Non-equilibrium Effective Field Theory for Gravity

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論　文　内　容　の　要　旨

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専　　攻　　　物理学専攻

論文題目（外国語の場合は，その和訳を併記すること。）

Non-equilibrium Effective Field Theory for Gravity

（重力に対する非平衡有効場理論）

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A black hole is a solution to classical gravity theories. In classical settings, a black hole can only absorb infalling matter, and its mass never decreases. However, when treated semi-classically, incorporating the effects of quantum fluctuations, a black hole radiates energy and loses mass through Hawking radiation. In this context, a black hole can be regarded as a non-equilibrium thermodynamic system, with its entropy defined in terms of the area of its 'horizon'.

Indeed, when the horizon area is interpreted as entropy, the mass as energy, and the conserved charge as particle number with an associated chemical potential, the relationship among these quantities aligns with the first law of thermodynamics:

$$T\frac{\delta A}{4G} = \delta M - \Omega_H\, \delta Q.$$

where A is the area of the black hole, M is the black hole mass, Q is a conserved charge, Ω_H is potential and G is the Newton constant. Also, the temperature of a black hole T is determined by its surface gravity. Furthermore, if a black hole absorbs only ordinary matter, the area of its horizon—and hence its entropy—continues to increase, satisfying the second law of thermodynamics:

$$\frac{\delta A}{4G} \geq 0.$$

Research on these calculations is particularly active for stationary black holes, as they are simpler to analyze. However, important extensions to these results remain. For example, when matter falls into a black hole, the black hole's area increases, but the entropy of the external matter S_{mat} decreases. This might appear to challenge the validity of the entropy-increase law for the matter outside. Moreover, when the black hole emits thermal radiation, its mass and area decrease, potentially violating the null energy condition and the second law.

To address these issues, it becomes necessary to consider a generalized second law of thermodynamics that incorporates the entropy of the matter outside the black hole:

$$\delta S_{mat} + \frac{\delta A}{4G} \geq 0,$$

where S_{mat} is the entropy of matter outside the black hole. This sum of entropies $\delta S_{mat} + \frac{\delta A}{4G}$ is called the 'generalized entropy'. Various attempts have been made to prove the entropy increase law for the generalized entropy.

In this thesis, we address this problem by considering the Schwinger-Keldysh (SK) formalism of effective field theory (EFT) for dynamical gravity theories. The SK formalism is a powerful tool for describing non-equilibrium processes, such as real-time evolution in finite-temperature systems and open systems. However, applying the SK formalism to construct an open system in dynamical gravity theories poses issues related to diffeomorphism symmetry. For instance, in open systems, energy conservation does not generally hold, whereas in dynamical gravity theories, the Bianchi identity, which stems from diffeomorphism symmetry, ensures the conservation law of the energy-momentum tensor. In fact, when attempting to construct a theory that includes dissipative terms, it can be shown that part of the diffeomorphism symmetry is broken and the energy-momentum tensor is not conserved. This issue is resolved using the Stuckelberg trick. By introducing Stuckelberg fields, the broken diffeomorphism symmetry is restored. Treating these Stuckelberg fields dynamically, they can behave like a fluid and play the role of an environment that receives the energy loss due to dissipation. This stems from the nature of gravity, which couples to all degrees of freedom.

Through these procedures, it becomes possible to construct an SKEFT that describes situations with a fluid surrounding a dynamical black hole, while maintaining symmetry and unitarity. Furthermore, by imposing the dynamical Kubo-Martin-Schwinger (KMS) symmetry on the effective action, the introduced entropy current enables us to define the generalized entropy. Here, the entropy of the dynamical black hole is characterized not by the event horizon but by the apparent horizon. And then, by calculating the time evolution of the generalized entropy defined in this way, one can examine the conditions under which the generalized second law holds.

In this thesis, we construct gravitational theory with a fluid in the SK formalism and discuss the generalized second law in a black hole spacetime with a fluid, based on our paper (Nishii et al., 2024).

This thesis is organized as follows.

- In Chapter 2, we review the black hole thermodynamics. First, after introducing Einstein's theory of gravity, we consider the Schwarzschild solution as the simplest black hole solution and see how the black hole is characterized by the horizon (Sec. 2.1). Then, using the Killing vector and Killing horizon, we confirm that the causal structure of such spacetimes can be understood through spacetime symmetries. Finally, in Sec. 2.2, we verify that the causal structure based on these symmetries can be understood in terms of thermodynamics by deriving the first and second laws of black hole thermodynamics, and comment on the issues in the thermodynamics of stationary black holes from the perspective of the generalized second law and the apparent horizon.

- In Chapter 3, we introduce the SK formalism. In Sec. 3.1, we first provide an overview of the SK formalism and the general structure of its EFT using a toy model. In Sec. 3.2, as preparation for constructing dynamical gravity theories in the SK formalism, we discuss the properties of diffeomorphism symmetry on a closed-time-path. Here, we explain how the doubled diffeomorphism symmetry separates into diagonal (physical diffeomorphism) and off-diagonal (noise diffeomorphism) parts in the classical limit. In Sec. 3.3, as an example, we construct a dynamical gravity theory in the SK formalism using the theory of a real scalar field. At this point, we explain the breaking of the noise diffeomorphism symmetry due to dissipation and the use of the Stuckelberg trick to resolve this issue. By treating the Stuckelberg fields dynamically, we demonstrate how an environment sector, such as a fluid, is naturally introduced. Here, from the perspective of the conservation law of energy-momentum tensor, the system is closed. Therefore, finally, it is schematically shown that an open system is realized when the energy of the environmental sector is sufficiently large, allowing it to behave as a heat bath. This corresponds to the so-called decoupling limit.

- Chapter 4 is the main part of the thesis, where we study dissipative gravity theories. First, in Sec. 4.1, we explain how the effects of dissipation in an effective field theory of gravity, including dissipation, can be characterized using a dissipative fluid introduced as an environmental sector. As an application, in Sec. 4.2, we consider a scenario where a black hole is surrounded by a fluid. In this context, the EFT of hydrodynamics defines a local temperature and an entropy current based on the dynamical KMS symmetry. As a result, by using the entropy current of the fluid, the time evolution of the generalized entropy is calculated, and it is explained that the temperature gradient and the direction of the fluid's velocity vector play a crucial role in satisfying the entropy increase law. Furthermore, considerations are made for both cases: ordinary fluids (satisfying the null energy condition) being accreted by the black hole and exotic matter (violating the null energy condition), such as Hawking radiation, escaping from the black hole. It is shown that the temperature gradient is enhanced by the blueshift factor determined by the direction of the fluid, ensuring that the generalized entropy increases in both scenarios. This chapter and the previous chapter are based on our paper (Nishii et al., 2024).

- Chapter 5 is devoted to the conclusion and the prospects.

（別紙１）　　　　　　　　　　　　論文審査の結果の要旨

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要　　旨

本論文の要旨は以下のとおりである。
本論文の骨子は、第１章が研究の背景、第２章がブラックホール熱力学に関するレビュー、第３章と第４章が重力に対する非平衡有効場理論とそのブラックホール熱力学への応用に関するオリジナルな研究成果、第５章が結論となっている。

第１章では導入として、重力理論における非平衡現象であるダイナミカルなブラックホールの重要性が述べられ、重力に対する非平衡有効場理論を研究することの動機付けが明確に記述されている。
第２章はブラックホール熱力学に関するレビューである。特に、定常ブラックホールの熱力学をダイナミカルなブラックホールに拡張する際の課題や現状の理解が簡潔にまとめられている。
第３章と第４章は本論文のオリジナルな部分である。まず、第３章では、非平衡現象の記述に有用な Schwinger-Keldysh (SK) 形式に基づく「重力に対する非平衡有効場理論」の構成法が提案されている。最初に、非平衡現象における散逸やノイズの起源、これらを記述する際の SK 形式の有用性、有効理論の満たすべき対称性やユニタリー性条件が調和振動子の模型を用いて詳しく説明されている。次に、SK 形式における一般座標変換不変性とエネルギー保存則の関係が散逸現象と関連付けながらまとめられている。これらを踏まえて有効場理論の構成法が提案され、宇宙論への応用も期待される「散逸スカラー場と重力の有効場理論」の解析が行われている。重力はすべての自由度と普遍的に結合するので、着目しているシステムだけでなく、エネルギーの散逸先である環境の効果も適切に取り入れる必要がある。環境の自然なモデルとして「非平衡流体の有効場理論」を採用することでこの点を克服している点も特徴的である。
第４章では、第３章で構成した有効場理論を散逸重力波やブラックホール熱力学に応用している。特に、ブラックホールの熱力学第二法則が成り立つためには「ブラックホールと流体の間の温度勾配」と「流体が作るエネルギー流入の方向」が一致する必要があることが指摘されている。
第５章では、本論文の結論として、まとめと展望が述べられている。

ブラックホールや宇宙論への応用を念頭に、重力理論・宇宙論研究の文脈で開放系や散逸系への注目が集まっている。実際、SK 形式に基づく非平衡有効場理論の方法をインフレーション宇宙論に応用しようという流れも近年生まれているが、ダイナミカルな重力の取り扱いが課題であった。そのような中、SK 形式における重力理論の対称性を丁寧に解析し、すべての自由度と普遍的に結合するという重力の性質を適切に取り入れてこの課題を解決した点は高く評価できる。また、本成果の応用も今後数多く期待される。

本研究は、SK 形式を用いて「重力に対する非平衡有効場理論」の構成法を整備したものであり、重力理論・宇宙論研究に重要な知見をもたらした価値ある研究の集積であると認める。

よって、学位申請者の西井莞治氏は，博士（理学）の学位を得る資格があると認める。

・　特記事項　なし
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