# P2IO report

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## 1 Project goals

The basic focus of my research is on understanding the fundamentals and applications of holographic correspondence in string theory. This correspondence opens a new door for understanding strongly interacting systems, and could lead to understanding of high temperature superconductivity, thermalization of quark gluon plasma formed by heavy ion collisions, some aspects of graphene and phase transitions in quantum hall systems, etc. The correspondence maps complicated otherwise untractable many body systems to classical dynamics of a few fields in one higher dimensional space. It is not known how to derive this correspondence from first principles other than some special explicit examples known in string theory.

The first goal of my research is to derive the holographic correspondence as a "highly efficient form of coarse graining" of strongly interacting systems. The second goal is to apply this understanding for generalizing the usual effective field theory framework for developing phenomenological descriptions of realistic strongly interacting systems, thereby facilitating solutions of some outstanding problems like high temperature superconductivity.

## 2 Description of work achieved

### The semi-holographic framework for non-Fermi liquids

The holographic correspondence maps a strongly interacting many body quantum system to the dynamics of a few classical fields in one higher dimension. This has been used to gain insights about real life strongly correlated systems, notably the emergence of non-Fermi liquid behaviour. Though theories exactly solvable by this method are exotic, it predicts emergent infrared scaling behaviour which can be argued to be similar to real life systems. In collaboration with G. Policastro, I have shown that coupling weakly interacting fermions to the low energy fluctuations of holographic theories generates a large family of systems which have more realistic behaviour than purely holographic theories. Furthermore, we can derive phenomenological equations which determine all low energy observables like susceptibilities, collective modes and transport properties in terms of a small number of parameters as in Landau's Fermi liquid theory. Our work may lead to development of novel quantum kinetic theory and a generalisation of BCS theory of superconductivity.

### Understanding emergence of spacetime as a RG flow

It is expected that the holographic principle can be understood as a special renormalization group (RG) flow in the field theory in the strongly interacting and large N limit. The radial direction should represent the scale in the field theory. To realize this one needs to understand first how on the classical gravity side of the holographic correspondence, we can define scale-dependent observables consistently. In collaboration with S. Kuperstein, I have worked out this geometric RG flow in the special hydrodynamic limit.

In this limit, the microscopic dynamics is given by an exact hydrodynamic expansion, captured by infinitely many transport coefficients which systematically correct Navier-Stokes equations. This describes the dynamics at the boundary according to the usual rules of the holographic correspondence. The physics at the scale of the mean-free path is captured by the so-called membrane paradigm, which describes the horizon dynamics in terms of the more familiar incompressible non-relativistic Navier-Stokes equations. Our geometric RG flow interpolates these two limits consistently. It describes a first order evolution of physical quantities - the transport coefficients. The equations of classical gravity can be directly written an an RG flow of these physical quantities in the Fefferman-Graham like foliation, where each hypersurface captures the effective hydrodynamics at the corresponding scale. Requiring that the incompressible non-relativistic Navier-Stokes fluid at the horizon emerges as a fixed point of the geometric RG flow in a scaling limit, we can solve the RG flow of the transport coefficients uniquely. The existence of this Navier-Stokes fixed point also requires unique choice of counter-terms for geometric renormalization of the energy-momentum tensor. Remarkably, the values of the transport coefficients at the boundary as determined by the RG flow are precisely those which are required to avoid naked singularities in the bulk geometry. We are now working in the direction to show that the bulk diffeomorphism symmetry is hidden in the automorphism group of the geometric RG flow.

**The nature of equilibrium in strongly interacting holographic systems**

In collaboration with K. Siampos, A. C. Petkou, M. Petropoulos and V. Pozzoli, I have shown that holographic systems can attain perfect fluid like equilibrium only in special kind of stationary backgrounds. A classification of such backgrounds is equivalent to classification of stationary black hole solutions in Einstein's gravity. For 2+1D holographic systems, the backgrounds which can support perfect fluid like equilibrium are those which have the Cotton tensor of a special form and can even be inhomogeneous. The presence of non-trivial vorticity allowed us to show that infinite number of certain kind of transport coefficients vanish in holographic systems. Experimentally this gives a very powerful way of characterizing 2+1D holographic systems by studying the nature of their equilibrium after bending and rotating the surfaces they live in.

## 3 Publications

- A. Mukhopadhyay, A. C. Petkou, P. M. Petropoulos, V. Pozzoli and K. Siampos, *"Holographic perfect fluidity, Cotton energy-momentum duality and transport properties,"* JHEP **1404**, 136 (2014) [arXiv:1309.2310 [hep-th]].
  Journal Impact factor : 5.618
- S. Kuperstein and A. Mukhopadhyay, "Spacetime emergence via holographic RG flow from incompressible Navier-Stokes at the horizon," JHEP **1311**, 086 (2013) [arXiv:1307.1367 [hep-th]].
  Journal Impact factor : 5.618
- A. Mukhopadhyay and G. Policastro, "Phenomenological characterisation of semi-holographic non-Fermi liquids," Phys. Rev. Lett. **111**, 221602 (2013) [arXiv:1306.3941 [hep-th]].
  Journal Impact Factor : 7.943

## 4 Relevance of the project within P2IO

My research fits well with the goals of P2IO which involves understanding fundamental intercations and basic laws of nature. In this respect, understanding strongly interacting systems is an important frontier, because this challenges us to go beyond perturbative quantum field theory which is the most sophisticated theoretical tool today for understanding the quantum world. Also this fundamental research is tied to important practical benefits including understanding of high temperature superconductivity, graphene (important ingredient for novel materials) and quantum hall systems (relevant for developing stable quantum computers).

My research also has helped developing collaborations between the string theory group in CPHT Ecole Polytechnique and the QCD group in IPhT CEA-Saclay. Personally I am working with Edmond Iancu on developing a holographic framework for quark gluon plasma. I am also collaborating with a condensed matter physicist Benoit Doucot at LPTHE UPMC Paris-6 and a string theorist Guiseppe Policastro at LPT-ENS Paris on developing a holographic understanding of high temperature superconducting materials. Thus my research activities have promoted collaborations with different research groups across different disciplines, which is another goal of P2IO.

# 5 Position after P2IO

I will be joining CTP, University of Crete in October this year. This position will be funded by an European Research Council Grant of Elias Kiritsis.