様　式　C－19、F－19－1、Z－19　（共通）

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研究課題名（和文）Uncovering the Local Dark Matter Density in Axion Dark Matter Scenarios

研究課題名（英文）Uncovering the Local Dark Matter Density in Axion Dark Matter Scenarios

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研究成果の概要（和文）：小惑星追跡データは十分に正確で、系統誤差も十分に制御されている為、太陽系の暗黒物質密度に対し、これまでの惑星を用いた制限と同レベルの制限を与えることが可能である事を初めて示した。また、本手法による制限は、近い将来に更新も見込まれる。他の成果は、非常に軽い暗黒物質が、太陽を含む天体周辺に効率的に捕捉されることを示したことである。これまでの文献予想とは異なり、非常に軽い暗黒物質の補足率が、ボーズ統計と重力収束の効果により指数関数的に増大することを示し、近傍の暗黒物質密度に対して非常に衝撃的な予言を行った。本研究は、惑星やブラックホール等にも応用でき、多くのフォローアップ論文を創出している。

研究成果の学術的意義や社会的意義
Our work has shown that asteroids can be used to set novel constraints on the local dark matter density, that dark matter can be captured in the solar system leading to new predictions for experiment, and proposed a novel space-based quantum sensing experiment to discover dark matter.

研究成果の概要（英文）：For the first time, we have shown that asteroid tracking data is precise enough, and systematic uncertainties are controlled well enough, to set a competitive constraint on the dark matter density in the solar system. Previous constraints from planets are unlikely to improve, but our method could allow for rapid improvement in the future.

The other key achievement was to show that ultralight dark matter can be efficiently captured around astrophysical bodies, including stars like the Sun. Contrary to the previous expectation in the research literature, we showed how the capture of these fields can be exponentially enhanced by bosonic statistics and gravitational focusing of the field, giving rise to extremely striking predictions for the local density of dark matter. Our method is extremely generic, and can be directly applied to other systems, including planets and black holes; indeed, since our work appeared a number of follow-up studies have begun to investigate these systems.

研究分野：Particle physics phenomenology

キーワード：Dark matter　Local density　Gravitational atoms　Dark matter capture

様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９（共通）

１．研究開始当初の背景

Dark matter (DM) is known to constitute 80% of the mass density in the universe, but its identity is unknown. Large-scale dynamics of dark matter suggest that dark matter should be present throughout the galaxy; in the absence of small-scale dynamics that modify the distribution, one can predict the density of dark matter in the solar system, and indeed near the Earth, which is known as the *local density of dark matter*. On this basis, many terrestrial experiments are ongoing which attempt to directly measure dark matter properties, including its mass and couplings to Standard Model fields.

However, this local density of dark matter has never been directly measured. The strongest constraints at present arise from the precise measurement of planetary trajectories over several centuries, which would be modified in the presence of a large DM density. Furthermore, in some DM models, small-scale dynamics do predict modifications to the local density: either a decrease, if e.g. DM forms a small number of isolated clumps whose average distance is much larger than the size of the solar system; or an increase, if e.g. DM is efficiently captured inside the solar system. Because all terrestrial DM search experiments use the local density as a key input, any such modification will have broad and critical implications.

２．研究の目的

This project was intended to pursue these critical open questions about the local density of dark matter, both through theoretical study of dark matter models and by exploring novel measurements which could improve on existing constraints. One branch of research was intended to investigate new observations which could directly probe the local dark matter density near the Earth, possibly improving on existing constraints from the dynamics of planets in the solar system. Any such probe would represent an extremely general constraint on dark matter models broadly, and an important factor in the sensitivity estimates of experimental searches.

Another research direction analyzes the widely-studied class of dark matter candidates known as *ultralight dark matter*, to see whether one can predict the local density of dark matter in this case. Ultralight dark matter is a particularly promising category to investigate in this context, because such models generally exhibit large-scale wave dynamics which are known to modify the dark matter distribution in a nontrivial way.

３．研究の方法

To investigate the local density of dark matter, we started by understanding the origin of the current best limits on this quantity, which arise from planetary motion data (also known as *solar system ephemerides*). The presence of dark matter in the solar system has a potentially measurable effect on planetary motion, namely, it can contribute to anomalous perihelion precession, i.e. the elliptical orbit of a planet will precess slightly (by a fraction of a degree) in each revolution; measuring the trajectory over many revolutions gives rise to an effect that can therefore constrain the presence of dark matter. This method, which is well-established in the literature, currently constrains the local density to be no more than 100,000 times larger than the usual expectation.

We wanted to see whether a different probe could do as well as (or better than) the existing data from planets. A promising approach is to use *asteroids*, whose trajectories are being mapped with very high fidelity in the modern day. Historically the systematic uncertainty in asteroid tracking data has been too large to allow for a strong constraint. However, recent data from the OSIRIS-ReX mission from NASA has led to a large improvement, making it worth investigating. We utilized cutting-edge tracking of the Bennu asteroid from this mission, along with proprietary force modeling from the Jet Propulsion Laboratory in California, to conduct this investigation, taking into account all systematic errors in the force modeling.

We also investigated the capture of ultralight dark matter in the gravitational field of an astrophysical body, for example the Sun. Employing the method of classical wave mechanics to determine the capture rate, we found that self-interactions of the dark matter field can induce exponential growth in the mass of a cloud of particles around such bodies. We explored the implications of this insight for a cloud of ultralight dark matter particles around the Sun, which we called a *solar halo*. We also investigated how this solar halo could be discovered by a future space-based mission with on-board quantum sensing experiment, especially one which orbits very close to the Sun where the dark matter density can be the largest based on our study.

４．研究成果

Using cutting-edge tracking of the Bennu asteroid from this mission, along with proprietary force modeling from the Jet Propulsion Laboratory in California, we were able to set a competitive constraint for the first time ever using asteroid tracking. Comparing to existing constraints from planets, our constraint using Bennu was within an order of magnitude, showing that this method is promising and represents an important advance in our understanding of the dynamics of the solar system. We are hopeful that this work, a proof-of-concept, will lead to further constraints in the future, and perhaps someday could lead to a positive detection of the presence of dark matter in the solar system. Our study was published in the Journal of Cosmology and Astrophysics with the title, 'OSIRIS-Rex constraints on dark matter and cosmic neutrino profiles through gravity', in 2024.

We also studied the implications of a solar halo of ultralight dark matter around the Sun. This is intriguing from the point of view of this project because it represents a scenario in which the local density of dark matter is predicted to be very different from the usual value. We showed how strong-enough self interactions of the dark matter particles led to very significant overdensities around the Sun, which can even extend to the position of the Earth. In this case, the local density of dark matter relevant for experimental searches on Earth's surface is significantly modified, being as large as 1000 or 10,000 times larger than the usual value assumed by the experiments. We published our study in the Journal of Cosmology and Astrophysics in 2023, and since its appearance many experiments have used our study as a benchmark for dedicated searches beyond the usual dark matter assumptions. Others have started to use our work to investigate dark matter capture in other systems, including around planets, neutron stars, and black holes, using our calculation as a guide to the dynamics of the capture process. Therefore this work has already had significant impact within the field internationally.

５．主な発表論文等

〔雑誌論文〕　計3件（うち査読付論文　2件／うち国際共著　3件／うちオープンアクセス　0件）

１．著者名 D. Budker, J. Eby, M. Gorghetto, M. Jiang, and G. Perez	４．巻 12
２．論文標題 A Generic Formation Mechanism for Ultralight Dark Matter Solar Halos	５．発行年 2023年
３．雑誌名 Journal of Cosmology and Astrophysics	６．最初と最後の頁 21
掲載論文のDOI（デジタルオブジェクト識別子） 10.1088/1475-7516/2023/12/021	査読の有無 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Y.-D. Tsai, J. Eby, J. Arakawa, D. Farnocchia, and M. S. Safronova	４．巻 2
２．論文標題 OSIRIS-REx Constraints on Dark Matter and Cosmic Neutrino Profiles through Gravity	５．発行年 2024年
３．雑誌名 Journal of Cosmology and Astrophysics	６．最初と最後の頁 29
掲載論文のDOI（デジタルオブジェクト識別子） 10.1088/1475-7516/2024/02/029	査読の有無 有
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１．著者名 Y.-D. Tsai, J. Eby, and M. S. Safronova	４．巻 7
２．論文標題 Direct detection of ultralight dark matter bound to the Sun with space quantum sensors	５．発行年 2022年
３．雑誌名 Nature Astronomy	６．最初と最後の頁 113～121
掲載論文のDOI（デジタルオブジェクト識別子） 10.1038/s41550-022-01833-6	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計6件（うち招待講演　6件／うち国際学会　2件）

１．発表者名 Joshua Eby
２．発表標題 Axion Solar Halos
３．学会等名 Phenomenology Seminar（招待講演）
４．発表年 2022年

1．発表者名 Joshua Eby
2．発表標題 Axion Solar Halos
3．学会等名 Particle and Astro Physics Seminar（招待講演）
4．発表年 2022年

1．発表者名 Joshua Eby
2．発表標題 Axion Solar Halos
3．学会等名 Instititue for Fundamental Physics Seminar（招待講演）
4．発表年 2022年

1．発表者名 Joshua Eby
2．発表標題 Axion Solar Halos
3．学会等名 Asian-European Institute for BSM / KIAS Workshop on Particle Physics（招待講演）（国際学会）
4．発表年 2022年

1．発表者名 Joshua Eby
2．発表標題 Probing Ultralight Dark Matter and the Very Local Density from Earth and Space
3．学会等名 Invited Seminar (virtual), Hebrew University of Jerusalem（招待講演）
4．発表年 2022年

１．発表者名 Joshua Eby
２．発表標題 Probing Ultralight Dark Matter and the Very Local Density from Earth and Space
３．学会等名 Dark Matter as a Portal to New Physics (APCTP, Korea)（招待講演）（国際学会）
４．発表年 2022年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関