Bad Metal Behavior and Mott Quantum Criticality

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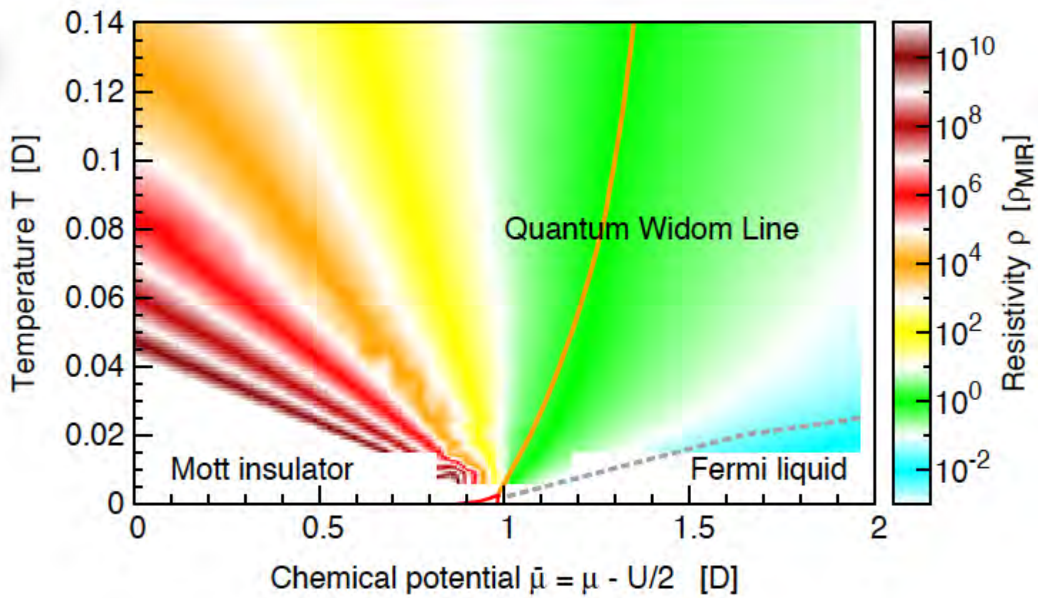
http://badmetals.magnet.fsu.edu

NATIONAL HIGH MAGNETIC FIELD LAB



Collaborators:

Jaksa Vucicevic *(Belgrade, Serbia)*
Hanna Terletska *(FSU, Ames Lab)*
Darko Tanaskovic *(Belgrade, Serbia)*
Marcelo Rozenberg *(Orsay)*

Abrahams, Chakravarty, Kotliar, Haule, Miranda, Pankov,...

Funding:

NSF grants:

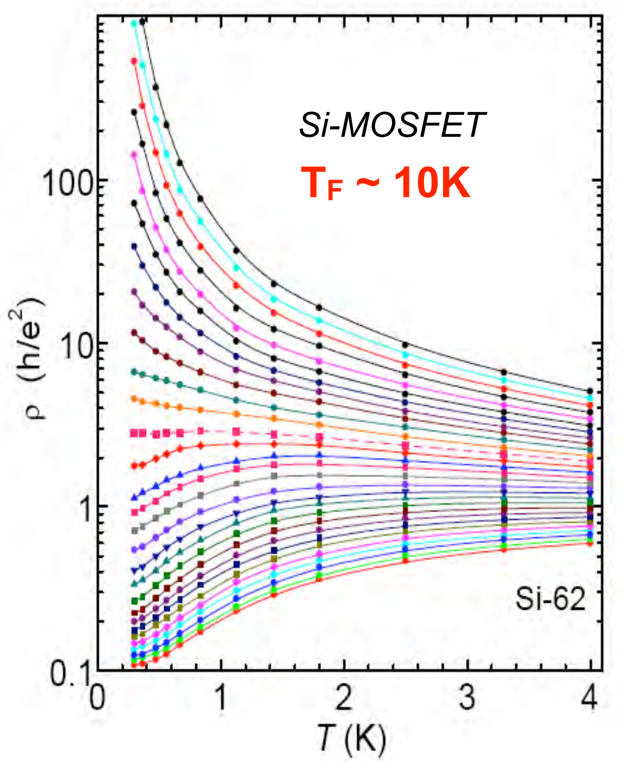
DMR-1410132

...

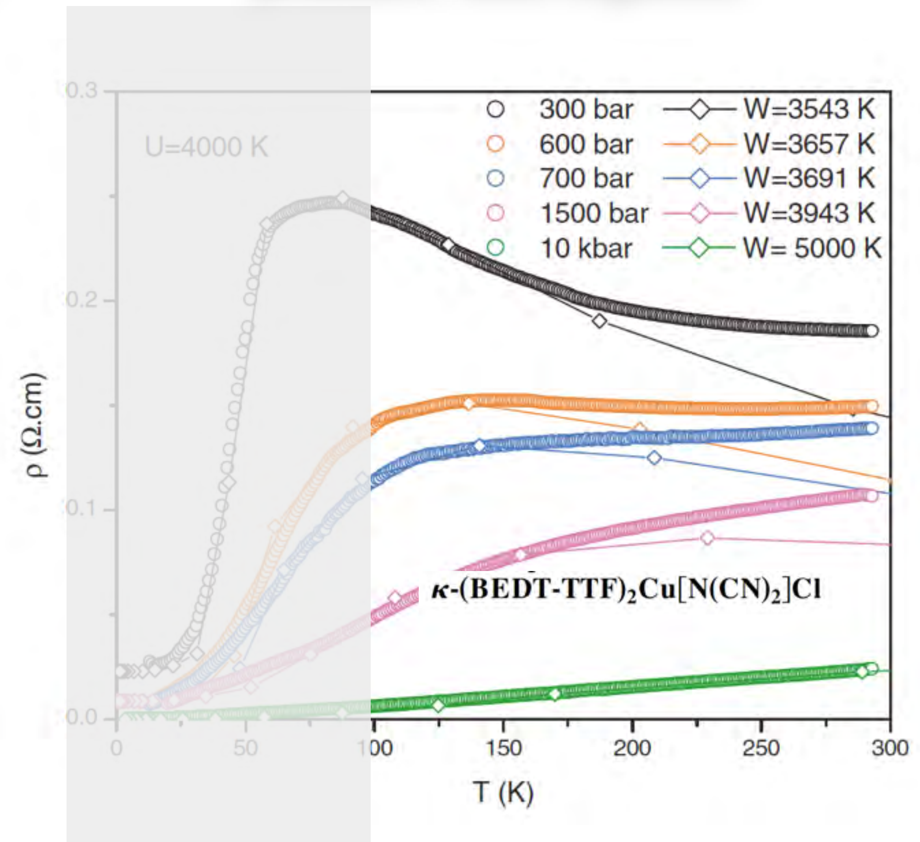
From Metals to Insulators:

universality at ``high temperatures”

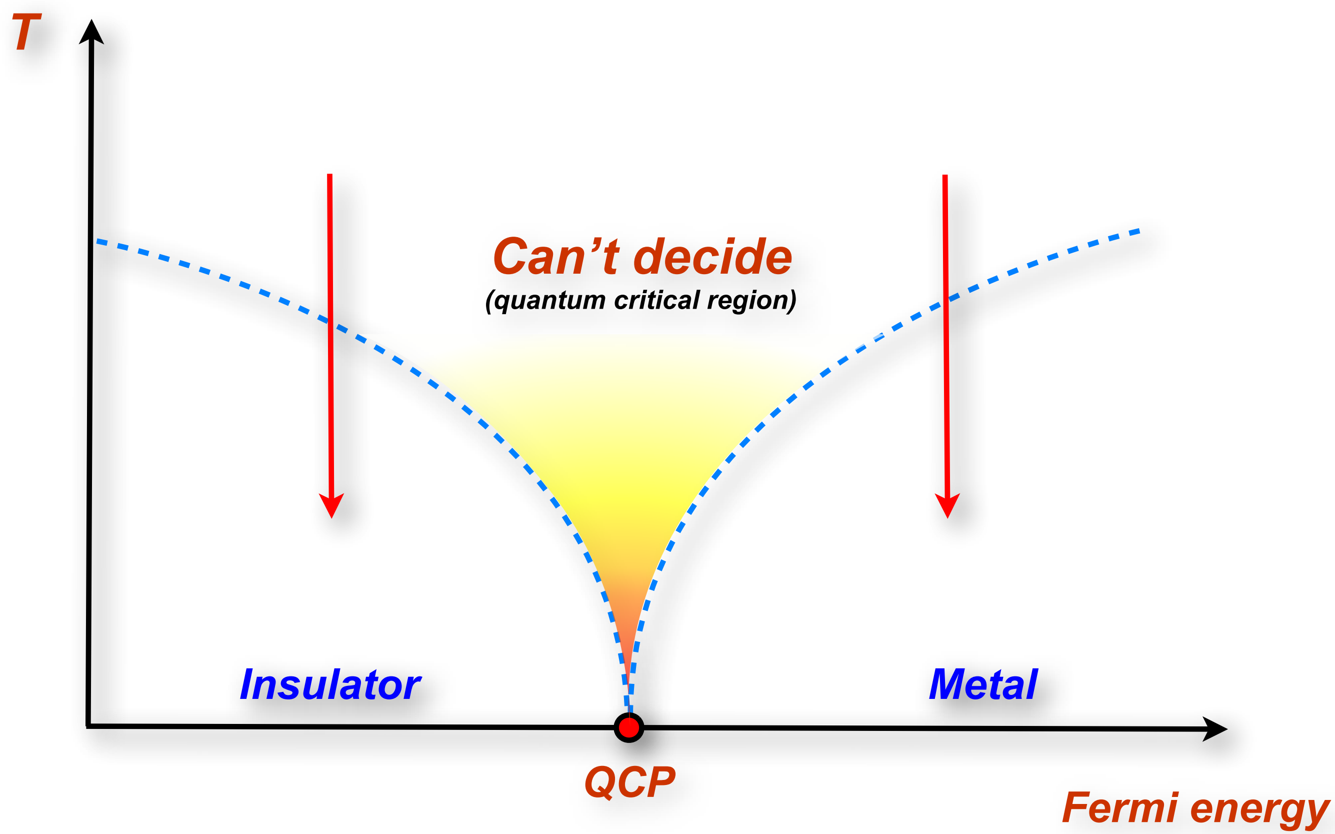
carrier density: Wigner-Mott 2DEG



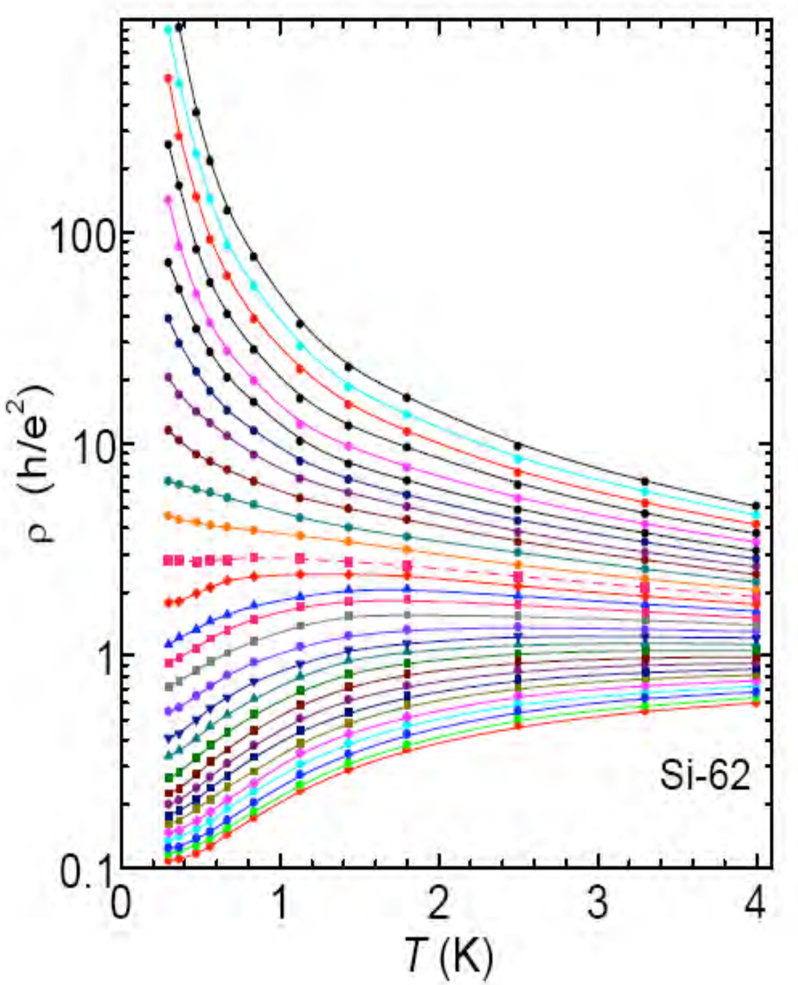
pressure: Mott organics

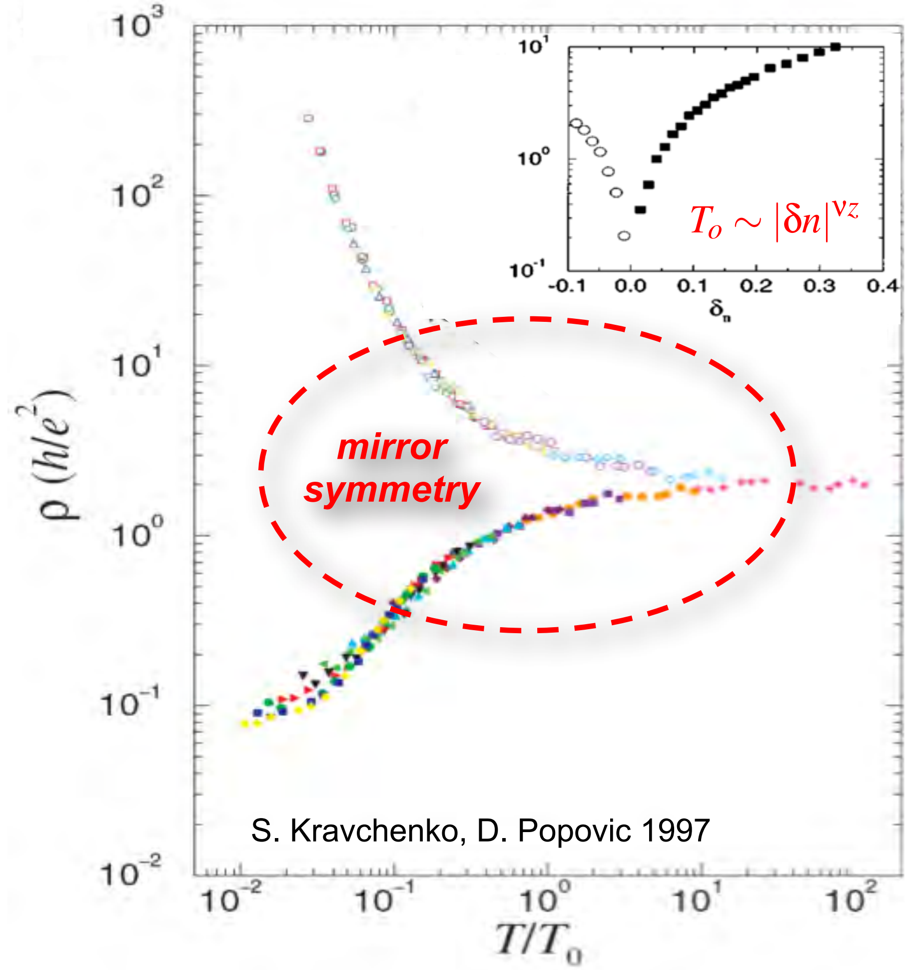


MIT Quantum Criticality?



2D-MIT: "Duality" Scaling???





Scaling Theory Redux

VOLUME 79, NUMBER 3 PHYSICAL REVIEW LETTERS 21 JULY 1997

Scaling Theory of Two-Dimensional Metal-Insulator Transitions

V. Dobrosavljević,[1] Elihu Abrahams,[1,2] E. Miranda,[1] and Sudip Chakravarty[3]
[1]*National High Magnetic Field Laboratory, Florida State University 1800 E. Paul Dirac Drive, Tallahassee, Florida 32306*
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[3]*Department of Physics and Astronomy, University of California Los Angeles, Los Angeles, California 90095-1547*

(Received 10 April 1997)

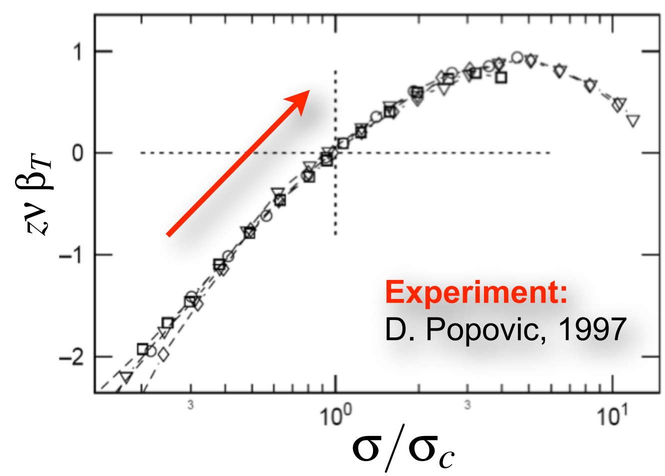
We discuss the recently discovered two-dimensional metal-insulator transition in zero magnetic field in the light of the scaling theory of localization. We demonstrate that the observed symmetry relating conductivity and resistivity follows directly from the quantum critical behavior associated with such a

"strong coupling" - dominated by insulator?

$$\beta_T(g) = -\frac{d\ln g}{d\ln T} \approx \frac{1}{\nu z}\ln g$$

$$g(T) \approx g_o \exp\{\delta n (T_o/T)^{1/\nu z}\}$$

$$g^*(\delta n, T = 1/g^*(-\delta n, T)$$



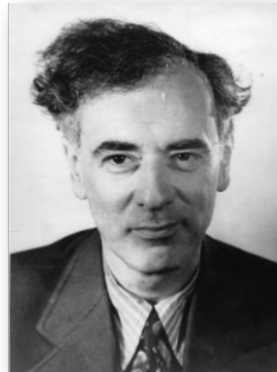
How to tackle Phase Transitions?

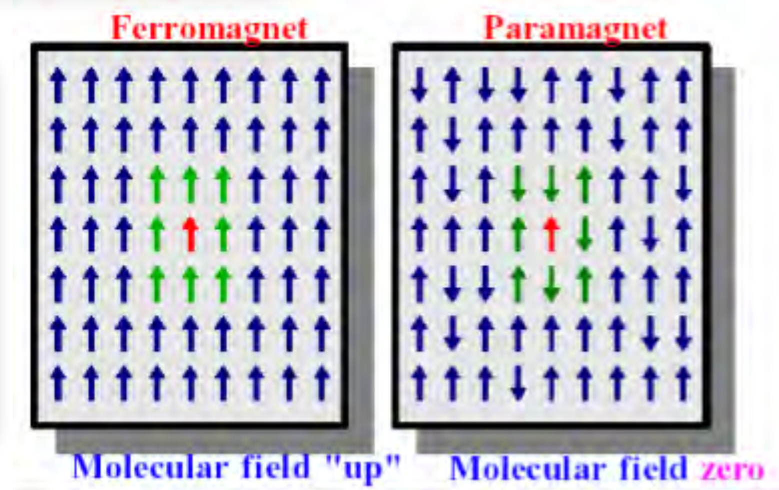
Standard critical points:

Spontaneous symmetry breaking

Order parameter, Landau-Ginzburg

Renormalization group, field theory

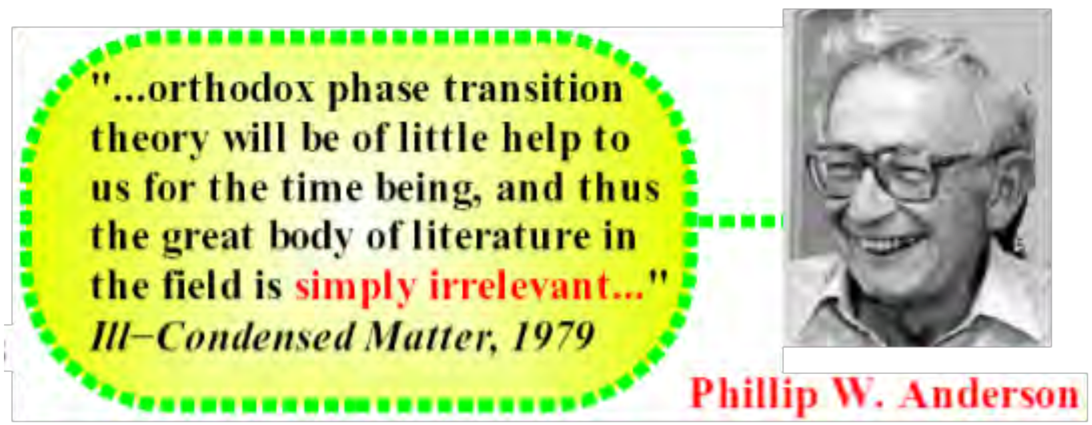




Metal-Insulator Transitions:

NO symmetry breaking!

Order parameter???



Maximally Frustrated Hubbard Model

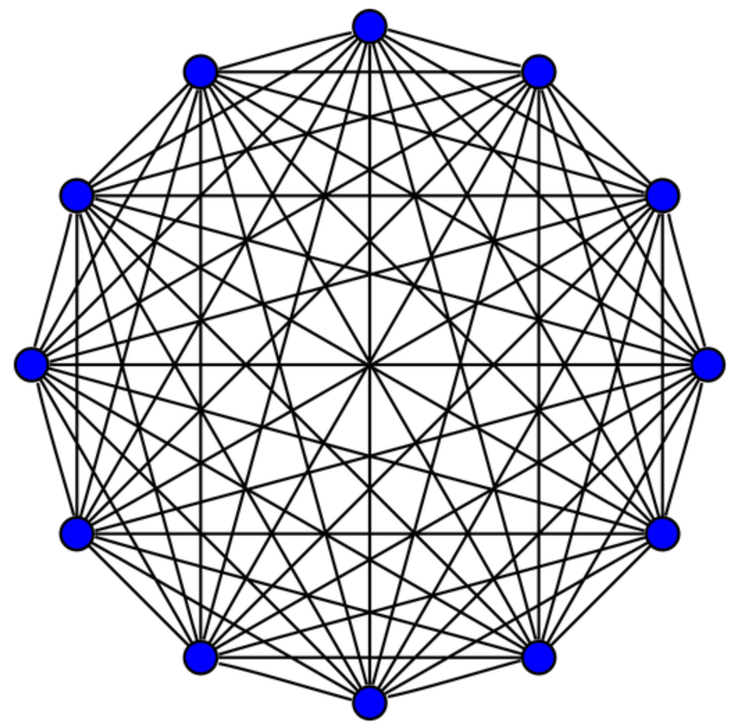
$$H = -t \sum_{\langle i,j \rangle, \sigma} \left(c^{\dagger}_{i\sigma} c_{j\sigma} + \mathrm{h.c.} \right) + U \sum_{i} n_{i\uparrow} n_{i\downarrow} - \mu \sum_{i,\sigma} c^{\dagger}_{i\sigma} c_{i\sigma}$$

Infinite-range model

Suppress all orders: “pure Mott”

Local self-energy: DMFT solution

“Kondo physics” forms Fermi liquid



Finite temperature transport: the Mott transition at half-filling

PRL 107, 026401 (2011) PHYSICAL REVIEW LETTERS week ending 8 JULY 2011

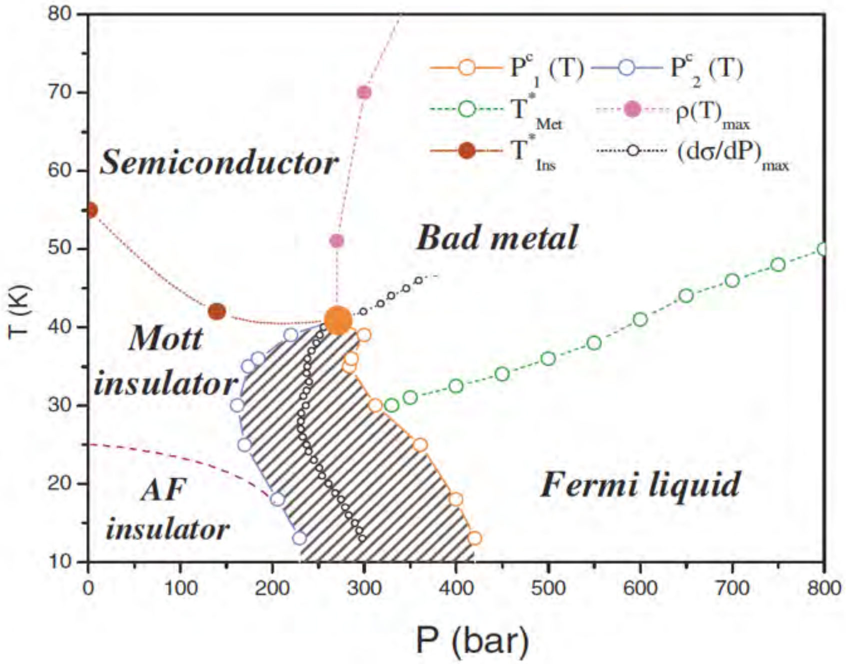
Quantum Critical Transport near the Mott Transition

H. Terletska,[1] J. Vučičević,[2] D. Tanasković,[2] and V. Dobrosavljević[1]

(also J. Vučičevic, et al., Phys. Rev. B, 88, 075143 (2013))

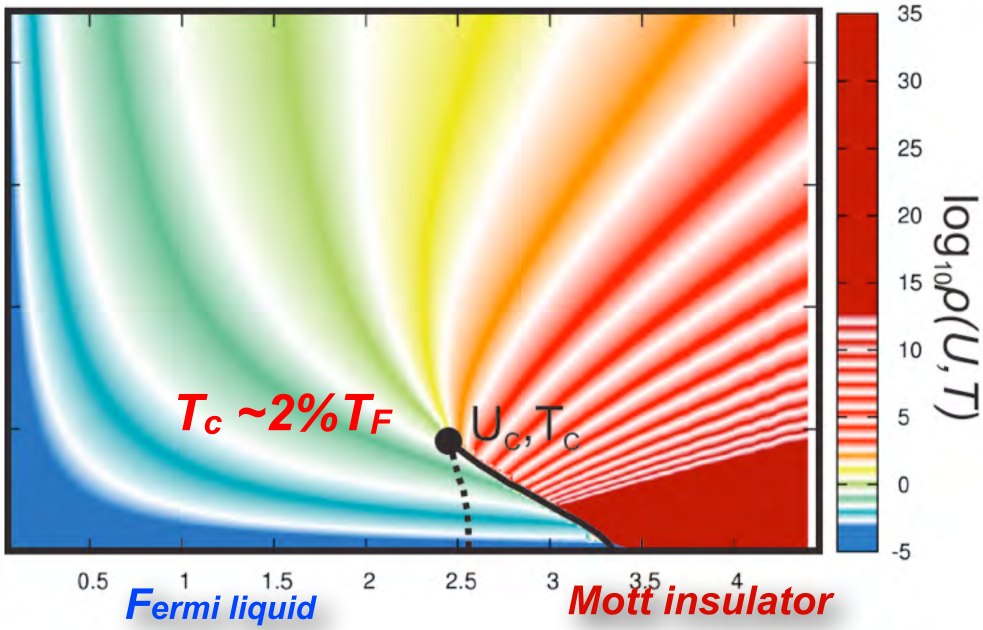
Experiment: organic Mott system

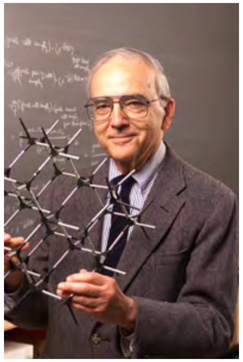
Jerome, PRL 2003



Theory (DMFT)

Early work: Kotliar, Rozenberg 1992, etc.

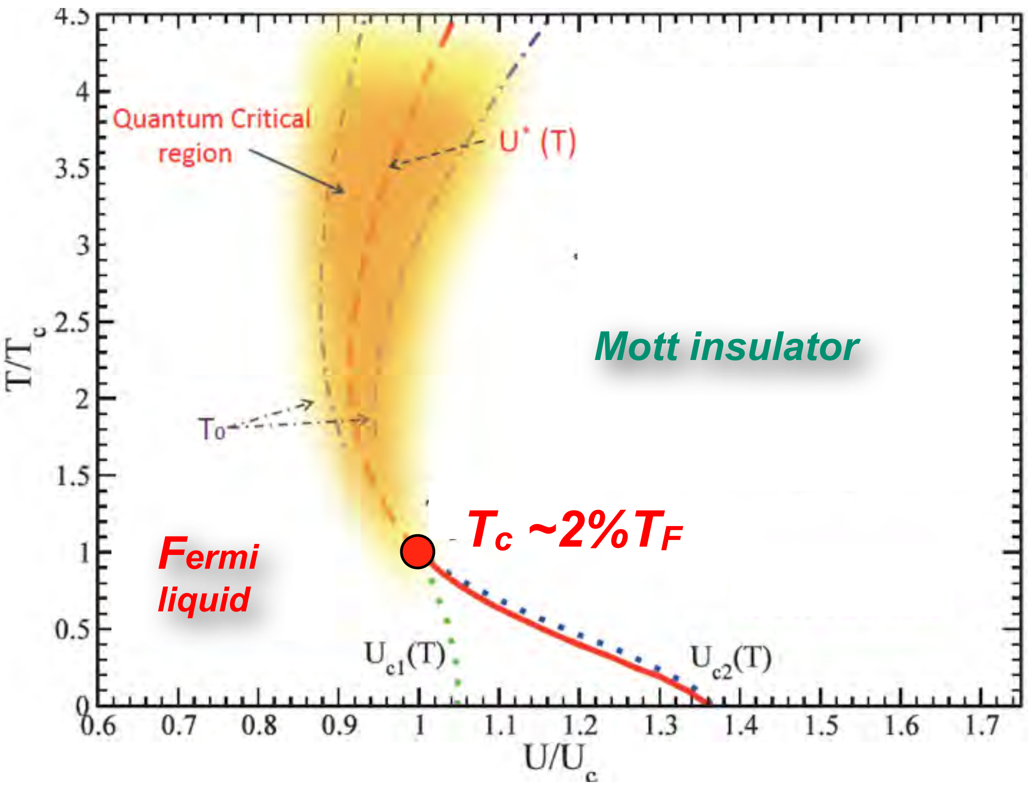




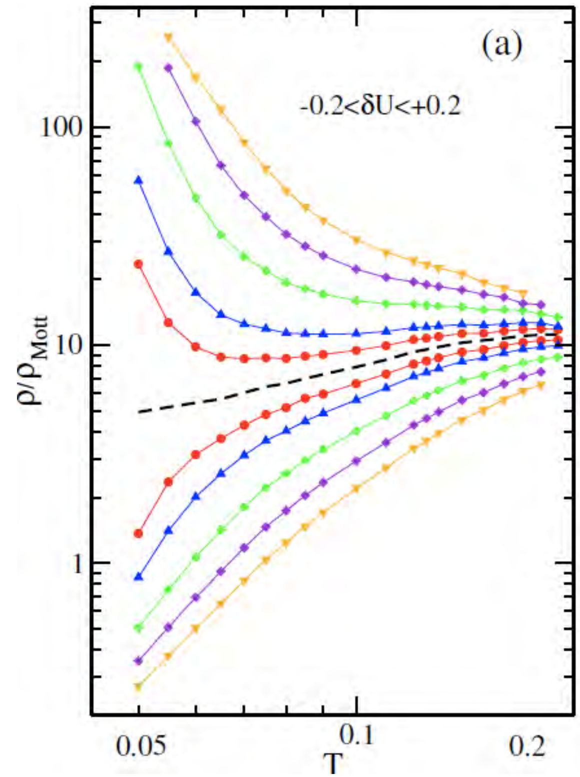
Crossover - *“quantum Widom line”* !

Recent work: Sordi, Tramblay, 2012, etc.

DMFT theory



around Widom line



$k_F l$ << 1

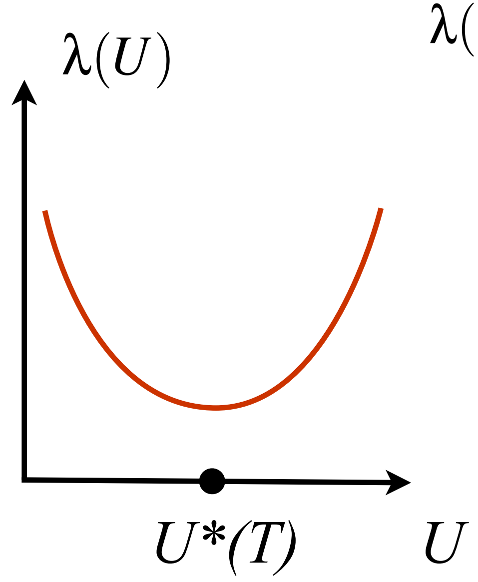
“impossible”

$k_F l$ = 1

MOSFET: T_c ~2%T_F ~ 200mK

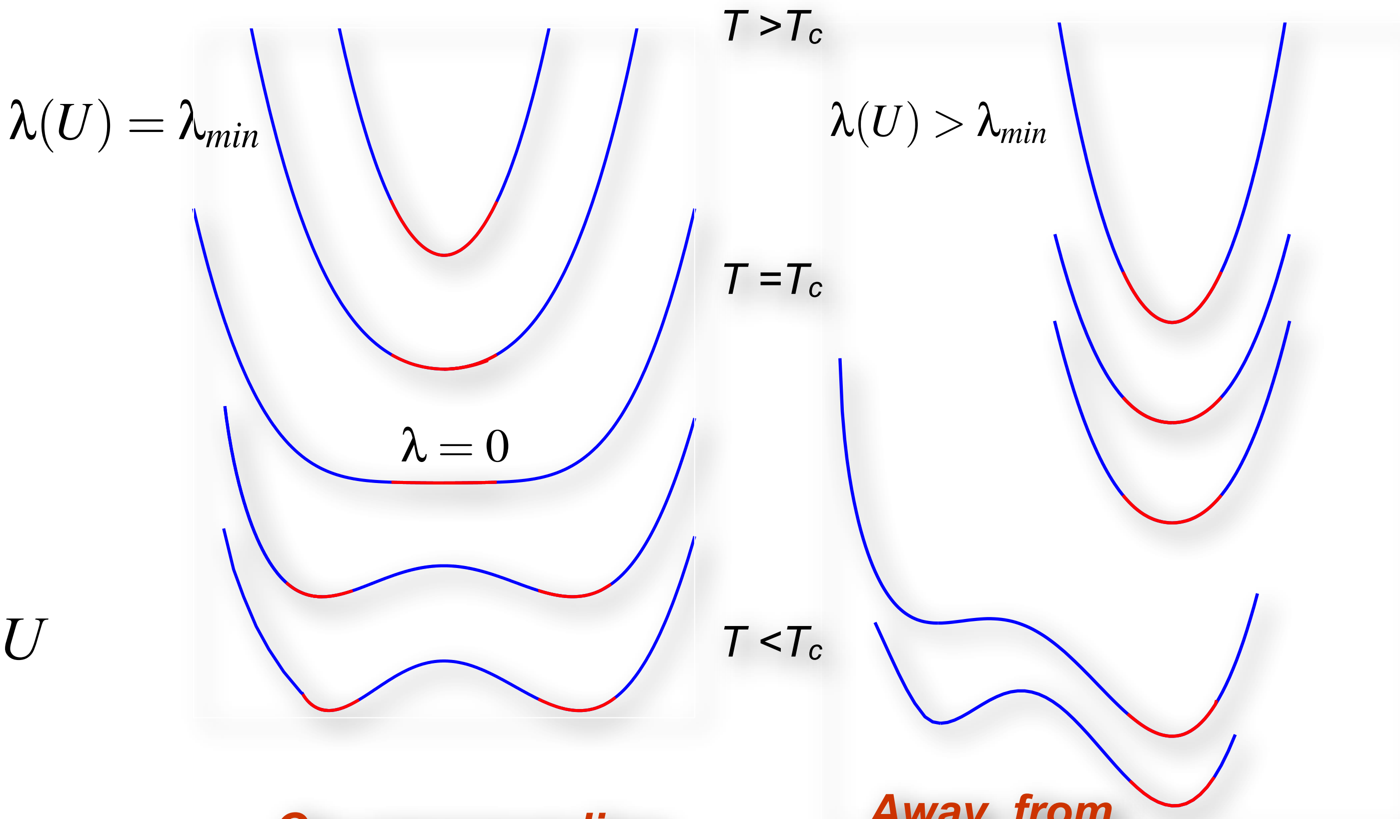
Crossover line: eigenvalue analysis

Curvature - eigenvalue



$$\delta U = U - U^*(T)$$

Free energy landscape
(actual quantitative results!)



On crossover line

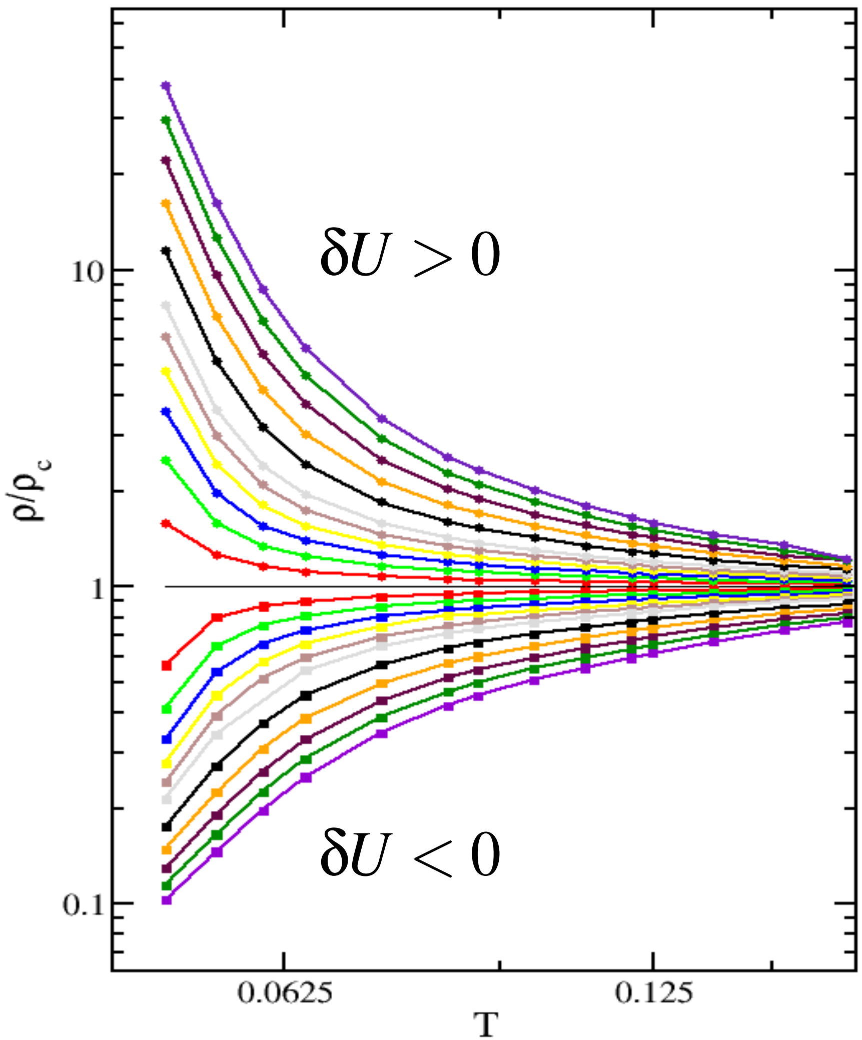
$$\delta U(T) = 0$$

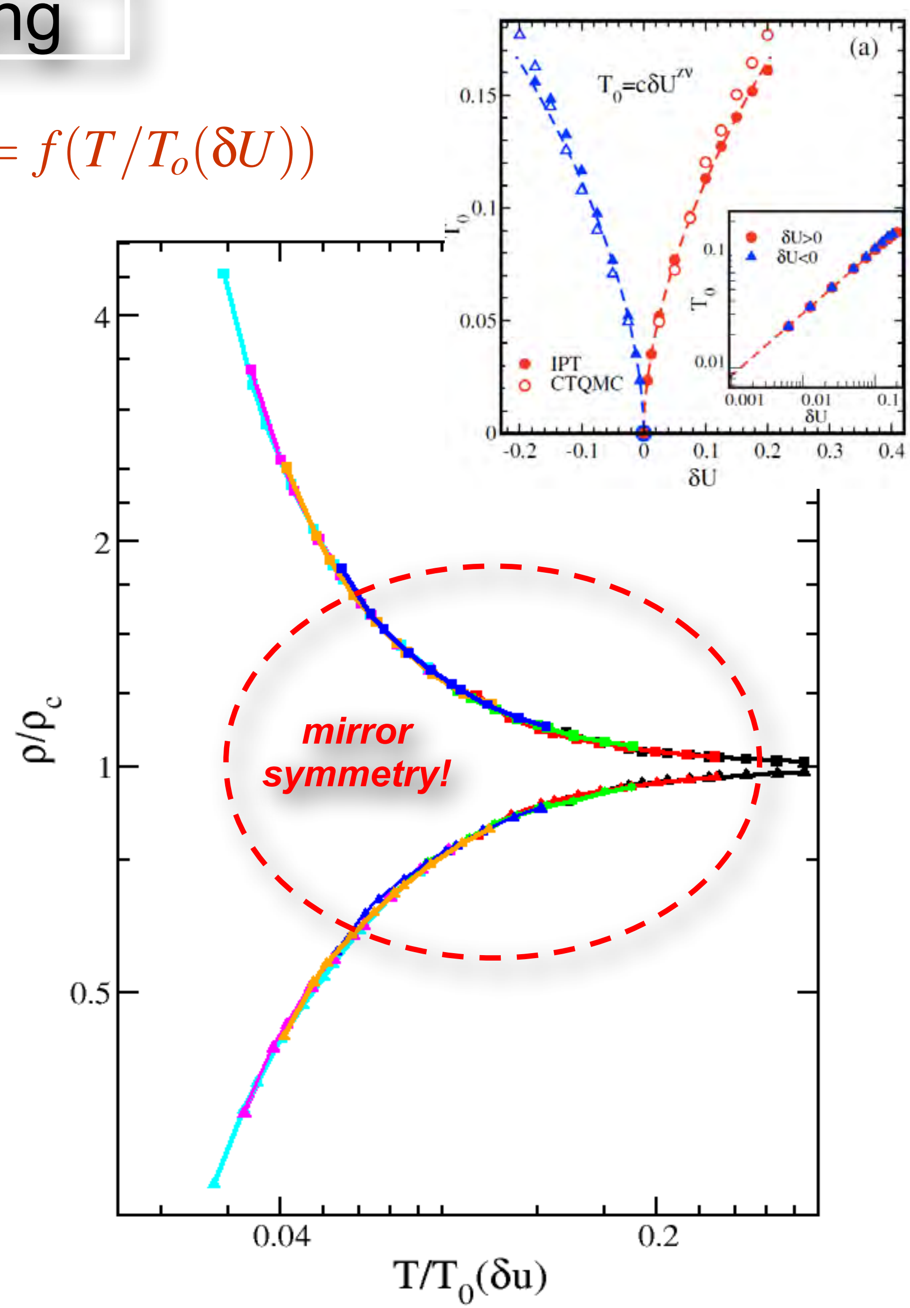
Away from crossover line

$$\delta U(T) \neq 0$$

Scaling

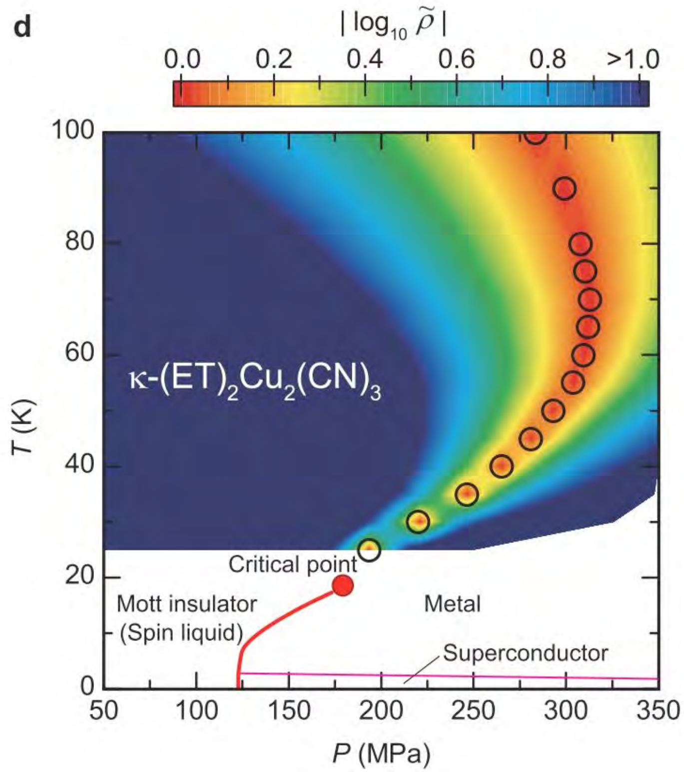
$$\rho(\delta U, T)/\rho_c(T) = f(T/T_o(\delta U))$$



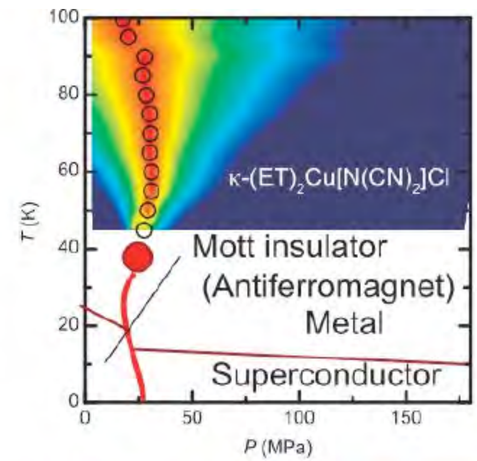


Mott organics: universal high-T scaling

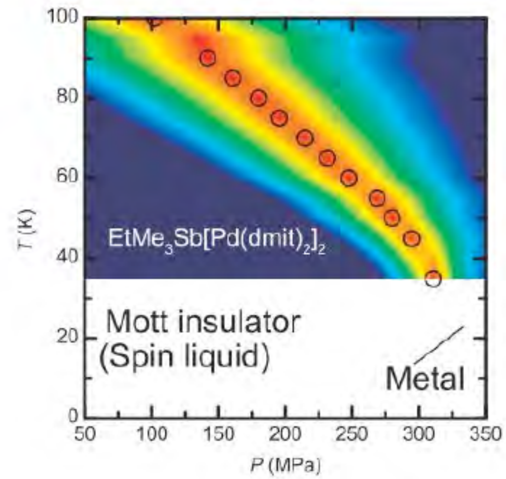
K. Kanoda et al., Nature Physics (2015)



Strong frustration:
spin liquid at low T

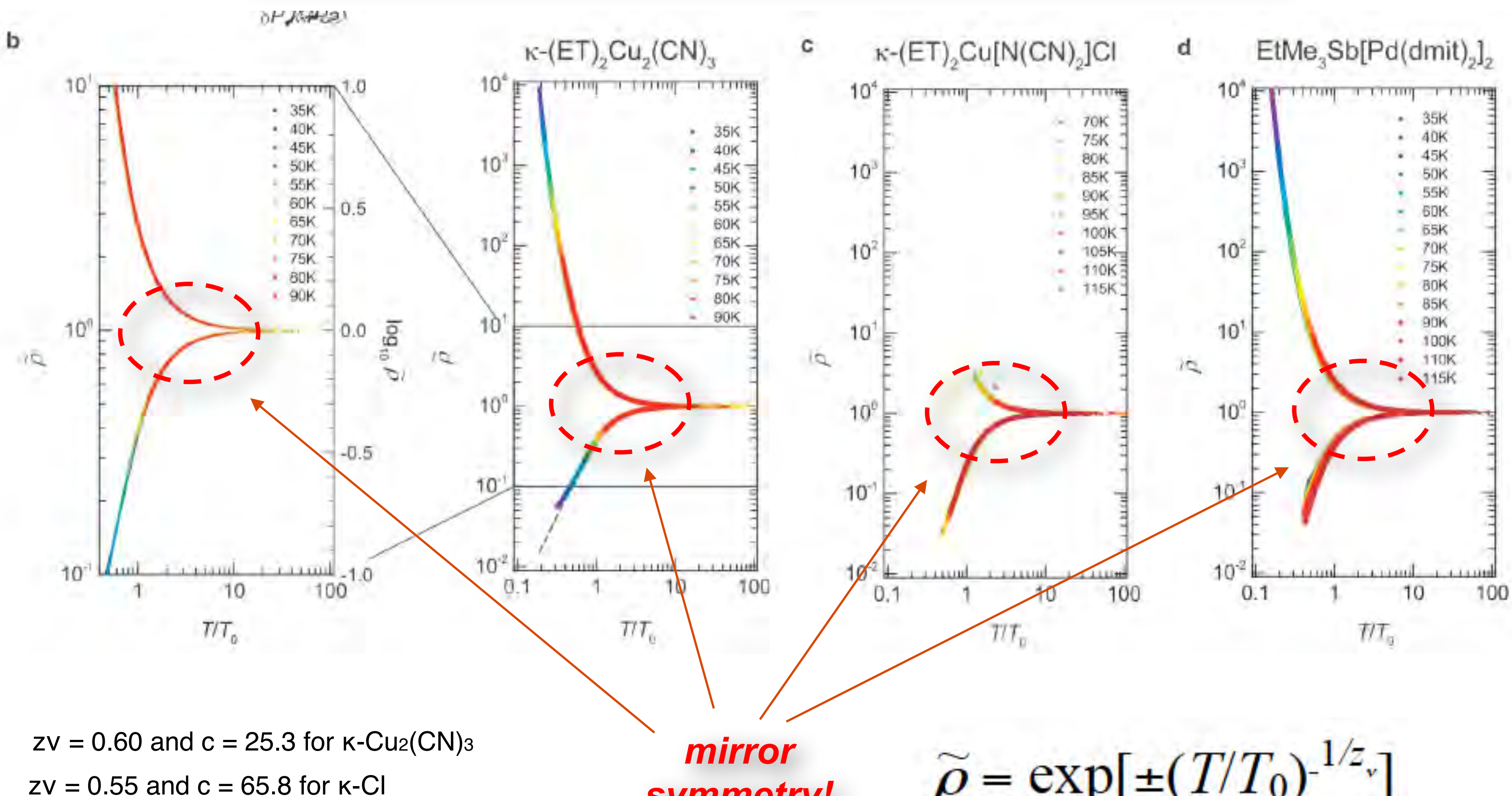


Weaker frustration:
AFM at low T



Mott organics: universal high-T scaling

K. Kanoda et al., Nature Physics (2015)



zν = 0.60 and c = 25.3 for κ-$Cu_2(CN)_3$

zν = 0.55 and c = 65.8 for κ-Cl

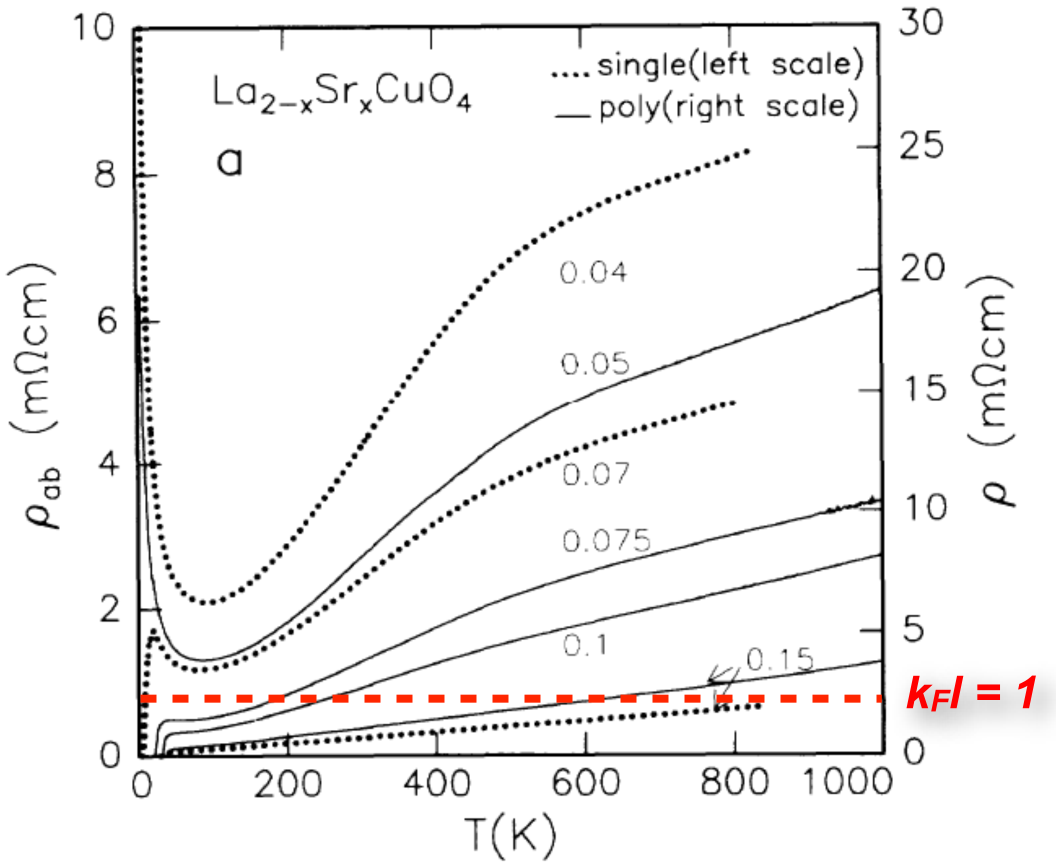
zν = 0.65 and c = 18.9 for $EtMe_3Sb$-dmit

$$\widetilde{\rho} = \exp[\pm(T/T_0)^{-1/z_\nu}]$$

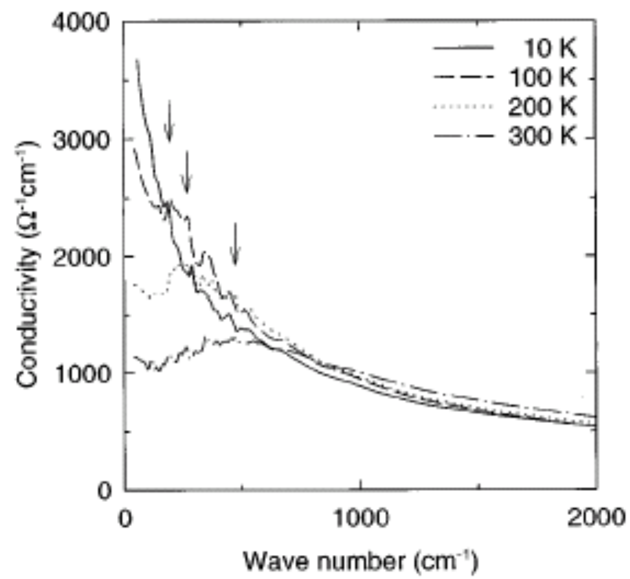
"stretched exponential"

Doped Mott insulators: Bad Metals vs. Quantum Criticality??

Mott-Ioffe-Regel limit: $k_F l > 1$



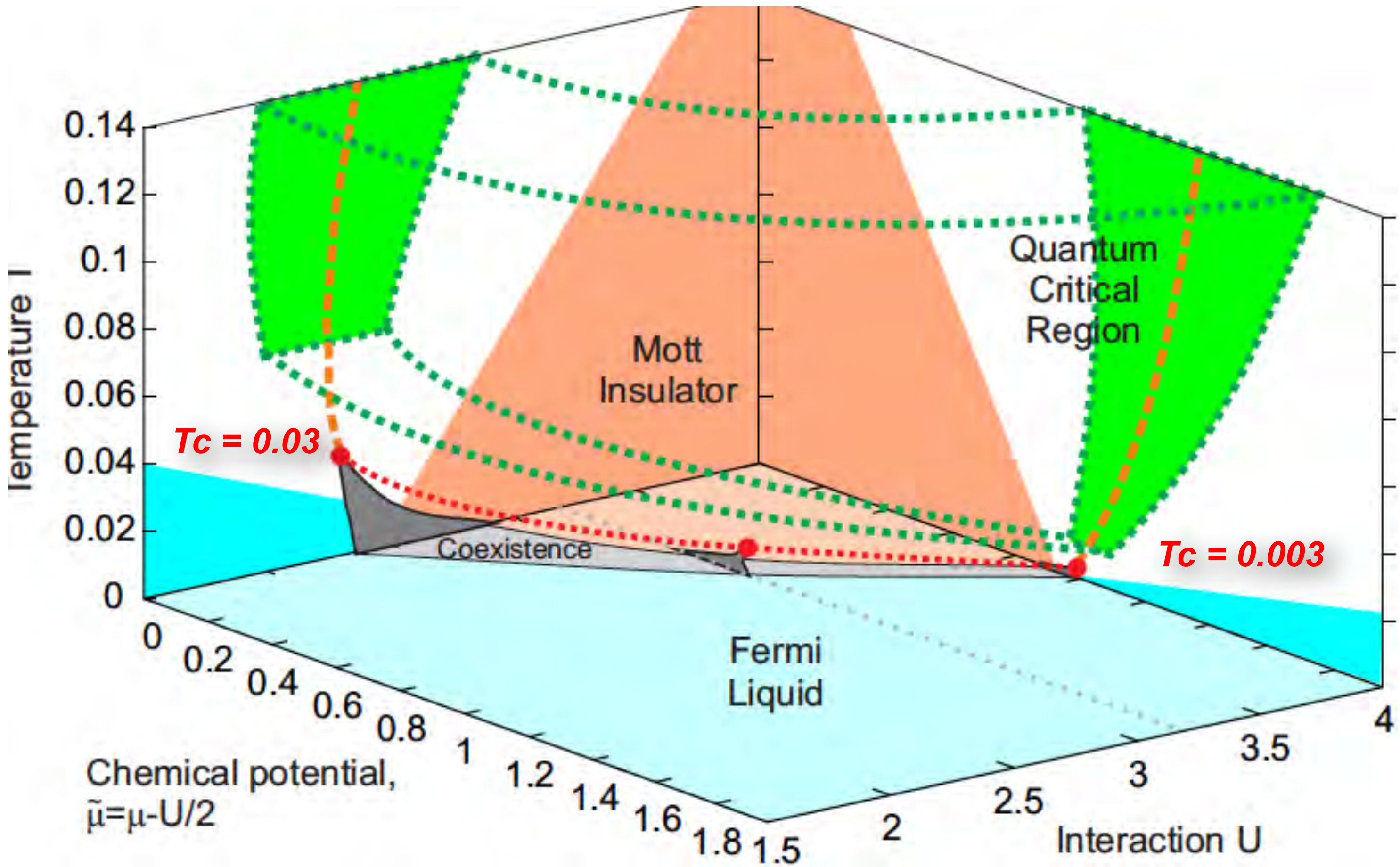
Experiment: H. Takagi, 1992



PRL 114, 246402 (2015) PHYSICAL REVIEW LETTERS week ending 19 JUNE 2015

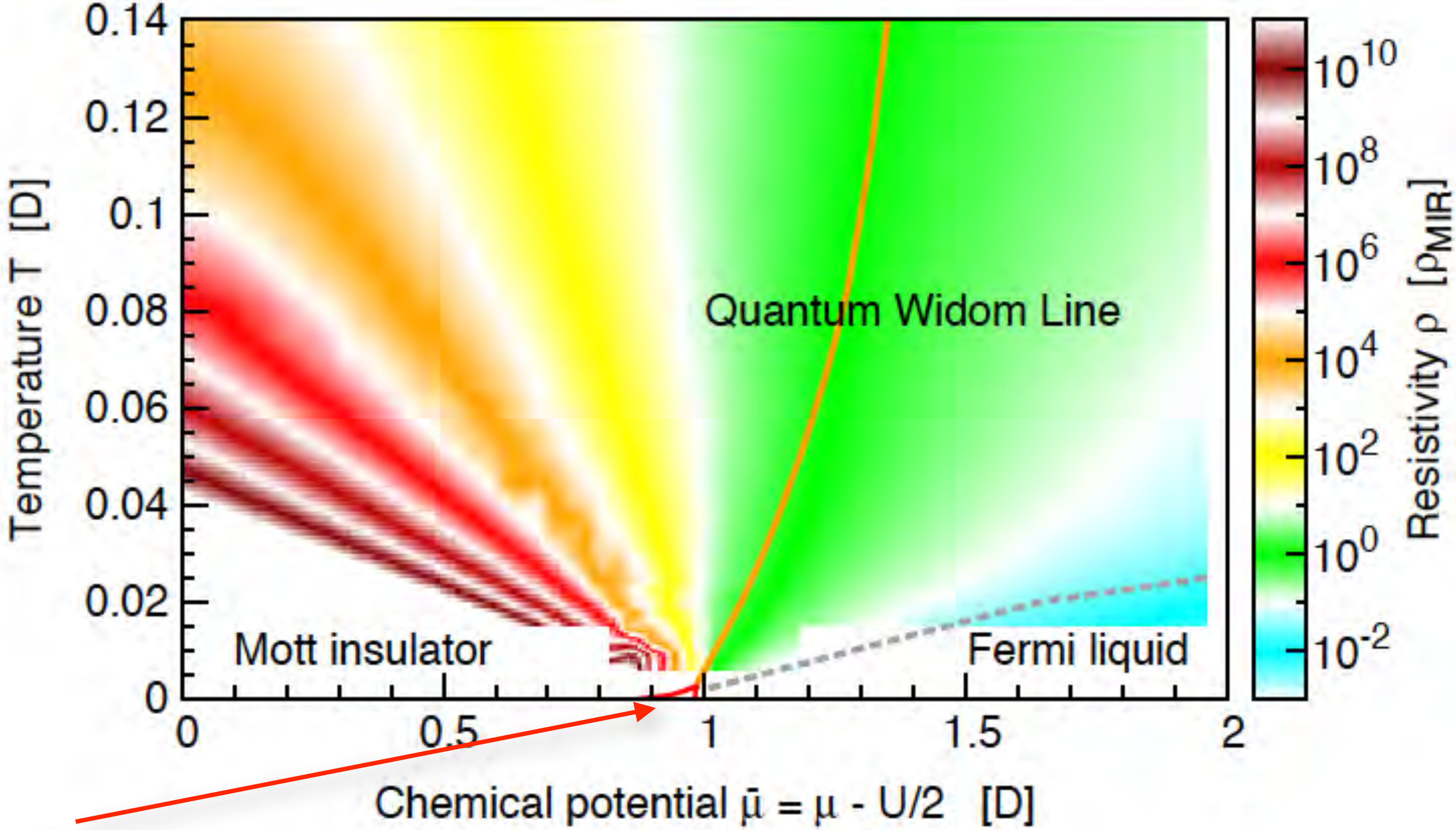
Bad-Metal Behavior Reveals Mott Quantum Criticality in Doped Hubbard Models

J. Vučičević,[1] D. Tanasković,[1] M. J. Rozenberg,[2] and V. Dobrosavljević[3]



Doped Mott: DMFT vs. QCP?

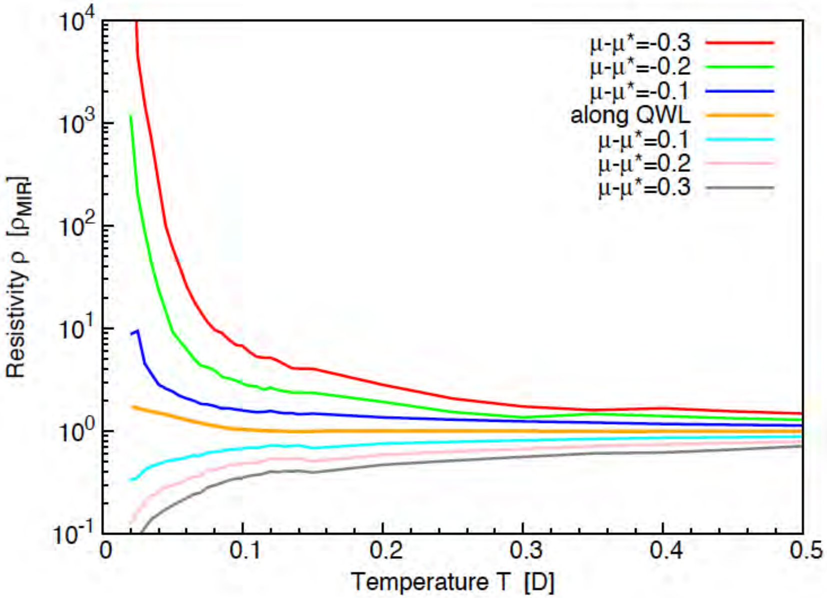
J. Vučičevic, D.Tanaskovic, M. Rozenberg, and V. D., 2014



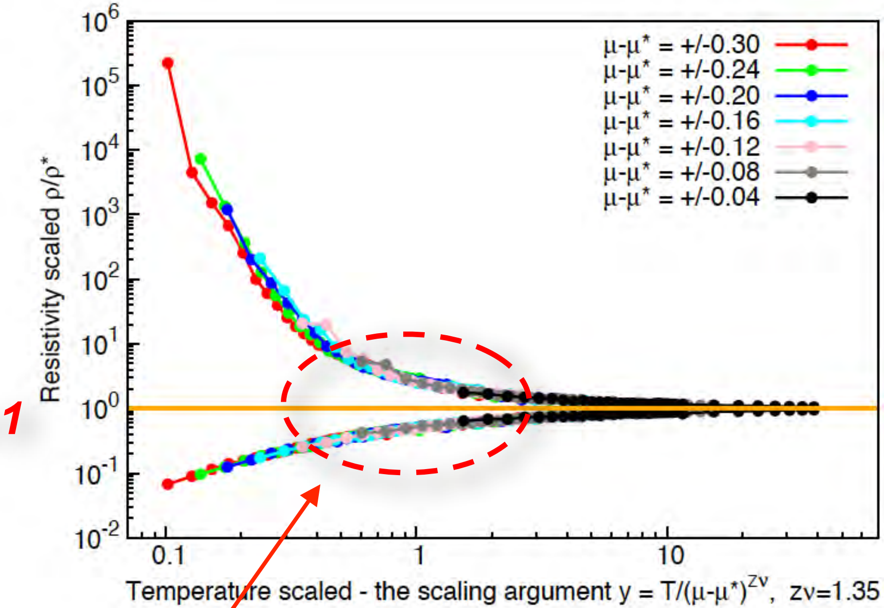
TINY coexistence dome
Tc = 0.003

Doped Mott: QC Scaling

J. Vučičevic, D. Tanaskovic, M. Rozenberg, and V. D., 2014



$k_F l = 1$



mirror symmetry:
defines QC region

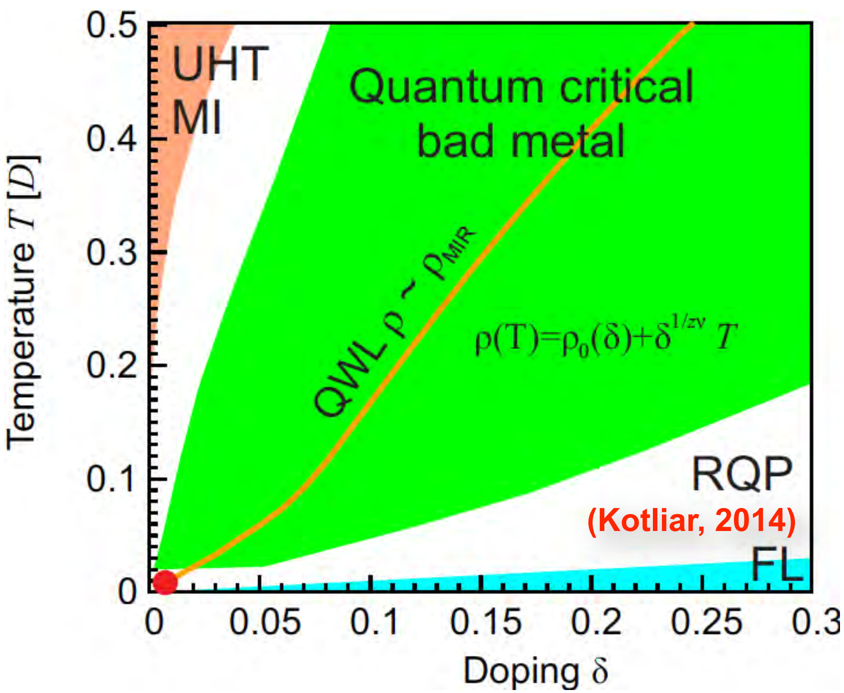
New feature:
Quantum Widom Line - MIR limit

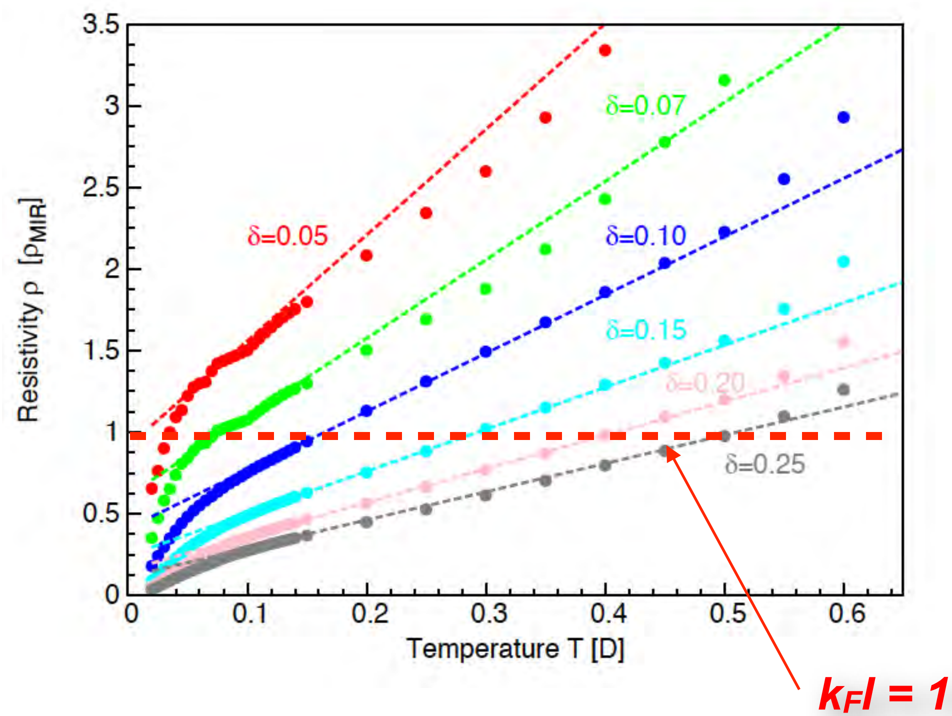
$$\rho(T,\mu) = \rho^* \exp\{A(\mu - \mu^*(T))/T^{\nu z}\}$$

"stretched exponential"

Doped Mott: Quantum Critical Region?

J. Vučičevic, D.Tanaskovic, M. Rozenberg, and V. D., 2014





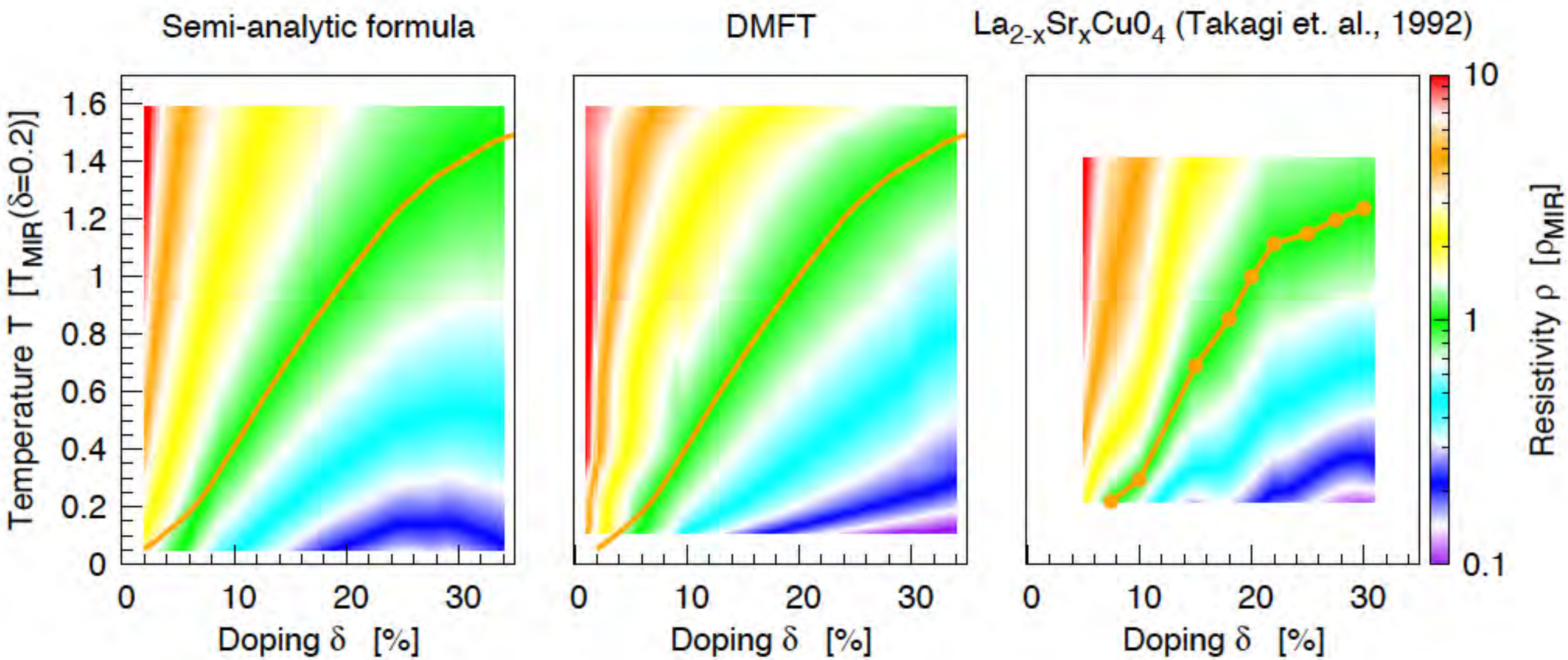
Key Results:

Bad Metal (linear resistivity ~ MIR limit) = Mott QC region

QC Scaling - (semi) analytical formula for linear-T resistivity

Doped Mott: Theory vs. Experiment

J. Vučičevic, D.Tanaskovic, M. Rozenberg, and V. D., 2014



Mott QC region: universal behavior at high temperatures

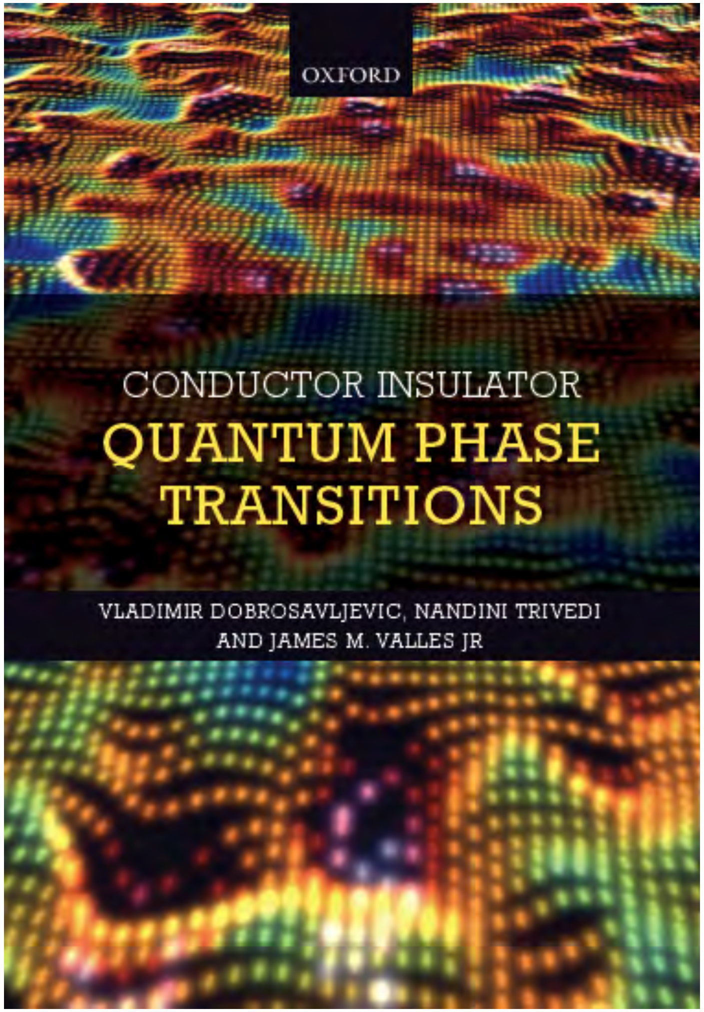
Moral of the story

- using words anyone can understand -

Bad Liquid:
AdS-CFT??

Viscous (quantum) liquid is not a gas (Landau quasiparticles)

To learn more:



http://badmetals.magnet.fsu.edu

(just Google "Bad Metals")

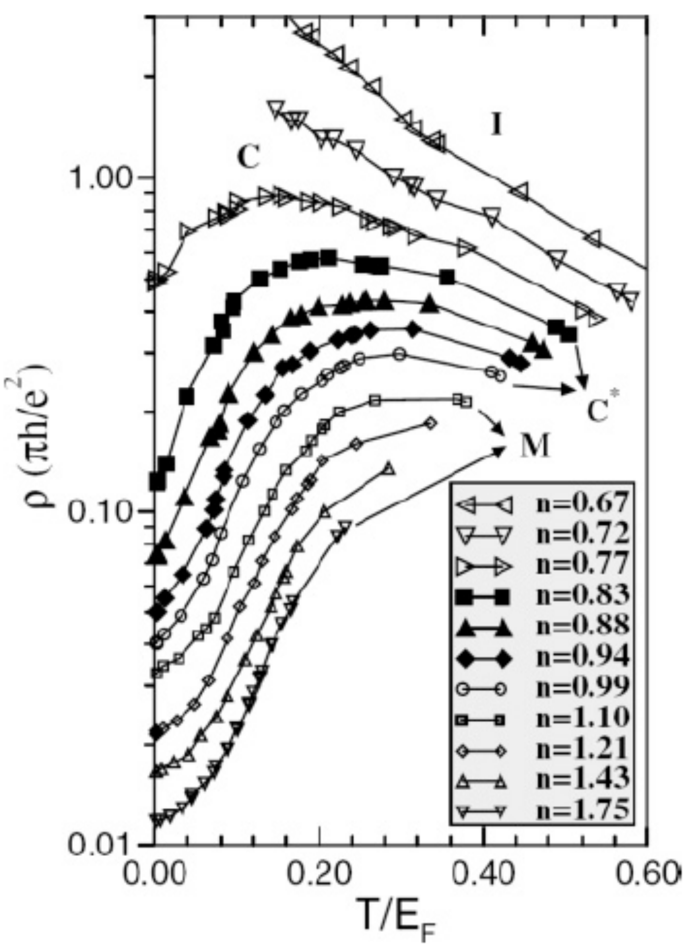
Book:

Oxford University Press, 2012

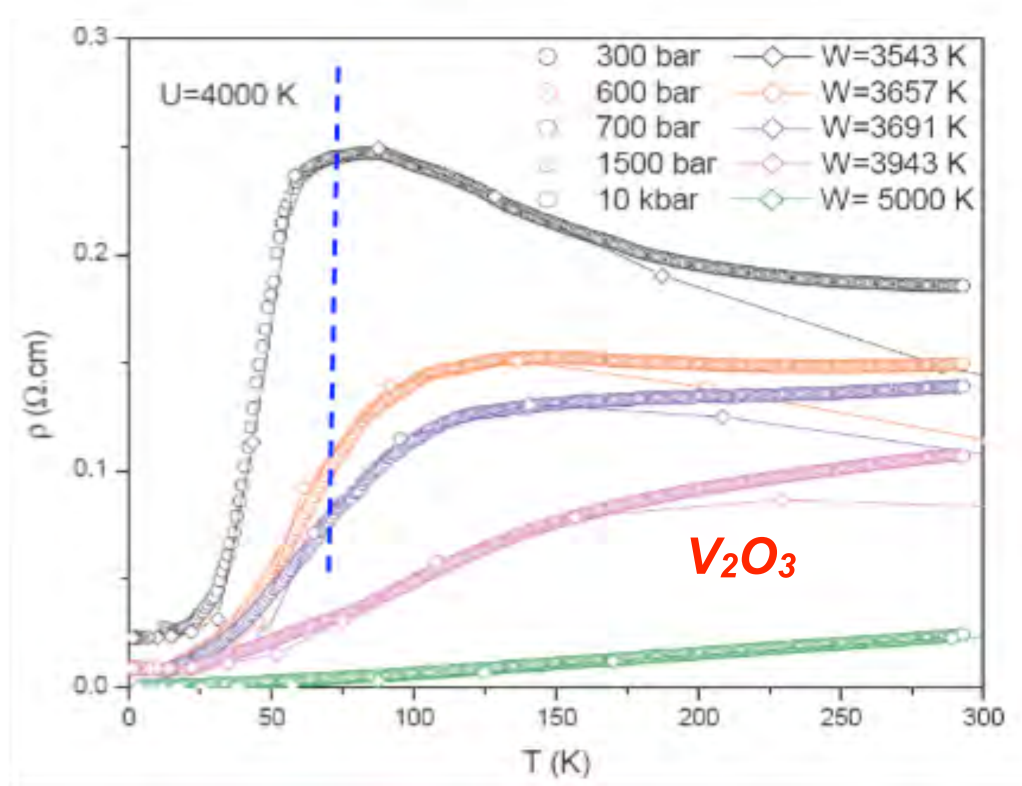
ISBN 9780199592593

Really, but really bad metals: resistivity maxima (experiments)

MOSFETs

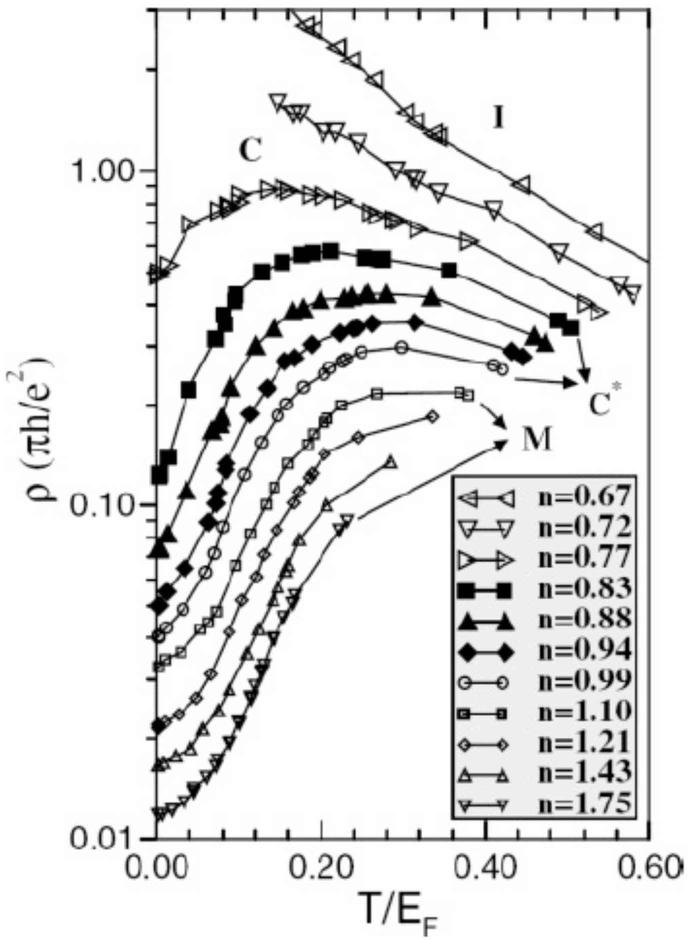


And now...
something completely different



Phenomenological scaling
(experiments)

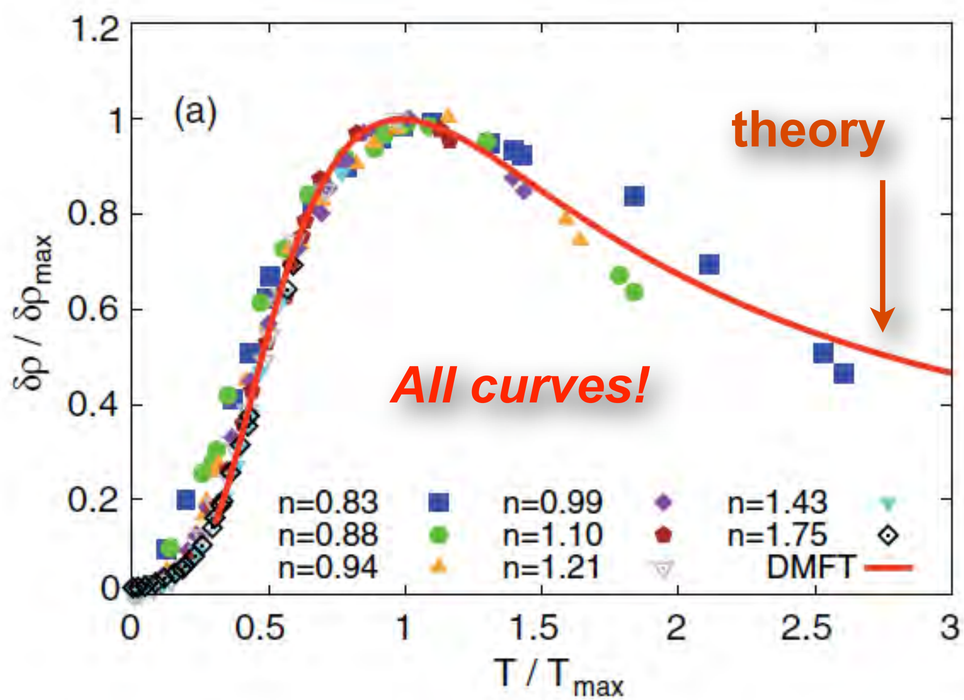
MOSFETs



$$\rho(T) = \rho_o + \delta\rho(T)$$

$$\delta\rho(T) = \delta\rho_{\max} f(T/T_{\max})$$

$$\delta\rho_{\max} = \rho_{\max} - \rho_o$$

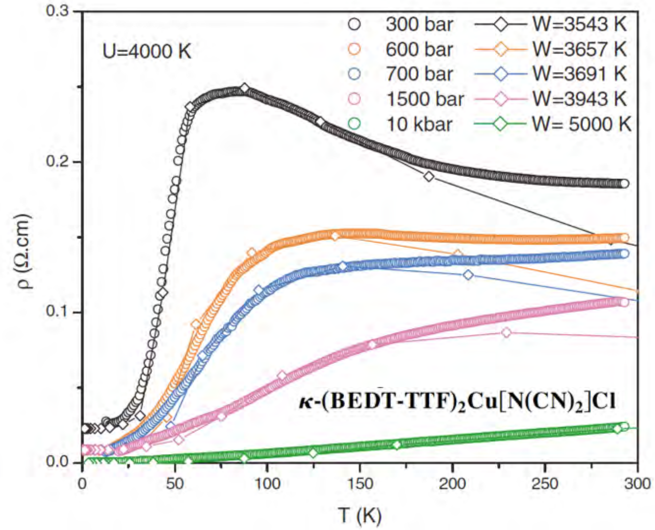


Evaporating the Fermi liquid

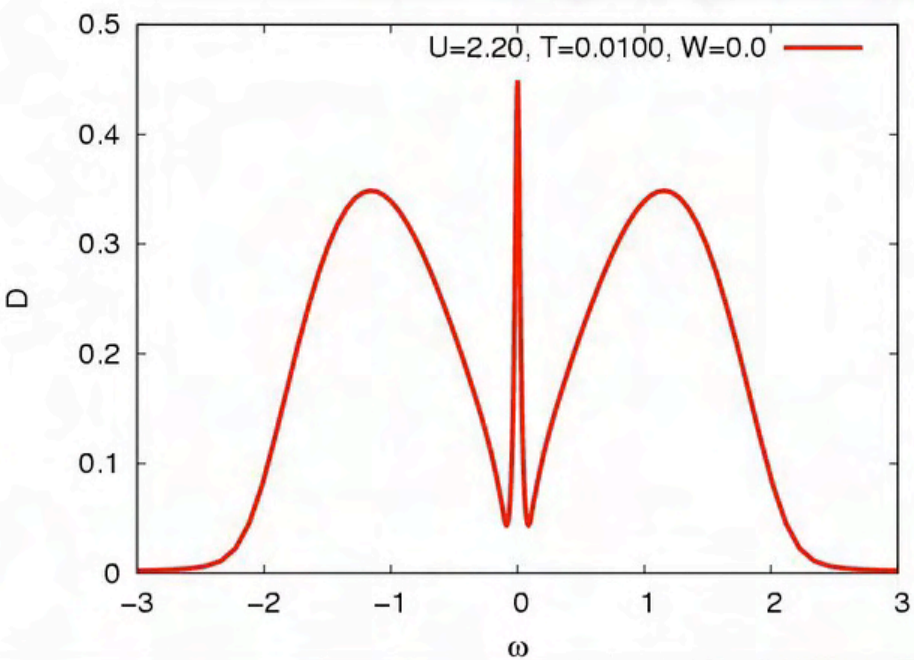
Darko Tanaskovich

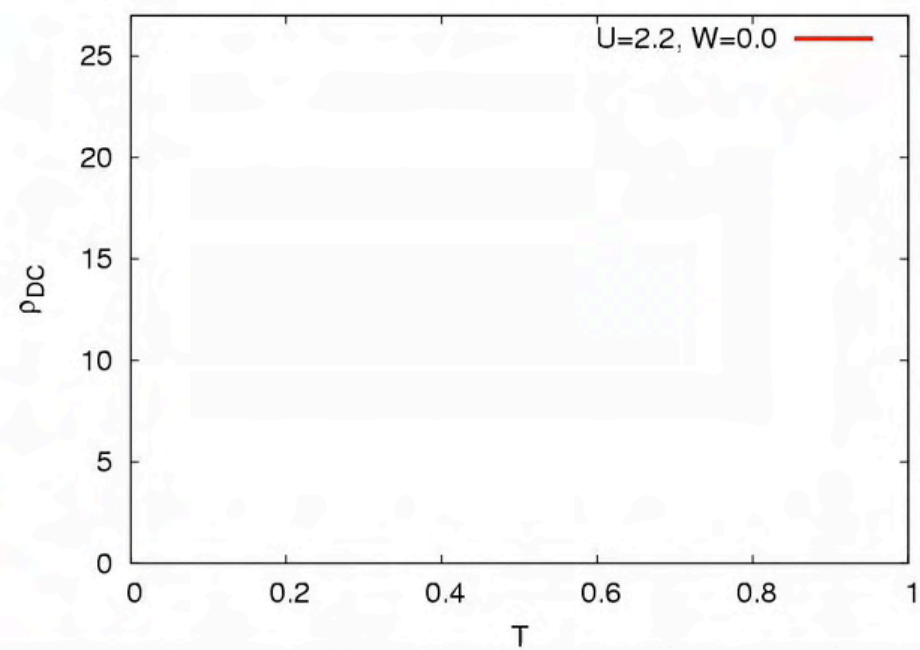
Low Fermi liquid coherence scale

$$T^*_{FL} \sim ZT_F \sim T_F/m^*$$



Thermal death of quasi-particles?



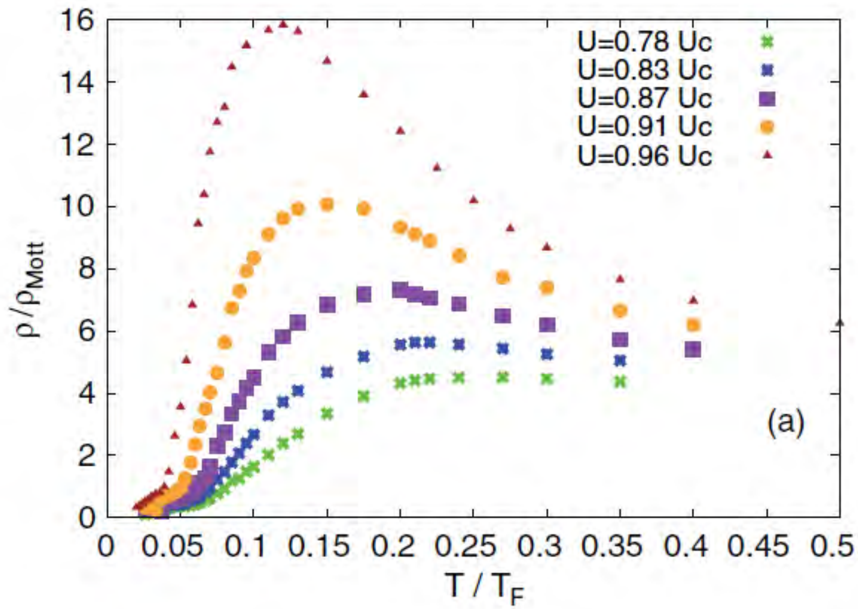


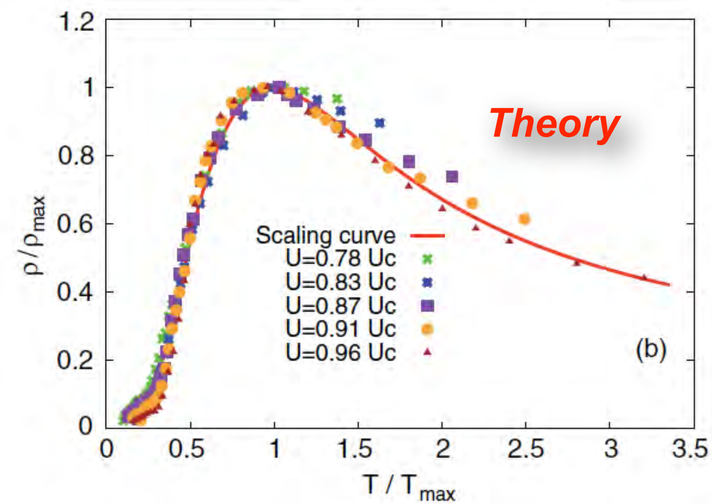
PHYSICAL REVIEW B **85**, 085133 (2012)

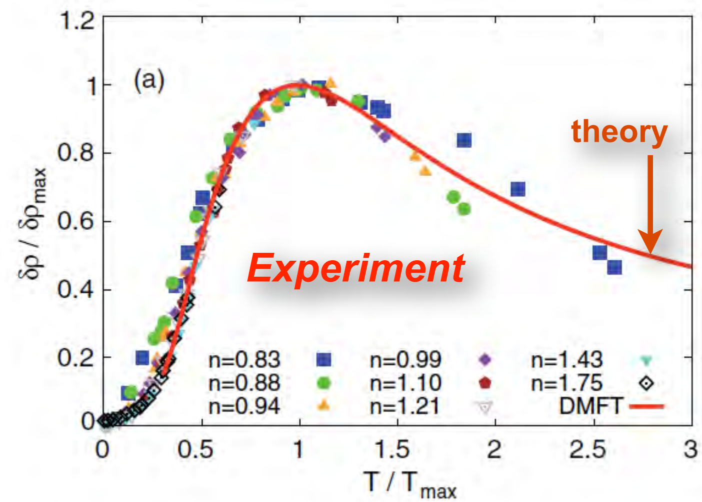
Wigner-Mott scaling of transport near the two-dimensional metal-insulator transition

M. M. Radonjić,[1] D. Tanasković,[1] V. Dobrosavljević,[2] K. Haule,[3] and G. Kotliar[3]

DMFT theory

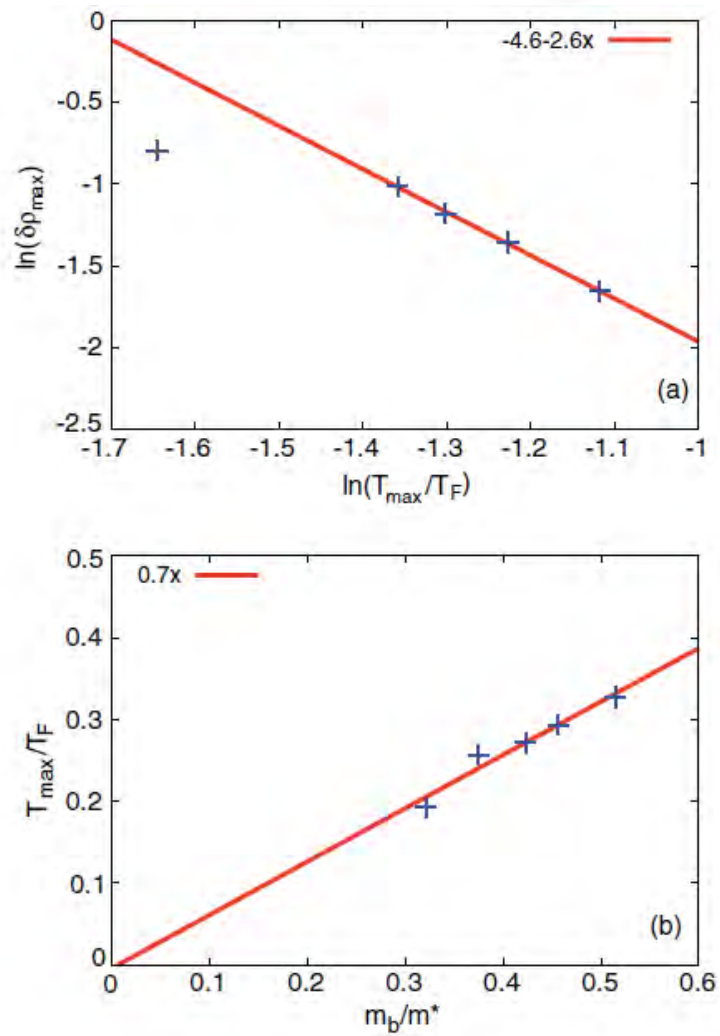






Approaching the transition - trends

DMFT Theory



Experiments