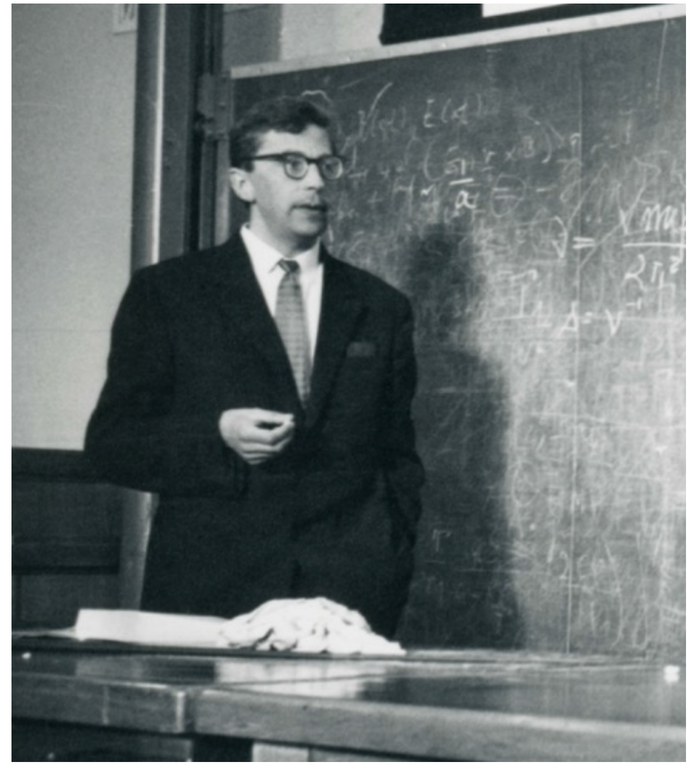
Landau Theory for Disorder-Driven Metal-Insulator Transitions in Deformable "Media"

Vladimir Dobrosavljevic
Florida State University

NATIONAL HIGH MAGNETIC FIELD LAB



Collaborators:

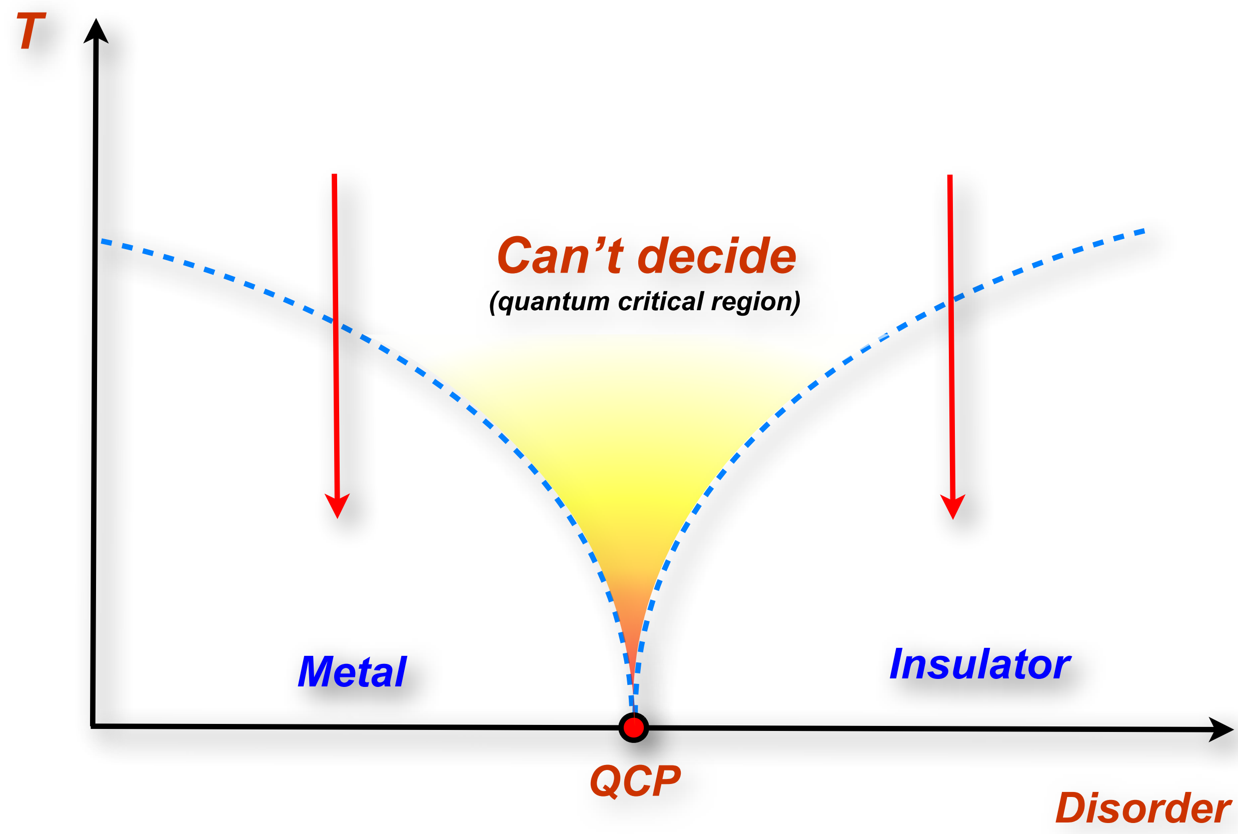
Simone Fratini (Grenoble)
Sergio Ciuchi (Rome)
Domenico Di Sante (Würzburg)

Funding: ***NSF grants:***

DMR-1822258
DMR-1410132
…

Modern Trends in Condensed Matter Physics
(Lev Gor'kov Memorial Conference)
June, 24-27, 2019 L. D. Landau Institute

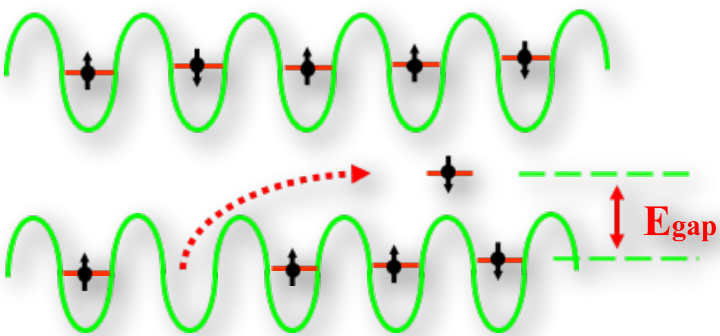
MIT Quantum Criticality?



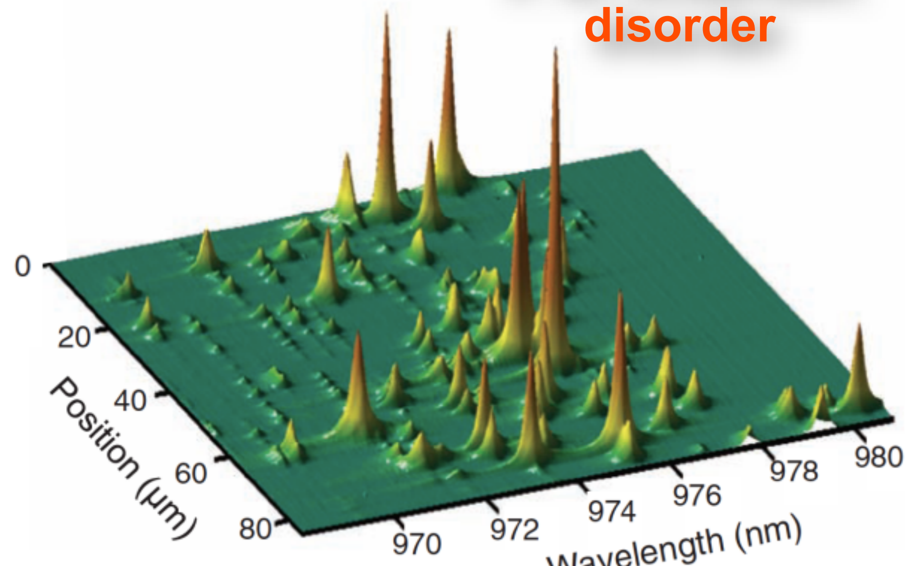
Mechanisms for Localization?

Friend or Foe???

Sir Neville Mott:
(whatever) interaction



P. W. Anderson:
disorder



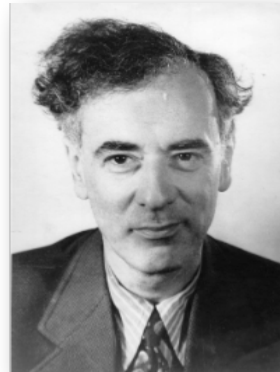
Theoretical Approaches

Standard critical points:

Spontaneous symmetry breaking

Order parameter, Landau-Ginzburg

Renormalization group, field theory



Metal-Insulator Transitions:

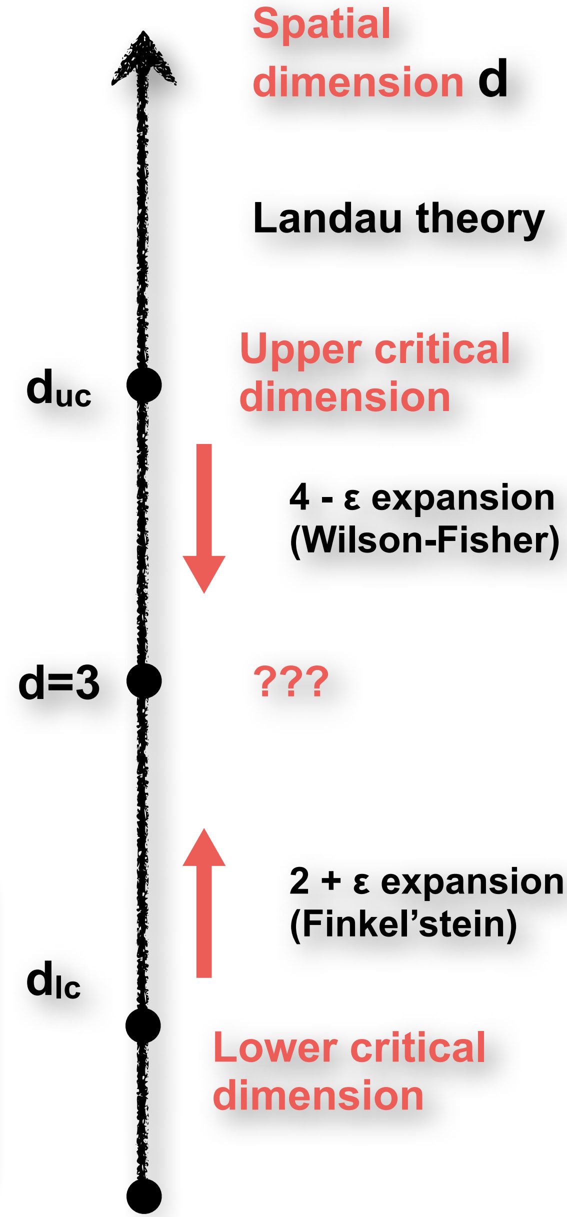
NO symmetry breaking!

Landau theory, upper critical dimension ???

“Forced” to use **2 + ε expansion**

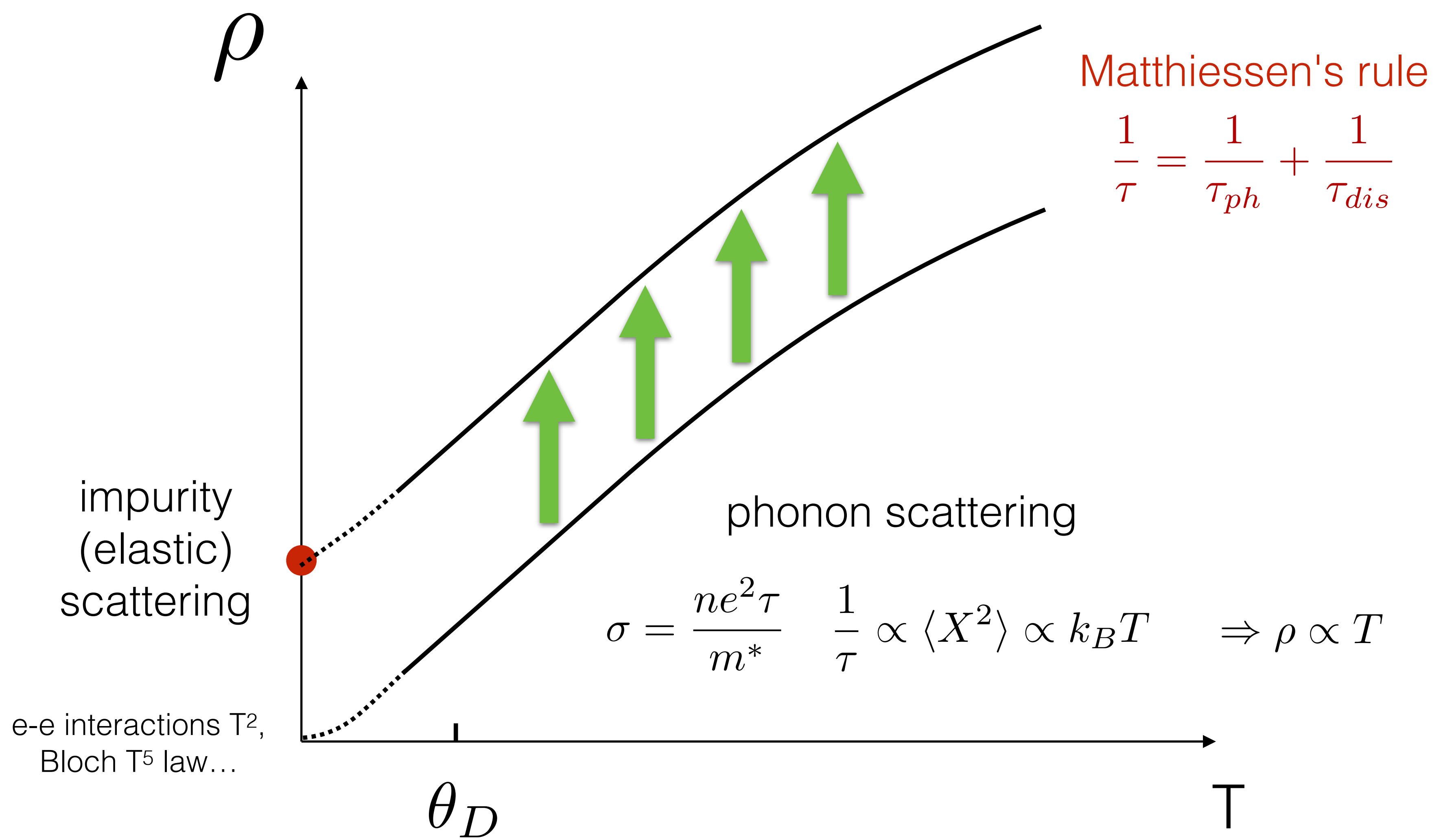
Problems:

weak-coupling, convergence in ε (Murthy)



$\rho(T)$ vs disorder in metals

What I remember from college:



Experimental puzzles I: Mott limit and Mooij Correlation

Lee and Ramakrishnan: Disordered electronic systems (Rev. Mod. Phys., Vol. 57, No. 2, April 1985)

VII. REMARKS AND OPEN PROBLEMS
A. High-temperature anomalies

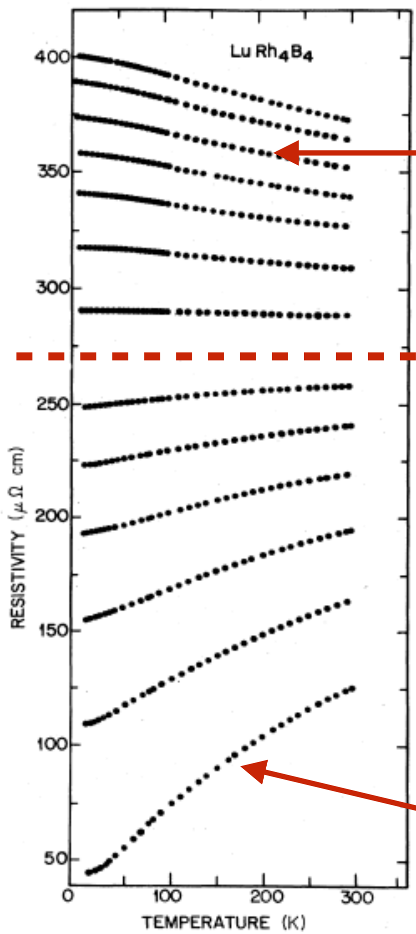


FIG. 20. Resistivity as a function of temperature for LuRh$_4$B$_4$ at various damage levels. The numbers represent the α-particle dose in units of 10^{16}/cm^2. From Dynes, Rowell, and Schmidt (1981).

ρ_0^c

A15 compounds: Effect of disorder by ion radiation
(Dynes et al., 1981)

Bad conductor: disorder+phonons???

"Mott-Ioffe-Rege (MIR) limit"
($k_F\ell$ ~ O(1))

Mooij (1973) correlation???

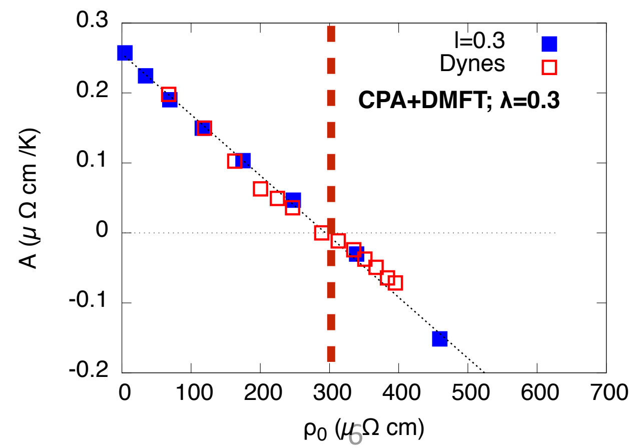
$$\boxed{\rho(T) = \rho_0 + (\rho_0^c - \rho_0) A T}$$

(all cross at T = 1/A)

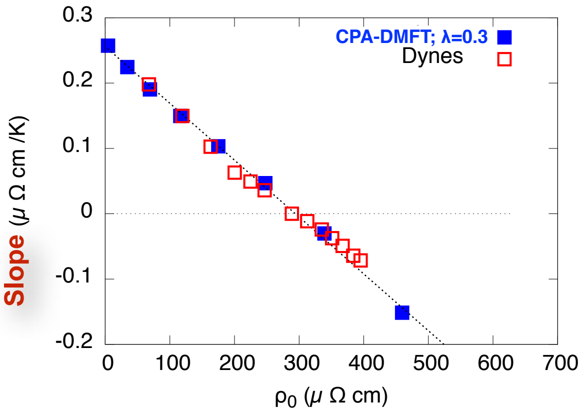
Breakdown of Mathiessen's rule:

$$\cancel{\rho_{\mathrm{ideal}}(T) = \rho_0 + \rho_{\mathrm{ph}}(T)}$$

Good metal: phonons



How common are Mooij correlations?



Mooij

$Fe_{80}B_{20}$
$Fe_{80}B_{18}Si_{2}$
$Fe_{80}B_{13}Si_{4}C_{3}$

$Fe_{78}Si_{10}B_{12}$
$Fe_{68}Co_{10}Si_{10}B_{12}$
$Fe_{63.5}Co_{15.6}Si_{10}B_{12}$
$Fe_{39}Co_{39}Si_{10}B_{12}$
$Fe_{7.8}Co_{70.2}Si_{10}B_{12}$
$Co_{78}Si_{10}B_{12}$
$Co_{70.2}Ni_{7.8}Si_{10}B_{12}$
$Co_{54.6}Ni_{23.4}Si_{10}B_{12}$
$Co_{39}Ni_{39}Si_{10}B_{12}$
$Co_{15.6}Ni_{62.4}Si_{10}B_{12}$
$Co_{10}Ni_{68}Si_{10}B_{12}$
$Ni_{78}Si_{10}B_{12}$

$Fe_{40}Ni_{40}P_{14}B_{6}$ (2826)
$Fe_{32}Ni_{35}Cr_{15}P_{12}B_{6}$ (2826A)
$Fe_{29}Ni_{49}P_{14}B_{6}Si_{2}$ (2826B)
$Fe_{80}P_{16}C_{3}B_{1}$ (2615)
$Fe_{80}B_{20}$ (2605)
$Fe_{78}Mo_{2}B_{20}$ (2605A)

$Fe_{80}P_{14}B_{6}$
$Fe_{60}Ni_{20}P_{14}B_{6}$
$Fe_{40}Ni_{40}P_{14}B_{6}$
$Fe_{30}Ni_{50}P_{14}B_{6}$
$Fe_{20}Ni_{60}P_{14}B_{6}$
$Ni_{80}P_{14}B_{6}$

$Fe_{20}Ni_{60}P_{14}B_{6}$
$Fe_{30}Ni_{50}P_{14}B_{6}$
$Fe_{40}Ni_{40}P_{14}B_{6}$
$Fe_{60}Ni_{20}P_{14}B_{6}$
$Fe_{70}Ni_{10}P_{14}B_{6}$
$Fe_{10}Ni_{70}B_{19}Si_{2}$
$Fe_{13}Ni_{67}B_{19}Si_{1}$
$Fe_{16}Ni_{64}B_{19}Si_{1}$
$Fe_{20}Ni_{60}B_{20}$
$Fe_{40}Ni_{40}B_{20}$
$Fe_{80}B_{20}$ (2605)

$Fe_{40}Ni_{40}P_{14}B_{6}$ (2826)
$Fe_{32}Ni_{36}Cr_{14}P_{12}B_{6}$ (2826A)
$Fe_{29}Ni_{49}P_{14}B_{6}Si_{2}$ (2826B)
$Fe_{80}B_{20}$ (2605)
$Ti_{50}Be_{40}Zr_{10}$ (2204)
$Co_{76}P_{24}$
$Ni_{74}P_{26}$
$Co_{92}Sm_{8}$

$Fe_{80}B_{20}$
$Fe_{60}Ni_{20}B_{20}$
$Fe_{50}Ni_{30}B_{20}$
$Fe_{40}Ni_{40}B_{20}$
$Fe_{30}Ni_{50}B_{20}$
$Fe_{20}Ni_{60}B_{20}$

$Fe_{80}P_{14}B_{6}$
$Fe_{60}Ni_{20}P_{14}B_{6}$
$Fe_{40}Ni_{40}P_{14}B_{6}$
$Fe_{30}Ni_{50}P_{14}B_{6}$
$Fe_{20}Ni_{60}P_{14}B_{6}$
$Fe_{10}Ni_{70}P_{14}B_{6}$
$Ni_{80}P_{14}B_{6}$

$Fe_{80}B_{20}$ (2605)
$Fe_{78}Mo_{2}B_{20}$ (2605A)
$Fe_{80}P_{16}C_{3}B_{1}$ (2615)
$Fe_{40}Ni_{40}P_{14}B_{6}$ (2826)
$Fe_{40}Ni_{38}B_{18}Mo_{4}$ (2826MB)
$Fe_{32}Ni_{36}Cr_{14}P_{12}B_{6}$ (2826A)
$Fe_{29}Ni_{49}P_{14}B_{6}Si_{2}$ (2826B)
$Fe_{40}Ni_{40}P_{14}B_{6}$ (2826)
$Fe_{32}Ni_{36}Cr_{14}P_{12}B_{6}$ (2826A)

$Fe_{29}Ni_{49}P_{14}B_{6}$ (2826B)
$Fe_{80}B_{20}$ (2605)
$Fe_{78}Mo_{2}B_{20}$ (2605A)
$Ti_{50}Be_{40}Zr_{10}$ (2204)

$Fe_{40}Ni_{40}P_{14}B_{6}$ (2826)
$Fe_{32}Ni_{36}Cr_{14}P_{12}B_{6}$ (2826A)
$Fe_{80}B_{20}$ (2605)
$Fe_{78}Mo_{2}B_{20}$ (2605A)
$Fe_{82}Si_{6}B_{12}$ (2605S)
$Cu_{50}Zr_{50}$

$(Ni_{50}Pd_{50})_{73.5}P_{26.5}$
$(Ni_{50}Pd_{50})_{72.5}P_{27.5}$

$(Ni_{20}Pt_{80})_{75}P_{25}$
$(Ni_{30}Pt_{70})_{75}P_{25}$
$(Ni_{40}Pt_{60})_{75}P_{25}$
$(Ni_{45}Pt_{55})_{75}P_{25}$
$(Ni_{50}Pt_{50})_{75}P_{25}$
$(Ni_{60}Pt_{40})_{75}P_{25}$

$(Pd_{90}Cu_{10})_{80}P_{20}$
$(Pd_{50}Cu_{50})_{80}P_{20}$

$Fe_{80}B_{20}$
$Fe_{60}Ni_{20}B_{20}$
$Fe_{50}Ni_{30}B_{20}$
$Fe_{40}Ni_{40}B_{20}$
$Fe_{30}Ni_{50}B_{20}$
$Fe_{70}Ni_{10}P_{14}B_{6}$
$Fe_{60}Ni_{20}P_{14}B_{6}$
$Fe_{40}Ni_{40}P_{14}B_{6}$
$Fe_{30}Ni_{50}P_{14}B_{6}$
$Fe_{20}Ni_{60}P_{14}B_{6}$
$Fe_{10}Ni_{70}P_{14}B_{6}$

$Fe_{40}Ni_{40}P_{14}B_{6}$ (2826)
$Fe_{29}Ni_{49}P_{14}B_{6}Si_{2}$ (2826B)

$Fe_{40}Ni_{40}P_{14}B_{6}$ (2826)
$Fe_{29}Ni_{49}P_{14}B_{6}Si_{2}$ (2826B)

$Fe_{80}P_{13}C_{7}$

$Fe_{90}Au_{10}$

$Fe_{88}B_{12}$
$Fe_{82}B_{18}$
$Fe_{68}B_{32}$
$Fe_{63}B_{37}$

$Fe_{85.7}P_{14.3}$
$Fe_{85.5}P_{14.5}$
$Fe_{84.1}P_{15.9}$
$Fe_{84.0}P_{16.0}$

$Fe_{82.0}P_{18.0}$
$Fe_{81.6}P_{18.4}$
$Fe_{80.6}P_{19.4}$
$Fe_{78.4}P_{21.6}$

$Ni_{84.5}P_{15.5}$
$Ni_{83.42}P_{16.58}$
$Ni_{82.5}P_{17.5}$
$Ni_{81.84}P_{18.16}$
$Ni_{79.9}P_{20.1}$

$Ni_{85}P_{15}$
$Ni_{80}P_{20}$
$Ni_{76}P_{24}$
$Ni_{74.5}P_{25.5}$

$Nd_{65}Co_{35}$
$Sm_{65}Co_{35}$
$Tb_{65}Co_{35}$
$Dy_{65}Co_{35}$
$Er_{65}Co_{35}$

$(Ni_{0.2}Pt_{0.8})_{75}P_{25}$
$(Ni_{0.3}Pt_{0.7})_{75}P_{25}$
$(Ni_{0.4}Pt_{0.6})_{75}P_{25}$
$(Ni_{0.45}Pt_{0.55})_{75}P_{25}$
$(Ni_{0.5}Pt_{0.5})_{75}P_{25}$
$(Ni_{0.60}Pt_{0.40})_{75}P_{25}$

$(Ni_{0.5}Pd_{0.5})_{85}P_{15}$
$(Ni_{0.5}Pd_{0.5})_{84}P_{16}$
$(Ni_{0.5}Pd_{0.5})_{83}P_{17}$
$(Ni_{0.5}Pd_{0.5})_{82}P_{18}$
$(Ni_{0.5}Pd_{0.5})_{80}P_{20}$
$(Ni_{0.5}Pd_{0.5})_{77}P_{23}$
$(Ni_{0.5}Pd_{0.5})_{76}P_{24}$
$(Ni_{0.5}Pd_{0.5})_{75}P_{25}$
$(Ni_{0.5}Pd_{0.5})_{73.5}P_{26.5}$
$(Ni_{0.5}Pd_{0.5})_{72.5}P_{27.5}$

$(Pd_{0.9}Cu_{0.1})_{80}P_{20}$
$(Pd_{0.5}Cu_{0.5})_{80}P_{20}$

$Ag_{50}Cu_{50}$
$Ag_{45}Cu_{45}Mg_{10}$
$Ag_{40}Cu_{40}Mg_{20}$
$Ag_{35}Cu_{35}Mg_{30}$
$Ag_{30}Cu_{30}Mg_{40}$
$Ag_{25}Cu_{25}Mg_{50}$
$Ag_{20}Cu_{20}Mg_{60}$
$Ag_{15}Cu_{15}Mg_{70}$
$Ag_{10}Cu_{10}Mg_{80}$

$Ag_{47.5}Cu_{47.5}Al_{5}$
$Ag_{45}Cu_{45}Al_{10}$
$Ag_{42.5}Cu_{42.5}Al_{15}$
$Ag_{40}Cu_{40}Al_{20}$
$Ag_{37.5}Cu_{37.5}Al_{25}$
$Ag_{35}Cu_{35}Al_{30}$
$Ag_{30}Cu_{30}Al_{40}$
$Ag_{25}Cu_{25}Al_{50}$
$Ag_{20}Cu_{20}Al_{60}$
$Ag_{15}Cu_{15}Al_{70}$

$Ag_{47.5}Cu_{47.5}Ge_{5}$
$Ag_{45}Cu_{45}Ge_{10}$
$Ag_{42.5}Cu_{42.5}Ge_{15}$
$Ag_{40}Cu_{40}Ge_{20}$
$Ag_{37.5}Cu_{37.5}Ge_{25}$
$Ag_{35}Cu_{35}Ge_{30}$
$Ag_{32.5}Cu_{32.5}Ge_{35}$
$Ag_{30}Cu_{30}Ge_{40}$
$Ag_{25}Cu_{25}Ge_{50}$
$Ag_{20}Cu_{20}Ge_{60}$
$Ag_{10}Cu_{10}Ge_{80}$

$(Mo_{0.6}Ru_{0.4})_{90}B_{10}$
$(Mo_{0.6}Ru_{0.4})_{88}B_{12}$
$(Mo_{0.6}Ru_{0.4})_{86}B_{14}$
$(Mo_{0.6}Ru_{0.4})_{84}B_{16}$
$(Mo_{0.6}Ru_{0.4})_{82}B_{18}$
$(Mo_{0.6}Ru_{0.4})_{80}B_{20}$
$(Mo_{0.6}Ru_{0.4})_{78}B_{22}$
$(Mo_{0.6}Ru_{0.4})_{76}B_{24}$
$(Mo_{0.6}Ru_{0.4})_{82}Si_{18}$
$(Mo_{0.6}Ru_{0.4})_{80}Si_{20}$
$(Mo_{0.6}Ru_{0.4})_{78}Si_{22}$
$(Mo_{0.6}Ru_{0.4})_{76}Si_{24}$
$(Mo_{0.6}Ru_{0.4})_{74}Si_{26}$
$(Mo_{0.6}Ru_{0.4})_{72}Si_{28}$
$(Mo_{0.6}Ru_{0.4})_{70}Si_{30}$
$(Mo_{0.6}Ru_{0.4})_{84}P_{16}$
$(Mo_{0.6}Ru_{0.4})_{80}P_{20}$
$(W_{0.5}Ru_{0.5})_{80}B_{20}$
$(W_{0.5}Ru_{0.5})_{80}P_{20}$

$Zr_{40}Cu_{60}$

$Pd_{37}Zr_{63}$, $Pd_{33}Z$
$Pd_{30}Zr_{70}$

$Zr_{70}Co_{30}$
$Zr_{70}Ni_{30}$
$Zr_{70}Pd_{30}$
$Zr_{65}Cu_{35}$
$Zr_{50}Cu_{50}$
$Zr_{35}Cu_{65}$

$Zr_{78}Ni_{22}$
$Zr_{76}Ni_{24}$
$Zr_{72}Ni_{28}$
$Zr_{66.4}Ni_{33.3}$
$Zr_{65}Ni_{35}$
$Zr_{62}Ni_{38}$
$Zr_{33}Ni_{67}$
$Zr_{81}Co_{19}$
$Zr_{80}Co_{20}$
$Zr_{78}Co_{22}$
$Zr_{75}Co_{25}$
$Zr_{66.7}Co_{33.3}$
$Zr_{64.5}Co_{35.5}$
$Zr_{73}Cu_{27}$
$Zr_{76.7}Cu_{33.3}$
$Zr_{40}Cu_{60}$
$Zr_{76}Fe_{24}$

$Zr_{40}Cu_{60}$
$Zr_{50}Cu_{50}$
$Zr_{55}Cu_{45}$
$Zr_{72.5}Cu_{27.5}$

$Ag_{71}Pb_{29}$
$Au_{50}Pb_{50}$

$Cu_{80}Sn_{20}$
$Cu_{61}Sn_{39}$
$Cu_{50}Sn_{50}$
$Cu_{40}Sn_{60}$
$Cu_{25}Sn_{75}$
$Cu_{16}Sn_{84}$
$Cu_{10}Sn_{90}$
$Au_{41}Ge_{59}$
$Ag_{15}Bi_{85}$

$Au_{80}Sn_{20}$
$Au_{60}Sn_{40}$
$Au_{50}Sn_{50}$
$Au_{25}Sn_{75}$
$Au_{20}Sn_{80}$
$Au_{15}Sn_{85}$
$Au_{10}Sn_{90}$
$Au_{50}Ga_{50}$
$Au_{50}In_{50}$

$Cu_{60}Al_{40}$
$Cu_{49}Al_{51}$
$Cu_{41}Al_{59}$
$Cu_{29}Al_{71}$

$Ti_{34}Cu_{66}$
$Ti_{45}Cu_{55}$
$Ti_{57}Cu_{43}$
$Hf_{40}Cu_{60}$
$Zr_{36}Ni_{64}$
$Zr_{63}Ni_{37}$
$Zr_{76}Ni_{24}$
$Ni_{66}Nb_{34}$
$Ni_{65}Nb_{35}$
$Ni_{60}Nb_{40}$

$Ni_{36}Zr_{64}$
$Ni_{40}Zr_{60}$
$Ni_{60}Zr_{40}$
$Ni_{65}Zr_{35}$

$La_{84}Ga_{16}$
$La_{80}Ga_{20}$
$La_{78}Ga_{22}$
$La_{76}Ga_{24}$
$La_{72}Ga_{28}$

$Ti_{50}Be_{40}Zr_{10}$

$Co_{15}Zr_{85}$
$Co_{19}Zr_{81}$
$Co_{20}Zr_{80}$
$Co_{22}Zr_{78}$
$Co_{25}Zr_{75}$
$Co_{28}Zr_{72}$
$Co_{30}Zr_{70}$
$Co_{33}Zr_{67}$
$Co_{35}Zr_{65}$
$Co_{40}Zr_{60}$
$Co_{45}Zr_{55}$
$Co_{47}Zr_{53}$
liquid Co

$Fe_{20}Zr_{80}$
$Fe_{24}Zr_{76}$
$Fe_{25}Zr_{75}$
$Fe_{27}Zr_{73}$
$Fe_{28}Zr_{72}$
$Fe_{29}Zr_{71}$
$Fe_{33}Zr_{67}$
$Fe_{35}Zr_{65}$
$Fe_{38}Zr_{62}$
$Fe_{40}Zr_{60}$
$Fe_{43}Zr_{57}$

$Fe_{90}Zr_{10}$
$Fe_{91}Zr_{9}$
liquid Fe*)

liquid La
$La_{82}Al_{18}$
$La_{80}Al_{20}$
$La_{78}Al_{22}$

$Ni_{67}Zr_{33}$
$Ni_{69}Zr_{31}$
$Ni_{70}Zr_{30}$
$Ni_{92}Zr_{8}$
liquid Ni*)

$Ni_{24}Ti_{76}$
$Ni_{30}Ti_{70}$
$Ni_{35}Ti_{65}$
$Ni_{40}Ti_{60}$
$Ni_{58}Ti_{42}$
$Ni_{62}Ti_{38}$
$Ni_{64}Ti_{36}$

$Ni_{89}Hf_{11}$

$Ni_{75}Nb_{25}$
$Ni_{65}Nb_{35}$
$Ni_{61}Nb_{40}$
$Ni_{60}Nb_{40}$
$Ni_{50}Nb_{50}$
$Ni_{46}Nb_{54}$
$Ni_{40}Nb_{60}$
$Ni_{36}Nb_{64}$

$Be_{40}Zr_{10}Ti_{40}$

$Cu_{50}Hf_{50}$
$Cu_{60}Hf_{40}$
$Cu_{70}Hf_{30}$
$Cu_{90}Hf_{10}$

$Au_{30}Zr_{70}$
$Pd_{30}Zr_{70}$
$Pt_{30}Zr_{70}$

$Ni_{20}Zr_{80}$
$Ni_{22}Zr_{78}$
$Ni_{24}Zr_{76}$
$Ni_{25}Zr_{75}$
$Ni_{29}Zr_{71}$
$Ni_{30}Zr_{70}$
$Ni_{33}Zr_{67}$
$Ni_{36}Zr_{64}$
$Ni_{40}Zr_{60}$
$Ni_{45}Zr_{55}$
$Ni_{50}Zr_{50}$
$Ni_{55}Zr_{45}$
$Ni_{60}Zr_{40}$
$Ni_{63}Zr_{37}$
$Ni_{64}Zr_{36}$
$Ni_{65}Zr_{35}$

liquid Zr*)
$Cu_{25}Zr_{75}$
$Cu_{27.5}Zr_{72.5}$
$Cu_{30}Zr_{70}$
$Cu_{35}Zr_{65}$
$Cu_{40}Zr_{60}$
$Cu_{45}Zr_{55}$
$Cu_{50}Zr_{50}$
$Cu_{55}Zr_{45}$
$Cu_{60}Zr_{40}$
$Cu_{65}Zr_{35}$
$Cu_{70}Zr_{30}$
$Cu_{90}Zr_{10}$
liquid Cu*)

liquid Ti*)

$Cu_{35}Ti_{65}$
$Cu_{40}Ti_{60}$
$Cu_{43}Ti_{57}$
$Cu_{47}Ti_{53}$
$Cu_{50}Ti_{50}$
$Cu_{53}Ti_{47}$
$Cu_{55}Ti_{45}$
$Cu_{60}Ti_{40}$
$Cu_{66}Ti_{34}$
$Cu_{68}Ti_{32}$
$Cu_{74}Ti_{26}$

$La_{76}Al_{24}$
$La_{75}Al_{25}$
$La_{73}Al_{27}$
$La_{72}Al_{28}$
$La_{70}Al_{30}$
$La_{68}Al_{32}$
$La_{66}Al_{34}$
liquid Al*)

$La_{85}Ga_{15}$
$La_{84}Ga_{16}$
$La_{83}Ga_{17}$
$La_{82}Ga_{18}$
$La_{80}Ga_{20}$
$La_{78}Ga_{22}$
$La_{76}Ga_{24}$
$La_{75}Ga_{25}$
$La_{72}Ga_{28}$
$La_{70}Ga_{30}$

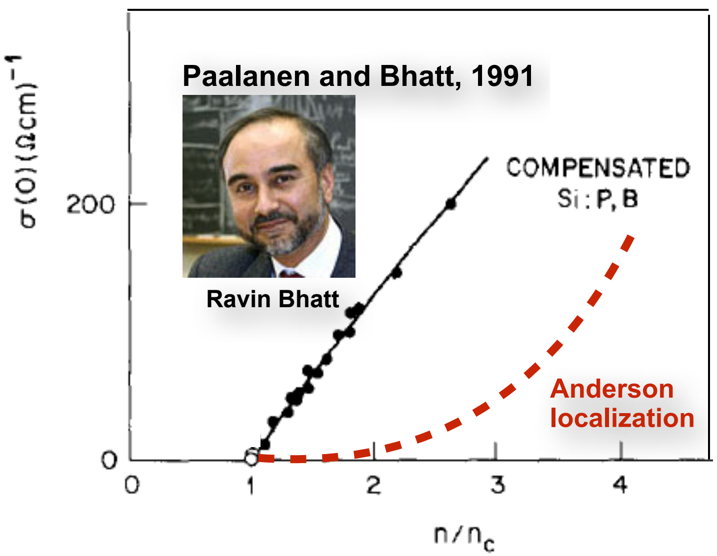
$Ca_{80}Al_{20}$
$Ca_{75}Al_{25}$
$Ca_{70}Al_{30}$
$Ca_{67}Al_{33}$
$Ca_{60}Al_{40}$
$Ca_{55}Al_{45}$

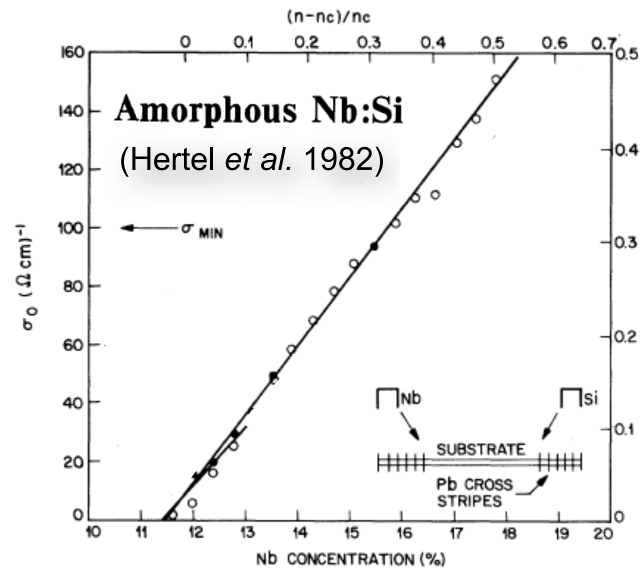
$Pd_{83.5}Si_{16.5}$
$Pd_{82}Si_{18}$
$Pd_{80}Si_{20}$
$Pd_{79}Si_{21}$
$Pd_{78}Si_{22}$
$Pd_{77.5}Si_{16.5}Cu_{6}$
$Pd_{80}Ge_{20}$
$Pd_{77.5}Ge_{22.5}$

$Ni_{85.7}P_{14.3}$
$Ni_{85}P_{15}$
$Ni_{82.8}P_{17.2}$
$Ni_{82.5}P_{17.5}$
$Ni_{81.9}P_{18.1}$
$Ni_{80.4}P_{19.6}$
$Ni_{80}P_{20}$
$Ni_{79.8}P_{20.2}$
$Ni_{78.7}P_{21.3}$
$Ni_{78.1}P_{21.9}$
$Ni_{76}P_{24}$
$Ni_{75.7}P_{24.3}$
$Ni_{74.5}P_{25.5}$

$(Ni_{50}Pd_{50})_{85}P_{15}$
$(Ni_{50}Pd_{50})_{84}P_{16}$
$(Ni_{50}Pd_{50})_{83}P_{17}$
$(Ni_{50}Pd_{50})_{82}P_{18}$
$(Ni_{50}Pd_{50})_{80}P_{20}$
$(Ni_{50}Pd_{50})_{77}P_{23}$
$(Ni_{50}Pd_{50})_{76}P_{24}$
$(Ni_{50}Pd_{50})_{75}P_{25}$

Experimental puzzles II: Robust Low-T Transport





Landau-like (?) critical behavior: $\sigma \sim (n-n_c)^{\mu}$ $\boxed{\mu = 1}$

Huge range of parameters: $(n-n_c)/n_c \sim O(1)$

~~Anderson localization:~~ $\mu = 1.6 >> 1$

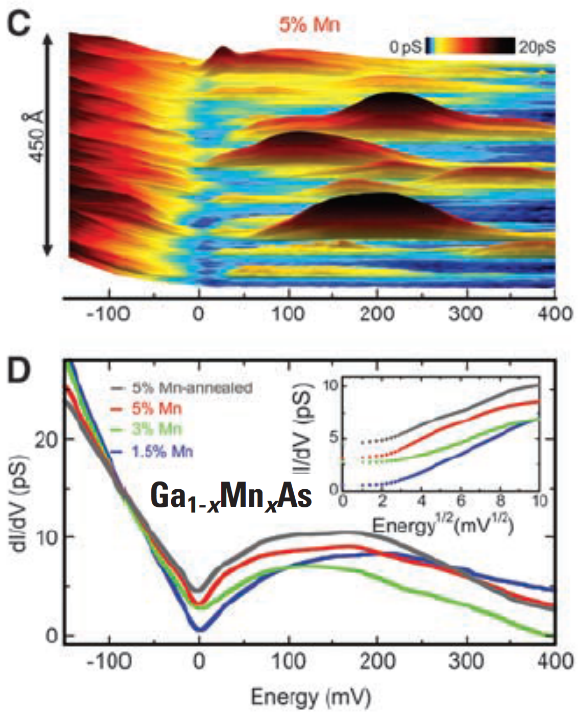
~~Percolation:~~ $\mu = 2 >> 1$

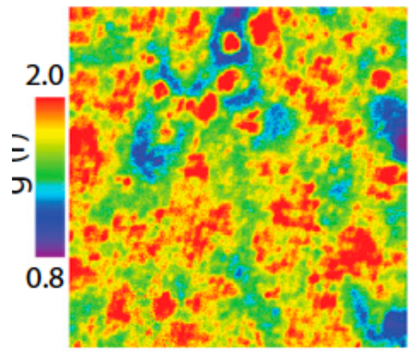
Experimental puzzles III: Pseudogap at criticality (STM)

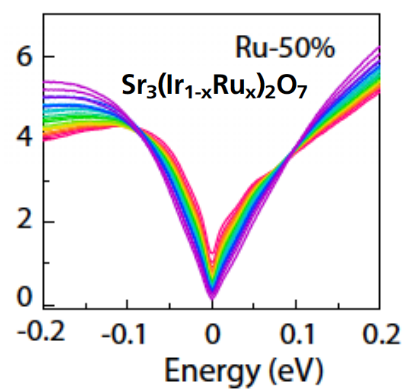
Ali Yazdani
SCIENCE, 2010

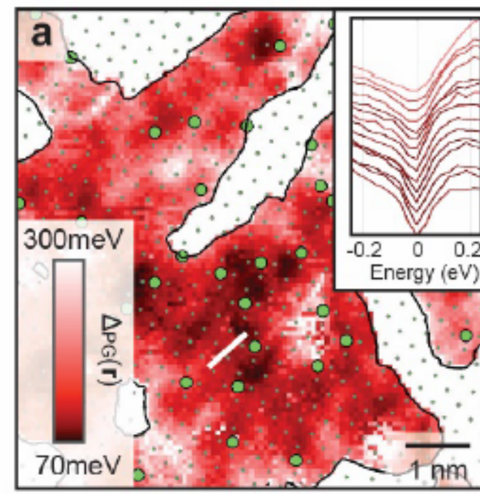
Vidya Madhavan
PNAS, 2018

Milan Allen
Nat. Phys. 2016









$(Sr_{1-x}La_x)_2IrO_4$

STM: LDOS statistics and spatial correlations at criticality?

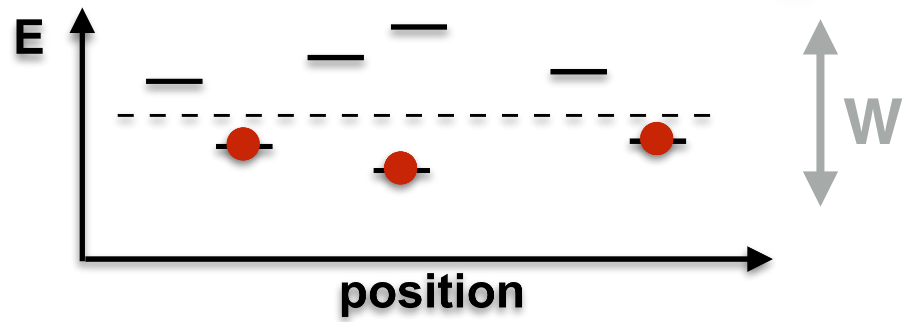
Strong disorder in a Deformable “Medium”

Early ideas: Anderson, Nature 1972

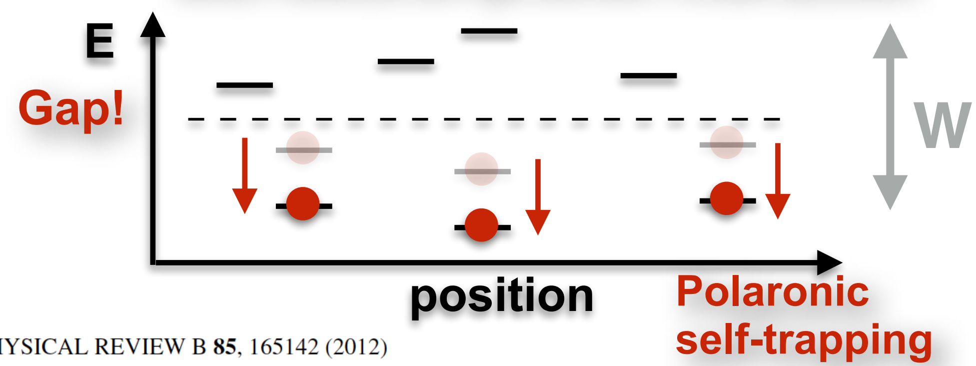
Effect of Franck–Condon Displacements on the Mobility Edge and the Energy Gap in Disordered Materials

IT has long been known that deep impurity centres in insulators, such as fluorescence centres, exhibit large Franck–Condon effects, involving energies of a few eV and many phonons, because the lattice nearby displaces considerably when the centre is occupied by an electron. This contrasts with the typical phonon self energy in a metal which is, by Migdal's theorem[1], confined to energies $\lesssim \hbar\omega_D$ and results entirely from virtual displacements. It has not, as far as I know, been realized previously that there is both a quantitative and qualitative difference between these two cases. An electron in a shallow donor state is shifted in energy by a finite displacement—but not very much—so qualitatively it resembles the deep state but quantitatively it is nearly free. The qualitative change from virtual to real atom displacements arises when the wave function becomes localized, because that is when recoil-free phonon emission is possible.

noninteracting



with electron-phonon interaction



PHYSICAL REVIEW B **85**, 165142 (2012)

Strong electron-lattice coupling as the mechanism behind charge density wave transformations in transition-metal dichalcogenides

Lev P. Gor'kov*
National High Magnetic Field Laboratory, Florida State University, Tallahassee, Florida 32310, USA

Similar also for: (1) Magnetic polarons, (2) Electronic polarons (Efros-Shklovskii),…??

Toy Model: Anderson-Holstein Model

PRL 118, 036602 (2017) PHYSICAL REVIEW LETTERS week ending 20 JANUARY 2017

Disorder-Driven Metal-Insulator Transitions in Deformable Lattices

Domenico Di Sante,[1,2] Simone Fratini,[3] Vladimir Dobrosavljević,[4] and Sergio Ciuchi[5,6]

$$H = H_{el} + H_{ph} + \boxed{H_{e-ph}} + \boxed{H_{dis}}$$

Einstein phonons, frequency $\boldsymbol{\omega_0}$

tight-binding half bandwidth **D** half-filled band

$$H_{e-ph} = g \sum_i c_i^\dagger c_i (a_i + a_i^\dagger)$$

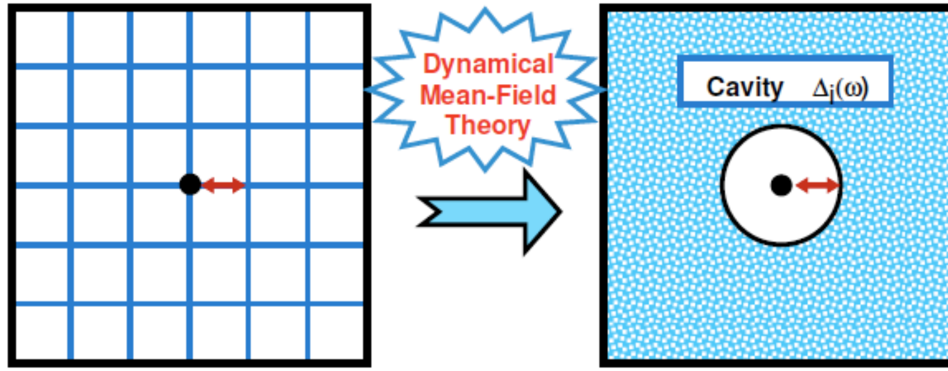
$E_{pot}=g^2/\omega_0$ $\lambda = 2E_P/D$

boson (any?)

Clean limit: polaron effects at (un-physically) strong coupling ~ O(1)

Local Perspective: Dynamical Mean-Field Theory

Gabi Kotliar



Non-perturbative treatment of interactions and disorder (Anderson-Yu, 1984)

Small polaron formation at strong disorder *(Millis et al.)*

TWO VERSIONS:

1. **TMT-DMFT** (with Anderson localization)

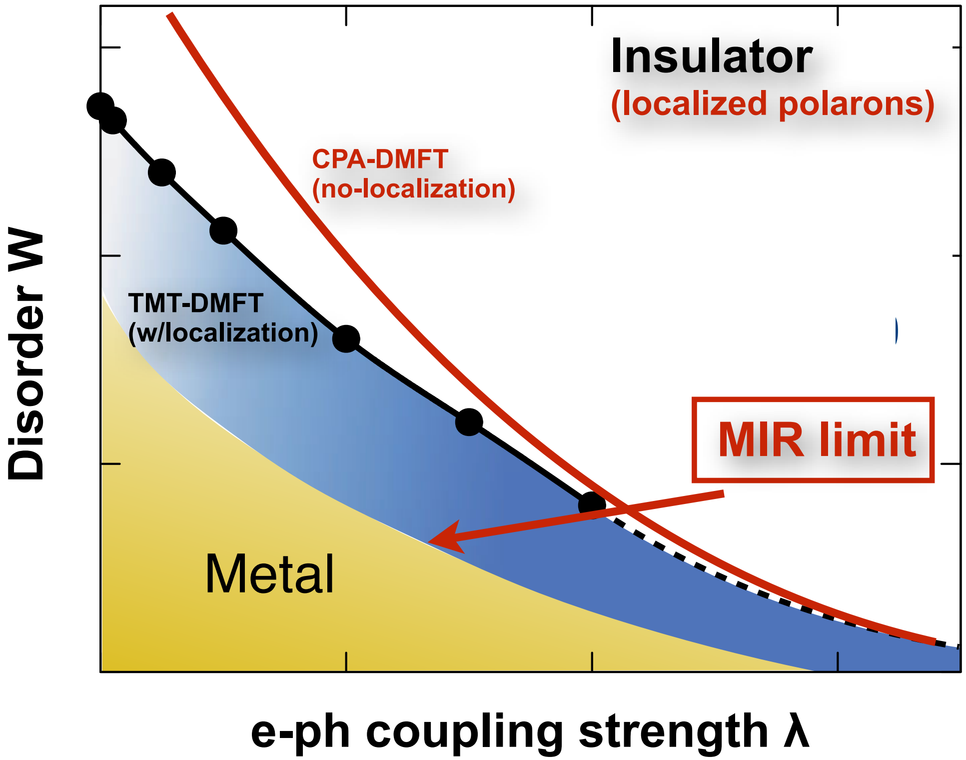
2. **CPA-DMFT** (no Anderson localization)

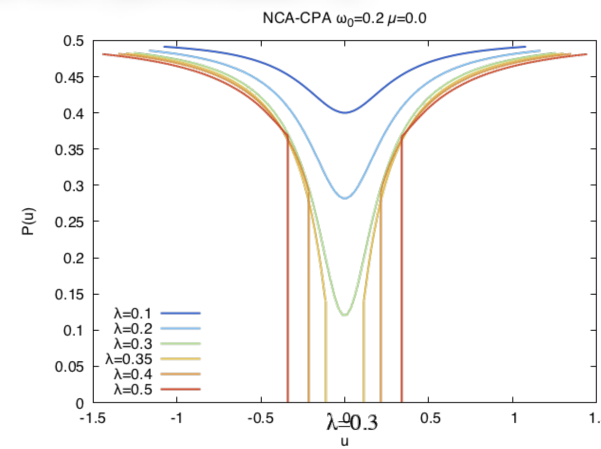
Exact in d=inf., new saddle-point for field theory

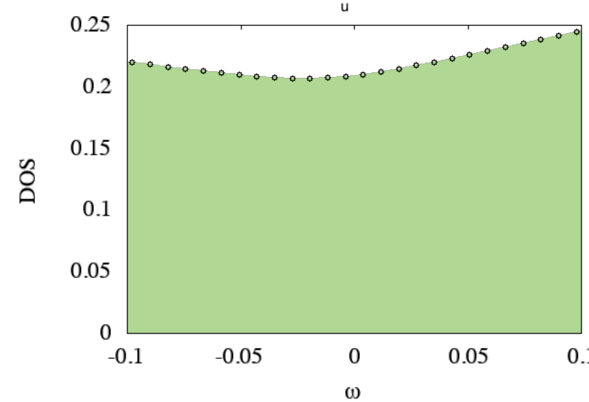
Anderson-Holstein Transition: Disorder-Induced Polarons

Qualitatively different critical behavior: gap opening at Fermi energy

Mechanism "survives" removing localization in d=inf. (CPA-DMFT)







Pseudogap opens in disorder distribution $\rho_c(\omega) \sim \omega^{1/3}$ $\sigma(T=0) \sim (W_c - W)$

Universal behavior at arbitrary band-filling, <u>finite compressibility</u> $\boxed{\mu = 1}$

npj Quantum Materials

www.nature.com/npjquantmats

npj Quantum Materials (2018)3:44 ; doi:10.1038/s41535-018-0119-y

ARTICLE OPEN

The origin of Mooij correlations in disordered metals

Sergio Ciuchi[1,2], Domenico Di Sante[3], Vladimir Dobrosavljević[4] and Simone Fratini[5]

A15 - experiment (Dynes)

CPA-DMFT theory

Breakdown of Mathiessen's rule:

$$\Sigma = \Sigma_{el} + G_{el}^{-1} \left\langle \hat{G}_{el}^{\xi} \, \hat{\Sigma}_{in}^{\xi} \, \hat{G}_{el}^{\xi} \right\rangle G_{el}^{-1}$$

MIR limit

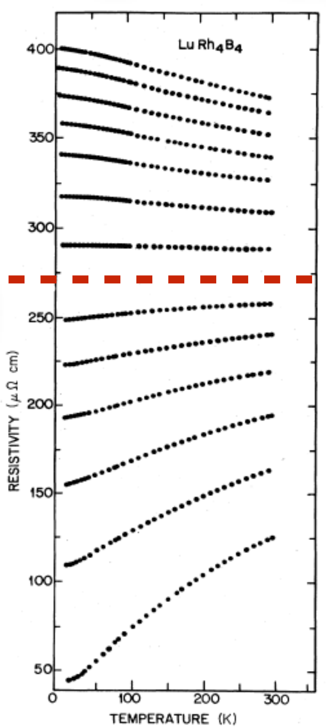
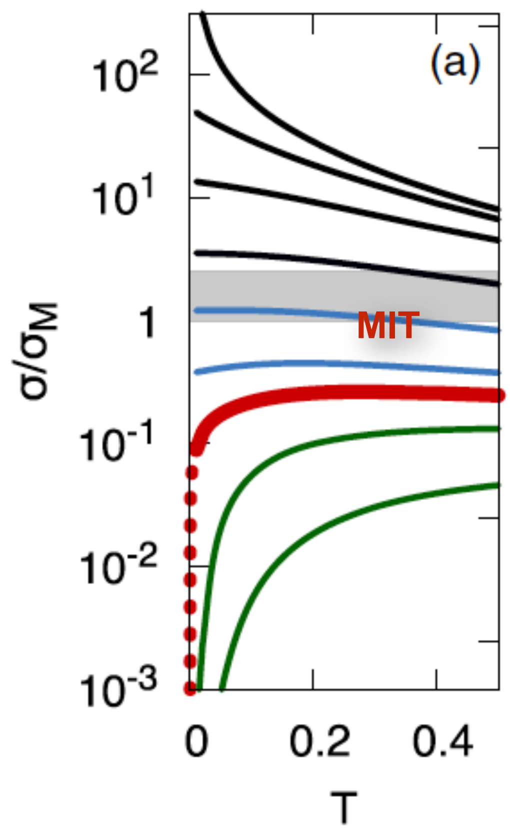
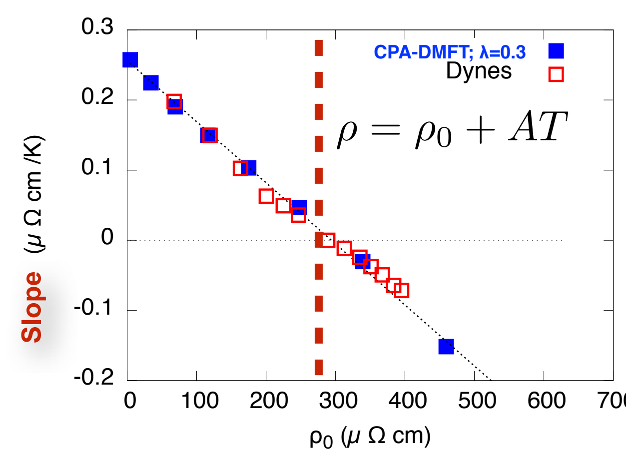


FIG. 20. Resistivity as a function of temperature for $LuRh_4B_4$ at various damage levels. The numbers represent the α-particle dose in units of $10^{16}/cm^2$. From Dynes, Rowell, and Schmidt (1981).





"Separatrix"= MIR Limit
$k_F\ell \sim O(1)$

Beyond DMFT: Field Theory Formulation

$$Z = \int \prod_i D\Psi_i^* D\Psi_i Dx_i D\varepsilon_i P(\varepsilon_i) Dt_{ij} P(t_{ij}), e^{-S[\Psi_i^*,\Psi_i,X_i]}$$

Wegner's "gauge invariant" model of disorder: $< t_{ij}^2 >= t^2/z$

$$S_o[\Psi_i^*, \Psi_i, \varepsilon_i] = \sum_{\alpha=1}^{n} \sum_{ij} \int_o^\beta d\tau \, \Psi_{i,\alpha}^*(\tau)[(\partial_\tau - \varepsilon_i \mu)\delta_{ij} - t_{ij}]\Psi_{j,\alpha}(\tau).$$

$$S_{int}[\Psi_i^*, \Psi_i, X_i] = g \sum_{\alpha=1}^{n} \sum_{i} \int_o^\beta d\tau \, \Psi_{i,\alpha}^*(\tau)\Psi_{i,\alpha}(\tau) X_{i,\alpha}(\tau)$$

$$S_{hop} = \frac{1}{2z} t^2 \sum_{\alpha,\beta} \sum_{ij} \int_o^\beta d\tau \int_o^\beta d\tau' \, \Psi_{i,\alpha}^*(\tau)\Psi_{i,\beta}(\tau')\Psi_{j,\beta}^*(\tau')\Psi_{j,\alpha}(\tau)$$

Introduce *Q*-fields: $Q_i^{\alpha\beta}(\omega_1, \omega_2) = \frac{1}{z} \sum_j f_{ij} \Psi_{j,\alpha}^*(\omega_1)\Psi_{j,\beta}(\omega_2)$

$$S_{hop}[Q] = -\frac{t^2}{2} \sum_{\alpha\beta} \sum_{ij} \sum_{\omega_1\omega_2} K_{ij} Q_i^{\alpha\beta}(\omega_1,\omega_2) Q_j^{\alpha\beta}(\omega_1,\omega_2)$$

$$S_{loc}[Q] = -\sum_i \ln \int d\varepsilon_i P(\varepsilon_i) D\Psi_i^* D\Psi_i DX_i \exp\{-S_{eff}[\Psi_i^*, \Psi_i, \varepsilon_i, Q_i, X_i]\}$$

$$S_{eff}[\Psi_i^*, \Psi_i, \varepsilon_i, Q_i, X_i] = -\sum_{\alpha\beta} \sum_{ij} \sum_{\omega_1\omega_2} \Psi_{i,\alpha}^*(\omega_1)[(i\omega_1 + \mu - \varepsilon_i)\delta_{\alpha\beta}\delta_{\omega_1\omega_2} \boxed{- t^2 Q_i^{\alpha\beta}(\omega_1,\omega_2)]} \Psi_{i,\beta}(\omega_2) + S_{int}[\Psi_i^*, \Psi_i, X_i] + S_{ph}[X_i]$$

local effective action (DMFT)

(fluctuating) cavity field

DMFT as Saddle-Point

CPA- DMFT as saddle-point: (exact in d=inf):

$$\frac{\delta S[Q]}{\delta Q_i^{\alpha\beta}(\omega_1,\omega_2)} = 0 \qquad [Q_i^{\alpha\beta}(\omega,\omega')]|_{SP} = \delta_{\alpha\beta}\delta_{\omega\omega'}Q_{SP}(\omega)$$

$$Q_{SP}(\omega) = \overline{G}(\omega) = \int d\varepsilon_i P(\varepsilon_i) G_i(\omega) \qquad G_i(\omega) =< \Psi^*_{i,\alpha}(\omega)\Psi_{i,\alpha}(\omega) >_{S_{eff}[\Psi^*_i,\Psi_i,\varepsilon_i,Q_{SP},X_i]}$$

Local density of states as order-parameter

Fluctuations about saddle-point: LG functional:

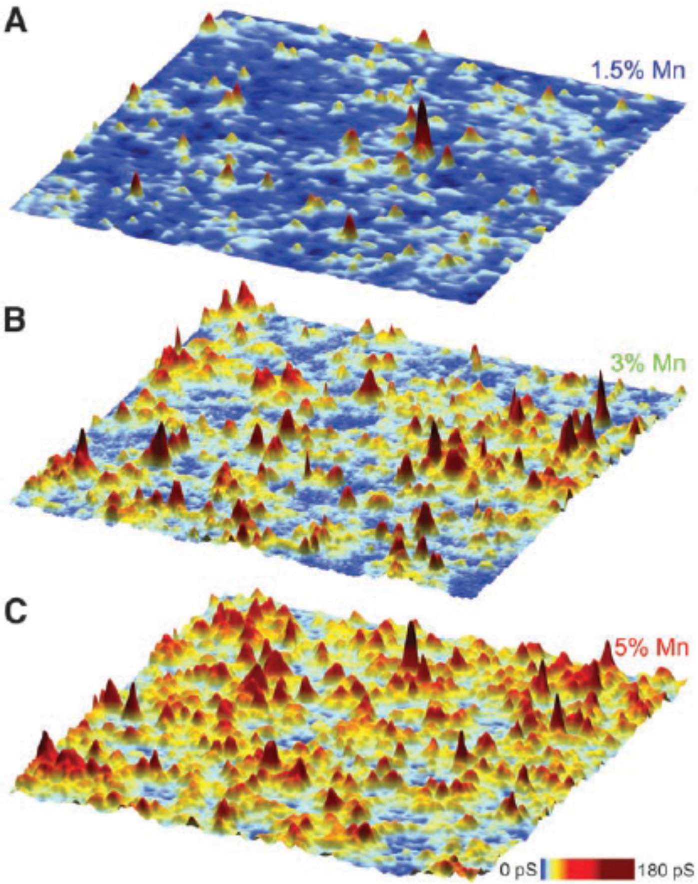
$$S[G] = \int dR \sum_{\omega_n} \left[-i\omega_n G(R,\omega_n) + \frac{1}{2} G(R,\omega_n)(r - \nabla^2) G(R,\omega_n) + \frac{1}{4} u G^4(R,\omega_n) + \cdots \right]$$

Spatial correlations: $\chi(R,\omega) =< \rho_\omega(0)\rho_\omega(R) > \sim \frac{1}{R^{d-2}} \exp\{-R/\xi(\omega)\}$

$\xi \sim |r|^{-1/2}$ at $\omega = 0$ $\qquad$ $\boxed{\xi \sim \omega^{-1/3} \text{ at } r = 0}$

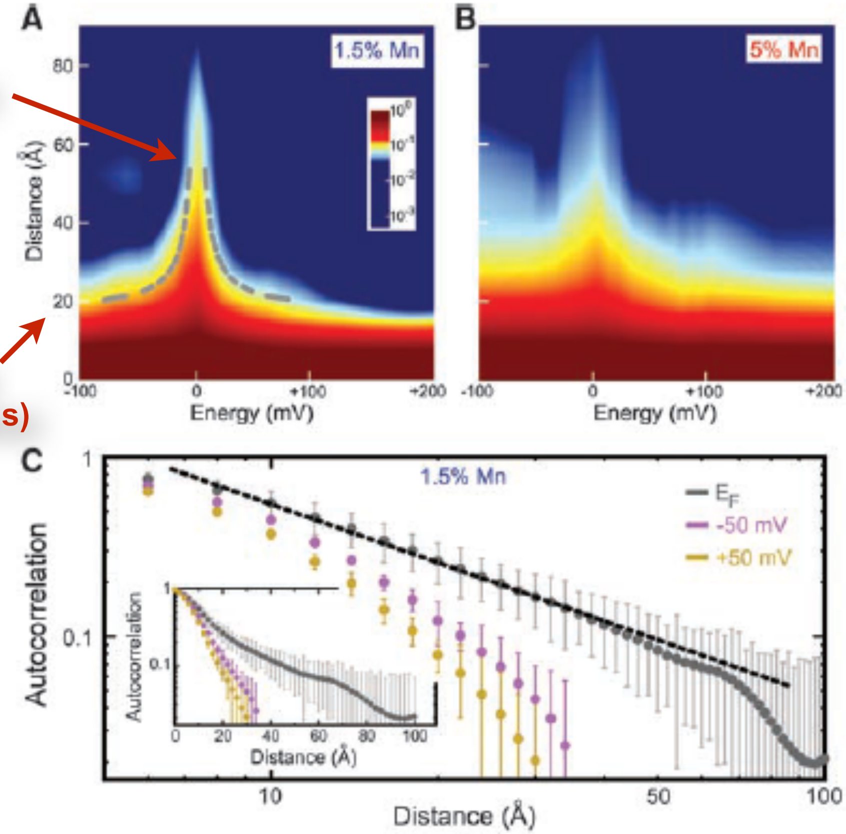
LDOS Spatial Fluctuations/Correlations

Ali Yazdani
SCIENCE, 2010



ζ_{max} ~ 3a

ζ_{min} ~ a
(Mg radius)



Agreement with LG theory: $\chi(R,\omega) = < \rho_\omega(0)\rho_\omega(R) >$ ~ *1/R* (d=3)

Probing only "modest" length scales a < ζ < 3a - Landau theory (mean-field) regime!

Perspectives and challenges

- Dominant disorder modification due to correlations (CPA+DMFT)
- Quantitative description Mooij correlation at MIR limit
- Robust low-T critical transport of Landau-like critical behavior!
- Landau-Ginzburg MIT theory explains pseudogap at criticality (STM)

- Other interaction effect: magnetic polarons, “electronic polarons”,…?
- Long-distance processes: “weak localization”, “interaction-localization”?
- Metastability and glassy behavior?
- Beyond Landau: ε - expansion