

## Future Research Plan

Based on Research Summary, I plan to pursue the following directions:

### I. Entropy in spherically symmetric spacetimes

To identify the heat source in thermodynamics, one needs to understand how heat flux arises. This motivates the definition of an entropy associated with the gravitational field. However, in dynamical situations such as gravitational collapse, the gravitational field is in general far from equilibrium, and a treatment based on nonequilibrium thermodynamics is required, which makes the problem highly nontrivial. In the context of BH thermodynamics, it has been shown that even when a BH evolves in time and is thus out of equilibrium, one can define a local notion of gravitational energy in spherically symmetric spacetimes, and thereby derive a first law of thermodynamics. This, in turn, allows for a natural definition of a time-dependent BH entropy. Since this argument can be generalized beyond BHs to generic spherically symmetric spacetimes, we plan to derive the first law of thermodynamics for general spherically symmetric spacetimes and define an associated entropy. We will then examine whether this quantity satisfies the second law and thus deserves to be called an entropy.

### II. Robustness of the wave function in quantum cosmology

We have mathematically shown, under certain assumptions, that the wave function of the Universe coincides with that predicted by the tunneling proposal. On the other hand, this result was obtained in a gravitational path integral where only homogeneous and isotropic degrees of freedom of the metric were taken into account, and it remains to be clarified how general this conclusion is. To address this issue, we are currently extending the analysis to include anisotropic degrees of freedom, as well as exploring higher- and lower- dimensional cases. Through these studies, we aim to clarify how robust the conclusion is that the Universe is created according to the tunneling proposal.

### III. Gravitational waves from binary BHs and greybody factors

We have shown, by statistically analyzing numerical simulations of binary BH mergers, that the gravitational waves emitted by such systems can be characterized by the greybody factor of the remnant BH. However, this result concerns the waveform from the merger to the subsequent ringdown phase, and it is not yet clear from which stage of the evolution the emission can be described in terms of the greybody factor. To investigate this point, we plan to study exact solutions describing binary BHs and analyze gravitational perturbations on these backgrounds, thereby testing and refining the connection between the waveform and the greybody factor.

### IV. Dynamical black hole shadows

In BH binary systems, it is known that, in addition to the main shadow, disconnected components called “eyebrows” appear in the BH shadow. As the binary inspirals and merges, the eyebrow structures evolve in time and gradually wrap around the central shadow, so that the overall image can appear as a single merged shadow. However, taking into account the definition of a BH, one

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expects that even after the BHs merge, the eyebrow regions cannot, in principle, merge with the central shadow. We plan to test this expectation by tracing the null geodesics corresponding to the light rays observed by a distant observer backward in time and examining whether and how the eyebrow structures remain distinct from the central shadow throughout the time evolution.