Holography, Second Law, and Higher Curvature Gravity

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Gravity being the manifestation of the curvature of spacetime can create regions which are inaccessible to a class of observers. An example of such a region is the event horizon of black objects which acts as a one way causal boundary. The thermodynamics of space time horizons is believed to be a crucial input to understand the quantum dynamics of gravity. The basis of this thermodynamic analogy is the area theorem by Hawking which asserts that the area of the event horizon can not decrease in any classical process. The proof of the area theorem depends on both the validity of Einstein's equation as well as on the cosmic censorship hypothesis.

Hawking's discovery that black holes radiate thermally strongly suggests that black hole thermodynamics is more than just an analogy; somehow the laws of black hole mechanics derived from general relativity are describing the thermodynamics of some unknown microstates of the black hole. Additional evidence for a deep connection comes from gauge-gravity duality, where a stationary black hole is conjectured to be dual to a non confined thermal state of an ordinary gauge field theory. In this case, the entropy of the black hole is equal to the ordinary thermodynamic entropy of the thermal fields at the boundary. Inspired by this relationship, Ryu and Takayanagi proposed that the entropy in an arbitrary region R of the field theory is given by a minimal area codimension 2 surface in the gravitational theory, anchored to the boundary of the region R. The entropy of a stationary black hole is then a special case, found by choosing R to be the entire boundary so that the minimal area surface is at the black hole horizon. Although much evidence was found to support of this "holographic entanglement entropy" conjecture, it was only recently given a derivation by Lewkowycz and Maldacena, who showed how to calculate the entropy of the boundary theory using a 1-parameter family of consistent solutions in the gravitational theory, and related this to the minimal area surface in the interior. But for this story to be truly consistent, it is necessary to be able to take into account higher curvature corrections to the action of general relativity.

A natural question in this regard could also be to ask whether the thermodynamic properties of space time horizons can be generalized beyond general relativity?

Interestingly, the first law for black holes holds for a general diffeomorphism invariant Lagrangian, and the entropy can be expressed as integral to a local geometric quantity evaluated on the horizon. This "Wald Entropy" is the Noether charge associated with the killing field which generates the horizon. This entropy suffers from various ambiguities which cannot be fixed by the first law.

In this seminar, I discuss our work where we fix these ambiguities in all quadratic curvature gravity theories, by demanding that the entropy is increasing at every time, for linear perturbations to a stationary black hole and our result matches with the entropy formula found previously in holographic entanglement entropy calculations. This holographic entropy is different from Wald entropy for nonstationary horizons. Our result seems to indicate that somehow the validity of black hole thermodynamics is already encoded in the holographic principle.

After fixing these ambiguities for a generic four derivative gravity theories by demanding the second law of black hole thermodynamics holds up to linear order in perturbations, we consider the validity of second law beyond linear order in perturbations and obtain bounds on the possible range of the higher curvature coupling coefficients. We also compare our results with known bounds imposed by causality violation studied in the AdS/CFT framework. These results can be considered as the first model-independent constraint on the coupling of higher curvature terms from the consistency of the classical theory. If these higher curvature terms are from the quantum corrections to GR, the existence of these bounds shows that a simple bottom-up approach based on the study of theoretical consistency could provide important clues about the necessary features expected from the quantum theory of gravity. The low energy approximation of any sensible quantum gravity theory should produce the higher curvature terms with coupling within the range allowed by the validity of the second law. In the absence of any experimental or observational constraints, such bounds on the higher curvature couplings could be crucial to identify the correct approach to quantum gravity.

References:

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