

# THE SEARCH FOR QUANTUM GRAVITY

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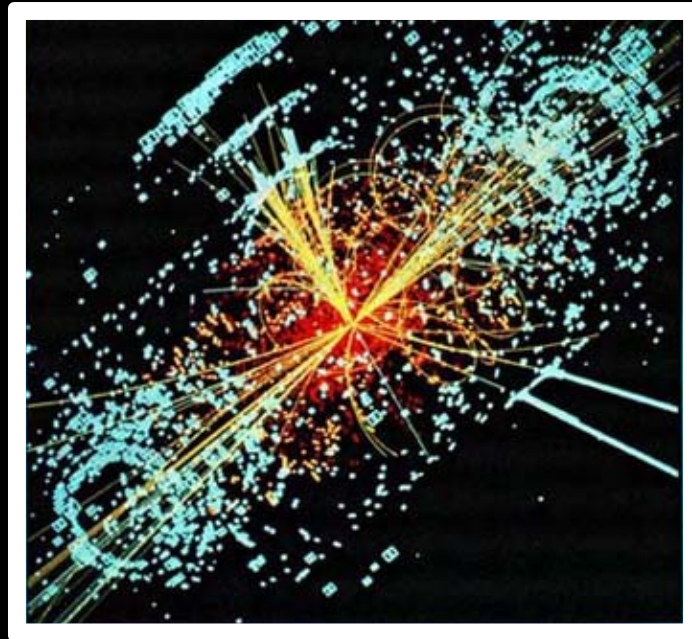
# QUANTUM GRAVITY

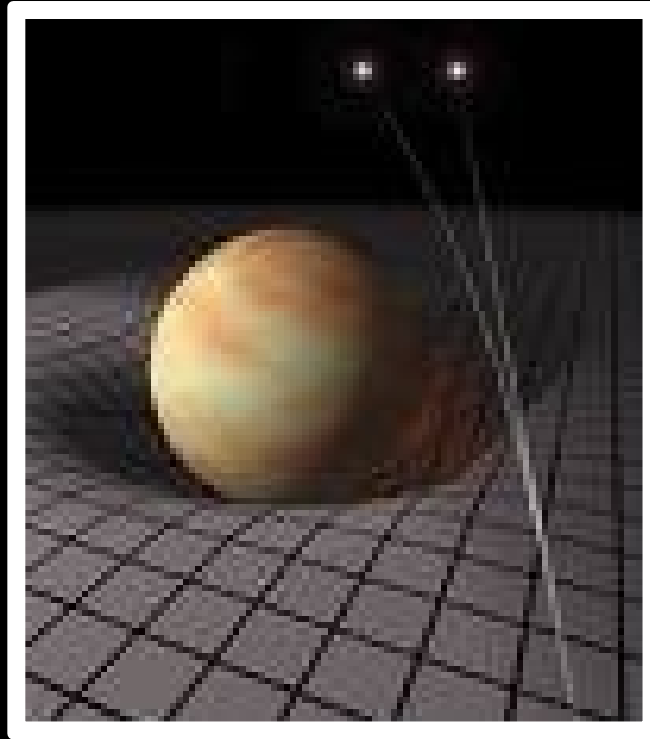
Theoretical physicists have developed increasingly sophisticated mathematical models that now describe an astoundingly wide variety of physical phenomena.

A handful of basic frameworks (i.e. fundamental mathematical and interpretative structures) underlie all of the models of physics.

In particular the quantum framework, developed between 1900-1930, is the basic grammar that has been used in the construction of all models of particle physics over the last 80 years.

In more detail modern theories of elementary particle physics are set within the framework of quantum field theory (QFT). Space and time form a non dynamical grid- a sort of unmoving stage - upon which dynamics is enacted. Each point in space hosts its own quantum `degrees of freedom' and `interactions' are `local'.





In contrast modern theories of cosmology are set within the framework of classical general theory of relativity (GTR). Space time is dynamical. Each point in space hosts a set of classical degrees of freedom, which interact locally with each other as well as the dynamically evolving geometry of space time.

QFT has been spectacularly successful in describing sub atomic scale physics.

## Fine Structure Constant

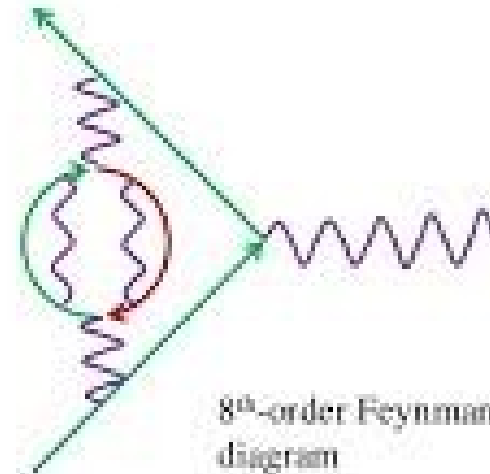
$$g = 2.00231930436146 \\ \pm 0.00000000000056$$

Extract value of  $\alpha$  from QED

$$\frac{1}{\alpha} = 137.035999166(34)$$

Value from atom interferometry

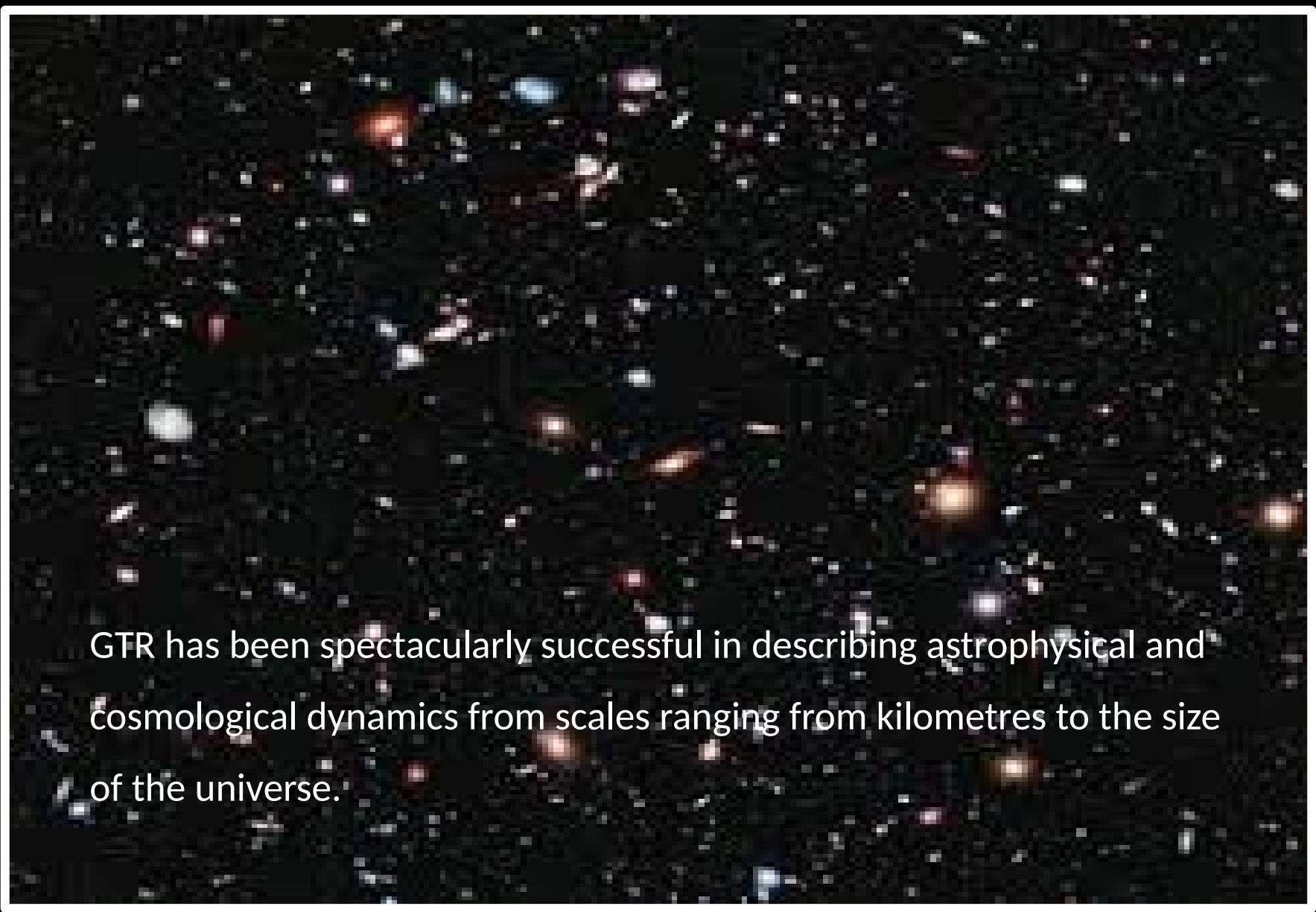
$$\frac{1}{\alpha} = 137.035999037(91)$$



Comparison tests high-order QED, including muons and hadrons

Extend to positrons, protons, antiprotons...



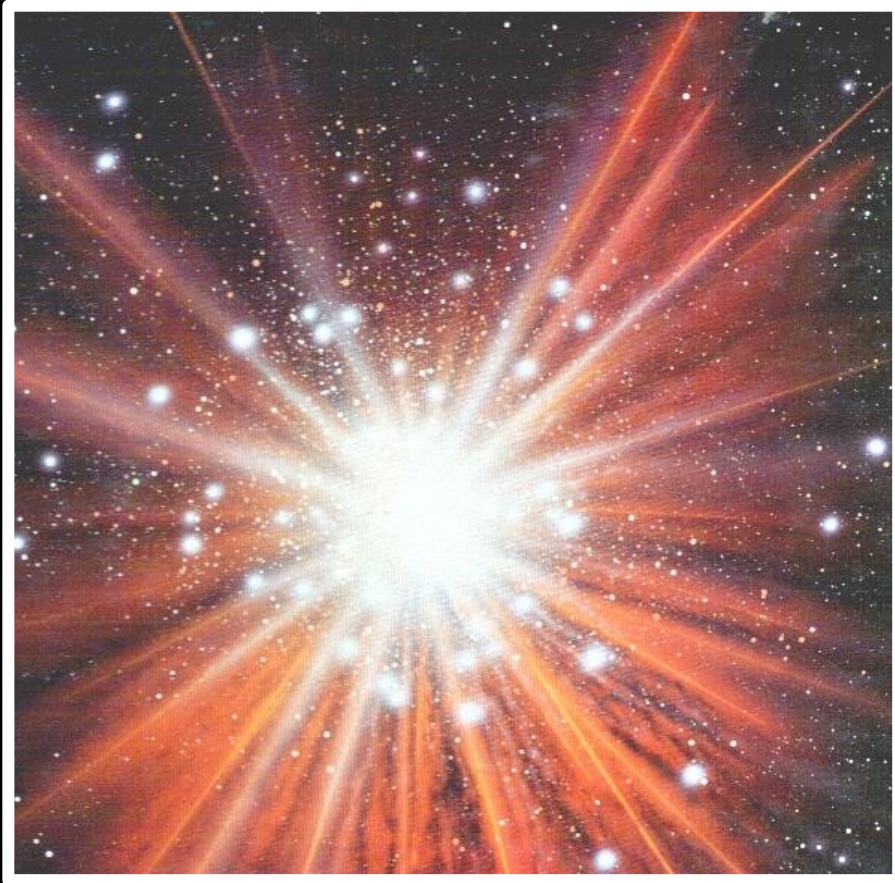


GTR has been spectacularly successful in describing astrophysical and cosmological dynamics from scales ranging from kilometres to the size of the universe.

However QFTs appear to ignore the dynamical nature of space time (more below), while general relativity ignores quantum fluctuations. Hence neither framework seems appropriate for modeling phenomena that are dominated by quantum fluctuations of space time.

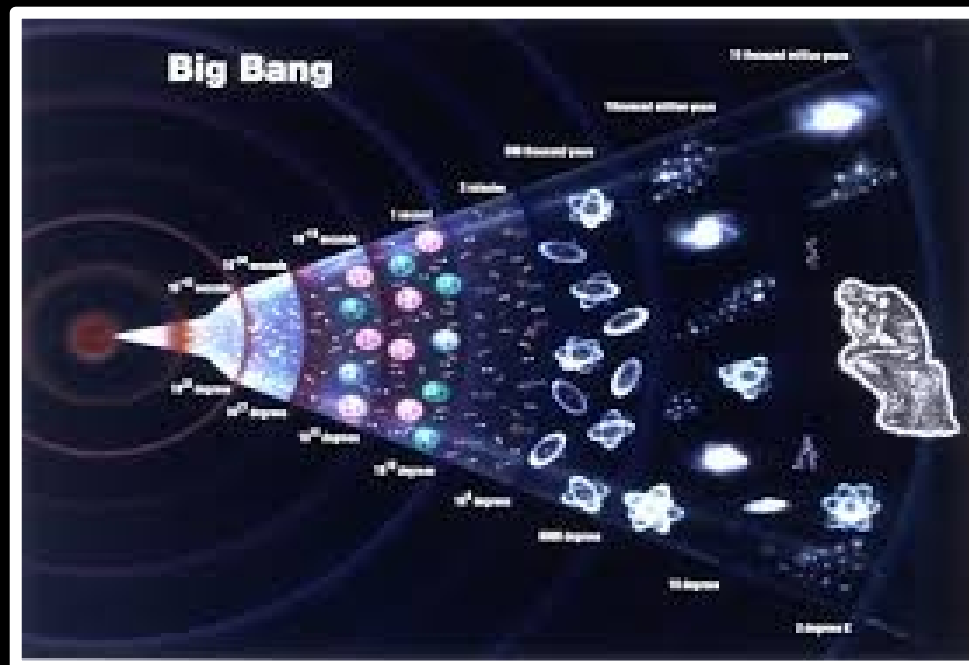


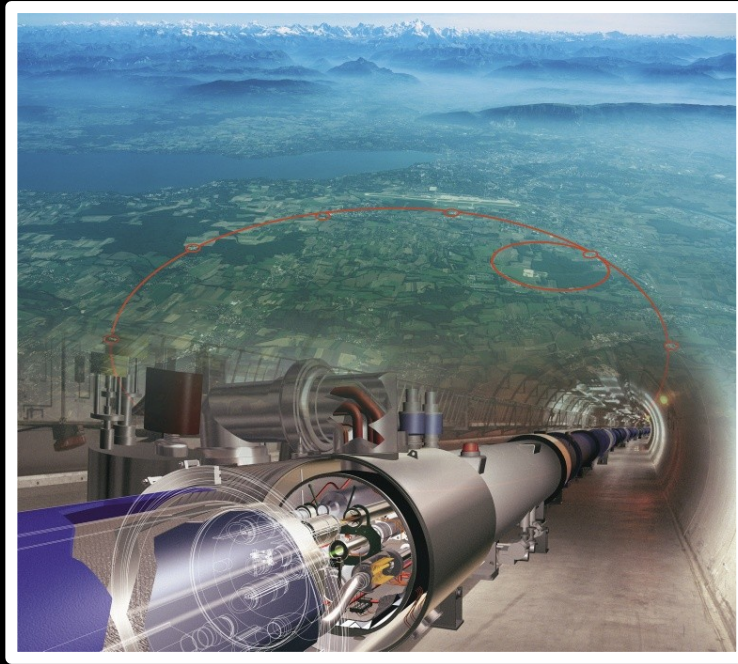




This is conceptually unsatisfactory. It is also practically unsatisfactory as quantum gravity is likely needed to study the 'birth' of the universe.

The general relativity based model of cosmology has been used to run the history of the universe backwards. This process takes us to an epoch, about 14 billion years ago, when universe was extremely 'small' and dense. At earlier times the framework of general relativity likely fails. We need quantum gravity.





The search for such a quantum theory of gravity is greatly hampered by an unfortunate circumstance.

Quantum fluctuations of space time geometry are important only at a very small length scale (the Planck scale). No collider experiment yet constructed or foreseen is directly sensitive to fluctuations at this extremely small scale.

For comparison, Planck Scale  $10^{-34}$  m. LHC probes  $10^{-18}$  m.

We expect that sizable quantum fluctuations of geometry in the very early universe should have left a subtle imprint on the universe today. However it will not be easy to use measurements performed 14 billion years later to characterize these fluctuations.

Other regions of the universe where quantum fluctuations of space time are qualitatively important – like the centre of black holes – seem even harder to access.

Consequently, we are constrained to embark on our quest for the quantum theory of gravity with very limited guidance from experiment.

We seem to be in a bit of a fix. Our question – what is quantum gravity – seems very important. However we have no guidance from experiment. How should we proceed? We have adopted the strategy of the ‘spherical cow’.



# ONE CONSISTENT THEORY OF QUANTUM GRAVITY

It has proved surprisingly difficult to construct even one nontrivial mathematically consistent model of quantum fluctuating space time.

Over the last 60 years or so, however, theoretical physicists have stumbled upon a theoretical framework of remarkable power and beauty that we still understand very incompletely – a framework that is (very poorly) named String Theory.

In 1997, a young Argentinian theorist named Maldacena was able to construct the first fully satisfactory model of this sort.

# A MODEL WITH QUANTUM SPACE TIME

I will now describe the complete formulation, presented by Maldacena, of one model of quantum fluctuating space times.

It is useful to first recall how this worked for the theory of the fluctuating electromagnetic field.

Question (1928-1950): Find the quantum theory of an electron interacting with an electromagnetic field.

Solution QED. Local classical variables replaced by local quantum variables. Reduction to classical physics guaranteed in appropriate limits. Getting it all to work was huge technical accomplishment. Seen in broad brush, however, it was conceptually unsurprising.

We now describe the quantum theory of gravity (IIB super gravity) propagating on the 10d space.

$$AdS_5 \times S^5$$

The solution is not given by replacing classical 10 dimensional fields by their quantum counterparts.

Instead given by a four dimensional quantum field theory

$$U(N) \mathcal{N} = 4 \ d = 4 \text{ SYM}$$



$U(N)$   $\mathcal{N} = 4$   $d = 4$  SYM is a theory of  $N$  times  $N$  matrices. It has long been known that matrix theories become classical at large  $N$ . However the form of the effective classical theory was impossible to derive and usually assumed to be a mess.

Actually, the effective theory for  $U(N)$   $\mathcal{N} = 4$   $d = 4$  SYM  
Is Einstein gravity, propagating on  $AdS_5 \times S^5$

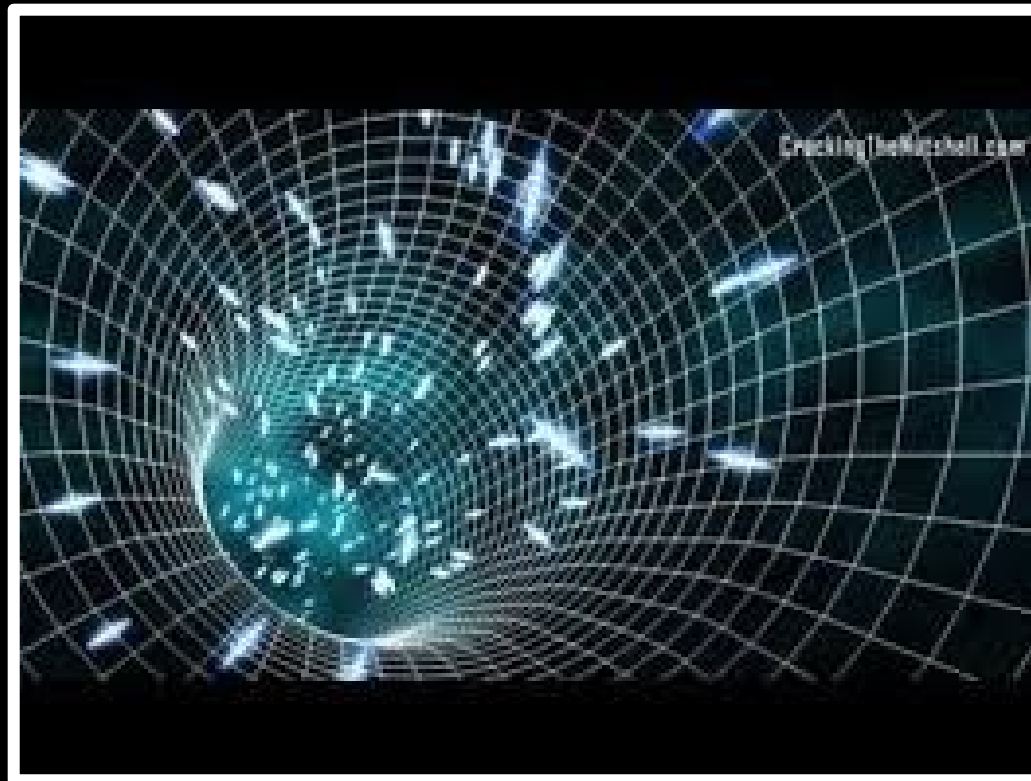
10-dimensional space time is an approximation that emerges in large  $N$  limit.

$1/N$  corrections lead to quantum fluctuations of 10-dimensional geometry.

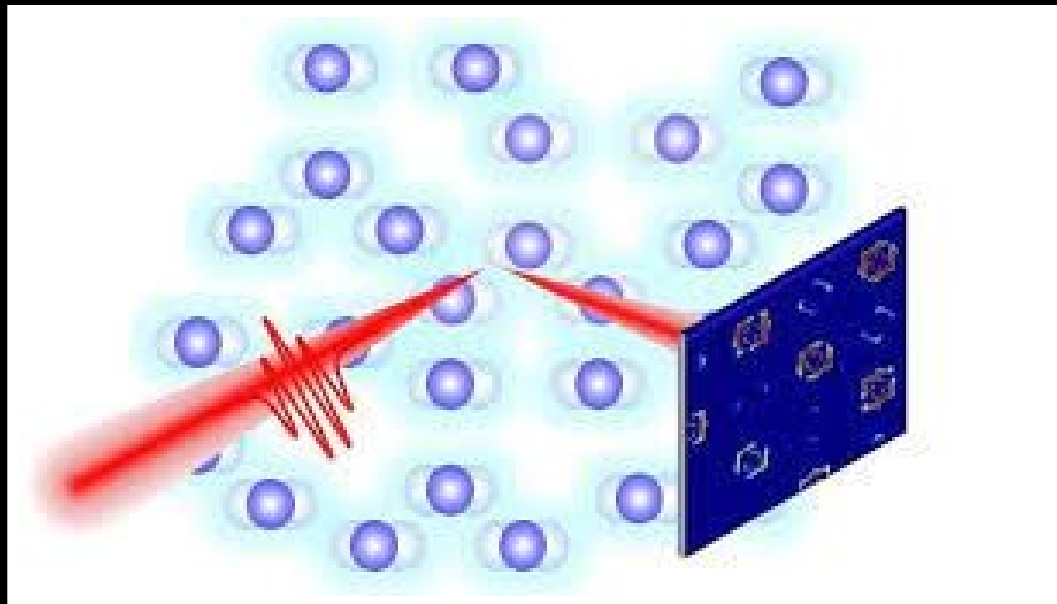
However once these fluctuations are summed up, at any finite  $N$ , we are left with a 4d field theory.

10-dimensional space time and gravity have disappeared; they play no role in the fundamental formulation.

Within this model, therefore, there is a sense in which space time is an illusion; an emergent notion that has precise meaning only at very large  $N$ , but whose reality becomes increasingly tenuous as  $N$  is decreased.

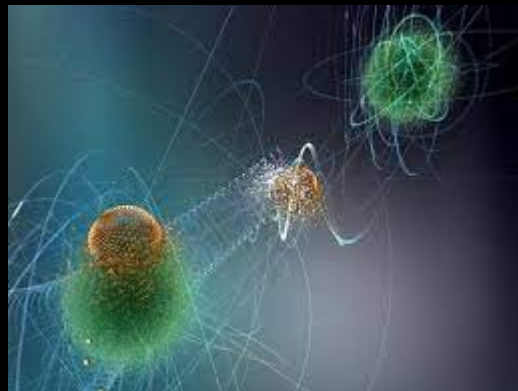


In our review of the structure of quantum field theories, we emphasized the local nature of these theories. An object located in some region is – at the fundamental level – a bunch of oscillations of the local fields in that region. That is how a quantum field theory works. This local nature precludes action at a distance, and ensures causality.



It has recently been understood that things can work differently in emergent spacetimes. The fundamental description of an object `here' is sometimes a bunch of very complicated oscillations of fields `there'. This happens when the degrees of freedom `here' and `there' are very highly entangled.

Many physicists (Hawking ...Mathur...AMPS...) had previously argued that the strange properties of black holes make them inconsistent with quantum mechanics, concluding that either quantum mechanics has to be modified or that quantum black holes are very different from their classical . Nonlocality gives a 3<sup>rd</sup> , and most likely correct – way out.



# APPLIED GRAVITY

At a much more mundane level all of this suggests a completely unanticipated role for theories of gravity. They emerge as the effective classical description of strongly coupled non gravitational systems in the limit of a large number of degrees of freedom.  $1/N$  corrections to the classical limit yield quantum fluctuations of gravity.

Thus theories of quantum gravity provide an effective large  $N$  mean field description for several strongly coupled non gravitational quantum systems. Over the years gravity may well turn into an increasingly useful tool for studying all sorts of non gravitational strongly coupled systems. I now describe one in which this has already played out.



On intuitive grounds we expect every nontrivial quantum field theory at high enough energy densities to be described, in the long wavelength limit, by the equations of hydrodynamics.

The main idea here is that stuff equilibrates locally very rapidly at high energy densities. However the parameters of local equilibrium – the local temperature and chemical potential – vary from point to point and form the variables of the long wavelength effective theory.

The equations of hydrodynamics were formulated in their modern form almost a hundred years old. The formulation of these equations was widely believed to be a settled subject.

Now if all 'locally equilibrated' quantum field theories are governed by the classical equations of hydrodynamics, this must also be true of supersymmetric Yang Mills. But we have already seen that supersymmetric Yang Mills, at large  $N$ , is governed by the classical equations of gravity. It turns out that Yang Mills in thermal equilibrium is 'dual to' a big black hole in 5 dimensional AdS space. So if everything I have said is to be consistent, it must be the case that the motion of big black holes in 5 dimensional AdS space is governed by the equations of four dimensional hydrodynamics.

A few years ago my collaborators set out to check whether this was indeed the case. The technicalities proved tractable, and we were able to derive the equations determined the long wavelength dynamics of black holes in AdS.

As hoped, these equations were those of four dimensional hydrodynamics – but with a twist. The hydrodynamical equations we found contained two terms did not appear in classic texts on fluid dynamics. A puzzle.

After some back and forth it was understood that the classic texts were not comprehensive (in some situations wrong), and needed to be updated.



We have thus seen examples of two rather different applications of gauge gravity duality. First to uncover a strange and unanticipated nonlocality of physics in dynamical spacetimes. (Suggests new questions. Action at a distance? Causality?). Second to clear up the details of an apparently completely unrelated subject - the study of hydrodynamics.

In both these cases the lessons learnt from gauge gravity were then rederived using more general methods. We now know that any theory of dynamical spacetimes (not just our spherical cow model) exhibits strange nonlocality. And we also know that the hydrodynamical equations of any QFT with certain features (not just our spherical cow) has new terms. Best situation. Lessons learnt from spherical cow apply very generally.

# OUTLOOK FOR THE FUTURE

Several aspects of the story I have outlined above remain unsatisfactorily understood. To start with, the fact that  $U(N) \mathcal{N} = 4 \ d = 4 \text{ SYM}$  reduces to 10d IIB super gravity at large  $N$  has been established only within the string framework. We lack a direct field theoretic understanding of this fact.

In other words we do not understand in detail precisely how space time and fluctuating metrics emerge out of strongly coupled gauge dynamics.

We certainly also do not understand the nonlocality of emergent spacetimes in any detail. It seems likely that we will learn important lessons by filling this gap.

As I have described, the formulation of a single complete nontrivial quantum theory of gravity has been a non trivial accomplishment that has yielded surprising insights. The string framework asserts the existence of many more such theories.

In order to address questions the birth of our universe, we would like a precise formulation of the quantum theory of gravity in our world, not just any old model system.

Does the quantum theory of gravity of the real world theory lie within the string framework? If so, where? How do we identify and understand this theory?

I do not know the answers to these questions, but I think it is likely that some input from experiment – perhaps in an unanticipated manner will play a role.

# SUMMARY

Quantum gravity likely needed to understand early universe.

String theory: an exciting but incompletely understood framework for quantum theories of gravity.

Has led to the complete but surprising formulation of a class of 10 d quantum gravity systems as lower dim non gravitational quantum systems.

The result is a great surprise. Space and time are emergent notions in this model. Sense in which spacetime is an illusion. Large entanglement in spacetime can result in a strange non locality.

Complete formulation of other gravitational systems an outstanding formal challenge. Much more waiting to be learnt. Formulation of the 'non spherical cow' quantum gravity of the real world an even bigger challenge.