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　６ 年　６ 月 １３ 日現在

機関番号：３２６８９
研究種目：基盤研究(C)（一般）
研究期間：2021～2023
課題番号：２１Ｋ０３６０４

研究課題名（和文）Combined Spectrum and Anisotropy Study of Cosmic Rays from the Vela SNR with CALET

研究課題名（英文）Combined Spectrum and Anisotropy Study of Cosmic Rays from the Vela SNR with CALET

研究代表者

Ｍｏｔｚ　Ｈｏｌｇｅｒ（Motz, Holger）

早稲田大学・理工学術院・教授（任期付）

研究者番号：３０６４７９０４

交付決定額（研究期間全体）：（直接経費）　2,900,000円

研究成果の概要（和文）：銀河宇宙線の起源は、超新星残骸に由来すると推測されるが、磁場の影響のため明らかにできない。しかし、高エネルギー電子宇宙線はすぐにエネルギーを失うため、地球に到達するものは、いくつかの近傍の超新星残骸から発生すると特定できる可能性がある。
ISSにあるCALET検出器は、TeV領域までの全電子宇宙線のスペクトルを測定している。本研究では、TeV領域における理論的なスペクトル形状を解析し、最新のCALETのデータと比較した結果、近傍の超新星残骸を起源とする兆候を明らかにした。スペクトルと異方性の解析方法の開発を行い、そのシミュレーションで有意性のある発見につながる将来的な検出の可能性が確認できた。

研究成果の学術的意義や社会的意義
This project paves the road for detecting the first direct observation of cosmic rays from an individual source, the Vela SNR, which would confirm and refine our theoretical understanding of the cosmic rays' origin, leading to a more comprehensive understanding of the universe.

研究成果の概要（英文）：Galactic cosmic rays (CR) are expected to originate from supernova remnants (SNR), but as charged particles, the magnetic fields scramble their arrival direction which thus does not reveal their sources. But very high energy (TeV-range) electron CR could only arrive at Earth from a few nearby SNR (distance < 1 kpc), since they quickly loose energy.
The ISS-based CALET detector measures the spectrum of all-electron CR up into the TeV region to find signatures of these nearby SNR, specifically the Vela SNR. The theoretical spectral shape in the TeV region was studied and compared to latest results by CALET, revealing a hint for a signature from this nearby SNR.
Towards a significant discovery, improved analysis methods for the spectral and anisotropy signatures (at close distance, the CR directional information may be not completely lost, causing an increased flux from the direction of Vela) have been developed and tested with simulations, confirming that detection is likely by 2030.

研究分野：Cosmic ray physics

キーワード：Cosmic rays　Supernova remnants　CALET

１．研究開始当初の背景

Cosmic-ray (CR) electrons of TeV energy are limited by energy loss to a propagation range of ~1 kpc, therefore the expected sources are a few nearby supernova remnants (SNR), with the Vela SNR dominating the spectrum. The CALET experiment on the ISS is measuring the $e^+ + e^-$ CR spectrum well into the TeV region. The spectrum up to 4.8 TeV as published by CALET in 2019 shows a flux reduction above 1 TeV, meaning that a spectral hardening indicating the onset of the signature peak of Vela would have to be above several TeV, with event numbers lower than assumed in earlier sensitivity studies.

２．研究の目的

This project aimed at realizing the most important goal of the CALET mission, to identify a signature of the Vela SNR. Vela is the prime candidate for a detectable nearby cosmic-ray source, but the signature depends strongly on the start time of cosmic ray release, injection duration and the propagation parameters. Direction dependent spectra have been calculated for benchmark models with parameters allowed by experimental constraints, including the background spectrum from more distant astrophysical sources and secondary particles with consistent propagation conditions. Using these benchmark models, improved analysis methods for the spectral and anisotropy signatures of nearby SNRs were developed and the sensitivity of CALET for the currently approved project duration until 2030 estimated.

３．研究の方法

(1) Theoretical Studies of Spectral and Anisotropy Signatures

To model the electron flux from astrophysical sources, combinations of three principal methods were used: (1) direct parametrization of the flux at Earth by power law functions (with breaks and exponential cut-offs as appropriate, (2) semi-analytical calculation of the propagated spectrum from the assumed source spectrum by a Green’s Function, (3) numerical calculation of the propagated spectrum with DRAGON. Method (3) is most precise in considering all aspects of the propagation and allows for calculation of the flux anisotropy, but it is only used for the nearby SNR due to the high calculation time requirement. Method (2) takes propagation into account, but not all aspects (e.g. diffusive reacceleration, spatial variation of the diffusion coefficient), while (1) ignores propagation altogether.

In studies of the nearby SNR signatures, the nearby SNR (Vela, Cygnus Loop, Monogem) contribution was calculated with (3), the pulsar contribution for explanation of the positron excess with (2), taking the source parameters from the ATNF catalog, and the contribution of distant SNR by method (1).

As the direct parametrization of the distant SNR contribution requires validation, in a separate study the data was fitted with the overlapping spectra all calculated with method (2) of randomly generated SNR and pulsars up to an age of 200 million years.

(2) Theoretical Studies of Cosmic Ray Propagation

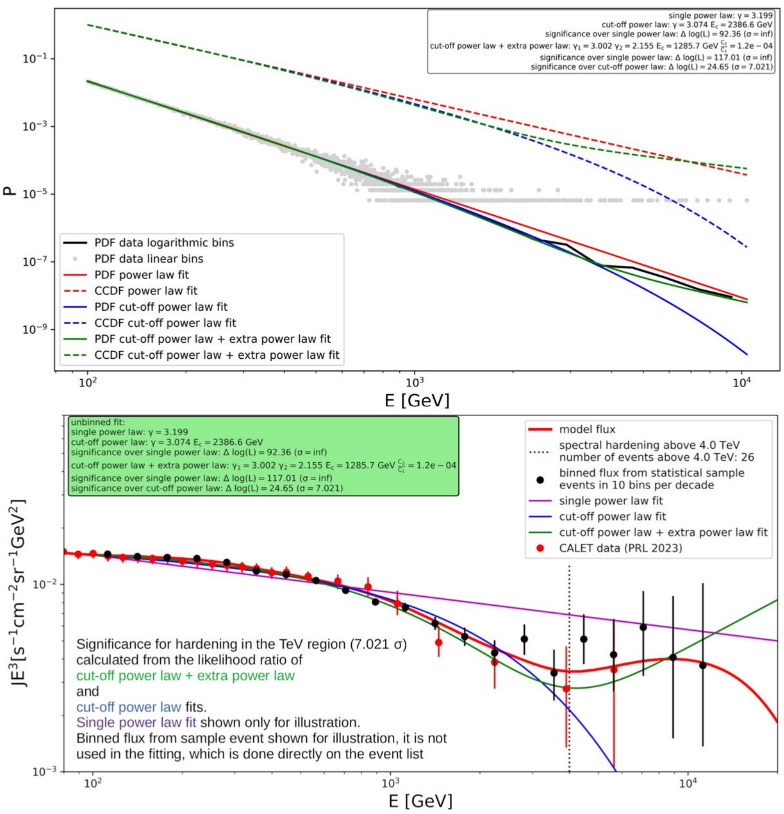
Spectral index breaks have been discovered in the cosmic-ray nuclei spectra, with slight differences in the indices and break positions between the nuclei species. Assuming these structure differences to be propagation effects caused by soft breaks in the power-law rigidity dependence of the diffusion coefficient, as well as a spatial variation of the diffusion coefficient within the galaxy, a model with a broken power law source spectrum common for all nuclei species is assumed.

Using a modified version of the numerical cosmic-ray propagation calculation code DRAGON and optimizing the model's input parameters in a random walk based on the fit quality with respect to the measured nuclei spectra, several reference propagation parameter sets were derived over the course of the project, adapting successively to new experimental results.

(3) Anisotropy Analysis Method

To enhance the sensitivity for anisotropy signature over the standard omnidirectional dipole anisotropy search, the dipole projected onto the direction towards Vela is taken as the main observable. To reduce the influence of statistical fluctuation, the dipole strength is calculated with the energy of each event in the sample successively used as lower bound, and the average dipole strength taken.

(4) Unbinned Spectral Fitting Method



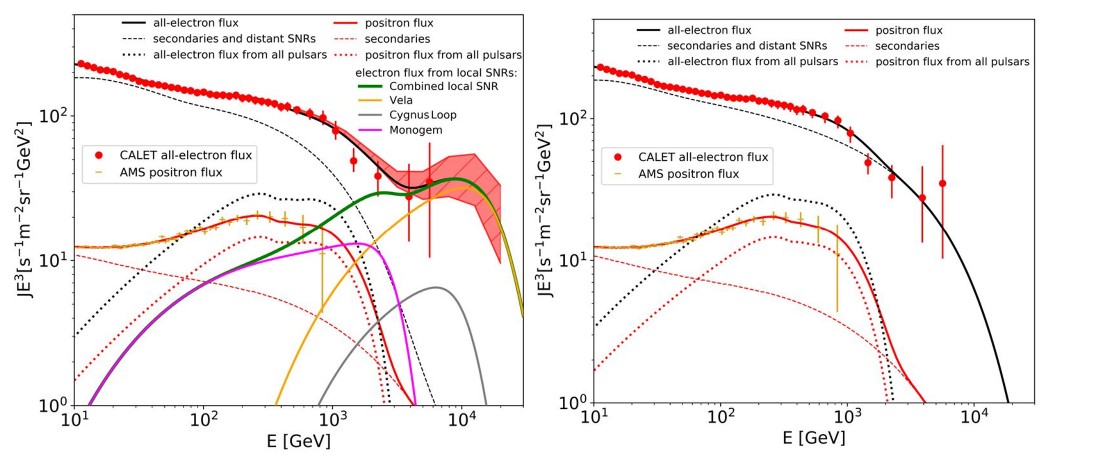
[Fig. 1] Example of using the unbinned fitting method on a simulated event sample based on the model shown in Fig. 2, with expected statistics of CALET data by 2030. Top panel: Fit of the PDF to the events. Bottom panel: Fit functions converted to back to flux using CALET's exposure function. Likelihood ratio between fit with and without extra power law for the nearby SNR yields a significance of 7σ for this sample. For the distribution of significance for several samples, see Fig. 4.

Given the low event numbers in the TeV region, much information is lost when generating a binned spectrum. Therefore, the following unbinned analysis method which works directly on the list of event energies has been developed. The parameters of the probability density function (PDF) are fitted by maximizing the likelihood $L = \prod_i PDF(E_i, params)$ where i loops over all events. To identify and quantify the contribution from the nearby SNR, a power law with exponential cut-off ($PDF_{base} = E^{-\gamma_1} e^{-(E/E_c)}$) is used as the PDF for the base model without nearby sources, while the same function with addition of another power law ($PDF_{model} = (1-a)E^{-\gamma_1} e^{-(E/E_c)} + aE^{-\gamma_2}$) represents the model with nearby source contribution. The PDF is normalized using the Complementary Cumulative Distribution Function (CCDF) which is $CCDF_{model} = (1-a)E_c^{(1-\gamma_1)} \Gamma_{inc}(1-\gamma_1, E/E_c) + a(E^{(1-\gamma_2)}/(1-\gamma_2))$
with $\Gamma_{\rm inc}$ being the incomplete gamma function. The fitting algorithms and functions were developed based on the "powerlaw" python package (Alstott J, Bullmore E, Plenz D, PLoS ONE 9(1): e85777 (2014)). The significance for the existence of the nearby source contribution is calculated from the likelihood ratio (Δlog(L)) between the fits of the model with the extra power law and the base model without extra power law.

４．研究成果

(1) Systematic study of expected spectral and anisotropy signatures from nearby SNR and comparison with CALET data

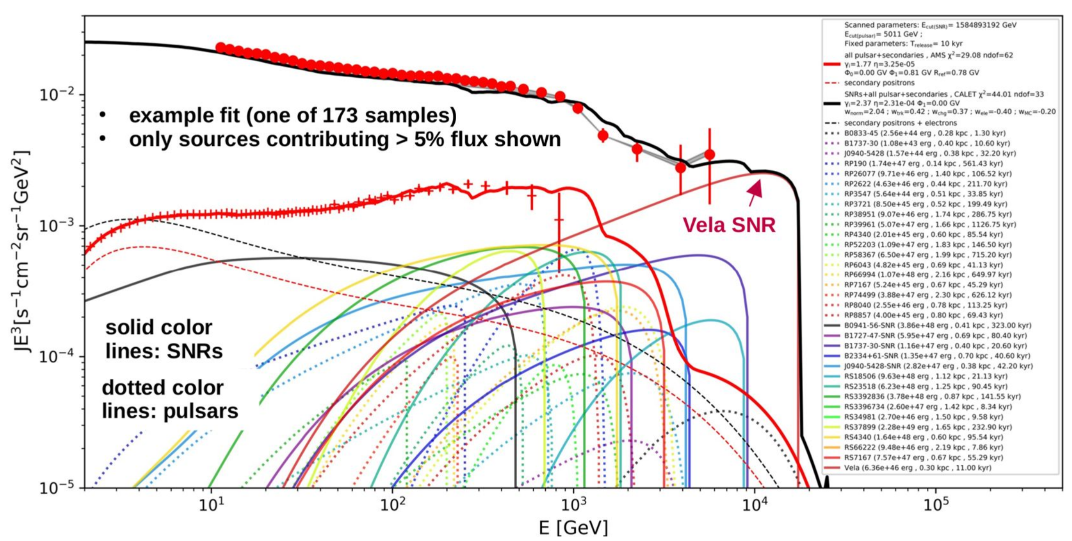
Limits and best-fit values for the total energy of electron cosmic ray emission from the nearby SNR have been calculated based on a standard binned analysis method and for generic emission scenarios (delayed instantaneous release, constant release for a duration). These results were shown at ICRC2021 and published in the proceedings. The modelling used in this study was used to illustrate in 2023 that the latest results by CALET published in Phys. Rev. Lett. 131, 191001(2023) show a hint for the existence of a signature from nearby SNR.



[Fig. 2] Left: Model fit including nearby SNR, predicting 11.0(4.2) events above 4.8(7.5) TeV matching 9(4) events from a special analysis of the highest energy electron candidates. Right Fit without near SNR predicting 4.6(1.0) events above 4.8(7.5) TeV. Better agreement with left fit published as a hint for the existence of the near SNR's contribution in Phys. Rev. Lett. 131, 191001(2023). By 2030 (double exposure compared to 2023 data) the statistical errors would be reduced to the red area in the left plot.

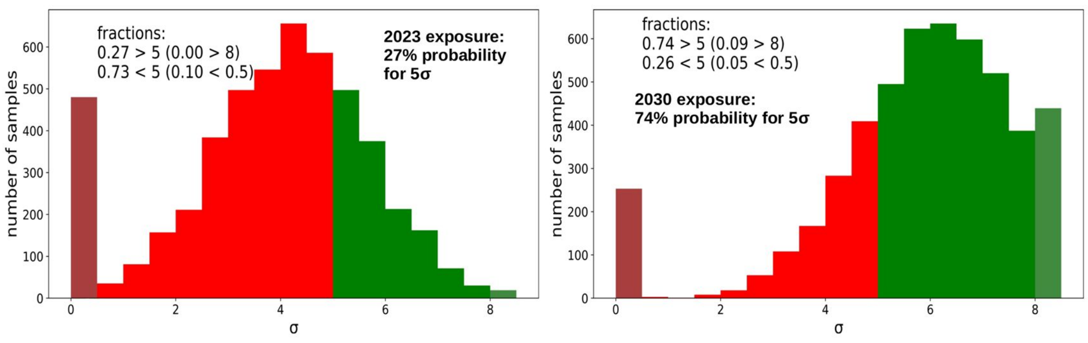
(2) Cosmic-Ray Propagation Models
As the outcome of the efforts to determine suitable propagation conditions, a model simultaneously explaining various nuclei spectra and primary-secondary ratios measurements by the CALET, AMS-02, and the CRS (Cosmic Ray Subsystem) on the Voyager space-probes was developed. These results were published in ICRC2023 proceedings.

(3) Study of Pulsar and SNR Properties based on CALET Data
Overlapping spectra from individual pulsar and SNR point sources randomly generated throughout the galaxy, together with known sources from electromagnetic wave observations, were fitted to the combination of CALET and AMS-02 data. Based on the study of many samples with randomized source locations and emission spectra parameters, best fitting ranges for these parameters have been determined. It was shown that these overlapping spectra can well fit the data with a wide range of possible values for the injection spectrum parameters of both pulsars and SNR. These results were published in ICRC2023 proceedings.



[Fig. 3] An example of fitting CALET all-electron and AMS positron data with the overlapping spectra of ~7.5 million SNR and pulsars, demonstrating that the measured mostly smooth spectrum can be composed in this way.

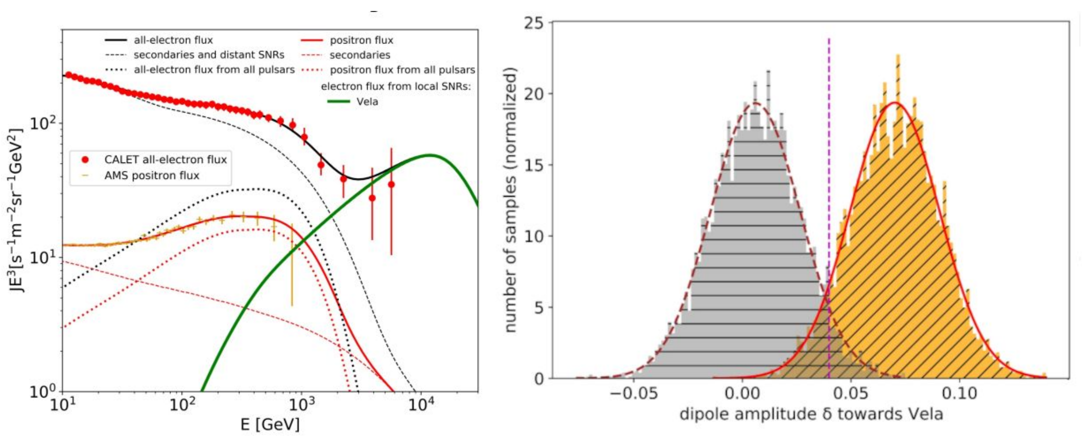
(4) Unbinned Spectral Fitting and Prediction of CALET Sensitivity



[Fig. 4] Distribution of expected significance (σ) derived from using the unbinned analysis on 5000 statistical event samples (list of event energies above 100 GeV) with exposure used in PRL2023 paper (left plot) and twice that for 2030 (right plot). The event samples were created based on the model fit shown in Fig. 2. Underflow bins contain samples where likelihood does not improve if including near SNR.

The performance of the unbinned spectral analysis method was evaluated using benchmark models from the ICRC2021 proceedings, and used to estimate CALET's sensitivity, comparing the case of 2023 statistics with those expected by 2030. It was shown that by 2030 there would be a high probability of a 5σ discovery for certain models, with strongly improved chances compared to the 2023 statistics.

(5) Anisotropy Analysis and Prediction of CALET Sensitivity



[Fig 5] For the model fit on the left (Vela only as near SNR), 5000 simulated samples (right panel) with 2030 statistics with anisotropy (orange) and without (grey) can be separated at 95% CL.

The performance of the anisotropy analysis method was tested using benchmark models from ICRC2021 proceedings, estimating the performance of CALET by 2030. For optimal conditions on the emission by Vela and propagation, it was shown that a 95% CL separation between the cases with anisotropy and without can be achieved.

(6) Dark Matter Limits with Individual Source Astrophysical Background Model

While this project focused on signatures of nearby SNR, the developed modelling of astrophysical sources was used for the background in indirect dark matter search. In a combined analysis of CALET all-electron and AMS-02 positron data, limits on the dark matter annihilation cross section and dark matter lifetime have been calculated for various annihilation/decay channels and dark matter masses over a wide range from a few GeV to several tens of TeV. The astrophysical background is modeled as samples of individual SNR and pulsar sources combining known nearby and randomly generated sources throughout the galaxy, with also randomized emission spectra parameters. This approach improves the reliability of the limits by analyzing many samples, thus taking background variability into account. Results were published in IDM2022 and ICRC2023 proceedings.

５．主な発表論文等

〔雑誌論文〕　計6件（うち査読付論文　2件／うち国際共著　6件／うちオープンアクセス　6件）

１．著者名 Holger Motz for the CALET collaboration	４．巻 444
２．論文標題 Dark Matter Limits from the CALET Electron+Positron Spectrum with Individual Astrophysical Source Background	５．発行年 2023年
３．雑誌名 Proceedings of Science, 38th International Cosmic Ray Conference	６．最初と最後の頁 1385
掲載論文のDOI（デジタルオブジェクト識別子） 10.22323/1.444.1385	査読の有無 無
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 Holger Motz for the CALET collaboration	４．巻 444
２．論文標題 Interpretation of the CALET Electron+Positron Spectrum by Astrophysical Sources	５．発行年 2023年
３．雑誌名 Proceedings of Science, 38th International Cosmic Ray Conference	６．最初と最後の頁 67
掲載論文のDOI（デジタルオブジェクト識別子） 10.22323/1.444.0067	査読の有無 無
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 Holger Motz	４．巻 444
２．論文標題 A Cosmic-Ray Propagation Model based on Measured Nuclei Spectra	５．発行年 2023年
３．雑誌名 Proceedings of Science, 38th International Cosmic Ray Conference	６．最初と最後の頁 68
掲載論文のDOI（デジタルオブジェクト識別子） 10.22323/1.444.0068	査読の有無 無
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 Yosui Akaike, Nicholas Cannady, Holger Motz, Shoji Torii, CALET collaboration	４．巻 131
２．論文標題 Direct Measurement of the Spectral Structure of Cosmic-Ray Electrons+Positrons in the TeV Region with CALET on the International Space Station	５．発行年 2023年
３．雑誌名 Physical Review Letters	６．最初と最後の頁 191001
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/physrevlett.131.191001	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	4．巻
Holger Motz	12
2．論文標題	5．発行年
Constraints on heavy dark matter annihilation and decay from electron and positron cosmic ray spectra	2023年
3．雑誌名	6．最初と最後の頁
SciPost Physics Proceedings	35
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.21468/scipostphysproc.12.035	有
オープンアクセス	国際共著
オープンアクセスとしている（また、その予定である）	該当する

1．著者名	4．巻
Holger Motz on behalf of the CALET collaboration	ICRC2021
2．論文標題	5．発行年
Investigating the Vela SNR's Emission of Electron Cosmic Rays with CALET at the International Space Station	2021年
3．雑誌名	6．最初と最後の頁
Proceedings of Science	100
掲載論文のDOI（デジタルオブジェクト識別子）	査読の有無
10.22323/1.395.0100	無
オープンアクセス	国際共著
オープンアクセスとしている（また、その予定である）	該当する

〔学会発表〕　計16件（うち招待講演　1件／うち国際学会　7件）

1．発表者名
Holger Motz for the CALET collaboration
2．発表標題
Interpretation of the CALET Electron+Positron Spectrum by Astrophysical Sources
3．学会等名
38th International Cosmic Ray Conference (ICRC2023)（国際学会）
4．発表年
2023年

1．発表者名
Holger Motz for the CALET collaboration
2．発表標題
Dark Matter Limits from the CALET Electron+Positron Spectrum with Individual Astrophysical Source Background
3．学会等名
38th International Cosmic Ray Conference (ICRC2023)（国際学会）
4．発表年
2023年

１．発表者名 Holger Motz
２．発表標題 A Cosmic-Ray Propagation Model based on Measured Nuclei Spectra
３．学会等名 38th International Cosmic Ray Conference (ICRC2023)（国際学会）
４．発表年 2023年

１．発表者名 Holger Motz
２．発表標題 Investigating the Properties of Astrophysical Cosmic-ray Sources based on the CALET Electron+Positron Spectrum
３．学会等名 JPS annual meeting 2023
４．発表年 2023年

１．発表者名 Holger Motz
２．発表標題 Model Calculations for Interpretation of CALET Results
３．学会等名 CALET 研究会@ICRR
４．発表年 2024年

１．発表者名 Holger Motz
２．発表標題 Limits on dark matter annihilation and decay from the CALET electron spectrum up to 7.5 TeV
３．学会等名 JPS spring meeting 2024
４．発表年 2024年

１．発表者名
Holger Motz

２．発表標題
Constraints on Heavy Dark Matter Annihilation and Decay from Electron and Positron Cosmic Ray Spectra

３．学会等名
14th International Conference on Identification of Dark Matter (IDM2022)（国際学会）

４．発表年
2022年

１．発表者名
Holger Motz

２．発表標題
Constraining the Dark Matter Parameter Space with Cosmic Ray Data from Space-based Detectors

３．学会等名
DM3 - Deep insights and Multiple strategies for Deciphering the Mystery of Dark Matter（招待講演）（国際学会）

４．発表年
2022年

１．発表者名
Holger Motz

２．発表標題
A Model for Propagation of Cosmic Rays from Nuclei Spectra Measurements

３．学会等名
The Physical Society of Japan 2022 Autumn Meeting

４．発表年
2022年

１．発表者名
Holger Motz

２．発表標題
Individual Astrophysical Sources as Background for Dark Matter Search with CALET

３．学会等名
The Physical Society of Japan 2023 Annual Meeting

４．発表年
2023年

１．発表者名
Holger Motz

２．発表標題
Search for TeV-Range Dark Matter with Electron and Positron Cosmic Rays

３．学会等名
FY2022 学術変革領域研究「ダークマター」シンポジウム

４．発表年
2023年

１．発表者名
Holger Motz on behalf of the CALET collaboration

２．発表標題
Investigating the Vela SNR's Emission of Electron Cosmic Rays with CALET at the International Space Station

３．学会等名
37th International Cosmic Ray Conference (ICRC 2021)（国際学会）

４．発表年
2021年

１．発表者名
Holger Motz for the CALET Collaboration

２．発表標題
Search for Signatures of Nearby Supernova Remnants with CALET

３．学会等名
The Physical Society of Japan 2021 Autumn Meeting

４．発表年
2021年

１．発表者名
Holger Motz

２．発表標題
Extending Dark Matter Limits from Electron and Positron Cosmic Rays to the TeV-region

３．学会等名
Kashiwa Dark Matter Symposium（国際学会）

４．発表年
2021年

１．発表者名 Holger Motz
２．発表標題 Indirect Search for Heavy Dark Matter with CALET
３．学会等名 The Physical Society of Japan 2022 Annual Meeting
４．発表年 2022年

１．発表者名 Holger Motz
２．発表標題 Search for TeV-Range Dark Matter with Electron and Positron Cosmic Rays
３．学会等名 FY2021 学術変革領域研究「ダークマター」シンポジウム
４．発表年 2022年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

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