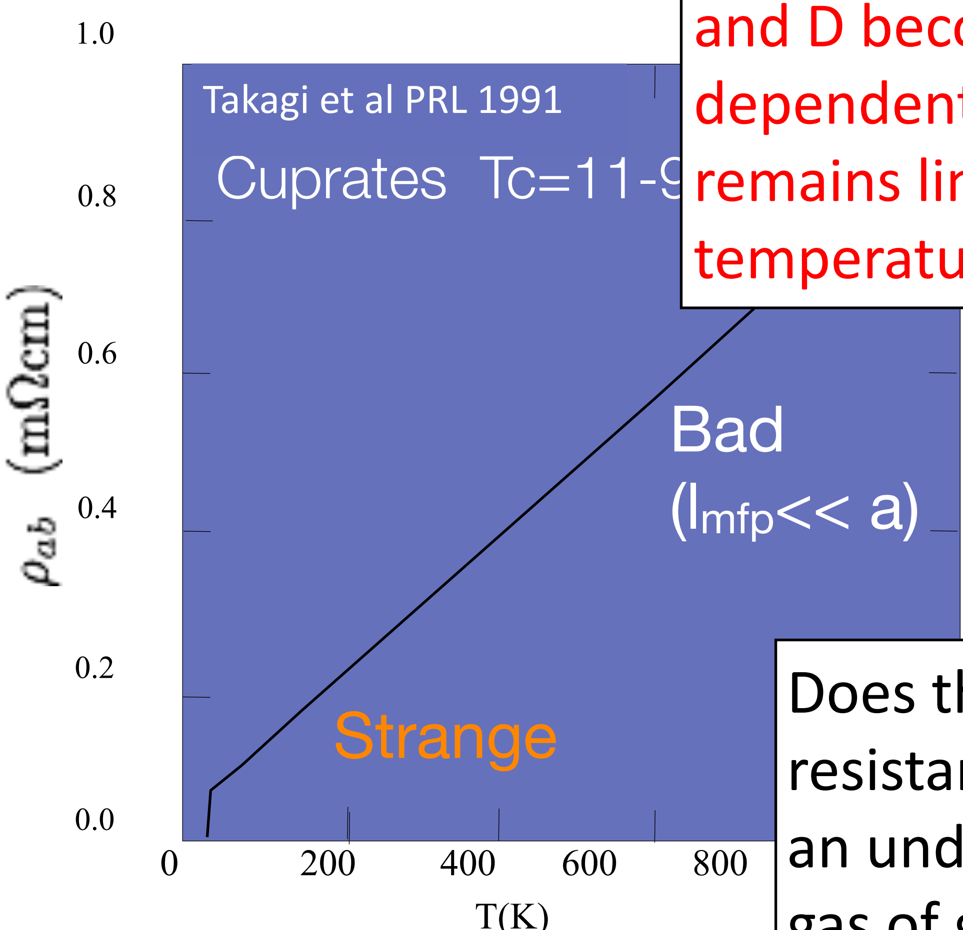
At high temperatures the incoherent transport is classical, with

$$D = \frac{l^2}{\tau} = \frac{\hbar}{m} \qquad \chi_c = \frac{ne^2}{k_B T}$$

$$\Rightarrow \sigma = \left(\frac{ne^2}{m}\right)\frac{\hbar}{k_B T}$$

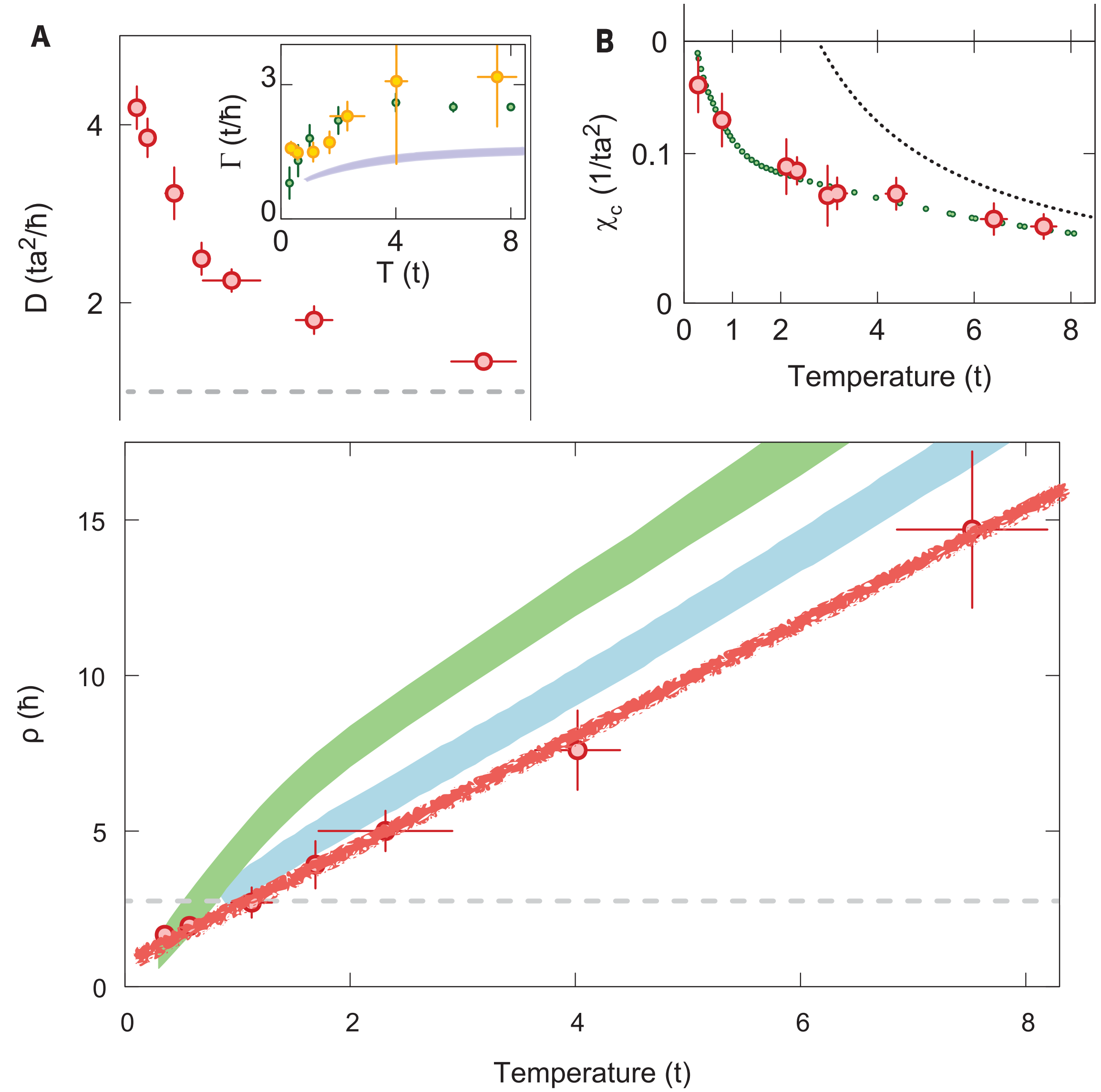
New Rule: Strange Metals are Bad Metals

Brown et al,
Science 363, 379 (2019)

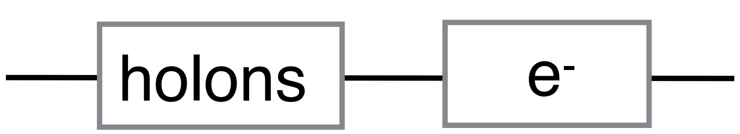


Remarkably, even though χ departs from its high temperature Curie law, and D becomes temperature dependent, the resistivity remains linear to low temperatures.

Does the linear resistance derive from an underlying classical gas of gapless holons formed at the QCP?

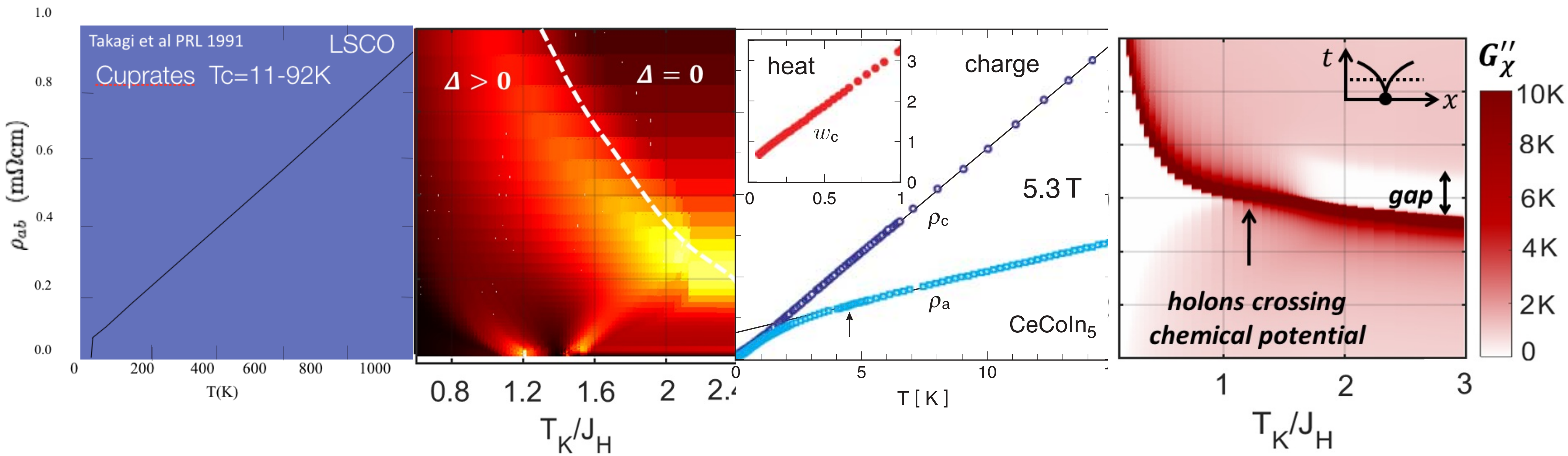


$$\Rightarrow \sigma = \left(\frac{ne^2}{m}\right)\frac{\hbar}{k_B T}$$



Resistors in <u>Series</u>
$R = R_h + R_e \sim AT + C$?
cf Ioffe Larkin

Kondo Breakdown and a possible connection with Strange and Bad metals: **Conclusions**



- Ubiquity of strange metal behavior, in transition metal and rare-earth materials.

- Common feature appears to be the partial Mott localization. AFM not necessary.

- Schwinger Boson Scheme allows unification of magnetic and Kondo entanglement physics

- Emergent charge fluctuations associated with small to large FS transition (Kondo breakdown/Mott) may have a link with the linear resistivity of Strange Metals.


Thank you!