PROJECT FINAL REPORT

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Scientific coordinator: Prof. Carlo Rovelli

Centre de Physique Théorique, 163 avenue de Luminy,
Campus de Luminy Case 907 Marseille 13288 – France

Tel: +33 614 59 3885 Fax: +33 491 26 9553

E-mail: rovelli@cpt.univ-mrs.fr

Researcher: Eugenio Bianchi

Centre de Physique Théorique, 163 avenue de Luminy,
Campus de Luminy Case 907 Marseille 13288 – France

E-mail: bianchi@cpt.univ-mrs.fr

1. Summary Report

1.1 Executive summary

The objective of this research project is to develop the Loop approach to Quantum Gravity, assess its physical viability as a description of gravity at the Planck scale, and develop approximation schemes for extracting low-energy predictions from the theory.

The project is articulated in three parts:

(a) identify coherent states peaked on a classical geometry of space;

(b) study the dynamics of semiclassical states, using the spin foam framework;

(c) apply the formalism developed in (a)-(b) to specific physics problems like: graviton propagation on flat space, black hole entropy, cosmological dynamics.

The methods involved in the analysis are: semiclassical expansions (WKB) and effective field theory techniques, applied to the background independent structure of Loop Quantum Gravity.

Thanks to CPT[1]'s exceptional scientific environment, to C.Rovelli's excellent skills in research training, and to the EU contribution[2], the results of the project have largely outperformed the original expectations in each of its three parts. In particular, reaching the stage of part (c) has contributed to establishing Loop Quantum Gravity as a strong candidate for the description of physics at the Planck scale – a description which provides a quantum picture of space-time at such microscopic scale, which is compatible with the present knowledge in quantum field theory and which may predict experimental signatures to be investigated in future.

The results of the project have been published in refereed journals (6 *Phys.Rev.D,* 1 *Phys.Rev.Lett.,* 1 *Nature,* 3 *Class.Quant.Grav.,* 1 *Nucl.Phys.B*) and have been presented at the major international conferences in quantum gravity in the period 2010-2011.

Background independent quantum gravity is becoming a structural part of research in theoretical physics in various countries of the European Union. By addressing within Loop Quantum Gravity the key question of the extraction of physical predictions from background independent theories, the project has further increased this competitiveness and CPT's leadership in the whole sector of theoretical physics.

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[1] CPT, Centre de Physique Theorique de Luminy, Case 907, F-13288 Marseille, France. Unite mixte de recherche du CNRS et des Universites de Provence, de la Mediterranee et du Sud; affilie a la FRUMAN.

[2] Marie Curie Actions, FP7 - PEOPLE - Marie Curie Intra European Fellowships, project EFTforLQG.

1.2 Description of project context and objectives

This research project focuses on the problem of quantum gravity and addresses directly the question: *What happens to gravity and space-time when quantum mechanical effects are important?* Thanks to progress of the last years, this question can now be posed within the framework of *Loop Gravity.* In fact, the two main difficulties that made this research direction incomplete until recently have now been addressed: there is now a clear definition of the dynamics of the theory and evidence that General Relativity and a classical spacetime emerge in the classical limit. The formal structure of Loop Gravity is now robust and stable enough that we believe it is time to start investigating what are its phenomenological consequences in specific physical processes.

Extracting physical predictions from Loop Gravity has the potential to assess its physical viability as a description of gravity at the Planck scale, and possibly identify its signatures. Moreover, focusing on specific physics problems, this project will provide feedback on the formal structure of the theory and clarify the main physical assumptions it is based on, in particular to address the question: *Why loops?*

The project is situated at the crossroads of some of the main currently explored approaches to quantum gravity: in particular (i) Canonical Quantum Gravity with Wilson loop variables, (ii) the path integral quantization of Regge gravity known as Spin Foam models, (iii) Matrix Models for 4d Gravity (Group Field Theory), (iv) topological field theories with 1d defect-networks. These four approaches to quantum gravity are characterized by their built-in general covariance, the gauge symmetry of General Relativity. They share also a second more technical feature: they capture a finite number of gravitational degrees of freedom via the Wilson loop of a gravitational connection. This provides a compactification of the momentum space of General Relativity that allows to define a robust quantum theory. In the following, I call this feature the *loop assumption.*

The recent remarkable convergence of these four approaches is leading to new developments in the field of quantum gravity and is making these approaches a promising common direction to explore. I refer to this direction simply as *Loop Gravity.* The project is articulated in three parts:

(a) Coherent spin-network states and classical geometry of space;

(b) Spin foams and the dynamics of semiclassical states;

(c) Derivation of the effective dynamics in the case of: gravitons on Minkowski spacetime, black hole entropy, quantum cosmology.

The results obtained in each part has contributed to establish Loop Gravity as a strong candidate for the description of gravity at the Planck scale. We describe below the specific objectives and the results obtained in each part.

1.3 Main results

Part (a): Coherent spin-network states and classical geometry of space.

"*Coherent spin-networks***",** E. Bianchi, E. Magliaro, C. Perini.
Phys. Rev. **D82,** 024012 (2010) DOI: 10.1103/PhysRevD.82.024012
Open-access repository http://arxiv.org/abs/0912.4054v4

We introduce a set of coherent states for Loop Quantum Gravity. These states are labeled by a point in the phase space of General Relativity as captured by a spin-network graph. They are defined as the gauge invariant projection of a product over links of Hall's heat-kernels for the cotangent bundle of SU(2). The labels of the state are written in terms of two unit-vectors, a spin and an angle for each link of the graph. The heat-kernel time is chosen to be a function of the spin. These labels are the ones used in the Spin Foam setting and admit a clear geometric interpretation. Moreover, the set of labels per link can be written as an element of SL(2,C). Therefore, these states coincide with Thiemann's coherent states with the area operator as complexifier. We study the properties of semiclassicality of these states and show that, for large spins, they reproduce a superposition over spins of spin-networks with nodes labeled by Livine-Speziale coherent intertwiners. Moreover, the weight associated to spins on links turns out to be given by a Gaussian times a phase as originally proposed by Rovelli.

"*Discreteness of the volume of space from Bohr-Sommerfeld quantizatino***",** E.Bianchi, H.Haggard. *Phys.Rev.Lett.107,011301(2011) DOI:10.1103/PhysRevLett.107.011301*
Open-access repository http://arxiv.org/abs/1102.5439

A major challenge for any theory of quantum gravity is to quantize general relativity while retaining some part of its geometrical character. We present new evidence for the idea that this can be achieved by directly quantizing space itself. We compute the Bohr-Sommerfeld volume spectrum of a tetrahedron and show that it reproduces the quantization of a grain of space found in loop gravity.

Part (b): Spin foams and the dynamics of semiclassical states.

"*Spinfoams in the holomorphic representation***",** E. Bianchi, E. Magliaro, C. Perini.
Phys. Rev. **D82,** 124031 (2010) DOI: 10.1103/PhysRevD.82.124031
Open-access repository http://arxiv.org/abs/1004.4550

We study a holomorphic representation for spinfoams. The representation is obtained via the Ashtekar-Lewandowski-Marolf-Mourao-Thiemann coherent state transform. We derive the expression of the 4d spinfoam vertex for Euclidean and for Lorentzian gravity in the holomorphic representation. The advantage of this representation rests on the fact that the variables used have a clear interpretation in terms of a classical intrinsic and extrinsic geometry of space. We show how the peakedness on the extrinsic geometry selects a single exponential of the Regge action in the semiclassical large-scale asymptotics of the spinfoam vertex.

Part (c): Effective low-energy dynamics.

"*LQG propagator from the new spin foams*", Bianchi, Magliaro, Perini.
Nucl. Phys. **B822,** 245-269 (2009) DOI: 10.1016/j.nuclphysb.2009.07.016
Open-access repository http://arxiv.org/abs/0905.4082

The question addressed is if Loop Gravity admits a regime that can be described in terms of a perturbative quantum theory of *gravitons* propagating in flat space. In this paper we show how the (scaling and the tensorial structure of the) graviton propagator is recovered (50 *Spires citations).* The paper is the end result of a series of works started in collaboration with Rovelli et al., and is considered as a key test that Loop Gravity is compatible with standard low-energy quantum field theory.

"*Black Hole Entropy, Loop Gravity, and Polymer Physics*", Bianchi.
Class. Quant. Grav. **28,** 114006 (2011) DOI: 10.1088/0264-9381/28/11/114006
Open-access repository http://arxiv.org/abs/1011.5628

This paper presents a semiclassical description of the Loop Gravity calculation of Black Hole entrop. The description amounts to a statistical counting of shapes of the horizon, with a physical UV cut-off coming from Loop Gravity: the microstates are given by the (intrinsic and extrinsic) geometry of a tessellated horizon. The calculation reproduces the area law (together with quantum corrections). Moreover this description is shown to be a classical statistical mechanics version of the exact quantum counting done in Loop Gravity, where the presence of a Black Hole is coded in a *isolated horizon* boundary condition for the quantum theory. What is gained in this analysis is a geometric interpretation of the degrees of freedom that contribute to the entropy of the Black Hole: they are microscopic shapes of the horizon. The result has been presented at a major General Relativity conference *GR19* and has been selected as best contribution of the QFT on curved space session.

"*Towards Spinfoam Cosmology*", E. Bianchi, C. Rovelli, F. Vidotto.
Phys. Rev. **D82,** 084035 (2010) DOI: 10.1103/PhysRevD.82.084035
Open-access repository http://arxiv.org/abs/1003.3483

We show that the effective dynamics of Spinfoams on a coherent state peaked on a homogeneous and isotropic geometry reproduces the gravitational part of Friedmann's equation, with quantum corrections. The resulting description is remarkably close to the one of Loop Quantum Cosmology, a well-explored framework for quantum effects in early cosmology that consists in a loop-inspired quantization of symmetry-reduced General Relativity. The advantage of starting from the full theory described in terms of spin foams is that their dynamics is largely determined by few general principles as spacetime locality and local Lorentz invariance. The result has attracted much attention in the field, and I have been invited to present a series of lectures on it at a summer school.

1.4 Dissemination activities

Articles published in refereed journals:

6 *Phys.Rev.D,* 1 *Phys.Rev.Lett.,* 1 *Nature,* 3 *Class.Quant.Grav.,* 1 *Nucl.Phys.B.*

. 1. **“On the geometrical interpretation of quantum groups and non-commutative spaces in gravity”,** E. Bianchi, C. Rovelli. *Phys. Rev.* **D84,** 027502 (2011) DOI: 10.1103/PhysRevD.84.027502

. 2. **“Discreteness of the volume of space from Bohr-Sommerfeld quantization”** E.Bianchi,H.M.Haggard. *Phys.Rev.Lett.107,011301(2011)DOI:10.1103/PhysRevLett.107.011301*

. 3. **“Cosmological constant in spinfoam cosmology”,** E. Bianchi, T. Krajewski, C. Rovelli, F. Vidotto. *Phys. Rev.* **D83,** 104015 (2011) DOI: 10.1103/PhysRevD.83.104015

. 4. **“Black Hole Entropy, Loop Gravity, and Polymer Physics”** E. Bianchi. *Class. Quant. Grav.* **28,** 114006 (2011) DOI: 10.1088/0264-9381/28/11/114006

. 5. **“Polyhedra in loop quantum gravity”** E.Bianchi,P.Dona,S.Speziale. *Phys.Rev.D83,044035(2011)DOI:10.1103/PhysRevD.83.044035*

. 6. **“Is dark energy really a mystery?”,** E. Bianchi, C. Rovelli, R. Kolb. *Nature* 466 Issue 7304 pages 321-322 (2010) DOI: 10.1038/466321a

. 7. **“Face amplitude of spinfoam quantum gravity”,** E. Bianchi, D. Regoli, C. Rovelli. Class. Quant. Grav. **27,** 185009 (2010) DOI: 10.1088/0264-9381/27/18/185009

. 8. **“Spinfoams in the holomorphic representation”,** E. Bianchi, E. Magliaro, C. Perini. *Phys. Rev.* **D82,** 124031 (2010) DOI: 10.1103/PhysRevD.82.124031

. 9. **“Towards Spinfoam Cosmology”,** E. Bianchi, C. Rovelli, F. Vidotto. *Phys. Rev.* **D82,** 084035 (2010) DOI: 10.1103/PhysRevD.82.084035

. 10. **“Coherent spin-networks”,** E. Bianchi, E. Magliaro, C. Perini. *Phys. Rev.* **D82,** 024012 (2010) DOI: 10.1103/PhysRevD.82.024012

. 11. **“LQG propagator from the new spin foams”,** E. Bianchi, E. Magliaro, C. Perini. *Nucl. Phys.* **B822,** 245-269 (2009) DOI: 10.1016/j.nuclphysb.2009.07.016

. 12. **“LQG propagator: III. The New vertex”,** E. Alesci, E. Bianchi, C. Rovelli. *Class. Quant. Grav.* **26,** 215001 (2009) DOI: 10.1088/0264-9381/26/21/215001

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Articles submitted to refereed journals

. 13. **"Lorentzian spinfoam propagator",** E. Bianchi, Y. Ding. Submitted to *Phys.Rev.D,* arXiv:1109.6538 [gr-qc]

. 14. **"Spinfoam fermions",** E. Bianchi, M. Han, E. Magliaro, C. Perini, C. Rovelli, W. Wieland. Submitted to *Phys.Rev.D,* arXiv:1012.4719 [gr-qc]

. 15. **"Why all these prejudices against a constant?",** E. Bianchi, C. Rovelli. Submitted to *Gen.Rel.Grav.,* arXiv:1002.3966 [astro-ph.CO]

. 16. **"Loop Quantum Gravity a la Aharonov-Bohm",** E. Bianchi. Submitted to *Phys.Rev.D,* arXiv:0907.4388 [gr-qc]

Presentations as guest speaker:

- 1 plenary lecture (invited speaker) at International Conference *SIGRAV*-Pisa 2010 (see [R1] below)

- 8 seminars at International Conferences (see [R2],[R3]) *Loops-Madrid* 2011, *QG at APC-Paris* 2011, QG2-Poland 2011, GR19-Mexico 2010, MG12-Paris 2009, Loops-Beijing 2009, QG2-UK 2008, *Loops-Mexico* 2007.

- 7 seminars at European workshops *Peyresq Cosmology* - France 2011, *NPQFT* -France 2011, *QG&QFT* -France 2011, *NPQFT* -France 2010, *ESF-Poland* 2009, QST-Netherlands 2008, Cortona - Italy 2007.

- 35 seminars during visits at research centers in Canada, Europe, Mexico.

- 2 contributions (invited) at the International Loop Quantum Gravity Seminar *ILQGS* (See [R5],[R6])

A selection of presentations with online material available:

R1. "**Loop Quantum Gravity,"** Invited review lecture (plenary speaker) SIGRAV XIX conference on General Relativity, Scuola Normale Superiore di Pisa – Italy, Sept 2010. webtheory.sns.it/sigrav2010 Attendancy: 150+ participants. Slides available at dl.dropbox.com/u/7356473/Bianchi.SIGRAV2010.pdf

. R2. "**Black Hole entropy and the shape of the horizon",** seminar in the Black Holes session International Quantum Gravity conference *Loops 11,* Madrid – Spain, May 2011. http://loops11.iem.csic.es/loops11/Archives/Parallel-Sessions

. R3. "**Black Holes, Loop Gravity and polymer physics",** International General Relativity conference *GR19,* Mexico City, July 2010 Slides available at dl.dropbox.com/u/7356473/Bianchi.GR19.pdf Selected as *best presentation of the QFT session.* Commitee: B. Unruh and D. Marolf.

. R4. "**Quantum Polyhedra in Loop Gravity",** invited talk in the Quantum

Gravity series Perimeter Institute – Canada, Nov 2010. Video recording available online pirsa.org/10110052

. R5. "**The cosmological constant (non-)problem,"** International Loop Quantum Gravity Seminar *ILQGS,* Oct 2010, (Invited contribution). Recording available online. relativity.phys.lsu.edu/ilqgs/bianchi101910.pdf

. R6. **"Aharonov-Bohm effect and Loop Gravity as a topological theory with defects,"** International Loop Quantum Gravity Seminar *ILQGS,* Oct 2009, (Invited contribution) relativity.phys.lsu.edu/ilqgs/bianchi100609.pdf

R7. **"Lectures on Spinfoam Cosmology",** at the *Third Quantum Gravity and Quantum Geometry School* – Poland (2011) organized by the European ESF network program coordinated by J. Barrett and H. Nicolai. The school focuses on recent progress in Quantum Gravity. Spinfoam Cosmology is a new line of research in quantum cosmology that we have started as part of the project together with C. Rovelli and F. Vidotto in 2010. Lectures to be published in POS. www.fuw.edu.pl/ kostecki/school3 Attended by 80 PhD students.

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1.5 Contact details

Scientific coordinator: Prof. Carlo Rovelli

Centre de Physique Théorique, 163 avenue de Luminy,
Campus de Luminy Case 907 Marseille 13288 – France

Tel: +33 614 59 3885 Fax: +33 491 26 9553

E-mail: rovelli@cpt.univ-mrs.fr

Researcher: Dr. Eugenio Bianchi

Centre de Physique Théorique, 163 avenue de Luminy,
Campus de Luminy Case 907 Marseille 13288 – France

E-mail: bianchi@cpt.univ-mrs.fr