Master Thesis topics 2023-2024

Theoretical High Energy Physics

Supervisors:
Michal P. Heller
Thomas Mertens

Topics offered by Prof. Heller

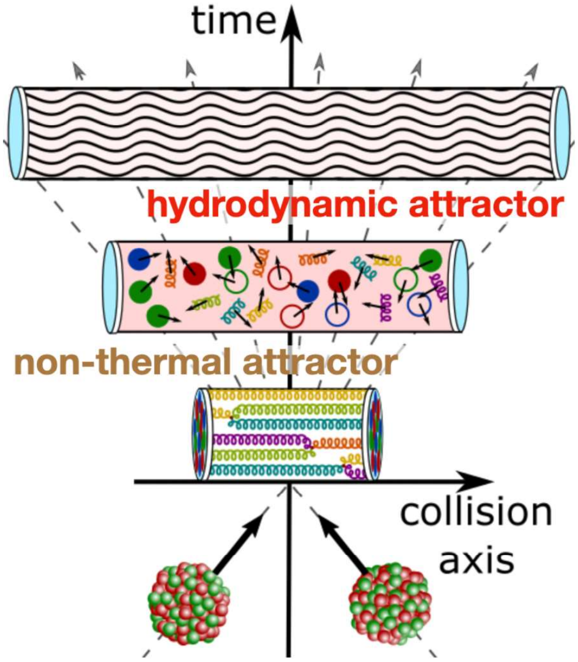
One of the most important contemporary research directions in theoretical high energy physics is studying emergent phenomena in quantum field theories. The notion of emergence means reorganization of degrees of freedom giving rise to phenomena not easily visible at the level of a relevant action or a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

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. Our group is actively pursuing goals along the lines of the thesis topics. Finally, all topics contain sufficient freedom for the student to divert focus towards interesting routes discovered along the way.

More information:
Thomas Mertens: Thomas.Mertens@ugent.be, Francesca.Mariani@ugent.be

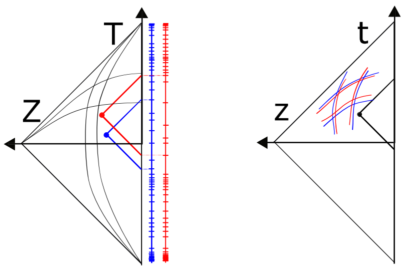
1 Bulk observers in Jackiw-Teitelboim gravity

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 using wormhole contributions to amplitudes as restoring information in the end and producing a unitary Page curve.

However, not everything is solved. In particular, the experience of infalling observers as they cross the event horizon is still ill-understood. In our group, we have in the past years used a particular way of constructing bulk operators and their correlation functions by using light rays to anchor the operator to the holographic boundary:



After a thorough introduction to JT gravity (contained in the first reference below), the student is tasked to understand the above procedure of defining bulk operators (as explained in the second reference). Once this is done, we will pursue two separate goals. Firstly, we will aim to generalize the construction to include charge and/or supersymmetry and aim to understand the changes in the physics. Secondly, we aim to construct operators behind black hole horizons as a stepping stone towards understanding black hole infallers.

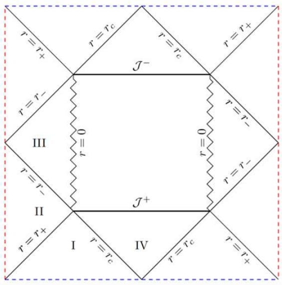
References:

https://arxiv.org/pdf/2210.10846
https://arxiv.org/abs/1902.11194
https://arxiv.org/abs/2005.13058

2 Black Holes in 3+1-dimensional de Sitter space

Black holes are characterized only by a few parameters: their mass, their charge and their angular momentum. Extremal and near-extremal solutions offer us a simplified set-up to resolve fundamental open questions in black hole physics. In particular, they have been proven to be extremely useful in investigating holographic dualities such as the AdS/CFT correspondence. Their dynamics is largely universal and is governed by a 2-dimensional theory that shares many features with JT gravity.

Among the requirements that a consistent theory of quantum gravity should satisfy, is the compatibility with the apparently observed positive, but small, value of the cosmological constant ($\Lambda > 0$). Recent astronomical observations, in fact, show that our universe is undergoing an accelerated expansion that could be driven by a small vacuum energy density. It is thus important to study solutions of Einstein theory with $\Lambda > 0$, namely 3+1-dimensional black holes embedded in de Sitter space. Compared to black holes in asymptotically flat space and in Anti-de-Sitter space, de Sitter black holes are somehow more puzzling. De Sitter space has a cosmological horizon and new extremal and near-extremal limits arise due to the black hole's embedding in this spacetime. Unlike a black hole horizon, this horizon can never be reached or probed by a local observer. Moreover, even if the cosmological horizon can be treated as a thermal entity in its own right, it is still not clear what the role of its entropy exactly is.



After a training on how theoretical aspects of black holes are understood in the context of the holographic principle (see 1st and 2nd references below), the goal would be to understand how the description of the near-extremal black hole is modified by the presence of a cosmological constant. Another important step could be to consider the specific case of Kerr black holes in de Sitter and understand how rotation modifies the description.

The 3rd reference is about holography in AdS_2 and its connection to black hole physics. The 4th reference is about gravity in 2d de Sitter space (dS_2) and its connection to a 3+1d theory with a positive cosmological constant.

References:

https://arxiv.org/abs/1801.07064
http://www.hartmanhep.net/topics2015/
https://arxiv.org/pdf/1711.08482
https://arxiv.org/abs/1904.01911

3 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 4-fermion 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 and important question.

We can distinguish three sets of proposals that aim towards constructing the holographic dual (contained in the second, third and fourth reference below).
A first 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. Recent progress has been made in a particular limit of the SYK model, the double-scaled SYK model where one takes $N \to \infty$ and simultaneously generalizes the interaction to a p-fermion interaction (see the last reference below), keeping p^2/N fixed in the limit. In this regime, correlation functions are exactly solvable and are governed by a quantum group symmetry.

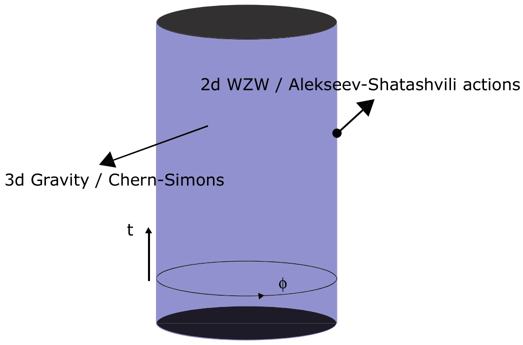
One of the main goals is to combine these different research programs and work towards the overarching picture.

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
https://arxiv.org/abs/2212.13668

4 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 $SL(2,\mathbb{R}) \times SL(2,\mathbb{R})$.
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:

$$S = \int d\tau d\sigma \left(i \left[\frac{c}{48\pi} \frac{\dot{f}}{f'} \left(\frac{f'''}{f'} - 2 \left(\frac{f''}{f'} \right)^2 \right) - b_0 \dot{f} f' \right] + \frac{c}{12\pi} \left\{ \tan \frac{\theta f}{2}, \sigma \right\} \right). \tag{4.1}$$

This set of relations is described thoroughly in the first two references 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. Realizing this result in 2+1d would be a very valuable result.

References:

https://arxiv.org/abs/1602.09021
https://arxiv.org/abs/1808.03263
https://arxiv.org/abs/2210.14196