Title: Covariant Loop Quantum Gravity, the State of the Art

Speakers: Carlo Rovelli

Series: Quantum Gravity

Date: April 16, 2020 - 2:30 PM

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Abstract: The covariant (spinfoam) formulation of loop gravity is a tentative physical quantum theory of gravity with well defined transition amplitudes. I give my current understanding of the state of the art in this research direction, the issues that are open and need to be explored, and the current attempts to use the theory to compute quantum effects in the early universe and in black hole physics.

Quantum Gravity at the time of the pandemics
PI online seminar - April 2020

Covariant LQG

The state of the art, as I see it

Carlo Rovelli

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- Covariant LQG

    - Formalism
    - Interpretation and basic ideas
    - Recent results and Questions to be addressed

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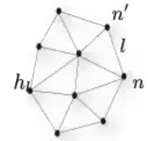
Theory: $(\mathcal{H}, \mathcal{A}, \mathcal{W})$



Γ spin network (nodes, links)

Kinematics **Boundary**

$\mathcal{H}$ Truncation: $\mathcal{H}_\Gamma \subset \mathcal{H} \quad \mathcal{H}_\Gamma = L^2[SU(2)^L/SU(2)^N]_\Gamma \quad \ni \psi(h_l)$

$$\psi(h_l) = \psi(\lambda_n h_l \lambda_{n'}^{-1})$$

$\mathcal{A}$ Operators: $f(h_l) \quad \vec{E}_l = i l_p^2 \vec{L}_l \qquad \vec{L}_l = \{L_l^i\}, i = 1,2,3$

$$[E_l^i, E_{l'}^j] = i l_p^2 \, \delta_{ll'} \, \epsilon^{ij}{}_k \, E_l^k \qquad L^i \psi(h) \equiv \frac{d}{dt}\psi(h e^{t\tau_i})\Big|_{t=0} \qquad l_p^2 = 8\pi\gamma\hbar G$$

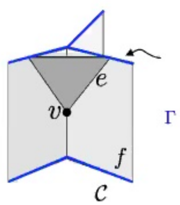
Dynamics **Bulk**

$\mathcal{W}$ $\quad \mathcal{W}_\mathcal{C} : \mathcal{H}_\Gamma \to \mathbb{C}$

$\partial\mathcal{C} = \Gamma$

Transition amplitudes

$$W_\mathcal{C}(h_l) = N_\mathcal{C} \int_{SU(2)} dh_{vf} \prod_f \delta(h_f) \prod_v A(h_{vf}) \qquad h_f = \prod_v h_{vf}$$



Vertex amplitude

$$A(h_{vf}) = \int_{SL(2,\mathbb{C})} dg'_e \prod_f \sum_j (2j+1) \; D^j_{mn}(h_{vf}) D^{\gamma(j+1)\,j}_{jmjn}(g_e g_{e'}^{-1})$$

spinfoam (vertices, edges, faces)

$$W = \lim_{\mathcal{C}\to\infty} W_\mathcal{C}$$

Smolin, Jacobson, Ashtekar, cr, Lewandowski, Pullin, Gambini, Bianchi, Thiemann, Dittrich, Iwasaki, Reisenberger, **Freidel**, Baez, Crane, Alesci, Perez, DiPietri, Krasnov, Pereira, Engle, Livine, Speziale, Lewandowski, Kaminski, Kisielowski, Barrett, Han, Ding, Wieland, …

Primer on math: Martin-Dussaud, Book on the theory: CR&Vidotto.

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Change interpretation and the use of this math:

NOT: a microscopic theory from which low energy physics is obtained only with a large number N of combinatorial elements

$$N \to \infty \qquad \textbf{or} \qquad N \sim \frac{\text{Length scale}}{\text{Planck scale}}$$

RATHER: an expansion in a (small) number of (relevant) degrees of freedom.

$$N \sim \#\ \text{of relevant degrees freedom}$$

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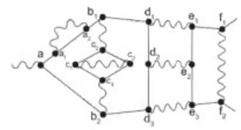
Feynman graphs QFT (as in QED): Almost all physically relevant calculations (including radiative corrections) are entirely in the subset of Fock space with a finite number of degrees of freedom!

$$\mathcal{H}_N = \oplus_{n=0}^{N} \mathcal{H}_n \qquad \hat{N}|n\rangle = n|n\rangle$$

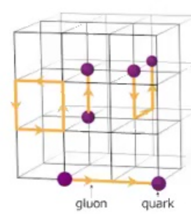
$$N \sim \text{number of particles (including virtual)}$$



Lattice QFT (as in QCD): Almost all physically relevant calculations (including radiative corrections) are entirely on the small lattice with a number L of lattice sites

$$L \sim (cN)^4$$

$$N \sim \frac{\text{size of the proton}}{\text{quark's Compton's length}}$$



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- “**Tentative**”:
  - Lacks empirical support (work is in progress, see ahead)
  - There are open questions about the coherence of the theory (work is in progress, see ahead).

- “**Complete**”:
  - Can be used, as it is, to do physics. Transition amplitudes are given explicitly.
  - Interpretation is well defined. There are no conceptual mysteries.

- **Long cumulative work**:
  - Quantum gravity is not going to be solved from a “new idea” out of the blue sky, but by building on existing results.
  - Starting from scratch over and over again is a waste of time. A good theoretical physicist knows extensively what has been done in a field earlier and builds on it.
  - “New ideas” are too easy to pull from the blue sky. History shows that most often they lead no where. They are the last resort.
  - I think that our community suffers from a wrong philosophy of science that misunderstands and over-emphasises “independence”, “new ideas”, “new principles”, producing far too many sterile branches (and too many jobless people).

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Extensions, variants, simplified versions

- **Matter** can be easily coupled: Yang Mills fields, fermions. (Thiemann; Bianchi Han Magliaro Perini Wieland, Han cr).
- There is a version (in fact, more versions) where Lie groups are replaced by **quantum groups** with an extra parameter interpreted as the cosmological constant (Fairbairn, Meusburger, Han, Ding, Haggard, Han, Kamiński, Riello. **See: Florian's talk last week**).
- Simplified versions:
  - **Euclidean version**, with difficulties that disappear in the Lorentzian case.
  - **BF theory** topological.
  - Truncation in the sum over the parameters of the booster function (see later) introduced by **Speziale**, (like quenched QCD).
  - **Ponzano Regge model**.

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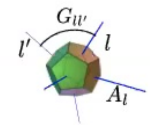
$G_{ij} = \vec{E}_l \cdot \vec{E}_{ll'}$ satisfies the assumptions of 1897 Minkowski theorem and 1971 Penrose spin-geometry theorem: semiclassical states have a geometrical interpretation as polyhedra.

Physical interpretation:

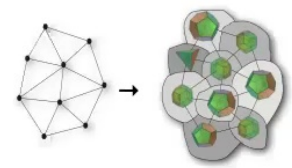


Polyhedron

In $\mathcal{H}_\Gamma$ there is a very well developed theory of **coherent states**.

- Intrinsic coherent states: minimise spread of $\vec{E}_l$,
- Extrinsic coherent states: minimise spread of $\vec{E}_l$ and $f(h_l)$.

This gives a classical theory of **3d discretised (int & ext) geometry**.



Thiemann, Bianchi, Perini, Magliaro, Ding Dittrich, Speziale, Freidel, Bayta, Yokomizo…

$(\mathcal{H}, \mathcal{A})$ Gives a complete mathematical description of a quantum physical space, which is **discrete**, **fuzzy**, respects the **superposition principle** and has GR's configuration space (3-geometries) in its classical limit.

- A discretised geometry is **not** a quantum geometry: it is simply a classical truncation of the degrees of freedom of the gravitational field,
- It gives an approximation to 3d geometry, (configuration gravitational field) up to some frequency: **Not a piecewise flat geometry**.

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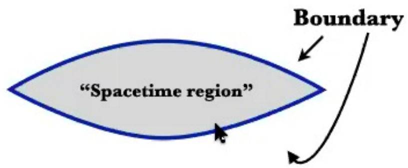
Physical interpretation:

$\mathcal{W}_C(\psi)$ is the (truncated) transition amplitude between this geometry



$S[q_3]$ is the Hamilton function of GR: it contains the entire classical dynamics of GR; in the form of a simple functional of a 3d geometrry

$$\mathcal{W}_C(\psi_{q_3}) \underset{\hbar\to 0}{\sim} \sum_n A_n \, e^{\frac{i}{\hbar} S_n[q_3]}$$

cfr: "Cosine Issue"

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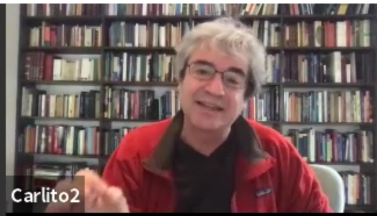
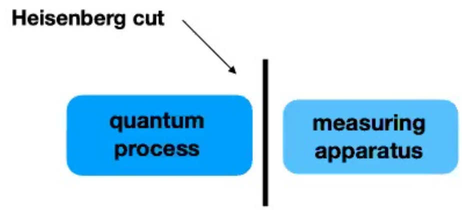


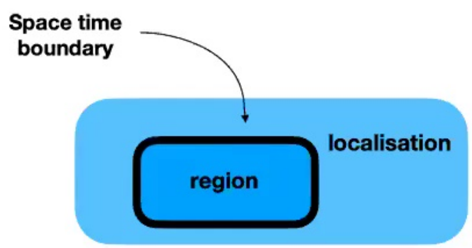
The main physical idea with which we can do Quantum Gravity:

QM



$$W(\psi_{q,t} \otimes \psi_{q't'}) \underset{\hbar\to 0}{\sim} \sum_n A_n \, e^{\frac{i}{\hbar} S_n[q,t,q',t']}$$

GR



$$\partial g = q, \quad Ricci[g_q] = 0$$

$$S_{GR}[q] = \int_{\partial R} q_{ab} k_q^{ab},$$

QG

Spacetime boundary = Heisenberg cut

$$W(\psi_q) \underset{\hbar\to 0}{\sim} A \, e^{\frac{i}{\hbar} S_{GR}[q]} + \dots$$

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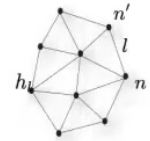

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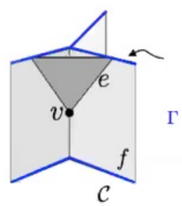

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Some results: old

N-point functions	Bianchi, CR, Perini, Magliaro, Han, Ding, Zhang, Shirazi, Engle, Vilensky.
Cosmology: classical limit	Vidotto, Bianchi, cr, Vilenki, Sarno, Speziale, Stagno, Bahr, Sebastian Kloser, Rabuffo
Entropy of non extremal black hole	Bianchi
Asymptotic behaviour: classical limit	Freidel, Conrady, Krasov, Barrett, Pereira, Huang, Han, Zhang, Bahr Steinhous Belov, Perini Magliaro, Kaminski, Sahlmann, de Lopes Marques, Engle, Vilenski Zipfel, Puchta, Krajewski, Bodendorfer, Neiman, Perini, Mikovic, Vojinovic, D'Amborsio, Thürigen

Some results: new

Analytical and numerical tools	Speziale, Donà
Flatness	Donà, Sarno, Gozzini
Early cosmology	Gozzini, Vidotto
Black holes	Christodoulou, cr, Soltan

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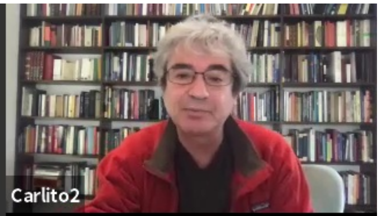
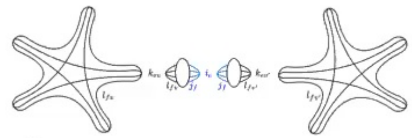


Analytical and numerical tools

How to compute with these amplitudes?

$$Z_{\mathcal{C}} = \sum_{j_f, i_e, l_{fv}, k_{ev}} \prod_f (2j_f+1) \prod_e A_e^\gamma(j_f, i_e, l_{fv}, k_{ev}) \prod_v \{nj\}_v(l_{fv}, k_{ev})$$



$$B^\gamma(j_i, l_i; i, k) = \sum_{p_i} \begin{pmatrix} j_1 & j_2 & j_3 & j_4 \\ p_1 & p_2 & p_3 & p_4 \end{pmatrix}^{(i)} \begin{pmatrix} l_1 & l_2 & l_3 & l_4 \\ p_1 & p_2 & p_3 & p_4 \end{pmatrix}^{(k)} \int d\mu(r) \left(\bigotimes_{i=1}^4 d^{(\gamma j_i, j_i)}_{j_i l_i p_i}(r) \right)$$

Speziale

Asymptotic behaviour for large boundary areas of the vertex extensively studied

$$\sum_{b \neq a} j_{ab} \vec{n}_{ab} = 0, \qquad R_a \vec{n}_{ab} = -R_b \vec{n}_{ba}.$$

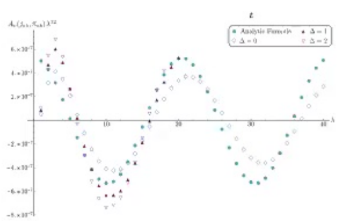
$$A_v^{\mathrm{EPRL}}(j_{ab}, \vec{n}_{ab}) \sim j^{-12} \cos\left(\gamma \sum_t j_t \theta_t^{\mathrm{L}}(j)\right)$$

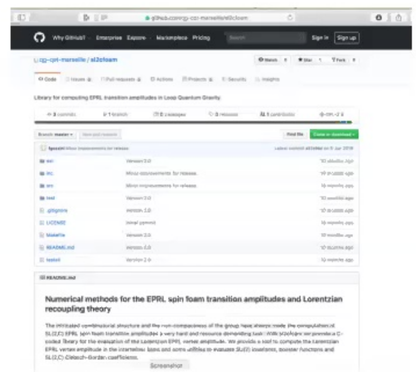
Speziale, Donà, Fanizza, Sarno.

A numerical code to compute these amplitudes has been developed

https://github.com/qg-cpt-marseille/sl2cfoam.

Sarno, Donà, Gozzini, Fanizza, Speziale, Collet,





Spinor formulation? (Banburski, Chen, Hnybida, Freidel)

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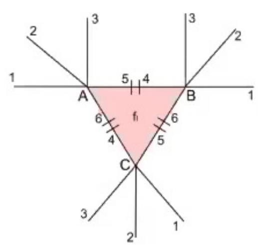
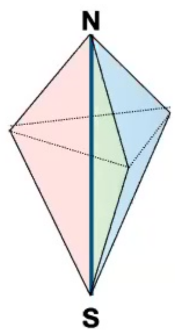
Flatness Donà, Sarno, Gozzini

Arguments suggest that in the classical limit the theory does not capture solutions where the 4 geometry is curved. The sum over spins in a face imply a delta function over a quantity that (if we read the amplitude as a Feynman integral over Regge triangulations) peaks on flat Regge geometries.

New result (numerical) : there is a simple example where the same arguments as in Bonzom, Oliveira, Hellmann, Kaminski, Engle apply, but it is not so, from numerical evidence.





3d analog

In 4d, the boundary data determine the value of the internal spin and the curvature of the internal face (assuming each 4-simplex flat).

The flatness argument can be run for the BF amplitude (Engle's talk) and the result is that the amplitude force the internal face to be flat.

The numerical calculation shows cleanly a stationary phase point in the sum over the internal spin at the value of the curved internal face.

This shows that the flatness arguments are wrong.

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Flatness

Bonzom, Oliveira, Hellmann, Kaminski, Engle

Flatness arguments are all based on various combinations several assumptions:

- An *exchange of limits*, the asymptotic limit and the sum over spins. (Engle's talk)
- The asymptotic analysis of *single* vertex amplitude: gauge issues? (Donà)
- *Swapping* the holonomy of the Ashtekar connection with the holonomy of the spin connection

$$W_{\mathcal{C}}(h_l) = N_{\mathcal{C}} \int_{SU(2)} dh_{vf} \prod_f \delta(h_f) \prod_v A(h_{vf})$$

Theorem: $F^{+-} = 0 \Longleftrightarrow Ricci = 0$

$$(F^+)^{IJ}_{ab} = F^{IJ}_{ab} + i\epsilon^{IJ}{}_{KL} F^{KL}_{ab}$$
$$(F^{+-})^{IJ}_{ab} = (F^+)^{IJ}_{ab} - i\tilde{\epsilon}_{ab}{}^{cd}(F^+)^{IJ}_{cd}$$

- A *literal* interpretation of the 4-d geometry in terms of Regge triangulations.

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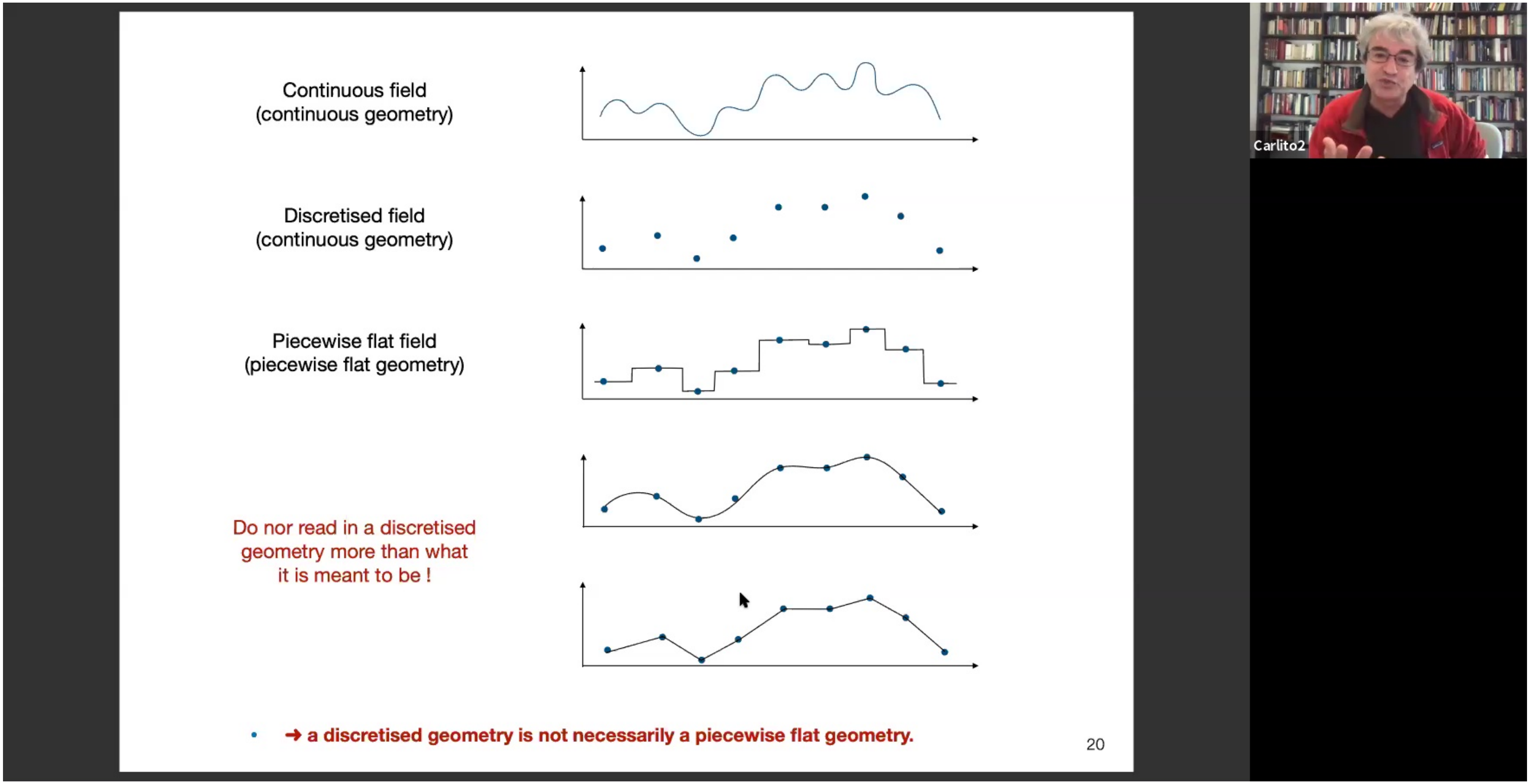
Continuous field
(continuous geometry)
Discretised field
(continuous geometry)
Piecewise flat field
(piecewise flat geometry)
Do nor read in a discretised
geometry more than what
it is meant to be !
• ➜ a discretised geometry is not necessarily a piecewise flat geometry.
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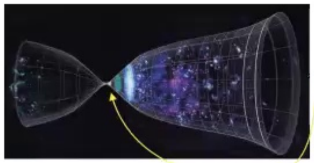
Carlito2

Early cosmology

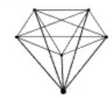
Gozzini, Vidotto, (Vilenski, Bianchi, Stagno, Kiselowski, Pucka,...)

Use the theory to study fluctuations and correlations between spacial regions, generated by the primordial quantum gravitational phase of the universe.



Transition from the state $\psi(h_l) = 1$ to a state ψ in $\mathcal{H}_\Gamma$ $\langle j, i_n | \varnothing \rangle = W(j, i_n) \equiv \langle j, i_n | \psi_o \rangle$

Cosmological truncation (always!) to few degrees of freedom

First truncation: $\Gamma =$  $\mathcal{C} =$ 

$$\langle A \rangle = \langle \psi_o | A | \psi_o \rangle \qquad \Delta A = \sqrt{\langle \psi_o | A^2 | \psi_o \rangle - \langle A \rangle^2} \qquad C(A_1, A_2) = \frac{\langle \psi_o | A_1 A_2 | \psi_o \rangle - \langle A_1 \rangle \langle A_2 \rangle}{(\Delta A_1)\ (\Delta A_2)}$$

(1) Expectation value of the quantum state of the geometry is a homogeneous. (Expected).
(2) Fluctuations are very large and correlations are strong! Although not maximal. (Surprising, significative).
(3) Quantum gravity effects may be sufficient to solve the horizon problem. (Intriguing.)

$$\langle A_{ab} \rangle = -0.333$$

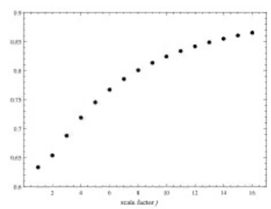


FIG. 2. Spread of angle operator.

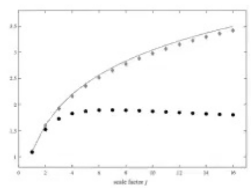
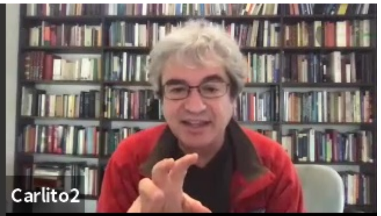
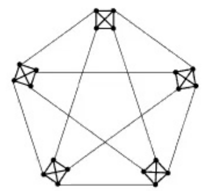
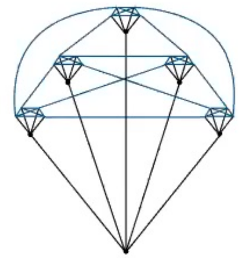
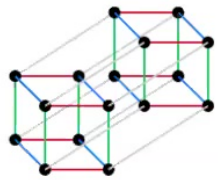
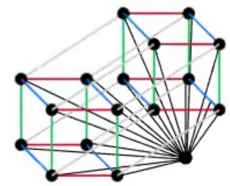


FIG. 4. The entanglement entropy of a node with respect to the rest of the graph. Grey continuous line shows the maximum entropy attainable for the given scale factor parameter. Grey diamonds report the result of [19]. Black circles show our result for $|\psi_o\rangle$.

Non Regge geometries matter and give physically reasonable amplitudes.



Next approximation: $\Gamma =$  $\mathcal{C} =$ 

Preliminary results for : $\Gamma =$  $\mathcal{C} =$ 

Expectations value and the correlations change little! Gozzini

Relevant for the meaning of " $W = \lim_{\mathcal{C}\to\infty} W_{\mathcal{C}}$ ".

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Black Holes

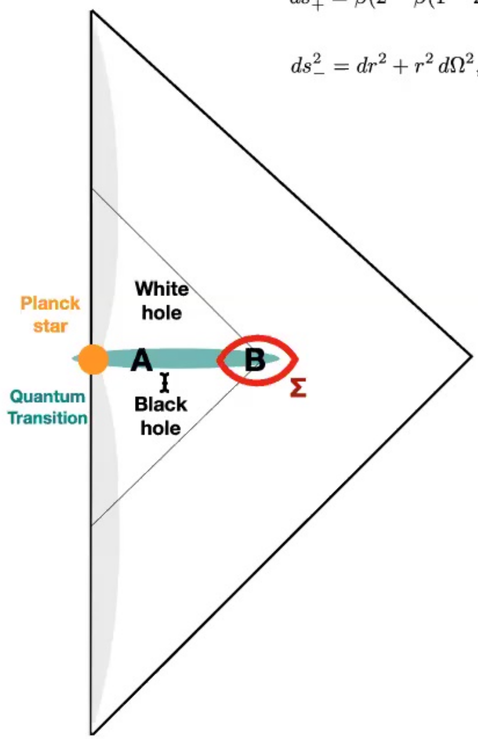
Haggard, Christodoulou, D'Amborsio, Bianchi, Vidotto, Vilenski Soltani, cr,

$$ds^2_+ = \beta(2-\beta(1-2m/r))dr^2 + r^2\, d\Omega^2.$$

$$ds^2_- = dr^2 + r^2\, d\Omega^2,$$

$$k^-_{ab} = \sqrt{\frac{m}{2r^3}}dr^2 - \sqrt{2mr}d\Omega^2$$

$$k^+_{ab} = \frac{m\beta^{3/2}(r(3-\beta)+2m\beta)}{\sqrt{r^5(r(2-\beta)+2m\beta)}}dr^2 - \frac{r(1-\beta)+2m\beta}{\sqrt{\beta(2-(1-2m/r)\beta)}}d\Omega^2$$



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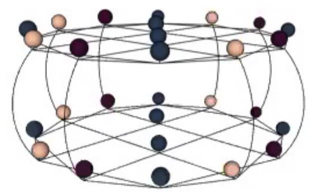
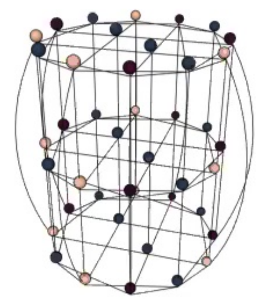


$\mathcal{C} =$



Soltani

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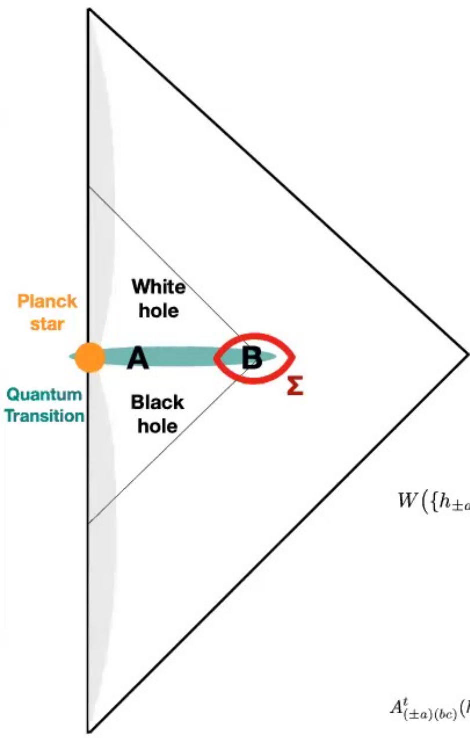
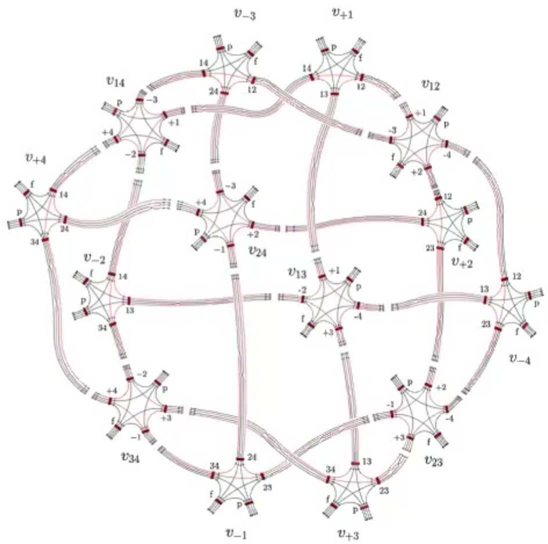
Black Holes

Soltani





$$W\big(\{h_{\pm a}\},\{h^t_{(\pm a)(bc)}\}\big) = \int_{SL(2,\mathbb{C})} \prod_a \prod_b \big(\mathrm{d}g_{(+a)(ab)}\ \mathrm{d}g_{(ab)(+a)}\big) \prod_a \prod_{b<c} \big(\mathrm{d}g_{(-a)(bc)}\ \mathrm{d}g_{(bc)(-a)}\big) \times \prod_{a<b} \mathrm{d}g^p_{ab}$$
$$\times \prod_{\pm a} \mathrm{d}g^p_{\pm a} \prod_{\pm a} A_{\pm a}(h_{\pm a}) \prod_t \prod_a \prod_b A^t_{(+a)(ab)}(h^t_{(+a)(ab)})$$
$$\times \prod_t \prod_a \prod_{b<c} A^t_{(-a)(bc)}(h^t_{(-a)(bc)}) \prod_a \prod_{b<c} A_{(ab)(ac)}$$

$$A^t_{(\pm a)(bc)}(h^t_{(\pm a)(bc)}) := A_{f^t_{(\pm a)(bc)}}(h^t_{(\pm a)(bc)}) = \sum_j d_j D^{(\gamma j,j)}_{jm\,jn}\big({g^t_{\pm a}}^{-1}\, g_{(\pm a)(bc)}\big) D^{(\gamma j,j)}_{jn\,jp}\big(g^{-1}_{(bc)(\pm a)}\, g^t_{bc}\big) D^j_{pm}\big(h^t_{(\pm a)(bc)}\big),$$

$$A_{(ab)(ac)} := A_{f_{(ab)(ac)}} = \sum_j d_j D^{(\gamma j,j)}_{jm\,jn}\big(g^{-1}_{(+a)(ac)}\ g_{(+a)(ab)}\big) D^{(\gamma j,j)}_{jn\,jp}\big(g^{-1}_{(ab)(+a)}\ g_{(ab)(-d)}\big)$$

$$A_{\pm a}(h_{\pm a}) := A_{f_{\pm a}}(h_{\pm a}) = \sum_i d_j D^{(\gamma j,j)}_{jm\,jn}\big({g^f_{\pm a}}^{-1}\ g^p_{\pm a}\big) D^j_{nm}(h_{\pm a}) \ ,$$

$$\times D^{(\gamma j,j)}_{jp\,jq}\big(g^{-1}_{(-d)(ab)}\ g_{(-d)(ac)}\big) D^{(\gamma j,j)}_{jq\,jm}\big(g^{-1}_{(ac)(-d)}\ g_{(ac)(+a)}\big) \ ,$$

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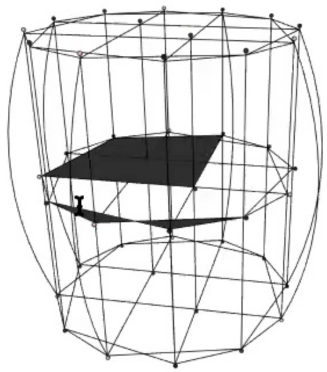
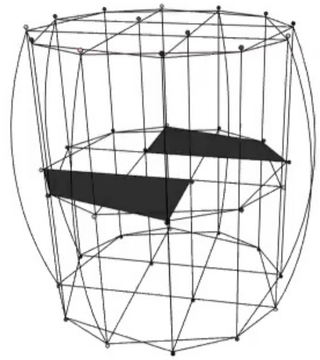
There is a bubble! Soltani





But: (1) for large spins, the amplitude is exponentially suppressed unless the parallelism relations $R_a\vec{n}_{ab} = -R_b\vec{n}_{ba}.$ and the closure relations are satisfied.

(2) Given generic boundary data, generically they cannot be all satisfied.

Hence the divergence is suppressed !

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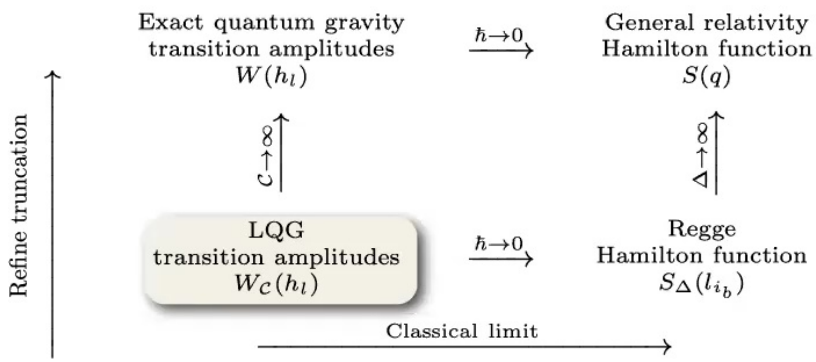
Renormalisation? Is a critical points needed to define the theory?



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Ditt(rich) - invariance:

Harmonic oscillator $S = \frac{m}{2}\int dt \left(\left(\frac{dq}{dt}\right)^2 - \omega^2 q^2\right)$

Discretise $a = t/N$. $S_N = \frac{m}{2}\sum_n^N a\left(\left(\frac{q_{n+1}-q_n}{a}\right)^2 - \omega^2 q_n^2\right)$

Rescale variables $Q_n = \sqrt{\frac{m}{a\hbar}}\, q_n$, $\Omega = a\omega$

$$\frac{S_N}{\hbar} = \frac{1}{2}\sum_n^N \left((Q_{n+1}-Q_n)^2 - \Omega^2 Q_n^2\right) \equiv S_{N,\Omega}(Q_n)$$

$$W(q_f, t_f; q_i, t_i) = \lim_{\substack{\Omega\to 0\\ N\to\infty}} \mathcal{N}\int dQ_n\, e^{iS_{N,\Omega}(Q_n)}$$

Parametrized theory $S = \frac{m}{2}\int d\tau \left(\frac{\dot q^2}{\dot t} - \omega^2 \dot t\, q^2\right)$

Discretize $S_N = \frac{m}{2}\sum_n^N a\left(\frac{\left(\frac{q_{n+1}-q_n}{a}\right)^2}{\frac{t_{n+1}-t_n}{a}} - \omega^2 \frac{t_{n+1}-t_n}{a}\, q_n^2\right). \quad = \frac{m}{2}\sum_n^N\left(\frac{(q_{n+1}-q_n)^2}{t_{n+1}-t_n} - \omega^2(t_{n+1}-t_n)\, q_n^2\right)$

Rescale variables $Q_n = \sqrt{\frac{m\omega}{\hbar}}\, q_n$

$$\frac{S_N}{\hbar} = \frac{1}{2}\sum_n^N\left(\frac{(Q_{n+1}-Q_n)^2}{T_{n+1}-T_n} - (T_{n+1}-T_n)Q_n^2\right)$$

$$W(q_f, t_f; q_i, t_i) = \lim_{N\to\infty}\int dQ_n\, dT_n\, e^{iS_N(Q_n, T_n)}$$

- Systems evolving in time: The continuum limit is obtained taking the number of steps to infinity and a coupling constant to a critical value. $N\to\infty$ $\Omega\to\infty$
- General covariant systems: The continuum limit is obtained taking just the number of steps to infinity. $N\to\infty$

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$$
\begin{tikzcd}
\text{Exact quantum gravity transition amplitudes } W(h_l) \arrow[r, "\hbar\to 0"] & \text{General relativity Hamilton function } S(q) \\
\text{LQG transition amplitudes } W_{\mathcal{C}}(h_l) \arrow[u, "\mathcal{C}\to\infty"] \arrow[r, "\hbar\to 0"] & \text{Regge Hamilton function } S_\Delta(l_{i_b}) \arrow[u, "\Delta\to\infty"']
\end{tikzcd}
$$

Refine truncation

Classical limit

- No critical point
- No infinite renormalization
- Physical scale: $L^2_{Planck} = \hbar G$
- Cfr: condensed matter away from critical points
- Same hint from string theory: finite UV scale and no infinities.

- QFT : critical phenomenon

- Quantum Gravity: <u>non</u>-critical phenomenon (cfr: strings.)

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Radiative corrections

Perez, Riello, Donà, Gozzini, Sarno, Dittrich, Bahr, Rabuffo, Steinhaus, Banburski.

- They are **finite** in the version of the theory with the cosmological constant (It is a theorem Fairbairn, Meusburger, Han).
- They are generated by "**bubbles**".
- Can they are frequent "less than expected" (crf Riello, Donà, Soltani result…)
- We have little control of them. They More work needed!
- Should be studied in the context of a complete calculation, because for instance they may be suppressed by the boundary data.

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Open Access Article

Spin Foam Vertex Amplitudes on Quantum Computer—Preliminary Results

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Abstract

Vertex amplitudes are elementary contributions to the transition amplitudes in the spin foam models of quantum gravity. The purpose of this article is to make the first step towards computing vertex amplitudes with the use of quantum algorithms. In our studies we are focused on a vertex amplitude of 3+1 D gravity, associated with a pentagram spin network. Furthermore, all spin labels of the spin network are assumed to be equal $j = 1/2$, which is crucial for the introduction of the intertwiner qubits. A procedure of determining modulus squares of vertex amplitudes on universal quantum computers is proposed. Utility of the approach is tested with the use of: IBM's *ibmqx4* 5-qubit quantum computer, simulator of quantum computer provided by the same company and QX quantum computer simulator. Finally, values of the vertex probability are determined employing both the QX and the IBM simulators with 20-qubit quantum register and compared with analytical predictions. View Full-Text

Keywords: Spin networks; vertex amplitudes; quantum computing

▼ Show Figures

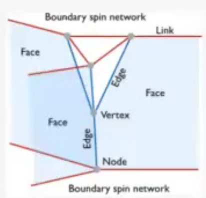

Figure 1

There is much more.....

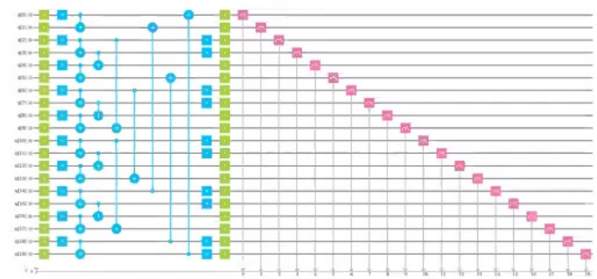

FIG. 9. Quantum circuit used to determine $|A(0_s, 0_s, 0_s, 0_s, 0_s)|^2$. Nodes of the spin network correspond to the following sets of qubits: $\{0,1,2,3\}$, $\{4,5,6,7\}$, $\{8,9,10,11\}$, $\{12,13,14,15\}$, $\{16,17,18,19\}$. The links are between the pairs of qubits: $\{0,19\}$, $\{1,14\}$, $\{2,9\}$, $\{3,4\}$, $\{5,18\}$, $\{6,13\}$, $\{7,8\}$, $\{10,17\}$, $\{11,12\}$ and $\{15,16\}$.

Han, Wan, Mielczarek

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In brief

- The theory is advanced enough to do physics with it.
  - Derive the primordial spectrum of density fluctuations.
  - Understand what happens to matter in the Planck Star bounce.
  - Physics of the remnants.

- Many issues of the theory need to be investigated.
  - Compute and study radiative corrections. Can we find one in a physical case? Can be trivially renormalised away? Or not?
  - Understand what is wrong in the flatness arguments.
  - Study if refining $\mathcal{C}$, the amplitude does not change too much.
  - Develop an Fermi-like first order approximation method.
  - Emergence of the Einstein equations ($F^{+-} = 0 \iff Ricci = 0$)?
  - If a different theory look better, write it down <u>completely</u> and compare it on physical grounds, not *a priori*, half way through, on issues of principle.

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