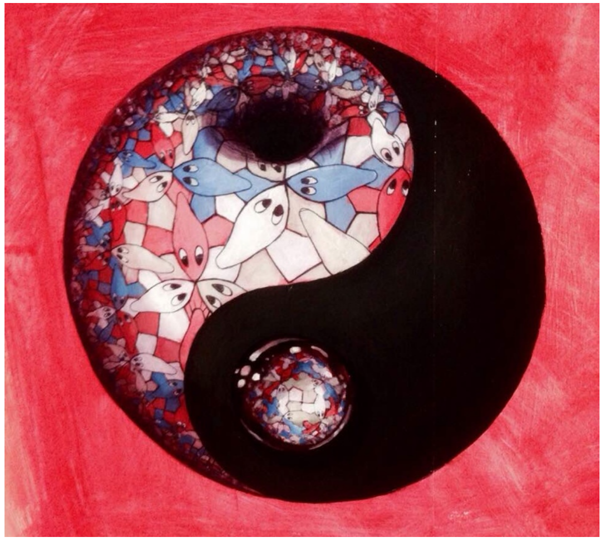
Applied String Theory: Bringing Holography to the Laboratory

Koenraad Schalm

Institute Lorentz for Theoretical Physics, Leiden University



NWO Netherlands Organisation for Scientific Research

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FOM

1998 - 2018

20 years of AdS/CFT = Holography = Gauge/Gravity duality

A new road to an old dream:

Apply string theory to explain experiment

1998 - 2018

20 years of AdS/CFT = Holography = Gauge/Gravity duality

A new road to an old dream:

Apply string theory to explain experiment

… AdS/QCD: The strongly coupled regime of QCD — '98 Witten,…

… AdS/RHIC: The collective many body physics of QCD — '04 Policastro, Son, Starinets, …

… AdS/CMT: Strongly correlated condensed matter

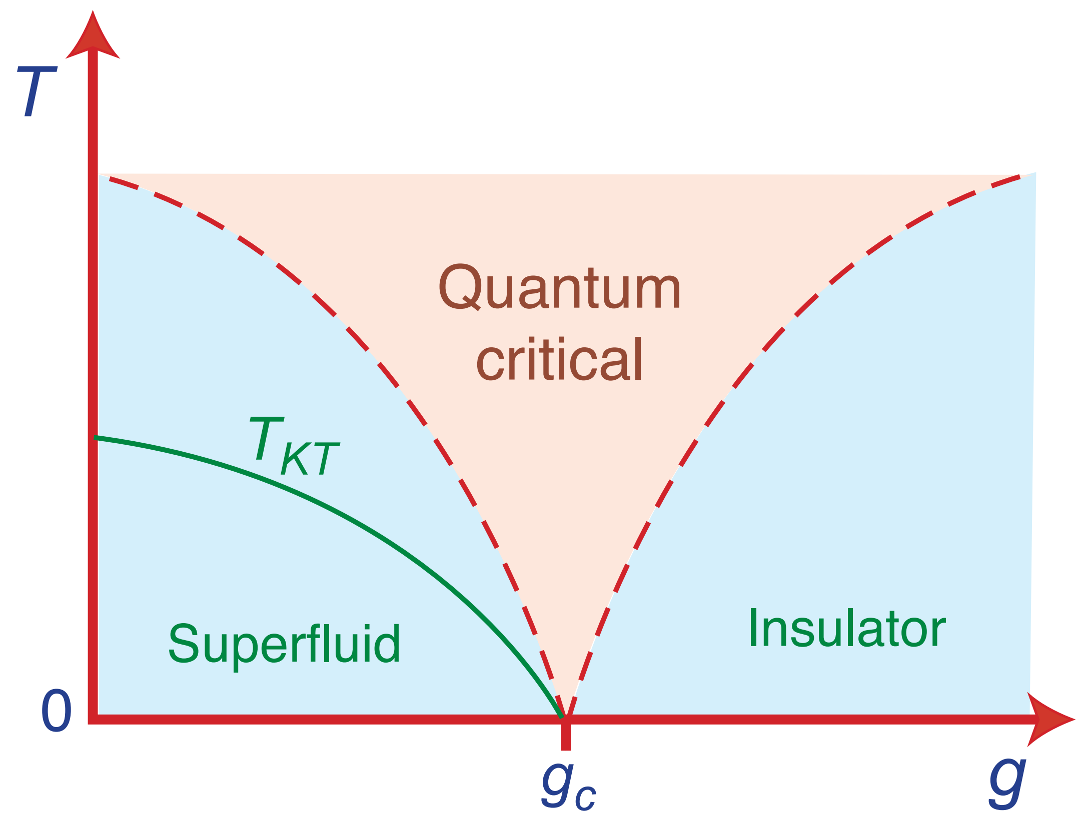
- Quantum Critical Systems — '07 Herzog, Kovtun, Sachdev, Son
- Holographic Superconductor — '08 Gubser; Hartnoll, Herzog, Horowitz
- MIT/Leiden Fermions — '09 Liu, McGreevy, Vegh; Cubrovic, Zaanen, Schalm

- 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

- Quantum Critical Phenomena
  - Physics controlled by a Quantum Critical Point
  - Theory without quasiparticles: Qualitatively different Macroscopics



Sachdev

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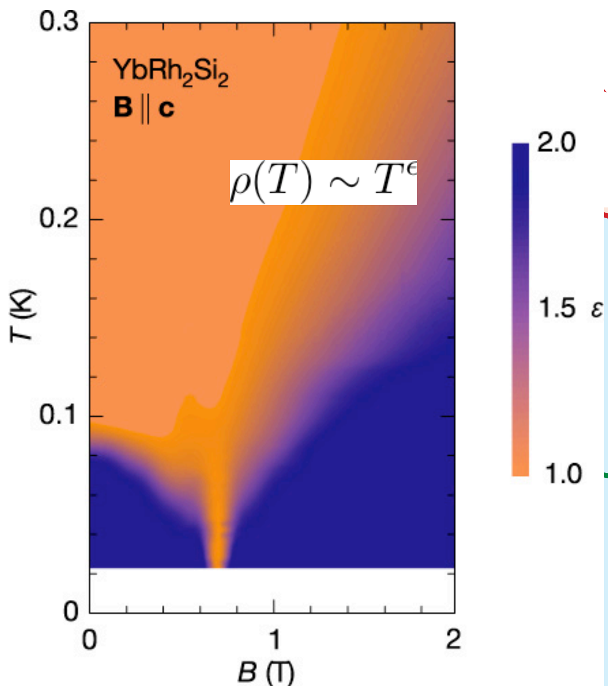
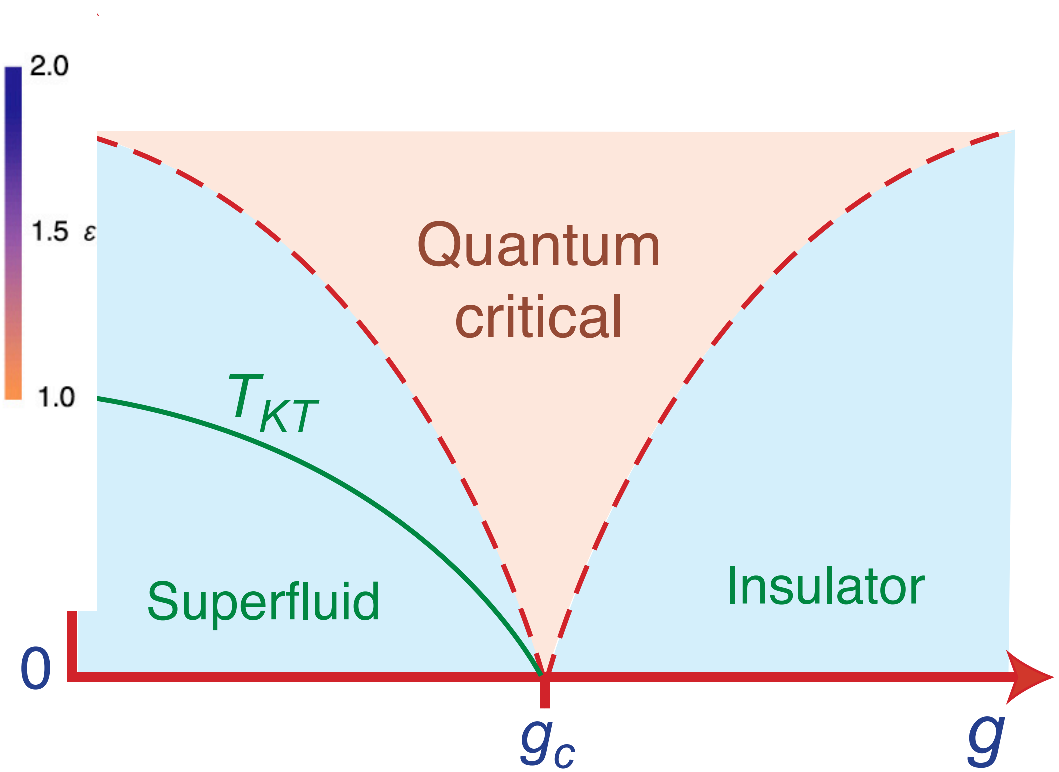
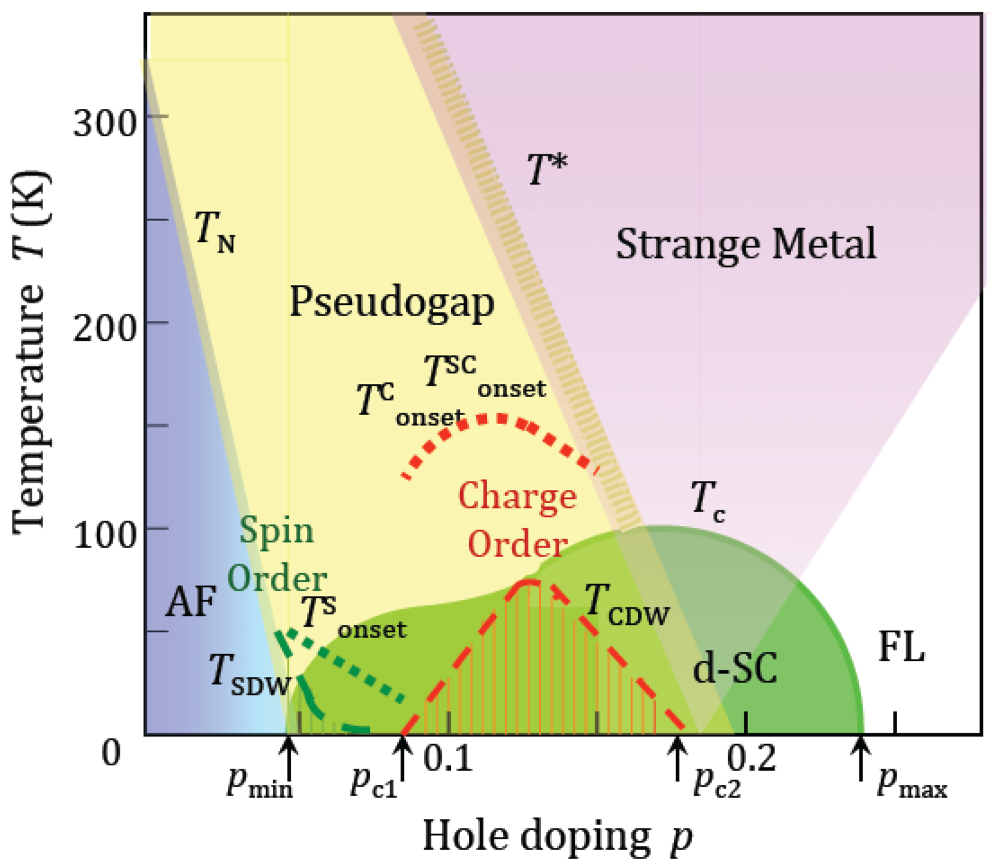




Custers et al, *Nature* **424**, 524 (2003)

Sachdev

The strange metal in high Tc cuprates



Keimer et al,
Nature 518 (2015) 179

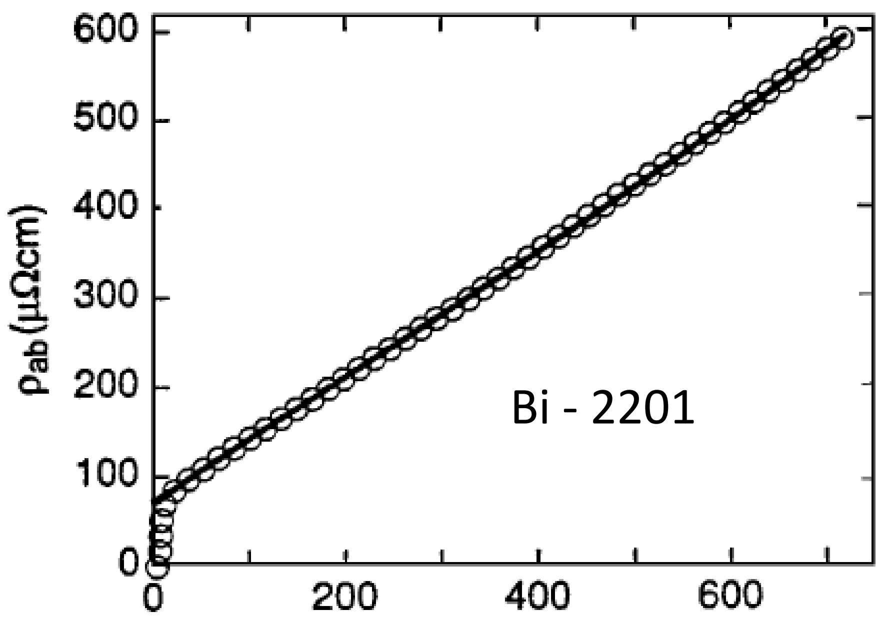
What is the theory of the strange metal?

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

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

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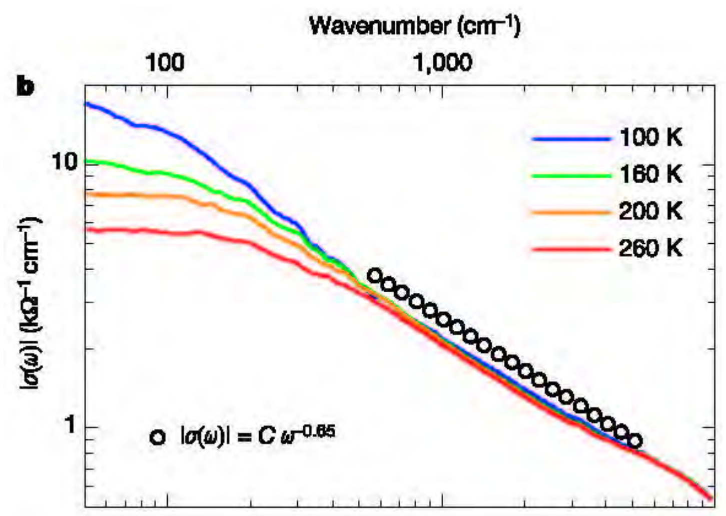
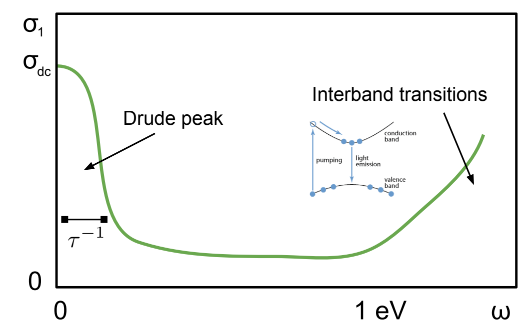
- Power Law in AC conductivity

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

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





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

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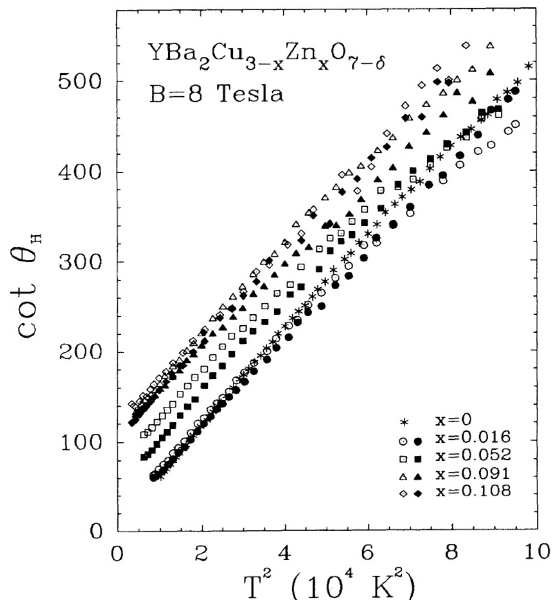
- Hall angle vs DC conductivity scaling

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

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



Chien et al,
PRL 67, 2088 (1991)

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- Inverse Matthiessen law

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

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

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- Inverse Matthiessen law

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

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

This is not an exhaustive list…

Two lifetimes

- Hall angle in "strange metals"

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

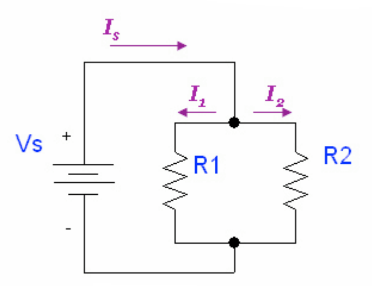
- Theory (e.g. Drude, memory matrix)

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

Fundamental puzzle:

Needs "Inverse Matthiessen"

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



Interacting ordinary systems are "Matthiessen"

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

Key insight from holography: (novel IR fixed point)

A strange metal is a state of matter consisting of two sectors, one of which is a quantum critical state.

two sectors: two simultaneously coexisiting nearly independent sets of low energy degrees of freedom (two lifetimes),

quantum critical state: long-range entangled charge conjugation symmetric Lifshitz scale invariant hyperscaling violating critical theory.

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1. anti-Matthiessen rule for DC transport
2. line widths are significantly broadened

quantum critical state:

long-range entangled
charge conjugation symmetric Lifshitz scale invariant
hyperscaling violating critical theory.

3. unparticle physics
4. lots of scaling behavior (linewidths)
5. universality
6. very unstable

Key role for holography: (superior computation)

A strange metal is a state of matter consisting of two sectors, one of which is a quantum critical state.
Holography provides the computational theoretical framework.

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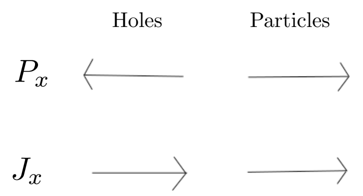
- Hall angle in "strange metals"

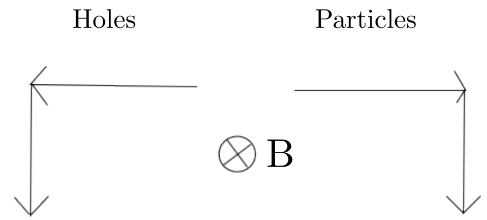
$$\sigma \sim \frac{1}{T} \qquad \tan\theta_H = \frac{\sigma_{xy}}{\sigma_{xx}} \sim \frac{1}{T^2}$$

- Holography: two sectors

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

- Holography: cc-invariant quantum critical





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

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

Blake, Donos
PRL 114 (2015) 021601

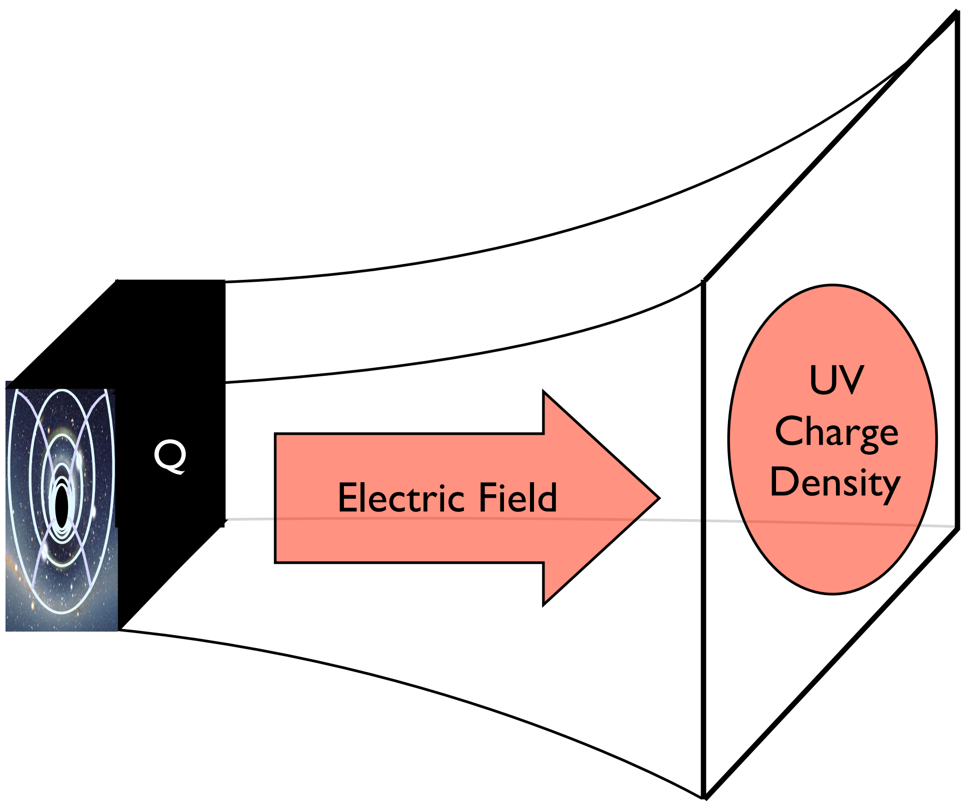
- AdS/CFT applied to condensed matter:

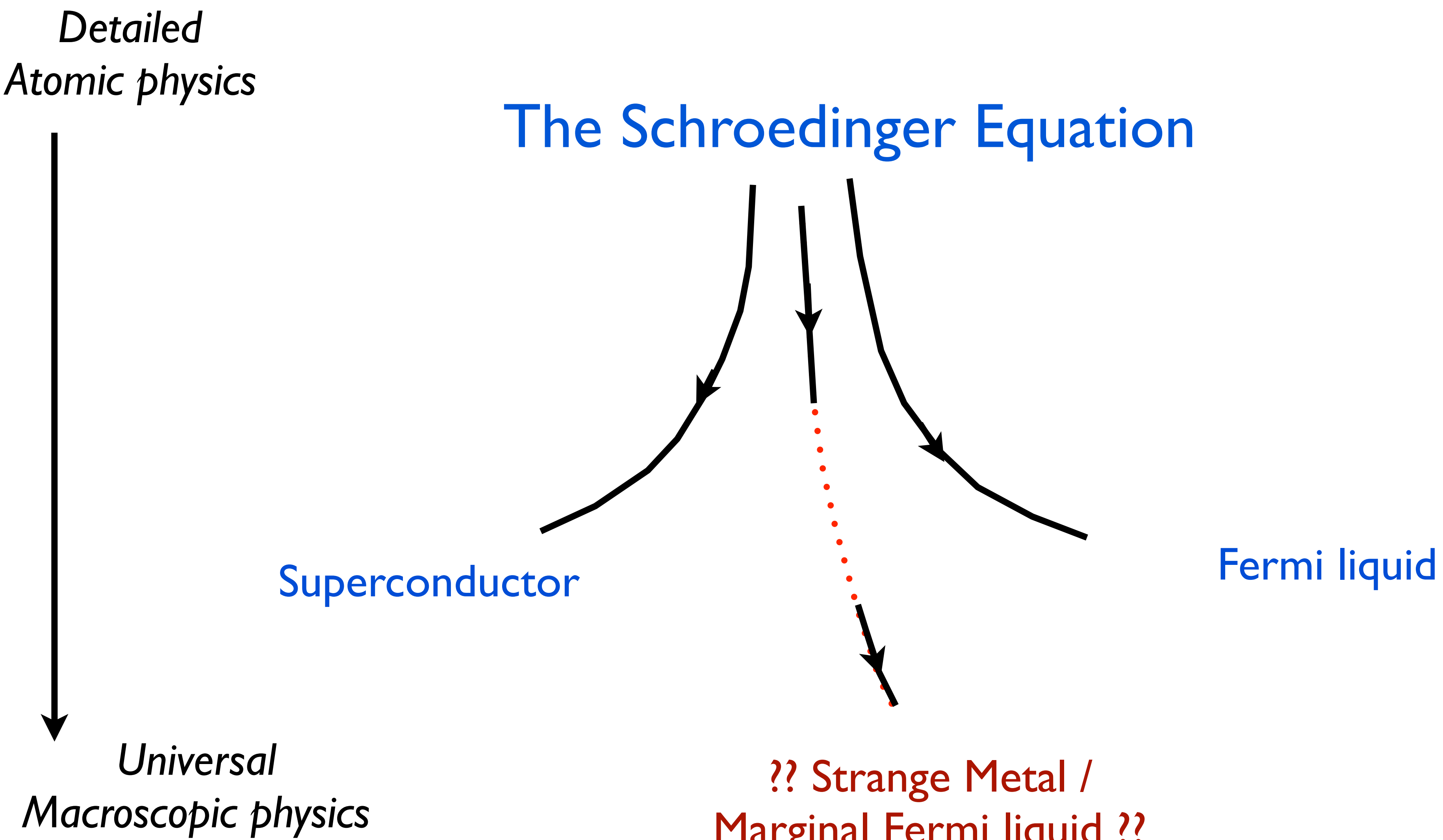
1. Generating functional for new non-trivial *unknown* IR fixed points

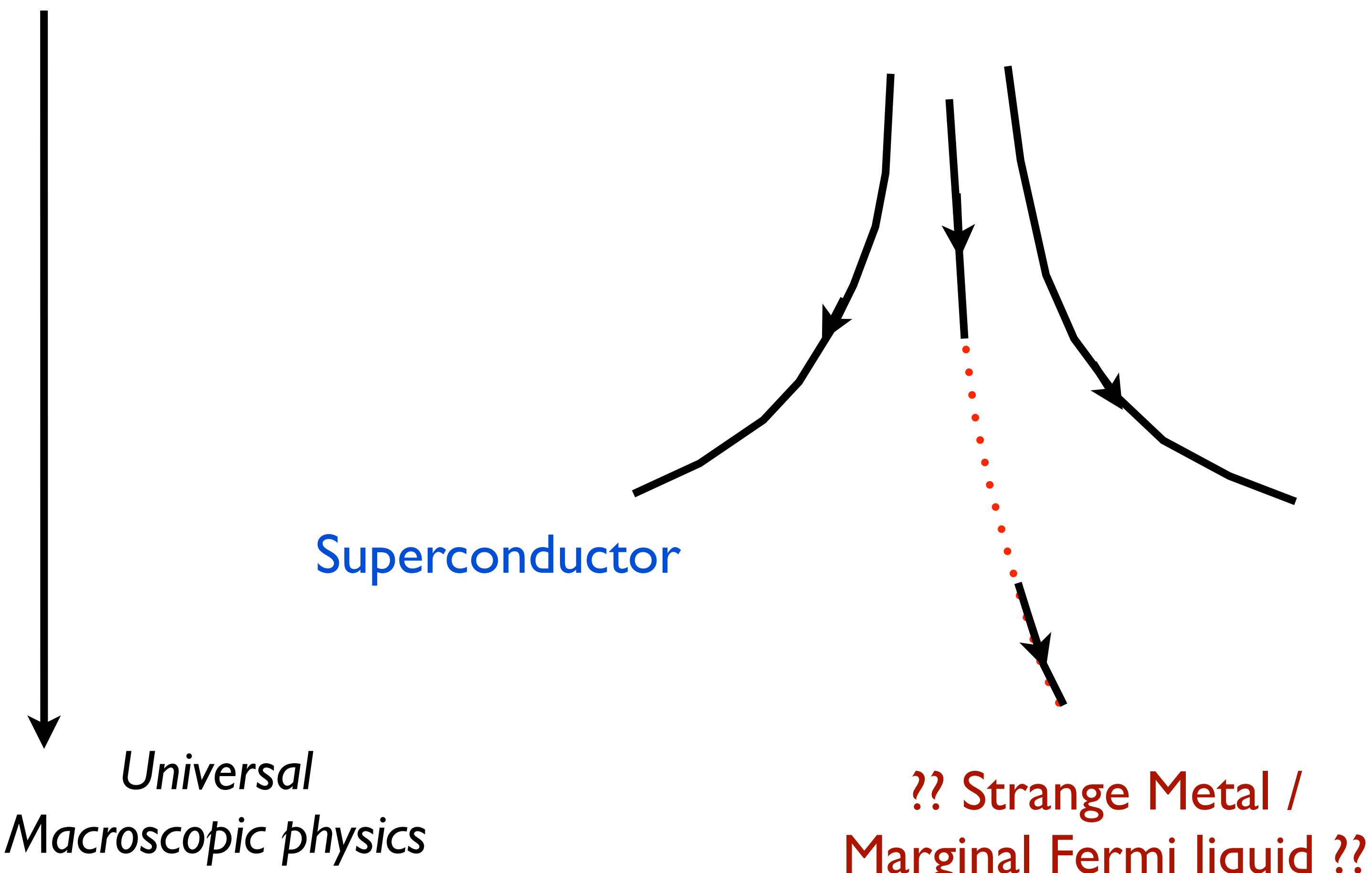
2. Far superior method to compute *real time* finite temperature/density correlation functions

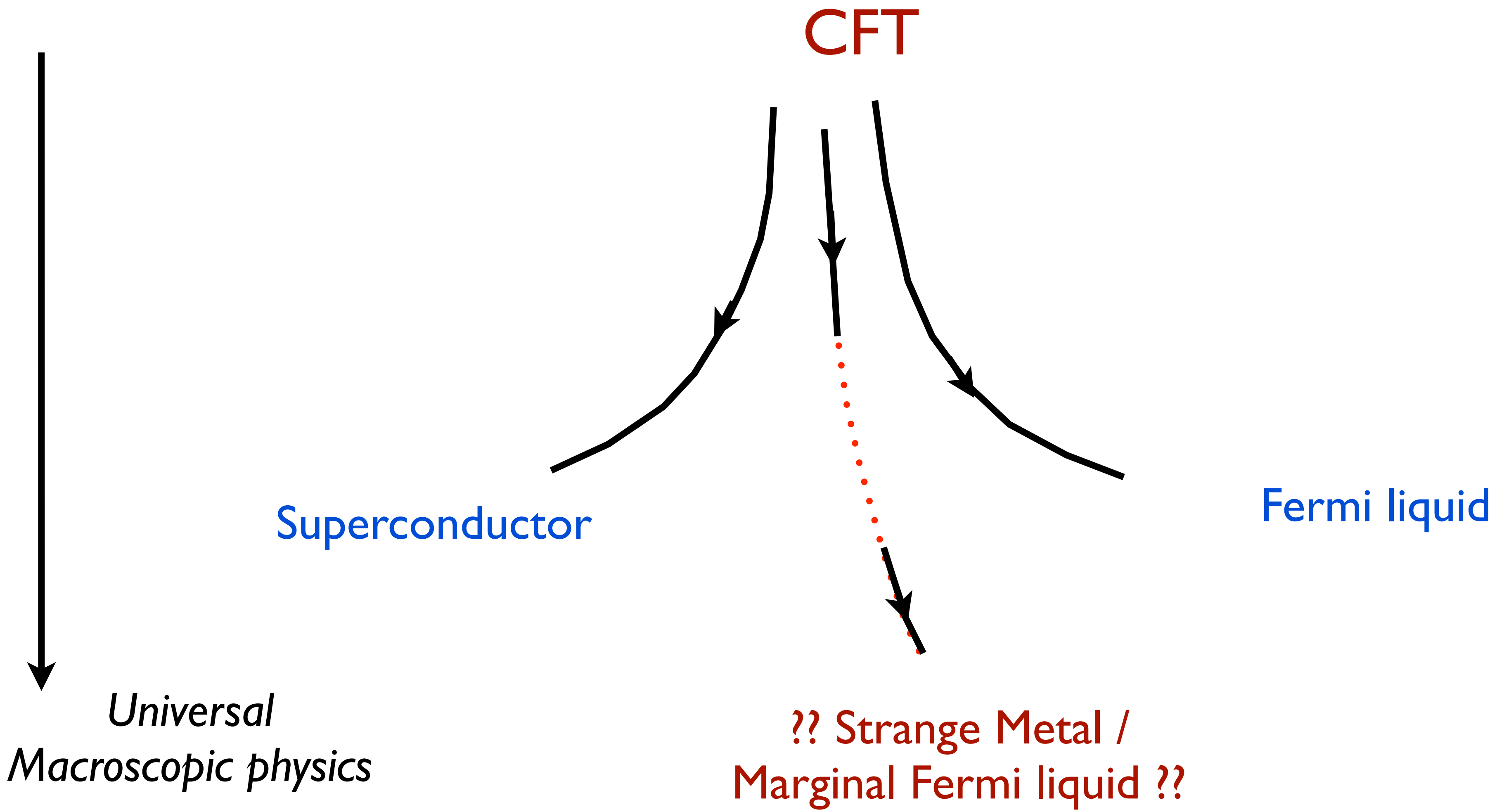
- AdS/CFT:
- a dual gravitational description of a (strongly) interacting quantum field theory.

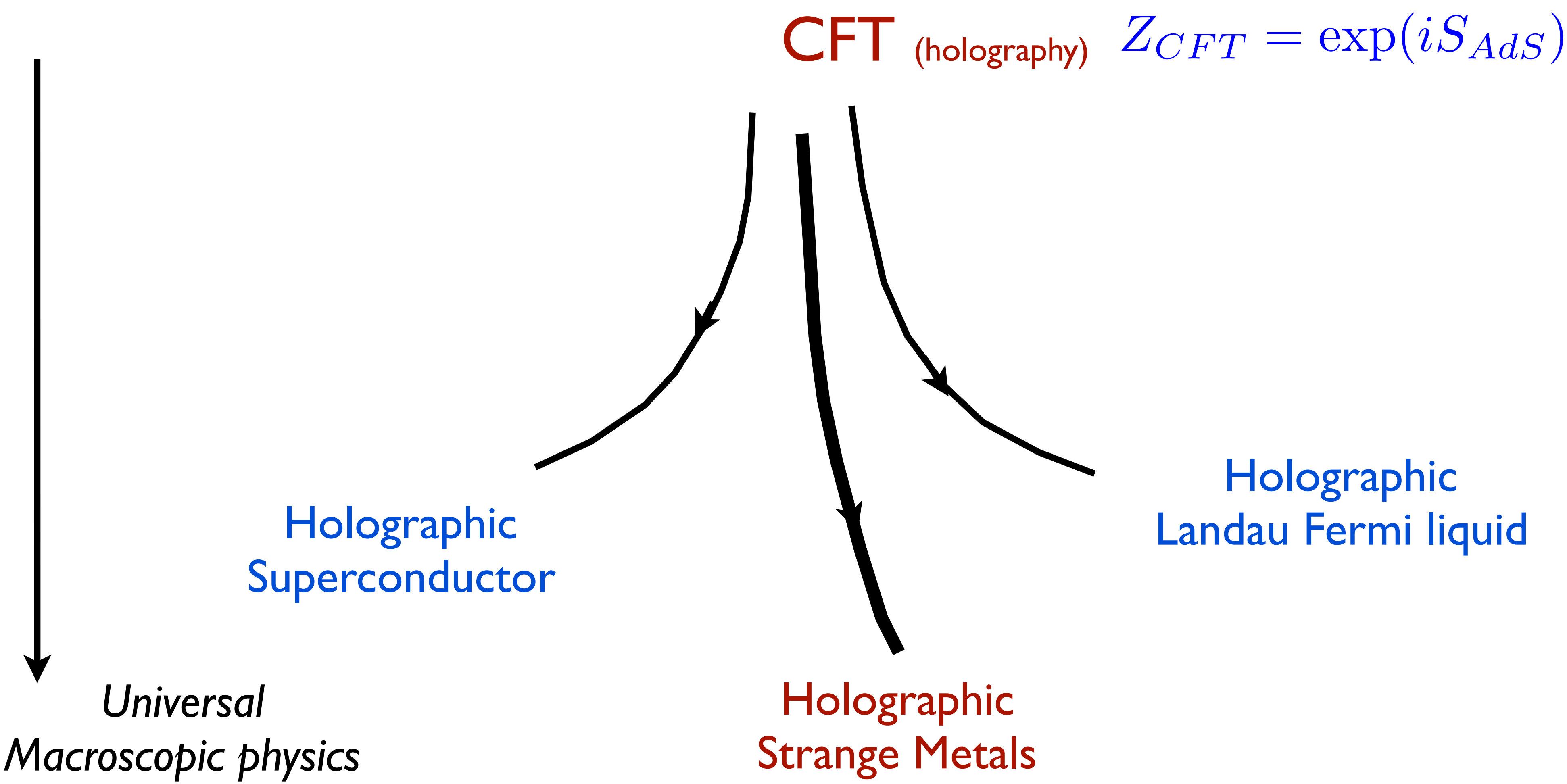
Systems at finite temperature/density $=$ AdS charged black hole




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


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


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

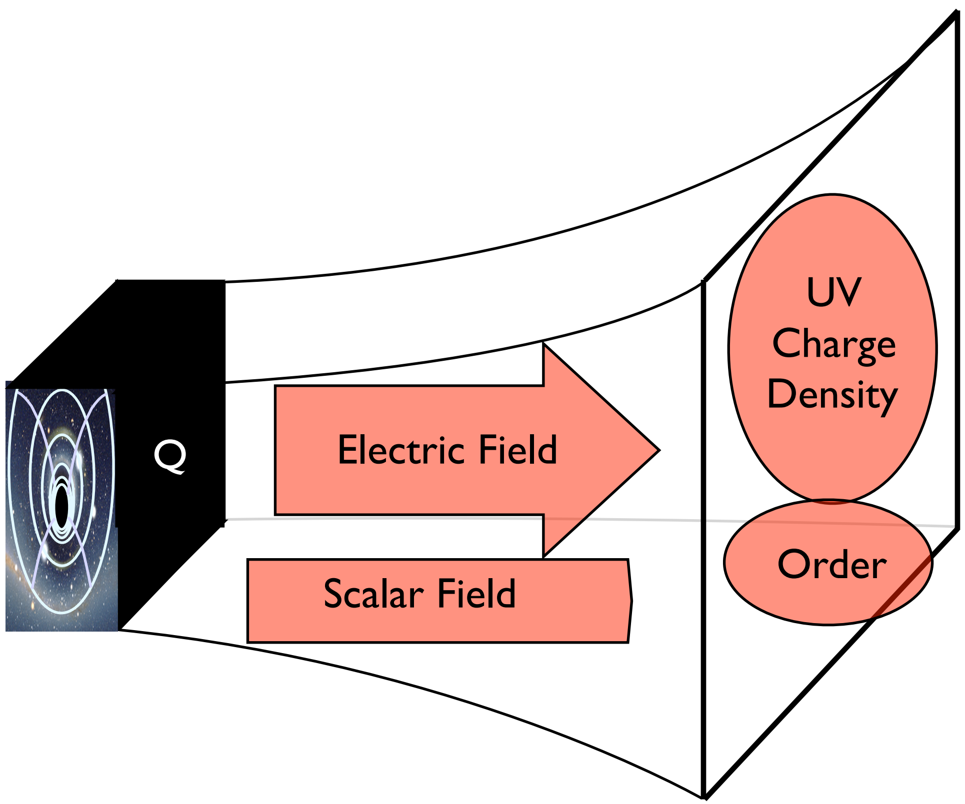

CFT (holography)
$Z_{CFT} = \exp(iS_{AdS})$
Holographic
Superconductor
Holographic
Strange Metals
Holographic
Landau Fermi liquid
Universal
Macroscopic physics

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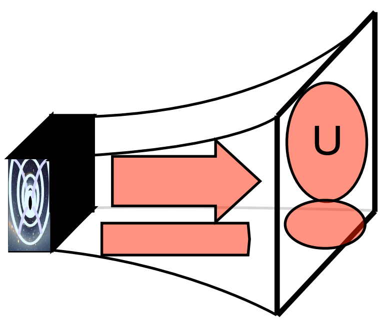
$$ds^2 = \frac{L^2}{r^2}\left[r^{2\theta/(d-\theta)}dr^2 - r^{-2d(z-1)/(d-\theta)}dt^2 + dx^2\right] \qquad A_t = Q\ r^{\zeta - z}$$

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



Many people:
Charmousis, Goutereaux, Gubser,
Gursoy, Hartnoll, Herzog, Horowitz,
Huijse, Kachru, Kim, Kovtun,
Kiritsis, Liu, Meyer, Mulligan, Sachdev, Swingle,
…

Holography describes new states of matter

- Holographic prediction:

Emergent scale invariant hyperscaling violating theories

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

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

- Holographic prediction:

Emergent scale invariant hyperscaling violating theories

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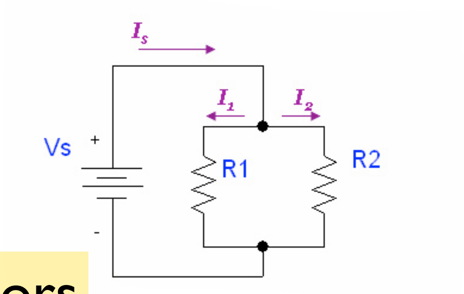
$$t \to \lambda^z t,\ x \to \lambda x$$

Lifshitz quantum critical theory supported by an ordered state

- Experimental signature: Thermoelectric response

Transport:
"Fluid Gravity"
Policastro, Son, Starinets;
Many people:
Davison, Donos, Gauntlett
Hartnoll, Herzog, Horowitz,
Iqbal, Liu,
...

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



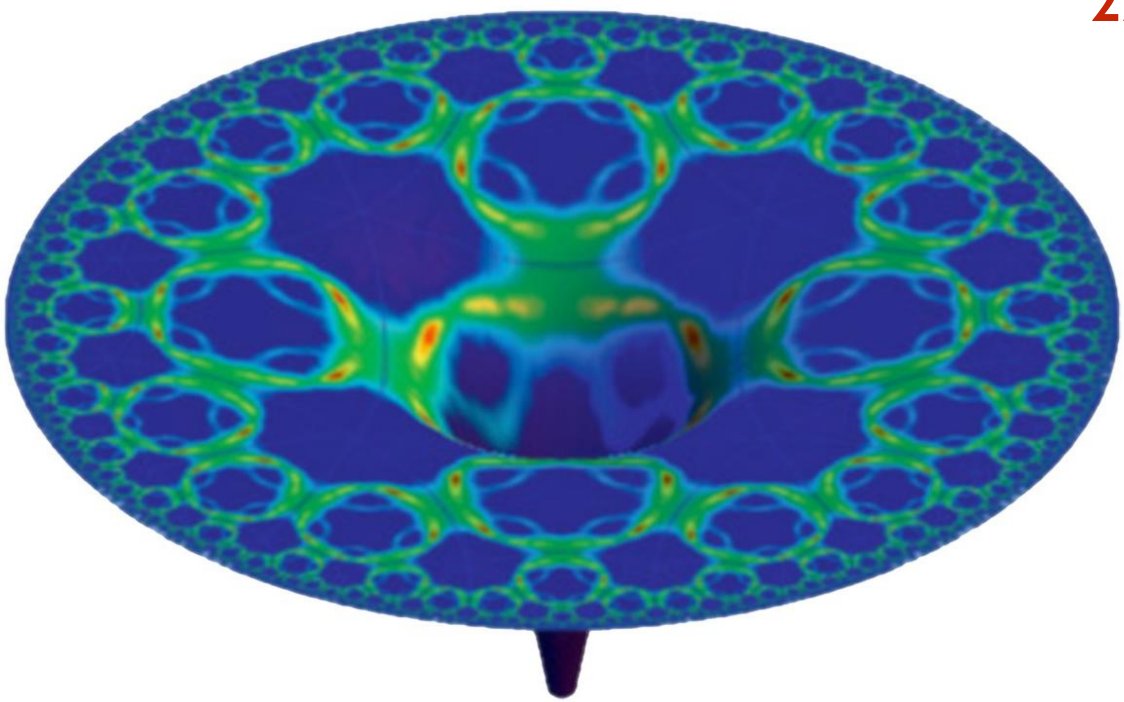
Inverse Matthiessen law: two independent sectors

Challenge to experiment

Can we show that the high T_c cuprate strange metals are 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

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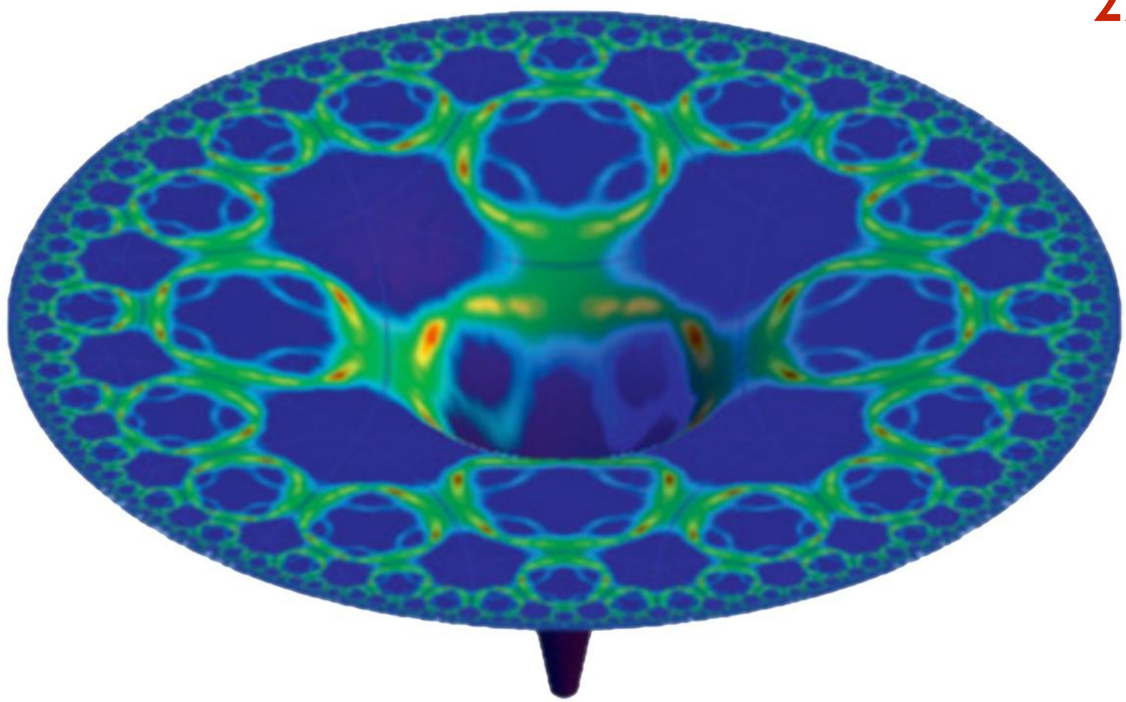

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N. Hussey M. Golden E. van Heumen M. Allan H. Stoof S. Vandoren K. Schalm J. Zaanen

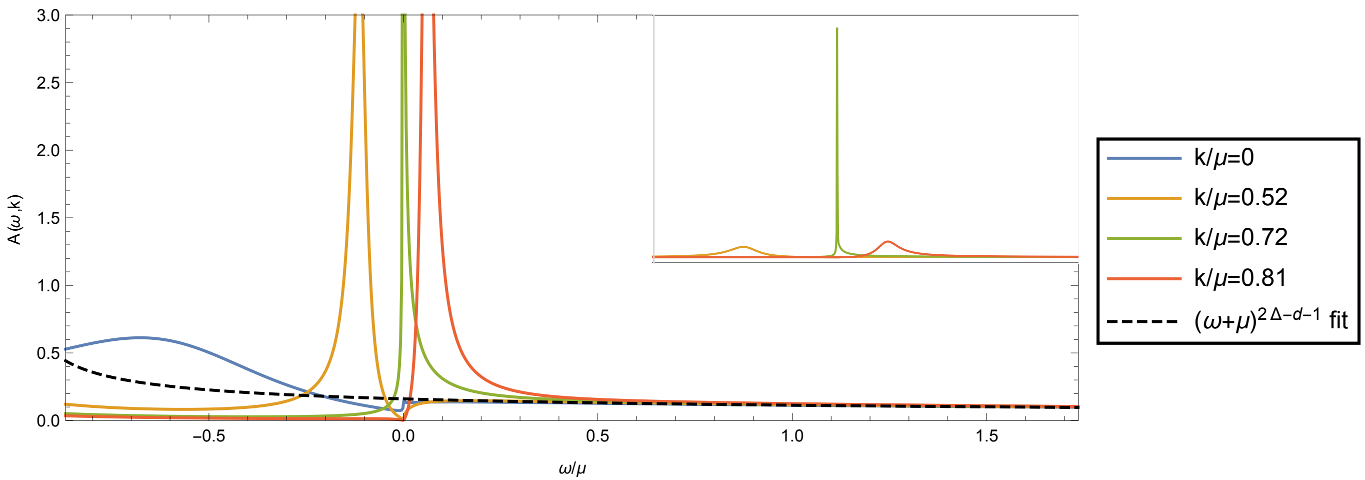
Netherlands Organisation for Scientific Research

- 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

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

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

- Fermi surface excitations disperse as

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

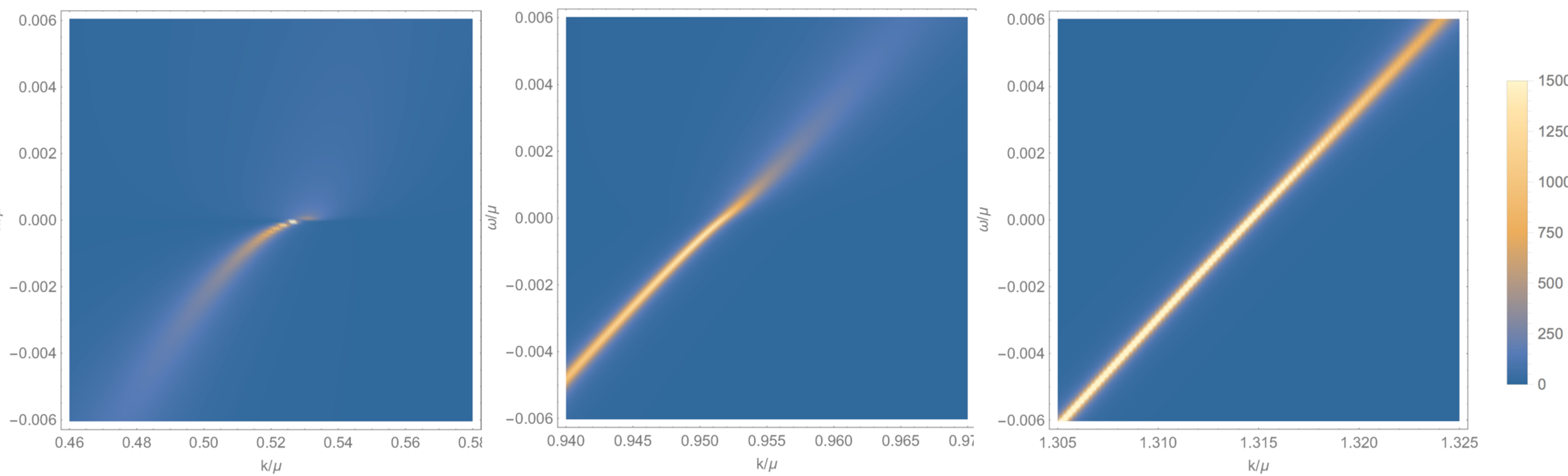
Holographic strange metals

- The single fermion function from AdS/CFT

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

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

artificially broadenend

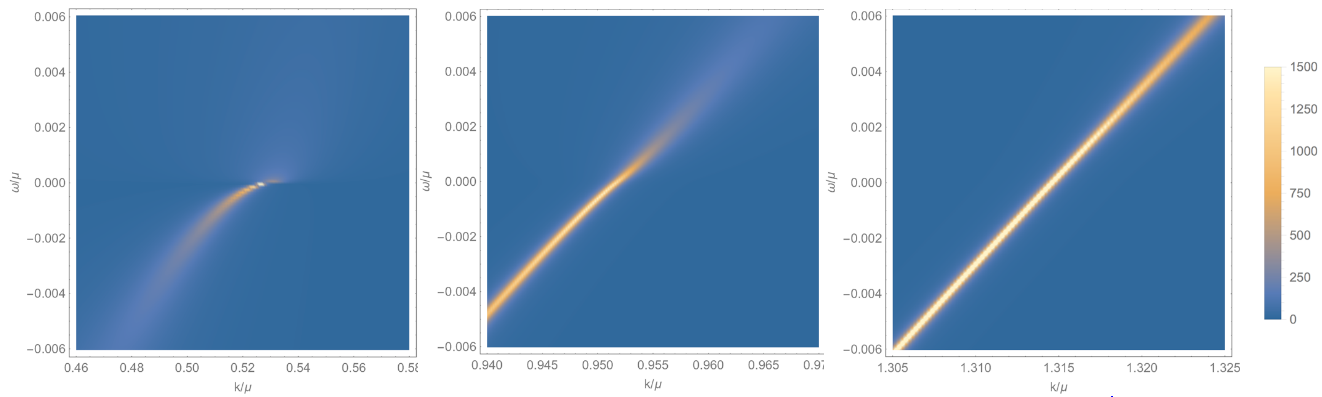


$\nu_{k_F} < 1/2$ — Non-Fermi Liquid

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

$\nu_{k_F} > 1/2$ — Fermi Liquid

Holographic strange metals

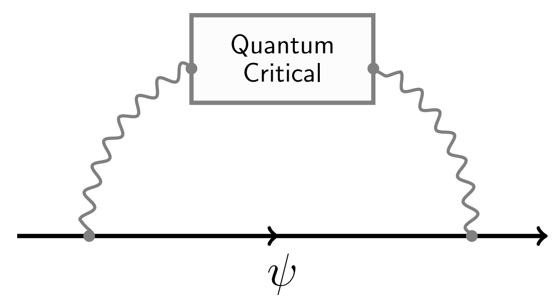


$\nu_{k_F} < 1/2$ $\nu_{k_F} = 1/2$ $\nu_{k_F} > 1/2$

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

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

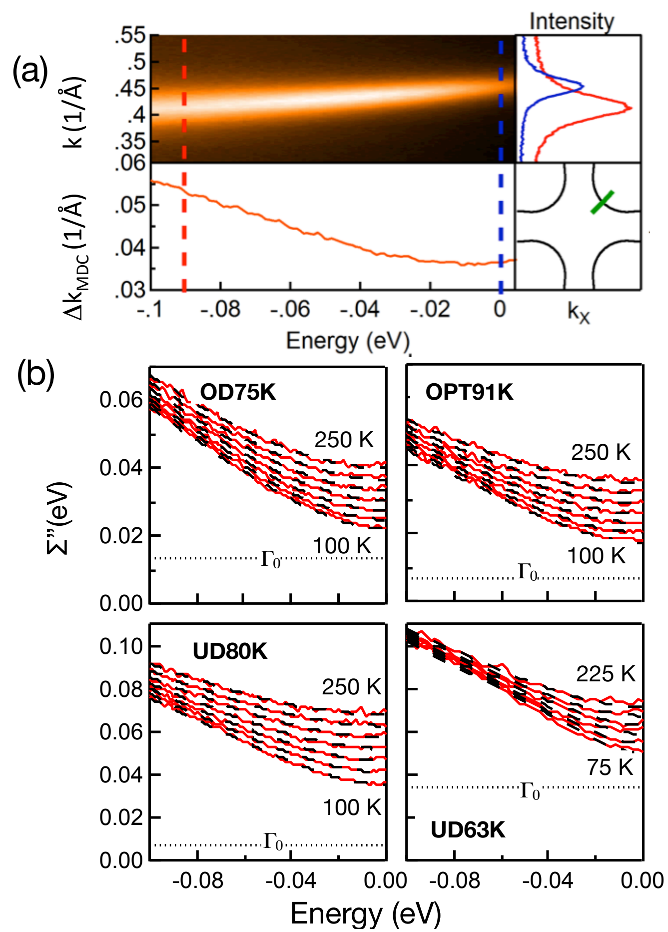
- Physics: the probe fermion interacts with a quantum critical sector



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

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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Condensed Matter > Strongly Correlated Electrons

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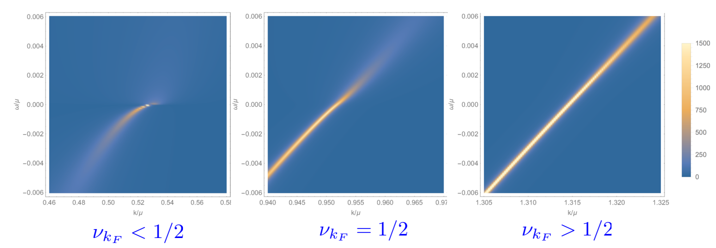
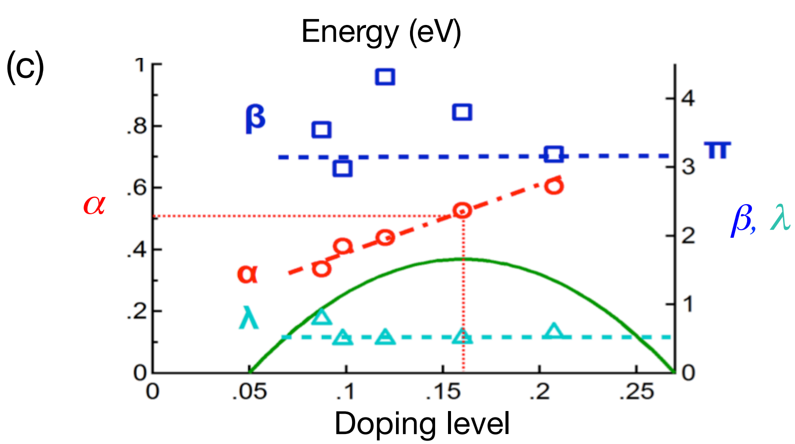
- Holographic prediction

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

- Experimental fit to

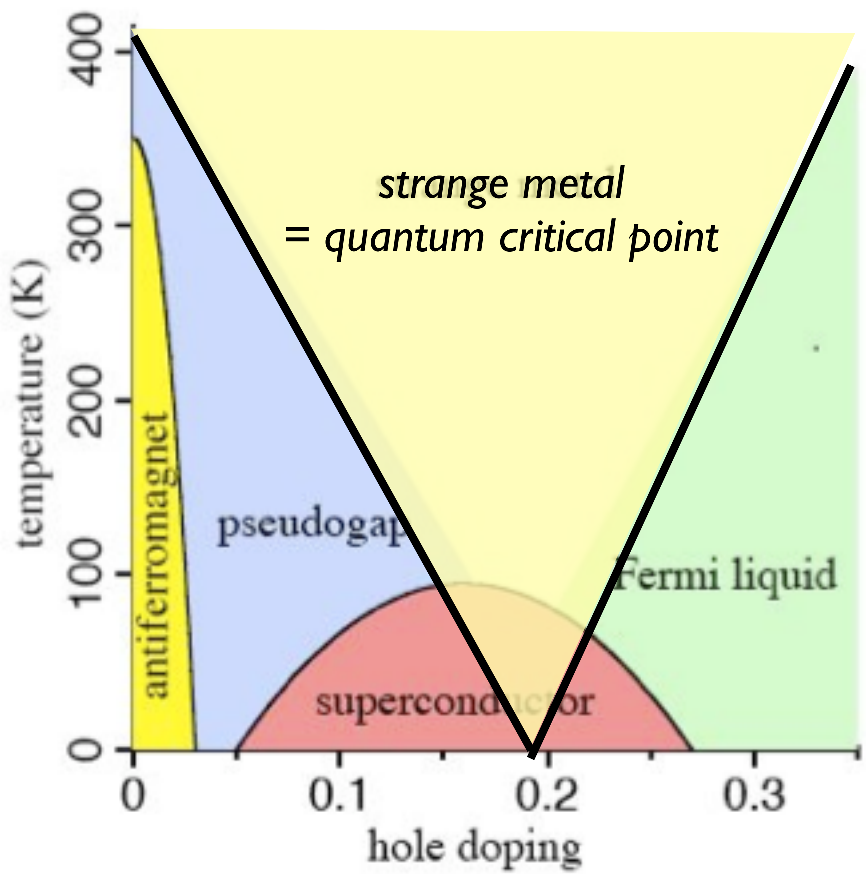
$$\Sigma = \lambda(\omega^2 + \beta^2 T^2)^\alpha$$



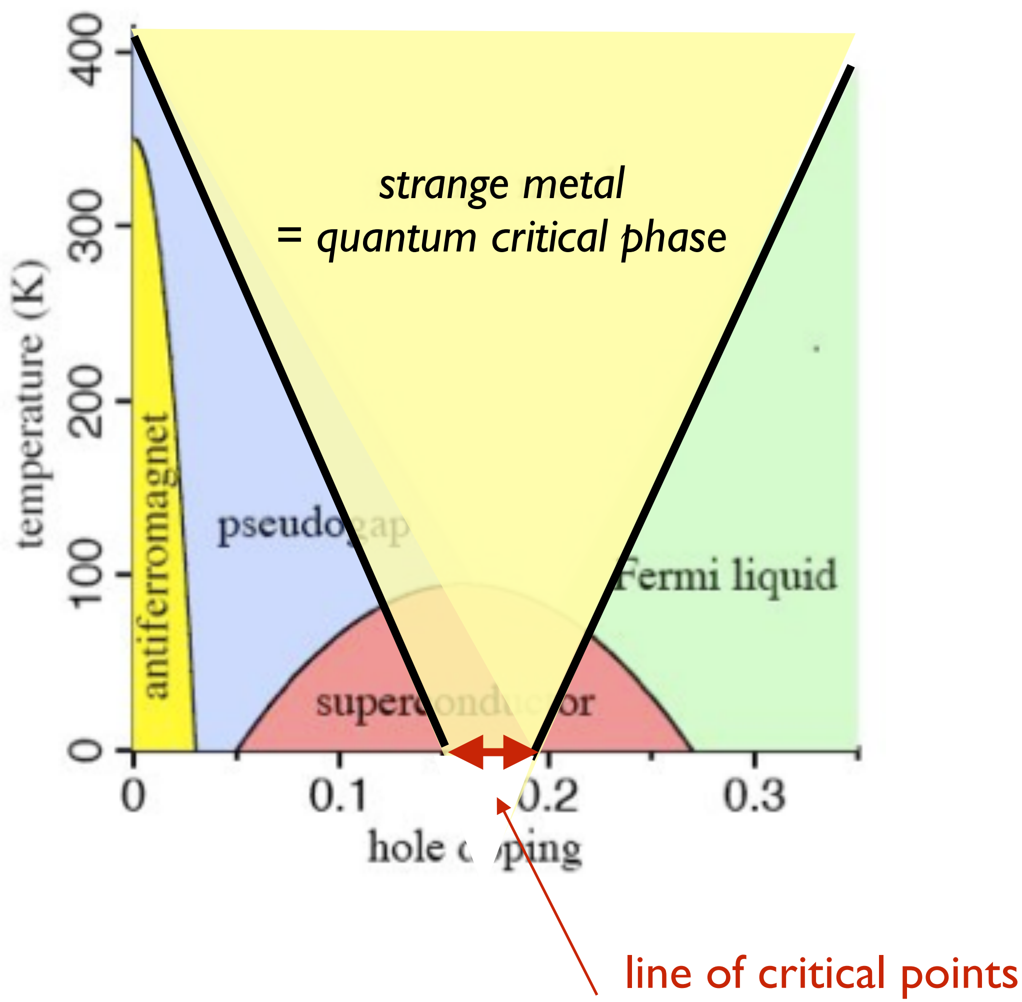


a quantum critical phase

The strange metal in high Tc cuprates

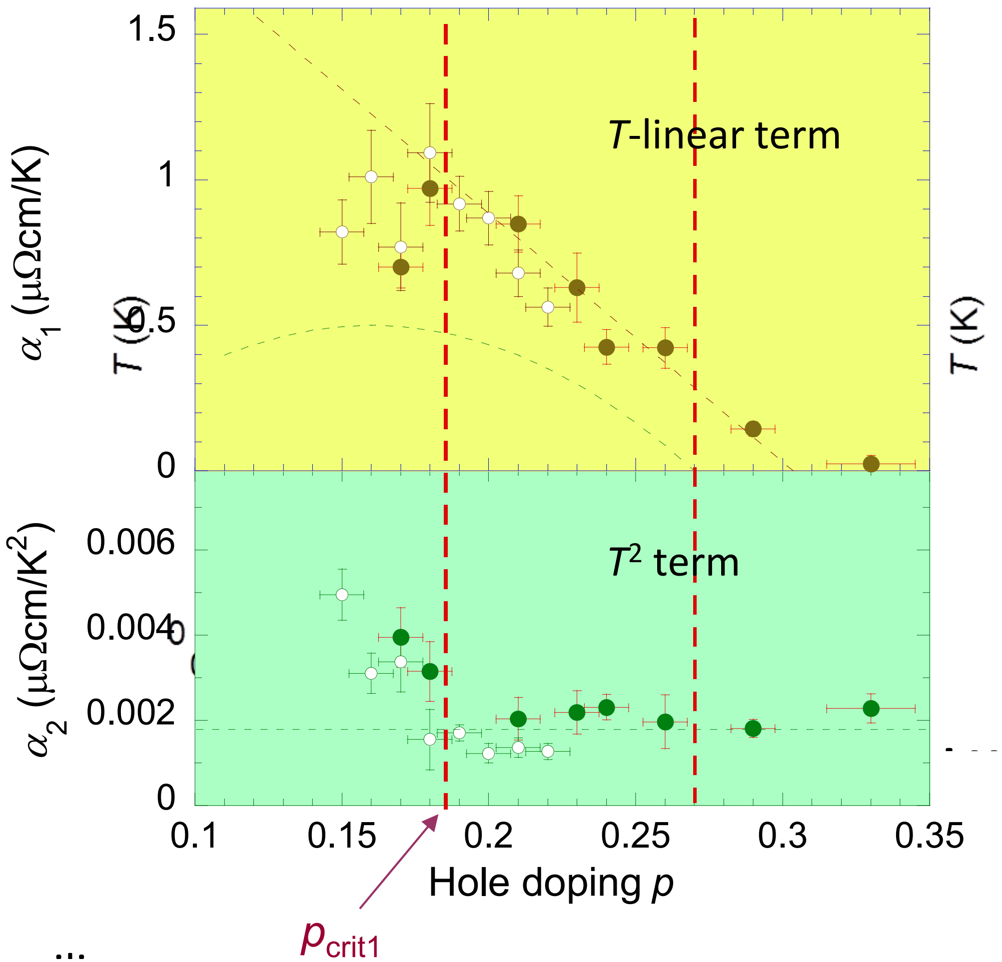


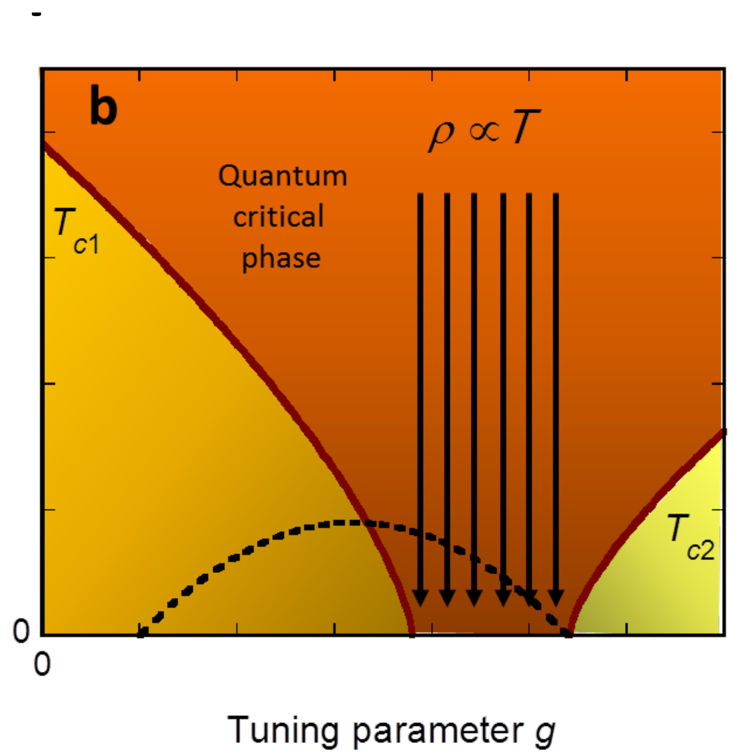
The strange metal in high Tc cuprates



- Linear resistivity in the High-Tc cuprates

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

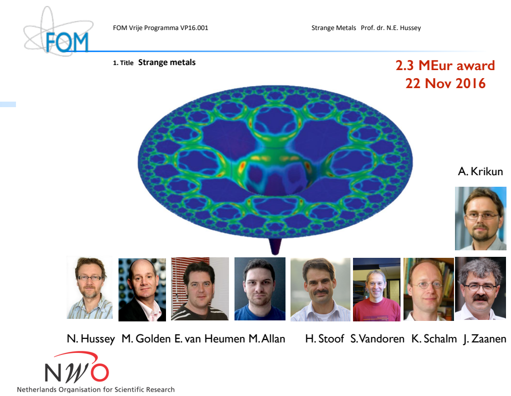




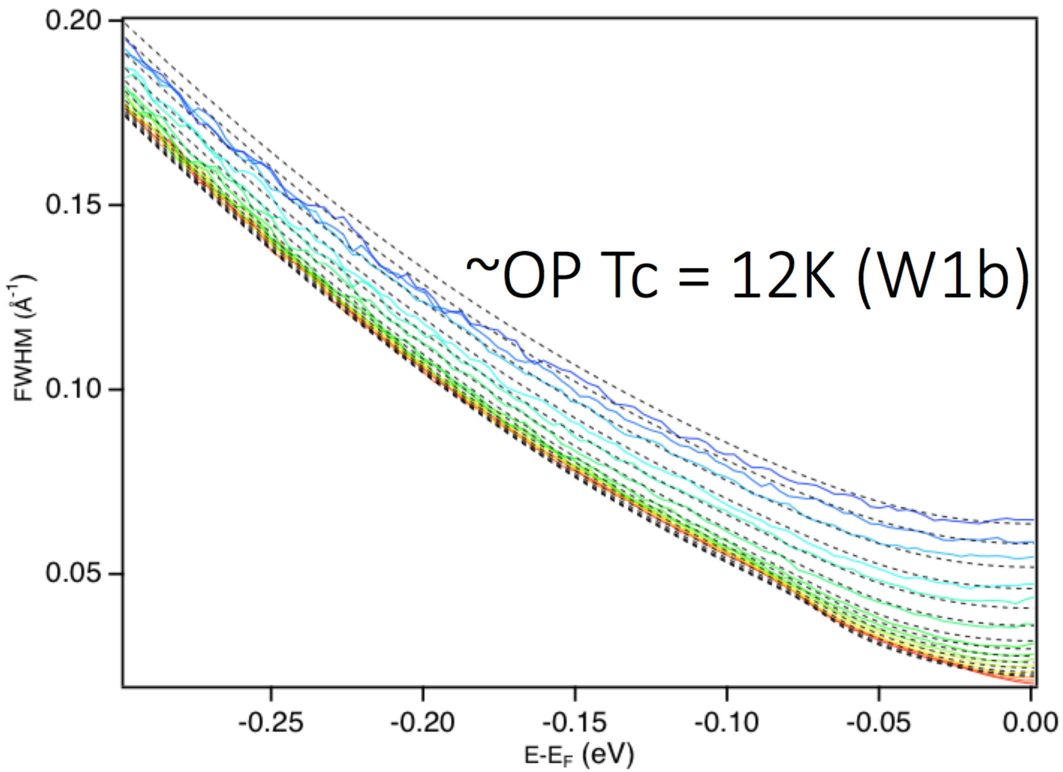
...

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

- Most recent data…



$$\Sigma''_{\text{measured}} = \Sigma''_{\text{intrinsic}} + \Sigma''_{\text{anything else}}$$

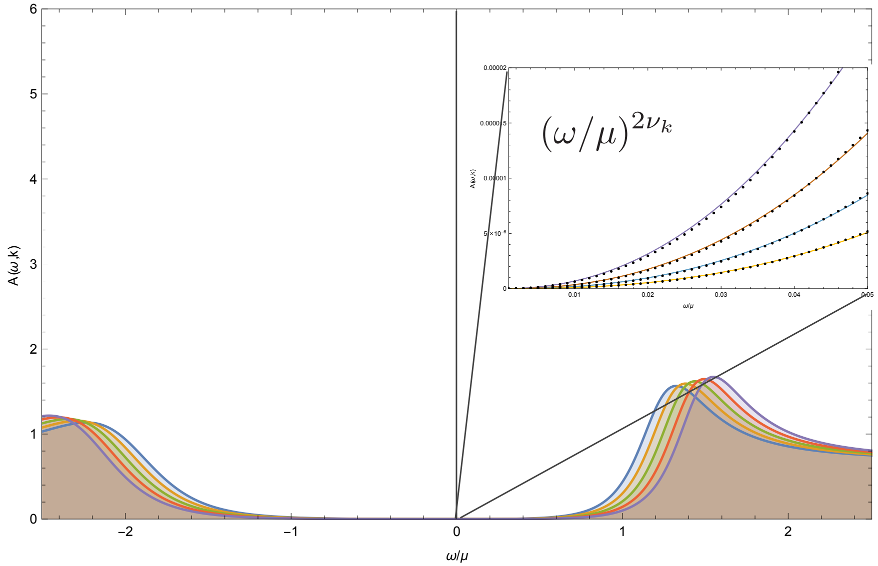


Thanks to
L. Bawden, M. Berben, M. Golden, S. Smit E. van Heumen,

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 $k \neq k_F$

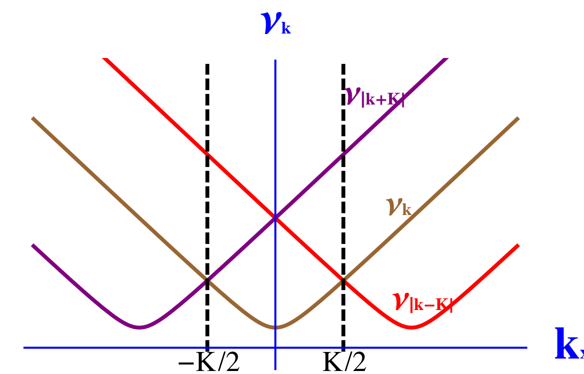
$$\mathrm{Im}G(\omega, k) \sim \omega^{2\nu_k} \qquad \nu_k \sim \sqrt{\frac{1}{\xi^2} + k^2}$$

- The quantum critical contribution to the spectral function

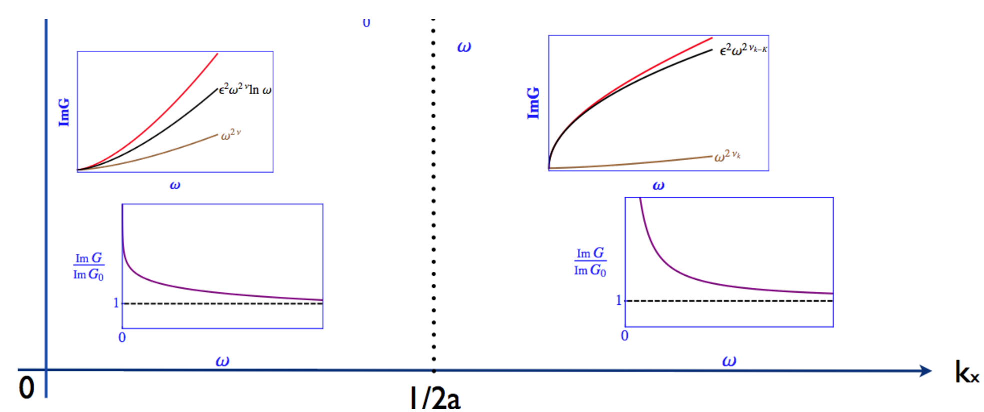
$$\mathrm{Im}G(\omega, k) \sim \omega^{2\nu_k} \qquad \nu_k \sim \sqrt{\frac{1}{\xi^2} + k^2}$$

- 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

Comparison to Experiment:
Dynamics of the superconducting gap

- In the superconducting state, massive fermionic quasiparticles

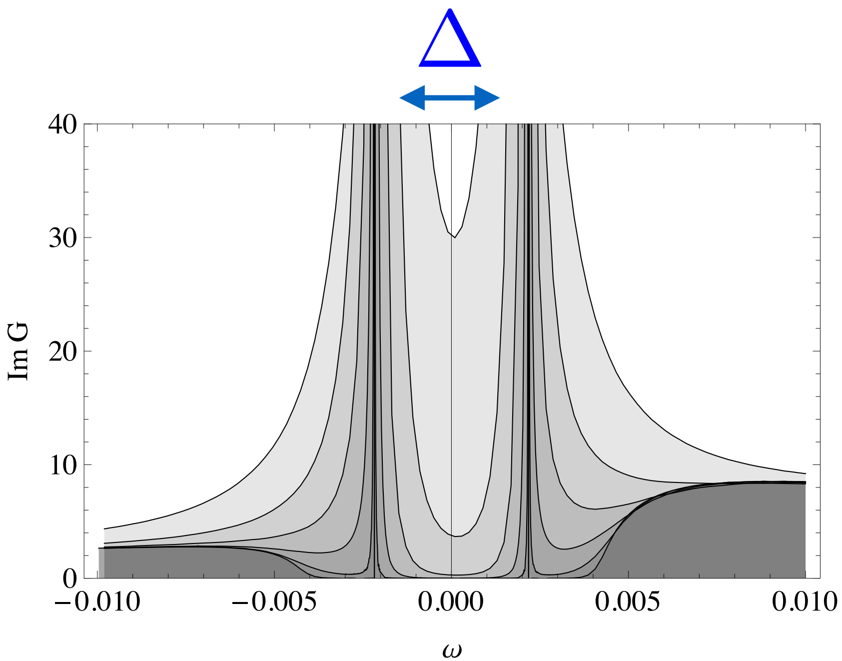
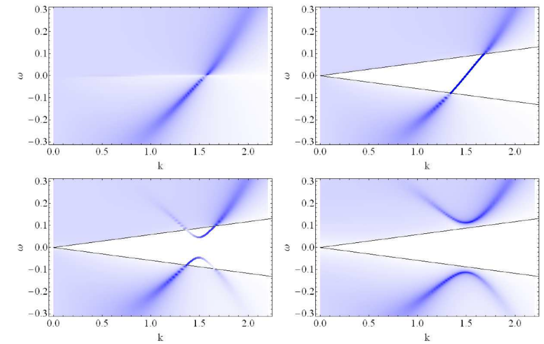
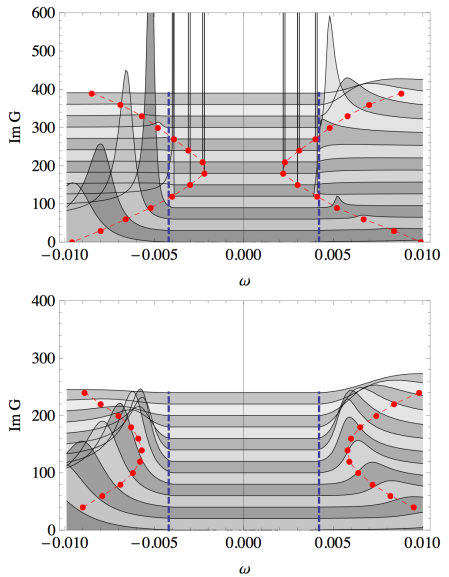


FIG. 7: The effect of temperature (much less than T_c) on the fermion spectral function. Shown are plots at $q_\varphi = 1, m_\varphi^2 = -1, q_\zeta = \frac{1}{2}, m_\zeta = 0, \eta_5 = .025$, and momenta where the peak is closest to $\omega = 0$. The different curves correspond to different temperatures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





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

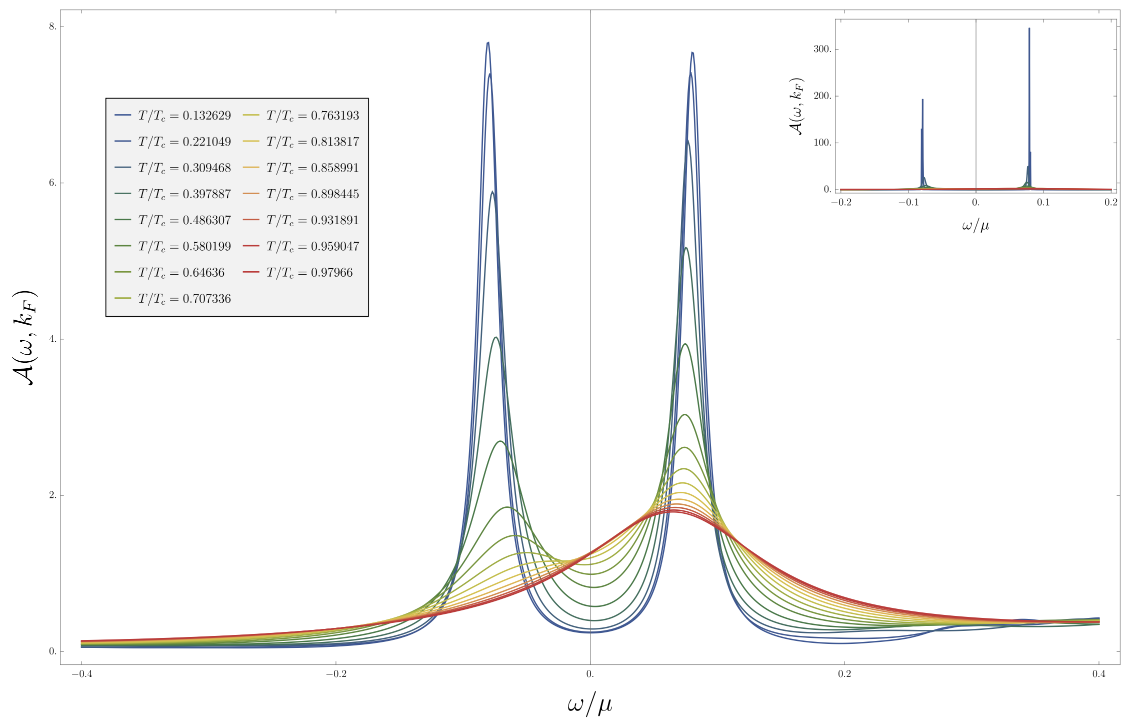
$$\Delta_{Hol} \sim 1$$

Faulkner, Horowitz, McGreevy, Roberts, Vegh

- In the superconducting state, massive fermionic quasiparticles

Δ

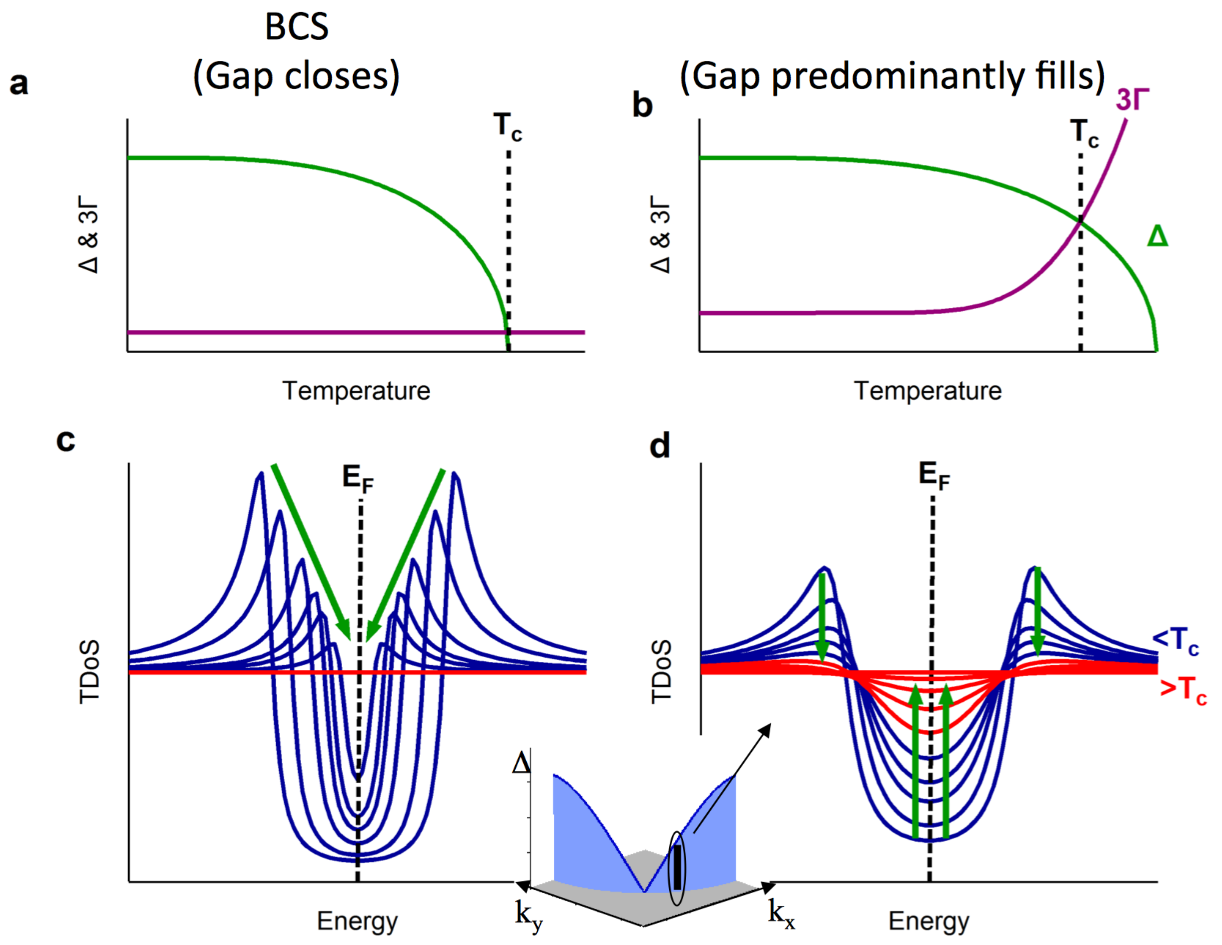
Spectral function at $\eta_5 = 0.25$



Poovuttikul, Straub, et al
unpublished

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

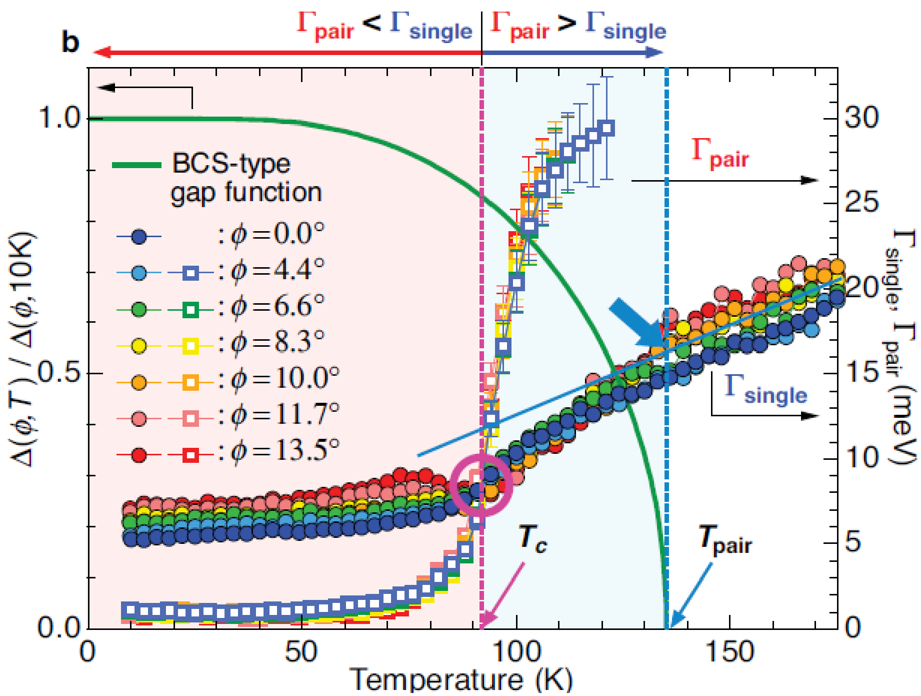
- In the superconducting state, fermionic quasiparticles are gapped



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

Point nodes persisting far beyond Tc in Bi2212

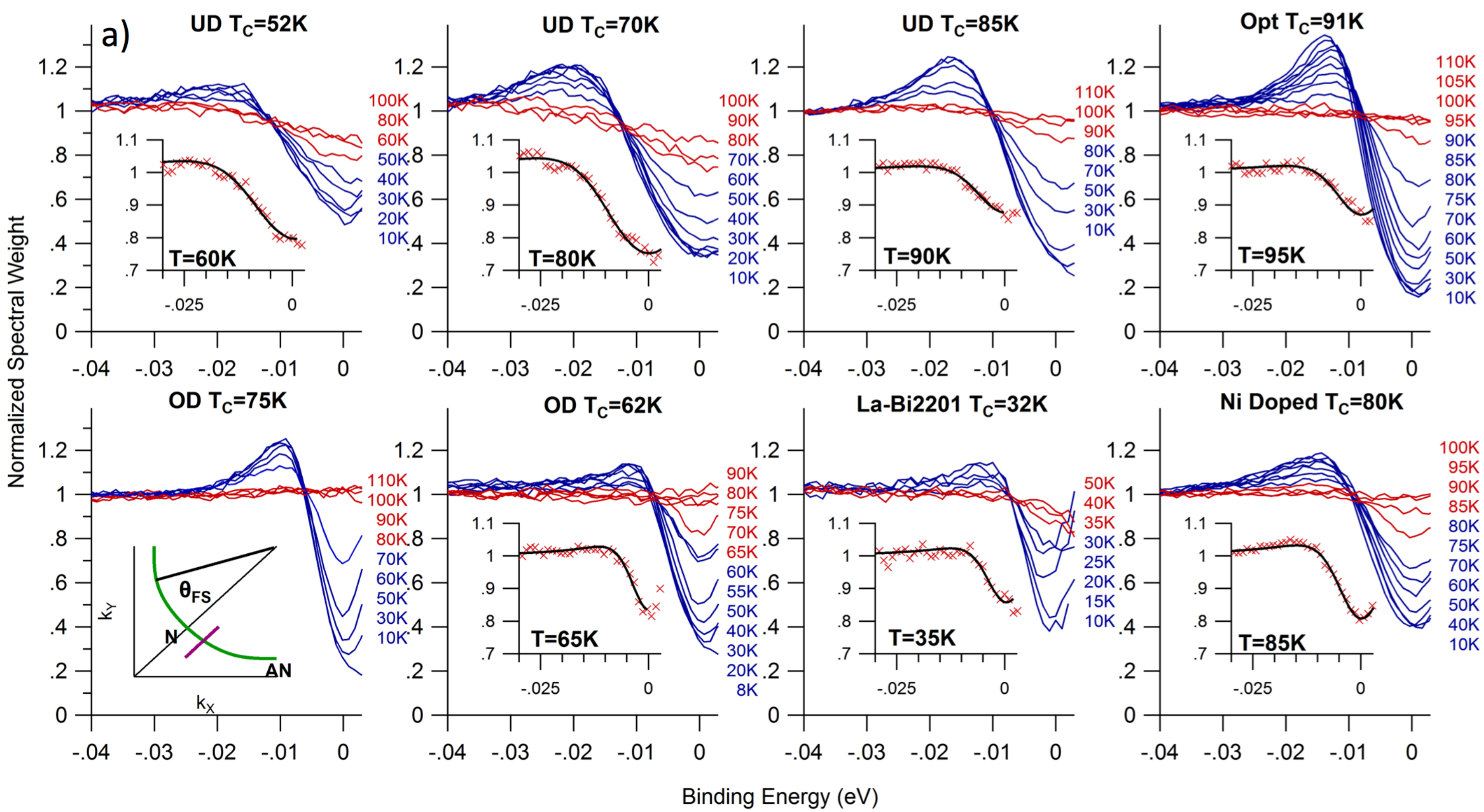
Takeshi Kondo, W. Malaeb, Y. Ishida, T. Sasagawa, H. Sakamoto, Tsunehiro Takeuchi, T. Tohyama, S. Shin



Kondo *et al.*,
Nat Commun **6** 7699 (2015)

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

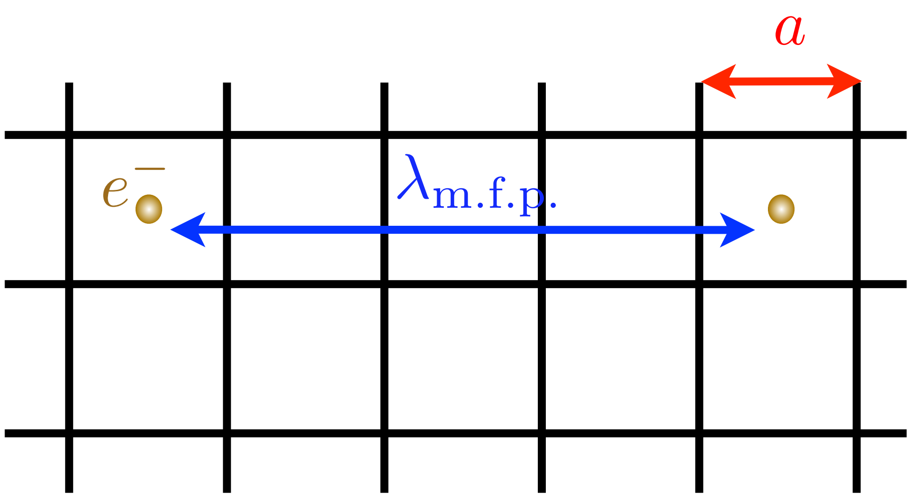


see also Li et al
Nat.Comm 9, 26 (2018)

A universal linear resistivity

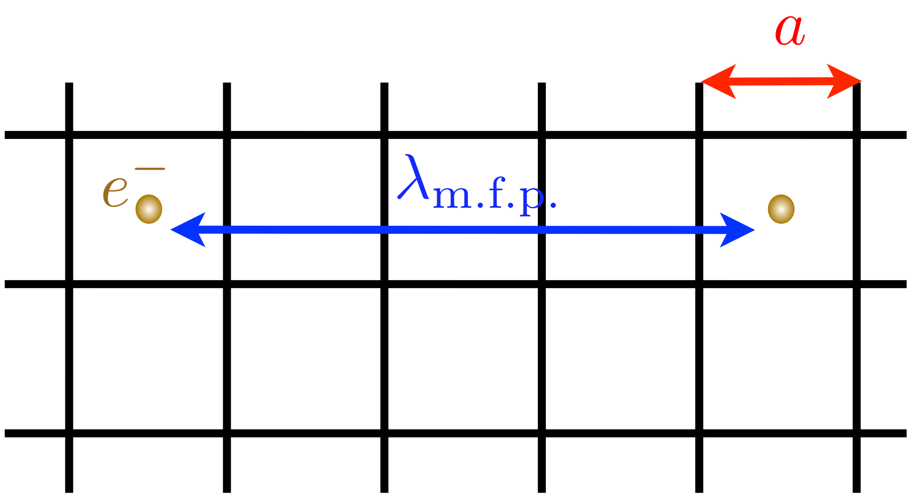
- Ordinary metals
- Momentum relaxes before collective behavior sets in

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



- Ordinary metals
- Momentum relaxes before collective behavior sets in

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



- Strongly correlated metals (no quasiparticles)

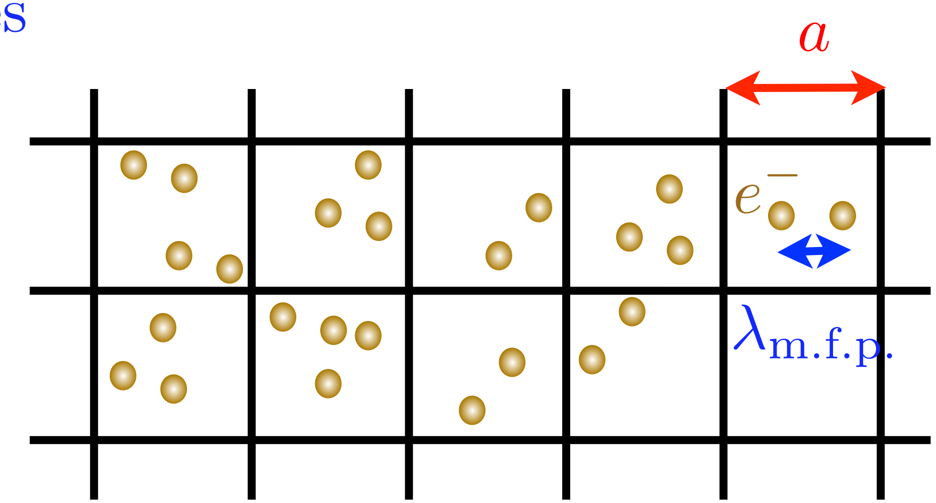
$$\lambda_{\text{m.f.p.}} \ll \text{external scales}$$

- 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

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

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

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

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

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

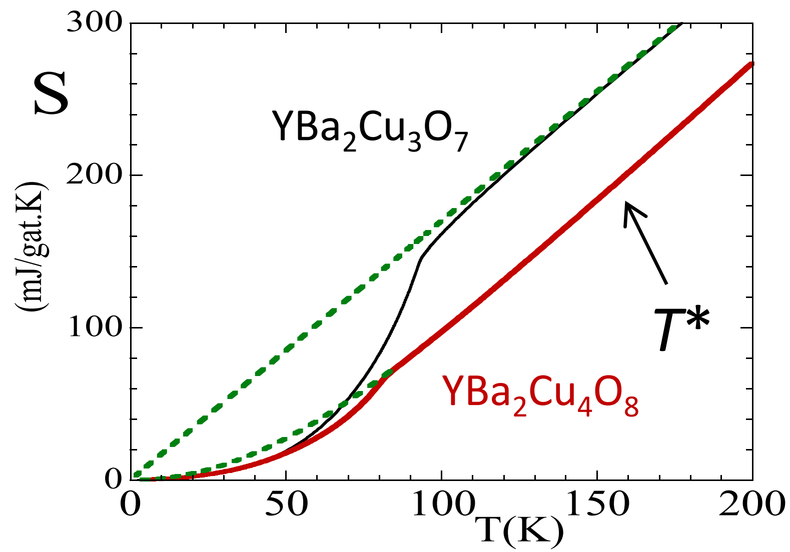
- Caveat: theory must be locally quantum critical $z \simeq \infty$

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



$$s(T) \sim T + \ldots$$

Loram et al

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

$$\rho_{DC} \sim s(T) \sim T + \ldots$$

- 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

arXiv.org > cond-mat > arXiv:1509.04713

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Condensed Matter > Mesoscale and Nanoscale Physics

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

Jesse Crossno, Jing K. Shi, Ke Wang, Xiaomeng Liu, Achim Harzheim, Andrew Lucas, Subir Sachdev, Philip Kim, Takashi Taniguchi, Kenji Watanabe, Thomas A. Ohki, Kin Chung Fong

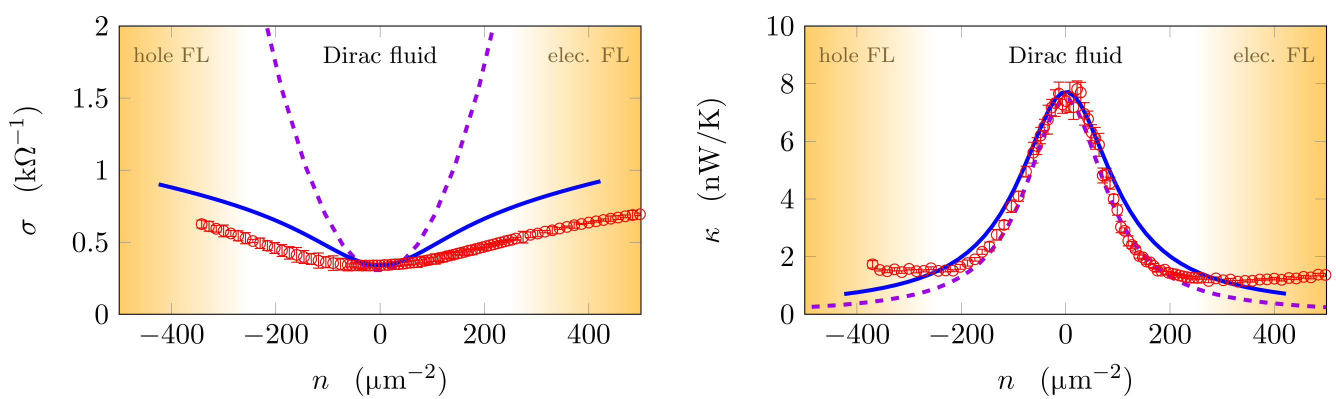


Figure 1: A comparison of our hydrodynamic theory of transport with the experimental results of [33] in clean samples of graphene at $T = 75$ K. We study the electrical and thermal conductances at various charge densities n near the charge neutrality point. Experimental data is shown as circular red 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 $\kappa(n)$.

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*]

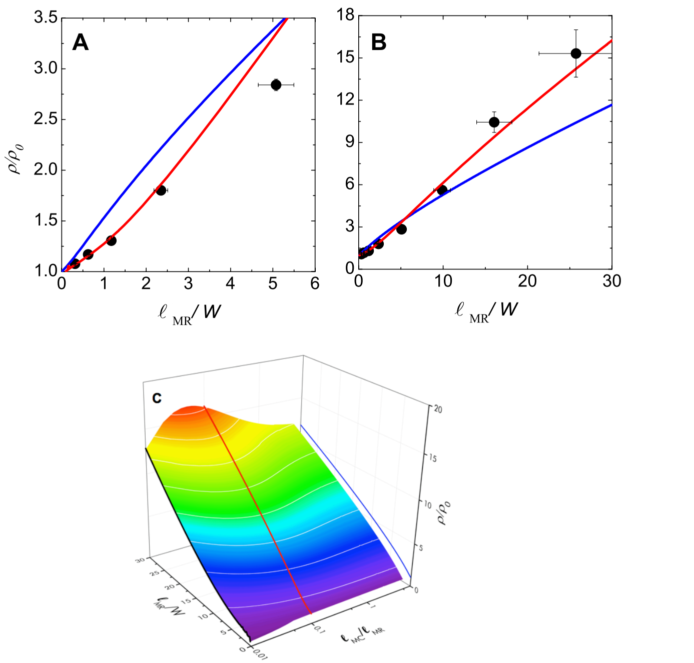


Fig. 4. Hydrodynamic effect on transport. (A, B) The measured resistivity of $PdCoO_2$ channels normalised to that of the widest channel (ρ_0), plotted against the inverse channel width $1/W$ multiplied by the bulk momentum- relaxing mean free path ℓ_{MR} (closed black circles). Blue solid line: prediction 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]

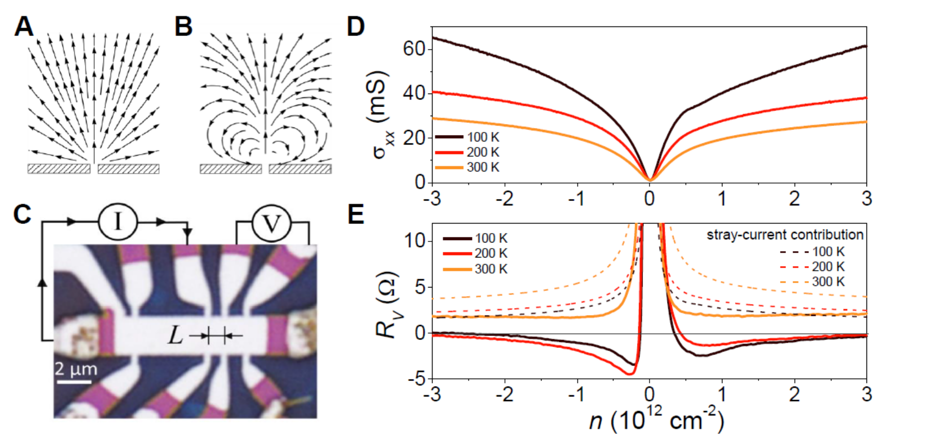
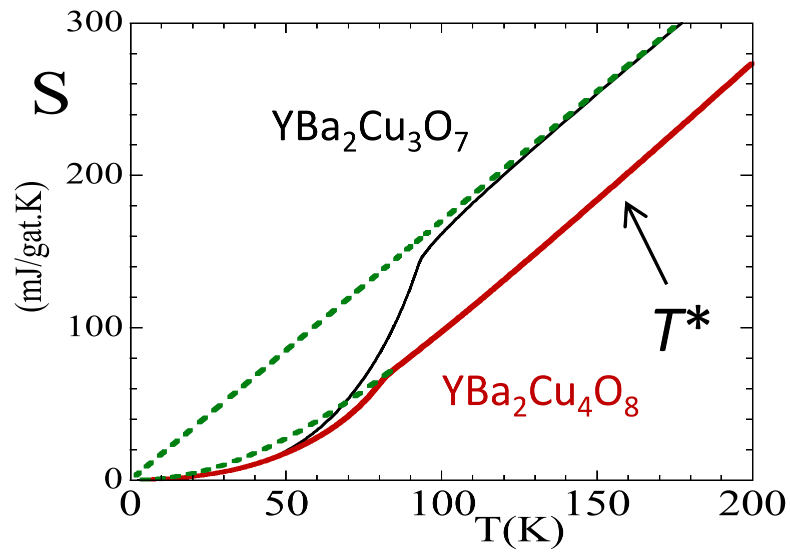


Fig. 1. Viscous backflow in doped graphene. (**A**,**B**) Calculated steady-state distribution of current injected through a narrow slit for a classical conducting medium with zero ν (A) and a viscous Fermi liquid (B). (**C**) Optical micrograph of one of our SLG devices. The schematic explains the measurement 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*).

A universal mechanism for a linear resistivity

- Entropy density at low T

Davison, Schalm, Zaanen
PRB89 (2014) 245116



$$s(T) \sim T + \dots$$

Loram et al

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

$$\rho_{DC} \sim s(T) \sim T + \dots$$

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

Two specific predictions from holography

arXiv.org > cond-mat > arXiv:1705.05806

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Condensed Matter > Strongly Correlated Electrons

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

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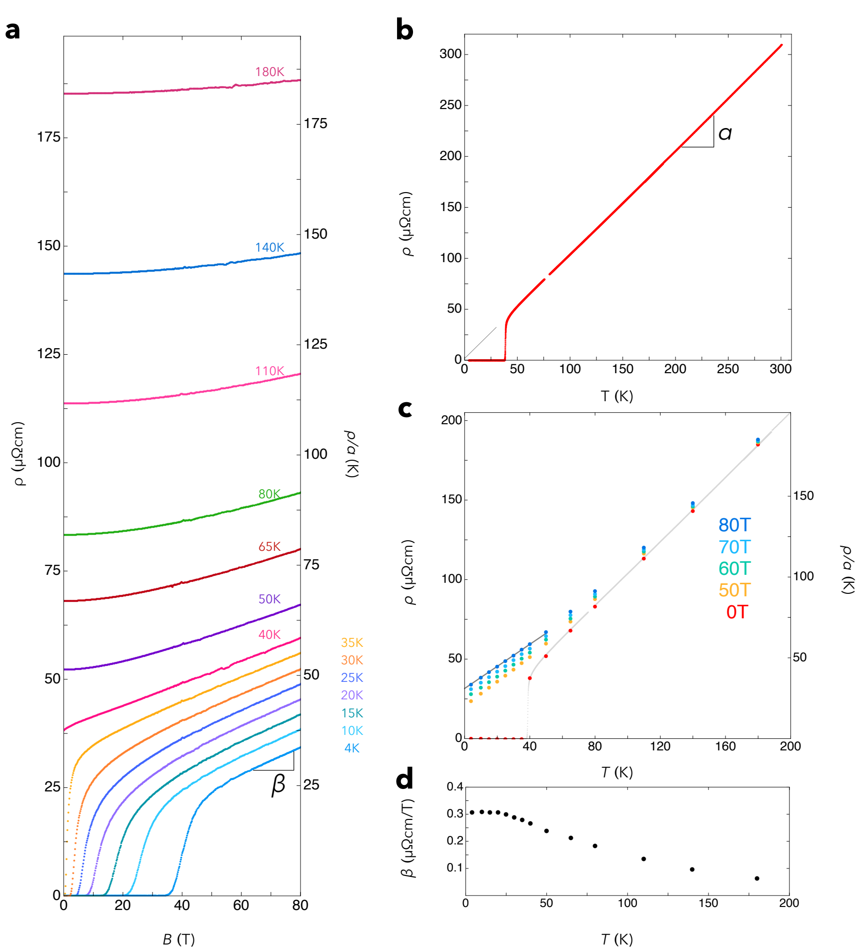

Figure 1. Magnetoresistance up to 80T of the thin-film $La_{2-x}Sr_xCuO_4$ at $x = 0.190$. **a** Field scans up to 80T for a set of temperatures up to 180K. The vertical ticks on the right indicate the resistivity in temperature units, ρ/α, obtained using linear fit in panel **b**. The aspect ratio is 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 $a \approx 1.5(\pm 1.5)\mu\Omega$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.

arXiv.org > cond-mat > arXiv:1705.05806

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Condensed Matter > Strongly Correlated Electrons

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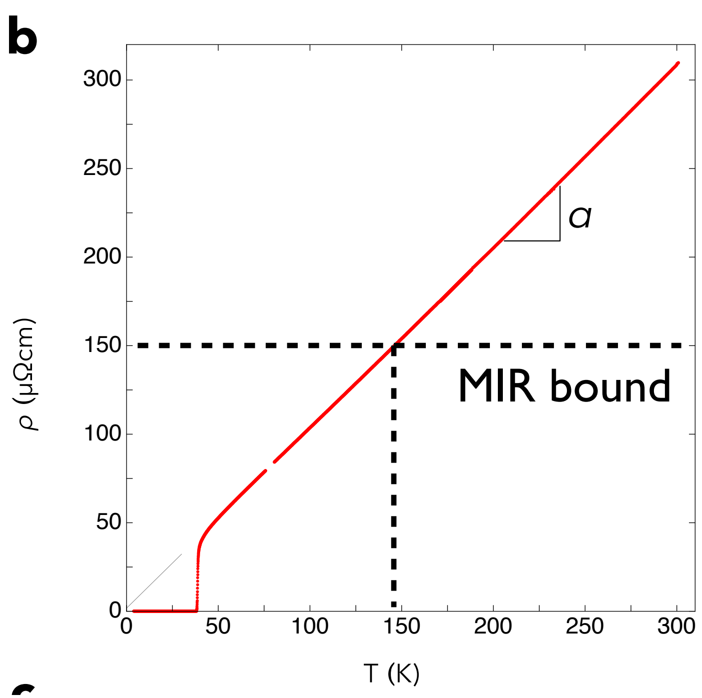
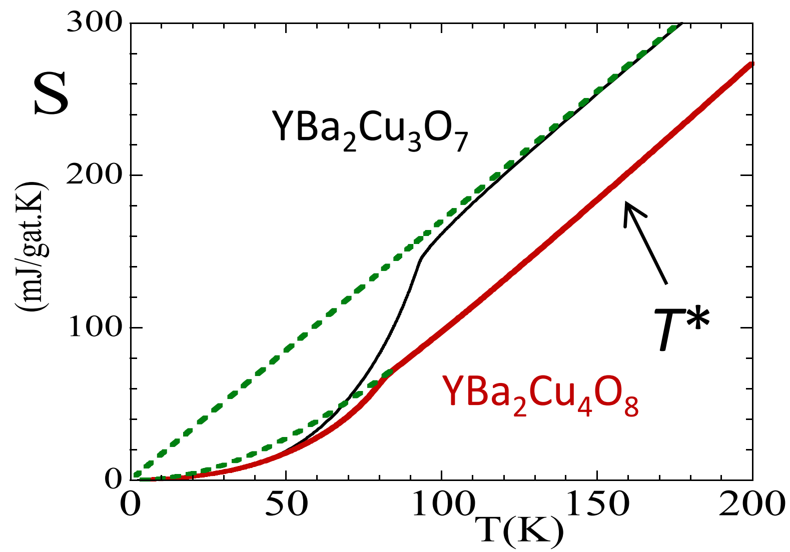


Intercept at T=0 is at $\rho = 0$
to *very high* precision

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

- Entropy density at low T

Davison, Schalm, Zaanen
PRB89 (2014) 245116



$$s(T) \sim T + \ldots$$

Loram et al

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

$$\rho_{DC} \sim s(T) \sim T + \ldots$$

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

Universal T-linear resistivity and Planckian limit in overdoped cuprates

A. Legros, S. Benhabib, W. Tabis, F. Laliberté, M. Dion, M. Lizaire, B. Vignolle, D. Vignolles, H. Raffy, Z. Z. Li, P. Auban-Senzier, N. Doiron-Leyraud, P. Fournier, D. Colson, L. Taillefer, C. Proust

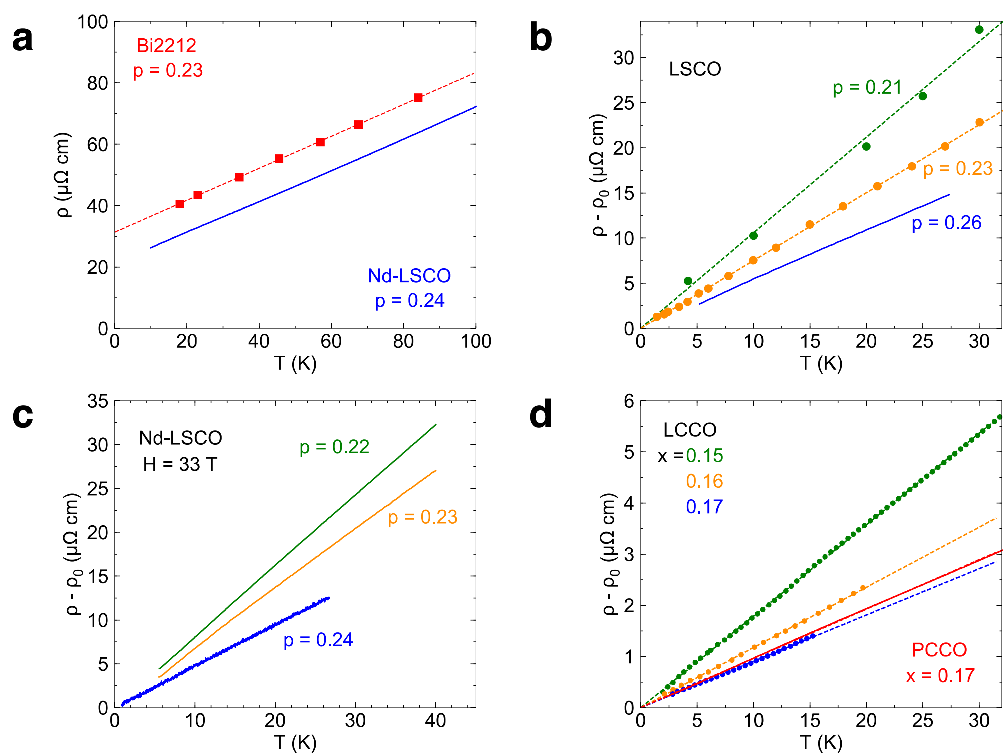


Fig. 1 | *T*-linear resistivity in five overdoped cuprates.

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Condensed Matter > Superconductivity

Universal T-linear resistivity and Planckian limit in overdoped cuprates

A. Legros, S. Benhabib, W. Tabis, F. Laliberté, M. Dion, M. Lizaire, B. Vignolle, D. Vignolles, H. Raffy, Z. Z. Li, P. Auban-Senzier, N. Doiron-Leyraud, P. Fournier, D. Colson, L. Taillefer, C. Proust

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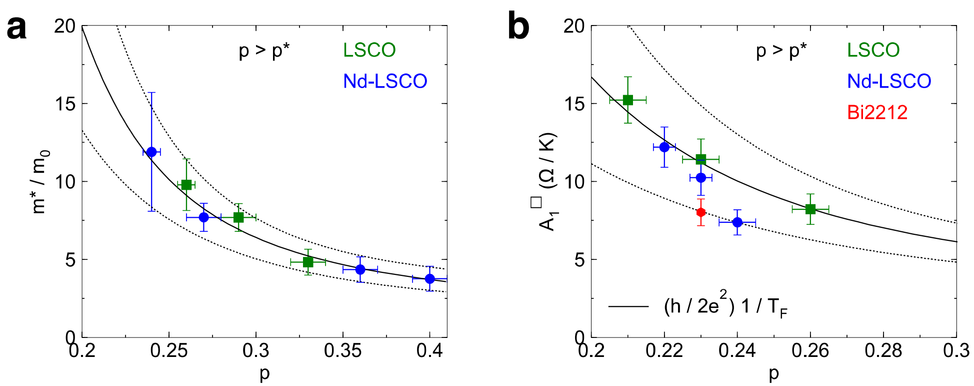

Fig. 3 | Effective mass m^* and slope of T-linear resistivity $A_1^\square$ vs p in hole-doped cuprates.

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

$$\frac{\partial}{\partial T}\rho_{DC} \sim \frac{\partial}{\partial T} s(T) = \frac{c_V}{T} \equiv \gamma$$

$* :$ 2D FL : $\gamma = (\frac{\pi}{3} N_A a^2) m^*$

specific heat γ is the measured quantity

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

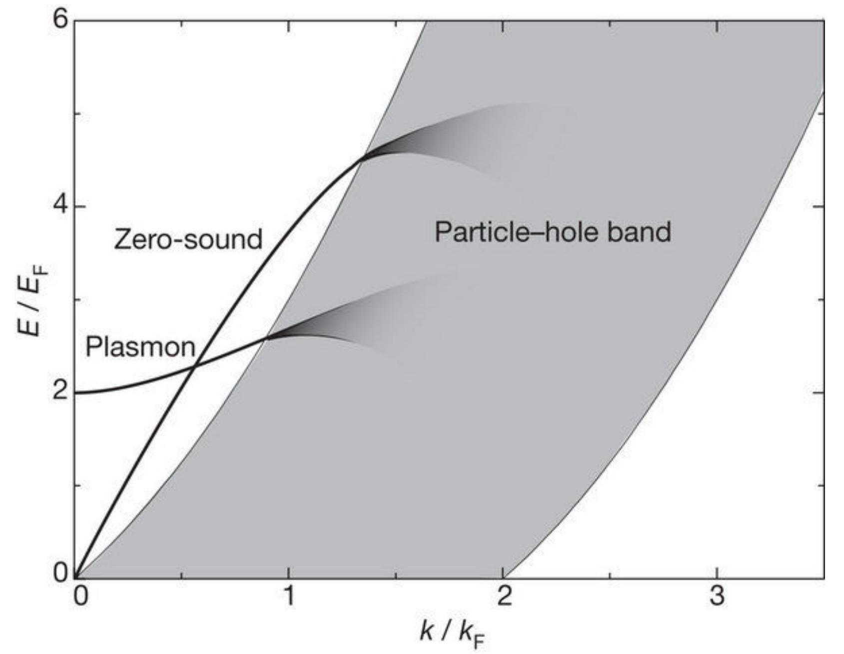
- Plasmon in Fermi liquids

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

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

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

Plasmon gap e^2



- Can be deduced from dielectric response

$$\chi \sim -\mathrm{Im} \frac{1}{\epsilon(\mathbf{q}, \omega)}$$

Condensed Matter > Strongly Correlated Electrons

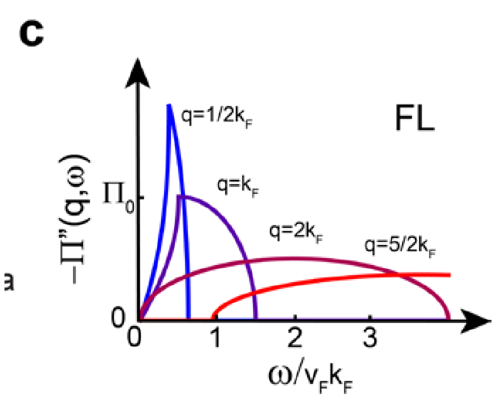
Singular density fluctuations in the strange metal phase of a copper-oxide superconductor

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)

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

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



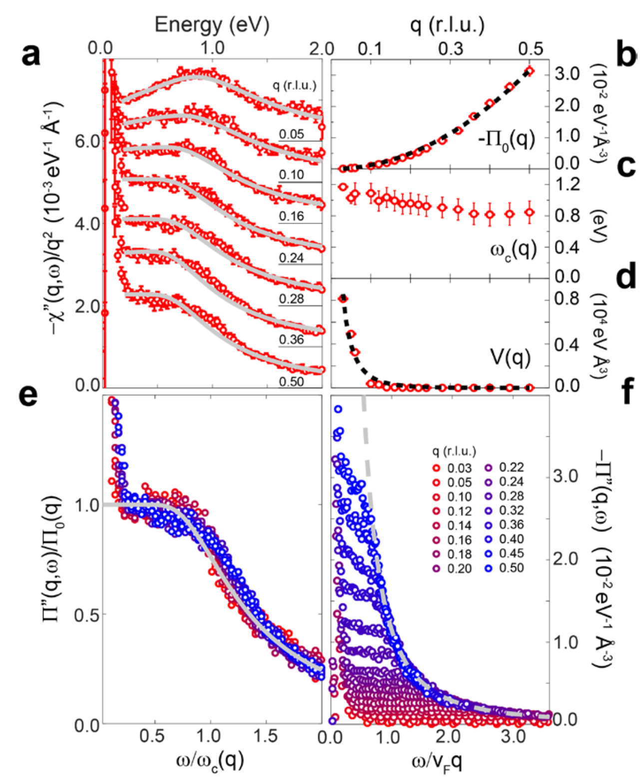


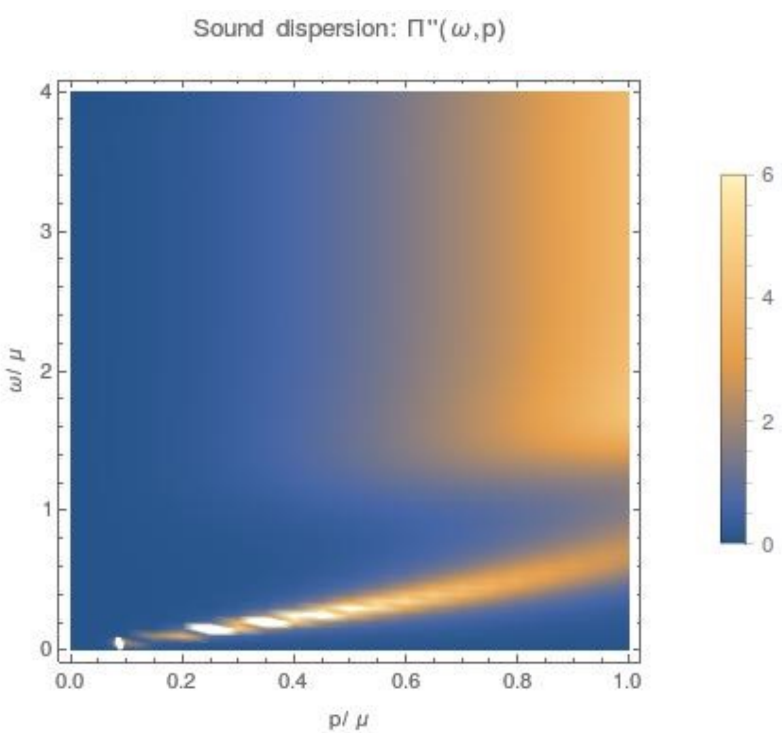
Fig. 2 – Scaling collapse of the continuum in optimally-doped BSCCO. (a) Dynamic charge susceptibility, $\chi''(q,\omega)$, for a selection of momenta along the $(1,\bar{1})$

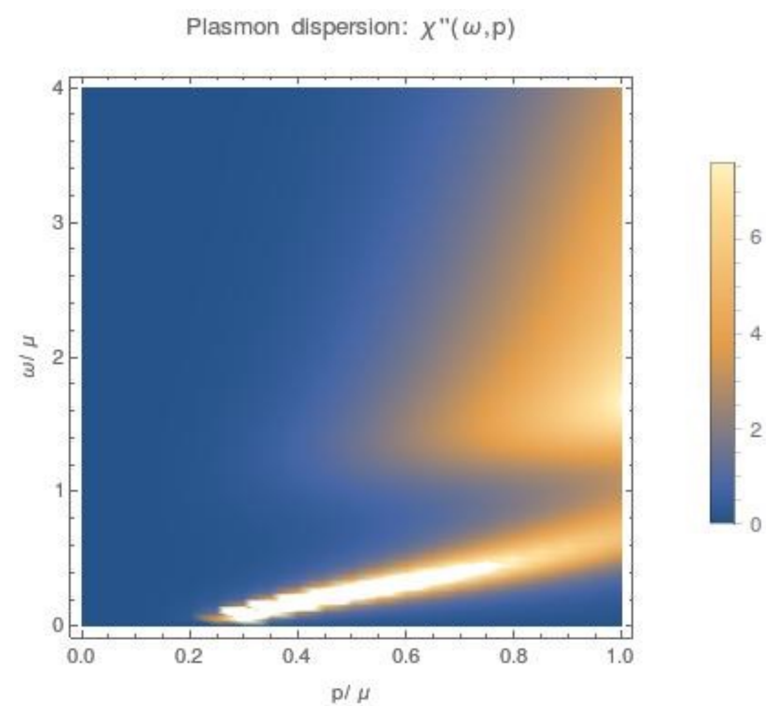
Density-density correlation functions in holography

- Zero sound — Karch, Son, Starinets
- Friedel oscillations — Puletti, Nowling, Thorlacius, Zingg; Faulkner, Iqbal; Blake, Donos, Tong
- Full frequency, momentum dependence — Krikun, Romero-Bermudez, Schalm, Zaanen; Aronsson, Gran, Zingg

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

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



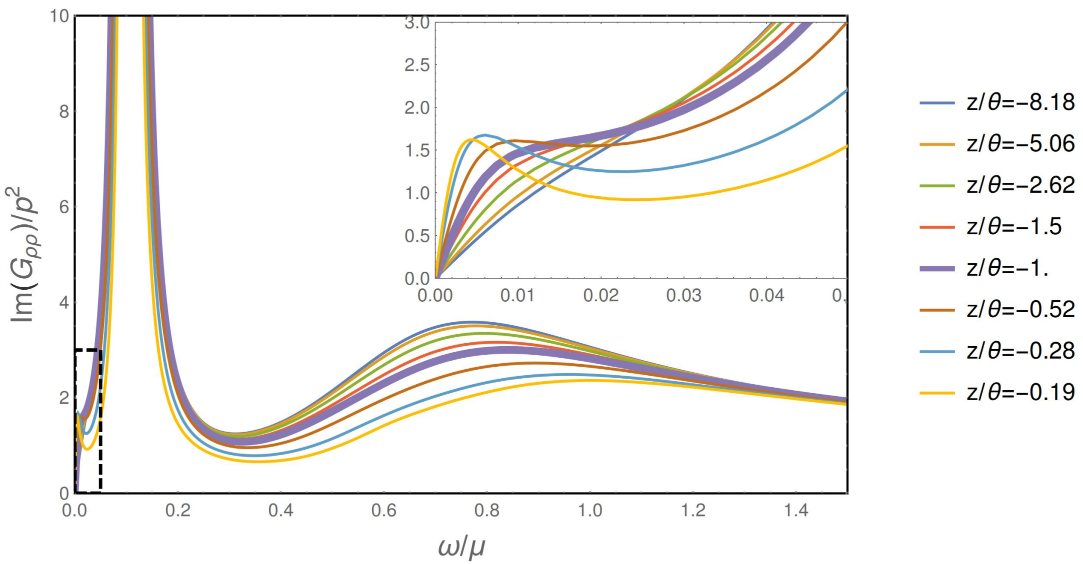


Density-density correlation functions in holography

- Zero sound — Karch, Son, Starinets; Puletti, Nowling, Thorlacius, Zingg
- Friedel oscillations — Faulkner, Iqbal; Blake, Donos, Tong
- Full frequency, momentum dependence — Krikun, Romero-Bermudez, Schalm, Zaanen; Aronsson, Gran, Zingg

Plasmon width should know about quantum critical sector

HSV backgrounds with $z\to\infty$, $\theta\to\infty$. (p/μ=0.15)



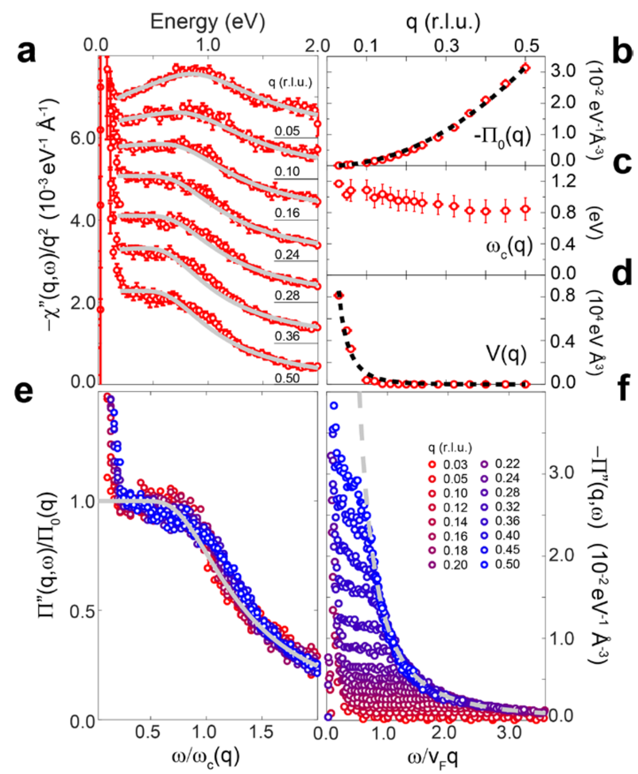
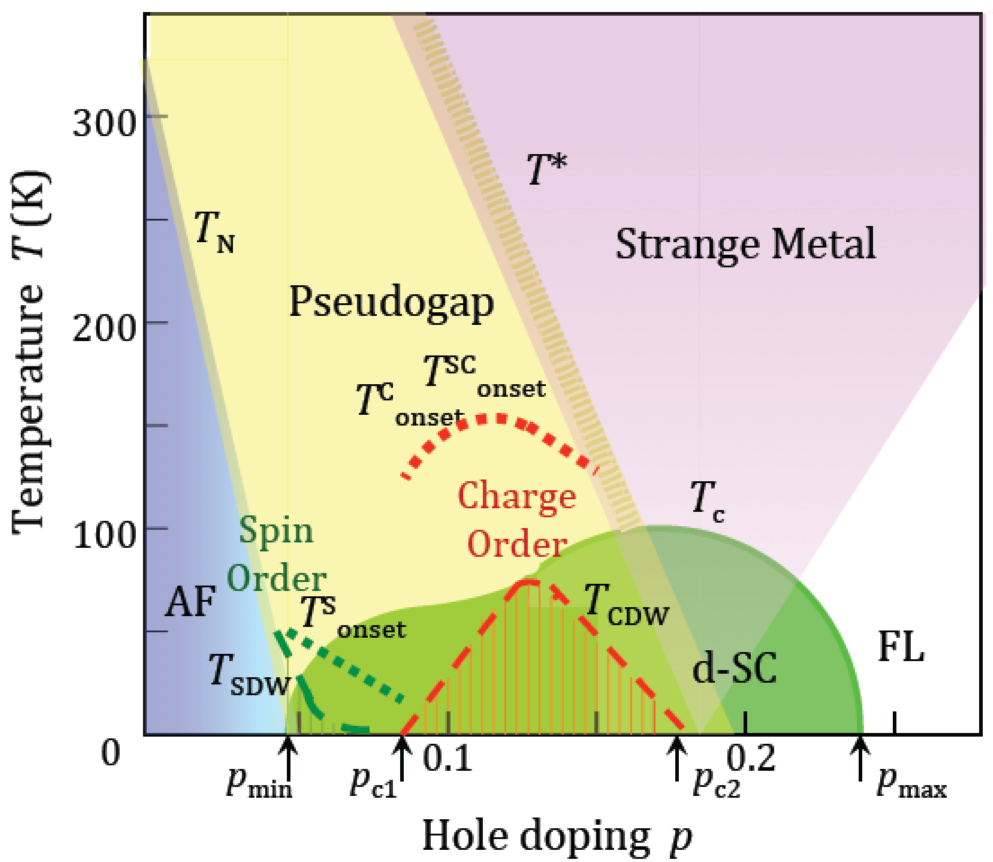


Fig. 2 – Scaling collapse of the continuum in optimally-doped BSCCO. (a) Dynamic charge susceptibility, $\chi''(q,\omega)$, for a selection of momenta along the $(1,\bar{1})$

- Towards experimental strange metals from Holography
  - 2D Lattice
    - d-wave superconductor
    - nodal-anti-nodal dichotomy
  - All phenomena in one model.
    - Scaling in the Optical Conductivity
    - Homes Law
    - Correlated scaling: Specific Heat, Magnetoresistance, Magnetic Hall
    - …
  - Phase transitions to …

The strange metal in high Tc cuprates

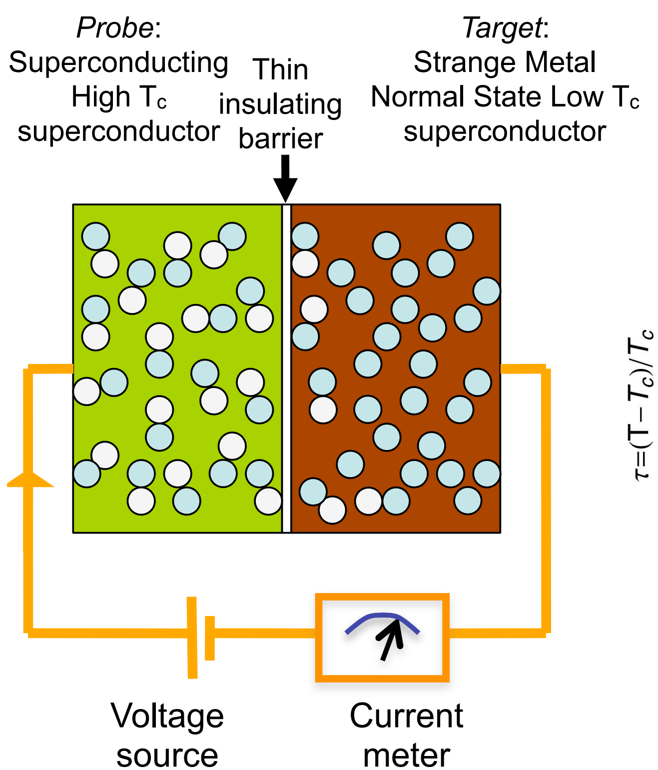


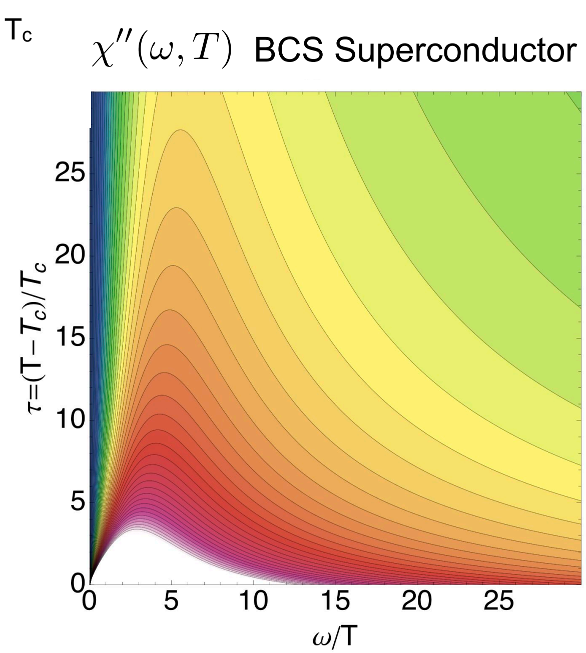
She, Overbosch, Sun, Liu, Mydosh, Zaanen, Schalm

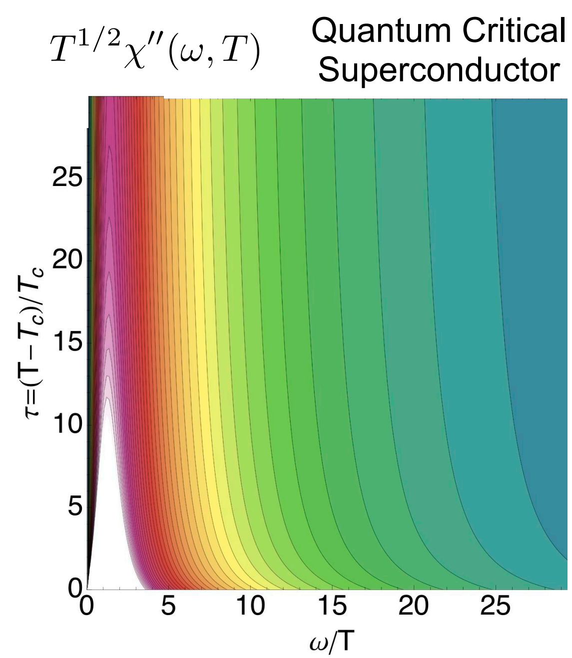
- Order parameter susceptibility
  - Non-canonical scaling dimension
  - Emergence from criticality

$$\Delta = \frac{d}{2} \pm \sqrt{\frac{d^2}{4} + m^2 L^2}$$

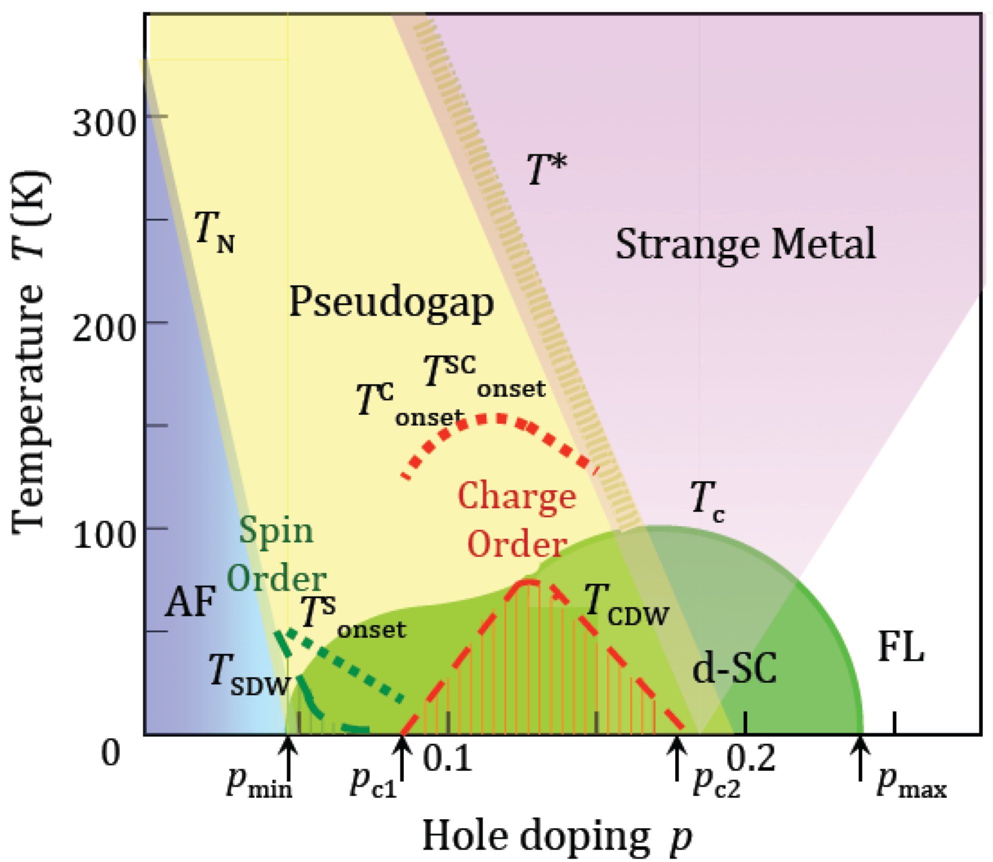
$$\chi(\omega) = \mathrm{Im} G_R(\omega) = \langle \mathcal{O}^\dagger(\omega) \mathcal{O}(0) \rangle$$







The strange metal in high Tc cuprates



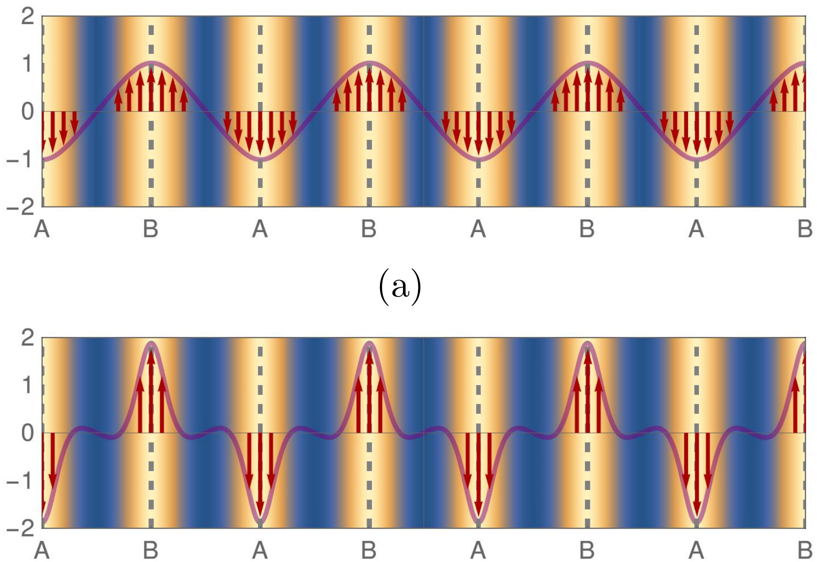
AF phase is a Mott insulator:

a Mott insulator is local “jammed” charge pinned to underlying lattice

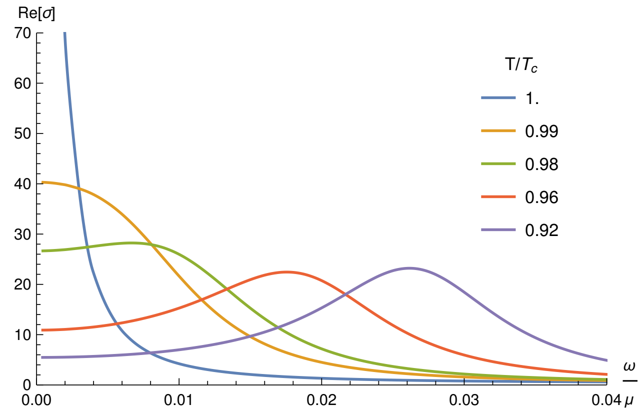
Doping a holographic Mott Insulator

Andrade, Krikun, Schalm, Zaanen

AF phase is a Mott insulator:
a Mott insulator is charge density wave pinned to underlying lattice



(a)

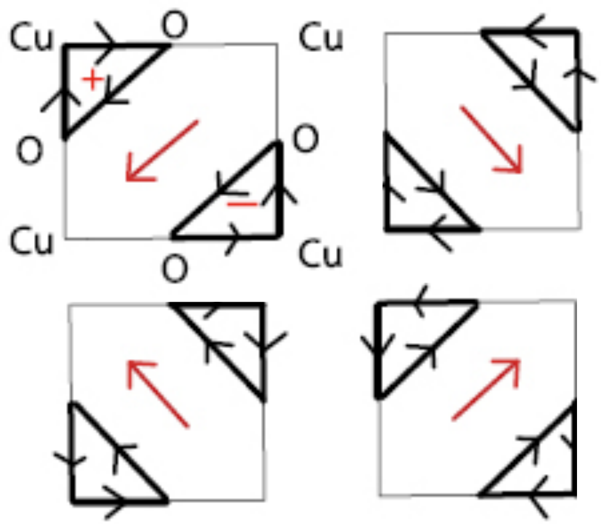


(c)

In holography charge density wave are naturally "intertwined" with loop current order

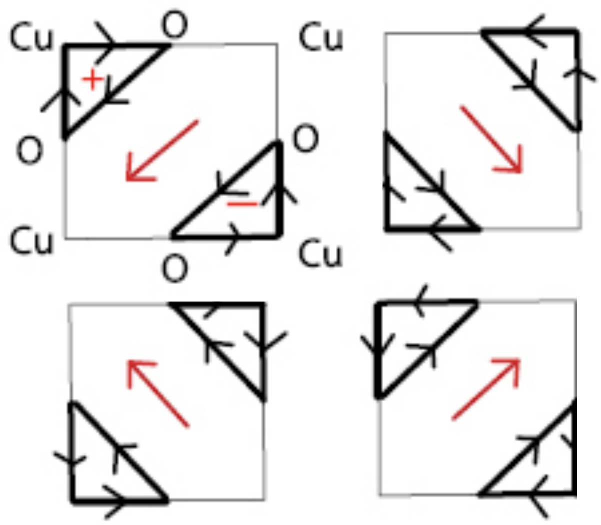
Nakamura, Ooguri, Park, Donos, Gauntlett, Varma

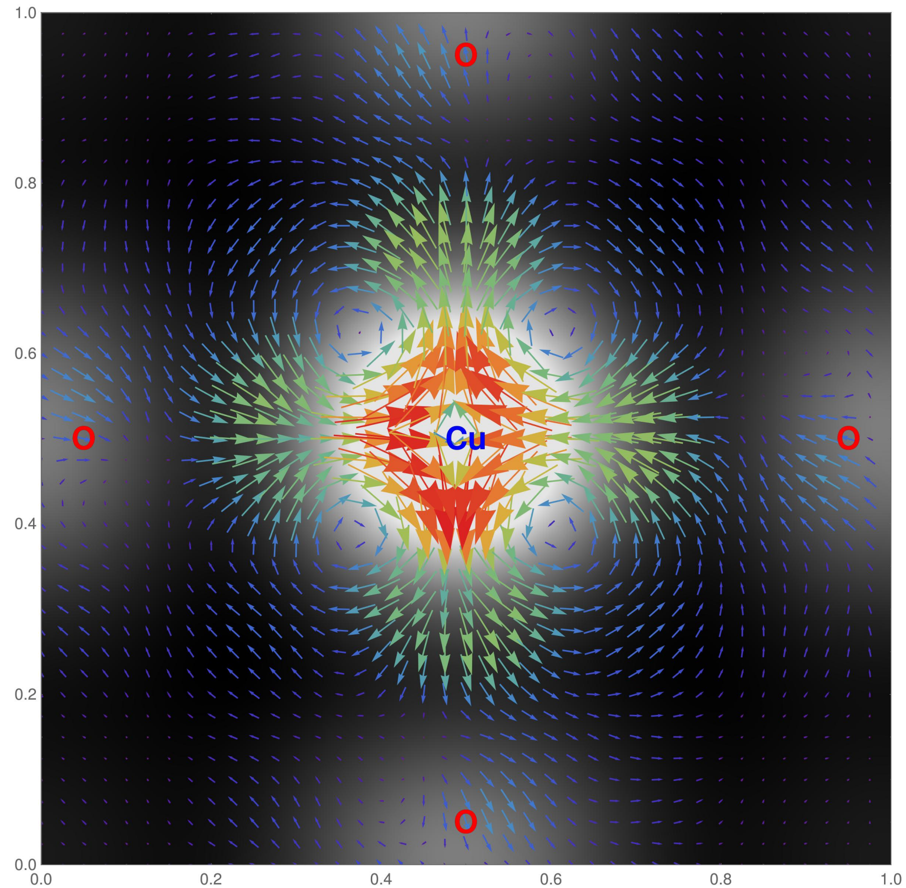
- Loop current order in high Tc cuprates



Varma

- Loop current order in high Tc cuprates





Varma

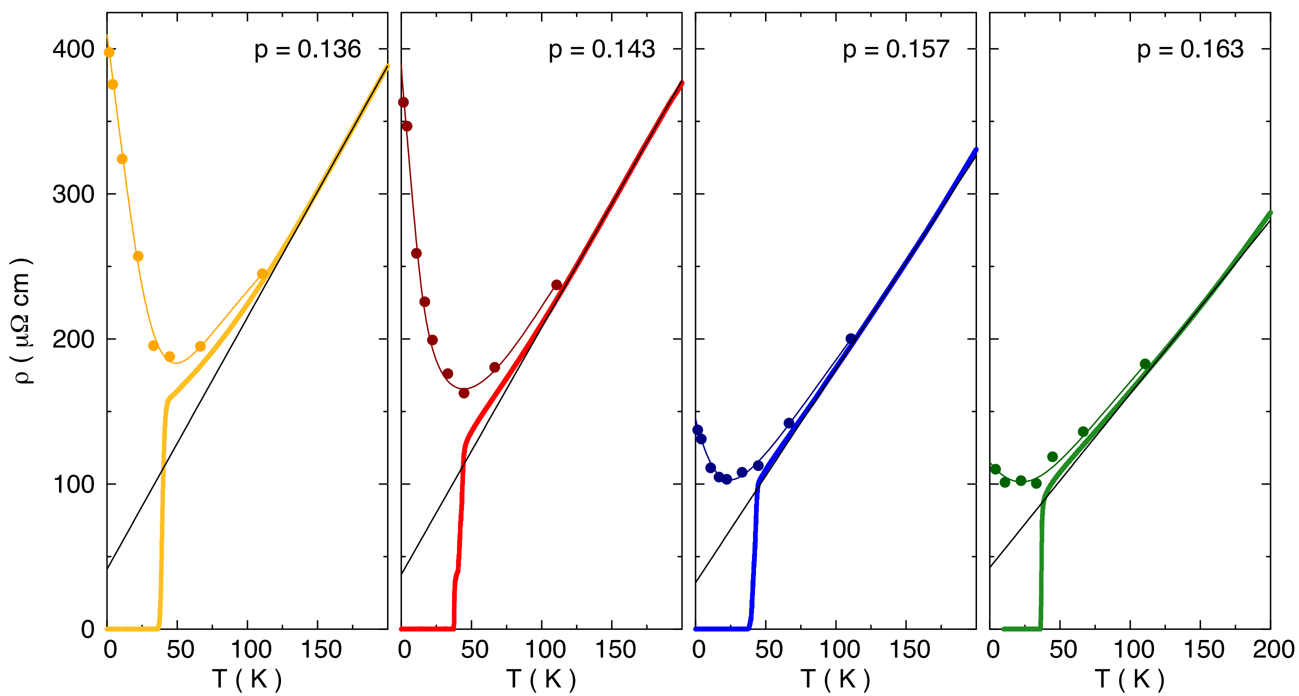
Krikun, Balm, Romero-Bermudez, Schalm, Zaanen

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

(Submitted on 14 Jun 2016)

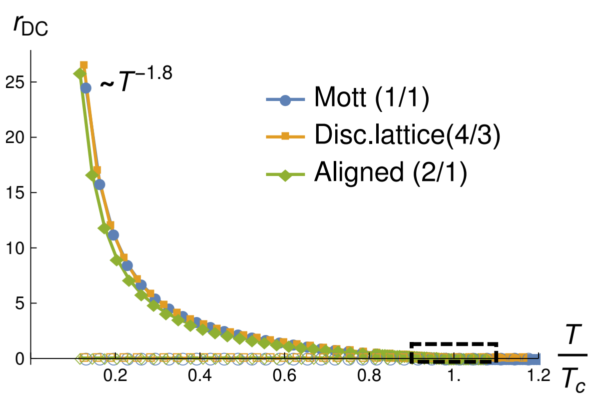


Charge Density Waves in Cuprates

- A doped holographic Mott insulator

  Andrade, Krikun, Schalm, Zaanen

  - Onset of insulating phase is "mild"
  - Remnant quantum critical conductivity



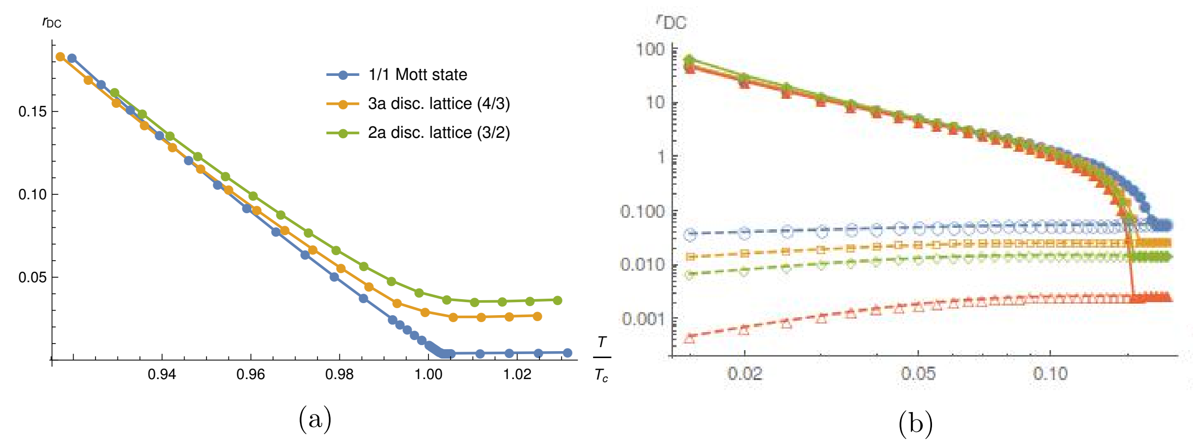


Figure 2: DC resistivity for various locked states. Left panel: linear-linear plot near the phase transition, Right panel: Log-log plot. The power law tail is seen at low temperature, signalling the reamining near horizon degrees of freadom, which are not gapped.

Lifshitz quantum critical theory supported by an ordered state

Inverse Matthiessen law: two independent sectors

Recent experimental results on strange metals

- 2015 Scaling in ARPES linewidths — Reber, Dessau et al; Bawden, van Heumen, Golden et al
- 2015, '18 Gap dynamics of superconductor — Kondo et al; Reber, Li, Dessau et al
- 2015 Transport without quasiparticles
  - Universal linear-in-T resistivity
  - 2017 with zero intercept — Latest: Boebinger, Shekhter et al
  - 2018 proportional to entropy (specific heat) — Legros, Taillefer et al
- 2017 Density fluctuations and anomalous plasmon physics — Abbamonte et al
- Charge density wave Mott insulator
  - 2014 doping independent commensuration — Davis and many others
  - 2016 mild insulator transition — Latest: Taillefer et al
- …

Many of these results follow from

The Theory of a Strange Metal

Many of these results follow from

The Theory of a Strange Metal

A strange metal is a state of matter consisting of two sectors, one of which is a quantum critical state.

Key insight from holography: (novel IR fixed point)

- Theory: A quantum critical system without quasiparticles, supported by an ordered state with transport characterized by collective behavior.
- Experiment: excitations around the FS do not determine transport.
- Experiment: quantum critical sector exhibits scaling and controls decay widths
- Experiment: particle intuition does not apply.

Many of these results follow from

The Theory of a Strange Metal

A strange metal is a state of matter consisting of two sectors, one of which is a quantum critical state.

Key insight from holography: (novel IR fixed point)

Key role for holography: (superior computation)

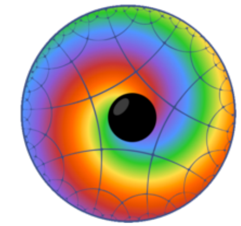
Holography provides the computational theoretical framework.

Gauge/Gravity duality Wuerzburg 2018

A new road to an old dream:

Apply string theory to explain experiment

Gauge/Gravity duality Wuerzburg 2018



A new road to an old dream:

Apply string theory to explain experiment

Holography gives a consistent, predictive framework
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

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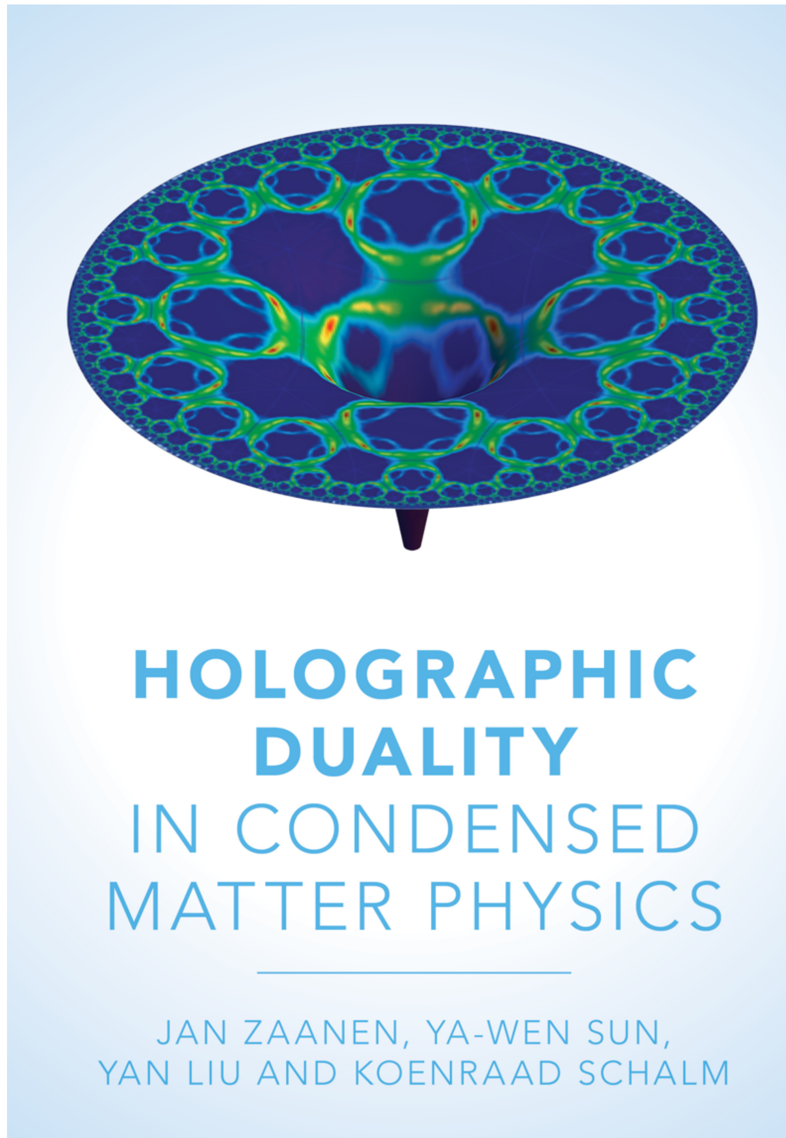
B. Herwerth, S. Klug, A. Krikun, Y. Liu, B. Meszena, R. Meyer, A. Romero-Bermudez,
Y-W Sun, P. Sabella-Garnier, S. Sachdev, P. Saeterskog, V. Scopelliti, E. van Heumen, J. Zaanen


HOLOGRAPHIC
DUALITY
IN CONDENSED
MATTER PHYSICS
JAN ZAANEN, YA-WEN SUN,
YAN LIU AND KOENRAAD SCHALM