# Thoughts on Quantum Gravity

David Tong
University of Cambridge

The Structure of Gravity and Spacetime, Oxford, February 2014

# Gravity is Weak

$$l_p = \sqrt{\frac{G\hbar}{c^3}} \approx 10^{-35}\ m$$

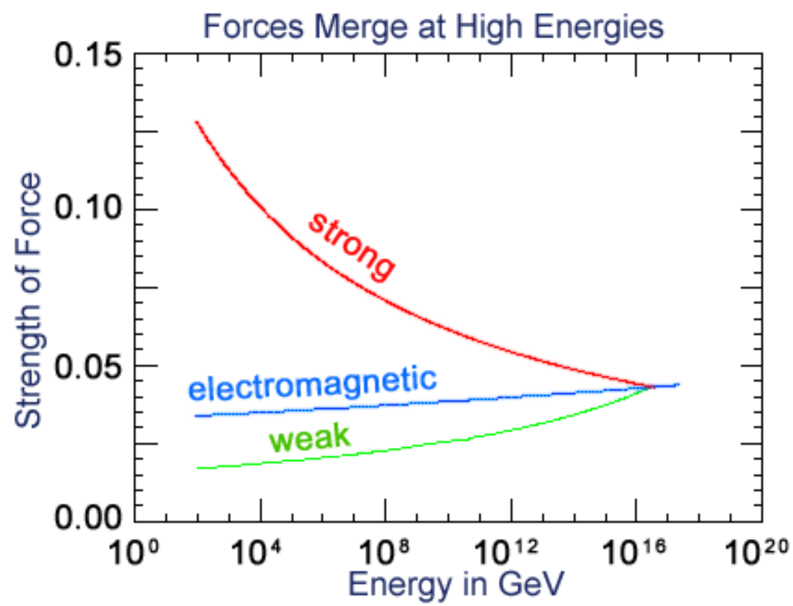
# …Really Weak

$$\frac{E_{\text{experiment}}}{E_{\text{Planck}}} \approx 10^{-15}$$

# How to Overcome This?

- Large extra dimensions?
- Planck suppressed operators in inflation?
- Large number of particles?
- Long periods of space/time?

# Why do we think it's even possible to talk about this?



# A Naïve Attempt at Quantum Gravity

# What goes wrong with the obvious approach?

$$[G] = (\text{Length})^2 = (\text{Energy})^{-2}$$

⇨ Dimensionless coupling is $GE^2$

⇨ Theory is weakly coupled in the IR and strongly coupled in the UV. We can only use it to compute IR quantities.

(This usually goes by the more scary sounding name of "non-renormalisability")

(in units with $c = \hbar = 1$ )

# So what happens in the UV?

- New degrees of freedom
  - String theory
  - (Also chiral lagrangian for pions, Fermi theory)
- A strongly interacting fixed point
  - Asymptotic safety
- Explicit Cut-Off
  - Causal Dynamical Triangulation
  - Loop quantum gravity?
  - Causal set theory
  - (Also many condensed matter contexts)

# A Toy Model: 5d Yang-Mills

$$S = \frac{1}{4g^2} \int d^5x \ \mathrm{Tr} \ F_{\mu\nu} F^{\mu\nu}$$

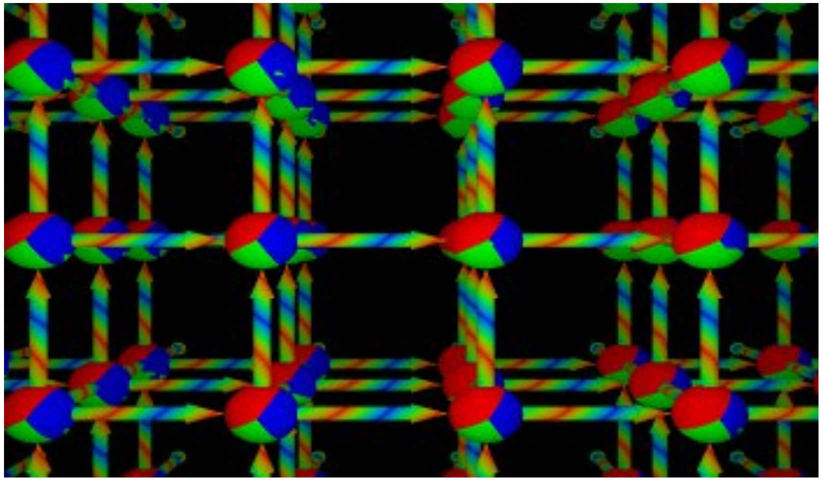
$$[g^2] = (\mathrm{Length}) = (\mathrm{Energy})^{-1}$$

- Theory is weakly coupled in the IR.
  - It is described by non-linear classical field theory

- It is strongly coupled in the UV
  - And non-renormalisable

# 5d Yang-Mills with a cut-off

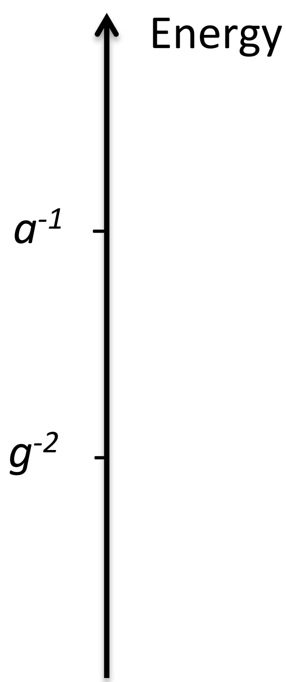
Lattice gauge theory in 5 Euclidean dimensions



Lattice spacing: $a$
Gauge coupling: $g^2$

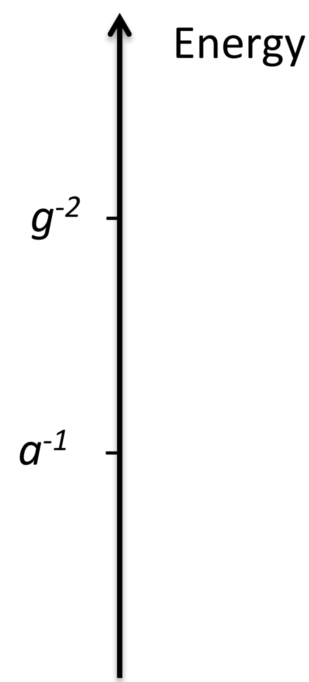
# Different Phases

$$a \ll g^2$$




- Strongly coupled at cut-off
- In confining phase in IR

$$a \gg g^2$$

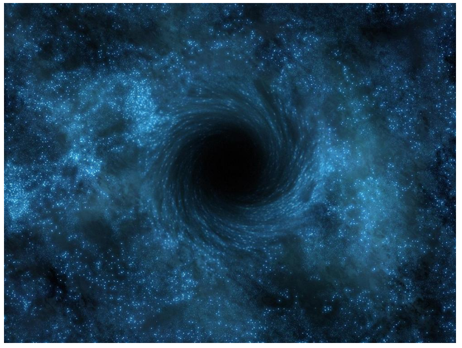



- Weakly coupled at cut-off
- 5d Yang-Mills at low energies
- Looks nothing like YM at scale $g^2$

# High Energies in Gravity

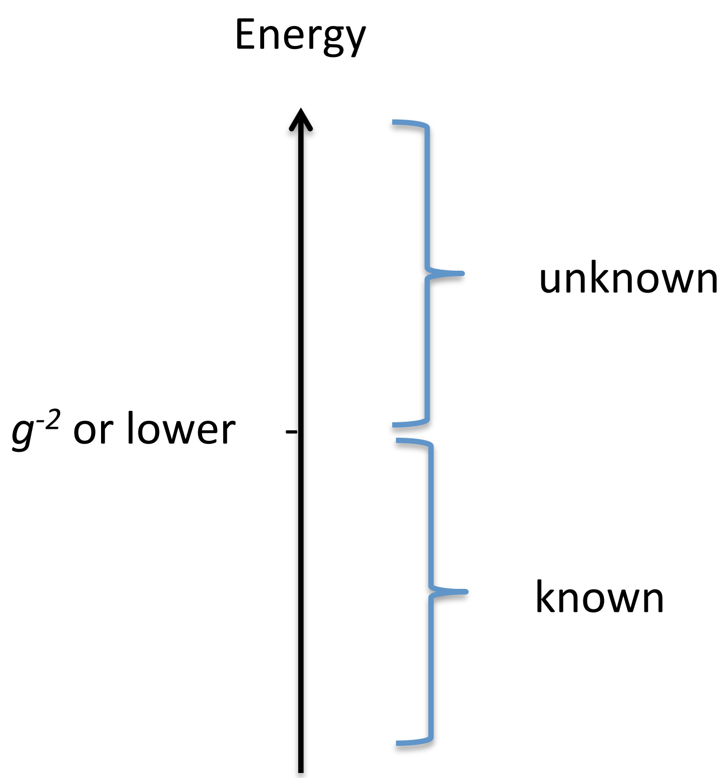
# High Energies in Gravity

Collide two particles at energies much greater than $E_p$. You create a black hole.

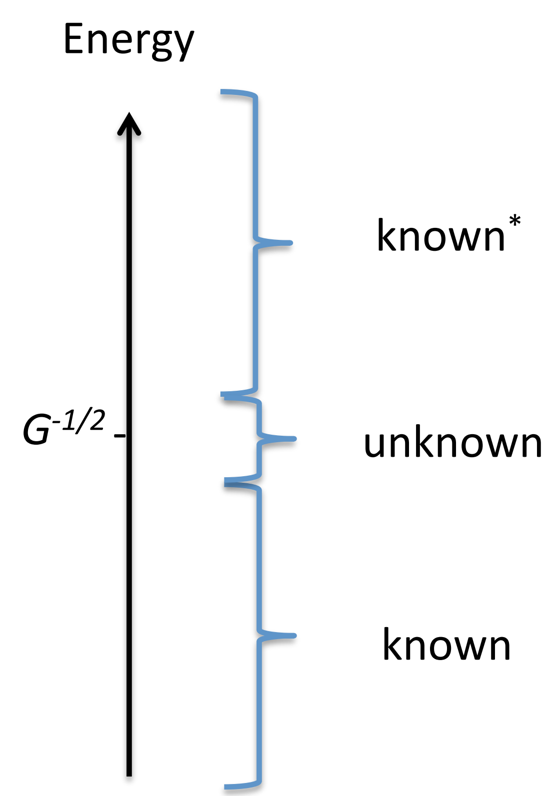


We don't need quantum gravity to tell us this. Classical gravity is enough.
All the quantum stuff is hidden behind the horizon, near the singularity.

# Scattering in Non-Renormalisable Theories



# Scattering in Gravity

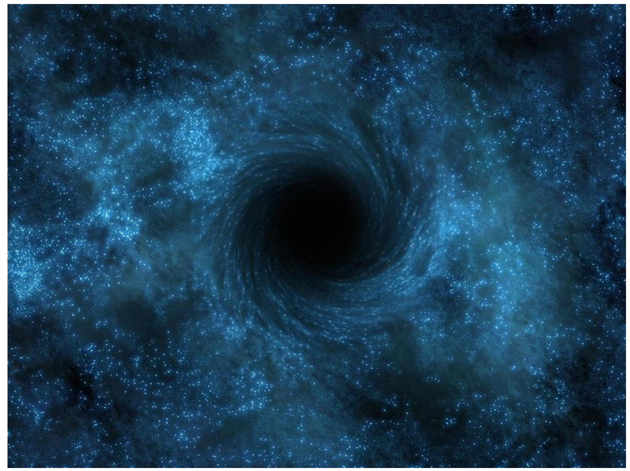



What does this mean?

*Until black hole evaporates!

# A Low Energy Handle on Fundamental Degrees of Freedom

# Black Hole Thermodynamics



$$T = \frac{1}{8\pi GM} \qquad S = \frac{A}{4G}$$

Likely interpretation: $e^S$ counts number of black hole microstates.

- Fundamental degrees of freedom
- Holography
- What about de Sitter entropy?

Bekenstein; Hawking

# Thermodynamics and Hydrodynamics

Why is there such a close relationship between gravity and thermodynamics?

- Well understood in anti de Sitter space
  - Thermodynamics of boundary field theory
  - Navier-Stokes = Einstein equation
- What is the comparable story with other asymptotics?

$$dQ = TdS \quad \Rightarrow \quad R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = T_{\mu\nu}$$

Jacobson

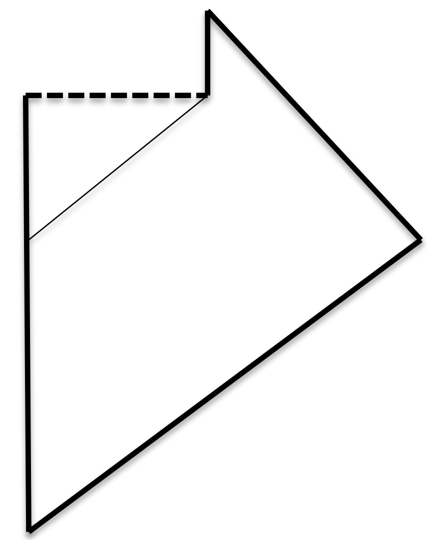
- Gravitational metric is an emergent, thermodynamic quantity
  - But why, then, is it governed by a Hamiltonian system?

# What we don't understand

Information Paradox

- Information preserved
  - QFT in curved spacetime breaking down when curvatures are small and GR says "trust me"

- Information lost
  - Quantum mechanics breaks down



# What can we measure?

# Observables

In quantum field theory we compute correlation functions

$$\langle \mathcal{O}(x_1) \dots \mathcal{O}(x_n) \rangle$$

In gravity these are no good. They are not gauge (diffeo) invariant.

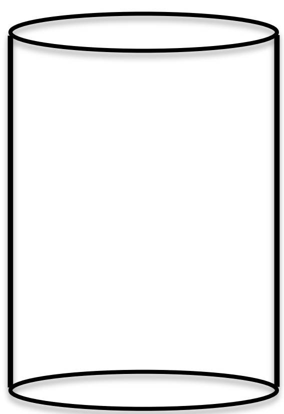
What replaces them?

# Boundary Observables

The simplest observables depend on the asymptotics of spacetime.

Anti-de Sitter

$\Lambda < 0$

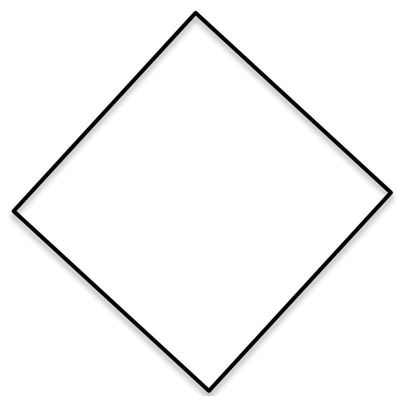


$\langle \mathcal{O}(x_1) \ldots \mathcal{O}(x_n) \rangle$

boundary correlation functions

Minkowski

$\Lambda = 0$

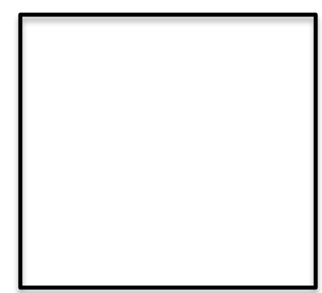


$\langle f | i \rangle$

S-matrix

de Sitter

$\Lambda < 0$



Spacelike boundary at future and past infinity. Observables not observable!

# Relational Observables

$$\langle \int d^4x \sqrt{-g}\, \mathcal{O}_1(x)\ \delta\left(\mathcal{O}_2(x) - 42\right)\rangle$$

- In AdS, same as boundary observables
- What about in Minkowski and dS?

# Quantum Gravity Hides

# Cosmic Censorship Conjecture

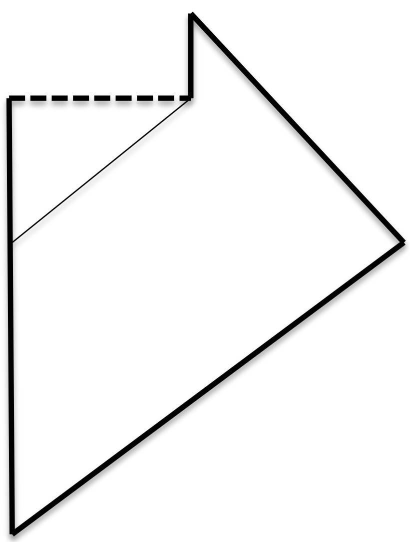

- Weak cosmic censorship: singularities buried behind horizons
  - Why?

- Not true in 5d GR (or 5d Yang Mills)

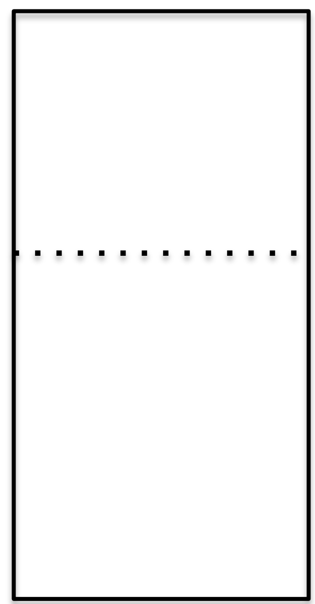
Penrose

# Testing Quantum Gravity is Harder Than it Should Be!

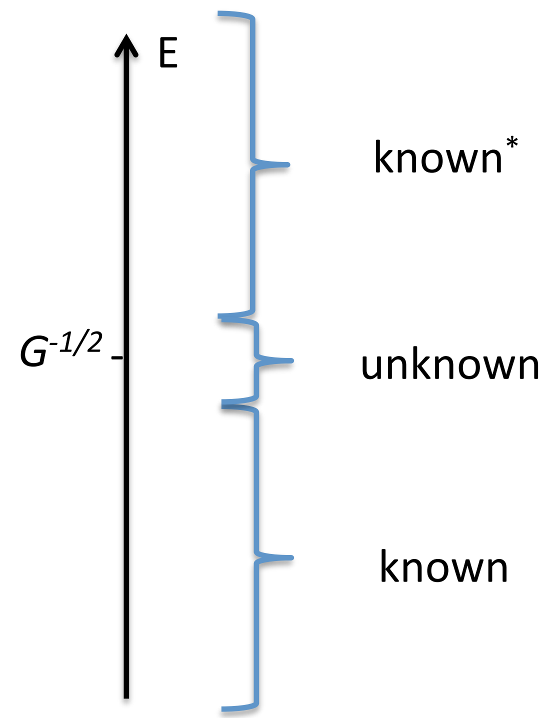
Cosmic Censorship



Inflation



Scattering




Why? What is this telling us?

Thank you for your attention