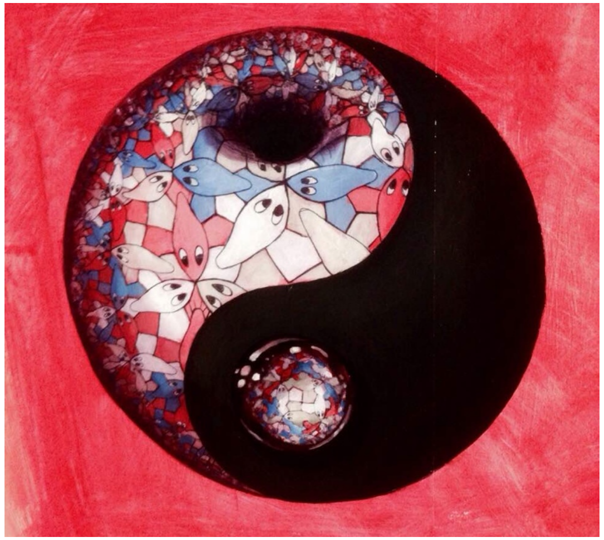
Holography and experimental quantum matter

Koenraad Schalm

Institute Lorentz for Theoretical Physics, Leiden University



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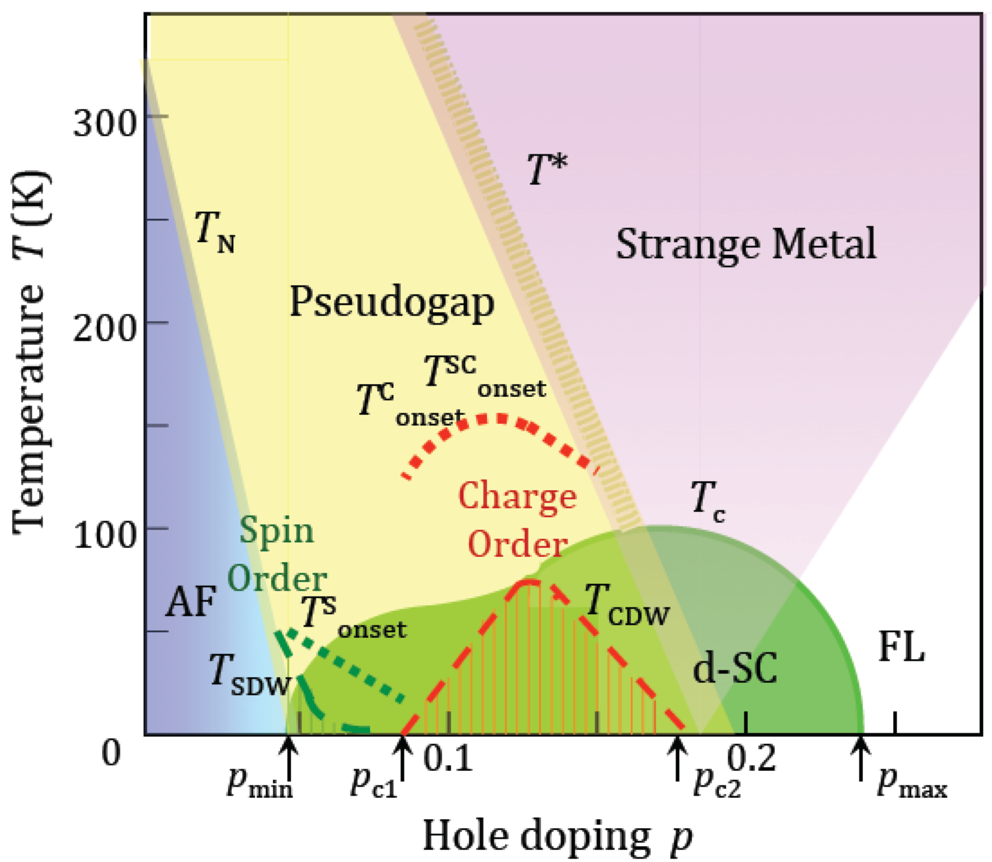
The strange metal in high Tc cuprates



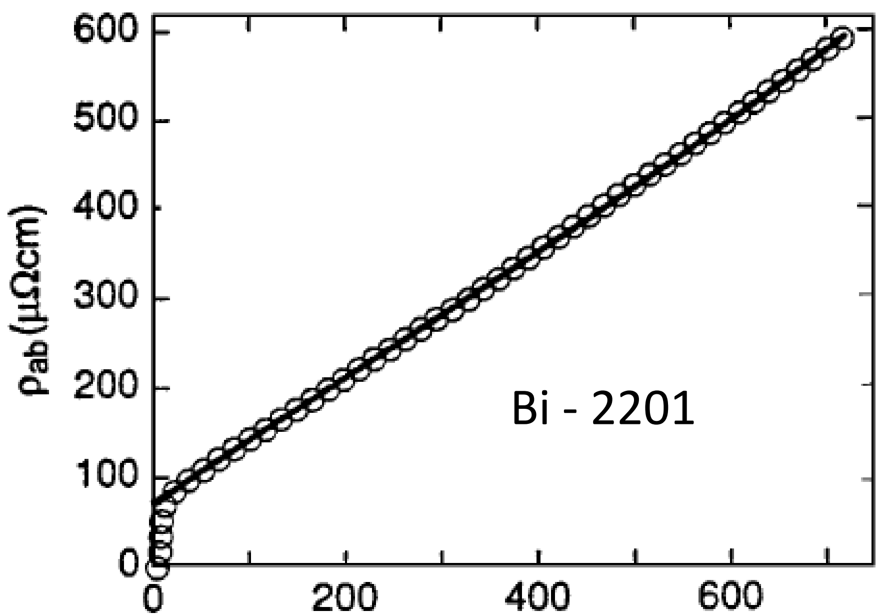
Keimer et al,
Nature 518 (2015) 179

Why is a strange metal “strange”? e.g. Anderson, Physics Today 2013

- Linear-in-T resistivity

$$\rho \equiv \frac{1}{\sigma} \sim T$$

$$\rho_{metal} \sim T^2$$



Martin et al,
PRB41 (1990) 846

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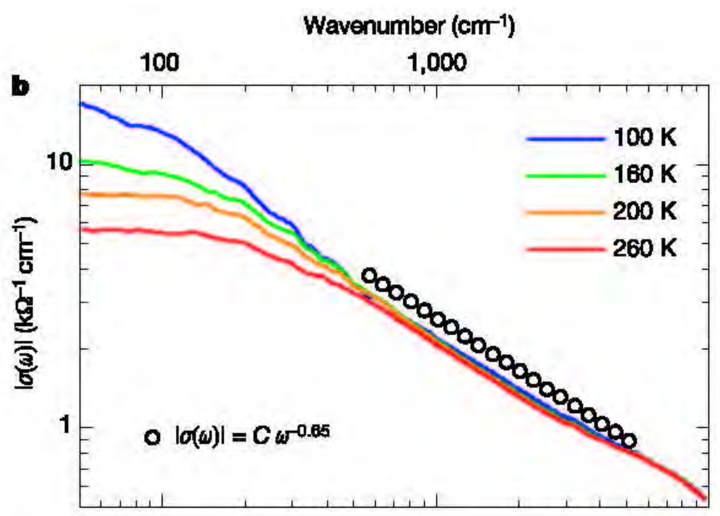
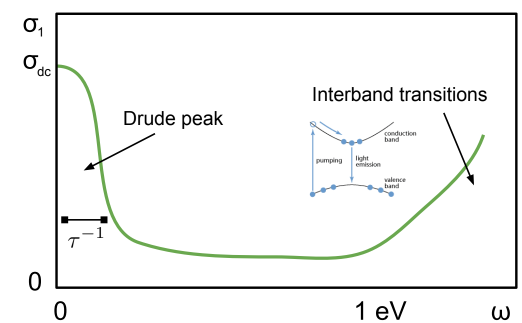
- Power Law in AC conductivity

$$\sigma(\omega) \sim \omega^{-2/3}$$

$$\sigma(\omega)_{metal} \sim C$$

Van der Marel et al, Nature 425, 271 (2003)





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$$\theta = \frac{\sigma_{xy}}{\sigma_{xx}} \sim \frac{1}{T^2}$$

$$\theta_{metal} \sim \sigma_{DC,metal} \sim \frac{1}{T}$$

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- Inverse Matthiessen law

$$\sigma \sim \sigma_I + \sigma_{II}$$

$$\rho_{metal} \sim \rho_I + \rho_{II}$$

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This is not an exhaustive list…

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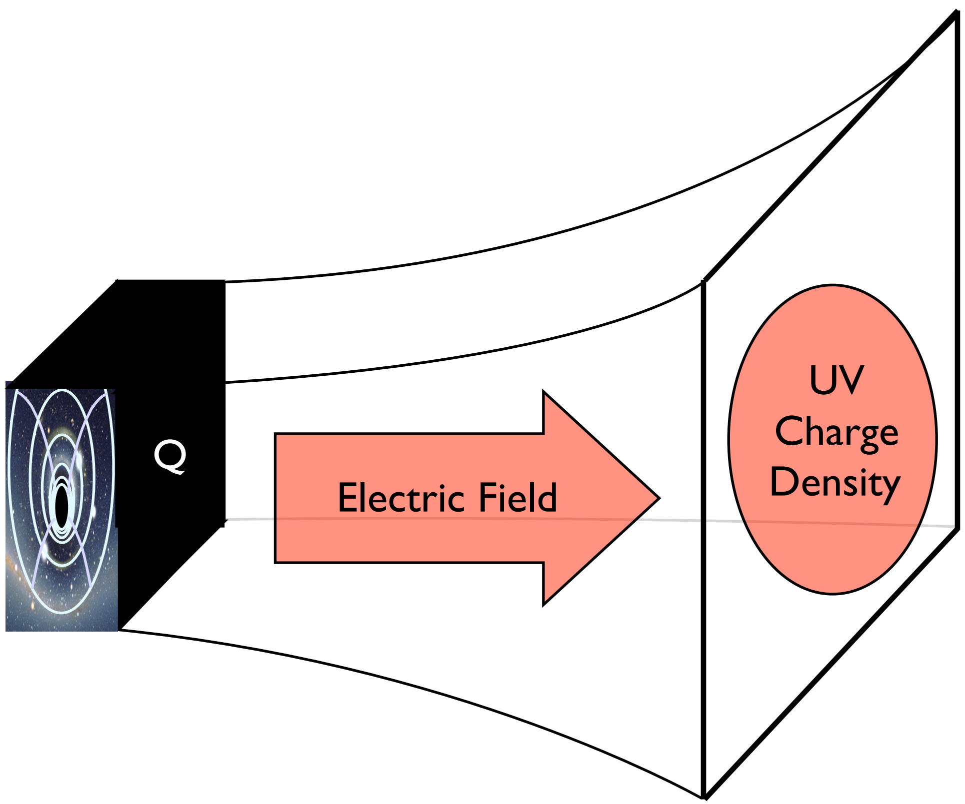
- AdS/CFT applied to condensed matter:

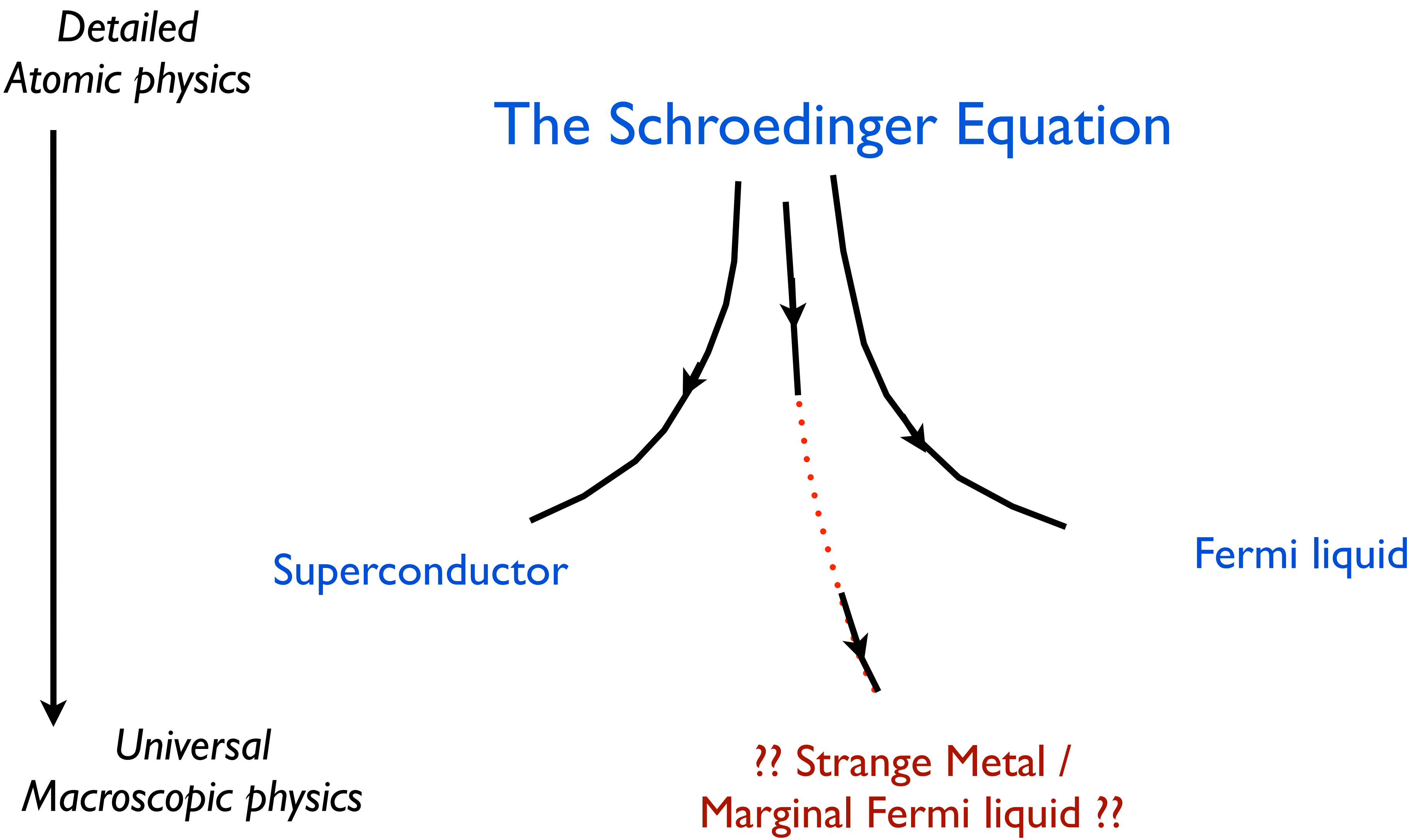
1. Generating functional for new non-trivial *unknown* IR fixed points

2. Far superior method to compute *real time* finite temperature/density correlation functions

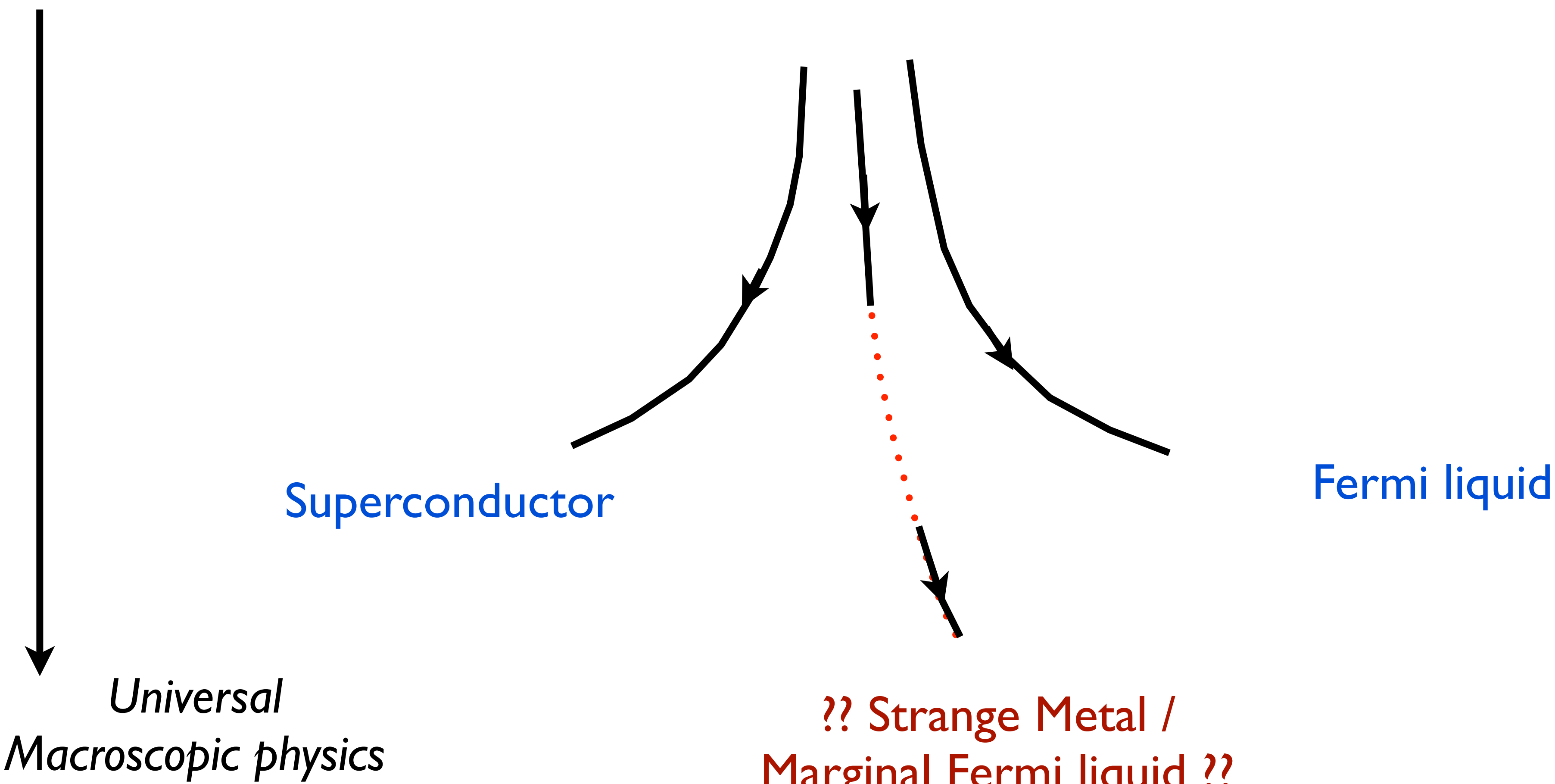
- AdS/CFT:
- a dual gravitational description of a (strongly) interacting quantum field theory.

Systems at finite temperature/density $=$ AdS charged black hole





Detailed
Atomic physics
The Schroedinger Equation
Superconductor
Fermi liquid
Universal
Macroscopic physics
?? Strange Metal /
Marginal Fermi liquid ??


Superconductor
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?? Strange Metal /
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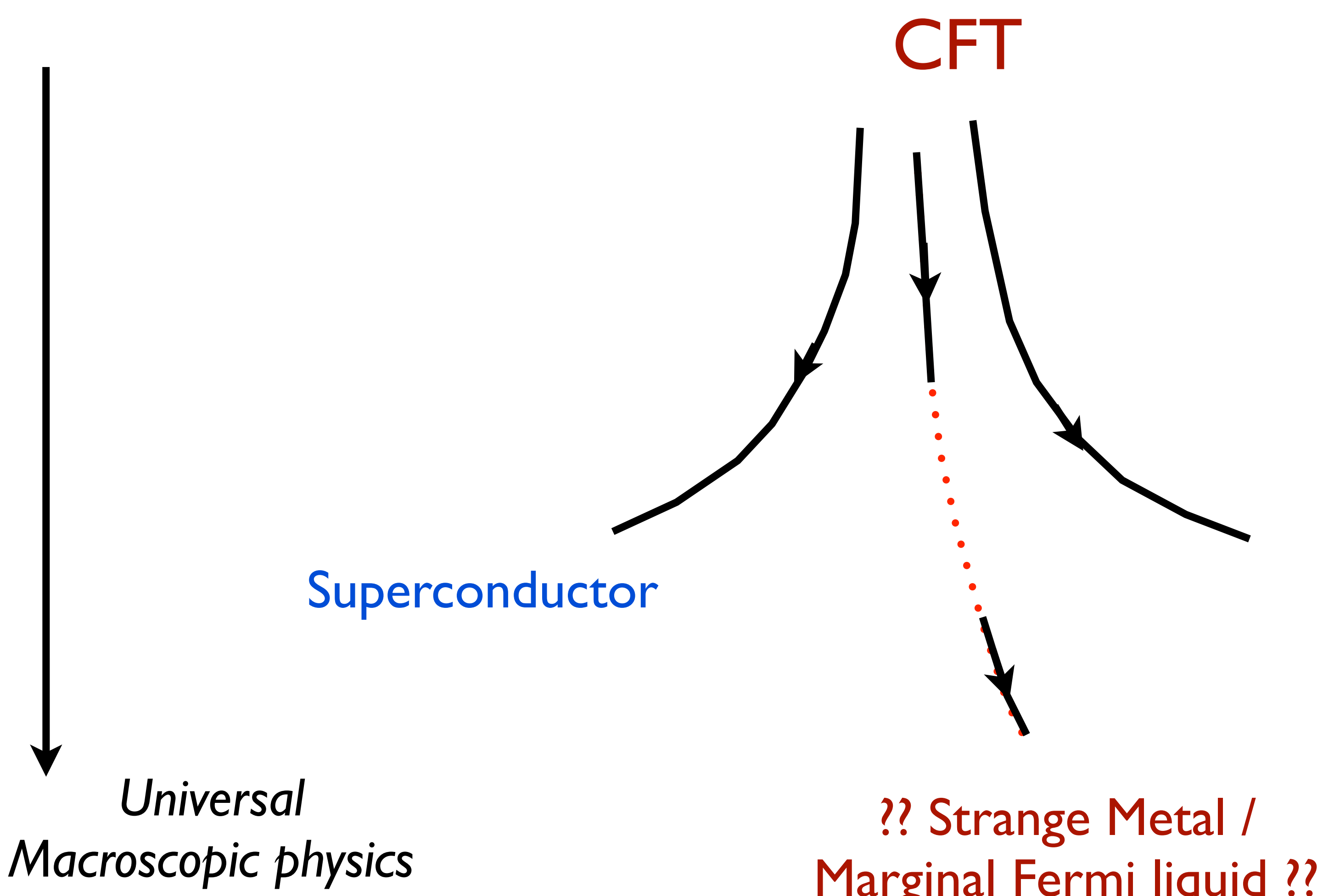
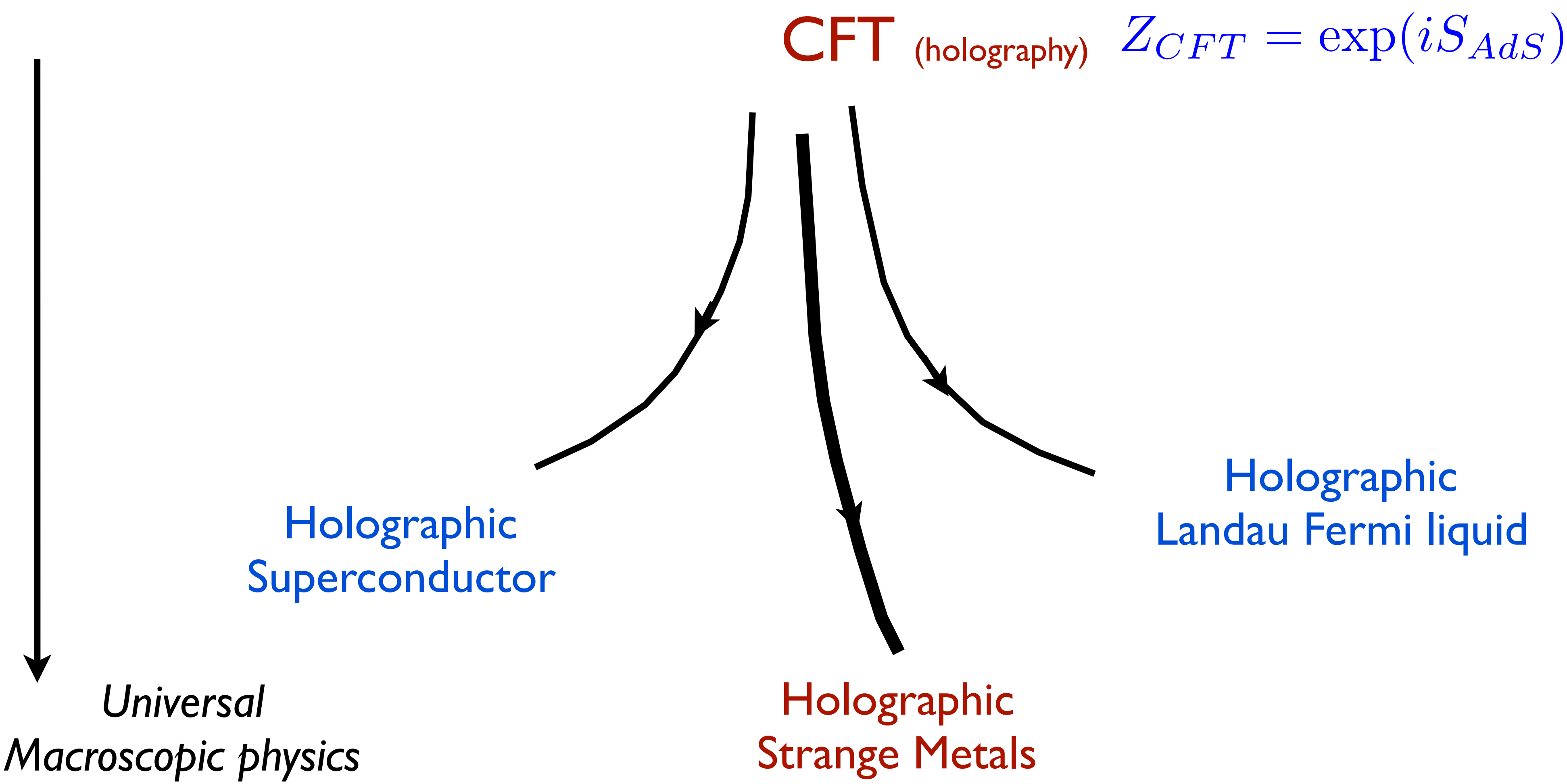
Universal
Macroscopic physics


CFT
Superconductor
Fermi liquid
?? Strange Metal /
Marginal Fermi liquid ??
Universal
Macroscopic physics

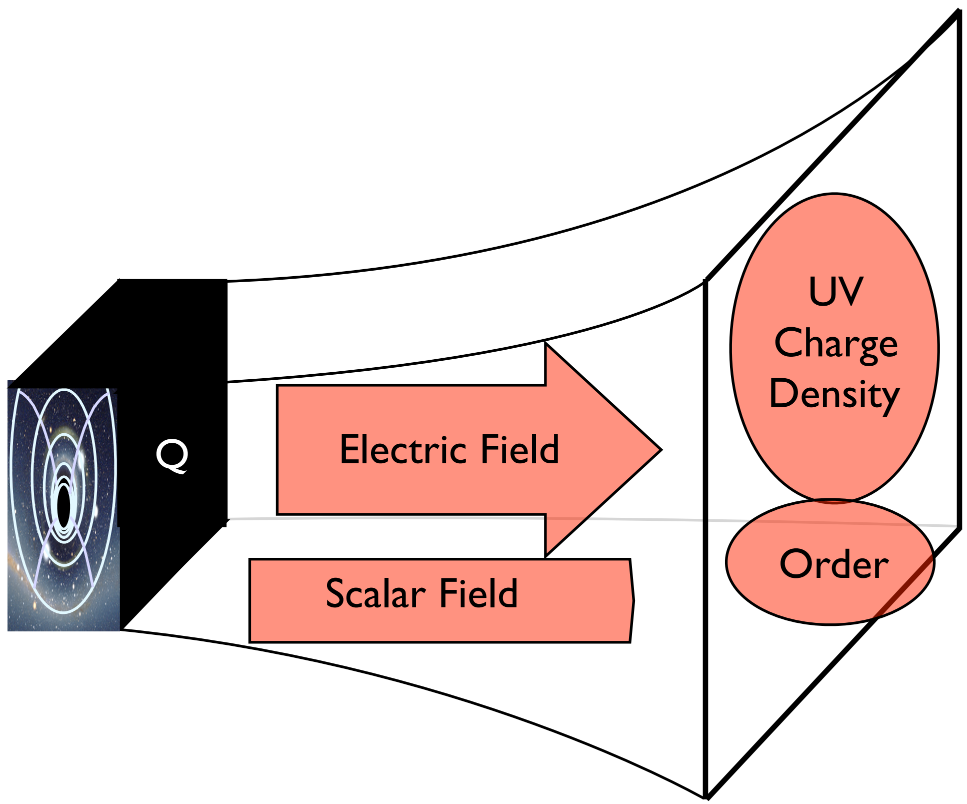

CFT (holography)
$Z_{CFT} = \exp(iS_{AdS})$
Holographic
Superconductor
Holographic
Strange Metals
Holographic
Landau Fermi liquid
Universal
Macroscopic physics

Holography describes new states of matter

- Holographic prediction:

  Emergent scale invariant hyperscaling violating theories

$$S = \frac{1}{2\kappa^2}\int d^{d+2}x\sqrt{-g}\left(R - \frac{Z(\Phi)}{4}F_{\mu\nu}F^{\mu\nu} - 2|\partial_\mu\Phi|^2 - V(\Phi)\right)$$



Φ : leading relevant operator

A_μ : dual to $U(1)$ *current*

$g_{\mu\nu}$: dual to EM-tensor

r : RG scale

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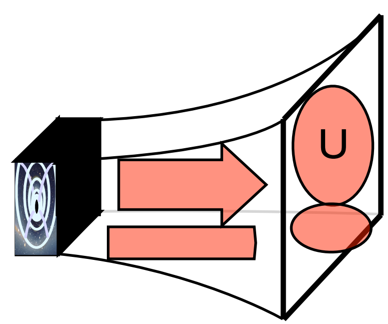
$$ds^2 = \frac{L^2}{r^2}\left[r^{2\theta/(d-\theta)}dr^2 - r^{-2d(z-1)/(d-\theta)}dt^2 + dx^2\right] \qquad A_t = Q\ r^{\zeta - z}$$

$$t \to \lambda^z t,\ x \to \lambda x$$



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Lifshitz quantum critical theory supported by an ordered state

$$s_{AdS-BH} \sim T^{(d-\theta)/z}$$

- At finite T , $z \sim \infty$, and quantum criticality is ultralocal

Holography describes new states of matter

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Lifshitz quantum critical theory supported by an ordered state

- Experimental signature: Quantum critical sector

Lots of power law scaling

Holography describes new states of matter

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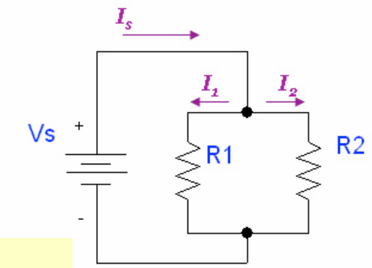
$$t \to \lambda^z t\ , \quad x \to x$$

Lifshitz quantum critical theory supported by an ordered state

- Experimental signature: Thermoelectric response

$$\sigma = \sigma_{ccs} + \sigma_{relax}$$



Inverse Matthiessen law: two independent sectors e.g. Anderson, Physics Today 2013

- Hall angle in "strange metals"

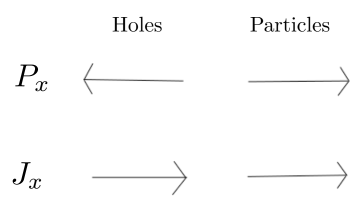
$$\sigma \sim \frac{1}{T} \qquad \theta_H = \frac{\sigma_{xy}}{\sigma_{xx}} \sim \frac{1}{T^2}$$

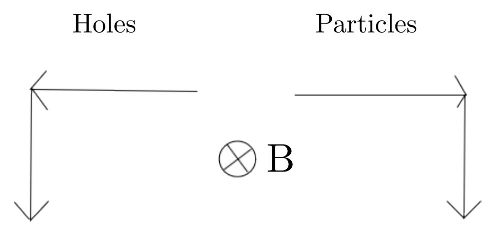
- Theory (e.g. Drude, memory matrix)

$$\sigma \sim \tau \qquad \theta_H \sim \tau$$

- Holography (no quasiparticles)

Blake, Donos
PRL 114 (2015) 021601





$\sigma_{\text{Lif.quant.crit}}$ does not contribute to σ_{xy}

$$\sigma = \sigma_{\text{Lif.quant.crit}} + \sigma_{\text{conv.order}}$$

$$\sigma_{\text{Lif.quant.crit}} \sim \frac{1}{T} \qquad \sigma_{\text{conv.order}} \sim \frac{1}{T^2}$$

- Real life condensed matter systems have
  - No supersymmetry
  - No large N limit
  - No UV CFT

… but can flow to "universal" IR.

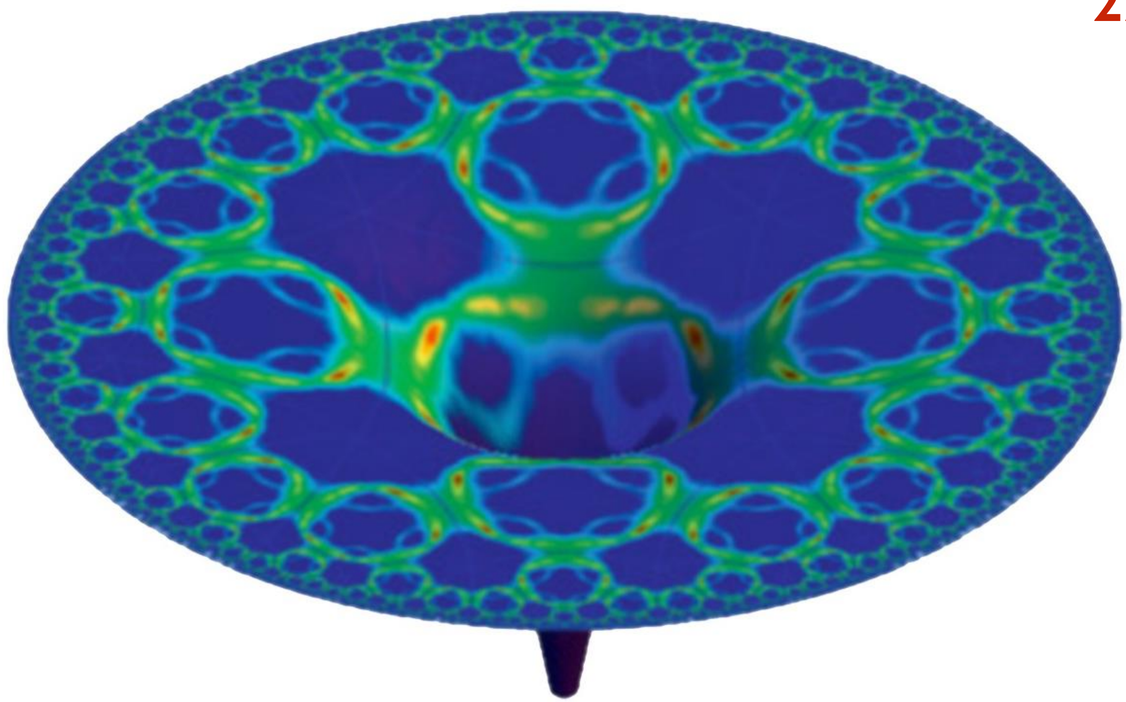
… but can flow to "universal" IR.

- Lifshitz ground states are unstable critical points
  - Semi-local quantum liquids: intermediate "fixed points" Iqbal, Liu, Mezei
  - The systems we will have in mind are similarly unstable
  - Critical sector of the theory has no quasiparticles

Are the high T_c cuprate strange metals
Lifshitz quantum critical theories supported by an ordered state?

1. Title **Strange metals**

2.3 MEur award
22 Nov 2016










N. Hussey M. Golden E. van Heumen M. Allan H. Stoof S. Vandoren K. Schalm J. Zaanen

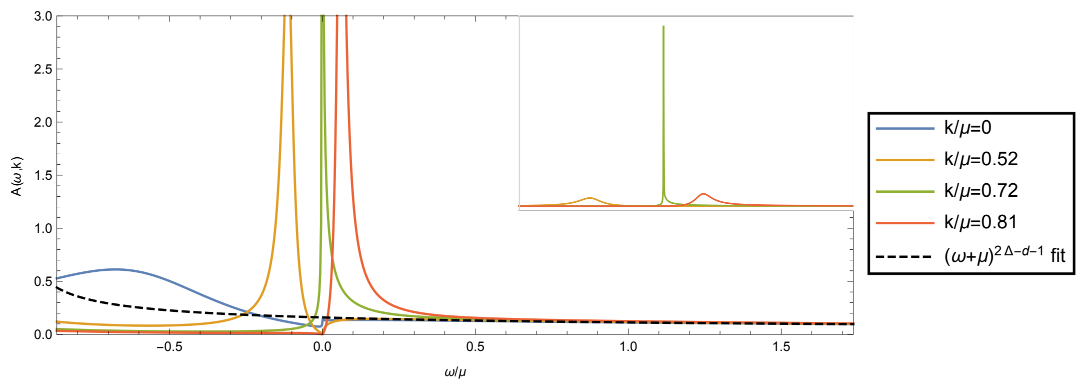
Netherlands Organisation for Scientific Research

- The single fermion function from AdS/CFT

Cubrovic, Zaanen, Schalm; Science 325 (2009) 439
Faulkner, Liu, McGreevy, Vegh PRD 83 (2011) 125002, Science 329 (2010) 1043

$$G(\omega, k) = \frac{1}{\omega - v_F k + \Sigma(\omega, k)}$$

$$A(\omega, k) = -\frac{1}{\pi}\mathrm{Im}G(\omega, k)$$



- The groundstate has a clear Fermi surface

- The single fermion function from AdS/CFT

Cubrovic, Zaanen, Schalm; Science 325 (2009) 439
Faulkner, Liu, McGreevy, Vegh PRD 83 (2011) 125002, Science 329 (2010) 1043

$$G(\omega, k) = \frac{Z}{\omega - v_F(k - k_F) - e^{i\gamma}\omega^{2\nu_{k_F}}} + \ldots$$

- The exponent $\nu_{k_F} \sim \sqrt{\frac{1}{\xi^2} + k_F^2}$ is a free parameter

- Fermi surface excitations disperse as

$$\omega \sim (k - k_F)^z \quad \text{with} \quad z = \begin{cases} 1/2\nu_{k_F} & \nu_{k_F} < 1/2 \\ 1 & \nu_{k_F} = 1/2 \\ 1 & \nu_{k_F} > 1/2 \end{cases}$$

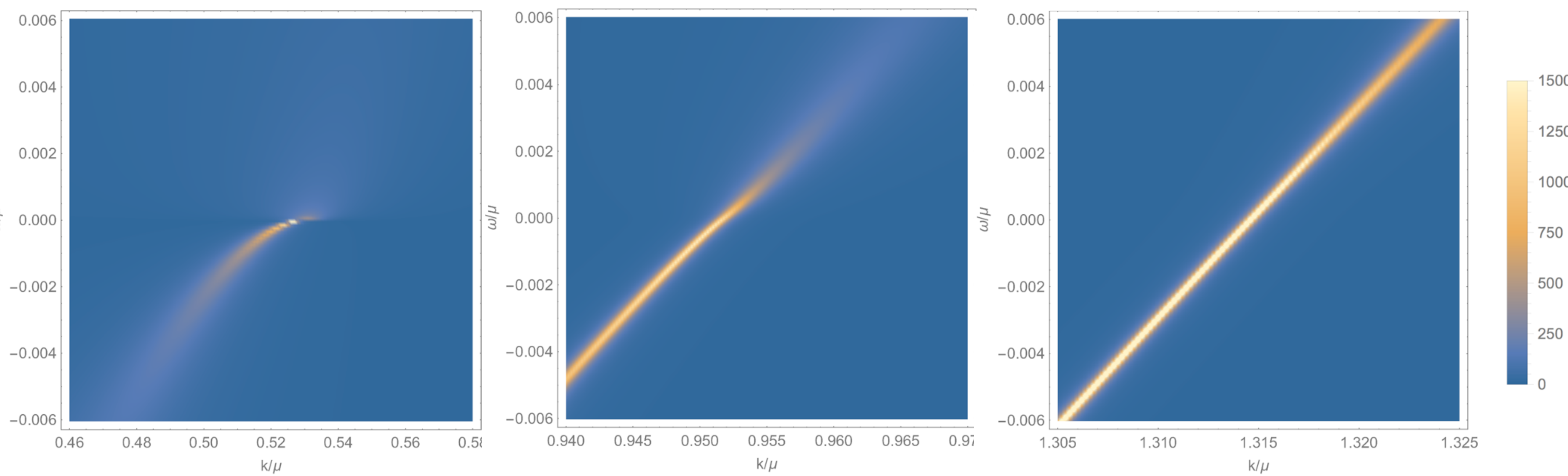
Holographic strange metals

- The single fermion function from AdS/CFT

Cubrovic, Zaanen, Schalm; Science 325 (2009) 439
Faulkner, Liu, McGreevy, Vegh PRD 83 (2011) 125002, Science 329 (2010) 1043

$$G(\omega, k) = \frac{Z}{\omega - v_F(k - k_F) - e^{i\gamma}\omega^{2\nu_{k_F}}} + \dots$$

artificially broadenend

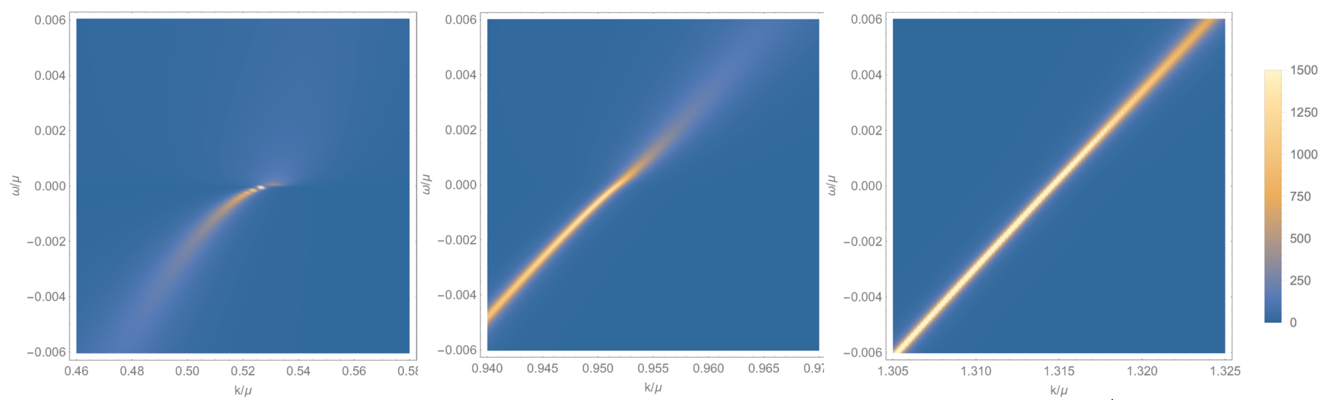


$\nu_{k_F} < 1/2$ — Non-Fermi Liquid

$\nu_{k_F} = 1/2$ — Marginal Fermi Liquid

$\nu_{k_F} > 1/2$ — Fermi Liquid

Holographic strange metals

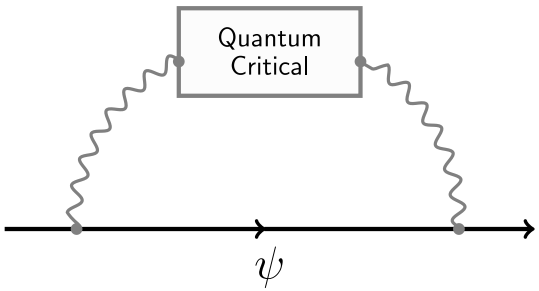


$\nu_{k_F} < 1/2$ $\nu_{k_F} = 1/2$ $\nu_{k_F} > 1/2$

$\Sigma \sim \omega^{2\nu_{k_F}}$

- The $\nu_{k_F} < 1/2$ NFL is a system *without* quasiparticles

- Physics: the probe fermion interacts with a quantum critical sector



- Transport does not follow from FS excitations (alone). The quantum critical sector contributes significantly

arXiv.org > cond-mat > arXiv:1509.01611

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Condensed Matter > Strongly Correlated Electrons

Power Law Liquid - A Unified Form of Low-Energy Nodal Electronic Interactions in Hole Doped Cuprate Superconductors

T.J. Reber, X. Zhou, N.C. Plumb, S. Parham, J.A. Waugh, Y. Cao, Z. Sun, H. Li, Q. Wang, J.S. Wen, Z.J. Xu, G. Gu, Y. Yoshida, H. Eisaki, G.B. Arnold, D. S. Dessau

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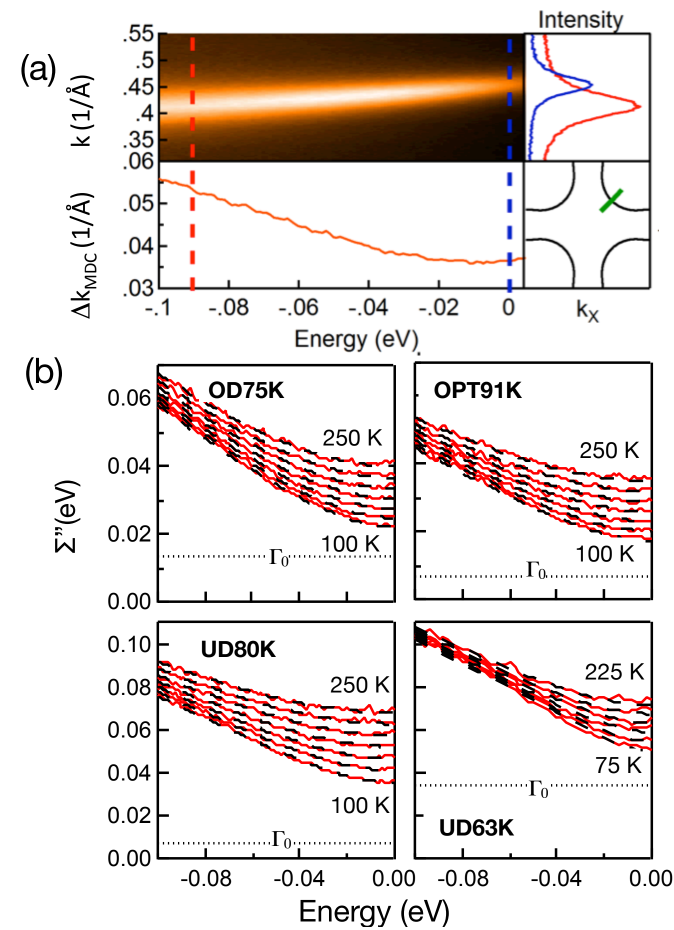
This situation changed recently with the introduction of ultra-resolution laser-ARPES [18] ..., which bypasses the unknowns of the ARPES lineshape and removes much of the effects of the heterogeneous “dirt” effects that are for example observed in STM experiments [22] (see supplementary materials). Combined with new methods for removing nonlinearities in the electron detection [23], a quantitative analysis of the small ... or scattering rates (a self-energy effect) ... in an ARPES measurement.



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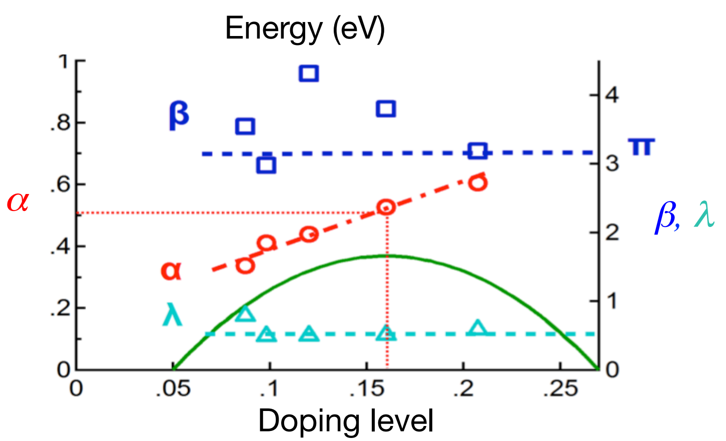
- Holographic prediction

$$\Sigma \sim \omega^{2\nu_{k_F}}$$

- Experimental fit to

$$\Sigma = \lambda(\omega^2 + \beta^2 T^2)^\alpha$$

(c)



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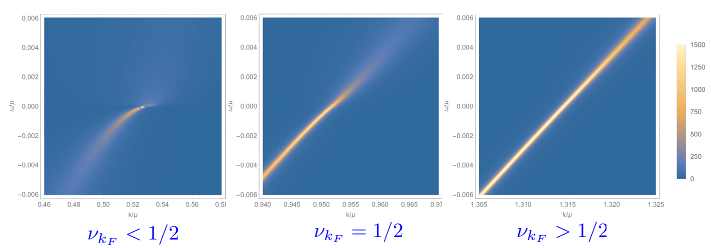

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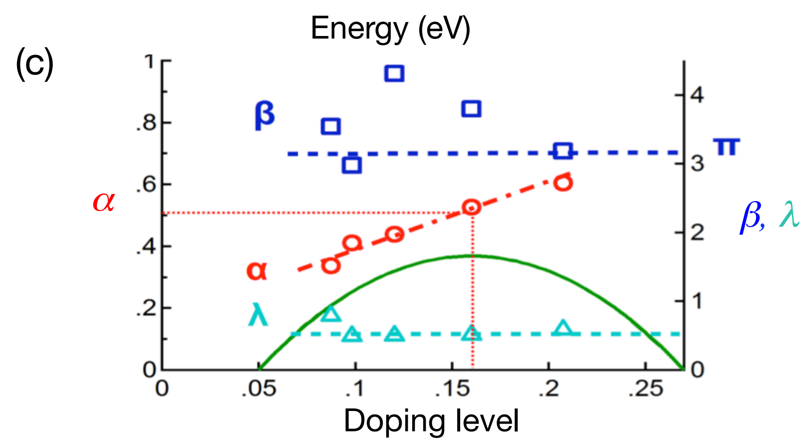
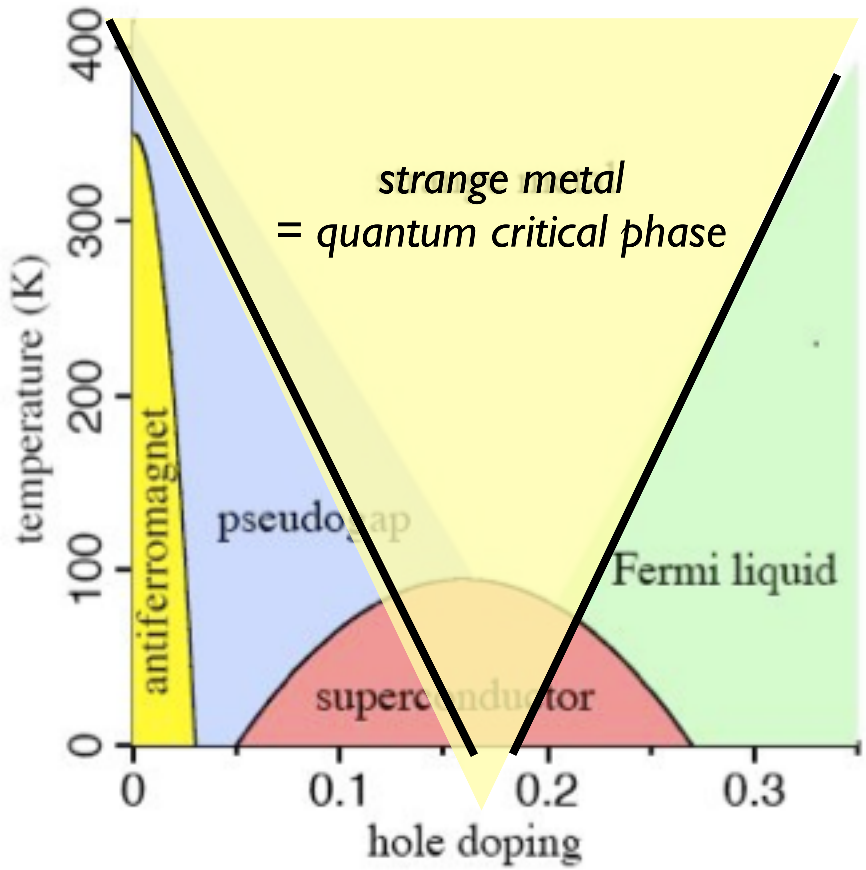


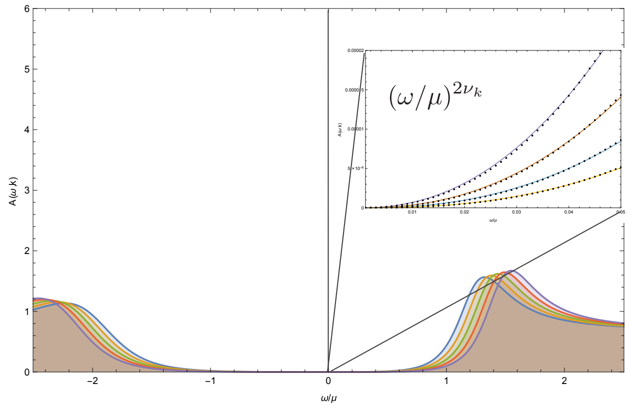
The strange metal in high Tc cuprates



Two specific predictions from holography

- Evidence of the quantum critical sector in the spectral function

Faulkner, Liu, McGreevy, Vegh
PRD 83 (2011) 125002,
Science 329 (2010) 1043
Gauntlett, Sonner, Waldram
JHEP 1111 (2011) 153



- Near $\omega = 0$ for $k \neq k_F$

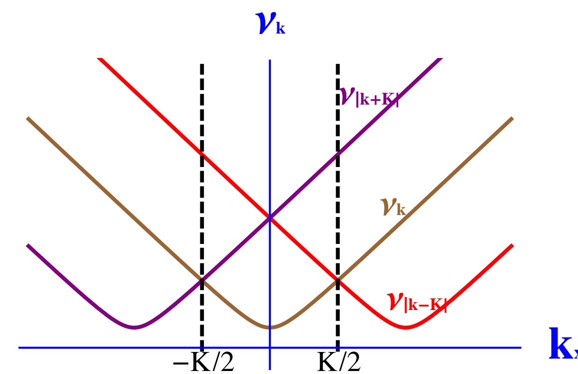
$$\mathrm{Im}G(\omega, k) \sim \omega^{2\nu_k} \qquad \nu_k \sim \sqrt{\frac{1}{\xi^2} + k^2}$$

- The quantum critical contribution to the spectral function

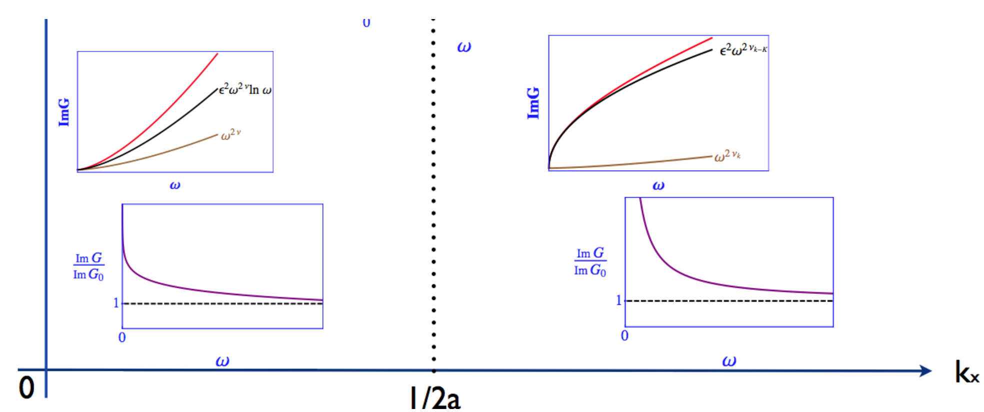
$$\mathrm{Im}G(\omega,k) \sim \omega^{2\nu_k} \qquad \nu_k \sim \sqrt{\frac{1}{\xi^2}+k^2}$$

- On a lattice

$$\mathrm{Im}G_{\mathrm{lattice}}(\omega,k) \sim \sum_{k\in\Lambda} \omega^{2\nu_k}$$



- The Green's function is no longer strictly periodic



Liu, Schalm, Sun, Zaanen,
JHEP 1210 (2012) 036

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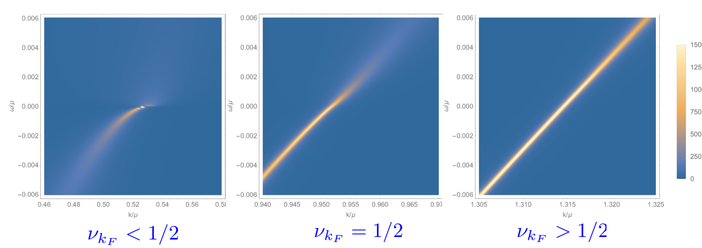
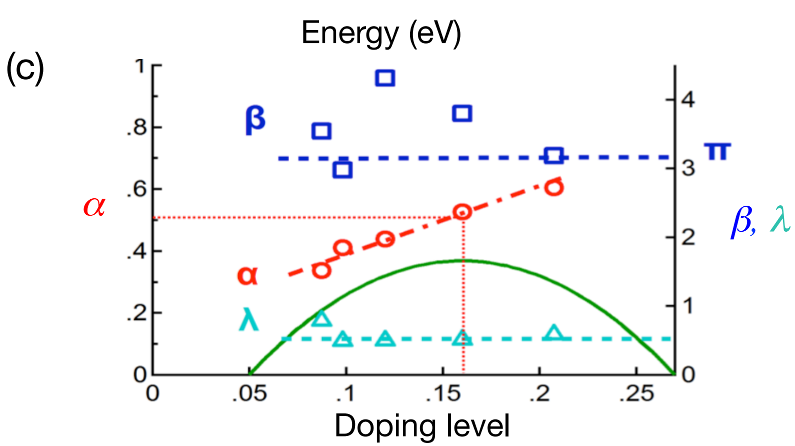


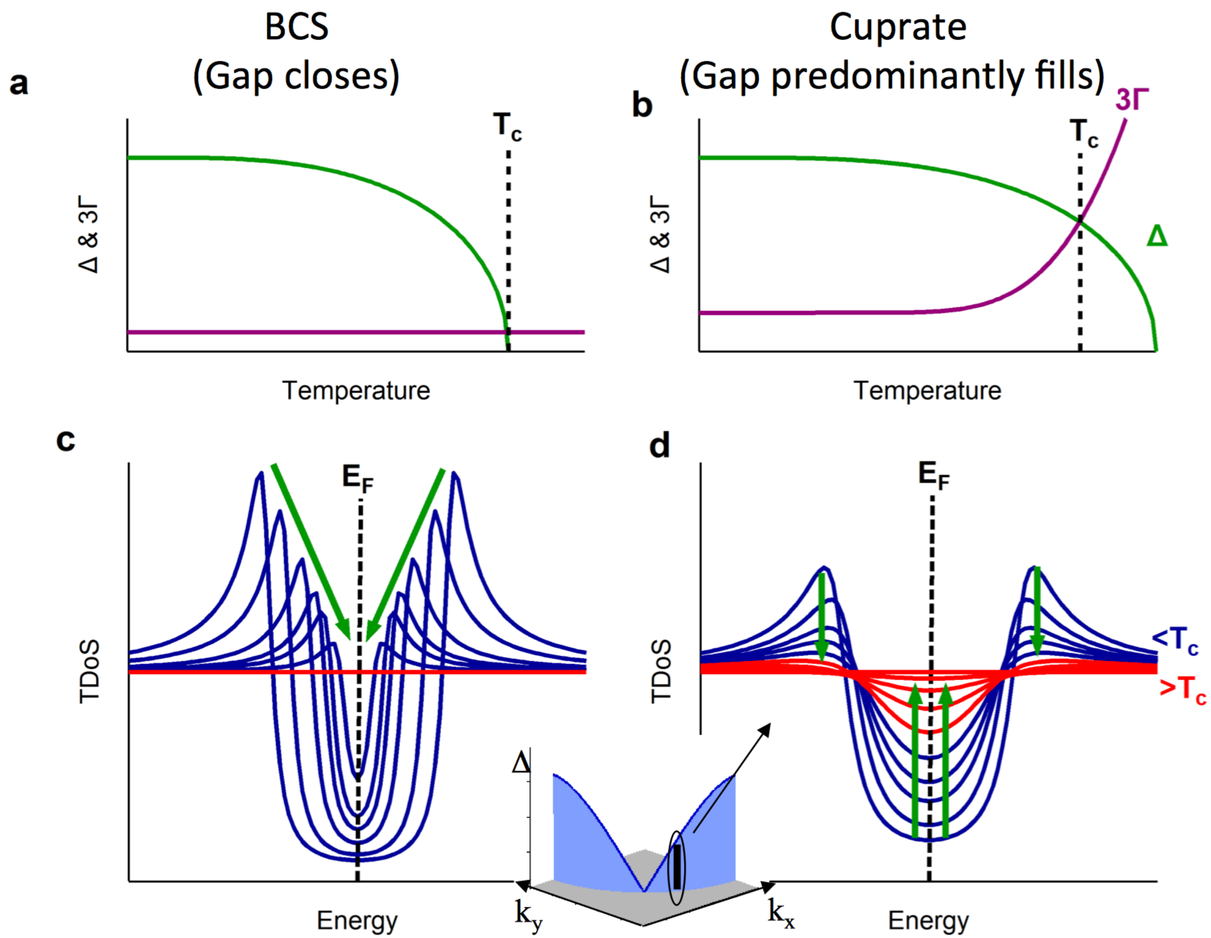
- Experimental fit to

$$\Sigma = \lambda(\omega^2 + \beta^2 T^2)^\alpha$$



Comparison to Experiment:
Dynamics of the superconducting gap

- In the superconducting state, fermionic quasiparticles are gapped



$$\Delta_{BCS} \sim \langle \mathcal{O} \rangle \sim T^{\alpha} \qquad \Delta_{Hol} \sim 1$$

Condensed Matter > Superconductivity

Pairing, pair-breaking, and their roles in setting the Tc of cuprate high temperature superconductors

T. J. Reber, S. Parham, N. C. Plumb, Y. Cao, H. Li, Z. Sun, Q. Wang, H. Iwasawa, M. Arita, J. S. Wen, Z. J. Xu, G.D. Gu, Y. Yoshida, H. Eisaki, G.B. Arnold, D. S. Dessau

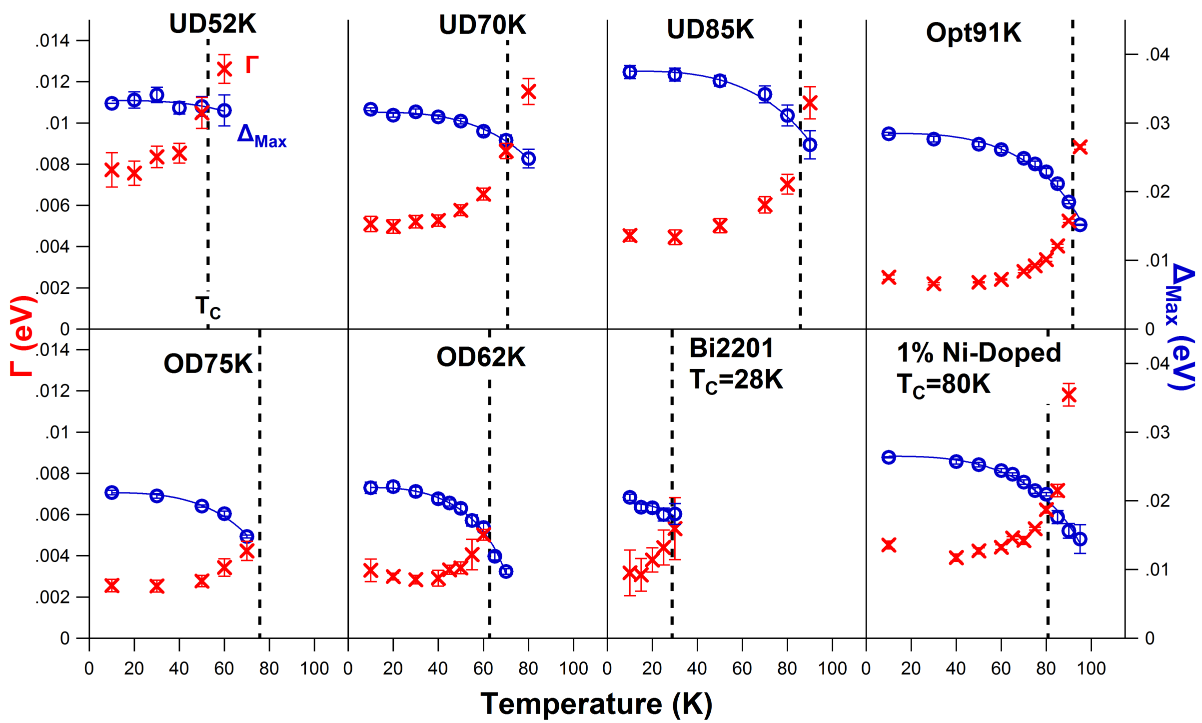


Fig 2. A compilation of Δ_{Max} (left axis) and Γ (right axis) for the 8 samples shown in figure 1, from fits to TDoS data over a full grid of many temperatures and angles (see for example Fig S1 for a grid on one sample). Δ_{Max} is the d-wave maximum superconducting gap determined from the near-nodal data (e.g. v_Δ) while Γ is the average zero-frequency pair-breaking self energy over the near-nodal region. Error bars are shown in all cases though are difficult to see when they are smaller than the symbol size.

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Condensed Matter > Superconductivity

Pairing, pair-breaking, and their roles in setting the Tc of cuprate high temperature superconductors

T. J. Reber, S. Parham, N. C. Plumb, Y. Cao, H. Li, Z. Sun, Q. Wang, H. Iwasawa, M. Arita, J. S. Wen, Z. J. Xu, G.D. Gu, Y. Yoshida, H. Eisaki, G.B. Arnold, D. S. Dessau

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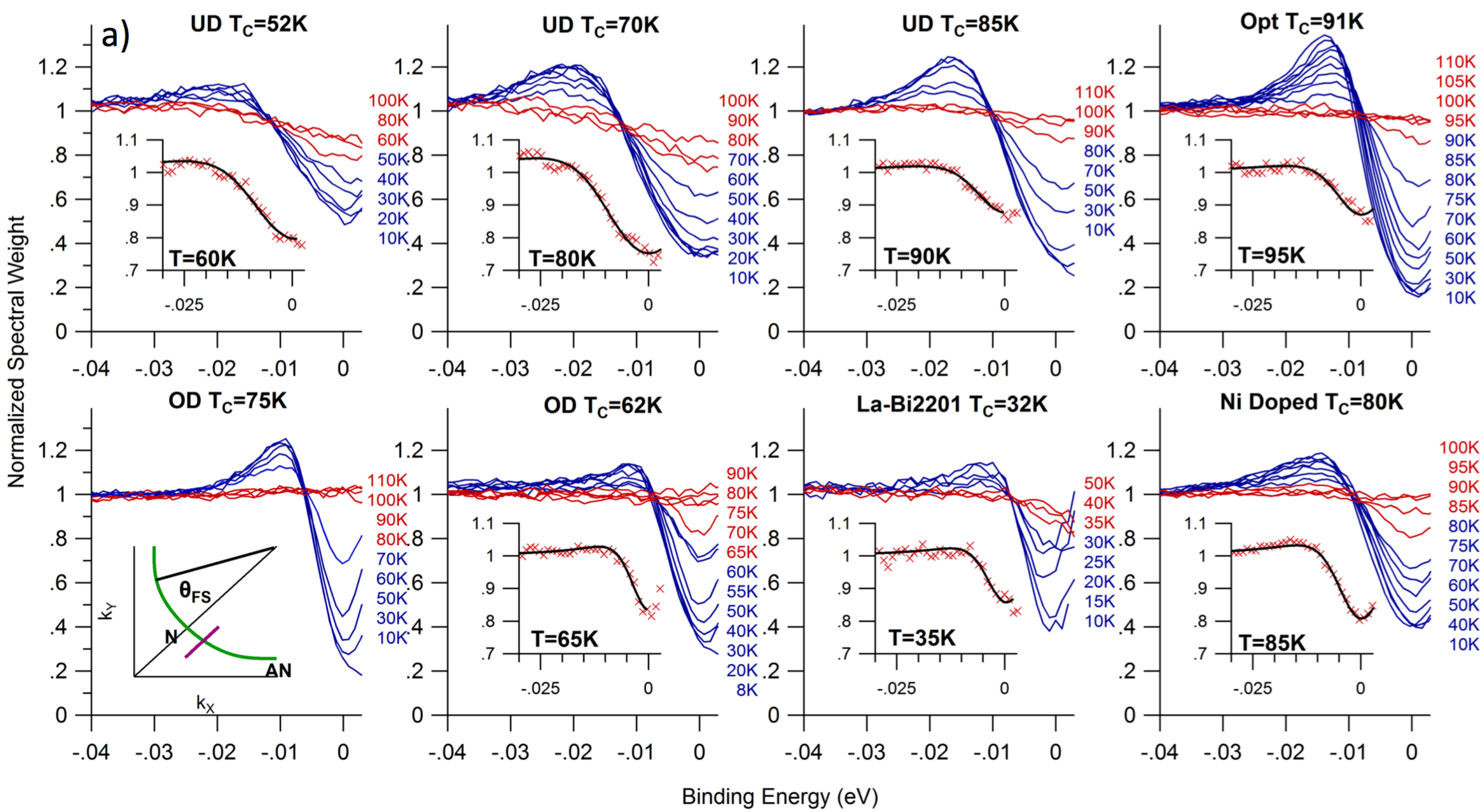


- In the superconducting state, massive fermionic quasiparticles

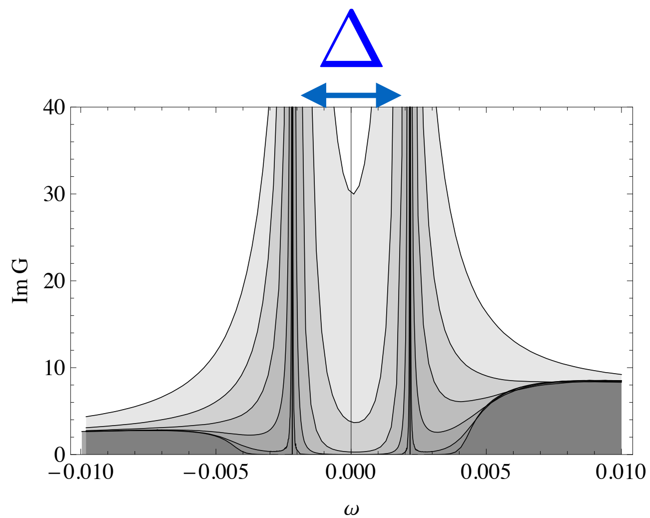
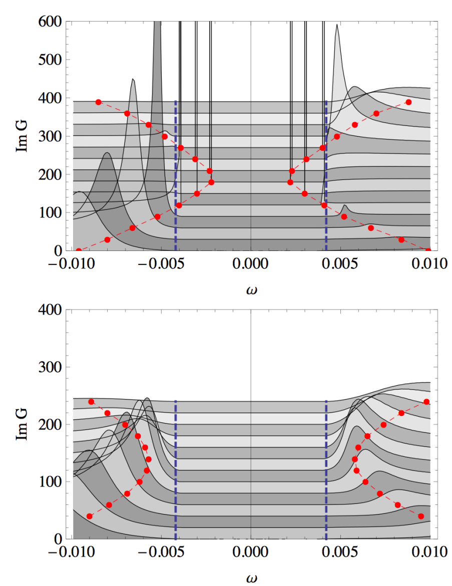
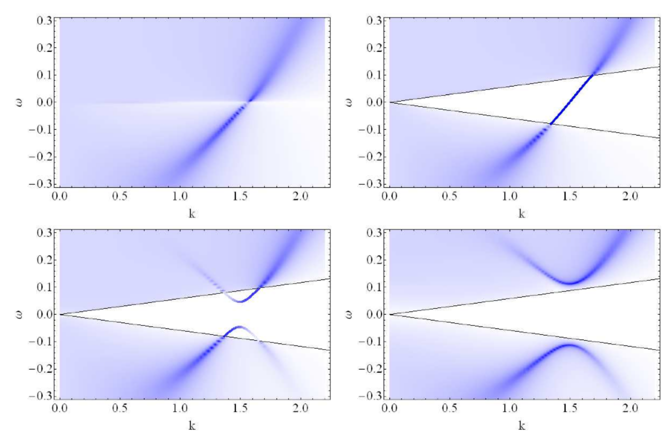


FIG. 7: The effect of temperature (much less than T_c) on the fermion spectral function. Shown are plots at $q_\varphi = 1, m_\varphi^2 = -1, q_\zeta = \frac{1}{2}, m_\zeta = 0, \eta_5 = .025$, and momenta where the peak is closest to $\omega = 0$. The different curves correspond to different temperatures approaching $T = 0$.

$$\Delta_{BCS} \sim \langle \mathcal{O} \rangle \sim T^\alpha$$

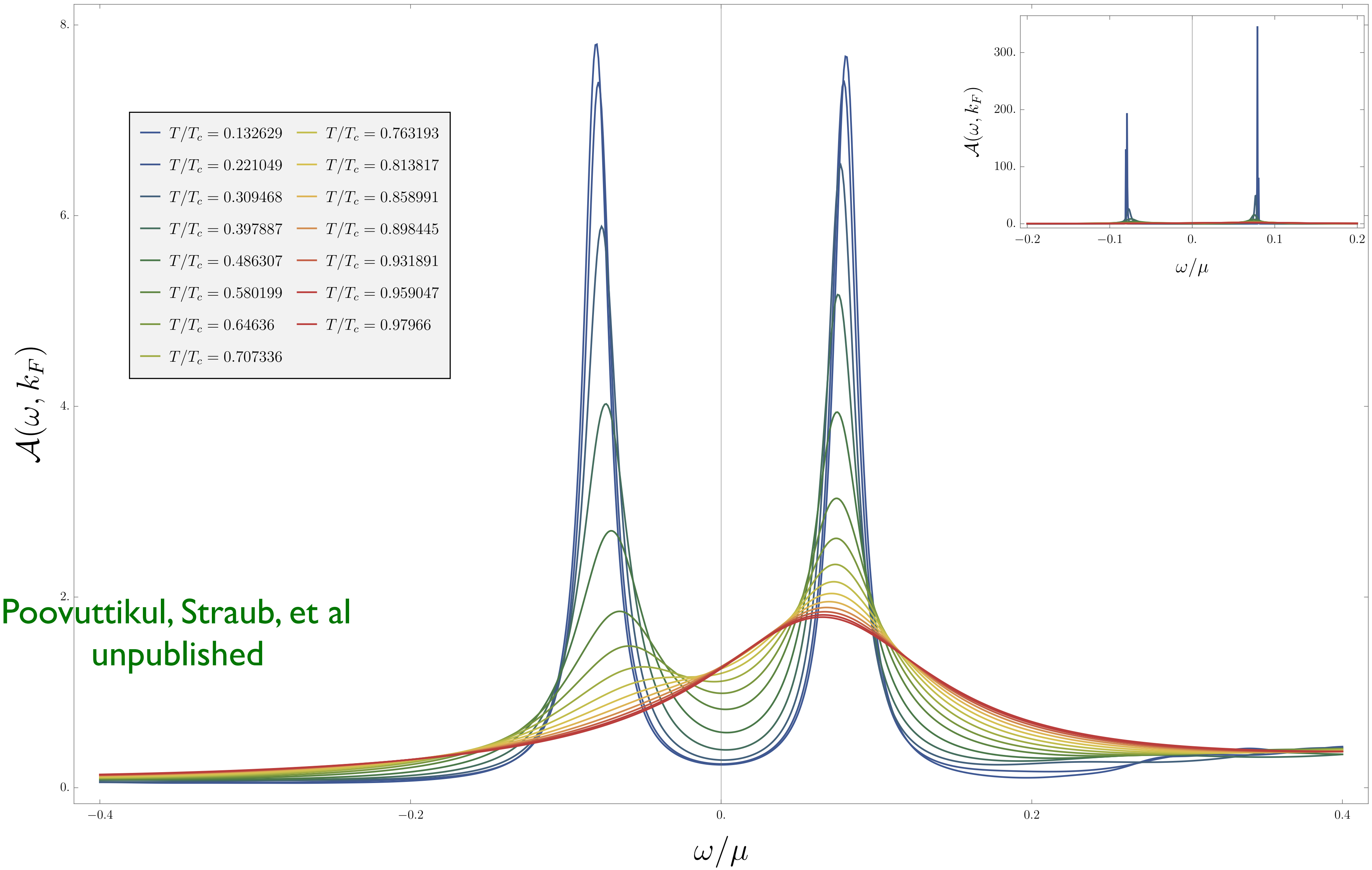
$$\Delta_{Hol} \sim 1$$





Faulkner, Horowitz, McGreevy, Roberts, Vegh

Spectral function at $\eta_5 = 0.25$

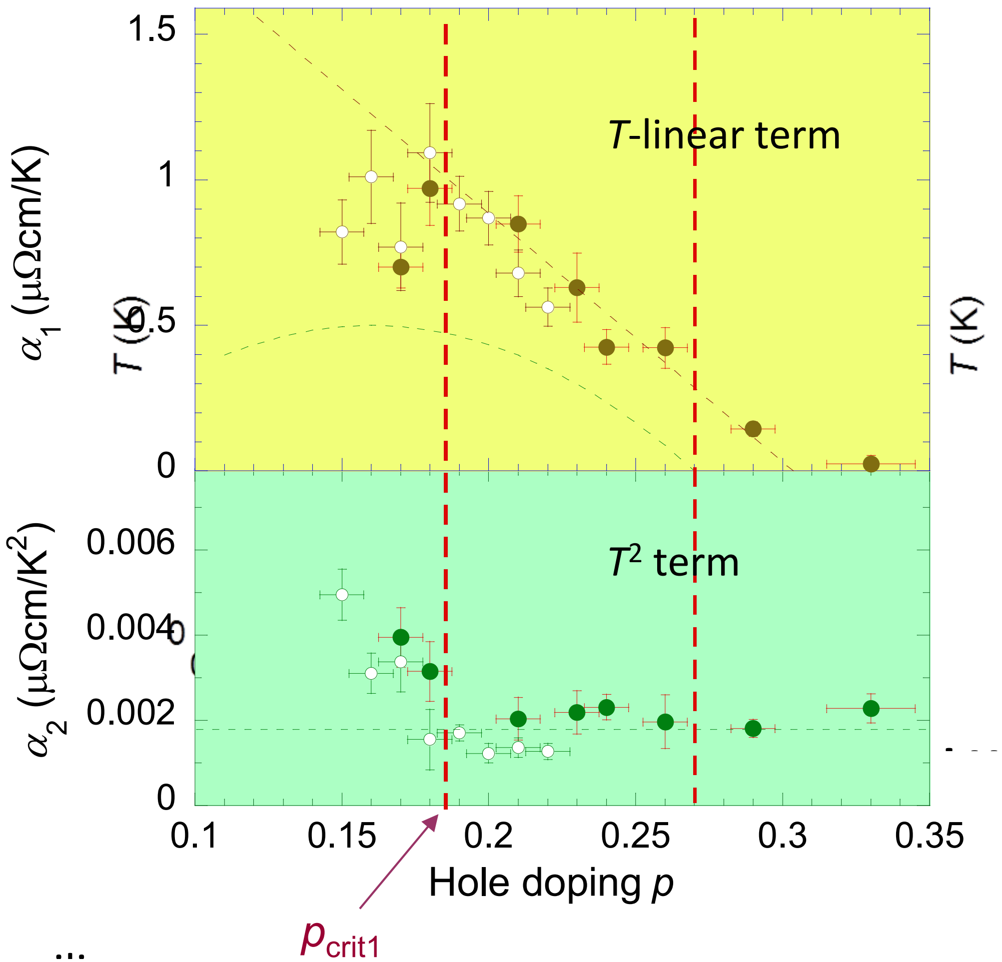


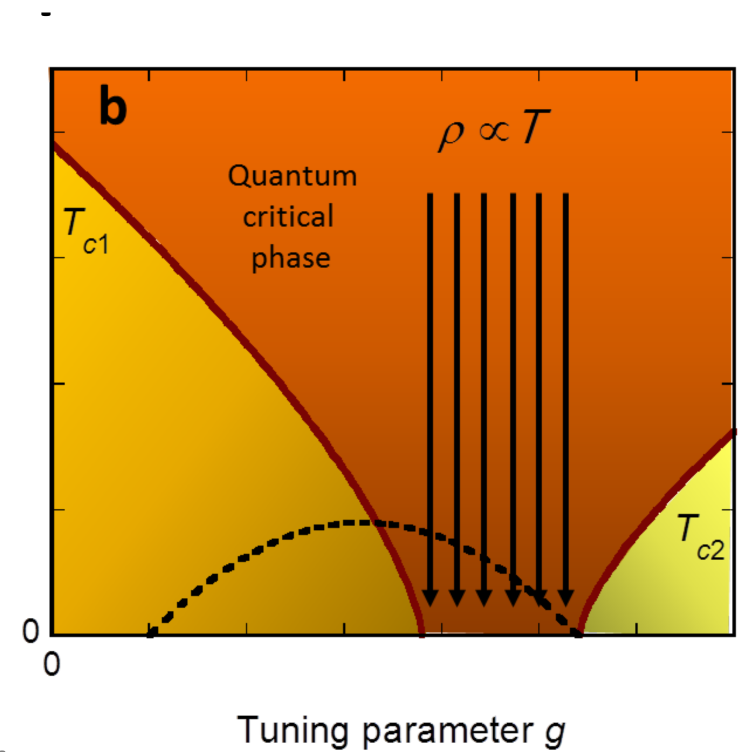
Poovuttikul, Straub, et al
unpublished

A universal linear resistivity

- Linear resistivity in the High-Tc cuprates

Cooper, Hussey et al.
Science 323 (2009) 609





...

$$\rho = \alpha_1 T + \alpha_2 T^2$$

- Linear resistivity in the High-Tc cuprates

Cooper, Hussey et al.
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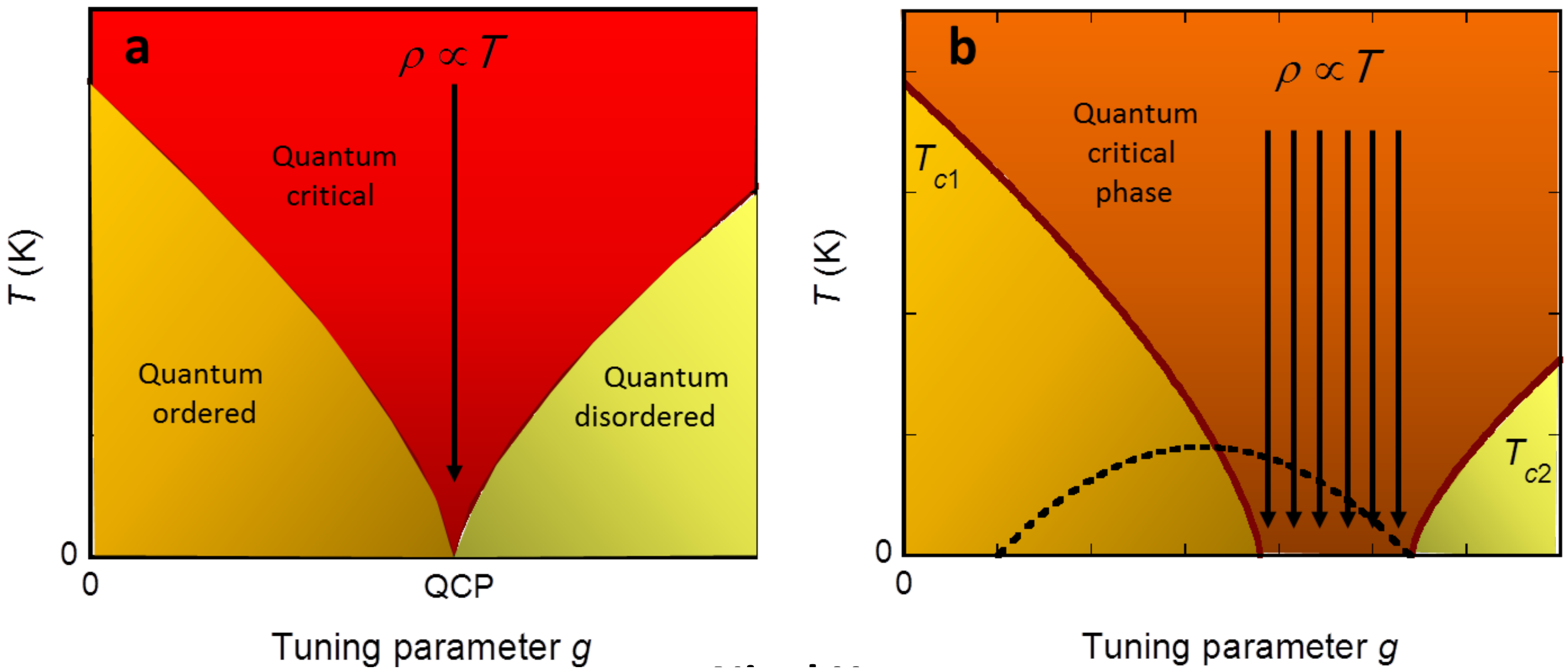


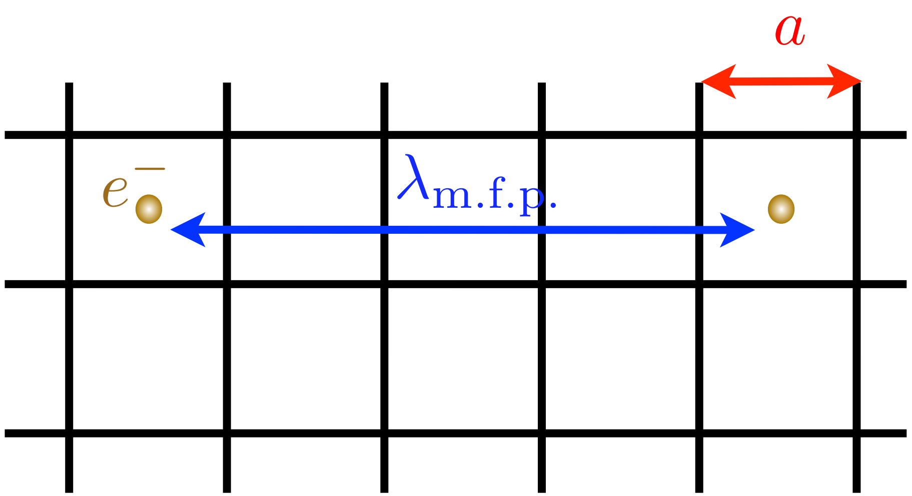
$$\rho = \alpha_1 T + \alpha_2 T^2$$

Inverse Matthiessen law also fits the data

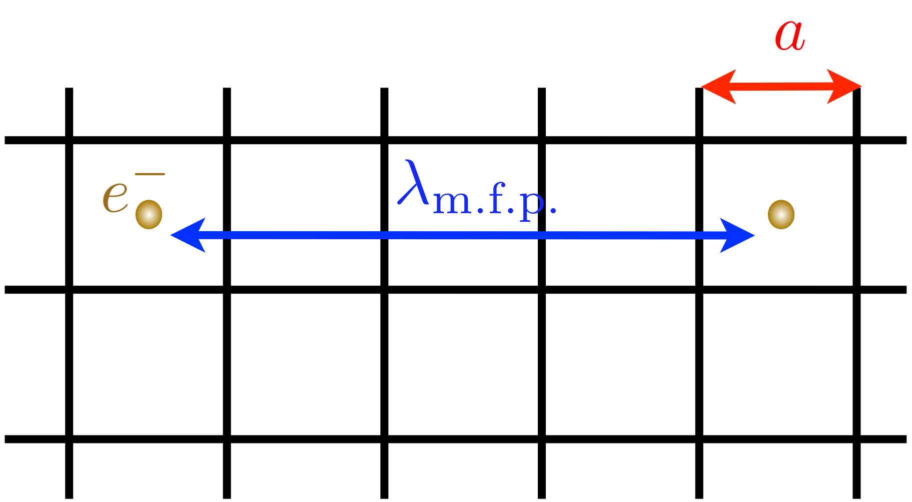
$$\sigma = \frac{\beta_1}{T} + \frac{\beta_2}{T^2}$$

- Ordinary metals
- Momentum relaxes before collective behavior sets in

$\tau_{\text{rel.}}^{-1} \sim \text{micro. physics}$



- Ordinary metals
- Momentum relaxes before collective behavior sets in



$$\tau_{\text{rel.}}^{-1} \sim \text{micro. physics}$$

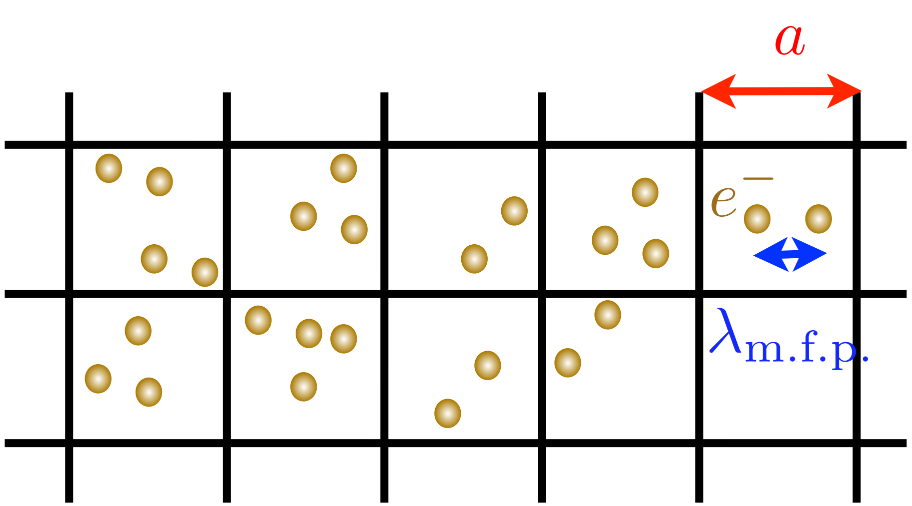
- Strongly correlated metals (no quasiparticles)

$$\lambda_{\text{m.f.p.}} \ll \text{external scales}$$

- Hydro sets in when

$$\lambda_{\text{m.f.p.}} \ll \frac{g_{\text{coupling}}}{T}$$

- Momentum relaxes after collective behavior sets in



$$\tau_{\text{rel.}}^{-1} \sim \text{macro. physics}$$

Resistivity and hydrodynamics

- Hydrodynamics is a universal LEET

Davison, Schalm, Zaanen
PRB89 (2014) 245116
Andreev, Kivelson, Spivak
PRL106 (2011) 256804

$$\rho_{DC} \sim \lim_{\omega \to 0} \int dk k^2 \frac{\mathrm{Im}\langle \mathcal{O}\mathcal{O}\rangle}{\omega}$$

- What choice for the impurity operator $\mathcal{O}$?
- Hydrodynamics: $T_{\mu\nu},\ J_\nu\ +\ \text{"irrelevant" ops}$
- For $\mathcal{O} = T^{00}$

$$\langle T^{00} T^{00} \rangle \sim \frac{1}{\omega^2 - k^2 + i\omega k^2 c_d \frac{\eta}{\epsilon + P} k^2 + \ldots}$$

$$\rho_{DC} \sim \lim_{\omega \to 0} \int dk k (\eta k^2 + \ldots) \sim s(T)$$

$$\eta = \frac{1}{4\pi} s$$

- Caveat: theory must be locally quantum critical $z \simeq \infty$

Lucas, Sachdev, Schalm, PRD89 (2014) 066018
Hartnoll, Mahajan, Punk, Sachdev PRB89 (2014) 155130

A universal mechanism for a linear resistivity

- Entropy density at low T

Davison, Schalm, Zaanen
PRB89 (2014) 245116

- *If* $s(T) \sim T + \ldots$ *Then* $\rho_{DC} \sim s(T) \sim T + \ldots$

Can be confirmed in a massive gravity model of a two-charge AdS black hole

$$S = \frac{1}{2\kappa^2} \int d^4x \sqrt{-g} \left(R - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{3}{2} |\partial_\mu \Phi|^2 + \frac{6}{L^2} \cosh \Phi - \frac{1}{2} m^2 (\mathrm{Tr}(\mathcal{K})^2 - \mathrm{Tr}(\mathcal{K}^2)) \right)$$

$$s_{BH} \sim T\mu + \ldots$$

- Universal linear-in-T resistivity from hydro + disorder

$$\rho_{DC} \sim T + \ldots$$

- Caveat: holography has many other "linear resistivity" scenarios

Resistivity and hydrodynamics

- Hydrodynamics is a universal LEET

$$\rho_{DC} \sim \lim_{\omega\to 0} \int dk k^2 \frac{\mathrm{Im}\langle \mathcal{O}\mathcal{O}\rangle}{\omega}$$

- What choice for the impurity operator $\mathcal{O}$?
- Hydrodynamics: $T_{\mu\nu},\ J_\nu\ +\ \text{"irrelevant" ops}$
- Full thermoelectric transport for $\mathcal{O}$ conserved current.

$\mathcal{O} = T^{00}$	*strange metal?*	Davison, Schalm, Zaanen Andreev, Kivelson, Spivak
$\mathcal{O} = J^0$	*charge disorder graphene*	Lucas, Lucas, Crossno, Fong, Kim, Sachdev
$\mathcal{O} = T^{0i}$	*strain disorder graphene*	Lucas, Schalm, Scopelliti, Schalm

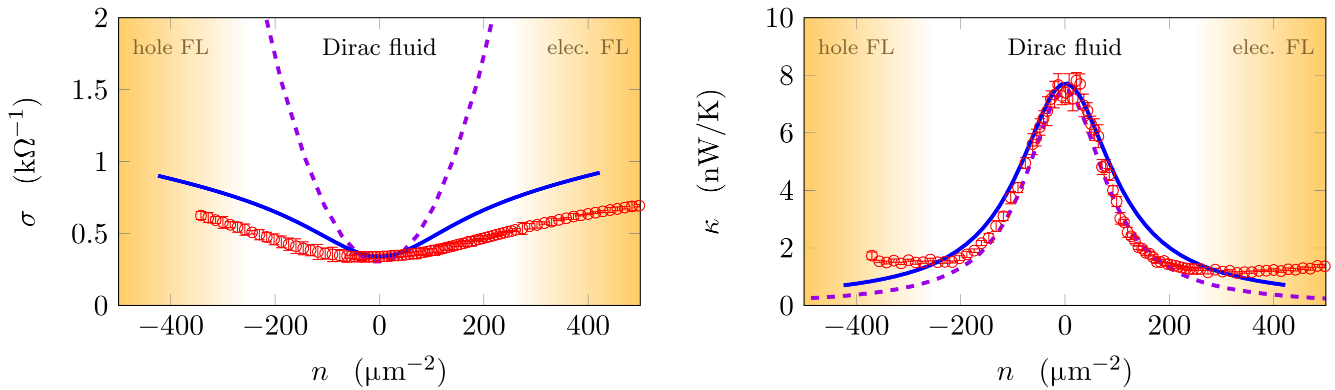


Figure 1: A comparison of our hydrodynamic theory of transport with the experimental results of [33] in clean samples of graphene at $T = 75$ K. We study the electrical and thermal conductances at various charge densities n near the charge neutrality point. Experimental data is shown as circular red data markers, and numerical results of our theory, averaged over 30 disorder realizations, are shown as the solid blue line. Our theory assumes the equations of state described in (27) with the parameters $C_0 \approx 11$, $C_2 \approx 9$, $C_4 \approx 200$, $\eta_0 \approx 110$, $\sigma_0 \approx 1.7$, and (28) with $u_0 \approx 0.13$. The yellow shaded region shows where Fermi liquid behavior is observed and the Wiedemann-Franz law is restored, and our hydrodynamic theory is not valid in or near this regime. We also show the predictions of (2) as dashed purple lines, and have chosen the 3 parameter fit to be optimized for $\kappa(n)$.

Observation of the Dirac fluid and the breakdown of the Wiedemann-Franz law in graphene

Jesse Crossno,[1,2] Jing K. Shi,[1] Ke Wang,[1] Xiaomeng Liu,[1] Achim Harzheim,[1] Andrew Lucas,[1] Subir Sachdev,[1,3] Philip Kim,[1,2,*] Takashi Taniguchi,[4] Kenji Watanabe,[4] Thomas A. Ohki,[5] and Kin Chung Fong[5,†]

[1] *Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[2] *John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA*
[3] *Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*
[4] *National Institute for Materials Science, Namiki 1-1, Tsukuba, Ibaraki 305-0044, Japan*
[5] *Raytheon BBN Technologies, Quantum Information Processing Group, Cambridge, Massachusetts 02138, USA*
(Dated: September 17, 2015)

Crossno, Kim et al.
Lucas, Crossno, Fong, Kim, Sachdev

Evidence for hydrodynamic electron flow in $PdCoO_2$

Philip J. W. Moll, [1,2,3] Pallavi Kushwaha, [3] Nabhanila Nandi, [3]
Burkhard Schmidt, [3] Andrew P. Mackenzie, [3,4*]

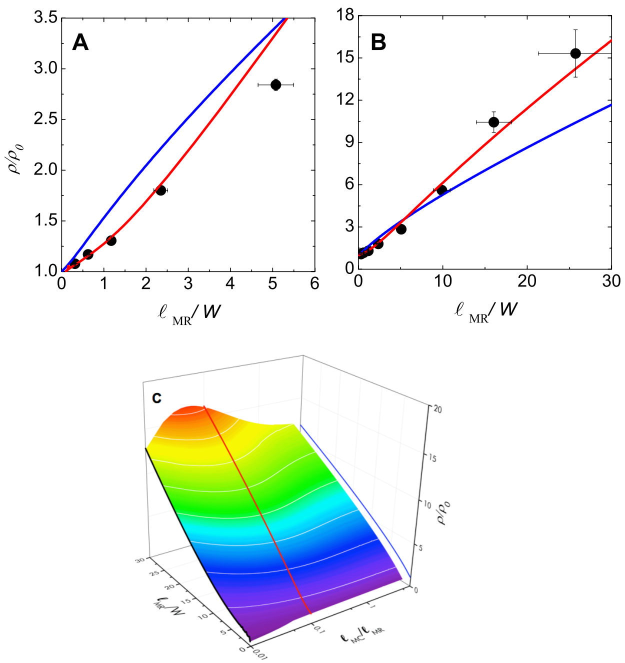


Fig. 4. Hydrodynamic effect on transport. (A, B) The measured resistivity of $PdCoO_2$ channels normalised to that of the widest channel (ρ_0), plotted against the inverse channel width $1/W$ multiplied by the bulk momentum- relaxing mean free path ℓ_{MR} (closed black circles). Blue solid line: prediction of a standard Boltzmann theory including boundary scattering but neglecting momentum-conserving collisions (Red line:prediction of a model that includes the effects of momentum-conserving scattering (see text). In (C) we show the predictions of the hydrodynamic theory over a wide range of parameter space.

Negative local resistance due to viscous electron backflow in graphene

D. A. Bandurin[1], I. Torre[2,3], R. Krishna Kumar[1,4], M. Ben Shalom[1,5], A. Tomadin[6], A. Principi[7], G. H. Autor
E. Khestanova[1,5], K. S. Novoselov[5], I. V. Grigorieva[1], L. A. Ponomarenko[1,4], A. K. Geim[1], M. Polini[3]

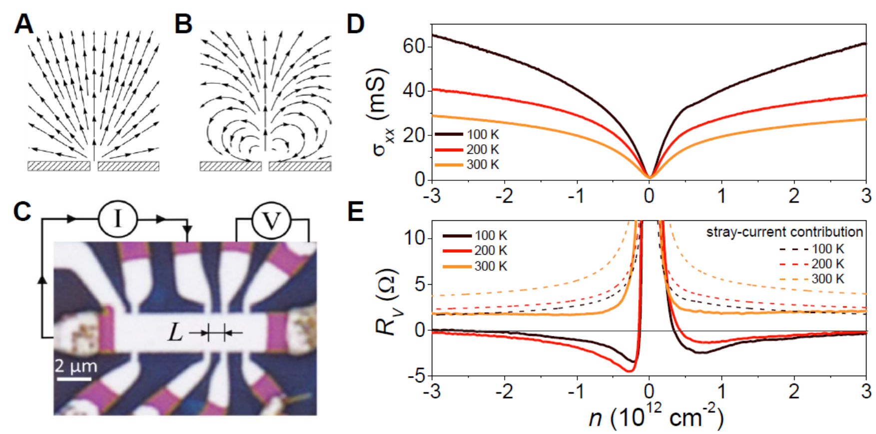


Fig. 1. Viscous backflow in doped graphene. (**A,B**) Calculated steady-state distribution of current injected through a narrow slit for a classical conducting medium with zero ν (A) and a viscous Fermi liquid (B). (**C**) Optical micrograph of one of our SLG devices. The schematic explains the measurement geometry for vicinity resistance. (**D,E**) Longitudinal conductivity σ_{xx} and R_V as a function of n induced by applying gate voltage. $I = 0.3$ μA; $L = 1$ μm. The dashed curves in (E) show the contribution expected from classical stray currents in this geometry (*18*).

- Most characteristic aspect of viscous flow

Negative local resistance due to viscous electron backflow in graphene

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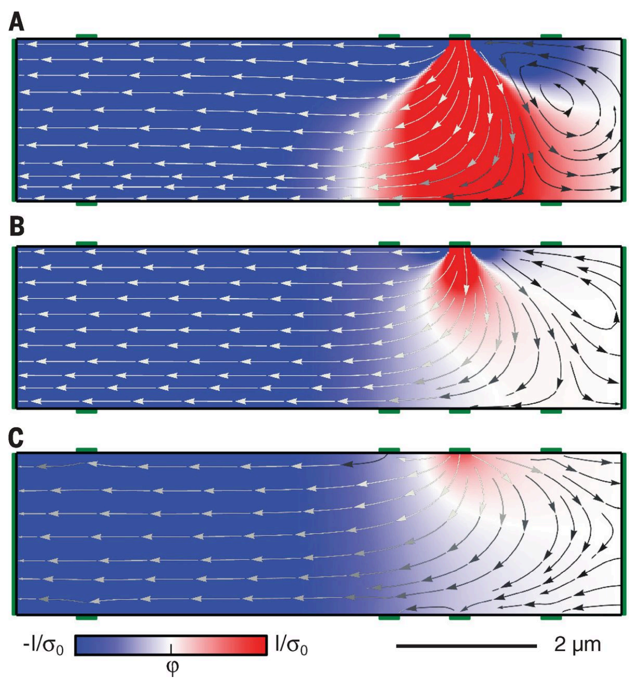


Turbulence

$$Re = \frac{\rho v L}{\eta}$$

Navier-Stokes fluid

$$Re = \frac{s}{\eta}\frac{T L v}{c^2}$$

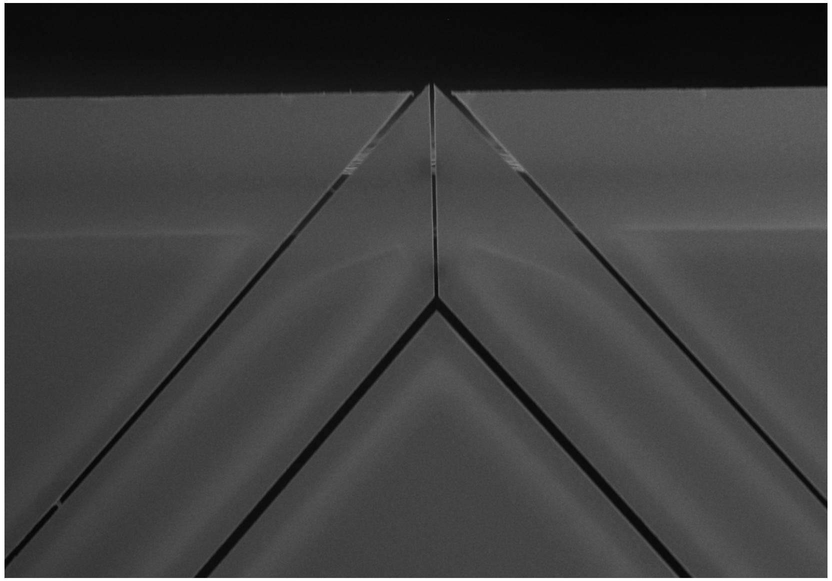
Mueller, Schmalian, Fritz

Graphene

- Most characteristic aspect of viscous flow

Turbulence in strange metals:
Relative flow patterns with double tip STM

M. Allan;
see J. Zaanen's talk tomorrow



Turbulence

$$Re = \frac{\rho v L}{\eta}$$

Navier-Stokes fluid

$$Re = \frac{s}{\eta} \frac{T L v}{c^2}$$

Mueller, Schmalian, Fritz

Graphene

Lucas....

Lucas, Schalm, Scopelliti, Schalm

- Microscopic transport: viscosities $\eta, \ \zeta$ plus microscopic cond. σ_Q

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu + Pg^{\mu\nu} - 2\eta \mathcal{P}^{\mu\rho}\mathcal{P}^{\nu\sigma}\nabla_{(\rho}u_{\sigma)} - \mathcal{P}^{\mu\nu}\left(\zeta - \frac{2\eta}{d}\right)\nabla_\rho u^\rho,$$

$$J^\mu = nu^\mu - \sigma_{\mathrm{Q}}\mathcal{P}^{\mu\nu}\left(\partial_\mu \mu - \frac{\mu}{T}\partial_\nu T - F_{\nu\rho,\mathrm{ext}}u^\rho\right)$$

- No thermal conductivity without charge current $\sigma_Q = 0$
  - Can we trust the result

$$\rho_{DC} \sim \lim_{\omega \to 0} \int dkk(\eta k^2 + \ldots) \sim s(T) \ \sim T$$

- Microscopic transport: viscosities $\eta,\ \zeta$ plus microscopic cond. σ_Q

$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu + Pg^{\mu\nu} - 2\eta\mathcal{P}^{\mu\rho}\mathcal{P}^{\nu\sigma}\nabla_{(\rho}u_{\sigma)} - \mathcal{P}^{\mu\nu}\left(\zeta - \frac{2\eta}{d}\right)\nabla_\rho u^\rho,$$

$$J^\mu = nu^\mu - \sigma_{\mathrm{Q}}\mathcal{P}^{\mu\nu}\left(\partial_\mu\mu - \frac{\mu}{T}\partial_\nu T - F_{\nu\rho,\mathrm{ext}}u^\rho\right)$$

- No thermal conductivity without charge current $\sigma_Q = 0$
  - Can we trust the result

$$\rho_{DC} \sim \lim_{\omega\to 0}\int dkk(\eta k^2 + \ldots) \sim s(T)\ \sim T$$

  - For neutral/strain disorder σ_Q does not play a role.

Scale-invariant magnetoresistance in a cuprate superconductor

P. Giraldo-Gallo, J. A. Galvis, Z. Stegen, K. A. Modic, F. F Balakirev, J. B. Betts, X. Lian, C. Moir, S. C. Riggs, J. Wu, A. T. Bollinger, X. He, I. Bozovic, B. J. Ramshaw, R. D. McDonald, G. S. Boebinger, A. Shekhter

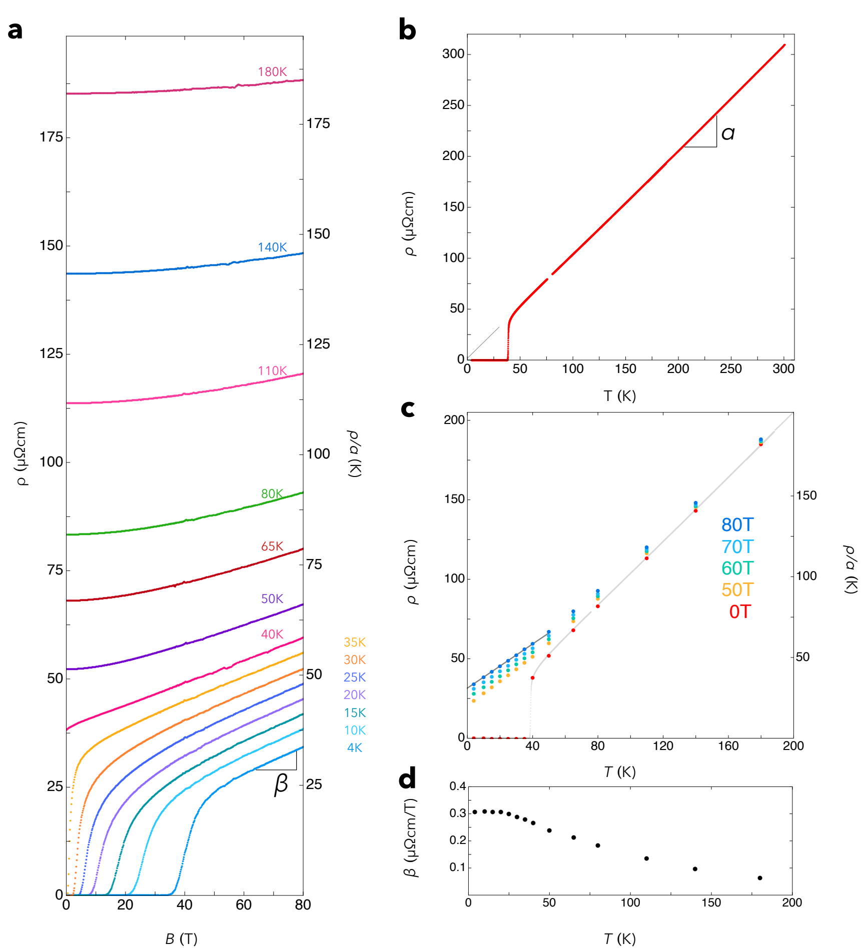


Figure 1. Magnetoresistance up to 80T of the thin-film $La_{2-x}Sr_xCuO_4$ at $x = 0.190$. **a** Field scans up to 80T for a set of temperatures up to 180K. The vertical ticks on the right indicate the resistivity in temperature units, ρ/α, obtained using linear fit in panel **b**. The aspect ratio is such that 1inch either horizontally or vertically represent the same value in natural energy units, $\mu_B B$ and $k_B T$ (80T corresponds approximately to 53.7K). **b** Zero-field resistivity in a broad temperature range up to room temperature. The gray line indicates a linear-fit for resistivity above superconducting transition temperature, T_c, $\rho = a + \alpha T$, where the intercept $a \approx 1.5(\pm 1.5)\mu\Omega\text{cm}$ and the temperature-slope $\alpha \approx 1.02(\pm 0.01)\mu\Omega\text{cm/K}$. The uncertainty in a, α reflects variation in a running slope analysis over broad temperature range. **c** Temperature dependence of resistivity at fixed field (indicated by color legend). Gray points indicate the zero-field resistivity from panel a. The vertical ticks on the right indicate the resistivity in units of temperature, ρ/α, same as in panel a. The solid line through a set of 80T points at low temperatures is a guide for the eye. **d** Temperature dependence of field-slope of resistivity at fixed field (calculated as linear regression for $65T < B < 77T$ field range). The slope saturates below about 25K.

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Condensed Matter > Strongly Correlated Electrons

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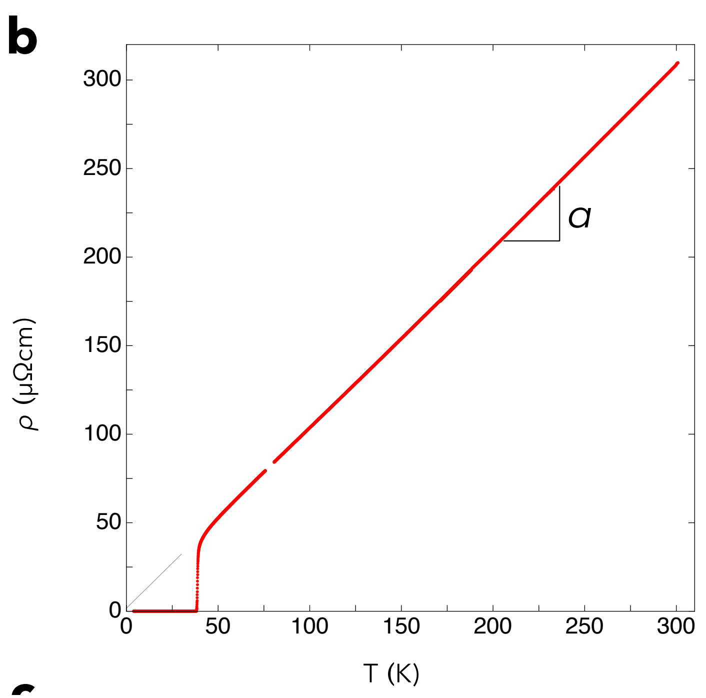

Intercept at T=0 is at $\rho = 0$
to *very high* precision

$$\rho_{DC} \sim \lim_{\omega\to 0} \int dk k(\eta k^2 + \ldots) \sim s(T) \quad \sim T$$

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Condensed Matter > Strongly Correlated Electrons

Scale-invariant magnetoresistance in a cuprate superconductor

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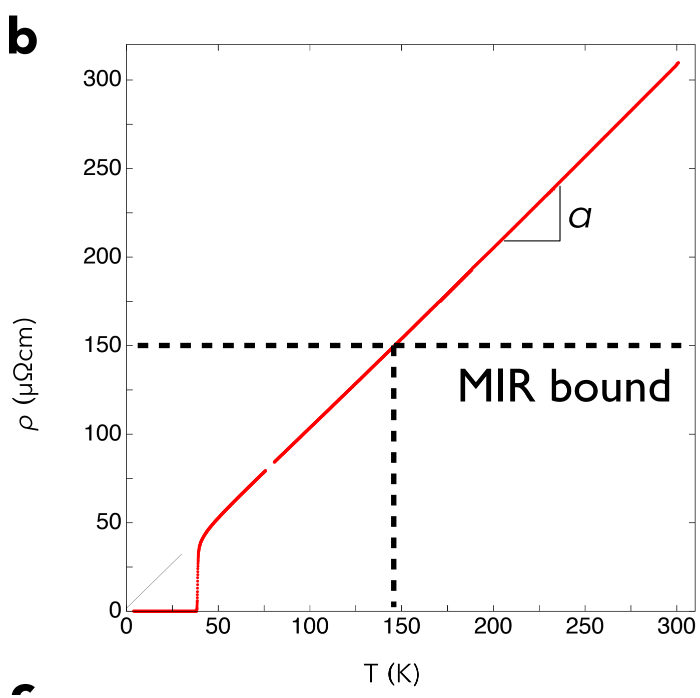
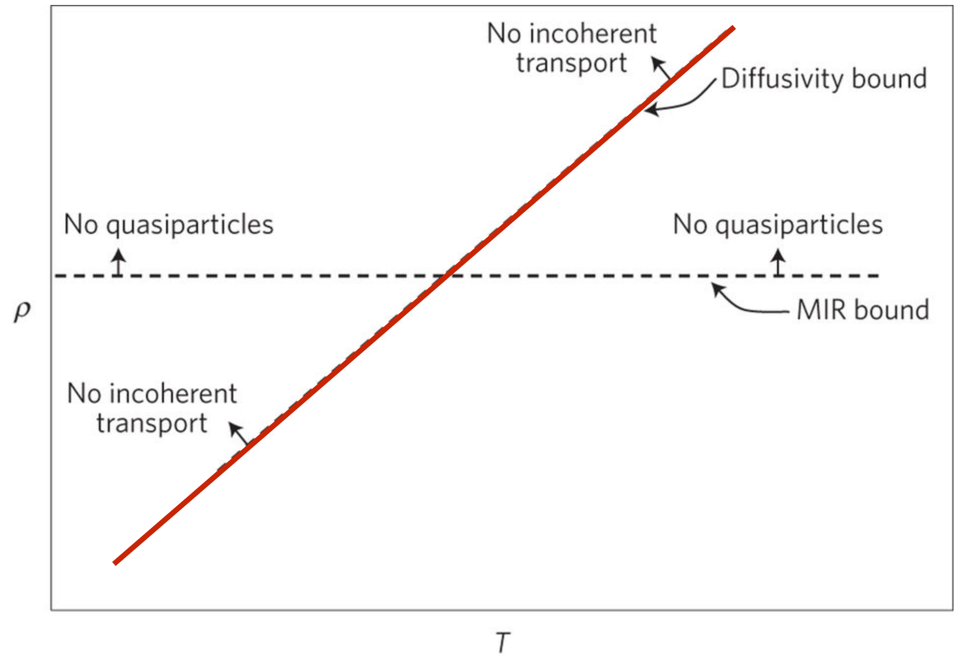


Intercept at T=0 is at $\rho = 0$
to *very high* precision

$$\rho_{DC} \sim \lim_{\omega\to 0}\int dk k(\eta k^2 + \dots) \sim s(T) \;\; \sim T$$

- Good and bad metals
  - A cuprate superconductor at low T is a good metal



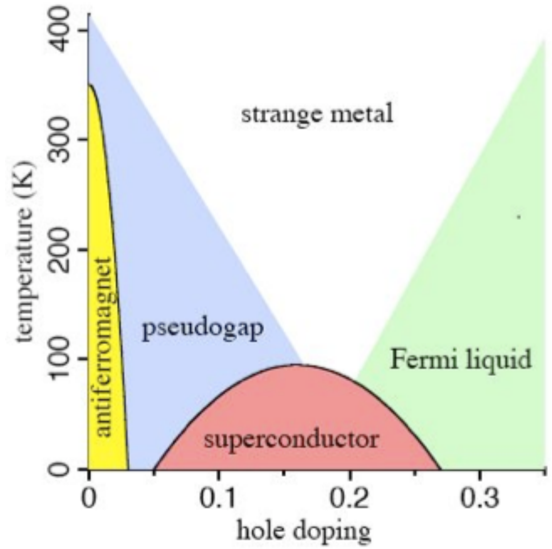
see
Davison
Blake
Mahajan
Grozdanov
Lucas
Faoro

$$D \sim v_B^2 \tau$$

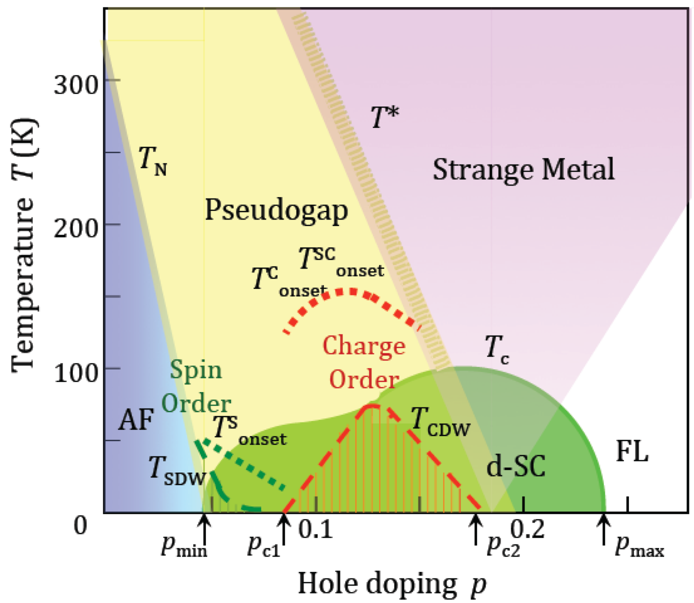
$$D \lesssim v^2 \tau$$

$$D \geq v^2 \tau$$

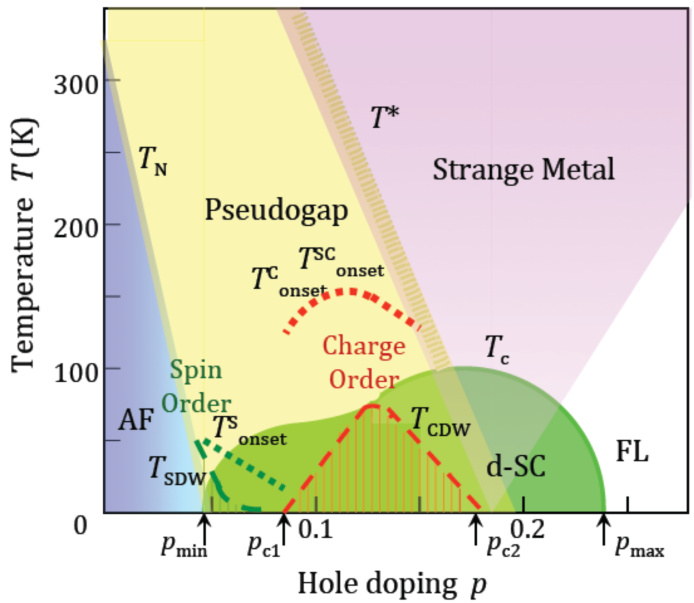
The strange metal in high Tc cuprates



The strange metal in high Tc cuprates



The strange metal in high Tc cuprates



AF phase is a Mott insulator:

a Mott insulator is local "jammed" charge pinned to underlying lattice

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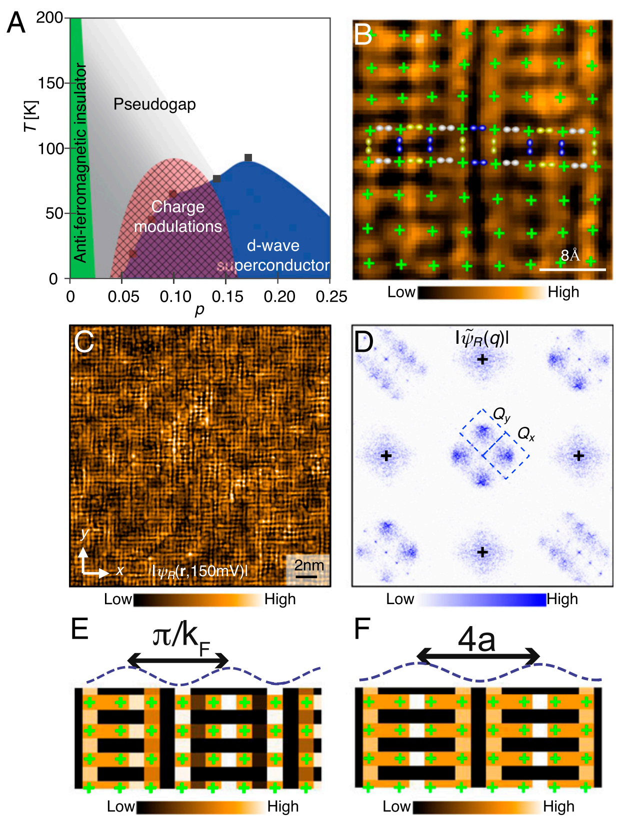
Commensurate $4a_0$-period charge density modulations throughout the $Bi_2Sr_2CaCu_2O_{8+x}$ pseudogap regime

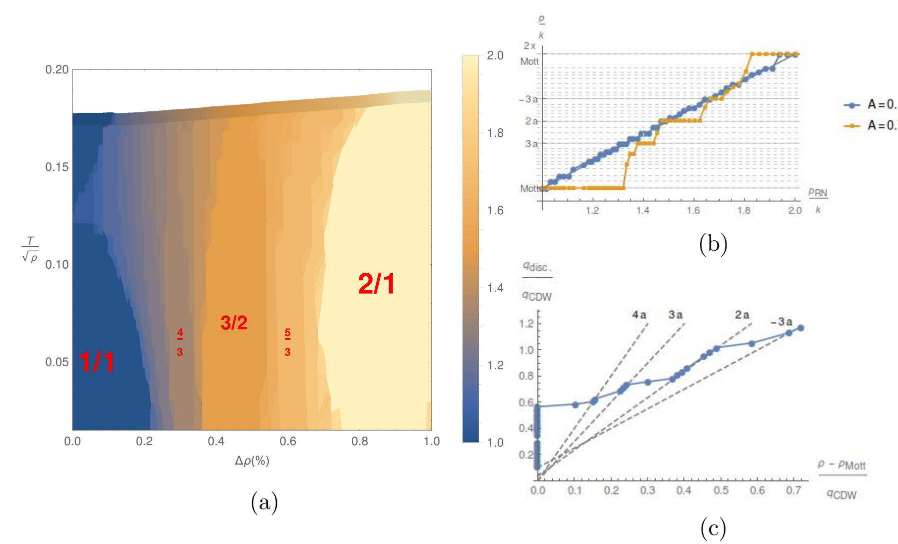
Andrej Mesaros[a], Kazuhiro Fujita[b], Stephen D. Edkins[a,c], Mohammad H. Hamidian[d,e], Hiroshi Eisaki[f], Shin-ichi Uchida[f,g], J. C. Séamus Davis[a,b,c,h,1], Michael J. Lawler[a,i], and Eun-Ah Kim[a,1]

[a]Laboratory of Atomic and Solid State Physics, Department of Physics, Cornell University, Ithaca, NY 14853; [b]Condensed Matter Physics and Materials Science Department, Brookhaven National Laboratory, Upton, NY 11973; [c]School of Physics and Astronomy, University of St. Andrews, St. Andrews, Fife KY16 9SS, Scotland; [d]Department of Physics, Harvard University, Cambridge, MA 02138; [e]Department of Physics, University of California, Davis, CA 95616; [f]Superconducting Electronics Group, Electronics and Photonics Research Institute, National Institute of Advanced Industrial Science and Technology, Tsukuba, Ibaraki 305-8568, Japan; [g]Department of Physics, University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan; [h]Tyndall National Institute, University College Cork, Cork T12R5C, Ireland; and [i]Department of Physics, Binghamton University, Binghamton, NY 13902-6000

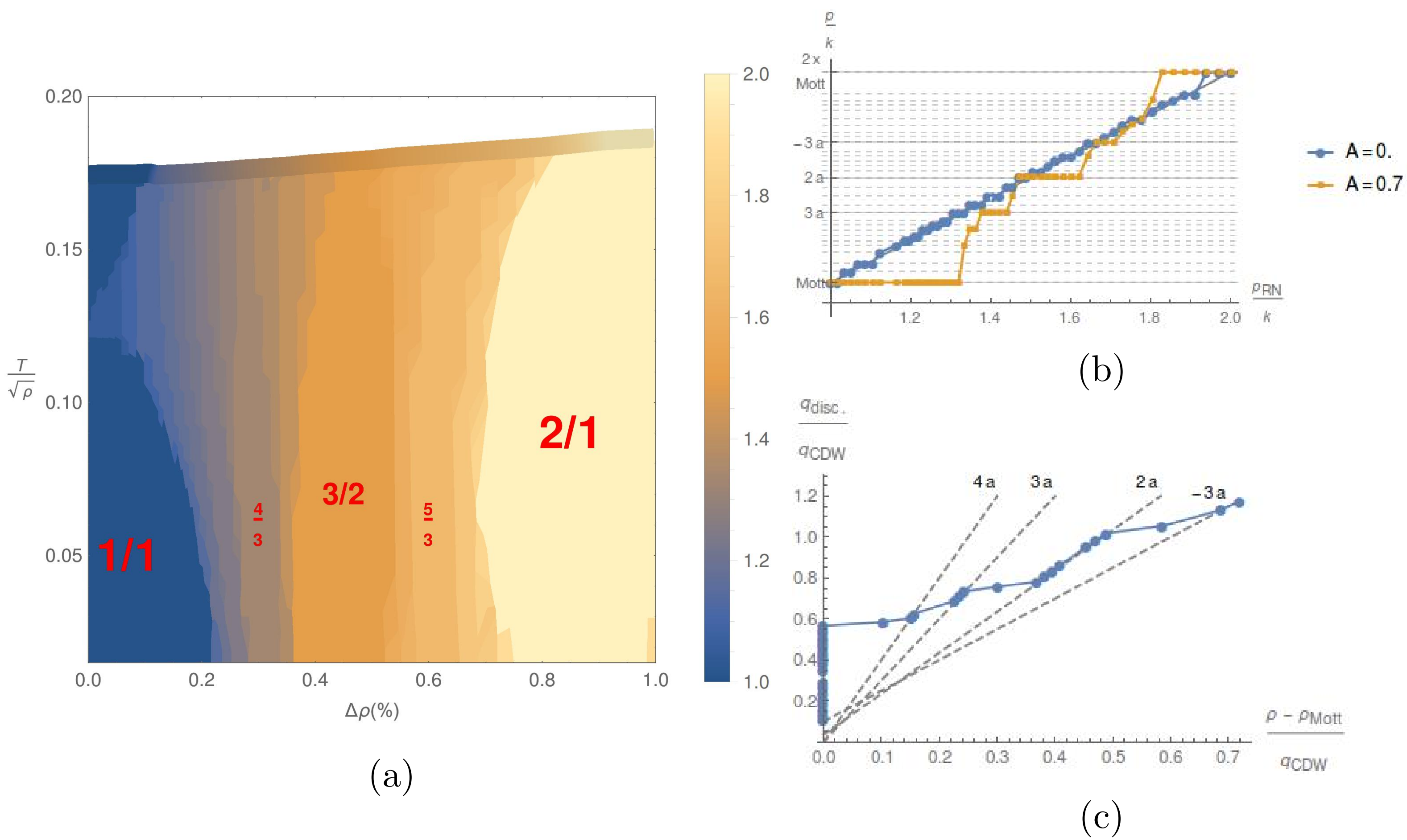
Contributed by J. C. Séamus Davis, September 1, 2016 (sent for review July 13, 2016; reviewed by Marc-Henri Julien and J. Zaanen)

PNAS | November 8, 2016 | vol. 113 | no. 45 | 12661–12666





- A doped holographic Mott insulator — Andrade, Krikun, Schalm, Zaanen
    - Shows doping independent commensuration in contrast to conventional Mott insulator models



arXiv.org > cond-mat > arXiv:1606.04491

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Condensed Matter > Superconductivity

Origin of the metal-to-insulator crossover in cuprate superconductors

F. Laliberte, W. Tabis, S. Badoux, B. Vignolle, D. Destraz, N. Momono, T. Kurosawa, K. Yamada, H. Takagi, N. Doiron-Leyraud, C. Proust, Louis Taillefer

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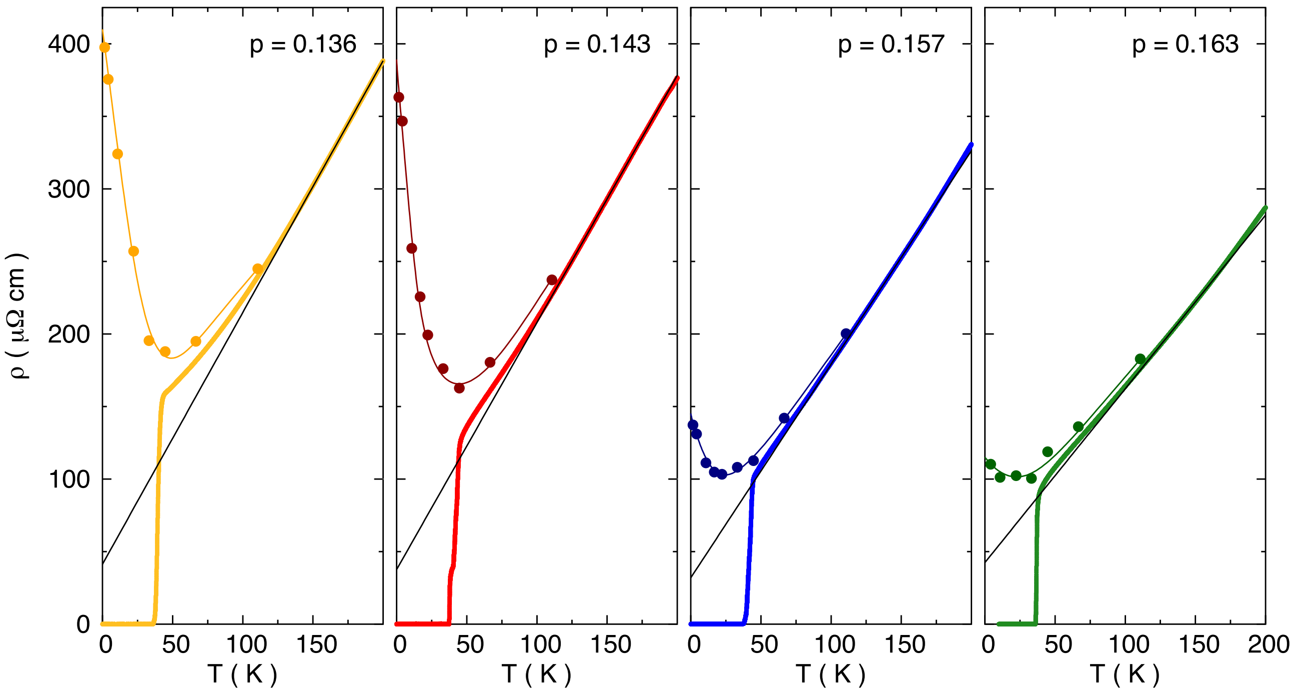
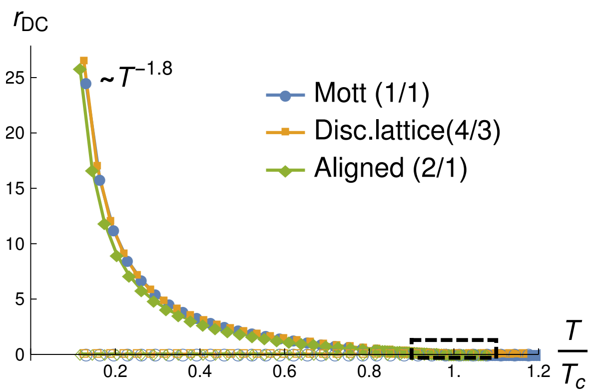
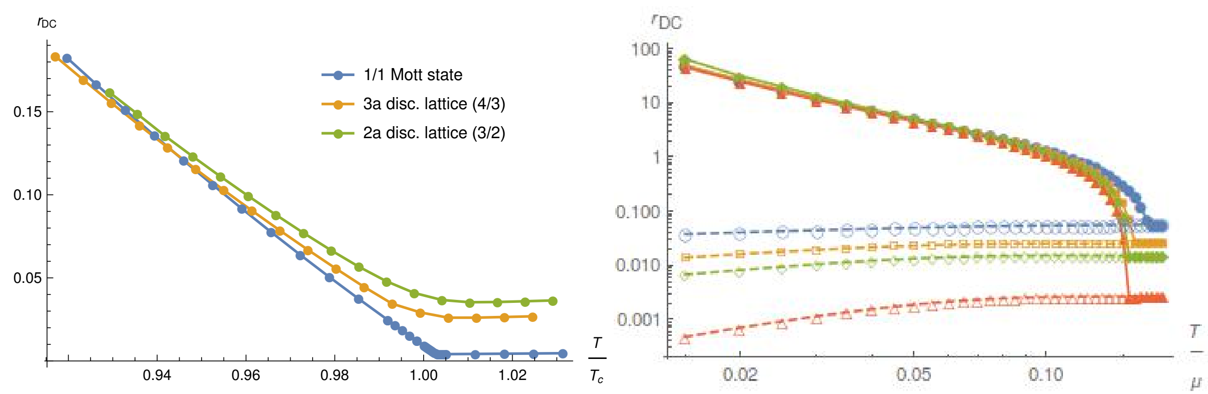


Charge Density Waves in Cuprates

- A doped holographic Mott insulator — Andrade, Krikun, Schalm, Zaanen
  - Onset of insulating phase is "mild"
  - Remnant quantum critical conductivity





(a) (b)

Figure 2: DC resistivity for various locked states. Left panel: linear-linear plot near the phase transition, Right panel: Log-log plot. The power law tail is seen at low temperature, signalling the reamining near horizon degrees of freadom, which are not gapped.

arXiv.org > cond-mat > arXiv:1708.01929

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Condensed Matter > Strongly Correlated Electrons

Singular density fluctuations in the strange metal phase of a copper-oxide superconductor

M. Mitrano, A. A. Husain, S. Vig, A. Kogar, M. S. Rak, S. I. Rubeck, J. Schneeloch, R. Zhong, G. D. Gu, C. M. Varma, P. Abbamonte

(Submitted on 6 Aug 2017)

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$$\Pi(\omega, k) = \langle n(\omega, k) n(-\omega, -k) \rangle$$

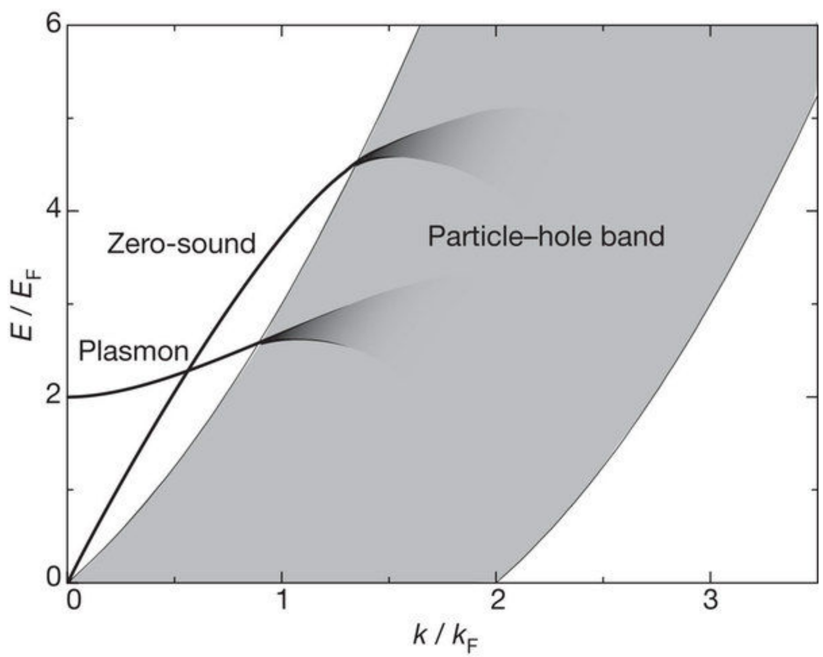
- Plasmon in Fermi liquids

$$\Pi(\omega, k) = \langle n(\omega, k) n(-\omega, -k) \rangle$$

$$\chi = \frac{\Pi}{1 - V_q \Pi}$$

$$V_q \sim \frac{e^2}{q^2} \qquad \Pi \sim q^2 + \dots$$

Plasmon gap e^2



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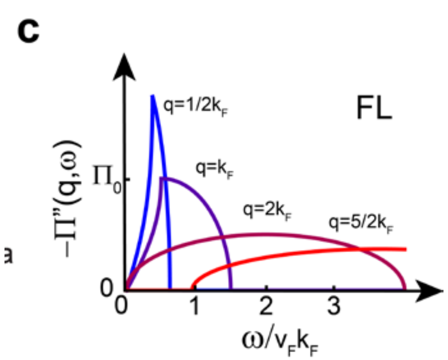

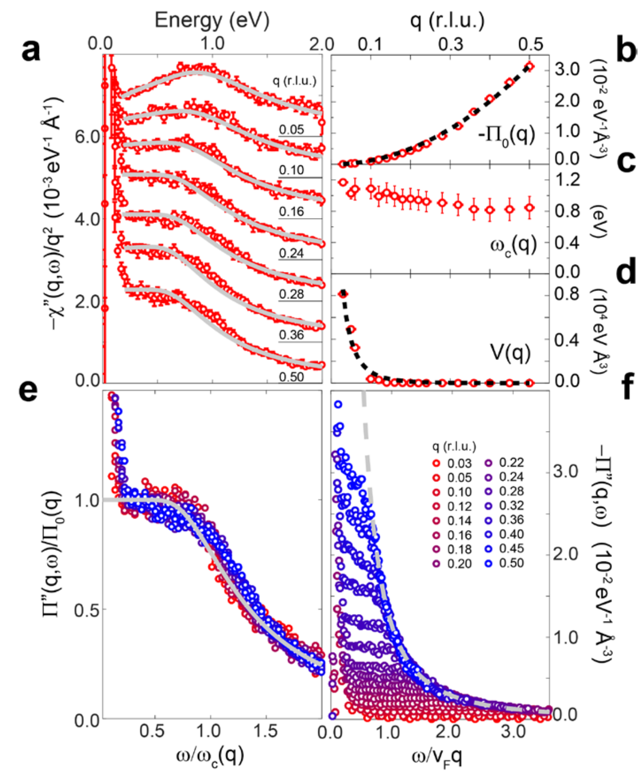

Fig. 2 – Scaling collapse of the continuum in optimally-doped BSCCO. (a) Dynamic charge susceptibility, $\chi''(q,\omega)$, for a selection of momenta along the $(1,\bar{1})$

Density-density correlation functions in holography

- Zero sound
- Friedel oscillations

Karch, Son, Starinets

Puletti, Nowling, Thorlacius, Zingg
Faulkner, Iqbal
Blake, Donos, Tong

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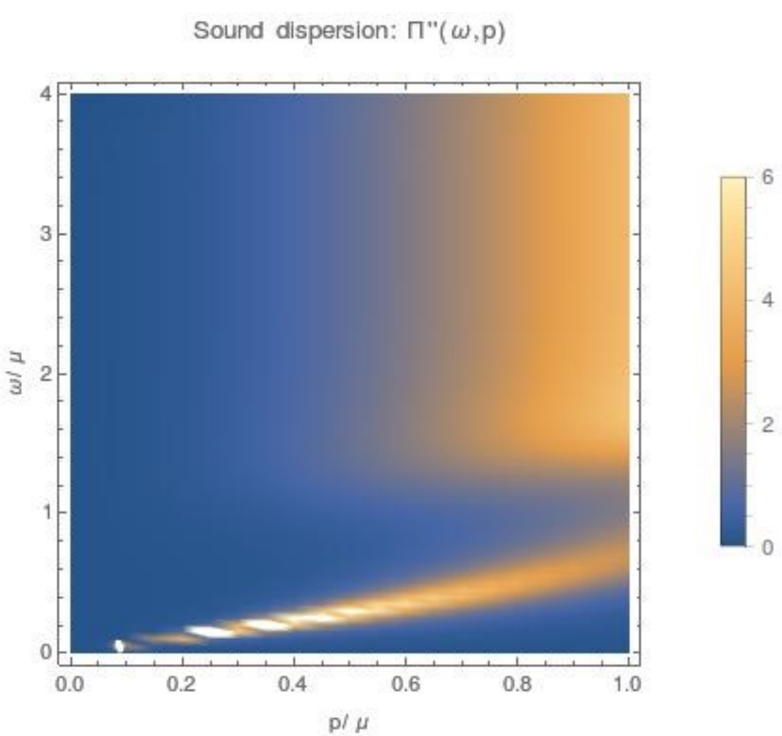

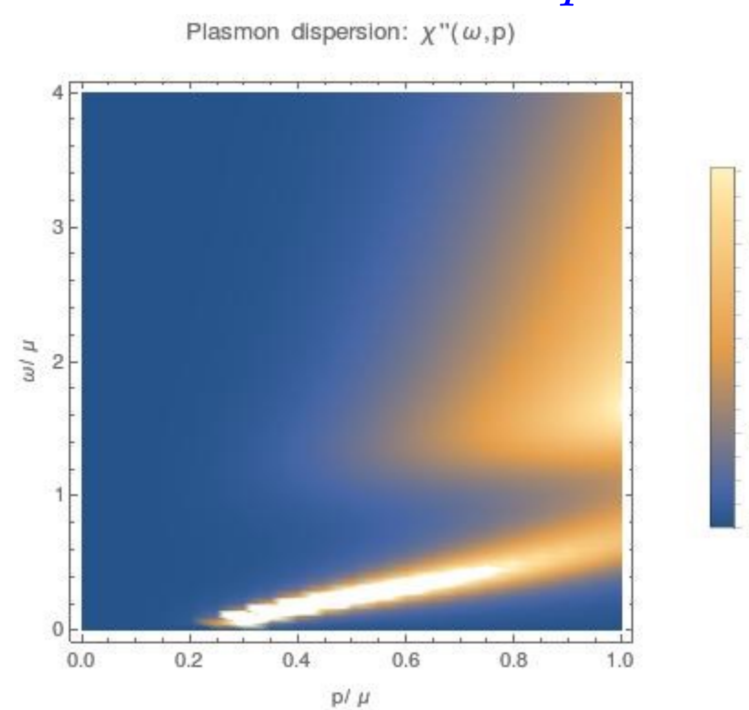

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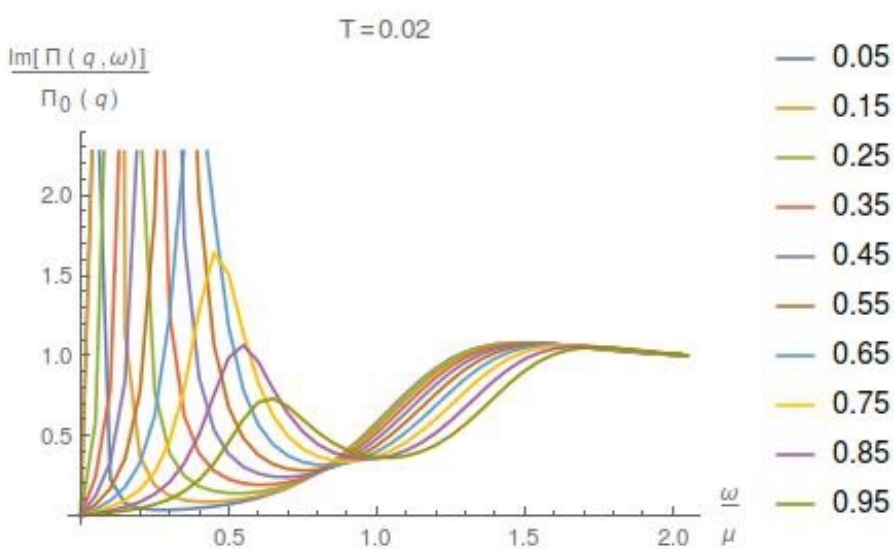
Plasmon width should know about quantum critical sector



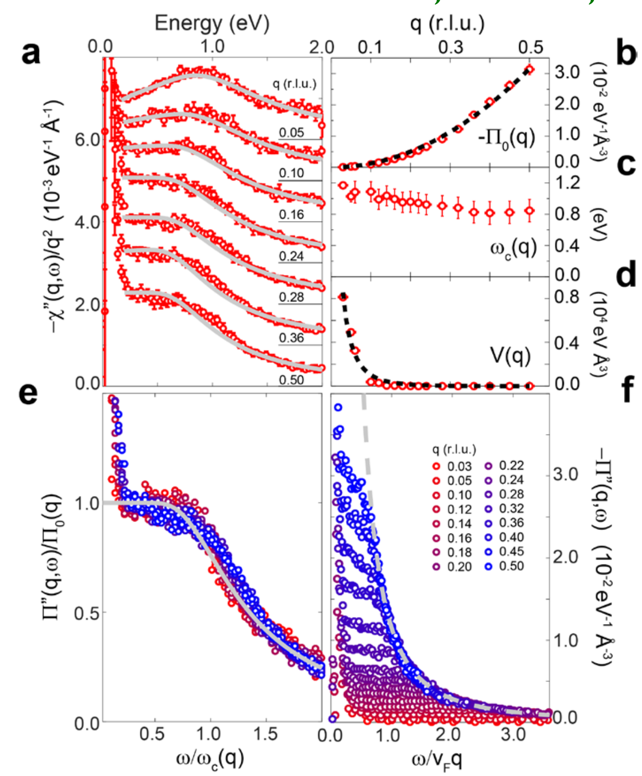


Fig. 2 – Scaling collapse of the continuum in optimally-doped BSCCO. (a) Dynamic charge susceptibility, $\chi''(q,\omega)$, for a selection of momenta along the $(1,\overline{1})$

Experimental efforts on strange metals

- 2015 — Scaling in ARPES linewidths — Dessau et al; van Heumen, Golden et al
- 2015 — Gap dynamics of superconductor — Dessau et al
- 2015 — Transport without quasiparticles
  - Universal linear-in-T resistivity
  - 2017 — with zero intercept — Latest: Boebinger, Shekhter et al
- 2014 — Charge density wave Mott insulator
  - doping independent commensuration — Davis and many others
  - mild insulator transition — Latest: Taillefer et al
- 2017 — Density fluctuations and anomalous plasmon physics — Abbamonte et al
- …

Many of these results follow from

the Theory of a strange metal

- A quantum critical system --- a theory without quasiparticles, supported by an ordered state with transport characterized by collective behavior.

- Experiment: Excitations around the FS do not determine transport.

$$\sigma = \sigma_{\rm Lif.quant.crit} + \sigma_{\rm conv.order}$$

- Experiment: quantum critical sector exhibits scaling and controls decay widths

- Experiment: particle intuition does not apply.

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- Theory: framework provided by an holography

Holography gives a consistent, predictive framework
that captures the right physics of experimental strange metals.

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that captures the right physics of experimental strange metals.

There is a real possibility and opportunity that it can explain
puzzling observations in actual experiment.

Thank you

with many thanks to:
T. Andrade, A. Bagrov, J. Bhaseen, M. Cubrovic, B. Doyon, R. Davison,
J. Erdmenger, M. Medvedyeva, E. Gubankova, S. Grozdanov, N. Kaplis, A. Lucas,
B. Herwerth, S. Klug, A. Krikun, Y. Liu, B. Meszena, R. Meyer, Y-W Sun,
S. Sachdev, P. Saeterskog, V. Scopelliti, J. Zaanen