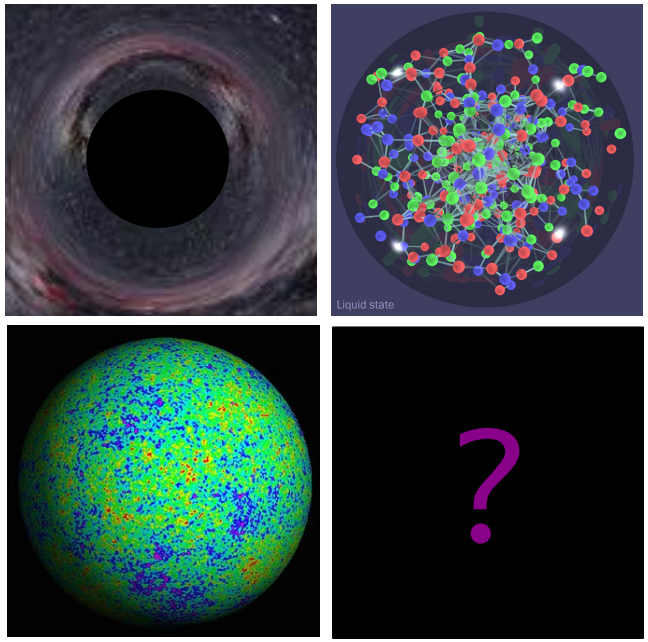
Duality and Holography



Joseph Polchinski

KITP UCSB

NSF FQXi Foundational Questions Institute

UC Davis, 5/16/11

Which of these interactions doesn't belong?

a) Electromagnetism
b) Weak nuclear
c) Strong nuclear
d) Gravity

a) Electromagnetism

b) Weak nuclear

c) Strong nuclear

The basic theoretical framework (Quantum Field Theory/Gauge Theory) is understood, to the extent that any calculation can be reduced to an algorithm (e.g. lattice gauge theory).

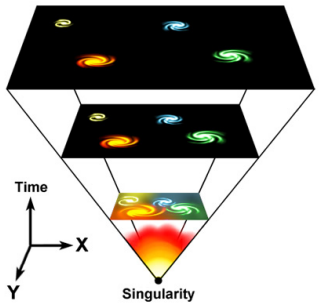
• Spacetime is dynamical, and quantum mechanical.

• UV divergences/ spacetime foam:

d) Gravity

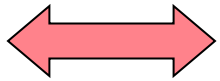
• Quantum black hole puzzles - entropy and information

• Spacetime singularities, initial conditions



• Space, and perhaps time, are probably emergent, not fundamental.

The remarkable discovery is that these two kinds of theory are dual.

gauge theory  Gravity

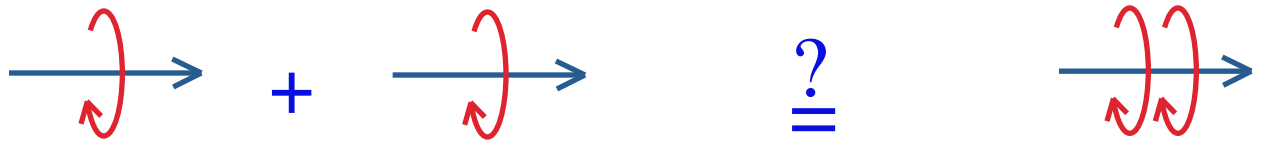
- The same theory, expressed in different variables

- Different classical limits of a single quantum theory (e.g. waves vs. particles).

Outline:

- Derivation 1: A wild idea
- Derivation 2: Another wild idea
- Derivation 3: Black branes and D-branes
- What this teaches us about gauge theory
- What it teaches us about gravity

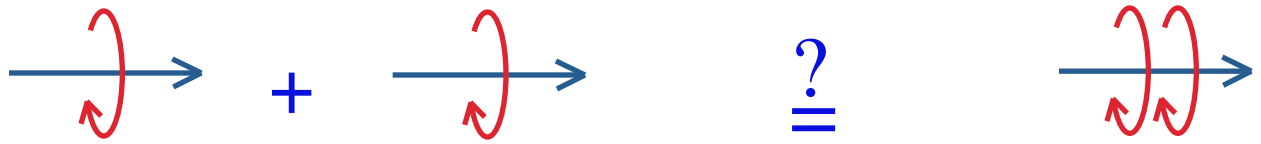
I. Wild idea: Could the spin-2 graviton be a bound state of two spin-1 gauge bosons?



photons, or gluons

graviton

I. Wild idea: Could the spin-2 graviton be a bound state of two spin-1 gauge bosons?



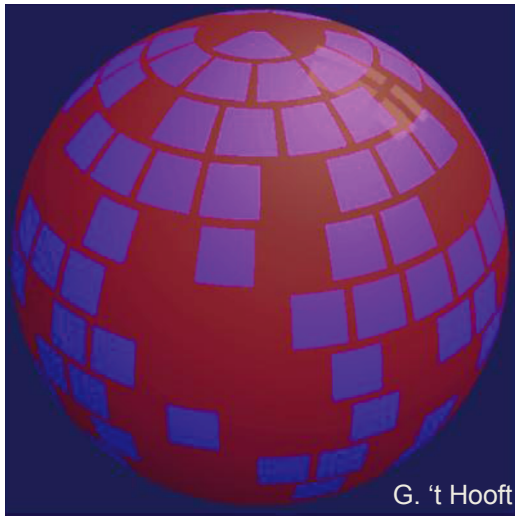
photons, or gluons graviton

No-go theorem! (Weinberg & Witten, 1980): *special relativity* and *general relativity* are very different, there are many fewer *observables* in GR. This leads to a contradiction.

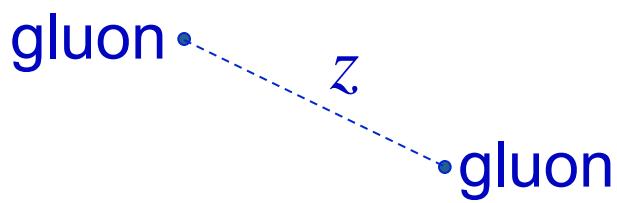
This is a powerful theorem, but has a hidden assumption that allows for an exception.

Hidden assumption: the graviton moves in the same space as the gauge bosons it is made of!

The *holographic principle* ('t Hooft, Susskind): quantum gravity in any space can be formulated in terms of degrees of freedom living on the *boundary* of the space. This is motivated by the Bekenstein-Hawking black hole entropy, $S_{\mathrm{BH}} = A/4l^2_{\mathrm{Planck}}$.



The holographic principle suggests that gauge theory in 3+1 dimensions should somehow give rise to gravity in 4+1 dimensions. But where does the extra dimension come from?

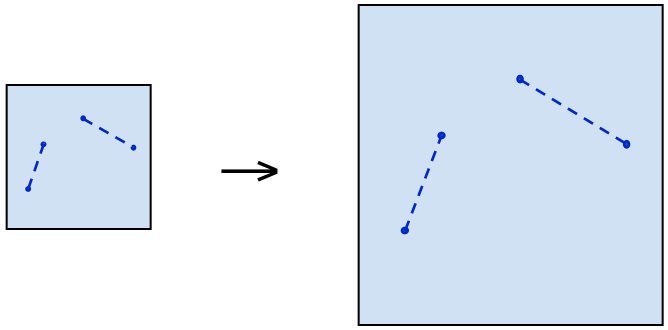


In QCD, sometime the interactions between gluon pairs are approximately local in the *separation* z (color transparency, BFKL). This behaves crudely like a fifth coordinate, where the usual four come from the center-of-mass.

`Emergent dimension'

The *shape* of the emergent spacetime:

QCD at high energy has approximate symmetry under scaling all lengths:



$$x^\mu \to \lambda x^\mu$$
$$z \to \lambda z$$

This determines the metric, up to overall radius L:

$$ds^2 = L^2 \frac{-dt^2 + dw^2 + dx^2 + dy^2 + dz^2}{z^2}$$

This is anti-de Sitter spacetime:

$$ds^2 = L^2 \frac{-dt^2 + dw^2 + dx^2 + dy^2 + dz^2}{z^2}$$

The 3+1 original dimensions are *warped.*
De-Sitter space is similar but expanding:

$$ds^2 = L^2 \frac{-dt^2 + dw^2 + dx^2 + dy^2 + dz^2}{t^2}$$

This describes 4+1 dimensional gravity from 3+1 gauge theory. To get 3+1 gravity start from 2+1 gauge theory.

'AdS/CFT'

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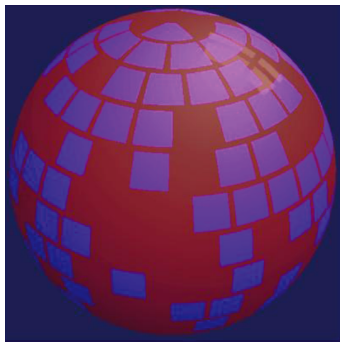
'AdS/CFT'

Two more ingredients:

- Large N (size of gauge matrices), to have enough states. 't Hooft (1974) showed that one gets an interesting limit if one replaced the 3 colors of QCD with a large number N.



- Very strong coupling, to get interesting bound states. (Precise statement: large anomalous dimensions).

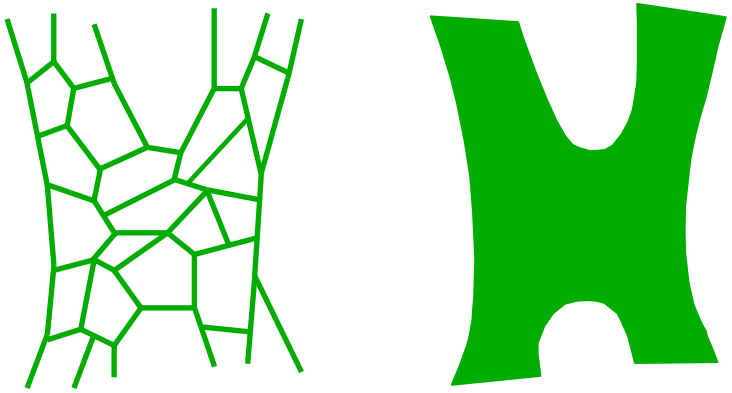
Under these conditions, gravity emerges!

We have not used *string theory.* This seems to be a new theory of quantum gravity, which only uses known principles (gauge fields).

But when we get gravity in this way, in fact we seem to get everything else: strings, branes, extra dimensions, ...

This is partly explained by an old argument of ‘t Hooft:

Large N = planar graphs.
Strong coupling limit becomes a string.



II. Another wild idea

QM + GR → spacetime fluctuations out of control at short distance. This suggests that there may be minimum distance l_P. Idea: space-space uncertainty principle:

$$[x^i, x^j] = O(l_P^2)$$

- Wild idea 1 led, with liberal hindsight, to the AdS/CFT duality of Maldacena.
- Wild idea 2 similarly leads to the Matrix Theory of Banks, Fischler, Shenker, Susskind, a close cousin.

III. Black branes and D-branes

The original derivation of gauge/gravity duality was driven by problems of black hole quantum mechanics - the *entropy puzzle* and the *information paradox*.

• The puzzle: Black hole entropy $S^2_{\rm BH} = A/4l_{\rm Planck}$ - what does this mean?

• Originally, an analogy: in classical GR, the total horizon area, like the entropy, is nondecreasing.

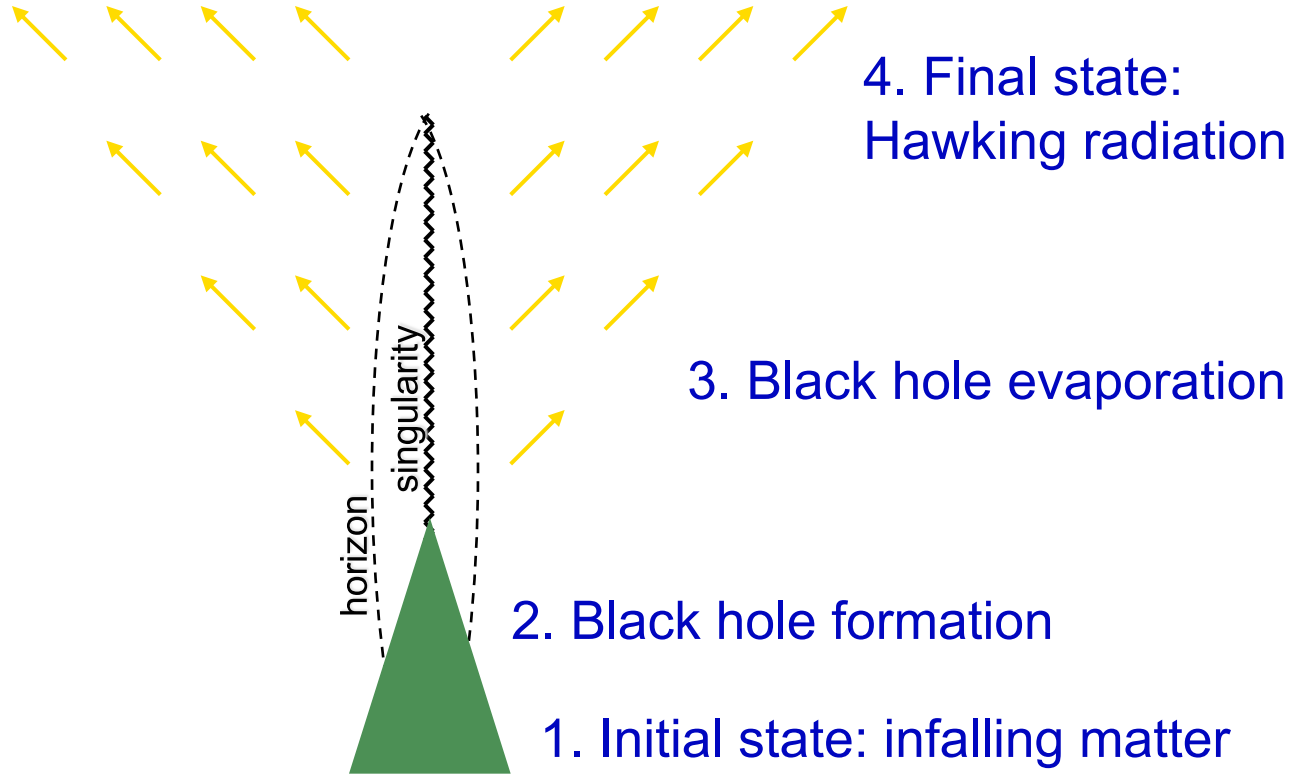
• With the discovery of Hawking radiation (1974), this is more than an analogy: only the *sum*

$$S_{\rm total} = S_{\rm BH} + S_{\rm ordinary}$$

is nondecreasing.

• But thermodynamics is a phenomenology, stat mech is the full story. What states is $S_{\rm BH}$ counting?

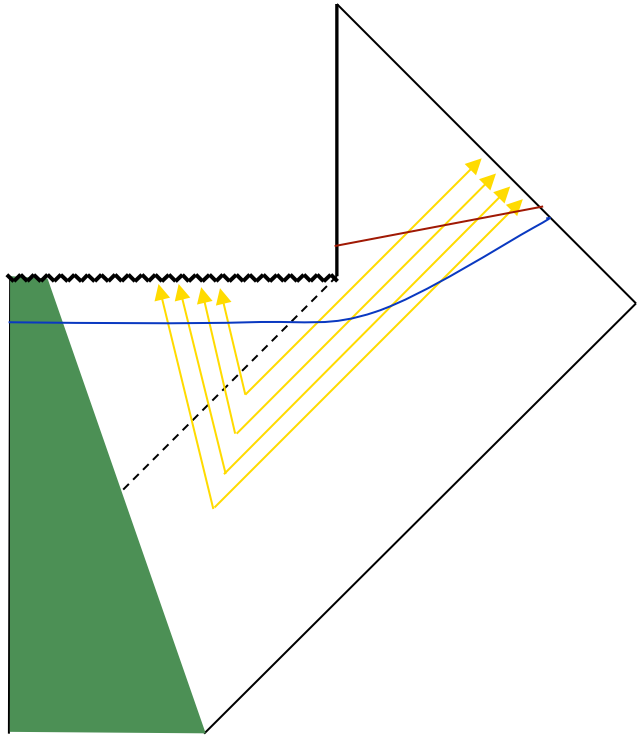
The information paradox: Hawking's thought experiment (1976).



Repeat many times, with same initial state and all possible measurements on the final state.

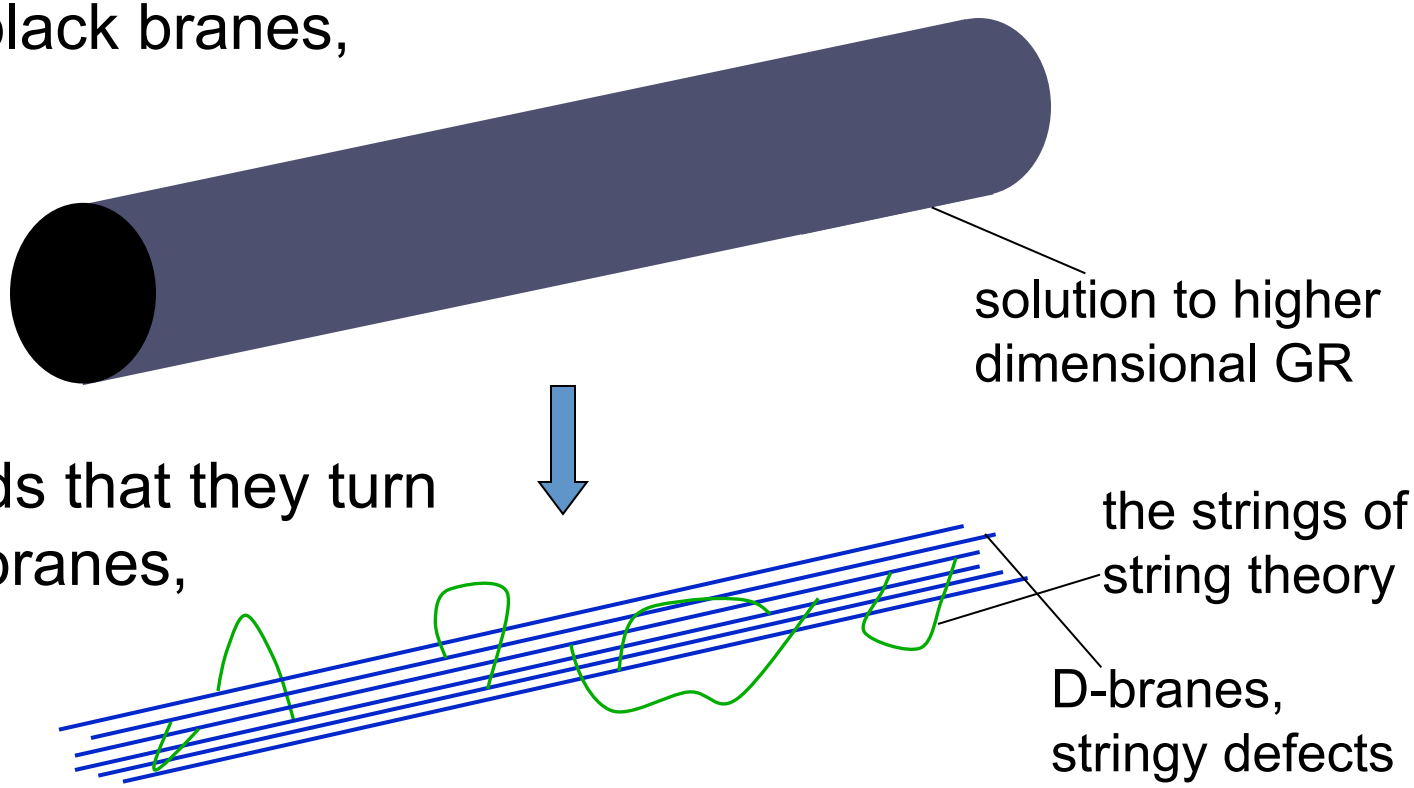
Conclusion: pure initial state evolves to mixed final state (information loss); ordinary QM is pure → pure.

Each Hawking particle is correlated with one behind the horizon; when evaporation is complete these correlations are lost.



Pure → mixed evolution is ugly and likely inconsistent. But there is no trivial resolution; the alternative seems to be a radical breakdown of spacetime locality.

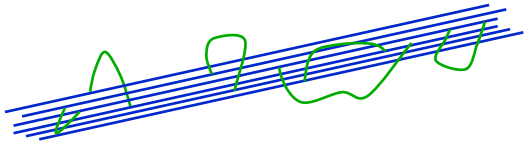
Explaining the entropy (Strominger and Vafa): imagine adiabatically reducing the gravitational coupling, so that a black hole is no longer black. For some string theory black branes,



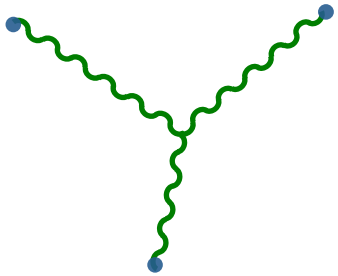
whose states we can count, and we do find S_{BH}.

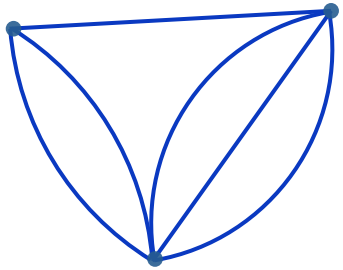
Repeat Hawking's calculation with

vs.

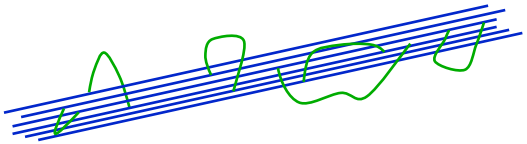


Result: very different calculations give identical answers in many cases.



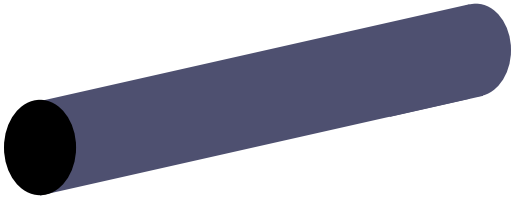


Explained by Maldacena as gauge/gravity duality.



coupling

weak strong



D-branes and strings

black hole or brane

low energy limit

low energy limit

$\mathcal{N}=4$ $SU(N)$ gauge theory

coupling

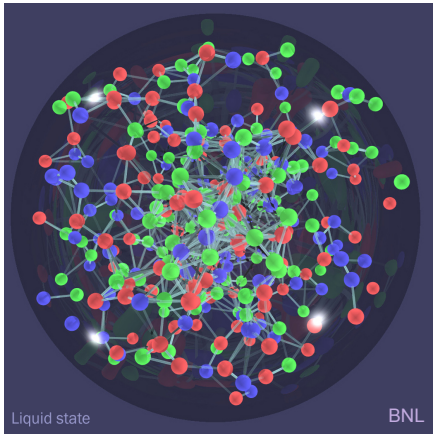
weak strong

IIB superstring with $AdS_5 \times S^5$ b.c.

A concrete example of *emergent gravity*.

One consequence: what happens if we heat the system up?

Gauge theory



Plasma

Gravity

Black hole
(highest entropy configuration)

The same object in different limits.

So, what do we learn from

Gauge theory = Gravity/string theory ?

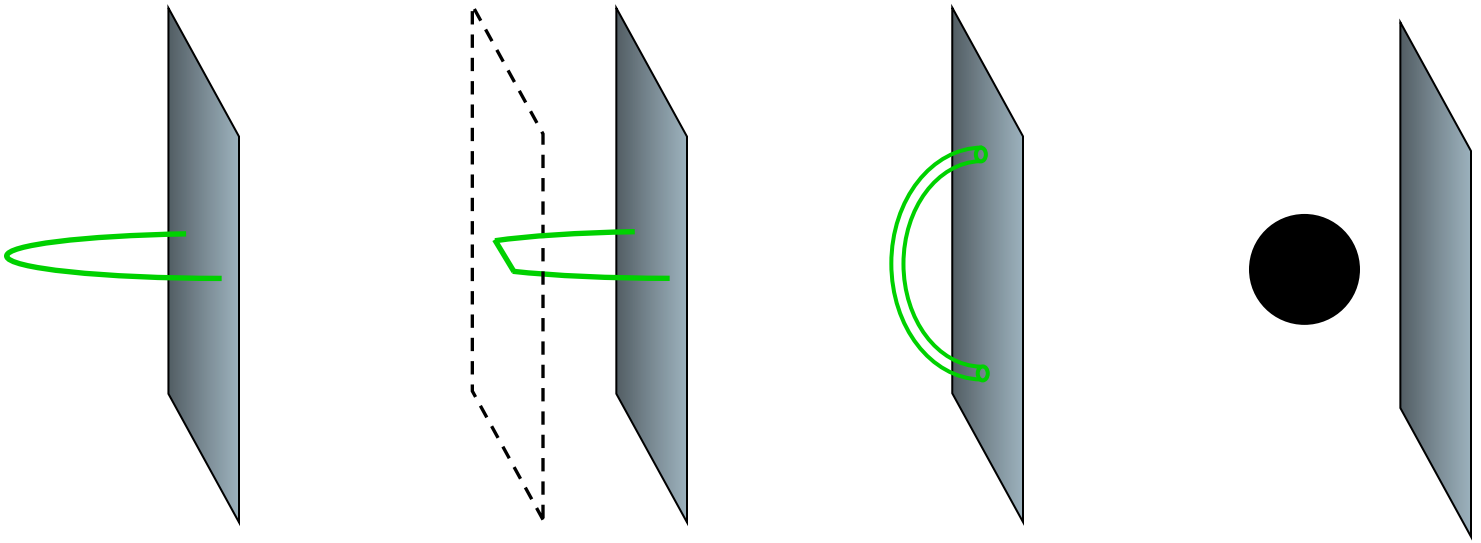
Information flows in both directions:

Gauge theory ⟵ Gravity/string theory

Gauge theory ⟶ Gravity/string theory

IV. Gauge theory ⟸ Gravity/string theory

Enables us to calculate things at strong coupling -



Coulomb force ~ g rather than g^2

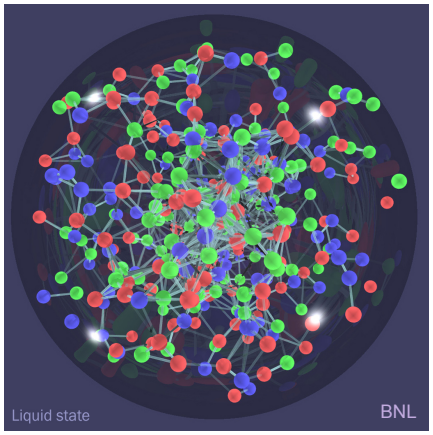
Confinement when scale symmetry broken

Anomalous dimensions ~ $(g^2 N_c)^{1/4}$

Free energy = 3/4 of free-field value.

What about real QCD?

The Relativistic Heavy Ion Collider has been making the quark-gluon plasma state. Surprise: it is much more liquid-like than gas-like --- that is, the interactions are *strong.*



QCD does not precisely fit the conditions for having a gravity dual, but it's not too far off, and much better than the ideal gas approximation. So calculate using the black hole description!

Successes:

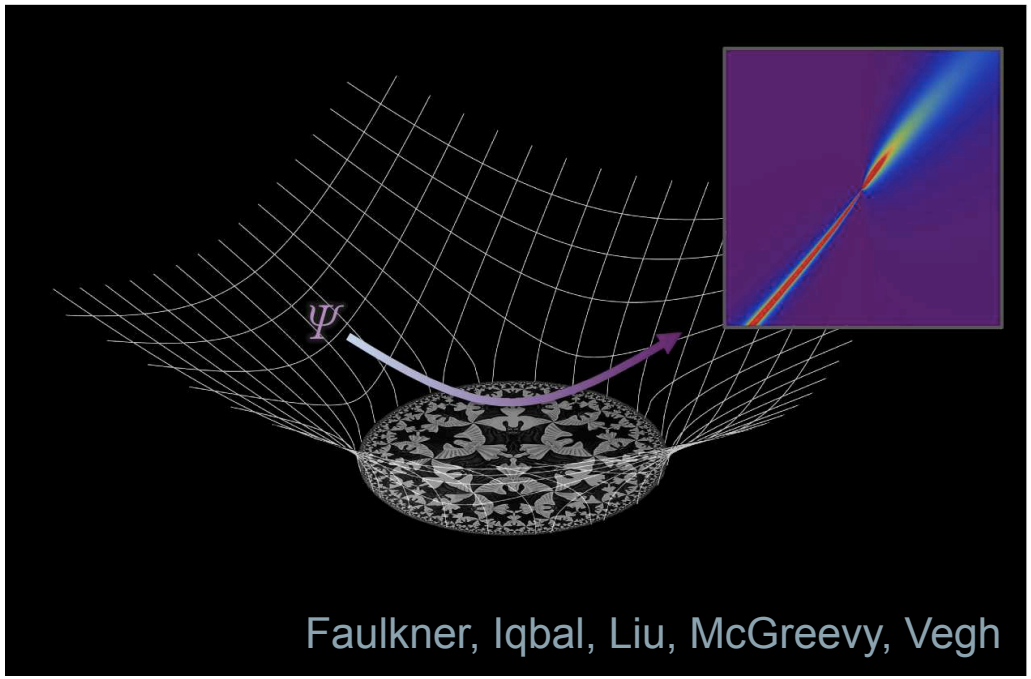
- Viscosity/entropy ~ $1/4\pi$ vs, $0.02-0.12$ measured.
  (Kovtun, Son, Starinets, 1994)
- Free energy ~ 0.8 x free field value.
- Jet quenching properties
- Heavy quark and heavy meson drag and screening.
- Higher order relativistic hydrodynamics

…

The black hole is the `spherical cow' for heavy ion collisions (K. Rajagopal).

Remarkable: using Einstein's equations for general relativity to understand nuclear collisions.

New direction: modeling strongly coupled condensed matter systems. E.g. non-Fermi liquids:



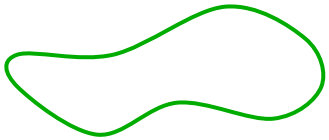
- Will this lead to new understanding of real materials?
- It is likely to lead to new ideas and universalities.
- In any case it is an remarkable connection between widely different parts of physics.

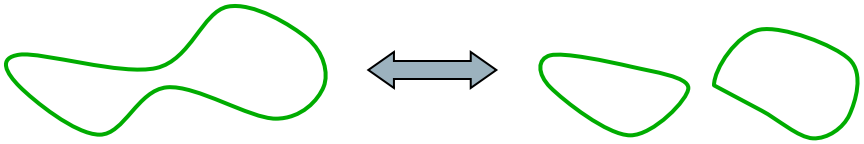
V. Gauge theory → Gravity/string theory

• AdS/CFT and Matrix Theory give a construction of string theory and quantum gravity.

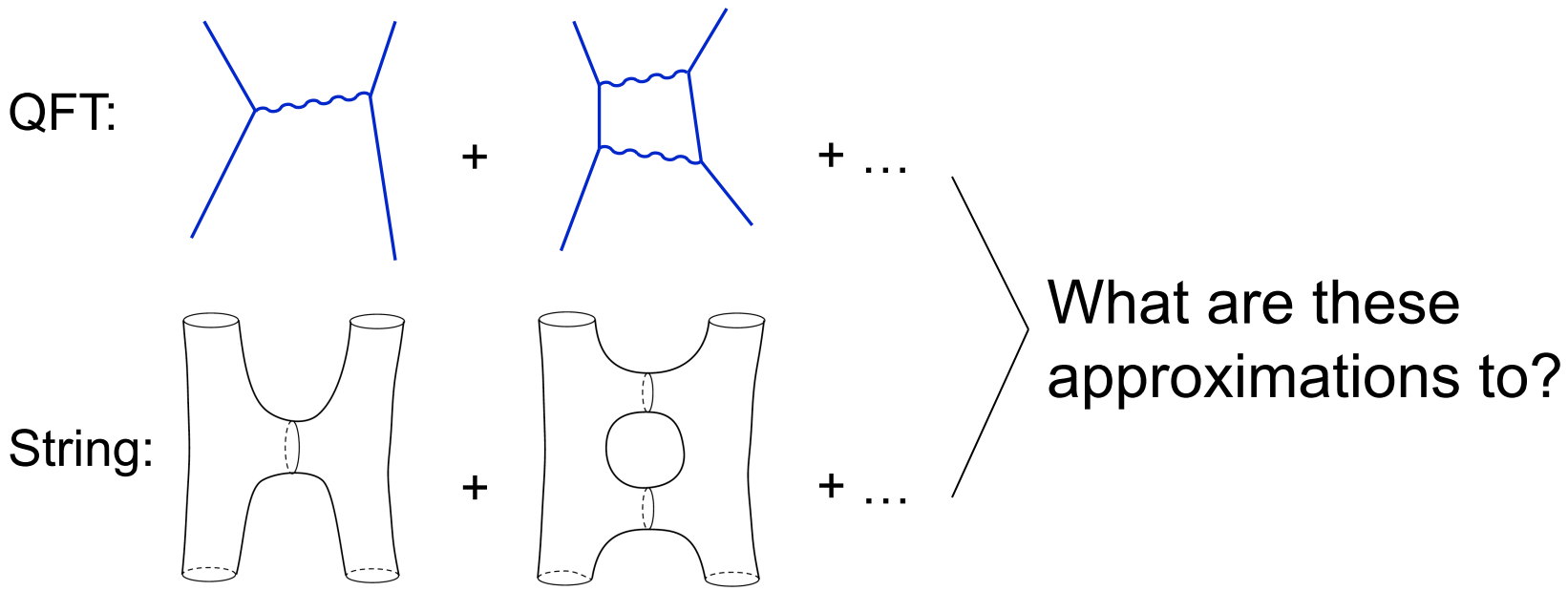
• Recall string theory:

QFT - quantize points: •

String theory - quantize curves: 

Splitting interaction: 

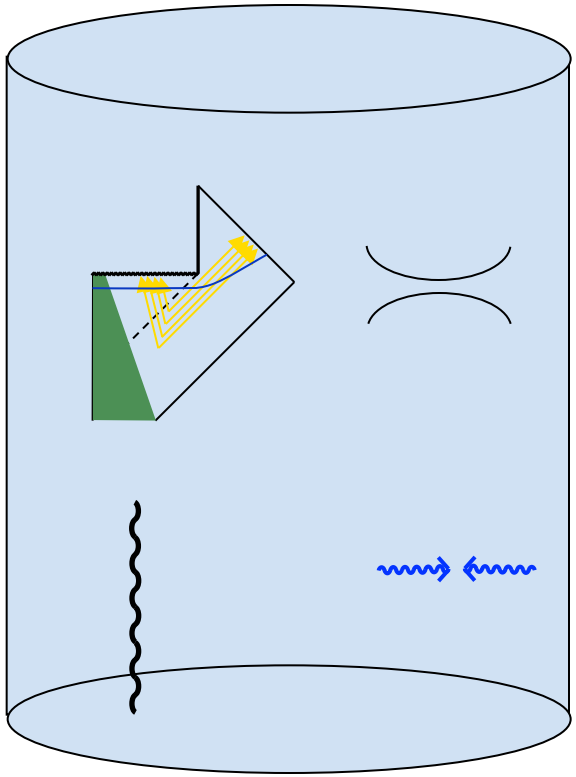
Solves UV problem. Limitation: perturbation theory only



For QFT, this was answered by Ken Wilson: precise description is path integral + renormalization group: the δ's and ε's of path integrals.

For string theory, "gauge theory ➡ string theory" now gives a partial answer, and it requires a radical new idea, holography.

Quantum gravity in an AdS box:



Black hole formation and evaporation

Spacetime topology change

Resolution of some spacetime singularities

Hyper-Planckian scattering

Any `scattering experiment' can be reduced to an algorithm.

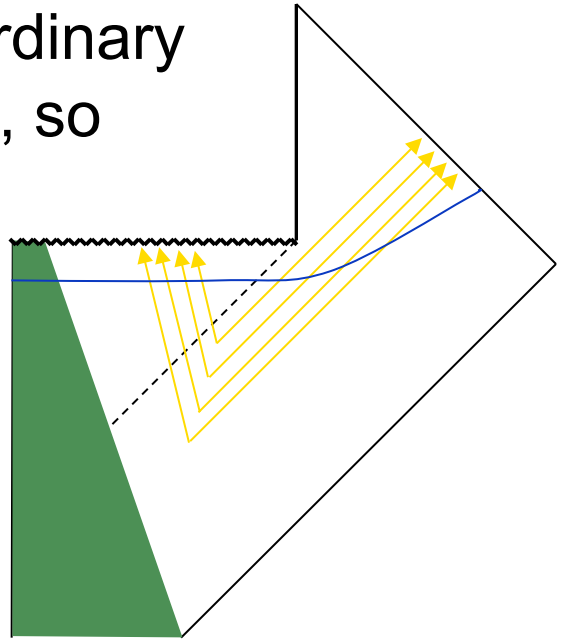
Gauge theory → Gravity/string theory

Resolves black hole puzzles and paradoxes:

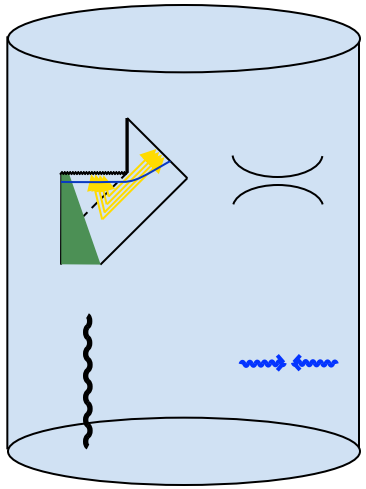
- Black holes behave like thermal systems because that is exactly what they are in the dual variables.

- Gauge theory plasmas satisfy ordinary quantum mechanics, pure → pure, so information is not lost.

- Locality must break down radically: holography.

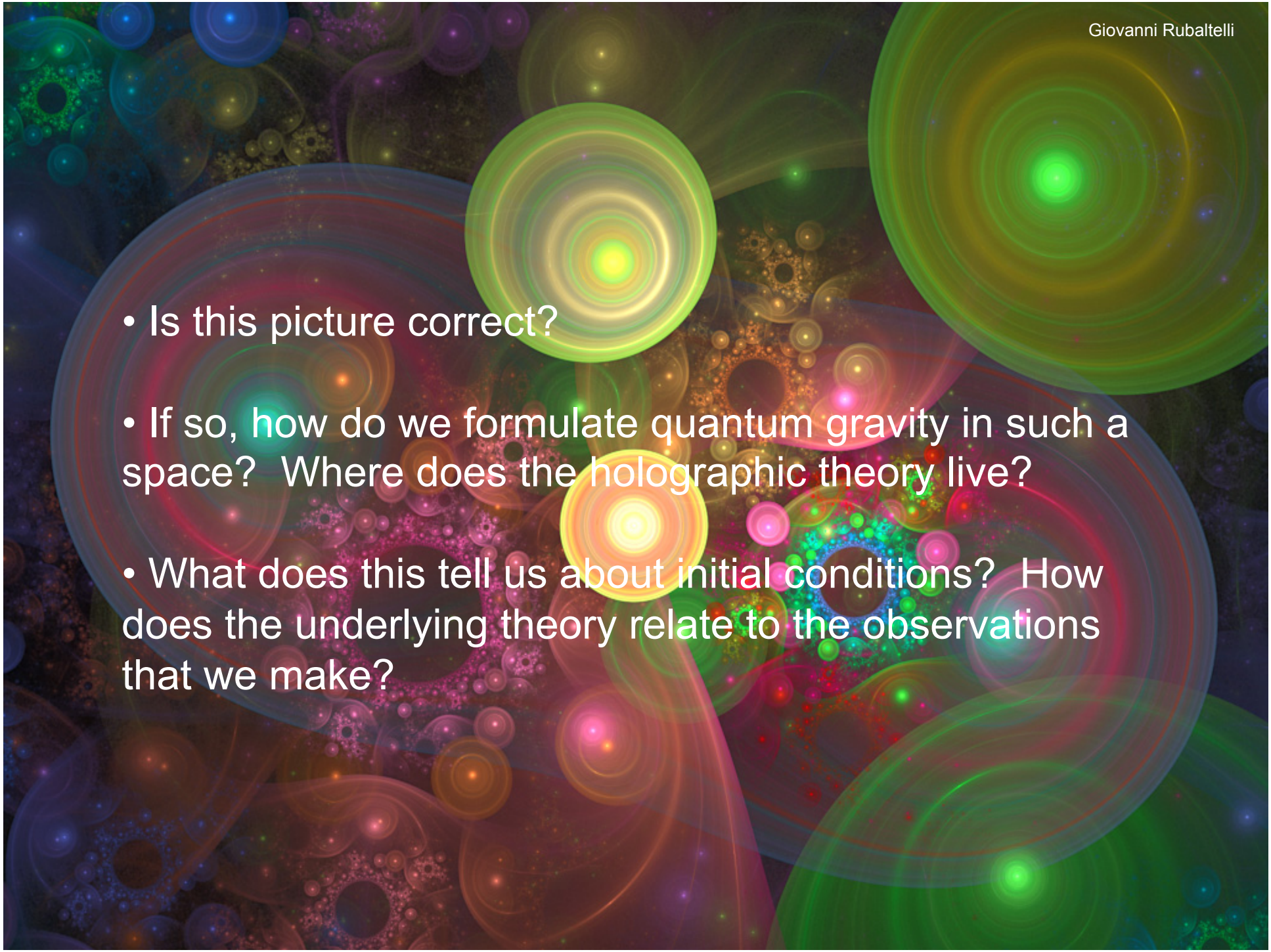


Main lesson: quantum gravity is holographic, the fundamental degrees of freedom are radically nonlocal; spacetime locality is emergent.



The challenge: we don’t live such a box…

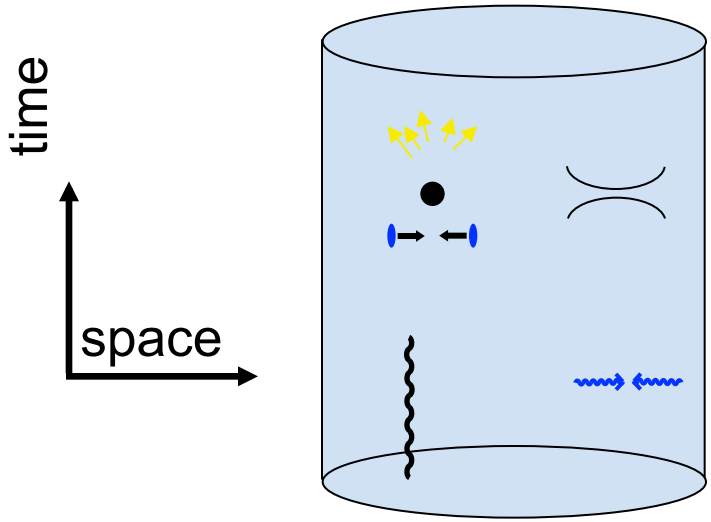

Giovanni Rubaltelli
We don’t see any walls. In fact, the universe is probably far vaster than what we see, and most of the rest very different from our own neighborhood.



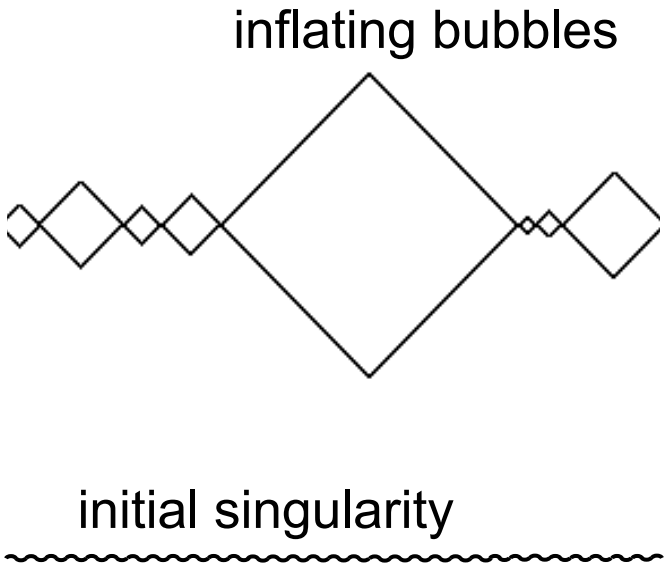
- Is this picture correct?
- If so, how do we formulate quantum gravity in such a space? Where does the holographic theory live?
- What does this tell us about initial conditions? How does the underlying theory relate to the observations that we make?

How to extend holography beyond the AdS box?

In a cosmological spacetime (de Sitter, FRW, choatic inflation) the natural boundaries are past and future, and so it is *time* that would have to emerge… what does this mean?



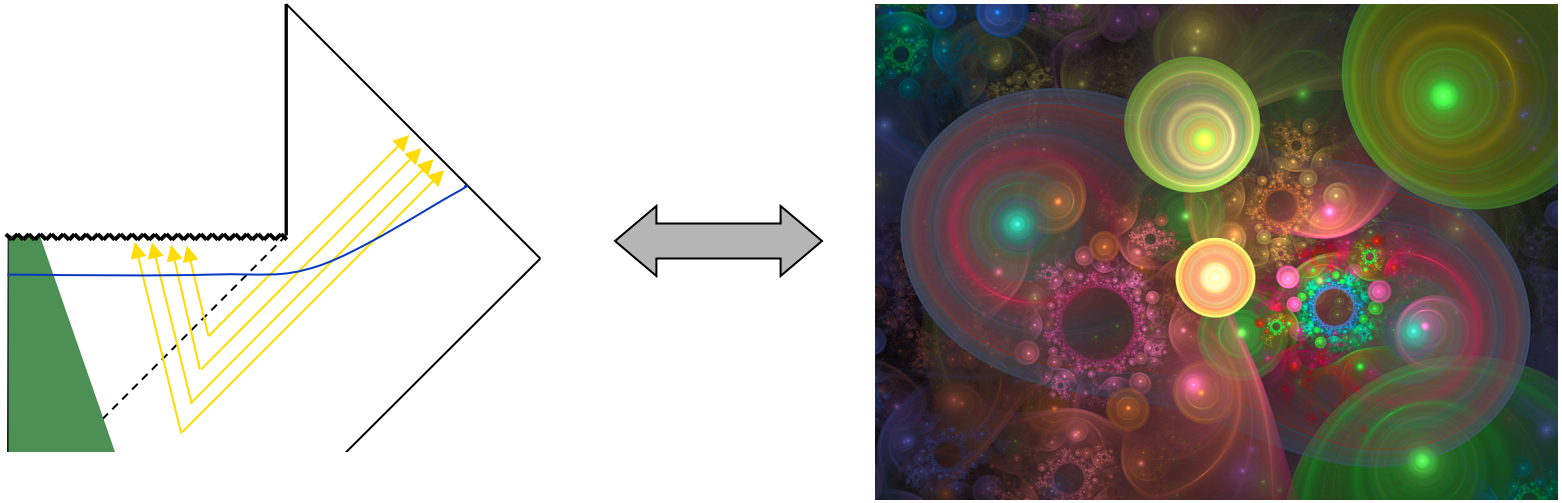
vs.



Attempts:

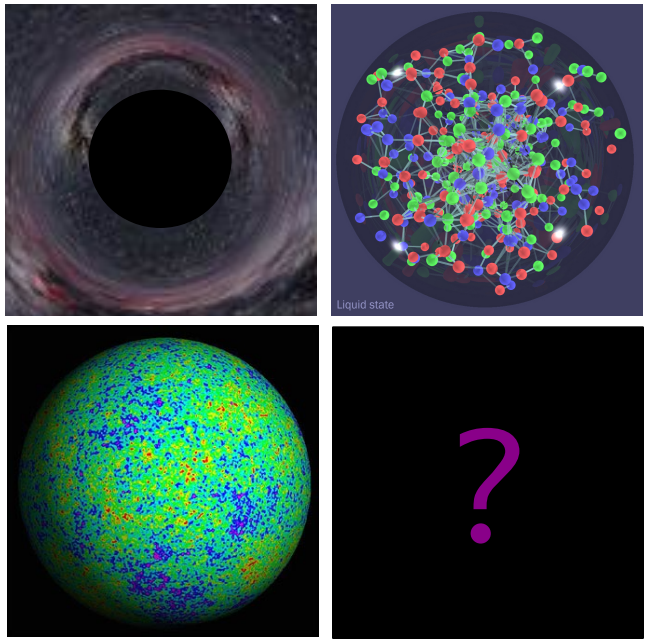
- Extend holography to sub-volumes of AdS using RG flow in the gauge theory.

- Further exploration of the information paradox: the information gets out, but how? How is the Hilbert space behind the horizon realized in the gauge theory.



- How does local bulk physics emerge from the gauge theory? Are we missing something in our understanding of gauge theory?

Conclusion:



The idea that physics must holographic, that the fundamental variables are nonlocal and locality is emergent, is a complete change from previous experience, and we have much to understand.