

EMERGENT PHENOMENA IN CONDENSED MATTER AND PARTICLE PHYSICS

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A sharp way to ask my question is this:

Could condensed matter physics help
in understanding quantum gravity?

There are a lot of reasons to think that
the answer would be “no.”

In many ways, condensed matter physics and particle physics are about as far apart as two areas of physics could be.

The energy scales are completely different, for one thing.

The experimental methods are completely different.

And so, regrettably, are the time scales!

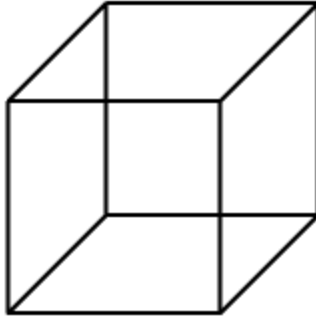
And the questions of interest are completely different – or at least, so it seems at first sight.

Nevertheless, many distinguished condensed matter physicists have thought about gravity, so obviously the question with which I began has some merit.

In fact, there is a close analogy between the two fields, as a result of which they have many tools and ideas in common:

- The Renormalization Group
- Spontaneous Symmetry Breaking
- Dimensional Transmutation

The origin of this analogy is easy to state:



Inside the box are some local, quantum mechanical degrees of freedom – whose large scale behavior we want to study

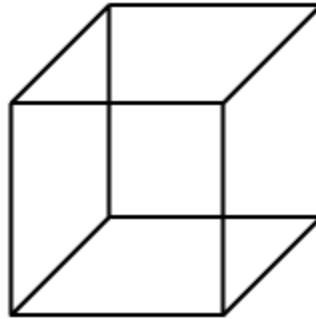
Their precise nature may not be important at much larger distances – be they spins, electrons, relativistic fields, or whatever.

The output does not depend too much on exactly what is inside the box.

This leads to the concept of “emergent phenomena,” which is a central idea in condensed matter physics, and also important in particle physics.

This talk will really have three parts.

First I'll describe in more detail the traditional analogy between condensed matter and particle physics



Then I will explain how this traditional analogy fails in the presence of gravity.

And finally, in the last part of the talk I will describe a modern version that does work in the presence of gravity -- and leads to the question with which I began.

Part I:

The Traditional Analogy
and how Physicists Came To Appreciate It

In the early days of the modern – i.e., quantum mechanical – study of solids, the focus was on quantitative calculations starting from the many body Schrodinger equation ... via Hartree approximations, band structure, and all that.

The modern focus, however, is less on quantitative solution of the Schrodinger equation and more on qualitative phenomena that emerge macroscopically through cooperative behavior and the magic of the renormalization group.

These are the “emergent phenomena” that are responsible for the richness of condensed matter physics....

Some, like hydrodynamics, long predate the modern era, while many, like the quantum Hall effect, are modern discoveries

Apart from the simple fact that condensed matter is a large part of the real world, the interest in condensed matter physics comes largely from the fact that such an incredible variety of intricate phenomena emerge from simple microscopic equations.

Meanwhile... what about particle physics?

Relativistic quantum field theory began by literally quantizing what we see – in the case of the electromagnetic field.

To include electrons took more guesswork – the Dirac equation for an anticommuting electron field, the filled Dirac sea, antimatter

Perturbation theory was hard to understand – one had to deal with renormalization – but once this was done, perturbation theory was entirely adequate, since $e^2/\hbar c$ is so small ...

Physical observables could be computed to astonishing accuracy

Though one could make an analogy between QED and condensed matter, and some people did, the analogy did not seem to go far as the problems arising in the two fields were so different.

In QED, even when it came to the dramatic and qualitatively new prediction of “antimatter,” the reasoning was formal...

in sharp contrast to the type of leap involved in “emergent phenomena”

In the case of the $SU(2) \times U(1)$ electroweak theory, the model could not be constructed by literally quantizing what one could see because, among other things, the W and Z bosons had not yet been discovered.

But once constructed, did it exhibit “emergent phenomena”?

This is one of the big unknowns – hopefully destined to be cleared up at Fermilab or the LHC....

In the original and still standard form of the model, the answer is taken to be “no” – all fields are weakly coupled and the observed phenomena are direct reflections of the underlying fields.

Moreover, this seems to be in good accord with the experimental evidence so far, which appears to favor a light and elementary Higgs boson.

However, the central phenomenon of the model is “gauge symmetry breaking”...

And this is highly suggestive of a dynamical mechanism such as occurs in superconductors.

So the question remains open, even though the original form of the model has held up so well.

Where particle physicists really learned about strong coupling and emergent phenomena was of course in grappling with **QCD**, the theory of strong interactions

Short distances – quarks and gluons

Long distances – a completely different cast of characters

For decades quantum field theory
had been understood mainly as a
formal machinery for generating
perturbative Feynman amplitudes,
...

But QCD led – starting in the mid-1970's – to a new phase of intense interest in strong coupling problems. The goal was to unravel the mysteries of quark confinement, generation of mass, chiral symmetry breaking, and all that.

Prominent in this work were condensed matter techniques such as lattice approximations, computer simulations, and high temperature expansions.

This type of analysis got a second wind in the 1990's with study of the supersymmetric case, by Seiberg and others ... it proved possible to get in four-dimensional supersymmetric gauge theories the sort of detailed understanding that we associate with integrable models in 1+1 dimensions

The resulting phenomena are often qualitatively similar to QCD, but sometimes even more exotic: new gauge symmetry that appears in the IR, solitons that behave in the IR like elementary degrees of freedom, duality transformations between electric and magnetic fields that must be made to relate the UV to the IR, etc.

The supersymmetric case is certainly an interesting playground; maybe we will even find out at the LHC that it is a very good approximation to the real world.

Part II

I've said a word so far on what
“emergent phenomena” mean or
don't mean for the usual particle
forces.

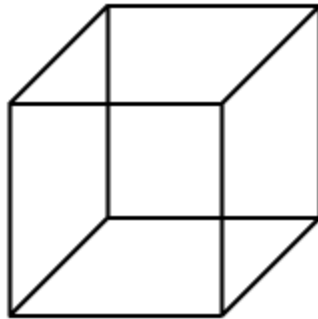
But what about gravity?

Gravity is different, because it spoils the usual paradigm:

Local degrees of freedom $\varphi(x) \rightarrow$ phenomena at long distances.

The problem is that “ x ” isn’t gauge invariant – so we cannot expect to have a gauge-invariant local observable $\varphi(x)$.

The whole framework for the **usual** analogy between condensed matter and particle physics



is lost when we include gravity ...
because gravity makes the box
fluctuate.

There may, however, be a new analogy ... as I will indicate in Part III.

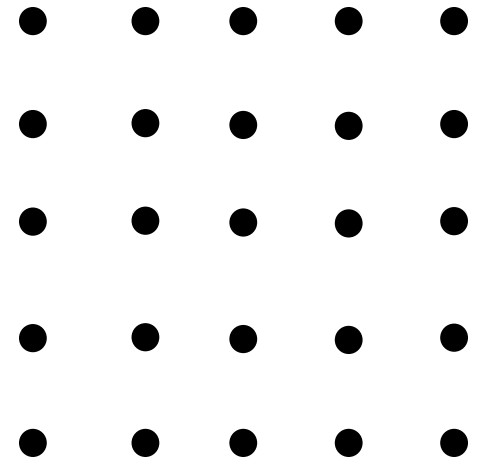
Whatever we do, we are not going to start with a conventional theory of nongravitational fields in Minkowski spacetime and generate Einstein gravity as an emergent phenomenon.

The conventional theory would have local operators $\phi(x)$, making gravity impossible

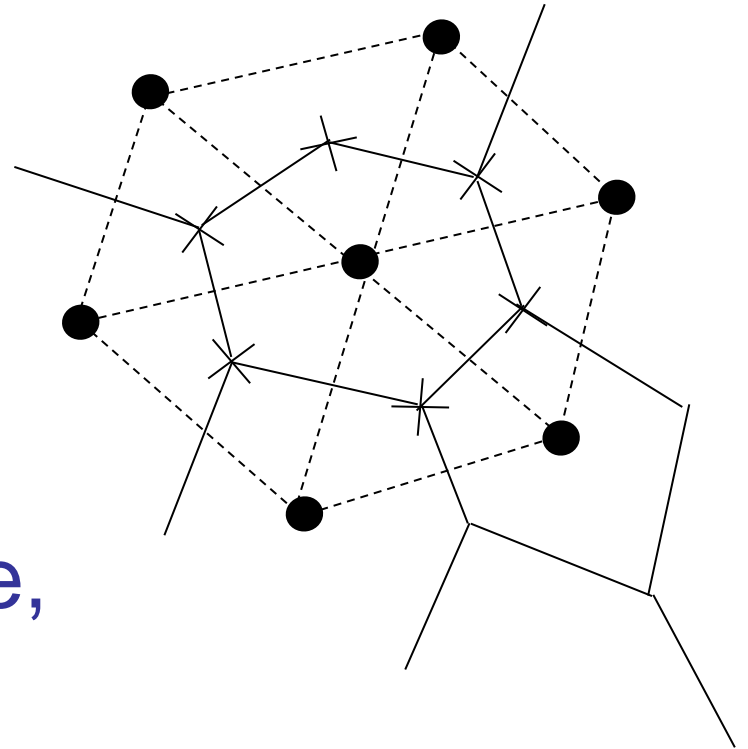
There is even a “Weinberg-Witten” theorem about this, proved in 1980 with cues from Sidney Coleman ...

A massless spin two particle cannot be generated as a bound state in a theory with a local stress-energy tensor – such as conventional flat space QFT's

It really doesn't help to start with a lattice theory – in a definite lattice – and somehow take a continuum limit. If one starts with a lattice, this means there is a lattice version of “x.”



A random lattice is another story as long as it is dynamic – in other words, it is not a quenched random lattice, but a dynamic one.



That basically means that the lattice model is a cutoff version of gravity.

It is actually known how to make this work in two dimensions, and there is no general reason that something like it could not work in higher dimensions.

The paradigm here would be “discrete gravity in ... continuum gravity out.”

But could we generate gravity from “nothing” in the same sense that we generate superconductivity from “nothing”?

Could all Einstein’s ideas of general covariance, dynamics of spacetime, etc., emerge from “nothing”?

If we want to generate gravity as an emergent phenomenon, we must go farther and generate spacetime itself as an emergent phenomenon.

In fact, it is generally believed – but not understood in any detail – that this is exactly what happens in string theory....

Spacetime and the fields and particles in it are a kind of large-scale approximation – generated from more primitive variables

We believe this because we find in the theory so many phenomena, such as mirror symmetry, topology change, and other nonperturbative symmetries and dualities, that couldn't occur if spacetime were fundamental

Though we do not have any good general point of view, there actually is a situation in which we have a pretty good picture of spacetime as an emergent phenomenon This comes from Maldacena's gauge/gravity duality.

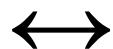
Part III

The New Analogy Between “Conventional Physics” And Gravity

The new paradigm says that, yes, relativistic physics with gravity is equivalent to a conventional physical system without gravity (such as is studied in condensed matter physics or traditional particle physics) – but not one in the same space.

So we don't run into any trouble with $\varphi(x)$.

Gauge theory in d
dimensions



Gravity in $d+1$
dimensions

GAUGE
THEORY

A light blue circle with a thin black outline. The word "GRAVITY" is written in black, bold, uppercase letters in the center of the circle.

GRAVITY

The analog condensed matter system
lives on the boundary of the Universe.

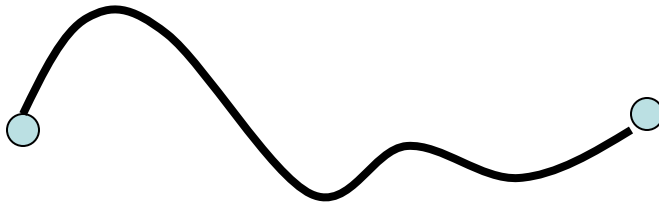
I should say that this picture really only works, in a known form, when the cosmological constant is negative.

Completely circumvents the usual objections to relating quantum gravity to a conventional theory without gravity.

From the boundary point of view the interior, with gravity, is “emergent.”

Several lines of thought converged to give this picture.

The oldest had to do with the problem of quark confinement



Quarks are confined and that seems to be because they are connected by strings

This interpretation is supported by the Regge slopes of strongly interacting particles, and also by computer simulations of QCD.

So to understand quark confinement, people wanted QCD to be equivalent to a string theory.

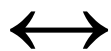
But strings lead to quantum gravity, which after all is the biggest single reason for interest in string theory.

This eventually grew into the idea that gauge theory (such as QCD) is equivalent to a theory of quantum gravity.

The obvious idea was that QCD in four dimensions was equivalent to a string theory in four dimensions. But this runs afoul of what I told you about $\varphi(x)$.

The version that works better is to relate gauge theory in four dimensions with string theory/gravity *above* four dimensions... and this led eventually to a picture I've already drawn....

Gauge theory in d
dimensions



Gravity in $d+1$
dimensions

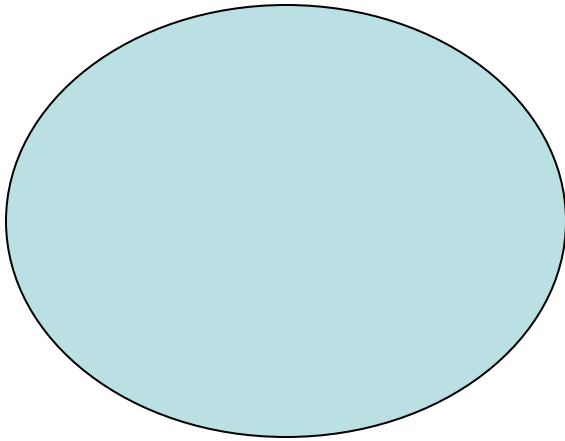
GAUGE
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GRAVITY

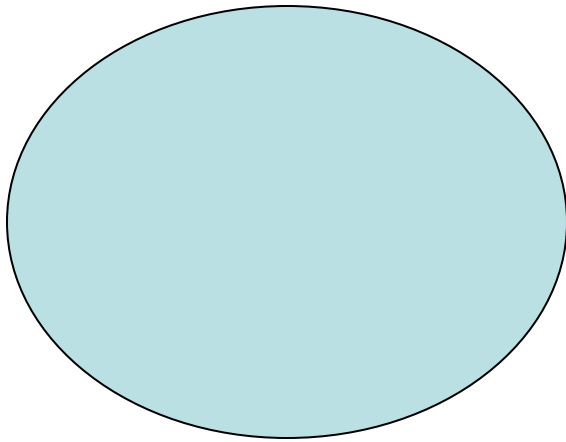
The analog condensed matter system
lives on the boundary of the Universe.

Another line of thought that ended up converging in the same place involved black holes.



The entropy of a black hole is proportional to the area of the event horizon – in Planck units.... according to Bekenstein and Hawking

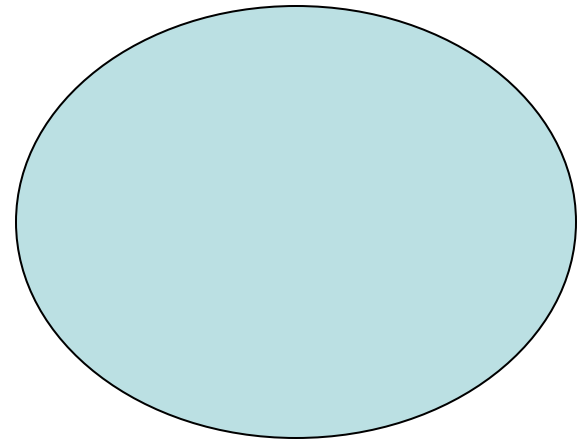
That is a very big entropy – since the Planck length is so tiny.



It means that a randomly chosen quantum state in a given region of space is almost certainly a black hole.

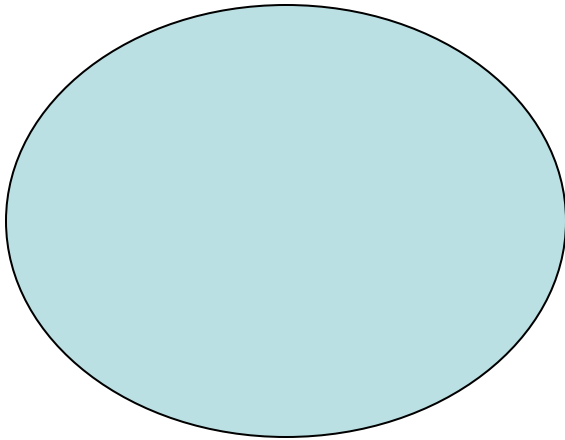
Anything else with a similar entropy would collapse to a black hole.

This is rather different from
the usual idea that for a large region,
the entropy is proportional to the volume.



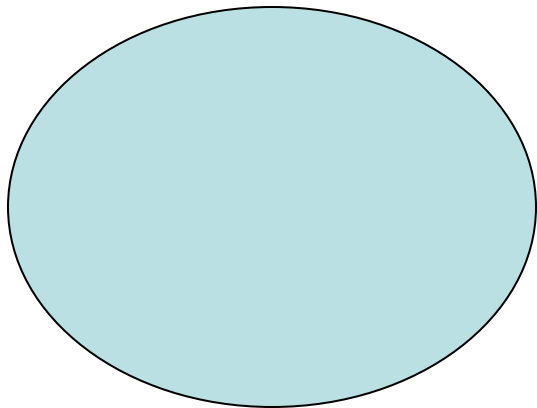
Somehow gravity reduces the entropy from
volume to area.

To make sense of this, 't Hooft and Susskind proposed the “holographic” hypothesis according to which a quantum gravity system in a given volume can be described by an ordinary system – without gravity – on the boundary of the system.



It sounds a little outlandish, but it has turned out to be the right way of looking at things, at least for the case of negative cosmological constant.

The holographic hypothesis links up to another idea about black holes, which is the “membrane paradigm.” This says that the horizon of a black hole behaves like a physical membrane with a certain temperature, entropy density, thermal conductivity, electrical conductivity, etc.



In short, the black hole horizon
Is a physical entity
in all respects.

This seems to contradict what textbooks say about black holes – to an infalling observer, nothing at all is special about the horizon.

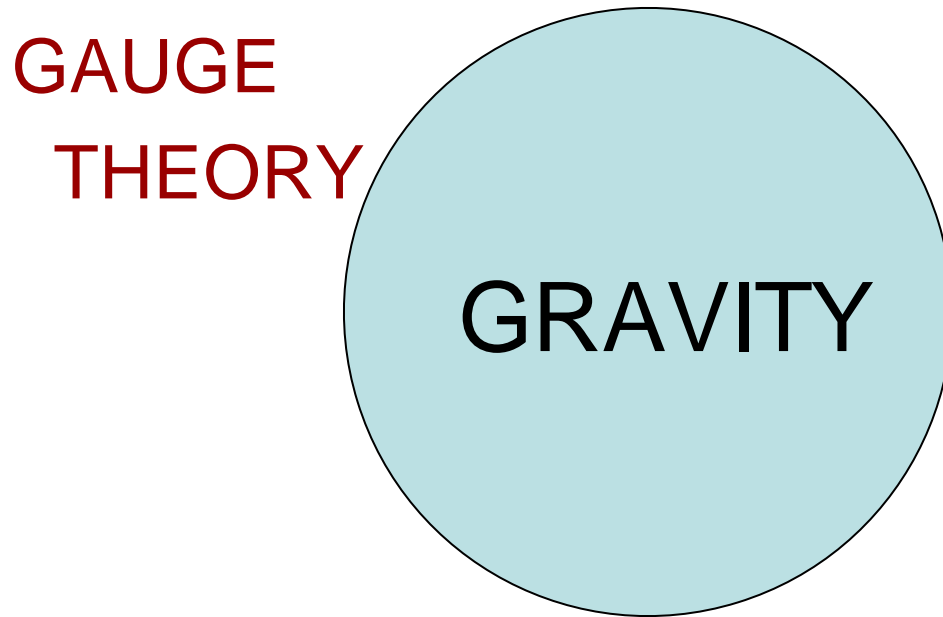
Reconciling the two requires another notion that is still somewhat speculative, the idea of “black hole complementarity.”

Anyway, if there is a description of nature in which the horizon of the black hole is similar to a physical membrane, what particular laws govern this membrane?

What Hamiltonian describes it?

This was completely unclear for a long time, until an answer suddenly emerged – at least for large black holes in a world with negative cosmological constant.

The answer is part of the picture I keep showing you:



The membrane is described by the analog condensed matter system that lives on the boundary of the Universe.

Applications?

The obvious ones are to the motivating questions.

New insights about quark confinement and the entropy of black holes.

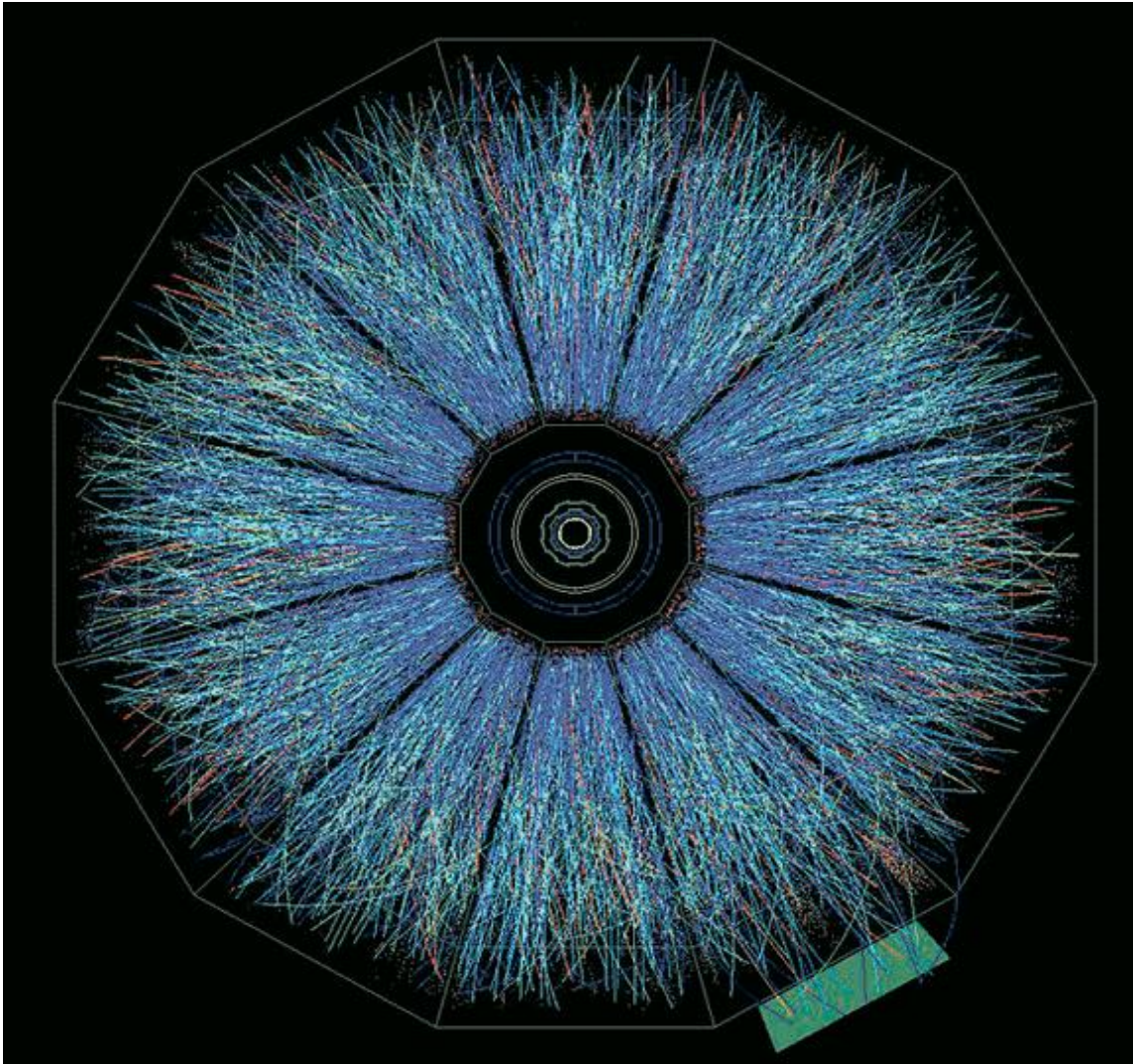
Part of the unification of different approaches to string theory.

But particularly satisfying have been totally unexpected applications in other areas of physics.

One spectacular development involves heavy ion physics.

In heavy ion collisions at RHIC, the simplest guesses based on asymptotic freedom of quarks and gluons have not quite worked out

In these events, in which thousands of particles may emerge from a single collision



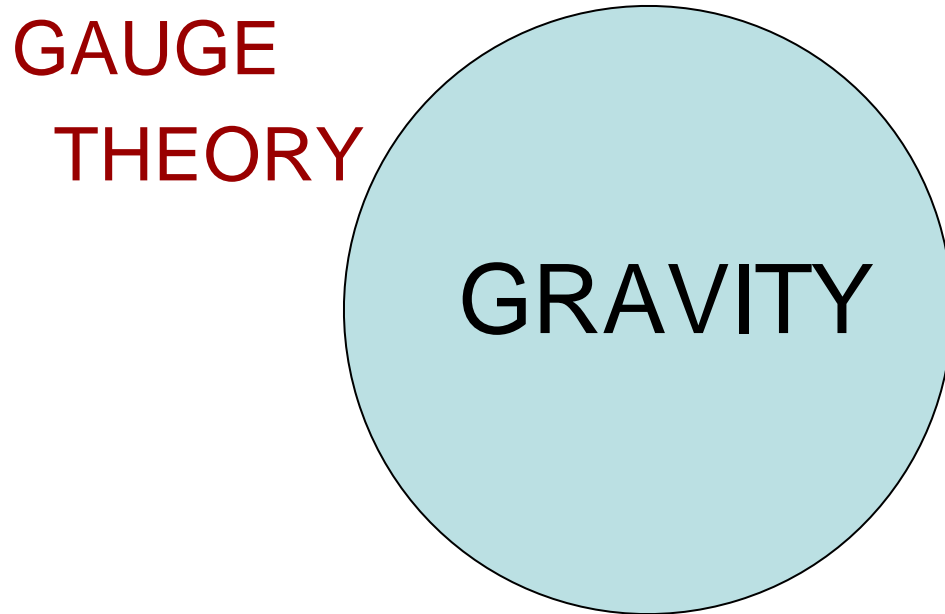
There is a phenomenon of large scale “elliptic flow” with an overall anisotropy.

Hydrodynamic simulations give a good fit by interpreting the “stuff” produced in the heavy ion collisions in terms of a fluid with a remarkably small viscosity – perhaps the most perfect fluid observed in nature.

What is a quantum model of such a fluid?

The black hole horizon.

In this interpretation of the picture, the black hole is in five dimensions



The analog condensed matter system is high temperature “QCD”

I put “QCD” in quotes because the known version of this picture doesn’t quite lead to QCD, but to a supersymmetric version.

Still, this picture, supplemented by semiclassical gravity computations in the interior (“black hole thermodynamics”) give a pretty interesting model of the “stuff” that is being probed at RHIC.

There is another kind of application also:

This involves the theory of quantum phase transitions.

One exploits the fact that the link to gravity enables one to compute properties of the analog condensed matter system that are usually very hard to get a handle on.

In a sense, the black hole horizon is an unusually simple model of a complex quantum system.

I hope to have at least convinced you that it is interesting to think about the relation between condensed matter physics and quantum gravity!

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