Gravity and Condensed Matter Physics: Beginnings Of A Dialogue ?

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Outline

1. Some Reminiscences
2. Introduction
3. Some Examples Of Connections
4. Conclusions

Reminiscences

John was my thesis advisor (1985-90) and then my post-doc mentor (1992-94).

The years I spent at Caltech were some of the most formative in my life and have shaped me in very important ways not only as a physicist but also as a human being.

It is therefore an especial privilege and honor for me to participate in these celebrations.

Reminiscences

I arrived at a wonderful time at Caltech.

Anomaly cancellation had just been discovered and John Schwarz was all excited. And Caltech has just hired two young professors, John Preskill and Mark Wise.

Reminiscences

I soon came under the spell of John and Mark. Both great physicists of course, but also wonderful human beings.

Gentle, and compassionate and always willing to hear the student out.

Some others might not have needed this, but for a student like me, in a strange land, all tongue tied, it made all the difference.

Reminiscences

It was only much later, when I had been in the field for some time, that I realized how truly special these qualities are amongsts scientists like us!

Reminiscences

John was offering a course, Advanced Quantum Field Theory (Physics 230) , that year and I decided to take it. I was keen to impress him in the hope that he would take me on as a student.

Soon a problem surfaced though. John was a great lecturer but the course was extremely demanding and I found myself struggling.

Reminiscences

One of the great things about Caltech grad. School was that you could pretty much do whatever you liked. So one by one I dropped all the other courses. But still could not keep up. I was really struggling.

Reminiscences

Attempts to ask intelligent question did not meet with much success. John’s famous ``W” smile did not help.

This smile was well known to all his students and was endlessly analysed. What did the ``W” mean – that he approved or disapproved? Had anyone seen the inverse ``W”?.

The smile added to my worry.

Reminiscences

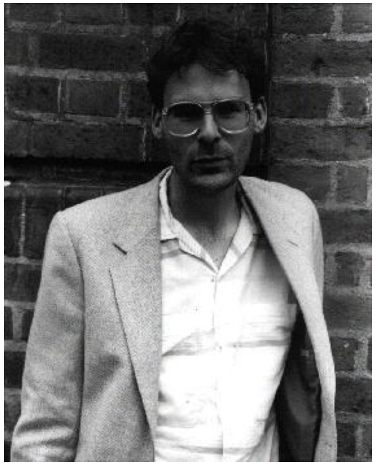
Time has not dulled, nor age diminished …

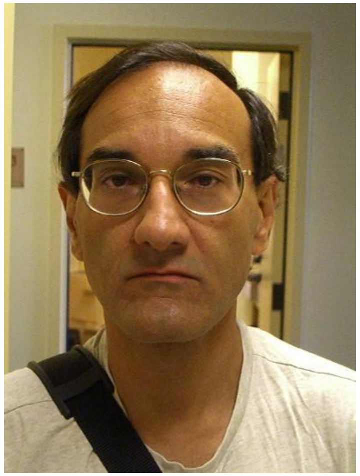
Reminiscences

On a really good day …

Reminiscenses

[Brian Warr had the most detailed critique of the ``W'' smile. Alexios Polychronakos once claimed he had seen the ``inverse W''.
To our question as to whether John was happier or more upset Alexi had only maintained a sphinx like silence, however.]





Reminiscences

My worries began to take a toll and I found I had developed a nervous tick in my eye.

Soon I found myself in the clinic of an eye doctor – one Dr. Kislinger.

We sat across a table while he peered into my retina and questioned me. I told him I was a grad. student at Caltech. ``What subject?" Particle Physics" I answered thinking the matter would end there. But it did not.

Reminiscenses

``Theory or Experiment ?''Kislinger asked.

This seemed like an unusually well informed doctor so I played along.

``What courses are you taking ?'' he continued.

``Only one, QFT taught by Professor Preskill'', I said.

Reminiscenses

``What! John is at Caltech now ?" the doctor asked.

By now I was seriously worried that the nervous attack had spread to my brain.

``I know they had Politzer, when did John move from Harvard? Who else do they have?"

Reminiscences

We continued in this vein for sometime.

After the exam Kislinger concluded:

``There's nothing the matter with your eyes. I know Preskill well. He teaches a very demanding course. That's your problem. As your doctor, I recommend that you drop it!".

Reminiscences

Seeing me dumbfounded the doctor finally decided to enlighten me.

``I was a particle physicist at Chicago but did not get tenure. So became an ophthalmologist. ''

His confession broke the tension and we both burst out laughing.

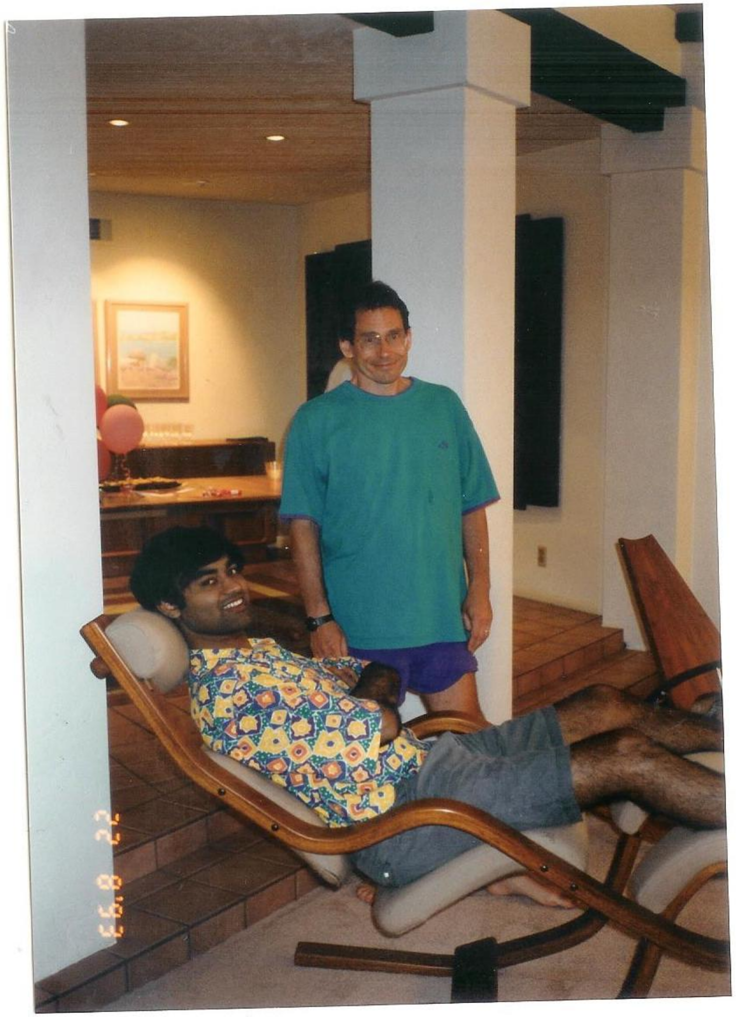
Reminiscences

Somehow things began to work out and I did get into John's good books at least to the extent of his taking me on as a student.

The years that followed in grad. school were amongsts some of the happiest in my life.

The wonderful poolside parties that John and Roberta hosted helped.

Reminiscences



Reminiscences

John was not a very hands on advisor.

At the same time he was always happy to discuss physics with his students.

This combination really worked for many of us.

He was immensely popular, with 6-8 students at any time!

Reminiscences

Reminiscences

Reminiscences

John’s sense of humor was understated.

It took awhile to catch onto …

Reminiscences

John overheard me the day before my candidacy wondering aloud to a fellow student whether I might be packing my bags at this time the next day to return home.

He walked by, flashed his W smile, and said nothing.

The next day after the exam emerging from the deliberations he was brief ``Those bags. I'd hold off on packing them!".

Reminiscences

Most of all, it was John's broad interests, then ranging from Particle Physics to Cosmology and Aspects of String Theory, and his willingness to always discuss and explain that made all the difference.

Lunch in Chandler could easily last two hours. And then one could formally meet John in the office. In fact the discussions would often continue in the corridors, on walks and even in the rest room.

Reminiscences

One day John and I were engaged in a discussion about beta functions in the restroom. I think it was about scheme dependence at higher orders in perturbation theory. A rather abstruse topic. At some point in the discussion Gell-Mann entered the rest room and headed for one of the stalls.

Reminiscences

Several minutes later when he reappeared we were still there.

Shaking his head Gell- Mann exited saying ``Remember, I was the one who first figured it out and even then it took me less time!”.

Introduction

In 1989 John taught a course on quantum field theory in curved space. Kip also attended. The atmosphere was electrifying.

Many of us learnt about the information puzzle during the discussions.

Introduction

Some time during the next few months, John came to my office on day and said, ``We should look at extremal Reissner Nordstrom black holes. The information puzzle can be stated very sharply in that context.

The comment was much ahead of its times.

Introduction

John, with Sidney Coleman and Frank Wilczek, explored the idea of whether additional quantum hair could be a way out of the information puzzle.

We built two-dimensional models and studied the entanglement entropy grow as a black hole evaporates.

Fiola, Preskill, Strominger, SPT

Introduction

The two dimensional models were introduced by Callan, Giddings, Harvey and Strominger.

Also developed by Russo, Susskind, Thorlacius.

Introduction

Although, the title of my talk is different.
Many of these ideas,
Extremal black holes, Hair and entanglement will play an important role in it.

Gravity and Condensed Matter Physics:
Beginnings Of A Dialogue

Introduction

Why should gravity and string theory have anything to do with condensed matter physics ?

String Theory: High energy
Condensed matter physics: low energy

Introduction

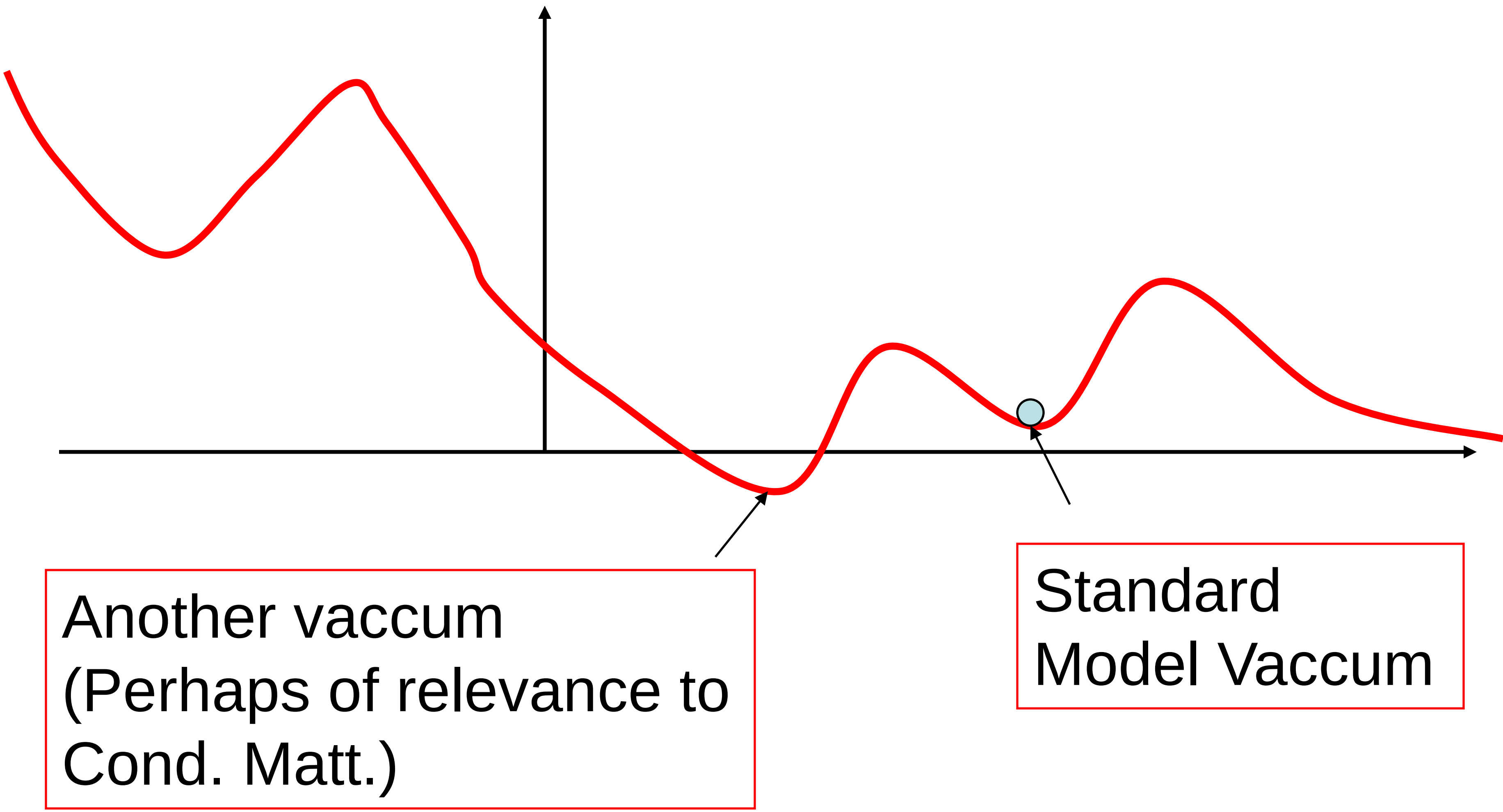
Few different ways to explain this.

1) Landscape : String Theory a general framework.

Hopefully Includes the completion of the standard model.

And Much more.

Landscape


Another vaccum
(Perhaps of relevance to
Cond. Matt.)
Standard
Model Vaccum

Connection Between Gravity and Cond. Matt. Physics

2) AdS/CFT correspondence

- Gravity (String Theory) In Anti deSitter space (d+1 dimensions) ↔ Dual or Equivalent Field Theory (d dimensions)

- Weak ↔ Strong

Introduction

Dual Nature of Correspondence

Makes gravity a useful ``tool" for the study of strong coupled field theories some of which might be relevant in the study of condensed matter physics.

Introduction

Dual Nature of Correspondence

Means that intuition acquired from the study of field theories in various branches of physics can be put to use for the study of gravity.

AdS/CFT Correspondence

A Theory Of Gravity in d+1 Dimensional Anti-deSitter Space	$\simeq$	Conformal Field Theory in d dimensions

AdS/CFT

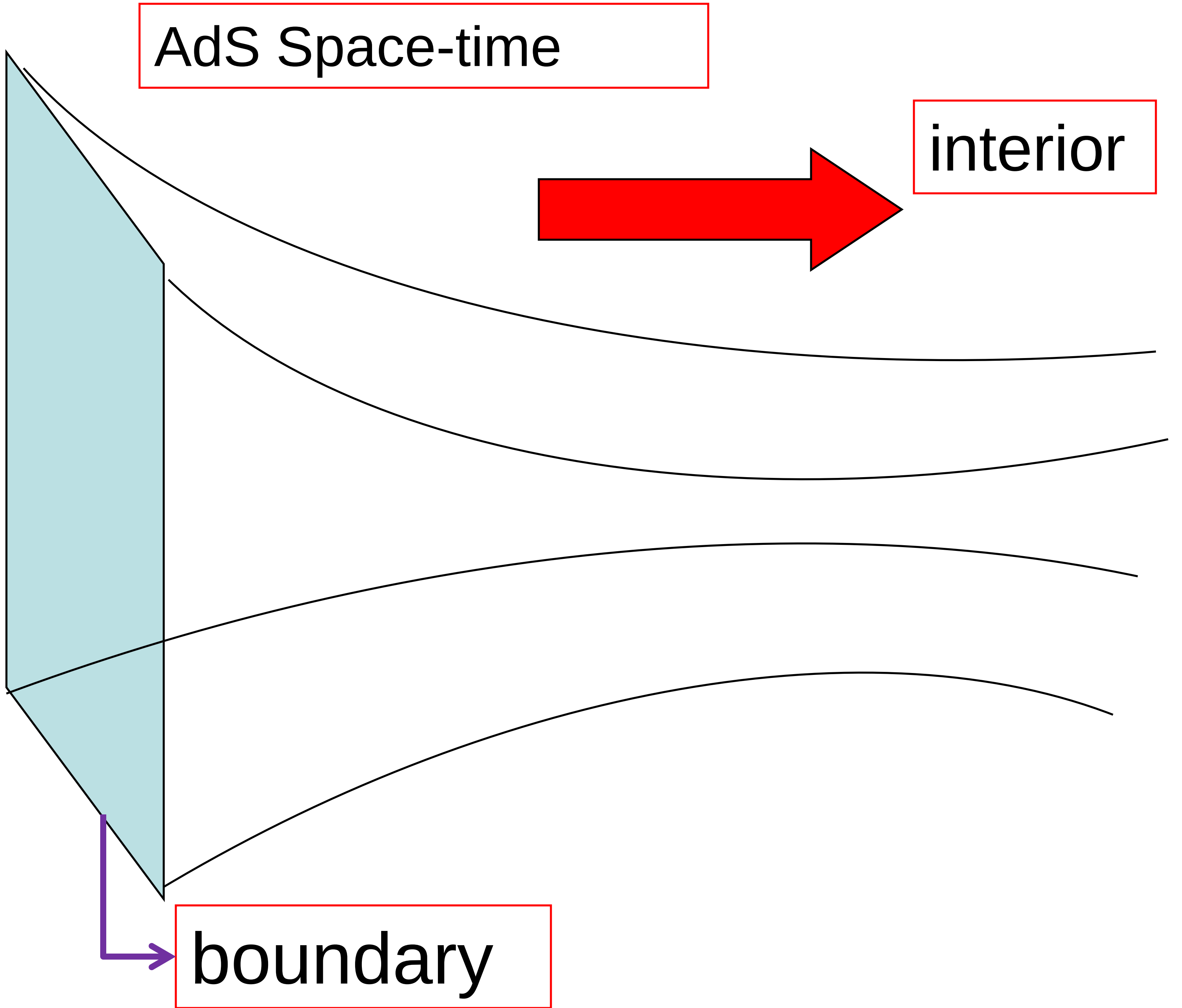
Can be extended so that

Gravity in Asymptotically AdS space	↔	Field Theory Scale invariant in UV
Deep Interior	↔	Infra Red (Low energy)

AdS/CFT Correspondence

The field theory can be roughly thought of as living on the boundary of AdS space.

It is a ``Hologram''.



AdS Space-time
interior
boundary

Introduction

- Anti deSitter Space AdS_{d+1}

$$ds^2 = (\frac{r^2}{R^2})(-dt^2 + \sum_{i=1}^{d-1} dx_i^2) + (\frac{R^2}{r^2})(dr^2)$$

- Characterised by one single parameter:

R: Radius of AdS space.

Introduction

A signal can reach the boundary, $r \to \infty$, and bounce back to the interior in finite time Δt .

AdS space is therefore like a finite box.

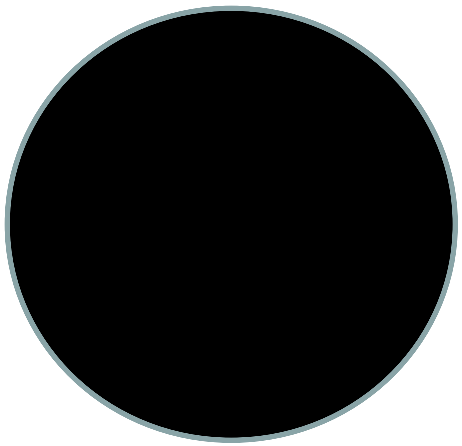
The boundary theory lives on the boundary of this box.

Introduction

AdS		CFT
Gravity	⟷	No Gravity
Black Hole/ Black Brane	⟷	Finite temperature

Introduction

Black Hole: Point Like



Introduction

Black Brane: Extended Domain Wall

Examples/Progress

We will consider two examples in this talk to illustrate how intuition from field theory/Condensed Matter Physics is furthering our understanding of gravity and vice versa.

Examples/Progress

Example 1)

On Cond. Matt. side: Many phases of nature.

On gravity side: No hair Theorems.

Black Holes/ Branes have no hair because of the intense pull of gravity on the horizon.

Examples/Progress

These two statements are in ``tension”. The different phases should correspond to different kinds of black branes.

Perhaps something is wrong with the no-hair lore on the gravity side?

Examples/Progress

Indeed this is what has been found.

Guided by the expectations from field theory many new kinds of black brane solutions have been found.

New Brane Solutions in Gravity

In the examples here we will mostly discuss zero temperature phases. The corresponding black branes are called Extremal Black Branes.

An interesting phase structure at zero temperature can emerge by varying the chemical potentials for other conserved charges (besides energy).

New Brane solutions

Example 1)

Holographic Superconductor (Gubser, Hartnoll, Herzog, Horowitz …)

Gravity	↔	Field Theory
Gauge Symmetry	↔	Global Symmetry
Broken Gauge Symmetry?	↔	Broken Global Sym

Example 1): Holographic superconductor

Natural way to try and break the gauge symmetry is to introduce a charged scalar (the Higgs) in the bulk.

However no hair theorems would suggest that the charged scalar would fall into the black brane and thus not be supported outside.

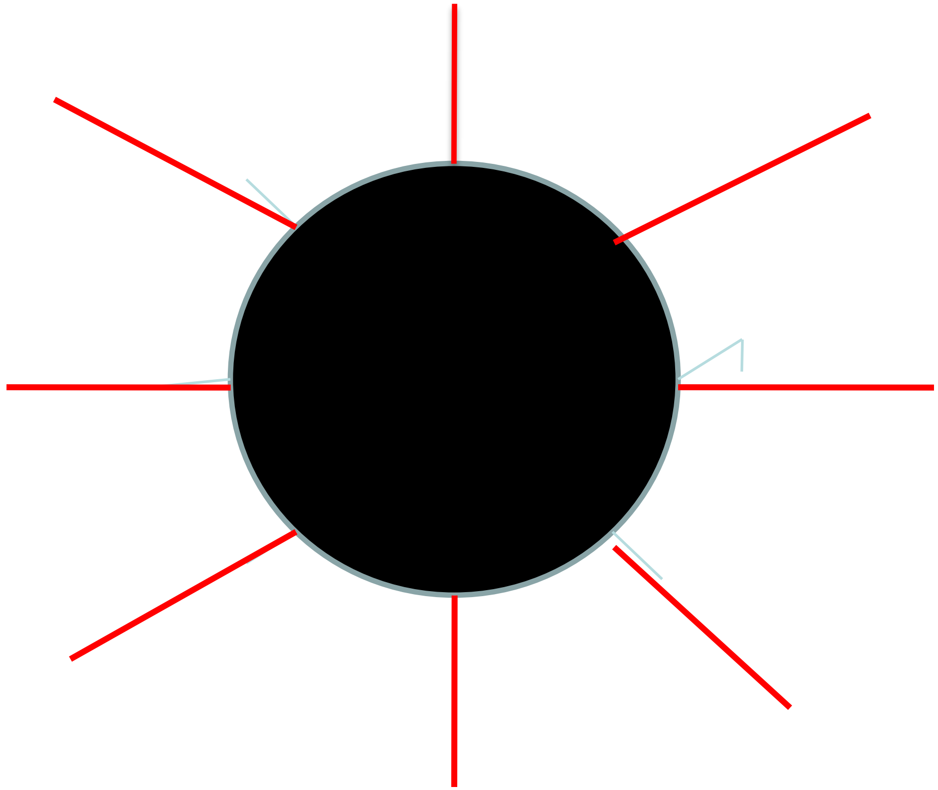
Example 1):

The No-Hair Theorems turn out to be not valid in asymptotically AdS space.

In an appropriate range of parameter space one gets new hairy black brane /hole solutions which break the gauge symmetry.

Introduction

Black Hole With Charged Scalar Hair



Holographic Superconductor

This happens in AdS space because it is like a box.

In flat space if one tries to evade the no-hair theorems by increasing the charge of the scalar field, there is dielectric break down of the vacuum near the horizon. Charged scalar particles escape to infinity allowing the black hole to sheds the scalar hair.

Holographic Superconductors

But AdS space is like a box.

The charged particles cannot escape and must return.

So that the eventual time independent solution is one with charged scalar hair.

New Brane Solutions

This kind of thinking can be extended to find many new kinds of brane solutions in AdS gravity.

After all there many many different kinds of phases seen in nature.

New Brane Solutions

For example: Brane solutions have been found for which the near-horizon geometry is Homogeneous but anisotropic (breaks rotational invariance).

They correspond to homogeneous phases of matter which break rotational invariance.

Iizuka, Kachru, Kundu, Narayan, Sircar, S. P. T, Wang

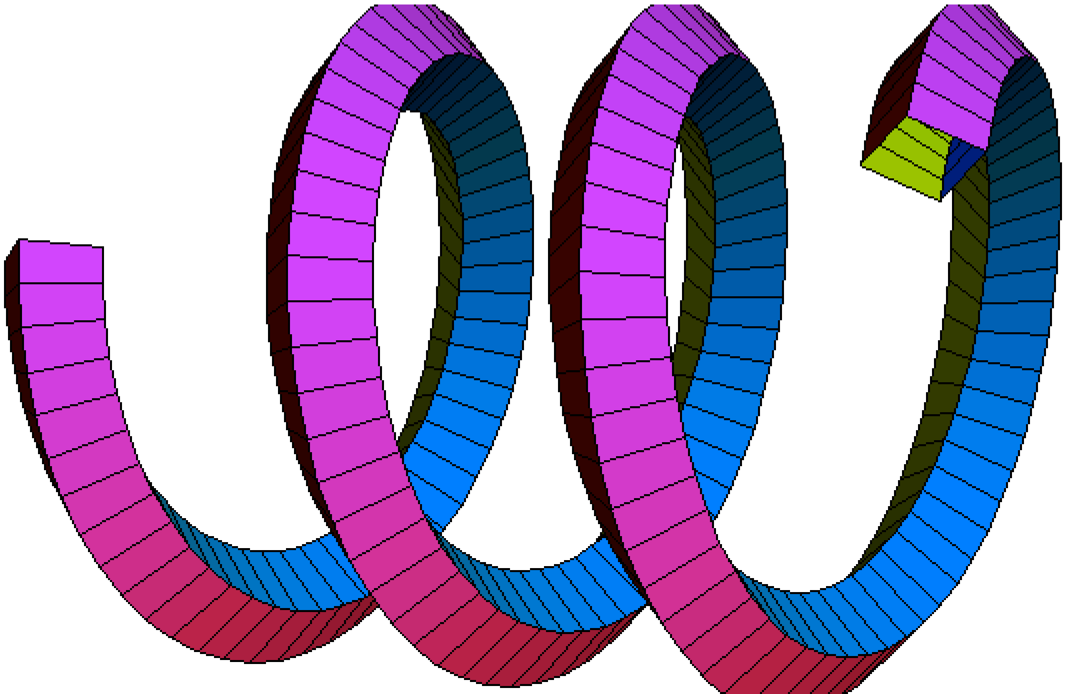
New Brane Solutions

In fact all such solutions, and corresponding phases of matter, can be classified using the Bianchi classification, first developed in cosmology.

New Brane Solutions

Example: Spin density wave phase

Domokos, Harvey; Nakamura, Ooguri, Park; Donos, Gauntlett



New Compressible Phases From Gravity

with: Goldstein, Iizuka, Kachru, Kundu, Narayan, Prakash, Sircar, Westphal

New Compressible Phases From Gravity

Consider field theory system with an global U(1) symmetry
(Think of this as Fermion number).

We will be interested in phases where this symmetry in not broken.

New Compressible Phases From Gravity

An important property is compressibility:

$$\frac{\partial n}{\partial \mu} \neq 0$$

n: charge density

μ: chemical potential

New Compressible Phases From Gravity

Essentially only one phase is known in condensed matter physics which is compressible with the global symmetry being unbroken:

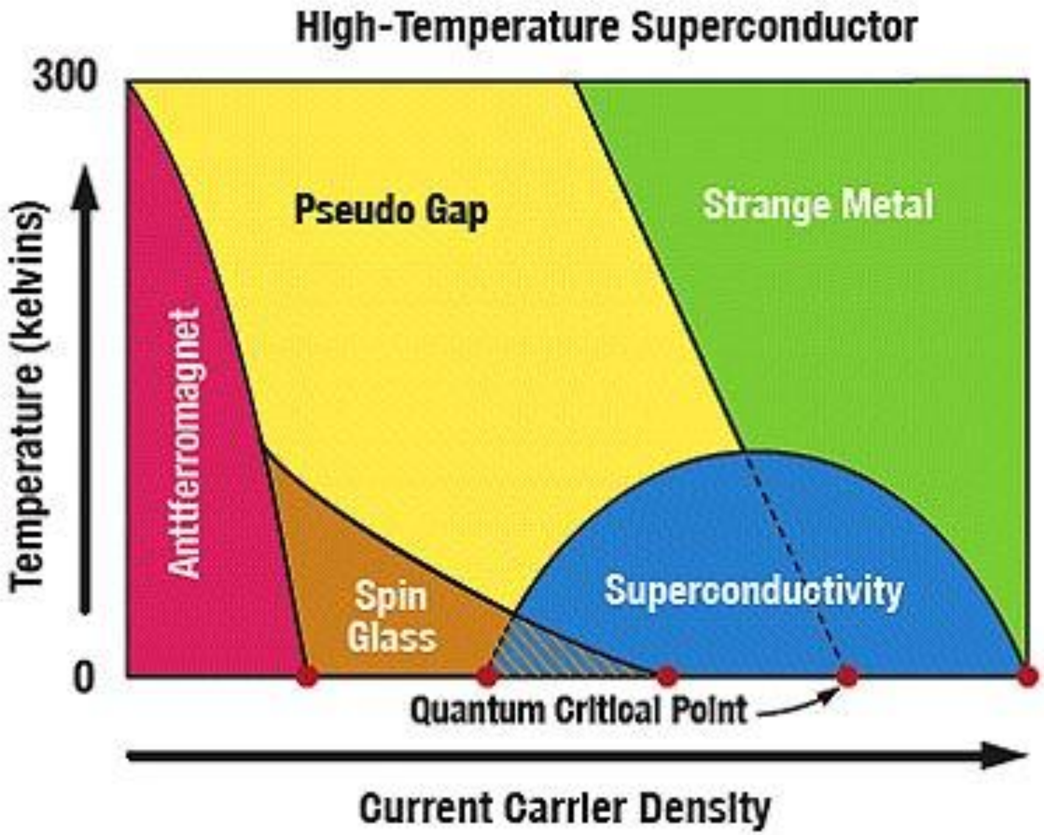
Fermi liquid.

(Subir Sachdev)

New Compressible Phases From Gravity

It is important to explore theoretically if other phases of this type are possible.

Some of these could perhaps help in understanding the High Tc materials for example which are well known to exhibit non-Fermi liquid behaviour.


High-Temperature Superconductor
300
0
Temperature (kelvins)
Pseudo Gap
Strange Metal
Antiferromagnet
Spin
Glass
Superconductivity
Quantum Critical Point
Current Carrier Density

New Compressible Phases From Gravity

It turns out that in gravitational systems many such compressible phases can arise quite easily!

NewCompressible Phases From Gravity

Here we will work in 3+1 dimensions in the gravity description.

The field theory will be in 2+1 dimensions.

New Compressible Phases From Gravity

The simplest example is the extremal Reissner Nordstrom Brane. This is a ``unphysical'' though due to the large entropy at zero temperature.

$$S = \int d^4x \sqrt{-g}[R - \Lambda + \frac{1}{e^2} F^2]$$

New Compressible phases

- Interesting but too exotic!
- Compressible: $n \propto \mu^2$
- Entropy density: $s \propto \mu^2$
- Possibly unstable.

Einstein-Dilaton-Maxwell System

Instead let us consider a system with an additional neutral scalar, the dilaton.

$$S = \int d^4x \sqrt{-g}[R - \Lambda - e^{2\alpha\phi}F^2 - \frac{1}{2}(\partial\phi)^2]$$

α: an important parameter

Rocha, Gubser; Goldstein, Kachru, Prakash, SPT

Dilatonic Extremal Branes

Intuition: For fixed charge the stress energy of the Maxwell field can change as the dilaton changes.

If the dilaton ``runs off'' to $\pm\infty$ the gauge coupling could go to zero and the gravitational radius could vanish.

Leading to zero entropy.

Dilatonic Extremal Branes

Indeed this turns out to be true.

Dilatonic Extremal Brane

Compressible: $n \propto \mu^2$

Specific heat: $C_v \sim T^p, p \neq 1$

Not Fermi liquid.

Dilatonic Extremal Branes

This system was generalised by Charmosis, Goteraux, Kim, Kiritsis, Mayer

The fields are the same but the couplings are more general with more parameters.

Dilatonic Branes

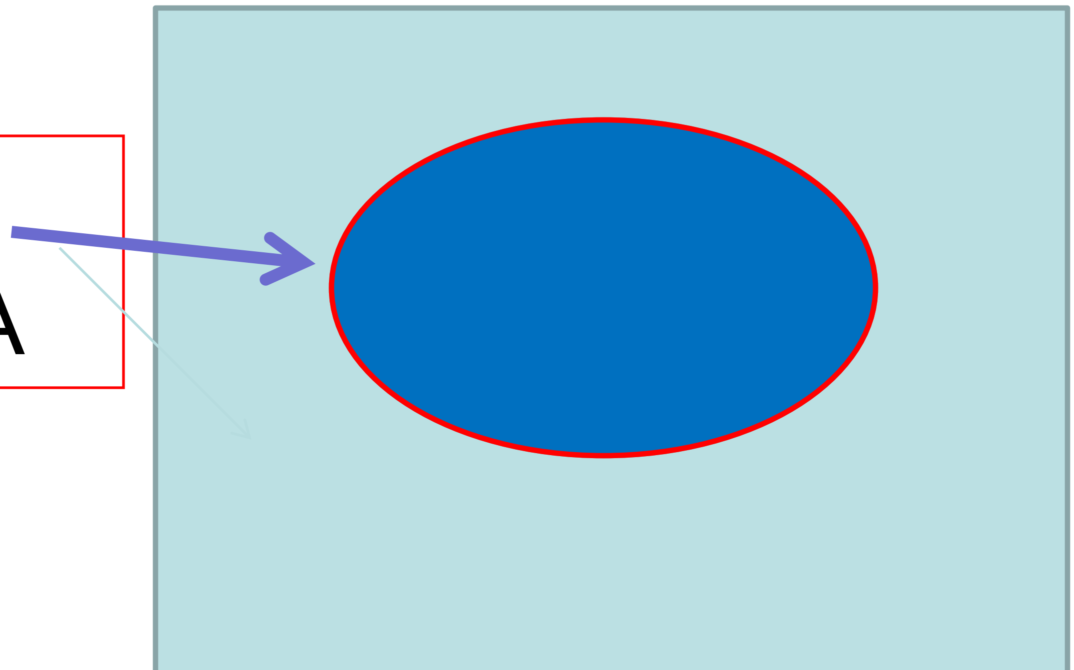
Key question: Is there a Fermi surface?

Key insight: Ogawa, Takyanagi, Ugajin

Dilatonic Branes

Key Insight: Use Entanglement

Boundary has area A



Entanglement

Fermi surface:

$$S_{EE} \sim A \log(A)$$

This same behaviour arises for some range of parameters in the Einstein-Dilaton-Maxwell system.

Dilatonic Branes

Specific heat can be understood in terms of gapless excitations which disperse with a dynamic exponent z.

Huijse, Sachdev, Swingle

Conclusions: Compressible Phases

These developments raise the tantalising possibility that some of the compressible phases found in gravity could describe non-Fermi liquids.

Perhaps some of these phases might even be of relevance in nature, although it is too early to tell.

Conclusions Of The Talk

- It is too early to tell whether a definite and useful connection between the study of gravity and condensed matter physics will be established.

- Some of the initial developments do hold promise and are exciting.

Conclusions Of The Talk

Such a connection would be a wonderful birthday present for John!

Who has always emphasised that the great ideas of physics are all connected and tied together.

Conclusions Of The Talk

In fact this thought has been very much a part of the ethos at Caltech.

As Feynman put it, ``Nature uses only the longest threads to weave her patterns, so that each small piece of her fabric reveals the organization of the entire tapestry.''

Dilatonic Branes

There are string embeddings.

K. Narayan; H. Singh;
Narayan, Takaynagi, SPT