Jeff Murugan
Professor of Mathematical Physics
The Laboratory for Quantum Gravity & Strings
Department of Mathematics & Applied Mathematics
University of Cape Town
Rondebosch, 7701, South Africa
(W) +27-21-650-3197
(C) +27-82-966-0568
jeff.murugan@uct.ac.za

Habilitation Report: Pawel Caputa

The Chair of the Habilitation Commission,

I am delighted to be able to provide a habilitation report for Dr Pawel Caputa. I have known Dr Caputa since his time as a graduate student at the Neils Bohr Institute working on integrability in string theory and then, later as a postdoctoral fellow at the University of the Witwatersrand in South Africa working on the physics of giant gravitons. It was during this latter time that he made the fortuitous transition to the emerging subfield of quantum information - specifically quantum entanglement and quantum complexity as physical resources in quantum gravity - in string theory, which has come to be the dominant theme of his research over the evaluation period for his habilitation. As such, I find myself in the fortunate position of having worked in all the same areas that Dr Caputa has, and feel confident that I can provide useful input to the committee both on his development as well as the impact that his research has had on a broad international community.

For his habilitation degree, Dr Caputa has presented a series of 10 articles that constitute a coherent body of work in the field of "quantum information in high energy physics". All of these, without exception, have been published in the leading journals - by impact factor - in physics. Even more remarkably, five of these articles have appeared in the *Physical Review Letters*. This is probably the single most prestigious journal in theoretical physics with exceptionally stringent criteria for publication. According to the PRL website, in order for a paper to warrant publication, in addition to it being scientifically correct, it must satisfy one or more of the following:

- Open a new research area, or a new avenue within an established area.
- Solve, or make essential steps towards solving, a critical problem.
- Introduce new techniques or methodologies with significant impact.
- Be of unusual intrinsic interest to PRL's broad audience.

That Dr Caputa has managed to get no less than 5 letters published in this journal, as a high energy theorist, is really testament to the exceptional quality and impact of his work. The other five are no less impressive. Each of these research articles has already met the high standards set by the international referees of the journals and I certainly do not need to re-review them individually again, so I will focus rather on their context and impact as a *collective* body of work .

A central theme of Dr Caputa's research program is *entanglement entropy* - a measure of the amount of quantum entanglement between two subsystems in a bipartite composite system - and its computation. This quantity has long been appreciated as a key physical resource among the quantum computation community but only recently been employed by the high energy community to understandHawking's information loss paradox in black holes. Much of this recent excitement has been precipitated by the Ryu-Takayanagi conjecture that effectively geometrizes the entanglement entropy by mapping it to the area of an extremal surface embedded in a space one dimension higher. Unlike many young people of the day, Dr Caputa was among the first to recognise the importance of this idea and initiated a collaboration with one of its founders, Prof. Tadashi Takayanagi of the Yukawa Institute. The dividends of this collaboration are clear from six of the ten papers in the portfolio. In each of these, the authors push the bounds of what is known about (holographic) entanglement entropy, to conformal field theories, higher dimensions and finite temperatures, all of which have had significant impact not only in high energy physics, but also in condensed matter theory as well as foundations of quantum field theory.

Among these papers, I would like to single out one (*PRL 119, 071602 (2017)*) that has had particular impact on my own research. Here, Dr Caputa and collaborators develop a new optimization scheme for Euclidean path integrals that involves optimizing the background metric in the base space over which the path integral is performed, in effect re-writing the path integral as a MERA[1] tensor network. This was a very very clever way to re-formulate an old problem to yield a wealth of new results. Among the advantages that this approach has over traditional tensor-networks is the ability do analyse *any* conformal field theory as well as the fact that instead of producing Euclidean hyperbolic space as an intermediate step, it reproduced directly the dual hyperbolic (AdS) spacetime. This circumvents one of the most detracting aspects of the whole MERA/Tensor-network program, in my opinion. If there is any hope of producing a convincing argument that spacetime is *emergent* from some underlying quantum substructure, some mechanism such as this must be at play.

A second thread of Dr Caputa's research program that deserves highlighting is that of the development of quantum complexity as a resource in quantum gravity. This is another of those ideas that were well utilised in the quantum computation community at the interface between physics and computer science, but that only gained prominence in the high energy theory community in the past four or five years, largely through the pioneering efforts of Susskind and Myers, among others. Here again, largely through the work presented in this portfolio and his membership in the Simons It From Qubit Collaboration, Dr Caputa has established himself at the vanguard of this line of research. A prime example of the impact of his ideas is (*PRL 122, 231302 (2019)*) in which, together with postdoctoral researcher Javier Magan, they managed to tie together two important, groundbreaking ideas that may well be groundbreaking in its own right. The first is one we are all familiar with; Einstein's realisation that gravity is a manifestation of the dynamical nature of the geometry of space-

[1] Multiscale entanglement renormalization ansatz

time. The second, less well known but certainly just as intriguing, is Nielsen's geometric formulation of circuit complexity, a notion from quantum information theory. Caputa and Magan used this to show how quantum computation - manipulation of quantum information with quantum gates - can be realised as 2-dimensional quantum gravity. In fact they go even further and conjecture that *gravity* itself sets the rules for optimal quantum computation in CFTs. Clearly, given the enormous surge of development of quantum computing currently, this idea has the potential to revolutionise developments in quantum computing.

Finally, in summary, in my opinion, Dr Caputa has more than met the stringent requirements set out by the Senate of the University of Warsaw. The 10 papers that he has presented constitute a coherent, impressive body of work that *in toto* make a significant contribution toward developing the field of high energy theoretical physics. Consequent to this assessment, I strongly support the award of the Habilitation Degree.

Sincerely,
Prof. Jeff Murugan