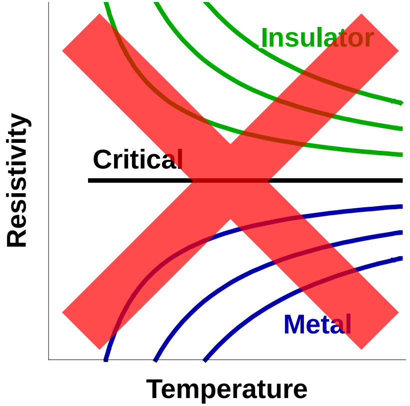
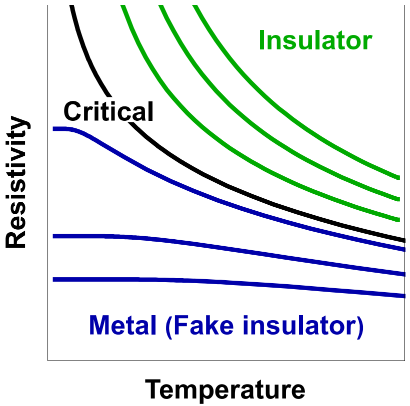
Fake Insulators

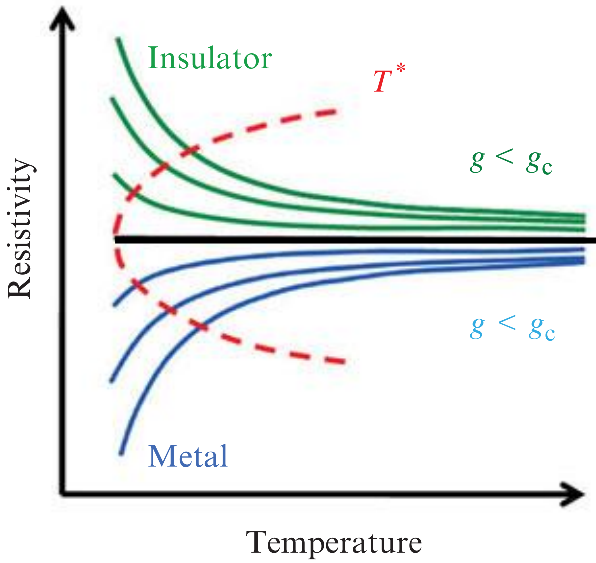




What are they, and how to spot them?

Louk Rademaker, SPICE, 26 May 2022

Metal vs. Insulator

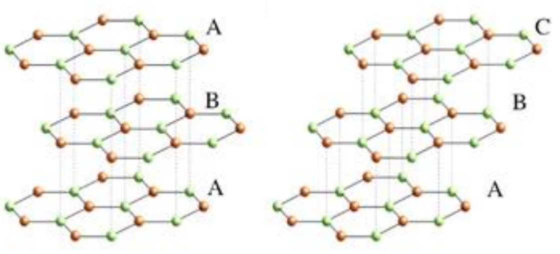


T=0		T>0
$\sigma = 0$	$\rho \sim e^{\Delta/T}$ *activated*	$d\rho/dT < 0$
Critical: constant	$\rho \sim \dfrac{h}{e^2}$ (25.8 kΩ)	
$\sigma > 0$	$\rho \sim \rho_0 + AT^2$ *Fermi liquid*	$d\rho/dT > 0$

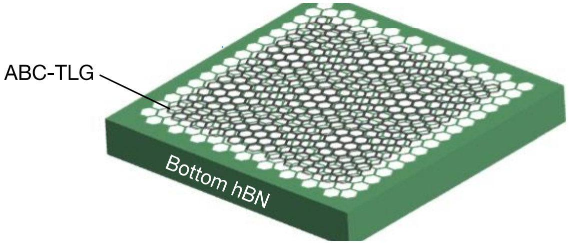
Ref: Dobrosavljevic et al., Conductor-Insulator Quantum Phase Transitions (CUP 2012)

ABC Trilayer Graphene on hBN

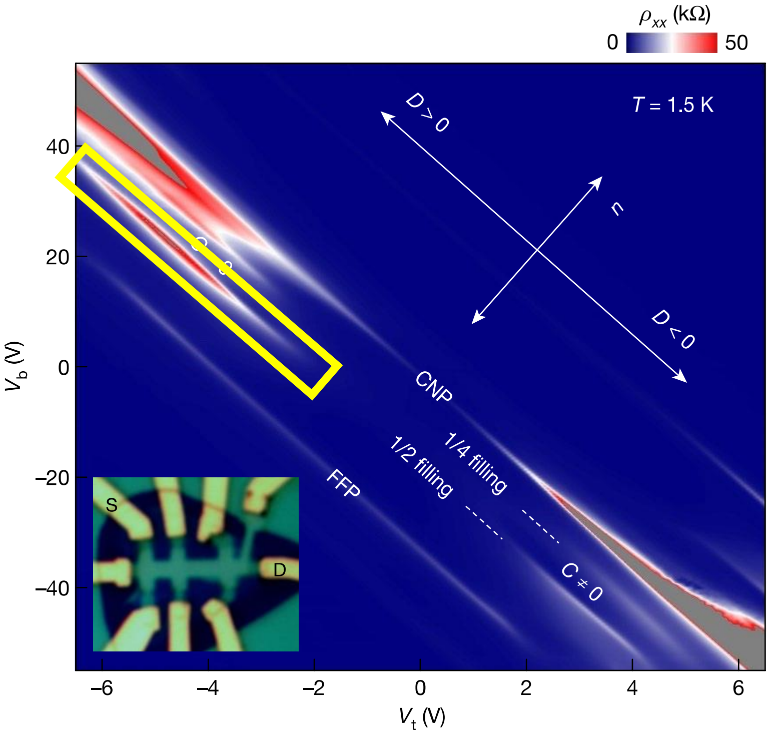
ABC trilayer graphene: **k³** dispersion



hBN substrate: **flat moiré bands**



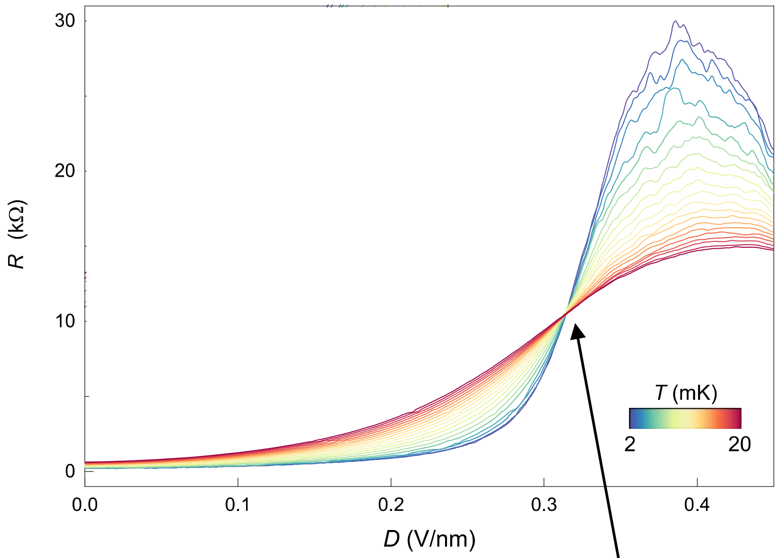
tune displacement field (**D**) & density (**n**)

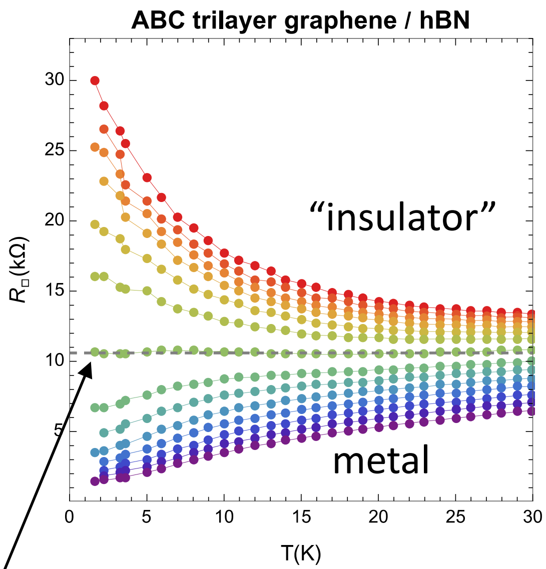


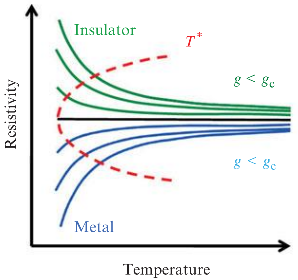
Ref: Chen Nature 2019; Chen Nature 2020

Metal-Insulator Transition

Resistivity as a function of **temperature** and **displacement field**





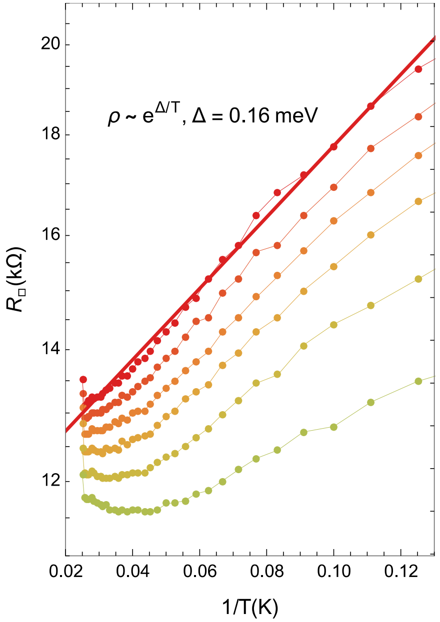


Critical D_c

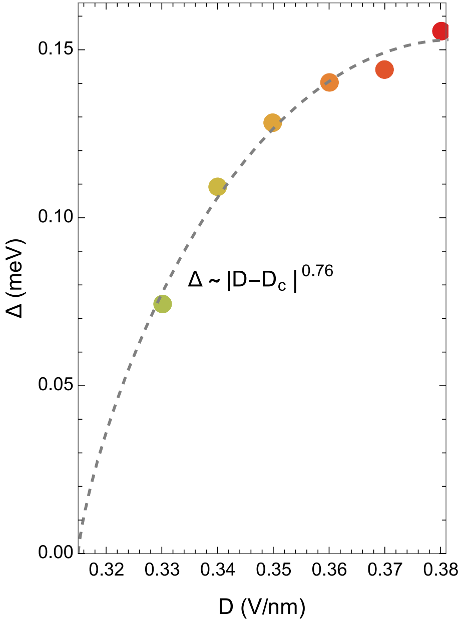
Ref: Chen, unpublished (2022)

Insulator side

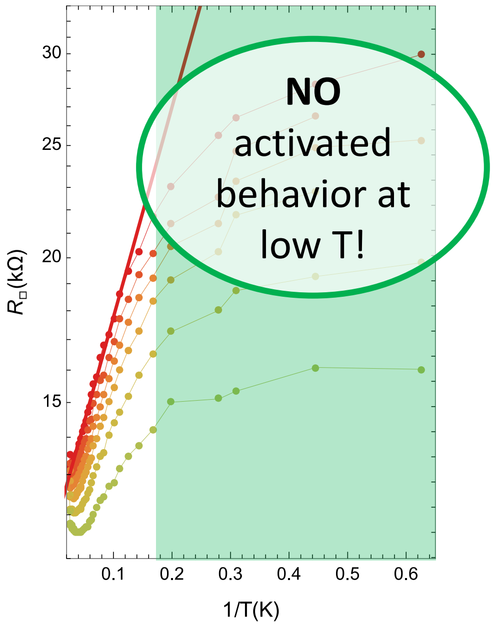
Arrhenius plot to extract insulating **gap**



Gap dependence on **displacement field**

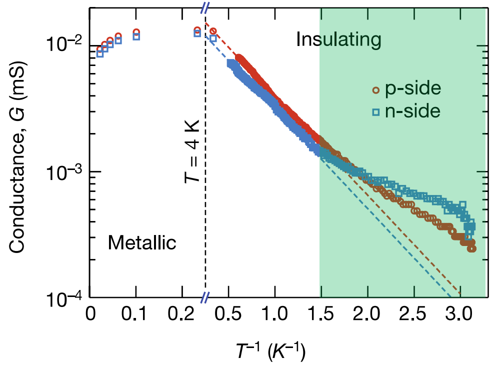


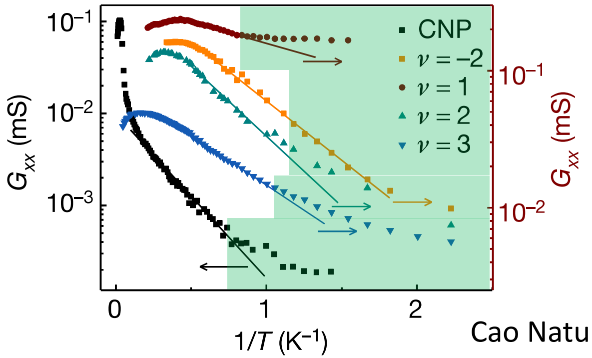
… but it's **WRONG!!**



Fake insulators are everywhere

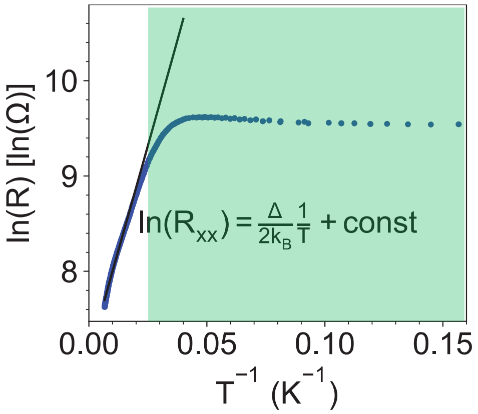
Twisted bilayer graphene





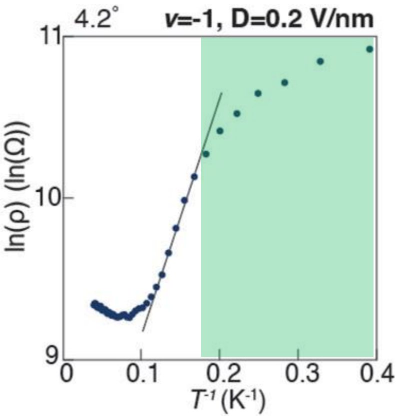
Cao Nature 2018; Lu Nature 2019

Twisted double bilayer graphene



Szentpéteri Nano Lett 2021

Twisted bilayer WSe2



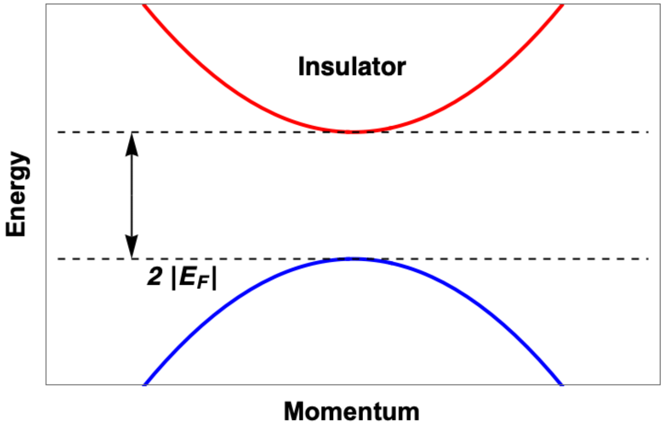
Ghiotto Nature 2021

Band theory of MIT: Kubo formula

Kubo formula:
(w/o vertex)

$$\sigma = \frac{\pi}{2}\sum_{\alpha=x,y}\int\frac{d^2p}{(2\pi)^2}\int dz\,\mathrm{Tr}\,[\underbrace{A(\mathbf{p},z)}_{\text{Density of states}}\overbrace{\mathbf{j}_\alpha(\mathbf{p})}^{\text{Current operator}}A(\mathbf{p},z')\mathbf{j}_\alpha(\mathbf{p})]\underbrace{\left(-\frac{\partial n_F(z)}{\partial z}\right)}_{\text{Fermi function}}$$

Apply to **band transition**:



Density of states $A(\mathbf{p},z) = \frac{1}{\pi}\frac{-\mathrm{Im}\Sigma(z)}{(z-\xi_\mathbf{p})^2 + (\mathrm{Im}\Sigma(z))^2}$

with **weak disorder** $-\mathrm{Im}\Sigma(z) = 1/\tau$

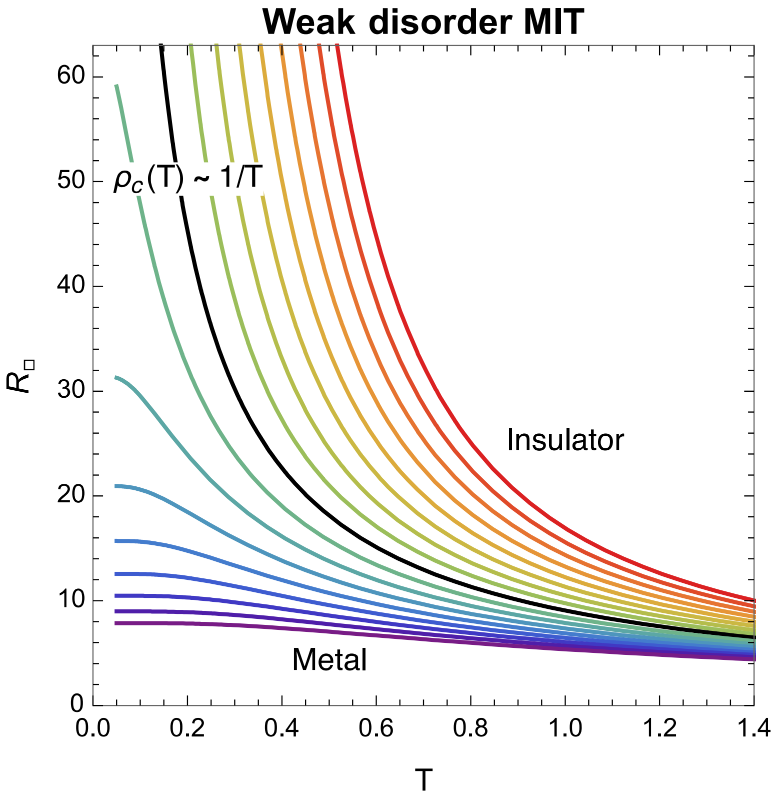
Drude formula $\boxed{\sigma(T=0) = \frac{e^2 n\tau}{m}}$

Particle density

Scattering rate

Effective mass

Band theory of MIT: Exact Solution



$$\sigma(T) = \frac{e^2\tau}{2\pi} T \left(\frac{E_F}{T} + \log\left[1 + e^{-\frac{E_F}{T}}\right]\right)$$

Insulator: activated

$$\rho \sim e^{|E_F|/T}$$

Critical: not constant

$$\rho_c \sim 1/T$$

Metal: negative slope!

$$d\rho/dT < 0$$

"fake insulator"

Band theory of MIT: Scaling

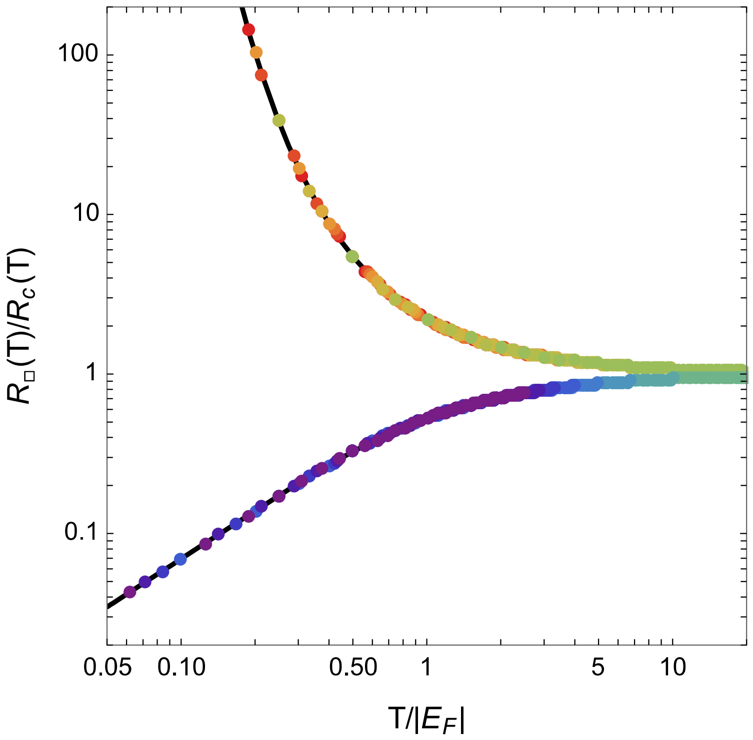
Exact solution

$$\sigma(T) = \frac{e^2\tau}{2\pi} T \left(\frac{E_F}{T} + \log\left[1 + e^{-\frac{E_F}{T}}\right] \right)$$

has **scaling form**

$$\sigma(T) = T^\alpha f\left(\frac{E_F}{T}\right)$$

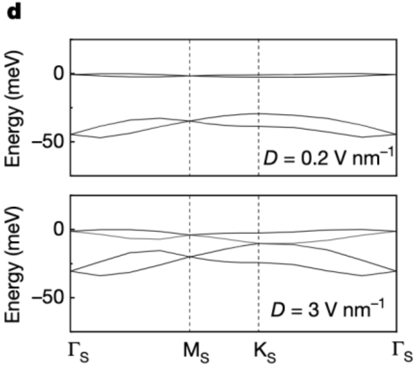
leading to **universal resistivity curves** close to the metal-insulator transition

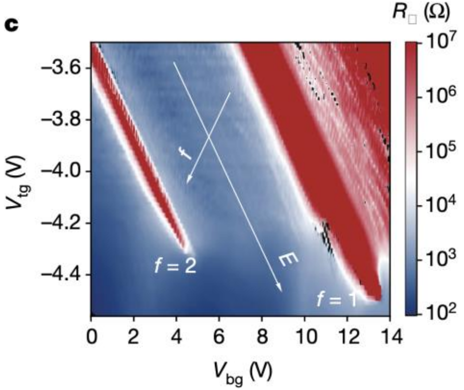


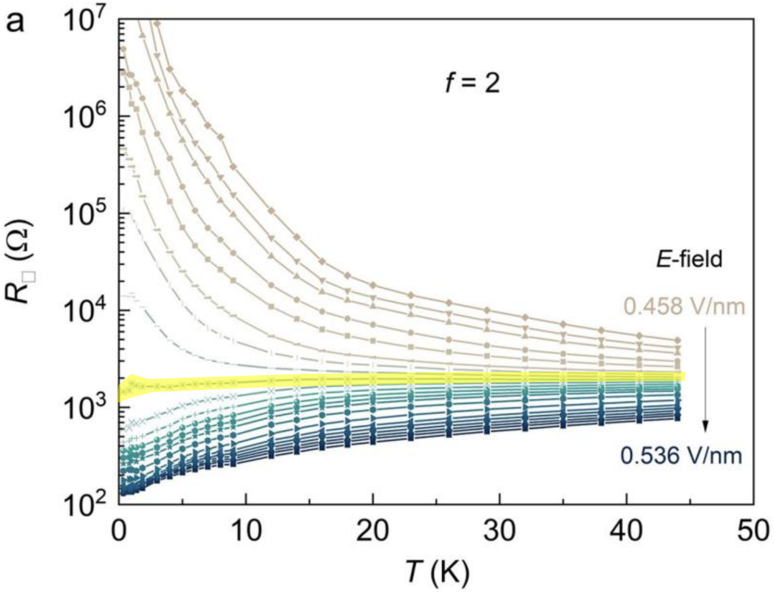
Application: $MoTe_2/WSe_2$

Aligned **TMD heterobilayer**
$MoTe_2/WSe_2$

Bandwidth can be tuned by **displacement** field





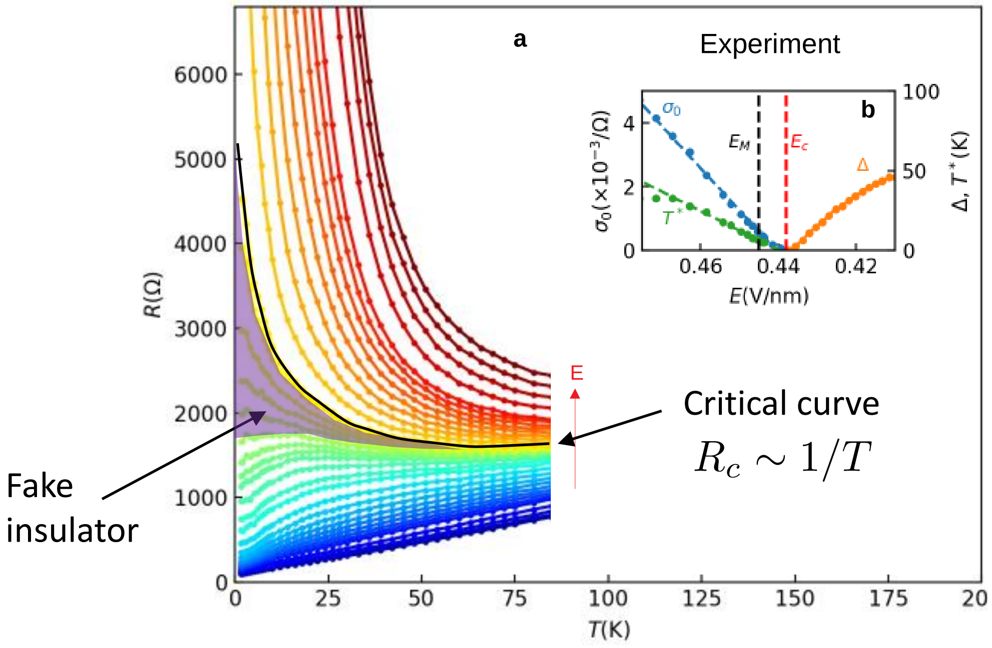


Extended Data Fig. 2 | Metal-insulator transition at $f = 2$. a, Temperature dependence of square resistance at varying electric fields at $f = 2$. MIT is observed near 0.49 V nm^{-1}. Compared to the MIT at $f = 1$, strong effective mass

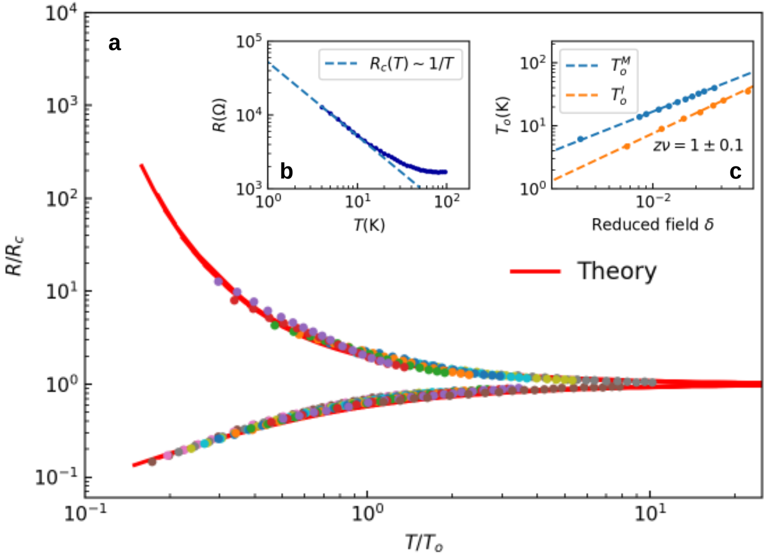
Ref: Li, Nature (2021)

Scaling in $MoTe_2/WSe_2$

Extrapolating the **zero-temperature conductivity** and **insulating gap** gives **critical D_c**

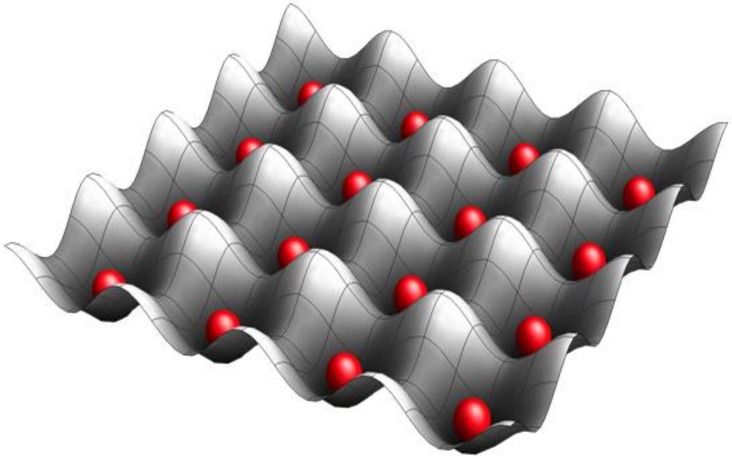


With **scaling** of the resistivity curves

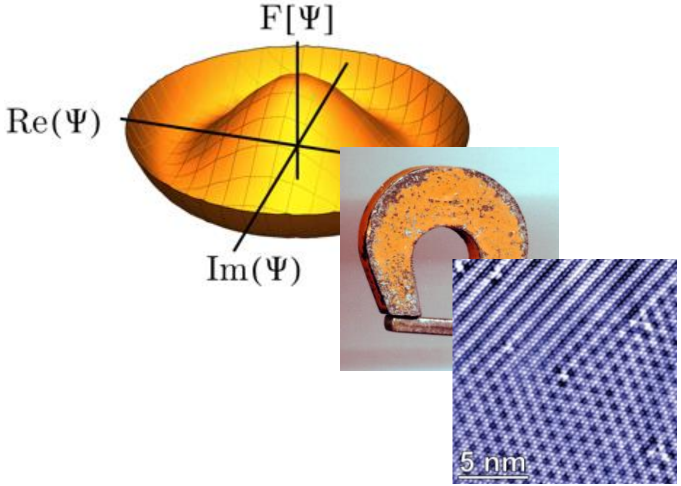


Ref: Li, Nature (2021); Tan, Tsang, Dobrosavljevic, arXiv:2112.11522 (2021)

Insulators at half-filling

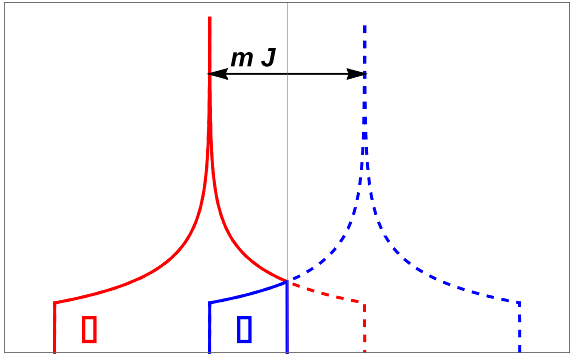


Mott insulator



Spontaneous Symmetry Breaking

Simplest example: Stoner ferromagnetism

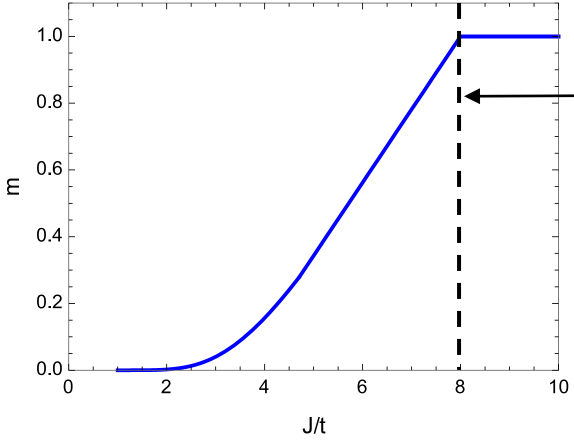


Ferromagnetic direct exchange $-J\vec{S}\cdot\vec{S}$

Spontaneous **polarization** shifts bands for up/down spins

Self-consistent Stoner **mean field theory**

$$m = n_\uparrow - n_\downarrow = \int d\omega A(\omega)\left[n_F(\omega - \tfrac{1}{2}mJ) - n_F(\omega + \tfrac{1}{2}mJ)\right]$$

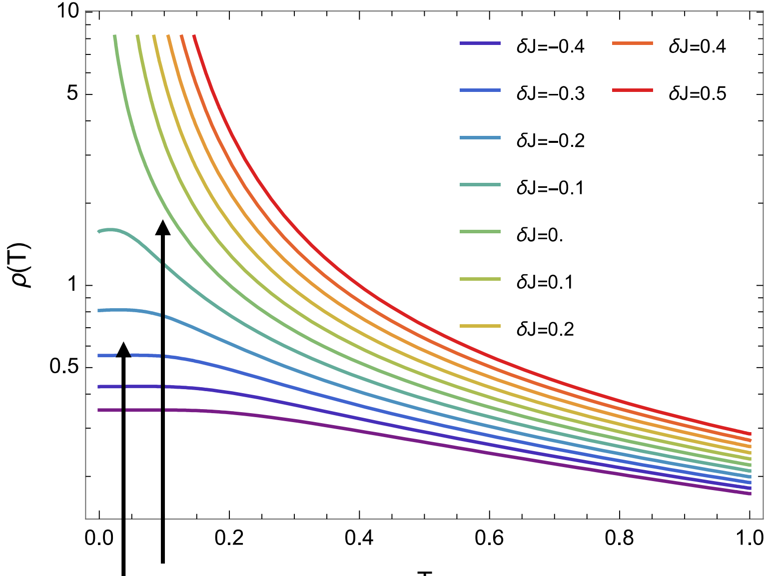


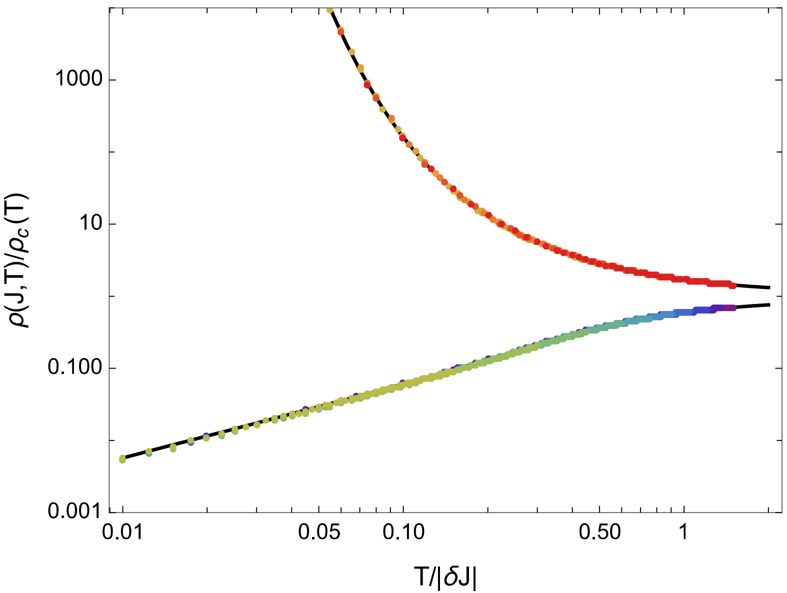
Metal-insulator transition when ***m J = W*** (bandwidth)

from *itinerant partially polarized* ferromagnet
to *insulating fully polarized* ferromagnet

Resistivity scaling near SSB-MIT

Resistivity close to “full polarization MIT” displays “**fake insulators**” and **scaling**





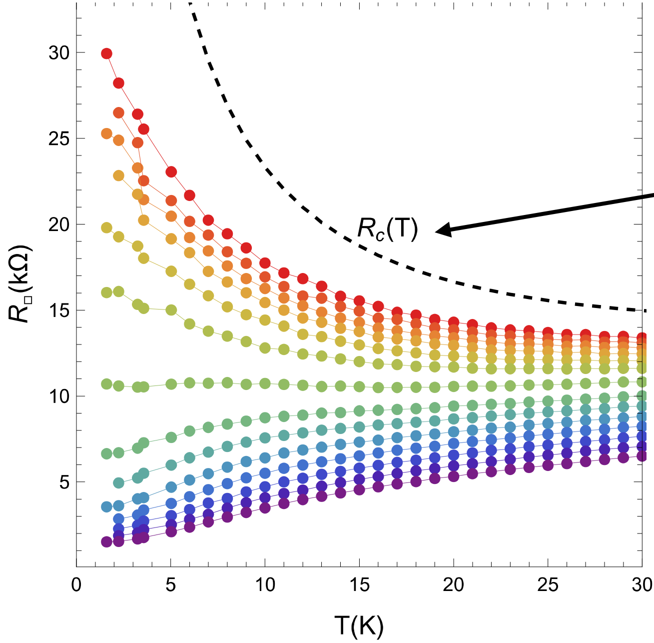
Critical curve $\rho(T) \sim 1/T$

Metallic region with $d\rho/dT < 0$

Application: ABC Trilayer Graphene

ABC trilayer graphene **is ferromagnetic:**

low-density two-dimensional electron systems[1–5]. Here we show that gate-tuned van Hove singularities in rhombohedral trilayer graphene[6] drive spontaneous ferromagnetic polarization of the electron system into one or more spin and valley flavours. Using capacitance and transport measurements, we observe a cascade of



Observed curves **never diverge** as 1/T

This is how a **critical curve** would look like

$$R_c(T) = \frac{a}{T} + b + cT$$

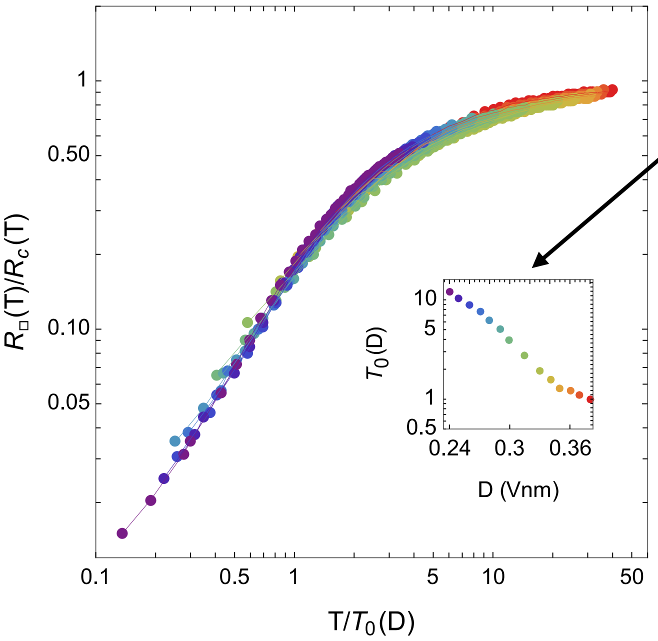
Hypothesis:

all resistivity curves correspond to the *metallic* side of a full polarization transition!

Ref: Zhou Nature 2021; Chen (unpublished 2022)

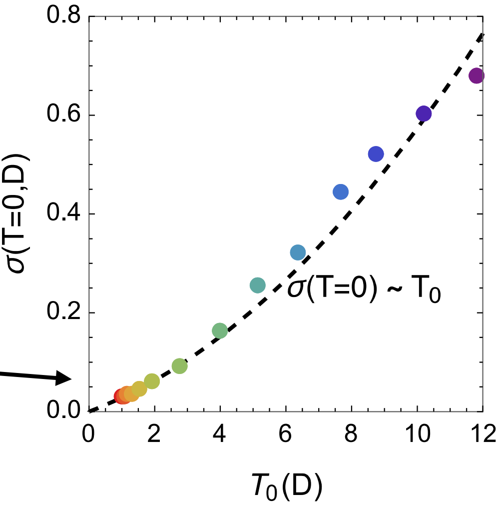
Scaling in ABC Trilayer Graphene

Indeed, **all** curves can be collapsed using a **scaling ansatz** of being **close to MIT**



“**Distance to MIT**” is measured by scaling parameter $\mathbf{T_0}$

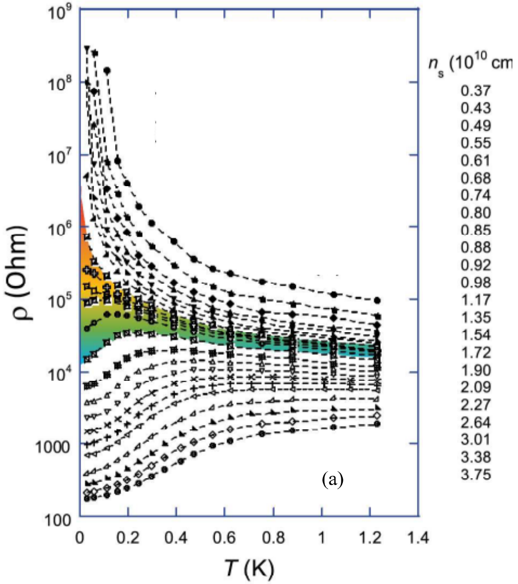
Zero T conductivity will vanish when T_0 vanishes



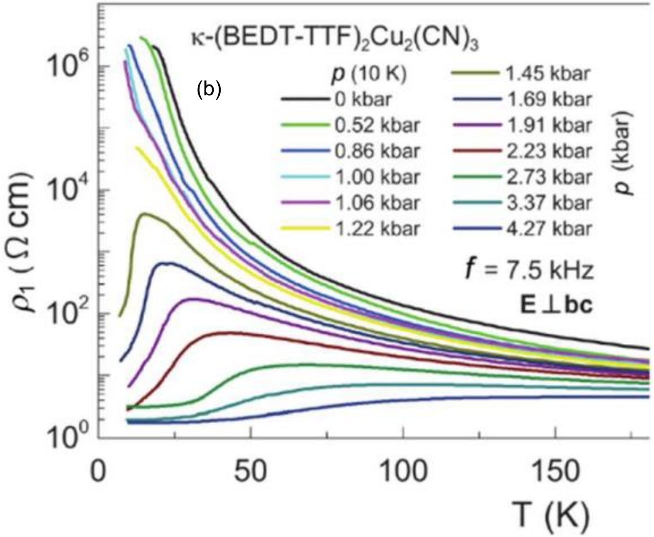
Ref: Chen (unpublished 2022)

Mott metal-insulator transition

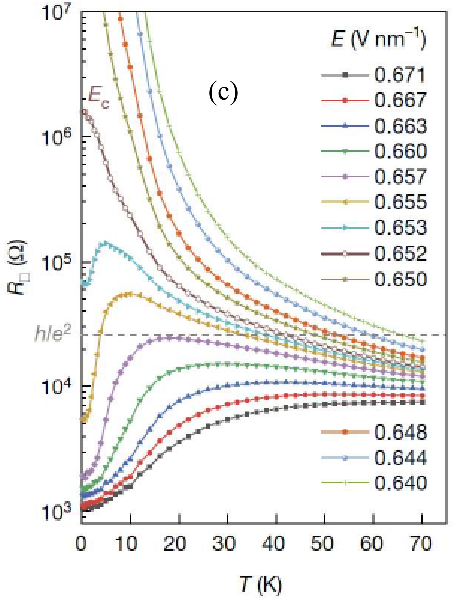
Dilute 2DEGs



Mott organics

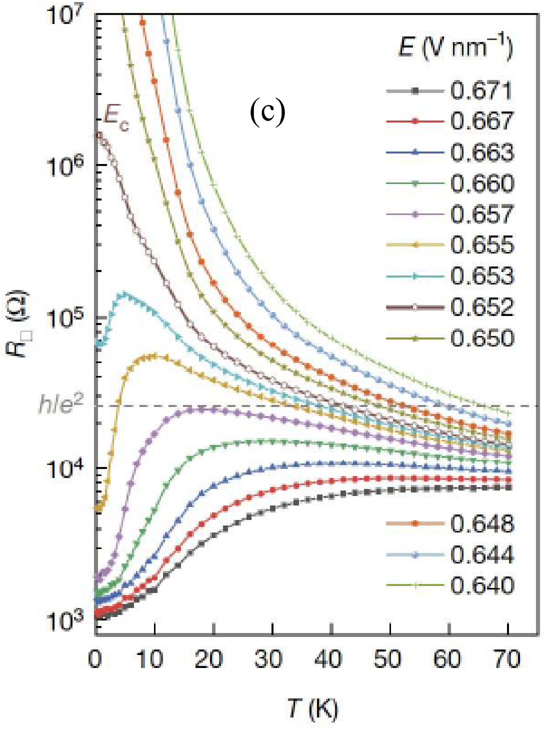


Half-filled $MoTe_2/WSe_2$



Ref: Tan, Dobrosavljevic, Rademaker, "*How to recognize the universal aspects of Mott criticality?*" (2022, soon on arXiv)

Mott metal-insulator transition in $MoTe_2/WSe_2$

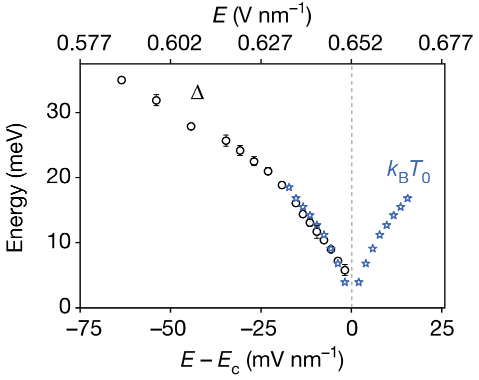


1. **Powerlaw** critical resistivity curve $R_c(T) \sim T^{-\alpha}$, α = 1.2

No "fake insulator" regime, but

2. Crossover scale $\mathbf{T_0}$ signaling end of Fermi liquid with a **resistivity maximum**

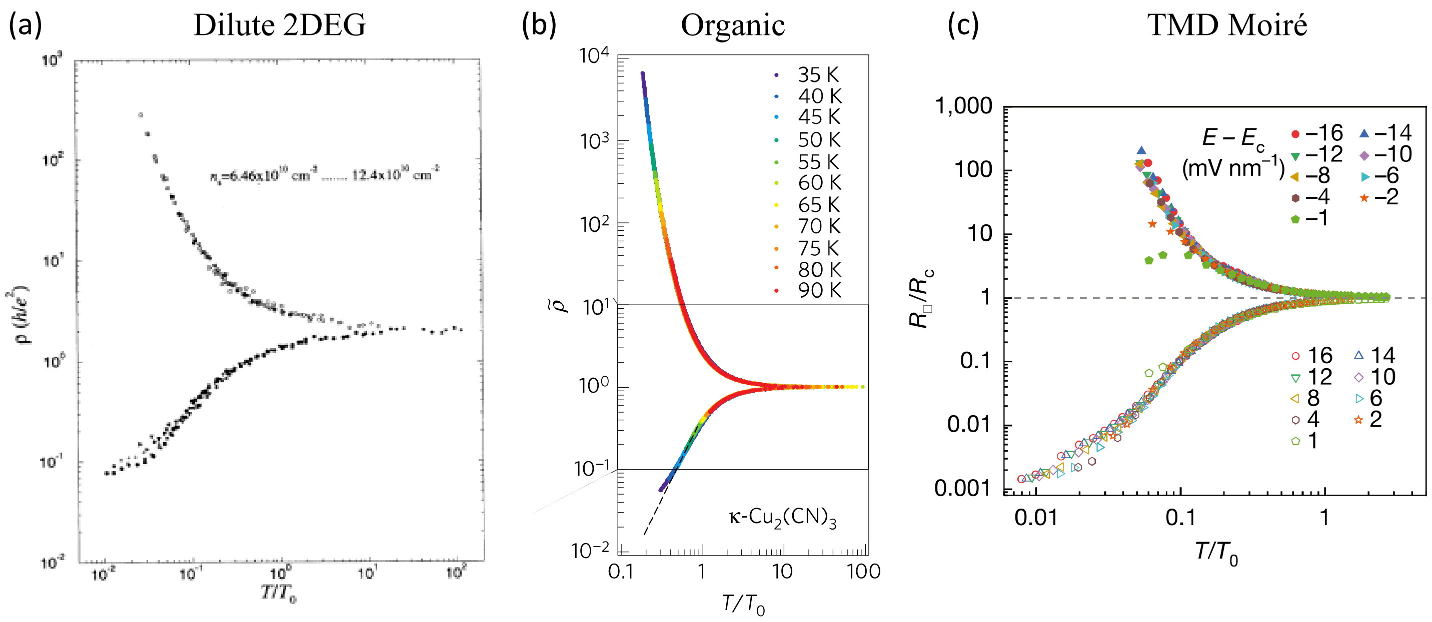
3. Insulator has continuous **vanishing gap Δ**



Ref: Tan, Dobrosavljevic, Rademaker (2022, soon on arXiv); Li Nature 2021

Scaling near Mott metal-insulator transition

4. Perfect **scaling** of insulating and metallic curves



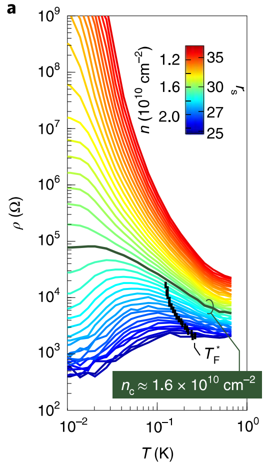
Ref: Tan, Dobrosavljevic, Rademaker, "*How to recognize the universal aspects of Mott criticality?*" (2022, soon on arXiv)

Theory of continuous Mott M-I-T

Theory predictions	2D Spinon theory	DMFT	Percolation theory
Transition Type	continuous	weakly first order (at $T < T_c \sim 0.01 T_F$)	first order
Δ	$\lvert g - g_c\rvert S^{\nu z}$, $\nu z = 0.67$	$\lvert U - U_{c1}\rvert^{\nu z}$, $\nu z \approx 0.8$	remains finite
m^*	weak: $\ln \frac{1}{\lvert g-g_c\rvert}$	strong: $\lvert U - U_{c2}\rvert^{-1}$	no divergence
$A/(m^*)^2$	?	constant (KW law obeyed)	diverges: $(x_o - x_c)^{-t}$; $t = s/m$
T_{FL}	$\lvert g - g_c\rvert^{2\nu}$	$\lvert U - U_{c2}\rvert$	$T^* \sim \lvert x_o - x_c\rvert$
T_{max}	$T_{max} = \infty$	$\lvert U - U_{c2}\rvert$	$T^* \sim \lvert x_o - x_c\rvert$

Ref: Tan, Dobrosavljevic, Rademaker, "*How to recognize the universal aspects of Mott criticality?*" (2022, soon on arXiv)

Caveats / Open problems



Fake fake insulators

Low temperature saturation in insulators can come from experimental issues

> quantum resistance value h/e^2. Data for $T \lesssim 20$ mK deviate from the systematic behaviour at higher temperatures, most likely due to the common issue of decoupling of the electron temperature from that of the immersion cryogen. The effect of an in-plane magnetic

Ref: Falson, Nat Mater 2022

Anderson insulation?

Standard theory predicts Anderson insulation at low density in presence of disorder in 2d

Phonons? Electron-electron interactions?

Still work to do in including further interactions mechanisms.

Are there different **universality classes** associated with scaling close to the MIT?

Collaborators

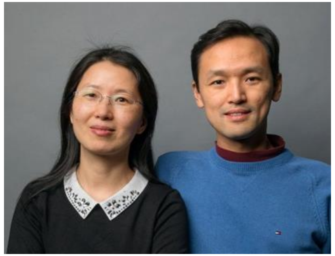
Theory collaborators:


Vlad Dobrosavljevic & Yuting Tan
Florida State U, USA

Simone Fratini
Grenoble, France

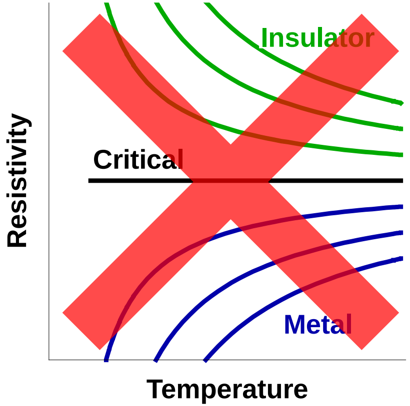
Experimental data from:

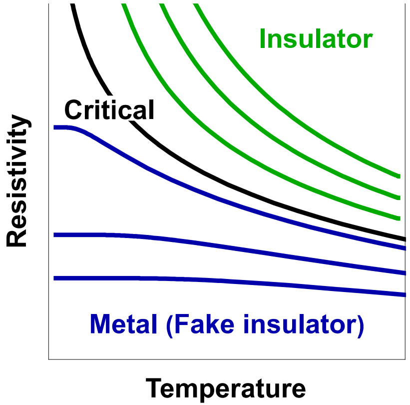
Guorui Chen
Shanghai Jiao Tong U, China



Jie Shan, Kin Fai Mak
Cornell U, USA

Conclusions: A New Perspective on Metal-Insulator Transitions





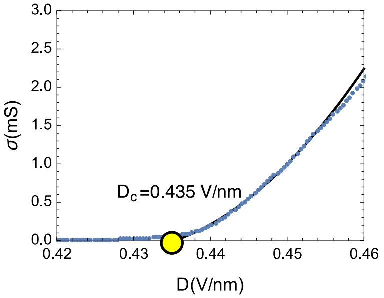
- Critical resistivity is **not constant** but diverges as a **powerlaw**
- Close to the MIT there is a **metallic regime** with $d\rho/dT < 0$ ("**fake**" insulator)
- Close to the MIT there is **universal scaling** of resistivity curves

$$\rho(T)/\rho_c(T) = f(T/T_0(\delta))$$

- Theory: weak disorder band transitions (with or without SSB)
- Applicable to experiments in **moiré systems** (graphene, TMDs)
- **Mott** MIT has different properties

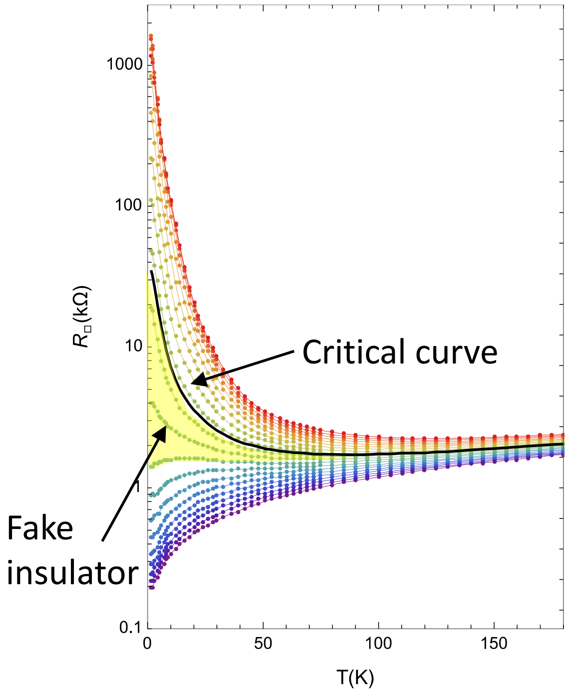
Scaling in $MoTe_2/WSe_2$

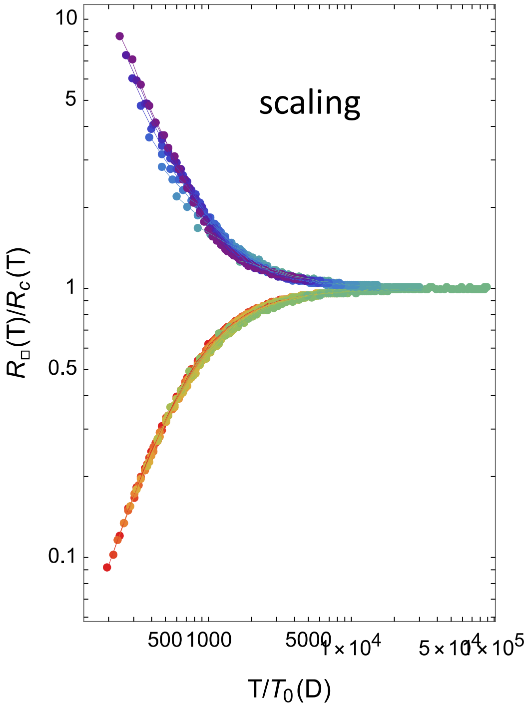
Extrapolating the **zero-temperature conductivity** gives **critical D_c**



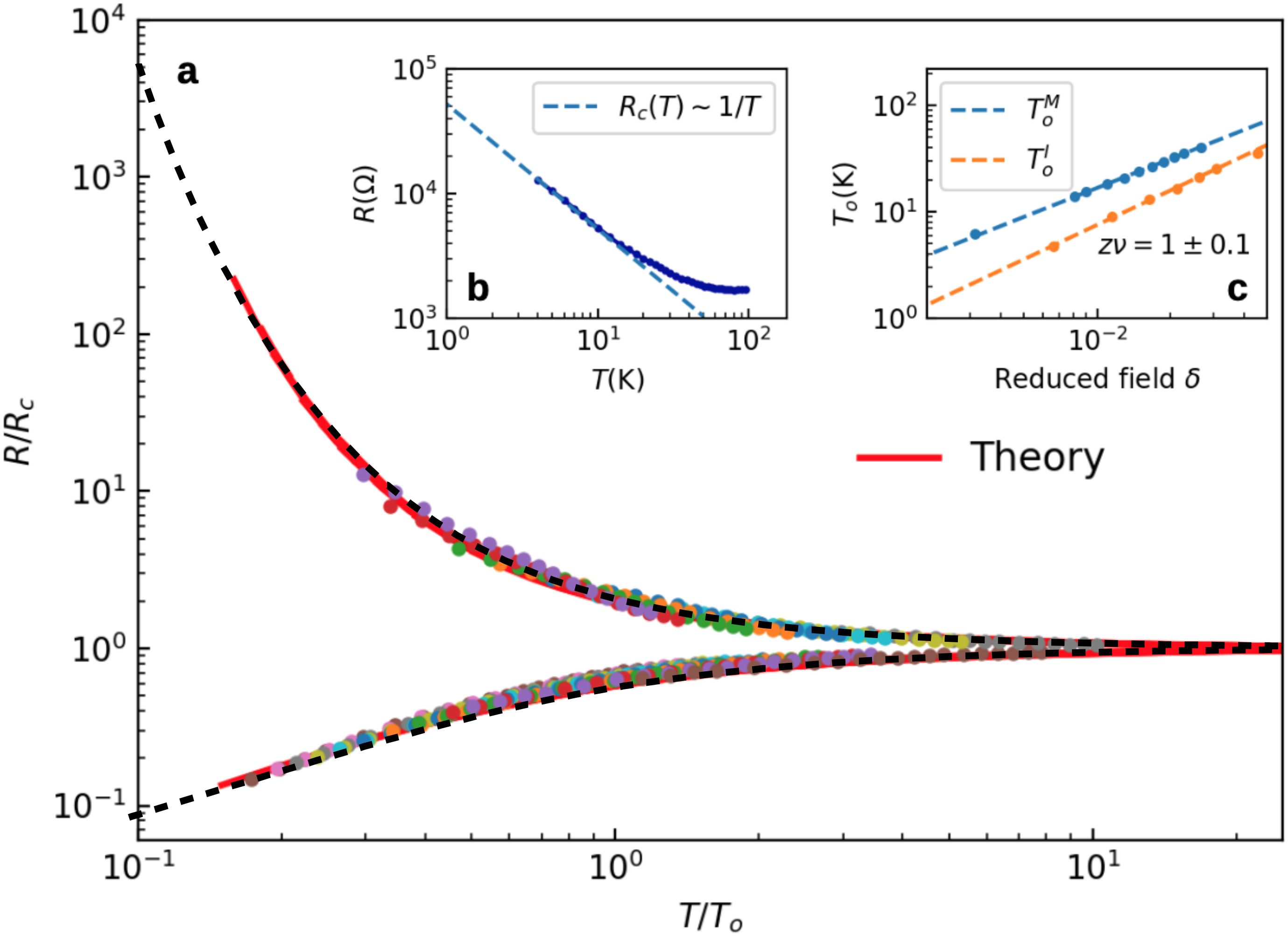
where the resistivity follows

$$R_c \sim 1/T$$





Ref: Li, Nature (2021); Tan, Tsang, Dobrosavljevic, arXiv:2112.11522 (2021)


a
b
c
R/R_c
T/T_o
Theory
$R_c(T) \sim 1/T$
$R(\Omega)$
$T(\mathrm{K})$
T_o^M
T_o^I
$T_o(\mathrm{K})$
$z\nu = 1 \pm 0.1$
Reduced field δ