

Multimessenger constraints on the dark matter interpretation of the *Fermi*-LAT Galactic center excess

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An excess of γ rays in the data measured by the *Fermi* Large Area Telescope in the direction of the Galactic center (GCE) has been reported in several publications. The characteristics of the GCE, recently measured with unprecedented precision, are all compatible with dark matter particles (DM) annihilating in the main halo of our Galaxy. We investigate the DM candidates that fit the observed GCE spectrum assuming a simple scenario with DM annihilating into a single channel but we inspect also more complicated models with two and three channels. We perform a search for a γ -ray flux from a list of 48 Milky Way dwarf spheroidal galaxies (dSphs) and since we do not find any significant signal from the dSphs, we put upper limits on the annihilation cross section that result to be compatible with the DM candidate that fits the GCE. However, we find that the GCE DM signal is excluded at the 95% confidence level by the AMS-02 \bar{p} flux data for all purely hadronic (semi-hadronic) channels unless the diffusive halo size L is smaller than 1.7 kpc (2.6 kpc). Such a small diffusion halo is at the 2σ significance lower limit for the results inferred from fluxes of radioactive cosmic rays and radio and γ -ray data. Furthermore, AMS-02 e^+ data rule out the GCE DM interpretation with pure or partial annihilation into e^+e^- . The only DM candidate that fits the GCE spectrum and fulfills all constraints obtained with the combined dSphs analysis and the AMS-02 \bar{p} and e^+ data annihilates purely (or very dominantly) into $\mu^+\mu^-$, has a mass of ~ 60 GeV and roughly a thermal cross section.

*37th International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany*

*Presenter

1. Introduction

Several groups have discovered an excess in the γ -ray data collected by the *Fermi* Large Area Telescope (*Fermi*-LAT) in the direction of the Galactic center (see, e.g., [1]). This signal, called the Galactic center excess (GCE), has been detected using different background models. The origin of the GCE is still a mystery. Ref. [1] has recently provided the most precise results for the GCE properties yet. The characteristics of the GCE published in Ref. [1] make γ rays from DM particle interactions a viable interpretation. In fact DM is predicted to be distributed in the Milky Way as a spherically symmetric halo with its centroid located in the dynamical center of the Galaxy. Moreover, the signal morphology is expected to be energy independent, i.e. the value of the NFW slope (γ) found to fit the GCE morphology data should not vary with energy. All these characteristics make the GCE very appealing for the DM interpretation. If DM is the origin of the GCE, γ rays should be emitted from these elusive particles also in Milky Way dwarf spheroidal galaxies (dSphs). dSphs are among the most promising targets for the indirect search of DM with γ rays because gravitational observations indicate that they have a high DM density, i.e. a large mass-to-luminosity ratio of the order of 100 – 1000 . The indirect search of DM is performed also with CR antiparticles, such as positrons (e^+) and antiprotons (\bar{p}), which are among the rarest cosmic particles in the Galaxy. e^+ and \bar{p} fluxes have been precisely measured by the AMS-02 experiment on the International Space Station up to almost 1 TeV. In this paper we investigate the DM interpretation of the GCE with a combined analysis of the targets that are the most promising for the search in γ rays, i.e. the Galactic center and dSphs, and using the flux data of AMS-02 for positrons and antiprotons which are among the rarest CRs. It is the first time ever that such an analysis for DM is performed at the same time in different astrophysical targets and cosmic particles and with a consistent model for the DM density distribution and coupling parameters.

1.1 Dark matter density

One of the main ingredients to calculate γ -ray fluxes from DM is its density distribution in the Galaxy that enters through the geometrical factor $\tilde{\mathcal{J}}$. We use the surface brightness data of the GCE reported in Ref. [1] and the recent results from the rotation curve of the Milky Way from Ref. [6] to estimate the values of the DM density parameters. We employ the results obtained in this section for the estimation of $\tilde{\mathcal{J}}$ for γ rays but also for the calculation of the \bar{p} and e^+ production from DM. We test the three DM density profiles: gNFW, Einasto and Burkert. We report in [7] the best-fit values for ρ_s and r_s that we find applying this technique to the three DM density models used in the paper. Since we assume three DM density profiles and we consider three possible choices of the quantities ρ_\odot and M_{200} , we end up with nine possible scenarios for the parametrization of ρ . We can thus choose three of the nine cases as representative of the variation of $\tilde{\mathcal{J}}$ due to the modeling of the DM density, and in particular in its local density and functional form. These are the cases gNFW with $\gamma = 1.2$ and $\rho_\odot = 0.300 \text{ GeV/cm}^3$, labeled as MIN, $\gamma = 1.3$ and $\rho_\odot = 0.345 \text{ GeV/cm}^3$, named as MED, and Einasto with $\rho_\odot = 0.390 \text{ GeV/cm}^3$ with MAX. The value of the geometrical factor varies by a factor of 6.2 between the MIN and the MAX models.

Channel	M_{DM} [GeV]	$\langle\sigma v\rangle$ [$\times 10^{-26}$ cm ³ /s]	$\chi^2(\tilde{\chi}^2)$
e^+e^-	30^{+4}_{-4}	$1.13^{+0.21}_{-0.12}$	161.61 (5.39)
$\mu^+\mu^-$	58^{+11}_{-9}	$3.9^{+0.5}_{-0.6}$	164.12 (5.47)
$\tau^+\tau^-$	$7.2^{+1.9}_{-1.2}$	$0.43^{+0.15}_{-0.10}$	1178.40 (39.3)
$q\bar{q}$	21^{+4}_{-4}	$0.77^{+0.19}_{-0.12}$	208.89 (6.96)
$c\bar{c}$	20^{+3}_{-5}	$0.70^{+0.16}_{-0.11}$	214.11 (7.14)
$b\bar{b}$	42^{+6}_{-7}	$1.41^{+0.35}_{-0.18}$	176.47 (5.88)
gg	19^{+3}_{-4}	$0.70^{+0.16}_{-0.11}$	214.14 (7.14)

Table 1: This table reports the best-fit for the DM parameters M_{DM} and $\langle\sigma v\rangle$ derived by fitting the GCE data obtained in Ref. [1] with different IEMs. The errors on M_{DM} and $\langle\sigma v\rangle$ represent the variation of the best-fit values due to the systematic on the IEMs. We also display the value of the χ^2 ($\tilde{\chi}^2$).

1.2 Fitting the Galactic center excess SED

In this section we fit the GCE SED measured in Ref. [1] in order to find the best-fit DM mass and annihilation cross section. First we assume the simplest scenario with DM particles annihilating into a single channel (i.e. $Br = 1$). We consider the following channels: leptonic (e^+e^- , $\mu^+\mu^-$, $\tau^+\tau^-$), quarks $q\bar{q}$ ($q = u, d, s$ denotes a light quark), $c\bar{c}$, $b\bar{b}$ and gluon Gauge bosons gg . All the results and χ^2 values are found by fitting the GCE data obtained in Ref. [1] with the Baseline IEM. In Tab. 1 we show the results for the best fit of M_{DM} and $\langle\sigma v\rangle$. The errors represent the variation of the DM parameters derived by fitting the GCE SED data obtained with the different IEMs in Ref. [1]. The annihilation channels that provide the best match with the data, with increasing values of the chi-square (χ^2), are: e^+e^- , $\mu^+\mu^-$, $b\bar{b}$, $q\bar{q}$, $c\bar{c}$, $g\bar{g}$ and $\tau^+\tau^-$. The reduced chi-square $\tilde{\chi}^2 = \chi^2/d.o.f.$ obtained for the quarks channels $b\bar{b}$, $c\bar{c}$, $q\bar{q}$ is between 6 and 7 while for the e^+e^- and $\mu^+\mu^-$ ones is about 5.4. The channel $\tau^+\tau^-$, instead, provides a much poorer fit with $\tilde{\chi}^2 = 39.3$. Therefore, this latter channel alone is not able to explain sufficiently well the GCE SED.

We also investigate a more complicated scenario where DM particles annihilate into two or three annihilation channels. In order to account for these cases we use a branching ratio Br that multiplies the annihilation cross section of the first channel while the second channel is multiplied by $1 - Br$. In [7] we report all the best-fit values for the DM parameters M_{DM} , $\langle\sigma v\rangle$ and Br found by fitting the GCE flux data obtained with the Baseline IEM. The DM candidates that provide the largest improvement in the goodness of fit with respect to the single channel are $\mu^+\mu^- - b\bar{b}$ and $\tau^+\tau^- - b\bar{b}$ with $\Delta\chi^2$ of 74 and 82, respectively. These values of $\Delta\chi^2$ are associated with the additional parameter Br and they imply 8.4 and 9.0 σ significance for the two channels with respect to the single one. The DM parameters required to fit the GCE flux data are $M_{\text{DM}} \sim 50$ (35) GeV, $\langle\sigma v\rangle \sim 3 \times 10^{-26}$ (1.4×10^{-26}) cm³/s and $Br \sim 0.7$ (0.2) for the $\mu^+\mu^- - b\bar{b}$ ($\tau^+\tau^- - b\bar{b}$) DM candidate. Other cases provide a significant improvements such as $c\bar{c} - b\bar{b}$, $e^+e^- - b\bar{b}$ and $e^+e^- - c\bar{c}$ at the 7.7, 5.5 σ level. In Fig. 1 we show the best fit we obtain for $\mu^+\mu^- - b\bar{b}$, $\tau^+\tau^- - b\bar{b}$ and $c\bar{c} - b\bar{b}$. In particular we see that the two channels provide a better fit to the GCE flux data because the total contribution of γ -ray from DM cover also the energies between 10-30 GeV where the single channel was not able to contribute significantly.

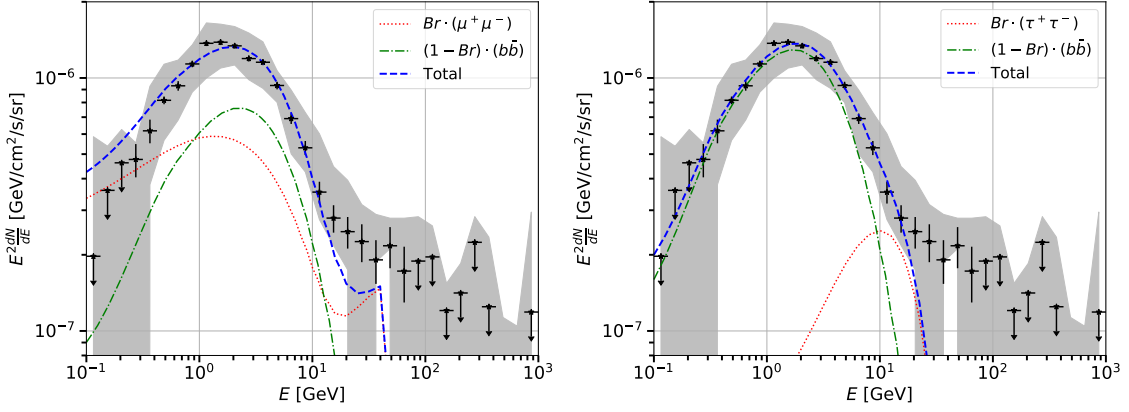


Figure 1: Flux of γ rays from DM particle annihilating into two channels. We show the contribution of both channels and the total flux compared to the GCE flux data.

2. Dwarf Spheroidal galaxies constraints on the Galactic center excess

In this section we investigate whether the DM candidates that explain GCE would generate a detectable signal in the analysis of data from dSphs. We consider for this scope the list of 48 dSphs published in [8] and the best-fit values and errors for the geometrical factors reported in Tab. 1 and A2. All the details of the data selected and analysis technique are reported in [7]. Among the dSphs selected the one detected with the highest TS is Reticulum II with a mass of 300 (40) GeV, $\langle\sigma v\rangle = 1.5 \times 10^{-26}$ (9×10^{-27}) cm^3/s for the $b\bar{b}$ ($\tau^+\tau^-$) annihilation channel and detected with a $TS \sim 10$, which corresponds to a p-value of 2.2×10^{-3} (4.4×10^{-3}) local, i.e. pre-trials, significance of $\sim 2.8\sigma$ (2.6σ). Since the signal detected from each individual dSph and for the stacked sample does not seem to be significant, we calculate upper limits for the annihilation cross section. We display them in Fig. 2 for different annihilation channels. The 95% CL upper limits are below the thermal cross section up to roughly 100 GeV for both channels. If DM is responsible for the GCE, an interesting question arises about its compatibility with the non detection of a signal from dSphs. In order to answer this question, we compare the coupling parameters of the DM candidates that explain the GCE with the limits found from dSphs. We take the values of the masses, annihilation cross sections and branching ratio the fit to the GCE flux. The GCE DM candidate obtained with the $\mu^+\mu^-$ is below the limits, even in the 68% CL level case, which is the strongest. For all these channels the properties of the DM candidate that explains the GCE in the MED DM model is roughly at the 95% CL upper limits of the dSphs limits. This implies a tension at about 2σ significance. However, considering the variation in $\langle\sigma v\rangle$ obtained by considering the MIN and MAX models, the GCE interpretation of DM is compatible with the 68% CL upper limits of the dSphs, that implies there is no tension.

3. Constraints on dark matter using AMS-02 \bar{p} data

Messengers that have provided tight constraints on DM in the past are \bar{p} CRs. It is thus very interesting to investigate the compatibility of the DM interpretation of the GCE with the newest \bar{p} flux data collected in 7 years of mission by AMS-02 [9]. This is particularly true since a tentative

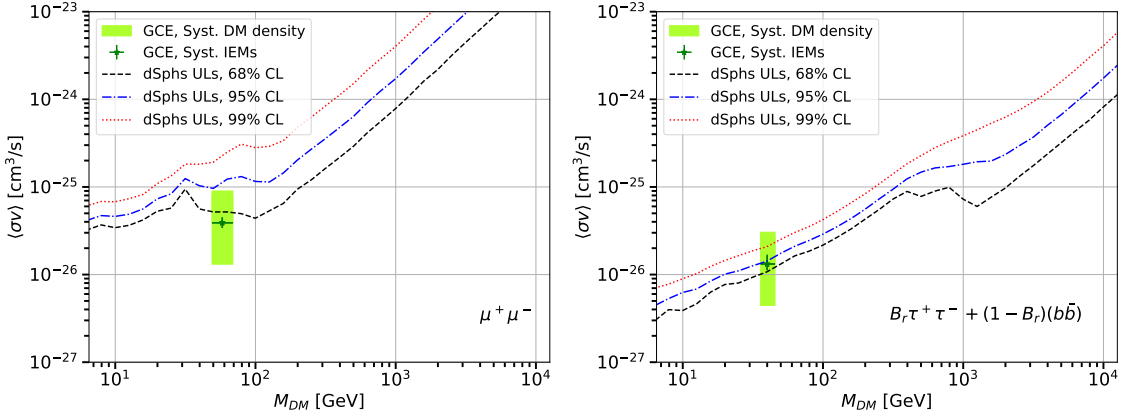


Figure 2: Comparison between the 95% (red dotted), 90% (blue dot-dashed) and 68% (black dashed) CL upper limits for $\langle\sigma v\rangle$ obtained from the analysis of the dSphs in Ref. [8] and the DM candidate that fit the GCE flux data obtained in with different IEMs (green data point). We also display with a green band the variation in $\langle\sigma v\rangle$ due to the modeling of the DM density in the inner part of the Galaxy (see Tab. ??). We display DM annihilating into $\mu^+\mu^-$, $\tau^+\tau^- - b\bar{b}$ channels.

DM signal has previously been found in the AMS-02 \bar{p} data [10] which was argued to be compatible with the GCE. We will perform our \bar{p} analysis mostly following the approach described in [11]. First, we perform a fit to the AMS-02 \bar{p} , B/C data and the antiproton flux ratio between AMS-02 and PAMELA without assuming any DM contribution. The goodness of fit is $\chi^2 = 173$ on 143 data points with 6 free parameters of the model. Therefore, the result for the reduced χ^2 is 1.26 which indicates that the AMS-02 data are consistent with pure secondary production within $\sim 2\sigma$. We report the best-fit propagation parameters in Tab. 2. One striking observation is, however, that the residuals between the best-fit model and the newest AMS-02 \bar{p} flux data in the range $\mathcal{R} = 10 - 20$ GV are practically flat.

In the next step, we add a DM contribution with free normalization $\langle\sigma v\rangle$ and mass $M_{DM} = 7 - 10000$ GeV, where we allow the propagation, solar modulation and cross section normalization parameters to float. As final states of the DM annihilation $b\bar{b}$ and $c\bar{c}$ are considered. Our fits confirm that the previously found \bar{p} excess [10] is completely gone in the new AMS-02 data. There is no longer any preference for a DM contribution within the range $M_{DM} = 30 - 100$ GeV. We, therefore, derived the 95% CL upper limits on the DM annihilation cross section within the mass range $M_{DM} = 7 - 10000$ GeV for values of $L = 1.5 - 5$ kpc and for the MIN, MED, MAX DM profiles. In order to include also the systematics on the branching ratio obtained by fitting the GCE with different IEMs, we define the partial hadronic annihilation cross section $\langle\sigma v\rangle_{b\bar{b}} = \langle\sigma v\rangle \cdot (1 - Br)$ (or analogously $\langle\sigma v\rangle_{c\bar{c}}$). For the semi-hadronic channels we determined the range of $\langle\sigma v\rangle_{b\bar{b}}$ or $\langle\sigma v\rangle_{c\bar{c}}$ within all IEMs, i.e. including the uncertainty on $\langle\sigma v\rangle$ and on Br simultaneously. We then compare the preferred range found from the GCE analysis with the upper limits found with antiproton data. Results for the channels with partial annihilation into $b\bar{b}$ are presented for different choices of L in Fig. 3. We find that, even picking the lowest partial hadronic cross section among the IEMs, a very small L is still required to reconcile the GCE candidates with antiproton constraints. Specifically, for the $e^+e^- - b\bar{b}$, $\mu^+\mu^- - b\bar{b}$, $\tau^+\tau^- - b\bar{b}$, $e^+e^- - c\bar{c}$ channels $L \leq 2.4, 2.6, 1.8$ kpc is required, respectively. For the channel $e^+e^- - c\bar{c}$ we find that in the case of two IEMs we can fit

K_0 [kpc ² /Myr]	δ	η	V_a [km/s]
0.042	0.459	-1.49	52.0

Table 2: Best-fit propagation parameters for $L = 4$ kpc from the combined fit to \bar{p} and B/C data (assuming pure secondary production of antiprotons). The best fit propagation parameters for different choices of L are obtained by rescaling K_0 with $L/4$ kpc and V_a by $\sqrt{L/4}$ kpc.

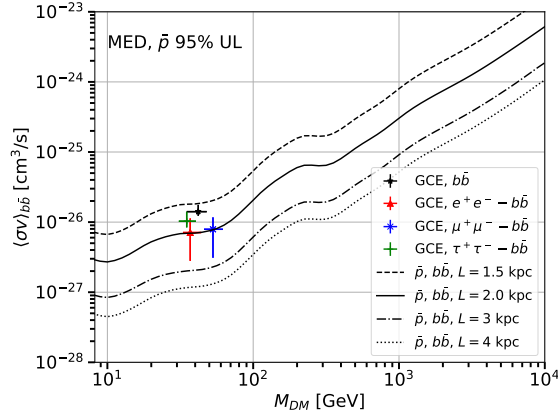


Figure 3: Best-fit values for the DM parameters M_{DM} and $\langle\sigma v\rangle$ that we find by fitting the GCE SED. We use the cross section into $b\bar{b}$ for both the single and double channels. For the latter cases we calculate the data points as $\langle\sigma v\rangle \cdot (1 - B_r)$ taking into account the errors on both $\langle\sigma v\rangle$ and $(1 - B_r)$. We also report the 95% CL upper limits we obtain from \bar{p} flux data using the $b\bar{b}$ channel. We assume the MED DM density model and $L = 1.5, 2.0, 3, 4$ kpc (black dashed, solid, dot-dashed and dotted lines).

the GCE with a $Br(c\bar{c}) = 0$, i.e. only the contribution of the e^+e^- channel is required. Considering the GCE SED obtained with all the other IEMs we have a signal compatible with \bar{p} upper limits if $L \leq 1.9$ kpc. As we will see in the next section the DM signal produced with the $e^+e^- - c\bar{c}$ channel is tightly constrained by the e^+ AMS-02 data.

4. Constraints on dark matter using e^+ data

CR e^+ measured by AMS-02 have been used in the past to put severe constraints on the leptonic annihilation channels of DM [12, 13]. We decide to make two simplistic assumptions to derive upper limits on the DM annihilation cross section with AMS-02 e^+ data [9]. In the *conservative approach* we assume that the astrophysical e^+ background is only given by the secondary production, i.e. there is no PWN contribution. Then, we add the DM flux of e^+ and we use a χ^2 calculation that penalizes models that overshoot the AMS-02 data points. Specifically, if the flux from the secondary production and DM is below the AMS-02 data the χ^2 remains unchanged, instead if it is above the data it is incremented by the typical factor $(\text{model} - \text{data})^2 / (\text{data error})^2$. The *optimistic approach* involves the usage of a smooth analytic function that is able to fit the AMS-02 data. Then, we add the DM contribution and find as 95% CL upper limit the value of $\langle\sigma v\rangle$ that worsens the χ^2 from the best fit by 2.71. In calculating the best-fit with DM the free parameters of the analytic functions are left free to float. This approach is thus similar to the one used by Ref. [12]. We use

a background model that is given by the superposition of a LogParabola and a power-law with an exponential cutoff. This function fits very well the data above 1 GeV, in fact the reduced χ^2 is $\tilde{\chi}^2 = 0.62$.

The constraints obtained with the *conservative approach* are compatible with the GCE best fit for all tested cases. As expected the DM annihilation channel with the strongest $\langle\sigma v\rangle$ upper limit is the e^+e^- one. Instead, the results for the *optimistic approach* are compatible with the GCE best fit for most single and mixed channels except for the ones with full or partial annihilation into e^+e^- . In fact, the GCE candidates annihilating into e^+e^- , $e^+e^- - b\bar{b}$ or $e^+e^- - c\bar{c}$ have a cross section one order of magnitude higher than allowed by the *optimistic e^+* limits. These conclusions do not change if we employ a lower value of the vertical size of the diffusion halo $L = 1.5$ kpc. Moreover, these leptonic channels are not compatible with the upper limits obtained with e^+ data even considering the uncertainties on the branching ratio that can vary for the $e^+e^- - c\bar{c}$ channel from the average of 0.73 to the lowest value obtained among all the IEMs of 0.42. Moreover, the pure channel e^+e^- has uncertainties on the cross section of only about 20% (see Tab. 1) which is insufficient to reconcile it with the upper limits.

5. Conclusions

To conclude DM particles annihilating into $\mu^+\mu^-$ with a mass of about 60 GeV and a cross section of 4×10^{-26} cm³/s, which is close to the thermal one, could fit the GCE spectrum. At the same time they are compatible with observations of dwarf spheroidal galaxies and would produce a flux of \bar{p} and e^+ compatible with the upper limits calculated with the latest AMS-02 data. All other DM annihilation channels we investigated for the GCE are in some tension with CR data once we include the latest constraints on the size of the CR diffusion zone. In particular, the two-channel final state $\mu^+\mu^- - b\bar{b}$ ($\tau^+\tau^- - b\bar{b}$) with $M_{\text{DM}} \sim 50$ (35), $\langle\sigma v\rangle \sim 3 \times 10^{-26}$ ($\sim 1.4 \times 10^{-26}$) cm³/s and $Br \sim 0.7$ (0.2) would improve the fit to the GCE spectrum, with respect to the $\mu^+\mu^-$ channel, but is compatible with the \bar{p} upper limits only for an unfavorably small diffusion zone of $L \leq 2.6$ (1.8) kpc.

Acknowledgments

MDM research is supported by Fellini - Fellowship for Innovation at INFN, funded by the European Union's Horizon 2020 research programme under the Marie Skłodowska-Curie Cofund Action, grant agreement no. 754496. MWW acknowledges support by the Swedish Research Council (Contract No. 638-2013-8993) and by the Department of Physics of the University of Texas at Austin. MDM acknowledges support by the NASA Fermi Guest Investigator Program Cycle 12 through the Fermi Program N. 121119 (P.I. MDM). The authors thank Regina Caputo, Judith L. Racusin, Miguel A. Sanchez-Conde, Michael Gustafsson for providing us comments on the paper.

The *Fermi* LAT Collaboration acknowledges generous ongoing support from a number of agencies and institutes that have supported both the development and the operation of the LAT as well as scientific data analysis. These include the National Aeronautics and Space Administration and the Department of Energy in the United States, the Commissariat à l'Énergie Atomique and the Centre National de la Recherche Scientifique / Institut National de Physique Nucléaire et de Physique des Particules in France, the Agenzia Spaziale Italiana and the Istituto Nazionale di Fisica Nucleare in Italy, the Ministry of Education, Culture, Sports, Science and Technology (MEXT), High Energy Accelerator Research Organization (KEK) and Japan Aerospace Exploration Agency (JAXA) in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the Swedish National Space Board in Sweden. Additional support for science analysis during the operations phase is gratefully acknowledged from the Istituto Nazionale di Astrofisica in Italy and the Centre National d'Études Spatiales in France. This work performed in part under DOE Contract DE-AC02-76SF00515.

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