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Referee Report on Ilkka Makinen PhD thesis

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Ilkka Makinen has pursued his PhD studies in the field of loop quantum gravity, under the supervision of Prof. Jerzy Lewandowski. His results have been published in 5 articles on the prestigious journal Physical Review D, plus 3 conference proceedings, and constitute the original body of the PhD thesis that I am reporting on here.

Loop quantum gravity offers a compelling picture of what the consistent merging of general relativity and quantum mechanics could look like, and has delivered promising results concerning the physical implications of this picture. The smooth, curved spacetime of general relativity is replaced by a collection of atoms of space, whose discrete nature leads to an effect similar to a quantum mechanical repulsion force. This effect addresses one of the key open questions of general relativity, namely the true nature of spacetime singularities. Thanks to the effective repulsion, the big bang singularity is replaced by a big bounce, and similarly, the final fate of an evaporating black hole has been recently advocated to undergo a tunnelling phenomenon. These promising applications have been developed mostly in mini-superspace models, namely simplified settings where one considers only a finite number of degrees of freedom of the quantum gravitational field. The work by Makinen aims at going beyond this simplification, and give us a more complete picture of the dynamics of the quanta of space.

Research in loop quantum gravity sits at the cutting edge of theoretical physics, and provides a challenging ground for any PhD student. It requires overcoming a steep learning curve and dealing with problems which are both conceptual and technical. The thesis presented by Makinen shows that the student has worked hard and fulfilled his PhD, he has thought deeply about the open questions and learn to master many sides of the subject. The original results obtained open interesting new perspectives in the field. His work can be broadly grouped in two different topics: the main one focusing around the use of a deparametrized model with a scalar field as a clock, and a second one developing coherent states as a basis for the Hilbert state.

The main topic identifies a crucial and broadly shared technical problem in the field: the limitations in studying the quantum dynamics using the existing definition of the Hamiltonian constraint, due to Thiemann. This definition makes the theory complete and well defined, and was a key achievement in the early stages. However, it suffers from ambiguities, and furthermore has proved itself reluctant to allow explicit calculations and derive quantitative physical predictions. The problem is mainly a technical one due to the details in definition of the operator, but intertwines with the more conceptual problem of time in quantum gravity, namely the difficulty to find interesting physical states in the kernel of the Hamiltonian. The work by Makinen addresses both issues. First, he studies a deparametrized model introducing a physical clock, to be used to identify physical states and their evolution. Second, he addresses the technical aspects of the Hamiltonian operator in this framework, clearly concluding that there are some fundamental obstructions to use Thiemann's prescription, and motivating a specific proposal for an alternative. The work done contains innovations like the introduction of the alternative operator, or a new type of approximation scheme to treat its most complicated part, as well as elaborated and precise calculations, based on graphical calculus, numerical calculations and other techniques, to compute the action and properties of the operator. The new proposal, and the results already obtained based on it, are in my opinion very interesting for future work in the field, and the published results have already had an impact.

The second topic investigates the use of coherent states to represents the quantum operators, in a way similar to the Bargmann-Fock representation for the harmonic oscillator. This is a topic that I have personally worked on, and I appreciate the developments that Makinen has contributed to, including revisiting generating functions for spin networks in the spinorial representation and an analysis of the basic operators in this representation. It would have probably been beneficial to the presentation of this material to comment more on existing applications, like the alternative volume operator based on polyhedra, and especially mention the twisted geometry framework that these states give access to, in partial answer to the conclusions to the last Chapter 18 of his thesis. Makinen also mentions future possible developments of these methods in applications to the Hamiltonian constraint which I agree is worth exploring. Indeed an added value of his thesis is to present complete work but also preliminary results and ideas for future developments. Finally, I would like also to especially praise the careful use of graphical calculus done by Makinen. Graphical calculus has the advantage of making many calculations much faster, but can hide tricky subtleties like phases and sign factors. The detailed presentation of the calculations and the summary of the rules in the Appendix shows the attention profused by Makinen, and provide useful reference material.

In summary, the thesis is very well written and clearly organized. It contains interesting original results of value to the research community. A great deal of effort has gone into presenting both the background material and the original work in a pedagogical and consistent way, which is to be appreciated; the student has clearly taken the writing of the manuscript has an opportunity to seat through the years of PhD work, reanalyse them, and produce a text which is at the same time a pleasant reading, and an introduction to the foundations of loop quantum gravity and to the current research by the student and his collaborators. In particular, Makinen has been able to clearly explain many of the the conceptual and technical aspects of loop quantum gravity, assess the relevance and context of the open questions he has worked on, and communicate his results and original contributions in a clear way, putting them in a broader perspective. The clarity of the text is a confirmation of the author's competence in the field, and I congratulate him.

For all these reasons, I recommend that Ilkka Makinen be awarded a PhD in theoretical physics, and I nominate his thesis as outstanding.

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