MSc Theses Topics 2022-2023

Theoretical High Energy Physics Group at Ghent University

Supervisors:
Michal P. Heller
Thomas Mertens

Topics offered by Prof. Heller

One of the most important contemporary research directions in theoretical high energy physics is studying emergent phenomena in quantum field theories. The notion of emergence means reorganization of degrees of freedom giving rise to phenomena not easily visible at the level of a relevant action or a Hamiltonian.

One type of such a notion are simple patterns of time dependence arising in nonequilibrium states undergoing in principle complicated thermalization dynamics. Another is dynamical spacetime, which in the case of negatively curved universes emerges from reorganization of degrees of freedom in quantum field theories.

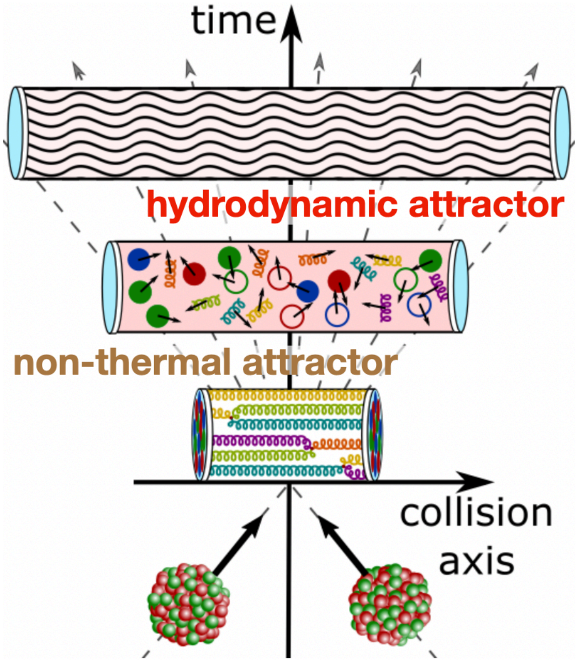
There are two topics that connect to these two notions of emergence in quantum field theory and related subjects. They are very much connected to cutting edge research results in their respective fields and contain a significant research component in theoretical physics that may lead to a publication.

More information: michal.p.heller@ugent.be

1 Hydrodynamic and non-thermal attractors: novel frontiers in far-from-equilibrium dynamics at high energies

Thermalization of closed quantum systems is central to modern understanding of matter, from ultracold to ultrahot. The project will study thermalization of quantum fields excited by nuclear collisions at RHIC and LHC to energy densities equivalent to trillions of Kelvins. In such extreme environments hadrons melt and the equilibrium state is the quark-gluon plasma. Theoretical control over thermalization at high energies is crucially needed for understanding when and how this equilibrium phase emerges in the experiment.

The current theoretical paradigm for thermalization in nuclear collisions is based on hydrodynamic and non-thermal attractors:



They are novel examples of universal dynamics of non-equilibrium quantum fields. Both were found in idealized settings of nuclear collisions with high degree of symmetries and in particular corners of microscopic parameter space. The aim of the master project is to review these cutting edge objects and to pursue exploratory study of their properties beyond the existing understanding. I envision one thesis focusing on hydrodynamic attractors and one thesis focusing on non-thermal fixed points. Both will require combining analytic understanding with numerical modelling. They build on recent results and, if fully successful, will be publishable.

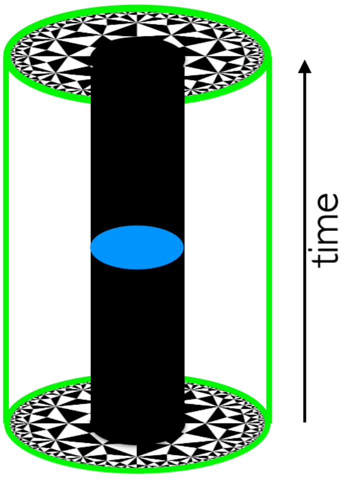
The project will provide you with opportunities to apply and master topics from relativity and cosmology, quantum field theory and computational physics. In particular, it will allow to put all that you learnt during the course on Relativistic Hydrodynamics: From Quantum Field Theory to Black Holes into action.

2 Complexity: new window on the emergence of spacetime

The past 25 years is a period of unprecedented progress on understanding quantum gravity. The reason for it is holography, which relates certain quantum gravitational theories in negatively curved universes and certain quantum field theories.

The vast majority of progress occurred upon recognition that quantum information properties of quantum field theories play a critical role in the gravitational description.

The project will focus on a novel notion that emerged in this context, which is hardness of quantum state preparation and its conjectured manifestation as a black hole volume.



Understanding these ideas is still in development, which makes it an exciting topic for a master thesis. The thesis will contain a review part, as well as a research part.

This topic provides a perfect opportunity to turn the knowledge from the Quantum Black Holes and Holography course into practice!

Topics offered by Prof. Mertens

Quantum gravity in 3+1 dimensions is hard due to several reasons. One is the non-renormalizability of the action, leading to the path of UV completions such as string theory. A second complication is due to confusions regarding how to think about topics such as causality when the background metric is fluctuating. To circumvent the first problem, we work in lower dimensions where the gravitational path integral does make sense. To tackle the second problem, we can use holography to have an anchoring point (the so-called holographic boundary), where we do understand physics.

Within the resulting set-up (lower-dimensional holography), the last couple of years have seen remarkable progress. Starting with Kitaev's construction of the Sachdev-Ye-Kitaev quantum mechanical models, going through Jackiw-Teitelboim gravity, wormholes and random matrix descriptions, we have learned valuable lessons concerning exact quantum gravity calculations, Hawking's information paradox ...

All of the thesis topics are related in one way or another to this set of developments, and are hence directly placed in a context that attracts widespread international attention.

All topics contain sufficient freedom for the student to divert focus towards interesting routes discovered along the way.

More information: thomas.mertens@ugent.be

3 Jackiw-Teitelboim gravity, replica wormholes and the information paradox

Jackiw-Teitelboim gravity is a 1+1 dimensional model of quantum gravity that is explicitly and analytically solvable, both classically and quantum mechanically.
The model is described by the action:

$$S = \frac{1}{16\pi G}\int d^2x\sqrt{-g}\Phi(R+2) + \frac{1}{8\pi G}\oint \sqrt{-h}\Phi_b K$$

possibly coupled to external matter. The Euler-Lagrange equation for Φ yields $R = -2$, or a constant Ricci scalar throughout spacetime. In 1+1 dimensions this is sufficient to conclude that spacetime is a patch of the AdS_2 geometry. By a suitable choice of boundary conditions, this model gets interesting dynamics localized solely on the holographic boundary.

Recently, by exploiting the exact solvability of this model, a new perspective was explored on Hawking's information paradox for black hole evaporation. Different routes were explored, but an important element is the presence of wormholes in the Euclidean calculation of the Page curve. This curve describes the entanglement entropy between the outgoing radiation and the black hole remainder during evaporation. Hawking's calculations in the '70s predicted information loss in this process, but Hawking did not account for wormholes.

After a thorough exploration of this model and its exact solvability, the goal is to study the recent developments that are treated in the second reference below. An important role is played here by the end-of the-world branes. A deeper study into these objects and how they behave in computations would be valuable.
The first reference below contains in its second half a convenient introduction into Jackiw-Teitelboim gravity.

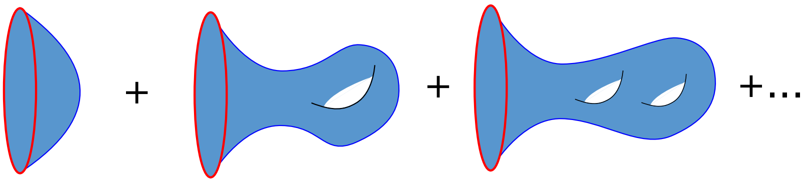
There is sufficient freedom to bend the topic towards interesting directions as the thesis project evolves.

References:

https://arxiv.org/abs/1711.08482
https://arxiv.org/abs/1911.11977
https://arxiv.org/abs/1911.12333

4 Multi-universes, the $c = 1$ matrix model, and 2d gravity

In the early '90s, several solvable models of strings theory in lower dimensions were proposed. An important example is the so-called $c = 1$ model, consisting of 2d Liouville CFT, a free boson and the bc ghost system. String theory in general however is notoriously difficult to solve, mainly due to interacties determined by higher topologies of the string worldsheet, such as:



A very important development is that the $c = 1$ model can be rewritten in a different language: firstly in terms of matrix quantum mechanics: this is a quantum mechanical model where the degree of freedom is a matrix $M(t)$. Secondly, as a free multi-fermion system. Both perspectives allow one to exactly write down amplitudes that in particular contain the above topological expansion. This is a very powerful result.

An interpretation that received somewhat less attention in the '90s, was the reinterpretation in terms of 2d gravity, where the above sum is reinterpreted as a sum over multi-universe amplitudes, where baby universes split off and rejoin the parent universe. Very recently, thanks to the developments in 2d Jackiw-Teitelboim gravity in the past three years, this interpretation takes a central place.

The goals is for the Master's student to attain the necessary knowledge surrounding 2d gravity using the first reference below. This will already take up a substantial part of the time.

In the second part, the goal is to compare results from these references to recent work done both within the group (the last reference below) for the $c < 1$ models, and the $c = 1$ model itself (the second reference below) done by another group.

References:

https://arxiv.org/abs/hep-th/9304011
https://arxiv.org/abs/2004.00002
https://arxiv.org/abs/2006.07072

5 The bulk dual of the SYK model

The Sachdev-Ye-Kitaev (SYK) model is a quantum mechanical system of N Majorana fermions $\psi_i(t)$, $i = 1..N$ which satsify $\{\psi_i, \psi_j\} = \delta_{ij}$ with interaction Hamiltonian

$$H = \frac{1}{4!} \sum_{i,j,k,l=1}^{N} J_{ijkl} \psi_i \psi_j \psi_k \psi_l$$

where the J_{ijkl} are random couplings drawn from a Gaussian distribution. After averaging over the random couplings, the resulting model is solvable at large N and was argued by Kitaev to be described at low energies by an emergent 1+1 dimensional model of gravity. This claim was later substantially investigated in the literature, and the low energy gravitational model was identified as the Jackiw-Teitelboim gravity model, providing evidence that the full SYK model is a holographic system. However, in spite of the large interest this model sparked, the actual bulk gravitational holographic dual of the full SYK model (and not just its low-energy approximation) has not been pinned down, and this remains an open question.

We can distinguish three sets of proposals that aim towards constructing the holographic dual (contained in the second, third and fourth reference below).
The goal is to perform a comparative survey of these proposals for the bulk dual and emphasize their interrelations and relative shortcomings.
For the second half, new research will be done. In particular, when probing the viability of any of these proposals, it is crucial to test how robust the proposals are with respect to generalizations of the original model. The student will hence investigate how these proposals can be generalized towards known extensions of the original SYK model (such as complex SYK, adding flavor degrees of freedom etc).

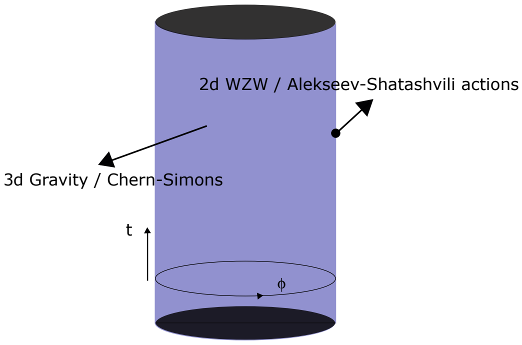
References:

https://arxiv.org/abs/1604.07818
https://arxiv.org/abs/1702.08016
https://arxiv.org/abs/1712.02725
https://arxiv.org/abs/2103.03187

6 Models of 3d pure gravity

Studying quantum gravity in our 3+1 dimensional spacetime is a notorious problem. Hence it is useful to obtain clues by studying related simplified models. One of the ways to achieve this simplification is to work in lower dimensions.

Gravity in 2+1 spacetime dimensions has a long history, and is to some extent exactly solvable. One of the reasons why this problem is so much more tractable is that there are no propagating waves (gravitons).



In 3d, pure gravity is writable in terms of a gauge theory, as first noticed by Witten, as the so-called Chern-Simons theory based on the gauge group $\mathrm{SL}(2,\mathbb{R}) \times \mathrm{SL}(2,\mathbb{R})$.

If one studies this theory on a manifold with a boundary, as illustrated here for a cylinder, the dynamics is governed by the Wess-Zumino-Witten (WZW) model; this statement is a crude version of holography.

In turn, this boundary model can be further simplified into 2 Alekseev-Shatashvili geometric actions in terms of the field $f(\sigma,\tau)$ of the type:

$$S = \int d\tau d\sigma \left(i \left[\frac{c}{48\pi} \frac{\dot{f}}{f'} \left(\frac{f'''}{f'} - 2 \left(\frac{f''}{f'} \right)^2 \right) - b_0 \dot{f} f' \right] + \frac{c}{12\pi} \left\{ \tan \frac{\theta f}{2}, \sigma \right\} \right) . \tag{6.1}$$

This set of relations is described thoroughly in the first two refernces below.

The goal is to firstly perform a thorough study of the literature of these interrelations between the models, and to compare the different results in the literature.

After this, new research can take place in 3d gravity. One important route is the following: the above described relation to go from 3d gravity to the geometric actions is indirect and goes through the Chern-Simons gauge theory. It would be useful to circumvent these intermediate steps and find a direct route that is purely geometrical. This indeed works in the analagous 1+1d case. Realising this result in 2+1d would be a very interesting result.

References:

https://arxiv.org/abs/1808.03263
https://arxiv.org/abs/1602.09021