Constraints on axion dark matter with pulsar timing array

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論 文 内 容 の 要 旨

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専　　攻　　　　　物理学

論文題目（外国語の場合は，その和訳を併記すること。）

Constraints on axion dark matter with pulsar timing array

パルサータイミングアレイによるアクシオンダークマターへの制限

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Abstract:

The dark matter problem is clearly one of the most important issues in modern cosmology. Recently, motivated by string theory, an ultralight scalar dark matter has been intensively studied. In particular, an ultralight scalar field with mass 10^{-23} eV can behave like the cold dark matter (CDM) on cosmological scales and resolve a core-cusp problem. In this thesis, we call it simply the fuzzy dark matter (FDM). The FDM can be treated as a classical scalar field because the occupation number of the FDM accounting for the energy density of the dark matter is very large. The main difference between FDM and CDM is that the pressure of the FDM is coherently oscillating, while that of CDM almost vanishes. Khmelnitsky and Rubakov have pointed out that the effect of oscillating pressure might be detected with the pulsar timing arrays (PTAs). Indeed, the oscillation of the pressure induces the oscillation of the gravitational potential, and as a result, it induces the oscillation of the arrival time of the pulse passing through the gravitational potential.

Nowadays, the PTAs are most sensitive to the gravitational effects with a few nanohertz frequency. There are three major pulsar timing projects: the European Pulsar Timing Array (EPTA), the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), and the Parkes Pulsar Timing Array (PPTA). The collaboration of the three projects is called the International Pulsar Timing Array (IPTA). Furthermore, observations of the pulsars have started by Five-hundred-meter Aperture Spherical Telescope (FAST) in China and MeerKAT in South Africa. From 2020 year, the Square Kilometre Array (SKA) will begin observations which is the next generation telescope. There are many projects observing the pulsars, therefore, the PTA is currently receiving much interest.

Porayko and Postnov gave upper limits for the FDM with the Bayesian analysis using the NANOGrav 5-year Data Set. Moreover, Porayko et al. gave upper limits for the FDM with the Bayesian and the Frequentist analyses using the PPTA 12-year Data Set. Following the previous articles, we search for the FDM by the Bayesian analysis in the time domain using the NANOGrav 11-year Data Set. We quantitatively investigate whether the ultralight scalar dark matter is detectable or not using the Bayesian model selection approach. We clarify the prior dependence of constraints on the amplitude of the FDM signal and obtain three times stronger constraints on the amplitude of the FDM signal in the frequency range from $10^{-8.34}$ to $10^{-8.19}$ Hz. We also discuss how the results of Bayesian analysis depend on the the solar system ephemeris noise in the model describing the observation data.

We use the Bayesian statistics instead of frequentist statistics, and we use the data in the time domain. We explain a little about why such an analysis is performed.

First, in the pulsar timing array, the number of parameters for parameter estimation is very large, and the likelihood function is multimodal. Therefore, it is more reasonable to estimate the likelihood function rather than to derive an analytical (or numerical) solution for the parameter that maximizes the likelihood function. In the Bayesian, a method for estimating the posterior distribution obtained by multiplying the likelihood function by the prior distribution is known, which is called Markov chain Monte Carlo method (MCMC). Therefore, we will use the Bayesian statistics instead of frequentist statistics.

Second The data used in the pulsar timing array is obtained by irregular observation intervals. The Fourier transform assumes uniform sampling, so the nature of the observation data in the Fourier domain of PTA is not well understood. In a pulsar timing array, it would be natural to handle

data in the time domain. Therefore, we will use the data in the time domain.

This thesis is organized as follows

Chapter2: We review the axion which is a candidate for the FDM and review the quantum behavior of the axion. Then we show that FDM behaves as dark energy in the early expanding universe and dark matter in later expanding universe. Finally we derive the time oscillation of the arrival time of the pulse which induced by the FDM. The time oscillation of the arrival time can be detected by the pulse timing array.

Chapter3: This section describes the pulsar timing array. First, we will explain a number of pulsar timing array projects. We will also explain how to remove known noise from fluctuations in pulse arrival time. The pulsar timing array analyzes whether there is an FDM signal in the residual after performing this operation.

Chapter4: We explain the data D, the model M, and the parameter θ used in Bayesian analysis, and define the posterior probability distribution $p(\theta|D, M)$, the likelihood function $p(D|\theta, M)$, and the prior probability distribution $p(\theta|M)$. Then we briefly describe the MCMC simulation an explain the analysis before the main analysis.

Chapter5: We describe the upper limits on the amplitude of the FDM signal. This upper limits are our main result. We quantitatively investigate whether the ultralight scalar dark matter is detectable or not using the Bayes factor. We obtain three times stronger constraints on the amplitude of the FDM signal in the frequency range from $10^{-8.34}$ to $10^{-8.19}$ Hz. The upper limit on the energy density was lower than 7 GeV/cm^3 in the range from $10^{-8.55}$ to $10^{-8.01}$ Hz where we analyze. In particular, at a frequency of $10^{-8.28}$ Hz, we obtained the strongest upper limit 2 GeV/cm^3. Finally, we show the analysis depend on the the solar system ephemeris noise.

Chapter6:We summarise this thesis and conclude our study.

（別紙１）　　　　論文審査の結果の要旨

氏名	加藤　亮
論文題目	Constraints on axion dark matter with pulsar timing array 「パルサータイミングアレイによるアクシオンダークマターへの制限」

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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章で研究の背景と研究の動機、第２章で暗黒物質の候補としての超軽量アクシオン場のコヒーレントな振動がパルサーからのパルス信号に及ぼす影響、第３章でパルサータイミングアレイに関するレヴュー、第４章ではオリジナルな解析、第５章で結果に関する考察があり、第６章で結論、となっている。

第１章では導入として、宇宙論の大問題である暗黒物質研究の現状、なぜアクシオンなのか、なぜパルサータイミングアレイを使うのか、どのような解析方法を使うべきなのかが明確に述べられ、論文のアウトラインが示されている。

第２章では、まず、超軽量アクシオン場の基本的な性質と、超軽量アクシオン場のダイナミクスが解説されている。さらに、パルサーを使って超軽量アクシオン場の直接観測をおこなう方法が丁寧に説明されている。

第３章では、パルサー観測の現状とパルサータイミング残差を得るためのモデルが、よくまとめられている。

第４章では、超軽量アクシオン場を検出するために、ベイズ解析の方法をパルサータイミングにどのように適用していくかがまとめられている。

第５章では、NANOGrav の 11 年目のデータを用いた、超軽量アクシオン場暗黒物質の検証解析が行われている。本論文の最も重要な成果は、これまでに解析されていないデータを用いて、これまでより３倍強い制限を得た点は評価に値する。本論文では、事前確率が結論にどのような影響を与えるかや、木星軌道の誤差の重要性を明らかにされており、今後のアクシオン探査において有用となる。その意味において本論文の成果は高い価値を有するものである。

第６章で結論が述べられている。

本研究は、暗黒物質としてのアクシオン場について、パルサータイミングデータを解析することで検証を試みたものであり，暗黒物質の有力な候補である超軽量アクシオン場の検証方法について重要な知見を得たものとして価値ある研究の集積であると認める。

よって，学位申請者の加藤亮氏は，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
- 特許登録数　０件
- 発表論文数　　査読付き　１編