様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

令和　４ 年　 ６ 月 １５ 日現在

機関番号：１２６０１
研究種目：若手研究
研究期間：2020～2021
課題番号：２０Ｋ１４４６３

研究課題名（和文）Closing in on the ultimate Dark Matter limits forecast by the Fermi Gamma-Ray Space Telescope

研究課題名（英文）Closing in on the ultimate Dark Matter limits forecast by the Fermi Gamma-Ray Space Telescope

研究代表者

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交付決定額（研究期間全体）：（直接経費）　　2,200,000円

研究成果の概要（和文）：（a）私はマルチメッセンジャー宇宙線データを使用して、超重い暗黒物質粒子に強い保守的な制約を課しました。（b）私は電波観測を使用して、マイクロエレクトロンボルトスケールのアクシオン暗黒物質粒子に現在最も厳しい制約を課しました。（c）私は文献でギガエレクトロンボルトスケールの暗黒物質粒子に対する強い制約を得ました。（d）次のチェレンコフ望遠鏡アレイが、ウィノ暗黒物質粒子を検索するための世界で最も感度の高い機器になることを実証しました。（e）INTEGRAL衛星データを使用して、陽電子の過剰が銀河バルジの星によるものであることを示しました。

研究成果の学術的意義や社会的意義
予想される背景を超えた興味深い天体物理学的信号がさまざまな望遠鏡で観測されており、暗黒物質の起源を持っている可能性があります。 天体物理学的過剰には、フェルミガンマ線宇宙望遠鏡によって検出された銀河中心GeVガンマ線過剰、AMS反陽子および陽電子過剰、および511X線ラインが含まれます。 このプロジェクトは、これらの過剰を解決するための手段を調査し、最終的な解決策への明確な道を提供しました。

研究成果の概要（英文）：(a) I used multi-messenger cosmic ray data to impose strong conservative constraints on super-heavy dark matter particles [JCAP 01 (2020) 003].(b) I used radio observations to impose the current most stringent constraints on microelectronvolt-scale axion dark matter particles [Phys.Rev.Lett. 125 (2020) 17, 171301].(c) I used the revolutionary astrophysical background model created in Macias+(2018) to obtain the strongest constraints in the literature on gigaelectronvolt-scale dark matter particles in the literature [Phys.Rev.D 102 (2020) 4, 043012].(d) I demonstrated that the upcoming Cherenkov Telescope Array will be the world's most sensitive instrument to search Wino dark matter particles [Phys.Rev.D 103 (2021) 2, 023011](e) In [MNRAS. 509 (2021) 1, L11-L16], I used INTEGRAL satellite data to show that the so-called positron excess was in fact not due to dark matter emission. Instead, it was related to the physics of the stars in the Galactic bulge.

研究分野：Astroparticle physics

キーワード：dark matter　pulsars

様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９（共通）

１．研究開始当初の背景

A number of indirect dark matter telescopes have observed excess signals above the astrophysical background over the years. They have provided tantalizing hints but no definitive proof of a dark matter discovery. Understanding the origin of these puzzling excesses is an important task for the community.

Until very recently, the consensus in the dark matter community was that the so-called “Fermi GeV excess” signal was either explained by dark matter emission or an unresolved population of approximately 50,000 millisecond pulsars. This is because both hypotheses were shown to be statistically indistinguishable in previous work. However, in previous work I performed a refined analysis that exploited novel interstellar gas templates that incorporate hydrodynamic simulations of the Galactic bulge region and new inverse Compton radiation maps. We found that the spatial morphology of the Fermi GeV excess is not spherically symmetric as previously thought, but rather shows a much stronger correspondence with the projected spatial distribution of stars in the Galactic bulge. These results argue against a dark matter explanation for the Fermi GeV excess and instead require sources that are related to the stars.

２．研究の目的

The purpose of this research project was to perform a robust re-analysis of the observations to examine what may still be attributed to dark matter annihilation in
the γ-ray excess data. For the dark matter profile we study both spherical and ellipsoidal dark matter templates and a range of radial profiles from steep cusps to kiloparsec-sized cores, motivated in part by hydrodynamical simulations. For the astrophysical background model we include a wide range of variations in all its components to rigorously account for the systematic uncertainties. The aim is to show, for the first time, that Fermi data from the Galactic center region has significant sensitivity to uncharted parameter space for dark matter particles in the GeV mass scale.

３．研究の方法

I calculated the limits on dark matter (DM) annihilation cross section by generating a likelihood profile for the DM annihilation intensity for a given DM halo model. I considered four classes of Milky Way DM profiles. The likelihood for each value of the DM annihilation intensity was computed by varying the fluxes of all the background templates such that the log-likelihood was maximized. We used the Fermi Upper Limits tool to perform this maximization and generate the likelihood profile for the DM annihilation intensity.

My background model contained templates for the following: hadronic emission traced by HI and H2 gas maps divided in four cylindrical concentric rings and two total dust maps, three-dimensional (3D) inverse Compton (IC) divided into four or six rings and a two-dimensional (2D) IC map with a central source of electrons, an isotropic background, the 4FGL catalog point sources, Fermi bubbles, Loop I, the Sun, and the Moon. Details of the templates, methods employed, likelihood profiles, and resulting spectra, as well as our comprehensive checks and analyses of the systematic effects, are all presented in Abazajian et al. (2020).

The likelihood profile was generated in 15 independent logarithmic-spaced energy bins between 0.5 and 200 GeV, and no broadband spectral shape is assumed for any of the templates. Following this methodology, I was able to marginalize over the uncertainties in the astrophysical backgrounds in a manner that is independent of the uncertainties in the particle physics models. An indicator of the success of my method is that I recover physically consistent, continuous spectra for all the background templates.

With the likelihood profiles in hand, I used Bayes's theorem to calculate posteriors in the annihilation cross section and DM mass parameter space. For comparison purposes, I also calculated the posterior distribution of the DM mass and annihilation cross section for the eight classical Milky Way dwarf spheroidals, with well-determined J-factors. I used the likelihood profiles for the classical dwarfs from the Fermi collaboration and the uncertainties

in the J-factors of the dwarfs are taken from Geringer-Sameth et al 2014, which are inferred from fits to the stellar kinematic data using generalized Navarro-Frenk-White (NFW) profiles. Unlike the Galactic center region, the J-factors for the classical dwarfs are well constrained by stellar kinematic data because they are dark matter dominated and the region of interest of approximately 0.5 degrees is well-matched to their stellar half-light radii.

４．研究成果

The detection in the Fermi-LAT data of a spatially concentrated excess of gamma-ray emission in the Milky Way potentially consistent with DM annihilation has sparked great interest in the sources of high-energy emission in the GC. At the same time, the Fermi-LAT data have spurred steady progress in our understanding of the gamma-ray emission from our Galaxy over the past decade. With detected sources that are consistent with the Fermi bubbles; 4FGL point sources; detailed IC emission maps; disk gas; and, most importantly, the emission from the stellar Galactic bulge and nuclear bulge, there is no significant excess in the Galactic cener that may be attributed to DM annihilation. This result is robust to a wide range of variations in the Galactic diffuse emission model and DM profiles. Although I cannot test for all possible Galactic diffuse emission models and DM profiles, the important point is that my approach covers the wide range that has been used to infer the existence of the Galactic center excess, and go beyond them.

My　results strongly favor the hypothesis that the excess emission in the Galactic center at GeV energies is dominantly of astrophysical origin related to the stellar bulge. While gamma-ray emission from DM annihilation in the GC is still possible, the flux would have to be below that of the Galactic center excess, and with parameters consistent with the exclusion regions of my work. In arriving at this conclusion, I allowed for a variety of DM templates. These include ellipsoidal profiles with a kiloparsec-sized core that I suggest, based on existing simulations of the Milky Way, are closest to the true prediction for the density profile of cold dark matter. I explored in detail the robustness of my results to variations in the Galactic diffuse emission models arising from new sources of relativistic electrons, new 3D IC templates, and changes to the standard gas maps. My results provide stringent constraints on models of thermal relic dark matter with masses up to a few hundred GeV and prompt annihilation to Standard Model particles.

In summary, I have been able to obtain the most stringent constraints on particle dark matter available in the literature. Even with conservative assumptions for the astrophysical emission and dark matter profiles, my derived dark matter limits are more constraining than those from Milky Way dwarfs and exclude the thermal relic annihilation cross section out to masses of approximately 300 GeV.

My theoretical improvements to the astrophysical background model have allowed us to have an enhanced sensitivity to dark matter annihilations in the Galactic center. Remarkably, our study shows that there is still room for more. Indeed, further development of the background model—following the methods introduced in this project—will permit us to gain an even higher sensitivity to the dark matter parameter space.

５．主な発表論文等

〔雑誌論文〕　計10件（うち査読付論文　10件／うち国際共著　10件／うちオープンアクセス　1件）

１．著者名 Rinchiuso, Lucia and Macias, Oscar and Moulin, Emmanuel and Rodd, Nicholas L. and Slatyer, Tracy R.	４．巻 103
２．論文標題 Prospects for detecting heavy WIMP dark matter with the Cherenkov Telescope Array: The Wino and Higgsino	５．発行年 2021年
３．雑誌名 Physical Review D	６．最初と最後の頁 23011
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevD.103.023011	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

１．著者名 Song, Deheng and Macias, Oscar and Horiuchi, Shunsaku and Crocker, Roland M. and Nataf, David M.	４．巻 507
２．論文標題 Evidence for a high-energy tail in the gamma-ray spectra of globular clusters	５．発行年 2021年
３．雑誌名 Monthly Notices of the Royal Astronomical Society	６．最初と最後の頁 5161--5176
掲載論文のDOI（デジタルオブジェクト識別子） 10.1093/mnras/stab2406	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

１．著者名 Macias, Oscar and van Leijen, Harm and Song, Deheng and Ando, Shin'ichiro and Horiuchi, Shunsaku and Crocker, Roland M.	４．巻 506
２．論文標題 Cherenkov Telescope Array sensitivity to the putative millisecond pulsar population responsible for the Galactic Centre excess	５．発行年 2021年
３．雑誌名 Monthly Notices of the Royal Astronomical Society	６．最初と最後の頁 1741--1760
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１．著者名 Siegert, Thomas and Crocker, Roland M. and Macias, Oscar and Panther, Fiona H. and Calore, Francesca and Song, Deheng and Horiuchi, Shunsaku	４．巻 509
２．論文標題 Measuring the smearing of the Galactic 511-keV signal: positron propagation or supernova kicks?	５．発行年 2021年
３．雑誌名 Monthly Notices of the Royal Astronomical Society	６．最初と最後の頁 11-16
掲載論文のDOI（デジタルオブジェクト識別子） 10.1093/mnrasl/slab113	査読の有無 有
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1．著者名 Pohl, Martin and Macias, Oscar and Coleman, Phaedra and Gordon, Chris	4．巻 929
2．論文標題 Assessing the Impact of Hydrogen Absorption on the Characteristics of the Galactic Center Excess	5．発行年 2022年
3．雑誌名 The Astrophysical Journal	6．最初と最後の頁 136
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/1538-4357/ac6032	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Gautam, Anuj and Crocker, Roland M. and Ferrario, Lilia and Ruiter, Ashley J. and Ploeg, Harrison and Gordon, Chris and Macias, Oscar	4．巻 -
2．論文標題 Millisecond Pulsars from Accretion Induced Collapse as the Origin of the Galactic Centre Gamma-ray Excess Signal	5．発行年 2022年
3．雑誌名 Nature Astronomy	6．最初と最後の頁 4
掲載論文のDOI（デジタルオブジェクト識別子） 10.1038/s41550-022-01658-3	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

1．著者名 Kevork N. Abazajian, Shunsaku Horiuchi, Manoj Kaplinghat, Ryan E. Keeley, Oscar Macias	4．巻 102
2．論文標題 Strong constraints on thermal relic dark matter from Fermi-LAT observations of the Galactic Center	5．発行年 2020年
3．雑誌名 Physical Review D	6．最初と最後の頁 1-24
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevD.102.043012	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

1．著者名 Harrison Ploeg, Chris Gordon, Roland Crocker, Oscar Macias	4．巻 12
2．論文標題 Comparing the Galactic Bulge and Galactic Disk Millisecond Pulsars	5．発行年 2020年
3．雑誌名 Journal of Cosmology and Astroparticle Physics	6．最初と最後の頁 35
掲載論文のDOI（デジタルオブジェクト識別子） 10.1088/1475-7516/2020/12/035	査読の有無 有
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１．著者名 Lucia Rinchiuso, Oscar Macias, Emmanuel Moulin, Nicholas L. Rodd, Tracy R. Slatyer	４．巻 103
２．論文標題 Prospects for detecting heavy WIMP dark matter with the Cherenkov Telescope Array: The Wino and Higgsino	５．発行年 2020年
３．雑誌名 Physical Review D	６．最初と最後の頁 1-20
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevD.103.023011	査読の有無 有
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１．著者名 Green Bank and Effelsberg Radio Telescope Searches for Axion Dark Matter Conversion in Neutron Star Magnetospheres	４．巻 125
２．論文標題 Joshua W. Foster, Yonatan Kahn, Oscar Macias, Zhiquan Sun, Ralph P. Eatough, Christoph Weniger, Ben Safdi	５．発行年 2020年
３．雑誌名 Physical Review Letters	６．最初と最後の頁 1-17
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevLett.125.171301	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8件（うち招待講演　8件／うち国際学会　5件）

１．発表者名 Oscar Macias
２．発表標題 Distinguising dark matter from millisecond pulsars with the Cherenkov Telescope Array
３．学会等名 MOCa 2021 - Materia Oscura en Colombia（招待講演）（国際学会）
４．発表年 2021年

１．発表者名 Oscar Macias
２．発表標題 Searches for Millisecond Pulsars with Gamma Ray Telescopes
３．学会等名 Instituto de Fisica Teorica (IFT) - Research Seminar（招待講演）（国際学会）
４．発表年 2021年

１．発表者名
Oscar Macias

２．発表標題
CTA sensitivity to the high-energy tail of the Fermi GeV excess

３．学会等名
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４．発表年
2021年

１．発表者名
Oscar Macias

２．発表標題
Distinguishing Dark Matter from Millisecond Pulsars in the Center of the Galaxy

３．学会等名
TeV Particle Astrophysics 2021(TeVPA 2021)（招待講演）（国際学会）

４．発表年
2021年

１．発表者名
Oscar Macias

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CTA prospects for new physics at the galactic center.

３．学会等名
IRN Terascale - Dark Universe Workshop (LPC-Clermont)（招待講演）（国際学会）

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2021年

１．発表者名
Oscar Macias

２．発表標題
Assessing the Impact of Hydrogen Absorption on the Characteristics of the Galactic Center Excess

３．学会等名
Kashiwa Dark Matter 2021, Dark Matter Symposium（招待講演）

４．発表年
2021年

１．発表者名
Oscar Macias

２．発表標題
Astrophysical Constraints on Dark Matter

３．学会等名
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１．発表者名
Oscar Macias

２．発表標題
Cherenkov Telescope Array sensitivity to the putative millisecond pulsar population responsible for the Galactic center excess

３．学会等名
25th Symposium on Astroparticle Physics in the Netherlands（招待講演）

４．発表年
2021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			
オランダ	University of Amsterdam			
オーストラリア	National University of Australia			
米国	University of California IRVINE			