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The 34th Jerusalem School in Theoretical Physics

NEW HORIZONS IN QUANTUM MATTER

27.12, 2016 — 5.1, 2017

Modern quantum materials realize a remarkably rich set of electronic phases. This school will explore the many new concepts and methods which have been developed in recent years, moving beyond the traditional paradigms of Fermi liquid theory and spontaneous symmetry breaking. In particular, long-range quantum entanglement appears in topological and quantum-critical states, and the school will discuss new techniques required to describe their observable properties.

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A mean field theory of strange metals and gapless spin liquids, and its connection to black holes

CIFAR Quantum Materials Program Meeting

Collège de France, Paris, October 5-7, 2016

Subir Sachdev

Talk online: sachdev.physics.harvard.edu

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

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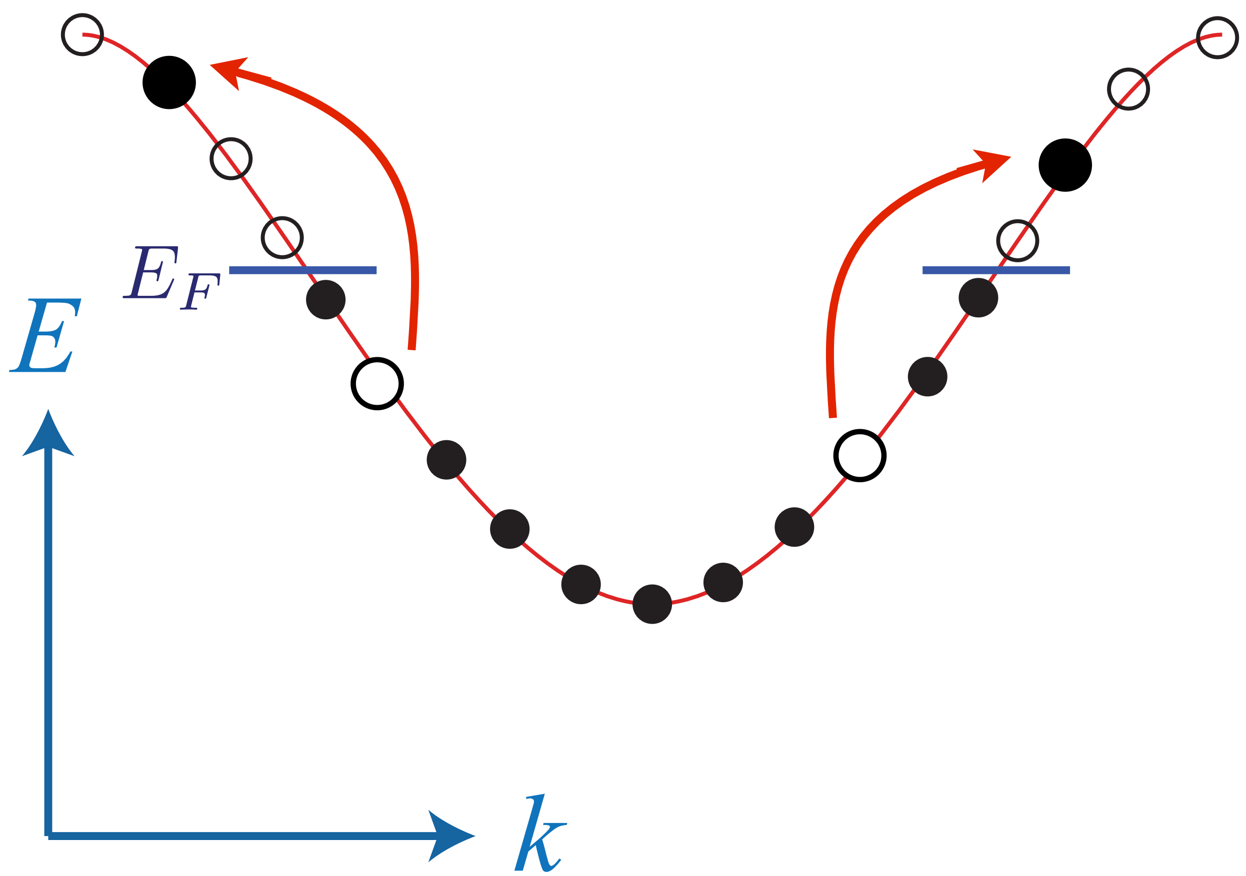
<u>Conventional quantum matter:</u>

1. Ground states <u>connected</u> adiabatically to independent electron states

2. Boltzmann-Landau theory of quasiparticles

<u>Metals</u>



Luttinger's theorem: volume enclosed by the Fermi surface = density of all electrons (mod 2 per unit cell). Obeyed in overdoped cuprates

Topological quantum matter:

1. Ground states disconnected from independent electron states: many-particle entanglement

2. Boltzmann-Landau theory of quasiparticles

(a) The fractional quantum Hall effect: the ground state is described by Laughlin's wavefunction, and the excitations are *quasiparticles* which carry fractional charge.

(b) The pseudogap metal: proposed to have electron-like quasiparticles but on a "small" Fermi surface which does not obey the Luttinger theorem.

Quantum matter without quasiparticles:

1. Ground states disconnected from independent electron states: many-particle entanglement

2. No quasiparticles

Strange metals:

Such metals are found, most prominently, near optimal doping in the the cuprate high temperature superconductors.

Quantum matter without quasiparticles:

1. Ground states disconnected from independent electron states: many-particle entanglement

2. No quasiparticles

Strange metals:

Such metals are found, most prominently, near optimal doping in the the cuprate high temperature superconductors.

But how can we be sure that no quasiparticles exist in a given system? Perhaps there are some exotic quasiparticles inaccessible to current experiments……..

Local thermal equilibration or phase coherence time, τ_φ:

- There is an *lower bound* on τ_φ in all many-body quantum systems of order $\hbar/(k_B T)$,

$$\tau_\varphi > C \frac{\hbar}{k_B T},$$

  and the lower bound is realized by systems *without* quasiparticles.

- In systems *with* quasiparticles, τ_φ is parametrically larger at low T;
  e.g. in Fermi liquids $\tau_\varphi \sim 1/T^2$,
  and in gapped insulators $\tau_\varphi \sim e^{\Delta/(k_B T)}$ where Δ is the energy gap.

S. Sachdev, *Quantum Phase Transitions*, Cambridge (1999)

A bound on quantum chaos:

- The time over which a many-body quantum system becomes "chaotic" is given by $\tau_L = 1/\lambda_L$, where λ_L is the "Lyapunov exponent" determining memory of initial conditions. This LYAPUNOV TIME obeys the rigorous lower bound

$$\tau_L \geq \frac{1}{2\pi} \frac{\hbar}{k_B T}$$

A. I. Larkin and Y. N. Ovchinnikov, JETP **28**, 6 (1969)

J. Maldacena, S. H. Shenker and D. Stanford, arXiv:1503.01409

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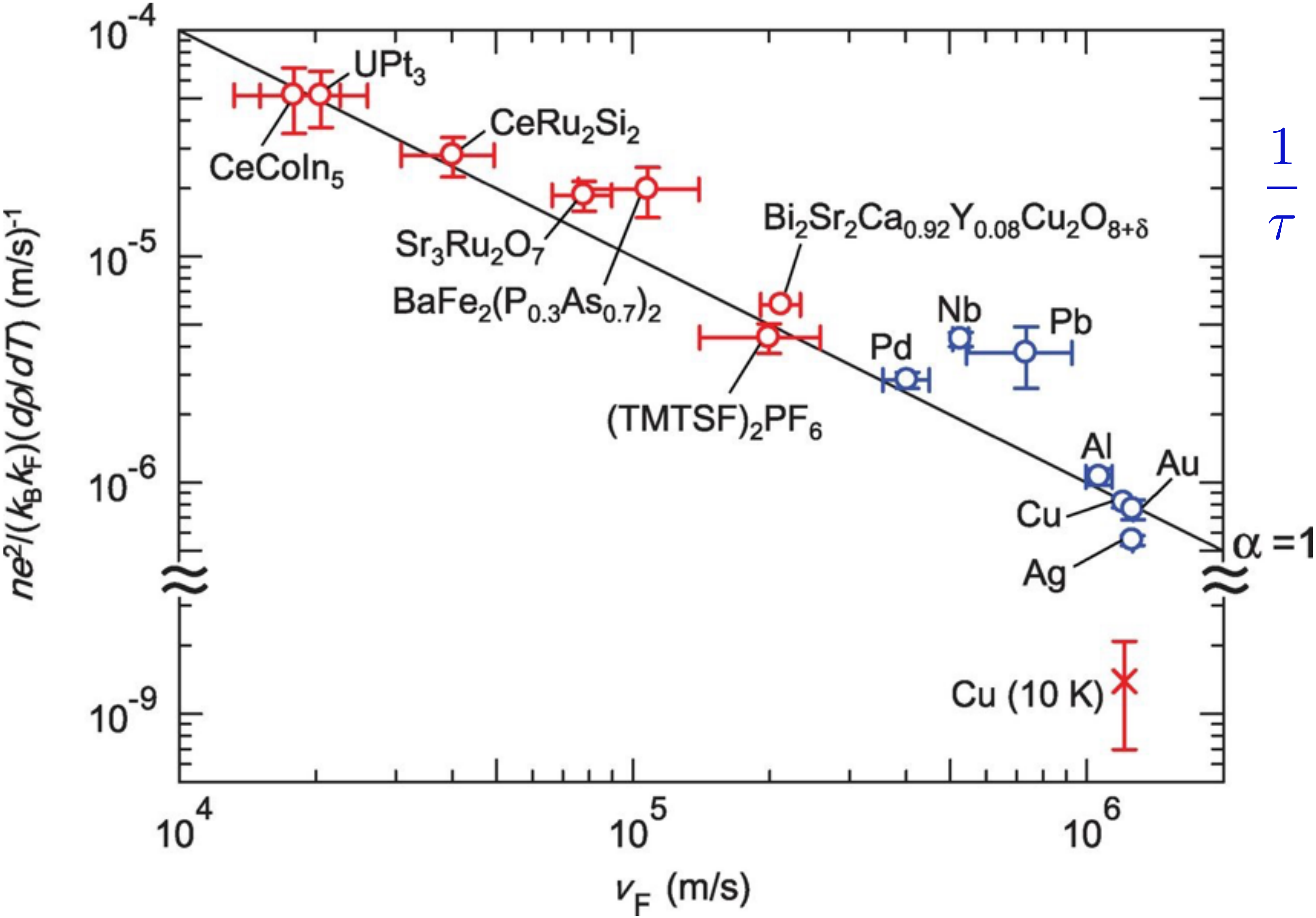
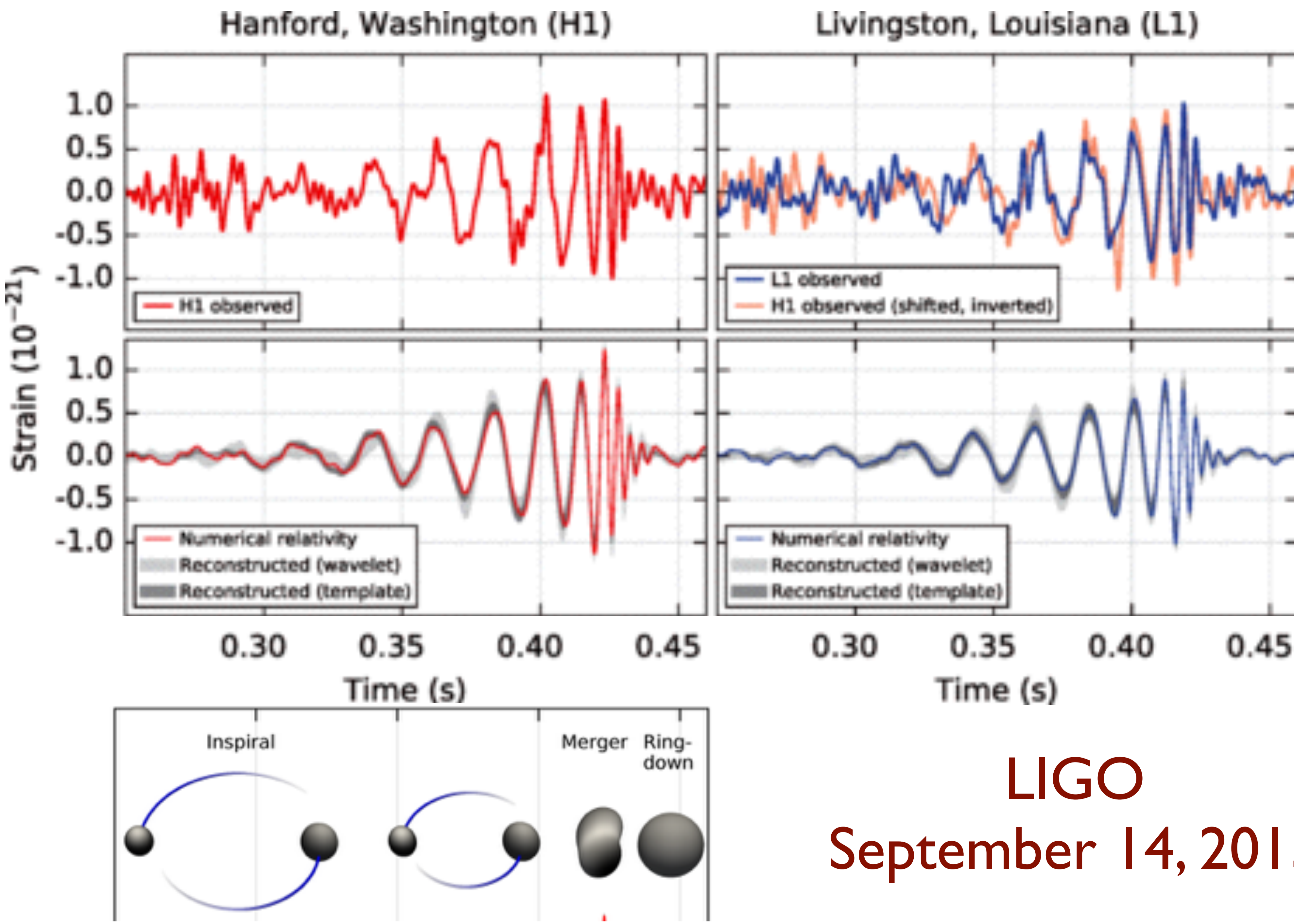
Quantum matter without quasiparticles
$\approx$ fastest possible many-body quantum chaos

Strange metals

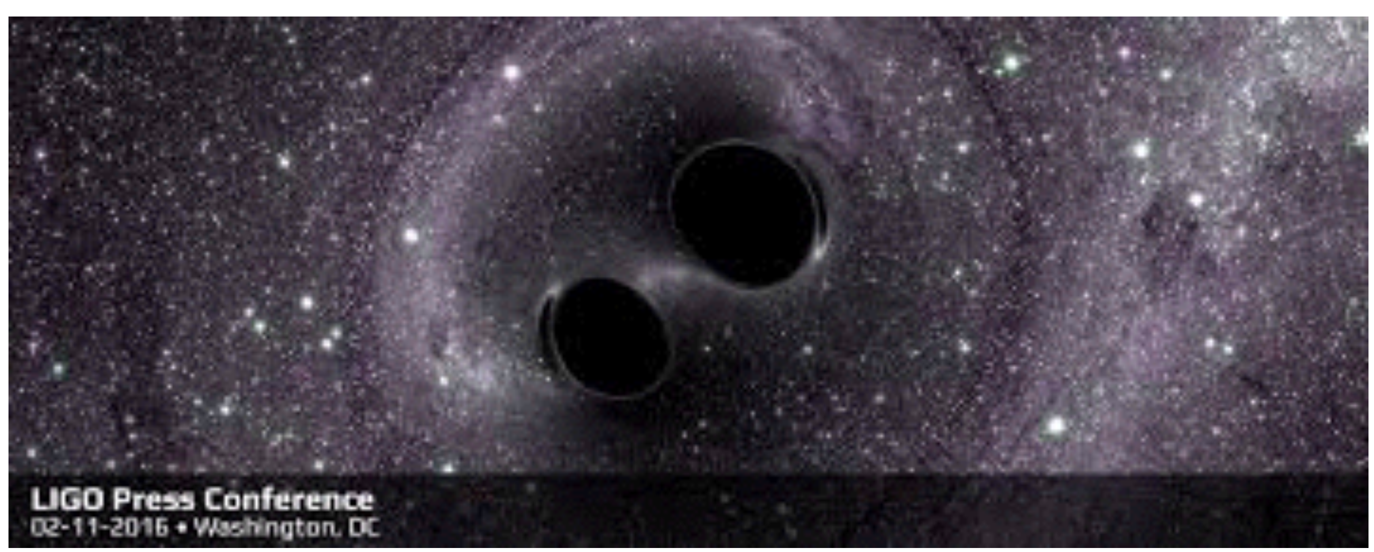


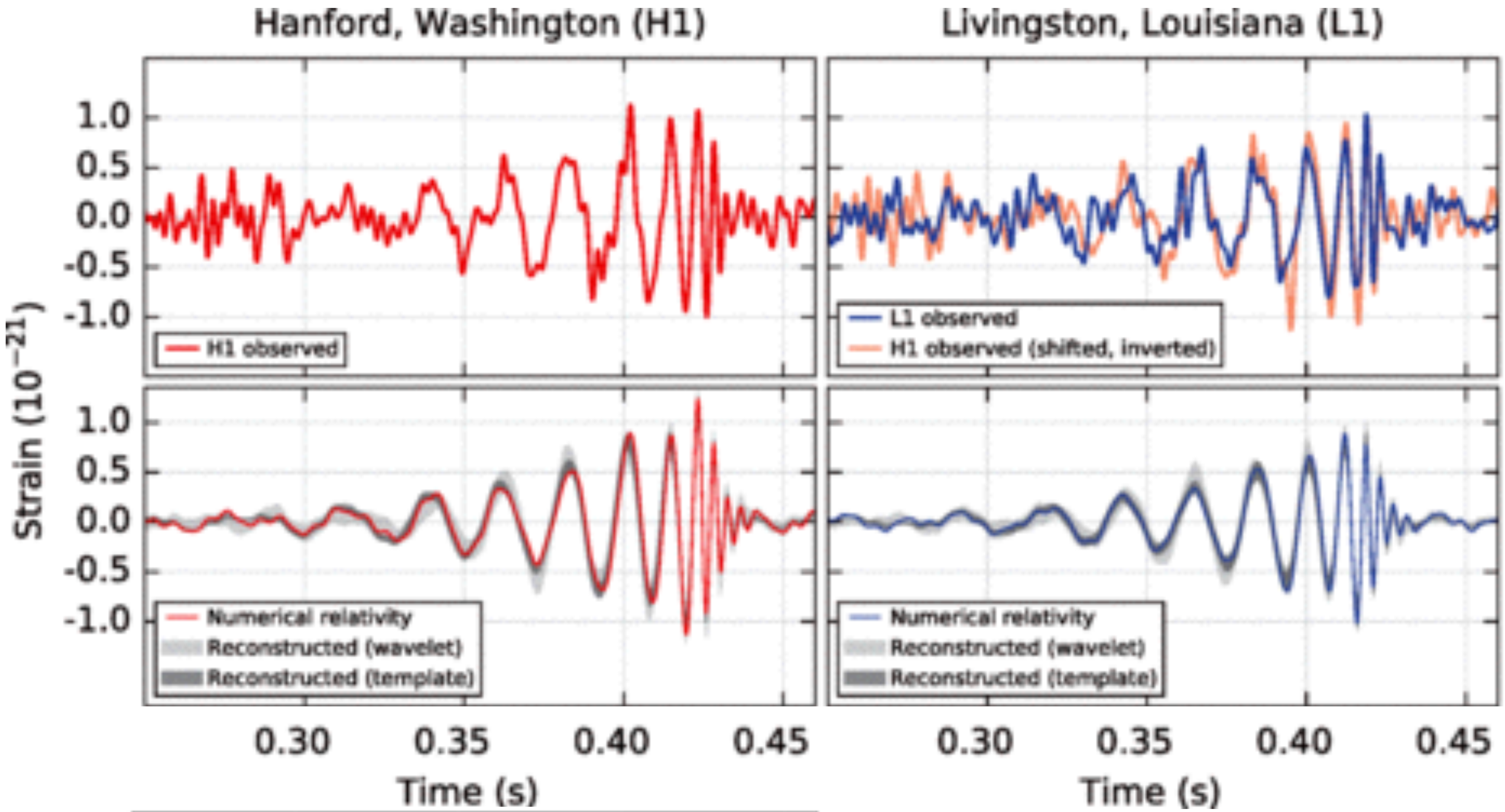
$$\frac{1}{\tau} = \alpha \frac{k_B T}{\hbar}$$

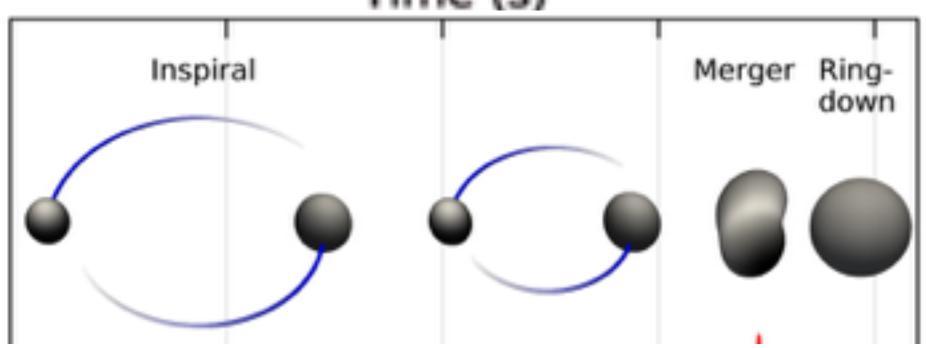
J. A. N. Bruin, H. Sakai, R. S. Perry, A. P. Mackenzie, *Science*. **339,** 804 (2013)



LIGO
September 14, 2015



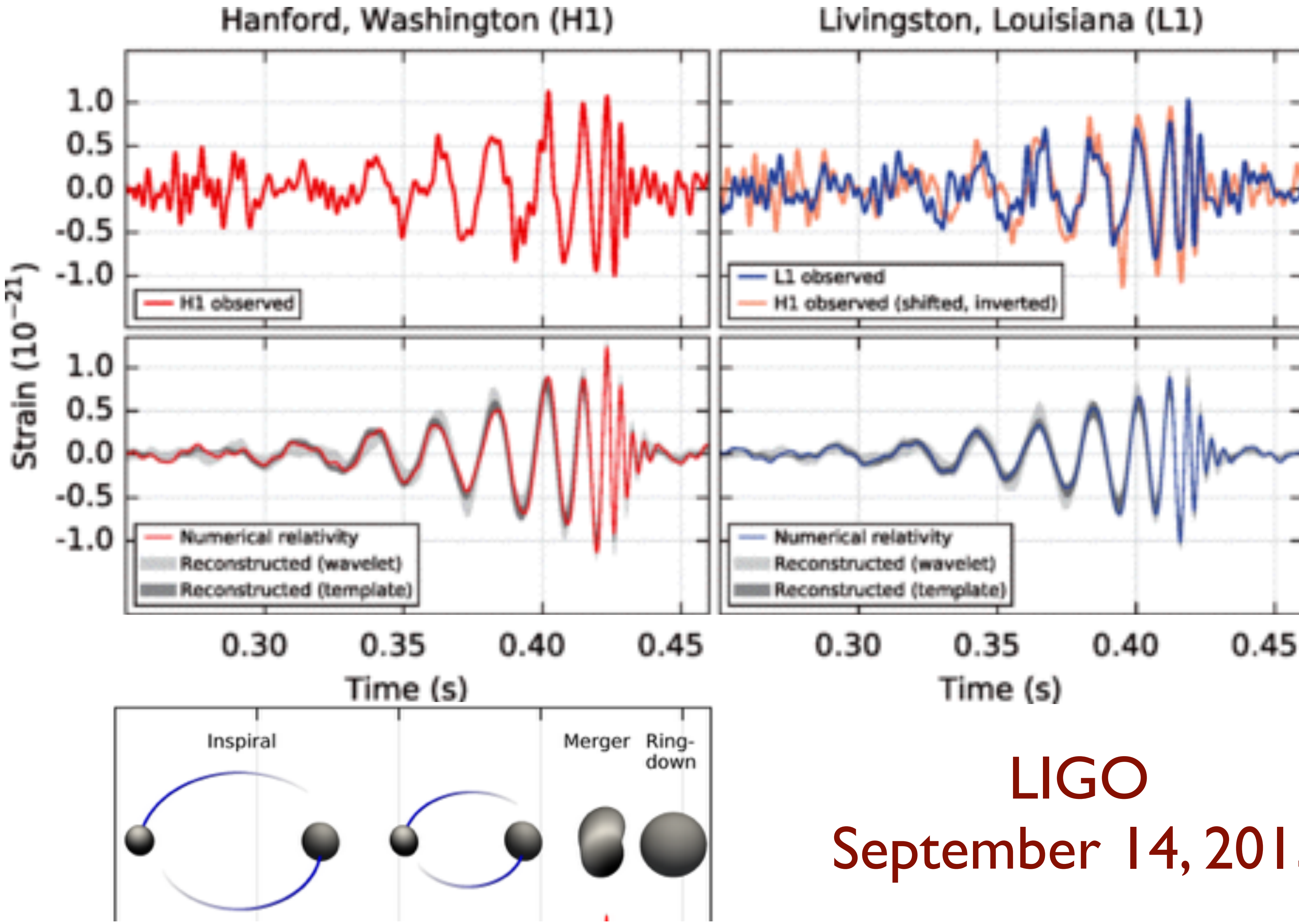




LIGO
September 14, 2015

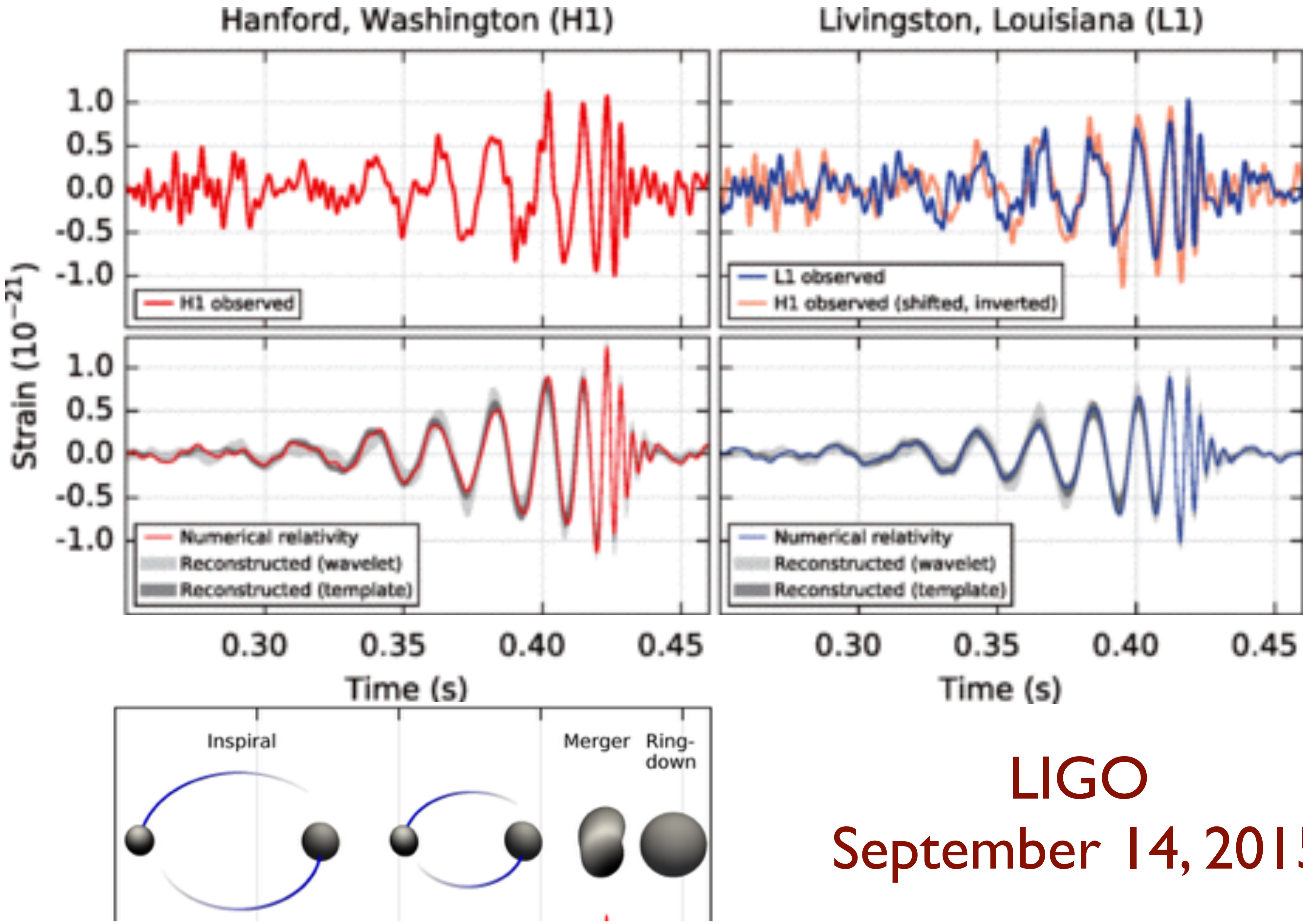
- Black holes have a "ring-down" time, τ_r, in which they radiate energy, and stabilize to a 'featureless' spherical object. This time can be computed in Einstein's general relativity theory.

- For this black hole $\tau_r = 7.7$ milliseconds. (Radius of black hole $= 183$ km; Mass of black hole $= 62$ solar masses.)



LIGO
September 14, 2015

- ‘Featureless’ black holes have a Bekenstein-Hawking entropy, and a Hawking temperature, T_H.



LIGO
September 14, 2015

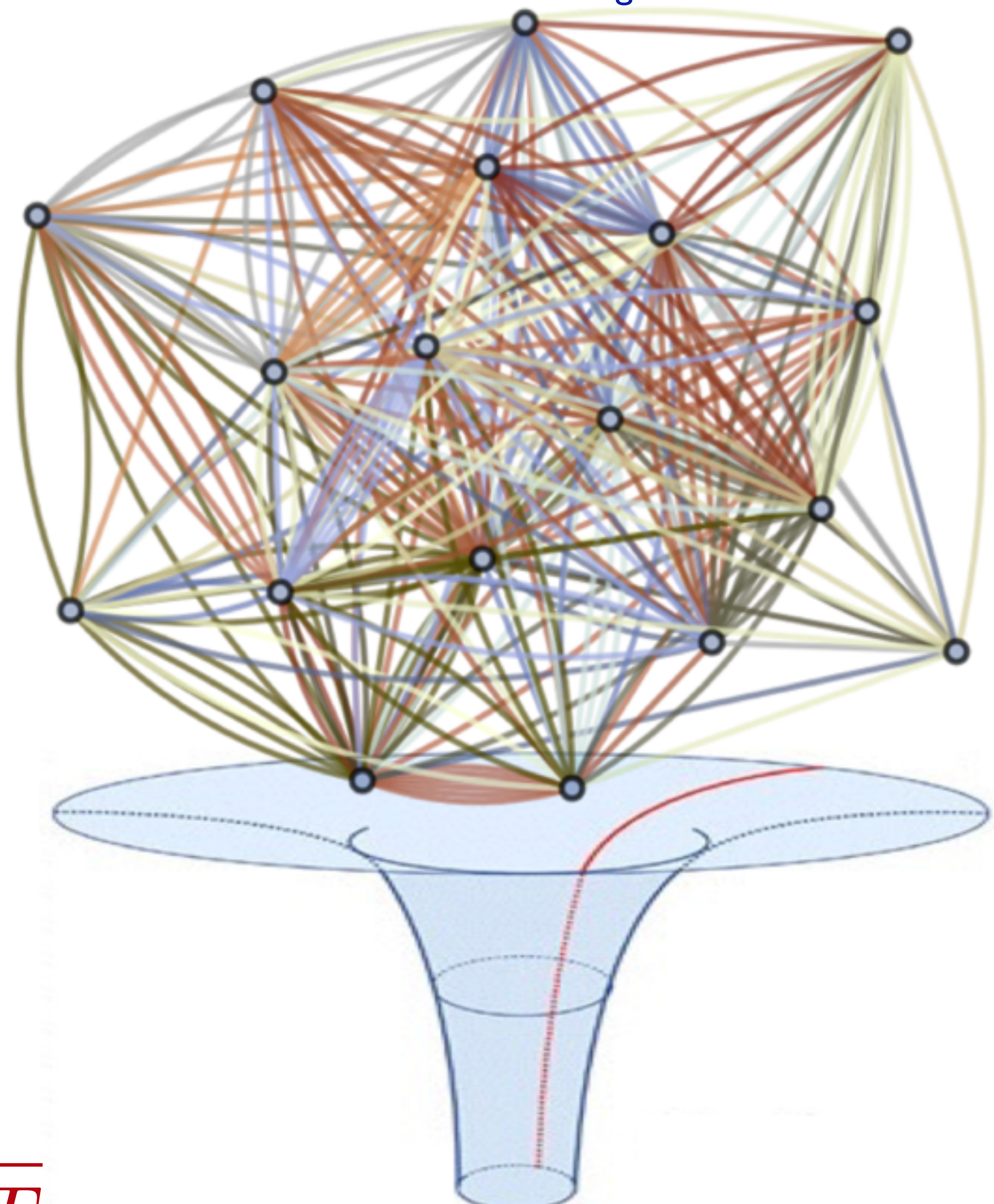
- Expressed in terms of the Hawking temperature, the ring-down time is $\tau_r \sim \hbar/(k_B T_H)$!

- For this black hole $T_H \approx 1$ nK.

The Sachdev-Ye-Kitaev (SYK) model:

- A theory of a strange metal
- Has a dual representation as a black hole
- Fastest possible quantum chaos with $\tau_L = \dfrac{\hbar}{2\pi k_B T}$

Figure credit: L. Balents



SY model

$$H = \frac{1}{(NM)^{1/2}} \sum_{i,j=1}^{N} \sum_{\alpha,\beta=1}^{M} J_{ij} \hat{S}_{i\alpha\beta} \hat{S}_{j\beta\alpha}$$

$$\hat{S}_{i\alpha\beta} \equiv c_{i\alpha}^\dagger c_{i\beta}$$

$$c_{i\alpha} c_{j\beta} + c_{j\beta} c_{i\alpha} = 0 \quad , \quad c_{i\alpha} c_{j\beta}^\dagger + c_{j\beta}^\dagger c_{i\alpha} = \delta_{ij} \delta_{\alpha\beta}$$

$$\frac{1}{M} \sum_{\alpha} c_{i\alpha}^\dagger c_{i\alpha} = Q$$

J_{ij} are independent random variables with $\overline{J_{ij}} = 0$ and $\overline{J_{ij}^2} = J^2$
$N \to \infty$ at $M = 2$ yields spin-glass ground state.
$N \to \infty$ and then $M \to \infty$ yields critical spin liquid

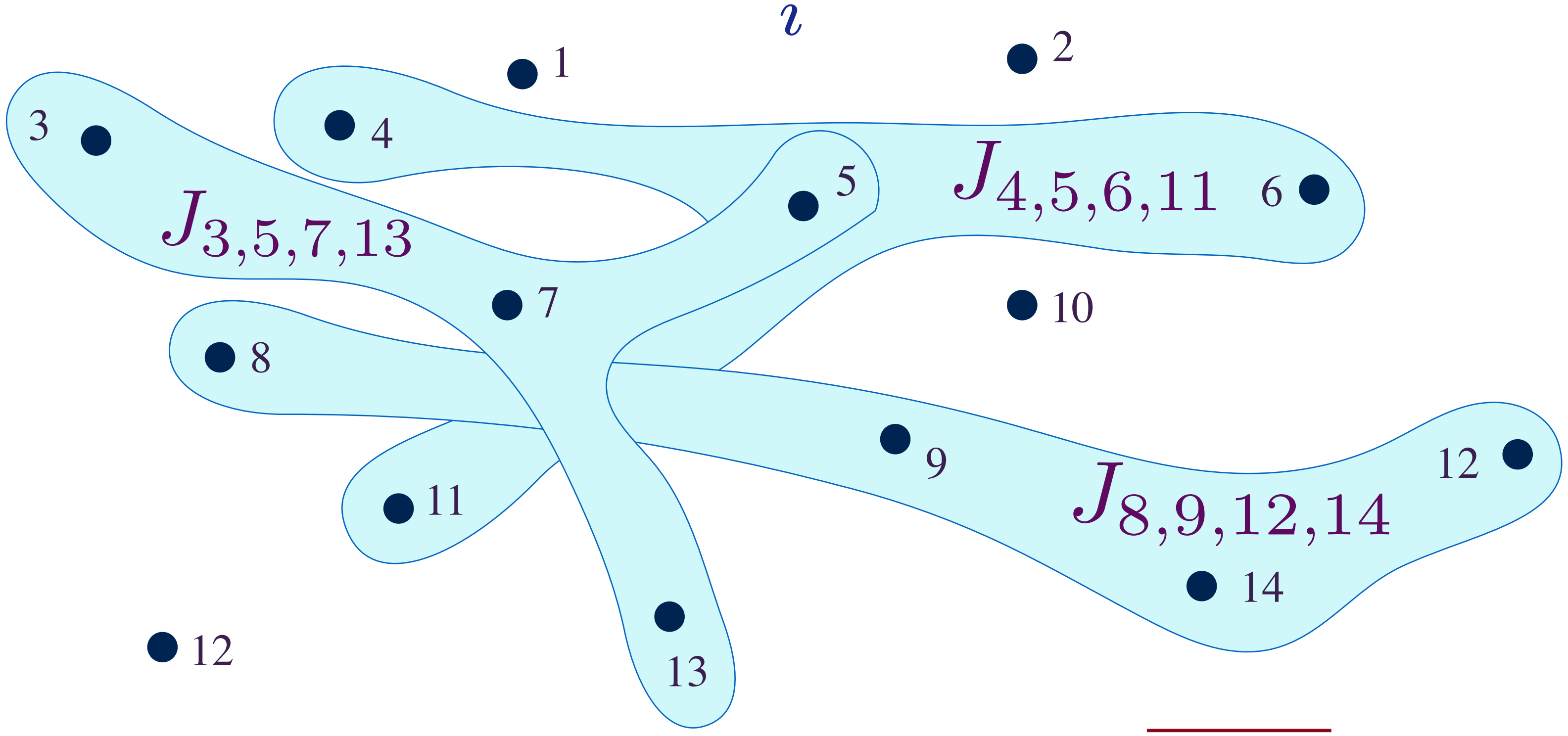
S. Sachdev and J. Ye, Phys. Rev. Lett. **70**, 3339 (1993)

SYK model

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} J_{ij;k\ell} \, c_i^\dagger c_j^\dagger c_k c_\ell - \mu \sum_i c_i^\dagger c_i$$

$$c_i c_j + c_j c_i = 0 \quad , \quad c_i c_j^\dagger + c_j^\dagger c_i = \delta_{ij}$$

$$\mathcal{Q} = \frac{1}{N} \sum_i c_i^\dagger c_i$$



$J_{ij;k\ell}$ are independent random variables with $\overline{J_{ij;k\ell}} = 0$ and $\overline{|J_{ij;k\ell}|^2} = J^2$
$N \to \infty$ yields critical strange metal.

S. Sachdev and J. Ye, PRL **70**, 3339 (1993)

A. Kitaev, unpublished; S. Sachdev, PRX **5**, 041025 (2015)

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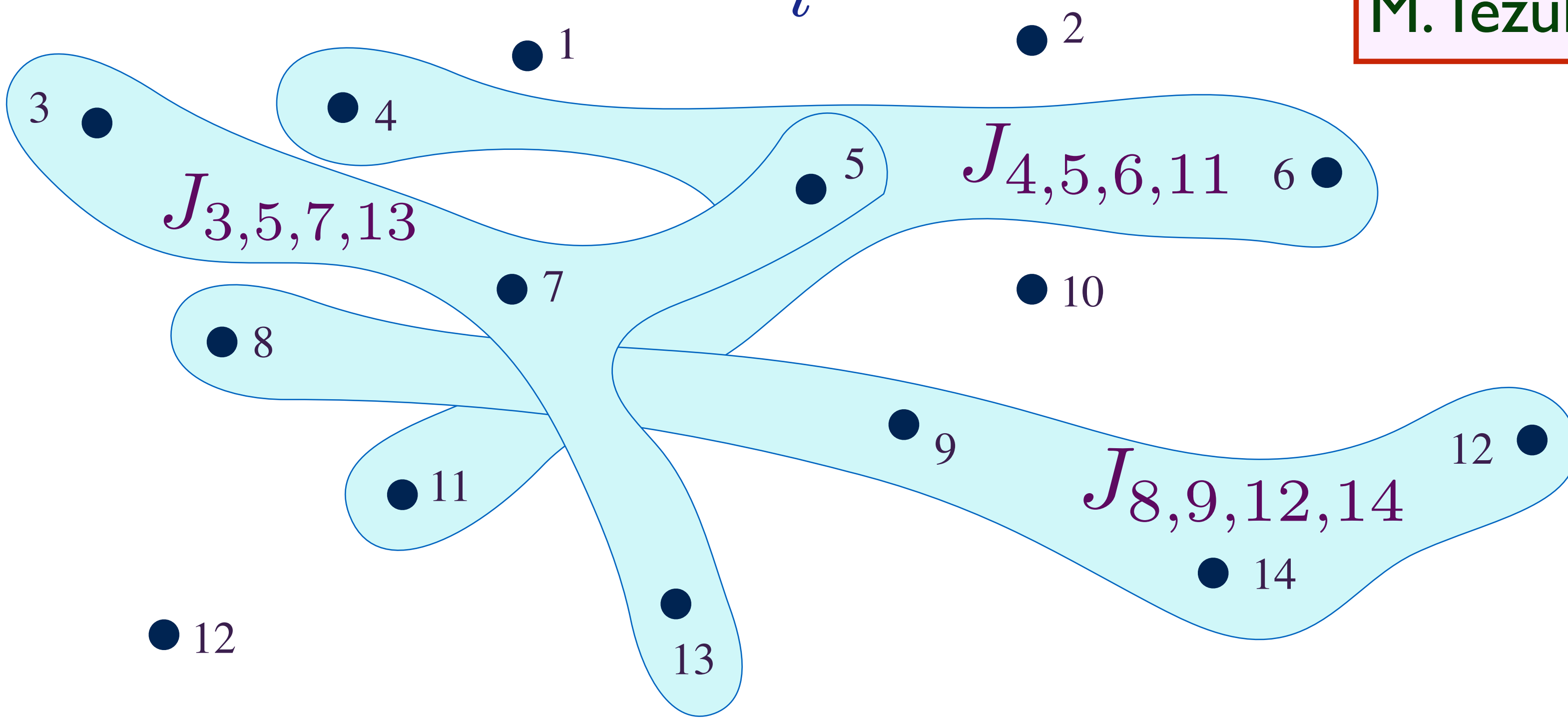
$$\mathcal{Q} = \frac{1}{N} \sum_i c_i^\dagger c_i$$

Cold atom realization:
I. Danshita, M. Hanada, and
M. Tezuka, arXiv:1606.02454



A fermion can move only by entangling with another fermion: the Hamiltonian has "nothing but entanglement".

S. Sachdev and J. Ye, PRL **70**, 3339 (1993)

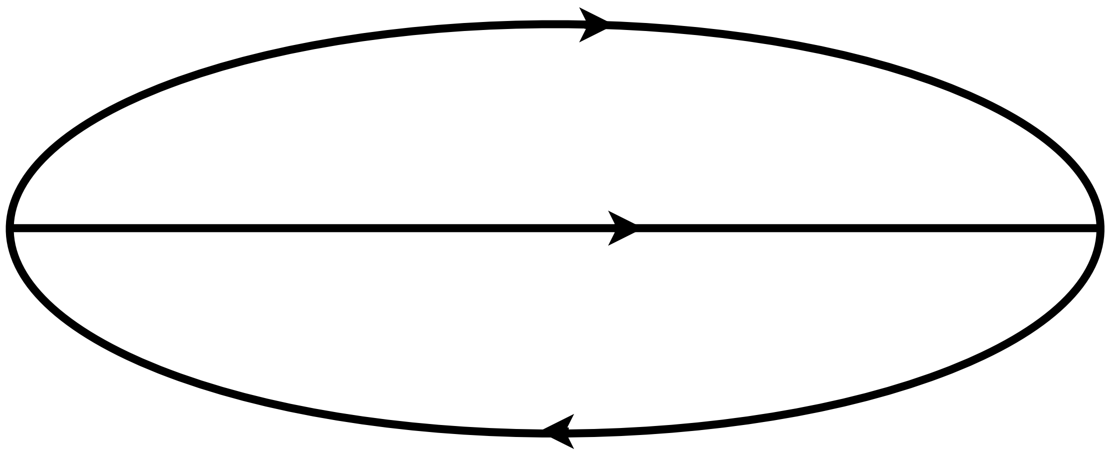
A. Kitaev, unpublished; S. Sachdev, PRX **5**, 041025 (2015)

SYK model

Feynman graph expansion in $J_{ij..}$, and graph-by-graph average, yields exact equations in the large N limit:

$$G(i\omega) = \frac{1}{i\omega + \mu - \Sigma(i\omega)} \quad , \quad \Sigma(\tau) = -J^2 G^2(\tau) G(-\tau)$$

$$G(\tau = 0^-) = \mathcal{Q}.$$

$\Sigma =$ 

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$$G(\tau = 0^-) = \mathcal{Q}.$$

Low frequency analysis shows that the solutions must be gapless and obey

$$\Sigma(z) = \mu - \frac{1}{A}\sqrt{z} + \ldots \quad , \quad G(z) = \frac{A}{\sqrt{z}}$$

for some complex A. The ground state is a non-Fermi liquid, with a continuously variable density $\mathcal{Q}$.

S. Sachdev and J. Ye, Phys. Rev. Lett. **70**, 3339 (1993)

SYK model

- $T = 0$ Green's function $G \sim 1/\sqrt{\tau}$

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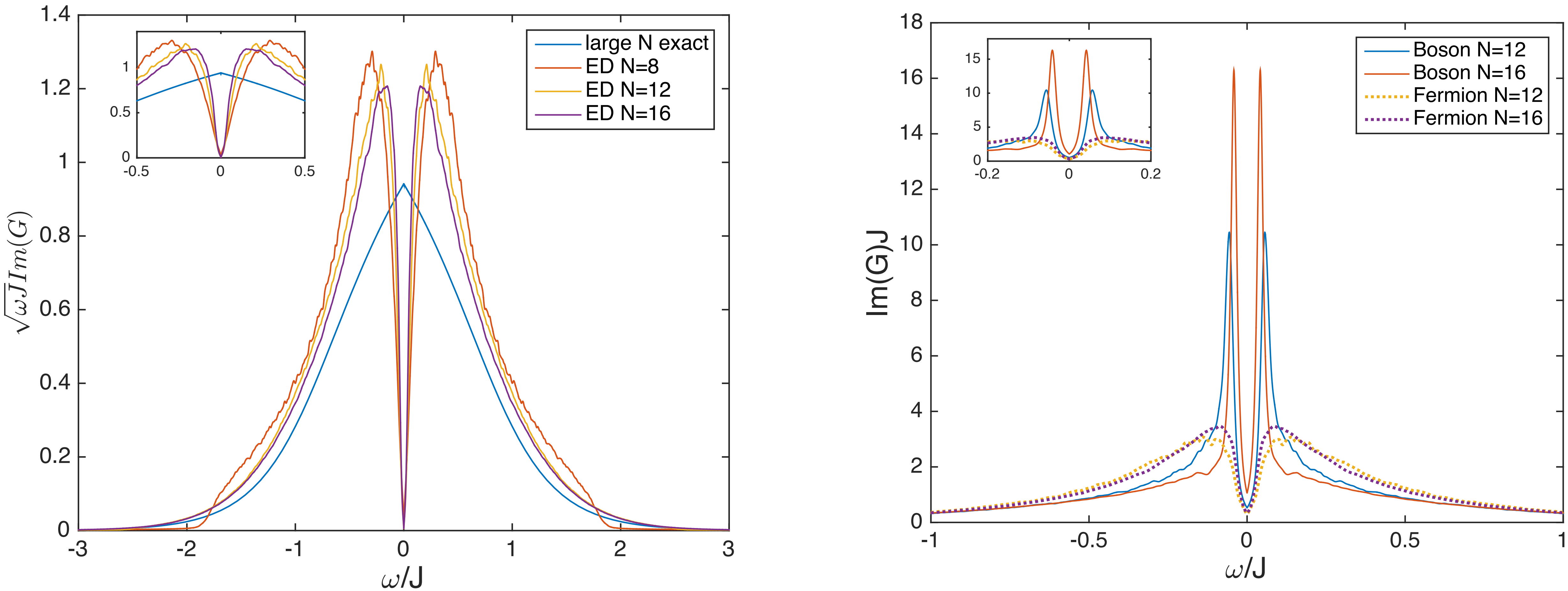
- $T = 0$ Green's function $G \sim 1/\sqrt{\tau}$
- $T > 0$ Green's function implies conformal invariance
  $G \sim 1/(\sin(\pi T \tau))^{1/2}$ A. Georges and O. Parcollet PRB **59**, 5341 (1999)

SYK model

- $T = 0$ Green's function $G \sim 1/\sqrt{\tau}$
- $T > 0$ Green's function implies conformal invariance $G \sim 1/(\sin(\pi T \tau))^{1/2}$
- Non-zero entropy as $T \to 0$, $S(T \to 0) = N S_0 + \ldots$

A. Georges, O. Parcollet, and S. Sachdev, Phys. Rev. B **63**, 134406 (2001)

SYK model



Large N solution of equations for G and Σ agree well with exact diagonalization of the finite N Hamiltonian $\Rightarrow$ no spin-glass order

However, exact diagonalization of the same model with hard-core bosons indicates the presence of spin-glass order in the ground state.

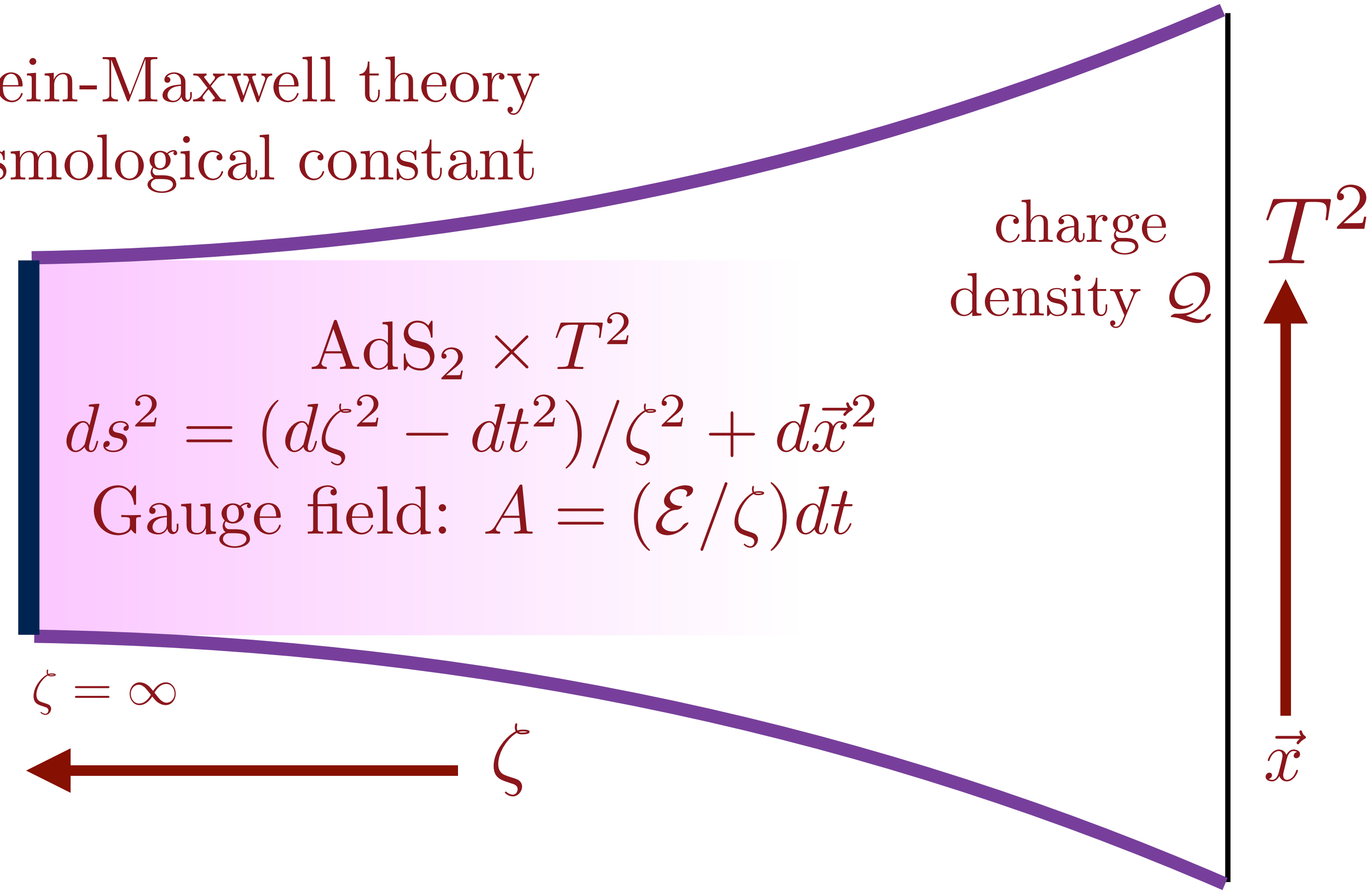
W. Fu and S. Sachdev, PRB **94**, 035135 (2016)

SYK model

- $T = 0$ Green's function $G \sim 1/\sqrt{\tau}$
- $T > 0$ Green's function implies conformal invariance $G \sim 1/(\sin(\pi T \tau))^{1/2}$
- Non-zero entropy as $T \to 0$, $S(T \to 0) = NS_0 + \ldots$
- These features indicate that the SYK model is dual to the low energy limit of a quantum gravity theory of black holes with AdS_2 near-horizon geometry. The Bekenstein-Hawking entropy is NS_0. S. Sachdev, PRL **105**, 151602 (2010)
- The dependence of S_0 on the density $\mathcal{Q}$ matches the behavior of the Wald-Bekenstein-Hawking entropy of AdS_2 horizons in a large class of gravity theories.

S. Sachdev, PRX **5**, 041025 (2015)

SYK and AdS$_2$



PHYSICAL REVIEW LETTERS 105, 151602 (2010)

Holographic Metals and the Fractionalized Fermi Liquid

Subir Sachdev
Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
(Received 23 June 2010; published 4 October 2010)

We show that there is a close correspondence between the physical properties of holographic metals near charged black holes in anti–de Sitter (AdS) space, and the fractionalized Fermi liquid phase of the lattice Anderson model. The latter phase has a "small" Fermi surface of conduction electrons, along with a spin liquid of local moments. This correspondence implies that certain mean-field gapless spin liquids are states of matter at nonzero density realizing the near-horizon, AdS$_2 \times$ R^2 physics of Reissner-Nordström black holes.

SYK model

After integrating the fermions, the partition function can be written as a path integral with an action S analogous to a Luttinger-Ward functional

$$Z = \int \mathcal{D}G(\tau_1, \tau_2)\mathcal{D}\Sigma(\tau_1, \tau_2) \exp(-NS)$$

A. Georges, O. Parcollet, and S. Sachdev,
Phys. Rev. B **63**, 134406 (2001)

$$S = \ln \det \left[\delta(\tau_1 - \tau_2)(\partial_{\tau_1} + \mu) - \Sigma(\tau_1, \tau_2)\right]$$
$$+ \int d\tau_1 d\tau_2 \Sigma(\tau_1, \tau_2) \left[G(\tau_2, \tau_1) + (J^2/2) G^2(\tau_2, \tau_1) G^2(\tau_1, \tau_2)\right]$$

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$$+ \int d\tau_1 d\tau_2 \Sigma(\tau_1,\tau_2)\left[G(\tau_2,\tau_1) + (J^2/2)G^2(\tau_2,\tau_1)G^2(\tau_1,\tau_2)\right]$$

A. Georges, O. Parcollet, and S. Sachdev, Phys. Rev. B **63**, 134406 (2001)

At frequencies $\ll J$, the time derivative in the determinant is less important, and without it the path integral is invariant under the reparametrization and gauge transformations

$$\tau = f(\sigma)$$

$$G(\tau_1,\tau_2) = \left[f'(\sigma_1)f'(\sigma_2)\right]^{-1/4}\frac{g(\sigma_1)}{g(\sigma_2)}G(\sigma_1,\sigma_2)$$

$$\Sigma(\tau_1,\tau_2) = \left[f'(\sigma_1)f'(\sigma_2)\right]^{-3/4}\frac{g(\sigma_1)}{g(\sigma_2)}\Sigma(\sigma_1,\sigma_2)$$

A. Georges and O. Parcollet PRB **59**, 5341 (1999)
A. Kitaev, unpublished
S. Sachdev, PRX **5**, 041025 (2015)

where $f(\sigma)$ and $g(\sigma)$ are arbitrary functions.

SYK model

Let us write the large N saddle point solutions of S as

$$G_s(\tau_1 - \tau_2) \sim (\tau_1 - \tau_2)^{-1/2} \quad , \quad \Sigma_s(\tau_1 - \tau_2) \sim (\tau_1 - \tau_2)^{-3/2}.$$

These are not invariant under the reparametrization symmetry but are invariant only under a SL(2,R) subgroup under which

$$f(\tau) = \frac{a\tau + b}{c\tau + d} \quad , \quad ad - bc = 1.$$

So the (approximate) reparametrization symmetry is spontaneously broken.

J. Maldacena and D. Stanford, arXiv:1604.07818
See also A. Kitaev, unpublished, and J. Polchinski and V. Rosenhaus, arXiv:1601.06768

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var

So ... en.

Connections of SYK to gravity and AdS_2 horizons

- Reparameterization and gauge invariance are the 'symmetries' of the Einstein-Maxwell theory of gravity and electromagnetism
- SL(2,R) is the isometry group of AdS_2.

J. Maldacena and D. Stanford, arXiv:1604.07818
See also A. Kitaev, unpublished, and J. Polchinski and V. Rosenhaus, arXiv:1601.06768

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So the (approximate) reparametrization symmetry is spontaneously broken.

Reparametrization zero mode

Expand about the saddle point by writing

$$G(\tau_1, \tau_2) = [f'(\tau_1) f'(\tau_2)]^{1/4} G_s(f(\tau_1) - f(\tau_2))$$

(and similarly for Σ) and obtain an effective action for $f(\tau)$. This action does not vanish because of the time derivative in the determinant which is not reparameterization invariant.

J. Maldacena and D. Stanford, arXiv:1604.07818

See also A. Kitaev, unpublished, and J. Polchinski and V. Rosenhaus, arXiv:1601.06768

SYK model

With $g(\tau) = e^{-i\phi(\tau)}$, the action for $\phi(\tau)$ and $f(\tau) = \dfrac{1}{\pi T}\tan(\pi T(\tau + \epsilon(\tau))$ fluctuations is

$$S_{\phi,f} = \frac{K}{2}\int_0^{1/T} d\tau (\partial_\tau \phi + i(2\pi \mathcal{E} T)\partial_\tau \epsilon)^2 - \frac{\gamma}{4\pi^2}\int_0^{1/T} d\tau \, \{f, \tau\},$$

where $\{f, \tau\}$ is the Schwarzian:

$$\{f, \tau\} \equiv \frac{f'''}{f'} - \frac{3}{2}\left(\frac{f''}{f'}\right)^2 .$$

The couplings are given by thermodynamics (Ω is the grand potential)

$$K = -\left(\frac{\partial^2 \Omega}{\partial \mu^2}\right)_T \quad , \quad \gamma + 4\pi^2 \mathcal{E}^2 K = -\left(\frac{\partial^2 \Omega}{\partial T^2}\right)_\mu$$

$$2\pi\mathcal{E} = \frac{\partial S_0}{\partial \mathcal{Q}}$$

Wenbo Fu, Yingfei Gu, S. Sachdev, unpublished

SYK model

With $g(\tau) = e^{-i\phi(\tau)}$, the action for $\phi(\tau)$ and $f(\tau) = \dfrac{1}{\pi T}\tan(\pi T(\tau + \epsilon(\tau))$ fluctuations is

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The correlators of the density fluctuations, $\mathcal{Q}(\tau)$, and the energy fluctuations $\delta E - \mu \delta \mathcal{Q}(\tau)$ are time independent and given by

$$\begin{pmatrix} \langle \delta \mathcal{Q}(\tau) \delta \mathcal{Q}(0) \rangle & \langle (\delta E(\tau) - \mu \delta \mathcal{Q}(\tau)) \delta \mathcal{Q}(0) \rangle / T \\ \langle (\delta E(\tau) - \mu \delta \mathcal{Q}(\tau)) \delta \mathcal{Q}(0) \rangle & \langle (\delta E(\tau) - \mu \delta \mathcal{Q}(\tau))(\delta E(0) - \mu \delta \mathcal{Q}(0)) \rangle / T \end{pmatrix} = T \chi_s$$

where χ_s is the static susceptibility matrix given by

$$\chi_s \equiv \begin{pmatrix} -(\partial^2 \Omega / \partial \mu^2)_T & -\partial^2 \Omega / (\partial T \partial \mu) \\ -T \partial^2 \Omega / (\partial T \partial \mu) & -T(\partial^2 \Omega / \partial T^2)_\mu \end{pmatrix}.$$

Wenbo Fu, Yingfei Gu, S. Sachdev, unpublished

Coupled SYK models

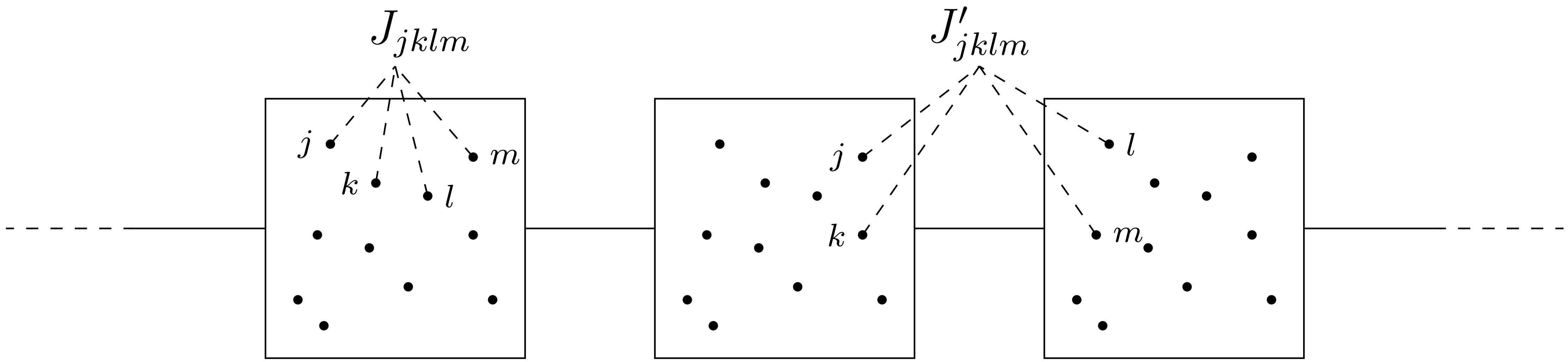

Figure 1: A chain of coupled SYK sites: each site contains $N \gg 1$ fermion with SYK interaction. The coupling between nearest neighbor sites are four fermion interaction with two from each site.

Yingfei Gu, Xiao-Liang Qi, and D. Stanford, arXiv:1609.07832

SYK model

The correlators of the density fluctuations, $\mathcal{Q}(\tau)$, and the energy fluctuations $\delta E - \mu\delta\mathcal{Q}(\tau)$ are time independent and given by

$$\left(\begin{array}{cc} \langle \delta\mathcal{Q}(\tau)\delta\mathcal{Q}(0)\rangle & \langle (\delta E(\tau) - \mu\delta\mathcal{Q}(\tau))\delta\mathcal{Q}(0)\rangle / T \\ \langle (\delta E(\tau) - \mu\delta\mathcal{Q}(\tau))\delta\mathcal{Q}(0)\rangle & \langle (\delta E(\tau) - \mu\delta\mathcal{Q}(\tau))(\delta E(0) - \mu\delta\mathcal{Q}(0))\rangle / T \end{array} \right) = T\chi_s$$

where χ_s is the static susceptibility matrix given by

$$\chi_s \equiv \left(\begin{array}{cc} -(\partial^2\Omega/\partial\mu^2)_T & \partial^2\Omega/(\partial T\partial\mu) \\ T\partial^2\Omega/(\partial T\partial\mu) & -T(\partial^2\Omega/\partial T^2)_\mu \end{array} \right).$$

Coupled SYK models

$$\left(\begin{array}{cc} \langle \mathcal{Q};\mathcal{Q}\rangle_{k,\omega} & \langle E - \mu\mathcal{Q};\mathcal{Q}\rangle_{k,\omega} / T \\ \langle E - \mu\mathcal{Q};\mathcal{Q}\rangle_{k,\omega} & \langle E - \mu\mathcal{Q}; E - \mu\mathcal{Q}\rangle_{k,\omega} / T \end{array} \right) = \left[i\omega(-i\omega + Dk^2)^{-1} + 1 \right] \chi_s$$

where the diffusivities are related to the thermoelectric conductivities by the Einstein relations

$$D = \left(\begin{array}{cc} \sigma & \alpha \\ \alpha T & \overline{\kappa} \end{array} \right) \chi_s^{-1}.$$

Wenbo Fu, Yingfei Gu, S. Sachdev, unpublished

Coupled SYK models

$$\begin{pmatrix} \langle \mathcal{Q}; \mathcal{Q} \rangle_{k,\omega} & \langle E - \mu \mathcal{Q}; \mathcal{Q} \rangle_{k,\omega} / T \\ \langle E - \mu \mathcal{Q}; \mathcal{Q} \rangle_{k,\omega} & \langle E - \mu \mathcal{Q}; E - \mu \mathcal{Q} \rangle_{k,\omega} / T \end{pmatrix} = \left[i\omega(-i\omega + D k^2)^{-1} + 1 \right] \chi_s$$

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$$D = \begin{pmatrix} \sigma & \alpha \\ \alpha T & \overline{\kappa} \end{pmatrix} \chi_s^{-1}.$$

The coupled SYK models realize a diffusive, metal with no quasiparticle excitations. (a "strange metal")

Wenbo Fu, Yingfei Gu, S. Sachdev, unpublished

• Graphene

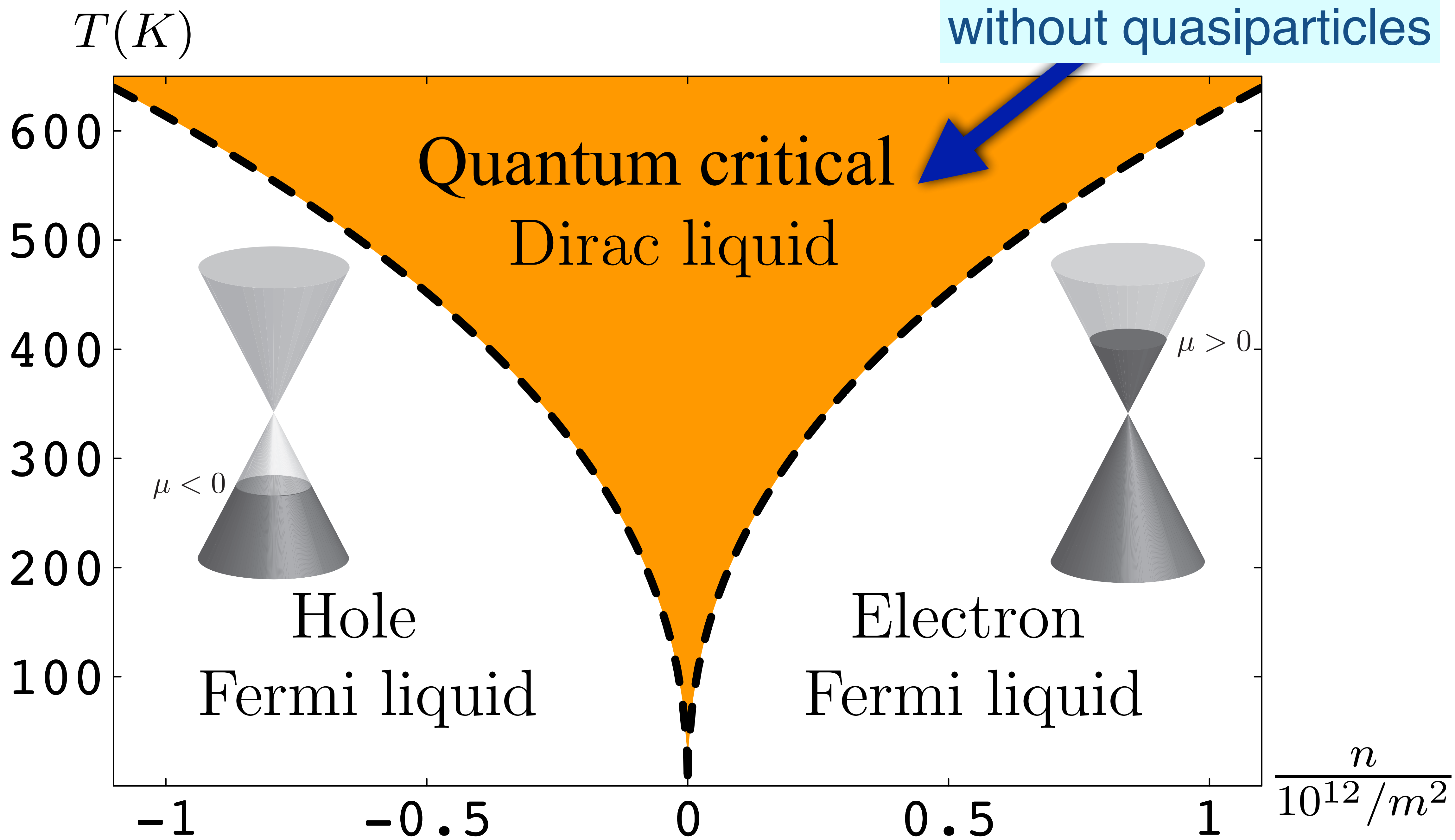
Strange metal transport

Theoretical predictions inspired by holography

Comparison with experiments

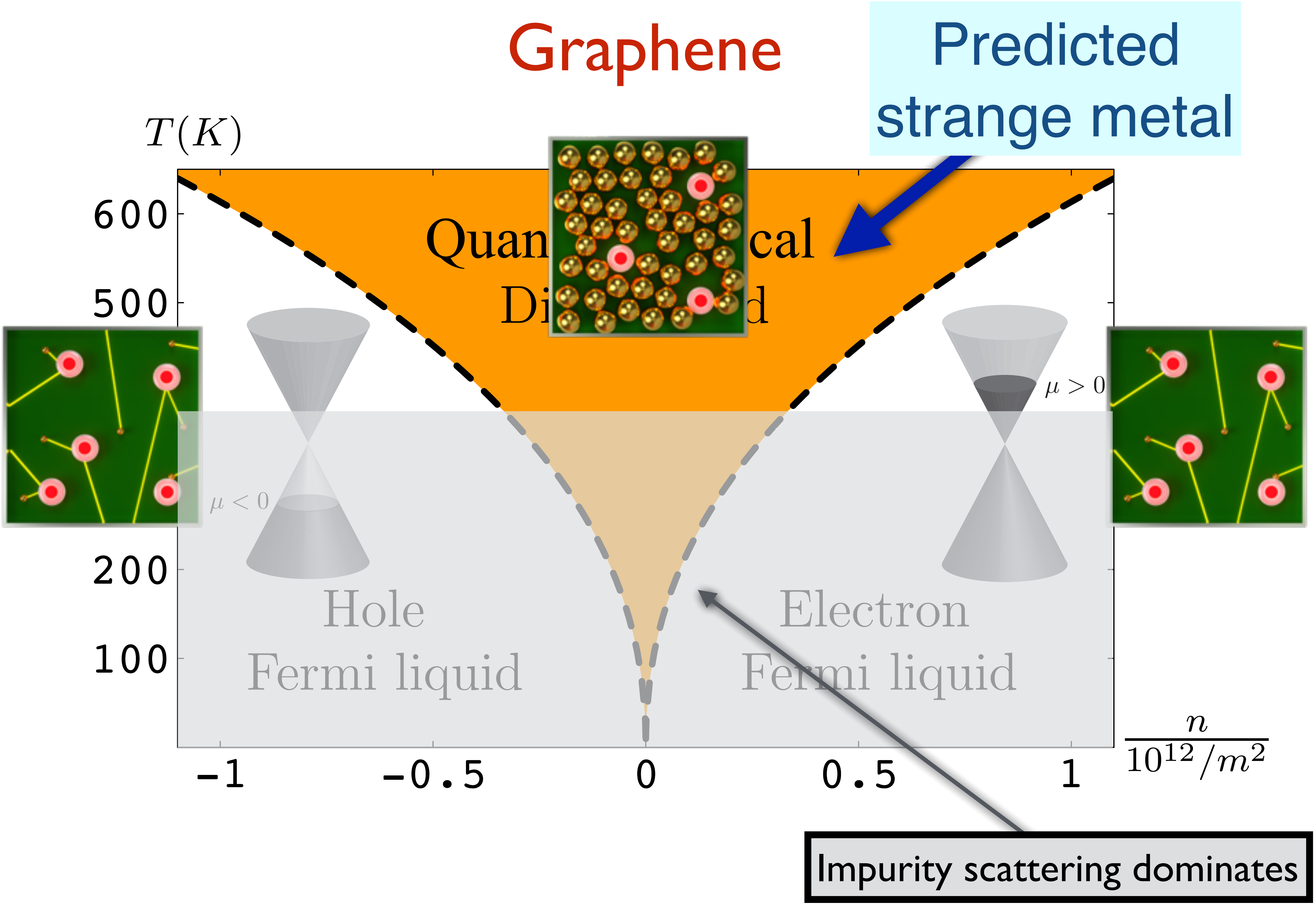
Graphene

Predicted "strange metal" without quasiparticles



K. Damle and S. Sachdev, PRB **56**, 8714 (1997)
M. Müller, L. Fritz, and S. Sachdev, PRB **78**, 115406 (2008)
M. Müller and S. Sachdev, PRB **78**, 115419 (2008)

Graphene



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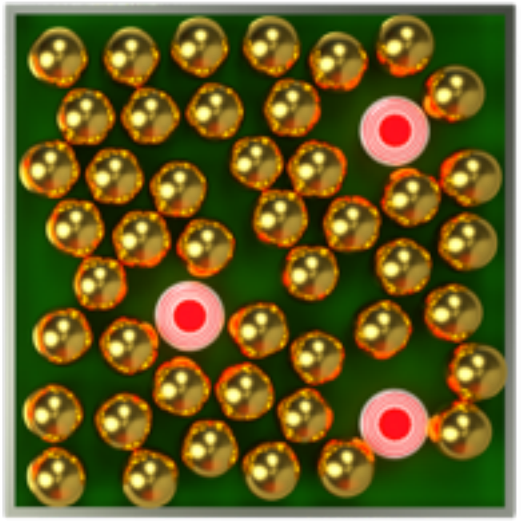


Transport in Strange Metals

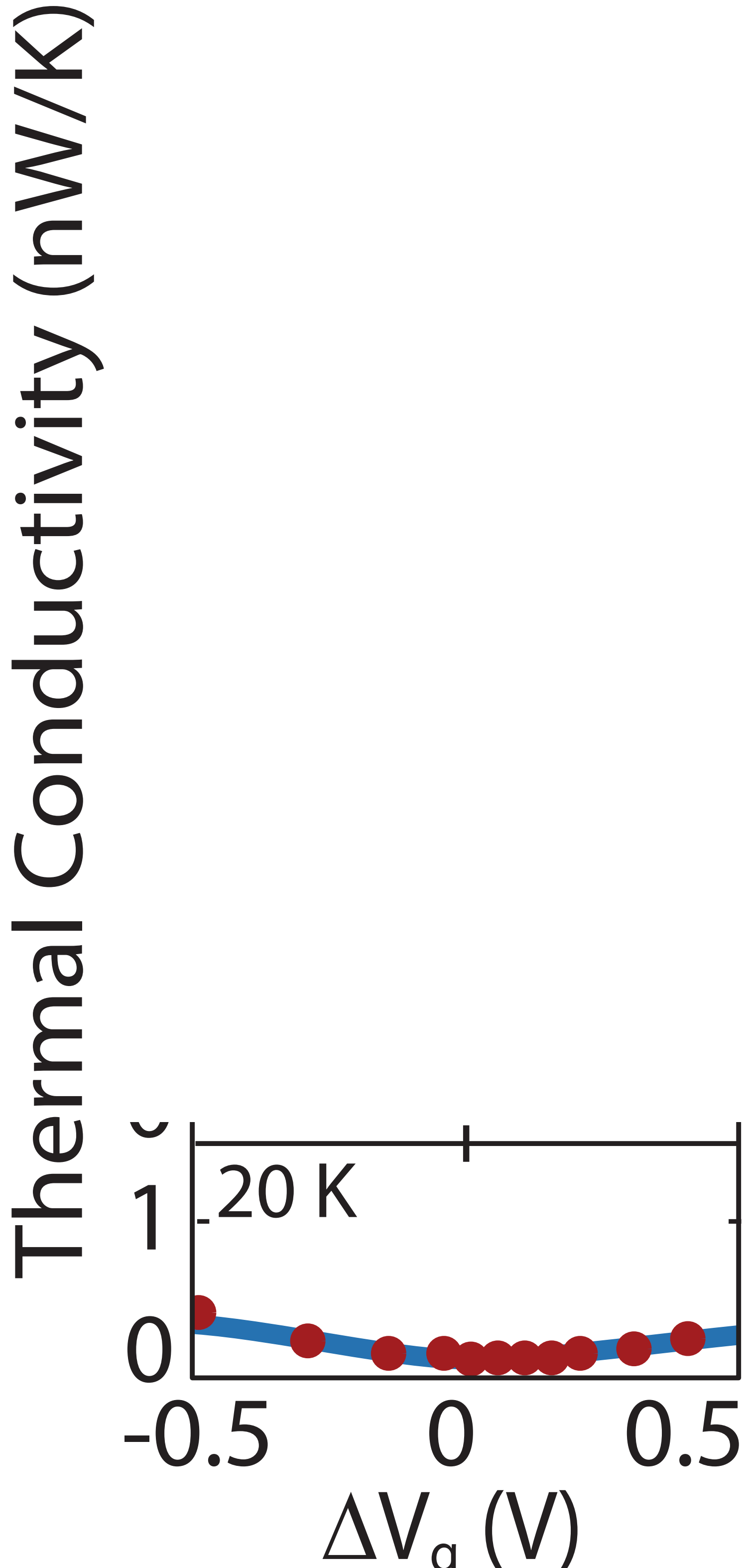
For a strange metal
with a "relativistic" Hamiltonian,
hydrodynamic, holographic,
and memory function methods yield
Lorentz ratio $L = \kappa/(T\sigma)$

$$= \frac{v_F^2 \mathcal{H} \tau_{\rm imp}}{T^2 \sigma_Q} \frac{1}{\left(1 + e^2 v_F^2 \mathcal{Q}^2 \tau_{\rm imp}/(\mathcal{H}\sigma_Q)\right)^2}$$

$\mathcal{Q} \rightarrow$ electron density; $\mathcal{H} \rightarrow$ enthalpy density
$\sigma_Q \rightarrow$ quantum critical conductivity
$\tau_{\rm imp} \rightarrow$ momentum relaxation time from impurities.
Note that for a clean system ($\tau_{\rm imp} \rightarrow \infty$ first),
the Lorentz ratio diverges $L \sim 1/\mathcal{Q}^4$,
as we approach "zero" electron density at the Dirac point.

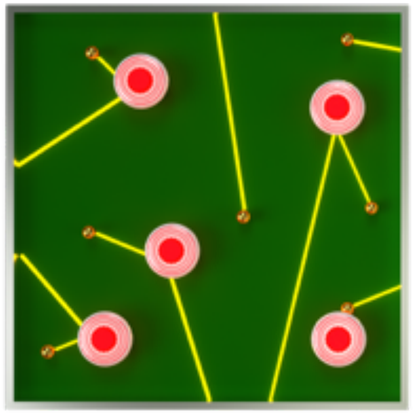
S. A. Hartnoll, P. K. Kovtun, M. Müller, and S. Sachdev, PRB **76**, 144502 (2007)
M. Müller and S. Sachdev, PRB **78**, 115419 (2008)

J. Crossno, Jing K. Shi, Ke Wang, Xiaomeng Liu, A. Harzheim, A. Lucas, S. Sachdev, Philip Kim, Takashi Taniguchi, Kenji Watanabe, T. A. Ohki, and Kin Chung Fong, Science **351**, 1058 (2016)

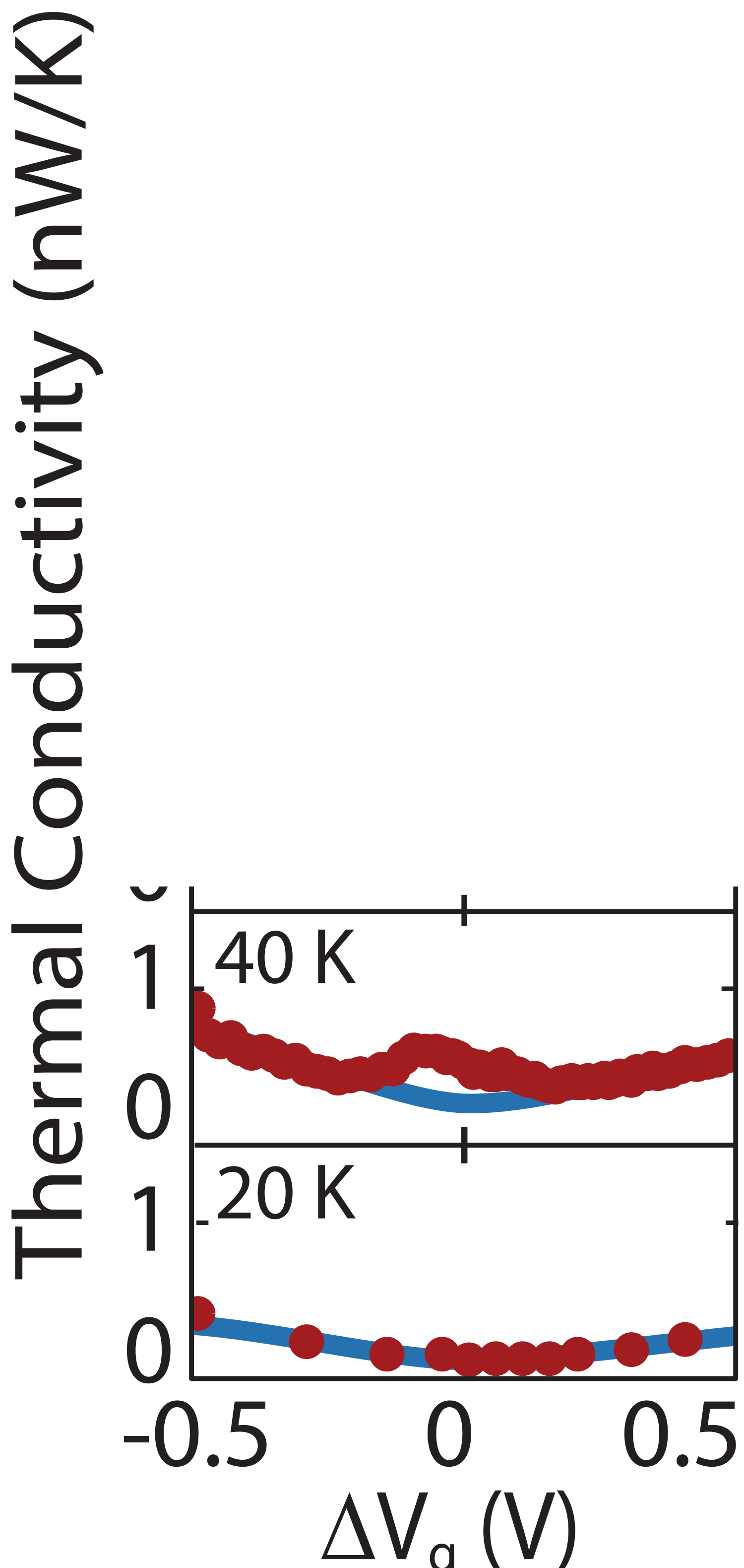


Red dots: data

Blue line: value for $L = L_0$



J. Crossno, Jing K. Shi, Ke Wang, Xiaomeng Liu, A. Harzheim, A. Lucas, S. Sachdev, Philip Kim, Takashi Taniguchi, Kenji Watanabe, T. A. Ohki, and Kin Chung Fong, Science **351**, 1058 (2016)



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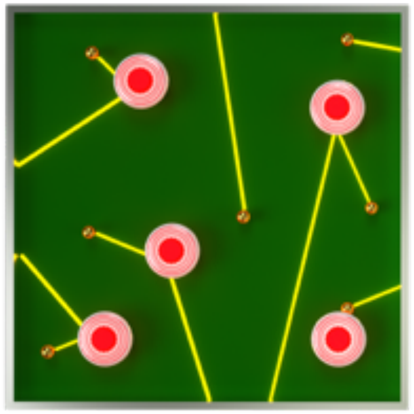
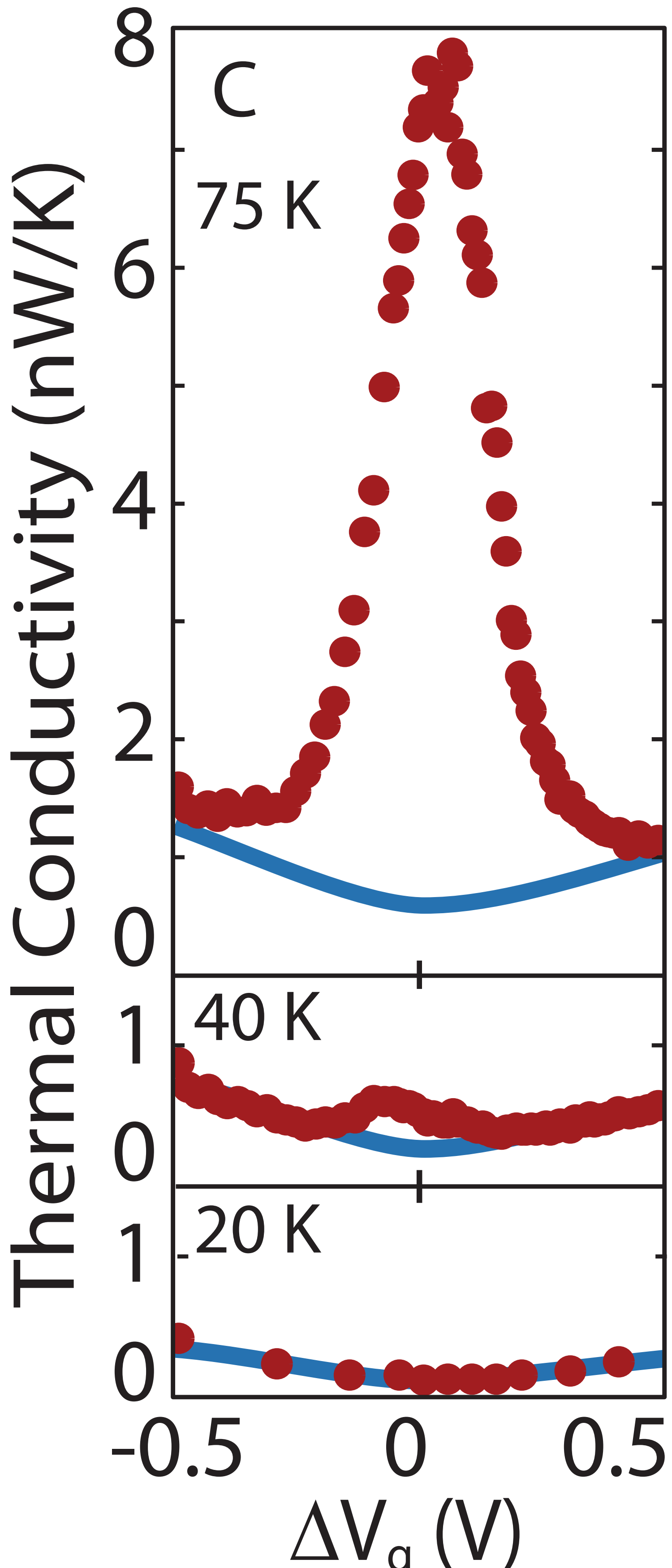
Blue line: value for $L = L_0$

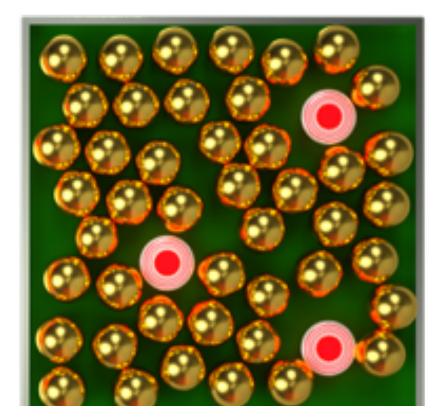


J. Crossno, Jing K. Shi, Ke Wang, Xiaomeng Liu, A. Harzheim, A. Lucas, S. Sachdev, Philip Kim, Takashi Taniguchi, Kenji Watanabe, T. A. Ohki, and Kin Chung Fong, Science **351**, 1058 (2016)

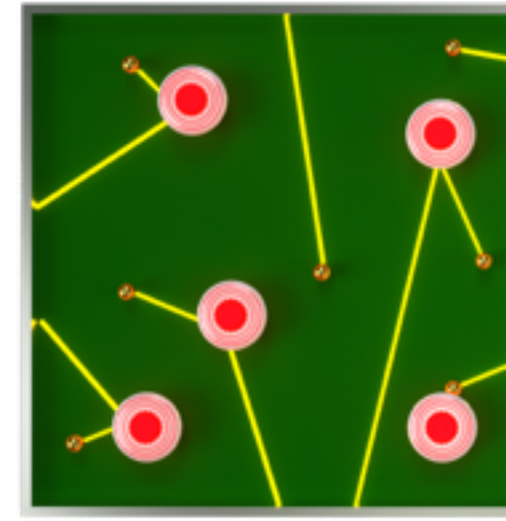


Red dots: data

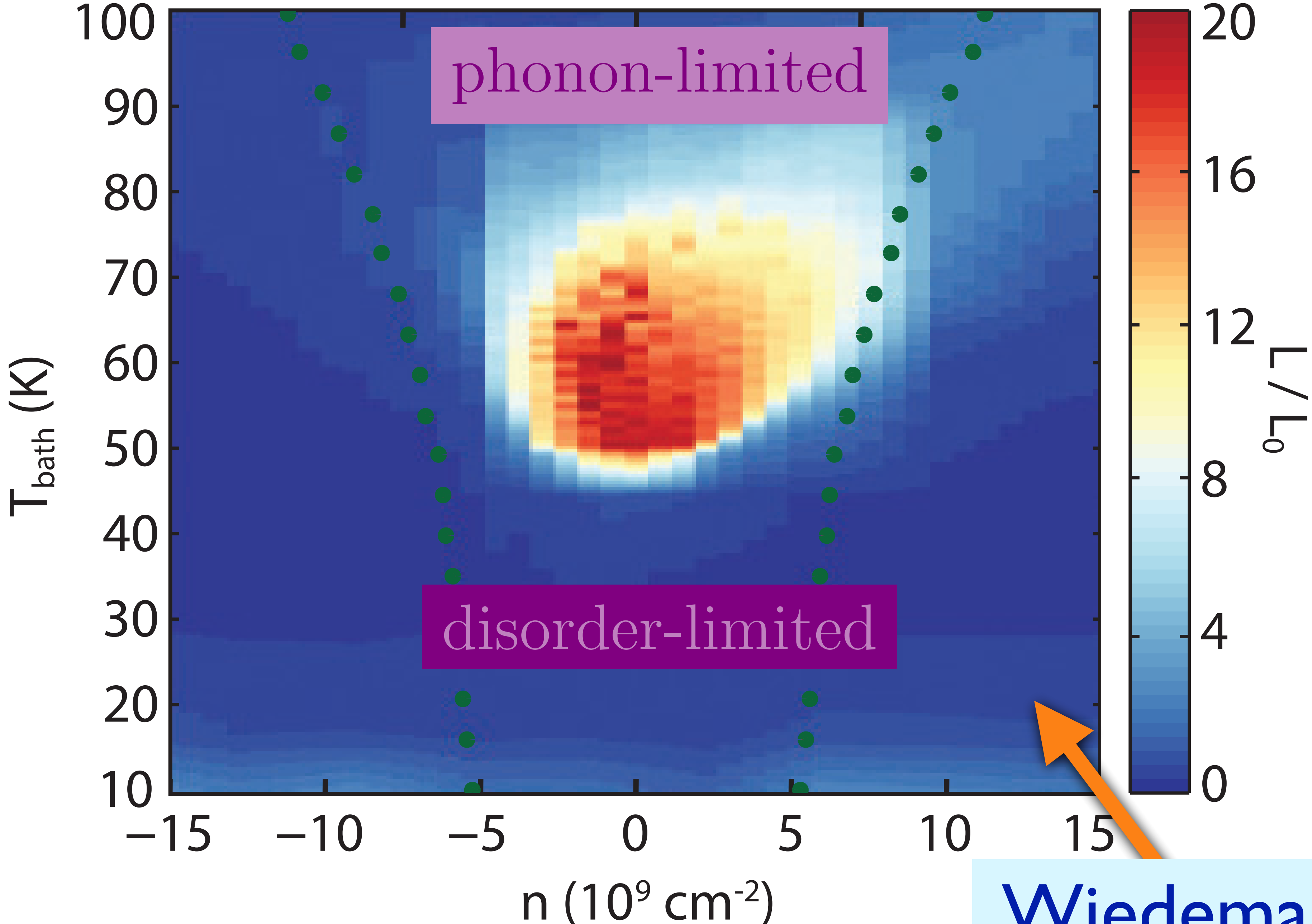
Blue line: value for $L = L_0$



J. Crossno, Jing K. Shi, Ke Wang, Xiaomeng Liu, A. Harzheim, A. Lucas, S. Sachdev, Philip Kim, Takashi Taniguchi, Kenji Watanabe, T. A. Ohki, and Kin Chung Fong, Science **351**, 1058 (2016)

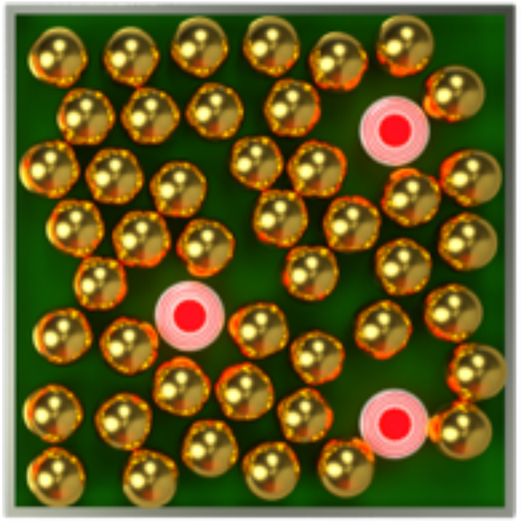


Strange metal in graphene

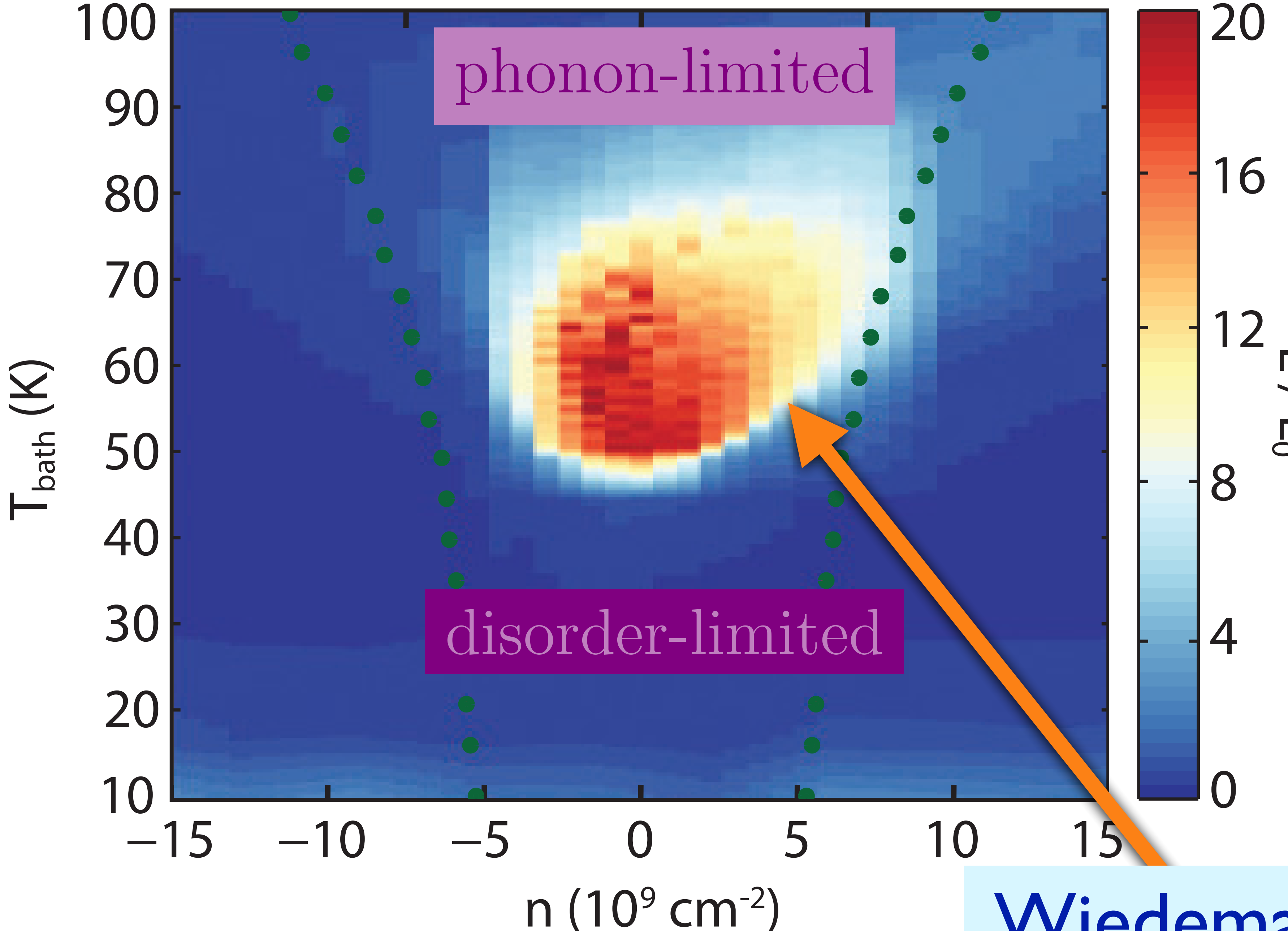


Wiedemann-Franz obeyed

J. Crossno, Jing K. Shi, Ke Wang, Xiaomeng Liu, A. Harzheim, A. Lucas, S. Sachdev, Philip Kim, Takashi Taniguchi, Kenji Watanabe, T. A. Ohki, and Kin Chung Fong, Science **351**, 1058 (2016)



Strange metal in graphene



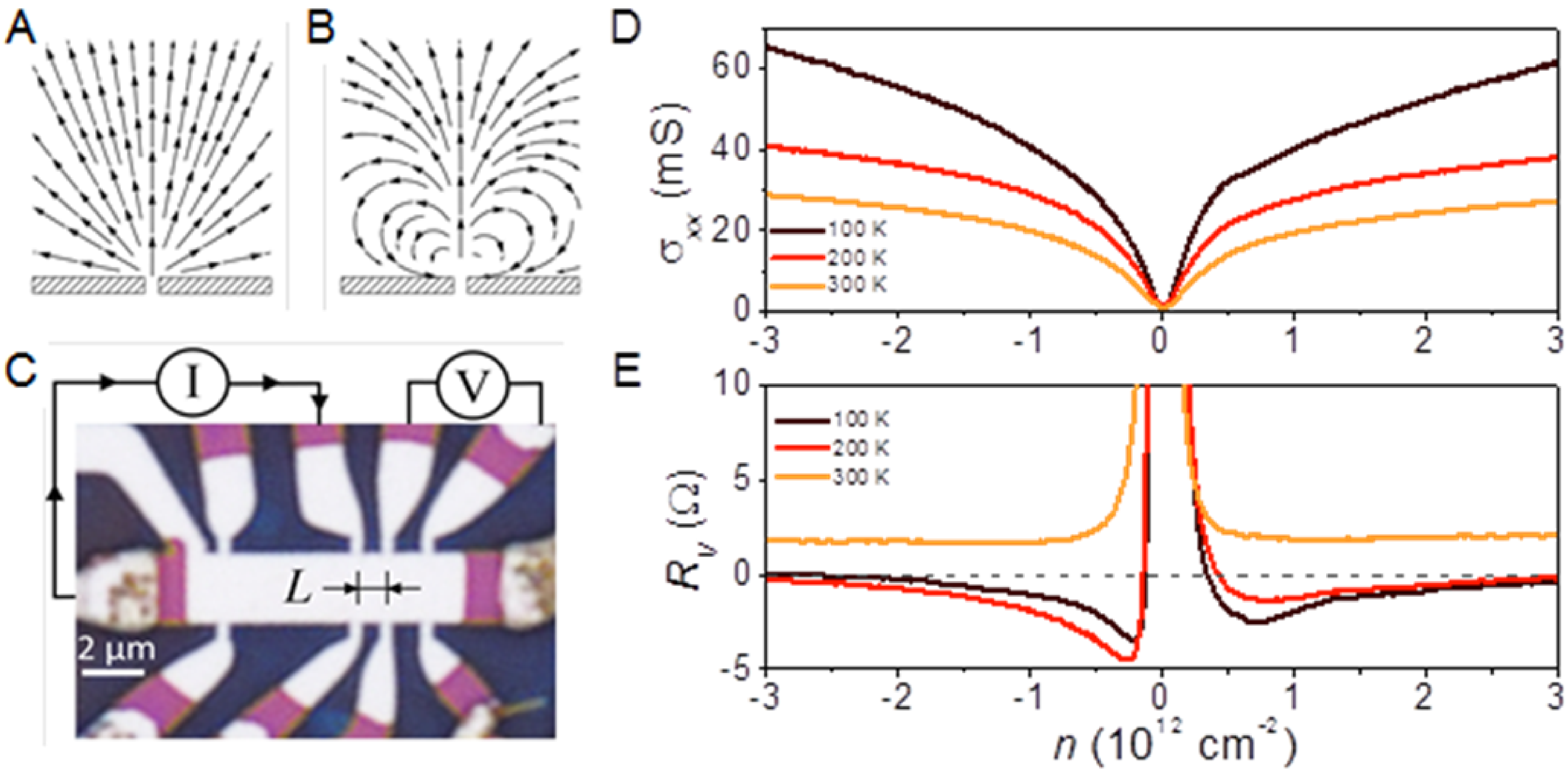
Wiedemann-Franz violated !

Strange metal in graphene

Science **351**, 1055 (2016)

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. Auton[5], E. Khestanova[1,5], K. S. Novoselov[5], I. V. Grigorieva[1], L. A. Ponomarenko[1,4], A. K. Geim[1], M. Polini[3,6]



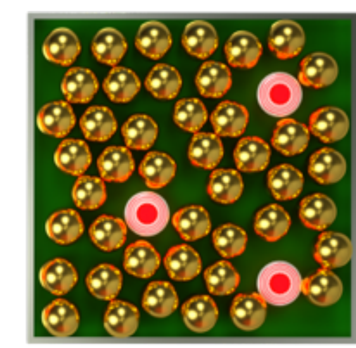
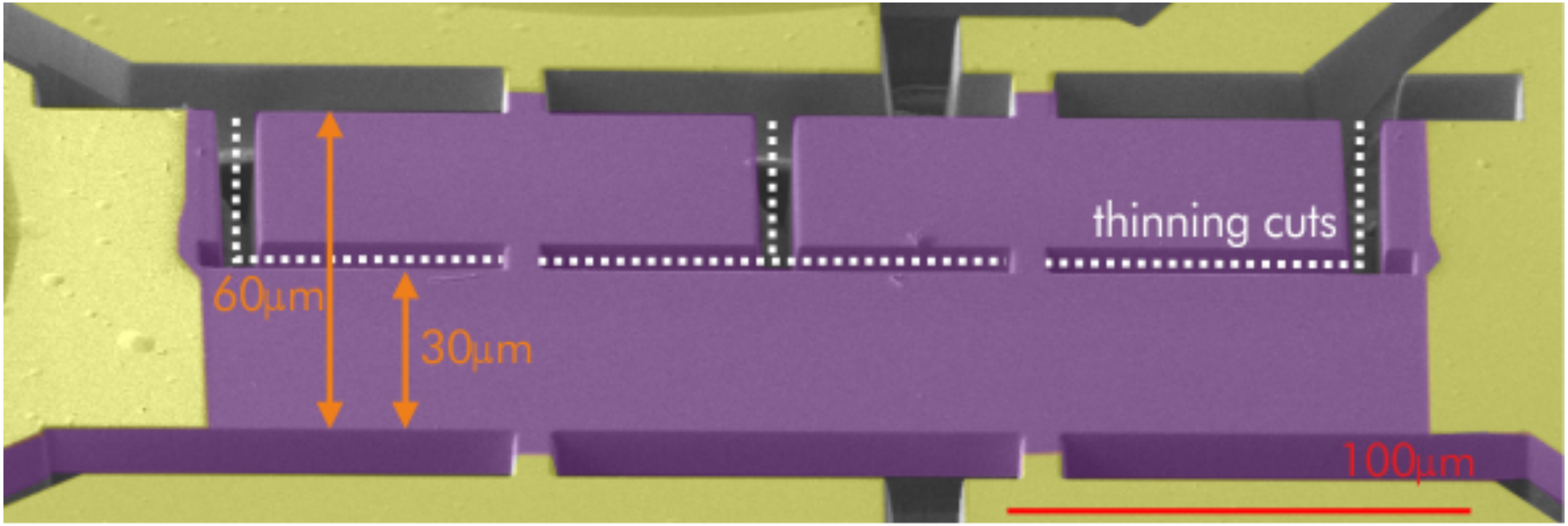


Figure 1. Viscous backflow in doped graphene. (**a,b**) Steady-state distribution of current injected through a narrow slit for a classical conducting medium with zero ν (a) and a viscous Fermi liquid (b). (**c**) Optical micrograph of one of our SLG devices. The schematic explains the measurement geometry for vicinity resistance. (**d,e**) Longitudinal conductivity σ_{xx} and R_{V} for this device as a function of n induced by applying gate voltage. $I = 0.3\ \mu\mathrm{A}$; $L = 1\ \mu\mathrm{m}$. For more detail, see Supplementary Information.

See also L. Levitov and G. Falkovich, *Nature Physics* **12**, 672 (2016)

Signature of Navier-Stokes hydrodynamic flow in $PdCoO_2$



Experiment: Successively narrow the channel in factors of 2, measuring the resistance after every step.

*P.J.W. Moll, P. Kushwaha, N. Nandi, B. Schmidt and A.P. Mackenzie, Science **351**, 1061 (2016)*

Entangled quantum matter without quasiparticles

- Is there a connection between strange metals and black holes?
  Yes, *e.g.* the SYK model.

- Why do they have the same equilibration time $\sim \hbar/(k_B T)$?
  Strange metals don't have quasiparticles and thermalize rapidly;
  Black holes are "fast scramblers".

- Theoretical predictions for strange metal transport in graphene agree well with experiments