The Emergence of Space and Time

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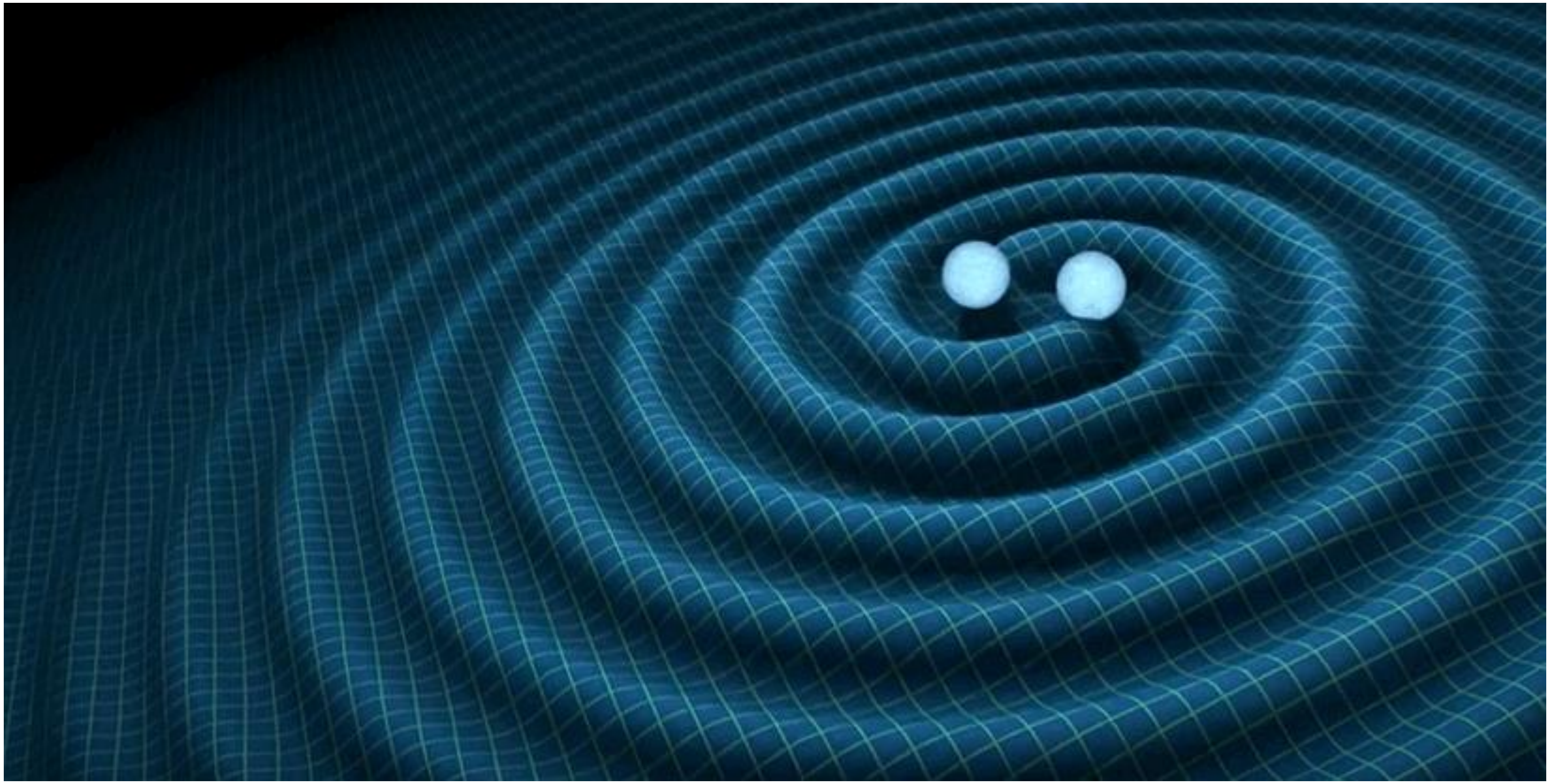
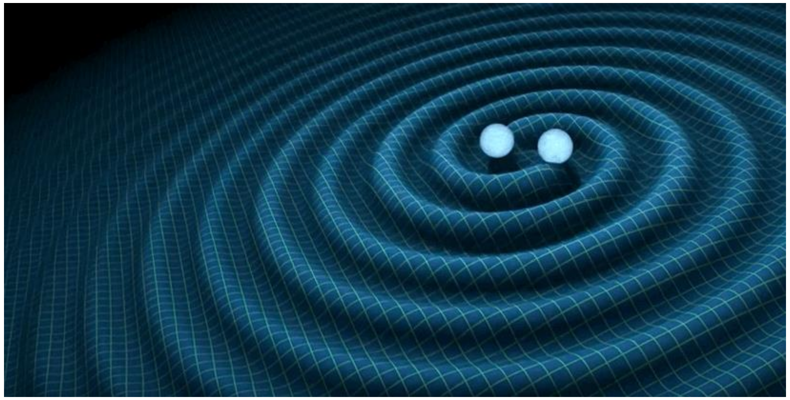
Veldhoven, January 22, 2019

General Relativity: the geometry of space and time are dynamical



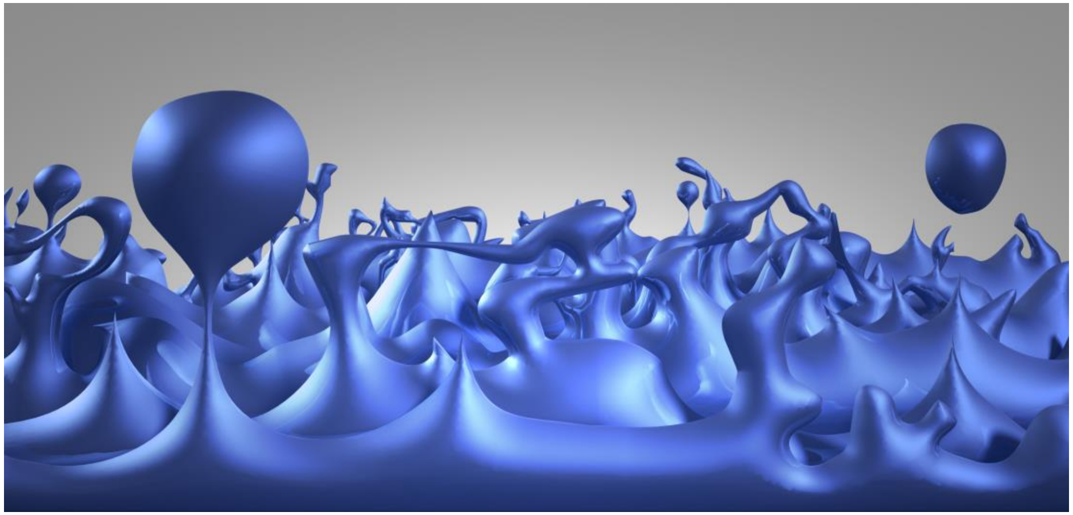
LIGO

Dynamics of spacetime is generated by matter.



Matter=quantum

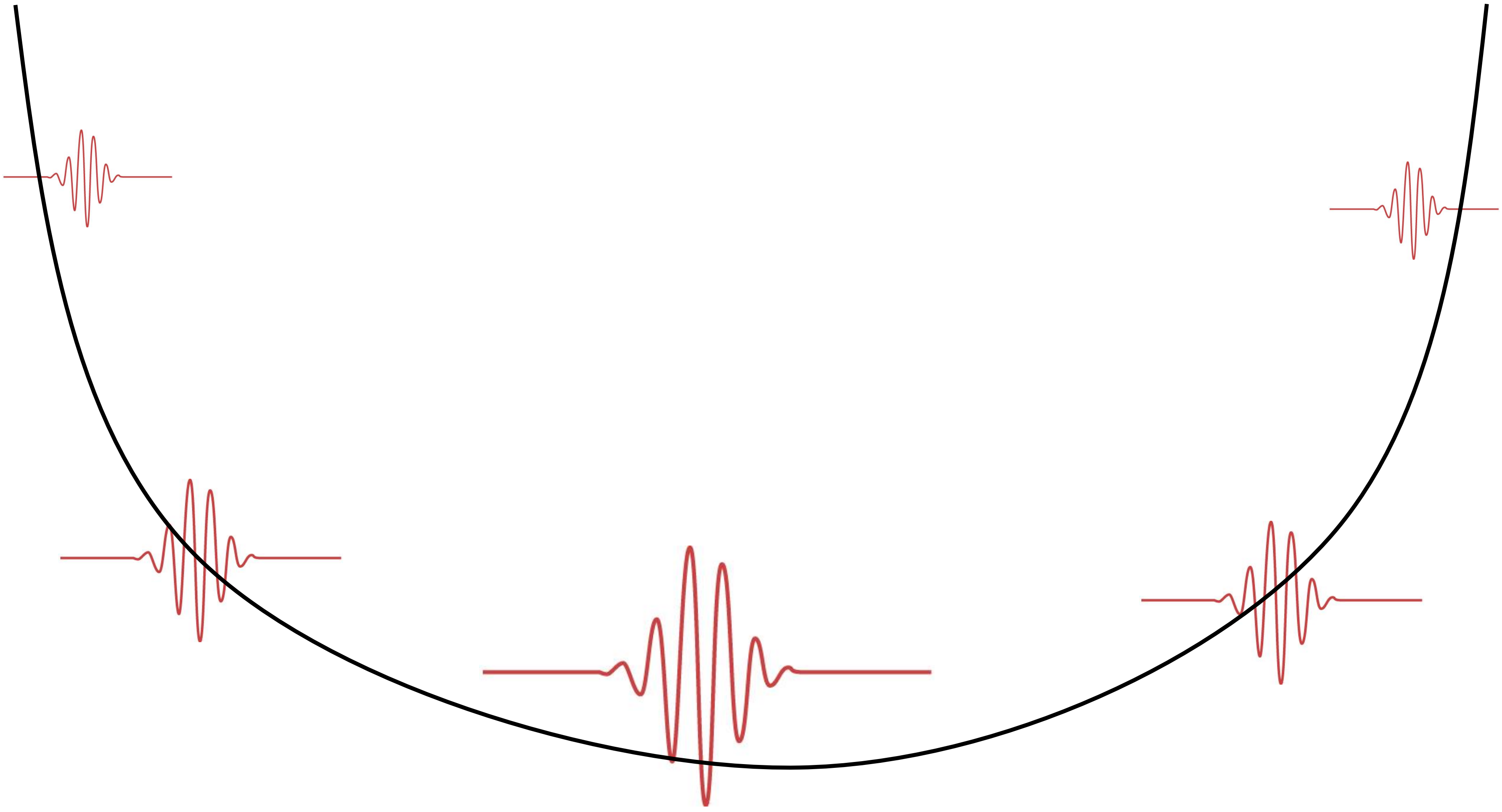
Spacetime=quantum



NASA/CXC/M.Weiss

How to even start describing such a mess?

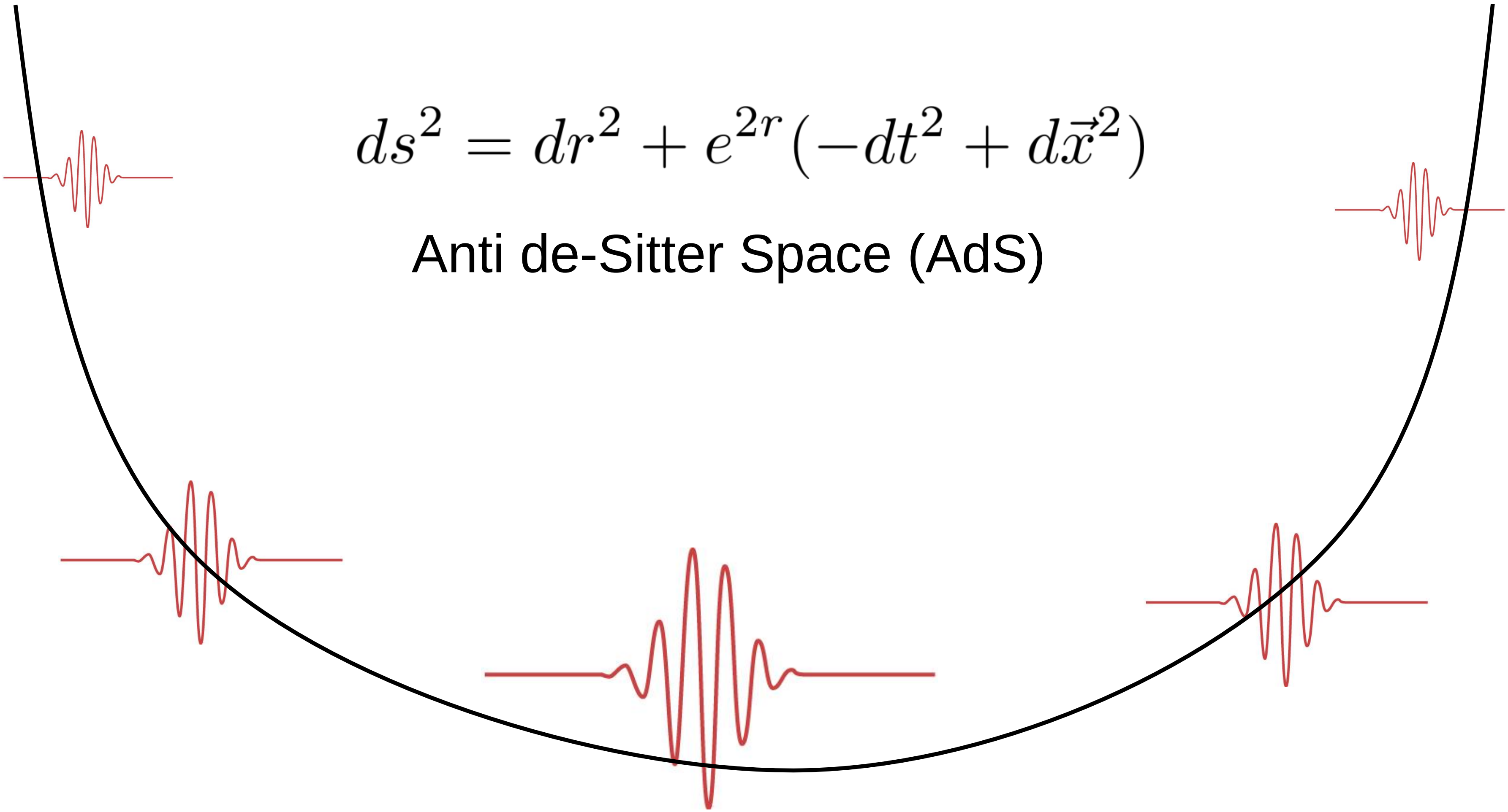
Idea: put gravity in a box



Quantum fluctuations near the boundary are suppressed. Time and space at the boundary are well-defined.

$$ds^2 = dr^2 + e^{2r}(-dt^2 + d\vec{x}^2)$$

Anti de-Sitter Space (AdS)



One could imagine that a more conventional quantum system can be described in terms of the coordinates on the boundary.

It appears that we lost a dimension, but that is a feature, not a bug:

- The Hamiltonian of general relativity is of the form

$$H = 0 + \text{boundary terms}$$

- A conventional (extensive) quantum system at the boundary has the right number of degrees of freedom to describe the entropy of black holes.

$$S_{\text{BH}} = \frac{A}{4G_N}$$

Bekenstein, Hawking, 1970’s

Suppose there is some quantum field theory (QFT) at the boundary.

If contained a free field

$$\left(\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial \vec{x}^2} + m^2\right)\phi(t,\vec{x}) = 0$$

it is hard to see how this matches to fields in AdS which obey a similar differential equation with r-dependence.

$\Rightarrow$ QFT must be strongly coupled.

Operators in strongly coupled theories do not obey simple field equations.

The entropy of a black hole at fixed energy can be made arbitrarily large as $G_N \to 0$

$$S_{BH} = \frac{A}{4G_N} \sim \frac{M^2}{G_N}$$

→ QFT must have a large number of degrees of freedom ("large N theories")

There are no light fields of spin larger than two in gravity
(there are various no go theorems)

$\Rightarrow$ QFT must not have simple low-energy operators of spin larger than two.

There are only a few light fields in gravity coupled to some matter degrees of freedom.

$\Rightarrow$ QFT must have only a few simple low-energy operators.

$$ds^2 = dr^2 + e^{2r}(-dt^2 + d\vec{x}^2)$$

Geometry has a symmetry under

$$\begin{aligned} r &\rightarrow r - a \\ t &\rightarrow e^{2a} t \\ \vec{x} &\rightarrow e^{2a} \vec{x} \end{aligned}$$

QFT must be scale invariant

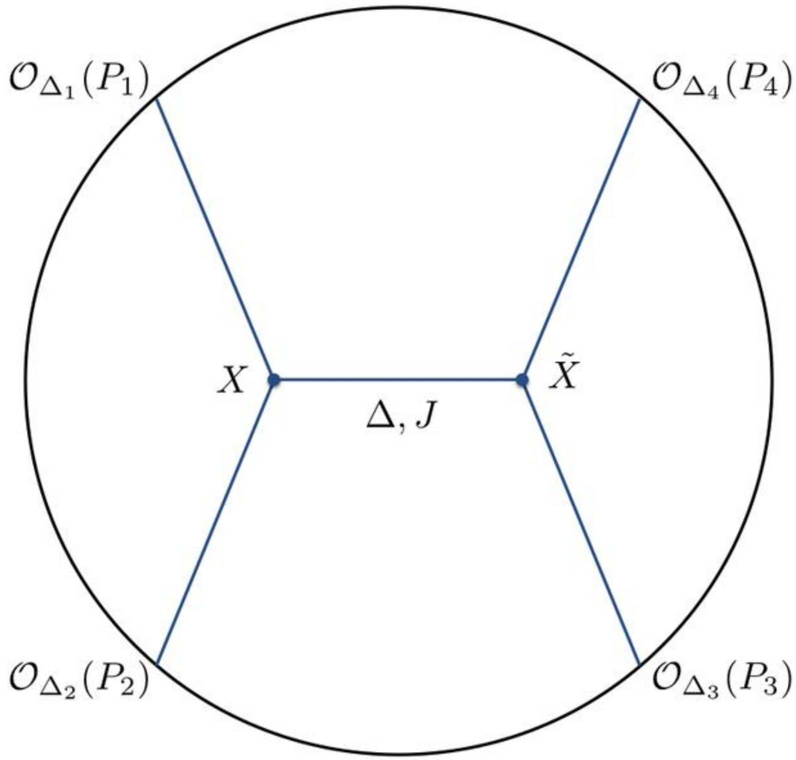
So the wish list is:

- QFT must be strongly coupled.
- QFT must have a large number of degrees of freedom (“large N theories”)
- QFT must not have simple low-energy operators of spin larger than two.
- QFT must have only a few simple low-energy operators.
- QFT must be scale invariant.

Do such QFTs exist? Yes, some examples were originally identified in string theory and were part of the original AdS/CFT correspondence proposal.

Maldacena 1997

Correlation functions in QFT = Green's functions (coordinate space Feynman diagrams) in AdS



To study spacetime is somewhat similar to medical imaging

If one were able to compute the correlation functions in the QFT directly one might have discovered that they admit a very convenient interpretation in terms of a spacetime of one dimension higher.

The radial direction geometrizes scale transformations.

JdB, Verlinde, Verlinde, ‘99

Emergence?

It is technically very difficult use this relation to study in detail what happens to e.g. observers who fall into a black hole.

Black Hole in AdS = QFT at finite temperature

Subset of Einstein Field Equations = equations of hydrodynamics for QFT (gravity knows about the right variables for hydrodynamics .. emergence?)

Bhattacharyya, Hubeny, Minwalla, Rangamani, ‘08

Falling into the black hole = dissipation

Black hole creation = thermalization

Gravitational predictions:

- Hydrodynamics has very low viscosity Kovtun, Son, Starinets,’01
- Thermalization proceeds maximally fast

  Balasubramanian, Bernamonti, JdB et al, ‘11
- QFT is maximally quantum chaotic

  Maldacena, Shenker, Stanford, ‘15

The Role of Quantum Information

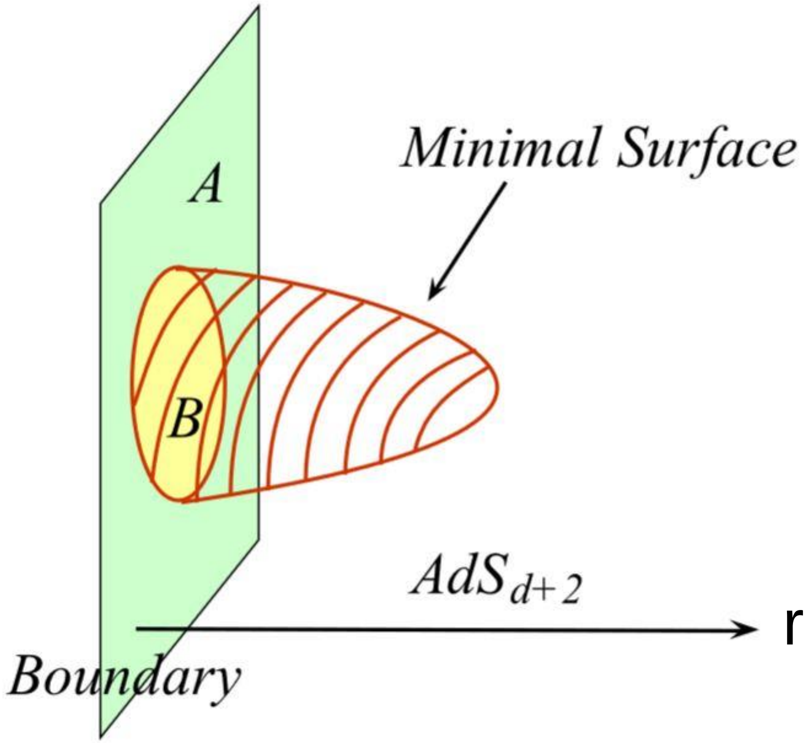
$$|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

Bell pair, entanglement: measurements are correlated.

$$|\psi\rangle \in \mathcal{H}_A \otimes \mathcal{H}_B$$

Entanglement entropy S_A ~ number of Bell pairs that entangle A and B.

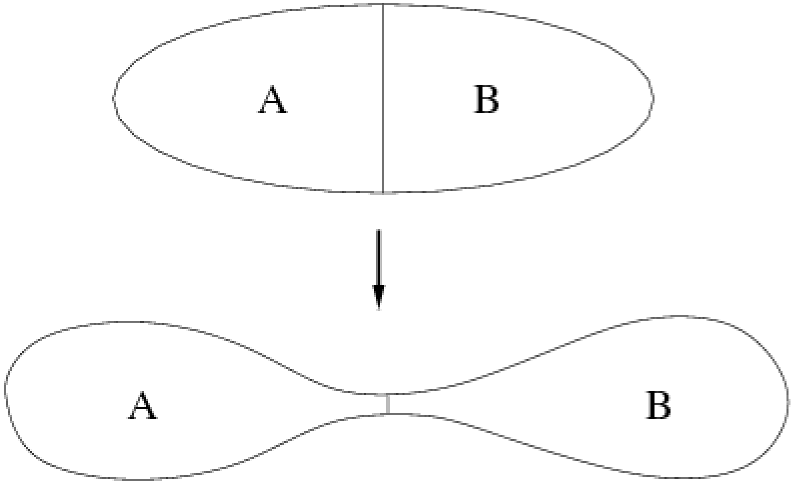
Ryu-Takayanagi ('06): entanglement entropy in QFT = area of minimal surface in gravity (S_A=area/4G).



Entanglement is needed to build op a connected spacetime (van Raamsdonk ‘10).

The correlations in entangled states are reproduced by making spacetime connected.

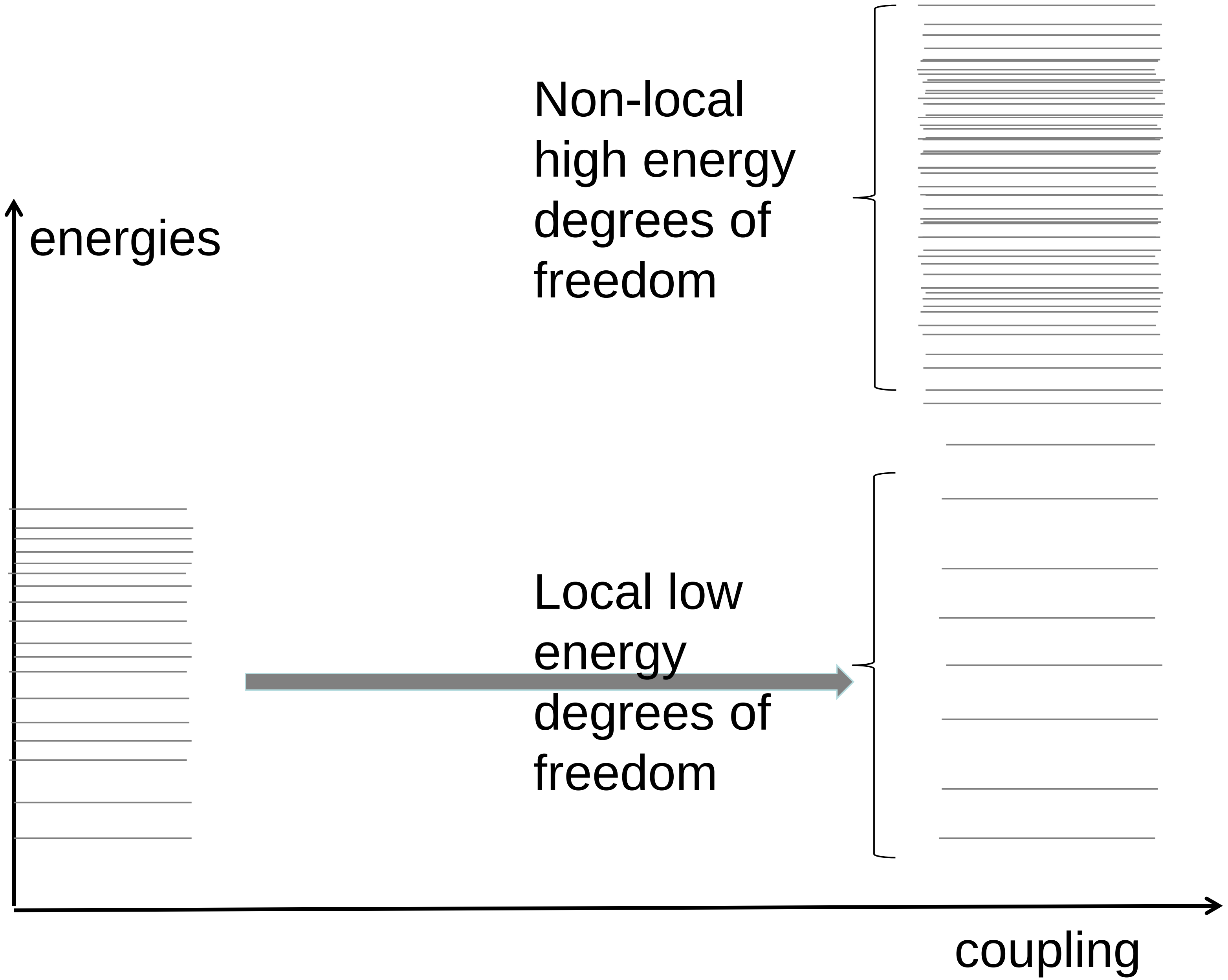
Exactly which types of entanglement have smooth geometric representations is not entirely clear.



Amazingly, many quantum information theoretic concepts have a gravitational interpretation:

- quantum error correction
- entanglement of purification
- various protocols
- differential entropy
- quantum teleportation
- relative entropy
- Renyi entropy
- mutual information
- entropy inequalities like strong subadditivity

which led to the idea that perhaps quantum gravity can be formulated purely in information theoretic terms (but this has not been achieved yet).



Important: spectrum

Picture:

- Conventional gravitational physics is described by the low lying part of the spectrum only.

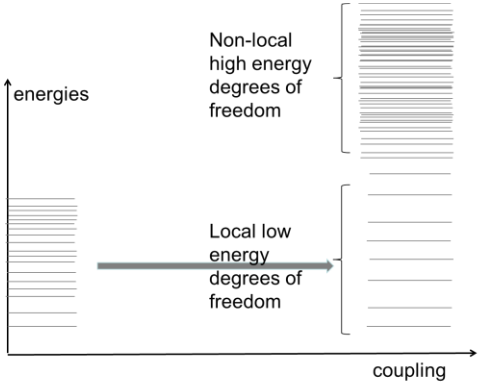
- Once a black hole forms one accesses the high-energy degrees of freedom.

- To describe infalling observer: need interaction between low-energy and high-energy degrees of freedom.

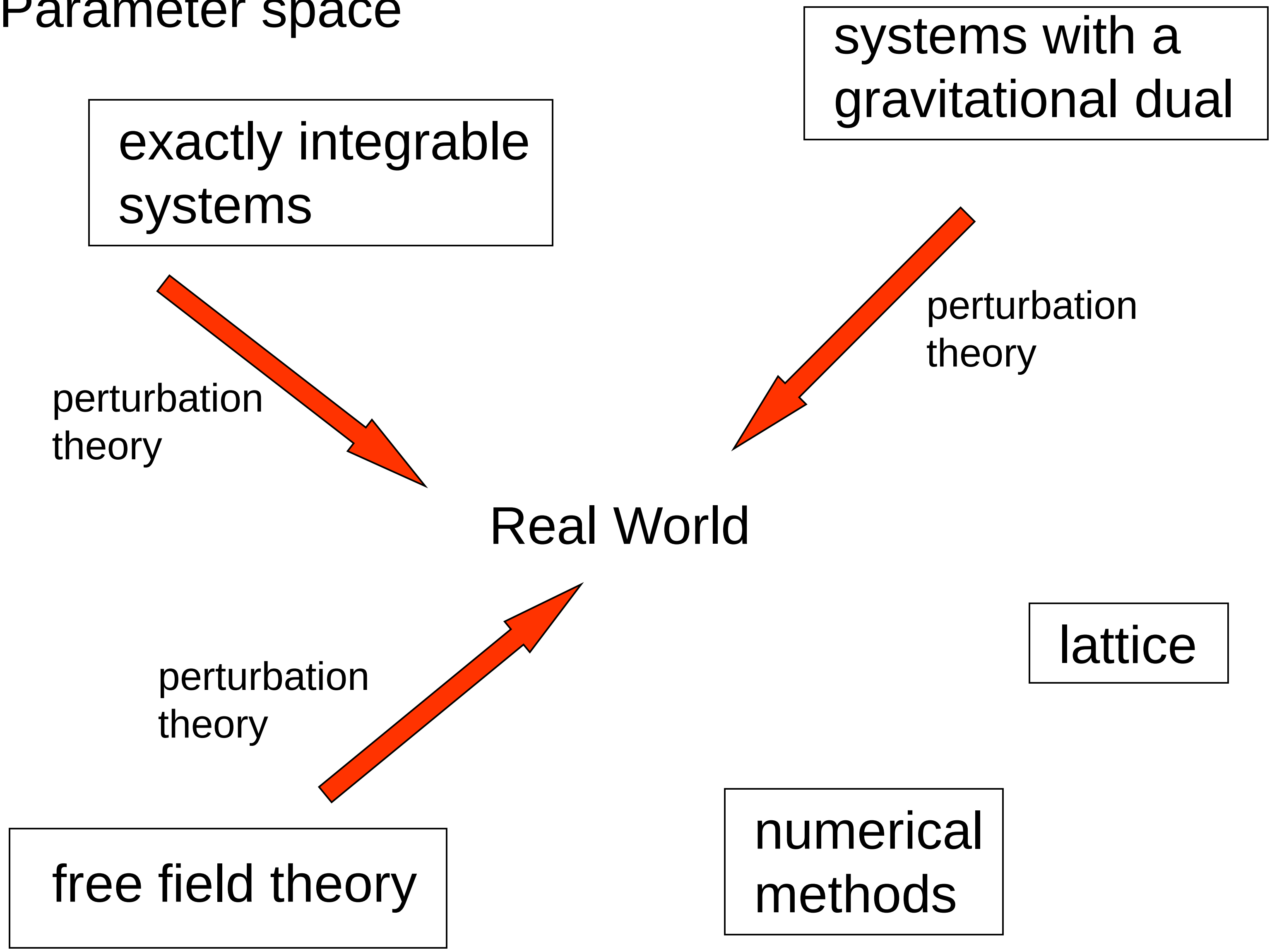
  → evidence from information theory

- The non-local nature of the high-energy spectrum allows a mild breakdown of locality and allows information to escape the black hole.

- Emergence?



Parameter space



Systems with a gravitational dual may represent an important universality class of physical systems.

There is evidence that certain strongly correlated electron systems, such as high-Tc superconductors, and the strongly coupled quark-gluon plasma are close to "systems with a gravitational dual".

(low viscosity, fast thermalization, applicability of a hydrodynamic description)

So did space and time really emerge?

At low energies they were merely a very useful set of variables to describe the physics. We did not really throw away or coarse grain over degrees of freedom.

At high energies (black hole regime), time and space were useful variables to describe the low-energy dynamics that arises – here we do coarse grain (a la thermodynamics) over the high-energy degrees of freedom. So perhaps here space and time can be called emergent.

Did not talk about:

- Complexity
- Wormholes
- Quantum gravity in an expanding universe (de Sitter space)
- Quantum gravity in flat space
- Do we need the large reservoir of high energy states in quantum gravity to allow decoherence and collapse of the wave function?
- Tensor networks
- Information paradox and firewalls
- And many other things..