Lecture 2: *Emergent Gravity and Nonequilibrium Thermodynamics – Does Quantum Matter?*

Abstract:

In the first part of this lecture we look at the nature and functionality of thermodynamics as a powerful theory which can capture succinctly many characteristics of the macroscopic world *without* appealing to the detailed knowledge of the microscopic constituents and their interactions. We examine how the collective variables of an effective theory such as thermodynamics are chosen / construed and to what degree they conceal / reveal the underlying micro-variables. We examine how some key issues in emergence manifest themselves, such as **nonlocality,** the notions of which differ at different levels of structure, and how **nonMarkovianity** necessarily appears in the dynamics of an effective / coarse-grained theory. The perspective we gain from this analysis can help us understand the dialectical natures and complementary tasks of quantum versus emergent gravity [1]. In the second part of this lecture, drawing on an old proposal of mine to view *general relativity as geometro-hydrodynamics*, [2] i.e., the low-energy long-wavelength limit of some underlying theories for the microscopic structure of spacetime, we revisit the suggestive theme: "gravity as thermodynamics" [3-5]. To see how this theme plays out I made the suggestion [6] to proceed in two stages: First understand the nonequilibrium thermodynamics of classical gravitational systems without invoking any quantum considerations. The **nonequilibrium nature of classical gravity** shares with other systems with long range interaction, such as its negative heat capacity, and is at the root of many salient features of black hole physics [7]. The second stage is to examine **how quantum fluctuations behave under some universal dictum** such as the maximum speed principle of special relativity and the equivalence principle of general relativity, and to see if they lead to well-known results such as the Hawking-Unruh effect, the Bekenstein-Hawking entropy, entanglement entropy and holography. If so, we can track down to a more basic level how thermo-dynamics enters and how quantum acts. I end with repeating **a challenge** I posed some years ago to all enthusiasts of this `gravity as thermodynamics' theme: "*Derive gravity from thermodynamics without invoking quantum physics*". Because both are classical theories about macroscopic phenomena it would be intellectually extremely gratifying to see a direct link. Though not easy, *this should in principle be possible for even a 19th century physicist.* More interestingly, what would *a failure to meet this challenge* say about the special **inter-relation of gravity, thermodynamics and quantum physics**?

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[1] B. L. Hu, "*Emergent / Quantum Gravity: Macro/Micro Structures of Spacetime*" [arXiv:0903.0878]

[2] B. L. Hu, "*General Relativity as Geometro-Hydrodynamics*" [arXiv:gr-qc/9607070]

[3] T. Jacobson, *Thermodynamics of Spacetime: The Einstein Equation of State*, Phys. Rev. Lett.75, 1260 (1995).

[4] T. Padmanabhan, *Thermodynamical Aspects of Gravity: New insights*, Rep. Prog. Phys. 73 (2010) 046901

[5] G.E. Volovik, *Fermi-point scenario for emergent gravity* [arXiv:0709.1258], and other invited talks at the Conference, "From Quantum to Emergent Gravity: Theory and Phenomenology". Proceedings in PoS (QG-Ph) 043 (2007).

[6] B. L. Hu, "*Gravity and Nonequilibrium Thermodynamics of Classical Matter*" [arXiv:1010.5837]

[7] Charis Anastopoulos and Ntina Savvidou, "*Entropy of singularities in self-gravitating radiation*", Class. Quantum Grav. 29, 025004 (2012)