Title: Exploring Quantum Matter with the High Temperature Superconductors

Date: Jun 23, 2015 09:50 AM

URL: http://pirsa.org/15060024

Abstract: Apart from high temperature superconductivity, the cuprate compounds also display fascinating new types of metallic states from which the superconductivity descends. These metals have served as a remarkable laboratory for modern ideas on long-range quantum entanglement and its consequences for the properties of quantum matter.

In the low carrier density â€œpseudogapâ€• regime we observe a metal which is similar in many respects to simple metals like silver; however, there is increasing evidence that the simple metallic character co-exists with more exotic topological order. At higher dopings we have the â€œstrange metalâ€• which differs in almost all respects from simple metals, and has no well-defined quasiparticle excitations. I will describe a mean-field model of a strange metal which, remarkably, yields the Bekenstein-Hawking entropy of charged black holes.

Flavors of Quantum Matter

A. Ordinary quantum matter

Independent electrons, or pairs of electrons

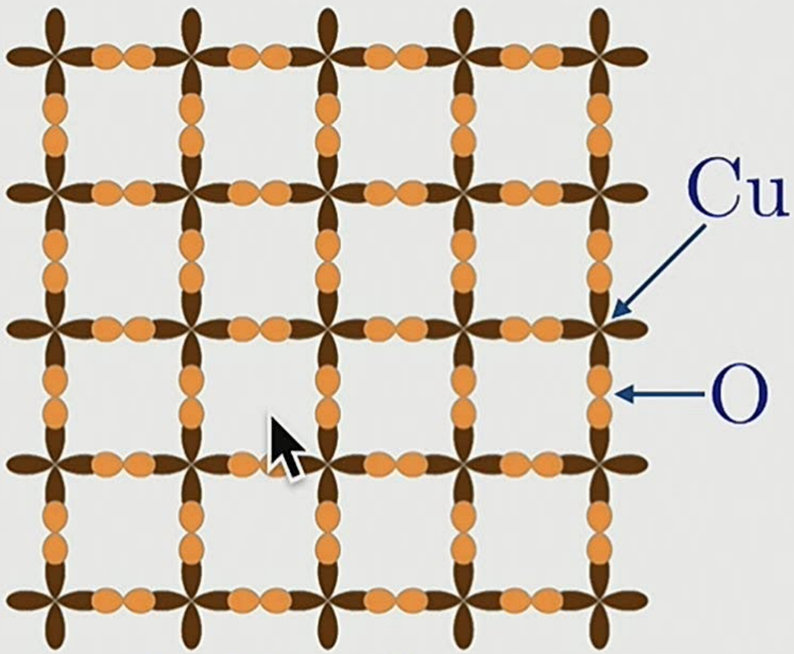
B. Topological quantum matter

Long-range quantum entanglement leads to sensitivity to spatial topology

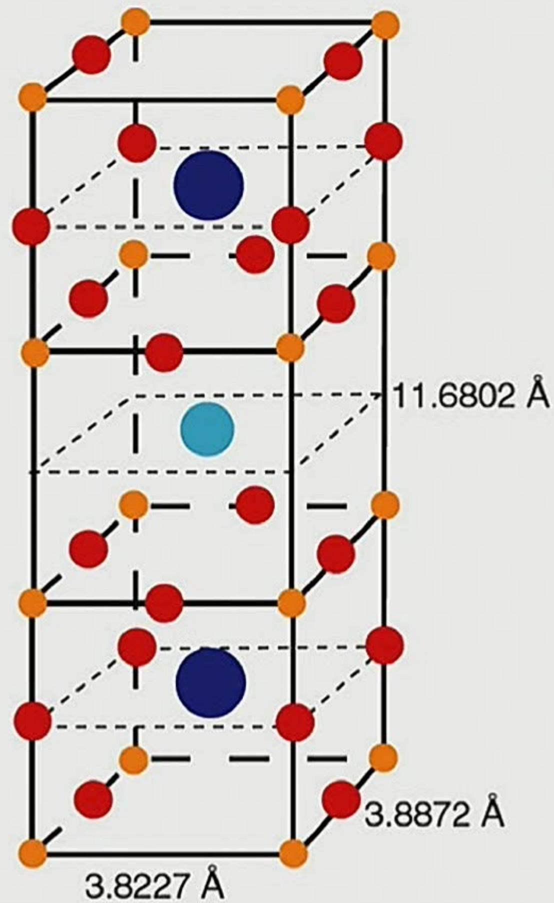
C. Quantum matter without quasiparticles

Strange metals: infinite-range model maps to extremal charged black holes and yields Bekenstein-Hawking entropy

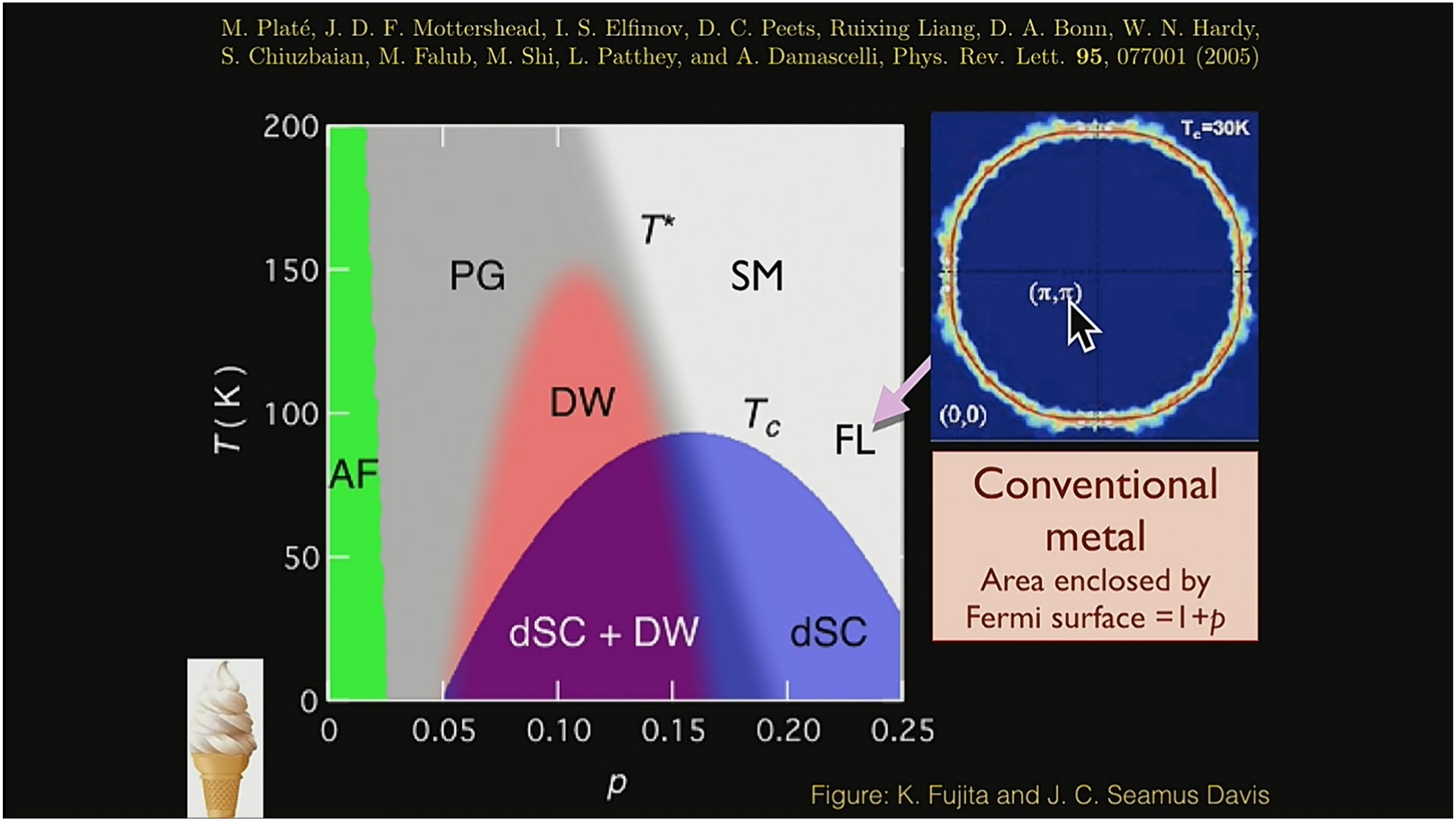
High temperature superconductors



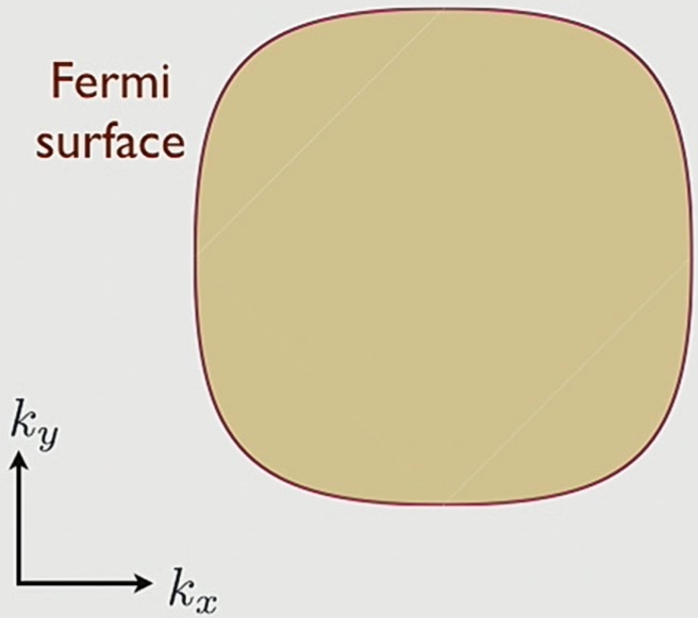
CuO_2 plane



$YBa_2Cu_3O_{6+x}$


M. Platé, J. D. F. Mottershead, I. S. Elfimov, D. C. Peets, Ruixing Liang, D. A. Bonn, W. N. Hardy, S. Chiuzbaian, M. Falub, M. Shi, L. Patthey, and A. Damascelli, Phys. Rev. Lett. 95, 077001 (2005)
200
150
100
50
0
T (K)
0
0.05
0.10
0.15
0.20
0.25
p
AF
PG
T*
SM
DW
Tc
FL
dSC + DW
dSC
Tc=30K
(π,π)
(0,0)
Conventional metal
Area enclosed by Fermi surface =1+p
Figure: K. Fujita and J. C. Seamus Davis

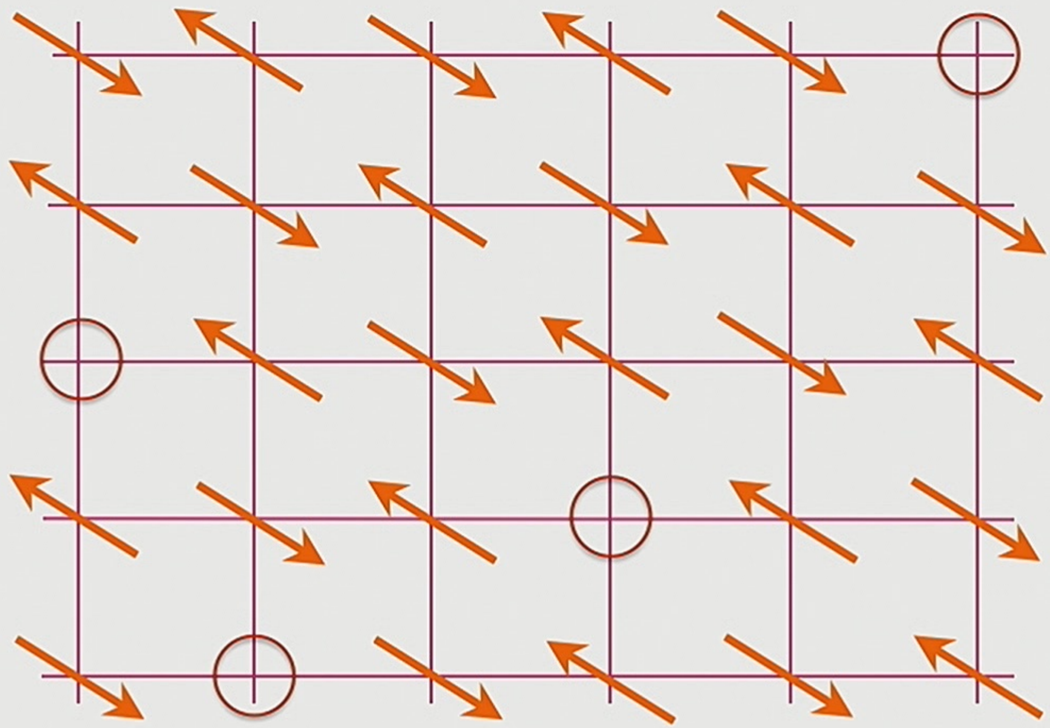
Ordinary quantum matter: the Fermi liquid (FL)



- Fermi surface separates empty and occupied states in momentum space.
- Density of electrons can be continuously varied.
- Long-lived electron-like quasiparticle excitations near the Fermi surface: lifetime of quasiparticles $\sim 1/T^2$.
- Area enclosed by Fermi surface = total density of electrons (mod 2) $= 1 + p$.

Evidence for Fermi surface of long-lived quasiparticles of density *p*

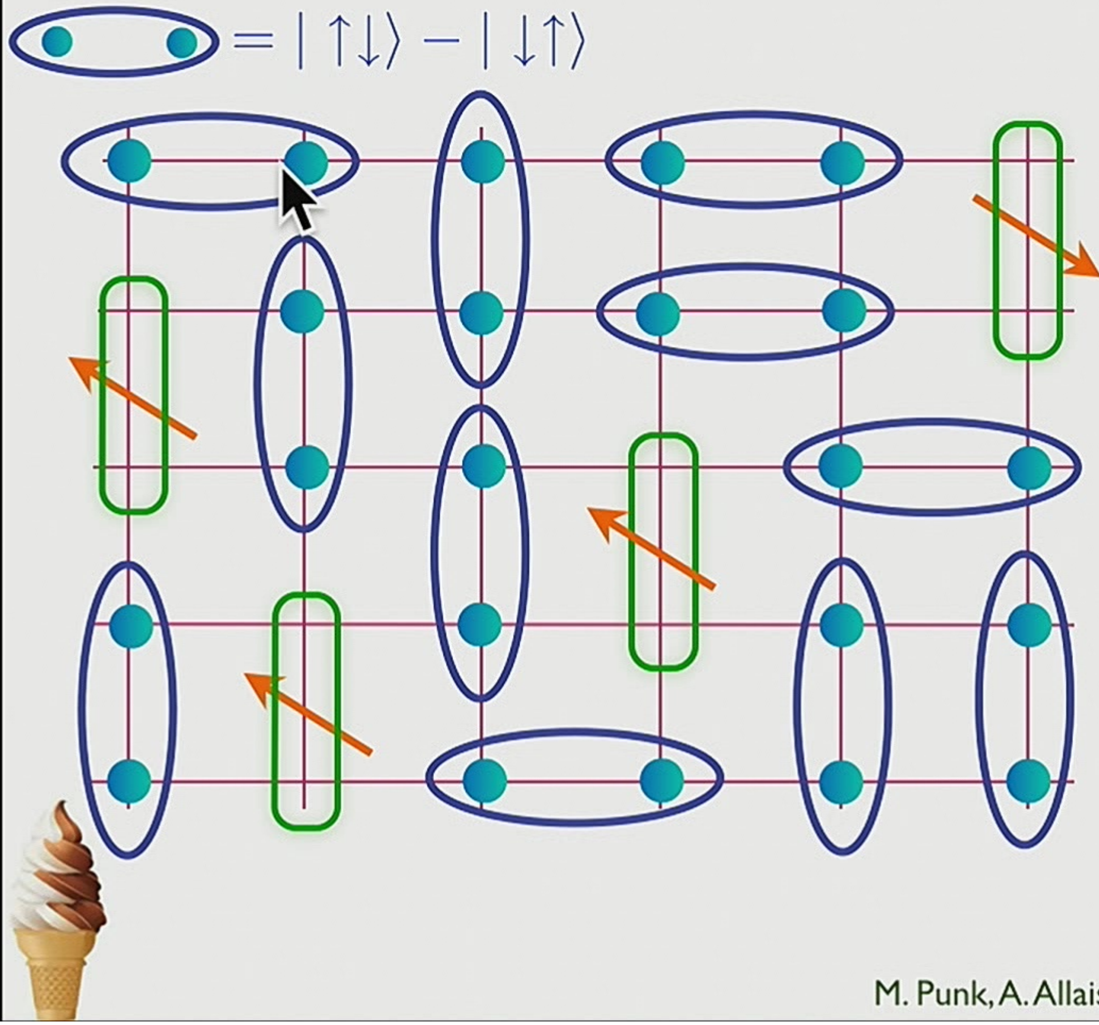
- Hall effect (Ando PRL 2004)
- Optical conductivity (van der Marel PNAS 2013)
- Magnetoresistance (Greven PRL 2014)
- Scanning Tunneling Microscopy (Seamus Davis, PNAS 2014): *d*-form factor density wave



Anti-ferromagnet with p holes per square

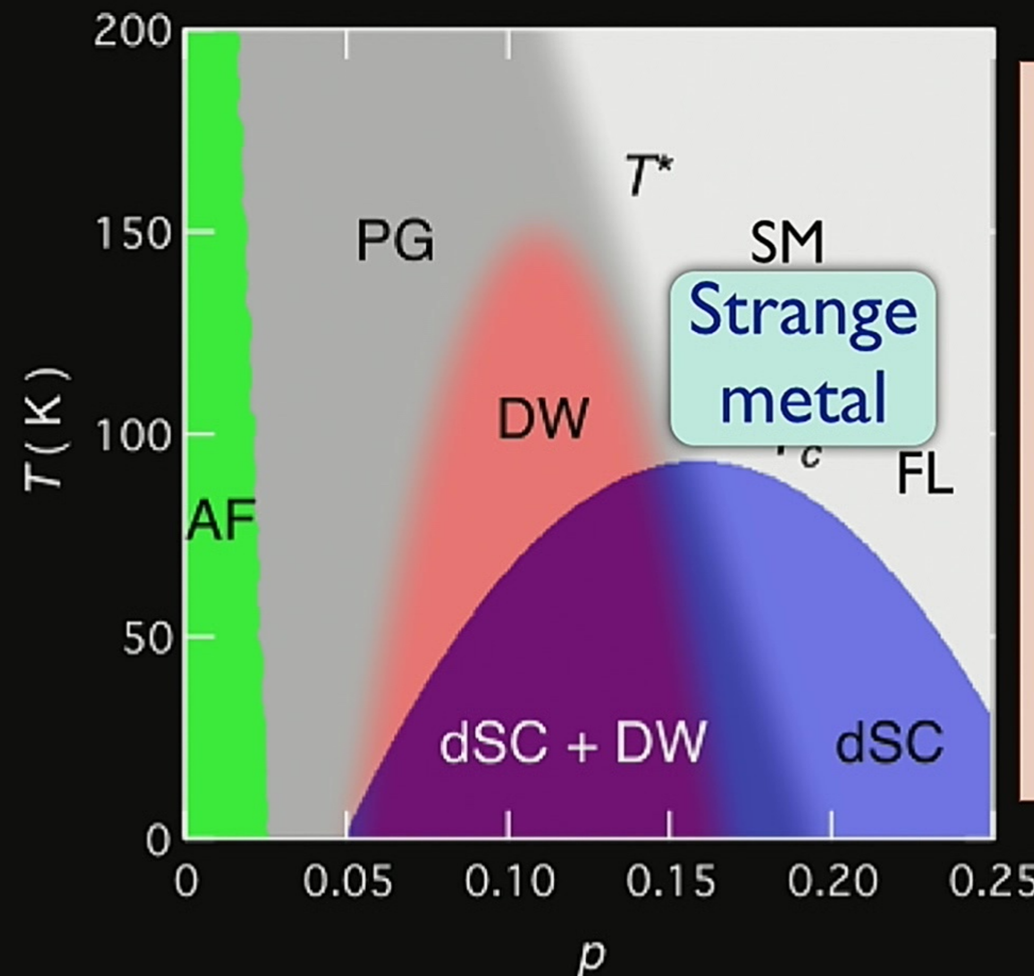
Note: relative to the fully-filled band insulator, there are $1+p$ holes per square

Fractionalized Fermi liquid (FL*)



Realizes a metal with a Fermi surface of area p co-existing with "topological order"

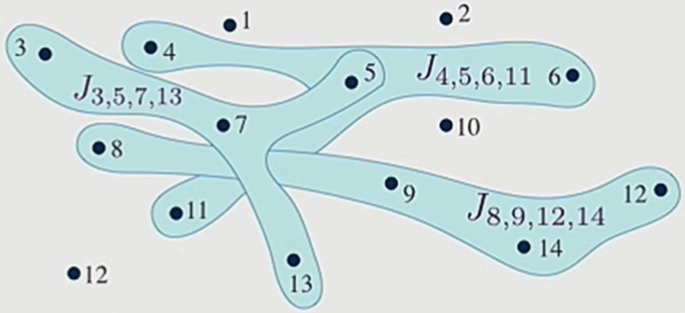
M. Punk, A. Allais, and S. S., arXiv:1501.00978.



Many experimental indications of a quantum state which has:

- a continuously variable density,
- bulk excitations of arbitrarily low energy,
- and no long-lived quasiparticles.

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



$$\mathcal{Q} = \frac{1}{N} \sum_i \left\langle c_i^\dagger c_i \right\rangle .$$

Local fermion density of states

$$\rho(\omega) \sim \begin{cases} \omega^{-1/2} & , \ \omega > 0 \\ e^{-2\pi\mathcal{E}}\, |\omega|^{-1/2}, & \omega < 0. \end{cases}$$

Known 'equation of state' determines $\mathcal{E}$ as a function of $\mathcal{Q}$

Microscopic zero temperature entropy density, $\mathcal{S}$, obeys

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

$$c_i c_j + c_j c_i = 0$$

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

$J_{ij;k\ell}$ independent random numbers

O. Parcollet, A. Georges, G. Kotliar, and A. Sengupta Phys. Rev. B **58**, 3794 (1998)

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

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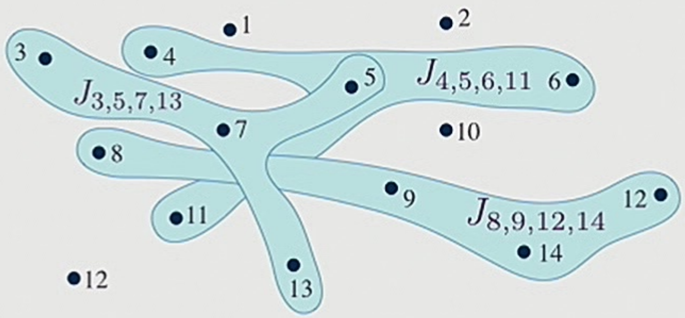

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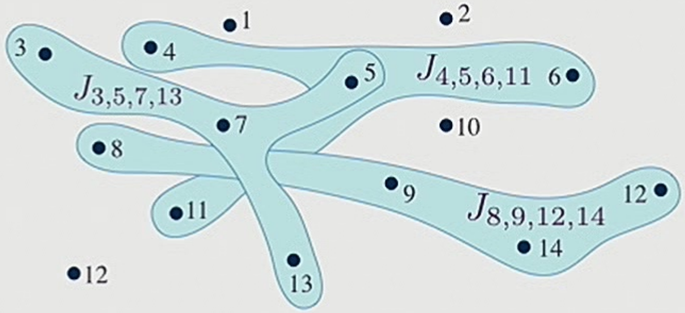

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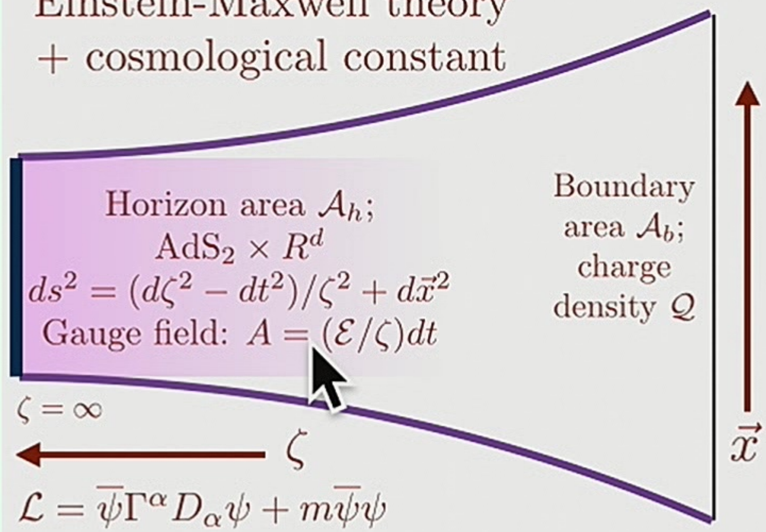
Einstein-Maxwell theory + cosmological constant



$$\mathcal{L} = \overline{\psi}\Gamma^\alpha D_\alpha \psi + m\overline{\psi}\psi$$

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T. Faulkner, Hong Liu, J. McGreevy, and D. Vegh
Phys. Rev. D **83**, 125002 (2011)

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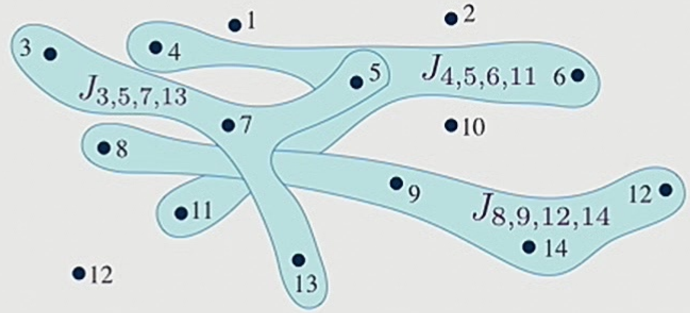

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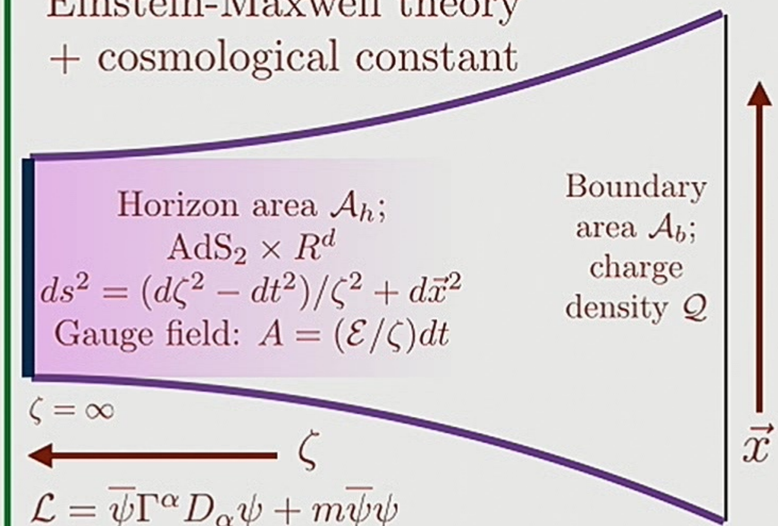

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'Equation of state' relating $\mathcal{E}$ and $\mathcal{Q}$ depends upon the geometry of spacetime far from the AdS_2

Eliminate r_0 between

$$\mathcal{Q} = \frac{r_0^{d-1}\sqrt{2d\left[(d-1)R^2 + (d+1)r_0^2\right]}}{\kappa^2 g_F}$$

$$\mathcal{E} = \frac{g_F r_0 \sqrt{2d\left[(d-1)R^2 + (d+1)r_0^2\right]}}{2\left[(d-1)^2 R^2 + d(d+1) r_0^2\right]}$$

S. Sachdev, arXiv:1506.05111

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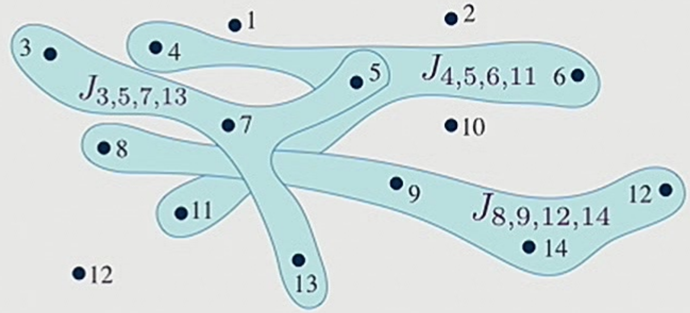

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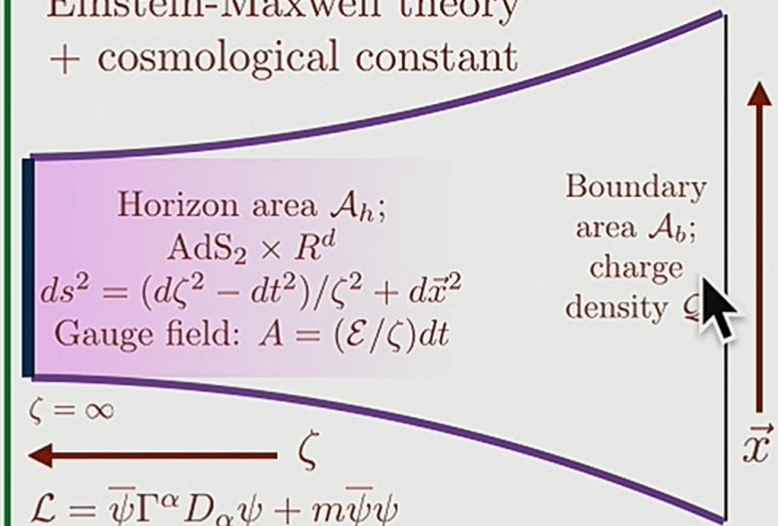

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Black hole thermodynamics (classical GR) yields

$$\frac{1}{\mathcal{A}_b} \frac{\partial \mathcal{A}_h}{\partial \mathcal{Q}} = 8\pi G_N \mathcal{E}$$

A. Sen, arXiv:0809.3304; S. Sachdev, arXiv:1506.05111

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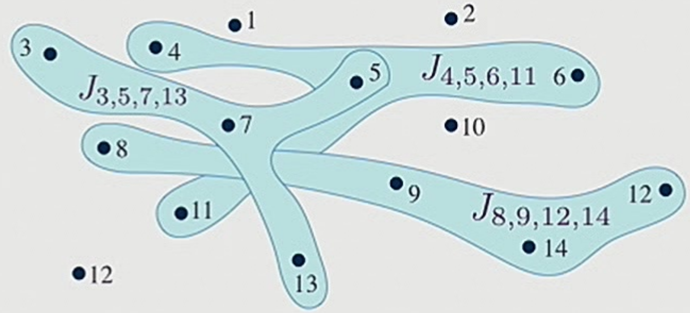

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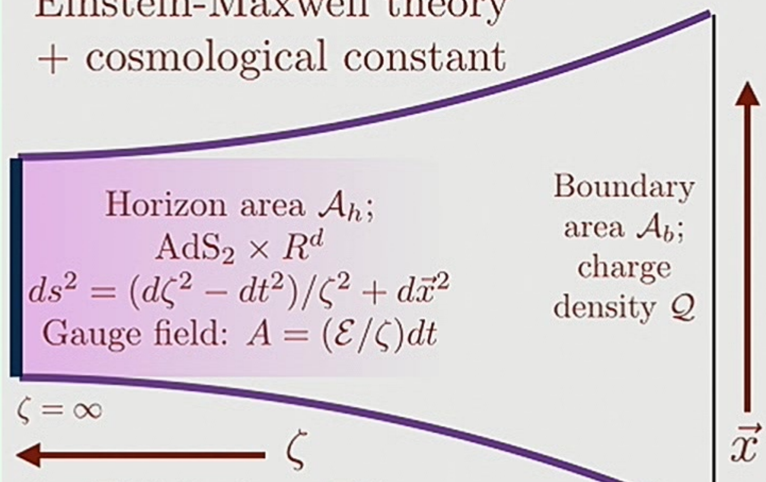

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$$\frac{\partial \mathcal{S}}{\partial \mathcal{Q}} = 2\pi\mathcal{E}$$

Combination:

$$\mathcal{S} = \frac{\mathcal{A}_h}{4G_N \mathcal{A}_b}$$

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S. Sachdev, arXiv:1506.05111