Bad metals and more

André-Marie Tremblay
Reza Nourafkan, Alexis Reymbaut, Charles-David Hébert, Simon Bergeron, C. Walsh, P. Sémon, D. Poulin, G. Sordi

Quantum Matter: Computation Meets Experiments
Aspen, Colorado, 8 – 13 March 2020

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Bad metals

Reza Nourafkan

Alexis Reymbaut

Charles-David Hébert

Simon Bergeron

Peter T. Brown, *et al.*
Bad metallic transport in a cold atom Fermi-Hubbard system
Science 10.1126/science.aat4134 (2018).

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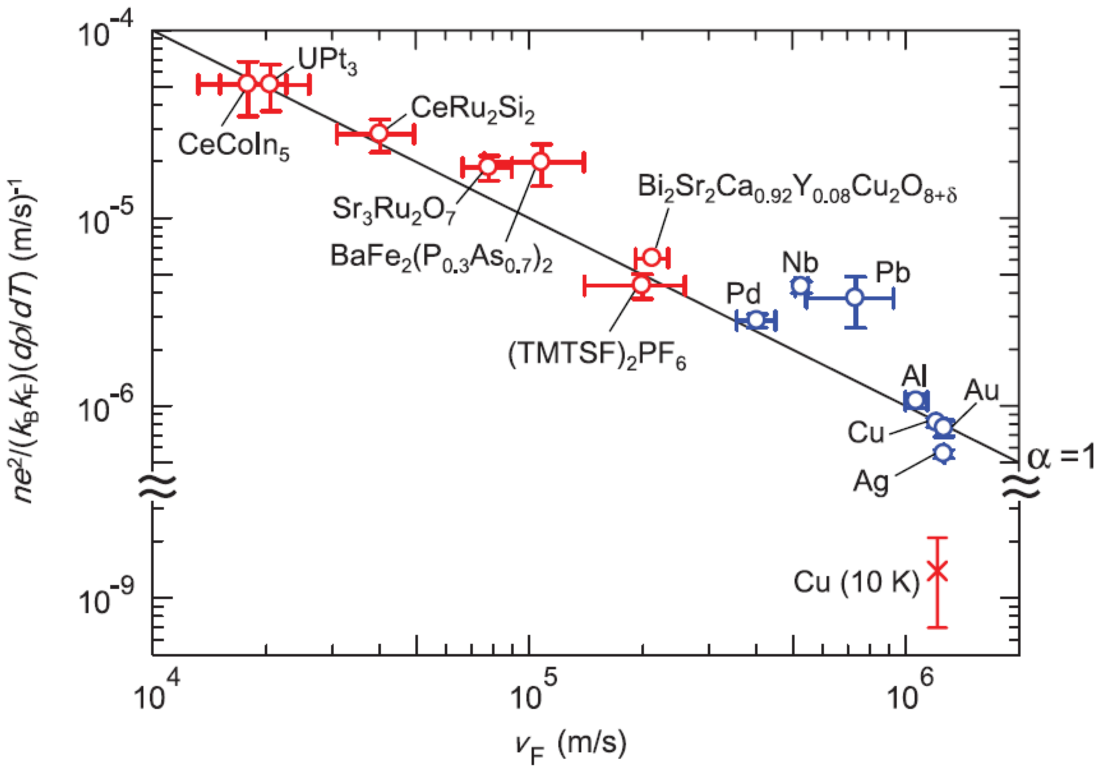
Motivation

$$\rho = (m^*/ne^2)\ (1/\tau)$$

$$\hbar/\tau = k_B T$$

$$(T\tau)^{-1} \sim \alpha k_B/\hbar$$

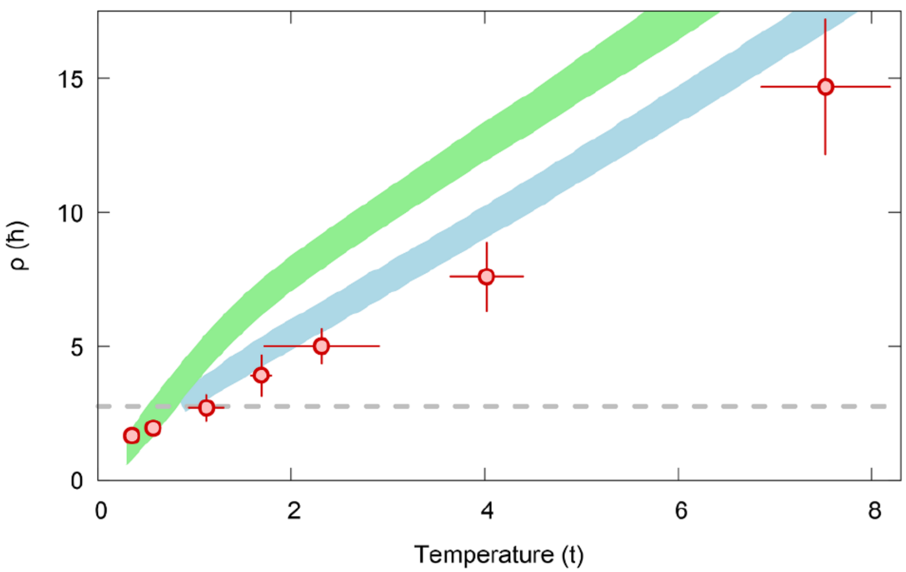


J. A. N. Bruin, H. Sakai, R. S. Perry, A. P. Mackenzie SCIENCE **339**, 804 (2013)

Cold atoms, high temperature

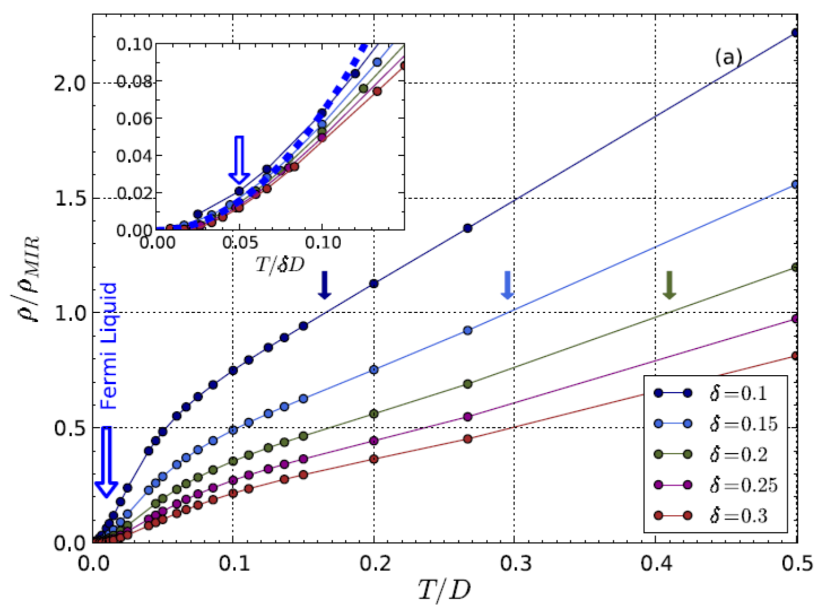
Linear resistivity at high temperature

DMFT (Green), FTLM (Blue)



$U = 7.5t, \ n = 0.825, t' = 0$

Deng *et al.* PRL **110**, 086401 (2013)

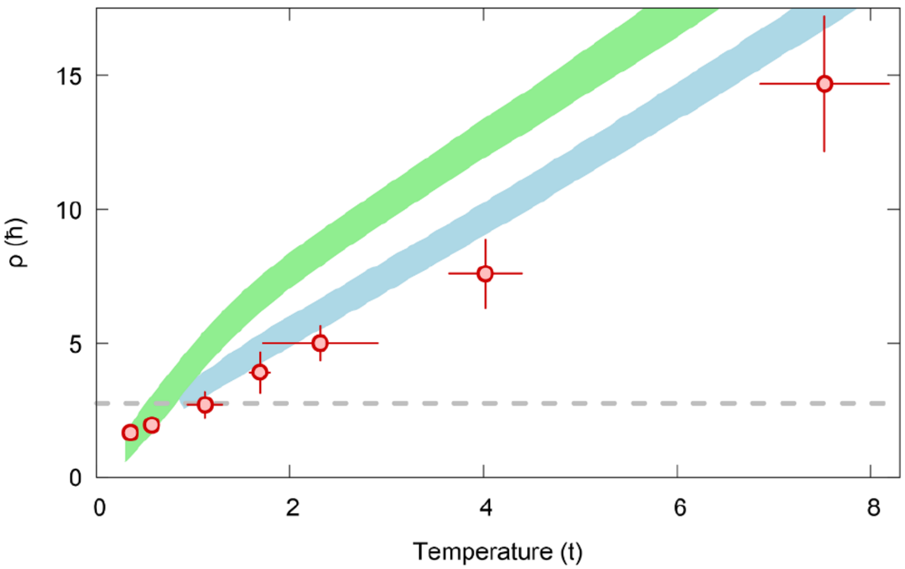


$U = 4D = 16t$

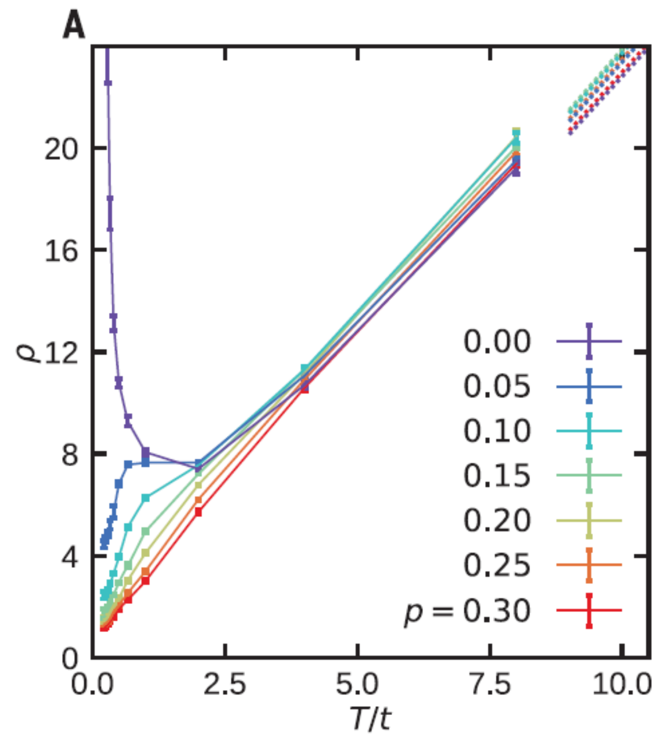
H. Terletska, *et al.* Phys. Rev. Lett. **107**, 026401 (2011).
X. Deng, *et al.* Phys. Rev. Lett. **110**, 086401 (2013).
W. Xu, *et al.* Phys. Rev. Lett. **111**, 036401 (2013).
J. Vučičević, Phys. Rev. Lett. **114**, 246402 (2015).

Linear resistivity at high temperature

DMFT (Green), FTLM (Blue)



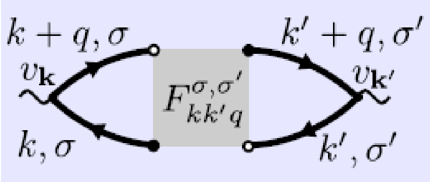
U = 7.5t, n = 0.825, t' = 0

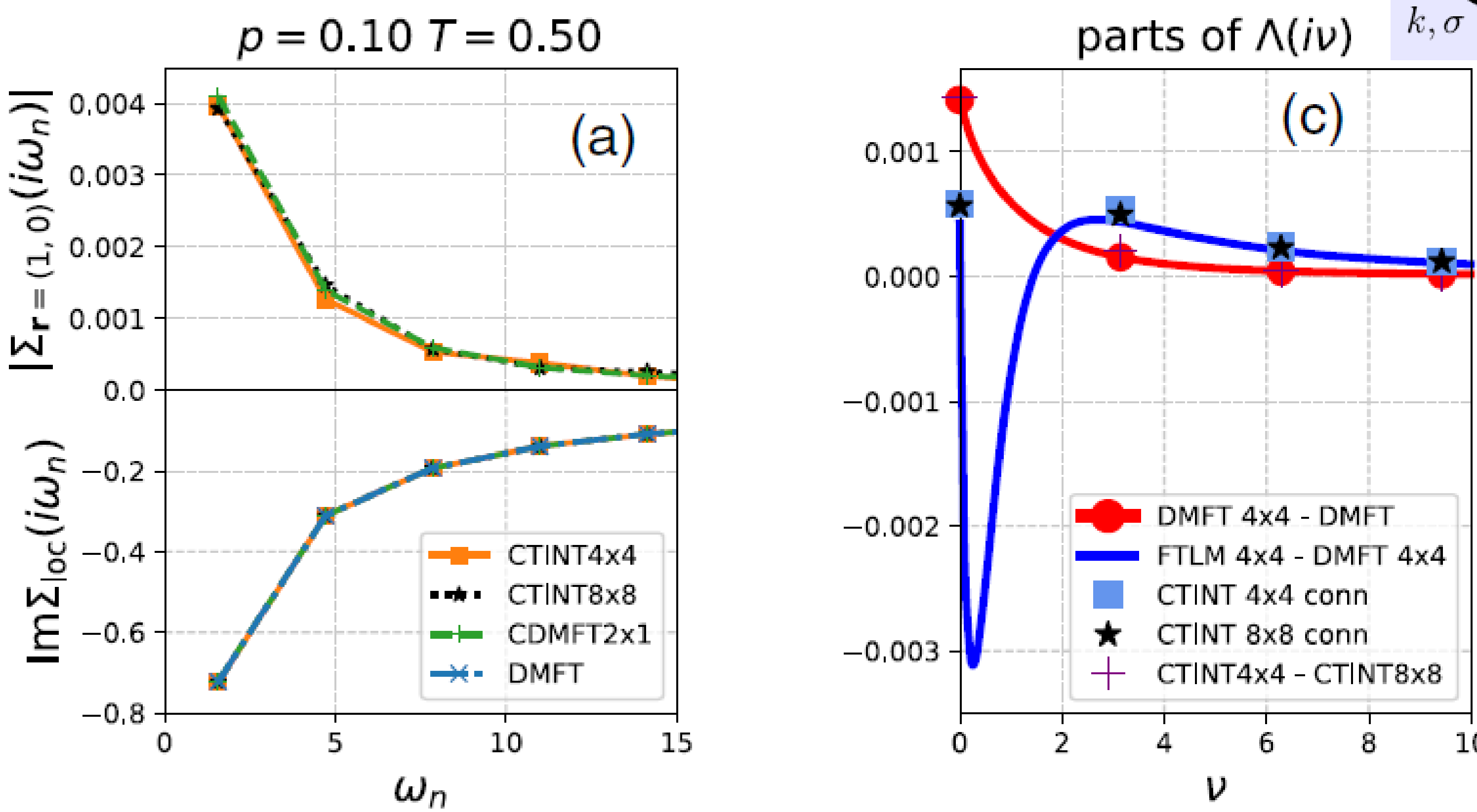


Huang *et al.* Science 366, 987 (2019)

U = 6t, t' = -0.25

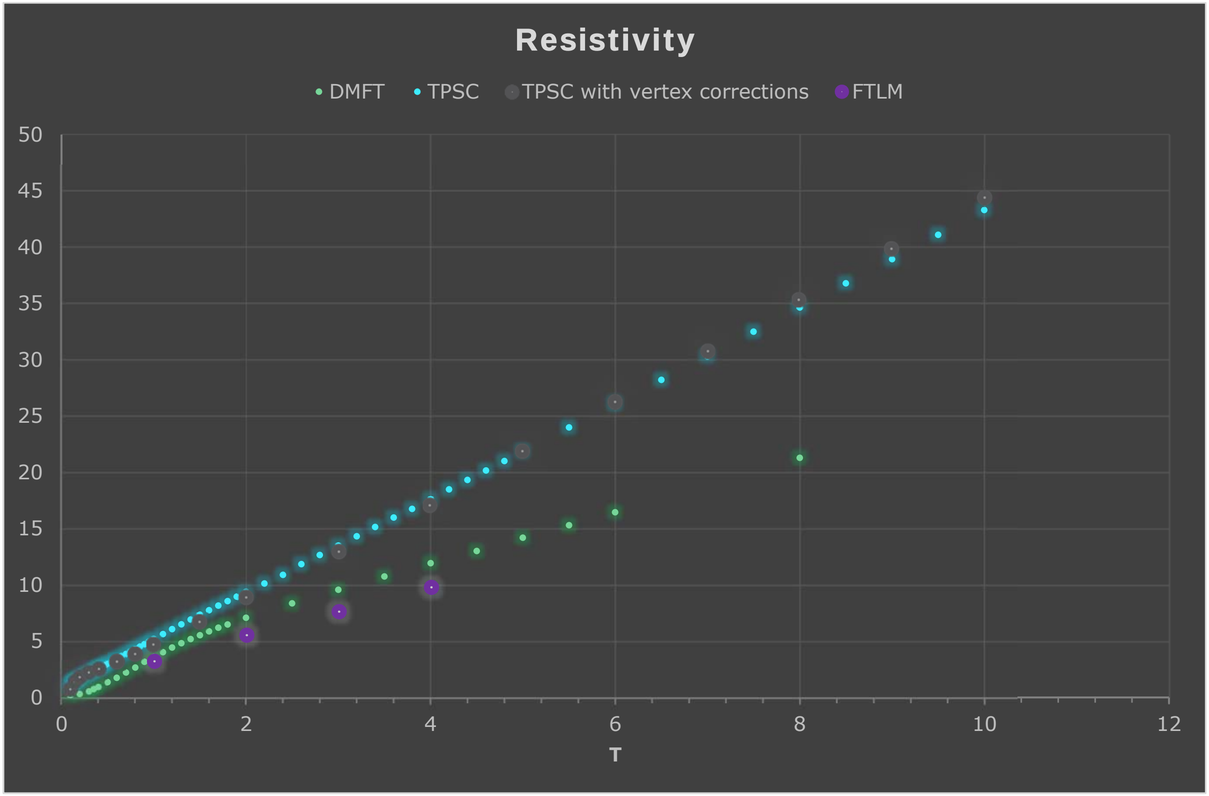
Linear resistivity at high temperature : vertex corrections





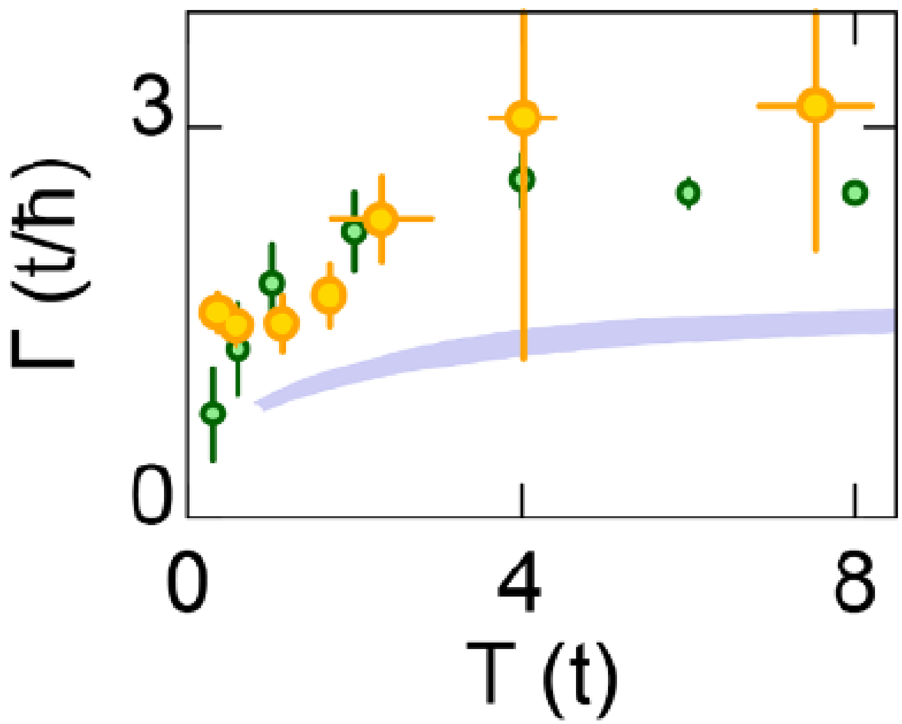
J. Vučičević *et al.* PRL **123**, 036601 (2019)

Another view of vertex corrections (TPSC)



Dominic Bergeron

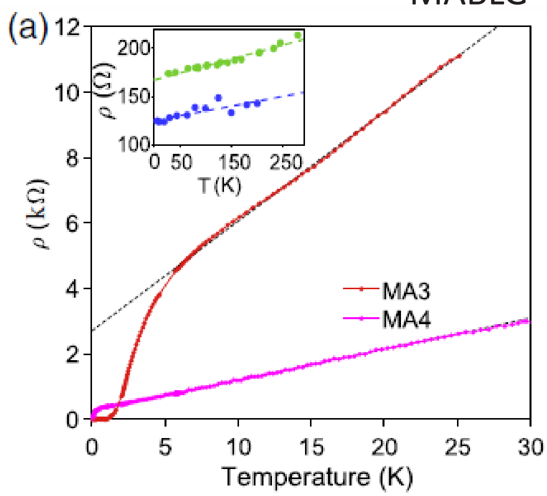
Unexplained : Width of the Drude Peak



Perspective

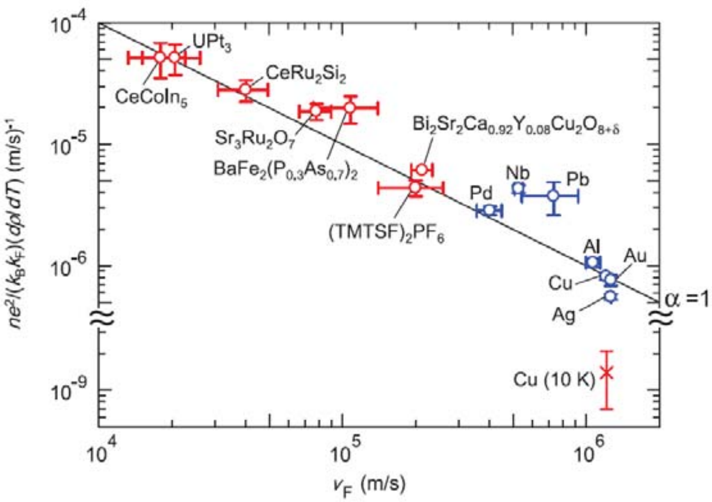
$$\rho = (m^{\star}/ne^2)\ (1/\tau)$$

$$\hbar/\tau = k_B T$$



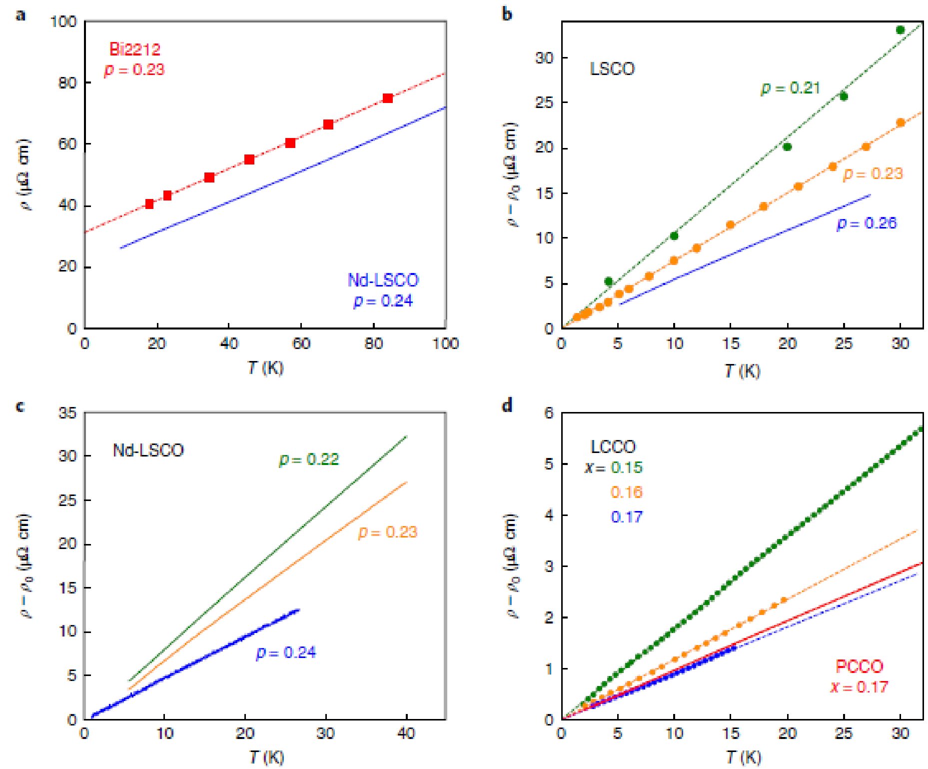
Cao *et al.* PRL **124,** 076801 (2020)

Low temperature ($k_B T << E_F$) experiments



J. A. N. Bruin, H. Sakai, R. S. Perry, A. P. Mackenzie SCIENCE **339**, 804 (2013)

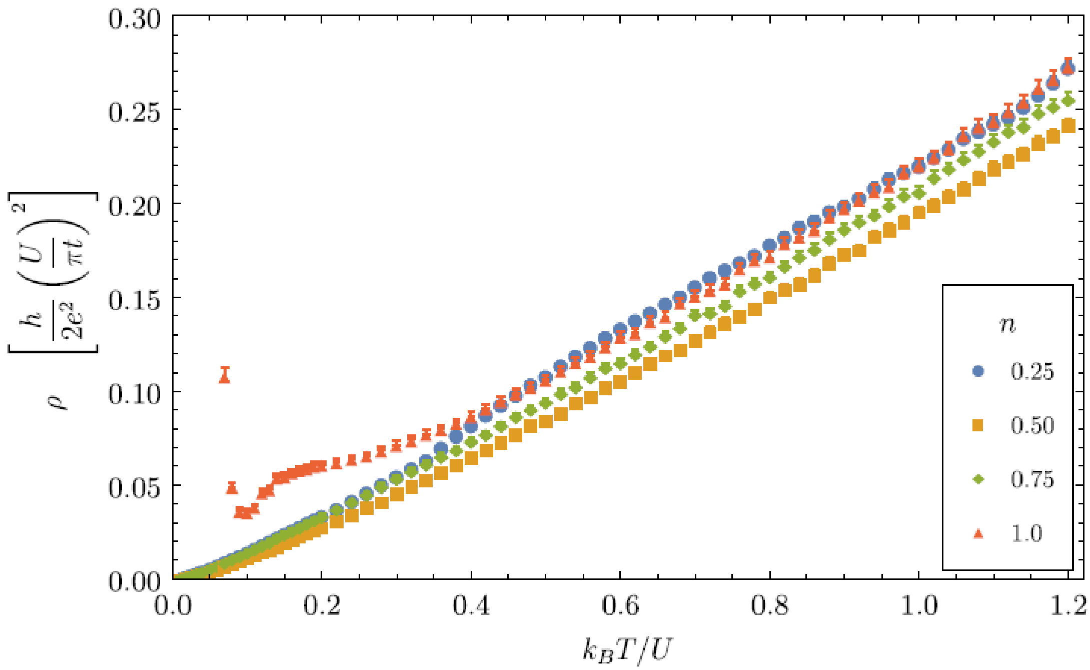
Cuprates



A. Legros *et al.* Nature Physics (2018)

Modifed Hubbard model

$$H = t\sum_{\langle ij\rangle,s} c^\dagger_{is}c_{js} + U\sum_i n_{i\uparrow}n_{i\downarrow} + \frac{V}{2}\sum_{i\neq j} e^{-|\vec{x}_i-\vec{x}_j|/\ell}\, n_i n_j.$$



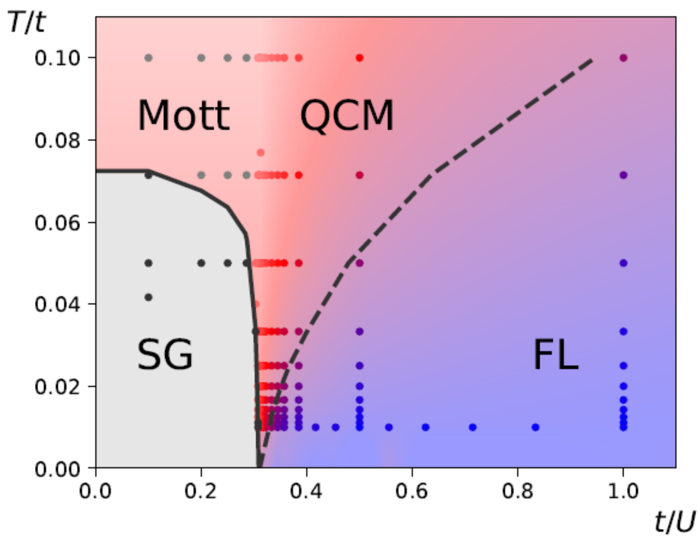
Mousatov *et al.* PRL **122**, 186601 (2019)

$V = 0.1U$

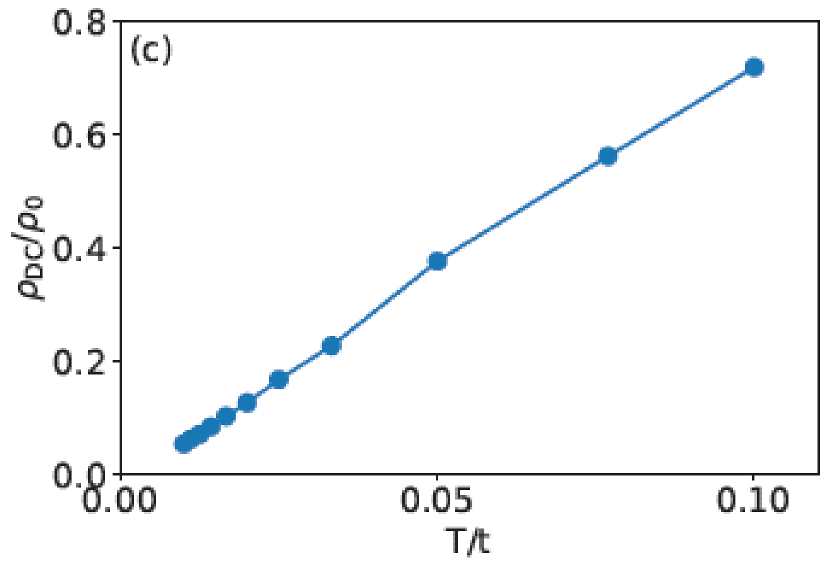
$t \ll k_BT \lesssim U$

SYK like models (similar to DMFT at high T)

$$H = -\sum_{\langle ij\rangle, s=\uparrow,\downarrow} t_{ij}\, c^{\dagger}_{is} c_{js} + U\sum_{i} n_{i\uparrow} n_{i\downarrow} - \sum_{i<j} \frac{J_{ij}}{\sqrt{N}} \vec{S}_i \cdot \vec{S}_j$$



P. Cha *et al.* arXiv:2002.07181

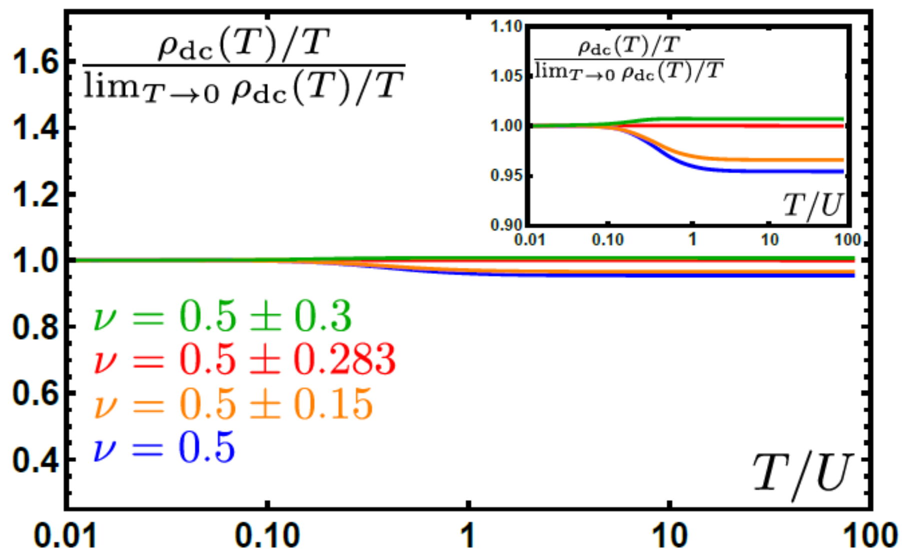


P. Cha *et al.* arXiv:2002.07181

- X.-Y. Song, *et al.* Phys. Rev. Lett. **119**, 216601 (2017).
- A. A. Patel, *et al.* Phys. Rev. X **8**, 021049 (2018).
- D. Chowdhury, *el al.* Phys. Rev. X 8, 031024 (2018).
- S. A. Hartnoll, A. Lucas, and S. Sachdev, *Holographic Quantum Matter* (MIT Press, Cambridge, MA, 2018).

SYK like models (similar to DMFT at high T)

« Slope invariance »

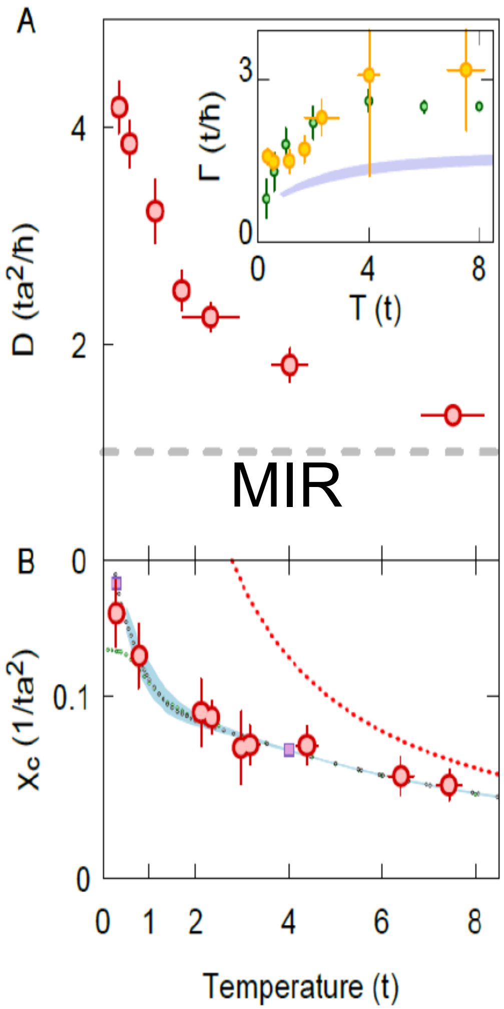


P. Cha *et al.* arXiv:1910.07530

- X.-Y. Song, *et al.* Phys. Rev. Lett. **119**, 216601 (2017).
- A. A. Patel, *et al.* Phys. Rev. X **8**, 021049 (2018).
- D. Chowdhury, *el al.* Phys. Rev. X 8, 031024 (2018).

Back to high temperature : Why linear?

Linear at high temperature, but not because of scattering



$$\sigma = \chi_c D$$

J. Kokalj, Phys. Rev. B 95, 041110(R) (2017)

$$D \gtrsim ta^2 / \hbar$$

$$\chi_c \sim n(1 - n/2)/T$$

E. Perepelitsky, *et al.* Phys. Rev. B **94**, 235115 (2016).

General Case

$$\sigma_{xx}(0) = \frac{\hbar}{k_B T} \sum_{n,m} \frac{e^{-\beta E_n}}{Z} \langle n|j_x|m\rangle\langle m|j_x|n\rangle \pi\delta(E_m - E_n)$$

Mukerjee *et al.* PRB **73**, 035113 (2006)

P. Cha *et al.* arXiv:1910.07530

E. Perepelitsky, *et al.* Phys. Rev. B **94**, 235115 (2016).

Entanglement entropy and mutual information near the Mott transition

Caitlin Walsh

Patrick Sémon

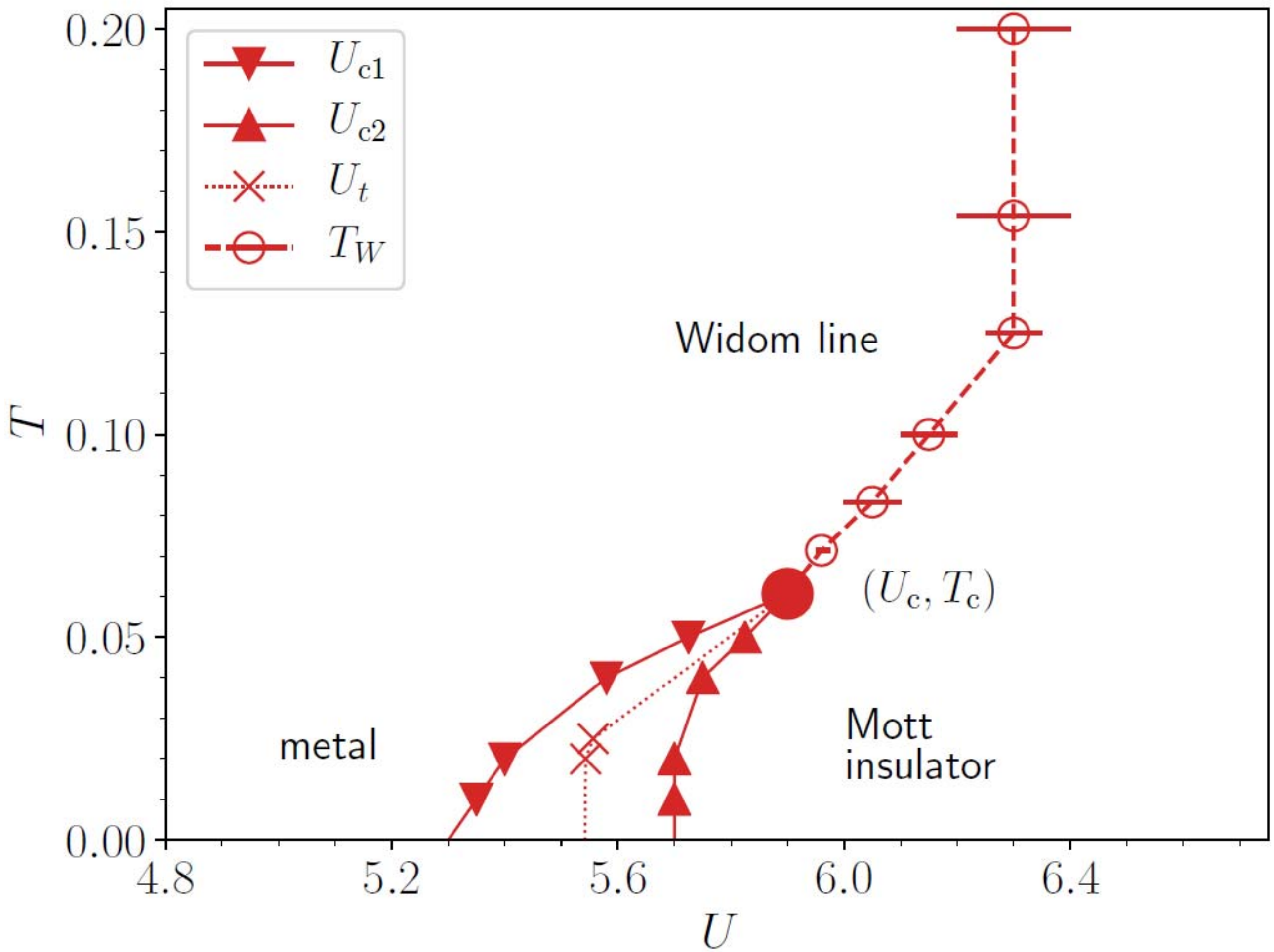
David Poulin

Giovanni Sordi

C. Walsh, *et al.*
Phys. Rev. Lett. **122**, 067203 (2019)
Phys. Rev. B **99**, 075122 (2019)

The Mott transition at half-filling

C. Walsh, *et al.* PRB **99**, 075122 (2019)
H. Park, *et al.* PRL **107**, 137007 (2011).



Motivation

PHYSICAL REVIEW X **7**, 031025 (2017)

Measuring Entropy and Short-Range Correlations in the Two-Dimensional Hubbard Model

E. Cocchi,[1,2] L. A. Miller,[1,2] J. H. Drewes,[1] C. F. Chan,[1] D. Pertot,[1] F. Brennecke,[1] and M. Köhl[1]

First-order nature of the transition,
universality class of the end point,
crossovers emanating from the end point.

For quantum critical or finite temperature critical points

A. Anfossi *et al.* Phys. Rev. Lett. **95**, 056402 (2005).
L. Amico *et al.* Europhys. Lett. **77**, 17001 (2007).
L. Amico *et al.* Rev. Mod. Phys. **80**, 517 (2008).
D. Larsson *et al.* Phys. Rev. A **73**,042320 (2006).
D. Larsson *et al.* Phys. Rev. Lett. **95**, 196406 (2005).

Single-site entanglement entropy

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What is measured (Using CDMFT CT-HYB on plaquette)

- Single site entanglement entropy for fermions [1]

$$\rho_A = \mathrm{Tr}_B[\rho_{AB}] \qquad s_A = -\mathrm{Tr}_A[\rho_A \ln \rho_A]$$

$$\rho = \mathrm{diag}(p_0, p_\uparrow, p_\downarrow, p_{\uparrow\downarrow}) \qquad s_1 = -\sum_i p_i \ln(p_i)$$

$$p_{\uparrow\downarrow} = \langle n_{i\uparrow} n_{i\downarrow} \rangle \qquad p_\uparrow = p_\downarrow = \langle n_{i\uparrow} - n_{i\uparrow} n_{i\downarrow} \rangle \qquad p_0 = 1 – 2p_\uparrow - p_{\uparrow\downarrow}$$

[1] P. Zanardi *et al.* Phys. Rev. A **65**, 042101 (2002).

What is measured

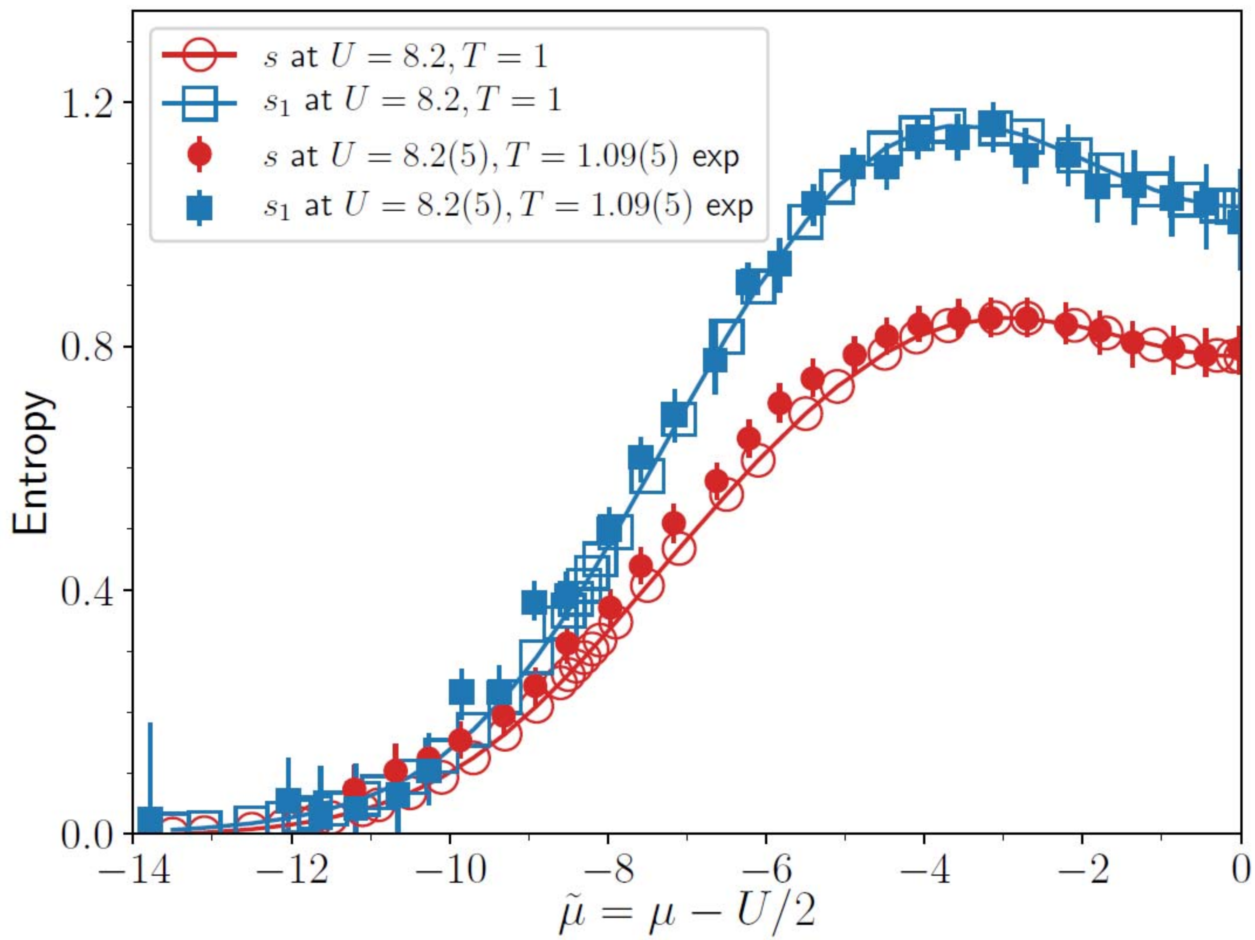
- Entropy

$$sdT - adP + nd\mu = 0$$

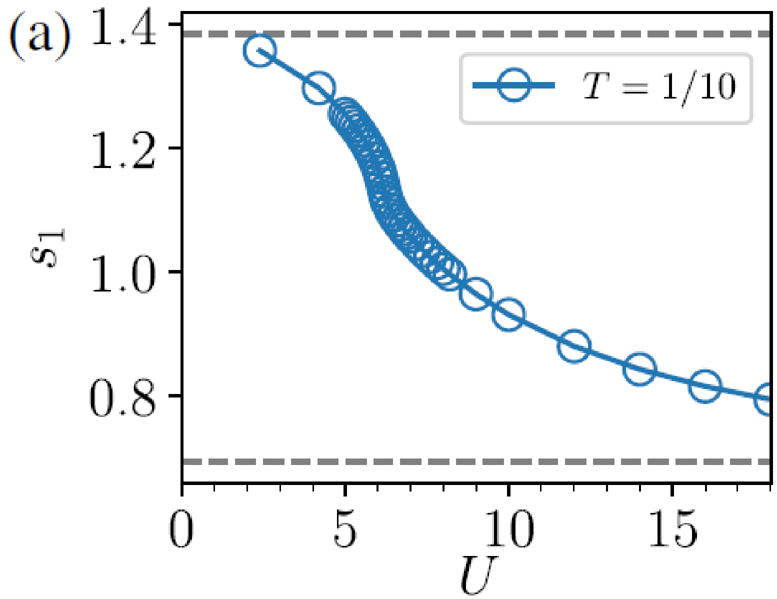
$$P(T)_U = \frac{1}{a}\int_{-\infty}^{U/2} n(\mu, T)d\mu$$

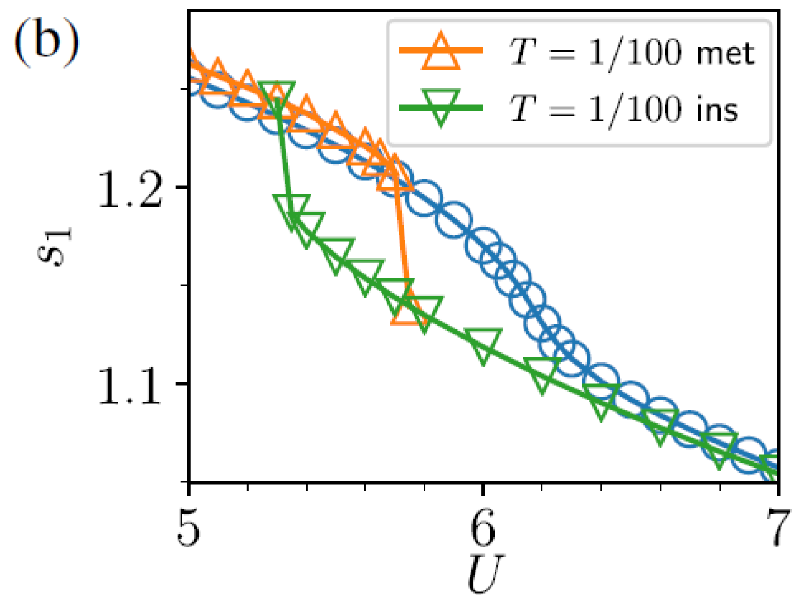
$$s = a(dP/dT)_\mu$$

Agreement with experiment



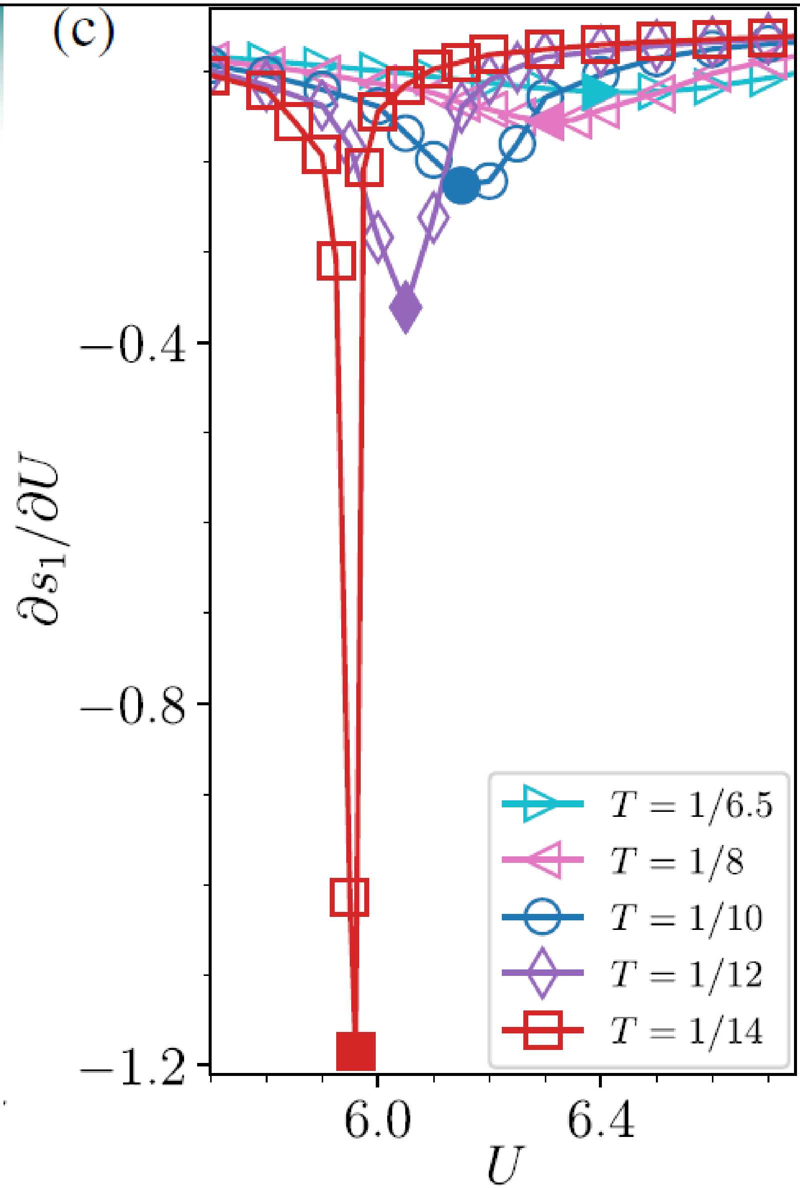
Results





$$\partial s_1 / \partial T < 0$$

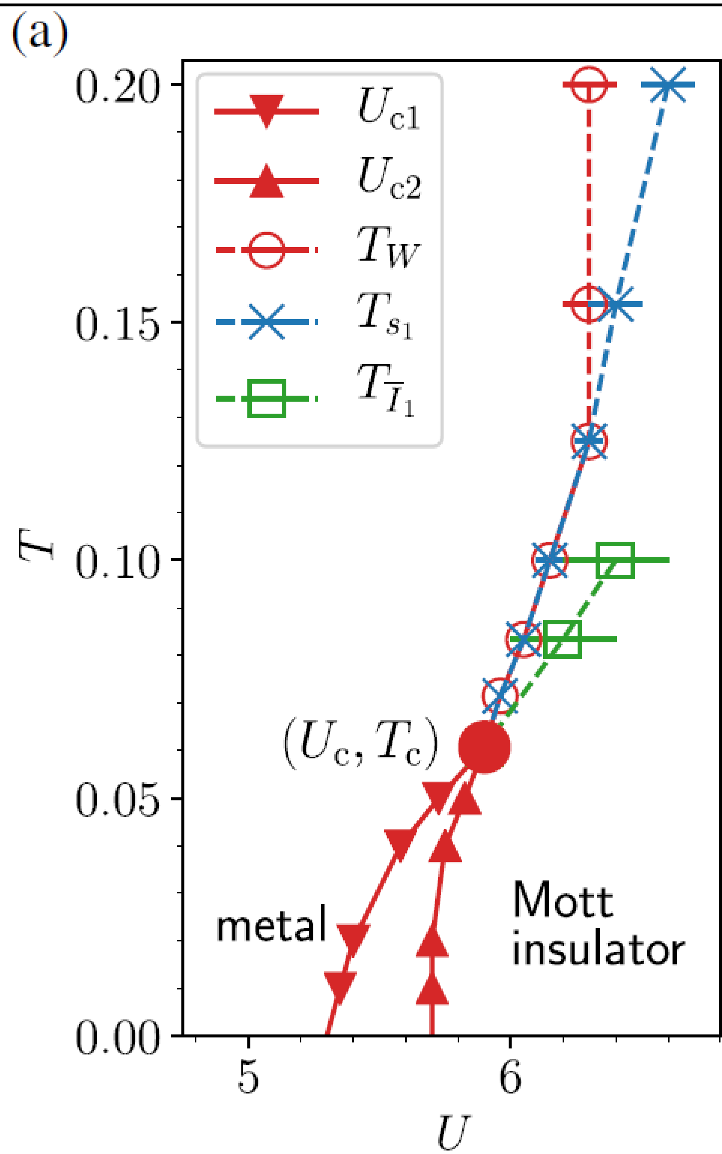
Results



$$(\partial s_1/\partial D)(\partial D/\partial U)$$

$$\partial D/\partial U \sim -|U - U_c|^{-1+1/\delta}$$

Transition and crossovers



From single-site entanglement entropy

- The Mott transition,
- Critical exponent (not usually the case)
- Associated high-temperature crossovers,
  - Without knowledge of the order parameter of the transition

Mutual information

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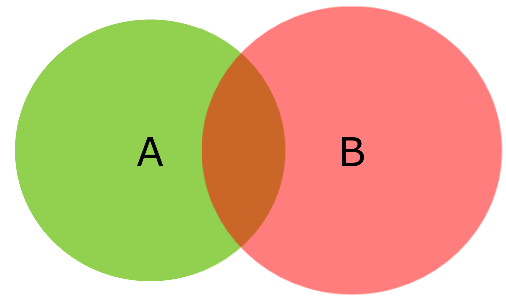
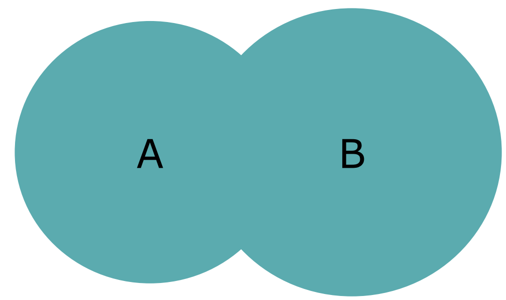
Mutual information

$$I(A:B) = s_A + s_B - s_{AB}$$



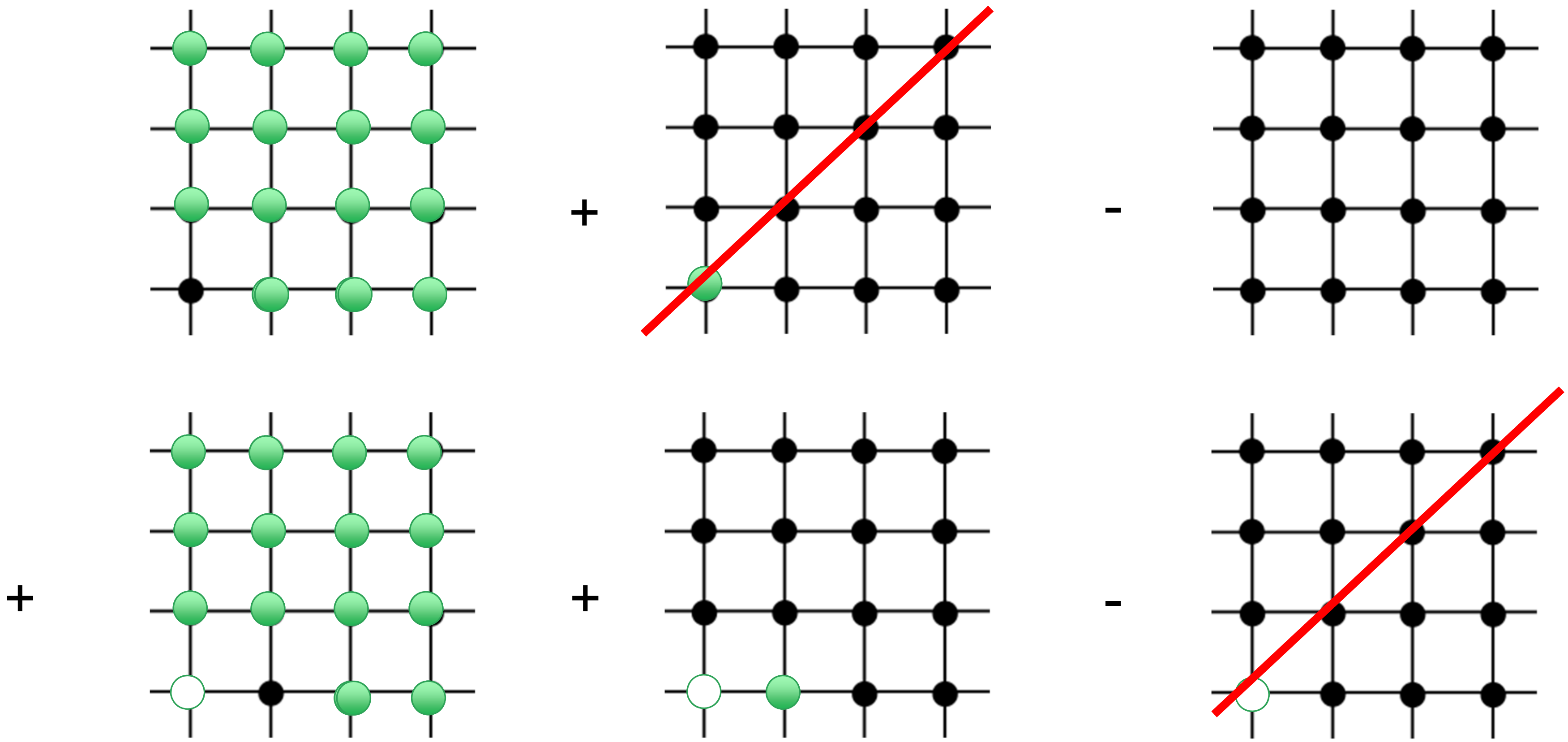
Here we are *not* looking at the area law



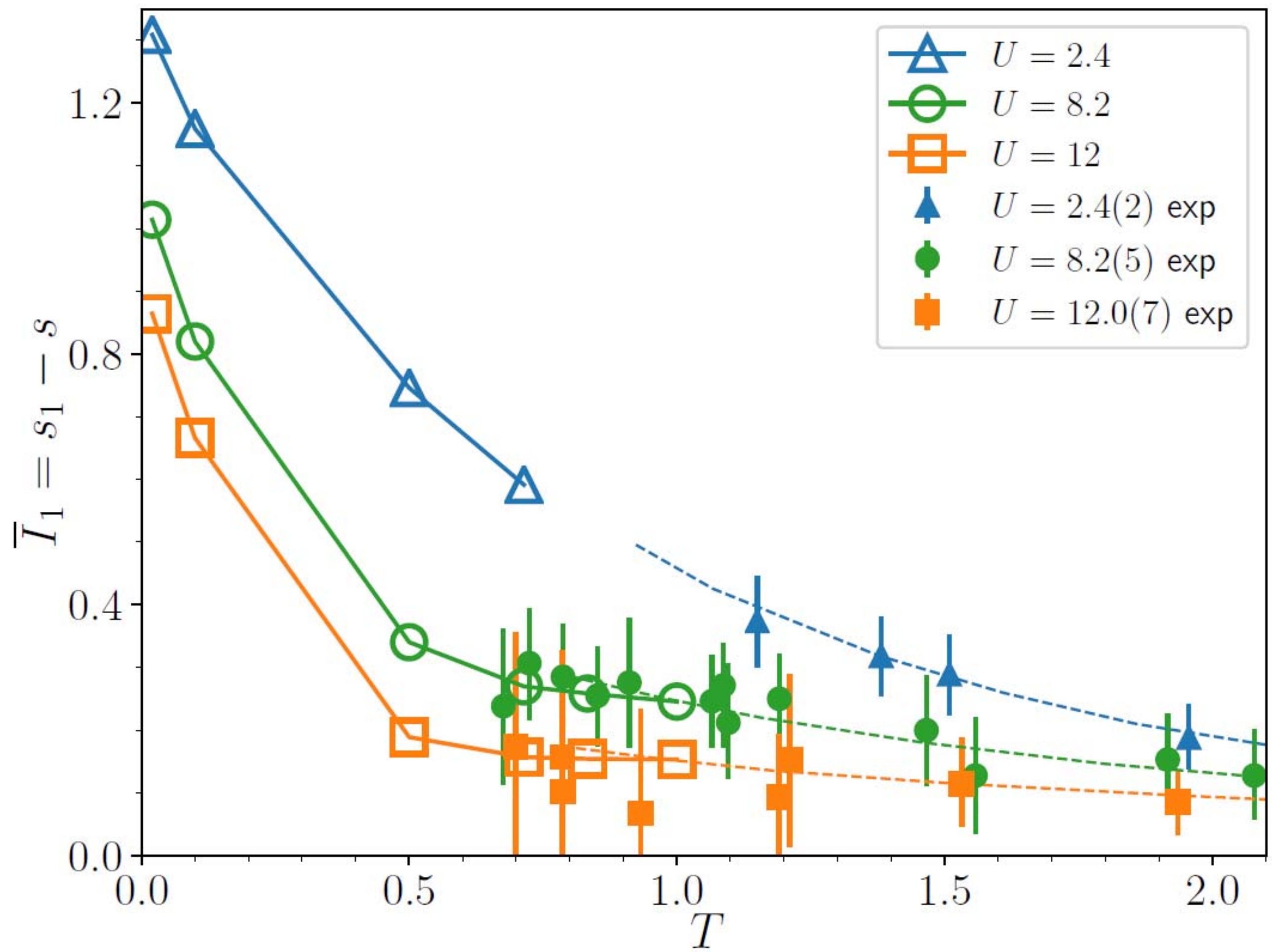
What is measured experimentally

$$\bar{I}_1 = s_1 - s$$

Total mutual information

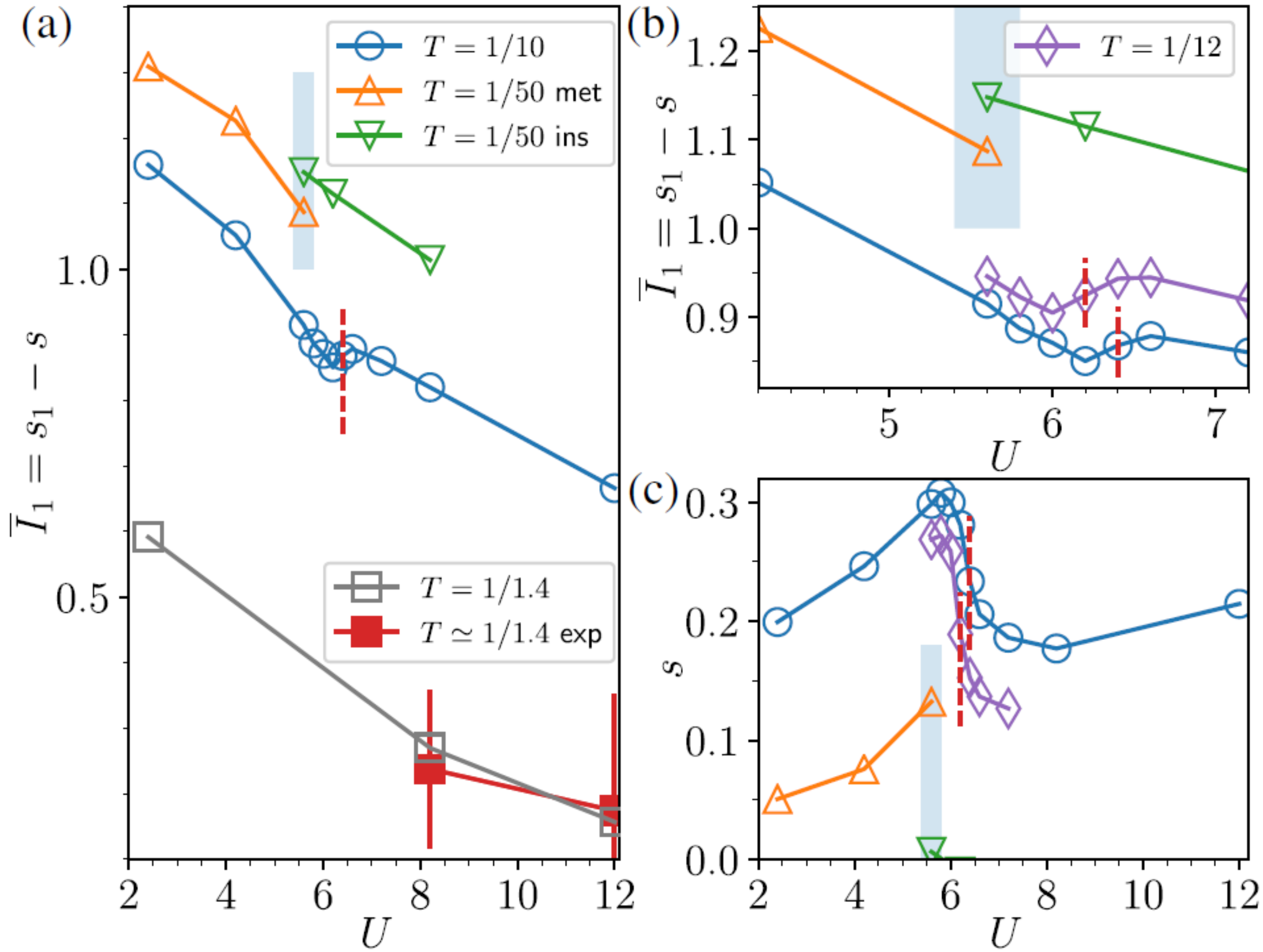


Agreement with experiment

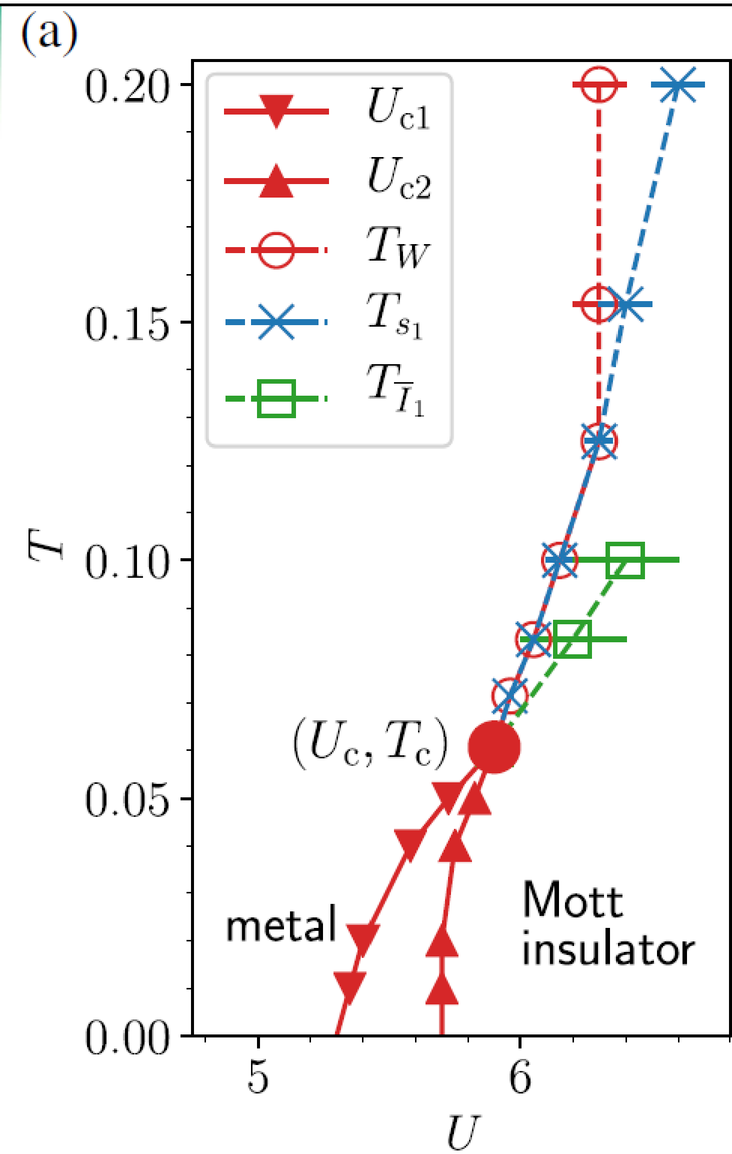


Results

$$\bar{I}_1 \sim \mathrm{sgn}(U - U_c)|U - U_c|^{1/\delta}$$



Transition and crossovers



From average mutual information

- The Mott transition,
- Critical exponent (not usually the case)
- Associated high-temperature crossovers,
  - Without knowledge of the order parameter of the transition

Merci

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