Title: Creating Spacetime

Date: Jul 19, 2011 04:50 PM

URL: http://pirsa.org/11070060

Abstract: Our understanding of the physical world at the most fundamental level is based on two theories: quantum theory and general relativity. They are impressively successful but only when each is considered on its own. In situations where both play a role, we are reduced to puzzles and absurdity. Hence the search for a quantum theory of gravity, the currently missing theory that will work sensibly in exactly these situations. To the great frustration of researchers in this field, candidate quantum theories of gravity tend to produce more puzzles instead of answers. We shall take a tour of some of the problems, focusing on the role of spacetime and causality. We will consider the possibility that spacetime did not always exist but is instead emergent and explore how one can create a spacetime from a world with no notion of "here" and "there".

Creating Spacetime: Spin Systems as Toy Models for Emergent Gravity

Fotini Markopoulou
Perimeter Institute / U.Waterloo / Albert Einstein Institute

T. Konopka, FM & S. Severini — Phys.Rev.D(2008), 0801.0
A. Hamma, FM, I. Prémont-Schwarz & S. Severini — PRL(2009) 0808.2
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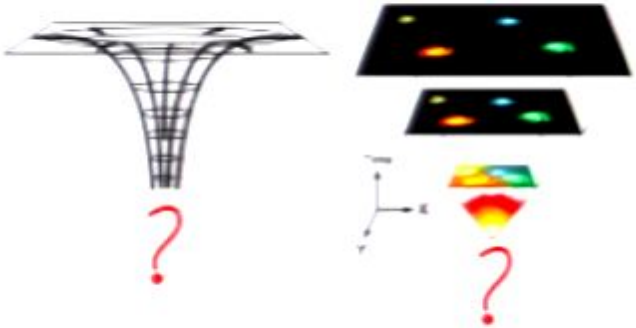
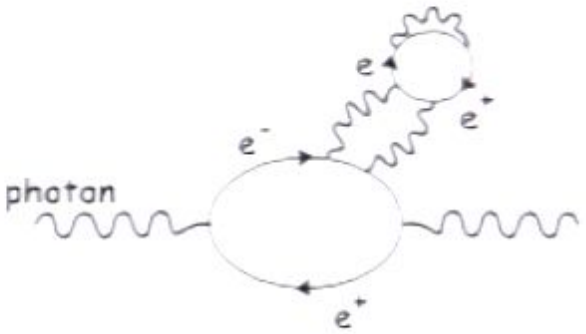
Quantum gravity=GR"+"QFT

General Relativity and Quantum Field Theory ultimately fail.





Quantum gravity seeks to reconcile general relativity and quantum theory

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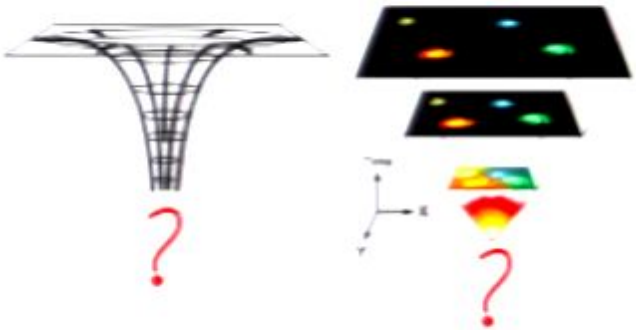
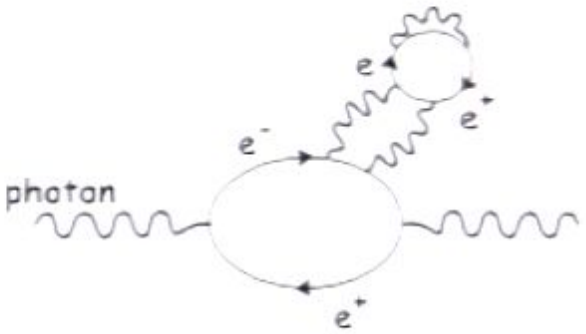
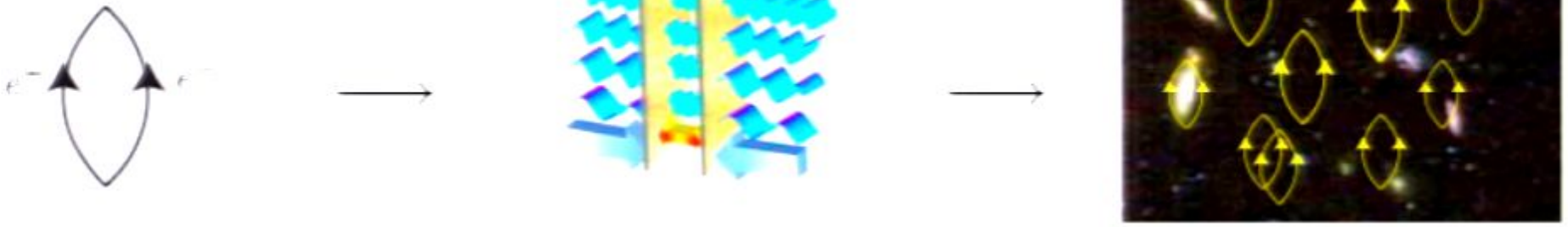




More bad things happen if we combine the two theories.

$$\Delta E \Delta t > h$$



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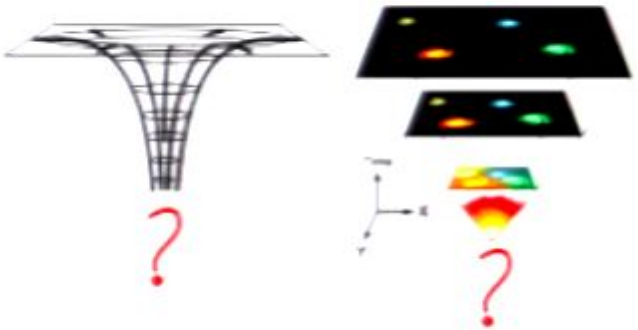

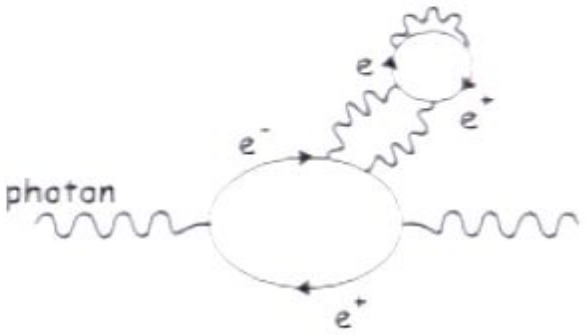

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Quantum gravity seeks to reconcile general relativity and quantum theory

Background Independence

- Matter tells spacetime how to curve

and spacetime tells matter where to go

- $R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - g_{\mu\nu}\Lambda = T_{\mu\nu}$
- $g_{\mu\nu}$ dynamical
- Physical quantity: $[g_{\mu\nu}]_{\mathrm{Diff}\,\mathcal{M}}$

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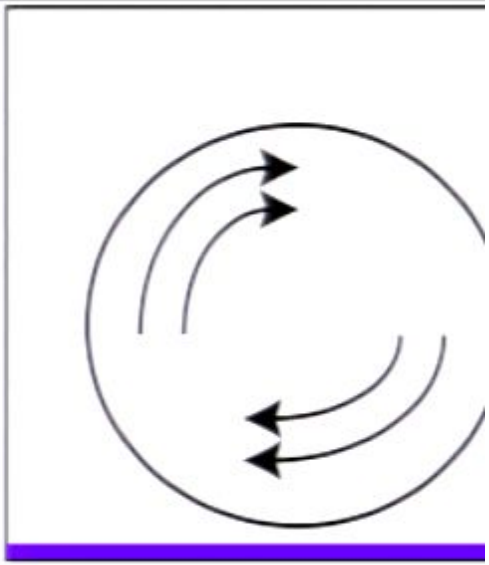

The problem of time in quantum gravity

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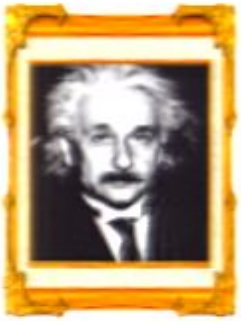

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Only *events* and their *causal relations* are physical; the metric is dynamical=

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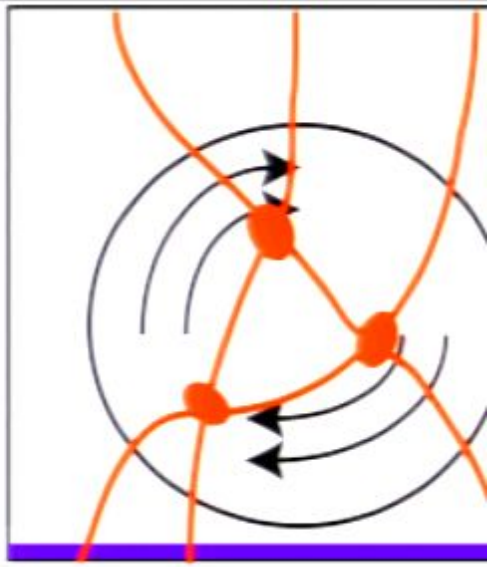

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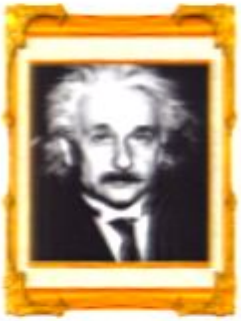

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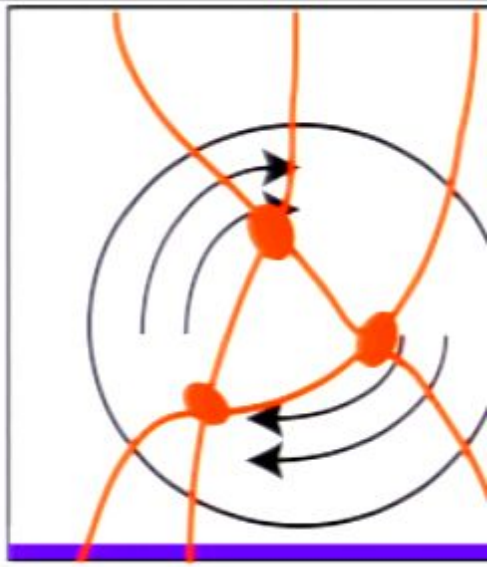


- In pure gravity ($T_{\mu\nu} = 0$), time evolution is a diffeomorphism (timelessness).
  - ➡ If we quantize GR we find that the Hamiltonian is a constraint:

$$\hat{H}\,|\Psi_U\rangle = 0$$

Wheeler-deWitt equation instead of a Schroedinger equation.
What does the RHS mean?

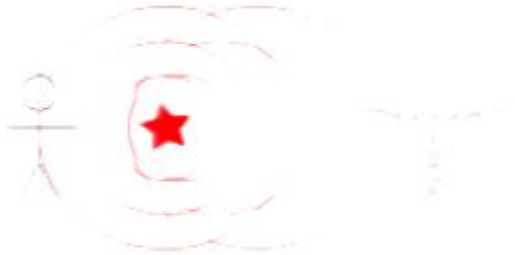
  - ➡ What is an observable?

The problem of time in quantum gravity

Quantum gravity=GR"+"QFT

Scale of quantum gravity: Planck length $l_{Pl} = \sqrt{\frac{G\hbar}{c^3}} = 10^{-35} m$

- at this scale the quantum effects of the gravitational field become important
- at this scale we reach fundamental limits to space and time measurements



Spacetime metric $\longleftrightarrow$ causal structure is dynamical

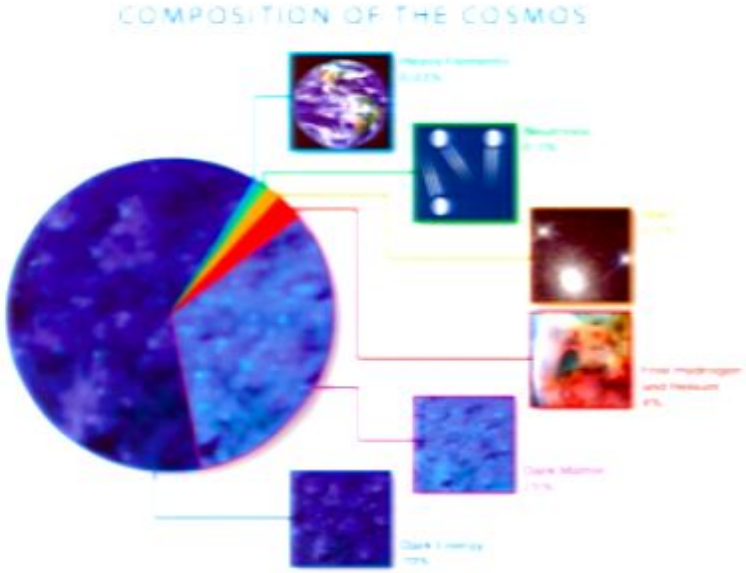
We need new physics at the Planck scale

The Planck scale is not beyond reach

The need for new physics is not restricted to l_{Planck}:

- Constraints on Lorentz invariance violation
- Dark energy and dark matter
- The inflaton (transplanckian signatures in inflation)
- The coincidence problem
- Quantum to classical transition in macroscopic systems
- ...

After all, we only know 5% of the universe!



We need a quantum theory of gravity

BE SIMPLE AND ELEGANT

BE MATHEMATICALLY RIGOROUS

TELL US IF THE UNIVERSE IS FINITE OR INFINITE

DESCRIBE THE ENTIRE UNIVERSE

DESCRIBE THE INTERIOR OF A BLACK HOLE

BE A UNIFIED THEORY OF EVERYTHING

EXPLAIN OBSERVATIONAL COSMOLOGY DATA

EXPLAIN DARK ENERGY AND DARK MATTER

EXPLAIN THE NATURE OF TIME

EXPLAIN QUANTUM THEORY

GO BEYOND GENERAL RELATIVITY

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Background independence: principle in quantum gravity

Background Independence I:

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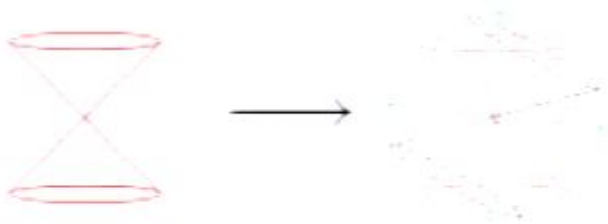

The science of quantum spacetimes

Spacetime = physical events

Physical events are Quantum

Quantum = superpositions

Superpositions of spacetimes?

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To make sense of a quantum superposition of spacetimes, we must show that it is possible to start from such a superposition and find a nice regular spacetime (our world) as the most likely one.

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Superpositions of spacetimes?

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First we need some tools...

Make a *model* of spacetime

What does it mean to be a model?

Make a *model* of spacetime

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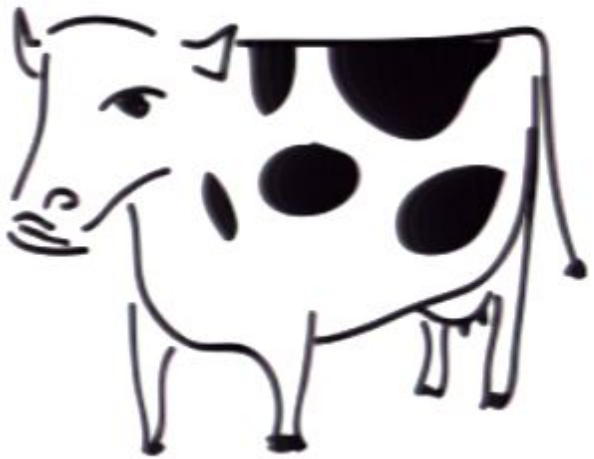

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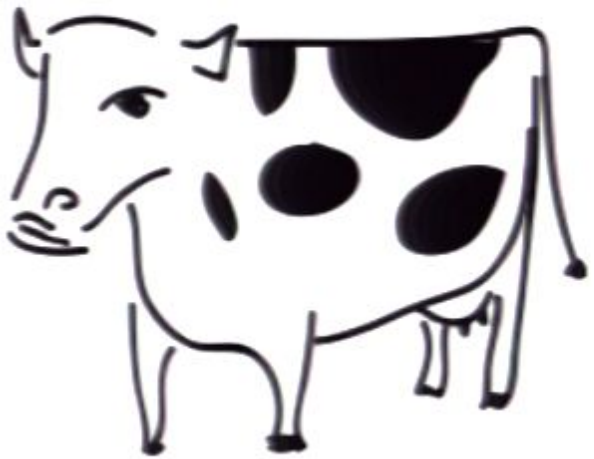
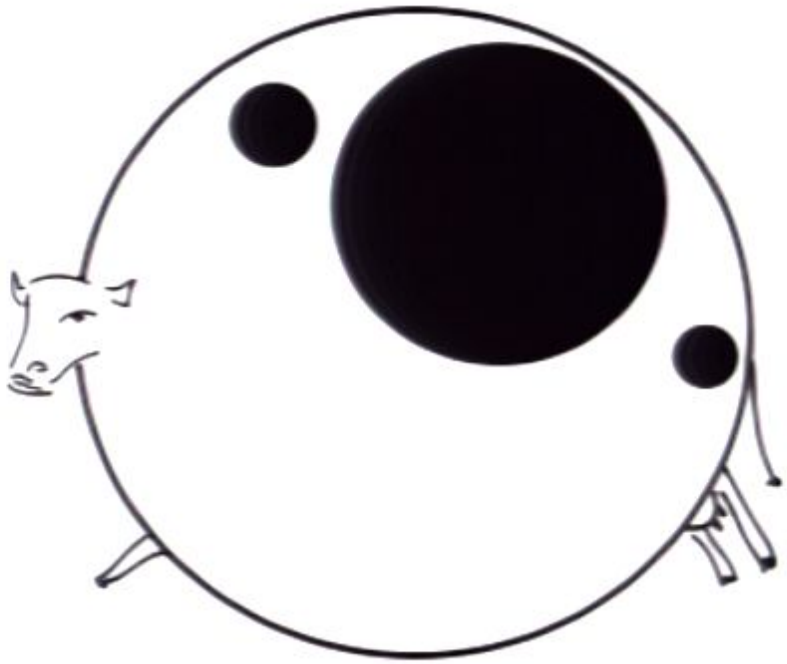
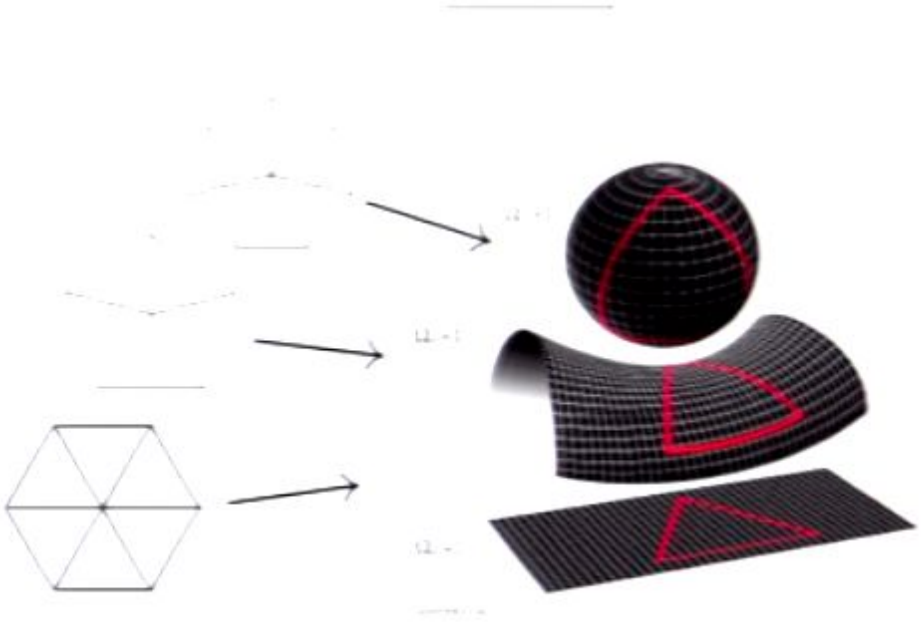




Make a *model* of spacetime

Curvature as a triangulation



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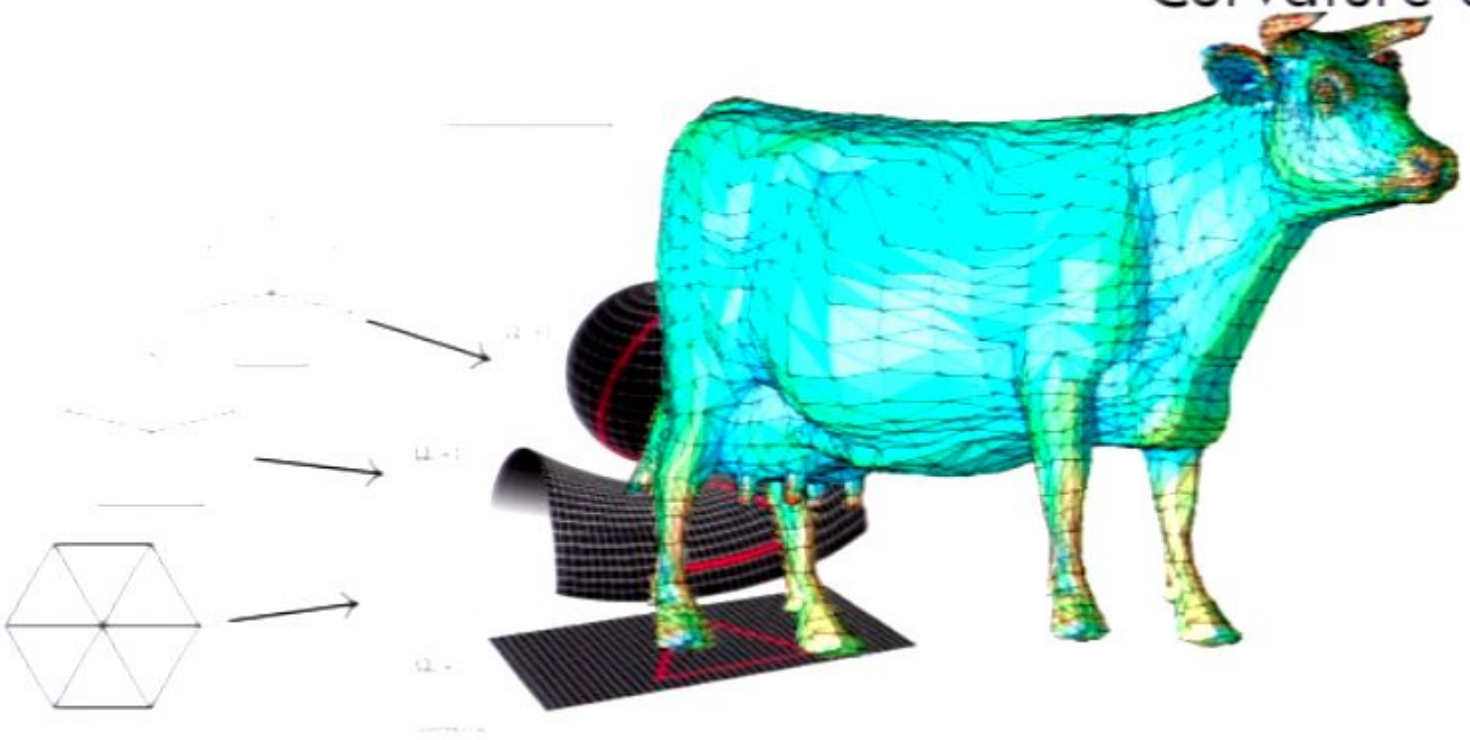

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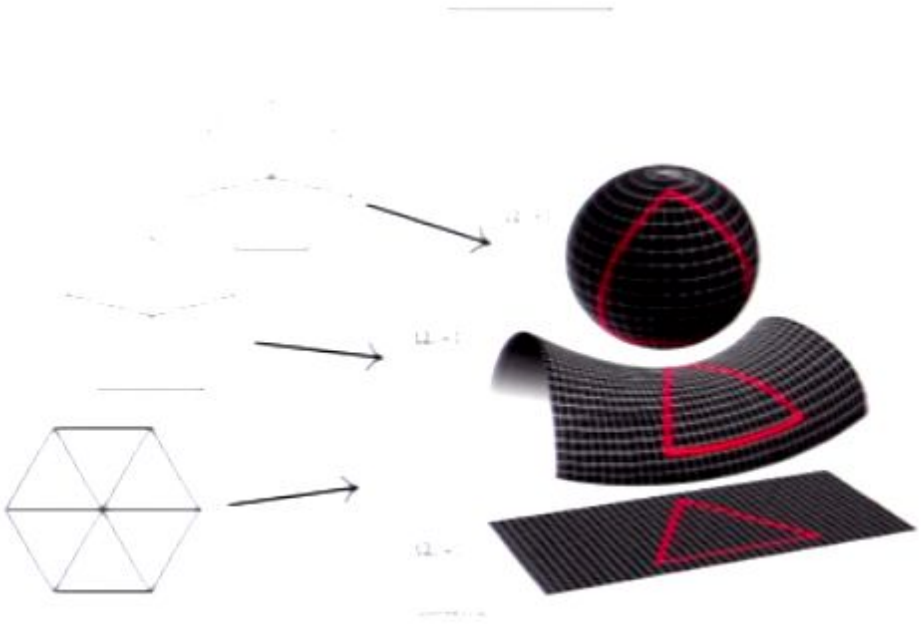

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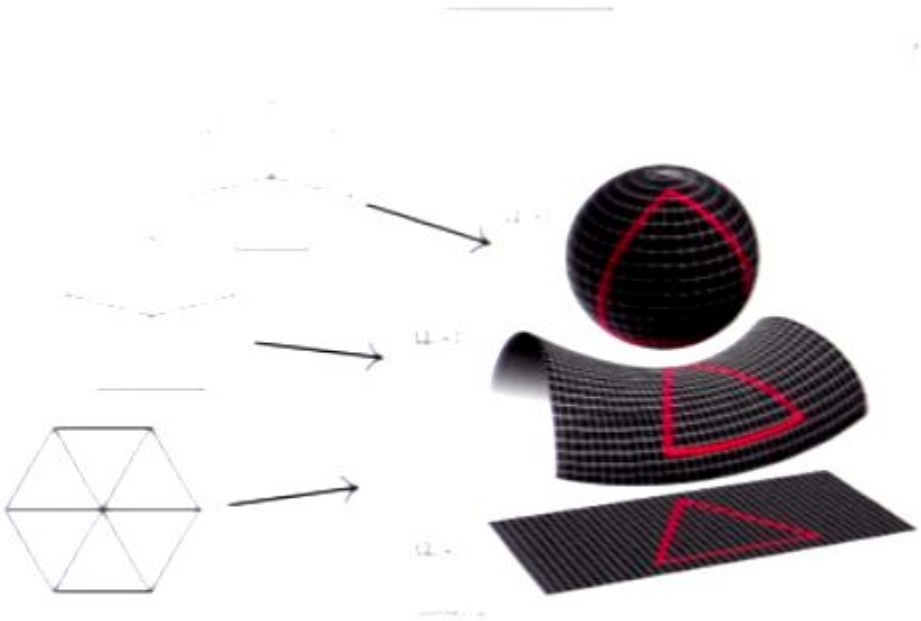
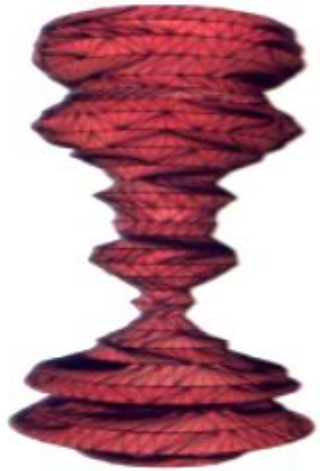
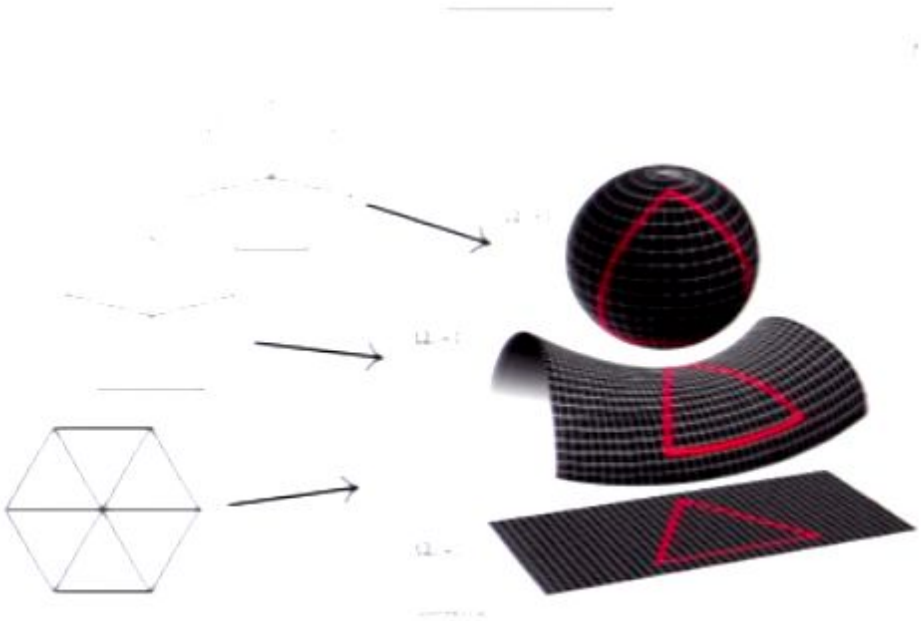




Make a *model* of spacetime

Triangulation
reduce the
problem to
combinatoric
Count!

Curvature as a triangulation



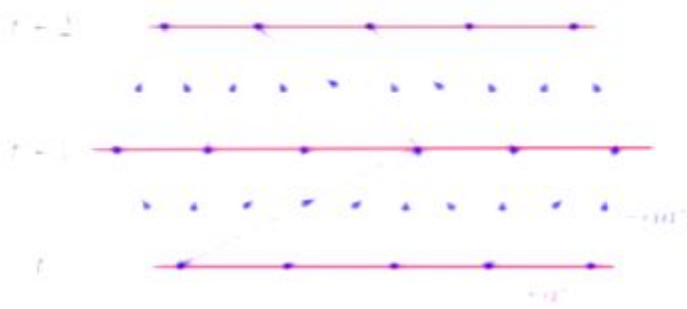
Make a *model* of spacetime

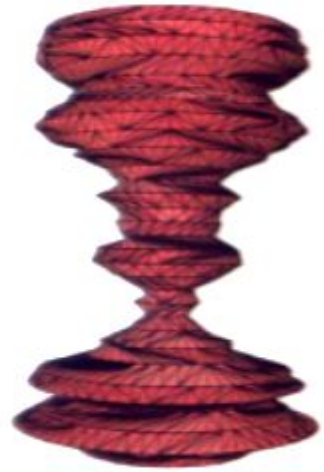
Causal Dynamical Triangulations:

A statistical model of quantum geometries.

$$A(L(in), L(out), 1) = \frac{g^2 L_1 L_2}{(1 - L_1)(1 - gL_1 - gL_2)}$$

$$A_{L(in)\to L(out)} = \sum_{t=0}^{\infty} A(L(in), L(out), t)$$

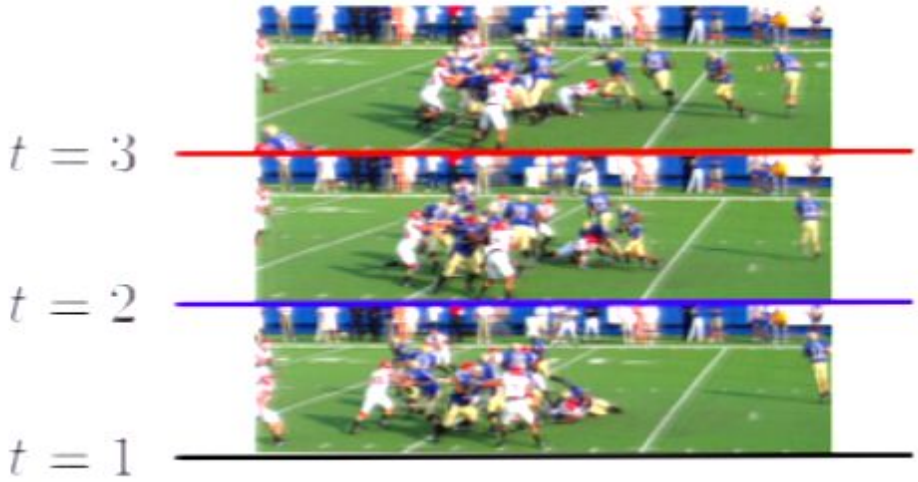




Causality condition: advance everyone at every step.

J. Ambjorn, R. Loll *et al*

Are we most likely? It depends on time



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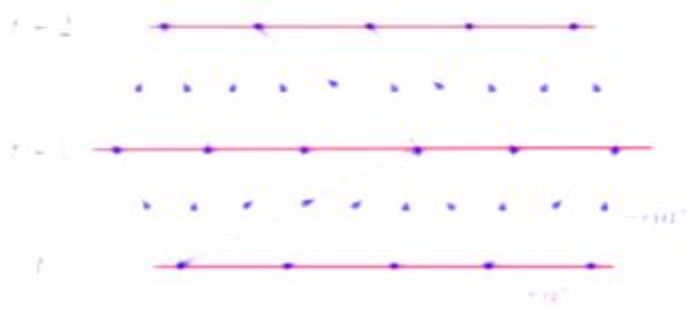

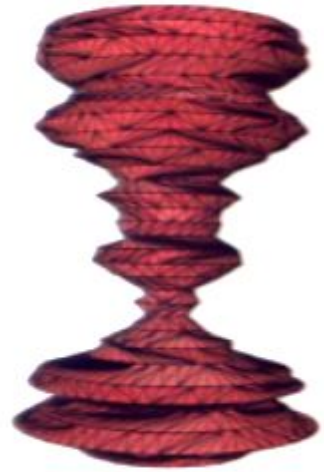

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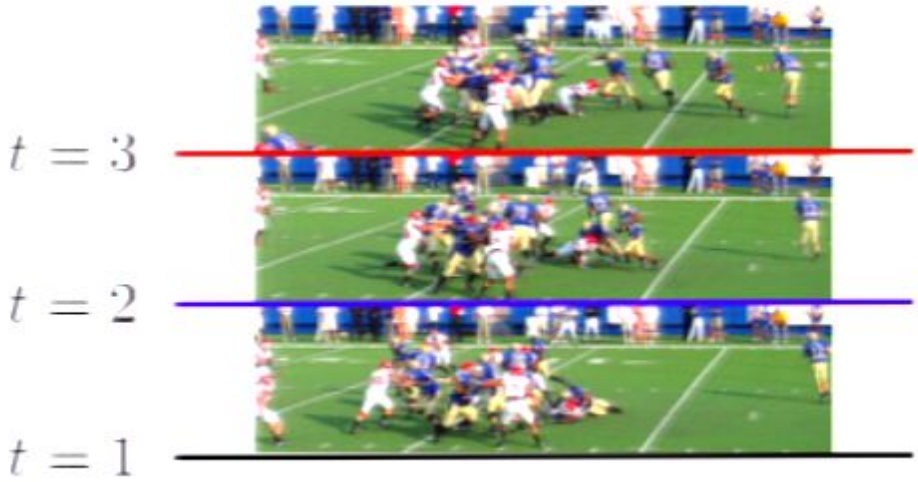

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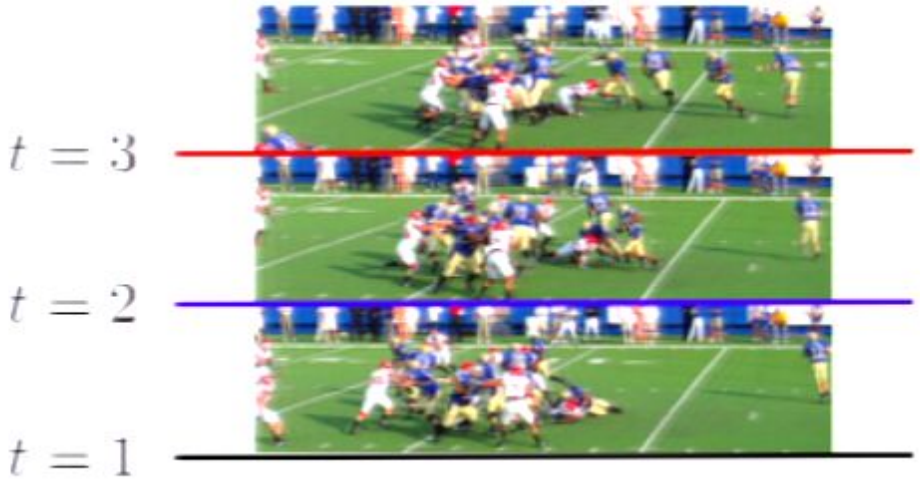
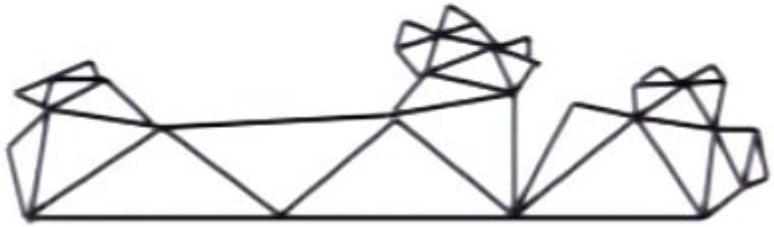


Time in general relativity:



Are we most likely? It depends on time

Most likely spacetime:

Dimension: $d_H = 3.10 \pm 0.15$

$d_H \sim \infty$

$d_H \sim 2$

J. Ambjorn, R. Loll *et al*

Are we most likely?

Yes, if by "we" we mean 3+1 dimensions and smoothly varying in time.

Requires a notion of time which may disagree with General Relativity.

- ✓ Convergent, tractable
- ✓ Well-behaved typical histories
- ✓ Also when matter is added
- ✓ Correct dimension
- ✓ High-energy prediction: evidence for 2d
- ✓ New universality class discovered.

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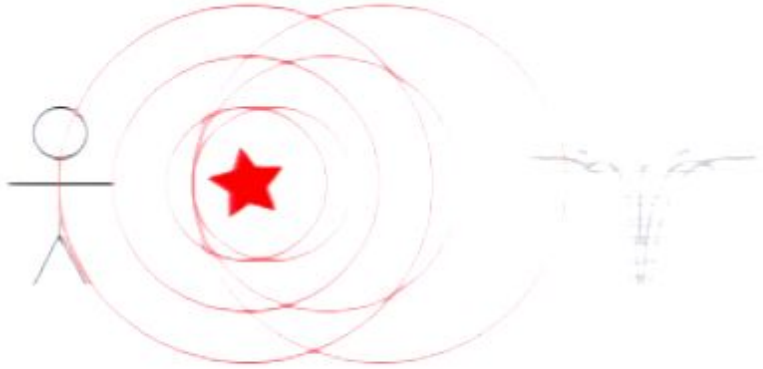
Is this the answer to the problem of Quantum Gravity?

We need more than smooth geometry and the correct dimension.

Verdict: Need to show that apples fall in quantum spacetimes

Back to start: does this make sense?



Maybe wrong

Background independence: principle in quantum gravity

Revisit Background Independence

Background Independence

There should be no preferred geometry in the formulation of the quantum theory of gravity.

Quantum gravity is given by a quantum superposition of quantum geometries.

Background Independence II:

There are no geometric or gravitational degrees of freedom in the fundamental theory.

Geometry is only a classical, emergent concept.

Emergent space(time)

Emergence: the behavior of the system has no explanation in terms of its constituent particles, but instead of their collective behavior and interactions.

The whole is more than its parts.

River or water molecules?

Would you say the river fundamentally exists?

Emergent space(time)

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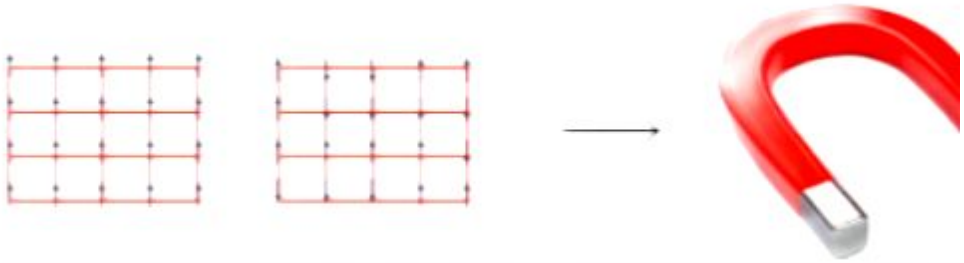
The paradigm: the Ising mode



What is the Ising model for gravit

Emergent space: *emergent locality* and *order*

What is space(time)?

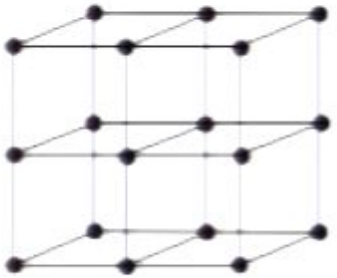
there

here

Space=locality

What is space(time)?

translation invariance

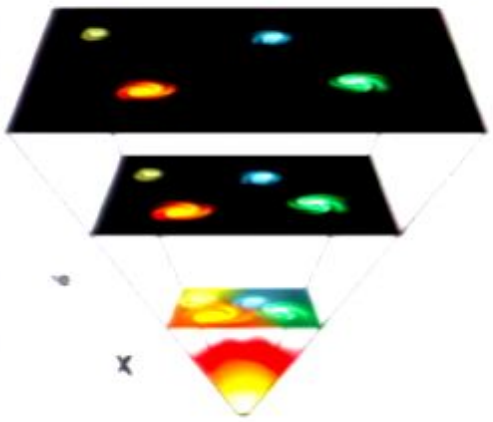


Space=order

Emergent space(time)

We currently assume an FRW geometry all the way to the Big Bang.

Alternative scenario: What if geometry is not fundamental?



geometric phase
- translations, etc
- locality
- 3+1 dim.

geometrogenesis

non-geometric phase
- no locality
- no geometric symmetries

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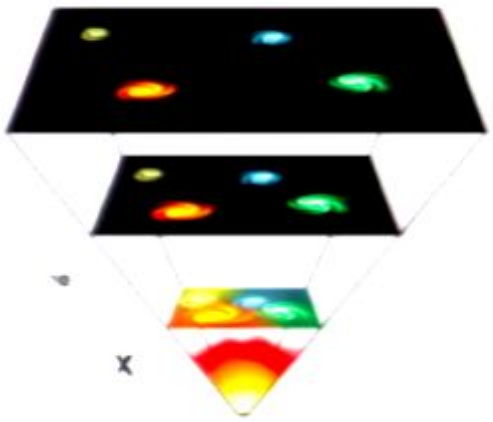

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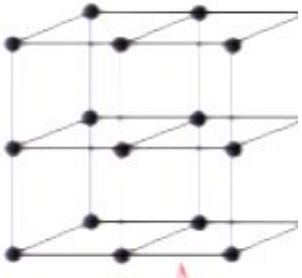
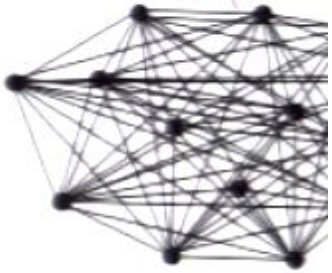
cold





hot

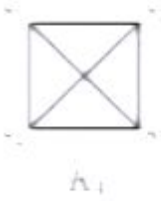
The dynamical lattice: lattice links as spins

T.Konopka, FM & L.Smolin, hep-th/0611

Basic idea:

Promote link to a quantum degree of freedom $\{1, 0\}$ qubits of adjacency

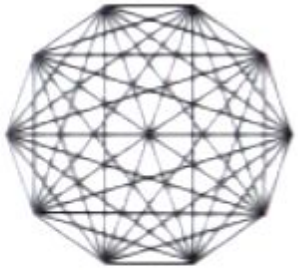
In a universe of N constituents, there are $\frac{N(N-1)}{2}$ possible links.



quantum geometry:
superposition of adjacent/not adjacent

State space of models: $\mathcal{H} = \bigotimes_{i \in K_N} \mathcal{H}_i$

Model 1: Emergent space and matter



- no locality
- no geometric symmetries

- translations, etc
- locality
- 3+1 dim.

Model 1: Emergent space and matter

T. Konopka, FM & S. Severini, PR

- $H_V = g_V \sum_i \left(\sum_{\alpha} n_{i\alpha} - \sum_{\alpha} N_{i\alpha} \right)^2$

- on $\mathcal{H}_{\{L,0\}}$

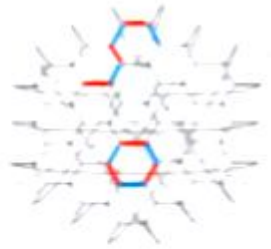
$$H_{\{L,0\}} = \sum_i \left(\sum_{\alpha} n_{i\alpha} - n_0 \sum_{L=1}^{\infty} \frac{1}{L!} N_{i\alpha}^L \right)$$

flat space is stable local minimum

- on full $\mathcal{H}$

$$H_{\{L,0\}} = -\sum_i \sum_{L=1}^{\infty} \frac{g_L}{L!} n_0 \prod_{\alpha} N_{i\alpha}^L$$

$$H_{\text{string}} = g_1 \sum_i \left(\sum_{\alpha} N_{i\alpha} \right)^2 - n_0 \sum_{i\alpha} N_{i\alpha}^2$$



emergent photons and fermions for

$g_B \gg g_C \cdot g_D$

X.G.Wen, *Quantum Field Theory of Many Body*

Emergent matter when space emerges.

Speed of light from local interactions

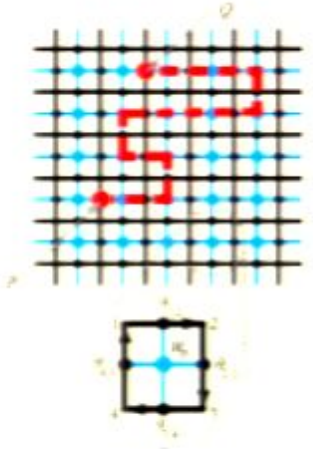
A.Hamma, FM, I. Premont-Schwarz, S.Severini, PRL 2

Given *local* Hamiltonian $H = \sum_{ij} h_{ij}$

Lieb-Robinson speed of information propagation:

$$\| [O_P(t), O_Q(0)] \| \leq 2 \| O_P \| \| O_Q \| \sum \frac{(2\, t\, h_{max})^n}{n!} N_{PQ}(n)$$

$$\| [O_P(t), O_Q(0)] \| \leq 2 \| O_P \| \| O_Q \| C \exp[-a(d_{PQ} - v t)]$$



Find: $v_{LR} = \sqrt{2 g_B g_C}$

- $v_{LR} = c$ in the emergent Maxwell equations
- Effective finite light cones consistent with non-relativistic quantum mechanics
- $v_{LR} \sim d$

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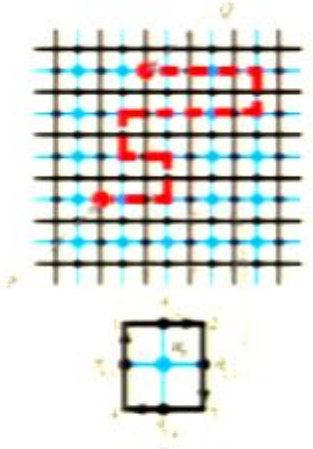
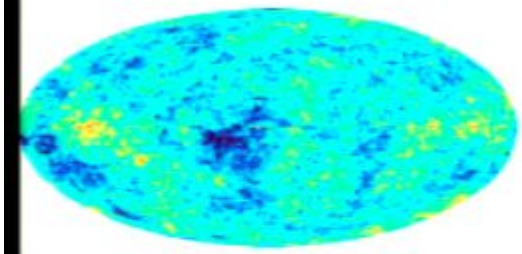


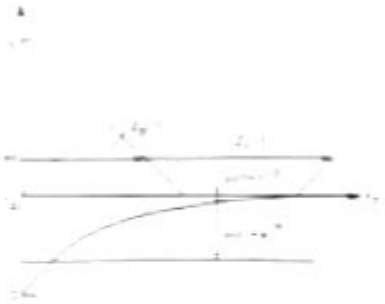
Does an emergent observer see Minkowski space?

Emergent locality is NOT a Planck scale effect

A.Hamma, FM, I. Premont-Schwarz, S.Severini, PRL 2

Evolving speed of light and the horizon problem:





inflation

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A.Hamma, FM, I. Premont-Schwarz, S.Severini, PRL 2

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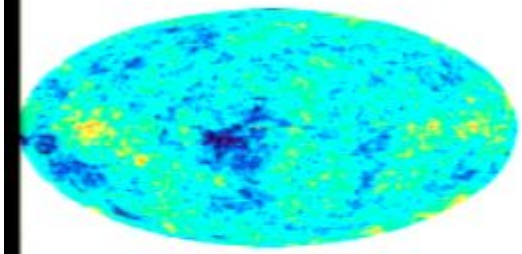
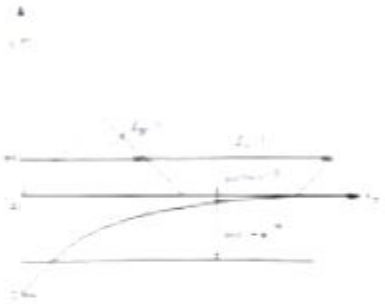
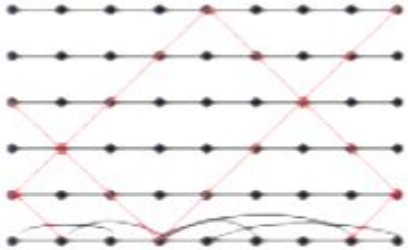




inflation



Model illustrates the effect of a transition in the local structure: in principle an observable effect (not a Planck scale effect).

Note: a phase transition in the speed of light can also reproduce the scale invariant CMB spectrum (Variable Speed of Light cosmology)

Model 2: Interacting matter-geometry

Hamma, Lloyd, FM, Caravelli, Severini, Markstrom, PR

Gravity  geometry tells matter where to go and matter tells geometry how to curve.

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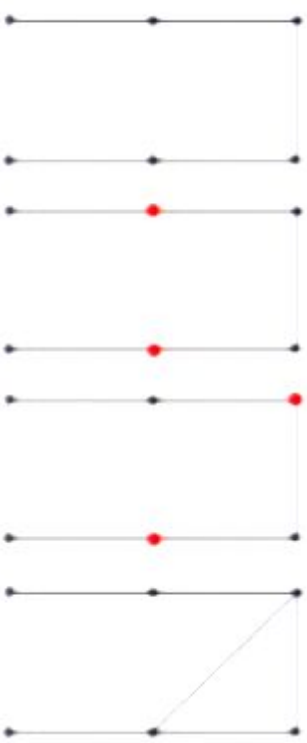
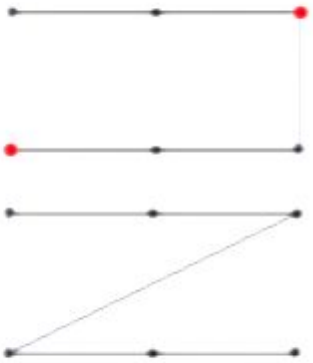


$$\mathcal{H} = \bigotimes_{v} \mathcal{H}_v \bigotimes_{e} \mathcal{H}_e$$

$$H_{ex} = \sum_{ij} P^L_{ij} \left(|0\rangle\langle 1|_{ij}\, b_i^\dagger b_j^\dagger - |1\rangle\langle 0|_{ij}\, b_i b_j \right)$$

$$H_{hop} = \sum_{ij} P_{ij} \left(b_i^\dagger b_j - b_i b_j^\dagger \right)$$

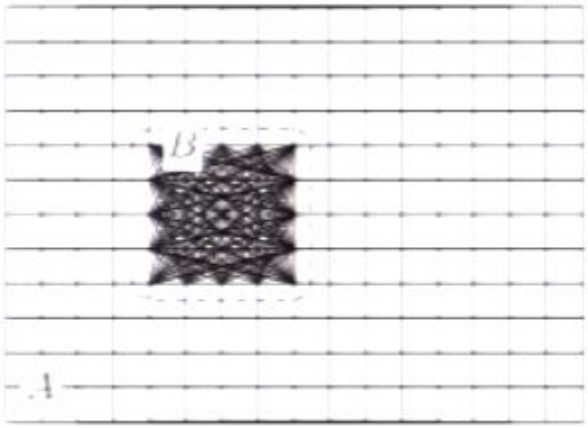
$$P_{ij} = |1\rangle\langle 1|_{ij}$$



The matter gives the graph the meaning of space:
Adjacency is defined by interactions. The graph determines where the matte
allowed to go.

Model 2: A toy black hole

Hamma, Lloyd,FM, Caravelli, Severini, Markstrom, PRL



$$c^A \propto 1$$

$$c^B \propto N^{-B}$$

$$\theta_c = \sin^{-1} \frac{c^B}{c^A} \sim \sin^{-1} N^{-B}$$

Probability of light escaping $\sim \frac{1}{N^B} \to 0$

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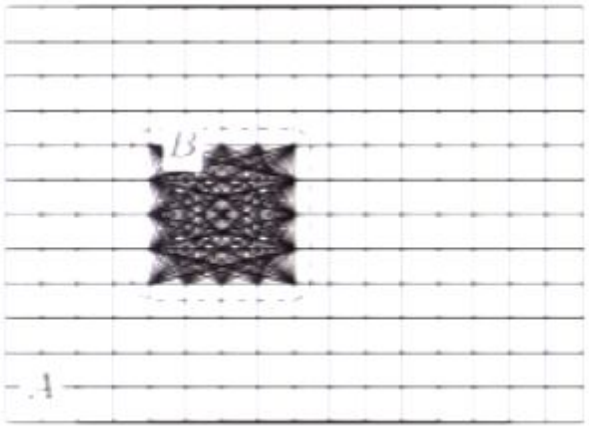

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- Eventually the "black hole" evaporates (faster as it gets smaller)
- Unitary evolution, mixed radiation (no singularity): matter entangled with remnant geometry

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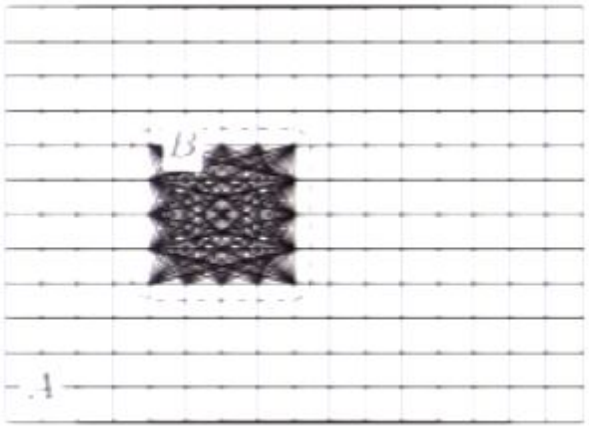

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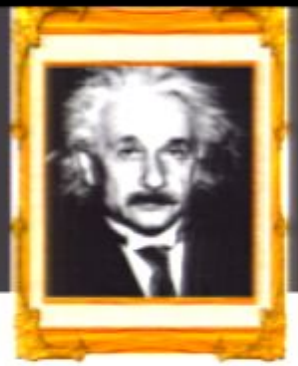
Can make all this very precise: particles obeying this Hamiltonian see an *effective curved geometry*.
Construct experimental realizations of such models in the lab? (Analogue models of gravity).



Background Independence: a guiding principle in quantum gravity, but how?

Background Independence I:

There should be no preferred geometry in the formulation of the quantum theory of gravity.
Quantum gravity is given by a quantum superposition of quantum geometries.

$$A_{L(in)\to L(out)} = \sum_{t=0}^{\infty} A(L(in), L(out), t)$$

Background Independence II:

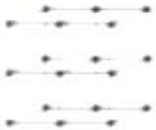
There are no geometric or gravitational degrees of freedom in the fundamental theory.
Geometry is only a classical, emergent concept.

From quantum to gravity?

A. Hamma, FM NJP(2011), 101

• Underlying spatial geometry is the notion of adjacency.

metric: neighbours or not?



E.g. a 3d euclidean geometry is a particular *order* of adjacencies that exhibits certain symmetries. Our geometric world is a *phase* (geometrogenesis), we froze to that phase.

• By promoting adjacency to a qubit and considering any network as a subgraph of K_N we have a convenient way to deal with superpositi of quantum geometries.

• When the adjacency qubits are dynamical dofs, we have an important ingredient of GR (dynamical geometry).

• Local interactions mean a finite speed of information propagation. Given local dynamics on a network of adjacencies, we can define a spacetime with finite lightcone structure. (Is it also universal?)

• If we find microscopic dynamics that simulate GR, we will have reconciled quantum with gravity.

• With emergent gravity, we need to *explain*, not quantize the Einstein Equations!

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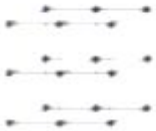

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Analogue models of gravity (simulating gravity):

If it looks like a duck, walks like a duck and quacks like a duck, can we call it a duck?

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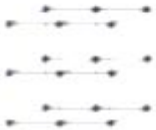

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If it looks like a duck, and quacks like a duck, we have at least to consider the possibility that we have a small aquatic bird of the family anatidae on our hands. Douglas Adams

Space does not exist

We only know 5% of our world. It will take a miracle to explain the other 95% without major change.

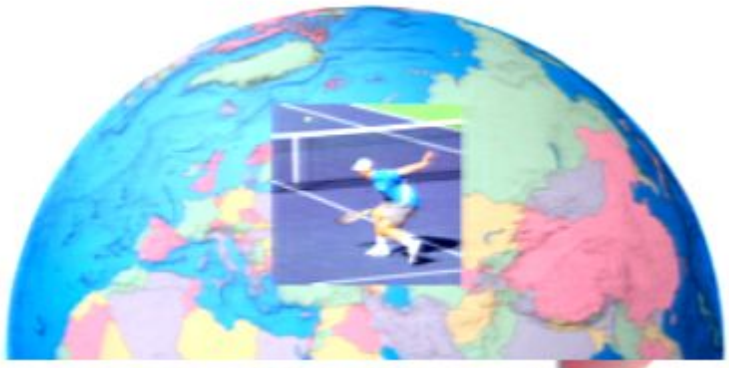
My bet: the major change is that space is not fundamental.

Can make models of emergent space and test them.

- Caution: Must not raise more problems that we solve!

- Good news: More observational data on the way, and we have models to test.

What is space(time)?



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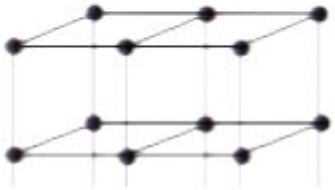
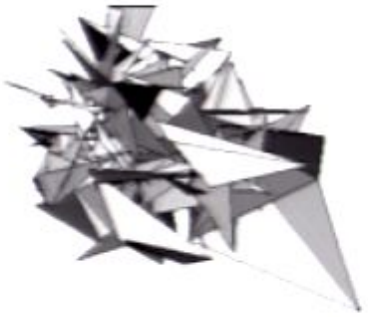


Space=locality

Are we most likely? It depends on time

Most likely spacetime:



Dimension: $d_H = 3.10 \pm 0.15$

$d_H \sim \infty$

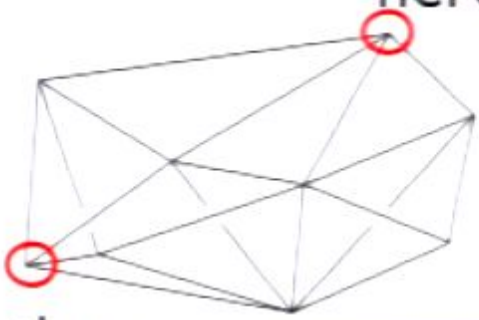
$d_H \sim 2$

J. Ambjorn, R. Loll *et al*

What is space(time)?

Model: networks

here



there

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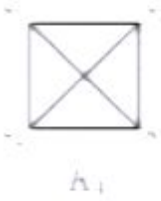

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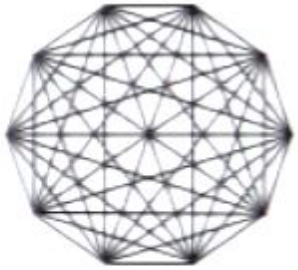


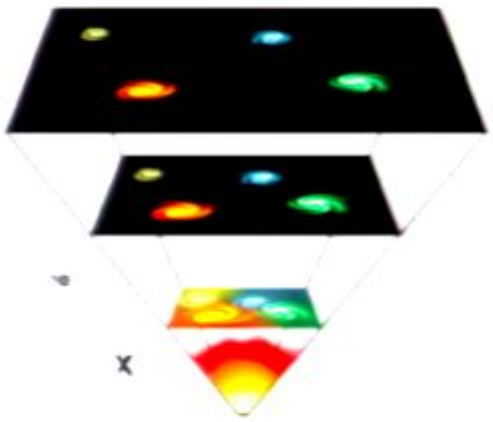
- no locality
- no geometric symmetries

- translations, etc
- locality
- 3+1 dim.

Emergent space(time)

We currently assume an FRW geometry all the way to the Big Bang.

Alternative scenario: What if geometry is not fundamental?



geometric phase
- translations, etc
- locality
- 3+1 dim.

geometrogenesis

non-geometric phase
- no locality
- no geometric symmetries

Background independence: principle in quantum gravity

Revisit Background Independence

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