Gauge-gravity duality and condensed matter physics

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Workshop on fluid-gravity correspondence
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Some review papers on applied AdS/CFT

MAGOO (1999)	older review of AdS/CFT (long)
Horowitz+Polchinski (2006)	newer review of AdS/CFT (short)
McGreevy (2009)	introduction to applied AdS/CFT
Hartnoll (2009)	quantum critical transport, superconductivity
Herzog (2009)	q.c. transport, superconductivity, superfluidity
Schäfer+Teaney (2009)	transport for QCD and cold atomic gases

Outline

1. Introduction
2. Quantum critical transport
3. BEC-BCS crossover
4. Other applications and things to do

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classical gravity	$\leftrightarrow$	quantum field theory
classical spacetime	$=$	state in field theory
e.g. black hole spacetime	$=$	thermal state in field theory

Gravity view

- Black holes have thermodynamics.
  Free energy = Euclidean on-shell action

  Bekenstein, Bardeen+Carter+Hawking (1973)
  Gibbons+Hawking (1977)

- Add different matter to gravity $\Rightarrow$ get all kinds of BH

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There are black holes

- whose free energy $F(T)$ mimics quantum critical points
- whose free energy $F(T)$ mimics the quark-gluon plasma
- whose free energy $F(T)$ shows superfluid phase transition

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short distance (lattice) physics	$\longleftarrow$	AdS/CFT probably not helpful
effective quantum field theory	$\longleftarrow$	AdS/CFT may be helpful

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AdS/CFT: models with different short-range interactions can have the same transport coefficients

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Why focus on transport?

- Thermodynamic properties in lattice spin models can be computed by MC simulations
- Static critical exponents can be computed by MC simulations or in ϵ-expansion

Focus on what's hard for numerical simulations

- Weak coupling, large N vector $\Rightarrow$ can use kinetic equation
- Strong coupling $+$ real time $+$ finite T $\Rightarrow$ need new tools

Example: 1+1 dimensional Ising model

$$H = -J \sum_i (\hat{\sigma}_i^z \hat{\sigma}_{i+1}^z + g\hat{\sigma}_i^x)$$

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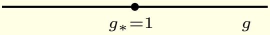

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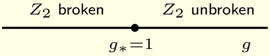

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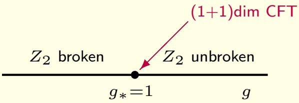

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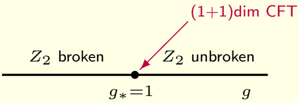

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What happens at non-zero temperature?

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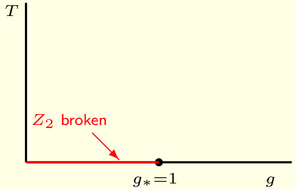

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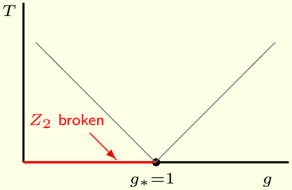

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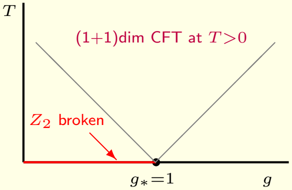

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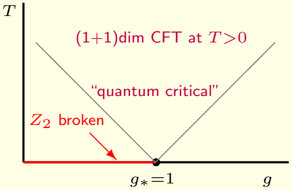

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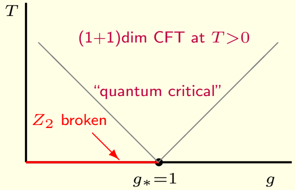

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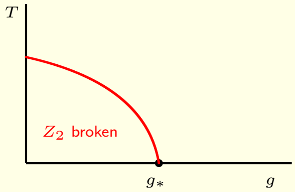

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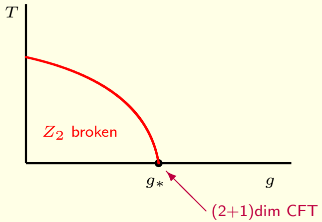

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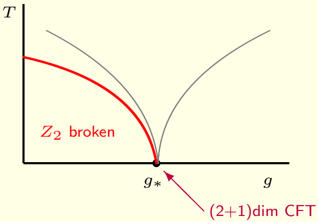

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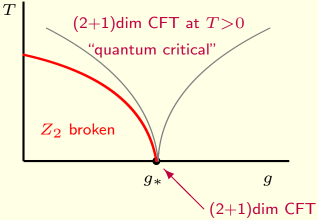

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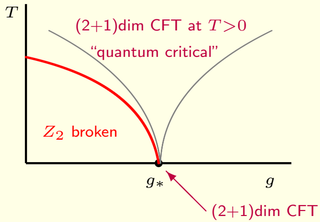

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See S.Sachdev's QPT book for more pictures like this

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E.g. in simplest AdS/CFT models

$$\frac{\sigma}{\chi} = \frac{1}{4\pi T}\frac{d+1}{d-1}$$

Kovtun+Ritz, Starinets (2008)

σ is d.c. conductivity
$\chi \equiv \partial n/\partial \mu$ is the static susceptibility

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Nature has:

- 1-st order transitions much more common
- In 3+1 dim, mean field is typical

Real world?

One can argue for relevance of QCP in

- Quantum Hall transitions E.g. Sondhi *et al* (1997)
- High-T_c cuprates E.g. Sachdev (2009)
- Heavy fermion materials E.g. Gegenwart+Si+Steglich (2007)
- Graphene E.g. Sheehy+Schmalian (2007)

Alternatively: Engineer QPT using cold atoms on optical lattices

Greiner *et al* (2002)

Wait and see

AdS/CFT approach

- Calculate first, think later:

  AdS/CFT likes strongly interacting CFT's
  so let's study transport phenomena in strongly interacting CFTs
  and hope to learn lessons about QC points in real materials

- Look for QCP:

  presumably there are infinitely more interacting CFTs in
  condensed matter physics than in high-energy physics

- Dimension is important:

  non-SUSY CFTs are hard to come by in 3+1 dimensions

Interesting dimension for QC transport is 2+1

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Fluctuations of Maxwell field in AdS_4-Schwarzschild $\Rightarrow$ response functions of conserved currents in (2+1)dim, $\mathcal{N} = 8$ super Yang-Mills CFT

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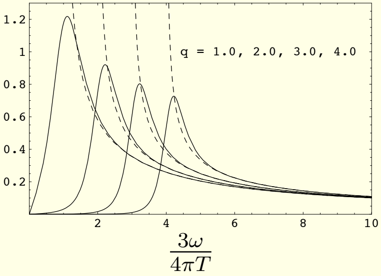

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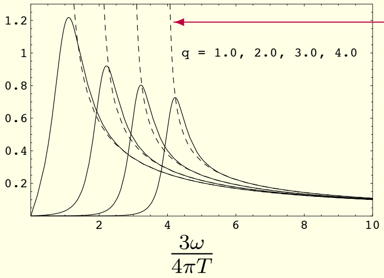

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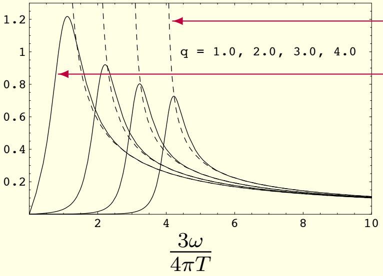

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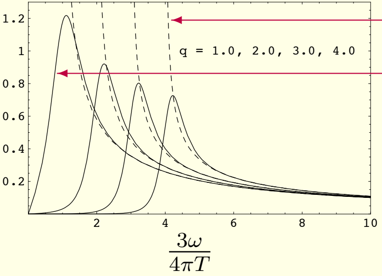

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Producing these curves at weak coupling is notoriously difficult

More of the same

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  Basu *et al* (2009)
- Do all of the above in different backgrounds; add probe branes; add defects; add higher-derivative corrections to gravity
  Mateos+Myers+Thomson (2006)
  Karch+O'Bannon, Brigante *et al.*,
  Myers+Thomson+Starinets,
  Erdmenger+Kaminski+Rust (2007)
  many more

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- In external magnetic field, linear response predicts cyclotron pole at $\omega_c = \frac{\rho B}{\epsilon + p}$ in hydro correlators. This is a new thermo-magnetic transport result, motivated by AdS/CFT. Also seen in gravity.
  Hartnoll+Kovtun+Muller+Sachdev (2007)
  Hartnoll+Herzog (2007)

Also related

- Non-linear electromagnetic response — Karch+O'Bannon (2007)
- Effects of impurities — Hartnoll+Herzog (2008); Fujita+Hikida+Ryu+Takayanagi (2008)
- Quantum corrections to gravity — Denef+Hartnoll+Sachdev (2009)

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$\underbrace{\text{new low-energy effective theories}}_{\text{direct connection to CM physics}}$

Outline

1. Introduction

2. Quantum critical transport

3. BEC-BCS crossover

4. Other applications and things to do

Many-body quantum mechanical system

- Cold fermionic neutral atoms in $d=3$ dimensions (^{6}Li, ^{40}K)
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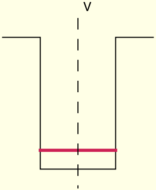

deep potential,

tightly bound states

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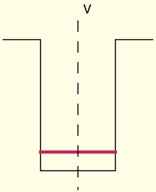

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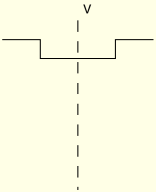

shallow potential,
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$n{\neq}0 \Rightarrow$ BCS

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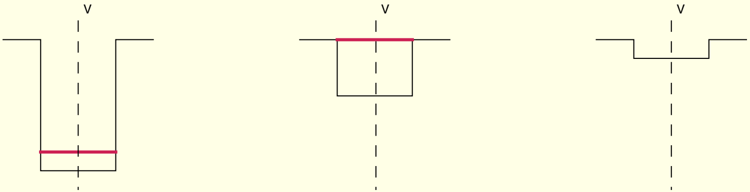
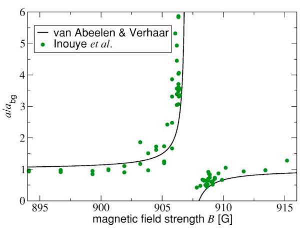


deep potential, tightly bound states	special point, $E_{b.s.}$=0	shallow potential, no bound states
$n\neq0 \Rightarrow$ BEC	$n\neq0 \Rightarrow$???	$n\neq0 \Rightarrow$ BCS

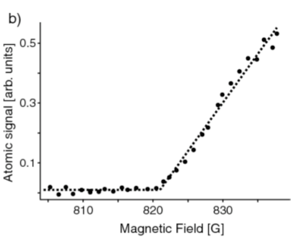
Can be done in the lab!

"Feshbach resonance": adjust interaction potential of two hyperfine states by tuning external magnetic field



a vs B in ^{23}Na (1998, BEC only)

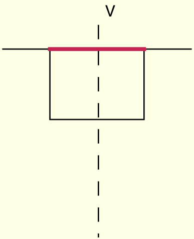
Figure from Köhler+Goral+Julienne (2006)



Feshbach resonance in ^{6}Li

Schunck *et al* (2004)

Resonance



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$E_{b.s.}\to 0 \;\Rightarrow\; a\to\infty$ (unitary limit)

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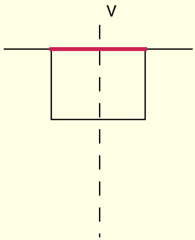

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strongly interacting quantum gas

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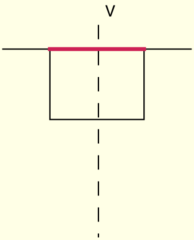

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strongly interacting quantum gas

- natural NR units: $\hbar = m = 1$
- short-range interactions: $r_0 \to 0$
- unitary limit: $a \to \infty$

$\therefore$ density n is the only scale

Comments

- Ground state energy

  free: $E/N = \frac{3}{5}E_F$ ($E_F \sim n^{2/3}$, Fermi energy in ideal gas)

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  $d \leqslant 2$ unitary limit $\Rightarrow$ non-interacting fermions

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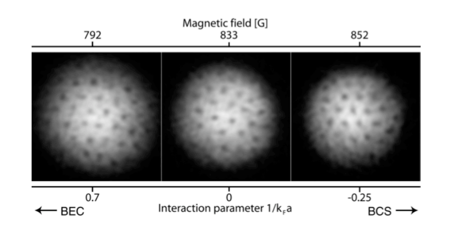
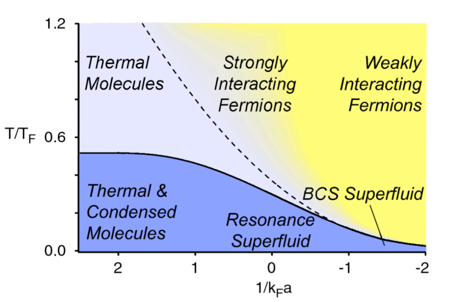
  Interesting dimension for BCS-BEC crossover is 3+1

Comments (cont.)

The system is a superfluid on both sides of the crossover



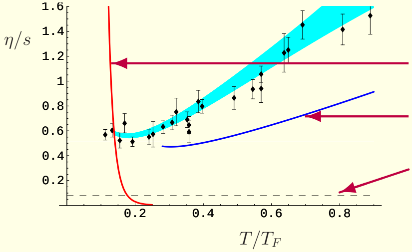
Zwierlein *et al* (2005)



Perali *et al* (2003)

Figure from Ketterle+Zwierlein (2008)

Comment on η/s



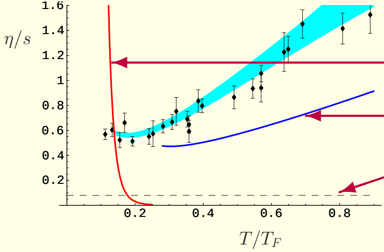
Low temperature, gas of phonons

High temperature, gas of atoms

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

Figure from Schäfer+Teaney (2009)

Comment on η/s



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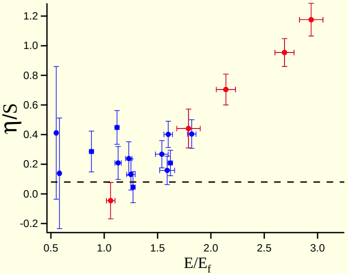

Figure from Thomas (2009)

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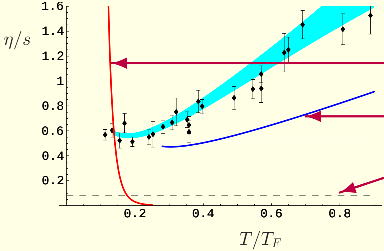

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Systematic uncertainties are hard to estimate!

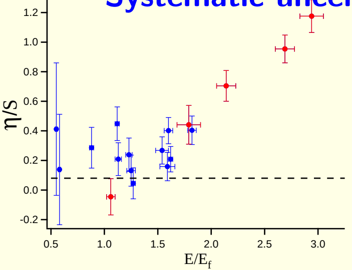

Figure from Thomas (2009)

Effective field theory

Short-range interactions ⇒ effective local NR QFT

$$\mathcal{L} = \sum_{a=1,2} \psi_a^\dagger \left(i\partial_t + \frac{\nabla^2}{2m} \right) \psi_a + u\, \psi_1^\dagger\, \psi_2^\dagger\, \psi_2\, \psi_1$$

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Expand around $d{=}2$ and $d{=}4$

Nishida+Son, Nikolic+Sachdev (2006)

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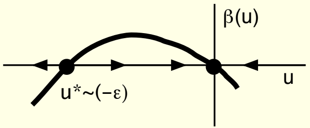
In $d = 2{+}\epsilon$ spatial dimensions, fermions are weakly interacting



Non-trivial UV fixed point

||

critical theory of unitary fermions

Effective field theory (cont.)

In $d = 4 - \epsilon$ spatial dimensions, bound states are weakly interacting

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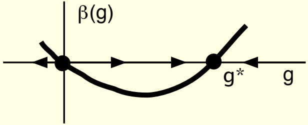

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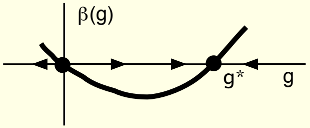

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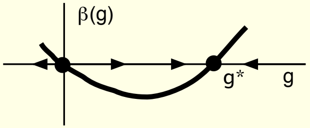

Non-trivial IR fixed point
||
critical theory of unitary fermions

∴ need Galilean scale-invariant QFT

Symmetry group is in fact larger (Schrödinger group) Mehen+Stewart+Wise (1999)

these are termed non-relativistic CFT or Schrödinger CFT

Nishida+Son (2007)

Where is "stuff"?

- Still need to add matter

$$\Delta\mathcal{L} = \mu(\psi_1^\dagger\psi_1 + \psi_2^\dagger\psi_2)$$

- This breaks conformal symmetry. E.o.s. at $\mu \neq 0$, $T \neq 0$:

$$2\epsilon = d\, p$$

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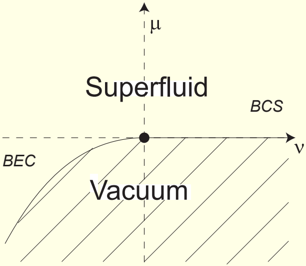

Phase diagram at $T{=}0$ (Nikolic+Sachdev, 2006)

$\nu = -1/a$

Phase boundary is $2\mu = E_{b.s.}$

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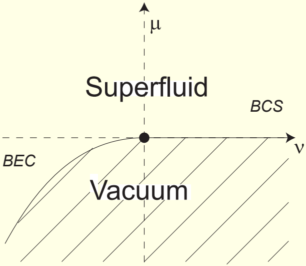

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$\therefore$ need Schrödinger CFT at non-zero μ

Apply AdS/CFT

Use gauge-string duality to study strongly interacting Schrödinger CFTs, and hope this will teach us something about BCS-BEC

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Q: Do we really need string theory to understand BCS-BEC?

A:
- Not unlike using AdS/CFT for quark-gluon plasma
- Look at problems which are hard for MC simulations
- May lead to new insights, keep exploring

Gauge-gravity duality

Symmetries of QFT are isometries of some spacetime

- Isometries of AdS_{d+2} give the algebra of relativistic CFT_{d+1}

$$\mathrm{AdS}_{d+2}: \quad ds^2_{d+2} = \frac{-dt^2 + d\mathbf{x}^2 + dz^2}{z^2}$$

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- Isometries of Schr_{d+3} give the algebra of non-relativistic CFT_{d+1}

Son, Balasubramanian+McGreevy (2008)

$$\mathrm{Schr}_{d+3}: \quad ds^2_{d+2} = -\frac{-dt^2}{z^4} + \frac{d\mathbf{x}^2 + dz^2 + 2\,dt\,d\xi}{z^2}$$

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$$\mathrm{Schr}_{d+3}: \quad ds^2_{d+2} = -\frac{-dt^2}{z^4} + \frac{d\mathbf{x}^2 + dz^2 + 2\,dt\,d\xi}{z^2}$$

One can obtain Schr_{d+3} in Einstein gravity with $\Lambda{<}0$ and massive A_μ

Vacuum state ($T=0$, $\mu=0$)

- Two-, three-, and four-point correlation functions of various operators computed in the vacuum
  Son (2008)
  Balasubramanian+McGreevy (2008)
  Volovich+Wen (2009)
  Fuertes+Moroz (2009)
  Akhavan+Alishahiha+Davody+Vahedi (2009)
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- Embedded in IIB supergravity for $d=2$ and $z=2$.
  Herzog+Rangamani+Ross
  Maldacena+Martelli+Tachikawa
  Adams,Balasubramanian+McGreevy (2008)

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- More vacuum supergravity solutions with Schrödinger symmetry for $d=2$, $z\geqslant 3/2$ and $d=1$, $z\geqslant 5/4$ Hartnoll+Yoshida (2008) Donos+Gauntlett (2009) Bobev+Kundu+Pilch (2009)

Thermal state

- BH solutions found and embedded in IIB supergravity ($d{=}2$, $z{=}2$). These correspond to Schrödinger CFT at $T{\neq}0$, $\mu{\neq}0$.
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  But: Kovtun+Nickel (2008)

$$\left(\frac{E}{N}\right)_{\text{gravity}} \sim n^{-2/7} T^{10/7}\,,$$

$$\left(\frac{E}{N}\right)_{\text{unitary fermions}} \sim n^{2/3}\left(1 + O(T^4)\right)$$

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  Adams,Balasubramanian+McGreevy (2008)
- Thermodynamics: BH give the right equation of state $2\epsilon = d\,p$. But: Kovtun+Nickel (2008)

$$\left(\frac{E}{N}\right)_{\text{gravity}} \sim n^{-2/7} T^{10/7} \,,$$

$$\left(\frac{E}{N}\right)_{\text{unitary fermions}} \sim n^{2/3} \left(1 + O(T^4)\right)$$

- This funny form of $E(n,T)$ can be obtained in free relativistic field theory compactified on a light-like circle Barbon+Fuertes (2009)

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Applied AdS/CFT is not yet at the stage of delivering useful results for cold atoms

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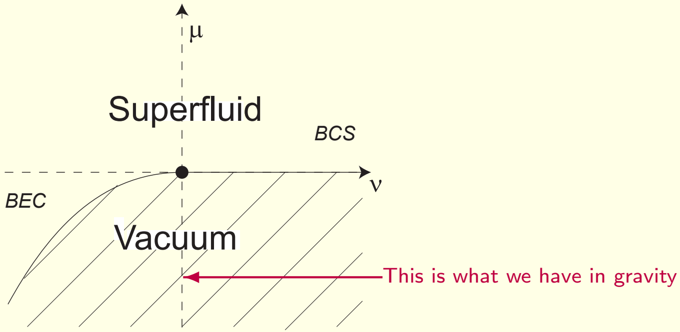

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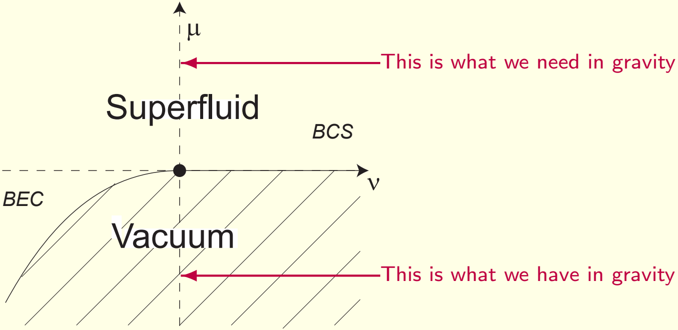

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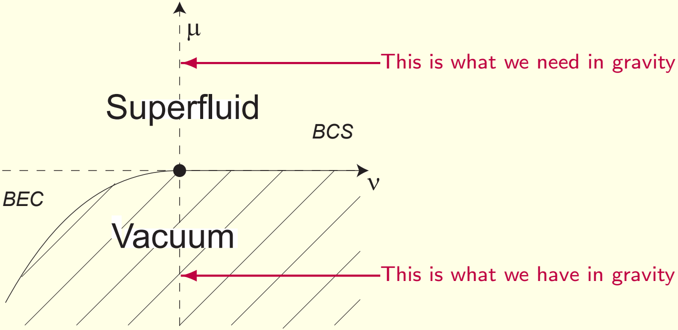

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I'd still like somebody to explain to me

- To what extent do these theories resemble anything in the real world (beyond symmetries)?
- What exactly is the quantum field theory which is dual to these Schrödinger BH? Can one do weak coupling calculations there?
- Can AdS/CFT be used to study Schrödinger CFTs which are not light cone reduction of relativistic CFTs?

Outline

1. Introduction

2. Quantum critical transport

3. BEC-BCS crossover

4. Other applications and things to do

Other AdS/CFT constructions

- Fluid-gravity correspondence
  Bhattacharyya+Hubeny+Minwalla+Rangamani
  Erdmenger+Haack+Kaminski+Yarom,
  Banerjee *et al.* (2008), Hansen+Kraus (2009)
  This workshop!
- Holographic superconductors/superfluids
  Gubser, Hartnoll+Herzog+Horowitz (2008)
  many more
- Lifshitz fixed points in gravity
  Kachru+Liu+Mulligan (2008)
  Li+Nishioka+Takayanagi (2009)
- Fermionic degrees of freedom
  Lee (2008), Policastro (2008),
  Liu+McGreevy+Vegh (2009)
  Cubrovic+Schalm+Zaanen (2009)
  Basu *et al* (2009)
- Quantum Hall effect
  Davis+Kraus+Shah (2008)
- Entanglement entropy
  Nishioka+Ryu+Takayanagi (2009)

Two examples to keep in mind

Some offsprings of applied AdS/CFT have a life of their own:

Low-frequency magneto-transport

- Apply relativistic hydro in magnetic field to QC transport
- Cyclotron singularity at $\omega_c = \frac{\rho B}{\epsilon + p}$
- Measurable in graphene!

Hartnoll+Kovtun+Muller+Sachdev (2007)
Hartnoll+Herzog (2007)
Muller+Sachdev (2008)

Holographic corrections to Landau-Lifshitz

- Use AdS/CFT to derive relativistic hydro equations
- Find a new dissipative term missed in classic derivations

Erdmenger+Haack+Kaminski+Yarom,
Banerjee *et al.* (2008)
Son+Surowka (2009)

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Let's keep exploring!

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THANK YOU