Title: Charge fractionalization and entanglement entropy for compressible phases in holography

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Abstract:

Charge fractionalization and entanglement entropy for compressible phases in holography

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Condensed Matter Seminar - PI

Sept 11, 2012

S. Hartnoll, S. Sachdev, B. Swingle

References:
LH, S. Sachdev, Phys Rev D 84, 026001 (2011)
S. Hartnoll, LH, Class. Quantum Grav. 29, 194001 (2012)
LH, S. Sachdev, B. Swingle, Phys Rev B 86, 035121 (2012)

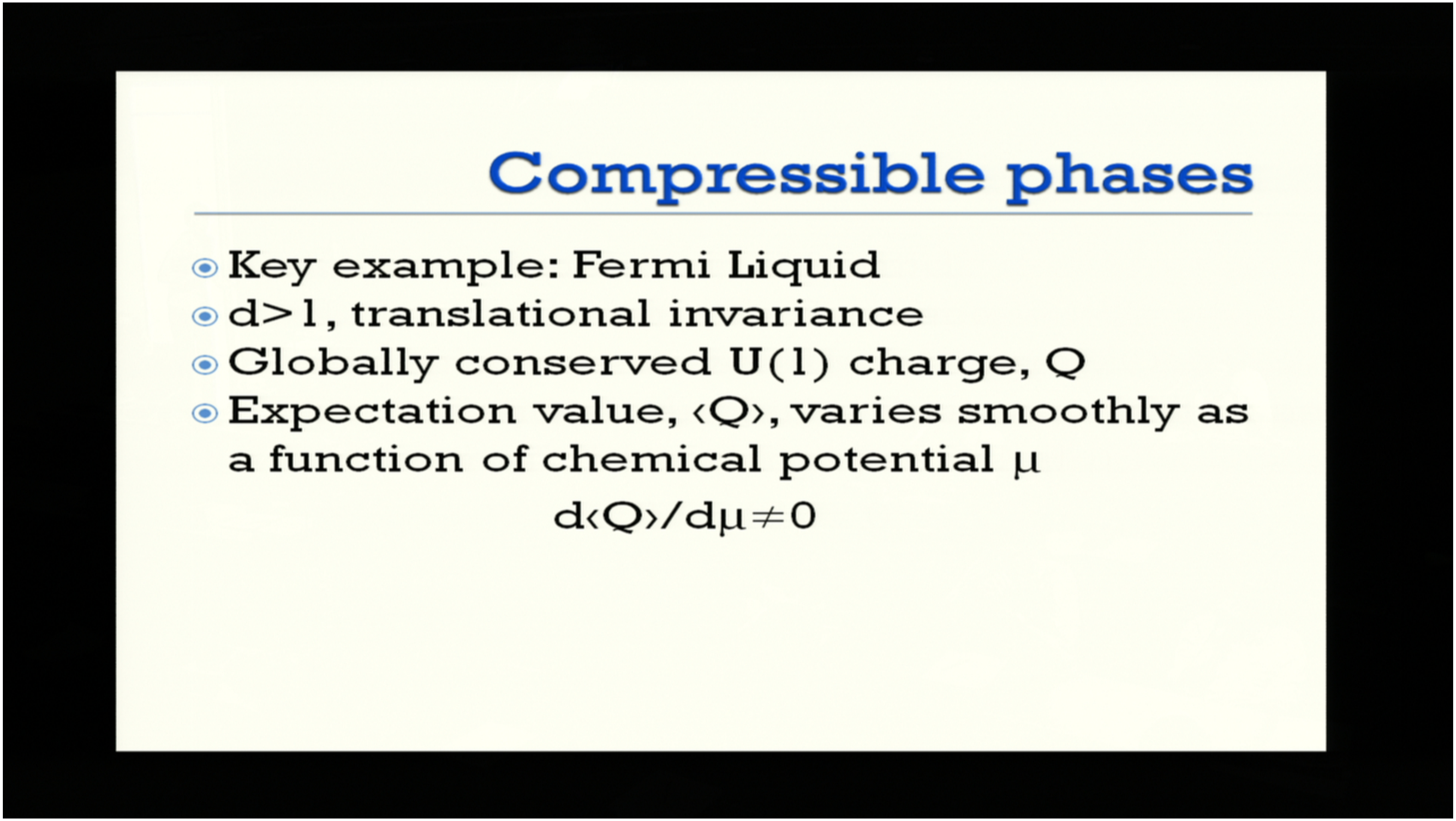
Motivation

- Challenge: strongly interacting electrons
- Holography as a tool?

- Here: focus on compressible phases (T=0)
- Arise naturally in holography
- Can we characterize these phases?

Outline

- Compressible phases
- Compressible phases in holography
- Characteristic features
  - Part 1: Charge fractionalization
  - Part 2: Holographic entanglement entropy
- Connection to compressible phases in condensed matter
- Recent developments and outlook


Compressible phases
Key example: Fermi Liquid
d>1, translational invariance
Globally conserved U(1) charge, Q
Expectation value, ‹Q›, varies smoothly as a function of chemical potential μ
d‹Q›/dμ≠0

Compressible phases

- Fermi Liquid
  - Interacting many-particle system adiabatically connected to non-interacting Fermi gas
  - Fermi Surface (Green's function pole)
  - Long-lived quasi-particles
  - Signatures: resistivity $\sim T^2$, specific heat $\sim T$
- Non Fermi Liquid
  - Strongly interacting system; fermions couple to emergent dynamical gauge field
  - Fermi Surface (Green's function singularity)
  - No long-lived quasi-particles
- FL*: both types of Fermi surfaces

Fermi surface

- Luttinger theorem relates total charge, $\langle Q \rangle$, to area, A, enclosed by Fermi surface:

$$\langle Q \rangle = A$$

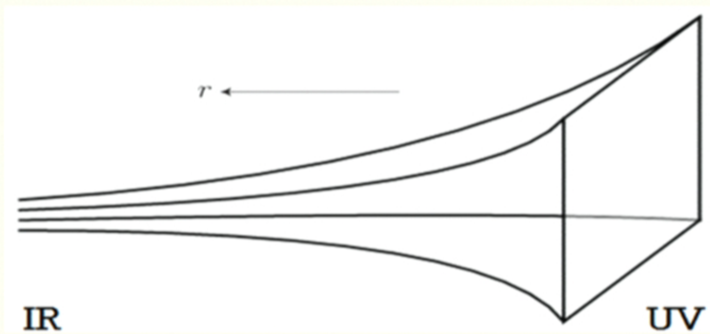
- The Fermi surface is locus in momentum space, $k=k_F$, where Green's function is singular
- *Compressible phases have Fermi surface*

Powell, Sachdev, Büchler, PRB 72, 024534 (2005);
Coleman, Paul, Rech, PRB 72, 094430 (2005);
LH, Sachdev, PRD 84, 026001 (2011)

Compressible phases in holography

AdS/CFT duality

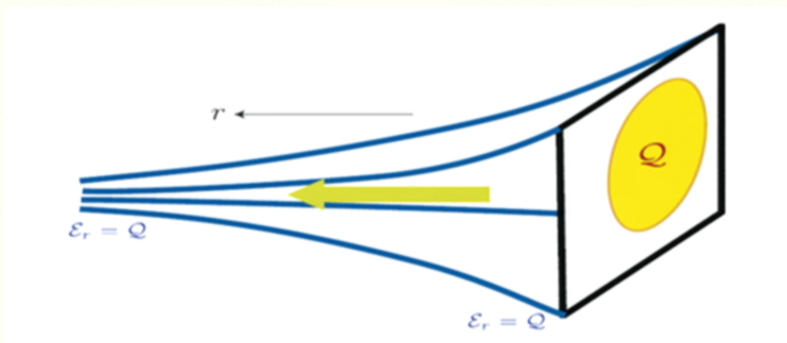
BULK	BOUNDARY
◉ Dimensions: d+1	◉ Dimensions: d
◉ AdS spacetime	◉ CFT



Maldacena, Adv. Theor. Math. Phys. 2, 231 (1998)

Finite charge density

BULK	BOUNDARY
Dimensions: d+1	Dimensions: d
AdS spacetime	CFT
Electric field sourced by bulk charges	Finite chemical potential



Electric field sources

- Boundary theory at finite chemical potential is dual to a bulk theory with charge sources
- Two types of charge sources:
  - Charged fermionic particles in the bulk
  - Charge hidden behind horizon
- Three possibilities: cohesive, fully fractionalized and partially fractionalized

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Einstein-Maxwell theory

- Effective field theory in the bulk

$$\mathscr{L} = \frac{1}{2\kappa^2}\left(R + \frac{6}{L^2}\right) - \frac{1}{4e^2}F_{\mu\nu}F^{\mu\nu}$$

- Simplest theory dual to a compressible theory
- Bulk solution is extremal black hole
- Zero temperature entropy
- Solution: include dilaton field

Einstein-Maxwell-dilaton theory

- Effective field theory in the bulk:

$$\mathscr{L} = \frac{1}{2\kappa^2}\left(R - 2(\nabla\Phi)^2 - \frac{V(\Phi)}{L^2}\right) - \frac{Z(\Phi)}{4e^2}F_{\mu\nu}F^{\mu\nu}$$

- Dilaton couples to Maxwell fields: $Z(\Phi)$
- Dilaton potential: $V(\Phi)$
- Dilaton (neutral scalar) mass is related to scaling dimension of dual operator, we choose it relevant
- UV theory at boundary will flow to an IR theory in the bulk under RG

Charged fluid

- Effective field theory in the bulk including fermions explicitly:

$$\mathscr{L} = \frac{1}{2\kappa^2}\left(R - 2(\nabla\Phi)^2 - \frac{V(\Phi)}{L^2}\right) - \frac{Z(\Phi)}{4e^2}F_{\mu\nu}F^{\mu\nu} + p(\mu_{\rm loc})$$

- Pressure of the fluid: $-p = \rho - \mu_{\rm loc}\sigma$
- Fluid description allows us to include backreaction

Hartnoll, Tavanfar, PRD 83,046003 (2011)

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Outline

- Solve eom in the UV and IR
- UV solution: AdS_4
- Multiple IR solutions:
  - Lifshitz solution
  - Fractionalized solution
  - Cohesive solution
- We obtain phase diagram as a function of coupling to relevant operator dual to dilaton

Hartnoll, LH, CQG 29, 194001 (2012)

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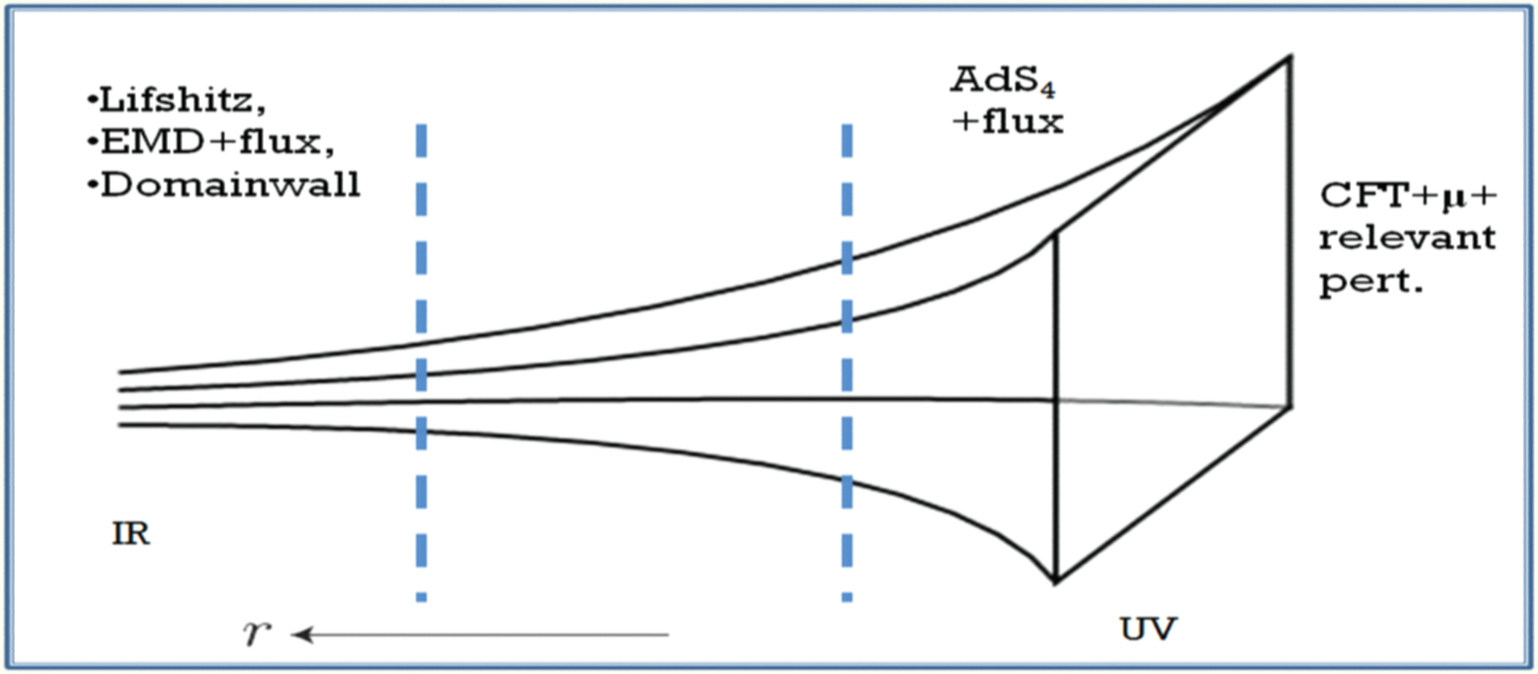
Phases in holography



Setup

- Metric:

$$ds^2 = L^2 \left(-f(r)dt^2 + g(r)dr^2 + \frac{dx^2 + dy^2}{r^2} \right)$$

- Maxwell potential and local chemical potential:

$$A = \frac{eL}{\kappa} h(r) dt \qquad \mu_{\rm loc} = \frac{e}{\kappa} \frac{h}{\sqrt{f}}$$

- Dilaton potential:

$$V(\Phi) = -6\cosh(2\Phi/\sqrt{3}) \qquad Z(\Phi) = e^{2\Phi/\sqrt{3}}$$

- Conventions: r→0 in UV, r→∞ in IR

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EOM

$$
\begin{aligned}
\frac{1}{r}\left(\frac{f'}{f}+\frac{g'}{g}+\frac{4}{r}\right)+\frac{gh}{\sqrt{f}}\hat{\sigma}+2\Phi'^2 &= 0\,,\\
\frac{1}{r}\left(\frac{f'}{f}-\frac{1}{r}\right)+g\left(\hat{p}-\tfrac{1}{2}V(\Phi)\right)-\frac{Z(\Phi)h'^2}{2f}+\Phi'^2 &= 0\,,\\
-\Phi''+\frac{1}{2}\left(-\frac{f'}{f}+\frac{g'}{g}+\frac{4}{r}\right)\Phi'+\frac{gV'(\Phi)}{4}-\frac{Z'(\Phi)h'^2}{4f} &= 0\,,\\
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\end{aligned}
$$

Asymptotic solutions for:

- UV: $r \to 0$ & $\Phi \to 0$
- IR: $r \to \infty$ &
  - $\Phi \to$ const
  - $\Phi \sim \log r \to +\infty$
  - $\Phi \sim -\log r \to -\infty$
- Full bulk solution numerically

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UV solution

- Dilaton potential:

$$V(\Phi) = -6 - 4\Phi^2 + \mathscr{O}(\Phi^4), \quad Z(0) = 1$$

- Dilaton mass: $-2/L^2$,
  scaling dimension dual operator: $\Delta=2$

$$\Phi = \phi_0 r + \frac{\langle \mathscr{O} \rangle}{2} r^2 + \dots$$

- Metric: AdS_4
- Maxwell potential: $h = c(\hat{\mu} - \hat{Q} r + \dots)$

Hartnoll, LH, CQG 29, 194001 (2012)

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relevant coupling

- Metric: AdS_4
- Maxwell potential: $h = c(\hat{\mu} - \hat{Q} r + \dots)$

Hartnoll, LH, CQG 29, 194001 (2012)

IR solution I: Lifshitz

- Dilaton to constant in IR ($r \to \infty$)

$$ds^2 = L^2\left(-\frac{dt^2}{r^{2z}} + g_L\frac{dr^2}{r^2} + \frac{dx^2+dy^2}{r^2}\right) \quad A = \frac{eL}{\kappa}h_L\frac{dt}{r^z} \quad \Phi = \phi_L$$

- Scale invariant solution
- Flux vanishes in IR, all charge carried by fluid
- There is a relevant perturbation of Lifshitz fixed point
  $\Rightarrow$ need to tune parameter in UV to hit fixed point in IR
- Parameter is relevant coupling ϕ_0
- Lifshitz solution characterizes phase transition between two phases

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IR solution II: Fractionalized

- Dilaton: $\Phi \sim \log r \rightarrow +\infty$ for $r \rightarrow \infty$
  $\Rightarrow Z \rightarrow \infty$, effective Maxwell coupling small
- Hyperscaling violation metric

$$ds^2 = L^2\left(-\frac{dt^2}{r^6} + g_0\frac{dr^2}{r^4} + \frac{dx^2 + dy^2}{r^2}\right)$$

- Flux to constant for $r \rightarrow \infty$
  $\Rightarrow$ must be sourced by charge hidden behind horizon
- Local chemical potential to zero, so no fluid in IR
- Solution for range of values of ϕ_0
  $\Rightarrow$ Entire class of solutions

Hartnoll, LH, CQG 29, 194001 (2012)

IR solution II: Fractionalized

- No fluid in IR
- Fluid can be present in the bulk if full solution has region with $\hat{\mu}_{\rm loc} > \hat{m}$
- Fully fractionalized: all charge behind horizon
- Partially fractionalized: total charge is sum of charge behind horizon and charge carried by fluid
- As we tune relevant coupling ϕ_0 charge leaks out from behind horizon and populates fluid

Hartnoll, LH, CQG 29, 194001 (2012)

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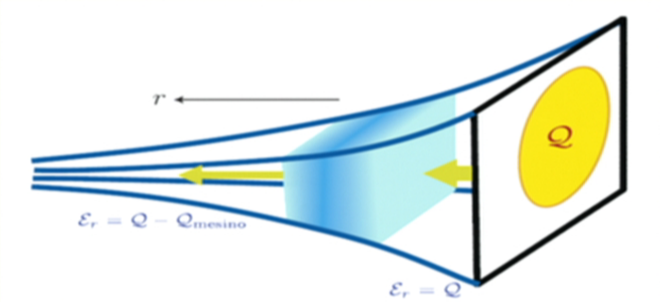

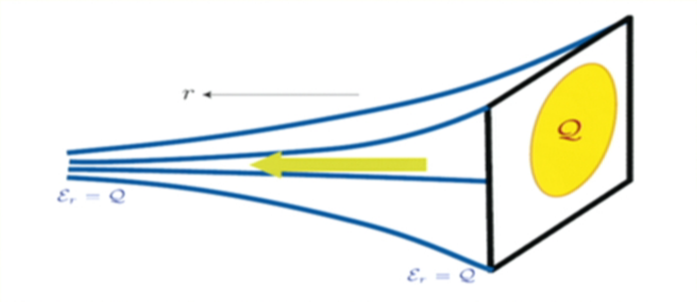

Partially fractionalized	Fully fractionalized
charge partially hidden behind horizon rest carried by fermions in bulk	all charge hidden behind horizon

Hartnoll, LH, CQG 29, 194001 (2012)

IR solution III: Cohesive

- Dilaton: $\Phi \sim -\log r \to -\infty$ for $r \to \infty \Rightarrow Z \to 0$
- Flux to zero for $r \to \infty$
  $\Rightarrow$ all charge sourced by fluid
- The metric is domain-wall solution

$$ds^2 = e^{G(r)}\left[-f(r)dt^2 + dx^2 + dy^2\right] + \frac{dr^2}{f(r)}$$

- Local chemical potential:
  $\hat{\mu}_{\text{loc}}(r \to \infty) = \text{const.} > \hat{\text{m}}$
  so fluid all the way to IR

Hartnoll, LH, CQG 29, 194001 (2012)

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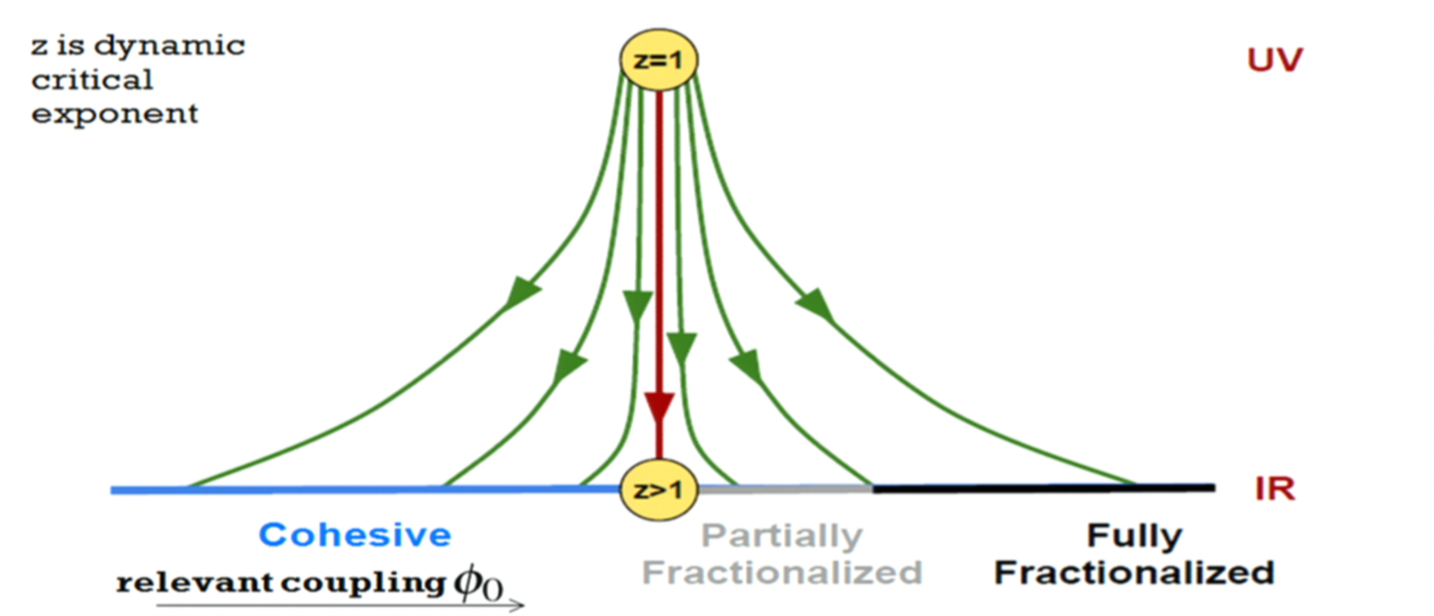
Phase diagram



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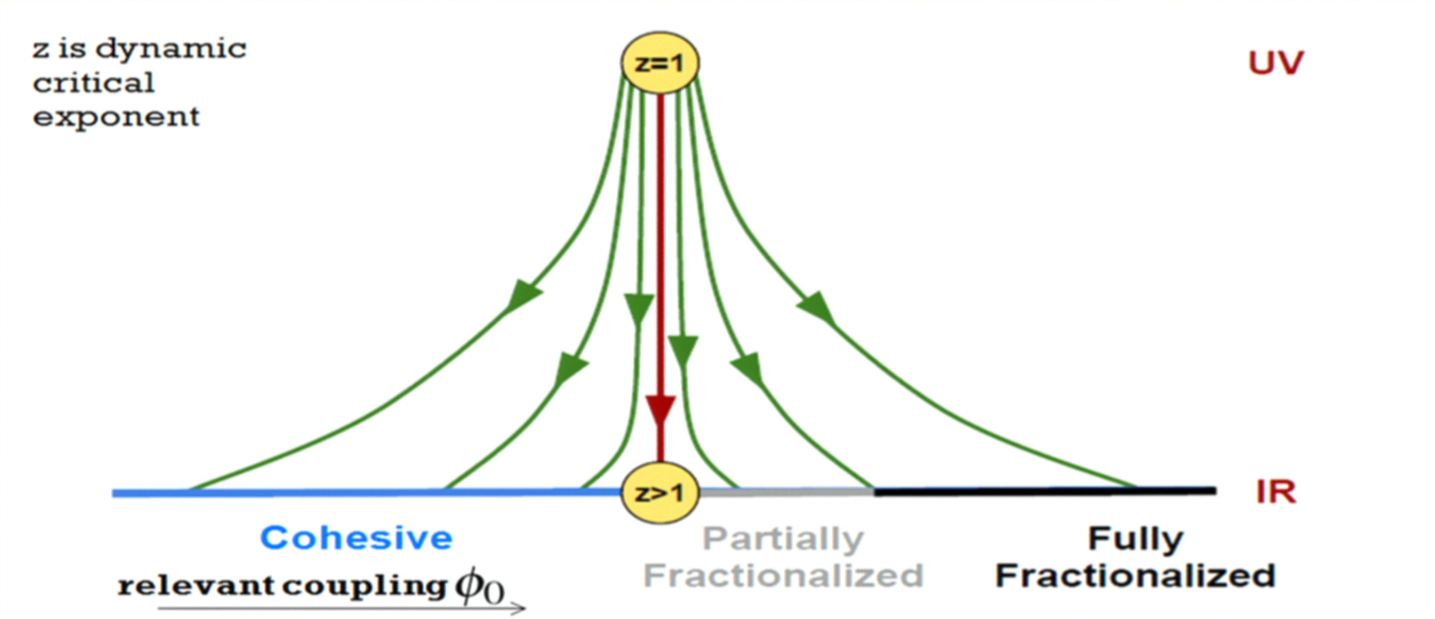
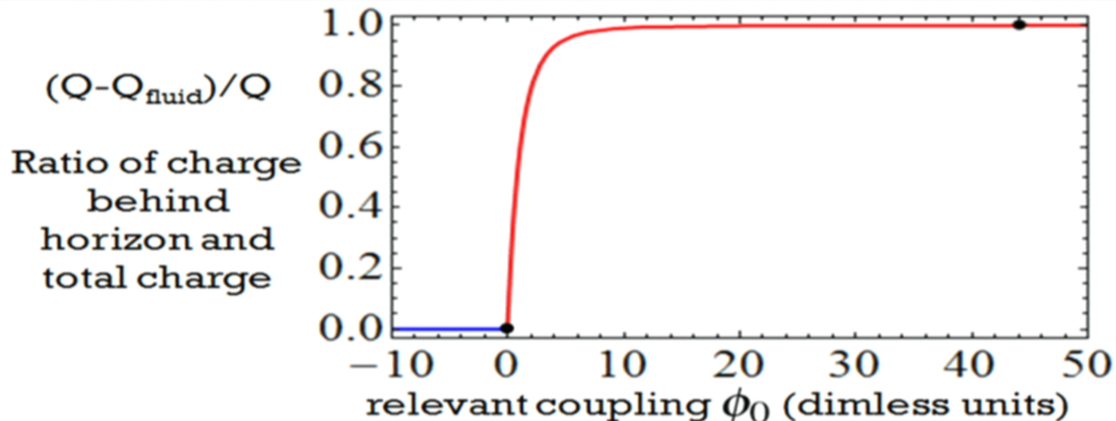


Hartnoll, LH, CQG 29, 194001 (2012)

Charge fractionalization



Cohesive	Partially fractionalized	Fully fractionalized
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Hartnoll, LH, CQG 29, 194001 (2012)

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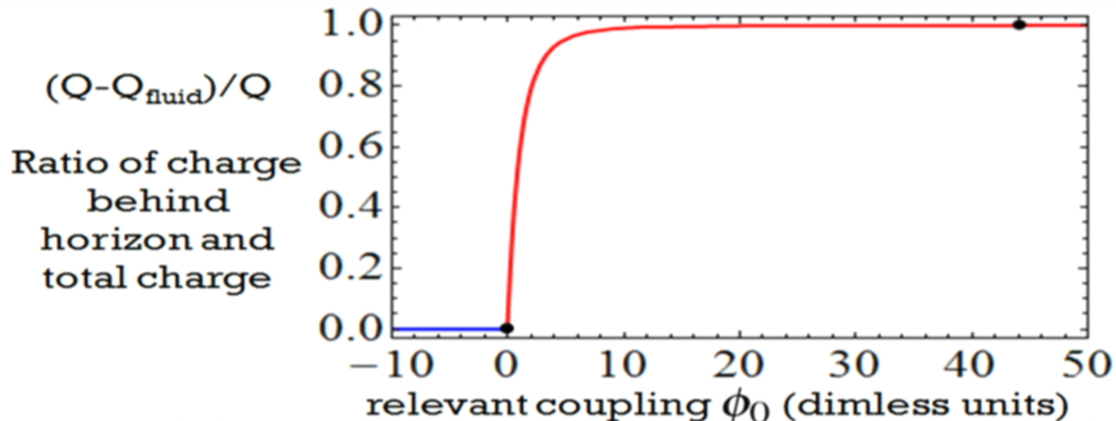

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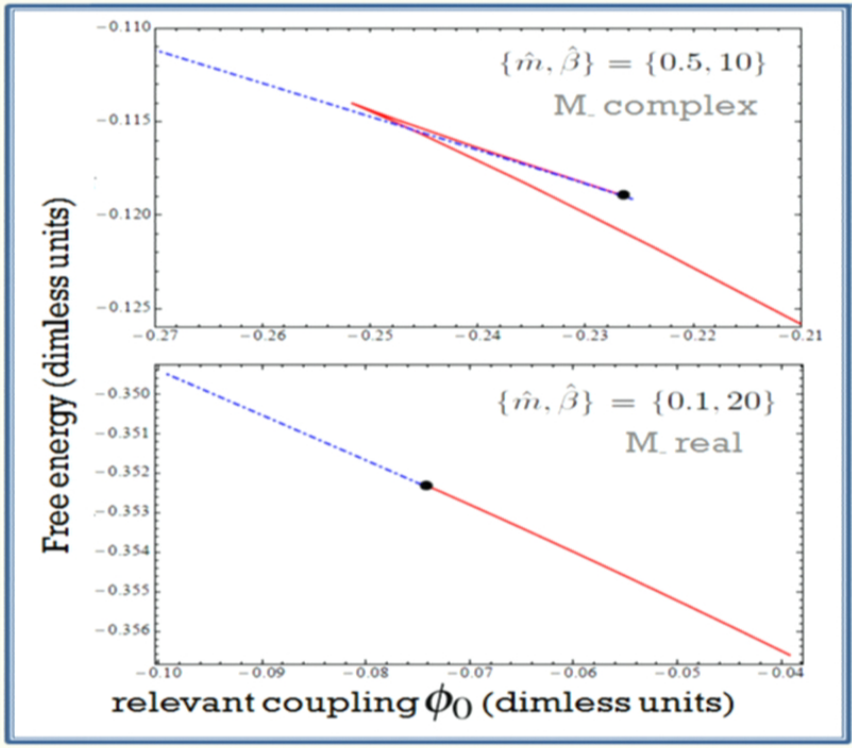
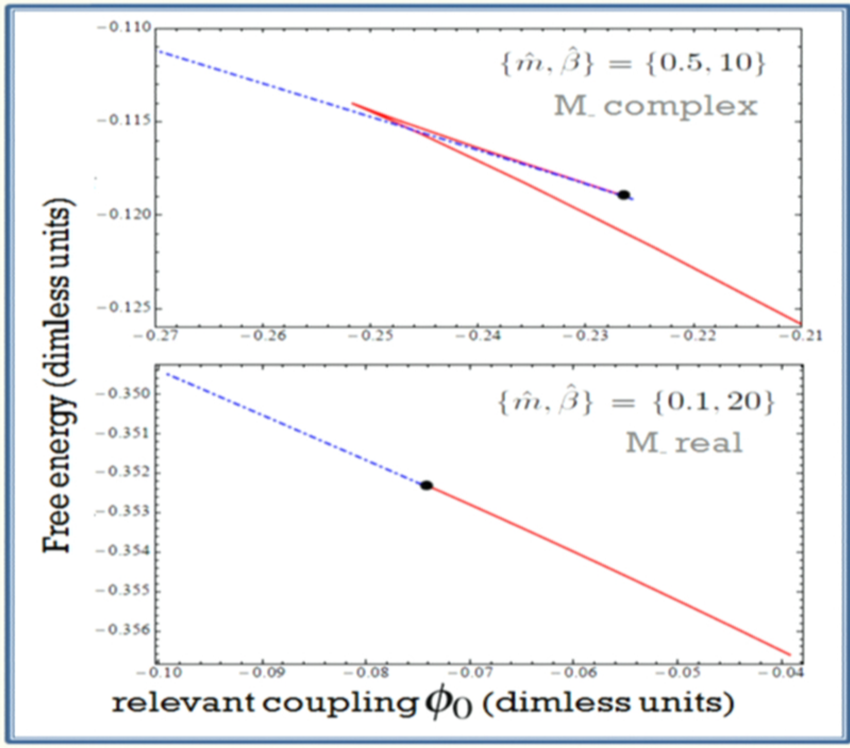
1st order vs 2nd order transition



- Lifshitz solution characterizes phase transition
- It depends on fluid parameters m and β
- Scaling dimension of relevant operator can be complex: indicates first order transition

Hartnoll, LH, CQG 29, 194001 (2012)

1^{st} order vs 2^{nd} order transition



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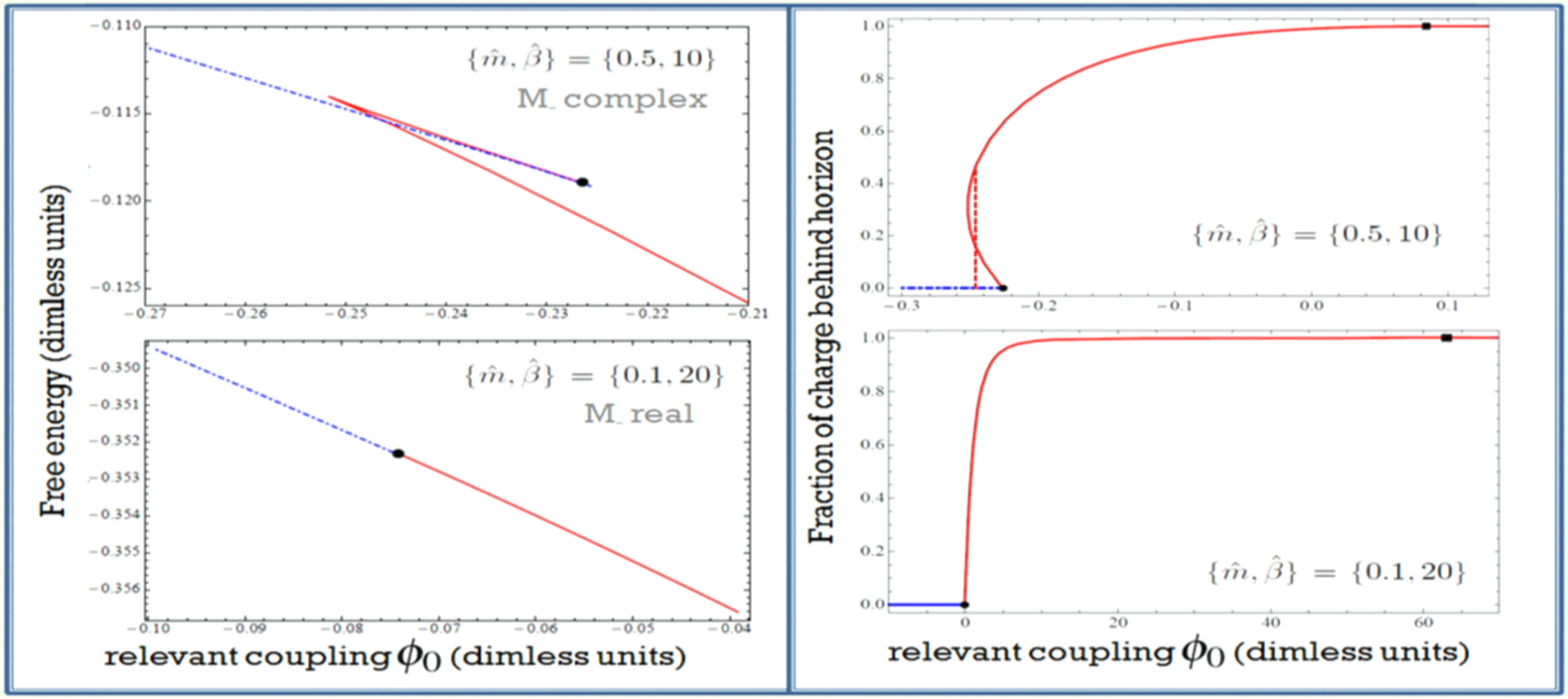
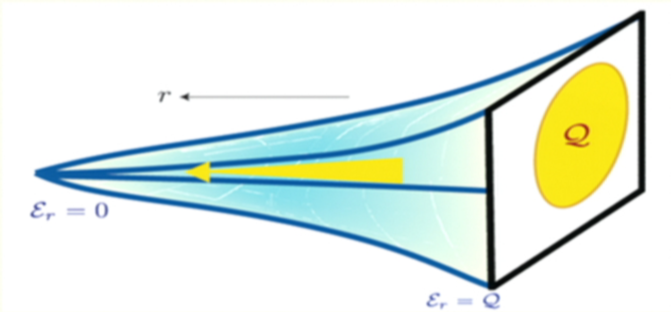


Fermi Surface?

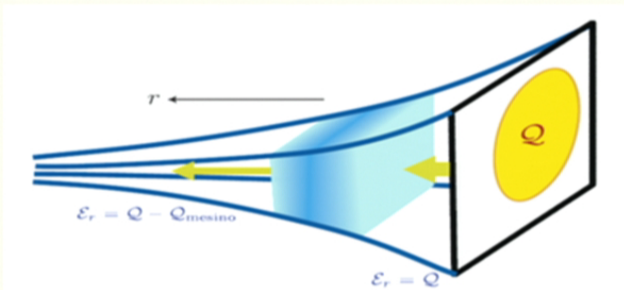
- Fermions in fluid can be studied in the bulk
- They obey Luttinger theorem
- *Cohesive phase is FL-like*

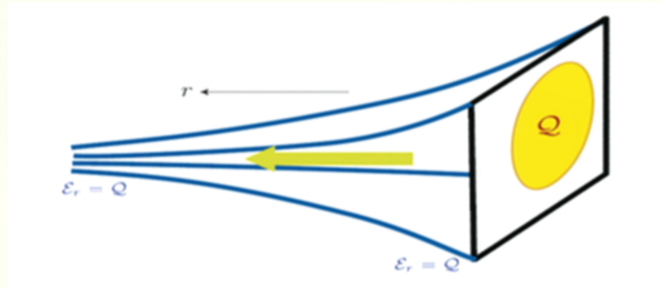


Hartnoll, Hofman, Vegh, JHEP 1108, 096 (2011);
Iqbal, Liu, Mezei, arXiv:1105.4621;
Sachdev, PRD 84, 066009 (2011)

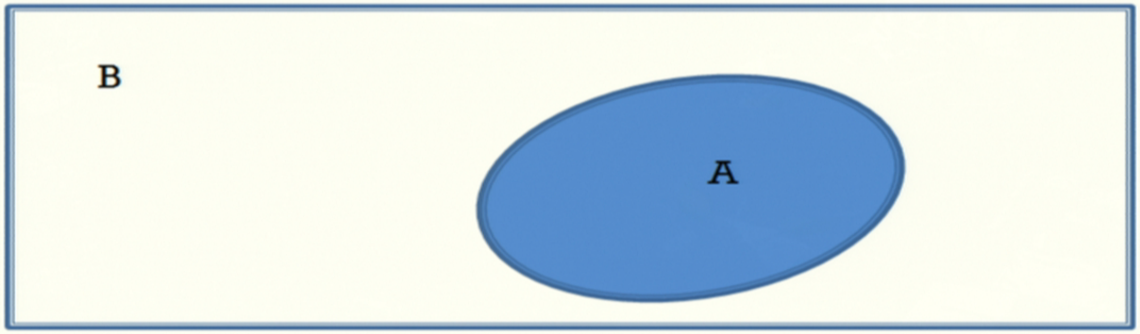
Fermi Surface?

- What about fractionalized phases?
- Is there a hidden Fermi surface?
- Holographic entanglement entropy provides indirect probe of the FS





Entanglement entropy



- $\rho_A = \mathrm{Tr}_B\, \rho$ =density matrix of region A
- Entanglement entropy:

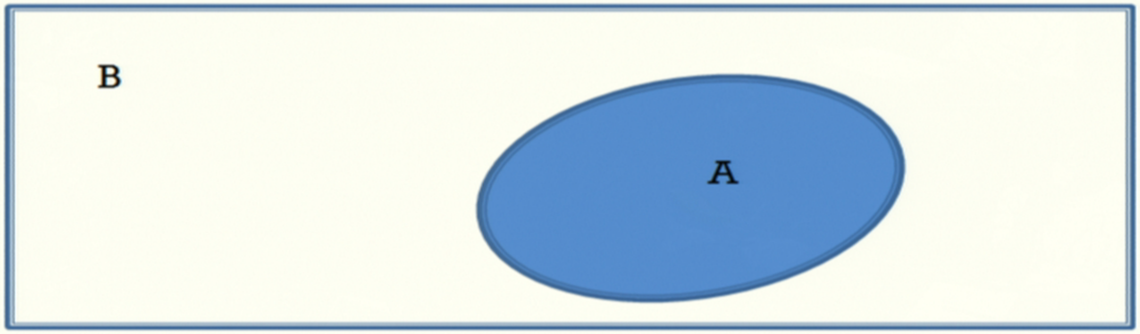
$$S_A = -\mathrm{Tr}(\rho_A \log \rho_A)$$

- Boundary law for gapped systems:

$$S_A \sim P$$

P is perimeter of region A

Entanglement entropy



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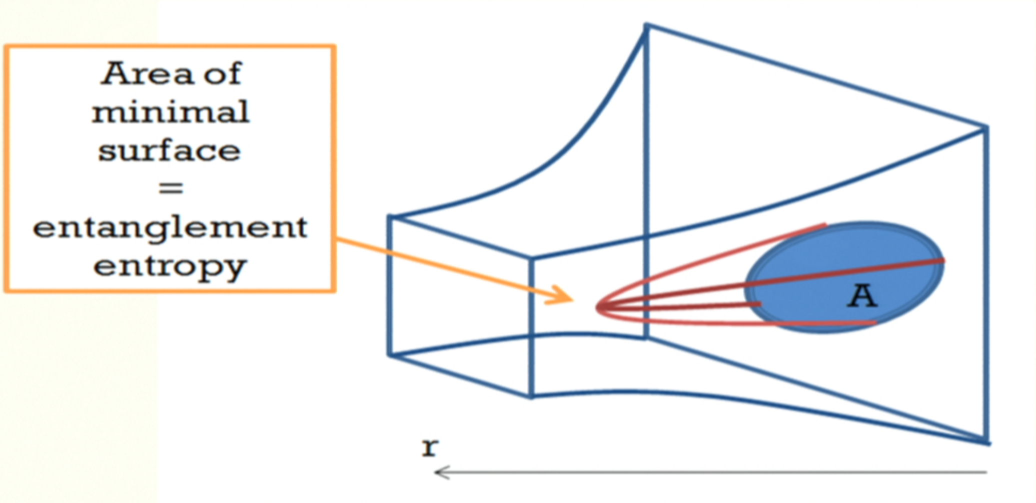
Holographic entanglement entropy



Ryu, Takayanagi, PRL 96, 18160 (2006)

Einstein-Maxwell-dilaton theory

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with $V(\Phi) = -V_0 e^{-\beta\Phi}$, $Z(\Phi) = Z_0 e^{\alpha\Phi}$

General solution for fractionalized phase:

$$ds^2 = \frac{1}{r^2}\left(- \frac{dt^2}{r^{2d(z-1)/(d-\theta)}} + r^{2\theta/(d-\theta)} dr^2 + dx_i^2 \right)$$

Scale trafo: $x_i \to \zeta x_i,\ t \to \zeta^z t,\ ds \to \zeta^{\theta/d} ds$

z dynamical critical exponent

θ hyperscaling violation exponent

θ and z depend on d, α and β

Ogawa,Takayanagi,Ugajin,arXiv:1111.1023;
LH,Sachdev,Swingle,PRB 85, 035121 (2012)

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θ and z depend on d, α and β

Ogawa, Takayanagi, Ugajin, arXiv:1111.1023;
LH, Sachdev, Swingle, PRB 85, 035121 (2012)

Log violation of area law

$$ds^2 = \frac{1}{r^2}\left(-\frac{dt^2}{r^{2d(z-1)/(d-\theta)}} + r^{2\theta/(d-\theta)}dr^2 + dx_i^2\right)$$

- For a specific choice of α and β, s.t. θ=d-1, we find log violation of area law (d=2): $S_A \sim \sqrt{Q}P\log[\sqrt{Q}P]$ with Q charge behind horizon
- Log violation of area law indicates hidden FS with $k_F \sim \sqrt{Q}$
- This matches precisely with Luttinger theorem (d=2): $Q \sim k_F^2$!

Ogawa,Takayanagi,Ugajin,arXiv:1111.1023;
LH,Sachdev,Swingle, PRB 85, 035121 (2012)

Inequalities

- Local QFT: at most log violation of entanglement entropy: $\theta \leq d-1$
- 'Null energy condition' yields for dynamical critical exponent: $z \geq 1+ \theta /d$
- NB for $d=2$ and $\theta=d-1$ we get $z \geq 3/2$
  $z=3/2$ is state of the art field theory result for NFL!

LH, Sachdev, Swingle, PRB 85, 035121 (2012)
M. A. Metlitski and S. Sachdev, Phys. Rev. B 82, 075127 (2010)

Synthesis

- We found different compressible phases via charge fractionalization
- Cohesive phase (all charge in bulk) is FL-like
- Fractionalized phases (some or all charge hidden) violate Luttinger theorem
- Holographic EE probe for hidden FS
- In certain Einstein-Maxwell-dilaton theories Luttinger theorem is restored via hidden FS
  - Partially fractionalized phase: hidden FS and FL-like FS ⟷ FL*
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Order parameters

- Confinement/deconfinement: Polyakov loop, Wilson loop, entanglement entropy
- Realizations in holography as surfaces in bulk
- Is there an order parameter for fractionalized/cohesive phases?
- Holographic proposal: flux through minimal surface
- Volume scaling in deconfined fractionalized phases and vanishing in confining cohesive phase

Hartnoll, Radičević, ArXiv:1205.5291

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Hidden FS continued

- Entanglement entropy in agreement with hidden Fermi surface
- BUT no low energy modes at finite momentum observed in spectral density of transverse current operator ...
- Probe Friedel oscillations via monopoles (1D)
- 1 large (~N) FS vs ~N small FSs
- Explore connection to dimensionally reduced pure gravity theories

Hartnoll, Shaghoulian, ArXiv:1203.4236
Iqbal, Faulkner, ArXiv:1207.4208
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More boundary law violations

- Einstein-Maxwell-Dilaton theories can exhibit boundary law violations up to volume scaling
- Extreme limit (volume scaling) in extremal Reissner-Nordström solution
- RN solution interpreted as extensive GS degeneracy
- What about intermediate violations?
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Conclusions

- Compressible phases in holography
- Phase diagram for Einstein-Maxwell-dilaton-fluid theory
- Lifshitz solution characterizes phase transition, 1^{st} order vs 2^{nd} order
- Cohesive, partially/fully fractionalized phases
- Similarities with FL, FL*, NFL
- Holographic entanglement entropy indirect probe for FS
- For certain dilaton theories we find hidden FS, consistent with Luttinger theorem
- Needed: more (direct) evidence for hidden FS, such as finite momentum operators…