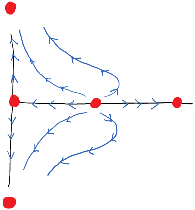
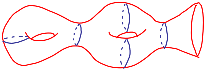
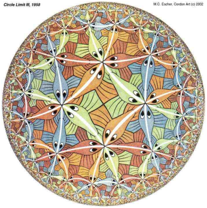
Quantum Field Theory & Quantum Gravity







Alex Maloney, McGill University

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Quantum Field Theory

Quantum Field Theory is the basic language of particle physics.

It is the most quantitatively successful predictive framework in the history of science.

The standard model is a remarkable success, but:

- Many important QFTs (e.g. QCD) are strongly coupled,
- It does not include gravity.

These two problems are related!

Quantum Gravity

General Relativity and Quantum Field Theory appear incompatible.

- In QFT, time evolution is *Unitary*
- In general relativity time is *dynamical*.

This is most apparent in studies of Black Hole physics:

- Hawking's information paradox.

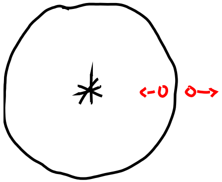
In resolving this paradox, it turns out that black holes:

- Describe universal aspects of field theory dynamics.
- Are effective tools for understanding strongly coupled QFT.

Hawking Radiation

A black hole is an object so dense that nothing, not even light, can escape from behind the event horizon.

But in quantum mechanics a black hole will decay



due to Hawking Radiation, with temperature

$$T_H = \frac{\hbar c^3}{8\pi GM} \ .$$

Black Hole Entropy

The first law of thermodynamics

$$dE = T\ dS$$

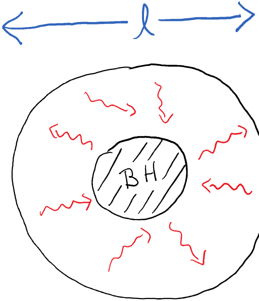
implies that black holes have an Entropy

$$S_{BH} = \frac{A}{4\ell_p^2} \qquad \ell_p = \sqrt{\frac{G\hbar}{c^3}} \sim 10^{-35}\ m$$

proportional to the area A of the event horizon.

Gravity in a Box

Black holes are unstable, so it is better to study gravity in a box.



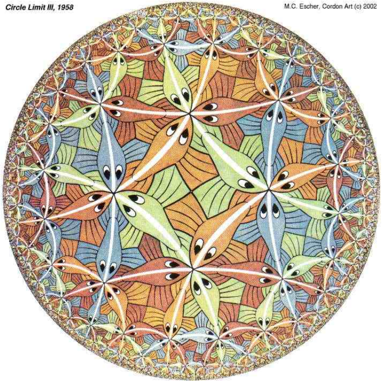
A typical high energy state, with

$$E \gg c \equiv \frac{\ell}{\ell_p}$$

is black hole in equilibrium with its Hawking radiation.

Anti-de Sitter Space

Let's build our box out of geometry: Anti-de Sitter space (AdS).



As you go towards the boundary, distances rescale in size by a constant factor.

- AdS has a conformal symmetry.

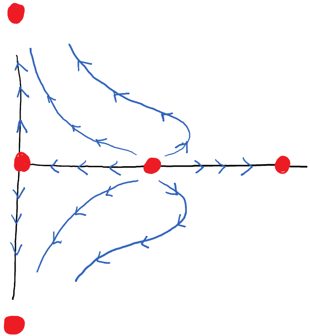
AdS/CFT

A theory of gravity in AdS is equivalent to a *Conformal Field Theory* (CFT) on the boundary of AdS.

CFTs are the building blocks of quantum field theory:

- They describe theories with no dimensionful scale.

They are fixed points of renormalization group flow:



AdS/CFT 2

Many examples can be understood precisely.

AdS Gravity	$c = \ell/\ell_p$	CFT
3D General Relativity	1/2	2d Ising Model
3D General Relativity	7/10	Tricritical Ising Model
$SL(3)$ gravity	4/5	2d Potts Model
Chiral Gravity	24	Monster CFT
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Higher Spin Gravity	N Large	3d $O(N)$ Model
IIB String Theory	N Large	4d $SU(N)$ Super Yang-Mills

They relate gravity to *gauge theories* much like the standard model.

CFT Universality

Black hole dynamics is *universal* and should apply generically.

- Every CFT is secretly a theory of black hole dynamics.
- This provides novel insights into strongly coupled QFT.

For example,

$$\rho(E) \approx \exp\left\{4\pi\sqrt{\frac{cE}{12}}\right\}$$

This is universal, in that it depends only on $c = \frac{\ell}{\ell_p}$.

It has a gravitational interpretation as black hole entropy:

$$\log \rho(E) = \frac{A}{4\ell_p}$$

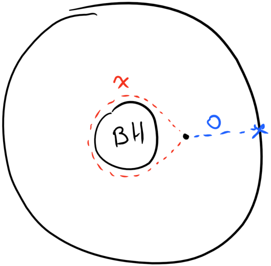
Black Hole Geometry

We can even see the black hole geometry emerging from the statistics of CFT observables.

For example,

$$\overline{\langle i|\mathcal{O}|i\rangle} \approx C_{\mathcal{O}\chi\chi} \sqrt{E_i}^{E_{\mathcal{O}}} e^{-2\pi\sqrt{E_i}E_\chi}$$

This matches Hawking emission by black holes:



Outlook

Gravity $\approx$ universal subsector of any theory with many DOF.

- Novel window on the dynamics of strongly coupled QFT.

Relations with:

- Strongly coupled QFTs, such as QCD.
- The classification of QFT.
- Deeper understanding of quantum gravity.
- Quantum information theory.
- Quantum chaos.
- Observational aspects of BH physics.
- Cosmology, both early and late time.

Thank you!