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Entropy production due to spacetime fluctuations

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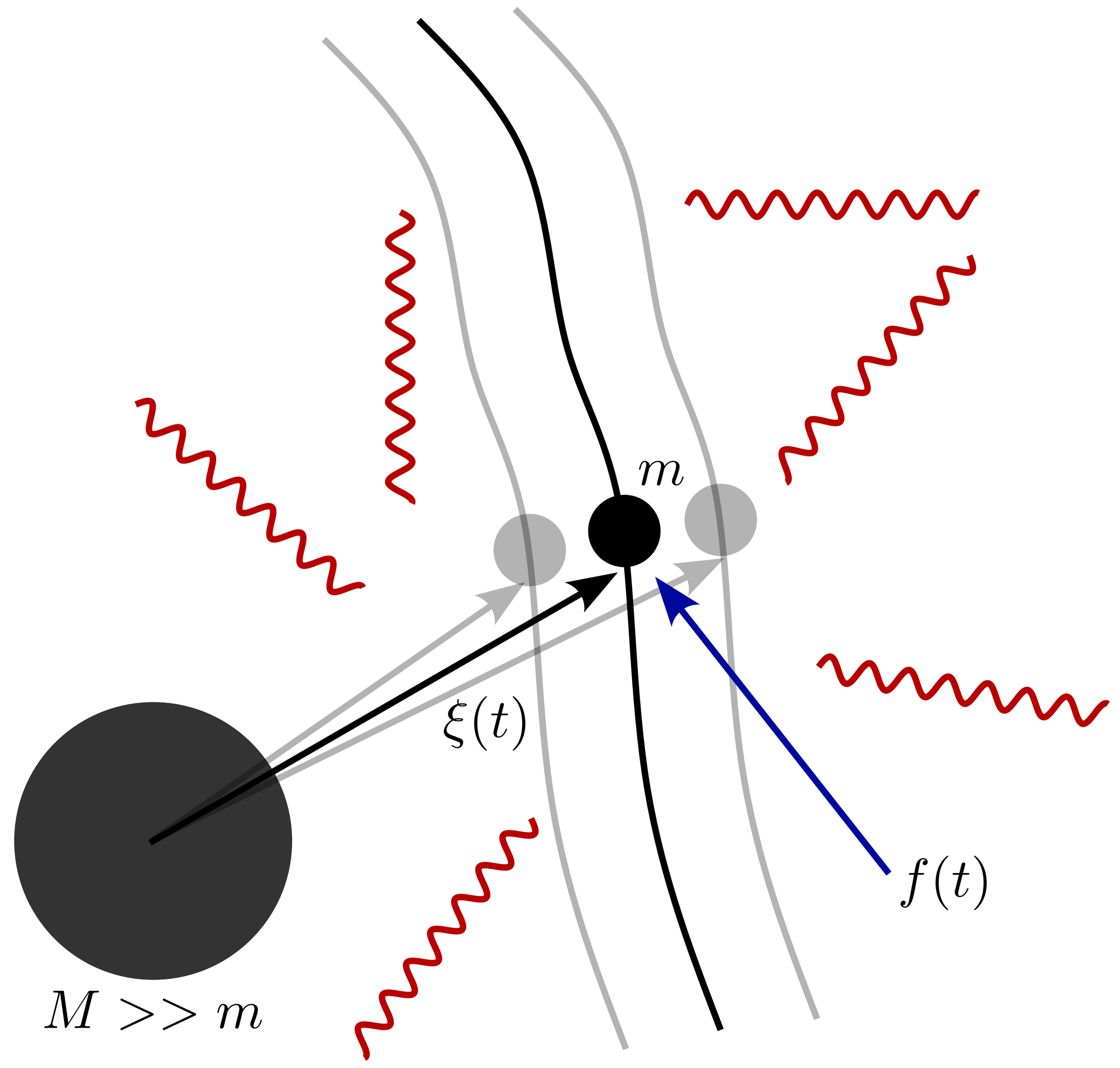
The problem

If the gravitational interaction requires a quantum description, like the other known forces in nature, one can expect this to lead to the quantization of gravitational waves in the weak-field limit, which gives rise to particle excitations called *gravitons*.

Since gravity affects all forms of energy and momentum, one can expect all quantum systems to behave as if constantly interacting with a bath of gravitons. Then it becomes natural to wonder what are the effects on irreversibility, as measured by thermodynamic entropy production, that arises when an external agent tries to move the system through the bath.

Entropy production

In order to answer this question, we consider a quantum system of mass m moving along a trajectory $\xi(t)$ (with respect to some observer) according to the combined interaction with a prescribed force protocol $f(t)$ and a bath of gravitons.



A quantum system of mass m, moving along coordinates $\xi(t)$ with respect to another mass $M >> m$, is acted upon by an external agent $f(t)$ while interacting with a bath of gravitons, here pictorially represented by the curly red lines. Being a quantum system, the mass m could, in principle, move in a superposition of paths, here represented by the blurred lines.

In principle, the system can move along a superposition of paths. The interaction of the gravitons will eventually lead to decoherence, however, and the path followed by the system is found to be the solution of a Langevin-like equation,

$$m\ddot{\xi}(t) = f(t) + 2\mathcal{N}(t),$$

where $\mathcal{N}(t)$ is a stochastic force term that encodes the interaction with the gravitons.

Then, we can compute the total work performed on the system and use the fluctuation theorem to find that the entropy production takes the form

$$\langle \Sigma \rangle = \frac{\beta^2}{2} \int_0^\tau dt dt' \, \dot{f}(t) \sigma(t,t') \dot{f}(t'),$$

where β is the initial temperature of the bath, τ is the time interval during which the force protocol f acts on the system and $\sigma(t,t')$ is a measure of the noise introduced on the system by the bath of gravitons.

Conclusions

Interaction with gravitons lead to decoherence of quantum systems. In fact, the more degrees of freedom are encoded in the system, the shorter will be the decoherence time.

We obtained an expression for the entropy production due to the interaction with the quantum fluctuations of spacetime.

Since gravity interacts with all forms of energy and momentum, this entropy production is universal.

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