Quantum Gravity

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100 years of quantum mechanics

ICTS

January 2025

The discovery of quantum mechanics generated a problem:

Quantum Mechanics
1925

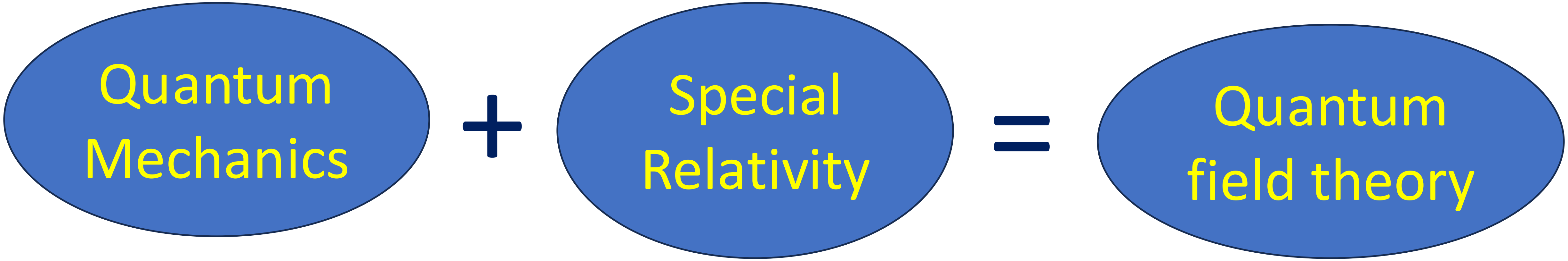
+

General Relativity
1915

= ?

This is the problem of developing a theory of <u>quantum gravity</u>

Side remark


Quantum Mechanics
+
Special Relativity
=
Quantum field theory

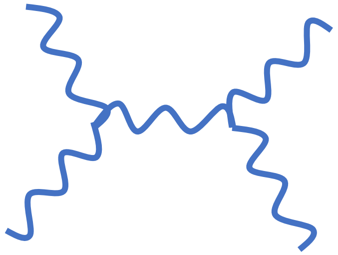
General Relativity is a field theory,
can we quantize it like any other field theory?

Yes and no

Yes:
As an ``effective field theory'', valid approximately at low energies.

$$I = -\frac{1}{16\pi G_N}\int \sqrt{g}R + \cdots$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$



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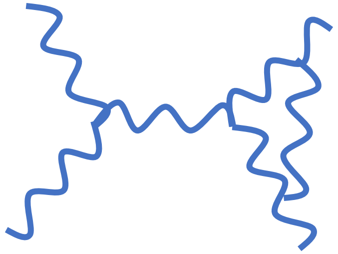


+

$G_N E^2$

$\frac{1}{\epsilon^2} \times (G_N E^2)$

$$I = -\frac{1}{16\pi G_N}\int \sqrt{g}(R + c_1 G_N R^2 + \text{counterterms})$$

Unknown coefficient

This is a well defined method that works well at low energies, $E \ll M_{Planck}$.

Works well for almost all practical purposes, almost anywhere in the universe!

Corrections → powers of $(E^2 G_N) = \frac{E^2}{M_{Pl}^2} \sim 10^{-30}$ (for LHC energies)

$$M_{pl}^2 = \frac{\hbar c}{G_N}$$

Why is this not good enough?

When $E \sim M_{Planck}$ we need an infinite number of coefficients to make a prediction.

The theory is not well defined!

We need something better…

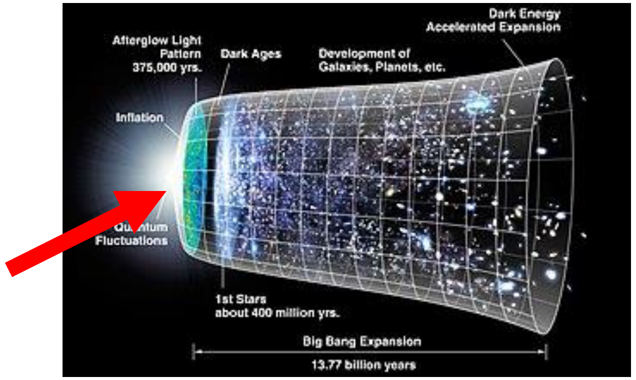
Why do we care ?

Two reasons:

1) Spacetime singularities:

Origin of the Big Bang (or before inflation)

Interior of black holes



2) Parameters of the Standard Models:

The full theory is expected to be more constrained than the effective theory.

→ determine parameters of the particle physics and cosmological “Standard Models”.
(or at least some relation between the parameters)

String theory is a candidate for a full theory of quantum gravity.

It has a lot of wonderful properties

But we do not know yet whether it is the right theory for our universe…

We will discuss some aspects of string theory later.

But, first, let us return to the semiclassical theory

There is a couple of very surprising predictions of the effective theory:

1) For black holes

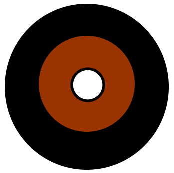
2) For inflationary cosmology

White Black Holes!

The laws of quantum mechanics imply that black holes emit thermal radiation. **Hawking 1974**

The temperature increases as the size decreases

$$T \propto \frac{1}{R_{BH}} = \frac{1}{\text{Size}} \,, \qquad \lambda = \text{Size}$$



Temperatures for black holes of various masses:

$T_{M=sun}$ = 0.000003 °K (This temperature is too small for astrophysical black holes)

$T_{M=continent}$ = 7000 °K (white light) has the size of a bacterium

Temperature → Entropy

Bekenstein

1st Law of thermodynamics

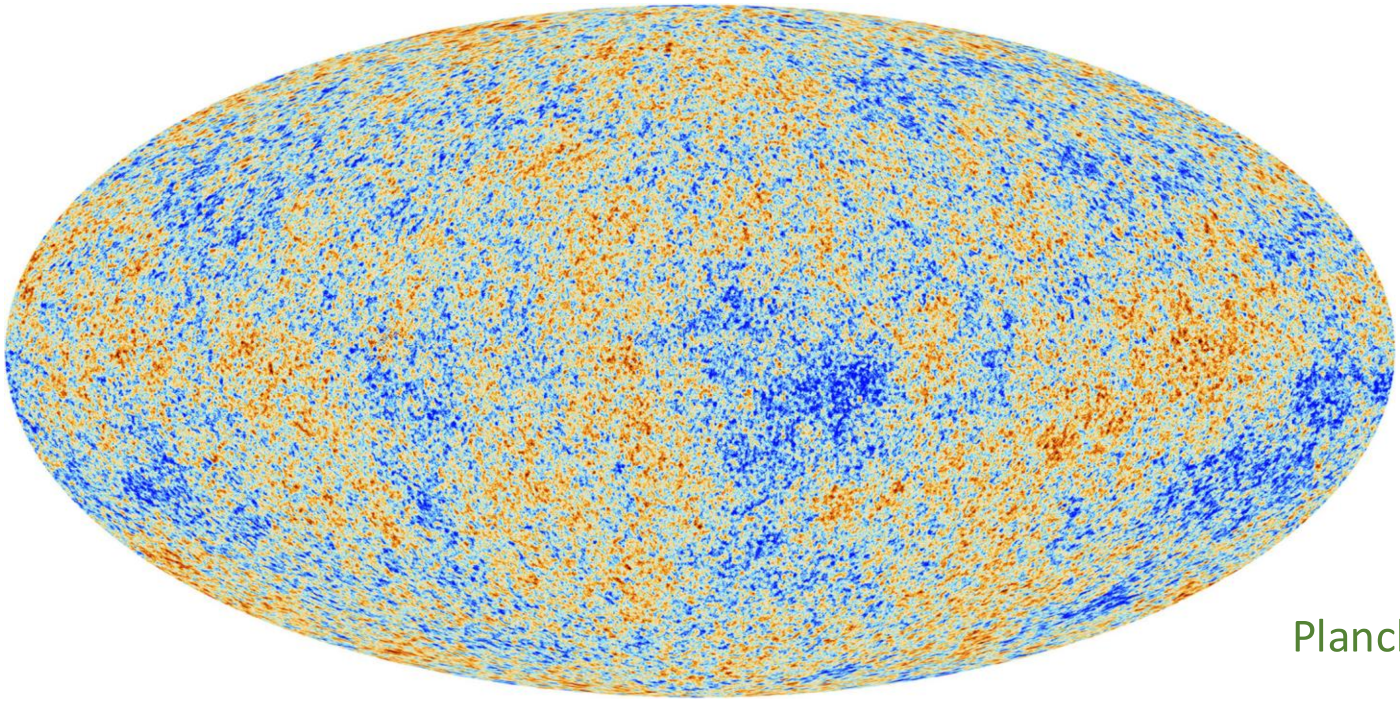
$$dS = \frac{dE}{T} = \frac{dM}{T} \longrightarrow S = \frac{\text{Area}}{l_p^2} = \frac{(\text{Area})\, k_B c^3}{4\hbar G_N}$$

Very large for a macroscopic black hole!

These properties lead to very interesting puzzles for a quantum theory of gravity

The second prediction of the effective theory involves cosmology.

During inflation, quantum effects generate the primordial fluctuations.



Planck satellite 2013

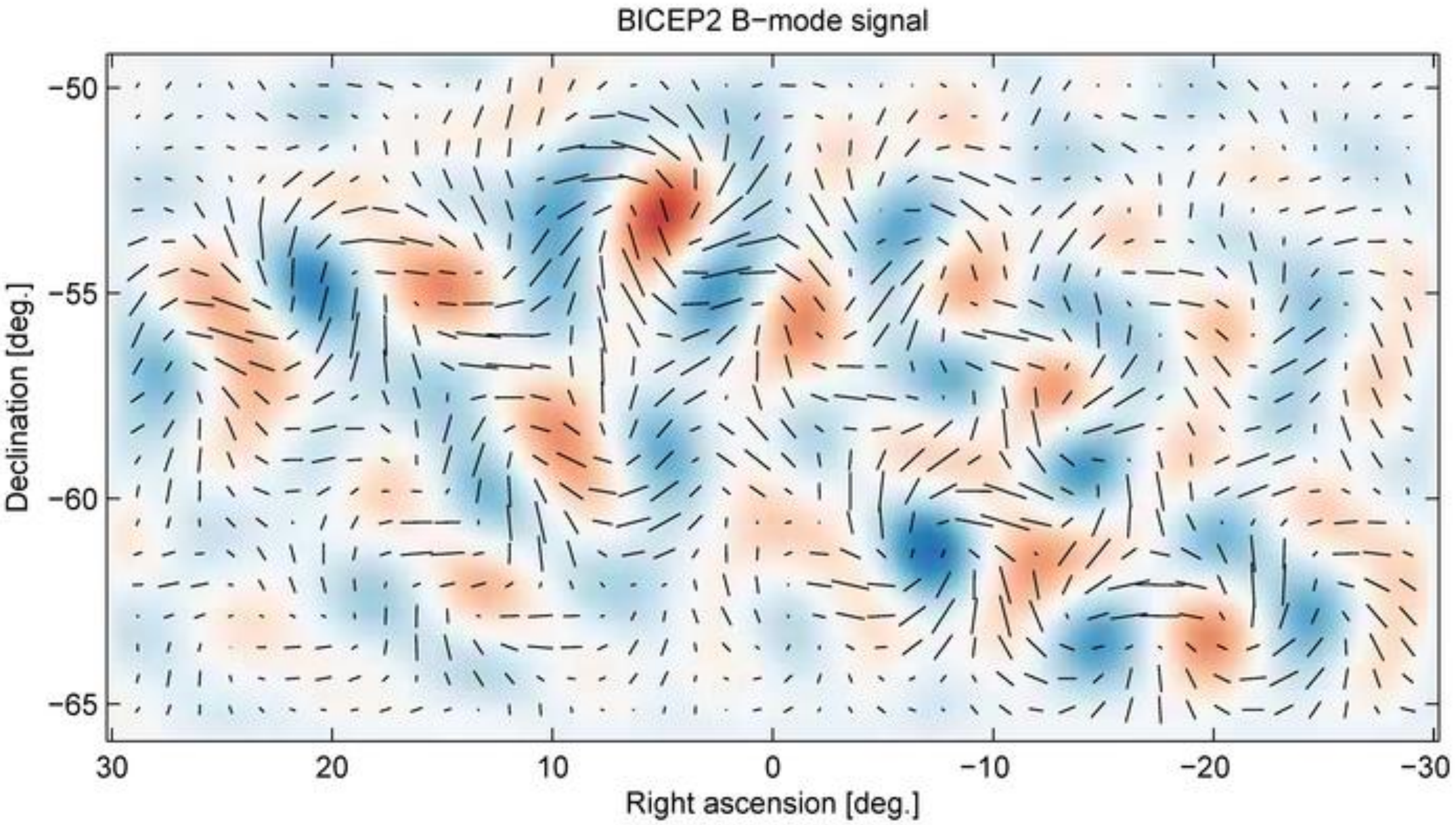
These fluctuations are ``scalar fluctuations”

The extent to which these require quantizing gravity is debatable…

However, the same mechanism gives rise to tensor fluctuations.

These start out as quantum gravitational waves that have been stretched to classical gravity waves the size of the universe.

They could be observed by measuring the "B modes" of the polarization in the CMB.



Let us emphasize that the physical mechanism giving rise to primordial fluctuations is the same as that of Hawking radiation

In an expanding universe, with constant Hubble constant, there is a horizon → Also a temperature

These particles created by the temperature can collide

Inflation is a ``cosmological collider” capable of reaching very large energies , 10^{13} Gev

The effects of these collisions appear through non-gaussianities.

Free particles during inflation → Gaussian distribution.

Interactions + new particles → non-gaussian features.

We see the quantum mechanical nature of the early universe:

We can only predict details of the statistical distribution, not the precise shape of the universe.

$$T_{dS} \sim H \sim \frac{1}{R_H}$$

Similar expression for the temperature in a universe with nearly constant Hubble constant

$$\langle h\, h \rangle \propto G_N H^2 \sim G_N E^2 \ < 10^{-12}$$

(not the 3 Kelvin of the CMB, which is due to later physics.

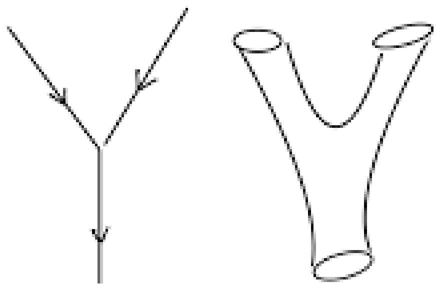
We are talking about the <u>fluctuations</u> in the CMB, not the temperature of the CMB).

In fact, historically, Hawking radiation was discovered first → temperature in de-Sitter → inflationary predictions

Lessons learnt for black holes → predictions for cosmology that we use to explain our universe.

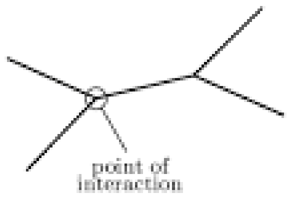
Let us now say a few comments on string theory

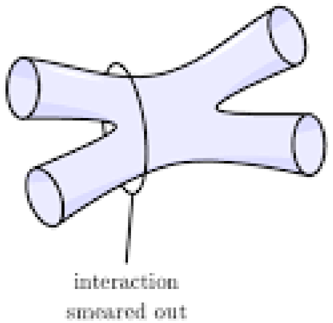
String theory started through a generalization of Feynman diagrams, replacing particles by strings.



This leads to a relatively simpler theory because interactions are not arbitrary, they are just set by the topology of the worldsheet.

And are also free of UV divergencies.





In addition, the simplest string theories defined in flat space → contain a graviton.

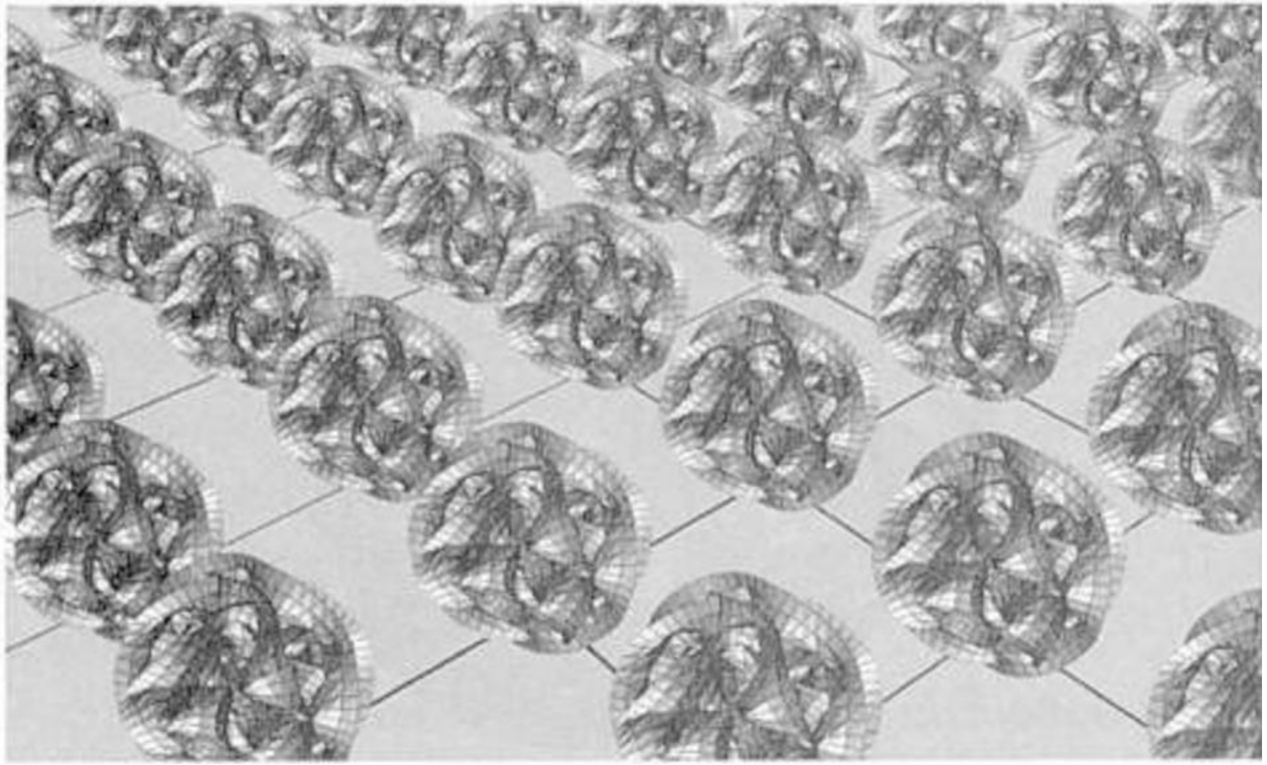
Scherk, Schwarz, Yoneya 1970’s

Supersymmetric string theory in flat space → requires 10 dimensions.

This looks bad, since we live in four dimensions!

We could have a spacetime that has 4 large dimensions and 6 small dimensions.

Kaluza, Klein 1920's



Depending on the internal dimensions →
different four dimensional physics.

In the 80's it was thought that there would be a relatively small number of possible internal spaces (with supersymmetry).

But this number kept growing and it is now very large $10^{\text{thousands}}$

The theory in 10d is essentially unique, with no free parameters.

All four dimensional parameters depend on the choice of internal manifold and fluxes of gauge fields in that space.

The theory in 10d is essentially unique, with no free parameters.

All four dimensional parameters depend on the choice of internal manifold and fluxes of gauge fields in that space.

This includes, in principle, parameters like the ones in the standard model

But also the corrections to gravity are fixed

$$I = -\frac{1}{16\pi G_N}\int \sqrt{g}(R + c_1 G_N R^2 + \text{counterterms})$$

Depends on the geometry of the internal dimensions.

The study of these compactification is continuing.

Cases with large amount of supersymmetry are being classified.

Some semi-realistic modes have been found.

But it is a vast space and it will require new ideas to tackle it efficiently.

People are exploring aspects of it using modern computer techniques, such as machine learning.

Also searching for universal properties for <u>all</u> compactifications…

Let us now turn again to black holes

Black body radiation played a key role for the development of quantum mechanics

Black holes are playing a key role for the development of quantum gravity!

Black hole thermodynamics

- Black holes appear to obey the laws of thermodynamics.
- 1st law → used to derive the entropy.
- 2nd law → Hawking's area theorem + Wall's proof including quantum corrections.

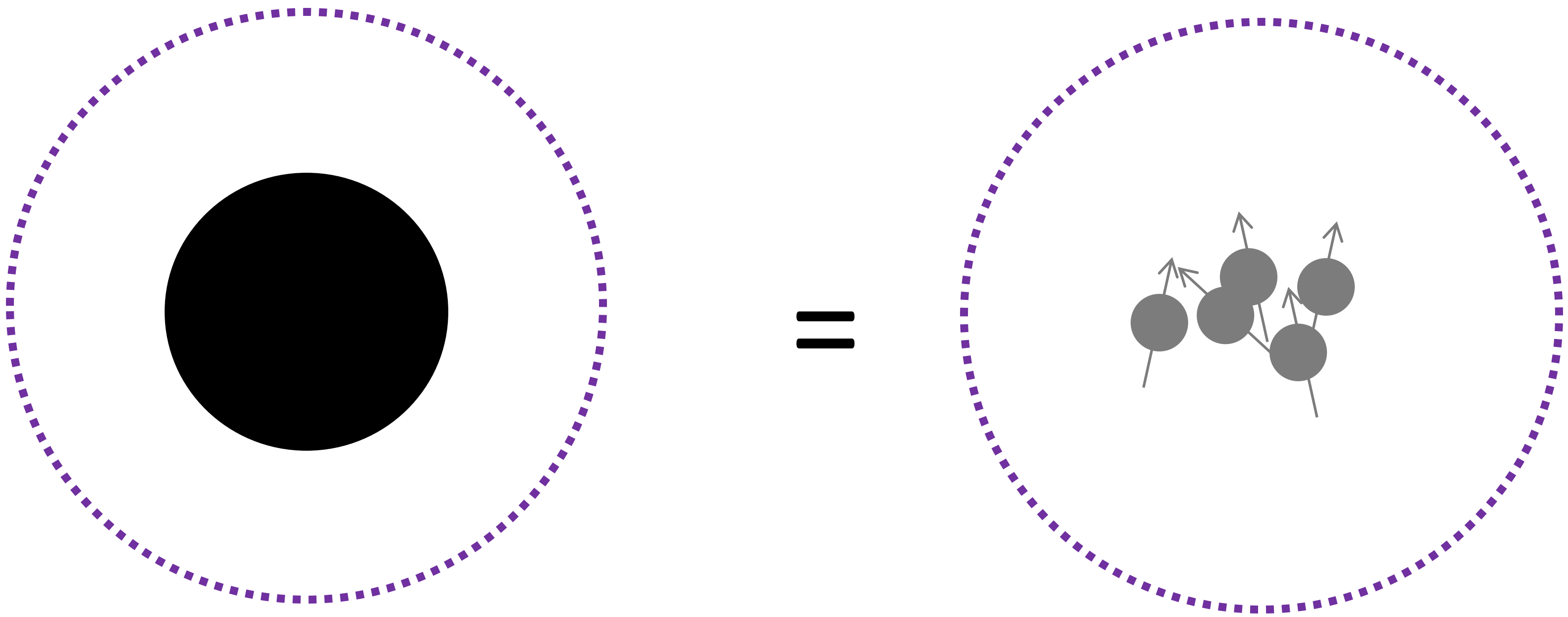
Wall 2011

Black hole thermodynamics leads to the following idea:

Black holes as quantum systems

"Central dogma"

- A black hole seen from the outside can be described as a quantum system with S degrees of freedom (qubits). S = Area/4 ($l_p = 1$)
- It evolves according to unitary evolution, seen from outside.



Hawking argued against it

Others argued in its favor

I would say that now the majority opinion is in favor.

For a few reasons that we will review

Before we review, let us say why we care…

We care because solving this problem seems to involve understanding the basic quantum gravitational degrees of freedom that make spacetime.

The ``qubits'' that make spacetime.

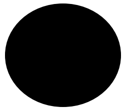
D-branes in string theory

Polchinski

Microscopic accounting for the entropy of some black holes

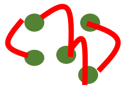
Strominger, Vafa, … Sen…

Strong coupling



Charged, extremal black hole. M=Q

Weak coupling



D-branes and strings.

Can be counted.

$$I = -\frac{1}{16\pi G_N}\int \sqrt{g}(R + c_1 G_N R^2 + \text{counterterms})$$

Including these corrections to gravity!

$$S = \frac{Area}{4G_N} + \#\, c_1 + \cdots = Log[Number\ of\ States]$$

This also lead to the idea of holography

Holography

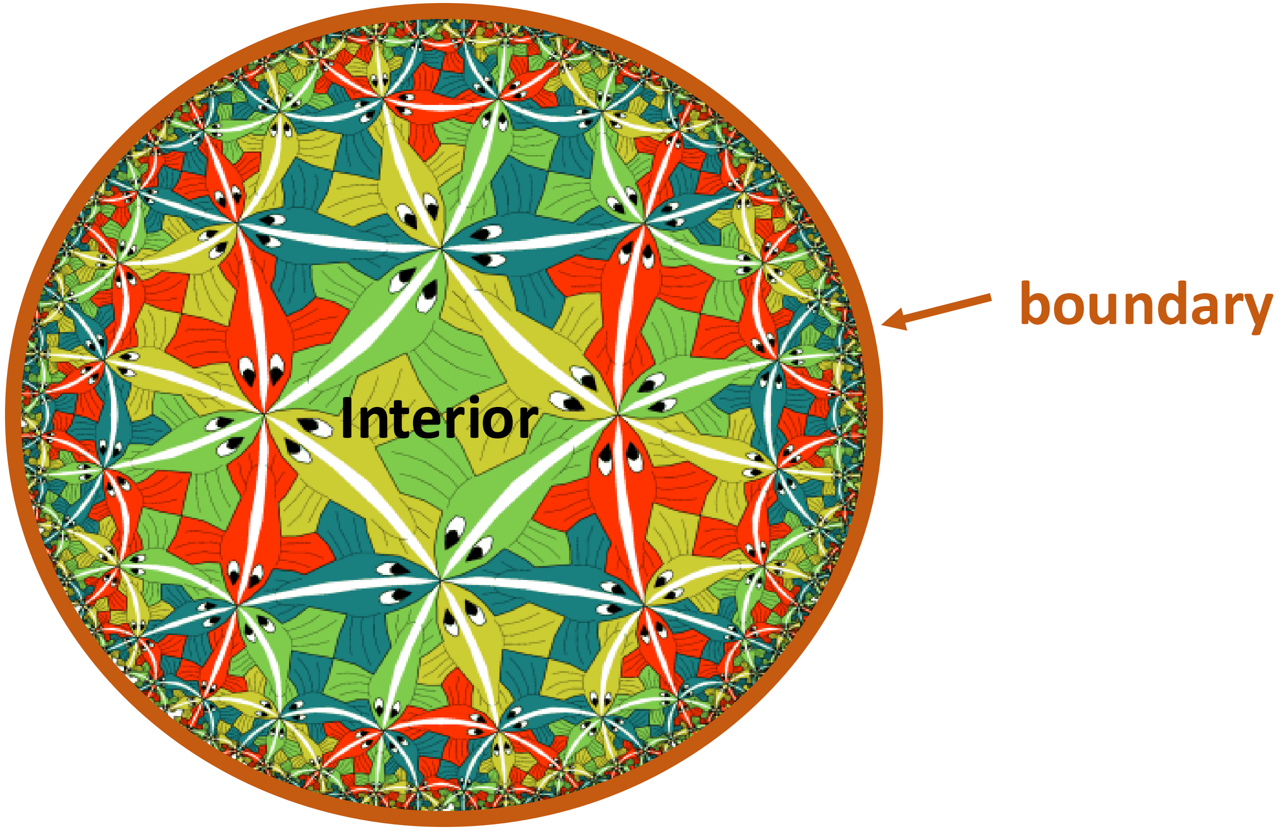
We can describe the physics of gravitational spacetimes in terms of particles (or qubits) living at its boundary.

The boundary theory is strongly interacting, but with no gravity.

Conjecture!
(with evidence)

JM 1997
Gubser, Klebanov, Polyakov, Witten

Lots of further development….



We have various examples.

But one of the simplest involves a four dimensional supersymmetric version of chromodynamics.

Its dual is a five dimensional spacetime (obtained from the 10 dimensional string theory on S^5).

Strings made with gluons → fundamental strings of string theory.

Let us expand on this last point

We have been discussing strings as a theory of quantum gravity.

These strings are a speculative idea…

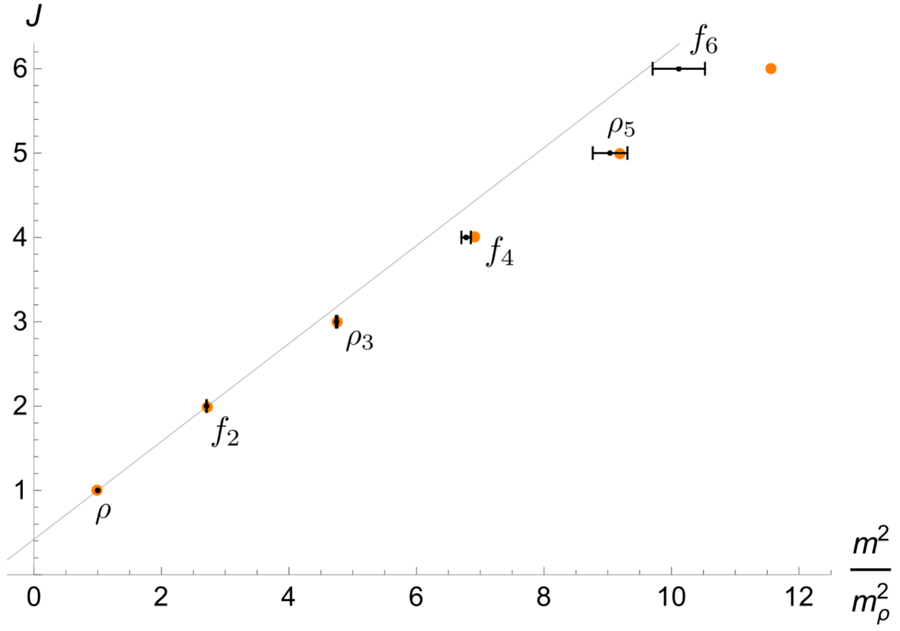
Tension = mass per unit length

↓

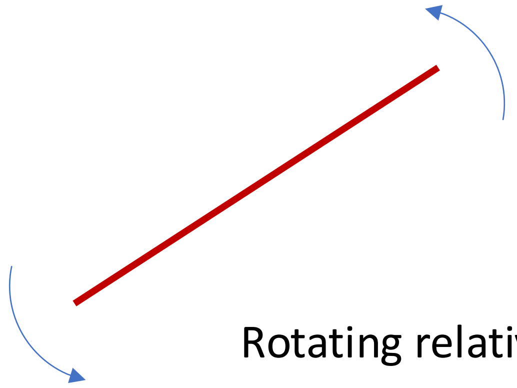
However, relativistic strings have already been observed in nature.

They were observed before string theory was invented, and they were the motivation to invent string theory!

These are the string like excitations produced by the strong interactions.



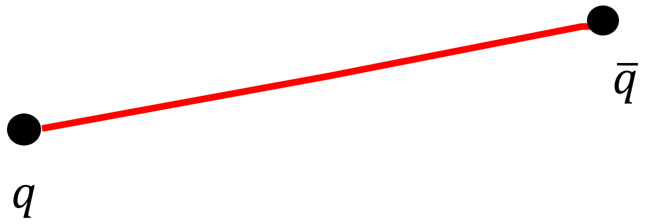
Plot from Henriksson, Rastelli, Vichi



Rotating relativistic string

We now think of them as made from gluons.

They appear if we separate a quark from an antiquark.



These strings are supposed to be simpler in the case of that the number of colors $3 \rightarrow N \gg 1$

The large N limit is precisely when the holographic duality is supposed to be valid

$$\frac{1}{G_N} \sim N^2$$

In conclusion, even if your only goal is to study four dimensional quantum field theories

→

you will encounter the ten dimensional string theory by trying to make a maximally supersymmetric version of QCD.

We will now turn to an interesting result that arose from holography

Formula for the fine grained entropy of a black hole

Ryu, Takayanagi, Hubeny, Rangamani, Faulkner, Lewkowycz, Dong, Engelhardt, Wall. (2006 – 2014)

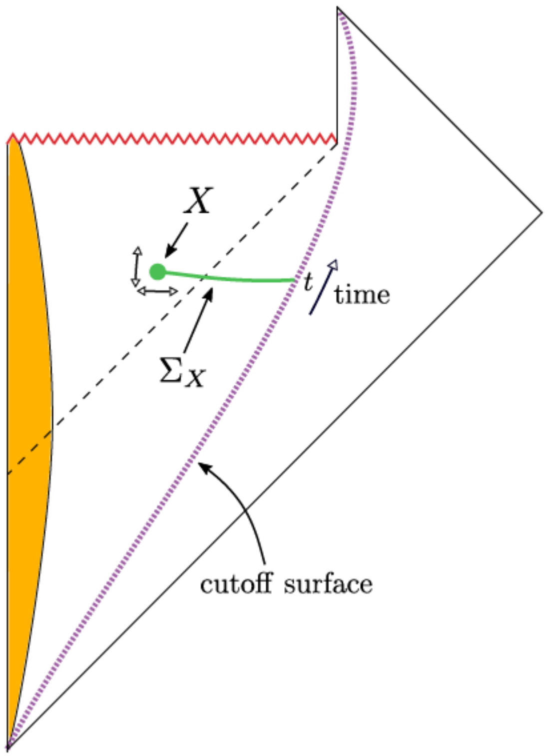
Density matrix describing the black hole in the full exact quantum theory

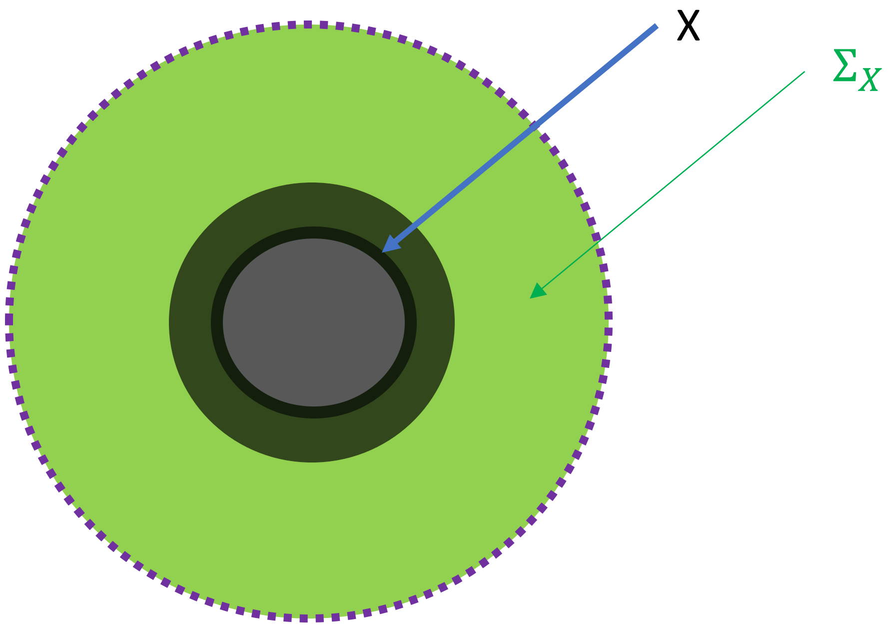
$$S = -Tr[\rho \log \rho] \sim \min_X \left\{ \text{ext}_X \left[\frac{A_X}{4G_N} + S_{\text{sm}}(\Sigma_X) \right] \right\}$$

Gravitational formula.
Partially geometric, involving an area

Formula for the fine grained entropy of a black hole

$$S = -Tr[\rho \log \rho] \sim \min_X \left\{ \text{ext}_X \left[\frac{A_X}{4G_N} + S_{\rm sm}(\Sigma_X) \right] \right\}$$





A remarkable property is that this formula depends on what is inside the black hole!

It is a guide for connecting the fundamental ``qubits’’ to the geometry of spacetime.

Also a guide for understanding how to think about the black hole interior.

The original Hawking Bekenstein formula should be interpreted as a coarse grained entropy formula. Sometimes called Boltzman entropy.

The two entropies are different for systems out of thermal equilibrium.

It is useful to distinguish between the two when thinking about dynamical processes, such as a the formation and evaporation of a black hole.

This subject has lead to fruitful collaboration with condensed matter physicists, quantum information theorists, complexity theorists, quantum chaos, etc…

Example: Ryu, Takayanagi, Hubeny, Rangamani, Faulkner, Lewkowycz, Dong, Engelhardt, Wall. (2006 – 2014)

Black holes have been a source of information

Black holes in the Lab

This connection between gravity and quantum systems suggests that we could create quantum many body systems that are strongly interacting and have a description in terms of an emergent universe governed by Einstein equations.

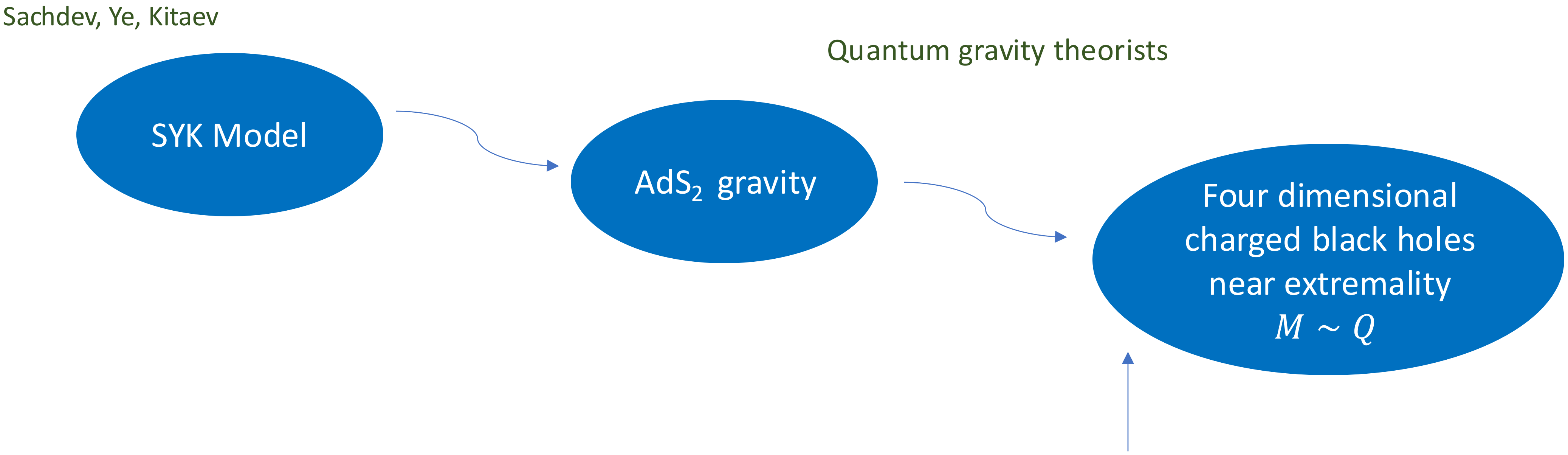
One can estimate that in order to create/simulate the simplest such universe (governed by Einstein equations) requires roughly as many qubits and number of operations, as it is necessary for breaking RSA codes with quantum computers.

These universes are small → 10^4 qubits. Our universe → 10^{120} qubits.

Number of qubits = $\frac{(Size)^2}{l_{Pl}^2}$

We will now discuss another example of a fruitful exchange of ideas with condensed matter physicists

SYK and near extremal black holes



There are important (and calculable) quantum gravity effects as we approach extremality, as M → Q

Could these black holes be observed in nature ?

We can envision magnetically charged blackholes, with magnetic monopole charge

These are interesting configurations that are compatible with the known laws of nature.

Unfortunately, they would be hard to produce in the early universe…

But if they were somehow produced… (a big wish…)

They would evaporate to extremality, M=Q. And would be long lived, even if they are small.

For example, they could weigh a few kilograms.

You could have them in your lab and one can measure their Hawking radiation
with table top energies in a regime dominated by quantum gravity.

Black holes with magnetic monopole charge.

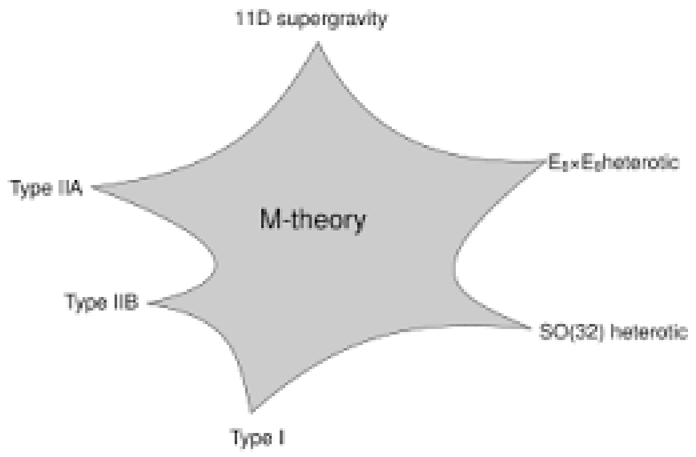
They could weigh a few kilograms and you could have them in your lab and one can measure their Hawking radiation with table top energies in a regime dominated by quantum gravity.

No exotic physics, only an exotic state within the known physics.

Unfortunately, it seems unlikely that they were naturally produced in the universe…

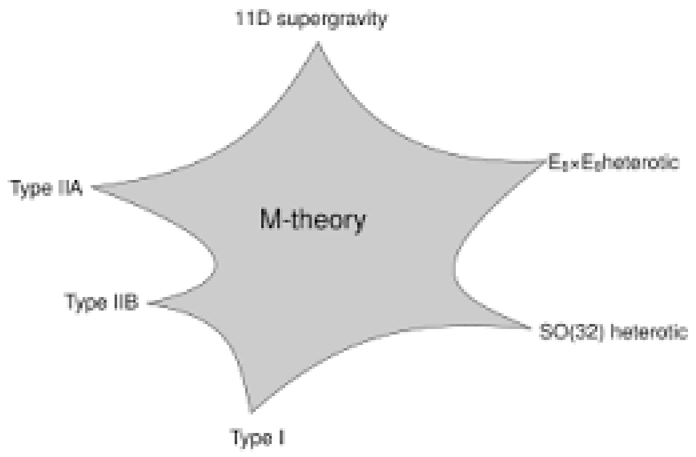
We have not discussed some other interesting ``dualities'' relating various variants of string theory.

And also an 11d phase of the theory that does not contain strings as elementary objects.



We only understand various corners.

There is a bigger structure, which is continues to be called ``string theory’’ …



In conclusion

- Quantum gravity remains an unfinished business from the 20th century
- We do not yet have a quantum gravity theory that can describe all phenomena of interest.
- String theory is a theory under construction has shown interesting theoretical connections with other areas of physics and mathematics.
- It has answered some theoretical questions involving thought experiments involving black holes.
- It seems to be rich enough to give rise to our universe, but also to many other alternative universes…

How can we imagine testing ideas of quantum gravity?

- Detecting gravity waves from inflation.
- Detecting cosmic strings (that are weakly interacting)
- Magnetic black holes.

} Require some luck..

- Finding some prediction for the parameters of the Standard Models.

- Quantum gravity from quantum systems. (Artificial universes, not our own, but interesting for exploring ideas in quantum gravity)

The Future

- Better understanding of quantum gravity/string theory.

- Find some prediction for parameters of the Standard Model.

- Explain some feature of our universe that we have not yet realized is connected to quantum gravity!

Thank you !

Topics

- 1) Quantum + GR
- 2) quantum GR as an effective theory
- 3) Successes : BH, Cosmological perturbations.
- 4) Black holes. Hawking radiation, entropy formula
- 5) Cosmological perturbations = intimate connection with black hole radiation. Formulas for the temperature.
- 6) Experiment → gravity waves from inflation.
- 7) Why do we need more? Why now?
- 8) Problems that the current approach cannot solve: BH, BB, SM par, others we don't yet recognize…
- 9) Black Bodies and BH.
- 10) Central dogma
- 11) Entropy formula philosophy. Coarse grained vs fine grained. New entropy formula.
- 12) Information about the interior.
- 13) New formulas for Hawking Radiation.
- 14) More concrete examples of black holes. Holography.
- 15) Black holes in the laboratory ?
- 16) Interaction between QI people, CM and quantum gravity theorists. (Particle theorists of course …).
- 17) Black holes and ``simple'' quantum systems, near extremal black holes.
- 18) Very near extremal black holes becomes strongly quantum mechanical at low temperatures → can be solved exactly → predictions & connections to SYK.
- 19) Near extremal black holes in nature? → Magnetic black holes.
- 20) String theory? (See what Ashoke says. I will not have time.).