QUANTUM GRAVITY AND EMERGENT LOCALITY

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QUANTUM GRAPHITY: a background independent condensed matter model of emergent space

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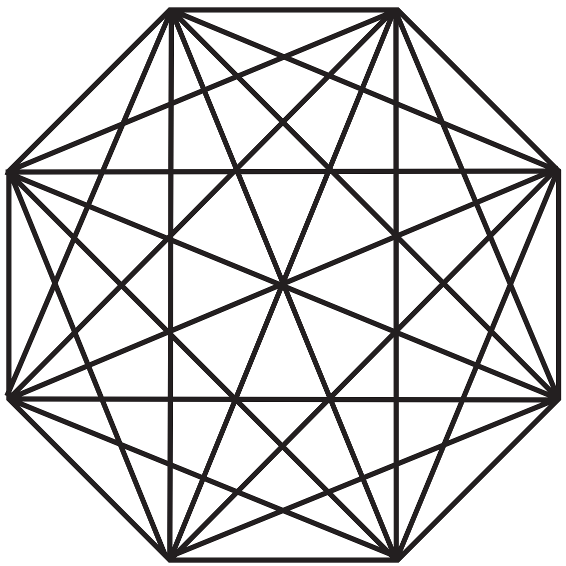
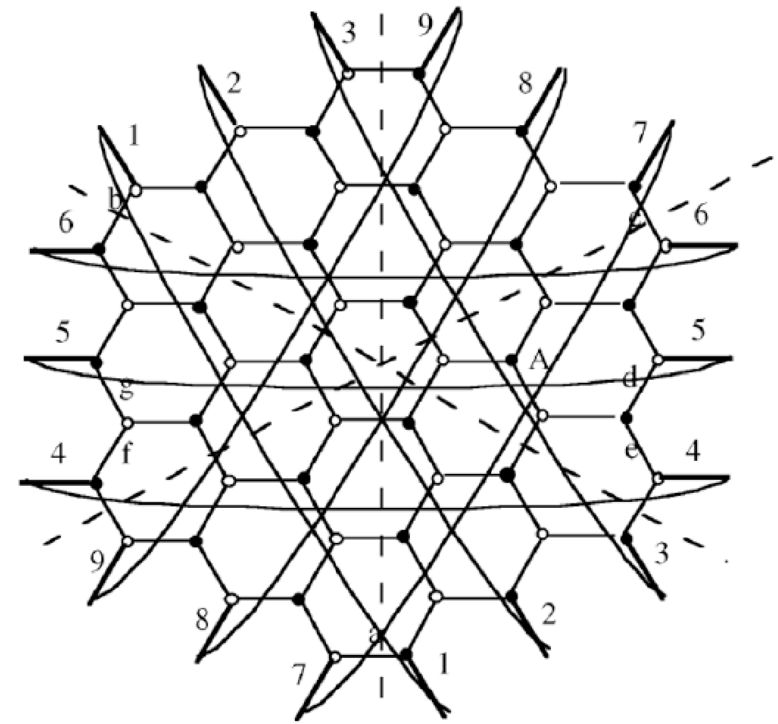
T. Konopka, FM & L.Smolin, hep-th/0611197

also with: O. Dreyer, S. Severini

Preview



geometrogenesis
phase transition



High- T

- Permutation symmetry
- No locality (no space)
- Relational

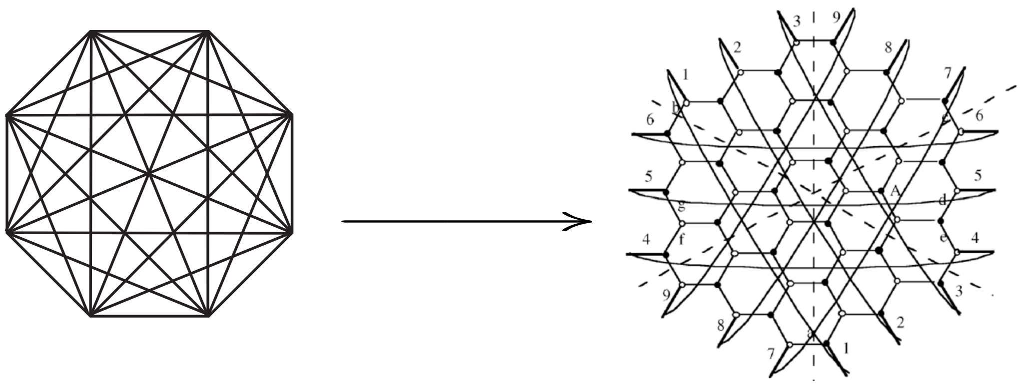
Low- T ground state

- Translations
- Local
- Relational

Outline.

1. Motivation

2. Quantum Graphity: A Model of emergent space (time)



3. Could we observe this? Early universe application

4. Discussion

Motivation for the model.

1. Emergence of near-flat geometry in low-energy limit of background independent quantum gravity: long-standing challenge. cf. Ambjorn talk

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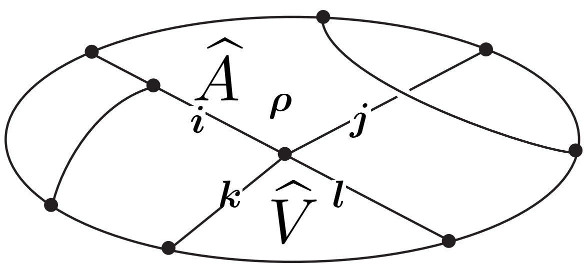
- combinatorial quantum geometry $\longrightarrow$ classical geometry



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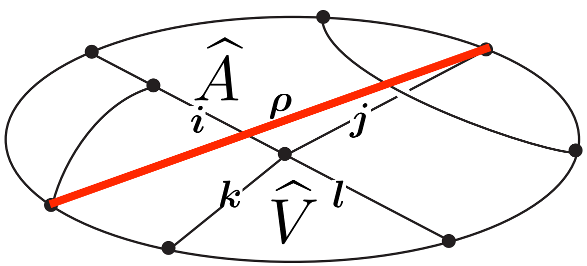


$\left.\begin{array}{l}\widehat{A}, \widehat{V}\text{: quantum geometry} \\ \text{spin foam vertex properties}\end{array}\right\}$ local statements

N nodes $\Rightarrow N^2$ one-edge perturbations $\}$ locality is unstable

$\sum_i |S_i\rangle \;\Rightarrow$ locality?

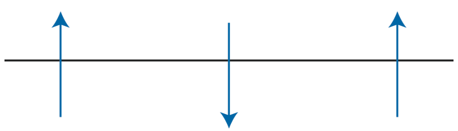
FM&L.Smolin, gr-qc/0702044

Motivation for the model.

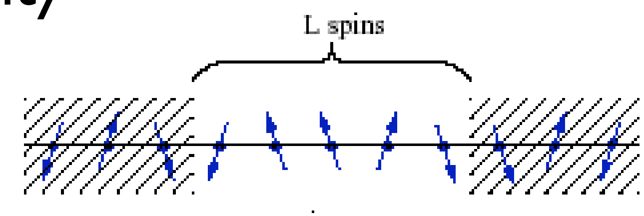
2. Locality, cont.

- Phase transition + background independence $\Rightarrow$

  micro-locality $\neq$ macro-locality



$\xrightarrow{\text{phase transition}}$



$$\mathcal{H}_{\text{spin chain}} = (\mathbf{C}_2)^{\otimes n} \qquad \mathcal{H}_{\text{spin waves}} = \bigoplus_n \mathcal{H}_1^{\ \otimes n}$$

background independence means dynamics determines locality.

O.Dreyer, hep-th/0409048
FM&D.Kribs, gr-qc/0510052
FM, gr-qc/0703097

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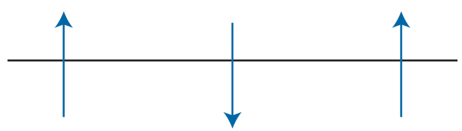

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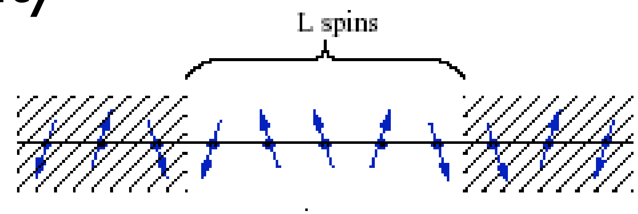

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- Lots of other hints: AdS/CFT, black holes, causets,...

Motivation for the model.

3. Background independence vs emergent gravity

Geometry and gravity are only classical, emergent concepts.

- condensed matter approaches (e.g. Volovik)
- string theory

Background independence: dynamical nature of spacetime geometry

What is the role of the lattice/geometry and the symmetries of the lattice?

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Background independence: dynamical nature of spacetime geometry

What is the role of the lattice/geometry and the symmetries of the lattice?

Background independence is normally implemented by a superposition of quantum geometries:

- loop quantum gravity
- dynamical triangulations
- causal sets

Reconcile:

- Background independence: *no fundamental geometric degrees of freedom*

- Today: *background independent condensed matter models.*

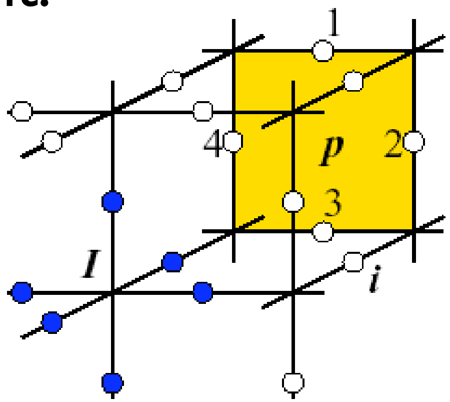
Dreyer 04, 06, Lloyd 05, FM&Kribs 05, FM07.

Motivation for the model.

4. Matter vs Geometry.

New results on emergent matter are suitable for a background independent treatment:

M.Levin & X-G.Wen, hep-th/0507118

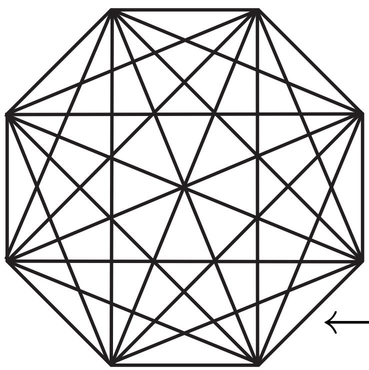


$\longrightarrow$ gauge theory -like excitations and fermions

5. No fundamental locality $\Longrightarrow$ large-scale observational consequences of quantum gravity.

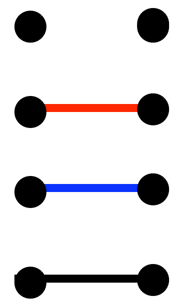
The model: kinematics.

Complete graph K_n: n vertices, $\frac{n(n-1)}{2}$ edges.



$\longleftarrow |j, m\rangle$

one-edge state space: $\mathcal{H}_1 = \mathrm{span}|j, m\rangle$



$|0, 0\rangle$ edge off

$|1, -1\rangle$

$|1, +1\rangle$

$|1, 0\rangle$

$\Big\}$ edge on

total state space: $\mathcal{H} = \mathcal{H}_1^{\otimes \frac{n(n-1)}{2}}$

$$J|j, m\rangle = j|j, m\rangle$$

$$M|j, m\rangle = m|j, m\rangle$$

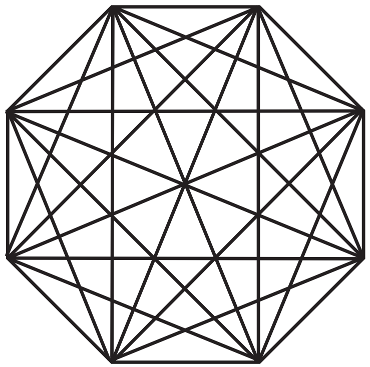
$$M^+|1, 0\rangle = |1, 1\rangle$$

$$M^-|1, 0\rangle = |1, -1\rangle$$

$$J|0, 0\rangle = M|0, 0\rangle = M^{\pm}|0, 0\rangle = 0$$

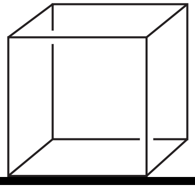
The model: dynamics.

Complete graph K_n: n vertices, $\dfrac{n(n-1)}{2}$ edges.



$$H = H_{\text{links}} + H_{\text{vertices}} + H_{\text{loops}}$$

want ground state



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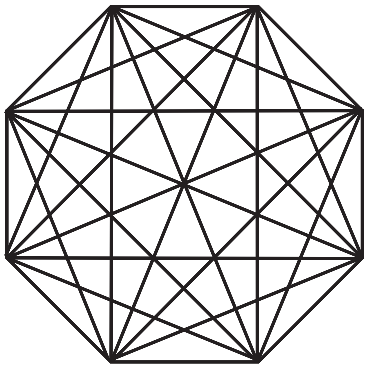

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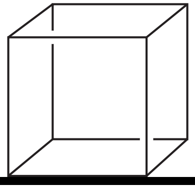
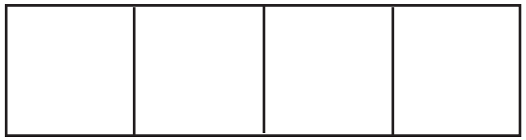


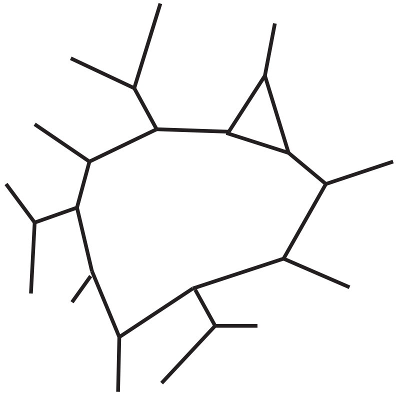
$$H_{\text{links}} = V \sum_a \left(v_0 - \sum_b \widehat{J_{ab}} \right)^2$$

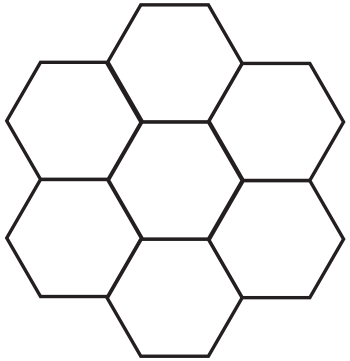
$a, b = 1, \ldots, N$
$V > 0$

H_{links} turns off edges and has minimum when all edges have degree v_0.

E.g., for $v_0 = 3$,







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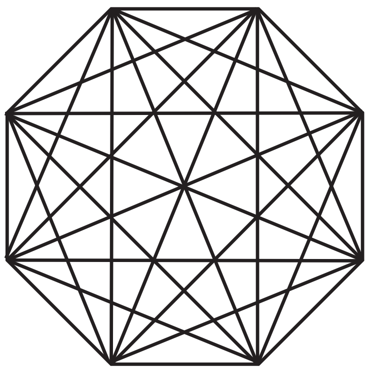

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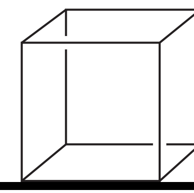
want ground state 

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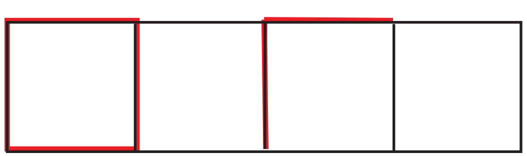
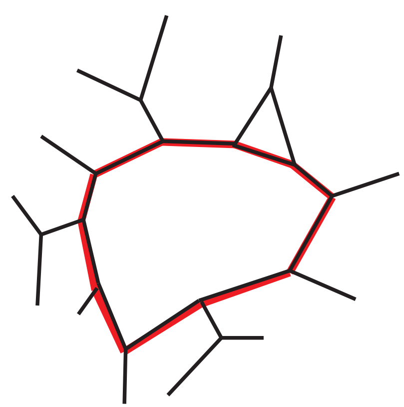
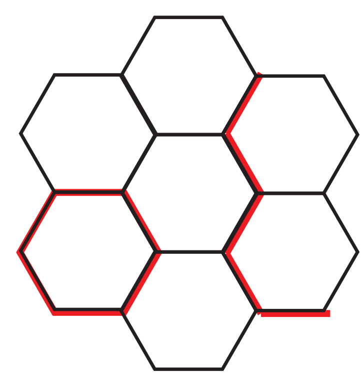


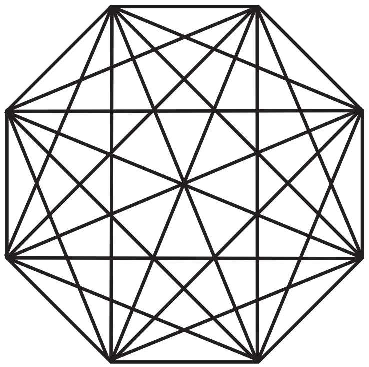




m values: strings

The model: dynamics.

Complete graph K_n: n vertices, $\dfrac{n(n-1)}{2}$ edges.



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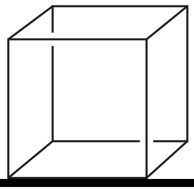


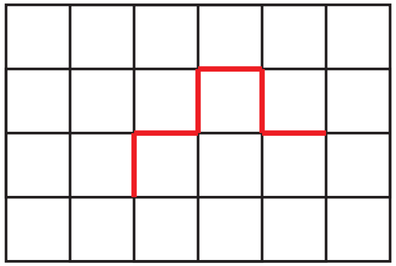
$$H_{\text{vertices}} = C \sum_a \left(\sum_b \widehat{M}_{ab} \right)^2 + D \sum_{ab} \widehat{M}_{ab}^2$$

does not like
open strings

tension

0

± 1



wants all $m = 0$

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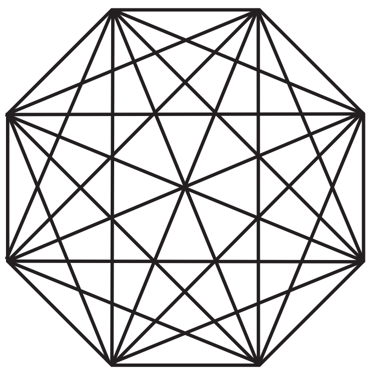

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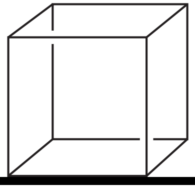
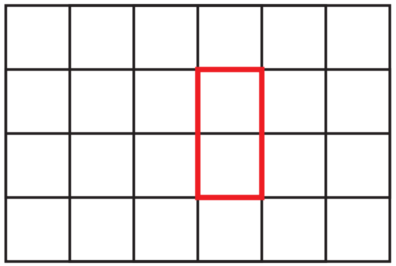


$$H_{\text{loops}} = - \sum_{\text{minimal loops}} \frac{1}{L!} B(L) \prod_{i=1}^{L} M_i^{\pm}$$

$L =$ length of loop

$$\prod_{i=1}^{L} M_i^{\pm} = M_{ab}^{+} M_{bc}^{-} \ldots M_{za}^{-}$$



cf. kinetic energy

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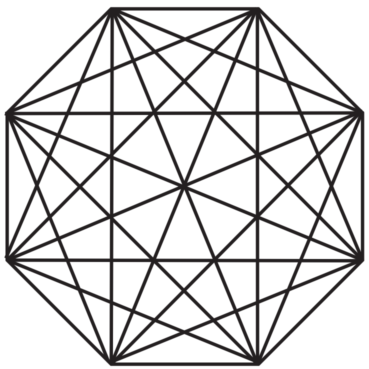

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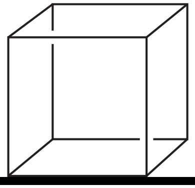
want ground state 

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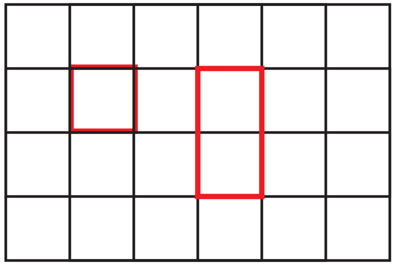

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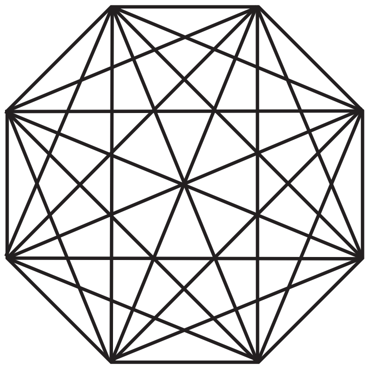

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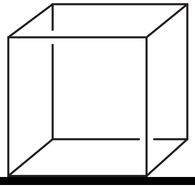

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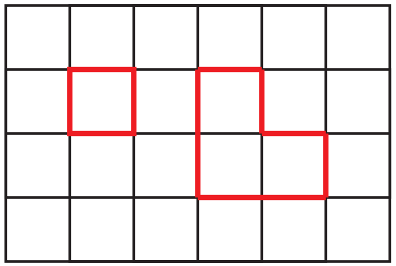

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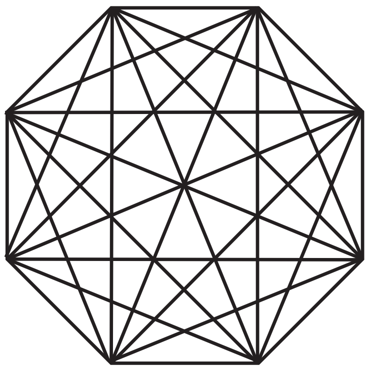

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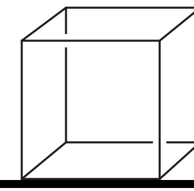

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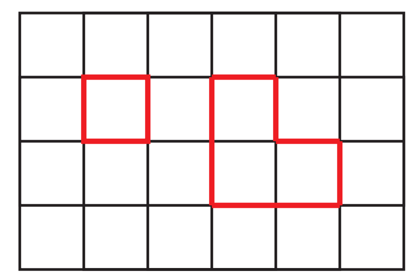

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$$\prod_{i=1}^{L} M_i^{\pm} = M_{ab}^{+} M_{bc}^{-} \ldots M_{za}^{-}$$

cf. kinetic energy

Let $B(L) = B_0 \; B^L$. There is a preferred loop length L_*:

$$\frac{B^{L_*}}{L_*!} > \frac{B^{L'}}{L'!} \qquad \forall\; L' \neq L_*$$

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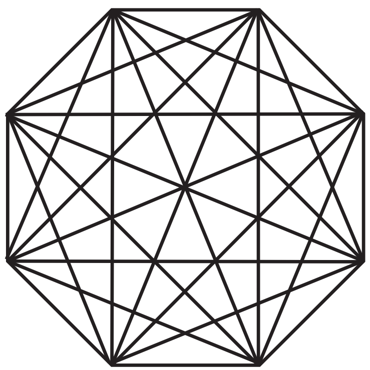

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$V \gg C, D$ erases edges to give lattice with extension

$C \gg D \quad B_0 \gg D$ makes lattice regular and gives macro-matter

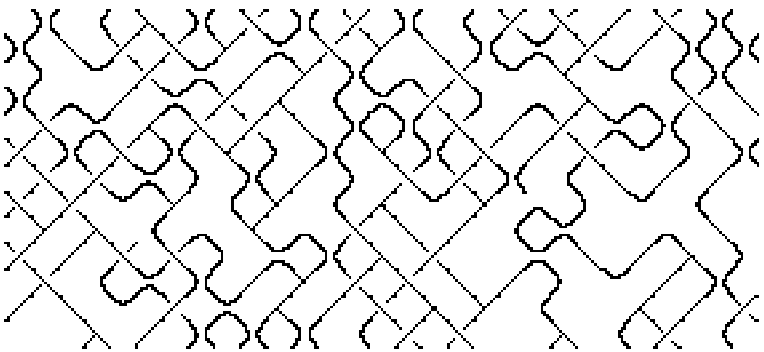
Matter.

H_{vertices} and H_{loops} are generalizations of the rotor model of string-net condensation of Levin and Wen to a dynamical lattice.

M.Levin & X-G.Wen, hep-th/0507118

- tension $\gg$ K.E. : ground state has almost no strings
- tension $\ll$ K.E. : ground state is a superposition of many closed strings,

  i.e., *string-net condensed*:



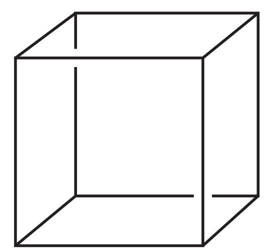
$$\underbrace{\text{high-energy charged excitations: open strings}}_{\text{emergent } U(1) \text{ gauge theory.}}$$

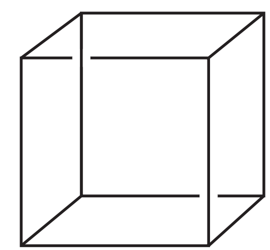
Ground state geometry plus matter.

$$N \gg 1,\ V \gg 1,\ C \gg D,\ B_0 \gg D$$

In our model: the balance between tension and K.E. controls both the loop size when the lattice is dynamical and gives the matter.

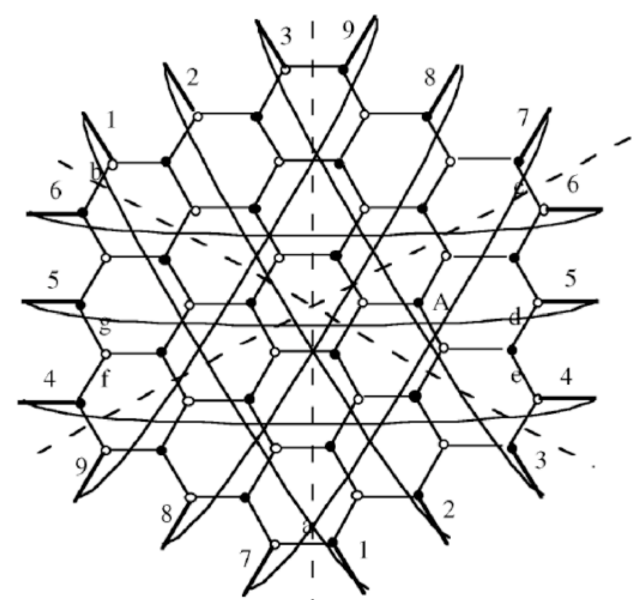
Local lattice: large average distance $\langle d_{ij} \rangle$.
Small vertex degree $\sim v_0$
Loops of average size L_*.
Possibly also regular?





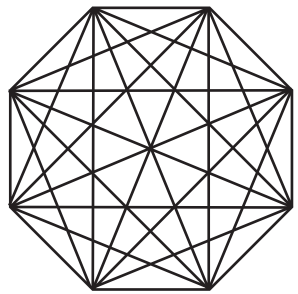
For $v_0 = 3, L_* = 6$ number of minimal loops is maximized by the honeycomb lattice:

T.Konopka, FM
& S.Severini

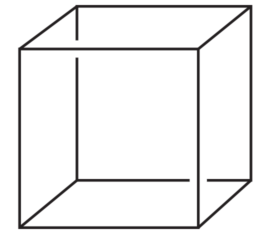


Plus string condensation on the ground state lattice, as in string nets.

Summary of quantum graphity.



geometrogenesis
phase transition



High- T

- Permutation symmetry
- No locality
- Relational
- $\langle d_{ij} \rangle = 1$
- $\sim \infty$-dimensional
- no subsystems
- external time
- micro-matter

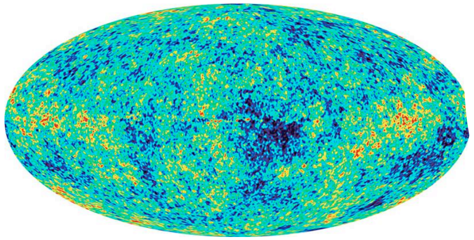
Low- T

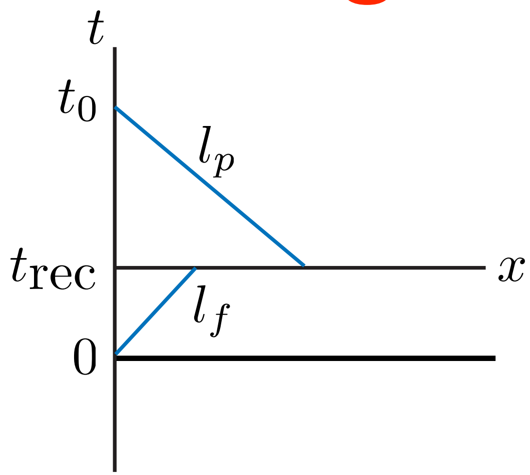
- Translations
- Local
- Relational
- $\langle d_{ij} \rangle$ large
- low-dimensional
- subsystems
- external and internal time
- macro-matter and dynamical geometry

Model has 4 couplings (V, C, D, B_0) and 3 parameters (N, L_*, v_0).
Some obey generic conditions: $N \gg 1,\ V \gg 1,\ C \gg D,\ B_0 \gg D$
Some have to be adjusted: $v_0 = 3, 4,\ L_* = 4, 6$

Cosmology of emergent space.

Horizon problem



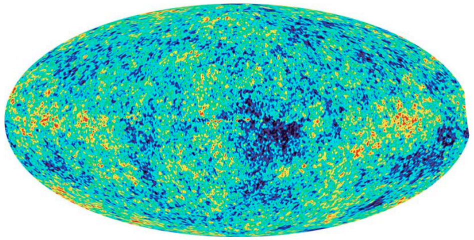


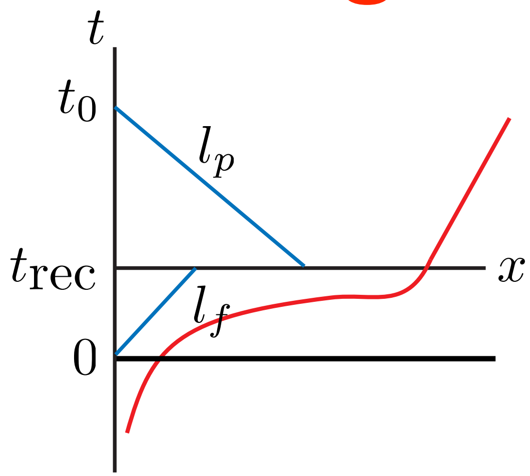
$l_p \gg l_f$

This is an extrapolation of our causal and local structure to the initial time

Cosmology of emergent space.

Horizon problem





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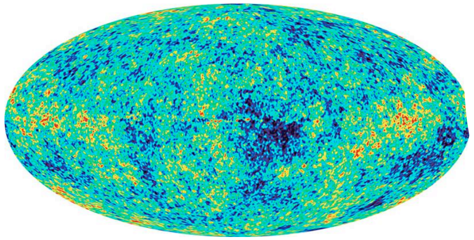
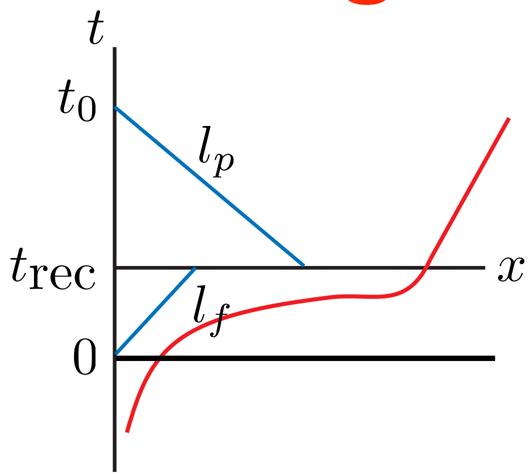
inflation

Cosmology of emergent space.

Horizon problem





$l_p \gg l_f$

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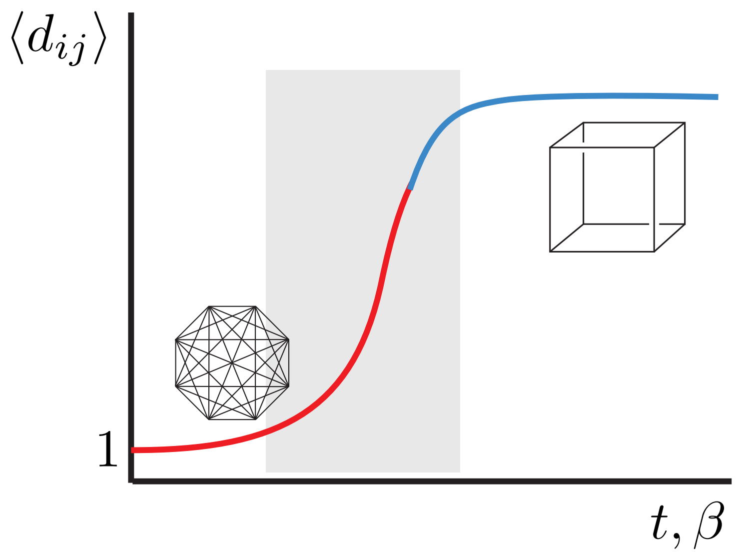
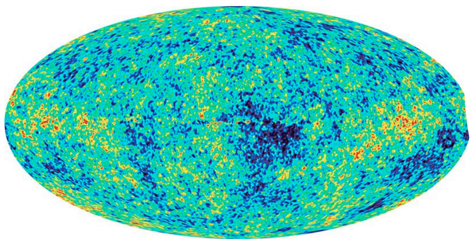
inflation

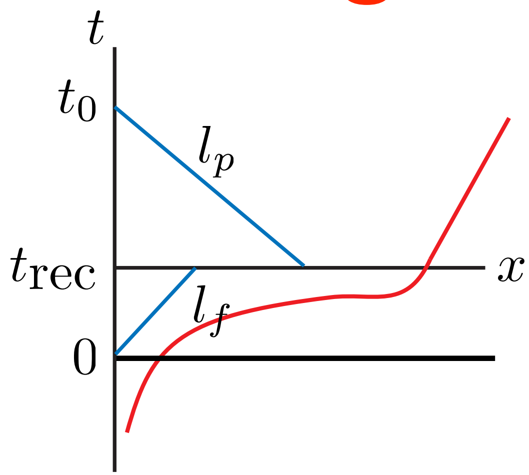
In our model:



Cosmology of emergent space.

Horizon problem





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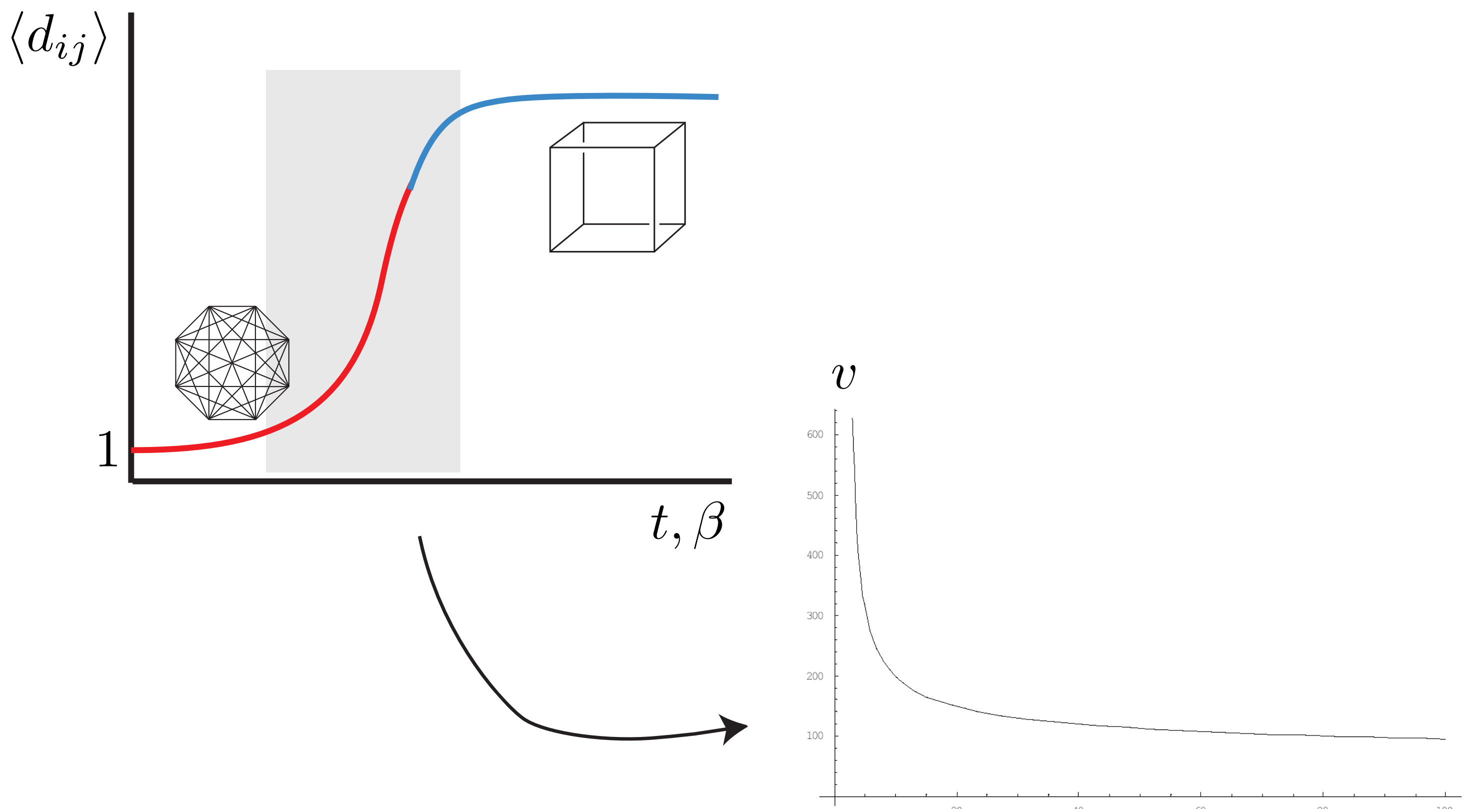
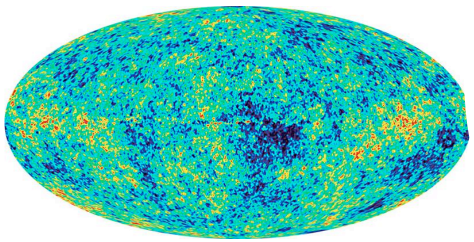
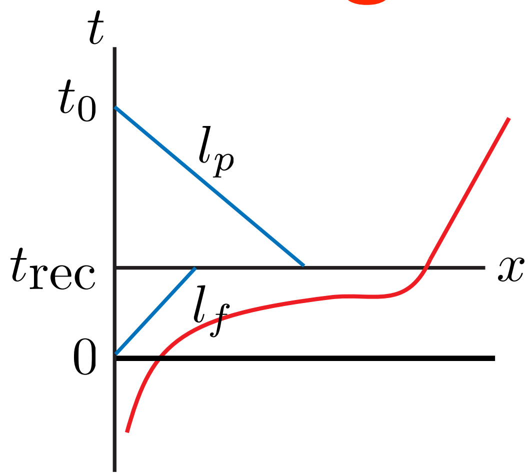


Cosmology of emergent space.

Horizon problem





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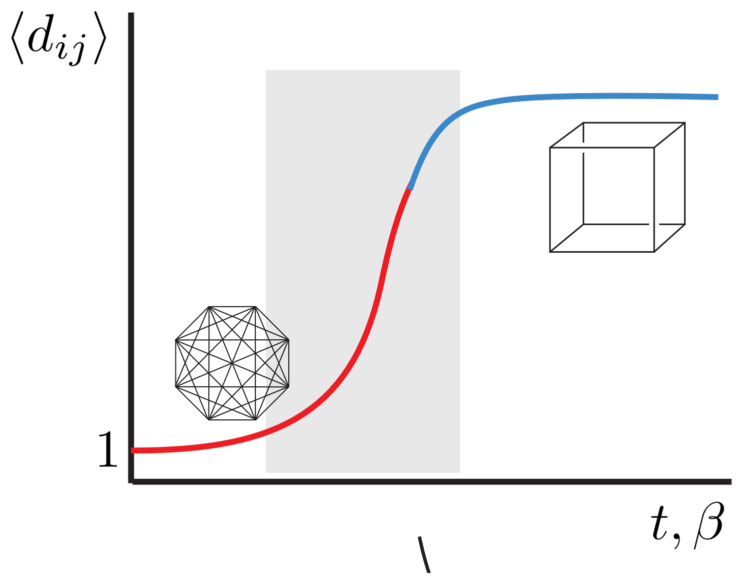
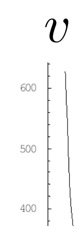
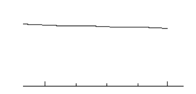




Are the CMB correlations a consequence of pre-geometry?

Compare, e.g., to the phenomenology of $\mathcal{O}\left(l_{\mathrm{Pl}}\right)$ discretization.

A geometrogenesis scenario has the potential of large-scale effects.



Comments.

1. Time, temperature?
   Emergent space or emergent spacetime?

   - Time-reparametrization invariance as the noiseless sector of a theory with time: T. Konopka and FM, gr-qc/0601028.

   - Does the temperature imply a bath?

   - Internal vs external time and geometry.
   Internal: subsystems observing subsystems. Our emergent space gives emergent spacecetime internally.

2. The terms that give rise to matter are also responsible for the geometry of the lattice: we don't just erase edges, we also order them.
This is a new use for unification.

To do.

- Understand the ground state
- Graph theory analysis of the terms in the Hamiltonian
- Cosmology: perturbations
- Effective disordered locality description
- Understand the role of the temperature